

LHC perspective, review and outlook

Mostly on the special high beta runs for forward physics involving roman pots IP1 + IP5

90 m w/o crossing angle 2011, 2012 ; 2015 (spin-off 30 m, VdM all IPs)

1000 m in 2012

2500 m in 2016

Outlook : lower energies, higher luminosity and some general remarks

Challenging (interesting) for the machine in many respects

Acknowledgements -- machine related side

TE-EPC Magnet powering Valerie Montabonnet et al., OP : et al.

OP - J. Wenninger, L. Ponce, M. Pojer, D.Nisbet. et al.; injectors; BI+ALFA Sune Jakobsen

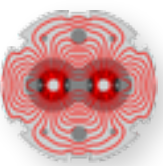
Collimation - Stefano Redaelli, Roderik Bruce, et al.;

ABP optics measurement team Rogelio Tomas et al.,

low/general optics Riccardo de Maria, Thys Risselada, Massimo Giovannozzi et al.

collective effects, Elias Metral, Tatiana Pieloni (BB), Impedance Benoit Salvant,

Fanouria Antoniou, Y.Papaphilippou (IBS) ...



Run 1

2011 : de-squeeze from 11 to 90 m, major tune change - global compensation

many steps, several iterations to get smooth, then very reliable

2012 : 90 m, up to 112 bunches / beam (no crossing angle)

reaching $\beta^* = 1000$ m, getting to CI region at 8 TeV cms (single physics fill)

vertical RPs at 3σ , prim. collimator scraping down to 2σ

Run 2

2015 : $\beta^* = 90$ m with ± 50 μ rad crossing angle, 100 ns spacing, 671 bunches

2016 : $\beta^* = 2500$ m, vertical RPs at 3σ , max 3×10^{11} p / beam, low $\epsilon_y \sim 1$ μ m

parasitic RP insertions in standard physics (modified IP5 bump to reduce Dx loss)

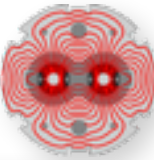
Overall going very well

LHC is a great machine -- re-producible, stable, well known properties

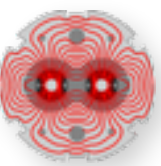
Major constraint time

$\sim 2 \pm 1$ days with beam for any special optics, when all goes well

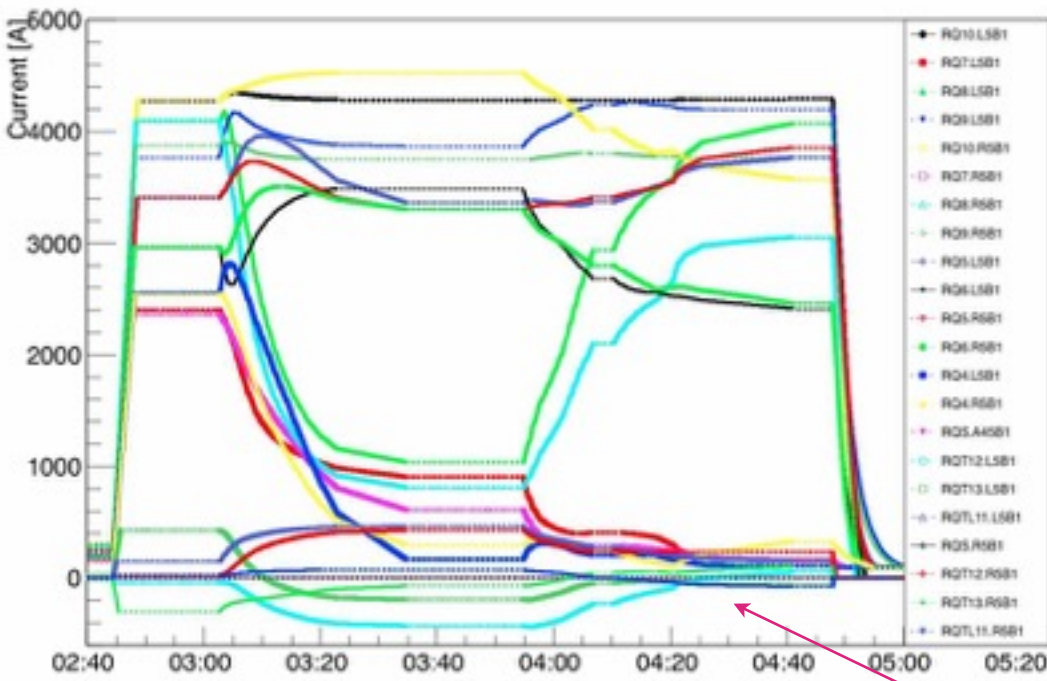
Example 2500 m run this year -->



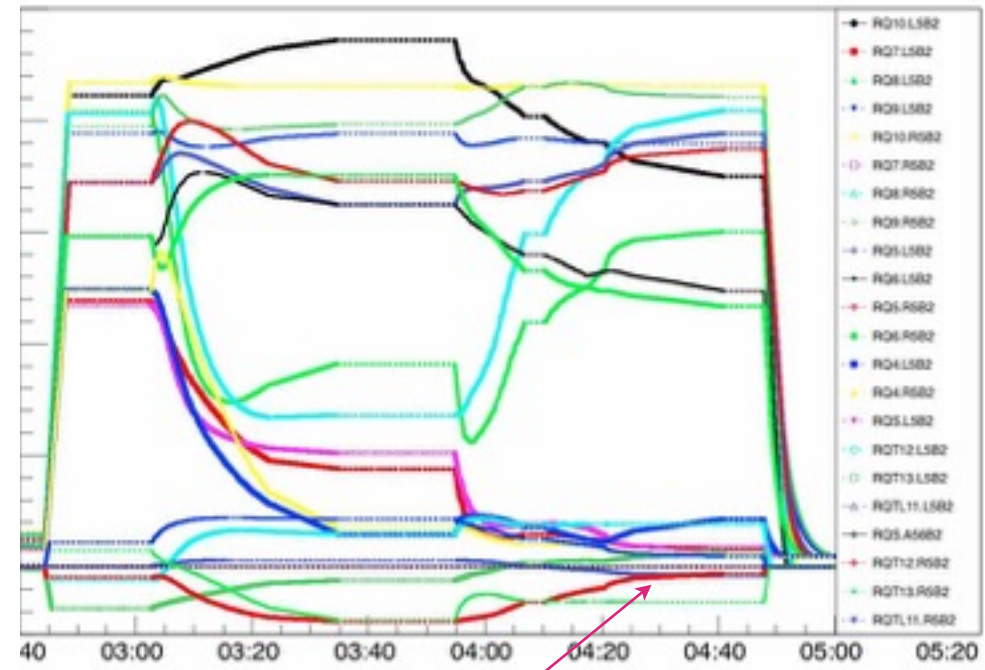
- **winter '15/'16 : weeks of high-beta optics matching** -- as extension of previous 90 m and 1000 m and starting from end of ramp optics of 11/10/11/10 m from 2015 ; would have been far to late to wait for the final 2016 optics
 - **16 Feb. 2.5 km first trial optics version given to ALFA / TOTEM**
 - **5 March successful powering test Q4 IR**
 - **5 April dry run (no beam), to 2.5 km without magnet trips**
 - **16 June, probe beams, getting successfully through ramp + de-squeeze to 60 m + de-squeeze to 2.5 km. optics meas. ✓ optics; but also (as could be expected) major tune + coupling corrections**
 - **22-23 June, 1-2 July, several iterations to clean and smooth, remove stops on the long way to 2.5 km**
 - **major matching campaign - added steps at 2.5 km to adjust phase advance for ALFA**
 - **31 July - 1 Aug. , first attempt to get collisions and RP adjust + re-adjust de-squeeze going to collision tunes from 90 m, cold checkout added 2.5km steps for ALFA ✓**
 - **20 Aug, 2.5 km, optics measurements modified ALFA optics**
 - **24 Aug. adjust collisions and compare ALFA before/after extensions**
 - **7 Sep. Collision, collimation and RP adjust**
- > few selected Figures to illustrate some of these efforts**



b1



b2



11 - 90 m
3:03-3:35

90 - 500 m
3:55-4:06

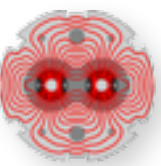
500 - 2500 m
4:10-4:41

many of the quadrupoles close to their close around lower limits

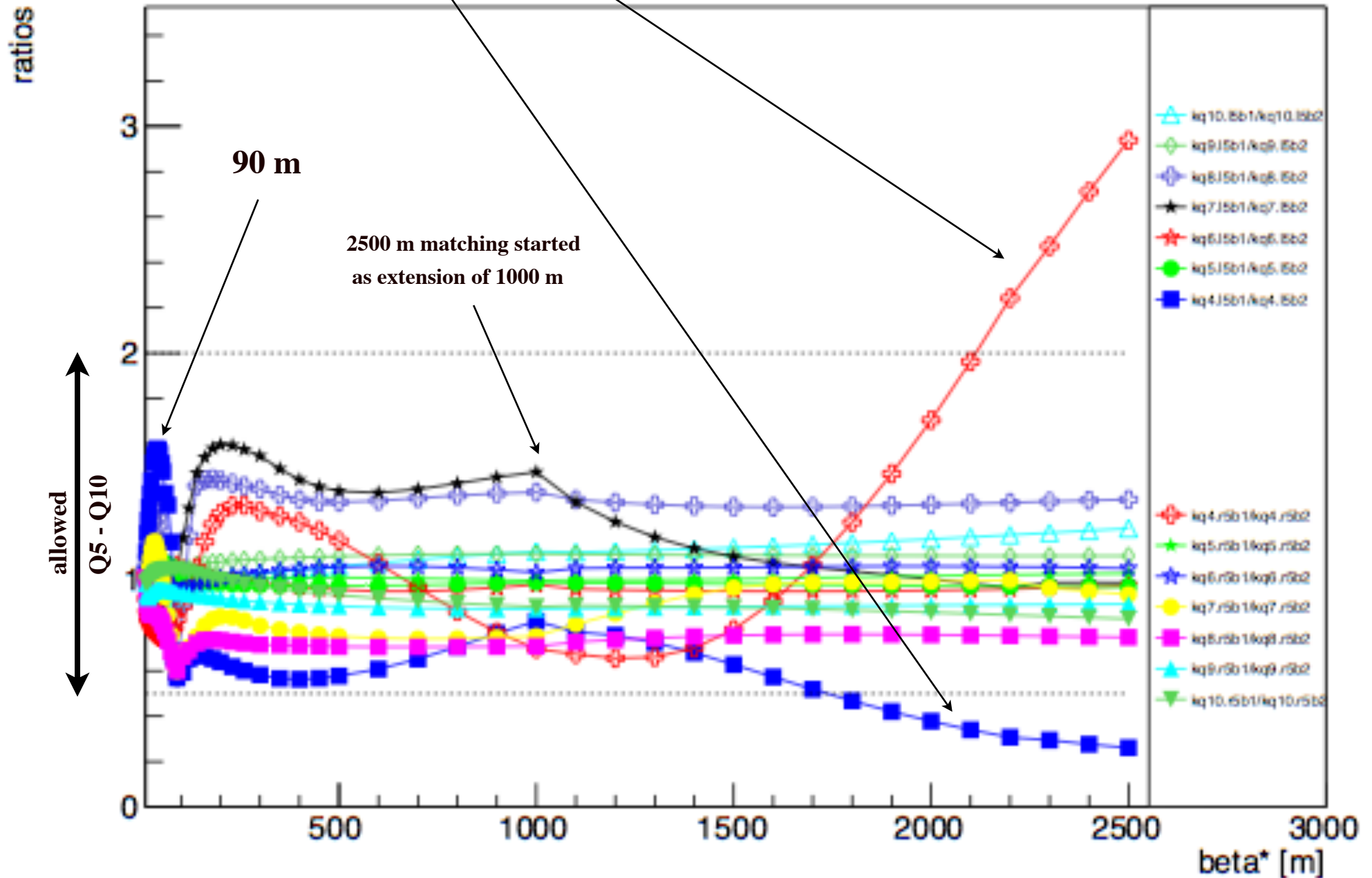
inserted during standard
commissioning during night
when no beam available

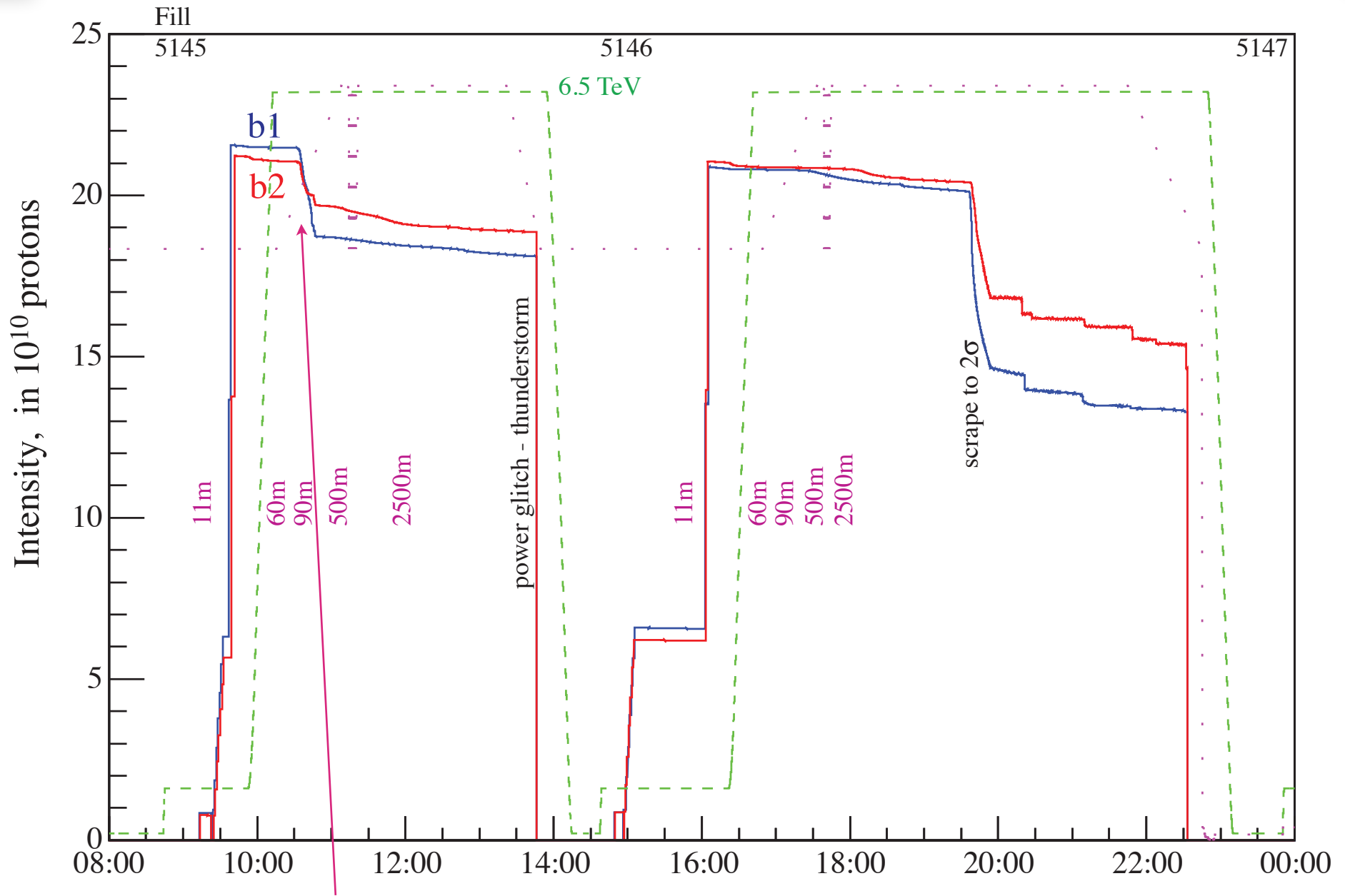
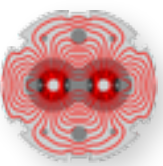


beam1 / beam 2 strength ratios



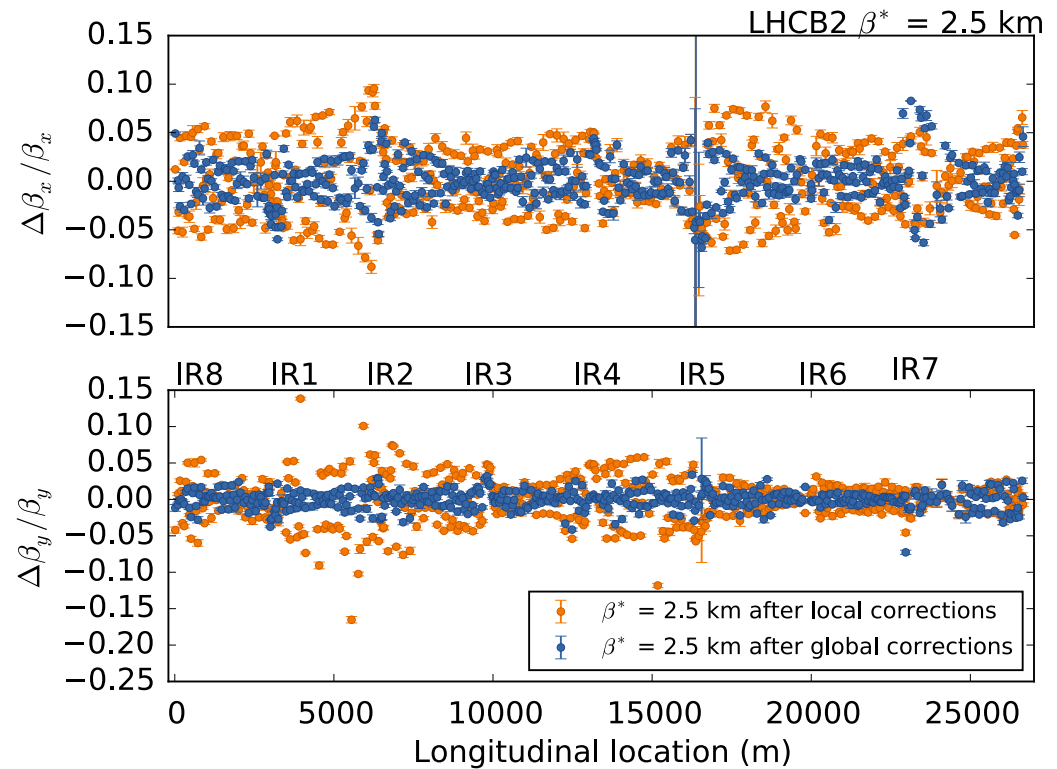
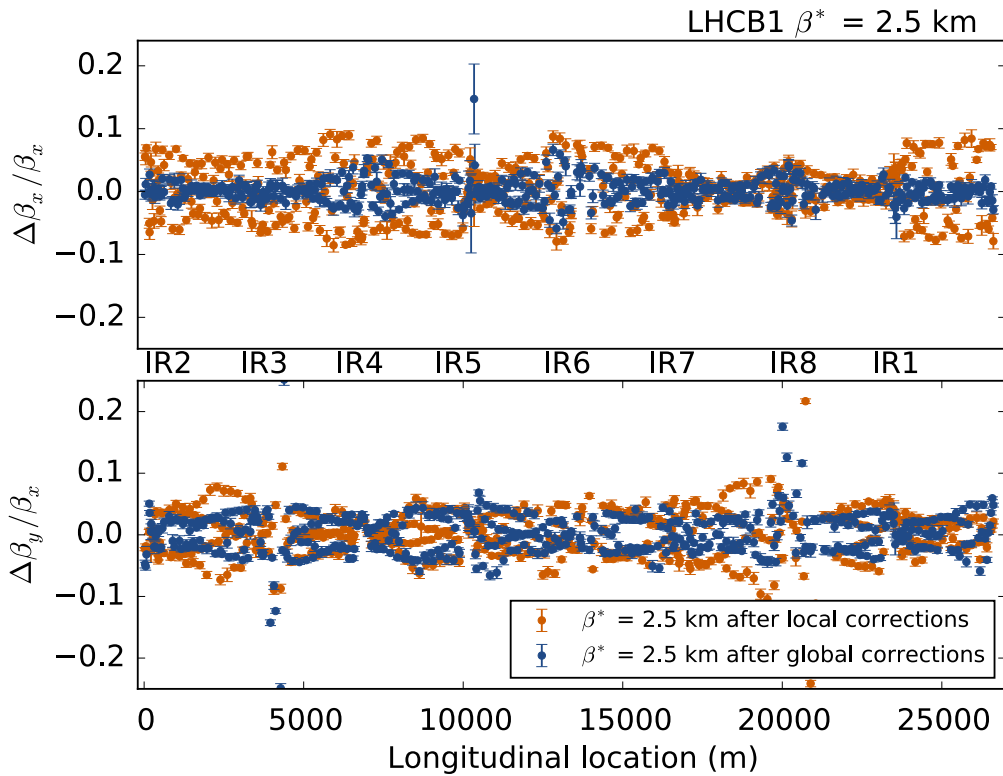
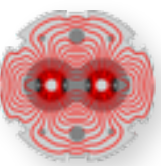
Q4 ratio < 0.5 > 2 now possible after cable installation



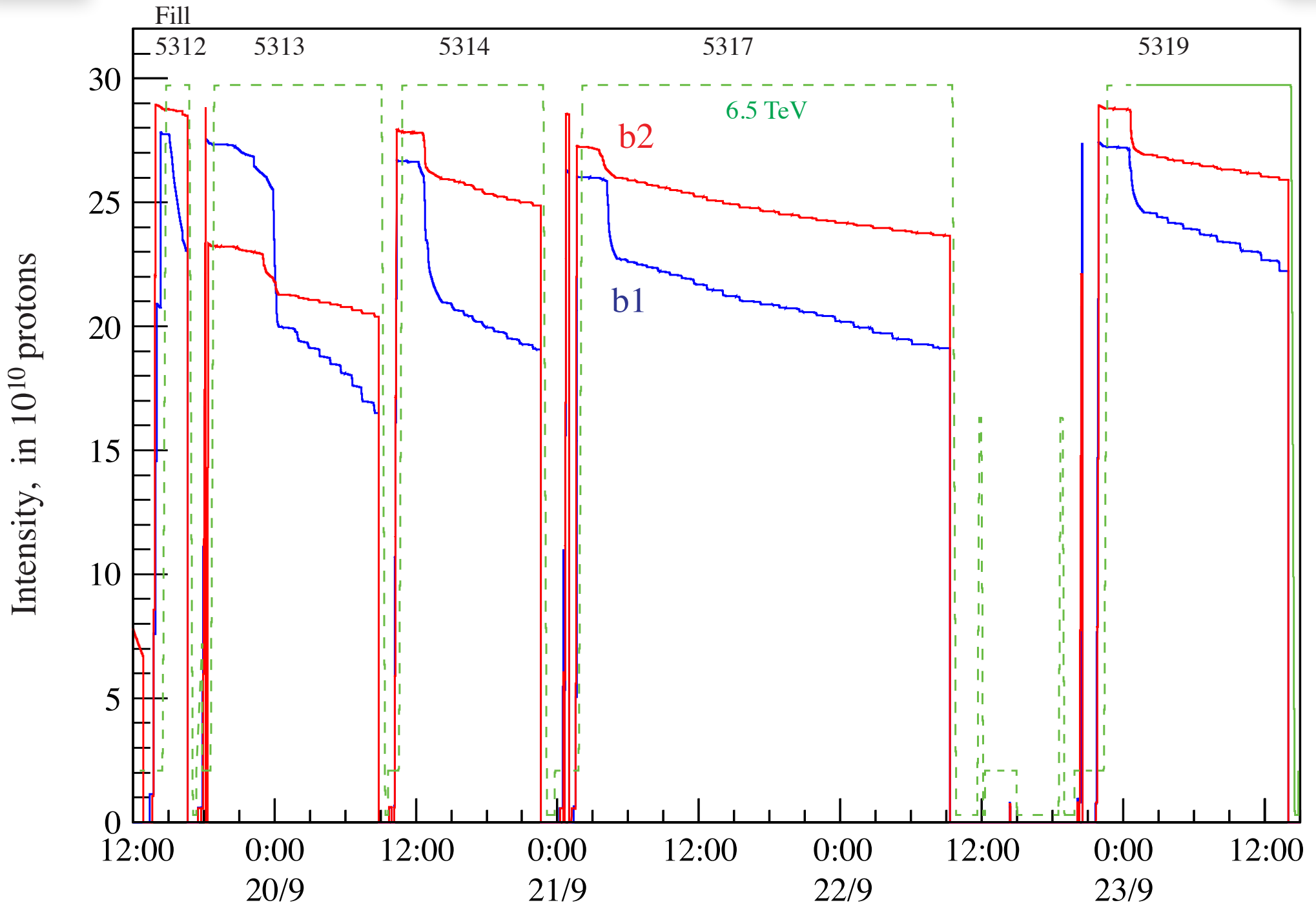
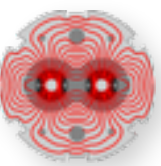


colliding from 90m, poor lifetime
injection tunes .27 / .295

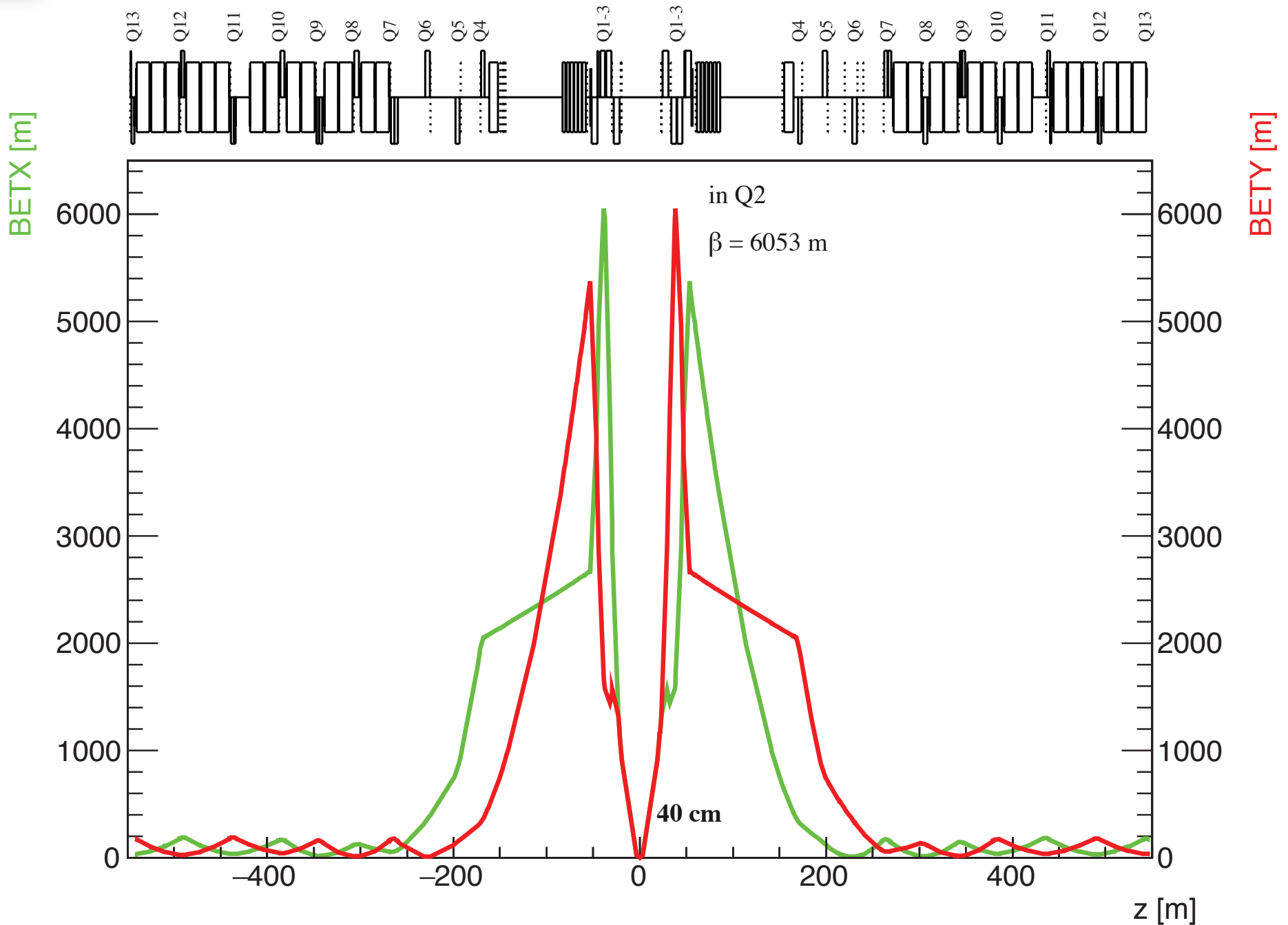
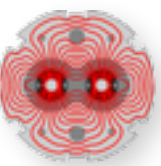
≥ 90 m, collision tunes 64.31, 59.32
reduced losses and blow up



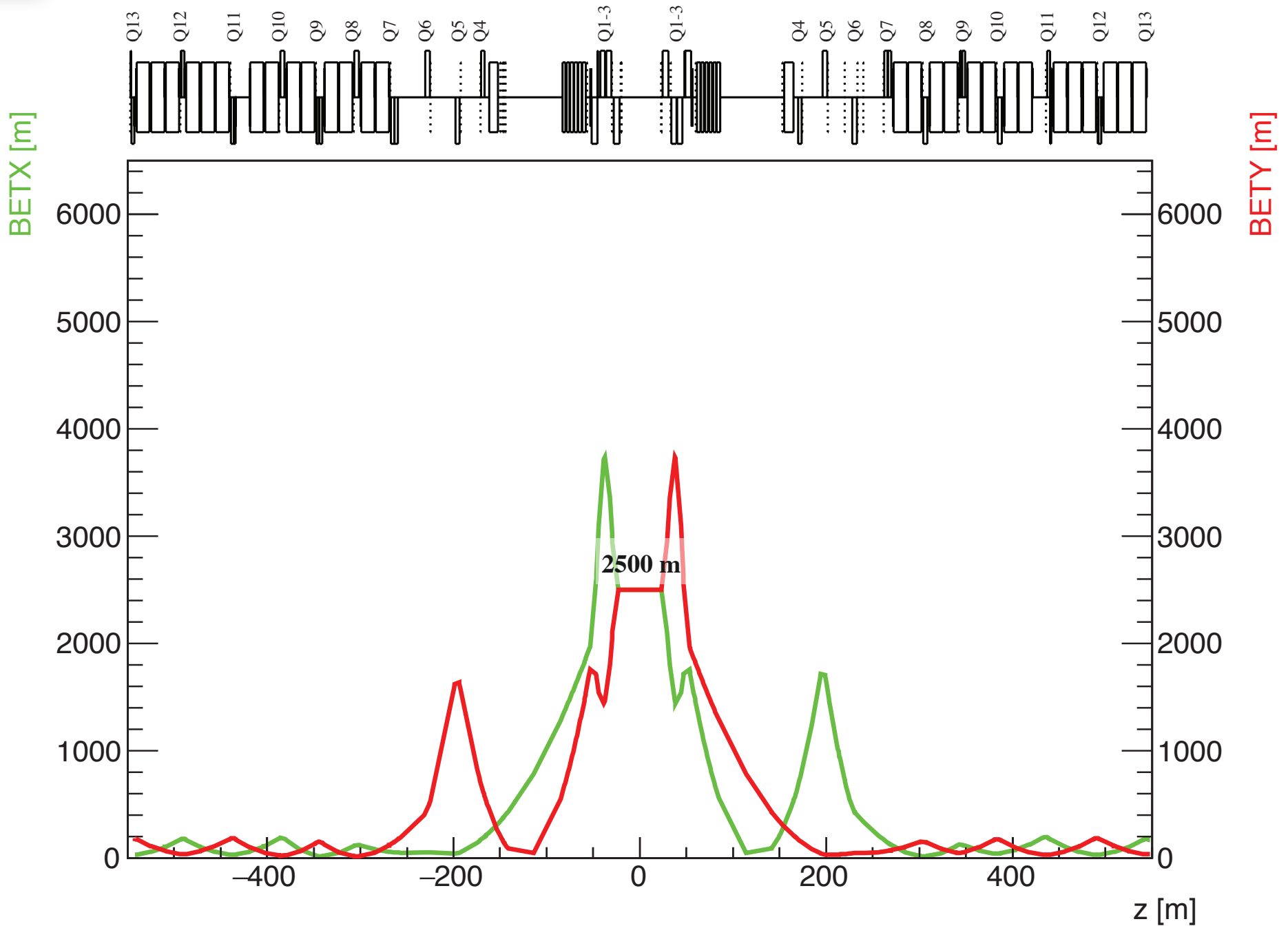
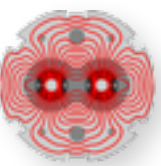
Being analyzed, ATS note by Ana Garcia-Tabares Valdivieso et al. in progress

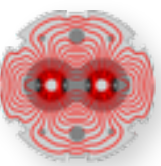


Low and very high- β on same scale

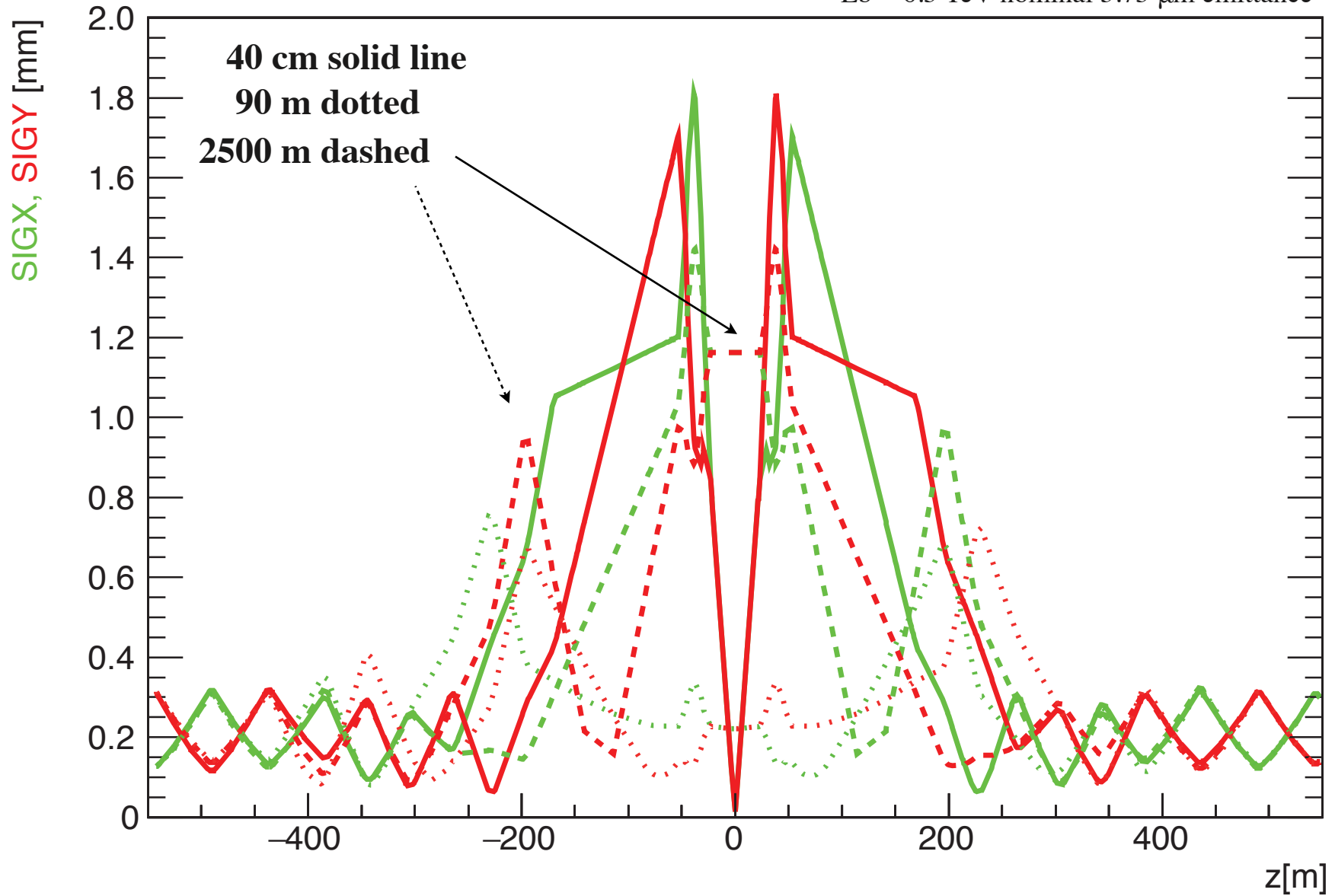


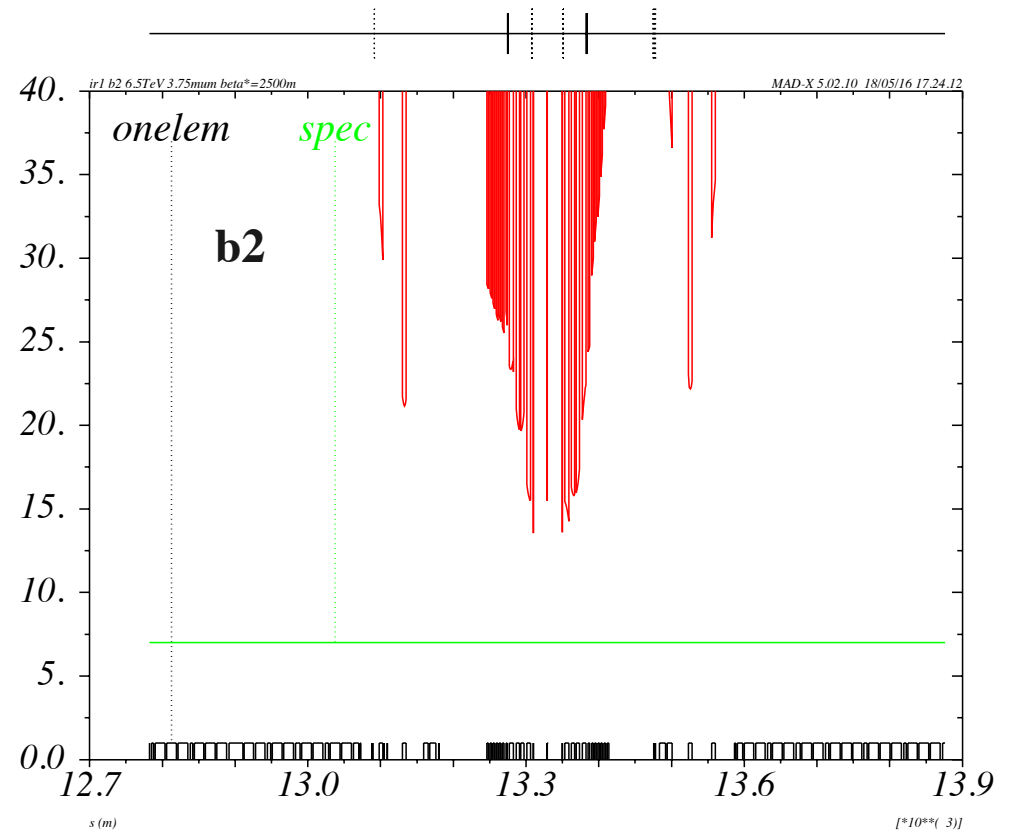
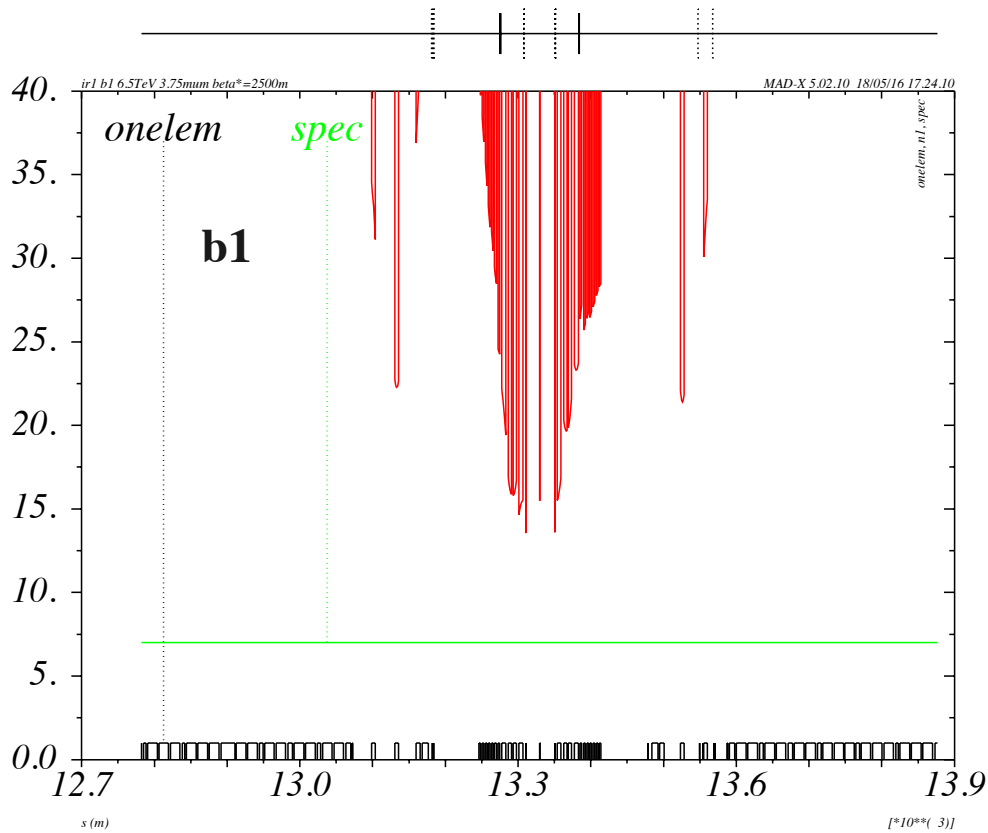
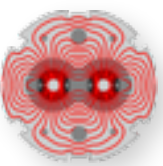
Low and **very high- β** on same scale





$E_b = 6.5 \text{ TeV}$ nominal $3.75 \mu\text{m}$ emittance

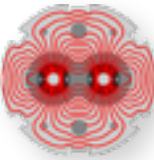




No separation, no crossing angle : beams big at IP, but well within physical aperture

inner beam pipe r = 23.5 mm

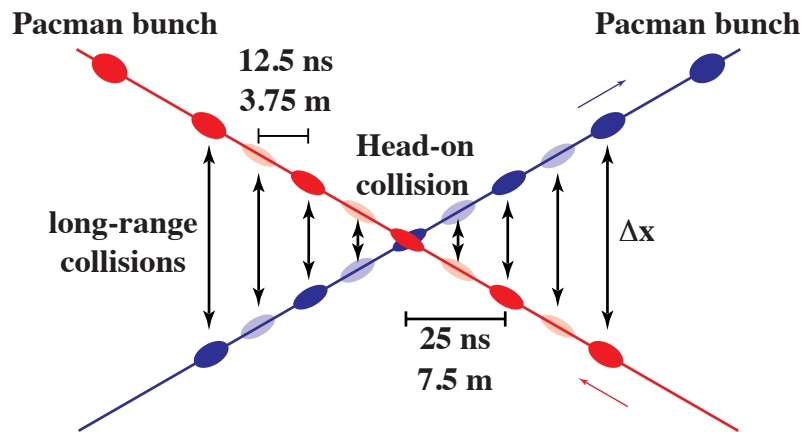
(nominal collimation) beam size for 3.5 μm normalized emittance $\sigma = 1.124$ mm



Low β^* ($< L^* \sim 25$ m)

- beam size and separation increase $\propto \Delta s$,
- \Rightarrow separation in units of σ about constant around IP
- all parasitic crossings adding up with similar contribution

V in IR1
H in IR5
for beam beam
and beam screen



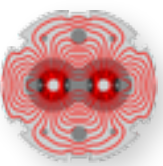
ns	sep in σ	nb max
25	2.4	2808
50	5.5	1404
75	8.3	936
100	11	702

90 m, 6.5 TeV, $\epsilon_N = 2 \mu\text{m}$

High β^*

- beam size \sim constant = σ^* , separation in σ increases as $\Phi \Delta s$
where Φ is the crossing angle, $\pm 50 \mu\text{rad}$ at high energy **limited by corrector strength**
- **dominated by 1st parasitic crossing**
- **75 ns not possible any more by injectors (RF)**
- **could try 50 ns for low emittance beams, but seem not ok for TOTEM / ALFA**

No crossing angle at very high- β (km) -- corrector strength + aperture limit

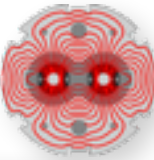


Optics / Aperture

**difficult, many coupled constraints -- β^* , phase advance to RP, time consuming
but have not yet reached fundamental limits in β^* and raw aperture (low emittance)**

Instead, getting close to rather fundamental limits relevant for the luminosity reach

beam-beam, IBS -->



High-beta implies lower luminosity, still running at limits in many respects including fundamental beam-dynamics limits (beam-beam, IBS, loss of Landau damping)

Independent of β^* and beam energy

$$\xi = -\frac{r_c N}{4\pi \epsilon_N} \quad \text{LHC design } -0.0037$$

Highest brightness & b.b. tune shifts in high- β !!

N	$\epsilon_N, [\mu\text{m}]$	ξ	
1.1×10^{11}	2×10^6	-0.00672	low β^* 2016 here
7×10^{10}	1×10^6	-0.00855	
6×10^{10}	0.7×10^6	-0.0107	

Max $\xi \sim 0.01$ (?) or $< 9 \times 10^{10}$ at $1 \mu\text{m}$

impact on beam very sensitive to imperfections, noise, minor tune changes

driving halo - repopulation and emittance blow-up

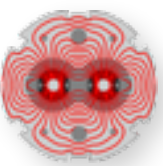
also non-negligible IBS --- mostly horizontal plane

at high β^* separation limited to few sigma by correctors

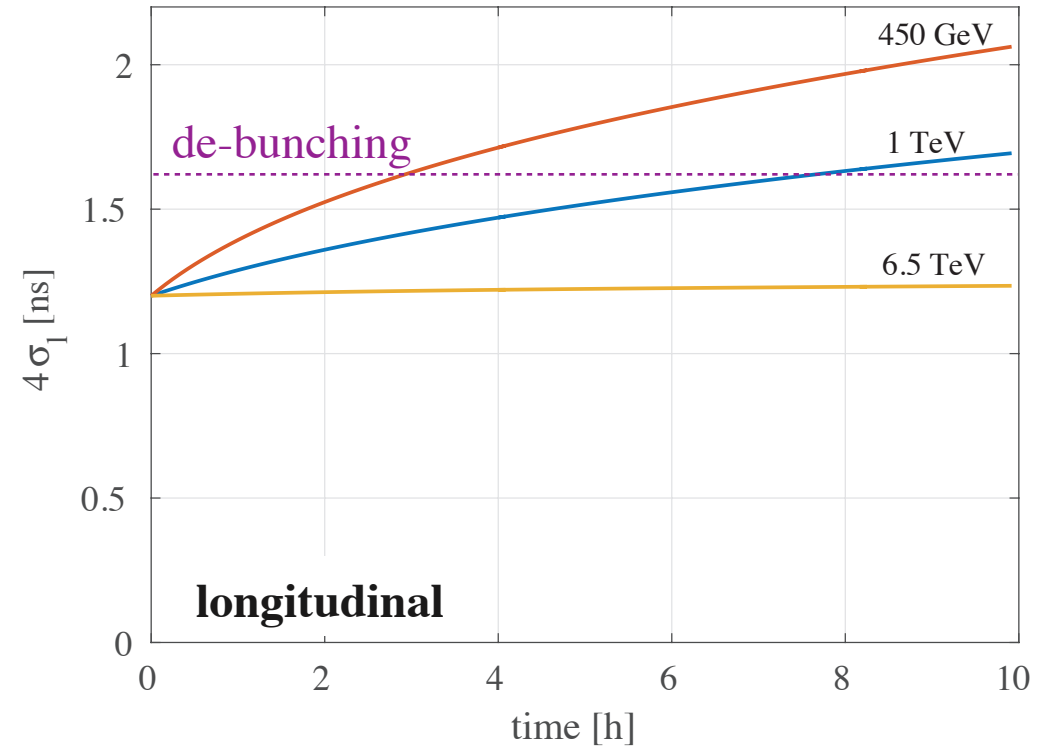
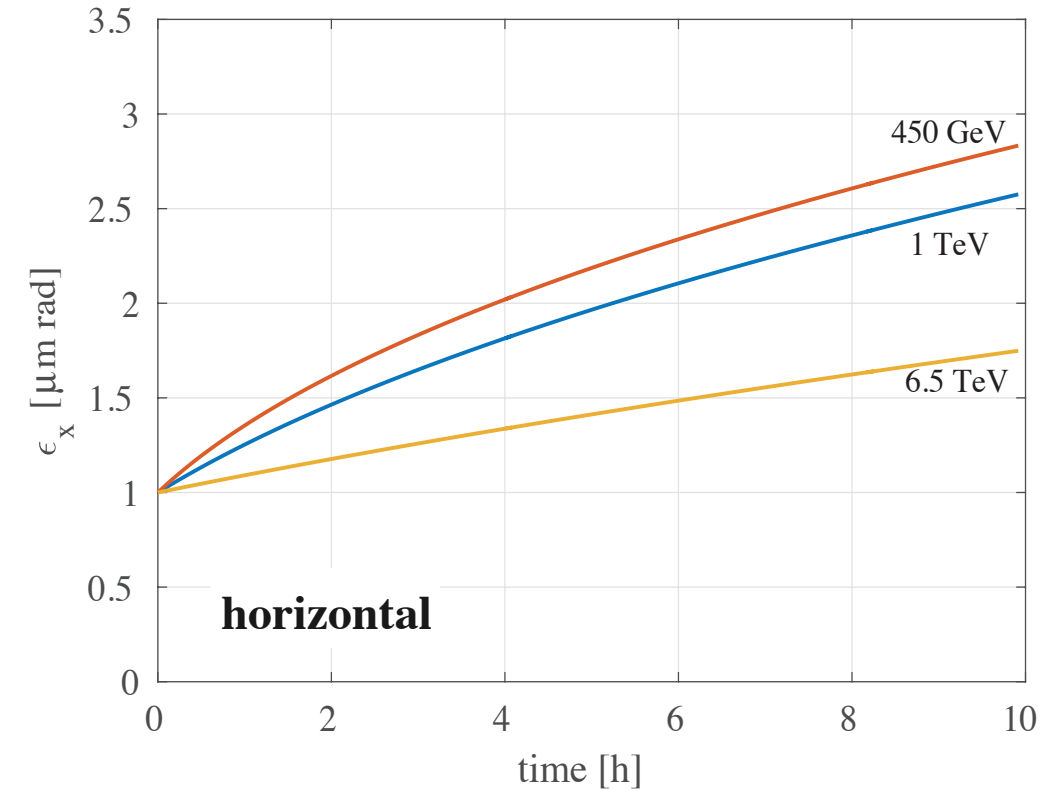
2.5 km, at the end better off to leave separation (3 - 4 mm total) during de-squeeze

separation off only just before physics at 2.5 km, used from fill 5313 on

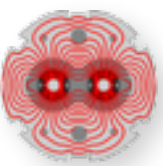
In 2016 : consistently more halo-repopulation / losses on beam 2 --- also seen standard low β operation



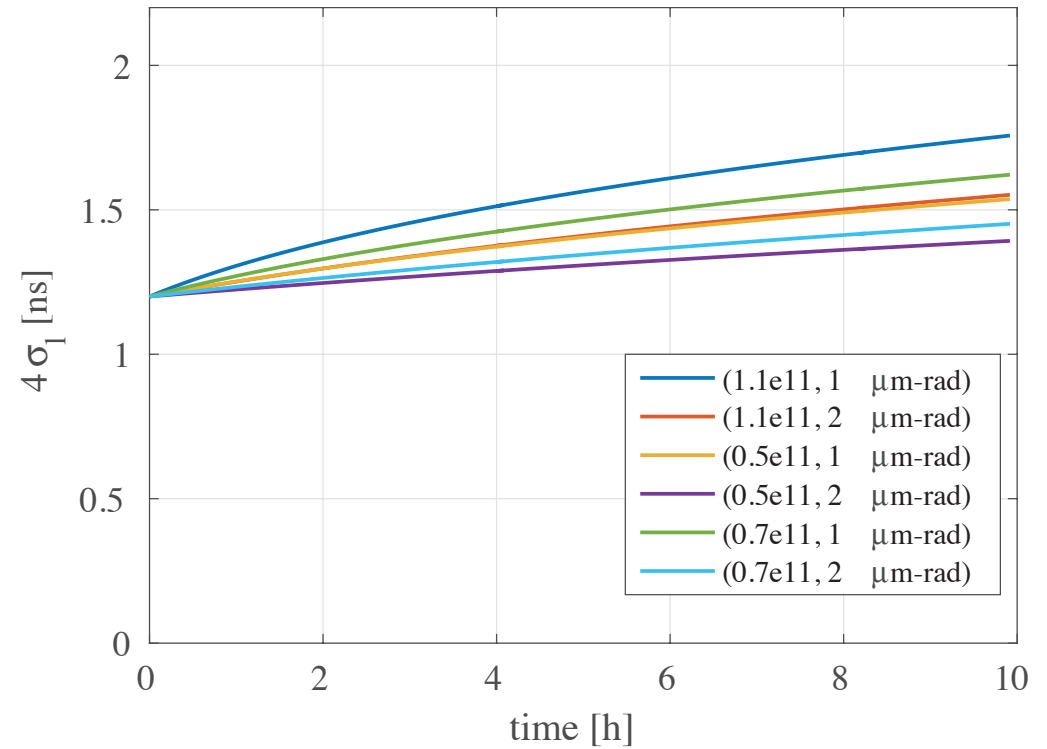
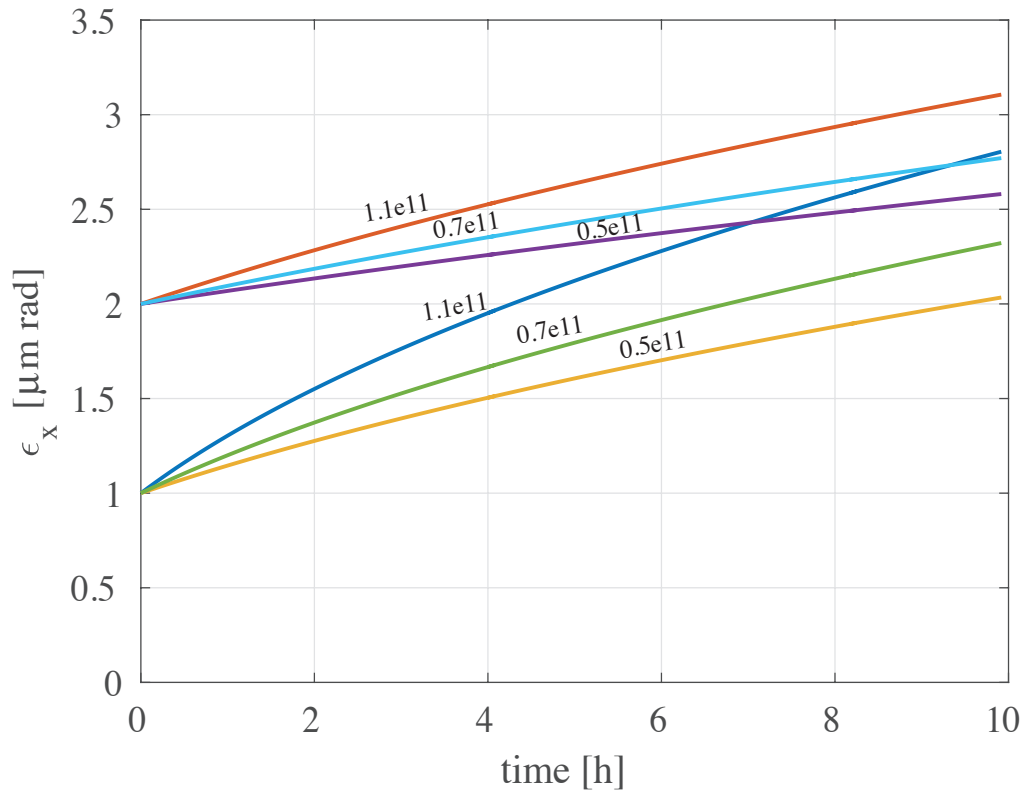
For $V_{RF} = 10$ MV, 9×10^{10} p / bunch



no growth in V (from IBS)

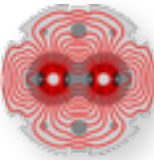


1 TeV beam energy, $V_{RF} = 10$ MV



Growth increases with brightness (more growth at higher luminosity)

Few % improved by full $V_{RF} = 16$ MV



High- β^* target to my knowledge to reach CI $t_{\min} = - 6.5 \times 10^{-4}$ GeV

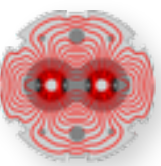
$$- t_{\min} = \frac{2 p n_{\sigma}^2 \epsilon_N m_p}{\beta^*}$$

i.e. linear scaling of β^* with beam energy

t scales with energy squared, normalized emittance with energy

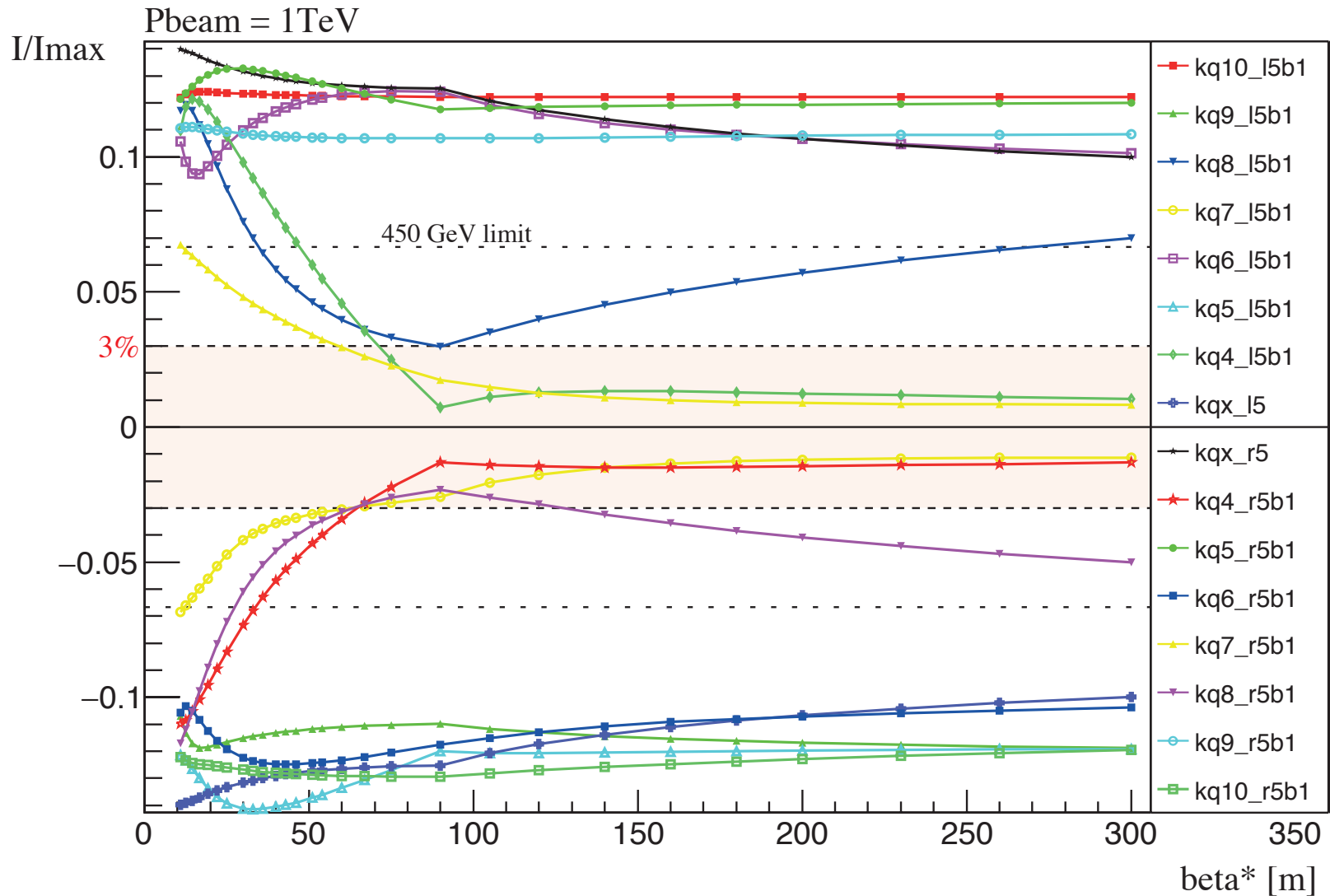
E_b [TeV]	$E_{\text{cms}} = 2 E_b$ [TeV]	β^* [m]
7	14	2690 m
6.5	13	2500 m
4	8	1540 m
2	4	770 m
1	2	380 m
0.45	0.9	170 m

High- β^* at lower energy ?

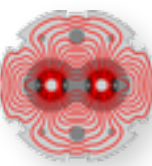


Quadrupole magnet powering, $I_{max} \sim 4000 - 6000$ A, I_{min} 3 % of I_{max}

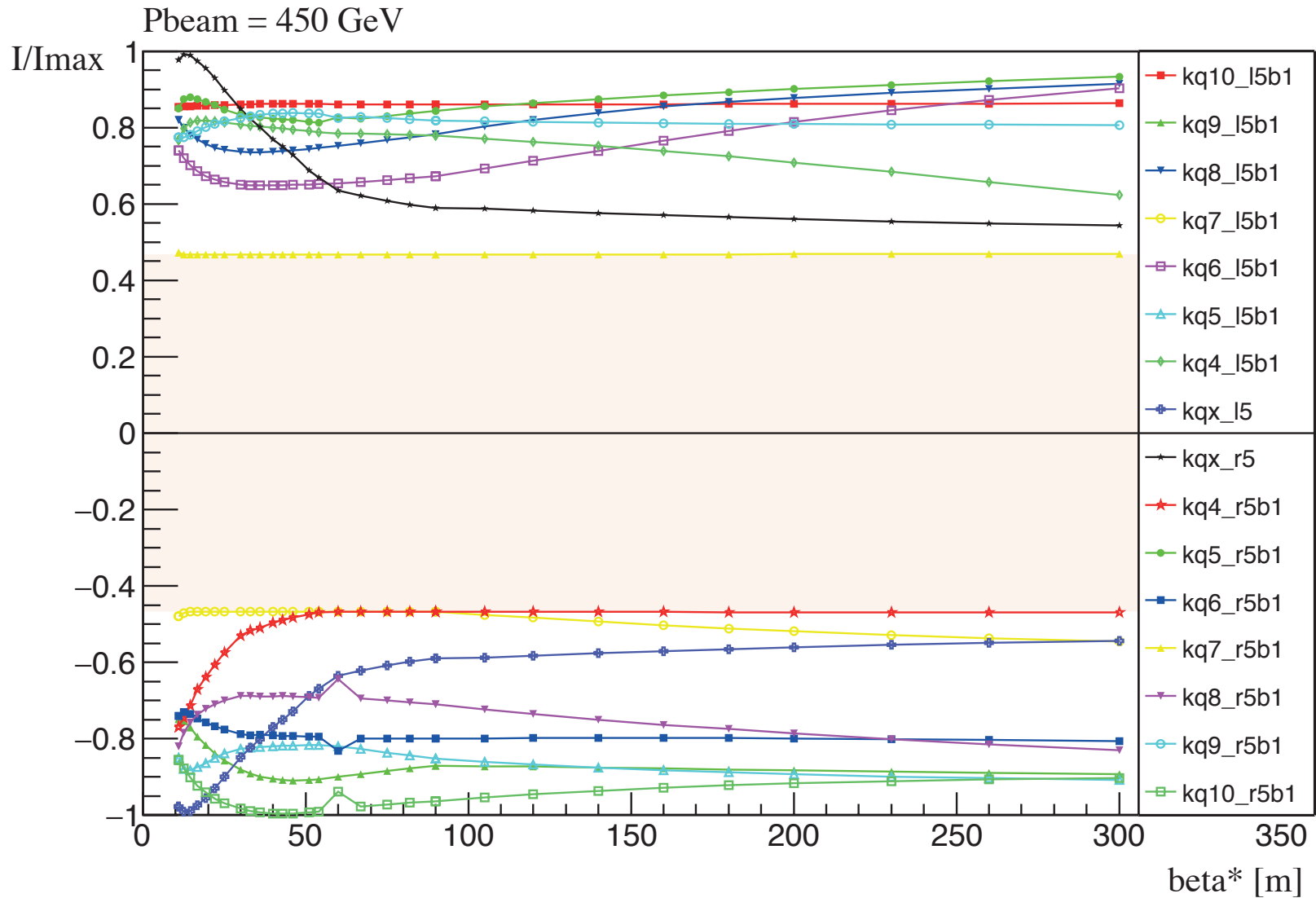
$$3\% \times 7000 / 450 = 47\% \text{ at injection energy}$$



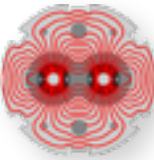
Current de-squeeze Q7, Q4, then Q6 hitting lower limits; $\beta^* < 50$ m at 1 TeV
 at 450 GeV Q7 already very close to lower limit --- **not compatible with low energy**



trial match for $\mu y = 90^\circ$ IP to Q6, for ≥ 90 m, L_y decreased from currently 290 m to 215 m @ 90 m



From optics / powering alone potential to go as high as $\beta^* \sim 500$ m even at injection energy



**Good experience in special high β runs for forward physics
and also with insertion of horizontal RPs to 15σ in standard physics**

Special runs --- setup time

**$\sim 2 \pm 1$ days with beam - in several pieces for anything new
significant fraction of a week**

also at ~ 90 m - less for optics -- more for protection due to higher intensity

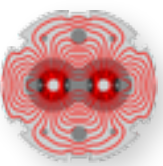
We learned a lot and got already very far 2.5 km this year

well beyond the original TOTEM request of 1535 m with reduced more restricted powering
but there is still potential room to push further

- **higher β^* at top energy**
- **high β^* at low energy**
- **higher luminosity at intermediate β^* 25 - 90 m**
- **increase local dispersion IP - RPs, bumps at 90 m and to some extent in standard physics**

Lengthy preparation --- important to set priorities and plan well in advance

Backup



$9. \times 10^{10}$, 1 μm , head-on, linear decrease with energy

L per crossing

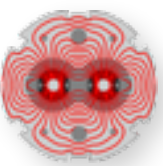
90 m :	$8.6 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$	$\sigma = 0.29 \text{ mm}$
300 m :	$2.6 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$	$\sigma = 0.53 \text{ mm}$
400 m :	$1.9 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$	$\sigma = 0.61 \text{ mm}$

Number of bunches

nb = 3 safe beams -- tight scraping ; maybe bit more due to lower energy ?

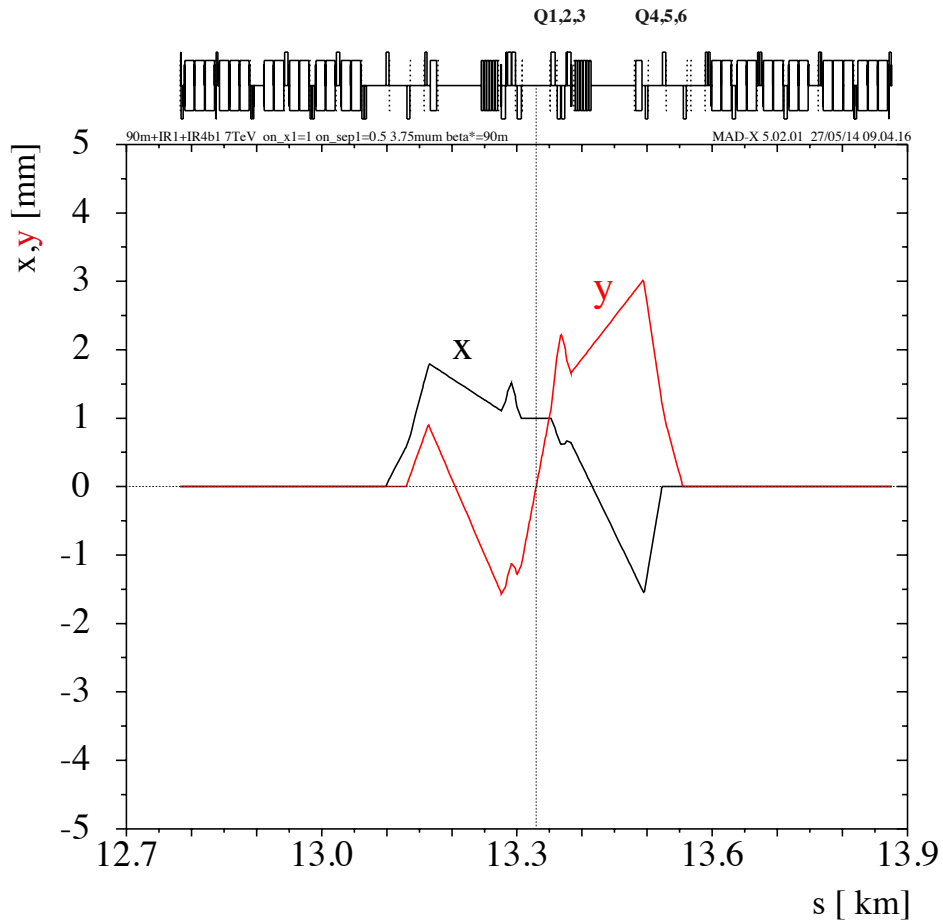
nb = 100 full collimation hierarchy, protection setup

no crossing angle - aperture (to be checked)



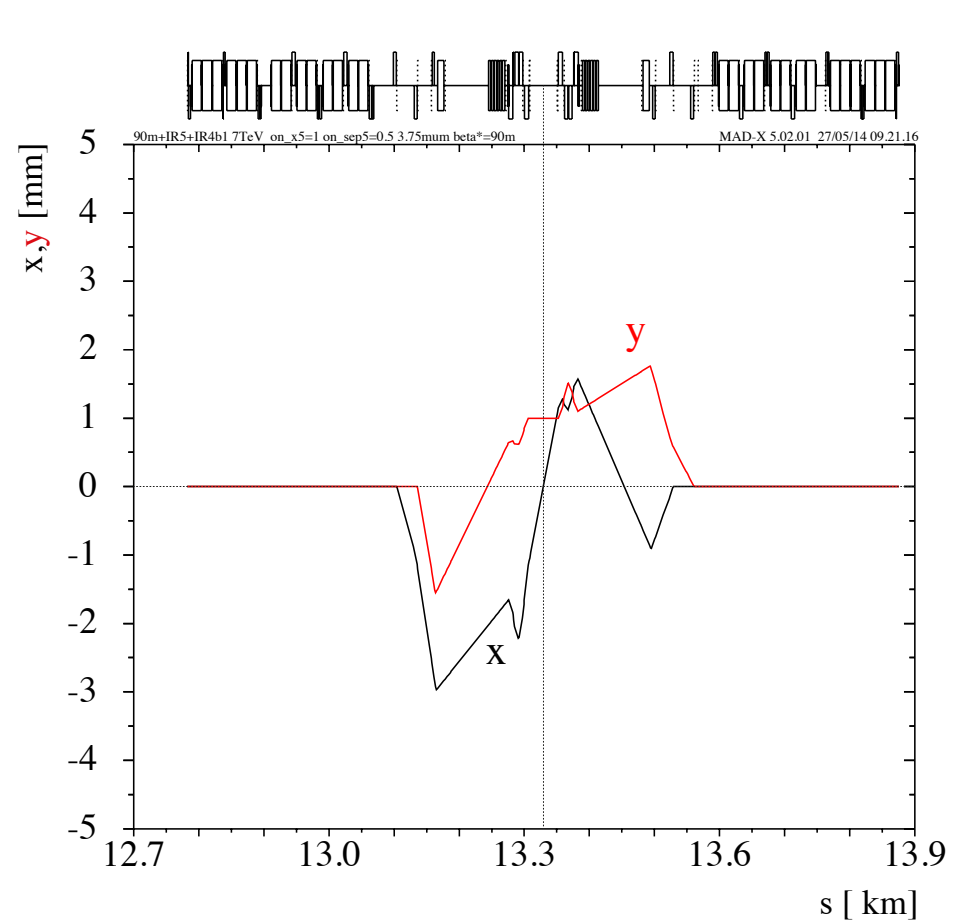
IR1, ATLAS

Vertical crossing

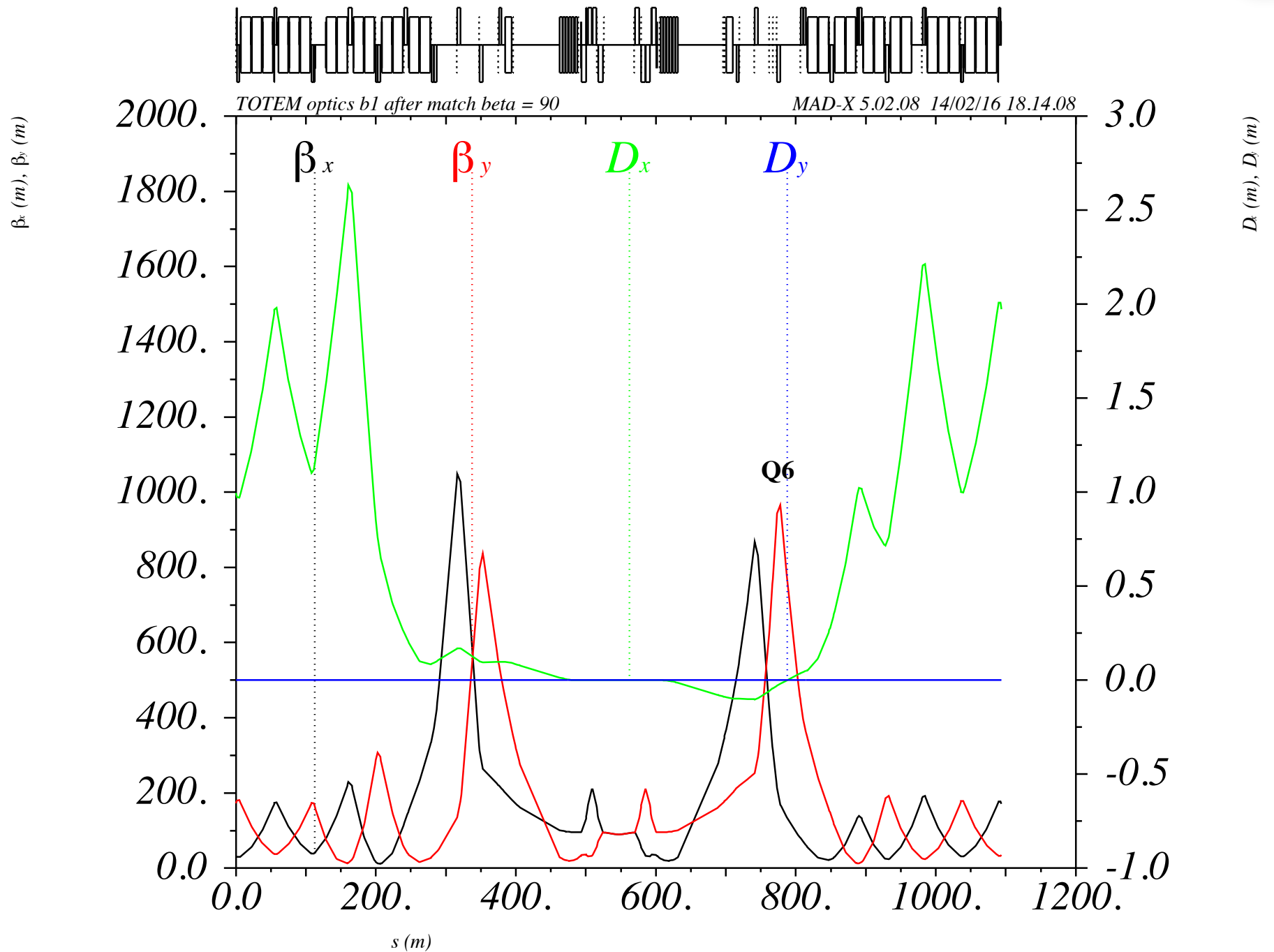
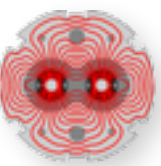


IR5, CMS-TOTEM

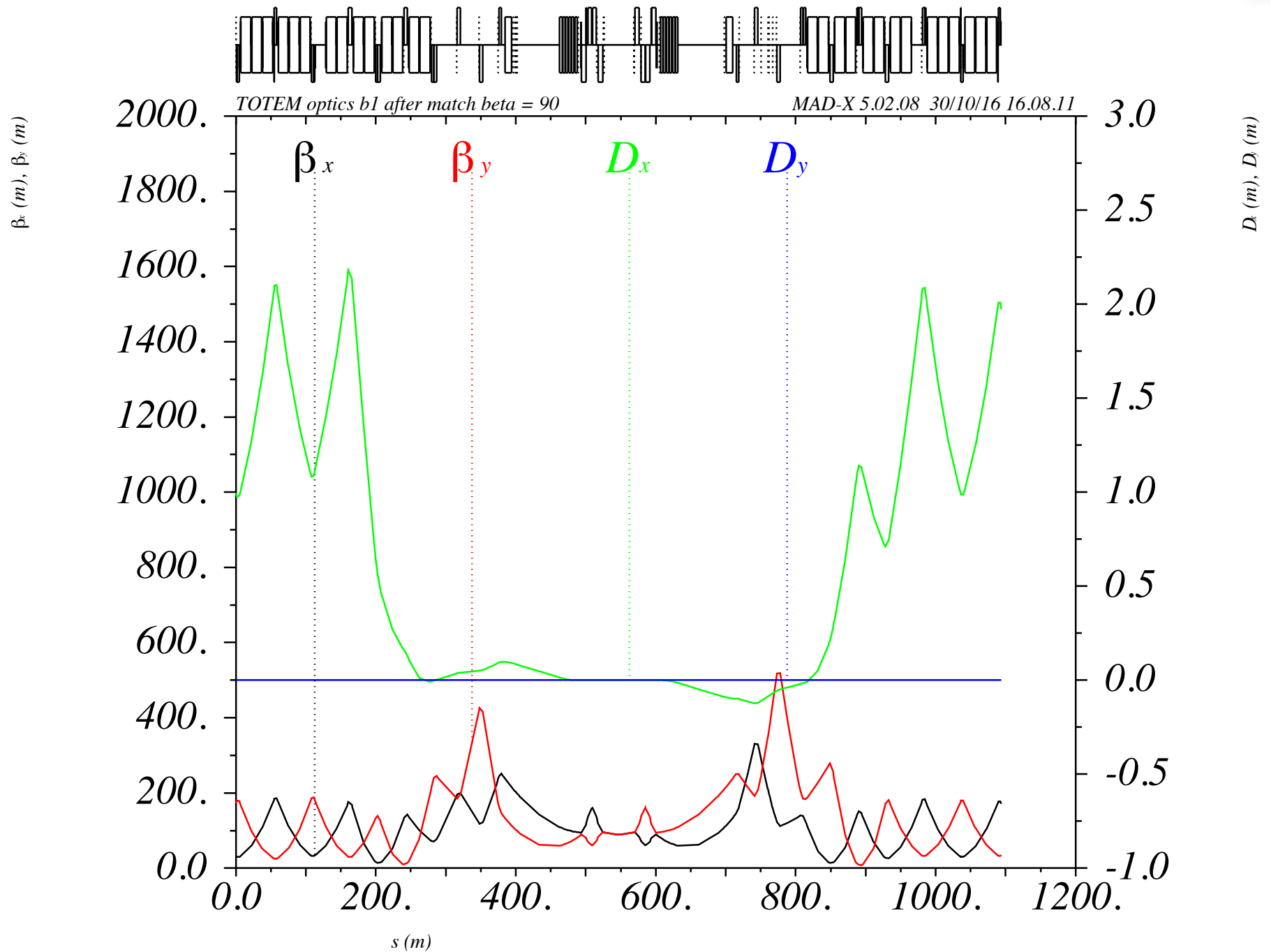
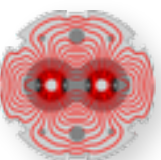
Horizontal crossing

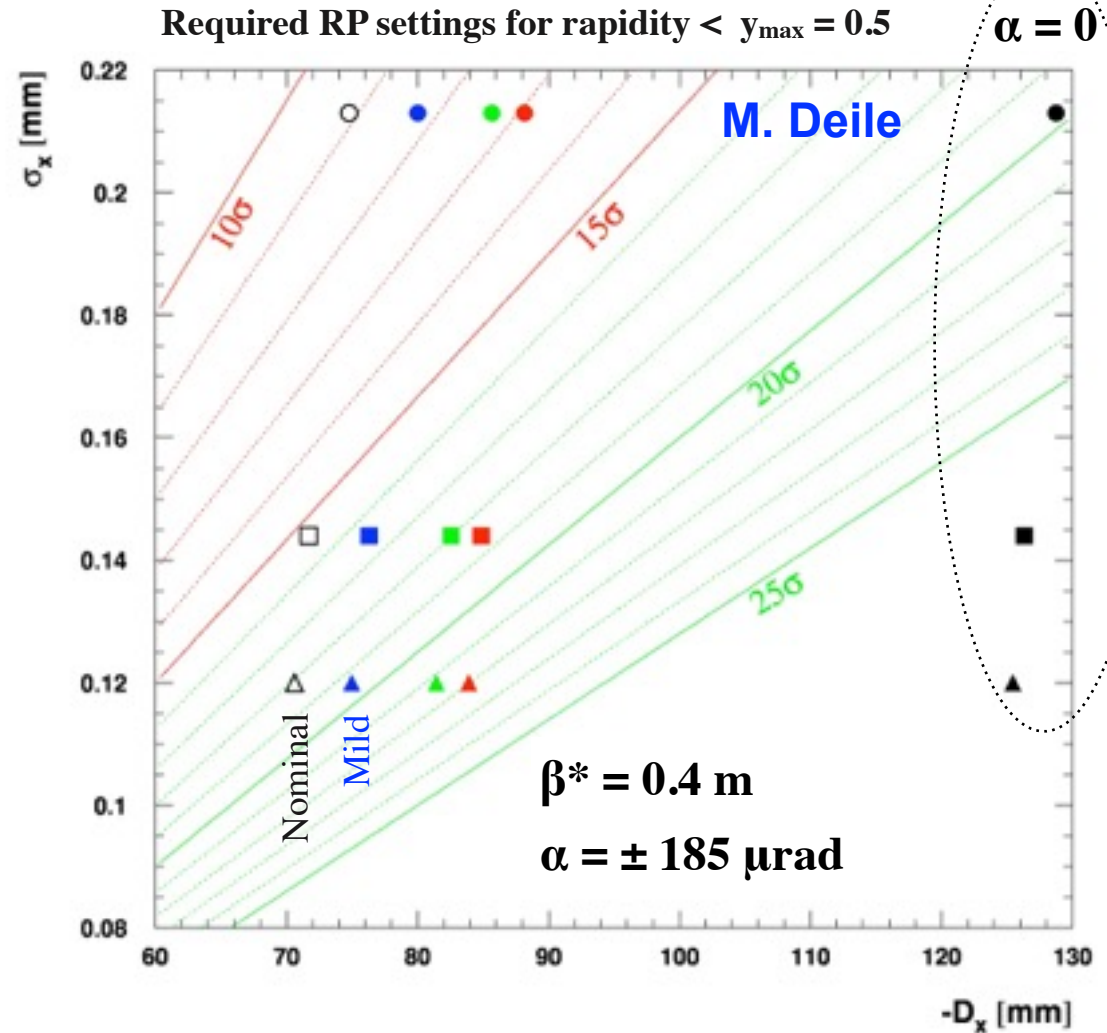
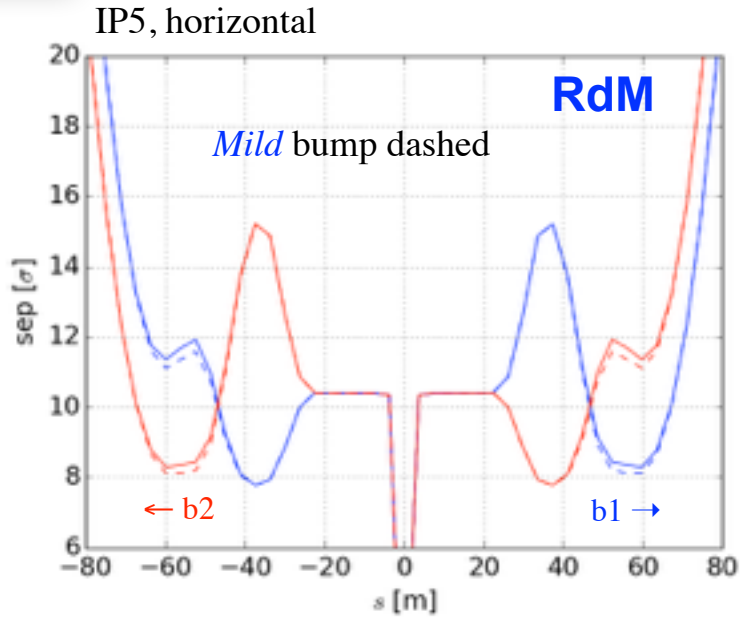
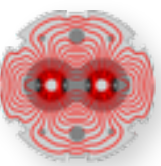


Shown for ± 1 mm separation (initial de-squeeze)
 ± 50 μ rad (half) crossing angle



90 m, rematch test for injection energy





Shifted, more extended
crossing bumps

Mild

Intermediate

Aggressive

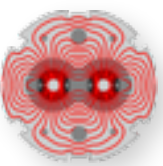
- ● 210-N
- ■ 210-F
- △ ▲ 220-C

[LMC#257](#) 6/4/2016, with presentations by Massimo Giovannozzi + Stefano Redaelli
decision to use *Mild*, 2/3 RPs in acceptance

RPs at 15 σ with initial 0.5 mm margin - now removed



$$\beta^* = 90 \text{ m}$$



Physics runs with $\beta^* = 90 \text{ m}$ in IP1 & IP5 were requested and scheduled in

2011 2x3.5 = 7 TeV 2 colliding bunches

2012 2x4 = 8 TeV 112 bunches

2015 2x6.5 = 13 TeV 671 bunches, 50 μrad crossing angle (\sim max at this β)

0.74 pb⁻¹ in 35h over \sim 3 days

Special runs. 90 m optics optimized for :

90° vertical phase advance IP to Roman Pots, 220 m for TOTEM, 240 m for ALFA

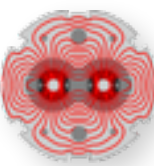
large “effective” length $L_y = r_{3,4} \sim 290 \text{ m}$

and originally also 180° in horizontal plane, close to what one naturally gets IP - RP

This year, 2016 : 90 m “physics” optics kept as intermediate point on the way to 2500 m

+ minimization of time needed in de-squeeze by

combined ramp & de-squeeze to 60 m, and smoothing with insertion of extra 82 m point



the β -function in a field free region has a form of a parabola with

$$\beta(s) = \beta^* + \frac{(s - s_0)^2}{\beta^*}$$

the beam size of a beam of emittance ϵ in a dispersion free region is

$$\sigma = \sqrt{\beta \epsilon}$$

and the angular beam size divergence

$$\sigma' = \sqrt{\frac{\epsilon}{\beta}}$$

the beam size increases about linearly from the IP to the first quadrupole, by a factor s / β^* (for $s \gg \beta^*$)

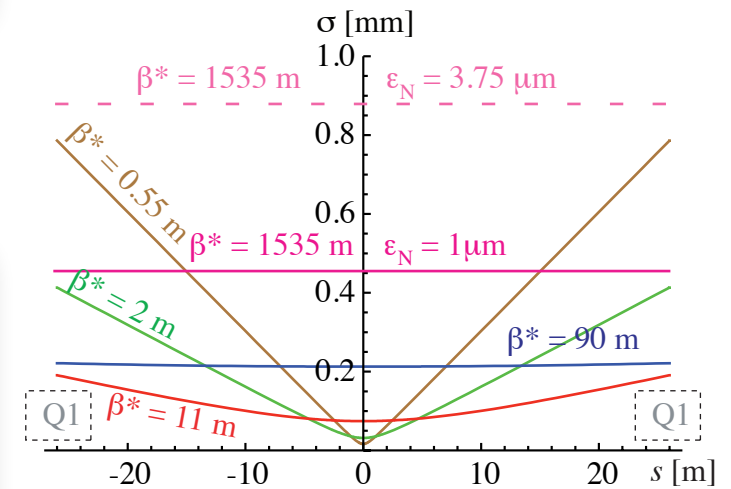
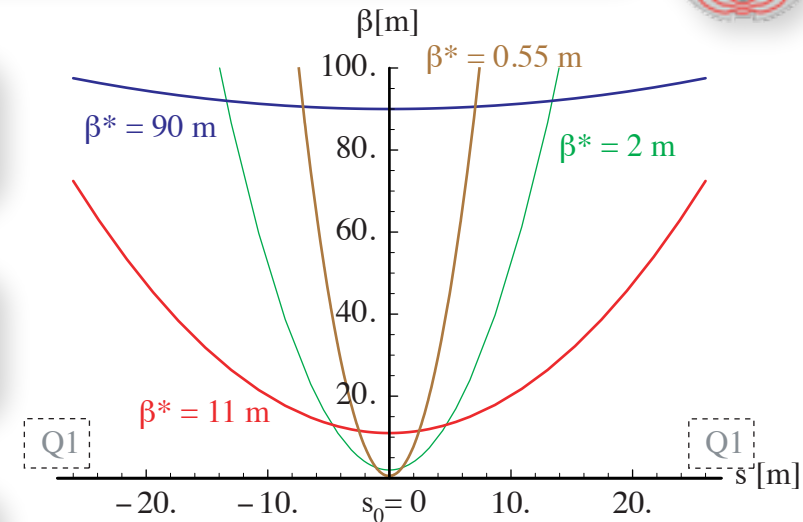
--> aperture limit for low β^*

LHC triplet aperture currently $r = 70$ mm

(50 mm with screen)

~ doubled for HiLumi

Central beam pipe CMS $r = 21.7$ mm



for the nominal emittance
 $\epsilon_N = 3.75 \mu\text{m}$, $\epsilon_N = \epsilon \beta \gamma$
 $\epsilon = 0.503 \text{ nm}$ at 7 TeV

