

SLHC V3: selected topics

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Introduction

Optics

Chromatic properties

Sextupole schemes

Long term stability

Conclusion

Introduction

The HL-LHC (formerly SLHC) effort attempts to increase the peak luminosity of the LHC with some hardware changes.

There are many parameters that can be tweaked together with new equipment to increase the luminosity (e.g.):

$$L = L_{\text{ho}} F_{\text{geo}} F_{\text{hr}}$$

$$\frac{2\beta_x^*}{\sigma_z d_s} > F_{\text{geo}} < 1 \quad F_{\text{hr}} \ll 1 \text{ for } \beta^* < \sigma_z$$

The following will focus only on the problems and possibilities for reducing β^* .

Introduction

The HL-LHC (formerly SLHC) effort attempts to increase the peak luminosity of the LHC with some hardware changes.

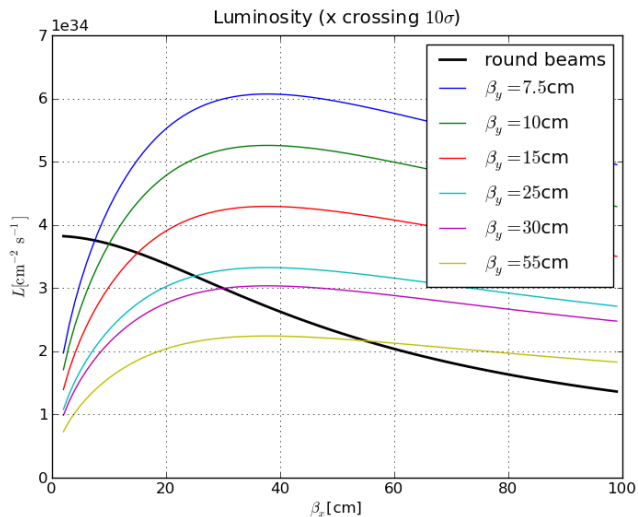
There are many parameters that can be tweaked together with new equipment to increase the luminosity (e.g.):

$$L = \frac{N_b^2 n_b f_{\text{rev}}}{4\pi\epsilon\sqrt{\beta_x^*\beta_y^*}} \frac{1}{\sqrt{1 + \left(\frac{\sigma_z d_s}{2\beta_x^*}\right)^2}} F_{\text{hr}}$$

$$\frac{2\beta_x^*}{\sigma_z d_s} > F_{\text{geo}} < 1 \quad F_{\text{hr}} \ll 1 \text{ for } \beta^* < \sigma_z$$

The following will focus only on the problems and possibilities for reducing β^* .

Example



$$N_b = 1.7 \cdot 10^{11}, n_b = 2808. \sigma_z = 7.55\text{cm}, d_s = 10, \epsilon_n = 3.5 \text{ mm mrad}$$

Motivation

Phase I upgrade (corresponding to the layout SLHCv2) showed that:

- ▶ β^* can be reduced only to 30 cm with no margin
- ▶ the main limitations is the chromatic aberrations and strength of the matching section quadrupoles
- ▶ the luminosity gain coming from β^* is 37%

SLHCv3 aims at overcoming those limitations using a new strategy to construct a collision optics. At this stage e proved that:

- ▶ the LHC layout is compatible with the new scheme excluding:
 - ▶ new larger aperture triplet and Q4-Q5 D1-2 TAS and new TAN in IR1 and IR5,
 - ▶ new MQY type Q5 in IR6,
 - ▶ possibly an additional MS per family and/or a recommissioning of the MS at 600A (see future studies at the end)
- ▶ the performance in terms of DA (excluding beam beam and the new elements) are barely acceptable of extreme cases ($\beta^* = 7.5, 30\text{cm}$ where the luminosity gain is a factor 2.5)

New scheme

The new squeezing strategy involves the following steps:

- ▶ IR1 and IR5 are squeezed to 60cm round beam in the usual way.
- ▶ The squeeze continues keeping the strength of the IR1-5 and the arcs constant and using the neighbor insertions (8-2, 4-6) quads to continue the squeeze at constant phase advance.

As a consequence there will be a betabeat in the neighbor arcs (strong arcs: 8-1 1-2 4-5 5-6).

If:

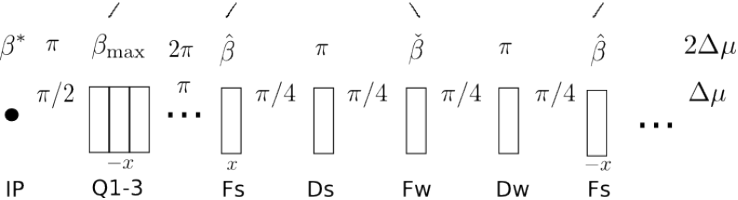
- ▶ the strong arcs phase advance is $\pi/2$,
- ▶ the phase advance from the IP and the first MS of one F and D family (strong families) is $\pi/2$ equivalent to π in the triplet,
- ▶ the strong MS are used to compensate the off momentum beta beat of the triplet at $\beta^* = 60\text{cm}$ or $\beta_{\text{max}} = 5.5\text{km}$.

Then:

- ▶ each MS of one family (*strong*) will experience a peak of the beta function proportional to the $1/\beta^*$ and to β_{max} in the triplet.
- ▶ each MS creates a off momentum beta beta perturbation that adds coherently and cancel exactly the perturbation from the triplet for any β_x^*, β_y^* at any stage of the squeeze.
- ▶ with a closed orbit peak at the strong sextupole, it is possible to create a dispersion perturbation that can compensate the spurious dispersion.

New scheme

Beta beat rotate with twice the phase advance.



$\hat{\beta}$: high beta peak: nominal + perturbation

$\check{\beta}$: low beta peak: nominal - perturbation

Fs,Ds: Strong focusing, defocusing sextupole location

Fw,Dw: Weak focusing, defocusing sextupole location

Optics

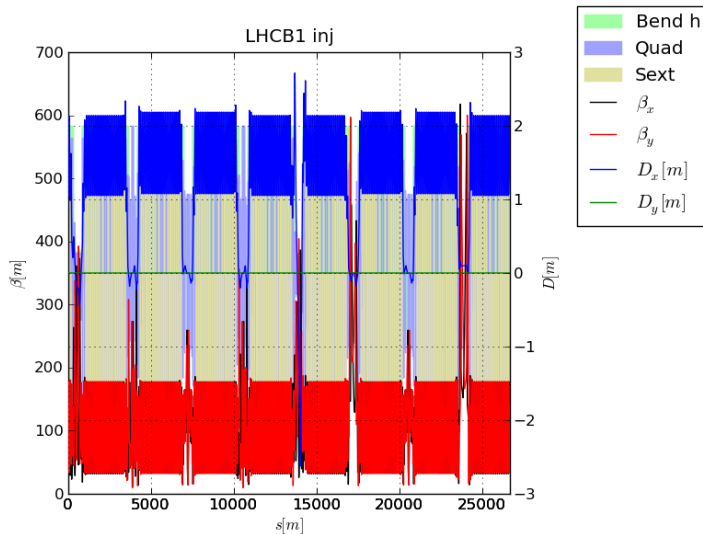
Name	IP1			IP5		
	β_x^* [m]	β_y^* [m]	X plane	β_x^* [m]	β_y^* [m]	X plane
inj	14	14	H or V	14	14	V or H
1111	0.60	0.60	H or V	0.60	0.60	V or H
2222	0.30	0.30	H or V	0.30	0.30	V or H
2828	0.30	0.075	H	0.30	0.075	H
2882	0.30	0.075	H	0.075	0.30	V
8228	0.075	0.30	V	0.30	0.075	H
8282	0.075	0.30	V	0.075	0.30	V

Inj: integer tune split reduced to 2, 4 arcs at $\pi/2$;

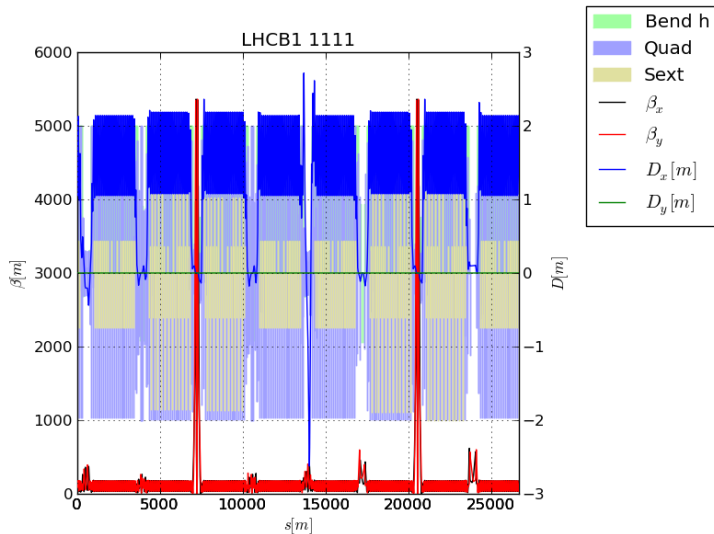
1111: pre-squeezed optics IR15 constant from now on, using Phasel elements;

others: squeeze using IR8, IR2, IR4, IR6, numbers refers to the β^* reduction factor.

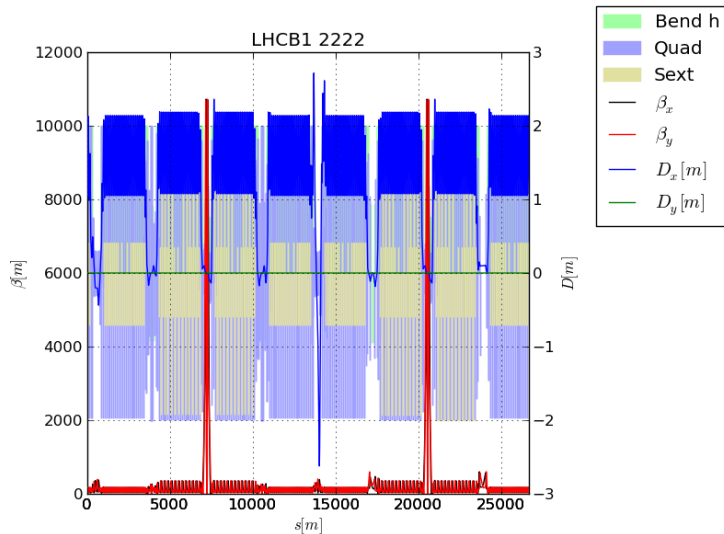
LHC Squeeze



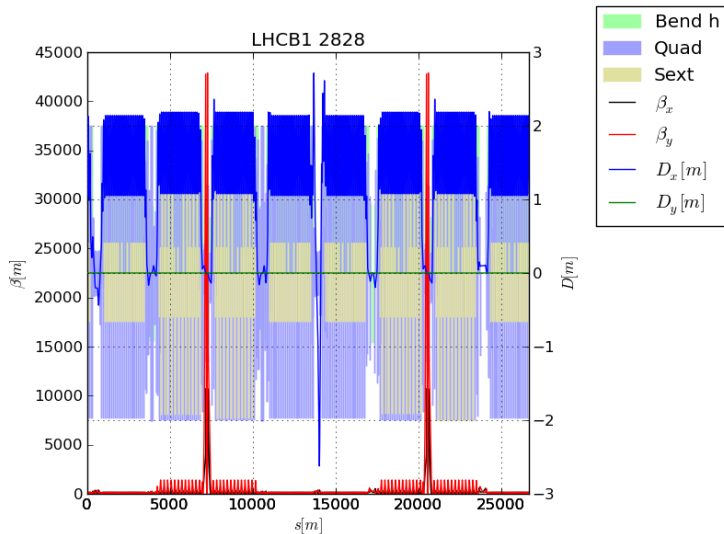
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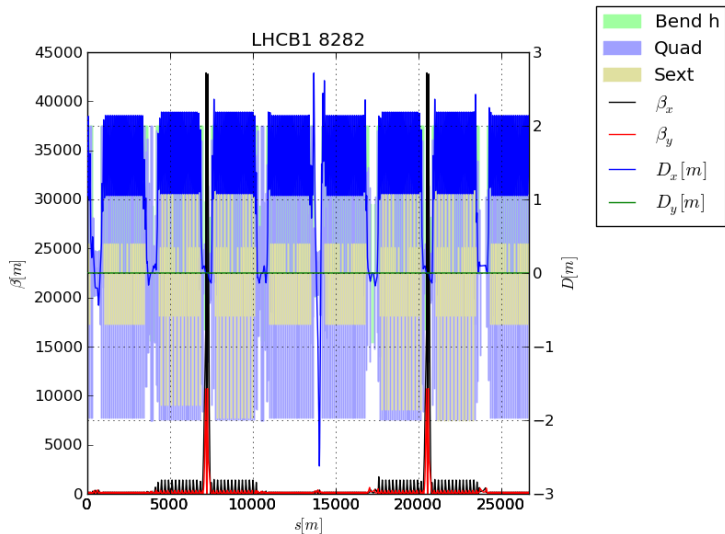
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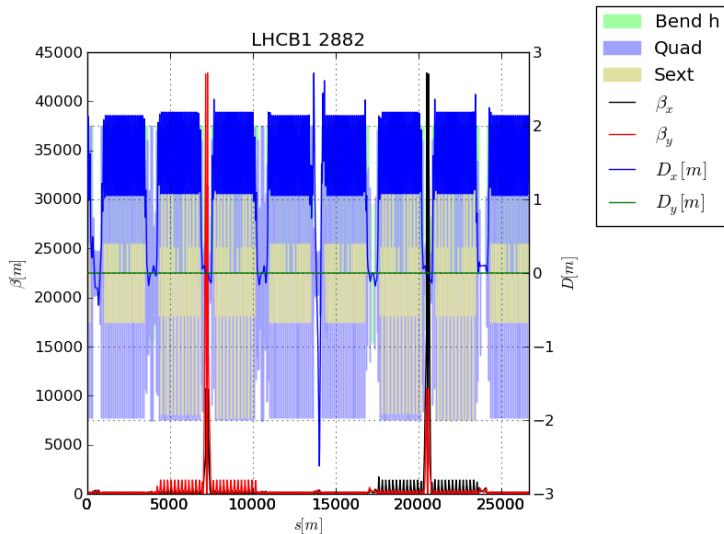
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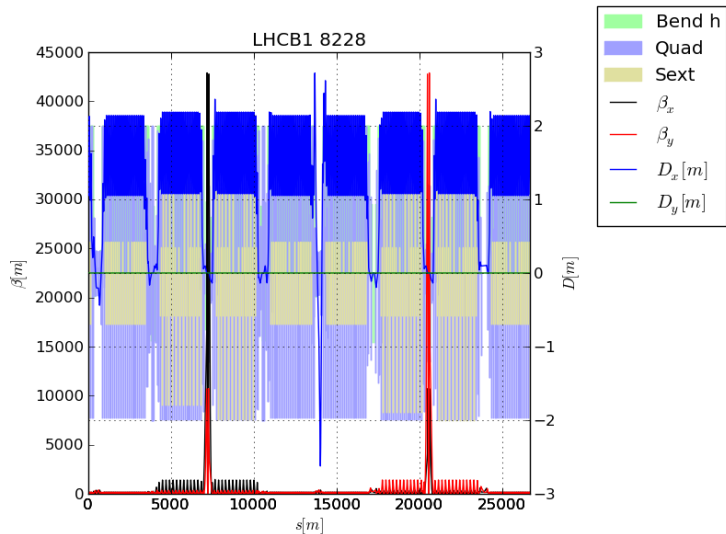
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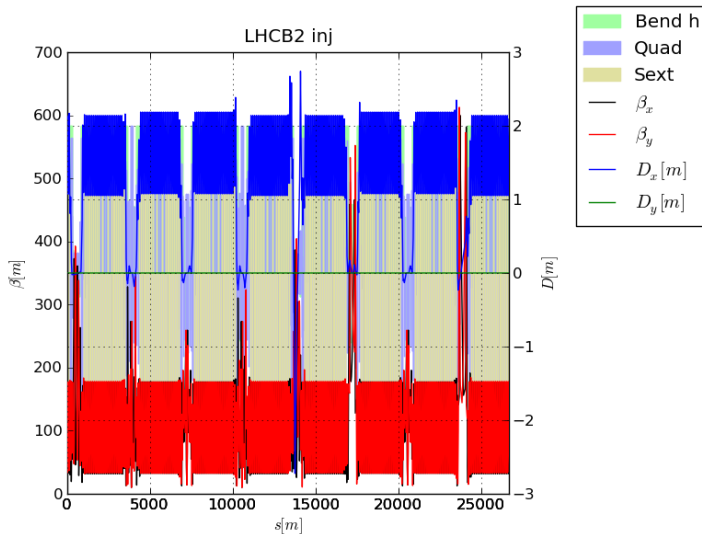
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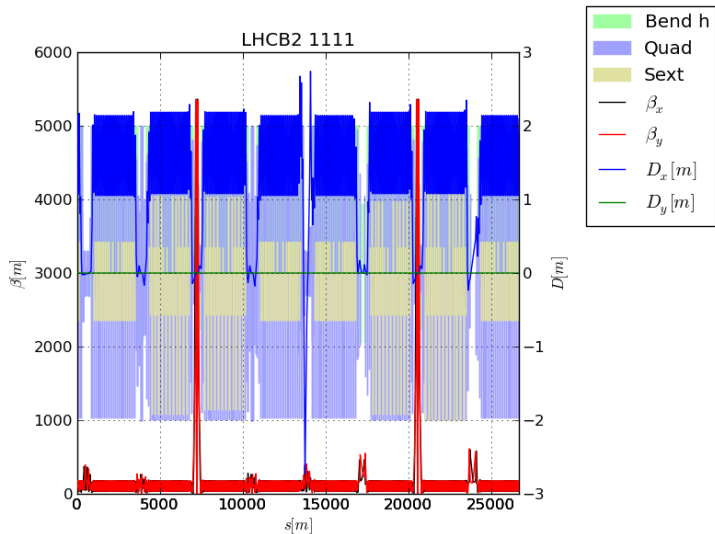
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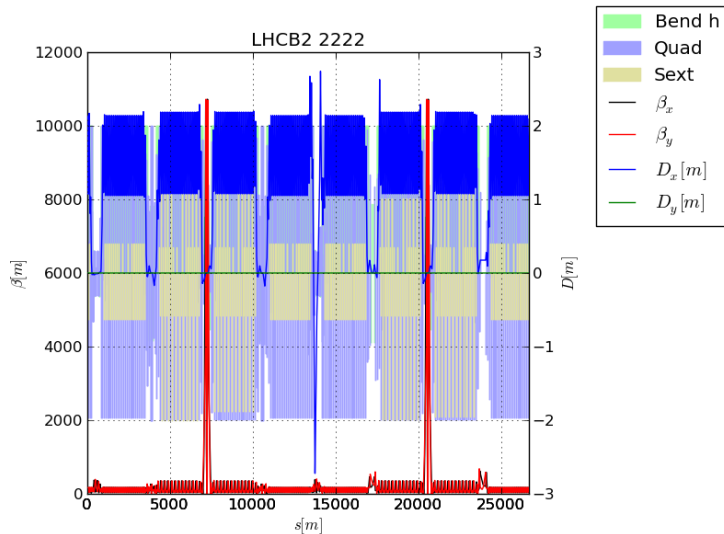
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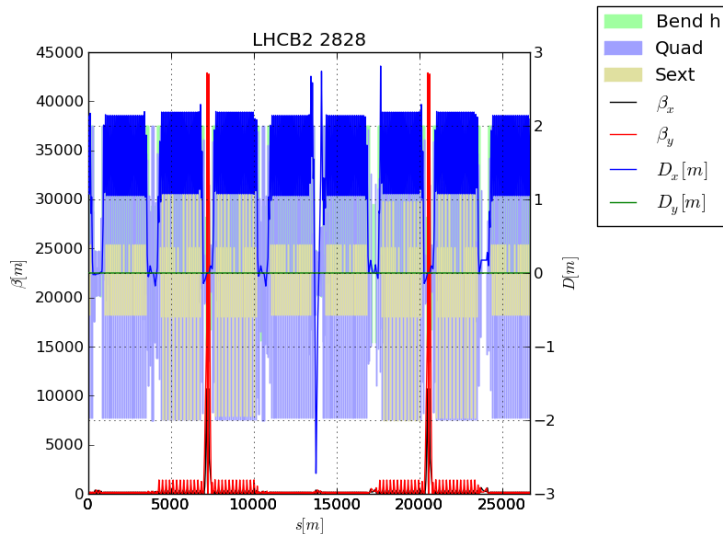
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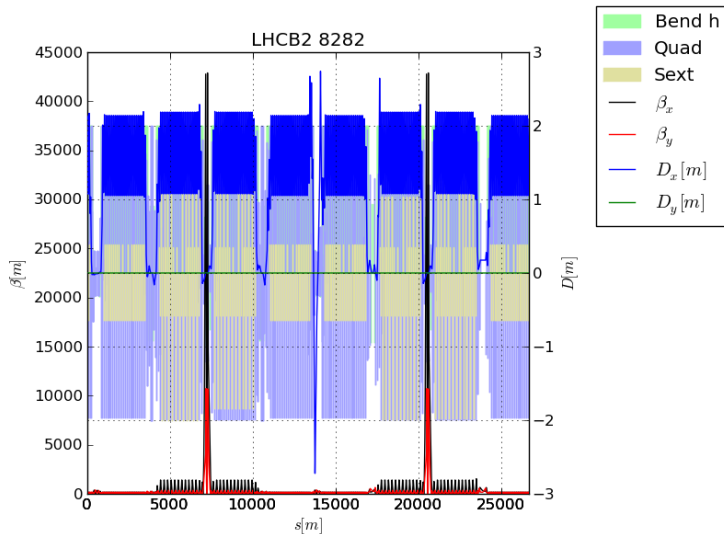
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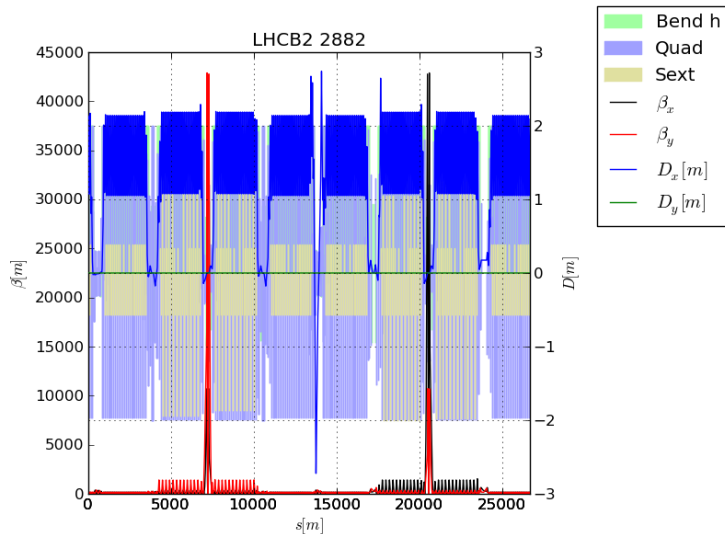
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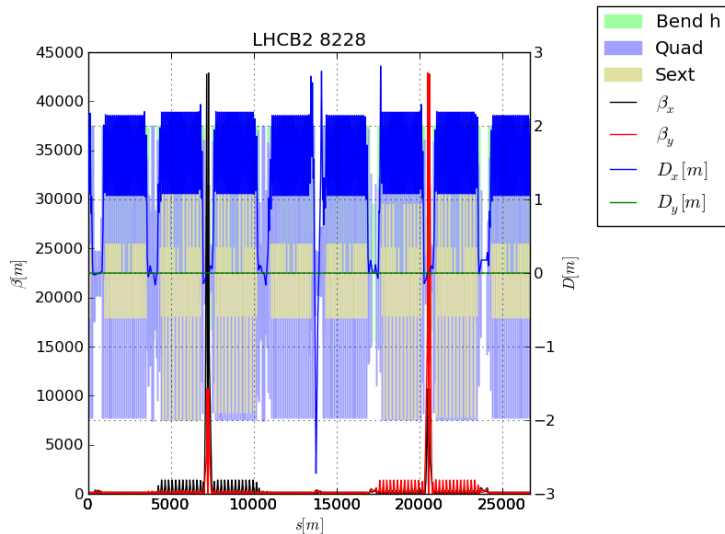
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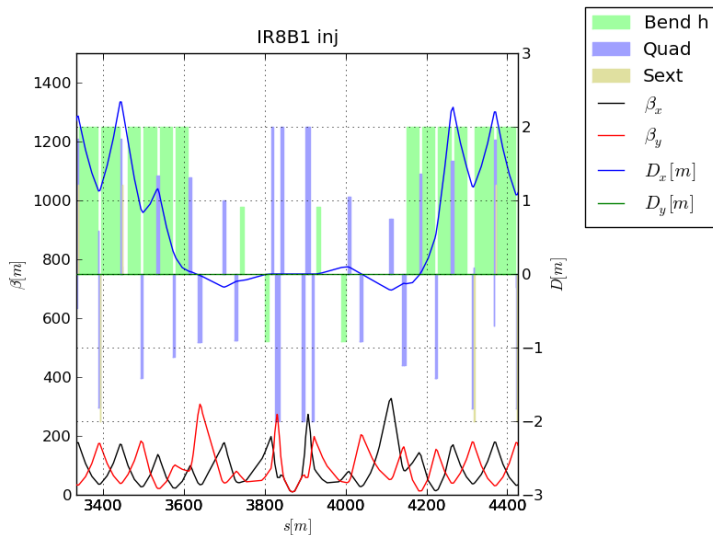
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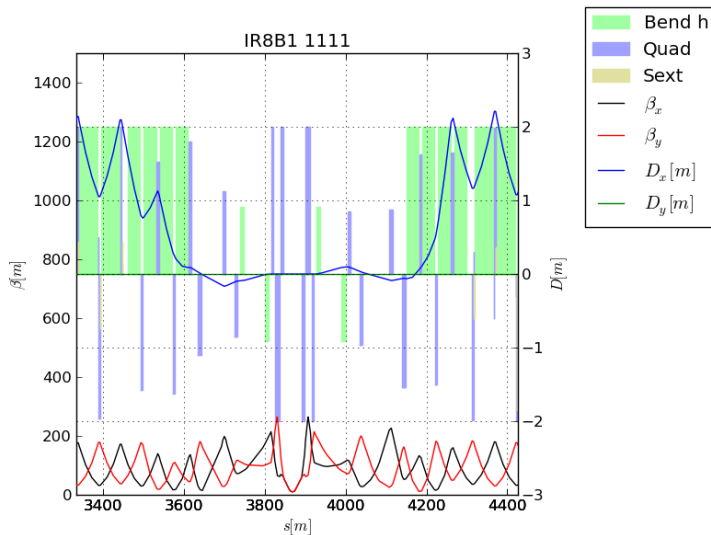
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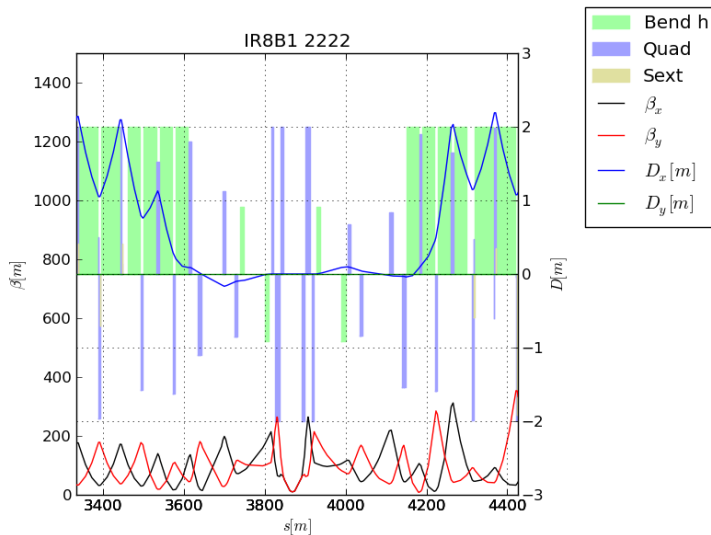
IR8 Squeeze



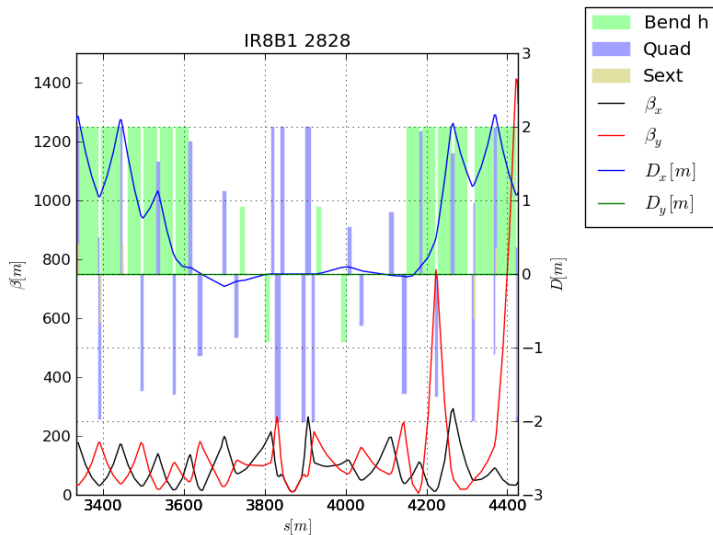
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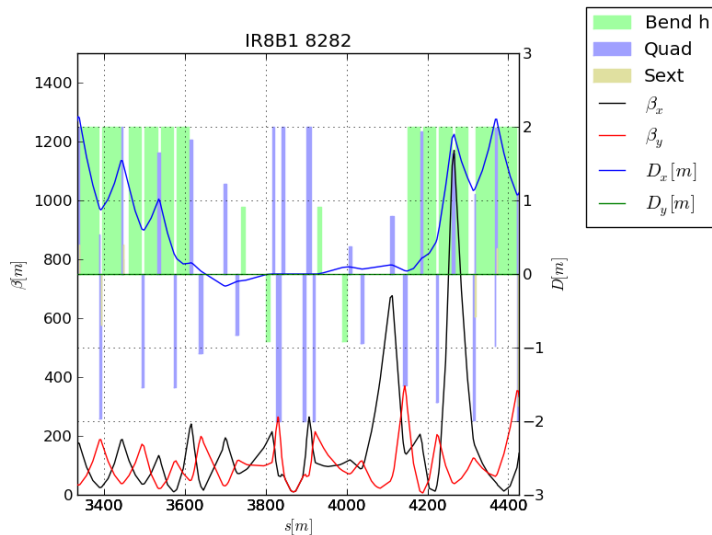
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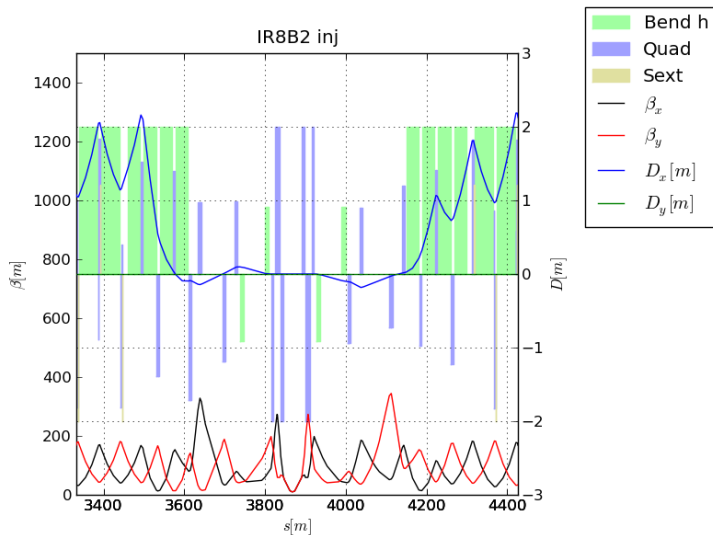
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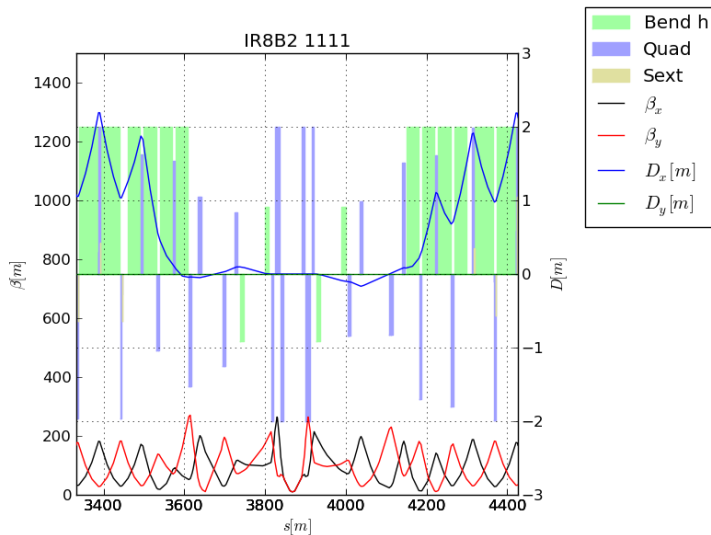
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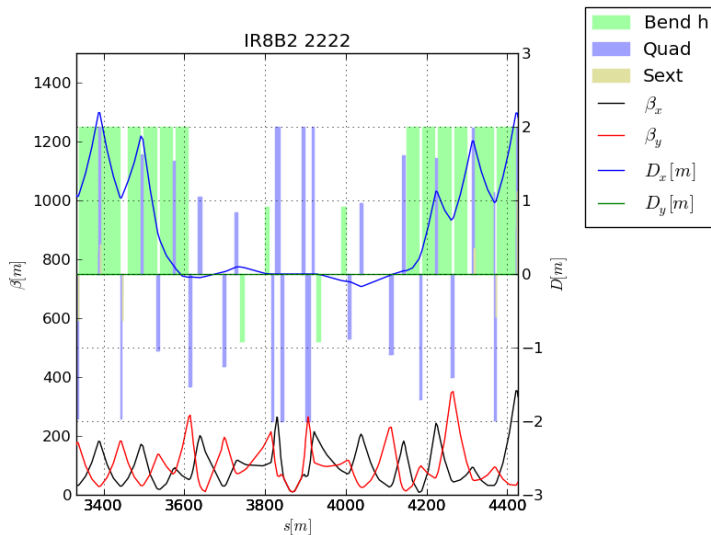
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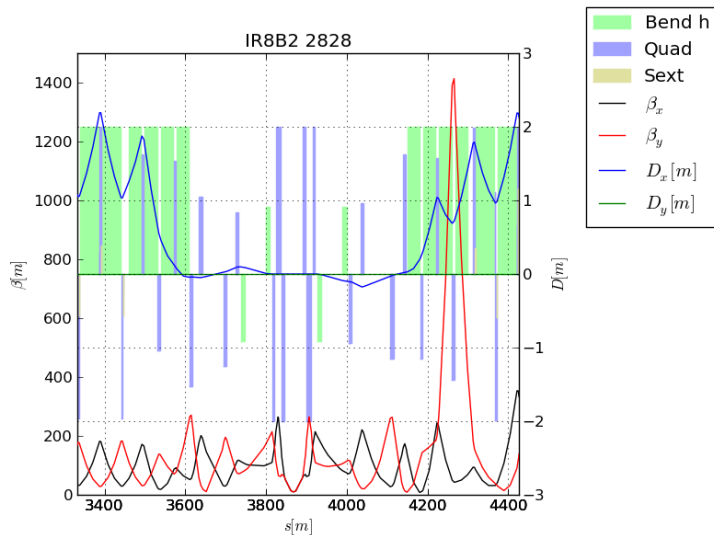
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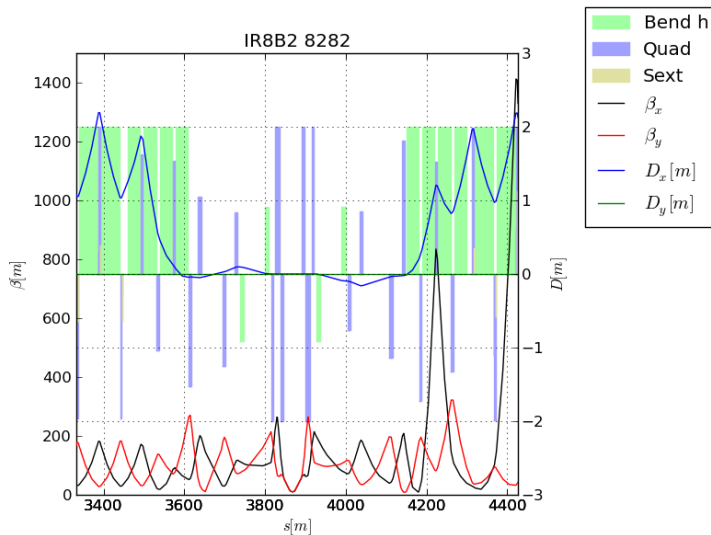
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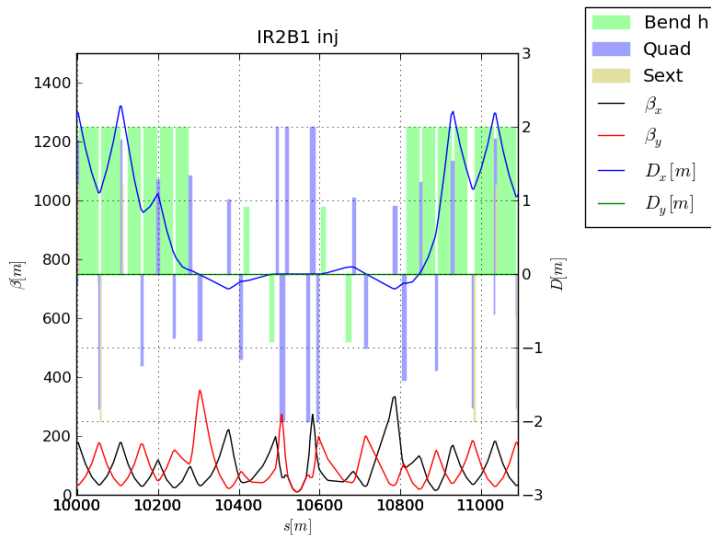
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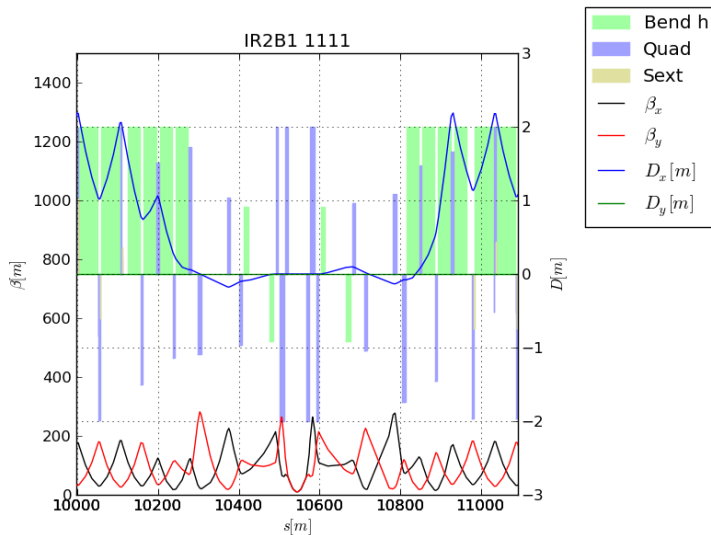
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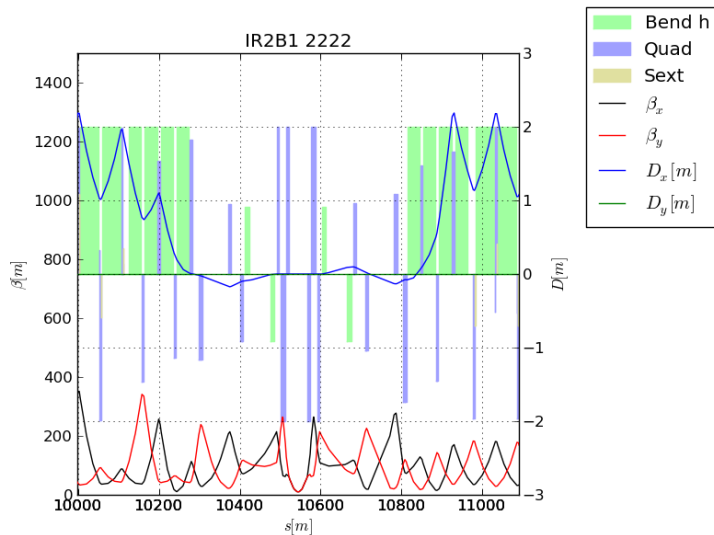
IR2 Squeeze



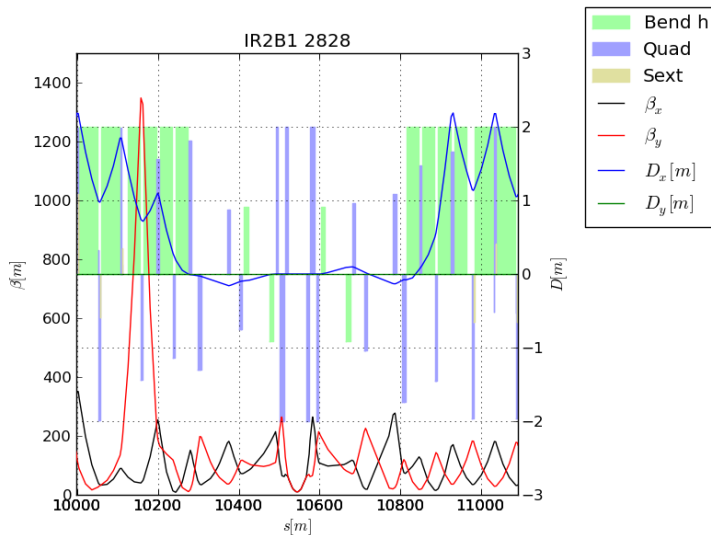
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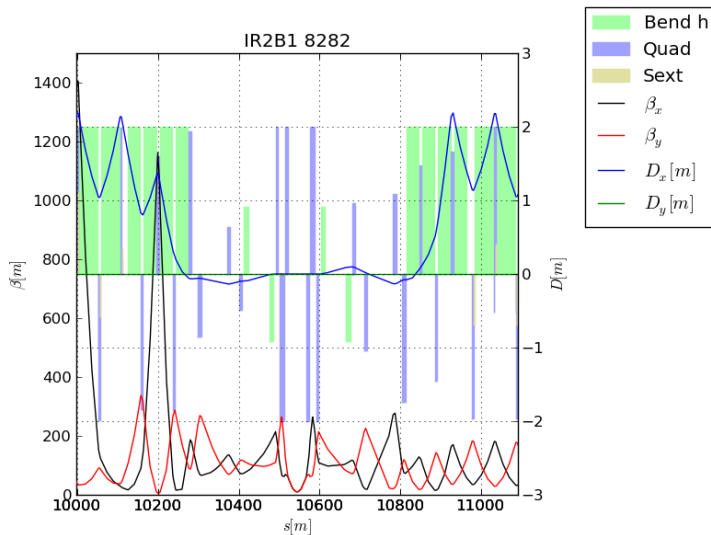
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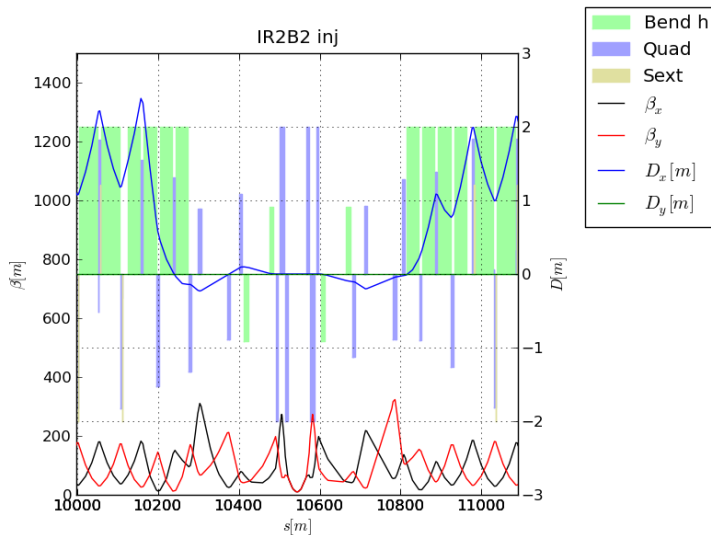
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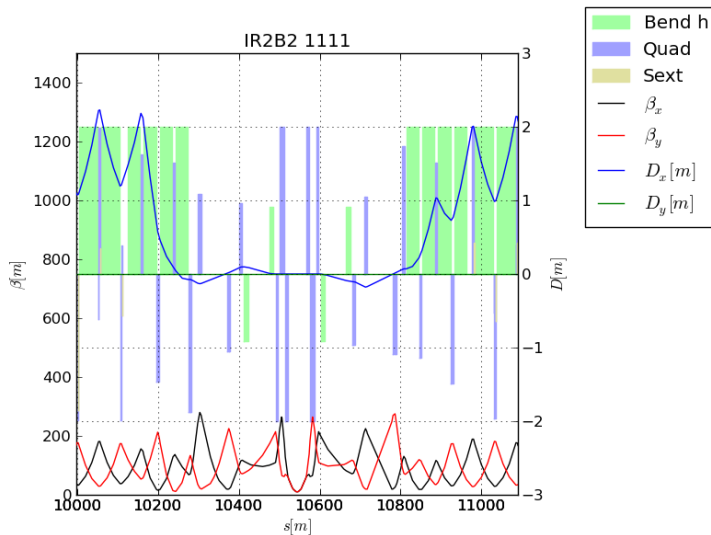
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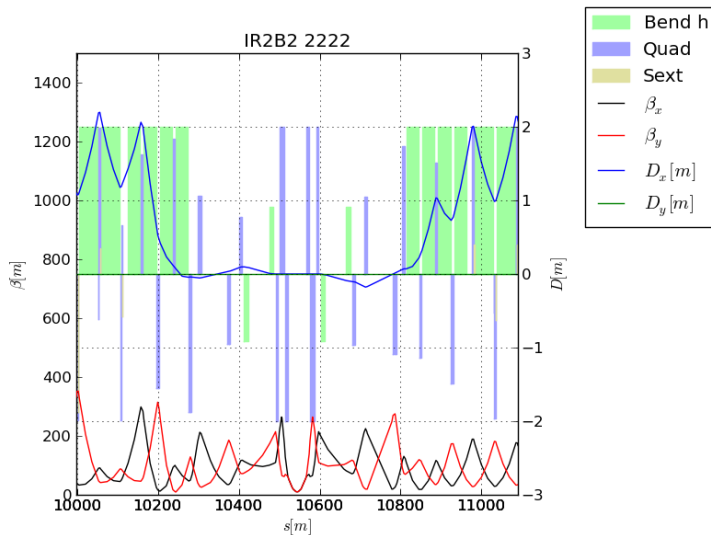
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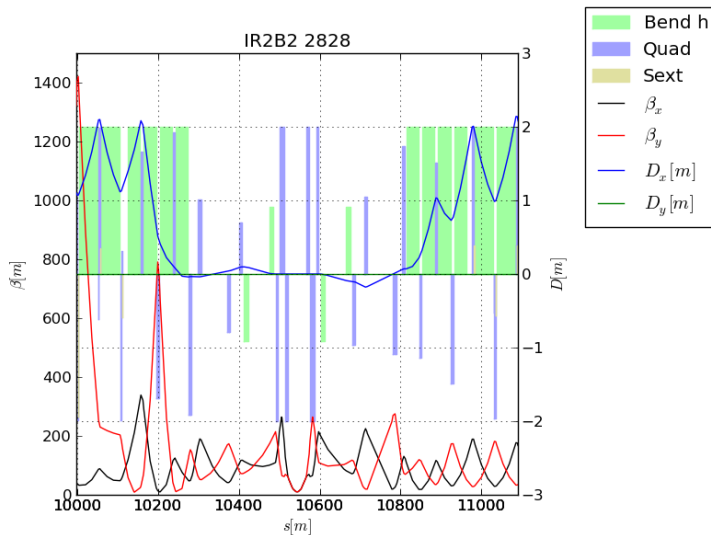
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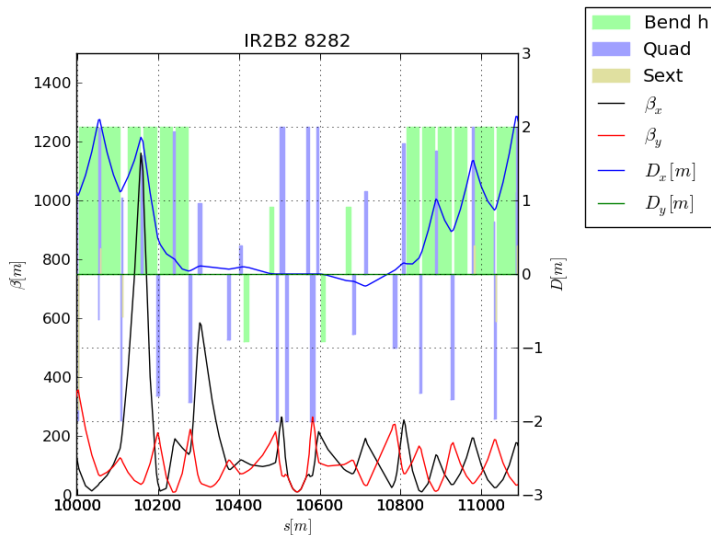
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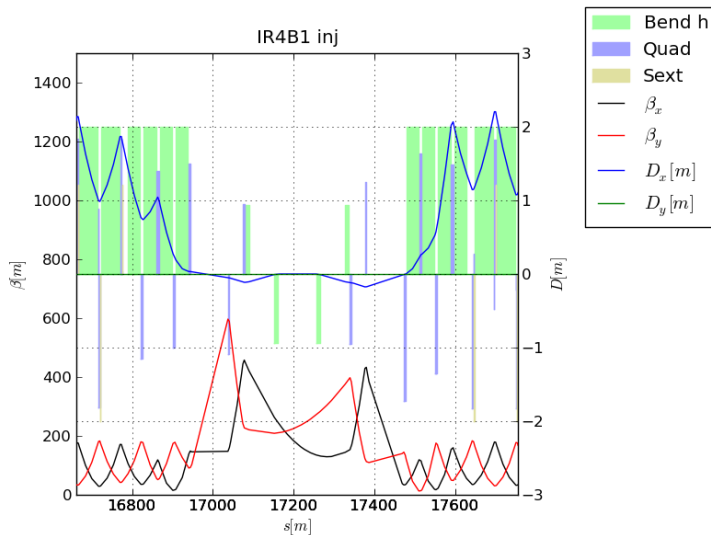
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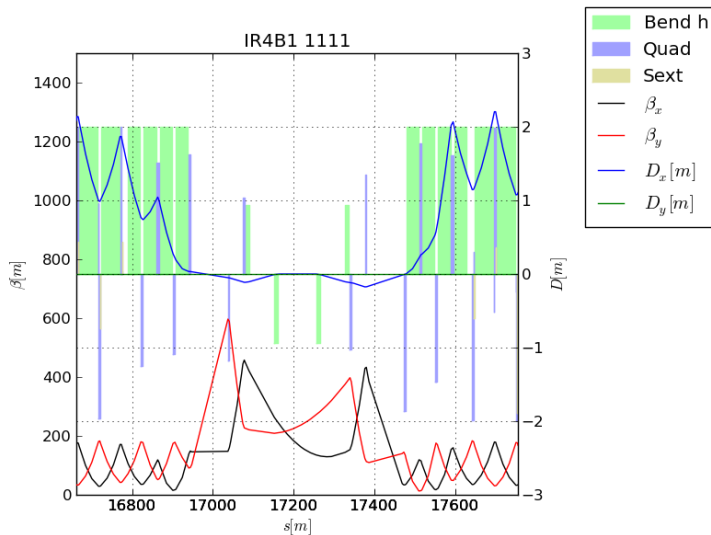
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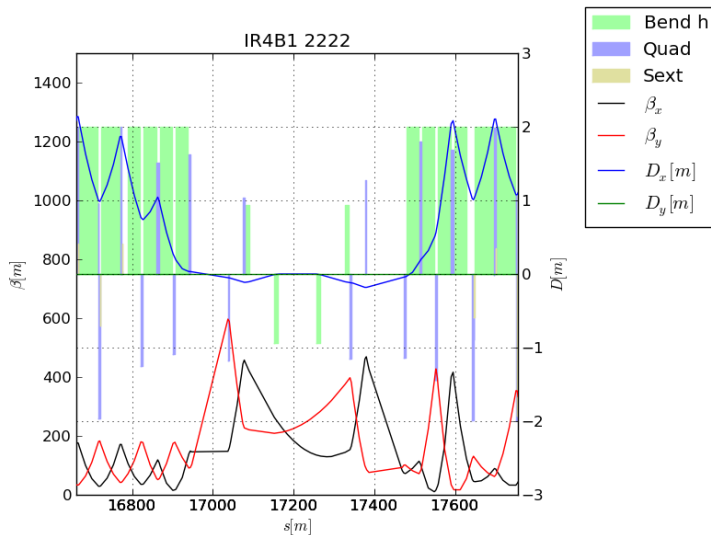
IR4 Squeeze



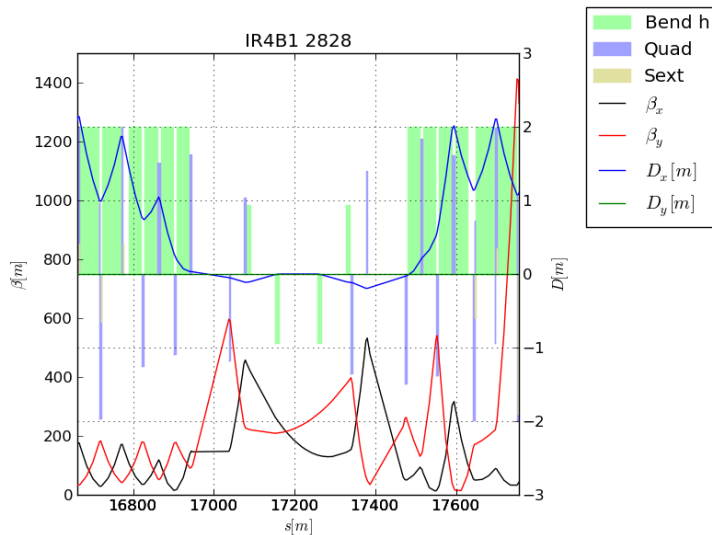
IR4 Squeeze



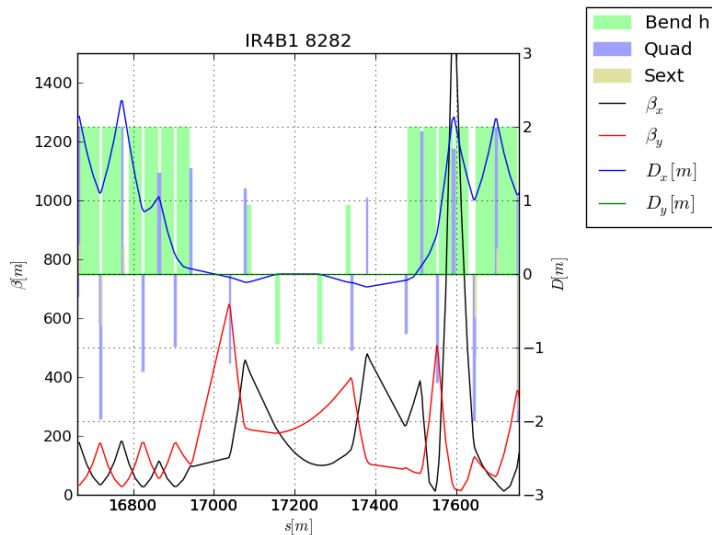
IR4 Squeeze



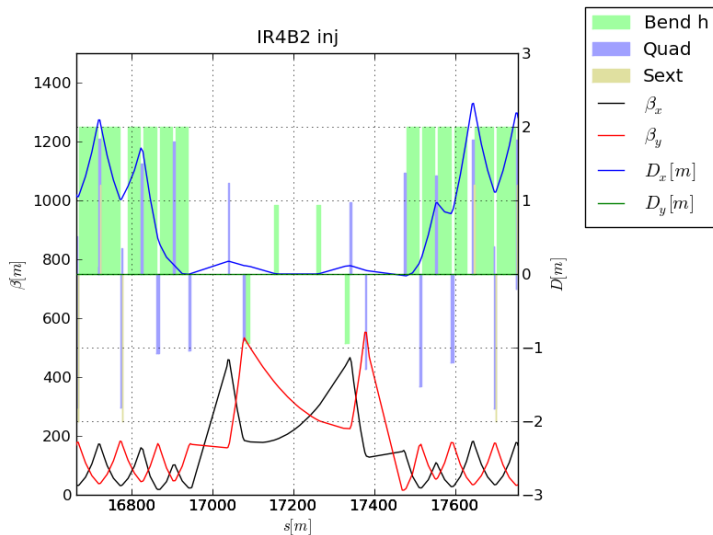
IR4 Squeeze



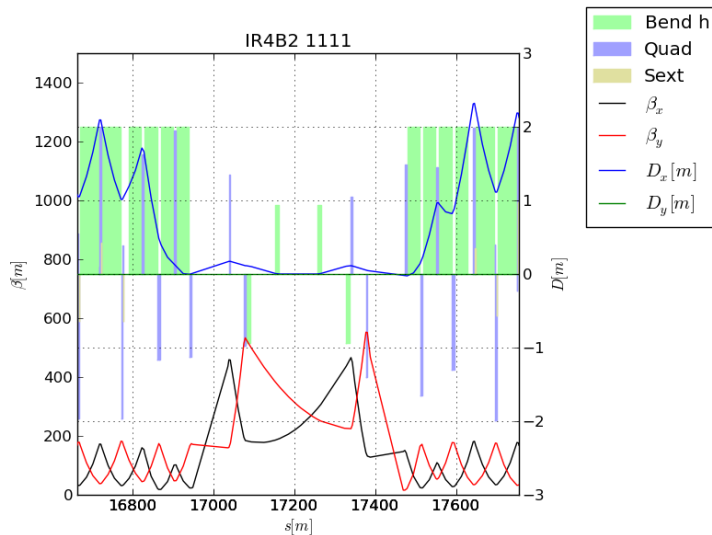
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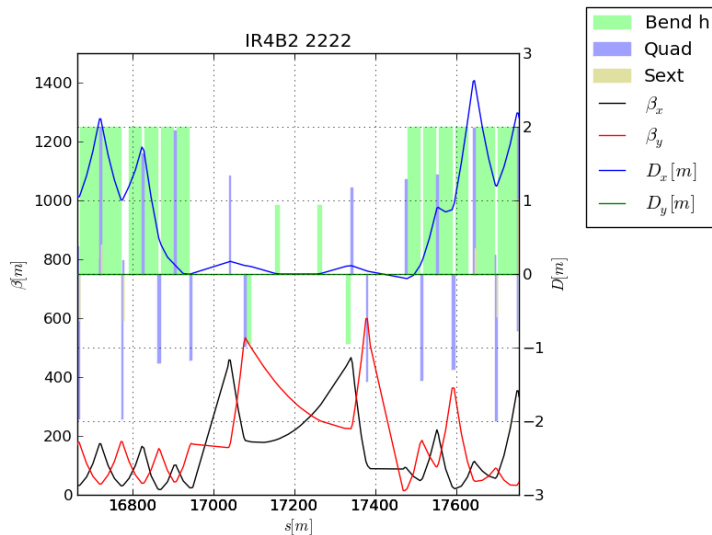
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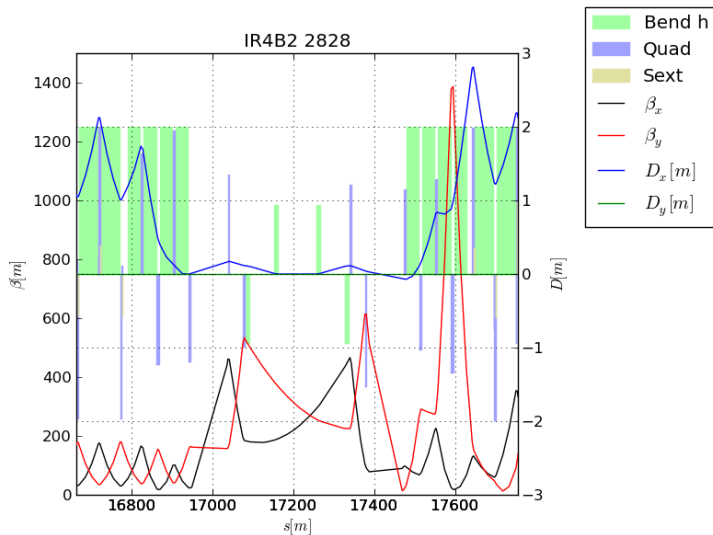
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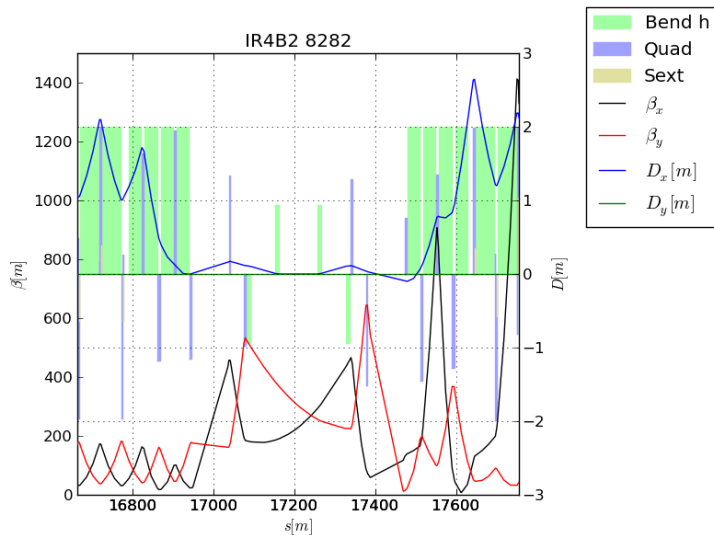
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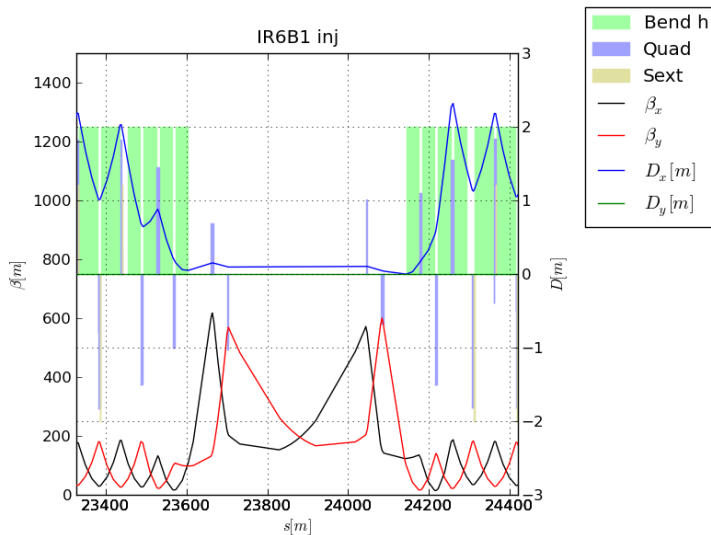
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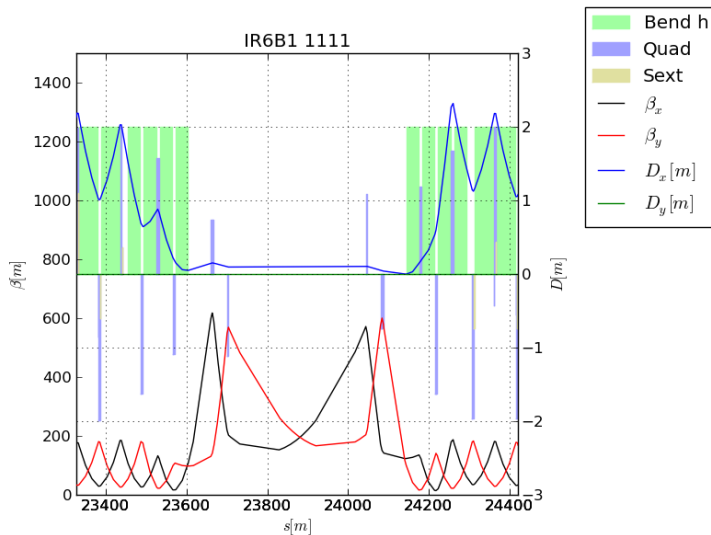
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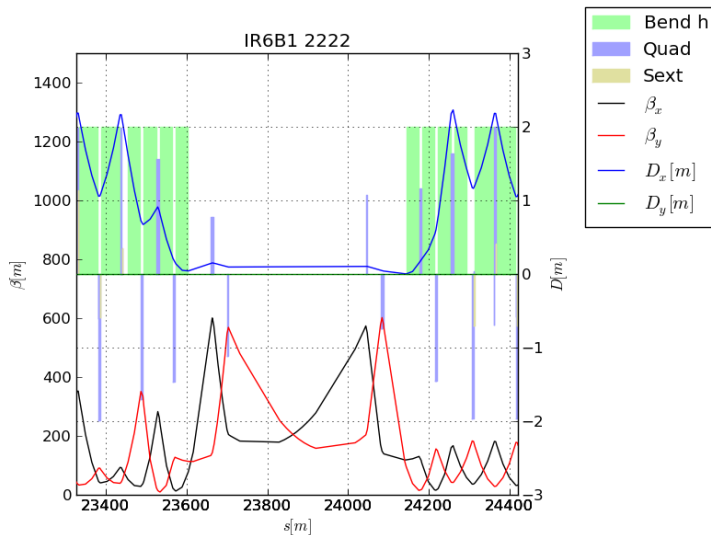
IR6 Squeeze



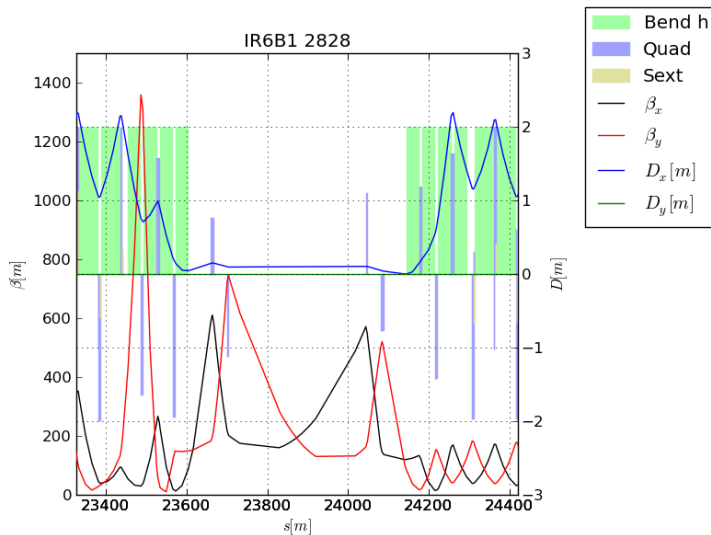
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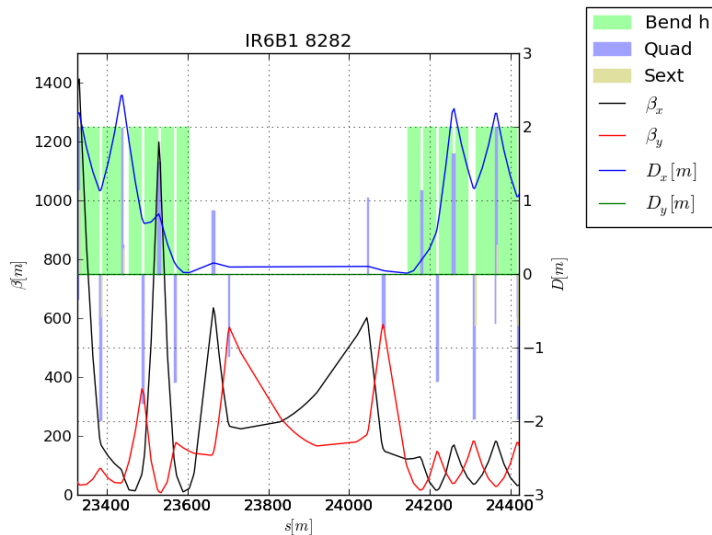
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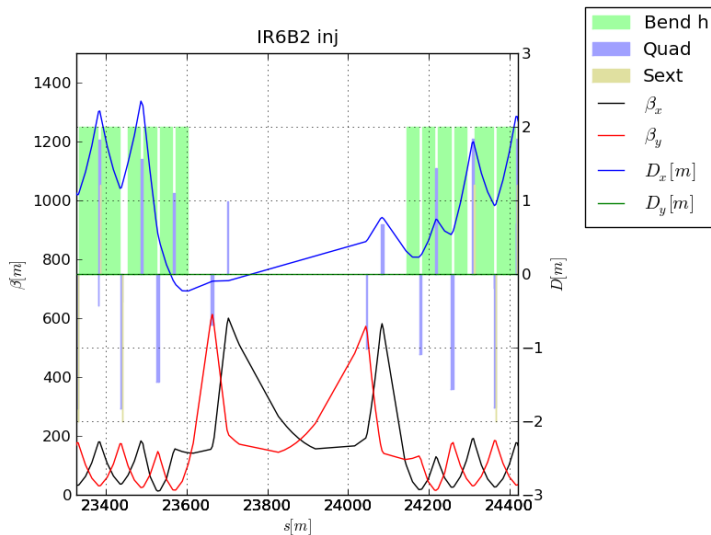
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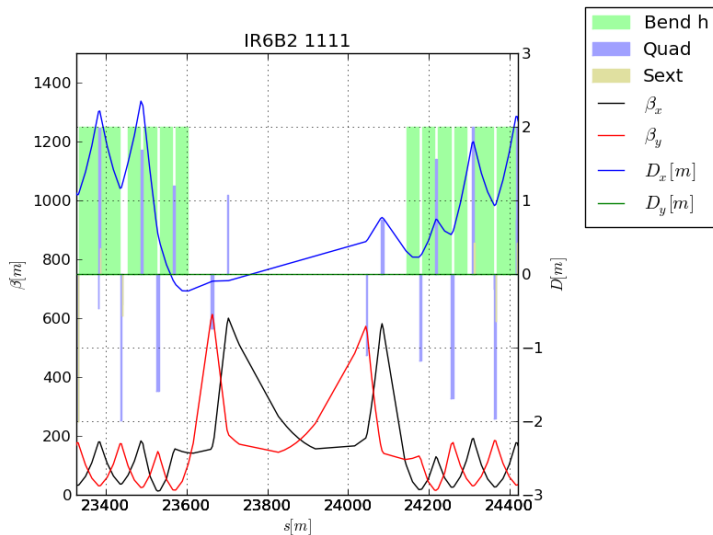
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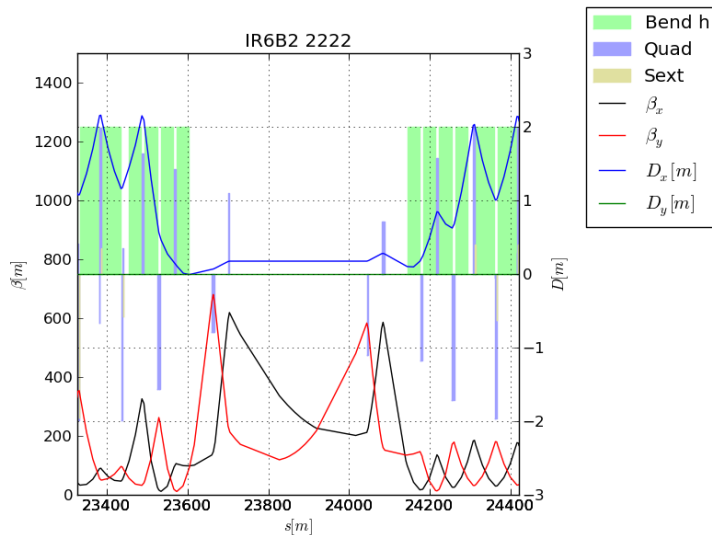
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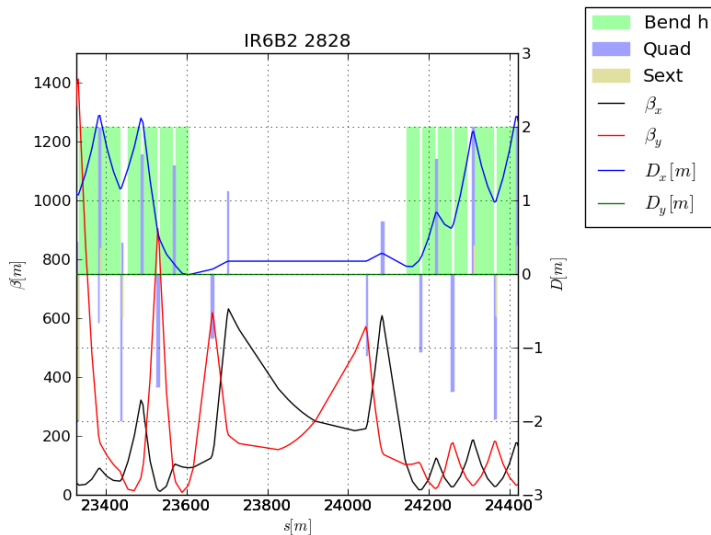
IR6 Squeeze



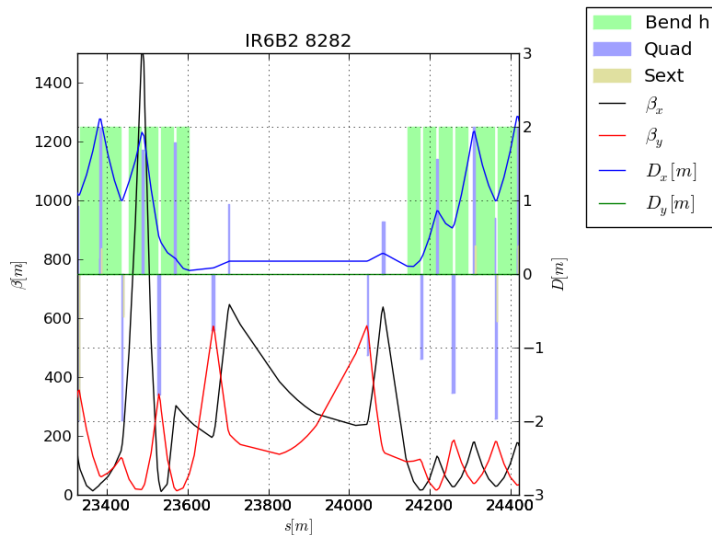
IR6 Squeeze



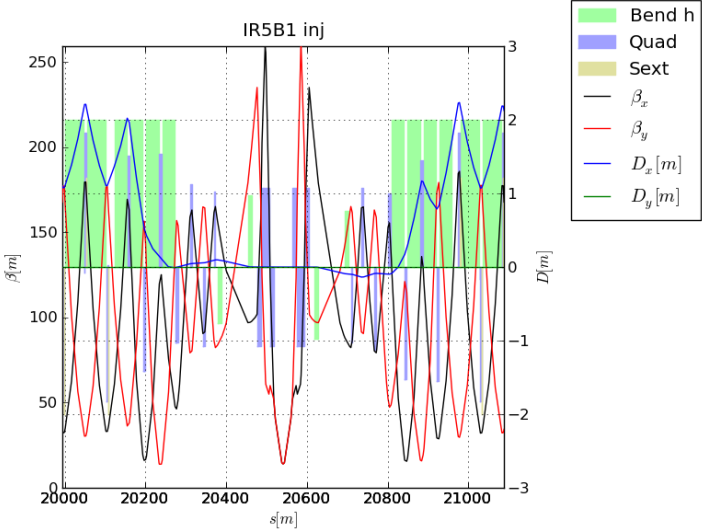
IR6 Squeeze



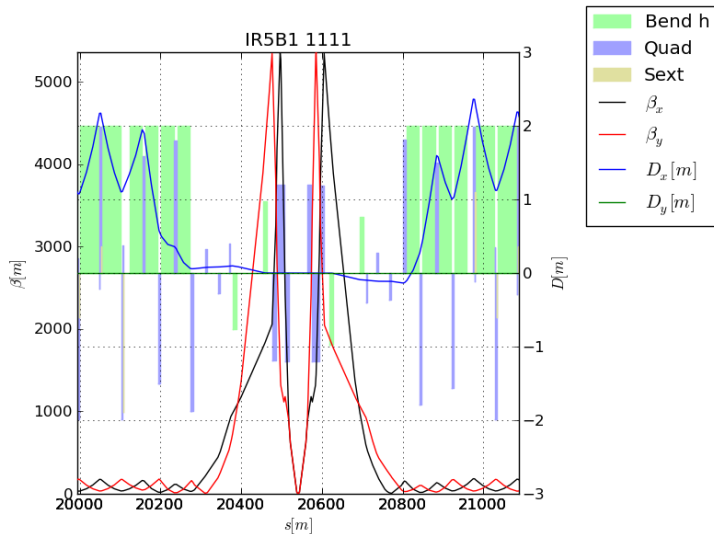
IR6 Squeeze



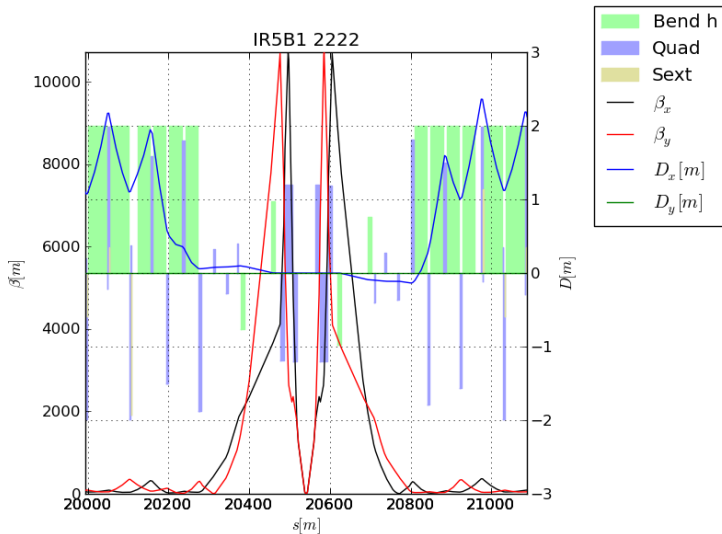
LHC Squeeze



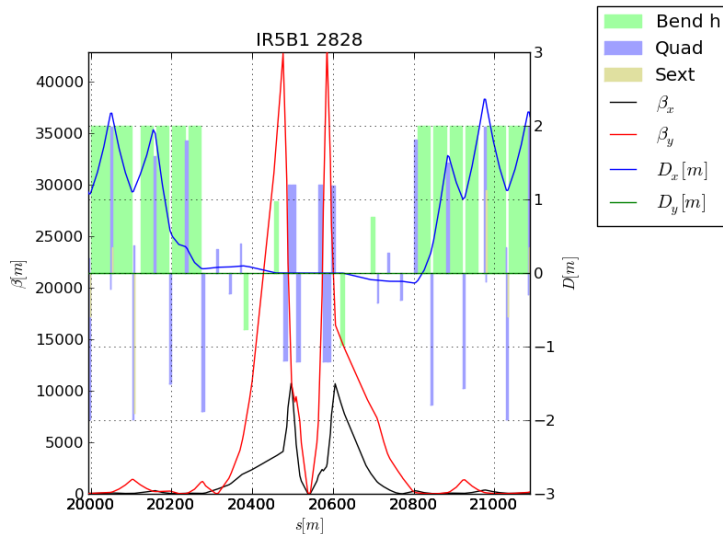
LHC Squeeze



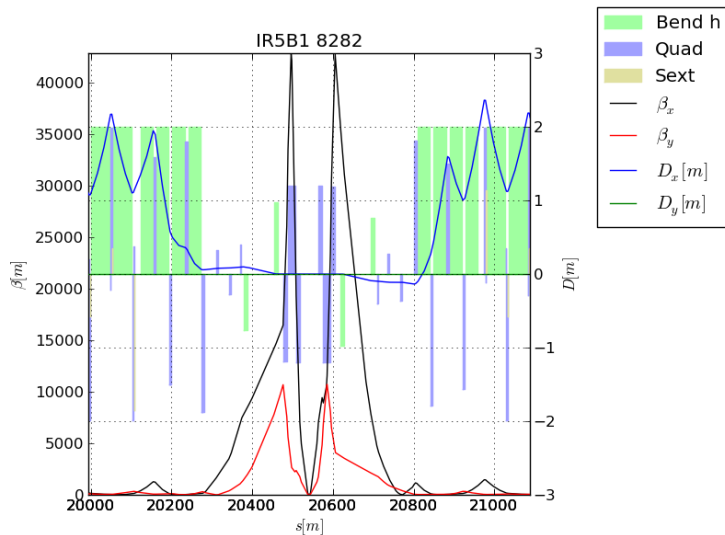
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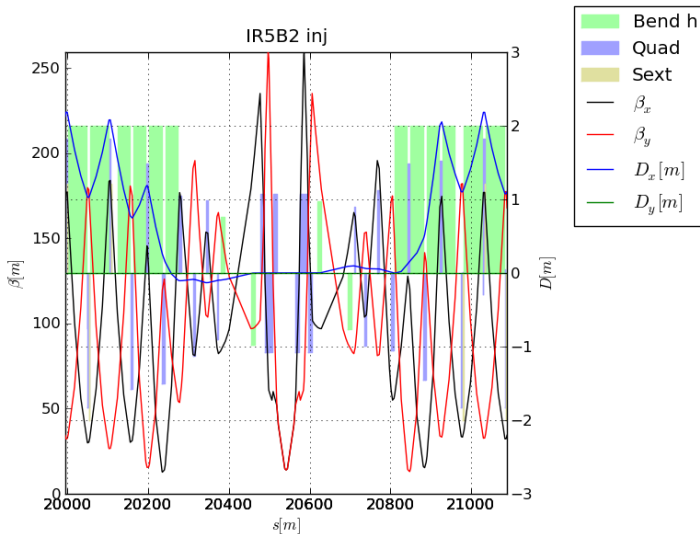
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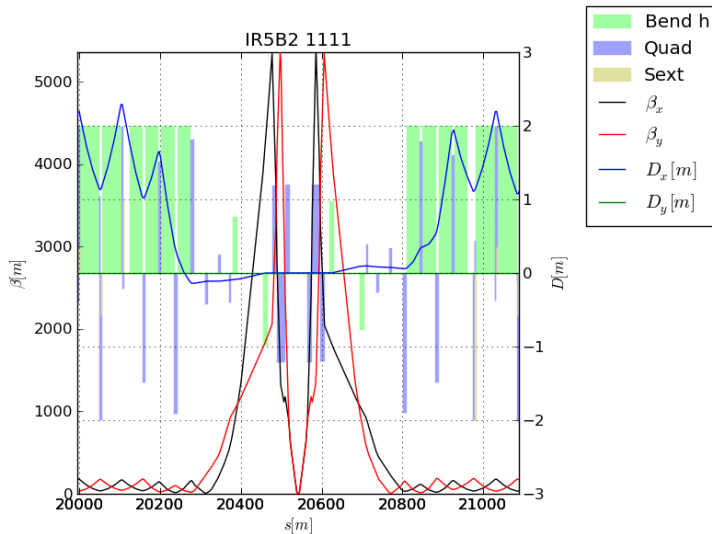
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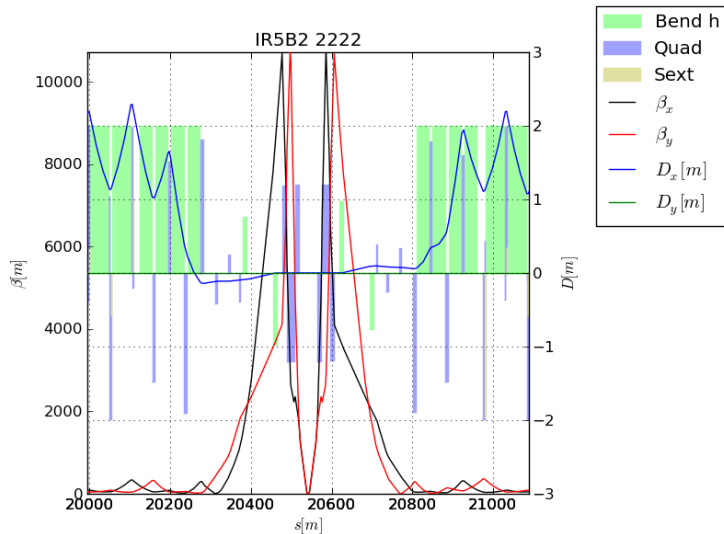
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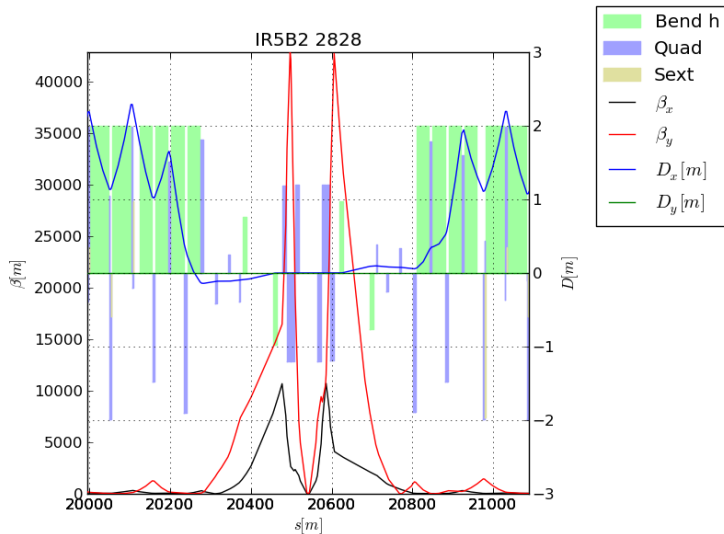
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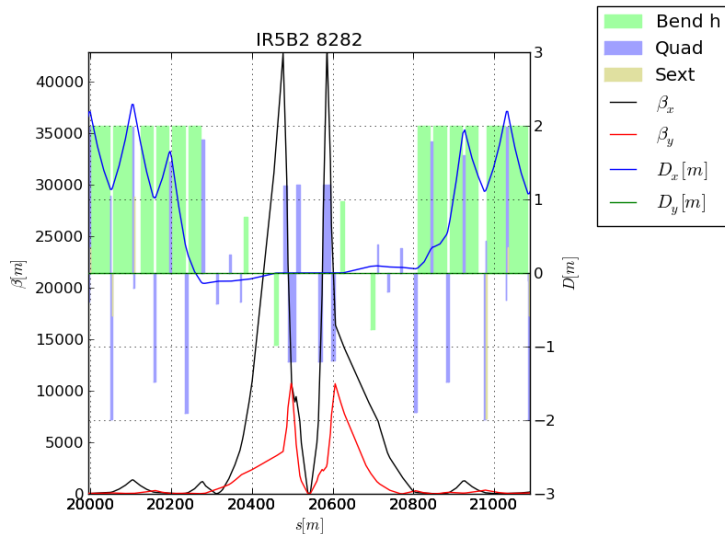
LHC Squeeze



LHC Squeeze



LHC Squeeze



IR1-5 triplet layout

As working assumption, we assumed the phase 1 project triplet layout with 120T/m gradient.

For the extreme cases we need the aperture be rescaled to 150mm, compatible then with Nb3Sn but with large margin.

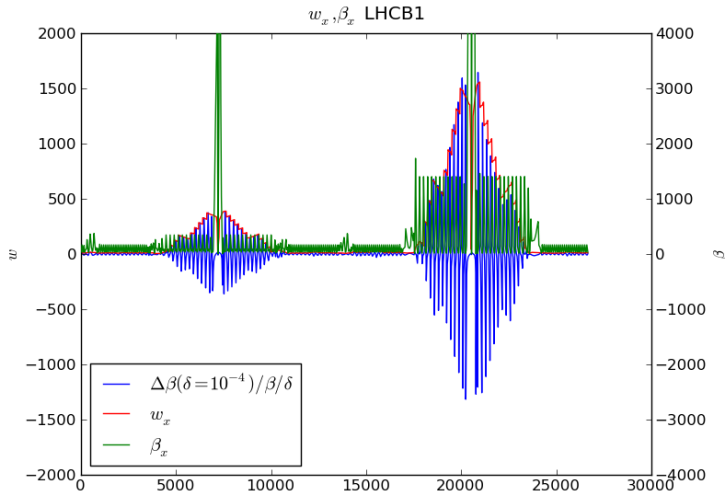
The scheme allows a triplet layout with NbTi technology with a minor changes of the optics and chromatic correction.

With Nb3Sn magnets it is anyway possible to gain in:

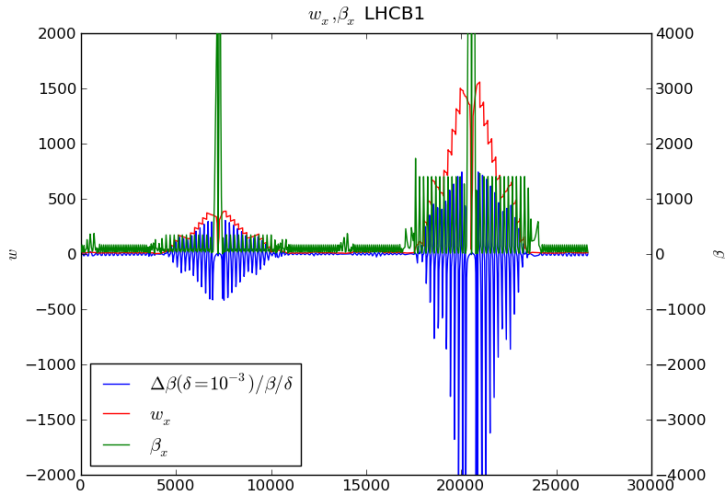
- ▶ parasitic encounters (shorter magnets)
- ▶ reduce beta max in the arcs at constant β^* (thanks to the reduction of β^* pre squeeze optics)

We will address the design of the triplet in layout in the next iteration when we optimize the β^* ratios.

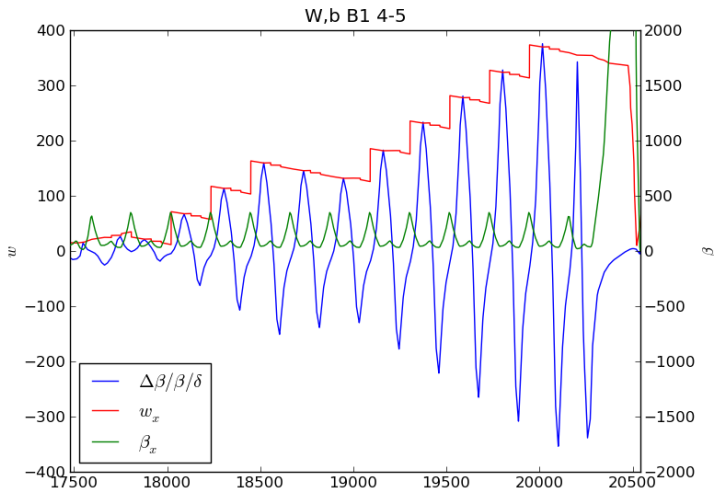
Chromatic properties: beta beat 2882



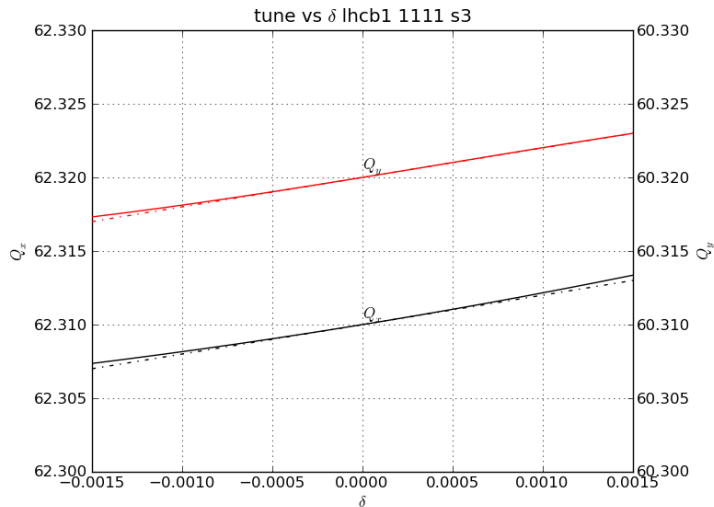
Chromatic properties: beta beat 2882



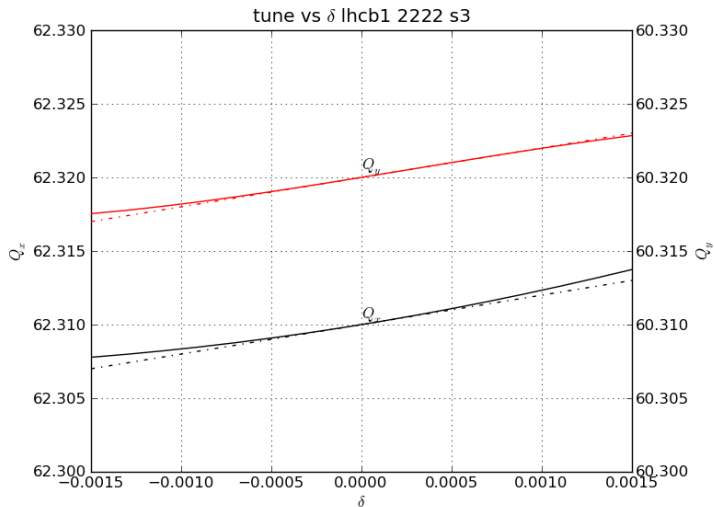
Chromatic properties: beta beta



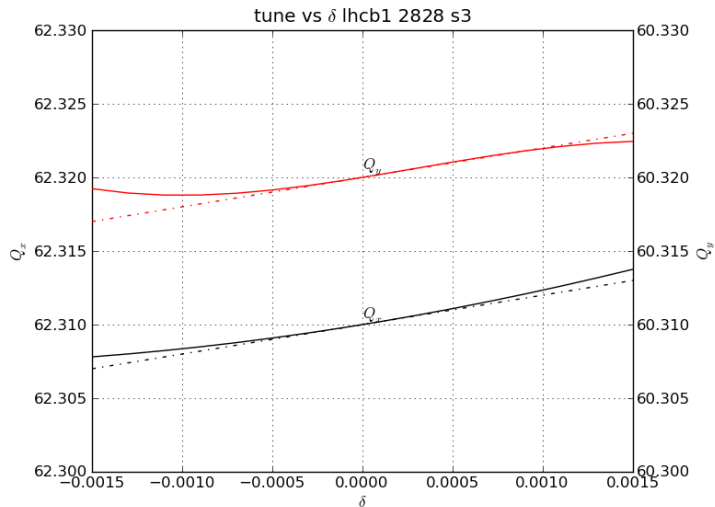
Chromatic properties: tune



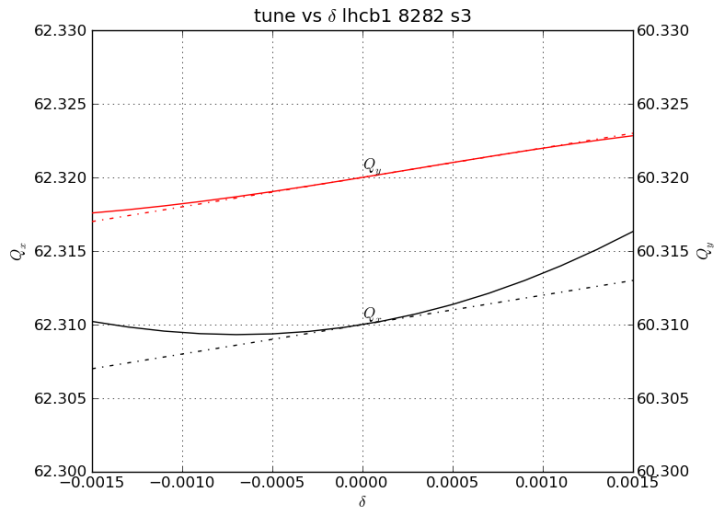
Chromatic properties: tune



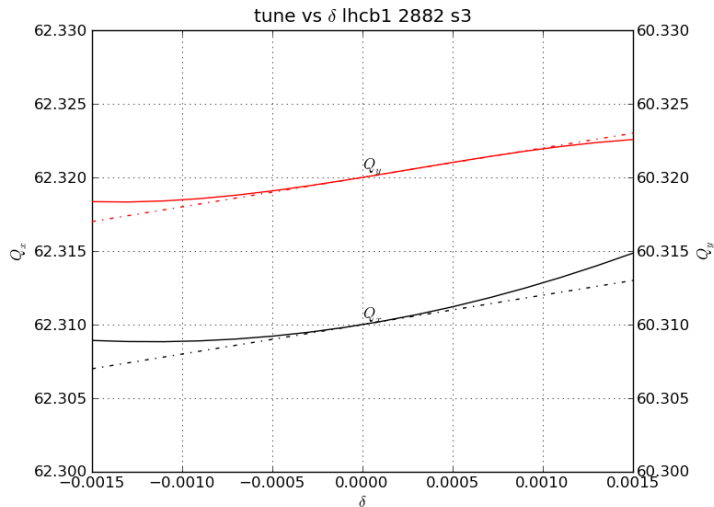
Chromatic properties: tune



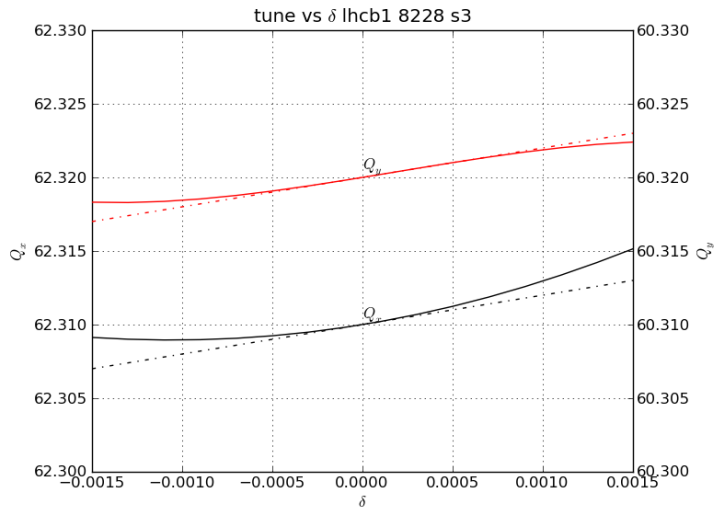
Chromatic properties: tune



Chromatic properties: tune



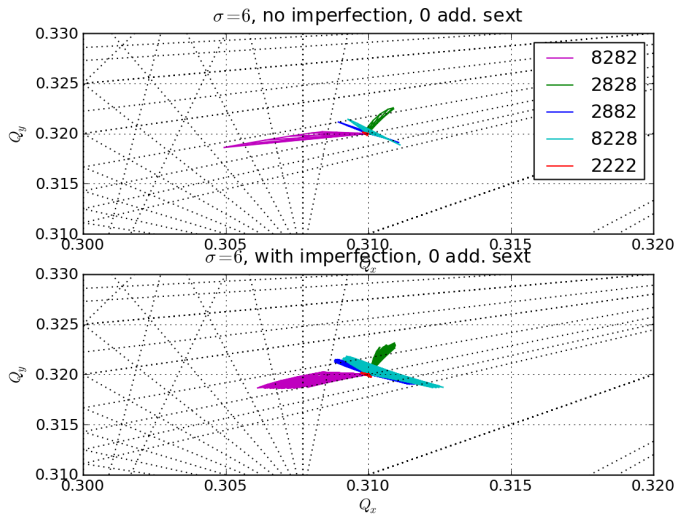
Chromatic properties: tune



Chromatic properties

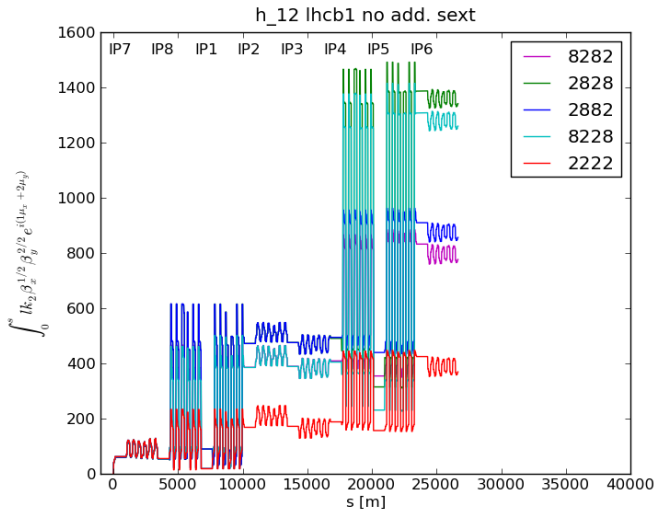
- ▶ Beta beat is local around the experiments.
 - ▶ Linear and non linear parts don't leak in the IRs and don't generate high order chromaticity.
 - ▶ Chromatic properties stable during the squeeze.
-
- ▶ We effectively trade the chromatic perturbations with the geometric perturbations in the arcs by increasing the beta function in the arcs.

Footprint with or without imperfection



Imperfections include all but new magnets (Q1-3/D1D2/Q4)
New regime for long term stability for the LHC!

Driving Terms



Not exact compensation even if strong sextupoles are at π ! The reason is that there are an odd number of strong sextupoles: only one is not compensated!

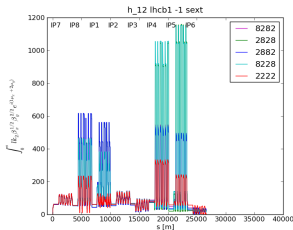
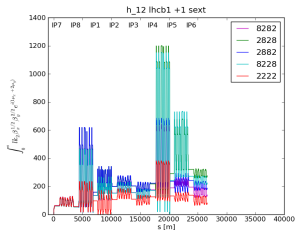
Alternative sextupole options

There are several mitigation strategies at constant luminosity:

- ▶ add sextupoles in Q10 (there is room, it increases sextupole budget and therefore optimization margin)
- ▶ remove sextupole MS14 (easy, but we loose overall sextupole strength and optimization margins)
- ▶ readjust phase advances such $\mu_{IP} \rightarrow \mu_{MS} = \pi/2$ in Q12 and not Q14 (if it is possible, we then loose flexibility in the IR)

In addition to that we can try to gain by decreasing β^* of the pre-squeeze optics to reduce the β -function in the arc at constant squeezed β^* but we loose optics flexibility.

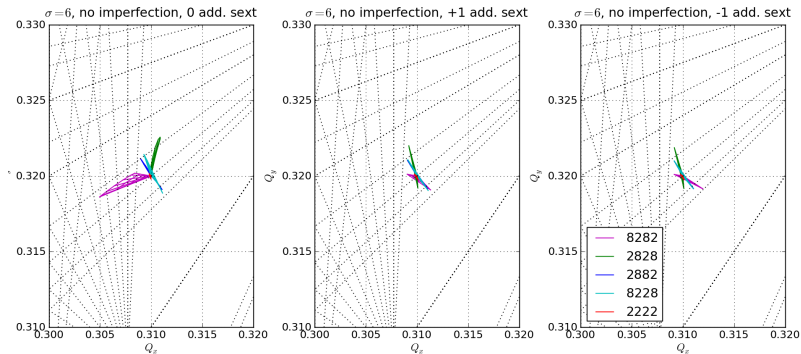
Alternative sextupole options: driving terms



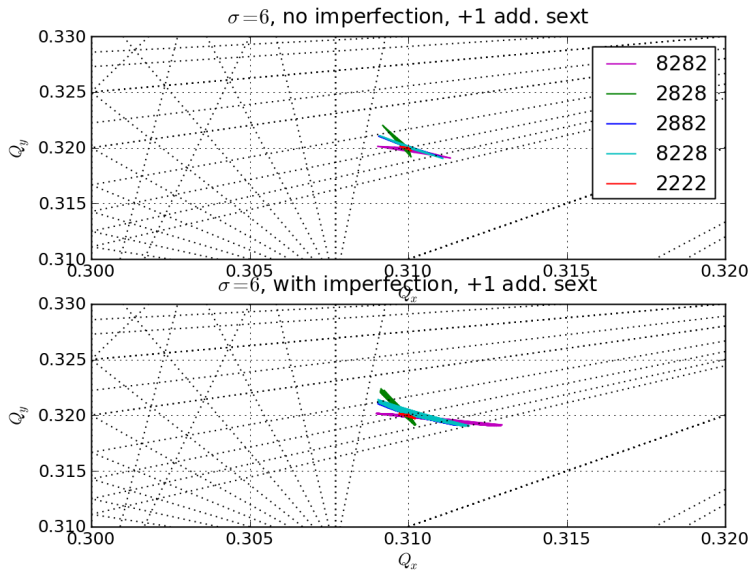
Adding a sextupole works not exactly because β at Q10 is not the same as in the arc.

Removing a sextupole cancels exactly the driving terms, but the individual kick are higher.

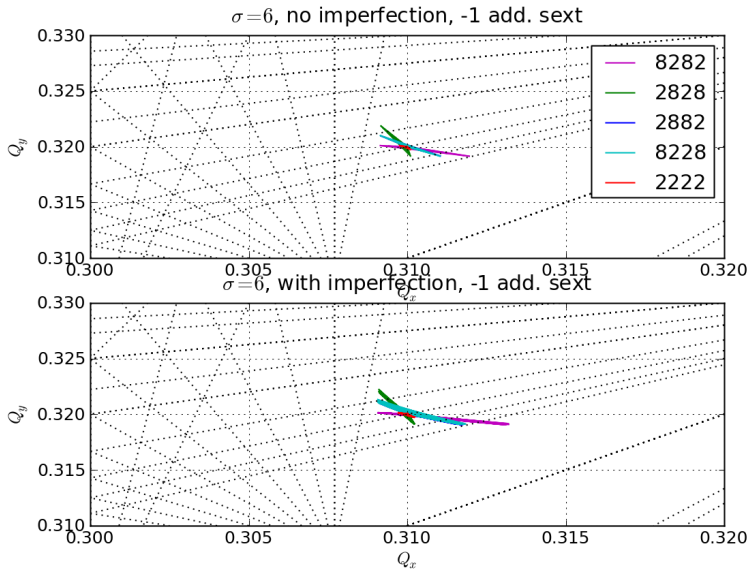
Alternative sextupole options: footprint



Footprint: adding sextupoles



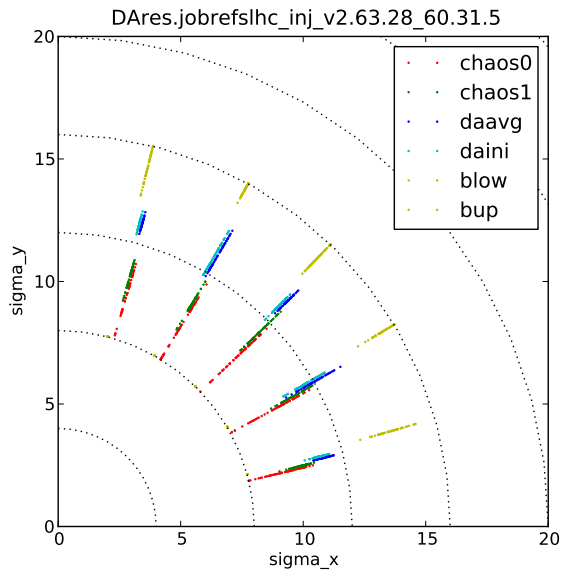
Footprint: removing sextupoles



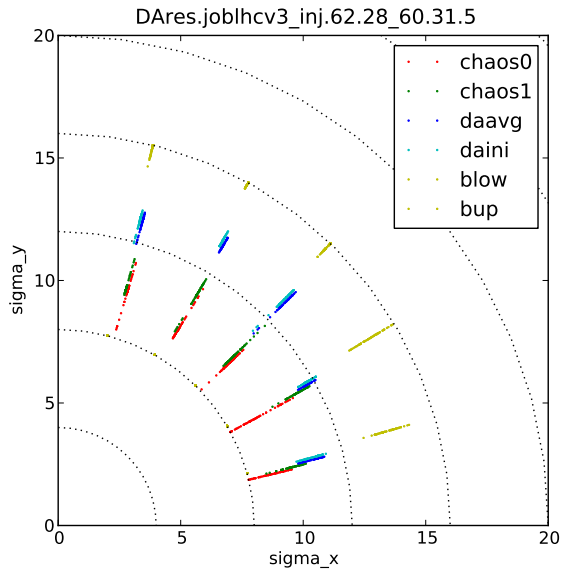
Tracking studies

- ▶ tune (62.28,60.31), (62.31,60.32)
- ▶ using $\delta = 0.00027 = (2.5\sigma_\delta)$
- ▶ include multipole error a,b from 2 to 15 order for: MB, MBRB, MBRS, MBX, MBW, MBXW
- ▶ include multipole error a,b from 3 to 15 order for: MQW, MQTL, MQMC, MQX, MQM, MQML, MQ
- ▶ exclude: MQY, new MQX, new D1/D2
- ▶ correct triplet error:
 - ▶ A2(1,-1), A3(2,1)(1,2) partial with MQSX
 - ▶ A3(0,3)(3,0), with MCSSX
 - ▶ A4(1,3), A4(3,1), with MCOSX
 - ▶ B4(4,0), B4(0,4), B4(2,2) partial with MCOX
 - ▶ B3(3,0)(0,3) partial, B3(1,2)(2,1) with MCSX
 - ▶ B6(6,0), B6(0,6), B6(4,2) partial, B6(2,4) partial, with MCTX
- ▶ correct other errors with MCX:
 - ▶ beta beating and tune with MQT
 - ▶ correct coupling with MQS
 - ▶ chromaticity with MS weak sector
 - ▶ chromatic coupling with MSS
 - ▶ b3 dipoles with MCS
 - ▶ b4 dipoles with MCO full strength
 - ▶ b5 dipoles with MCD

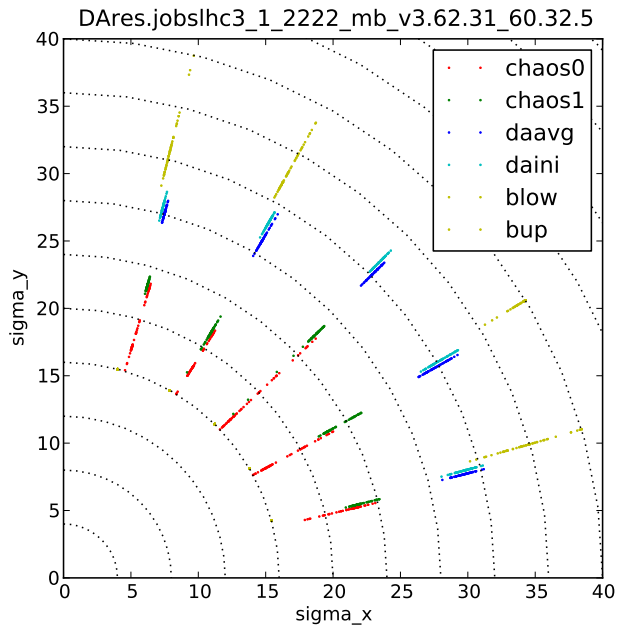
Injection results



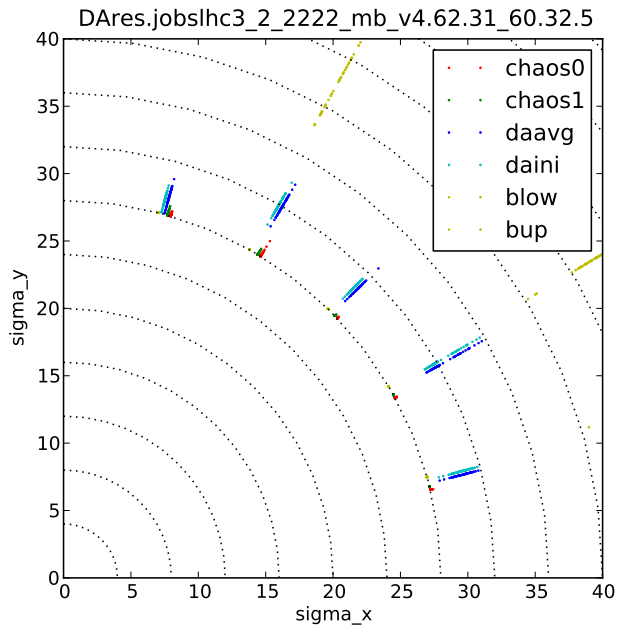
Injection results



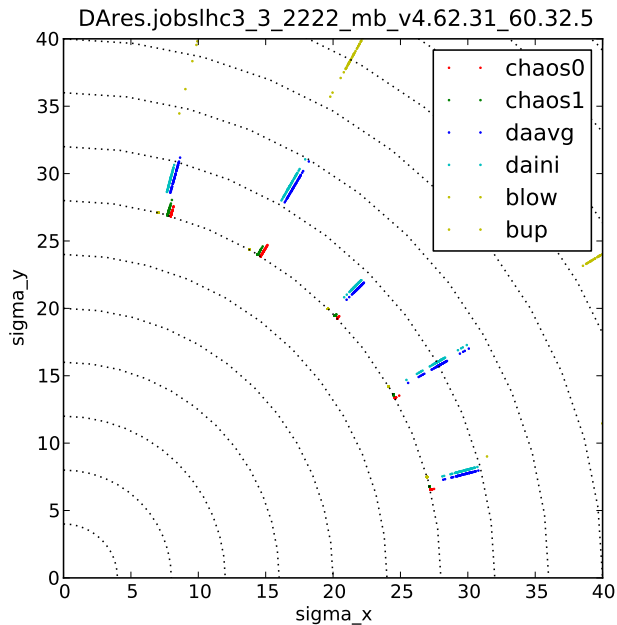
Collision results



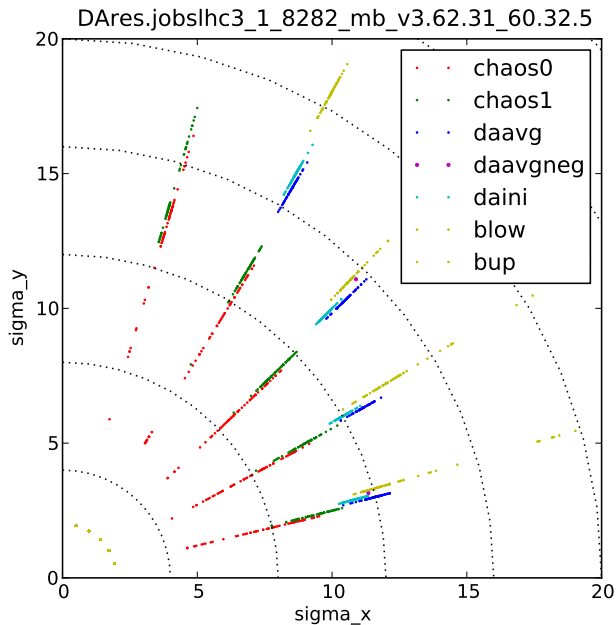
Collision results



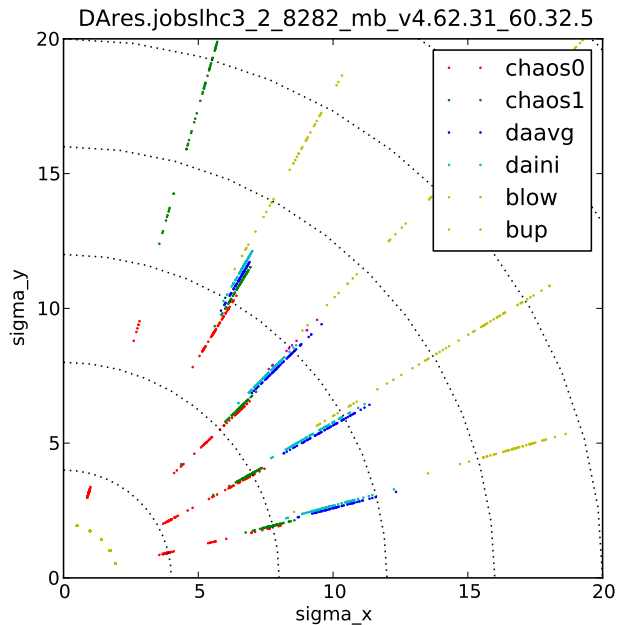
Collision results



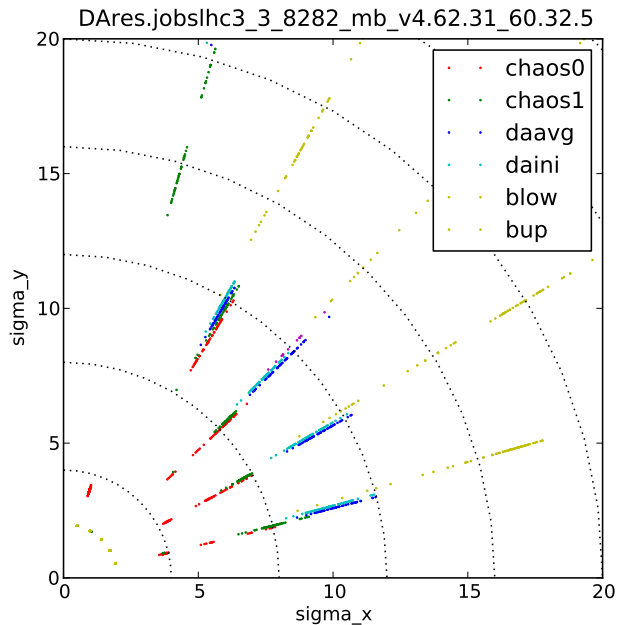
Collision results



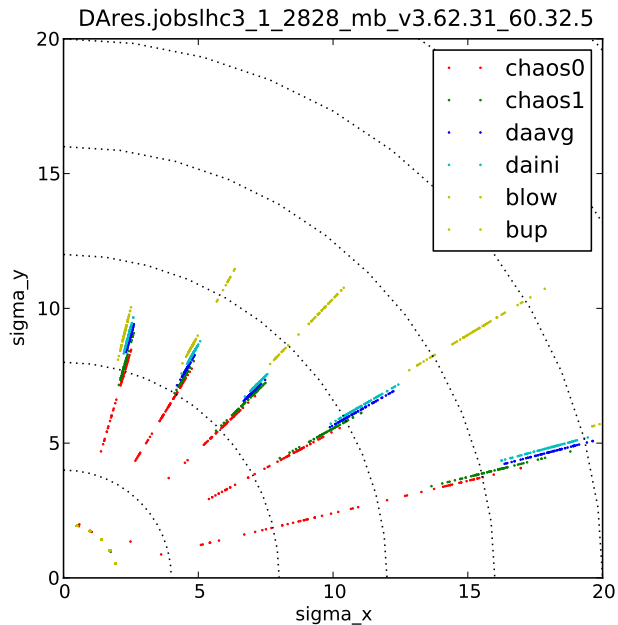
Collision results



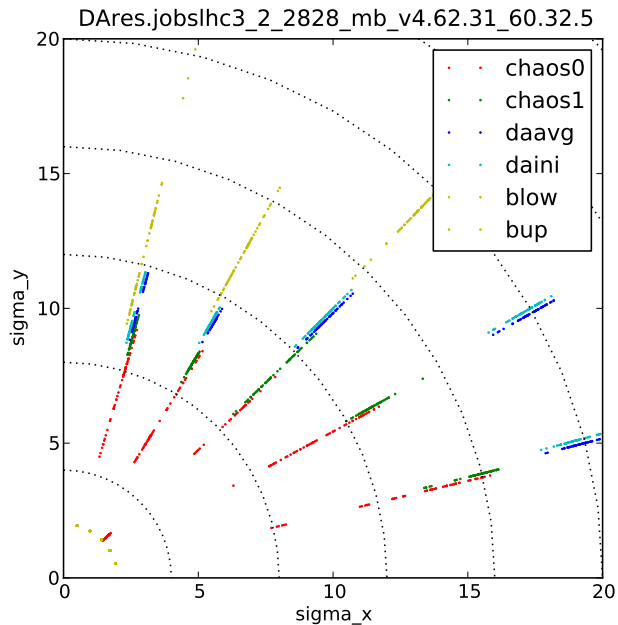
Collision results



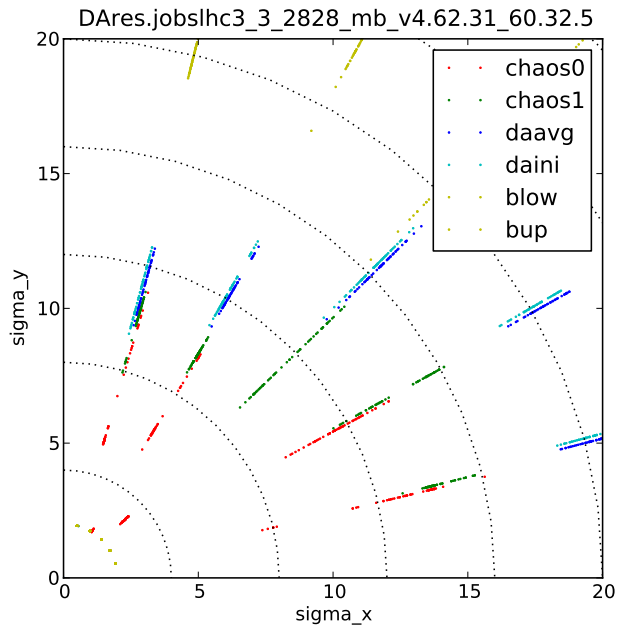
Collision results



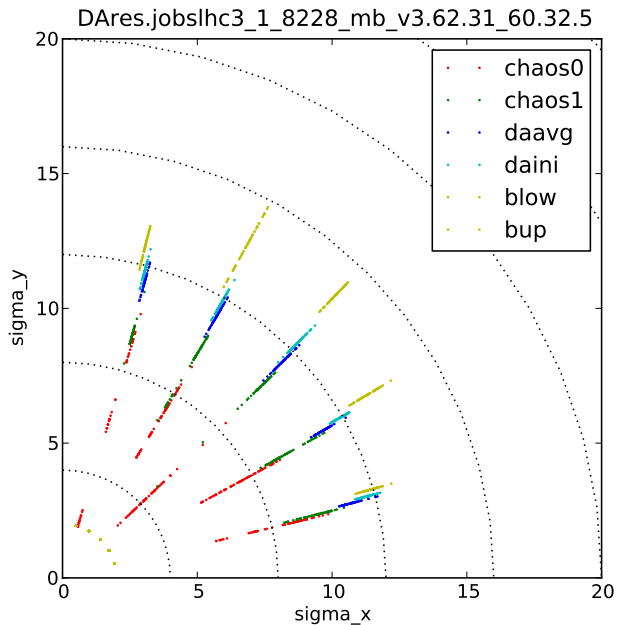
Collision results



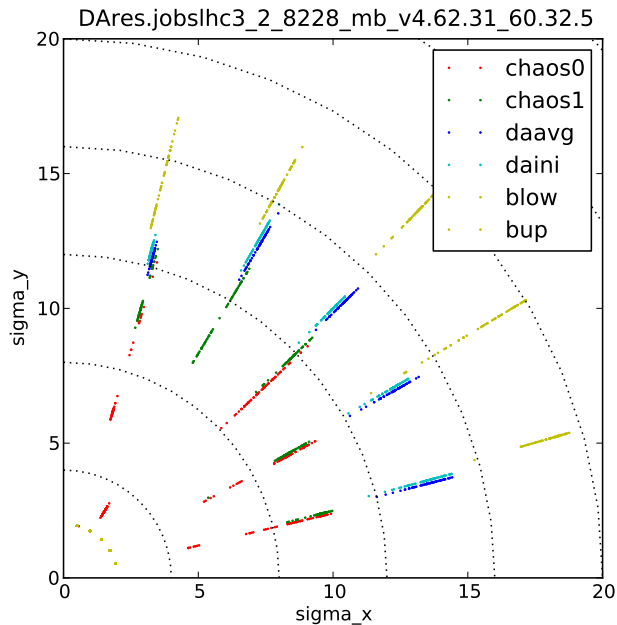
Collision results



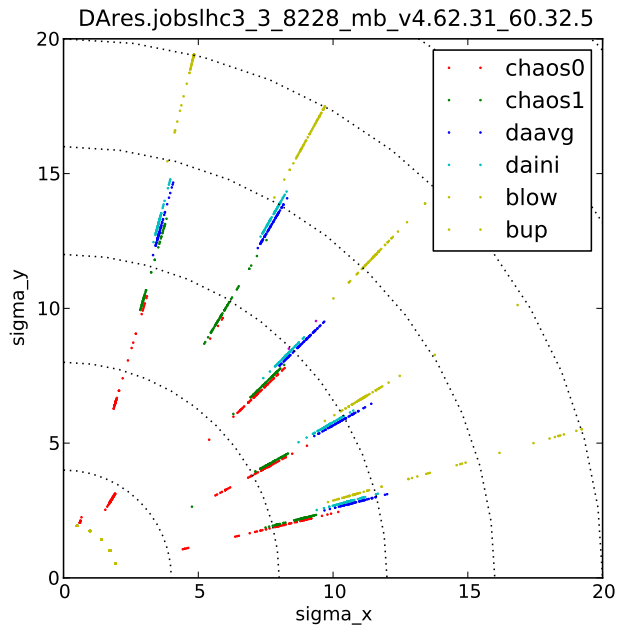
Collision results



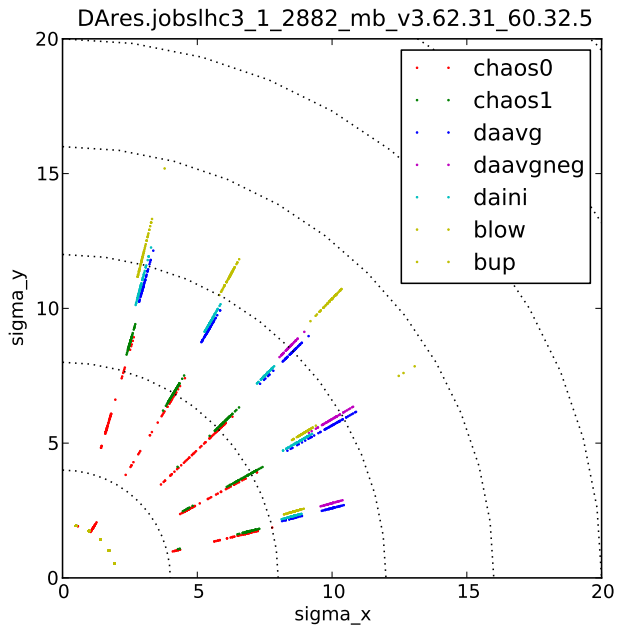
Collision results



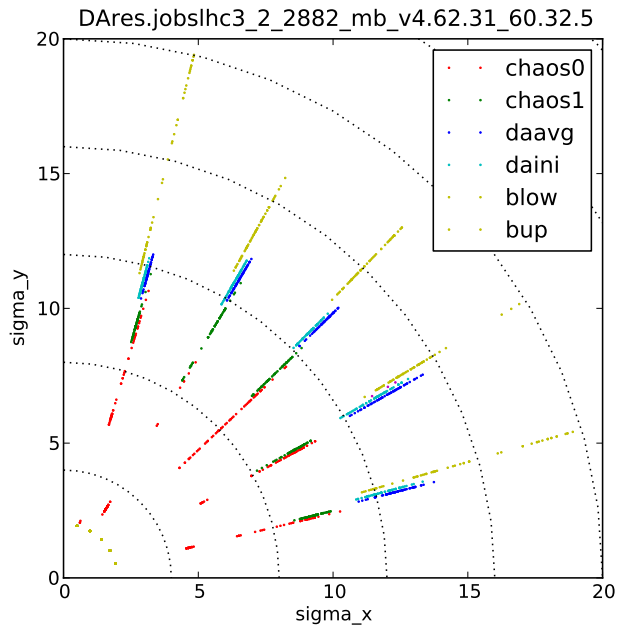
Collision results



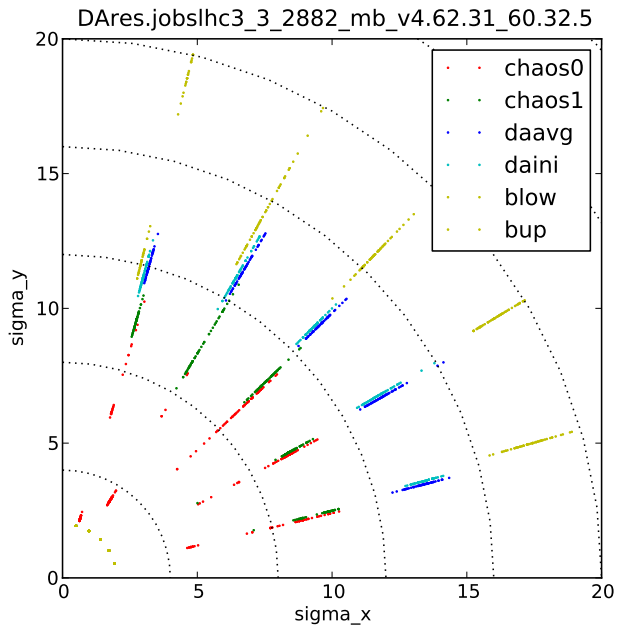
Collision results



Collision results

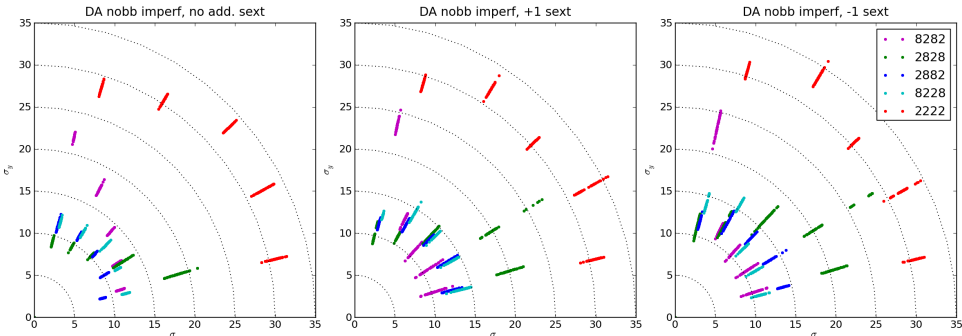


Collision results



DA results without beam beam

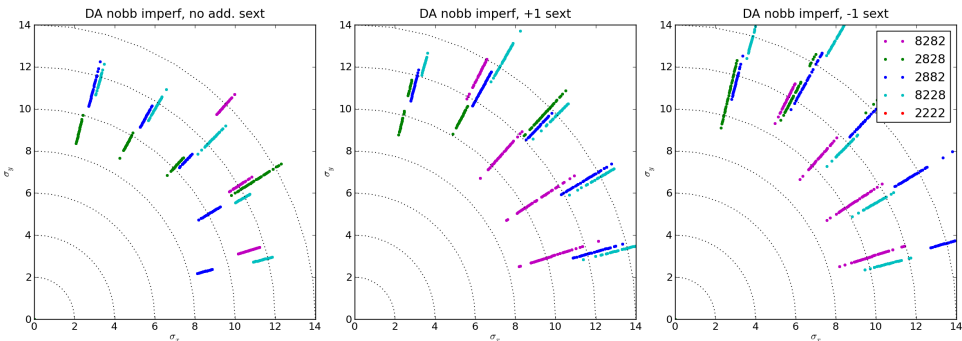
- ▶ inj : $> 10.13\sigma$, slightly smaller than nominal
- ▶ 1111 : very large no issue



- ▶ 2222 : well beyond the limit: no issue
- ▶ 2882, 8228: at the limit ($>$ mechanical aperture): to be checked with imperfection of new magnets (Q1-3,D1,D2,Q4) and beam beam, adding a sextupole raises DA a small angle
- ▶ 2828, 8282: already not acceptable

DA results without beam beam

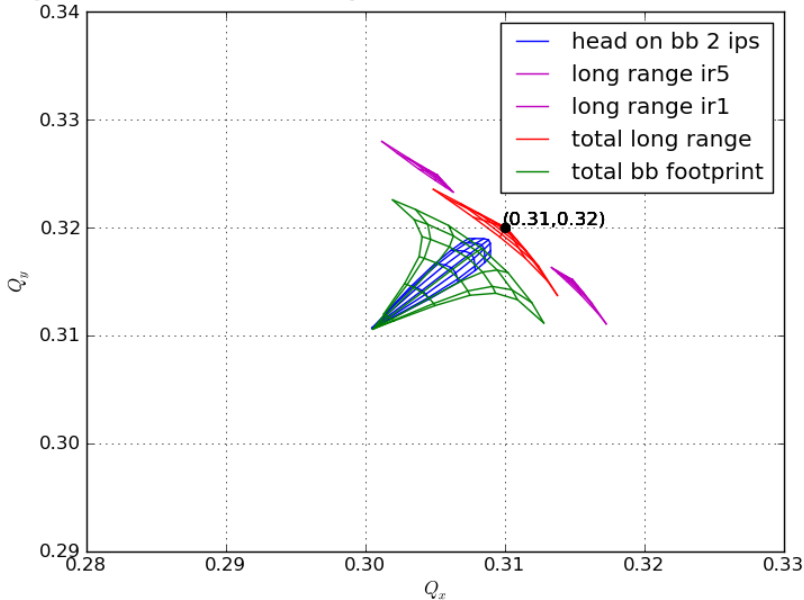
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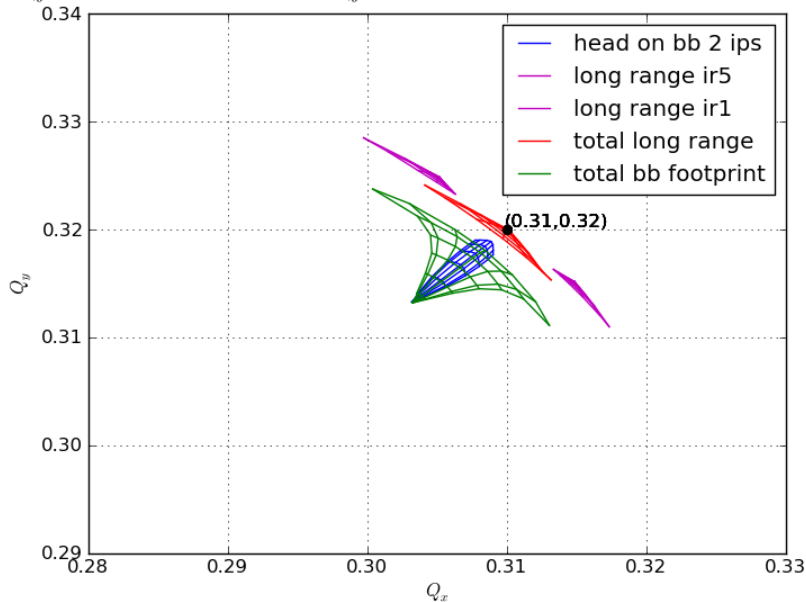
Beam beam foot print

$\beta_{x,y}^{\text{IR1}} = 60,60 \text{ cm (V crossing)}$ $\beta_{x,y}^{\text{IR5}} = 60,60 \text{ cm (H crossing)}$ $\theta_c = 10\sigma$ $\sigma_z = 7.5 \text{ cm}$



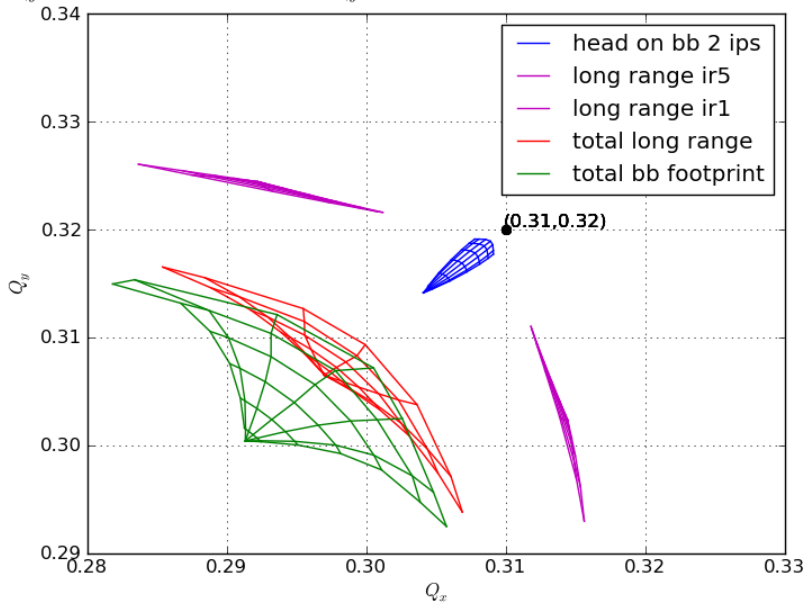
Beam beam foot print

$$\beta_{x,y}^{\text{IR1}} = 30,30 \text{ cm (V crossing)} \quad \beta_{x,y}^{\text{IR5}} = 30,30 \text{ cm (H crossing)} \quad \theta_c = 10\sigma \quad \sigma_z = 7.5 \text{ cm}$$



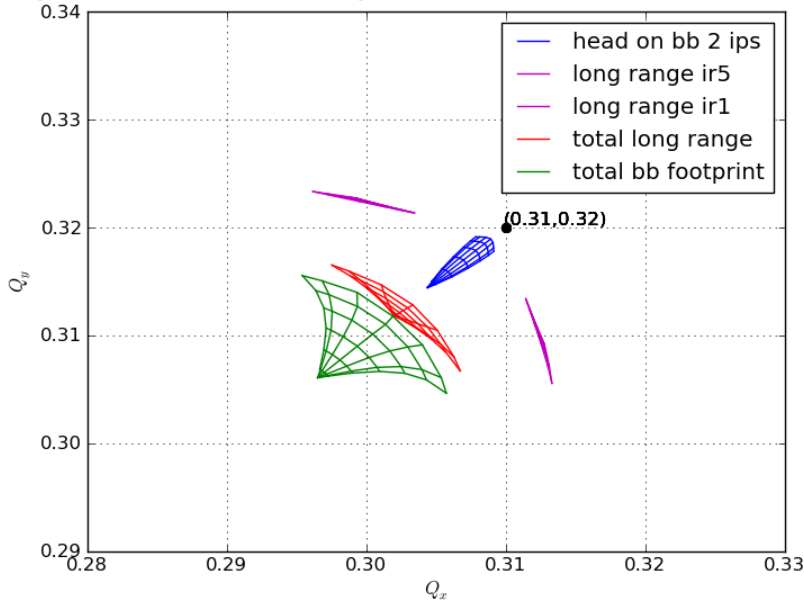
Beam beam foot print

$\beta_{x,y}^{\text{IR1}} = 7.5, 30 \text{ cm}$ (V crossing) $\beta_{x,y}^{\text{IR5}} = 30, 7.5 \text{ cm}$ (H crossing) $\theta_c = 10\sigma$ $\sigma_z = 7.5 \text{ cm}$



Beam beam footprint

$\beta_{x,y}^{\text{IR1}} = 7.5, 30$ cm (V crossing) $\beta_{x,y}^{\text{IR5}} = 30, 7.5$ cm (H crossing) $\theta_c = 13\sigma$ $\sigma_z = 6$ cm



What do we have to learn from additional studies

We explored the edges of our parameters space:

- ▶ optics and layout of the non experiment region looks ok
- ▶ first beam dynamics results are encouraging, but not conclusive

That defines the next steps:

- ▶ Fine tune beam and optics parameters (in particular β^* pre-squeeze, β^* aspect ratio) without and eventually with realistic magnet specs with the main goal of reducing the beta max in the arcs at constant luminosity.
- ▶ Understand beam beam long term stability with low β^* and/or flat beams
- ▶ Specify triplet, D1, D2, Q4 field quality requirements (must not sensibly reduce DA w.r.t to ideal IR magnets, unless...)
- ▶ Understand sources of DA reduction (tune spread or resonances?) and find strategies to optimize it.
- ▶ Understand whether high betas in the arcs allow footprint control with multipole correctors.

What can we learn from the machine and the experts

- ▶ By just commissioning:
 - ▶ Collimation system requirements (chromatic beating specs, aperture specs)
 - ▶ Long range beam beam and angle requirements (allow more accurate prediction on layout aperture constraints and luminosity gain)
- ▶ By dedicated studies:
 - ▶ Dynamic squeeze in IR4 (may benefit damper and crab cavities)
 - ▶ Operational issues with 90 degree in the arcs (ultimate test for almost all features)
 - ▶ Benchmark real dynamic aperture with simulations (this scheme allows to build case with $DA < \text{mechanical aperture}$, a better understanding may relax requirements on field quality)