# New LSS optics for the LHC

20-09-2012

R.B. Appleby
The University of Manchester/Cockcroft Institute, UK

Many thanks to everyone in our optics team, especially Riccardo, Bernhard, Stephane

https://espace.cern.ch/HiLumi/wp2/Wiki/Home.aspx

## Motivation

So we would like small beta* but have optics limitation, including

1) Match-ability and generating phase advance to the arc sextupoles

2) Magnet strengths, particularly magnets going to 0 or maximum current when squeezing

3) Aperture

4) Aberrations e.g. Chromaticity correction

One solution to delivering the low beta* is the ATS optics, which is a clever solution to match-ability and chromatic correction but uses neighboring IR matching sections and gives beta waves in the arcs.

The goal here is **alternatives** to the ATS to deliver small beta* through **smaller** surgery than an entirely new LSS. This confronts the match-ability problem but, through the lack of beta waves in the arcs (for example), does not confront the chromaticity problems.

Or, rephrased, how much (with minor) surgery can we expect from our nominal LSS layout? This can be small beta* or enhanced optics flexibility to, for example, generate phase from IT to sextupoles to correct aberrations.

We'll try and extend the optics **flexibility** of the nominal layout by replacing Q6 with a doublet.

To keep the FODO structure Q5 will also become a doublet.

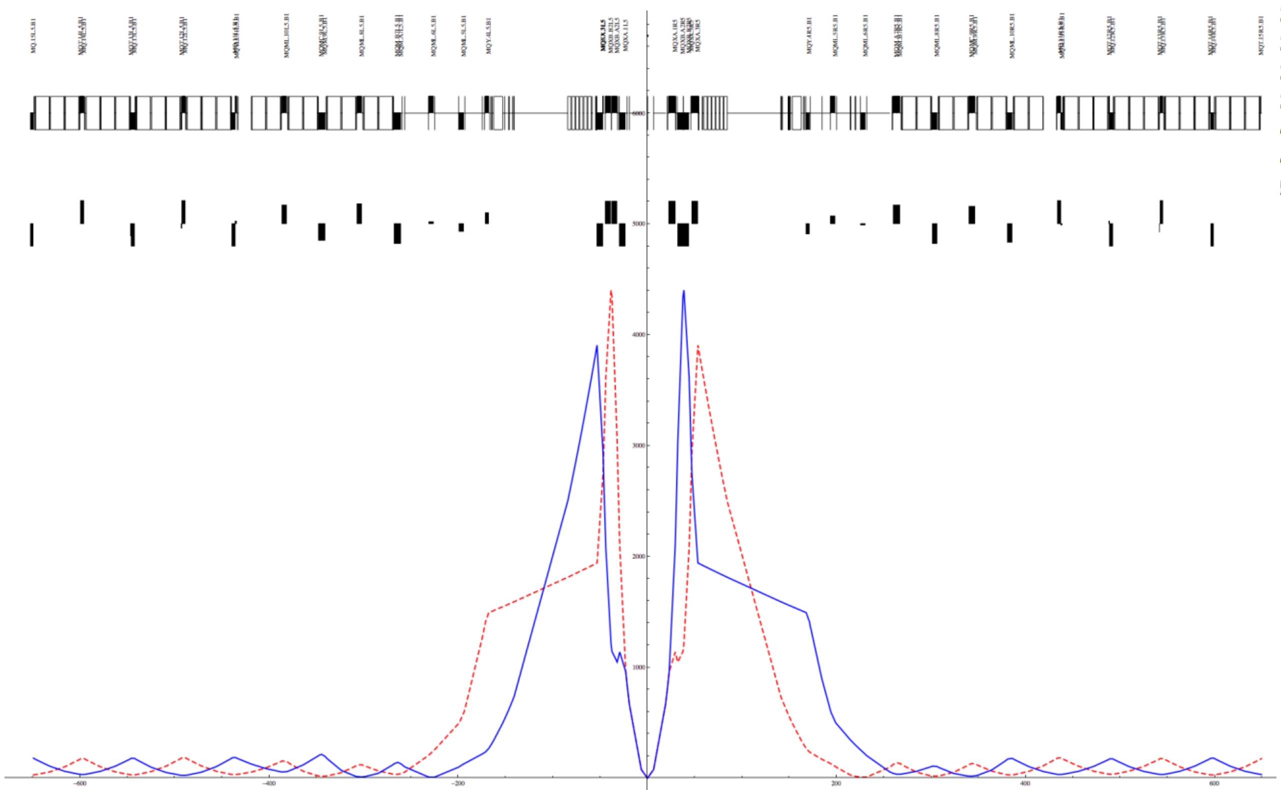
We can imagine many new LSS layouts, but this scheme should give an idea of potential benefits in more flexible optics, lower beta* with just the target IR quads and the ability to generate phase advance to the arc sextupoles for correction of off-momentum beta-beat and possible future local chromaticity correction schemes. (e.g. Barbara's crab talk)

An obvious extension is totally new LSS layouts (Angeles) and local chromaticity correction (Jacques) (?)

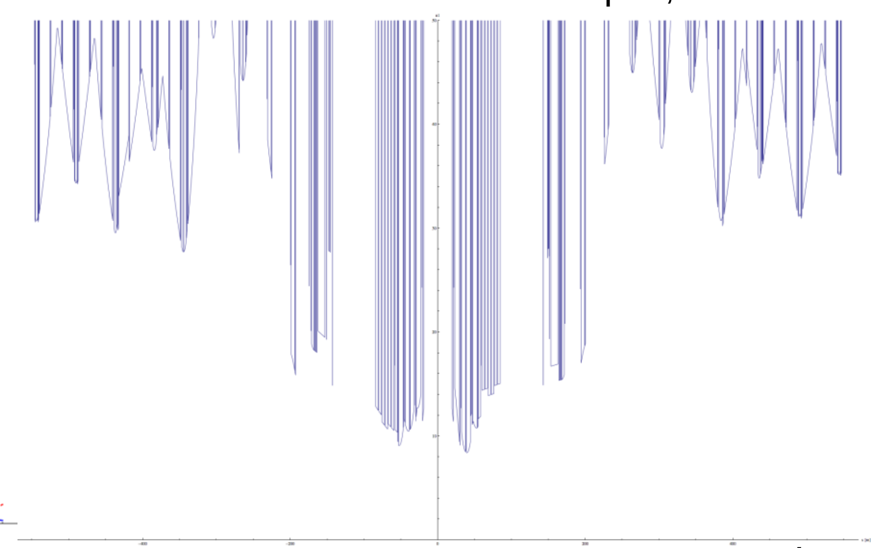
# Nominal LHC optics beta*=0.55m

The nominal LHC optics, for a beta* of 0.55m, known for a
very long time. The structure, after the inner triplet, is an array of matching quads into the arc, Q4, Q5 etc.

| S | NAME | K1 | % STRENGTH | GRAD T/M |
|---|---|---|---|---|
| -545.787 | MQT.13L5.B1 | -0.00459958 | -89.4959 | -107.395 |
| -492.338 | MQT.12L5.B1 | -0.00169699 | -33.019 | -39.6228 |
| -434.238 | MQTLI.11L5.B1 | 0.00107246 | 20.0327 | 25.0408 |
| -381.478 | MQML.10L5.B1 | 0.00710465 | 82.9429 | 165.886 |
| -344.782 | MQMC.9L5.B1 | -0.00640842 | 74.8148 | -149.63 |
| -341.016 | MQM.9L5.B1 | -0.00640842 | 74.8148 | -149.63 |
| -301.95 | MQML.8L5.B1 | 0.00771167 | 90.0295 | 180.059 |
| -264.284 | MQM.B7L5.B1 | -0.00775883 | 90.58 | -181.16 |
| -260.517 | MQM.A7L5.B1 | -0.00775883 | 90.58 | -181.16 |
| -225.99 | MQML.6L5.B1 | 0.00061684 | 9.00158 | 14.4025 |
| -194.09 | MQML.5L5.B1 | -0.00297373 | 43.3959 | -69.4334 |
| -167.853 | MQY.4L5.B1 | 0.00408976 | 59.6822 | 95.4915 |
| -46.965 | MQXA.3L5 | -0.0087302 | 88.8194 | -203.84 |
| -38.55 | MQXB.B2L5 | 0.0087302 | 88.8194 | 203.84 |
| -32.05 | MQXB.A2L5 | 0.0087302 | 88.8194 | 203.84 |
| -22.965 | MQXA.1L5 | -0.0087302 | 88.8194 | -203.84 |
| 29.335 | MQXA.1R5 | 0.0087302 | 88.8194 | 203.84 |
| 37.55 | MQXB.A2R5 | -0.0087302 | 88.8194 | -203.84 |
| 44.05 | MQXB.B2R5 | -0.0087302 | 88.8194 | -203.84 |
| 53.335 | MQXA.3R5 | 0.0087302 | 88.8194 | 203.84 |
| 171.253 | MQY.4R5.B1 | -0.00408976 | 59.6822 | -95.4915 |
| 198.89 | MQML.5R5.B1 | 0.00297373 | 43.3959 | 69.4334 |
| 230.79 | MQML.6R5.B1 | -0.00061684 | 9.00158 | -14.4025 |
| 263.404 | MQM.A7R5.B1 | 0.00719661 | 84.0165 | 168.033 |
| 267.171 | MQM.B7R5.B1 | 0.00719661 | 84.0165 | 168.033 |
| 306.243 | MQML.8R5.B1 | -0.0076628 | 89.459 | -178.918 |
| 342.941 | MQMC.9R5.B1 | 0.00659235 | 76.962 | 153.924 |
| 346.707 | MQM.9R5.B1 | 0.00659235 | 76.962 | 153.924 |
| 385.775 | MQML.10R5.B1 | -0.00709037 | 82.7762 | -165.552 |
| 438.579 | MQTLI.11R5.B1 | -0.000613653 | -11.4625 | -14.3281 |
| 488.653 | MQT.12R5.B1 | 0.00093506 | 18.1938 | 21.8326 |
| 542.105 | MQT.13R5.B1 | -0.00317669 | -61.8101 | -74.1722 |



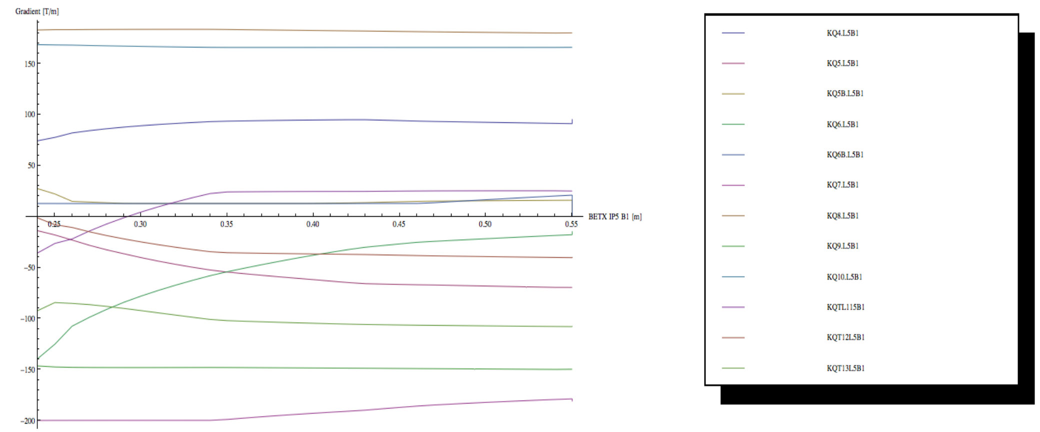
The n1 bottleneck is in the inner triplet, where n1=8

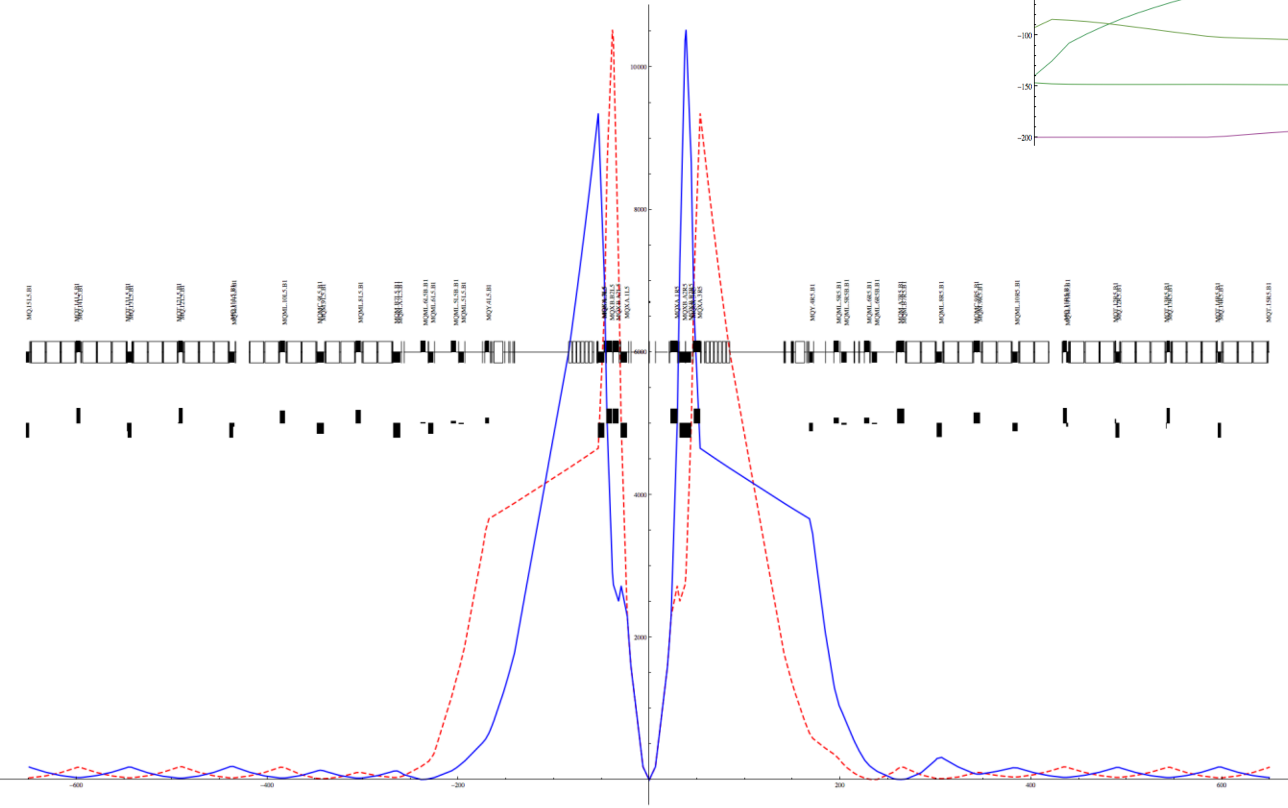


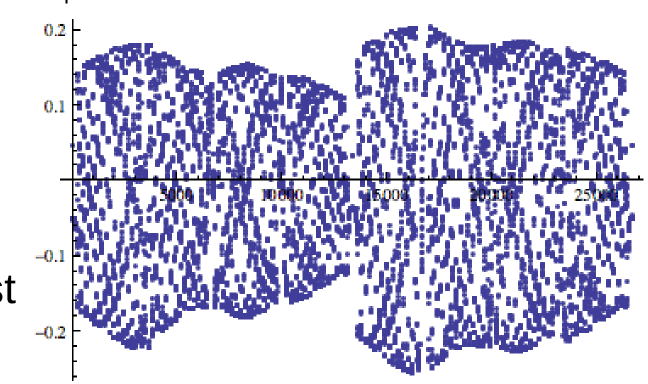
# What we had a few months ago : Q5/Q6 doublet optics with beta*=0.23m beam 1

Now Q5 and Q6 are doublets of the same magnet type. We see, for constant left-right IR phase (0.25 [2Pi] to sexts from inner triplet) we can match down to **0.23m**

**(There was no good injection optics)**




The Q' is corrected to +2 units during the squeeze. The off-momentum beta-beat gets large at beta*=0.23m. No matching is yet done (or at least successfully!) of the real part of W (=B function) but we have the right phase advance to the sextupoles for this to work.

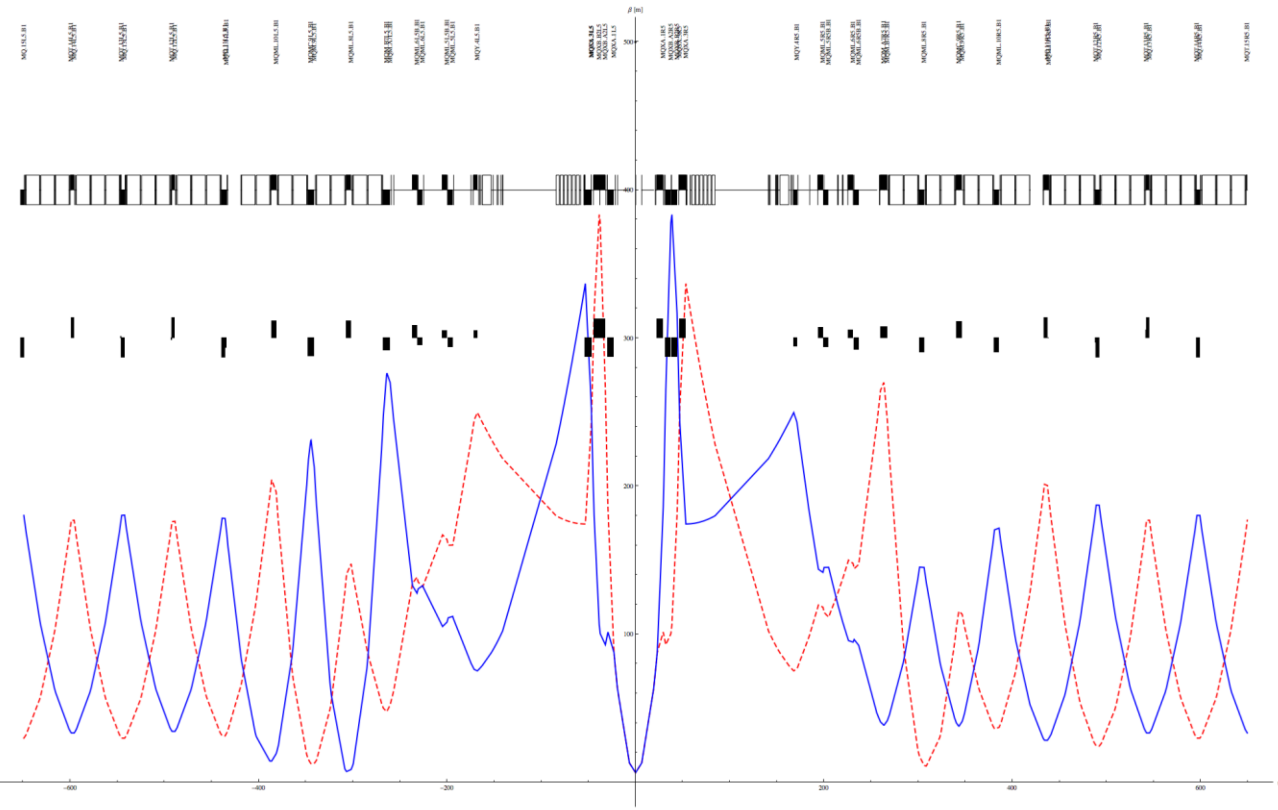
## And now we have a new optics…

Done for a nominal IT with g=200 T/m, aperture=70mm

(And yes, I know this gives severe aperture problems!)

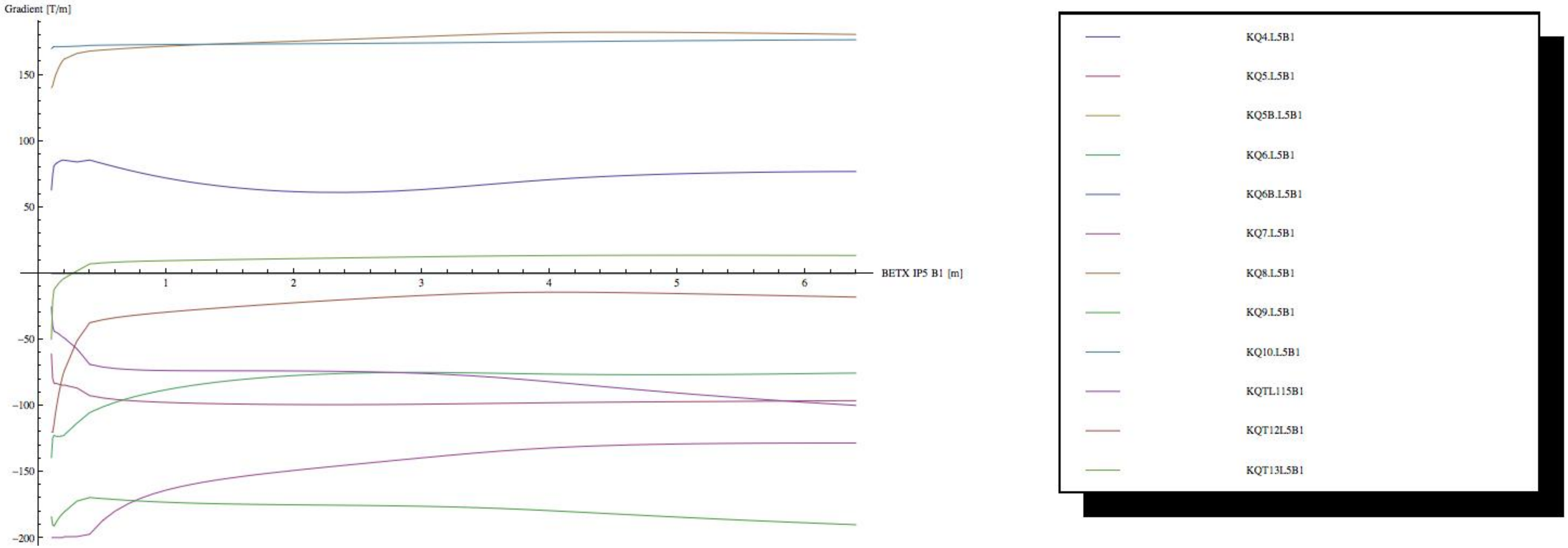
## An injection optics, nominal layout, Q5/Q6 turned into doublets

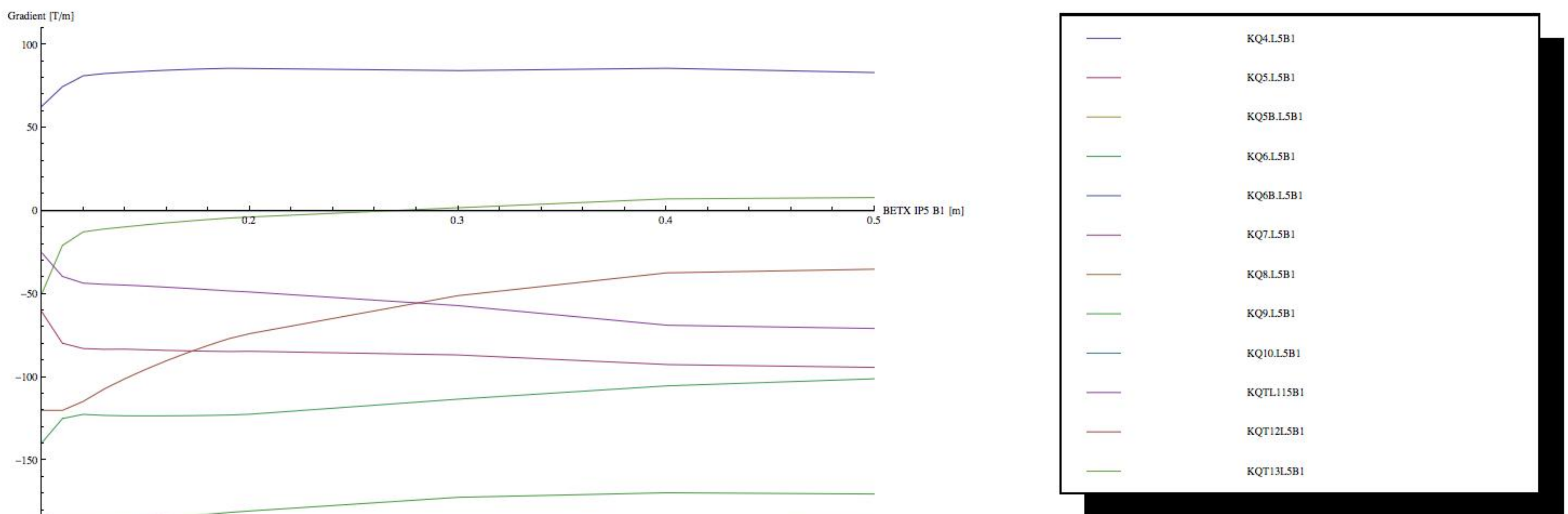
For the injection optics, we need to have a minimum in all the magnets of 3% of the maximum current (=0.43 of maximum k taking the 7 TeV rigidity), be ramp-able to 7 TeV in terms of magnet strengths and also have sufficient aperture in the LSS magnets (so beta peaks controlled). We also need a flat tune during the squeeze and corrected chromaticity. We have a suitable optics with beta*=6.5 m.



| S | NAME | K1 | % STRENGTH | GRAD T/M |
|---|---|---|---|---|
| -545.787 | MQT.13L5.B1 | 0.000580314 | 0.725876 | 0.871051 |
| -492.338 | MQT.12L5.B1 | -0.000776834 | -0.971691 | -1.16603 |
| -434.238 | MQTLI.11L5.B1 | -0.00430103 | -5.16468 | -6.45585 |
| -381.478 | MQML.10L5.B1 | 0.00756921 | 5.68069 | 11.3614 |
| -344.782 | MQMC.9L5.B1 | -0.00815808 | 6.12264 | -12.2453 |
| -341.016 | MQM.9L5.B1 | -0.00815808 | 6.12264 | -12.2453 |
| -301.95 | MQML.8L5.B1 | 0.00773476 | 5.80494 | 11.6099 |
| -264.284 | MQM.B7L5.B1 | -0.00549383 | 4.12312 | -8.24625 |
| -260.517 | MQM.A7L5.B1 | -0.00549383 | 4.12312 | -8.24625 |
| -231.99 | MQML.6L5B.B1 | 0.00562735 | 5.27916 | 8.44666 |
| -225.99 | MQML.6L5.B1 | -0.00322376 | -3.02429 | -4.83886 |
| -200.09 | MQML.5L5B.B1 | 0.00323167 | -3.03171 | 4.85074 |
| -194.09 | MQML.5L5.B1 | -0.00412113 | 3.86613 | -6.18581 |
| -167.853 | MQY.4L5.B1 | 0.00330017 | 3.09597 | 4.95356 |
| -46.965 | MQXA.3L5 | -0.00855339 | 5.59418 | -12.8387 |
| -38.55 | MQXB.B2L5 | 0.00855339 | 5.59418 | 12.8387 |
| -32.05 | MQXB.A2L5 | 0.00855339 | 5.59418 | 12.8387 |
| -22.965 | MQXA.1L5 | -0.00855339 | 5.59418 | -12.8387 |
| 29.335 | MQXA.1R5 | 0.00855339 | 5.59418 | 12.8387 |
| 37.55 | MQXB.A2R5 | -0.00855339 | 5.59418 | -12.8387 |
| 44.05 | MQXB.B2R5 | -0.00855339 | 5.59418 | -12.8387 |
| 53.335 | MQXA.3R5 | 0.00855339 | 5.59418 | 12.8387 |
| 171.253 | MQY.4R5.B1 | -0.00381124 | 3.57542 | -5.72067 |
| 198.89 | MQML.5R5.B1 | 0.00467191 | 4.38284 | 7.01254 |
| 204.89 | MQML.5R5B.B1 | -0.00401607 | -3.76758 | -6.02812 |
| 230.79 | MQML.6R5.B1 | 0.00361806 | -3.39419 | 5.43071 |
| 236.79 | MQML.6R5B.B1 | -0.0051289 | 4.81155 | -7.69849 |
| 263.404 | MQM.A7R5.B1 | 0.00485276 | 3.642 | 7.28399 |
| 267.171 | MQM.B7R5.B1 | 0.00485276 | 3.642 | 7.28399 |
| 306.243 | MQML.8R5.B1 | -0.00635501 | 4.76944 | -9.53888 |
| 342.941 | MQMC.9R5.B1 | 0.00731257 | 5.48808 | 10.9762 |
| 346.707 | MQM.9R5.B1 | 0.00731257 | 5.48808 | 10.9762 |
| 385.775 | MQML.10R5.B1 | -0.00635984 | 4.77306 | -9.54612 |
| 438.579 | MQTLI.11R5.B1 | 0.0000650467 | 0.0781081 | 0.0976352 |
| 488.653 | MQT.12R5.B1 | -0.00215225 | -2.69211 | -3.23053 |
| 542.105 | MQT.13R5.B1 | 0.00356658 | 4.4612 | 5.35344 |

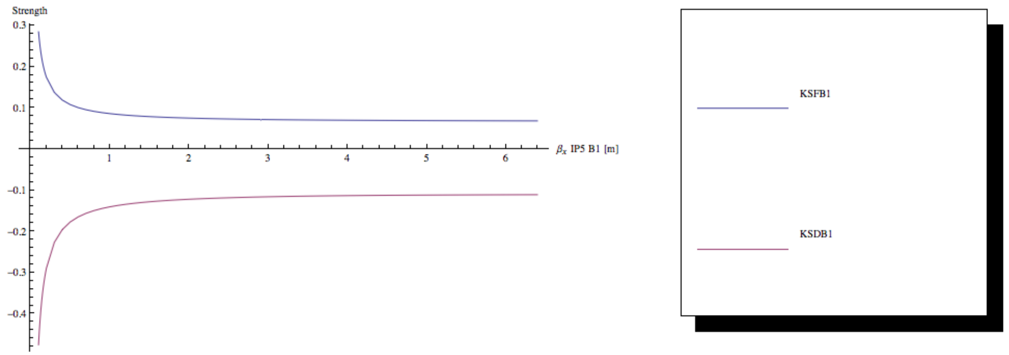
# The squeeze from 6.5m to 0.1m  : quad strengths (not quite anti-symmetric at Q4)

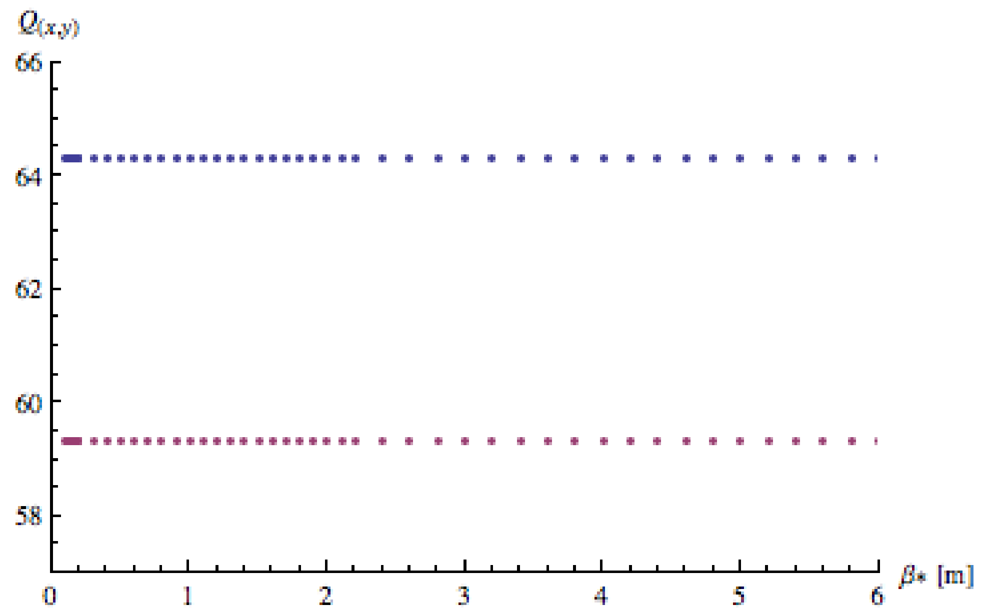


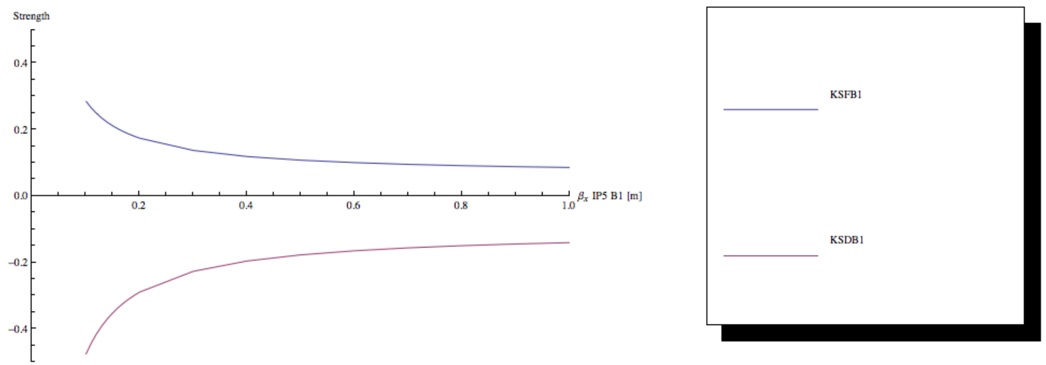



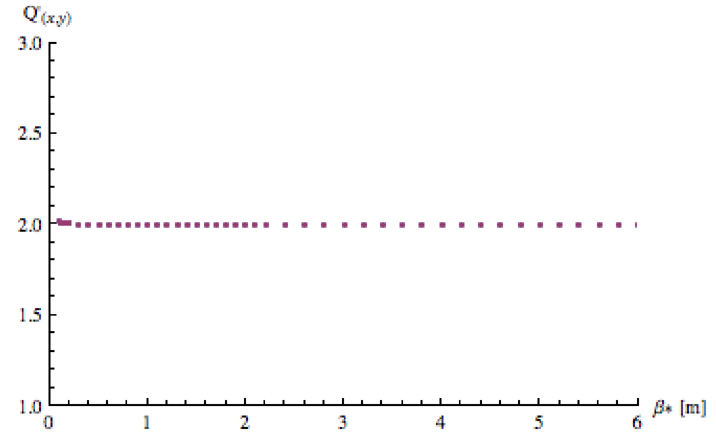

Does it need to be monotonic?

# The squeeze from 6.5m to 0.1m : sextupoles, tune and chromaticity

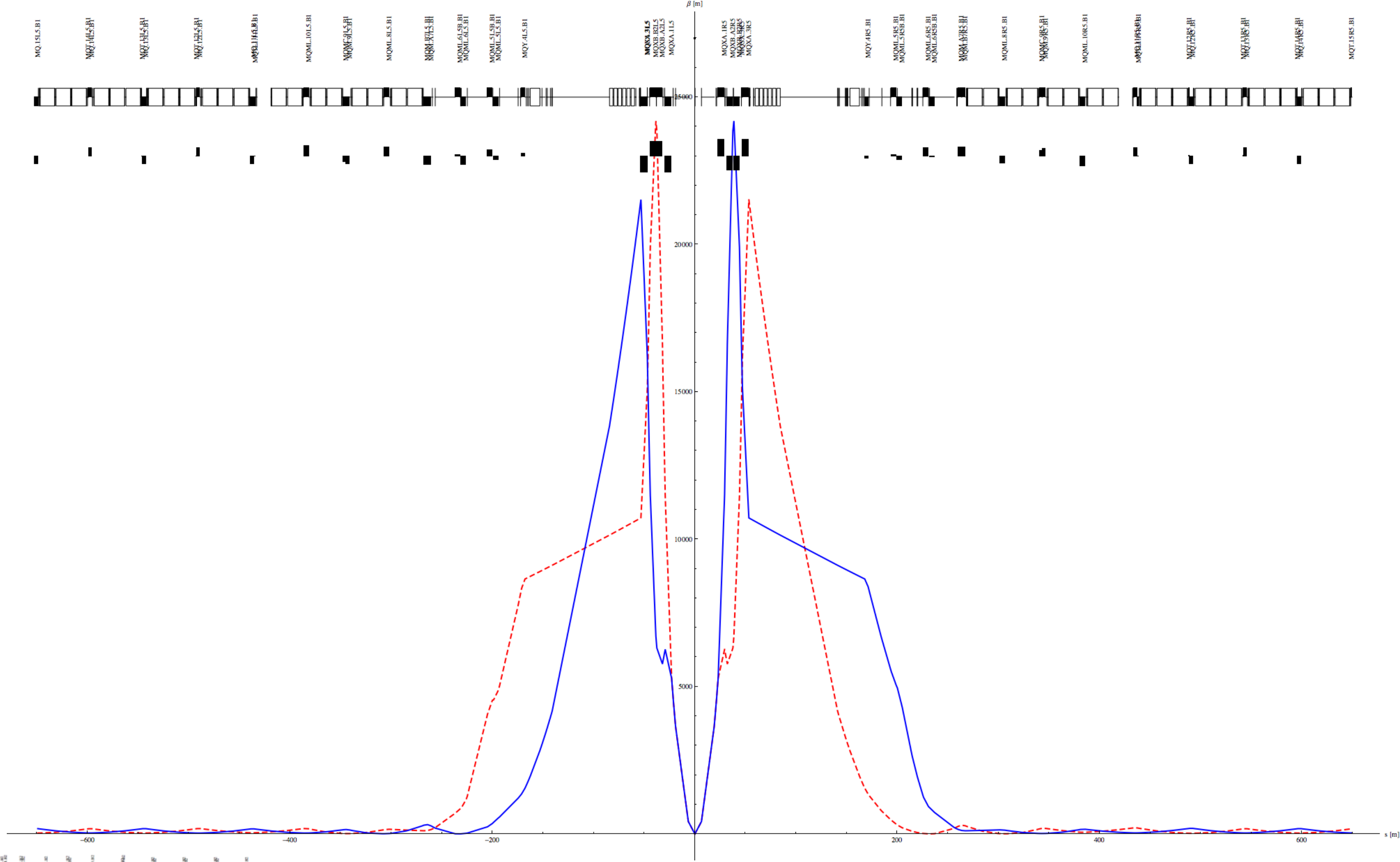


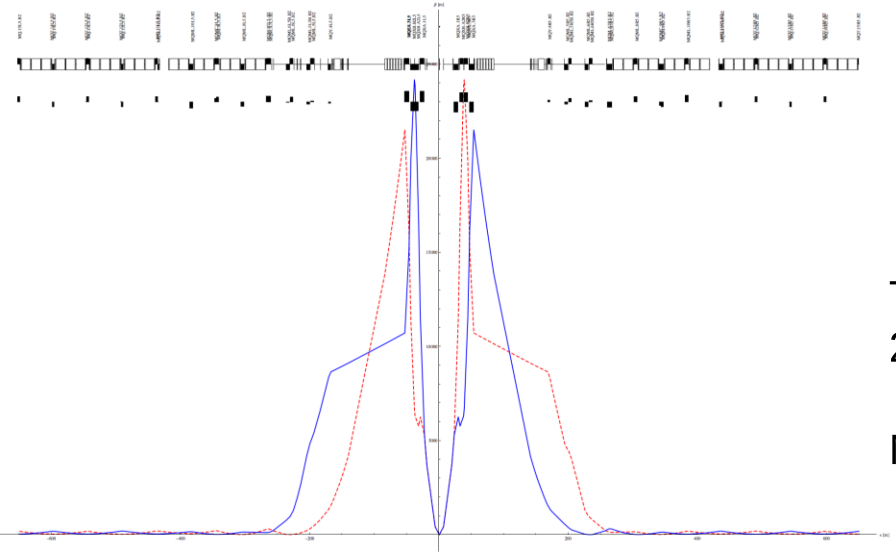



## Q5/Q6 doublet optics with beta*=0.1 m beam 1



This gives an equivalent optics for beam 1. Note the large betas in the final triplet.
Q7 is still the limit.

(What happens is the doublets let you reduce Q7 for a given beta*, so you gain slightly more margin to push on beta*)



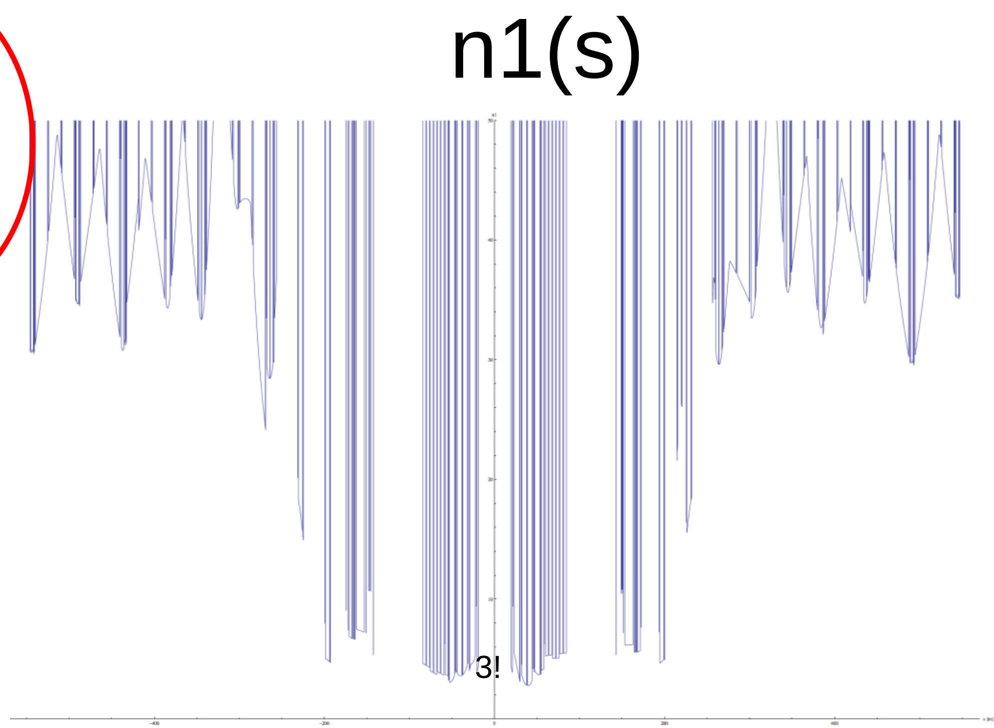
This gives an equivalent optics for beam 2.

Note the large betas in the final triplet.

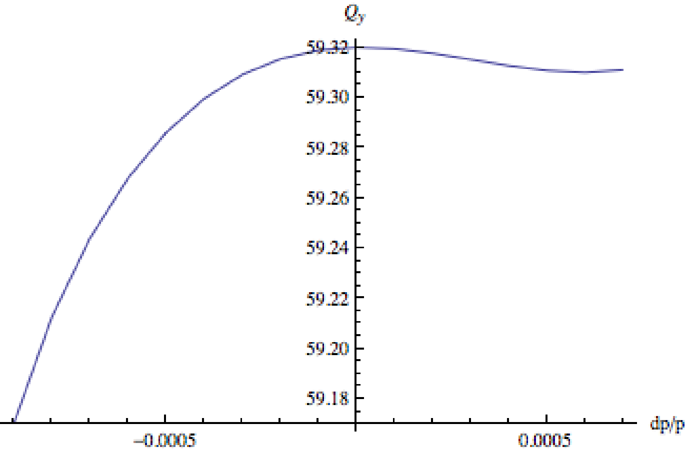
# Q5/Q6 doublet optics with beta*=0.1 m : magnet strengths and aperture

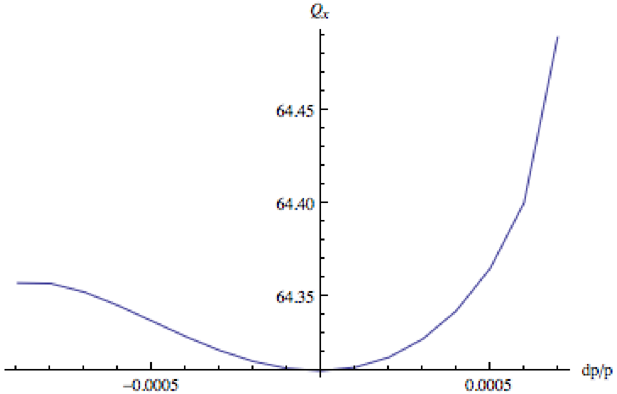
| S | NAME | K1 | % STRENGTH | GRAD T/M |
|---|---|---|---|---|
| -545.787 | MQT.13L5.B1 | -0.00214958 | -41.8253 | -50.1903 |
| -492.338 | MQT.12L5.B1 | -0.00513934 | -99.9984 | -119.998 |
| -434.238 | MQTLI.11L5.B1 | -0.00107381 | -20.0579 | -25.0724 |
| -381.478 | MQML.10L5.B1 | 0.00726712 | 84.8396 | 169.679 |
| -344.782 | MQMC.9L5.B1 | -0.00787109 | 91.8907 | -183.781 |
| -341.016 | MQM.9L5.B1 | -0.00787109 | 91.8907 | -183.781 |
| -301.95 | MQML.8L5.B1 | 0.00600162 | 70.0656 | 140.131 |
| -264.284 | MQM.B7L5.B1 | -0.00856345 | 99.9736 | -199.947 |
| -260.517 | MQM.A7L5.B1 | -0.00856345 | 99.9736 | -199.947 |
| -231.99 | MQML.6L5B.B1 | 0.000817212 | 11.9256 | 19.081 |
| -225.99 | MQML.6L5.B1 | -0.00598357 | -87.3187 | -139.71 |
| -200.09 | MQML.5L5B.B1 | 0.00414423 | -60.477 | 96.7632 |
| -194.09 | MQML.5L5.B1 | -0.00259296 | 37.8393 | -60.5429 |
| -167.853 | MQY.4L5.B1 | 0.00268631 | 39.2015 | 62.7224 |
| -46.965 | MQXA.3L5 | -0.00871219 | 88.6361 | -203.42 |
| -38.55 | MQXB.B2L5 | 0.00871219 | 88.6361 | 203.42 |
| -32.05 | MQXB.A2L5 | 0.00871219 | 88.6361 | 203.42 |
| -22.965 | MQXA.1L5 | -0.00871219 | 88.6361 | -203.42 |
| 29.335 | MQXA.1R5 | 0.00871219 | 88.6361 | 203.42 |
| 37.55 | MQXB.A2R5 | -0.00871219 | 88.6361 | -203.42 |
| 44.05 | MQXB.B2R5 | -0.00871219 | 88.6361 | -203.42 |
| 53.335 | MQXA.3R5 | 0.00871219 | 88.6361 | 203.42 |
| 171.253 | MQY.4R5.B1 | -0.00212478 | 31.0071 | -49.6114 |
| 198.89 | MQML.5R5.B1 | 0.000587828 | 8.57821 | 13.7251 |
| 204.89 | MQML.5R5B.B1 | -0.00269167 | -39.2797 | -62.8475 |
| 230.79 | MQML.6R5.B1 | 0.00568938 | -83.0254 | 132.841 |
| 236.79 | MQML.6R5B.B1 | -0.000571044 | 8.33329 | -13.3333 |
| 263.404 | MQM.A7R5.B1 | 0.00856571 | 99.9999 | 200. |
| 267.171 | MQM.B7R5.B1 | 0.00856571 | 99.9999 | 200. |
| 306.243 | MQML.8R5.B1 | -0.00538324 | 62.8463 | -125.693 |
| 342.941 | MQMC.9R5.B1 | 0.00707416 | 82.5869 | 165.174 |
| 346.707 | MQM.9R5.B1 | 0.00707416 | 82.5869 | 165.174 |
| 385.775 | MQML.10R5.B1 | -0.00712505 | 83.1811 | -166.362 |
| 438.579 | MQTLI.11R5.B1 | -0.00151442 | -28.288 | -35.36 |
| 488.653 | MQT.12R5.B1 | 0.0019672 | 38.2767 | 45.932 |
| 542.105 | MQT.13R5.B1 | 0.00511386 | 99.5024 | 119.403 |

| S | NAME | K2 | % STRENGTH | GRAD T/M^2 |
|---|---|---|---|---|
| 439.125 | MS.11R5.B1 | 0.285634 | 75.2893 | 6669.23 |
| 492.581 | MS.12R5.B1 | -0.476677 | -125.646 | -11 129.9 |
| 546.032 | MS.13R5.B1 | 0.285634 | 75.2893 | 6669.23 |
| 599.484 | MS.14R5.B1 | -0.476677 | -125.646 | -11 129.9 |

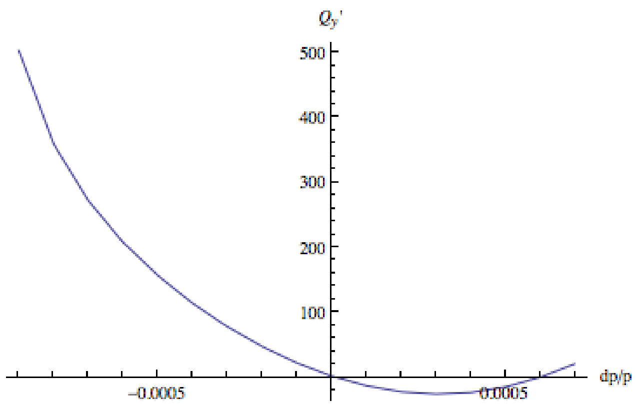


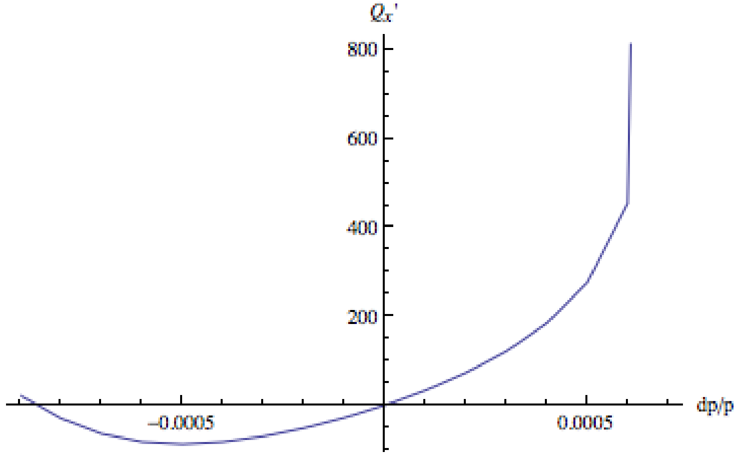
# Chromatic behaviour for fully squeezed optics

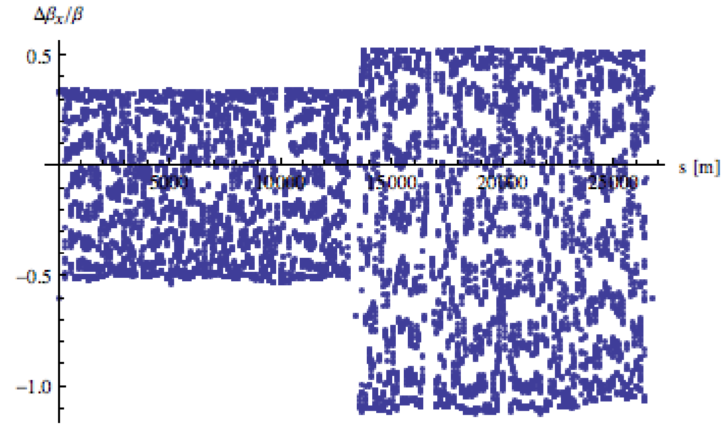


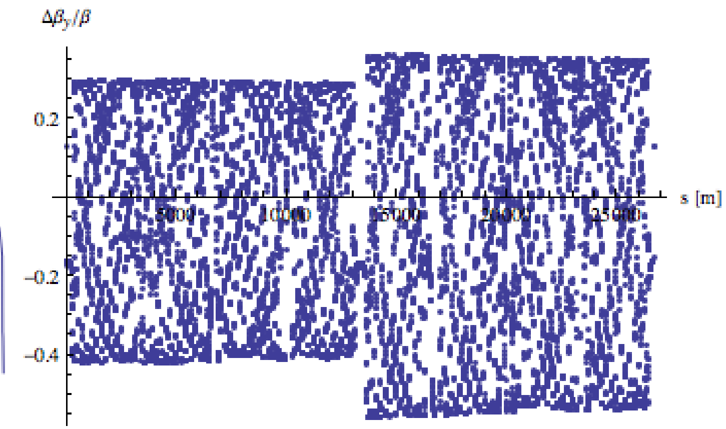



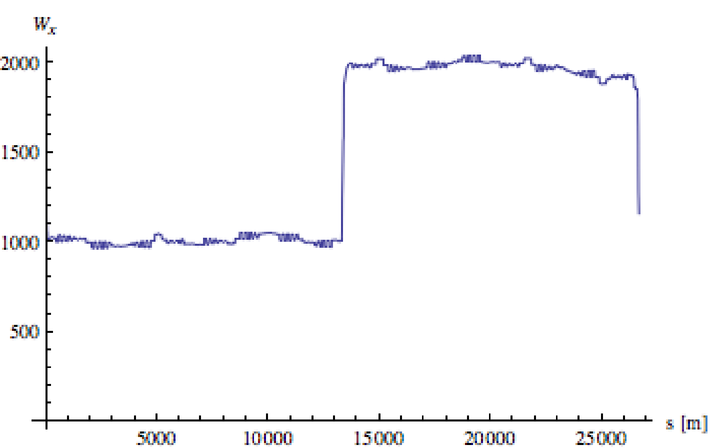

We use pretty much all of the sextupole strength for the linear chromaticity correction (+2 units)

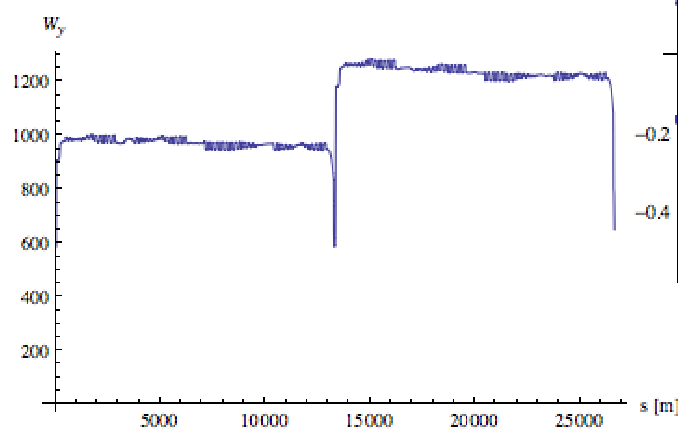


This was the previous optics (beta*=23cm), with well defined phase relationships from the IT to the sextupoles

The phase advances from the IT to the arc sextupoles are 0.25 [2PI]

| | | | | | | |
|---|---|---|---|---|---|---|
| 0.369 | SEXTUPOLE | -648.756 | MS.15L5.B1 | -0.0646303 | -1.13771 | -1.49938 |
| 0.369 | SEXTUPOLE | -595.308 | MS.14L5.B1 | 0.0777643 | -1.01533 | -1.36963 |
| 0.369 | SEXTUPOLE | -541.859 | MS.13L5.B1 | -0.130663 | -0.874367 | -1.2563 |
| 0.369 | SEXTUPOLE | -488.411 | MS.12L5.B1 | 0.0398396 | -0.756056 | -1.10108 |
| 0.369 | SEXTUPOLE | -433.691 | MS.11L5.B1 | -0.0646303 | -0.609088 | -0.972414 |

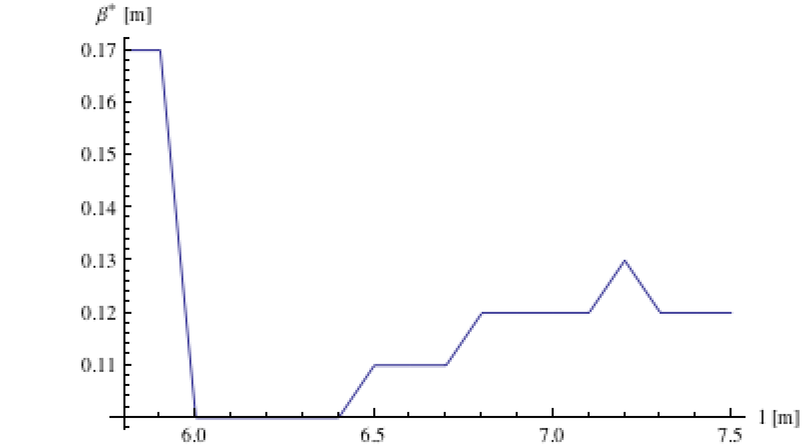
| | | | | | | |
|---|---|---|---|---|---|---|
| 0.369 | SEXTUPOLE | 439.125 | MS.11R5.B1 | 0.0777643 | 0.99317 | 0.645325 |
| 0.369 | SEXTUPOLE | 492.581 | MS.12R5.B1 | -0.130663 | 1.12087 | 0.753665 |
| 0.369 | SEXTUPOLE | 546.032 | MS.13R5.B1 | 0.0398396 | 1.2321 | 0.885518 |
| 0.369 | SEXTUPOLE | 599.484 | MS.14R5.B1 | -0.0646303 | 1.37321 | 0.998832 |

This was too not maintained in the new scheme as we have no beta wave in the arc and so we won’t use the sextupoles efficiently enough to correct any more than Q’

| | | | | | $\mu^{IT}_x$ | $\mu^{IT}_y$ |
|---|---|---|---|---|---|---|
| 0.369 | SEXTUPOLE | -648.756 | MS.15L5.B1 | -0.175894 | -1.00146 | -1.64285 |
| 0.369 | SEXTUPOLE | -595.308 | MS.14L5.B1 | 0.105399 | -0.879082 | -1.5131 |
| 0.369 | SEXTUPOLE | -541.859 | MS.13L5.B1 | -0.175894 | -0.738047 | -1.39978 |
| 0.369 | SEXTUPOLE | -488.411 | MS.12L5.B1 | 0.105399 | -0.617667 | -1.25845 |
| 0.369 | SEXTUPOLE | -433.691 | MS.11L5.B1 | -0.175894 | -0.497824 | -1.13113 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 0.369 | SEXTUPOLE | 439.125 | MS.11R5.B1 | 0.105399 | 1.05859 | 0.512473 |
| 0.369 | SEXTUPOLE | 492.581 | MS.12R5.B1 | -0.175894 | 1.22013 | 0.614138 |
| 0.369 | SEXTUPOLE | 546.032 | MS.13R5.B1 | 0.105399 | 1.36677 | 0.740422 |
| 0.369 | SEXTUPOLE | 599.484 | MS.14R5.B1 | -0.175894 | 1.50788 | 0.853735 |

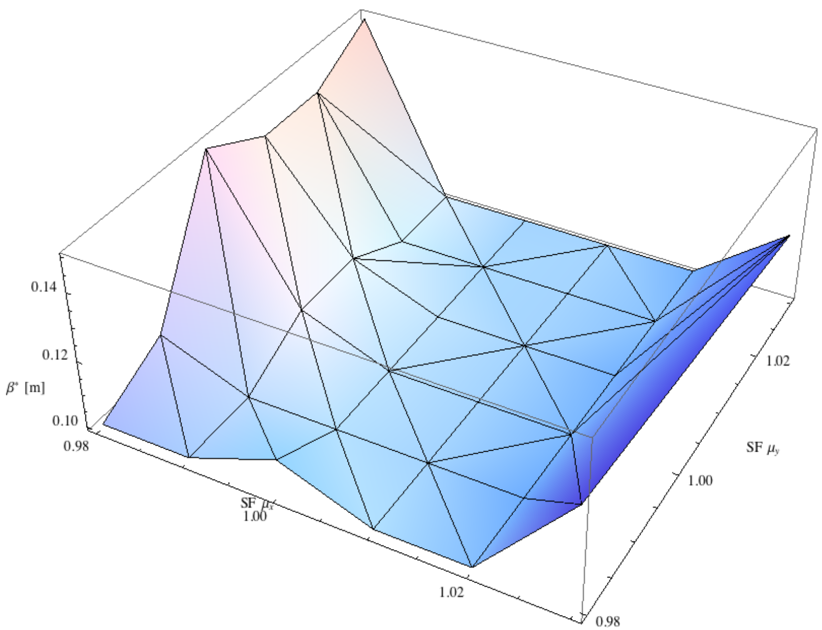
An intra-doublet distance of 6 – 6.5 m works well



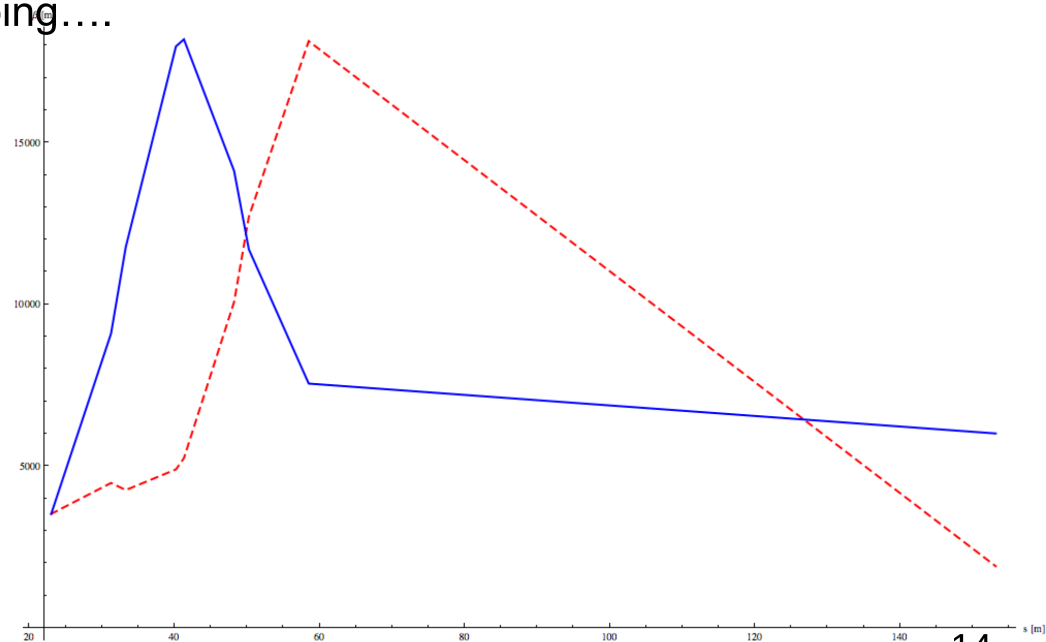

We clearly need the layout with lower gradient, higher aperture IT magnets to account for the big beams in the IT.

Here we aim for a solution with 155 T/m IT, with doublet Q5 and Q6, matched into the nominal layout of the LSS. (Using mktriplet to generate the triplet and then do some matching into the rest of the LSS).

For l=6.2m we have some phase flexibility (especially vertically)




The triplet matched to the IP and the betas at 153m is made, and the matching into the <u>nominal</u> LSS is on-going….



## Open questions

Replacing Q5 and Q6 by doublets (to maintain the FODO structure) gives a LSS optics with more flexibility and the ability to squeeze to 0.1 m while maintaining overall phase advance across the IR but not the left-right phase advance.

The collision optics seem interesting and now we should aim for i) a new large aperture IT (almost there) ii) enhanced Q'' and off-momentum beta-beat control through tighter phase advances (Q'=2 but OMBB big!)

There's a solution for the injection optics (beta*=6.5 m) which satisfies aperture and magnet constraints. Note we maintain the phase advances for the injection optics.

The squeezed beta optics is matched to Q'=2, but no matching on Montague B function (Re(W)).

Chromaticity correction is a big issue, as we simply don't have enough sextupole strength to do more than correct the linear chromaticity to +2 (The 'A' in ATS is important!)

Any extra ability to create phase advance should help any local chromaticity correction schemes, as we need sextupoles at a phase advance of pi for geometric aberration cancellation.

As usual, all comments / advice is well received.

# Back-up slides

# Some background…

Luminosity (round beams):

$$L = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot R(\phi, \beta^*, \varepsilon_n, \sigma_s)$$

1) maximize bunch brightness (beam-beam limit) ➔ [$N_b/e_n$]
2) minimize beam size
3) maximize number of bunches
4) compensate for ‘R’

Pushing on beta* gives a zoo of potential issues:

- Aperture
- **Optics matchability** to the arcs (some IR quads going to 0, others to max. field).
- Chromatic aberrations -> sext strength -> novel squeezing mechanisms
- Event pile up and bunch luminosity limit -> detectors upgrade

Slide from the HL-LHC kick-off meeting

# Motivations (2/2)

→ **Bare minimum $\beta^* \cong$ 30 cm** found for the former upgrade project (Phase I) with a **120 T/m - 120 mm NbTi triplet.**

→ **3 options** to reach the **HL-LHC $\beta^*$ of 15cm (or below)**

**1) 480 T/m - 120 mm ultra-short triplet (~ 40 T critical field)**

**→ Not for this Project!**

**2) Heavy surgery in the ring:**

**a)** double (triple?) the length of the low-beta insertions, eating in the arcs and with more matching standalone quadrupoles to solve the optics matchability limit.

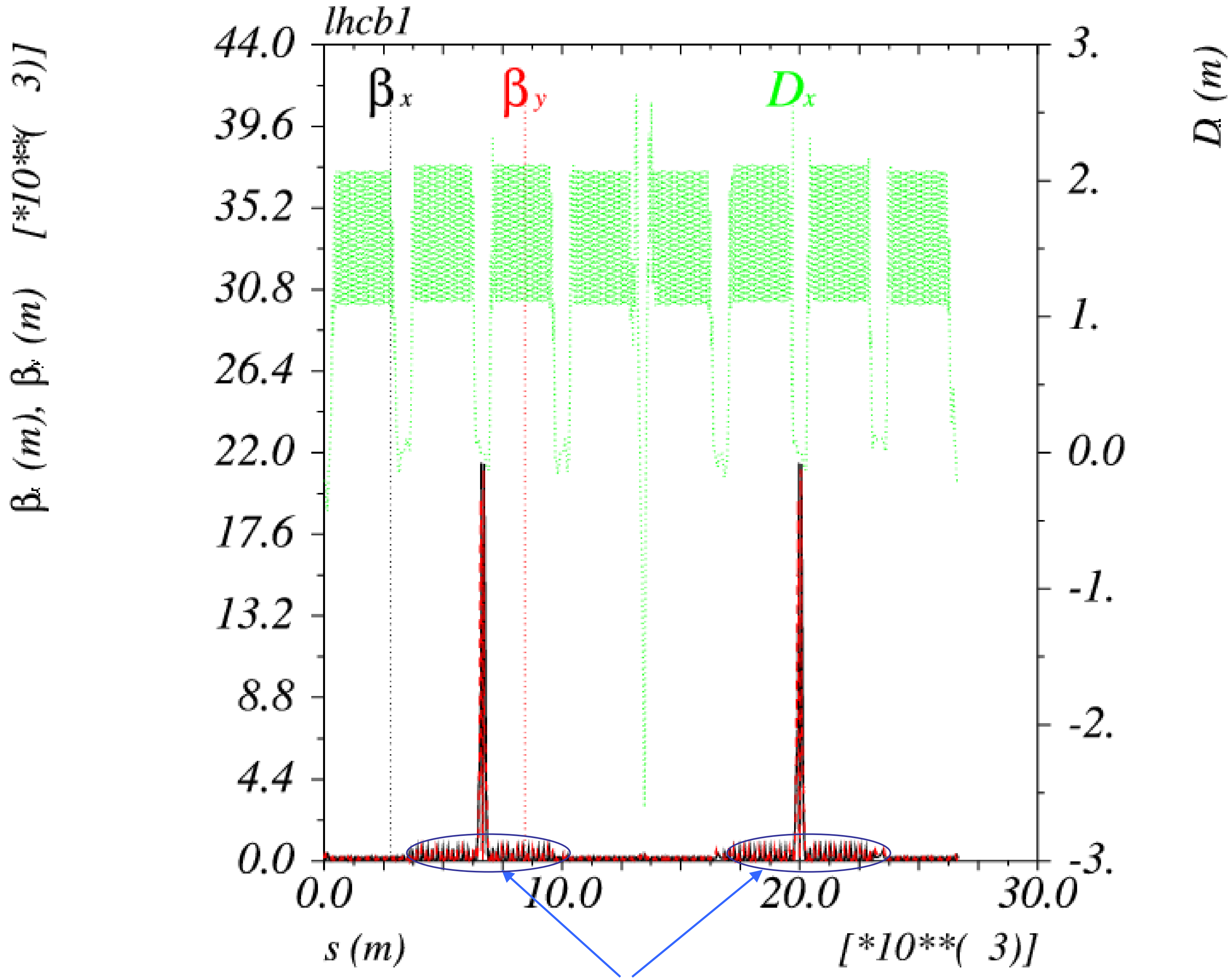
**b)** profit from above to find a local chromatic correction scheme for the triplet (if possible?), or equip ~500 arc quadrupoles with twice stronger chromatic sextupoles.

**→Hardly fit within the planning/budget!**

**3) Look for non-classical and new concepts**

**→ The ATS scheme which does the above surgery (almost) for free!**

# Squeezed optics (round): $\beta^* = 15$ cm in IR1 and IR5 (120 T/m IT)

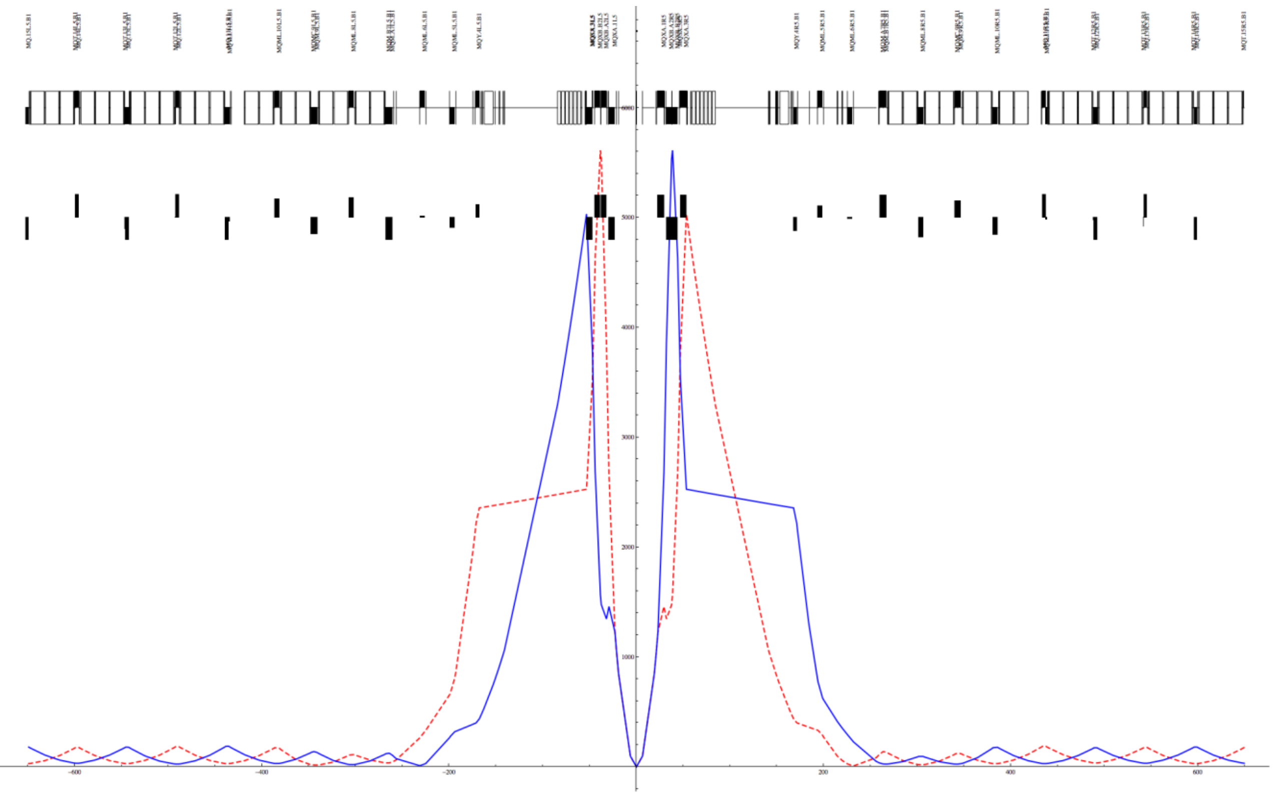



$\beta_{arc}$ increased by a factor of 4 in s45/56/81/12 starting from a relaxed pre-squeezed optics at $\beta^*$=60 cm

# Pushing nominal optics beta* to 0.43m

For efficient correction of off-momentum beta-beat, we want to keep the betatron phase from the inner triplet to one of the arc cell sextupoles to be 0.25 [2 Pi], plus constant phase across the whole IR. Keeping these conditions we can push beta* with the nominal layout to some smaller value. What limits us?

| | | | | | $\mu^{IT}_x$ | $\mu^{IT}_y$ |
|---|---|---|---|---|---|---|
| 0.369 | SEXTUPOLE | -648.756 | MS.15L5.B1 | -0.0702147 | -1.13909 | -1.50076 |
| 0.369 | SEXTUPOLE | -595.308 | MS.14L5.B1 | 0.0424538 | -1.01672 | -1.37101 |
| 0.369 | SEXTUPOLE | -541.859 | MS.13L5.B1 | -0.0702147 | -0.875751 | -1.25768 |
| 0.369 | SEXTUPOLE | -488.411 | MS.12L5.B1 | 0.0424538 | -0.757382 | -1.10288 |
| 0.369 | SEXTUPOLE | -433.691 | MS.11L5.B1 | -0.0702147 | -0.612799 | -0.974011 |
| 0.369 | SEXTUPOLE | 439.125 | MS.11R5.B1 | 0.0424538 | 1.00056 | 0.633884 |
| 0.369 | SEXTUPOLE | 492.581 | MS.12R5.B1 | -0.0702147 | 1.1235 | 0.754445 |
| 0.369 | SEXTUPOLE | 546.032 | MS.13R5.B1 | 0.0424538 | 1.23316 | 0.886628 |
| 0.369 | SEXTUPOLE | 599.484 | MS.14R5.B1 | -0.0702147 | 1.37426 | 0.999942 |



| S | NAME | K1 | % STRENGTH | GRAD T/M |
|---|---|---|---|---|
| -545.787 | MQT.13L5.B1 | -0.0044173 | -85.9492 | -103.139 |
| -492.338 | MQT.12L5.B1 | -0.0000948849 | -1.84622 | -2.21546 |
| -434.238 | MQTLI.11L5.B1 | -0.00155004 | -28.9534 | -36.1918 |
| -381.478 | MQML.10L5.B1 | 0.00725645 | 84.7151 | 169.43 |
| -344.782 | MQMC.9L5.B1 | -0.006344 | 74.0627 | -148.125 |
| -341.016 | MQM.9L5.B1 | -0.006344 | 74.0627 | -148.125 |
| -301.95 | MQML.8L5.B1 | 0.00774331 | 90.3989 | 180.798 |
| -264.284 | MQM.B7L5.B1 | -0.00856315 | 99.9701 | -199.94 |
| -260.517 | MQM.A7L5.B1 | -0.00856315 | 99.9701 | -199.94 |
| -225.99 | MQML.6L5.B1 | 0.000567825 | 8.28631 | 13.2581 |
| -194.09 | MQML.5L5.B1 | -0.00406301 | 59.2918 | -94.8669 |
| -167.853 | MQY.4L5.B1 | 0.00491129 | 71.6707 | 114.673 |
| -46.965 | MQXA.3L5 | -0.00865735 | 88.0783 | -202.14 |
| -38.55 | MQXB.B2L5 | 0.00865735 | 88.0783 | 202.14 |
| -32.05 | MQXB.A2L5 | 0.00865735 | 88.0783 | 202.14 |
| -22.965 | MQXA.1L5 | -0.00865735 | 88.0783 | -202.14 |
| 29.335 | MQXA.1R5 | 0.00865735 | 88.0783 | 202.14 |
| 37.55 | MQXB.A2R5 | -0.00865735 | 88.0783 | -202.14 |
| 44.05 | MQXB.B2R5 | -0.00865735 | 88.0783 | -202.14 |
| 53.335 | MQXA.3R5 | 0.00865735 | 88.0783 | 202.14 |
| 171.253 | MQY.4R5.B1 | -0.00509562 | 74.3607 | -118.977 |
| 198.89 | MQML.5R5.B1 | 0.004363 | 63.6696 | 101.871 |
| 230.79 | MQML.6R5.B1 | -0.000555816 | 8.11106 | -12.9777 |
| 263.404 | MQM.A7R5.B1 | 0.00855234 | 99.8439 | 199.688 |
| 267.171 | MQM.B7R5.B1 | 0.00855234 | 99.8439 | 199.688 |
| 306.243 | MQML.8R5.B1 | -0.00762642 | 89.0342 | -178.068 |
| 342.941 | MQMC.9R5.B1 | 0.00645336 | 75.3394 | 150.679 |
| 346.707 | MQM.9R5.B1 | 0.00645336 | 75.3394 | 150.679 |
| 385.775 | MQML.10R5.B1 | -0.006807 | 79.4679 | -158.936 |
| 438.579 | MQTLI.11R5.B1 | -0.000680109 | -12.7038 | -15.8798 |
| 488.653 | MQT.12R5.B1 | -0.00102929 | -20.0273 | -24.0327 |
| 542.105 | MQT.13R5.B1 | -0.00340562 | -66.2646 | -79.5175 |

e.g. for this run, beta*=0.43m.

We get limits from Q7 running to maximum and Q6 running to zero.

We also see a growing beta in the inner triplet.

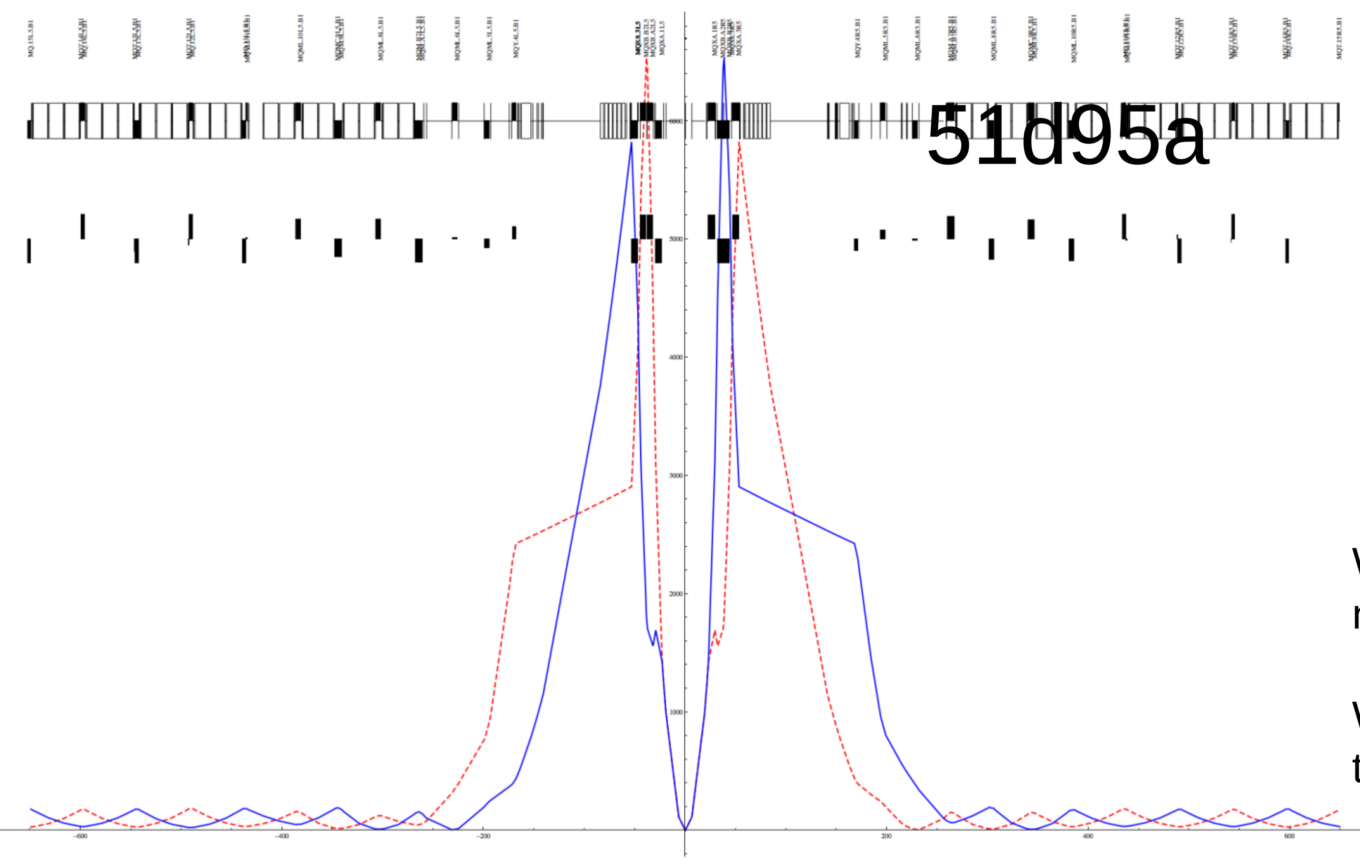
## Pushing nominal optics beta* to 0.37m

If we relax the phase constraint to the arc sextupoles, but maintain the overall IR phase we can push to smaller beta* of 0.37m

| | | | | | $\mu^{IT}_x$ | $\mu^{IT}_y$ |
|---|---|---|---|---|---|---|
| 0.369 | SEXTUPOLE | -648.756 | MS.15L5.B1 | -0.0754057 | -1.08634 | -1.53044 |
| 0.369 | SEXTUPOLE | -595.308 | MS.14L5.B1 | 0.0455202 | -0.96397 | -1.40069 |
| 0.369 | SEXTUPOLE | -541.859 | MS.13L5.B1 | -0.0754057 | -0.823005 | -1.28737 |
| 0.369 | SEXTUPOLE | -488.411 | MS.12L5.B1 | 0.0455202 | -0.70476 | -1.13167 |
| 0.369 | SEXTUPOLE | -433.691 | MS.11L5.B1 | -0.0754057 | -0.572399 | -1.00062 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 0.369 | SEXTUPOLE | 439.125 | MS.11R5.B1 | 0.0455202 | 1.03141 | 0.61611 |
| 0.369 | SEXTUPOLE | 492.581 | MS.12R5.B1 | -0.0754057 | 1.16759 | 0.725586 |
| 0.369 | SEXTUPOLE | 546.032 | MS.13R5.B1 | 0.0455202 | 1.28517 | 0.856198 |
| 0.369 | SEXTUPOLE | 599.484 | MS.14R5.B1 | -0.0754057 | 1.42628 | 0.969512 |

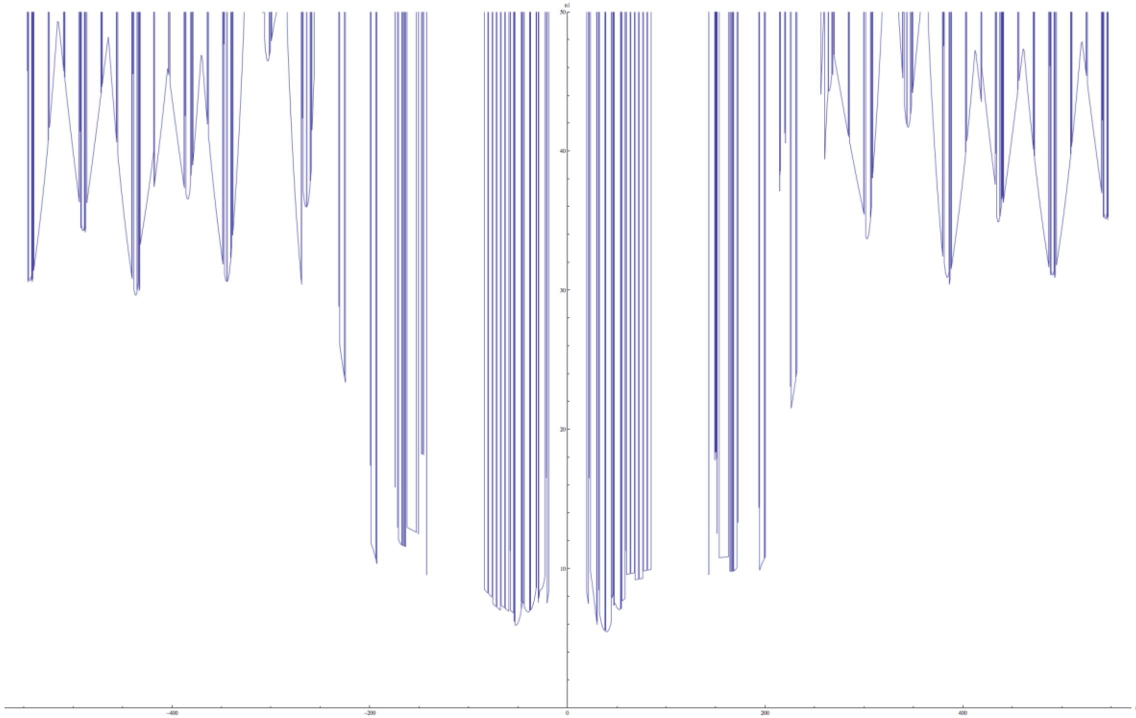
| S | NAME | K1 | % STRENGTH | GRAD T/M |
|---|---|---|---|---|
| -545.787 | MQT.13L5.B1 | -0.00454583 | -88.4502 | -106.14 |
| -492.338 | MQT.12L5.B1 | -0.0022637 | -44.0458 | -52.8549 |
| -434.238 | MQTLI.11L5.B1 | 0.000583642 | 10.9019 | 13.6274 |
| -381.478 | MQML.10L5.B1 | 0.00712861 | 83.2226 | 166.445 |
| -344.782 | MQMC.9L5.B1 | -0.00654994 | 76.4669 | -152.934 |
| -341.016 | MQM.9L5.B1 | -0.00654994 | 76.4669 | -152.934 |
| -301.95 | MQML.8L5.B1 | 0.00723738 | 84.4924 | 168.985 |
| -264.284 | MQM.B7L5.B1 | -0.00848755 | 99.0875 | -198.175 |
| -260.517 | MQM.A7L5.B1 | -0.00848755 | 99.0875 | -198.175 |
| -225.99 | MQML.6L5.B1 | 0.000554554 | 8.09263 | 12.9482 |
| -194.09 | MQML.5L5.B1 | -0.00327582 | 47.8043 | -76.4869 |
| -167.853 | MQY.4L5.B1 | 0.00436029 | 63.63 | 101.808 |
| -46.965 | MQXA.3L5 | -0.00869996 | 88.5118 | -203.135 |
| -38.55 | MQXB.B2L5 | 0.00869996 | 88.5118 | 203.135 |
| -32.05 | MQXB.A2L5 | 0.00869996 | 88.5118 | 203.135 |
| -22.965 | MQXA.1L5 | -0.00869996 | 88.5118 | -203.135 |
| 29.335 | MQXA.1R5 | 0.00869996 | 88.5118 | 203.135 |
| 37.55 | MQXB.A2R5 | -0.00869996 | 88.5118 | -203.135 |
| 44.05 | MQXB.B2R5 | -0.00869996 | 88.5118 | -203.135 |
| 53.335 | MQXA.3R5 | 0.00869996 | 88.5118 | 203.135 |
| 171.253 | MQY.4R5.B1 | -0.00425527 | 62.0974 | -99.3559 |
| 198.89 | MQML.5R5.B1 | 0.00317434 | 46.3234 | 74.1174 |
| 230.79 | MQML.6R5.B1 | -0.000548525 | 8.00466 | -12.8075 |
| 263.404 | MQM.A7R5.B1 | 0.00827646 | 96.6231 | 193.246 |
| 267.171 | MQM.B7R5.B1 | 0.00827646 | 96.6231 | 193.246 |
| 306.243 | MQML.8R5.B1 | -0.00752956 | 87.9034 | -175.807 |
| 342.941 | MQMC.9R5.B1 | 0.00684398 | 79.8997 | 159.799 |
| 346.707 | MQM.9R5.B1 | 0.00684398 | 79.8997 | 159.799 |
| 385.775 | MQML.10R5.B1 | -0.00780975 | 91.1745 | -182.349 |
| 438.579 | MQTLI.11R5.B1 | -0.000602313 | -11.2507 | -14.0634 |
| 488.653 | MQT.12R5.B1 | 0.00141931 | 27.6162 | 33.1394 |
| 542.105 | MQT.13R5.B1 | -0.00121046 | -23.5525 | -28.263 |




We get limits from Q7 running to maximum and Q6 running to zero.

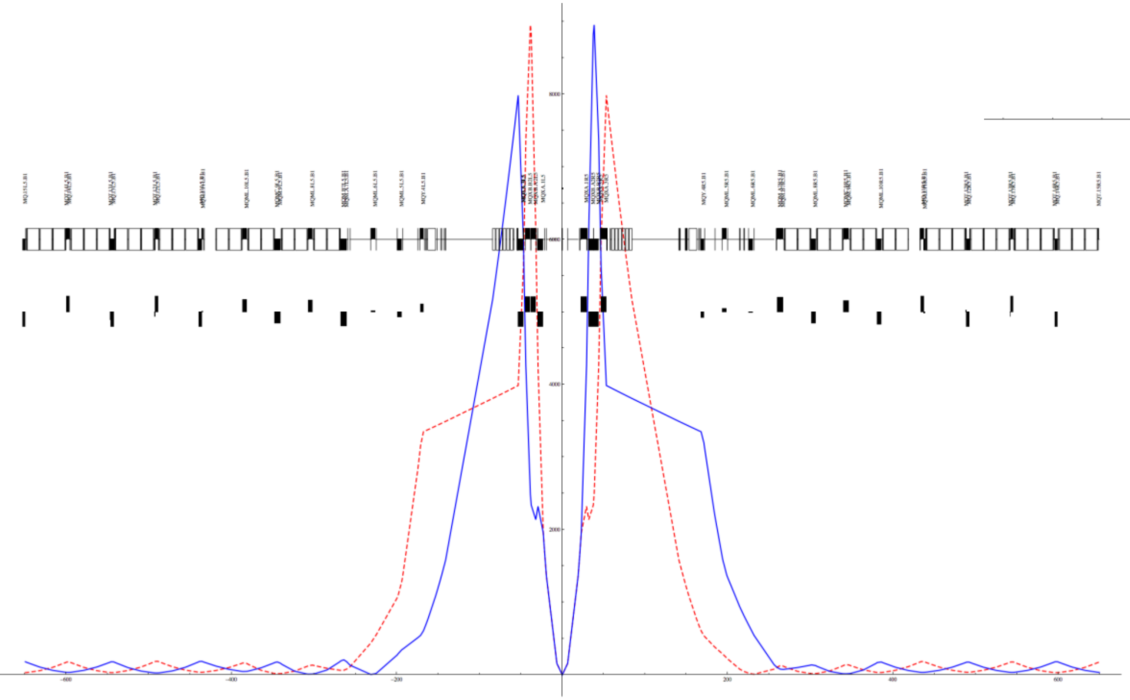
We also see a growing beta in the inner triplet.

Finally, for fun, we can let the IR phase vary by p/m 10% (assume we can compensate in the other IRs) to reach a beta* of 0.27



Again, we get limits from Q7 and QT13 running to maximum and QT11 and Q6 running to zero.

We also see large betas in the inner triplet, and a significant aperture problem



Again we are limited by Q6 running to zero and Q7 running to maximum. For Q6, this suggests replacing it by a doublet. We need to replace Q5 also to maintain the FODO structure we need for injection to keep small beam sizes.

The next few slides show a trial layout and optics.