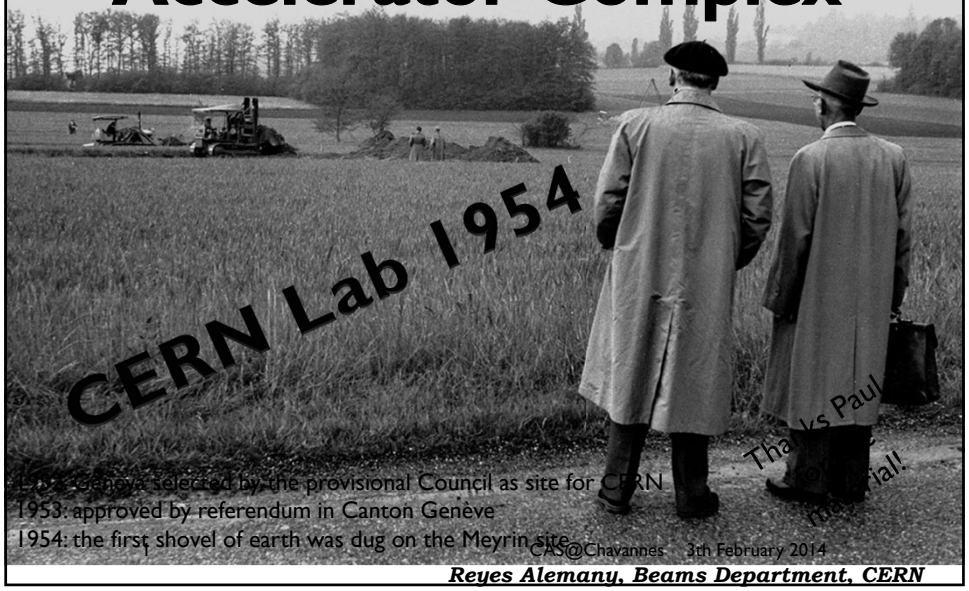
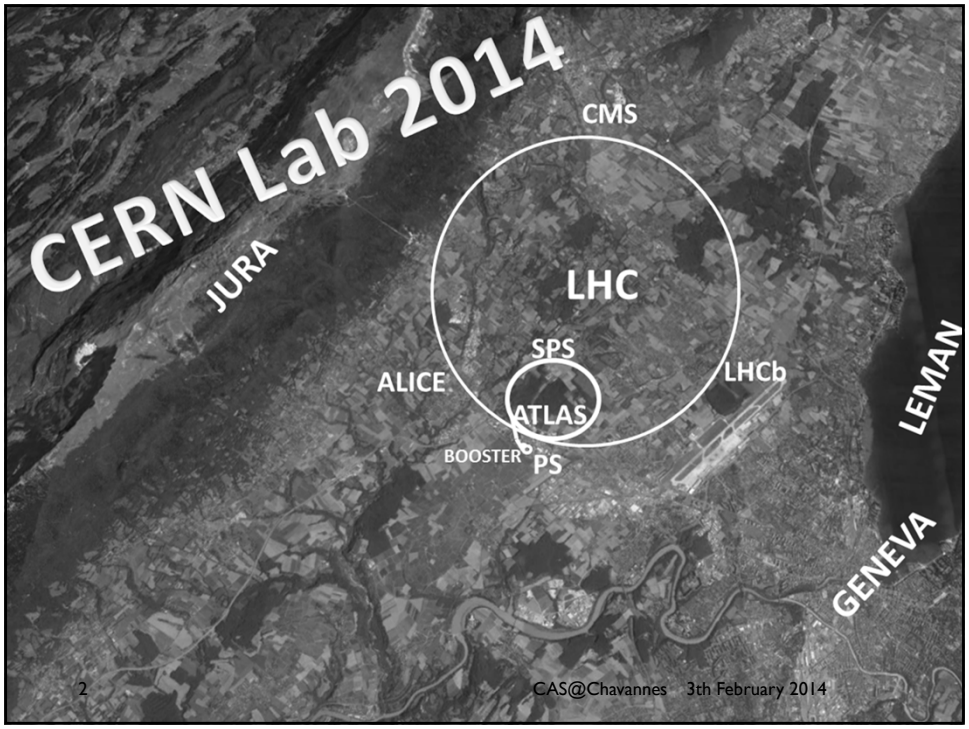
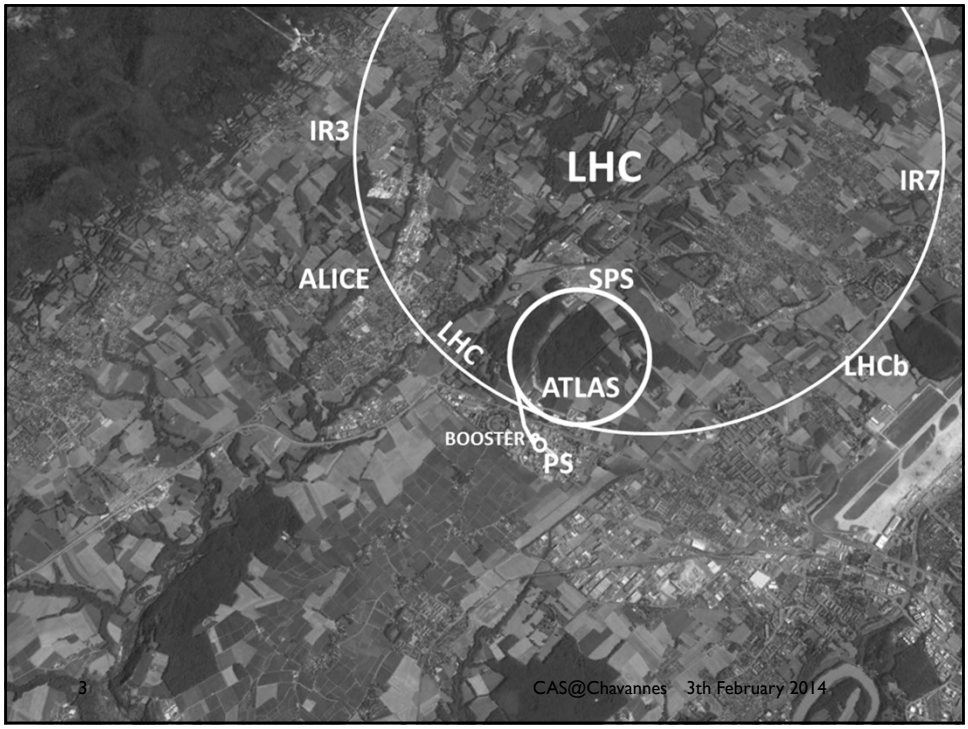
Overview of the CERN Accelerator Complex

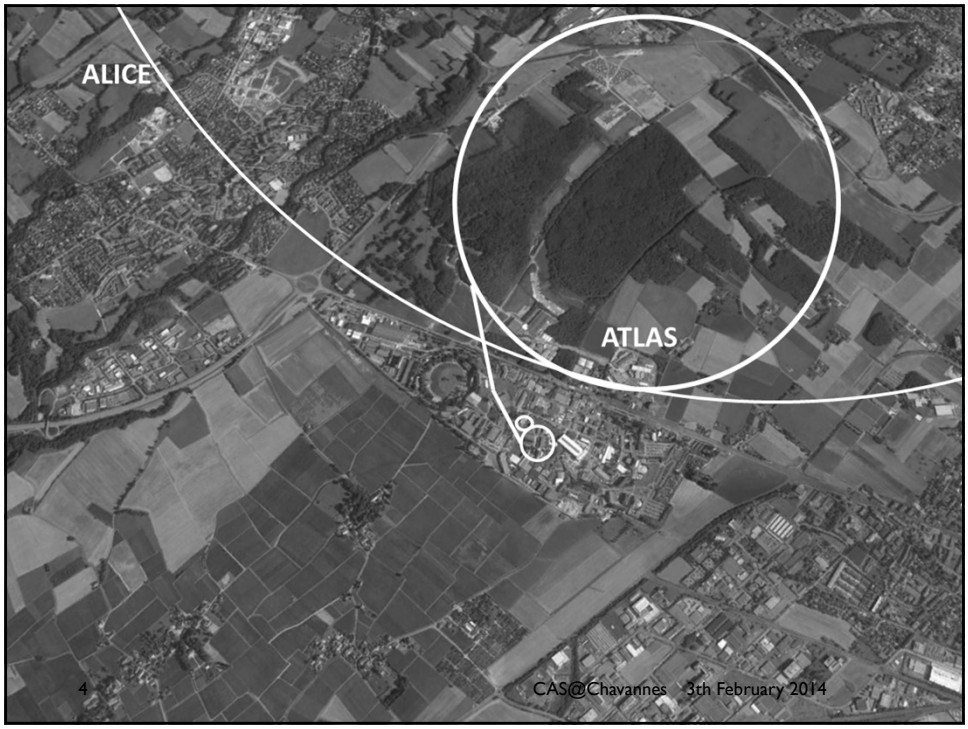


1952: Geneva selected by the provisional Council as site for CERN
1953: approved by referendum in Canton Genève
1954: the first shovel of earth was dug on the Meyrin site

Reyes Alemany, Beams Department, CERN




IR3
LHC
IR7
ALICE
SPS
LHC
ATLAS
LHCb
BOOSTER
PS
3
CAS@Chavannes 3th February 2014


ALICE
ATLAS
4
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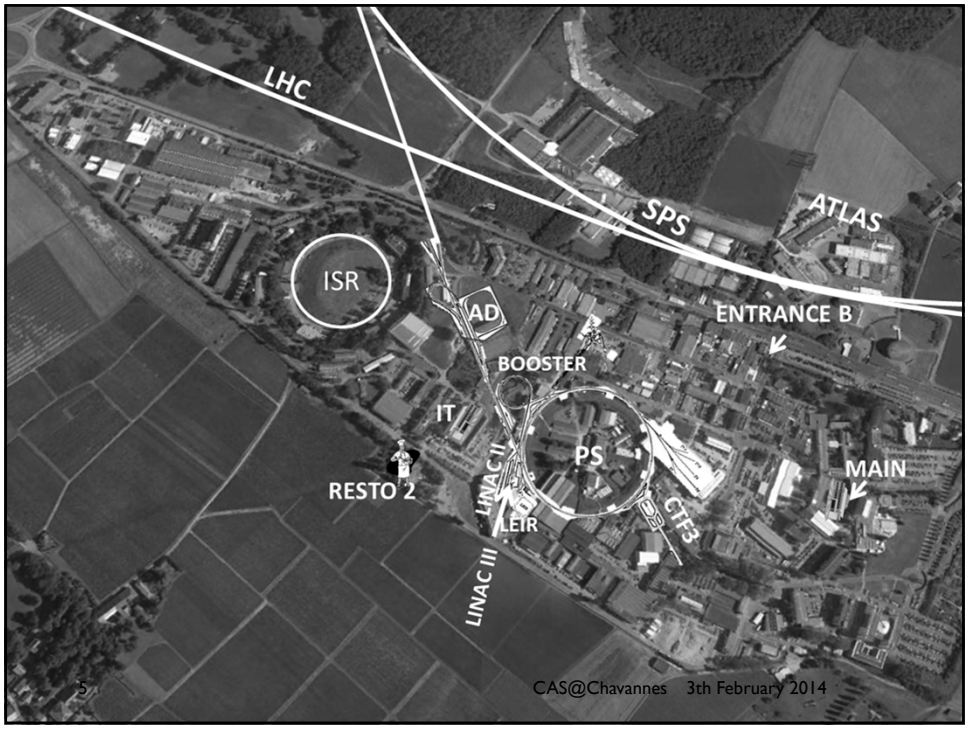
LHC
SPS
ATLAS
ISR
AD
ENTRANCE B
BOOSTER
IT
PS
MAIN
RESTO 2
LINAC II
LEIR
CTF3
LINAC III
5
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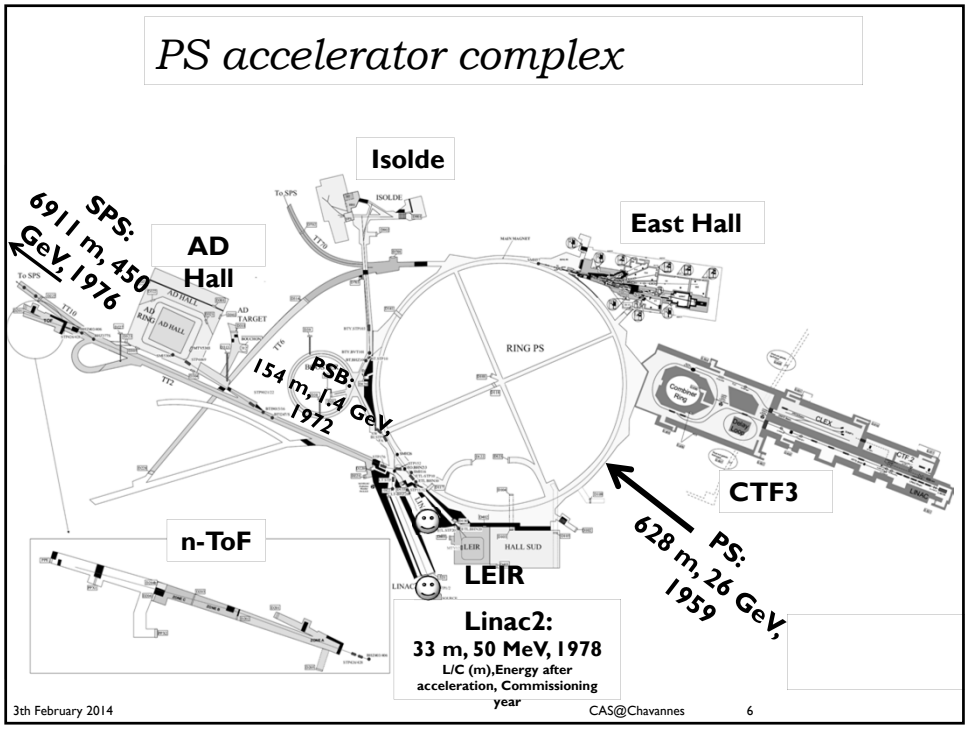
PS accelerator complex
Isolde
East Hall
SPS: 6911 m, 450 GeV, 1976
AD Hall
PSB: 154 m, 1.4 GeV, 1972
RING PS
CTF3
n-ToF
LEIR
PS: 628 m, 26 GeV, 1959
Linac2:
33 m, 50 MeV, 1978
L/C (m),Energy after acceleration, Commissioning year
3th February 2014
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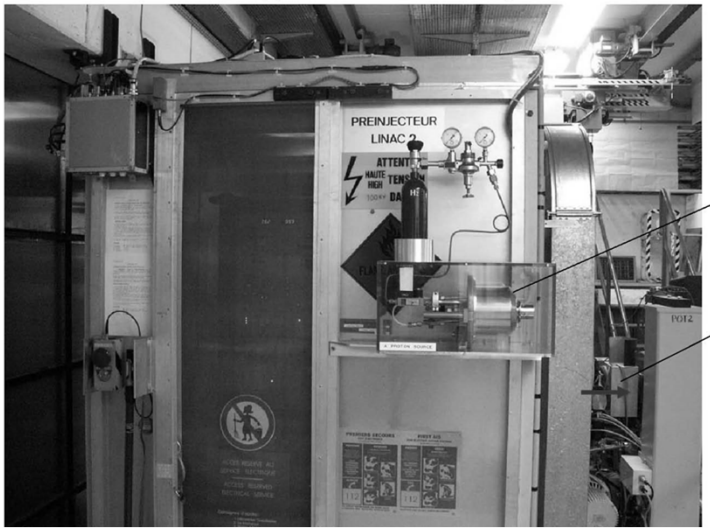
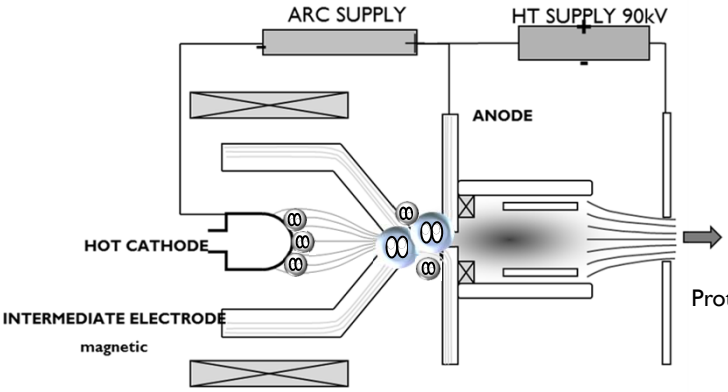
6

The Proton Beam Starts Here …

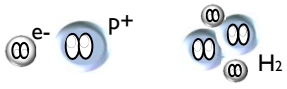
- **The source cage houses the HV platform at 90 kV.**



Duoplasmatron Proton Source



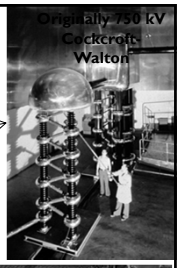
Proton beam @ 90 keV to the RFQ

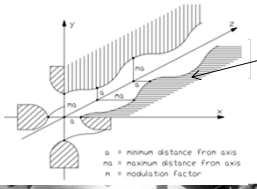


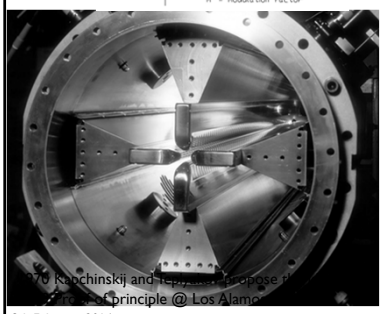
Protons (at 90 keV) are produced by creating a plasma using H_2 which is charged due to interaction with free electrons from the cathode. The plasma is then accelerated and becomes an ion beam.

Radio Frequency Quadrupole (RFQ)

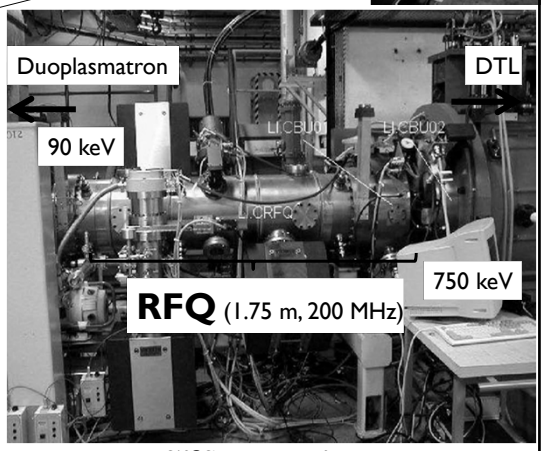
- RFQ is a linear accelerator that **FOCUSES, BUNCHES & ACCELERATES** with **HIGH EFFICIENCY** (90% w.r.t. 50% of conventional accelerators) and **PRESERVES THE EMITTANCE**
- The whole beam dynamics depends upon the shape of the vane tips





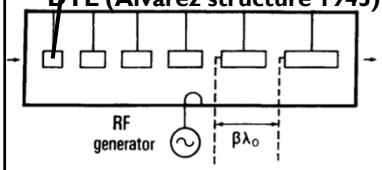


I.M. Kapchinskij and [illegible] propose the ... principle @ Los Alamos

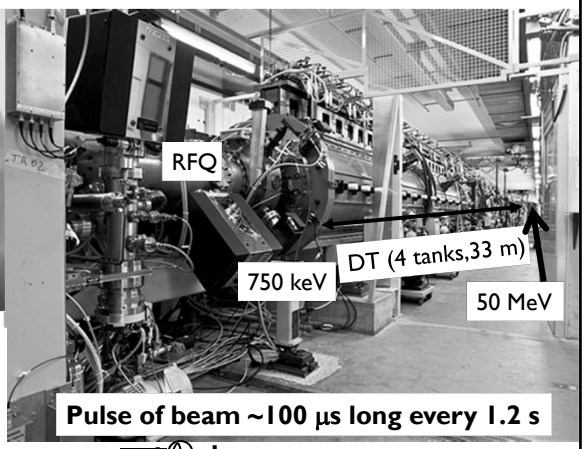


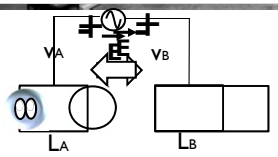
Linac 2

DTL (Alvarez structure 1945)



Drift tubes and spacing become larger as the energy increases
Focusing quads inside drift tubes

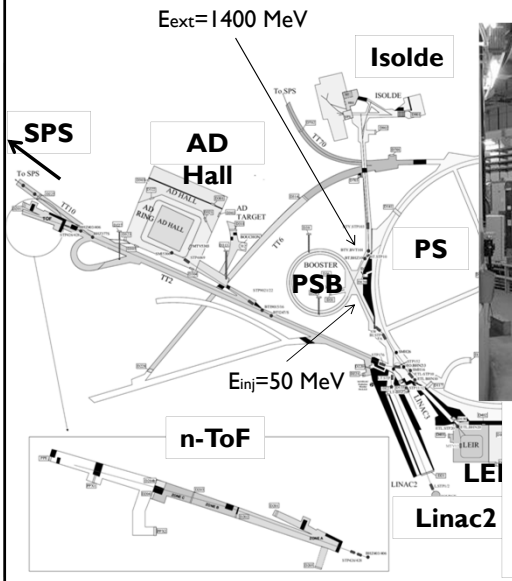




$v_A < v_B \rightarrow L_B > L_A$

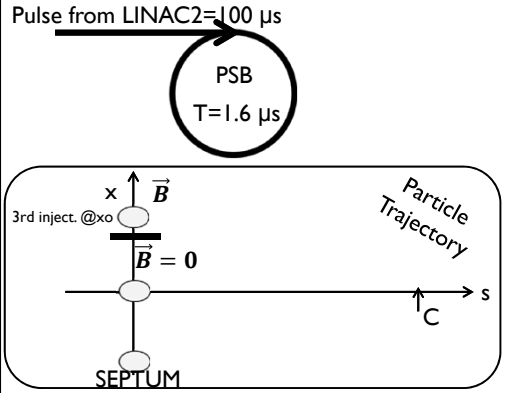
$\rightarrow L = vT_{rf} = \beta\lambda_o$

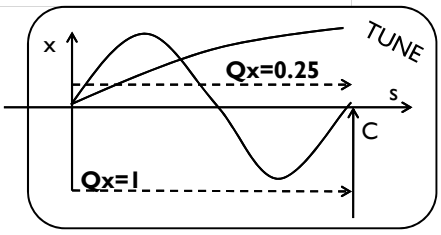
PS Booster

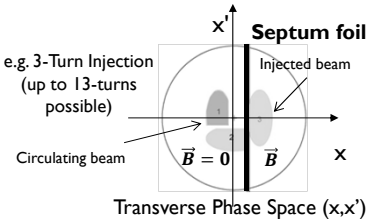


- **Synchrotron with 4 vertically stacked rings, each ¼ of PS Circumference**
- **Duty cycle 1.2 s ➔ two cycles needed to fill the PS with protons for LHC**

PS Booster: E_{inj}=50MeV, C=154 m







Transverse Phase Space (x,x')

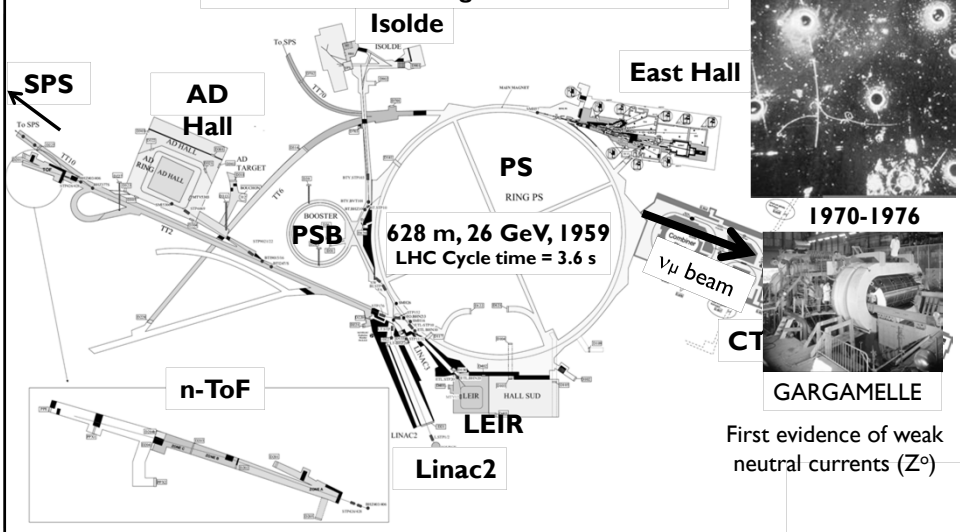
- The bigger the number of turns the more intensity we can accumulate
- The problem is that the longer the injection takes, the more time the particles have to fill the whole available phase space + SPACE CHARGE ➔ emittance increases ➔ beam size increases
- **The Booster is the machine in the LHC Injector Chain where the <u>transverse brightness</u> of the LHC beam is determined**

Brightness = Intensity/Emittance

Proton Synchrotron (PS)

The oldest functioning machine at CERN

The first Alternating Gradient Machine!



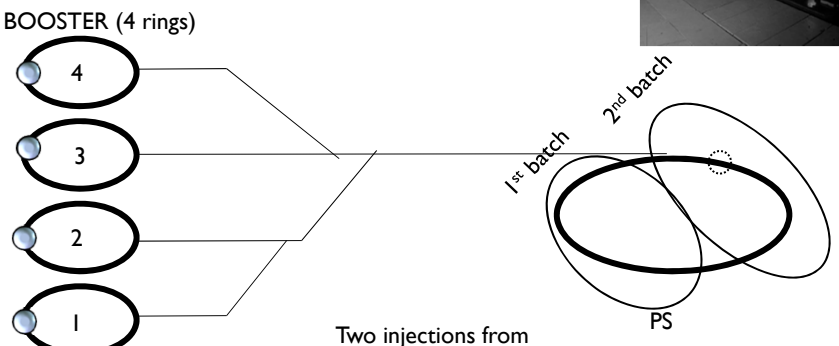
1970-1976

GARGAMELLE

First evidence of weak neutral currents (Z^o)

Proton Synchrotron (PS)

BOOSTER (1.4 GeV) ➔ PS (26 GeV) ➔ SPS (450 GeV) ➔ LHC



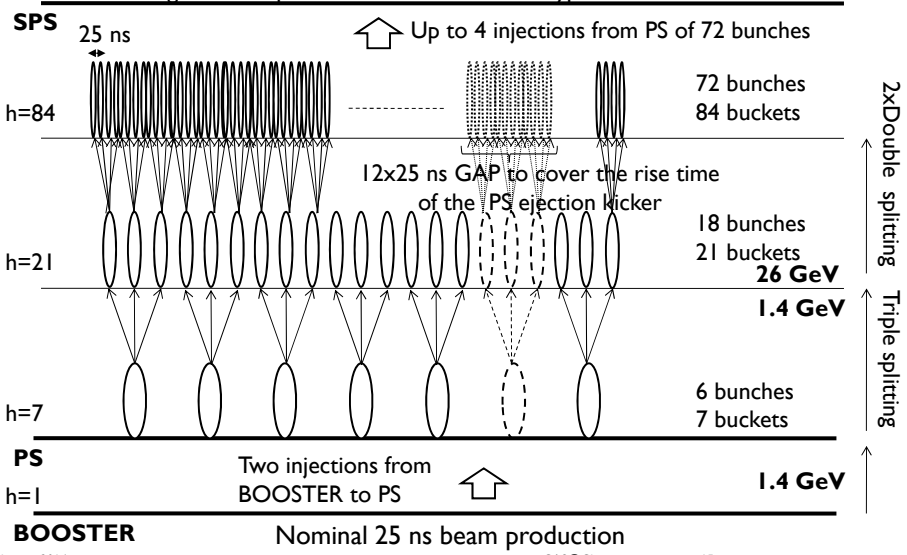
Two injections from BOOSTER to PS (2 x 1.2 s)

h=1

h=7 (6 buckets filled + 1 empty)

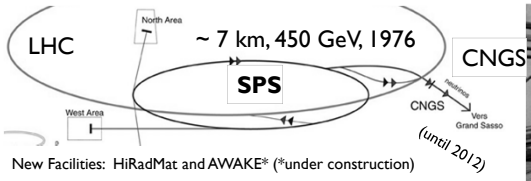
Proton Synchrotron (PS)

Longitudinal bunch splitting ➔ Reduce voltage on principal RF harmonic and simultaneously rise voltage on multiple RF harmonic ➔ several type of RF cavities needed



Super Proton Synchrotron (SPS)

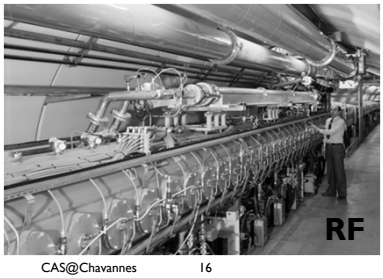
North area



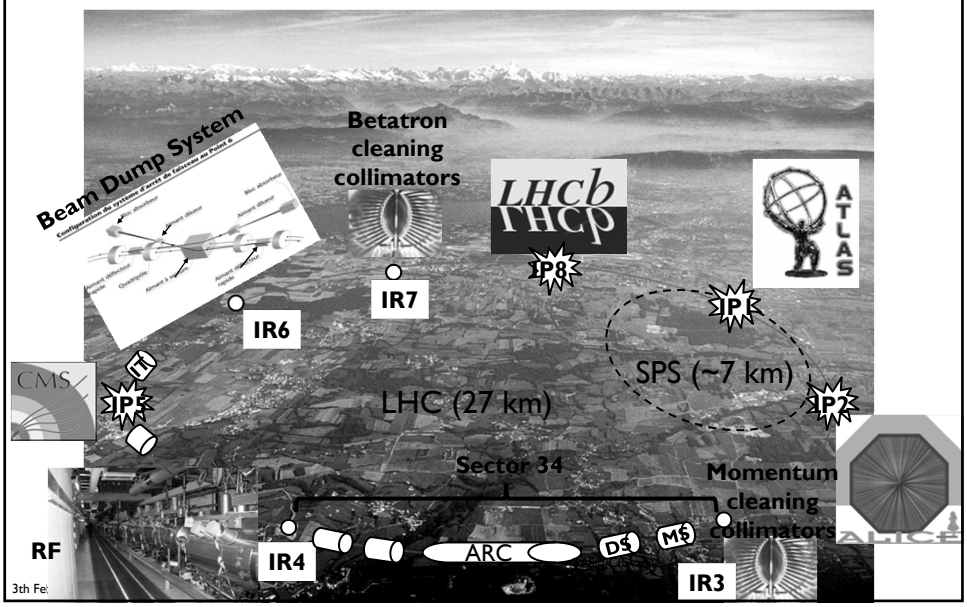
New Facilities: HiRadMat and AWAKE* (*under construction)

SppS

- has probed the inner structure of protons
- investigated matter antimatter asymmetry
- searched for exotic forms of matter

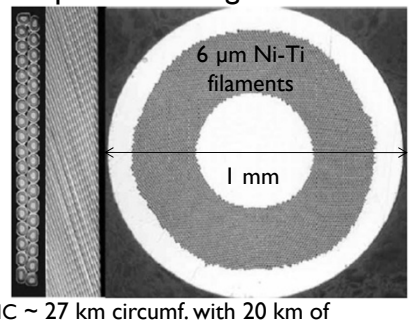


Large Hadron Collider (LHC)



Large Hadron Collider (LHC)

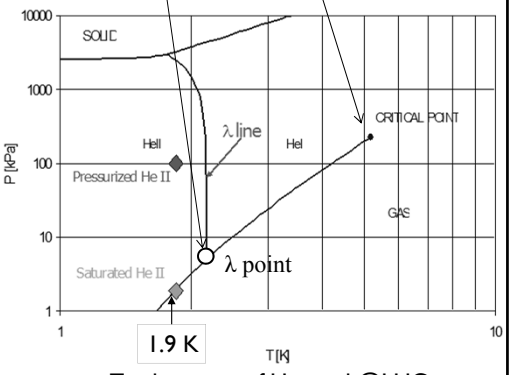
Superconducting cables of Nb-Ti



LHC ~ 27 km circumf. with 20 km of superconducting magnets operating @8.3 T. An equivalent machine with normal conducting magnets would have a circumference of 100 km and would consume 1000 MW of power ➔ we would need a dedicated nuclear power station for such a machine. LHC consumes ~ 10% nuclear power station

Liquid Nitrogen → Cold compressors

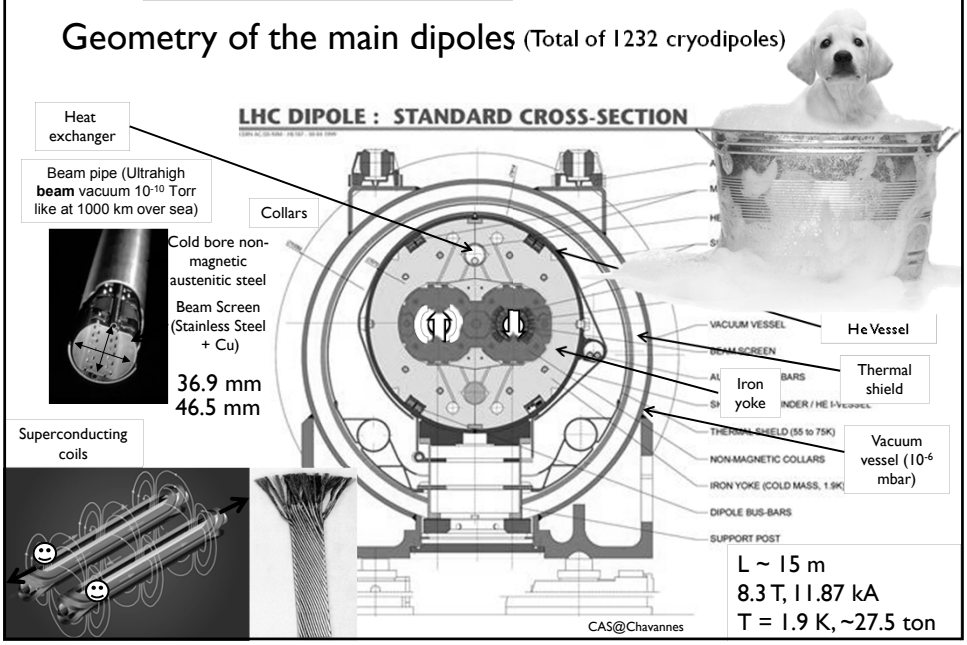
He gas ➔ liquid @ 4.2 K ➔ superfluid @ 2.17 K



Total amount of He used @LHC ~500-700 T

Large Hadron Collider (LHC)

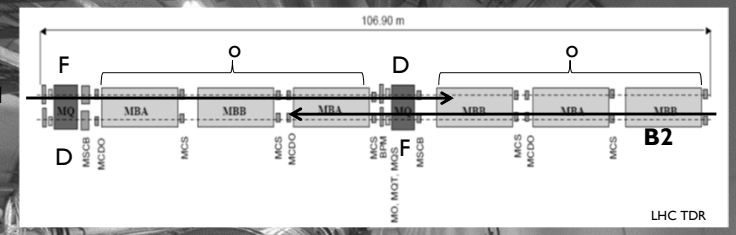
Geometry of the main dipoles (Total of 1232 cryodipoles)



L ~ 15 m
8.3 T, 11.87 kA
T = 1.9 K, ~27.5 ton

Large Hadron Collider (LHC)

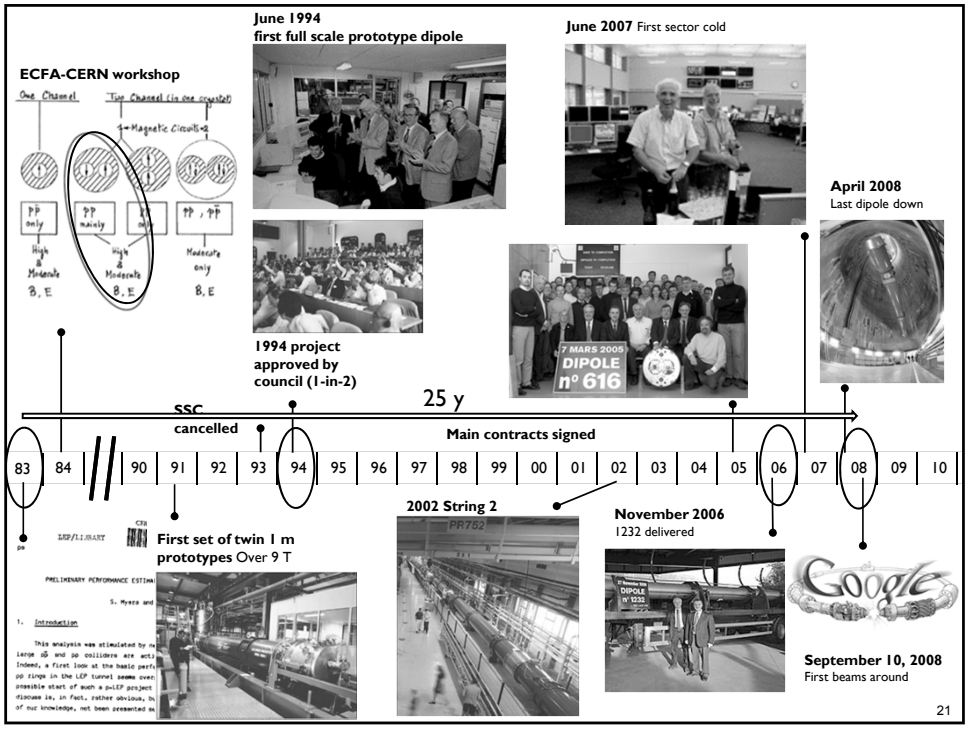
LHC arc cells = FoDo lattice* with ~ 90° phase advance per cell in the V & H plane

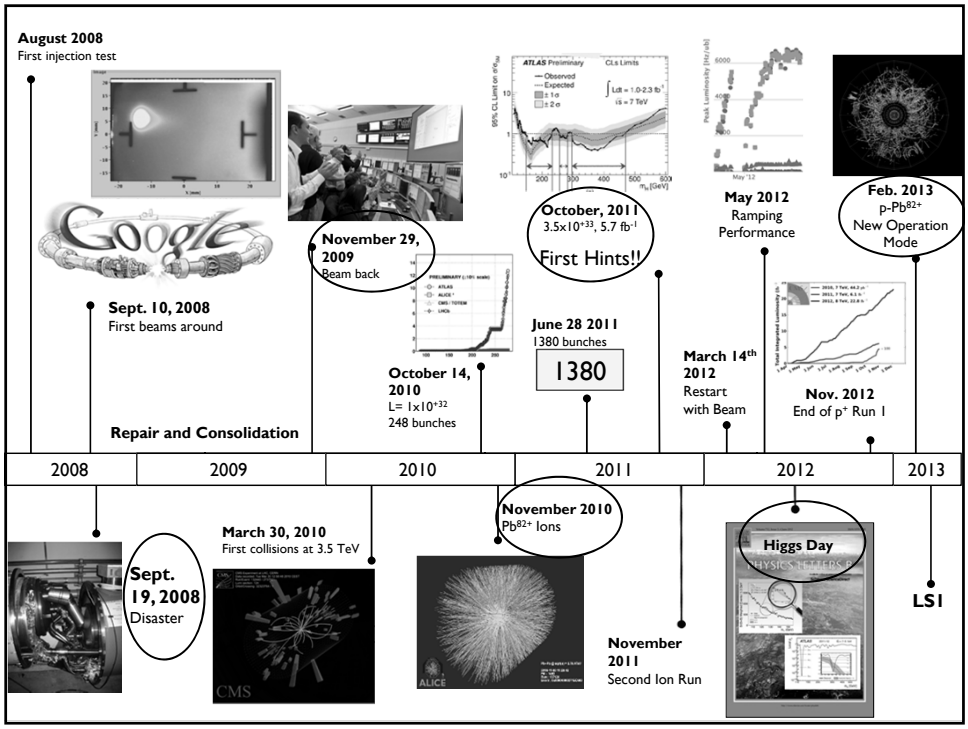


The FoDo-Lattice

A magnet structure consisting of focusing and defocusing quadrupole lenses in alternating order with nothing in between.
(Nothing = elements that can be neglected on first sight: drift, bending magnets, RF structures ... and especially experiments...)

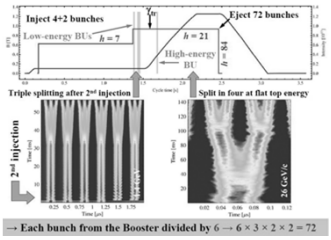
MB: main dipole
MQ: main quadrupole
MQT: Trim quadrupole
MQS: Skew trim quadrupole
MO: Lattice octupole (Landau damping)
MSCB: Skew sextupole + Orbit corrector (lattice chroma+orbit)
MCS: Spool piece sextupole
MCDO: Spool piece octupole + Decapole
BPM: Beam position monitor


ECFA-CERN workshop
June 1994
first full scale prototype dipole
June 2007 First sector cold
April 2008
Last dipole down
1994 project
approved by
council (1-in-2)
7 MARS 2005
DIPOLE
nº 616
25 y
SSC
cancelled
Main contracts signed
83 84 90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06 07 08 09 10
2002 String 2
November 2006
1232 delivered
First set of twin 1 m
prototypes Over 9 T
September 10, 2008
First beams around
21

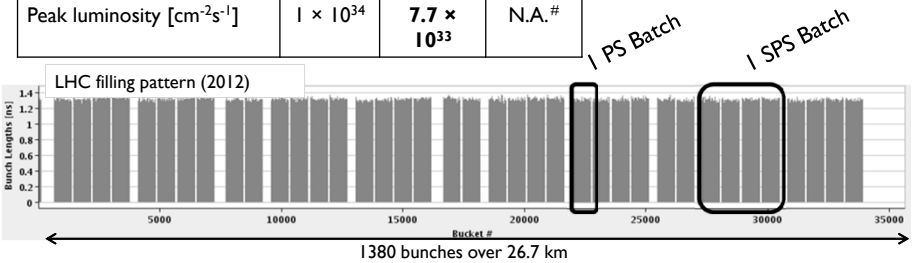

August 2008
First injection test
Sept. 10, 2008
First beams around
November 29, 2009
Beam back
October 14, 2010
L= 1x10+32
248 bunches
October, 2011
3.5x10+33, 5.7 fb-1
First Hints!!
June 28 2011
1380 bunches
1380
March 14th 2012
Restart
with Beam
May 2012
Ramping
Performance
Nov. 2012
End of p+ Run 1
Feb. 2013
p-Pb82+
New Operation
Mode
Repair and Consolidation
2008 2009 2010 2011 2012 2013
Sept. 19, 2008
Disaster
March 30, 2010
First collisions at 3.5 TeV
November 2010
Pb82+ Ions
November
2011
Second Ion Run
Higgs Day
LS1

Filling the LHC (2012)

	25 ns (design)	50 ns (2012)	25 ns (2012)#
Energy per beam [TeV]	7	**4**	4
Intensity per bunch [x10^{11}]	1.15	**1.7**	1.2
Norm. Emittance H&V [μm]	3.75	**1.8**	2.7
Number of bunches	2808	**1380**	N.A.#
β* [m]	0.55	**0.6**	N.A.#
Peak luminosity [$cm^{-2}s^{-1}$]	1×10^{34}	**7.7×10^{33}**	N.A.#



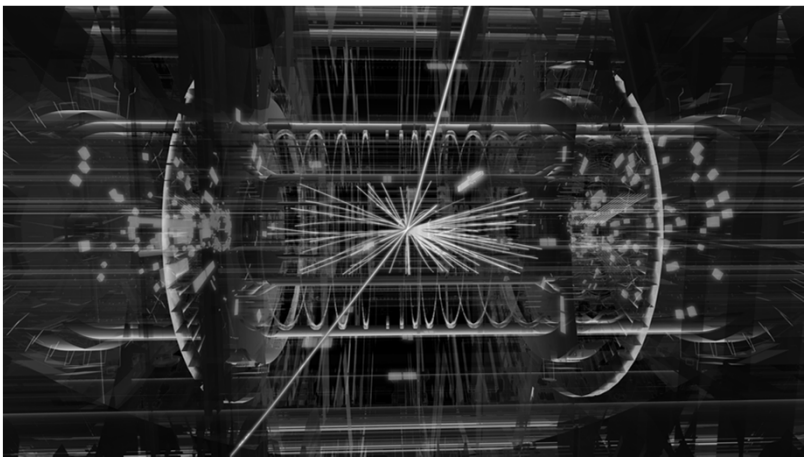
The 25 ns PS production scheme (2012)



1380 bunches over 26.7 km

The 25 ns was only used for scrubbing and tests in 2012

High Light Of HEP -Year



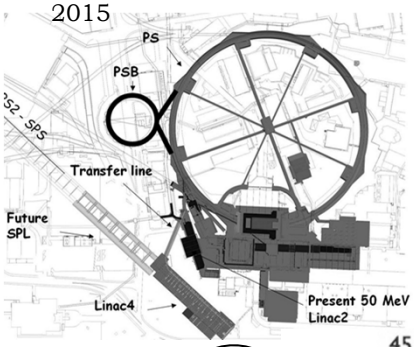
ATLAS event display: Higgs => two electrons & two muons

1400 clearly identified Higgs particles "on-tape" (per experiment)

Linac4 : Replacing Linac2

Linac4 : Approved in 2007 as a replacement to Linac2

- Energy 160 MeV (cf 50 MeV in Linac2) Doubles the space charge tune shift limit at injection into the PS Booster
- H- Injection : CERN is one of the few labs still using p^+
- Connection to PSB depends on finding a ~8 month shutdown of LHC after 2015



50 Mev ➔ 160 MeV

0.31*1.12=0.35 ➔0.52*1.37=0.70

$\Delta Q_{LINAC4} \approx 0.5 \Delta Q_{LINAC2}$

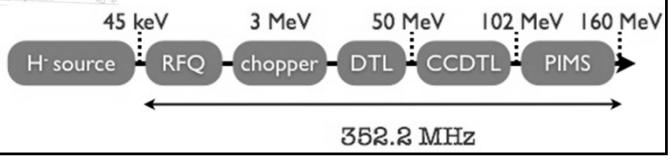
$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

with N_b : number of protons/bunch

$\varepsilon_{X,Y}$: norm. transvers e emittances

R : mean radius of the accelerator

Delivers 40 mA, 400 μs pulses at 2 Hz



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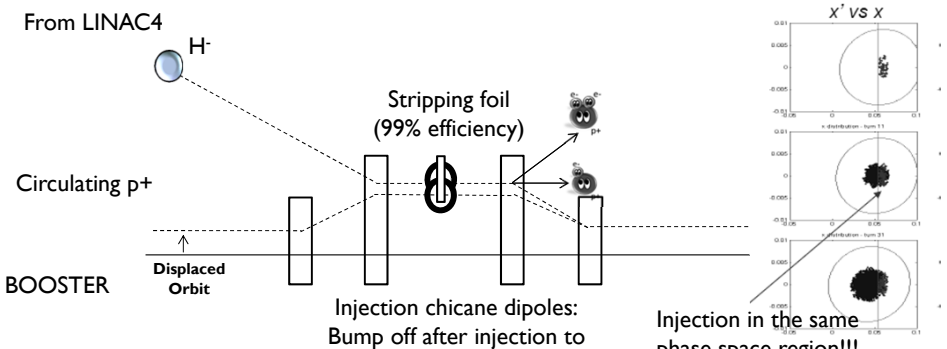
H- Injection



The most important plus! ➔ since we can afford a SPACE CHARGE ΔQ_{50MeV} ➔

But $\Delta Q_{LINAC4(160MeV)} \approx 0.5 \Delta Q_{LINAC2(50MeV)}$

$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

$N_b^{LINAC4} \approx 2\ N_b^{LINAC2}$!!!!

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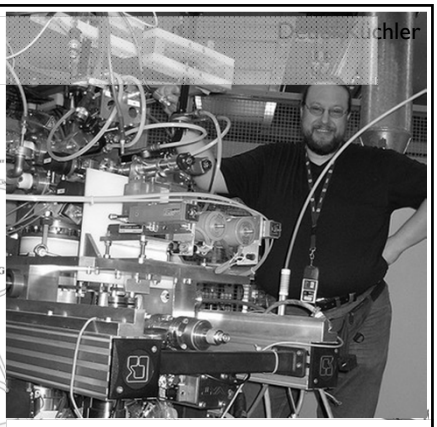
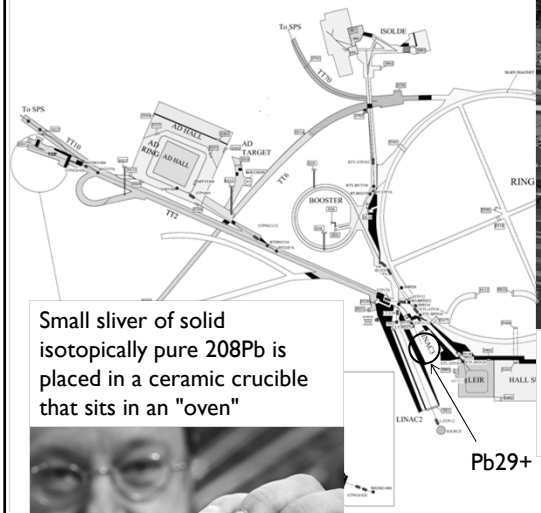
Ion Chain



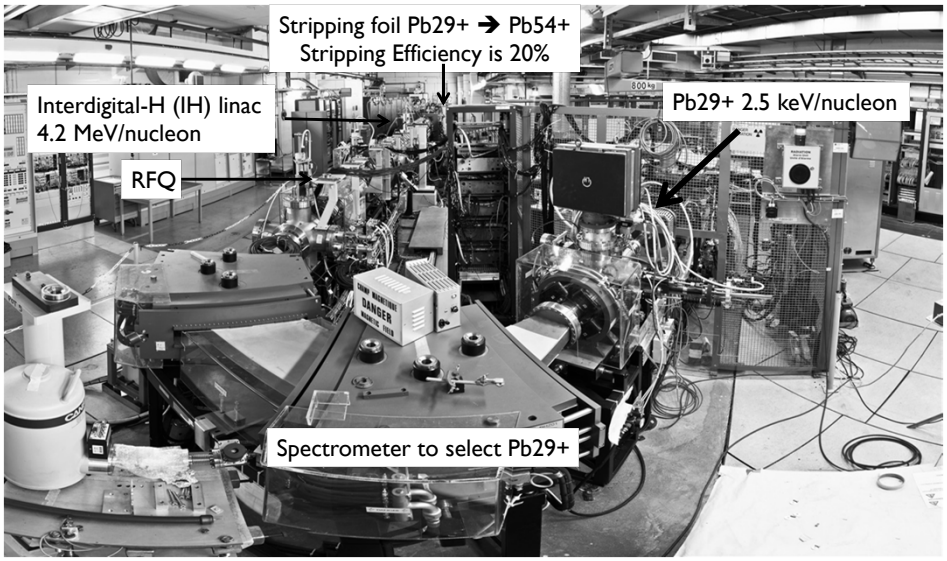


Small sliver of solid isotopically pure 208Pb is placed in a ceramic crucible that sits in an "oven"

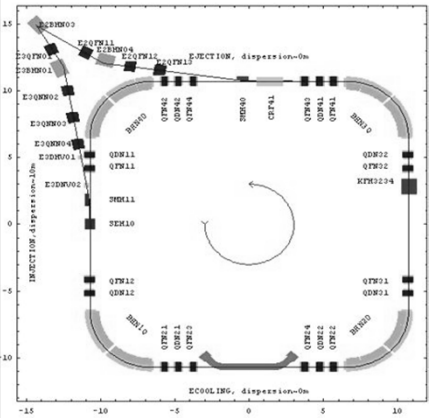
The metal is heated to around 800°C and ionized to become plasma. Ions are then extracted from the plasma and accelerated up to 2.5 keV/nucleon.

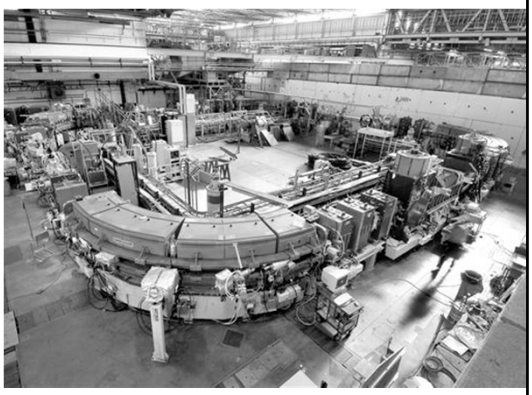
The source can also be set up to deliver other species…
Ar and Xe being prepared for the SPS Physics programme

Linac 3



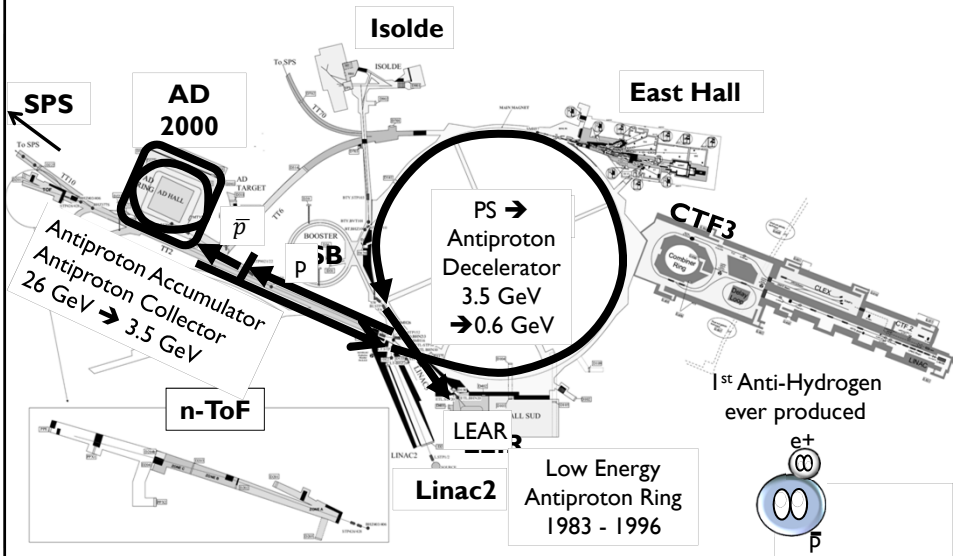
Ion Chain : Low Energy Ion Ring (LEIR)



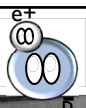


LEIR Accumulates the 200 ms pulses from Linac3 into 2 bunches
Electron Cooling is used to achieve the required brightness
Acceleration to 72 MeV/nucleon before transfer to the PS
LEIR Cycle is 3.6 s
The Pb54+ is finally fully stripped to Pb82+ in the transfer line from PS to SPS

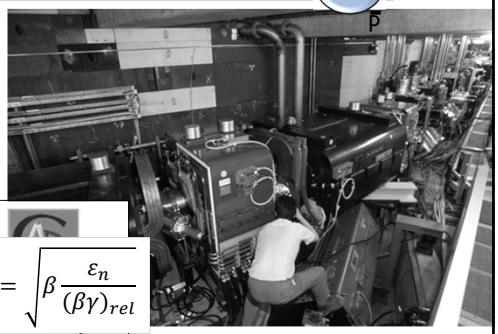
History of the Antiproton Decelerator Chain

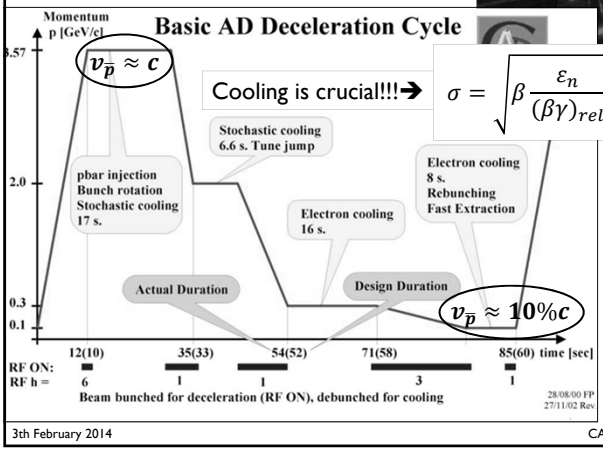


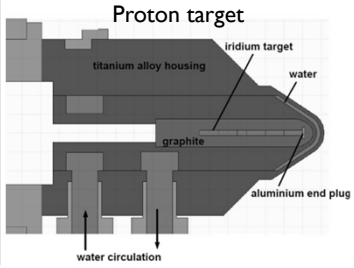
Antiproton Decelerator : AD



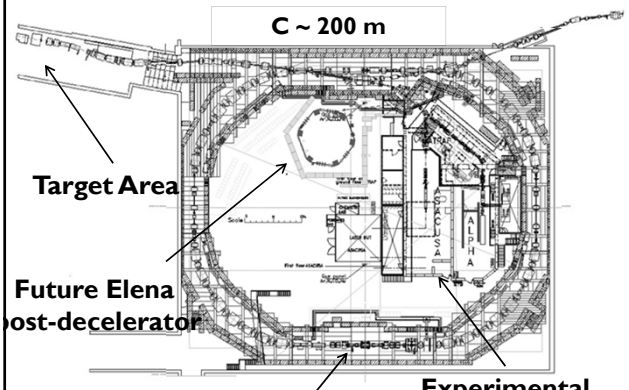
Built in 1999 (from the old AC)
26 GeV/c PS Proton beam produces $\bar{p}$ (1 in 10^7) which are focused and captured in the AD and decelerated to 100 MeV/c (5.3 MeV)

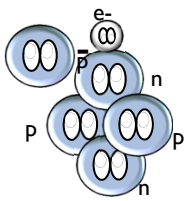






AD Layout





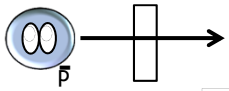
ASACUSA
Antiprotonic helium ➔ $m_{\bar{p}}$
ALPHA
2011 $\bar{H}$ trapped for 16'
ATRAP
2002 first glimpse inside $\bar{H}$
AEGIS
1st meas. of gravitational effect on $\bar{H}$
ACE
$\bar{p}$ for cancer therapy
GBAR(1)
Gravitational effect on $\bar{H}$
BASE(1)
$\bar{p}$ magnetic moment

(1) In construction

Elena … More Deceleration

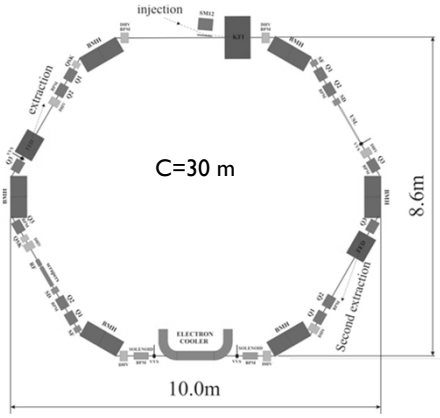
Today's set-up

Degrader foil
(Efficiency=0.1%)



5.3 keV

5 keV



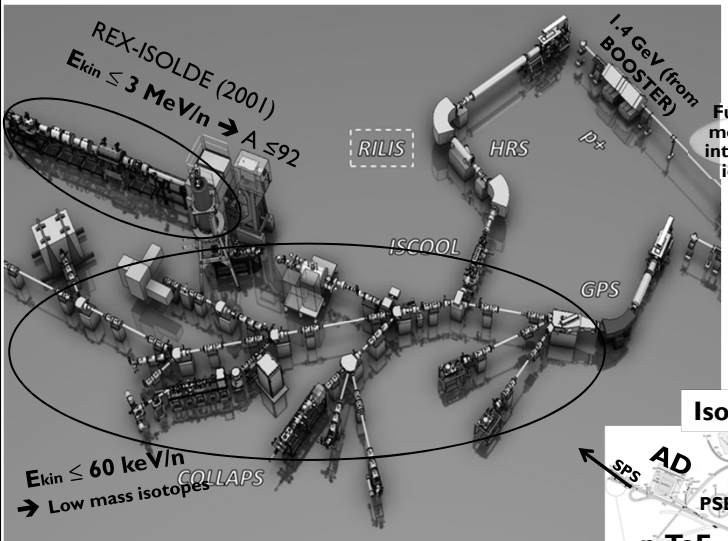
ELENA will overcome this problem + will be able to deliver beams almost simultaneously to all four experiments resulting in an essential gain in total beam time for each experiment. This also opens up the possibility to accommodate an extra experimental zone.

Under Construction
A second stage of deceleration after
AD Momentum: 100 – 13.7MeV/c
Kinetic : 5.3 – 0.1 MeV

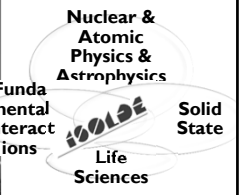
In operation 2017

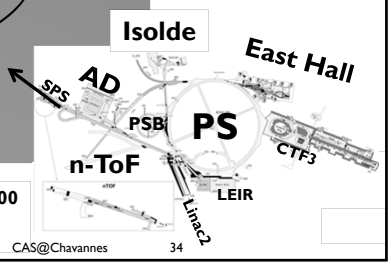
ISOLDE SC in 1967 (until 1990)
ISOLDE PSB in 1992

PSB Experimental Areas: ISOLDE



GPS: Global Purpose Separator
HRS: High Resolution Separator

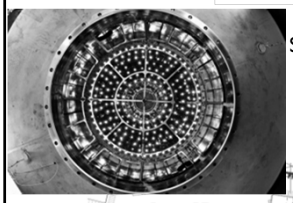




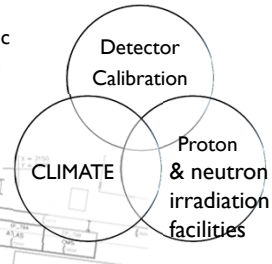
Next generation of nuclear physics:

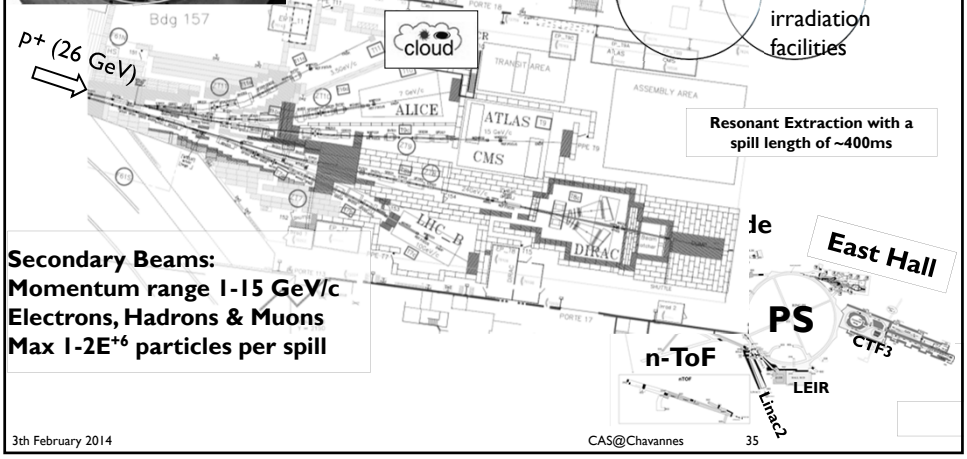
HIE-ISOLDE (+SC RF): Ekin ≤ 10 MeV/n → A ≤200
PHASE 1: 2015 → 5.5MeV/u (On track)
PHASE 2: 2017? → 10 MeV/u **PHASE 3** (+ chooper)

PS Experimental Areas: East Hall



Study the influence of galactic cosmic rays on the Earth's climate through the media of aerosols and clouds



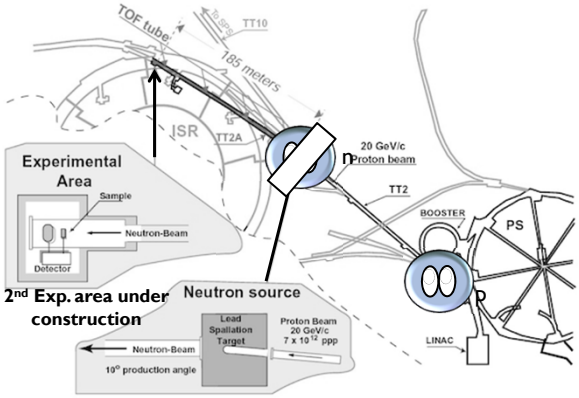


Resonant Extraction with a spill length of ~400ms

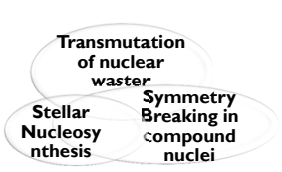
Secondary Beams:
Momentum range 1-15 GeV/c
Electrons, Hadrons & Muons
Max 1-2E^{+6} particles per spill

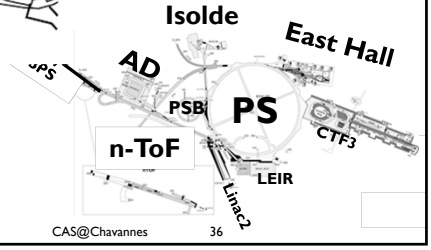
PS Experimental Areas: n-TOF

Study of neutron-induced reactions

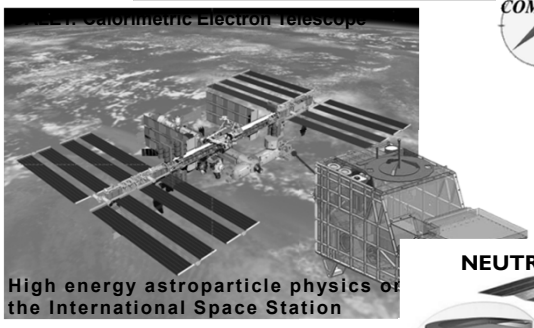


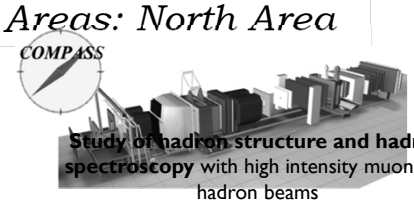
Each primary proton produces ~300 neutrons
Eneutron ➔meV - GeV





SPS Experimental Areas: North Area

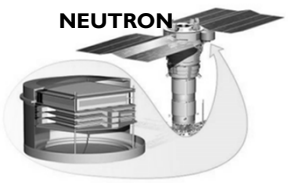




Study of hadron structure and hadron spectroscopy with high intensity muon and hadron beams

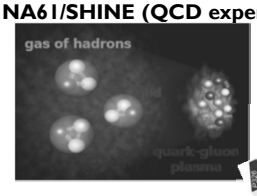
7 beam lines (tot:5.8 km)
3 experimental halls
~ 2000 scientist/year
Slow extraction
3 primary targets
Ion physics program:
(Be, Ar, Xe)

NEUTRON

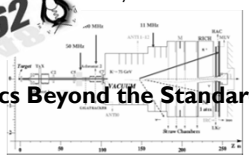


Russian regular satellite
Clarify the Cosmic Rays origin

NA61/SHINE (QCD experiment)

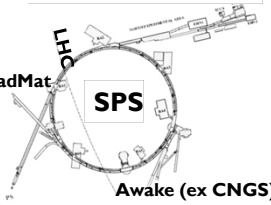


NA62



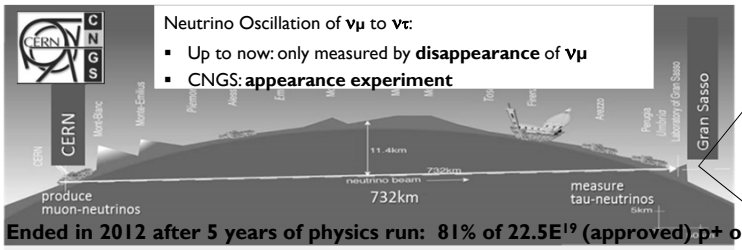
Physics Beyond the Standard Model

North Experimental Area



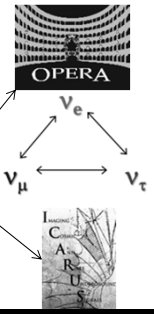
COMPASS: Common Muon and Proton Apparatus for Structure and Spectroscopy
3th February 2014

SPS Experimental Areas: Awake & CNGS



Neutrino Oscillation of $\nu\mu$ to $\nu\tau$:

- Up to now: only measured by **disappearance** of $\nu\mu$
- CNGS: **appearance experiment**

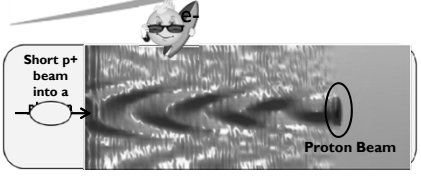


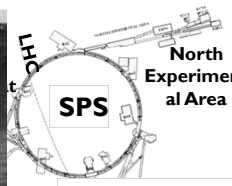
Ended in 2012 after 5 years of physics run: 81% of 22.5E^{19} (approved) p+ on target

$\sim 4 \cdot 10^{19}$ p/year $\sim 2 \cdot 10^{19}$ ν_μ/year ~ 2 ν_τ/year

AWAKE

Proof-of-principle: → Inject 10-20 MeV electron beam
→ acceleration of electrons to **multi-GeV energy range** in the wakefield driven by protons.





3th February 2014

SPS Experimental Areas:

HiRadMat
High-Radiation to Materials

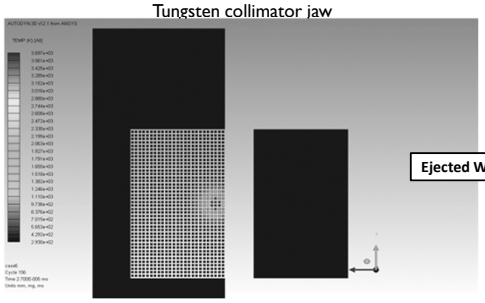
Current and Future Accelerators operate with higher energy, higher intensity, smaller size beams.

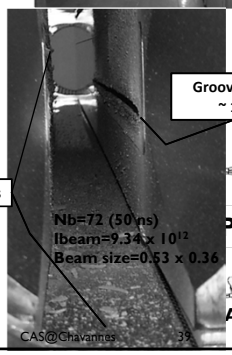
LHC nominal beam (2808 bunches with 1.5 1011 p+/b at 7 TeV) energy = **362 MJ/beam** ➔ energy equivalent to

HiRadMat is a facility designed, to study the impact of intense pulsed beam on materials

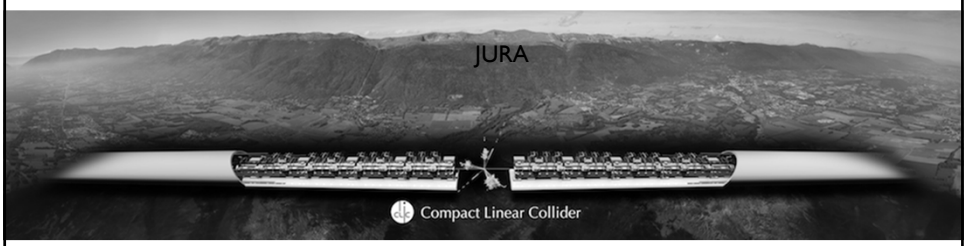
- **Thermal management**
- **Radiation Damage to materials**
- **Thermal shock – beam induced pressure waves**

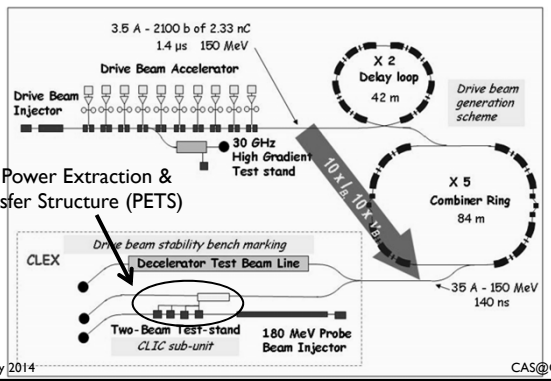
Simulation: 8 LHC bunches @5 TeV impacting a Tungsten collimator jaw





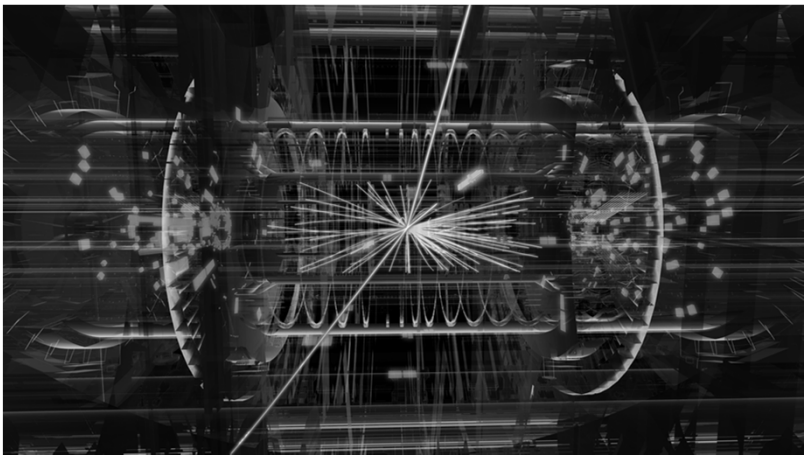
CTF 3 – CLIC Test Facility



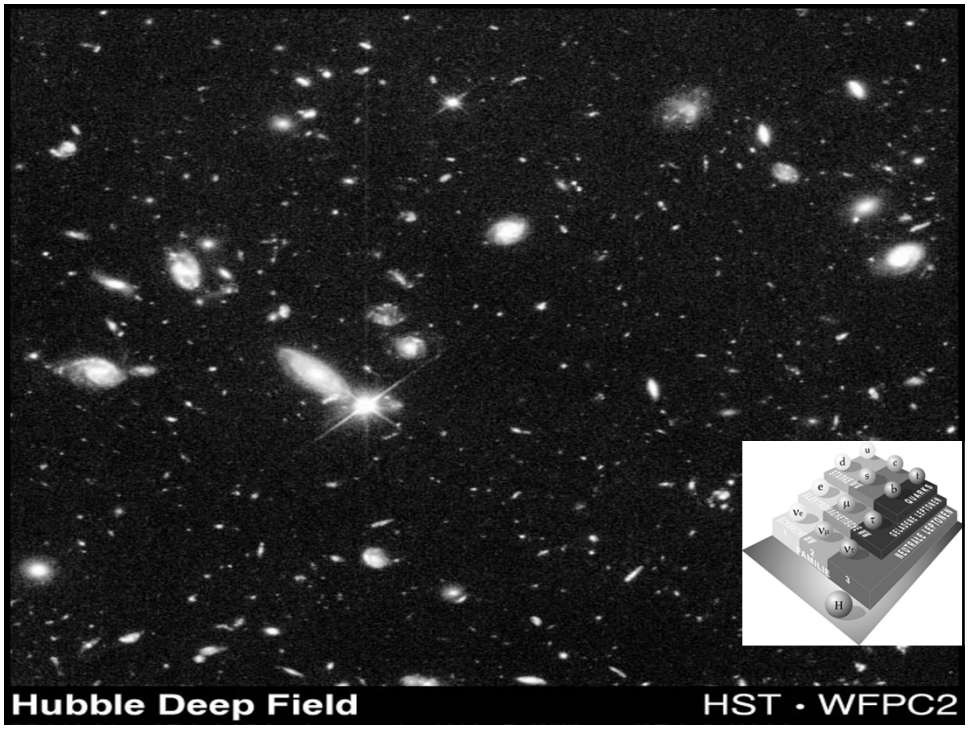


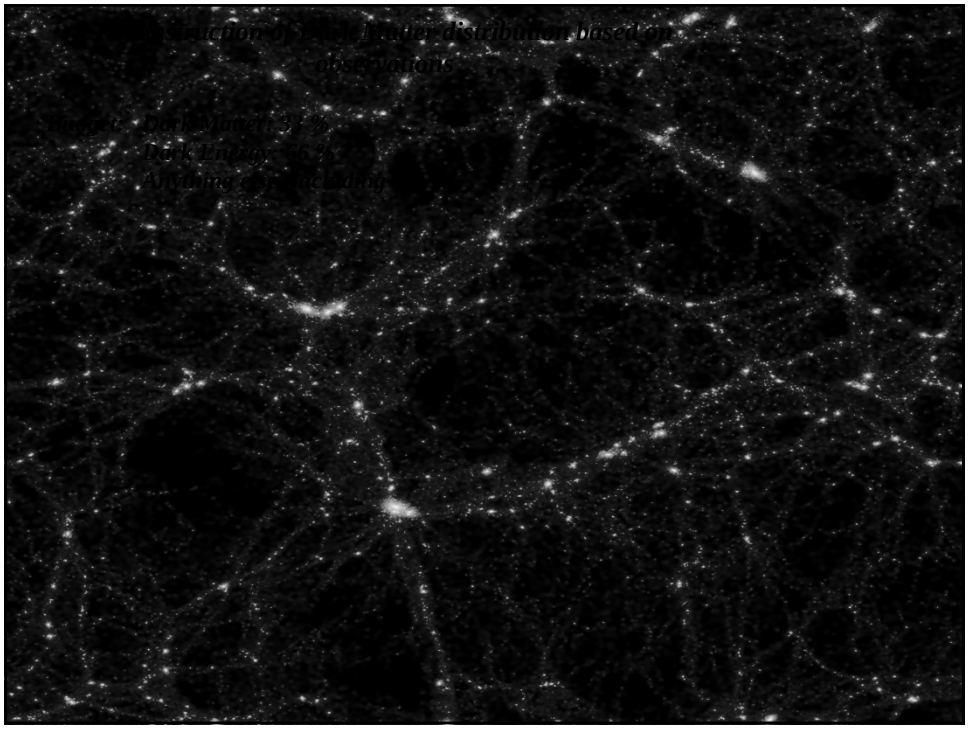
CLIC goal:
Drive Beam 100 A, 239 ns
2.38 GeV ➔240 MeV
Main Beam 1.2 A, 156 ns
9 GeV ➔ 1.5 TeV

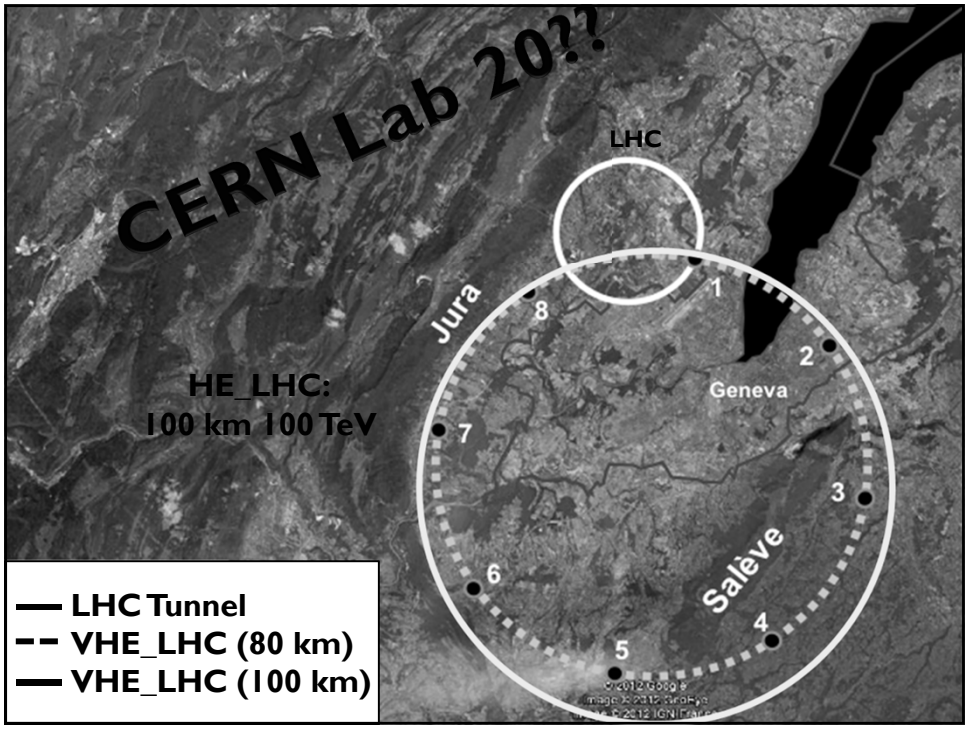
High Light Of HEP -Year



ATLAS event display: Higgs => two electrons & two muons

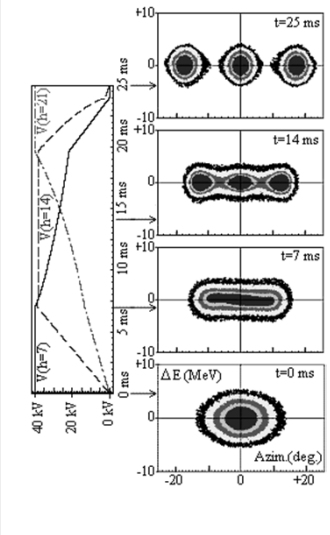


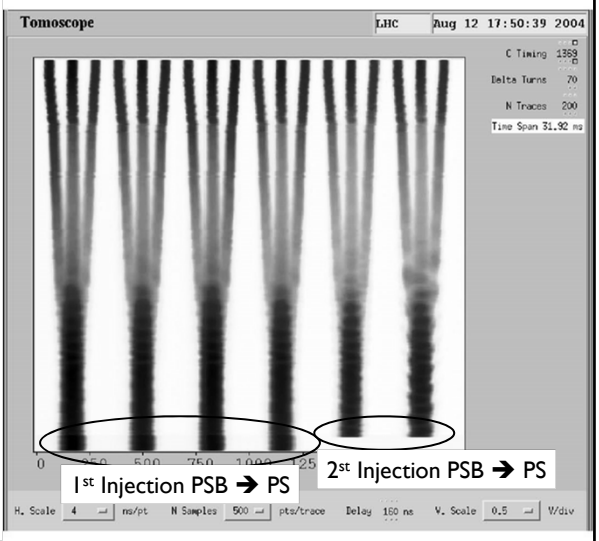

Simulation of dark matter distribution, based on observations
Baryons: 4.6 %
Dark Matter: 23 %
Dark Energy: 72 %
Anything we can't explain


CERN Lab 20?!
LHC
Jura
Geneva
Salève
HE_LHC:
100 km 100 TeV
1
2
3
4
5
6
7
8
LHC Tunnel
VHE_LHC (80 km)
VHE_LHC (100 km)

Spare Slides

Proton Synchrotron (PS)





The PS is the machine in the LHC Injector Chain where the Longitudinal characteristics of the LHC beam are determined

Large Hadron Collider (LHC)

Golden formula (you should know by heart)

$$B\rho = \frac{p}{Ze}$$

Circumference ➔ FIXED!!! by LEP

FIXED, no choice

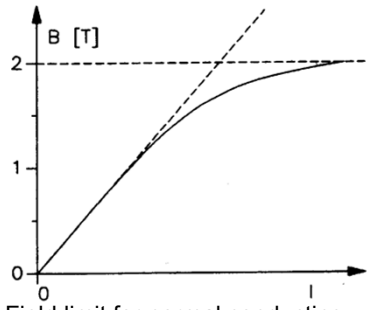
$$\rho \approx \frac{26658.9\ m}{2\pi} \cdot 66\% \approx 2780\ m$$

~ 66% of the lattice elements are dipoles

p = nucleon momentum ➔ defined by the physics case ➔ TeV range ➔ **7 TeV**

$$B = \frac{p}{\rho Ze} \approx 3.33 \frac{p\left(\frac{GeV}{c}\right)}{\rho(m)} = 8.39\ T$$

We need SUPERCONDUCTING technology



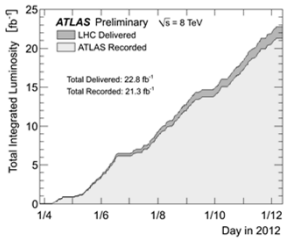
Field limit for normal conducting magnets due to saturation

3th February 2014

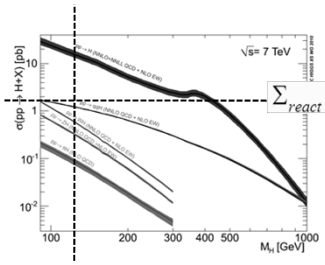
Large Hadron Collider (LHC)

Production rate of events is determined by the cross section Σ_{react} and a parameter L that is given by the design of the accelerator: … the luminosity

$$R = L * \Sigma_{react} \approx 25 \frac{1}{10^{-15} b} 10^{-12} b = some\ 1000 H$$



remember:
$1b = 10^{-24}\ cm^2$



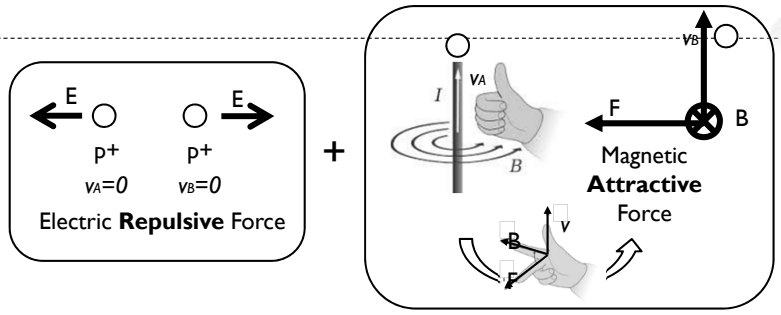
$\Sigma_{react} \approx 1 pb$

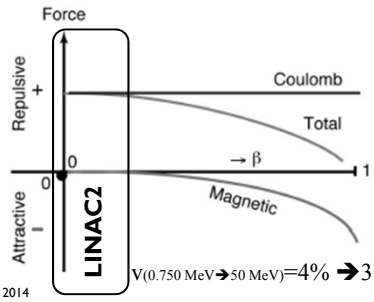
Integrated luminosity during RUN I

$$\int Ldt \approx 25\ fb^{-1}$$

Official number: 1400 clearly identified Higgs particles "on-tape"

Parenthesis: Space Charge in One Slide





$\beta = \frac{v}{c}$

Particles in the beam feel a strong repulsive force ➔

change in tune

V(0.750 MeV➔50 MeV)=4% ➔31% of c