Some nice facts and numbers.

Saturday, July 21, 2012 6:51 PM

Comparing scale of atoms to the Solar system (from: Odyssey in zepto space.).

Solar system until Neptune.

Diameters:	Sun : Till Neptune = 1 : 6000
Masses:	Sun : ∑ all planets = 700 : 1

He atom.

Diameters:	Nucleus : Electron shell = 1 : 20000
Masses:	Nucleus : ∑ all electrons = 4000 : 1

What do these numbers teach us?

- The atom is much more 'empty' than the solar system.
- The atom's nucleus is much more 'massive' than the solar system's nucleus, the sun, when comparing to their resp. 'planets'.

Conclusion:
Yes, in a sense, we might compare an atom to the solar system but there are significant differences!

But this puts forward a new question: Why? ... Answer: See the relative magnitudes of the implied forces from the SM!

When does Helium become solid? (info from: WikiPedia).

This was the question a pupil of around 17-18 years asked during the visit of the Keizer Karel College (NL) on Mai 9th, 2012 when I explained the state of 'Super fluidity' of He II as being a 'sort of 4th aggregation state' next to the 3 normal ones of gaseous, fluid and solid and which occurs slightly above the LHC dipole's operation temperature of 1.9K (i.e. under the λ transition point of 2.17K; He I → He II).

As we are at 1.9K so close to absolute zero, that was quite a reasonable question but I had never asked it myself and did not know the answer.

It appears that He under normal circumstances theoretically never gets solid, even at 0K. However if fluid He of 1-1.5K is compressed with more than 25bar it undergoes a state change, and a sort of crystalline atomic structure appears that can be considered as a 'solid'.
In that state He remains however rather flexible, behaving a bit like the gel filling that can be found in e.g. bicycle saddles.

Properties of liquid helium	Helium-4	Helium-3
Critical temperature	5.2 K	3.3 K
Boiling point at one atmosphere	4.2 K	3.2 K
Minimum melting pressure	25 atm	29 atm at 0.3 K
Superfluid transition temperature at saturated vapor pressure	2.17 K	one millikelvin in a zero magnetic field

Pasted from <http://en.wikipedia.org/wiki/Liquid_helium>

Also see: http://en.wikipedia.org/wiki/Helium#Solid_and_liquid_phases

Some nice facts and numbers. - (suite 1).

Some order of sizes of matter particles (from: LHC guide and WikiPedia).

Size of an atom:	10^{-10}m
Size of the atom's nucleus:	10^{-14}m
Size of a proton or neutron:	10^{-15}m
Size of quarks:	$<10^{-19}$m

Relative strength, long distance behavior and range of the gauge bosons (via: http://en.wikipedia.org/wiki/Standard_Model).

PROPERTIES OF THE INTERACTIONS

Property / Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Extracted and pasted from: http://www.pha.jhu.edu/~dfehling/particle.gif

distance: 10^{-18}M	1	8.10^{40}	10^{41}	25.10^{41}	-
distance: 30.10^{-18}M	1	10^{37}	10^{41}	60.10^{41}	-
distance: $\sim10^{-15}$M	1	10^{29}	10^{36}	-	20.10^{36}

Relative strength of the gauge bosons on the scale size of quarks (from: http://www.cpepphysics.org/images/2014-fund-chart.jpg)

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Remark about the relative strength between the four fundamental forces.
The two tables above show significant differences in these relative strengths. This is due to the fact that the forces behave so differently with the distance. Gravitational and Electromagnetic forces follow the inverse square law behavior while Weak and Strong nuclear forces are only available within the nucleus or even within proton/neutron on the level of quarks. Within the limitation of the respective range, the Strong force becomes stronger when distance increases and the Weak force vanishes very rapidly . This makes comparison awkward; we should specify on which scale we speak.

Some nice facts and numbers. - (suite 2).

Number of protons accelerated by CERN during its lifetime (reasonable estimate).

Considering:
1 mol of hydrogen contains $6.022E^{23}$ atoms (Avogadro's number) and weighs 1gram.
Linac2 today accelerates maximally approx. $5.0E^{15}$ protons to 50MeV every 1.2sec, note that this was of course much less in the past!

Assuming 24 / 24 hour service, Linac2 provides for every 24hours:
(24 * 3600) [sec] / 1.2 [sec] = 72000 ejections into the PS Booster
and therefore: $5.0E^{15}$ * $7.2E^{4}$ = $3.6E^{20}$ protons / day.

Assuming furthermore that CERN operates its accelerators 9 months out of 12 per year (3 months shutdown in winter for general maintenance), we arrive at:
($3.6E^{20}$ / $6.022E^{23}$) * 1 [gram] * (9 / 12) * 365 * 60 [years of existence] = *9.8 gram of hydrogen* in total accelerated...

How much time would it take for CERN's Anti-proton Decelerator to produce 1 gram of anti-hydrogen? (reasonable estimate; compare with Dan Brown's Angels and Demons).

Considering:
1 mol of anti-hydrogen contains $6.022E^{23}$ atoms (Avogadro's number) and weighs 1gram.
AD today decelerates maximally approx. $3.5E^{7}$ anti-protons from 3.57GeV/c to 100MeV/c every 60sec.

Assuming 24 / 24 hour service, AD provides for every 24hours:
(24 * 3600) [sec] / 60 [sec] = 1440 ejections of decelerated anti-protons
and therefore: $3.5E^{7}$ * $1.44E^{3}$ = $5.04E^{10}$ anti-protons / day.

Assuming furthermore that CERN operates its accelerators 9 months out of 12 per year (3 months shutdown in winter for general maintenance), we arrive at:
($6.022E^{23}$ / $5.04E^{10}$ [days/gram]) / ((9 / 12) * 365 [days / year of operation]) = *$43.647E^{9}$ years of operation for 1 gram of anti-hydrogen* to be produced...

Note: The age of the Universe is estimated at *$13.8E^{9}$ years*

And how much energy would then be liberated when 1 gram of anti-hydrogen annihilates with 1 gram of regular hydrogen?

Considering:
1 mol of hydrogen (or anti-hydrogen) contains $6.022E^{23}$ atoms (Avogadro's number) and weighs 1gram.
1 proton (or anti-proton) has a rest mass of 938.27231 MeV/c^2 or $1.672614E^{-27}$ kg in the SI units system.
1 electron (or positron) has a rest mass of 0.5109906 MeV/c^2 or $9.109558E^{-31}$ kg in the SI units system.
Equivalences in the SI units system: $1.602176565E^{-19}$ joule = 1 eV and: 1 kgm^2/s^2 = 1 joule.

Annihilation of 1 atom anti-hydrogen with 1 atom hydrogen (in total: p, pbar, e^-, e^+) would liberate:
E = m * c^2 =
(2 [p, pbar, e^-, e^+] * ($938.27231E^{6}$ + $0.5109906E^{6}$) [eV/c^2]) * (1 [c])^2 = $1.8775666E^{9}$ [eV]
$1.8775666E^{9}$ [eV] * $1.602176565E^{-19}$ [joule/eV] = $3.0081946E^{-10}$ [J]
Or, directly in SI units:
(2 [p, pbar, e^-, e^+] * ($1.672614E^{-27}$ + $9.109558E^{-31}$) [kg]) * ($299.792458E^{6}$ [m/s])^2 = $3.0081946E^{-10}$ [J]

Annihilation of $6.022E^{23}$ atoms (1 mol) of each would then yield: ($3.0081946E^{-10}$ [J] * $6.022E^{23}$) = *$1.8115760E^{14}$ [J].*

Equivalent to approx. 0.1% of the daily liberated kinetical energy of a hurrcane with average winds of 40m/sec on a scale of radius of 60km.
(From:: http://www.aoml.noaa.gov/hrd/tcfaq/D7.html)

Active experiments at CERN.

Apart from the 4 well known experiments at LHC, CERN's accelerators currently provide particle beams for a total some 60 other active experiments. All experiments are payed for, conceived, built and operated by collaborations of institutions with a few (less than 10 people) up till some thousands of physicist and engineers (for the LHC experiments). The infra structure for the experiments (accelerated protons e.g.) are taken care of by CERN; one could consider the experiments themselves therefore to be 'not really CERN'...

Some nice facts and numbers. - (suite 3).

Interesting remark resulting from Einstein's formula $E = m.c^2$ and relativity.

If a particle has an amount of kinetical energy, E_k, that is equal to its rest mass energy, $E_0 = m_0 . c^2$, then it has a speed of movement equal to 0.866 times the speed of light in vacuum.

The Lorentz gamma factor (γ), used in many calculations involving relativity, is in that case exactly equal to 2.

Conclusion from: http://hyperphysics.phy-astr.gsu.edu/hbase/Relativ/releng.html

There are twenty prefixes officially specified by SI.

Metric prefixes

Prefix	Symbol	1000^m	10^n	Decimal	Short scale	Long scale	Since[n 1]
yotta	Y	1000^8	10^{24}	1000000000000000000000000	septillion	quadrillion	1991
zetta	Z	1000^7	10^{21}	1000000000000000000000	sextillion	trilliard	1991
exa	E	1000^6	10^{18}	1000000000000000000	quintillion	trillion	1975
peta	P	1000^5	10^{15}	1000000000000000	quadrillion	billiard	1975
tera	T	1000^4	10^{12}	1000000000000	trillion	billion	1960
giga	G	1000^3	10^9	1000000000	billion	milliard	1960
mega	M	1000^2	10^6	1000000	million		1960
kilo	k	1000^1	10^3	1000	thousand		1795
hecto	h	$1000^{2/3}$	10^2	100	hundred		1795
deca	da	$1000^{1/3}$	10^1	10	ten		1795
		1000^0	10^0	1	one		–
deci	d	$1000^{-1/3}$	10^{-1}	0.1	tenth		1795
centi	c	$1000^{-2/3}$	10^{-2}	0.01	hundredth		1795
milli	m	1000^{-1}	10^{-3}	0.001	thousandth		1795
micro	µ	1000^{-2}	10^{-6}	0.000001	millionth		1960
nano	n	1000^{-3}	10^{-9}	0.000000001	billionth	milliardth	1960
pico	p	1000^{-4}	10^{-12}	0.000000000001	trillionth	billionth	1960
femto	f	1000^{-5}	10^{-15}	0.000000000000001	quadrillionth	billiardth	1964
atto	a	1000^{-6}	10^{-18}	0.000000000000000001	quintillionth	trillionth	1964
zepto	z	1000^{-7}	10^{-21}	0.000000000000000000001	sextillionth	trilliardth	1991
yocto	y	1000^{-8}	10^{-24}	0.000000000000000000000001	septillionth	quadrillionth	1991

1. ^ The metric system was introduced in 1795 with six prefixes. The other dates relate to recognition by a resolution of the CGPM.

Pasted from <http://en.wikipedia.org/wiki/SI_prefix>

Some nice facts and numbers. - (suite 4).

Some orders of magnitude of magnetic field strength.

Info from WikiPedia.

Note:

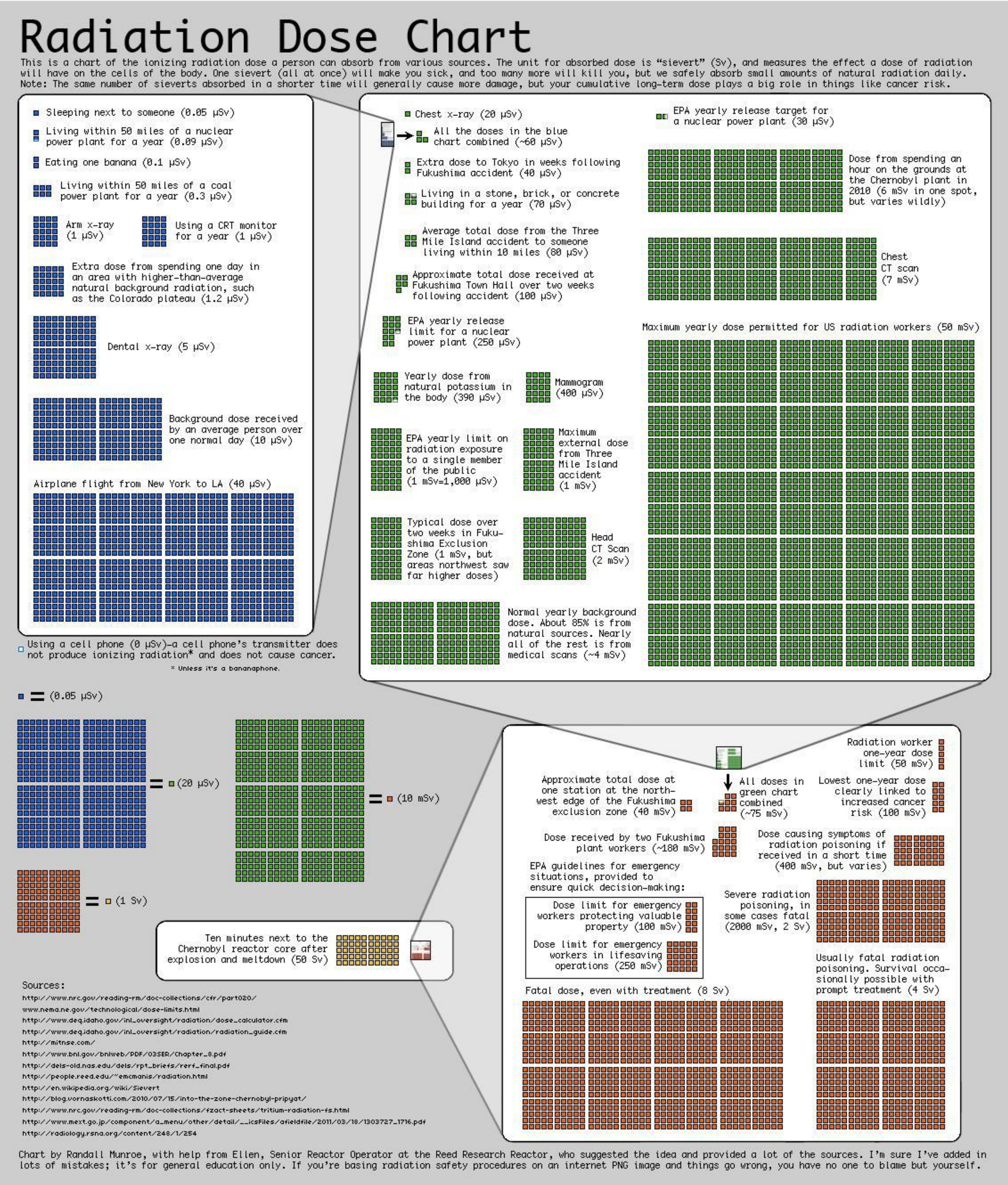
- Traditionally, magnetizing field H, is measured in amperes per meter. Magnetic induction B (also known as magnetic flux density) has SI units teslas (T) or Wb/m^2. When we are using these units in vacuum, one tesla is equal to 10^4 gauss.
- Magnetic field drops off as the cube of the distance from the source (for a dipole). These examples attempt to make the measuring point clear, usually the surface of the item mentioned.

List of orders of magnitude for magnetic fields

Factor [tesla]	SI prefix	Value	Item
10^{-18}	attotesla	5aT	SQUID magnetometers on Gravity Probe B gyros measure fields at this level over several days of averaged measurements
10^{-15}	femtotesla	2fT	SQUID magnetometers on Gravity Probe B gyros measure fields at this level in about one second
10^{-12}	picotesla	0.1-1.0pT	Human brain magnetic field
10^{-11}		$1x10^{-11}$T	In September 2006, NASA found "potholes" in the magnetic field in the heliosheatth around our solar system that are 10pT as reported by Voyager 1
10^{-9}	nanotesla	0.1-10nT	Magnetic strength in the heliosphere
10^{-6}	microtesla	24µT	Strength of magnetic tape near the tape head
10^{-5}		31µT 58µT	Strength of the Earth's magnet field at 0° latitude Strength of the Earth's magnet field at 50° latitude
10^{-3}	millitesla	0.5mT 5mT	Exposure limit for cardiac pacemakers Strength of a typical refrigerator magnet (decoration object)
10^{-1}		0.15T	Magnetic field strength of a sunspot
10^{0}	tesla	1-2.4T 1.25T 1.5-3.0T 9.4T	Coil gap of a typical loudspeaker magnet Strength of a modern neodymium-iron-boron rare earth magnet. Can lift >9kg. Strength of a typical medical MRI system Strength of a high resolution research MRI system
10^{1}		11.7T 16.0T 36.2T 45.0T	Field strength of a 500MHz NMR spectrometer Field strength used for levitate a frog Strongest continuous magnetic field produced by non-superconductive magnet Strongest continuous magnetic field produced in a laboratory
10^{2}		100.75T 730.0T	Strongest pulsed field obtained in a laboratory (non destructive) Strongest pulsed field obtained in a laboratory (destructive)
10^{3}	kilotesla	2.8kT	Strongest magnetic field ever obtained (with explosives)
10^{6}	megatesla	1-100MT	Strength of a neutron star
10^{9}	gigatesla	0.1-100.0GT	Strength of a magnetar

Also see: http://en.wikipedia.org/wiki/Orders_of_magnitude_%28magnetic_field%29

Some nice facts and numbers. - (suite 5).



Radiation dose comparison chart. Beware: Read the very last 2 lines! (Pasted from: https://xkcd.com/radiation/)

Some interesting things to remark from this chart and: http://www.radioactivity.eu.com/site/pages/Radioactivity_in_Flight.htm

Radiation year dose received while living within 50 miles of a nuclear powerplant	0.09 µSv
Radiation year dose received while living within 50 miles of a coal powerplant	0.3 µSv
Aeroplane flight from Paris to New York cosmic ray dose	80 µSv
Legal US year dose for the general public	1.0 mSv
Legal US year dose for a radiologic worker (controlled with dosimeter)	50.0 mSv
Legal European year dose for a radiological worker (controlled with dosimeter)	20.0 mSv
Erik's accumulated dose working at CERN from 01/02-1973 until 31/12-2019	5.2 mSv

Some nice facts and numbers. - (suite 6).

LHC injection accelerator chain characteristics. (From: PS Itinerary.)

- Linac 2, length: 30m: injects protons (max. 180mA; approx. $5.0E^{15}$ protons every 1.2sec) into PS Booster at 50Mev (310.36MeV/c). Speed of protons is then approx. 31.4% of speed of light. Linac2 operates on a frequency of 202.56MHz, like its predecessor Linac1 which is exposed in the MicroCosm exhibition.
- PS Booster, 4 superposed rings of 157m circumference, in service since 1971: PSB makes more intense bunches possible for injection into PS. PSB is used for protons only . The 4 superposed rings receive each 1/4 of an ejected linac2 batch; acceleration to 1.4Gev (2.14GeV/c) of each batch takes place every 1.2sec. Speed of protons attains then approx. 91.6% of the speed of light.
- PS, circumference 628m, in service since 1959: For LHC filling requirements two ejected PSB batches are necessary during injection into the PS; one containing the protons of all 4 rings the other containing only those of 2 rings (max. total of approx. $7.5E^{15}$ protons). Acceleration to 25GeV (26GeV/c) of these 2 injections is done by PS every 3.6sec. The protons travel then at 99.93% of the speed of light. We are now well above transition, energy gets added to the protons but their speed hardly increases anymore. The energy increase translates from now on into mass increase; at the ejection from PS the protons have approx. 25x their mass when they were at rest.

  For LHC fills PS is splitting the 6 PSB batches, in a total of 72 bunches of protons, spaced at 25nSec (=10 wavelengths of LHC RF). One such an ejection is termed a 'bunch train'. Splitting occurs by changing the RF frequency in a so called operational phase of 'RF gymnastics' (higher RF harmonic frequency taking over from a fundamental acceleration frequency) that occurs 3 times before ejection to SPS. It proceeds by first tripling each of the PSB batches (yielding: 6 x 3 = 18 bunches) before acceleration and then twice doubling every new bunch (6 x 3 x 2 x 2 = 72 bunches) after acceleration to 26GeV. In the RF scheme of PS is already accounted for the place in LHC RF phase space (RF bucket) where these bunches must be located in order for them to collide inside the 4 LHC experiments. The RF's of SPS, PS and LHC are precisely synchronized. This makes the successive transfer of the bunches, once they are accelerated, in the correct 'bucket' (RF phase space) of the next machine in the injection chain possible.
  Info: https://op-webtools.web.cern.ch/op-webtools/beamdoc/

- SPS, circumference: 6.9kM (Radius: 1.1kM), in service since 1976: Requirements for filling LHC state that either 2, 3 or 4 ejected PS 'bunch trains', are necessary during injection into SPS. The number of injections for each acceleration of SPS amount to successively 2, 3, 4, 3, 3, 4, 3, 3, 4, 3, 3, 4, totaling 39 injections into SPS (each injection with a total of max. 72 bunches of protons) and 12 acceleration cycles to 450GeV (450.9GeV/c). Speed of protons attains then approx. 99.9998% of the speed of light.

  Note that the first 'missing' bunch train injection plus the other of the empty 756 empty 25nSec LHC RF buckets (see: 'LHC fill for top energy of 7TeV.') yield 'empty RF bucket time holes' in the circulating beam of LHC. These are required for rise / fall time of the various fast injection and ejection kicker magnets in the whole PS, SPS and LHC accelerator chain. See document: pcollier_20080813.pdf; page 7, 8

  We so arrive at the maximum number of proton bunches of 2808 that LHC can accept. The SPS injection 'flat bottom' lasts thus for 4 x 3.6 = 14.4sec after which an acceleration phase to 450GeV (450.1GeV/c) takes place that lasts for approx. 7.2sec. At SPS ejection energy, the speed of the protons attains some 99.9998% of the speed of light and their mass is now equivalent to 450x their mass at rest.
- LHC, circumference: 26.658883kM (Radius: 2.80395kM), in service since 2010: The injection flat bottom of LHC, where the 12 ejections from SPS will be accumulated, lasts for 12 x (14.4 + 7.2) = 259.2sec i.e. 4.32min. per acceleration direction, CW (B1, blue) and CCW (B2, red). Acceleration from 450GeV to max. 7TeV (7.0005TeV/c) takes in the order of 20min (stable phase <=3°; practically 'stationary bucket'!) due to constraints imposed by the supra conductivity of the magnets. After acceleration the protons will have their mass increased by a factor of approx. 7000 as compared to when they were at rest while moving at a speed of 99.999999991% of the speed of light.

  RF harmonic number and frequency is resp. 35640 and 400.8MHz; Revolution frequency is 11.245kHz. During acceleration the beam gains per turn through the RF cavities only:
  ((7000 - 450) [Energy gain GeV]) / ((20 x 60) [Acceleration duration Sec] x 11245 [sec^{-1}]) = 485keV
  However, at the same time, at 7TeV, the RF voltage required for maintaining correct phase in the accelerator cavities might attain some 16MV due to the heavy beam loading!
  Energy loss, per turn, due to synchrotron radiation varies between $1.15E^{-1}$ eV at 450GeV (injection energy) and $6.71E^{+3}$ eV at 7TeV.

Relativistic kinetic energy and momentum calculations via sites:
http://hyperphysics.phy-astr.gsu.edu/hbase/Relativ/releng.html#c5
http://hyperphysics.phy-astr.gsu.edu/hbase/Relativ/relmom.html#c1

Some nice facts and numbers. - (suite 7).

LHC fill for top energy of 7TeV. (Distilled from: PS Itinerary.)

Fill with a total of 12 ejections from SPS (450GeV); each SPS ejection was built with either 2, 3 or 4 bunch train injections from PS in the order like this:
2 + 3 + 4 + 3 + 3 + 4 + 3 + 3 + 4 + 3 + 3 + 4 = 39 bunch trains.

The SPS acceleration cycle lasts for 21.6sec; filling LHC takes therefore, per accelerator direction CW or CCW, 12 x 21.6 = 259.2sec (4.32min) on LHC's flat bottom. Acceleration by LHC to top energy of 7TeV proceeds thereafter very slowly in approx. 20min. A time lapse due to constraints imposed by the supra conductivity of the magnets .

The first 'missing' bunch train injection plus the other of the empty 756 empty 25nSec LHC RF buckets (see below) yield 'empty RF bucket time holes' in the circulating beam of LHC. These are required for rise / fall time of the various fast injection and ejection kicker magnets in the whole PS, SPS and LHC accelerator chain. See document: pcollier_20080813.pdf; page 7, 8

RF harmonic number and acceleration frequency is resp. 35640 and 400.8MHz; Revolution frequency is 11.245kHz (88.924µSec). Bunch spacing is 25nSec, i.e. 10 wavelengths of 400MHz apart, but this 25nSec pattern is not always regular. See document: pcollier_20080813.pdf
Only 2808 of the max. 3564 LHC RF 25nSec buckets are filled with protons in designed operation.
Total available: 756 x 25 [nSec] = 18.9µSec. Abort gap for LHC beamdump requirement: ca. 3µSec.

During acceleration the beam gains per turn through the RF cavities only:
((7000 - 450) [Energy gain GeV]) / ((20 x 60) [Acceleration duration Sec] x 11245 [sec^{-1}]) = 485keV
However, at the same time, at 7TeV, the RF voltage required for maintaining correct phase in the accelerator cavities might attain some 16MV due to the heavy beam loading!

Energy loss, per turn, due to synchrotron radiation varies between $1.15E^{-1}$ eV at 450GeV (injection energy) and $6.71E^{+3}$ eV at 7TeV.

PS is filled by 2 ejections from PS Booster:
4 + 2 rings = 6 proton batches.

Each ejected PS bunch train contains at the end of the cycle 72 bunches spaced at 25nSec (=10 wavelengths of LHC RF) and each bunch contains currently nominally approx. $1.1E^{11}$ protons. This number of bunches is obtained by a process of splitting each of the 6 injected proton batches (RF gymnastics) according to the following scheme:

1st split:	1 proton batch into 3 bunches	After injection, before acceleration
2nd split:	3 bunches into 6 bunches	After acceleration to 26GeV
3rd split:	6 bunches into 12 bunches	After acceleration to 26GeV

which gives the overall total of 6 x 12 = 72 bunches in the bunch train for ejection towards SPS.

Conclusion:
With a total of 39 injected bunch trains this yields 39 x 72 = 2 808 bunches in each LHC circulating beam.

Some nice facts and numbers. - (suite 8).

ATLAS 'interesting' event rate and acquired measurement data. (From: ATLAS Itinerary.)

In LHC 2808 'clockwise' bunches collide with 2808 'anti clockwise' bunches. Each bunch contains $1.5E^{11}$ protons, has a length of 50-30cM and a diameter of 1mM in the machine and is further compressed to 50-10µM just before the collision point. Each bunch passes the center of the detector with a rate of 11245 turns / sec (speed of light). With 2808 bunches from both directions this gives (mean value) in total: $31.57596E^{6}$ intersections / sec.

Considering that, in 2010 LHC, only 20 real proton on proton collisions per intersection occur, we can conclude that only a maximum of 20 * $31.57596E^{6}$ = $631.15192E^{6}$ potentially 'interesting events' per second might be created. (Note: As from 2025 HiL-LHC might increase this with at least a factor 7. Today, 2017, this number of collisions per intersection has already increased to around 40 - 60 which corresponds then to $1263.036E^{6}$ - $1894.554E^{6}$ potentially 'interesting events' per second.)

However, the yield of 'really' interesting events is much lower. Before storing measurement data of ATLAS, its on-line electronics and computers forming the measurement Trigger and Data AcQuisition system of the detector, can filter the 'uninteresting events' away before actual acquired measurement data is stored. The Trigger system only allows a measurement to be stored after some of its raw collision data passed the 3 filtering layers:

After the 1st filter we find:	approx. 10^{5} interesting events / sec left over
After the 2nd filter we find:	a few times 10^{3} events / sec left over
After the 3rd filter we find:	200 interesting events / sec left over

In this way, these remaining 200 events/sec produce an amount of the 'raw' measurement data of some 3200 Tbytes per year. From this data is also locally produced at CERN, by the detector's 3000 on-line PC's, approx. 2000 Tbytes per year of reconstructed particle track data. The latter is further analyzed with specialized software and finally produces yet another 200 Tbytes per year of physics data.

All this data is flushed (8Gbit/sec; 1Gbyte/sec) onto computers in the 15 computing centers, located on 3 continents, that are connected to each other and CERN as the worldwide CERN LHC Data Grid for off-line analysis. From the 'Grid' the physicists of the ATLAS collaboration (>3000 people of 182 physics institutes in 38 countries) have free access to the integrality of all gathered data.

We can conclude that the yearly recorded data of the ATLAS detector amounts to some 3.5-5 peta bytes (10^{15} bytes).

ATLAS experiment work principle. (From: ATLAS Itinerary.)

Around the collision interaction point we find successively while going from there to the outside:

- The Track (or Trigger) Data AcQuisition system of the inner detector (6m20 x 2m10) consisting of:
  - In front of the Pixel detector is mounted the Insertable B-layer pixel detector at 3.3cm radial distance from the collision vertex. (See: The Atlas Insertable B-Layer.pdf)
  - Pixel- (3 layers) and micro strip (4 layers) SemiConductor Tracker detector.
    Spatial resolution: <14microns for the pixel detector; 20microns for the strip detector.
    In total: 80million pixels and 6million readout strips covering some $60m^2$ of detection area.
    The semiconductor tracker dissipates up to 30kW and is cooled to -7°C by an evaporative cooling system.
  - Transition Radiation Tracker.
    Hundreds of thousands of gas filled 'straws' each with a central detector wire at several 100volts. Timing of the electrical (ionization) pulse resolves the distance of the track within the 'straw' to better than 0.17mM. Special shielding between the tubes allow for X-ray production (transition radiation) by the passing electrons, thus enhancing their discrimination from other charged particles.

  These trackers are sensitive to all high energetic, charged particles:
  - electrons and positrons (Rest mass: $511keV/c^2$)
  - charged pions (Rest mass: ~$140Mev/c^2$)
  - protons (Rest mass: $938MeV/c^2$)
  - muons (Rest mass: ~$106MeV/c^2$)

  They are insensitive to all neutral particles:
  - photons (not really a particle...)
  - neutral pions (Rest mass: ~$135Mev/c^2$)
  - neutrons (Rest mass: $940MeV/c^2$)
  - neutrinos (Rest mass: probably <$0.3eV/c^2$, but: >0)

  The TDAQ system determines the point of a proton-proton interaction (collision point or vertex) with a spatial precision of approx. 50microns. It also pins down the moment 'zero' for all things that happen during the evolution of the interaction product within ATLAS' measurement volume.
- The supra conductive Solenoid Magnet (He cooled 4.7K; 7730A; 5ton; 5.30m x 2.40m Ø).
  Provides for a 2T homogeneous magnetic field within the inner detector, field lines parallel to the incoming LHC beams. It provides for curving the trajectory of charged particles according to their momentum (p = m.v) and charge (positive or negative). This allows for particle type identification.
- The Electromagnetic Calorimeter.
  Measures the energy of electrons and photons. It consists of 'accordion' shaped layers of thin stainless steel and lead in between which there is liquid Argon of 88K. A copper grid immersed in the Argon allows for spatial detection of ionization current while high energy electrons and photons loose all of their energy by creation of many secondary, low energy electrons and Argon ions. The charge is collected by the copper grid and is proportional to the energy of the incoming electron or photon.
- The Hadronic Calorimeter.
  Same principle as the EM calorimeter except that we find here thousands of 'interleaved' steel and scintillator sheets where the incoming high energetic hadrons produce a shower of lower energy particles from interaction with the steel. The incoming Hadron is fully stopped and the shower of lower energy particles creates light when passing through a scintillator. This light is recovered and led to photomultipliers where its intensity translates to an electric signal proportional to the energy of the incoming Hadron.
- The Muon Spectrometer.
  Within the volume of the toroidal magnet field we find 3 consecutive layers of chambers with long, gas filled tubes (Ø 3cM) that each have a central wire (much like the TRT). The total surface of ATLAS' Muon detection chambers amounts to that of several football fields. Muons, passing through the chambers, ionize the gas and the time it takes for the drifting electrons toward the wire, allows spatial resolution of the Muon track to be determined to 80microns. The collected charge is proportional to the Muon energy. The magnet field gives information about the Muon momentum (thus its mass).

(Continued overleaf.)

(Continued.)

- <u>The supra conductive Toroidal Magnet</u> (8 coils, He cooled, 4.7K, 20500A, 100ton/coil)
  Provides for a 4T - 1T non-homogeneous magnetic field from coil surface to middle between 2 coils. This magnet field is located around the hadronic calorimeter, field lines circular, coaxial, with respect to the incoming LHC beams. It provides for curving the trajectory of Muons, the only charged particles flying along outward from the collision point and that did not get stropped by the EM and Hadronic calorimeters.
  The non-homogeneous field of the Toroidal Magnet is very well defined in space and the Muon track computing from the spectrometer chamber signals takes this into account for the momentum calculation of these particles.

Energy balance differences with respect to the known collision energy is attributed to the energy that was taken along by escaping neutrinos. These latter, elusive, particles do not interact at all with matter; thus neither they do with Atlas's detection systems.

All detectors within Atlas are continuously scanned with laser light in order to calibrate their relative position within Atlas. The fixation of the various detection chambers is such that a little bit of freedom is given for temperature expansion movement (thus avoiding mechanical stress to the detection system) and therefore spatial definition must be checked. The overall spatial accuracy of the detection systems in Atlas lies in the range of a few tens of microns to less than 0.1mM.

With a collision frequency of 40MHz (25nSec LHC bunch spacing) a next collision takes place while the former collision energy is still expanding within the volume of the Atlas detector.
With the speed of light, the expanding collision energy sphere has a radius of:
$25.0E^{-9}$ [Sec] x $3.0E^{8}$ [m/Sec] = 7.5 [m]
Also, with this collision frequency, note that in 5Sec Atlas can take 200.000.000 3D 'photos' of events. That number corresponds to approx. the same number of events that were registered during the ~10 years of existence of all bubblechamber detectors / experiments in the world!
Remember: Atlas's weight is 7000ton and its size is 25m in diameter and 46m in length.

It is interesting to know that in spite of Atlas's seemingly massive and weighty appearance, it is in fact rather 'airy'. Indeed, if we could pack whole Atlas in a watertight jacket and throw it into water, it would float!

Atlas is a collaboration of some 3000 physicists and engineers from 182 institutes spread over 38 countries. Scientific publications are usually signed as 'The Atlas collaboration' rather than by individual collaboration members.

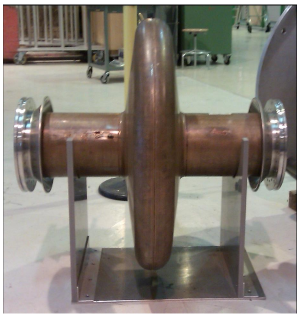
Erik's remark during the SM18 training session of 05/10-2017 (From: SM18 Itinerary.):

While at the entry of the SM18 Visitor zone (bldg. 3198 - 2173) we find the map of the CERN premises projected on the floor. Estimated scale: 1:2000. At this scale the size of the 'real' accelerator of LHC, i.e. the 4 tanks each of them measuring 7M50 and each housing 4 RF cavities, is in total only approx. 1.6cM, i.e. the width of one's index finger! It is situated in LHC point 4, Echenevex, slightly under the Jura mountains.

LHC Super Conductivity Components. (From: SM18 Itinerary.)

With the help of a prototype single cell cavity explain the principle of acceleration:

Remember: A magnetic field can never accelerate particles in the direction of movement; it can only change the particle's trajectory. A magnetic field exercises a force on the charged, moving particle which is transverse, 90°, with respect to its movement. For acceleration we need a force in the direction of movement and that can only be created by an electrical field. This is described by the formula of Lorentz (1853-1928), a Dutch physicist, winner of the 2nd Nobel prize physics, attributed to him and Pieter Zeeman in 1902. (1st Nobel 1901: Wilhelm Conrad Röntgen)



A proton traversing the beam pipe along its length will induce a mirror current in the electrically conductive beam pipe. This current is flowing in opposite direction with respect to the direction of the proton's movement.

Upon traversing the cavity region, this current has to make a 'detour' along the cavity's shape. The proton just follows its 'straight forward' path in the beam pipe.

The result of this 'de-phasing' between the proton and its induced mirror current in the conductive wall of the beam pipe is that some of the proton's kinetic energy is transferred as electromagnetic energy in the cavity which then starts to (electrically) resonate.

The cavity thus behaves as an ordinary parallel LC resonating circuit: the cavity's 'detour path' along its shape corresponds to the self-inductance; the areas where the horizontal beam pipe goes vertical to become the cavity, and vice versa at the other side, thus forming a pair of flat metal rings, left and right side, facing each other, are the 'plates' of the capacitance.

This electrical resonance is much like the acoustical resonance, also an oscillation of energy, that can be heard from an empty bottle while someone is blowing over the bottle's opening: a small quantity of kinetic energy of the air particles flying over the bottle's opening is transferred into the 'cavity' (empty bottle) which then starts acoustically resonating.

The proton in the beam pipe, while traversing the region between the 'rings' of the cavity will experience a deceleration; its loss of velocity, kinetic energy, marks the transfer of that energy as electro magnetic energy to the cavity. Indeed, the proton forms a 'suddenly present ' electrical charge between the plates ('rings') of the 'capacitor' of the oscillatory system, the cavity. The capacitor discharges over the self inductance ('detour' path) of the cavity and the EM oscillation takes place; the amplitude of which will be a function of the quality factor of the oscillatory system; mechanical dimensions of the cavity determine its principal resonance frequency.

In fact, the proton generates its own decelerating electrical field between the 'plates' of the oscillatory system of the cavity. Inverting this situation allows for acceleration in stead of deceleration of the proton. Here is how it works:

By applying a strong electrical signal at the entry of the cavity we can force the cavity to oscillate, resonate, in absence of protons. Keeping very precise control of amplitude and phase of this oscillation we are able to impose an accelerating electrical field between the 'rings' of the cavity at the moment when the proton is actually flying in between the cavity's 'rings', the capacitor plates. It will thus be accelerated.

At the prototype LHC RF single cell cavity tank (currently exposed in the LHC tunnel mockup):

The electrical signal for each individual cavity is provided by RF power amplifiers: 300kW Klystrons (made by Thales - FR). Such an amplifier is capable of generating an accelerating field of 2MV amplitude in the cavity. For acceleration however the bunches are kept on a phase, rather close to the zero crossing of the descending slope of the sine wave, around 180°. While LHC is in coasting beams mode or during the beam injection phase, the phase is kept exactly at 180°, i.e. 0V accelerating field. (Actually, during coast, a little acceleration still takes place for compensation of energy loss due to synchrotron radiation, see at the page end, below.)
Interesting visible details of the prototype single cell module:

- The RF power radiating antenna in the cavity (moving, adjustable coupling)
- The 1-2µM Nb-Ti layer in the inside (RF skin effect at 400.8MHz; hi-Q RF 'stiffness' against beam loading)
- The HOM antenna windows
- The coarse mechanical frequency adjustment (1-2mM tuning range requiring 20'000N force)

Per tour in LHC the protons only gain approx. 485keV. The extra RF power is needed for maintaining, forcing, the right phase and amplitude of the oscillation in the cavity. Indeed, the strong proton beam also induces a voltage in the cavity; the mechanism by which the working of the cavity was earlier explained is also present and therefore the actual amplitude and phase of the electrical field is the vector sum of both imposed voltage and induced voltage. The induced voltage of the high energetic proton beam is enormous. We need much more power to maintain the required voltage (phase and amplitude) than the actual voltage gain does suspect! The greater part of all this RF power is reflected from the cavity (impedance mismatch to the RF power system) and is diverted with the help of a circulator into a water cooled dummy load. Only a very small percentage of the RF power is actually transferred onto the proton beam for its acceleration.

Four of these cavities are placed in a vacuum tank and 2 tanks (8 cavities) accelerate one beam. For the 2 beams of LHC the 'real' accelerator consists therefore of a total of 4 of these tanks, approx. 4x 7.5m long. The rest of the 27kM circumference of LHC is only required to bring back the protons to the entry of the accelerator ...

Each cavity is coated on its inside with Nb-Ti (1-2µM only; because of RF skin effect at 400MHz) and the room between its outside and its stainless steel housing is filled with liquid He of 4.3K such that the coating becomes supra conductive. It makes that the electrical quality factor of the resonating cavity is enormous (2-5E^9 unloaded but damped to 20-200E^3 due to coupling to the power amplifier) and thus helps the stabilizing of the accelerating field while the protons traverse the cavities and represent a pulsating load for the RF power amplifier.

The heat in-leak in the tanks is in the order of 110W. This must be cooled away and it is due to the unavoidable multiple accesses for HOM dampers and other RF control parts as well as the required fixations inside the vacuum tank causing heat bridges. FYI: an LHC bending magnet has a leak-in of only 3W!

Acceleration is done very slowly, very delicately, 20 minutes from 450GeV to 7TeV because of the supra conductivity of the magnets; they don't like rapid changes in magnetic field strength. Danger for quenches!

The frequency of the RF voltage in the accelerator cavity of LHC is 400.8MHz which corresponds to a wavelength of 75cM when considering that RF waves progate with the speed of light. Protons in LHC also progress in the machine with the speed of light (well, between 99.9998c and 99.999999991c, see footnote) . In this condition the distance between proton bunches in LHC can be compared to, expressed in the wavelength of the RF acceleration voltage.

The RF Low Level control system tunes the RF frequency to the magnetic path length of LHC such that an exact integer number times the RF wavelength is always equal to this magnetic path length. In that case we can guarantee that a proton, leaving the RF cavity and making the tour of LHC will find exactly the same phase of the electrical accelerating field in the cavity when it returns.

This integer is called the 'harmonic number' of a synchrotron accelerator and for LHC it is 35640. Distance between proton bunches is 25nSec, i.e. 10 wavelengths or 7.5m distance. Bunch length varies between 51-30cM from injection to coast. This means that under these conditions max. 3564 bunches could be placed in the 'RF buckets' around LHC. However, only 2808 bunches will maximally be present in LHC; the 'missing bunches', 'empty buckets', allow for sufficient 'no beam' time for the beamdump extraction kickers to rise to their full strength when the beams must be extracted within 1 tour from the machine. The revolution frequency of the proton bunches is 11.245kHz (88.93microSec/tour).

Energy loss, per turn, due to synchrotron radiation varies between 1.15E^{-1} eV (450GeV injection) and 6.71E^{+3} eV at 7TeV. This loss of energy has to be compensated for by the RF acceleration system in order to maintain the protons in orbit around the LHC. Therefore, even in coast, collision mode, the beam is continuesly accelerated!

Note: For what follows it would be exact to calculate this RF wavelength with the velocity of the proton rather than with the speed of light as is usually done. The word synchrotron means synchronism between the particle revolution frequency and the accelerating RF field frequency!

On the prototype LHC bending magnet:

- Magnet current: 11800A for a field of 8.3T homogenous in approx. 28mM aperture. Therefore the cold bore in the magnet is already slightly bend: approx. 0.29° (sagitta, deviation, of 9mM between chord and arc) per magnet. Bending radius in the magnet arcs is 2803.95M; this means that the required current precision of the bending magnet must be at least an order of magnitude better than:
  $28E^{-3}$ [M] / 2803.95 [M] = $10.0E^{-6}$.
- The bending magnet coils have 80 windings total (2x 40: one coil above and one coil under the cold bore) and are kept in place around the cold bore by means of stainless steel collars that are pre-stressed with an hydraulic press during assembly of the magnet.
- Pre-stress is done with 700t/M onto the 2 stainless steel, 10mM thick, half shells that surround the collars and a robot welds these then together while the press pre-stresses the assembly. Because of the half shells now being welded together, the applied pre-stress creates, due to the material elasticity, a horizontally, outward directed force and which cannot be relieved at the moment pressing is stopped.
  Cooling down the magnet to 1.9K releases some of the pre-stress, but the collars can still take the inward directed magnetic forces created by the fully powered magnet coils. These forces amount to some 300t/M. Thanks to collars and pre-stress mechanical stability is thus obtained.
- The collars have a small deformation stamp (3 marks) around each of the connecting rod holes that make a spacing of 0.2mM in between them for allowing the super fluid Helium penetrate into the magnet coils for their cooling. (See further remarks on super fluid He on the next page.)
- The amount of He in the pores between the collars of the cold mass is 11l/M; approx. 157l per bending magnet is required.
- While cooling down to 1.9K a bending magnet shrinks some 5cM. For the 27kM of supra conducting LHC magnets this means altogether some 80M of shrinkage! Hence: bellows.
- Bellows in the connecting ducts, RF sliding fingers in the beam shields inside the cold bores and expansion 'Lyres' in the electrical cables allow for this shrinkage.
- Vacuum (rest gas pressure) inside the cryostat before cool down is $1.0E^{-4}$ atm, $1.0E^{-9}$ atm after cool down, and in the cold bores it amounts to some $1.0E^{-13}$ atm ($7.5E^{-11}$ torr).

On the 2 adjacent bending magnets coupling stand :

- The cold bore beam tubes of 2 adjacent magnets are electrically spoken continuous thanks to the RF sliding fingers. During cool down and heating up some 5cM of possible movement should be allowed for. During cool down LHC shrinks in total some 80M over its 27kM circumference.
- No electrical discontinuity is however tolerable for the beam induced currents in the beam pipes when the beam passes from one magnet into the adjacent one. A parasitic RF cavity could otherwise occur and the resulting RF voltage arising between the beam pipes of the two adjacent bending magnets (the 'gap' of the parasitic RF cavity) creates immediately beam instability. Eventually beam loss might result in causing damage due to its energy deposit in the super conducting magnets.

- The September 19th, 2008 (9 days after the first beam in LHC going around) accident in sector 3-4 was due to a bad current conducting splice between 2 magnet cables which had some 200x more resistance than the normal 1 nano ohm ($10^{-9}\Omega$).
- Heat developed and the cable that carried some 5000A melted and an arc occurred (self inductance and lot of energy available in the energized magnet). That arc burnt a hole in the bellows between the "technical galleries" of the 2 adjacent magnets.
- Super fluid He coolant (1.9K) became gaseous and expanded inside the vacuum tank which provoked a pressure wave in the vacuum tanks.
- During the accident 2 magnets were completely lost and the pressure wave of the gaseous He in the vacuum tanks of a series of magnets damaged yet some further 52 more dipole magnets.
- Repair of LHC required approx. one year. LHC was thereafter in service for physics around March 2010.

Cryogenic wires, cables and magnet windings for LHC were produced by 3 European firms:

- Siemens - Germany
- Thomson - France
- Ansaldo - Italy

Some nice facts and numbers. - (suite 14).

On the LHC bending magnet super conductivity:

- The super conductive cable (Rutherford cable), used for the bending magnet's windings, is constructed of 36 strands of wire, made out of copper with some 8900 Nb-Ti alloy filaments embedded in one process. The copper matrix will never become super conductive and can thus be considered as an insulator at 1.9K. All current flows through the Nb-Ti filaments.
- Filaments are necessary in order to maintain as much as possible a laminar electrical current flow thus avoiding as much as possible remnant eddy currents in the super conductor. These remnant currents remain steady in the super conductor and it is not possible (without forcing a quench) to get them out again. They influence negatively the magnet field quality.
- The wire is approx. 1.065mM in diameter; the individual filaments have a diameter of 7μM each. The positioning of the filaments inside the copper matrix is controlled to better than 1-2μM during its manufacture. The copper matrix of the wire also takes care of the magnetic forces between the filaments when these are energized.
  In comparison: a human hair is approx. 50-60μM in diameter.
- The cable is insulated with 2 layers of Kapton but the 'overlap room' between these layers largely allows the super fluid He for penetrating into the cable for full contact with the individual strand wires.
- Superconductivity of the magnet coils is attained at 4.5K but in order to obtain the He II state of super fluidity cooling must further go down to 1.9K
- Advantages of super fluid He are that its heat conductivity is enormous: some 1000-3000x better than copper. When filled with 157l of He, the whole cold mass thus becomes a 'thermal unit' ; heat anywhere generated will be distributed very rapidly by conduction of the Helium over the full volume of the cold mass.
  Furthermore its high specific heat with respect to the loss in specific heat of the super conductor due to the low temperature, enhances the protection against (partial, local) quenches and compensates well the difficulty due to the loss of specific heat of the stainless steel collars and steel yoke of the magnet by quickly pulling out heat from the windings that can then be evacuated by the cooling plant.
- Cooling down or warming up of LHC takes several weeks to accomplish.
- The cooling plant for LHC is distributed in 5 cryogenic islands. The system contains some 120tons of He of which eventually some 90tons are found in the magnets; the rest is in the conducts and in the refrigerator units.
  For the liquefying process of all this He the first stage of cooling to 80K some 10.000tons of liquid nitrogen are necessary. The turbines will then take over and refrigerate the He to 4.5K where it will be fluid and it is at the highest temperature at which it is allowed for filling the cold masses of the magnets. Further cooling takes place until the He arrives finally at its 1.9K operating temperature.
  The LHC cooling plant provides for some 150kW of cooling capacity at 4.5K and 20kW at 1.9K. Note that for each 1W of cooling power at those temperatures approx. 600W are required from the utility 380V AC electricity line!

- Remark the High Temperature Super conductors for the electrical power connection. The phenomenon of these cuprate mixtures ($Bi_2Sr_2Ca_2Cu_3O_{10}$; AKA Bi-2223) was discovered around 1985 and immediately used by CERN to economize on the LHC supra conductor cooling effort. The HTS's critical temperature is around 77K (liquid N_2: 77K!) and stretch the temperature gradient from 50K to 1.9K to where the Nb-Ti supra conductor cables lead the current to the magnets.
  The (for us: negative and thus unusable for making a magnet coil) characteristic of this HTS is:
  - 20-50x more expensive than Nb-Ti
  - ceramic like texture, brittle
  - very sensitive to magnetic fields.
- These electrical power connectors use He gas of 20K to obtain a temperature gradient from 50K (He gas injection in the middle copper part towards the top copper part) to room temperature. The He gas is recovered close to the big 11.800A copper power cable connection.
- From the 50K copper block the HTS brings the current further over the final temperature gradient to the lower copper block which is immersed in the liquid He having a temperature of 1.9K. Here we find the Rutherford cable leading to the magnets.
- In a tunnel sector (IP<->IP) of 3.3kM are powered in series (3 electrical circuits): all main dipole coils (120 - 150 MB's); all main focussing Q-pole coils (20 - 25 MQ's) and all main defocussing Q-pole coils (20 - 25 MQ's).

Some nice facts and numbers. - (suite 15).

CC and WLCG characteristics. (From: Computer Center Itinerary.)

- Visitors area at the ground floor. Museum with posters.
    - Wim Klein (Guinness BoR: 1974: 19th root from a number of 133 digits in 1min. 30sec).
      Info: http://www.historici.nl/Onderzoek/Projecten/BWN/lemmata/bwn5/klein
    - Currently used backup tape storage units (T10000 cassette and Oracle-StorageTek reader) on expo on the right side of the room. Cassette storage capacity: 5Tbyte. The tape storage system uses a robot for loading and unloading the some xxx readers of the system. For data access time reduction it has some pre-fetch capability, making it to fetch a successive cartridge while the current cartridge is still being read.
    - WLCG originated at CERN around 1991; it started operating in 2003.
      Info: https://espace.cern.ch/WLCG-document-repository/Dissemination/flyers/WLCG-Nutshell-New.pdf
      Currently more than 35 countries are involved in Tier-1 and Tier-2. Computing power of WLCG distributed in the Tiers amounts to:

Tier-0	CERN	20%
Tier-1	15 institutes in: Canada, France, Germany, Italy, 2 sites in the Netherlands, the Nordic countries, S.-Korea, 2 sites in Russia, Spain, Taiwan, UK, 2 sites in the USA	30%
Tier-2	153 sites located around the globe.	50%

      See: https://wlcg-rebus.cern.ch/apps/topology/
      From <http://wlcg-public.web.cern.ch/resources>

    - On-line status screen of the Worldwide LHC Computing Grid. CERN-Wigner Tier-0: 235.000 processing cores in 15.000 servers; 59.000 disks (240Pbytes); >350Pbytes tape. Connections to Tier-1 (15 institutes): 10Gb/Sec.
      For PC/MAC/Linux available WLCG dashboard hook for Google Earth:
      http://dashb-earth.cern.ch/dashboard/doc/guides/service-monitor-gearth/html/user/index.html
    - One of the two first WWWeb servers used by Tim Berners-Lee and Robert Cailleau. Noteworthy: 'Next' was the firm setup by Steve Jobs when he had to dismiss from Apple in 1988.
    - History of mass storage devices. Recall of the 'holy war' for computer memory between silicon type and magnetic core type memory defenders.

Personal anecdote.
In 1974-75 I was in charge of building the electronic memory system of a large series of Function Generators mainly used by power supplies for the magnets in the transfer lines (injection, ejection) of the SPS, at the time CERN's largest accelerator under construction. This computer controlled memory should be capable of retaining the parameters describing the 32 or 64 vectors (angle, duration) that the function generator had thus at its disposal for the generation of a random form voltage as function of time. The specification for these vectors were such that the parameters should have a precision, resolution, of 16bits; 1 to 65536. The voltage function generated by the Function Generator was used as the reference signal for big power supplies delivering the current for the magnets in the transfer lines.

At the time of the memory design, National Semiconductor had just available a semiconductor chip (MM2102 was its reference) capable of randomly accessible 1024 1-bit 'words'. It was in a novel technology, 'static RAM' and an alternative to the original Intel i2102 which was of 'dynamic RAM' technology. These chips of a new generation were rather expensive, over CHF 100.- a piece. It was therefore decided to incorporate a jumper lead that allowed my memory system to be equipped and operated with either one or two of these chips...

Today a similar sort of memory chip is used in e.g. a USB key and their capacity can be over 32Gbyte, i.e. 256Gbit. This is a capacity increase of a factor of 256.000.000 in merely 40 years. We pay for such a chip, in its nice casing, today less than € 20.-

Some nice facts and numbers. - (suite 16).

- Gallery at the first floor. Overview of the CERN computer farm.
  - Impossibility to further expand the computer farm due to lack of electrical and cooling power of the building although physically there is still room for more computers (empty racks). CERN is waiting, as in the past was done, for the next generation, less power consuming, hardware (to be mentioned: Openlab partnership with HP, Intel and Oracle for evaluation of new IT technologies).
    An energy-efficiency implementation project allowed to save some 4.5GWh since 2011.
  - Along the far wall we find several server clusters that are 'critical' for CERN functioning and they have their own no-break electricity and cooling. We distinguish (right to left): the 3 server clusters for CERN WWW home page access, CERN administrative DataBase (also one cluster at the extreme left), CERN E-mail services, CERN CIXP service (see below), CERN network backbone.
  - In the far middle is the CIXP, the CERN Internet eXchange Point. It is the backbone point for the global Internet of the Geneva region. All public Internet providers in France and Switzerland connect their subscribers via this exchange point to the global Internet. CERN is therefore its own Internet provider; independent of any private enterprise. CERN is responsible for the 24/24 hour availability of this public service.
  - In front of this 'critical' row we find the CERN desktop servers, CERN WWW servers, CERN Engineering servers.
  - On the left side of the gallery of this building level and in front of us is the computer farm for the WLCG: disk storage racks and processor racks. It represents WLCG's Tier-0 with its 11.500 servers housing 174.000 processing cores and some 62.000 disks with 150Pbyte of storage.
  - Note that the cellar floor, under what is visible from the gallery, is also fully exploited for installation of PC's for the WLCG. We also find here supplementary electricity and cooling distribution systems.
  - Total power consumption of the building is now in the order of 3.5Mwatt. An extension of approx. 0.5Mwatt was recently constructed, but it is 'the end of de road'.
    Improvements in energy efficiency during 2011 have led to an estimated energy saving of some 4.5GWh per year.
  - A second CERN Data Center has therefore been organized in Hungary (Wigner Center, Budapest). Three direct optical fibre links of 100Gb/Sec are extending CERN's 170.000 cores with another 56.000 cores in 3500 servers and the 61900 CERN disk drives with 29700 drives. CERN and Wigner form together WLCG's Tier 0 and they alone represent some 20% of the grid's computing power..
    This center also ensures full business continuity for the critical systems in case of a major problem on CERN's Meyrin site.

    Pasted from <http://information-technology.web.cern.ch/about/computer-centre> and < https://espace.cern.ch/cern-guides/Documents/Data%20Centre/CERNDataCentre_KeyInformation_October2018V1.pdf >

Some nice facts and numbers. - (suite 17).

Data Centre's semi-transparent window projection system.

Somewhat awkward control for starting a chapter. Select the wanted chapter via the 'Forward / Backward' arrows next to the chapter identificator and (re-)start the selected chapter with the usual CC (Compact Cassette) symbol 'Start/Pause' arrow. Note that this button always re-starts the movie from the beginning! The film can be 'Paused' by toggling the usual CC symbol 'Start/Pause' button. For continuation of the movie after a pause use the 'Forward' arrow, right side, on the same screen line as the 'Start/Pause' toggle.

Available movie chapters:

- CERN introduction movie.
  Shows accelerator chain from the H_2 gas bottle to LHC collisions in the experiments. For 'Group Visits', not 'Open Visits', this is normally already explained during the CERN introduction conference. Could possibly be skipped.
- Data deluge.
  - Data production by the LHC experiments. Crossing bunch rate mean value 31MHz (25nSec burst; 2808 bunches around the accelerator per direction) giving some $600E^6$ collisions per second. The upgrade programme HiL-LHC hopes to boost this with at least a factor 7 by 2025.
  - First, second and third layers of data reduction to approx. 200 potentially interesting collisions per second; see e.g. with Atlas.
  - At CERN's Data Centre raw- and initial track reconstruction data copies are made for local storage at Tier 0 and backup streaming to the other Tier 1 computer centres of the WLCG (440Gb/Sec fibers).
  - Connections between Tier 1 and Tier 2 institutions run over 220Gb/s fibers.
  - Note the extension of CERN's Data Center at the Wigner institute with 3 dedicated 100Gb/s communication fibres. Its 3500 servers with 56000 cores and 29700 disks are added to CERN's 11500 servers with 174300 cores and 61900 disks to form together the WLCG's Tier 0.
- Bits & Bytes.
  - Definitions of a bit, a byte, kbyte etc. and the amount of storage units involved as compared to storage size of a regular DVD (approx. 5Gbyte).
  - CERN produces yearly in total approx. 100Pbyte of data that must be stored, backed-up for 'ever'. A byte, produced by the LHC experiments is very expensive... The raw data represents Nature as it has shown itself to us at the moment of data taking by an experiment. Therefore it should be available for analysis at any time, now and in the future whenever new physics theories are developed.
  - CERN's total storage capacity amounts to approx. 280Pbyte of diskstorage and 400Pbyte of tape storage.
- Mass storage history.
  - From big reel tape systems to tape robots. Examples in the exhibition:
    - Tape reel: 140Mbyte (1960 until 1980)
    - IBM honeybee structure mass storage, CERN's 1st robot operated storage system: 50Mbyte (1975)
    - Currently used StorageTek tape cassette: 5 Tbyte
  - Hard disk storage examples in the exhibition:
    - Huge CDC disk platter: 10Mbyte (1974)
    - IBM hard disk system consisting of 8 platters: 34Gbyte (1991)
    - Recent 3.5" hard disk as used e.g. in our home PC: 2Tbyte
  - Today magnetic tape is still the best, most reliable (hard magnetic) and lowest cost mass storage medium available. Currently used StorageTek cassettes can store up to 5Tbyte.
- Processor evolution.
  - 1960's: Single processing unit with ferrite core memory (exhibition) in a cupboard together with cupboards full of subsystem electronics (tubes) filling up the floor of the building.
  - 1970-80-90's: From multiple chip processor(s) mainframes (exhibition) to super computing with Cray XMP/48 and HP Shift multiple processor machines served from a network of desktop workstations.
  - Today: Scalable networked, interconnected multiple servers in 19" rack mount chassis built from commercially available fast PC motherboards (2 boards; each 2 processors; 2x 4 cores. See exhibition).
- Networking history at CERN.
  - 1960's: Data transport on tape reels, punch cards and paper was done by bicycle from an experiment, the data source, to the mainframe computer in the Data Centre building. Analysis jobs were written (Fortran) and read in for execution by operators; result data could be retrieved some time later (next day) at the operator desk.
  - In the 1970's the first networks between mainframe and a simple teletype like keyboard-display were 'in house' conceived. It allowed work on the mainframe to be done remotely, from the office.

Some nice facts and numbers. - (suite 18).

Data Centre's semi-transparent window projection system. (suite)

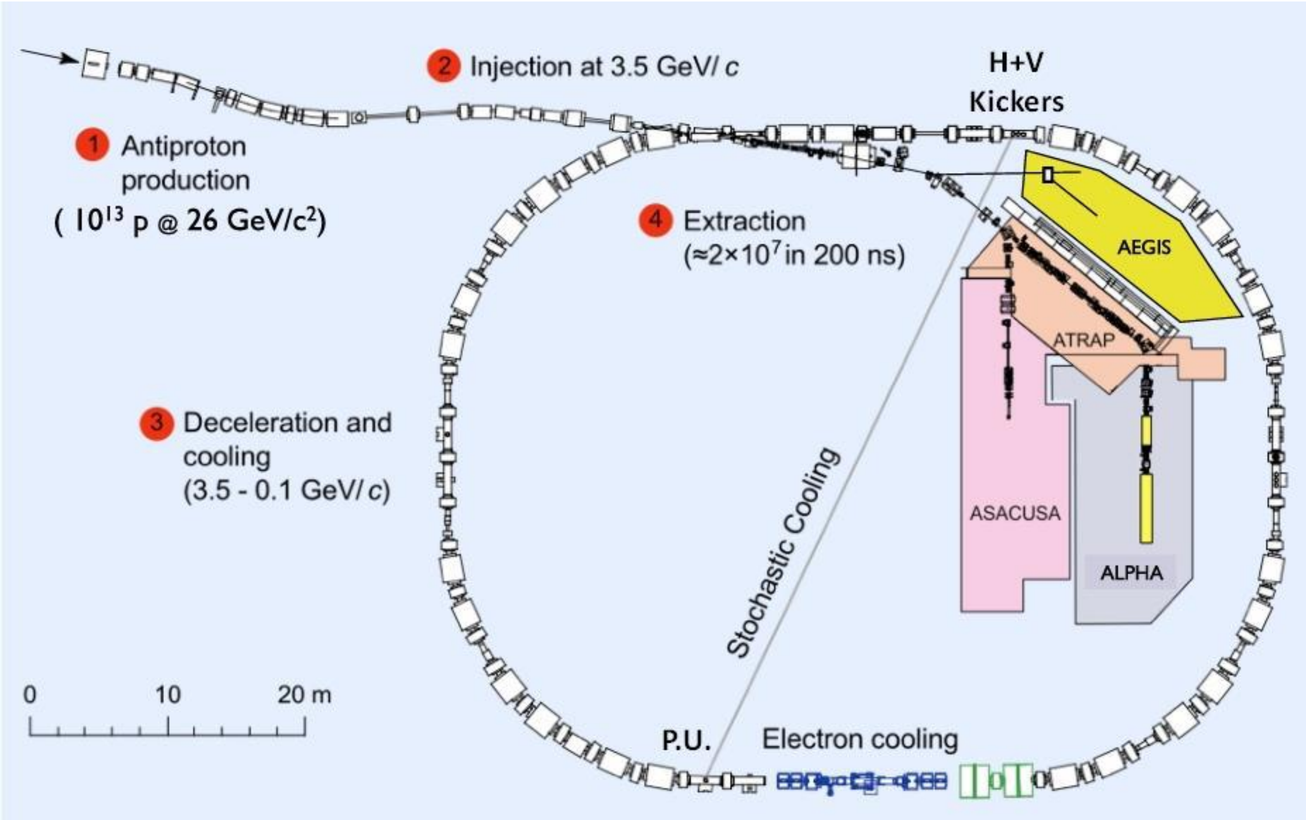
- Evolution of computing power at CERN.
  Comparing today's 100Pbyte per year data processing with the time required by CERN's former mainframe computers for processing of the same amount of data.
  - 1960's Mercury: $13.2E^8$ years, i.e. approx. from the start of the Universe until today.
  - 1970's CDC 7090, 7600: $426E^6$ to $65E^6$ years.
  - 1985: CRAY XMP/48: $3.2E^6$ years.
  - 1995: HP Shift: $11E^3$ years.
  - 2005: IBM 1401: 35 years.
  - today: 1 year.
- Virtual visit to the Data Centre building bldg. 513.
  Shows hardware installation and geographical situation on a building layout drawing.
  - Electricity.
    Required is some 3.5MW. The building cannot be furthermore extended; no room, no cooling capacity. Note many empty racks waiting for less consuming electronics... Battery UPS's for short power cuts keeping the systems alive for saving crucial data.
  - Cooling.
    Cold water cooling plant on the roof for cooling circulating air in the building. Storage of cold water for cooling during short power cuts, when the systems shut down.
  - Permanent tape storage. Robots manipulating the StorageTek cassettes.
  - CERN's operational network. Optical fibre junction of the network backbone.
  - Extension of CERN Data Centre in Budapest, the Wigner institute. Three direct optical fibre links of 100Gb/Sec extending CERN's 170.000 cores with another 56.000 cores. CERN and Wigner form together WLCG's Tier 0 and they alone represent some 20% of the grid's computing power.
  - CIXP.

Some nice facts and numbers. - (suite 19).

AD characteristics. (From: AD Itinerary.)

Info extracted from AD home page: https://espace.cern.ch/AD-site/default.aspx
and subsequent links from there.

Introduction.
AD is short for 'Anti-proton Decelerator' and has nothing to do with Dan Brown's Angels and Demons... ;-) It is a machine of approx. 182.4M circumference that slows down anti protons which are created by hitting an iridium target with a proton beam coming from the PS accelerator. AD was formerly AA (Anti proton Accumulator) which was used for the creation of an anti proton beam in the time that SPS ran as a proton-anti proton collider (SppbarS 1981-1991).



From: https://espace.cern.ch/cern-guides/Documents/AD_for_guides.pdf

Detail about stochastic cooling:
From the drawing's scale, deduction: AD circumference: 180.6m; Stochasting Cooling P.U -> Kickers signal line: 52.4m

- Δ Path length = (circumference / 2) - S.C. signal line length = 37.9m
- For a Pbar at c speed: Δ t = 37.9 / c = 126.4nsec (assuming Flexwell cable for the P.U -> Kickers signal line)

We are decelerating, so the Pbar's speed is always << c. (Actually: .97c < v < .1c during the AD cycle.)
Conclusion: There is always at least some 126nsec time available for signal treatment between P.U. and Kickers.

Currently there are 6 experiments built in the center of the AD ring that use the anti protons provided by AD for creation of anti Hydrogen and the study of its properties thereafter:

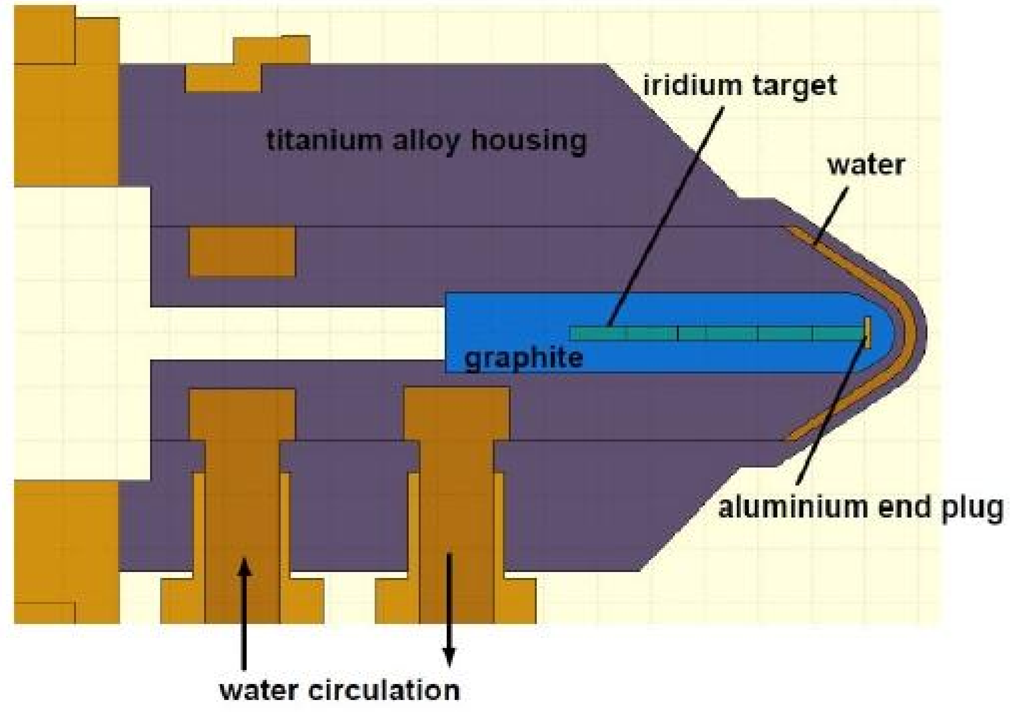
- AEGIS (Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy)
- ATRAP (Antihydrogen TRAP)
- BASE (Baryon Antibaryon Symmetry Experiment)
- ALPHA 2 (Antihydrogen Laser PHysics Apparatus version 2)
- ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons)
- GBAR (Gravitational Behaviour of Antihydrogen at Rest)

From: https://greybook.cern.ch/greybook/

Some nice facts and numbers. - (suite 20).

AD characteristics. (From: AD Itinerary.) - suite

Primary target for AD.
Info extracted from AD home page: https://espace.cern.ch/AD-site/default.aspx
and subsequent links from there.



From: ATS_Note_2012_069_TECH.pdf

The target is constructed from 6 iridium rods, diameter 3mM, together having a length of 55mM embedded in graphite which in turn is embedded in a titanium alloy, water cooled, housing. When hit by the extracted protons from PS, the heat developed makes that during a short moment (mSec) the temperature rises to some 2.200°C. To avoid this thermal shock to propagate through the target it is executed in the form of several short rods rather than in a solid one.

The target is irradiated by a beam of 26GeV/c protons coming from the PS accelerator; 8-10 shots every 10Sec. Each shot from PS consists of 4 bunches (bunch length: 30nSec) spaced 105nSec. Altogether approx. $1.5E^{13}$ protons. The beam size is 1mM horizontally and 0.5mM vertically.

This yield many different particles (sec. protons, electrons, positrons, pions, kaons, muons etc.) amongst which also some $5.88E^{7}$ anti protons with a broad momentum spread.

Of these, after mass/energy separation in the AD target area, approx. $8E^{5}$ anti protons with a correct momentum of 3.57GeV/c (acceptance of AD) is selected and get finally injected into AD.
I.e. 1 usable anti proton per $19E^{6}$ protons on target.

It should be noted that these numbers here are at the moment somewhat outdated. Today (2015) AD output attains some $3.5\text{-}4.0E^{7}$ anti protons with a momentum of 0.1GeV/c ...

Supplementary detail info on next 2 pages.
Target and 'dog-leg' mass separator particle fluence table and equipment layout in the AD target area, extracted from: CERN-ACC-NOTE-2014-002.pdf

Table 1. The table presents particles fluence at different positions along the dog-leg magnets and the ratio to the antiproton fluence for the respective positions. The fluence is integrated over the energy range between [0.1, 26] GeV per one pulse of 1.5×10^{13} protons.

particle	After the collimator		After the BHZ6025		After the BHZ6035		After the BHZ6045	
	p/cm²/pulse	R	*p/cm²/pulse*	R	*p/cm²/pulse*	R	*p/cm²/pulse*	R
p	1.27×10^{11}	2164	2.44×10^{7}	4	2.84×10^{6}	2.9	2.25×10^{5}	0.28
e-	2.95×10^{9}	50	8.98×10^{7}	14	8.10×10^{6}	8	6.05×10^{6}	7.6
e+	1.53×10^{9}	26	6.27×10^{6}	1	8.49×10^{5}	0.8	5.82×10^{4}	0.07
K-	4.51×10^{8}	8	3.74×10^{7}	6	4.62×10^{6}	4.7	3.17×10^{6}	4
K+	1.93×10^{8}	3	1.02×10^{6}	0.16	9.67×10^{4}	0.09	4.04×10^{3}	0.005
Pi-	1.21×10^{10}	206	1.19×10^{9}	186	1.65×10^{8}	167	1.34×10^{8}	164
Pi+	2.66×10^{9}	45	1.60×10^{7}	2.5	1.64×10^{6}	1.6	1.52×10^{5}	0.2
mu-	2.23×10^{8}	4	4.97×10^{7}	8	1.09×10^{7}	11	7.59×10^{6}	9.6
mu+	3.62×10^{7}	0.6	5.03×10^{5}	0.07	1.06×10^{4}	0.03	0	0
pbar	5.88×10^{7}	1	6.38×10^{6}	1	9.86×10^{5}	1	7.91×10^{5}	1

The results clearly indicate that the position after the dog-leg (after the BHZ6045) is the optimal one to measure the negatively charged particles with the right momentum required by the AD ring acceptance. Among the considered BCT locations only this one can provide a very narrow antiproton spectrum fully contained in the energy range of [2, 3] GeV. The particles spectra after the dog-leg are dominated by the negative pion contribution (see Table 1). The antiproton fluence at this location is two orders of magnitude lower, while non-negligible contribution from neagtive kaons, muons and electrons components is expected. The positive particles contribution (in particular protons) to the overall particle fluence is negligible. Negative pions of 3.57 GeV/c momentum (corresponding to a kinetic energy of 3.43 GeV) are transported together with the antiproton beam in the AD ring where mainly decay after few turns. We can anticipate that electrons injected at the same time lose their energy by synchrotron radiation, spiral towards the central orbits and are lost on the various shutters belonging to injection and cooling devices [4], [5].

As expected, at the TFA6006 position, the antiproton fluence is more than three orders of magnitude lower than the proton one (Table 1). Fluence maps have also been produced (see Figures [7-16]) averaged over a vertical range of ±20 cm centered on the beam axis, for each of the species listed in Table 1. Due to the specific shape of the QDE6030 quadrupole (see Ref. [3]) a sizeable particles fraction, for most of the considered particle species, is deflected towards the target area lateral shielding.

1 Introduction

The AD (Antiproton Decelerator) target area is the source of low-energy antiprotons for the antimatter experiments at CERN. In order to guarantee the reliable production of antiprotons for the AD physics program in the ELENA-era, an ambitious consolidation program has been launched in the AD target area. In order to support specific requirements of the upgrade project, a set of FLUKA simulations have been already carried out. The presented studies are the continuation of the extensive work on antiproton production described in CERN-ATS-Note-2012-069 TECH [3]. This note extends the study with a more detailed evaluation of particle fluence in various areas of the dog-leg.

2 The ADT FLUKA geometry and BCT positions

The antiproton production assembly together with the focusing horn, collimators, beam dump and bending/focusing magnets present in the AD-target area are shown in Fig. 1. [7]. Based on the detailed FLUKA model of the AD-target area (Fig. 2.) described in ref. [3], further extensive investigation on the particles' fluence distribution in the AD-target zone have been carried out.

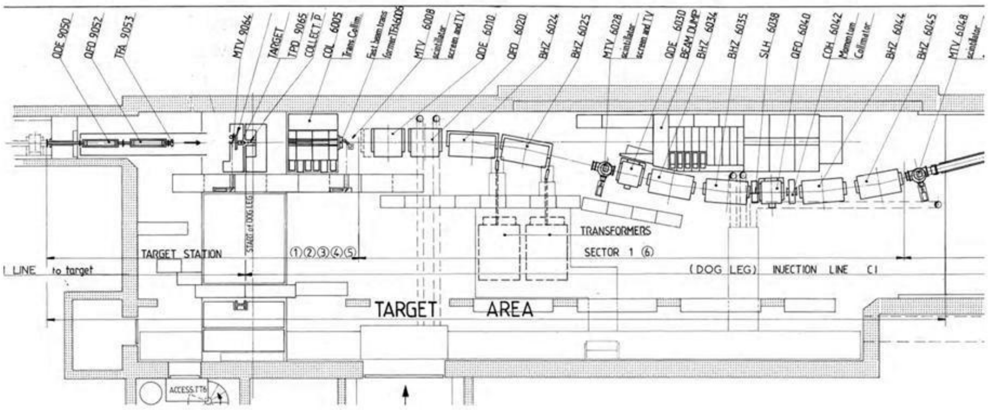


Fig. 1: The AD-target area technical drawing with the antiproton beam production and bending/focusing elements [7].

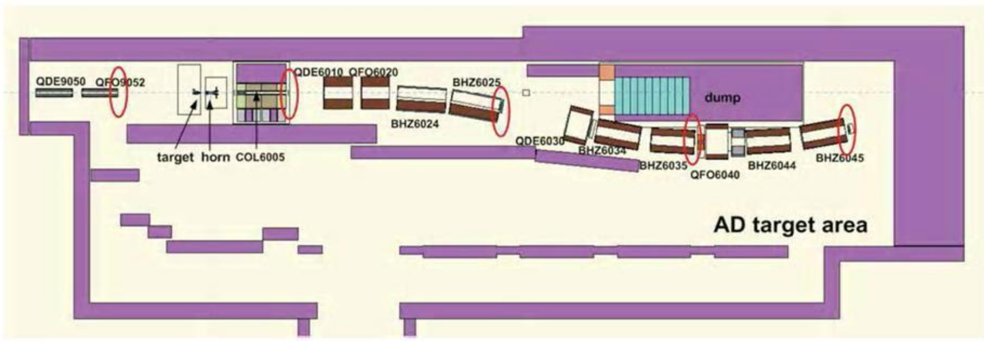


Fig. 2: The AD-target area FLUKA model. The existing BCT positions (downstream the QFO9052 magnet and the COL6005 collimator) and the considered for future installation ones (along the dog-leg) are indicated in red.

Positron source.
(Info: Discussion with Simon van Gorp (ASACUSA) on 09/10-2014 and Lars Varming Joergensen on 25/03-2015.)

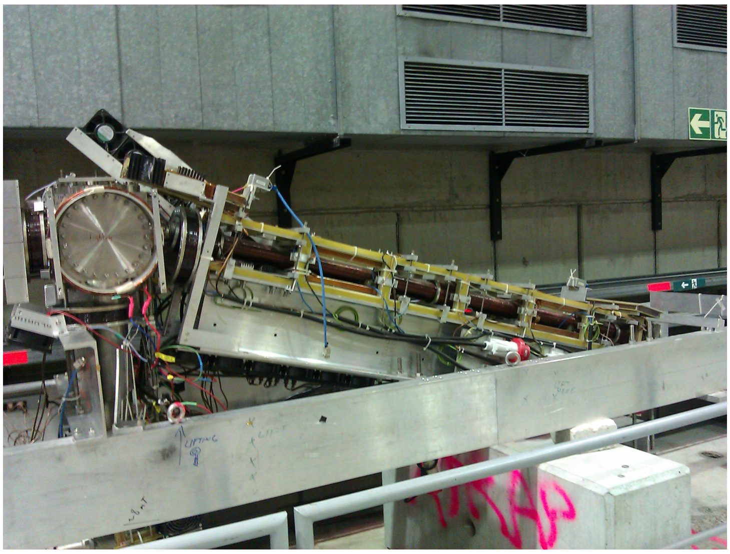
Positrons are obtained with a naturally radioactive source of ^{22}Na (atomic number: 11) which decays into ^{22}Ne (atomic number: 10) by emitting a positron and an electron neutrino (a proton converts into a neutron). The Sodium source had an initial radioactivity of some 300MBq (300E^{6} disintegrations per second. Very radioactive!) and has a half life of 2.6years. The emitted positron has a kinetic energy spectrum of between .55 and 1.8 MeV. In other words 'it moves' fast, too fast to be captured by an anti proton in order to form an anti hydrogen atom.

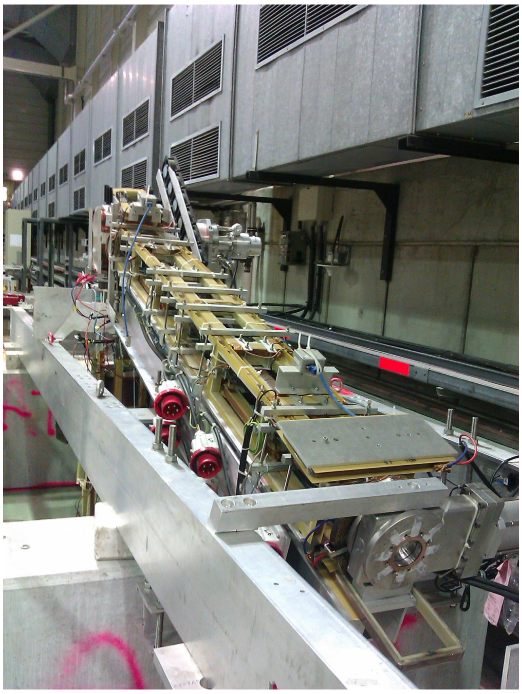
By leading the positron radiation from the Sodium source through a layer of 10µM of Neon ice at 4K the positron looses most of it kinetic energy which is transferred to the Neon crystal grid and then annihilate. Approximately 1% of the positrons however manage to diffuse to the surface of the ice where the surface tension, which normally pulls back free electrons (negative) into the material, will expel the positively charged positrons that did not annihilate (also see ALPHA-2 experiment).

Upon leaving the sheet of Ne-ice these positrons have slowed down corresponding to an energy of a approx. 4eV. They can now easily be transported in a simple solenoid field (see photos below) to a device in which are also present, stored, slowed down (<5keV), very cool anti protons (a so-called 'trap').

Note that this solenoid is sloping upward because the fringe field of ATRAP's magnet (1.5T) interferes with the transport channel solenoid. Once above the trap a vertical transport takes the positrons into the trap.

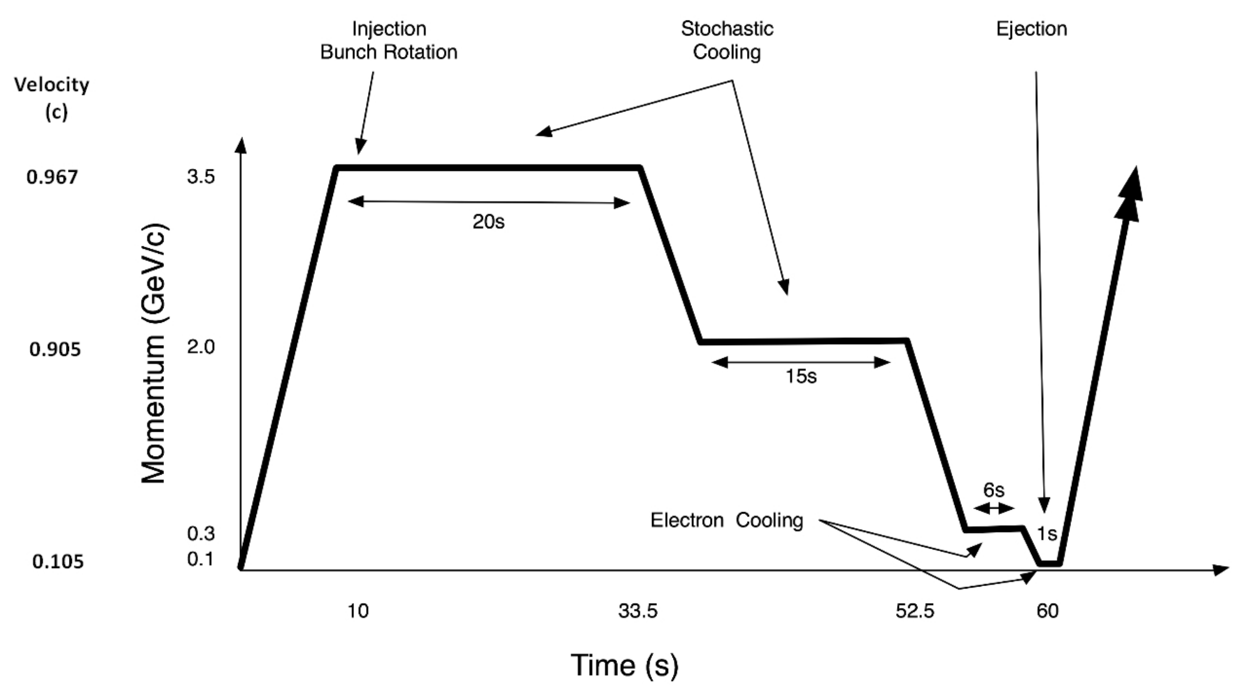
Here the anti Hydrogen can then be created when an anti proton captures a positron.





Solenoid positron transport coil for the ATRAP experiment.
(spare module)

The AD machine.



The AD Machine Cycle. Overall cycle time: 60Sec.
Velocity calculation: http://hyperphysics.phy-astr.gsu.edu/hbase/Relativ/relmom.html#c4

The order of things happening during an AD Machine Cycle are:

High energy injection platform.

Injection of 4 short bunches (105nSec apart; 30nSec long) of together some $8E^5$ anti protons of 3.57GeV/c (2.75GeV kinetic energy) have the correct, sufficiently small, momentum spread for being accepted by AD. (Since 2001 this seems to be increased to some $3E^7$ anti protons per pulse after an improvement program. See: CERN/PS 2002-046 (OP)) Their velocity is approx. 95% of the speed of light. RF gymnastics (bunch rotation) makes them longer with less momentum spread. Stochastic cooling during the injection platform reduces momentum spread even more while making the bunches shorter, more intense. Stochastic cooling is more effective at higher energy of the anti protons. This phase lasts for 20Sec. Stochastic cooling was invented in 1972 at CERN by Simon van der Meer and allowed for creation of anti proton beams of sufficient intensity and thus for SPS to be operated as a p-pBar collider.

Deceleration to 2.0GeV/c.

Stochastic cooling is switched off during deceleration.

Intermediate energy platform.

Arriving at the intermediate energy platform of 2.0GeV/c (1.27GeV kinetic energy) stochastic cooling is again applied during 15Sec. Again it reduces momentum spread in all transversal and longitudinal phase spaces making the bunches more intense and shorter. This phase lasts for 15Sec.

(continued on next page)

The AD Machine - suite

Deceleration to .3GeV/c.
Stochastic cooling is switched off during deceleration.
Intermediate energy platform.
At the .3GeV/c (46.8MeV kinetic energy) intermediate energy platform electron cooling (invented by Gersh Budker in 1966) is now applied for less momentum spread and more intense bunches. Electron cooling is more effective at lower energy. This phase lasts for 6Sec.
Deceleration to .1GeV/c.
Electron cooling is switched off during deceleration .
Intermediate energy platform.
At the .1GeV/c (5.31MeV kinetic energy) intermediate energy platform electron cooling is again applied for less momentum spread and more intense bunches. This phase lasts for 1Sec.
Now the anti protons have become slow (10% of the speed of light) and will be ejected towards one of the experiments where they are recombined with positrons to form anti hydrogen.

The latest developments in the AD cycle show that the stochastic cooling platforms have been shortened a bit and the electron cooling platforms have been lengthened. Overall cycletime has not changed. Today (2015) AD output attains some 3.5-4.0E^7 anti protons with a momentum of 0.1GeV/c (5.31MeV kinetic energy). The numbers earlier mentioned are somewhat outdated ...

Note that AD has a dynamic deceleration range of approx. 35. The accelerators at CERN do not go beyond a range of 20-25! Also, deceleration is a more delicate process. As the particle's forward momentum decreases during the process, its transversal movement becomes more pronounced (hence the necessity of cooling). This is exactly the contrary with acceleration of particles where the forward momentum continuously increases; the beam tends to take 'less and less space' in the vacuum chamber!

(Info from Lars Varming Joergensen on 25/03-2015.)

The ELENA machine.

A new supplementary decelerator, ELENA (Extra Low ENergy Antiproton ring), is currently under construction. It is a hexagonal machine with a circumference of 30.4M. It will accept the decelerated anti protons from AD and decelerate them from 5.3Mev (100MeV/c) further down to approx. 100keV (13.7MeV/c) kinetic energy. See:
https://espace.cern.ch/elena-project/SitePages/Home.aspx

The aim of ELENA is to increase efficiency for obtaining very low energy antiprotons with a higher efficiency than currently can obtained. Today, AD's lowest obtainable antiproton momentum of 100MeV/c (5.3MeV kinetic energy) is further lowered by means of passing the antiprotons through a set of 'degrading foils'. Indeed, with this process of 'deceleration' some 99% of the 3.5-4.0E^7 anti-protons from AD is lost; only ~1-0.5% of these arrive finally at the required energy for the experiments.

ELENA will increase this efficiency from ~1-0.5% to approx. 60% (conservative guess).

The AD experiments traps, where the antihydrogene atoms are produced, are operated at some 5kV. Therefore ideally the antiprotons extracted from ELENA should have a kinetic energy in the order of max. 5keV.
This is not possible to obtain with ELENA; space charge and rest gas scattering effects blow up the very slowly moving (<< 1% of c) antiproton beam. Also production of very slow (very cool) electrons for the electron cooler becomes problematic and the cooler thus becomes less efficient.
The best compromise that can be made is therefore to go as low as 100keV kinetic energy and that became the design value for ELENA. See:

http://cds.cern.ch/record/1694484/files/CERN-2014-002.pdf	ELENA-Design report_CERN-2014-002.pdf

Some nice facts and numbers. - (suite 26).

Some technical information.

ELENA uses a FineMet loaded deceleration RF cavity. FineMet technology, invented by Hitachi, gives an RF cavity a wideband characteristic and so it does not need a tuning device during deceleration. It also means low cavity Q-factor so deceleration fieldstrength in the cavity gap is low; therefore it requires relatively more RF power for a required fieldstrength. This is not a problem here because for deceleration the antiprotons already are 'quite' slow and the fieldstrength for deceleration can consequently be low as well.
Furthermore, because of its wider bandwidth, spuriously beam induced signals are now in the passband of the cavity and the RF feedback systems must handle, damp, these in order to avoid interaction with the beam.

Some numbers:

- Frequency sweep during the deceleration cycle (h=1): 1150kHz to 143kHz
  max. frequency with h=2 is 2300kHz (injection; 2 bunches)
- Max. available cavity RF voltage: 500V if freq. is >500kHz; 100V if freq. is <500kHz (The ELENA designbook speaks of some 100V at injection and less than 10V, even less than 1V, at extraction. E. B.)
- Currently ELENA is in the phase of 'beam commisioning'. (September 2017)

(Info from John Molendijk on 20/09-2017)

Interesting beam transfer line details:

- The ELENA injection beamline uses magnetic elements, septum and injection kicker.
- The ELENA ejection beamline is made with electrostatic elements, septum and ejection kicker.
- Advantages of electrostatic elements in the transferline are:
  - Economic construction of electrodes and powerconverters.
  - Low power consumption.
  - No hysteresis gives easy operation for a pulsed machine.
  - No (water-)cooling needs.
  - Simple shielding against stray magnetic fields.

Note by Erik on the extract from the ELENA design report of the next page.
It says:

The basic scenario is to extract four bunches to four experiments during one turn [3]. This will increase significantly the time available for physics for each of the users. At the same time, the main intensity limitations, such as the transverse space charge and the IBS, are also relaxed. The extraction of a smaller number of bunches at the RF harmonic number $h = 1, 2,$ or 3 in the event of a smaller number of experiments ready for a physics run is also foreseen. Fast electrostatic deflectors in ELENA

... etc.

It gives the first impression that 'four bunches ... during one turn' could be decelerated and extracted at 'RF harmonic number h=1, 2 or 3...'. Read like this that is of course not true.

The original text consists actually of 2 separate paragraphs and should be interpreted also separately:

- Par.1 start: The basic scenario ....
  Par.1 end: ... are also relaxed.
- Par.2 start: The extraction of a ...
  Par.2 end: ... is also foreseen.

2.6 Beam extraction and the main machine parameters

The basic scenario is to extract four bunches to four experiments during one turn [3]. This will increase significantly the time available for physics for each of the users. At the same time, the main intensity limitations, such as the transverse space charge and the IBS, are also relaxed. The extraction of a smaller number of bunches at the RF harmonic number h = 1, 2, or 3 in the event of a smaller number of experiments ready for a physics run is also foreseen. Fast electrostatic deflectors in ELENA transfer lines provide the true destination for each bunch. The extraction of one or two bunches might be performed with a reduced number of particles per bunch, or with bigger emittances due to the space charge limit. Table 1 below illustrates the main ELENA parameters.

Table 1: The main ELENA parameters

Momentum range, MeV/c	100–13.7
Energy range, MeV	5.3–0.1
Circumference, m	30.4055
Intensity of injected beam	3×10^7
Intensity of ejected beam	1.8×10^7
Number of extracted bunches	1–4
Emittances (h/v) at 100 keV, $h = 4\ \pi\cdot$mm·mrad [95%]	4/4

2.7 The ELENA cycle

The ELENA cycle is very similar to that of the AD ring. It consists of three principal plateaus and two ramps (Fig. 7). The bunched beam is transferred from the AD and injected into ELENA, into the RF bucket with harmonic h = 1. It is then decelerated from 100 MeV/c down to an intermediate momentum in the range of 35–40 MeV/c (to be defined precisely during commissioning). Here, electron cooling is applied to the coasting antiproton beam for the first time, to counteract the emittance blow-up during deceleration. After cooling, the beam is bunched again and decelerated down to the extraction momentum of 13.7 MeV/c. There, the beam is debunched and cooled again. When the beam has been cooled down to certain emittance and momentum spread values (probably close to equilibrium values), the RF voltage is applied to compress the beam. When the beam achieves the required values for the emittances and the bunch length, it is extracted using the electrostatic deflecting device(s) into the experimental areas that are ready to use it. The number of extracted bunches depends on the number of experiments requesting a beam, but the nominal mode of operation is to assume the extraction of four bunches. The approximate cycle length is about 20 s.

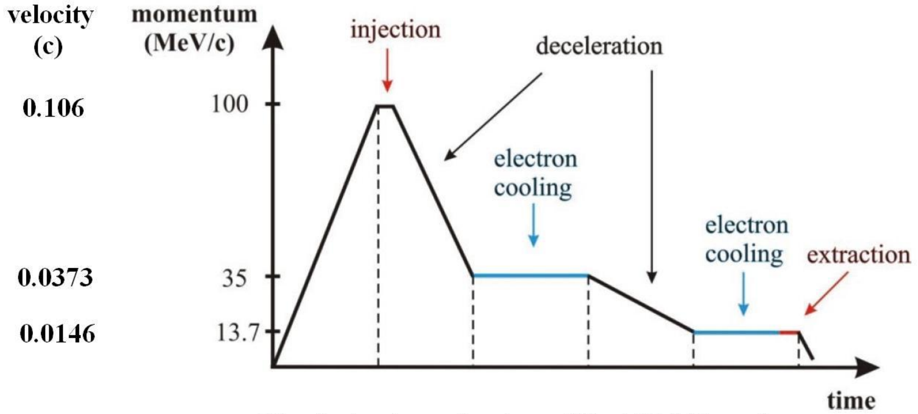


Fig. 7: A schematic view of the ELENA cycle

From: ELENA-Design report_CERN-2014-002.pdf
Velocity calculation: http://hyperphysics.phy-astr.gsu.edu/hbase/Relativ/relmom.html#c4

Some nice facts and numbers. - (suite 28).

Linac2 and LEIR characteristics. (From: Linac2 and LEIR Itineraries.)

The main distinguishable parts of the Linac2 complex with their characteristics are:

- The duoplasmatron proton source.
  Here the hydrogen gas coming from the bottle is heated (exited) and fully ionized with the help of a potential of approx. 90kV. The maximum output current of the proton source amounts to max. 500mA.
- The RF Quadrupole buncher and pre-accelerator.
  A first pre-acceleration and pre-bunching of the continuous flow of protons coming from the proton source takes place inside this approx. 1M long structure. The acceleration of proton bunches goes to approx. 750keV. The RFQ system replaced in the past the voluminous Cockcroft-Walton pre-injector that is currently exhibited in the Leon van Hove square in front of the MicroCosm exhibition.
  RFQ was proposed, invented, in 1970 by Russian physicists Kapchinskij and Teplyakov and came to the western world in 1977. First prototype experiments in Los Alamos National Laboratory demonstrated superior efficiency (90%) as compared to conventional pre-injectors (Cockroft-Walton: approx. 50%).
  Note that the mechanical machining precision of this device is in the order of 20µM.
- The Linac2 itself.
  Acceleration takes here place from 750keV to 50Mev. Linac2 is 30M long, consists of 3 resonating tanks and delivers every 1.2Sec max. 180mA of accelerated bunched protons at its end. Operating frequency is 202.56MHz. At 50MeV the protons attain a speed of approx. 31% of the speed of light.

A nice document with photo's of, amongst others, the Linac2 system is D. Manglunki's (BE/OP) 'The LHC injection chain.pdf'. On the RF Quadrupole, see Alessandra Lombardi's slideshow document PDF-1.pdf or Maurizio Vretenar's note CERN-2013-001-p207.pdf

The 3 functions of the LEIR machine are:

- Accumulation of sufficient $^{208}Pb^{54+}$ ion bunches for injection in PS, ultimately, LHC.
- Reduction of Horizontal, Vertical and Longitudinal emittances of the lead ions.
- Acceleration to injection energy of PS.

Accumulation of $^{208}Pb^{54+}$ ions is done during the 2.4Sec injection phase of LEIR in a so-called '3-plane vertical stacking' scheme. It proceeds by a multi-turn injection (~70 turns) and vertical stacking of each of the 4 injected batches with approx. $1.15E^{9}$ $^{208}Pb^{54+}$ ions at the injection energy (given by Linac3) of 4.2Mev/u. On the injection platform the lead ions are also 'cooled' in all H, V and longitudinal phase planes by the electron cooler (Invented in 1966 by the Russian physicist Gersh Budker). It operates by mixing electrons, that move at the same speed as the ions, over a fraction of LEIR's circumference (~3%) alongside these latter. The 'hot' excitation in the 3 phase planes of the heavy lead ions is now transferred to the lighter, 'cool', electrons, which reduces in that way the emittances in the 3 phase planes of the ions; bunches become thus more mono energetic and dense.
Note: The accelerated lead ions are inside LEIR not yet fully ionized: only 54 of the total of 82 electrons are eliminated. The rest of the electrons will be eliminated during the acceleration and extraction processes in the PS machine, later on.

During the following 1.2Sec phase of acceleration to 72.2MeV/u cooling of the lead ions continues and the 4 injected batches merge into one dense and mono energetic one.
The ions are accelerated to an energy of 72.2Mev/u in LEIR; ready for ejection towards PS. Their number amounts to approx. $9.0E^{8}$ per extracted batch. The total cycle time of LEIR is 3.6Sec, like the acceleration cycle of PS.

LEIR's circumference is 78.54M (=1/8 of PS; 1/88 of SPS). Its acceleration operates below transition and a particularity is that the injection transfer line coming from Linac3 is also partially used as the extraction transfer line towards PS.

A nice document with photo's and numbers of, amongst others, the LEIR system is D. Manglunki's (BE/OP) 'The LHC injection chain.pdf'

Some nice facts and numbers. - (suite 29).

LHCb and CAST characteristics. (From: LHCb - CAST Itinerary.)

LHCb experiment.

Description of the LHCb detectors, seen downstream wards from the pp interaction point.

- The VErtex LOcator detector.
  The pp collision point lies inside VELO. Its two slightly overlapping half moon shaped silicon strip detectors surround the LHC proton beams at a distance of 7mM during data taking. During beam setup of LHC VELO can be mechanically retracted to a distance of 7cM with respect of each half-moon to avoid being damaged while beams are not yet stabilized.
  Particles studied by LHCb are so-called B- and D-Mesons. Particles built from a quark and an anti-quark.
  VELO does not detect these mesons directly; they do not interact with the detector but their well known decay signature is detected. Their time of living is short: order of a few picoSeconds; just enough time to travel a few mM inside VELO. The distance between the pp collision point and the point where the mesons decay products are detected (muons, pions) allows VELO to determine the position where the B-meson was created to within a precision of 10microM.
  VELO consists of 2x 21 modules and delivers 22.000 channel (position) signals.
- The Ring Image CHerenkov 1 and 2 detectors.
  Uses the Cherenkov effect for measuring the speed of traversing decay particles. This principle can be described like a 'sonic boom'; the particle moves faster than the speed of light in the medium. The 'boom' in this case is a cone of light, whose top angle depends on the speed of the particle. Together with the analysis magnet it enables LHCb to make particle identification.
  RICH1, situated before the magnet, measures low momentum (order of a few GeV/c) particles by using a high refractive index radiator (Silica Aero gel) together with a radiator gas filling ofC_4F_{10}.
  RICH2 is situated after the magnet and is setup for measuring high momentum particles. It uses as radiator a gas filling of CF_4.
  Both RICH's cover together a particle momentum measuring range of approx. 10-115GeV/c
- The semiconductor Trigger Tracker.
  Located immediately after RICH1 and before the dipole magnet.
- The track analysis dipole magnet.
  By curving the trajectory of the passing electrically charged particles their momentum (p=m.v) can be determined. Together with the RICH detectors, which measure the speed (v), the mass (m) of the traversing particle can now also be determined. Total weight is approx. 1500 ton. (Total LHCb weight: 4500 ton.)
- The Inner and Outer tracking detectors.
  Located immediately after the dipole magnet. It consists of a semiconductor 'Inner' detector part, around the traversing LHC beam pipe, and an 'Outer' part, surrounding the Inner tracker and located somewhat radially further away from the beampipe. It is made of gas filled tubes with a thin wire (so-called 'straws'). A high voltage is applied between the wire and the tube; the place of gas ionization is measured along the wire when a particle traverses the tube. Spatial resolution in the order of 0.2mM.
- The Electro magnetic Calorimeter.
  Here all low massive particles (HE electrons and positrons) and photons are completely stopped in many consecutive lead sheets which are interleaved with scintillator plastic sheets. This produces a shower of secondary, lower energy electrons in the lead which create on their turn scintillation effects in the plastic. Integrating the amount of light thus obtained (photomultipliers) is a measure of the Energy of the stopped electron, positron or photon.
- The Hadronic Calorimeter.
  Same functionality, but for Hadron like particles: Protons, Neutrons. The stopping sheets are made of steel.
- The Muon spectrometer.

CAST Axion experiment.

- CAST means: CERN Axion Solar Telescope.
- Outside the building, note the window that allows the 2x per year (equinox) calibration of the telescope to point to the Sun!
- First thing to do when entering the visitor's area of CAST is to close the staircase gate towards ground floor. No visitors allowed down there!
- Example of a small experiment at CERN, it does not even use beams from the CERN accelerators but uses the Sun as particle source. Many components of it were obtained from 'scrap parts' from industry and CERN prototypes (dismantled experiments, accelerator design).

- The telescope, detector, is a prototype (10M) standard LHC dipole magnet with the beam pipes that can be filled or not with a gas (^4He, ^3He). The gas makes that photons do not move with the speed of light in vacuum anymore and to that phenomenon one can attribute a 'virtual' mass to them. By varying this virtual mass (selection of vacuum, type of gas, pressure of gas) the probability of axion to photon conversion (the coupling factor) can thus be varied. It allows for scanning an energy range of the photons and thus of the energy, mass, of the axion.
- The magnetic field (9T @ 13kA) is supposed to transform the Axion particle into low energy gamma rays (2.10^{-10} - 10^{-9} GeV) which can then be detected. A full scan as a function of the studied energy is obtained by setting the telescope's sensitivity for Axion to gamma ray conversion via the type of gas used (vacuum, ^4He, ^3He), its pressure (16.4-135.6mbar) and the magnet's magnetic field strength.
- Due to mechanical limitations of the used magnet (the cold mass of the magnet could break away) the telescope can only be elevated some 8°, azimuthally the telescope can move approx. 80° in order to follow the Sun during 2x 1.5 hours per day. The rest of the time gamma background measurements are done.
- The telescope can be setup twice per day, the side looking towards the building window is pointed at the Sun at sunrise, the other side can be pointed at the Sun at sunset.
- When looking at sunrise, the far end of the telescope's 2 cold bores is equipped with a CCD + X-ray telescope and a Micromegas (sort of MWPC) strip detector, the latter is capable of distinguishing between a background X-ray and one coming from the direction of pointing of CAST. At sunset the far end uses 2 Micromegas. See expo and files: 'Cast CCD.pdf' and 'Cast Micromegas.pdf'.
- CAST was built with components (SC magnet, cooling plant, photon telescope and pixel CCD) that were 'recovered material' from other, dismantled experiments (LHC magnet prototype, Delphi, Abrixas).

- The Axion particle was named after a soap brand, 'Axion'. The official story says that the Axion nicely washes away the 'Strong CP Problem' (see: CAST, a little physics background). Unofficially however, it seemed that initially there was an inaccuracy in the theory and certain measurements showed the fault. The theorists corrected their theory and therefore named the particle, that repaired their theory, after the soap brand for 'washing away' their shame...

CAST, a little physics background.

In the years 1950, according to the 'particle physics rule book' called the Standard Model certain symmetries were thought to exist between the processes of creation and decay of particles and their anti-particles . These reactions should be the same, i.e. conservation of energy and of certain other parameters, in the 2 directions: either when decay occurs or, on the contrary, when synthesis from pure energy is seen. Furthermore, these processes should work in the same way whether matter or anti-matter were involved (except for the electric charge differences between matter and anti-matter, of course: symmetry!).

It was observed however that sometimes this was not true and it was said that 'symmetry was broken'. Notably in processes where the weak nuclear force is involved.The 'rule book' was then extended with theories that explained the phenomena and subsequent experiments proved these extensions to the theory to be indeed correct.

At the same time however the now extended 'rule book' obliged us to accept these symmetry breaking phenomena for other processes as well. Notably for the symmetry of CP (Charge conjugation - Parity) by which the 'Strong force' from our 'rule book' was involved. Here, unfortunately, Nature showed a perfect symmetrical behaviour. The so called 'Strong CP problem' presented itself to the physicists...

It was therefore theoretically assumed (Peccei & Quinn amongst others) that when the Strong force was involved in a process, another, global symmetry operated that compensated the symmetry breaking phenomenon as predicted by the 'rule book' and therefore in this case, where the Strong force acted, symmetry remained perfectly conserved.

If this new add-on theory were indeed correct, then a particle would also be associated with it and it was called the Axion after a washing detergent because it so neatly 'washed away' the 'Strong CP problem'.

Axions are thought to be produced when gammy rays traverse a strong electrical or magnetic field. This situation occurs e.g. in the Sun's core where strong electrical fields and strong gamma rays are produced by the nuclear fusion process . Likewise, theory predicts that Axions can be transformed back into gamma rays when they pass through a strong electrical or magnetic field.

This latter (hypothetical) process is exploited at the CAST experiment because detecting gamma rays is much easier than directly detecting Axions.

The Axion has practically no mass ($1\mu eV/c^2 < m < 1eV/c^2$), has no charge, therefore extremely little interaction with other matter, much like to the neutrino. For that reason, like the neutrino, they can easily escape from the Sun where they are thought to be produced in large quantities.

Some nice facts and numbers. - (suite 32).

AMS info. (Distilled from: AMS Itinerary.
Info from: AMS-02 WWW site: http://www.ams02.org/ and Mark Tyrrell: AMS notes.doc)

- AMS-02, what is it?
  - A HE (High Energy) particle physics experiment.
  - AMS stands for: Alpha Magnetic Spectrometer. 'Alpha' because NASA thought there would surely be some more spectrometers be coupled to ISS.
  - Some numbers: height 5M; diameter 3M; weight 7500kg (compare: space shuttle: 2800kg!).
  - Located outside the Earth's atmosphere, coupled to the ISS.
  - Launched May 16th, 2011 with the very last flight of the Endeavour space shuttle; the fore last shuttle flight in the US Space Shuttle Program. It takes less than 10 minutes before arriving at the ISS orbit.
  - It will stay with ISS as long as the latter will exist; it is said until at least 2020, but also 2028 is heard. It will not return back to Earth.
- Who's idea was it?
  - AMS-02 is a scientific collaboration between 56 institutes in 16 countries all over 3 continents. They brought together the $ 1.5 billion for the construction and the operation of AMS-02. Altogether some 600 scientists and engineers work on AMS-02.
  - The collaboration came into being under the auspices of the US DoE (Department of Energy).
  - NASA is the responsible organization for launching and operation at the ISS of AMS-02.
  - The 'motor' behind the collaboration is prof. Samuel Ting, Nobel price for physics 1976 (discovery of the charm quark; J/Psi).
- What is the aim of AMS-02?
  - AMS-02 tries to find indications which lead to answering the questions:
    - What happened to the anti matter in the Universe?
    - What exactly is 'Dark Matter'? (See next page: A small memory refresher from the Standard Model)
- Why AMS- '02'?
  - AMS-01 also existed. It was a prototype for AMS-02.
  - AMS-01 was sent up to ISS with an earlier flight of a space shuttle but it never left the shuttle and was also never attached to ISS.
  - AMS-01 was brought back to Earth for studying the influence of the transport flight on the mechanical structure and the very sensitive, fragile in a sense, electronics and detectors.
  - Indeed, the flight to ISS is a real torture to a device like a spectrometer of this kind! What was learned from this test flight was incorporated in the final design which became then AMS-02.
- Why in space?
  - Anti matter coming from space to the Earth would annihilate with the air molecules of the atmosphere and can therefore not be studied on Earth.
- About the ISS (International Space Station) and the POCC (Payload Operational Control Center).
  - ISS circles the Earth at a height of 383kM.
  - ISS orbits Earth every 93 minutes.
  - ISS has approx. the size of a football field: : 110x74x30M (length x height x large).
  - We can see in real time the position of ISS in its orbit on the wall screen at the end of the Control Center. The circle around ISS is the horizon when looking to the Earth from ISS.

  - The technicians/physicists in the control room verify the various subsystems of AMS-02. They are responsible for the correct functioning of the whole of AMS-02. They also take care for the retrieval of buffered measurement data and dispatching of it to the data storage centers on Earth (surveillance of the up/down data links).
  - The operator with the headset is the AMS control room shift leader; he is in continuous contact with the 'voice' communication between ground control (Houston) and ISS.
  - This contact is called the 'voice loop' and all discussion is recorded.
  - Communication over the voice loop is done in a special, military like language that one has to learn. The shift leader masters this language.
  - All requests from AMS POCC for intervention by astronauts on AMS-02 or its sub systems have to pass via the voice loop to Houston, who will, after their acceptance of the request, transmit it to the astronauts on board of ISS for execution.
  - It is not possible for the shift leader to directly communicate with the astronauts.
  - The central chair around the table in the center, the one with the high back, is Samuel Ting's chair. No one else but he uses this chair...

Some nice facts and numbers. - (suite 33).

- A small memory refresher from the Standard Model:
  5% of the mass in the Universe is visible matter and is 'explained' by the SM.
  But, for understanding the Universe as we observe it, we need to add to our theory:
  27% more mass in the Universe which is however invisible, we call it dark matter and we don't know what exactly it is...
  68% more energy in the Universe which is however unmeasurable, we call it dark energy and we don't know what exactly it is...

- Sonia Natale (guide instructor) mentions an anecdote during the assembly of AMS at CERN when she actively worked on the project. At a certain moment she had to assemble detector parts with flatcables and wanted to mark, number, these with a simple black ink marker. However, before she was allowed to do so, NASA had to be consulted in order to obtain permission for the type of marker which had to be used for that job. A special, space compliant, marker needed to be bought and used for it!

- The AMS-02 detector lay-out (the 'maquette') from top to bottom.

  Note that the links ... www.ams02.org/what-is-ams/tecnology/ ... in the next part of the text are now obsolete (20230920). The detector construction and functionning information can now be found at a new site via URL: https://ams02.space/detector

  - Transition Radiation Detector
    - Only sensitive for HE electrons, positrons.
    - The detector is built of 328 modules each consisting of:
      - 20 mm of radiator made of polypropylene/polyethylene fiber fleece corresponding to 0.06 g/cm³. The large number of interfaces increases the probability of production of X-rays.
      - 16 tube straws filled with a $Xe:CO_2$ (80%:20%) gas mixture operating at 1,600 V (full avalanche regime). The Xenon-rich gas mixture has an high efficiency for X-rays conversion.
        Pasted from <http://www.ams02.org/what-is-ams/tecnology/trd/>
    - The HE particles produce 'showers' of X rays when flying through the medium transitions inside the detector. The X rays are consecutively measured by the gas filled straw tube detectors.
    - This helps distinguishing between e.g. HE positrons and LE protons which both leave the same track (bending radius) in the tracking system.
  - Time Of Flight detector.
    - Sensitive for all HE particles.
    - Consists of 2 parts: one before the passage of the magnet field and one after the passage through the magnet field,
    - Functions like a 'stopwatch' and yields this way the distinction between particles flying from 'top' to bottom' (the interesting ones) and those flying from 'bottom' to 'top'.
    - These latter particle are rejected from measurement.
    - Time resolution: order of 100pSec.
  - The analysis magnet.
    - Originally intended was a SC (Super Conducting) magnet (1T) for a mission of 2 years.
    - Disadvantage: required replenishing of the (liquid) He for the SC cooling. Advantage: strong magnet field, higher measurement resolution.
    - Finally was chosen for a permanent magnet system (0.15T) because US government decided to stop the Space Shuttle program.
    - The magnet has a dipole magnet field in the X-axis of the coordinate (measurement) system.
    - It is a so called 'Magic Ring' Halbach array magnet (built from >6000 little neodimium-iron-boron magnets) which shows the characteristic of a dipole magnet although it takes shape as a 'ring'. Another characteristic is that it has a very low stray magnet field outside of the ring. This is required by NASA because a stray field interacts with the Earth magnetic field and would influence negatively the orbit and orbiting speed of ISS.
      (See e.g.: http://www.ams02.org/what-is-ams/tecnology/magnet/pmmagnet/ and:
      http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.908.3198&rep=rep1&type=pdf)

- The Tracking System.
  - Inside the magnet ring is a silicon tracking system consisting of seven layers of strip detectors.
  - Outside the magnet ring is mounted, just before the TRD and just before the ECAL, in total 2 other layers of strip detectors that make part of the tracking system (9 planes altogether).
  - The basic element of the AMS Silicon Tracker is the double-sided micro-strip sensor. The sensor consists on a substrate of high purity doped silicon 300 μm thick. On the two sides of the substrate tiny aluminum strips are running in orthogonal directions (the typical inter-strip distance is 50 μm).
    When a charged particle crosses the Silicon substrate about 24,000 electron/hole pairs are created. These charges are drifting in opposite directions within 10 ns (= 10^{-8} s) due to the electric field generated by the voltage *bias* applied between the two sides (80 V). Only strips near to the migrating charges will give signal. The charge center of gravity of these strips provides a position resolution of 10 μm. The sum of the electric signals on the hit strips is proportional to the square of the absolute charge of the particle.
    Pasted from <http://www.ams02.org/what-is-ams/tecnology/tracker/>
  - It forms this way a volume, 3D pixel unit, comparable to the 2D pixel chip in a photo camera.
  - The tracking system measures the momentum of the HE particles going through AMS and it is the main measurement system for particle identification via determination of their relativistic momentum ($p = \gamma . m_0 . v$).
- The second part of the Time Of Flight detector.
  - See above.
- The Ring Imaging CHerenkov detector.
  - The AMS-02 RICH, sensitive to all HE particles having mass, consists of a radiator plane, a conical mirror and a photon detection plane.
  - The radiator is the responsible for the Cherenkov radiation production. It consists of a dodecahedral polygon with a 118.5 cm internal tangent diameter. An array of 2.7 cm thick aerogel tiles with a refractive index between 1.03–1.05 surrounds a central 35×35 cm^2 region equipped with 5 mm thick Sodium Fluoride (NaF) radiator (nNaF = 1.335). This radiators combination optimizes the overall counter acceptance since the Cherenkov photons radiated by the NaF in large cones will fall within the detection area.
    Indeed the detector plane has an empty 64×64 cm^2 area in its center, matching the active area of the electromagnetic calorimeter located below. Through the empty aerea pass directly to ECAL the HE photons; they don't produce a signal in RICH, they fly at lightspeed!
  - Outside the ECAL hole, 680 4×4-multi-anode PMTs (gain 10^6 at 800 V) are arranged to cover the circular 134 cm diameter surface at the basis of the conical mirror.
    Pasted from <http://www.ams02.org/what-is-ams/tecnology/rich/>
  - Particles flying faster than light in the radiator medium emit a cone of energy (photons, light); the top angle of this cone is a function of the speed of the flying particle. The phenomenon is comparable to an aircraft flying faster through the air than the speed of sound when it emits the sonic 'boom'.
  - The cone projects itself via the mirror onto a detector as a ring; the diameter of which represents the speed and the 'thickness' of the ring gives information about the internal structure of the particle (either elementary or nuclide).
  - Together with the momentum info from the tracking system we are thus able to determine the mass of the HE particle that flies through AMS-02.

- The Electromagnetic CALorimeter.
  - All electrons, positrons and photons, flying from top to bottom through AMS-02 are inside ECAL completely stopped; their kinetic (or photonic) energy is here dissipated in the material that makes up the calorimeter.
  - ECAL is constructed as a sandwich from successive sheets of lead and (plastic) light fiber scintillators.
  - Kinetic (or photonic) energy of the particles (or photons) is transformed into a shower of secondary, LE electrons, kicked off from the braking lead sheet atoms. These LE electrons on their turn exite the electrons of the scintillator atoms that then emit light.
  - By integration of all generated light of a stopped HE particle (or photon) a measure for its energy can be determined.
  - The total weight of ECAL amounts to 496kg.

- Furthermore there are control sub-systems for:
  - Anti-Coincidence Counter, elimination of unusable 'non single event' data.
  - Tracker Alignment System, a laser beam system guarantees the correct alignment of the various detectors on the particle path through AMS.
  - Star tracking and GPS system, a spatial orientation system that allows direction location of detected particles and gamma ray sources.
- The electronics of AMS-02.
  - Altogether AMS-02 has some 300.000 electronic measurement channels. That is approx. the same number as all control channels of ISS! These AMS-02 channels are contained in its 650 electronic boards that make up the control system.
  - Downlink data transmission speed is in the order of max. 9Mb/Sec.
  - Total electrical power consumption is 2500W. ISS generates in total with its 8 big solar panel arrays (16 panels) some 84kW of electrical power.
- AMS-02 other info:
  - AMS-02 will be operated to at least 2020, maybe longer, maybe as long as ISS's lifetime.
  - It will not return to Earth at the end of its mission.

- Some physics results.
  - In September 2014 the AMS collaboration published some papers in which they stated to have found after 41 billion measurements that the positron fraction (measured number of positrons divided by the sum of number of positrons plus number of electrons) as a function of energy, did not follow the theoretically decreasing value above 8GeV but instead was increasing.
    (See: ams_new_results_-_18.09.2014.pdf)
    From <http://press.cern/press-releases/2014/09/latest-measurements-ams-experiment-unveil-new-territories-flux-cosmic-rays#overlay-context=>

    Were these excess positrons created due to collisions between HE dark matter particles? Exciting hypothesis.
  - In a presentation by Samuel Ting at CERN in May 2018 mr. Ting said that: "... none of the AMS results were predicted..." and that after 116 billion measurements AMS had found 2 candidate events for anti He-4. In a previous publication was already reported about having found candidate events for anti He-3. Furthermore:

    Ting also explained how the galactic cosmic-ray flux ratios between carbon and oxygen (C/O) and between nitrogen and oxygen (N/O), as measured by AMS, are unexpectedly different from the abundance ratios of these elements in the solar system: the C/O and N/O flux ratios from AMS are 0.9 and 0.09 respectively, whereas C/O and N/O abundance ratios in the solar system are 0.54 and 0.17.

    From <https://home.cern/scientists/updates/2018/05/latest-results-ams-experiment>

Some nice facts and numbers. - (suite 36).

COMPASS info. (Distilled from: COMPASS Itinerary.
Info from: COMPASS WWW site: http://wwwcompass.cern.ch/compass/ , Erwin Bielert: COMPASS_VISITS.pdf, Edda Gschwendtner: CNGS and North Area operation.pdf and Han Dieperink: private communication.)

- COMPASS, what is it?
  - A HE (High Energy) particle physics experiment.
  - COMPASS stands for: COmmon Muon Proton Apparatus for Structure and Spectroscopy.
  - Some numbers: height 8M; width 8M; length 60M. It is CERN's largest surface experiment.
  - It is an SPS fixed target experiment (NA58) and is located in the North Experimental Area, EHN2, building 888, at the Prévessin site.
  - It was first agreed as project in September 1998 (Memorandum of Understanding) and reviewed for a 2nd physics phase (MoU) in January 2013.
  - Installed in EHN2 during 1999-2000, physics data taking started in 2002. At this moment (June 2014, LS1) it is being prepared for the 2nd phase of data taking as from end October 2014.
- Who's idea was it?
  - COMPASS is a scientific collaboration between 24 institutes in 13 countries. Approx. 220 physicists are working for COMPASS.
- What is the aim of COMPASS?
  - COMPASS studies hadron structure (spin) and does spectroscopy with the help of high intensity muon and hadron (protons or pions) beams.
  - COMPASS is interested in how Nature functions at this moment and it studies matter in the state as is exists today.

- Something about the extraction of the SPS proton beam.
  - SPS provides a primary, slow extracted proton beam (spill: 4.8Sec) of 450GeV/c from extraction area LSS2.
  - Dipole and quadrupole magnets bring the beam via tunnel TT20 to approx. ground level (-10M), to the TCC2 splitter and primary target zone which is situated at the beginning of the North Experimental Area, close to the entrance of the EDF 400kV power line.
  - The primary beam is split into 3 sub-beams (slow extraction) that can be shot at the 3 primary targets T2, T4 and T6 in TCC2 (Han Dieperink: in BA80). Target T6 is dedicated for the production of secondary beams for COMPASS.
  - Target T6 consists of a beryllium rod of some 500mM length.

- On the M2 beam line for COMPASS.
  - Beam line M2 starts as from the T6 target.
  - Length of the beam line from T6 to COMPASS is 1131.8M.
  - The beam line is built with normal, not super conductive, quadrupole and dipole magnets.
  - Also are found dipoles together with collimators that serve for mass separation (momentum, 5% accuracy) of the secondary beam particles (secondary beam particle selection).
  - Interaction of the primary protons with the Be target yields various types of secondary particles, mainly kaons and pions (mesons).
  - Approx. 10% of these decay in a 700M long vacuum decay tunnel by which muons are produced.
  - An SPS proton beam of $1.2E^{13}$ protons on T6 yield approx. $2E^{8}$ muons at the COMPASS target. Momentum range: 60-190GeV/c (selectable with the mass separator). Spot size: ~8x8mM.
  - A 9.90M long Be filter stops all particles except the muons that form in this way the (secondary-) beam for use by COMPASS.
  - Particularity: the physical decay process of the kaons and pions makes that the resulting muon beam is polarized.
  - Other beams used for COMPASS:
    - hadrons (<$1.0E^{8}$ppp; p<280GeV/c limited by magnet strength; spot size: ~3x3mM)
    - electrons ($1.0E^{3}$epp; p=40GeV/c)

- Beam line M2 Visitor zone.
  - The beam line M2 has been designed for conducting either muons or hadrons (protons and pions) towards COMPASS.
  - We see CEDARs, detectors that allow observation of the beam quality (beam particle composition, identification) via the Cherenkov effect. These detectors are only put into the beam line trajectory when hadrons (protons, pions) are transported for COMPASS.
  - A gas ionization intensity detector follows the CEDARs (if present) and which is capable of measuring the beam intensity with a resolution of approx. 7000 particles per measurement unit on a total beam intensity of some $1E^{8}$-$1E^{12}$ particles.
  - A scintillator with photomultiplier (PM) gives an early trigger signal when the beam passes.
  - Note that on various places the beam simply traverses the air. Because this only happens once for the beam, one pass, almost no degradation to the beam line occurs.
  - The big QPL quadrupoles weigh some 10ton, are operated with 150V at a current of 750A.
  - These quadrupoles take care of focusing the beam such that the required beam specification is obtained for the COMPASS target.
  - The dipoles weigh 25ton and bend the beam upward and sideward with an angle of approx. 2° for steering accurately onto the COMPASS target.

  - Upon exiting the visit zone show the five 1000l tanks that take the Hydrogen for the liquid Hydrogen target when this target is not used by COMPASS. The gas is stored at room temperature and the pressure in the tanks is at that moment some xxbar. In its liquid form, at 20K, the target only contains a volume of 5l!

Some nice facts and numbers. - (suite 38).

- The COMPASS experiment layout.
  - The target platform.
    - Various targets are used by COMPASS:
      - Solids: Carbon, Copper, Nickel, Lead.
      - Liquid hydrogen: Container length: 1M50, 70mM diameter. Contains approx. 5l H_2 at 20K. When this target is not in use, the gas is stocked at room temperature in five 1000l tanks.
      - Polarized targets of either Lithium-Deuterate (^6LiD) or Ammonia (NH_3). Polarization is obtained with the help of a 2.5T super conductive magnet and a 70GHz RF source. The actual COMPASS 'target' consists of its Hydrogen (or Deuterium) in the nucleus.
    - The polarized target is used at a working temperature of 60mK.
    - This temperature makes that an extremely high degree of polarization can be obtained: approx. 2 out of 100 atoms are polarized; at room temperature this would be approx. 4 out of 1'00'000!
    - In front of the target we find 3 Scintillating Fibers detectors and 2 Silicon Strip detectors for the position / timing measurement of the incoming beam with respect to the target.
  - The 'Large Angle Spectrometer', the first spectrometer after the target.
    - Particles flying away with relatively large angles with respect to the through going beam are analyzed by this spectrometer.
    - In front of the analysis magnet SM1 we find the 1st part of the tracking system consisting of 2 layers (2 coordinates) MicroMegas detectors, a Scintillating Fibers detector and a Drift Chamber detector.
    - After SM1 follows the 2nd part of the tracker consisting of 2 Gas Electron Multiplier detectors and a Drift Chamber detector.
    - Next follows the Ring Imaging Cherenkov detector, surrounded with, in front, a Straw Tube detector plus a Scintillating Fibers detector and , after, a Multi Wire Proportional Chamber with a GEM detector followed by a Straw Tube detector.
    - The spectrometer's next detection stage, that of the particle's energy, is done by the two calorimeters (ECAL, HCAL). Here the particles are completely stopped, all of their kinetic energy dissipated in the detector. No 'large angle' particles remain flying on; no 'large angle' particles reach the second spectrometer (except possibly some muons...).
    - The last detection stage is the one of a muon spectrometer. Muons, the only particles that came so far through COMPASS, can hardly be stopped by matter, but spectrometry with 2 Multi Wire Proportional Chambers and heavy matter (steel; so called 'muon filter') in between will yield their kinetic energy.
    - Dead zones approx. in the center of this spectrometer's detectors let only pass particles with small angles with respect to the through going beam without being detected. These will consecutively be analyzed by the second spectrometer.
    - There also exist supplementary holes for letting pass through the incident beam on the COMPASS target. Indeed, only a small part of this incident beam reacts with the target and most of it flies through holes in all detectors, offset with respect to the experiment's centerline because of bending by SM1 and SM2, only to be stopped by the beam stop at the end of COMPASS.
  - The 'Small Angle Spectrometer', the second spectrometer.
    - Particles flying away with relatively small angles with respect to the through going beam were not analyzed by the 'Large Angle Spectrometer'; they flew through the special dead zones of it. Now they are analyzed by this second spectrometer.
    - We find here essentially the same components as those for the 'Large Angle Spectrometer:
      - An analysis magnet (SM2) surrounded with a tracker system (GEMs).
      - Place for a Ring Imaging CHerenkov detector for determination of the velocity of the particles. (Never constructed. Actually there was no money left in the budget...)
      - Electromagnetic and hadronic calorimeters for measuring their kinetic energy.
      - A muon spectrometer.

- The COMPASS experiment layout (suite 1).
  - The following components are found in both spectrometers:
    - Scintillator Fibers.
      (SF) Found in front of the target, before and after the analysis magnets. They give spatial information (fiber position) and very fast timing information when particles fly through. Six layers of fibers make up a detector: row-column give spatial coordinates.
    - MicroMegas (Micromesh Gaseous Structure).
      (MM) Precision spatial measurement device. Resolution is 90µM. Found in front of the analysis magnets. Capable of measuring the angle with which a particle traverses the detector. Makes use of proportional ionization in the gas filling, like in the MWPC (see later).
    - Spectrometer magnets.
      (SM1 and SM2) Changes trajectory of charged particles from straight line into circular. The radius of the circle is proportional to the momentum (p=m.v). Allows for finding the mass of a particle if the speed is known: particle identification.
      Characteristics: SM1: 2.5kA, 600V, 1.5MW, 120ton, 1.0Tm
      SM2: 5.0kA, 600V, 3.0MW, 420ton, 4.4Tm
    - Silicon strip detectors.
      (SI) Precision spatial measurement device. Resolution is 50µM. Found in front of the target. Metal strips on thin (100-200µM) silicon chips create a PN junction. Depleting the diode with a some 100V make an 'ionization-able' volume in the silicon for traversing particles; the 50µM spaced strips give spatial information in the form of an electrical signal.
    - Drift Chambers.
      (DC) Similar construction and functionality as the Multi Wire Proportional Chamber (see later). Distance between the wires is however 4-5cM. Very accurate time-of-arrival measurement of the electrical signals between adjacent wires allows for interpolation and thus finding the exact place where the traversing particle passed. Accuracy is ~100µM. Advantage of considerable reduction in the number of readout measurement channels (electronics).
    - Straw Tubes.
      (ST) Gas ionization chambers made of PET plastic tubes, diam. 4-6mM, inside surface made as a conductive (gold flash) ground plane; argon gas filled and with a wire under 800-1000V. Ionization by traversing particles and proportional amplification due to secondary ionization by the accelerated electrons of the primary ionization. Four layers of tubes make up a detector: row-column give spatial coordinates. Some 700-900 tubes are required for one layer.
    - Ring Imaging Cherenkov detectors.
      (RICH) Gas (C_4F_{10}) filled chamber in which particles generate a light cone if they move faster than light in that same gas. Comparable to the sonic 'boom' of the sound barrier. The top angle of the cone is proportional to the particle's speed. A parabolic mirror projects the cone as a ring, diameter of which gives the speed; thickness of the ring gives some info about the internal structure of the particle (elementary, hadronic).
    - Gas Electron Multipliers.
      (GEM) Gas filled chamber with several (3) kapton foils (50-70µM) copper clad on both sides with etched holes (30-50µM) that isolate the 2 copper clads. A voltage of 150-400V between the copper create strong fields in the holes where traversing electrons are accelerated and ionize the gas creating an avalanche per incoming electron of some 100-1000 electrons. These electrons are guided (drifting) to the next foil which has a mean higher potential and where again they create another avalanche effect in the holes. Detection strips on the chamber's wall give the intensity and spatial information (electrical signal) about the incoming particle.
    - Multi Wire Proportional Chambers.
      (MWPC) Spatial detection device, made from large surface, gas filled chambers; one side a ground plane, the other side many 1-2mM spaced, 20µM wires at 800-1000V potential. Traversing particles ionize the gas and the positive potential of the wires attract and accelerate the ionization electrons that at their turn ionize even more, but proportionally with their number, the gas. Upon arrival of all these electrons at the wire an electrical impulse is created at its end and consecutively detected by electronics. The wire placement give the spatial information about the traversing particle.

- The COMPASS experiment layout (suite 2).
    - The following components are found in both spectrometers (suite 1):
        - Electromagnetic Calorimeter.
          (ECAL) Built with lead glass bars in which HE electrons, positrons and photons deposit their kinetic or photonic energy (electromagnetic force interaction) and create a shower of secondary, low energy, electrons. The electrons generate a scintillation effect in the glass that can be measured with photomultipliers. The light is proportional to the deposited energy.
        - Hadronic Calorimeter.
          (HCAL) Built with heavy steel plates, interleaved with plastic scintillators. Hadrons are fully stopped in the steel by the nuclear strong force interaction and generate secondary electrons that take along the hadron's kinetic energy. The electrons generate a scintillation effect in the plastic sheets. This light is readout by photomultipliers (PM) thus creating a (hadron energy-) proportional electrical signal.

    - Physics trigger and data acquisition systems of both spectrometers together.
        - A total of 320.000 channels provide for physics data acquisition.
        - Light signal measurement with photomultipliers (PM) having a sensitivity that would allow to detect a candle at some 20kM distance.
        - The maximum data acquisition rate COMPASS is capable of handling is max. 40kHz.
        - Amount of physics data gathered by COMPASS amounts to some 2petaByte/year.
        - With a beam of approx. $2.0E^8$ muons per spill (spill duration: 4.8Sec) and the number of measurement channels from above, this would yield a data rate of some 1teraByte/Sec.
          It would be impossible to handle such a high rate. Therefore the trigger system must take very rapidly a decision of which measurement contains 'interesting' physics data and which one does not. The former should be stored for off-line analysis and the latter could be discarded; this process is called data rate reduction.
        - The standard trigger rate is therefore limited to approx. 10kHz.
    - The Detector Control System.
        - There are approx. 32500 technical parameters (temperature, gas pressure, voltages, currents, humidity etc.) that are surveyed, time stamped and archived.
        - Of these approx. 21000 have alarm functionality in the control room.

Synchro-cyclotron info. (Distilled from: SC Itinerary.
Info from: A guides' guide to the synchro-cyclotron Visit Point.)

On radiation security.

Visitors can see various radiation warning signs at the visitor exhibition zone. This will certainly generate questions. Some info here: everywhere at the visitor platform radiation dose rate is below 2.5µSv/hour, thus well below the legal limit for a non-designated area of low occupancy. No special requirements with respect to RP for guides and visitors apply.
The part behind the glass barriers (inclusive the levels -1 and -2) remains however Supervised Radiation Area where the usual requirements apply (dosimeter). The effective dose rate at these areas is however not really much higher than at the visitor platform. Near the beam extraction zone, to the right of the film projection screen, the dose rate is at maximum in the order of 1µSv/h, due to remnant radioactivity and it is the highest value of the zone.
it should be noted that an object that a visitor lets fall down onto level -1 cannot be fetched by the guide; ask help from the VTC, he will contact an RP technician for picking it up and checking before handing it over to the visitor.

On the building.

For radiation shielding during operation, the walls of the building are made of 4-5M thick concrete, either constructed from blocks (80x80x80cM) or from solid concrete. The entrance corridor was normally closed with these (removable) blocks and a sliding door made of solid concrete provided for normal access. The left side of the entrance corridor is actually one side of this sliding door. The building has 3 stories: street level and levels -1 and -2. Two sliding doors exist, one left to the entrance corridor and another approx. diagonally on the other side of the building, invisible for the visitors. The sliding doors close / open the radiation shielding of all three levels of the building. A sturdy electromotor with gear reduction is required for moving these doors in position. (Motor is visible at the left side on the visit zone.)

The cyclotron stands on level -1 and the top half of it is accessible from street level. This is done so that the beam extraction system can be constructed on the street level as well, together with the external beam transfer system and the 2 experimental zones: proton and pion$^+$ 'North' hall (behind the left wall) and neutron and pion$^-$ 'South' hall (behind the right wall). See printout 'SC hall layout' on the following pages.

On level -2 we find the axial support for the ion source (injector) and for the hydraulic bearings of the two heavy sliding doors.

On the synchro-cyclotron.

The 600MeV synchro-cyclotron was CERN's first particle accelerator and it was designed and built by CERN. The energy of 600MeV was suggested by Enrico Fermi and the construction was done by a team led by C. J. Bakker who became later CERN's second DG. Bakker was, before coming to CERN, the director of IKO, a Dutch national nuclear physics laboratory in Amsterdam where also a synchro-cyclotron provided accelerated particles for research. Now IKO has been absorbed by a new institution at the same place: NIKHEF.

CERN's 5M synchro-cyclotron was operated from August 1st, 1957 until December 17th, 1990. From an initial beam intensity of 0.3-1µA the output was gradually, after upgrade (axial ion source, Tuning fork / ROTCO freq. swing: 30.4->16.6MHz both SCv1 and v2, rep. rate SCv1 55Hz -> SCv2 360Hz), increased to finally 7µA (aim was 10µA). Extraction efficiency was also improved at the same time from 5% to 70%.

Between the 5M poles of the dipole a field of 2T can be attained. This field is made progressively slightly less (1.8T) at the edges for obtaining a focusing effect at high energy just before the extraction channel. The field is generated by two 37 winding coils (water cooled hollow aluminum) that carry a current of 1850A. Details see printout 'SC main parameters' on the following pages.

Some nice facts and numbers. - (suite 42).

<u>SC Machine hall layout</u>.

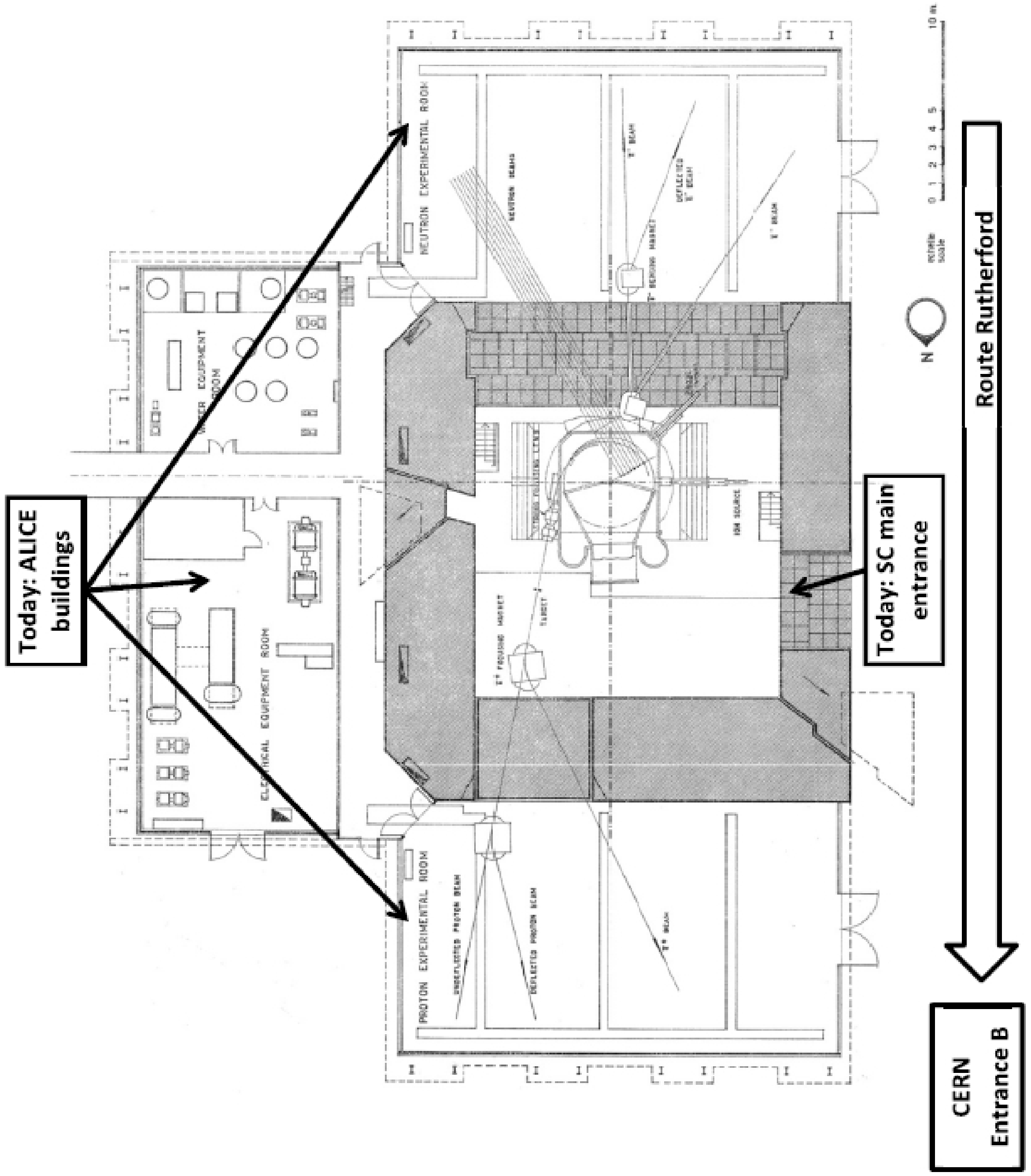


Figure 4. Schematic view of the SC ground level and its experimental rooms.

South Experimental zone: Neutron and Pion$^-$ experiments.
North Experimental zone: Proton and Pion$^+$ experiments.

Some nice facts and numbers. - (suite 43).

SC Machine main parameters.

C. Main parameters of CERN synchro-cyclotron

The table lists the SC performance before (SC1) and after (SC2) the improvement programme, along with some mechanical parameters

Machine parameters	SC1	SC2
Proton kinetic energy (MeV)	600	600
Internal proton beam (µA)	1.5 (~ 6 x 10^{12} protons per seconds)	7 (~ 6 x 10^{13} protons per seconds)
Extracted proton beam (µA)	0.07 (~ 4.4 x 10^{11} protons per seconds)	7 (~ 4.4x 10^{13} protons per seconds)
Extraction efficiency (%)	5	50 to 70
Energy spread (FWHM) (MeV)	5	0.5
Acceleration time (ms)	8.5	1.3
Average energy gain per turn (keV)	3	30
Number of revolutions	2 × 10^5	3 × 10^4
Repetition rate (Hz)	55	360
Protons per pulse	1.2 x 10^{11}	1.3 x 10^{11}
RF frequency swing	30.6 – 16.6 MHz	30.4 – 16.6 MHz

Magnet	Peak magnetic field	1.94 T
	Total weight	2500 t
	Pole diameter	5 m
Coils	Diameter	7.2 m
	Weight of each coil	60 t
	Weight of the aluminium of each coil	27 t
RF system	Weight of ROTCO	9 t
Vacuum system	Residual pressure	5 x 10^{-7} torr

Protons: E_k = 600MeV -> v = 0.792c (Note: If a particle has $E_k = m_0 . c^2$ then v = 0.866c and Lorentz γ (gamma) = 2!)
Vacuum system: 5.10^{-7} torr = $6.67E^{-5}$ P = $6.67E^{-10}$ B