Optics follow up: Alternative crossing scheme and field quality modeling

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CERN, Geneva

LHC-CC 11, November 15, 2011

Content

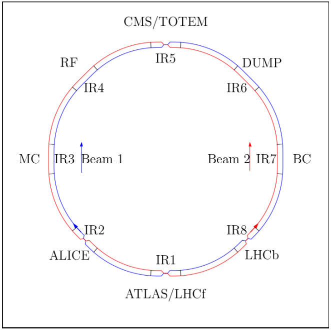
Transparent crossing scheme for local crab cavities

Crab cavity field quality modeling

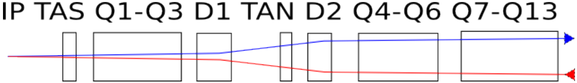
References:

- R. De Maria, S. Fartoukh, “Optics and layout for the HL-LHC upgrade project with a local crab cavity scheme”,sLHC-PROJECT-Report-0055, 2011.
- R. De Maria, S. Fartoukh, “Matching section and corrector new hardware requirements for the HL-LHC”, HL-LHC Kick off Internal Meeting, April 15, 2011.
- R. De Maria, “Review of the crossing schemes for SLHCV3 crab cavity optics”, LCU meeting, February 8 2011.
- R. De Maria, “Symplectic integrator for a relativistic particle in a RF cavity”, LCU meeting, April 19 2011.

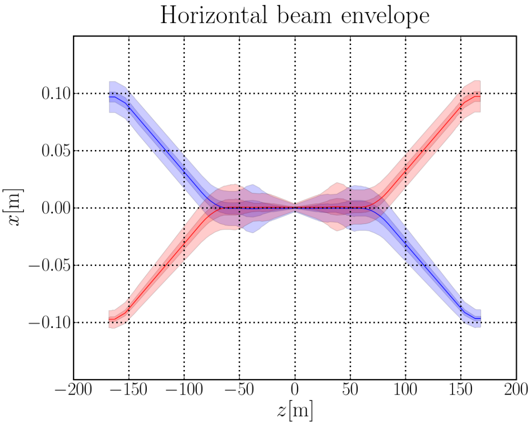
LHC IR layout



IR1 and IR5 layout:

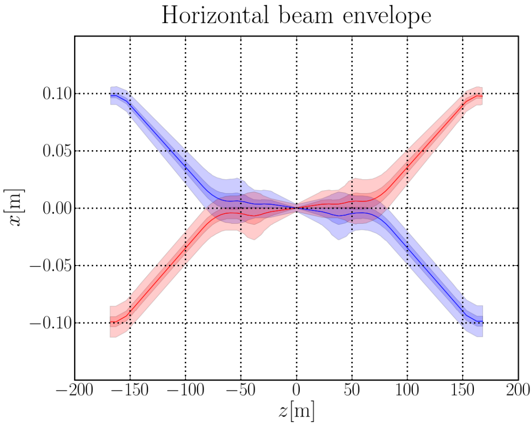


Nominal beam crossing



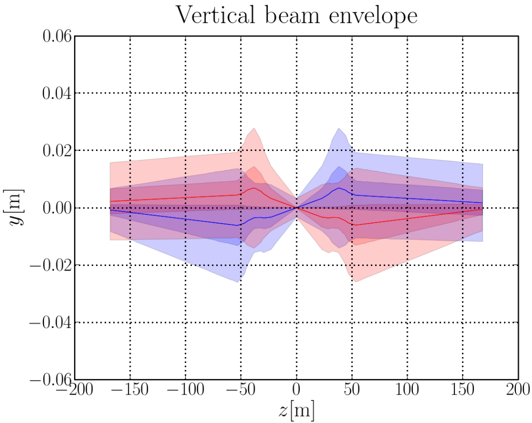
IR1 No horizontal crossing angle

Nominal beam crossing



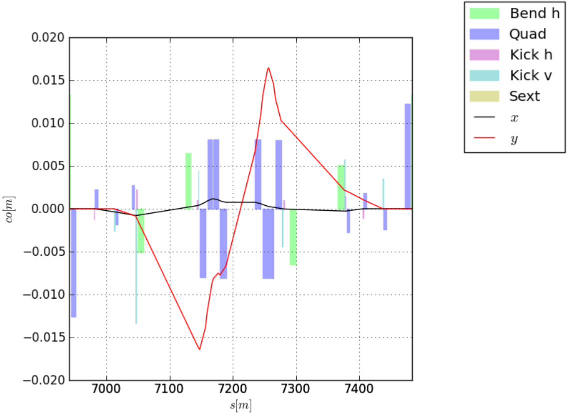
IR5 With horizontal crossing angle

Nominal beam crossing



IR1 Side view, vertical crossing angle

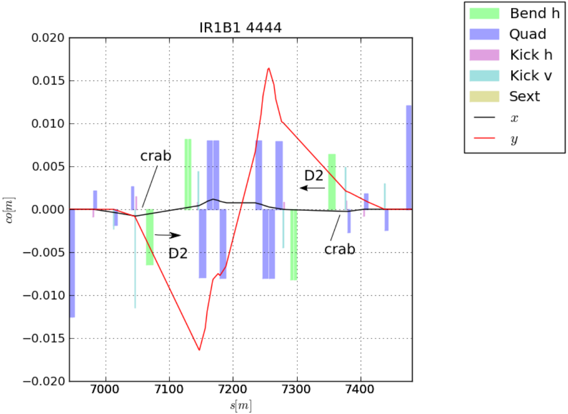
Upgrade optics with present crossing scheme orbits



- In collision:
  - $\beta^* = 15$cm, crossing angle $580\,\mu\mathrm{rad}$, separation 1.5mm
- The close orbit excursion at the cavity is:
  - $3.35\,\mathrm{mm}$ for 10σ crossing angle
  - $0.7\,\mathrm{mm}$ for $1.5\,\mathrm{mm}$ separation

This displacement needs to be compensated.

Upgrade optics with present crossing scheme orbits



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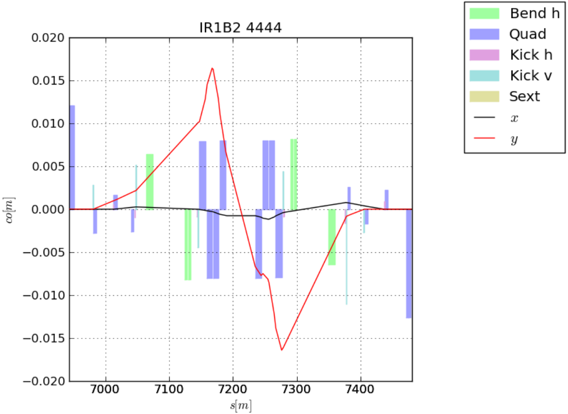

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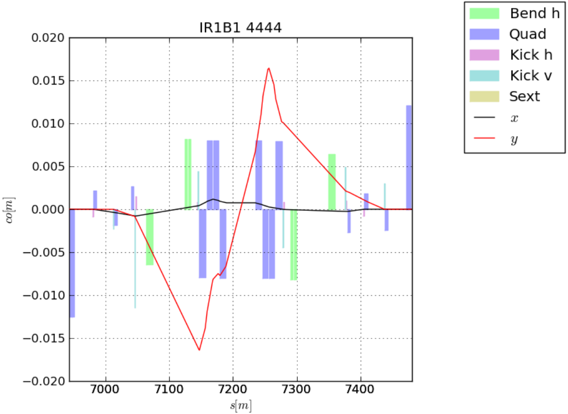
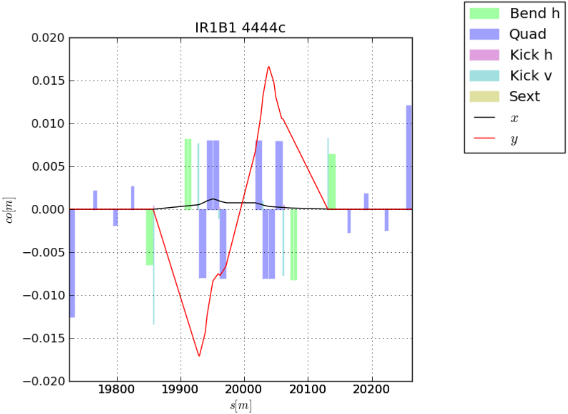
Upgrade optics with present crossing scheme orbits



- In collision:
  - $\beta^* = 15$cm, crossing angle $580\,\mu\mathrm{rad}$, separation 1.5mm
- The close orbit excursion at the cavity is:
  - $3.35\,\mathrm{mm}$ for 10σ crossing angle
  - $0.7\,\mathrm{mm}$ for $1.5\,\mathrm{mm}$ separation

This displacement needs to be compensated.

New crossing scheme



- No orbit displacement at the crab cavity location
- nor in D2 and Q4.
- the corrector in D2 can be placed in the non-IP side to save strength and gain some aperture for horizontal crossing

Single bore orbit corrector strengths

MCBX[1] type orbit correctors in the non-IP side for Q1, Q2, Q3. Function: orbit correction due to misalignments and crossing scheme

Strength orbit correction: $x_{tol} g_{\mathrm{triplet}} l_{\mathrm{triplet}} = 0.6\,\mathrm{Tm} \rightarrow 25\,\mu\mathrm{rad}$

Strength Crossing scheme:

Element	Plane	crossing		separation	
		kick[μrad]	field [Tm]	kick[μrad]	field [Tm]
nominal-like round β^*					
MCBX.3	H&V	49*1.5 $=$73	1.7	11*2	0.51
closed round β^*					
MCBX.1	H&V	17*1.5 $=$25	0.6	5*2	0.23
MCBX.3 [2]	H&V	140*1.5 $=$210	4.9	10*2	0.46

---

[1] nominal: 3.3T, 1.5Tm

[2] may be partially absorbed by D1

2-in-1 orbit corrector strength

MCBY type (but wider aperture) either in the IP side of D2 to save vertical aperture or in the non-IP side[3] to save strength and aperture for positive crossing angle.

Strength for crossing scheme:

Element	Plane	crossing		separation	
		kick[μrad]	field [Tm]	kick[μrad]	field [Tm]
nominal-like round β^*					
MCBYY.4	H&V	126*1.5=189	4.4	22*2	1.0
MCBY.5	H or V	32*1.5 = 48	1.1	10*2	0.46
MCBC.6 [4]	H or V	35*1.5 = 53	1.2	12*2	0.28
closed round β^*					
MCBYY.4 [5]	H&V	244*1.5 =366	8.5	8*2	0.37

---

[3] suggestion from S. Fartoukh

[4] Nominal 2.5T, 2.27 Tm

[5] may be partially absorbed by D2

Conclusion

- An alternative crossing scheme can make the cavity region transparent from crossing and separation scheme gymnastic;

- The cost is strong combined plane orbit correctors single bore ($5\,\mathrm{Tm}$) and 2-in-1 ($8.5\,\mathrm{Tm}$). (One plane can be much smaller compromising on arbitrary h/v crossing);

- Additional aperture margin in D2 and Q4 as side effect.

Introduction and eq. of motion

Realistic crab cavities provides non-uniform kicks in the transverse plane, which may or may not have measurable effects on the beam dynamics [6].

Is it possible to model this effect with few parameters that can be extracted from em simulations?

Equation of motion:

$$\dot{p}(t) = e\left[E(x,y,s,t)) + v(t) \times B(x,y,s,t)\right]$$

Solving exactly the equation of motion requires the knowledge of the field at every point and it does not offer analytical understanding.

With few approximation it is possible to simplify and parametrize the motion in a similar fashion of what is routinely done for magnets.

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[6] point raised by S. Fartoukh

Approximations

- Thin lens: a 3d field region is replaced by two drifts around a thin layer with infinite fields. It is equivalent of assuming that the particle trajectory is not affected by the field while traversing the cavity and a kick is transmitted in the particle at center of the cavity.
- Axial approximation: the trajectory is a straight line parallel to z. Imply neglecting any B_s.

These approximations imply (e.g. in x):

$$x^{\mathrm{k}} = x^{i} + p_x^{\mathrm{i}} L/2 \qquad p^{\mathrm{f}} = p^{\mathrm{i}} + \Delta p_x(\vec{x}_{\mathrm{k}}) \qquad x^{\mathrm{f}} = x^{\mathrm{k}} + p_x^{\mathrm{f}} L/2,$$

where

$$\Delta \vec{p}(x, y, z) = \int_{-\infty}^{\infty} \vec{F}(x, y, \beta c t - z, t)\mathrm{d}t$$

$$\vec{F}(x, y, s, t) = q\left[\vec{E}(x, y, s, t) + \beta c \hat{s} \times \vec{B}(x, y, s, t)\right]$$

- By adding ultra-relativistic beam ($\beta = 1$), and vanishing field at the extremities of the cavity...

Consequences

...and using Maxwell equations it is possible to demonstrate that [7]

$$\nabla \times \Delta\vec{p}(x,y,z) = 0 \qquad \nabla \cdot \Delta\vec{p}(x,y,z) = \frac{\partial}{\partial z}\Delta p_s$$

equivalent to

$$\frac{\partial}{\partial z}\Delta\vec{p}_\perp = \nabla_\perp \Delta p_s \qquad \frac{\partial \Delta p_x}{\partial y} = \frac{\partial \Delta p_y}{\partial x} \qquad \frac{\partial \Delta p_x}{\partial x} + \frac{\partial \Delta p_y}{\partial y} = 0$$

The approximations lead to a transverse kick which is harmonic in the transverse coordinates, which allow to expand the kick in multipoles.

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[7] W.K.H. Panofsky and W.A. Wenzel, Rev. Sci. Instrum. 27 (1956), p. 967. Goldberg, D.A.; Lambertson, G.R., "Dynamic devices: A primer on pickups and kickers", 1991. S. Vaganian and H. Henke, Particle Accelerators, 1995, Vol. 48, pp. 239-242. Ng, Physics of Intensity Dependent Beam Instabilities, 2005. E. Metral, "USPAS course on Collective Effects in Beam Dynamics", 2009.

RF Harmonic (symplectic) kick

$$H(x,y,z) = -\Re\left[\sum_{n=0}^{\infty} W_n(z)(x+iy)^n\right]\delta(s) \qquad \frac{\mathrm{d}}{\mathrm{d}t}\vec{p}(x,y,z) = -\nabla H(x,y,z)$$

$$\Delta p_s = \Re\left[\sum_{n=0}^{\infty} W_n'(z)(x+iy)^n\right] \qquad \Delta p_x - i\Delta p_y = \sum_{n=1}^{\infty} W_n(z)\frac{(x+iy)^{n-1}}{n}$$

For RF cavities excited by one frequency ω:

$$W_n(z) = B_n\cos(\omega z/c + \phi_n) + iA_n\cos(\omega z/c + \psi_n)$$

One way to extract the coefficient from simulation is (with another imaginary units j for complex fields $\vec{E}(x,y,s,t) = \Im_j[\mathcal{E}(x,y,s)e^{j\omega t}]$):

$$B_n e^{j\phi_n} + iA_n e^{j\psi_n} = \frac{c}{\omega}\frac{q}{2\pi r_0^n}\int_0^{2\pi}\mathrm{d}\theta$$

$$\int_{-L/2}^{L/2}\mathrm{d}s\,\mathcal{E}_s(x = r_0\cos\theta, y = r_0\sin\theta, s)e^{j\omega s/c}e^{-in\theta}$$

Another for $n > 0$ would be by computing the transverse kick.

Conclusion

The usual accelerator approximations lead to simplified equation of motion with suitable for perturbation analysis and particle tracking.

Any cavity can be parametrized by few constants that can, in principle, be extracted by e.m. simulations.

Alexej (who is already using this method for CLIC studies) will show the application for few crab cavities...

Acknowledgment

I wish to thanks all collegues for their ideas, comments and discussions: T. Baer, O. Brüning, R. Calaga, S. Fartoukh, E. Forest, M. Giovannozzi, A. Grudiev, E. Jensen, A. Latina, E. Metral, L. Rossi, R. Tomas, E. Todesco, J. Wenninger, F. Zimmermann.

Backup

CC10: Crossing scheme strengths

```
acbxh3.l1    :=   10.80E-6 * on_sep1;  acbxh3.l5    :=   49.00E-6 * on_x5  ;
acbxv3.l1    :=   49.00E-6 * on_x1  ;  acbxv3.l5    :=   10.80E-6 * on_sep5;

acbyvs4.l1b1 := -126.26E-6 * on_x1  ;  acbyvs4.l5b1 :=   13.18E-6 * on_sep5;
acbyvs4.r1b1 :=   54.68E-6 * on_x1  ;  acbyvs4.r5b1 :=   20.58E-6 * on_sep5;
acbcv5.l1b1  :=  -24.71E-6 * on_x1  ;  acbcv5.l5b1  :=   -9.25E-6 * on_sep5;
acbcv6.r1b1  :=   33.33E-6 * on_x1  ;  acbcv6.r5b1  :=  -11.07E-6 * on_sep5;
acbyhs4.l1b1 :=   20.77E-6 * on_sep1;  acbyhs4.l5b1 :=  -53.69E-6 * on_x5  ;
acbyhs4.r1b1 :=   13.88E-6 * on_sep1;  acbyhs4.r5b1 :=  123.55E-6 * on_x5  ;
acbch6.l1b1  :=  -11.30E-6 * on_sep1;  acbch6.l5b1  :=  -34.55E-6 * on_x5  ;
acbch5.r1b1  :=   -9.86E-6 * on_sep1;  acbch5.r5b1  :=   27.04E-6 * on_x5  ;

acbyvs4.l1b2 :=   57.33E-6 * on_x1  ;  acbyvs4.l5b2 :=  -21.71E-6 * on_sep5;
acbyvs4.r1b2 := -121.14E-6 * on_x1  ;  acbyvs4.r5b2 :=  -11.48E-6 * on_sep5;
acbcv6.l1b2  :=   31.06E-6 * on_x1  ;  acbcv6.l5b2  :=   12.09E-6 * on_sep5;
acbcv5.r1b2  :=  -29.71E-6 * on_x1  ;  acbcv5.r5b2  :=    7.69E-6 * on_sep5;
acbyhs4.l1b2 :=  -12.07E-6 * on_sep1;  acbyhs4.l5b2 :=  117.95E-6 * on_x5  ;
acbyhs4.r1b2 :=  -21.93E-6 * on_sep1;  acbyhs4.r5b2 :=  -56.43E-6 * on_x5  ;
acbch5.l1b2  :=    8.21E-6 * on_sep1;  acbch5.l5b2  :=   32.51E-6 * on_x5  ;
acbch6.r1b2  :=   12.36E-6 * on_sep1;  acbch6.r5b2  :=  -32.05E-6 * on_x5  ;
```

closed: Crossing scheme strengths

```
acbxh2a.l1    :=    5.02E-6 * on_sep1; acbxh2a.l5    :=  -17.66E-6 * on_x5  ;
acbxh2a.r1    :=    5.02E-6 * on_sep1; acbxh2a.r5    :=   17.66E-6 * on_x5  ;
acbxv2a.l1    :=  -17.66E-6 * on_x1  ; acbxv2a.l5    :=    5.02E-6 * on_sep5;
acbxv2a.r1    :=   17.66E-6 * on_x1  ; acbxv2a.r5    :=    5.02E-6 * on_sep5;

acbxh3.l1     :=    9.83E-6 * on_sep1; acbxh3.l5     :=  140.89E-6 * on_x5  ;
acbxh3.r1     :=    9.83E-6 * on_sep1; acbxh3.r5     := -140.89E-6 * on_x5  ;
acbxv3.l1     :=  137.67E-6 * on_x1  ; acbxv3.l5     :=    9.60E-6 * on_sep5;
acbxv3.r1     := -137.67E-6 * on_x1  ; acbxv3.r5     :=    9.60E-6 * on_sep5;

acb2h_l1b1    :=    7.10E-6 * on_sep1; acb2h_l5b1    := -152.92E-6 * on_x5  ;
acb2h_l1b2    :=    2.49E-6 * on_sep1; acb2h_l5b2    := -243.11E-6 * on_x5  ;
acb2h_r1b1    :=    2.49E-6 * on_sep1; acb2h_r5b1    :=  243.11E-6 * on_x5  ;
acb2h_r1b2    :=    7.10E-6 * on_sep1; acb2h_r5b2    :=  152.92E-6 * on_x5  ;
acb2v_l1b1    := -239.89E-6 * on_x1  ; acb2v_l5b1    :=    2.71E-6 * on_sep5;
acb2v_l1b2    := -149.70E-6 * on_x1  ; acb2v_l5b2    :=    7.33E-6 * on_sep5;
acb2v_r1b1    :=  149.70E-6 * on_x1  ; acb2v_r5b1    :=    7.33E-6 * on_sep5;
acb2v_r1b2    :=  239.89E-6 * on_x1  ; acb2v_r5b2    :=    2.71E-6 * on_sep5;
```

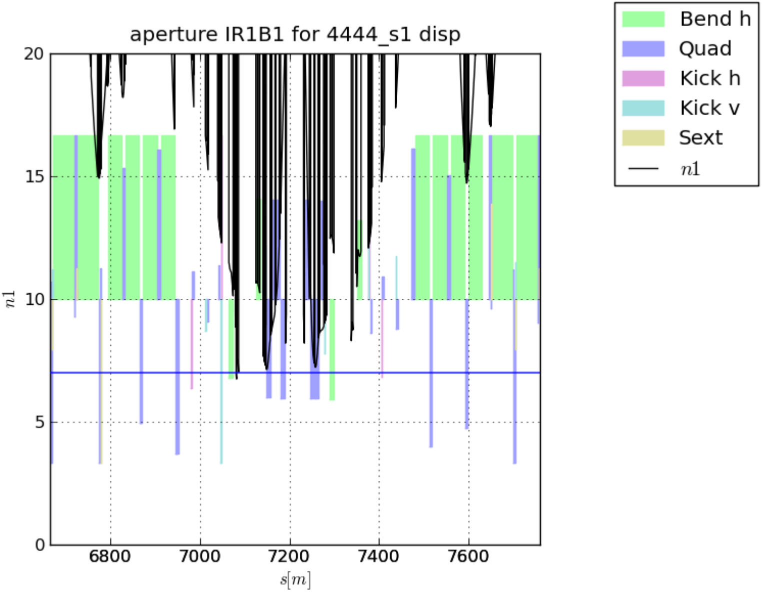
closed inj.: Crossing scheme strengths

```
acbxh2a.l1   :=    6.01E-6 * on_sep1;  acbxh2a.l5   :=   12.26E-6 * on_x5  ;
acbxh2a.r1   :=    6.01E-6 * on_sep1;  acbxh2a.r5   :=  -12.26E-6 * on_x5  ;
acbxv2a.l1   :=   12.26E-6 * on_x1  ;  acbxv2a.l5   :=    6.01E-6 * on_sep5;
acbxv2a.r1   :=  -12.26E-6 * on_x1  ;  acbxv2a.r5   :=    6.01E-6 * on_sep5;

acbxh3.l1    :=   39.32E-6 * on_sep1;  acbxh3.l5    :=   72.65E-6 * on_x5  ;
acbxh3.r1    :=   39.32E-6 * on_sep1;  acbxh3.r5    :=  -72.65E-6 * on_x5  ;
acbxv3.l1    :=   70.98E-6 * on_x1  ;  acbxv3.l5    :=   38.42E-6 * on_sep5;
acbxv3.r1    :=  -70.98E-6 * on_x1  ;  acbxv3.r5    :=   38.42E-6 * on_sep5;

acb2h_l1b1   :=   21.49E-6 * on_sep1;  acb2h_l5b1   :=  -86.17E-6 * on_x5  ;
acb2h_l1b2   :=    3.98E-6 * on_sep1;  acb2h_l5b2   := -131.73E-6 * on_x5  ;
acb2h_r1b1   :=    3.98E-6 * on_sep1;  acb2h_r5b1   :=  131.73E-6 * on_x5  ;
acb2h_r1b2   :=   21.49E-6 * on_sep1;  acb2h_r5b2   :=   86.17E-6 * on_x5  ;
acb2v_l1b1   := -130.07E-6 * on_x1  ;  acb2v_l5b1   :=    4.88E-6 * on_sep5;
acb2v_l1b2   :=  -84.51E-6 * on_x1  ;  acb2v_l5b2   :=   22.39E-6 * on_sep5;
acb2v_r1b1   :=   84.51E-6 * on_x1  ;  acb2v_r5b1   :=   22.39E-6 * on_sep5;
acb2v_r1b2   :=  130.07E-6 * on_x1  ;  acb2v_r5b2   :=    4.88E-6 * on_sep5;
```

CC10: Crossing scheme apertures [8]



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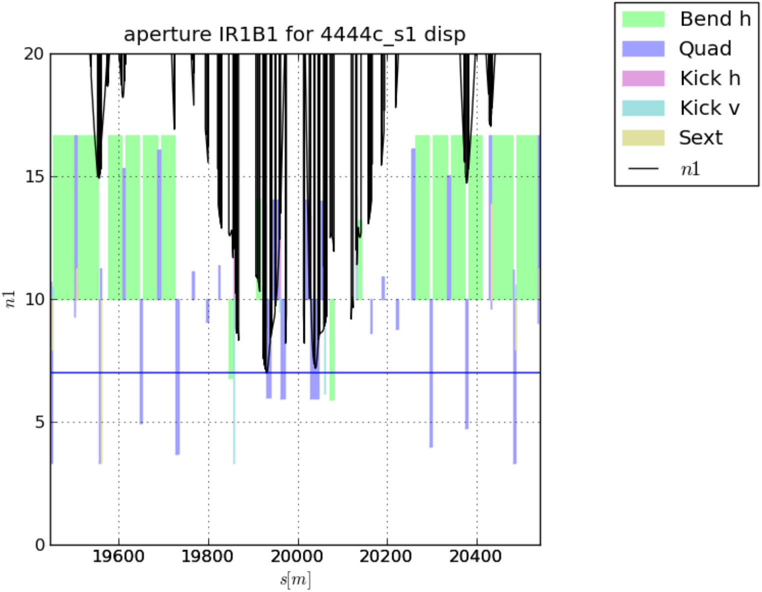
[8] TAN not optimized

CC10: Crossing scheme apertures [8]



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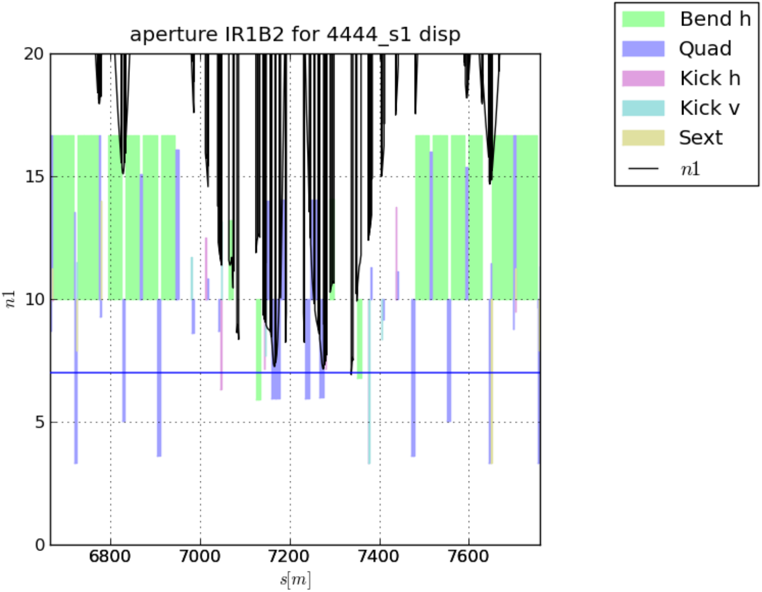
CC10: Crossing scheme apertures [8]



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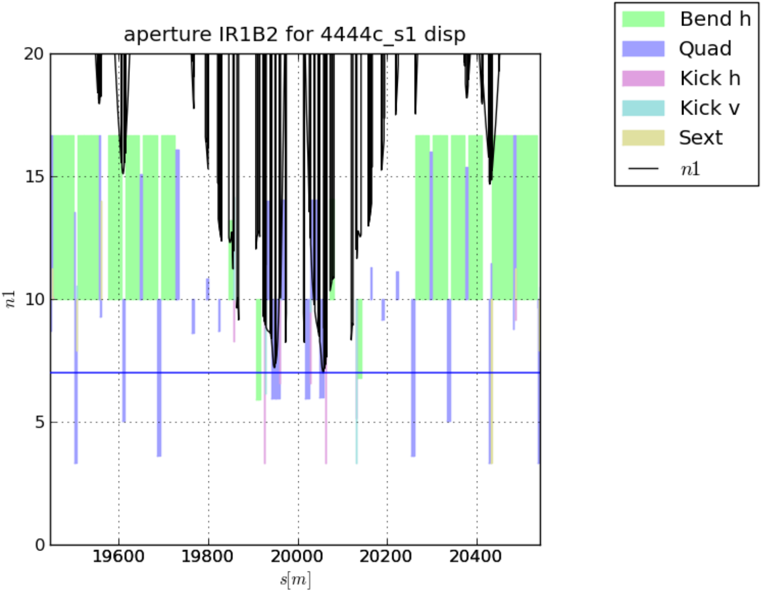
[8] TAN not optimized

CC10: Crossing scheme apertures [8]



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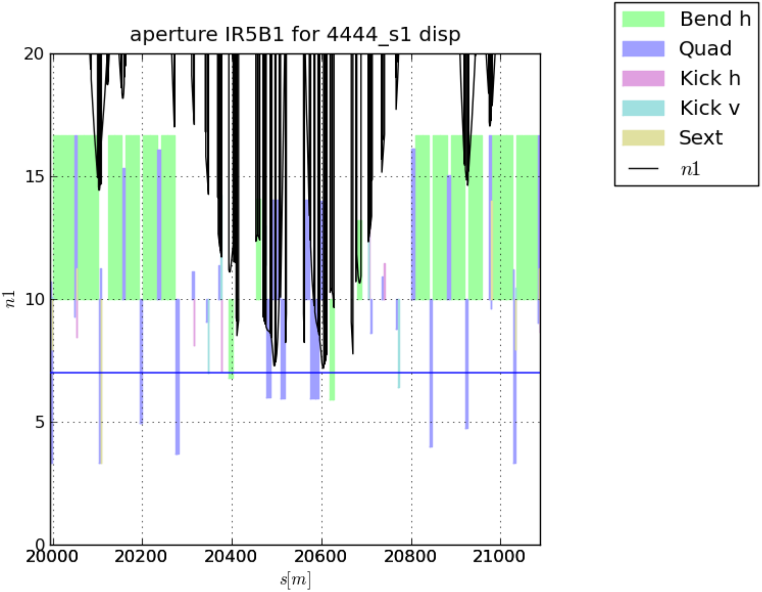
[8] TAN not optimized

CC10: Crossing scheme apertures [8]



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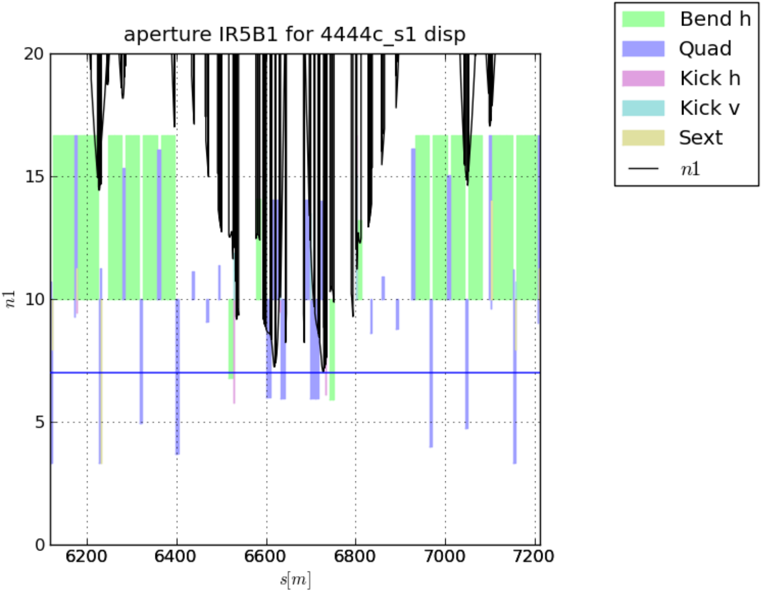
[8] TAN not optimized

CC10: Crossing scheme apertures [8]



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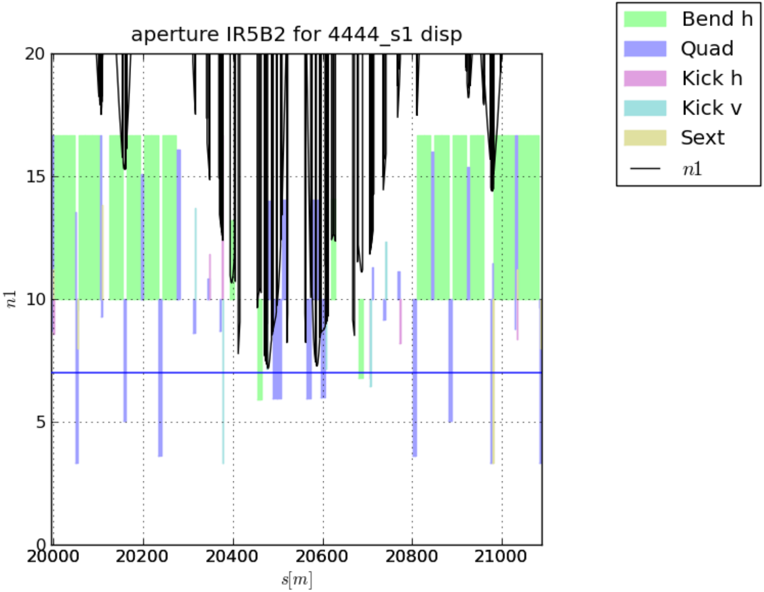
CC10: Crossing scheme apertures [8]



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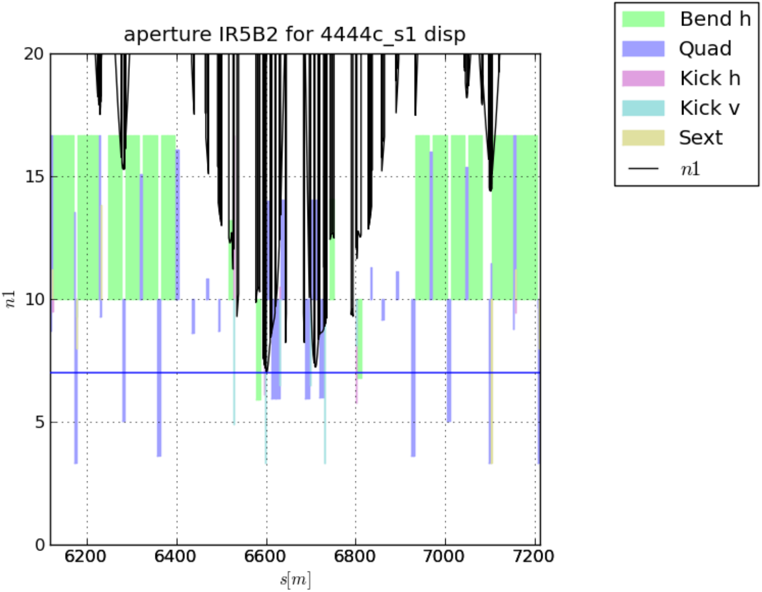
[8] TAN not optimized

CC10: Crossing scheme apertures [8]



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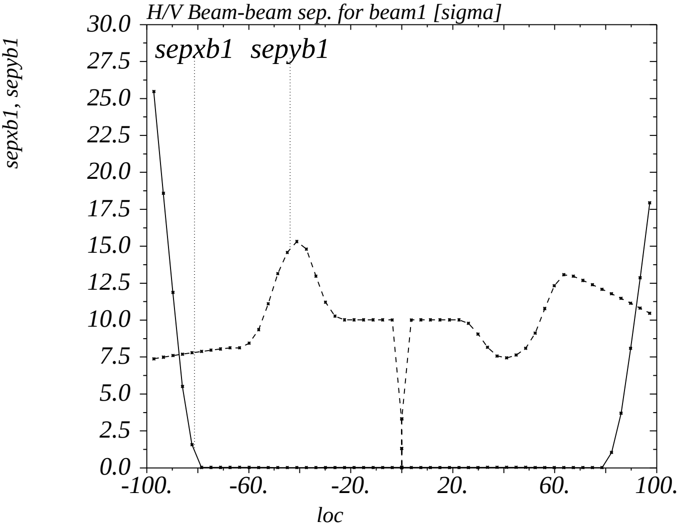
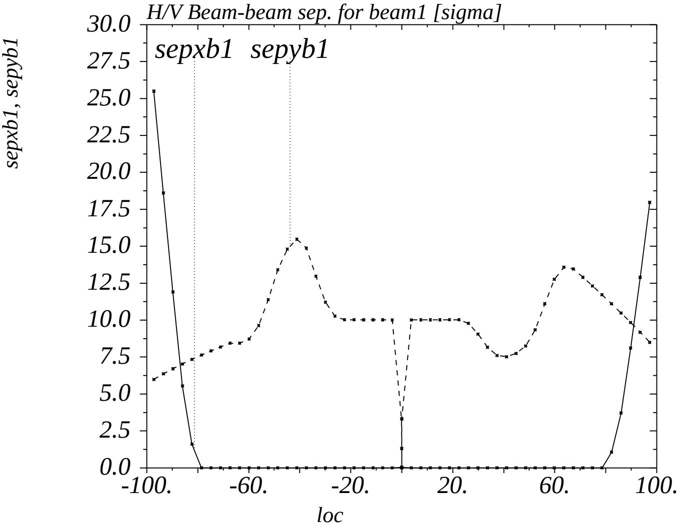
[8] TAN not optimized

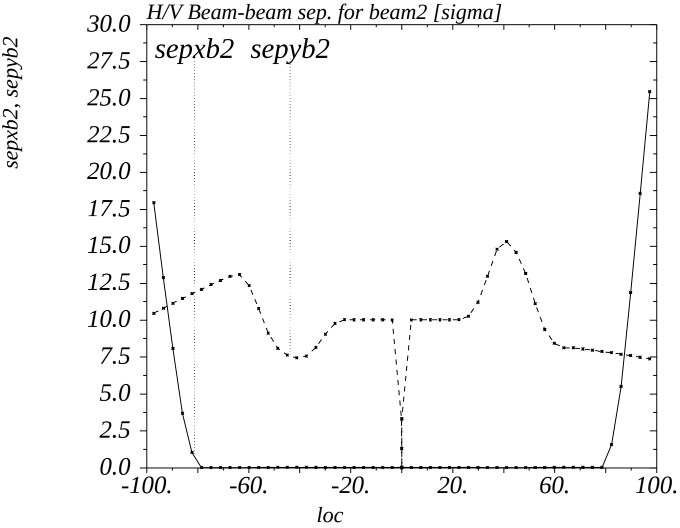
Beam beam separation CC10: IR1 beam1 sep



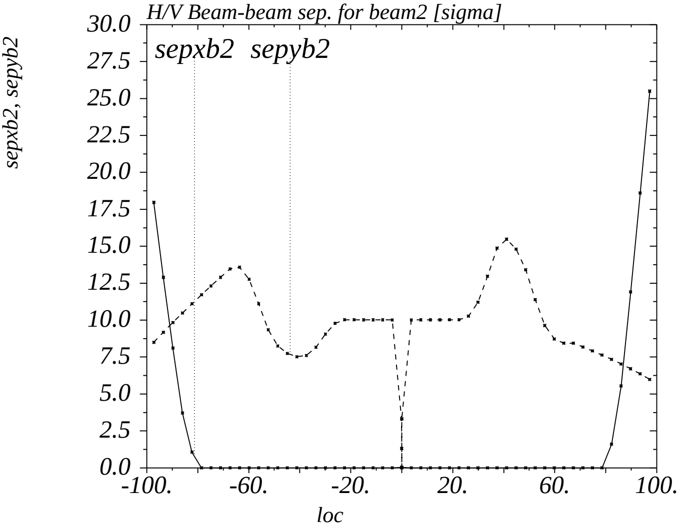
Beam beam separation closed: IR1 beam1 sep



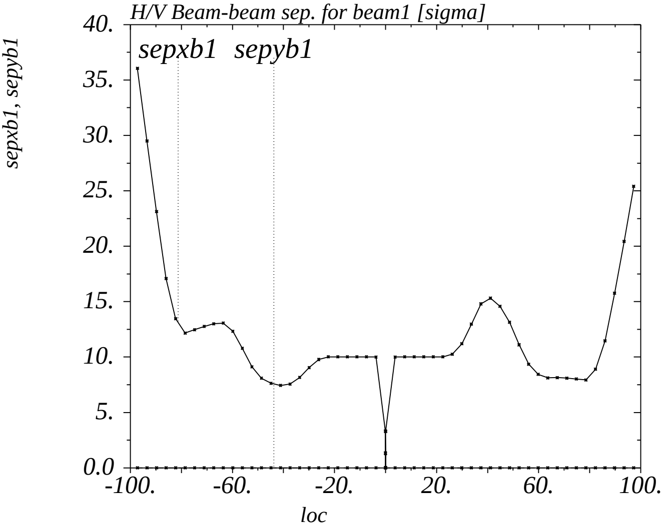
Beam beam separation CC10: IR1 beam2 sep



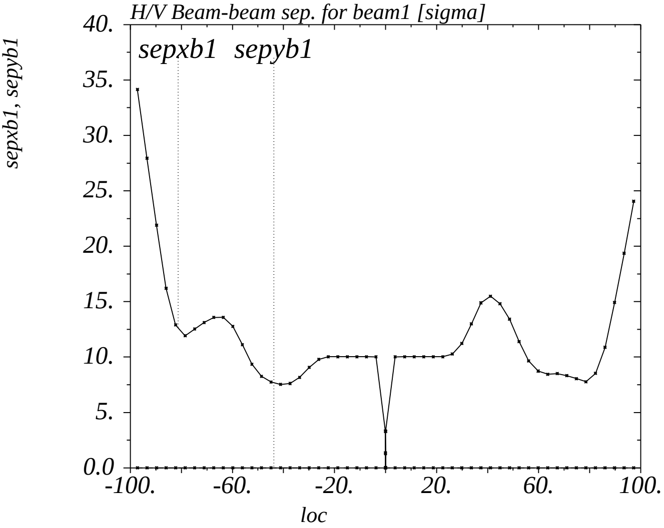
Beam beam separation closed: IR1 beam2 sep



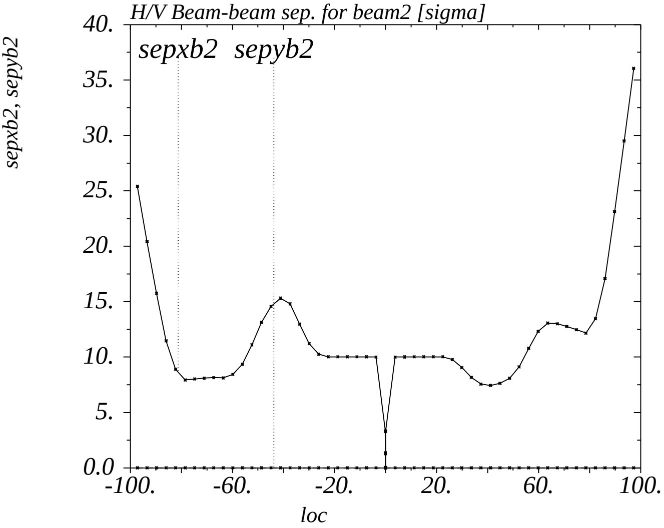
Beam beam separation CC10: IR5 beam1 sep



Beam beam separation closed: IR5 beam1 sep



Beam beam separation CC10: IR5 beam2 sep



Beam beam separation closed: IR5 beam2 sep