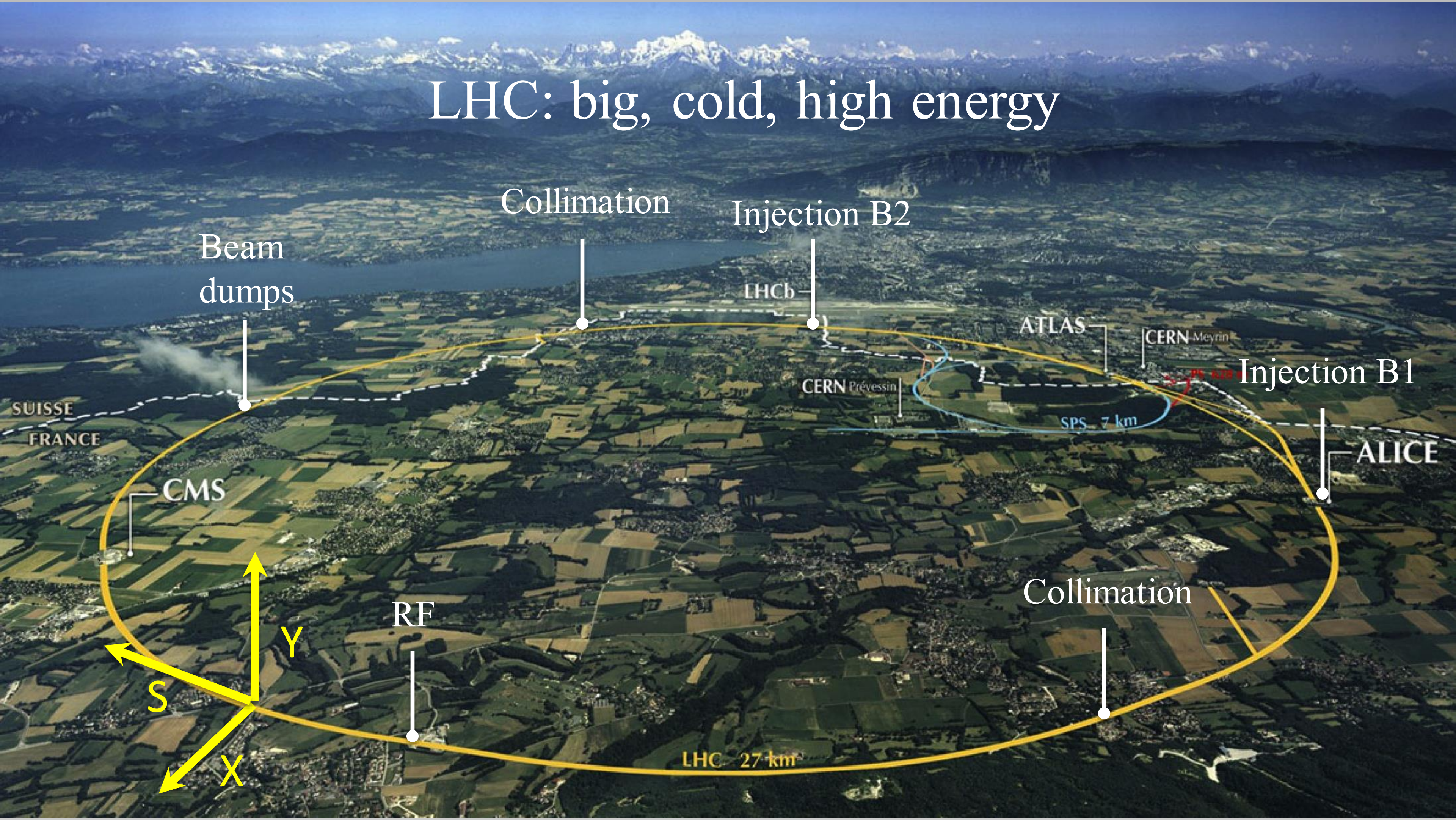
The LHC machine - present and future

- Overview of the current machine, performance and limitations
- Upgrades towards ultimate luminosity
- Possibilities and challenges for higher energy

Mike Lamont
with acknowledgements to the people whose material I've used

LHC: big, cold, high energy

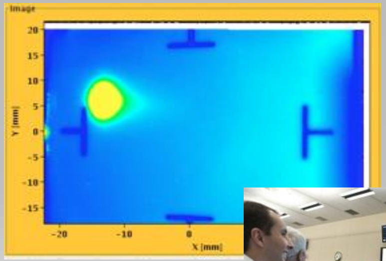


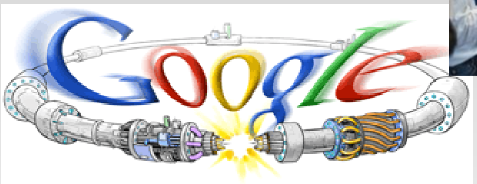
1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
~4000 Beam loss monitors

150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
450 MJ magnetic energy per sector at 4 TeV

LHC Timeline

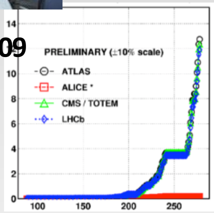
August 2008
First injection test





September 10, 2008
First beams around

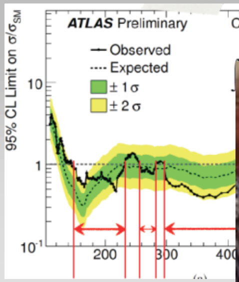
November 29, 2009
Beam back



October 14 2010
1e32
248 bunches

June 28 2011
1380 bunches

1380



Augus
2.3e33,
1380 b

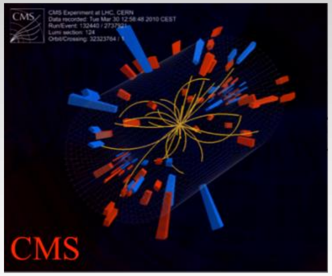
6 June, 2012
6.8e33

4 July, 2012

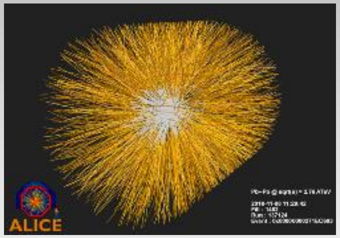
2008 | 2009 | 2010 | 2011 | 2012

September 19, 2008
Disaster
Accidental release of 600 MJ stored in one sector of LHC dipole magnets

March 30, 2010
First collisions at 3.5 TeV



November 2010
Ions

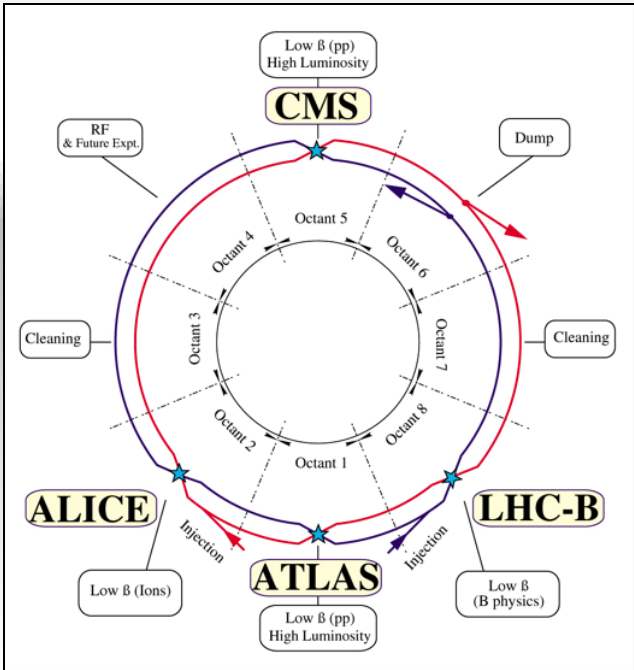


18 June, 2012
6.6 fb^{-1}
to ATLAS & CMS

- High energy
- High bunch intensity
- Many bunches
- Small beam size

LHC – PRINCIPLES & REALITY

- LEP tunnel defines the bending radius
- Superconducting magnet technology
- 1.9 K cryogenics
- Bending radius & achievable field strength -> 7 TeV/c
- Two beam pipes - 2 in 1 magnet design
- Separated function - strong focusing
- Luminosity insertions



Superconductivity

- To produce the high magnetic fields we need very high currents…

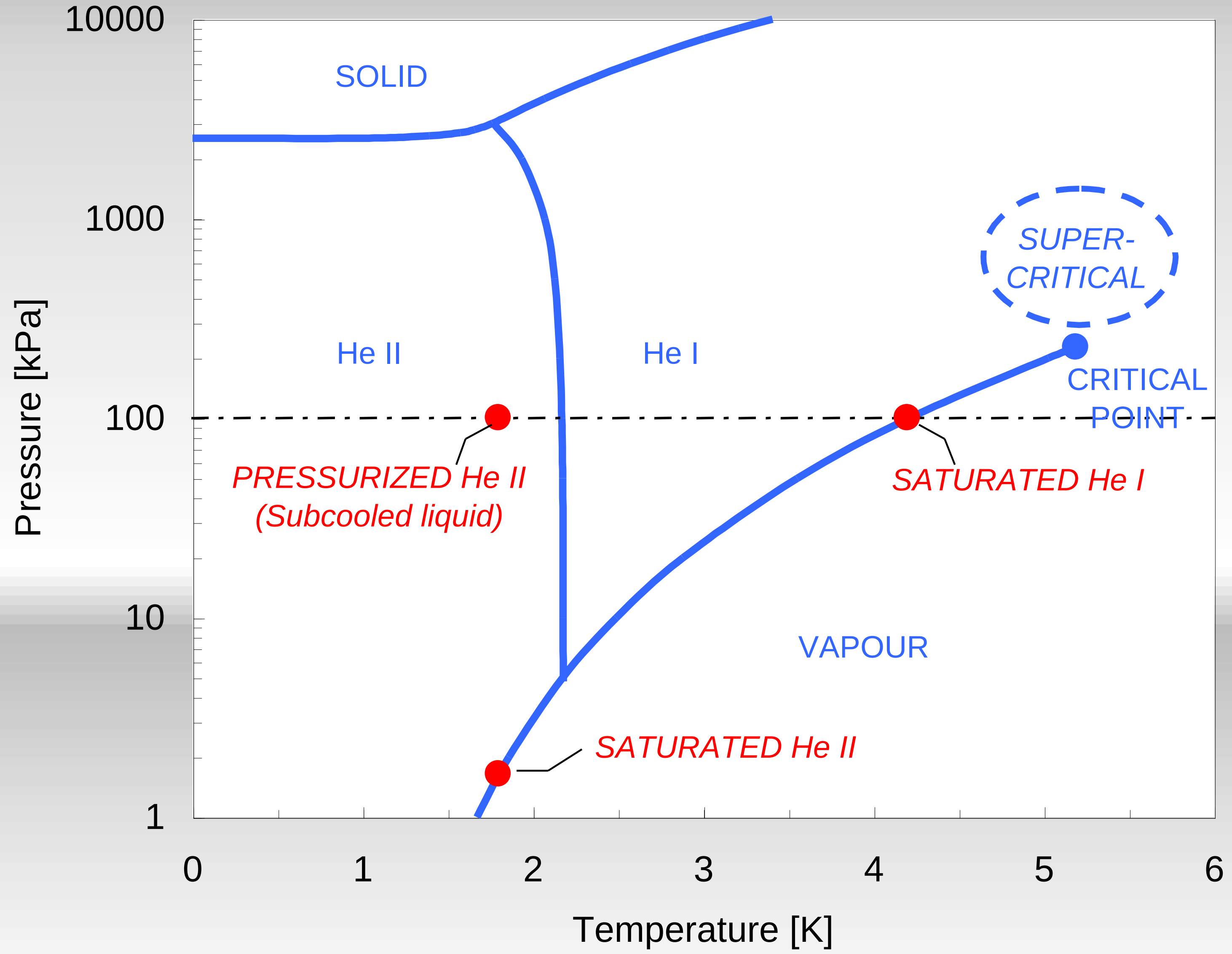
- Make use of the remarkable properties of He II

- Superfluid helium:

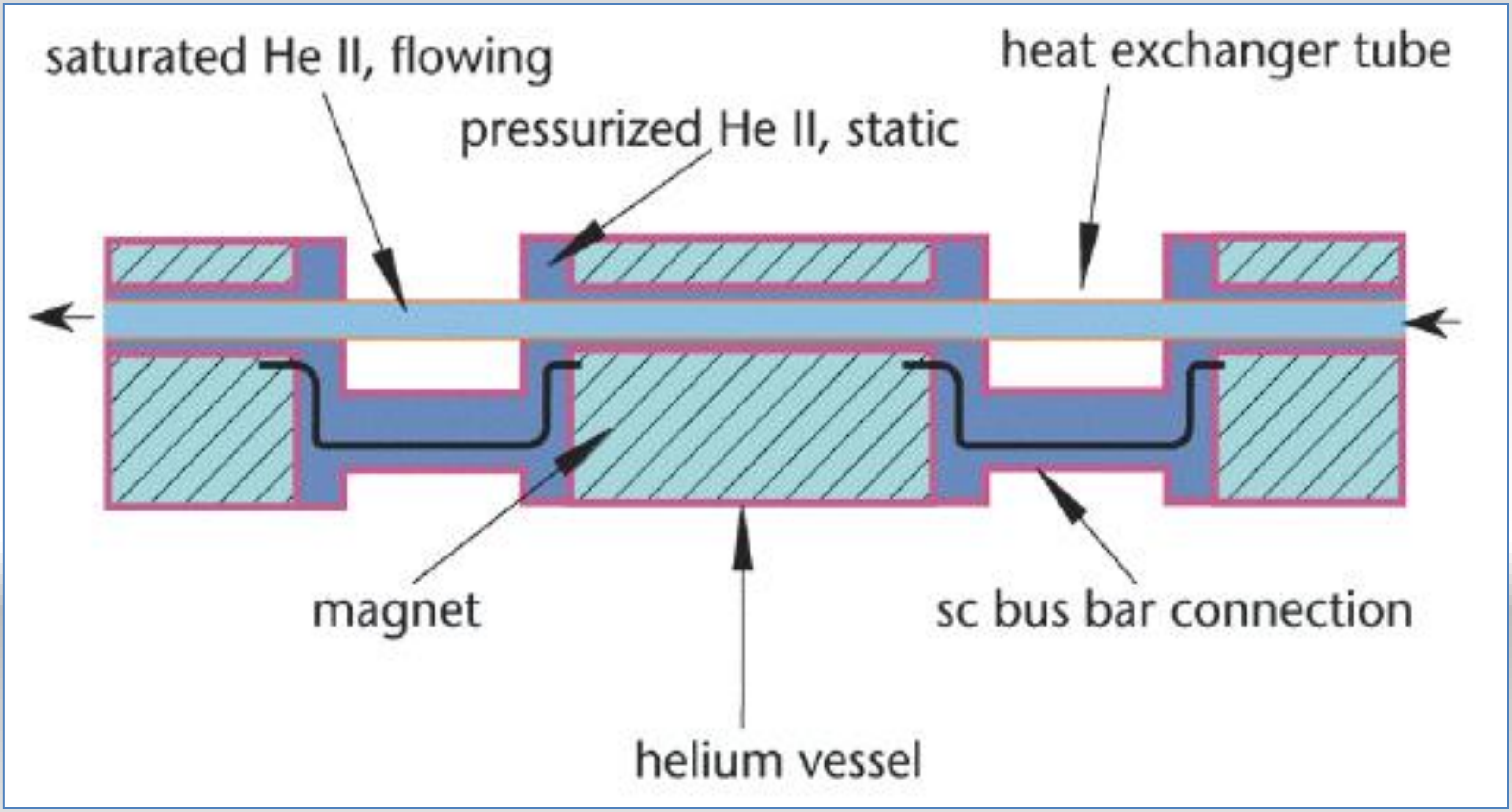
  - Very high thermal conductivity (3000 time high grade copper)
  - Very low coefficient of viscosity… can penetrate tiny cracks, deep inside the magnet coils to absorb any generated heat.
  - Very high heat capacity…stablizes small transient temperature fluctuations

How many Bose-Einstein condensates are there in the LHC?

Phase diagram of Helium



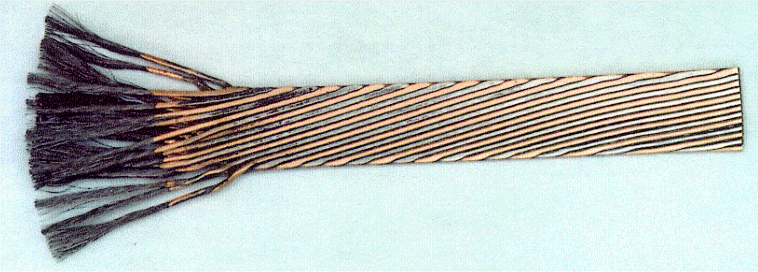
Cooling magnets with superfluid helium



The superconductor

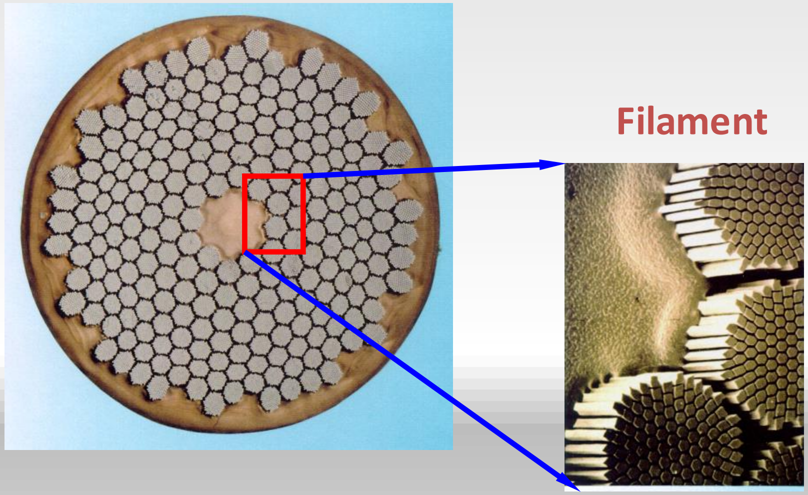
Niobium-titanium Rutherford cable

Cable



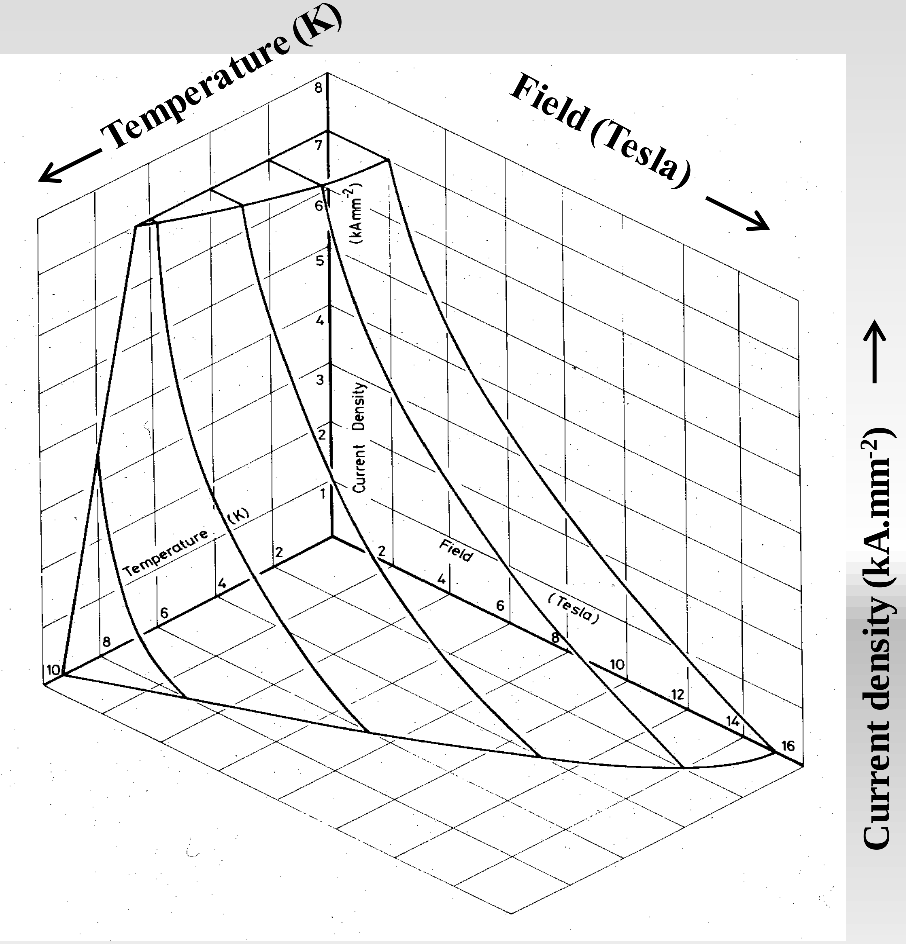
Strand

Filament

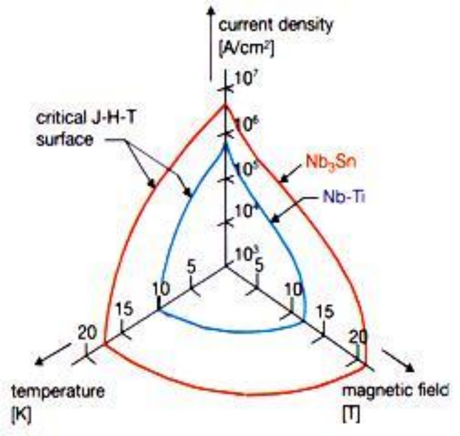


Used 1200 tonnes/7600 km of cable

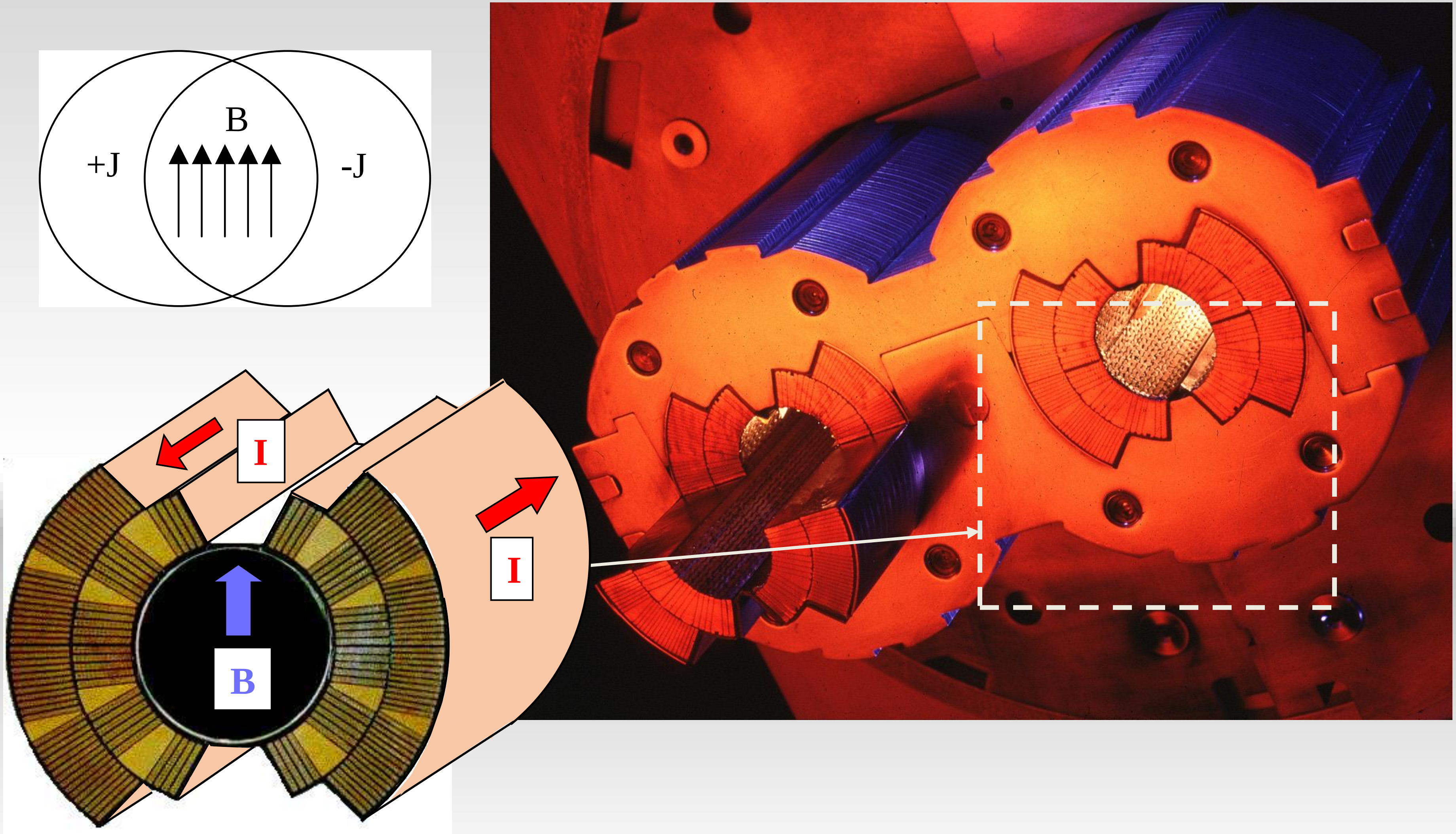
Critical surface of niobium-titanium



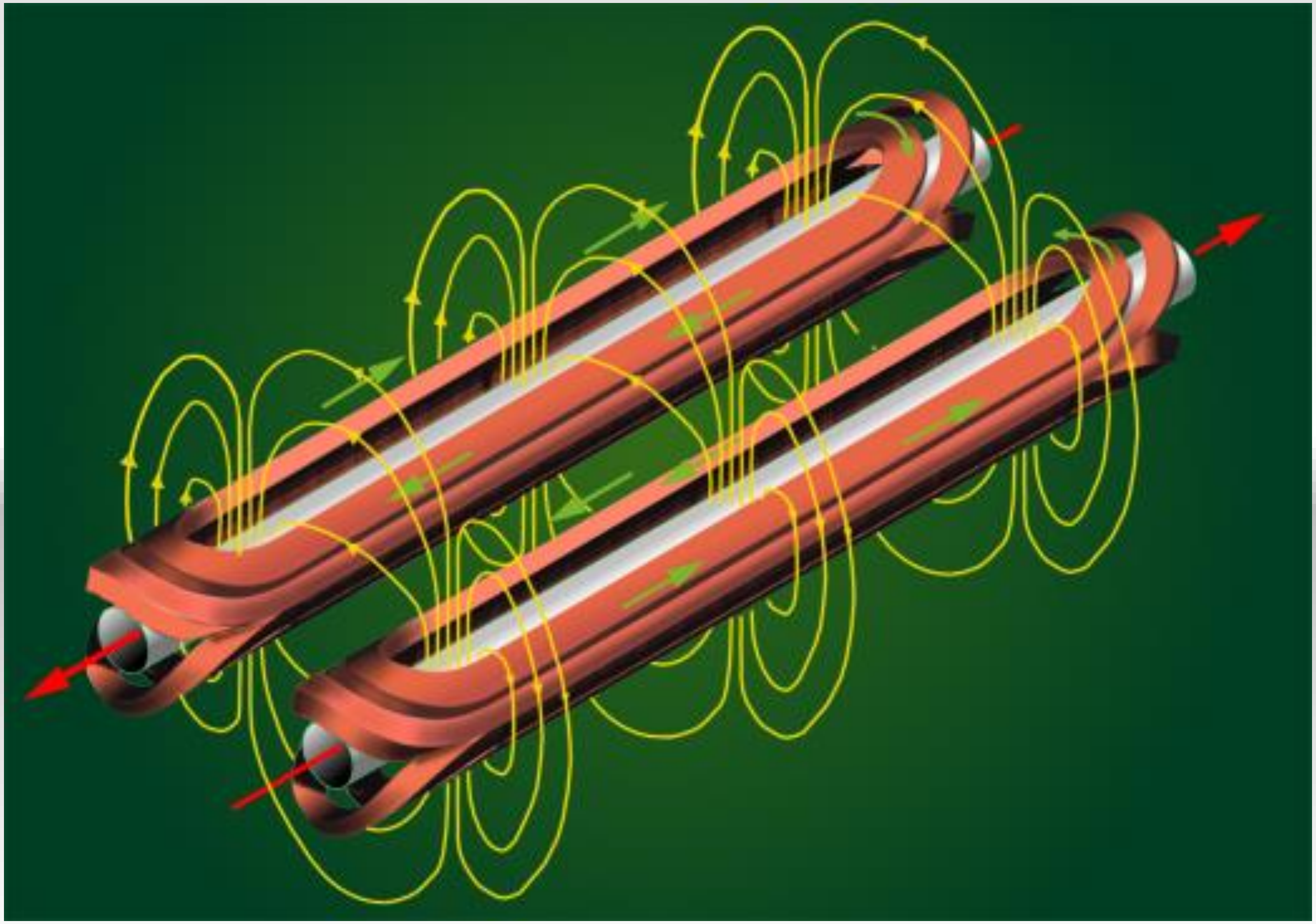
- Niobium-titanium **NbTi** is the standard ‘work horse’ of the superconducting magnet business
- Picture shows the **critical surface**, which is the boundary between superconductivity and normal resistivity
- Superconductivity prevails everywhere below the surface, resistance everywhere above it



Main components – dipole magnets



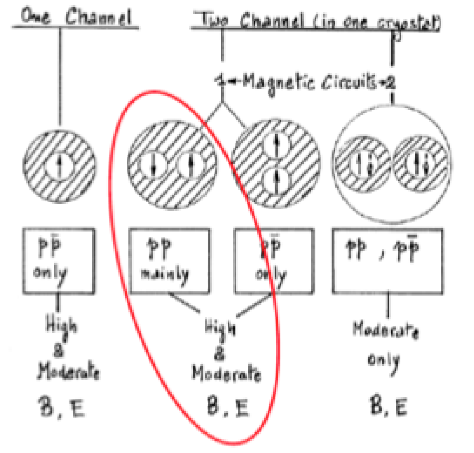
Number of dipoles	1232
Dipole field at 450 GeV	0.535 T
Dipole field at 7 TeV	8.33 T
Bending radius	2803.95 m
Main Dipole Length	14.3 m



Horizontal force component per quadrant (nominal field) 1.7 MN/m

Force tends to “open” the magnet, hence the Austenitic steel collars

ECFA-CERN workshop



June 1994
first full scale prototype dipole

1994 project approved by council (1-in-2)

SSC cancelled

Main contracts signed

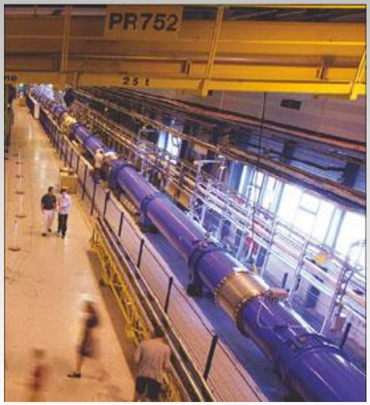
June 2007 First sector cold

April 2008
Last dipole down

1984 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10

First set of twin 1 m prototypes
Over 9 T

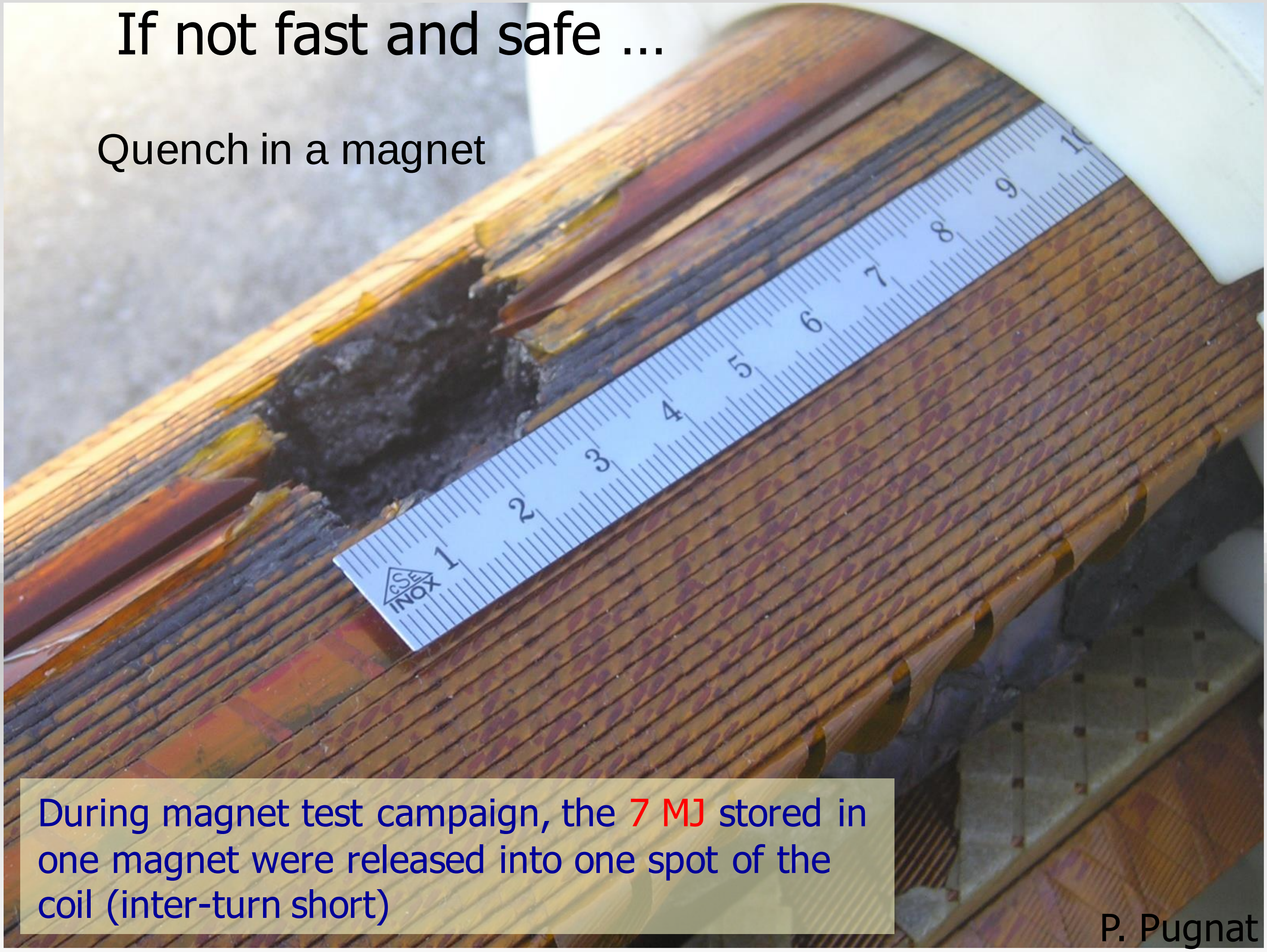
2002 String 2



November 2006
1232 delivered

September 19, 2008

Energy stored in the magnets: quench



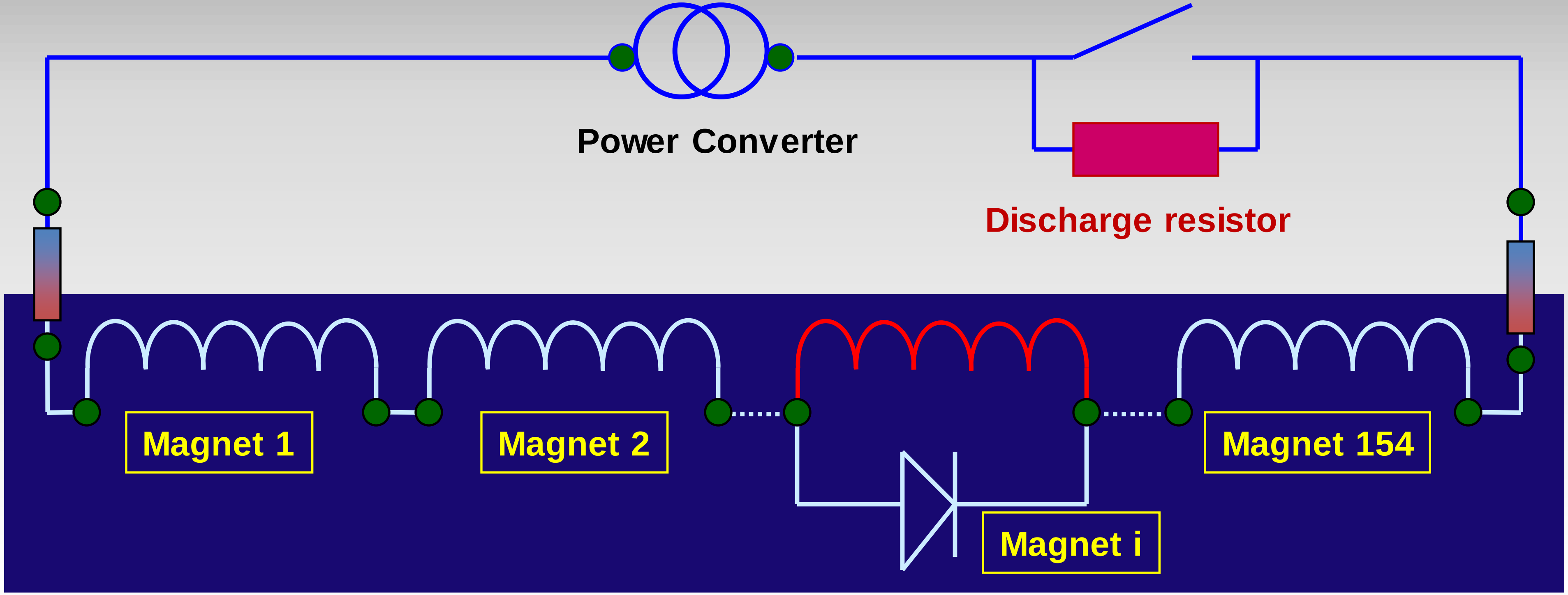
If not fast and safe …

Quench in a magnet

During magnet test campaign, the 7 MJ stored in one magnet were released into one spot of the coil (inter-turn short)

P. Pugnat

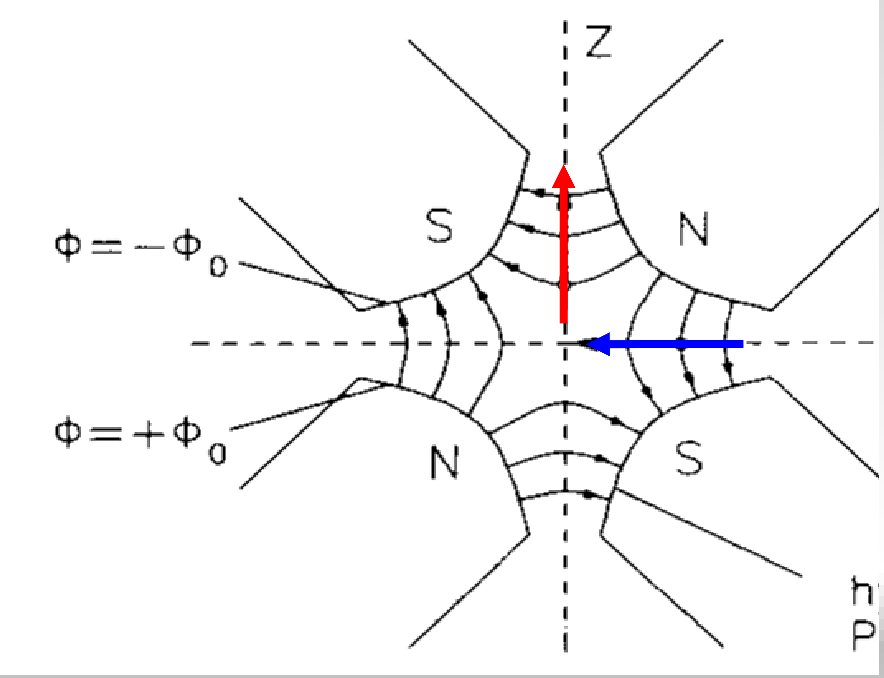
Quench - discharge of the energy

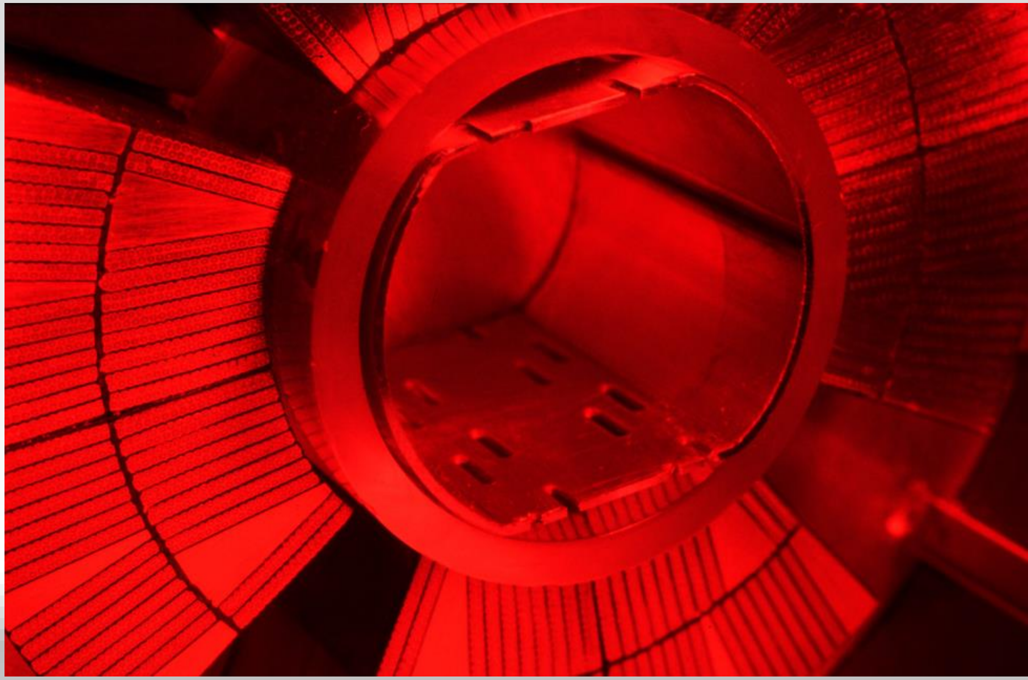


Protection of the magnet after a quench:

- The quench is detected by measuring the **voltage increase** over coil.
- The energy is distributed in the magnet by force-quenching using quench heaters.
- The current in the quenched magnet decays in < 200 ms.
- The current flows through the bypass diode (triggered by the voltage increase over the magnet).
- The current of all other magnets is discharged into the dump resistors.

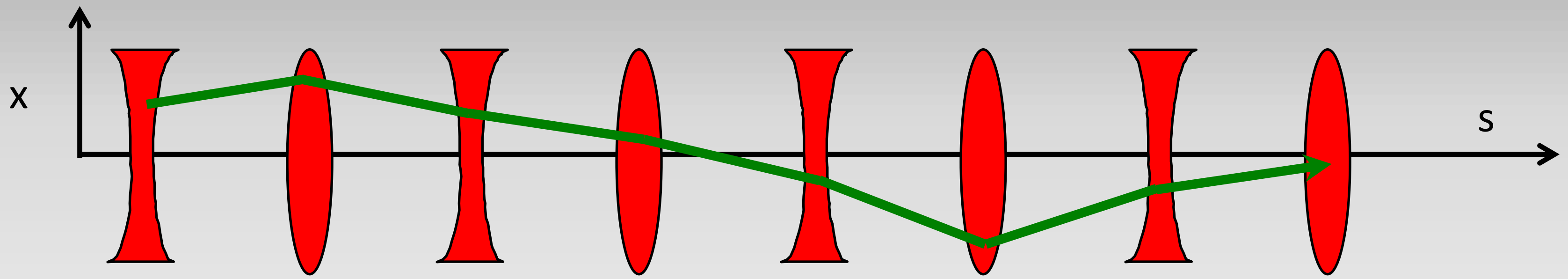
OPTICS





- Recall: a quadrupole magnet will focus in plane and de-focus in the other.
- Convention: a “focusing” quadrupole focuses in the horizontal plane

Alternate gradient focusing



The general linear magnet lattice can be parameterized by a ‘varying spring constant’, K=K(s)

$$\boxed{\frac{d^2x}{ds^2}+K(s)\,x=0}$$

(and similarly for the vertical plane y)

K(s) describes the distribution of focusing strength along the lattice.

This is Hill’s equation. The solution:

Oscillatory term

$$\boxed{x(s)=A\sqrt{\beta_x(s)}\cos\left(\phi(s)+\phi_0\right)}$$

Amplitude term

Betatron function

$$x(s) = A\sqrt{\beta_x(s)}\cos\left(\phi(s) + \phi_0\right)$$

- A and ϕ_0 are constants, which depend on the initial conditions.
- $\beta(s)$ = the amplitude modulation due to the changing focusing strength.
- $\phi(s)$ = the phase advance, which also depends on focusing strength.

Stick the assumed solution into Hill's equation and turn the handle…

$$\phi' = \frac{d\phi}{ds} = \frac{1}{\beta}$$

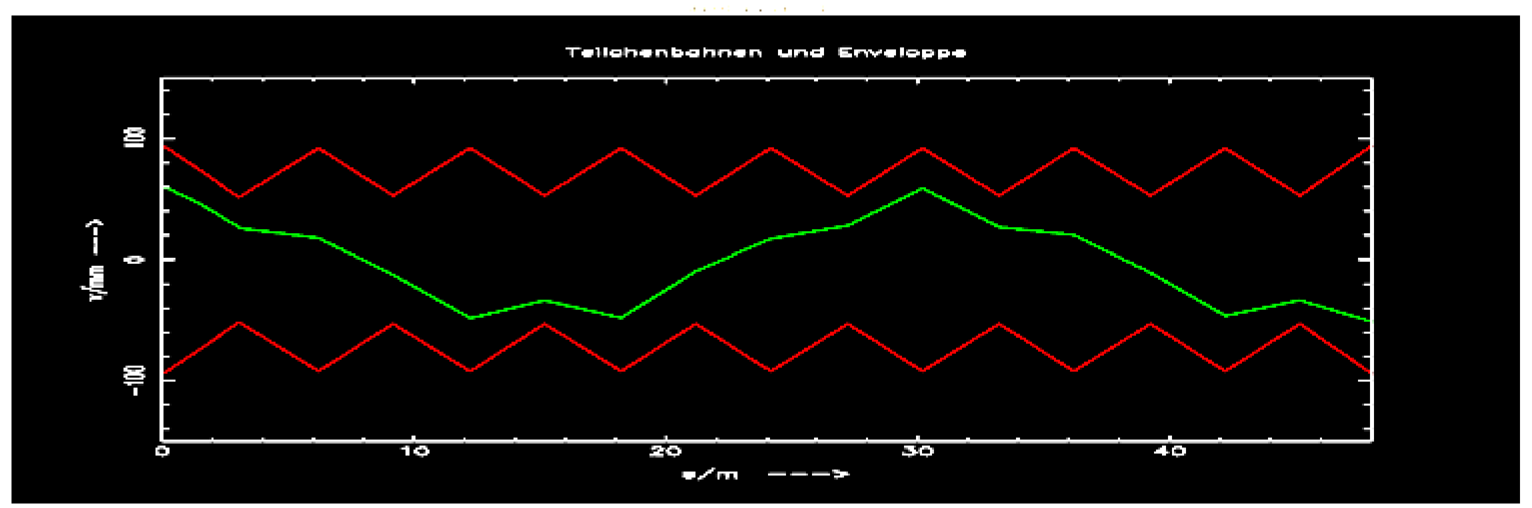
$$\Delta\phi\left(s_1 \rightarrow s_2\right) = \int_{s_1}^{s_2} \frac{1}{\beta(s)}$$

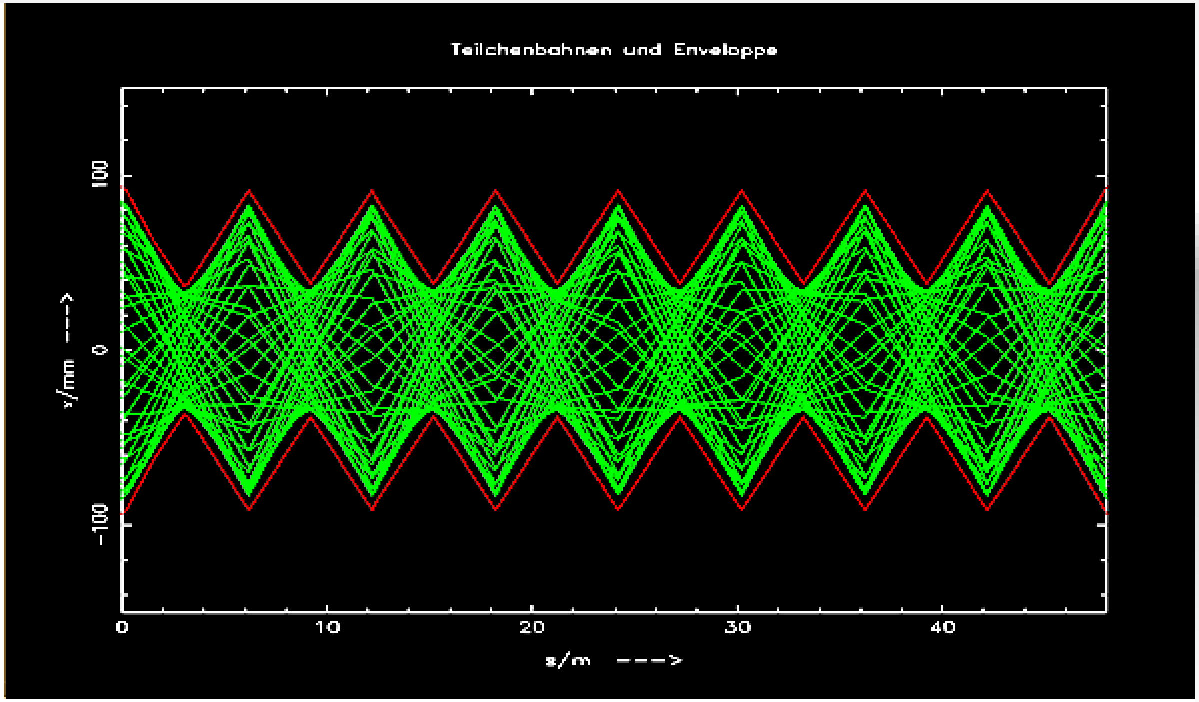
- beta(s) maybe interpreted as the local wavelength of the oscillation (divided by 2 pi)

$$Q_x \equiv \frac{1}{2\pi}\oint \frac{1}{\beta_x(s)}$$

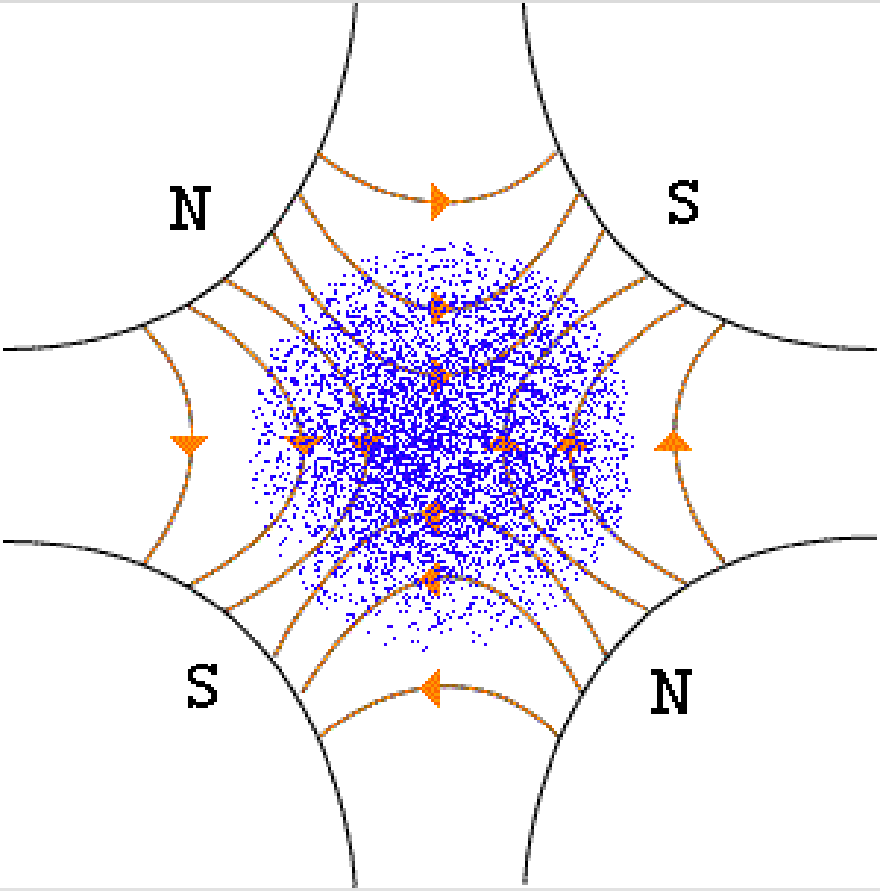
Number of oscillations per turn is called the tune of the accelerator

Betatron oscillations



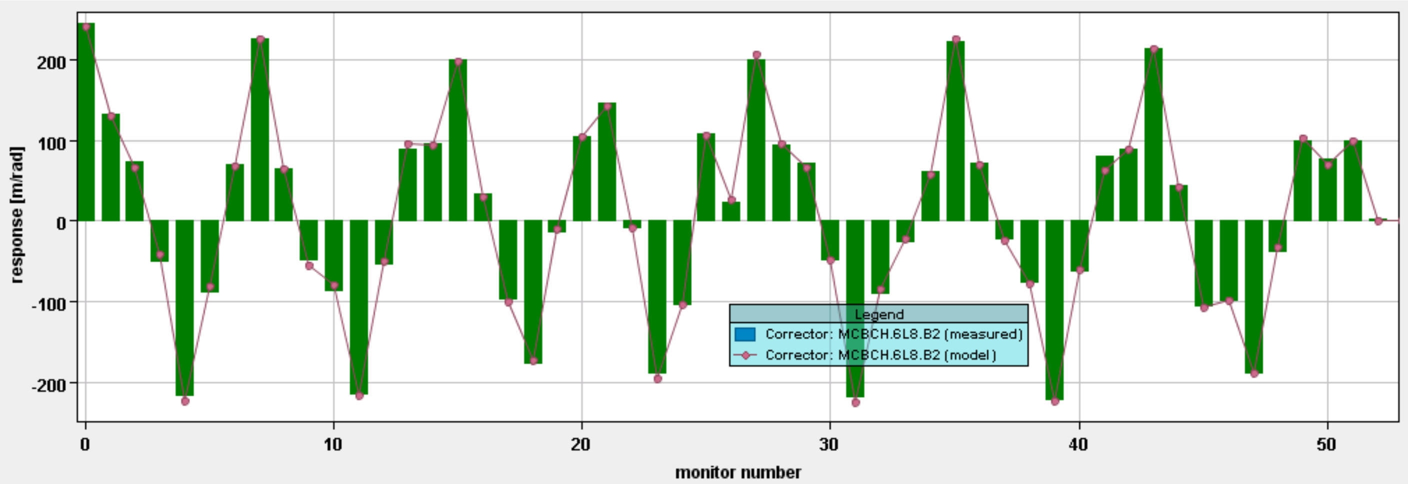


Amplitude modulation

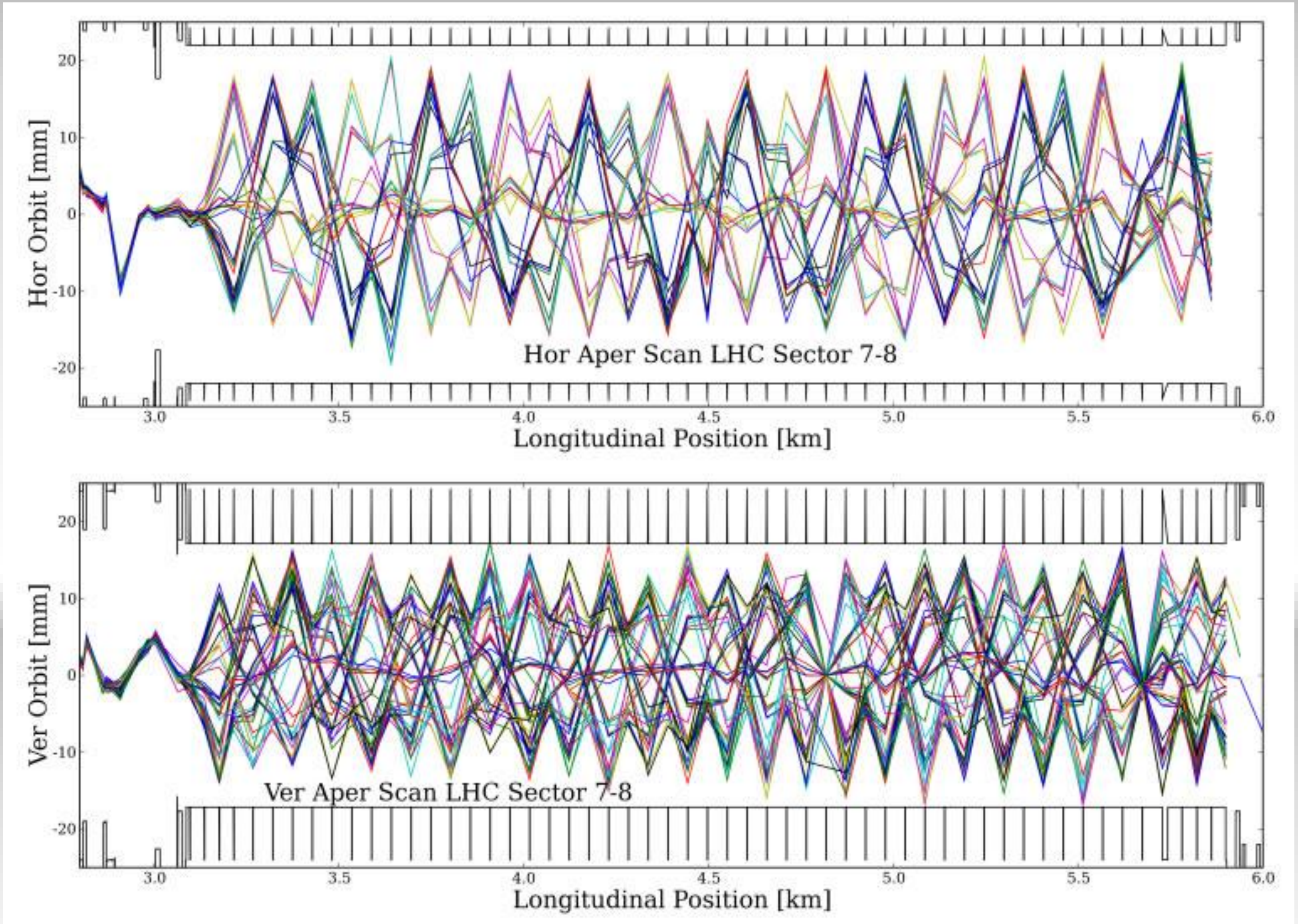


Betatron oscillations

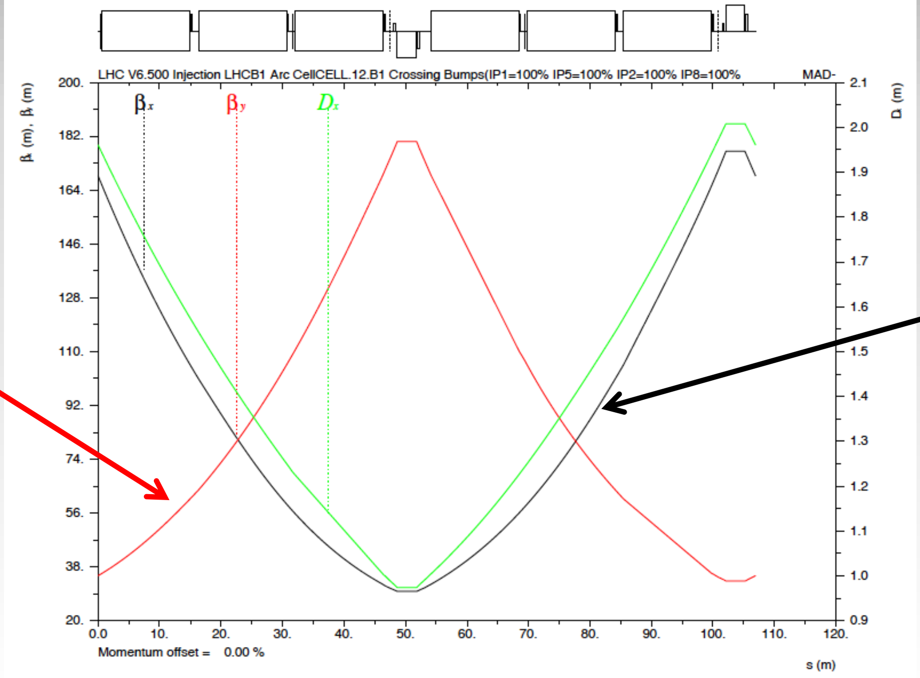
- Typical beam position monitor does not resolve individual particles.
- However, if the beam is deviated from the ideal trajectory it will oscillate due to the (de)-focusing fields of the accelerator.



Injection test – 5 years ago

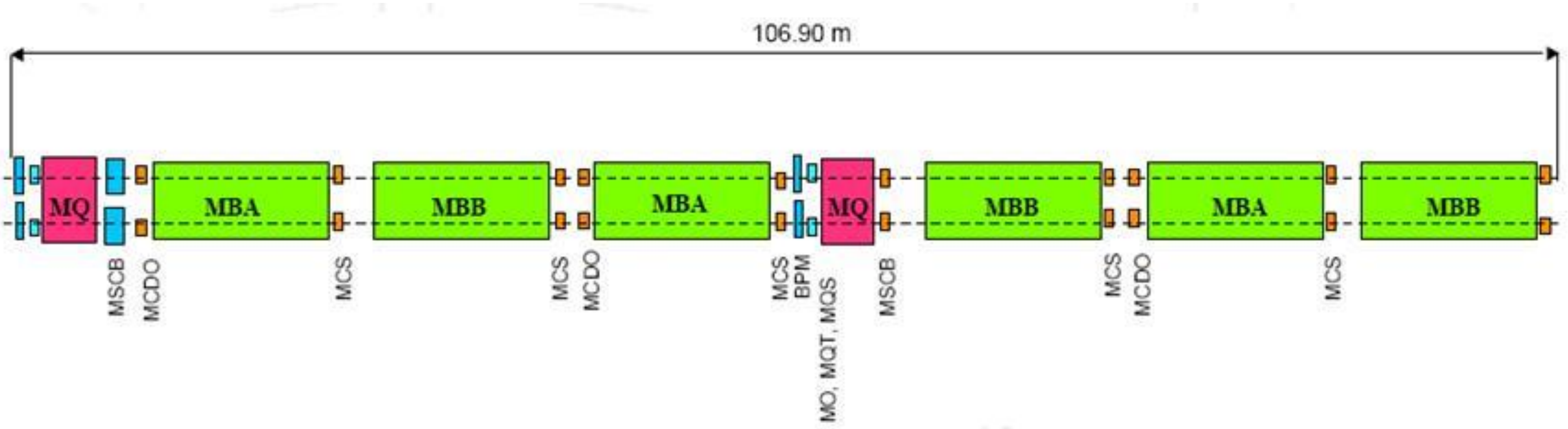


LHC lattice in the arc



beta_y

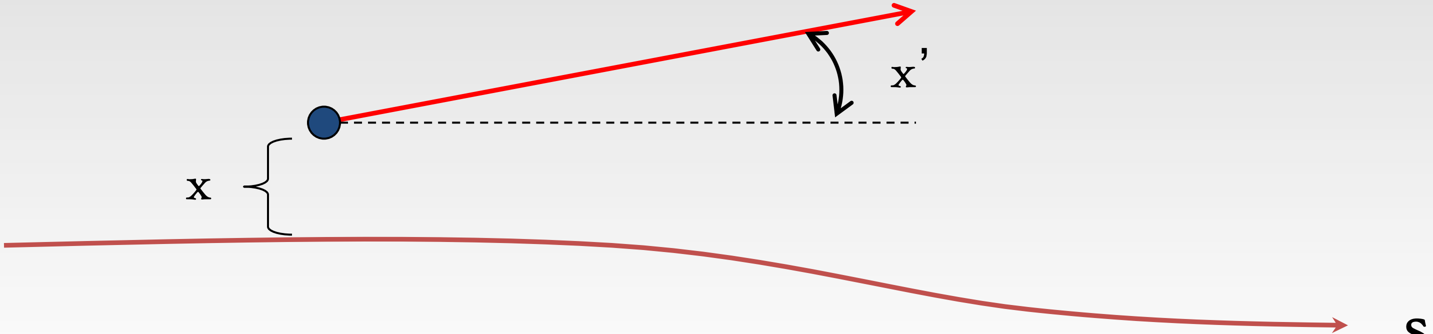
beta_x



For real

TRANSVERSE ACCELERATOR COORDINATES

We are discussing the **paraxial** (small deflection angles => linear), **uncoupled** (x & y independent) **transverse motion** of **on-momentum** particles around the design trajectory/orbit for a magnet lattice:

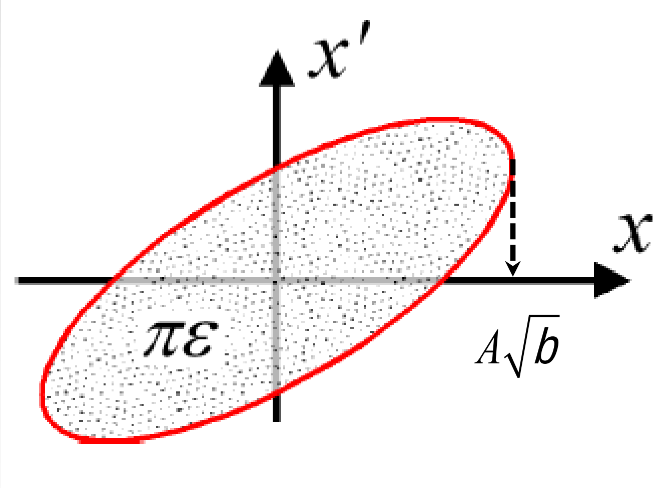


(and similarly for y view)

$$\boxed{x' = \frac{dx}{ds}; \quad y' = \frac{dy}{ds}}$$

s = coordinate along design orbit

Emittance



- Linear motion → beam ellipse in 2-d-space

- Ellipse area in (x,x') plane:

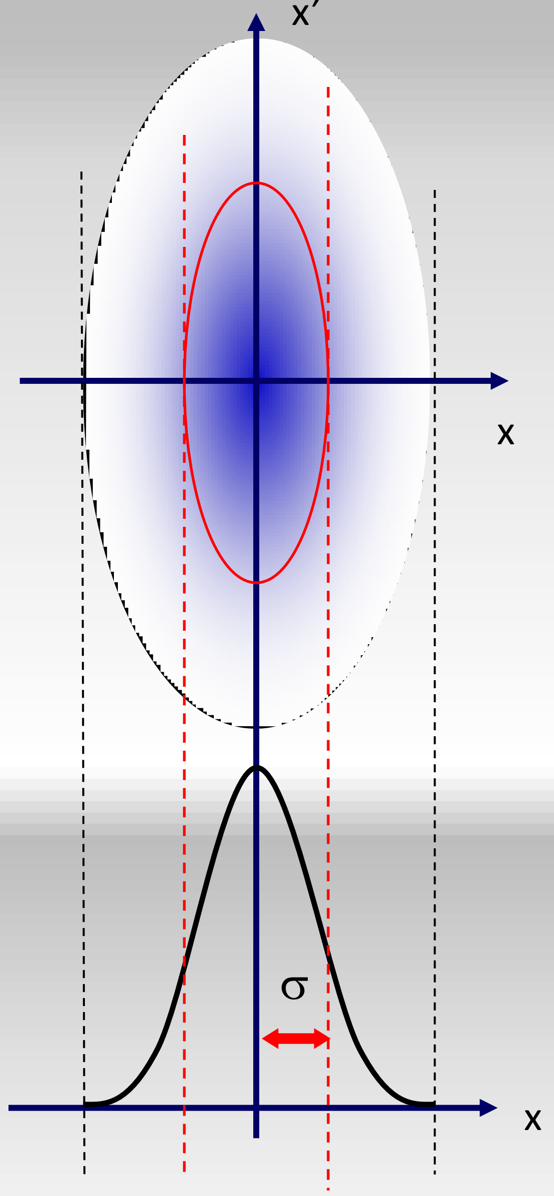
$$A = p \times \epsilon$$

- Define emittance by a contour confining some fraction of particles depending on distribution (typically Gaussian)

- Units: mm.mrad (but you will see microns)

  - *Imagine sitting at one location and plotting x,x' of all particles*
  - *Or tracking one particle over many turns*

Emittance



Area of phase space ellipse = πε

$$\boxed{\begin{array}{l} \sigma = \sqrt{\varepsilon\beta} \\[2ex] \varepsilon = \dfrac{\sigma^2}{\beta} \end{array}}$$

Practical view: $\sigma_x = \underbrace{\sqrt{\text{Betafunction } \beta}}_{\text{magnet structure}} \times \underbrace{\sqrt{\text{Emittance } \epsilon}}_{\text{particle ensemble}}$

Theoretical view: $H = \frac{p_x^2}{2} + \frac{k(s)x^2}{2} \xrightarrow{\text{c.t.}} \tilde{H} = \frac{J}{\beta(s)}, \quad \epsilon = \langle J \rangle$

Normalized emittance

Geometric emittance {x,x’} shrinks naturally as we go up in energy

$$\boxed{\Delta p_s > 0, \quad \Delta p_x = 0, \quad \varepsilon \sim \frac{1}{p_s}}$$

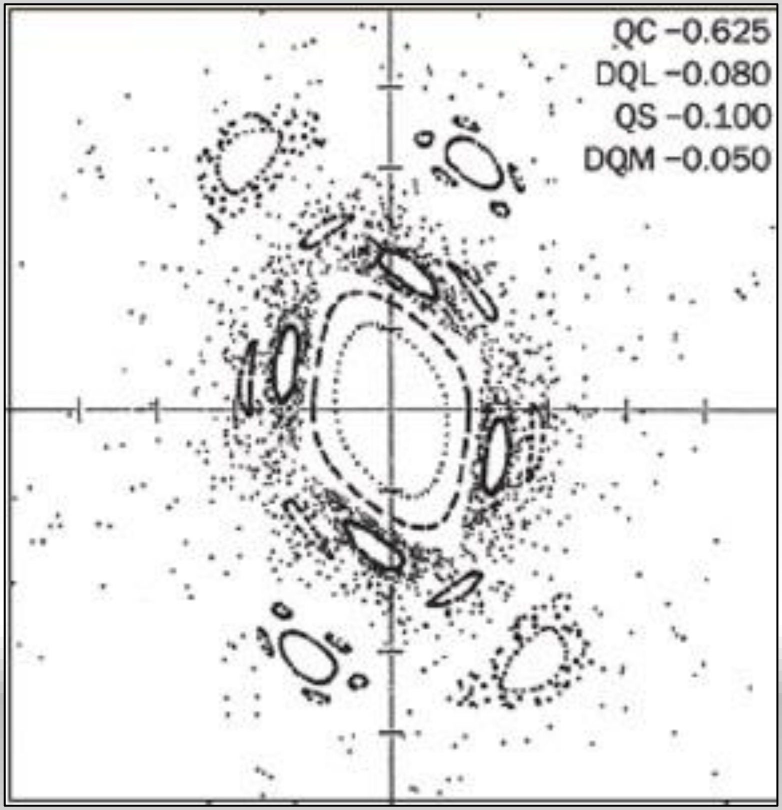
$$\boxed{\varepsilon_n = \beta\gamma\varepsilon}$$

Important – it’s energy independent and can be used across the accelerator complex and will show up later in a useful formulation of luminosity

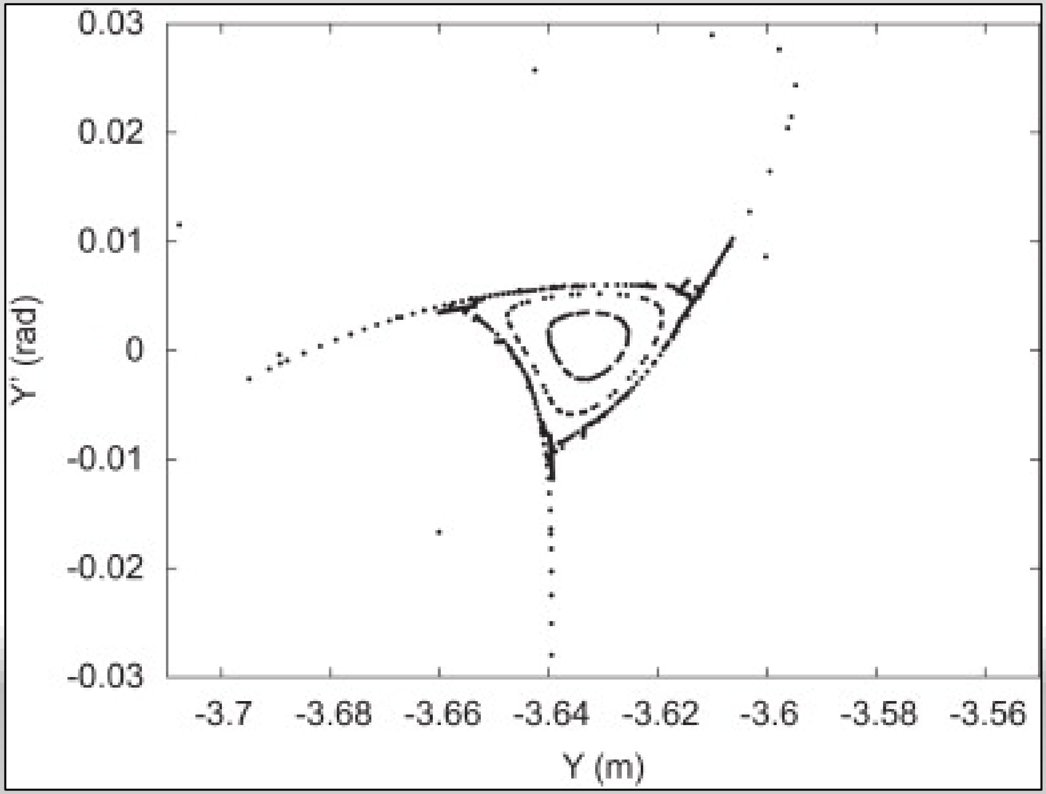
Normalized emittance	2.5 mm.mrad
Emittance 450 GeV	5.2 nm.rad
Emittance 7000 GeV	0.34 nm.rad

Beta [m]	Sigma 450 GeV micron	Sigma 7 TeV
180	967	246
30	395	100
4000	4566	1158
0.6	56	14

Phase space



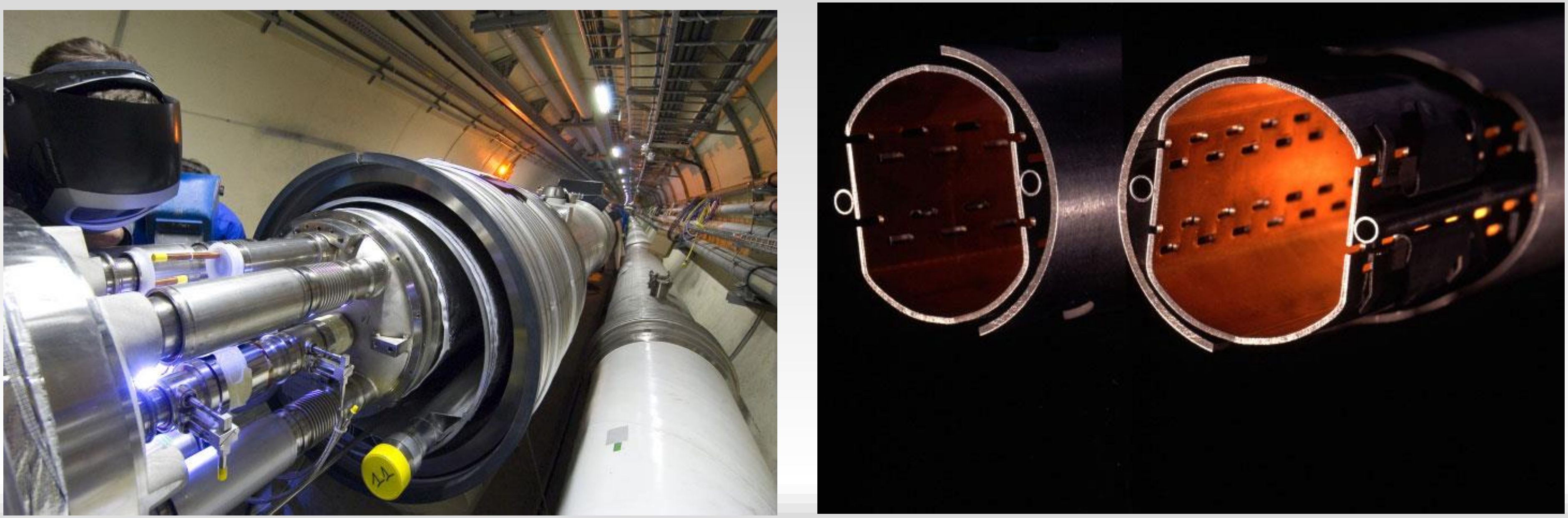
Simulation showing the chaotic effect of the beam–beam interaction



Phase space trajectories near the septum of a compact synchrotron during low extraction

Vacuum

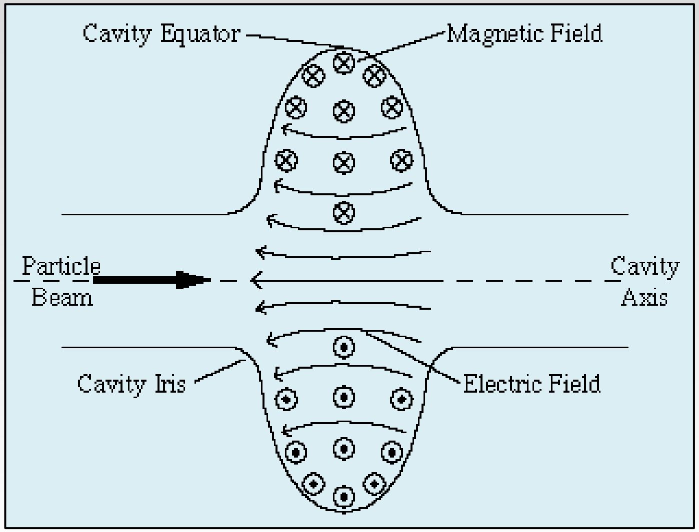
Beam vacuum ~10^{-10} mbar (~3 million molecules/cm^3)

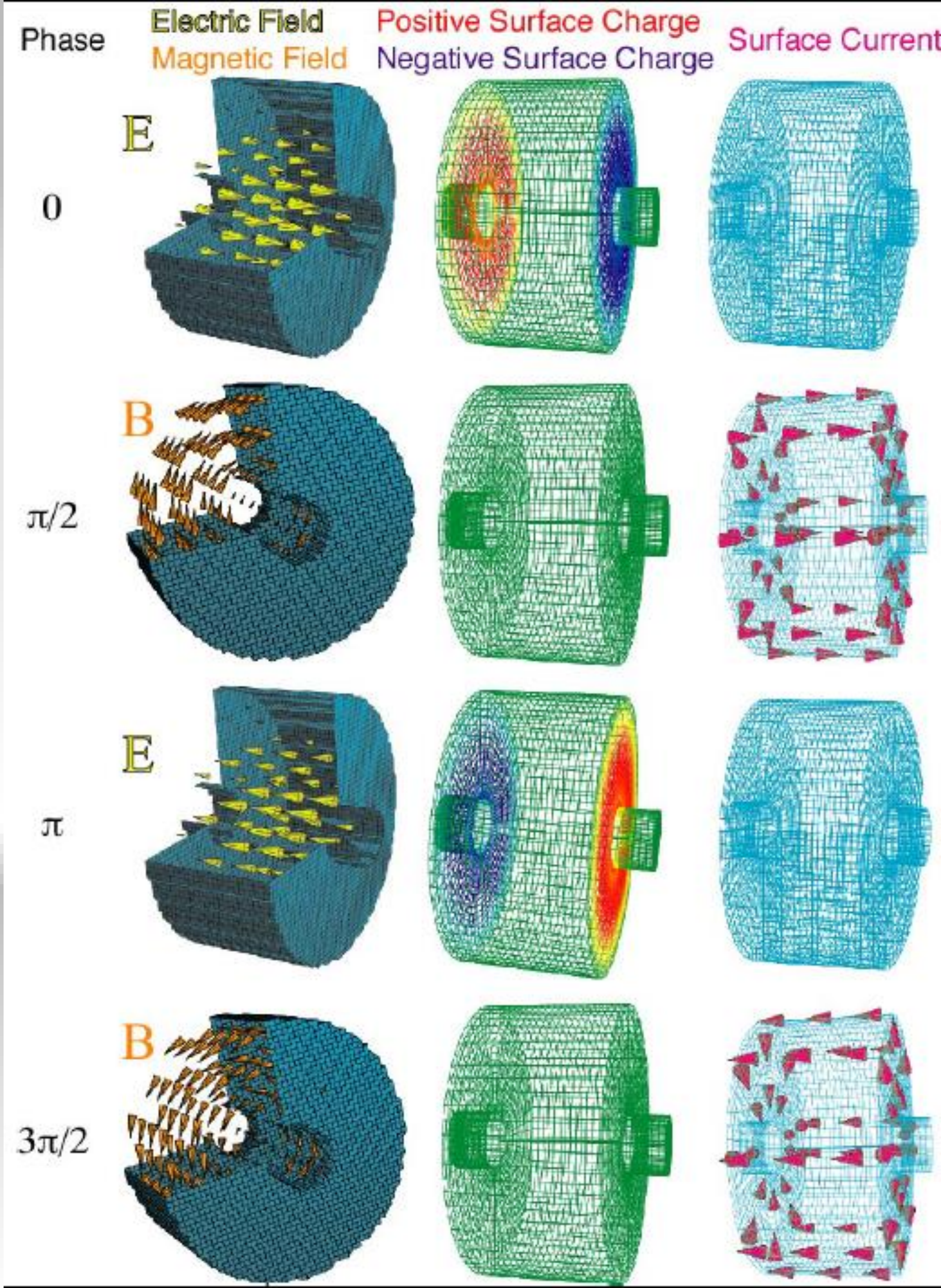


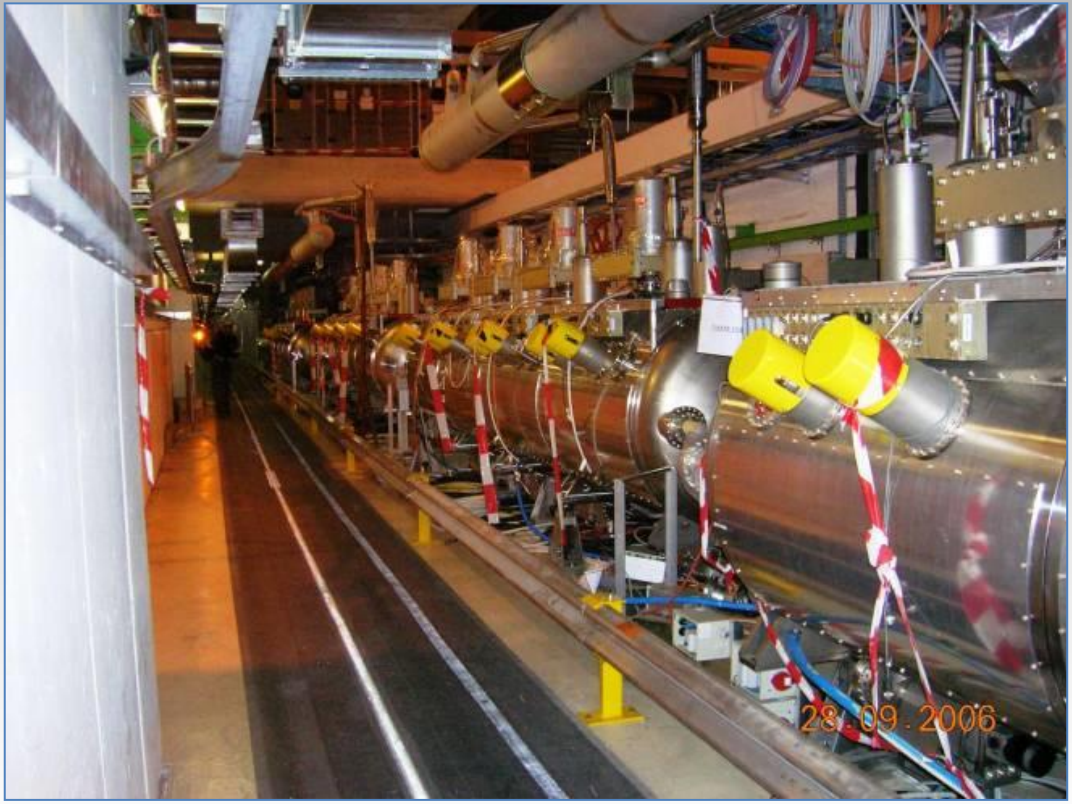
- **Cold**
  - Pumping is insured by cold surfaces for all gases except helium. To avoid subsequent desorption, low initial pressures are required before cool-down, and this is ensured by turbo molecular pumps etc.
- **Warm**
  - NEG provides most of the pumping capacity, with additional ion pumps for the noble gases which are not pumped by the NEG

RADIO FREQUENCY

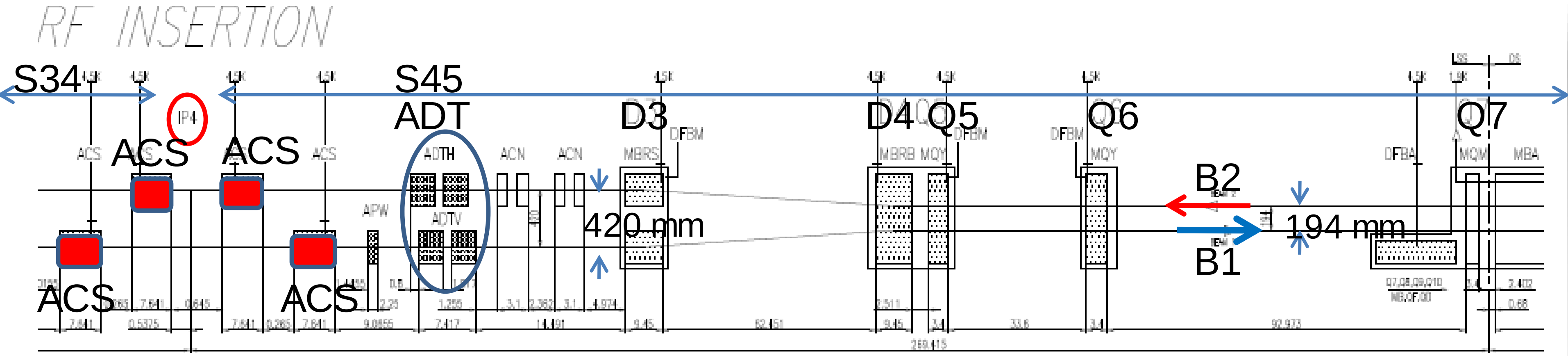
Briefly!





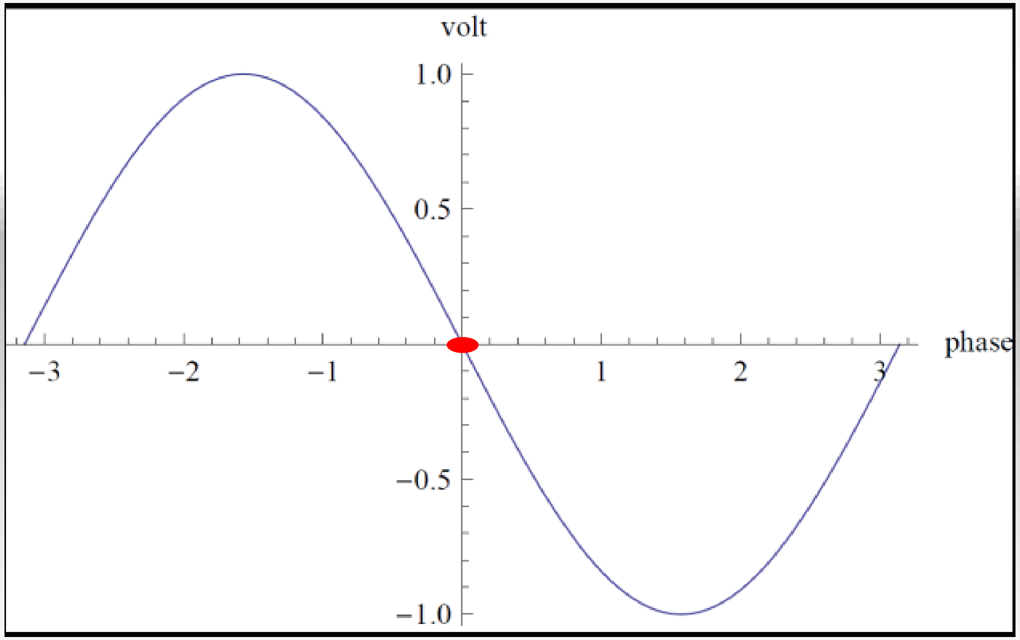


- 4xfour-cavity cryo module
- 400 MHz
- 16 MV/beam
- Nb on Cu cavities @4.5 K
- Beam pipe diam.=300 mm



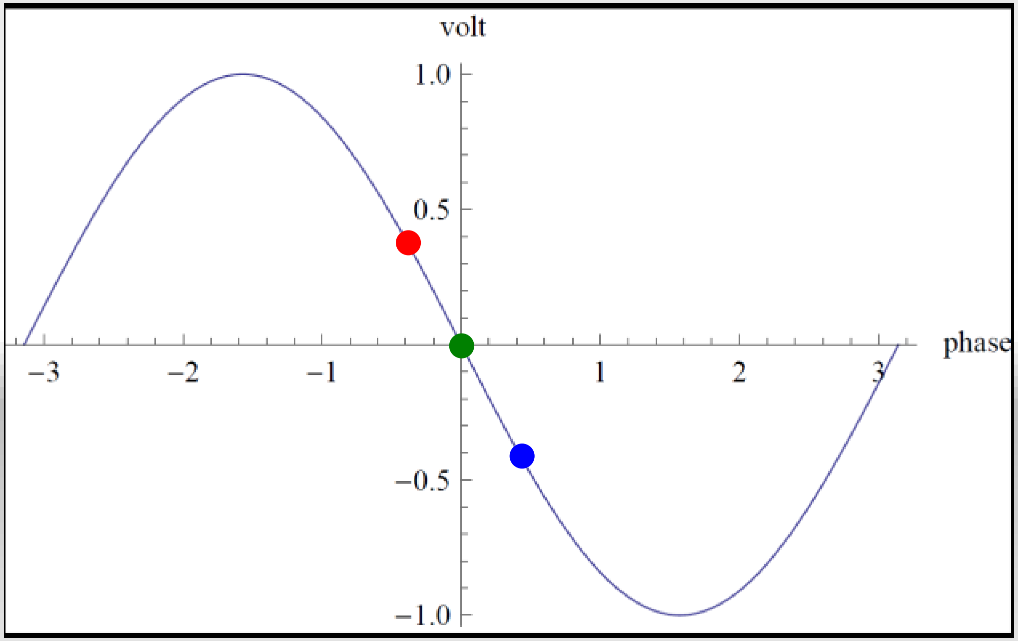
RF basics

- We will use a RF cavities operating on resonance to produce an oscillating electric fields (400 MHz in the LHC)
- In the time a bunch takes to travel around the ring the RF performs 35640 cycles – the harmonic number (or $f_{rf} = hf_{rev}$)



Now…

- A particle with lower momentum than p_0 will go round faster and will arrive at the RF cavity earlier. It will get a higher energy kick and arrive relatively later the next turn.
- A particle with higher momentum than p_0 will go round slower and will arrive at the RF cavity later. It will get a lower energy kick and arrive relatively earlier the next turn.



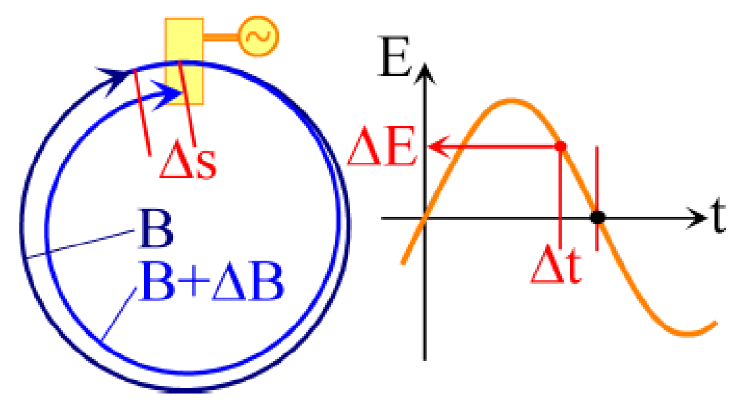
$\phi = \phi_s$

(In the LHC when dp/dt=0, the stable phase is 180 degrees. During the ramp it reaches 176.5 degrees)

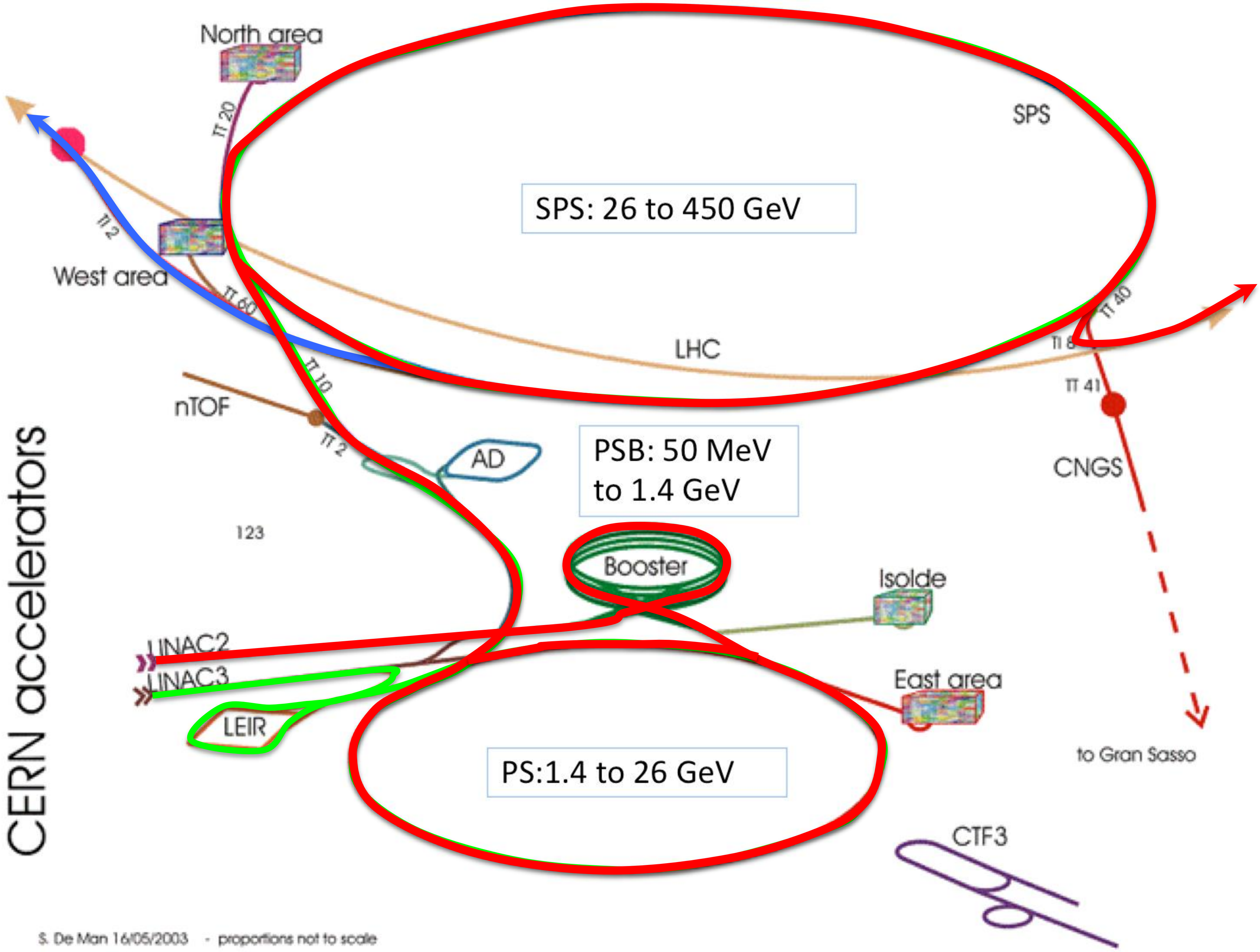
$$\boxed{\frac{mv^2}{R} = qvB \rightarrow p = qRB \rightarrow p(t) = qRB(t)}$$

Momentum follows magnet field variation due to RF phase focussing:

- inject beam into ring at B_0 with momentum $p_0 = qRB_0$
- increase B-field → B + ΔB
- bending radius shrinks
- path becomes shorter by 2πΔR
- particles arrive earlier by $\Delta t = (2\pi\Delta R)/\beta c$
- RF cavity: $U(\Delta t) = U_0 \sin(\omega\Delta t + \phi) > 0$
- Acceleration by $\Delta p = \beta q U(\Delta t)$



- ⇒ self-synchronization of p(t) with B(t)
- Constraints: $\phi \approx \pi$ and $2\pi R = n\beta\lambda_{rf}$

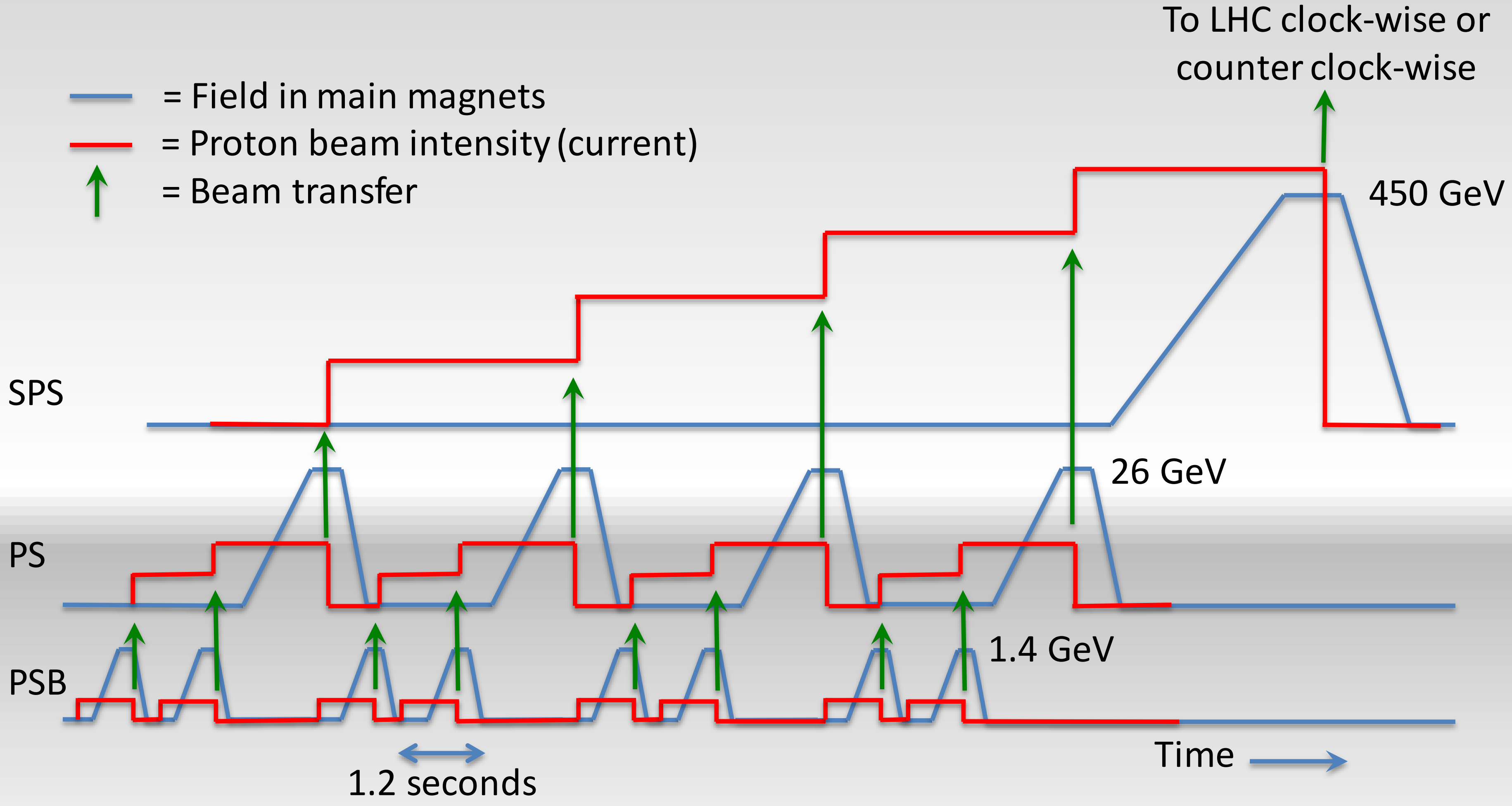

SPS: 26 to 450 GeV

PSB: 50 MeV to 1.4 GeV

PS:1.4 to 26 GeV

S. De Man 16/05/2003 - proportions not to scale

LHC Injector Cycling



— = Field in main magnets
— = Proton beam intensity (current)
↑ = Beam transfer

To LHC clock-wise or counter clock-wise

450 GeV

SPS

26 GeV

PS

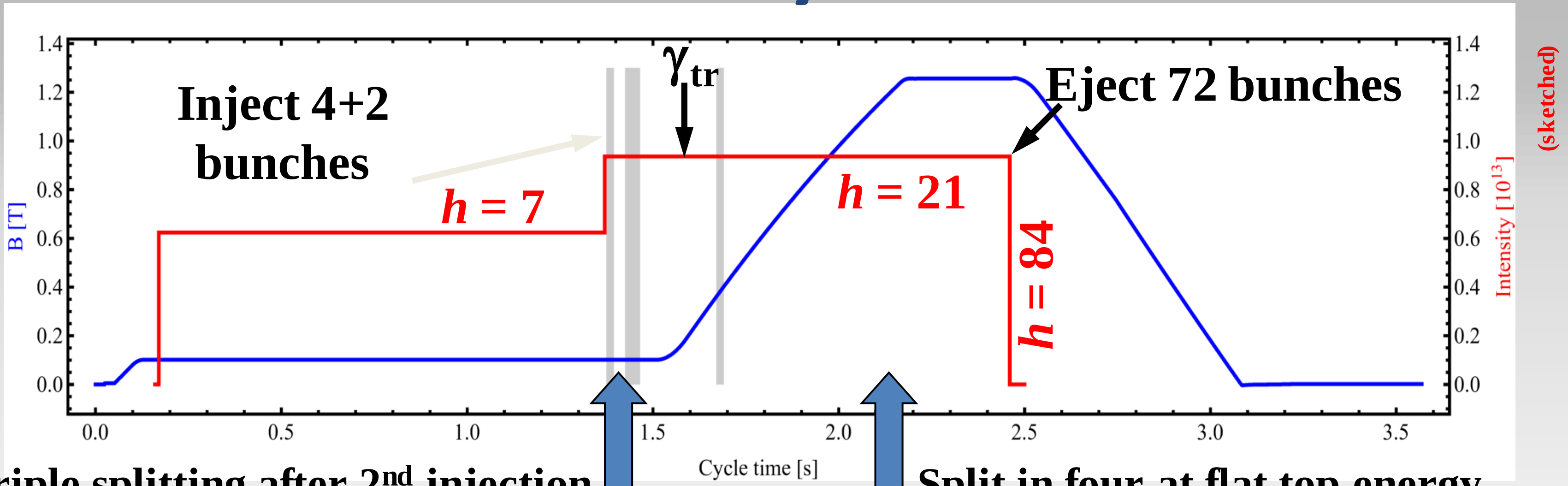
1.4 GeV

PSB

1.2 seconds

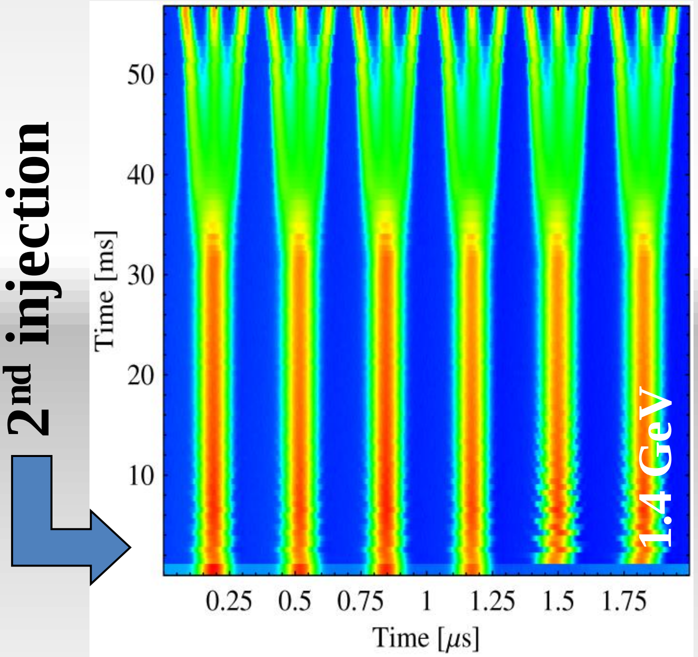
Time

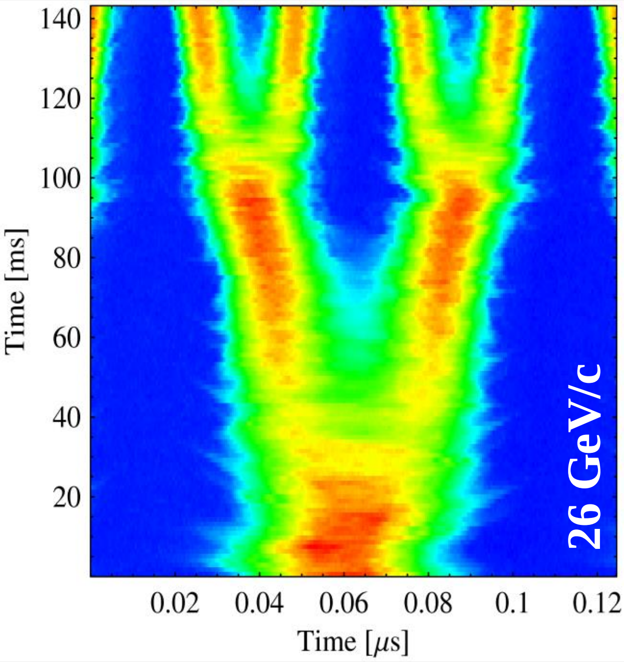
The LHC 25 ns cycle in the PS



Triple splitting after 2nd injection

Split in four at flat top energy

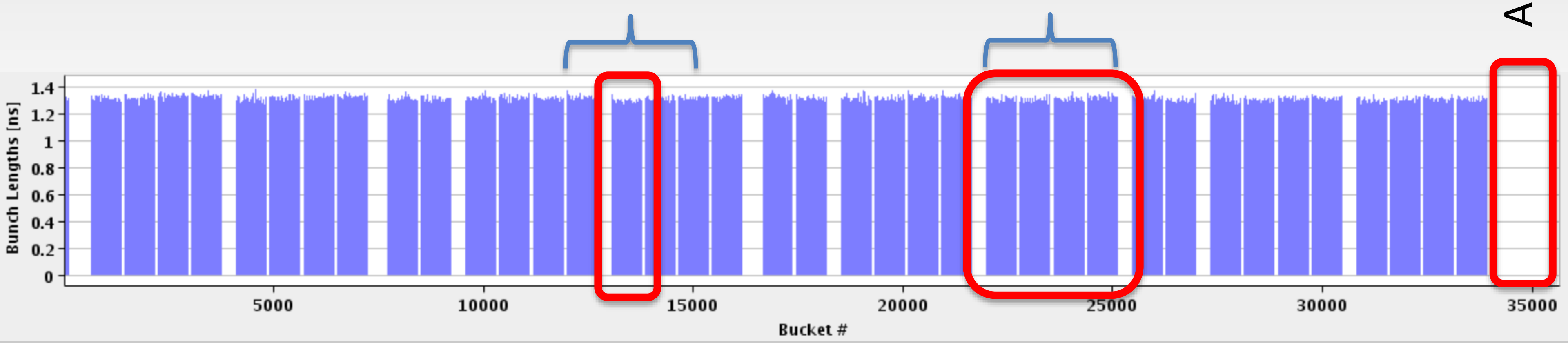




→ Each bunch from the Booster divided by 12 → 6 × 3 × 2 × 2 = 72

LHC bunch structure - 2012

- 50 ns bunch spacing
- Maximum bunch intensity 1.7 x 10^{11} protons per bunch



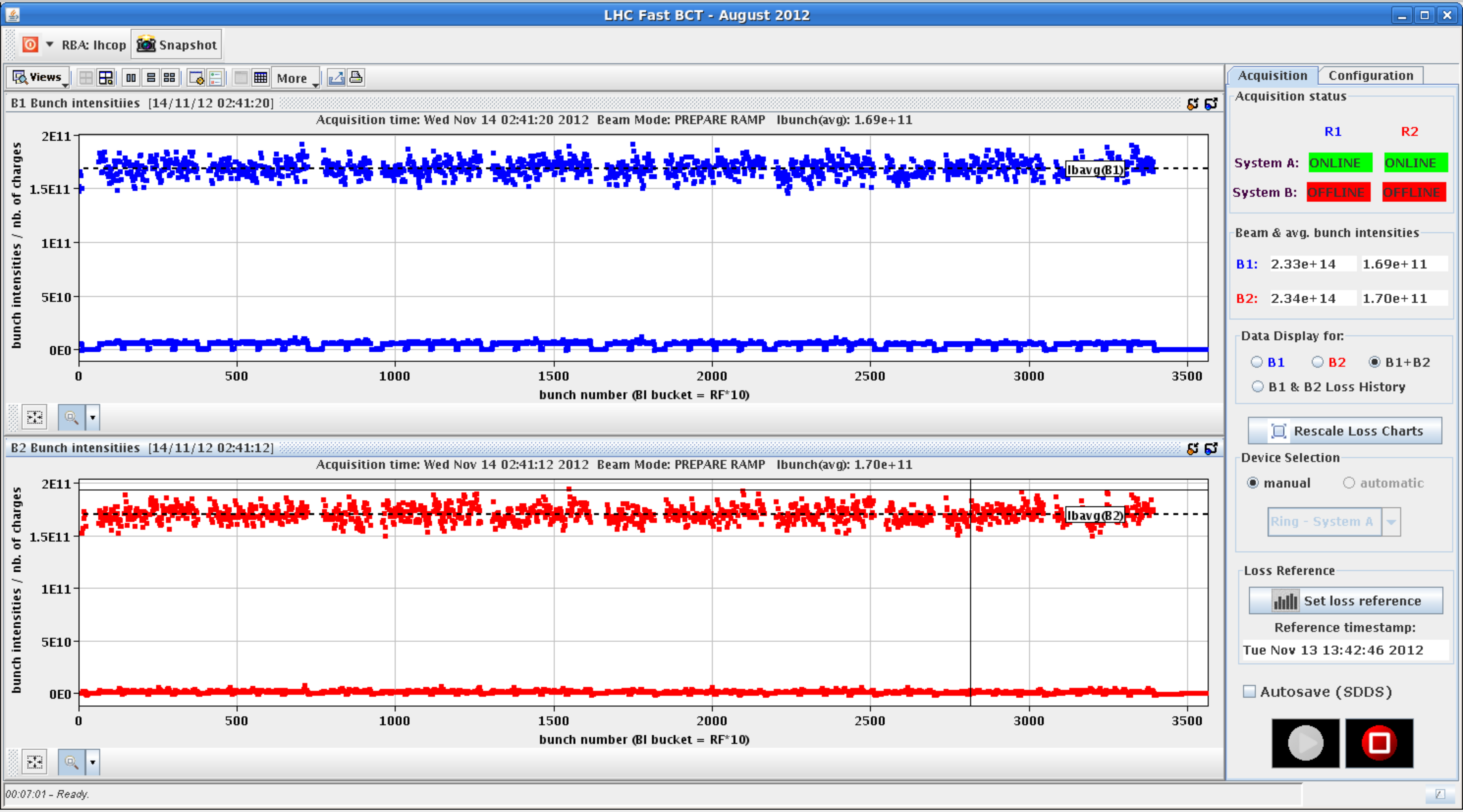
1 PS batch
(36 bunches)

1 SPS batch
(144 bunches)

Abort gap

26.7 km 1380 bunches

From the control room



LHC Fast BCT - August 2012

B1 Bunch intensitiies [14/11/12 02:41:20]

Acquisition time: Wed Nov 14 02:41:20 2012 Beam Mode: PREPARE RAMP Ibunch(avg): 1.69e+11

B2 Bunch intensitiies [14/11/12 02:41:12]

Acquisition time: Wed Nov 14 02:41:12 2012 Beam Mode: PREPARE RAMP Ibunch(avg): 1.70e+11

Acquisition status

	R1	R2
System A:	ONLINE	ONLINE
System B:	OFFLINE	OFFLINE

Beam & avg. bunch intensities

B1:	2.33e+14	1.69e+11
B2:	2.34e+14	1.70e+11

Data Display for: ○ B1 ○ B2 ● B1+B2 ○ B1 & B2 Loss History

Device Selection: ● manual ○ automatic

Ring - System A

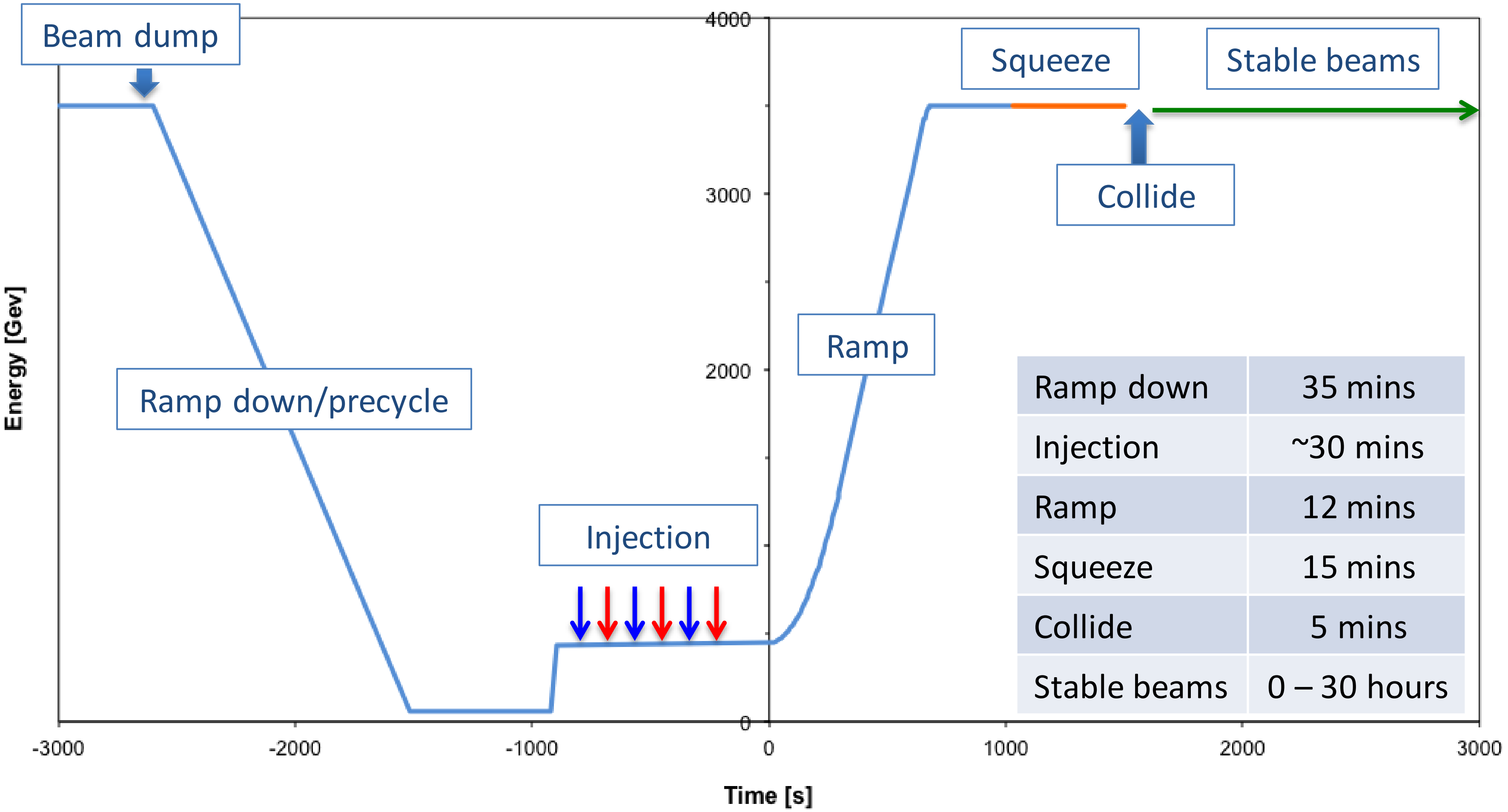
Loss Reference

Reference timestamp:
Tue Nov 13 13:42:46 2012

☐ Autosave (SDDS)

00:07:01 - Ready.

Operational cycle

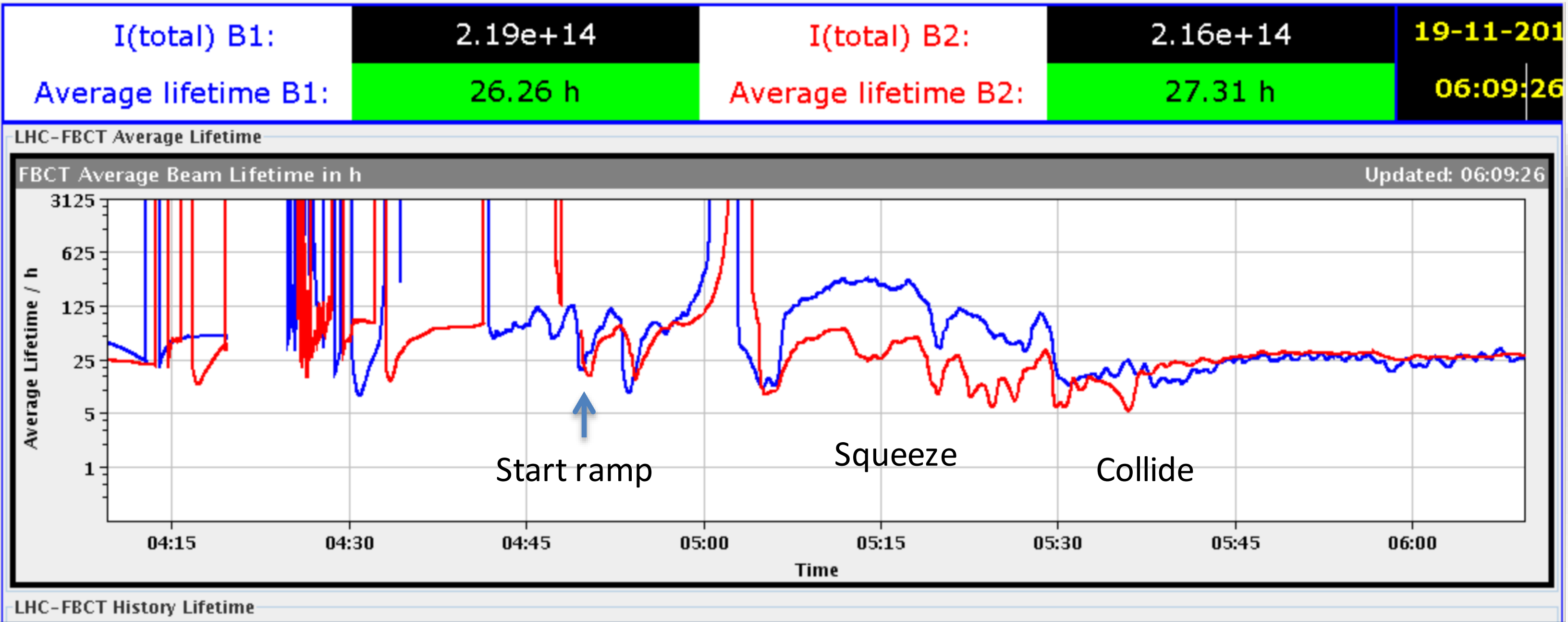


Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 – 30 hours

Turn around from stable beams to stable beams - 2 to 3 hours on a good day

Beam

- Excellent single beam lifetime – good vacuum conditions
- Excellent field quality, good correction of non-linearities
- Low tune modulation, low power converter ripple, low RF noise



I(total) B1:	2.19e+14	I(total) B2:	2.16e+14	19-11-201
Average lifetime B1:	26.26 h	Average lifetime B2:	27.31 h	06:09:26

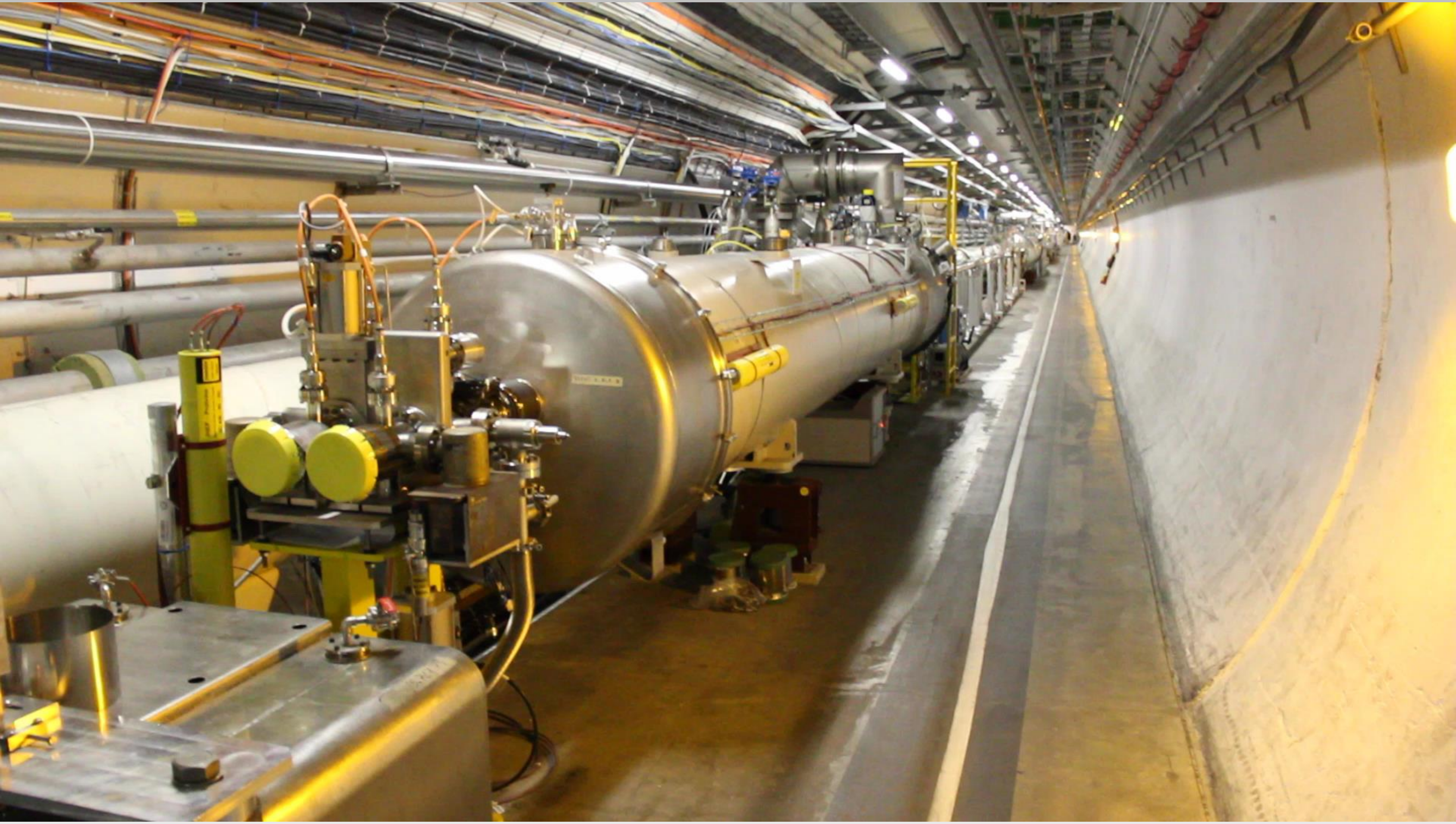
LHC-FBCT Average Lifetime

FBCT Average Beam Lifetime in h

Updated: 06:09:26

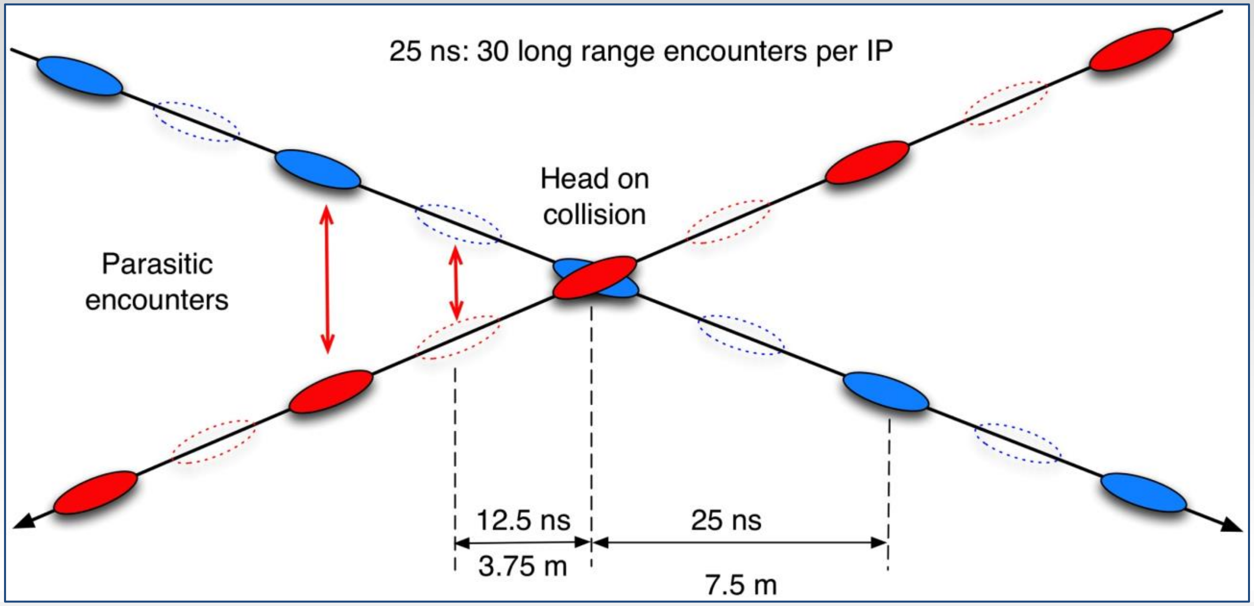
LHC-FBCT History Lifetime

In the long straight section



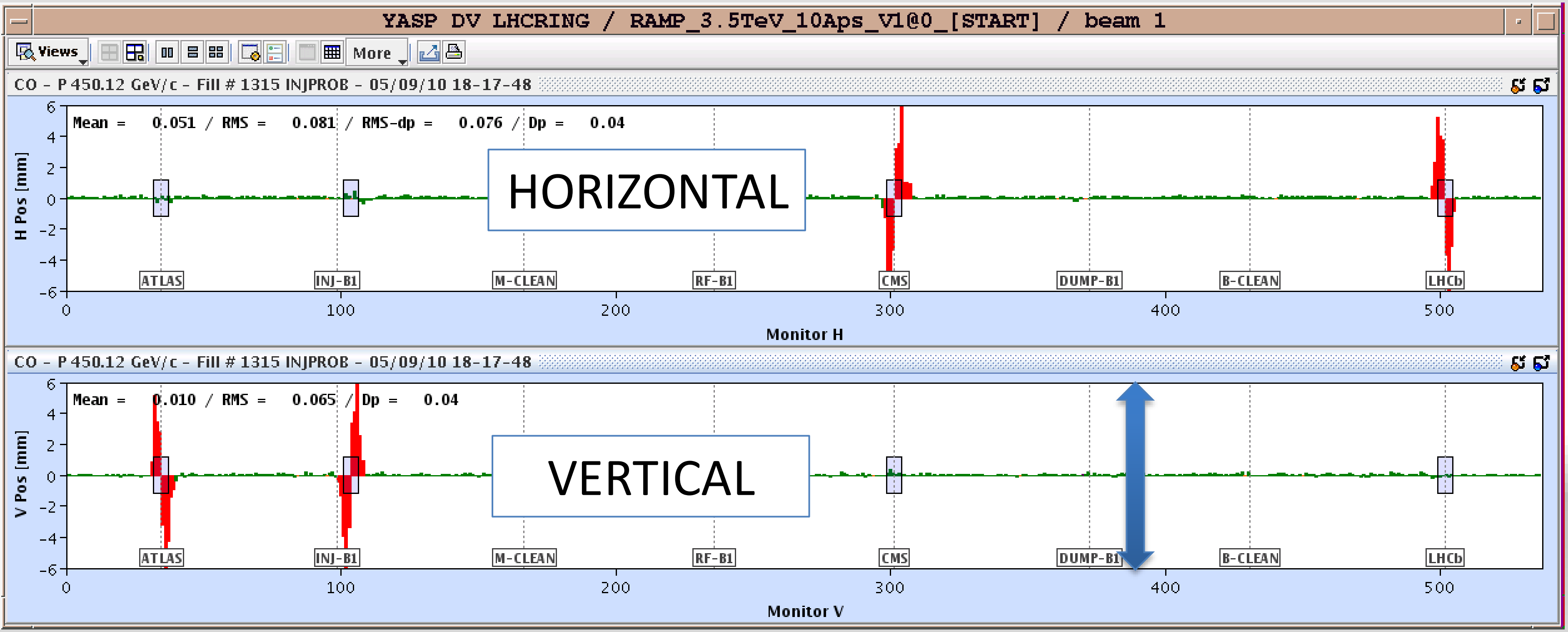
Crossing angle

work with a crossing angle to avoid parasitic collisions.



- generates additional tune shift
- requires larger triplet magnet aperture
- breaks symmetry between x,y planes
- odd order resonances are exited
- couples longitudinal and transverse motion
- breaks the bunch symmetry
- lowers available luminosity

In practice



YASP DV LHCRING / RAMP_3.5TeV_10Aps_V1@0_[START] / beam 1

CO - P 450.12 GeV/c - Fill # 1315 INJPROB - 05/09/10 18-17-48

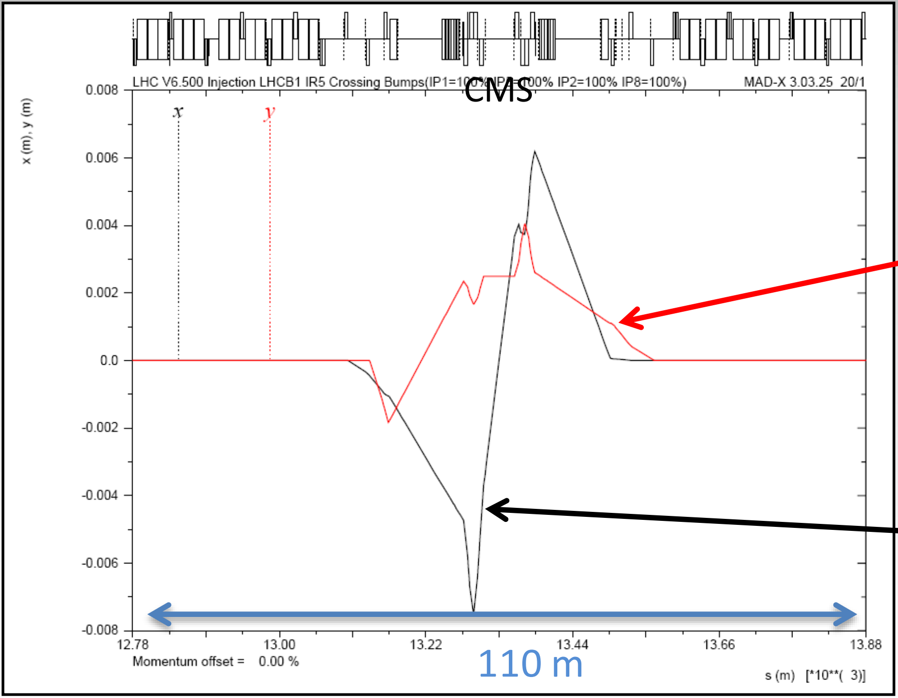
Mean = 0.051 / RMS = 0.081 / RMS-dp = 0.076 / Dp = 0.04

CO - P 450.12 GeV/c - Fill # 1315 INJPROB - 05/09/10 18-17-48

Mean = 0.010 / RMS = 0.065 / Dp = 0.04

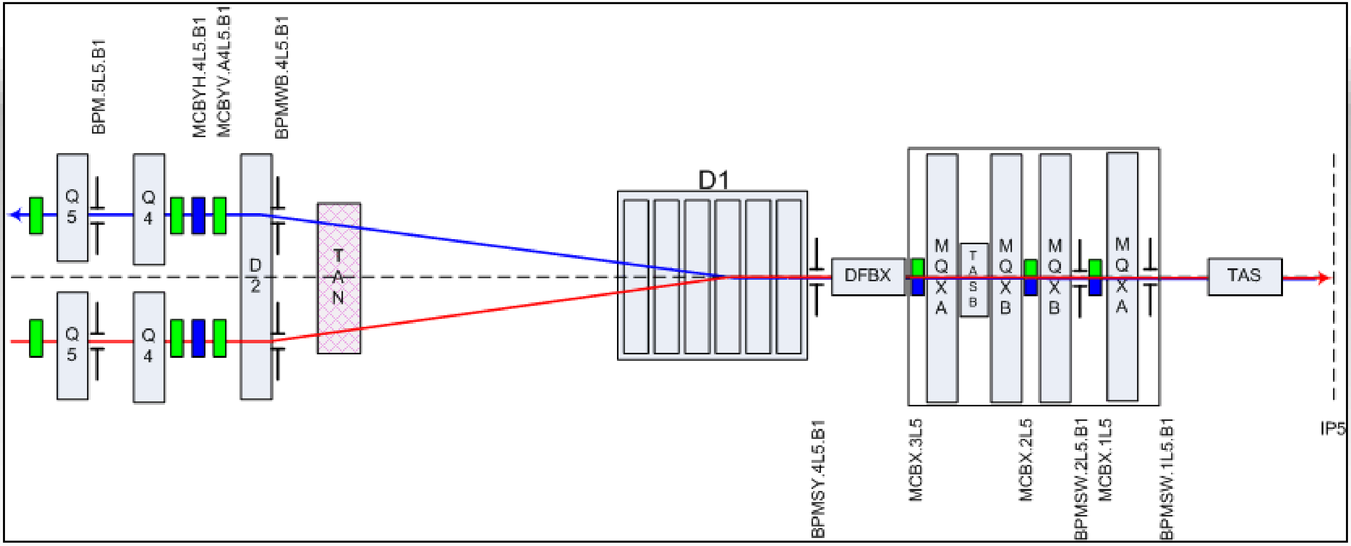
+/- 6 mm at 450 GeV

Crossing and Separation Bumps

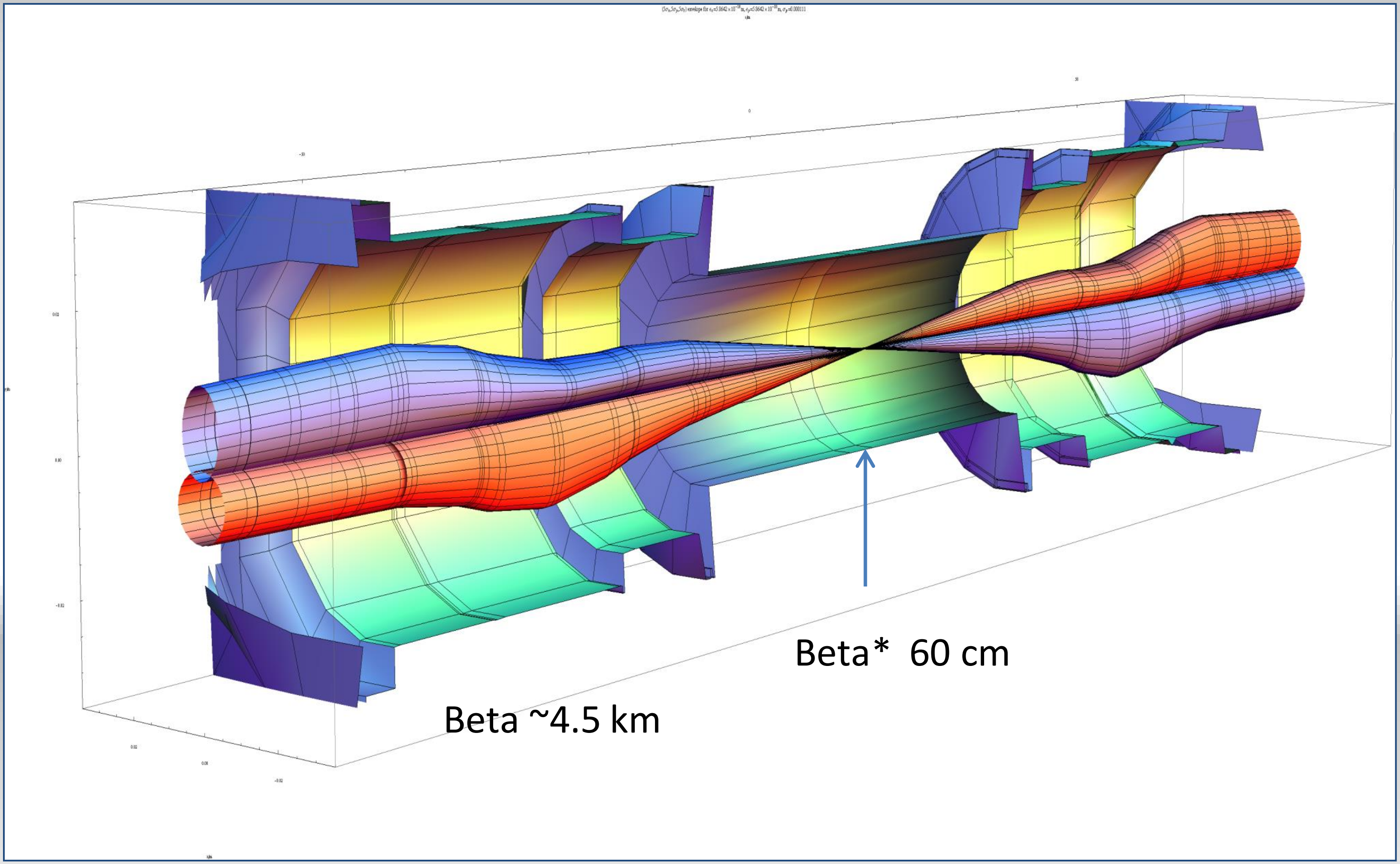


Collapse the separation bump after the squeeze to bring the beams into collision

Crossing angle bump

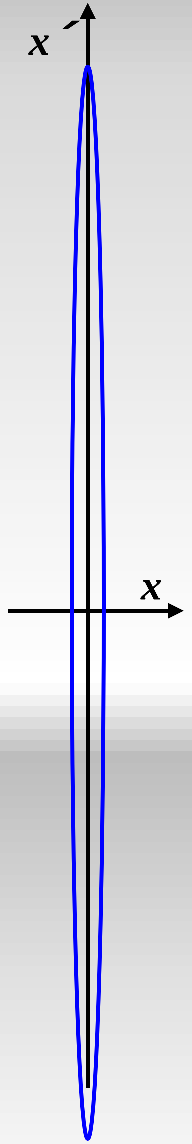


Squeeze in ATLAS



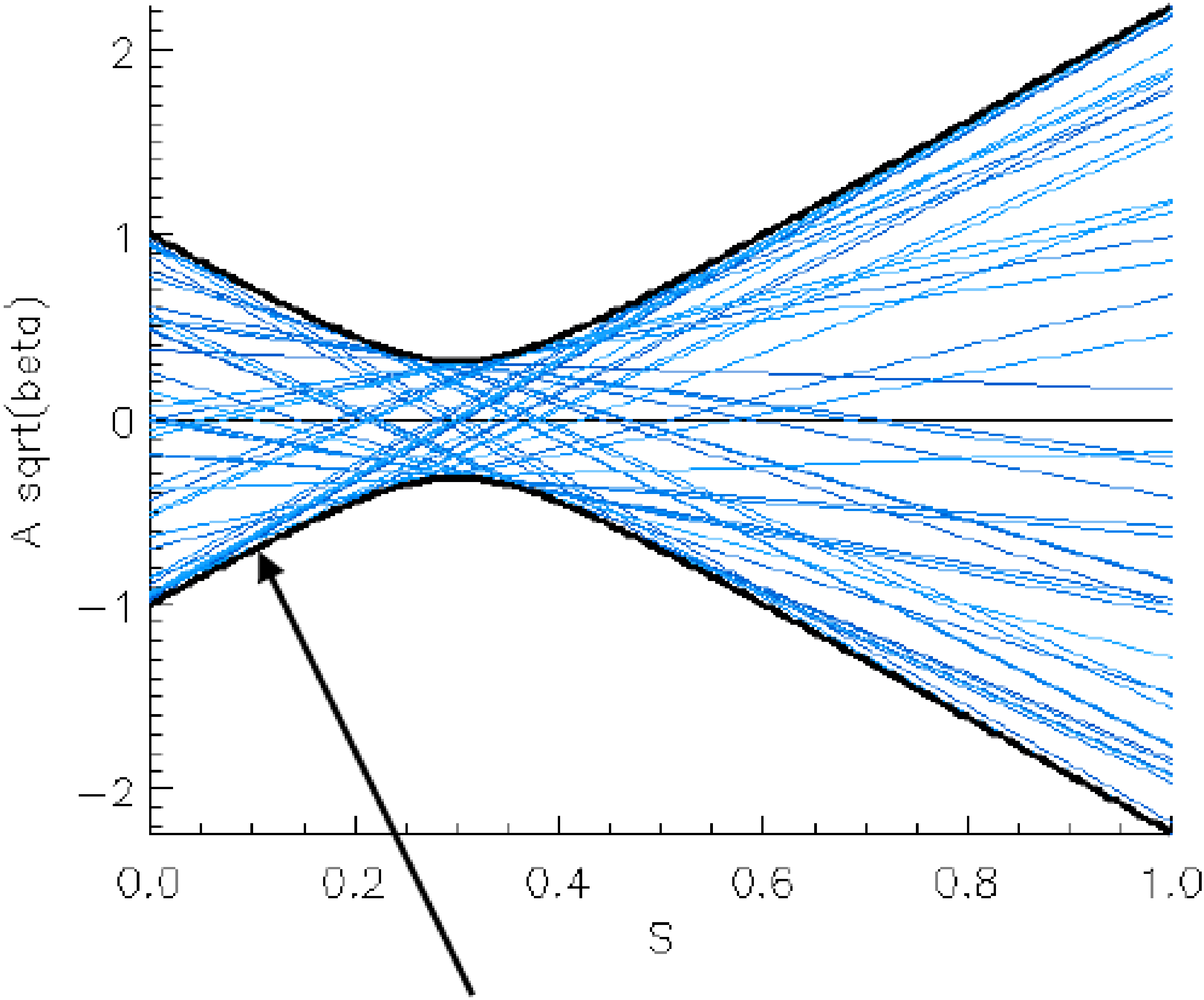
Beta* 60 cm

Beta ~4.5 km



NB: round beams

Image courtesy John Jowett



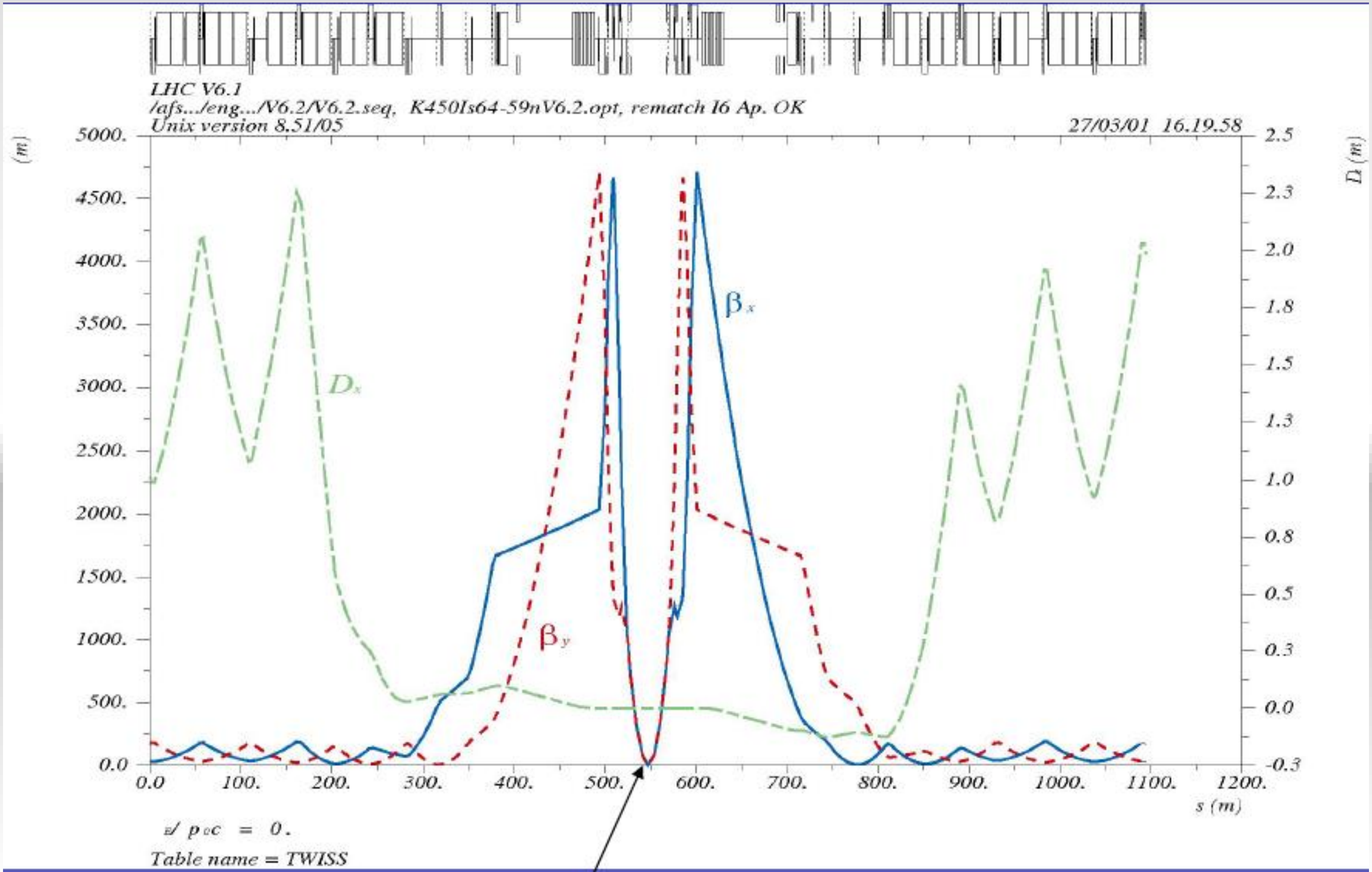
beam envelope

$$x_{\max}(s) = A\sqrt{\beta(s)}$$

Beam - Squeeze

Small beam in the IP → big beams in the inner triplets → reduced aperture

Therefore inject & ramp with bigger beam sizes at IP.

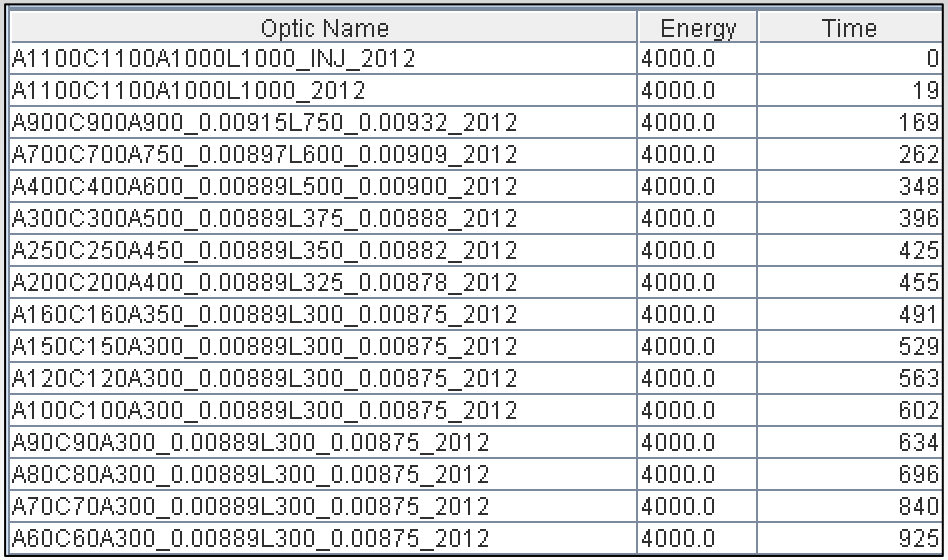


Triplets

Squeeze in practice

Matched optics

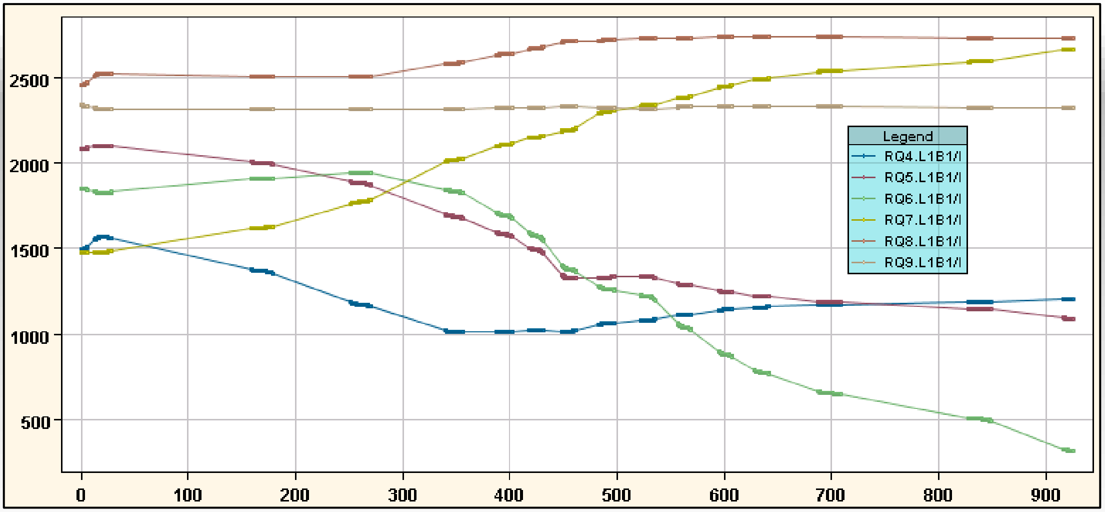
Time in seconds



Optic Name	Energy	Time
A1100C1100A1000L1000_INJ_2012	4000.0	0
A1100C1100A1000L1000_2012	4000.0	19
A900C900A900_0.00915L750_0.00932_2012	4000.0	169
A700C700A750_0.00897L600_0.00909_2012	4000.0	262
A400C400A600_0.00889L500_0.00900_2012	4000.0	348
A300C300A500_0.00889L375_0.00888_2012	4000.0	396
A250C250A450_0.00889L350_0.00882_2012	4000.0	425
A200C200A400_0.00889L325_0.00878_2012	4000.0	455
A160C160A350_0.00889L300_0.00875_2012	4000.0	491
A150C150A300_0.00889L300_0.00875_2012	4000.0	529
A120C120A300_0.00889L300_0.00875_2012	4000.0	563
A100C100A300_0.00889L300_0.00875_2012	4000.0	602
A90C90A300_0.00889L300_0.00875_2012	4000.0	634
A80C80A300_0.00889L300_0.00875_2012	4000.0	696
A70C70A300_0.00889L300_0.00875_2012	4000.0	840
A60C60A300_0.00889L300_0.00875_2012	4000.0	925

Beta* - 11 m ATLAS, CMS; 10 m in ALICE, LHCb

Beta* - 0.6 m ATLAS, CMS; 3 m in ALICE, LHCb



Current during the squeeze in a few quads at point 1

Luminosity

$$L = F\,\frac{N_{b1}N_{b2}\,f_{rev}k_b}{2\pi\sqrt{\left(\sigma_{x1}^2+\sigma_{x2}^2\right)\left(\sigma_{y1}^2+\sigma_{y2}^2\right)}}\,.\exp\left\{-\frac{\left(\bar{x}_1-\bar{x}_2\right)^2}{2\left(\sigma_{x1}^2+\sigma_{x2}^2\right)}-\frac{\left(\bar{y}_1-\bar{y}_2\right)^2}{2\left(\sigma_{y1}^2+\sigma_{y2}^2\right)}\right\}$$

$$F = \frac{1}{\sqrt{1+\left(\frac{\theta_c\sigma_z}{2\sigma^*}\right)^2}}$$

N_1, N_2 number of particles per bunch

k – number bunches per beam

f – revolution frequency

σ* – beam size at IP

θ_c – crossing angle

σ_z – bunch length

Make some simplifying assumptions:

- **beam 1 = beam 2**
- **round beams at interaction point**

Luminosity

$$L = \frac{N^2 k_b f}{4\pi\sigma_x^*\sigma_y^*}F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*}F$$

N	**Number of particles per bunch**
k_b	**Number of bunches**
f	Revolution frequency
σ*	**Beam size at interaction point**
F	Reduction factor due to crossing angle
ε	Emittance
ε_n	**Normalized emittance**
β*	**Beta function at IP**

$$\sigma^* = \sqrt{\beta^*\varepsilon}$$

$$\varepsilon_N = 2.5 \times 10^{-6}\ \text{m.rad}$$

$$\varepsilon = 3.35 \times 10^{-10}\ \text{m.rad}$$

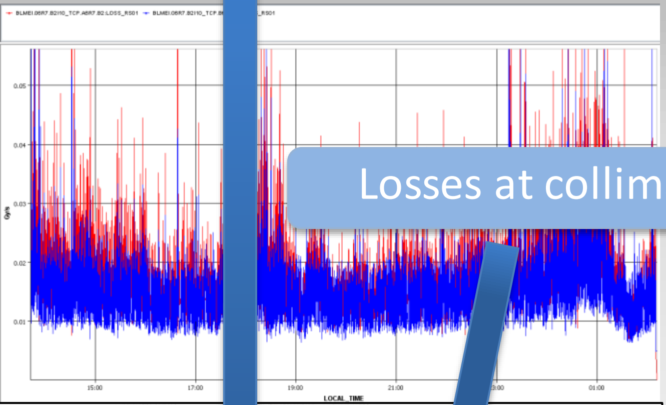
$$\sigma^* = 11.6 \times 10^{-6}\ \text{m}$$

$$\left(p = 7\ \text{TeV},\ \beta^* = 0.4\ \text{m}\right)$$

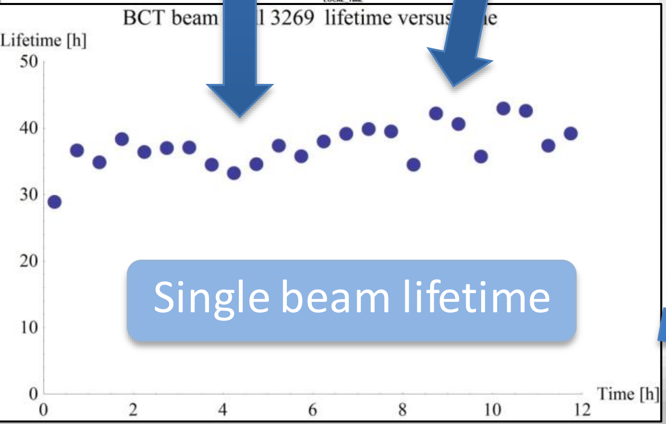
Reasonably comfortable life in Stable Beams

Luminosity burn

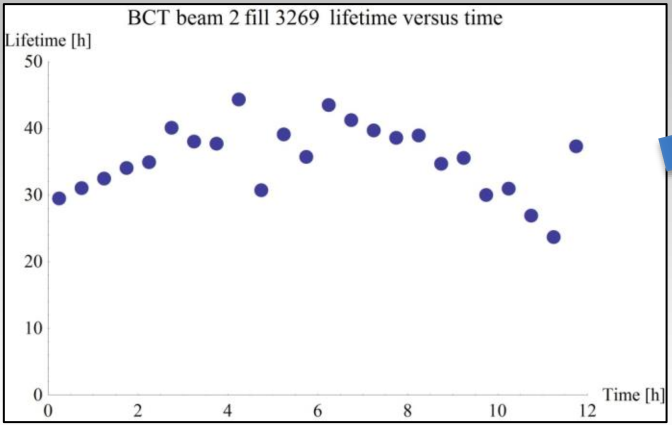
Beam-gas

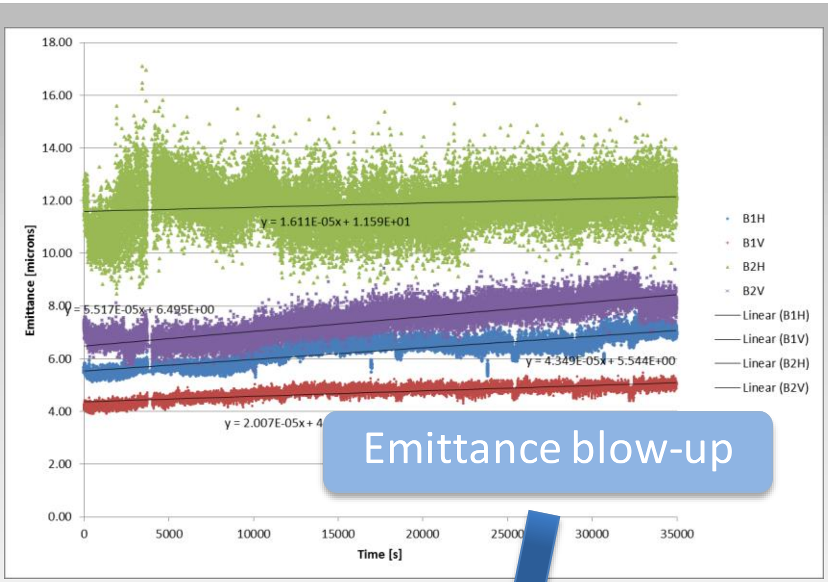


Losses at collimators

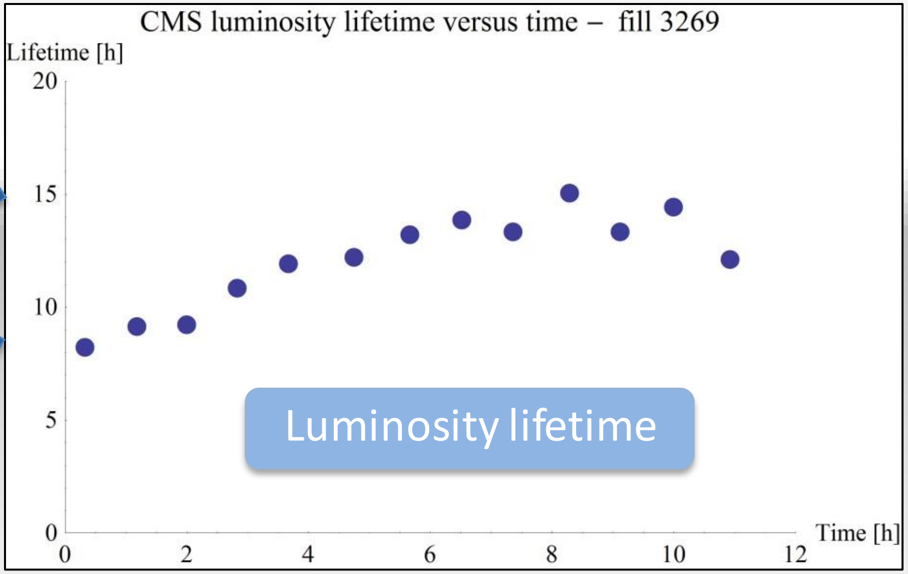

BCT beam 1 fill 3269 lifetime versus time

Single beam lifetime


BCT beam 2 fill 3269 lifetime versus time



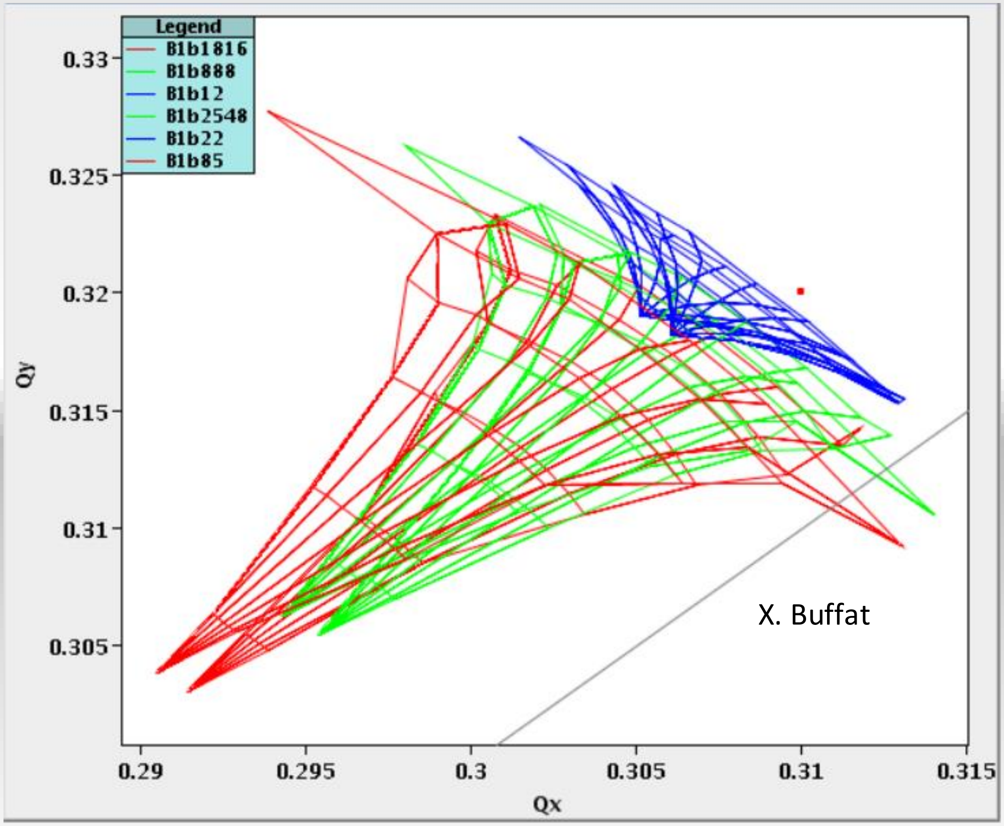
Emittance blow-up


CMS luminosity lifetime versus time – fill 3269

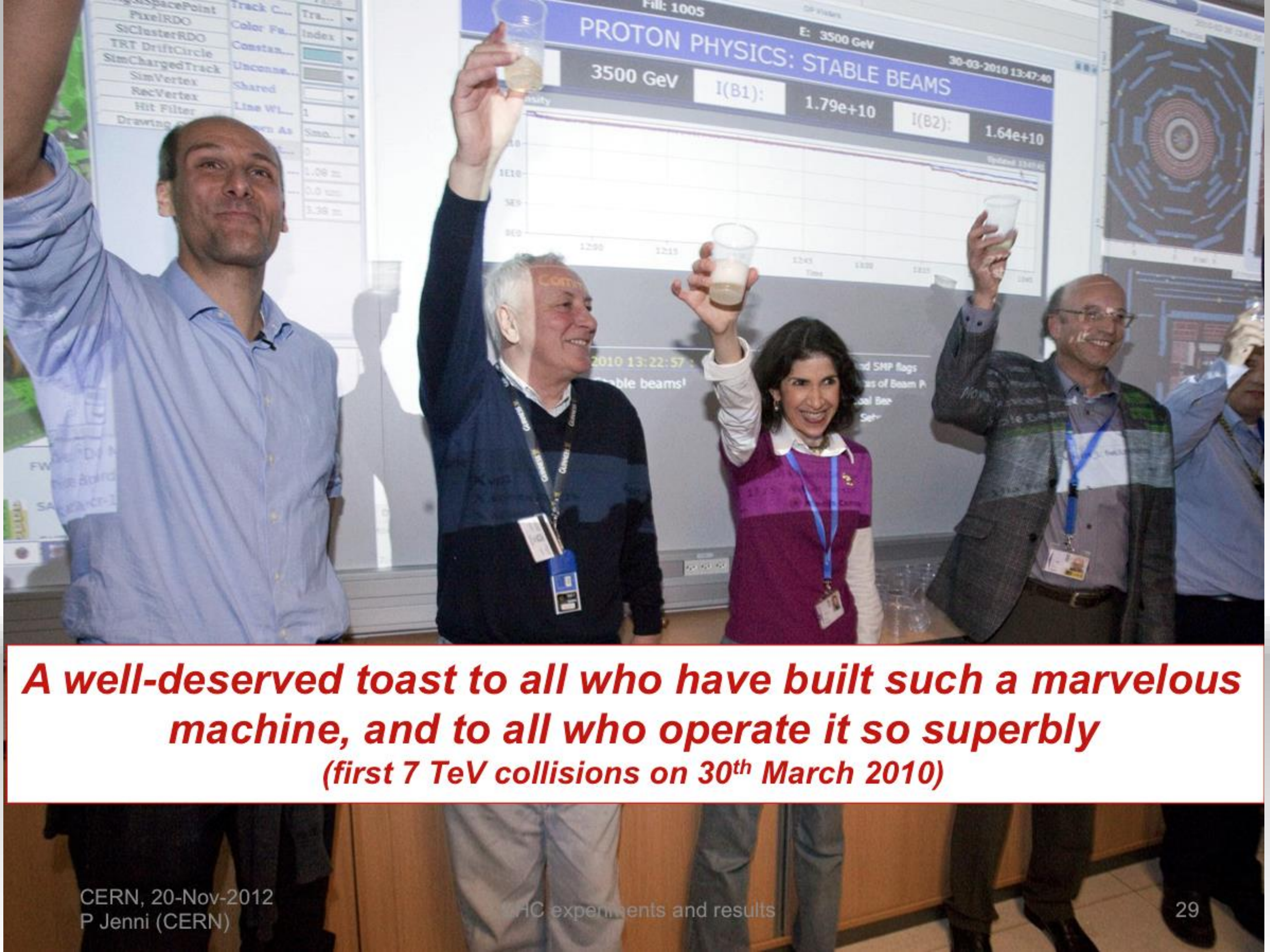
Luminosity lifetime

Beam-beam

- Head-on beam-beam is not an operational limitation
- Linear head-on parameter in operation ~0.02 (up to 0.034 in MD)
- Long range taken seriously
- Interesting interplay with the instabilities seen in 2012…



X. Buffat



A well-deserved toast to all who have built such a marvelous machine, and to all who operate it so superbly

(first 7 TeV collisions on 30th March 2010)

First 7 TeV collisions – another view

You lucky, lucky buggers!!!

30-Mar-2010 12:28:46 Fill #: 1005 Energy: 2982.0 GeV I(B1): 2.00e+10 I(B2): 2.01e+10

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	PHYSICS	STANDBY	STANDBY
Instantaneous Luminosity	1.746e-05	0.000e+00	1.621e-07	0.000e+00
BRAN Count Rate	2.987e+00	6.158e-02	2.166e+01	1.779e+00
BKGD 1	0.002	0.011	0.002	0.150
BKGD 2	0.000	0.000	0.000	0.373
BKGD 3	0.000	0.005	0.000	0.034

LHCf STANDBY Count(Hz): 0.000 | LHCb VELO Position OUT Gap: 58.0 mm | TOTEM: CALIBRATION

Monitoring set: S34-A34-RB 30 March, 2010, 12:28:49

RB.A34 [5023 A] [2.97 TeV]

LHC Page1 Fill: 1005 E: 2986 GeV 30-03-2010 12:28:49

BEAM SETUP: RAMP

Energy: 2986 GeV I(B1): 1.82e+10 I(B2): 1.85e+10

Comments 30-03-2010 11:52:19 :

Ramping again

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

PM Status B1 ENABLED PM Status B2 ENABLED

LHC Operation in CCC : 77600, 70480

MACHINE PROTECTION

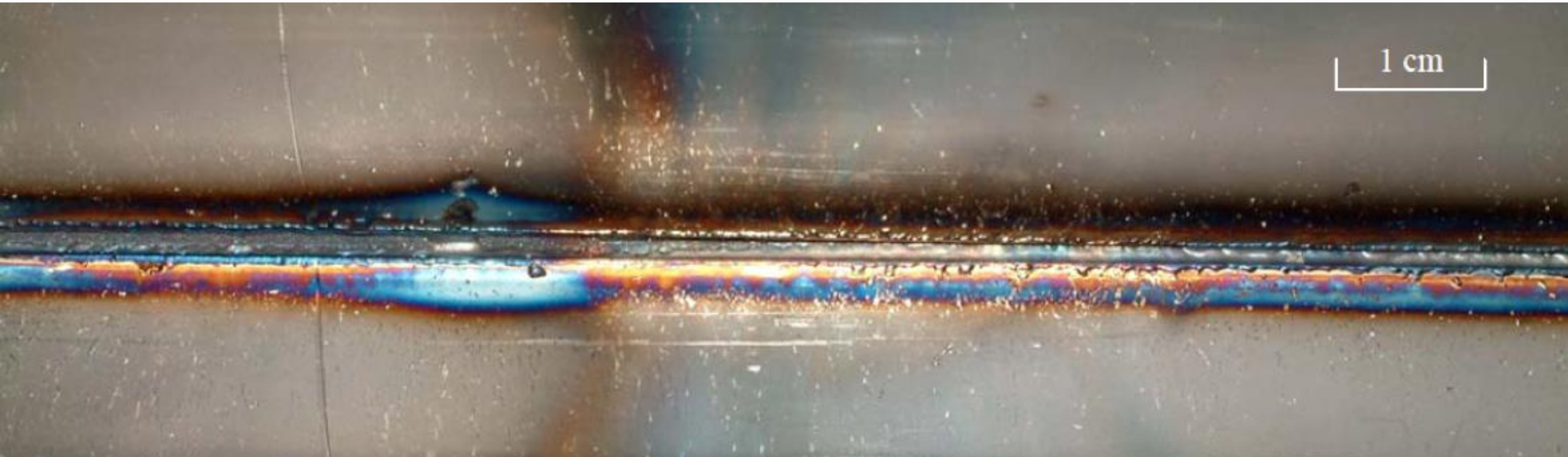
Energy

4 TeV with 1380 bunches – 2012

- ❑**~3.6 GJ** of energy stored in the main dipoles
- ❑**140 MJ** stored in each beam ~21 kg of TNT.

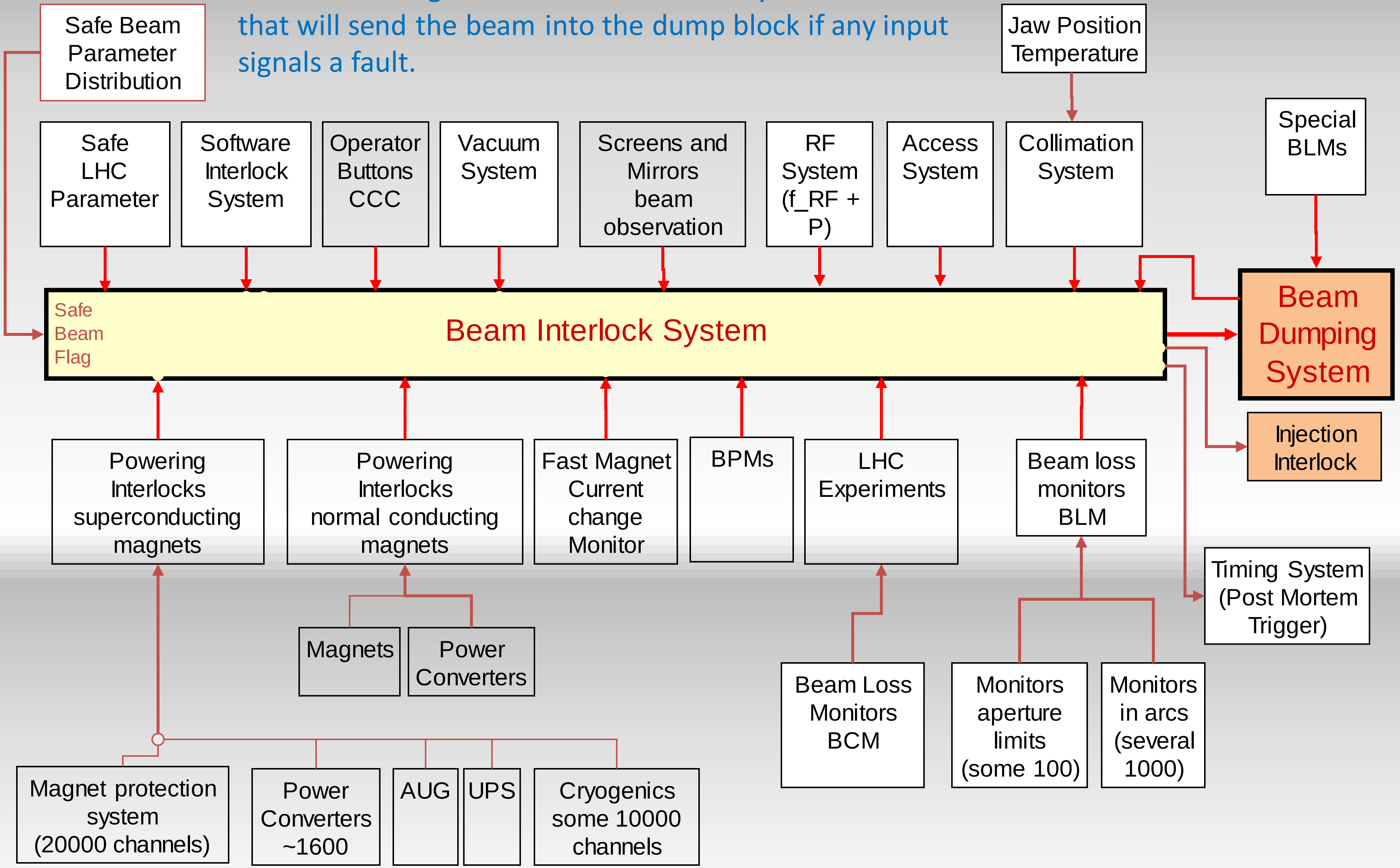
During an SPS extraction test in 2005…

The beam was a 450 GeV full LHC injection batch of 3.4 10^{13} p+ in 288 bunches **[2.5 MJ]**

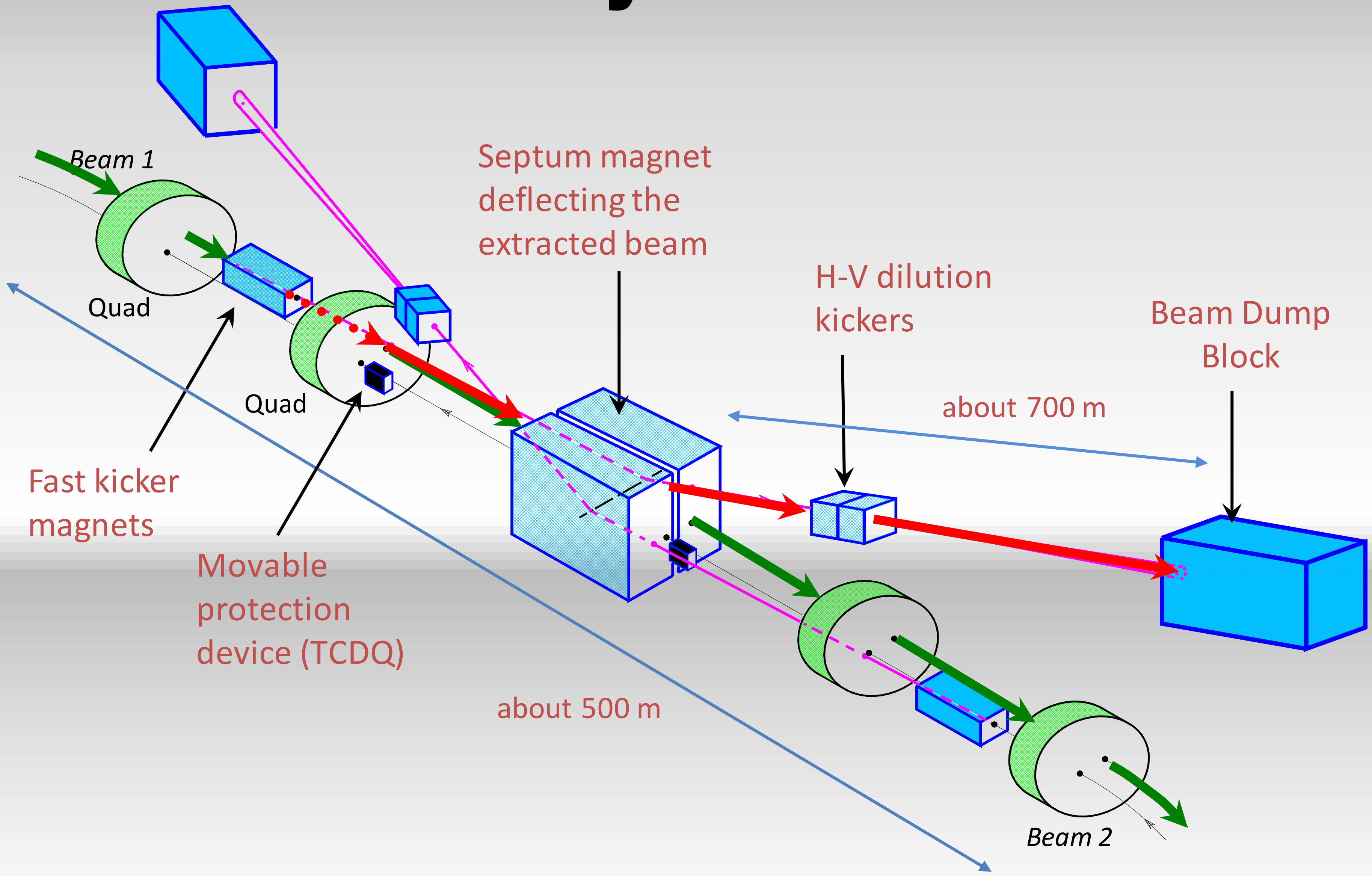


Beam Interlock System

Over 10’000 signals enter the interlock system of the LHC that will send the beam into the dump block if any input signals a fault.



Layout of LHC beam dumping system



Septum magnet deflecting the extracted beam

H-V dilution kickers

Beam Dump Block

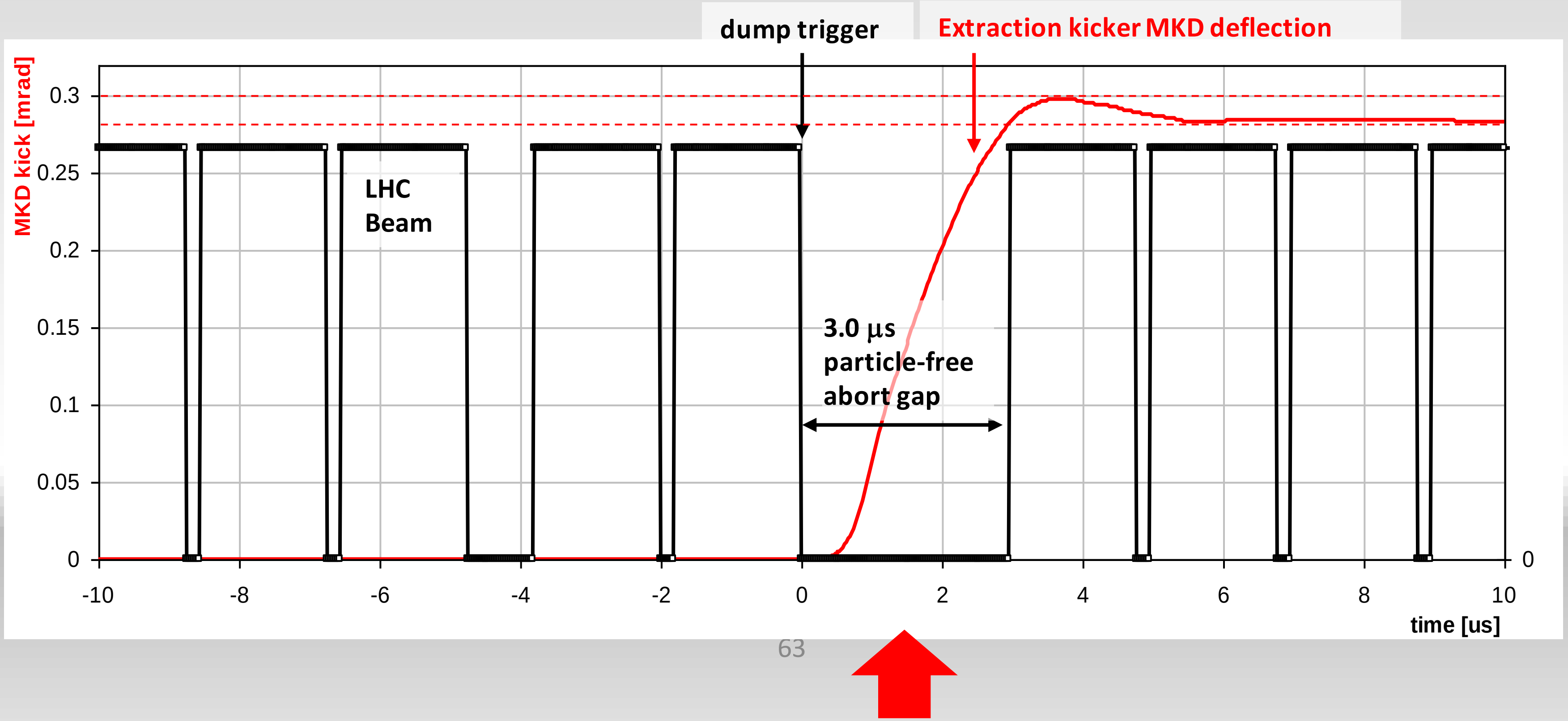
about 700 m

Fast kicker magnets

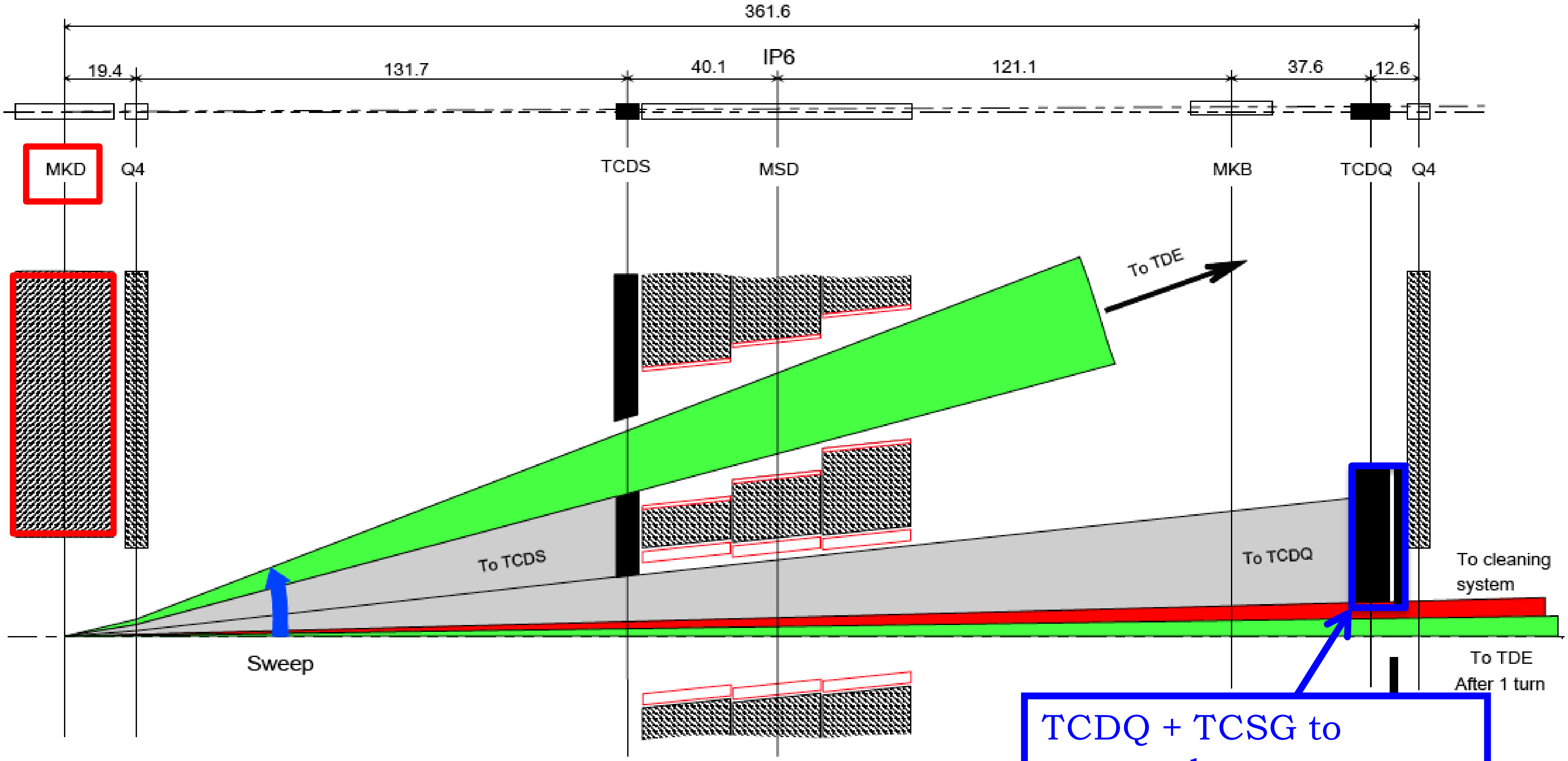
Movable protection device (TCDQ)

about 500 m

Abort Gap


dump trigger
Extraction kicker MKD deflection
MKD kick [mrad]
0.3
0.25
0.2
0.15
0.1
0.05
0
LHC
Beam
3.0 μs
particle-free
abort gap
-10
-8
-6
-4
-2
0
2
4
6
8
10
time [us]
0

Asynchronous Beam Dump



TCDQ + TCSG to protect downstream superconducting magnets (Q4)

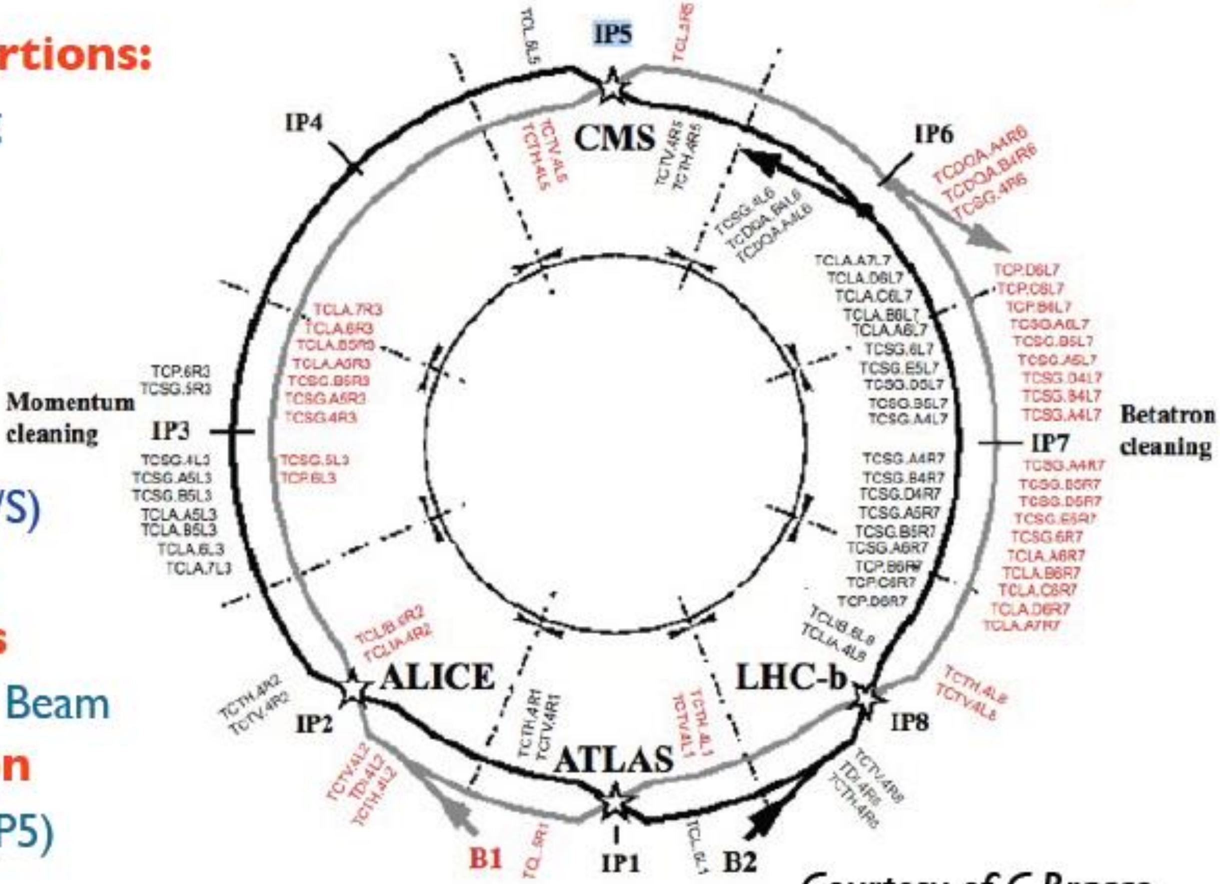
TCDQ = 6 m long CFC* one-sided collimator
TCSG = 1 m long CFC* two-sided collimator

*CFC = carbon fibre compound

Estimated occurrence : at least once per year, 0 events up to now!

LHC Collimation Layout

- **Two warm cleaning insertions:**
  - IR3: momentum cleaning
    - 1 Primary (H)
    - 4 Secondaries (H/S)
    - 4 Shower Abs. (H/V)
  - IR7: betatron cleaning
    - 3 Primaries (H/V/S)
    - 11 Secondaries (H/V/S)
    - 5 Shower Abs. (H/V)
- **Local cleaning at triplets**
  - 8 tertiaries: 2 per IP per Beam
- **Physics debris absorption**
  - 2 TCL (1 per beam IP1/IP5)



Courtesy of C.Bracco

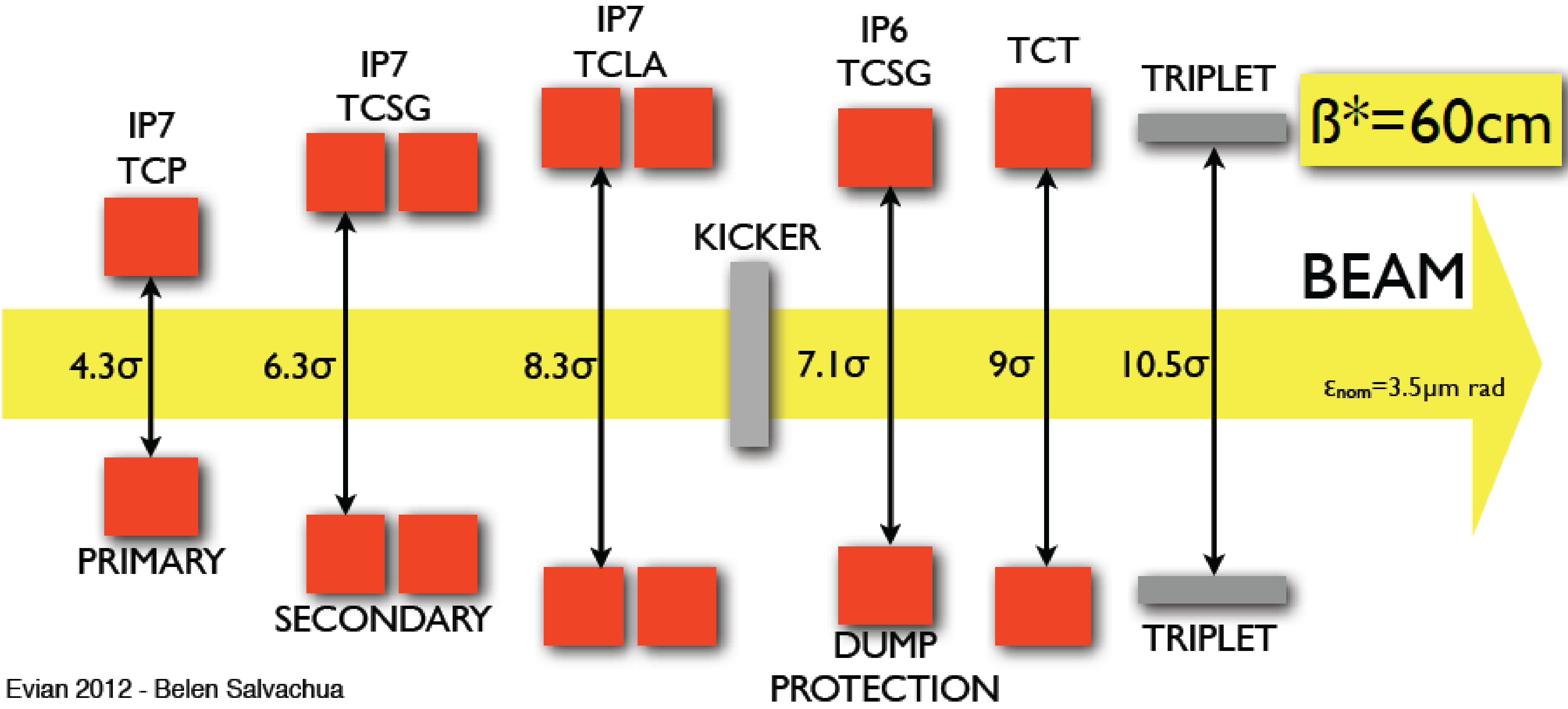
8 passive absorbers for warm magnets in IP3/IP7

Transfer lines (13 collimators)

Injection and dump protection (10 collimators)

Total of 108 collimators
(100 movable)

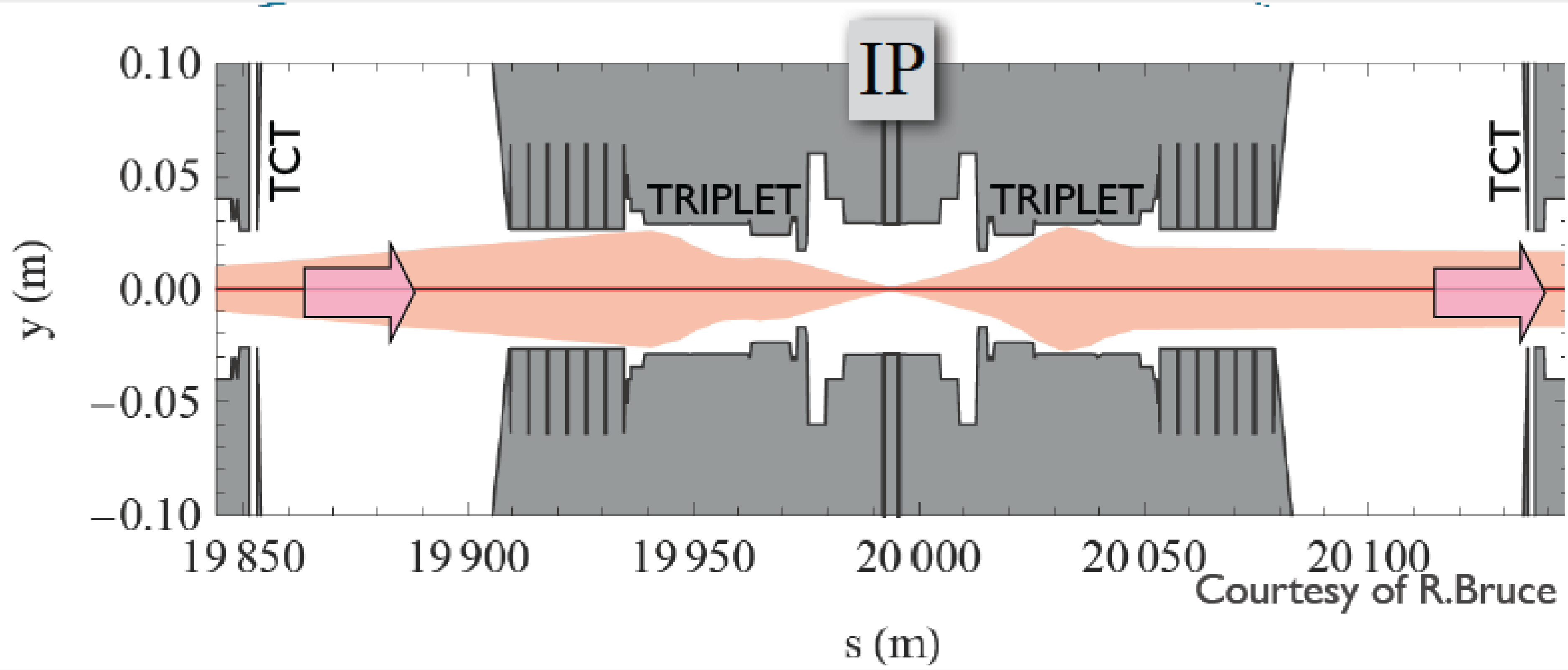
Collimator hierarchy



Evian 2012 - Belen Salvachua

Collimator hierarchy

- Normalized Triplet aperture decreases when reducing β*
- Triplet aperture MUST be protected by the tertiary collimators (TCTs)
- At the same time, TCTs must be shadowed by the dump protection
- Dump protection must be outside the primary and secondary collimators

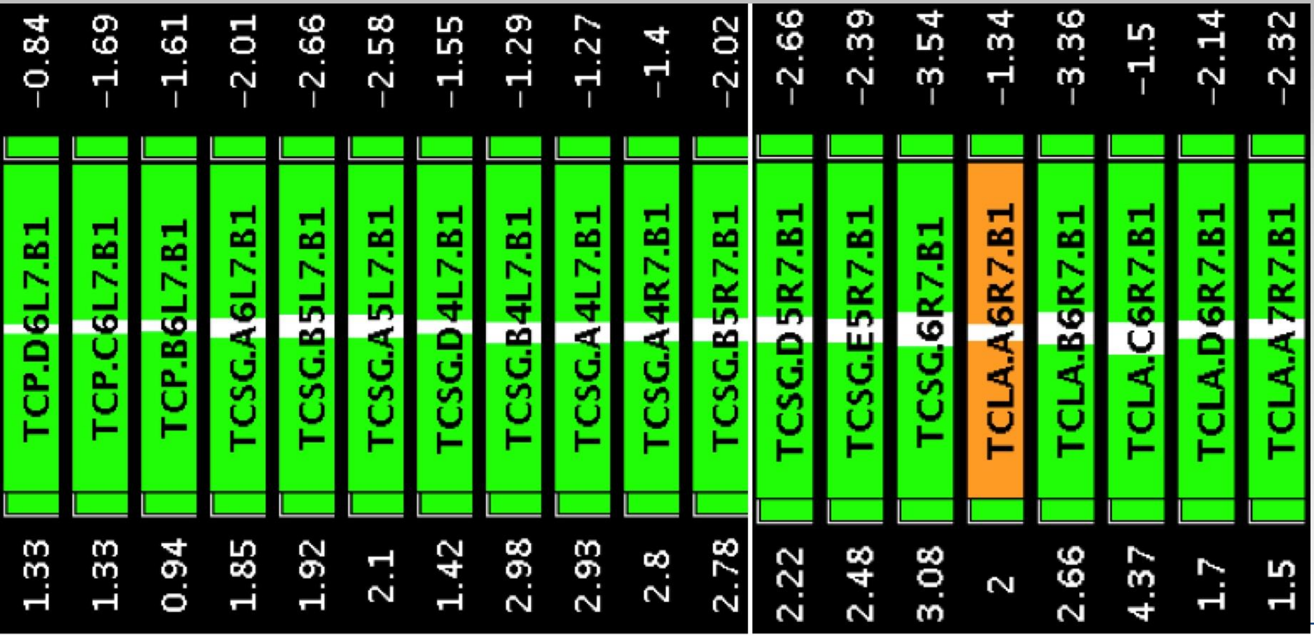


Courtesy of R.Bruce

Collimator hierarchy

- The hierarchy must be respected at all times.
- The collimators and protection devices are positioned with respect to the closed orbit
- Therefore the closed orbit must be in tolerance at all times.
- This includes the ramp and squeeze.
  - Orbit feedback becomes mandatory
  - Interlocks on orbit position become mandatory

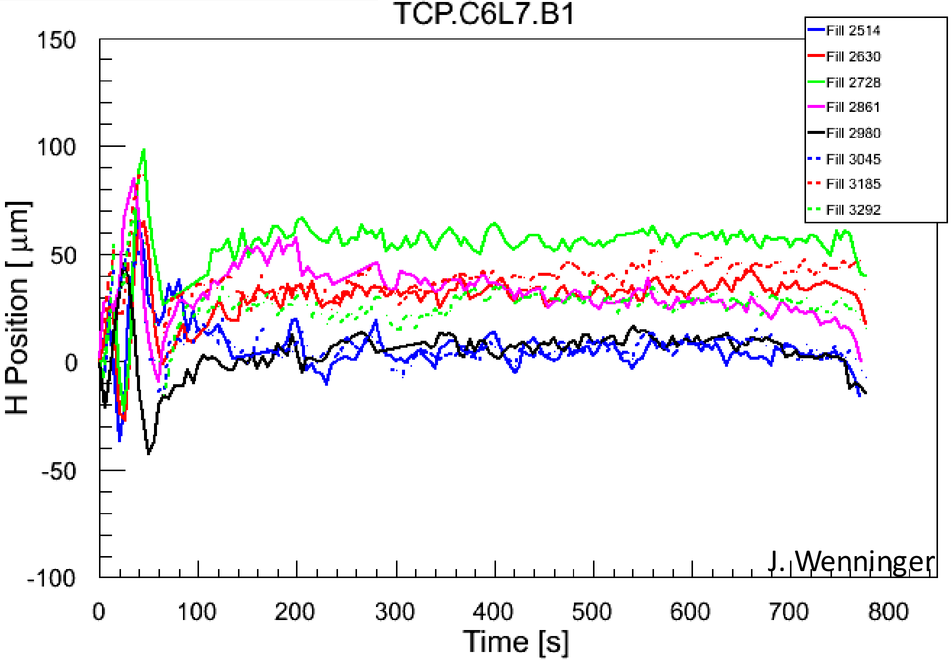
Collimation/reproducibility



TCP.D6L7.B1	-0.84	1.33
TCP.C6L7.B1	-1.69	1.33
TCP.B6L7.B1	-1.61	0.94
TCSG.A6L7.B1	-2.01	1.85
TCSG.B5L7.B1	-2.66	1.92
TCSG.A5L7.B1	-2.58	2.1
TCSG.D4L7.B1	-1.55	1.42
TCSG.B4L7.B1	-1.29	2.98
TCSG.A4L7.B1	-1.27	2.93
TCSG.A4R7.B1	-1.4	2.8
TCSG.B5R7.B1	-2.02	2.78
TCSG.D5R7.B1	-2.66	2.22
TCSG.E5R7.B1	-2.39	2.48
TCSG.6R7.B1	-3.54	3.08
TCLA.A6R7.B1	-1.34	2
TCLA.B6R7.B1	-3.36	2.66
TCLA.C6R7.B1	-1.5	4.37
TCLA.D6R7.B1	-2.14	1.7
TCLA.A7R7.B1	-2.32	1.5

IR7 collimators – beam 1

Orbit at primary

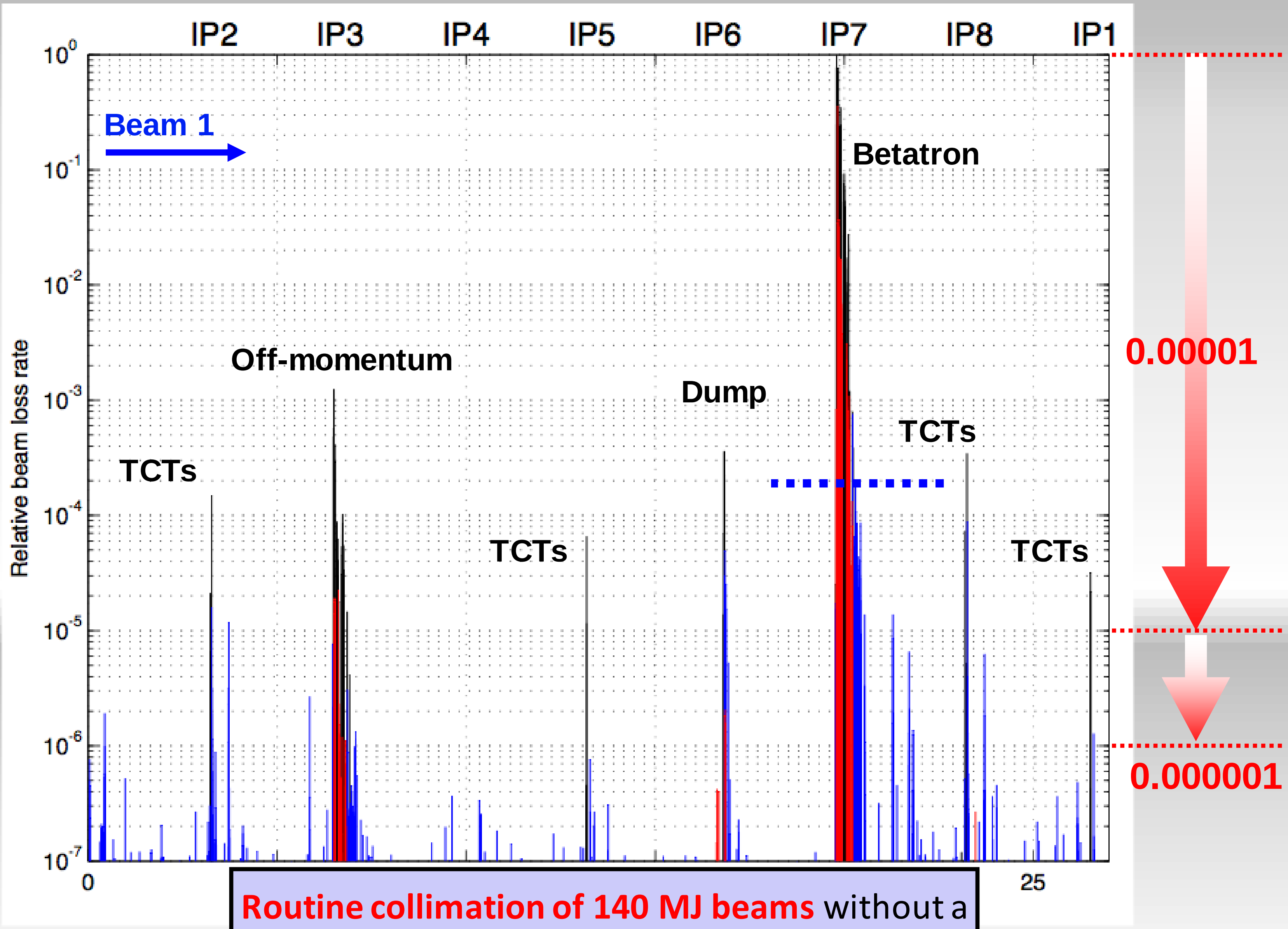


J. Wenninger

2011-2012: only ONE full alignment in IR3/IR7

Collimation

Generate higher loss rates: excite beam with transverse dampers



Legend:
Collimators
Cold losses
Warm losses

Routine collimation of 140 MJ beams without a single quench from stored beam