ÉCOLE DE PHYSIQUE
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The LHC Machine: prospects

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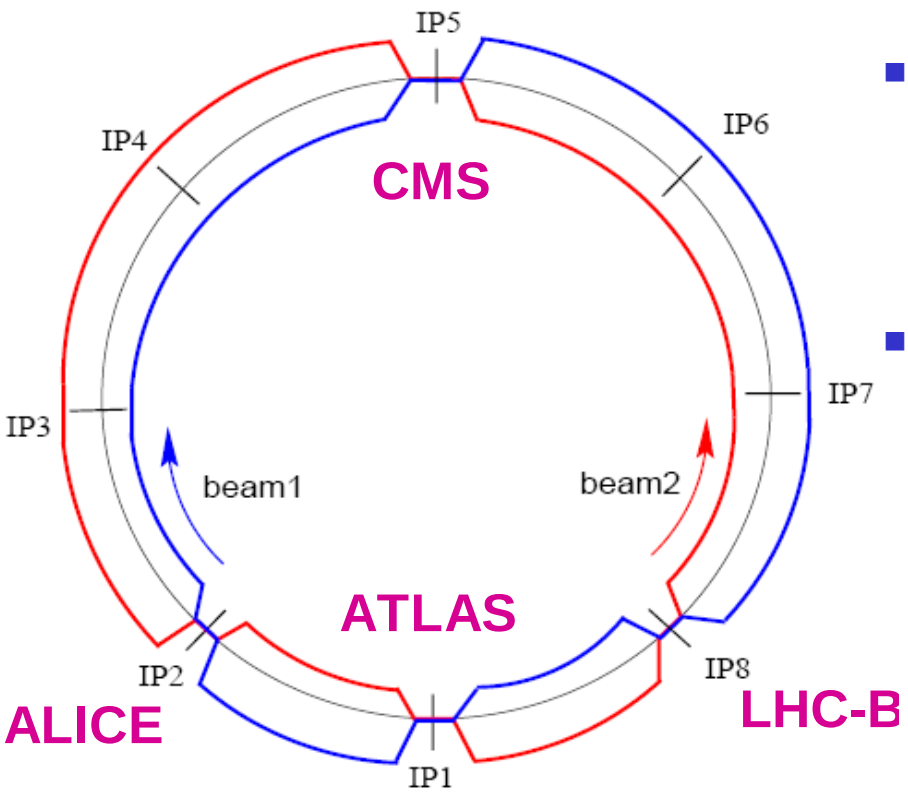
- Introduction and a bit of history
- Upgrade options
- LHC upgrade
- MD studies
- Injectors' upgrade
- The far future

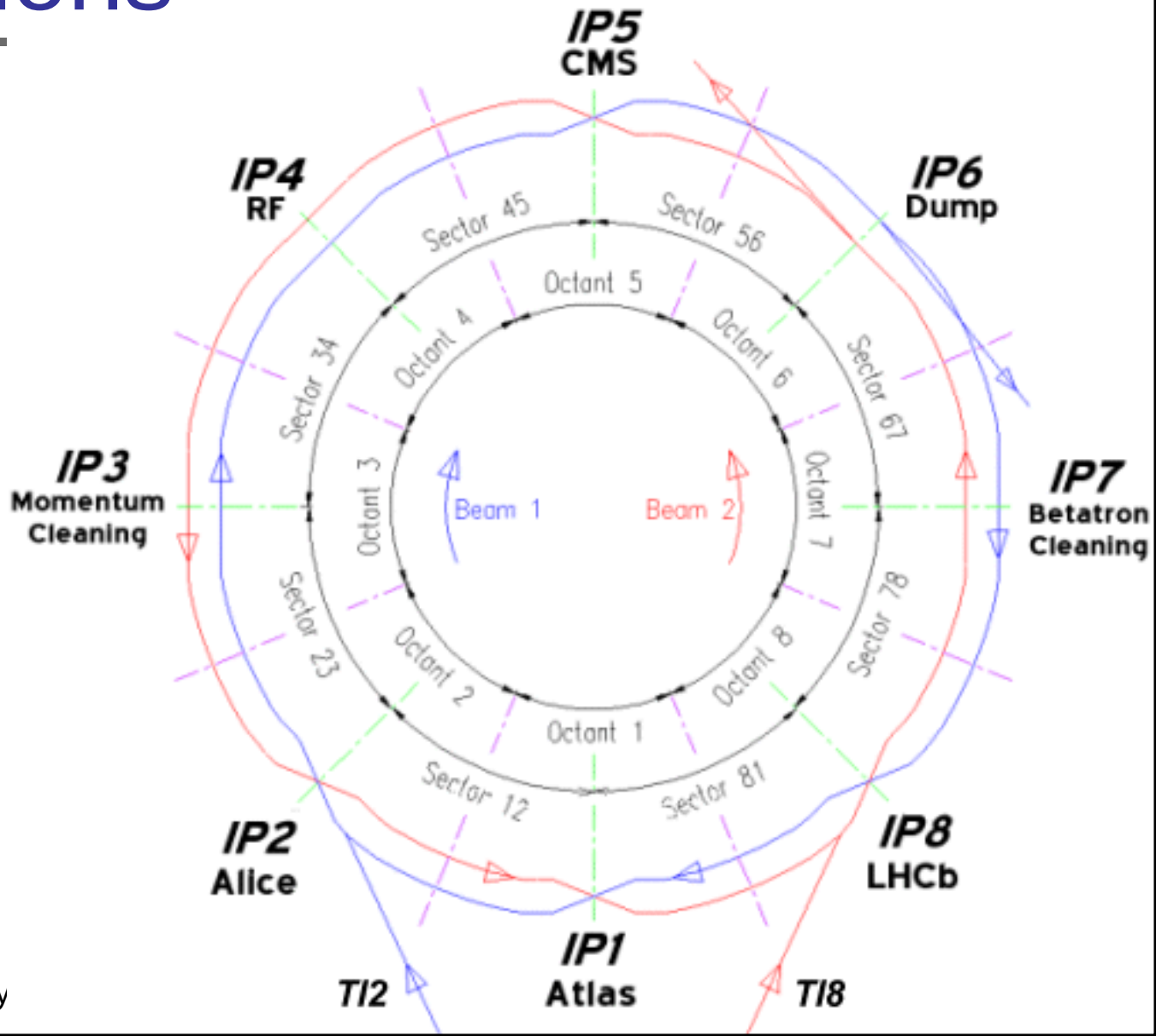
Acknowledgements: R. Assmann, H. Bartosik, E. Benedetto, O. Brüning, R. Calaga, S. Fartoukh, R. Garoby, W. Herr, J. Jowett, **R. de Maria**, E. Métral, Y. Papaphilippou, L. Rossi, E. Todesco, R. Tomás, M. Vretenar, F. Zimmermann *et al.*

Introduction - I



- 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: the other insertions

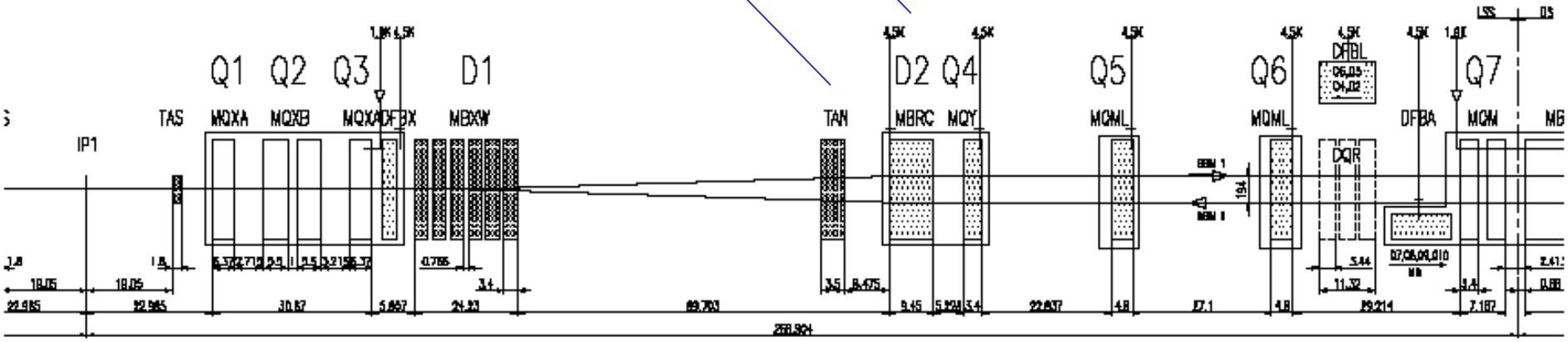


Introduction - II

Towards dispersion suppressor and arc

Separation/ricombination dipole

Absorber (neutral particles)



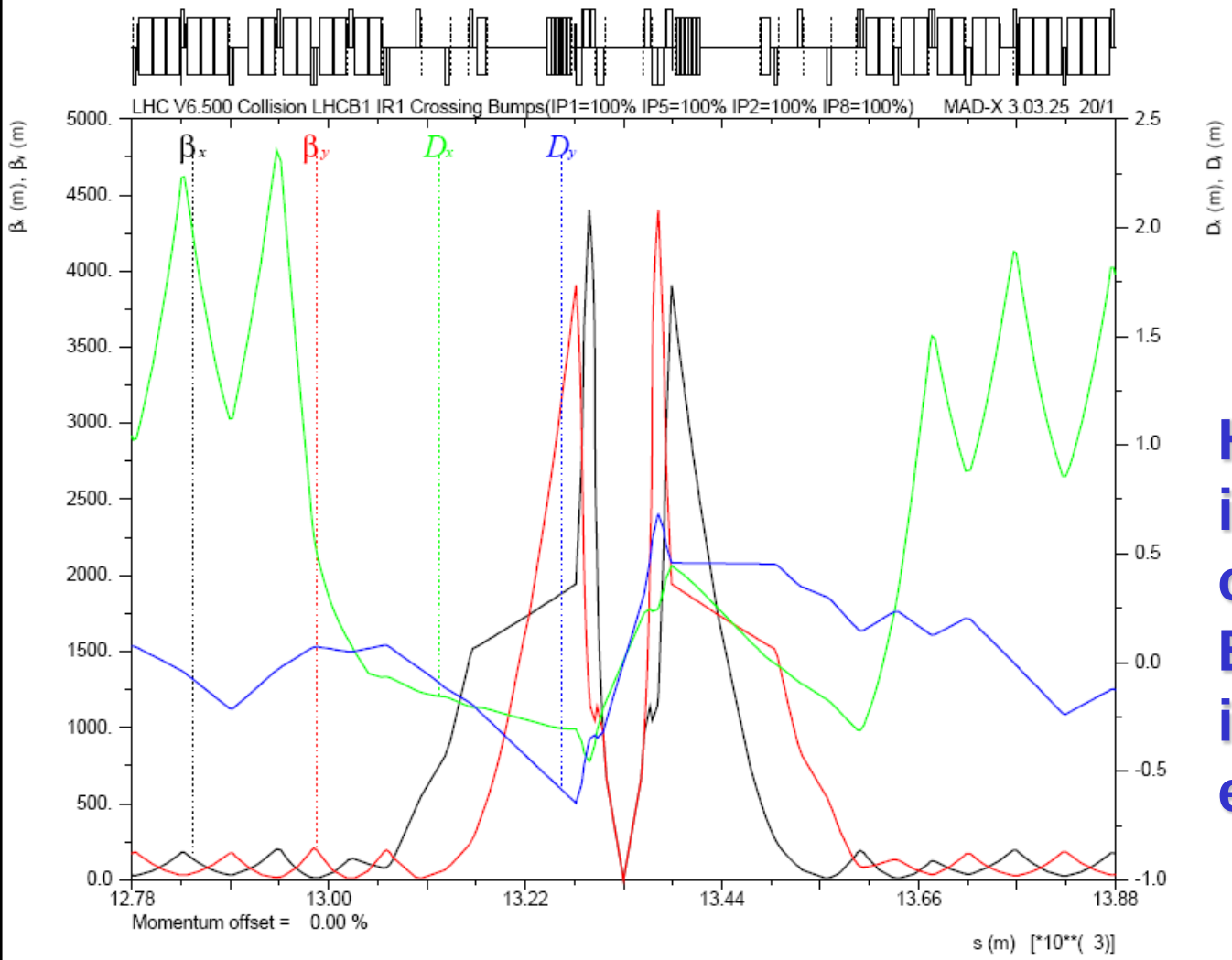
Separation/ricombination dipole

Low-beta quadrupoles (23 m away from IP)

Interaction point

High luminosity insertions

Introduction - IV

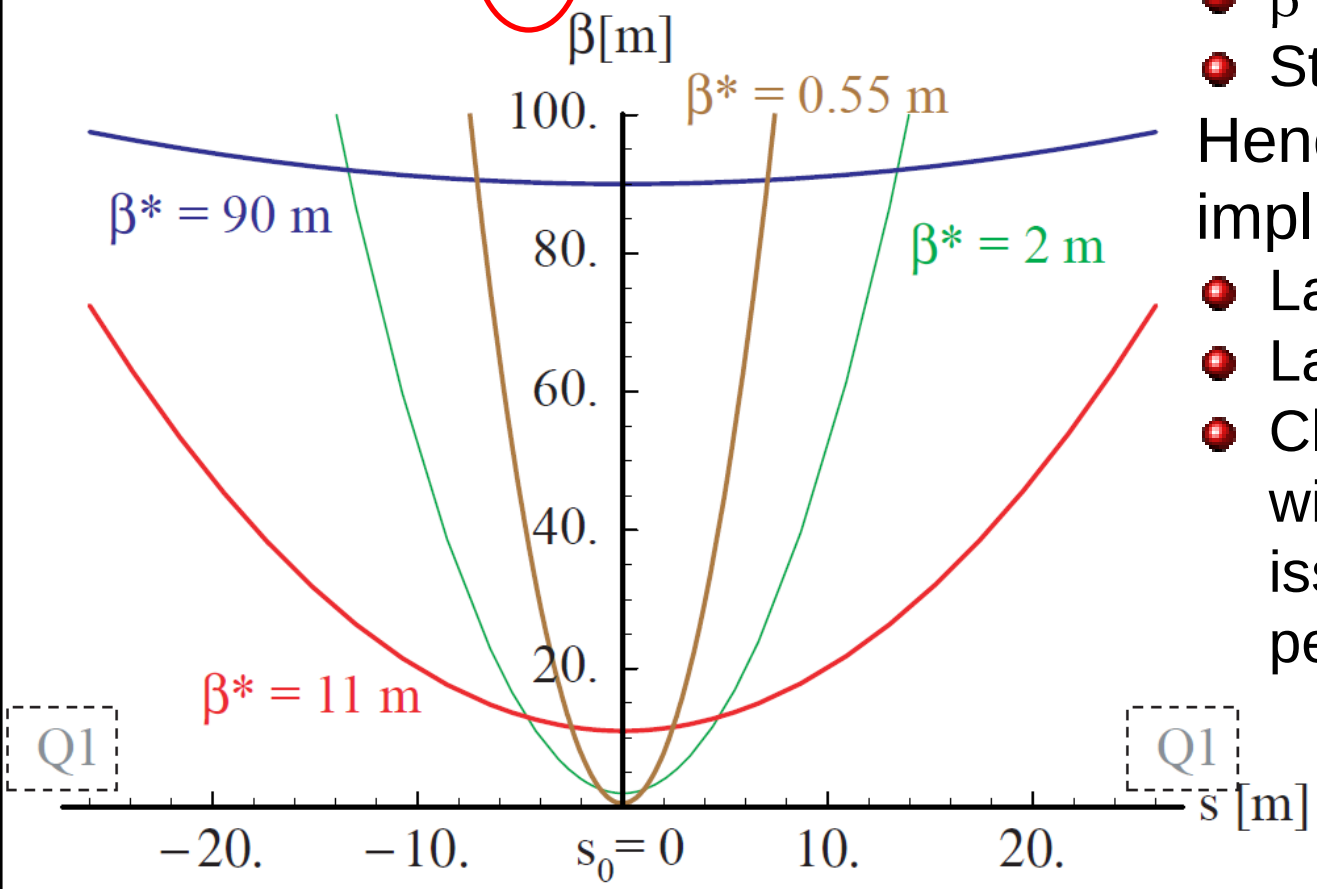


High luminosity insertions: collision optics. Beta at interaction point equals 0.55 m.

Few facts from optics

$$\beta(s) = \beta^* + \frac{(s - s_0)^2}{\beta^*}$$

In a drift space



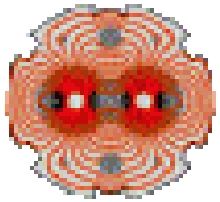
β_{max} in the triplets depends on:

- L*
- β*
- Strength of the triplets

Hence reducing β* implies:

- Larger aperture triplets
- Larger strength
- Chromatic effects scale with β_{max}^n -> potential issue for collimation performance

Nominal performance and beyond



- The nominal LHC parameters allow to reach 10^{34} cm^{-2} s^{-1}
- Some margin in bunch intensity was assumed originally: 1.15×10^{11} to 1.7×10^{11}. This is the so-called ultimate intensity.
- The corresponding ultimate luminosity is ~ 2.18×10^{34} cm^{-2} s^{-1}.
- Anything beyond this value requires a deep review of the LHC machine (and injectors!)

Figure-of-merit for an upgrade - I

- The luminosity formula is the key ingredient:

$$L = \frac{N_b^2 \; M \; f_{rev} \; \gamma_r}{4 \, \pi \, \varepsilon_n \, \beta^*} F \qquad F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

- But:
  - Many hidden constraints between parameters
  - Not all the parameters are determined by the LHC machine
  - The formula gives the peak luminosity, the average is different

Figure-of-merit for an upgrade - II

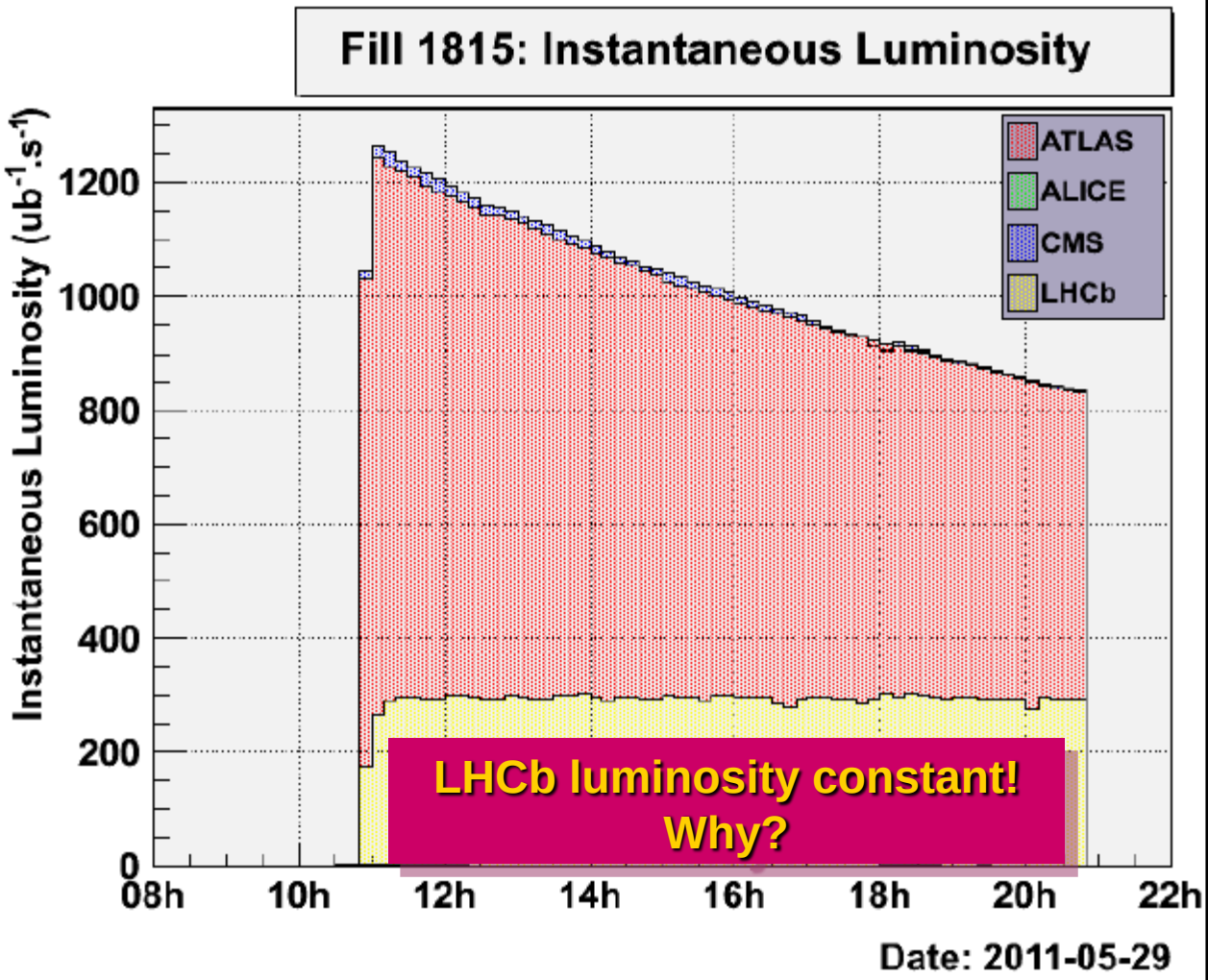
- Constraints between parameters: crossing angle

$$L = \frac{N_b^2 \, M \, f_{rev} \, \gamma_r}{4 \pi \, \varepsilon_n \sqrt{\beta_x^* \beta_y^*}} F \qquad \theta_c = d_s \sqrt{\varepsilon / \beta^*_x} \qquad F = \frac{1}{\sqrt{1 + \left(\frac{\sigma_z \, d_s}{2 \beta^*_x} \right)^2}}$$

- Luminosity saturates for round beams.
- Flat beams can optimise the situation.

Luminosity evolution

- The luminosity decays because of proton burn-off.
- Luminosity decay is proportional to peak luminosity!
- Luminosity leveling is an important ingredient in LHC upgrade



$L_{\text{peak}} = 1.2 \cdot 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ $\int L dt = 38\,\text{pb}^{-1}$

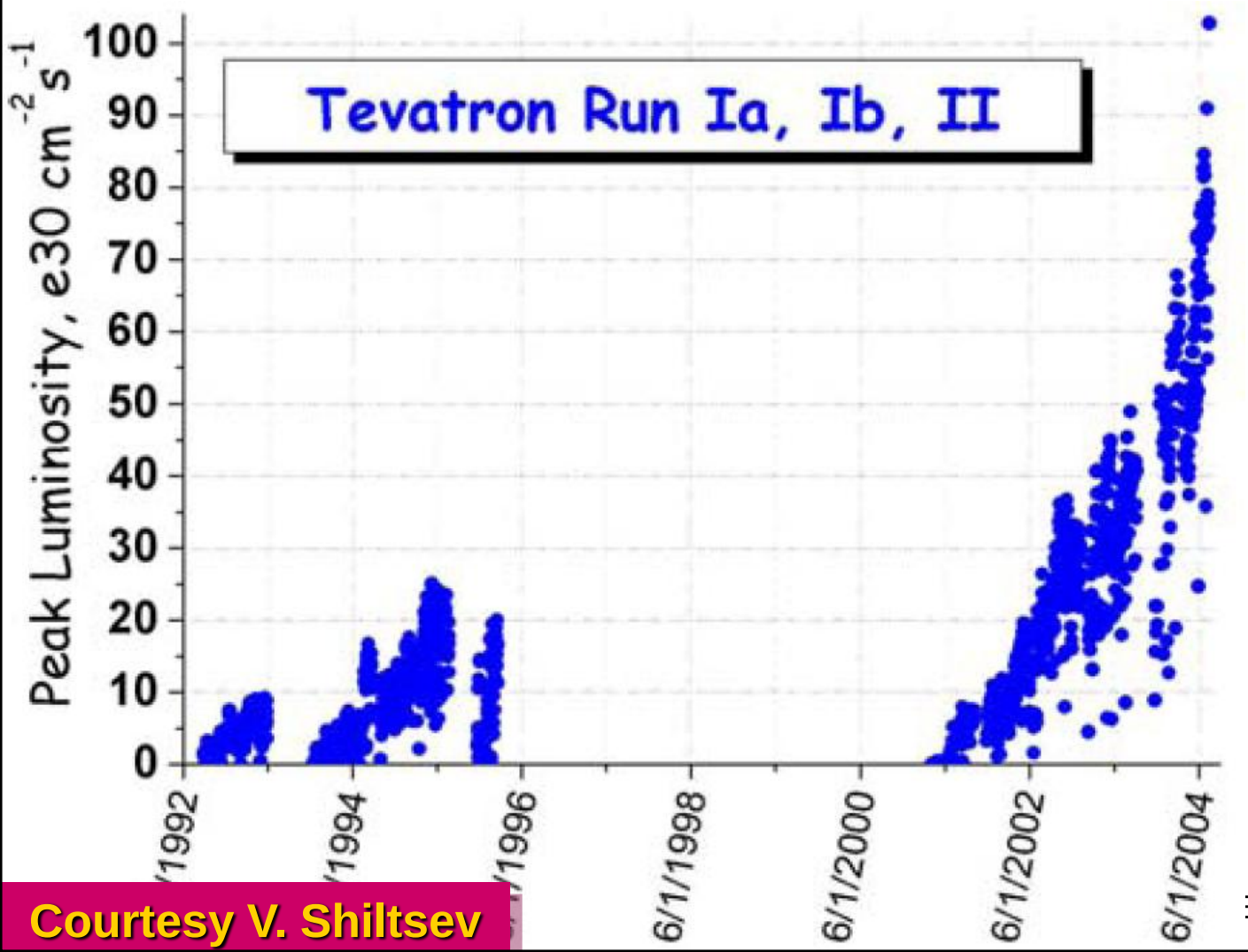
Upgrade ideas (until 2010)

- Assumptions (or common belief)
  - Lifetime of triplets under nominal conditions is few years (radiation due to debris) -> they should be replaced
  - Nominal parameters are probably tight and nominal luminosity might be difficult to achieve (triplets aperture)
- Hence, two-stage approach:
  - Phase 1: “Consolidate” the machine with new triplets aiming at reaching ~ 2-3×10^{34} cm^{-2} s^{-1}.
  - Phase 2: “Real” luminosity upgrade aiming at 10^{35} cm^{-2} s^{-1}. This includes a major upgrade of the detectors.

Phase 1 in short

- Rough summary of Phase 1 approach
  - Replace “only” triplets with larger aperture magnets to enable reaching smaller β^*.
- Intense studies performed:
  - Minimum β^* achievable: ~ 30 cm
  - Limits have been highlighted in other parts of the machine -> much more elements than the triplets should be changed!
  - Very complex optical gymnastics in order to fulfill the correction of chromatic aberrations -> not much operational flexibility left.

How many upgrades?



Courtesy V. Shiltsev

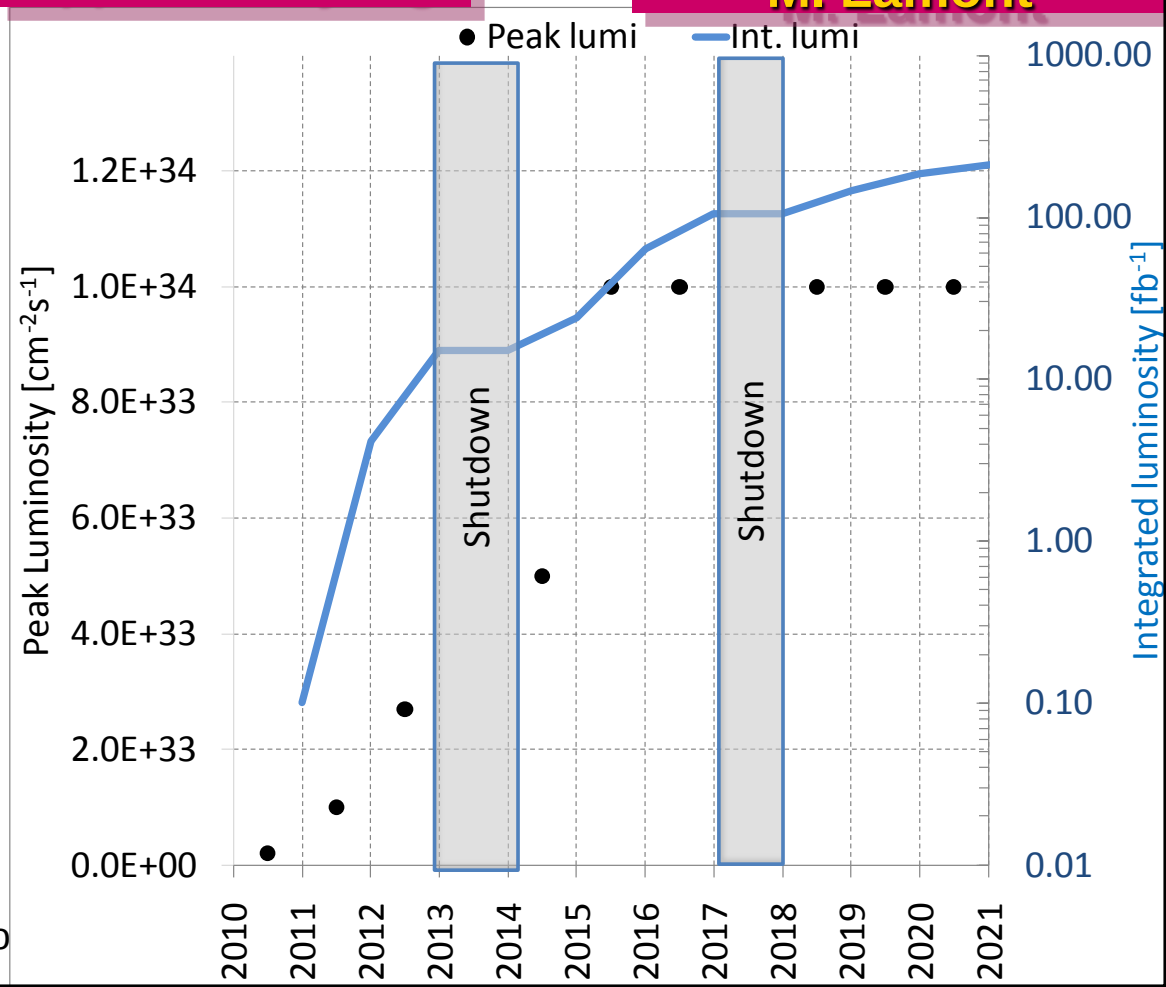
Each upgrade will require a non-negligible time to recover from the stop and gain in INTEGRATED luminosity.

Upgrade ideas (after 2010)

- One single upgrade.
- The time horizon is based on the projection of actual performance of the running LHC.
- For the injectors see later.

Data not approved by Mgt

Courtesy L. Rossi, M. Lamont



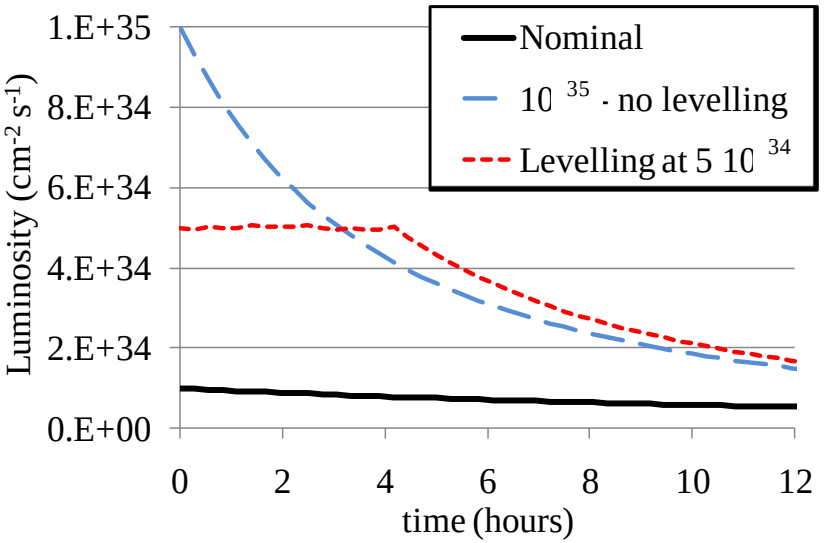
Latest unofficial 10 year plan

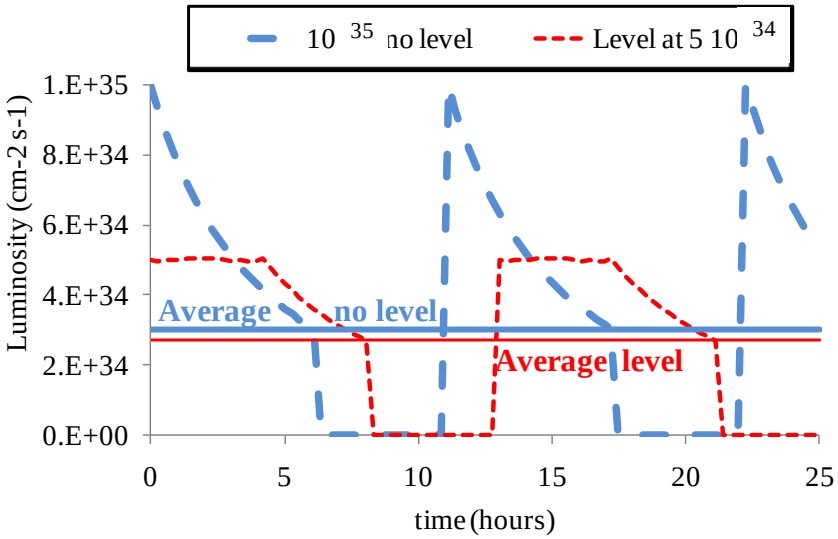
	J	F	M	A	M	J	J	A	S	O	N	D
2011		1	2	3	4	5	6	7	8	9	Ions	
2012			1	2	3	4	5	6	7	8	Ions	
2013	LS1 - SPLICE CONSOLIDATION											
2014									1	2	3	4
2015		1	2	3	4	5	6	7	8	9	Ions	
2016		1	2	3	4	5	6	7	8	9	Ions	
2017		1	2	3	4	5	6	7	8	9	Ions	
2018	LS2											
2019		1	2	3	4	5	6	7	8	9	Ions	
2020		1	2	3	4	5	6	7	8	9		
2020		1	2	3	4	5	6	7	8	9		
2022	HL-LHC upgrade											

Technical stop or shutdown
Proton physics
Ion Physics

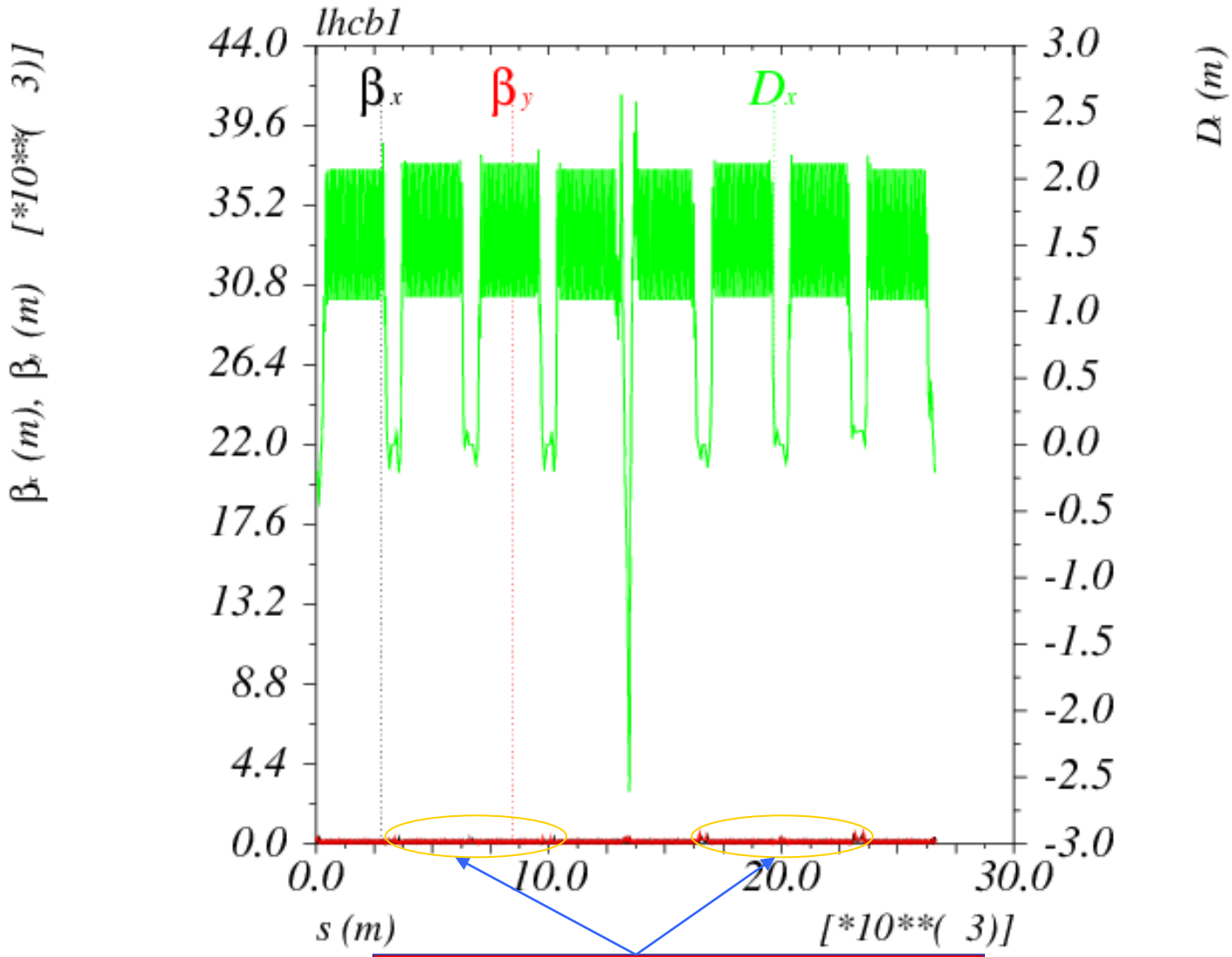
Scope of High-Luminosity upgrade of LHC

- Targets:
  - A peak luminosity of 5×10^{34} $cm^{-2}s^{-1}$ **with leveling**
  - An integrated luminosity of 250 fb^{-1} per year, enabling the goal of 3000 fb^{-1} in twelve years (nominal LHC is around 300 fb^{-1}in ten years).





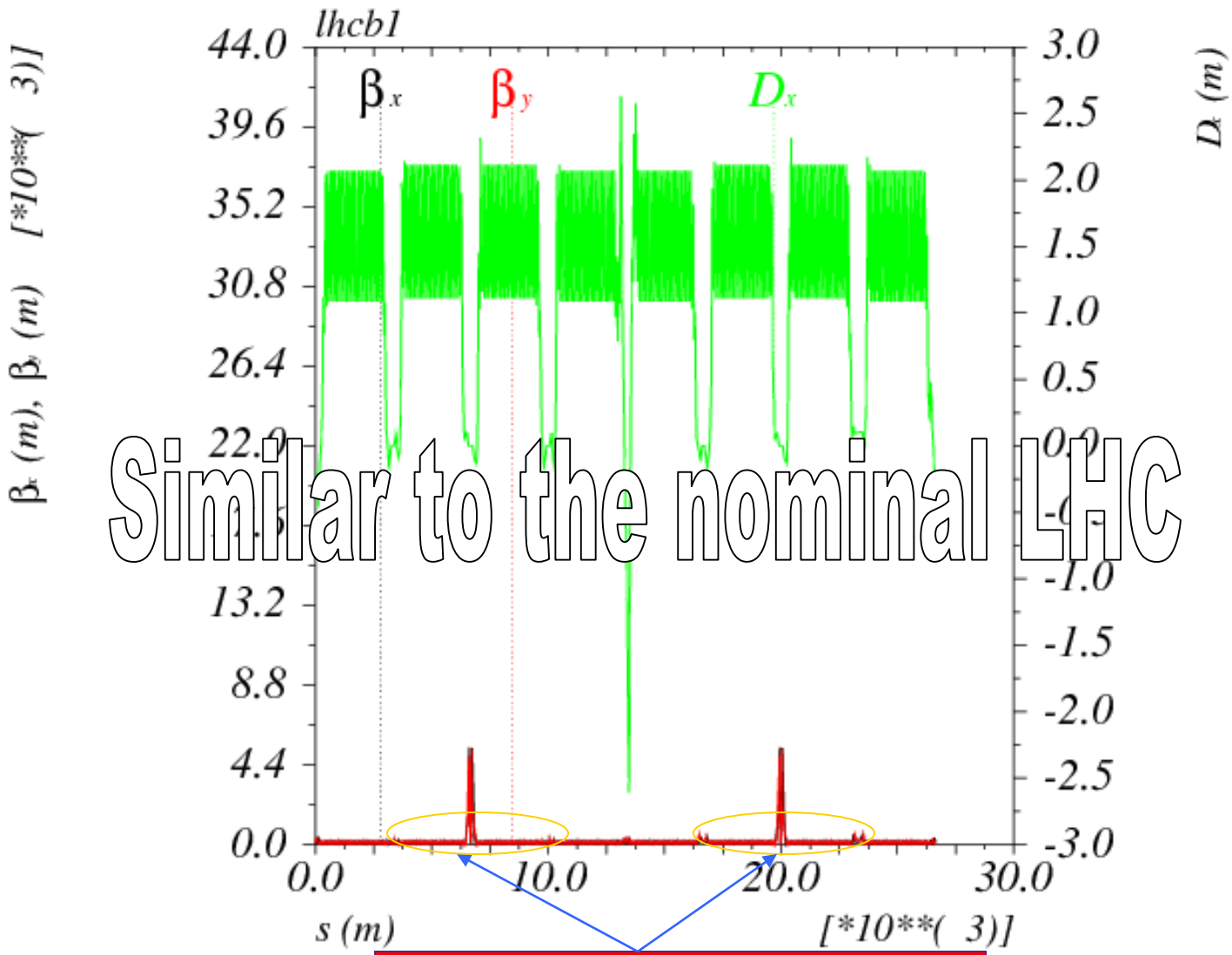
Injection optics: $\beta^* = 14$ m in IR1 and IR5



Nominal β_{arc} (180m) in s45/56/81/12

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh

Pre-squeezed optics: β^* = 60 cm in IR1 and IR5: "1111"

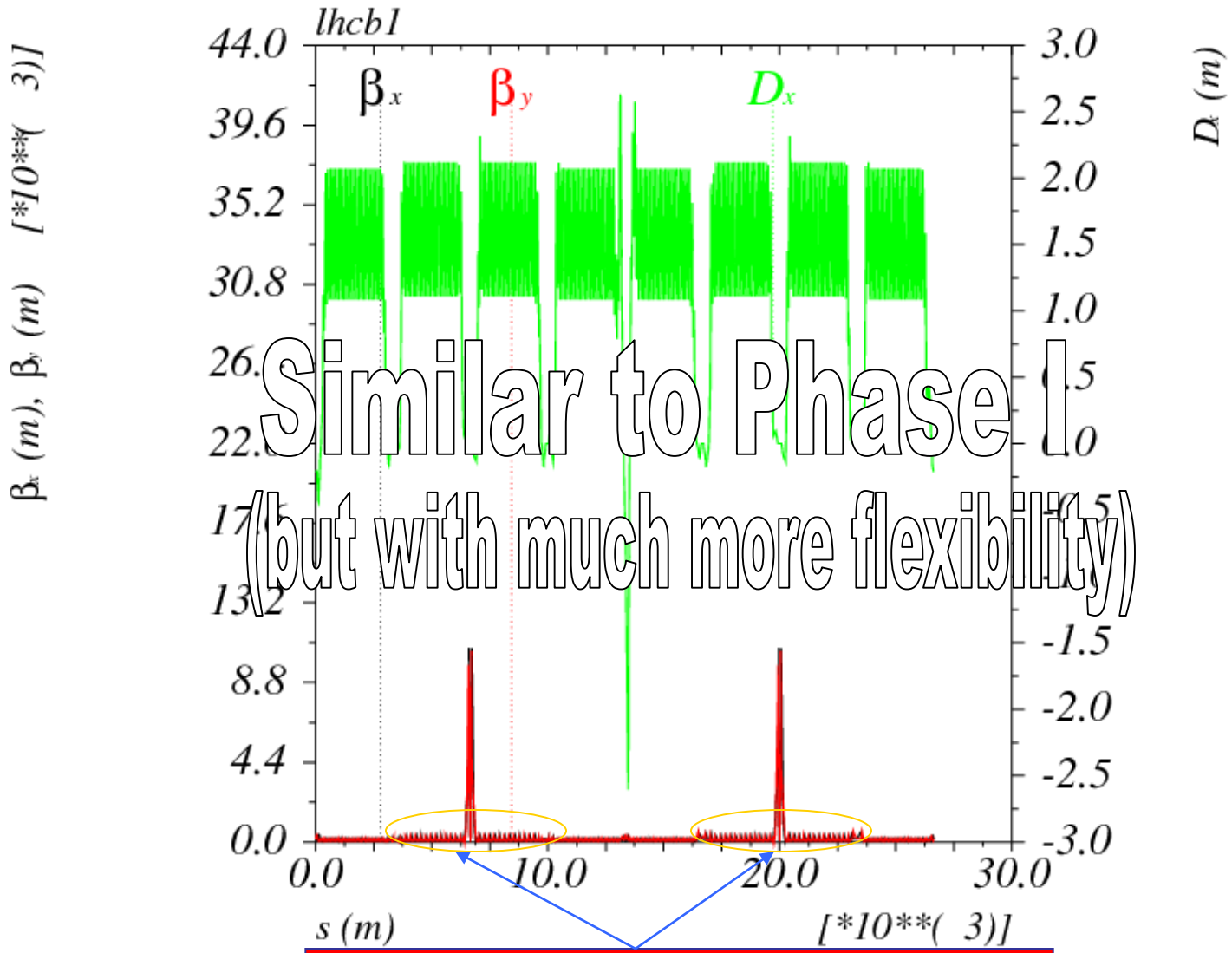


Similar to the nominal LHC

Nominal β_{arc} (180m) in s45/56/81/12

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh

Intermediate squeezed optics: $\beta^* = 30$ cm in IR1 and IR5: "2222"



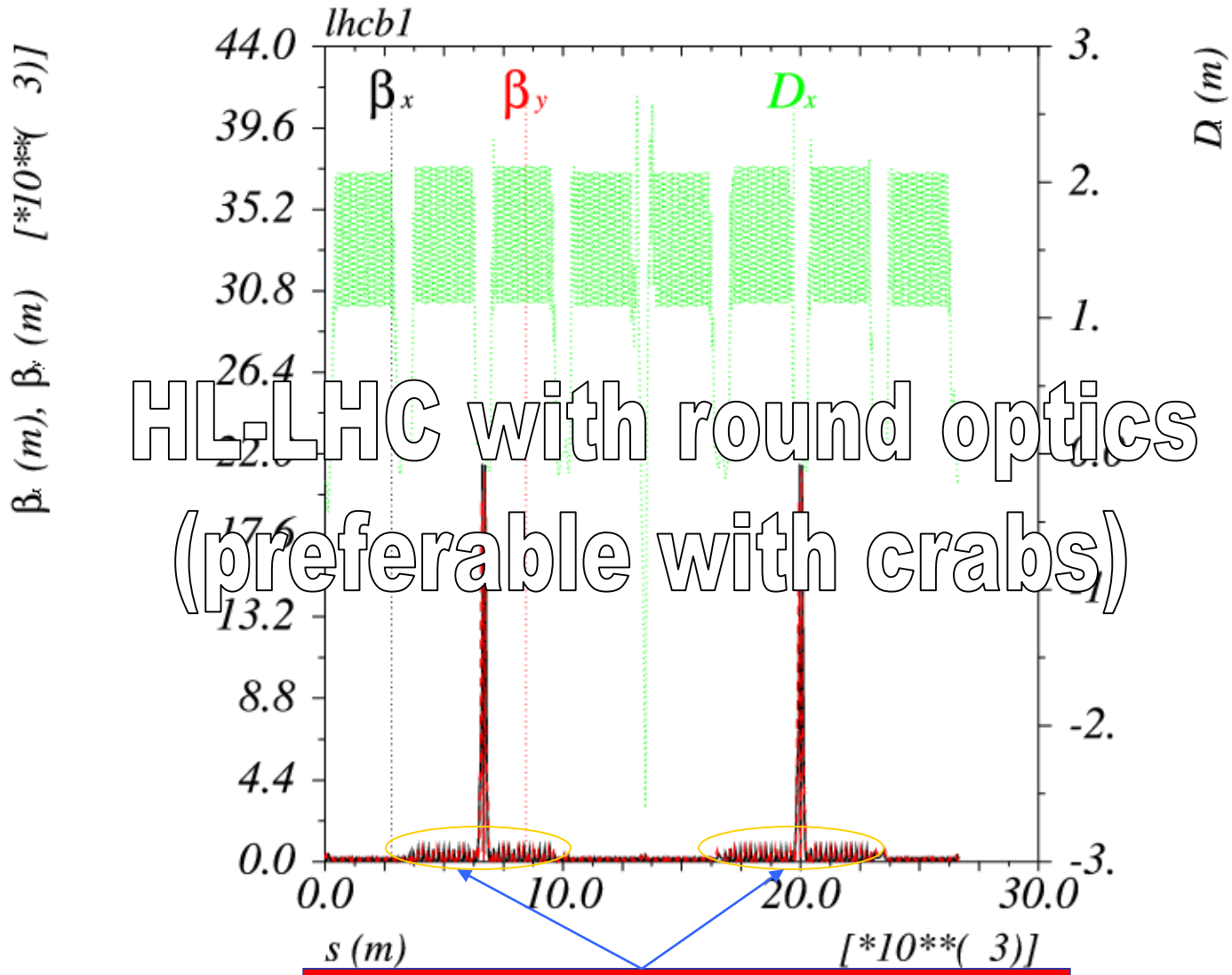
Similar to Phase I

(but with much more flexibility)

β_{arc} increased by a factor of 2 in s45/56/81/12

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh

Squeezed optics (round): $\beta^* = 15$ cm in IR1 and IR5: "4444"

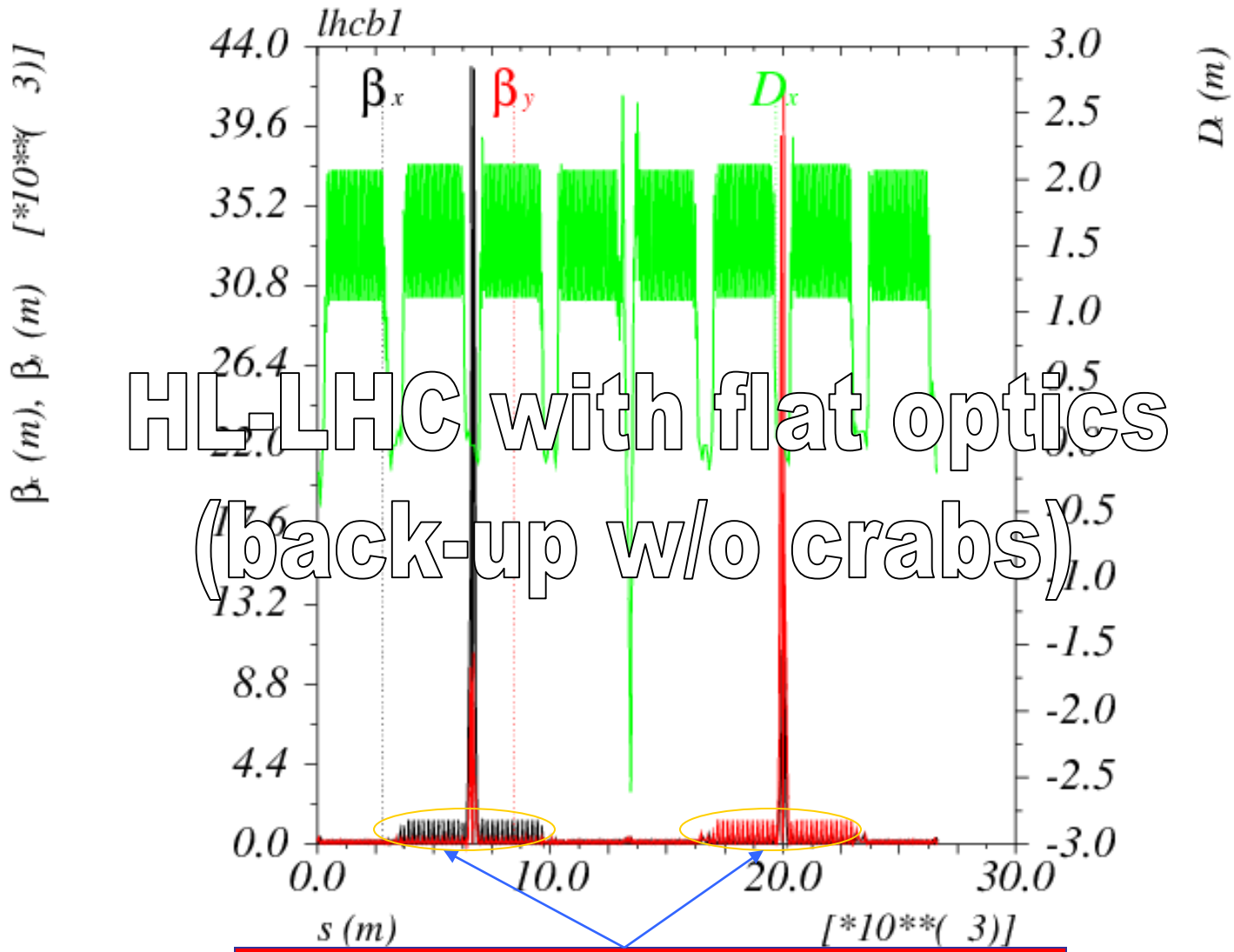


HL-LHC with round optics (preferable with crabs)

β_{arc} increased by a factor of 4 in s45/56/81/12

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh

Squeezed optics (flat): $\beta^*_{x/y}$ = 7.5/30 cm alternated in IR1 and IR5: "8228"

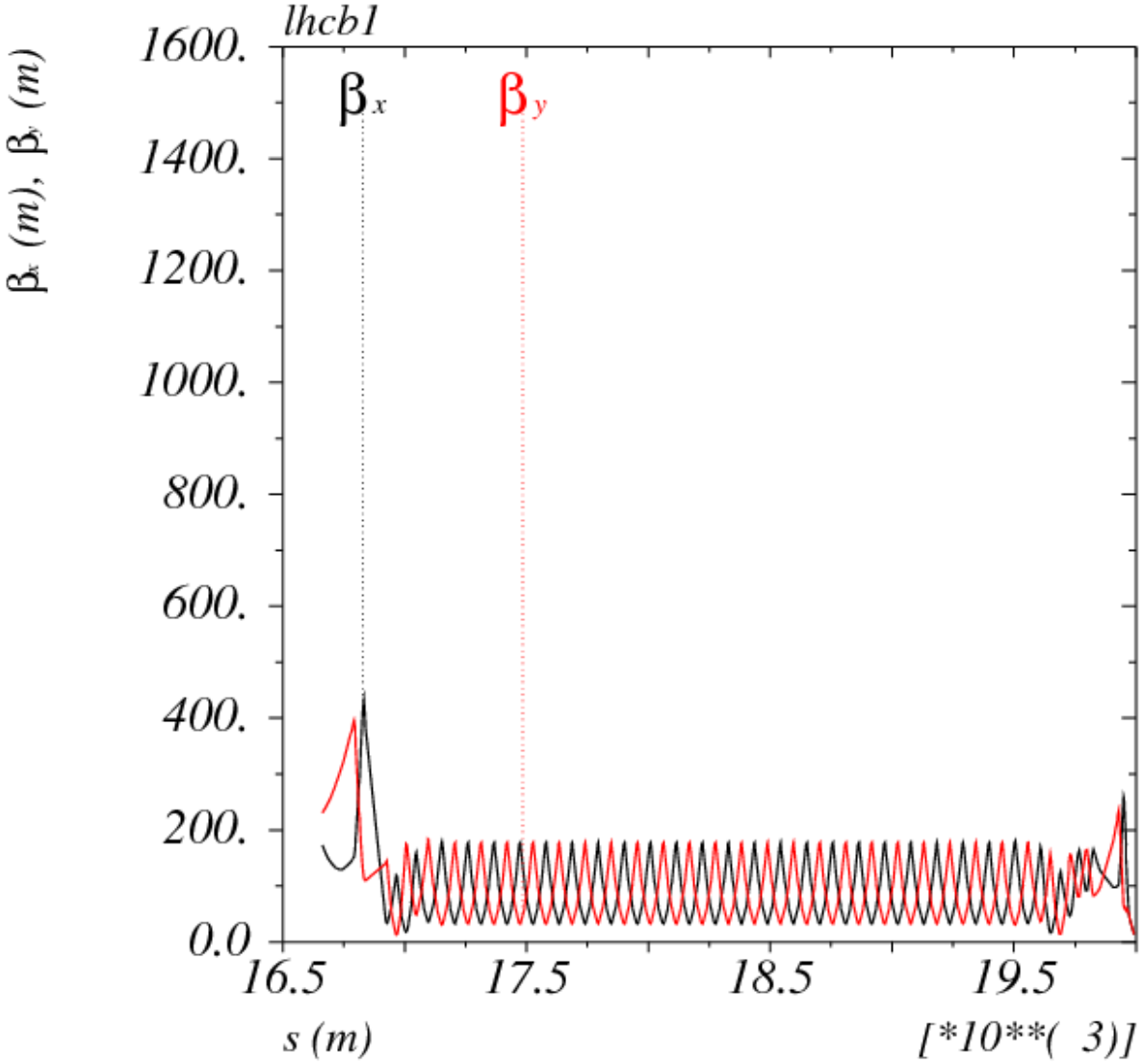


HL-LHC with flat optics (back-up w/o crabs)

β_{arc} increased by a factor of 2 or 8 in s45/56/81/12 depending on the β* aspect ratio in IP1 and IP5

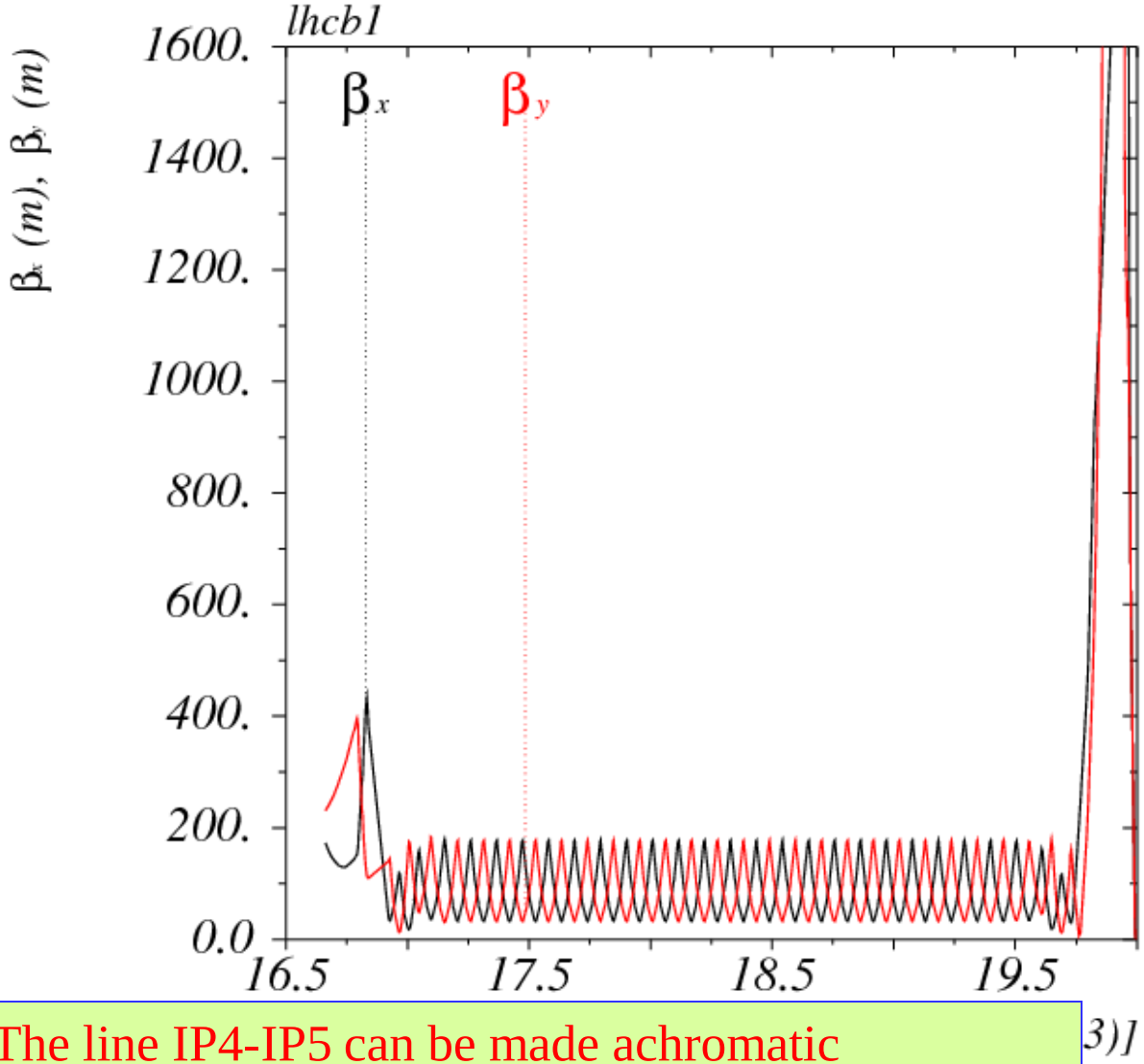
New Achromatic Telescopic Squeezing concept invented by S. Fartoukh

Injection optics: zoom from IP4 to IP5 (beam1)



New Achromatic Telescopic Squeezing concept invented by S. Fartoukh

Pre-squeezed optics "1111": zoom from IP4 to IP5 (beam1)

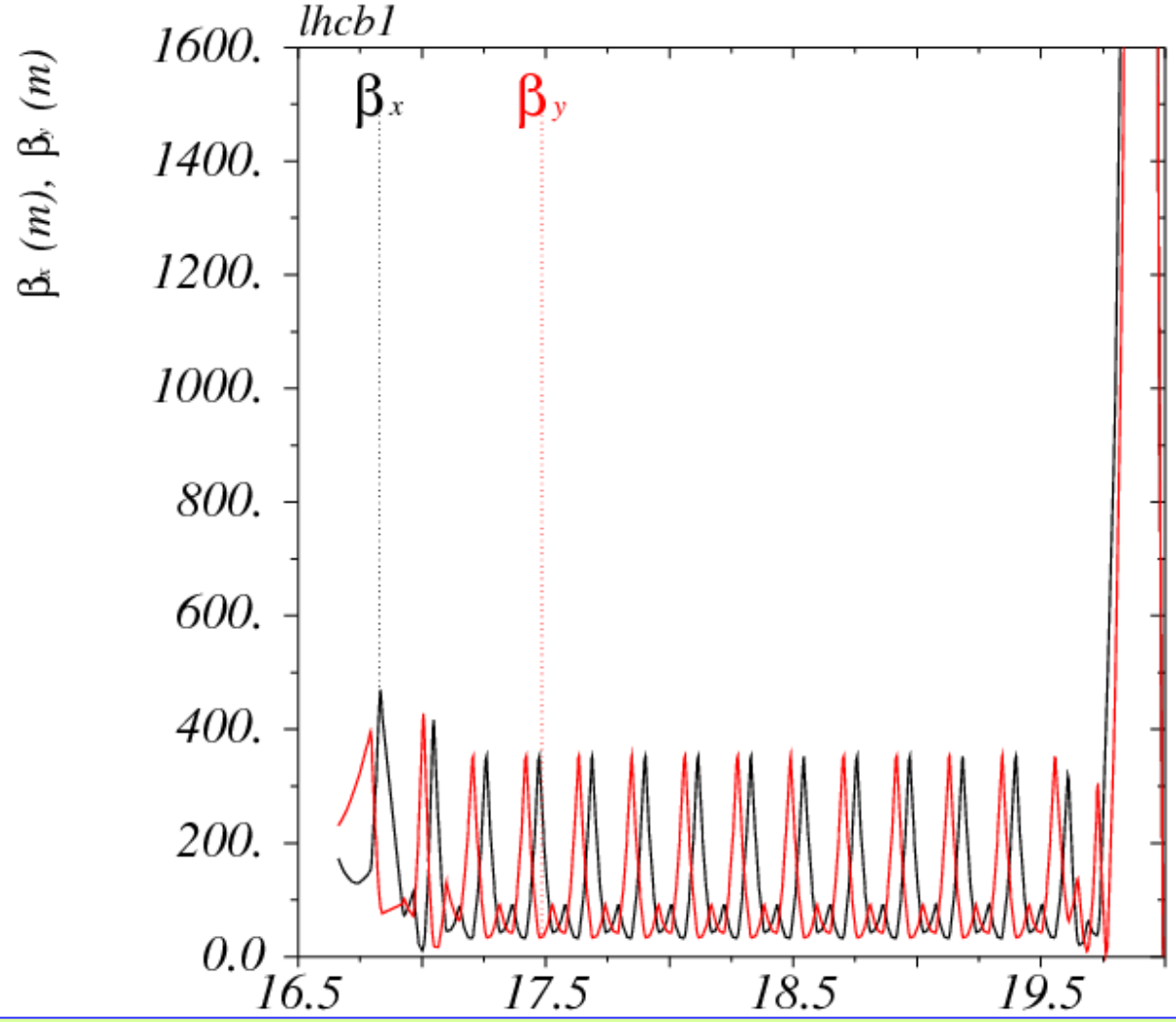


→The line IP4-IP5 can be made achromatic

(SD2 family close to 550 A, but still big margin on the SF1 circuit)

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh

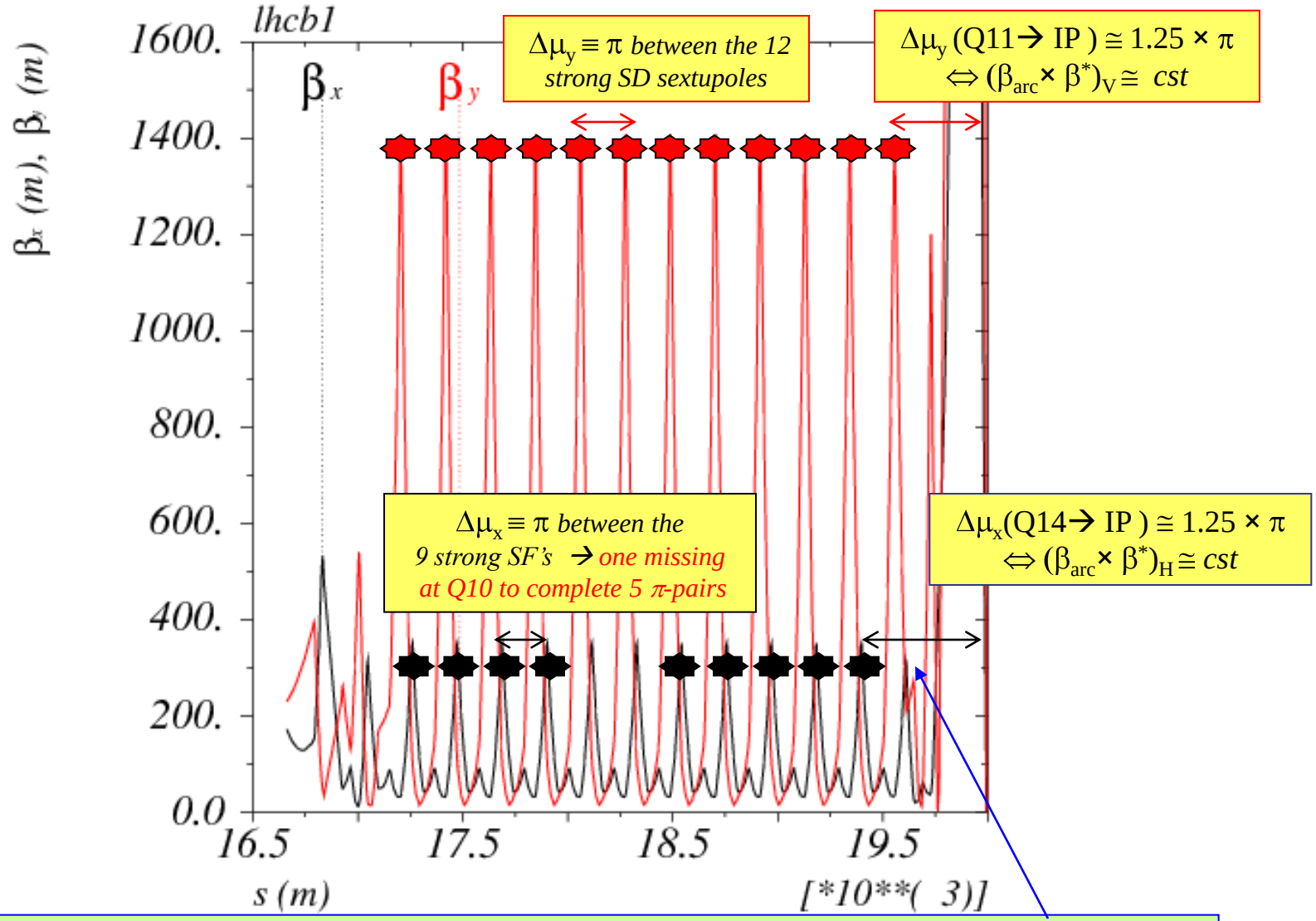
Intermediate squeezed optics “2222”: zoom from IP4 to IP5 (beam1)



→ β* is further squeezed at IP5 by a factor of 2 by rematching IR4 only.
→The line IP4-IP5 is kept achromatic at ~ cst sextupole strength.

New Achromatic Telescopic Squeezing concept invented by S. Fartoukh

Flat squeezed optics "8228": zoom from IP4 to IP5 (beam1)



Equipping Q10 (MQML) with an MS becomes highly desirable for high β_{arc}

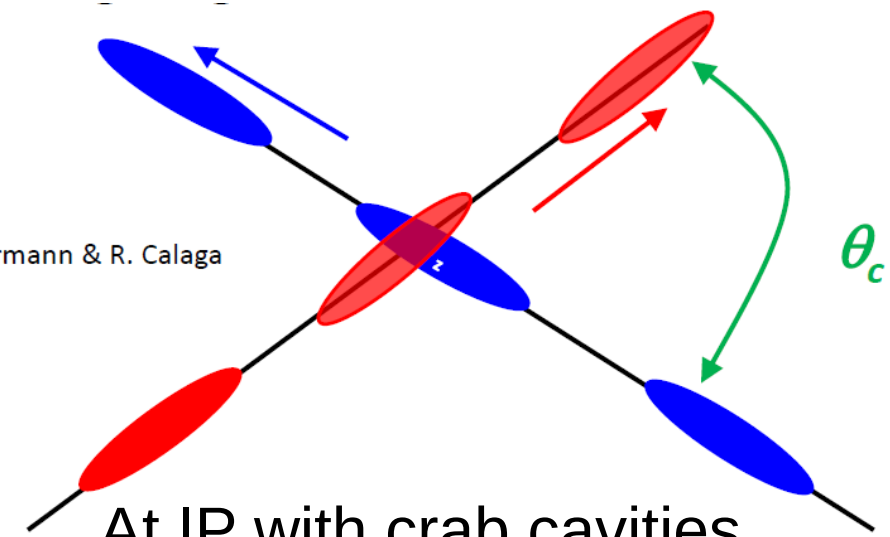
New Achromatic Telescopic Squeezing concept invented by S. Fartoukh

Luminosity levelling

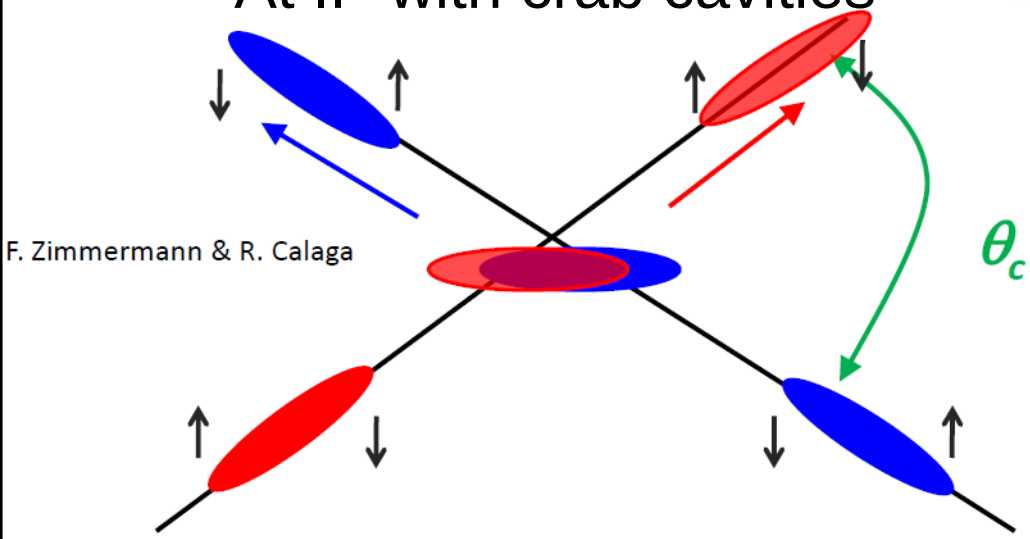
- Three options at hand:
  - Vary crossing angle (crab cavities help here!)
    - It can be performed with dipoles
    - Easy, but requires aperture in triplets
  - Vary separation
    - It can be performed with dipoles
    - Easy (already tried with Alice), but requires aperture
  - Vary β^*
    - Never tried in existing machines
    - Requires an excellent control of optics and crossing scheme

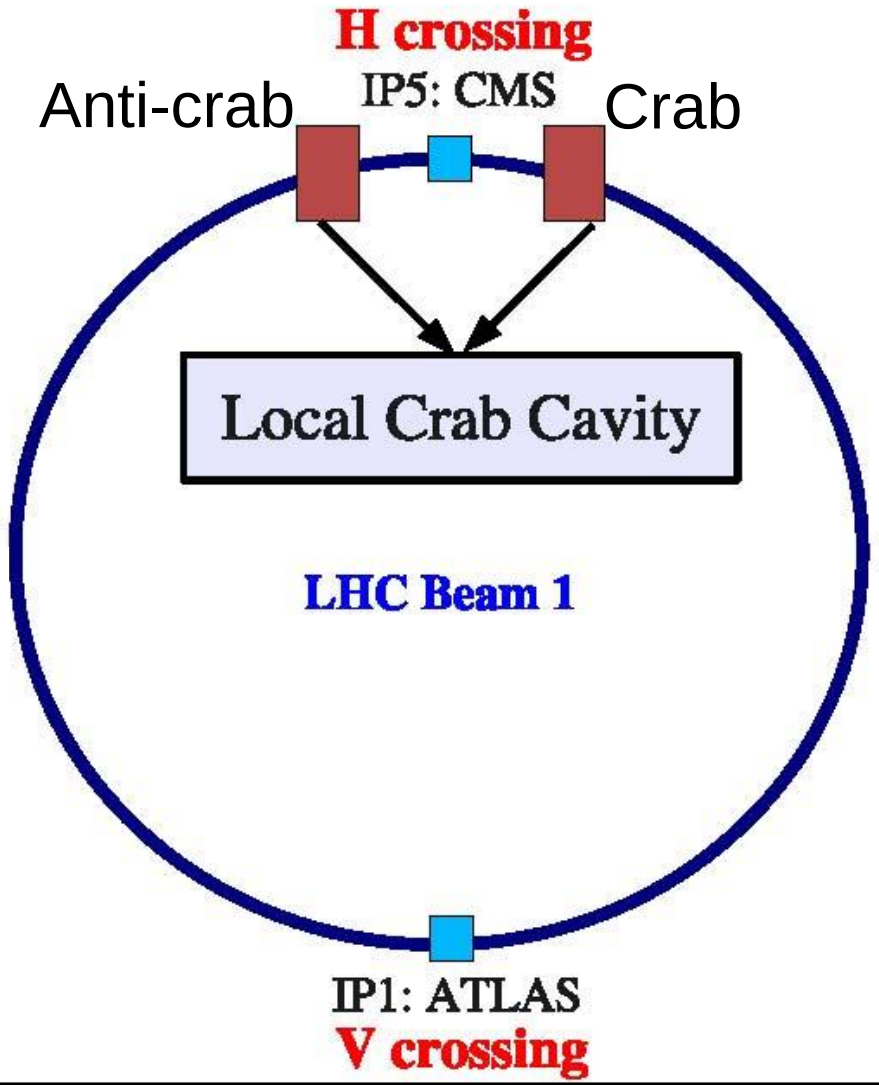
Crab cavities - I

At IP without crab cavities



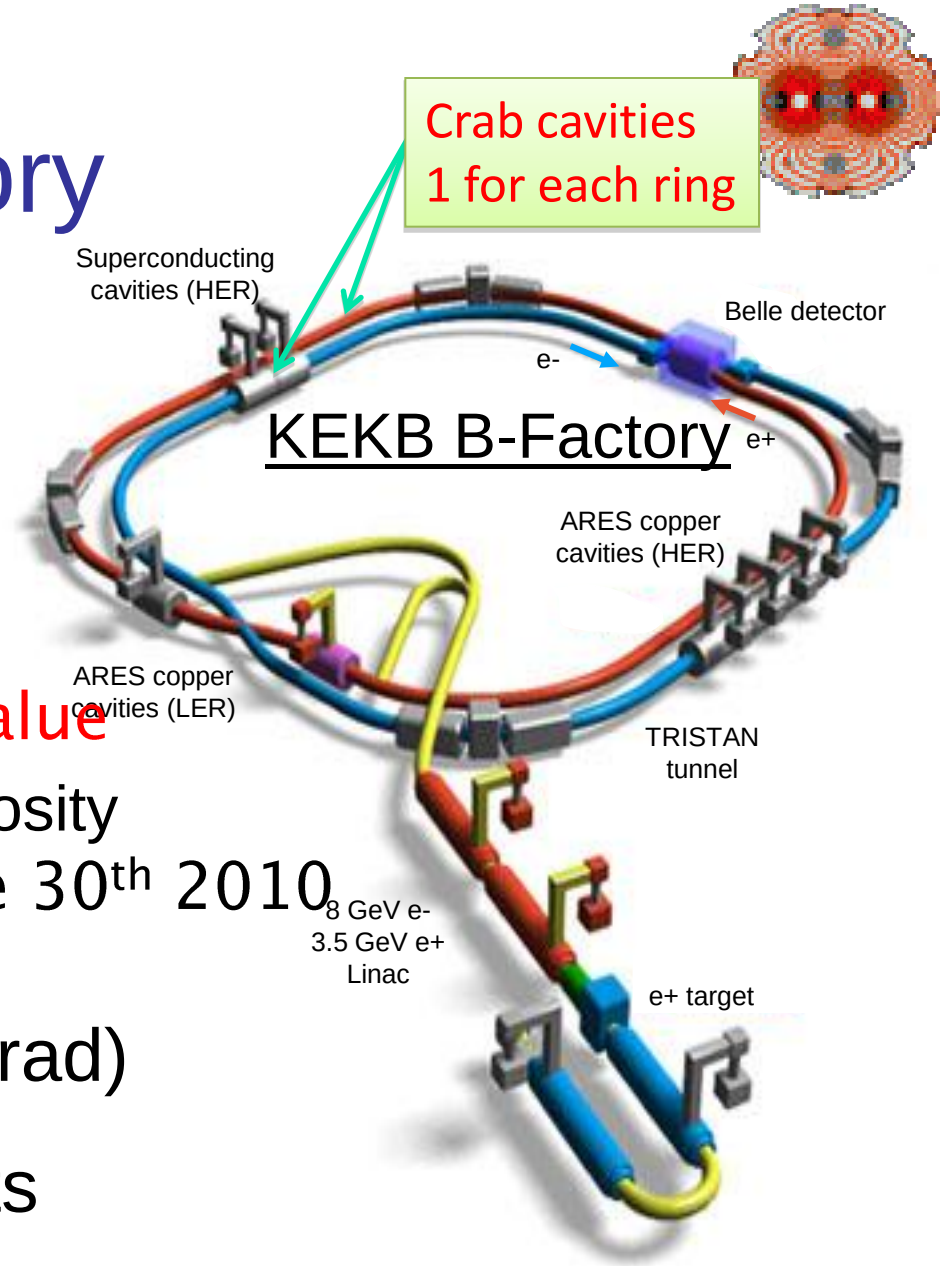
At IP with crab cavities





KEKB B-Factory

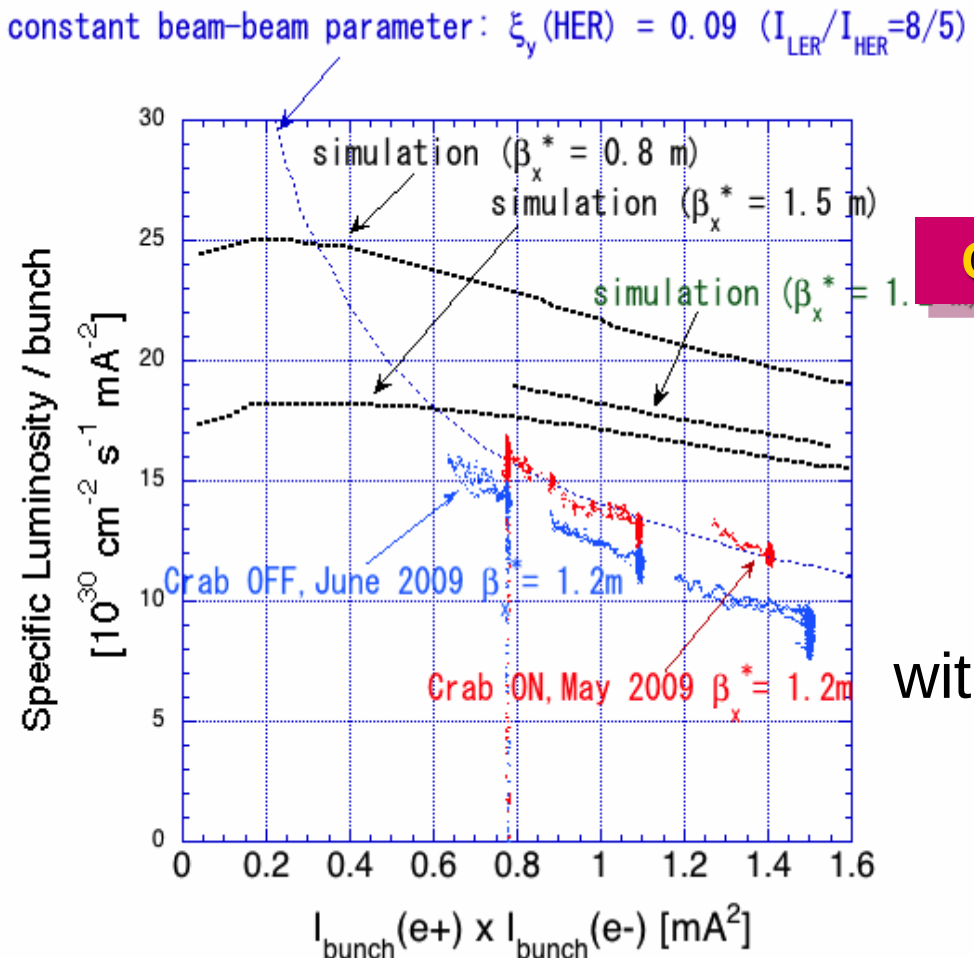
Courtesy Y. Funakoshi



- ♦World-highest Peak Luminosity
  - •$2.11 \times 10^{34} cm^{-2} s^{-1}$
  - •Twice as high as design value
- ♦World-highest Integrated Luminosity
  - • Total: $1040 fb^{-1}$ as of June 30th 2010
- ♦Crab crossing (ϕ = 11 mrad)
- ♦Skew-sextupole magnets

The KEKB operation was terminated at the end of June 2010 for the upgrade toward SuperKEKB.

Impact on luminosity



Courtesy Y. Funakoshi

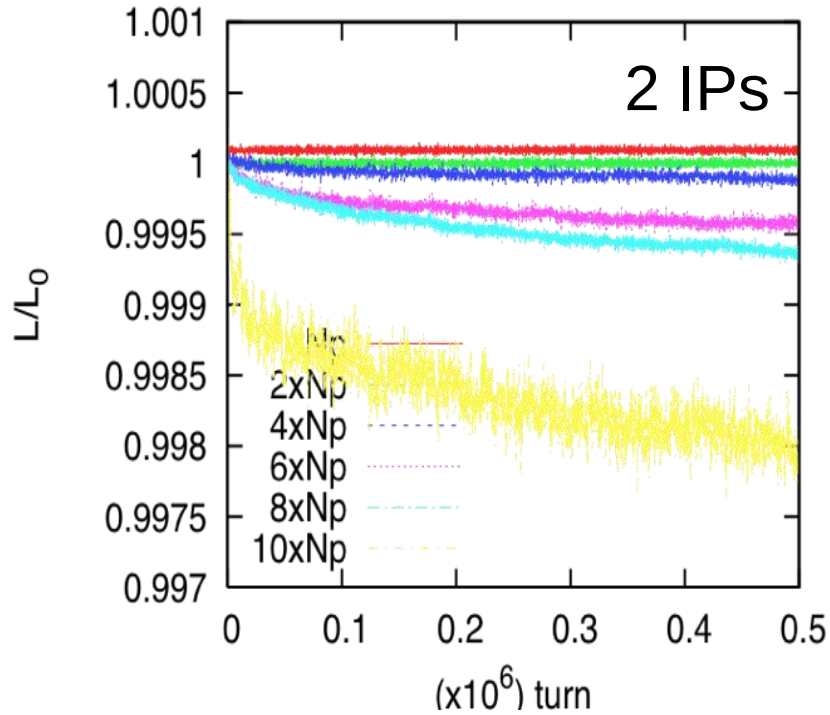
with skew sextuples

Luminosity improvement by crab cavities is about 20%.

Geometrical loss due to the crossing angle is about 11%.

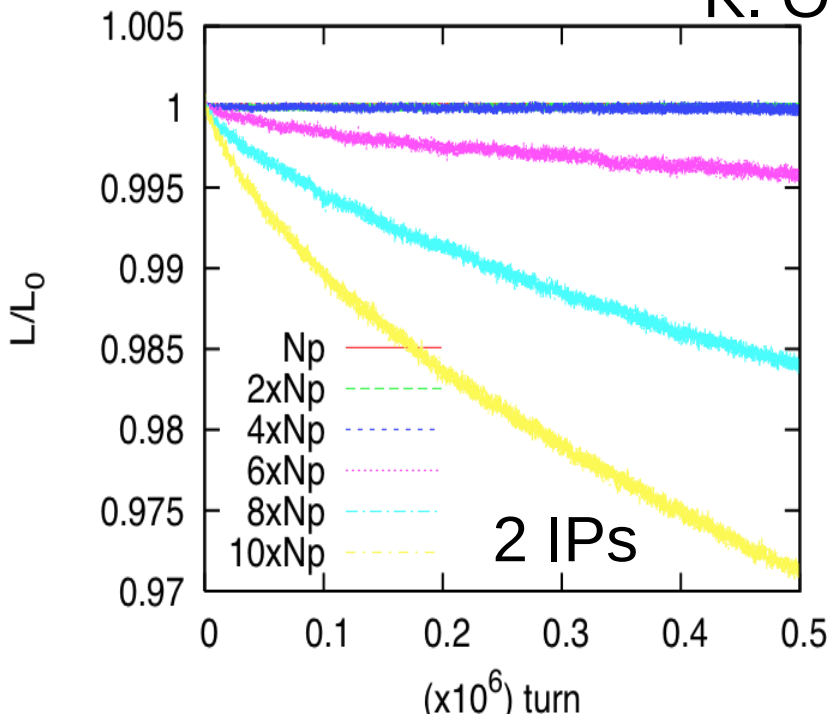
(HL-)LHC: KEK simulation

crab crossing



collisions with 280 μrad crossing angle

K. Ohmi

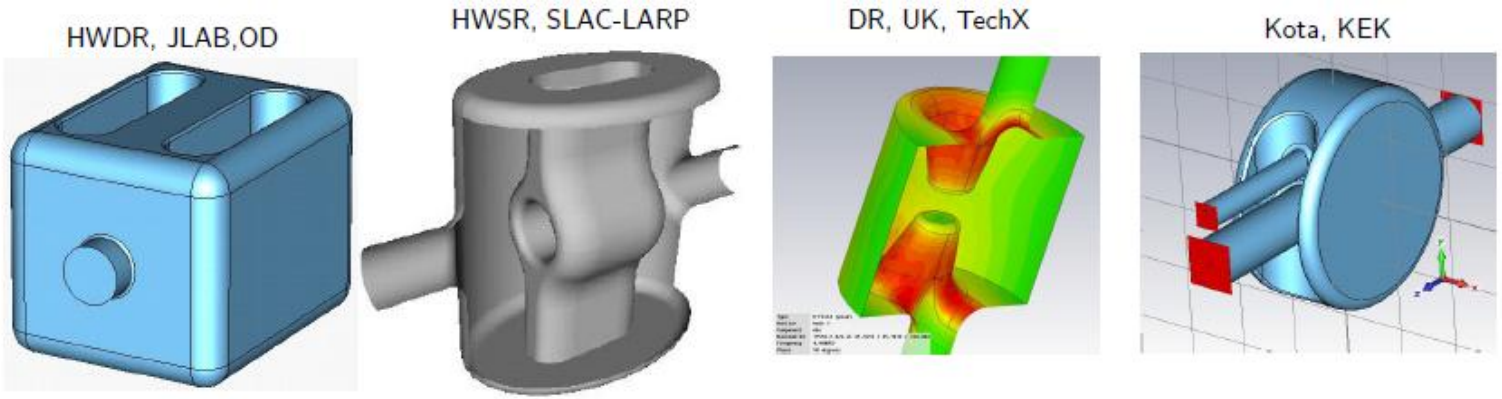


simulated luminosity lifetime with crab crossing is 10 times better than without crab crossing

Courtesy F. Zimmermann

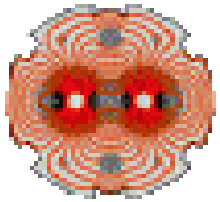
Potential issues of crab cavities - I

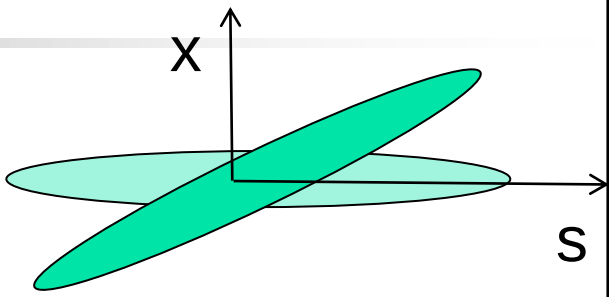
- RF Noise
  - It could induce emittance growth. So far never used in any proton machine!
- Design
  - Very limited transverse space in the LHC
  - Imposes creative designs
  - Two types are needed: H and V crossing



Compact cavities aiming at small footprint & 400 MHz, ~5 MV/cavity

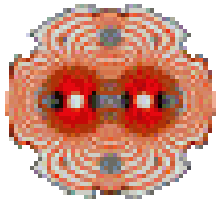
Potential issues of crab cavities - II





- Machine protection
  - The crab cavity kicks head and tail.
  - In the local scheme two crab cavities are used to cancel the transverse kick outside the insertion.
  - What happens in case of a cavity failure?
    - Head and tail would start to oscillate all around the circumference.
    - The “effective” transverse size of the beam is increased.
    - The tails could scrape some parts of the machine (few % of beam is in the tails – around 5σ – corresponding to 3-10 MJ!)

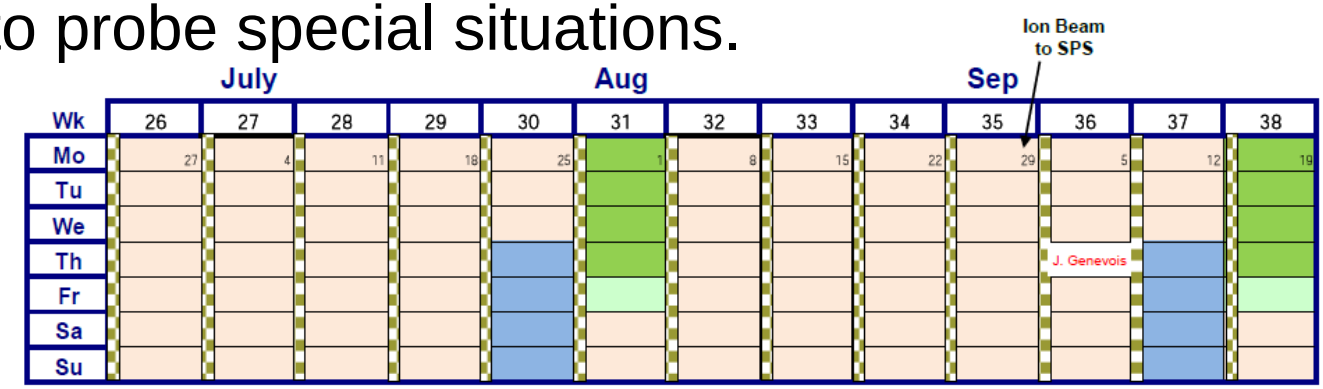
Potential issues of crab cavities - III



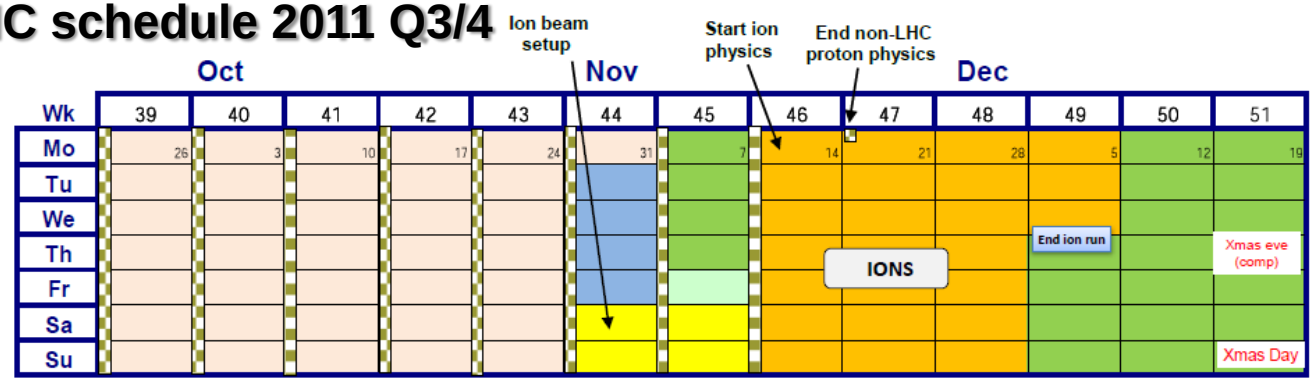
- The point is the speed of the failure.
- The voltage could drop significantly in 1 turn!
- The machine protection is not capable of handling these ultra-fast failures.
- The only solution is to ensure that “by design” the probability of such an event is extremely rare.
- No clear solution at hand…

MD studies at the LHC

- Most of the key ingredients/assumptions for the LHC upgrade can be tested in the nominal machine!
- Starting from this year a series of blocks of five days are dedicated to Machine Developments (MD) studies: the actual machine is used to probe special situations.
- Two topics of particular interest for upgrade:
  - Beam-beam limits
  - ATS optics



LHC schedule 2011 Q3/4

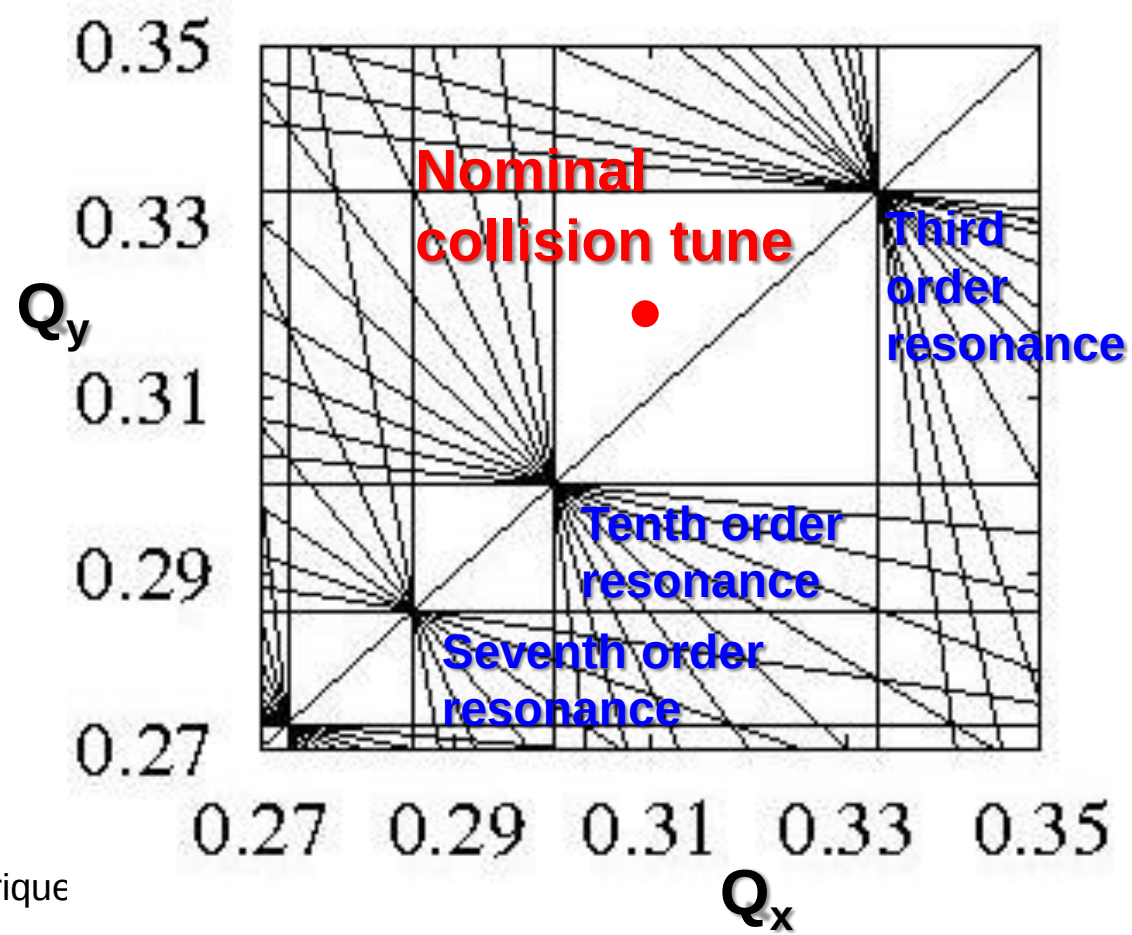


Reminder

- Resonances have a negative impact on beam dynamics (emittance growth).
- The nominal tunes have been chosen far away from low order resonances.
- This is the minimum optimisation: also the tune spread should be included in the optimisation!

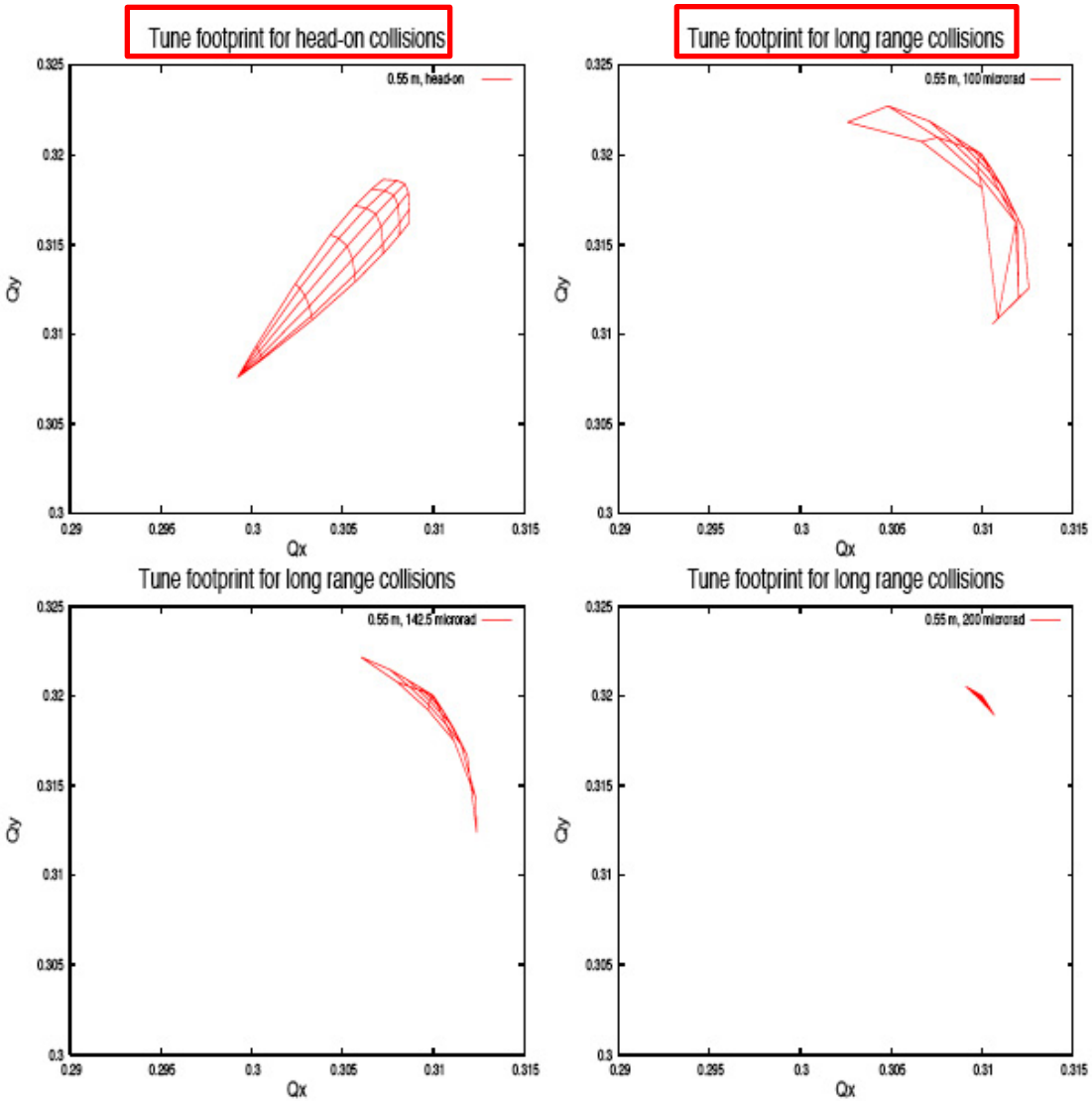
$$m\,Q_x + n\,Q_y = p$$

m+n=resonance order



Beam-beam limit - I

- A matter of tune shift, i.e., interaction with resonances
- Increasing crossing angle is beneficial for tune spread.

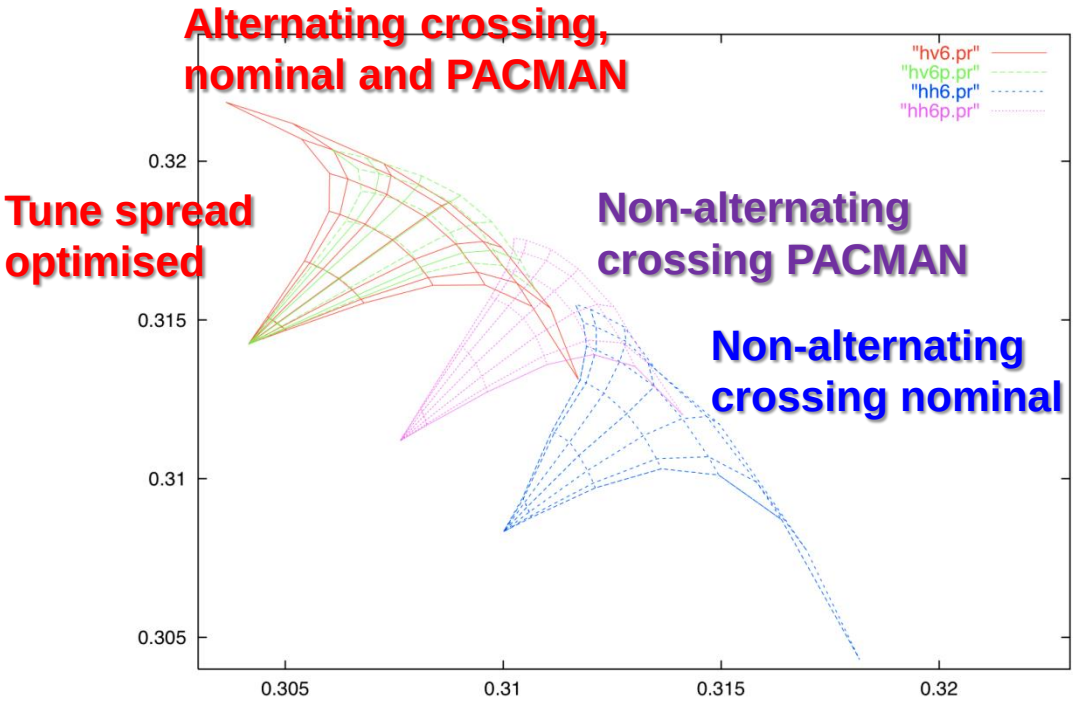


Crossing angle configurations:
Top Left:
only head-on
Top right: = 200μrad
Bottom left: = 285μrad
Bottom right = 400μrad

Courtesy W. Herr

Beam-beam limit - II

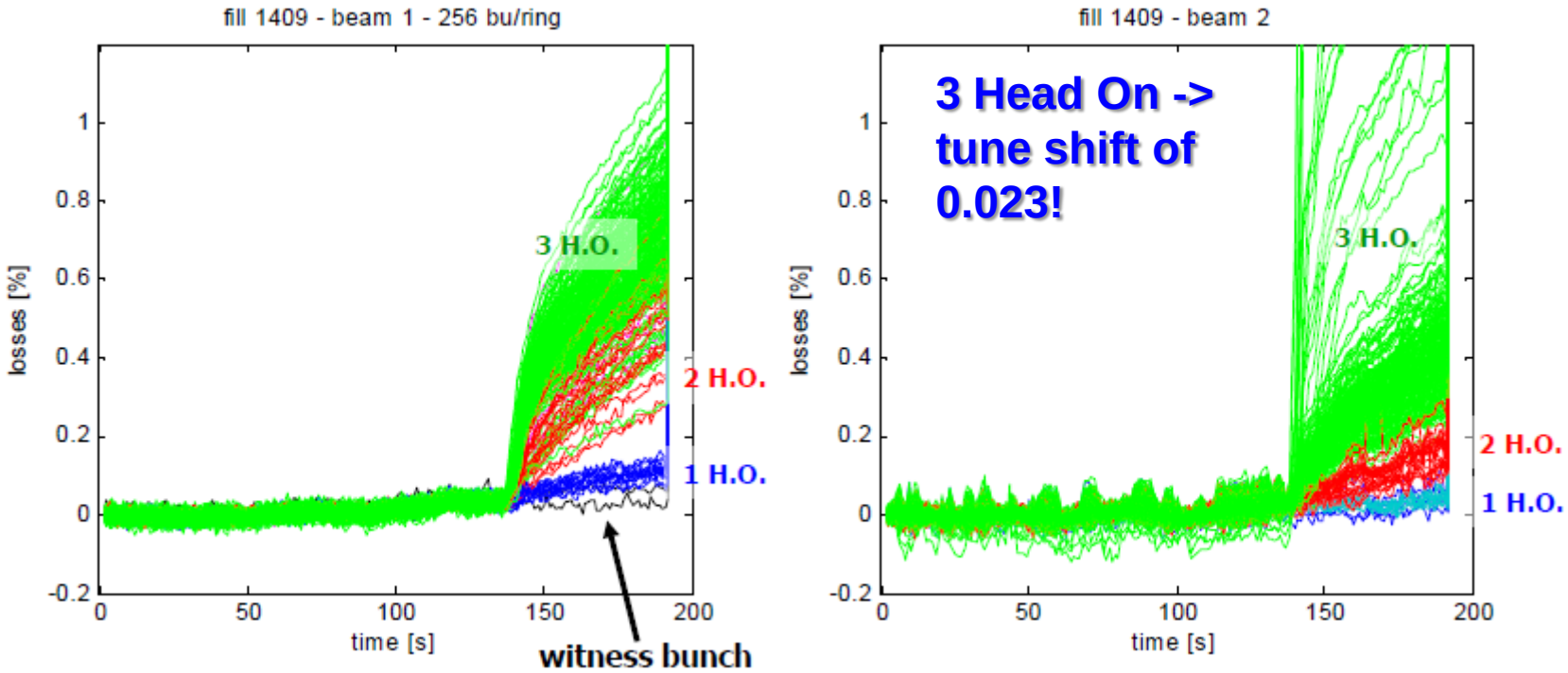
- Beneficial effect of alternating crossing on tune spread (nominal and PACMAN bunches)
- For LHC design, maximum tune shift tolerable assumed to be 0.01.
- Other machines:
  - SppbarS: 0.018
  - Tevatron: 0.02



Courtesy W. Herr

LHC experience and MDs

- Beam-beam can be lethal for bunches!

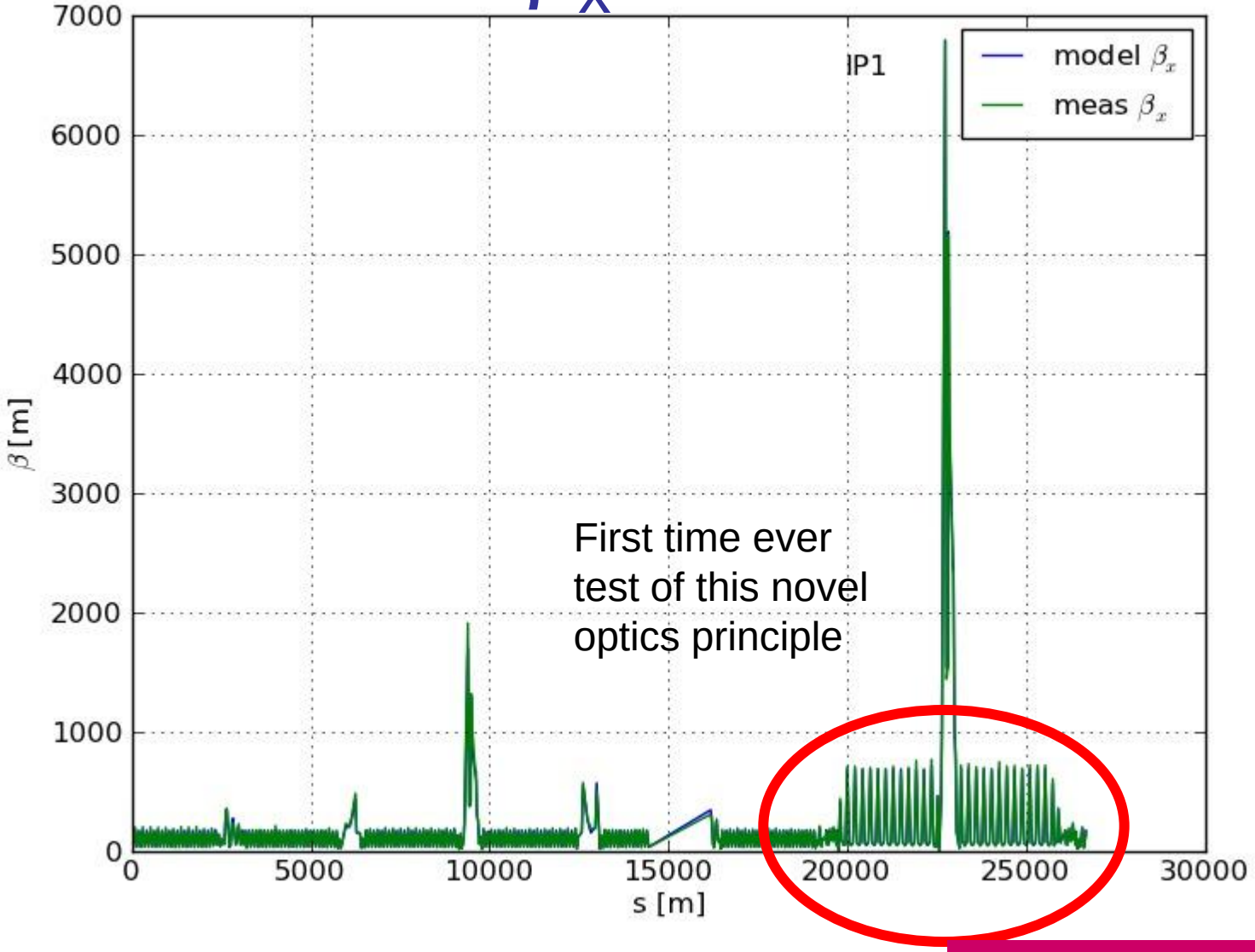


- MD results:
  - Head On: factor of five margin!
  - Long Range: as expected, no margin

PRELIMINARY!!!

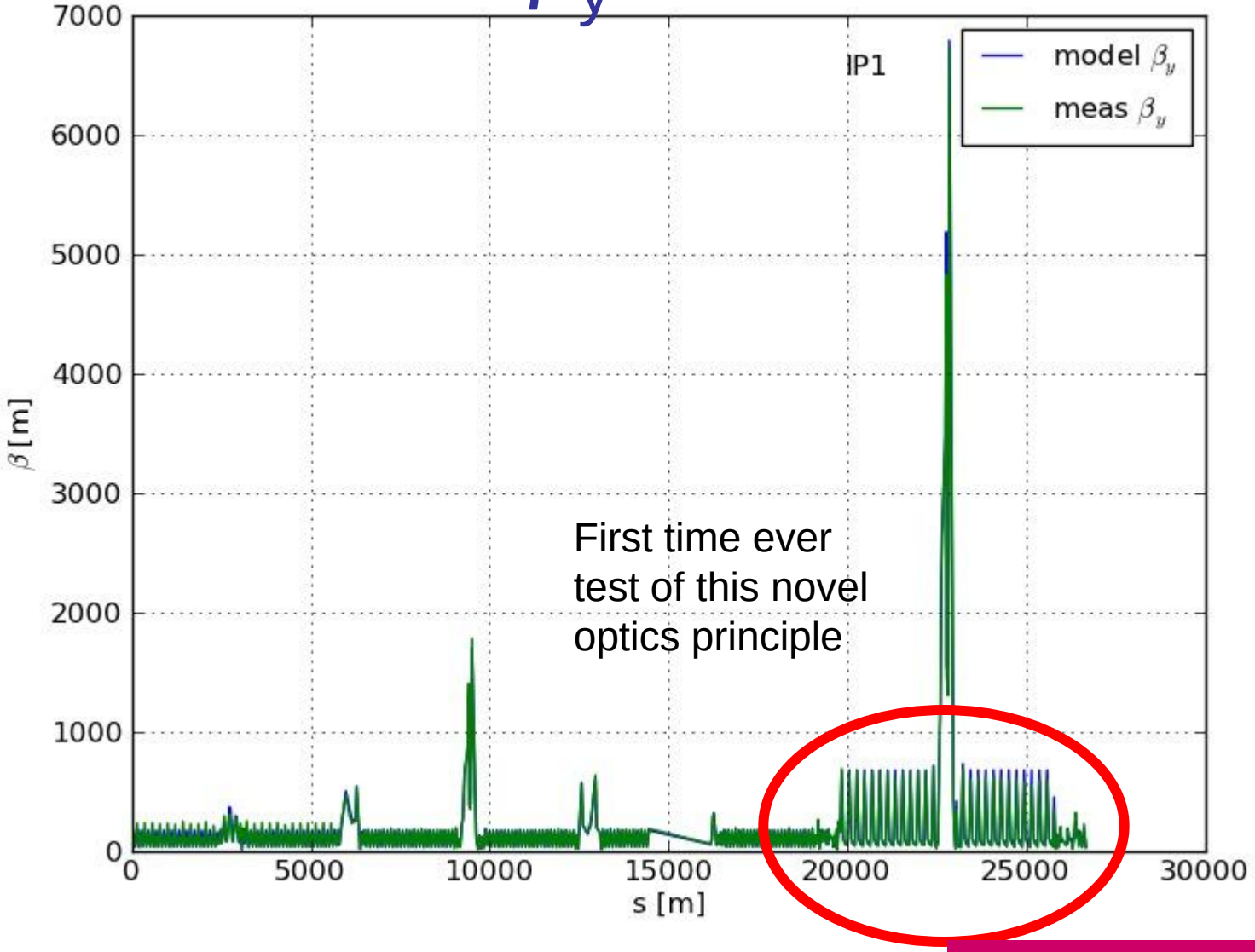
Smaller emittance would be an advantage for upgrade

ATS: 30 cm β* in IP1: Measured β_x



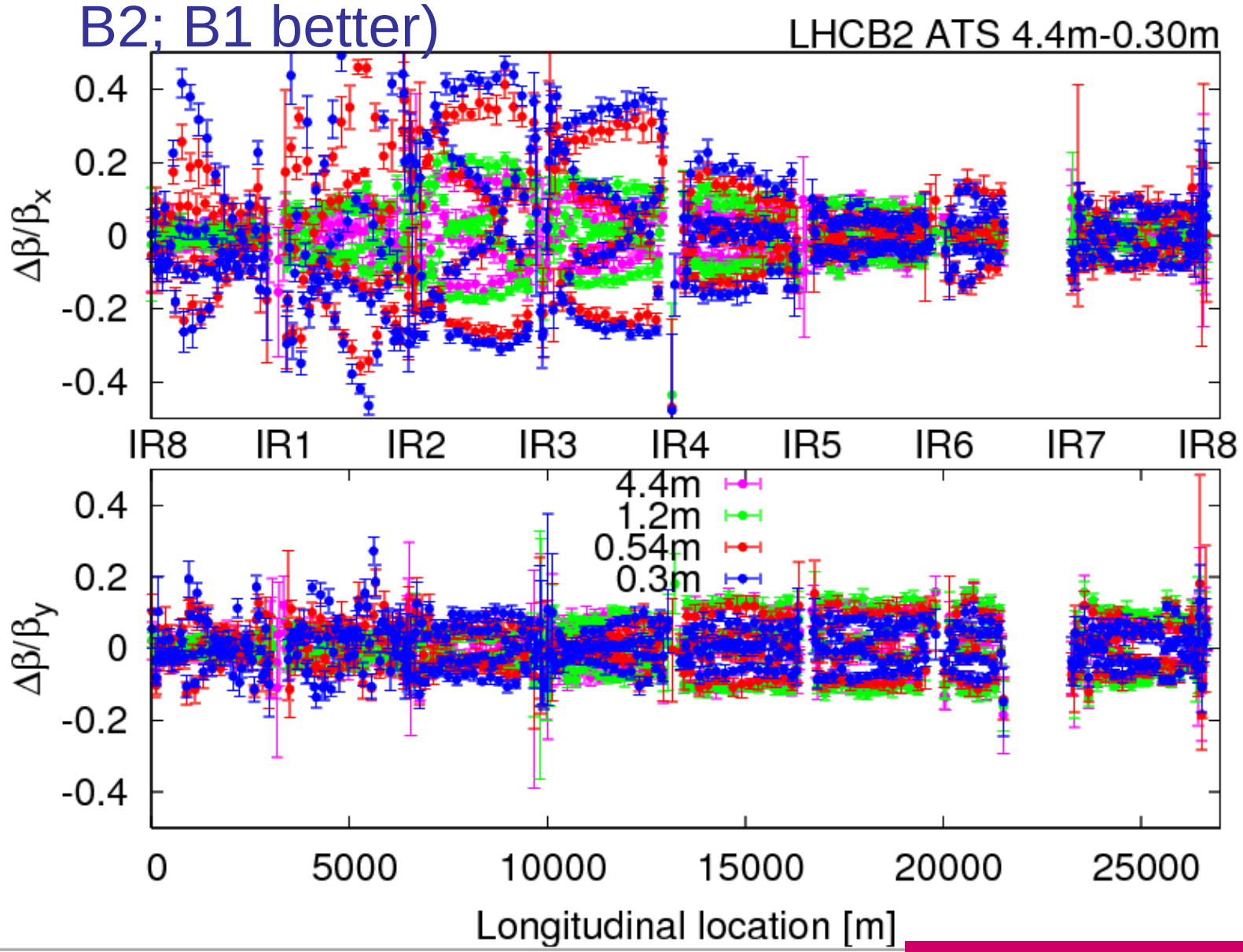
Courtesy S. Fartoukh

ATS: 30 cm β* in IP1: Measured β_y



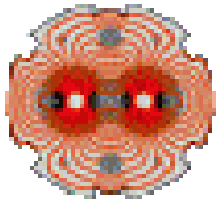
Courtesy S. Fartoukh

ATS: Meas. Beta Beat Err (here B2; B1 better)



Courtesy S. Fartoukh

LHC upgrade: parameter space (tentative)



- Optics:

Efforts on LHC

  - ATS is the most promising candidate.
  - β^* is in the range of 15 cm, with the possibility of decreasing to 7.5 in one plane (flat beams).
  - Magnet R&D on-going to provide the required performance.
  - Leveling is mandatory and many options at hand.
- Beam:

Efforts on injectors

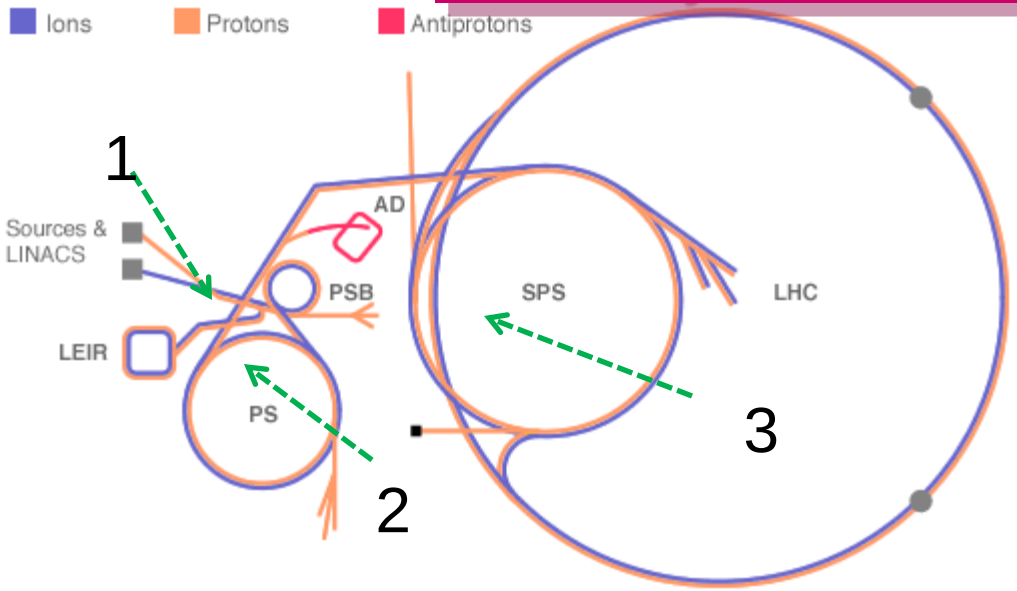
  - Both 25 ns and 50 ns spacing should be available.
  - Bunch intensities around $2\text{-}3\times10^{11}$ depending on bunch spacing (25 ns or 50 ns).
  - Emittance around 2 μm or 3.75 μm depending on bunch spacing (25 ns or 50 ns).

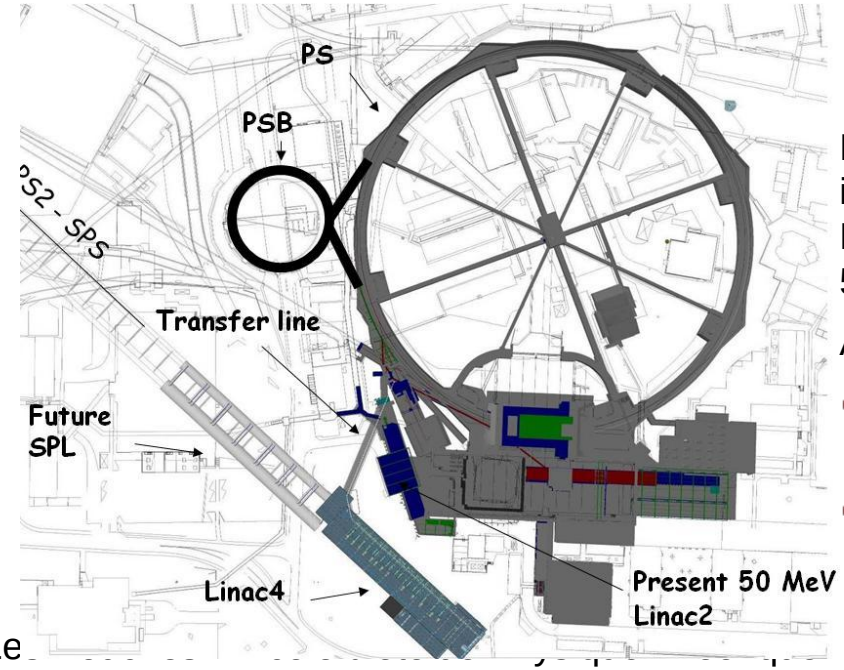
Upgrade of the injectors

Courtesy M. Vretenar

Three bottlenecks identified for higher intensity and/or brightness from the LHC injectors:

1. Space charge tune shift at PSB injection (50 MeV).
2. Space charge tune shift at PS injection (1.4 GeV).
3. Electron cloud and other





Low injection energy into the PSB is the first and most important bottleneck →
Decision (2007) to build a new linac (Linac4) to increase from 50 to 160 MeV (no space for energy upgrade of Linac2).

After Linac4, new program (2010):

- Upgrade of PSB final energy to 2 GeV. (or Rapid Cycling Synchrotron)
- Upgrade (coating, new RF) of SPS. Instabilities control.

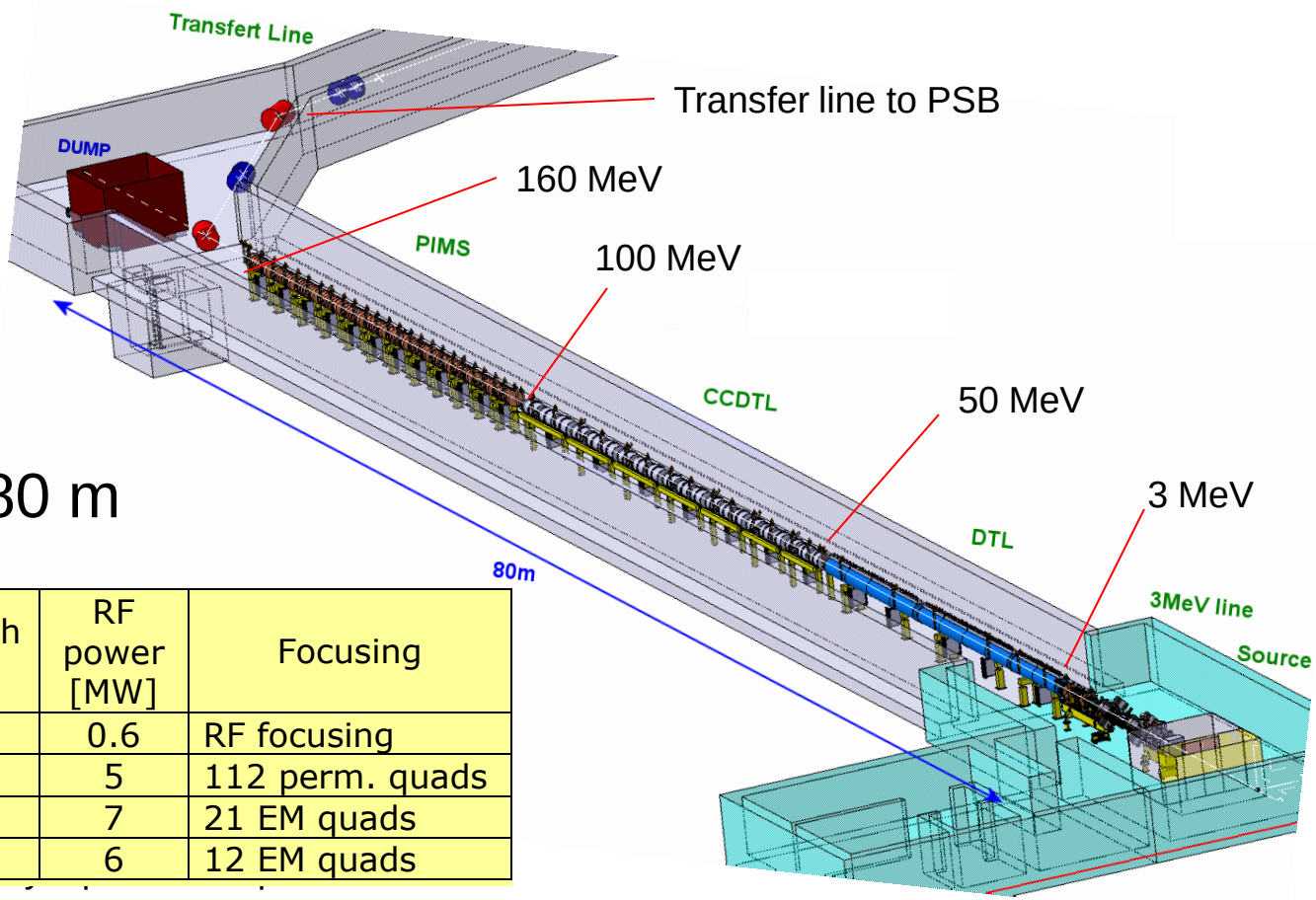
Linac4 description

Courtesy M. Vretenar

- Conventional (normal-conducting) layout:

1. Pre-injector (source, magnetic LEBT, 3 MeV RFQ, chopper line)
2. Three types of accelerating structures, all at 352 MHz.
3. Beam dump at linac end, switching magnet towards transfer line – PSB.

From 50 MeV to 160 MeV: a gain of a factor two in space charge tune shift

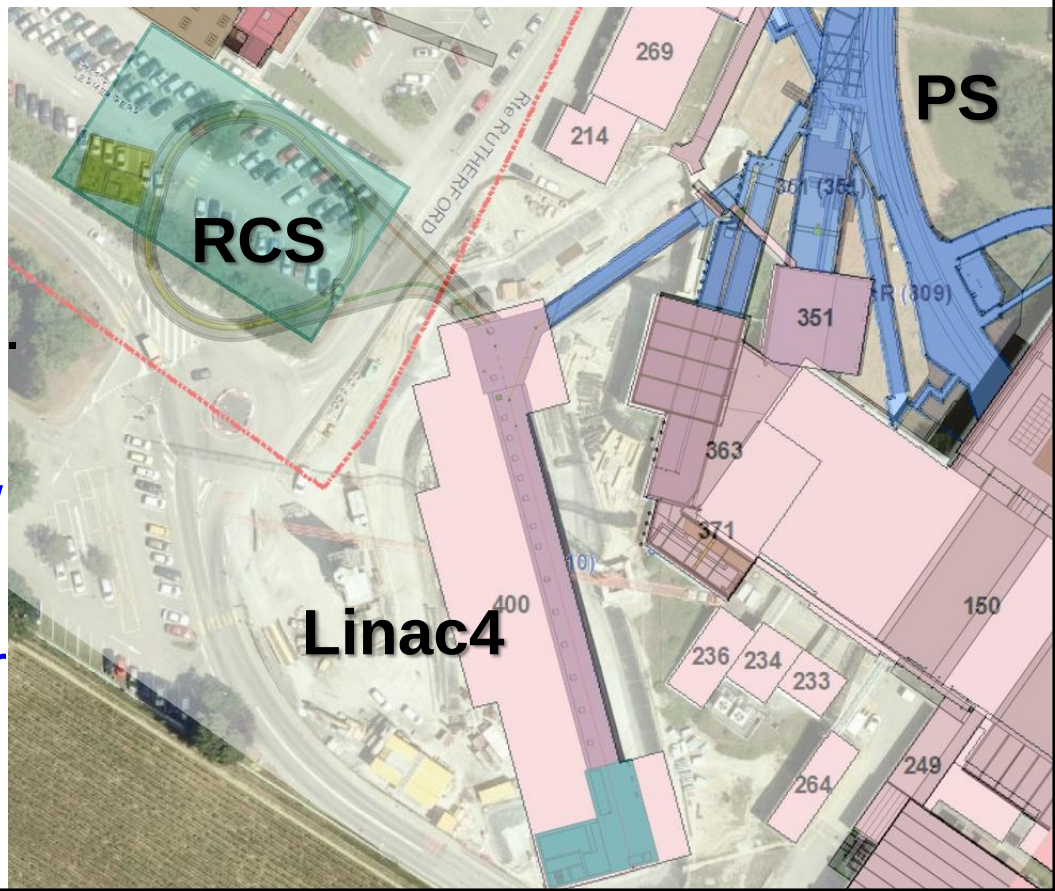


Linac length ~ 80 m

	Energy [MeV]	Length [m]	RF power [MW]	Focusing
RFQ	0.045 – 3	3	0.6	RF focusing
DTL	3 – 50	19	5	112 perm. quads
CCDTL	50 – 102	25	7	21 EM quads
PIMS	102 – 160	22	6	12 EM quads

PSB upgrade

- Injection: to be adapted to the new Linac4 energy and new particle type (from protons to H-).
- To overcome the space charge limit at PS injection -> increase the extraction energy from 1.4 GeV to 2 GeV. This could open the possibility of generating LHC bunches of ~ 2.7×10^{11} (nom. 1.15×10^{11}).
- Good news: there is margin in the PSB magnets to allow for such an upgrade!
- An RCS option is also under consideration.



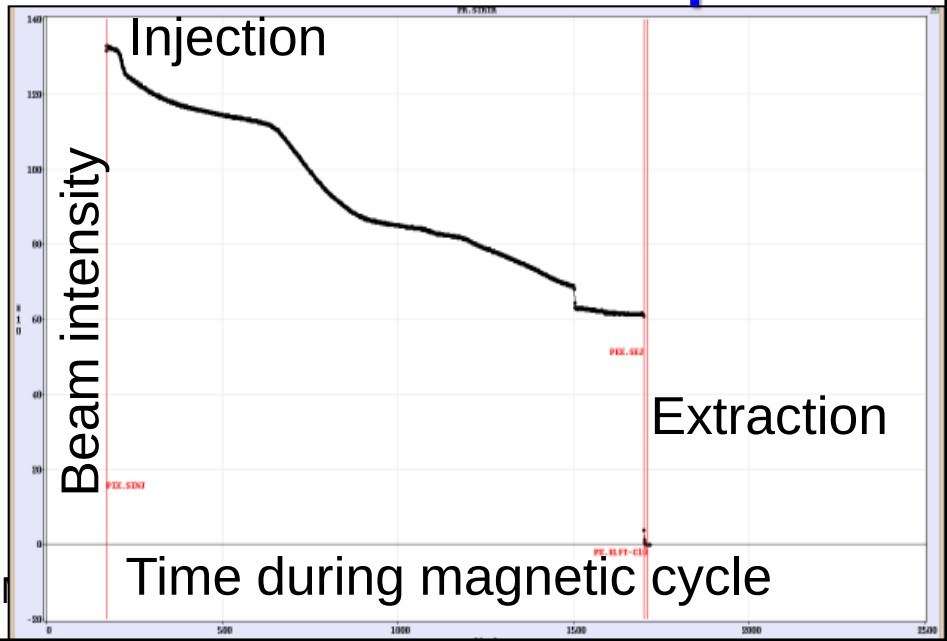
MD studies in the injectors

- The hot topic is the assessment of the actual performance limits in the PSB, PS, and SPS.
- Specifically, the space charge limits (e.g., maximum tune shift tolerable for a given emittance blow up) should be measured in detail.
- The starting point is probing the strength and harmfulness of resonances in a regime not dominated by space charge.
  - The excited resonances could then interact with space charge to spoil the beam quality.
  - This might require to implement schemes to compensate sone resonances.

Technique and results - I

- Beam
  - Low intensity -> similar to a single-particle case, no space charge
  - Large transverse emittance -> it almost fills the vacuum chamber, very sensitive to any emittance growth
- The tune space is scanned (one tune is kept constant and the other varied)

PS example



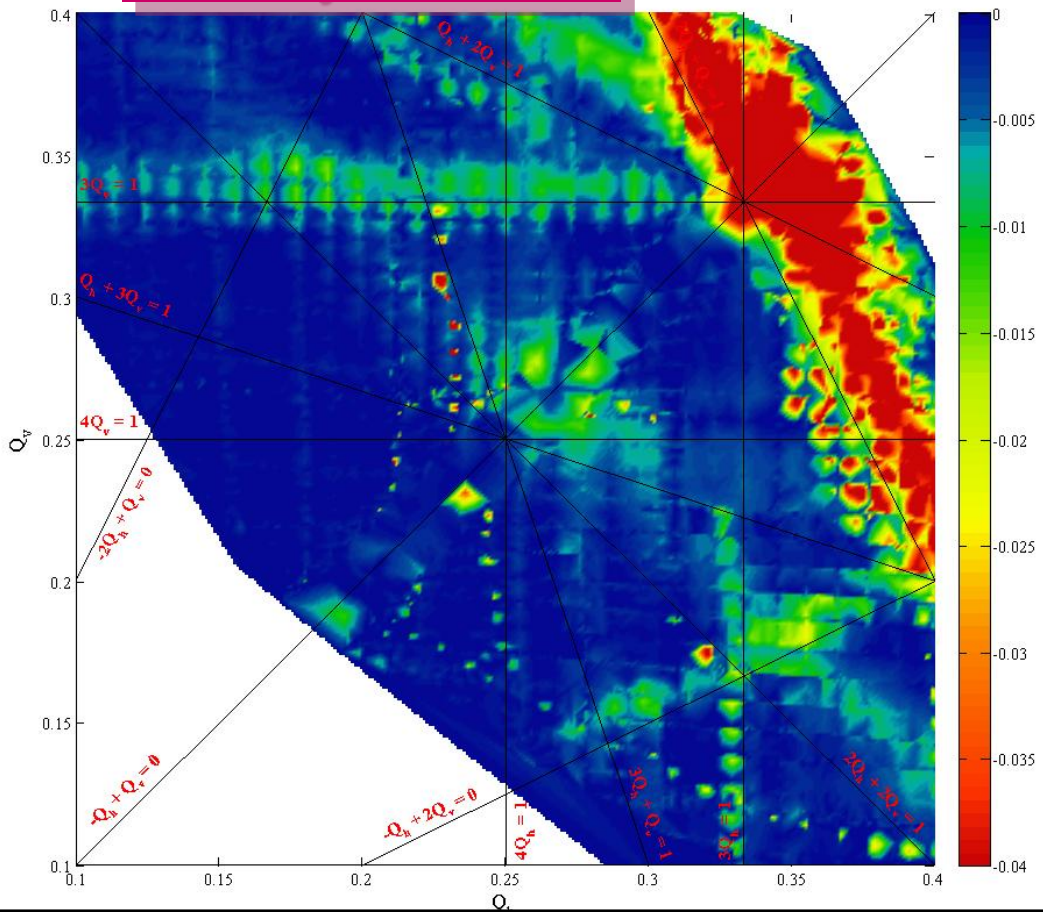
- Energy is kept constant.
- The losses occur when a resonance is crossed.
- The derivative of the losses is proportional to the resonance strength.

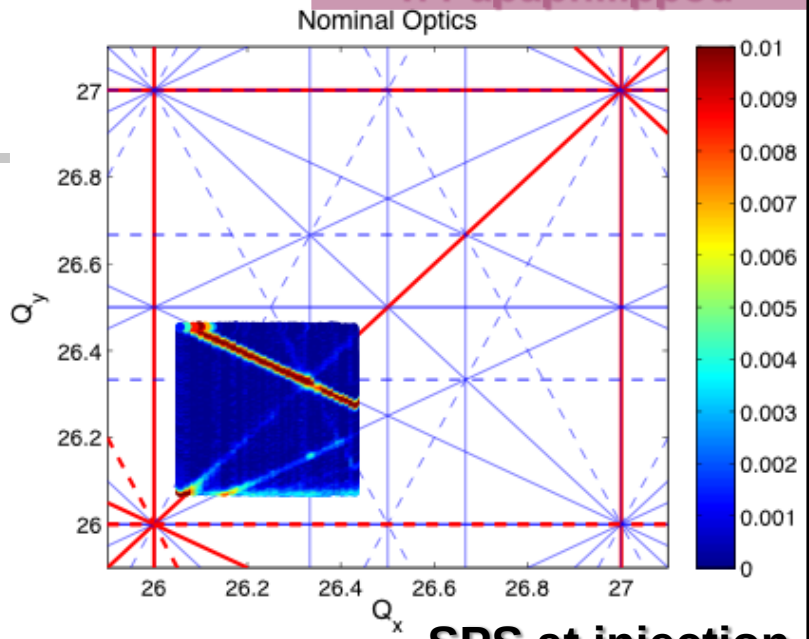
Technique and results - II

Courtesy H. Bartosik, Y. Papaphilippou

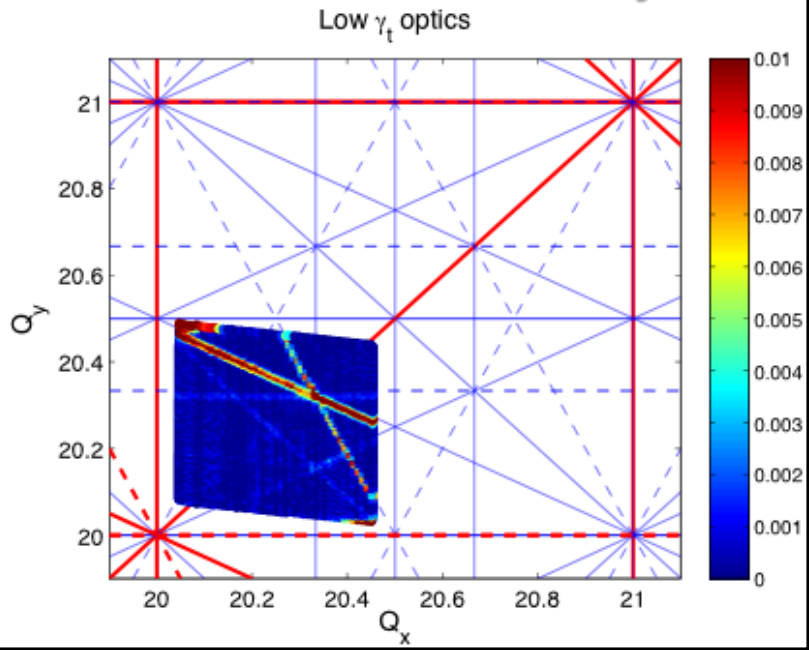
PS at 2 GeV (new injection energy)

Courtesy E. Benedetto





SPS at injection



High Energy-LHC

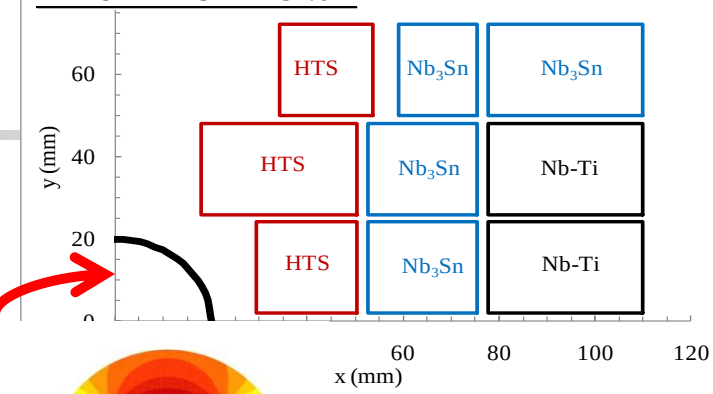
BE-EN-TE working group since April 2010

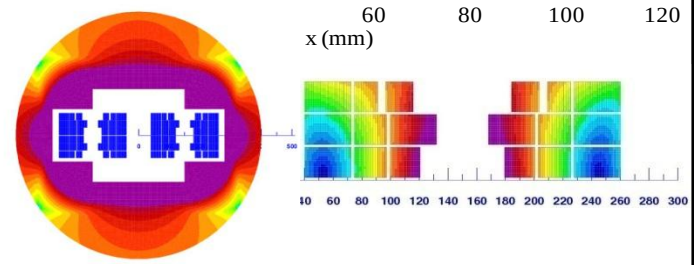
EuCARD AccNet workshop HE-LHC'10 ,

14-16 October 2010

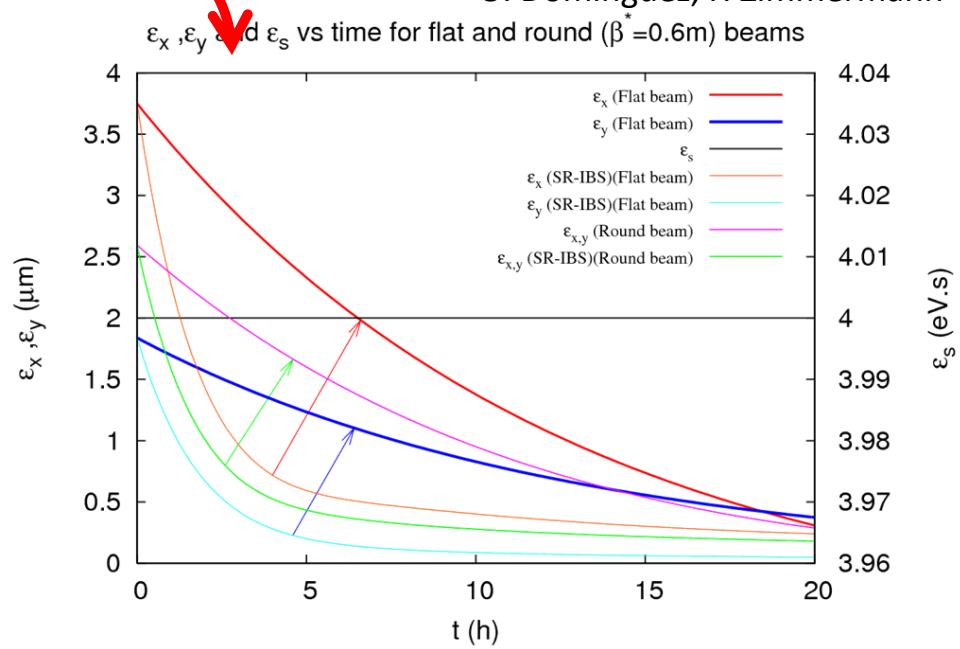
	Turns	%
Nb-Ti	40	28%
Nb_3Sn	58	41%
HTS	45	31%

E. Todesco





O. Dominguez, F. Zimmermann



key topics

beam energy 16.5 TeV; 20-T magnets

cryogenics: **synchrotron-radiation heat load**

radiation damping & emittance control

vacuum system: synchrotron radiation

new injector: energy > 1 TeV

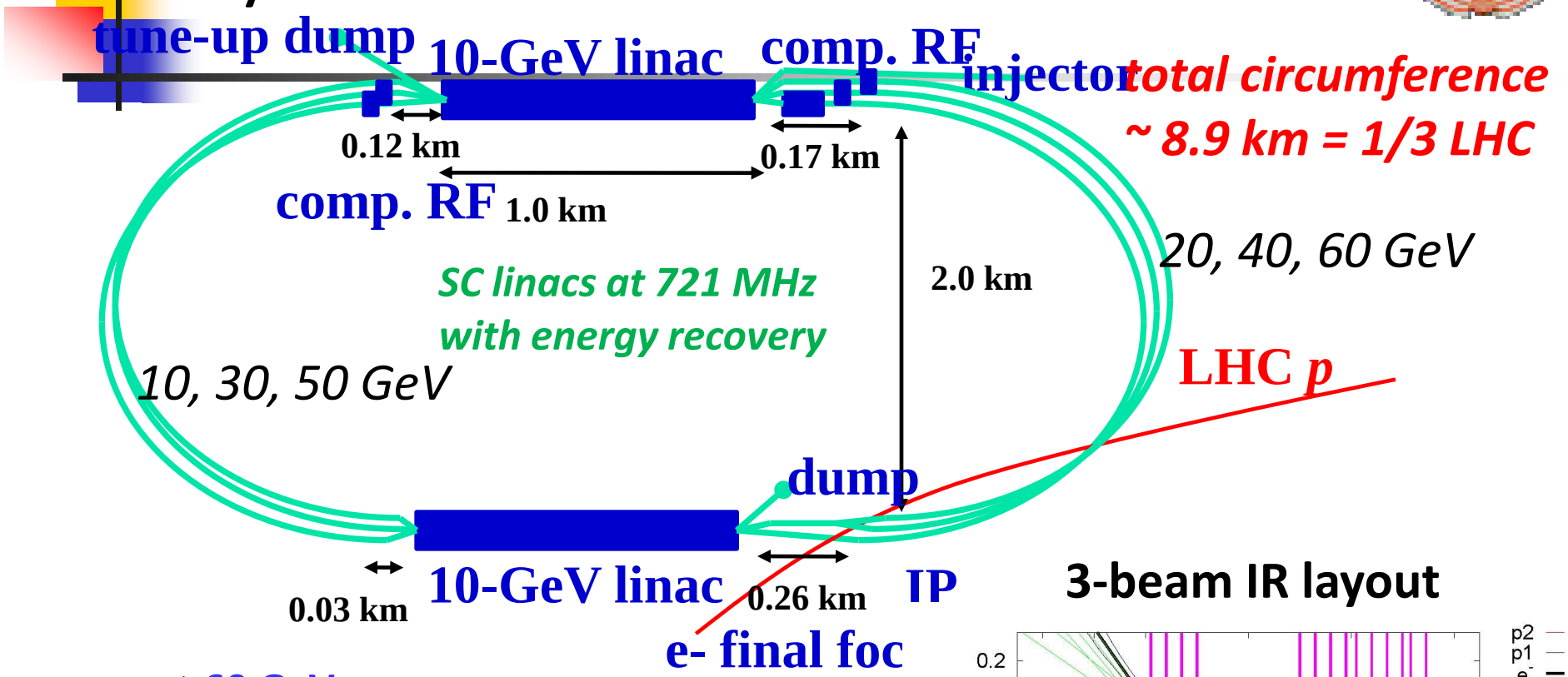
parameters

	LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
#bunches	2808	1404
IP beta function [m]	0.55	1 (x), 0.43 (y)
number of IPs	3	2
beam current [A]	0.584	0.328
SR power per ring [kW]	3.6	65.7
arc SR heat load dW/ds [W/m/ap]	0.21	2.8
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	2.0
events per crossing	19	76

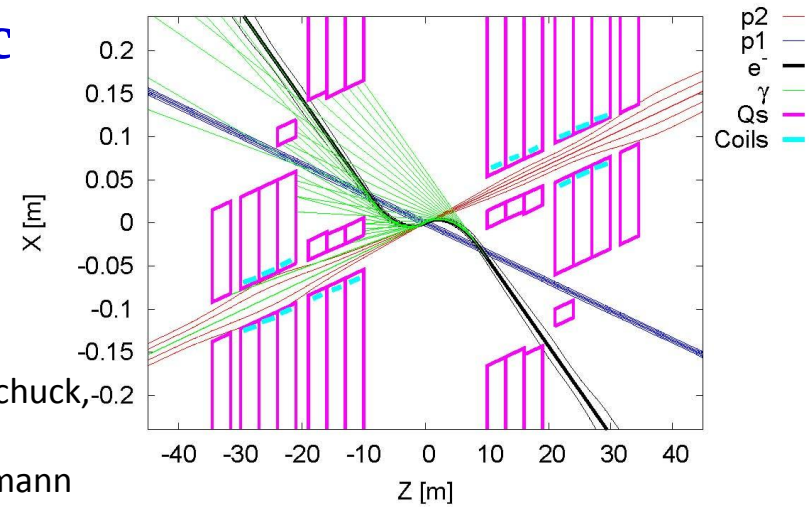
Linac-Ring LHeC

O. Brüning, M. Klein, D. Schulte, R. Tomas, F. Zimmermann, et al

overall layout



3-beam IR layout



S. Russenschuck,
R. Tomas,
F. Zimmermann

e- energy ≥60 GeV

luminosity ~10^{33} $cm^{-2}s^{-1}$

total electrical power for e-: ≤100 MW

e^+p collisions with similar luminosity?

simultaneous with LHC *pp* physics

e^-/e^+ polarization

detector acceptance down to 1°