The Large Hadron Collider

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HELMHOLTZ GEMEINSCHAFT

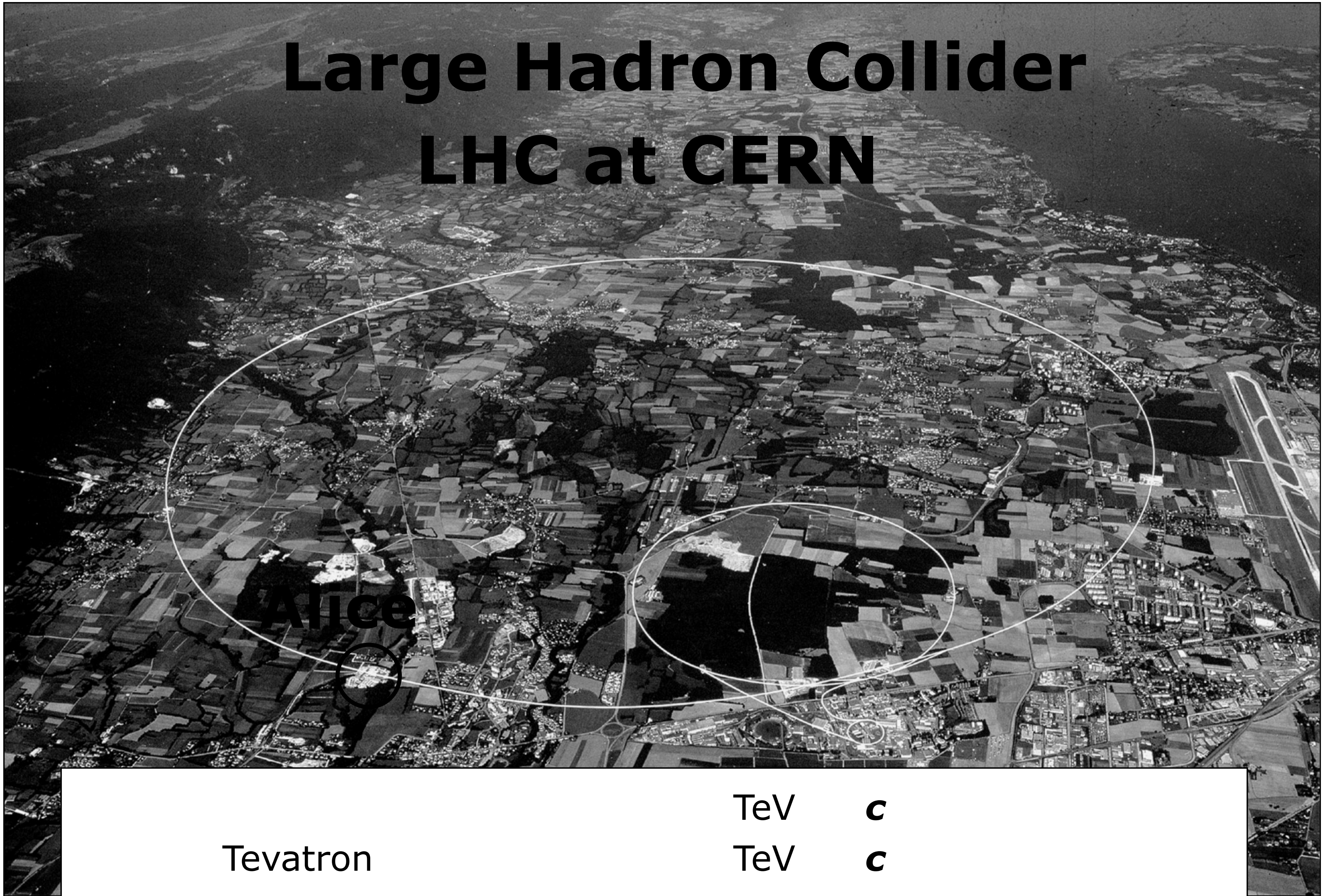
BMBF Forschungsschwerpunkt ALICE Experiment 201

ALICE

EMMI

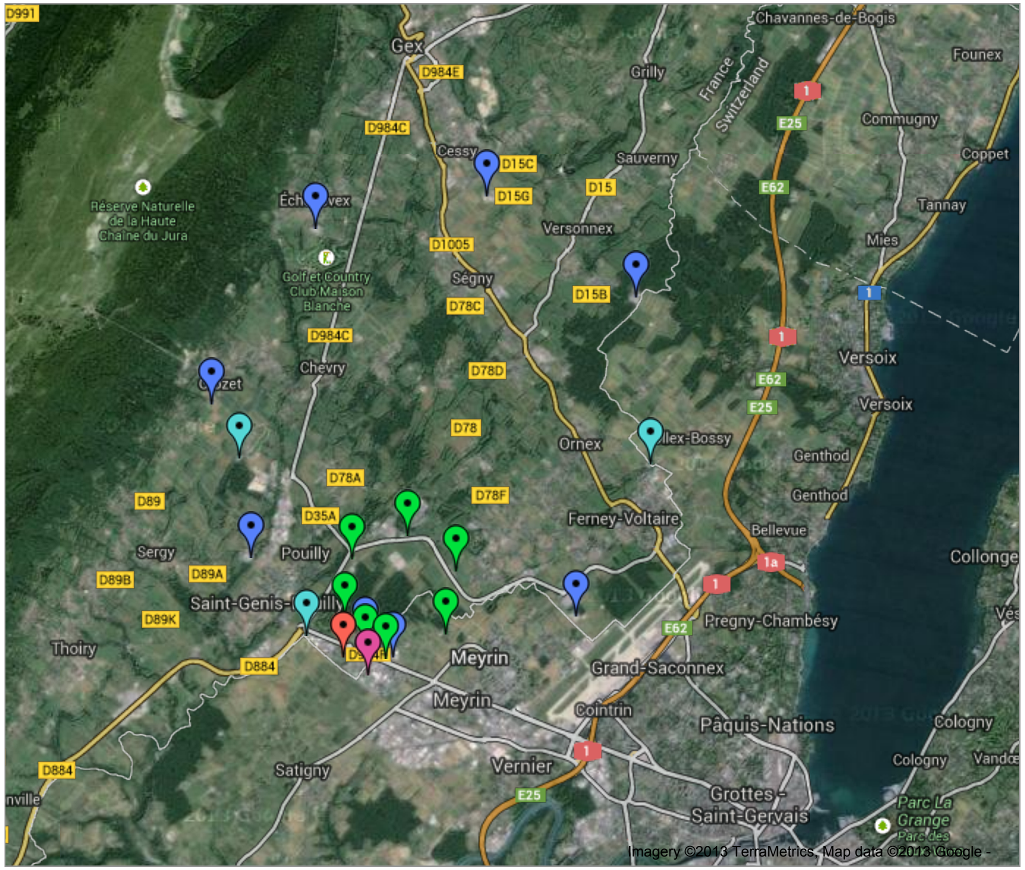
GSI

Large Hadron Collider
LHC at CERN



		TeV	***c***
Tevatron		TeV	***c***
		GeV	***c***
and Marsden	1	MeV	***c*** * 5%

To see all the details that are visible on the screen, use the "Print" link next to the map.



Large Hadron Collider

Cern Surface Locations for the LHC, SPS, and associated sites.

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Point 1
CERN LHC Surface Point 1

Point 1.2
CERN LHC Surface Point 1.2 (SM12)

Point 1.8 - ATLAS
CERN LHC Surface Point 1.2 (SM18)

Point 2 - ALICE
CERN LHC Surface Point 2

Point 3.2

19 Jul 2013

Outline

- Introduction
- Beam transport
- The LHC complex at CERN
- Summary

Energy and Luminosity

- Particle physicists wish collider with energies substantially E >> 1 TeV
- Observation of rare events requires luminosity of L = 10^{34} [cm-2s-1] (challenge for the LHC accelerator)
- Event rate:

$$\frac{N}{\Delta t} = L[cm^{-2} \cdot s^{-1}] \cdot \sigma[cm^{2}]$$

- Cross section for p+p collisionsis s » 100 mb , thus event rate for this luminosity is about 10^{9} events/second (challenge for the LHC experiments)
- Nuclear and particle physics require high-energy collisions of heavy nuclei in the LHC to create and study quark-gluon plasma

LEP: e^+e^-

104 GeV/c
(1989-2000)

Circumference
26.8 km

LHC
proton-proton
Collider
7 TeV/c in the
LEP tunnel

LHC also collides nuclei, e.g. Pb + Pb at up to 2.76 TeV/c per nucleon

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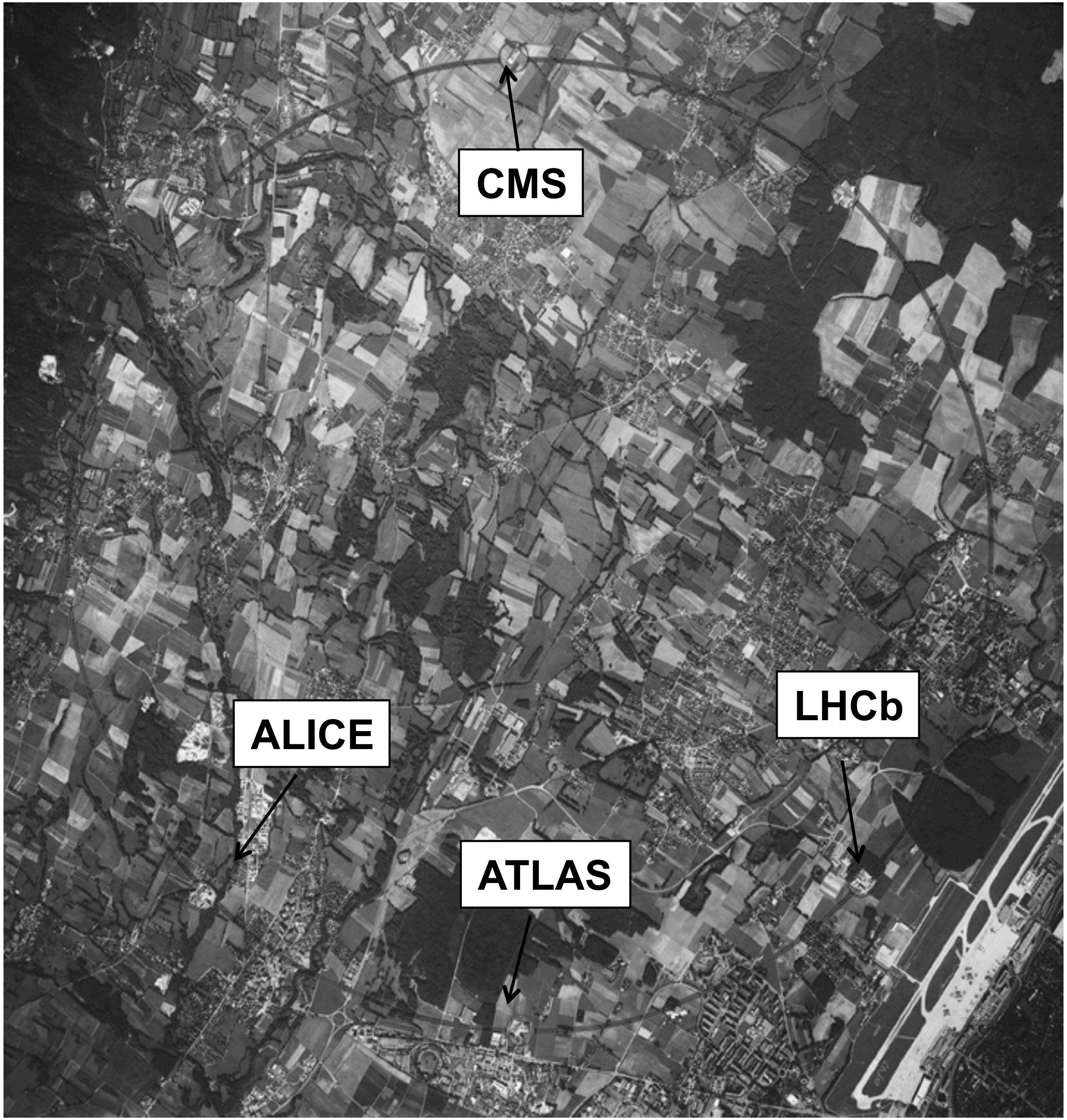
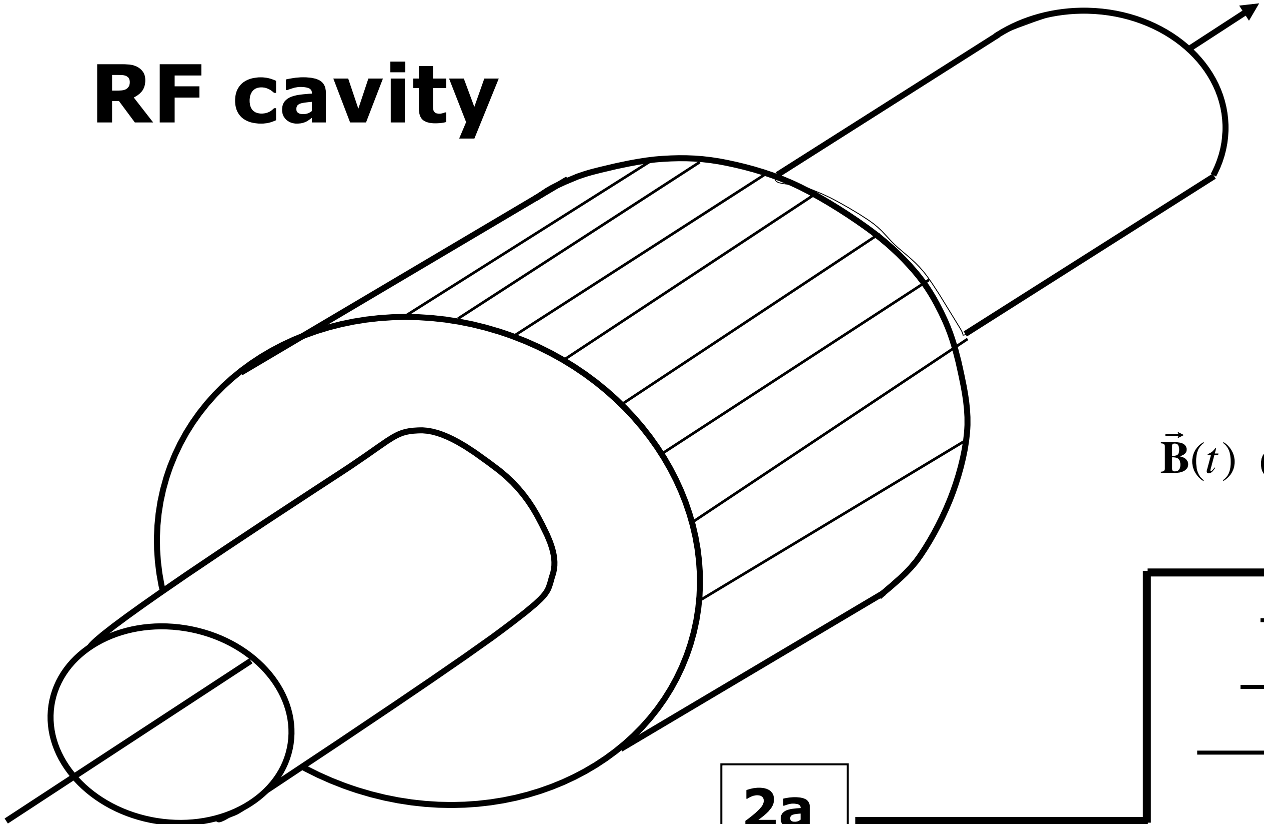
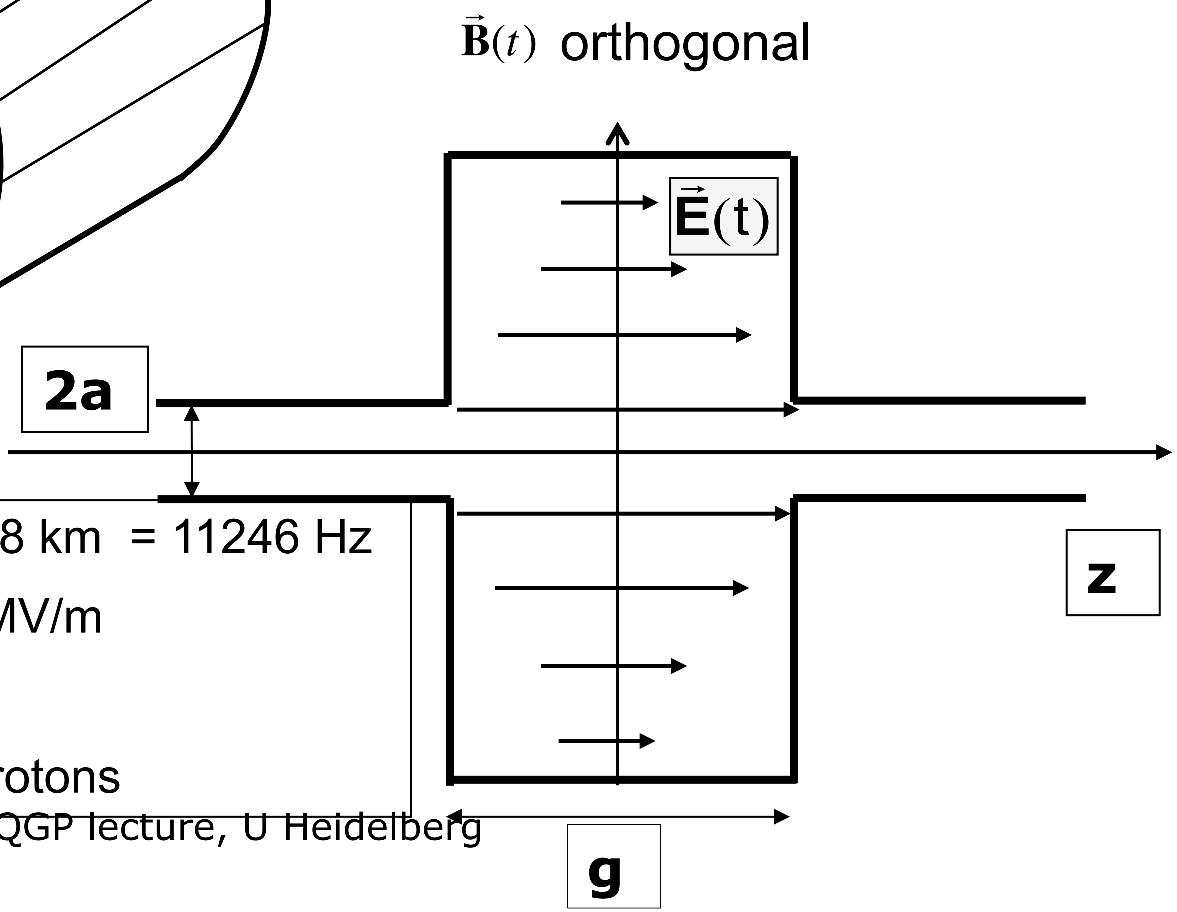


RF cavity





Revolution frequency: c / 26.8 km = 11246 Hz

Time varying field, up to 20 MV/m

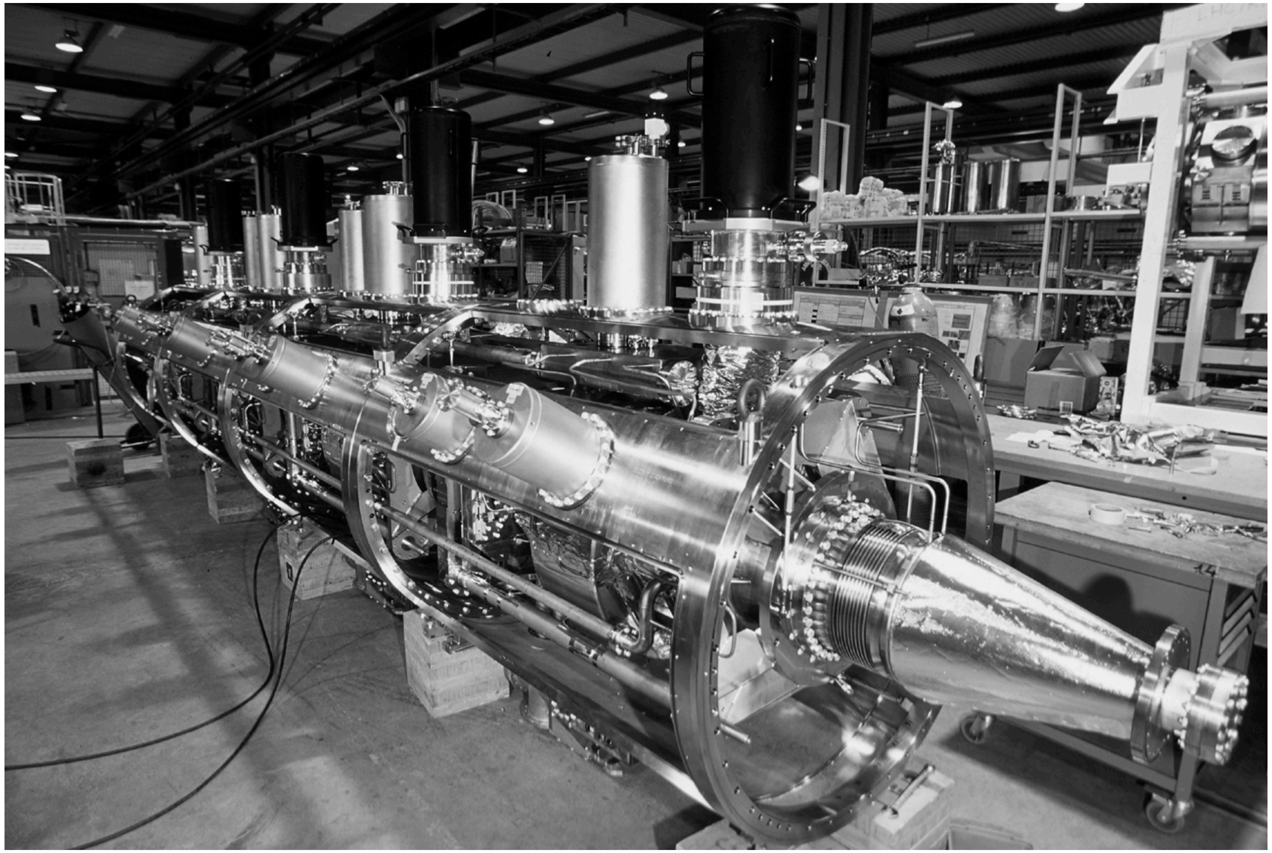
LHC RF frequency 400 MHz

Consequence: bunches of protons

RF systems: **400 MHz**

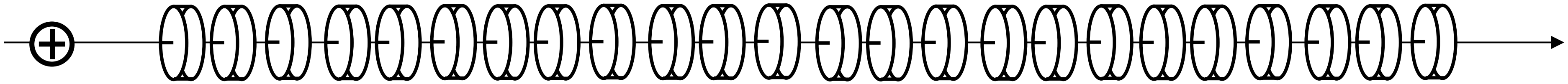
400 MHz system:

16 sc cavities (copper sputtered with niobium) for 16 MV/beam were built and assembled in four modules

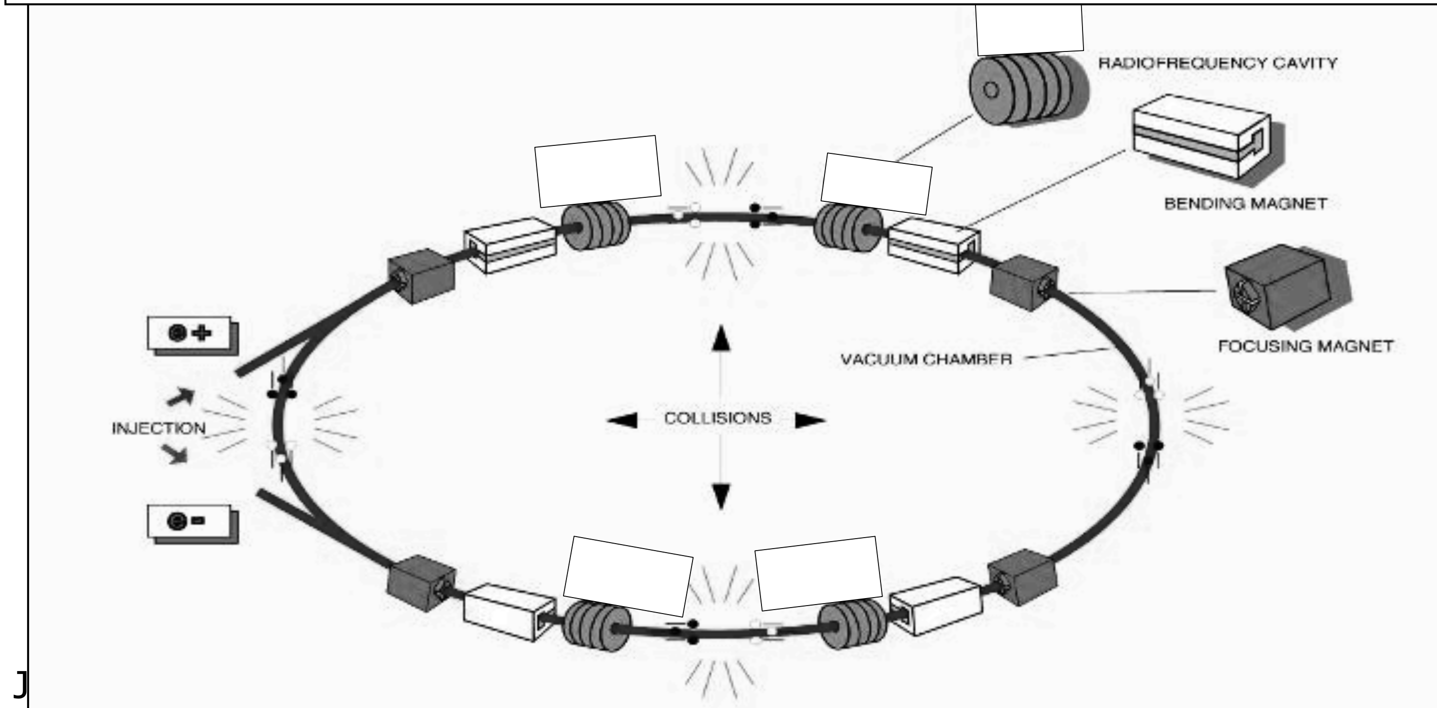


Circular accelerator and many passages in RF cavities

LINAC (planned for several hundred GeV - but not above 1 TeV)



LHC **circular machine** with energy gain per turn some MeV
acceleration takes about 20 minutes



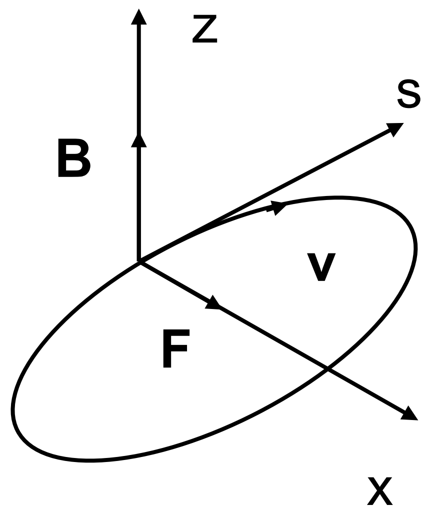
….requires deflecting magnets (dipoles)

Particle deflection: Lorentz Force

$$\vec{\mathbf{F}} = q \cdot (\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}})$$

$\Rightarrow$

$$B = \frac{p}{e_0 \cdot R}$$



- Maximum momentum 7000 GeV/c
- Bending radius 2805 m fixed by LEP tunnel
- Magnetic field B = 8.33 Tesla
- Iron magnets limited to 2 Tesla, therefore superconducting magnets are required
- Deflecting magnetic fields for two beams in opposite directions

Energy loss by synchrotron radiation

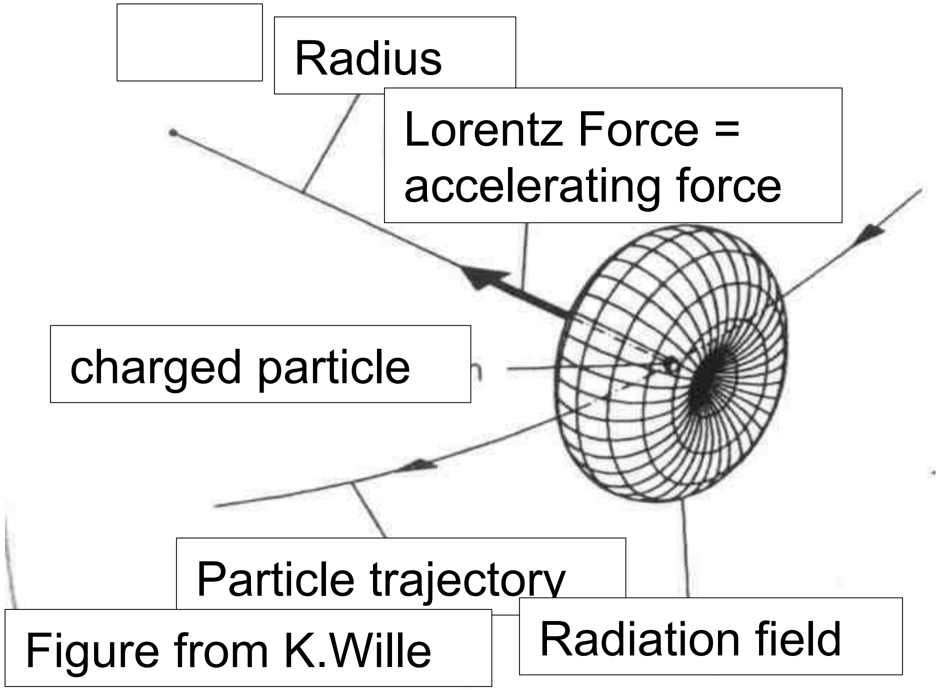


Figure from K.Wille

Power emitted for one particle: $P_s = \frac{e_0^2 \cdot c}{6 \cdot \pi \cdot \varepsilon_0 \cdot \left(m_0 \cdot c^2\right)^4} \cdot \frac{E^4}{\rho^2}$

with E = energy, m_0 = rest mass, e_0 = charge, and ρ = radius

Energy loss of electrons and protons in LEP tunnel

$E_{lep} := 100\text{GeV}$ $E_{lhc} := 7000\text{GeV}$

Energy loss for one particle per turn:

$U_{lep} = 3.844 \times 10^{9}\,\text{eV}$ $U_{lhc} = 8.121 \times 10^{3}\,\text{eV}$

Total power of synchrotronradiation:

Number of electrons in LEP: $N_{lep} := 10^{12}$ Number of protons in LHC $N_{lhc} := 10^{14}$

$P_{total\_lep} := N_{lep} \cdot P_{lep}$ $P_{total\_lhc} := N_{lhc} \cdot P_{lhc}$

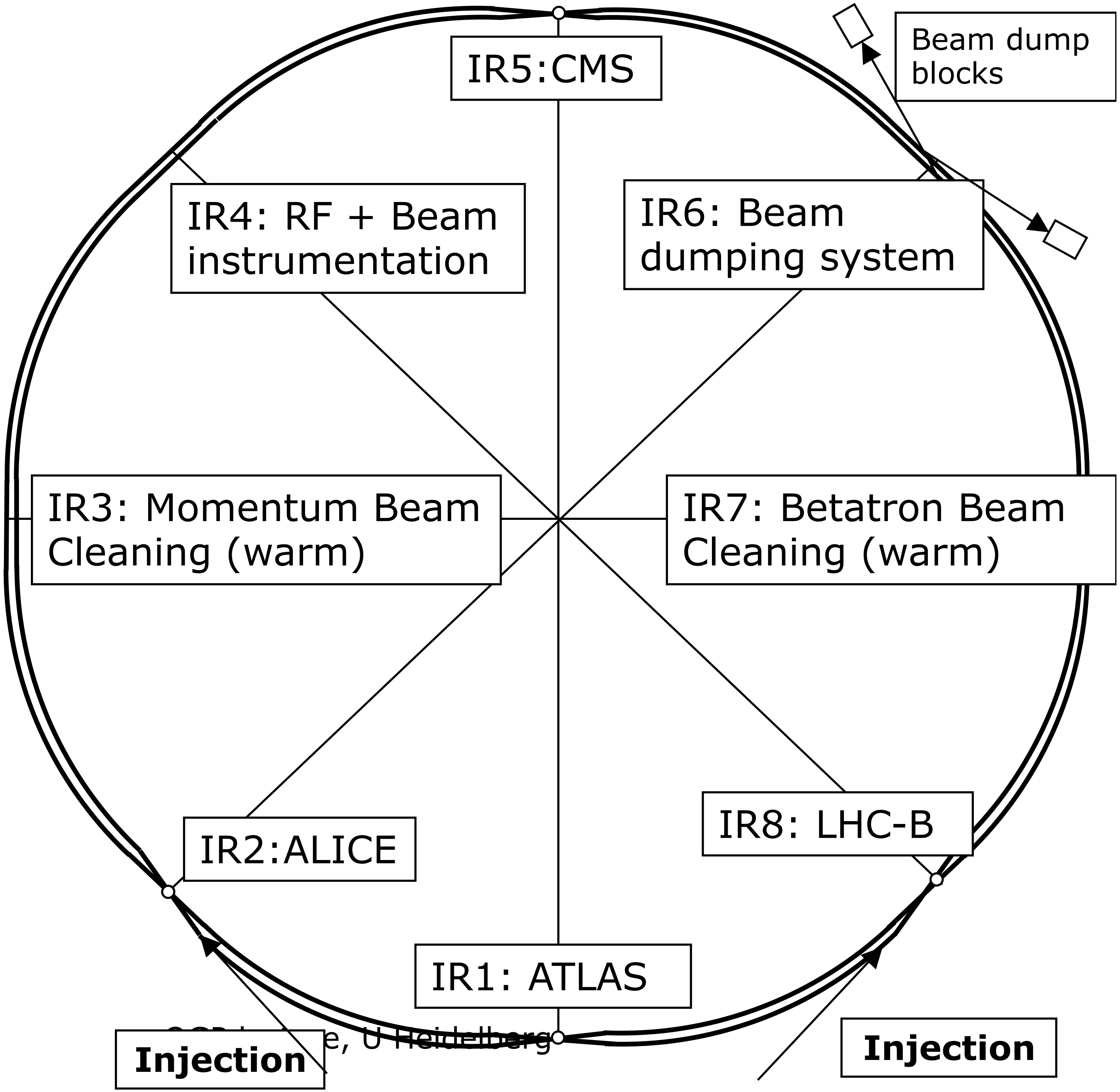
$P_{total\_lep} = 1.278 \times 10^{7}\,\text{W}$ $P_{total\_lhc} = 2.699 \times 10^{3}\,\text{W}$

The power of the synchrotronradiation emitted at the LHC is very small, but the radiation goes into the supraconducting magnets at 1.9 K ... 20 K

LHC Layout

eight sectors
eight arcs

eight long straight sections (insertions) about 700 m long



Main dipole magnets: making the circle

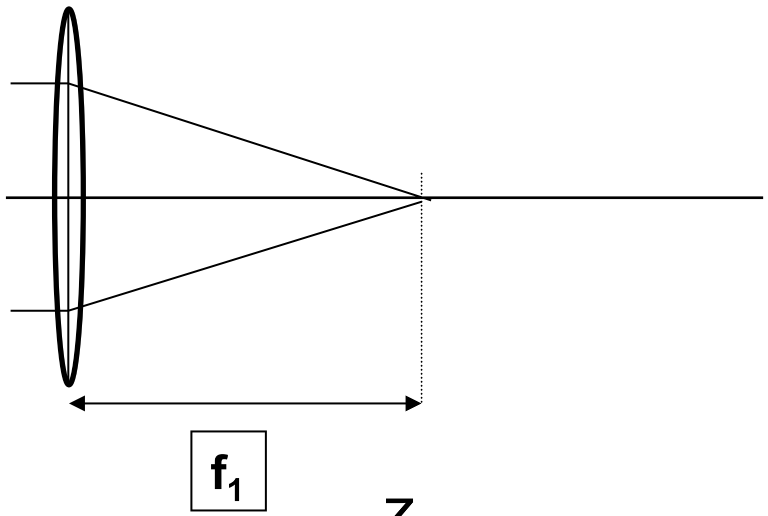
Beam transport

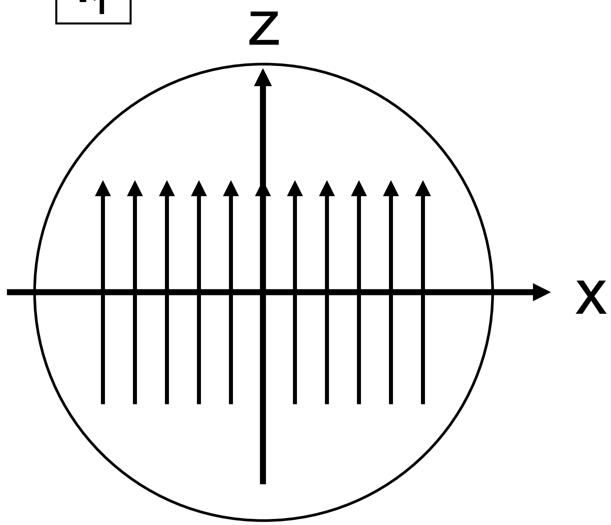
Keep protons on a circle: dipole magnets

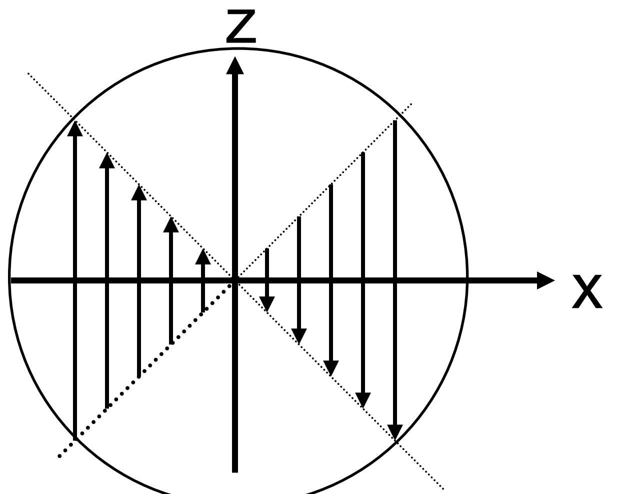
Keep beams focussed:

- Particles with different injection parameters (angle, position) separate with time
  - Assuming an angle difference of 10^{-6} rad, two particles would separate by 1 m after 10^{6} m. At the LHC, with a length of 26860 m, this would be the case after 50 turns (5 ms !)
- Particles would „drop" due to gravitation
- The beam size must be well controlled
  - At the collision point the beam size must be tiny
- Particles with (slightly) different energies should stay together

Focusing: using lenses as for light







Dipole-magnet – B-field in aperture constant

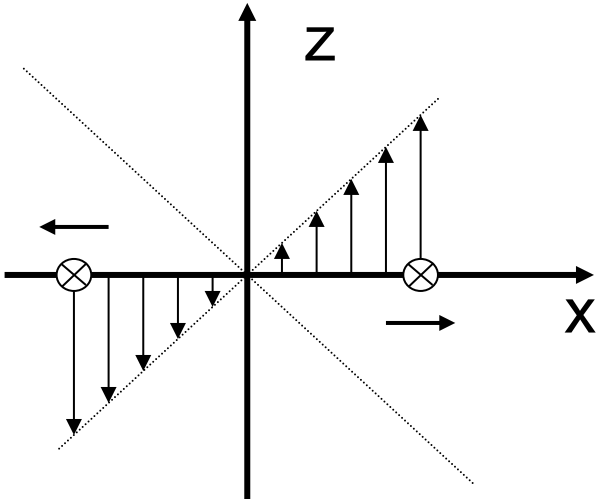
Quadrupole-magnet – B-field zero in centre, linear increase (as an optical lense)

From Maxwell equations:

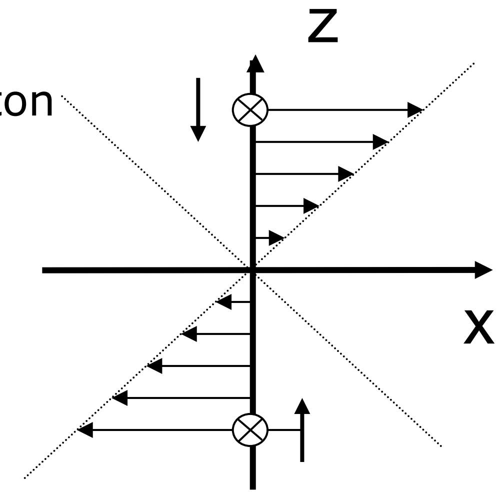
$$B_z(x) = \text{const} \cdot x$$

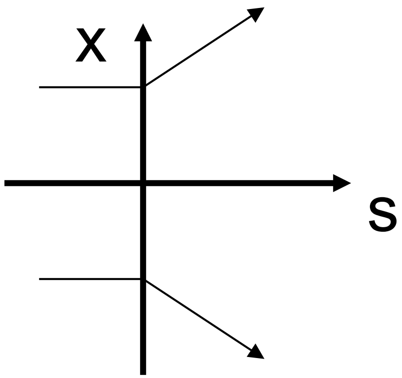
$$B_x(z) = \text{const} \cdot z$$

Assuming proton runs along s (=y), perpendicular to x and z

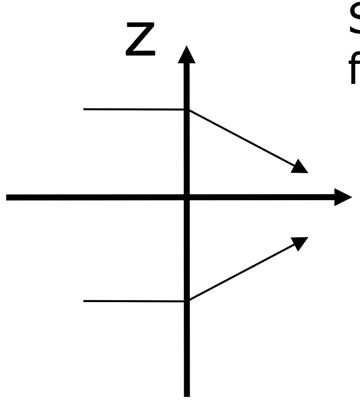


Looking along proton trajectory



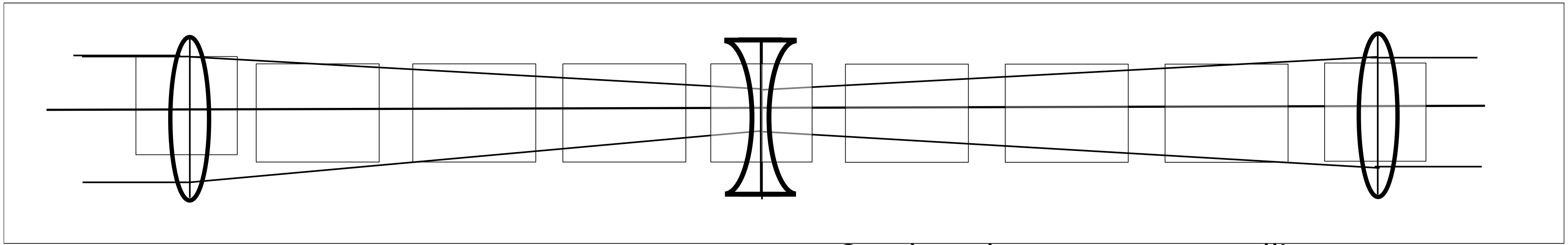


Top view defocusing



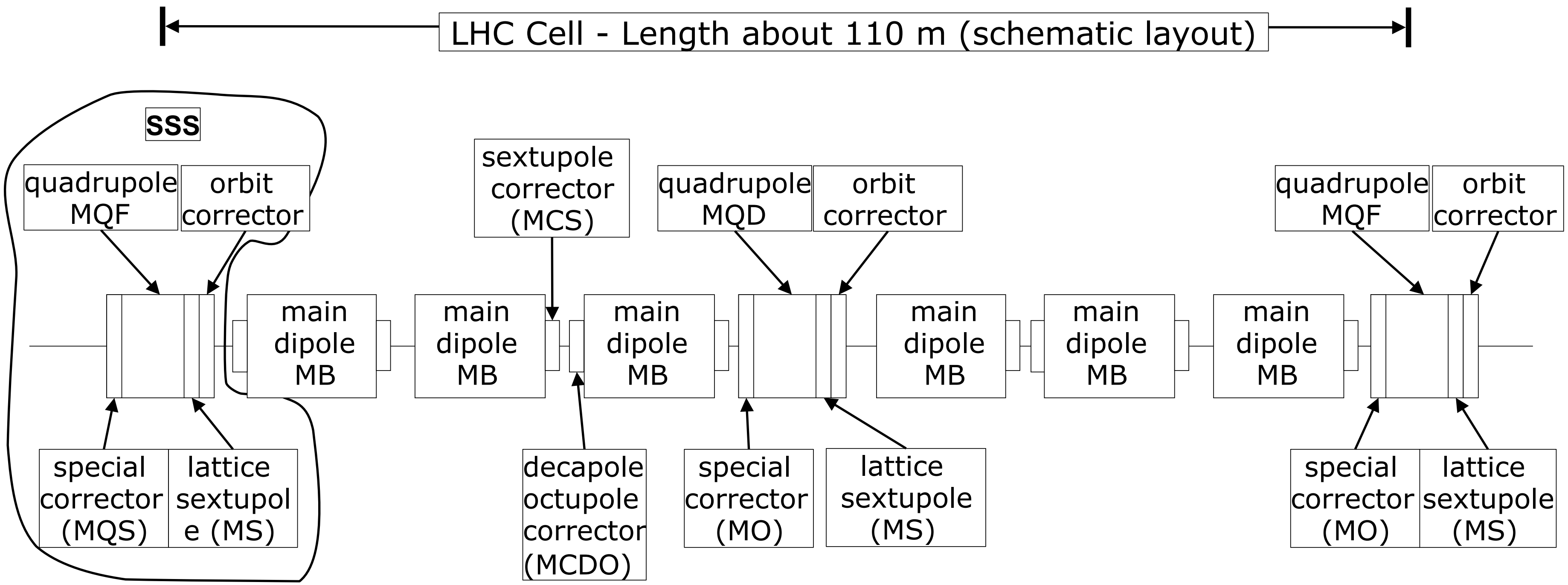
Side view focusing

A cell in the LHC arcs



Vertical / Horizontal plane
(QF / QD)

Quadrupole magnets controlling the beam size „to keep protons together“ (similar to optical lenses)



High luminosity by colliding trains of bunches

Number of events per unit of time:

$$\frac{N}{\Delta T} = L\left[cm^{-2} \cdot s^{-1}\right] \cdot \sigma\left[cm^{2}\right]$$

The objective for the LHC as proton – proton collider is a luminosity of about 10^{34} [$cm^{-2}s^{-1}$]

- LEP (e+e-) : 3-4 10^{31} [$cm^{-2}s^{-1}$]
- Tevatron (p-pbar) : ~ 10^{32} [$cm^{-2}s^{-1}$]
- B-Factories: > 10^{34} [$cm^{-2}s^{-1}$]

Luminosity parameters

$$L = \frac{N^2 \cdot f \cdot n_b}{4\pi \cdot \sigma_x \cdot \sigma_y}$$

with:

N = Number of protons per bunch

f = revolution frequency

n_b = number of bunches per beam

$\sigma_x \cdot \sigma_y$ = beam dimensions at interaction point

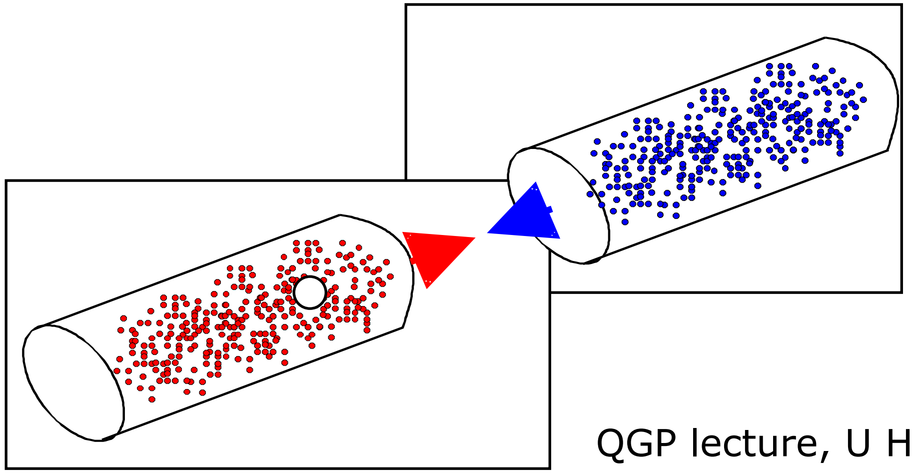
Every proton experiences the em-fields of 10^{11} protons in the other beam

Beam-beam interaction limits $N < 10^{11}$

f = 11246 Hz

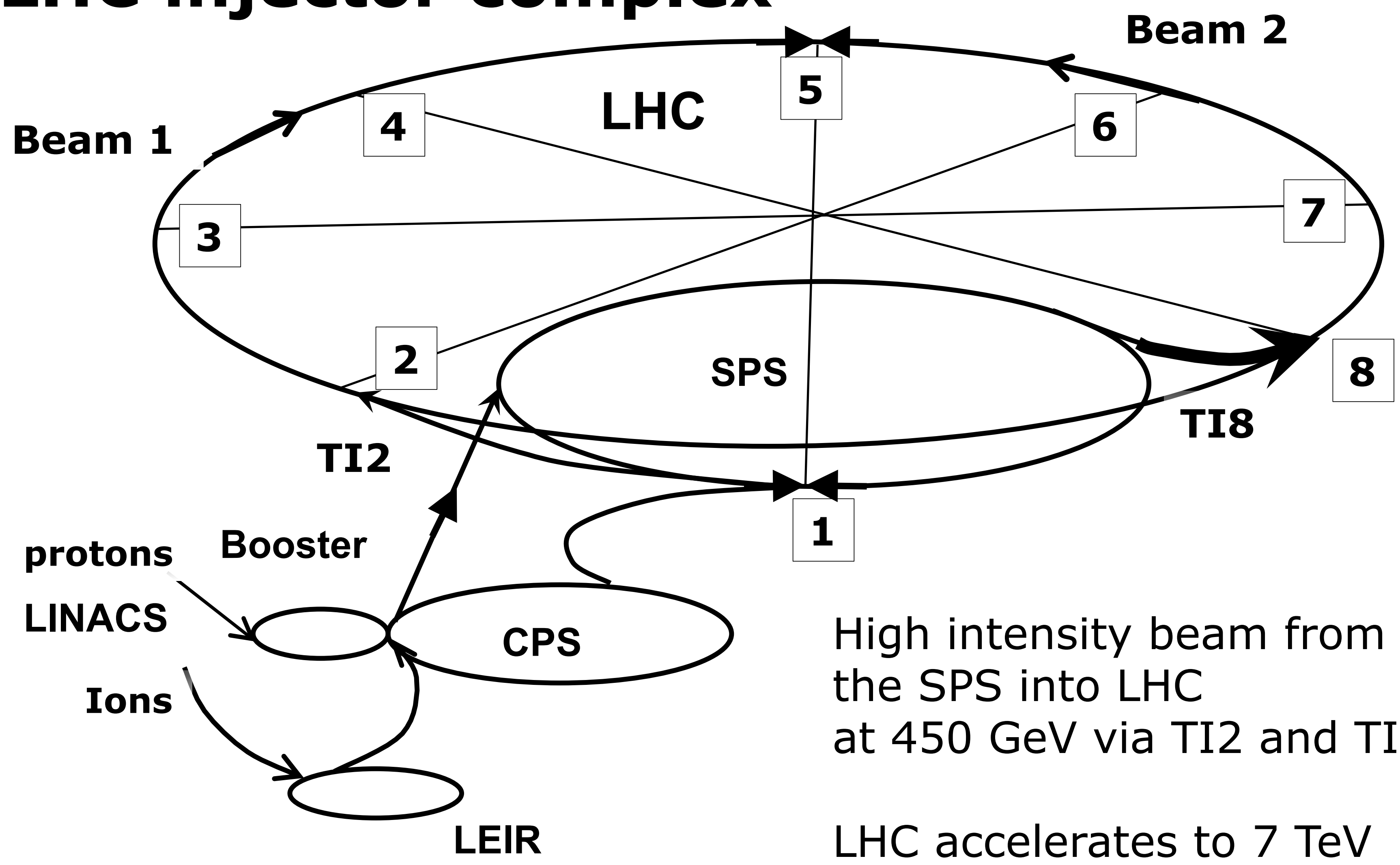
n_b = 2808 bunches

σ_x, σ_y = 16 μm



$L = 10^{34}$ [$cm^{-2}s^{-1}$]

LHC injector complex



High intensity beam from the SPS into LHC at 450 GeV via TI2 and TI8

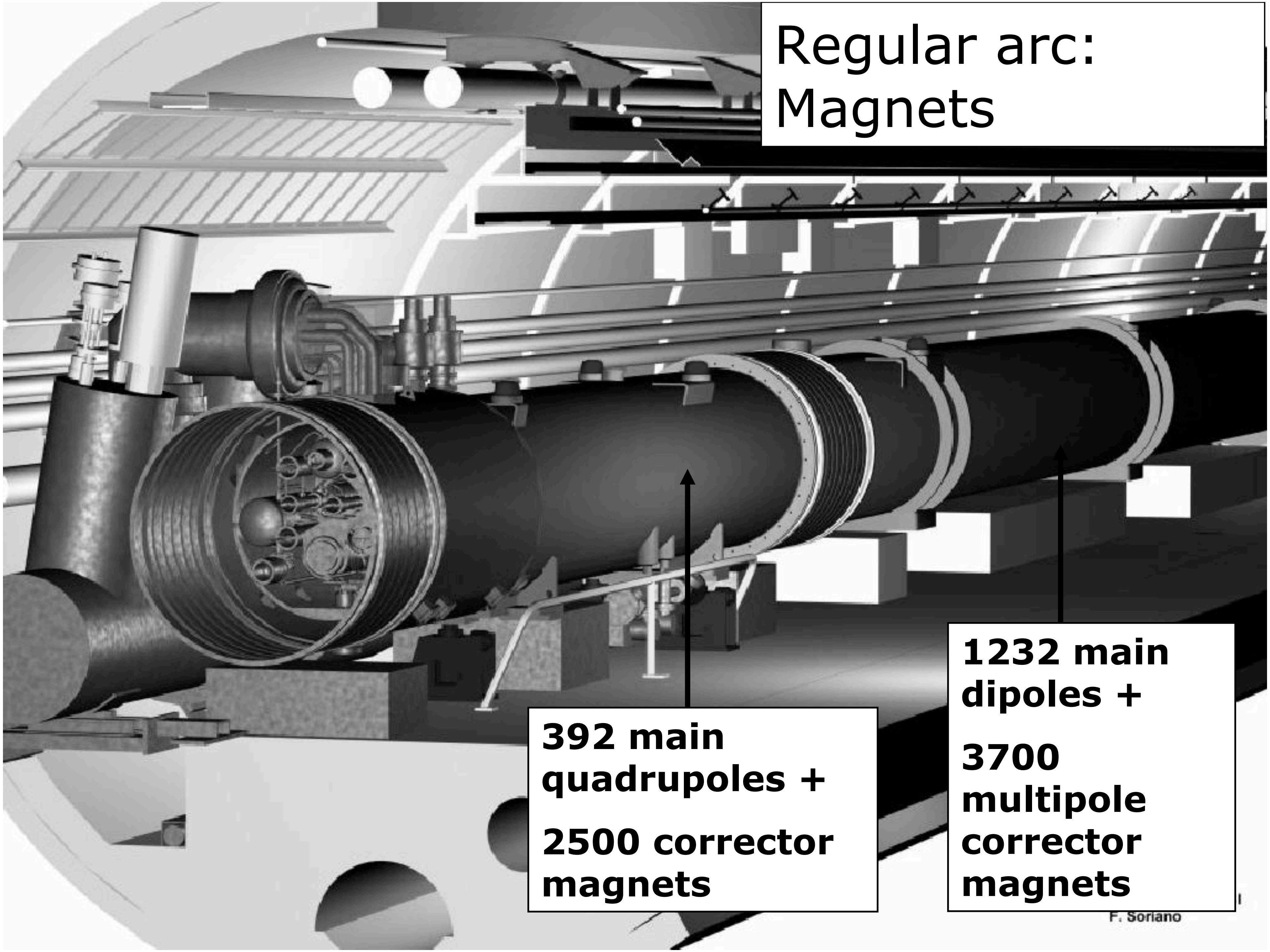
LHC accelerates to 7 TeV

Beam size of protons decreases with energy: $\sigma^2 = 1 / E$

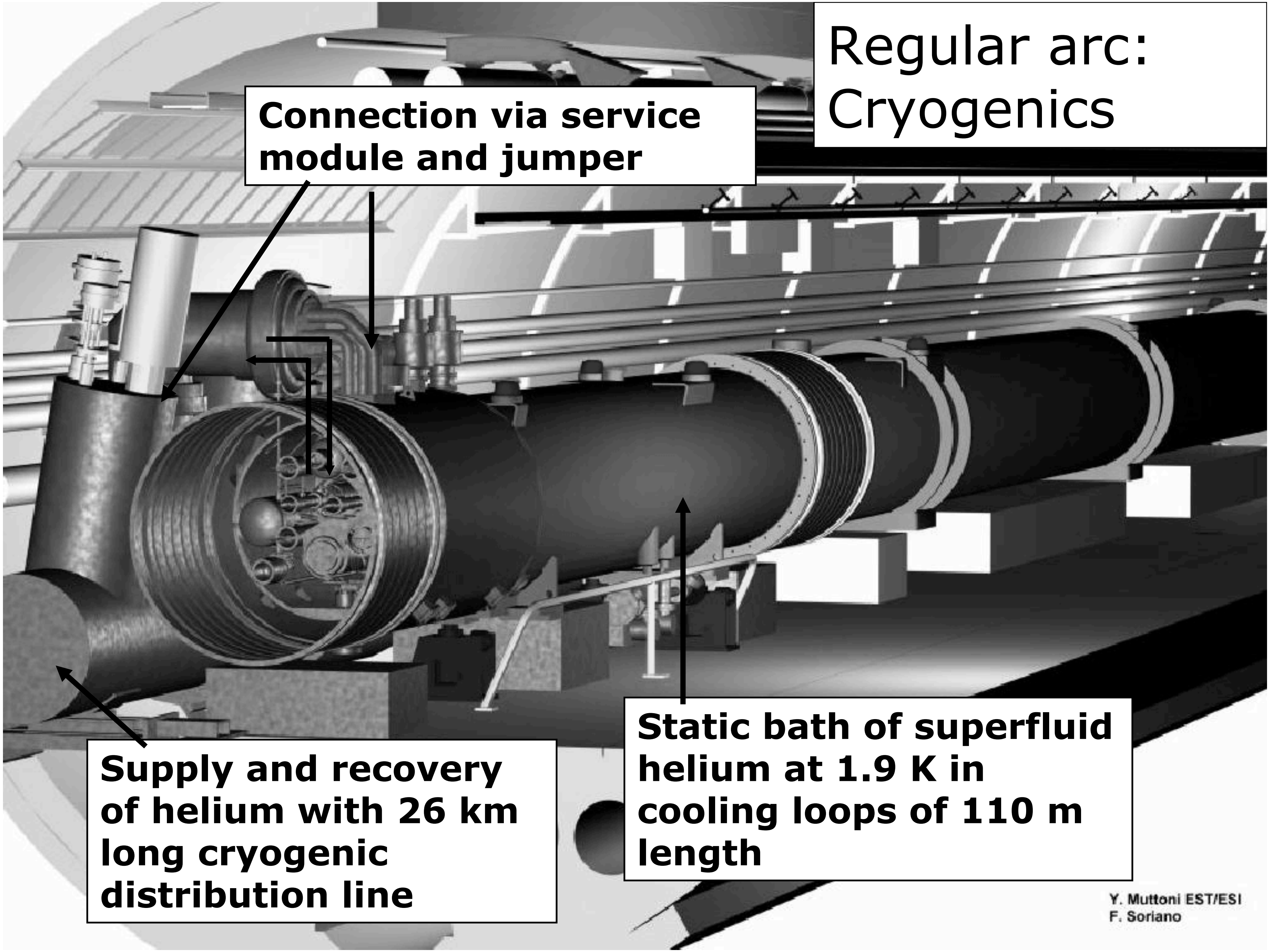
Beam size large at injection

Beam fills vacuum chamber at 450 GeV

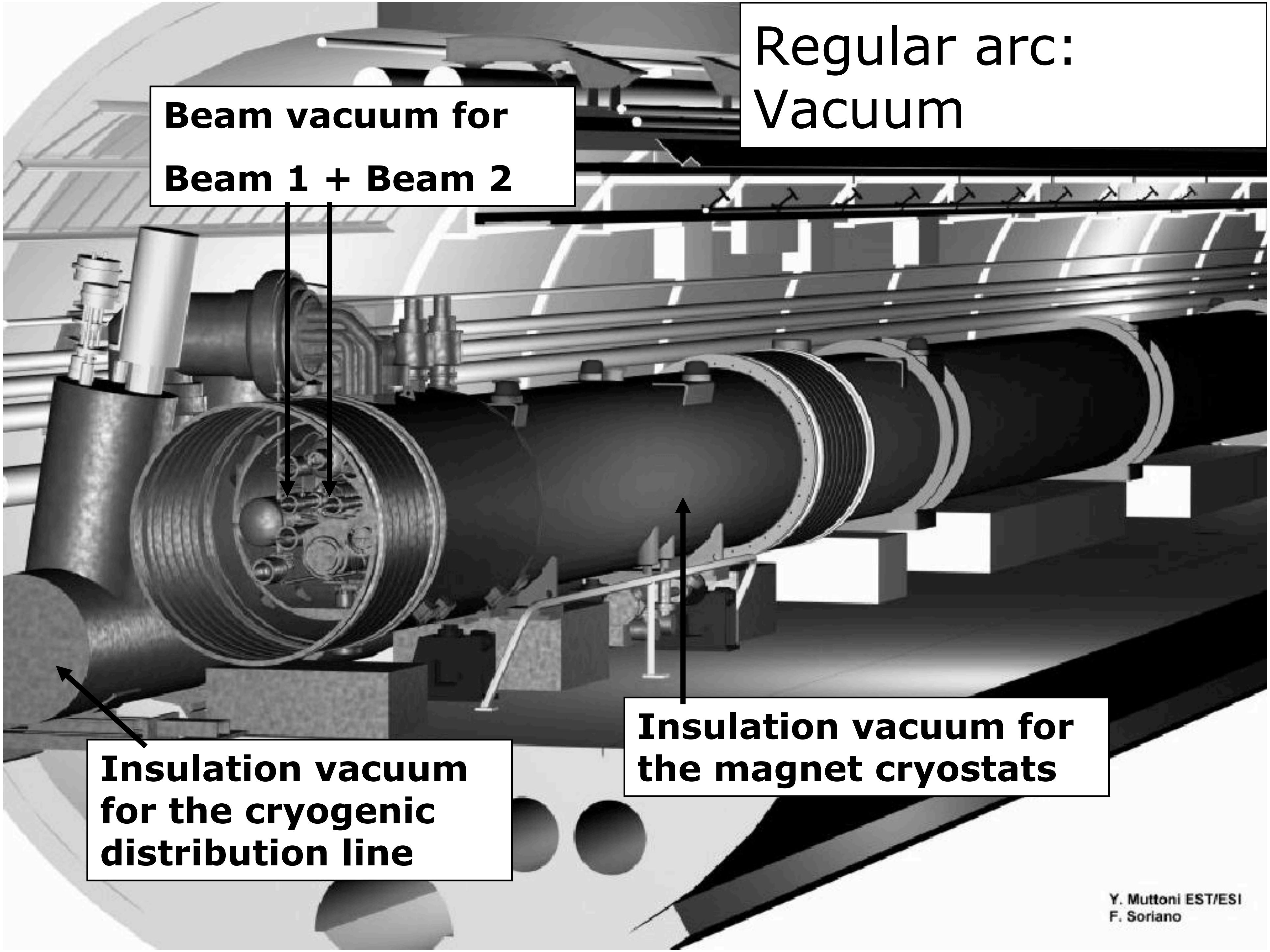
Regular arc: Magnets



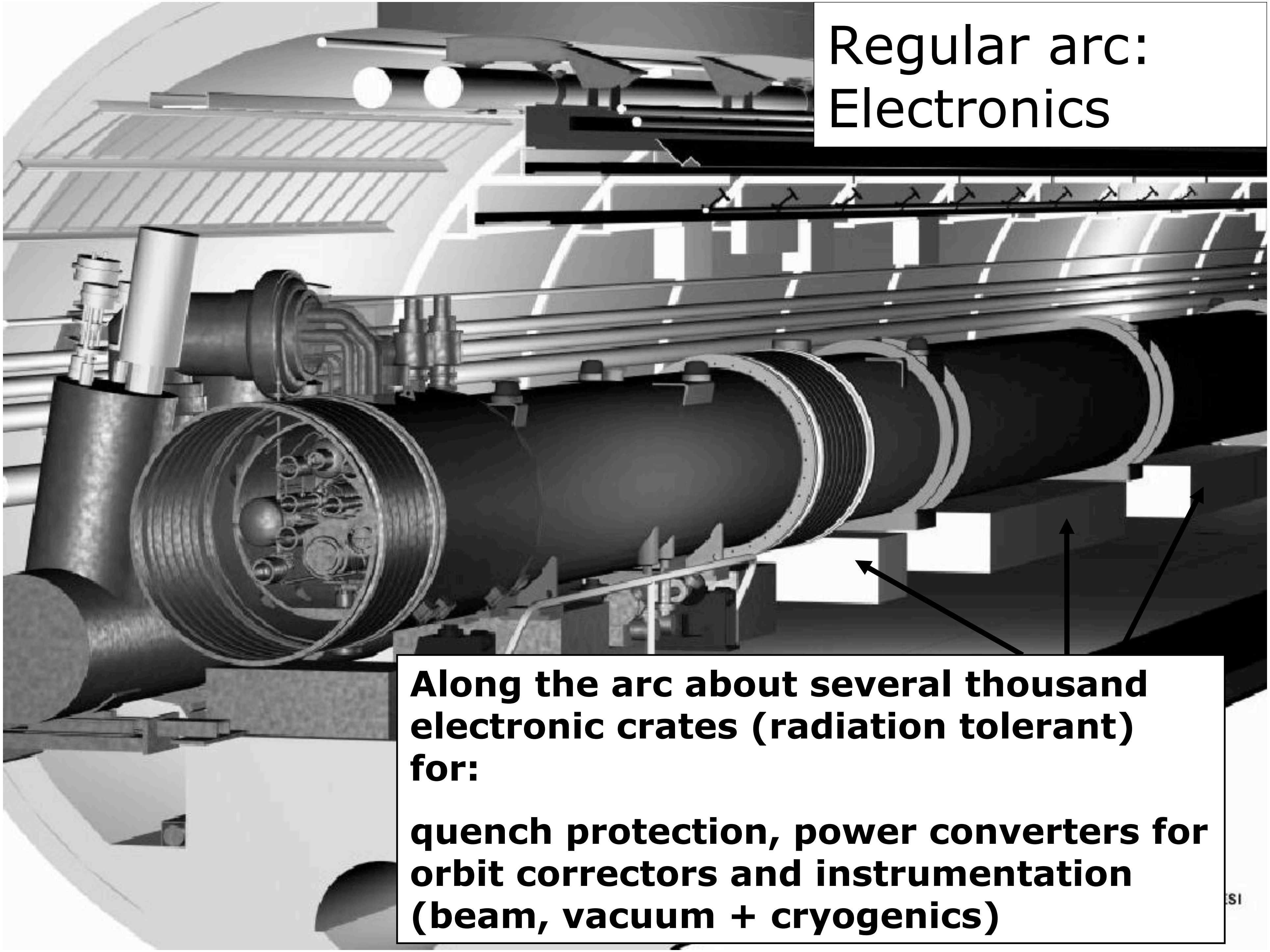
Regular arc: Cryogenics



Regular arc: Vacuum



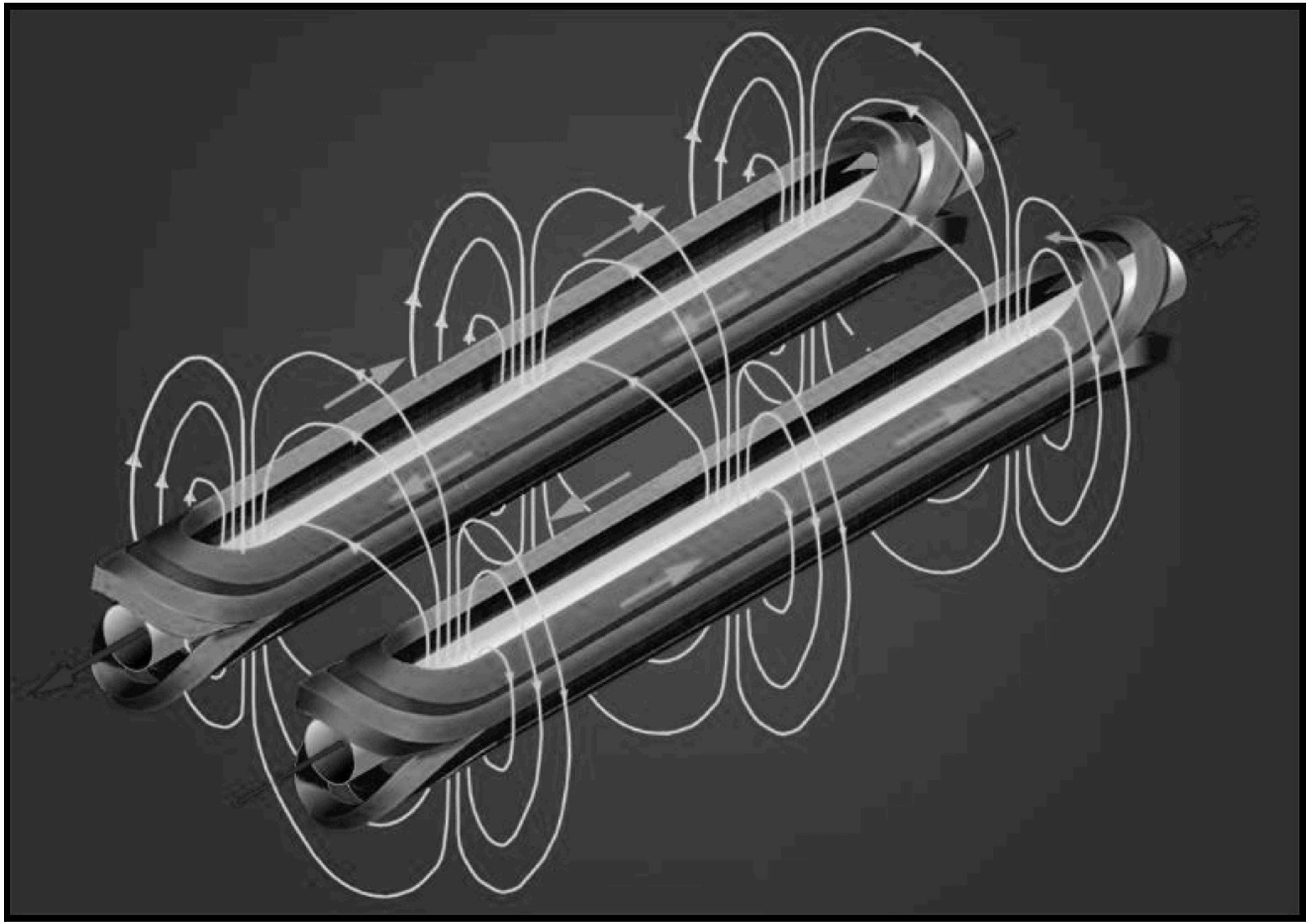
Regular arc: Electronics

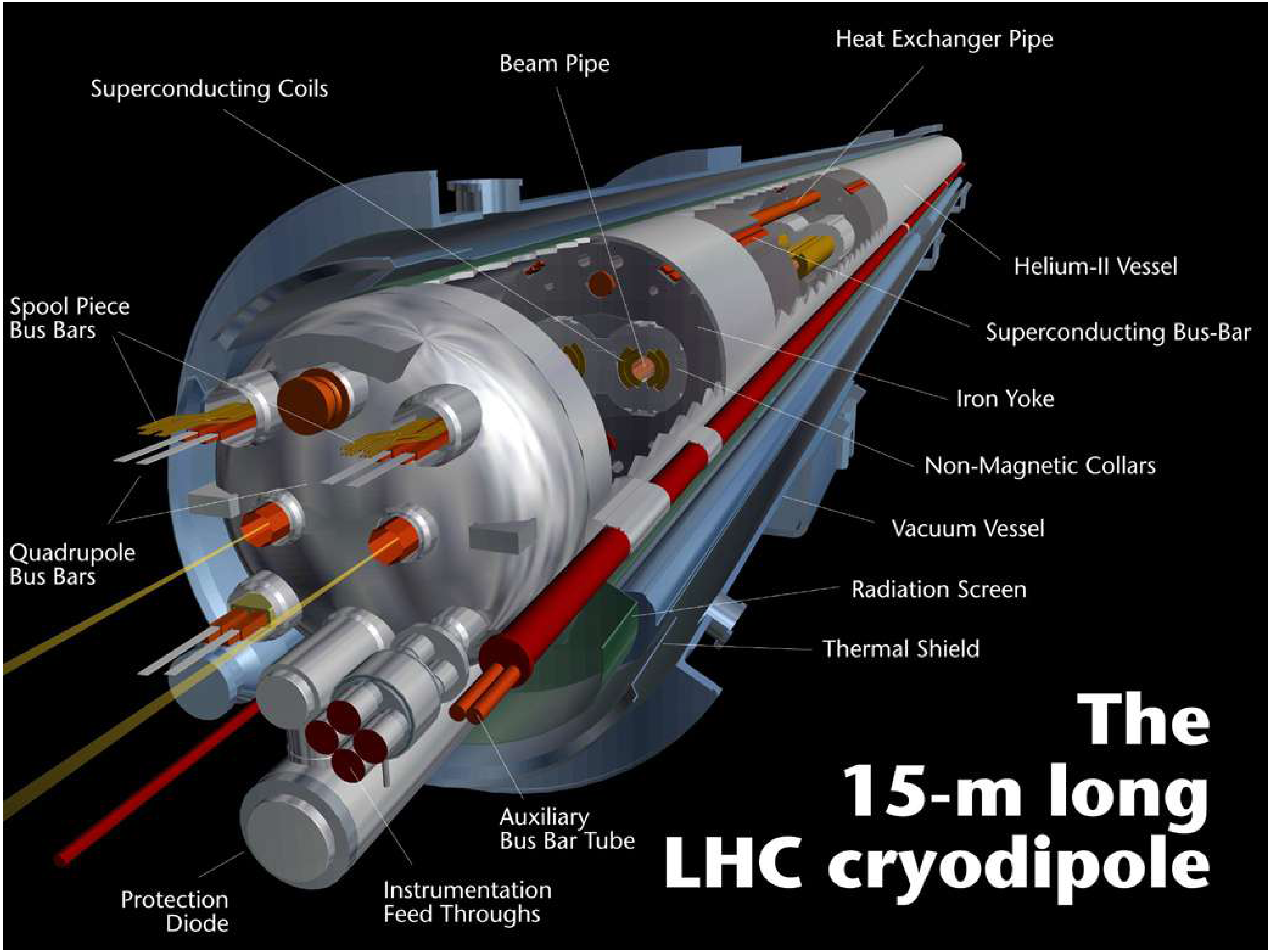


Along the arc about several thousand electronic crates (radiation tolerant) for:

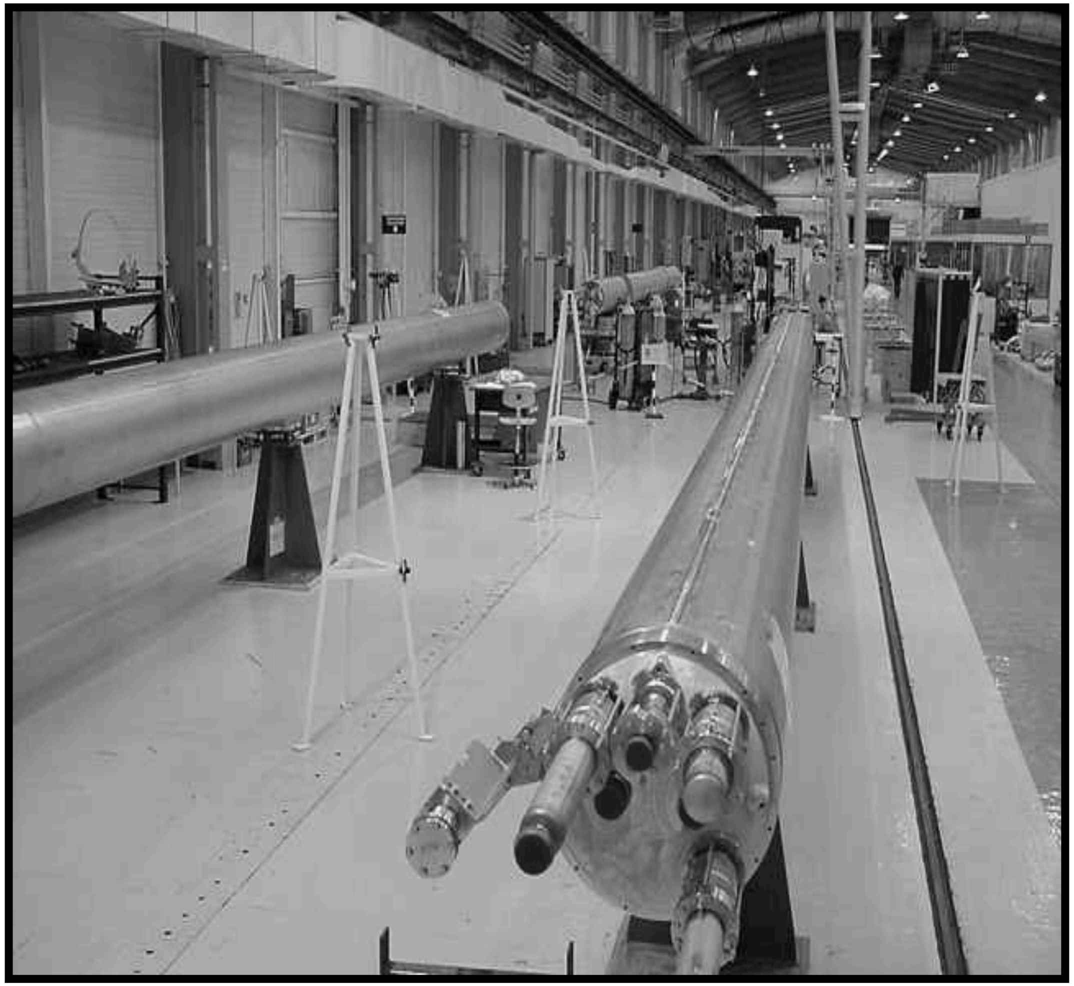
quench protection, power converters for orbit correctors and instrumentation (beam, vacuum + cryogenics)

Coils for Dipolmagnets



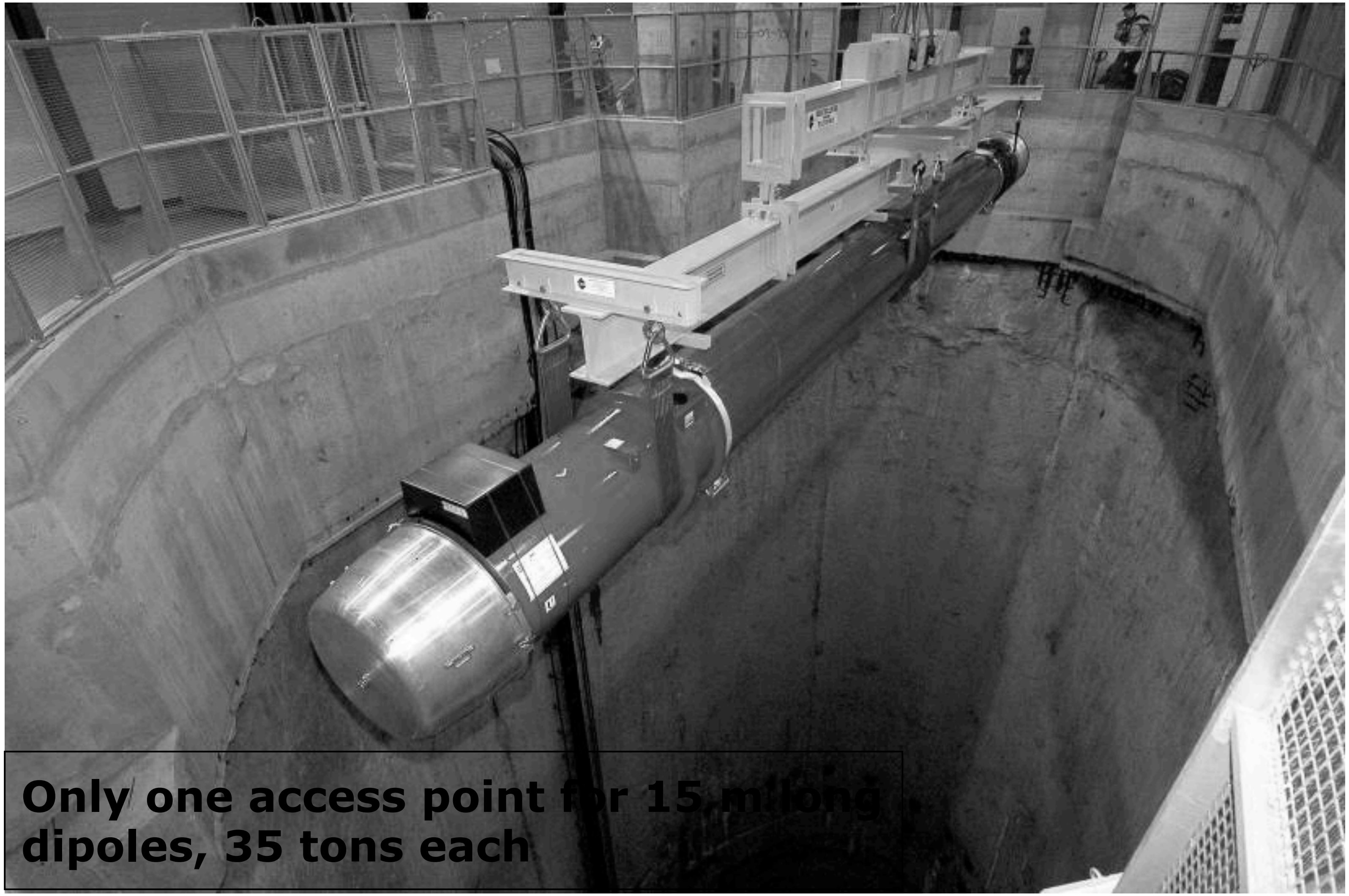

Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Thermal Shield
The
15-m long
LHC cryodipole
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs

Fabrication of superconducting dipoles



Dipole assembly in industry

First cryodipole lowered on 7 March 2005



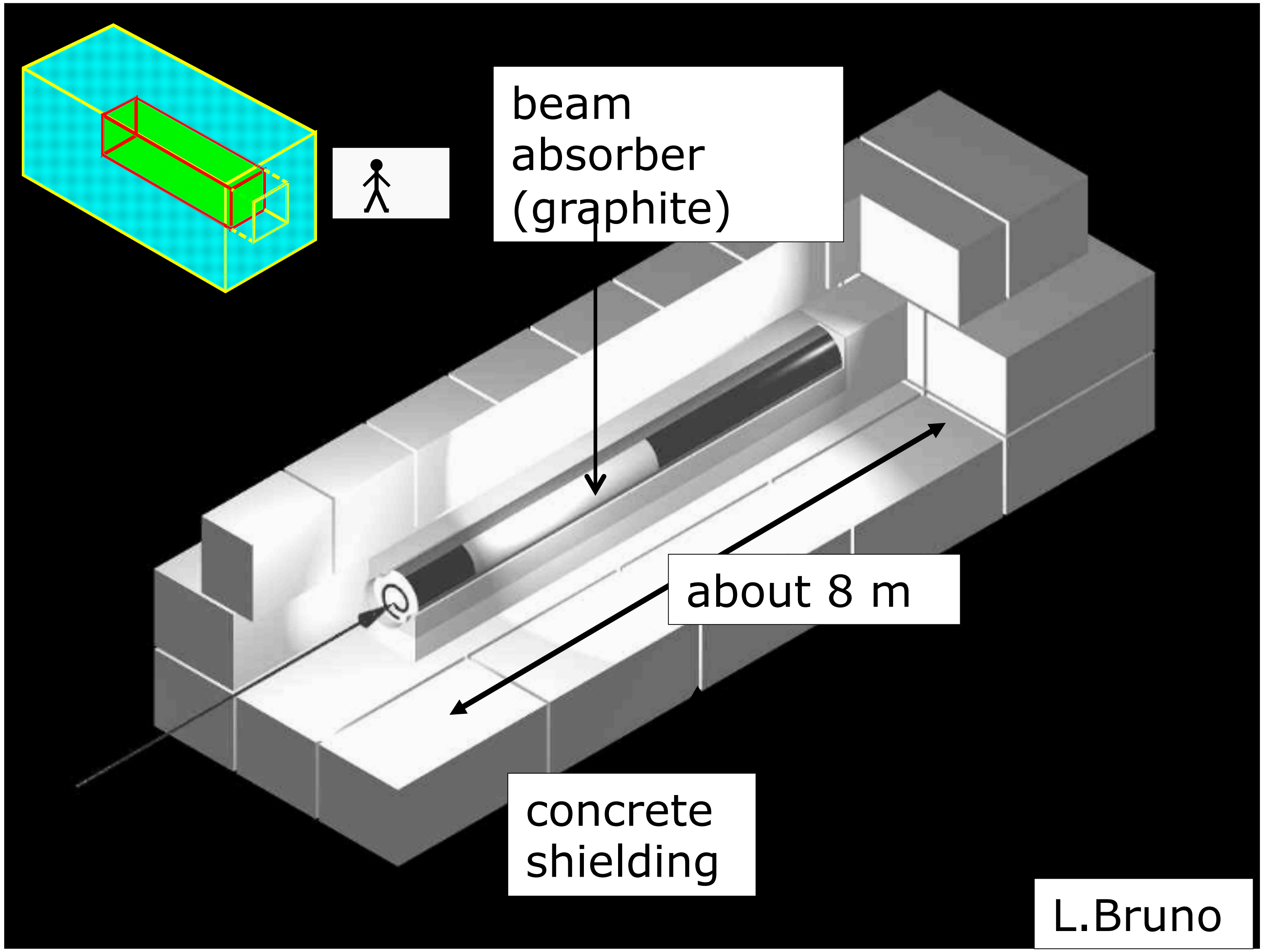
Only one access point for 15 m long dipoles, 35 tons each

Transport in the tunnel with an optical guided vehicle

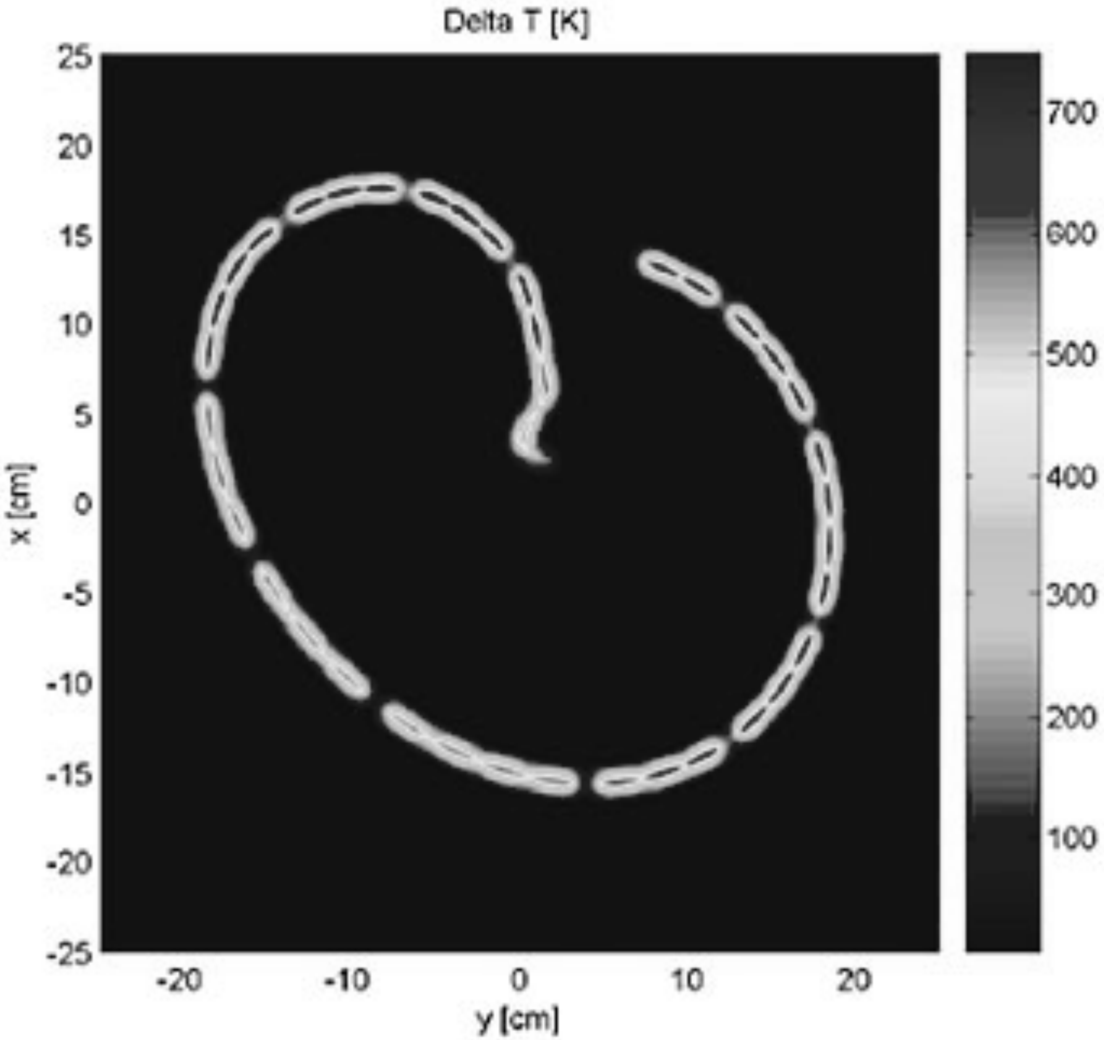
about 1600 magnets to be transported for 15 km

at 2-3 km/hour

Beam Dump Block - Layout



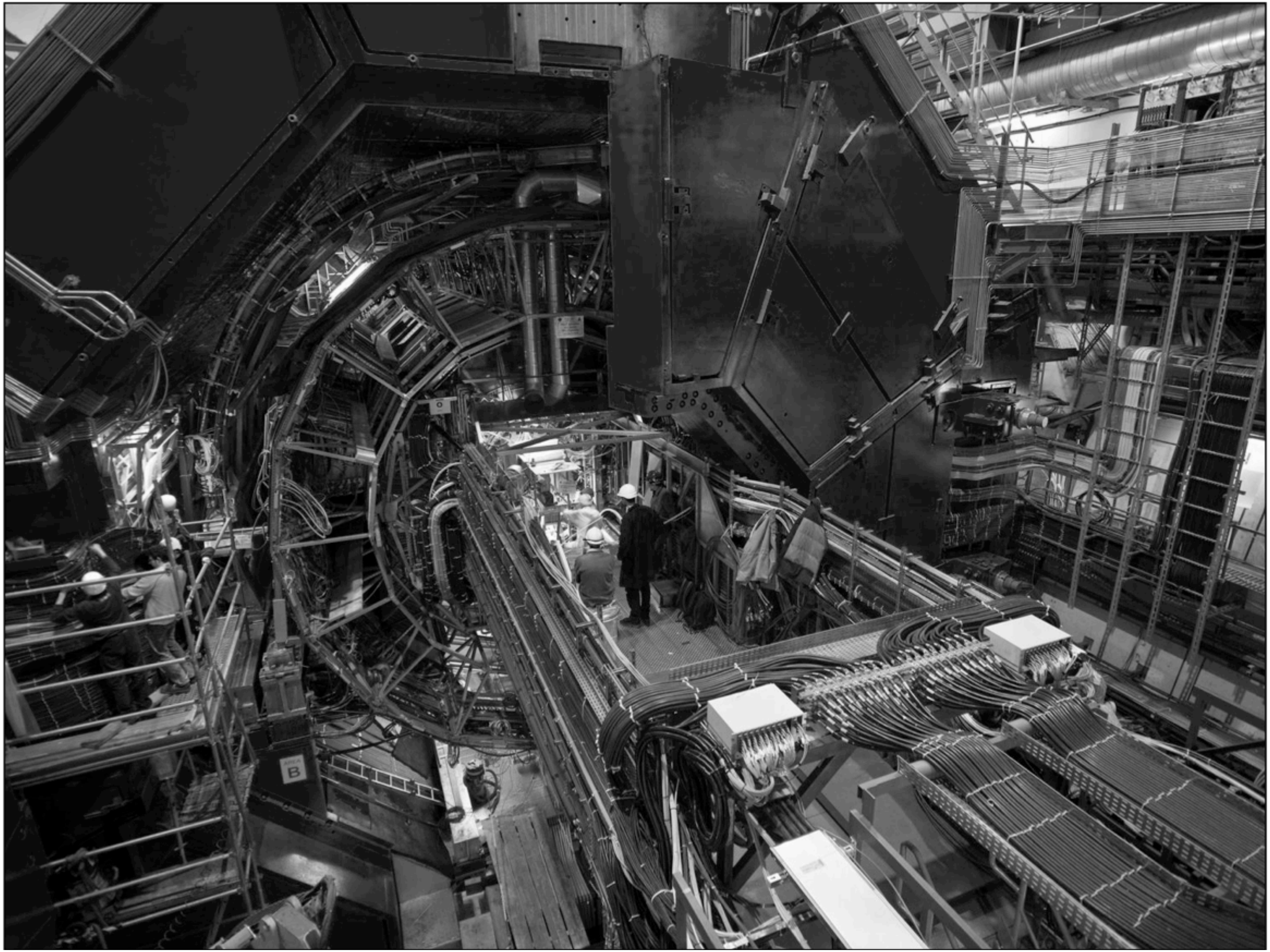
Temperature of beam dump block at 80 cm inside

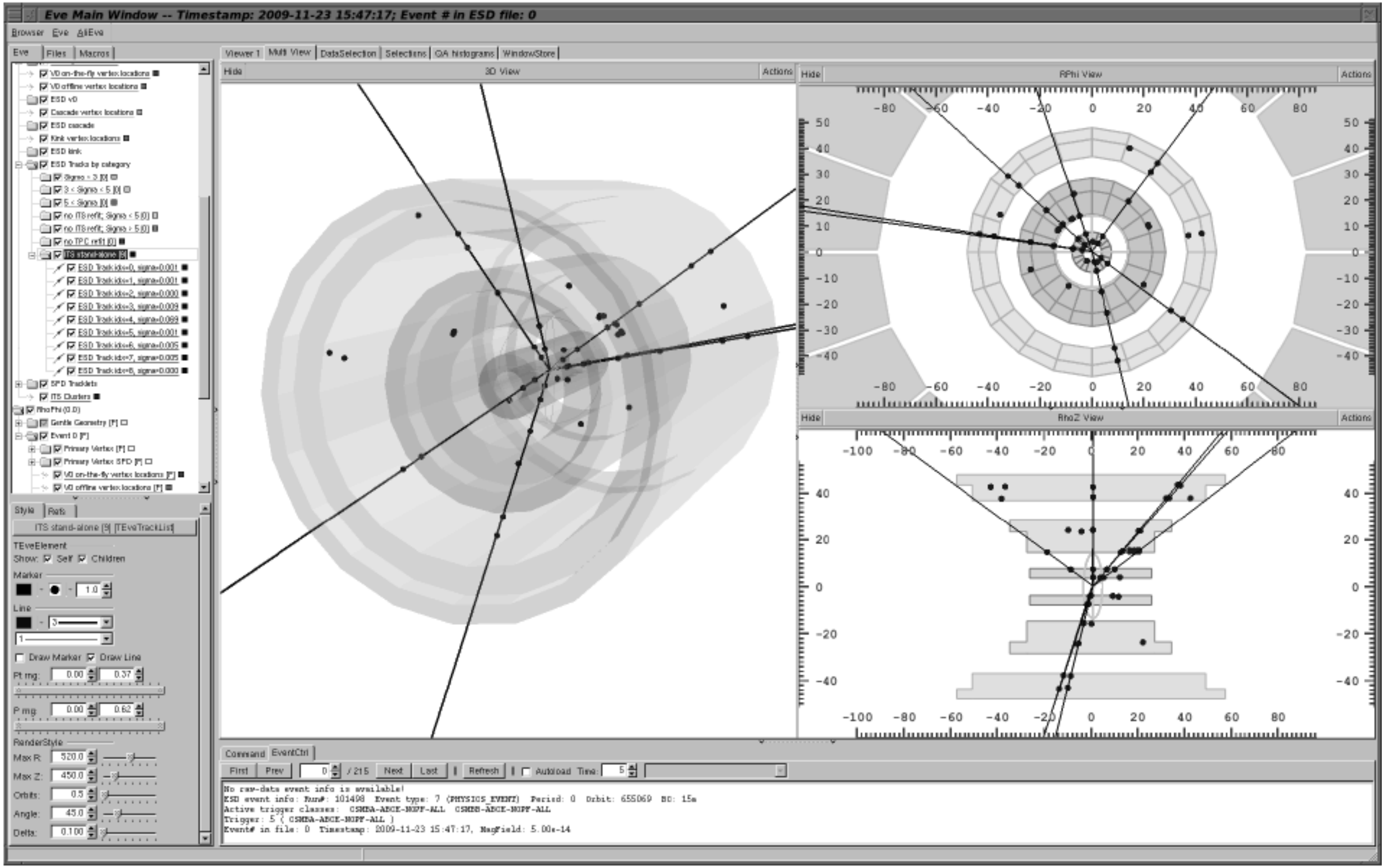


Nominal LHC Running Conditions

Collision system	$\sqrt{s_{NN}}$(TeV)	L_0 ($cm^{-2}s^{-1}$)	Run time (s/year)	σ_{geom} (b)
p + p	**14.0**	**10^{34} ***	**10^7**	**0.07**
Pb + Pb	**5.5**	**10^{27}**	**10^6 ****	**7.7**
p + Pb	8.8	10^{29}	10^6	1.9
Ar + Ar	6.3	10^{29}	10^6	2.7

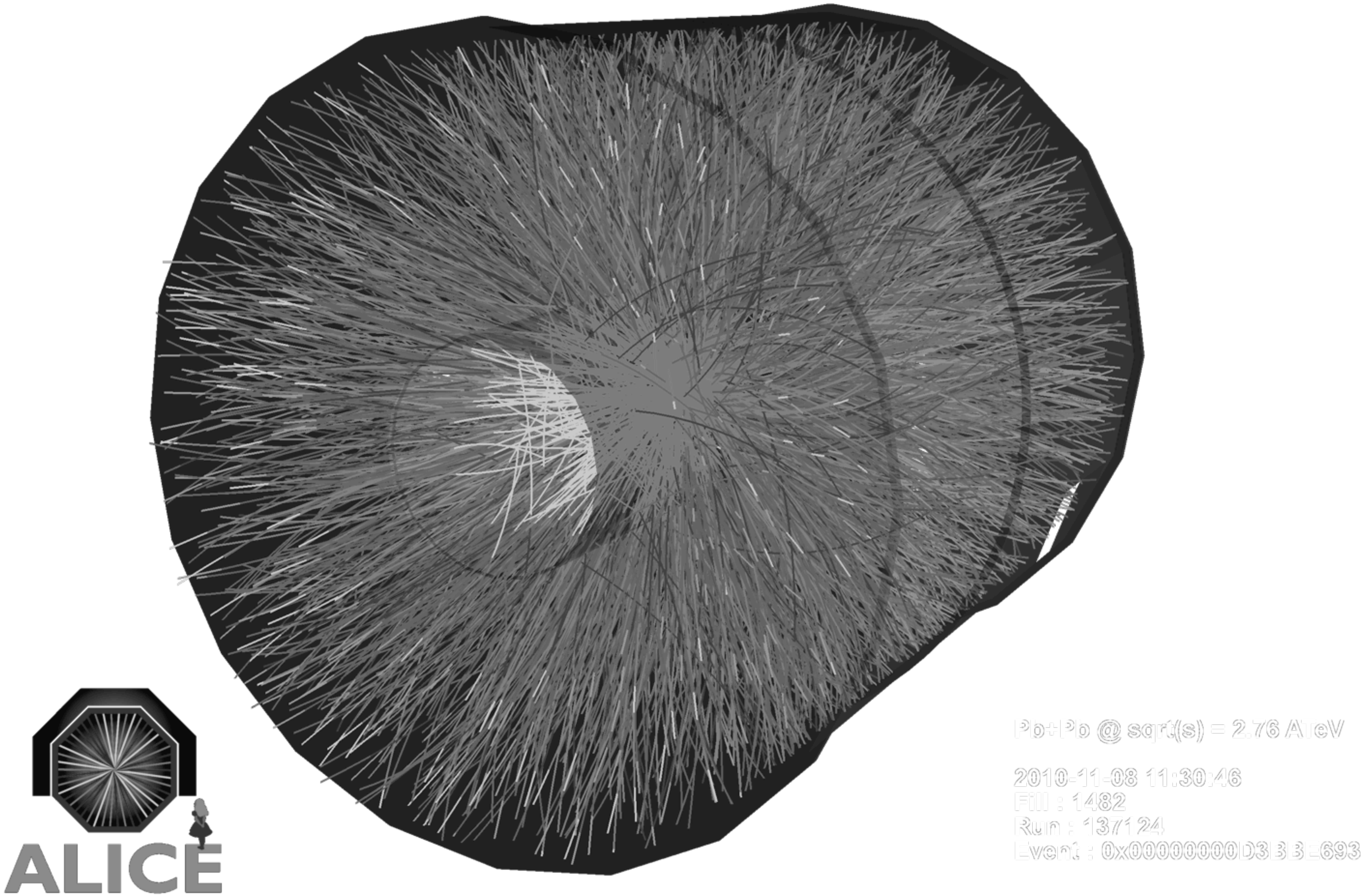
***$\mathcal{L}_{max}$ (ALICE) = $10^{30}cm^{-2}s^{-1}$**
**** $\mathcal{L}_{int}$ (ALICE) ~ 0.5 nb^{-1}/year**





23-November-2009: first p+p collision recorded in ALICE !

First Pb+Pb collisions in ALICE !



LHC: Tentative Schedule

23-Nov-2009: **1st pp collisions** at **900 GeV**

Dec-2009: **1st pp collisions** at **2.36 TeV**

2010*/11*/12: **long run** with **pp** collisions at **7(8) TeV**

1 month of **Pb+Pb** collisions each year

08-Nov-2010: **1st Pb+Pb collisions** at **2.76 TeV**

Jan/Feb 2013: **p+Pb collisions** at 5.02 TeV

2013/14: Machine consolidation and training – LS1

2015-17: **pp** (@14 or 13 TeV) and **Pb+Pb** at **full energy**

2018: **luminosity** and **detector upgrades** – LS2

2019-22: **LHC** at **high luminosity** (5x design)

*technical stop during Dec/Jan

ALICE - harvesting physics!