ÉCOLE DE PHYSIQUE
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The LHC Machine: commissioning and operation

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- Introduction and key parameters
- The injectors
- Milestones
- Beam commissioning and beam physics
- Ions

Acknowledgements: G. Arduini, R. Assmann, R. Bailey, O. Brüning, L. Evans, W. Herr, J. Jowett, M. Lamont, E. Métral, K.-H. Mess, G. Rumolo, E. Todesco, R. Tomás, J. Wenninger, F. Zimmermann *et al.*

Introduction

- Large Electron Positron (LEP) collider:
  - It was essentially a Z_0 factory.
  - It allowed accurate measurements of standard model features.
  - Unfortunately, it did not find the Higgs!
- The characteristics of the next collider (in the same LEP tunnel):
  - Higher energy then LEP.
    - This imposes to switch to hadrons due to synchrotron radiation.
    - This imposes to use superconducting magnets due to the fixed tunnel radius.
  - High luminosity
    - This imposes to have p-p collisions. The generation of p-bar is very inefficient and it is difficult to produce enough intensity.
    - This, in turn, imposes to have two separate rings.
- In summary:

LHC is a two-ring, high-energy, high-luminosity, p-p collider.

Synchrotron radiation - I

- Power radiated by an accelerating particle (in our case on a curved trajectory)

$$P_{\perp} = \frac{q^2 \, c \, \beta^4 \, E^4}{6 \, \pi \, \varepsilon_0 \, \rho^2 \, E_0^4}$$

- Energy radiated in one turn

$$U_0 = \frac{q^2 \, \beta^3 \, E^4}{3 \, \varepsilon_0 \, E_0^4 \, \rho}$$

- Average power radiated over one turn

$$P_{av} = \frac{U_0}{T_0}$$

Synchrotron radiation - II

- Comparison between the energy radiated per turn in LEP and LHC.

	LEP	LHC
ρ [m]	**3096.175**	**2803.95**
p_0 [GeV/c]	**104**	**7000**
U_0 [GeV]	**3.3**	**6.7 10^{-6}**

- In LEP the RF system compensated for an energy loss of ~3% of the total beam energy per turn!
- In LHC the RF should compensate for an energy loss of 10^{-7}% of the total beam energy per turn!
- The total average power radiation (per beam) is 3.9 kW.

Magnetic field

- The magnetic field required to keep a particle of momentum p_0 on a trajectory of radius ρ is given by

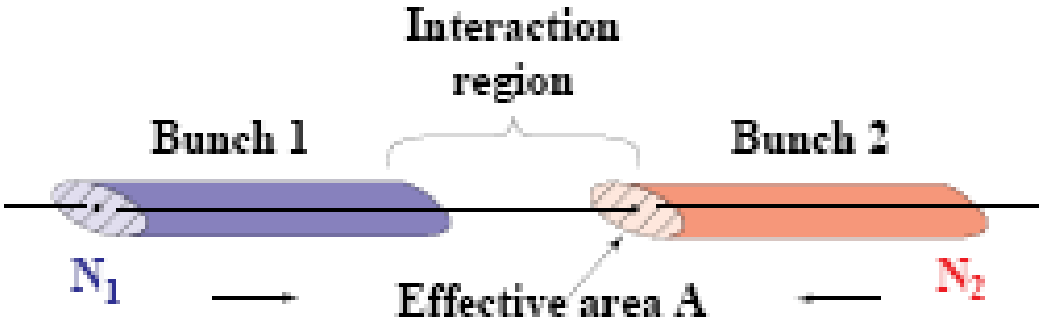
$$B\rho\left[\mathrm{T\,m}\right]=3.3356\ p_0\left[\mathrm{GeV/c}\right]$$

	LEP	LHC
ρ [m]	**3096.175**	**2803.95**
p_0 [GeV/c]	**104**	**7000**
B [T]	**0.11**	**8.33**

- The magnetic field chosen is the current technological limit.
- The slightly different ρ for LEP and LHC is due to some slight changes in the ring geometry.

Luminosity - I

$$L = \frac{N_{events/second}}{\sigma_{event}}$$



- The Luminosity depends only on beam parameters

$$L = \frac{N_b^2\ M\ f_{rev}\ \gamma_r}{4\,\pi\,\varepsilon_n\,\beta^*}\ F$$

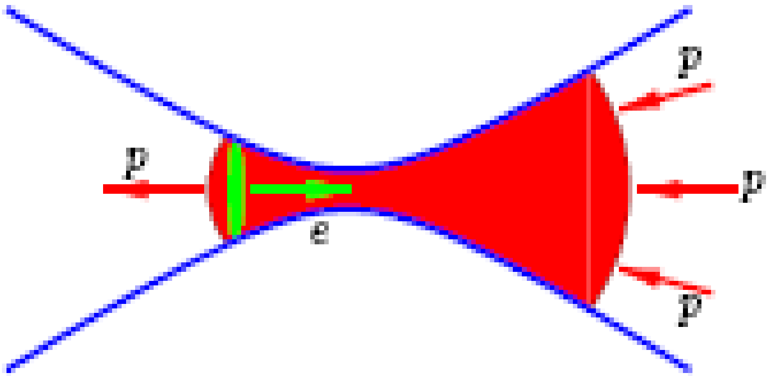
- Unfortunately, head-on collisions are not always possible. In this case a geometrical reduction factor F has to be taken into account

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

Luminosity - II

- Unfortunately, the beam size is changing along the bunch (hourglass effect). This introduces an additional factor of luminosity reduction. This effect is not relevant for the LHC.

- Peak luminosity for ATLAS and CMS in the LHC is $1\times10^{34}\text{cm}^{-2}\text{s}^{-1}$.



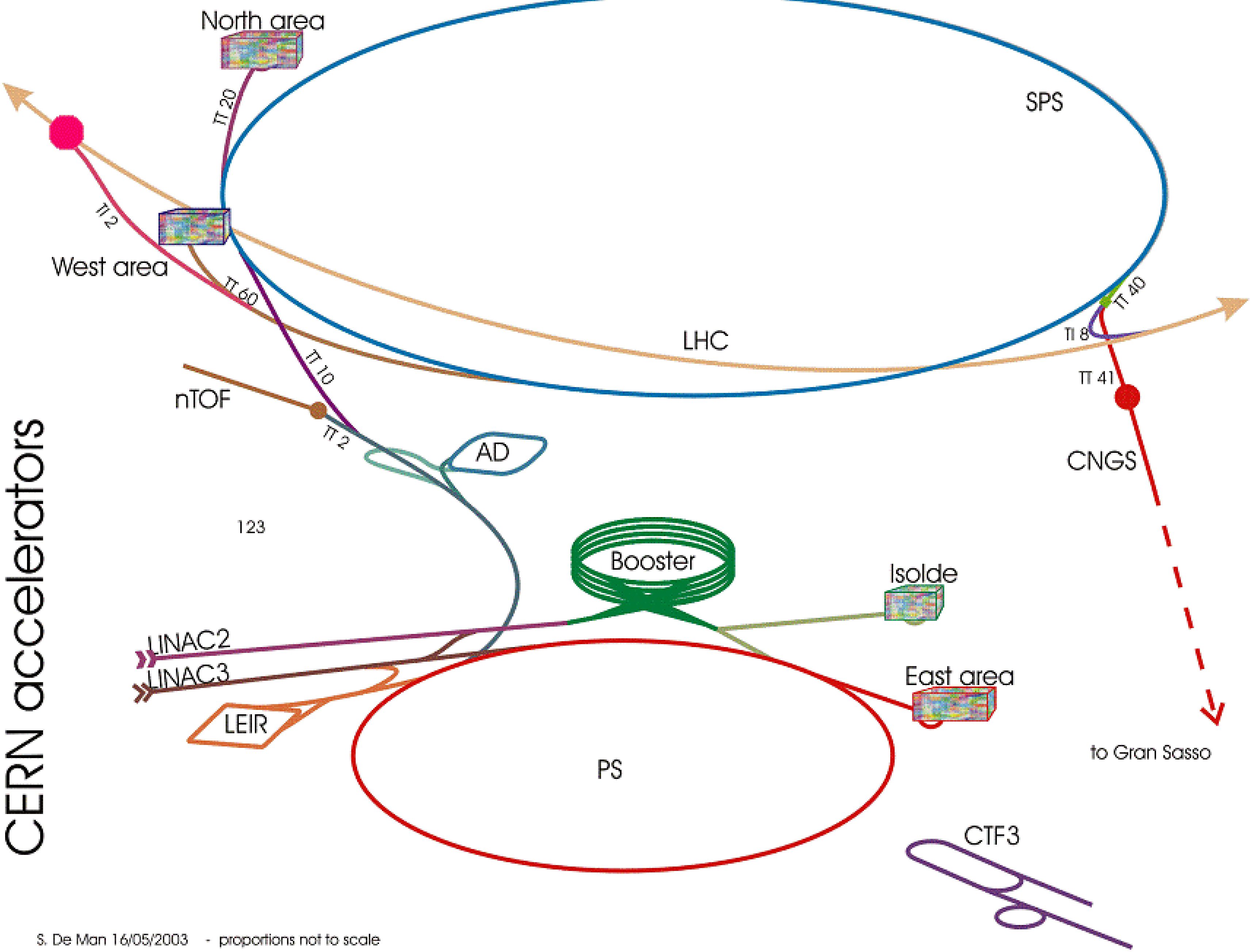
- Expected LHC integrated luminosity per year (~10^7 s) is 80-120 fb^{-1}.

$$L_{\text{int}} = \int_0^T L(t)\,dt$$

Key parameters

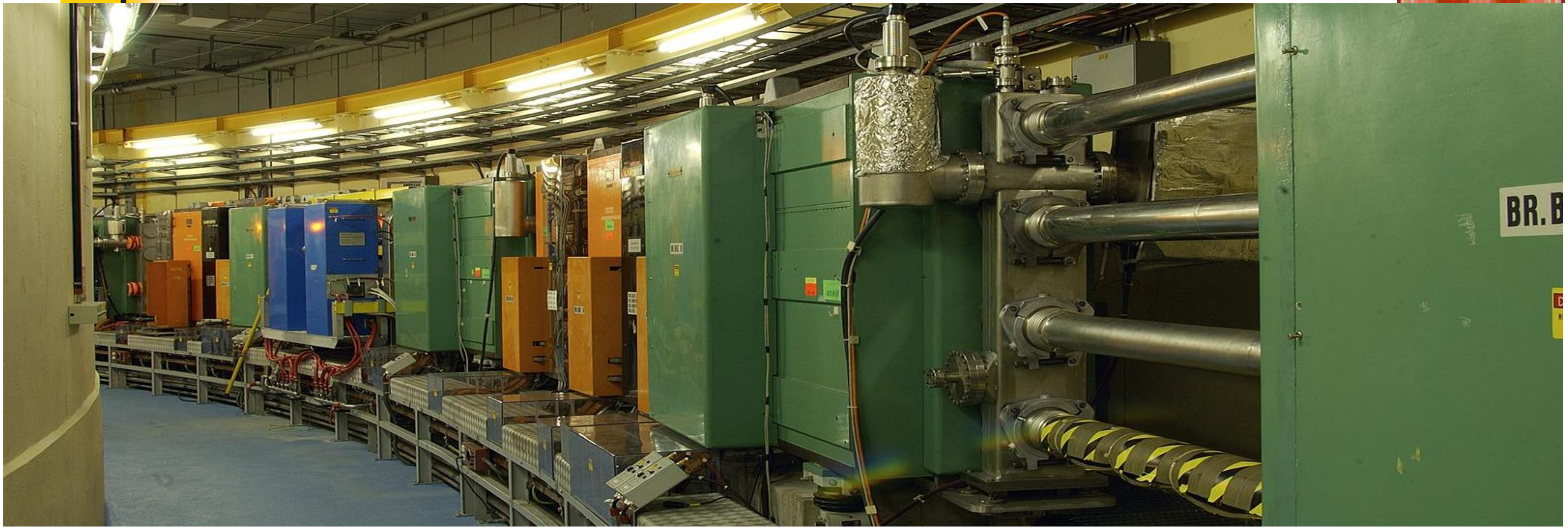
		Injection	Collision
Beam Data			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		1.15×10^{11}	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eVs]	1.0	2.5^a
Transverse normalized emittance	[μm rad]	3.5^b	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
Peak Luminosity Related Data			
RMS bunch length[c]	cm	11.24	7.55
RMS beam size at the IP1 and IP5[d]	μm	375.2	16.7
RMS beam size at the IP2 and IP8[e]	μm	279.6	70.9
Geometric luminosity reduction factor F[f]		-	0.836
Peak luminosity in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	1.0×10^{34}
Peak luminosity per bunch crossing in IP1 and IP5	[$cm^{-2}sec^{-1}$]	-	3.56×10^{30}

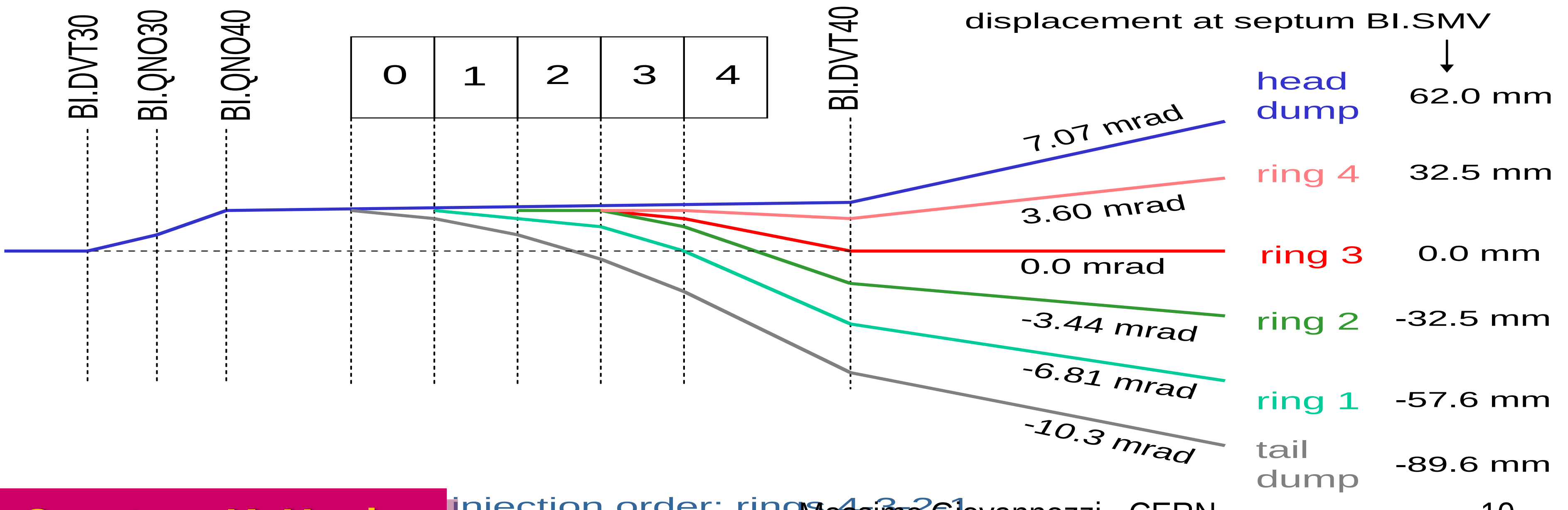
Courtesy E. Métral



Trip of the LHC proton beam along the CERN injectors' chain

Some features: PS-Booster

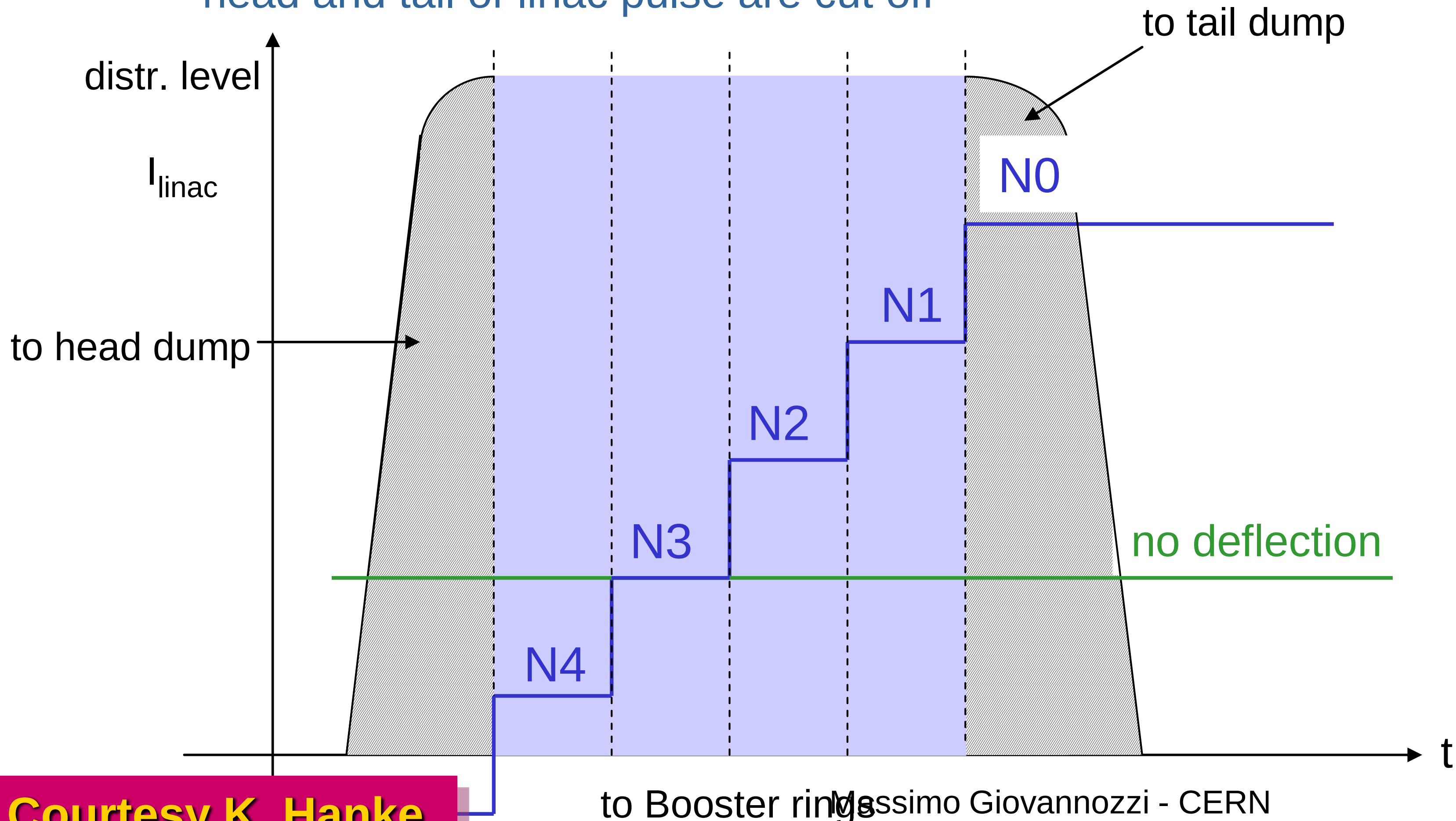




Courtesy K. Hanke

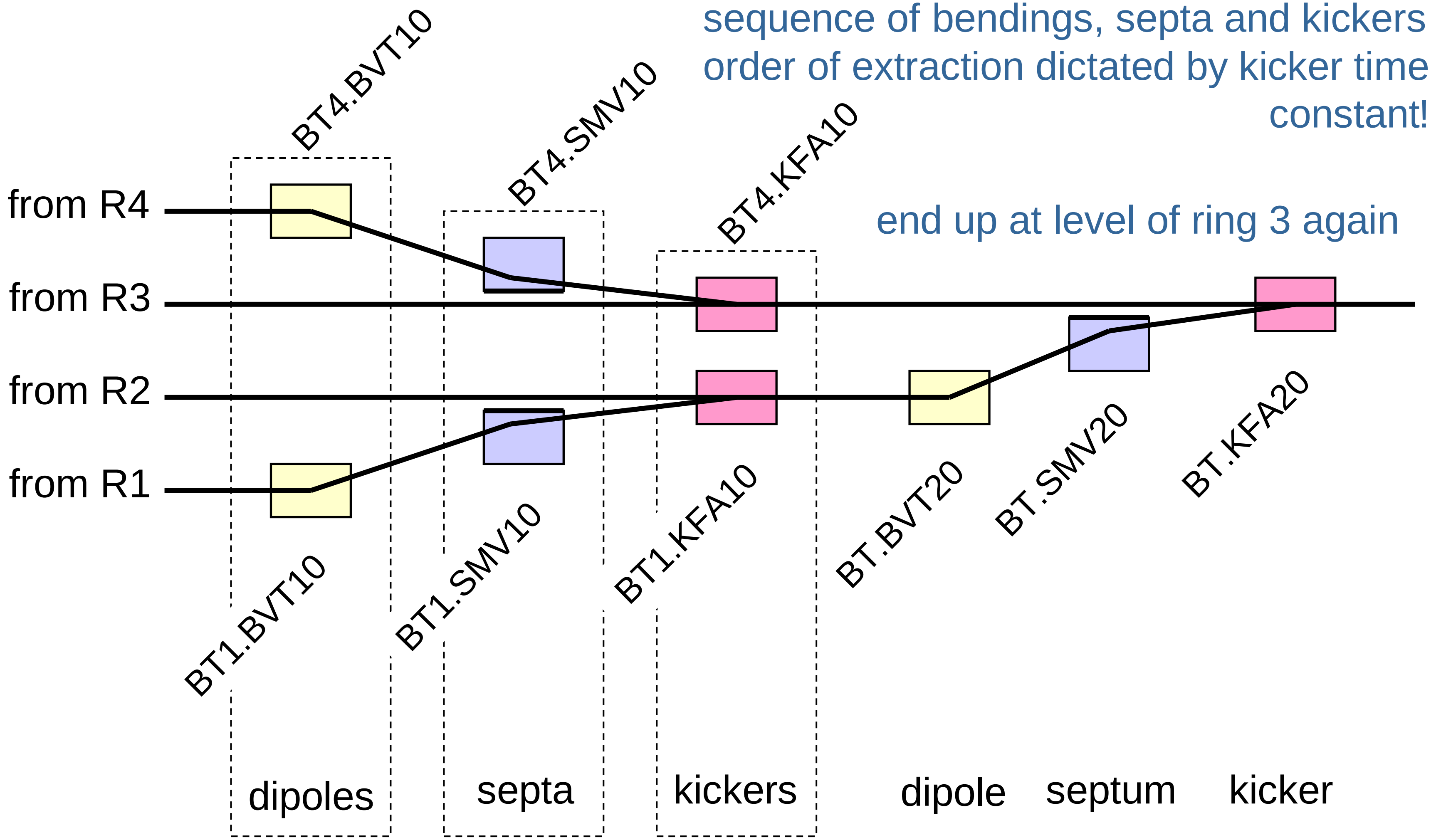
Some features: PS-Booster

separation of linac beam slices done by 5 modules (levels 0,1,…4)
the length of the linac pulse and of the distributor levels is determined by the number of turns to be injected (operator's choice!)
head and tail of linac pulse are cut off



Courtesy K. Hanke

Some features: PS-Booster



sequence of bendings, septa and kickers
order of extraction dictated by kicker time constant!

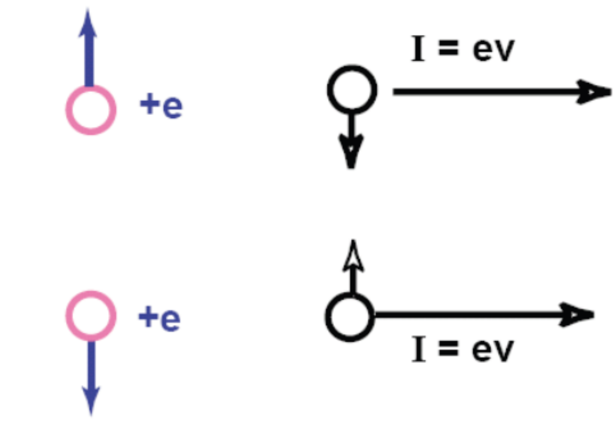
end up at level of ring 3 again

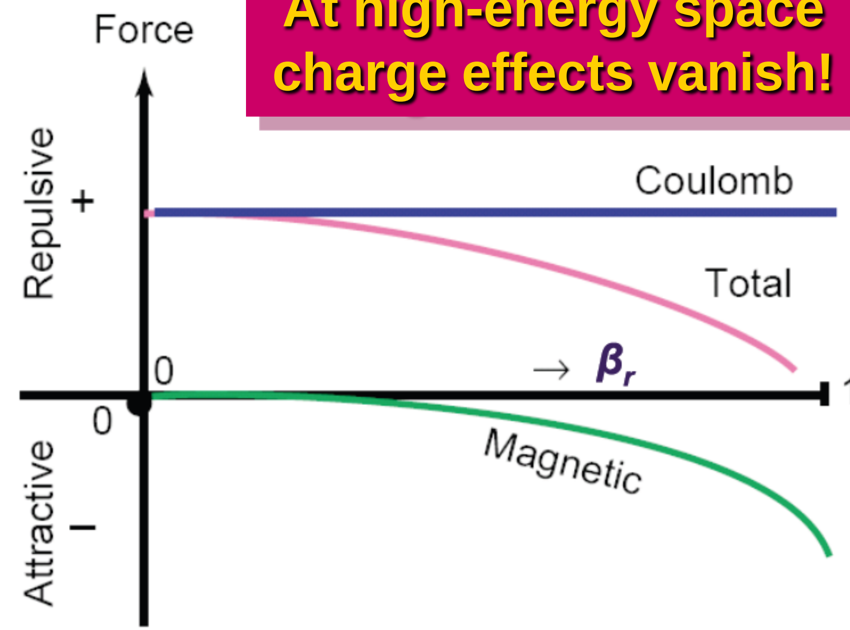
Courtesy K. Hanke

Space charge - I

At high-energy space charge effects vanish!

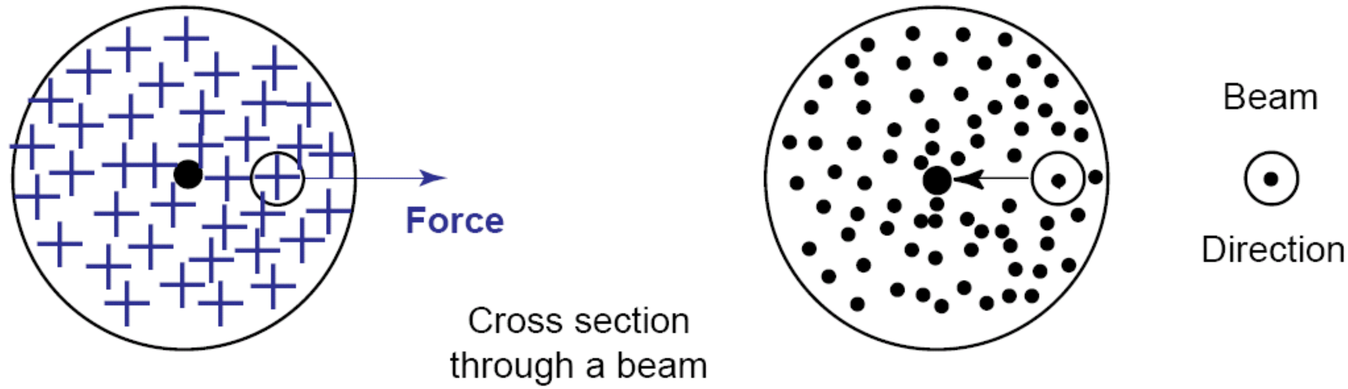
Courtesy K.-H. Schindl





Charges

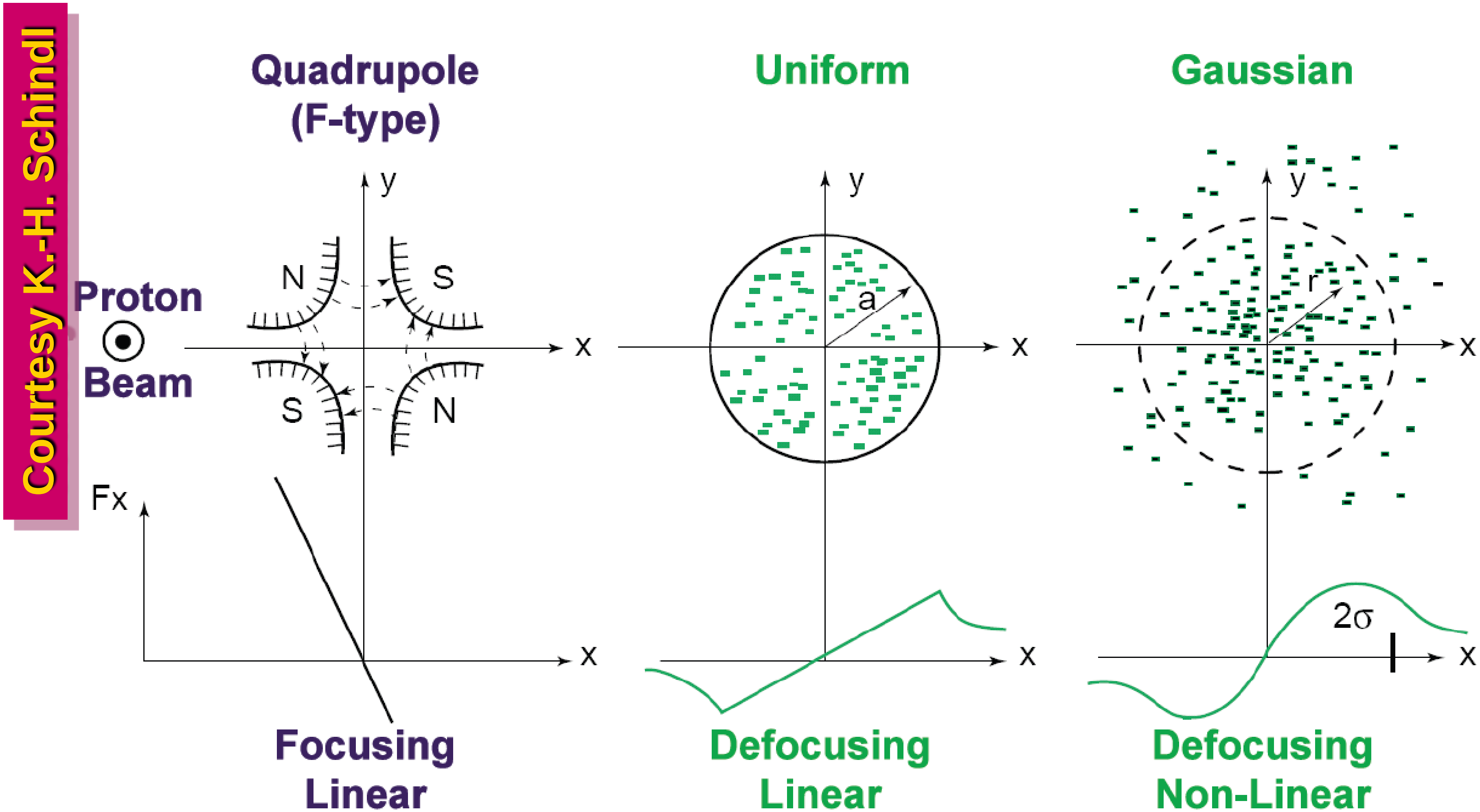
Parallel currents



Repulsive

Attractive

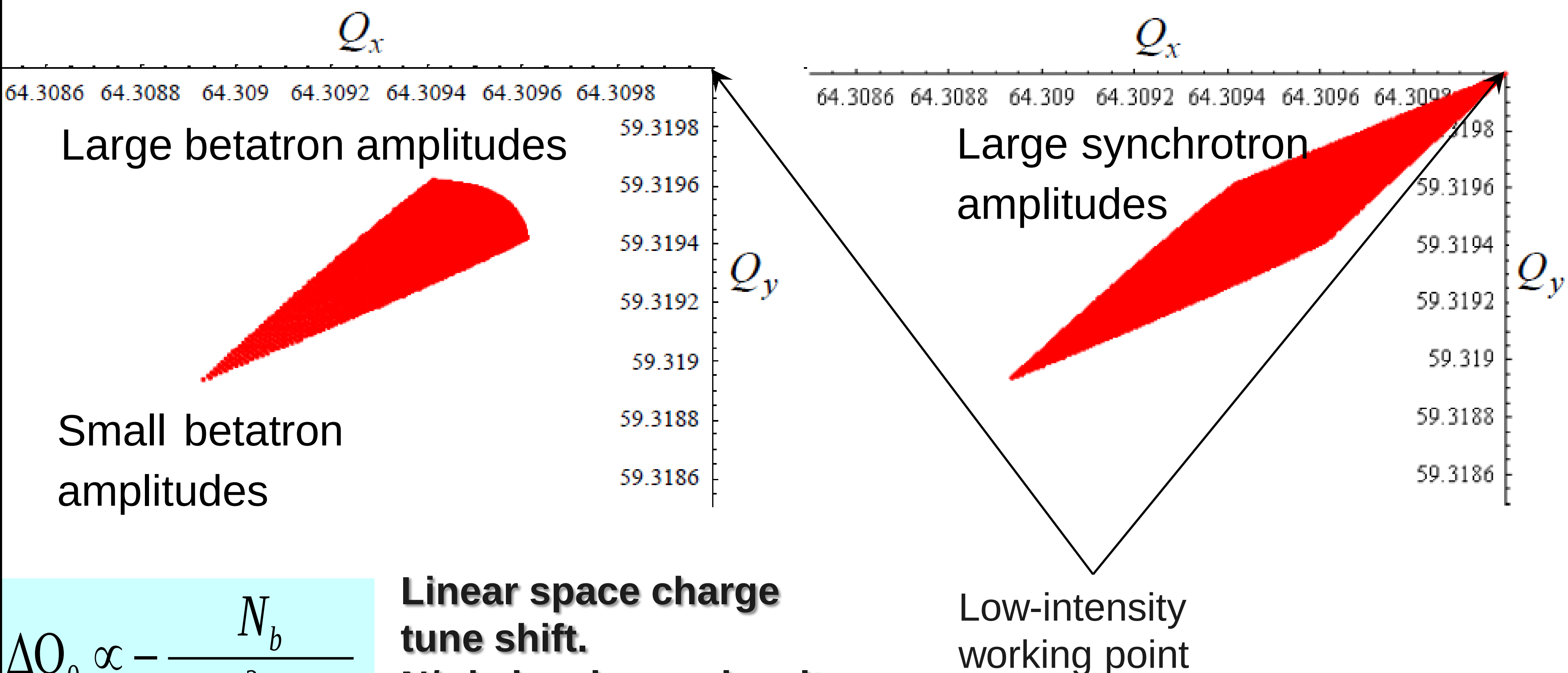
Space charge - II



Space charge - III

Courtesy E. Métral

No synchrotron motion included | Synchrotron motion included



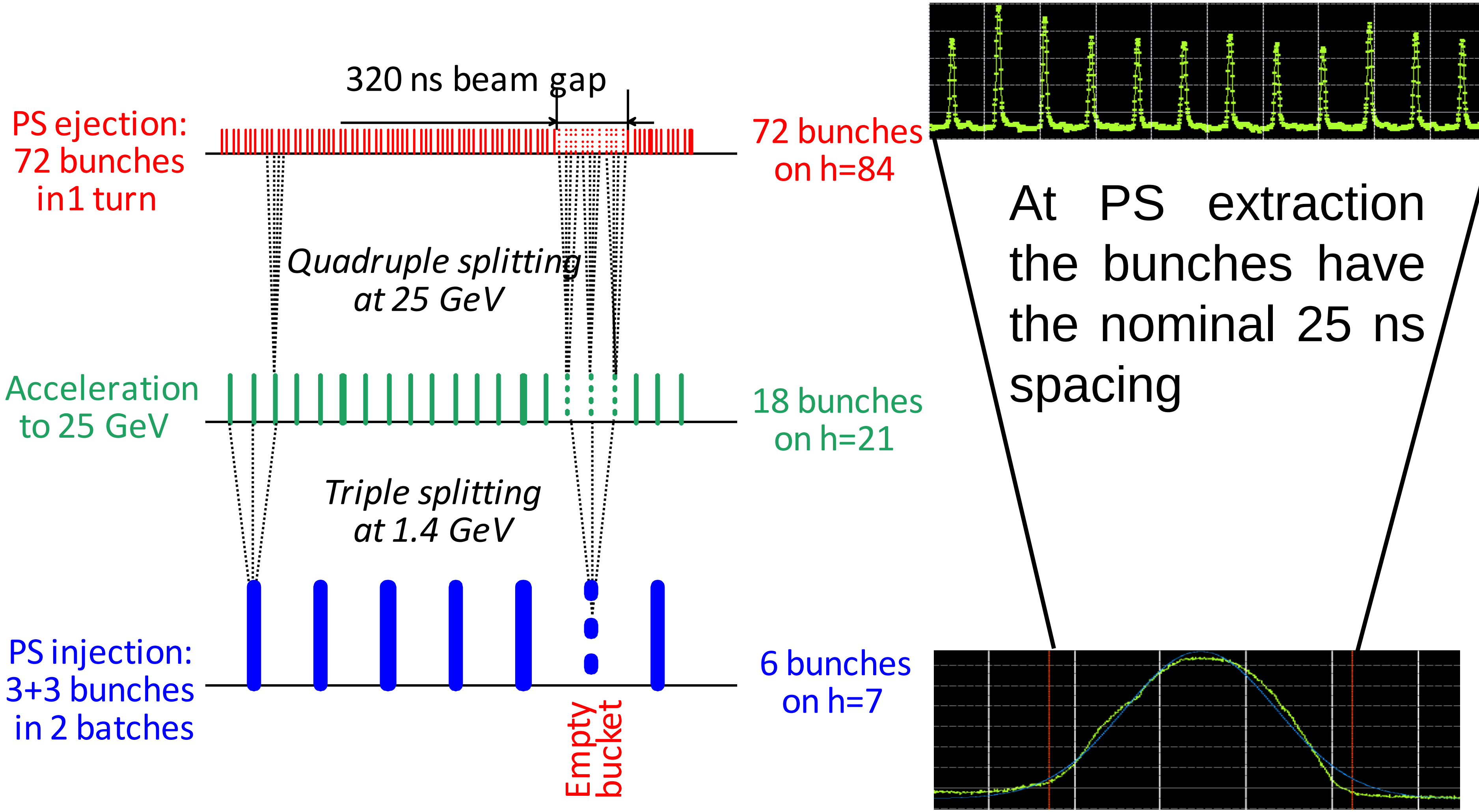
$$\Delta Q_0 \propto -\frac{N_b}{\beta_r \gamma_r^2 \varepsilon_{rms}^{norm}}$$

Linear space charge tune shift.
N/ε is be charge density in phase space

Space charge: summary

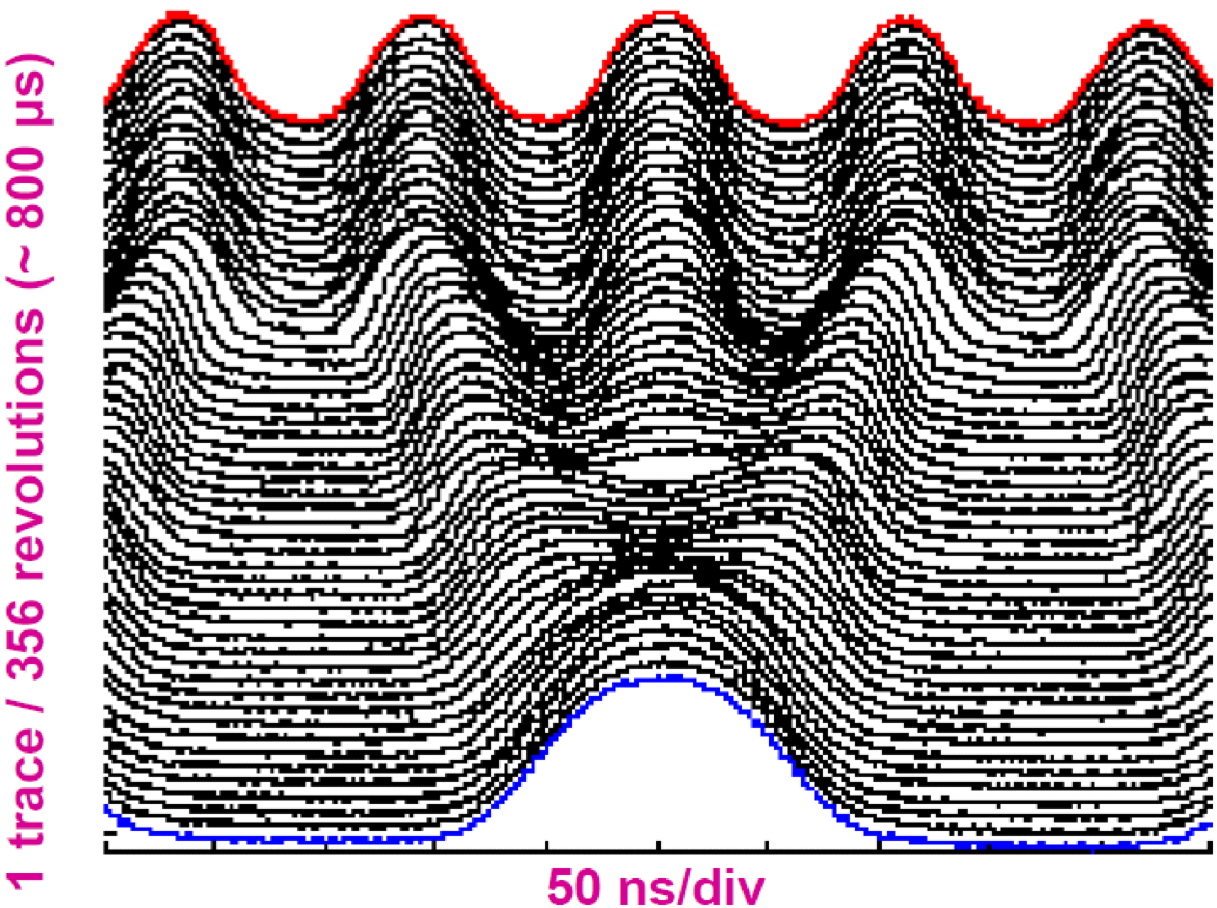
- Space charge introduces:
  - Tune shift
  - tune spread
- Interaction with resonances might induce:
  - Emittance growth -> loss of brightness
  - Losses
- LHC beam exceeds brightness limits in injectors. A number of improvements/beam manipulations are needed:
  - Double-batch injection in PS -> alleviates PSB space charge
  - Increase of PSB extraction energy -> alleviates PS space charge
  - Longitudinal bunch splitting in PS-> reduces longitudinal emittance

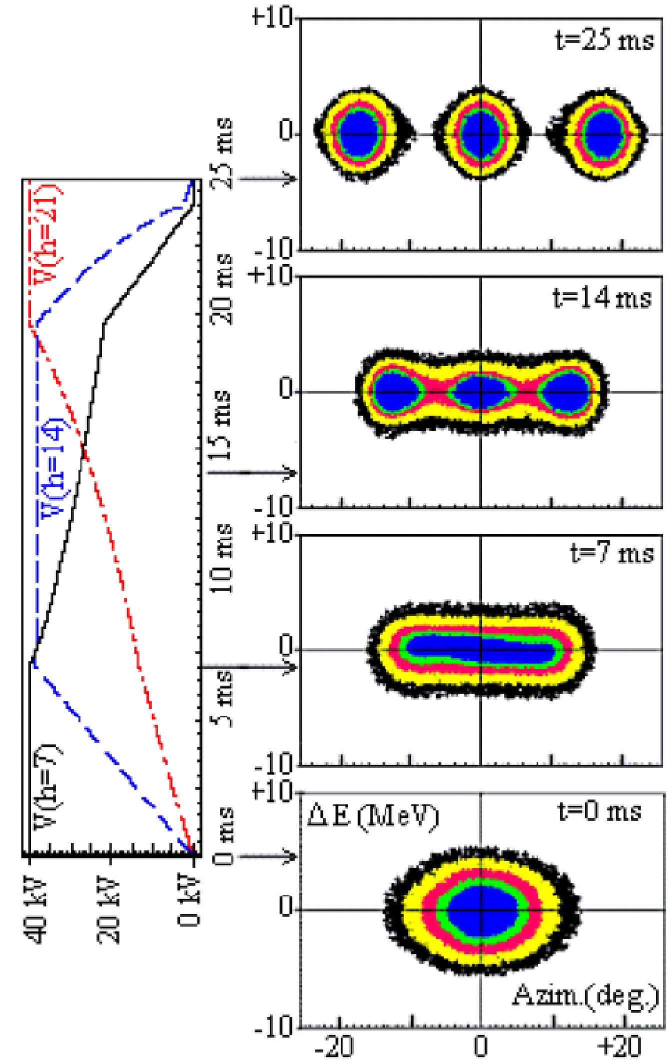
Nominal LHC beam in PS



Triple bunch splitting

The stable fixed point bifurcates and three stable ones are generated.

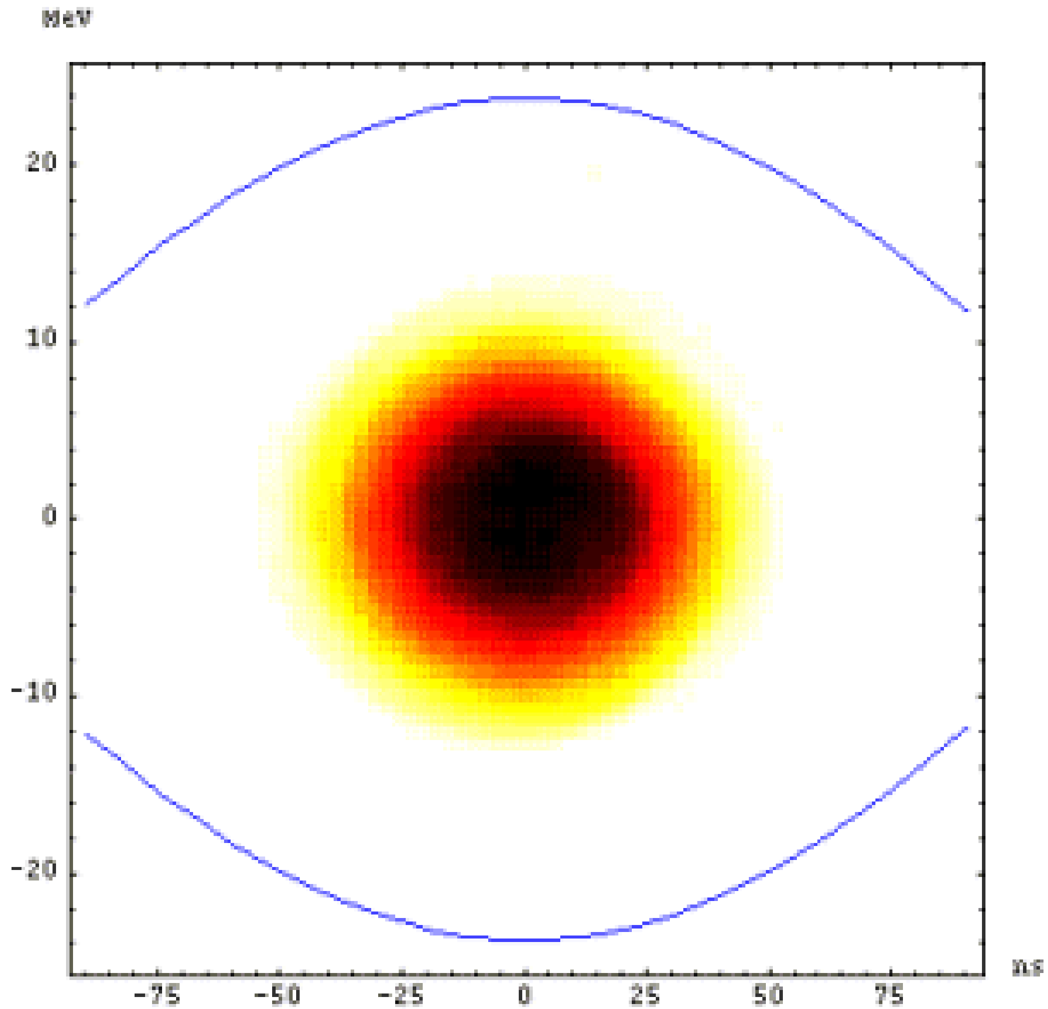




Courtesy R. Garoby

Double bunch splitting

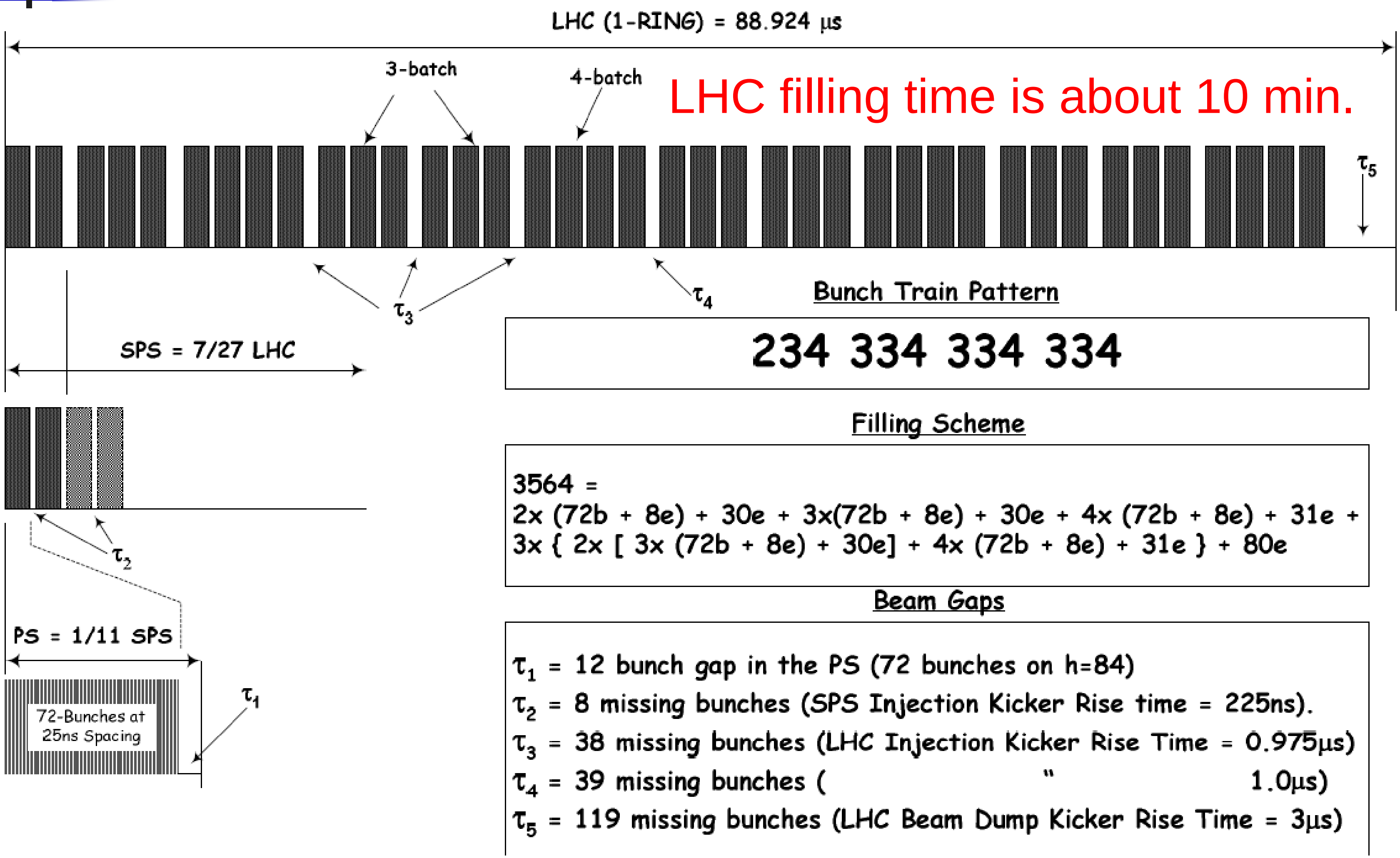
The stable fixed point bifurcates and two stable ones are generated.



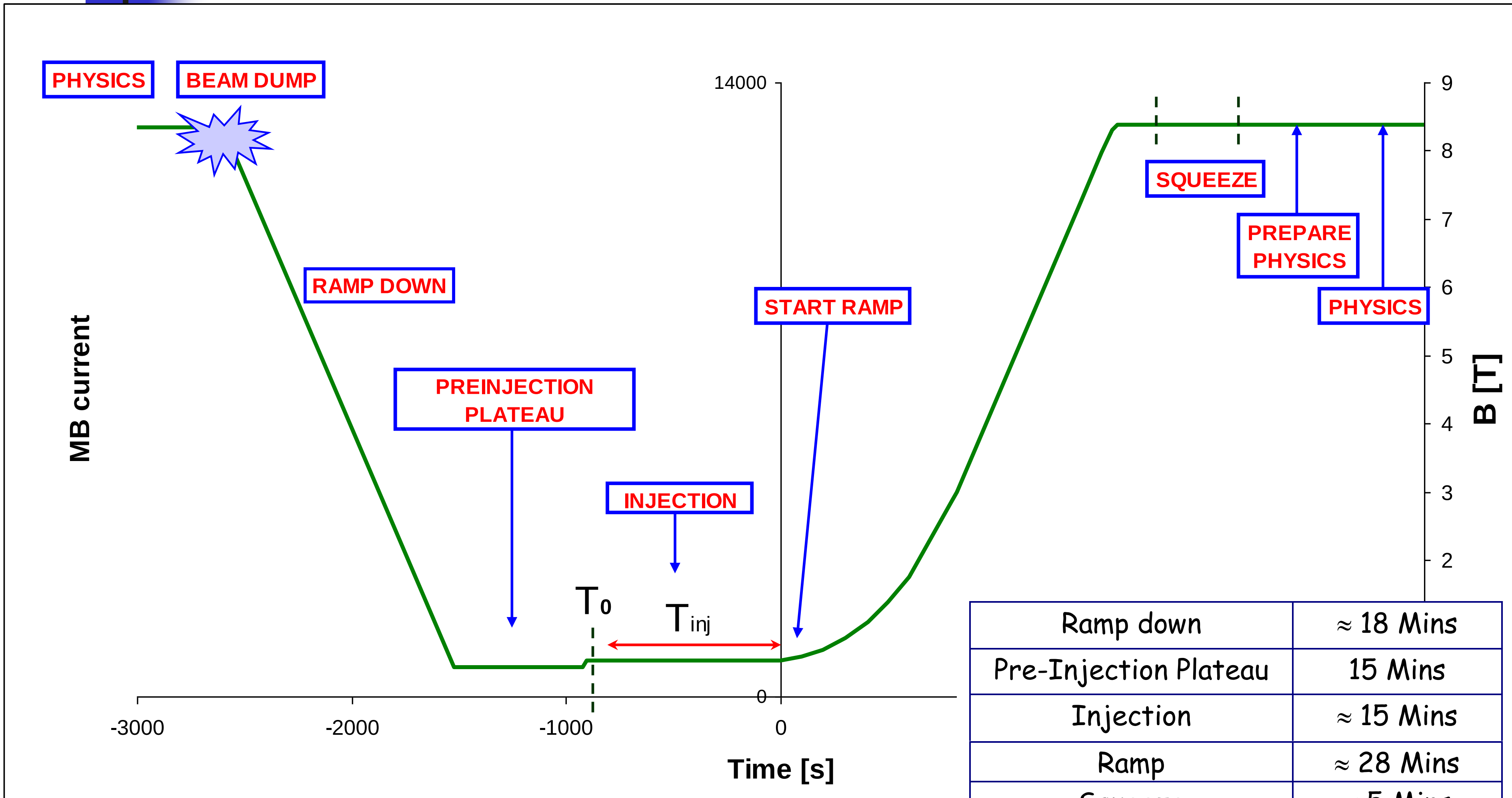
Courtesy S. Hancock

Nominal LHC filling scheme

LHC filling time is about 10 min.



LHC beam commissioning - I



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

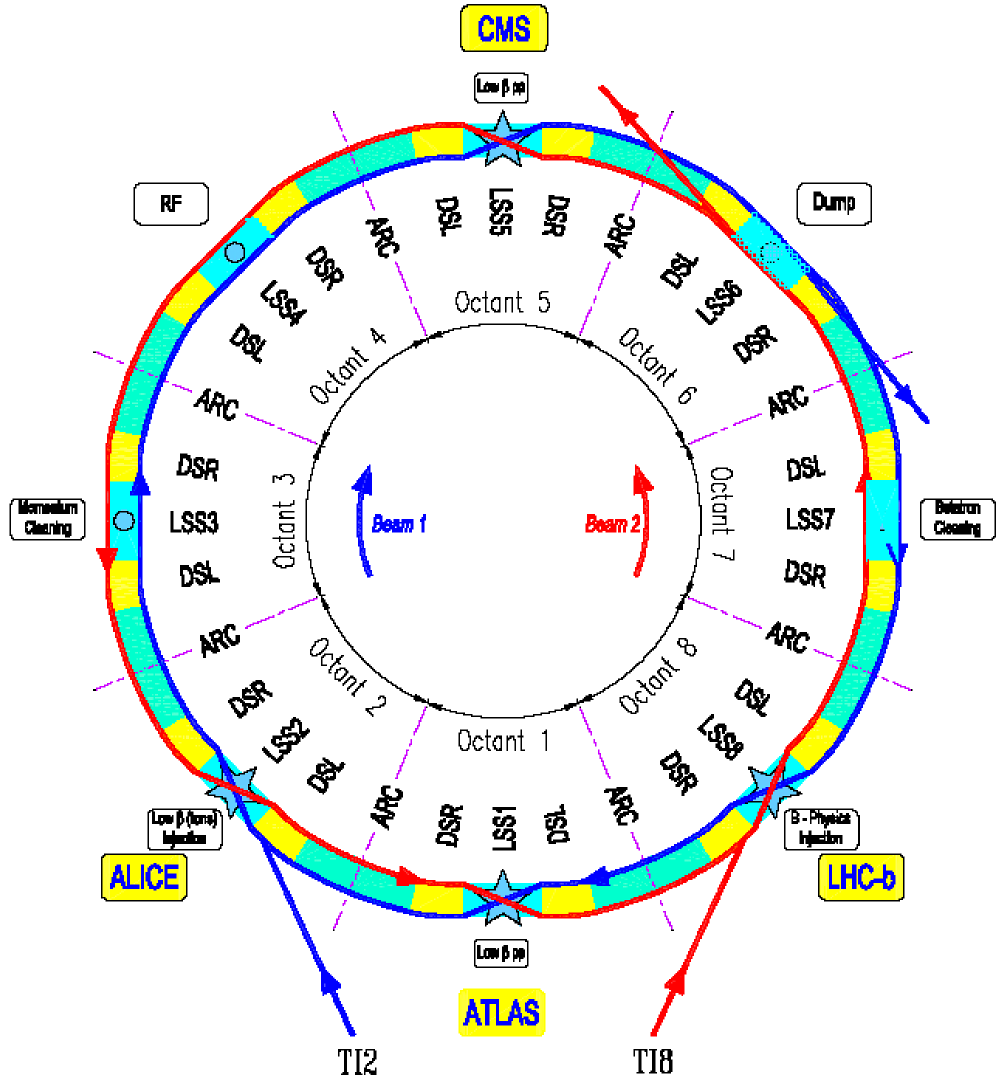
- no squeeze -> reduce risk from

LHC beam commissioning - II

- Gradually increase performance in steps to allow for periods of stable beams where machine performance, reproducibility, and stability is monitored.
- Use bunch trains in the process of increasing performance: once you mastered the physics of one train, the addition of more trains does not bring new physics!

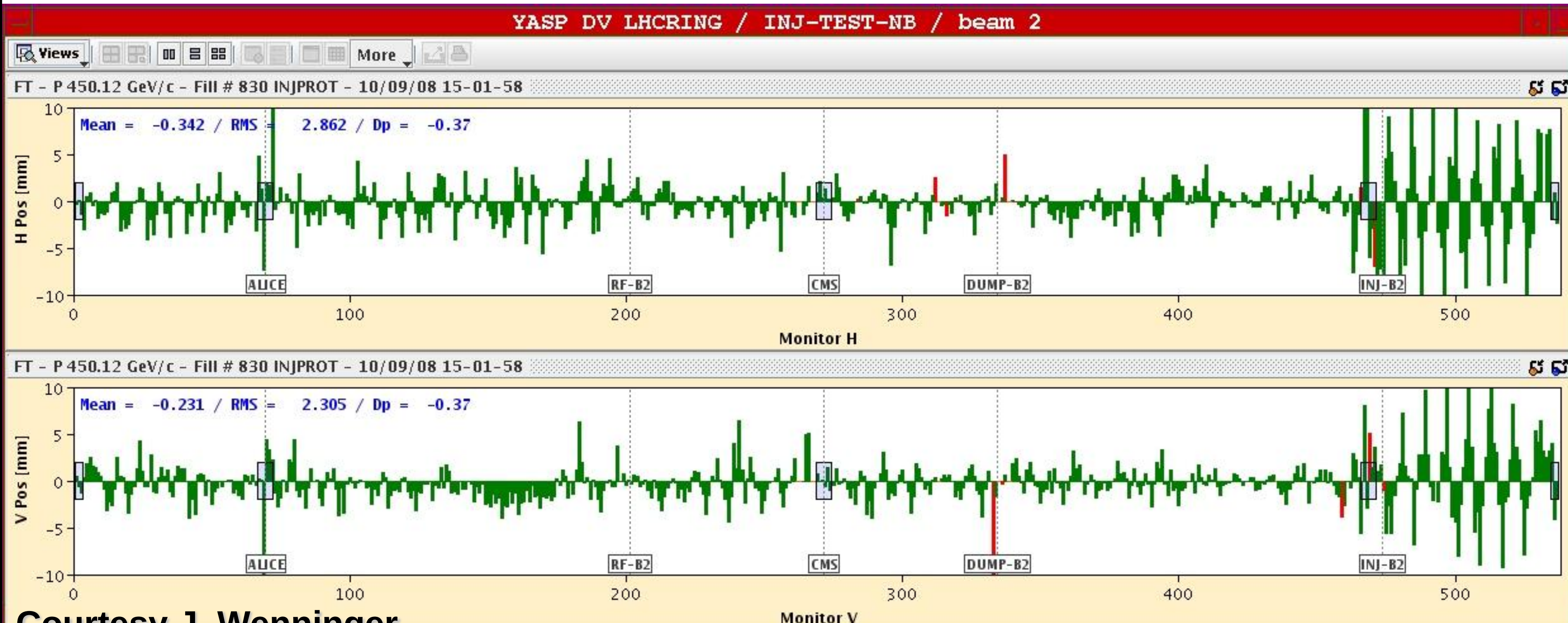
Milestones - I

- 2008
  - Accelerator complete
  - Ring cold and under vacuum
- September 10th 2008
  - First beams around
- September 19th 2008
  - The incident



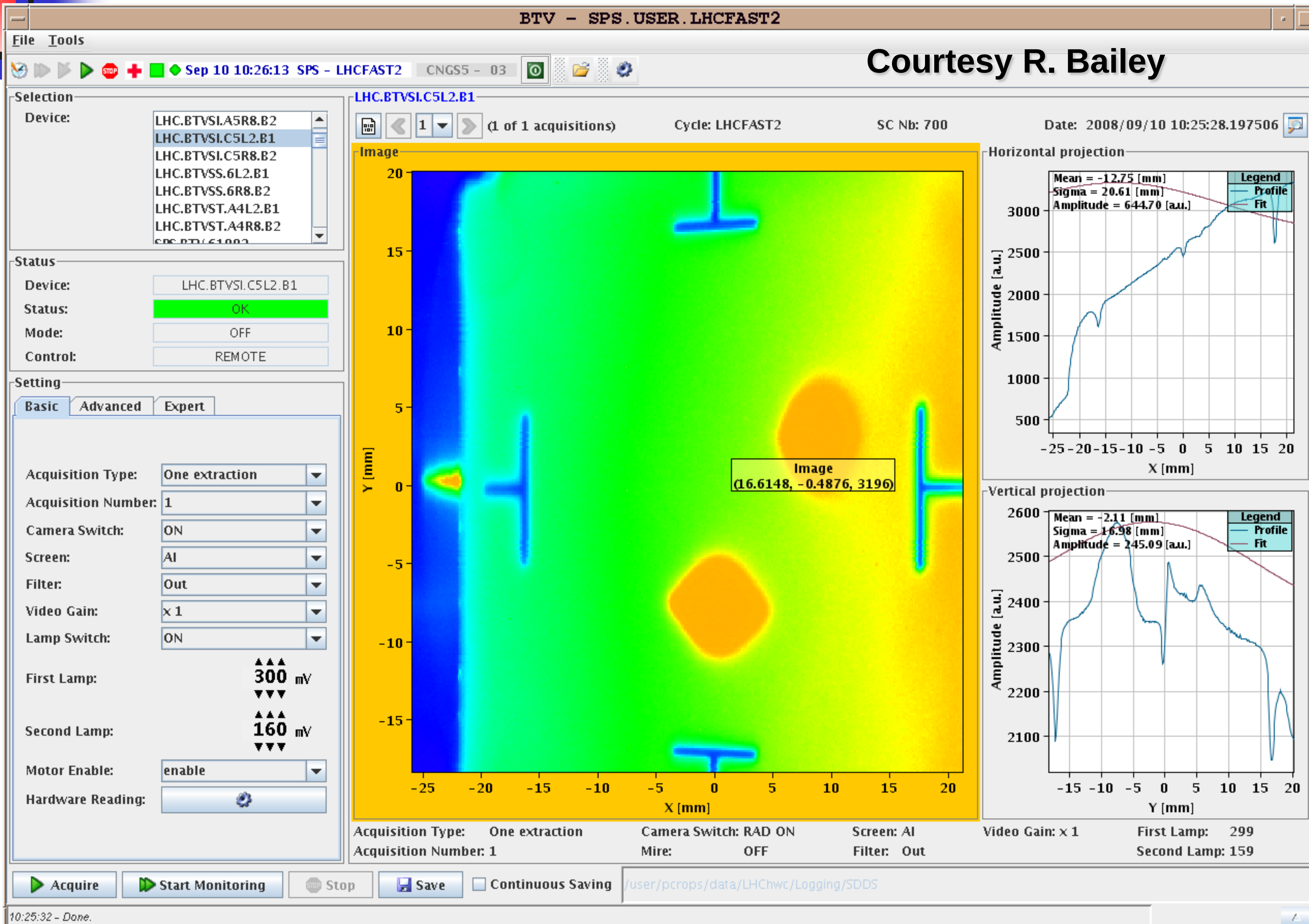
Beam threading on 10/09/08

Initial threading: alignment might not be perfect -> aperture issues, magnetic feed down effects, etc. In the end everything went very fast!



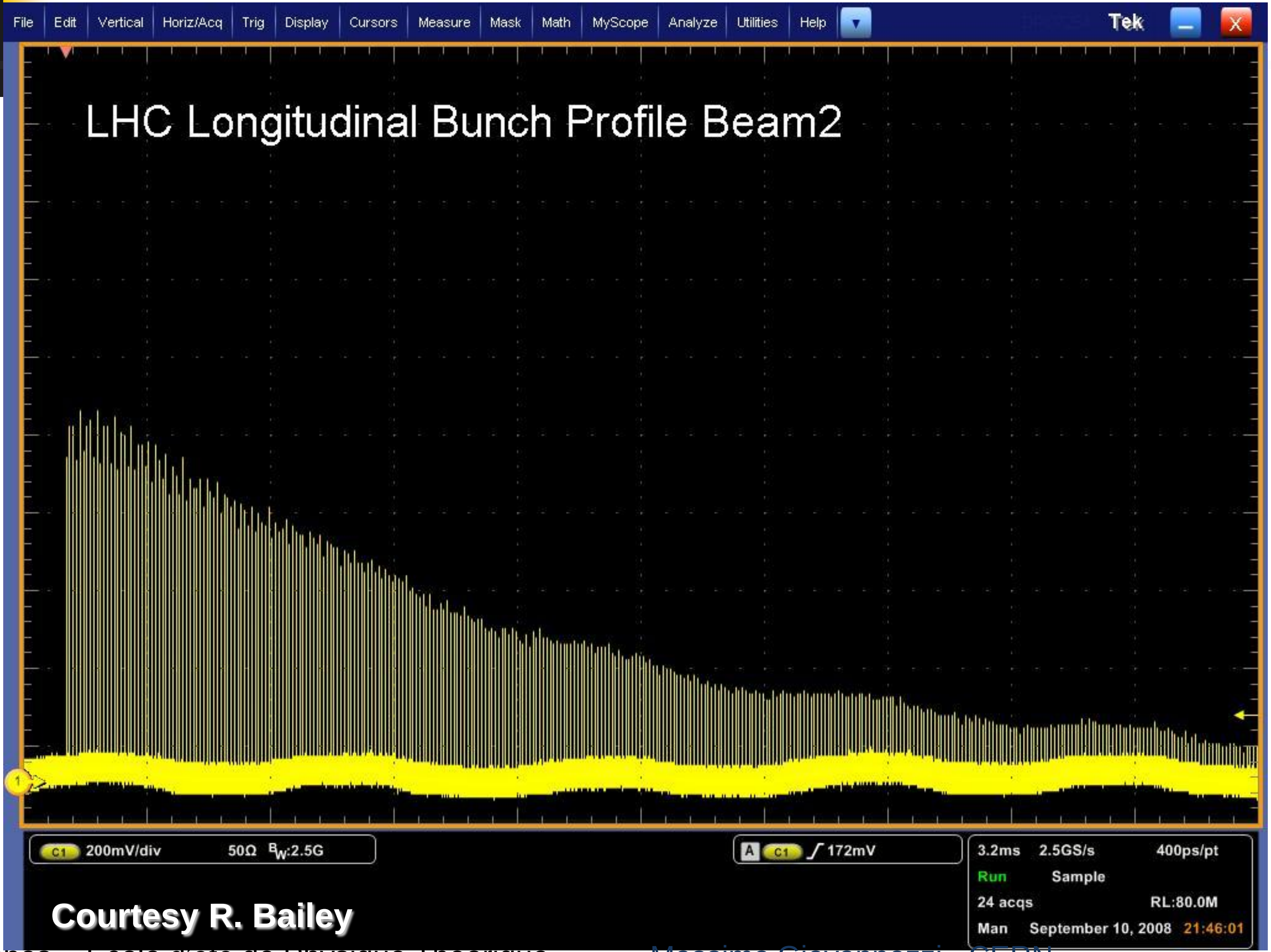
Courtesy J. Wenninger

Closing the first turn



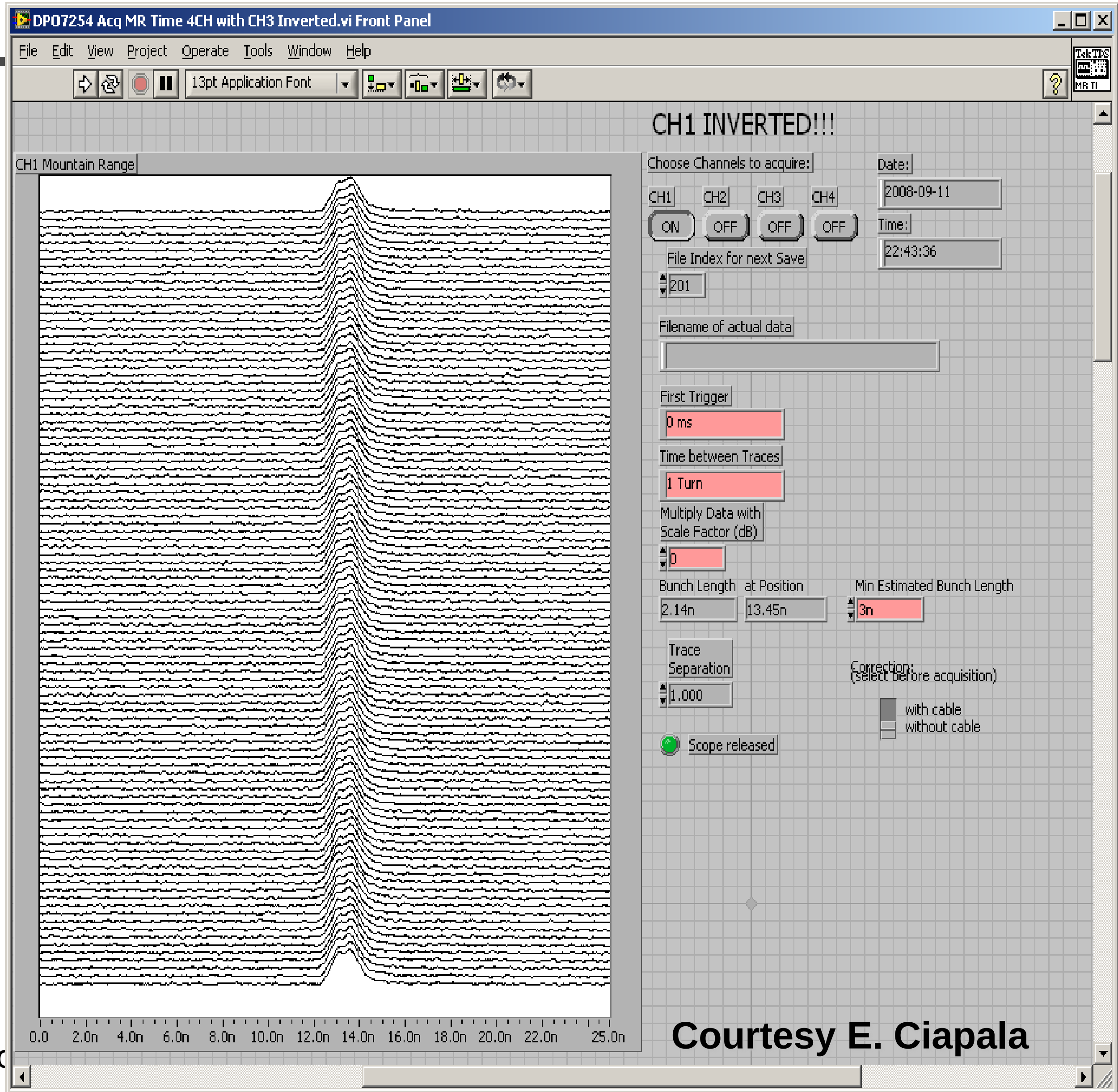
Courtesy R. Bailey

RF still OFF



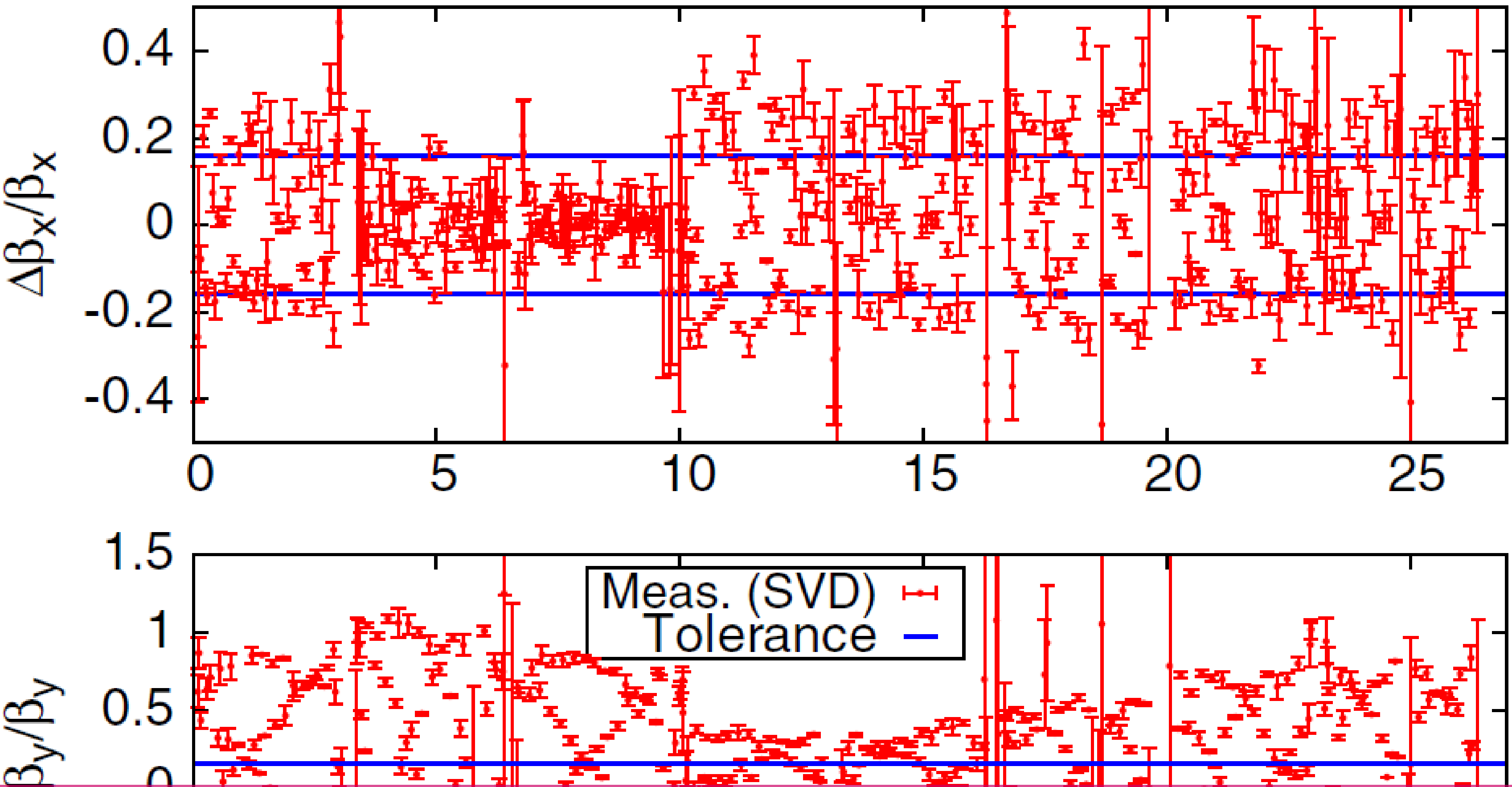
File
Edit
Vertical
Horiz/Acq
Trig
Display
Cursors
Measure
Mask
Math
MyScope
Analyze
Utilities
Help
Tek
LHC Longitudinal Bunch Profile Beam2
C1 200mV/div 50Ω BW:2.5G
A C1 172mV
3.2ms 2.5GS/s 400ps/pt
Run Sample
24 acqs RL:80.0M
Man September 10, 2008 21:46:01
Courtesy R. Bailey

First RF setting up



Courtesy E. Ciapala

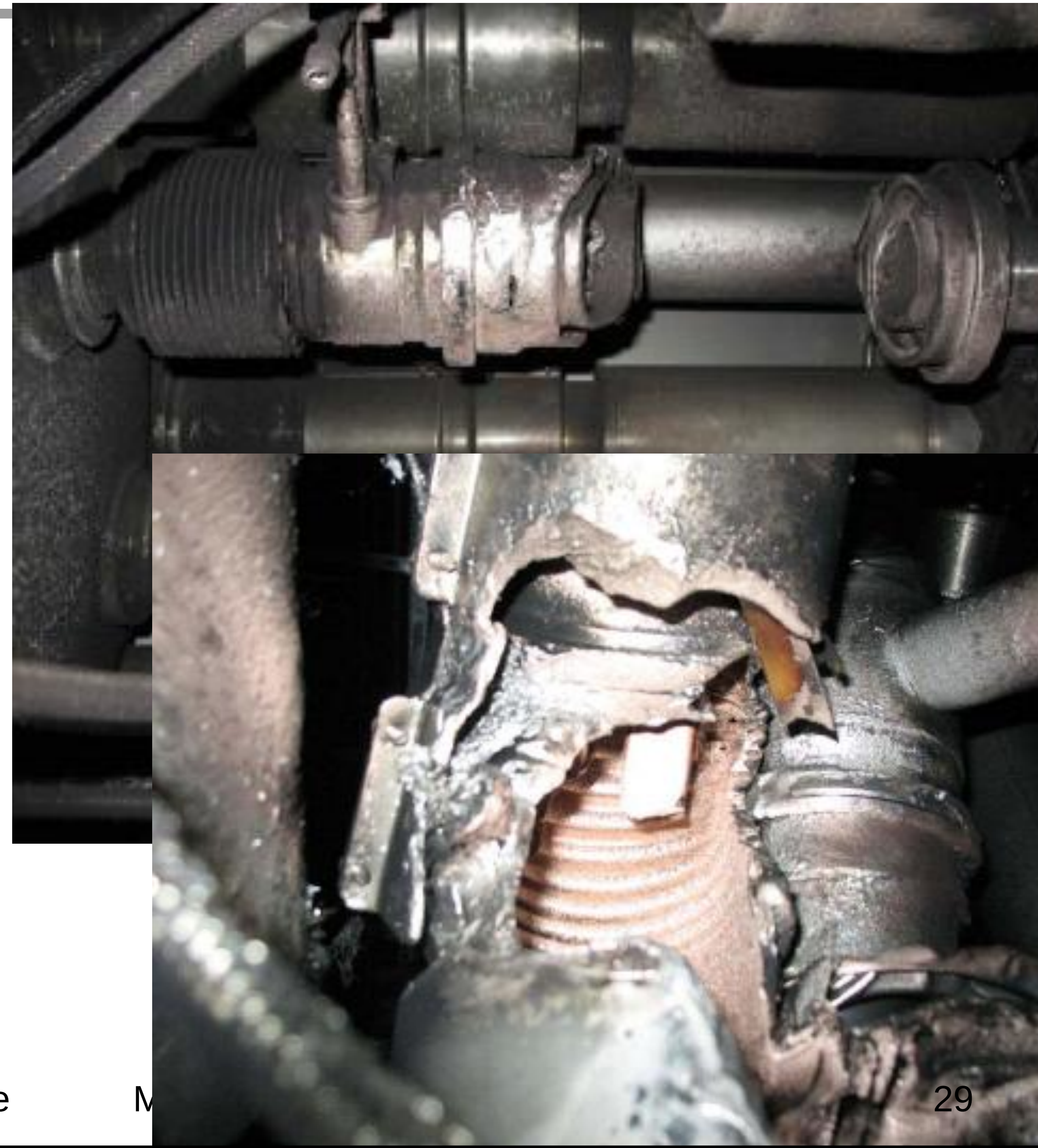
Optics measurements



R. Tomás, G. Vanbavinckhove et al.

With the data cumulated in few hours of run in 2008 it was possible to detect a wrong cabling of a quadrupole! Optics almost in tolerance!

The accident: 19/09/08



Milestones - II

- 2008 – 2009
  - 14 months of major repairs and consolidation
  - New Quench Protection System for online monitoring and protection of all joints.
  - However: uncertainties about the splice quality suggested to limit beam energy to 3.5 TeV

Busbar splice: the guilty

Upper Copper

Uppe
Solderin

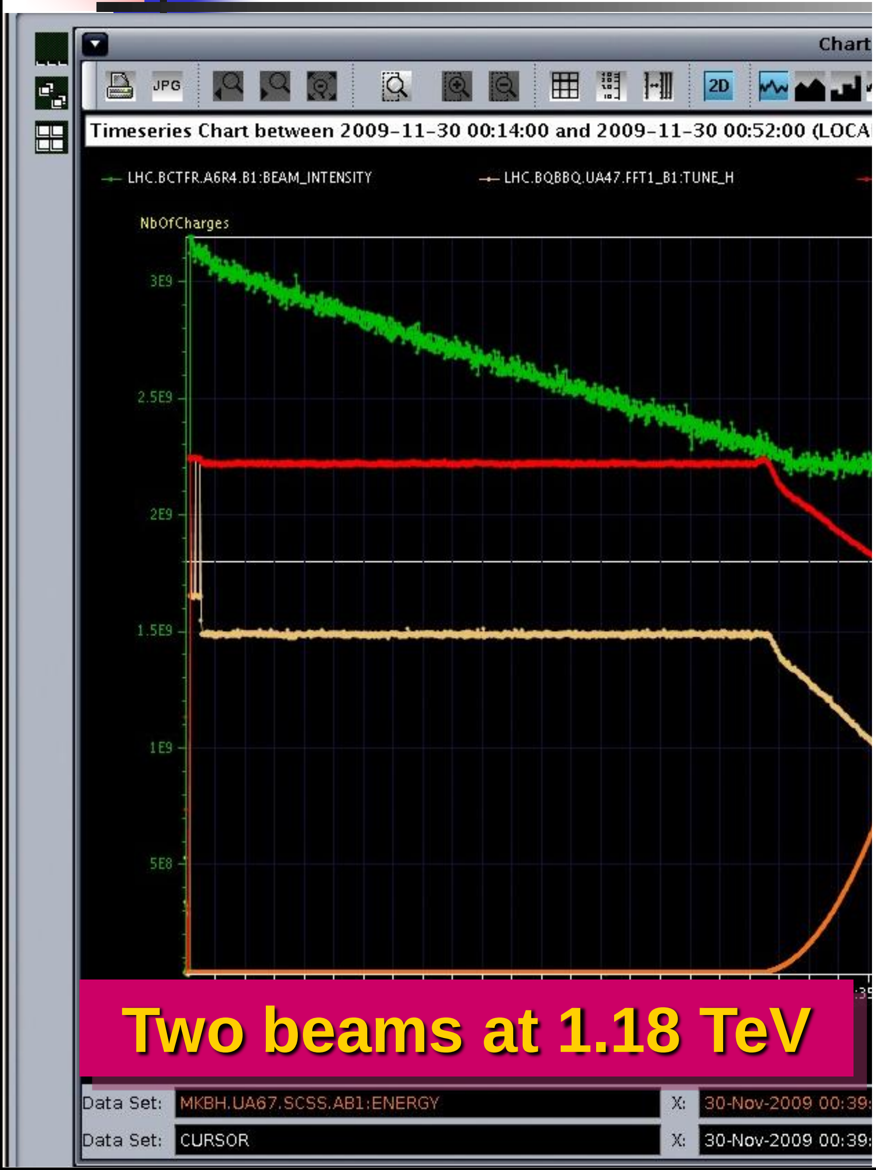
Inter-Ca
Solderi

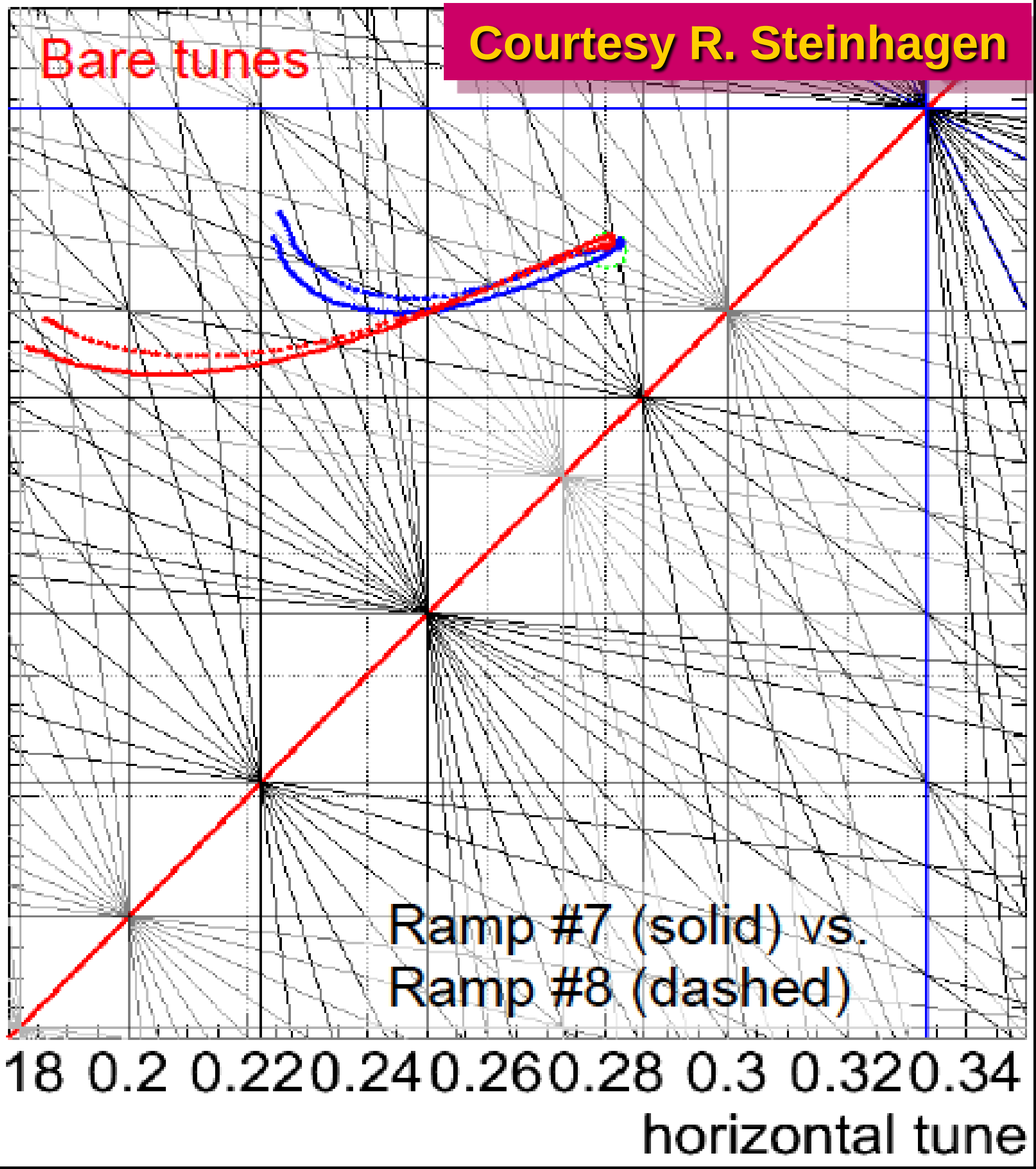
Extensive repair and consolidation programme launched during 2008/9

Milestones - III

- November 20th 2009
  - First beams around again
- November 29th 2009
  - Both beams accelerated to 1.18 TeV simultaneously
- December 8th 2009
  - 2x2 accelerated to 1.18 TeV
  - First collisions seen before beam lost!
- December 14th 2009
  - Stable 2x2 at 1.18 TeV
  - Collisions in all four experiments with ≈ 10^{10} ppb

Back again on 30/11/09

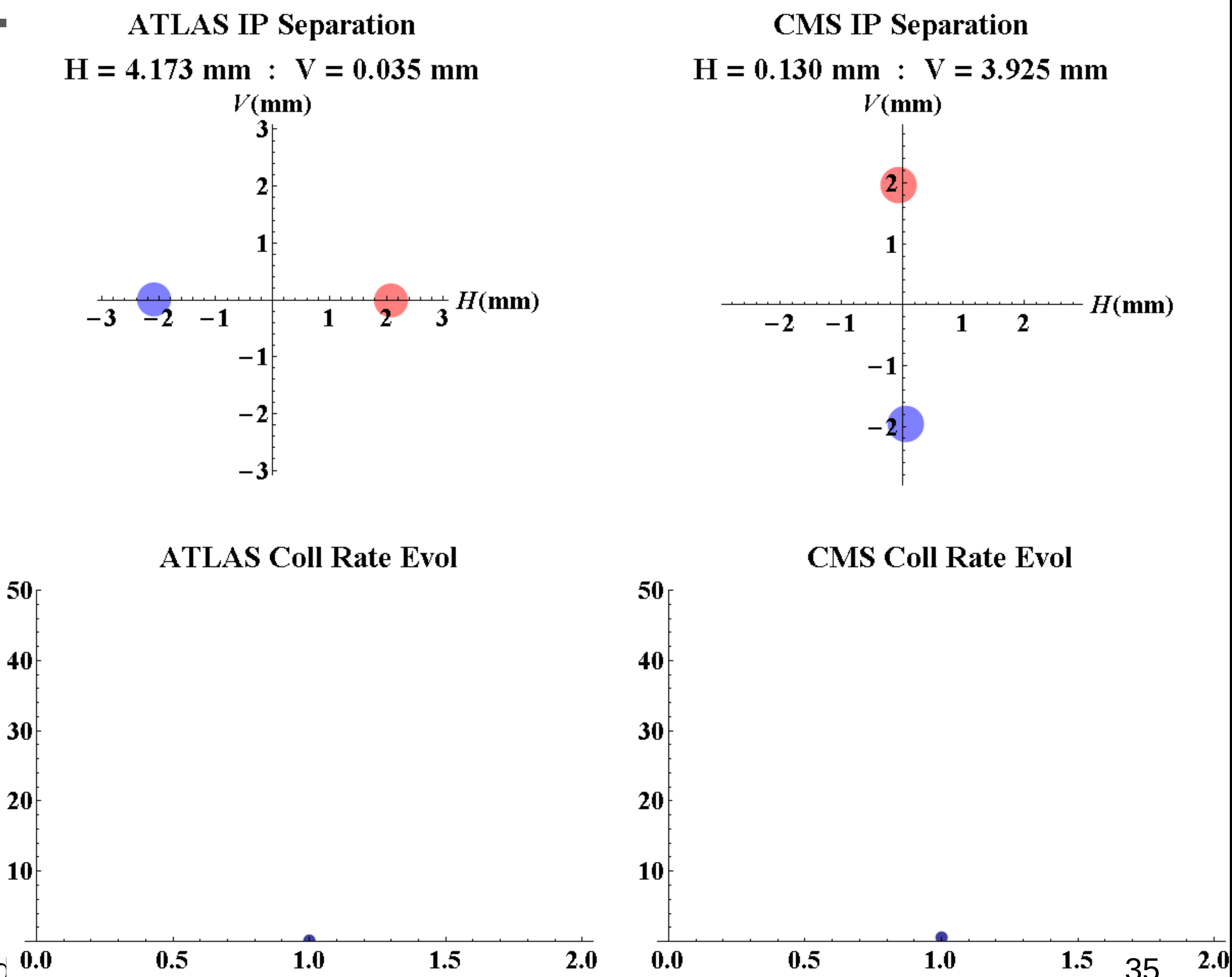




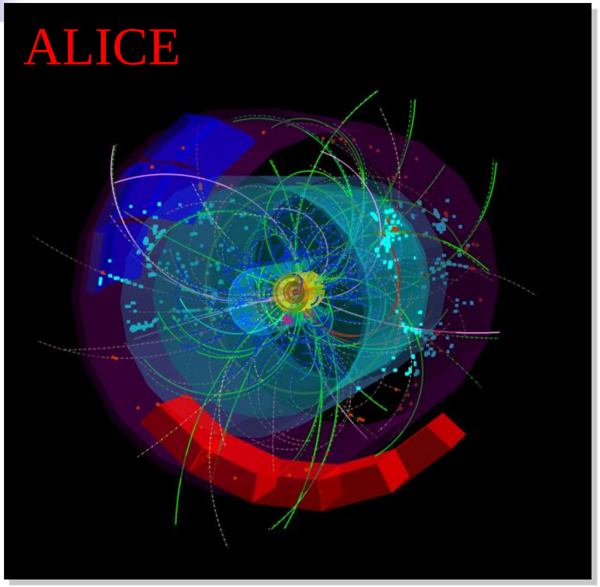
Milestones - IV

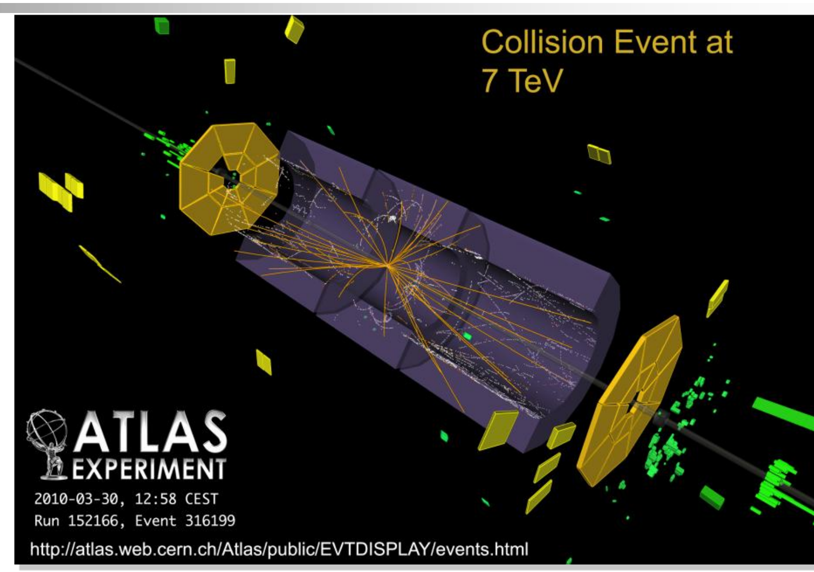
- February 27th 2010
  - First injection
- February 29th 2010
  - Both beams circulating
- March 5th 2010
  - Two-beam operation at L 10^{27} cm^{-2} s^{-1}
- March 15th – 18th
  - Technical stop to prepare main dipoles for 3.5 TeV operation
- March 30th
  - Collisions in all four experiments at 3.5 TeV

Up to 3.5 TeV on 30/03/10

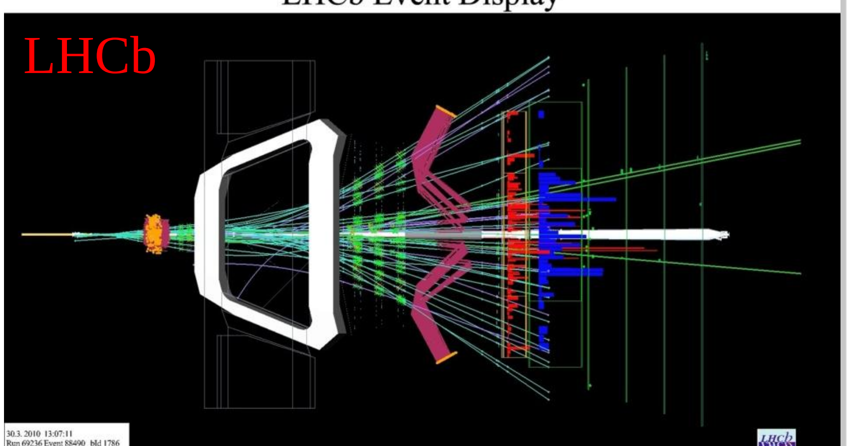


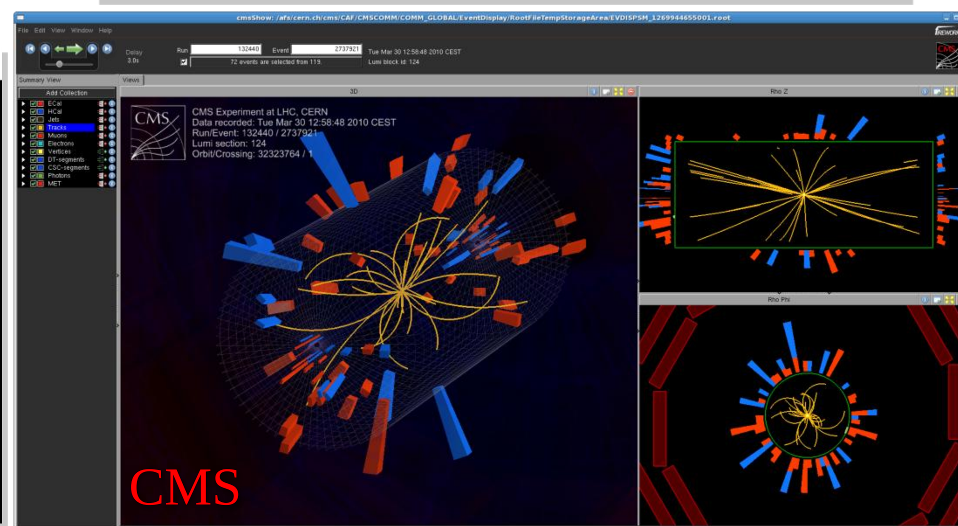
First collisions at 3.5 TeV on 30/03/10





LHCb Event Display





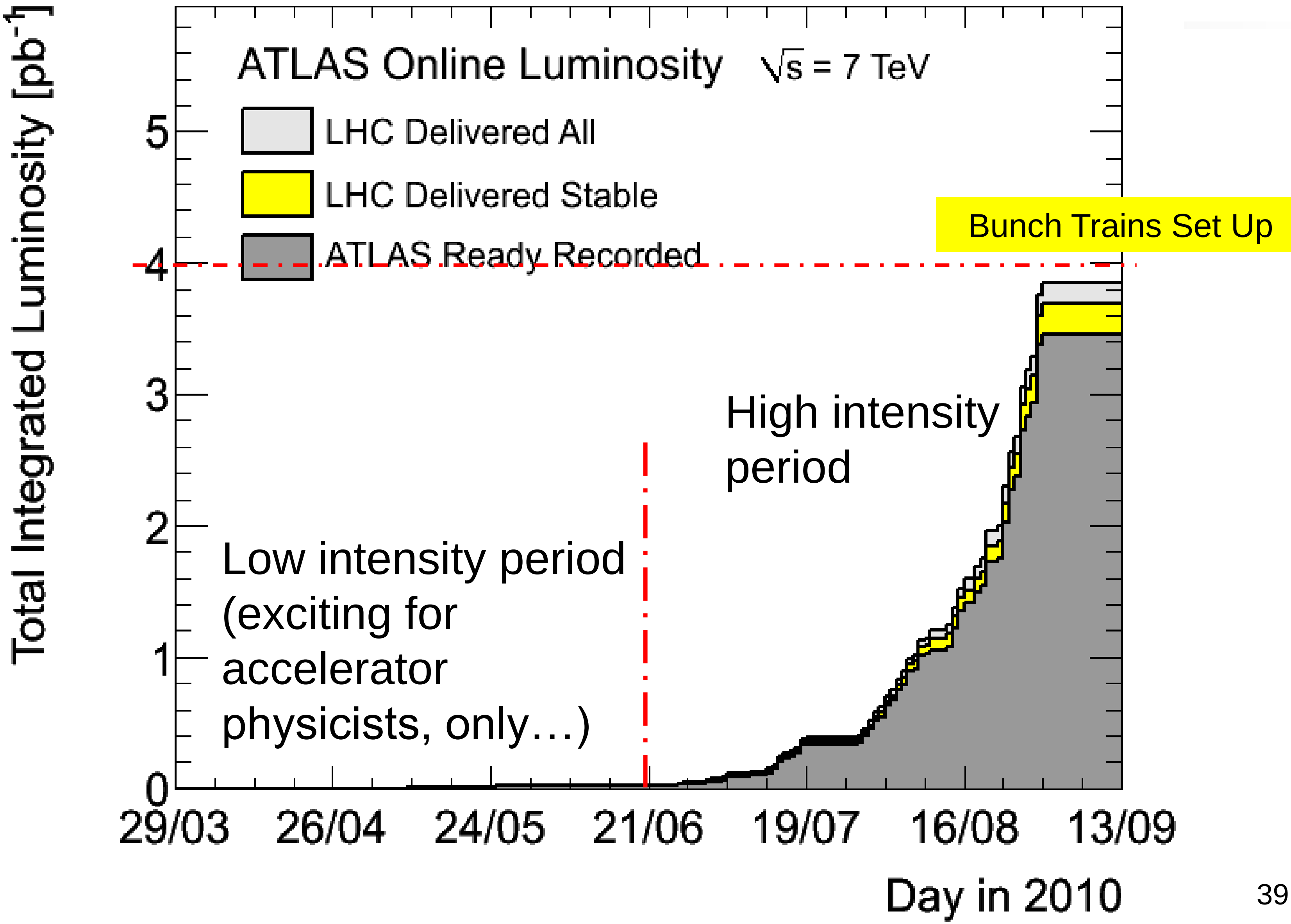
Goals for 2010

- Main goal for 2010: commissioning of peak luminosity of 10^{32} cm^{-2} s^{-1}
  - Not achievable with 2×10^{10} bunch intensity
  - Requires several hundred bunches.
  - Implies operation with stored beam energies above 30 MJ
- NB: Tevatron operated at 2 MJ and previous LHC operation was at 170 kJ!

First two periods - I

Event	TeV	OEF	β*	Nb	Ib	Itot	MJ	Nc	Peak luminosity	Date
1	3.5	0.2	10	2	1.00E+10	2.0E+10	0.0113	1	8.9E+26	30 March 2010
2	3.5	0.2	10	2	2.00E+10	4.0E+10	0.0226	1	3.6E+27	02 April 2010
3	3.5	0.2	2	2	2.00E+10	4.0E+10	0.0226	1	1.8E+28	10 April 2010
4	3.5	0.2	2	4	2.00E+10	8.0E+10	0.0452	2	3.6E+28	19 April 2010
5	3.5	0.2	2	6	2.00E+10	1.2E+11	0.0678	4	7.1E+28	15 May 2010
6	3.5	0.2	2	13	2.60E+10	3.4E+11	0.1910	8	2.4E+29	22 May 2010
7	3.5	0.2	3.5	3	1.10E+11	3.3E+11	0.1865	2	6.1E+29	26 June 2010
8	3.5	0.2	3.5	6	1.00E+11	6.0E+11	0.3391	4	1.0E+30	02 July 2010
9	3.5	0.2	3.5	8	9.00E+10	7.2E+11	0.4069	6	1.2E+30	12 July 2010
10	3.5	0.2	3.5	13	9.00E+10	1.2E+12	0.6612	8	1.6E+30	15 July 2010
11	3.5	0.2	3.5	25	1.00E+11	2.5E+12	1.4129	16	4.1E+30	30 July 2010
12	3.5	0.2	3.5	48	1.00E+11	4.8E+12	2.7127	36	9.1E+30	19 August 2010

First two periods - II



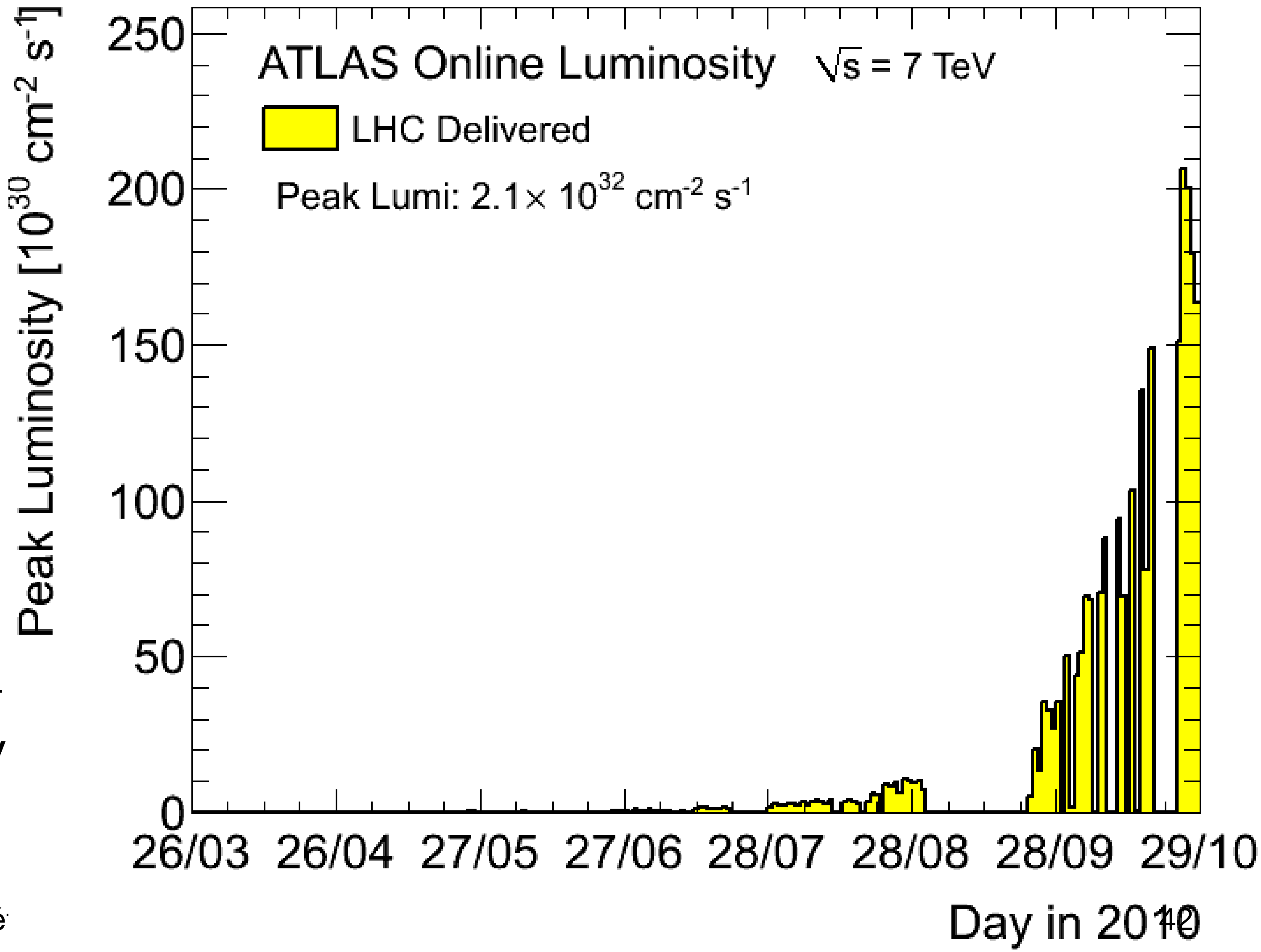
Bunch trains - I

- Parameters and Conditions
  - Nominal bunch intensity 1.1 10^{11}
  - smaller than nominal emittances: 2.5-3 μm
  - Stick to β^* = 3.5 m in all IPs with crossing angle
  - Go to 150 ns bunch spacing
  - Commission faster ramp (thus reducing ramp time from 46 min to 16 min).

Bunch trains - II

Nb	Ib	MJ	Nc	Peak luminosity (design parameters)	Maximum luminosity (measured)	Beam-beam shift from measured Lumi	Date
56	1.10E+11	3.5	47	1.203E+31	2.000E+31	0.0157	23/09/2010
104	1.10E+11	6.5	93	2.381E+31	3.500E+31	0.0139	25/09/2010
152	1.10E+11	9.4	140	3.584E+31	5.000E+31	0.0132	29/09/2010
204	1.10E+11	12.7	186	4.762E+31	7.000E+31	0.0139	04/10/2010
248	1.10E+11	15.4	233	5.965E+31	1.030E+32	0.0164	14/10/2010
312	1.10E+11	19.4	295	7.552E+31	1.500E+32	0.0188	16/10/2010

Bunch trains - III



delivering up to 2×10^{32} cm^{-2} s^{-1} peak luminosity with 368 bunches)

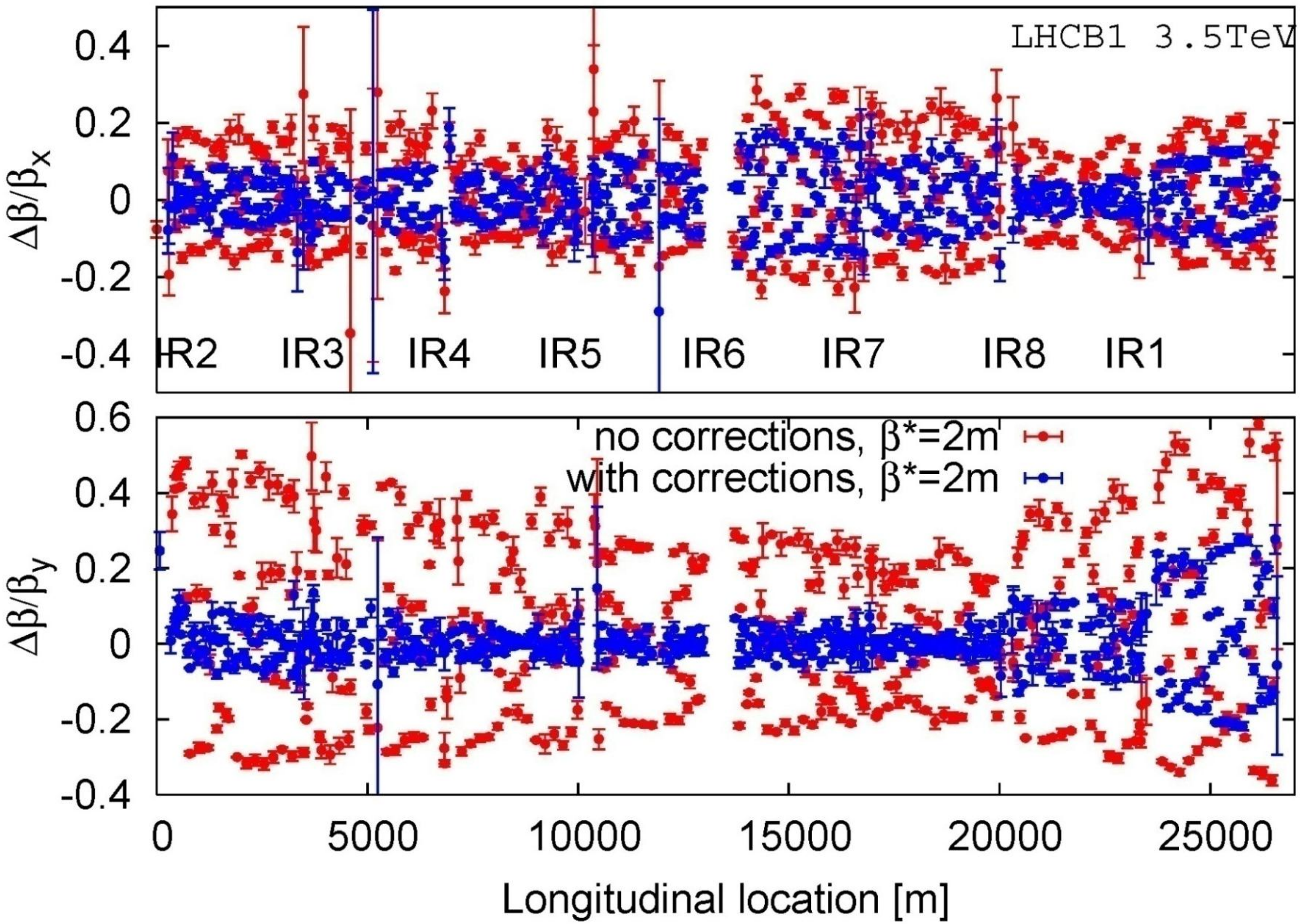
Intermezzo

- Injectors:
  - Outstanding performance: delivered lower-than-nominal (about 2.5 μm) emittance and larger than nominal bunch intensity!
- LHC
  - Mechanical aperture: better than anticipated
  - Optics: in good control
  - Beam-beam: operated with a factor of two larger beam-beam parameter!
  - Collimation performance: up to spec.

Thanks (also) to sorting of main dipoles and quadrupoles

Optics measurements

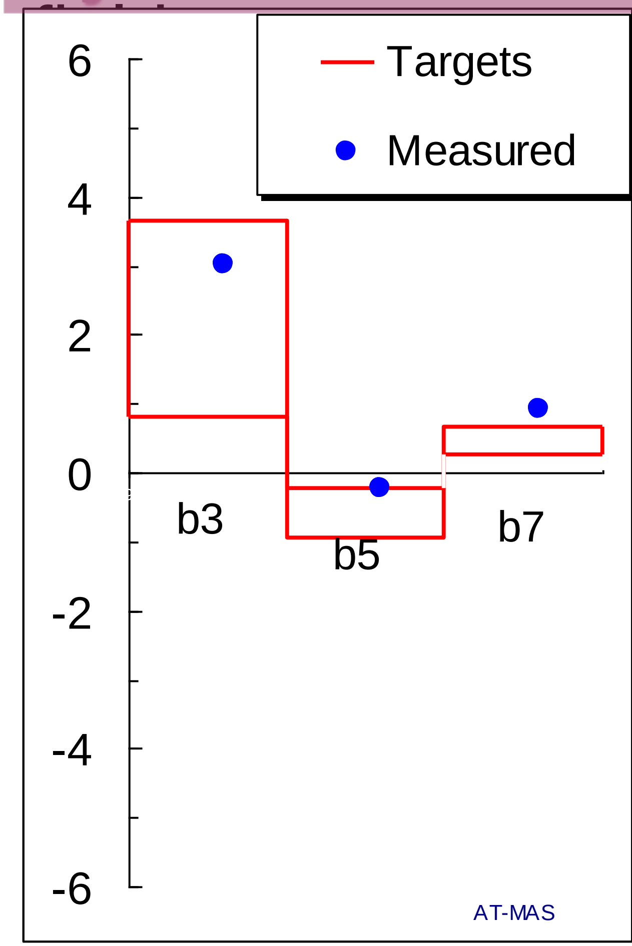
M. Aiba, R. Calaga, R. Miyamoto, F. Schmidt, R. Tomás, G. Vanbavinckhove

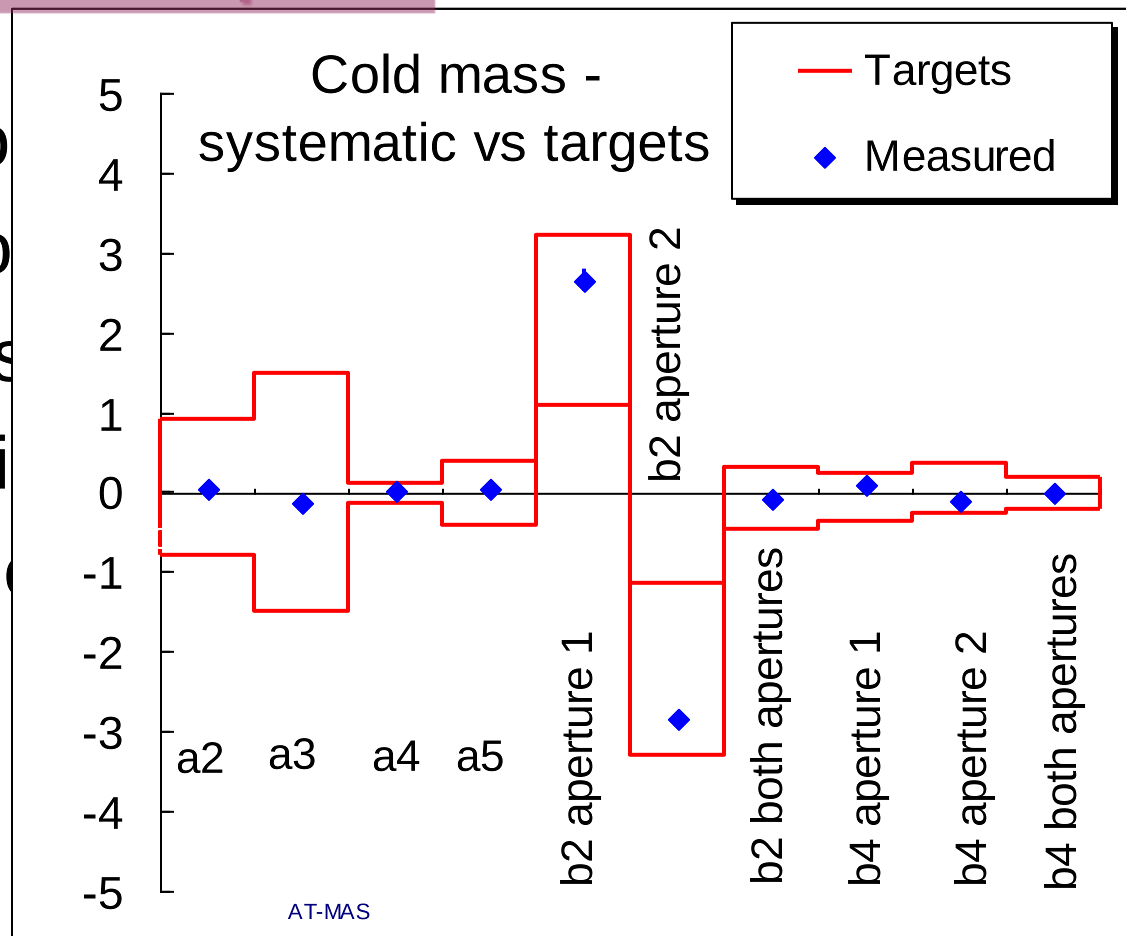


Superconducting magnets' model

Systematic field errors in dipoles

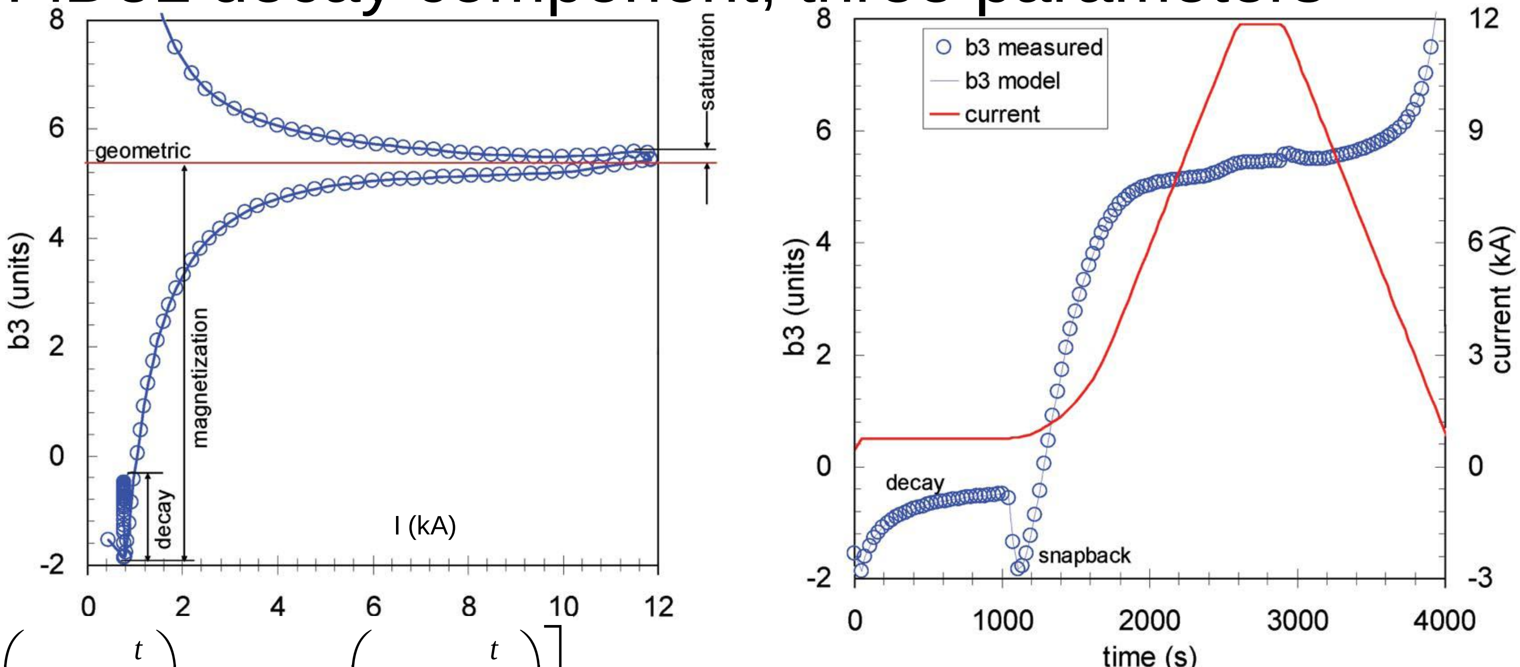
yers -> unavoidable



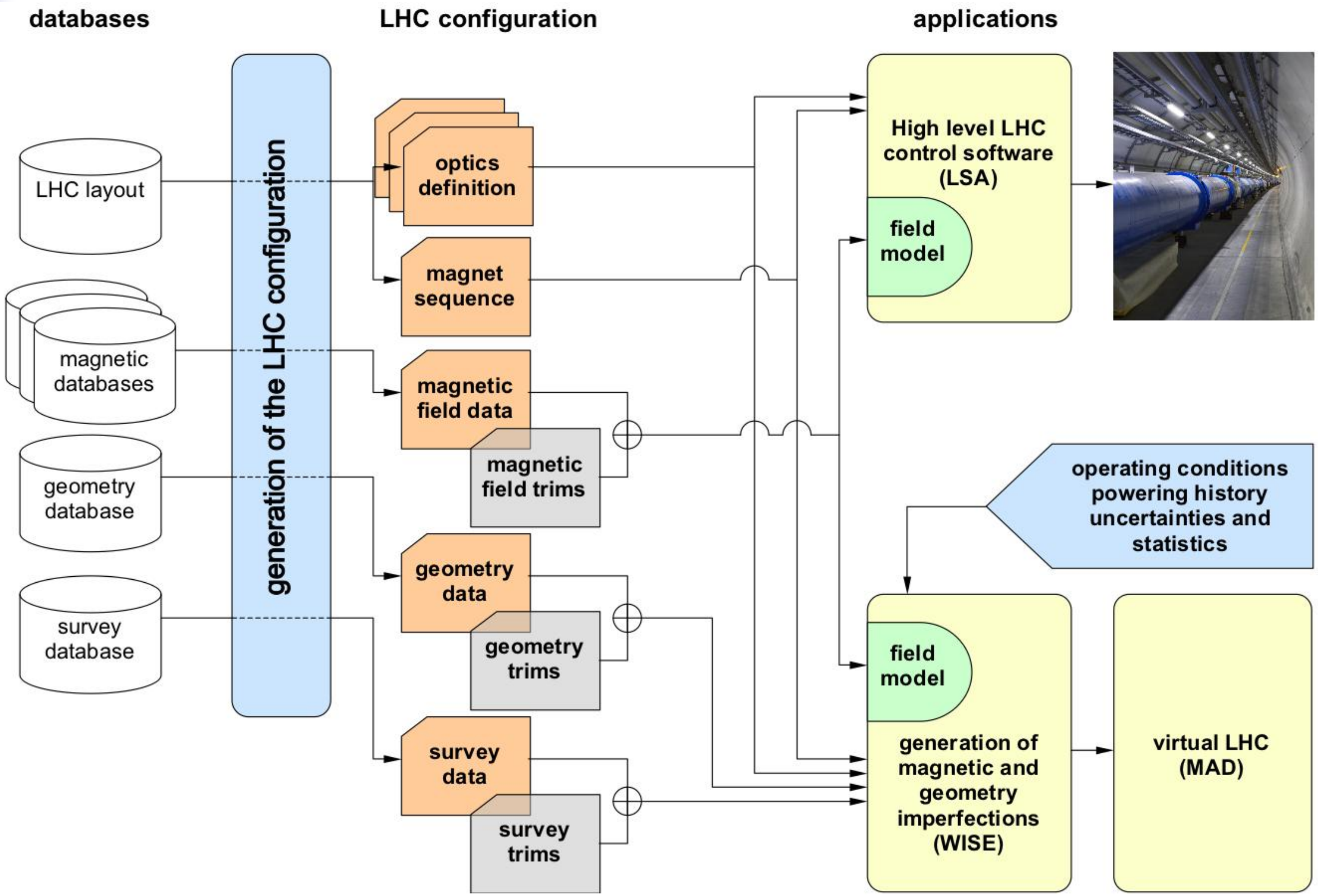


Setting generation

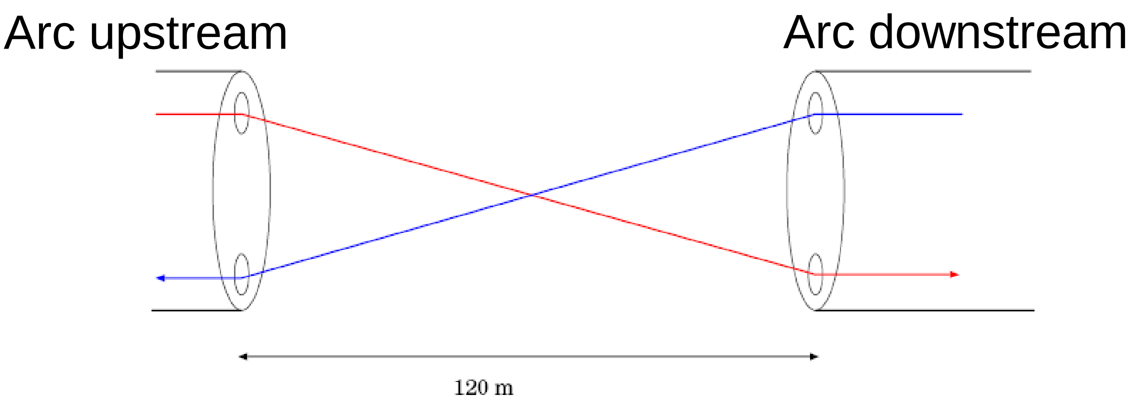
- A good magnetic model is needed
- The large set of magnetic measurements made during production is analysed and fits are computed
- Example: FiDeL decay component, three parameters



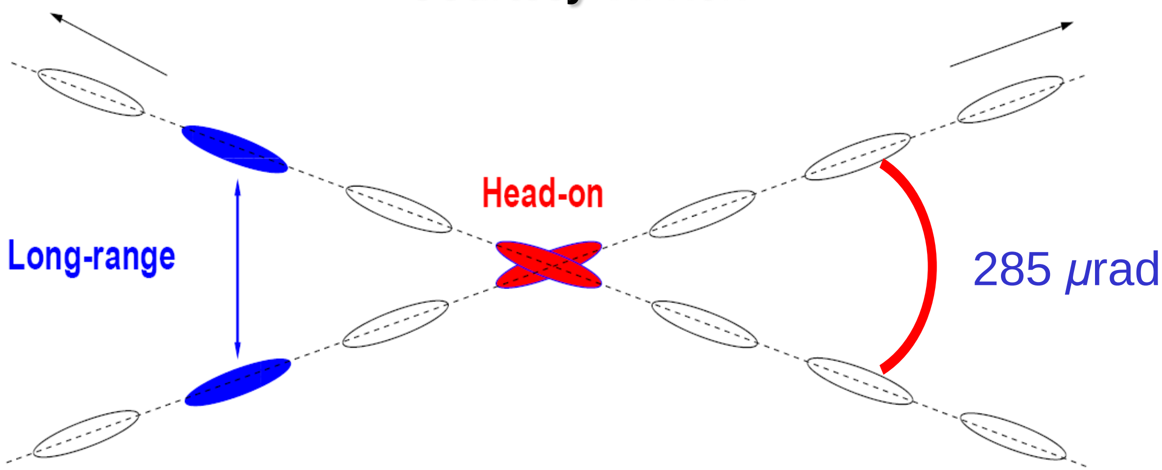
$$\Delta b_3(t; c, \tau, d) = c\left[d\left(1 - e^{-\frac{t}{\tau}}\right) + (1-d)\left(1 - e^{-\frac{t}{9\tau}}\right)\right]$$


databases
LHC configuration
applications
LHC layout
magnetic databases
geometry database
survey database
generation of the LHC configuration
optics definition
magnet sequence
magnetic field data
magnetic field trims
geometry data
geometry trims
survey data
survey trims
High level LHC control software (LSA)
field model
operating conditions powering history uncertainties and statistics
field model
generation of magnetic and geometry imperfections (WISE)
virtual LHC (MAD)

Beam-beam – I



Courtesy W. Herr



In case the collisions would occur head-on, plenty of parasitic collisions would take place in the common vacuum pipe.

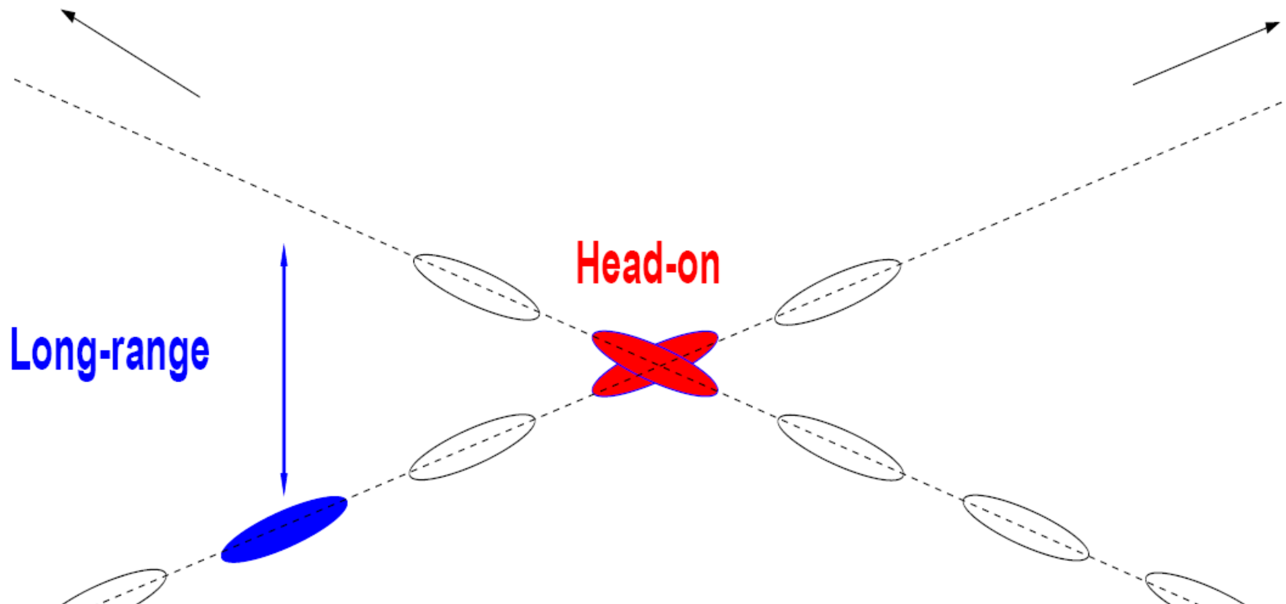
A crossing angle is used to separate bunches after the first wanted collision.

Even in this case, the various bunches are coupled together via Coulomb interaction. The crossing angle should provide enough separation for making the parasitic collisions harmless.

Beam-beam - II

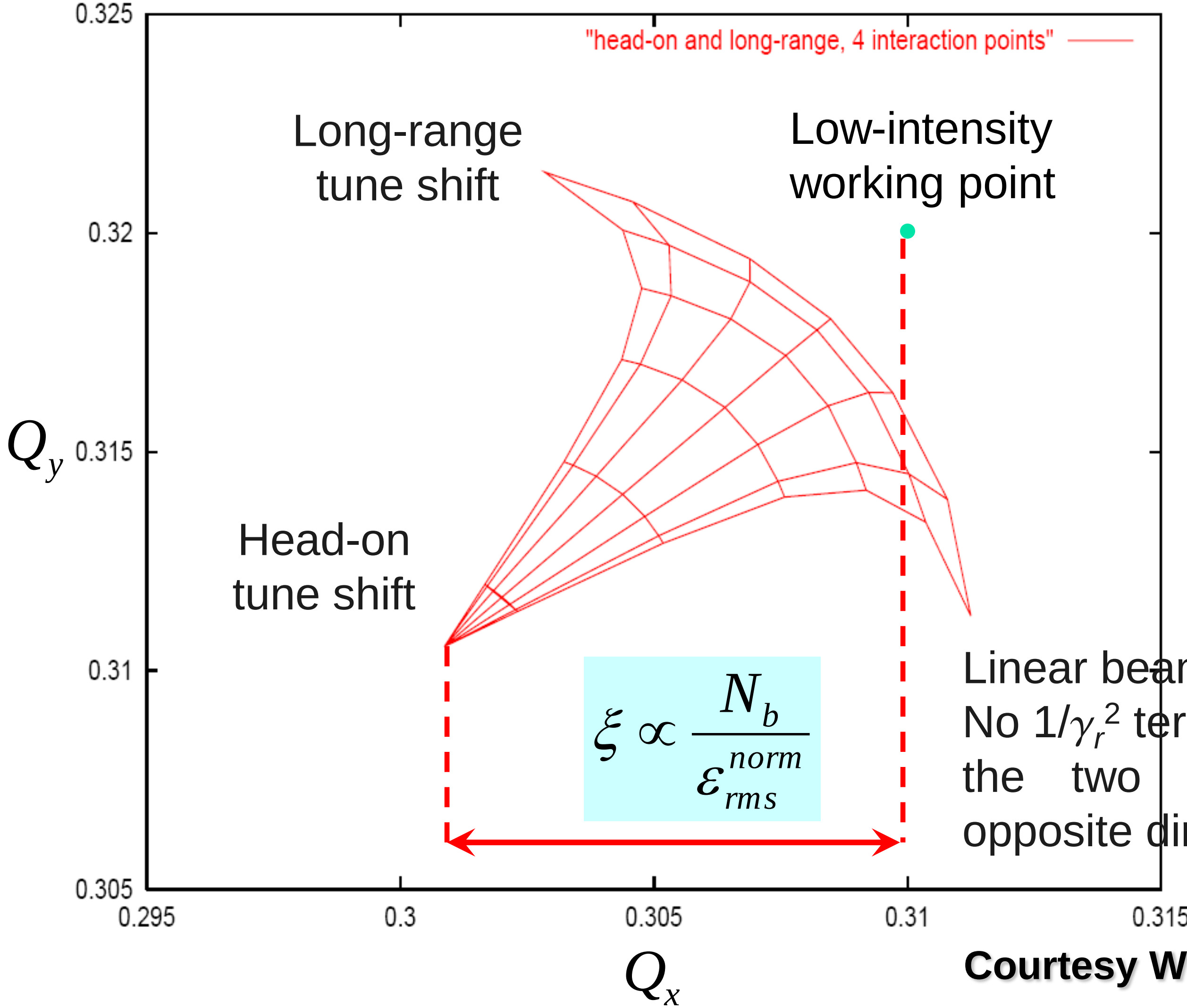
- Unfortunately, the crossing angle cannot cope with additional effects, the so-called PACMAN bunches.
- The LHC filling pattern is not continuous, but gaps have to be included.
- Hence three types of collisions can occur:
  - Bunch-bunch
  - Bunch-hole
  - Hole-hole

Alternating the crossing plane mitigates the PACMAN effect!



Courtesy W. Herr

Beam-beam - III



2D tune footprint for nominal LHC parameters in collision. Particles with amplitudes up to 6 σ are included

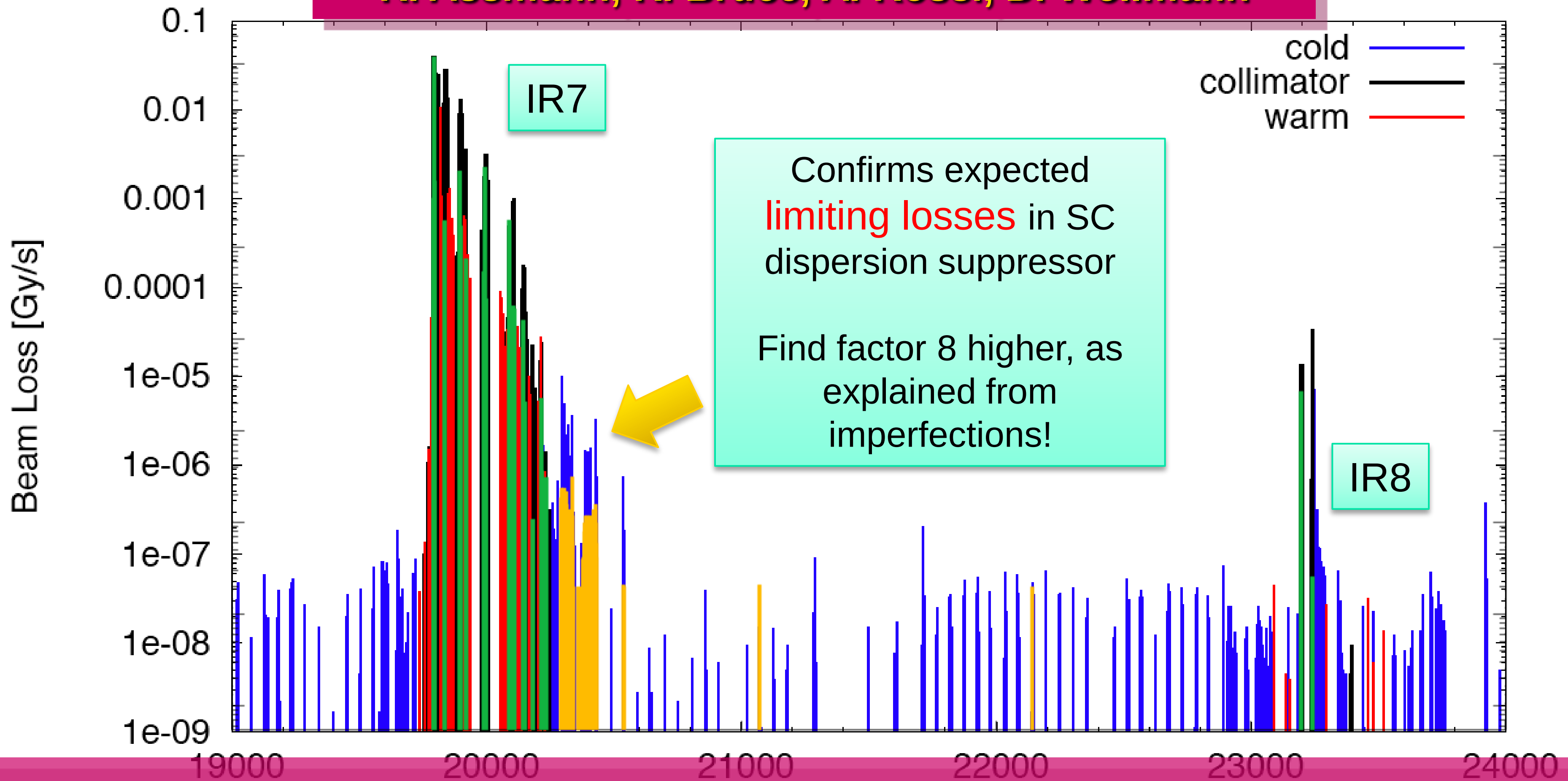
Linear beam-beam tune shift.
No $1/\gamma_r^2$ term as for space charge, as the two beams are moving in opposite direction.

Courtesy W. Herr

Meas. & Sim. Cleaning at 3.5 TeV

(beam1, vertical beam loss, intermediate settings)

R. Assmann, R. Bruce, A. Rossi, D. Wollmann



Excellent performance of collimation system: cleaning efficiency 99.98% - 99.99%.

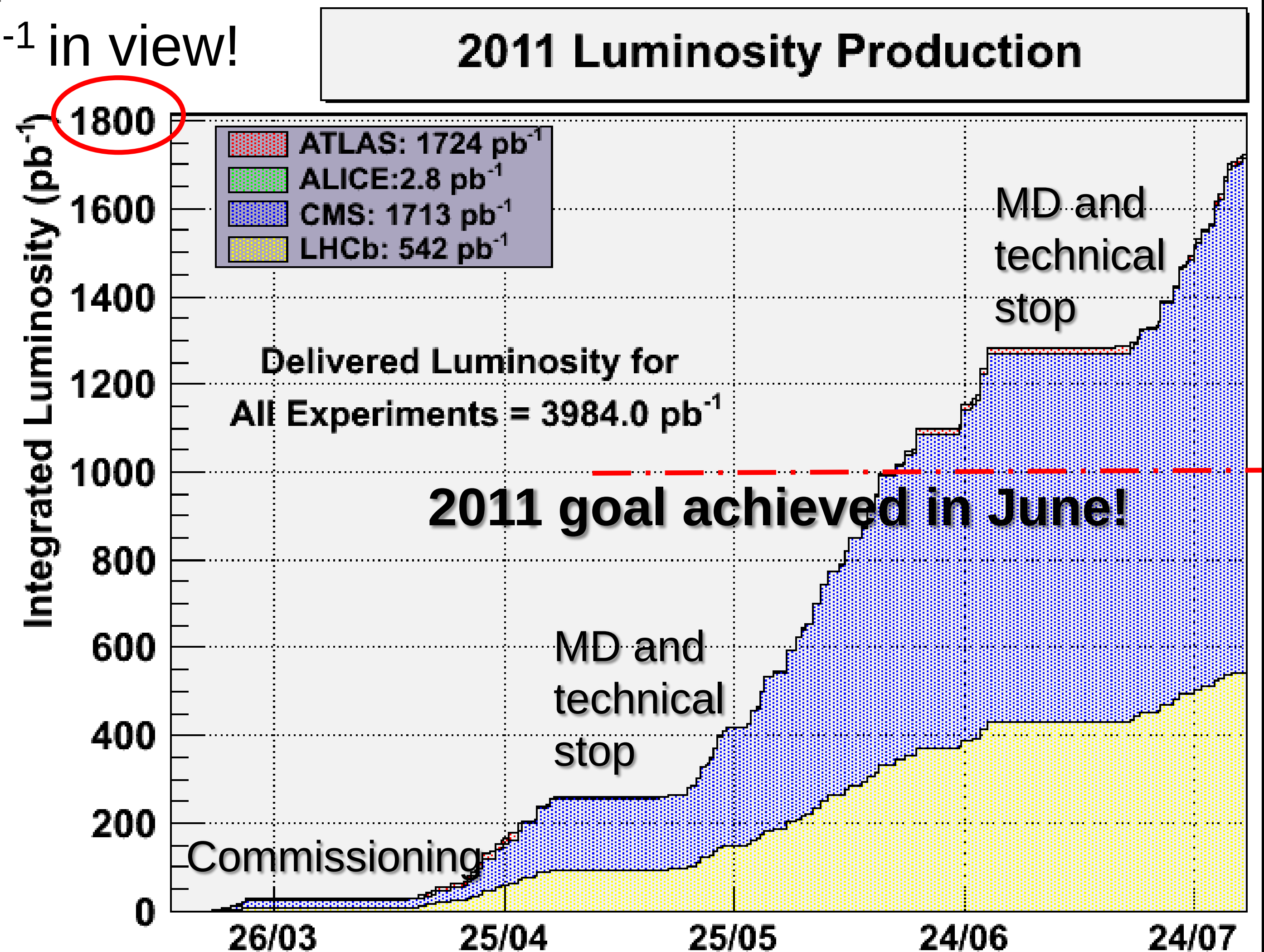
Current situation - I

- Goal for 2011: 1 fb^{-1} (conservative). It requires:
  - moving to 50 ns bunch spacing
  - reducing β*
  - further reducing emittance to about 2 μm
  - Increasing intensity
  - fighting against:
    - Electron-cloud
    - UFO
    - Single Event Upset

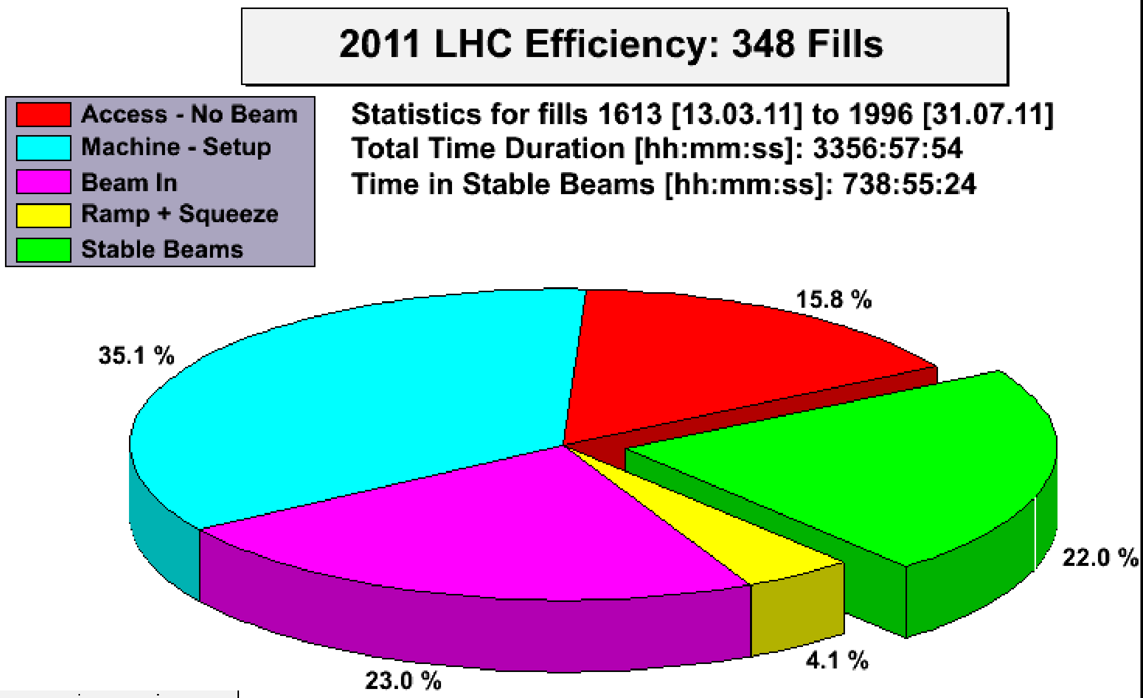
Energy [TeV]	3.5
beta* [m]	1.5, 10.0, 1.5, 3.0 m
Emittance [μm]	**~2.5 – 2.8**
Bunch intensity	1.2e11
Number of bunches	1380 1317 collisions/IP
Stored energy [MJ]	up to 90
Peak luminosity [$cm^{-2}s^{-1}$]	up to 2×10^{33}
Beam-beam tune shift	0.015 - 0.02

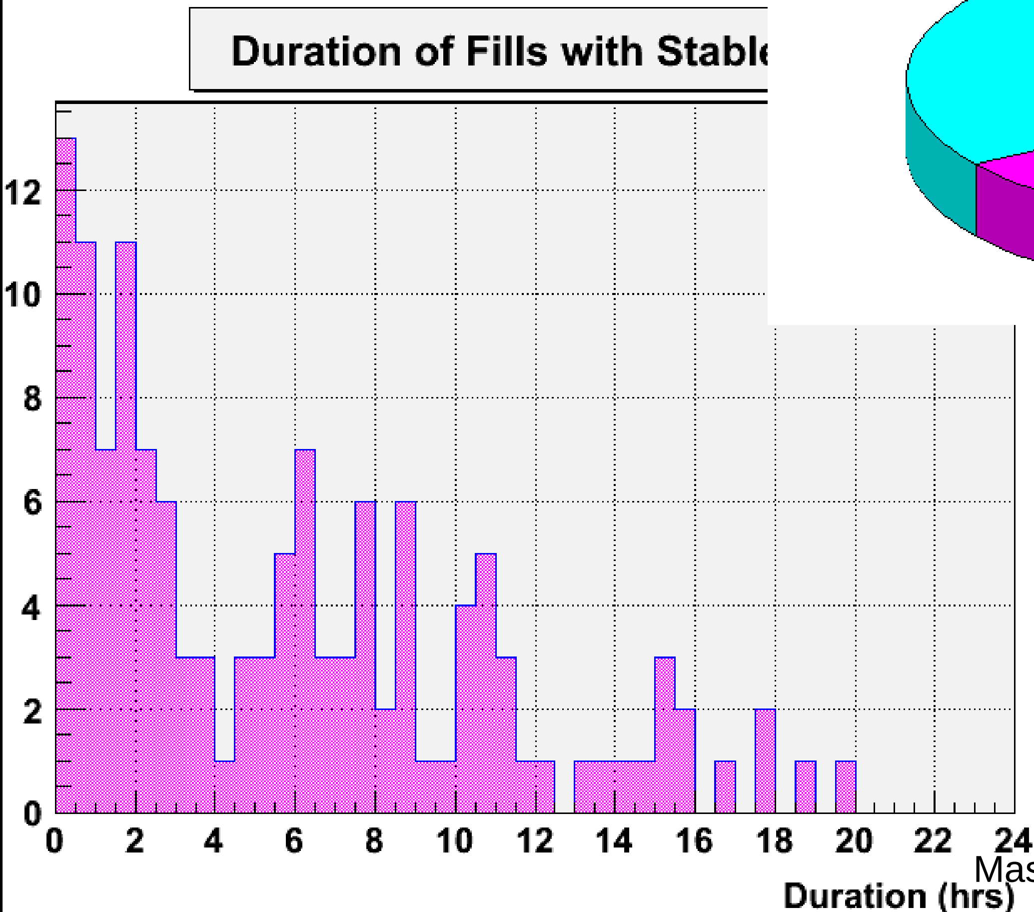
Current situation - II

2 fb^{-1} in view!



Current situation - III

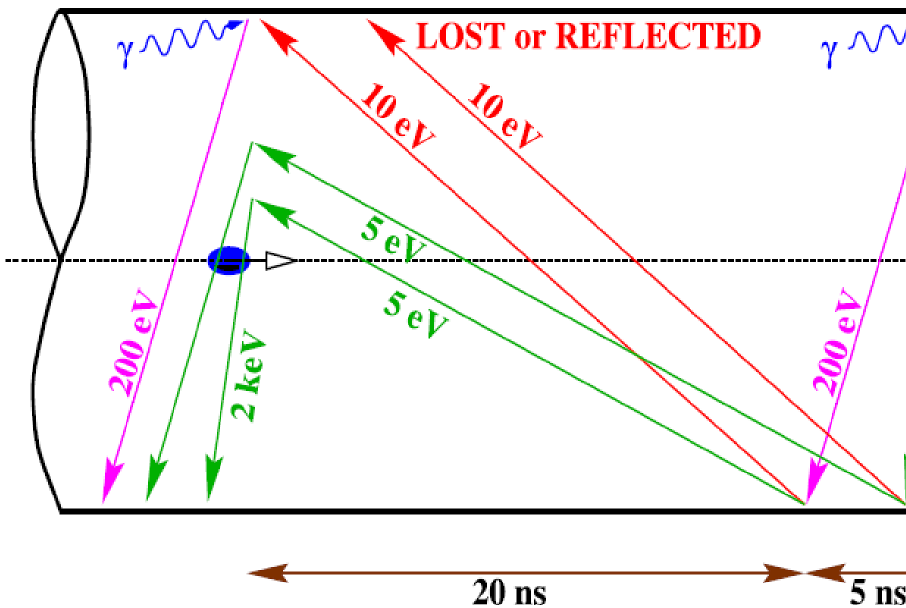




The number of short fills tend to increase!

Electron-cloud - I

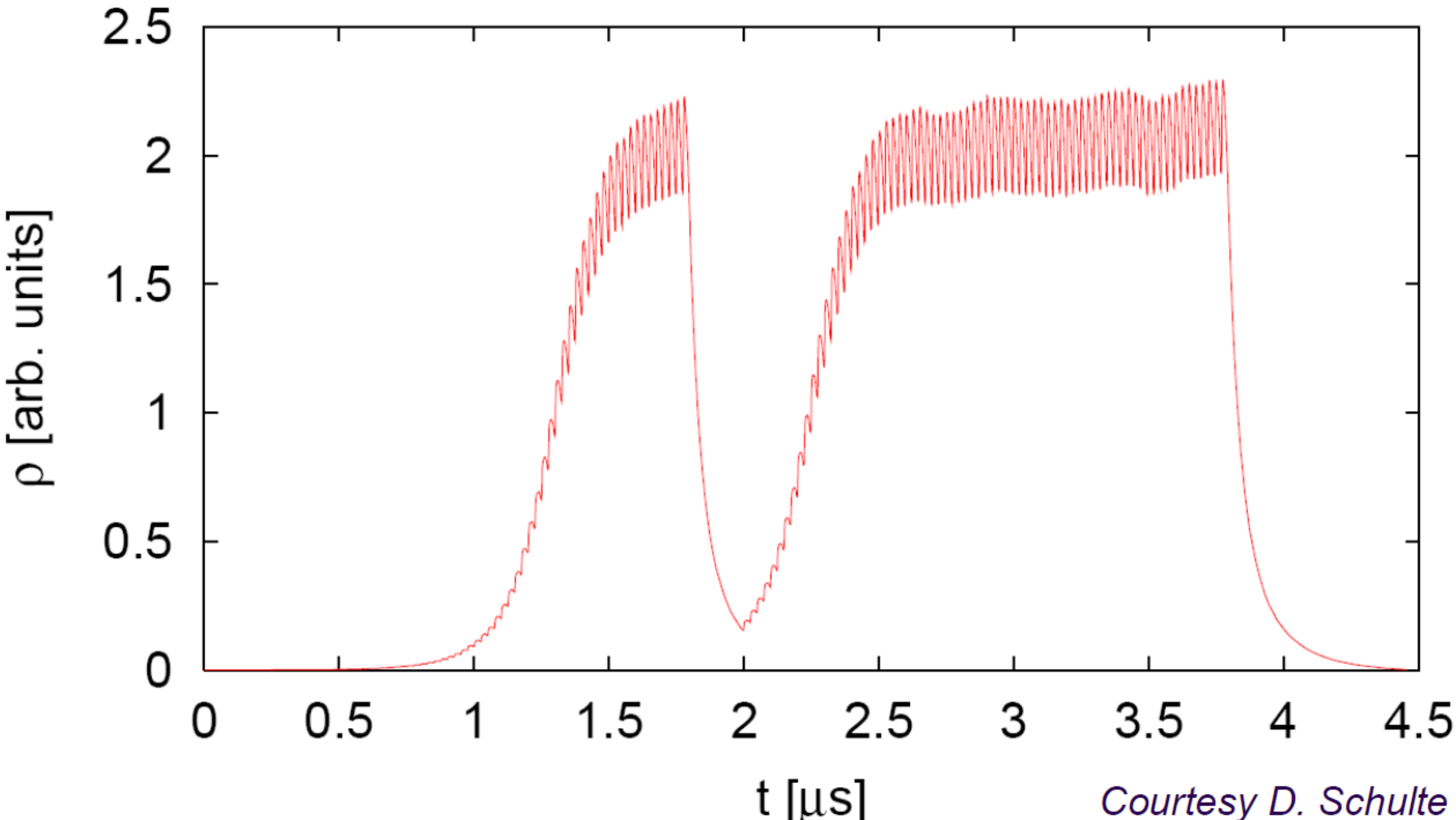
- Schematic of electron-cloud build up in the LHC beam pipe during multiple bunch passages, via photo-emission (due to synchrotron radiation) and secondary emission.



Courtesy F. Ruggiero

Electron-cloud - II

Electron density due to two batch of 72 bunches (25 ns spacing)



Courtesy D. Schulte

Electron-cloud - III

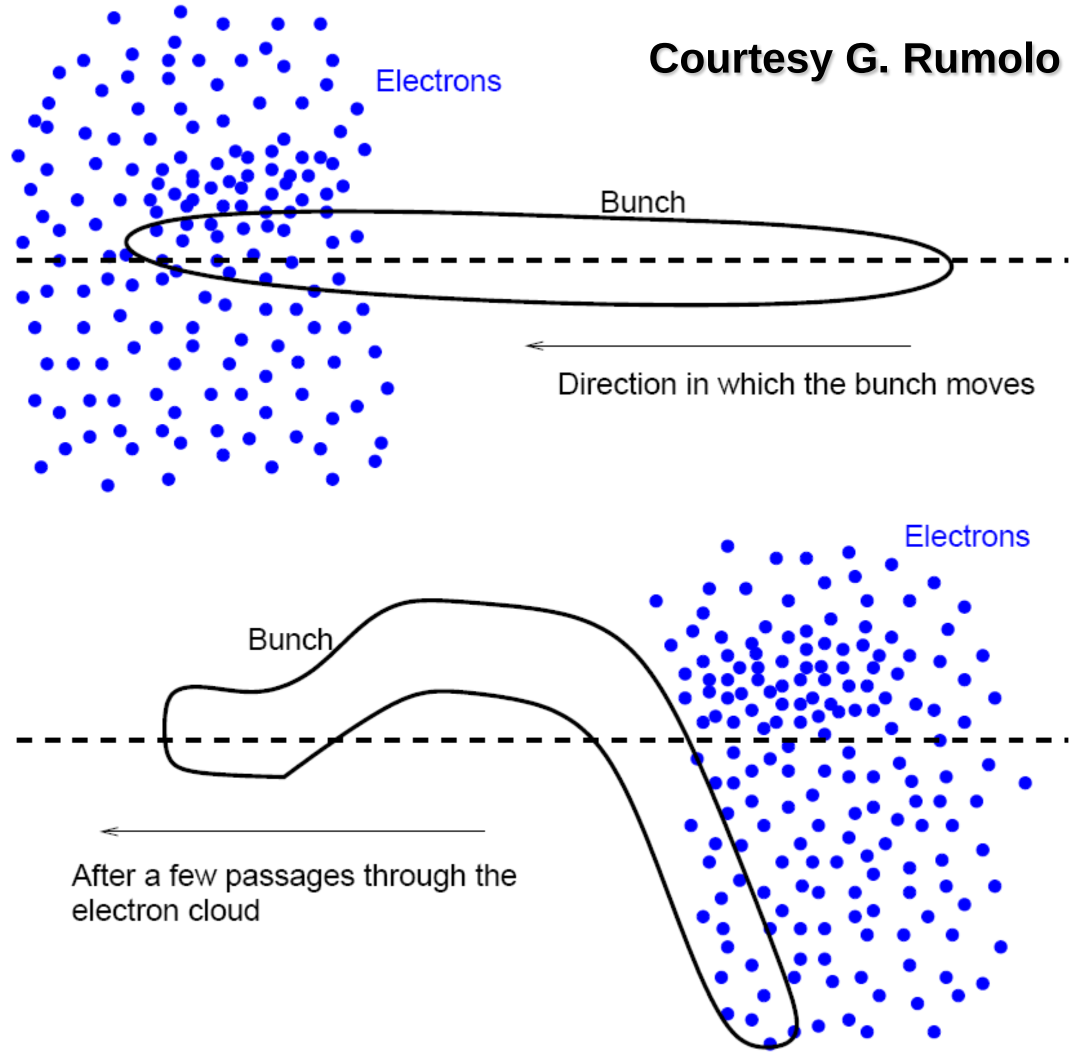
Schematic of the single-bunch (coherent) instability induced by an electron cloud.

How can we cure such phenomenon?

The phenomenon depends strongly on the bunch spacing.

25 ns is the worst case, 50 ns is much better!

Courtesy G. Rumolo

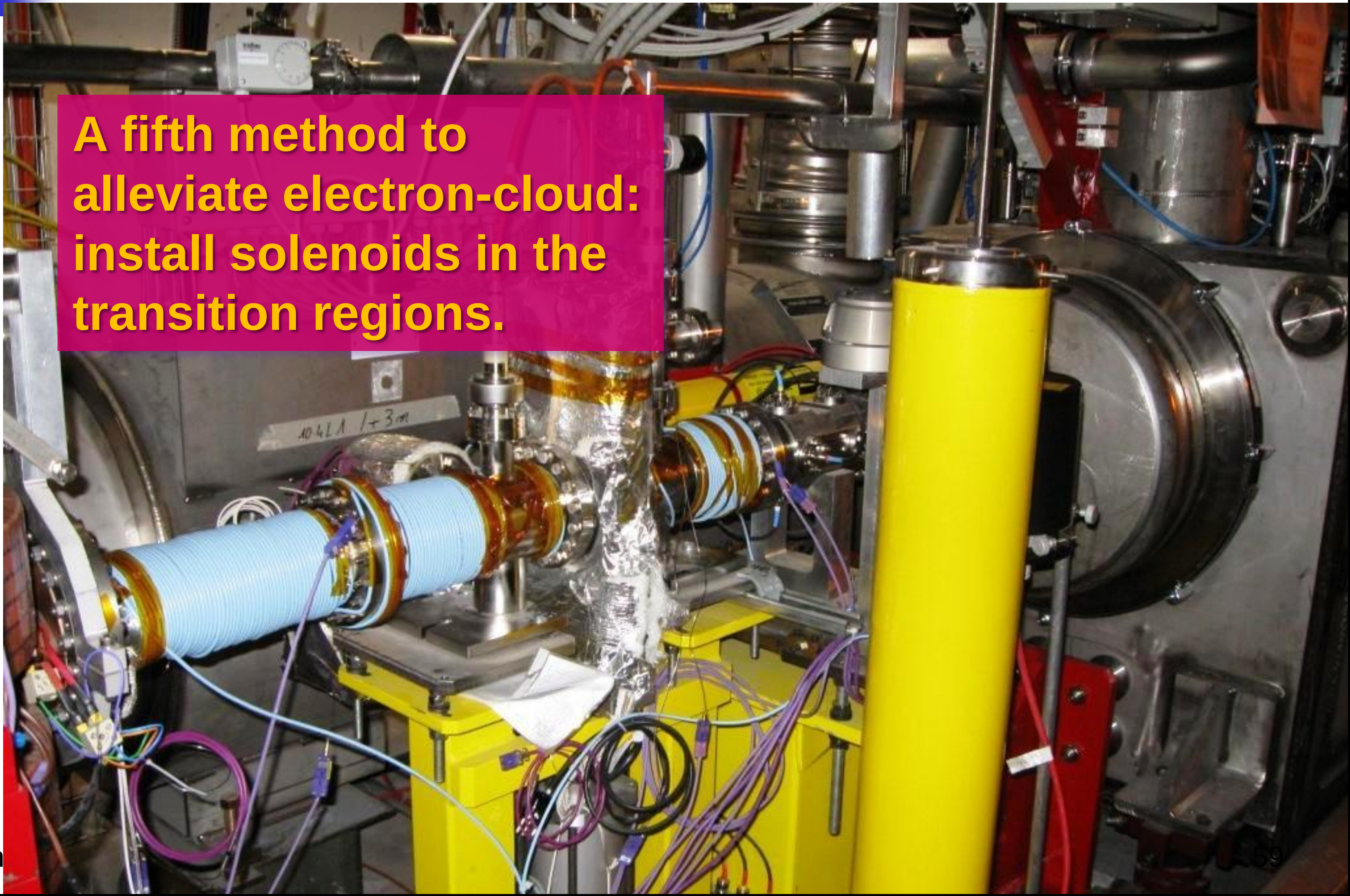


Electron-cloud - IV

- Four approaches are used to suppress/alleviate electron-cloud build-up:
  - A saw tooth chamber in the arcs (a series of 30-μm high steps spaced at a distance of 500 μm in the longitudinal direction) to reduce the photon reflectivity.
  - Shielding the pumping holes inside the arc beam screen so as to prevent multipacting electrons from reaching the cold bore of the dipole magnet.
  - Coating the warm regions by a special Non Evaporable Getter (NEG) material, TiZrV, with low secondary emission yield.
  - Conditioning of the arc chamber surface by the cloud itself (beam scrubbing), which will ultimately provide a low secondary emission yield.

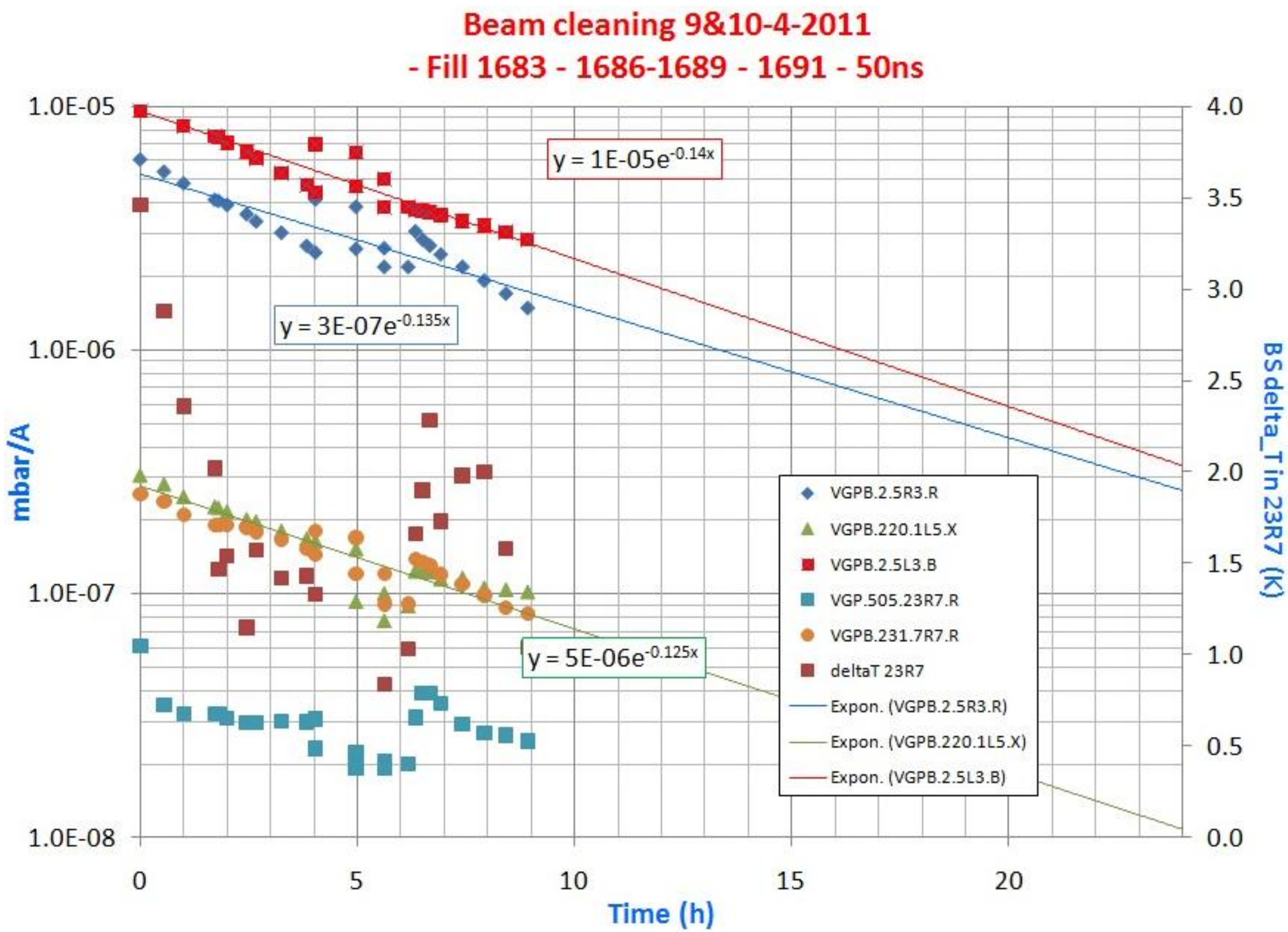
Electron-cloud - V

A fifth method to alleviate electron-cloud: install solenoids in the transition regions.



Electron-cloud - VI

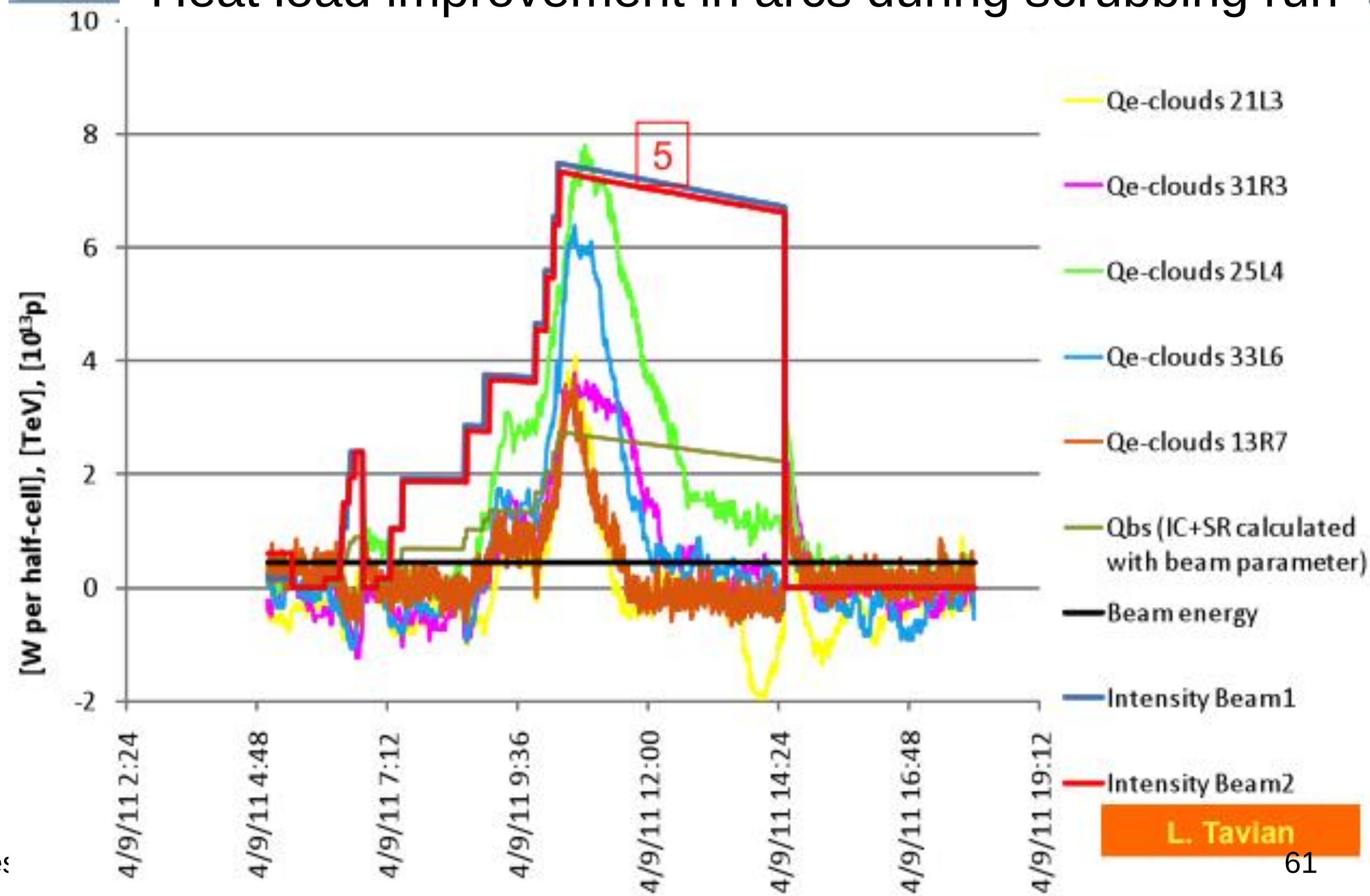
Vacuum improvement during scrubbing run



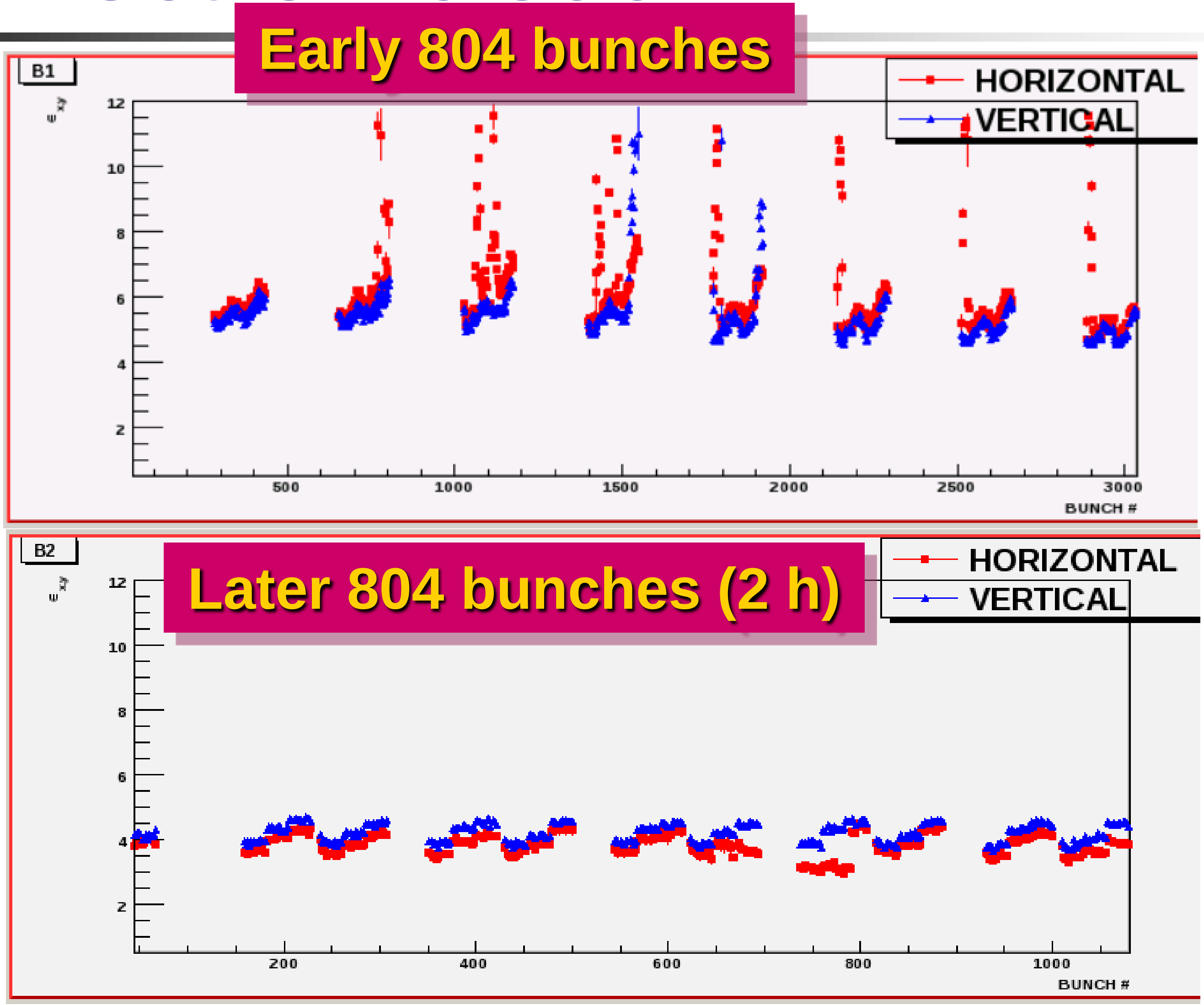
Courtesy V. Baglin

Electron-cloud - VII

Heat load improvement in arcs during scrubbing run

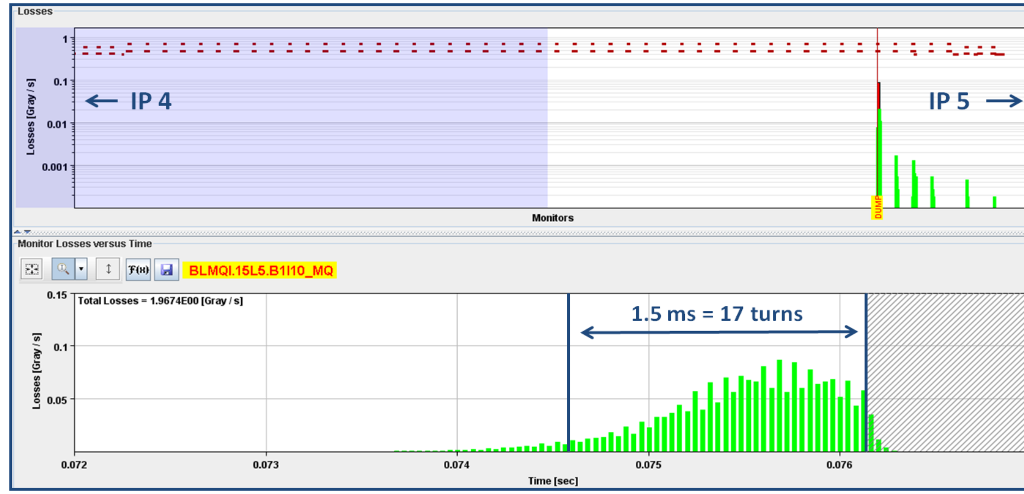


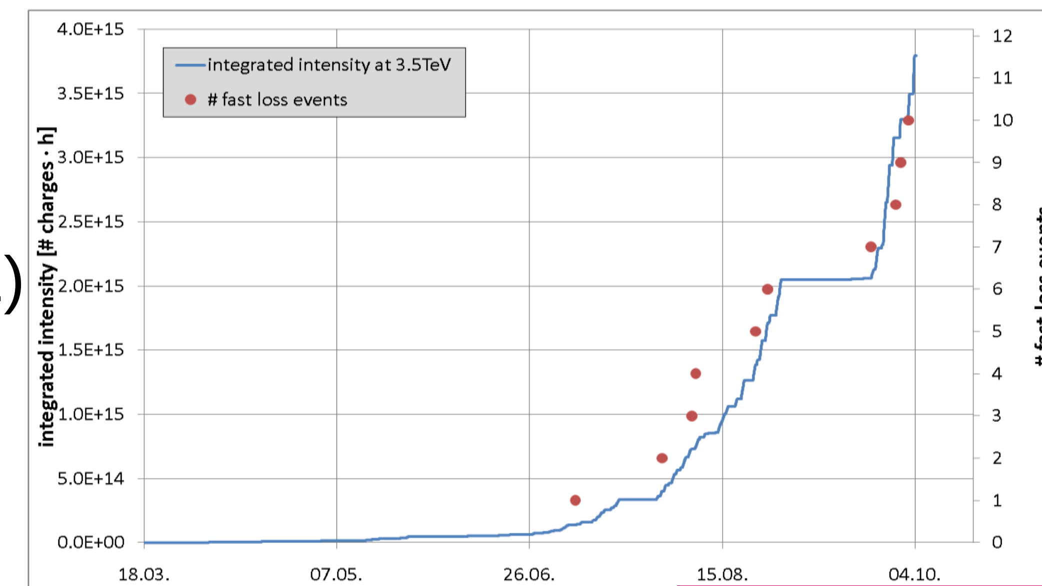
Electron-cloud - VIII



UFO: unidentified falling objects - I

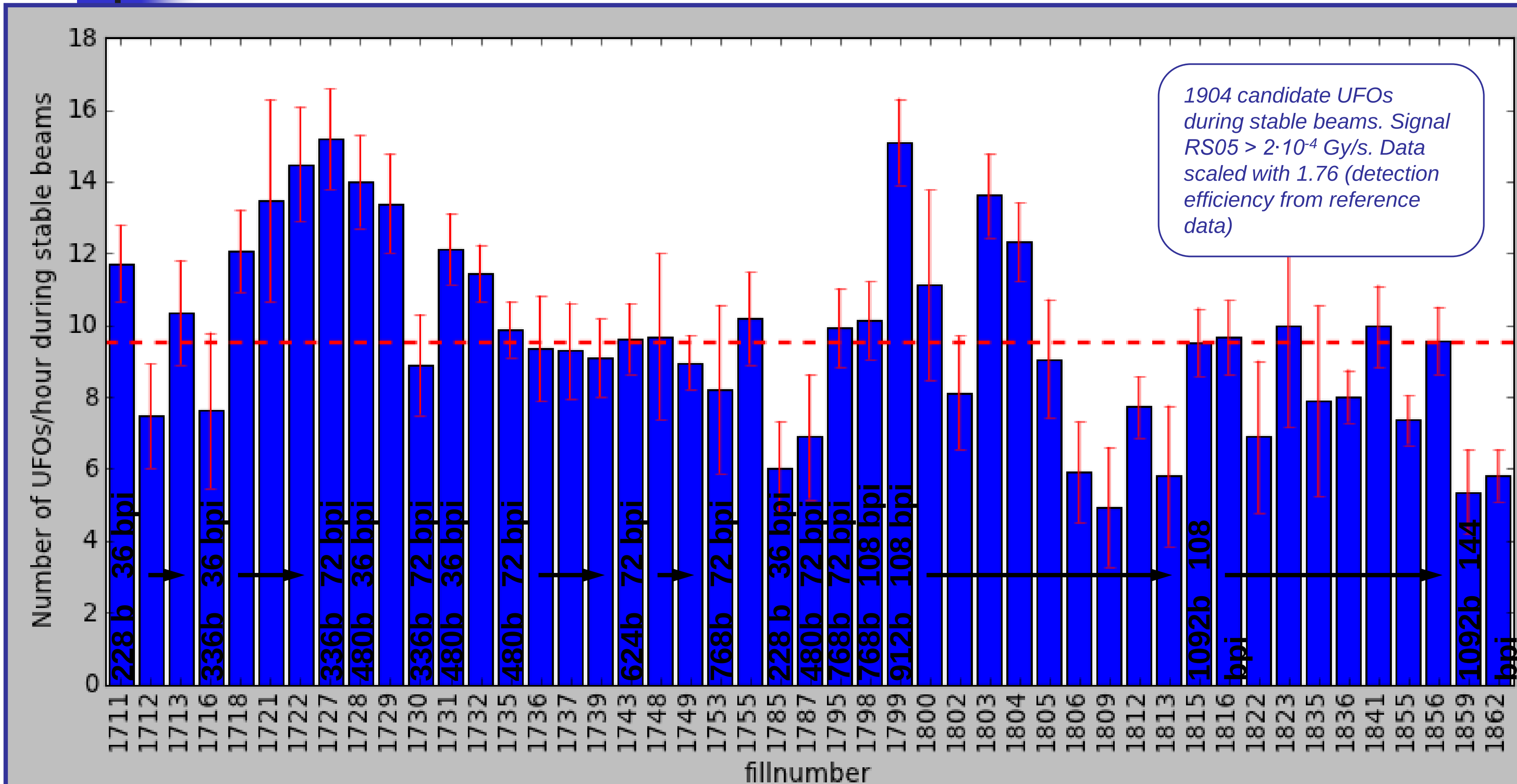
- **18 beam dumps** due to UFOs in 2010.
  - UFOs are fast beam losses (loss duration some 10 turns)
  - UFOs occur often at unconventional loss locations (e.g. in the arc)
- **11 beam dumps** due to UFOs in 2011 (on 14/06/11)
  - 8 in injection region
  - 1 dump at 450 GeV.





Courtesy T. Baer

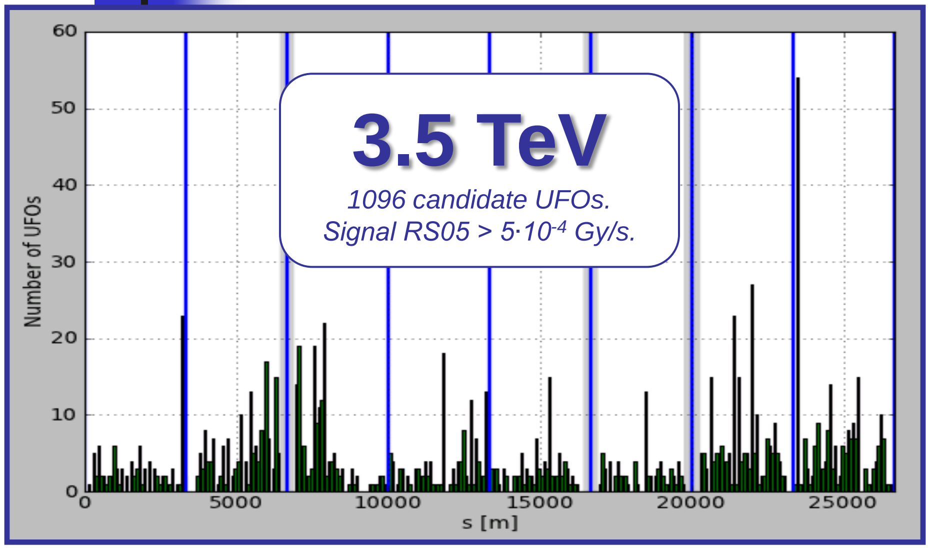
UFO: unidentified falling objects - II

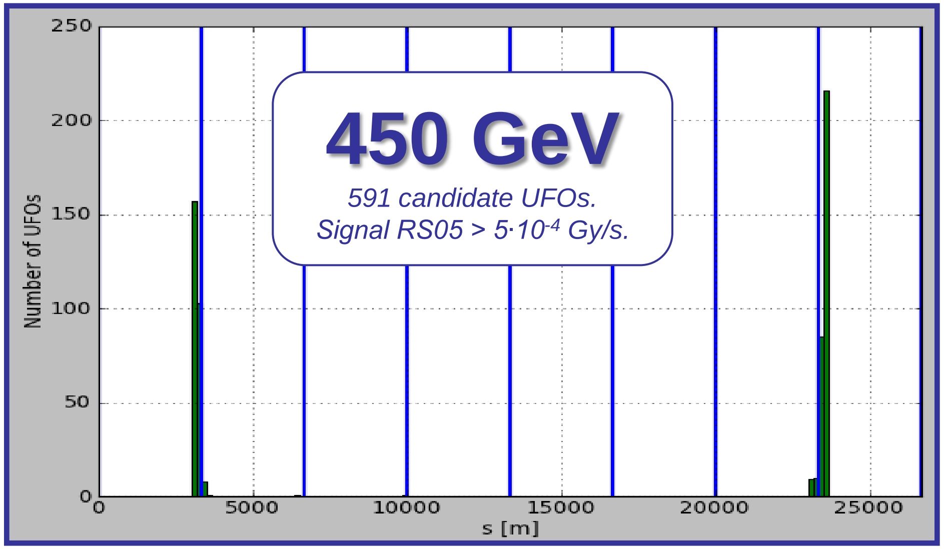


UFO rate in 2011: on average 10 UFOs/h!

Courtesy T. Baer

UFO: unidentified falling objects - III





The UFOs are distributed all around the machine.

Mainly UFOs around injection kickers

Candidates: Dust particles falling onto the beam could explain the observations.

The particle would charge up when falling.

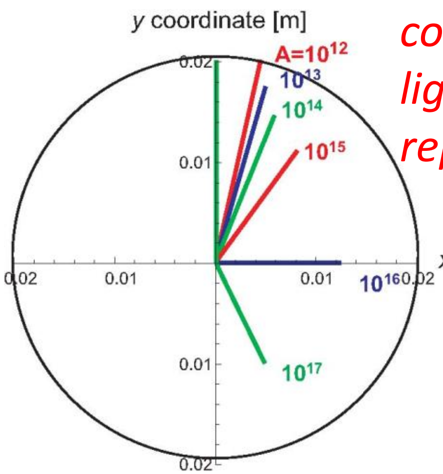
Depending on the mass it could move through the beam or be repelled.

Simulations are in progress…

Courtesy T. Baer

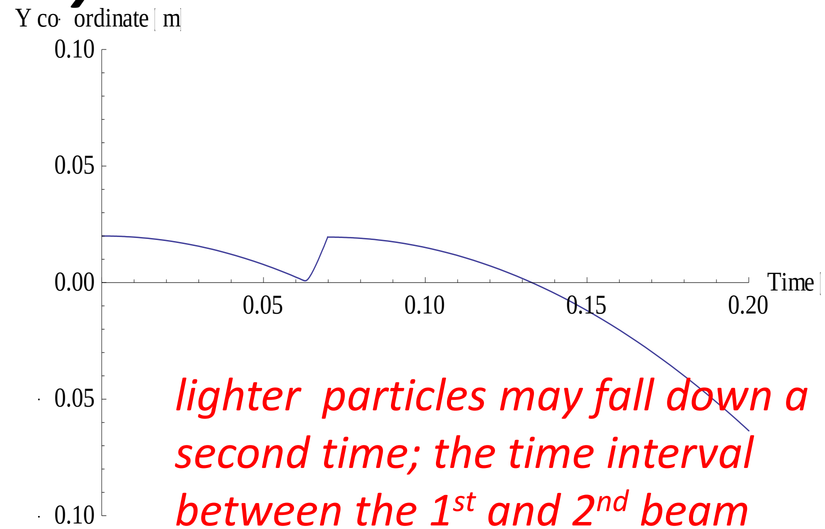
UFO: unidentified falling objects - IV

trajectories



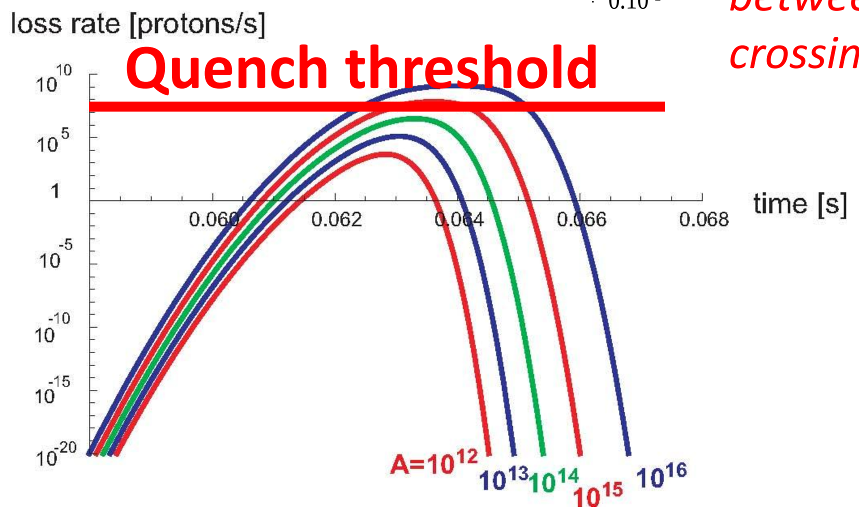
particles heavier than A=10^{16} proton masses continue to fall down; lighter particles are repelled after charging up

y coordinate vs. time



lighter particles may fall down a second time; the time interval between the 1st and 2nd beam crossing is ~70 ms

resulting loss rates



$N_{tot}=2.3\text{x}10^{12}$

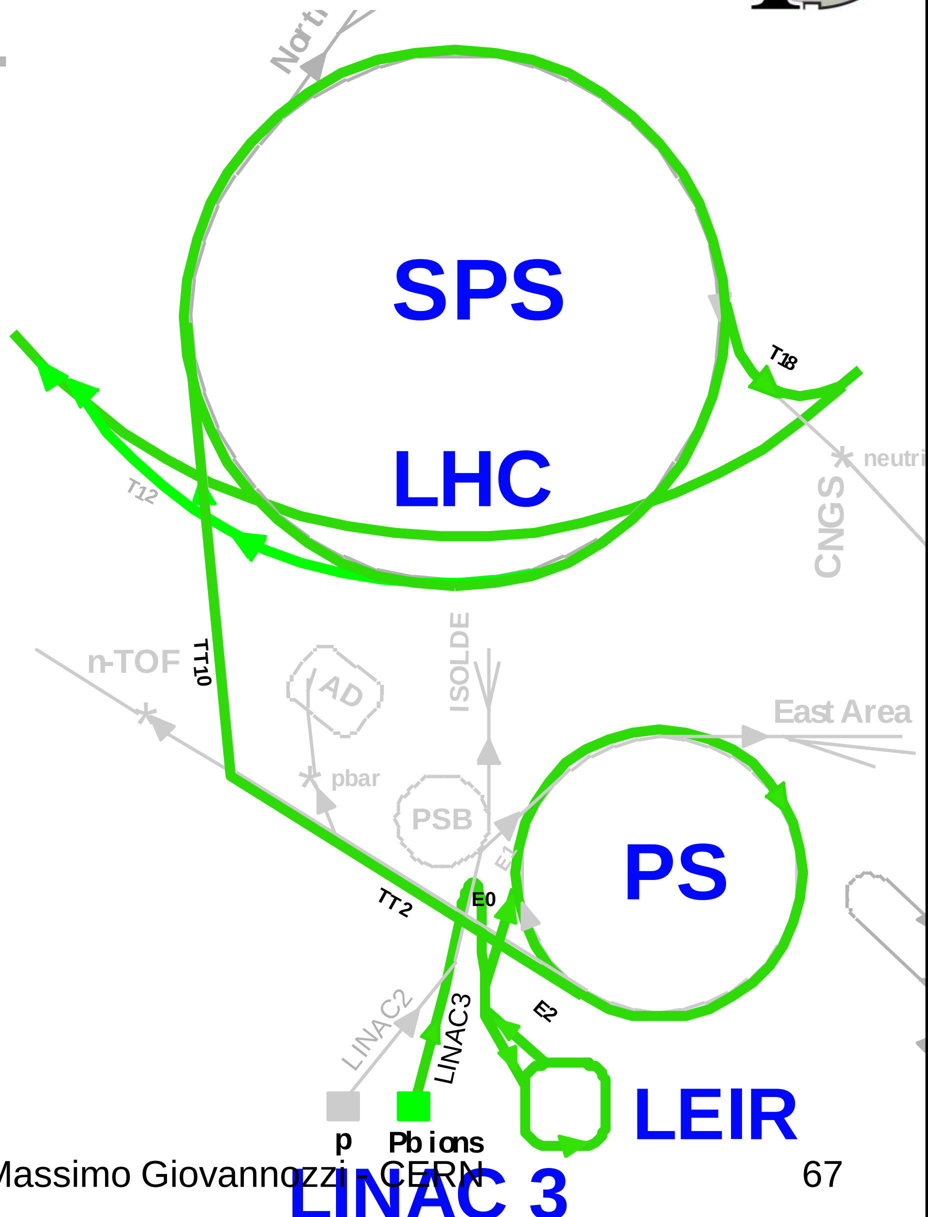
longer and higher losses for present beam current!

total loss duration ~a few ms

Courtesy F. Zimmermann

LHC Ion Injector Chain

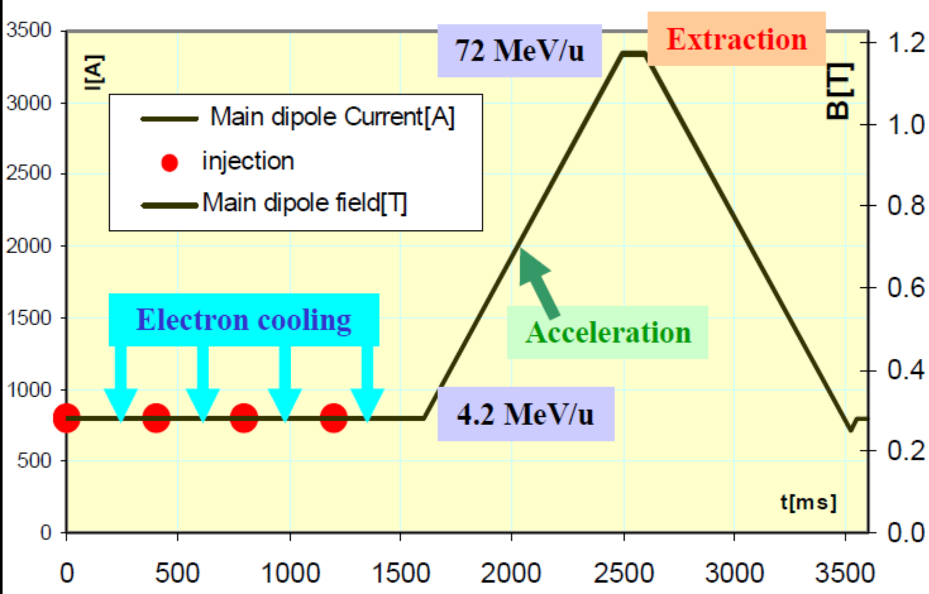
- ECR ion source (2005)
  - Provide highest intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC

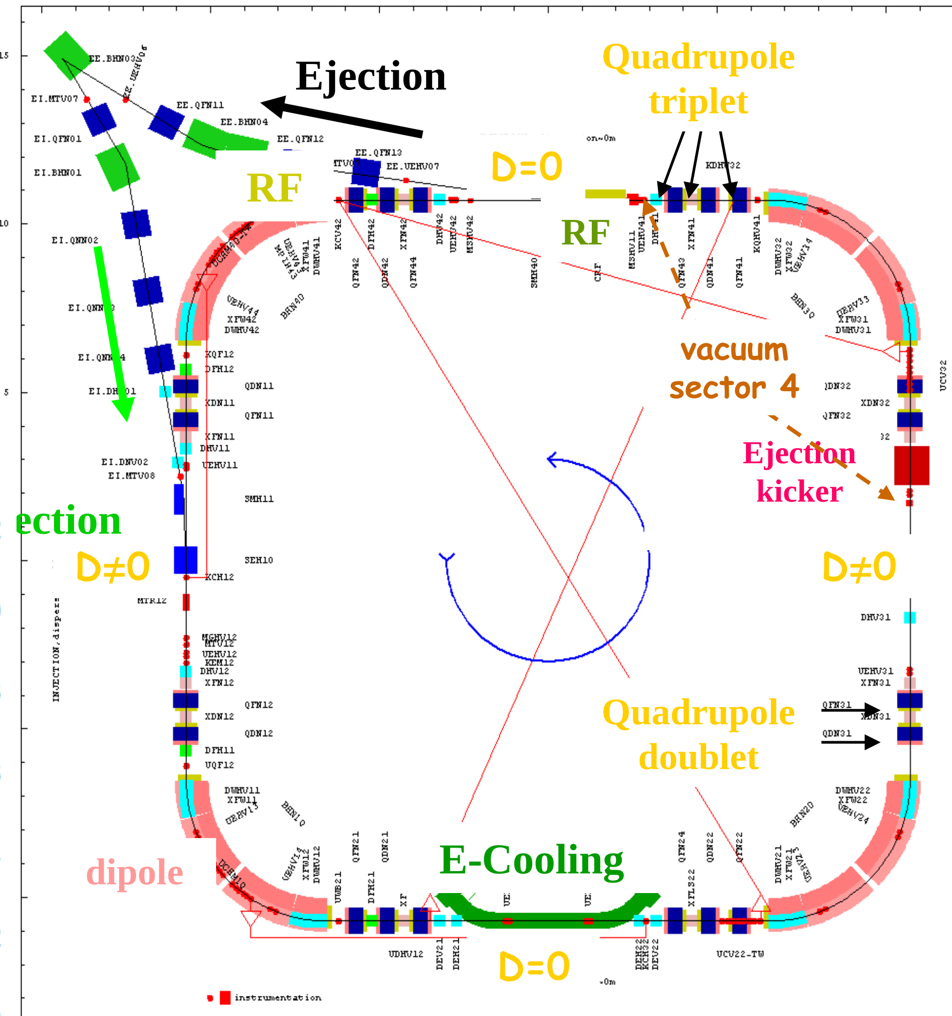


LEIR (Low-Energy Ion Ring)

- Prepares beams for LHC using electron cooling
- circumference 25 π m (1/8 PS)
- Multiturn injection into horizontal+vertical+longitudinal phase planes

Expected Cycle for Lead Ions





LHC Pb Injector Chain

Design Parameters for luminosity 10^{27} cm^{-2} s^{-1}

	ECR Source →	Linac 3 → (4) →	LEIR →	PS → (13,12,8) →	SPS → (12) →	LHC
Output energy	**2.5 KeV/n**	**4.2 MeV/n**	**72.2 MeV/n**	**5.9 GeV/n**	**177 GeV/n**	**2.76 TeV/n**
^{208}Pb charge state	**27+**	**27+ → 54+**	**54+**	**54+ → 82+**	**82+**	**82+**
Output Bρ [Tm]		2.28 → 1.14	4.80	86.7 → 57.1	1500	23350
bunches/ring			2 (1/8 of PS)	4 (or 4x2)[4]	52,48,32	592
ions/pulse	$9\ 10^9$	$1.15\ 10^9$ [1])	$9\ 10^8$	$4.8\ 10^8$	$\leq 4.7\ 10^9$	$4.1\ 10^{10}$
ions/LHC bunch	**$9\ 10^9$**	**$1.15\ 10^9$**	**$2.25\ 10^8$**	**$1.2\ 10^8$**	**$9\ 10^7$**	**$7\ 10^7$**
bunch spacing [ns]				100 (or 95/5)[4]	100	100
ε*(nor. rms) [μm][2]	**~0.10**	**0.25**	**0.7**	**1.0**	**1.2**	**1.5**
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	**~10’fill/ring**
ε_{long} per LHC bunch[3]			0.025 eVs/n	0.05	0.4	1 eVs/n
total bunch length [ns]			200	3.9	1.65	1

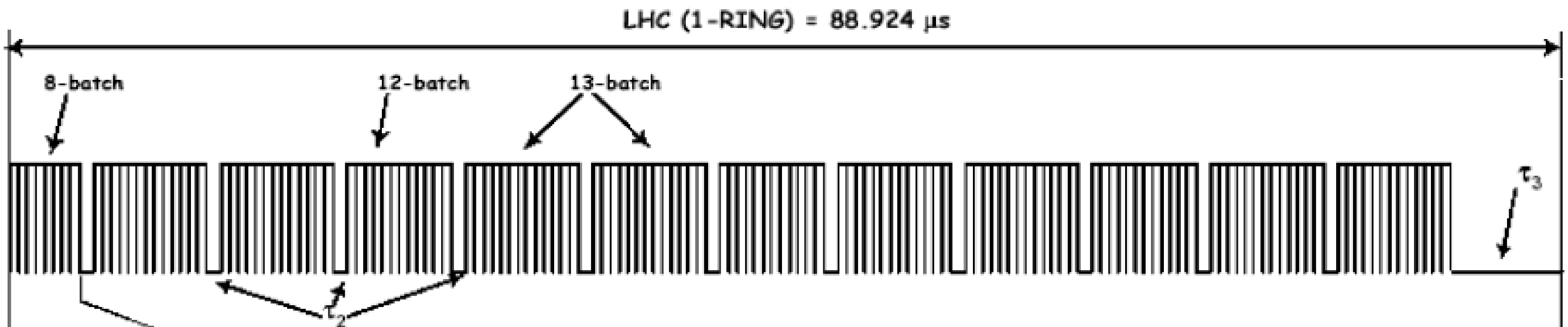
[1] 50 eμA_e x 200 μs Linac3 output after stripping

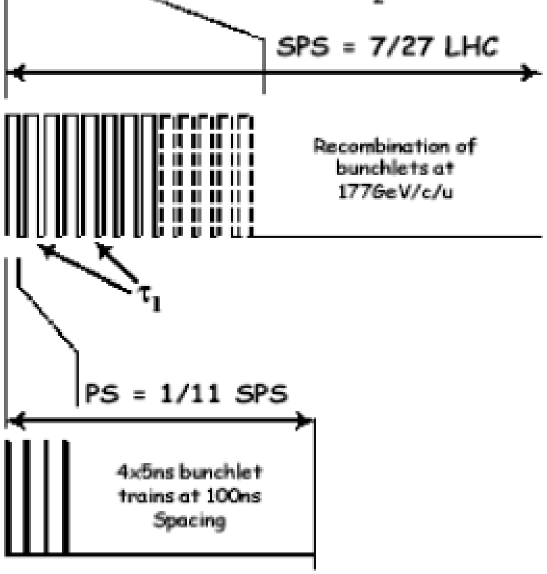
[2] Same physical emittance as protons. The normalised emittance is a relativistic invariant

Stripping foil

Filling schemes for Pb-Pb

Nominal Ion Bunch Pattern in the LHC





Bunch Train Pattern

81313 121313 121313 121313

Filling Scheme (100ns Bunch Spacing)

891 = (8 x [4b + 1.25e] + 7.75e) + {2 x (13 x [4b + 1.25e] + 7.75e)}
+ 3 x [(12 x [4b + 1.25e] + 7.75e) + {2 x (13 x [4b + 1.25e} + 7.75e)}]
+ 21e

Beam Gaps

τ_1 = 1.25 missing bunches (SPS Injection Kicker Rise Time = 225ns).
τ_2 = 9 missing bunches (LHC Injection Kicker Rise time = 1.0μs).
τ_3 = 30 missing bunches (LHC Beam Dump Kicker Rise Time = 3.1μs).

Design Parameters for Pb-Pb

Parameter	**Units**	**Early Beam**	**Nominal**
Energy per nucleon	TeV	2.76	2.76
Initial ion-ion Luminosity L_0	$cm^{-2}\ s^{-1}$	$\sim 5 \times 10^{25}$	1×10^{27}
No. bunches, k_b		62	592
Minimum bunch spacing	ns	1350	99.8
β^*	m	1.0	0.5 /0.55
Number of Pb ions/bunch		$\mathbf{7 \times 10^7}$	$\mathbf{7 \times 10^7}$
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	14, 7.5, 5.5	8, 4.5, 3

Do something like this at reduced energy in 2010

Probably unattainable without "cryo-collimators" at least

At full energy, luminosity lifetime is determined mainly by collisions ("burn-off" from ultraperipheral electromagnetic interactions) $\sigma \approx 520$ barn

Pair Production in Heavy Ion Collisions

Racah formula (1937) for free pair production in heavy-ion collisions

$$Z_1 + Z_2 \rightarrow Z_1 + \mathrm{e}^- + \mathrm{e}^+ + Z_2$$

$$\sigma_{PP} = \frac{Z_1^{\,2} Z_2^{\,2} \alpha^2 r_e^2}{\pi}\left[\frac{224}{27}\log\left(2\gamma_{CM}\right)^3 + \cdots\right] \approx \begin{cases} 1.7\times10^4\,\mathrm{b} \text{ for Au-Au RHIC} \\ 2.\times10^4\,\mathrm{b} \text{ for Pb-Pb LHC} \end{cases}$$

Cross section for Bound-Free Pair Production (BFPP) (several authors)

$$Z_1 + Z_2 \rightarrow \left(Z_1 + \mathrm{e}^-\right)_{1s_{1/2},\ldots} + \mathrm{e}^+ + Z_2$$

has very different dependence on ion charges (and energy)

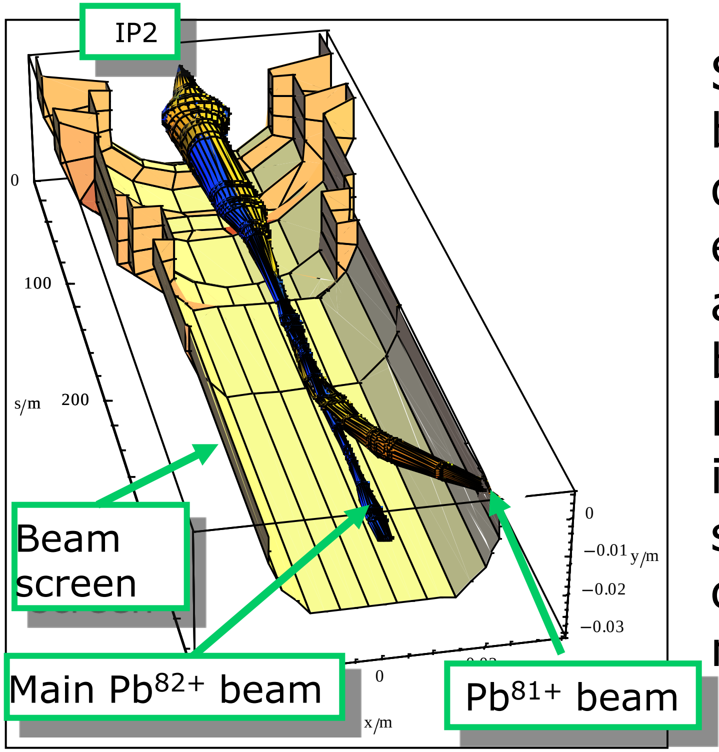
$$\sigma_{PP} \propto Z_1^{\,5} Z_2^{\,2}\left[A\log\gamma_{CM} + B\right]$$

$$\propto Z^7\left[A\log\gamma_{CM} + B\right] \text{ for } Z_1 = Z_2$$

$$\approx \begin{cases} 0.2\text{ b for Cu-Cu RHIC} \\ 114\text{ b for Au-Au RHIC} \\ 281\text{ b for Pb-Pb LHC} \end{cases}$$

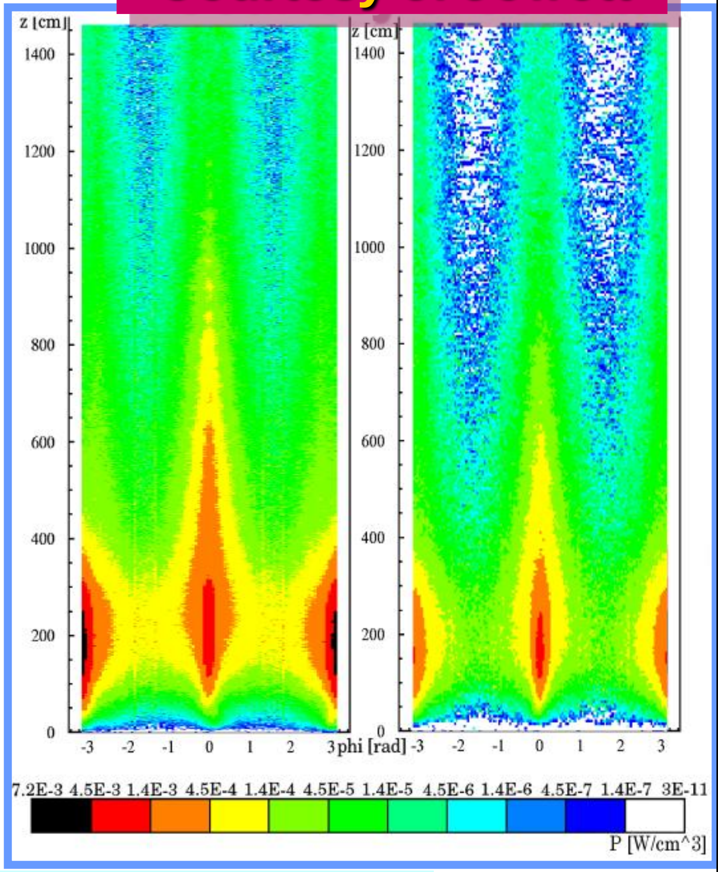
Luminosity Limit from bound-free pair production

$$^{208}Pb^{82+} + ^{208}Pb^{82+} \xrightarrow{\gamma} ^{208}Pb^{82+} + ^{208}Pb^{81+} + e^{+}$$



Secondary Pb^{81+} beam (25 W at design luminosity) emerging from IP and impinging on beam screen. Hadronic shower into superconducting coils can quench magnet.

Courtesy J. Jowett



Distinct EMD process (similar rates) does not form spot on beam pipe

$$^{208}Pb^{82+} + ^{208}Pb^{82+} \xrightarrow{GDR} ^{208}Pb^{82+} + ^{207}Pb^{82+} + n$$

Collimation of heavy ions

- LHC proton collimation principle:
  - Halo protons encounter primary collimator and are diffractively scattered to larger betatron oscillation amplitude, cleaned by secondary collimators
- Collimation of heavy ions is very different!
  - Nuclear interactions (hadronic fragmentation, EM dissociation) in primary collimator material.
  - Staged collimation principle does not work.
  - Single stage system, reduced collimation efficiency

Other limits on performance

- Total bunch charge is near lower limits of visibility on beam instrumentation, particularly the beam position monitors
- Intra-beam scattering (IBS)
  - Multiple Coulomb scattering within bunches is significant
- Vacuum effects (losses, emittance growth, electron cloud …) should not be significant

Commissioning strategy for Pb

- *Use the working p-p configuration*
  - Magnetically identical : Transfer, injection, ramp, orbits, optics, tunes, chromaticity…
  - Same beam sizes : aperture, collimators, …
  - Collimation and machine protection to be checked
  - Reduce crossing angle to zero in CMS and ATLAS.
  - Real zero crossing angle in ALICE
- Differences in basic setup
  - RF frequency (Pb mass), energy matching to SPS

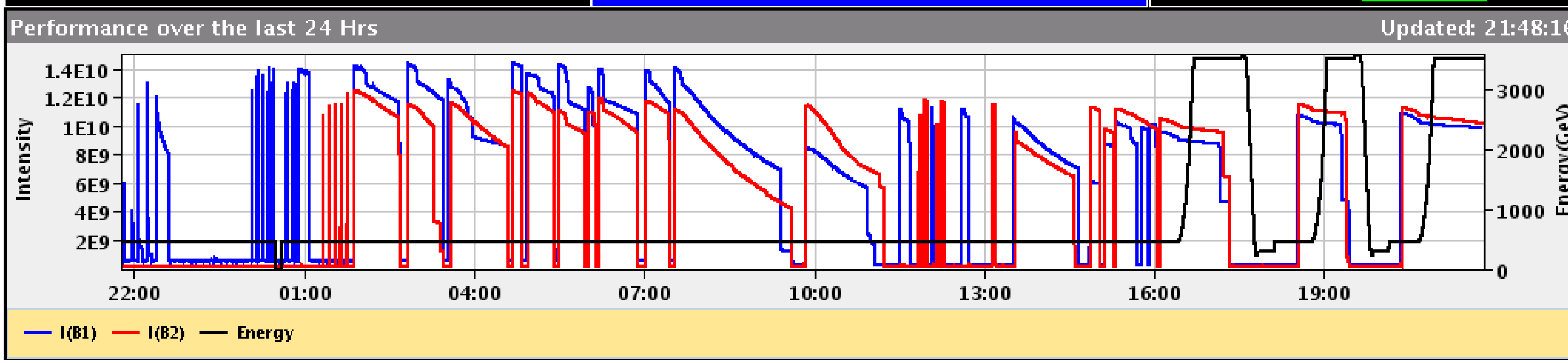
Ion Commissioning

Courtesy J. Jowett

05-Nov-2010 21:48:18 Fill #: 1473 Energy: 3500 Z GeV I(B1): 9.86e+09 I(B2): 1.02e+10

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	0.000	0.000	0.000	0.000
BRAN Luminosity (ub.s)^-1	0.000	0.000	0.000	0.000
Inst Lumi/CollRate Parameter	1.00e+00		0.00e+00	
BKGD 1	0.002	0.244	0.000	0.122
BKGD 2	0.000	0.000	0.000	0.407
BKGD 3	0.000	1.628	0.098	0.044

LHCb VELO Position OUT Gap: 58.0 mm SQUEEZE TOTEM: STANDBY



Beam 1 Inj., Circ. & Capture

Beam 2 Inj., Circ. & Capture

Optics Checks
BI Checks
Collimation Checks

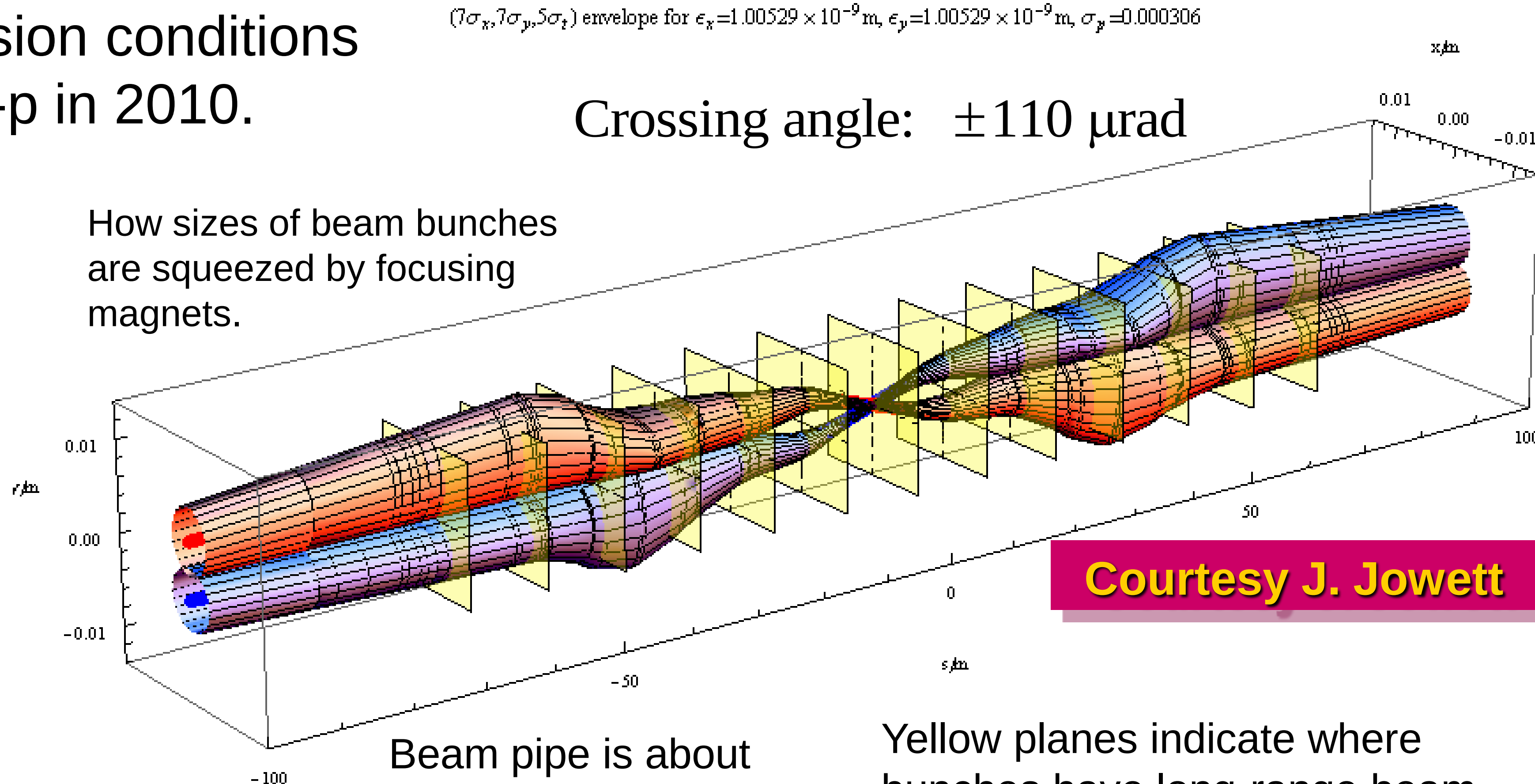
First Ramp
Collimation Checks
Squeeze

Beam envelopes around ALICE experiment

Collision conditions for p-p in 2010.

Crossing angle: $\pm 110\ \mu\text{rad}$

How sizes of beam bunches are squeezed by focusing magnets.



Courtesy J. Jowett

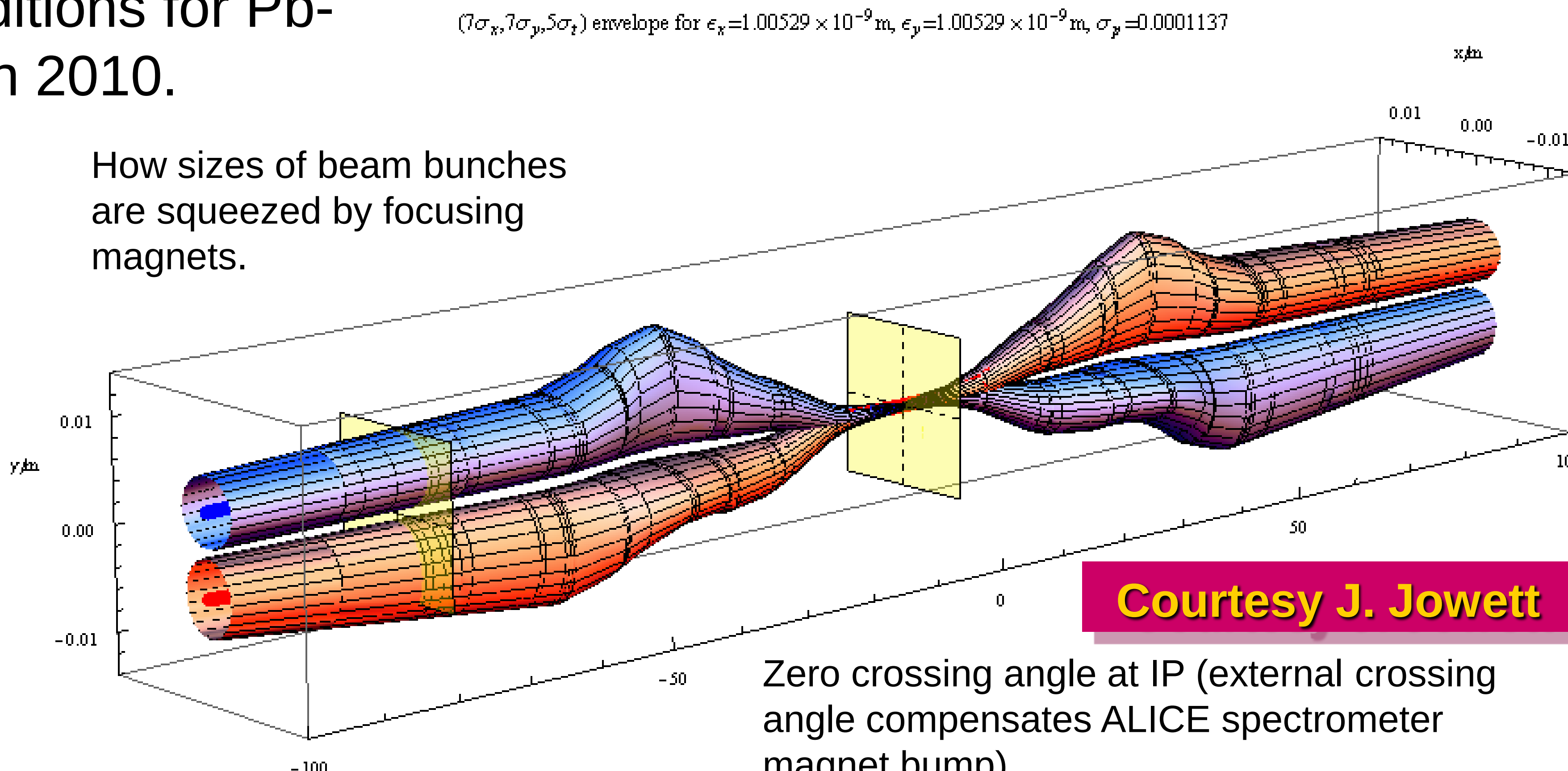
Beam pipe is about twice transverse size of box.

Yellow planes indicate where bunches have long-range beam-beam interactions on their way in and out of the collision point (75 ns bunch spacing).

Beam envelopes around ALICE experiment

Collision conditions for Pb-Pb in 2010.

How sizes of beam bunches are squeezed by focusing magnets.



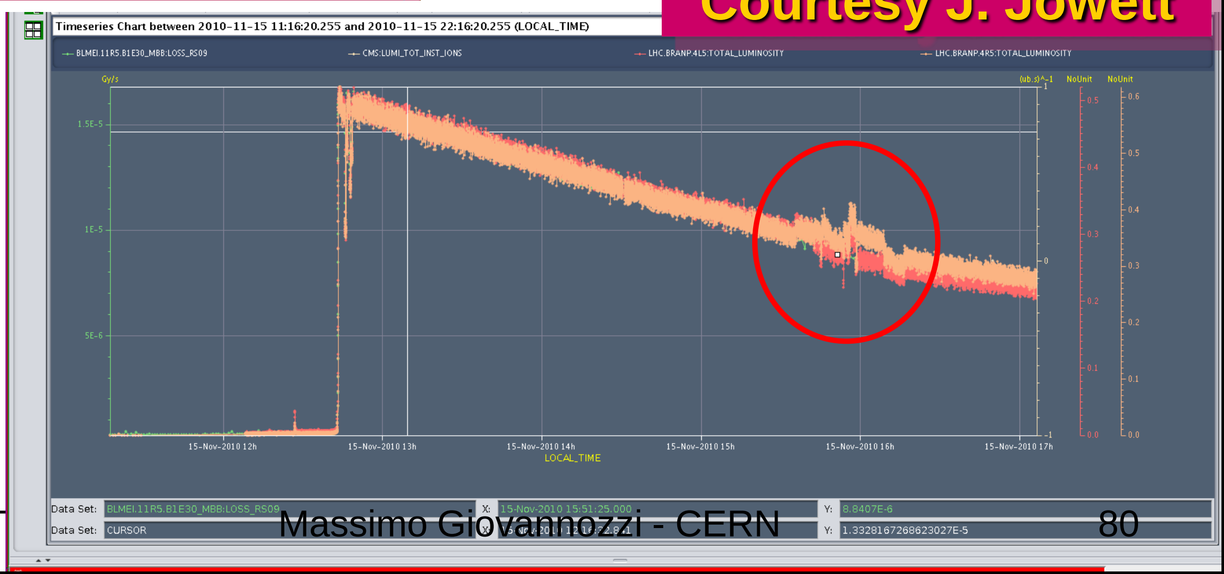
Courtesy J. Jowett

Zero crossing angle at IP (external crossing angle compensates ALICE spectrometer magnet bump).
Beam pipe is about twice transverse size of box.

Bound-free pair production

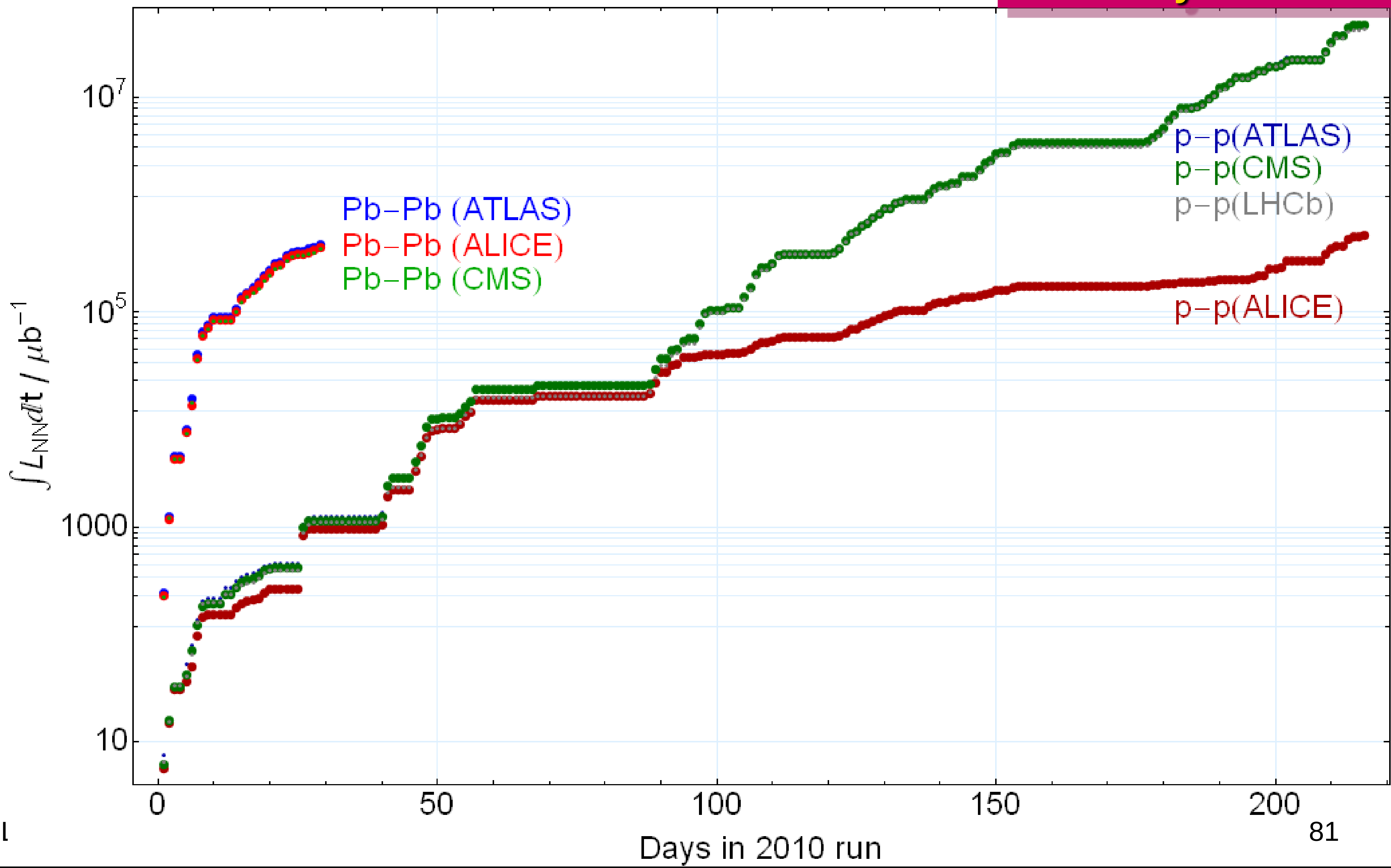
Perfect correlation of Beam Loss Monitor at Q11 with luminosity

Courtesy J. Jowett

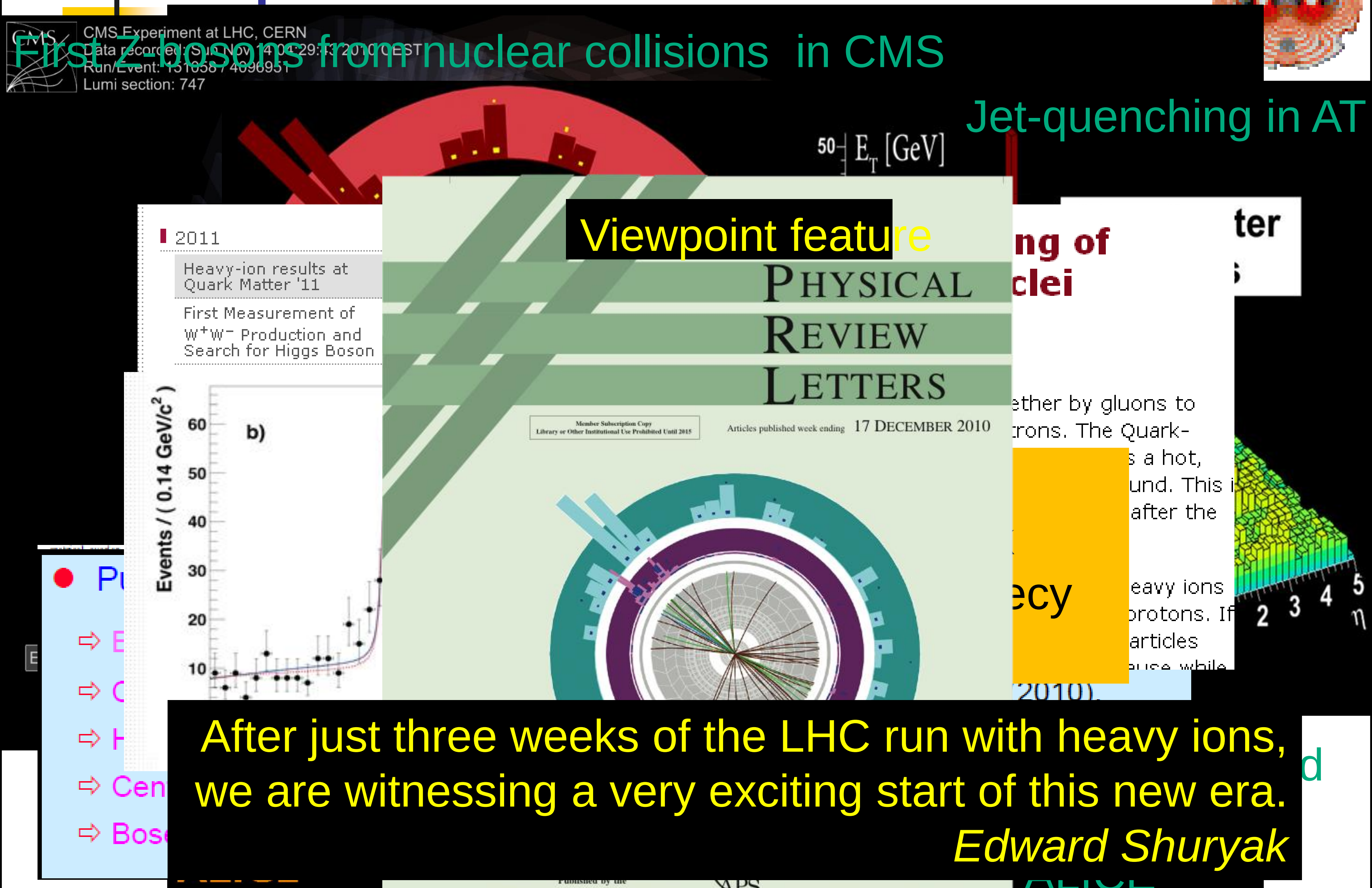


Integrated nucleon-nucleon luminosity for 2010

Courtesy J. Jowett



Spectacular collisions … and

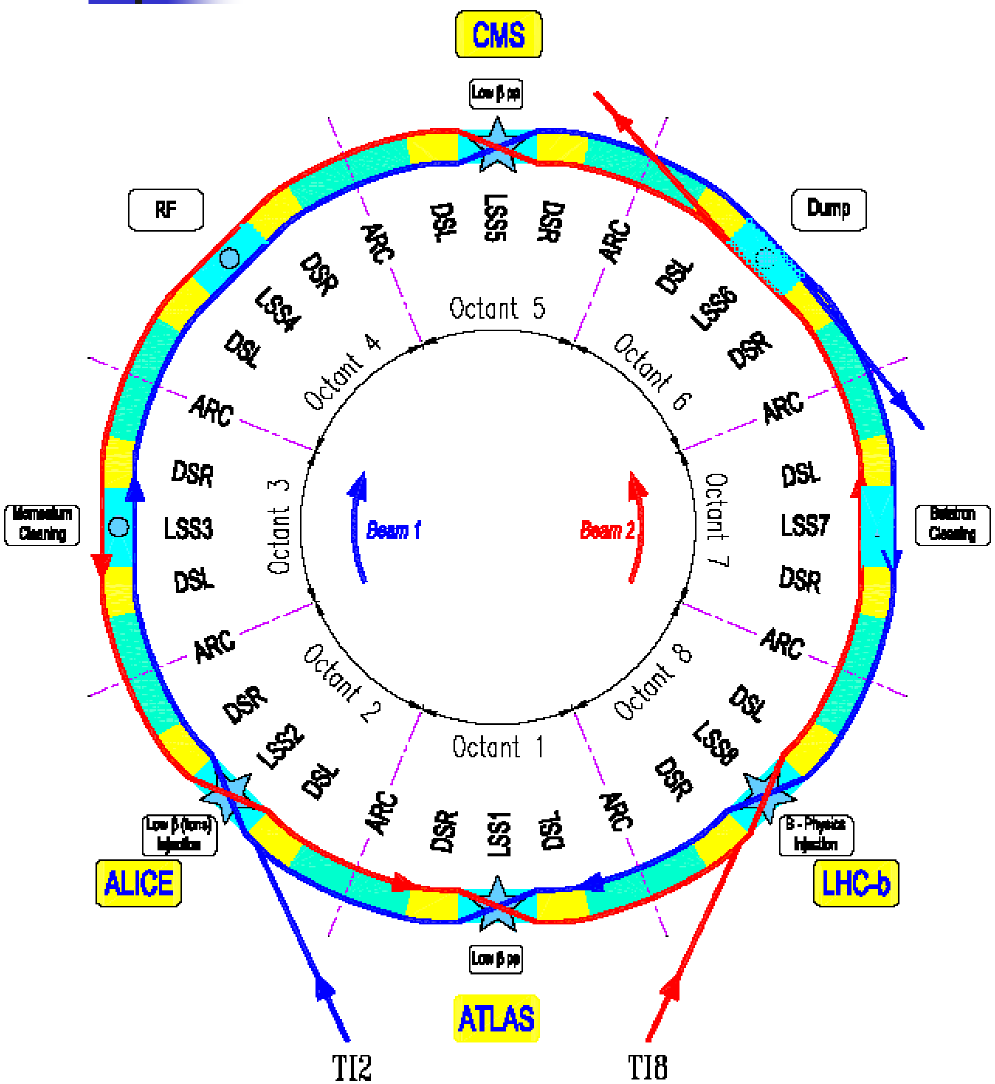


Next steps for Pb-Pb physics run

- 2011: continue at beam energy 1.38 A TeV
  - increase number of bunches
  - Reduce β^* (the commissioning of the squeeze will be done at the beginning of the Pb run)
  - Perform tests in view of p-Pb collisions in 2012.

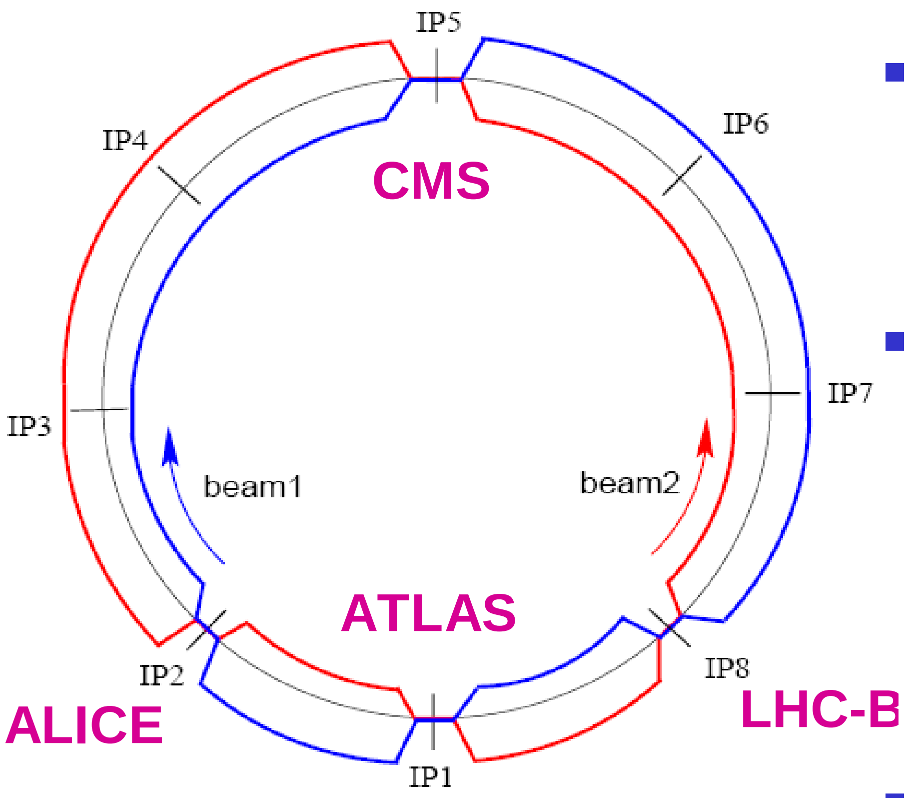
Spare slides

LHC layout - I



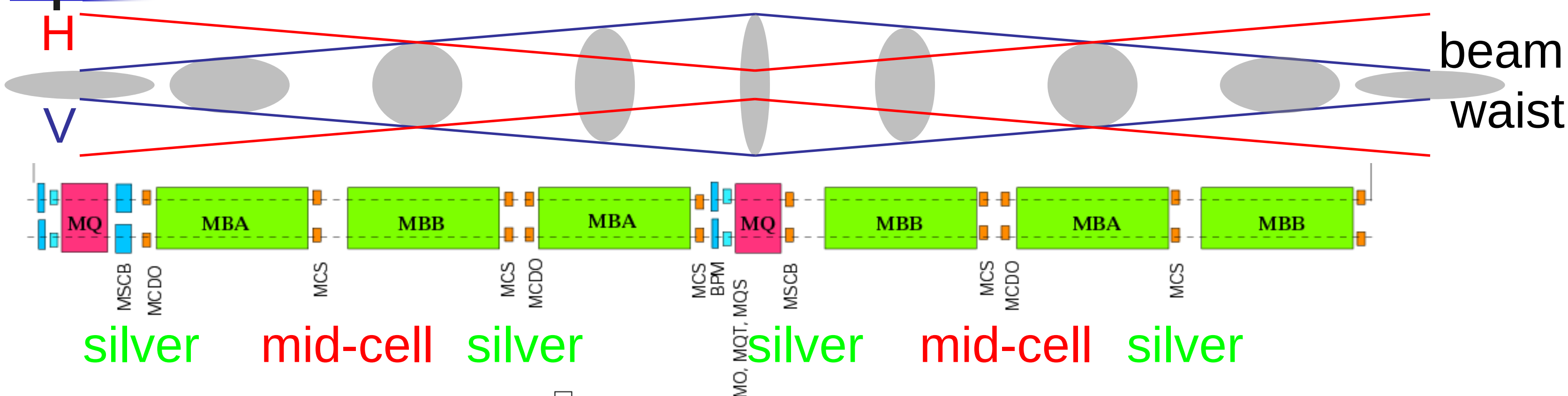
- The LHC machine has an height-fold symmetry.
- Eight arcs (arc is the curved periodic part of the machine).
- Sixteen dispersion suppressors to match the arc with the straight sections (geometry and optics).
- Eight long straight sections (also called insertion regions).

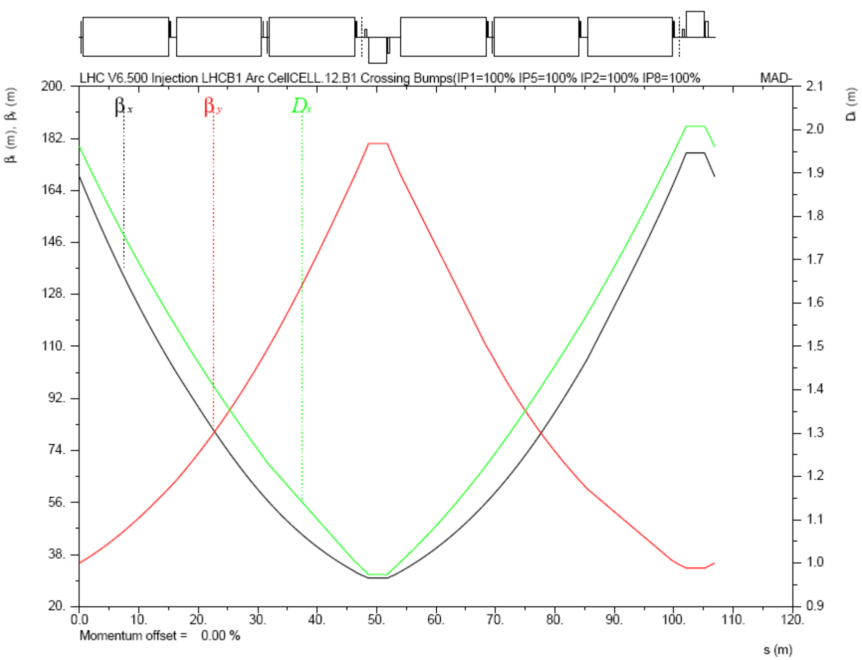
LHC layout - II



- ATLAS: High luminosity experiment. Search for the Higgs boson(s).
- A Large Ion Collider Experiment (ALICE): Ions. New phase of matter expected (Quark-Gluon Plasma).
- Compact Muon Solenoid (CMS): High luminosity experiment. Search for the Higgs boson(s). In this insertion is also located TOTEM for the measurement of the total proton-proton cross-section and study elastic scattering and diffractive physics.
- LHCb: Beauty quark physics for precise measurements of CP violation and rare decays.

LHC layout - III





Six dipoles are located in each cell. Each dipole comprises correctors:

- Sextupoles
- Octupoles and decapoles

Two quadrupoles are located in each cell. Each quadrupole is equipped with:

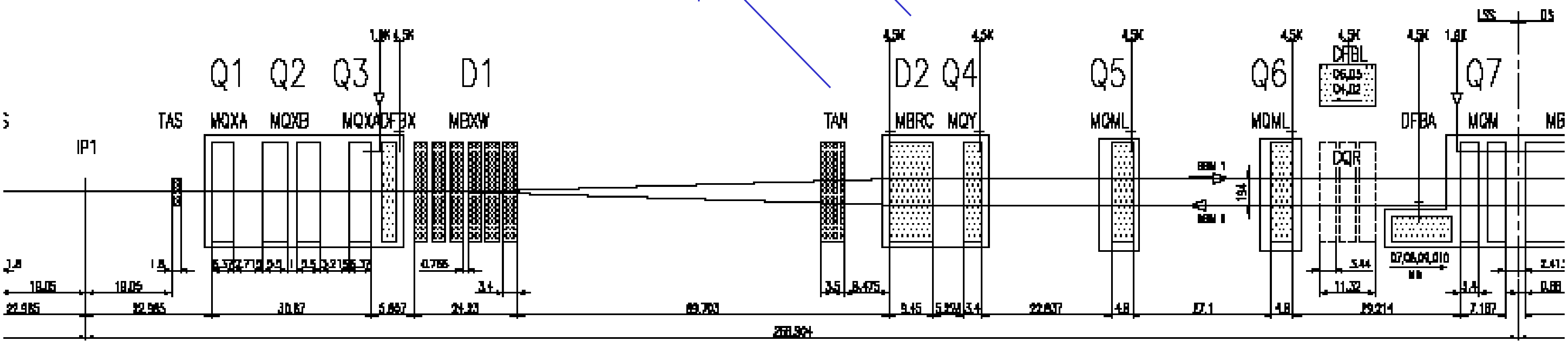
- Beam Position Monitor
- Dipole corrector (for closed orbit)
- Sextupoles (for chromaticity)

LHC layout - IV

Towards dispersion suppressor and arc

Separation/ricombination dipole

Absorber (neutral particles)



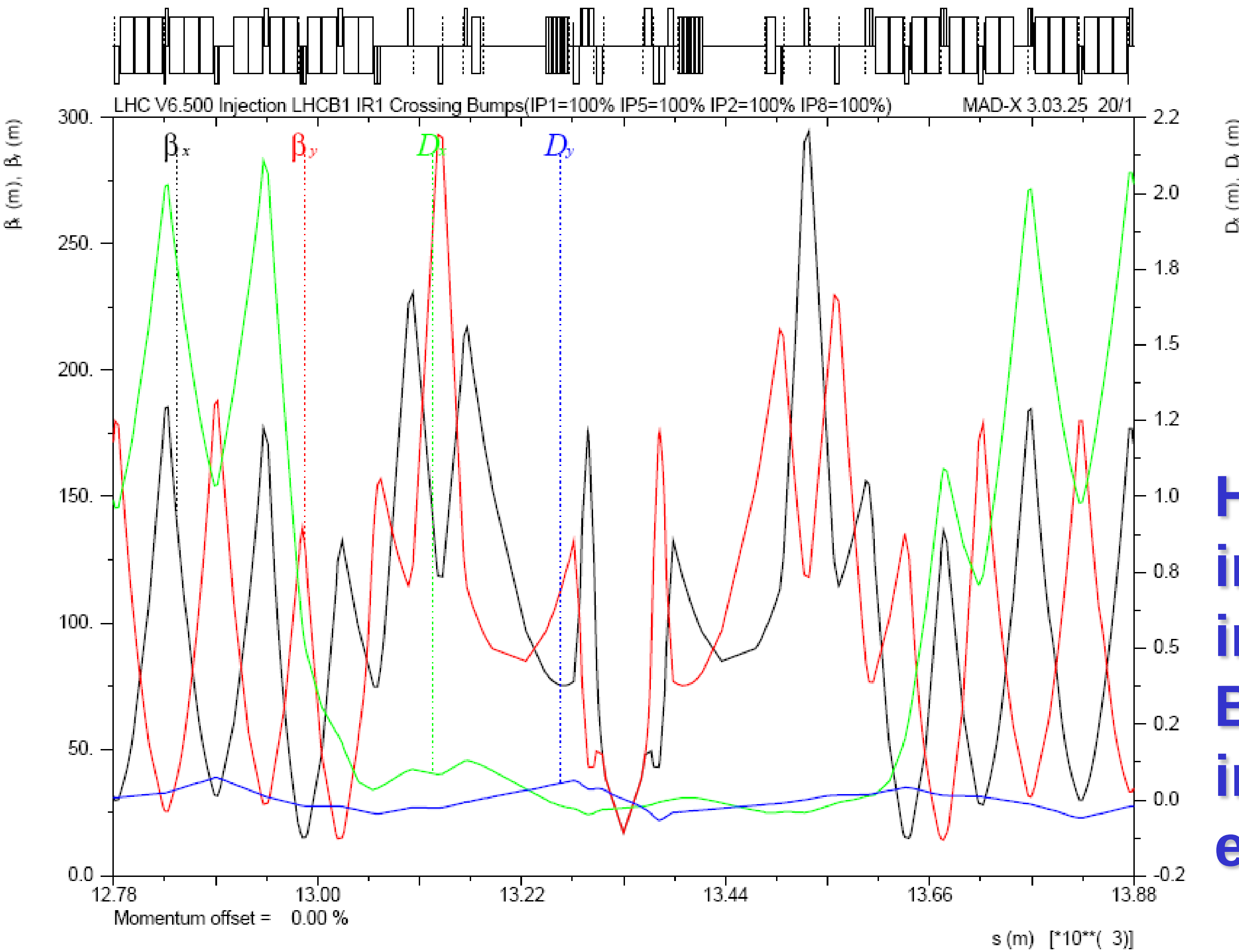
Separation/ricombination dipole

Low-beta quadrupoles

Interaction point

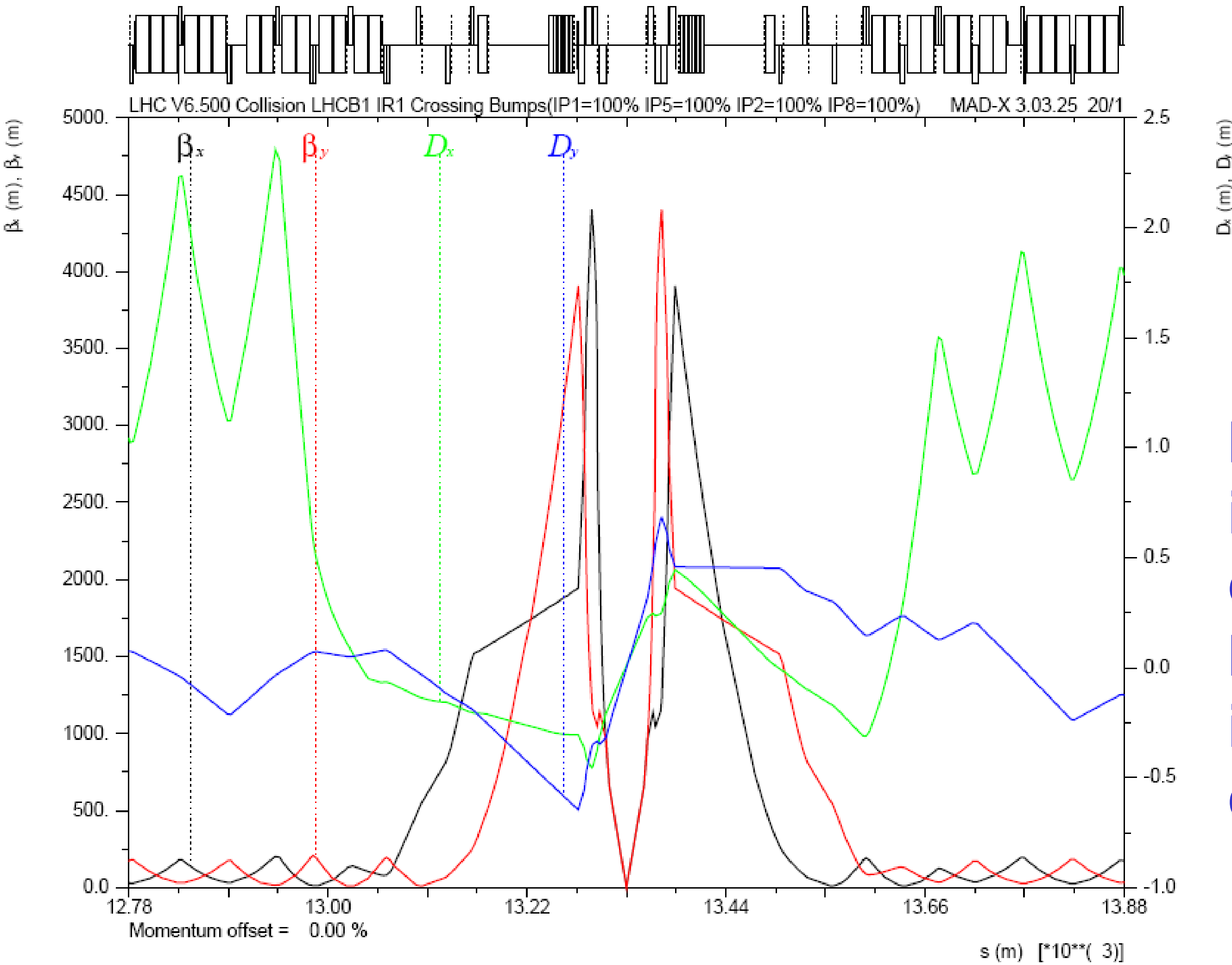
High luminosity insertions

LHC layout - V



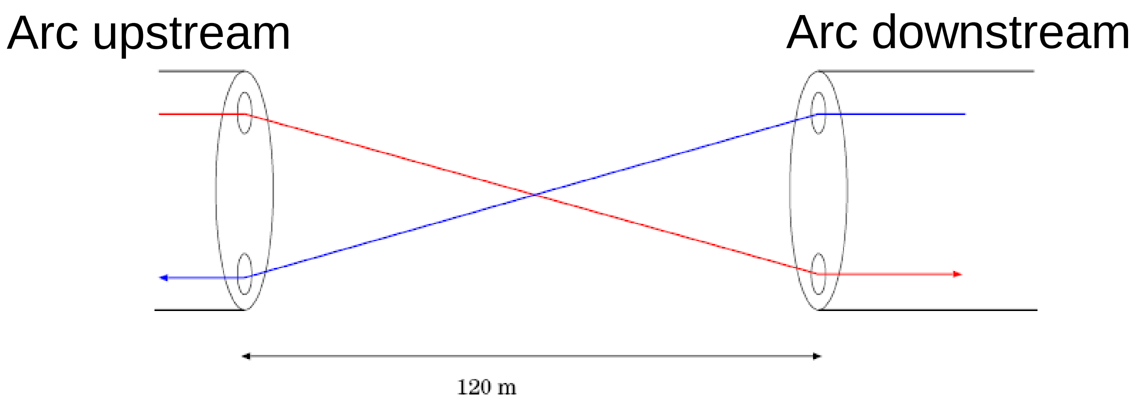
High luminosity insertions: injection optics. Beta at interaction point equals 11 m.

LHC layout - VI

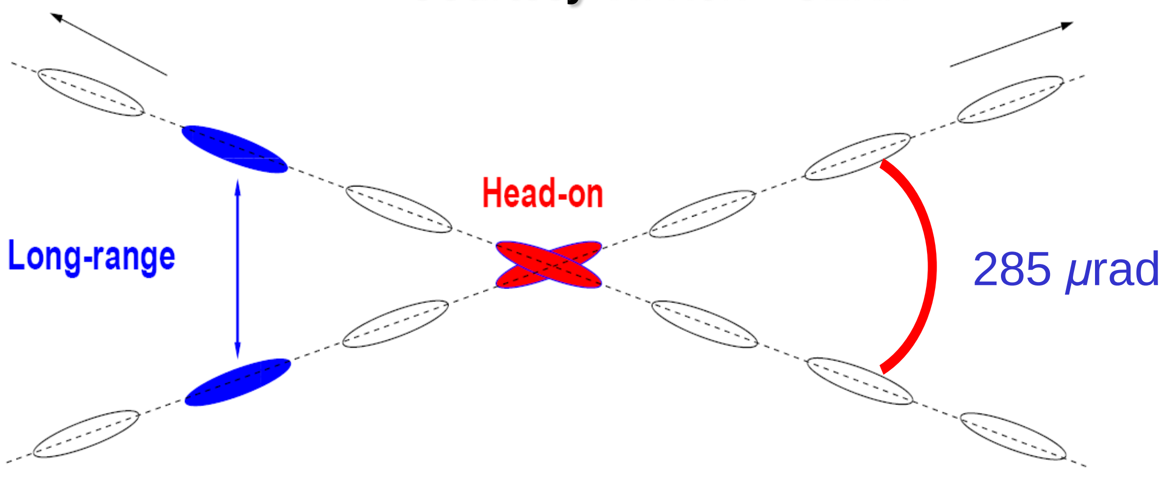


High luminosity insertions: collision optics. Beta at interaction point equals 0.55 m.

LHC layout - VII



Courtesy W. Herr - CERN



In case the collisions would occur head-on, plenty of parasitic collisions would take place in the common vacuum pipe.

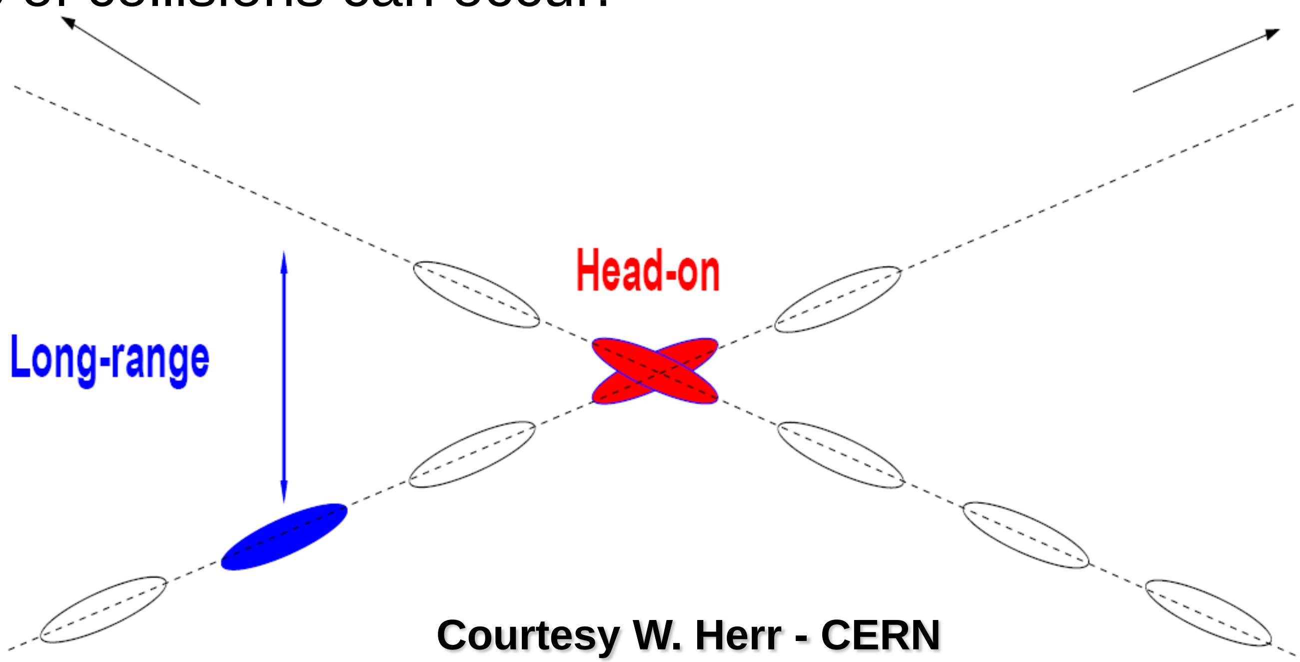
A crossing angle is used to separate bunches after the first wanted collision.

Even in this case, the various bunches are coupled together via Coulomb interaction. The crossing angle should provide enough separation for making the parasitic collisions harmless.

LHC layout - VIII

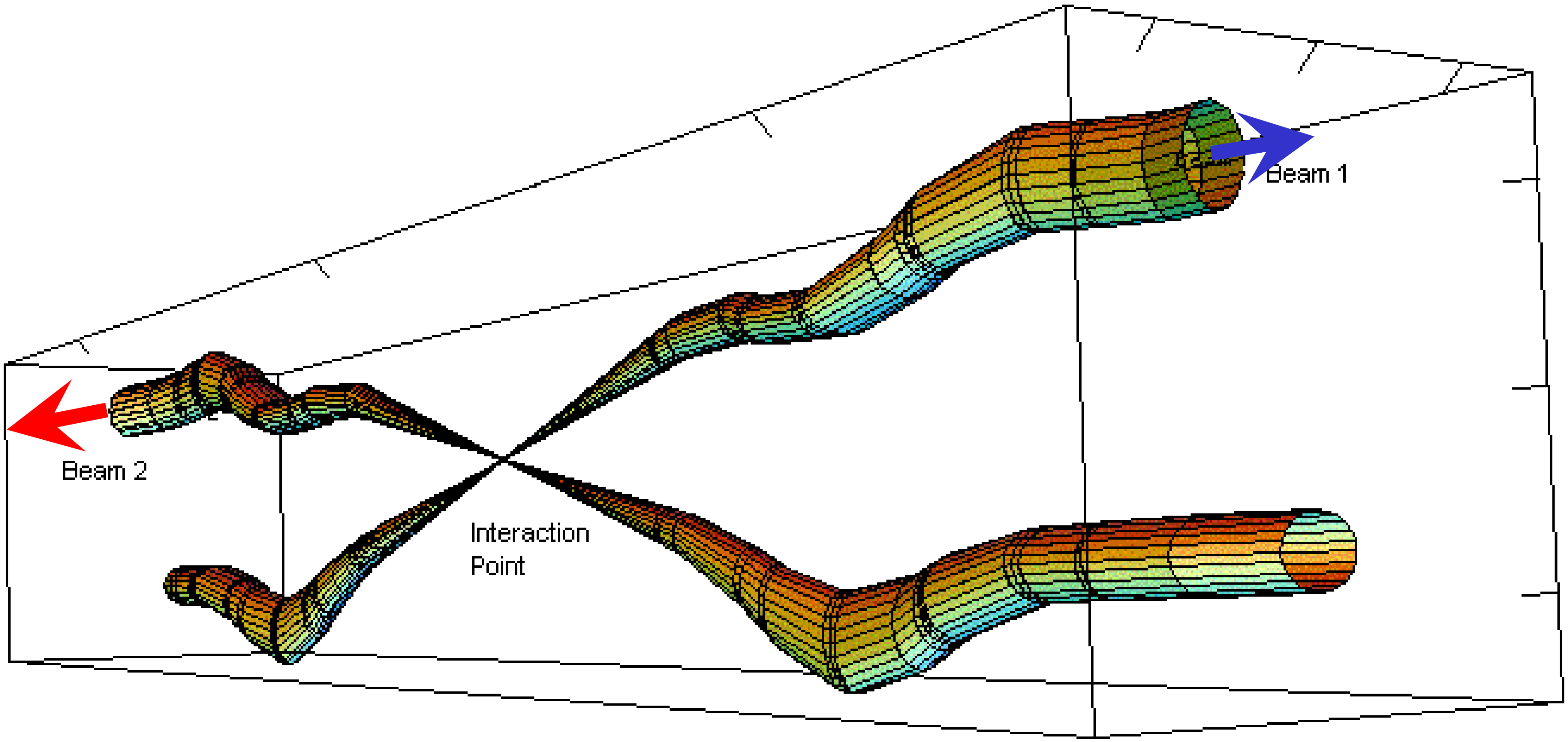
- Unfortunately, the crossing angle cannot cope with additional effects, the so-called PACMAN bunches.
- The LHC filling pattern is not continuous, but gaps have to be included.
- Hence three types of collisions can occur:
  - Bunch-bunch
  - Bunch-hole
  - Hole-hole

Alternating the crossing plane mitigates the PACMAN effect!



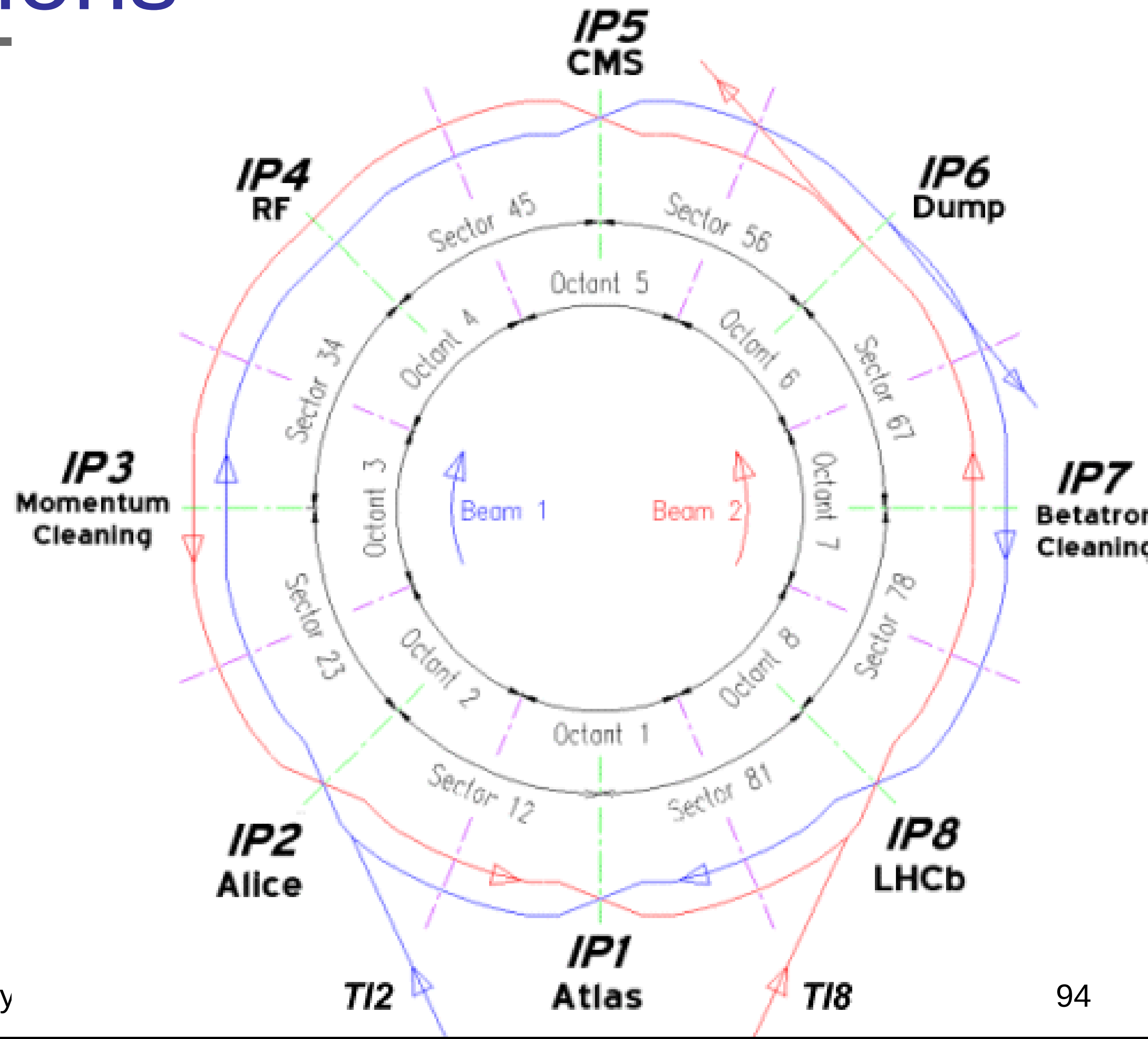
Courtesy W. Herr - CERN

LHC layout - IX



3D view of the crossing in IP1.

LHC layout: the other insertions



IR4: RF and instrumentation

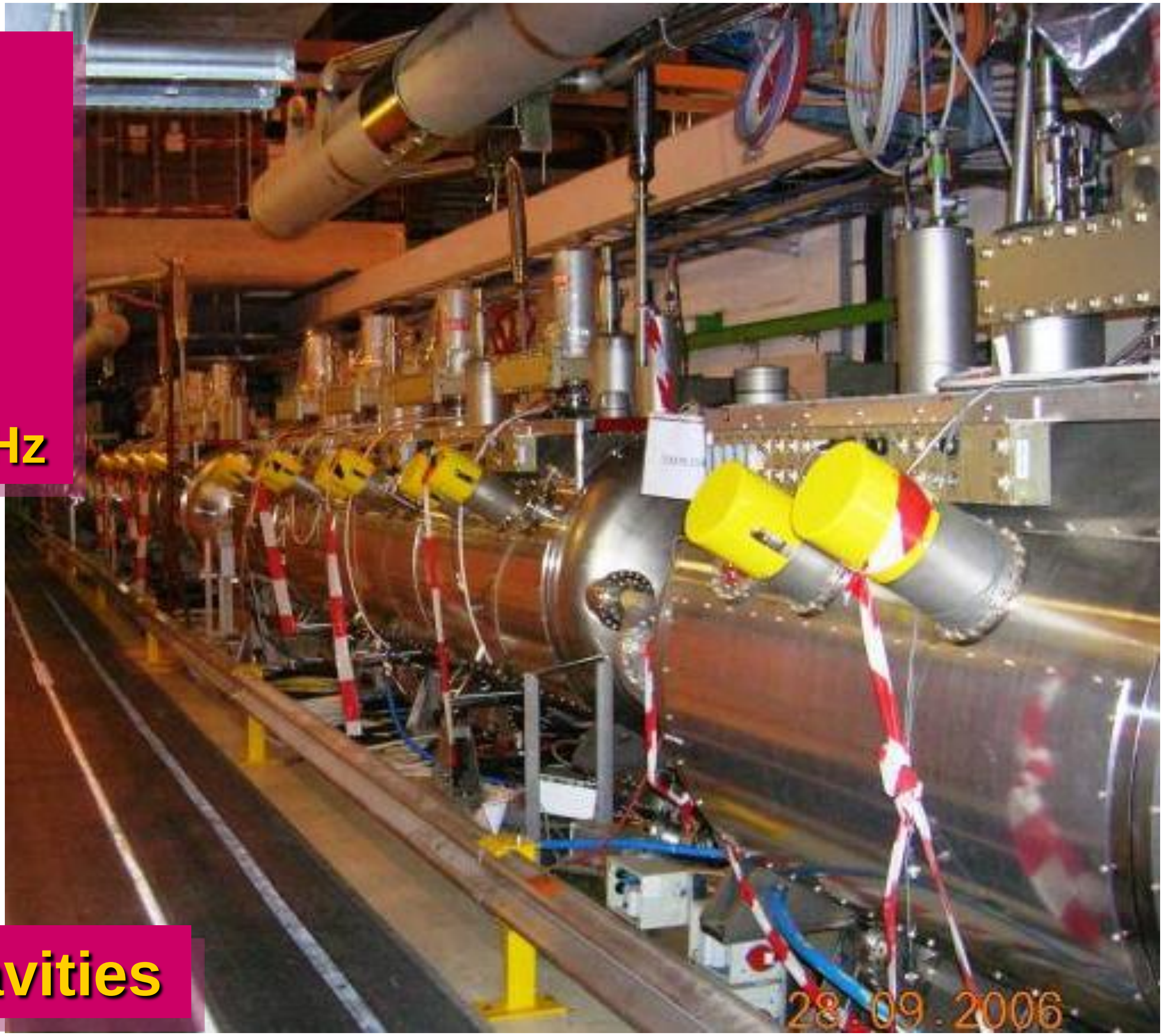
f: 400 MHz

Harmonic number: 35640

Voltage: 8/16 MV

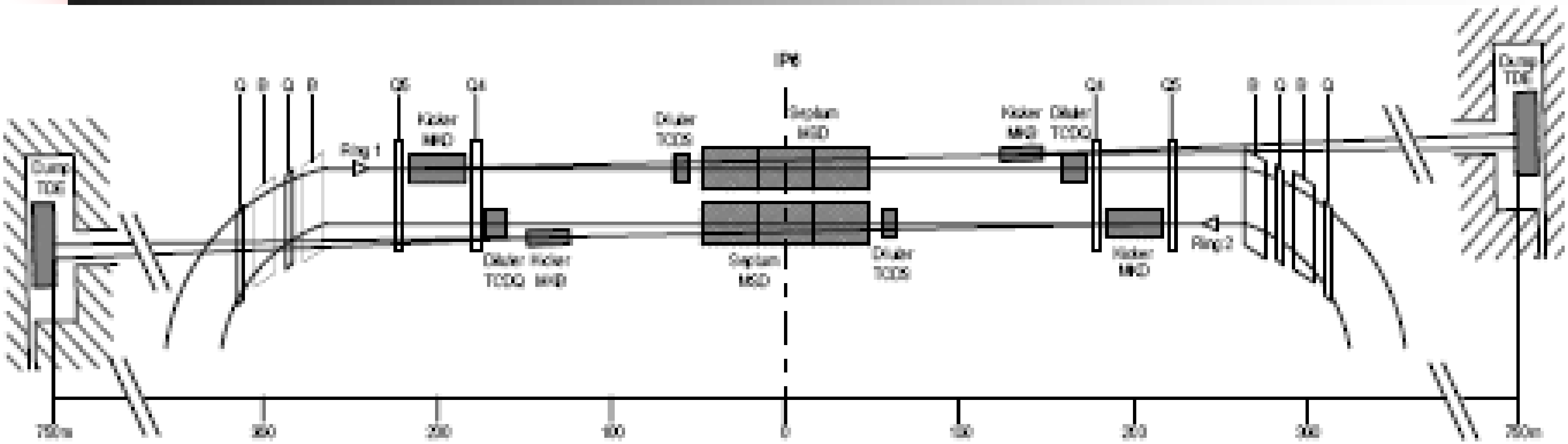
Energy gain/turn: 485 keV

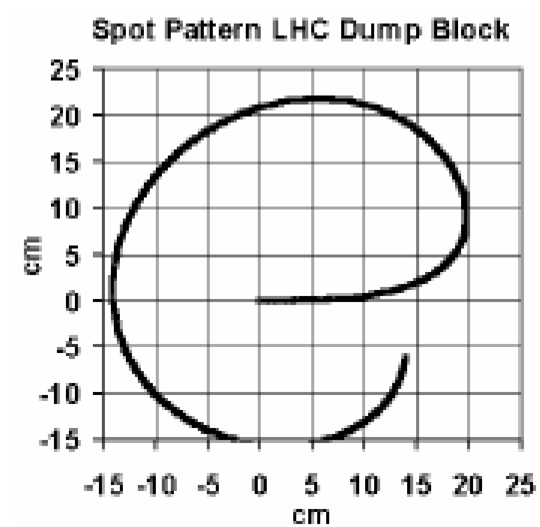
Synchrotron freq.: 63.7/23 Hz



Superconducting cavities

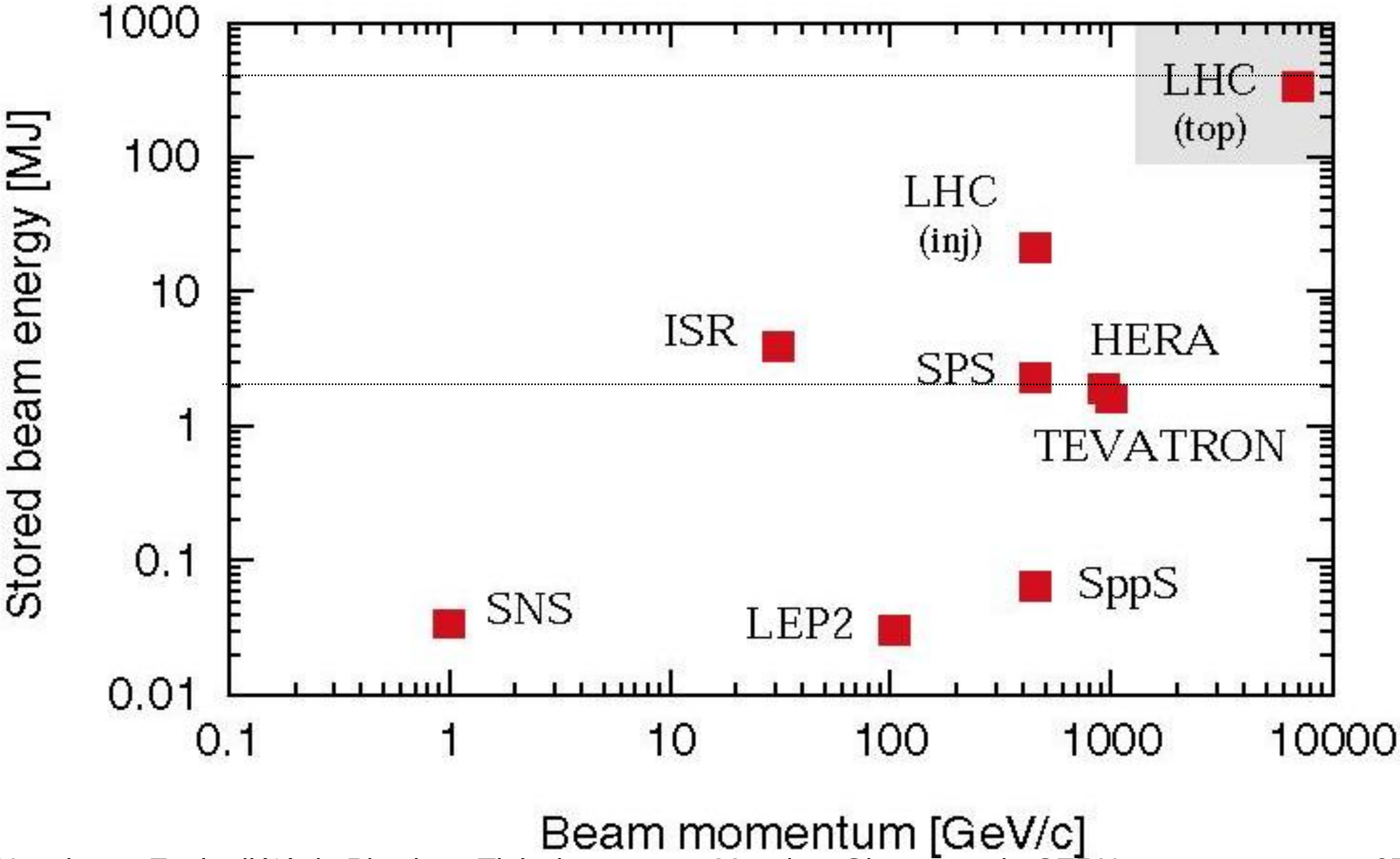
IR6: Beam dumping system





- The beam dumping system will fast-extract the beam in a loss-free way from each ring of the collider and transport it to an external absorber.
- Given the destructive power of the LHC beam, the dumping system must meet extremely high reliability criteria, which condition the overall and detailed design.

IR3/7: Collimation system - I

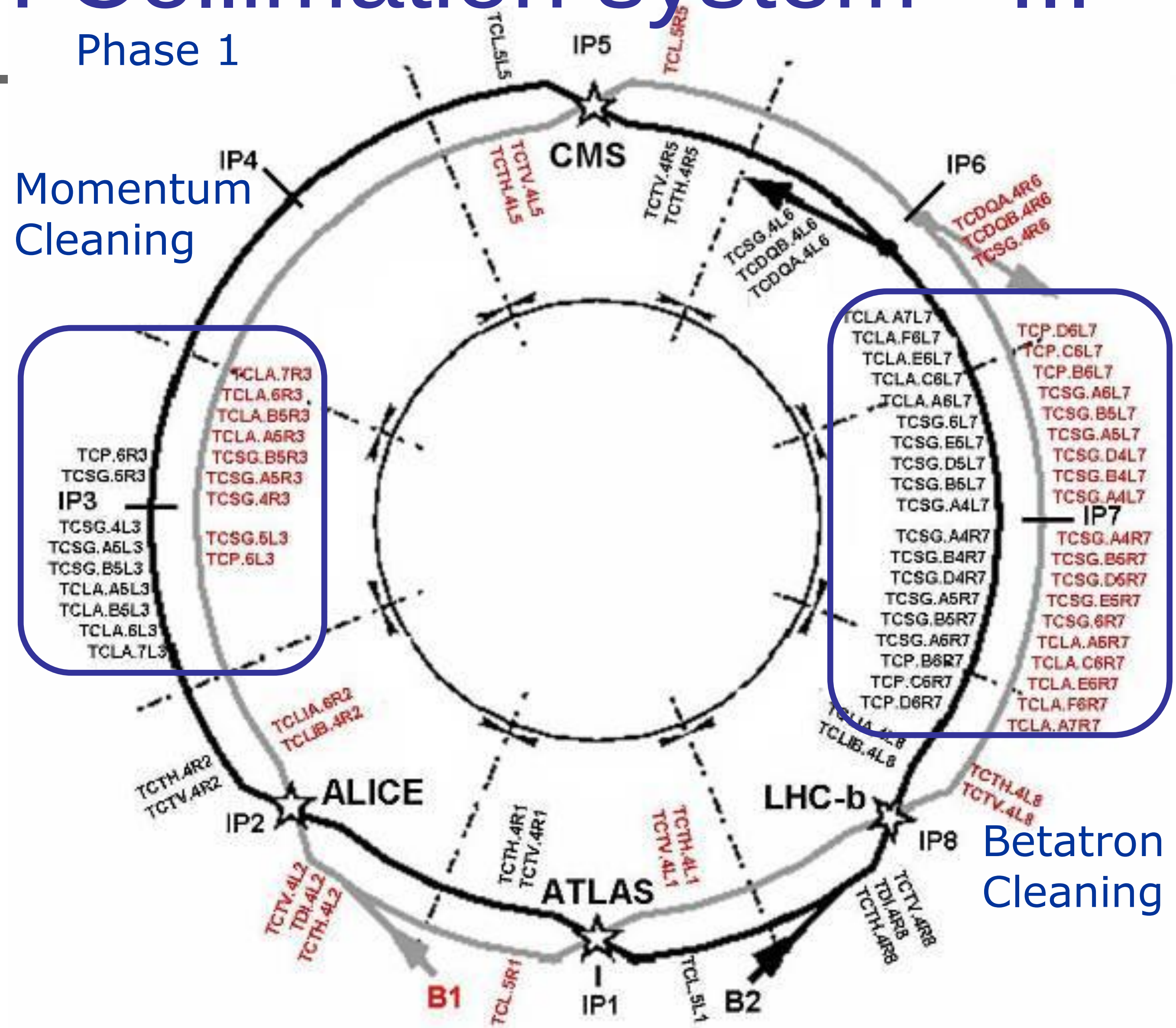


IR3/7: Collimation system - II

- The transverse energy density of the nominal beam is 1000 times higher than previously achieved in proton storage rings (1 GJ/mm^2).
- Tiny fractions of the stored beam suffice to quench a super-conducting LHC magnet or even to destroy parts of the accelerator.
- Note that a 10^{-5} fraction of the nominal LHC beam will damage copper.
- The energy in the two LHC beams is sufficient to melt almost 1 ton of copper!
- The tolerable inefficiencies of the collimation system are about 10^{-3} at collision.

IR3/7: Collimation system - III

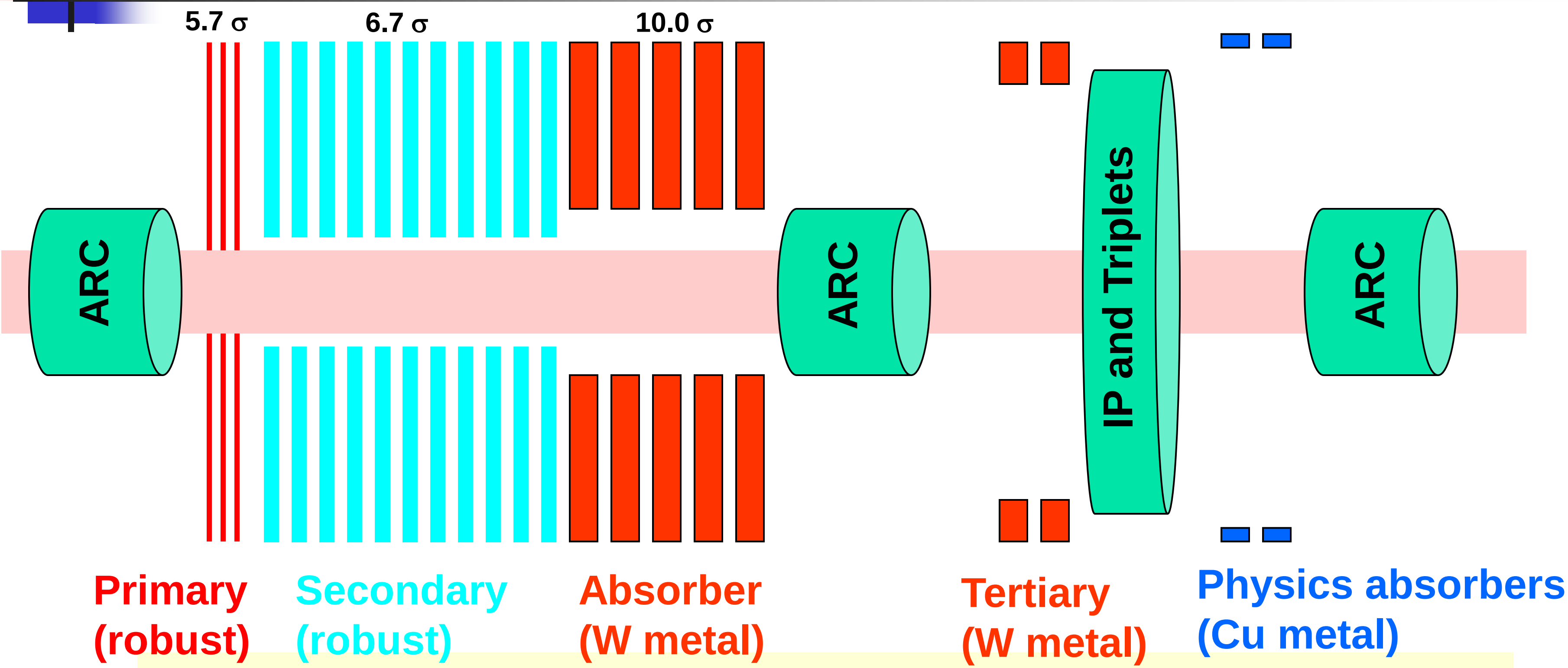
Phase 1



In the insertion regions IR3/7 the magnets are normal conducting!

This is imposed by the high beam losses due to the collimation system.

IR3/7: Collimation system - IV



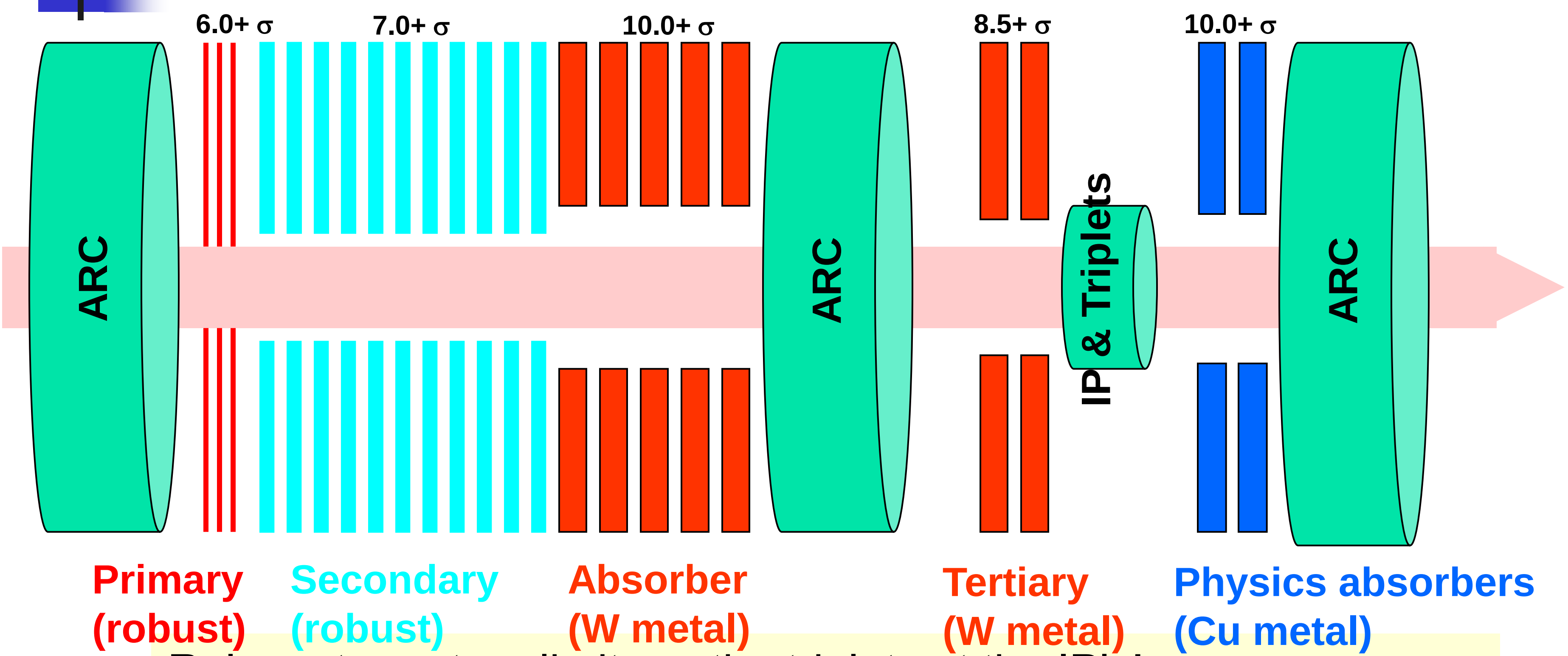
Relevant aperture limit is the arc!

Protected by 3 stages of cleaning and absorption!

First and second aperture limits by robust collimators!

Then metallic collimators with good absorption but very sensitive!

IR3/7: Collimation system - V



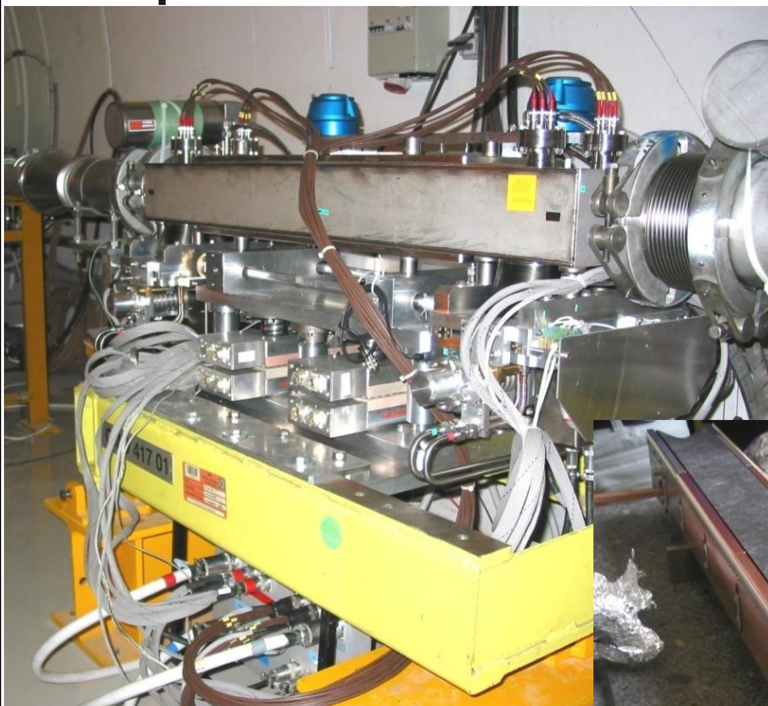
Relevant aperture limit are the triplets at the IP's!

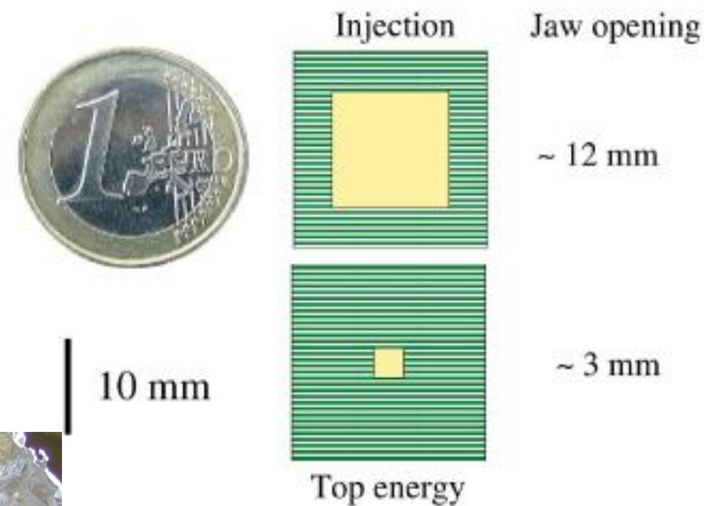
Protected by 4 stages of cleaning and absorption!

First and second aperture limits by robust collimators!

Then metallic collimators with good absorption but very sensitive!

IR3/7: Collimation system - VI





IR3/7: Collimation system - VII

- There is tradeoff between robustness and impedance (interaction with the electromagnetic fields generated by the bunches) of the collimators, namely:
  - Low Z materials: high robustness, but low conductivity. Hence they feature high impedance. They will limit the value of the beam size at the interaction region.
  - High Z materials: low impedance, but low robustness. They will limit the total current in the ring.
- In both cases the luminosity will be limited to a smaller value than nominal.
- Staged approach is applied.
  - Stage 1 collimation system will be implemented with low Z materials.
  - Stage 2 aim at removing the limitations. It requires heavy R&D programme.