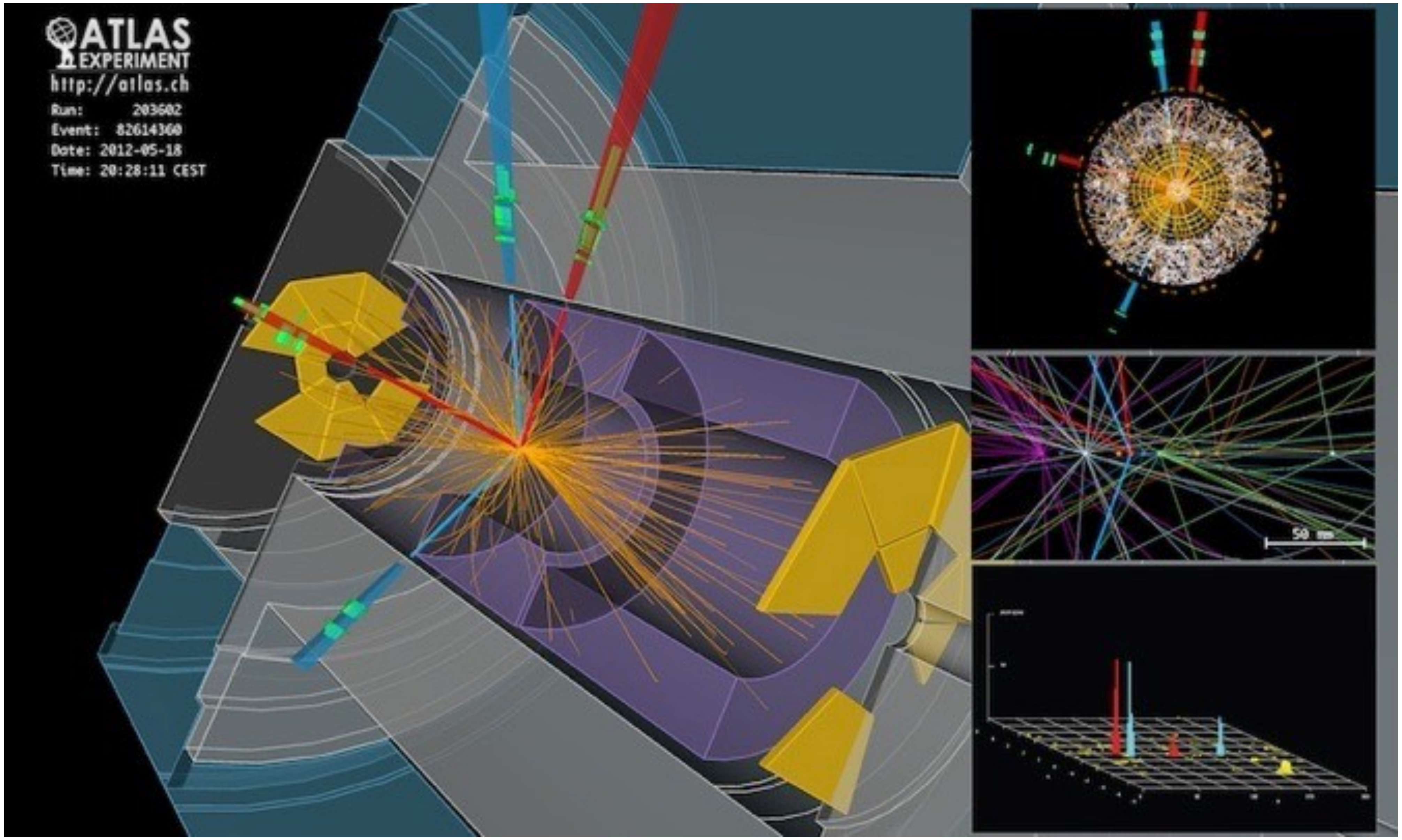
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



2. Hadron Accelerators

23.10.2017

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(Werner-Heisenberg-Institut)

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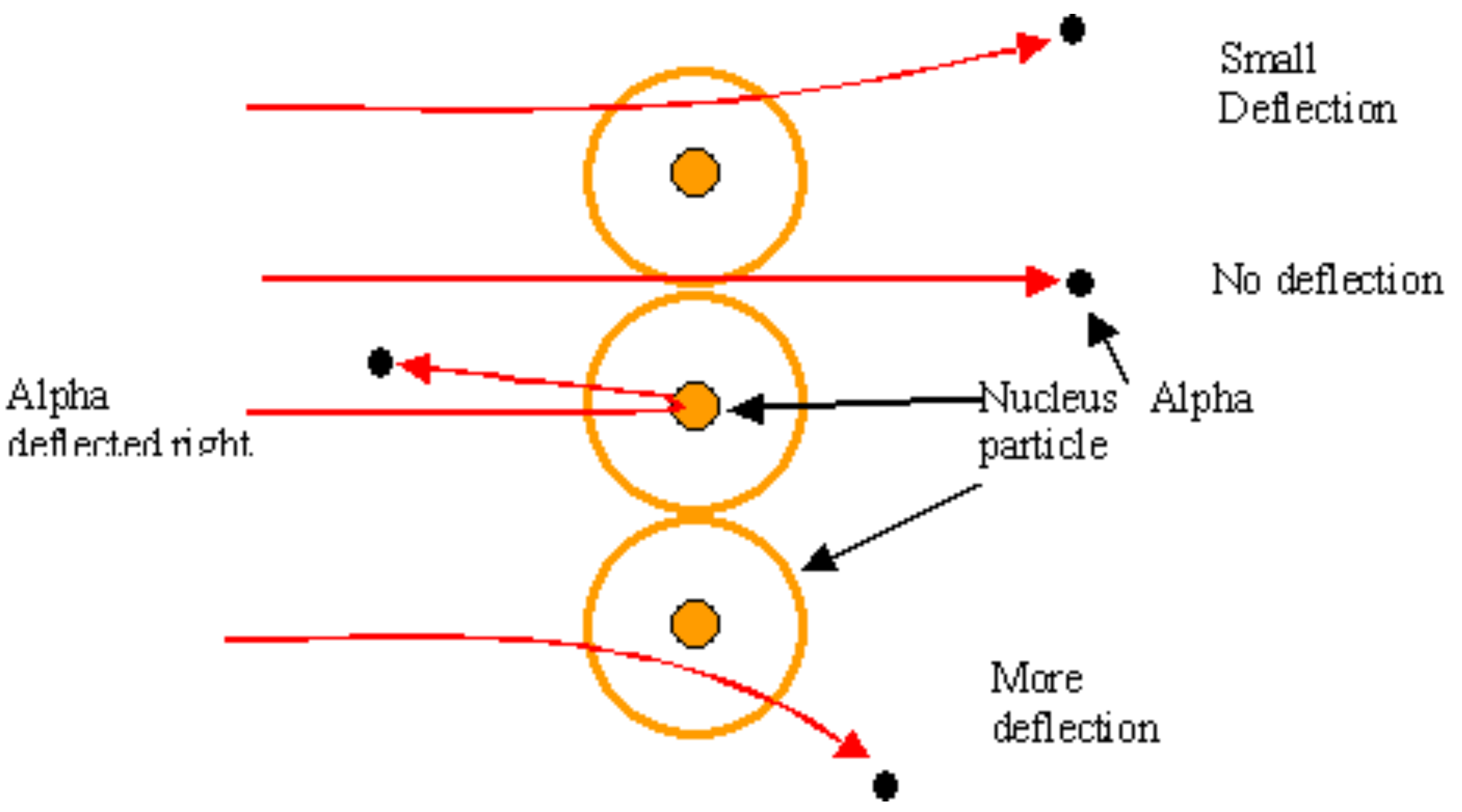
Dr. Frank Simon

Overview

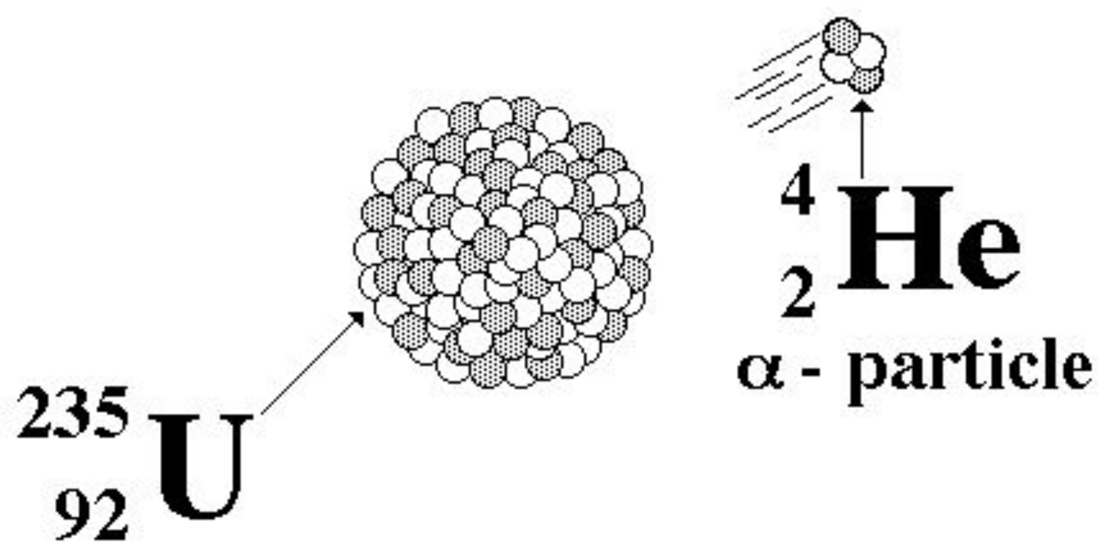
- Historical Introduction, The Role of Accelerators Today
- Accelerator Basics
- The Tevatron
- The Large Hadron Collider

100 Years ago: How it started

- 1911 Rutherford discovered the atomic nucleus by experiments with α particles on a thin Gold foil



- Uranium as natural “accelerator” MeV - scale particles from radioactive decay



Motivation for Accelerators

- Initially, accelerators were only used for basic research:
  To look into the structure of matter, you need short wavelengths, e.g. high energies

$$\lambda = \frac{h}{p} \approx \frac{(1.2\ \mathrm{fm})}{p\,(\mathrm{in\ GeV/c})}$$

1 GeV probes the size of the proton!

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- If you are looking for something that is rare (small cross-section!), you need

Intensity

Historical Overview

- 1928: R. Wideroe reports the operation of the first linear accelerator (Ka and Na-Ions)
- 1931: Van de Graaff constructs the first high voltage generator
- 1932: Lawrence and Livingston present first proton beams from a 1.2 MeV Cyclotron
- 1939: Hansen, Varian and Varian invent the Klystron
- 1941: Kerst and Serber introduce the Betatron
  Touschek and Wideroe invent the principle of ring accelerators
- 1947: Alvarez develops the first proton linear accelerator
- 1950 Christofilos formulates the concept of strong focusing


E.O. Lawrence

Accelerators - Today

Accelerators - Today

More than **400 B€** of end products are produced, sterilized, or examined using industrial accelerators annually worldwide.

More than **24 000** particle accelerators have been built globally over the past **60 years** to produce charged particle beams for use in industrial processes. This number does not include the more than **11 000** particle accelerators that have been produced exclusively for medical therapy with electrons, ions, neutrons, or X-rays.

More than **24 000** patients have been treated by hadron therapy in Europe.

More than **75 000** patients have been treated by hadron therapy in the world.

Around **200** accelerators are used for research worldwide, with an estimated yearly consolidated cost of **1 B€**.

The world's largest particle accelerator, the Large Hadron Collider (LHC), is installed in a tunnel **27 km** in circumference, buried 50-175 m below ground.

The temperature of the superconducting magnets in the LHC reaches **– 271 °C.** In contrast, the temperature at collision point is 1000 million times hotter than that of the Sun's core.

Accelerator Basics

The Basics of Particle Acceleration

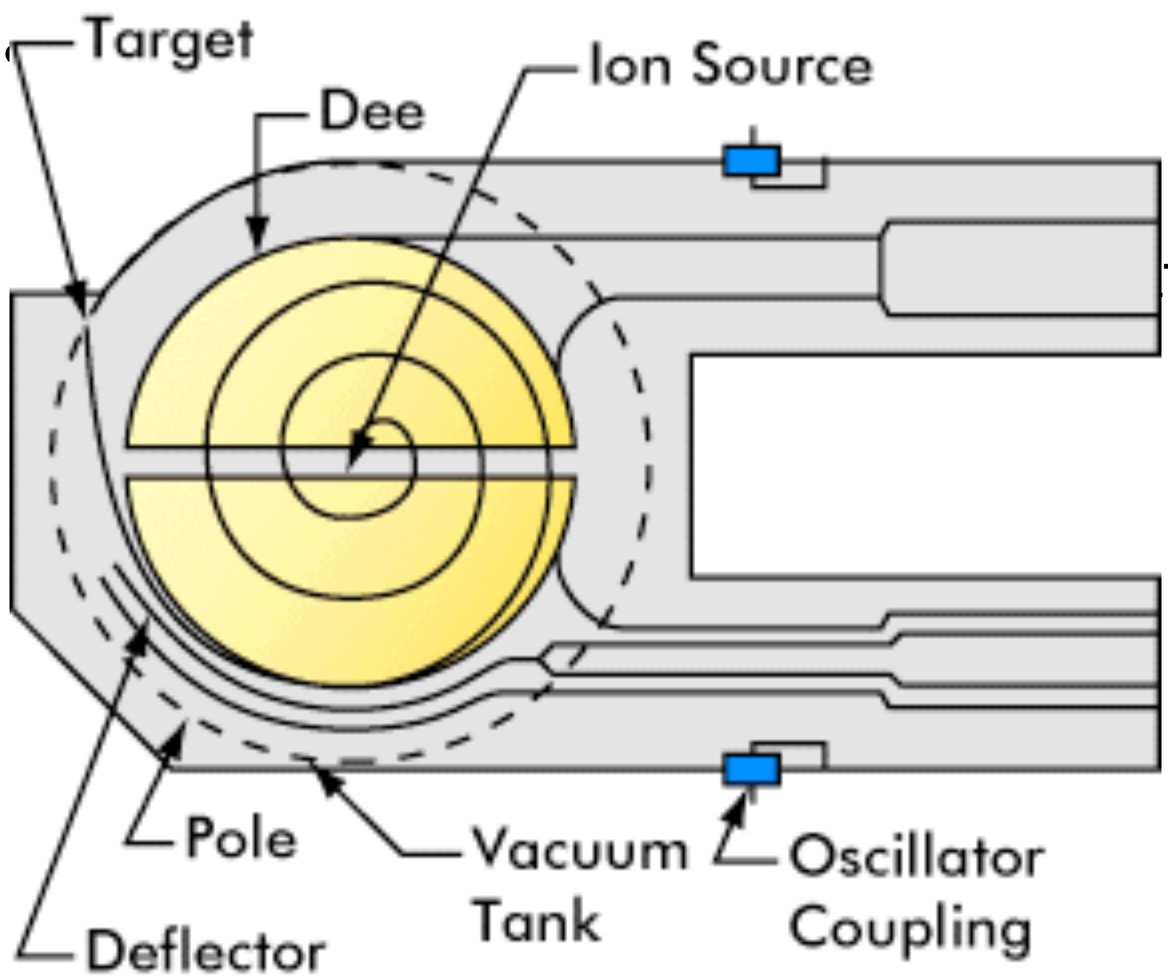
- The underlying equations: Maxwell-Equations

Differentialform	Integralform
$\mathrm{div}\,\vec{D} = \rho_{frei}$	$\oint \vec{D}\cdot d\vec{A} = Q$
$\mathrm{div}\,\vec{B} = 0$	$\oint \vec{B}\cdot d\vec{A} = 0$
$\mathrm{rot}\,\vec{E} = -\frac{\partial \vec{B}}{\partial t}$	$\oint \vec{E}\cdot d\vec{s} = -\frac{d}{dt}\int \vec{B}\cdot d\vec{A}$
$\mathrm{rot}\,\vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}$	$\oint \vec{H}\cdot d\vec{s} = I + \frac{d}{dt}\int \vec{D}\cdot d\vec{A}$

The key: Lorentz-Force $\vec{F} = q\left(\vec{E} + \vec{v}\times\vec{B}\right)$

n.b.: The Lorentz-force is non-conservative for time-dependent fields!

Basic Accelerator Types: Cyclotron, Linac



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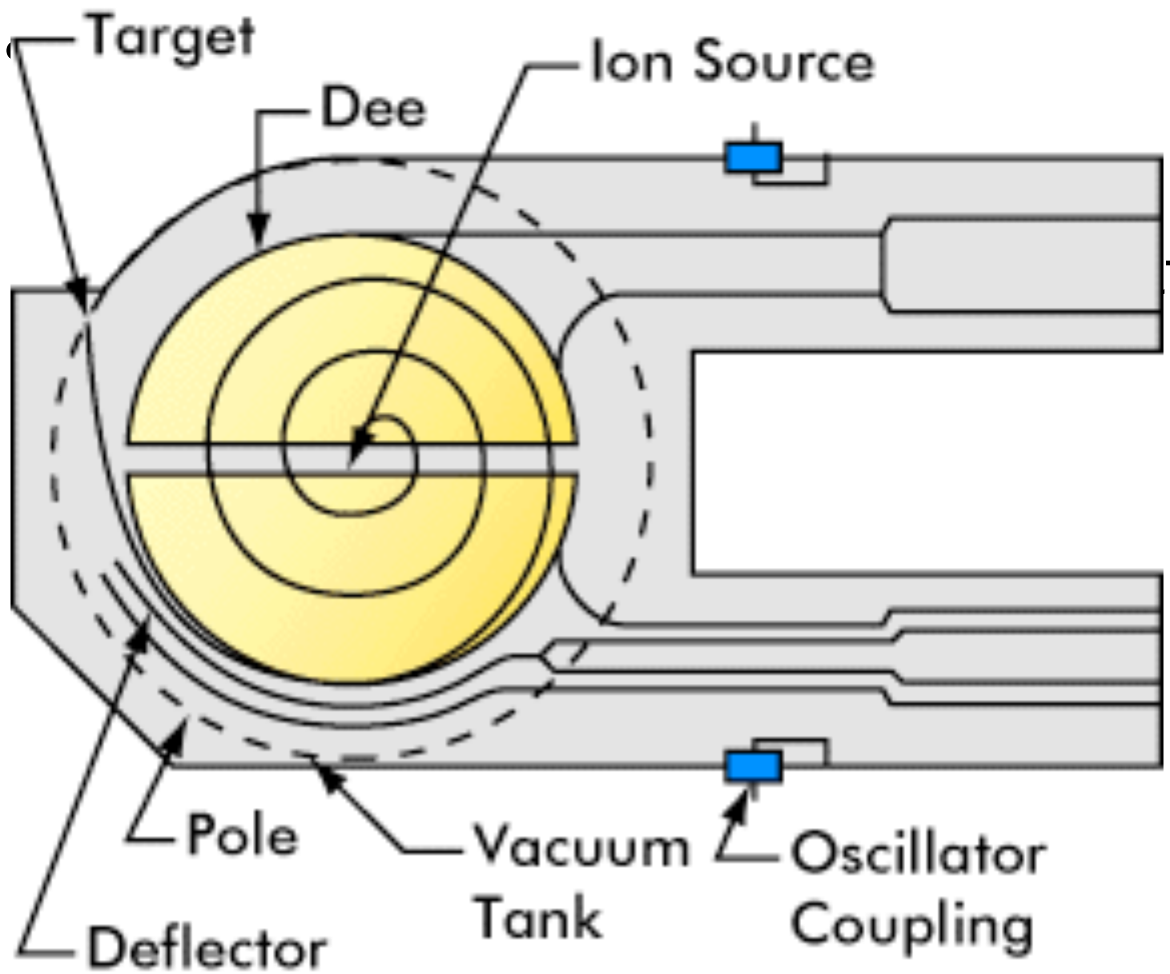

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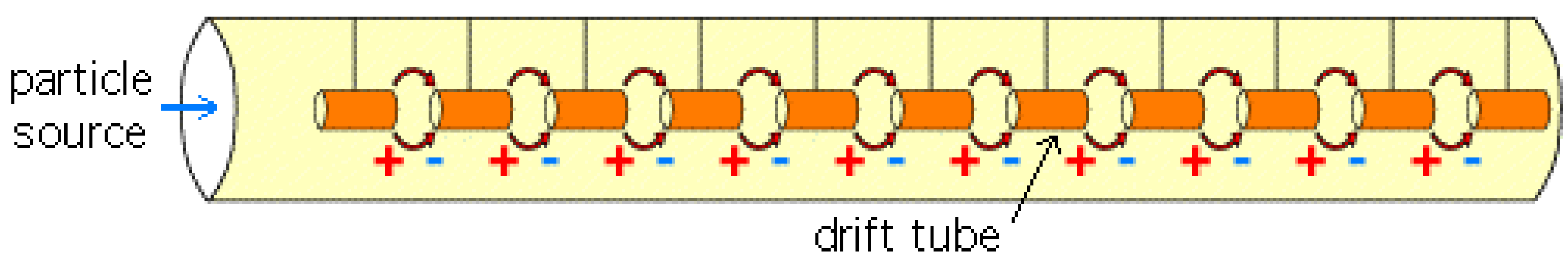
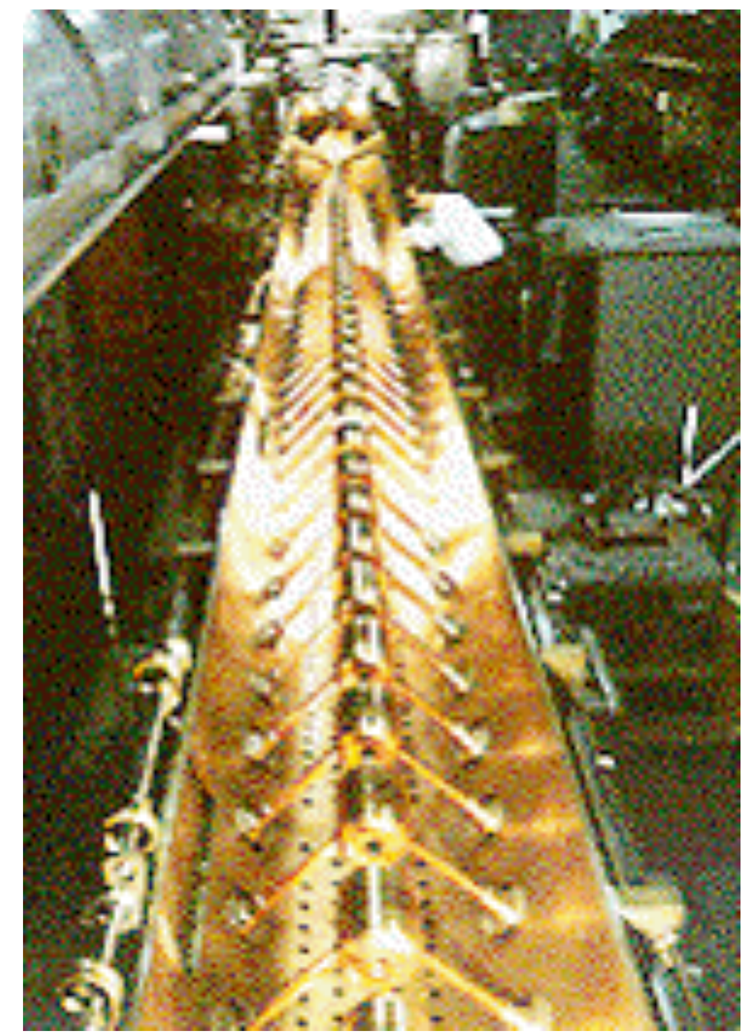
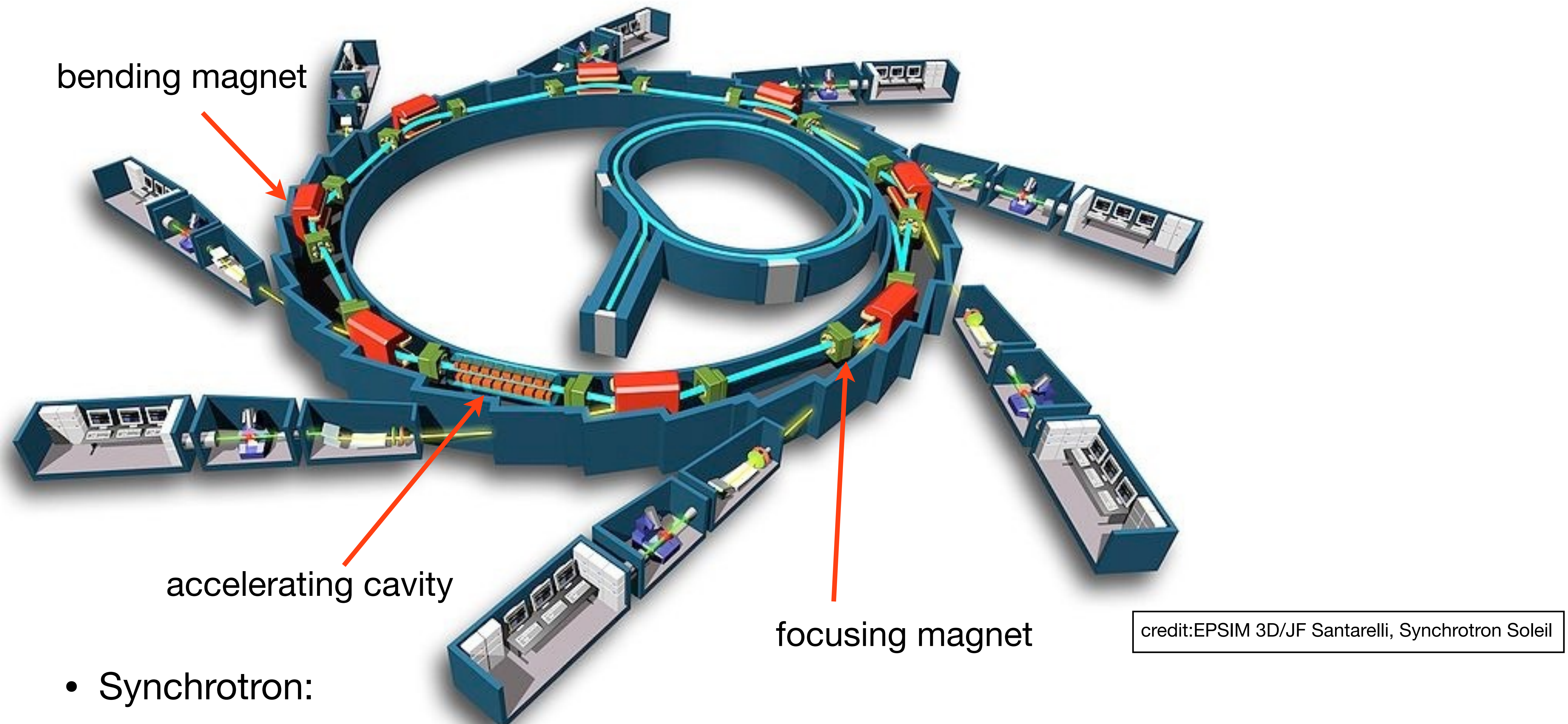




- Linear accelerator:
  - Alternating electric field for acceleration

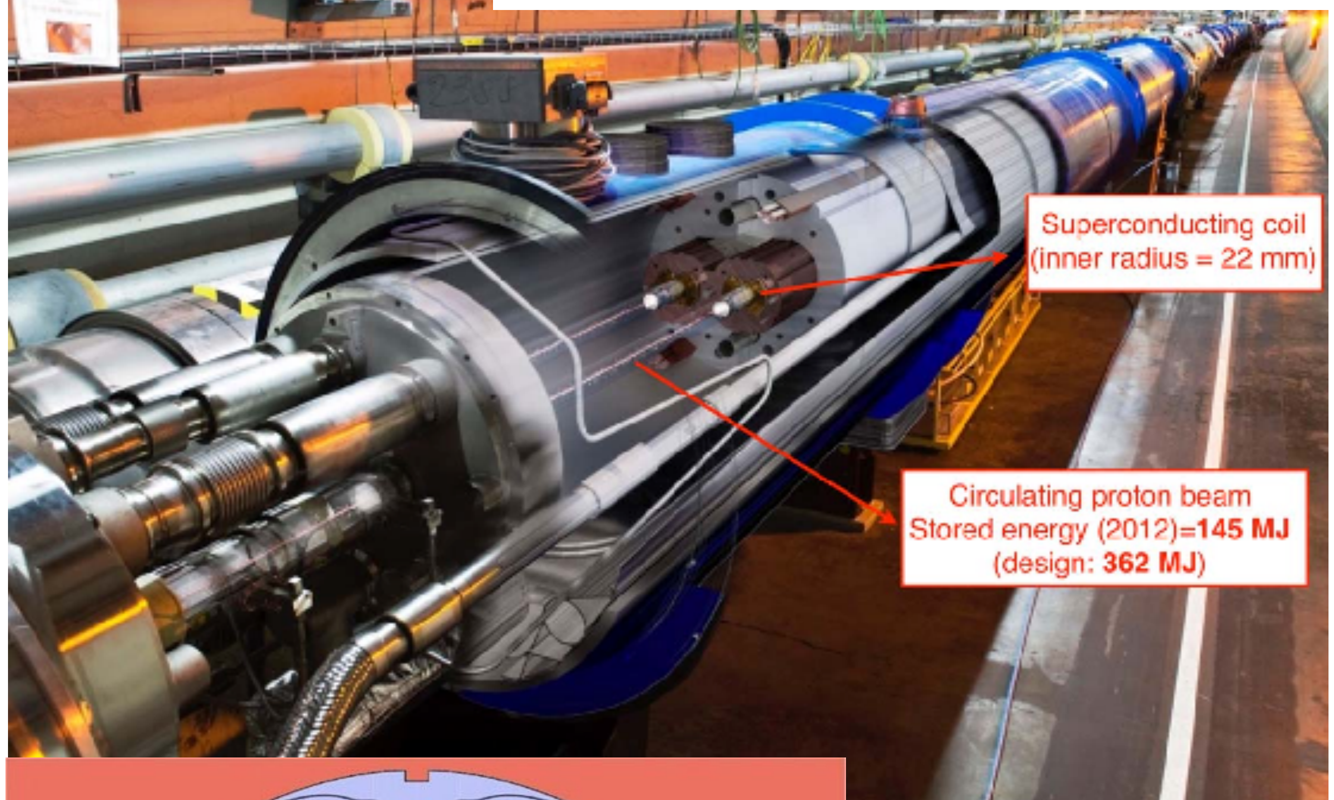
Basic Accelerator Types: Synchrotron

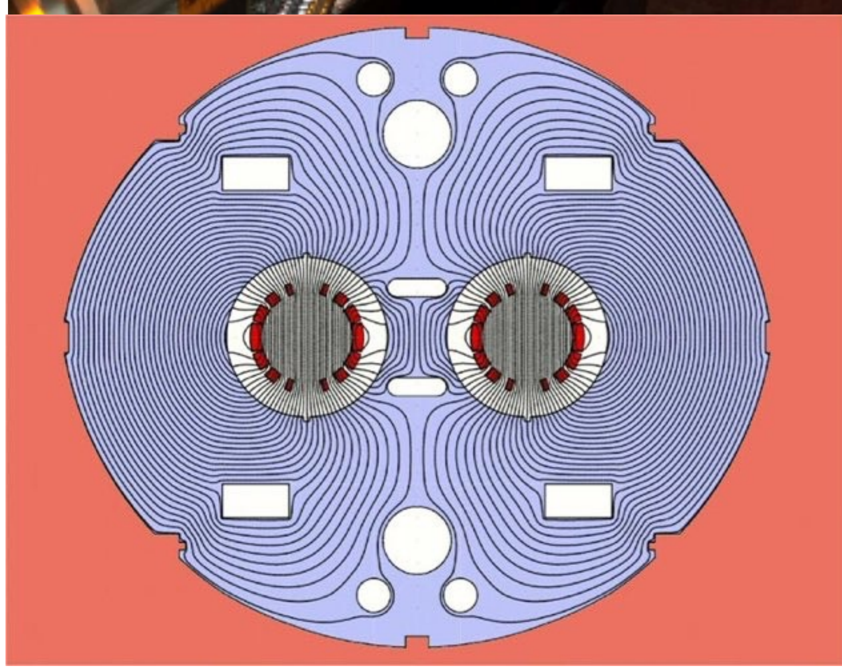


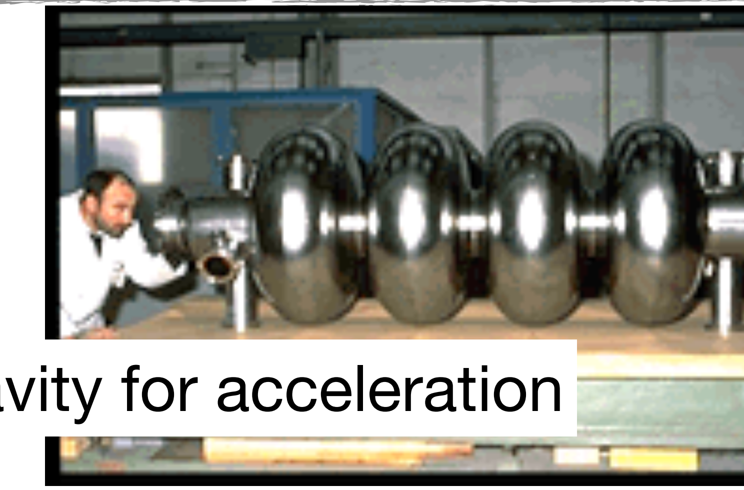
- Synchrotron:
  - Magnetic bending field gets ramped up with particle energy: Particles can stay on fixed path
  - Magnetic field only needed locally
  - Same accelerating cavities get passed many times

Functional Parts of Ring Accelerators

Dipole to keep circular track

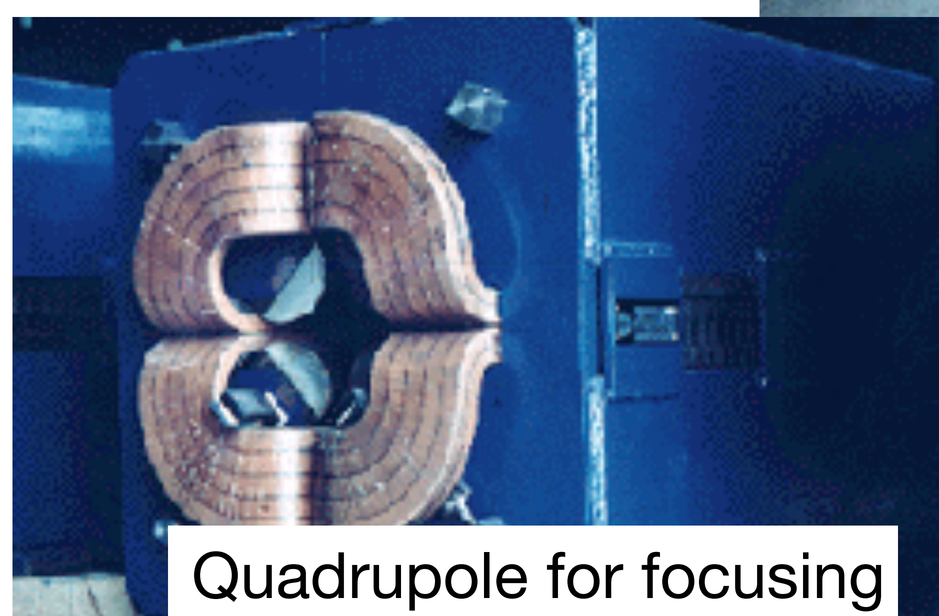






RF cavity for acceleration

Sextupole for higher order focusing, additional beam line elements: beam pipe, pumps, …



Quadrupole for focusing

Limits for Ring Accelerators: Bending Power

- Strong dipole magnets keep particles on their track in a synchrotron
  Magnetic field and radius define energy!

$$\vec{F} = \frac{d\vec{p}}{dt} = q\left(\vec{v} \times \vec{B}\right)$$

Lorentz force acts on moving charge

It forces the particle on a circular track:

$$\rho = \frac{p}{qB} \quad \Rightarrow \quad \rho[\mathrm{m}] \approx \frac{p[\mathrm{MeV/c}]/300}{B[\mathrm{T}]}$$

Often, the term “stiffness” is used:

$$(B\rho) = \frac{p}{q} \Rightarrow (B\rho)[\mathrm{Tm}] \approx \frac{p[\mathrm{MeV/c}]}{300}$$

LHC : (Bρ)~23000 Tm

Maximum dipole field and radius define maximum energy

Limits for Ring Accelerators: Synchrotron Radiation

- Charged particles loose energy when accelerated:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3}\gamma^4 \qquad a = \frac{v^2}{\rho}$$

ρ: bending radius

scales with γ^4, at constant energy with $1/m^4$ ➪ Electrons loose 10^{13} times more energy than protons!

- Energy loss of electrons per turn in a storage ring

$$\Delta E = 8.85 \times 10^{-5}\frac{E^4[\mathrm{GeV}^4]}{\rho[\mathrm{km}]}\mathrm{MeV}$$

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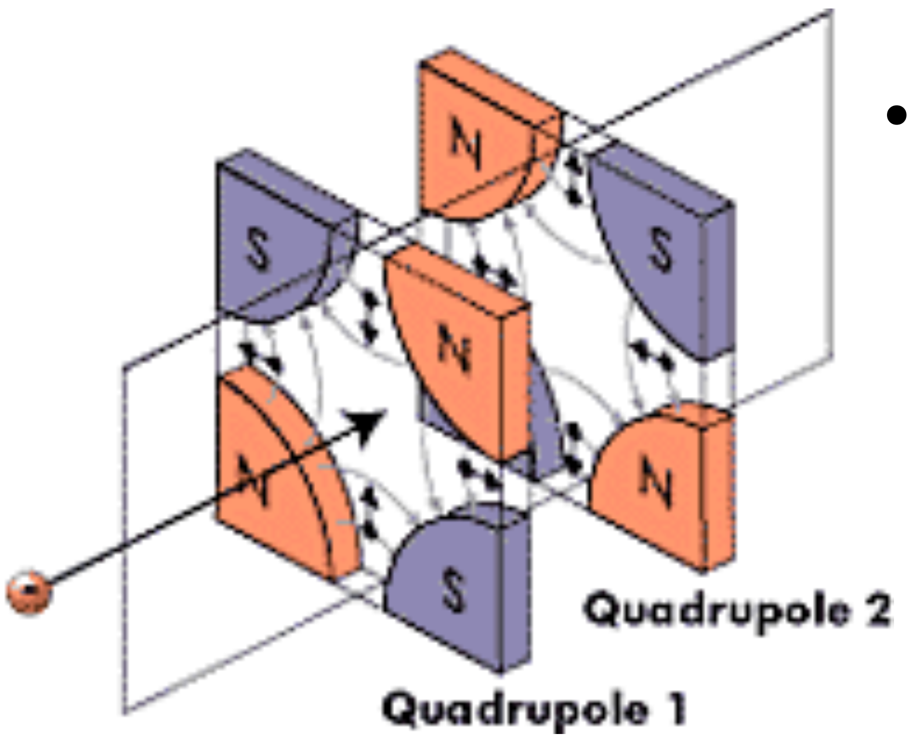
➾ Highest energies are not possible with electrons using synchrotrons!

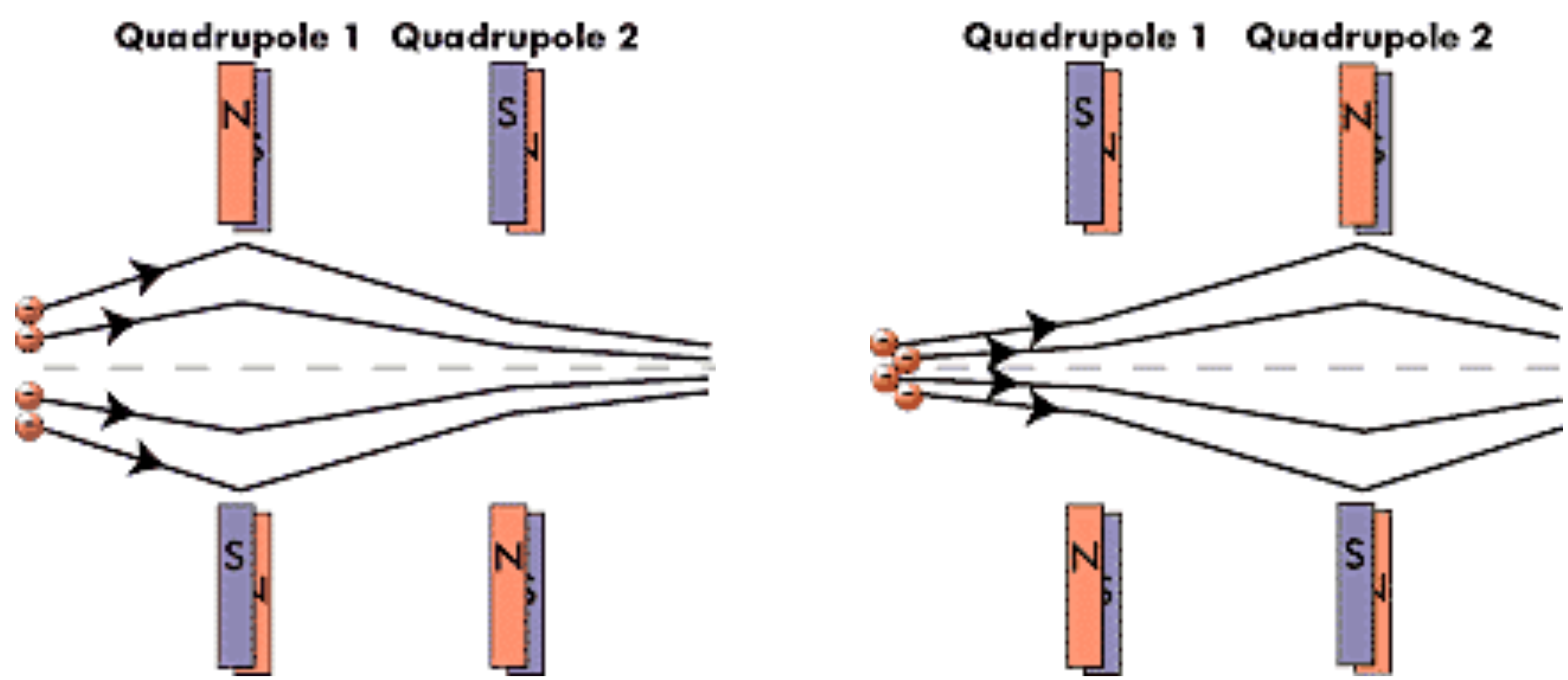
Strong Focusing

- Strong Focusing, or Alternating Gradient Synchroton: Breakthrough that allowed to reach high energies of 10 GeV and more



- Two crossed quadrupole fields have a net focusing effect, if they are placed at the right distance d (smaller than the focal length) - Just like a lens system in optics!

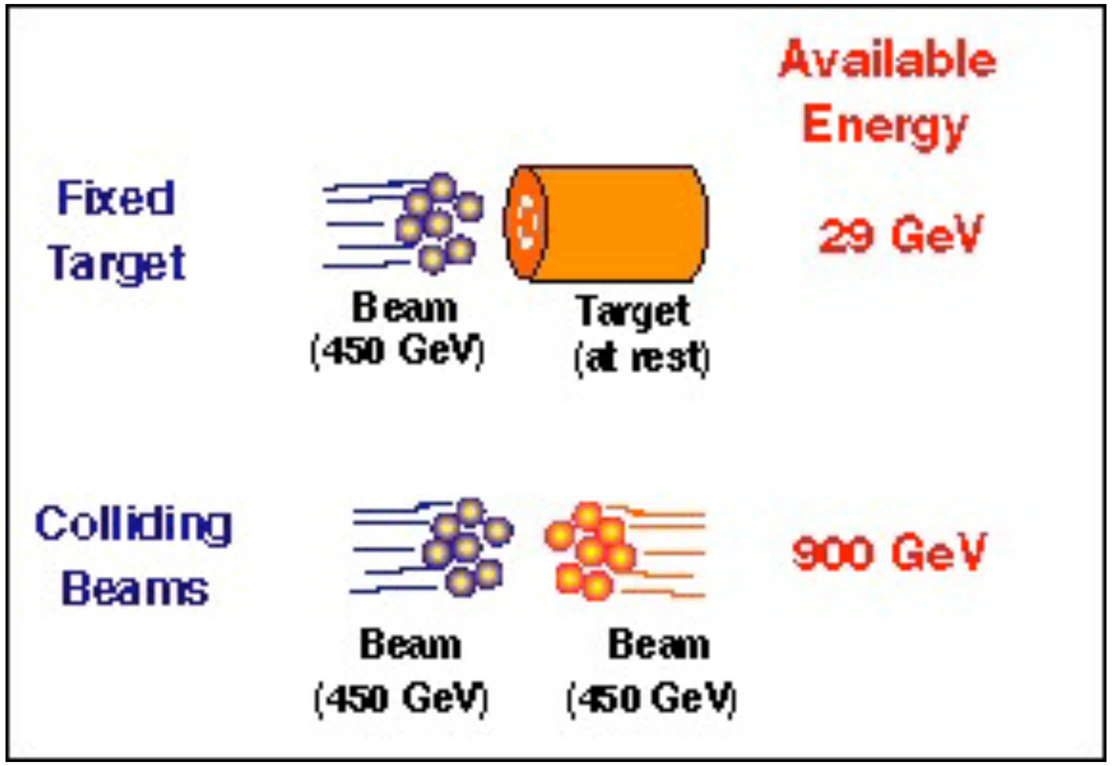
$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$



High Energies: Colliders

- The first experiments with accelerators were fixed-target experiments: (Relatively) easy to manage: Shoot a beam at a target

- Much higher energy can be obtained in collider mode: Two beams collider, the center of mass can be at rest in the laboratory



For colliding protons

$$E_{cm} = \sqrt{2(\gamma + 1)} m_p c^2$$

$$E_{cm} = 2E = 2\gamma m_p c^2$$

Key Collider Parameters

- Event Rate $$R = L \cdot \sigma$$

- Luminosity $$L = f \frac{n_1 n_2}{4\pi\sigma_x \sigma_y}$$

f: Collision frequency

n_i: Number of particles in bunch i

σ_x: horizontal beam size

σ_y: vertical beam size

... assuming a gaussian beam profile and perfect overlap

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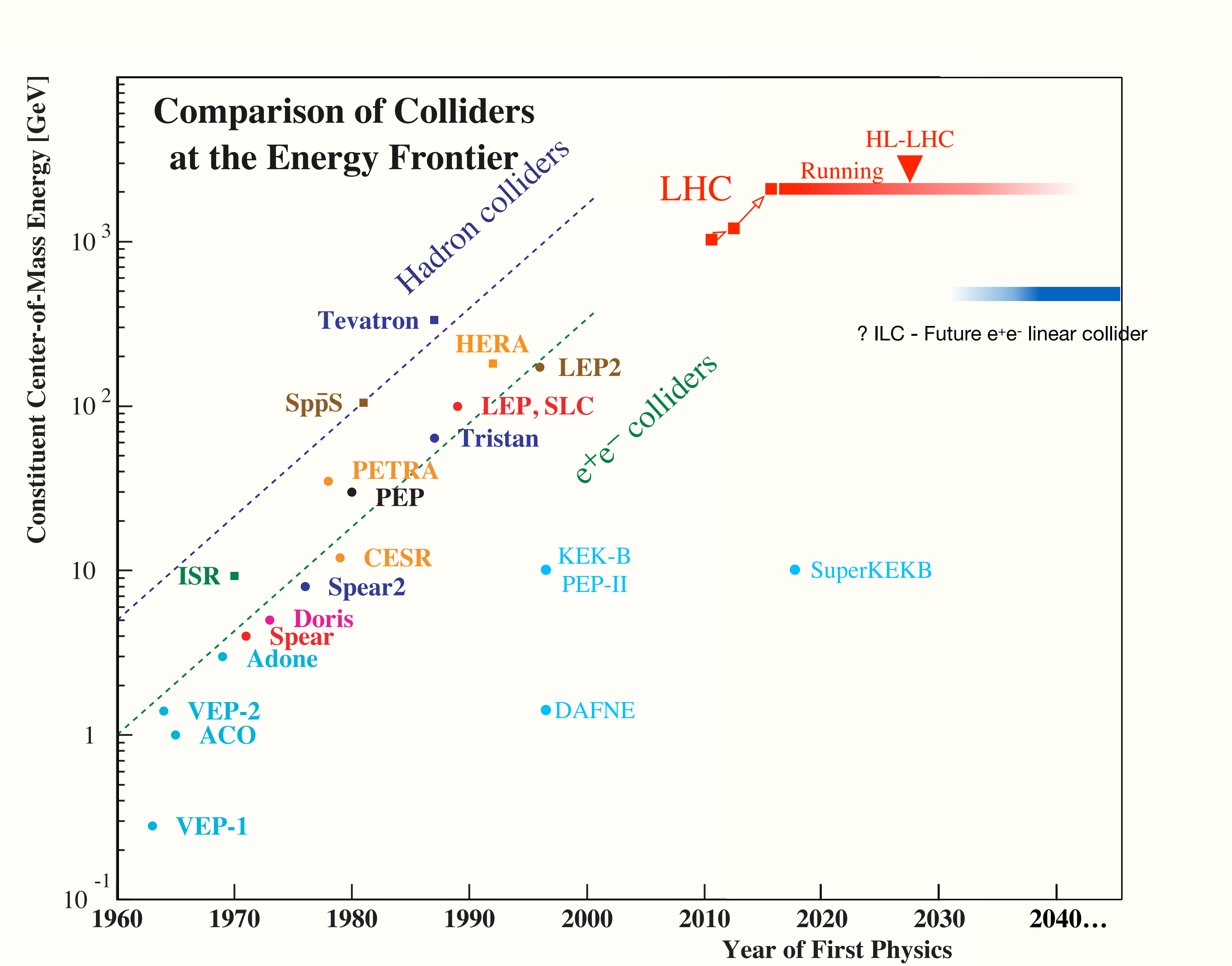
- Luminosity is often expressed in terms of the “β function” at the collision point and in terms of “emittance”
  - β^* is related to the beam optics
  - ε is related to the beam quality, and gives the phase space of the beam particles (units length * angle)

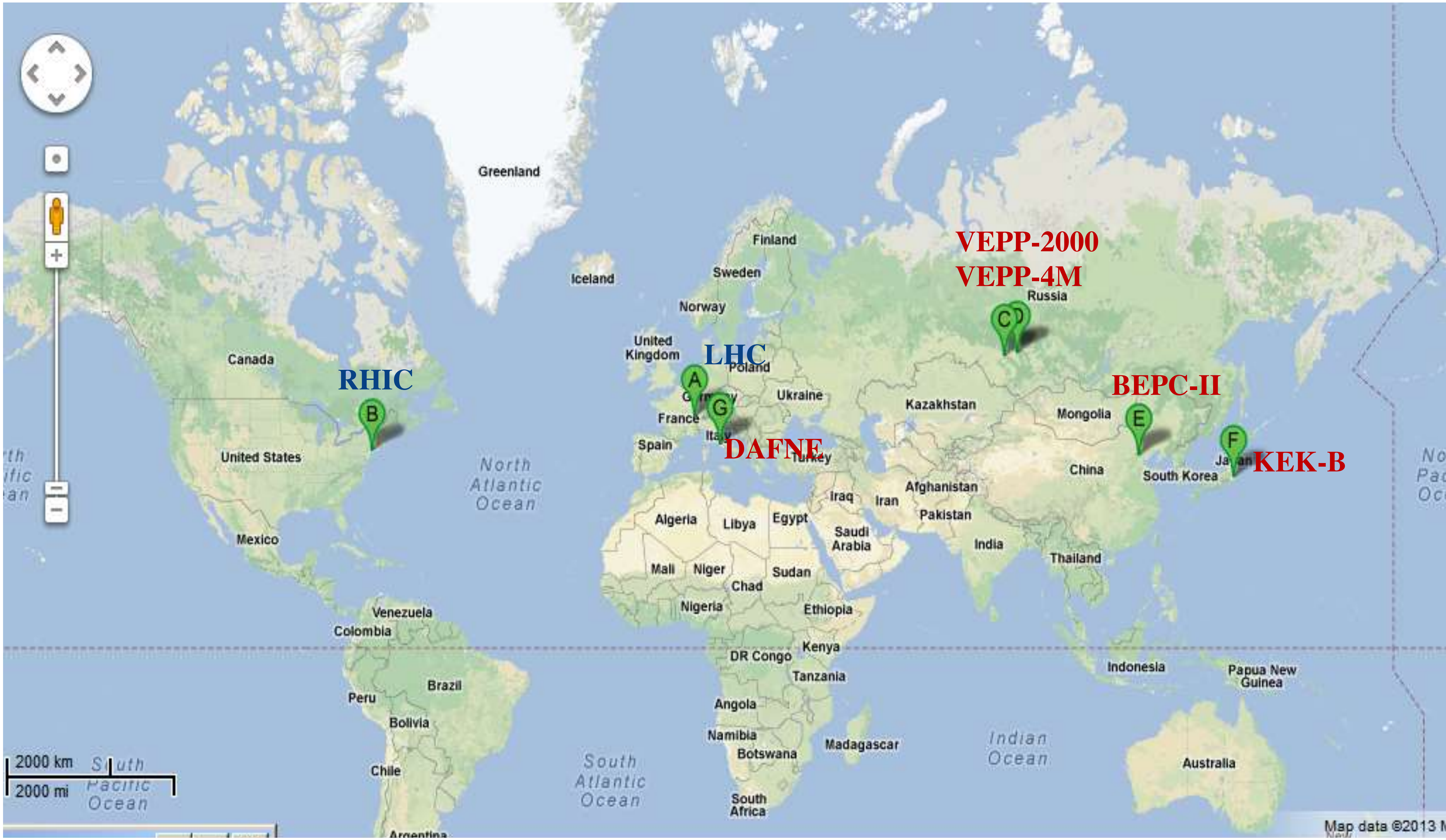
$$L = f\frac{n_1 n_2}{4\sqrt{\varepsilon_x\beta_x^*\varepsilon_y\beta_y^*}}$$

Evolution of Energy - The Livingston Plot



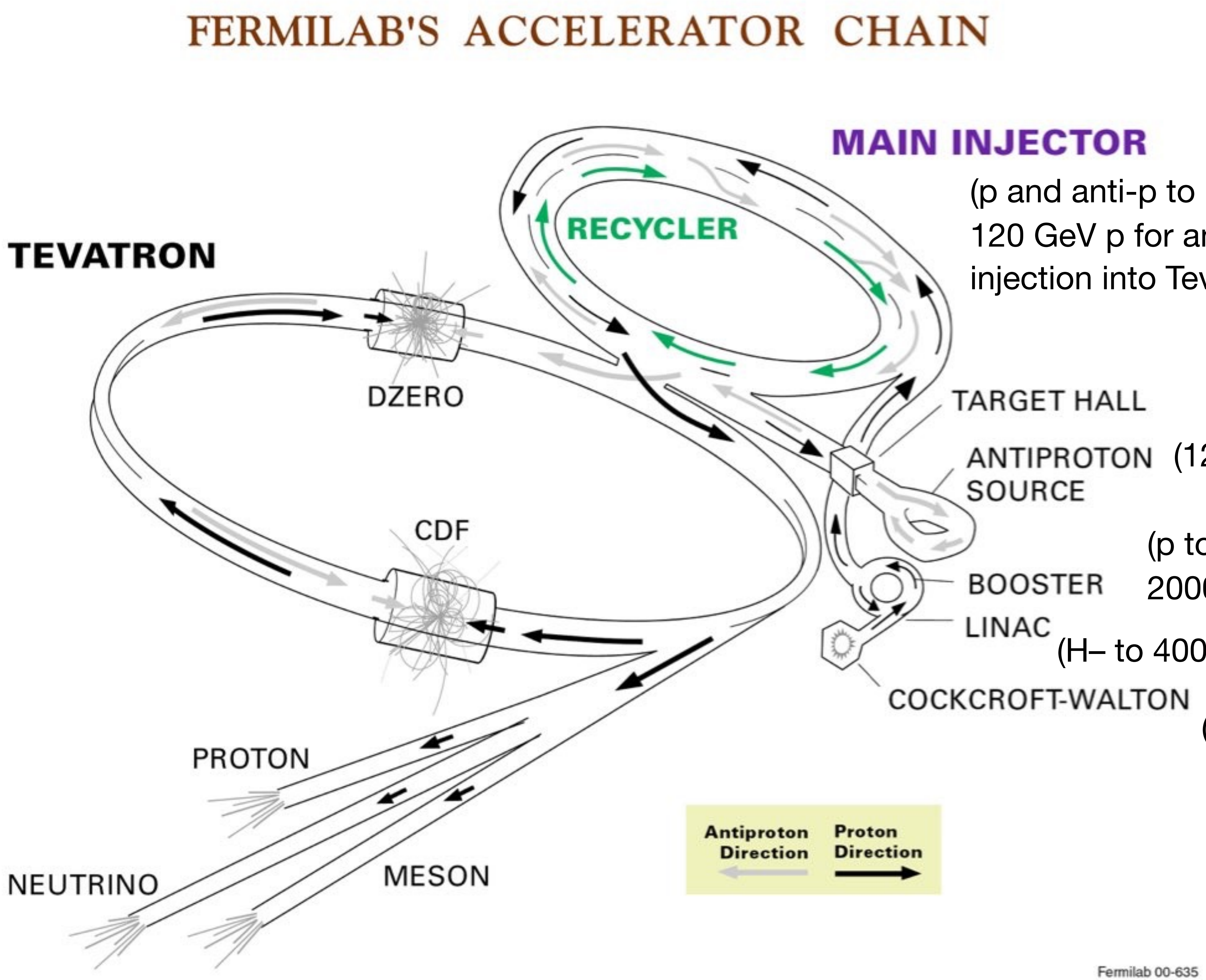
Colliders - Now and Then

- 29 Colliders built, 7 work ”now”



The Tevatron

Fermilab Tevatron



(p and anti-p to 150 GeV;
120 GeV p for anti-p target;
injection into Tevatron)

(120 GeV p to Ni target)

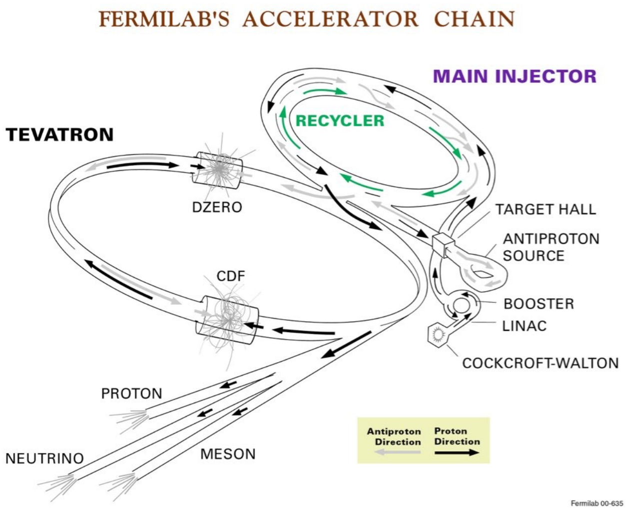
(p to 8 GeV after
20000 turns)

(H– to 400 MeV)

(H– to 750 keV)

The Fermilab Accelerator Complex

The Fermilab Accelerator Chain



Cockcroft-Walton
DC accelerator

LINAC

Booster

Main Injector

Antiproton Source

Tevatron

Why Antiprotons?

- Can fly in opposite direction of protons using the same magnetic fields in one beam pipe: One ring instead of two!
- Up to energies of 3 TeV the production cross sections for many particularly interesting processes are higher for proton - antiproton collisions than for pp collisions (valence-quark annihilation!)

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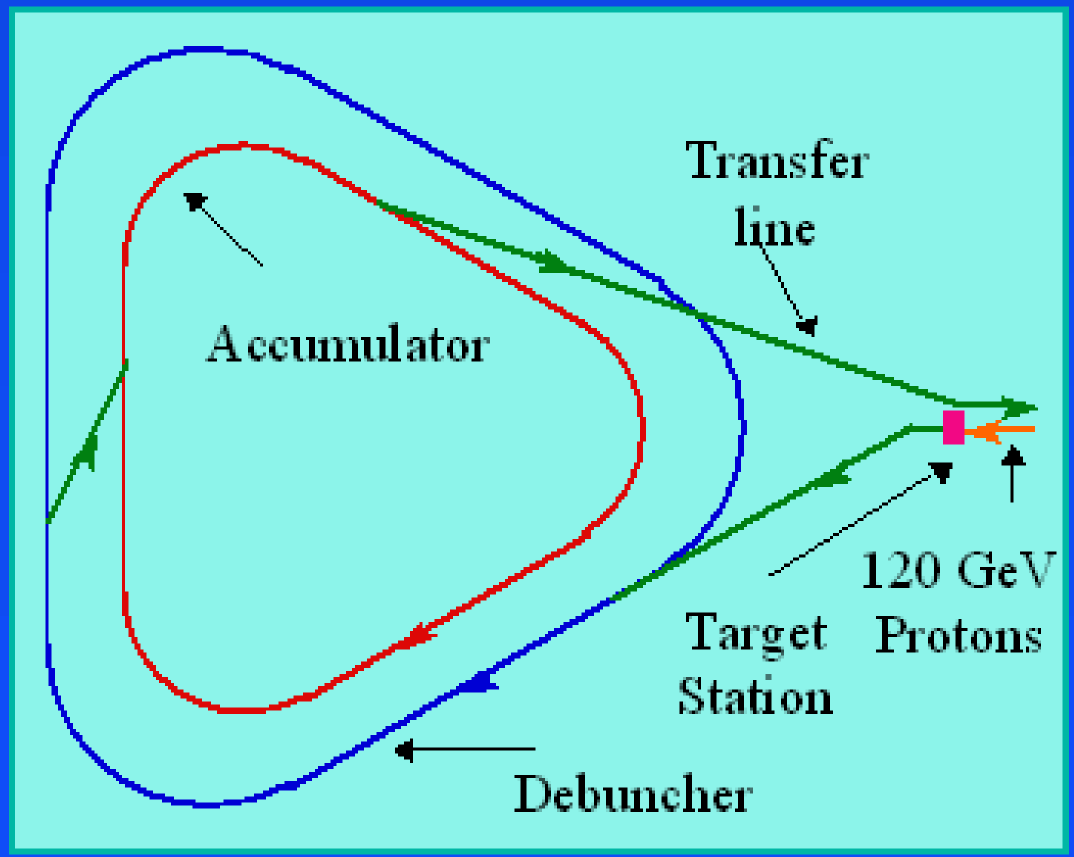
But:

Antiprotons have to be produced first!

Antiproton Production

Fermilab Beams Division

- The Anti-Proton Source consists of three major components:
  - The Target Station
  - The Debuncher
  - The Accumulator
- For every 1 million 120 GeV protons smashed on the pbar target, only about twenty 8 GeV pbars survive to make it into the Accumulator.

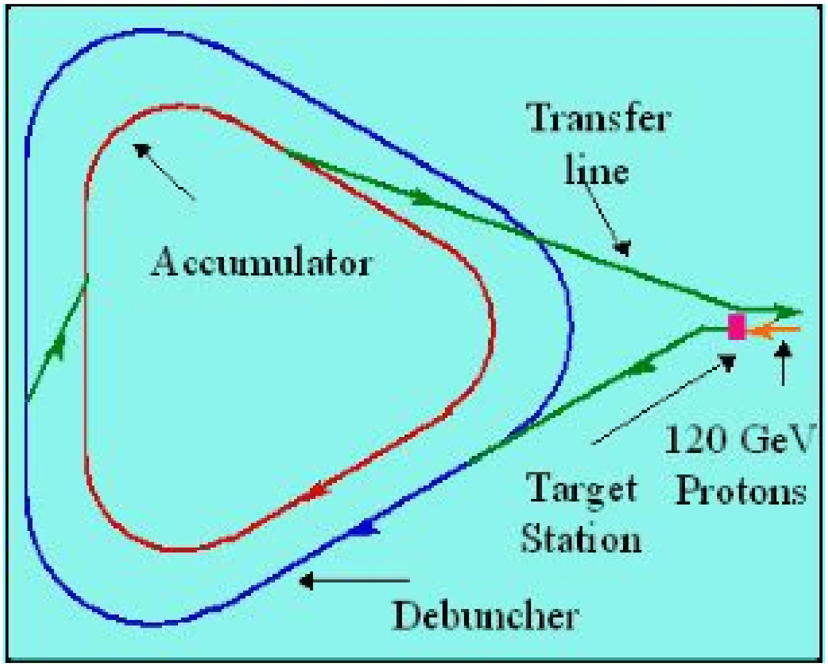


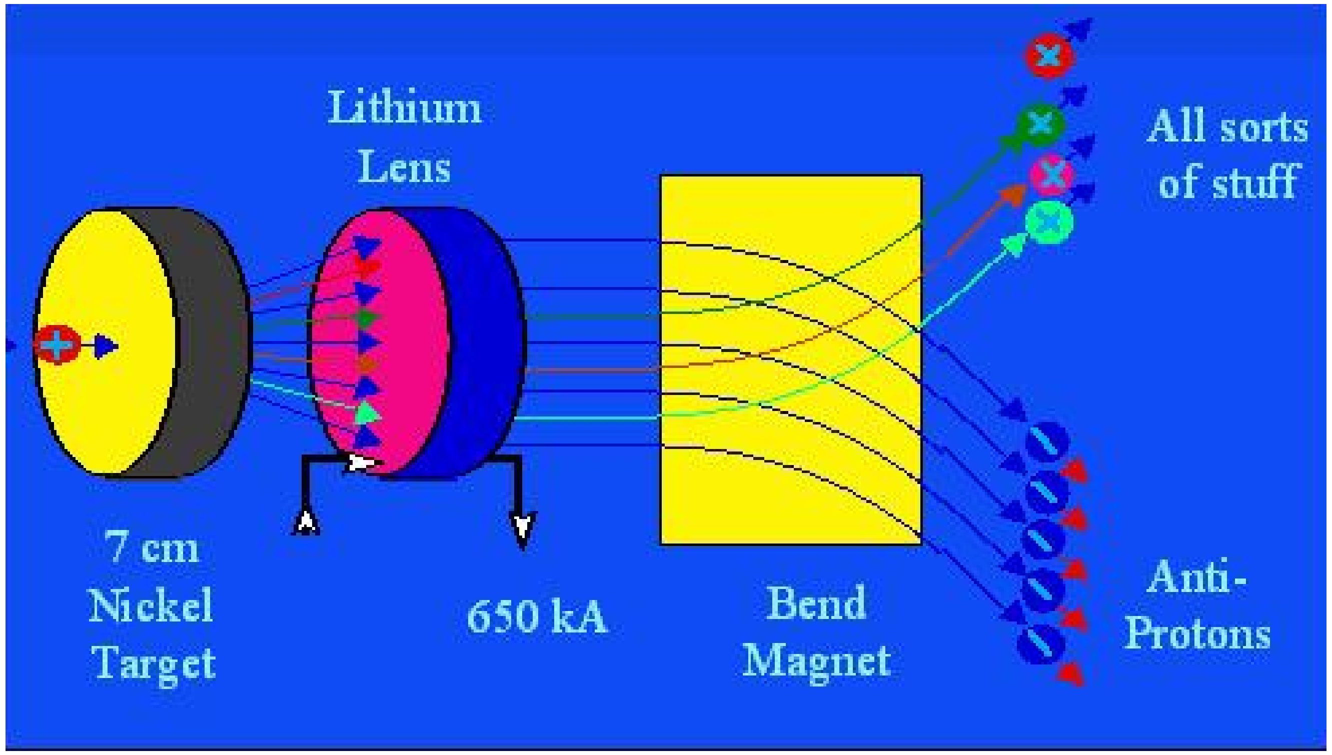
800 Billionen USD / g !

The price of pbars

$$\frac{15\,\text{MW} \times \$45\ /\ \text{MW}-\text{hr}}{5\times 10^{10}\ \frac{\text{pbars}}{\text{hr}} \times 9.5 \times 1.67 \times 10^{-27}\ \frac{\text{kg}}{\text{pbar}} \times 2.2\ \frac{\text{lbs}}{\text{kg}} \times 16\ \frac{\text{oz}}{\text{lbs}}} = \$24{,}000 \times 10^{12}\ /\ \text{oz}$$

The Antiproton Source

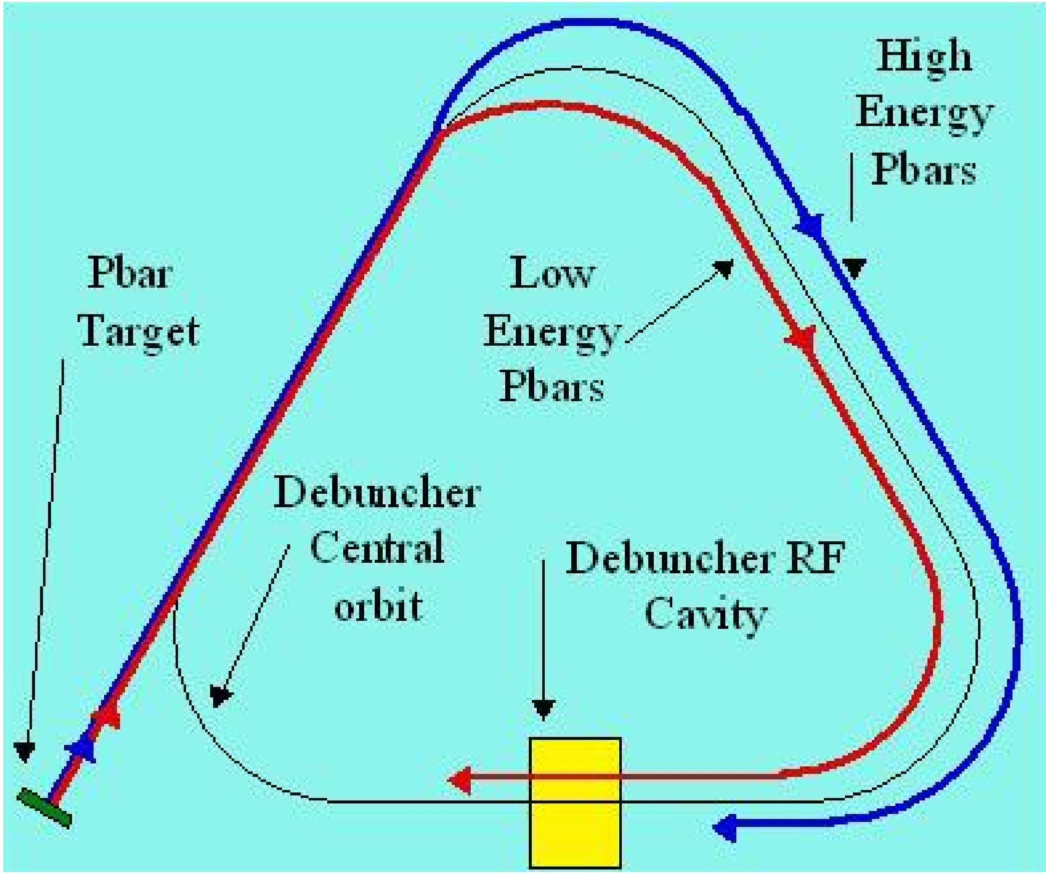


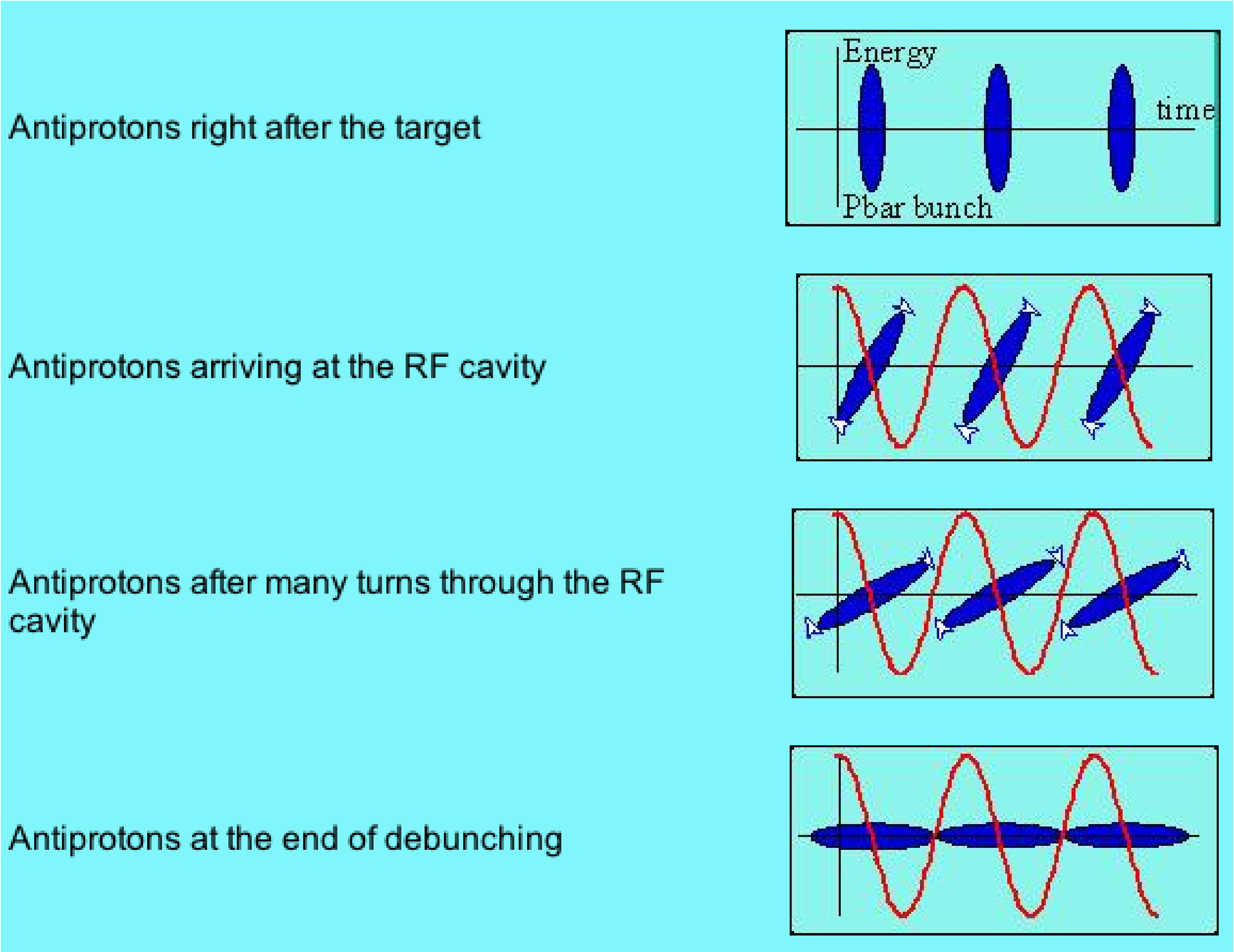


Debuncher & Accumulator

The Antiproton Debuncher

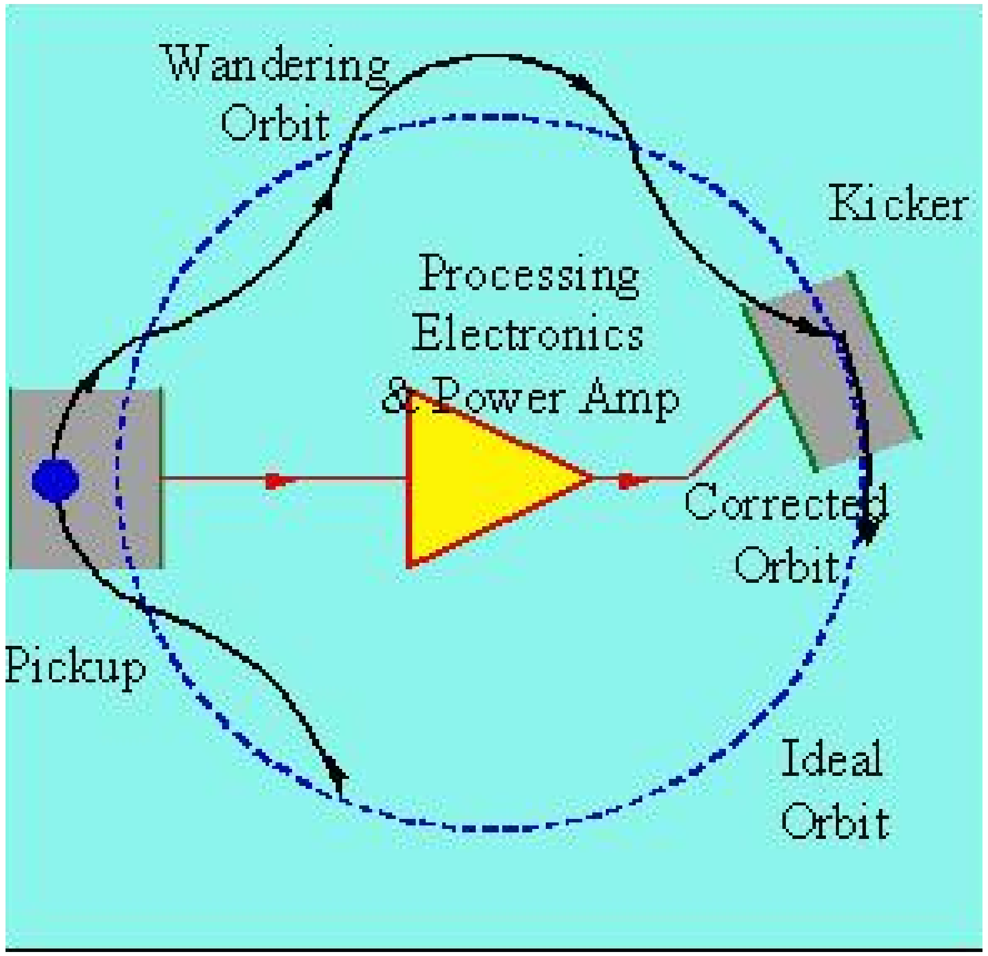
- transfer of large energy- and small time spread to small energy spread with long time structure





Stochastic Cooling

- Nobel prize to Simon van der Meer (1984)
- Reduction of transversal phase space of antiprotons, carried out in debuncher (retention time 1.5 sec) and in accumulator (several hours)

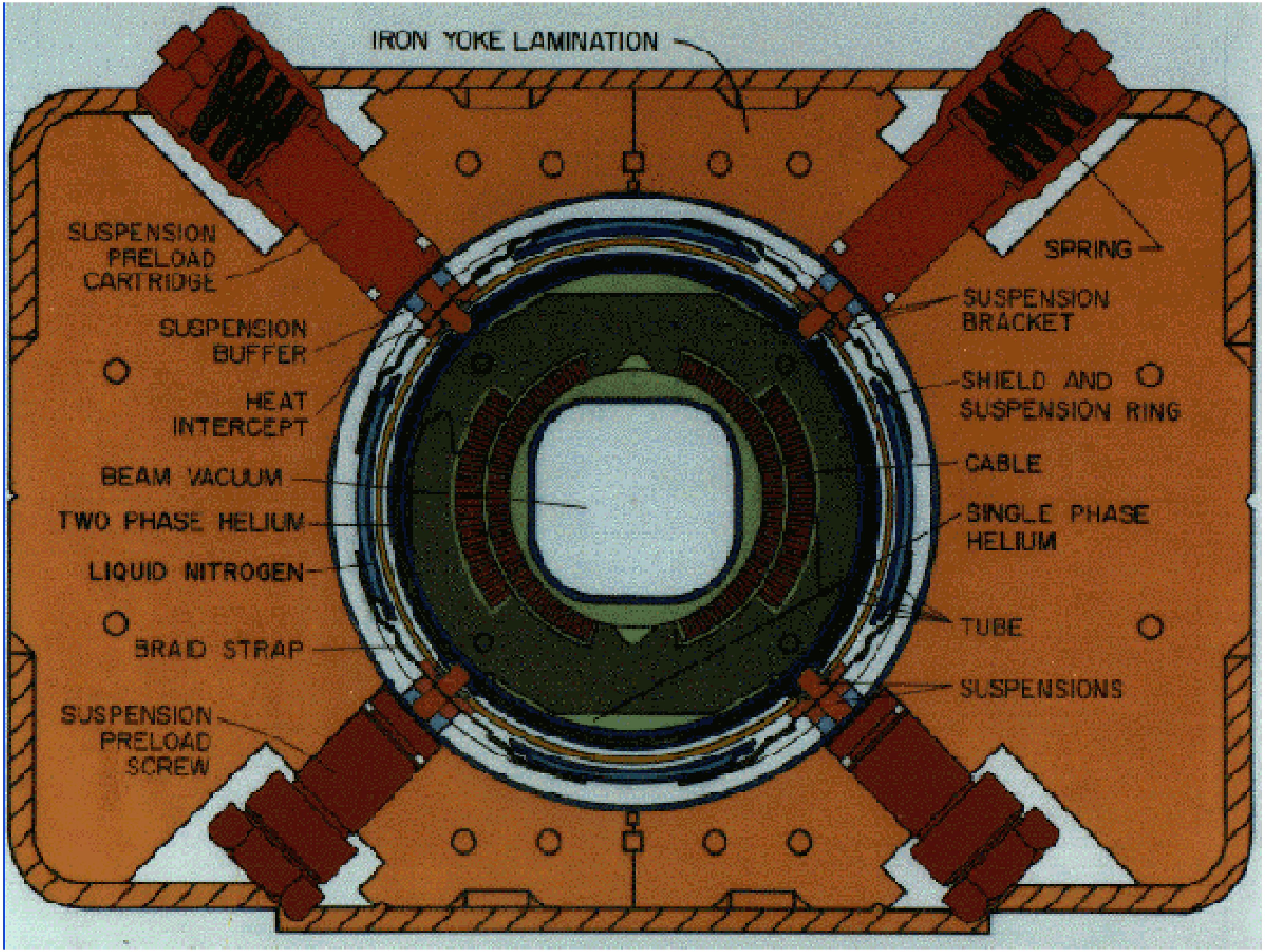


amplification of pick-up signal by 150 dB (10^{15}).

Superconducting Magnets in Tevatron

- Magnets in the TEVATRON are superconducting.
- There are about 1000 magnets in the TEV
- The coils are made of niobuim-titanium alloy wire.
  - The size of the wire is 0.0003 inches (8 um)
  - There are 11 million wire-turns in a coil.
  - The dipole magnet is 21 feet long
  - There are 42,500 miles of wire in a magnet
- For 900 GeV operation, the magnets are kept at 4.6° Kelvin.
- For 1000 GeV operation, the cryogenic system has been upgraded to obtain a temperature of 3.6° Kelvin (-453°F)

Tevatron Magnets



Superconducting Magnets

- The field in the magnets at 900 GeV is 4 Tesla (The Earth's magnetic field is 0.0003 Tesla, 13,000 times weaker then a TEV magnet)
  - An LHC magnet (Large Hadron Collider in Geneva, Switzerland) will have a magnetic field between 8-10 Tesla.
  - The theoretical limit for mechanically constraining a superconducting magnet is about 15 Tesla.
- The current flowing through a magnet at 900 GeV is 4000 Amperes.
  - The total inductance of the TEVATRON is 36 H.
  - The total magnetic stored energy in the TEVATRON at 900 GeV is 288 MegaJoules.
  - The time constant of the current dump system is 12 seconds.
  - If all the current in the TEV needed to be dumped, the dump resistors would have to dissipate energy at 24 megawatts

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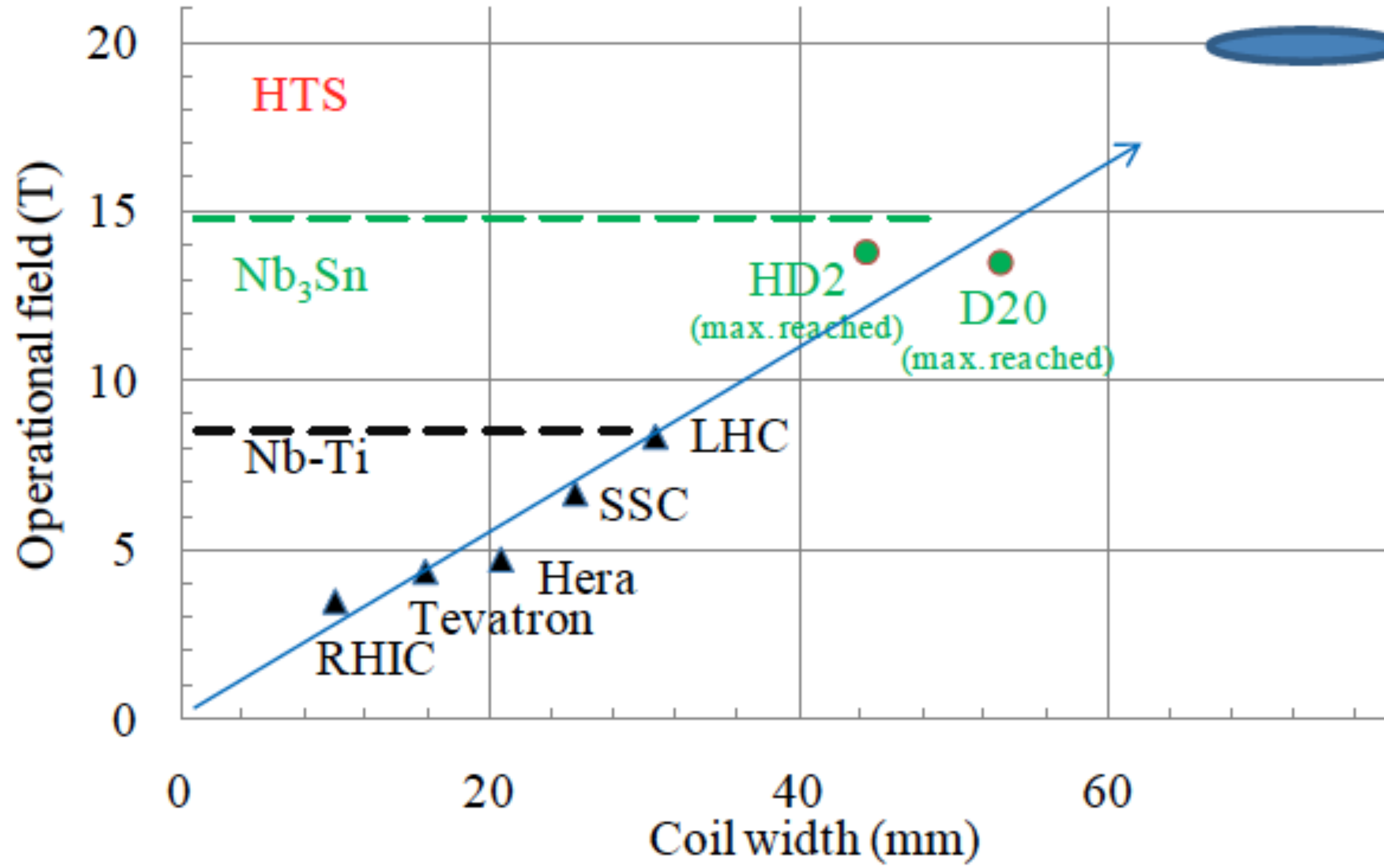

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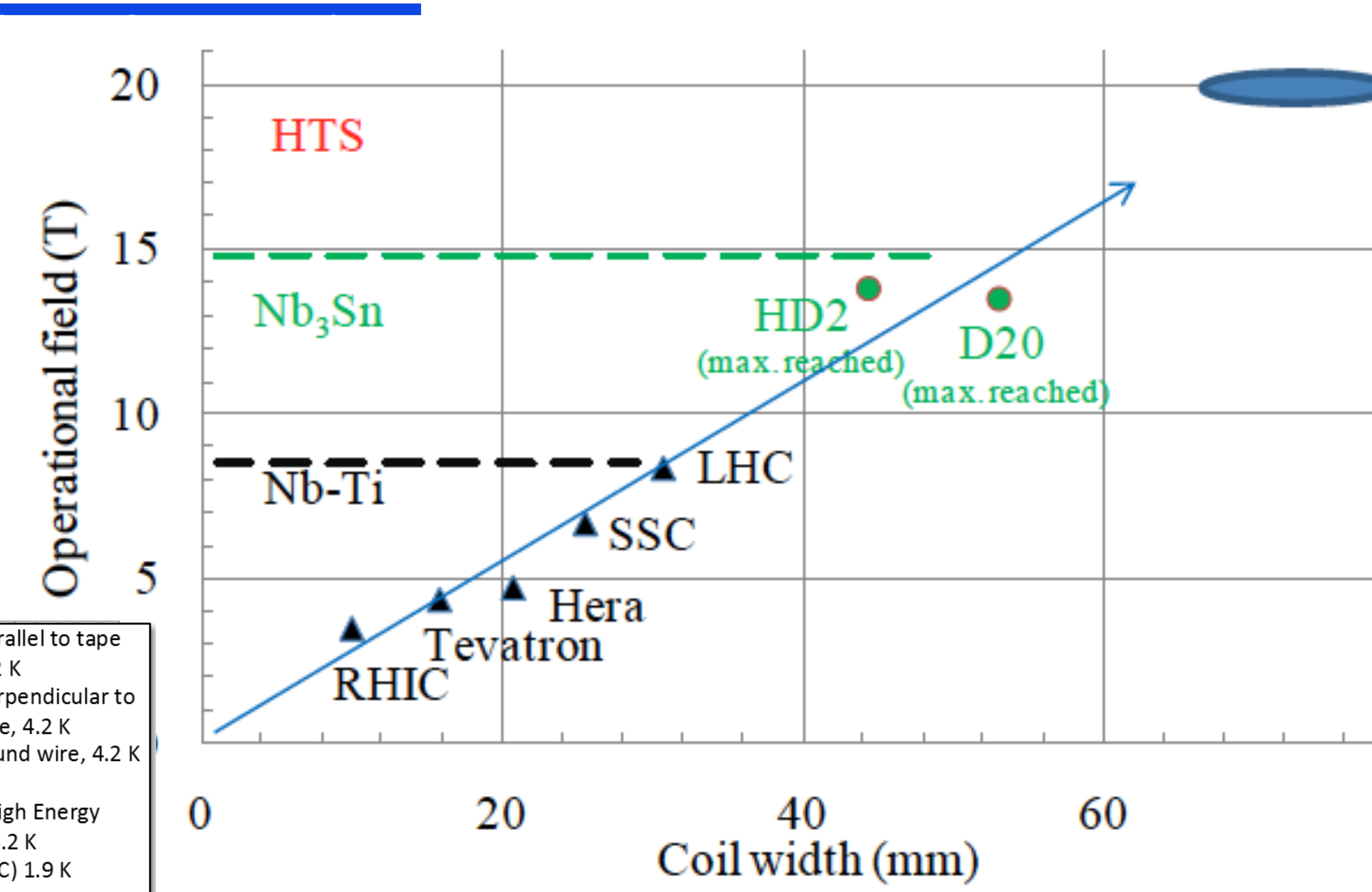
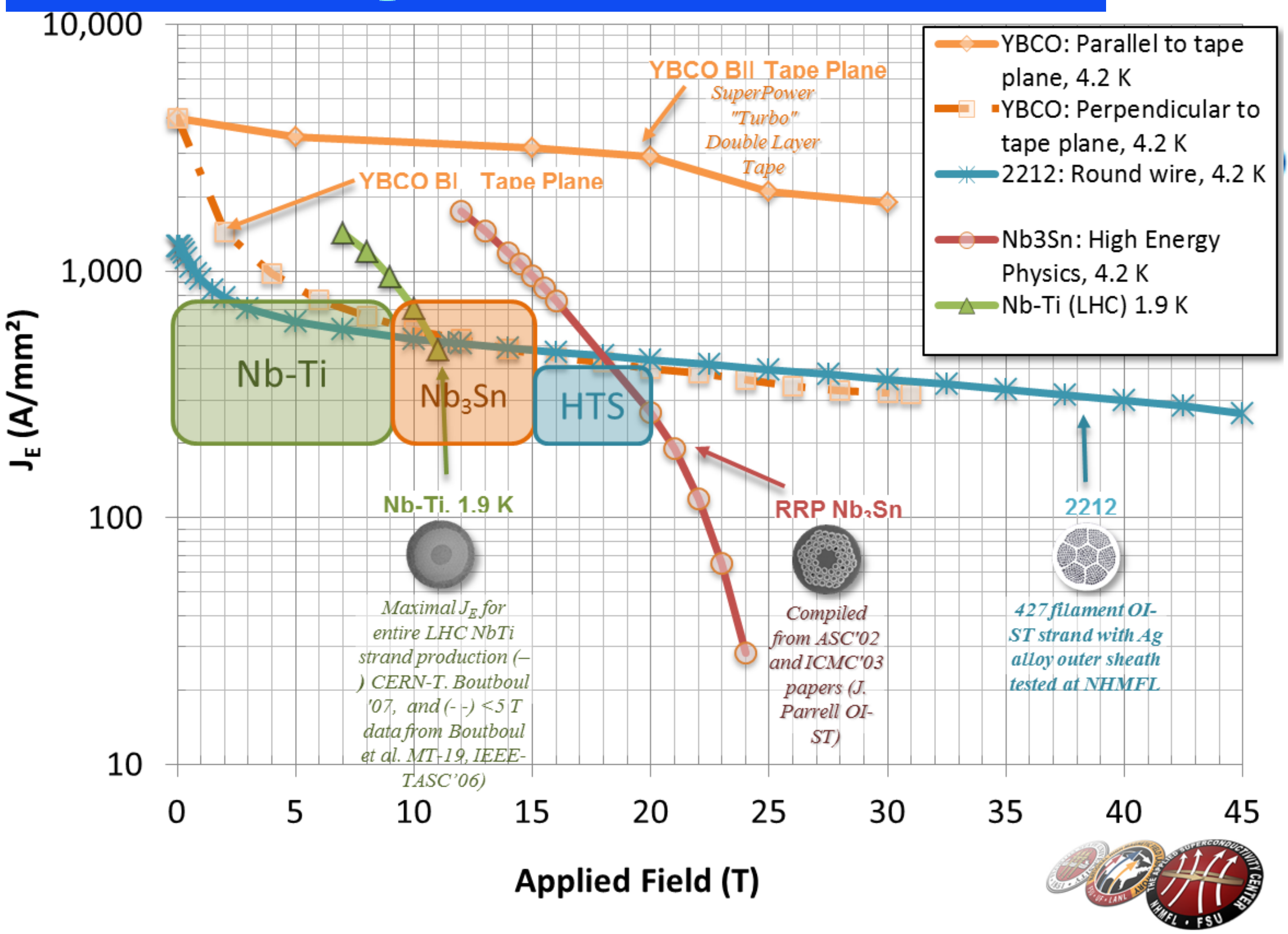
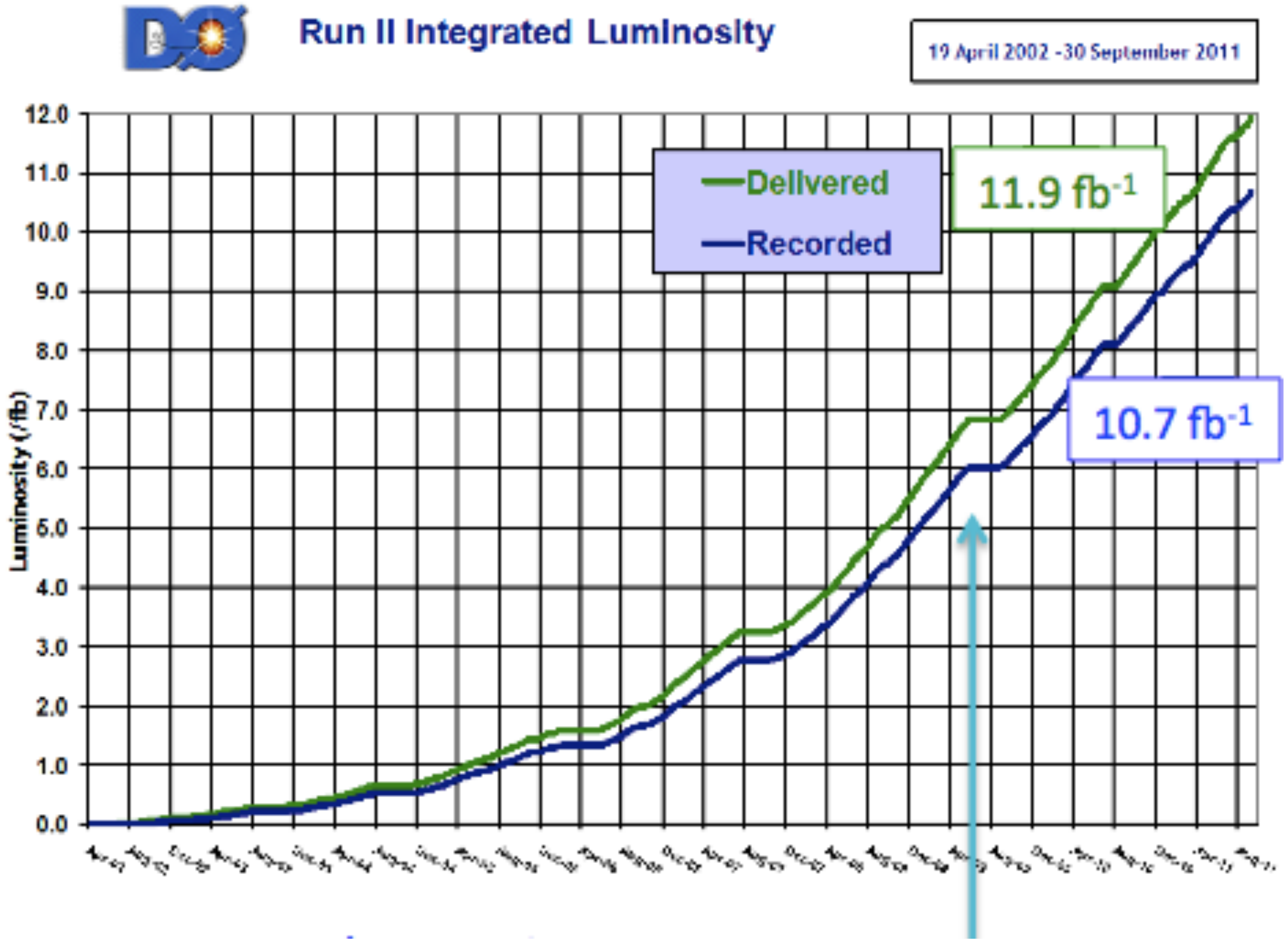




Tevatron: Integrated Luminosity

- Project termination on September 30, 2011



peak luminosity ~ 10^{32} $cm^{-2}s^{-1}$

The Large Hadron Collider

The LHC: Visions (1980ies)

- particle accelerator with the highest collision energies aiming at:
  - test of the Standard Model beyond energies of 1 TeV
  - finding the missing pieces of the SM: top quark
  - investigate the mechanism of electroweak symmetry breaking: find the Higgs boson
  - search for New Physics beyond the Standard Model (Supersymmetry, large extra dimensions, …)
  - find the unexpected

The Challenges

- “fast“ and „cheap“ ➫ use existing LEP tunnel and pre-accelerators of CERN

The Challenges

• "fast" and „cheap"	➫	use existing LEP tunnel and pre-accelerators of CERN
• highest energies at given radius of tunnel	➫	accelerate protons (instead of electrons at LEP)

The Challenges

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• highest energies at given radius of tunnel	➯	accelerate protons (instead of electrons at LEP)
• collision energies of constituents of ~TeV	➯	Proton energies of at least 5 TeV

The Challenges

• “fast“ and „cheap“	➪	use existing LEP tunnel and pre-accelerators of CERN
• highest energies at given radius of tunnel	➪	accelerate protons (instead of electrons at LEP)
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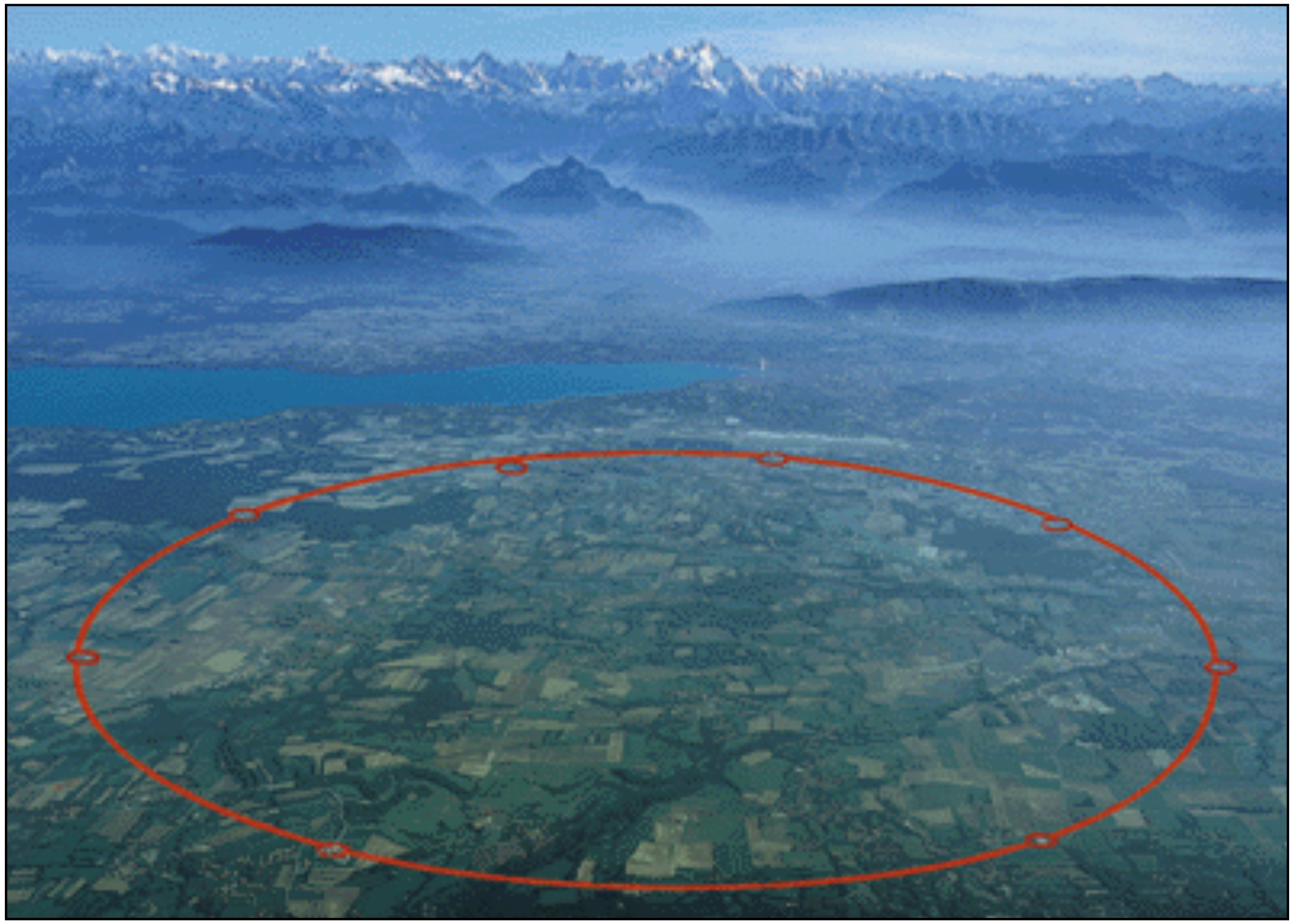
• $L \sim 10^{34}\ cm^{-2}\ s^{-1}$	➫	high data rates; radiation damage

The Large Hadron Collider LHC

- Proton-proton collider in a 27 km tunnel at CERN

- Highest collision energies
- Highest luminosity

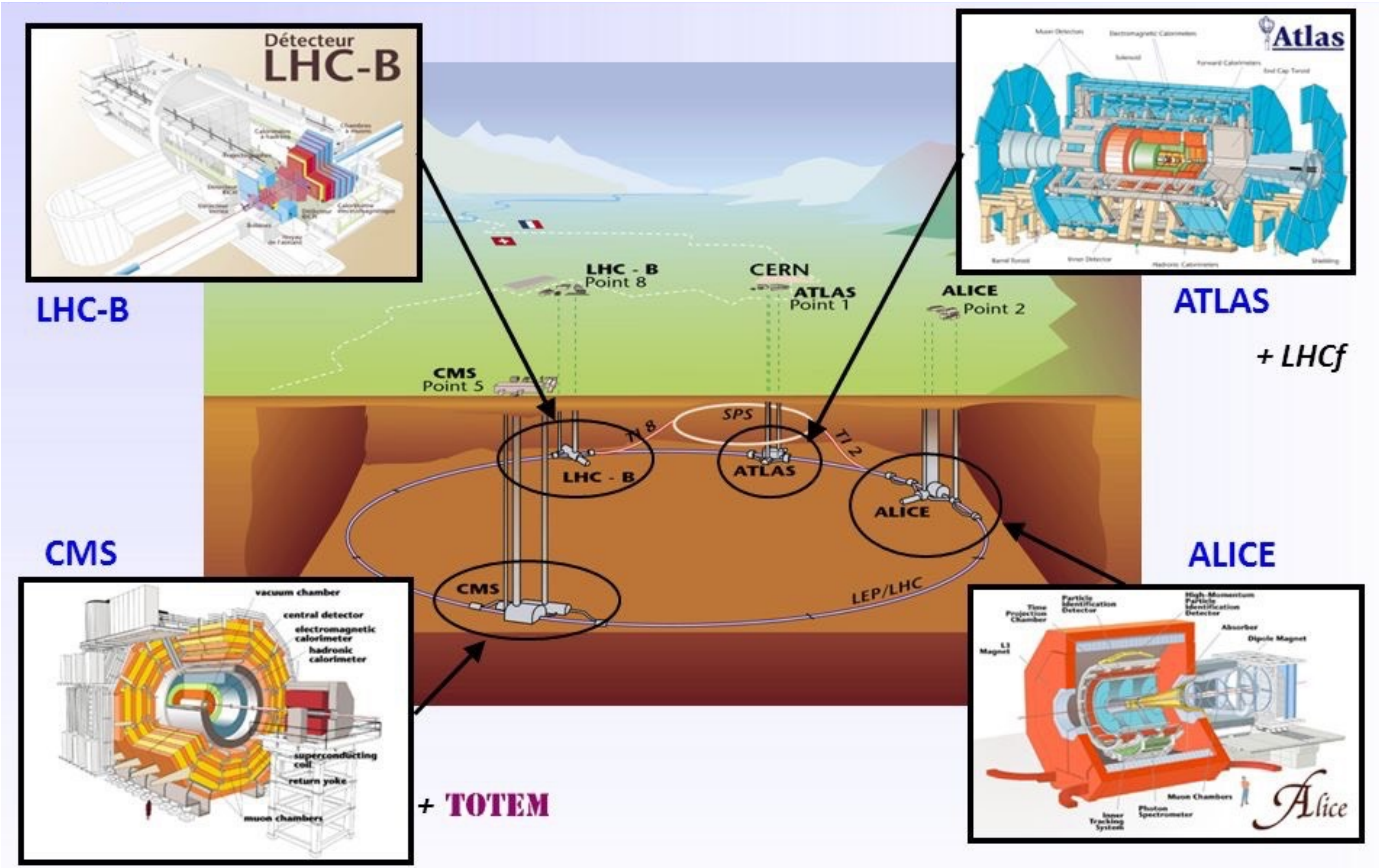


- 4 large experiments:
  - ATLAS & CMS (general purpose p+p)
  - ALICE (Heavy Ion collisions)
  - LHCb (heavy quark physics)

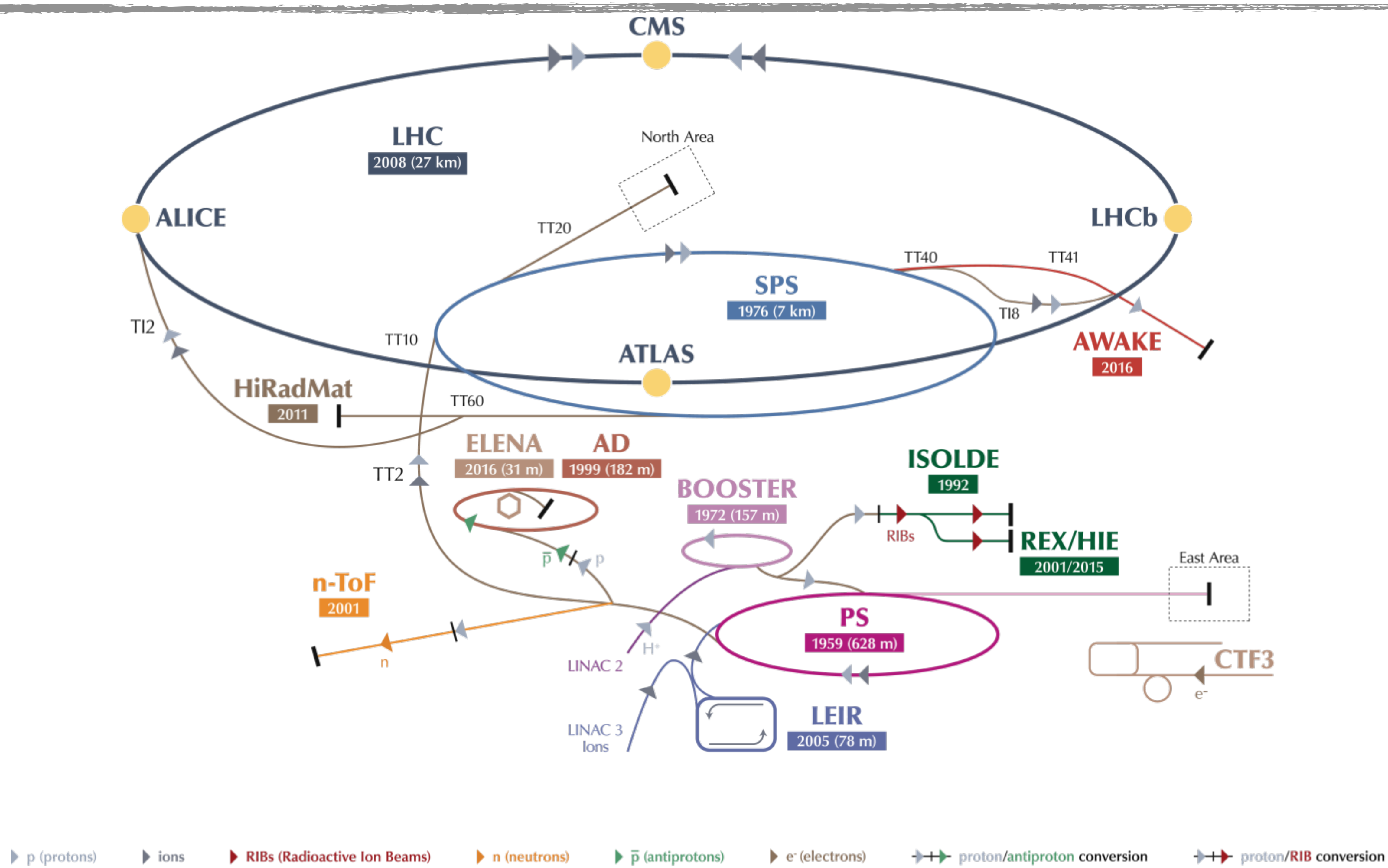
constructed & operated in collaboration with ~ 40 nations

- Start of operations 2009 (originally planned for 2005), running until ~ 2035

The LHC Complex at CERN



The Full CERN Accelerator Complex

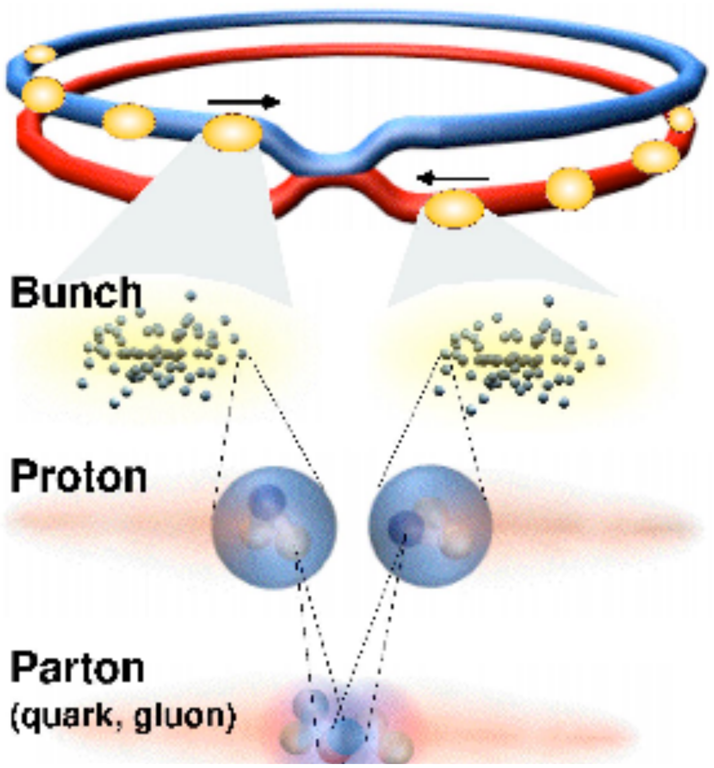


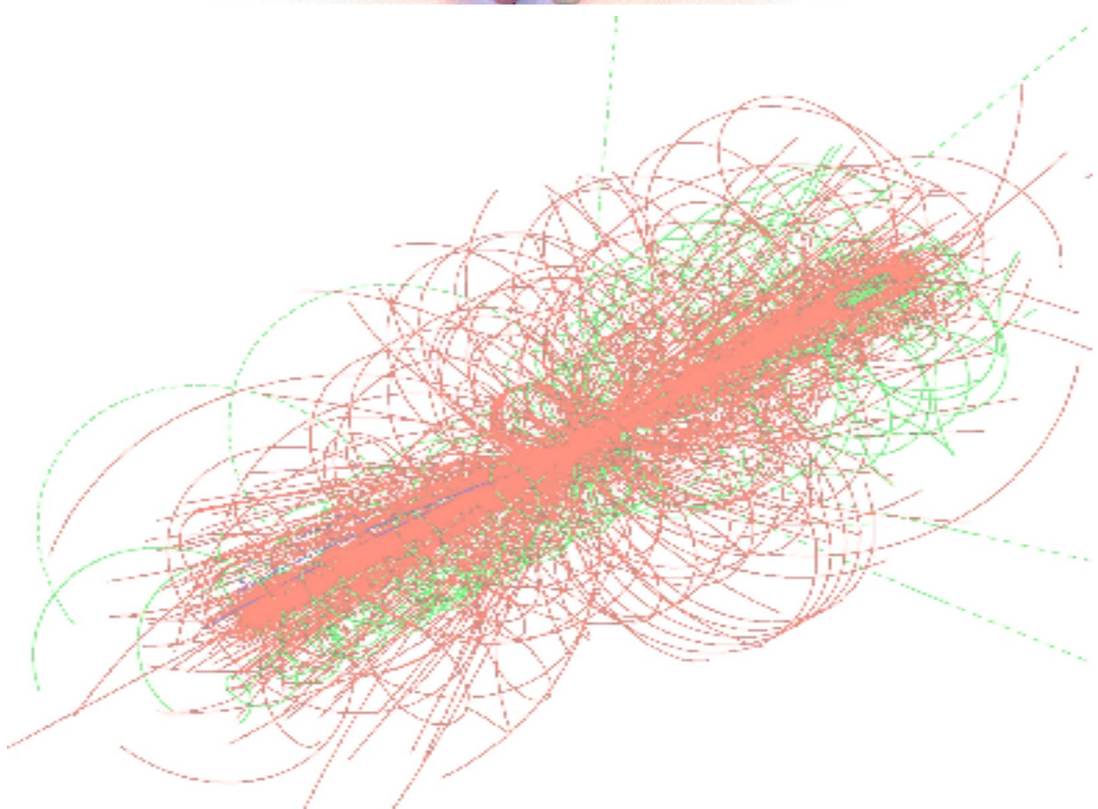
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKefield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

LHC: Parameters





Proton – Proton collisions:

2835 x 2835 bunches
distance: 7.5 m (25 ns)

10^{11} protons / bunch
collision rate: 40 million / second
Luminosity: L = 1034 cm-2 s-1

Proton-Proton collisions: ~10^{9} / s
(pile-up of 20-30 pp-interactions
for each beam crossing)

~1600 charged particles in detector

⇒ highest demands on detectors

Production Cross Sections: Physics Expectations

N_{events} /s = σ x L

N_{events} = σ x ∫ L dt

1 nb = 10^{-33} cm^2

calculus (example):

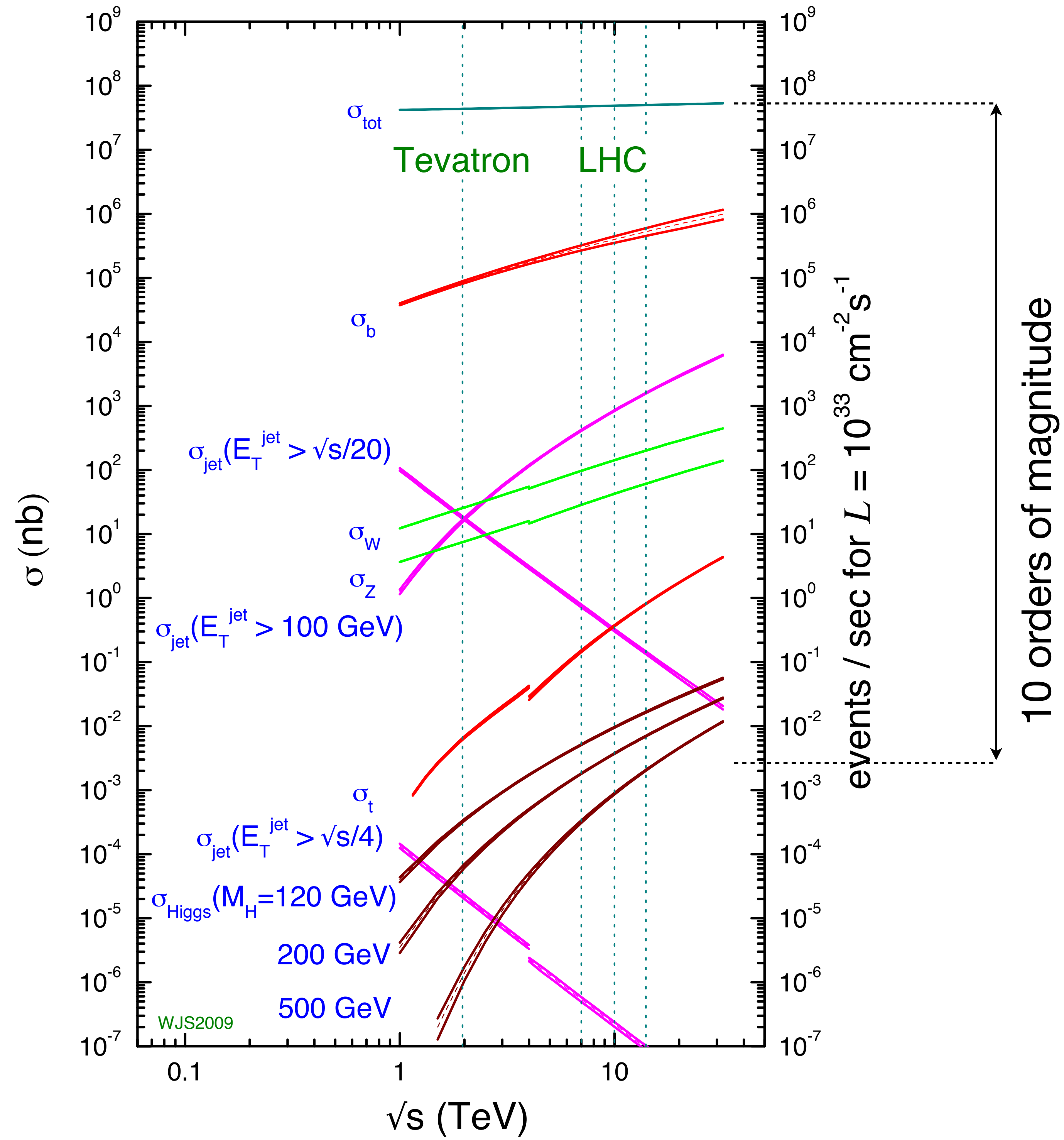
End of 2010:
∫Ldt = 40 pb^{-1} = 40 x10^3 nb-1

corresp. to ~ 4 x10^3 top-quark-events (σ_t ~ 10^{-1} nb at 7 TeV)

corresp. to ~200 Higgs-evts. with M_H =120 GeV at 7 TeV

data sample 2011: ~ 5 fb^{-1}
data sample 2012: ~20 fb^{-1}
data sample 2015: ~4 fb^{-1}
data sample 2016: ~40 fb^{-1}
data sample 2017: ~40+ fb^{-1}

proton - (anti)proton cross sections



Production Rates at LHC

• Inelastic Proton-Proton collisions:	1 Billion / second
• Quark -Quark/Gluon scatterings with large transverse momenta (> 20 GeV)	~100 Millions/ sec
• b-Quark pairs	5 Millions / sec
• top-Quark pairs	8 / sec
• W $\rightarrow$ e ν	150 / sec
• Z $\rightarrow$ e e	15 / sec
• Higgs (Mass = 150 GeV)	0.2 / sec
• Gluino, Squarks (Mass = 1 TeV)	0.03 / sec

- Interesting physics processes are extremely rare:
  $\Rightarrow$ high luminosities !

extremely powerful detectors (to suppress background)

LHC Parameters: Technical Details

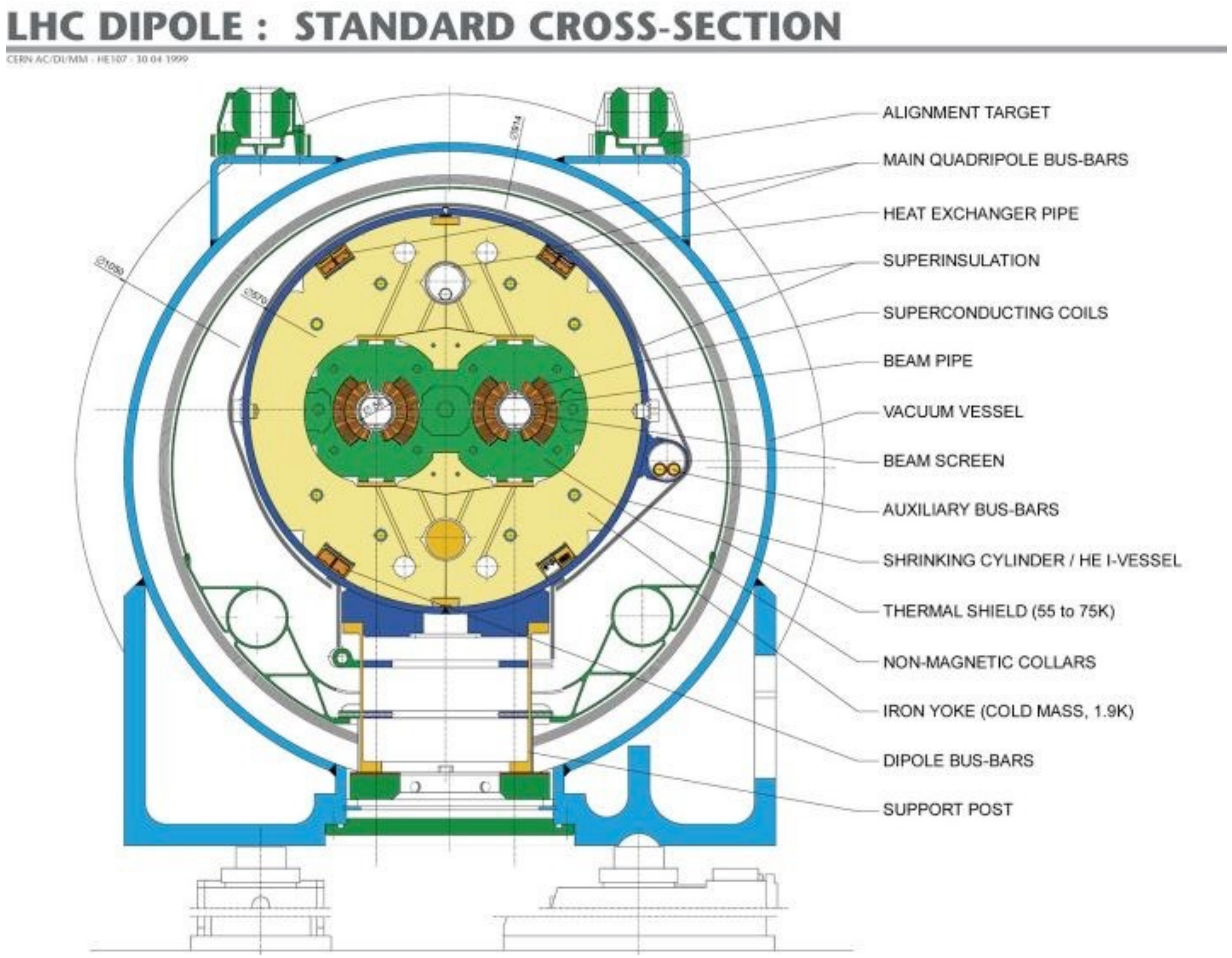
General LHC Parameters Version 4.0
(These parameters correspond to optics version 6.4 and the RF parameter update from the 14. LTC meeting (15. October 2003))
(the Version 3 parameters can be found here)

Momentum at collision	7	TeV / c
Momentum at injection	450	GeV / c
Machine Circumference	26658.883	m
Revolution frequency	11.2455 (*)	kHz
Super-periodicity	1	
Lattice Type	FODO, 2-in-1	
Number of lattice cells per arc	23	
Number of insertions	8	
Number of experimental insertions	4	
Utility insertions	2 collimation 1 RF and 1 extraction	
Dipole field at 450 GeV	0.535	T
Dipole field at 7 TeV	8.33	T
Bending radius	2803.95	m
Main dipole coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Main Dipole Length	14.3	m
Main Dipole Ends	236.5	mm
Half Cell Length	53.45	m
Phase advance per cell	90	degree
Horizontal tune at injection	64.28	
Vertical tune at injection	59.31	
Horizontal tune at collision	64.31	
Vertical tune at collision	59.32	
Maximum beta-function (cell)	177 / 180 (**)	m
Minimum beta-function (cell)	30 / 30 (**)	m

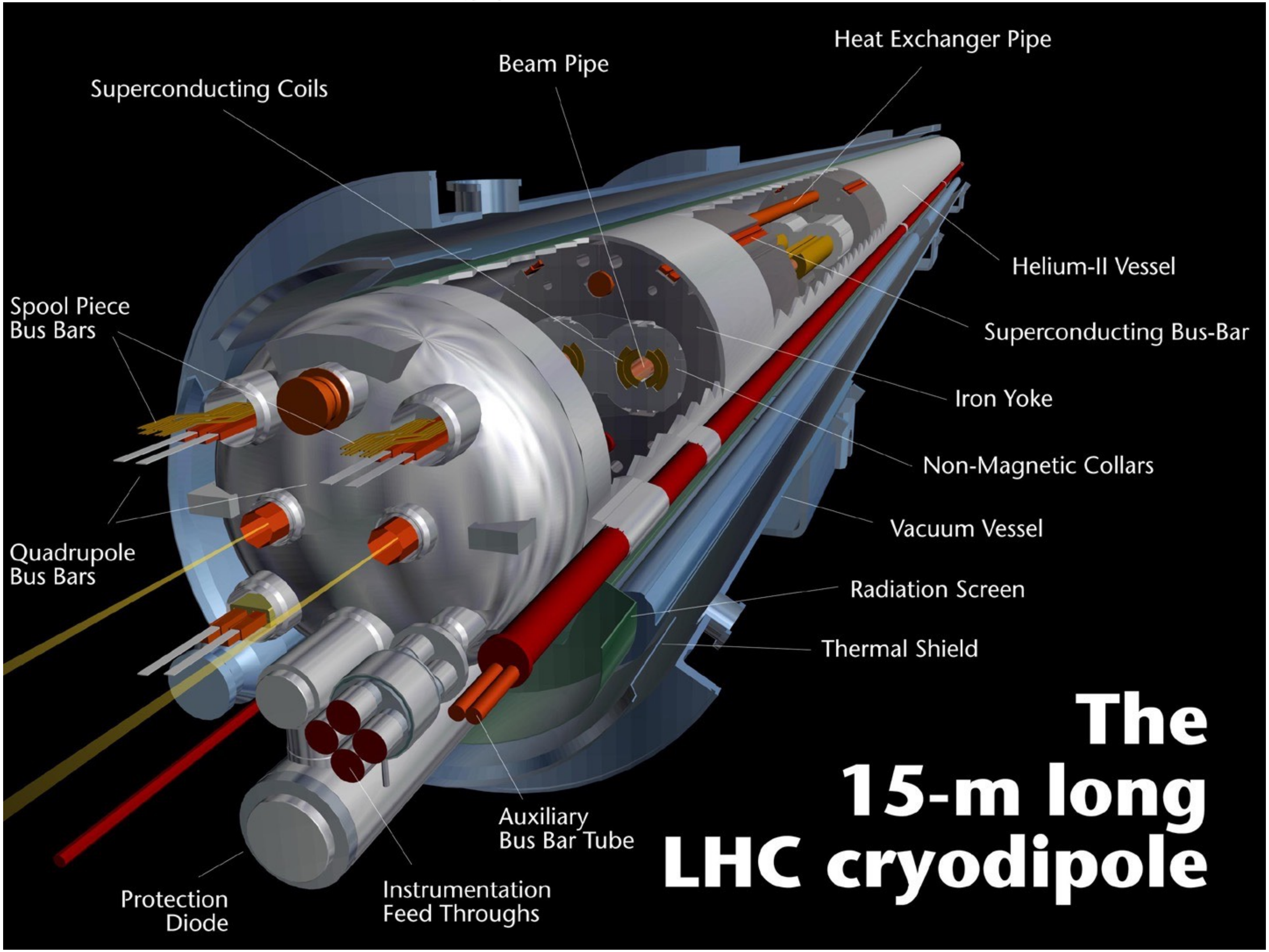
Maximum dispersion (cell)	2.018 / 0.0 (**)	m
Maximum beta-function (service insertions)	594.5 / 609.3 (**)	m
Free space for detectors	+/-23	m
Gamma Transition	55.678	
Momentum Compaction	0.0003225 (**)	
Main RF System	400.8	MHz
Harmonic number	35640	
Voltage of 400 MHz RF system at 7 TeV	16	MV
Synchrotron frequency at 7 TeV	23.0	Hz
Bucket area at 7 TeV	7.91	eV.s
Bucket half-height at 7 TeV	3.56	10^{-4}
Voltage of 400 MHz RF system at 450 GeV	8	MV
Synchrotron frequency at 450 GeV (without 200 MHz RF)	63.7	Hz
Bucket area at 450 GeV	1.43	eV.s
Bucket half-height at 450 GeV	10	10^{-4}
Capture RF system	200.4	MHz

The LHC Magnets

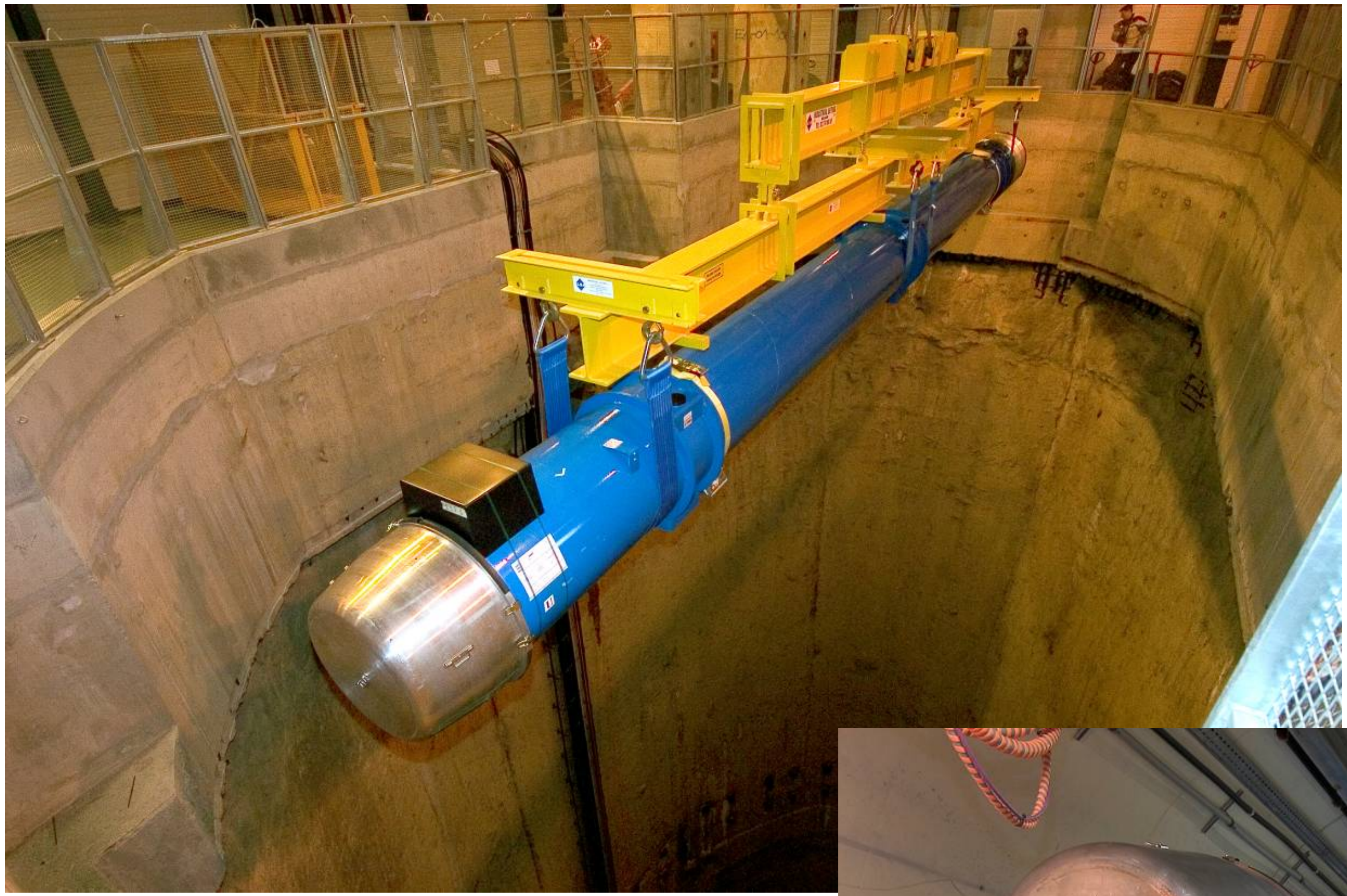
- Superconducting main dipoles
  - biggest challenge: magnetic field of ~ 9 T
  - overall 1300 main dipoles, each 15 m long
  - operated at 1.9 K (superfluid helium)



The LHC Magnets



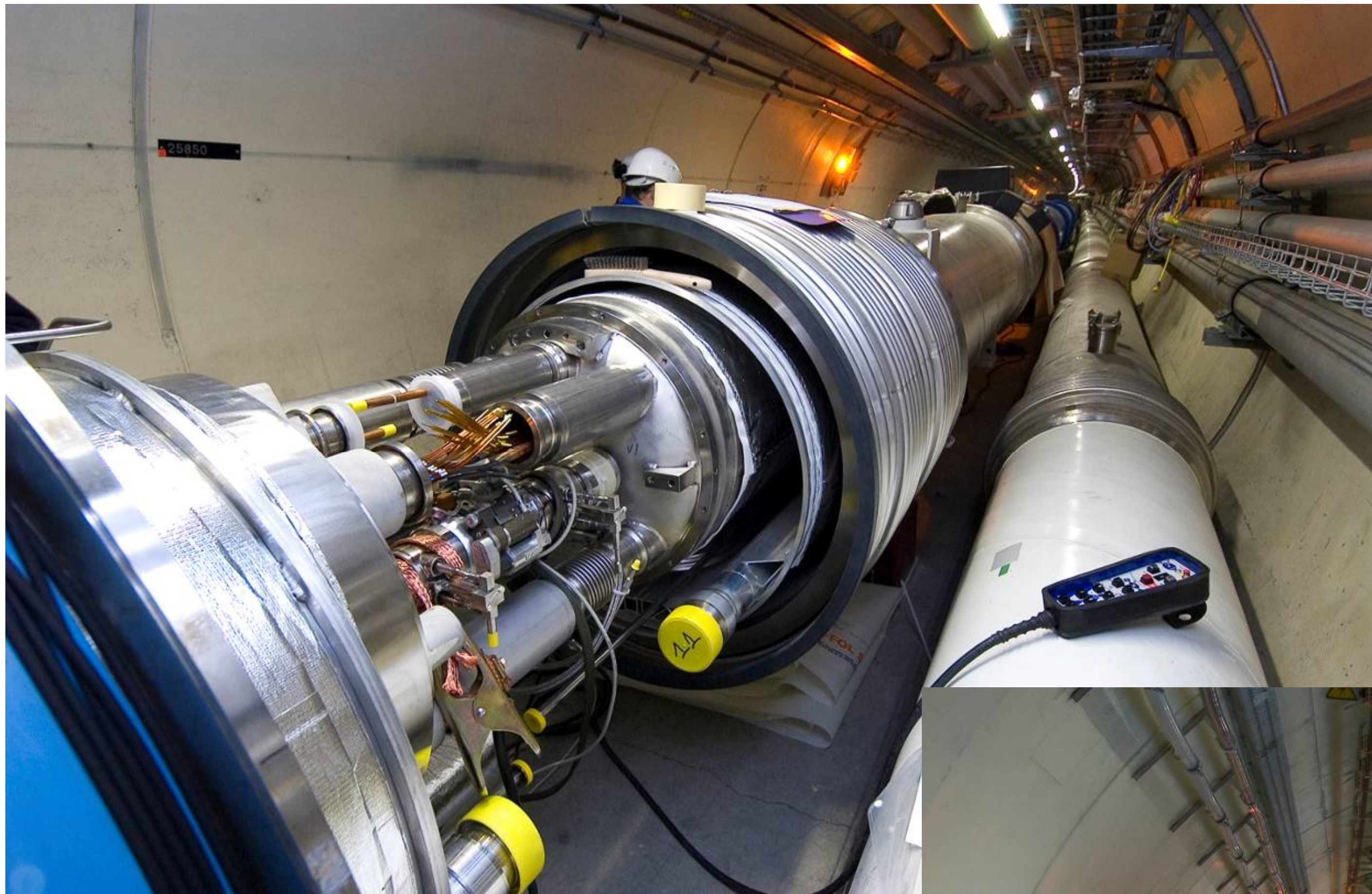
LHC Installation



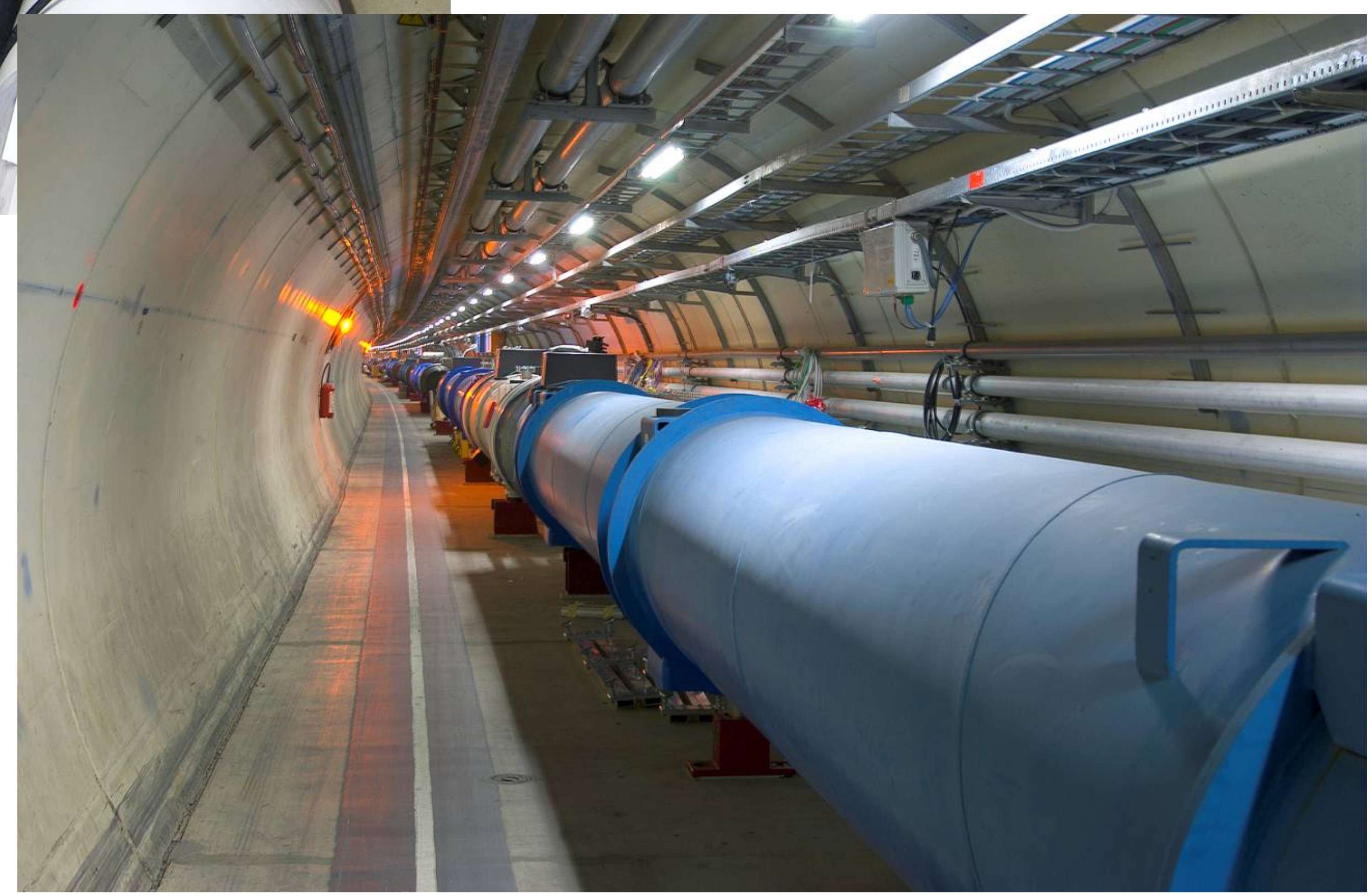
Lowering of the first dipole into the tunnel (March 2005)

Installation of dipoles in the LHC ring

LHC Installation



Interconnection of the dipoles and connection to the cryoline



A view of the tunnel…

LHC Installation

LHC Status

- 09.09.2008: first stable „beam“ in LHC
- 19.09.2008: technical problems with large impact: destruction of parts of LHC ring; repair of ~1 Jahr.
- 20.11.2009: restart after repair; first collisions!
- 11.12.2009: world record: collisions at 2.36 TeV! (2·1.18 TeV)
- 30.03.2010: collisions at 7 TeV (2 · 3.5 TeV)
- Nov. 2011: 5 fb-1 at 7 TeV per experiment
- 2012:
  - collisions at 8 TeV
  - until Dec: ~20 fb-1
  - 4. July 2012: a new Boson ...
- 2013/14: long shut-down (LS1);
- 2015: operation at 13 TeV; 25 ns bunch spacing

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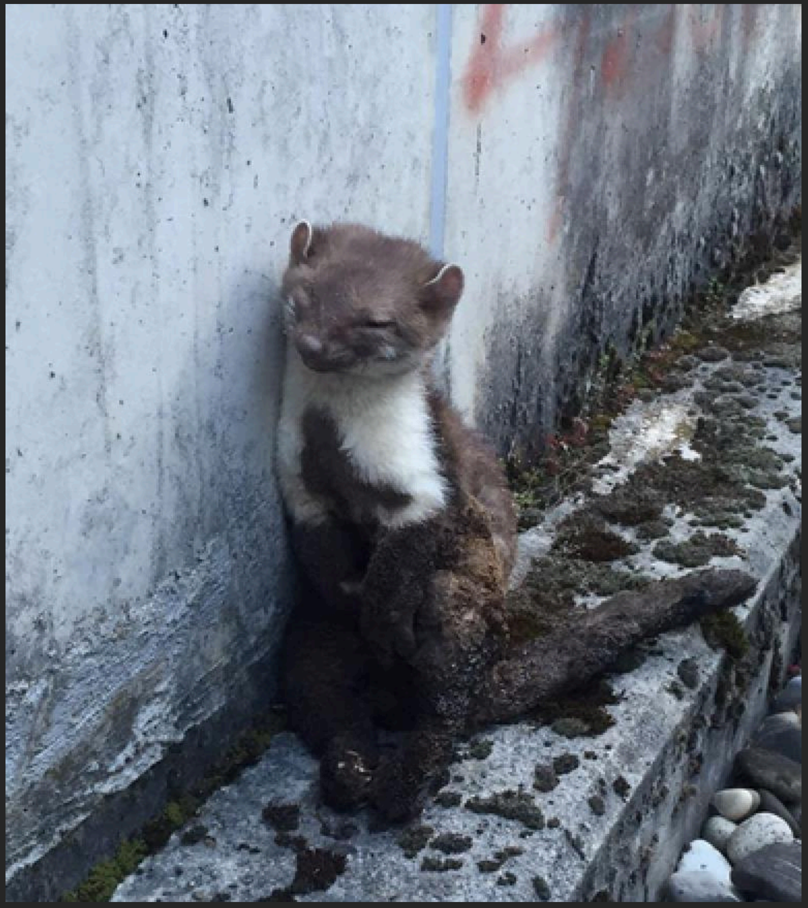
LHC Operations: Always an Adventure

WEASEL

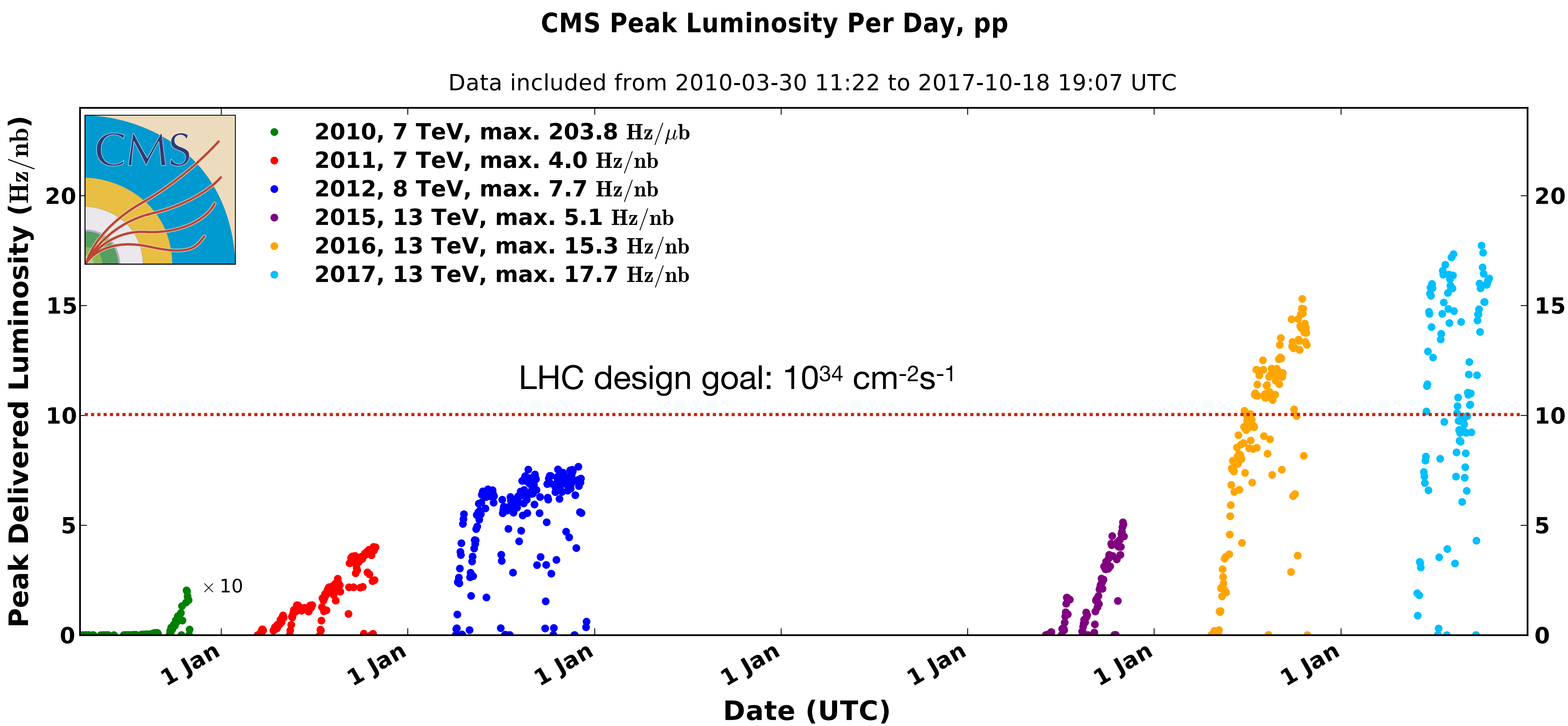


PS MAIN POWER SUPPLY

SPS BEAM DUMP

- **Limited to 96 bunches per injection**
- **2076 bunches per beam cf. 2750**

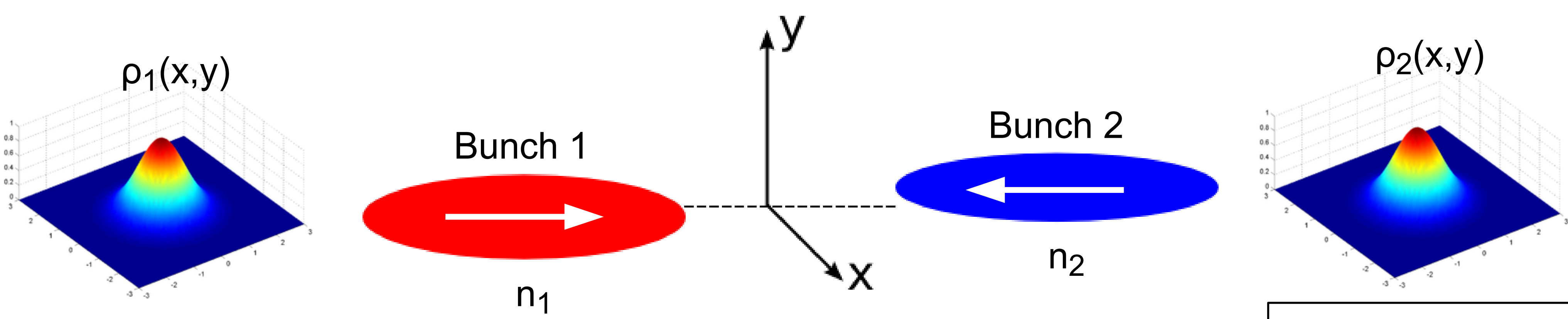
LHC Luminosity



- Design luminosity reached end of June 2016

Measuring the Luminosity

- Different techniques in use - the most “basic” one: Van der Meer - Scans



$$\mathcal{L} = n_b f_r n_1 n_2 \iint \rho_1(x,y)\rho_2(x,y)\,dxdy = \frac{n_b f_r n_1 n_2}{2\pi\Sigma_x\Sigma_y}$$

number of bunches (n_b) · revolution frequency (f_r) · no. of protons per bunch (n_1, n_2) · beam width (Σ_x, Σ_y)

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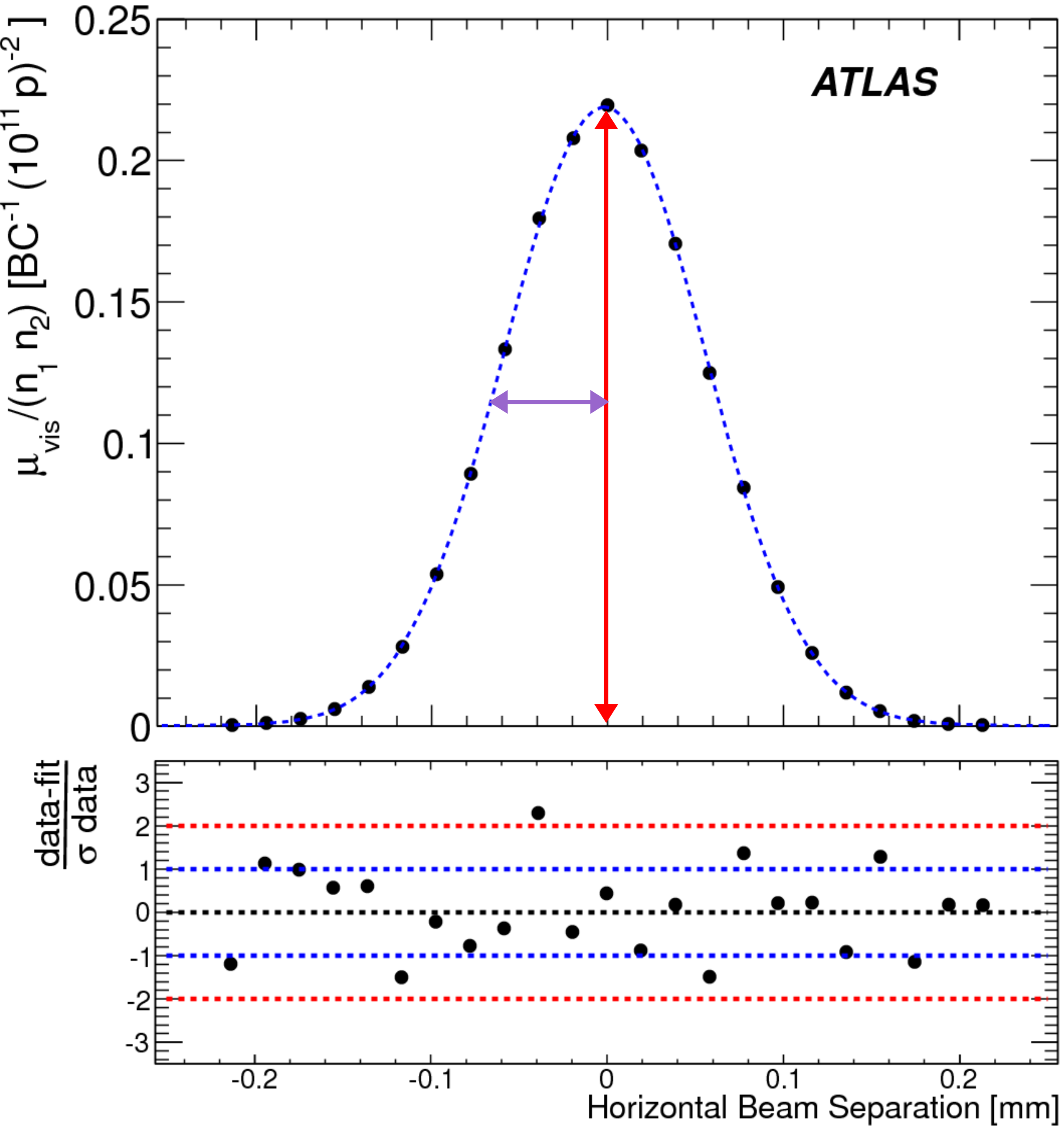
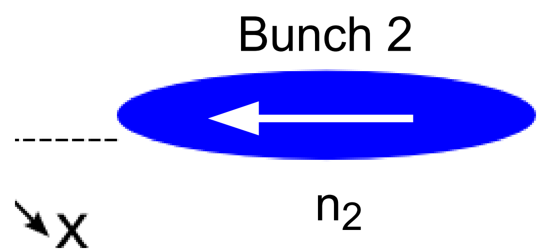
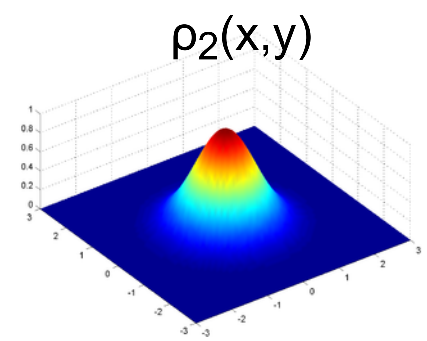






number of bunches

revolution frequency

no. of protons per bunch

$$\rho_2(x,y)\,dxdy = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

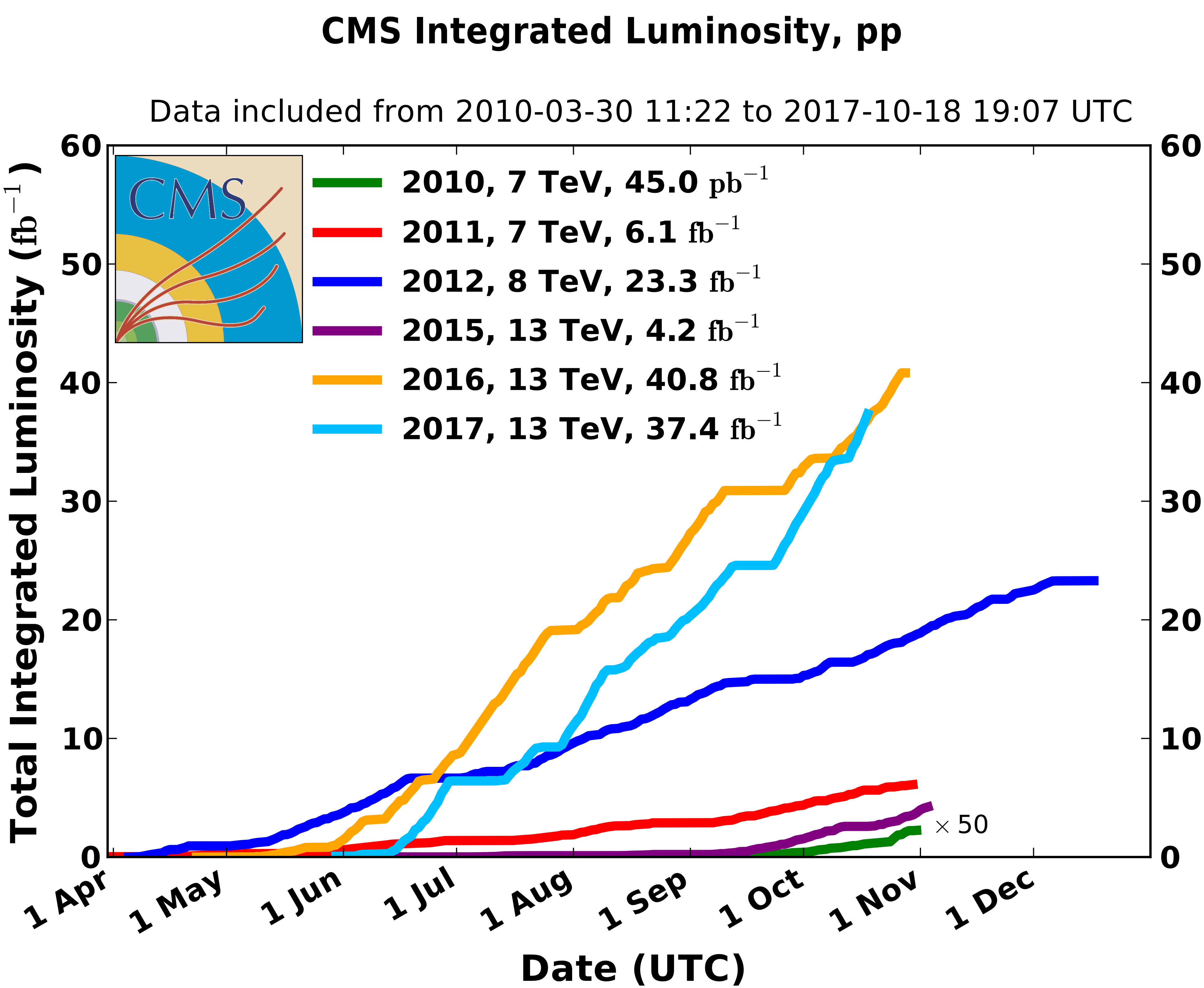
beam width

Scan determines beam width

bunch population from external measurement

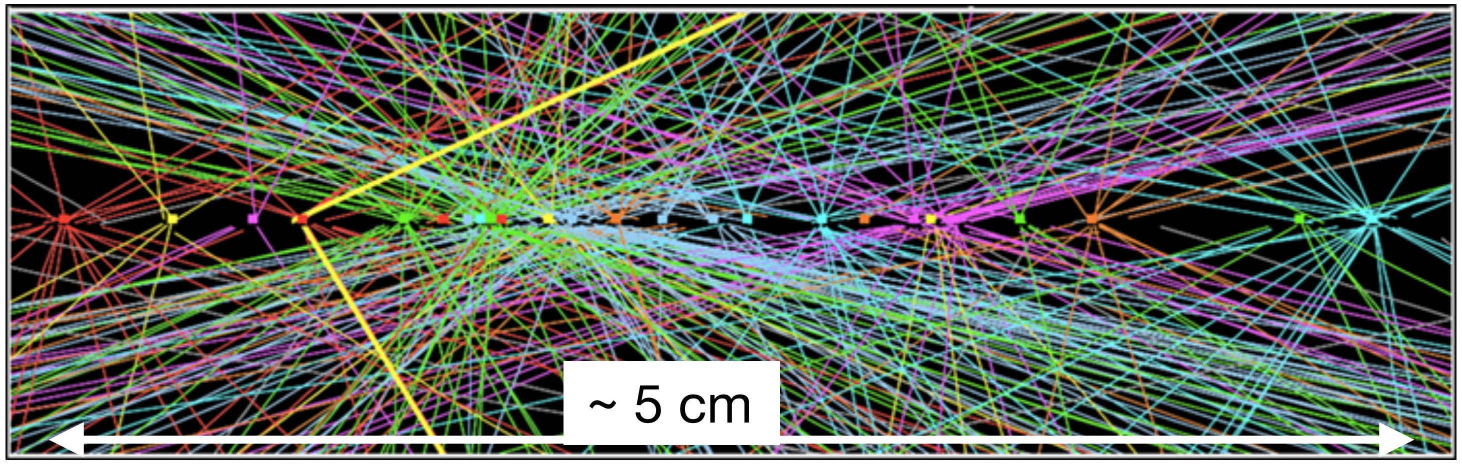
Accuracy on the 2% level

LHC Integrated Luminosity

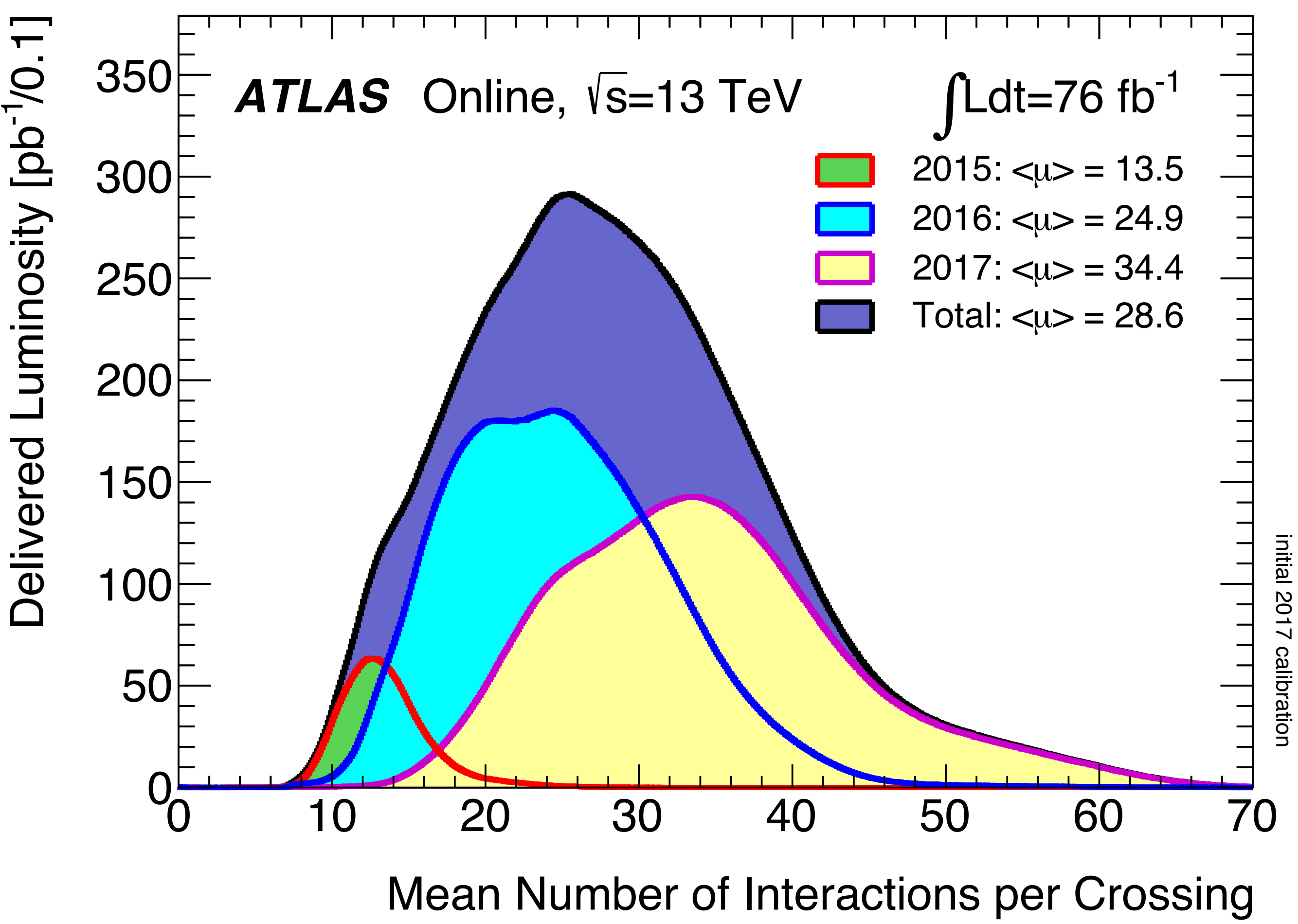


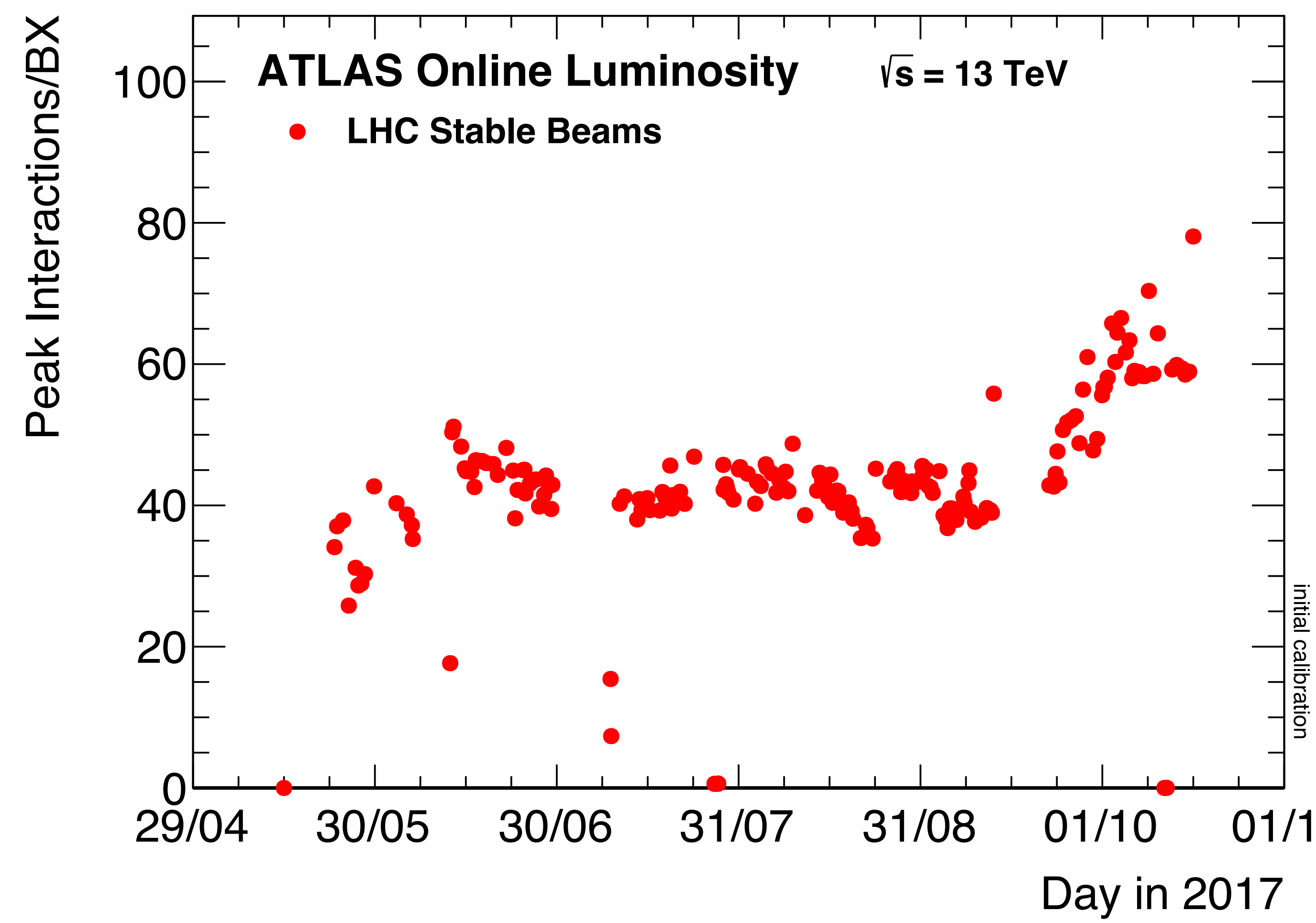
A Consequence: Pile-Up

- High luminosity results in multiple interactions per bunch crossing

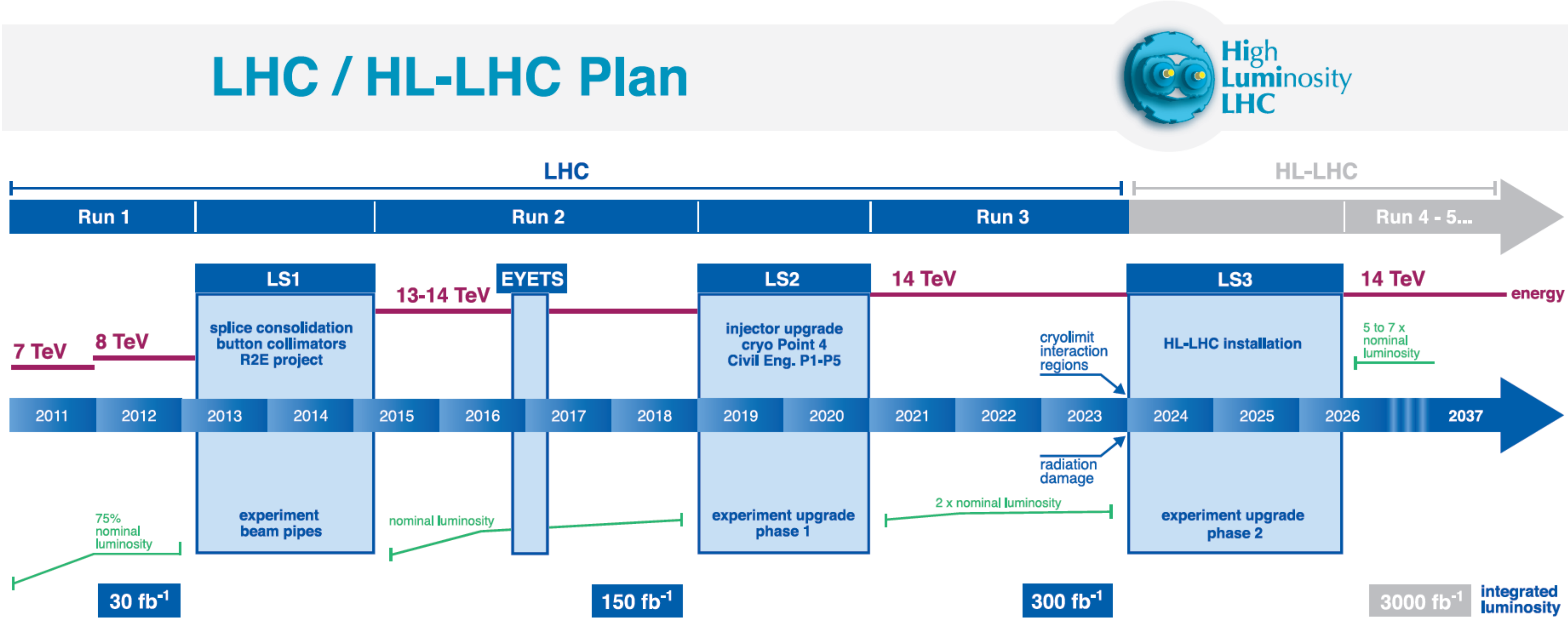


Example: Z->μμ process, in an event with 25 reconstructed interaction vertices





LHC Long Term Plan

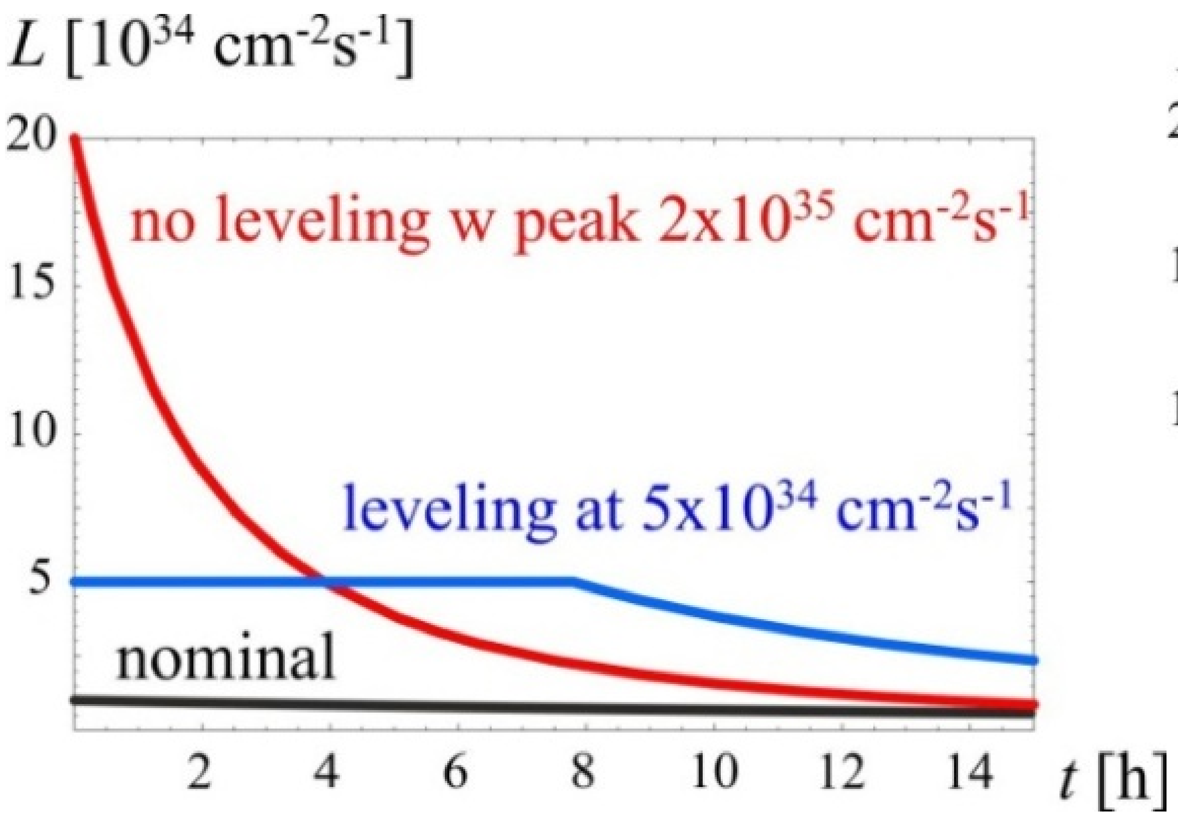


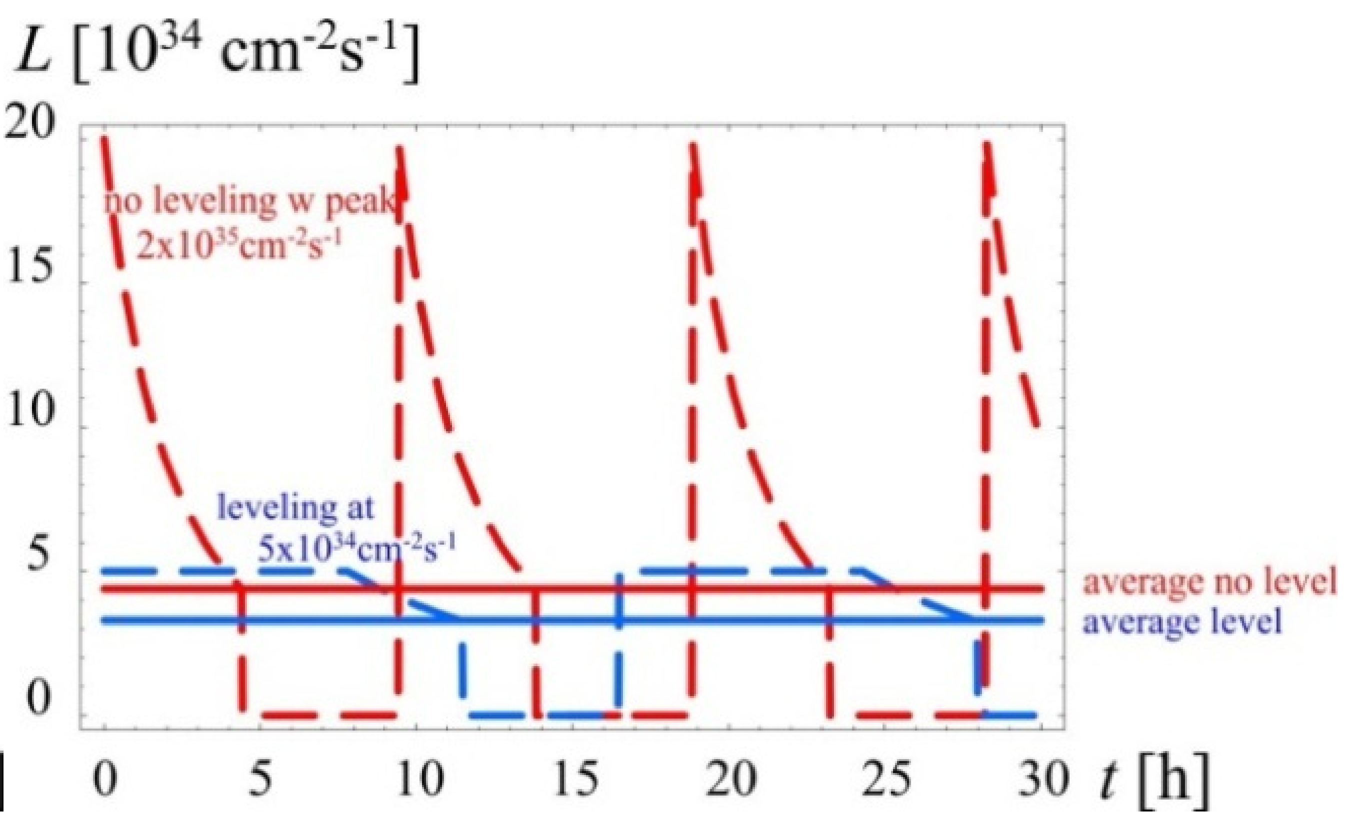
- Continuing current run until 2018
- “mild” luminosity upgrade (injector upgrade) 2019/20
- HighLuminosity LHC upgrade 2024-26:

  4 - 7 x 10^{34} $cm^{-2}s^{-1}$ peak luminosity

HL-LHC: Luminosity Levelling

- A key “feature” to limit excessive pileup: Luminosity levelling





- Allows longer running at high luminosity per fill, only mild impact on average luminosity, with substantial gain in terms of experimental conditions

Summary

- Accelerators are key instruments in particle physics - with many applications beyond fundamental research

- Proton synchrotrons in “collider mode” reach the highest energies - limited by accelerator radius and main dipole field

- The Large Hadron Collider LHC is the current energy record holder - and has just exceeded its design luminosity
    - Physics program with luminosity upgrade extending to 2035

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Next Lecture: 30.10., “Detectors I”, F. Simon

Schedule

1.	Introduction	16.10.
2.	Accelerators	23.10.
3.	Particle Detectors I	30.10.
	----------- **no lecture** -------------	**06.11.**
4.	Particle Detectors II	13.11.
5.	Monte Carlo Generators and Detector Simulation	20.11.
6.	Trigger, Data Acquisition, Computing	27.11.
7.	QCD, Jets, Proton Structure	04.12.
8.	Top Physics	11.12
9.	Topic Open - Wishes, Ideas?	18.12.
	----------- Christmas ---------------------	
10.	Tests of the Standard Model	08.01.
11.	Higgs Physics I	15.01.
12.	Higgs Physics II	22.01.
13.	Physics beyond the SM	29.01.
14.	LHC Outlook & Future Collider Projects	05.02.