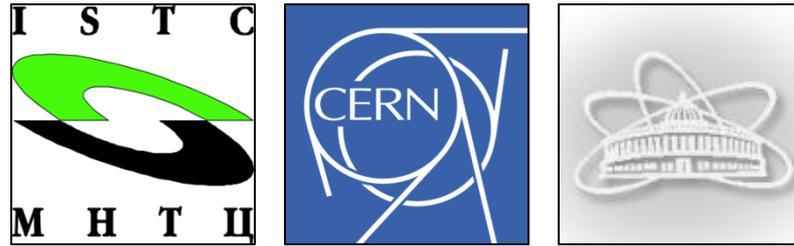


JOINT ISTC-CERN-JINR SUMMER SCHOOL ON HIGH ENERGY PHYSICS AND ACCELERATOR PHYSICS



Frontier High Energy Accelerators

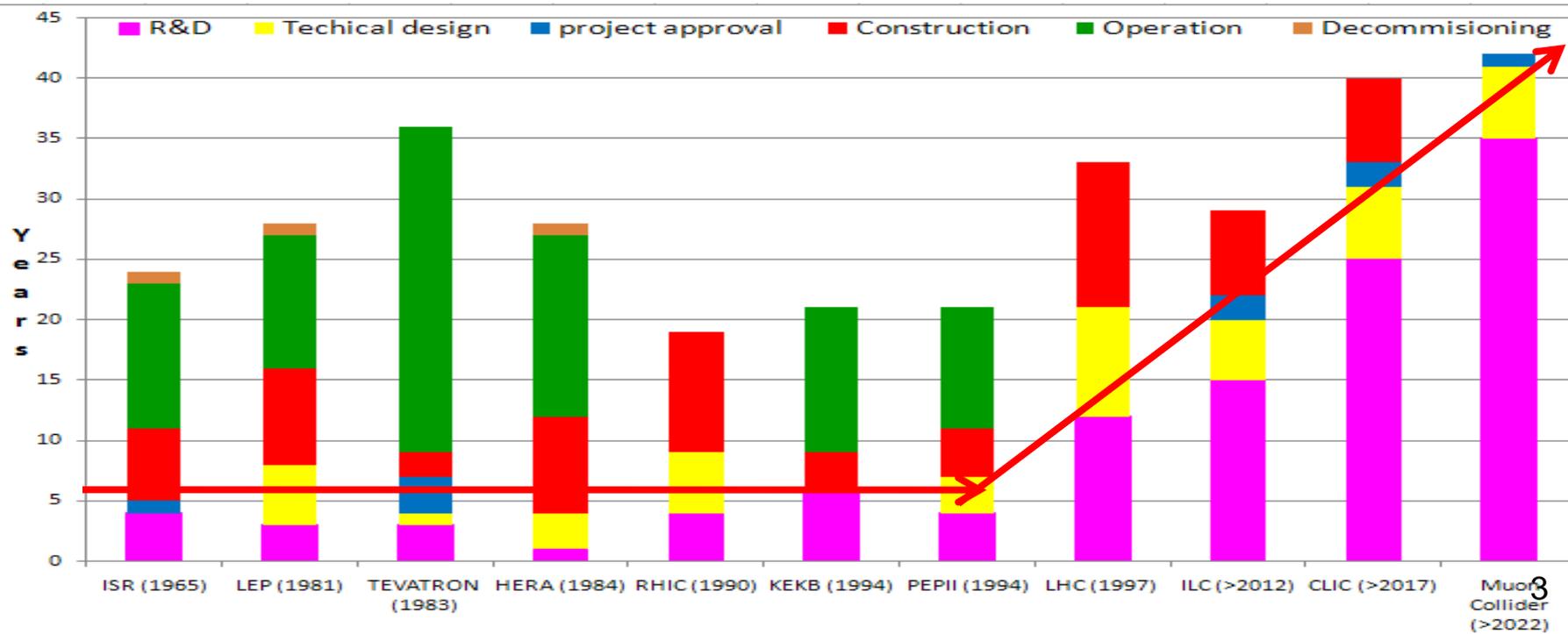
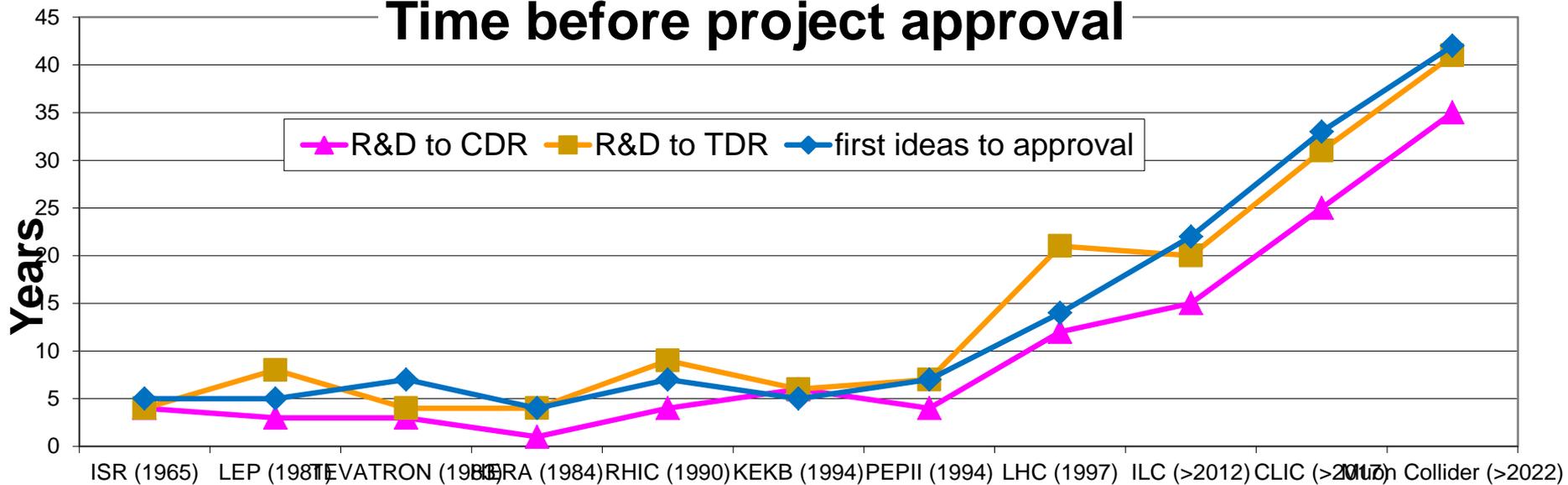
Hermann Schmickler - CERN

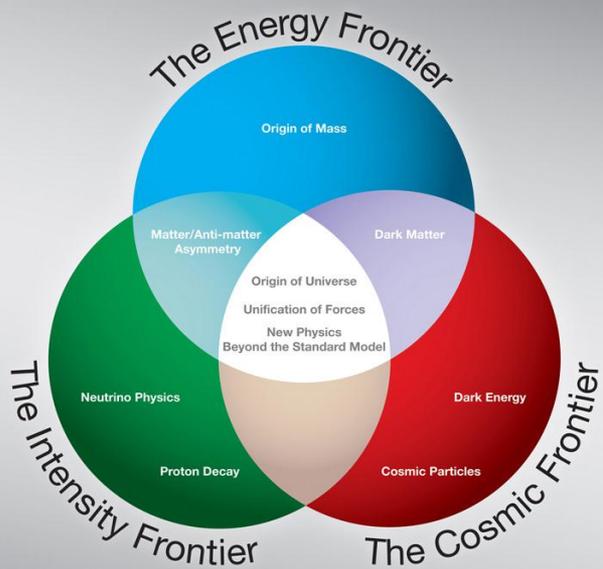
Tuesday, 27th September 2011

- **Today:**
Overview of frontier accelerators
the LHC and upgrades
- **Tomorrow:**
The next possible e+e- linear collider
Accelerator Controls



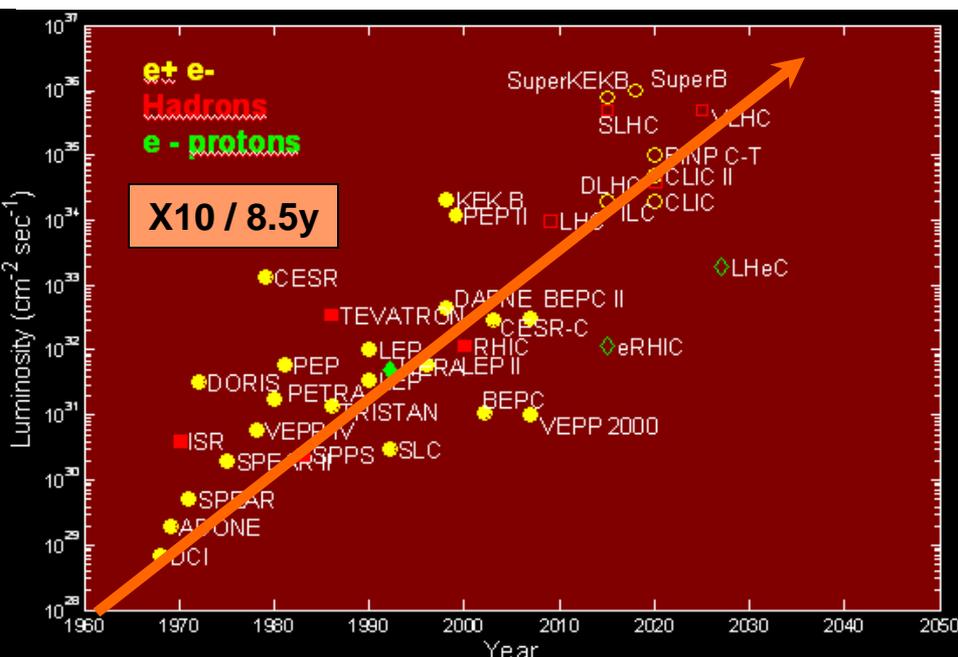
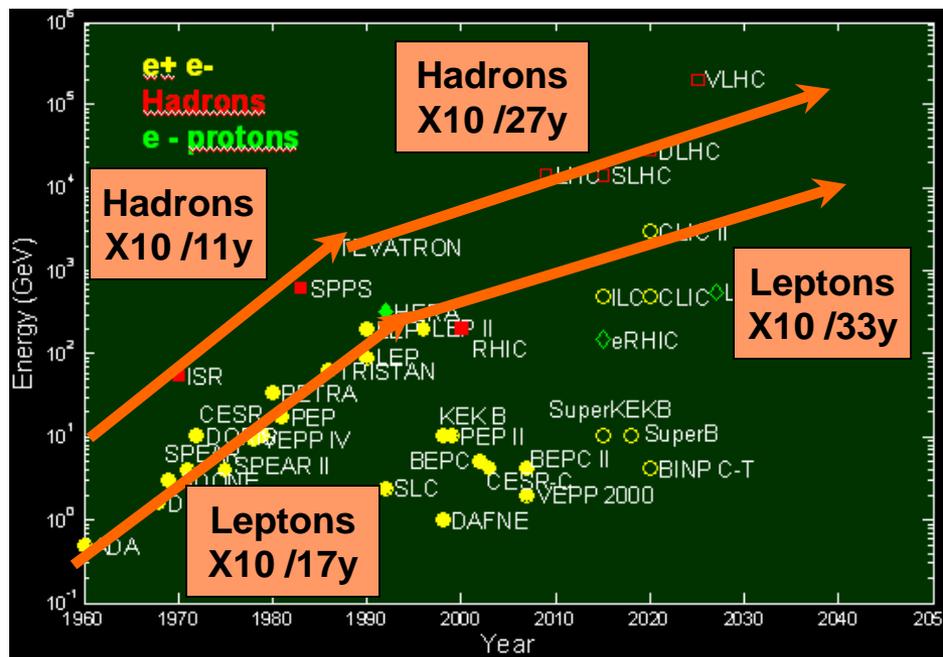
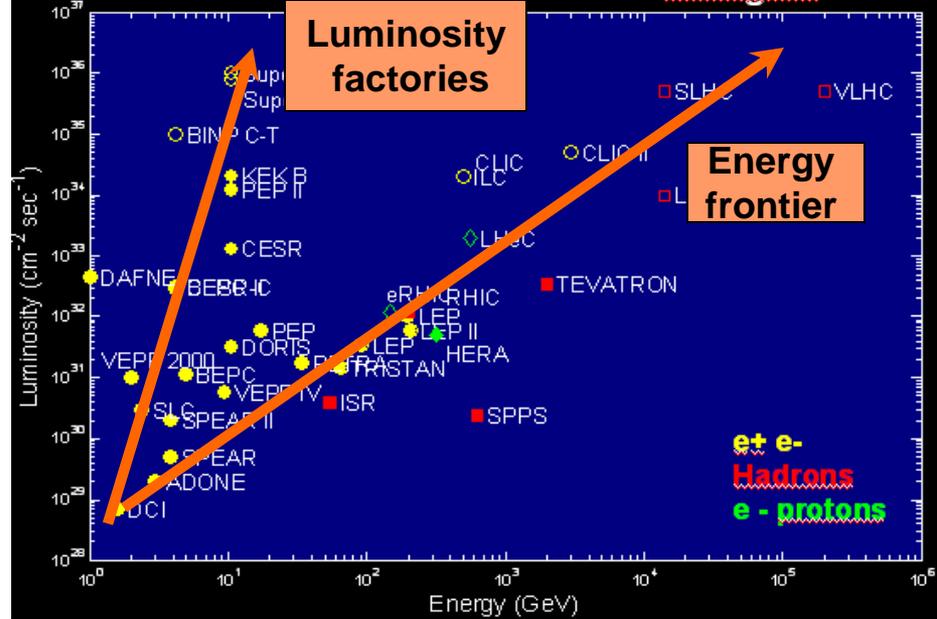
Time before project approval





Trends of HEP facilities

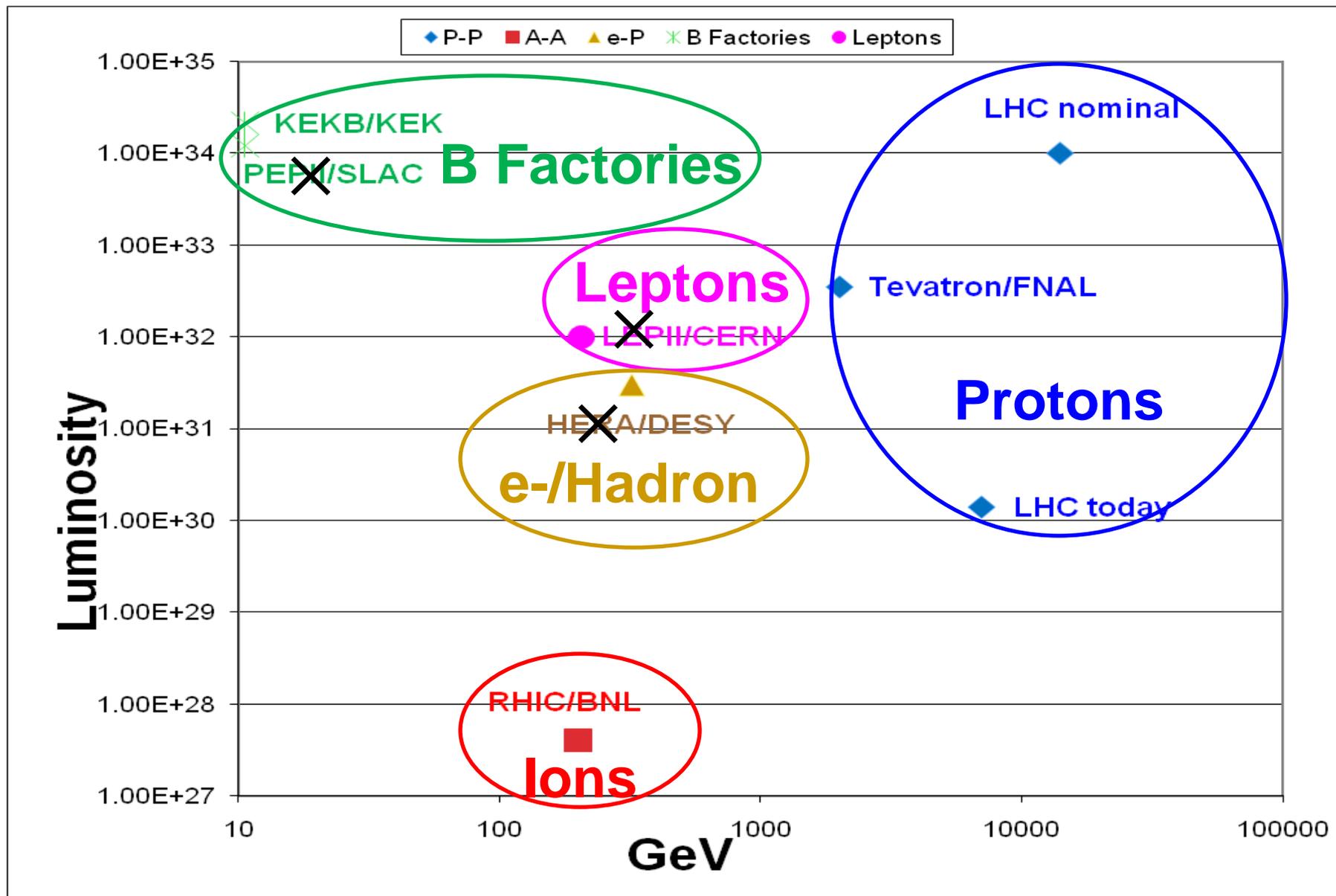
Courtesy of M.Biscari EPS-HEP09



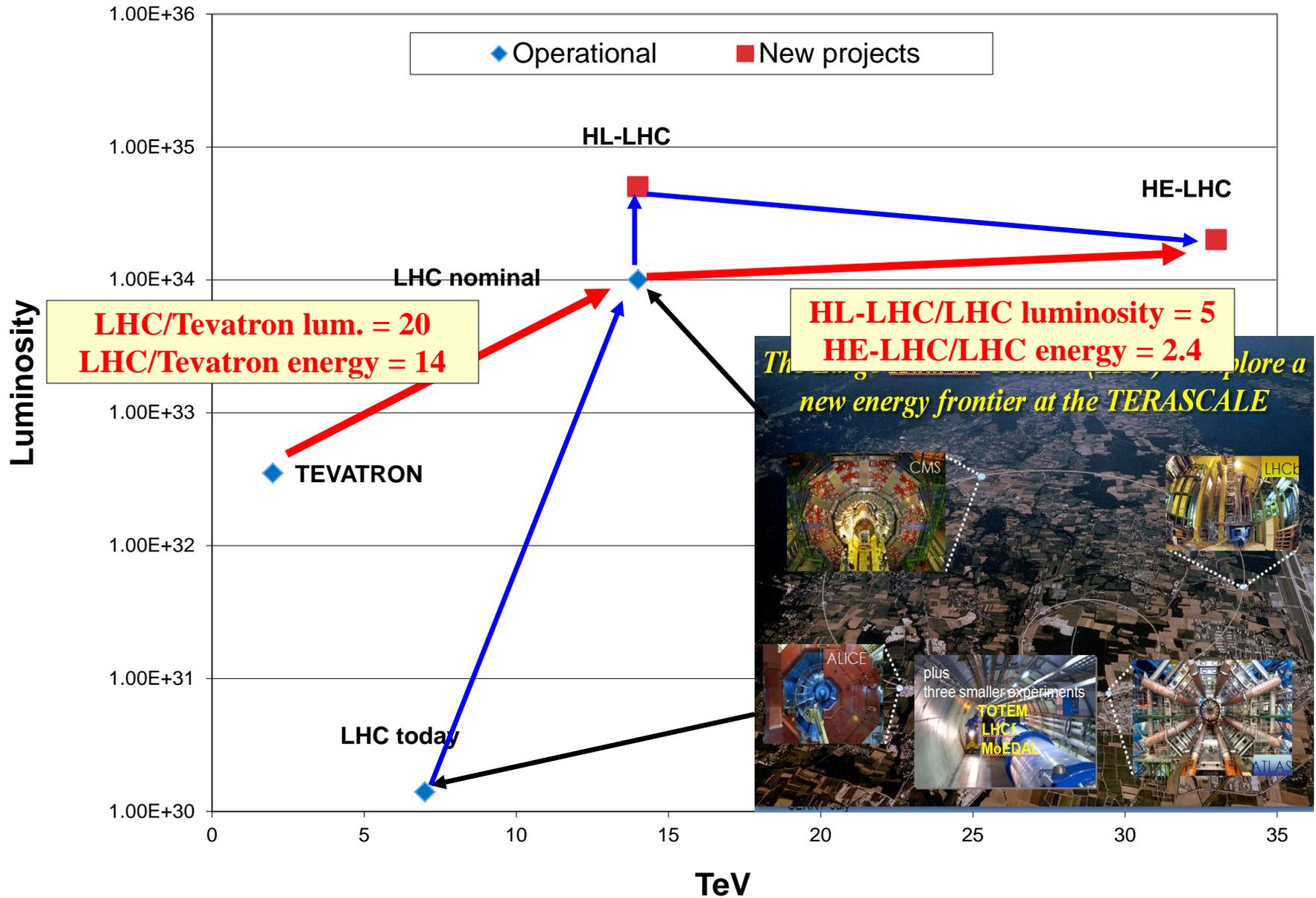
Towards Energy frontier

Towards Luminosity frontier

Present HEP colliders at Energy/Luminosity frontiers

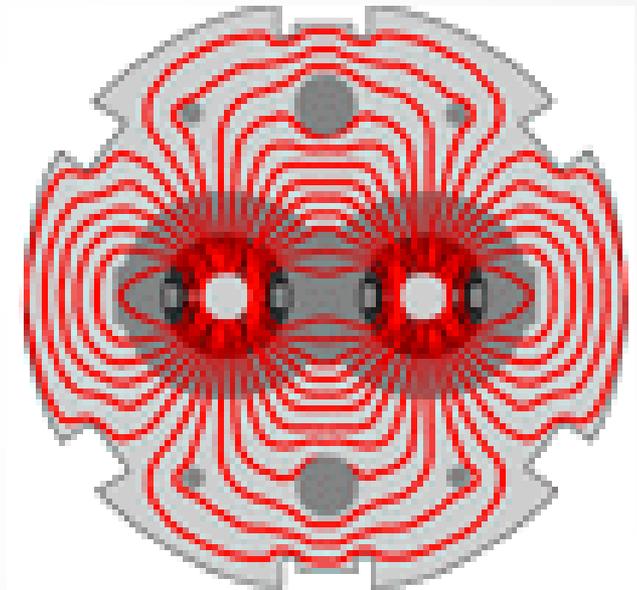


Proton Colliders @ High Energy Frontier



The LHC

- **Overview**
- **Parameters**
- **Critical Components**
 - **Dipoles**
 - **Insertions**
 - **Collimation**
 - **Beam Dump**



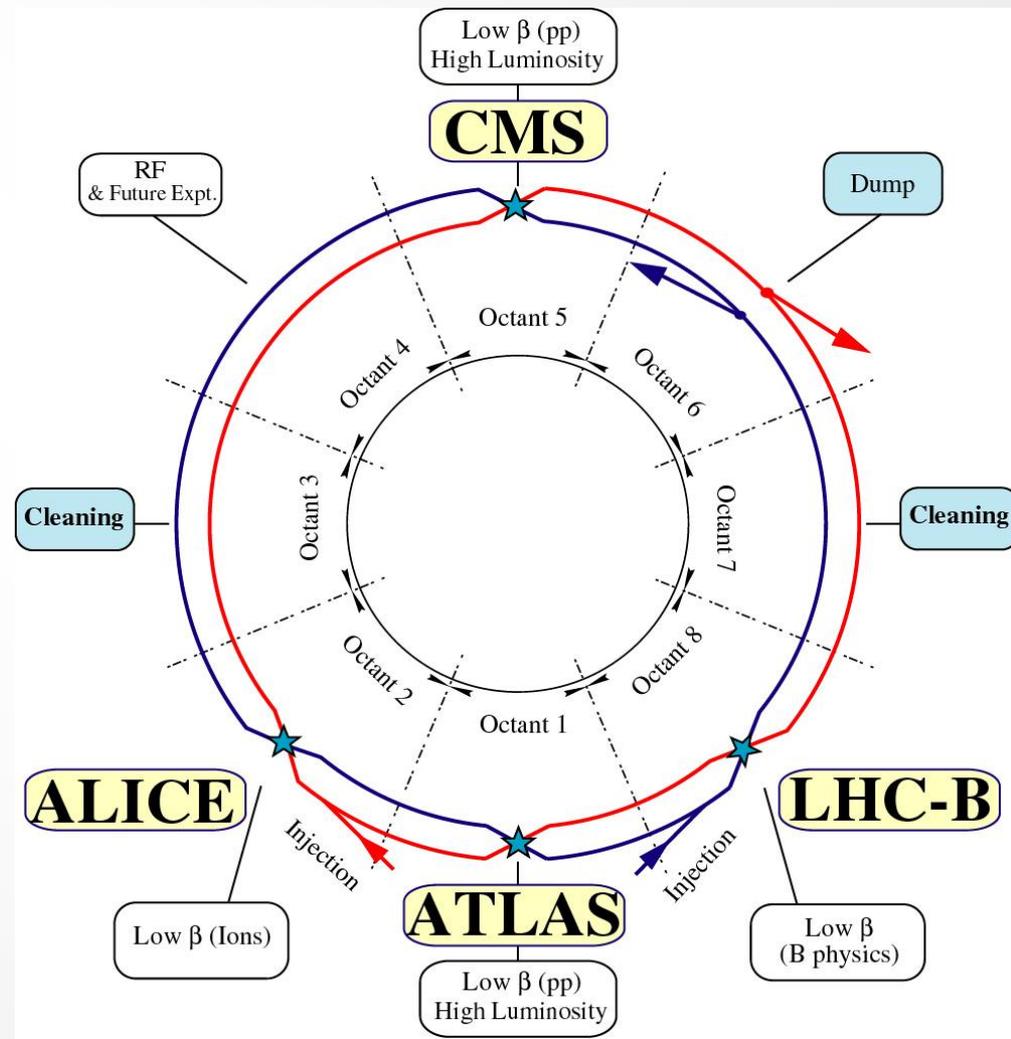
Key features

We want to produce high luminosity at high energy so we can discover the Higgs, supersymmetry and other exciting stuff.

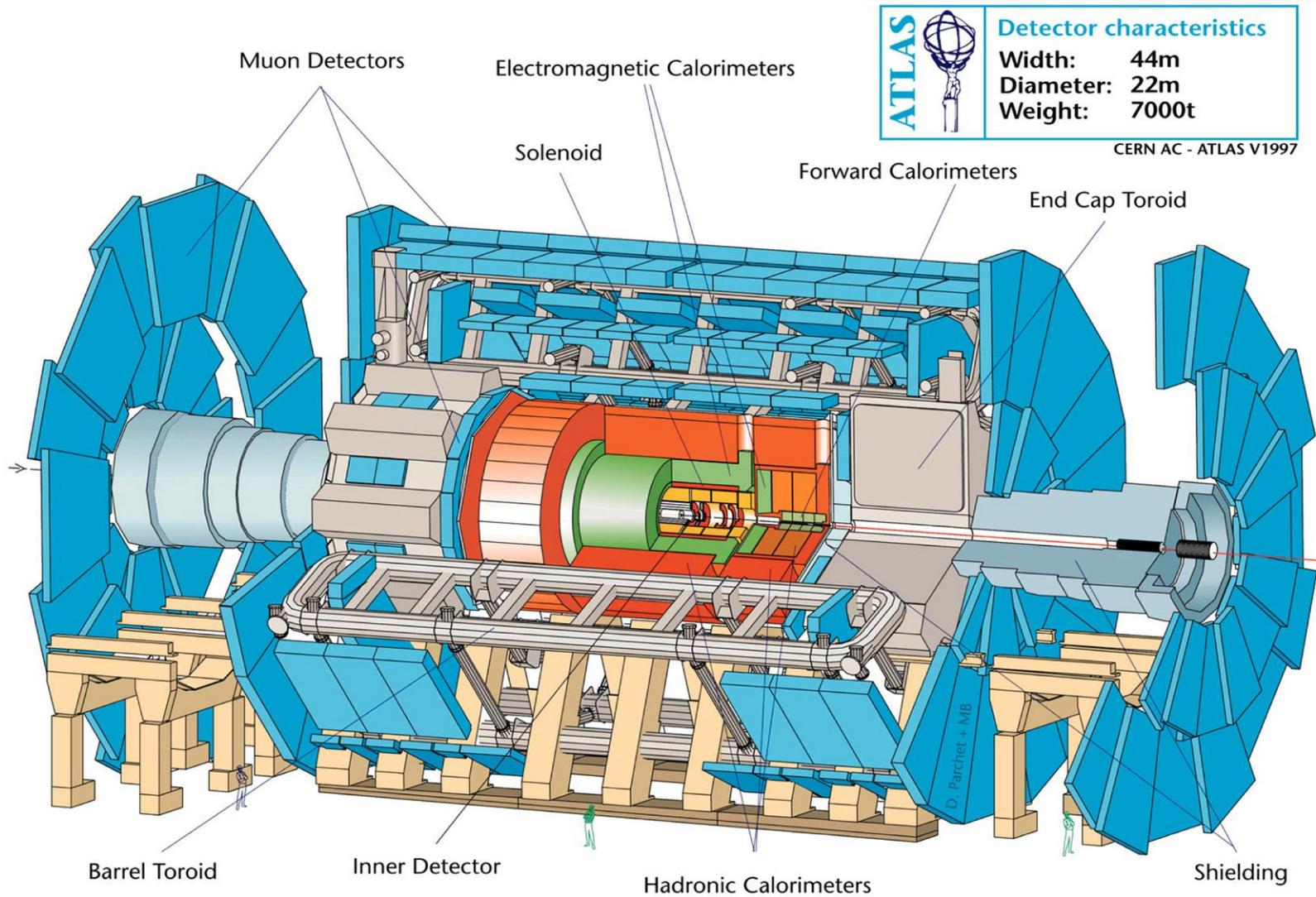
- **Protons and Ions**
- **450 GeV to 7 TeV**
- **High luminosity:**
 - Many bunches: 2808 bunches per beam
 - High beam currents
 - Small beam size at the interaction points
- **Two rings:**
 - Got to keep the beam apart
 - 2 in 1 dipole design
- **LEP tunnel: reuse** → $B \approx 8.4 \text{ T}$
- **High field:** Superconducting magnets for the most part with dipoles and lattice quadrupoles working at 1.9 K – superfluid helium (30 kTons cold mass; 90 Tons of Helium)
- **Two high luminosity experiments**
- **Two more specialised experiments (lons and b physics) – lower luminosity**

Layout - insertions

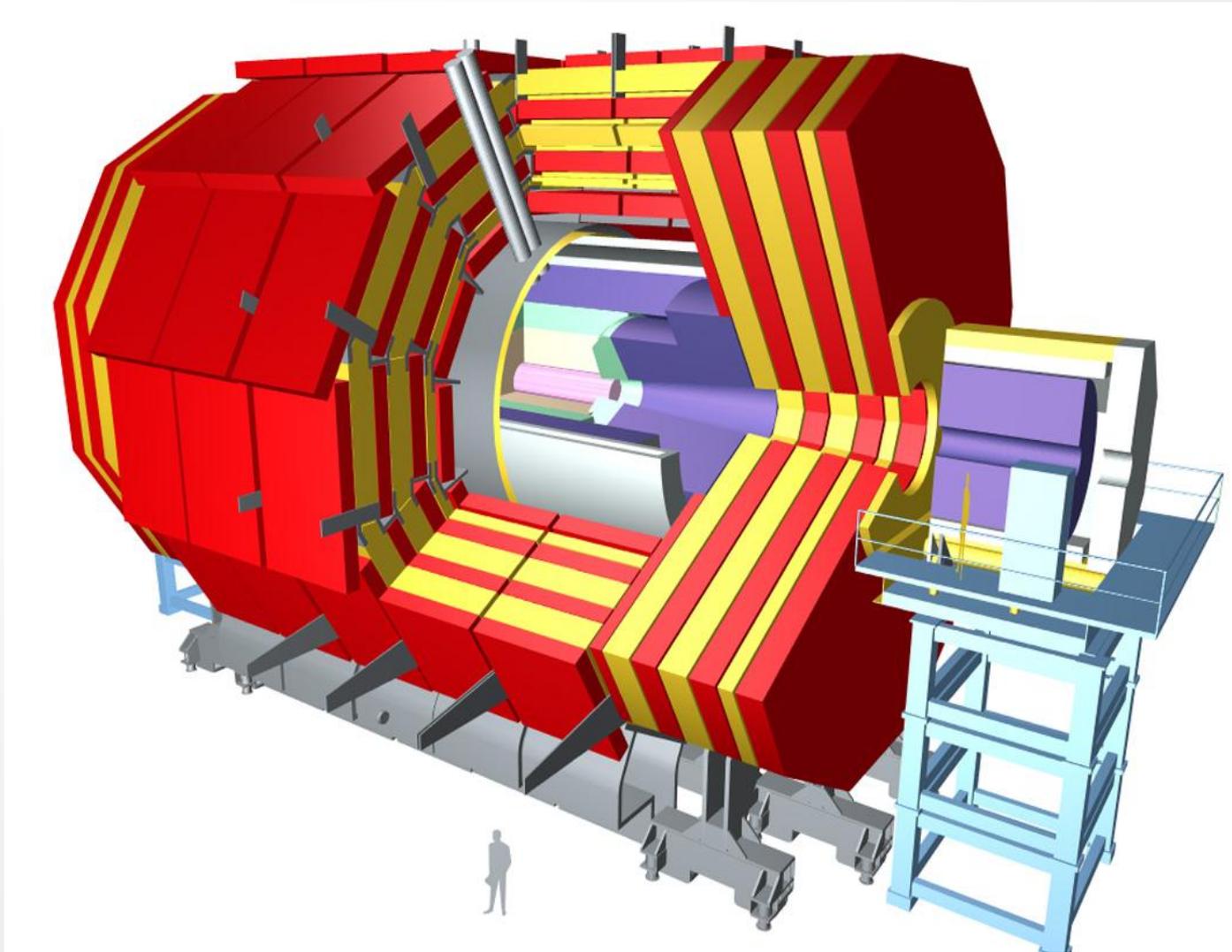
- Point 1
 - **Atlas**, big, high luminosity experiment
- Point 2
 - **Alice**, little less big, heavy ion experiment
 - Injection
- Point 3
 - Momentum cleaning
- Point 4
 - RF
- Point 5
 - **CMS**, another big, high luminosity experiment
- Point 6
 - Beam Dump
- Point 7
 - Betatron cleaning
- Point 8
 - **LHCb**, experiment, B physics
 - injection



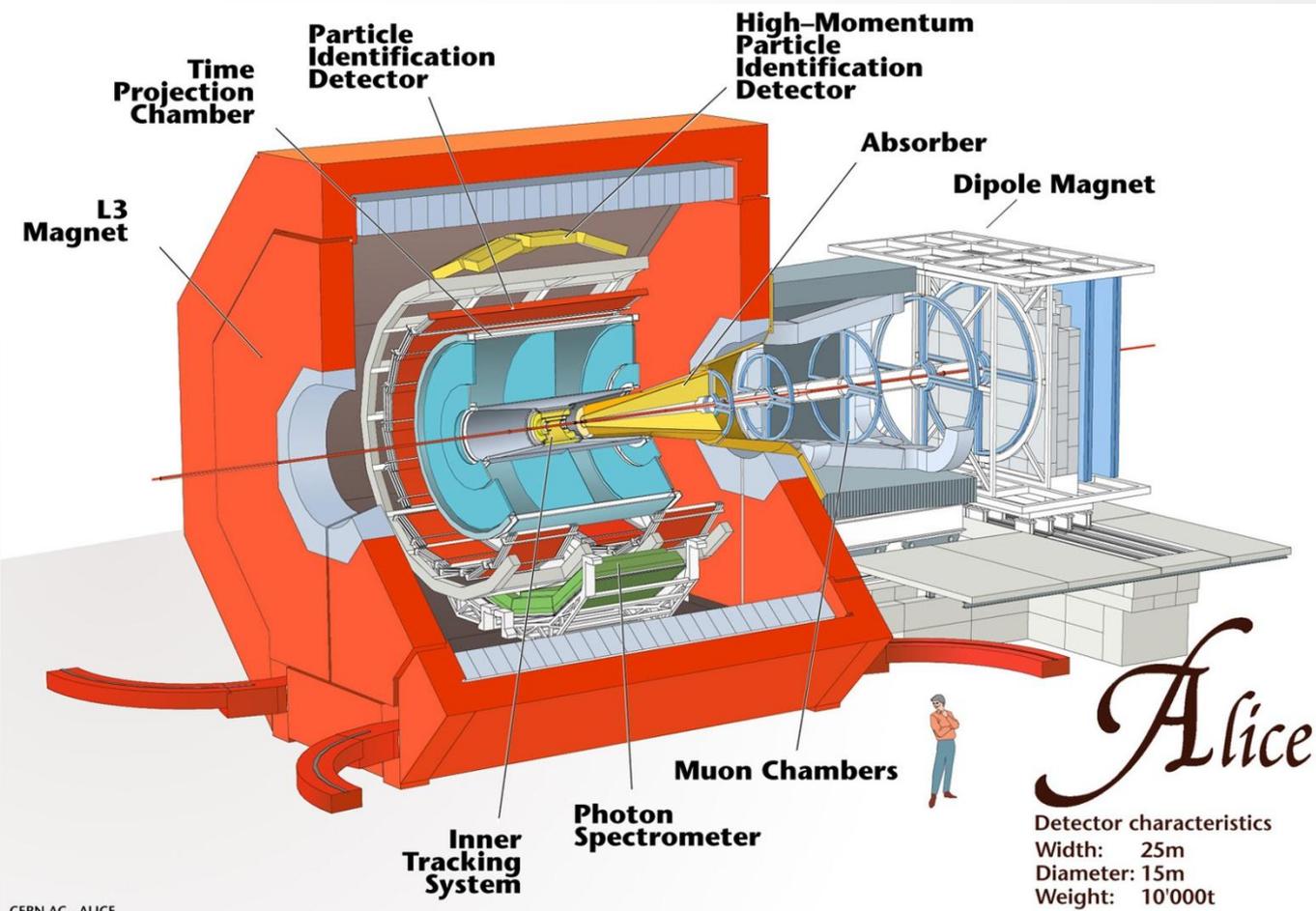
Atlas



CMS

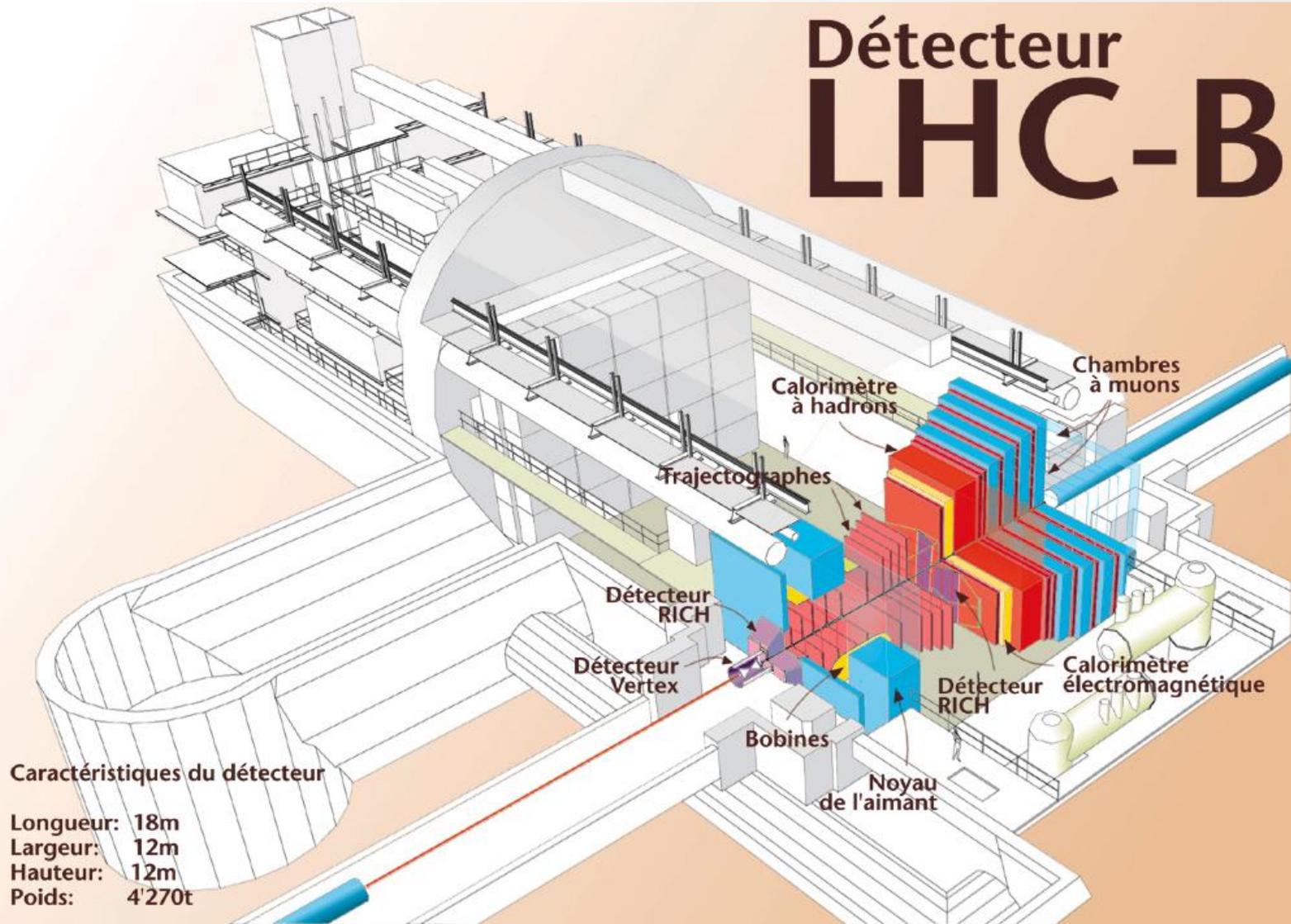


Alice

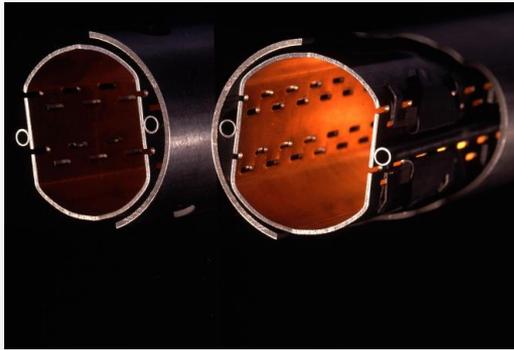


LHCb

Détecteur LHC-B



Actors: before beam



- Cryogenics
- Vacuum
- Quench Protection System
- Magnets
- Magnet protection system
- Interlocks
- Access
- Technical services: cooling, ventilation, electricity, safety
- Radiation protection



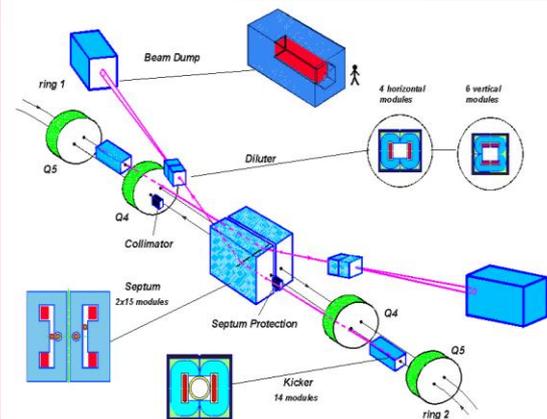
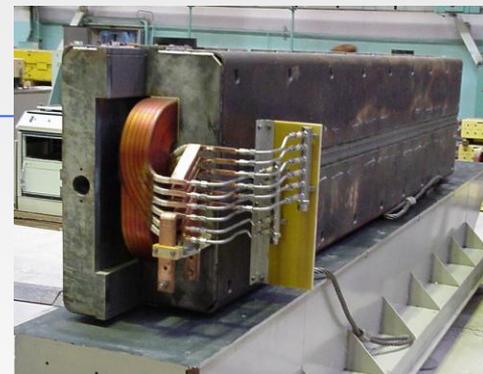
More-or-less going to assume that this lot is working



Actors: with beam



- Power converters
- RF
 - transverse damper
 - 400 MHz (& LFB)
- Collimators
- TDI
- Beam Dump
- Kickers
- Beam Instrumentation
- Multipole Factory
- Interface to cryogenics & vacuum
- Interface to experiments
- Control System



Let's bend the beam

- **Momentum at collision** 7 TeV / c
- **Momentum at injection** 450 GeV / c
- **Machine Circumference** 26658.883 m
- **Revolution frequency** 11.245 kHz
- **Super-periodicity** 1
- **Lattice Type** FODO, 2-in-1
- **Number of lattice cells per arc** 23

- **Number of dipoles** 1232
- **Dipole field at 450 GeV** 0.535 T
- **Dipole field at 7 TeV** 8.33 T
- **Bending radius** 2803.95 m
- **Main Dipole Length** 14.3 m

Concrete Numbers

$$B\rho = \frac{mv}{e} = \frac{p}{e}$$



$$\frac{1}{\rho} = \frac{eB}{p} = \frac{0.2998 \times B[T]}{p[GeV / c]}$$

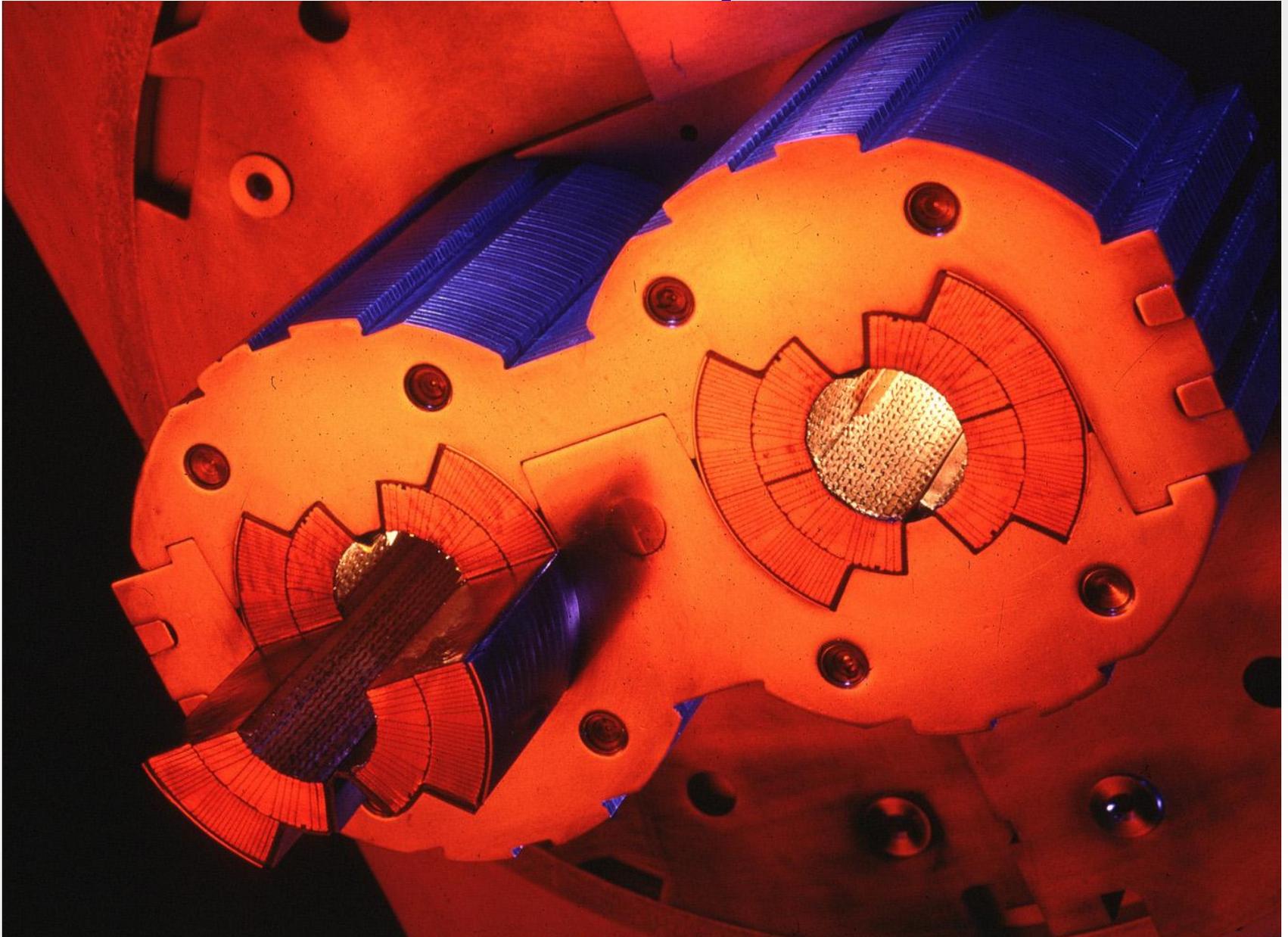
1232 magnets to get us round
in a circle



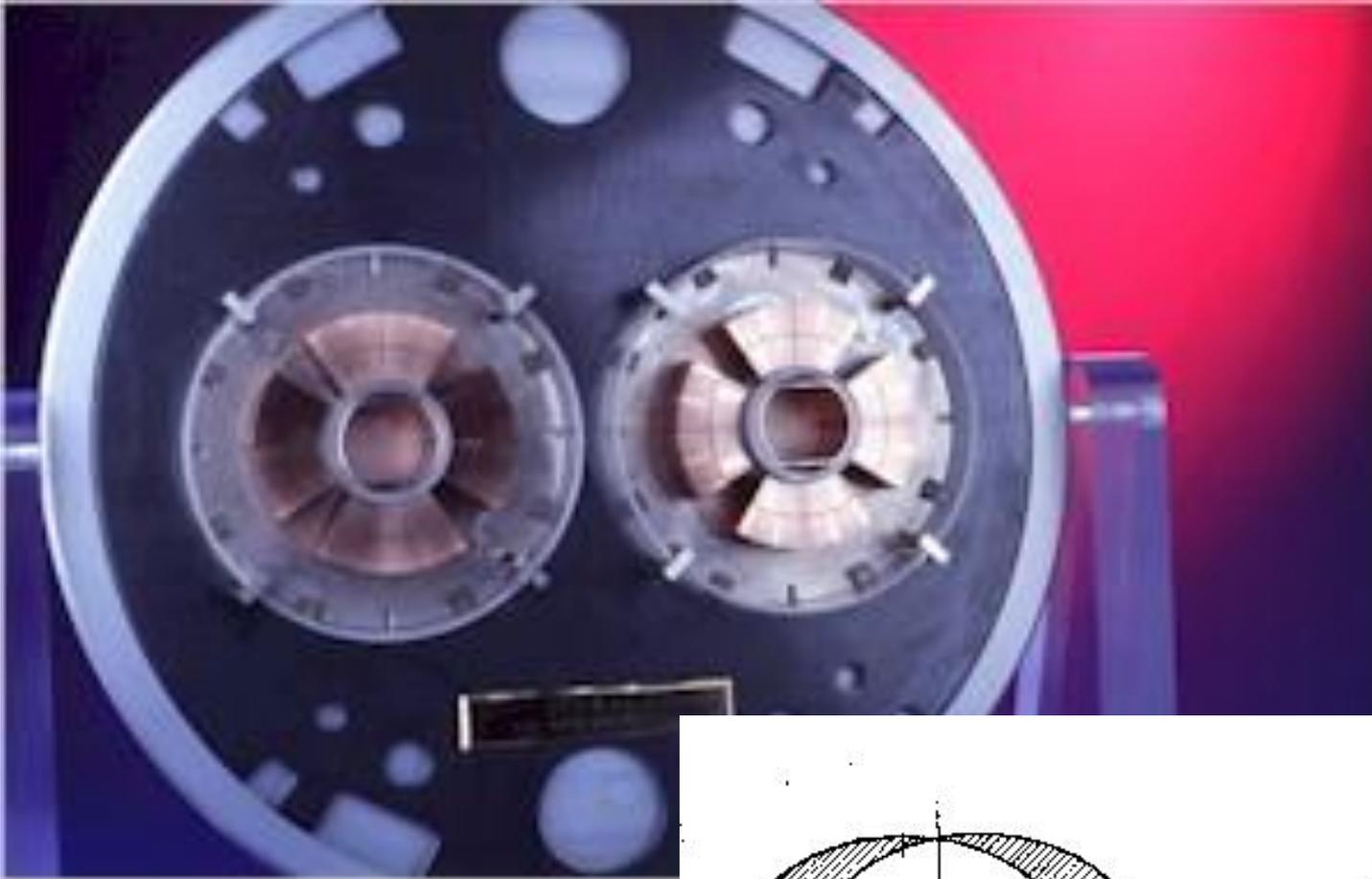
$$\theta = \frac{l}{\rho} = \frac{2\pi}{1232} = 5.1 \times 10^{-3}$$

$$B[T] = \frac{\theta \times p[GeV / c]}{l \times 0.2998} = \frac{5.1 \times 10^{-3} \times 7000}{14.3 \times 0.2998} = 8.33T$$

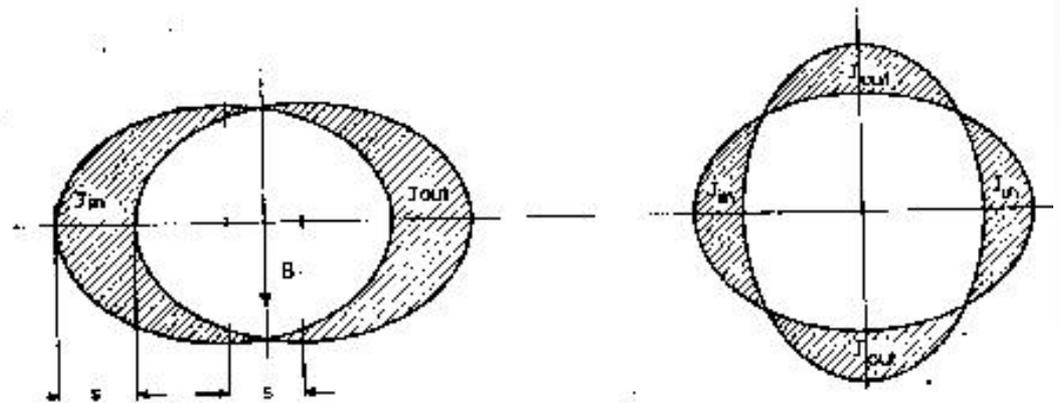
LHC - dipole



LHC - quadrupole

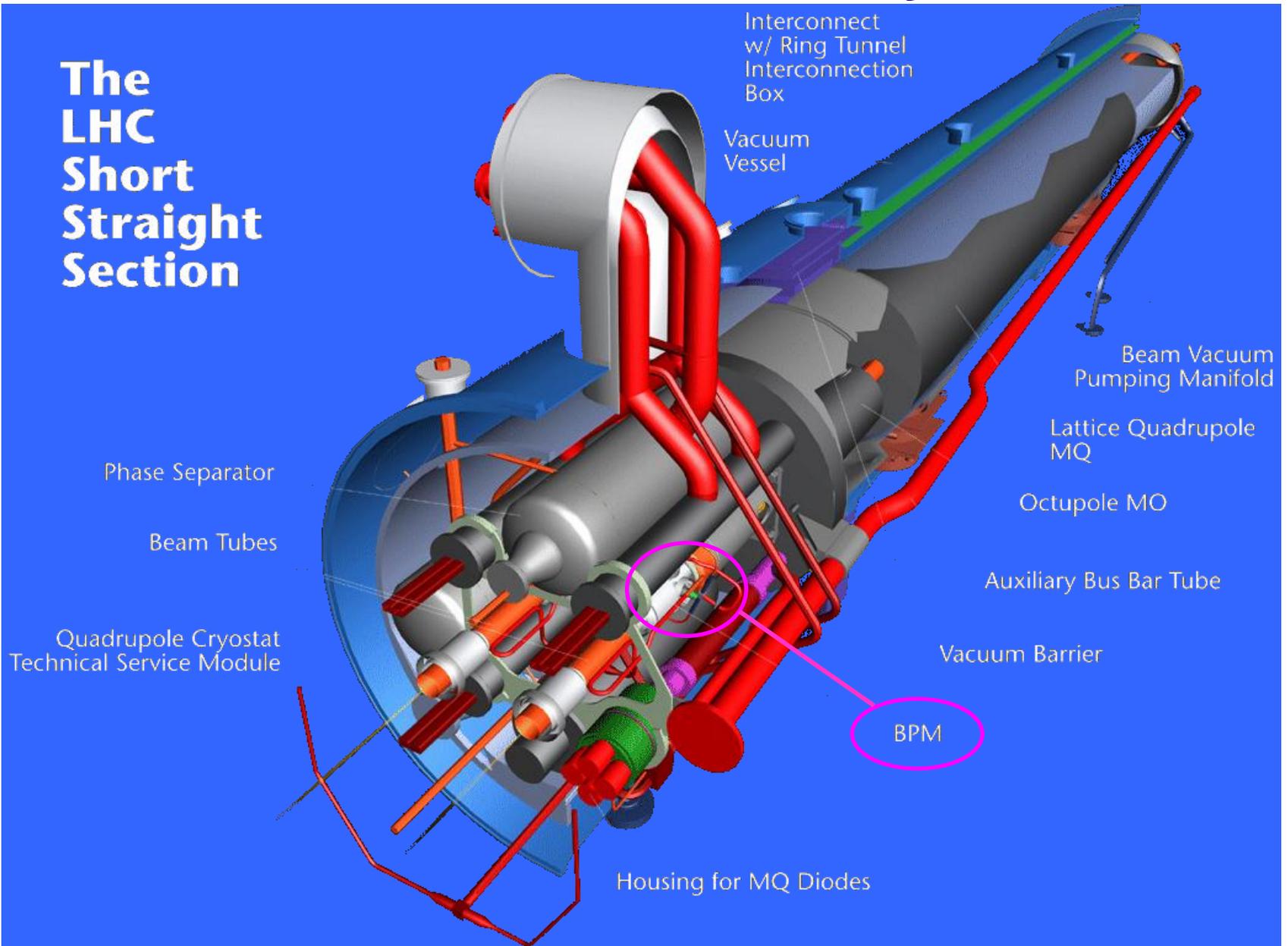


Two intersecting ellipses, rotated by 90° , generate perfect quadrupole fields

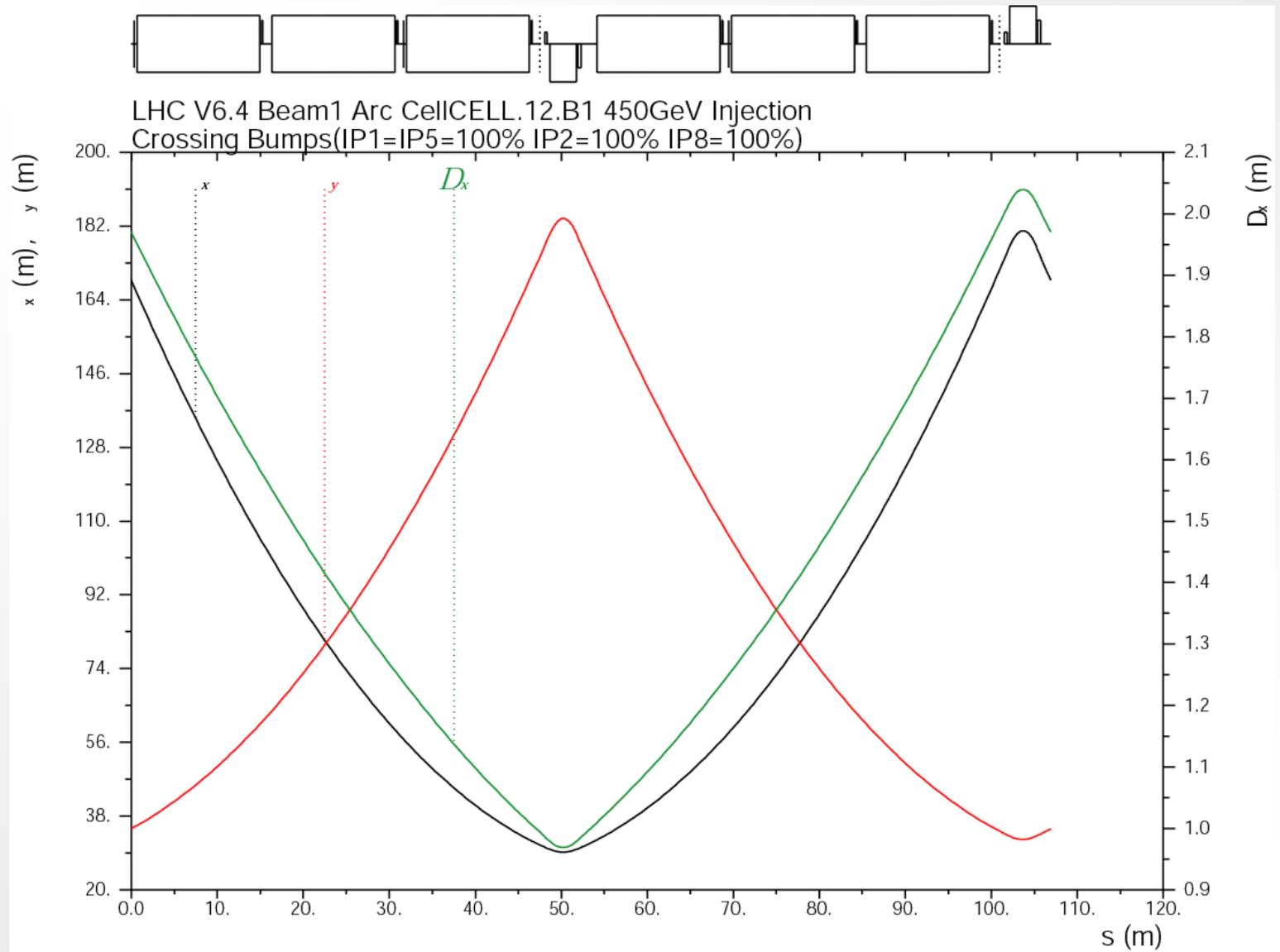


The Arc BPM - SSS Layout

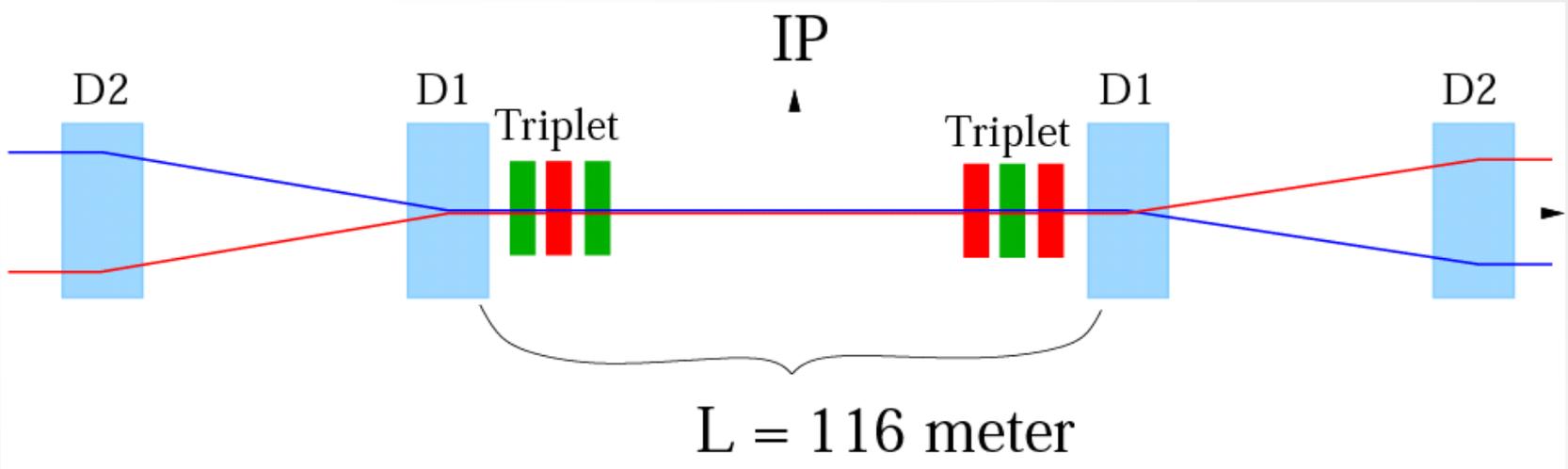
The LHC Short Straight Section



FODO optics



Insertion



$$L = \frac{n_b I_b^2}{4\pi e^2 f_0 \sigma_x \sigma_y}$$

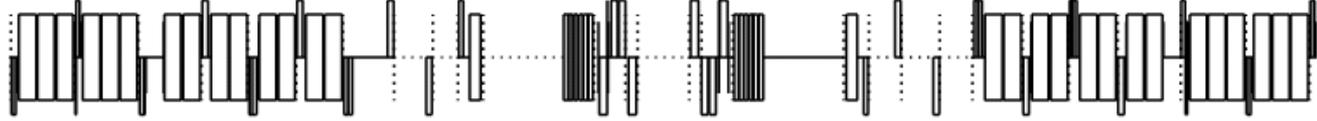
Clearly we have to collide the beams

And then get the beam sizes at the interaction point as small as possible

• $\beta^* = 0.5 \text{ m}$

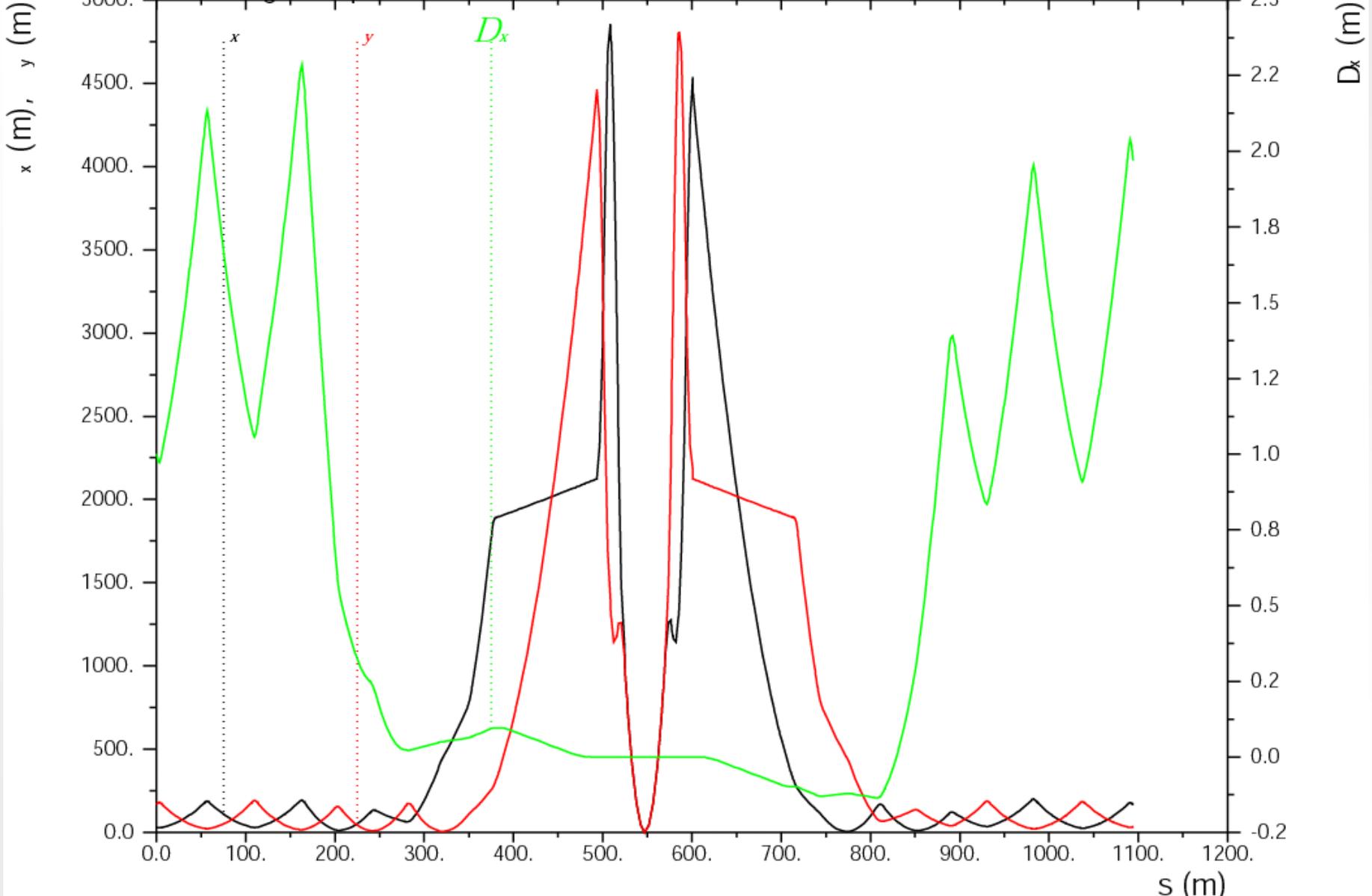
• $\varepsilon = 5 \times 10^{-10} \text{ m} \rightarrow \sigma^* = 16 \text{ } \mu\text{m}$

$$\varepsilon = \frac{\sigma^2}{\beta}$$



LHC V6.4 Beam1 IR1 7000GeV Collision
Crossing Bumps(IP1=IP5=100% IP2=100% IP8=100%)

MAD-X 1.07 05/12/02 11



Lot of energy out there...

Two very cold, very dark, very small holes...

- **High energy, high intensity beam:**

- energy per beam up to 0.35 GJ
- Or 102 kg TNT

**One guy in a
Subaru going
at 1600 mph**

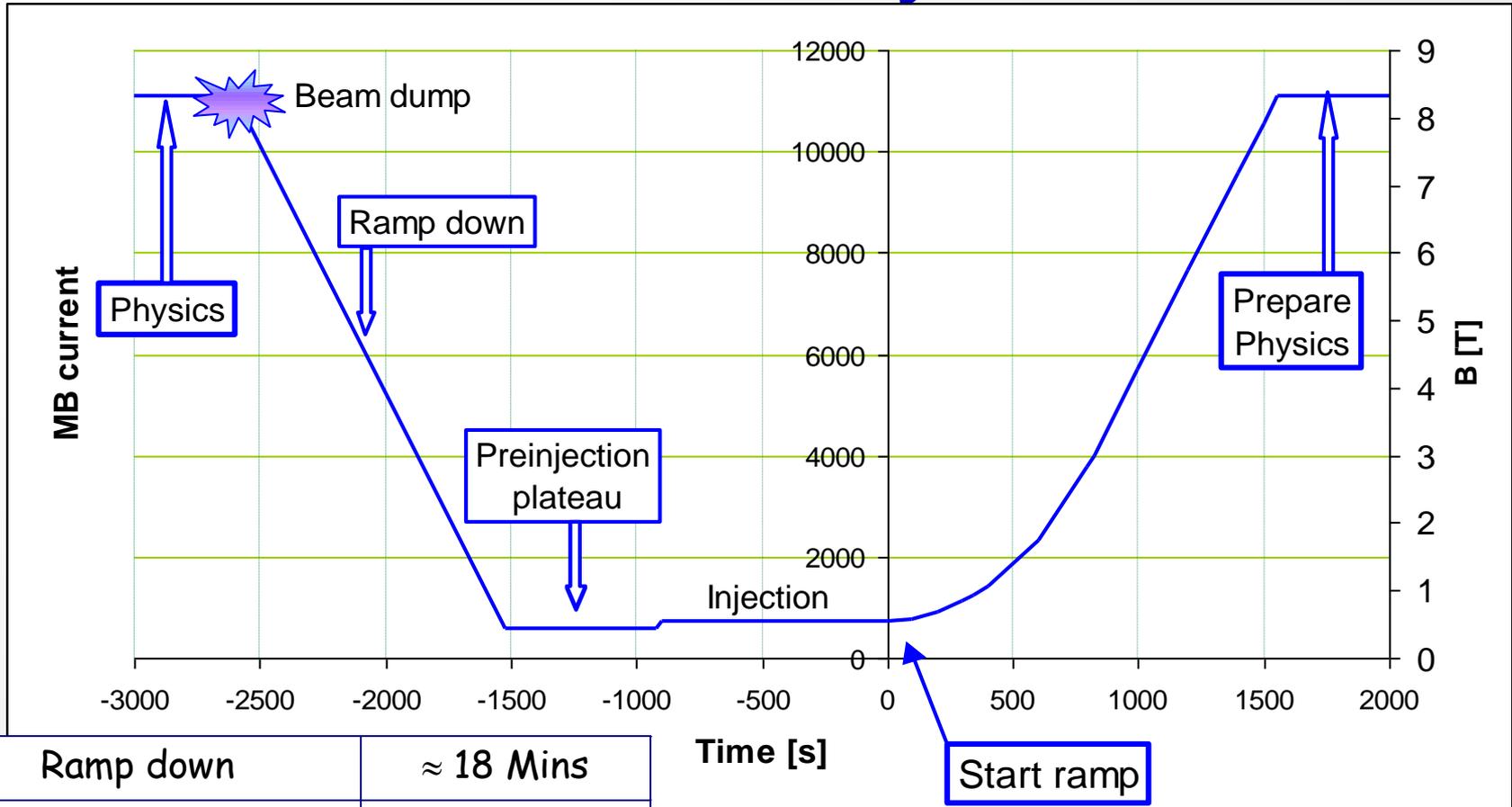
- **Huge amount of energy in the magnets**

- Stored magnetic energy up to 1.29 GJ per sector

**One girl in a
Porsche doing
6700 mph**

- Energy has got to be extracted in case of a quench otherwise we end up with scrap metal.

Baseline cycle

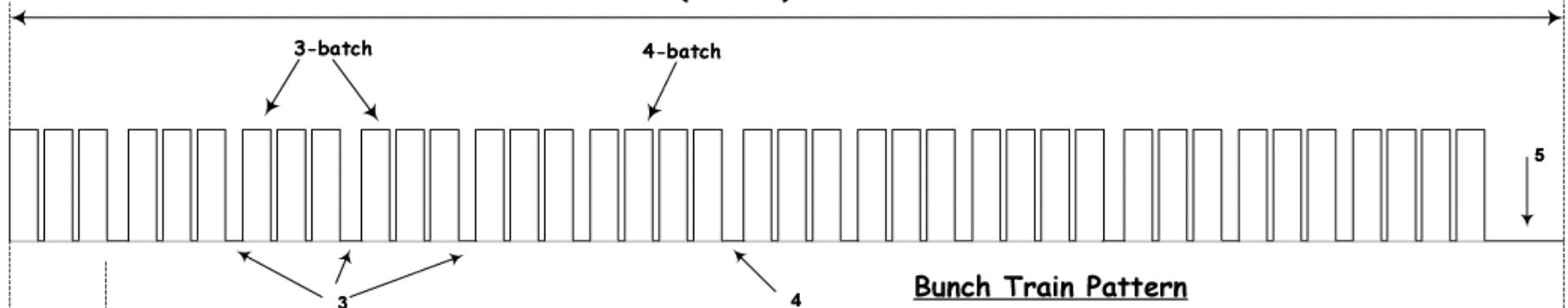


Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

In the normal operations the LHC will perform a standard cycle which will be more-or-less set in stone.

Nominal Proton Bunch Pattern in the LHC for 25ns Spacing

LHC (1-RING) = 88.924 s



SPS = 7/27 LHC

333 334 334 334

Filling Scheme

$$3564 = \{3 \times [(72b + 8e) \times 3 + 30e]\} + 1e$$

$$+ \{2 \times [(72b + 8e) \times 3 + 30e] + [(72b + 8e) \times 4 + 31e]\} \times 3$$

$$+ 80e$$

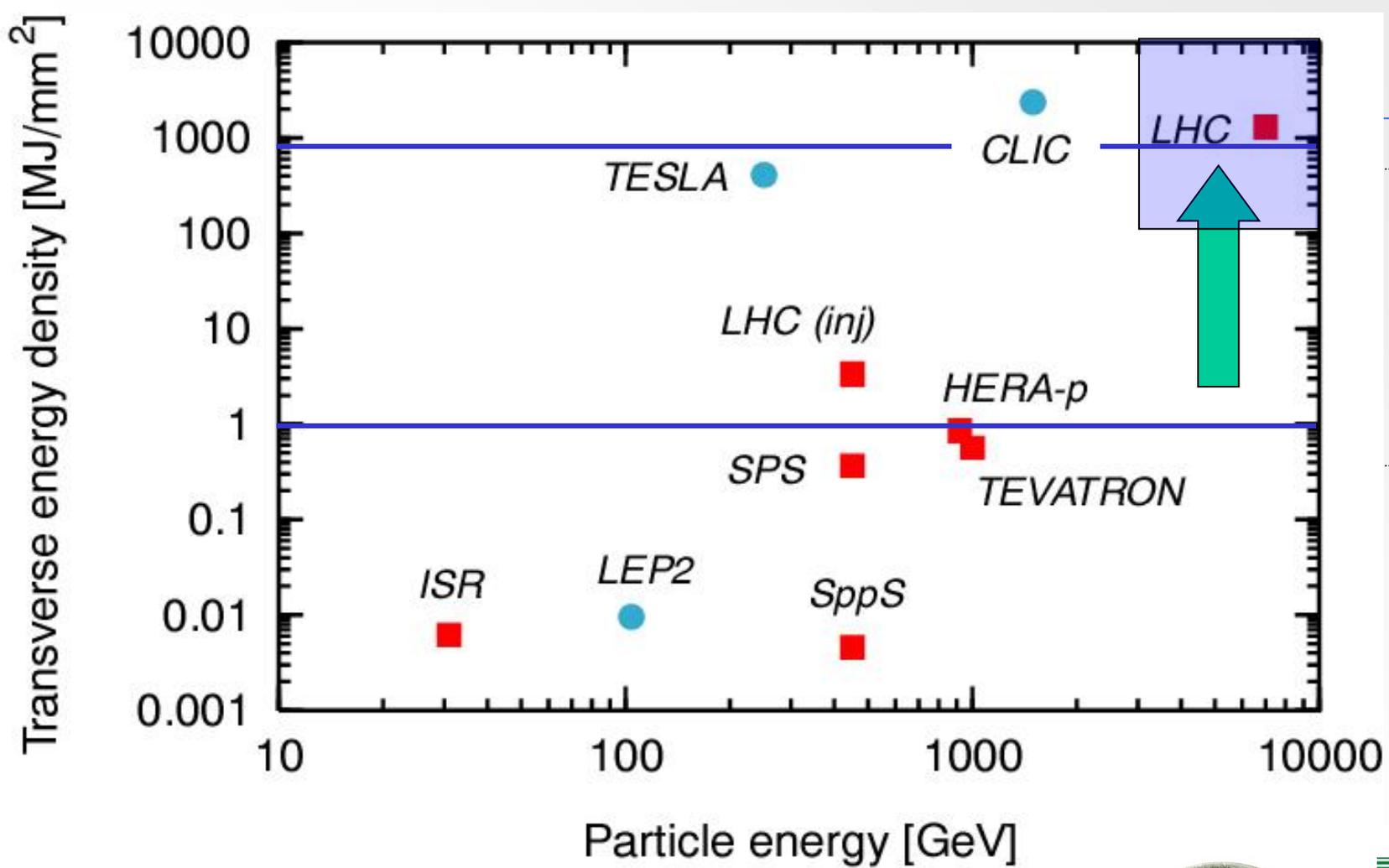
Beam Gaps

- 1 = 12 bunch gap in the PS (72 bunches on h=84)
- 2 = 8 missing bunches (SPS Injection Kicker Rise time = 225ns).
- 3 = 38 missing bunches (LHC Injection Kicker Rise Time = 0.975 s).
- 4 = 39 missing bunches (" " " " 1.0 s).
- 5 = 119 missing bunches (LHC Beam Dump Kicker Rise Time = 3 s).



PS = 1/11 SPS

72-Bunches at
25ns Spacing



At less than 1% of nominal intensity LHC enters new territory.

There is no easy start-up for collimation!



10 mm

The LHC Challenge for Collimation

- **High stored beam energy**
 - (melt 500 kg Cu, required for $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity)
- **Small spot sizes at high energy**
 - (small 7 TeV emittance, no large beta in restricted space)
- **Large transverse energy density**
 - (beam is destructive, 3 orders beyond Tevatron/HERA)
- **High required cleaning efficiency**
 - (clean lost protons to avoid SC magnet quenches)
- **Collimation close to beam**
 - (available mechanical aperture is at $\sim 10 \sigma$)
- **Small collimator gap**
 - (impedance problem, tight tolerances: $\sim 10 \mu\text{m}$)
- **Activation of collimation insertions**
 - (good reliability required, very restricted access)
- **Big system**

$\sim 350 \text{ MJ/beam}$

$200 \mu\text{m}$ (at coll.)

1 GJ/mm^2

99.998% ($\sim 10^{-5}$)

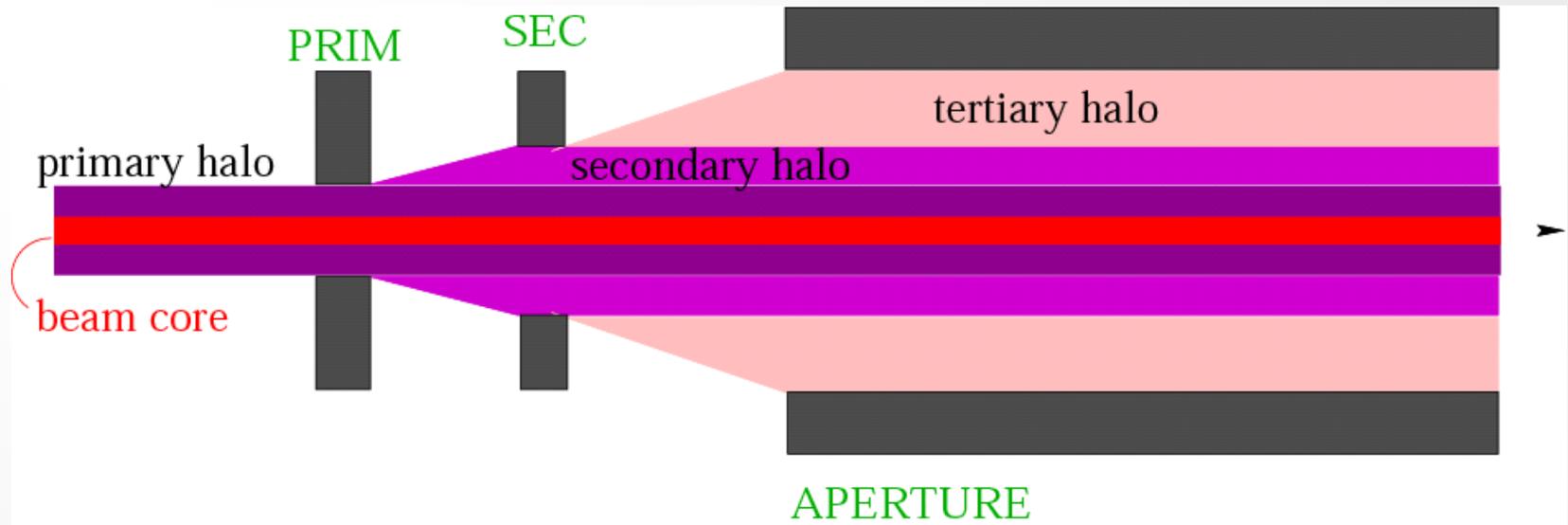
$6-7 \sigma$

$\sim 3 \text{ mm}$ (at 7 TeV)

$\sim 1-15 \text{ mSv/h}$

60 coll / 2 insertions

Basic Collimation



- **Beam core $\approx 2\sigma$**
- **Primary beam halo $\approx 2\sigma$ to 6σ**
 - generated by non-linearities (beam-beam...)
 - noise
- **Secondary beam halo $\approx 6\sigma$ to 8σ**
 - generated by primary collimator
- **Tertiary beam halo: $> 8\sigma$**
 - generated by secondary halo \rightarrow harmless losses

Collimators

Two warm LHC insertions dedicated to cleaning:

IR3 Momentum cleaning
 1 primary
 6 secondary

IR7 Betatron cleaning
 4 primary
 16 secondary

Two-stage collimation system

Strategy:

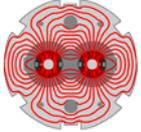
Primary collimators are closest.

Secondary collimators are next.

Absorbers for protection just outside secondary halo before cold aperture.

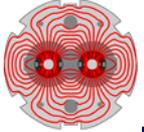
Relies on good knowledge and control of orbit around the ring!

54 movable collimators for high efficiency cleaning, two jaws each + *other absorbers for high amplitude protection*

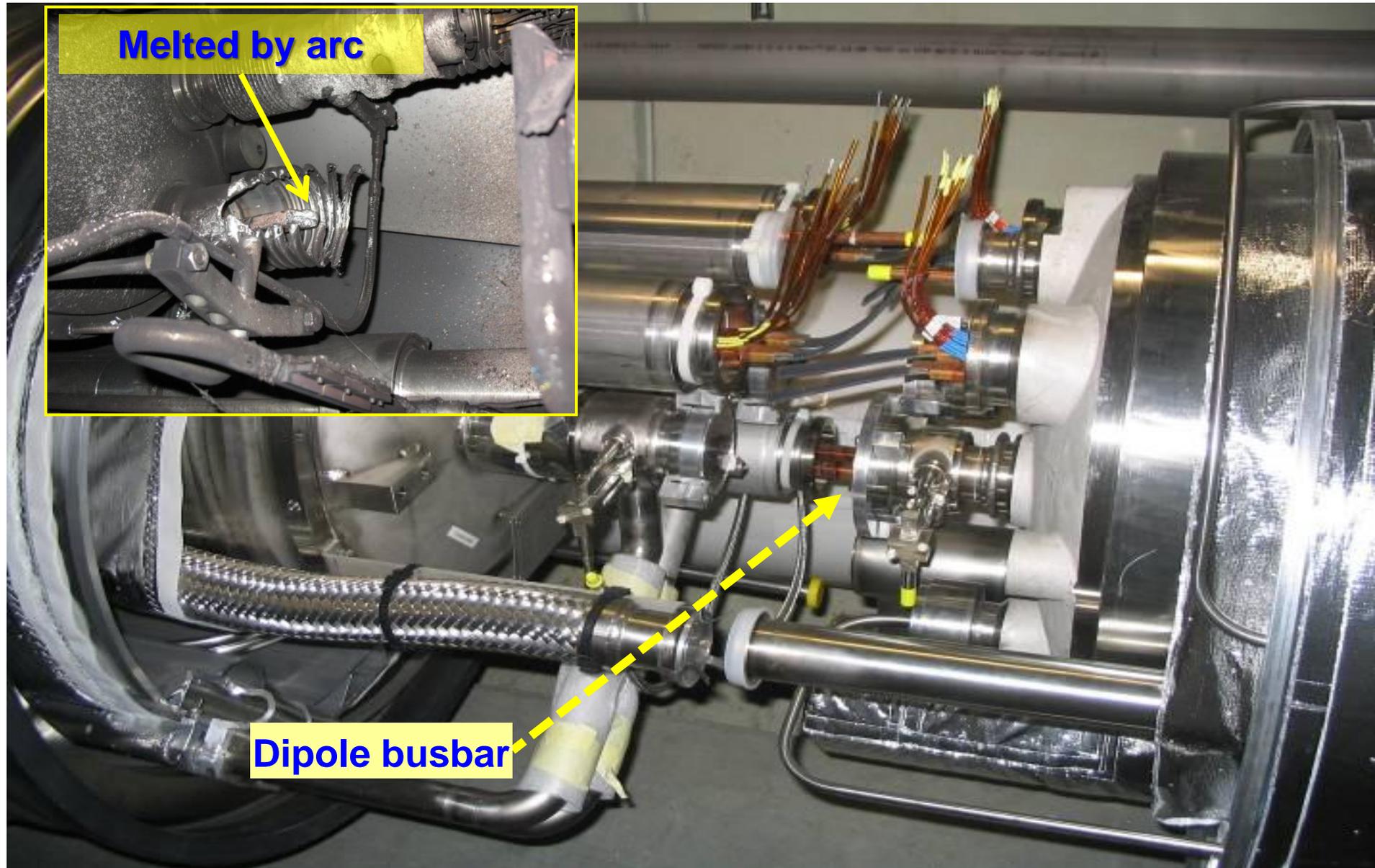


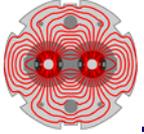
Recent timeline

- 2008
 - Accelerator complete
 - Ring cold and under vacuum
- September 10th 2008
 - First beams around – made it to Google
- September 19th 2008
 - The incident
- 2008 – 2009
 - 14 months of major repairs and consolidation
 - New **Quench Protection System** for online monitoring and protection of all joints.
 - However...



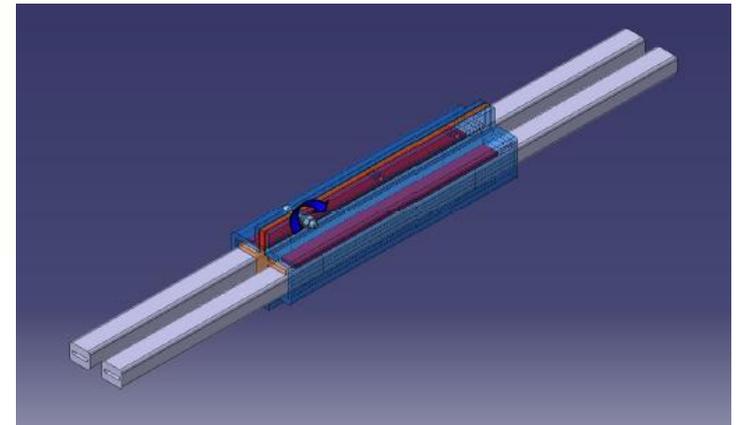
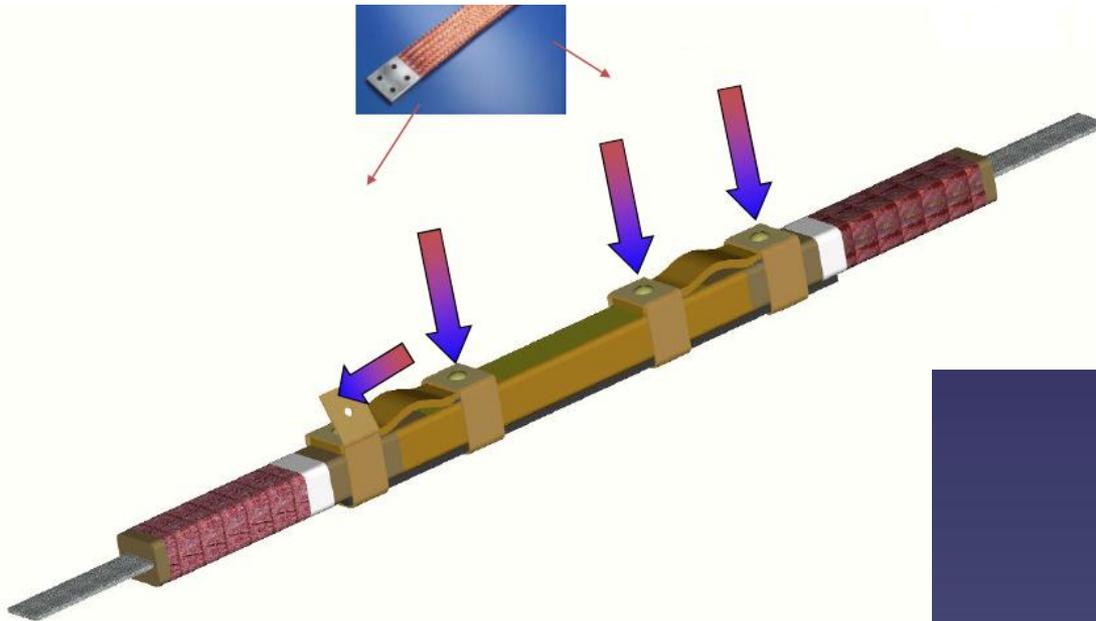
Magnet Interconnection



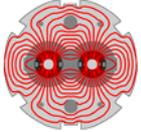


To go to 7 TeV per beam

Splice consolidation is required
- options under examination



Everywhere

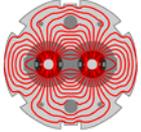


To conclude on this issue

- Splice issues not fully resolved
- To be 100% sure that we can go safely to 7 TeV per beam - eradication of joint issue requires a complete warm-up and long shutdown (2013).
- The **LHC beam energy will be limited to 3.5 TeV** in 2010/2011/2012

In the meantime

- New Quench Protection System fully deployed and tested
- All magnet circuits qualified for 3.5 TeV
 - Main bends and quads to 6000 A and looking good so far

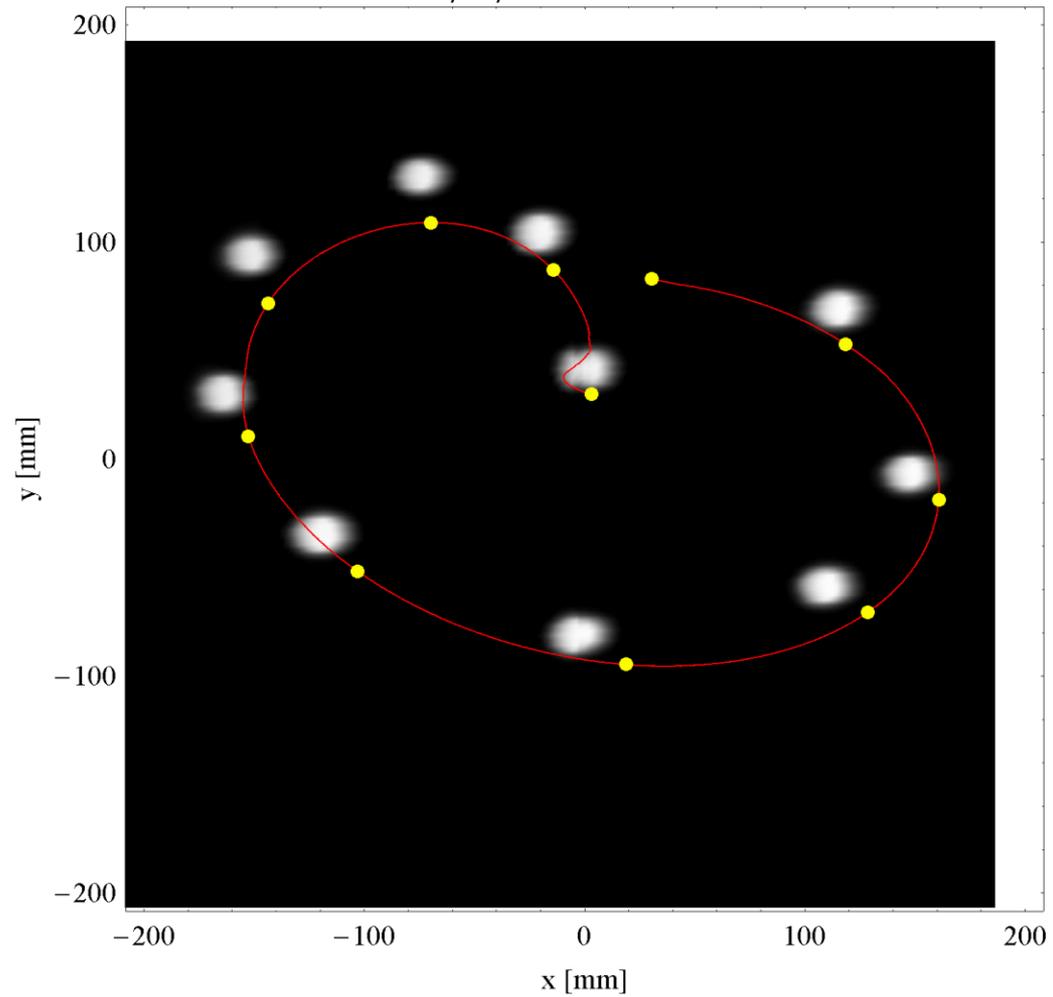


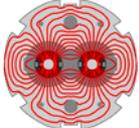
Beam dump

Beam dumping systems working very well
Systematic and very thorough testing and set-up in progress

Kickers sweep
bunches to “dilute”
intensity on dump

TD68.BTVDD.689339.B1
2010/03/24 03:23:34.600000





Beam Instrumentation

The enabler – excellent

■ Beam Position Monitors

- Excellent performance
- Very stable orbit (V drift ~ 15 μ m/h)

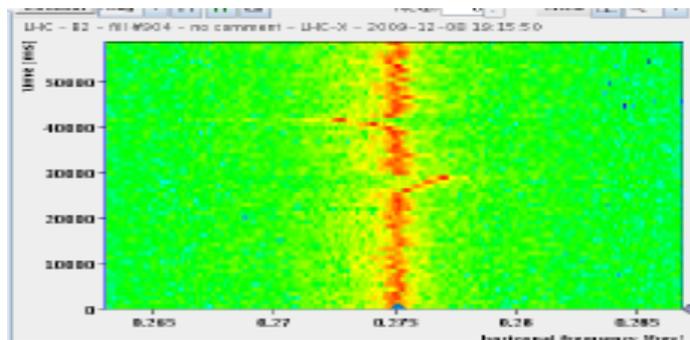
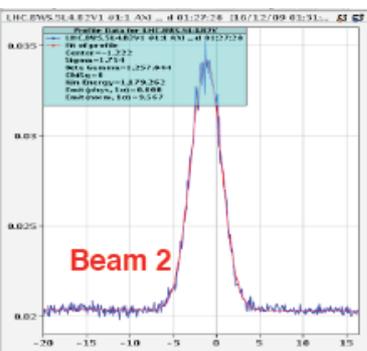
■ Beam Loss Monitors

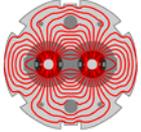
- BLMs correctly removes the BEAM PERMIT signal if measurements are over threshold. Almost no reliability issues observed.

■ Profile monitors

- Synchrotron light, wire-scanners operational

Base-Band-Tune (BBQ) system was a work horse from day one giving tune, chromaticity, coupling, feedback.



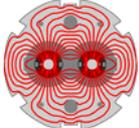


Machine Protection System

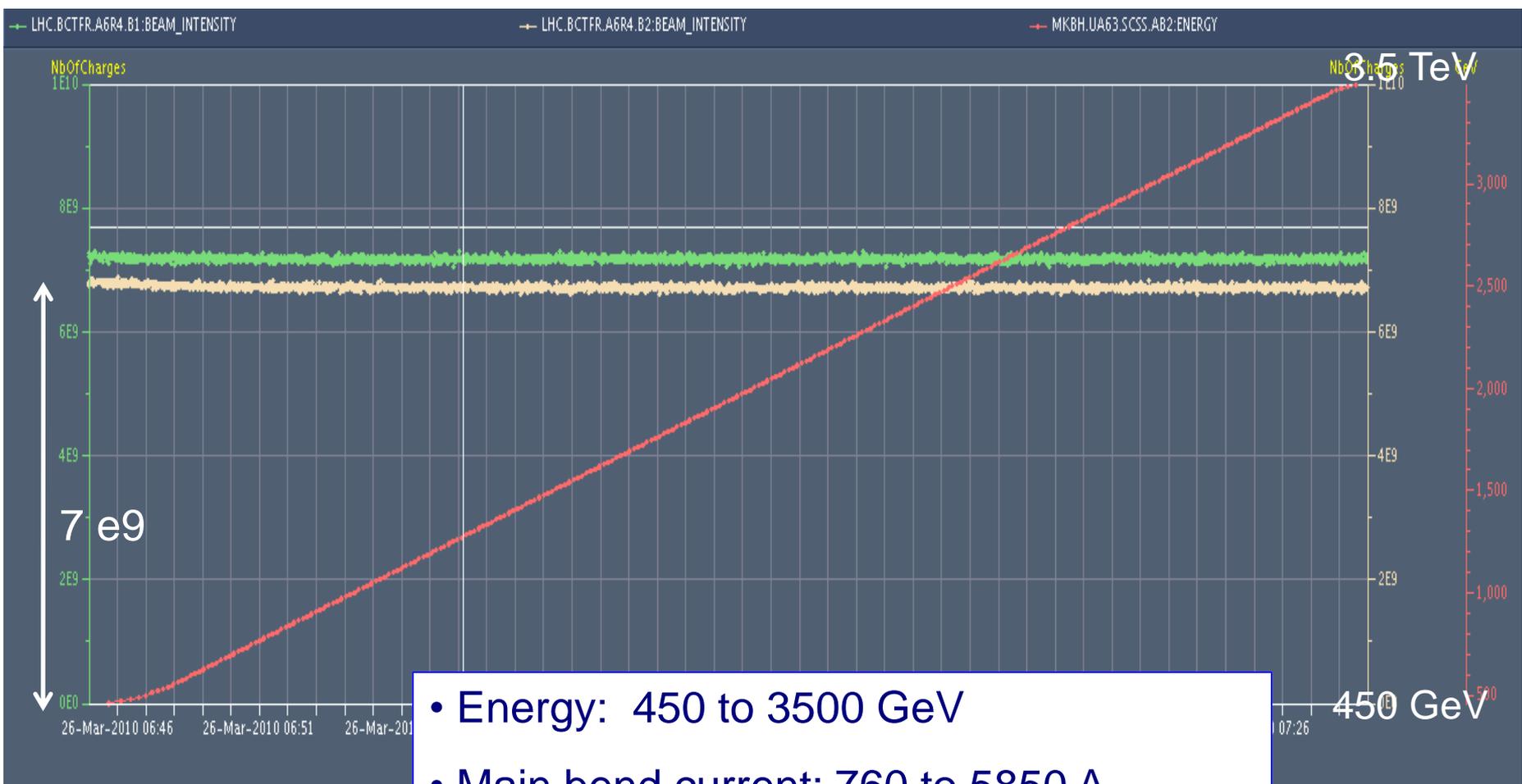
Provides the mechanism to dump the beam in around 3 turns if anything out there decides it's had enough

- Mission critical backbone
 - Beam Interlock System
 - Safe Machine Parameters
 - Plus inputs to/from other systems (e.g. timing, BCT)
- Multitude of 'user' inputs
- In additions the beam drives a subtle interplay of:
 - Beam dump system, Collimation, protection devices, RF...
 - Instrumentation (BLMs, BCT, BPMs...)
 - Aperture
 - Optics

Absolutely, absolutely critical

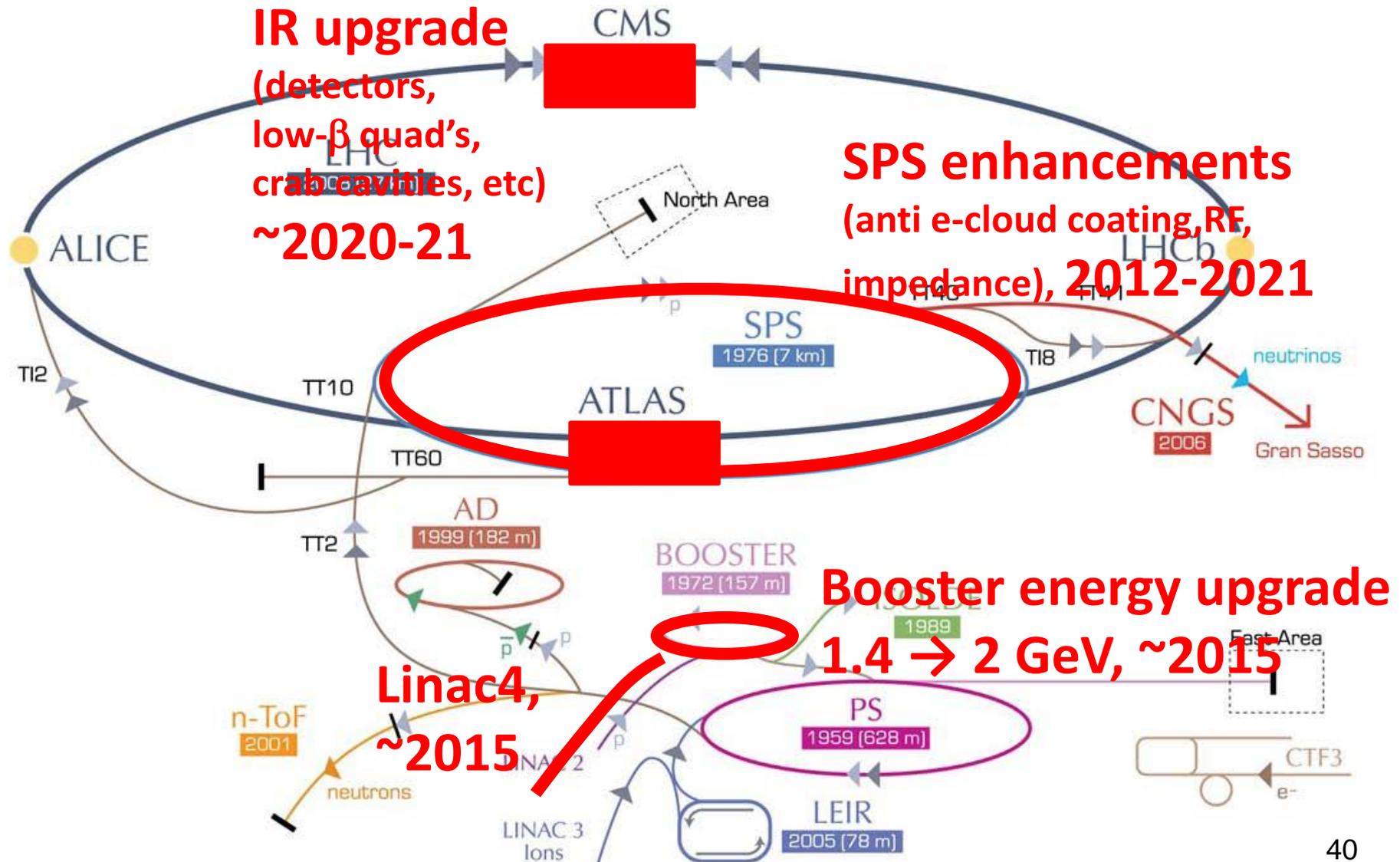


Ramp

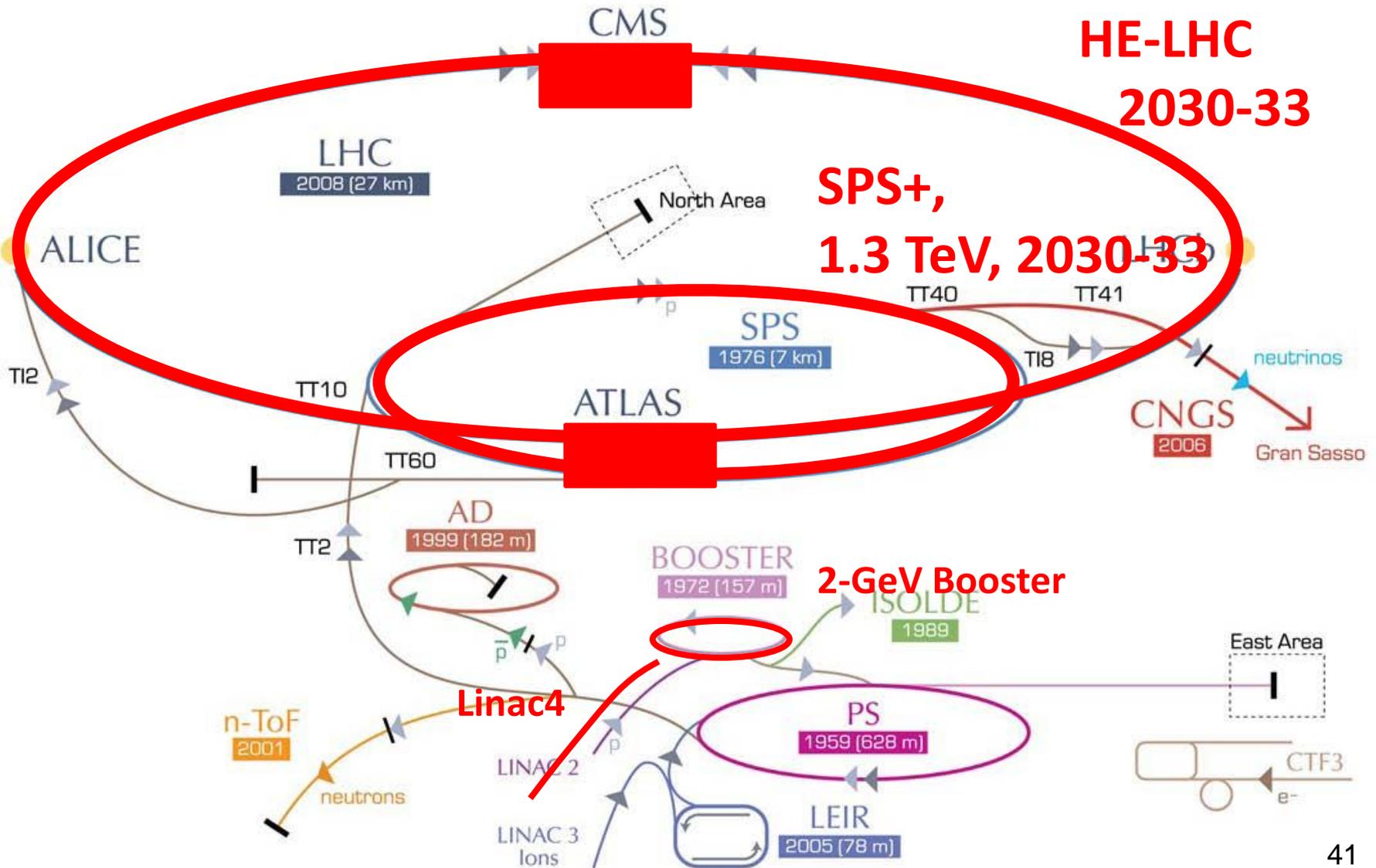


- Energy: 450 to 3500 GeV
- Main bend current: 760 to 5850 A
- Ramp rate: 2 A/s
- Length: 47 minutes

HL-LHC – LHC modifications



HE-LHC – LHC modifications



LHC upgrade issues and R&D

Issues	High Luminosity LHC	High energy LHC
Super-Cond. quadrupoles	15 T for low beta @IR	for IR and Ring
Super-Conducting dipoles		20 T (Nb3Sbn, HTS)
Fast cycling SC magnets		For 1.3 TeV injector
Mini beta operation	Chromatic correction and large aperture of matching section	Cryogenic handling of SR heat load
Crab cavities	Novel compact design compatible with machine protection	
Machine protection (500 MJ beam power)	Collimation with high effic, & reliability, low impedance	Cryogenic handling of SR heat load
Luminosity leveling	Control q_c , V_{crab} or b^*	Control emittances
Dynamic vacuum		Synchrotron radiation

High Field Super-Conducting magnet R&D

LHC upgrades

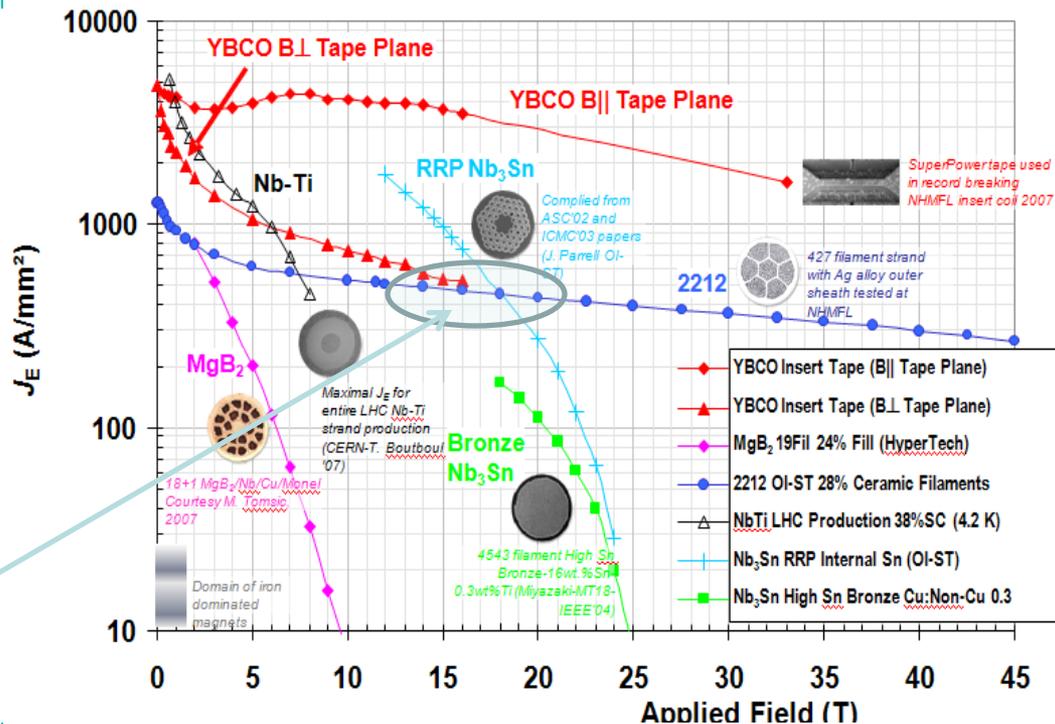
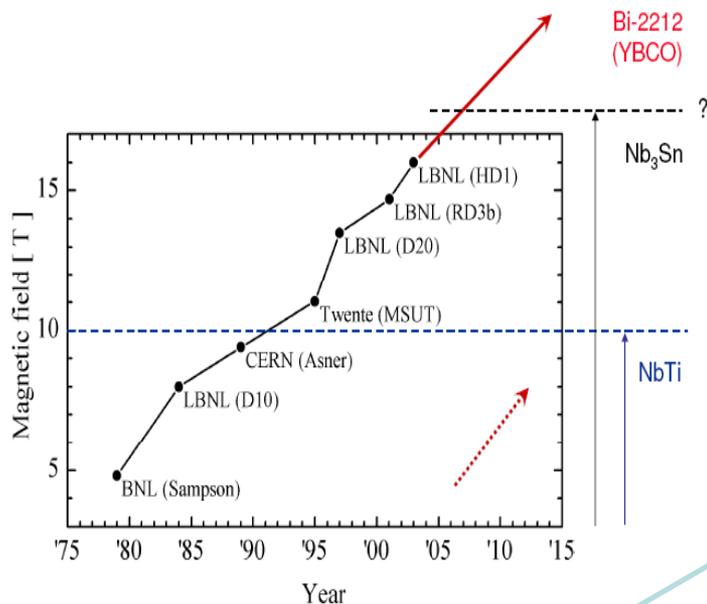
HL-LHC: $L = 5 \cdot 10^{34}$

Low β quads (15T)

HE-LHC: $E_{cm} = 33 \text{ TeV}$

Dipoles (20T)

High Field Dipoles



15 to 24 T Possible Super-conductors: Nb_3Sn existing up to 17-18 T
High Temperature SC : Bi-2212 (existing) or YBCO (small tapes only)

Promising but lots of R&D