Update of the HL-LHC layout and optics

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P. Fessia, R. Kersevan, H. Prin, S. Redaelli, E. Todesco, J. Wenninger.

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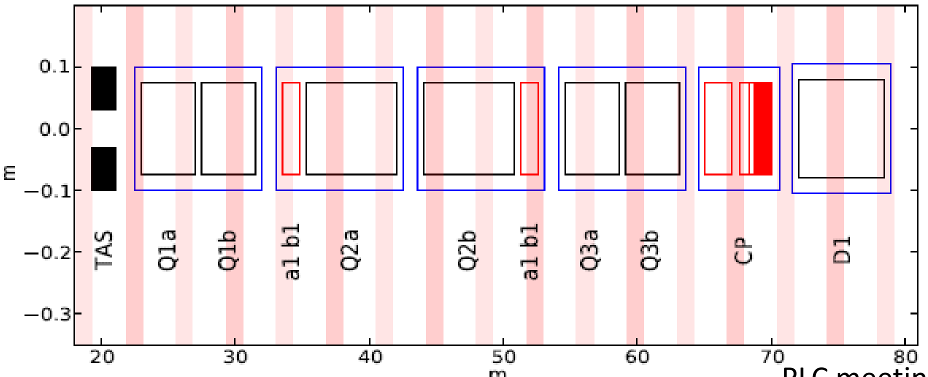
Introduction - I

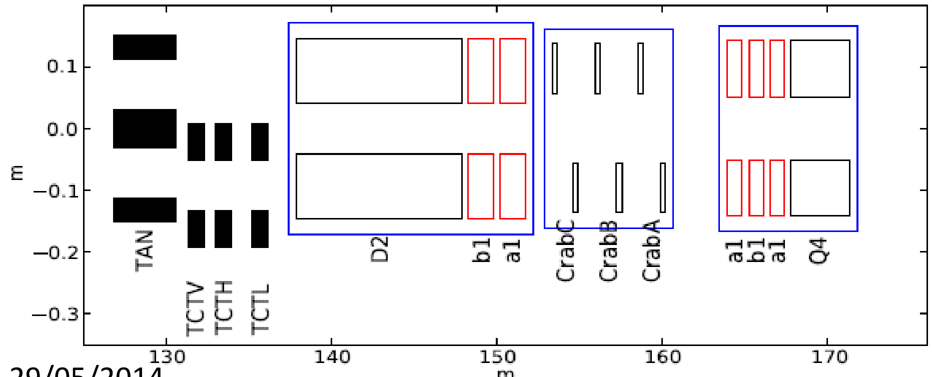
- The historical evolution
  - SLHCV3.1b:
    - **ITs: 140 mm, 150 T/m**
    - S. Fartoukh, R. De Maria. Optics and layout solutions for HL-LHC with large aperture Nb3Sn and Nb-Ti inner triplets, IPAC12 Proceedings.
  - HLLHCV1.0:
    - **ITs: 150 mm, 140 T/m**
    - R. De Maria, S. Fartoukh, A. Bogomyagkov, M. Korostelev. HLLHCV1.0: HL-LHC Layout and Optics Models for 150 mm Nb3Sn Triplets and Local Crab-cavities, IPAC13 Proceedings.
  - HLLHCV1.1: the proposed updated layout
  - All layouts are based on the **Achromatic Telescoping Squeeze**.
    - S. Fartoukh. Achromatic telescopic squeezing scheme and application to the LHC and its luminosity upgrade, Phys. Rev. ST Accel. Beams 16, 111002, 2013.

Introduction - II

- HLLHCV1.0 in a nutshell

Name	Type	Changes with respect the LHC as built
TAS	Absorber	60 mm aperture instead of 34 mm
Q1a/b, Q3a/b	Quadrupole	140 T/m, 150 mm aperture (instead of 70 mm), 4.002 m instead of 6.37 m.
Q2a, Q2b	Quadrupole	140 T/m, 150 mm aperture (instead of 70 mm), 6.792 m instead of 5.50 m hosted in separated cryostats
MCBXD	Corrector	1.2 m nested H and V orbit correctors (2.5 T.m) on the IP-side of Q2a and non-IP side of Q2b
MCBXC	Corrector	longer nested H and V orbit correctors (4.5 T.m) on the non-IP side of Q3
MC...X	Corrector	non-nested $a_2, b_6, a_6, b_5, a_5, b_4, a_4, b_3, a_3$ superferric magnet coils
D1	Dipole	6.69 m long, 35 Tm, 160 mm aperture (cold magnet instead of 6 warm modules)
TAN	Absorber	2-in-1, 145 mm aperture separation, elliptical aperture (82, 74) mm instead of (52, 52) mm
D2	Dipole	10m, 35 Tm, 2-in-1 105 mm aperture (instead of 80 mm) moved by 15 m towards the IP
MCBRD	Corrector	2-in-1, H (or V) strong orbit corrector (7 Tm) on the non-IP side of D2
ACRAB	RF deflector	3 modules offering a 12.5 MV deflecting voltage per beam and IP side
Q4	Quadrupole	2-in-1, 90mm aperture (instead of 70 mm), 160 T/m × 3.2 m
Q5	Quadrupole	2-in-1, 70mm aperture (instead of 56 mm), 160 T/m × 4.8 m moved by 11 m towards the arc
MS	sextupole	in Q10 in series with the main sextupoles
Q5 in IR6	Quadrupole	2-in-1, 70mm aperture (instead of 56 mm), 160 T/m × 4.8 m (longer version of the existing MQY type)





Introduction - III

- Why changing the layout?
  - Progress with the integration.
  - Progress with the hardware, e.g., magnets' specifications.
  - New results, e.g., energy deposition studies.
  - New results from beam dynamics, e.g., generation of crossing schemes.
- Summary of main changes:
  - Aperture: review of specifications (criteria, dimensions, shapes).
  - Layout: review of positioning of elements, addition of new elements (masks).
- Side effects:
  - Analysis of points needing further consideration.
  - Keep flexibility for future options.

Aperture

- In-depth review of criteria used to evaluate aperture needs.
  - Based on LHC experience on aperture measurements (see R. Bruce, n1 clarification and alignment and error budget, 7th PLC meeting 3/12/2013).
- Definition of target aperture: 12 σ.
  - Based on collimation system performance.

TAS aperture review

Layout	Element	Target[1] [σ]	Aperture estimate + imperfections [σ]	Sensitivity[2] [σ/mm]
V1.0	TAS r=30 mm	≥12	12.82	0.57
V1.1	TAS r=28.5 mm	≥12	12.00	
	TAS r= 27 mm	≥12	11.10	
	Q1	≥12	13.64	0.31
	Q2-Q3	≥12	10.97	0.21

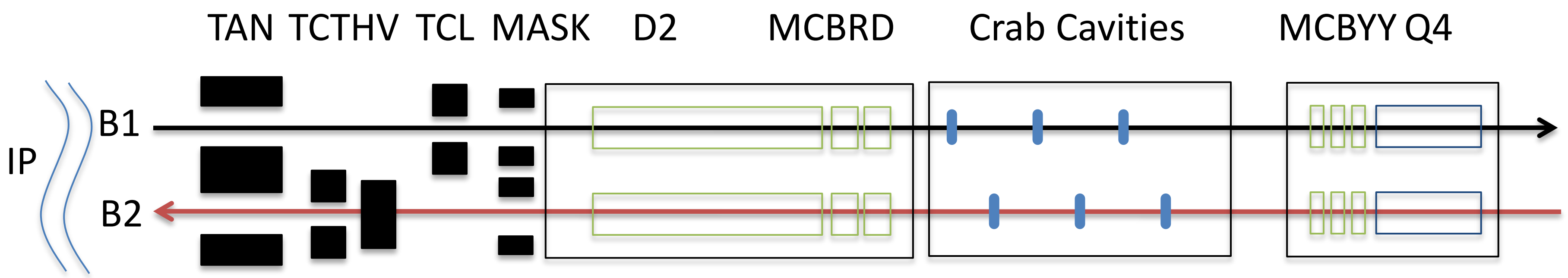
- V1.0: aperture estimate for TAS exceeds specifications.
- Alternatively, aperture could stick strictly to specifications.
- V1.1: it is proposed to use **r-> 28.5** mm.
- A reduction in TAS aperture should be based on considerations based on failure scenarios -> **to be reviewed by WP8**.

D1 Update

Layout	Length [m]	Field [T]	Integral [Tm]	Load line
V1.0	6.7	5.2	35	70%
V1.1	6.3	5.6	35	75%

- Length reduction has been proposed to avoid rebuilding tooling facilities.
- There is a very mild cost of load line margin (see E. Todesco, PLC 18/2/2014).
- No issues from beam dynamics point of view.

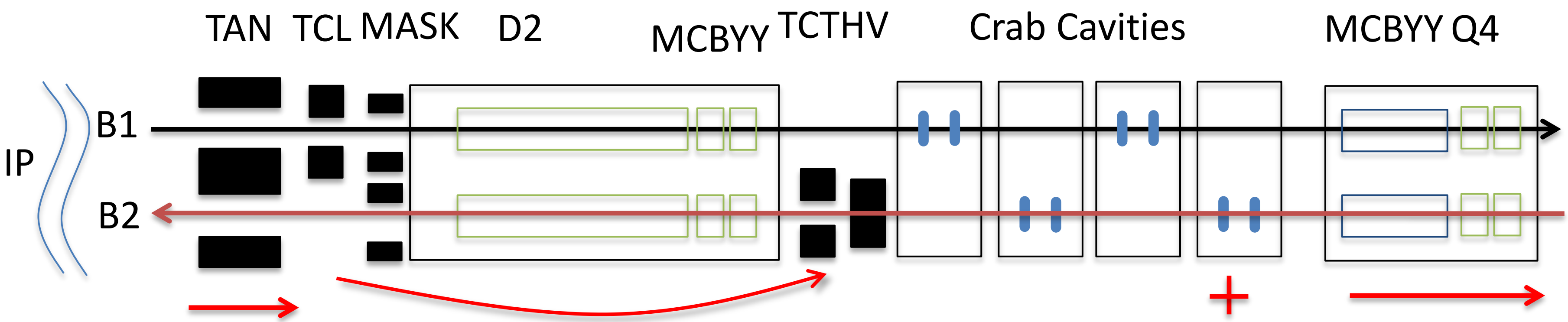
TAN-Q4 area V1.0



Open points to be addressed:

- Need of considering 4 cavities per side.
- Need of recovering space between D2 and Q4.
- Review of crossing scheme to optimise strength requirements for orbit correctors (MCBRD).
- Optimisation of TAN performance.
- Energy deposition effects.

TAN-Q4 area V1.1



Main changes:

- Shift of Q4 towards the arc (in the range 3 m to 10 m).
- Add one cavity/beam per side and group them in pairs.
- Extend crossing scheme to the crab cavity area.
- Introduce one design for orbit correctors close to D2 and Q4.
- Move TCT on non-IP side of D2.
- Move TAN towards the D2.

TAN optimization - I

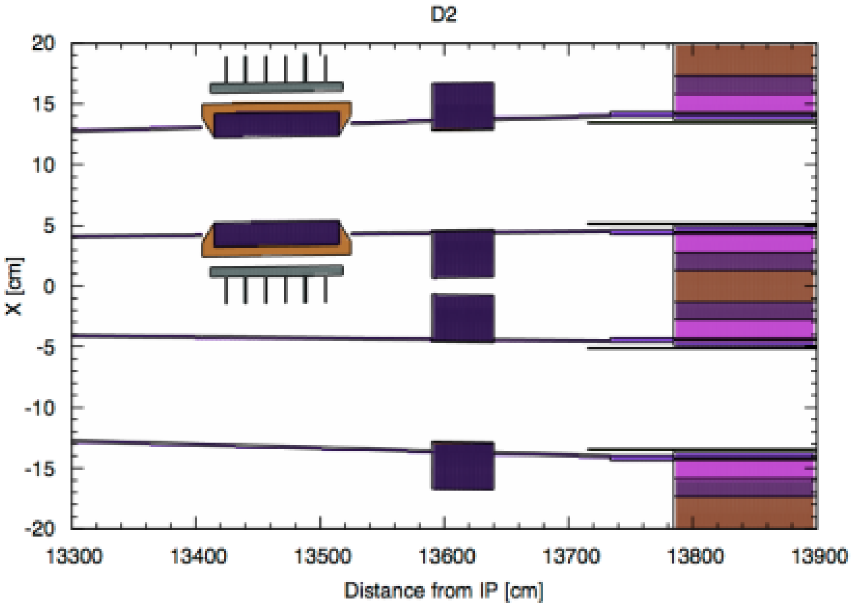
V1.0 analysis by WP10:

- < 2 mW/cm^3 at 5×10^{34} cm^{-2}s^{-1} for D2/Q4
- < 40 MGy after 3000 fb^{-1} for D2
- < 40 MGy after 3000 fb^{-1} for Q4

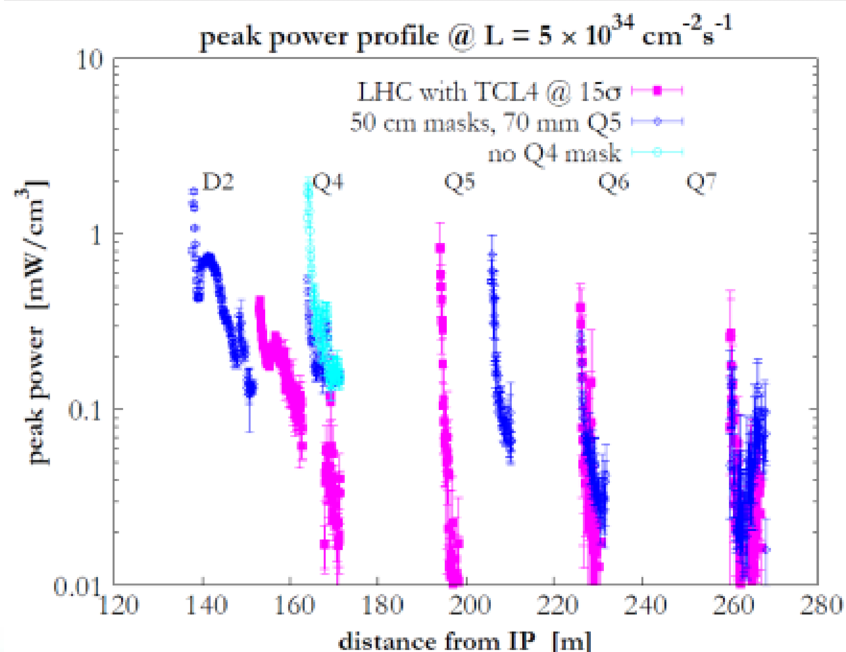
If non-parallel TAN apertures and fixed masks are as close as possible to D2, Q5.

Next steps:

- Understand mask positioning constraints (vacuum valves).
- Re-optimize apertures based on new mask positions.
- Re-asses energy deposition estimates



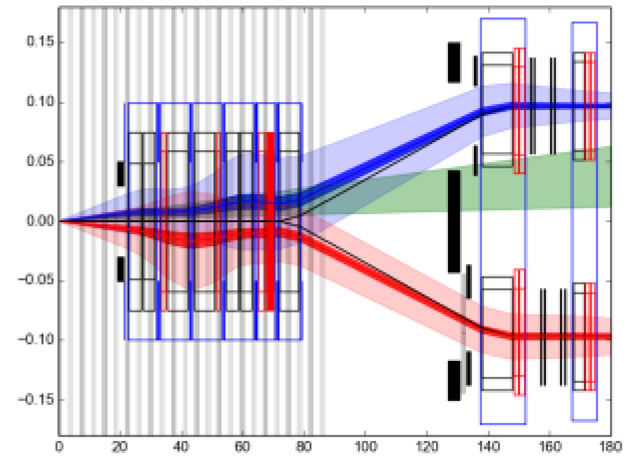
L. Esposito, F. Cerutti, WP2 TL Meeting , 21/1/2014



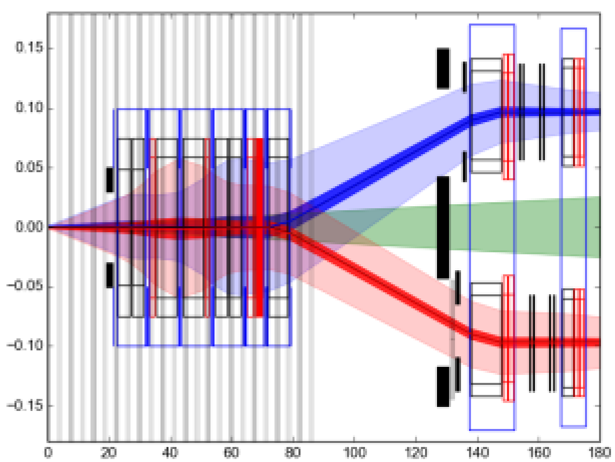
TAN optimization - II

- Beam 1, Beam 2, Neutral (devris at 400 µrad)
- Energy deposition critical for H crossing.
- TAN aperture is dominated by flat beams.
- Impact of neutral debris dominated by horizontal crossing angle $\propto 1/\sqrt{\beta^*}$ in the crossing plane.

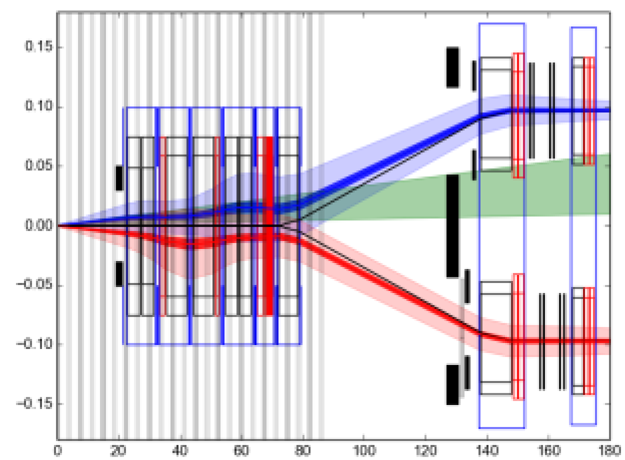
Round optics: H crossing



Flat optics: V crossing



Flat optics: H crossing



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TAN optimization - III

- Need to design for worse case scenarios for fixed absorber.
- Better protection could be achieved if TAN had horizontal jaws. However:
  - Movable parts more sensitive to radiation, therefore passive absorbers still needed.
  - Possible improvements:
    - TCL could increase absorption material,
    - Mask could be integrated in the cold mass. **NB: if in the warm region, masks lose effectiveness (partially evaluated by L. Esposito, F. Cerutti)**

D2 Update

Layout	Length	Field	Integral	Coil AP	CB OD/ID	BS OD/ID	BS Ogap/IGap	Shape
	m	T	Tm	mm	mm	mm	mm	
V1.0	10	3.5	35	105	_/_	_/82	_/72	Rectellipse
V1.1	9	4	35	105	_/_	_/88.5	_/82.5	Octagon

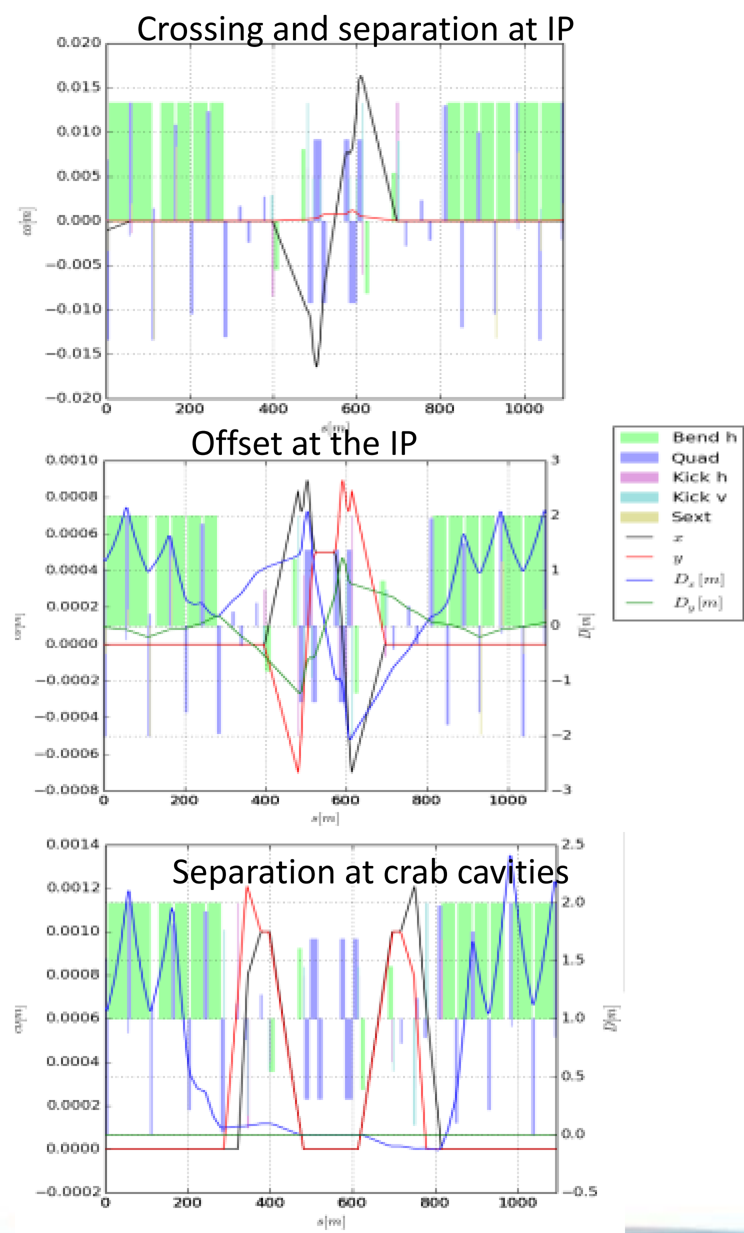
- Length reduction thanks to stronger field. Under discussion even shorter version (8 m).
  - In progress: Field quality validation.
- Aperture
  - Shape: **octagon** is optimal for flat optics. Crossing plane is free.
  - Dimensions: derived from scaling applied to D1 used as reference.

  Missing information: BS design to be reviewed by WP3 / WP12.

IR Orbit manipulations

- At the IP in both planes: crossing, separation, offset (or a combination of the last two for individual adjustments).
- At the crab cavities if not active alignment is provided: separation, offset between beams and between first and second module.
- Correction of triplet misalignment.
- Correction of arc orbit imperfections.
- Orbit feedback for time dependent imperfections.

- Correctors needs to be stronger due to larger crossing angles.
- Very reproducible transfer functions in particular MCBX due to larger β functions in the triplet and smaller β^*.
- Fast ramp rate to speed up operations (directly link to integrated luminosity).

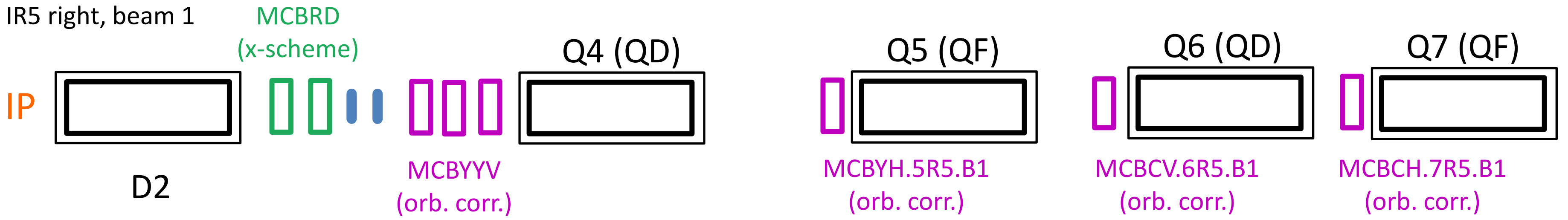


Orbit corrector strategies

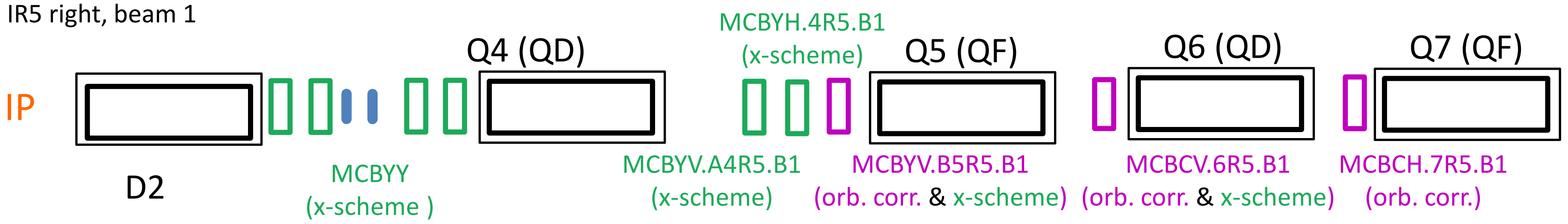
- V1.0: Crossing bump closed at D2 to be transparent for crab cavities, correctors in Q4 for steering and alignment.
  - Features: strong orbit correctors in D2, different corrector types for Q4.
- Input from WP4:
- Crab offset allowed to be 1 mm (3 mm at low voltage).
- Assuming 0.5 mm for operational margin and 0.5 mm for alignment accuracy (See P. Baudrenghien, WP2 TL meeting 21/3/2014).
- V1.1: Crossing bump extended to Q4 correctors, sharing strength between correctors in D2 and Q4.
- Features: lower strength of correctors, same corrector types in D2 and Q4. **Ramp rate and hysteresis effects to be checked**.

Orbit correctors in IR1/5 in the Matching section

HLLHCV1.0: D2 (MCBRD): H and V corr. for x-scheme, Q4(MCBYY) H/V corr. for orbit corr.
Q5 (MCBY), Q6 (MCBC), Q7 (MCBC): one H/V corr. for orbit corr.



HLLHCV1.1: same corr. for D2 and Q4,
reuse Q4 (MQY) of nominal LHC as Q5 of HL-LHC



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Orbit corrector budget

	opt round/ opt inj	MCBX [Tm]			MCBYY [Tm]		MCBY|C [Tm]
		1	2	3	D2	Q4	
X-ing at IP	590 µrad	0.1/0.7		1.8/0.7	2.3/1.9	2.5/2.5	0.4/0.4
Sep. at IP	1.5/4.0 mm	0.1		0.2/0.7	0.2/0.4	0.0	0
Triplet Mis.	2 sigma	1.0/1.0	1.4/1.4	0.8/0.8	0.0	0	0
Offset IP (x-ing)	+/-0.5 mm	+0.3/-0.3		-0.7/+0.7	+0.2/+0.2	0.0	0
Crab cavities alignment	+/-0.5 mm ($p_{x/y}$=0)	0.2/0.2		0.4/0.4	0.3/0.3	0/0	0.4/0.3
	+/-0.2 mm delta	0/0			0.5/0.5	0.7/0.7	0.2/0.2
Arc. Imperf.	to be assessed	0			0	0	2.3-1.5
Sum		1.6/1.4	2.0/1.8	2.3/2.6	3.3/2.9	3.2/3.2	1.0/0.9
Nominal Str.		2.5	2.5	4.5	3.5	3.5	3.3[1)]-2.5

Offset at IP: optimization of corr. strength and IT aperture for collision (0.5-0.8 mm)
Collision optics: Orbit gymnastics assumes loss of aperture (radial):

- misalignment: triplet: 1 mm
- x-scheme with orb corr. at D2/Q4:
  crab cavities: 0.5 mm, entrance TAN: 0.5 mm, entrance/exit D2: 0.7 mm

1) At 1.9K

see M.Fitterer, HSS meeting 14/04/2014

Q4-Q5 types in IR1 and IR5

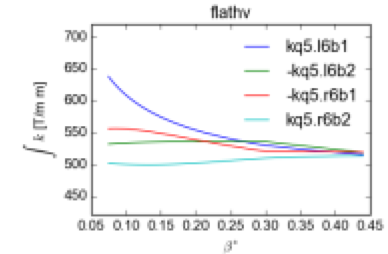
Layout	Name	Type	Coil Ap.	Grad	Length	Integral
			mm	T/m	m	T
V1.0	Q4	MQYY	90	120	3.5	420
	Q5	MQYL	70	160	4.8	768
V1.1	Q4	MQYY	90	120	3.5	420
	Q5	MQY (1.9 K)	70	200	3.4	680
Alternative	Q4	MQYY	90	120	3.5	420
	Q5	2xMQYY	90	120	3.5	840

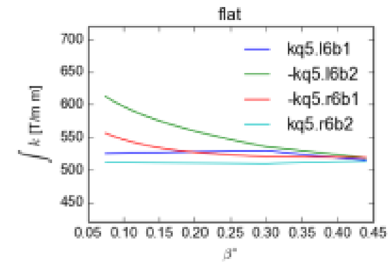
V1.1 relies on: existing 3xMCBY+MQY in Q4 being separated by D2, replacing heat exchangers to allow 1.9 K cooling, move it to Q5 position, train MQY to 200 T/m (short sample already tested at 1.9 K, E. Todesco).

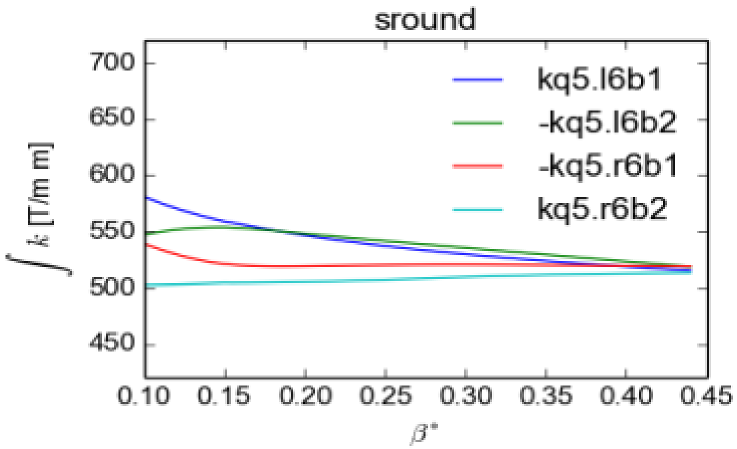
As an alternative, change design of MQYY to lower current version (MQM cable 20kA ->8kA), build 8 additional MQYYs + spares.
The solution is compatible also with other optics solutions (**D. Dalena, S. Fartoukh, M. Fitterer**), which would bring lots of benefits in terms of conditions at crab cavities.

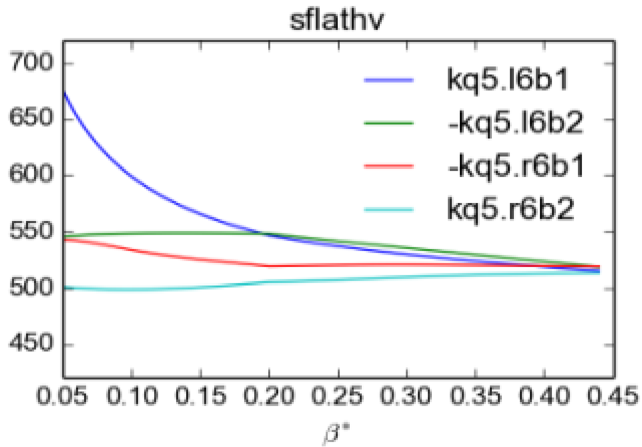
Q5 Type in IR6 (needed for ATS)

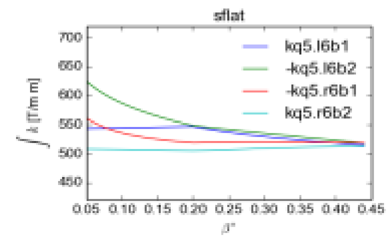
Layout	Name	Type	Coil Ap.	Grad	Length	Integral
			mm	T/m	m	T/m·m
LHC	Q5	MQY	70	160	3.4	544
V1.0	Q5	MQYL	70	160	4.8	768
V1.1	Q5	2xMQY	70	160	3.4	1088











For V1.1 we propose adding an additional MQY in the non-IP side of Q5 (spares available, E. Todesco) since the squeeze are not being fully validated.

Main elements in HL-LHC v1.1

Element	IR	Type		Length [m]		Nom. Field [T or T/m]	
		V1.0	V1.1	V1.0	V1.1	V1.0	V1.1
Q1/3a/b	15	MQXF		4		140	
Q2a/b	15	MQXFL		6.8		140	
D1	15	MBXA		6.7	6.3	5.2	5.6
D2	15	MBRD			9	3.5	4
Q4	15	MQYY		3.5		120	
Q5	15	MQYL	MQY@1.9K	4.8	3.4	160	200
Q5	6	MQYL	2xMQY	4.8	2x3.4	160	160

Aperture model in HL-LHC

Element	Coil ap. [mm]	Sep. [mm]		Shape		BS inner specs [mm] (radius, half-gap)	
		V1	V2	V1	V2	V1	V2
TAS	n/a	n/a		Circle		30	
Q1	150	n/a		Octagon		53, 49	
Q2-Q3 to D1	150	n/a		Octagon		63, 59	
TAN	n/a	144	(1)	Ellipse	Circle	42, 36	(1)
MASK D2	n/a		175		Octagon		(1)
D2	105	186	188	RE	Octagon	41,36	44 ,42
MCBYY	100	194	194		Octagon		41,39
Crab Cavities	84	194		Circle		42	
Q4	90	194		Rectellipse		37, 32	
MASK Q5	n/a		194		RE		30, 26
Q5	70	194		Rectellipse			30, 26

(1) Pending vacuum valve locations

Conclusions

- New layout with recent changes ready
- Open points for V1.1:
  - Masks integration and vacuum layout to be finalised.
  - IT and D2 beam screen design to be discussed and finalised.
  - MQY at 1.9 K to be demonstrated and selection of best MQYs among spares.
  - Validation of aperture margins and collimator settings.
  - BPMs in the triplet area to be studied (number, aperture, performance)

- Remarks:
  - Active alignment costly for corrector strength but beam base alignment.
  - Decision on MQYY design is awaited: it will provide flexibility for future design.
  - If the BBLR is included in the baseline specifications should be provided and the integration studied.

Backup

HL-LHC layout and optics targets

- Nominal targets:
  - β*: 15cm/15cm and 7.5/30cm;
  - Crossing angle 590 μrad at 7 TeV in both planes in both IR.
  - ±2mm (±11σ at β*=6 m, ϵ=2.5 μm, E=7 TeV) in separation
  - ±1mm in offset.
- Ultimate targets (relying on smaller retraction of collimators, higher crab cavity gradient , better protection from neutrals)
  - β*: 10cm/10cm and 5/20cm;
  - Crossing angle 720 μrad at 7 TeV.

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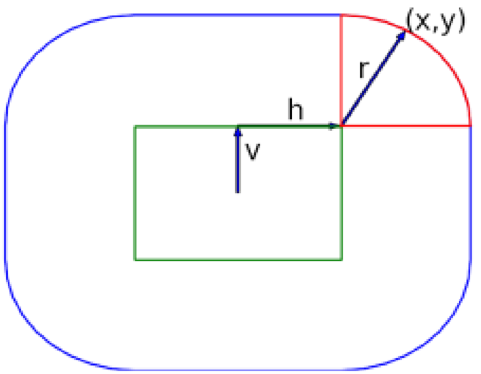
Ground motion and fiducialization to be reviewed by SU

- Ground motion span a racetrack area[1]:
  - Triplet (r=0.6 mm, h= 0, v=0)
  - Matching sections (r=0.84 mm, h= 0.36, v= 0)
- Fiducialization for MQ (h=0.9 mm, v= 0.6 mm)
- Summary[2]:



Element	r_m+r_f [mm]	h_m+h_f [mm]	v_m+v_f [mm]
TAS	2+0	0+0.5	0+0.5
IT	0.6+0	0+1	0+1
D1/D2	0.84+0	0.36+1	0+1
TAN	0.6+0	0+1	0+1
Q4/Q5	0.84+0	0.36+0.9	0.6

[1]JB. Jeanneret, LHC Report 1007, 2007. [2]S. Fartoukh, SLHC aperture models.

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D2 Aperture update

	Coil AP	CB OD/ID	BS OD/ID	BS Ogap/IGap
	mm	mm	mm	mm
LHC D2	80	73/69	67.1/62.6	57.5/52.8
LHC D1	80	78/74	72.0/67.4	62.3/57.6
V1.0 D2	105	_/_	_/82	_/72
New D2 r.e.	105	_/_	_/88.5	_/78.5
New D2 octagon	105	_/_	_/88.5	_/82.5

- Scaling 105/80 from the present D1 (1 mm between coil and cold bore instead of 3 mm, thanks to 1.9 K).
- Octagon shape (with 3 mm for capillaries instead of 5 mm) for optimal for flat optics without constraining crossing plane.

Not addressed: Validate/optimize capillaries cross sections to be reviewed by WP3 / WP12.

https://edms.cern.ch/file/334961/1.3/LHC-VSS-ES-0002-10-30.pdf

https://edms.cern.ch/document/110392/2

D2 Aperture expectations

Element	Dim R/HG [mm]	Target[1] [σ]	+ imp. [σ]	Sensitivity [2] [σ/mm]
D2 V1.0	41/36	≥14-20	12.74	0.39
Mask V1.0	41/36	≥12	12.35	0.37
D2 r.e.	44/39	≥14-20	13.91	0.39
Mask r.e.	44/39	≥12	12.47	0.37
D2 oct	44/41	≥14-20	14.69	0.39
Mask oct	44/41	≥12	13.11	0.37

D2 may be only protected by TCT in Q5, but target may be reduced if TCT are displaced in between D2 and crabs (to be confirmed by WP5).

Still possible to use r.e. with optimal orientation at the cost of freezing the crossing plane.

Orbit control in the IR1 and IR5

- Orbit correctors in the LSS are designed for:
  - Crossing angle, separation, offset at the IP.
  - Orbit correction due to triplet misalignment and external imperfections.
  - Aperture optimization for ground motion if between realignment.
  - Beam based alignment in the crab cavities, if not active alignment is provided.

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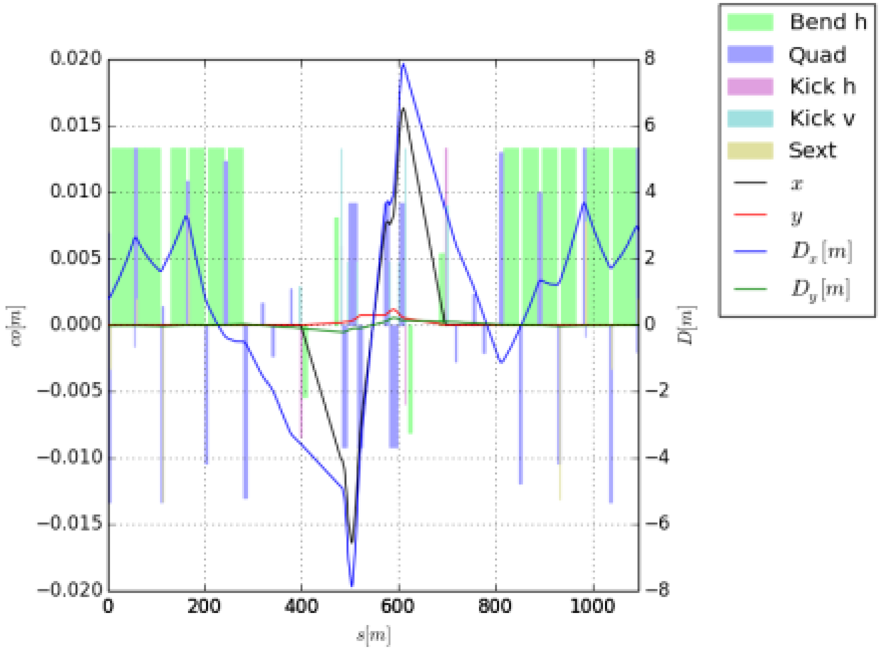
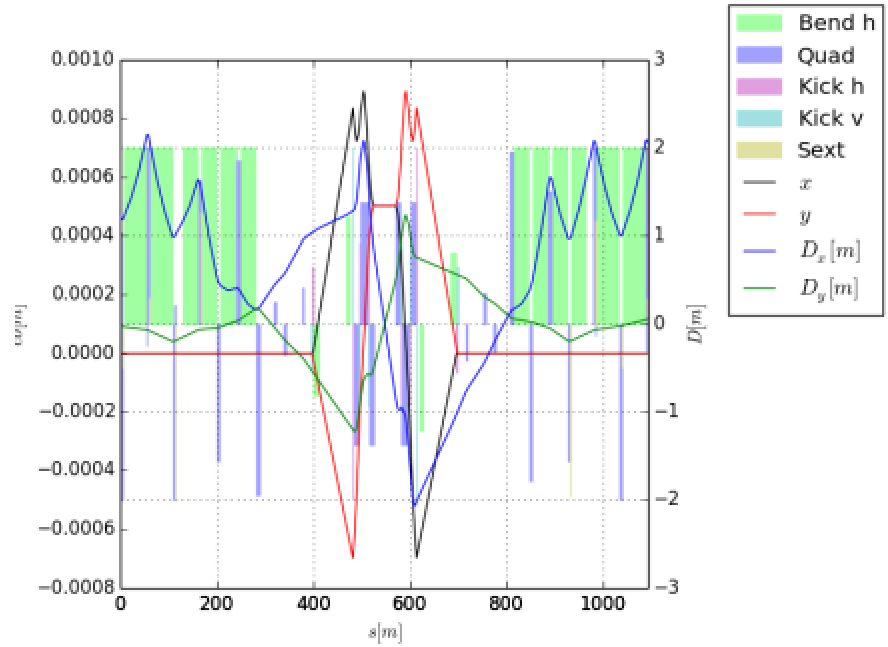
Crossing scheme

- Status: MCBX1,2,3 in the triplet in spec. Correctors in D2 short if max field is below 4T (D2 field is in between 3.5 - 4.3 T for 10-8 m long magnet).
- Ezio proposed 3 T for orbit correctors for double layer design excluding nested magnets.
- Choose strategy for D2/Q4 orbit correctors
  - Option 1: Use two big orbit correctors H/V close D2.
  - Option 2: Share the strength of the D2 correctors with two other equal orbit correctors in Q4.
  - Option 3: Use D1/D2 for H crossing and 1 V corrector in D2 for the V crossing.

Crossing, separation offset knobs



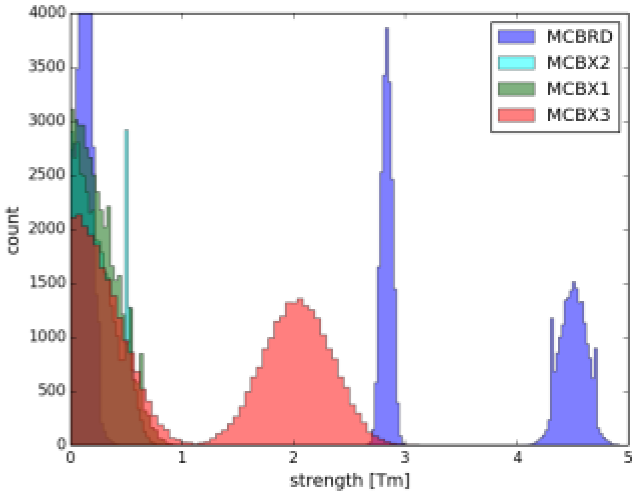
Crossing 590 murad and separation 1.5 mm.

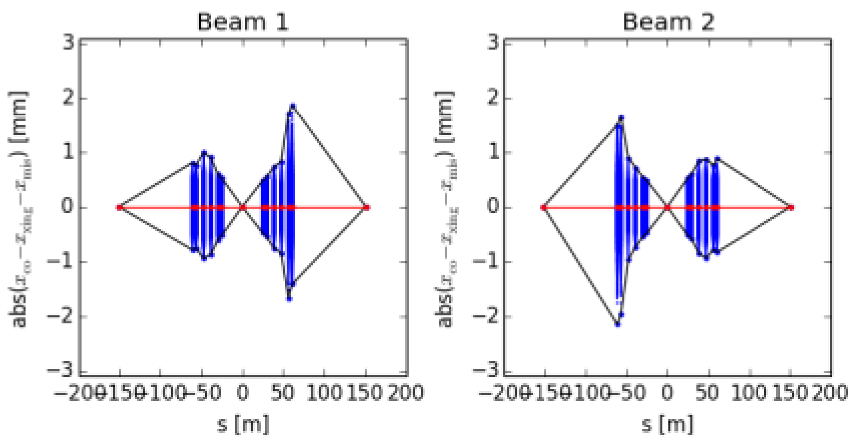


Offset knob 1mm: can be used to reduce aperture in Q2,Q3 and strength in MCBX3 at the cost of aperture in TAS,Q1 and MCBX1.2 strength.

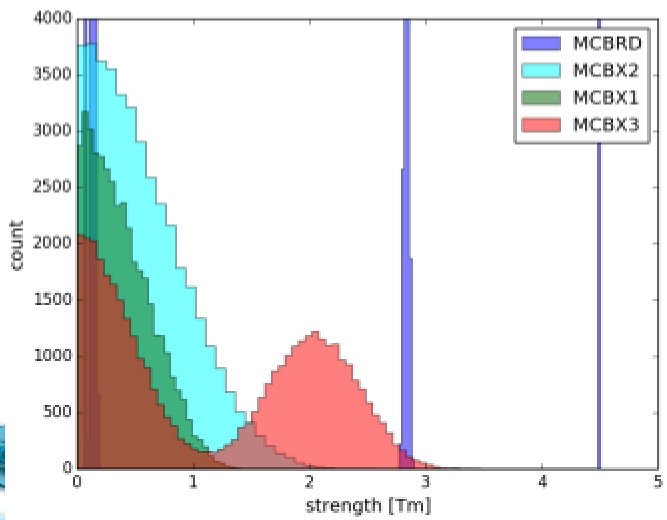
Misalignment, Transfer function errors

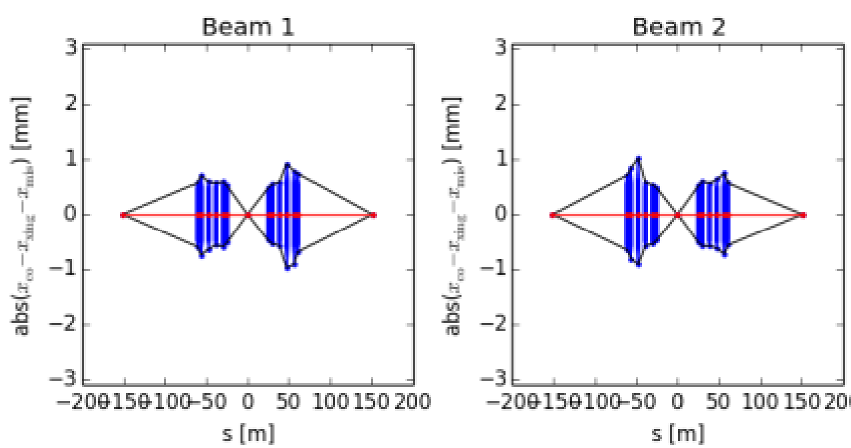
Including transverse and longitudinal misalignment and transfer function error
(opt_round_thin, +/- 295 μrad x-ing, +/- 0.75 mm separation)





a) limit corr. strength





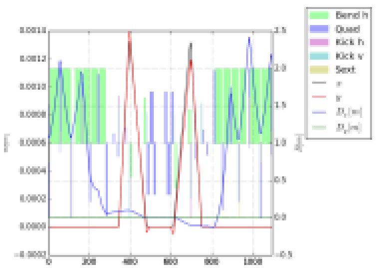
b) use only 2 (out of 4) MCBRD

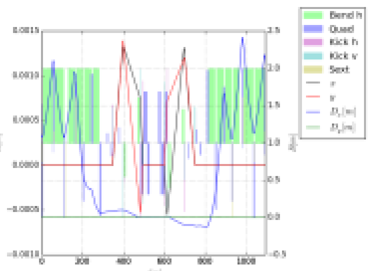
Beam based alignment in crab cavities

corrector scheme	plane	corrector strength ($x_{b1}=x_{b2}$ | $x_{b1}=-x_{b2}$) [Tm]									
		MCBX1		MCBX2		MCBX3		MCBRD		MCBY.5	
MCBX1+MCBX3	hor.	0.95	0.00	0.00	0.00	1.02	0.37	1.44	1.01	0.64	0.64
MCBX2+MCBX3		0.00	0.00	1.06	0.01	1.26	0.37	1.17	1.01	0.64	0.64
MCBX1+MCBX3	vert.	0.90	0.07	0.00	0.00	1.00	0.43	1.49	1.12	0.59	0.59
MCBX2+MCBX3		0.00	0.00	1.02	0.08	1.24	0.45	1.24	1.10	0.59	0.59

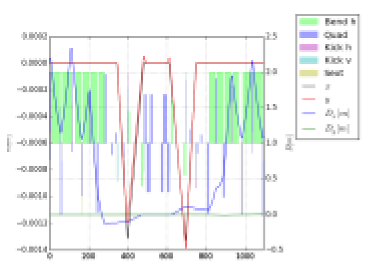
Beam 1

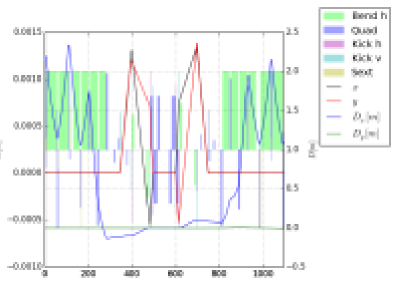
Beam 2





Shift the orbit in the same direction





Shift the orbit in the opposite directions

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Shorter possible knob, by using corrector in Q6 and Q7, MCRD strength will decrease.

TAN apertures

Element	Sep	Radius [mm]	Target[1] [σ]	Ideal beam [σ]	+ imp. [σ]	Sensitivity[2] [σ/mm]
TAN V1.0	144	42/37	≥12	13.05	10.95	0.34
New TAN	148- 158.6	38	≥12	13.95	11.78	0.33
TAN V.10	148- 158.6	39	≥12	13.50	12.11	0.33

- TAN needs small reduction with new tolerances.
- If 1 m mask needed in front of D2, aperture should increase and separation decrease by ~1-2 mm (protection to be reviewed).
- If TCT displaced towards the arc aperture TCT aperture and separation could be by ~5 mm.

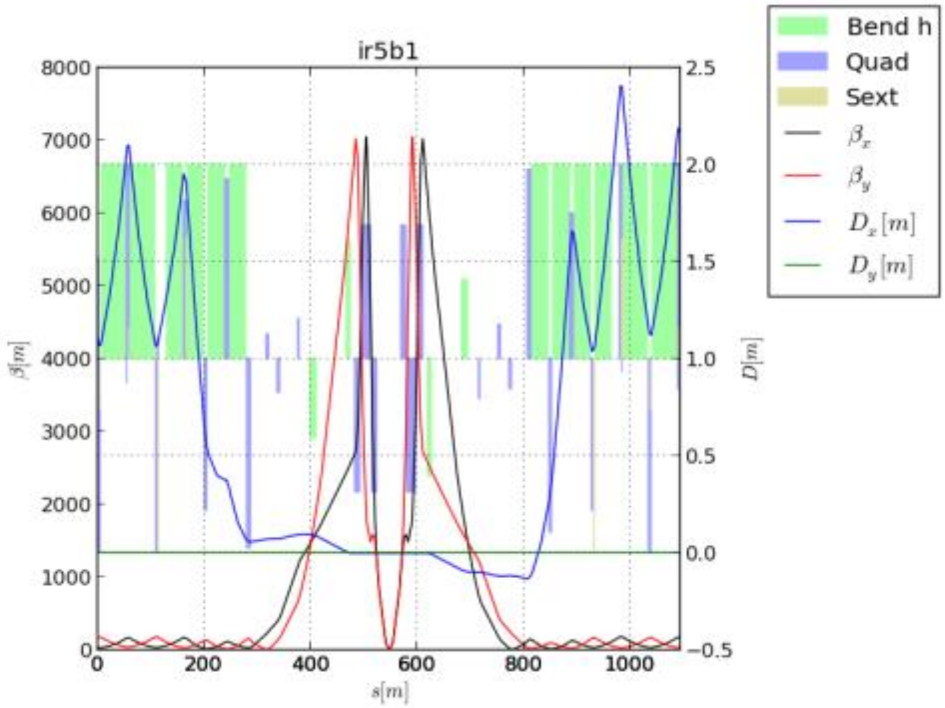
Q4 Position

- Optics allow a displacement of Q4 towards the arc. Pending full squeeze calculation (and Q5 strength reduction) up to about 10 m look possible (pre-squeeze, inj. optics, rough squeeze generated) .
- Create room in between D2 – Q4.
- It is possible to reduce crab cavity voltage (5-10%) at the cost of
  - TAN aperture
  - shifting of the beta x/y crossing point towards the crab cavities (might not be good for wires if very far from cavities)

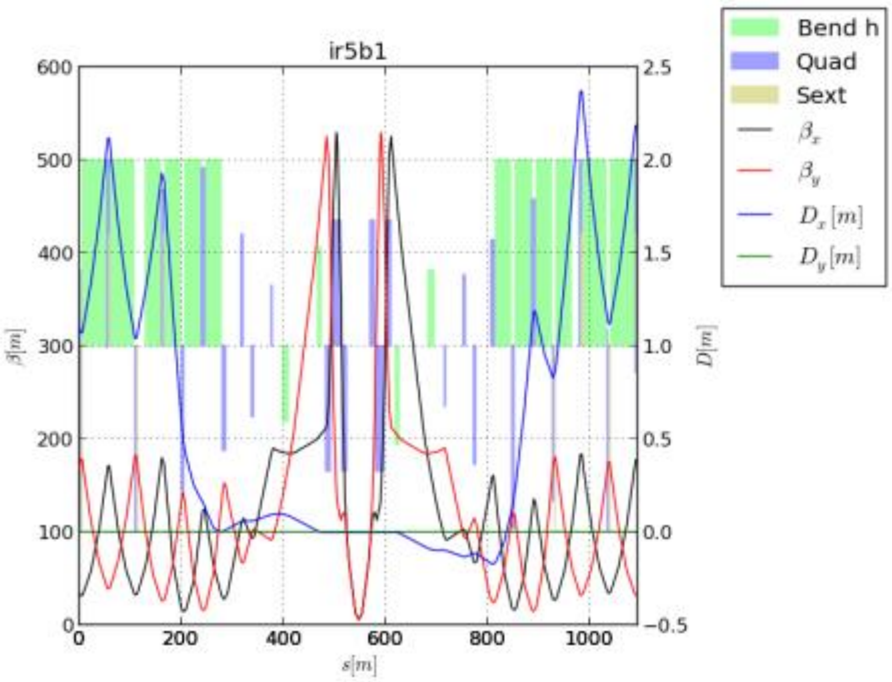
Not addressed:

- Is the mask in Q4 needed again with increase D2 –Q4 distance? (WP10)
- Can wire/TCT be hosted in between D2 – Q4 as well? (WP5)

Nominal optics



Pre-squeeze



Injection

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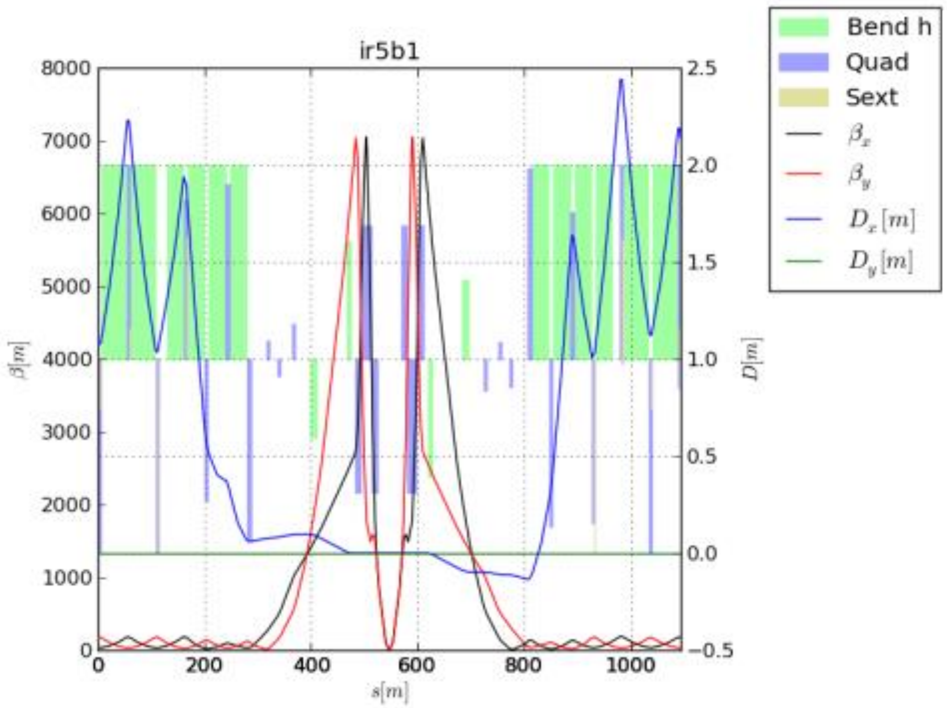
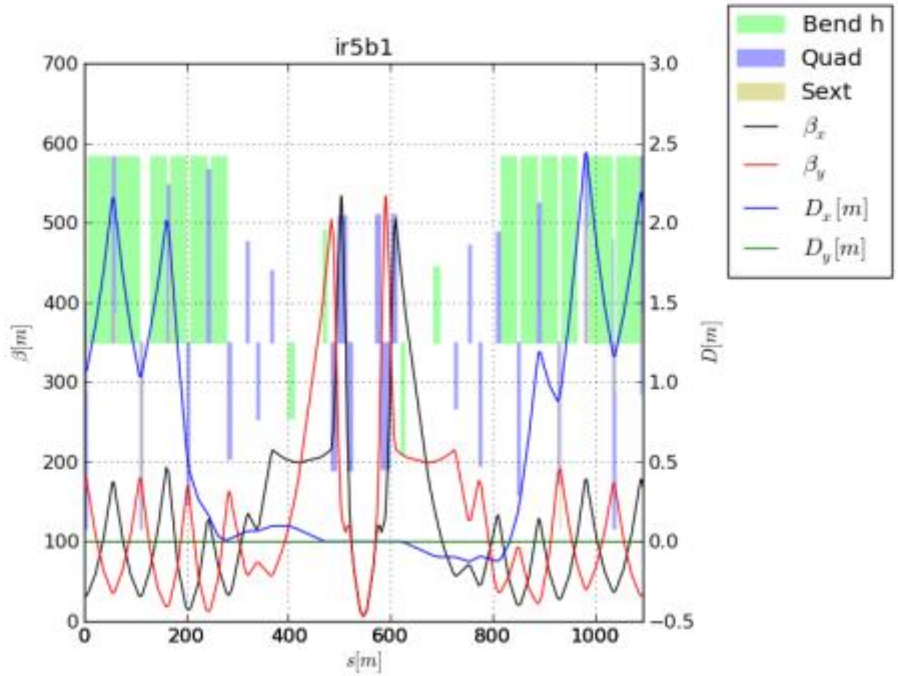
Q4 displaced preliminary optics

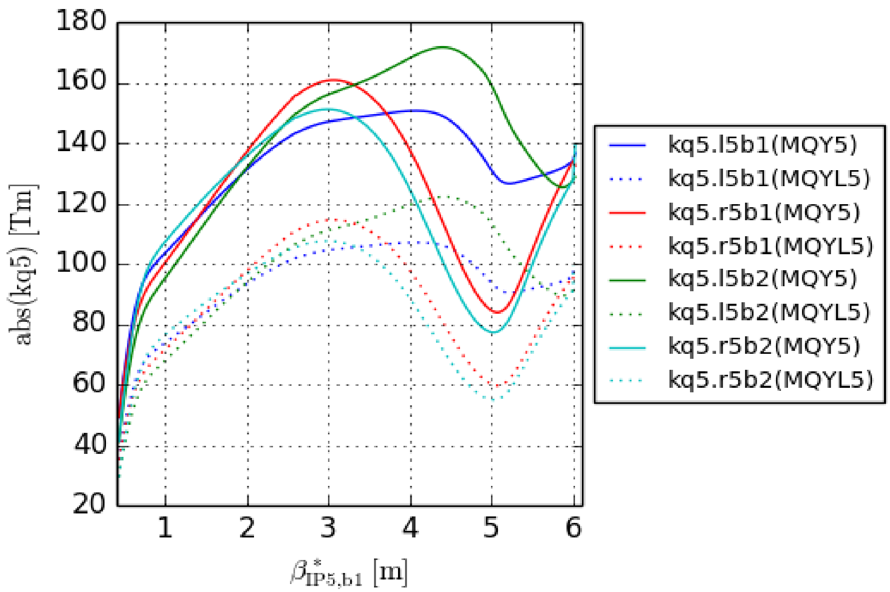


Pre-squeeze

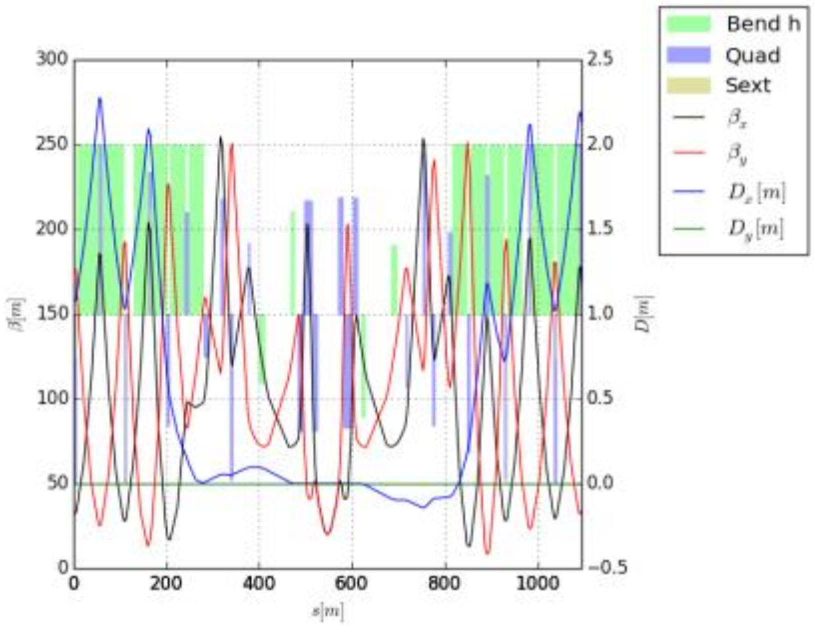


Injection

Q5 in IR5



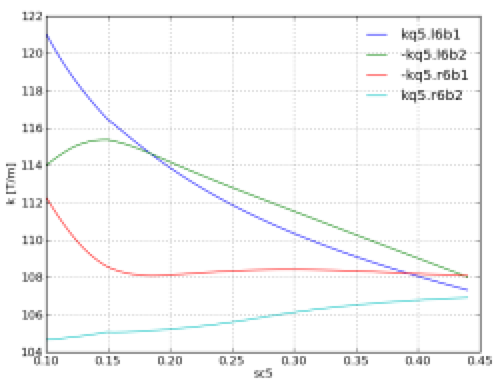
Q5 variation during the squeeze for MQYL and MQY.



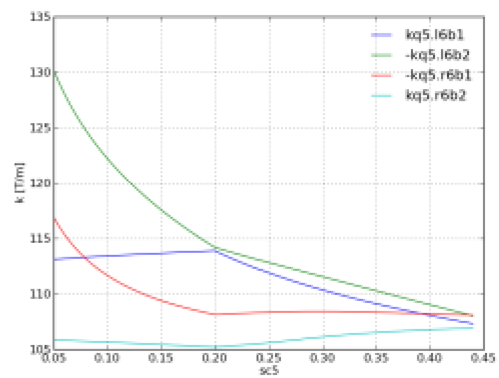
VDM optics possible only at half to top Energy.

Q5 type in IR6

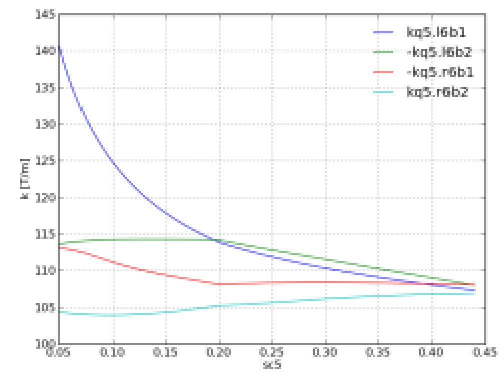
- Adding a MQY to in the arc side of the existing MQY should be possible (space + spare available to be verified by WP3).
- Squeeze to be readapted, but in principle possible.
- 200T/m at 1.9 K barely OK (IR6 squeeze pending optimization).



10/10 cm squeeze
With MQYL



20/5 squeeze



5/20 squeeze

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Request for input

- New optics if displacing Q4.
- Wire optics constraints.
- Confirm 200 T/m for MQY at 1.9K and spare/space for MQY in IR6.
- Evaluate cost of active alignment vs corrector strength
- Review ground motion and fiducialization.
- Update MS energy deposition with new TAN and mask aperture.
- Decide TCT location.
- Design D2 Beam screen.
- Failure scenario for TAS aperture deacrease.