IR2 squeeze for 3.5 TeV

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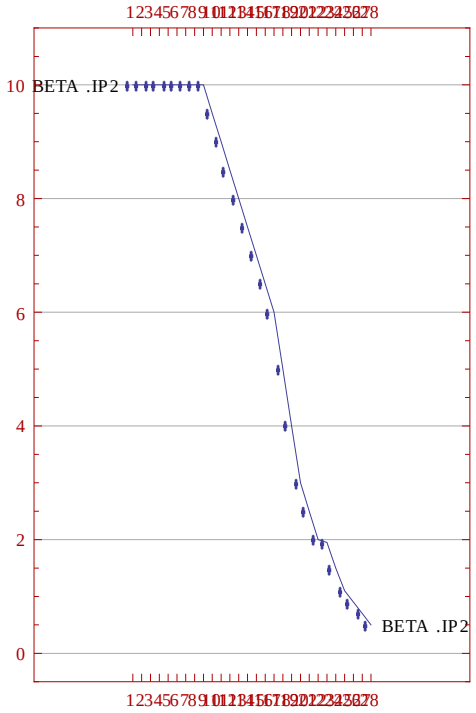
With important contributions from Thys Risselada

IR2 squeeze background

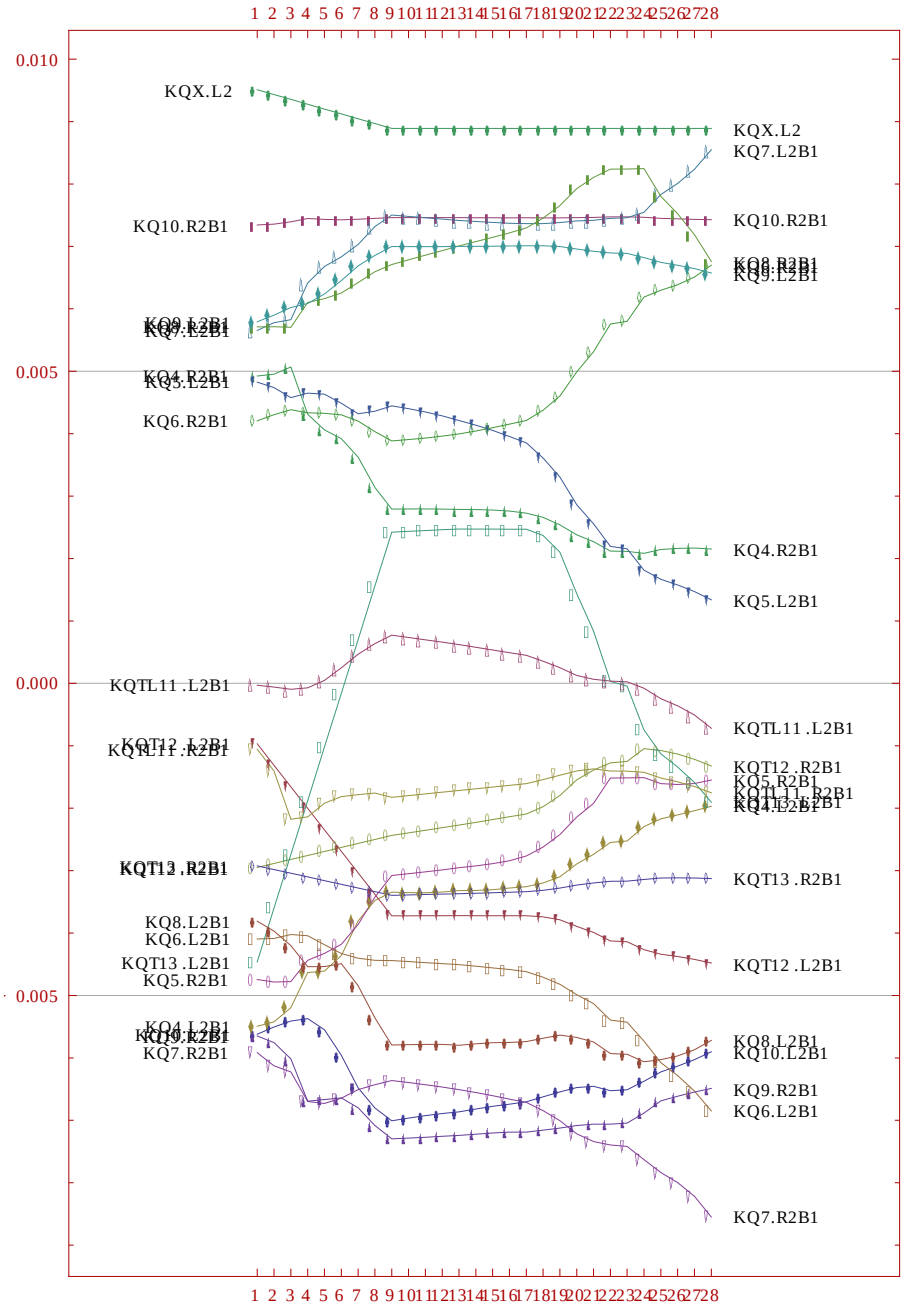
- Injection optics in IR2 is highly constrained
  - Injection phase advance constraints
  - Aperture limitations (n_1 criterion)
  - Solution found requires high value of (normalised) gradient, in triplet quadrupoles, must be reduced for 7 TeV. Only IR2 optics in machine so far.
- For Pb-Pb operation at 7*Z* TeV, the squeeze to β*=0.5 m requires a *pre-squeeze*, in which injection constraints are relaxed at constant β*=10 m and triplet gradient is reduced.
  - Pre-squeeze takes additional time.
- Squeeze then proceeds at constant triplet K1.
- For 3.5 Z TeV, p p operation mostly at β*=10 m but a squeeze to β*=3 m is requested.
  - Pre-squeeze no longer necessary/wanted and could be suppressed to save time in operation.

Squeeze with pre-squeeze for 7 TeV

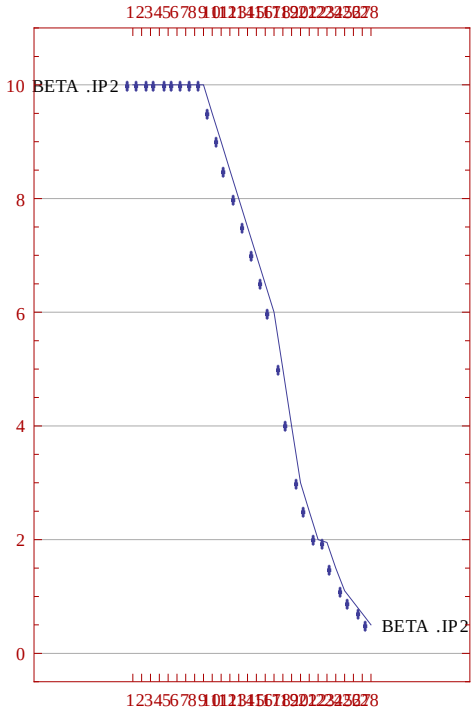


Beam 1

28 steps, some awkward variations of trim quads – very ugly.

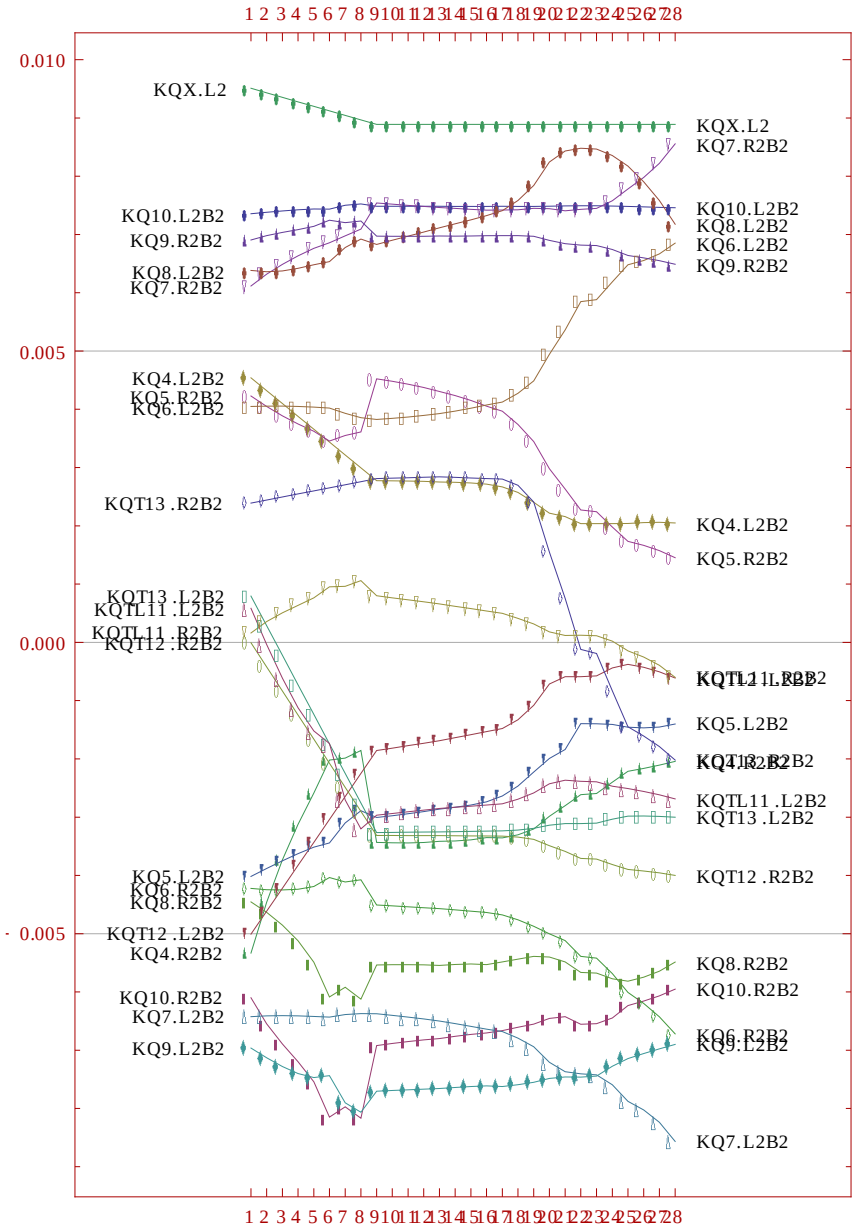


Squeeze with pre-squeeze for 7 TeV



Beam 2

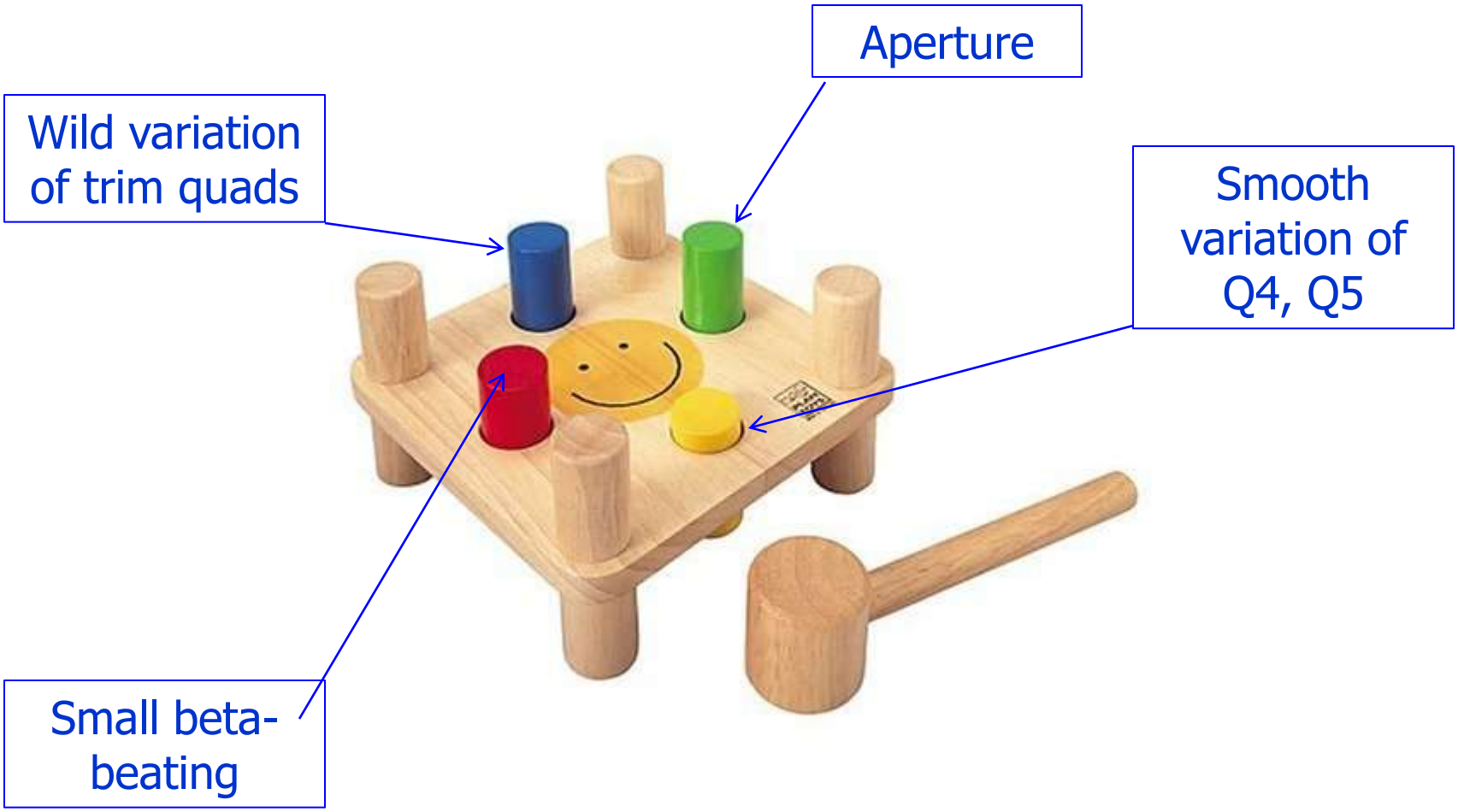
Also ugly.



New squeeze for 3.5 TeV

- Previous presentations showed that it is extremely difficult to make a smooth transition from injection optics to later points in the existing squeeze
- Numerous approaches have been tried, eg, varying triplet and β^* together from injection optics according to various schemes towards later points in squeeze.
  - Somewhere there is always a bad step with large beating, reflecting the fact that there is no smooth, possibly no continuous, path between injection and fully-squeezed optics.
  - Also hard to avoid big peaks in β at Q6.

IR2 matching reminded me of earlier work…

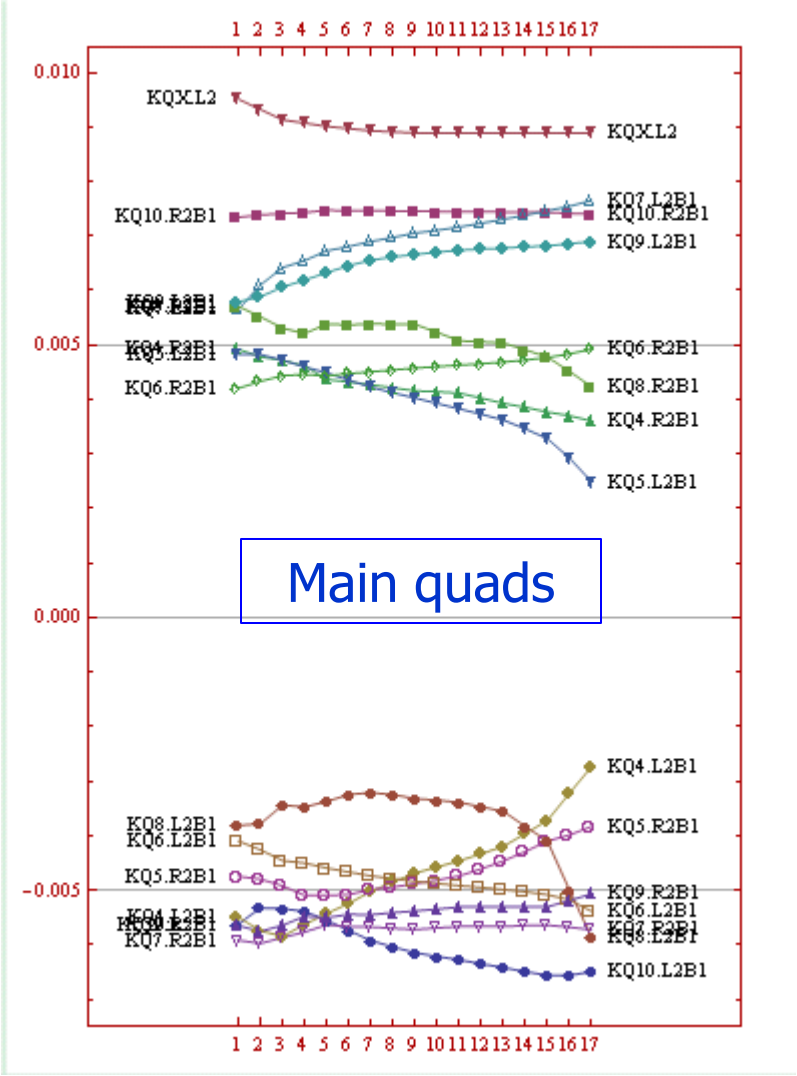


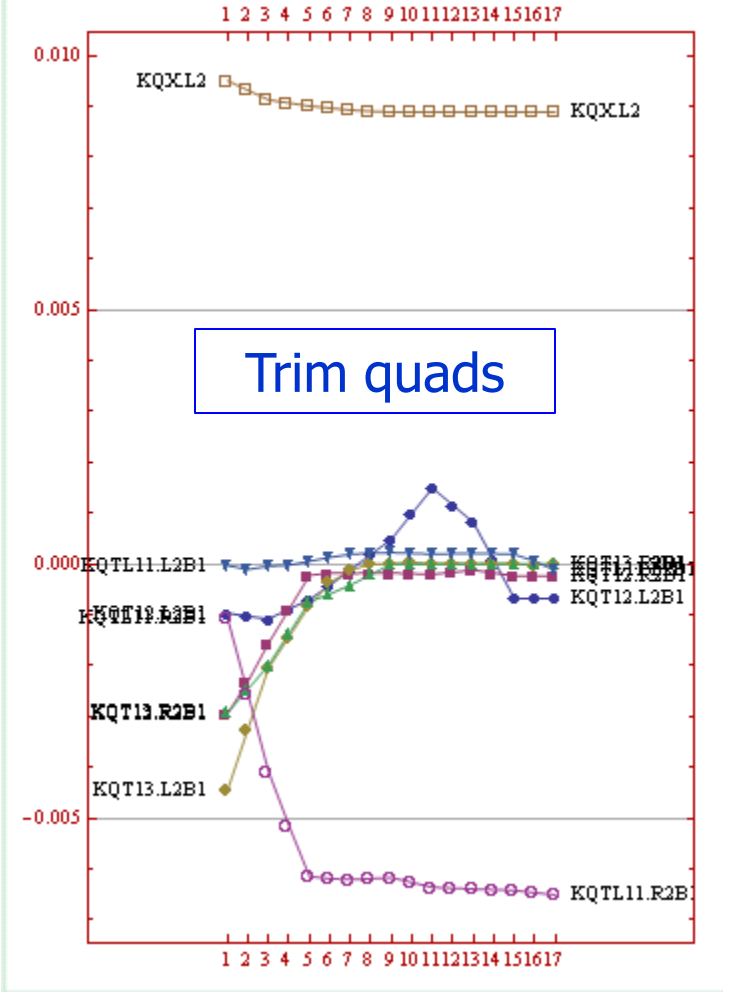
And it also has to work for Beam 2 …

New squeeze by T. Risselada (TRSqueeze)

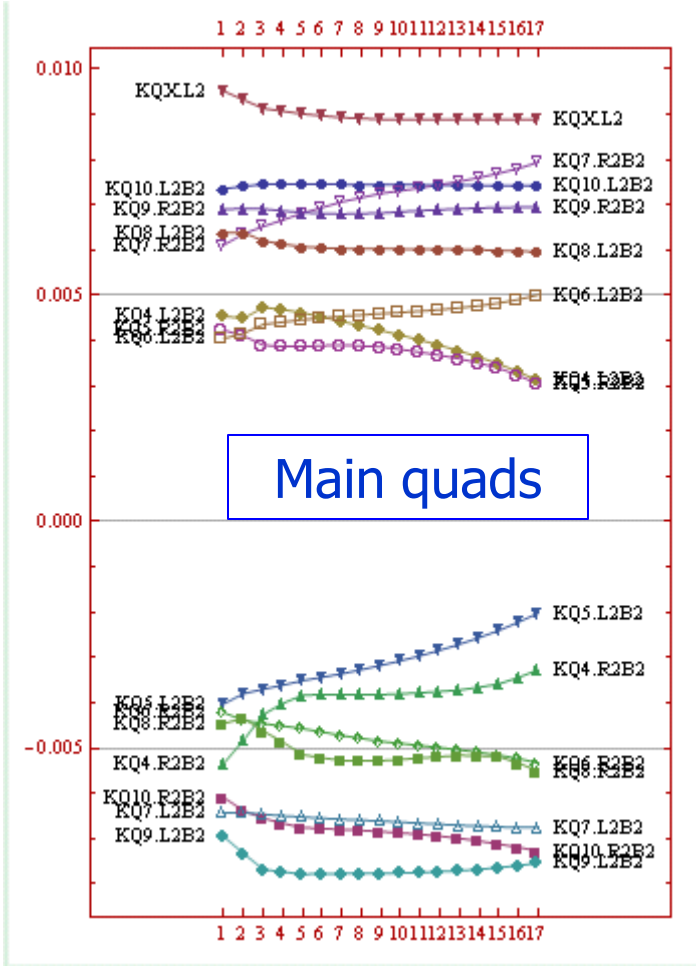
- Abandon all previous squeeze optics except the injection one
- Allow b-functions to peak much more strongly in Q6
- Find special variation of triplet strength KQX.L2 with β^*
  - Empirically, as far as I know
- Control variations of the trim quads between squeeze steps
  - Otherwise they vary a lot, which is OK for hardware, but does not help in finding smooth optical solutions
- Possibly other tricks …

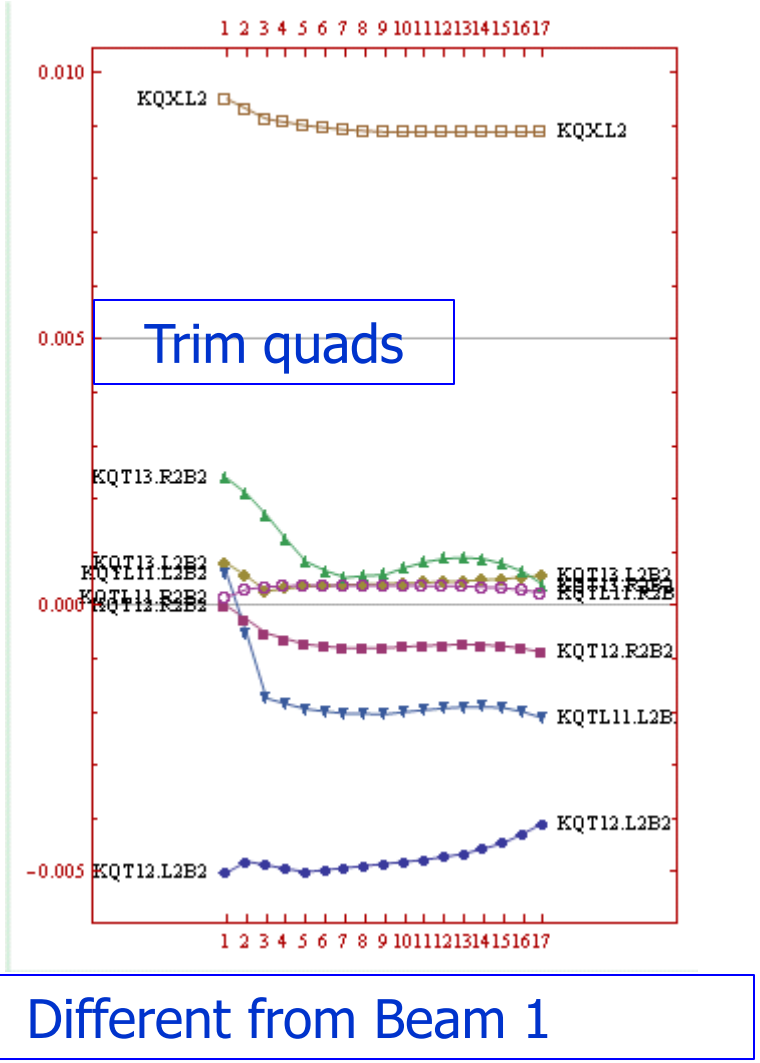
TRSqueeze, Beam 1





TRSqueeze, Beam 2



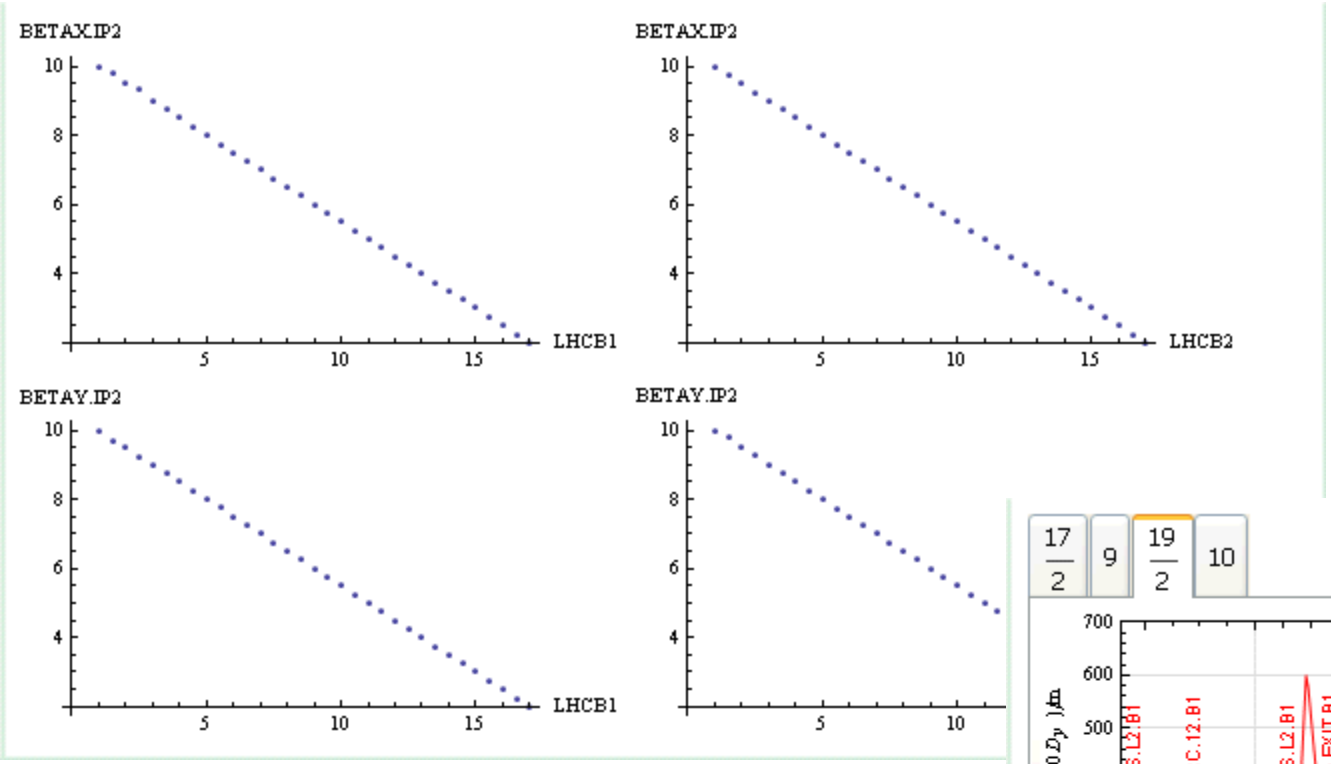


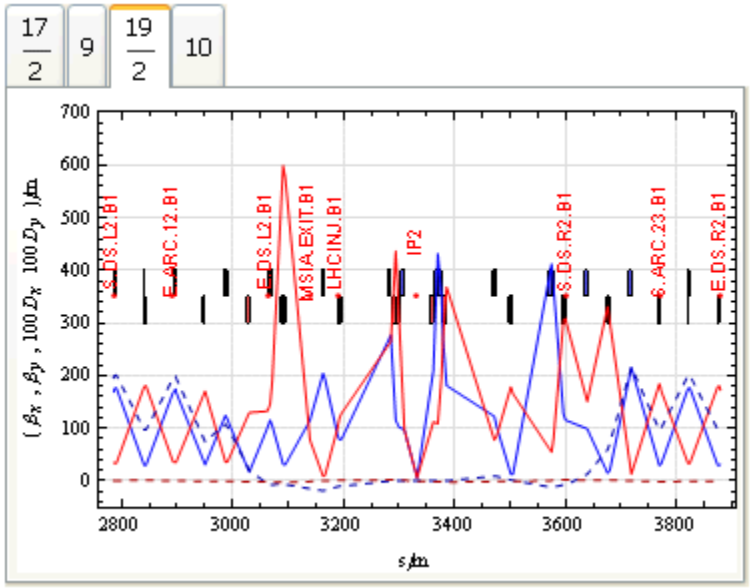
Different from Beam 1

Analysis of TRSqueeze

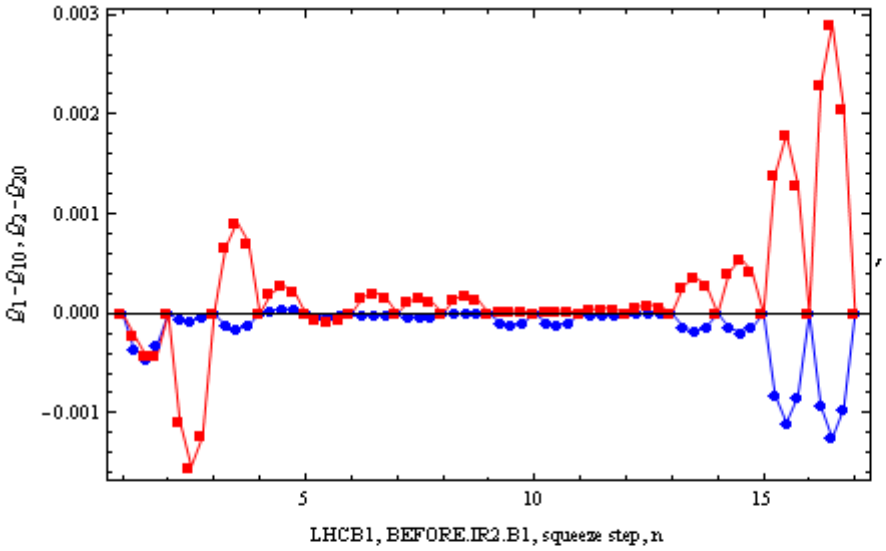
- Squeeze settings defined at integer squeeze index points *n*
- For non-integer *n* (1/4 steps), linear interpolation of all strengths (essentially as in control system)
  - Evaluate tune-variation, chromaticity variation, beta and dispersion beating, aperture, etc.
- Collection of functions in Madtomma to automate this
- For beta-beating, always compare with an optics with other IRs squeezed to 2 or 2.5 m (most sensitive).

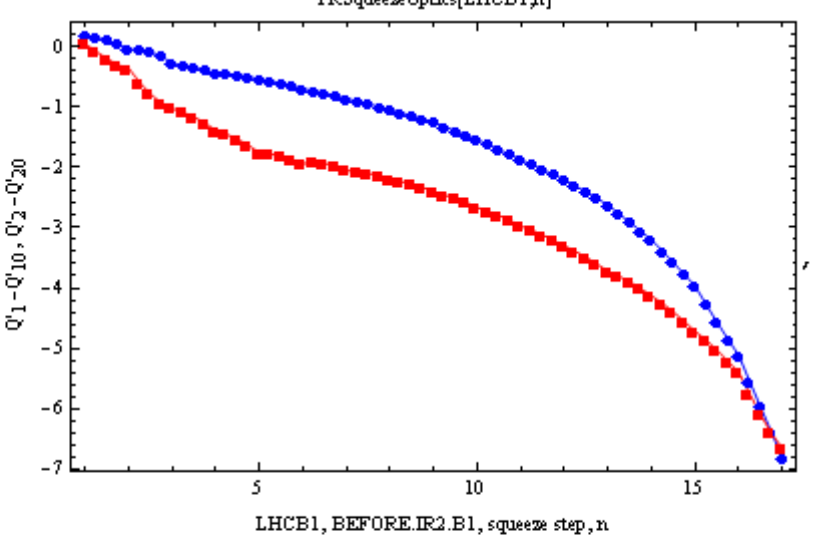
Variations in TRSqueeze

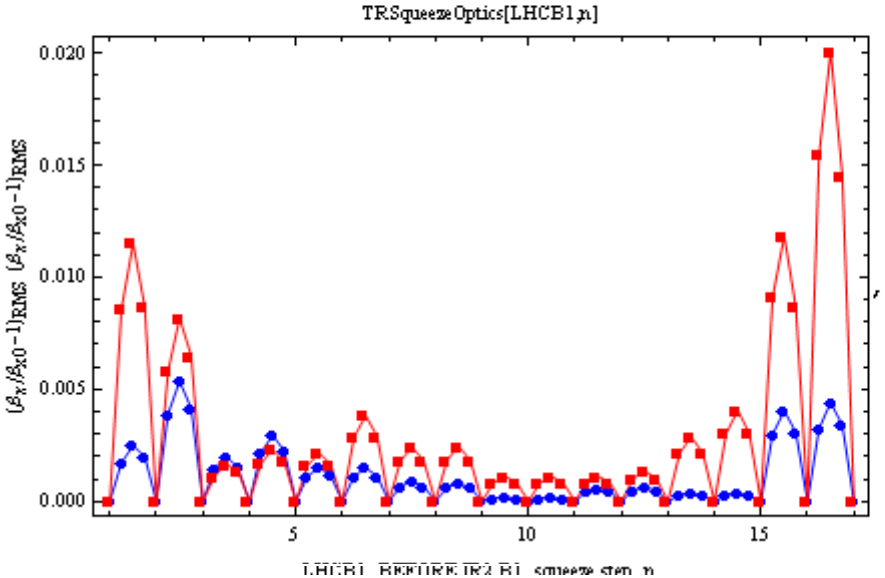


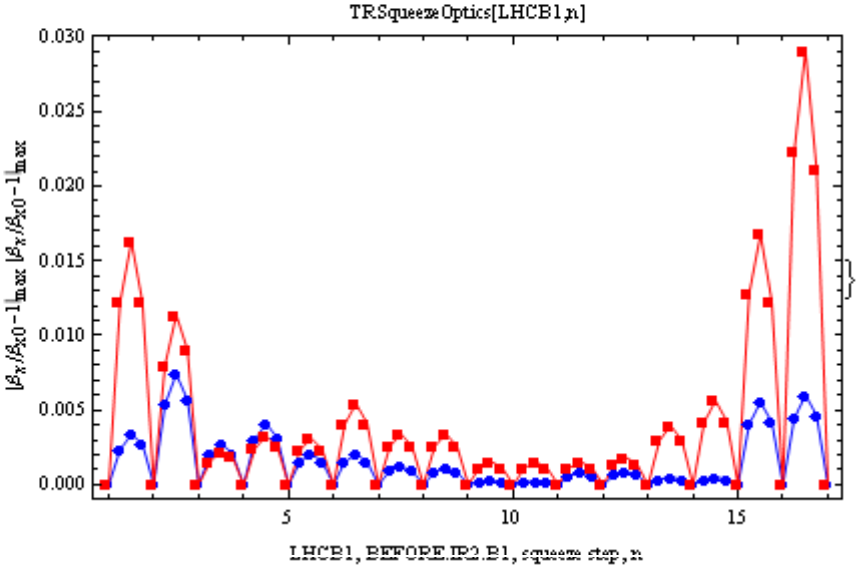


Tune and beta-beating in TRSqueeze, Beam 1



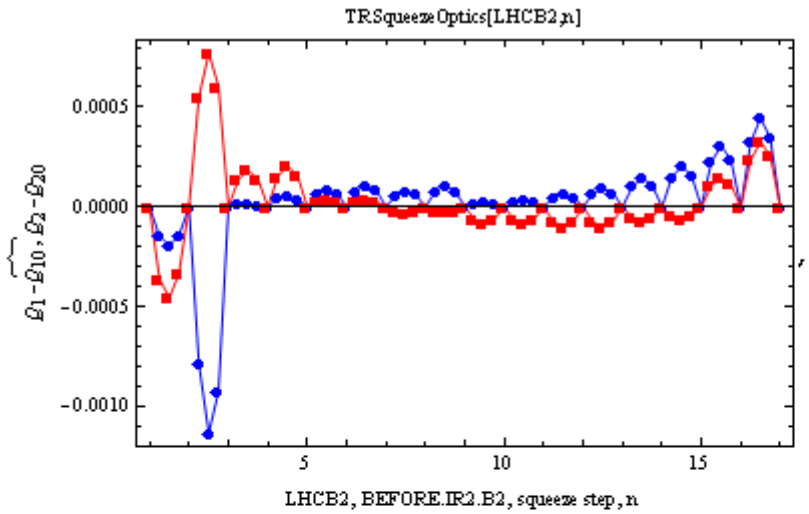


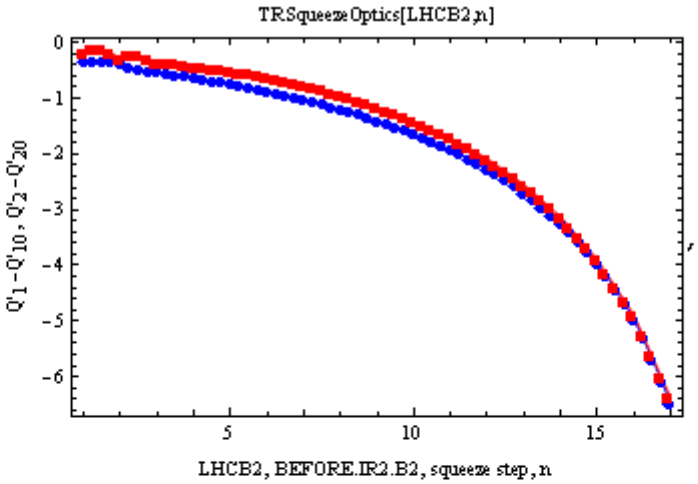


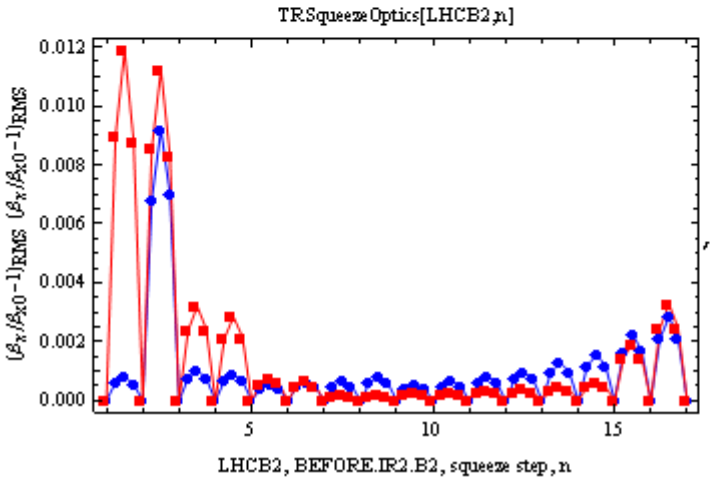


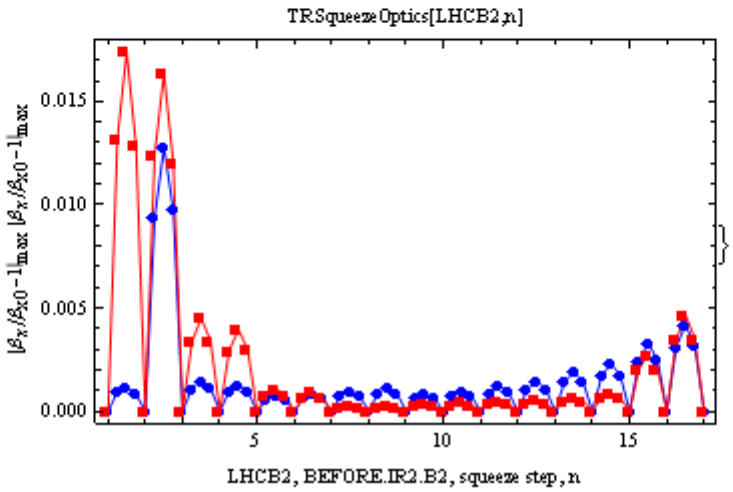
Beta-beating exceeds 1% level (RMS and peak)

Tune and beta-beating in TRSqueeze, Beam 2



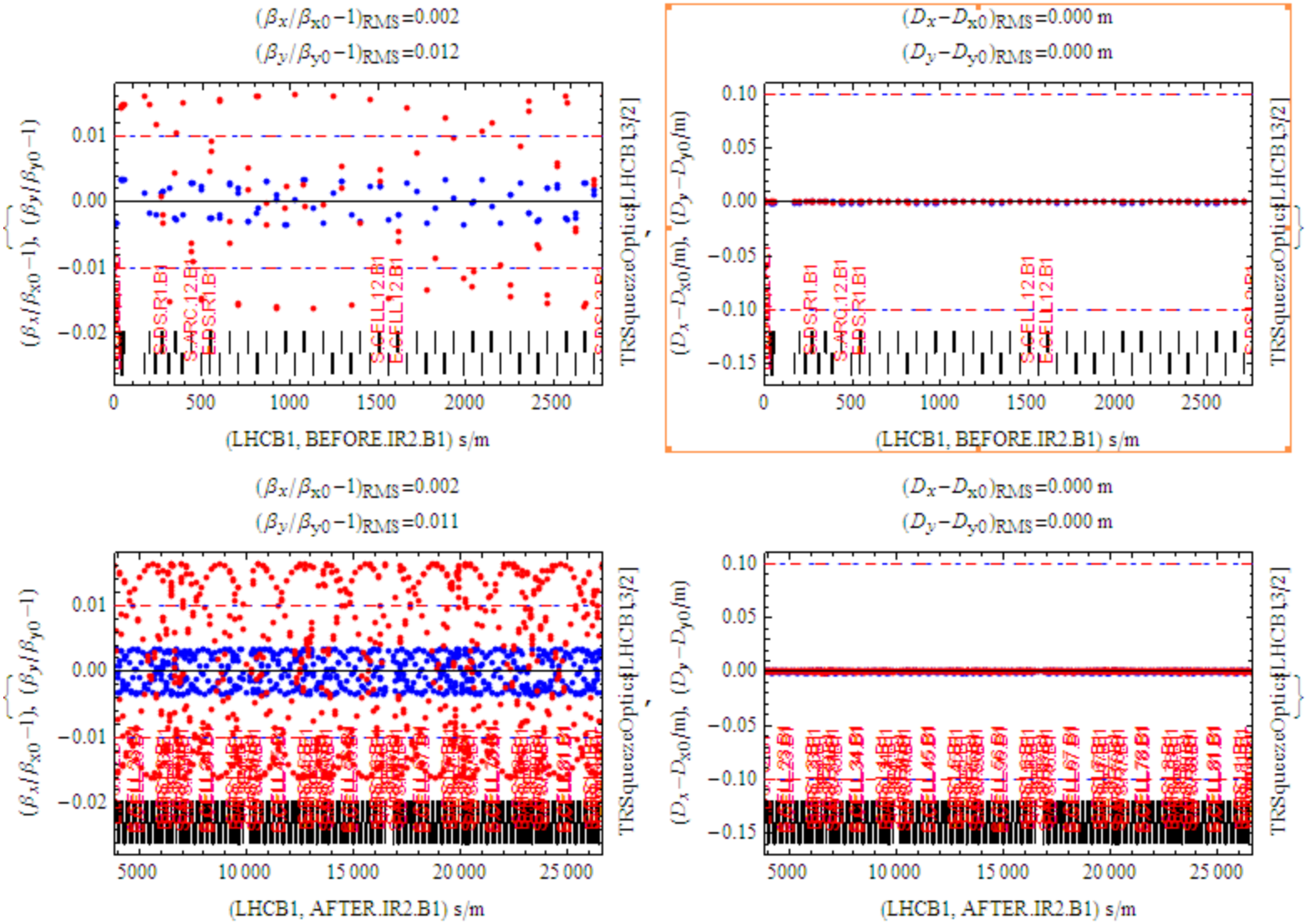






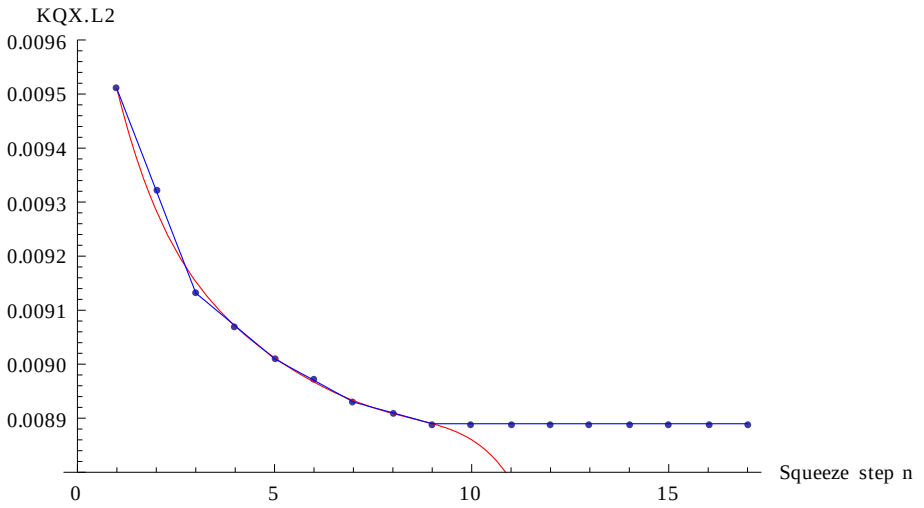
Beta-beating exceeds 1% level (RMS and peak)

Beta-beating at step 3/2



Construct another squeeze (TJSqueeze)

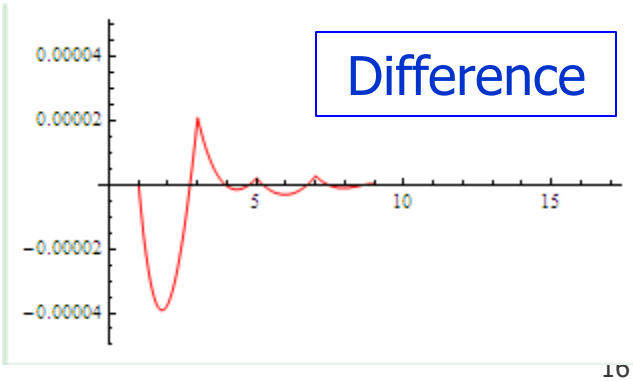
- Look at empirical variation of triplet strength found by TR



Fit with 5th order polynomial,
excluding steps 2,3 and beyond 9.
Use this to find new optics for
$\beta^* = 9.5, 9.0$ m
Works for $n = 3$ but not $n = 2$.
Try small variations of n around 2 but
$n = 2$ found to be optimum for beating.
Insert another squeeze point at
$n = 1.38$, matching to $\beta^* = 9.82$ m
(numbers optimised in matching/beating loop).

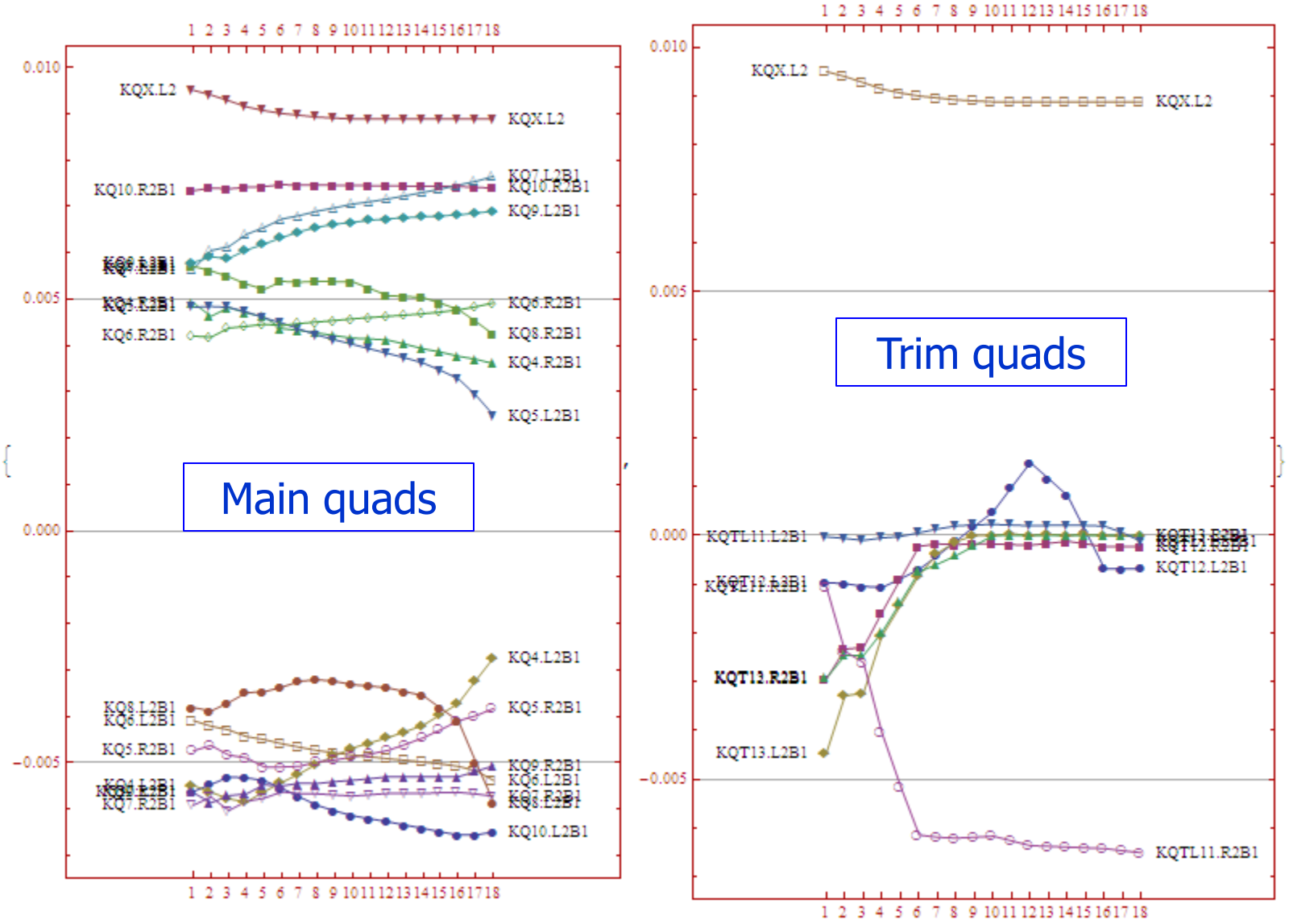
```
In[450]:= kqxfit[ n_ ] :
           ( Fit[ Pick[ kqxn, { 1, 0, 0, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0} , 1] ,
             Table[ n^k , { k , 0 , 5} ] , n] )

Out[450]= 0.00990427 - 0.000511244 n + 0.000136126 n^2 -
          0.0000209523 n^3 + 1.67458 x 10^-6 n^4 - 5.33796 x 10^-8 n^5
```

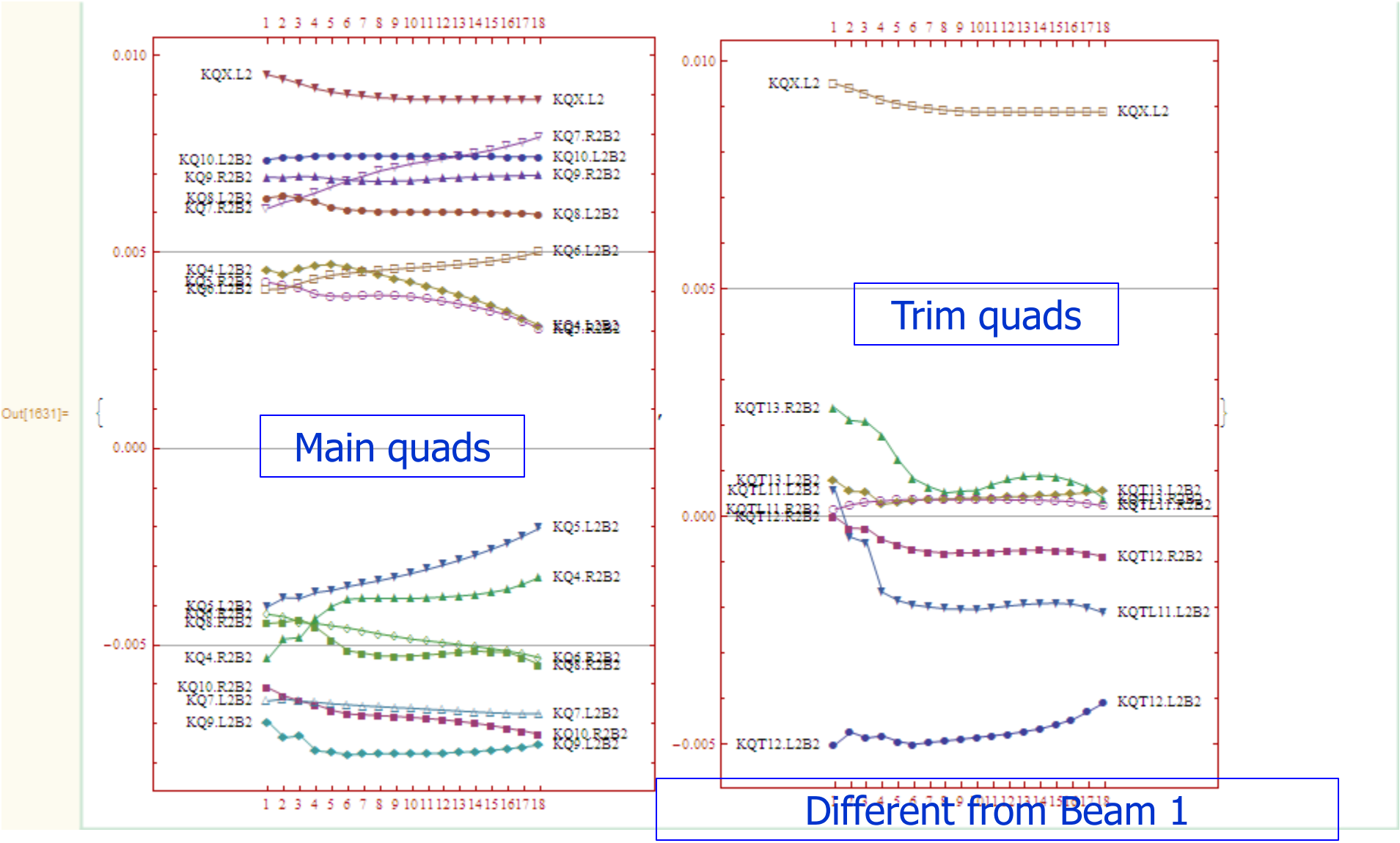


TJSqueeze, Beam 1

Out[1630]=



TJSqueeze, Beam 2



Analysis of TJSqueeze

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- For non-integer *n* (1/4 steps), linear interpolation of all strengths (essentially as in control system)
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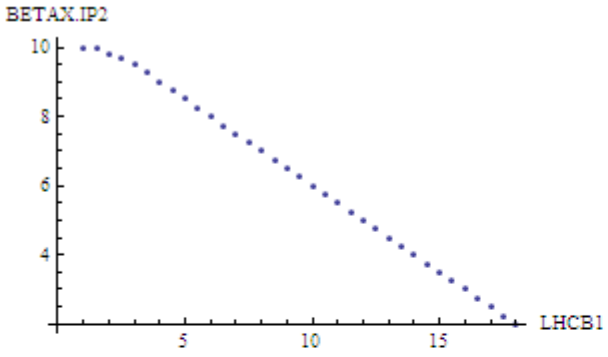
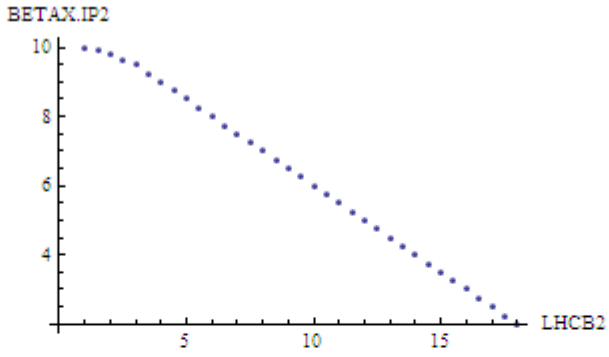
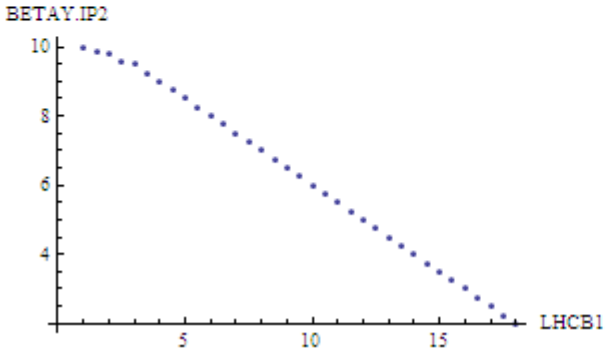
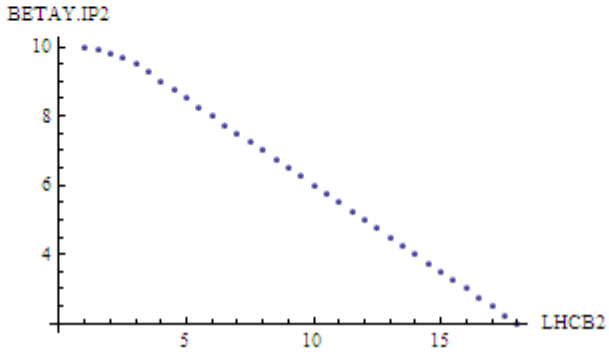
Variations in TJSqueeze









Tune and beta-beating in TJSqueeze, Beam 1

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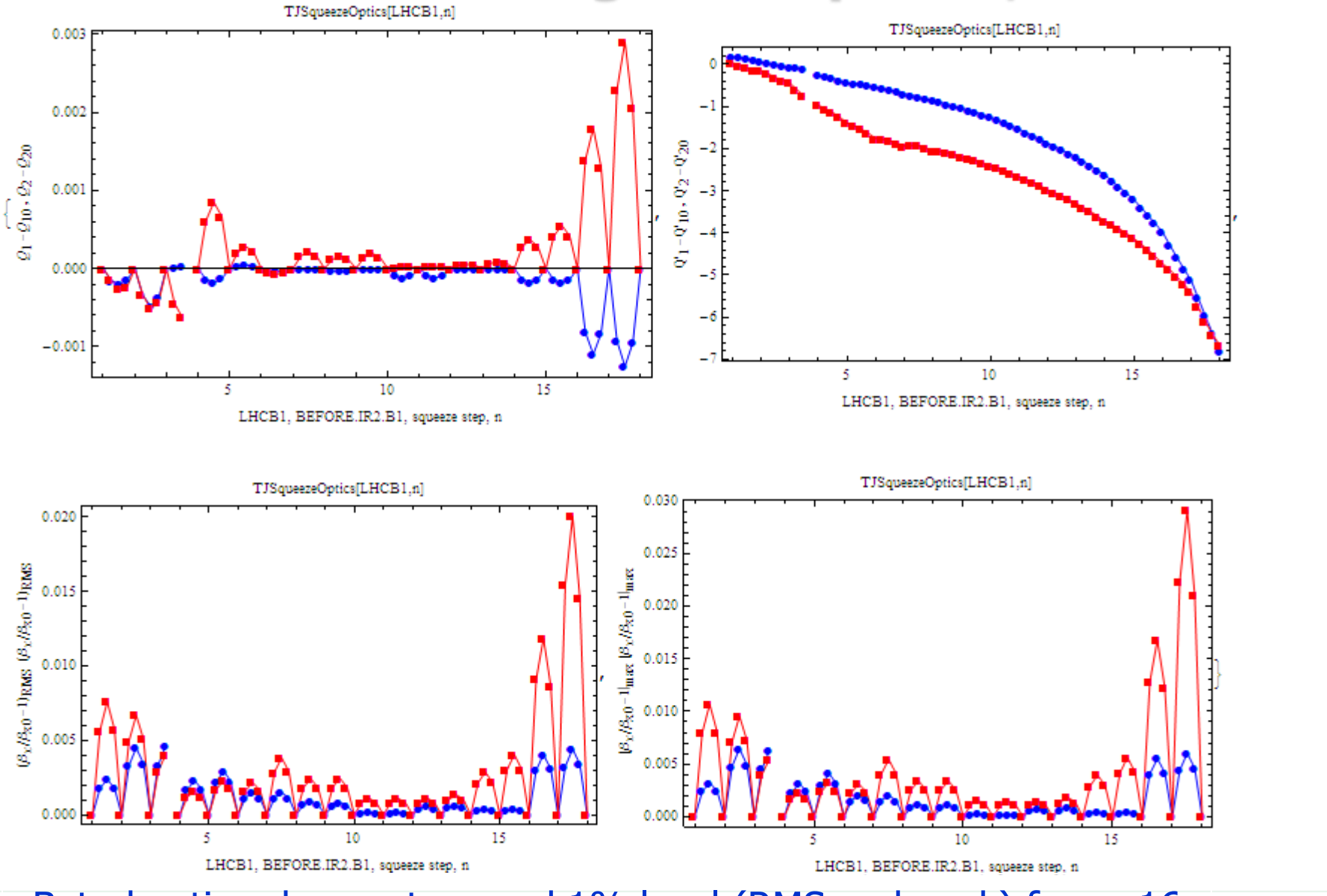
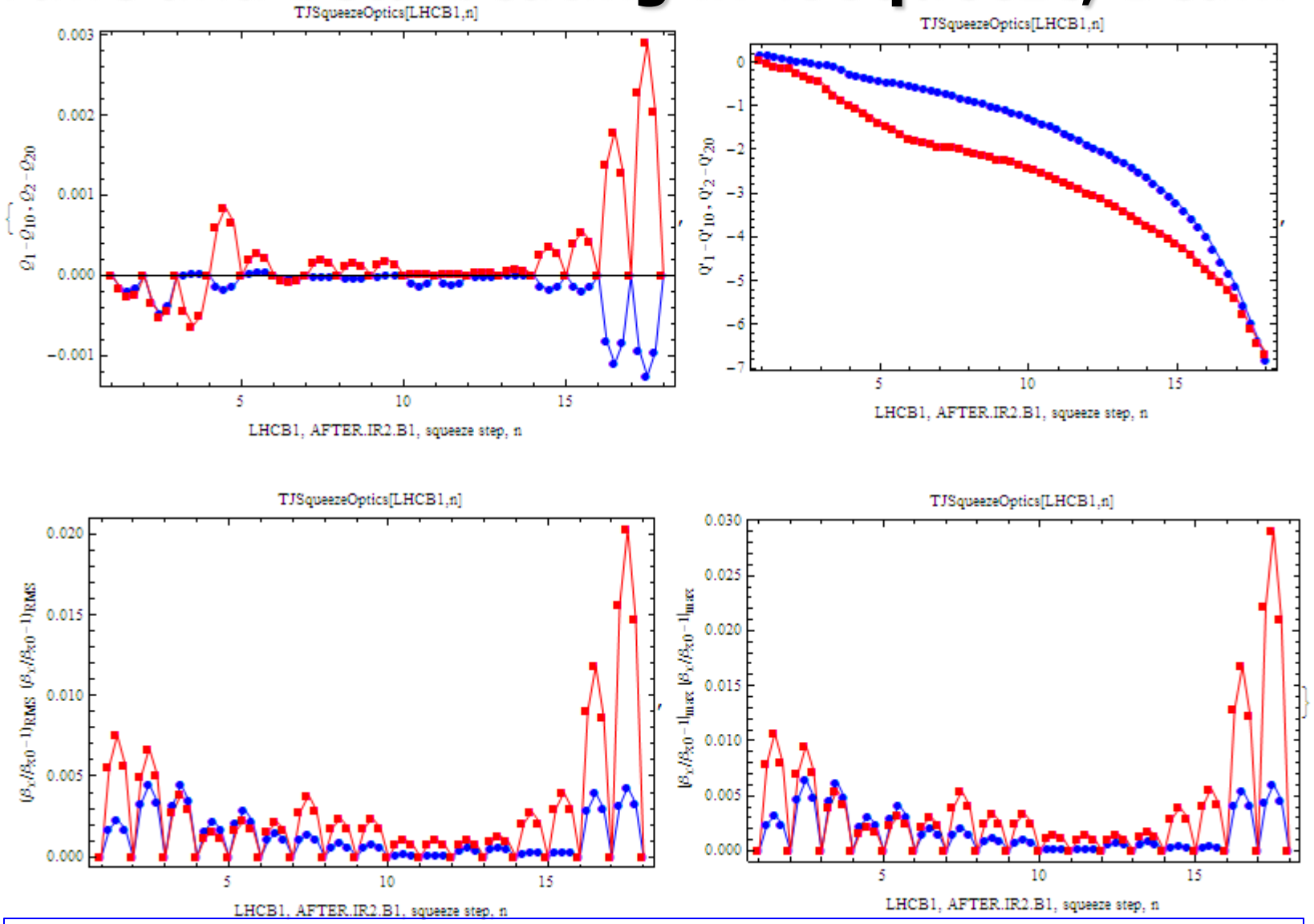


Beta-beating does not exceed 1% level (RMS and peak) for n<16

Tune and beta-beating in TJSqueeze, Beam 2

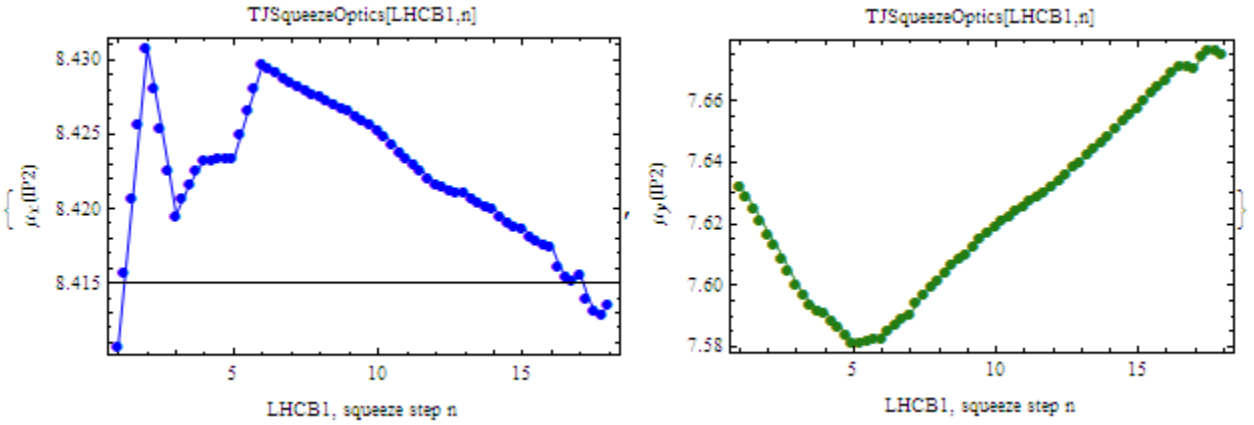
Out[1690]=

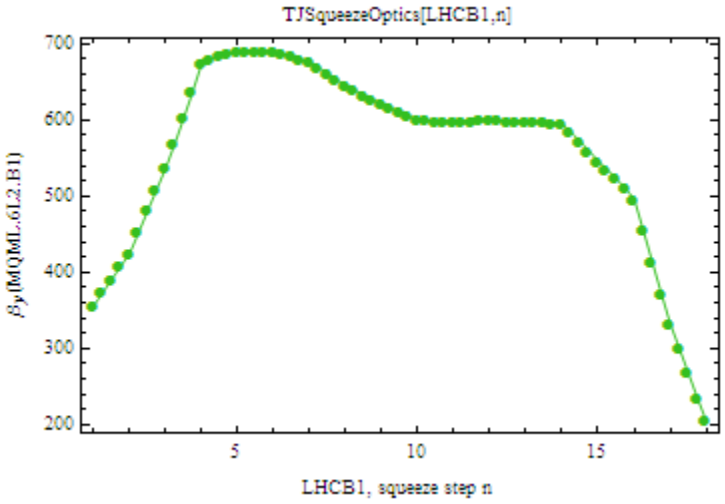


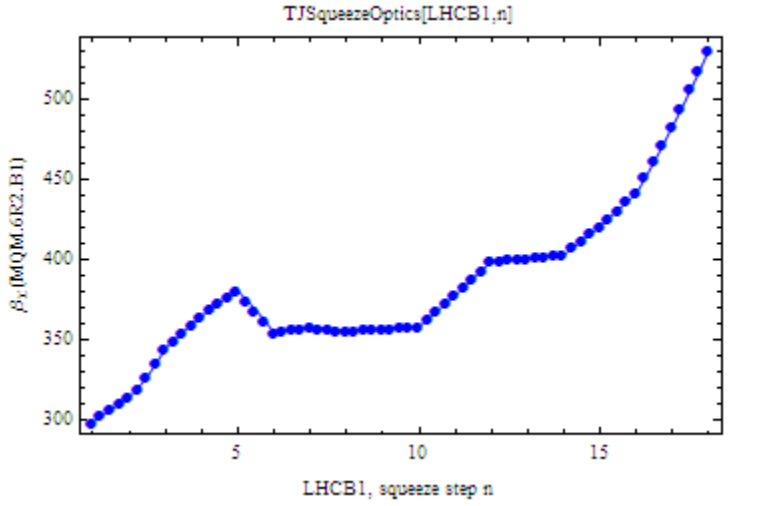
Beta-beating does not exceed 1% level (RMS and peak) for n<16

Other variations

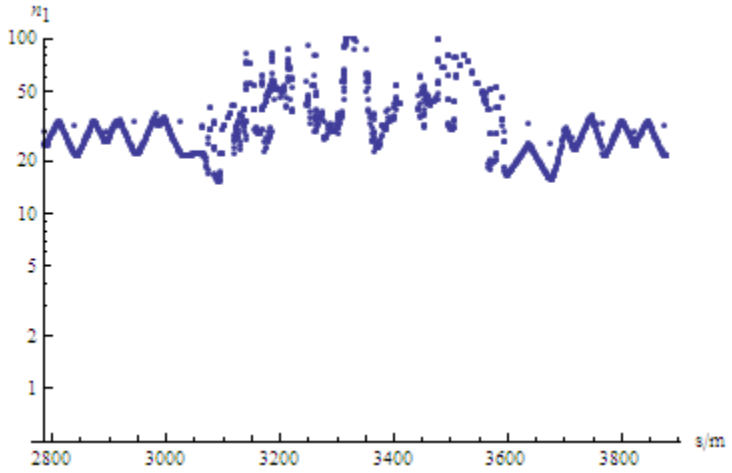
Out[1694]=







Aperture quantity n1 at worst point



Chromaticity variation after correction (1)

At each integer squeeze index, there will be a setting of the two sextupole families to correct this chromaticity to the desired value (+2, say). We know that this contribution is linear in the sextupoles strengths:

$$Q'_{x,y}(K_{2SF}, K_{2SD}) = \frac{\pm 1}{4\pi}\int K_2(s)\, D_x(s)\, \beta_{x,y}(s)\, ds$$

$$= \pm\left(\frac{K_{2SF}\, L_{SF}\, D_{xSF}}{4\pi}\sum_{SF}\beta_{x,y} + \frac{K_{2SD}\, L_{SD}\, D_{xSD}}{4\pi}\sum_{SD}\beta_{x,y}\right)$$

$$= A_{x,y}\, K_{2SF} + B_{x,y}\, K_{2SD}$$

We know that, to a very good approximation, $\sum_{SF}\beta_{x,y}$ and $\sum_{SD}\beta_{x,y}$ will reduce to a sum over pairs of adjacent sextupoles in one of which the β function will be larger and smaller by the same amount (the typical pattern for small beta-beating in the arcs). Therefore the coefficients $A_{x,y}$ and $B_{x,y}$ will be constant to a very good approximation throughout the squeeze. At each integer squeeze point, we can compensate the chromaticity to the value 2 in each plane by solving

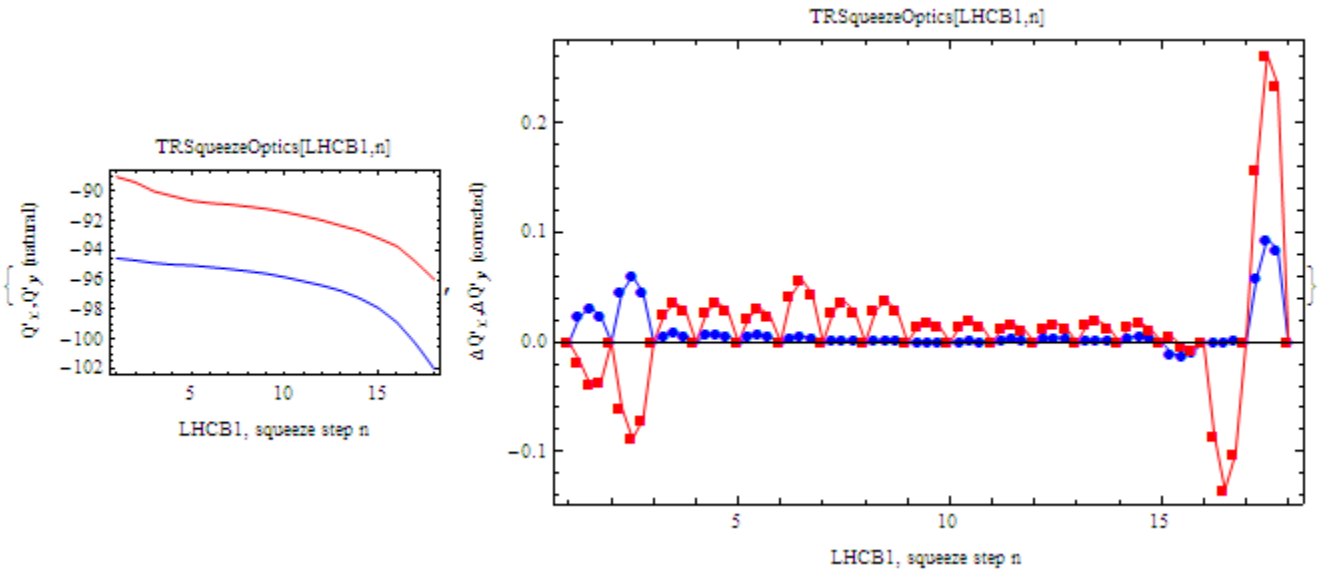
$$Qpxnat(n) + A_x\, K_{2SF}(n) + B_x\, K_{2SD}(n) = 2$$
$$Qpynat(n) + A_y\, K_{2SF}(n) + B_y\, K_{2SD}(n) = 2$$

for the sextupole strengths.

At non-integer squeeze points, the control system will make a linear interpolation of the sextupole strengths between these values and the resulting chromaticity will be

Chromaticity variation after correction (2)

Out[1737]=



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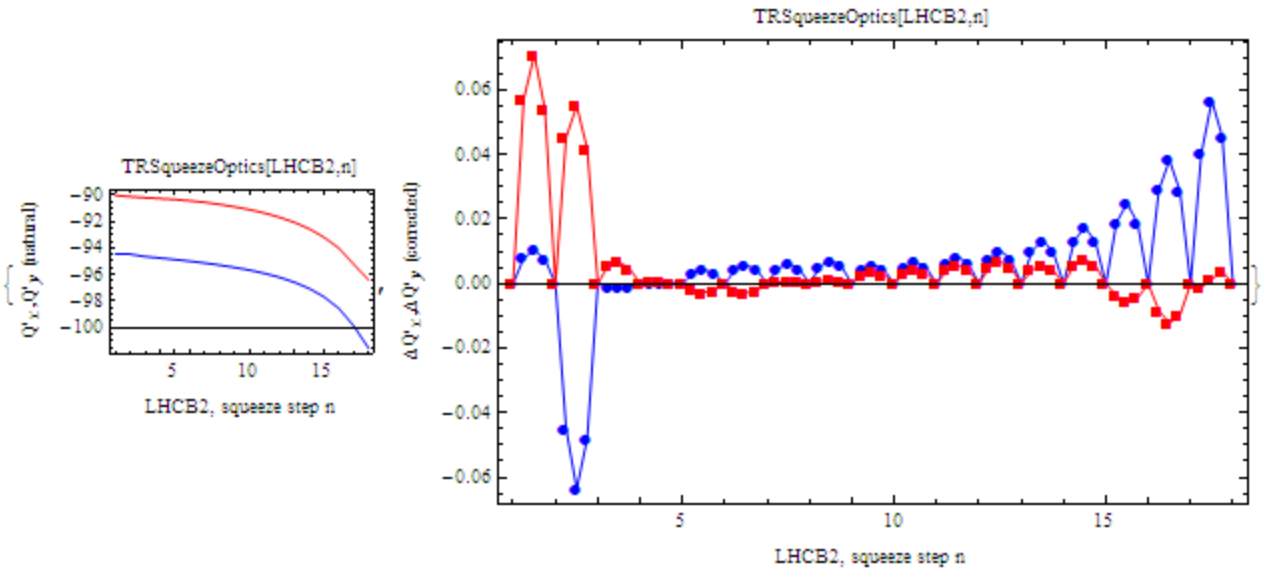

Beta-beating at step 3/2

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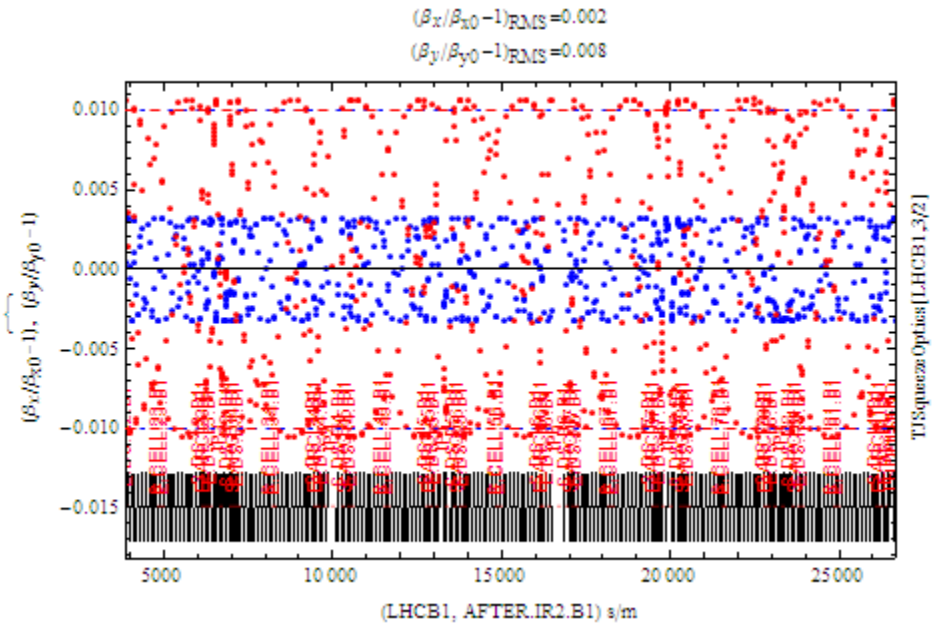
{0.422, {



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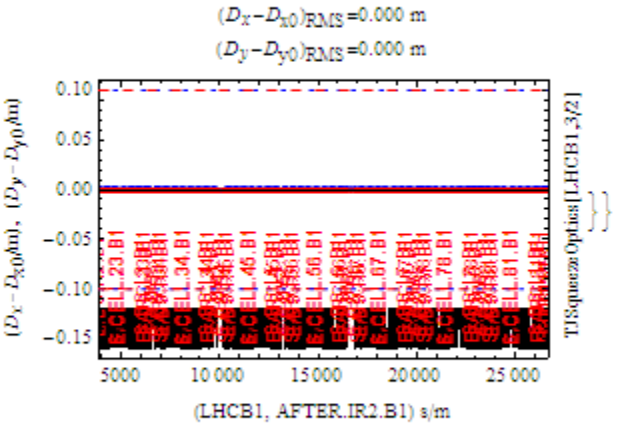

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Conclusion

- Finally found a new squeeze without the pre-squeeze for IR2
  - Had to abandon previous squeeze completely
- Beta-beating etc are acceptable
- Bumps mostly matched (E. Laface)
- Aperture (n1 value) also acceptable – final checks with bumps to be made.
- This optics can be used for p-p, squeezed to 3 m and for Pb-Pb this year at 3.5 Z TeV (and up to ~6.5 TeV later).
- Going beyond 3 m should be possible with more steps.
- Start in ramp to avoid pre-squeeze at 7 TeV?