(1)Modified Collimation Layout & Optics (2) Performance Limits for Ion Beams

John Jowett (CERN, Beams Dept.)

With thanks for contributions from:

Ralph Assmann, Giulia Bellodi, Roderik Bruce, Thomas Weiler

Plan of talk

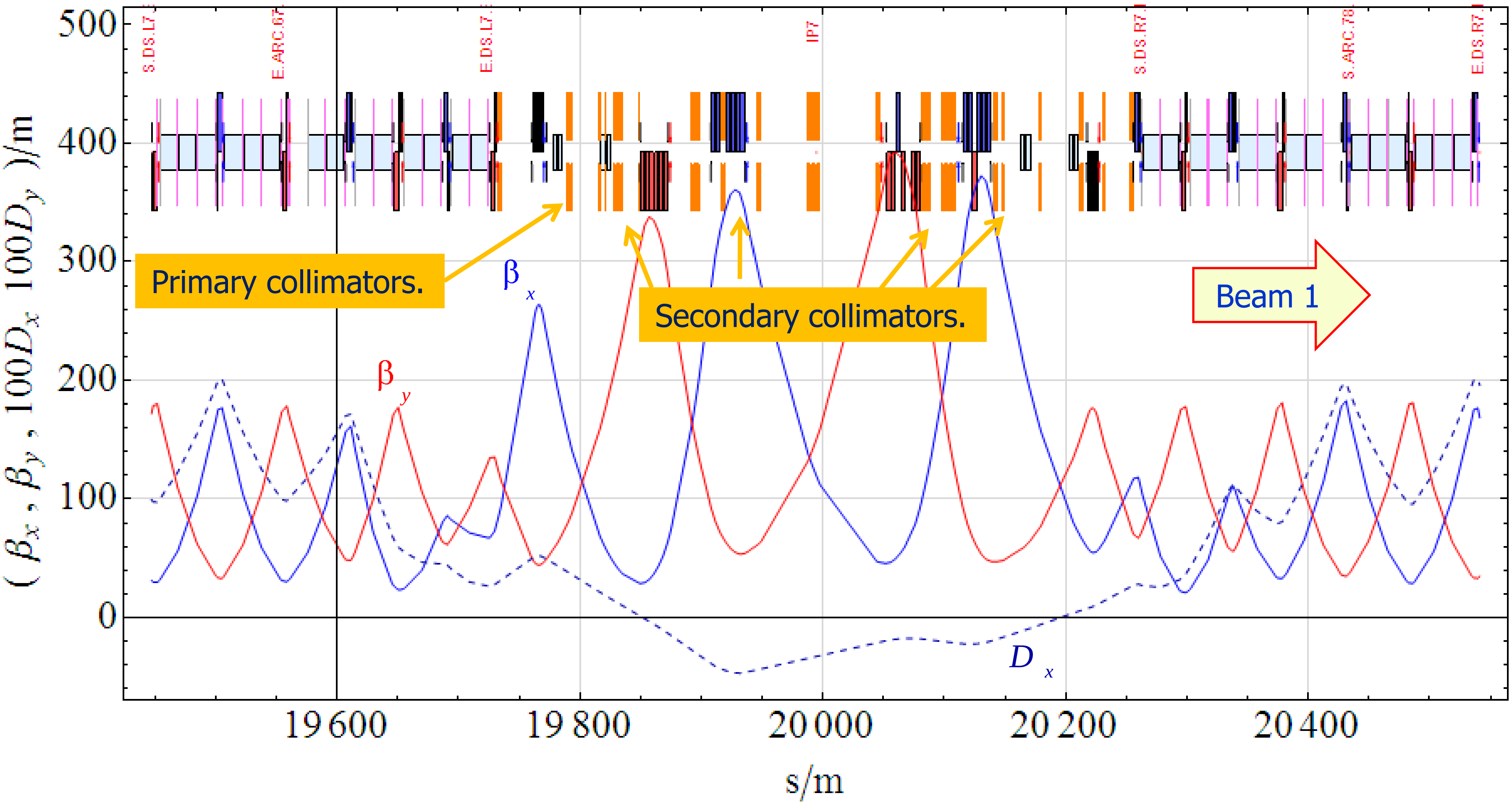
- (1)
  - Modified layout of IR7 for cryo-collimators
  - Rematch of IR7 optics
  - Collimation problem for ion beams
- (2)
  - Performance limits with heavy ion beams
  - Reference to Executive Summary on ion collimation
  - BFPP Luminosity limit for ion beams
  - Cryo-collimators in IR2 for ALICE experiment
  - Further possible installations
- Conclusions

(1)Modified Collimation Layout & Optics (for cryogenic collimators)

LHC Collimation Insertions

- IR7: Betatron collimation insertion
  - Treat changes for installation of cryogenic collimators
  - Effects in later talks (T. Weiler, G. Bellodi)
- IR3: Momentum collimation insertion
  - Similar layout, different optics
  - Expect to install cryogenic collimators there too but details not treated yet
- For further details:
  - All layout and optics plots shown in this talk, plus more, are available at http://cern.ch/jowett/Talks/2009-04-02 in a form where you can mouse-over to see details of elements names etc.

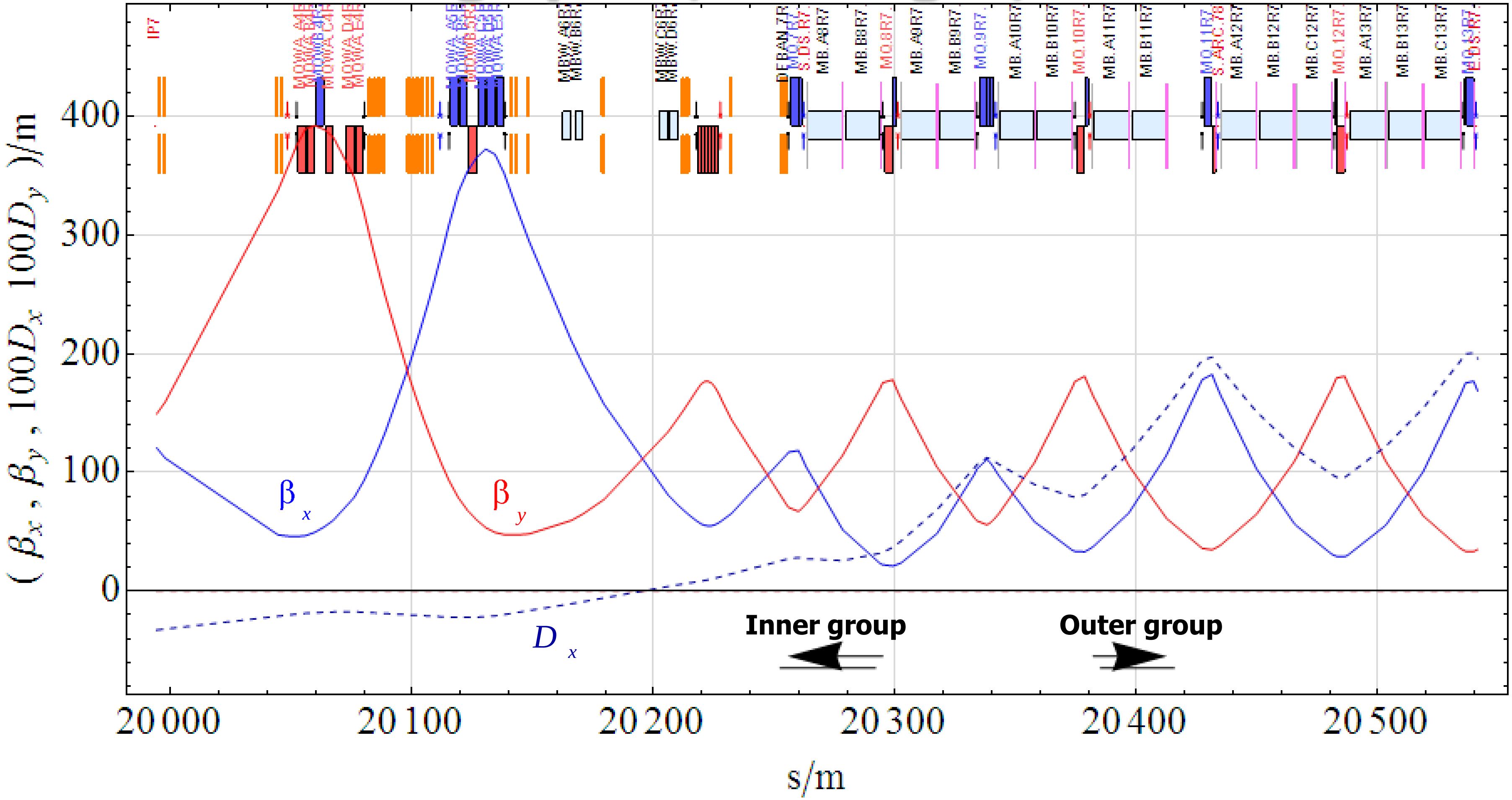
IR7 Optics overview, Beam 1



Beam 2 has F and D quads inverted, but imperfect (left-right, *x-y*) asymmetry, so has to be treated separately.

IR7 optics is **constant** – no change with energy, β-squeeze, etc.

Making space, IR7 right, Beam 1

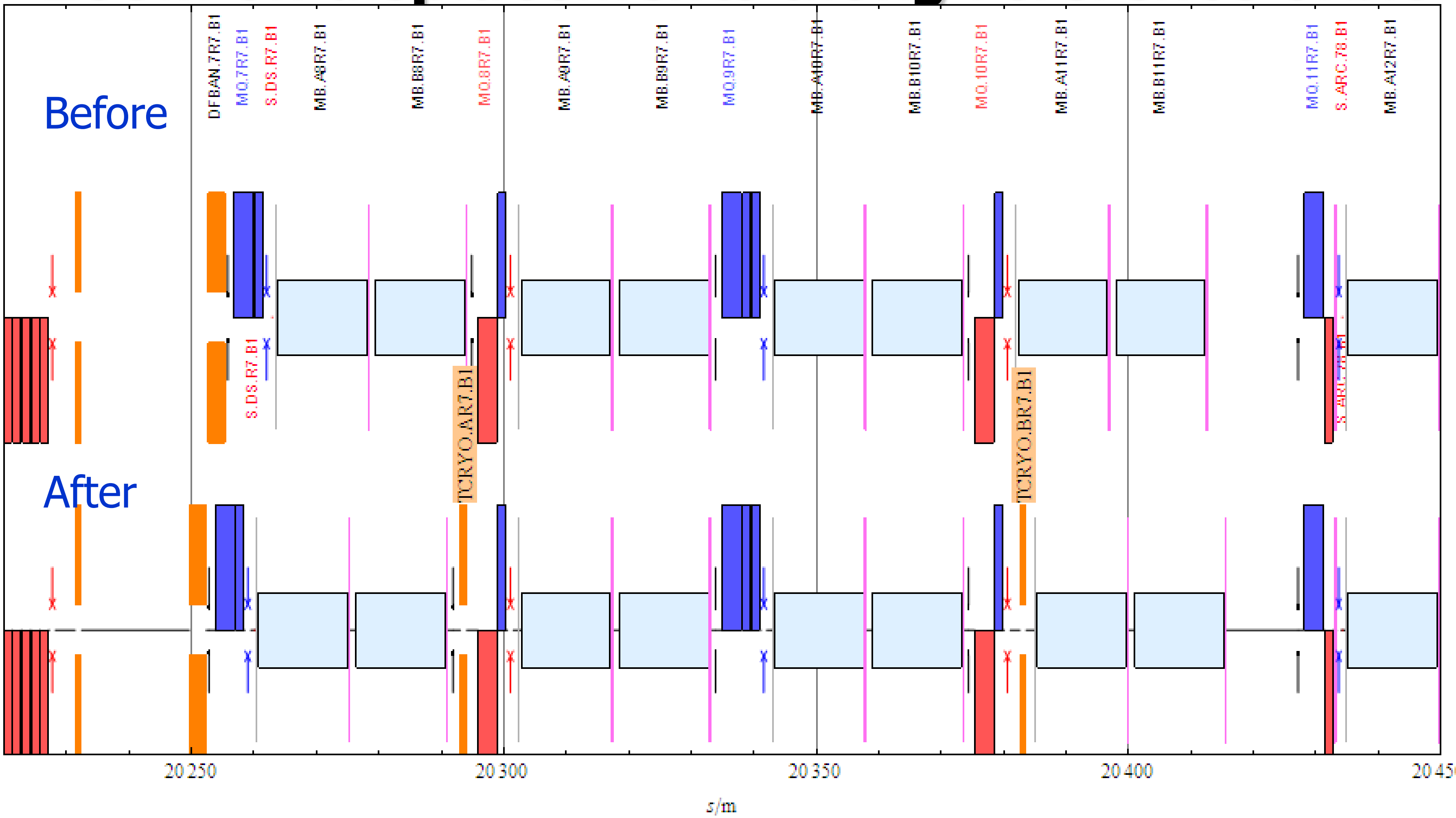


Move outer group of elements 3 m away from IP into missing dipole space.

Move inner group of elements 3 m towards IP to (roughly) compensate change in geometry.

Similarly on right of IP7.

Zoom on displacements along reference orbit



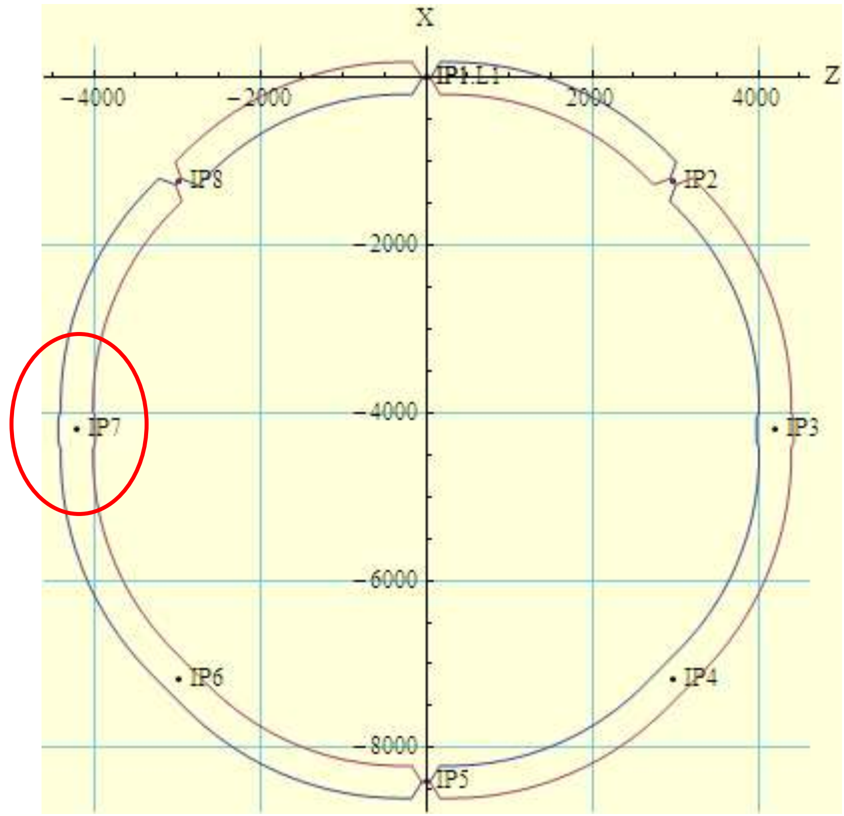
This vacates enough space in the right places to install the cryogenic collimators.

N.B. this is in Courant-Snyder coordinate *s*, so we do not see the change in geometry of the LHC.

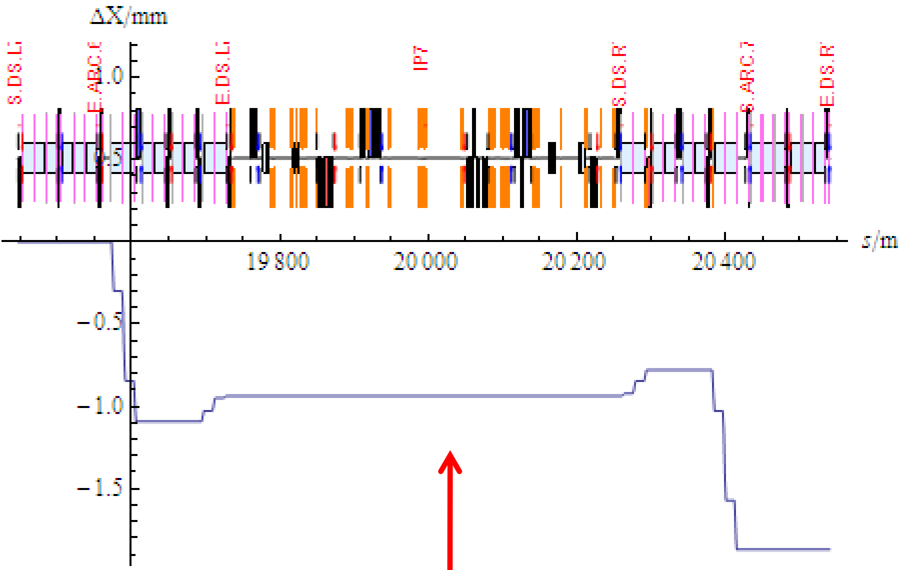
Global Cartesian Coordinate System

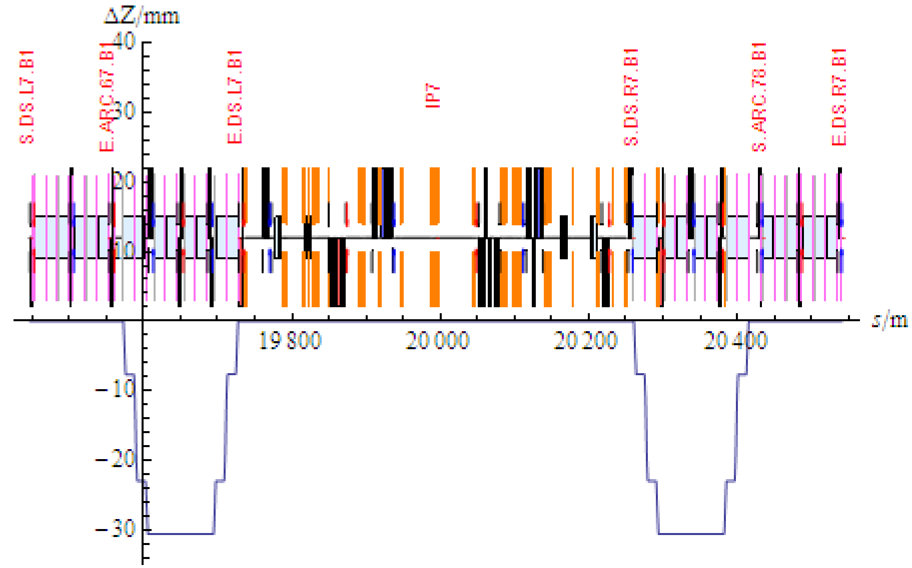
- Global coordinates, in the straight part of the betatron collimation insertion section around IR7:
  - *X* is longitudinal
  - *Y* is vertical
  - *Z* is radial

  w.r.t. Courant-Snyder coordinates.
- Use (*Z*,*X*) as coordinates in the machine plane

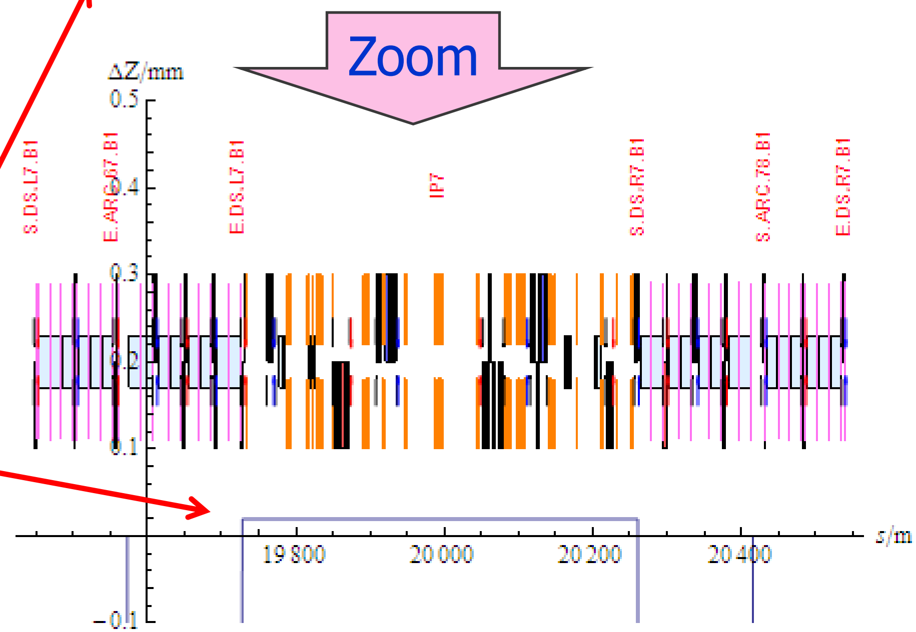


Displacements of reference orbit, Beam 1





Longitudinal displacement mainly reflects change in length of reference orbit – can be fixed.



Radial displacement of reference orbit between shifted sections by 30 mm. N.B. Not the displacement of elements!

Radial displacement of IP7 and straight section due to non-commutativity of rotations and translations is small enough (0.019 mm) to neglect.

Displacements of moved elements, Beam 1, left of IP7

In the global cartesian frame, the displacements of the outer and inner groups of elements include a component from the angle ("curvature") of the initial reference orbit.

MAD - and the LHC Layout Database - use the "beads on a necklace" method of laying out the machine so everything downstream of IR7 moves and the ring does not close … this is not real of course but has to be corrected in our description.

Outer group

	ΔZ/m	ΔX/m
MCO.11L7.B1	0.1224	-2.998
MCD.11L7.B1	0.1224	-2.998
MB.B11L7.B1	0.1224	-2.998
MCS.B11L7.B1	0.1224	-2.998
MB.A11L7.B1	0.1224	-2.998
MCS.A11L7.B1	0.1224	-2.998

Inner group

	ΔZ/m	ΔX/m
MCO.8L7.B1	-0.00001910	3.001
MCD.8L7.B1	-0.00001910	3.001
MB.B8L7.B1	-0.00001910	3.001
MCS.B8L7.B1	-0.00001910	3.001
MB.A8L7.B1	-0.00001910	3.001
MCS.A8L7.B1	-0.00001910	3.001
E.DS.L7.B1	-0.00001910	3.001
BPM.7L7.B1	-0.00001910	3.001
MQ.7L7.B1	-0.00001910	3.001
MQTLI.7L7.B1	-0.00001910	3.001
MCBCV.7L7.B1	-0.00001910	3.001
DFBAM.7L7.B1	-0.00001910	3.001

	ΔZ/m	ΔX/m
IP1	0	0
IP2	0	0
IP3	0	0
IP4	0	0
IP5	0	0
IP6	0	0
IP7	-0.00001910	0.0009361
IP8	0	0.001872
IP1.L1	0	0.001872

Corrected layout

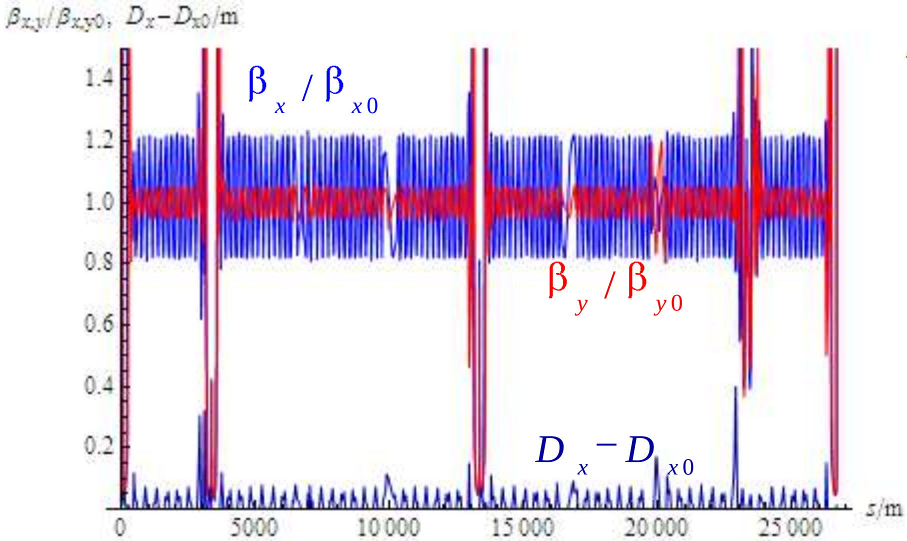
Small negative displacements of all elements downstream of IR7 along the reference orbit restores them to their original position in the global cartesian system and closes the ring.

New sequence descriptions created for both rings.

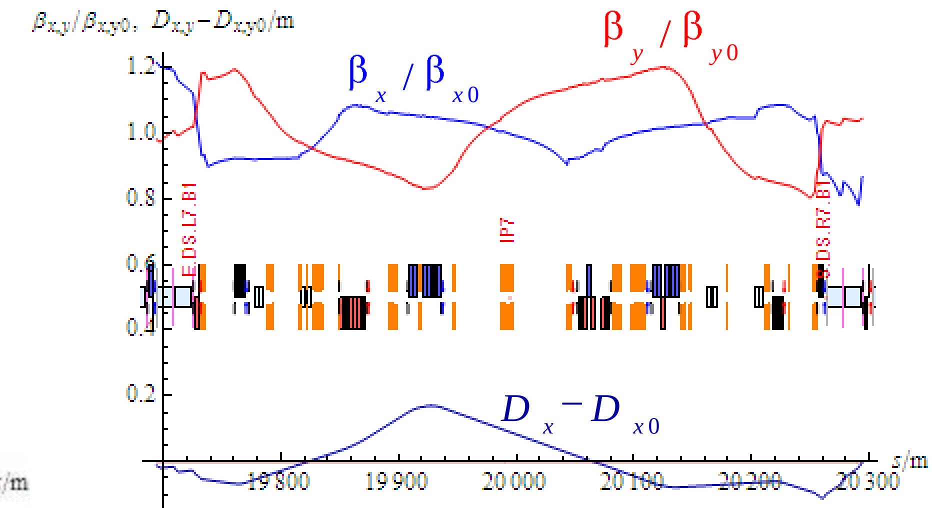
	$\Delta Z/\mathrm{m}$	$\Delta X/\mathrm{m}$
IP1	0	0
IP2	0	0
IP3	0	0
IP4	0	0
IP5	0	0
IP6	0	0
IP7	-0.00001910	0
IP8	0	4.183×10^{-10}
IP1.L1	0	4.184×10^{-10}

LHC circumference is changed by -1.872 mm.

Optical perturbations



β-beating in whole Ring 1

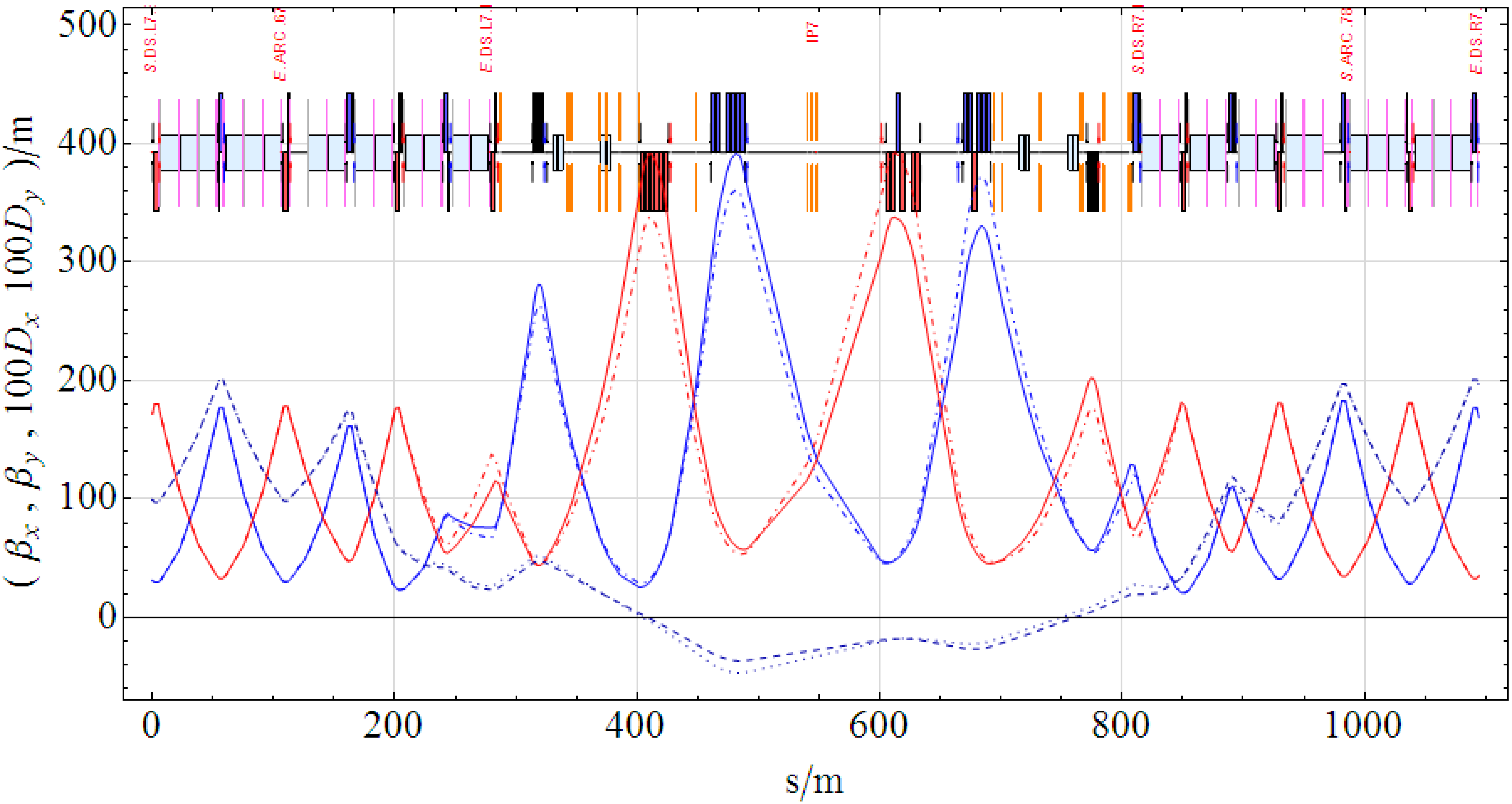


β-beating in IR7, Ring 1

Change in layout perturbs the optical functions, giving about 20% β-beating which must be corrected.

Rematch IR7 for each ring without using the common quadrupoles that affect both.

Rematch of IR7, Beam 1

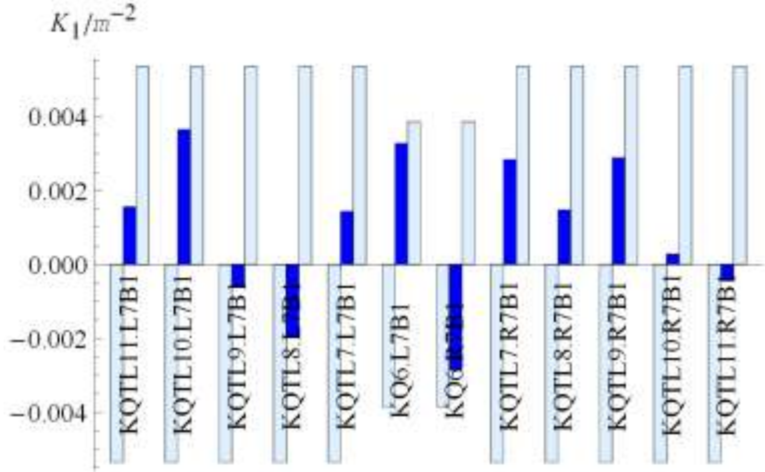


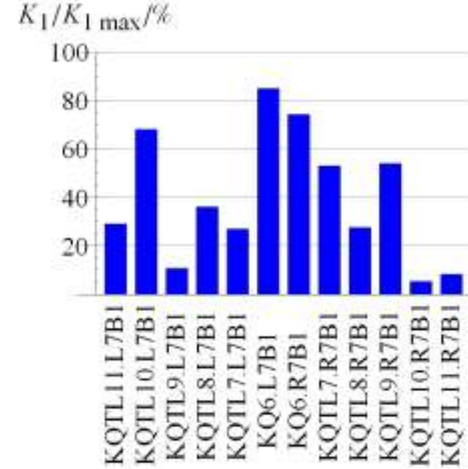
Perfect match – same transfer matrix over IR7 - (also for Ring 2) so can be used in modular way with all existing LHC optics configurations.

Adjusted β-function peaks so available aperture is not changed significantly.

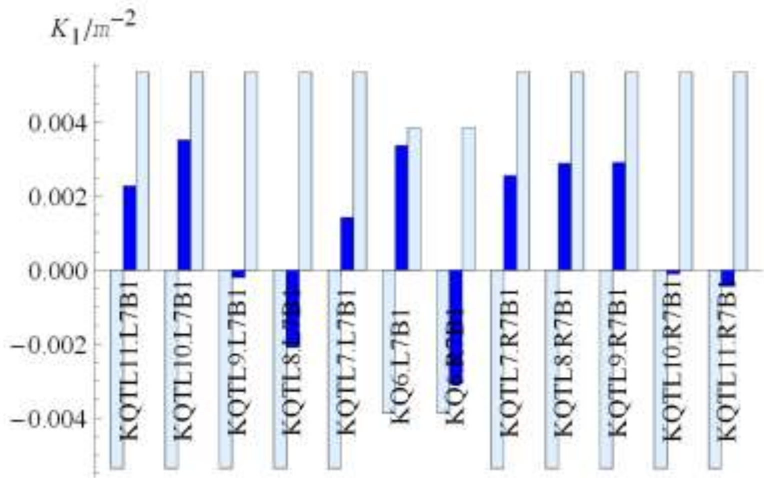
Quadrupole strengths before/after rematch

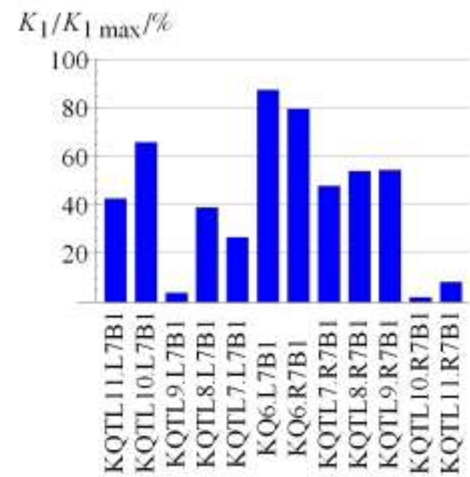
Before:





After:

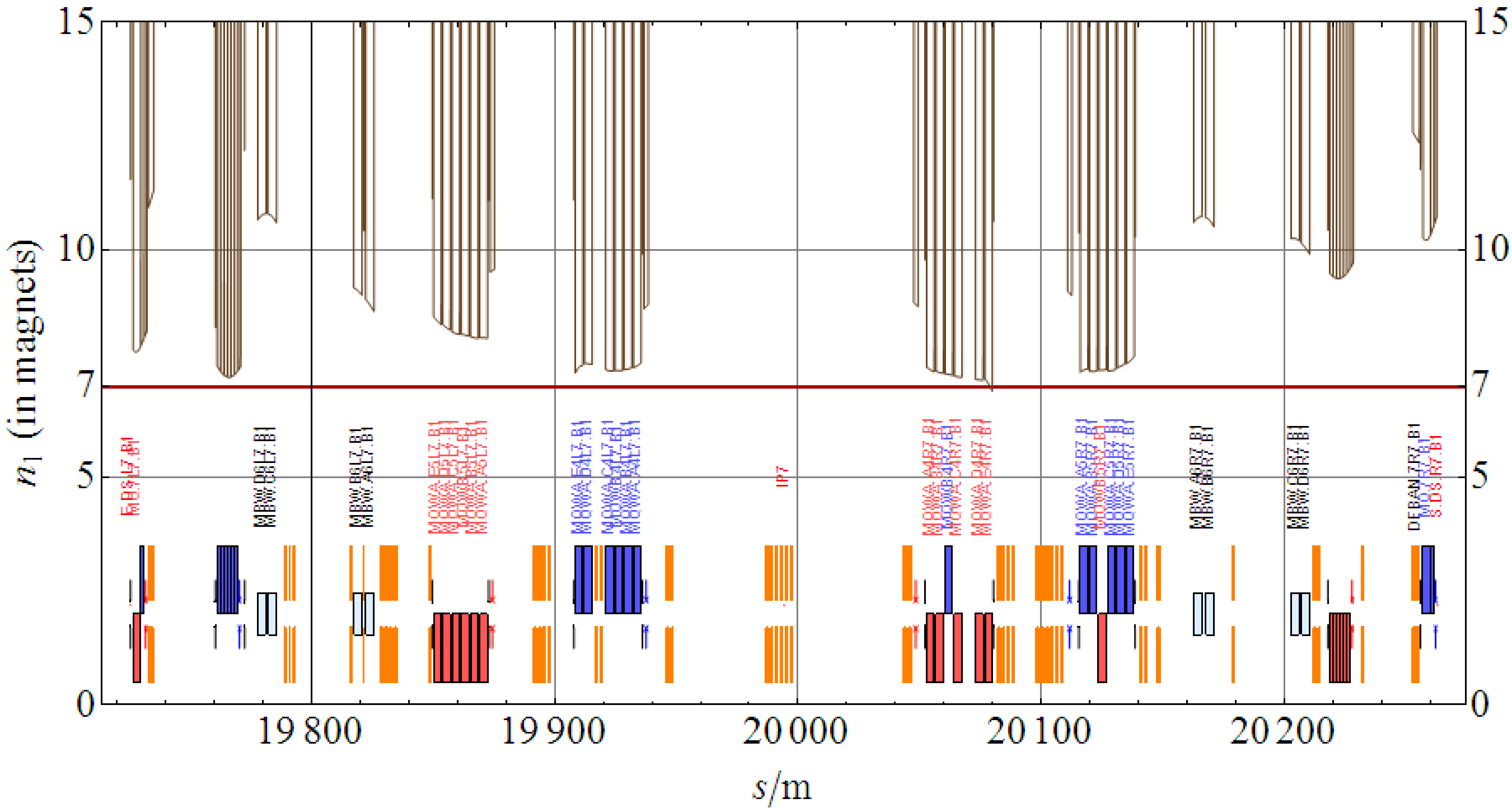




Before and after matching the strengths used for Beam 1.

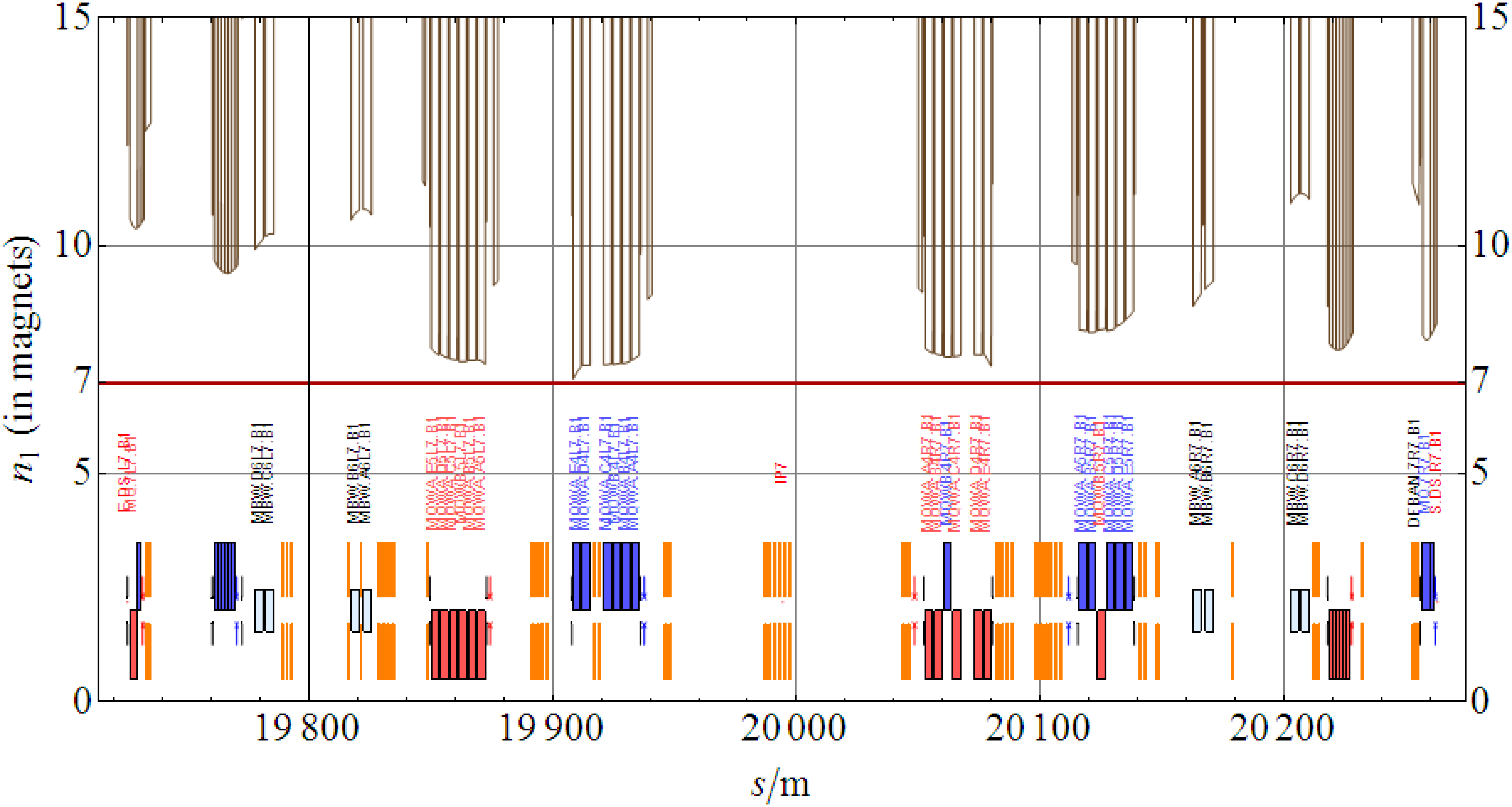
Light blue bars on left hand side plots are the maximum strengths available at 7 TeV.

Aperture of nominal IR7, Beam 1 at injection



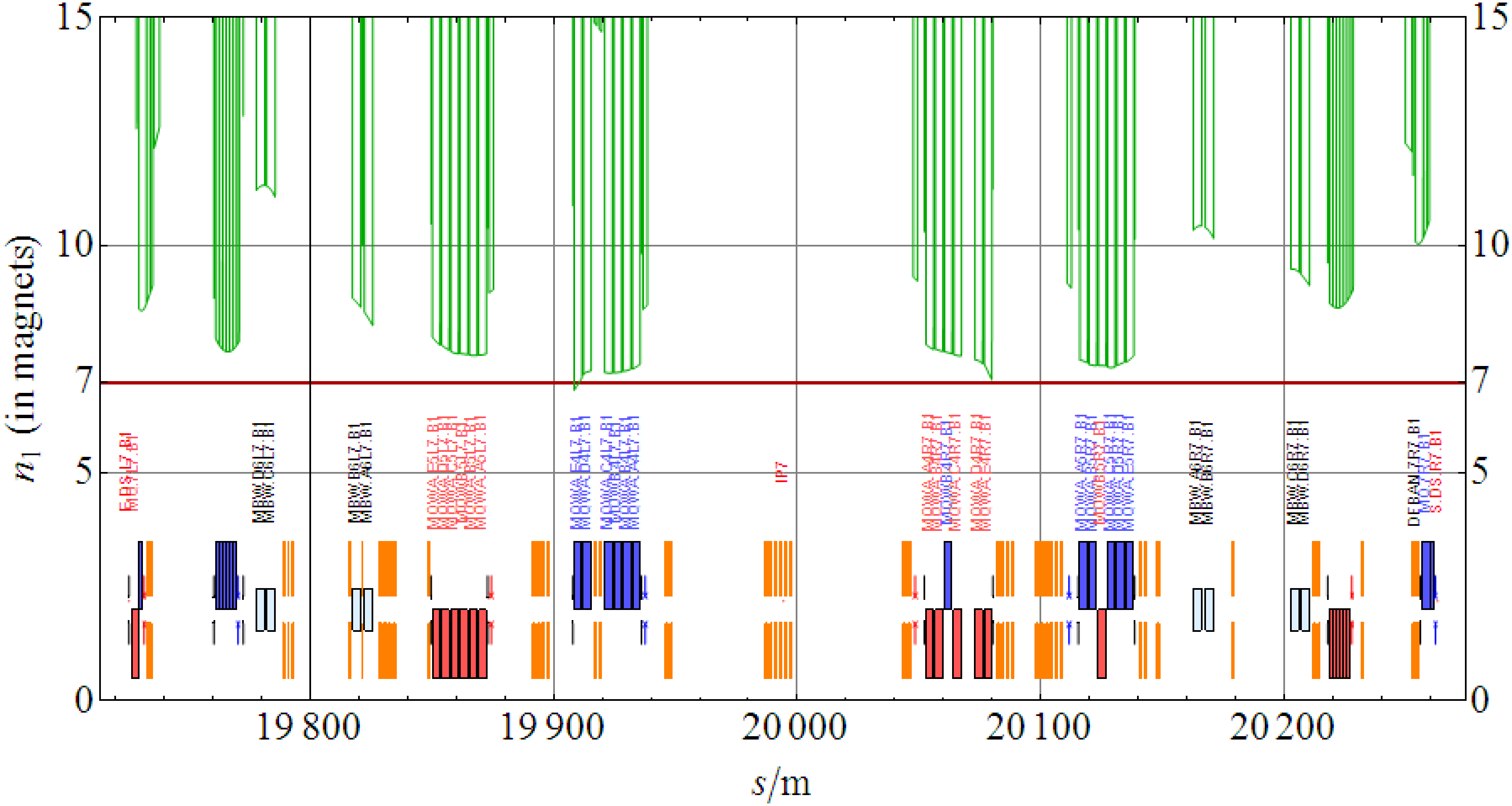
(n_1 is a quantity conventionally used to assess aperture available to beams in the LHC. It includes *x* and *y* planes and various “tolerances” in a single number according to a recipe coded in MAD.
Normally require $n_1 > 7$.)

Aperture of nominal IR7, Beam 2 at injection



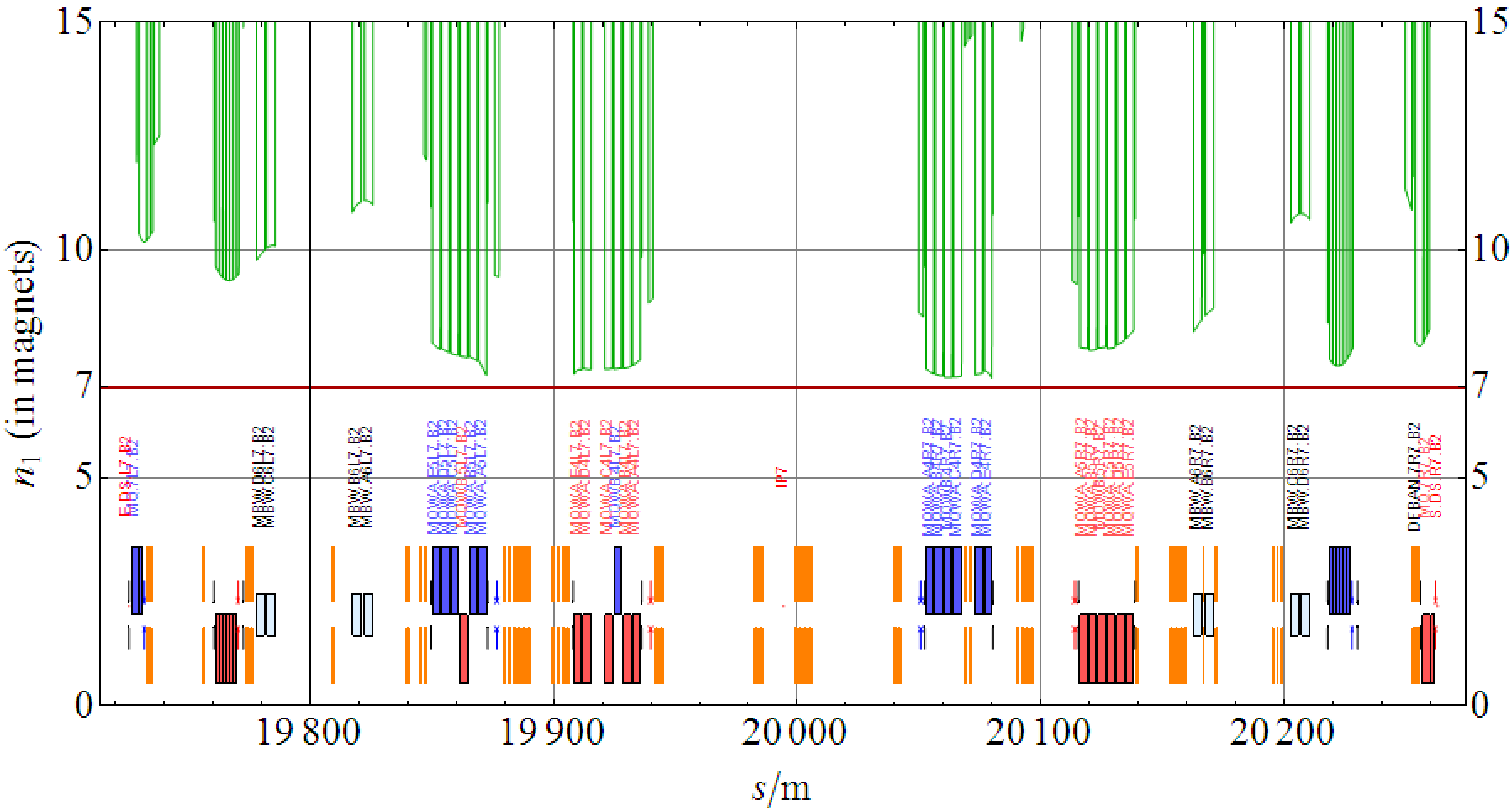
Somewhat different from reflected Beam 1

Cryo-collimator optics IR7, Beam 1 at injection



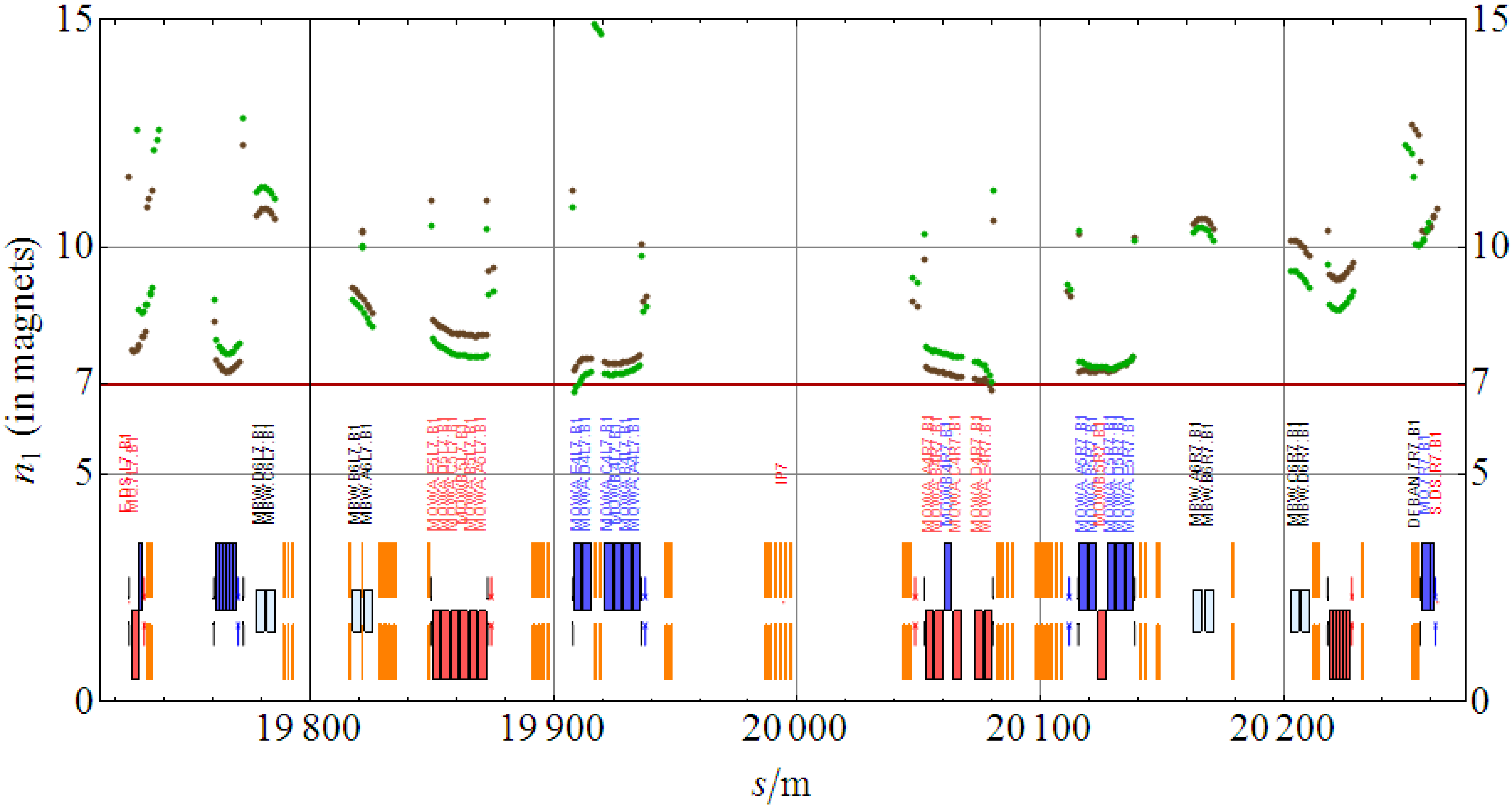
n_1 of the cryo-collimator optics is different

Cryo-collimator optics IR7, Beam 2 at injection

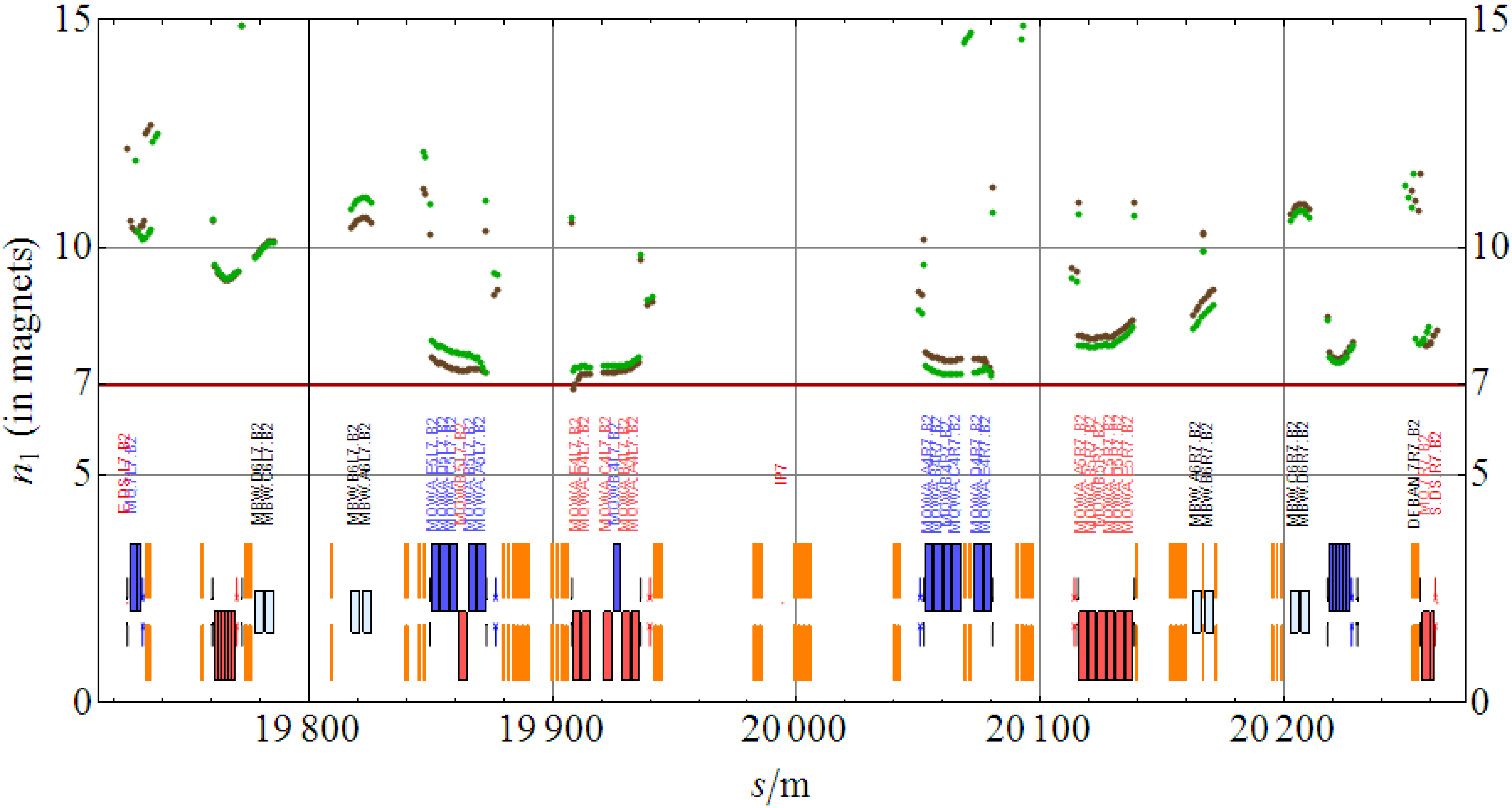


n_1 of the cryo-collimator optics is different

n_1 before and after, Ring 1, IR7



n_1 before and after, Ring 2, IR7



min n_1 in IR7	Ring 1	Ring 2
Optics V6.503	6.84	6.91
Cryo-collimator optics	6.83	7.19

(2) Performance of LHC with Heavy Ion Beams

Design parameters with $^{208}Pb^{82+}$ nuclear beams

- The LHC will run ~1 month/year with ion beams, initially Pb

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

- Although the stored energy in the Pb beam is much lower than in the proton beam, beam loss mechanisms peculiar to ions may limit luminosity. Most serious are:
  – Collimation inefficiency (different physics from protons)
  – Bound free pair production (BFPP)

Ultraperipheral reactions in nuclear collisions

Magnetic rigidity change in nuclear reaction

$$(Z_0, A_0) \to (Z_1, A_1) \Rightarrow \delta = \frac{Z_0 A_1}{A_0 Z_1} - 1$$

Bound-free pair production(BFPP), $\sigma \approx 280$ b:

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + \underbrace{{}^{208}\mathrm{Pb}^{81+}}_{[\delta=0.012]} + e^{+}$$

Electromagnetic dissociation (EMD), $\sigma \approx 100$ b:

does not form spot on beam pipe

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\mathrm{GDR}} {}^{208}\mathrm{Pb}^{82+} + \underbrace{{}^{207}\mathrm{Pb}^{82+}}_{[\delta=0.048]} + n$$

2-neutron EMD process, $\sigma \approx 29$ b

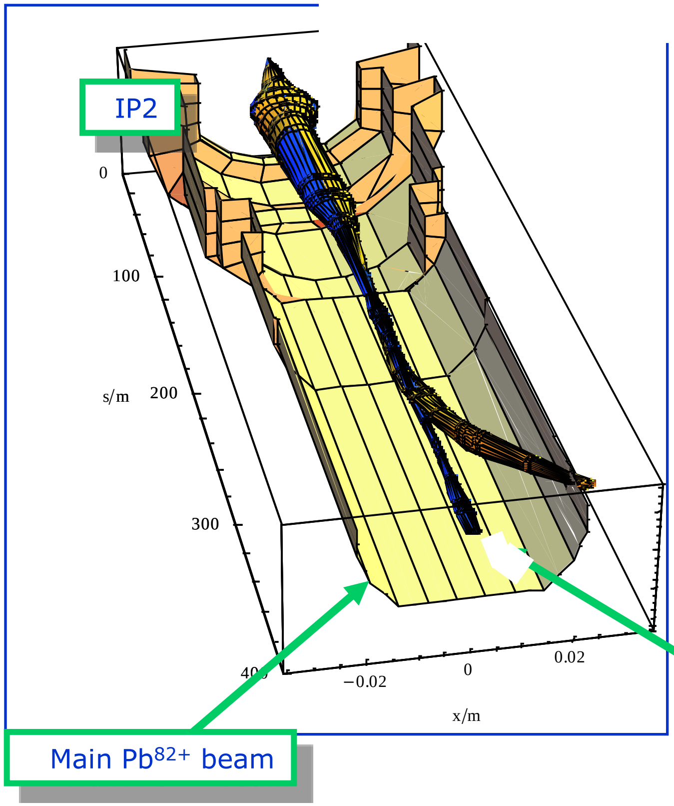
forms spot on other side of pipe from BFPP

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\mathrm{GDR}} {}^{208}\mathrm{Pb}^{82+} + \underbrace{{}^{206}\mathrm{Pb}^{82+}}_{[\delta=-0.0096]} + 2n$$

C.f. hadronic interactions, $\sigma \approx 8$ b

Luminosity Limit from BFPP in collisions

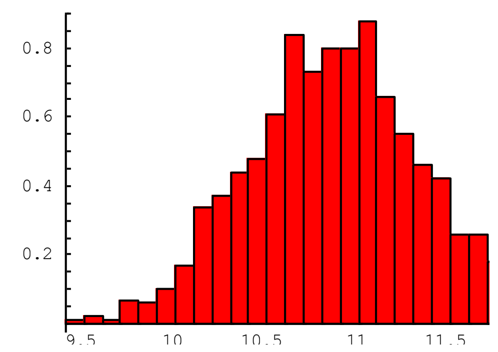
$$^{208}Pb^{82+} + ^{208}Pb^{82+} \xrightarrow{\gamma} ^{208}Pb^{82+} + \underbrace{^{208}Pb^{81+}}_{[\delta = 0.012]} + e^{+}$$



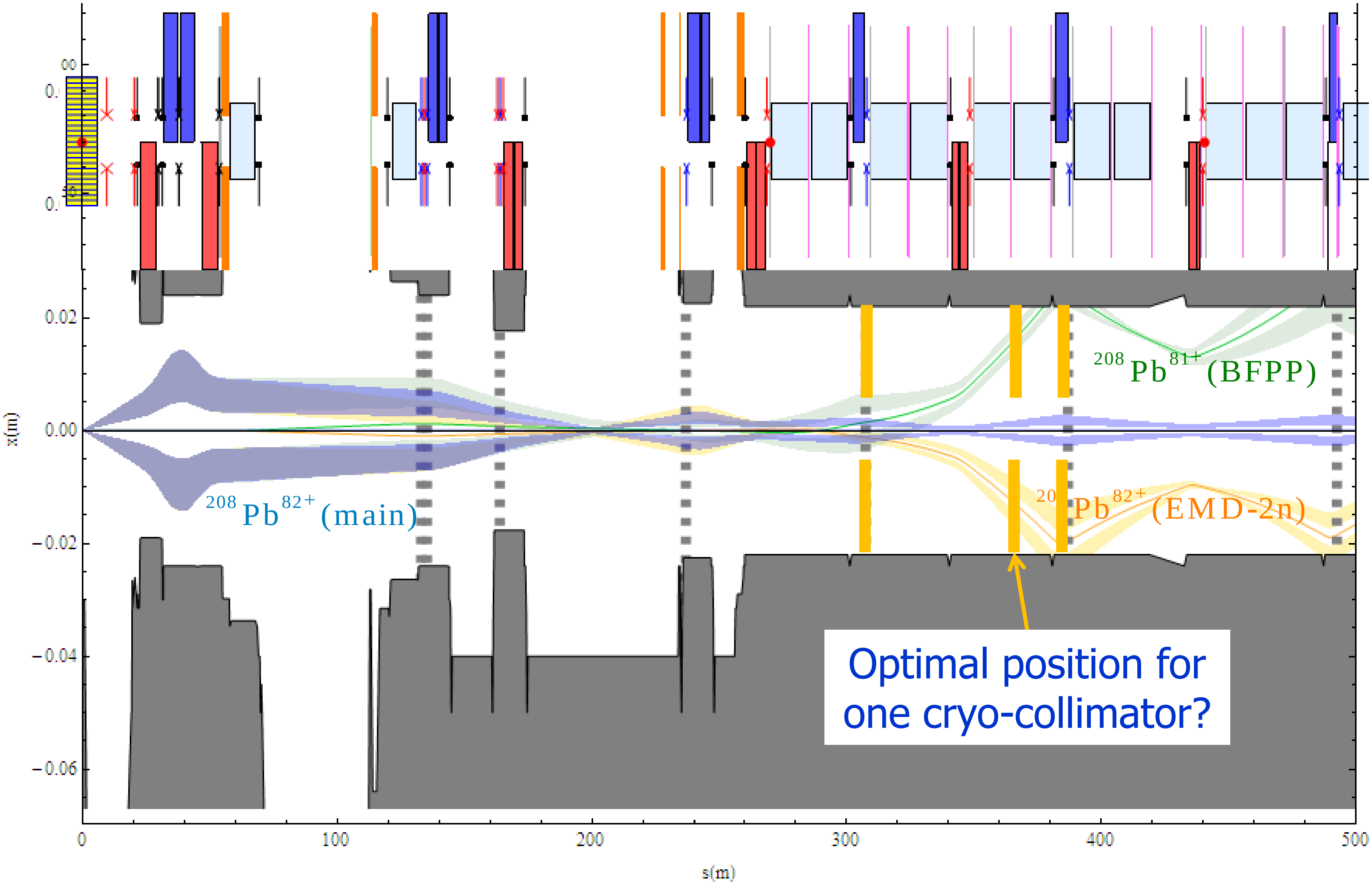
Secondary Pb^{81+} beam emerging from IP and impinging on beam screen,
~ 25 W of power at design luminosity may quench dipole magnet in dispersion suppressor at fraction of design luminosity (see other papers and talks).

Very similar to isotopes emerging from primary collimator (see G. Bellodi talk).

Longitudinal Pb^{81+} ion distribution on screen



Main and secondary beams from IP2



Cryo-collimators as cure for BFPP

- Not considered up to now because of inviolability of cold sections of LHC
- Location of cryo-collimators may need to be different from IR7 (one seems enough).
  - Smaller movements of more dipoles?
  - Requires further detailed study
- Layout adjustments and optics rematch in IR2 should be acceptable
  - More work to do because of multiple optics in ramp and squeeze
- Comparison with FLUKA studies for IR7 (talk by F. Cerruti) suggests that 25 W at design L should be OK

Further possible installations

- Momentum collimation insertion IR3
  - Expected to be similar to IR7, details to be worked out
- Other experimental IRs?
  - ALICE (IR2) is dedicated heavy-ion detector but ATLAS (IR1) and CMS (IR5) also want heavy-ion collisions
  - Consider cryo-collimators in those IRs also ?
  - Possible interference with FP420 ?
  - Need for same luminosity? With design luminosity in 3 experiments, short lifetime from burn-off would impose time-sharing or luminosity levelling with β^* (A. Morsch).

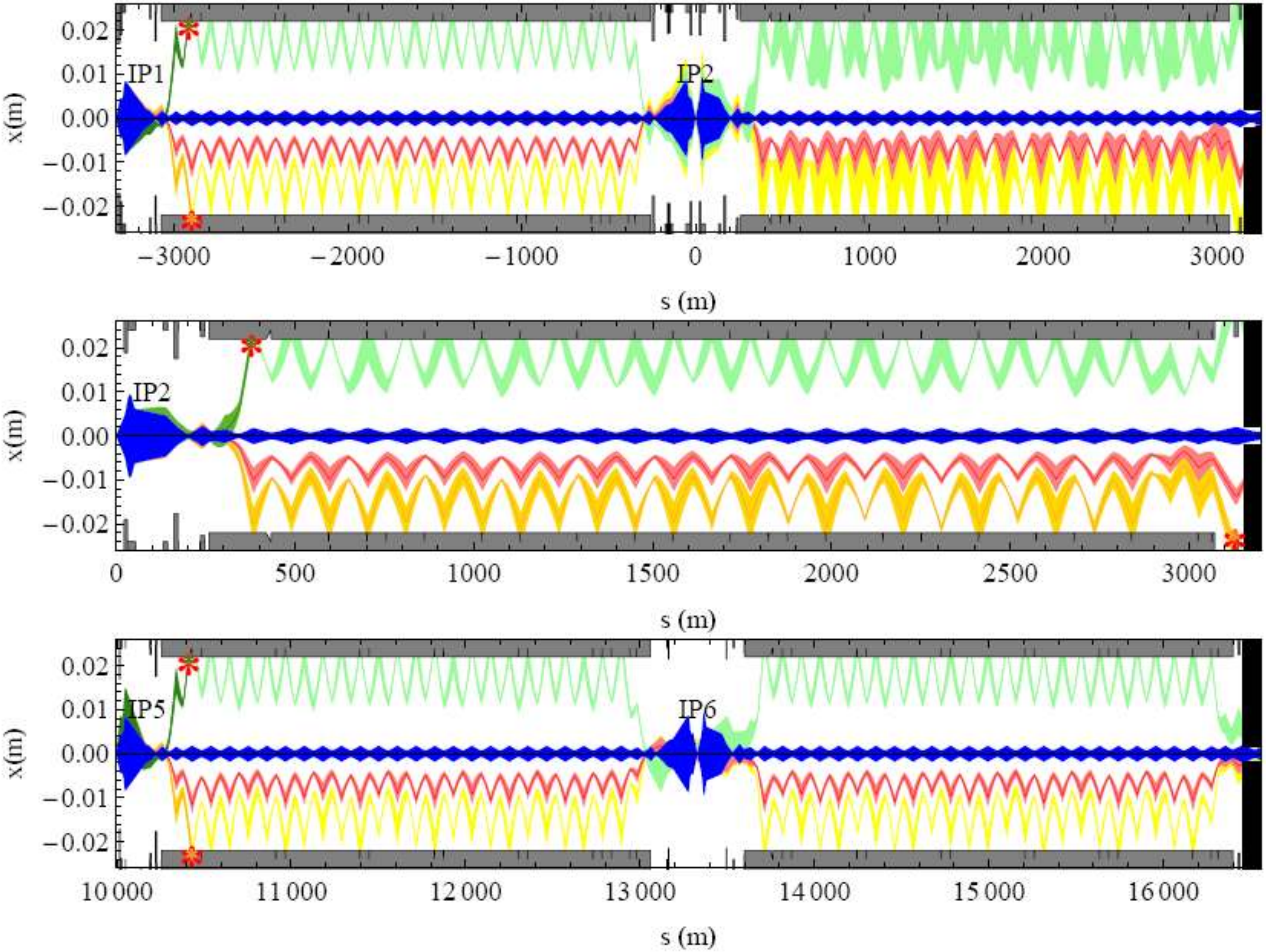


FIG. 1: The simulated horizontal 6 σ envelopes of the nominal $^{208}Pb^{82+}$beam (blue), the $^{208}Pb^{81+}$BFPP beam (green), the $^{207}Pb^{82+}$ EMD1 beam (red) and the $^{206}Pb^{82+}$ EMD2 beam (yellow) coming out of IP1 (top), IP2 (middle) and IP5 (bottom) in the LHC, with the machine aperture superimposed. The envelopes are plotted in a lighter color after the first impact (indicated by a red star) of the central orbit on the aperture. The horizontal scale has $s = 0$ at IP2 and the closest horizontal collimators are represented as black boxes at 6 σ to the right. The length of the collimators is not to scale for enhanced readability. lost.

Conclusions

- Installation of cryogenic collimators in IR7
  - New layout, geometry and optics satisfying all requirements
  - Solution for collimation in both p-p and ion modes (talks by T. Weiler and G. Bellodi)
- IR3 still to be treated but should be similar
- Cryo-collimators in IR2 can raise luminosity limit for Pb-Pb collisions
  - Needed soon! Pb-Pb is earliest phase and design luminosity to be approached in 2-3 years
- Possible installations in IR1 and IR5
  - Requires decisions, guidance on luminosity sharing in heavy-ion operation, and further study
  - Possibly useful in p-p running