New Geometry & Optics for LHC IR3

(for IR3MC "cryogenic" collimators in IR3 with maximum 4.5 m displacement of elements)

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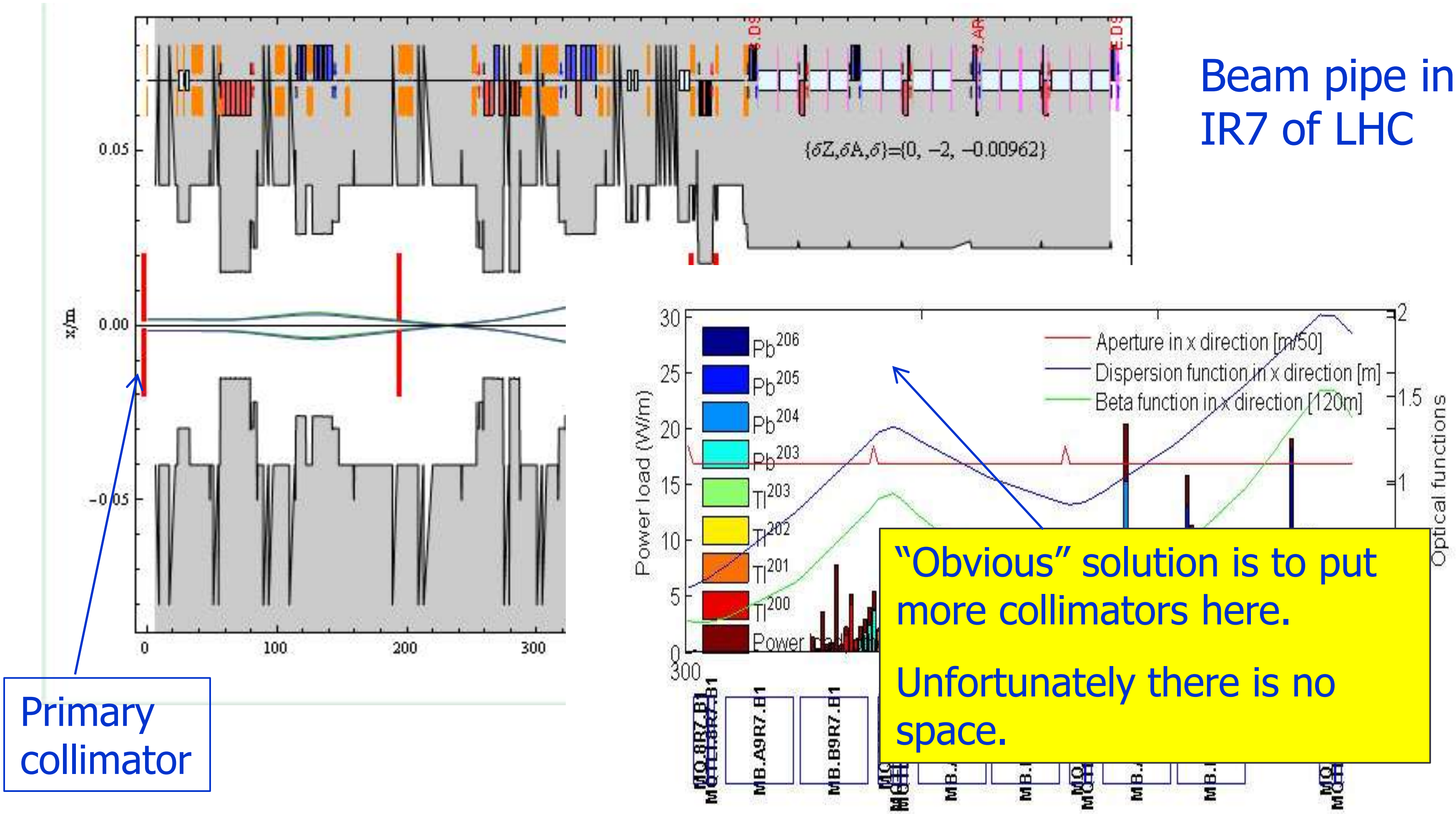
Motivation

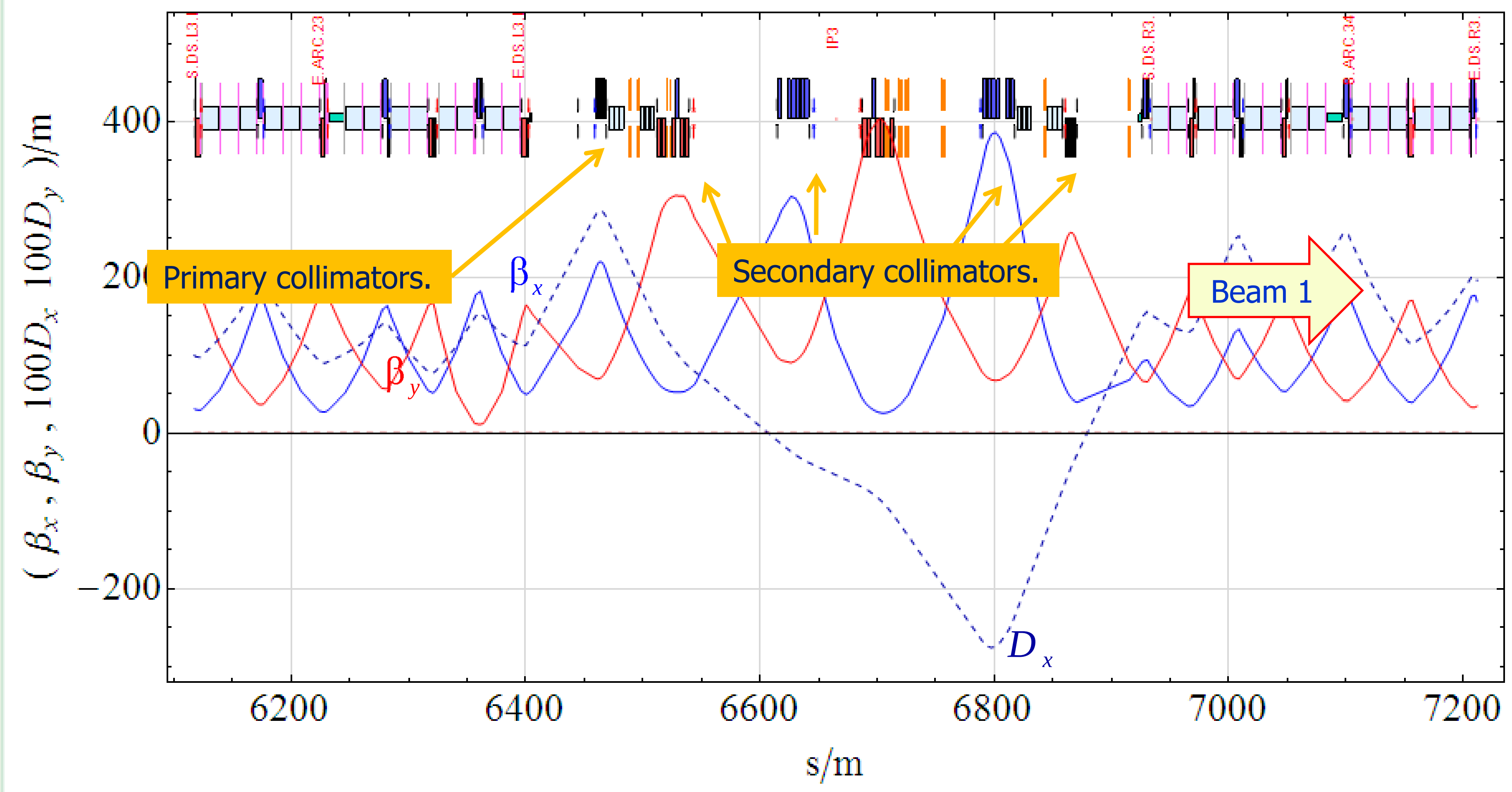
- Collimation of both proton and nuclear beams in the LHC leads to losses in superconducting magnets of the dispersion suppressors, limiting intensity
- Collimators in the dispersion suppressors could prevent most of these losses, opening the way to higher performance
- Proposal to equip IR3 with these "cryo-collimators" and use it for combined betatron-and momentum- cleaning.
  - Hardware and integration being studied in detail in Collimation Working Group.

Example of ^{206}Pb created by 2-neutron EMD

- Green rays are ions that almost reach collimator
- Blue rays are ^{206}Pb rays with rigidity change



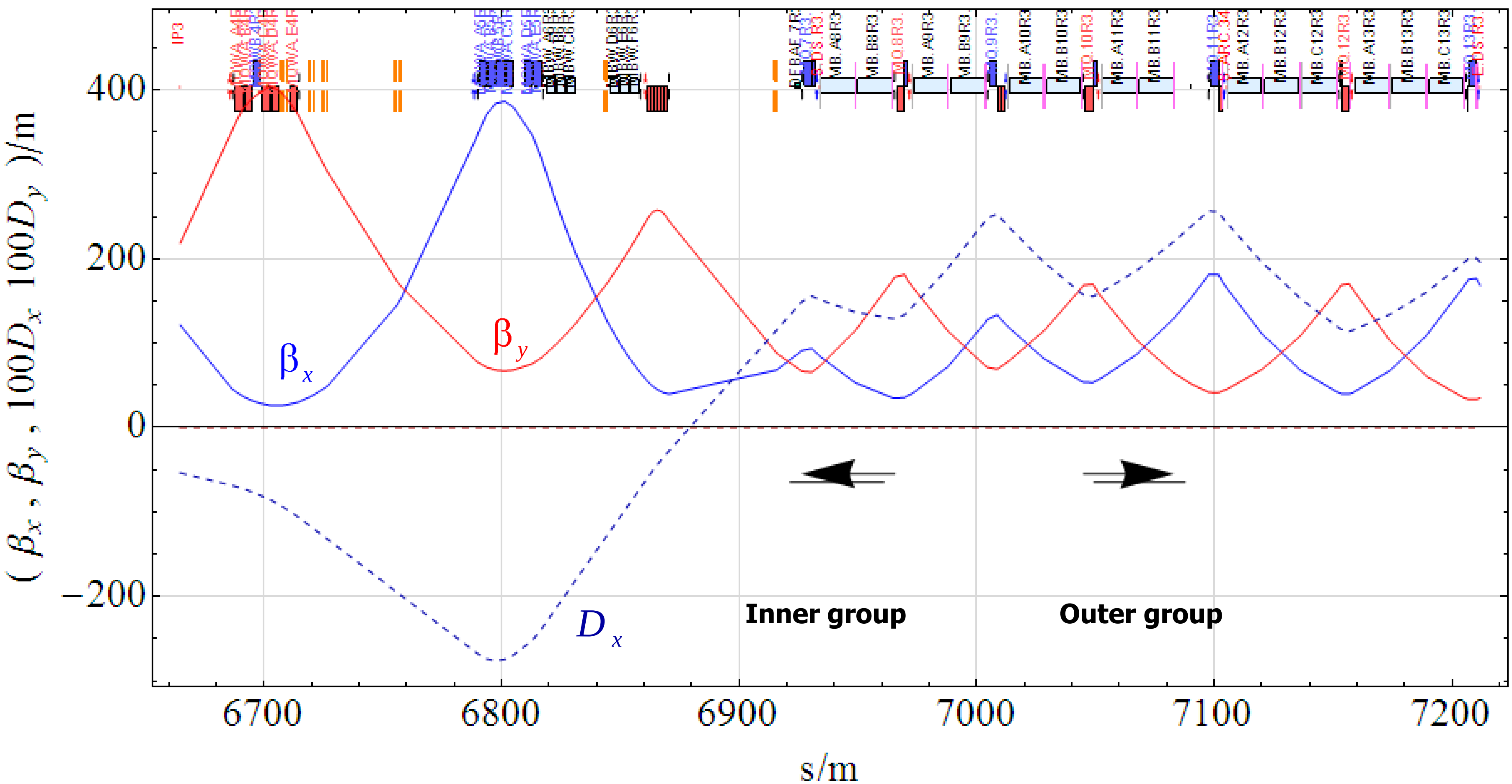
Present IR3 Optics overview, Beam 1



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

IR3 optics is **constant** – no change with energy, β-squeeze, etc.

Making space, IR3 right, Beam 1

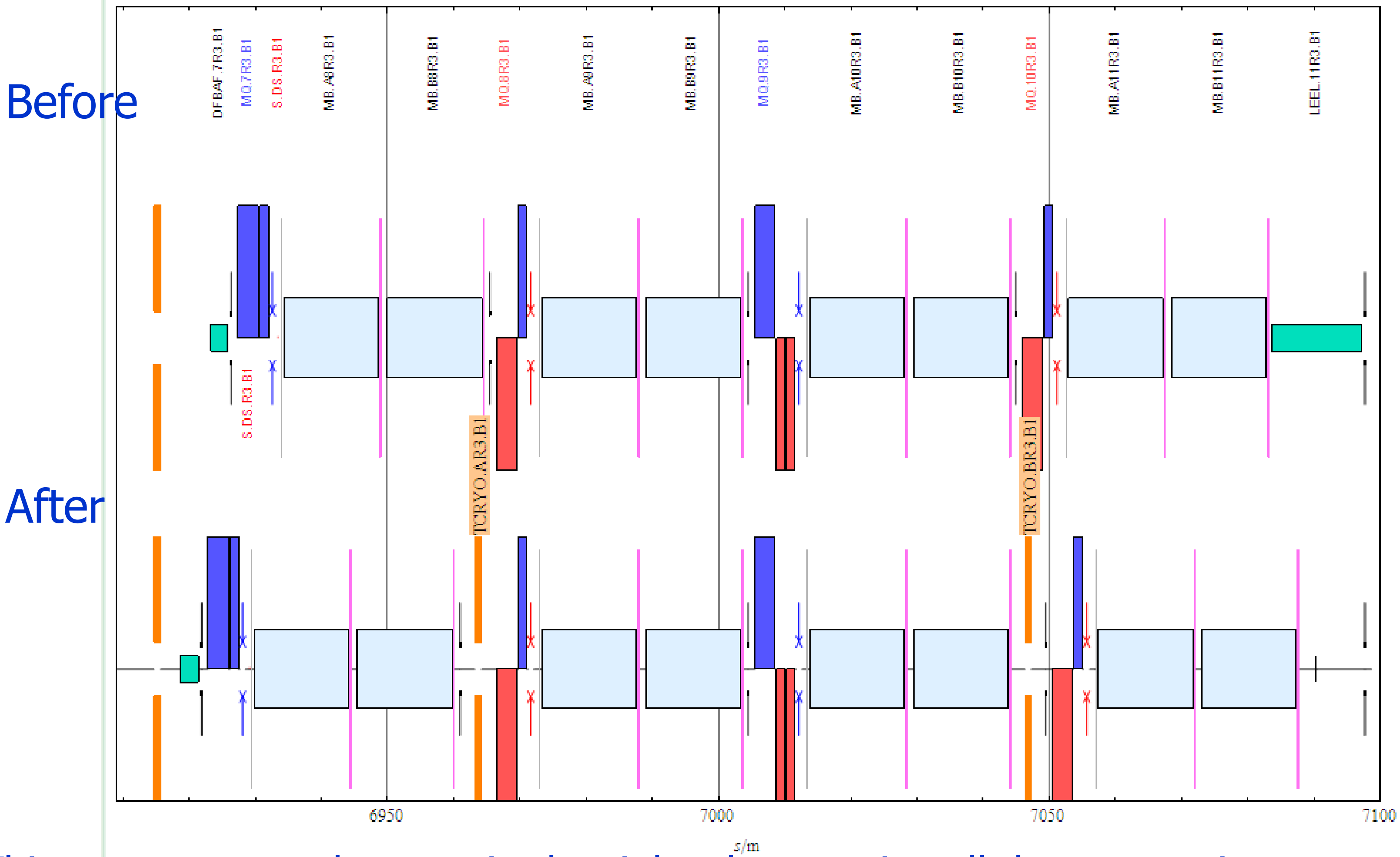


Move outer group of elements 4.5 m away from IP into missing dipole space.

Move inner group of elements 4.5 m towards IP to (roughly) compensate change in geometry.

Similarly on left of IP3.

Zoom on displacements along reference orbit



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

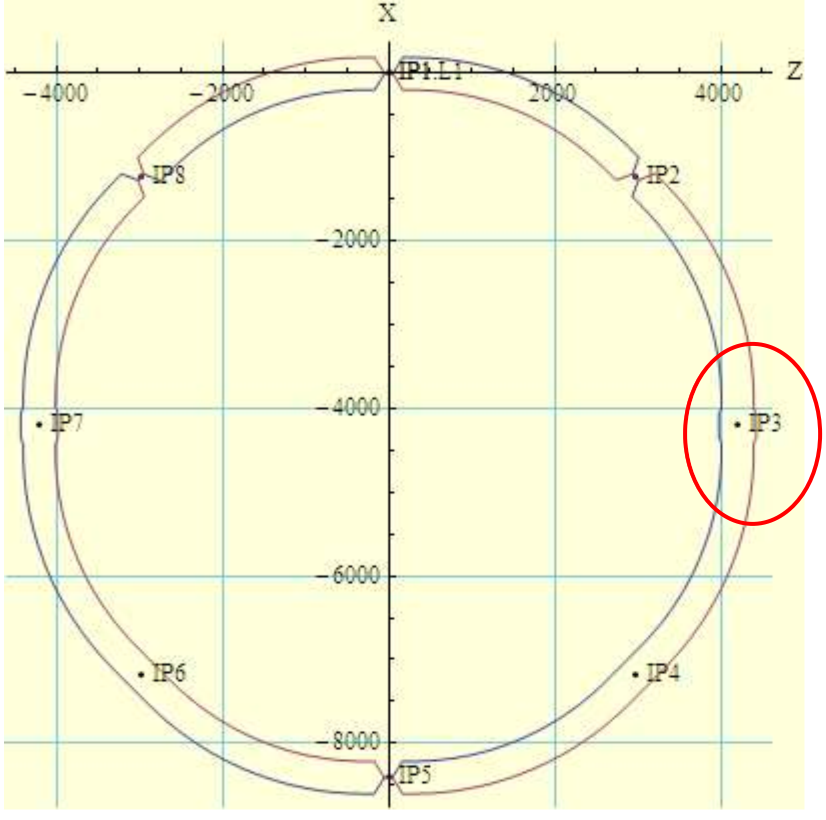
N.B. this is in Courant-Snyder coordinate *s*, so we do not see the change in geometry of the LHC.

Global Cartesian Coordinate System

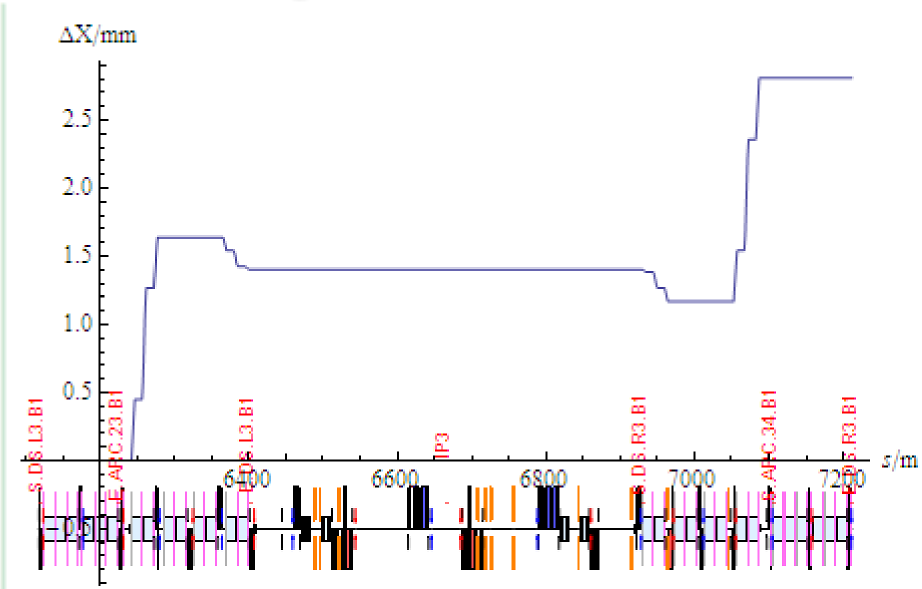
- Global coordinates with origin at IP1

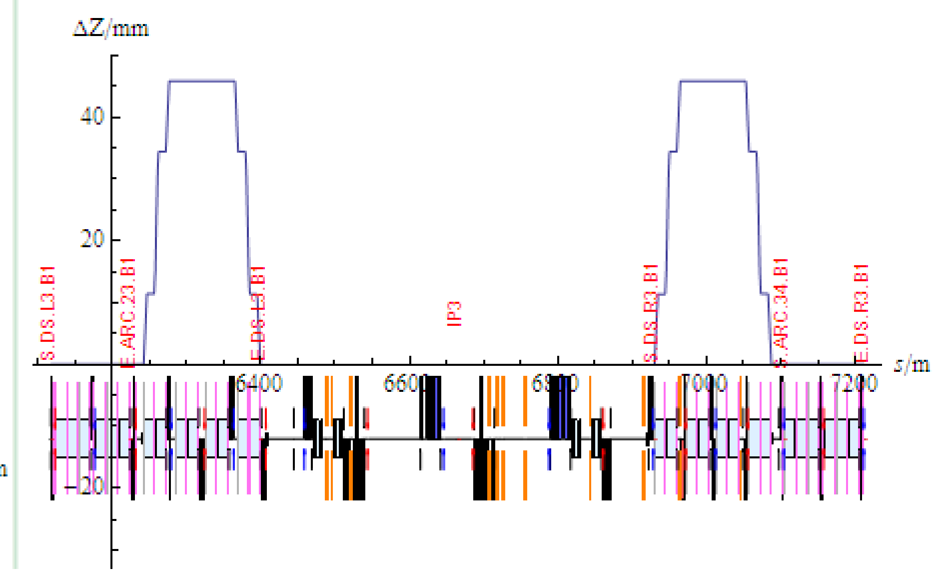
  In the *straight section including* IP3, it happens that:
  - *X* is longitudinal
  - *Y* is vertical
  - *Z* is "radial"

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



Displacements of reference orbit, Beam 1

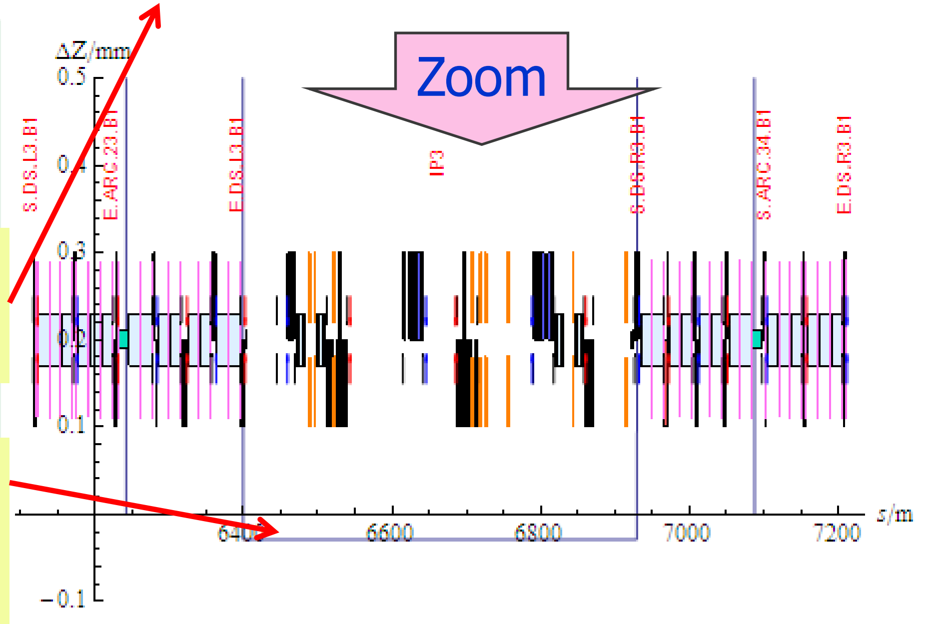




Longitudinal displacement mainly reflects change in length of reference orbit – can be fixed.

Radial displacement of reference orbit between shifted sections by 46 mm. N.B. Not the displacement of elements!

Radial displacement of IP3 and straight section due to non-commutativity of rotations and translations is small enough (-0.026 mm) to neglect.



Displacements of moved elements, Beam 1, left of IP3

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 IR3 moves and the ring does not close … this is not real of course but has to be corrected in the MAD description.

Outer group

	ΔZ/m	ΔX/m
MCO.11L3.B1	-0.1835	4.496
MCD.11L3.B1	-0.1835	4.496
MB.B11L3.B1	-0.1835	4.496
MCS.B11L3.B1	-0.1835	4.496
MB.A11L3.B1	-0.1835	4.496
MCS.A11L3.B1	-0.1835	4.496
BPM.10L3.B1	-0.1835	4.496
MQ.10L3.B1	-0.1835	4.496
MQTLI.10L3.B1	-0.1835	4.496
MCBCH.10L3.B1	-0.1835	4.496

Inner group

	ΔZ/m	ΔX/m
MCO.8L3.B1	0.00002865	-4.501
MCD.8L3.B1	0.00002865	-4.501
MB.B8L3.B1	0.00002865	-4.501
MCS.B8L3.B1	0.00002865	-4.501
MB.A8L3.B1	0.00002865	-4.501
MCS.A8L3.B1	0.00002865	-4.501
E.DS.L3.B1	0.00002865	-4.501
BPM.7L3.B1	0.00002865	-4.501
MQ.7L3.B1	0.00002865	-4.501
MQTLI.7L3.B1	0.00002865	-4.501
MCBCV.7L3.B1	0.00002865	-4.501
DFBAE.7L3.B1	0.00002865	-4.501

	ΔZ/m	ΔX/m
IP1	0	0
IP2	0	0
IP3	0.00002865	-0.001404
IP4	0	-0.002808
IP5	0	-0.002808
IP6	0	-0.002808
IP7	0	-0.002808
IP8	0	-0.002808
IP1.L1	0	-0.002808

Corrected layout

Small negative displacements of all elements downstream of IR3 along the reference orbit restores them to their original position in the global cartesian system and closes the ring.

	$\Delta Z/m$	$\Delta X/m$
IP1	0	0
IP2	0	0
IP3	0.00002865	0
IP4	0	-6.294×10^{-10}
IP5	0	-6.294×10^{-10}
IP6	0	-6.303×10^{-10}
IP7	0	-6.330×10^{-10}
IP8	0	-6.330×10^{-10}
IP1.L1	0	-6.331×10^{-10}

New sequence descriptions created for both rings.

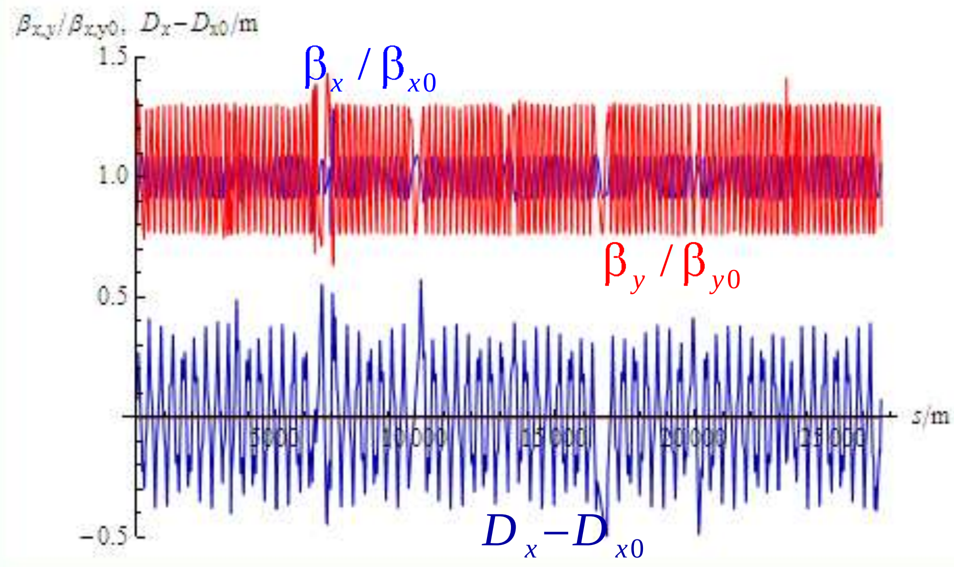
LHC circumference is changed by -2.808 mm.

Some freedom to distribute IP movements with RF phase.

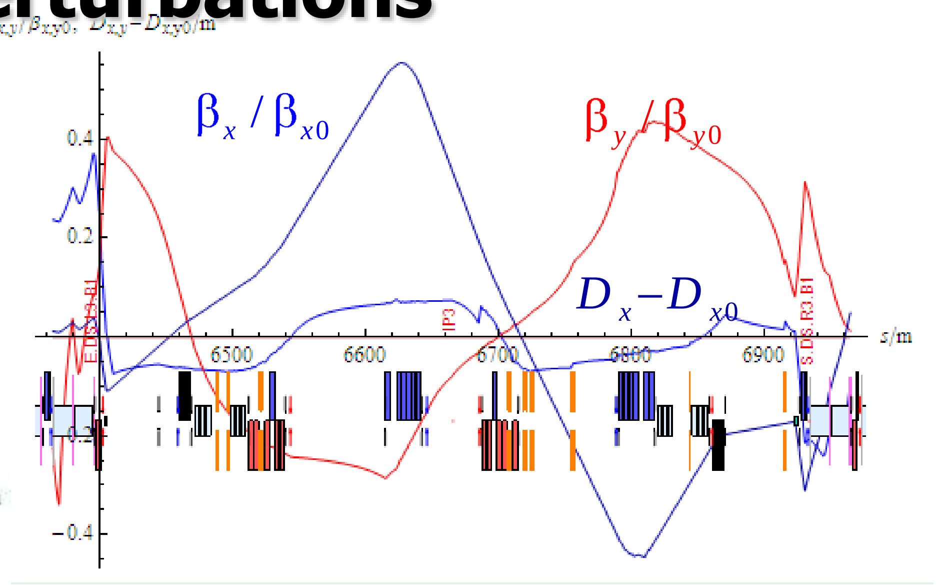
/afs/cern.ch/eng/sl/ilhc/JMJ/CryoCollimatorOptics/IR3/LHCCC.seq

Use new sequence names LHCB1CC, LHCB2CC.

Optical perturbations



β-beating in whole Ring 1



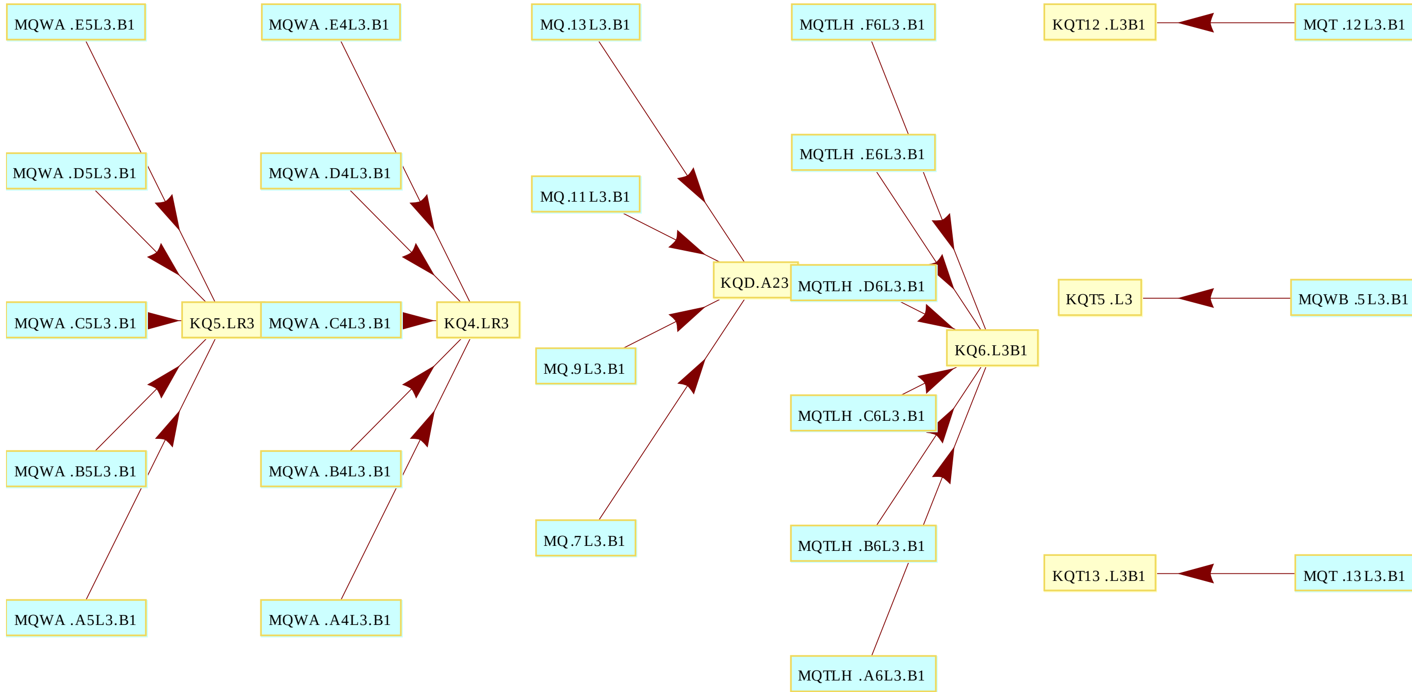
β-beating in IR3, Ring 1

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

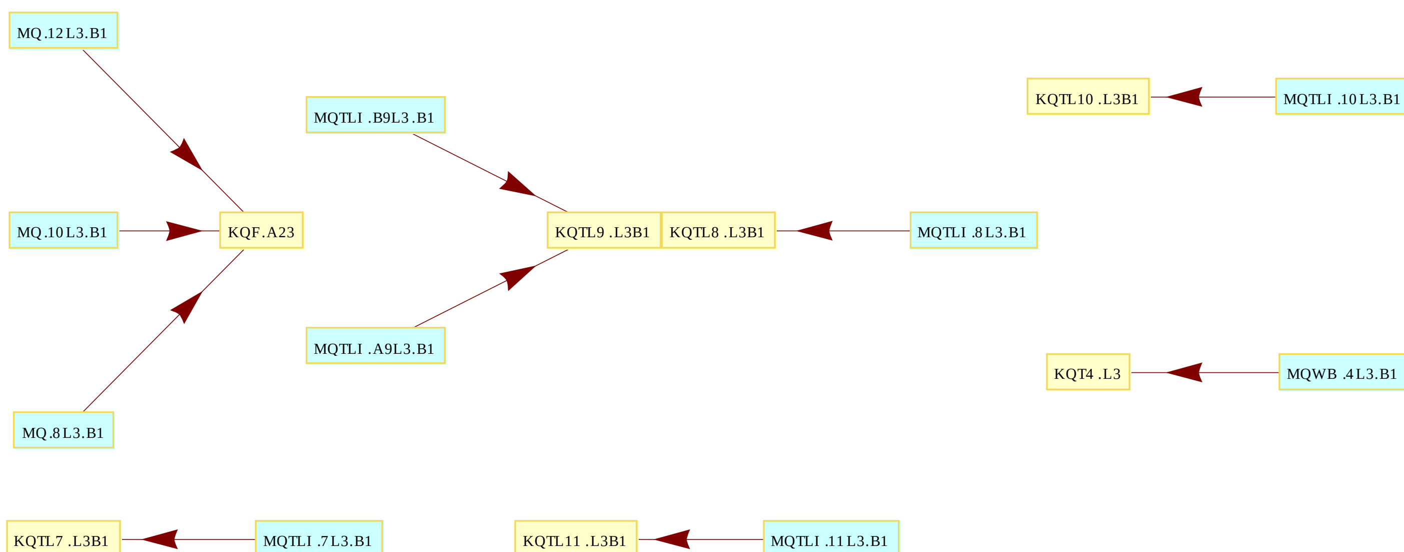
Optics perturbation in IR3 would cause significant aperture loss.

Rematch IR3 for each ring without using the common quadrupoles that affect both.

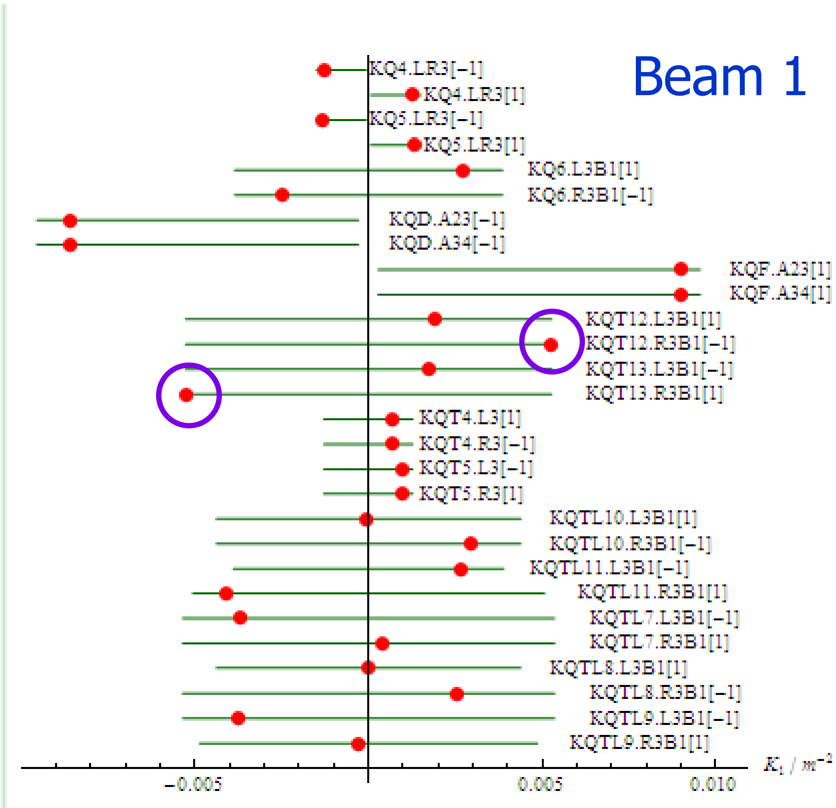
Powering scheme for quadrupoles on left side of IR3, Beam 1.

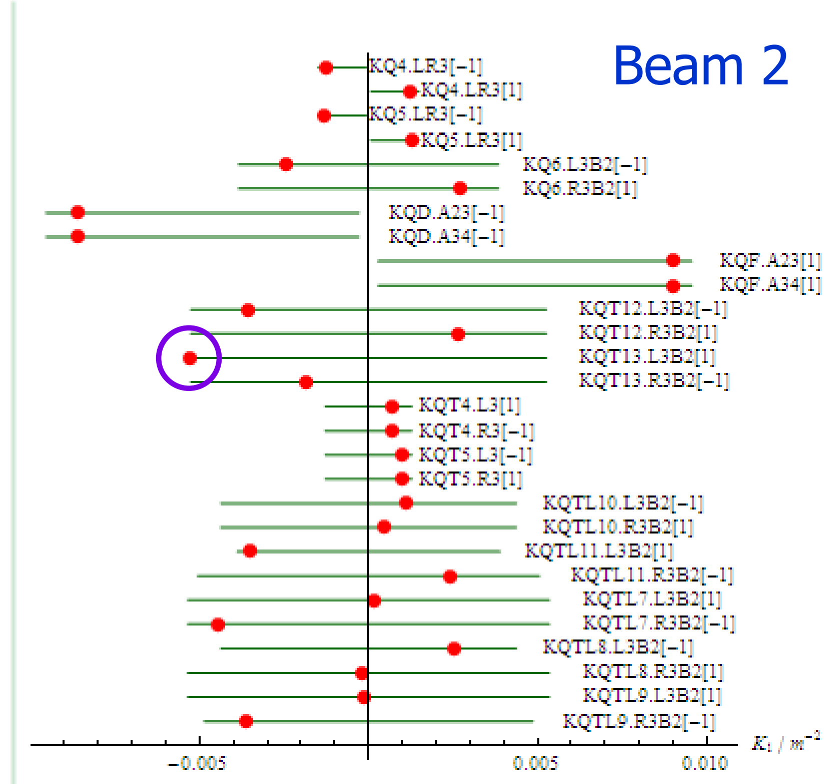


Graphs are computed by parsing sequence file.



Quadrupole strengths in present IR3 optics





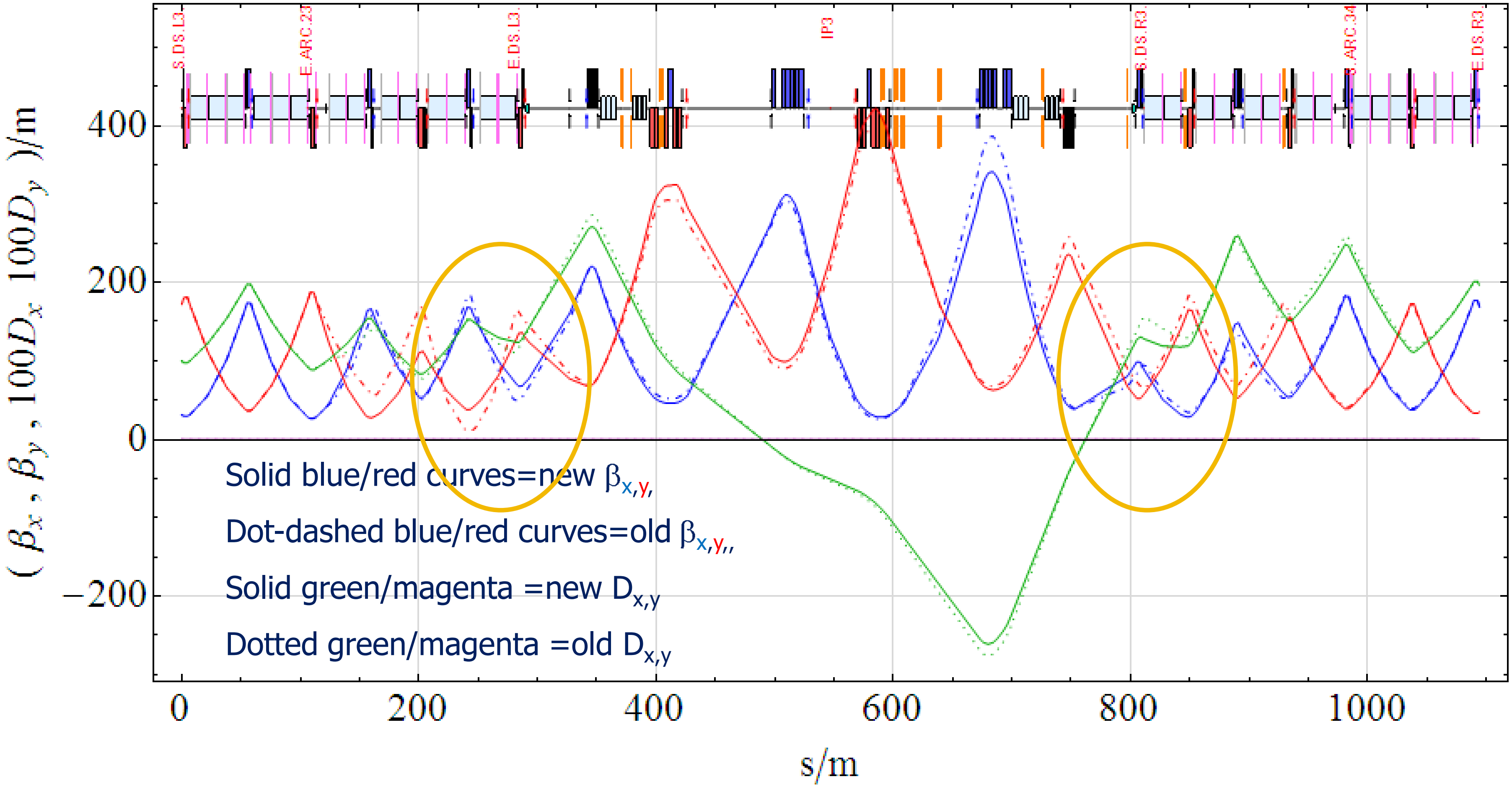
Strength display function takes an optics, derives limits at its energy and computes relevant part of powering tree.

Some trim quadrupoles at ~99.8 % of limits at 7 TeV – potential problem for full energy operation.

A rematch, allowing optics to vary in warm section, multiple constraints applied to improve aperture.

SOLUTION LHCB1CC, LHCB2CC

Rematch of IR3, Beam 1



Perfect match – same transfer matrix over IR3 - so can be used in modular way with all existing LHC optics configurations.

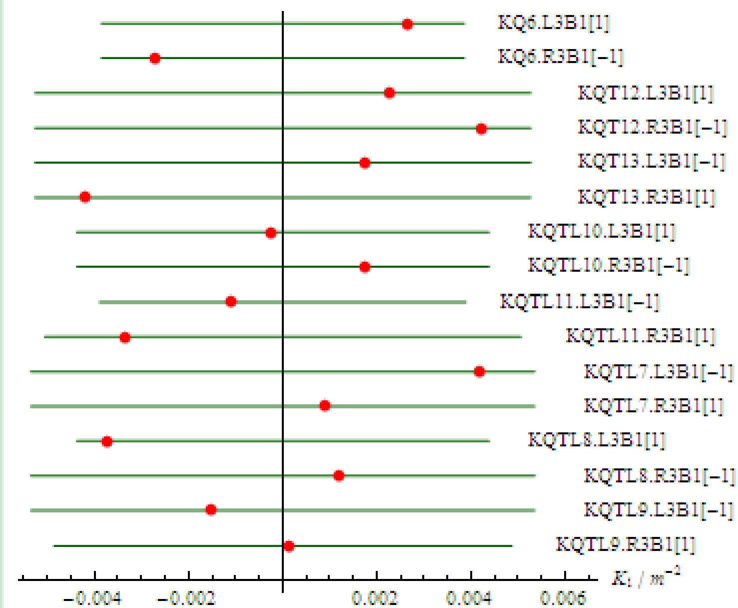
Adjusted β-function peaks (many iterations) to avoid loss of mechanical aperture.

Optics in central (warm) part is close (not identical) to old optics.

Strengths and limits, Beam 1 at 7*Z* TeV

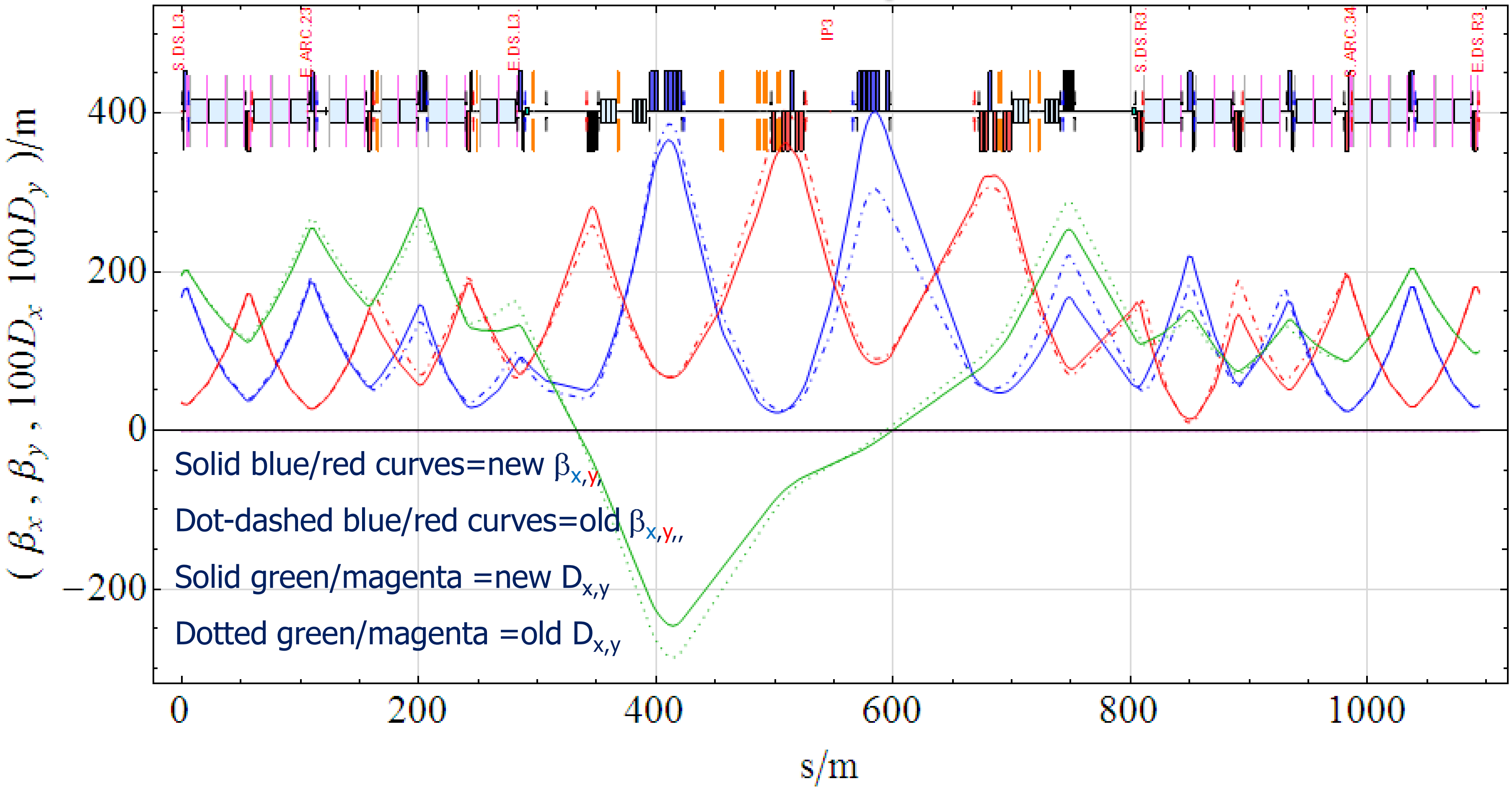
K1NAMES	K1MIN	K1	K1MAX	K1PERCENTMIN	K1PERCENTMAX	POLARITY
KQ6.L3B1	-0.00385447	0.00262806	0.00385447	-68.1821	68.1821	1.
KQ6.R3B1	-0.00385447	-0.00269269	0.00385447	-69.8589	69.8589	-1.
KQT12.L3B1	-0.00526778	0.00226608	0.00526778	-43.0177	43.0177	1.
KQT12.R3B1	-0.00526778	0.0042	0.00526778	79.73	-79.73	-1.
KQT13.L3B1	-0.00526778	0.00174159	0.00526778	33.0611	-33.0611	-1.
KQT13.R3B1	-0.00526778	-0.0041889	0.00526778	79.5193	-79.5193	1.
KQTL10.L3B1	-0.00438008	-0.000265725	0.00438008	6.06667	-6.06667	1.
KQTL10.R3B1	-0.00438008	0.00173865	0.00438008	39.6945	-39.6945	-1.
KQTL11.L3B1	-0.00389341	-0.0011182	0.00389341	-28.7205	28.7205	-1.
KQTL11.R3B1	-0.00506143	-0.00334624	0.00506143	66.1125	-66.1125	1.
KQTL7.L3B1	-0.00535343	0.0041715	0.00535343	77.9219	-77.9219	-1.
KQTL7.R3B1	-0.00535343	0.000919078	0.00535343	-17.168	17.168	1.
KQTL8.L3B1	-0.00438008	-0.0037296	0.00438008	85.149	-85.149	1.
KQTL8.R3B1	-0.00535343	0.00117709	0.00535343	21.9876	-21.9876	-1.
KQTL9.L3B1	-0.00535343	-0.0015067	0.00535343	-28.1446	28.1446	-1.
KQTL9.R3B1	-0.00486676	0.000134876	0.00486676	-2.77138	2.77138	1.

Strength limits are computed automatically from sequence file and optics data.



All now comfortably within range (green).

Rematch of IR3, Beam 2



Perfect match – same transfer matrix over IR3, so can be used in modular way with all existing LHC optics configurations.

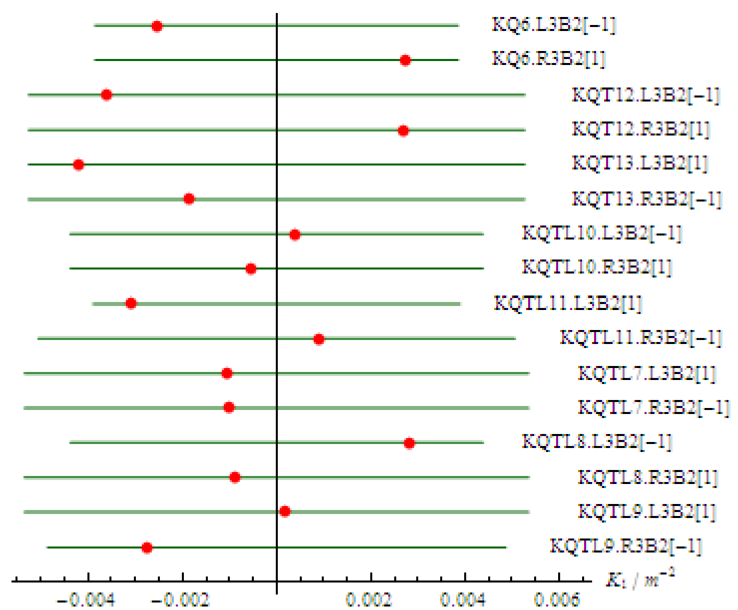
Adjusted β-function peaks so available aperture is not changed significantly.

Transfer matrices within warm collimation section are NOT identical.

Strengths and limits, Beam 2 at 7Z TeV

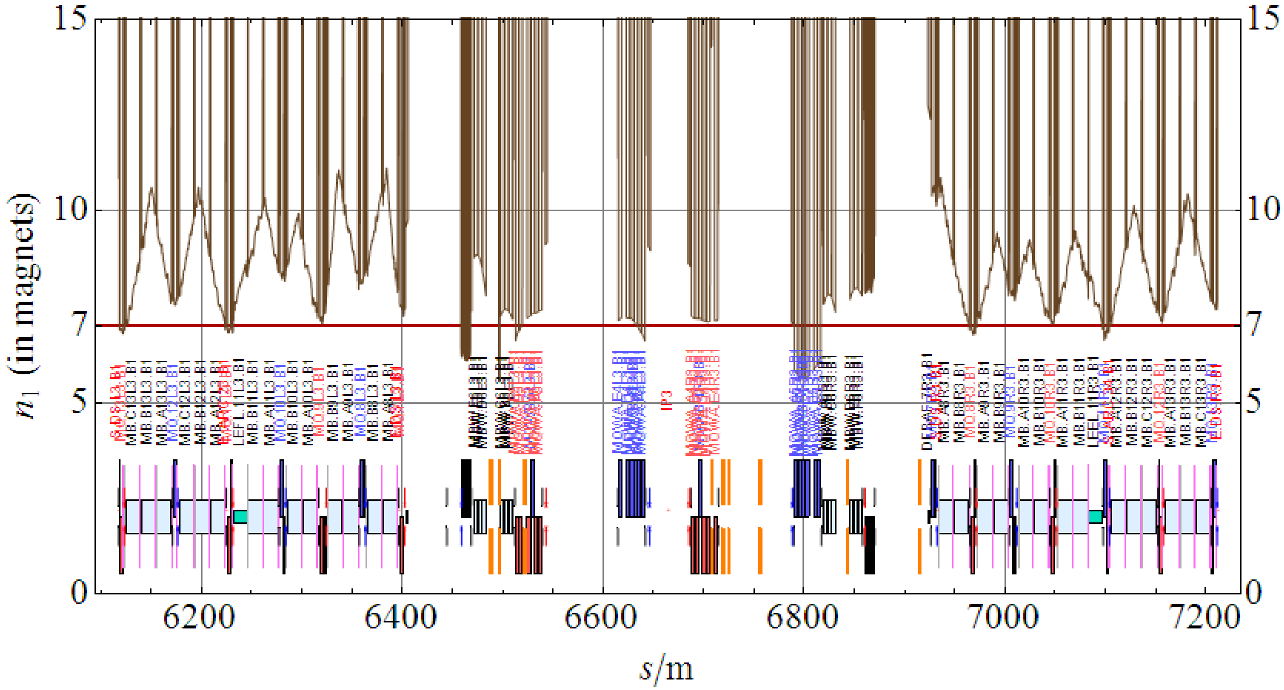
K1NAMES	K1MIN	K1	K1MAX	K1PERCENTMIN	K1PERCENTMAX	POLARITY
KQ6.L3B2	-0.00385447	-0.00253953	0.00385447	-65.8854	65.8854	-1.
KQ6.R3B2	-0.00385447	0.00271316	0.00385447	-70.3899	70.3899	1.
KQT12.L3B2	-0.00526778	-0.00359761	0.00526778	-68.2947	68.2947	-1.
KQT12.R3B2	-0.00526778	0.00267827	0.00526778	-50.8424	50.8424	1.
KQT13.L3B2	-0.00526778	-0.00420853	0.00526778	79.8919	-79.8919	1.
KQT13.R3B2	-0.00526778	-0.00186511	0.00526778	-35.4061	35.4061	-1.
KQTL10.L3B2	-0.00438008	0.00037109	0.00438008	8.47221	-8.47221	-1.
KQTL10.R3B2	-0.00438008	-0.000558353	0.00438008	12.7475	-12.7475	1.
KQTL11.L3B2	-0.00389341	-0.0031138	0.00389341	79.9762	-79.9762	1.
KQTL11.R3B2	-0.00506143	0.000882391	0.00506143	17.4336	-17.4336	-1.
KQTL7.L3B2	-0.00535343	-0.00106291	0.00535343	19.8548	-19.8548	1.
KQTL7.R3B2	-0.00535343	-0.00101363	0.00535343	-18.9342	18.9342	-1
KQTL8.L3B2	-0.00438008	0.00279349	0.00438008	63.7771	-63.7771	-1
KQTL8.R3B2	-0.00535343	-0.000895177	0.00535343	16.7215	-16.7215	1.
KQTL9.L3B2	-0.00535343	0.000158161	0.00535343	-2.95439	2.95439	1.
KQTL9.R3B2	-0.00486676	-0.00276434	0.00486676	-56.8004	56.8004	-1

Strength limits are computed automatically from sequence file and optics data.

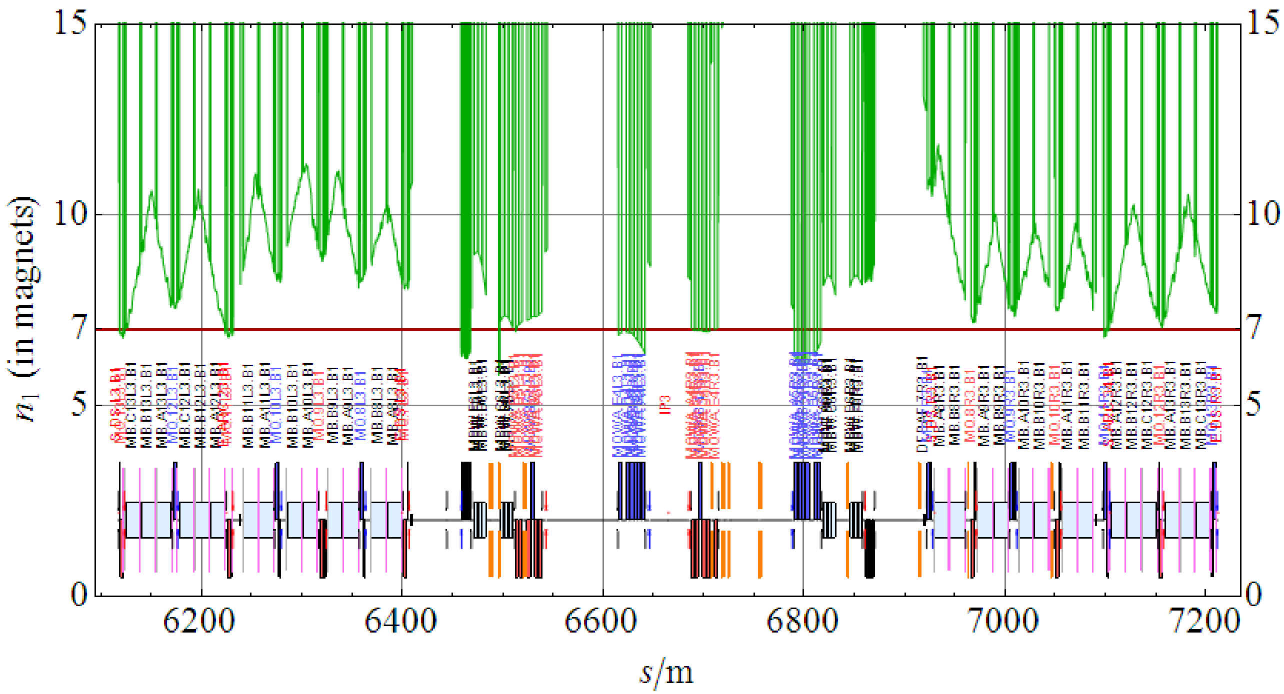


All now comfortably within range (green).

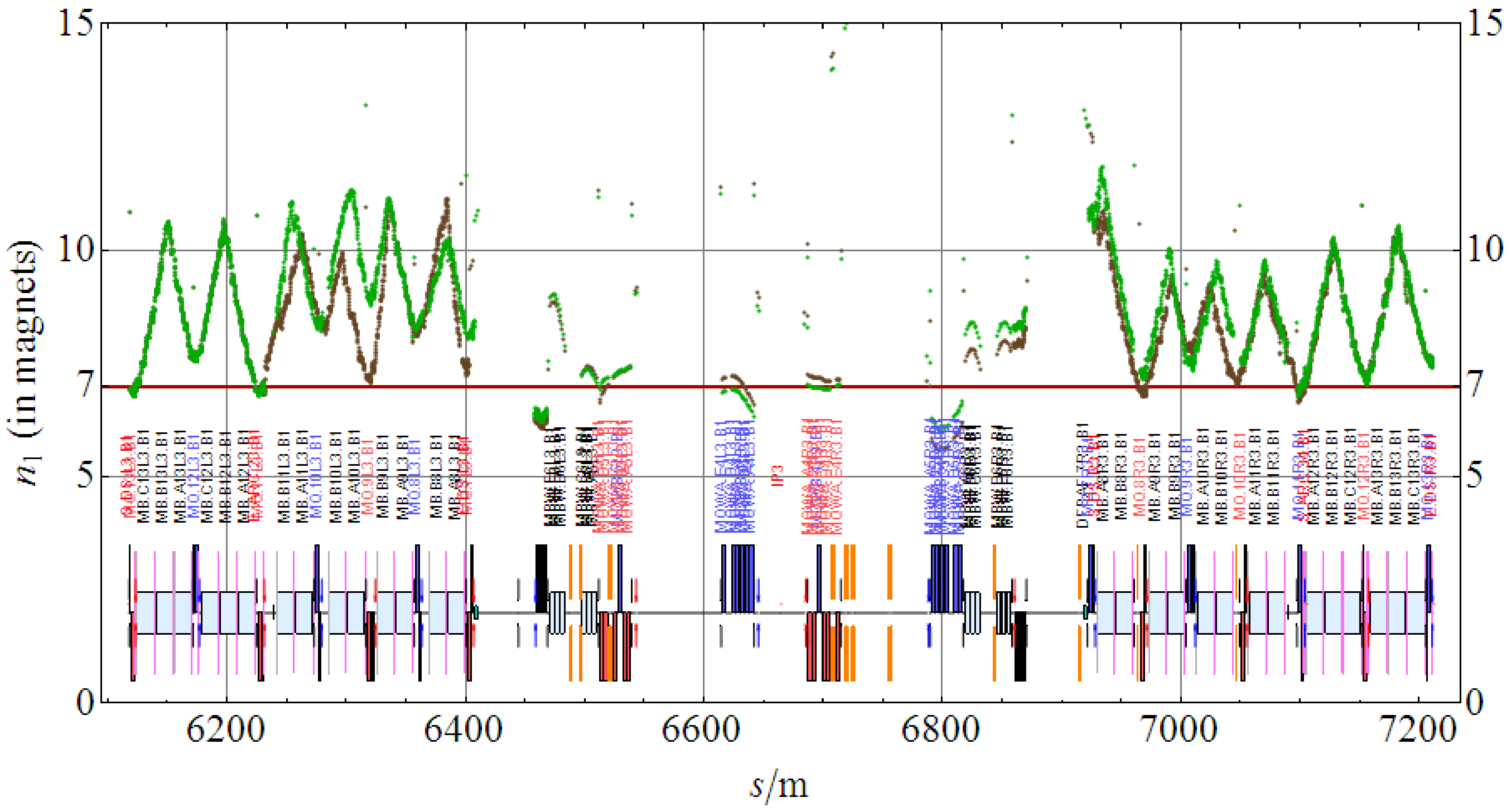
Mechanical aperture of standard IR3.B1 optics at injection.



Mechanical aperture of IR3.B1 LHCB1CC optics at injection.

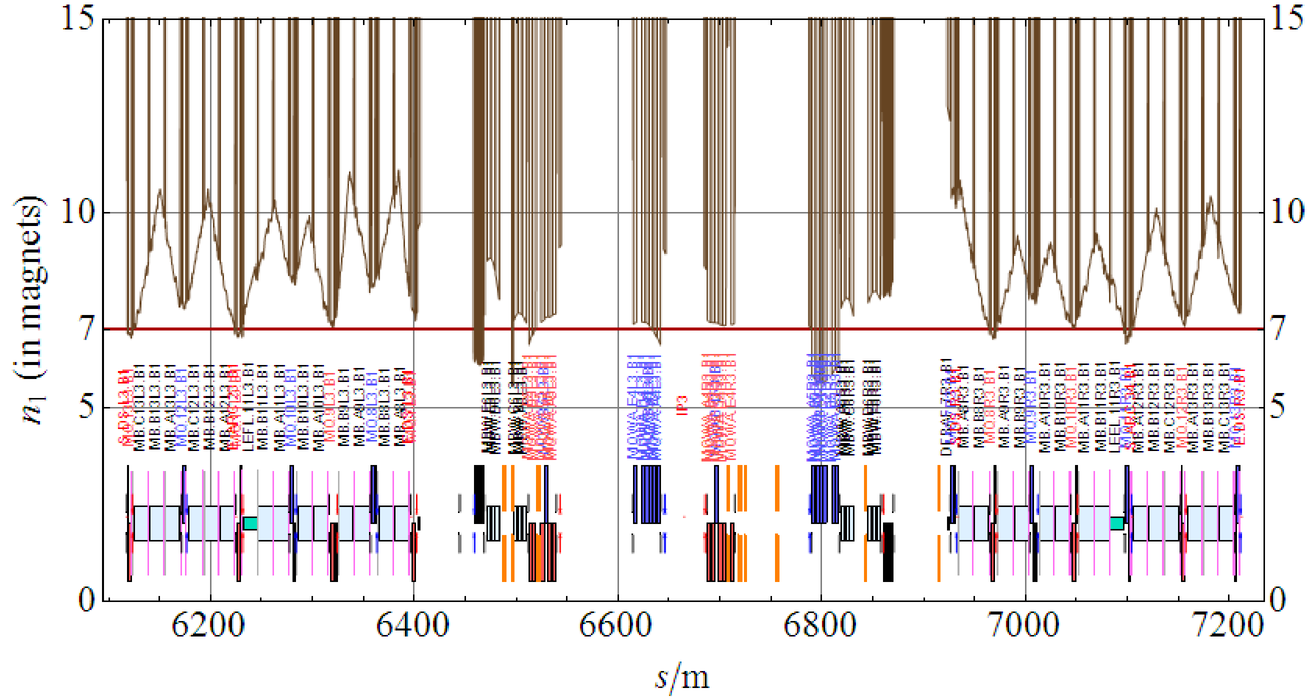


Mechanical aperture comparison, Beam 1

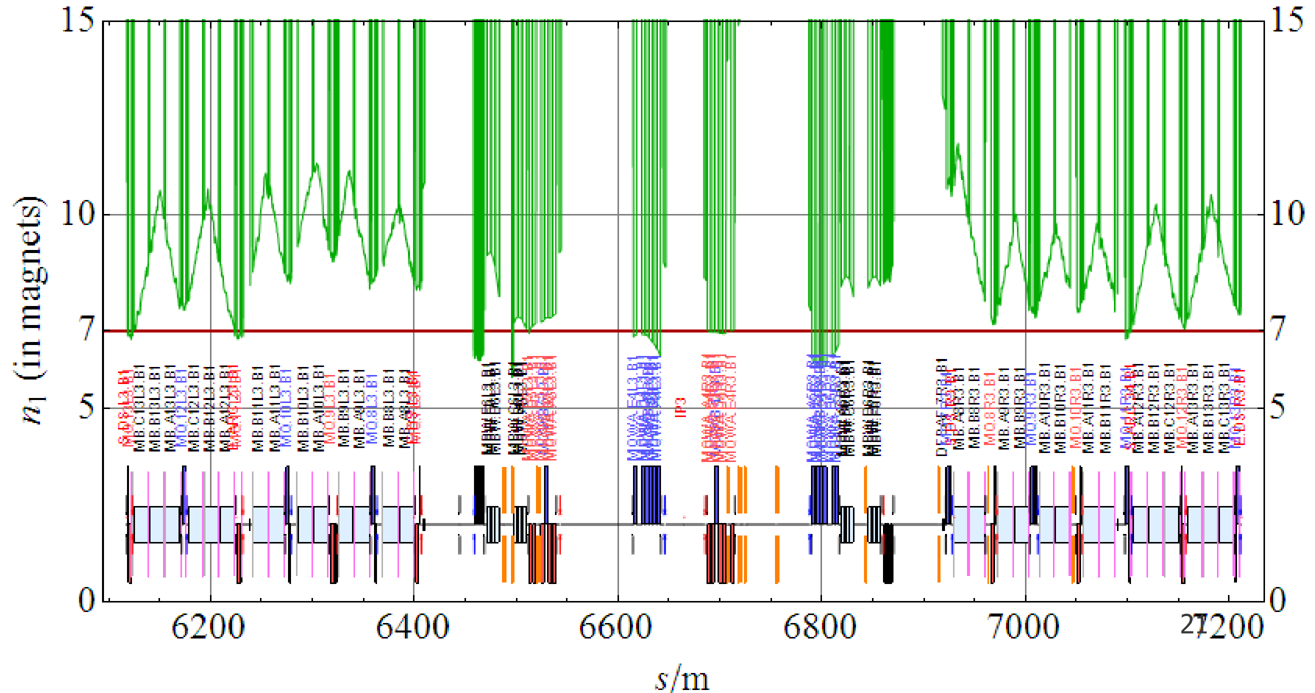


New optics (green) with new layout is better than present optics (brown) almost everywhere.

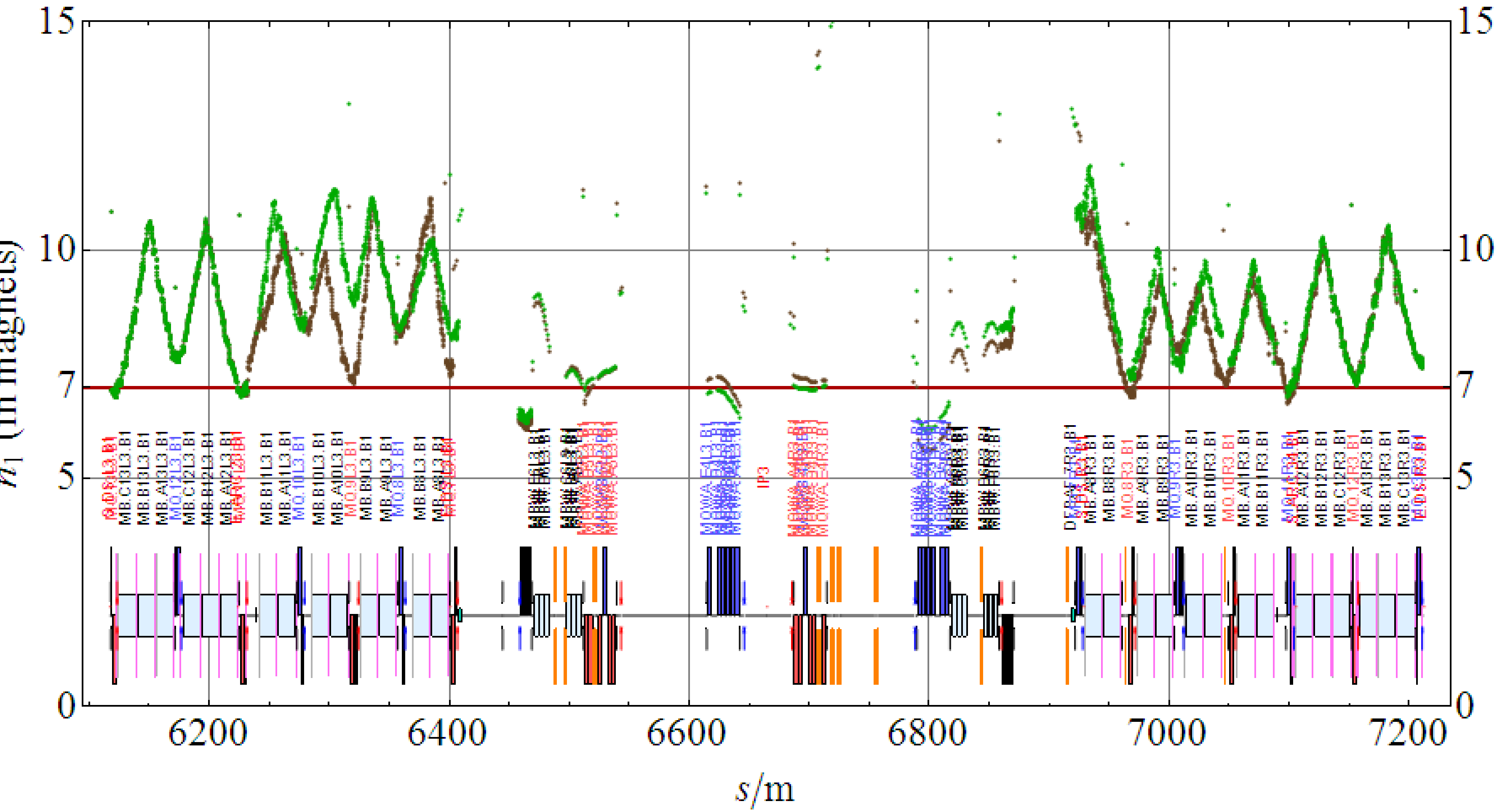
Mechanical aperture of standard IR3.B2 optics at injection.



Mechanical aperture of IR3.B2 LHCB2CC optics at injection.



Mechanical aperture comparison, Beam 2



New optics (green) with new layout is better than present optics (brown) almost everywhere.

Momentum collimation efficiency

Momentum collimation efficiency depends on the

"normalised dispersion" $\frac{D_x}{\sqrt{\beta_x}}$ at the primary collimator.

Momentum Collimation efficiency comparison				
SEQUENCE	TCP	β_x	D_x	$\frac{D_x}{\sqrt{\beta_x}}$
LHCB1	TCP.6L3.B1	131.5	2.177	0.1898
LHCB1CC	TCP.6L3.B1	126.9	2.06	0.1829
LHCB2	TCP.6R3.B2	131.5	2.207	0.1924
LHCB2CC	TCP.6R3.B2	99.33	1.93	0.1936

Transverse impedance effects, Beam 1

Collimator gap: $b \propto n\sigma_{x,y} \propto \sqrt{\beta_{x,y}}$

Resistive impedance depends (very roughly!) on

$$Z^T_{x,y} \propto b^{-3}$$

Transverse instabilities depends on the product of

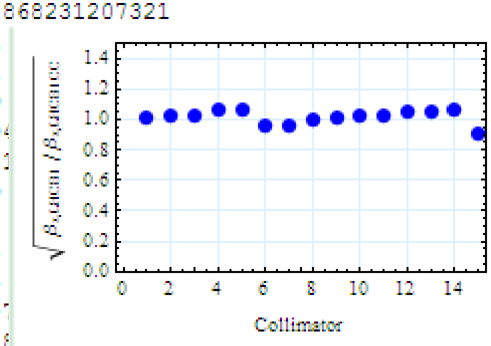
optical function and transverse impedance

$$\beta_{x,y} Z^T_{x,y} \propto \frac{1}{\sqrt{\beta_{x,y}}}$$

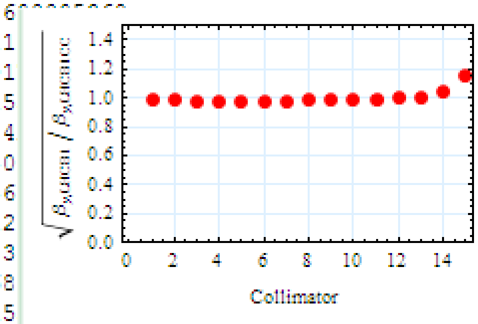
Use this to compare different optics, possibly improve

beam stability at few % level (collimators to be weighted relative to one another).

Collimator	$\sqrt{\beta_{x,\mathrm{LHCB1}} / \beta_{x,\mathrm{LHCB1CC}}}$
TCP.6L3.B1	1.01814667213171971
TCHSH.6L3.B1	1.02001868231207321
TCAPA.6L3.B1	1.02801
TCSG.5L3.B1	1.05952
TCSM.5L3.B1	1.06089
TCSG.4R3.B1	0.96079
TCSM.4R3.B1	0.96604
TCSG.A5R3.B1	1.00299
TCSM.A5R3.B1	1.008
TCSG.B5R3.B1	1.02073
TCSM.B5R3.B1	1.02455
TCLA.A5R3.B1	1.05810
TCLA.B5R3.B1	1.05888
TCLA.6R3.B1	1.06090199295078544
TCLA.7R3.B1	0.913714

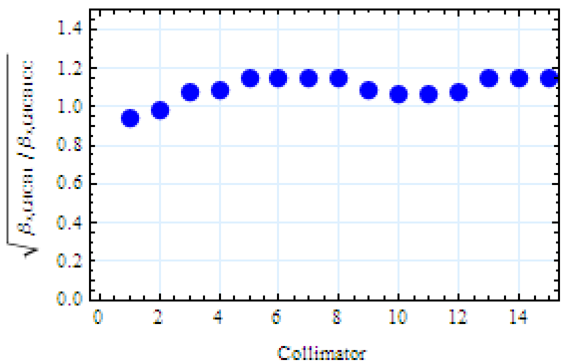


Collimator	$\sqrt{\beta_{y,\mathrm{LHCB1}} / \beta_{y,\mathrm{LHCB1CC}}}$
TCP.6L3.B1	0.98519120976820881
TCHSH.6L3.B1	0.98404849263187548
TCAPA.6L3.B1	0.980289476
TCSG.5L3.B1	0.972417111
TCSM.5L3.B1	0.972053201
TCSG.4R3.B1	0.980140115
TCSM.4R3.B1	0.980459484
TCSG.A5R3.B1	0.982728930
TCSM.A5R3.B1	0.983111336
TCSG.B5R3.B1	0.984276422
TCSM.B5R3.B1	0.984704543
TCLA.A5R3.B1	0.996283868
TCLA.B5R3.B1	0.997393715
TCLA.6R3.B1	1.04758420906383244
TCLA.7R3.B1	1.15952

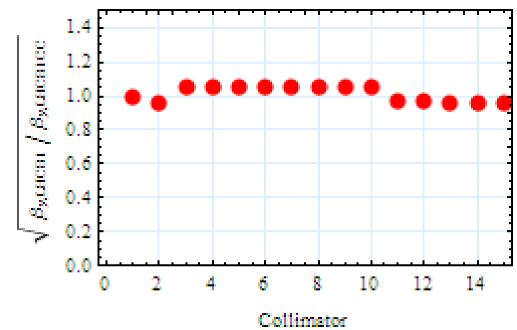


Transverse impedance effects, Beam 2

Collimator	$\sqrt{\beta_{x,LHCB1}/\beta_{x,LHCB1CC}}$
TCLA.7L3.B2	0.937381
TCLA.6L3.B2	0.9785586
TCLA.B5L3.B2	1.0784879
TCLA.A5L3.B2	1.0823037
TCSM.B5L3.B2	1.14798
TCSG.B5L3.B2	1.1508
TCSM.A5L3.B2	1.15042
TCSG.A5L3.B2	1.14582
TCSM.4L3.B2	1.08863
TCSG.4L3.B2	1.06222
TCSM.5R3.B2	1.06503
TCSG.5R3.B2	1.07808
TCAPA.6R3.B2	1.14628
TCHSH.6R3.B2	1.15036
TCP.6R3.B2	1.1507



Collimator	$\sqrt{\beta_{y,LHCB1}/\beta_{y,LHCB1CC}}$
TCLA.7L3.B2	0.996869
TCLA.6L3.B2	0.9637405
TCLA.B5L3.B2	1.0485956
TCLA.A5L3.B2	1.0492538
TCSM.B5L3.B2	1.0543656
TCSG.B5L3.B2	1.0545828
TCSM.A5L3.B2	1.0548343
TCSG.A5L3.B2	1.0549986
TCSM.4L3.B2	1.0554387
TCSG.4L3.B2	1.0555315
TCSM.5R3.B2	0.9734180
TCSG.5R3.B2	0.9726753
TCAPA.6R3.B2	0.9642751
TCHSH.6R3.B2	0.96116763259675509
TCP.6R3.B2	0.96058401602835966



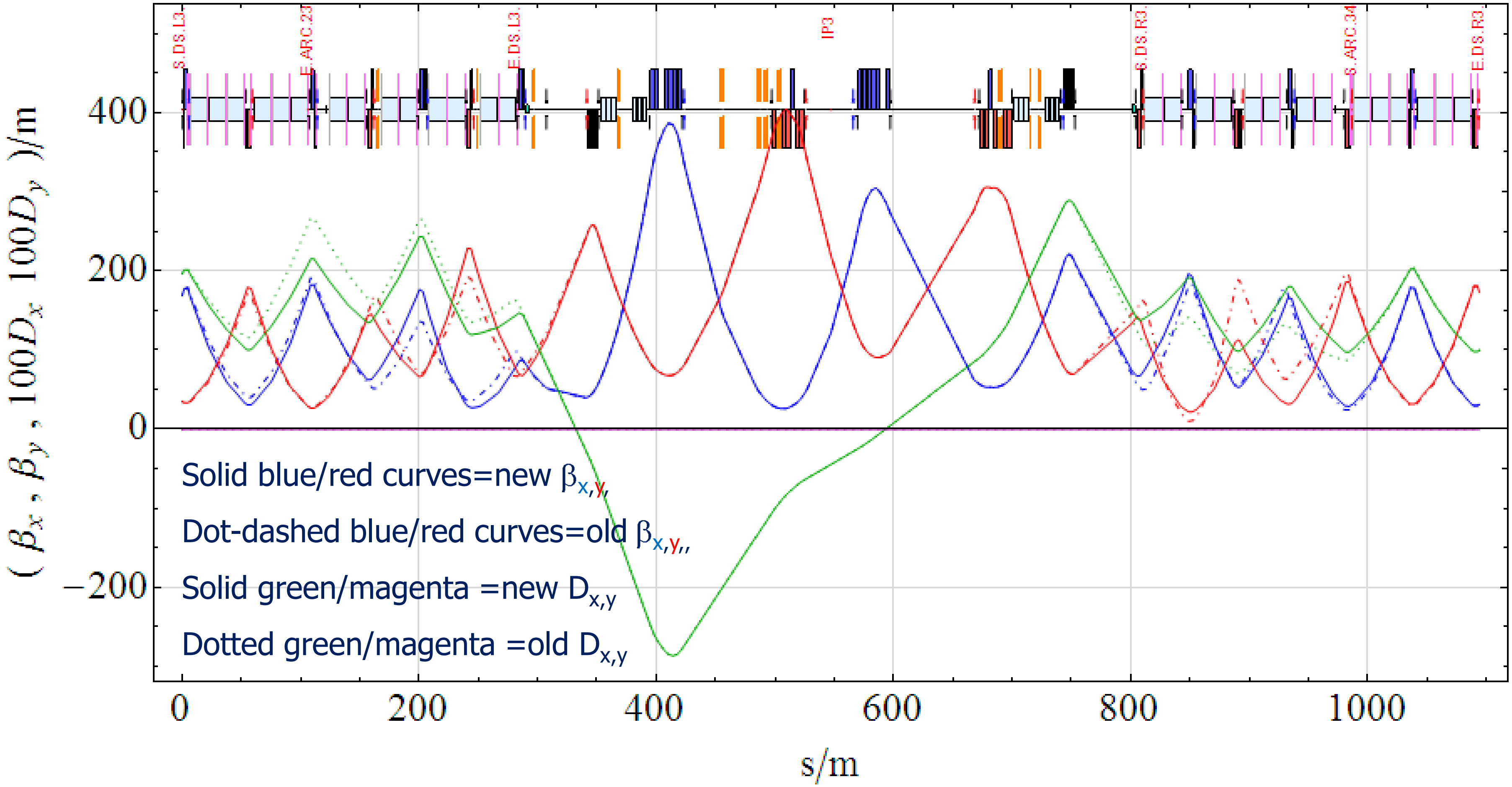
Of course, a proper comparison requires much more elaborate calculations.

May be some scope to improve beam stability

A rematch, maintaining previous optics in warm section, multiple constraints applied to improve aperture.

SOLUTION LHCB1CC1, LHCB2CC1

Rematch of IR3, Beam 1

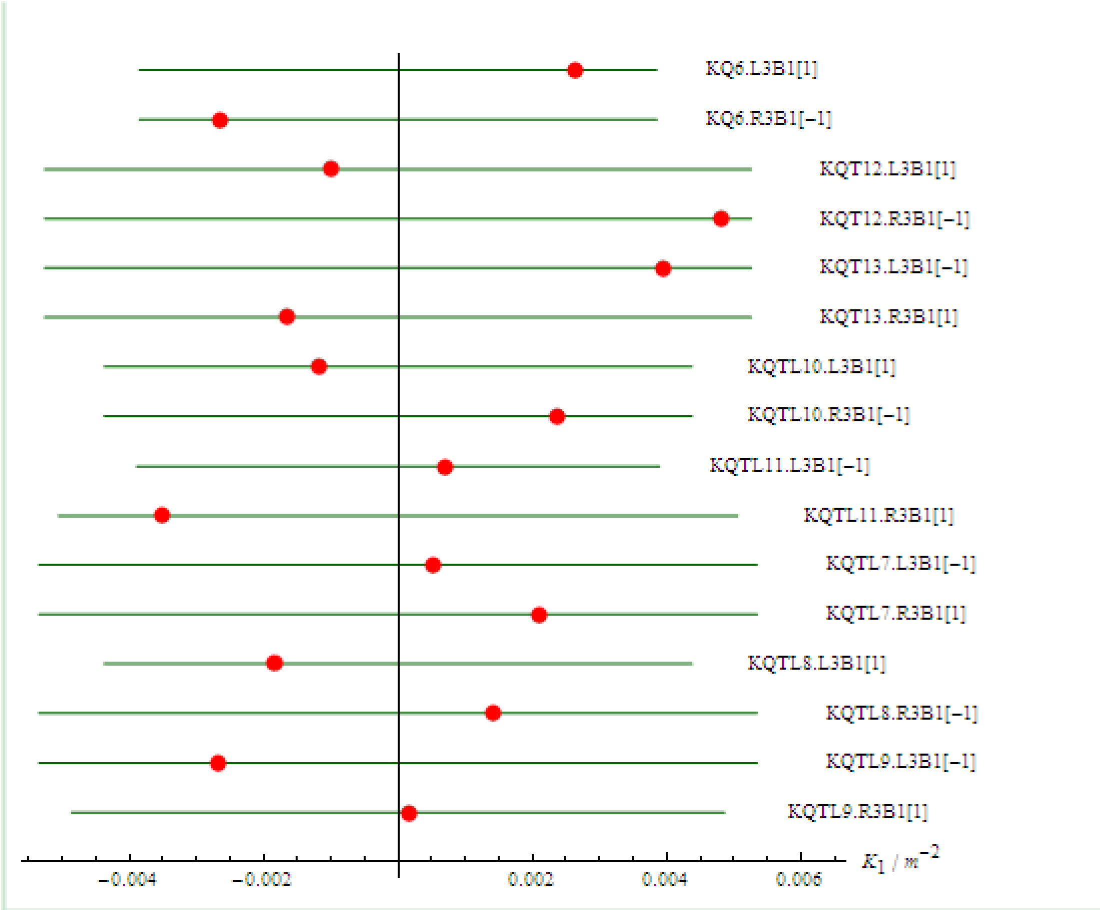


Perfect match – same transfer matrix over IR3 - so can be used in modular way with all existing LHC optics configurations.

Adjusted β-function peaks (many iterations) to avoid loss of mechanical aperture.

Optical functions (except phases) in central (warm) part now identical to old optics.

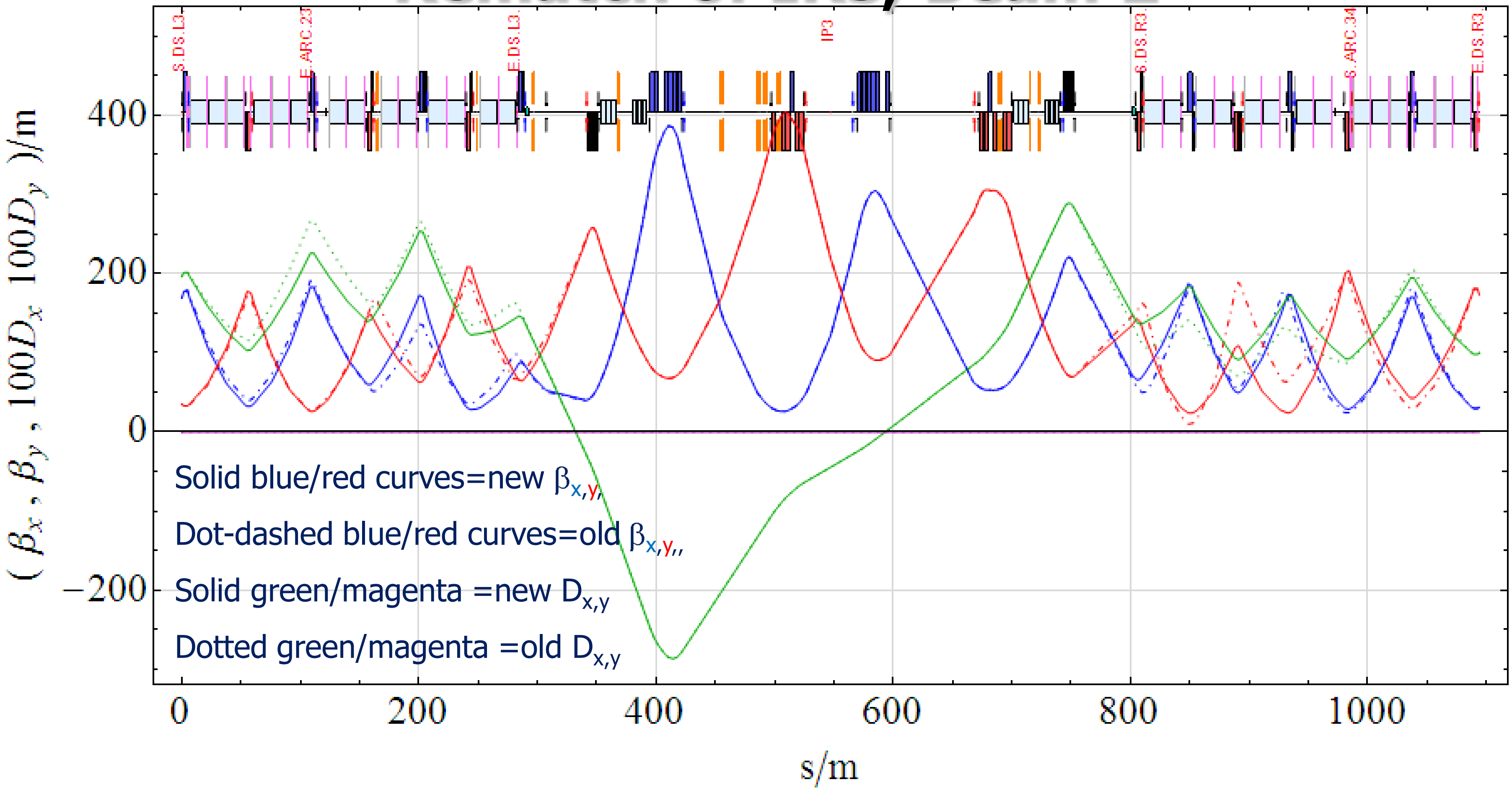
Strengths and limits, Beam 1 at 7*Z* TeV



Strength limits are computed automatically from sequence file and optics data.

All now comfortably within range (green).

Rematch of IR3, Beam 2

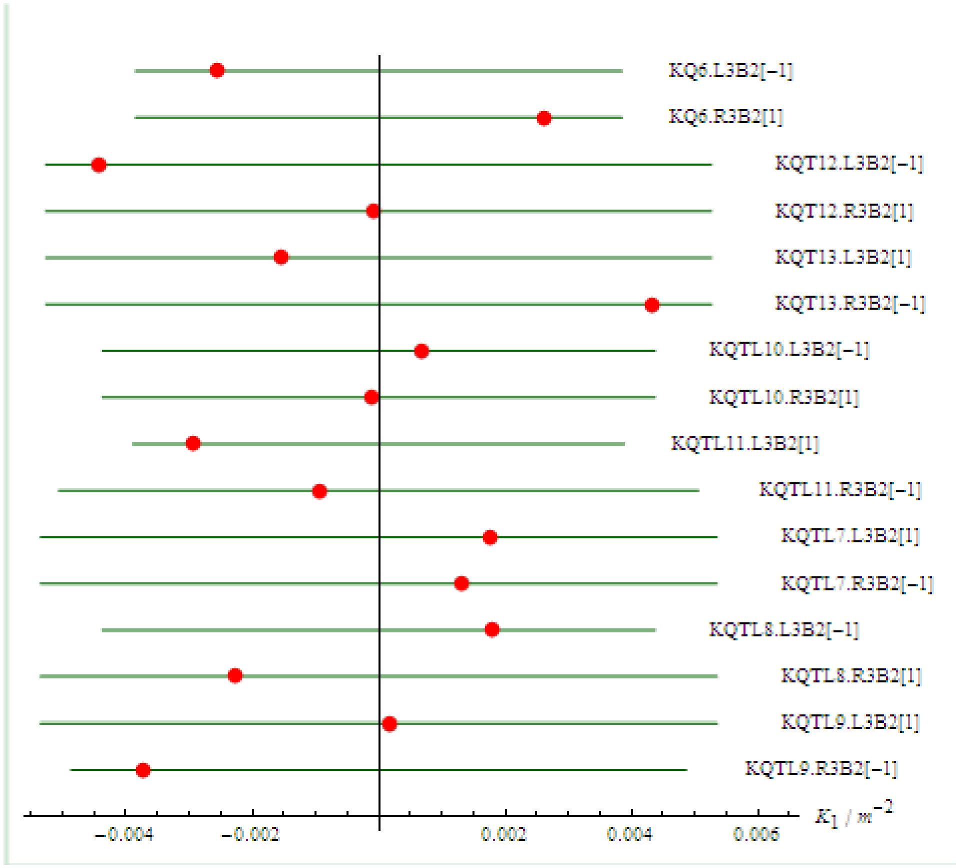


Perfect match – same transfer matrix over IR3, so can be used in modular way with all existing LHC optics configurations.

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

Transfer matrices within warm collimation section are NOT identical.

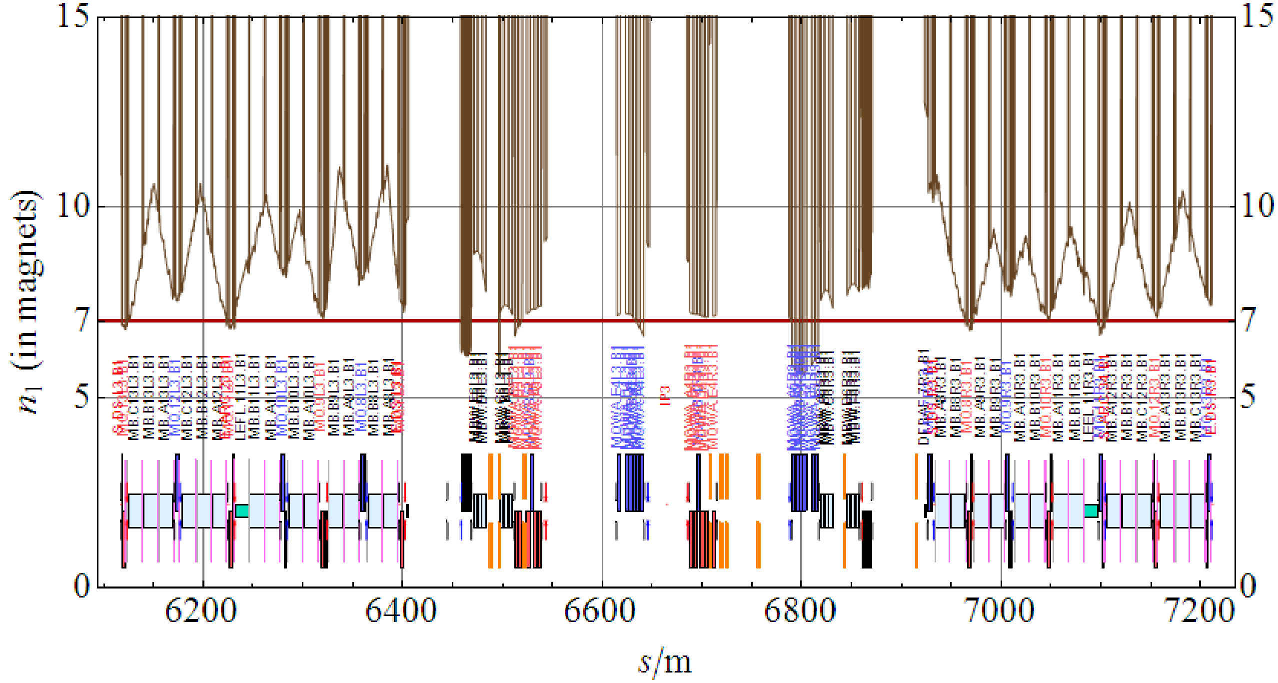
Strengths and limits, Beam 2 at 7Z TeV



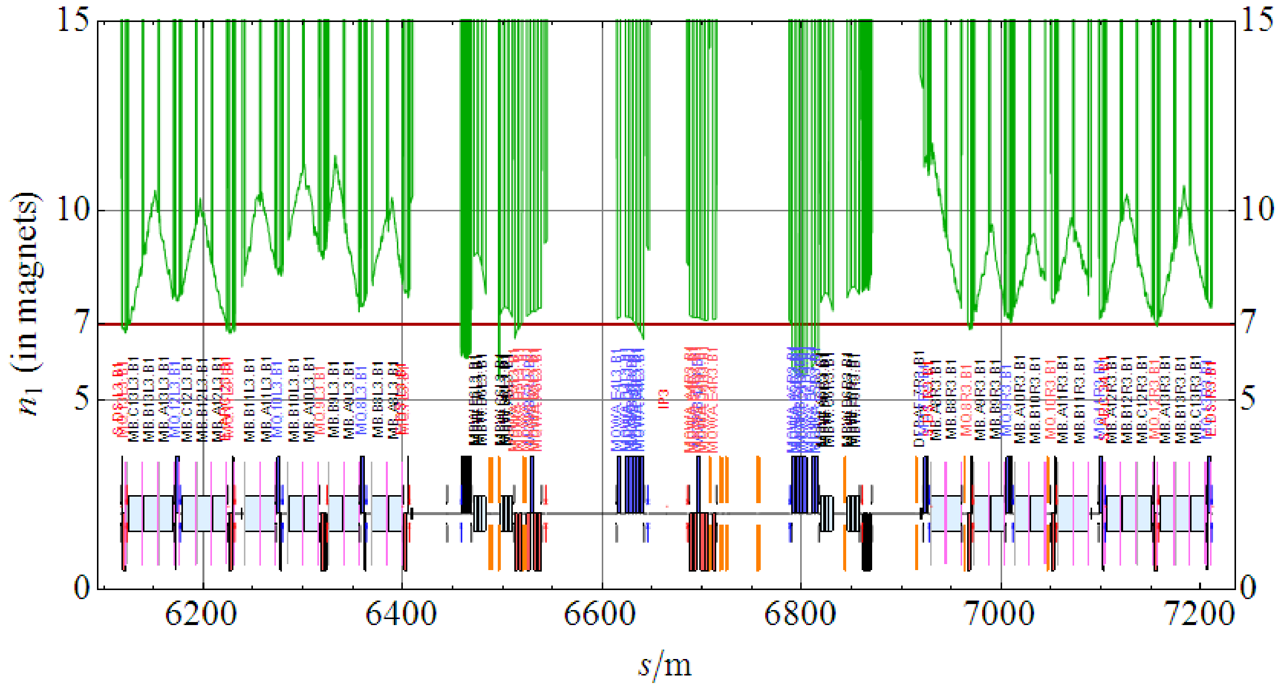
Strength limits are computed automatically from sequence file and optics data.

All now comfortably within range (green).

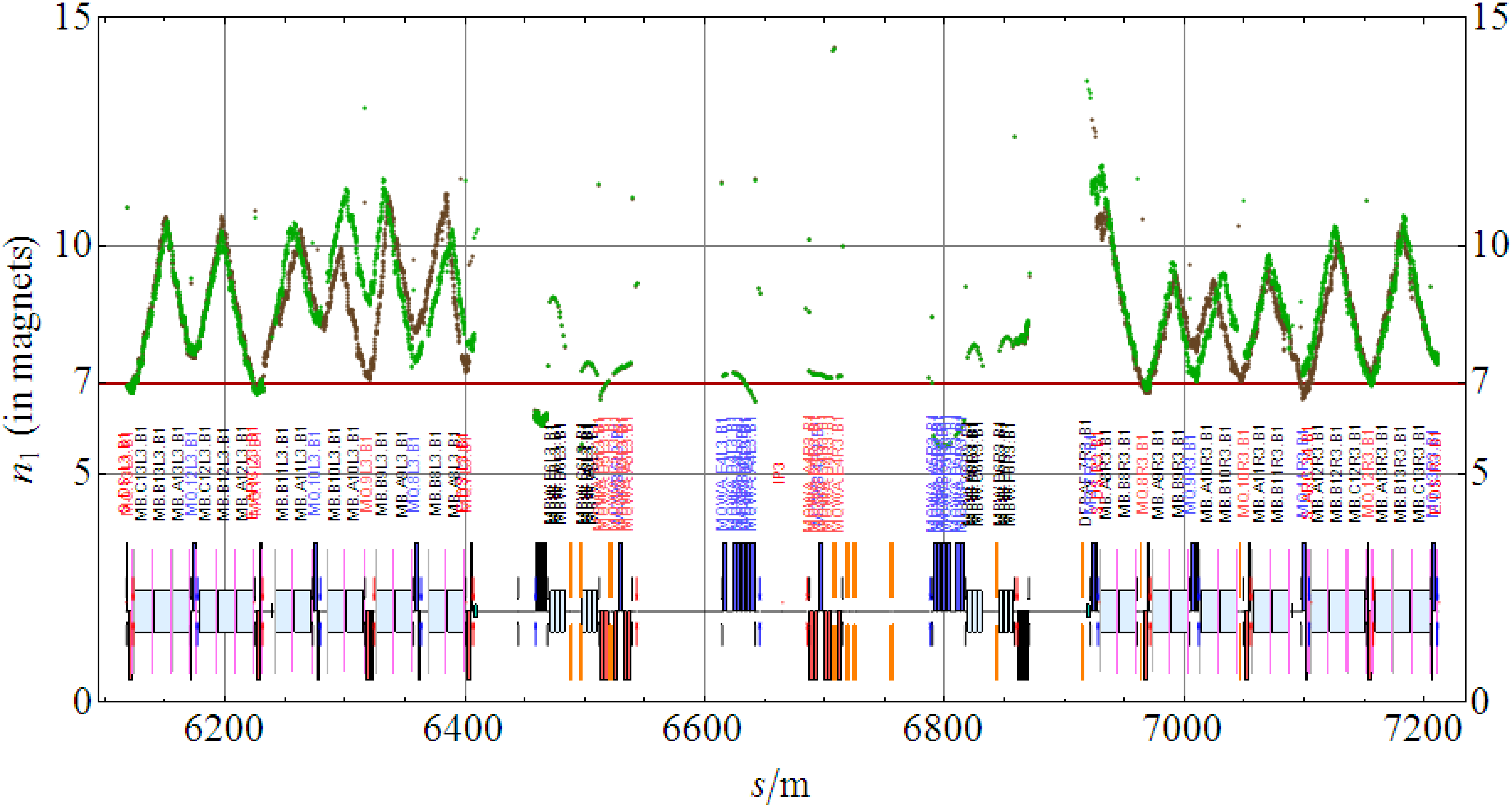
Mechanical aperture of standard IR3.B1 optics at injection.



Mechanical aperture of IR3.B1 LHCB1CC1 optics at injection.

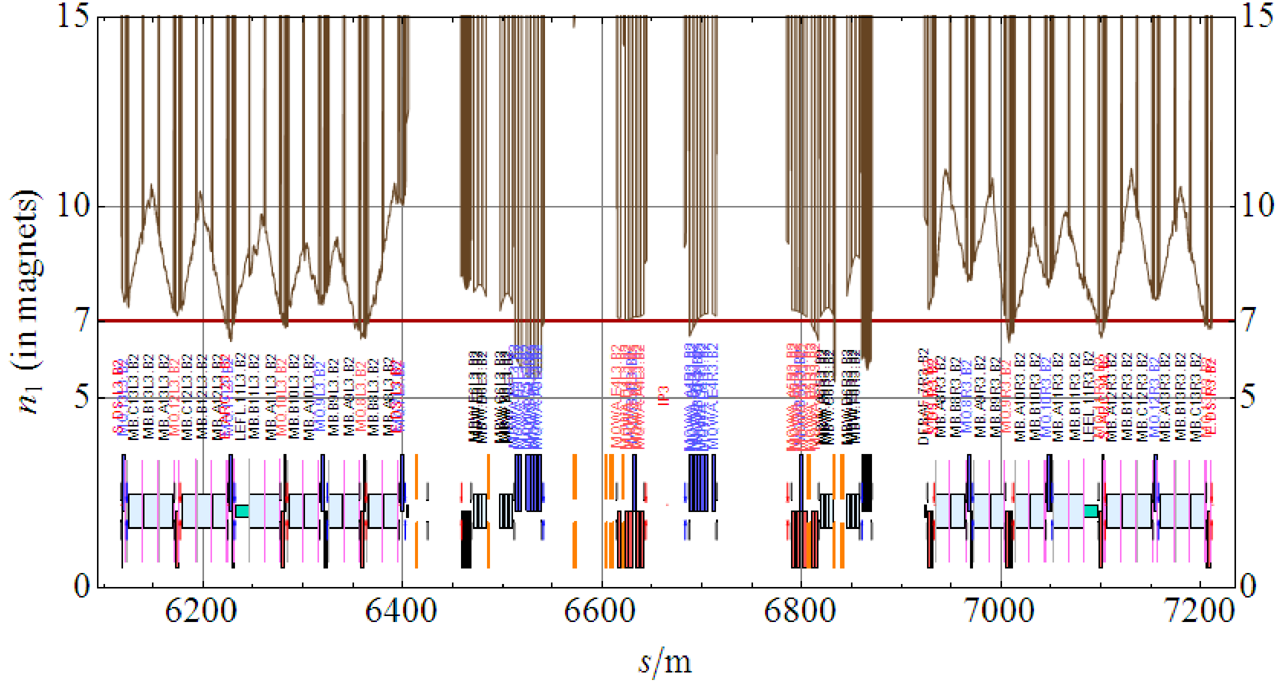


Mechanical aperture comparison, Beam 1

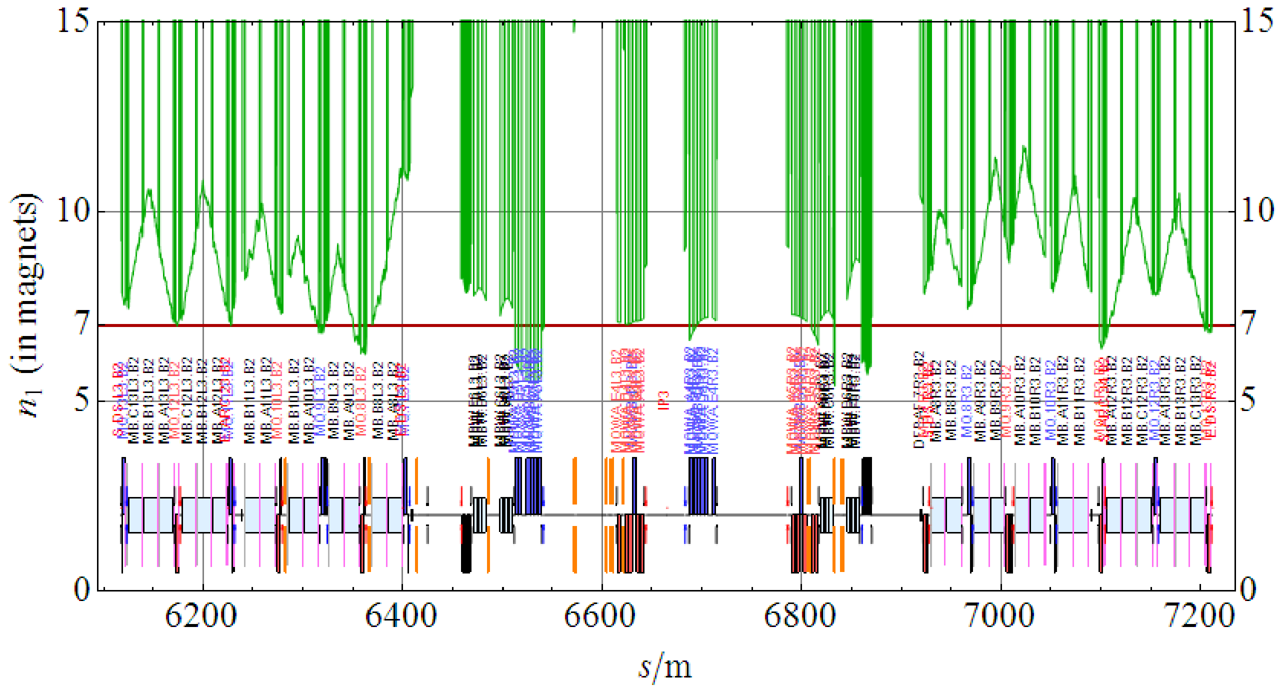


LHCB1CC1 optics (green) with new layout is better than present optics (brown) almost everywhere (should be same in warm part).

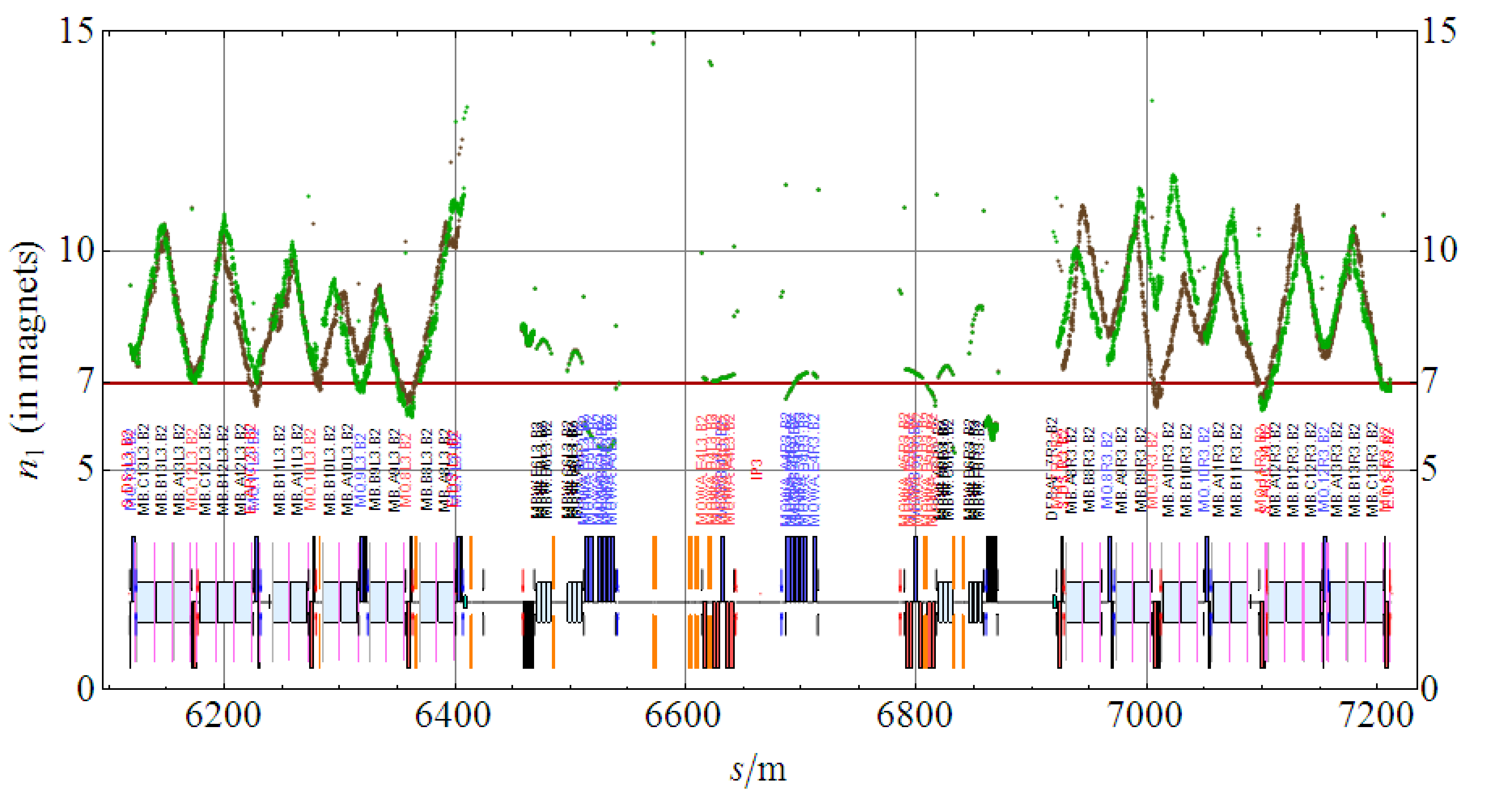
Mechanical aperture of standard IR3.B2 optics at injection.



Mechanical aperture of IR3.B2 LHCB2CC1 optics at injection.



Mechanical aperture comparison, Beam 2



New optics LHCB2CC1 (green) with new layout is better than present optics (brown) in some places.

Results as MAD files

All files in directory:

`/afs/cern.ch/eng/sl/ilhc/JMJ/CryoCollimatorOptics/IR3/`

Sequence file: **`LHCCC.seq`**

Seqedit patch to create new sequences from old:
`LHCCryoCollimatorLayoutIR3.madx`

Strengths for the two optics shown:

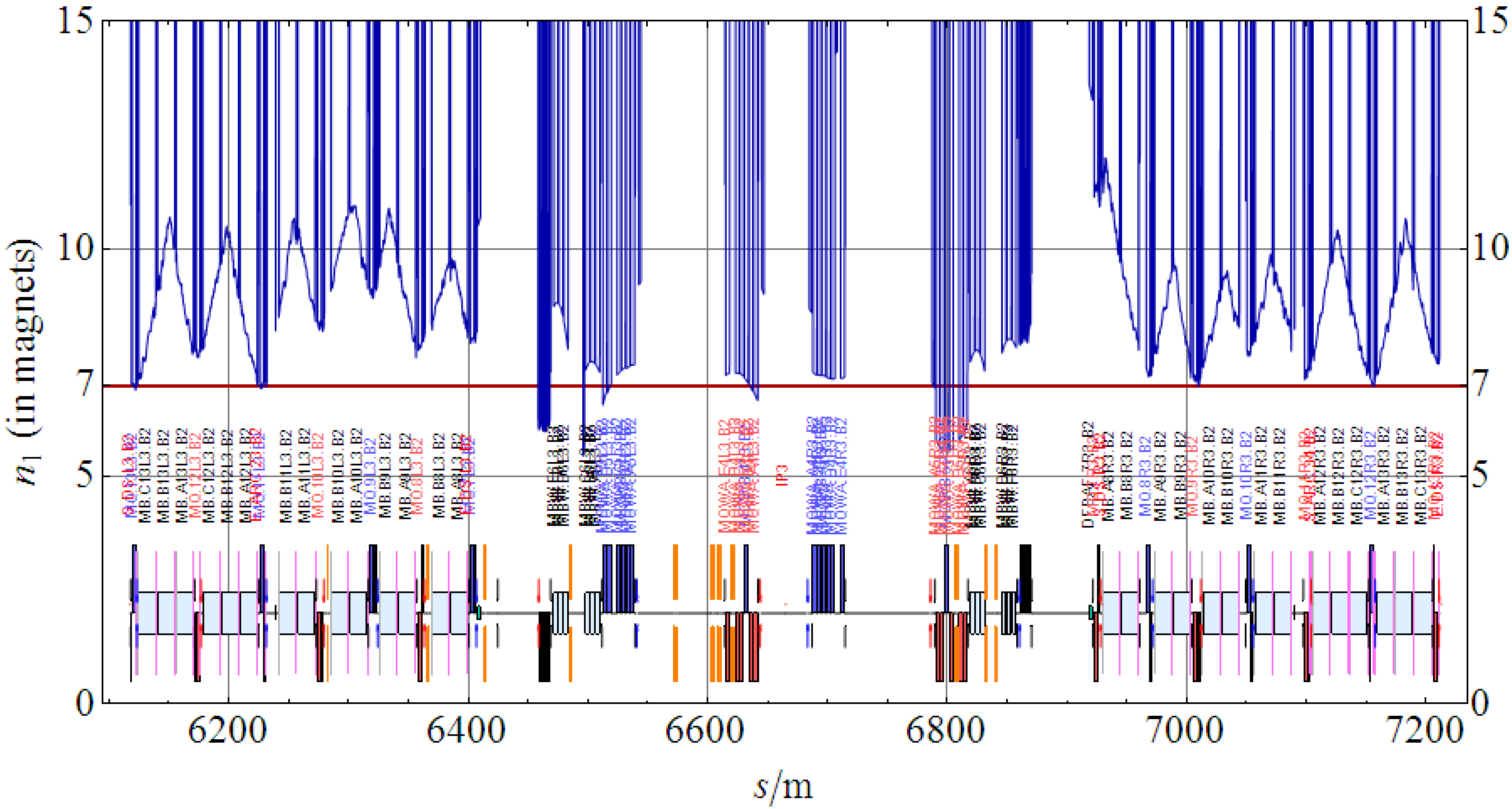
`LHCCryoCollimatorOpticsIR3.str`

`LHCCryoCollimatorOpticsIR3CC1.str`

To be used on top of any other set of strengths for LHC optics V6.503, with the new sequences LHCB1CC, LHCB2CC.

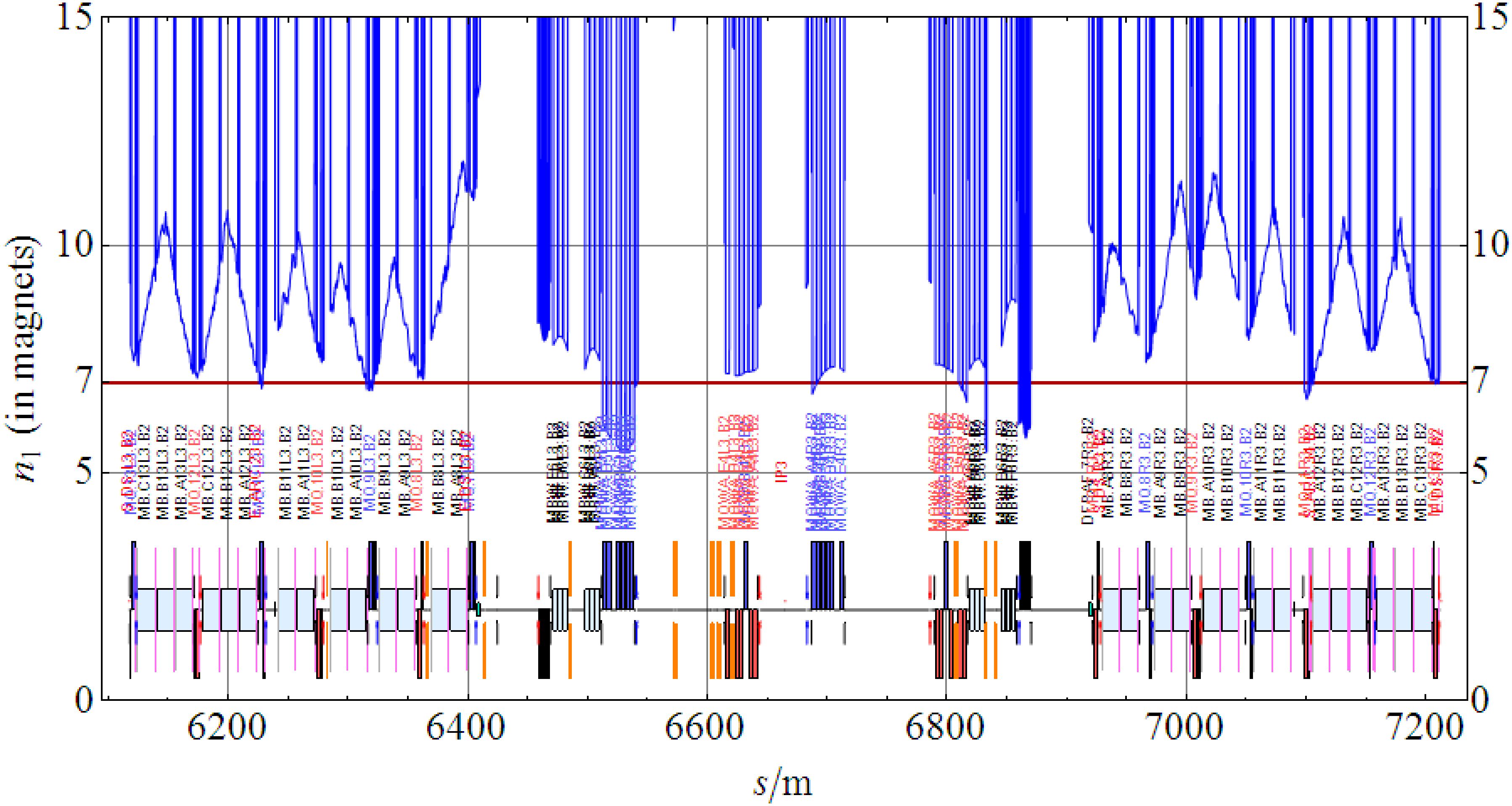
Will be moved to “usual” place soon.

Another matched solution



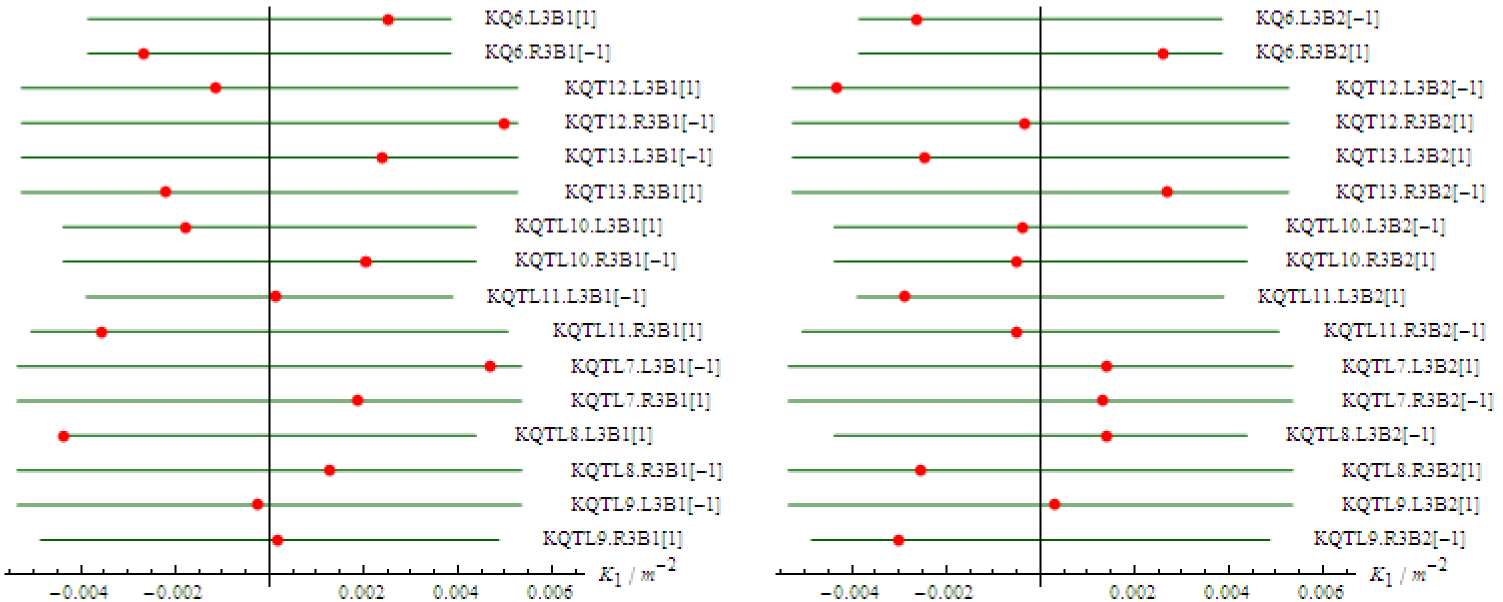
Beam 1, from Thys Risselada.

Another matched solution



Beam 2, from Thys Risselada.

Strengths in TR solution



Conclusions

- A new "cryo-collimator" layout for maximum 4.5 m shift of the dipoles and Q10 has been worked out and is being used as base for hardware integration.
- Optics for both beams re-matched with general improvement in n1 aperture over standard IR3 optics
  - Various solutions available, at least as good as present optics. Can probably be tweaked further.
  - All trim quadrupole strengths now comfortably inside 7 TeV limits.