The LHC: Status and Performance

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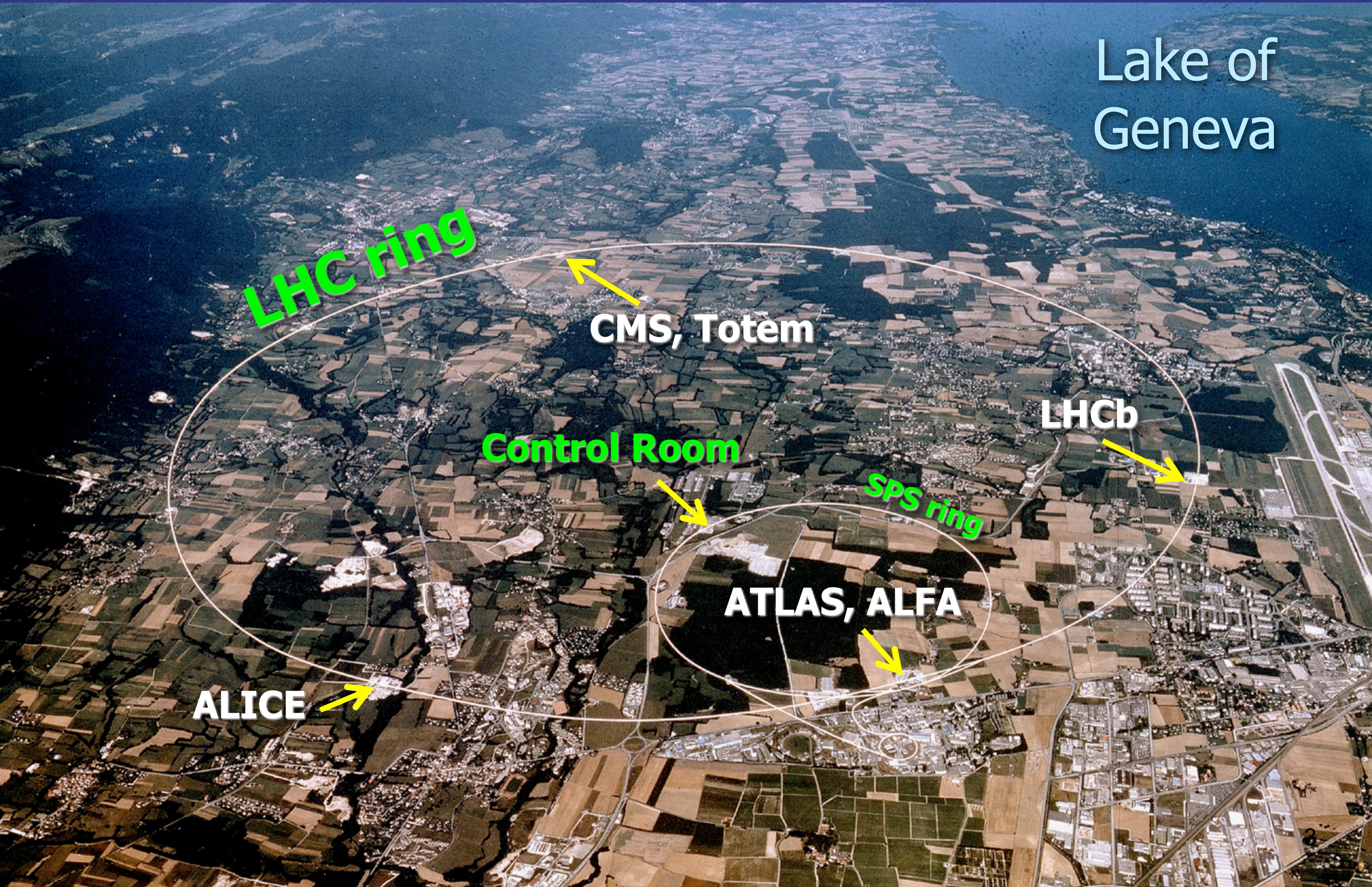
Introduction

- Introduction to the LHC
- LHC performance to date
- What holds us back
  - Electron Cloud
  - Beam Induced Heating
  - UFOs
  - Implications of Radiation to Electronics and single event upsets
- Outlook: where we think we improve (2011 & 2012)

The LHC: Installed in 26.7 km LEP tunnel

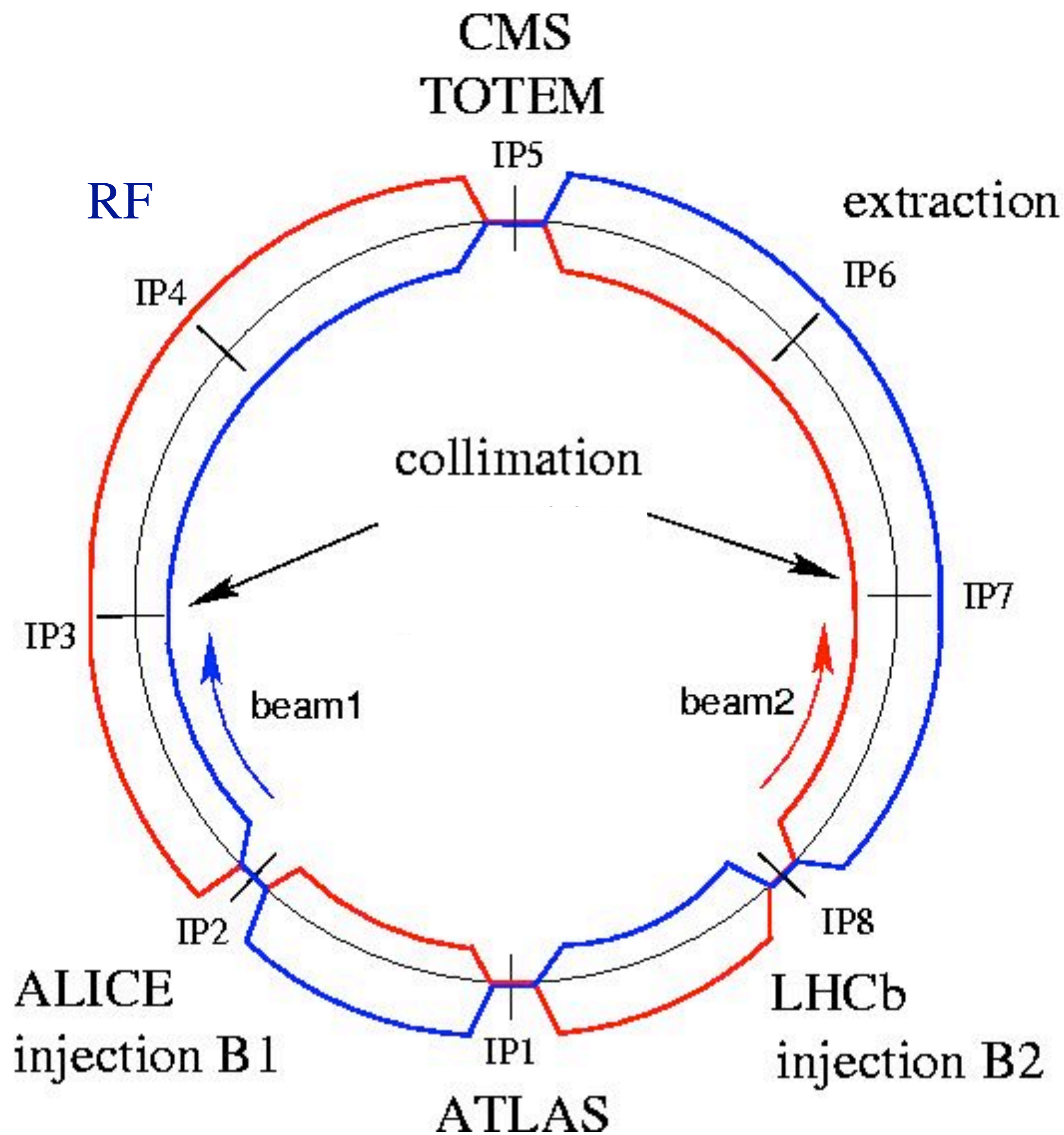
Depth of 70-140 m



LHC layout and parameters

- 8 arcs (sectors), ~3 km each
- 8 long straight sections (700 m each)
- beams cross in **4 points**
- 2-in-1 magnet design with separate vacuum chambers → *p-p* collisions

Nominal LHC parameters	
Beam energy (TeV)	7.0
No. of particles per bunch	1.15×10^{11}
No. of bunches per beam	2808
Stored beam energy (MJ)	362
Transverse emittance (μm)	3.75
Bunch length (cm)	7.6



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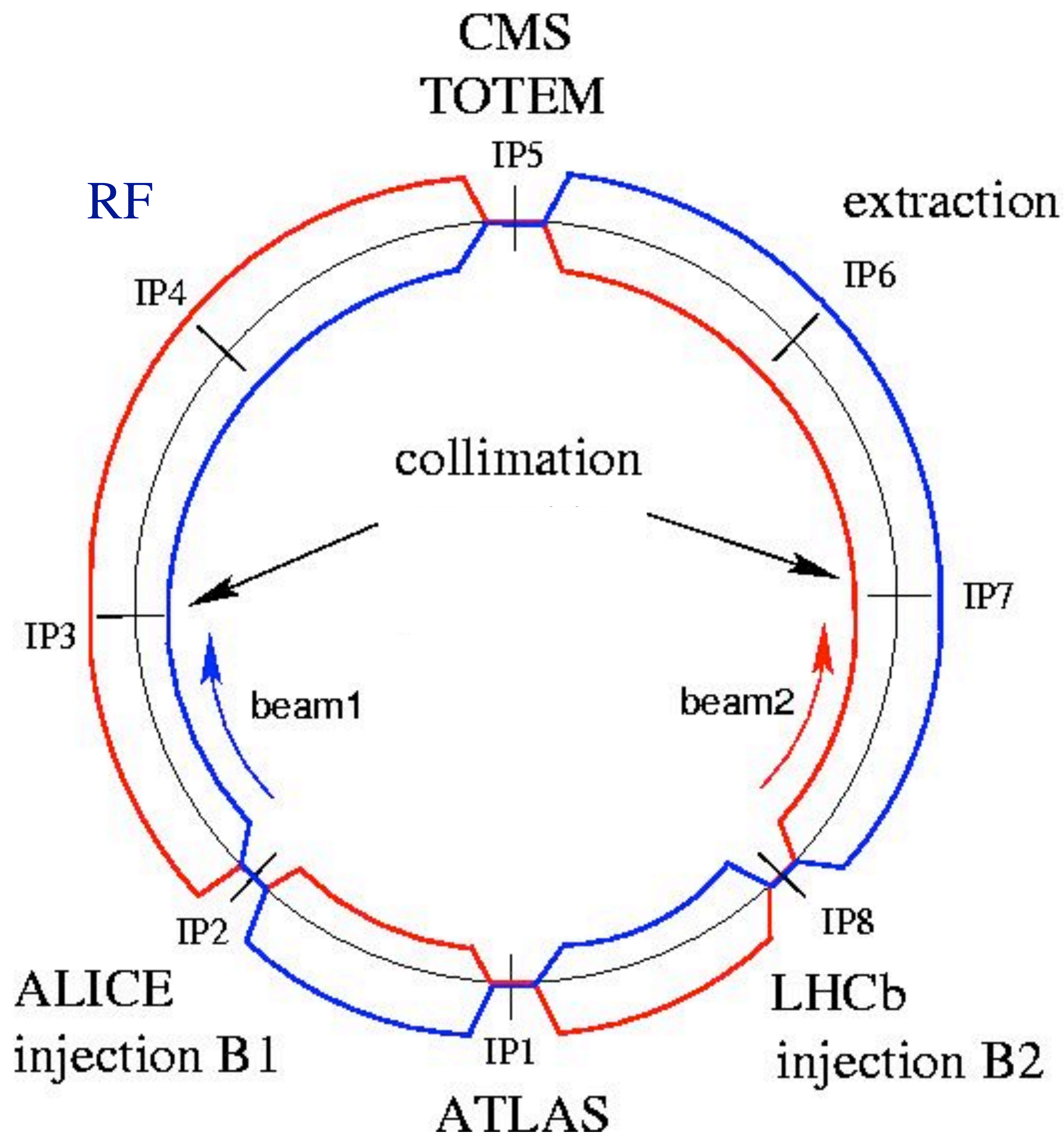
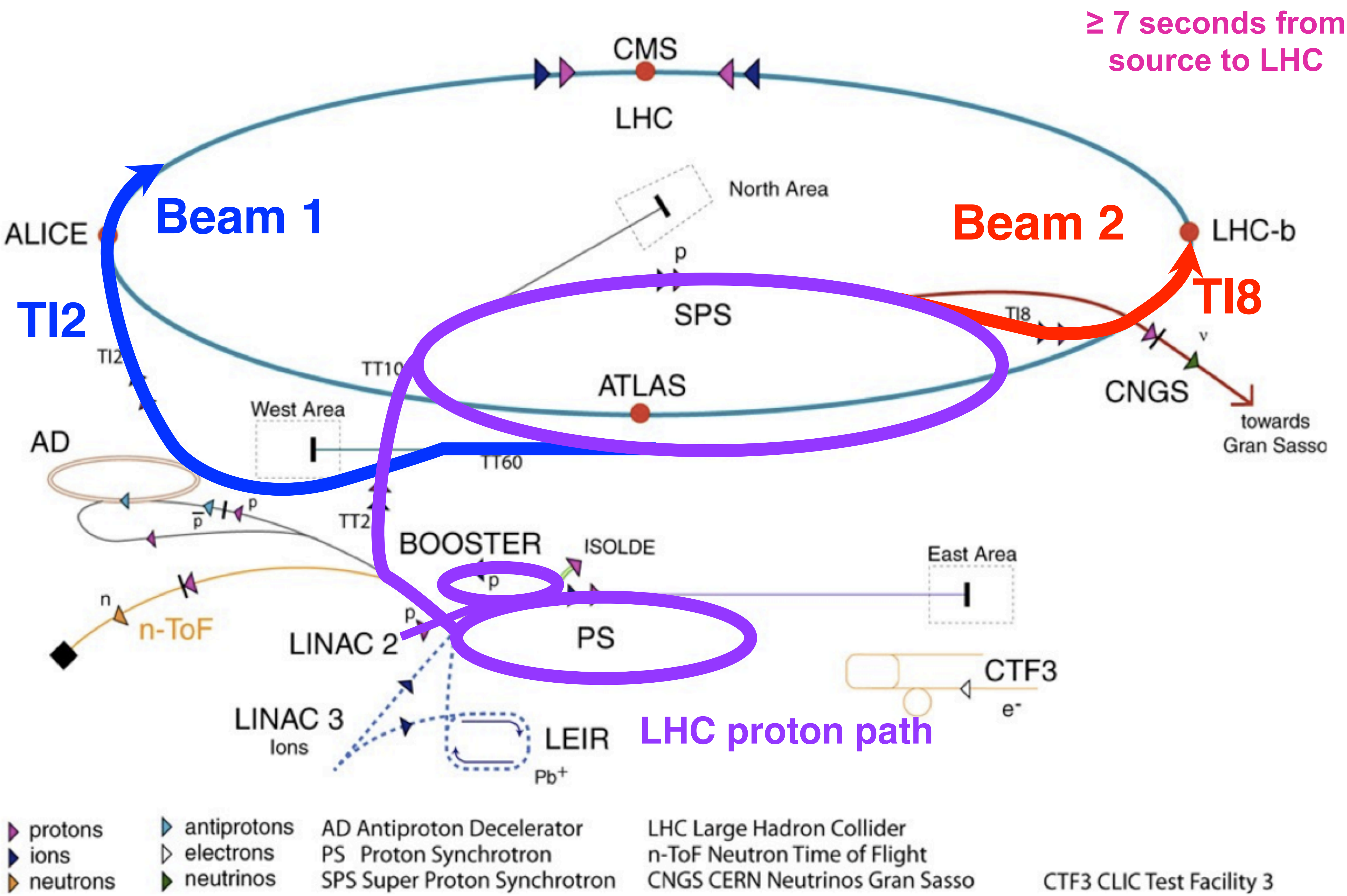
β^* = 0.55 m (beam size =17 μm)

Crossing angle = 285 μrad

$L = 10^{34}$ cm^{-2} s^{-1}



LHC accelerator complex



The LHC needs most of the CERN accelerators...

Tunnel View

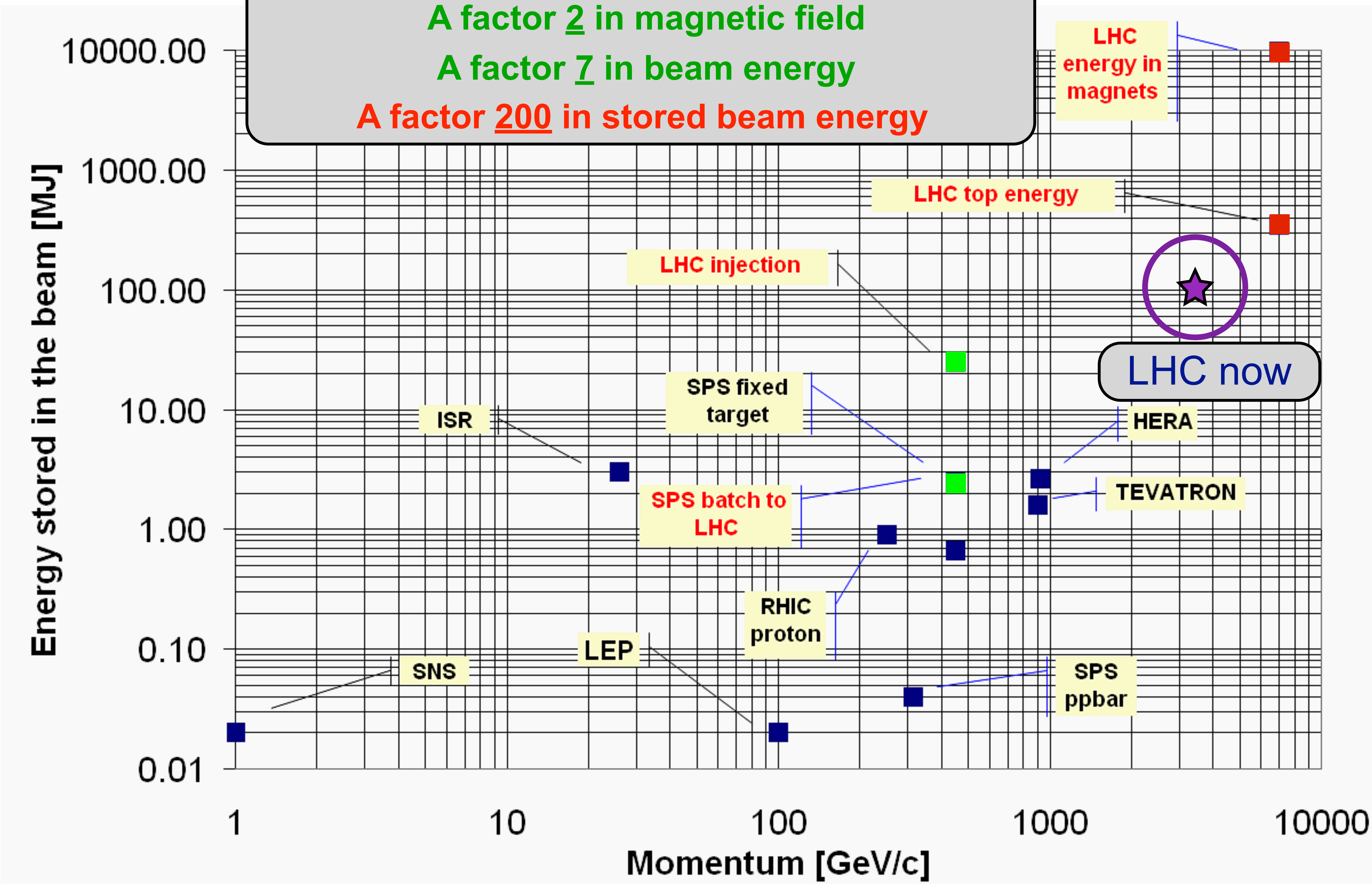
Stored Energy

Increase with respect to existing accelerators :

A factor 2 in magnetic field

A factor 7 in beam energy

A factor 200 in stored beam energy



Energy: Damage potential ... setting the scale

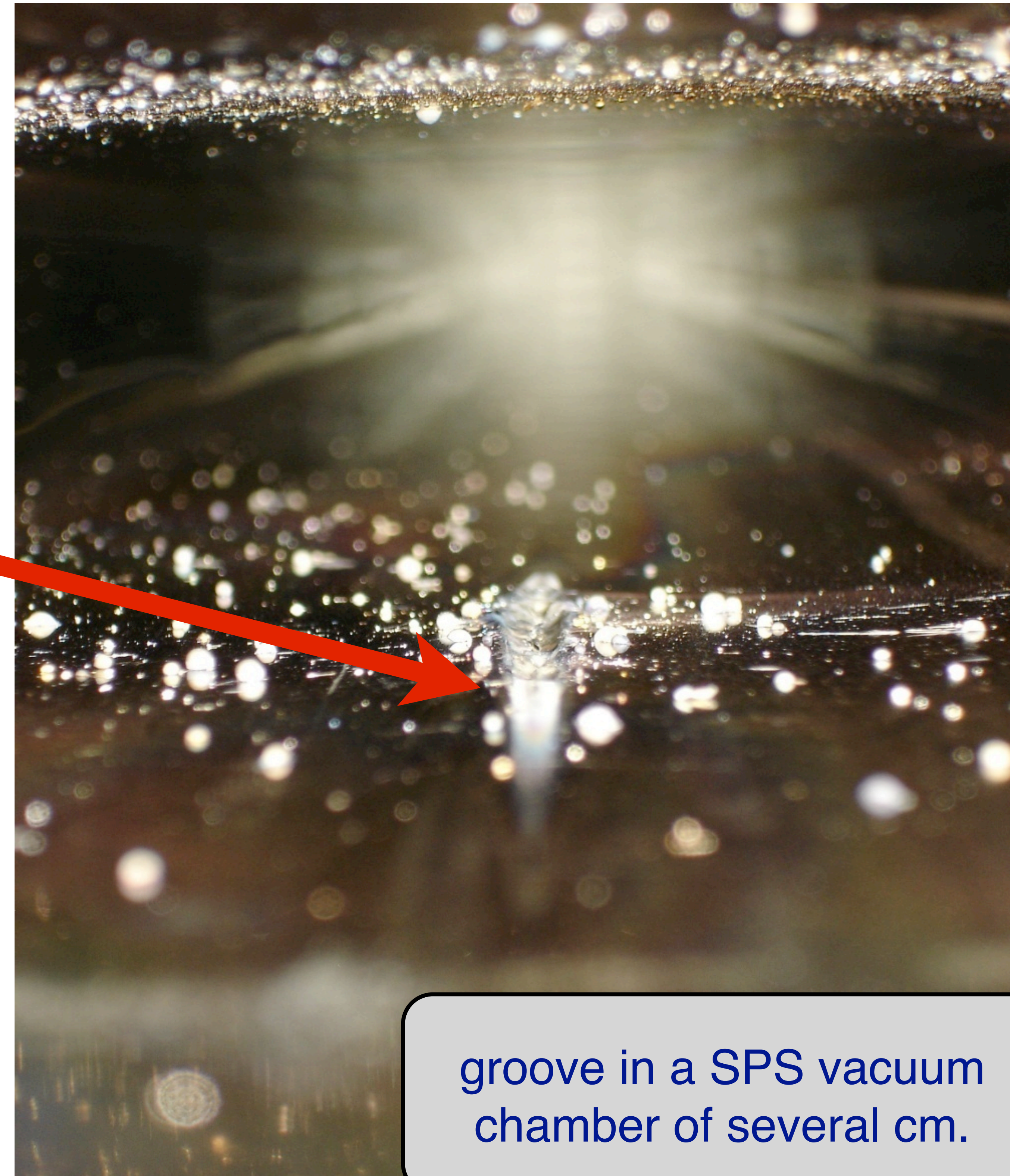
Beam impact with SPS vacuum chamber

Beam Energy: 2MJ

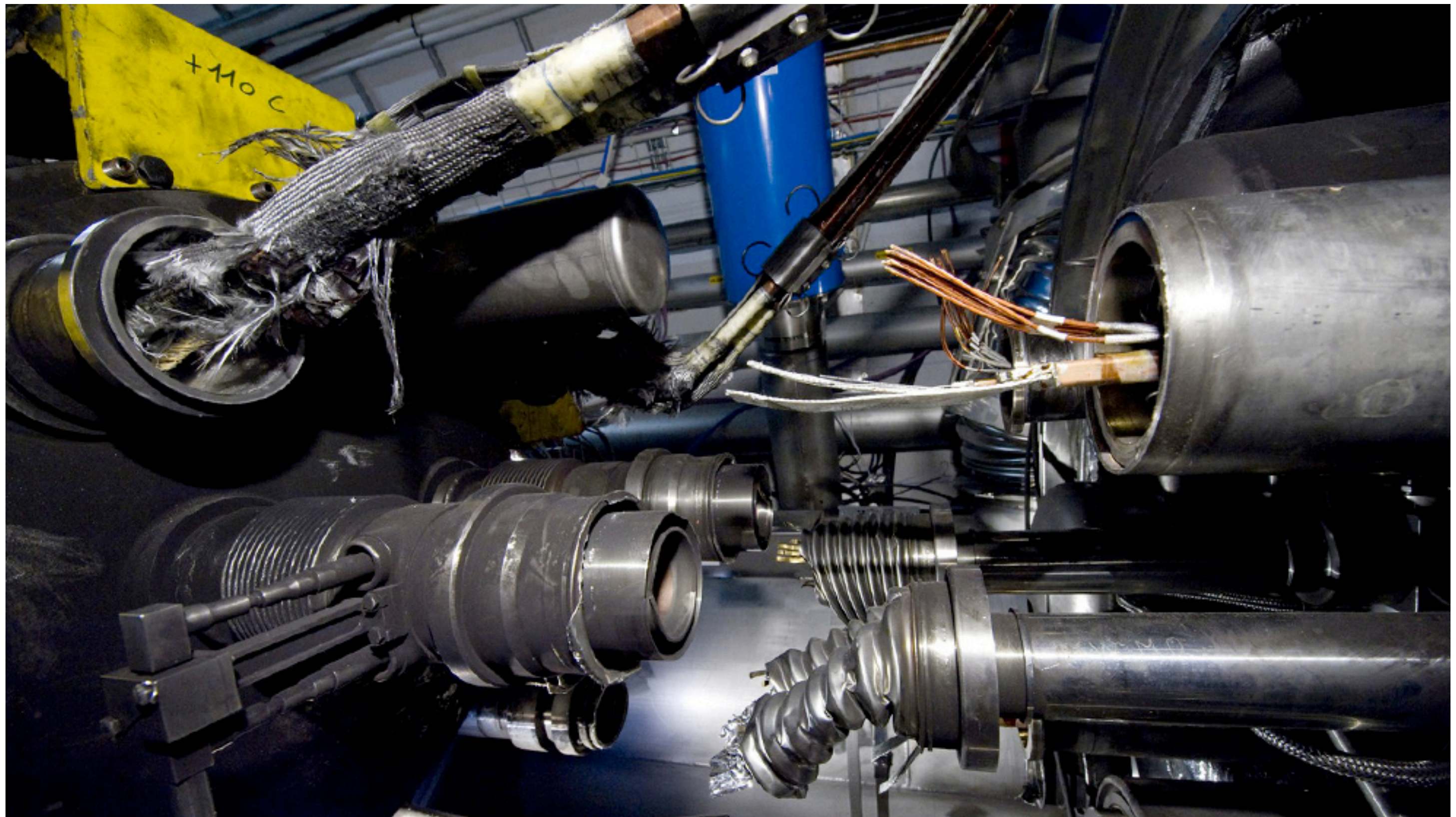
< 1% of a nominal LHC beam

We now routinely operated the LHC with ~100 MJ

... But this is not the worst

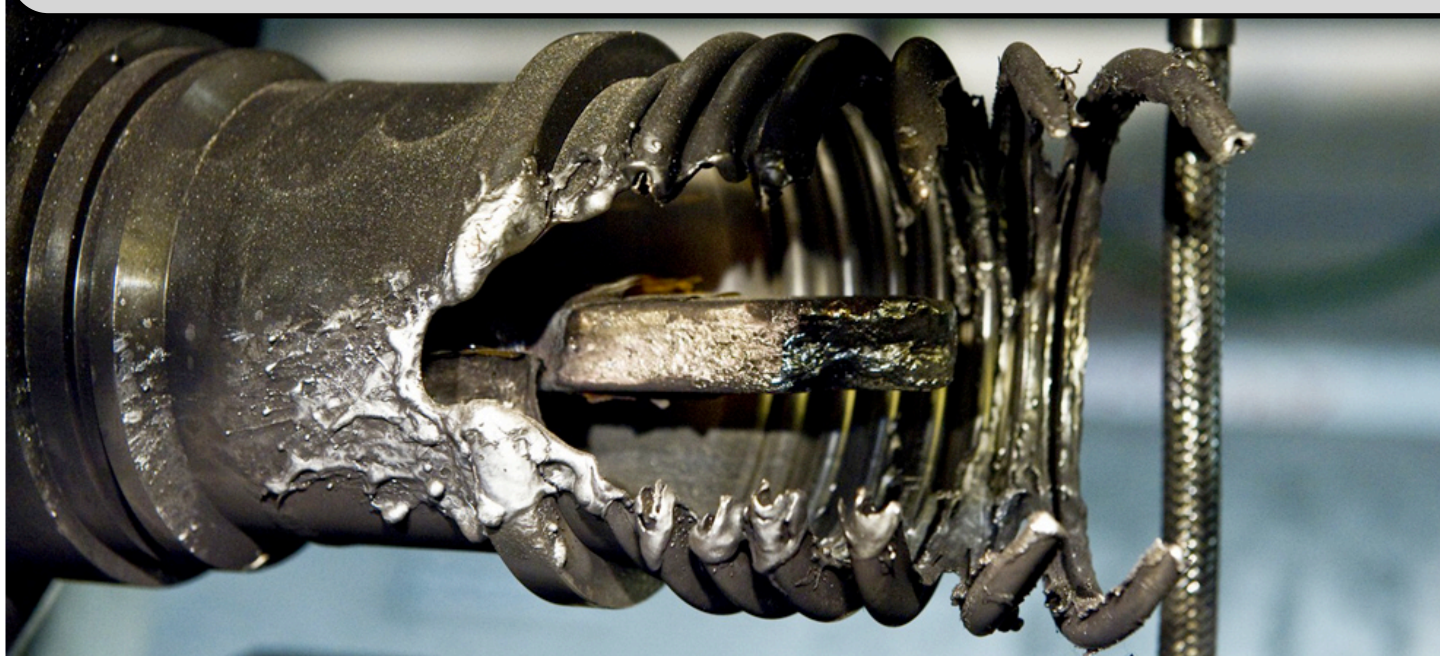


groove in a SPS vacuum chamber of several cm.



Cryogenics has up to 11GJ of store energy

... that should not be released

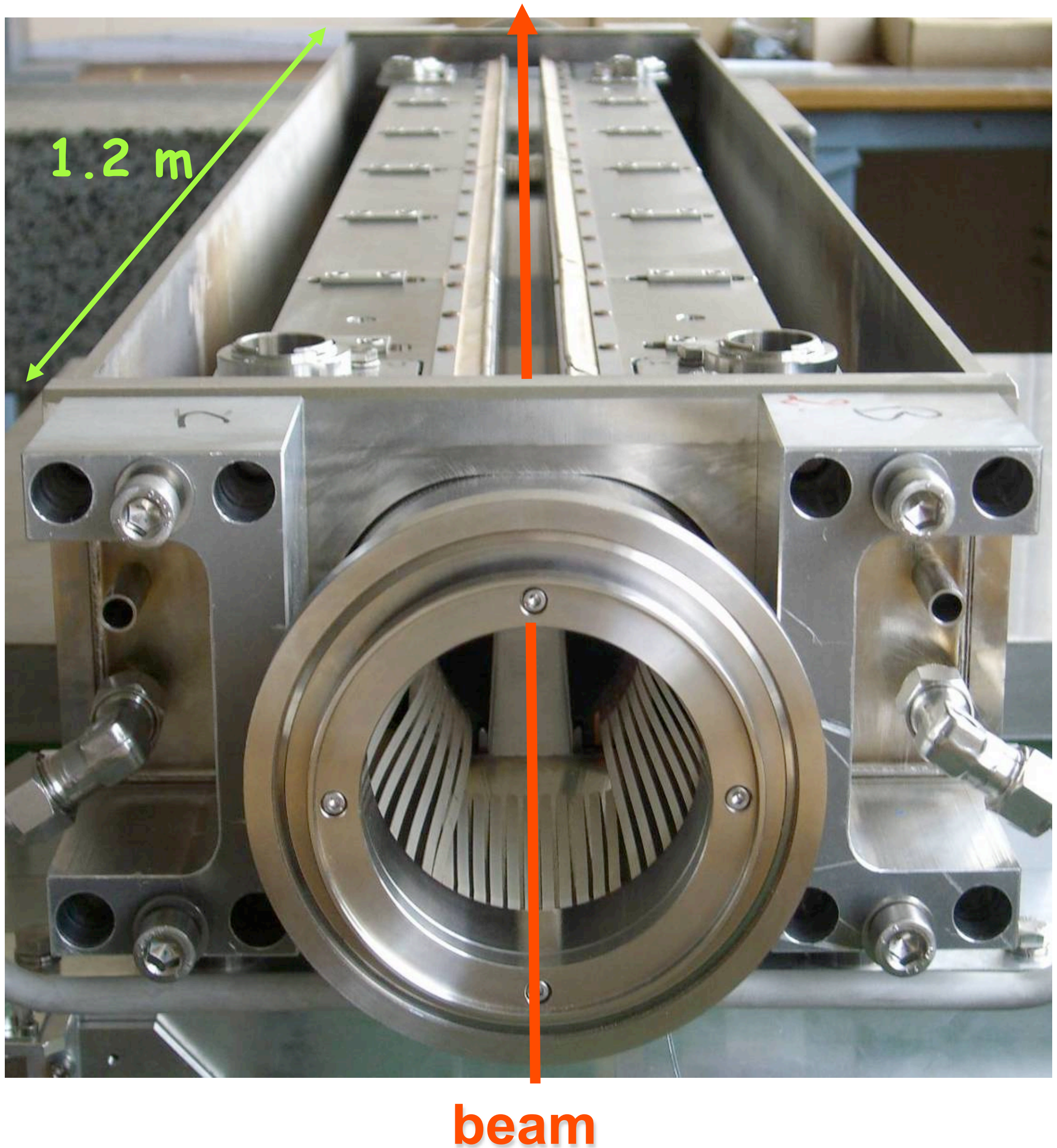


S34 Incident in 2008

Energy dissipated was less than the LHC nominal beam energy

Collimation

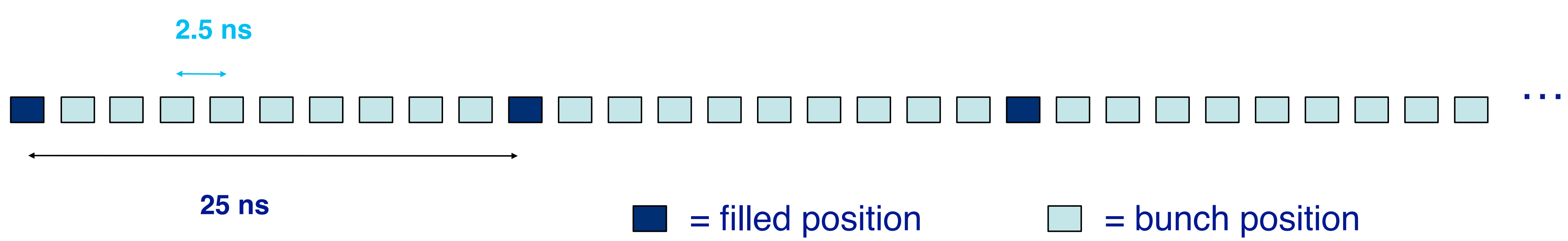
- The LHC requires a large and complex collimation system
  - *Previous colliders used collimators mostly for experimental background conditions - **the LHC can only run with collimators**.*



- Ensure 'cohabitation' of:
  - **100's of MJ** of stored beam energy,
  - super-conducting magnets with quench limits of **few mJ/cm^3**
- Almost 100 collimators and absorbers.
- Alignment tolerances <0.1 mm to ensure a collimation cleaning efficiency over **99.99%**
- **Operation**: Regular collimation hierarchy and cleaning efficiency validation

Beam in the LHC: Bunches

- The LHC 400 MHz Radio-Frequency system provides **35’640 possible bunch positions** every 2.5 ns (0.75 m) along the LHC circumference.
  - *A priori any of those positions could be filled with a bunch…*
- Smallest bunch-to-bunch distance = 25 ns: ***max. number of bunches is <u>3564</u>***



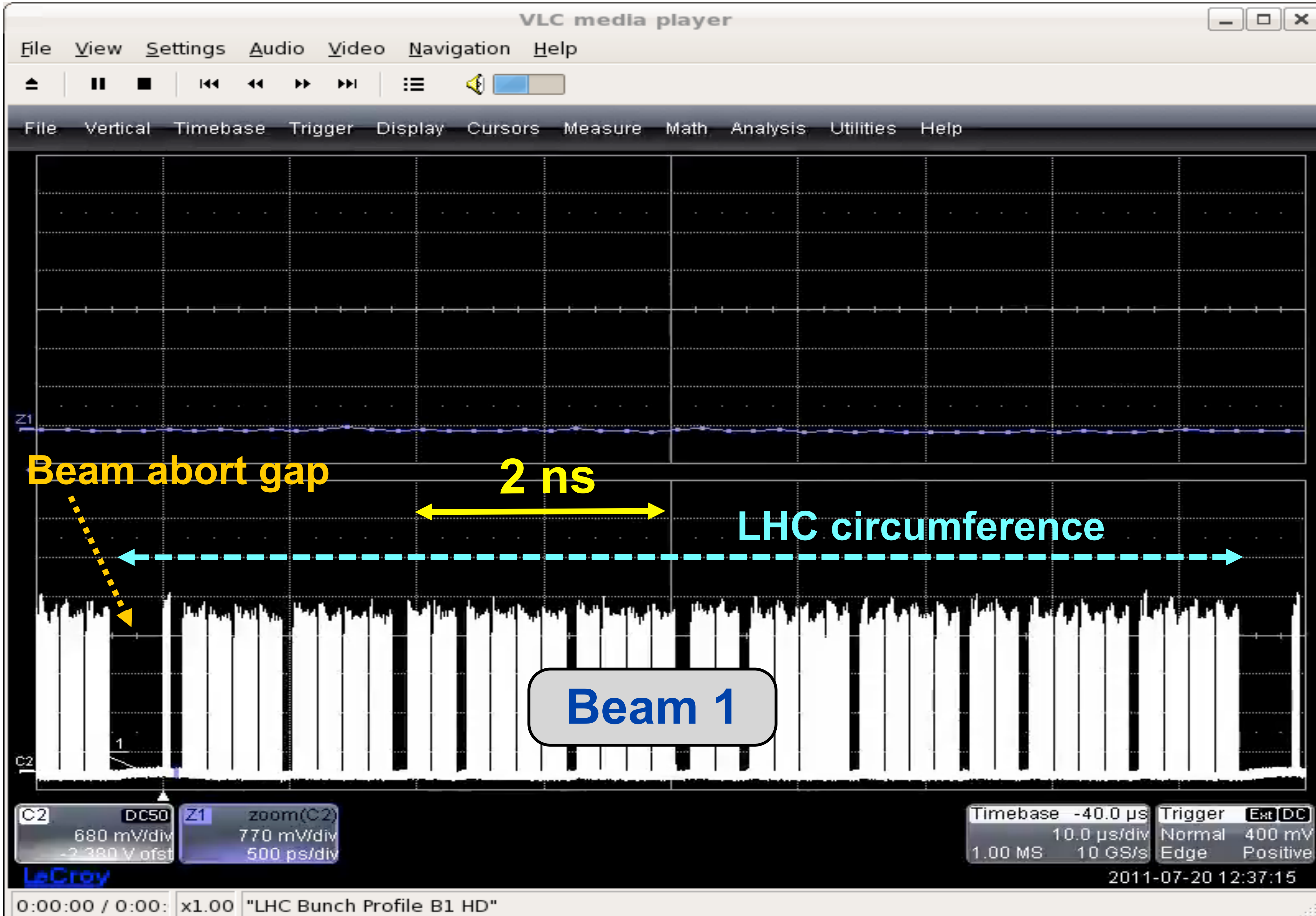
- Injector flexibility: LHC can operate with ***isolated bunches*** or with ***Bunch trains***

Startup 2010 :	*up to 50 isolated bunches*
Fall 2010 :	*150 ns spacing - up to 368 bunches.*
2011 :	***start-up with 75 ns, now 50 ns.***

2011 Standard running: 1380 bunches, 50 ns spacing

Bunch Crossings/turn: ATLAS & CMS: 1318, LHCb: 1296, ALICE: 39

1380 bunches with 50 ns spacing



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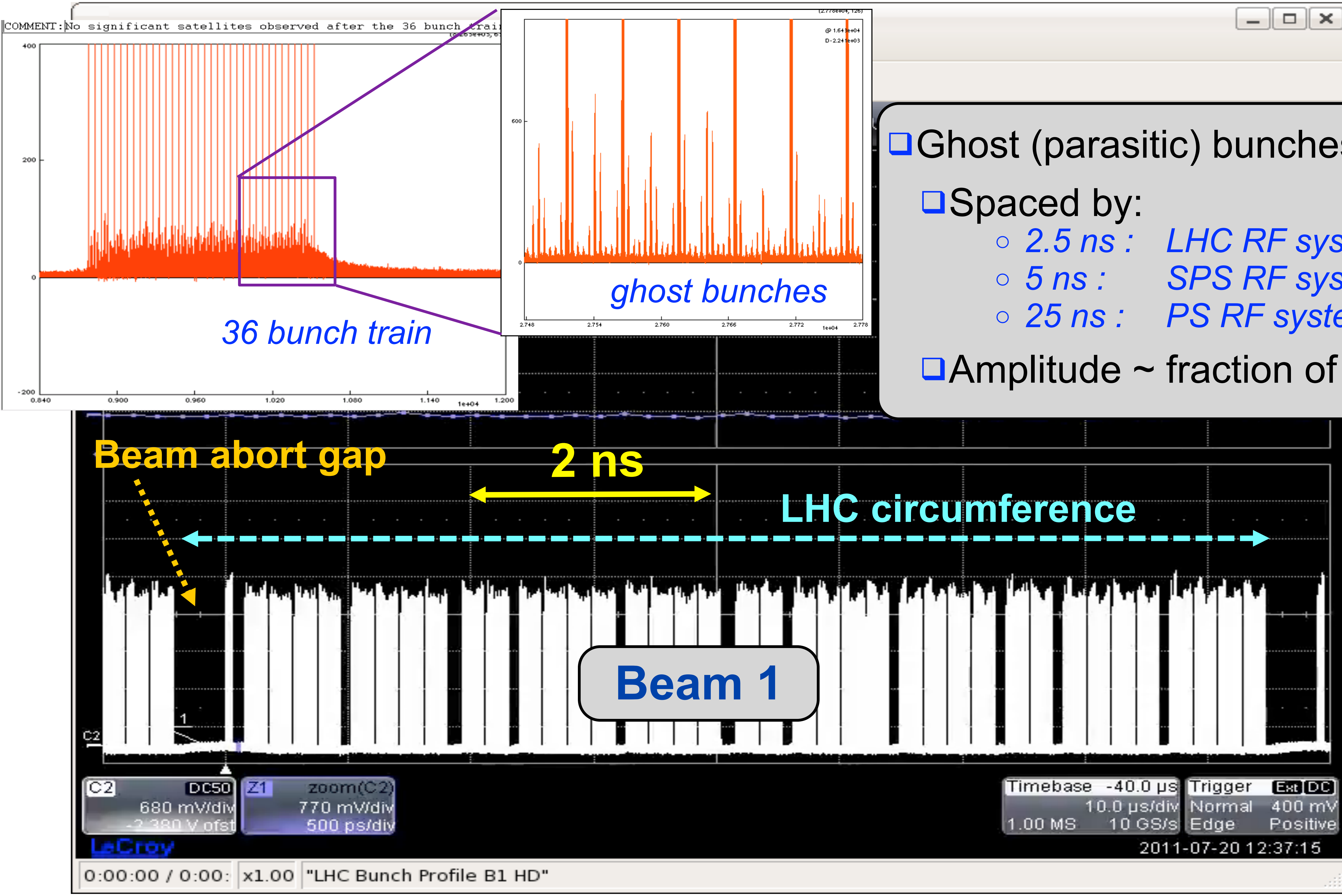
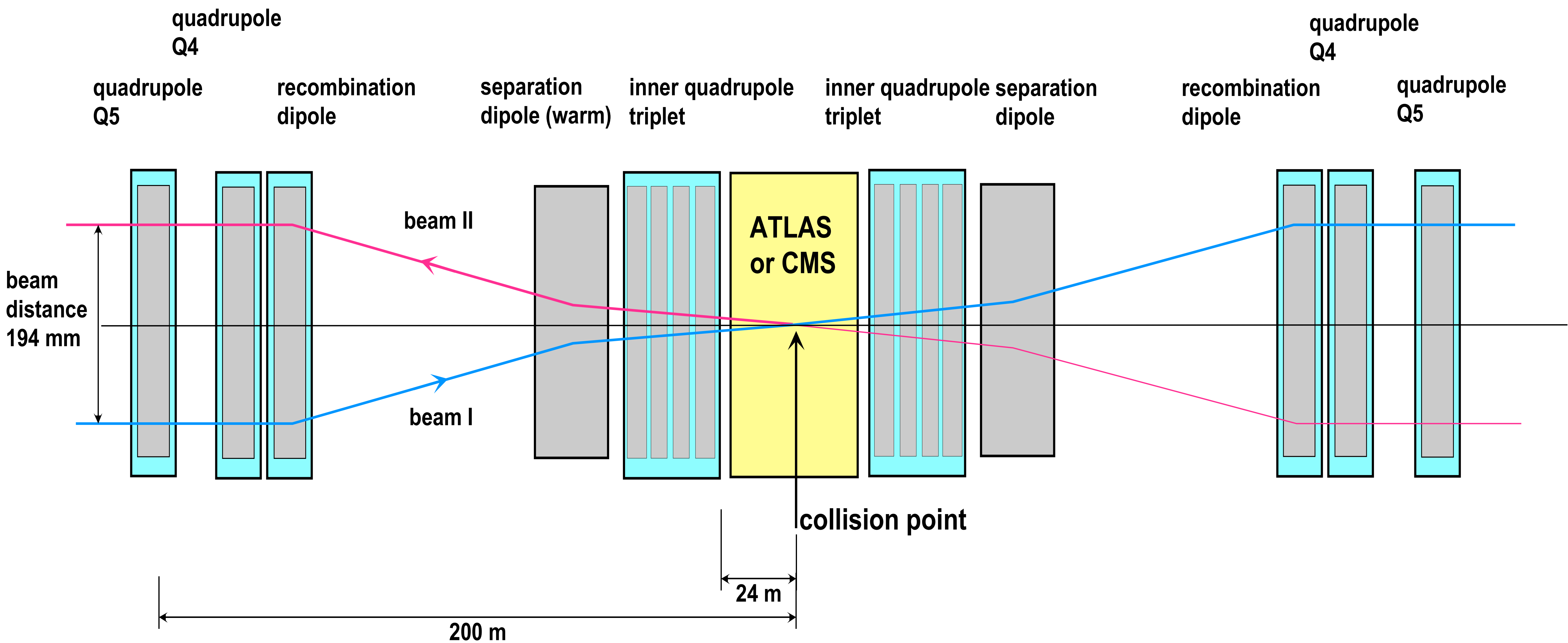


- Ghost (parasitic) bunches
  - Spaced by:
    - *2.5 ns : LHC RF system*
    - *5 ns : SPS RF system*
    - *25 ns : PS RF system*
  - Amplitude ~ fraction of %.

Experimental long straight sections

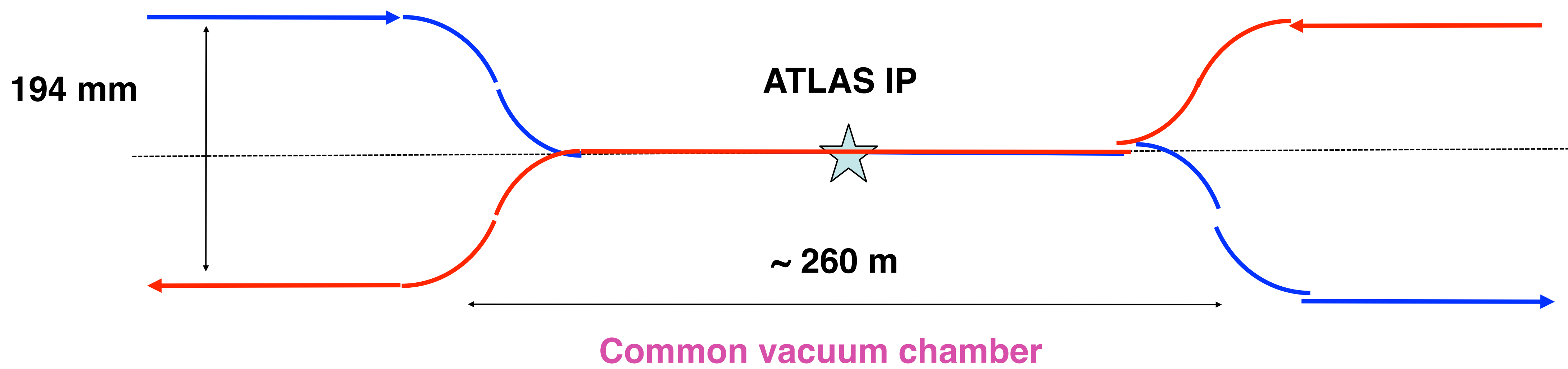


Example for an LHC insertion with ATLAS or CMS

- The 2 LHC beams are brought together to collide in a ‘common’ region.
- Over **~260 m, beams circulate in the same vacuum chamber**
  - Potential ‘parasitic’ **beam-beam** encounters (with small bunch spacing)

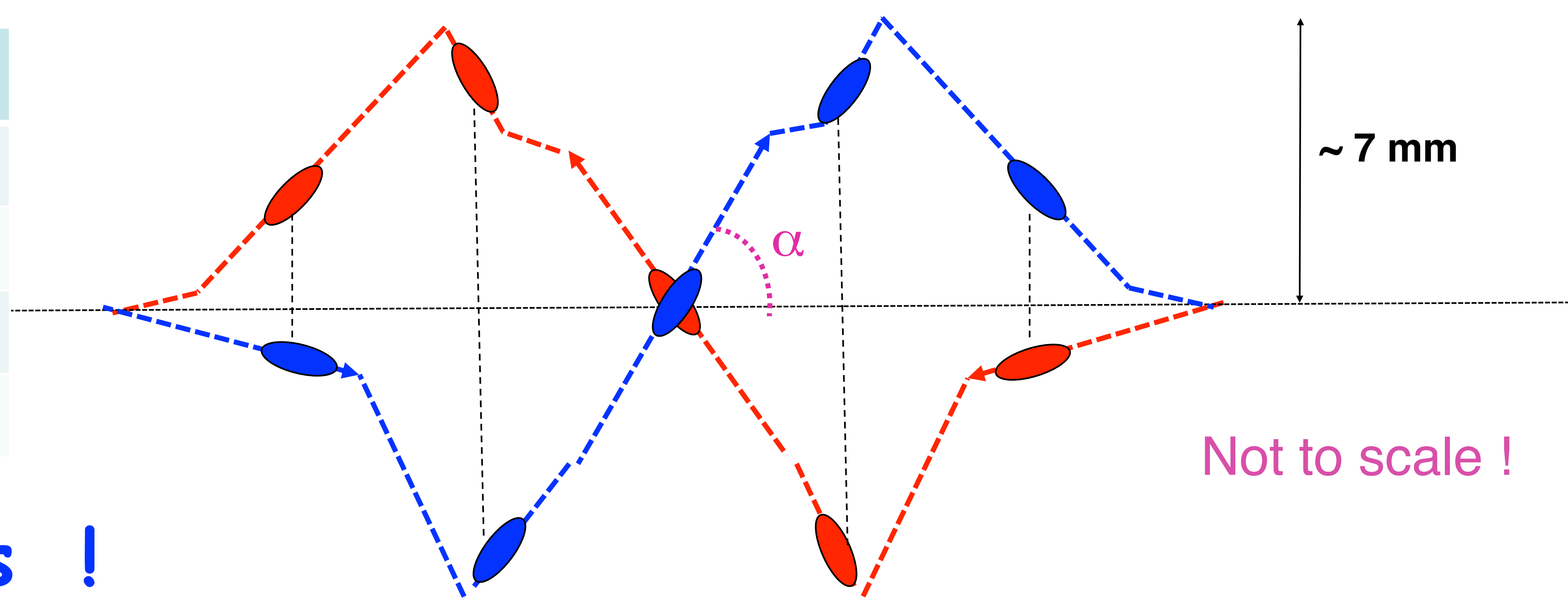
Separation and crossing: example of ATLAS

Horizontal plane: the beams are combined and then separated



Vertical plane: the beams are deflected to produce a **crossing angle** at the IP
Reason: **avoid undesired encounters in the common vacuum region.**

	α (μrad)
ATLAS	**-120 / ver.**
ALICE	**80 / ver.**
CMS	**120 / hor**
LHCb	**-250 /hor**



2011 @ 50 ns !

Beam size: aperture and β^* limits at an IP

- Focusing at the IP is defined by β^* which relates to the **beam size** σ

$$\sigma^2 = \beta^* \varepsilon$$

- β^* is limited by aperture of **triplet quadrupoles** around the collision point .

Smaller size σ at the IP implies:

→ Larger divergence (phase space conservation !)

→ Faster beam size growth in the space from IP to first quadrupole !

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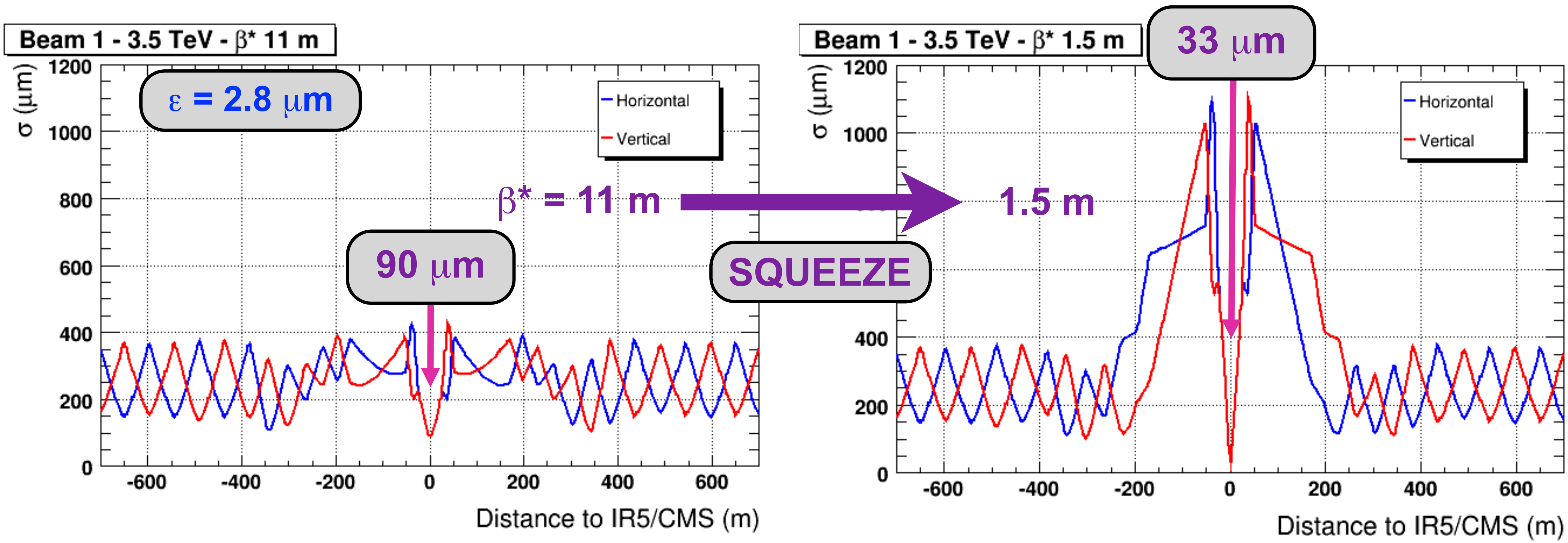
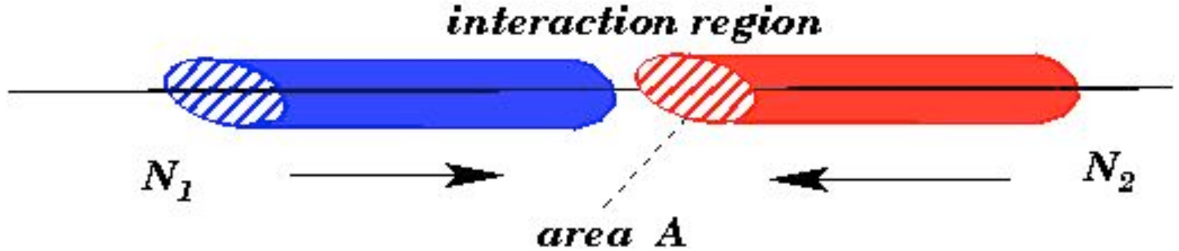


Luminosity: collider figure-of-merit

- Event rate N for a physics process with cross-section σ is proportional to the collider Luminosity *L*

$$N = L\sigma$$



$$L = \frac{kN^2 f}{4\pi\sigma^*_x\sigma^*_y} = \frac{kN^2 f\gamma}{4\pi\beta^*\varepsilon}$$

k = number of bunches
N = no. protons per bunch
f = revolution frequency = 11.25 kHz
σ^*_x, σ^*_y = beam sizes at collision point

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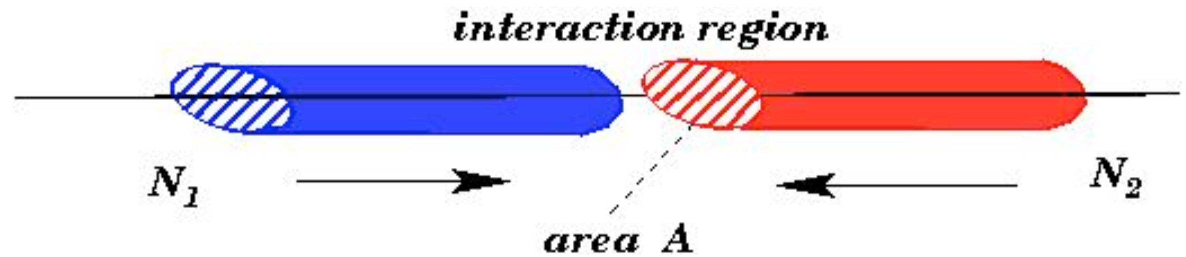

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k = number of bunches
N = no. protons per bunch
f = revolution frequency = 11.25 kHz
σ^*_x,σ^*_y = beam sizes at collision point

- **How to Maximize Luminosity**
  - Many bunches (k)
  - Many protons per bunch (N)
  - Small beam sizes $\sigma^*_{x,y} = (\beta^*\varepsilon)^{1/2}$
    - β* : **beam envelope** (optics)
    - ε : **beam emittance**
      - ε = phase space volume occupied by the beam (constant along ring)

Injection Property

High beam "brilliance"
→ **Injector chain performance**

Optics property

Beam property

Small envelope
→ **Strong focusing**

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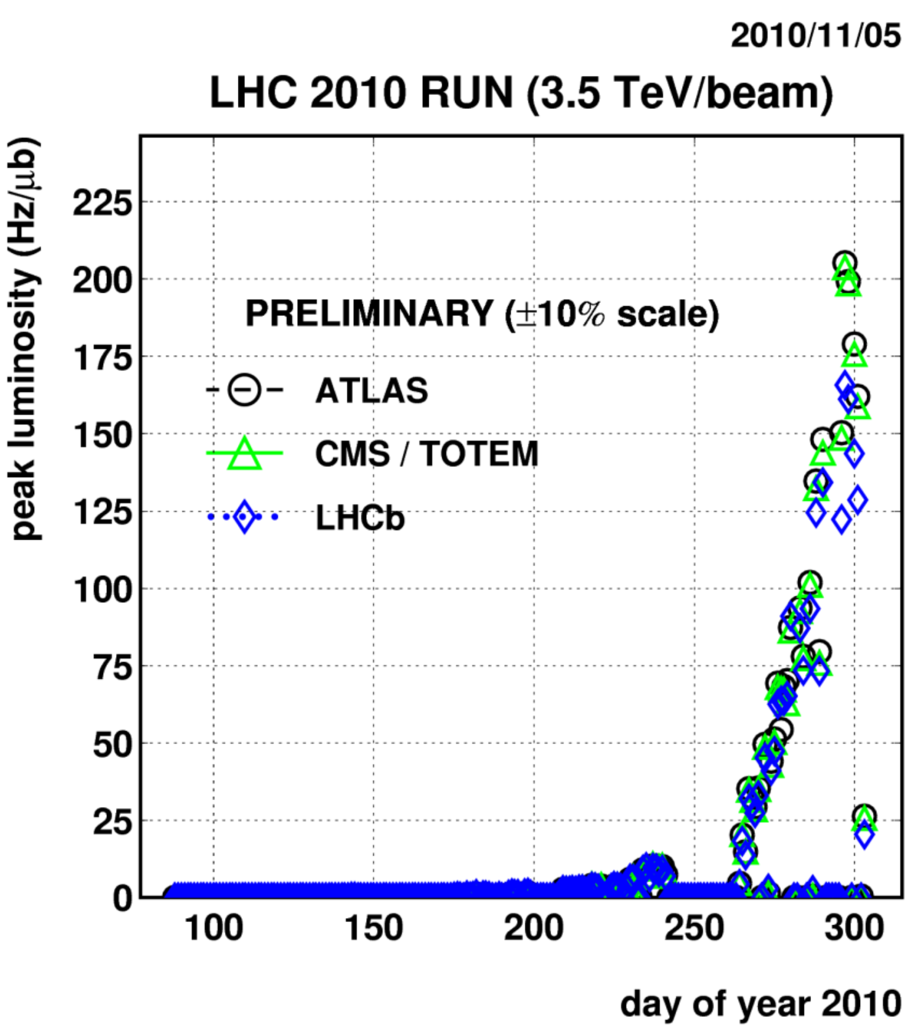
  - Implications of Radiation to Electronics and single event upsets
- Outlook: where we think we improve (2011 & 2012)

The LHC in 2010

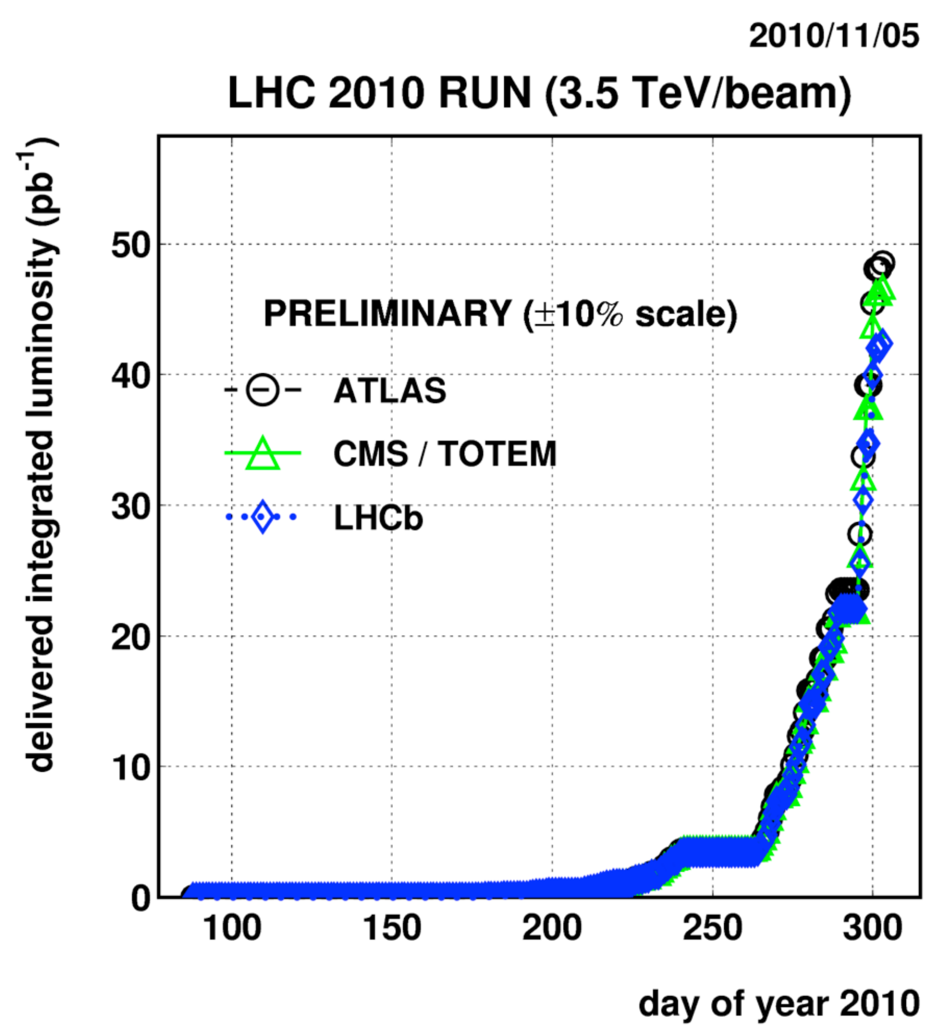
- The 2010 run was the '**learning to handle high intensity**' year.
  - *Progressive intensity ramp up.*
  - *Initial operation with isolated bunches, then moved to **150 ns spacing**.*
  - *Got up to **368 bunches** .*
- *Test with 75 and 50 ns beams: → Limitations due to **Electron clouds.***



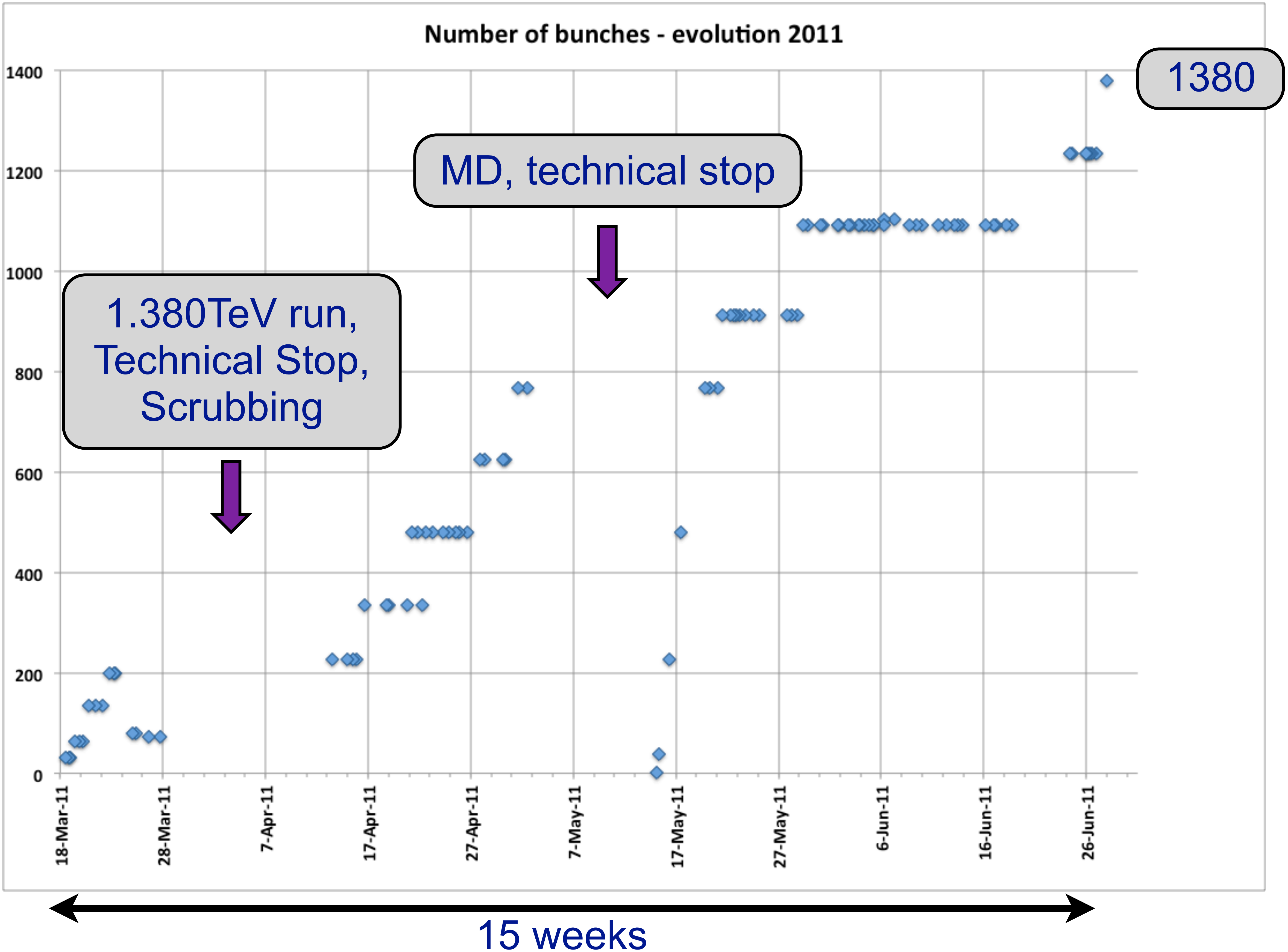
Peak Luminosity
2×10^{32} cm^{-2}s^{-1}

Delivered Luminosity
45 pb^{-1} (ATLAS)

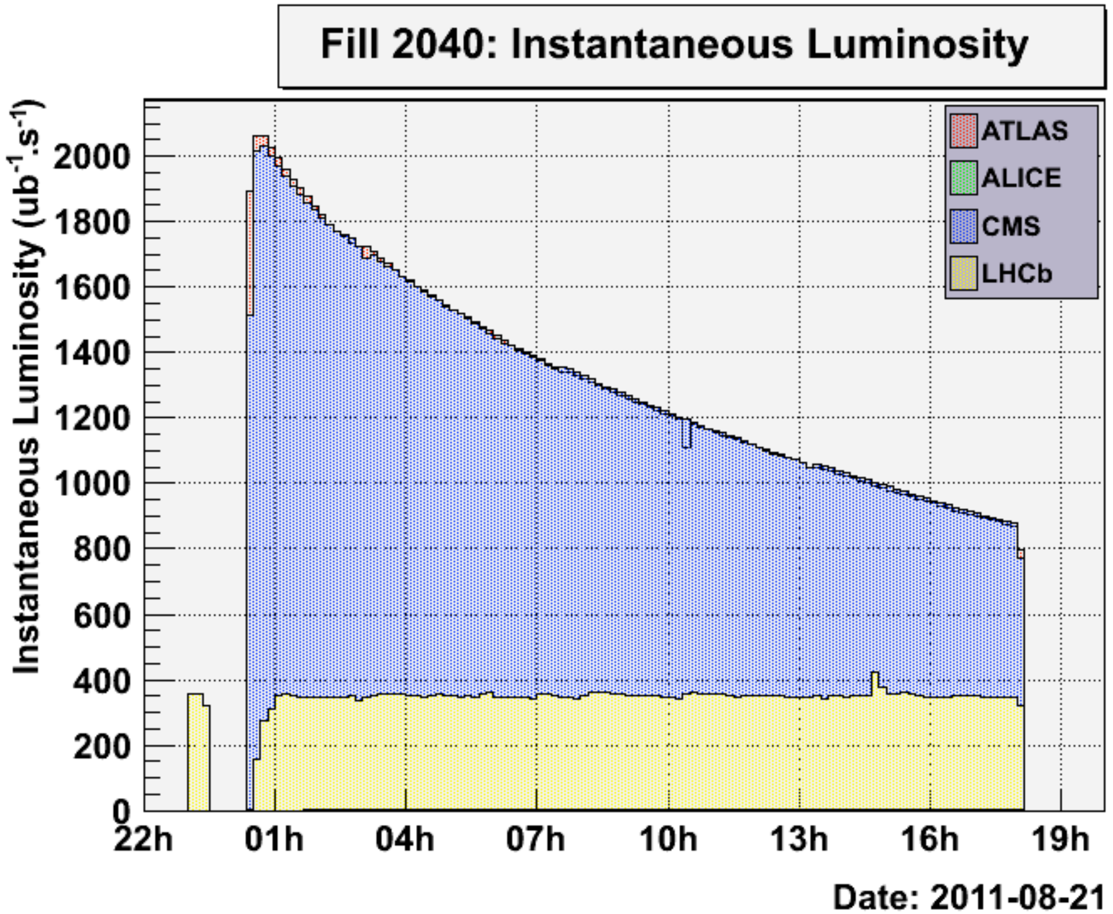
p-p & Pb-Pb runs

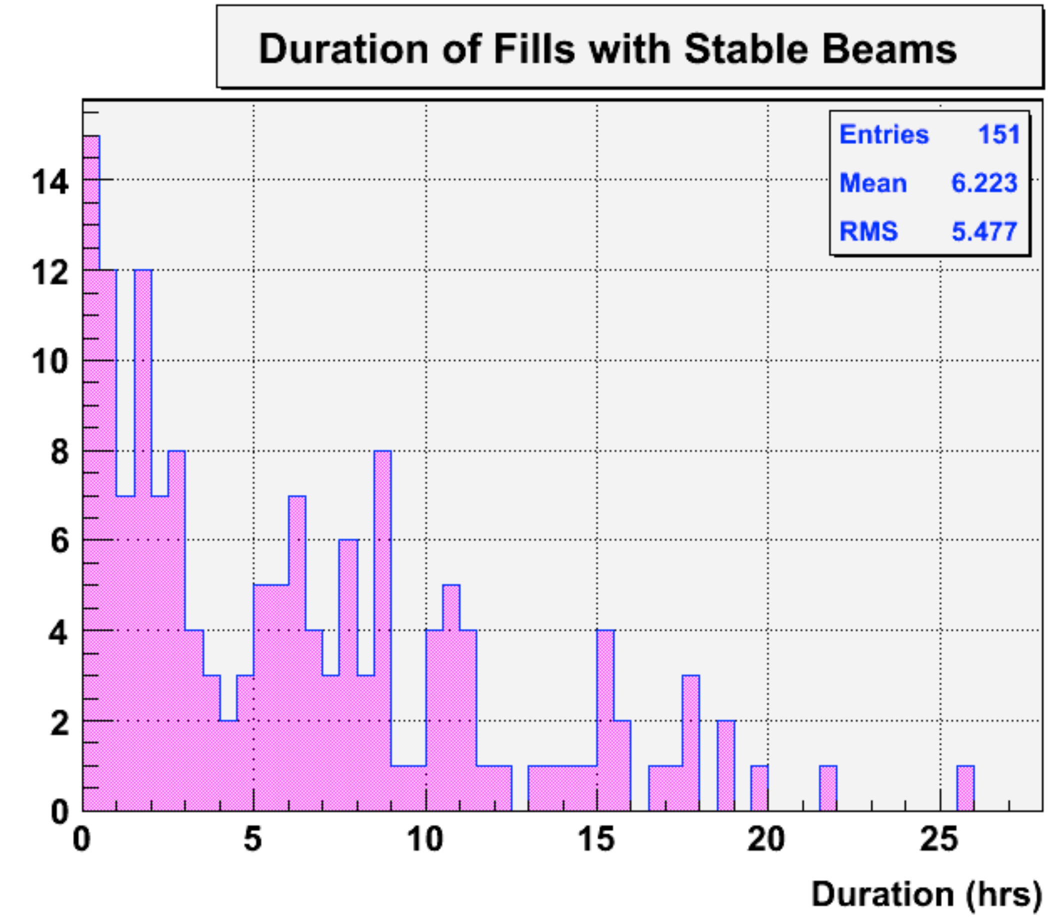


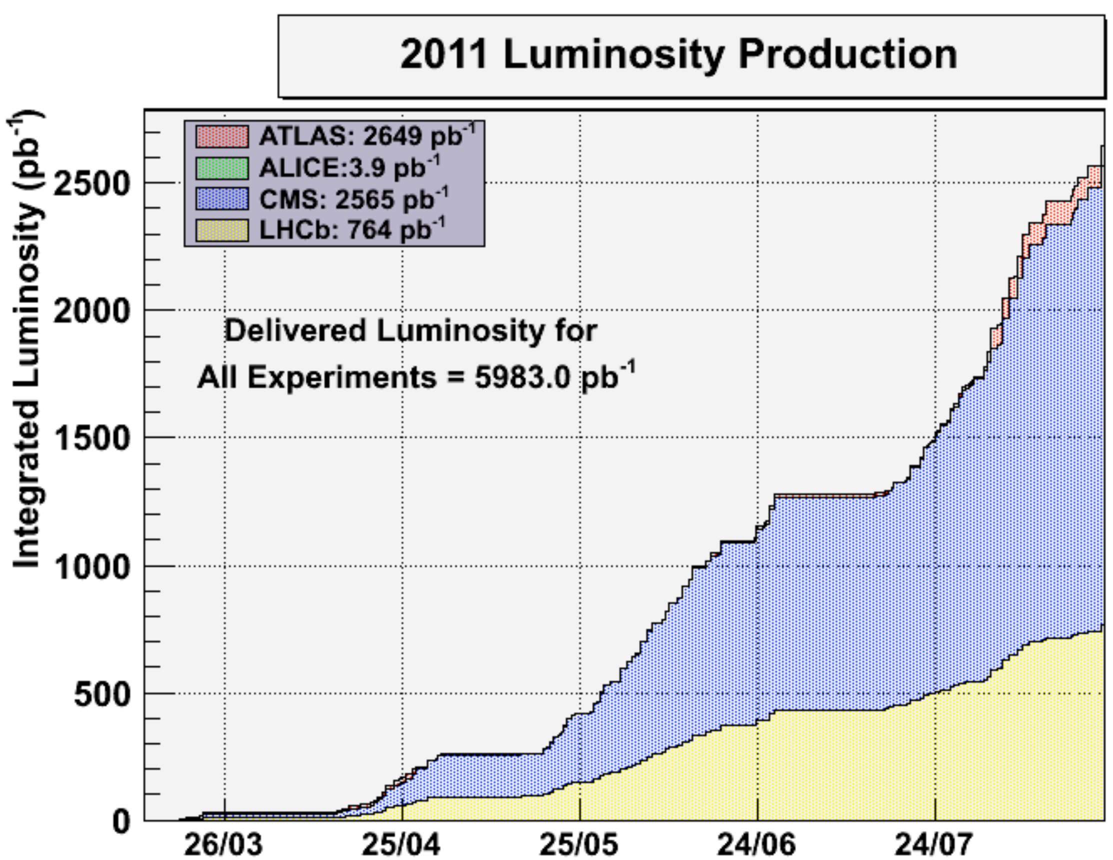
2011: Beam Intensity Ramp-up (# of bunches)

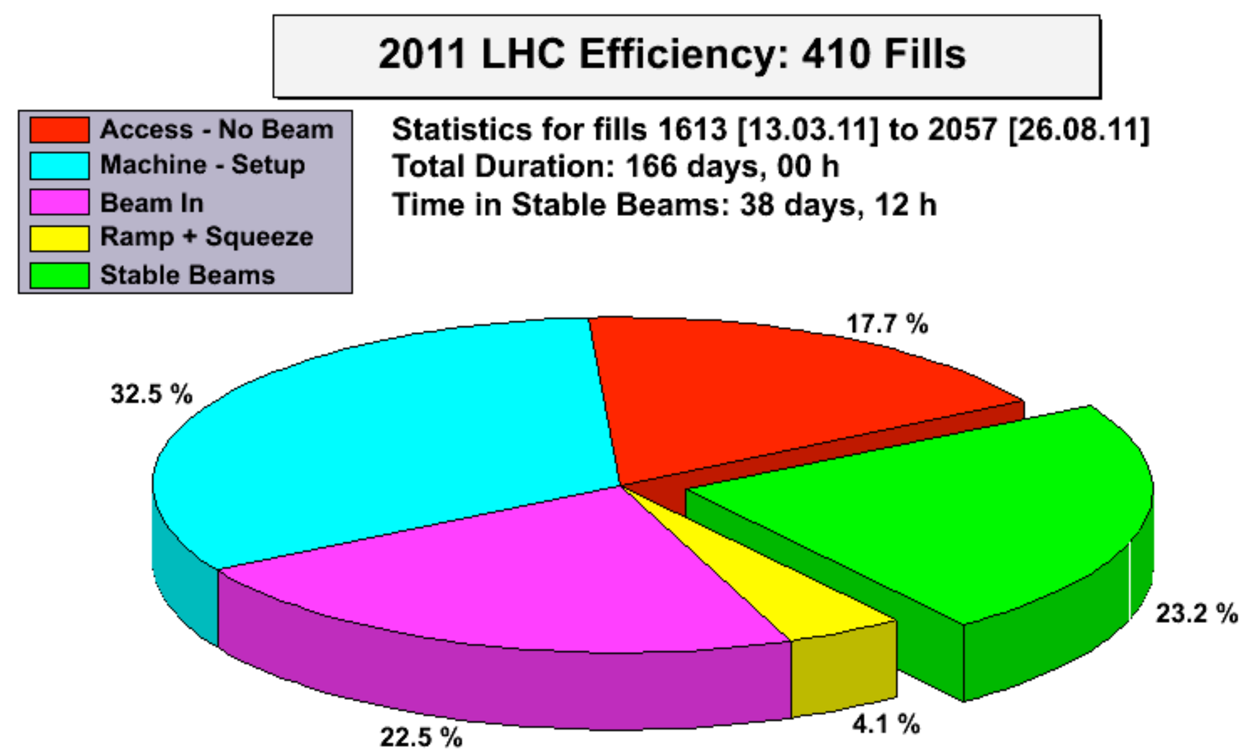


2011 Proton Run - to date









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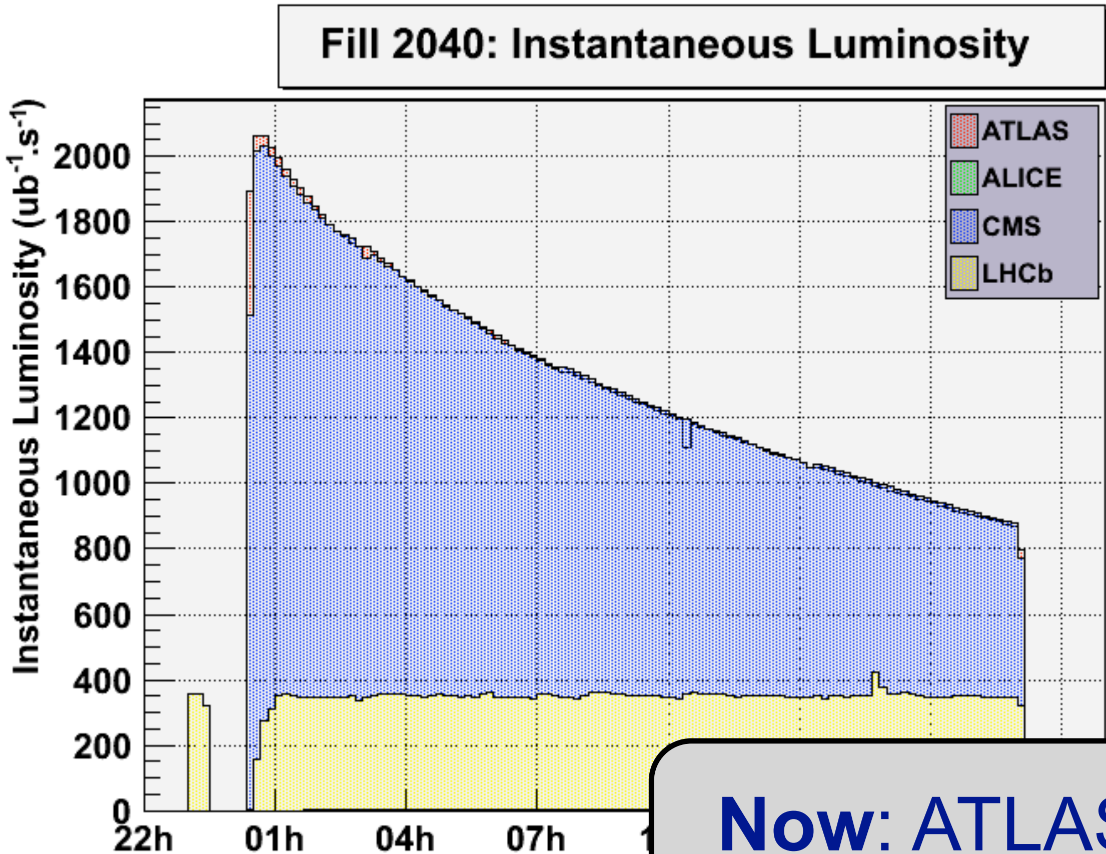
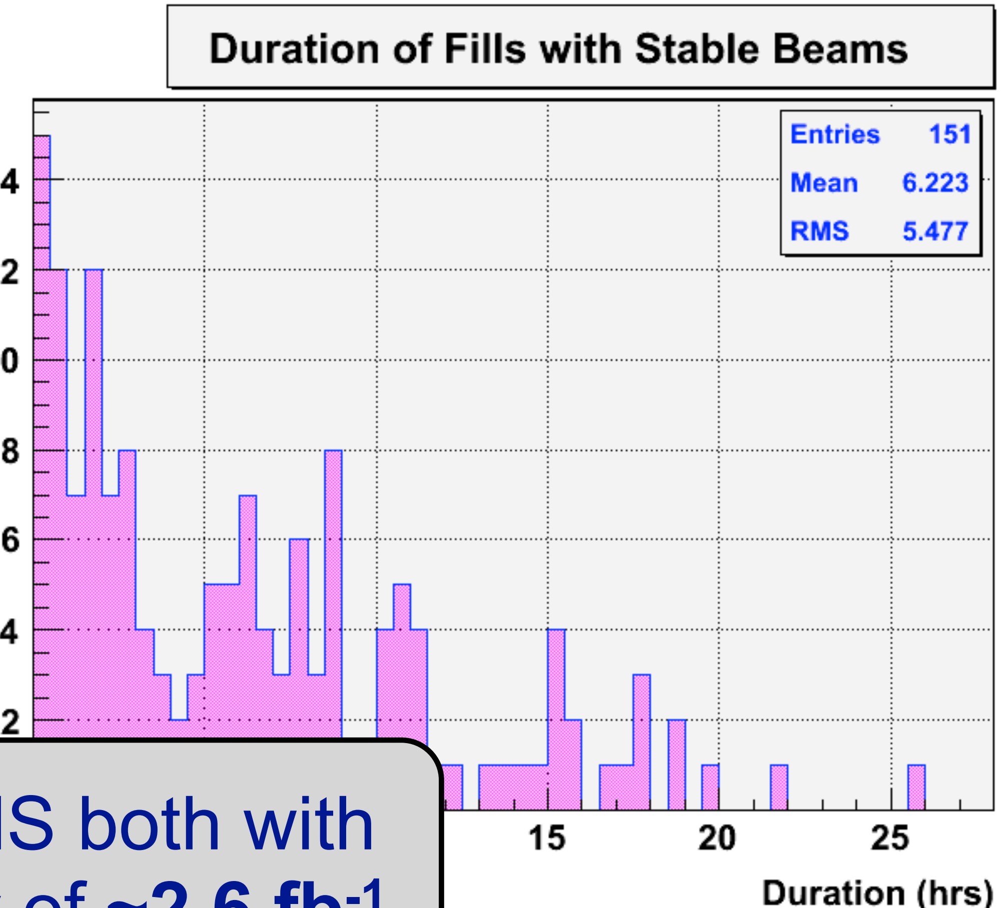
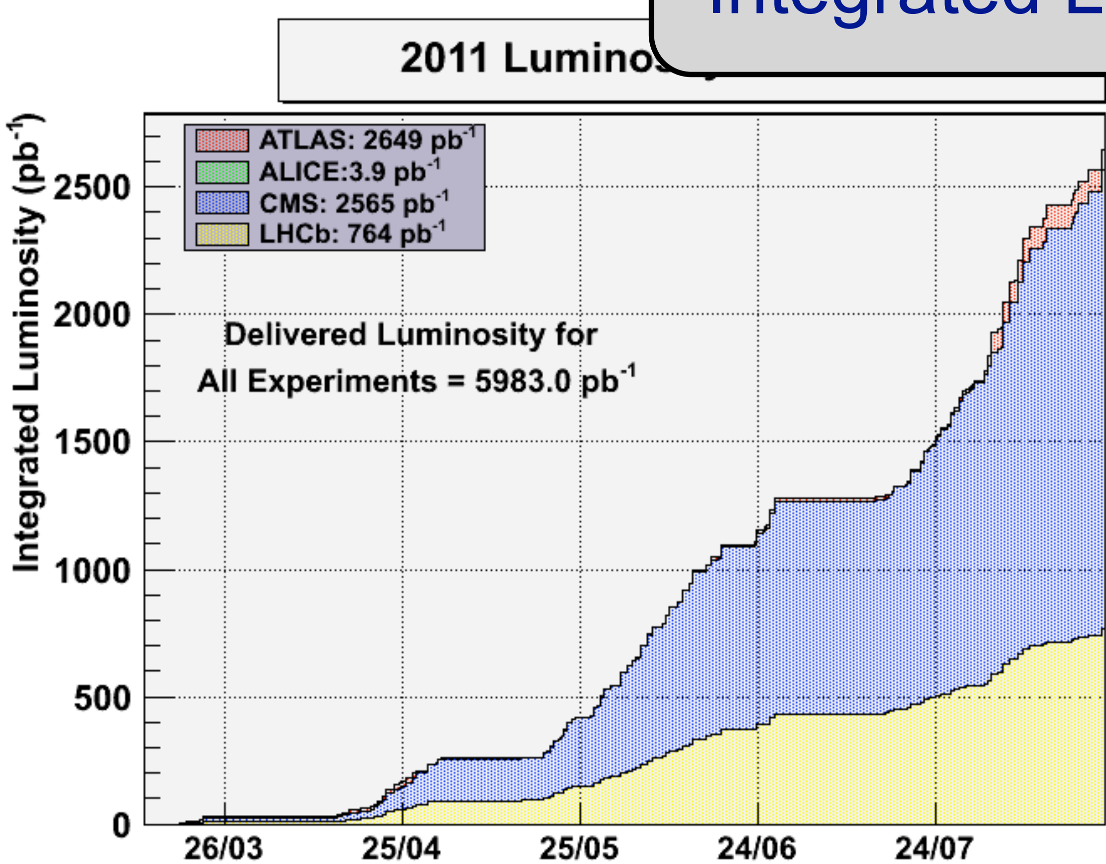
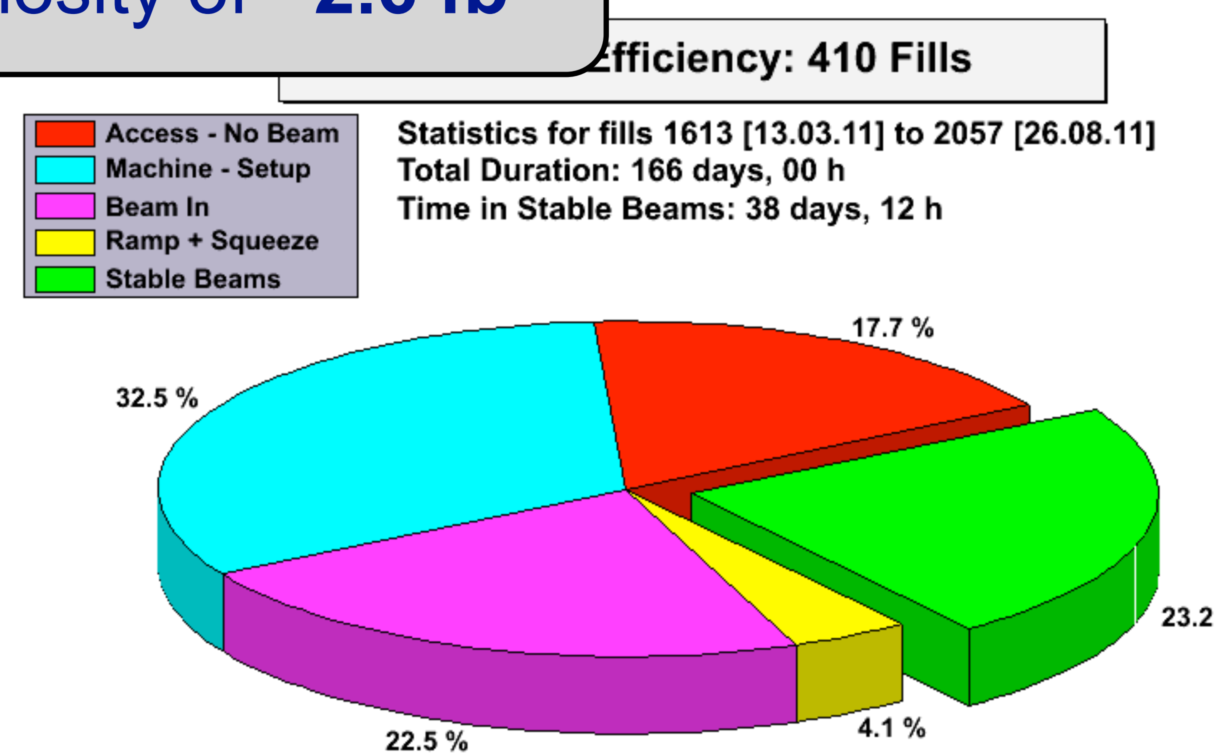




Now: ATLAS and CMS both with Integrated Luminosity of **~2.6 fb^{-1}**

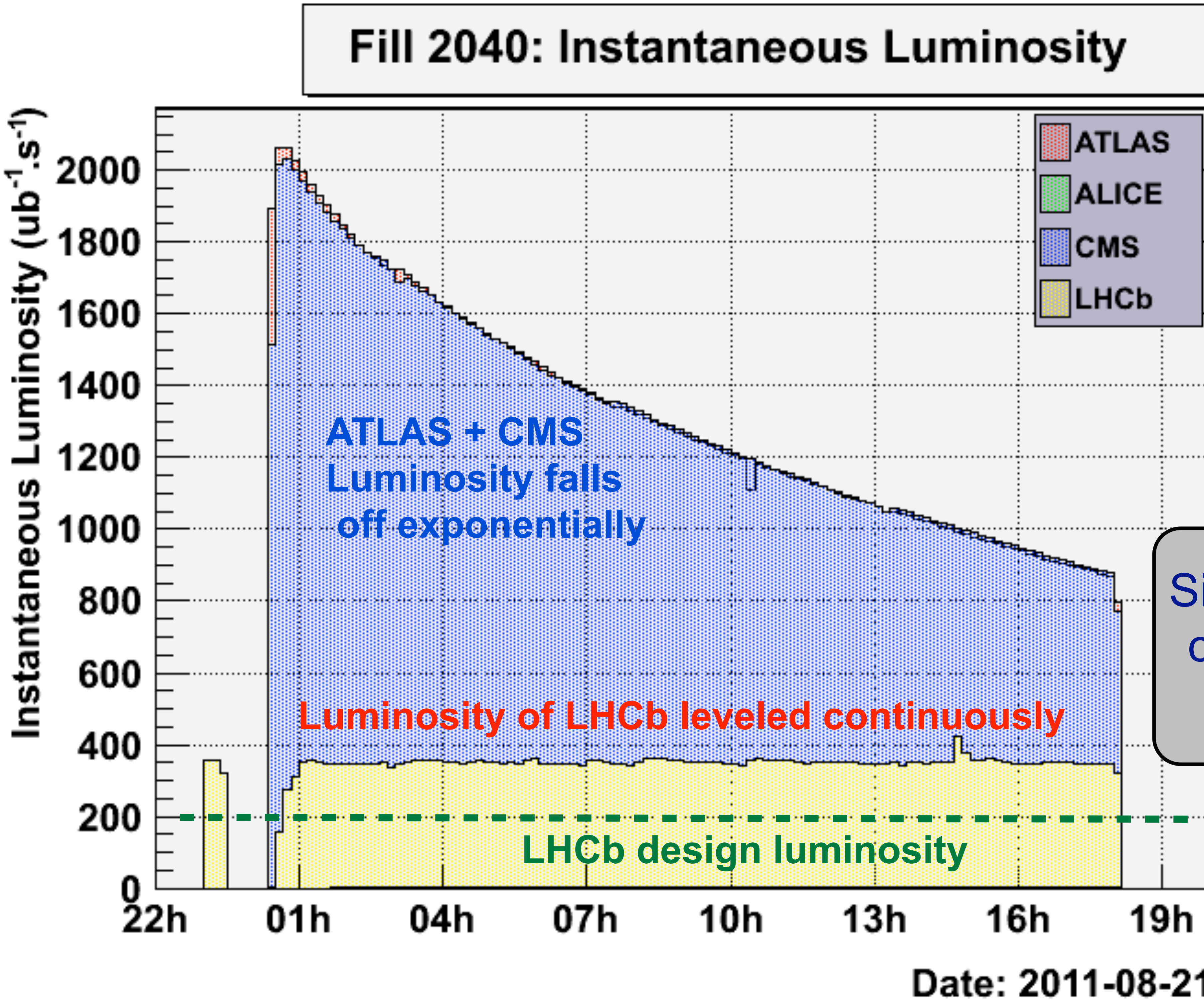




Expected integrated luminosity for LHCb in

Introduced luminosity leveling for LHCb and ALICE

=> LHCb can run at optimal μ and L_{max}



μ = mean number of collisions per bunch crossing

Since June LHCb running at constant L ~ $3 \cdot 10^{32}$ $cm^{-2}s^{-1}$ with μ ~ 1.5

Achievements To date

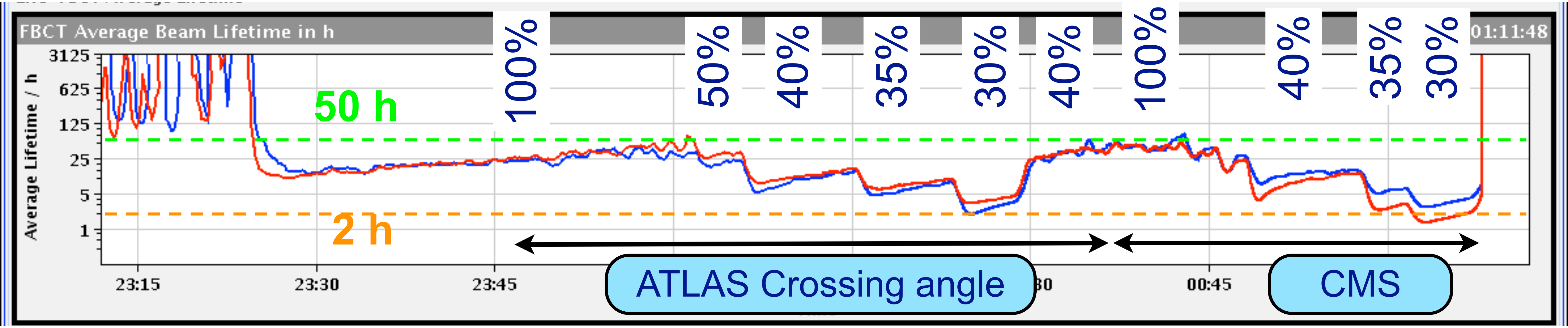
	2010	2011	Nominal
Energy [TeV]	3.5	3.5	7
β* [m] (IP1,IP2,IP5,IP8)	3.5, 3.5, 3.5, 3.5	1.5, 10, 1.5, 3.0	0.55, 10, 0.55, 10
Emittance [μm] (start of fill)	2.0 – 3.5	**1.5 – 2.2**	3.75
Transverse beam size at IP1&5 [μm]	60	28	16.7
Bunch population	1.2×10^{11} p	**1.35×10^{11} p**	1.15×10^{11} p
Number of bunches	368	1380	2808
Number of collisions (IP1 & IP5)	348	1318	-
Stored energy [MJ]	28	110	360
Peak luminosity [$cm^{-2}s^{-1}$]	2×10^{32}	**2.41×10^{33}**	1×10^{34}
Max delivered luminosity (1 fill) [pb^{-1}]	6.23	100.7	-
Longest Stable Beams fill [hrs]	12:09	25:59	-

LHC operation so far:

- Proton-proton Collisions at 450, 1380, and 3500 GeV
- Lead-lead collisions at 450 and 3500 Z GeV
- Low Luminosity 90m Beta* optics (TOTEM, ALFA) tested

Beam beam interactions

- Head on Beam Beam: **No limit found so far**
  - 2 x nominal bunch intensity, 0.5 x nominal emittance!
- Long-range beam-beam
  - Reduced crossing angle in steps from 120 µrad to 36 µrad
    - **100% = 120 µrad = 12 σ** beam-beam separation for ε~2.5µm!
  - Strong correlation of losses with number of long range interactions (PACMAN effects).



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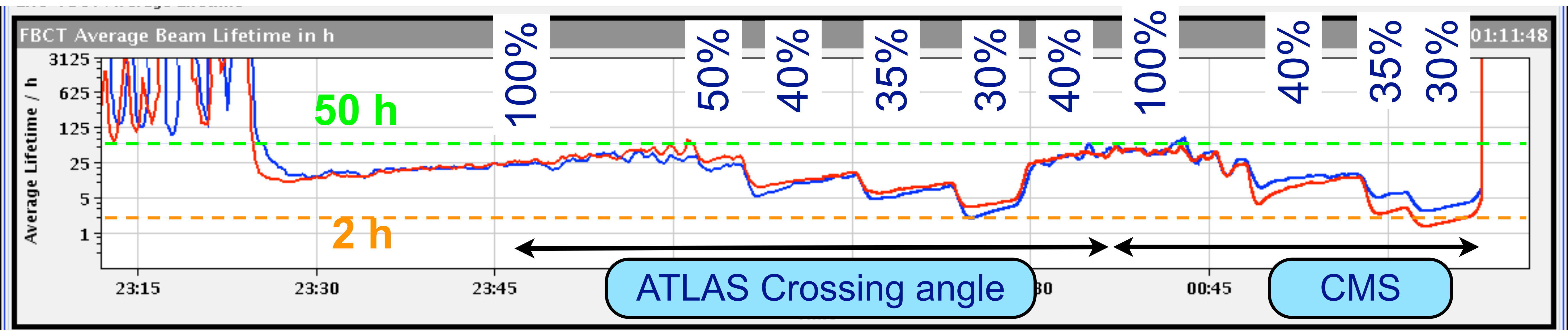

Long range Beam beam effects and Crossing angle reduction

50% fine (no lifetime drop),40% (5 σ b-b) still OK, 30% too low!

=> paves the way for Beta* reduction

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  - Beam Induced Heating
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- Outlook: where we think we improve (2011 & 2012)

Electron Cloud and beam scrubbing

- **Vacuum pressure increase at expts** when switched to bunch trains
  - more critical as intensity increases and bunch spacing decreases
    - *Effects can be suppressed by solenoids (CMS, ALICE stray fields…).*
  - For 50ns spacing: **vacuum pressure increase prevented operation**
    - *1000 fold increase => exceeded 10^{-6} mbar => closure of vacuum valves.*
  - *Signature Consistent with the signature of* **electron clouds**.

- ***Electron Cloud:***
  - Electrons generated at vacuum chamber surface by beam impact, photons ...
  - **Multiplication**: Caused by bunches accelerating secondary emission electrons
    - Generates electron cloud: Electron energies are in the 10- 300 eV range.
    - electron cloud => pressure rise, beam instabilities, detector backgrounds, and possible overload of cryogenic system by beam induced heating
  - Electron cloud build-up is a **threshold phenomenon**

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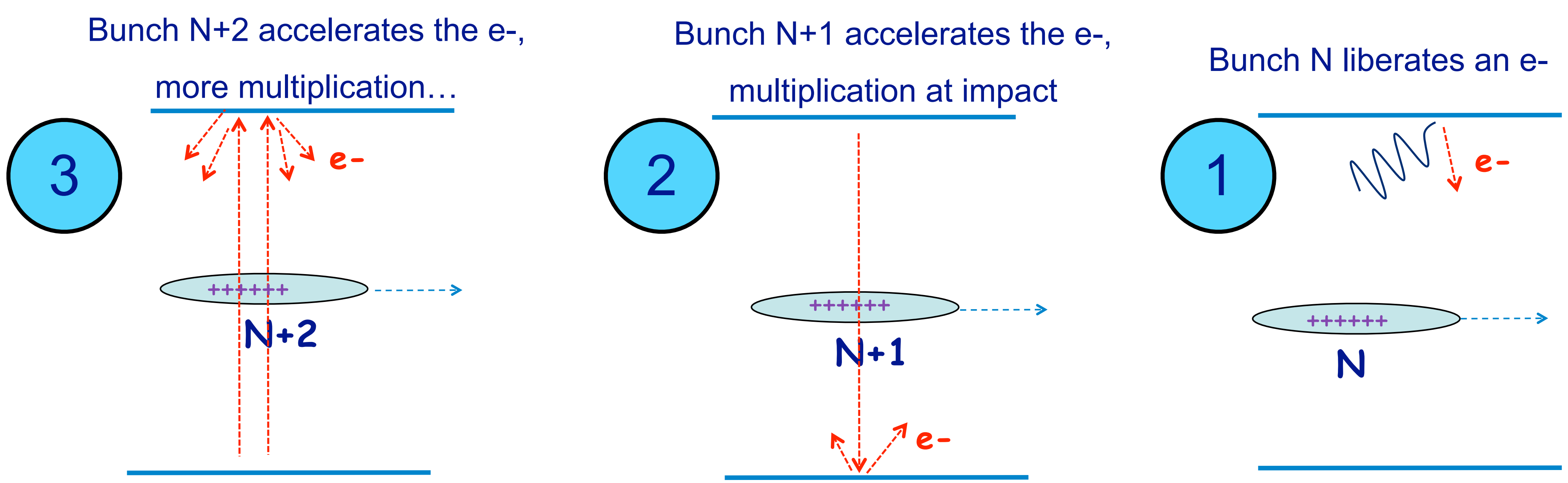
Solution: **Beam scrubbing** => many bunches, large beam size

impact of the electrons **cleans** the surface (Carbon migration), reduces the electron emission and eventually the cloud disappears – ***'beam scrubbing'***

Electron Cloud effects



Later bunches in the train see effects from bunches earlier in the train

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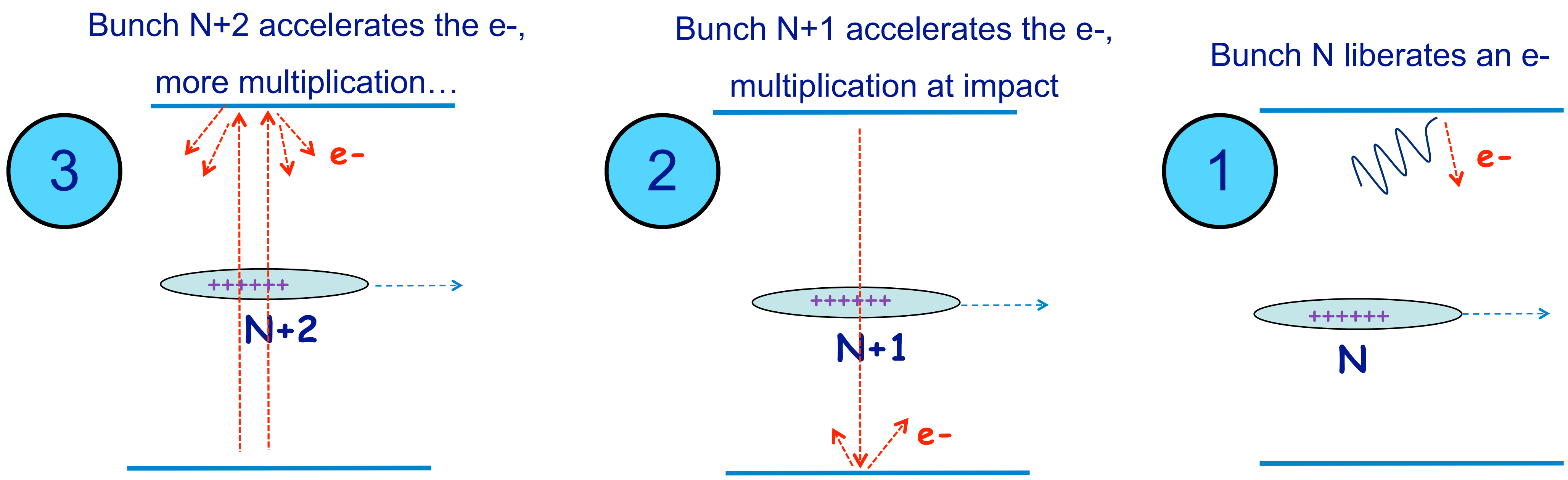
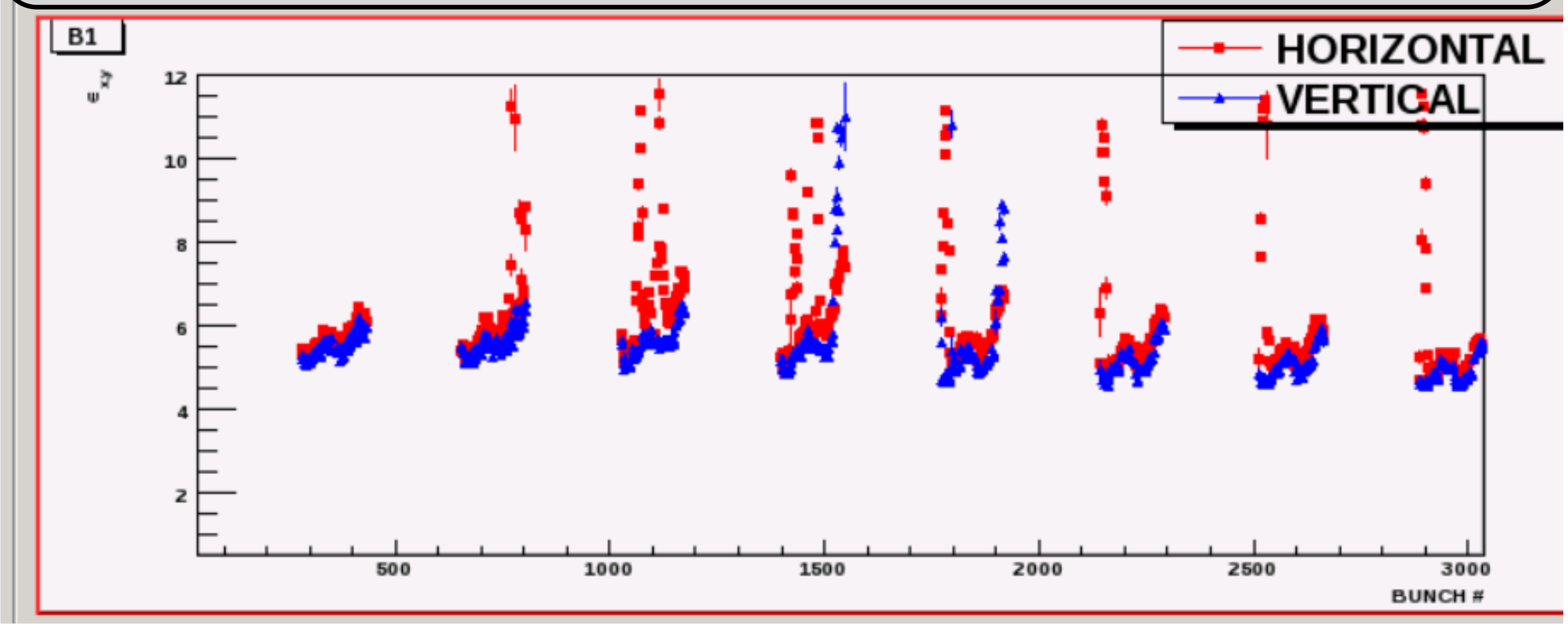


Later bunches in the train see effects from bunches earlier in the train

Bunch sizes with strong electron cloud activity



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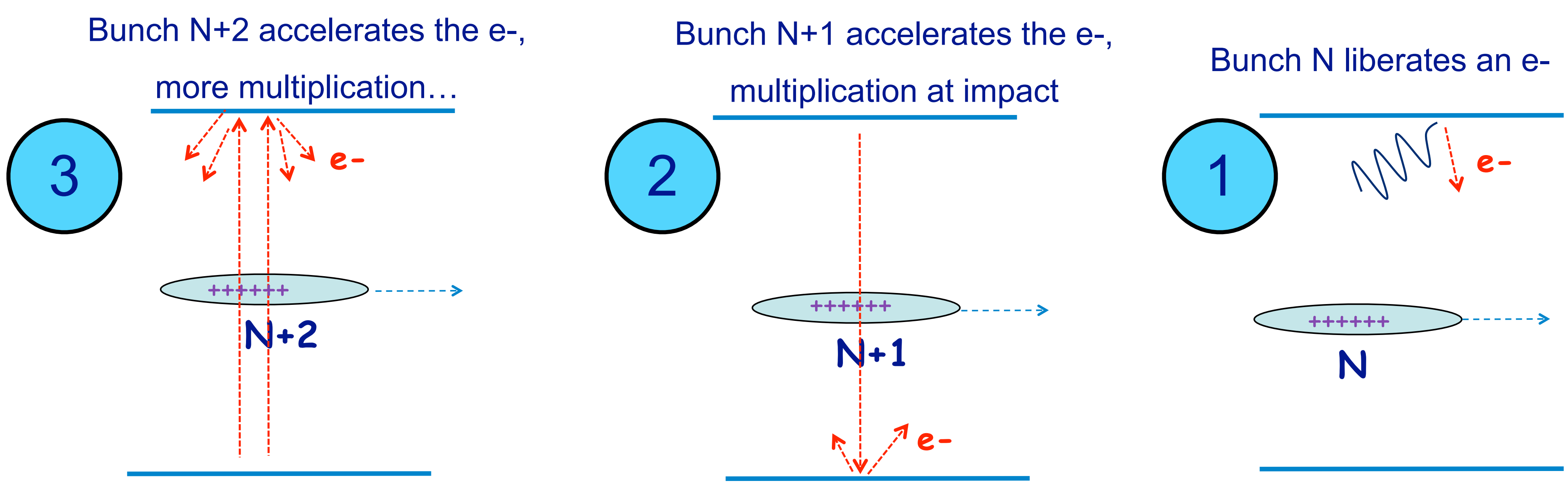

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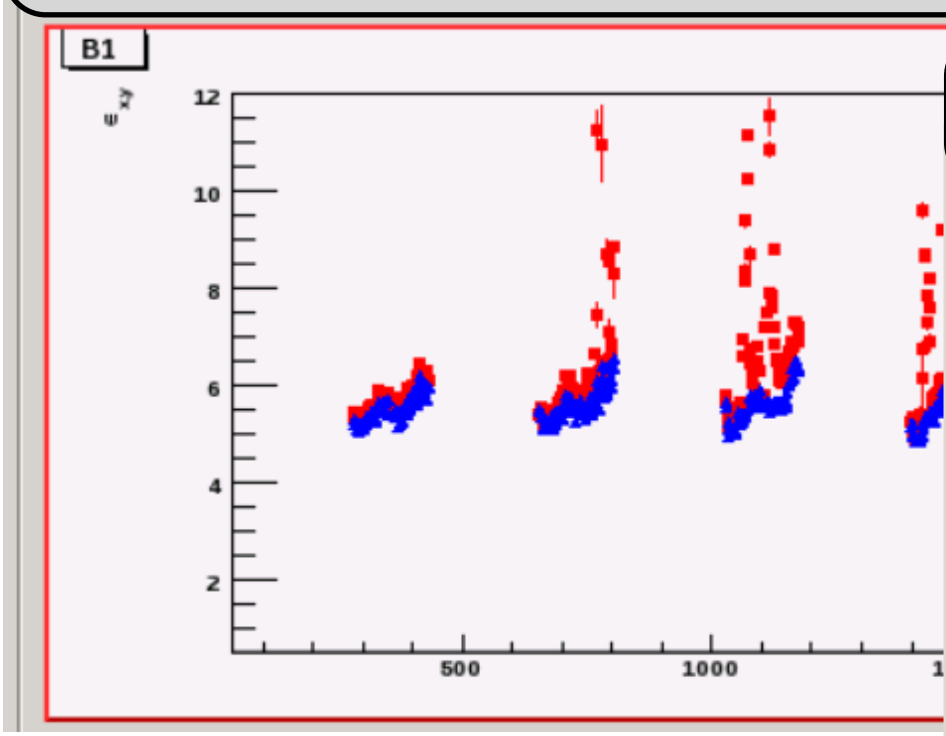
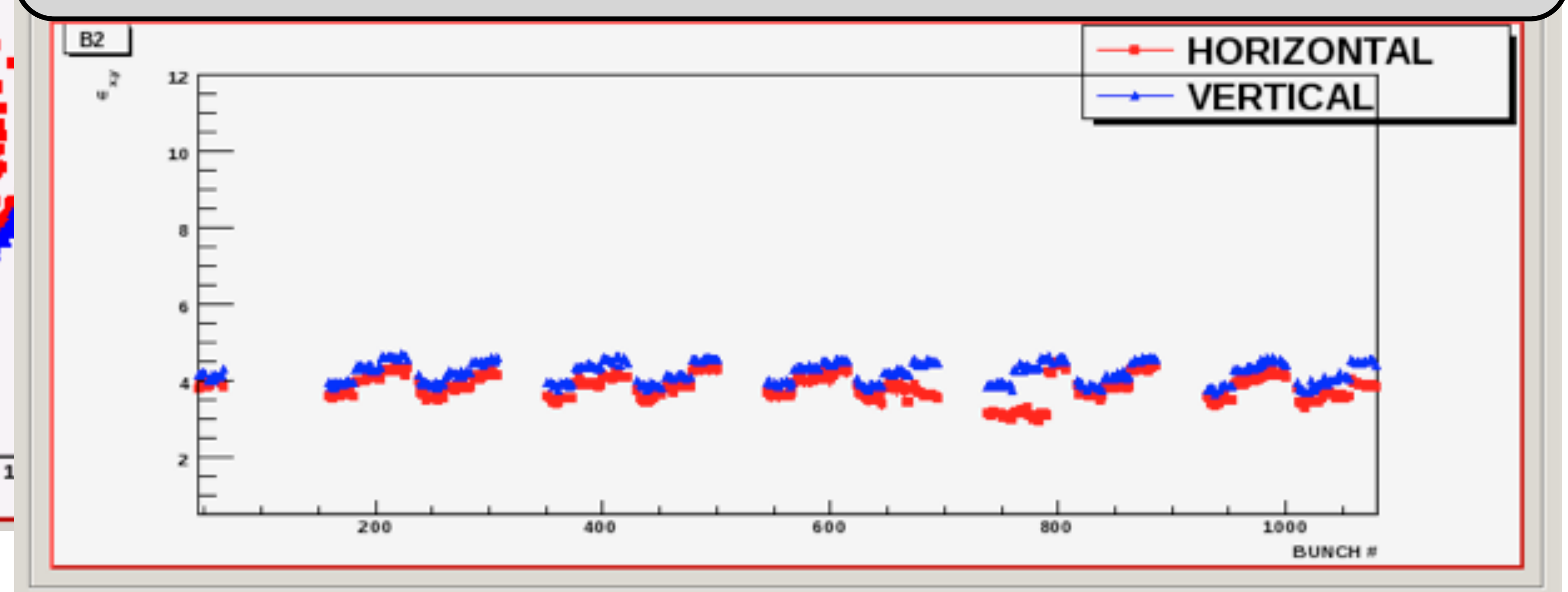


… and after some time of vacuum scrubbing



Beam Scrubbing in 2011

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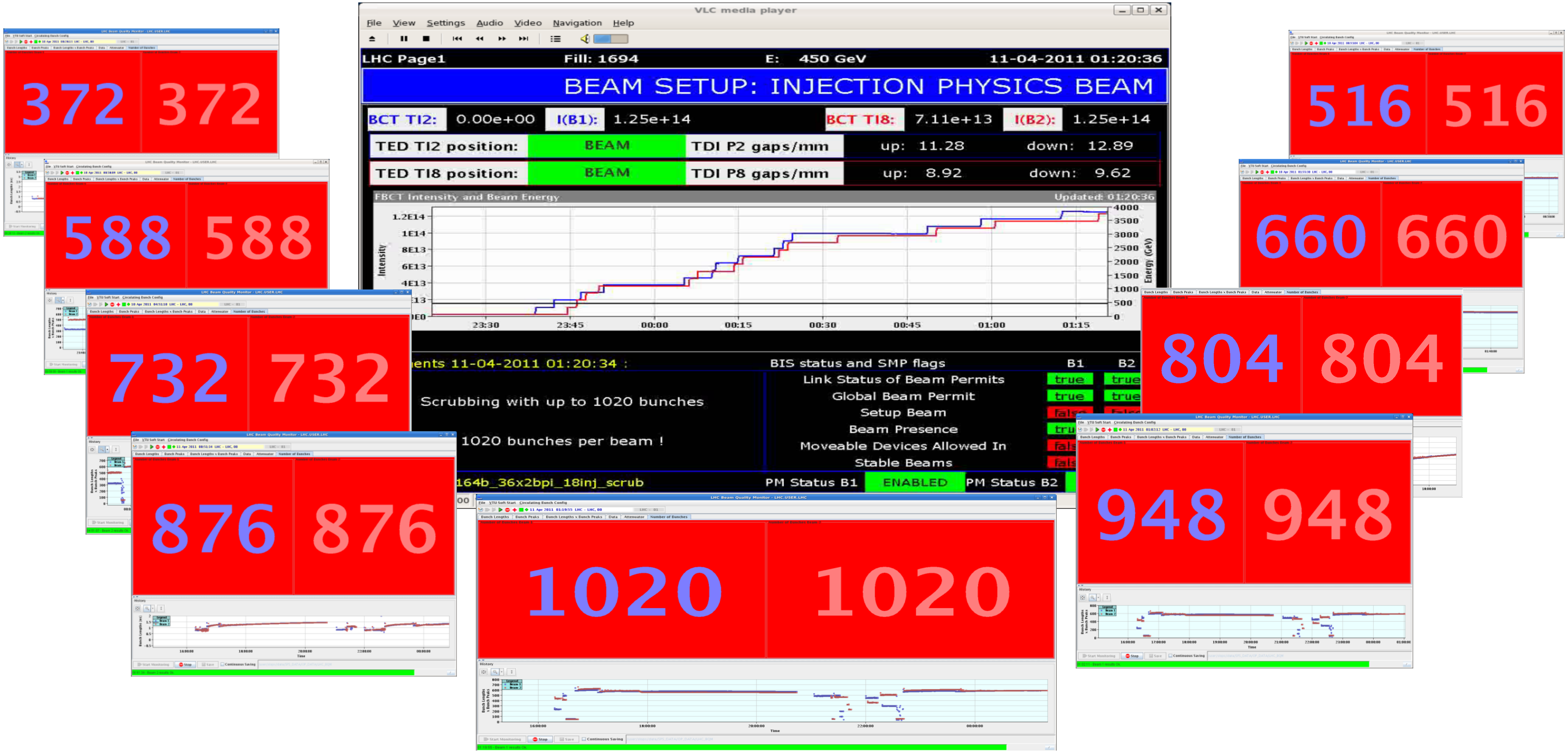
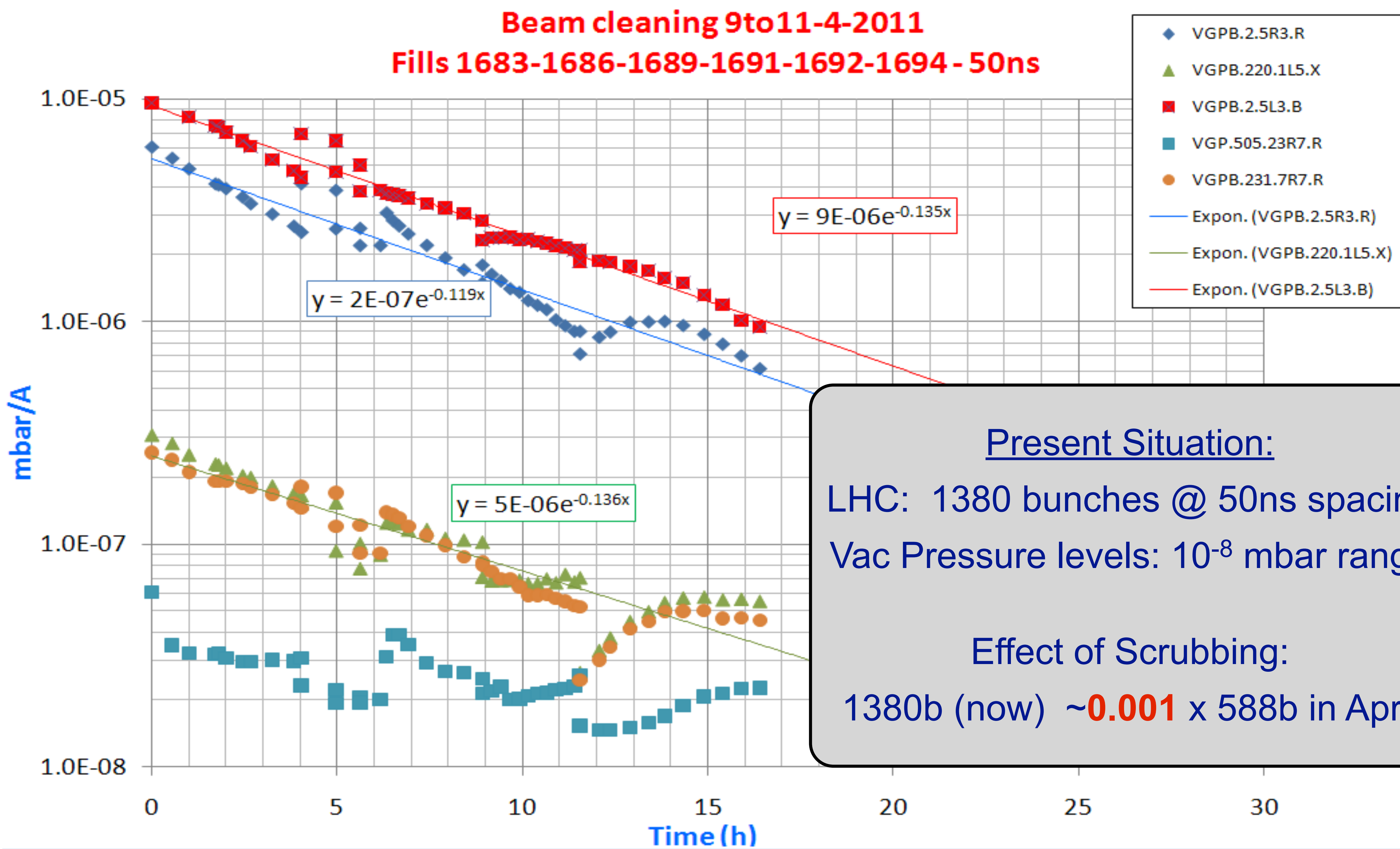


1020 bunches injected (50 ns bunch spacing) after only **15 hours** of scrubbing

Scrubbing' @ 450 GeV prepared vacuum for 50ns operation

2012: scrubbing for 25ns operation: ~150hrs of beams => **2-3 wks of scrubbing**

Beam cleaning by scrubbing



Present Situation:

LHC: 1380 bunches @ 50ns spacing

Vac Pressure levels: 10^{-8} mbar range

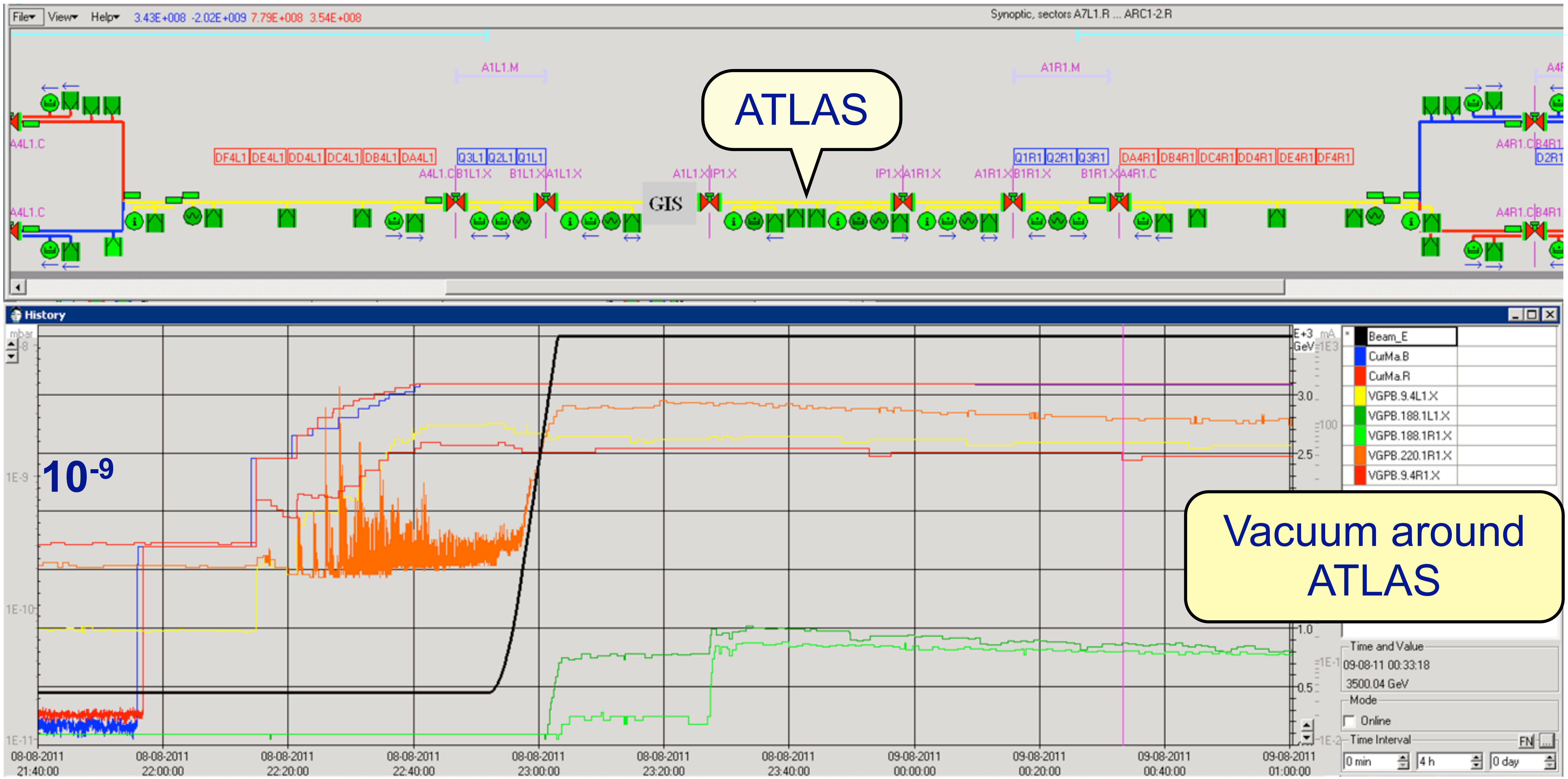
Effect of Scrubbing:

1380b (now) ~**0.001** x 588b in April

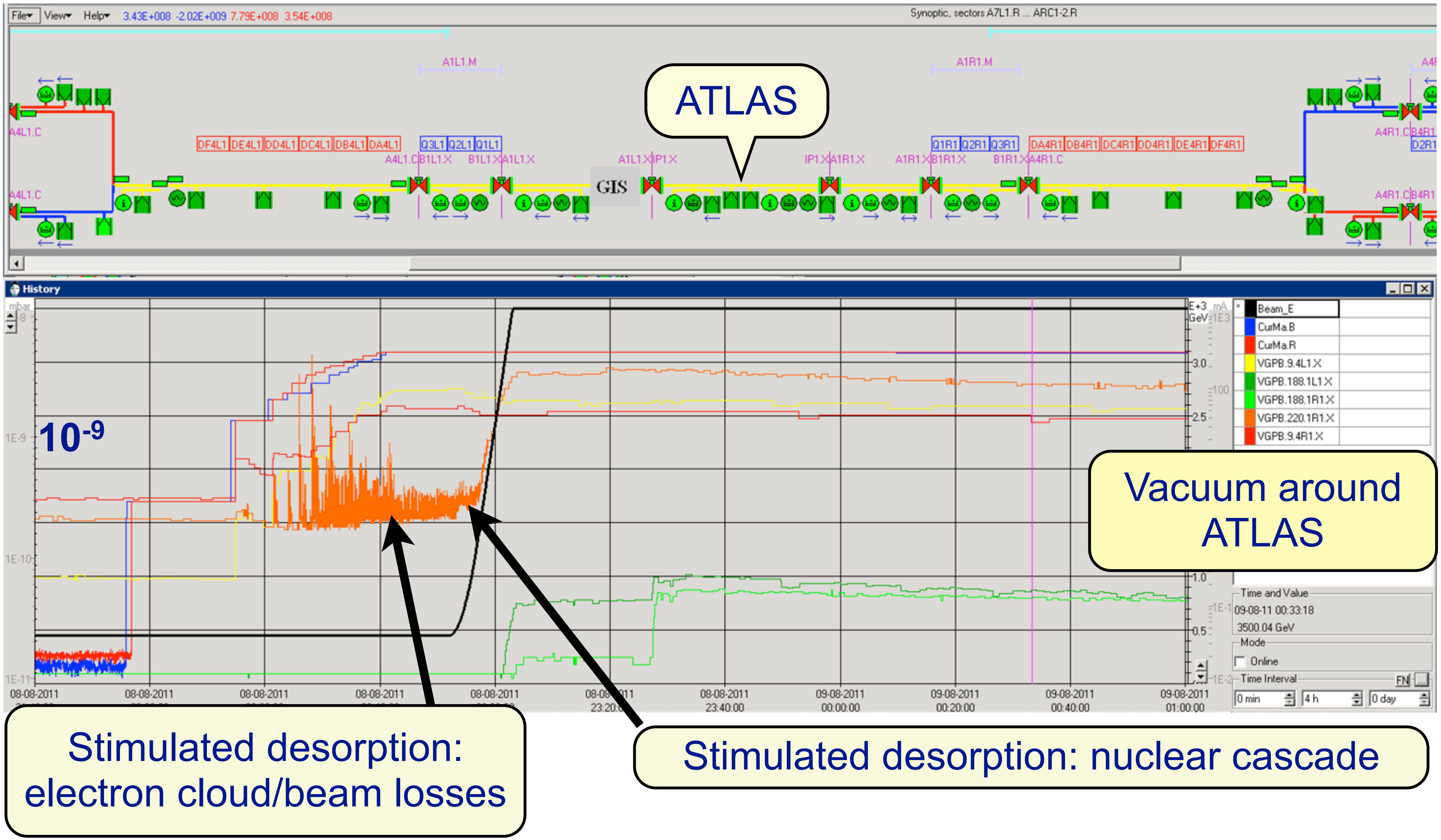
Now: No electron cloud in Arcs or NEG coated beampipes (@50ns)

... but for 25ns bunch spacing electron cloud is expected

Situation Now: 50 ns Beams in Physics



Situation Now: 50 ns Beams in Physics

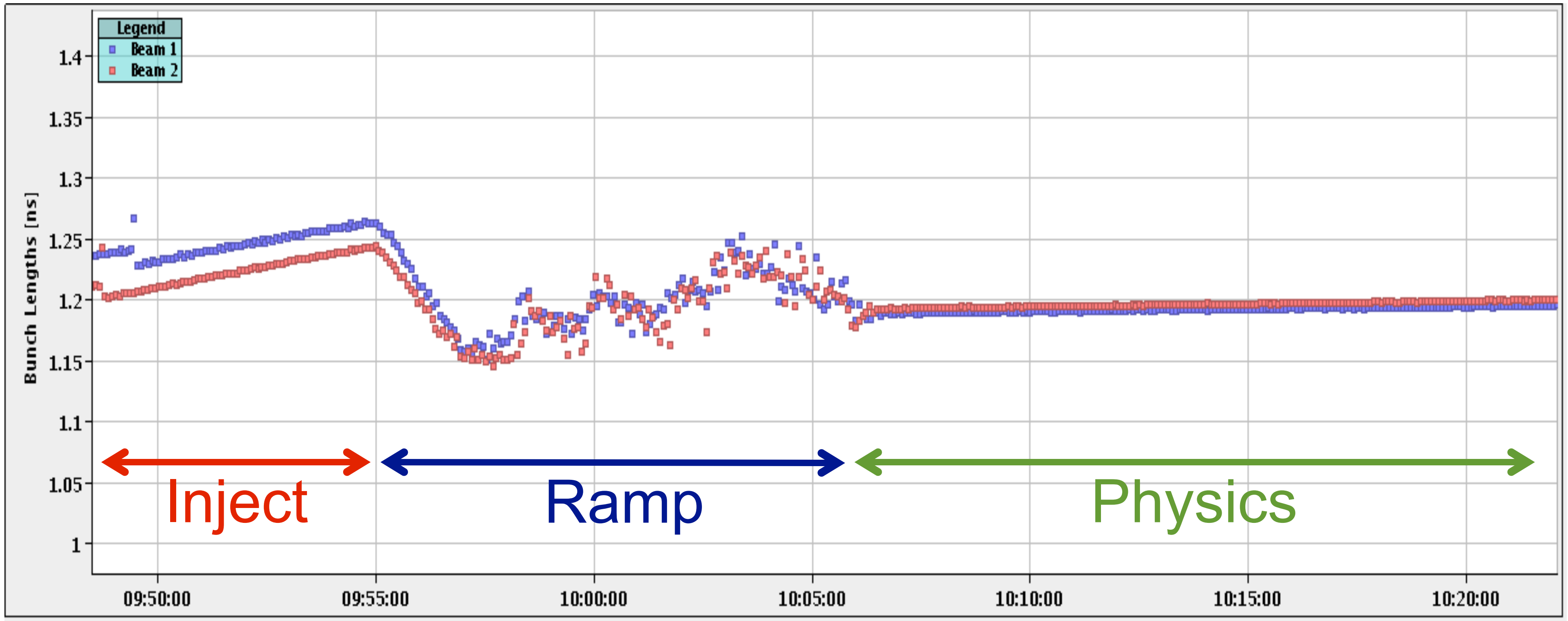


Beam Induced Heating

- **Significant measured temperature rise due to heating by the beam**
  - LHC injection kickers (MKI)
  - Cryogenic beam screens
  - Collimator(s)

Beam induced heating has strong bunch length dependence

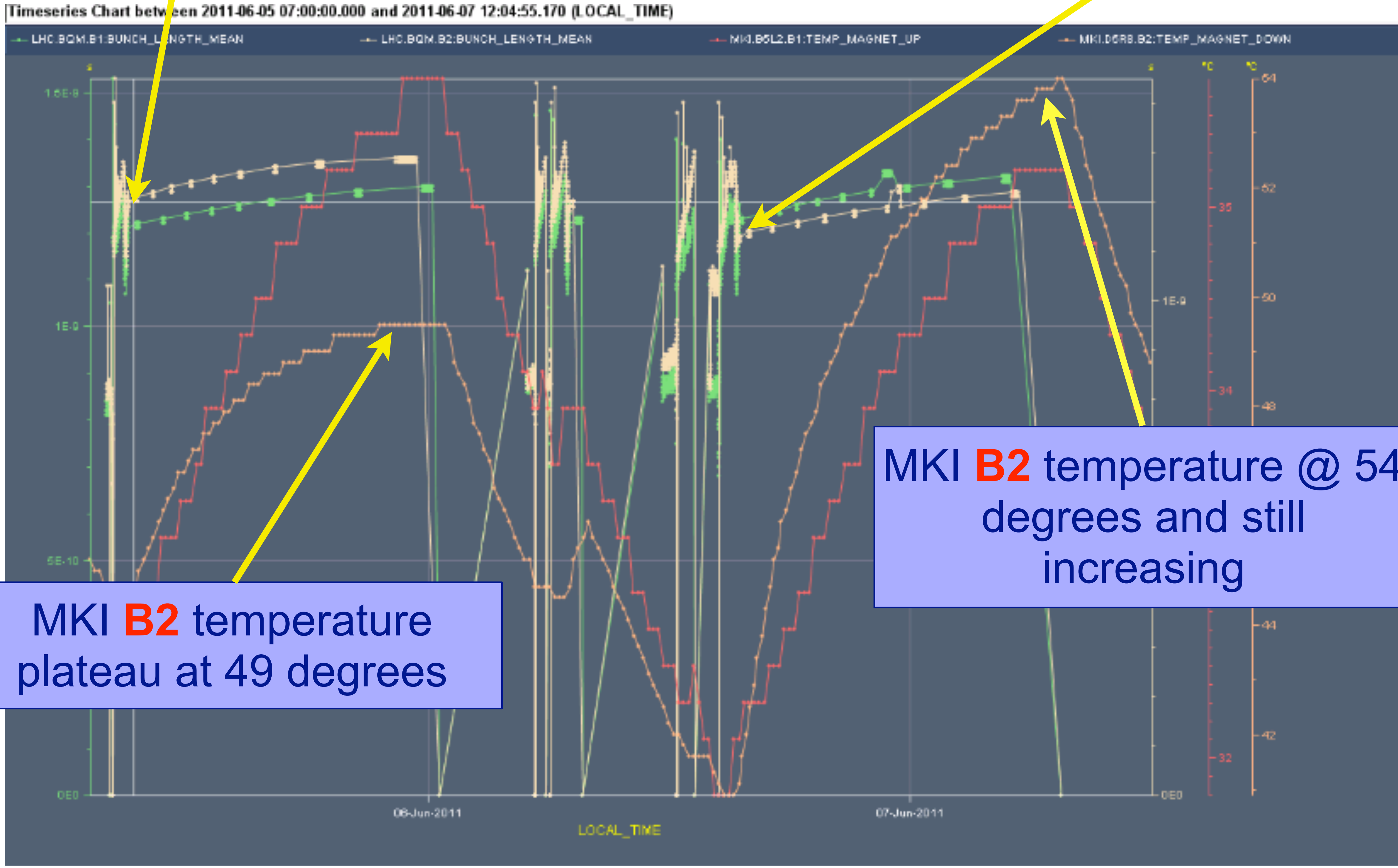
- Operational solution: **run with bunch length increased to 1.2 ns**
  - Possible increase of longitudinal losses and population of abort gap
  - Improving beam blow-up control during the ramp (RF)
  - Trapped Higher Order Modes: could an explain bunch length dependence
    - dynamic beam impedance study ongoing



Example: Injection kicker heating

B2 bunch length 1.2 ns

B2 bunch length 1.13 ns

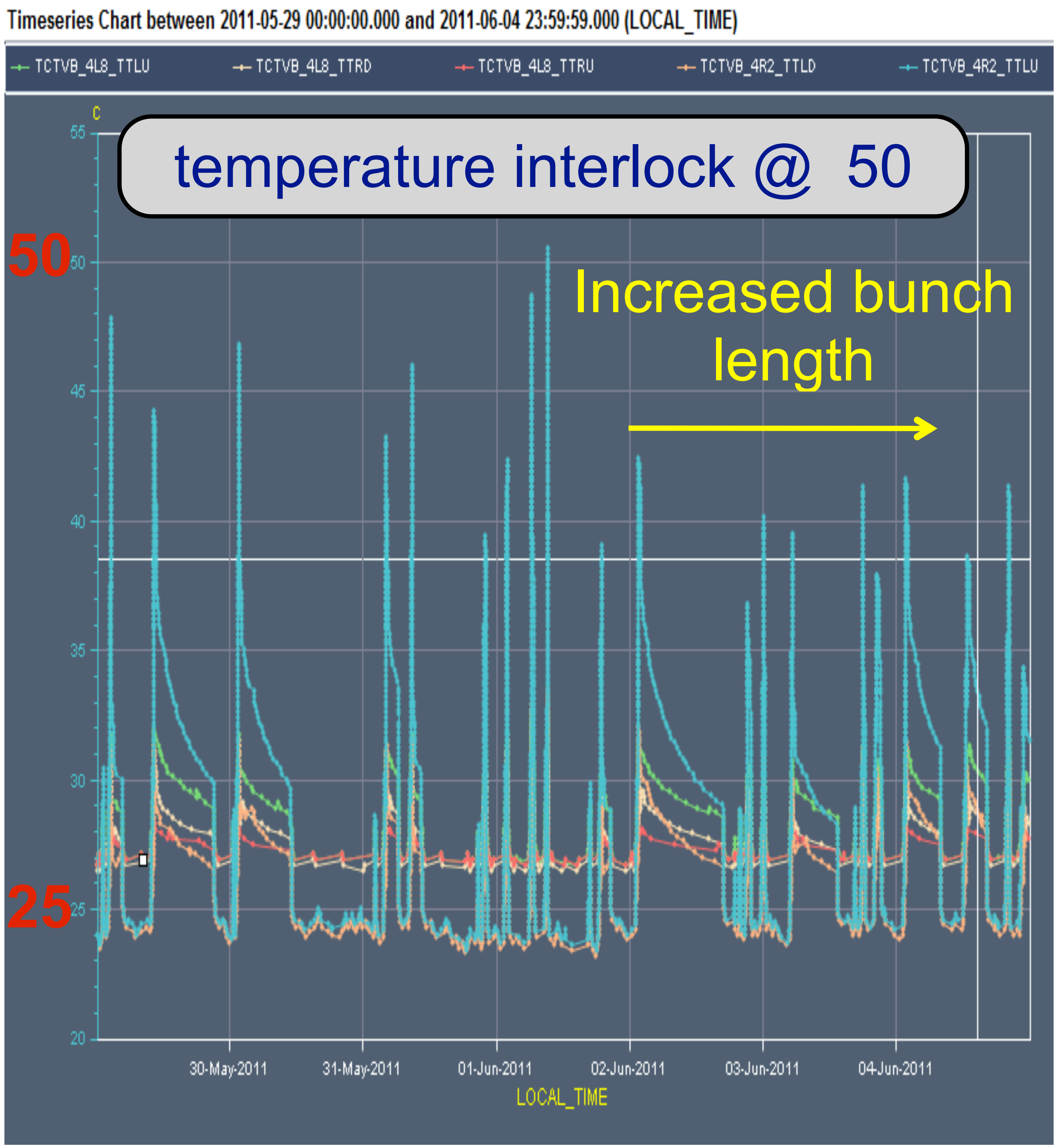


MKI **B2** temperature plateau at 49 degrees

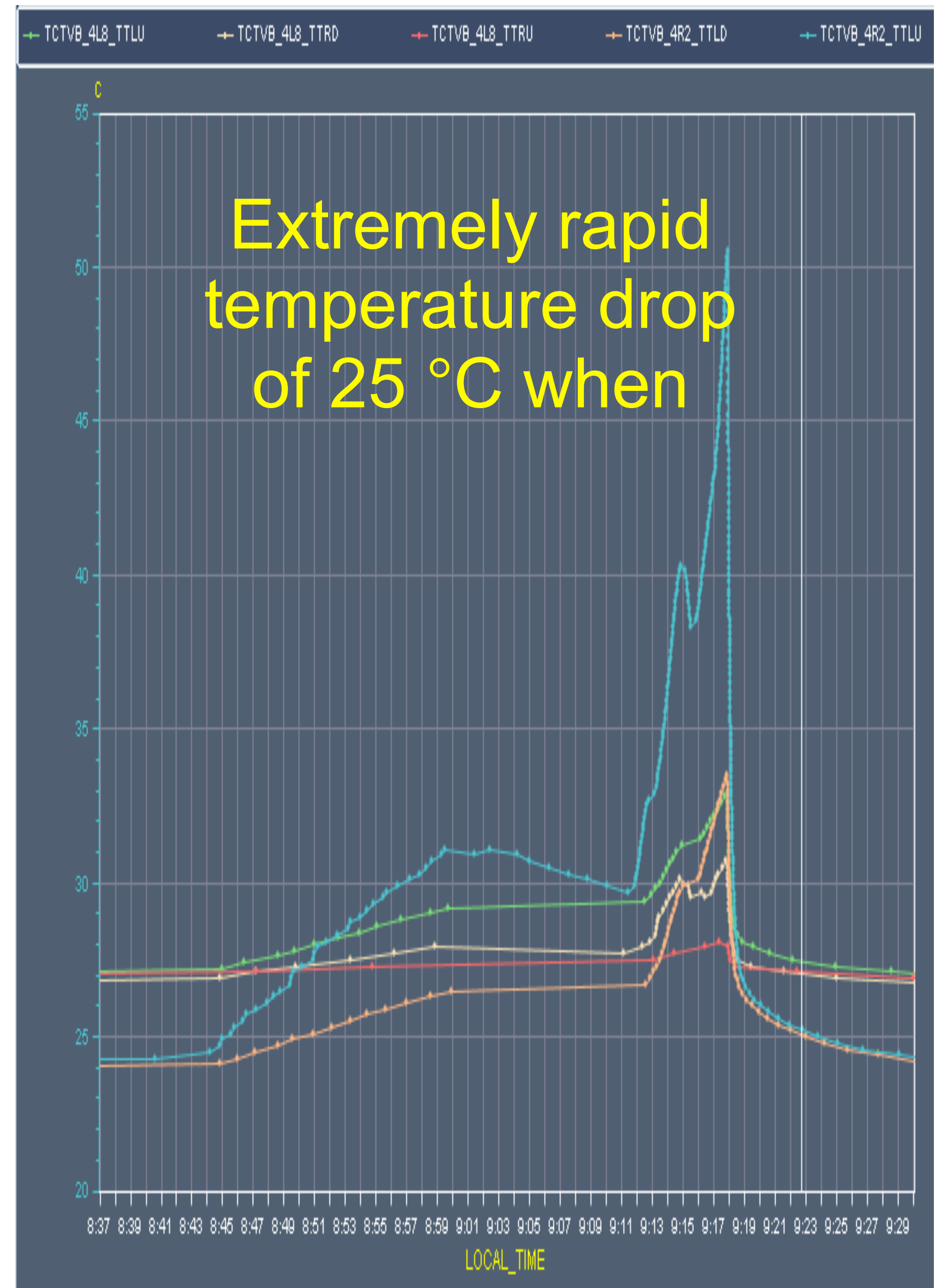
MKI **B2** temperature @ 54 degrees and still increasing

Example: Collimator heating (TCT)

- Temperature Rise on Tertiary Collimators (close to expts)
  - maximum rise typically when ramping: bunch length is shortest

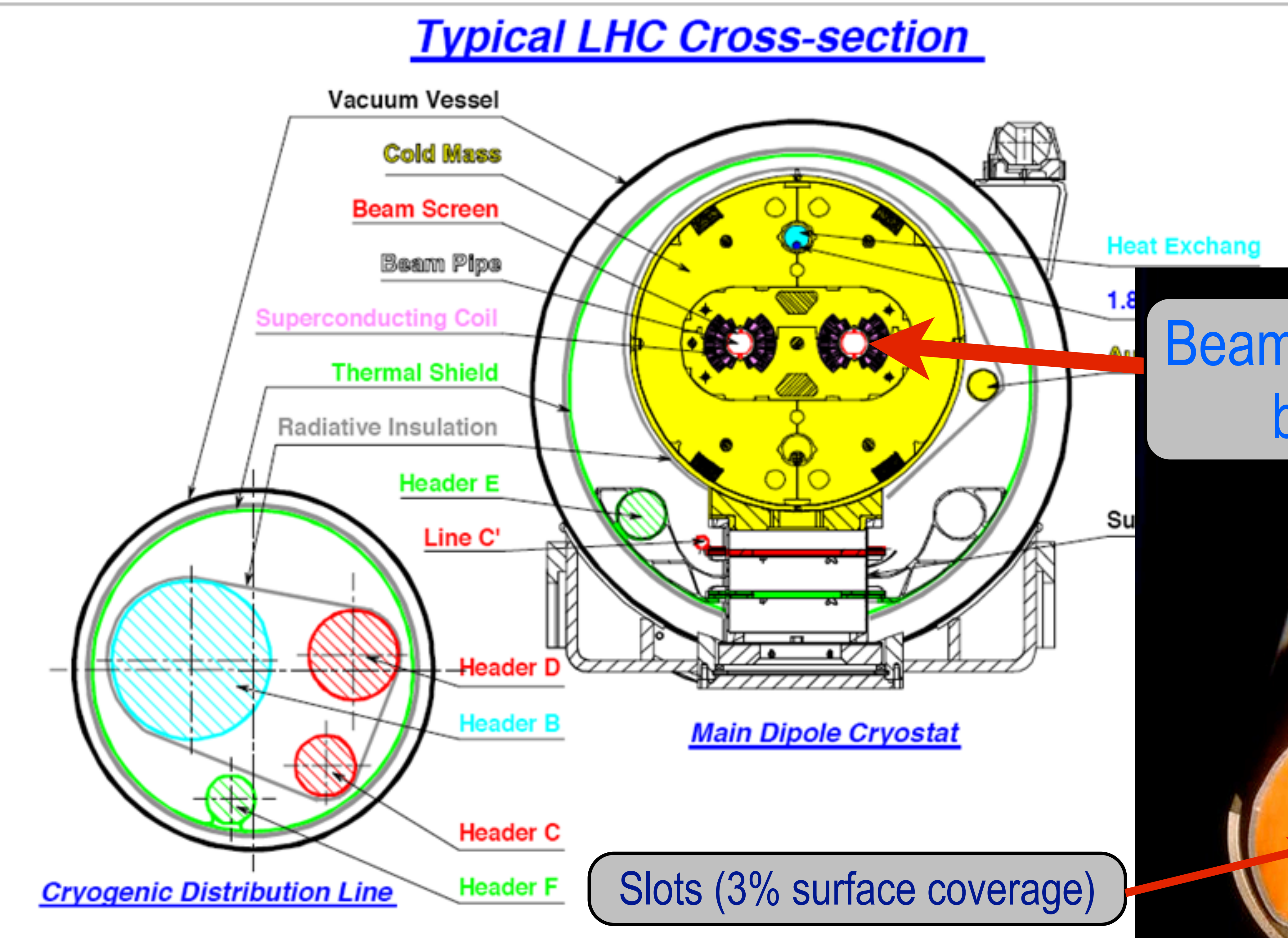


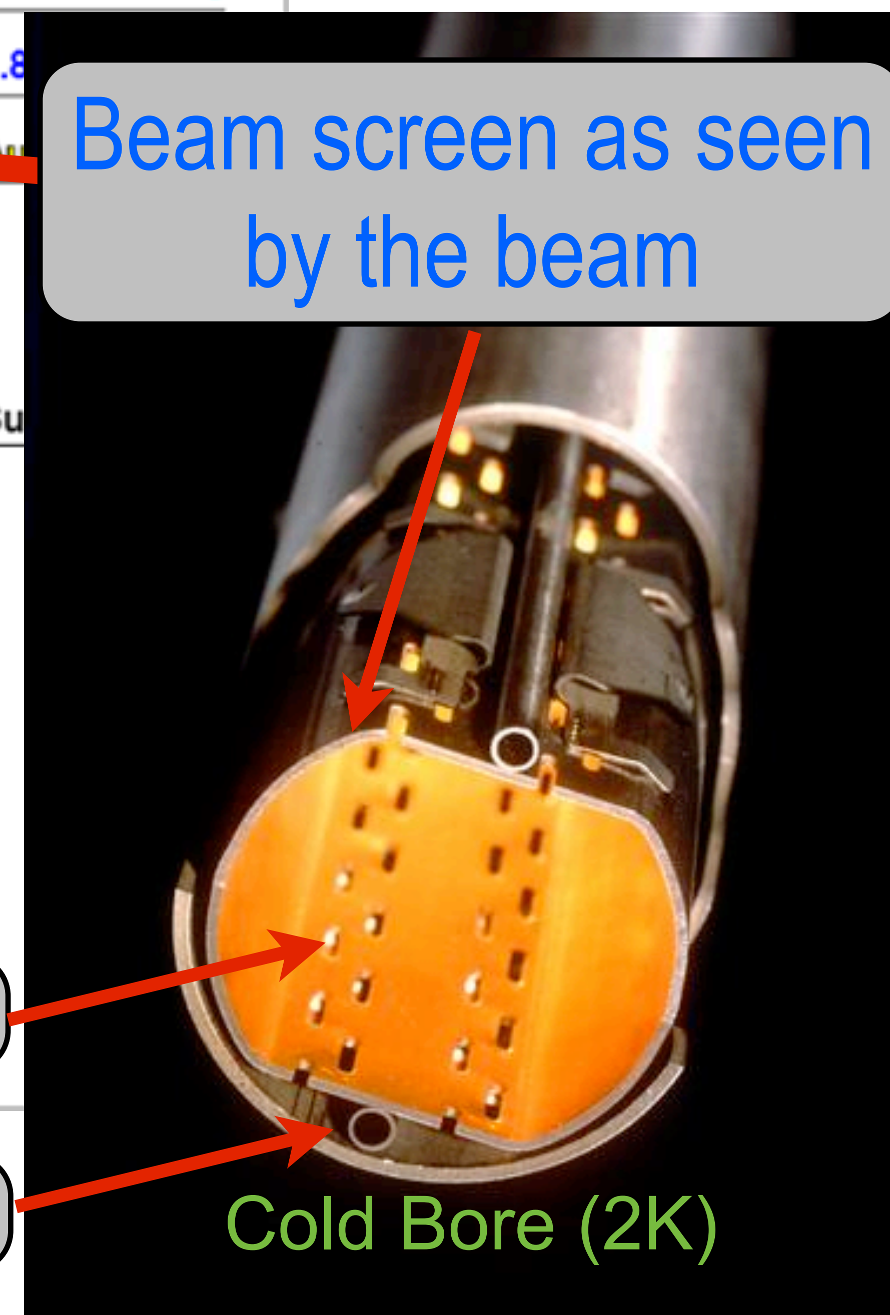
7 Days



12 minutes

LHC Cryogenic Dipoles & Beam Screens



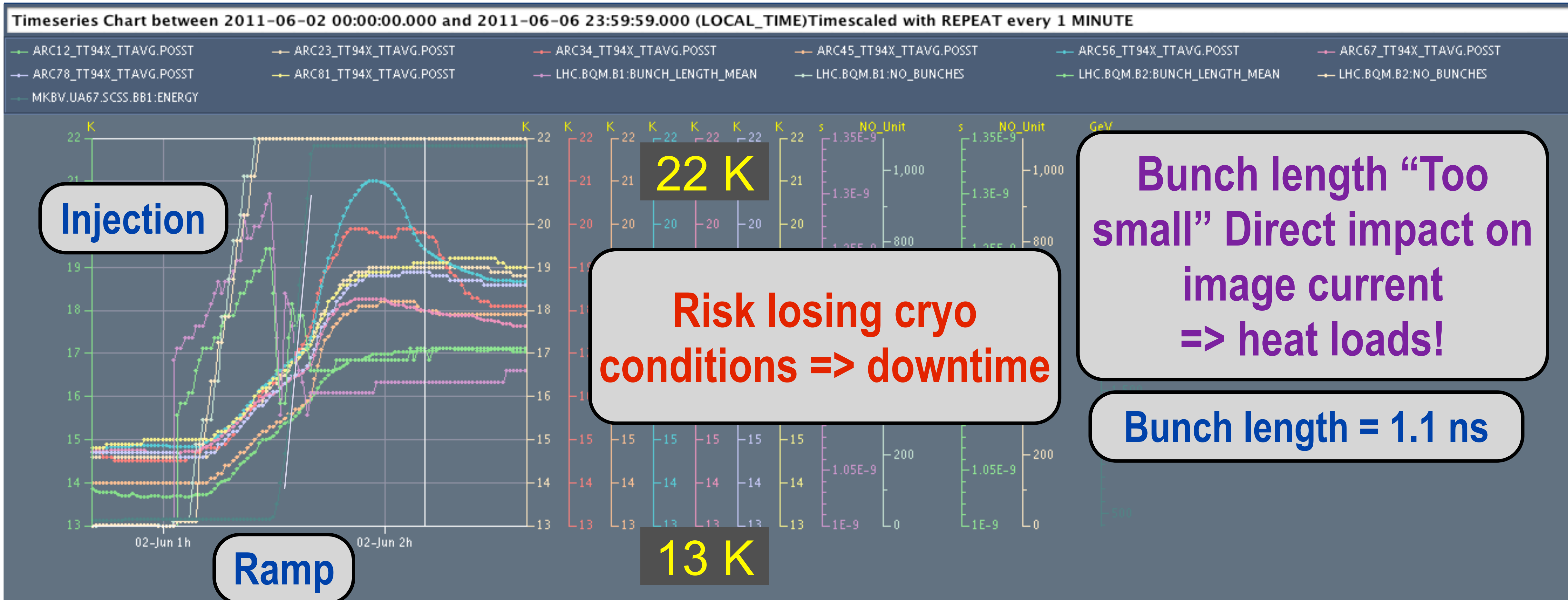


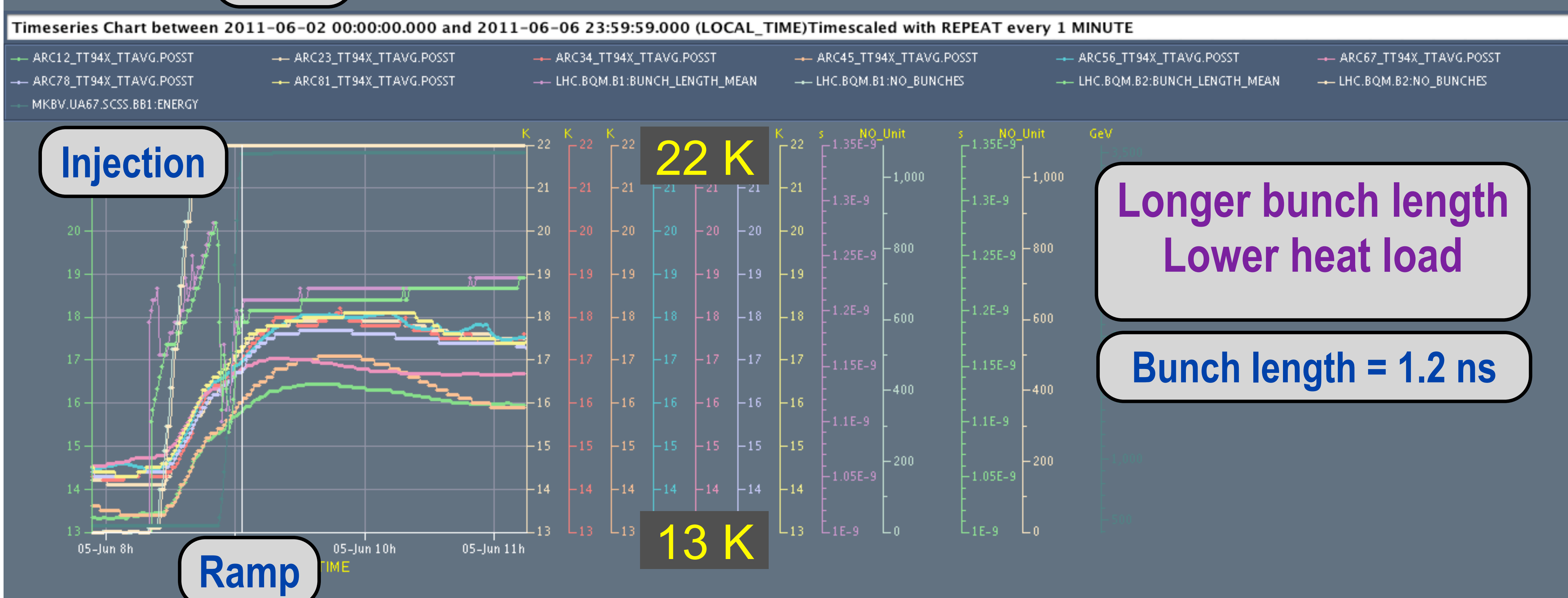
Beam screen as seen by the beam

Slots (3% surface coverage)

Beam Screen cooling pipes

Beam Heating and Beam Screens



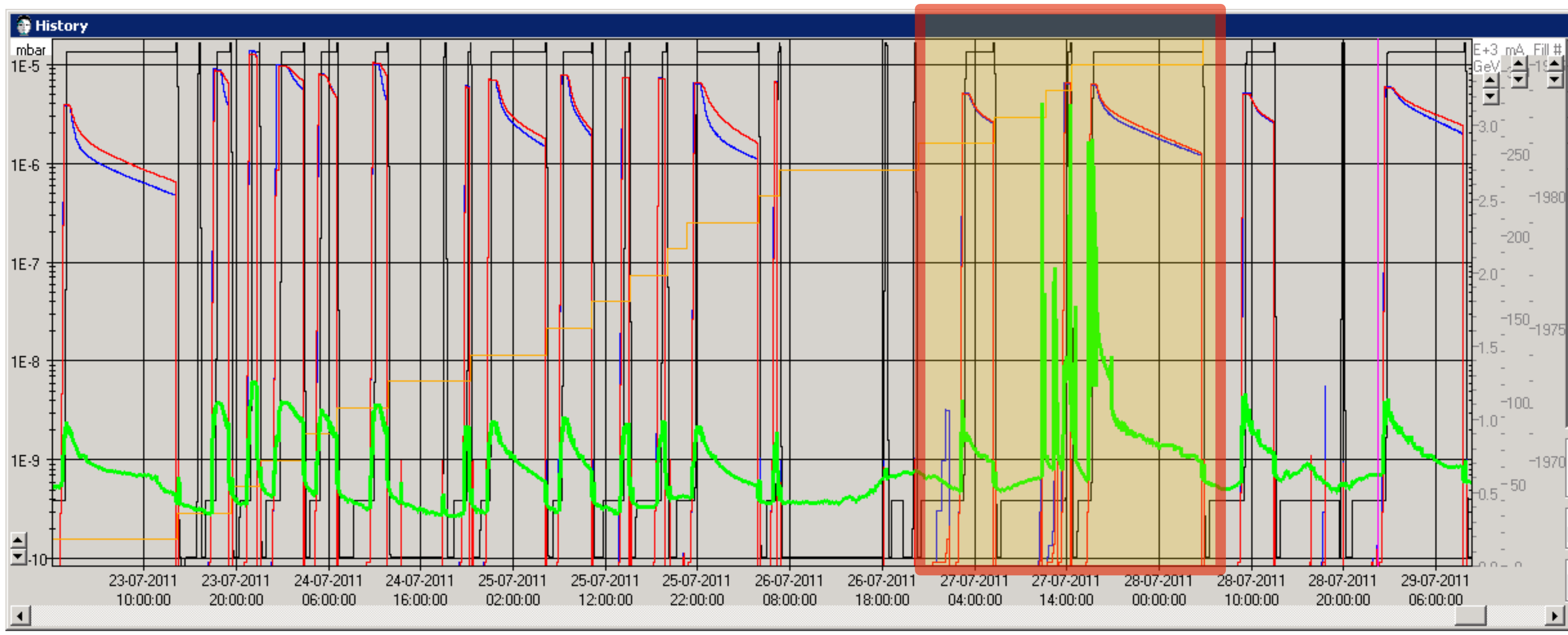


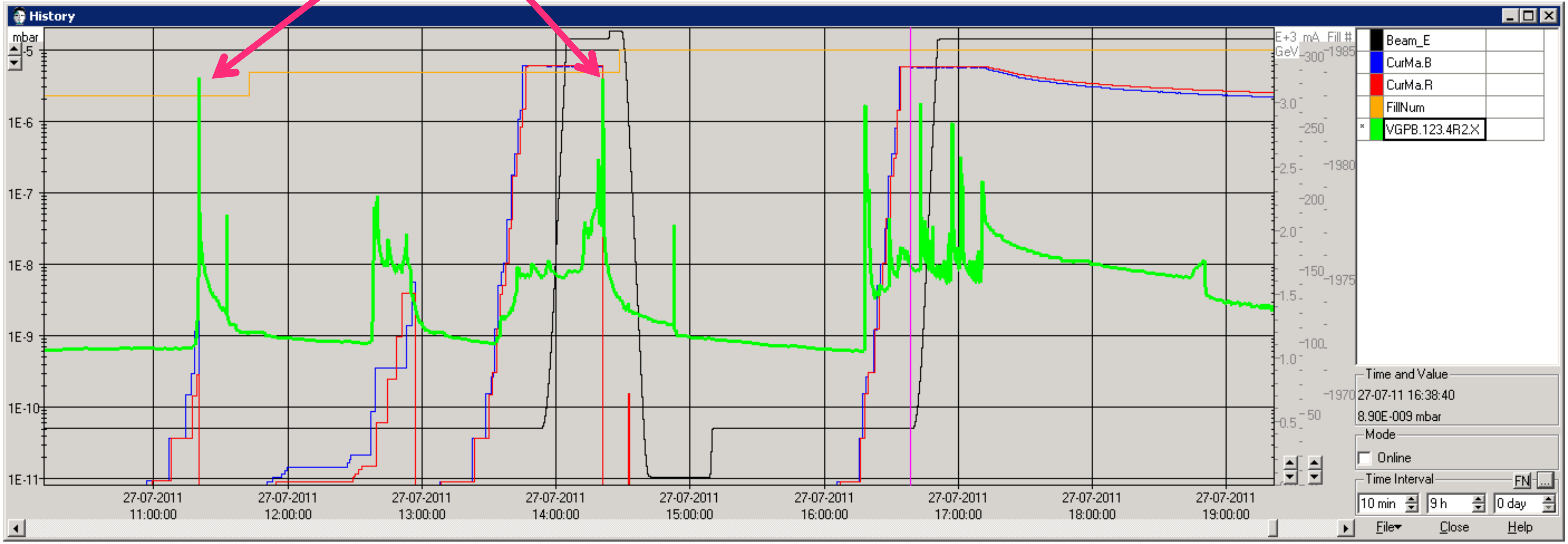
Pressure Spikes close to the expts

Vacuum Pressure at the D1 (Right side of ALICE)

Pressure spikes at injection

Reason not clear but triggered beam dump (ie not e-cloud and not vacuum Ion pumps)





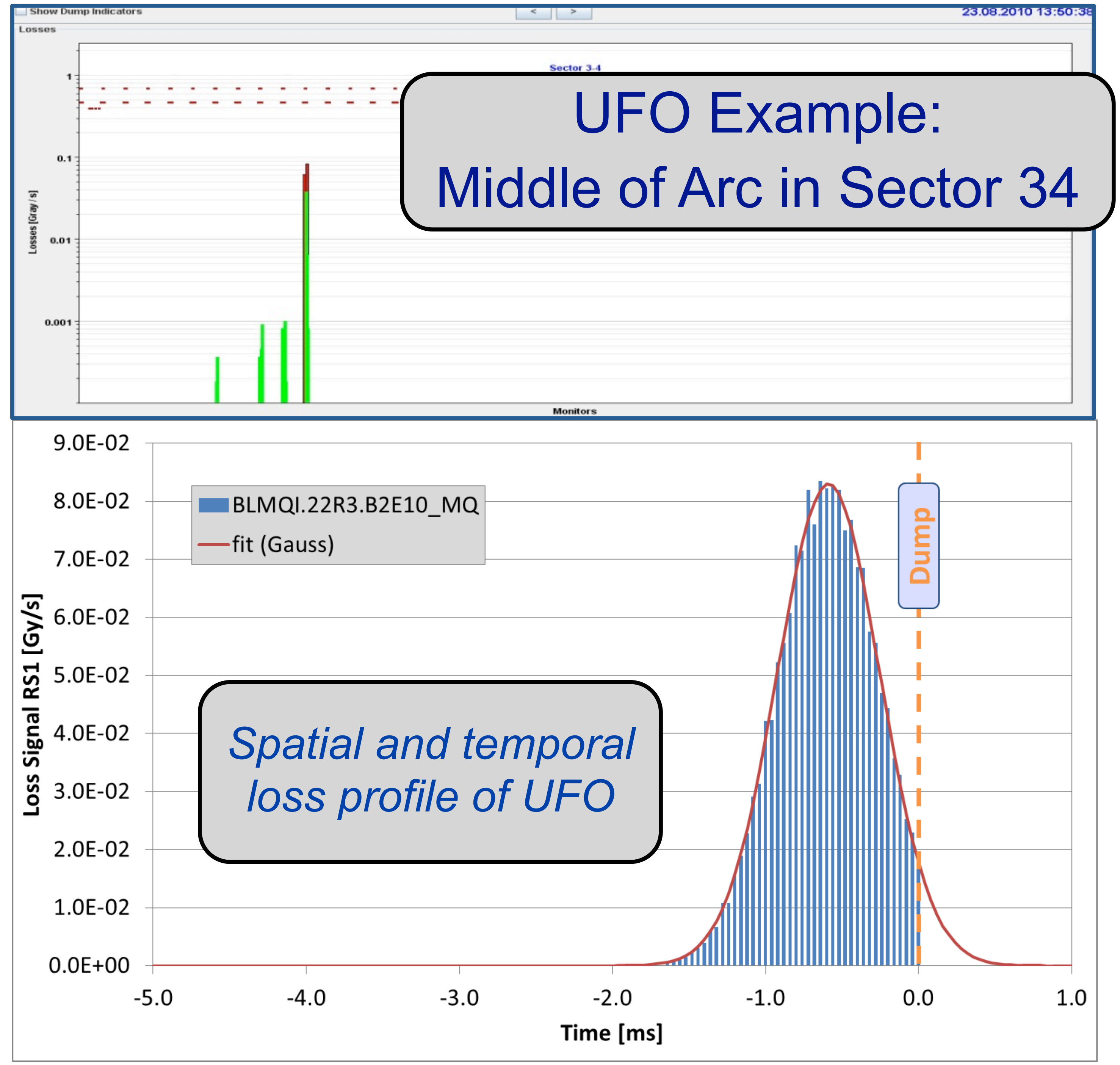
UFOs in the LHC

- Since July 2010:

  35 fast loss events led to a beam dump.

  18 *in 2010,* ***17*** *in 2011.*
  13 *around MKIs.*
  6 *dumps by experiments.*
  1 *at 450 GeV.*

- Typical characteristics:
  - Loss duration: **~10 turns**
  - Often unconventional loss locations (e.g. in the arc)



The events are due to UFOs (**U**nidentified **F**alling **O**bjects).

Another UFO ...

Over 10000 candidate UFOs below threshold detected.

On average **~6 UFOs/hour** during stable beams in the arcs.

Micrometer sized macro-particles are most plausible explanation.

UFOs cause beam dumps at all energies

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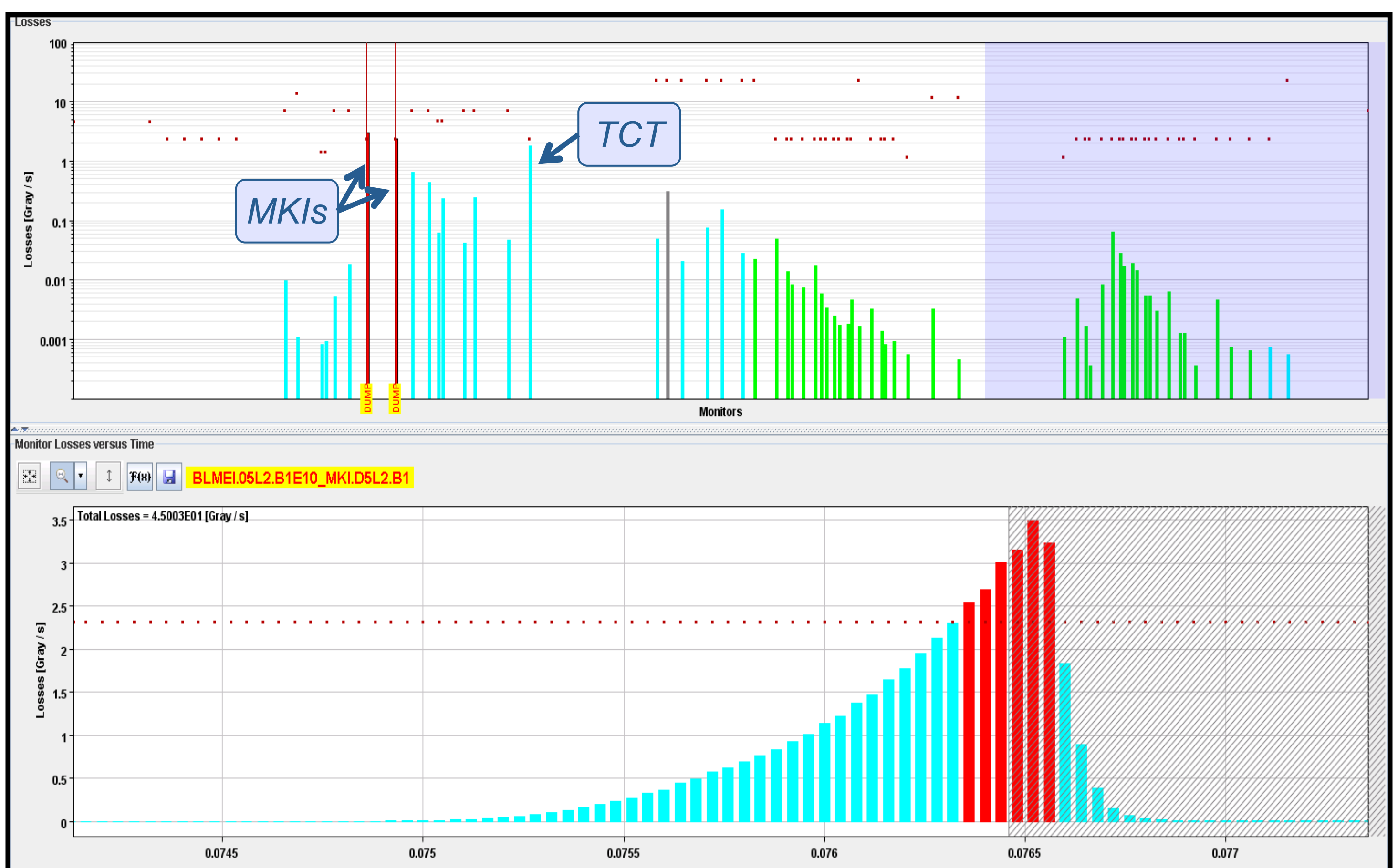
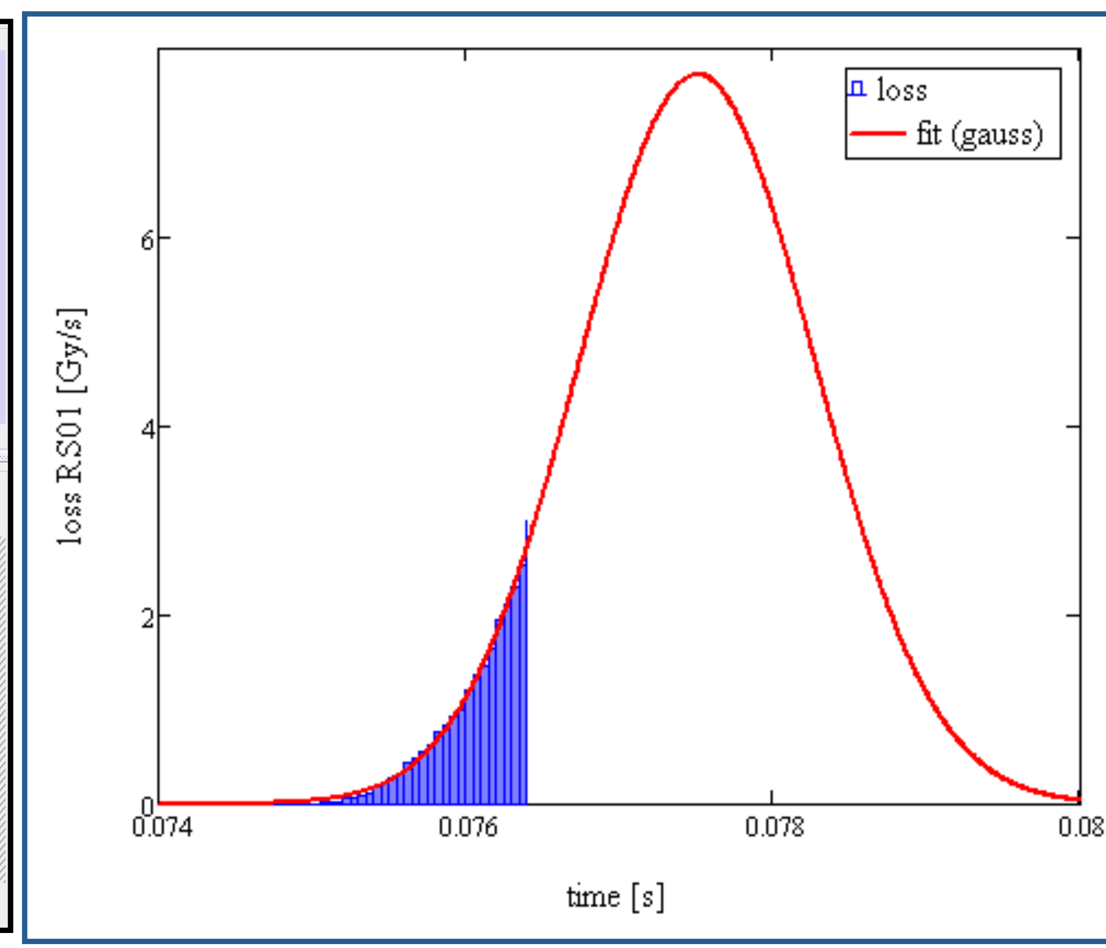
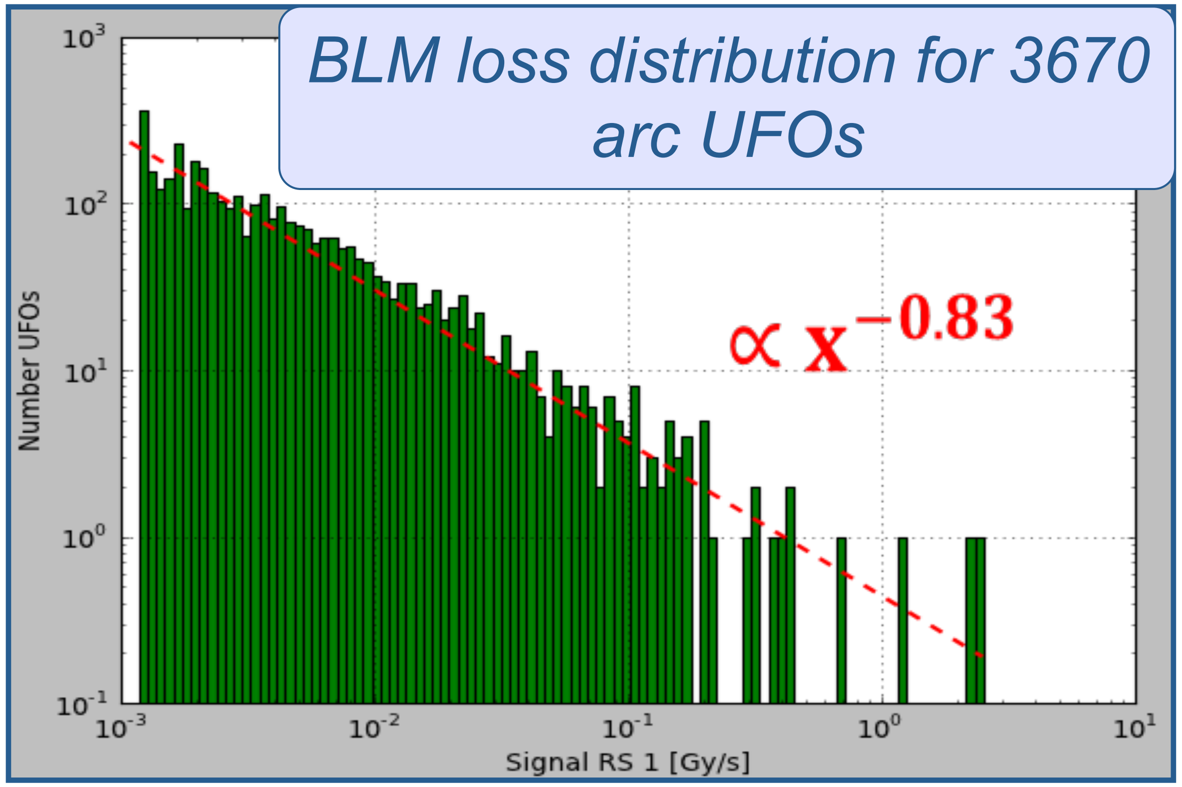
UFOs cause beam dumps at all energies

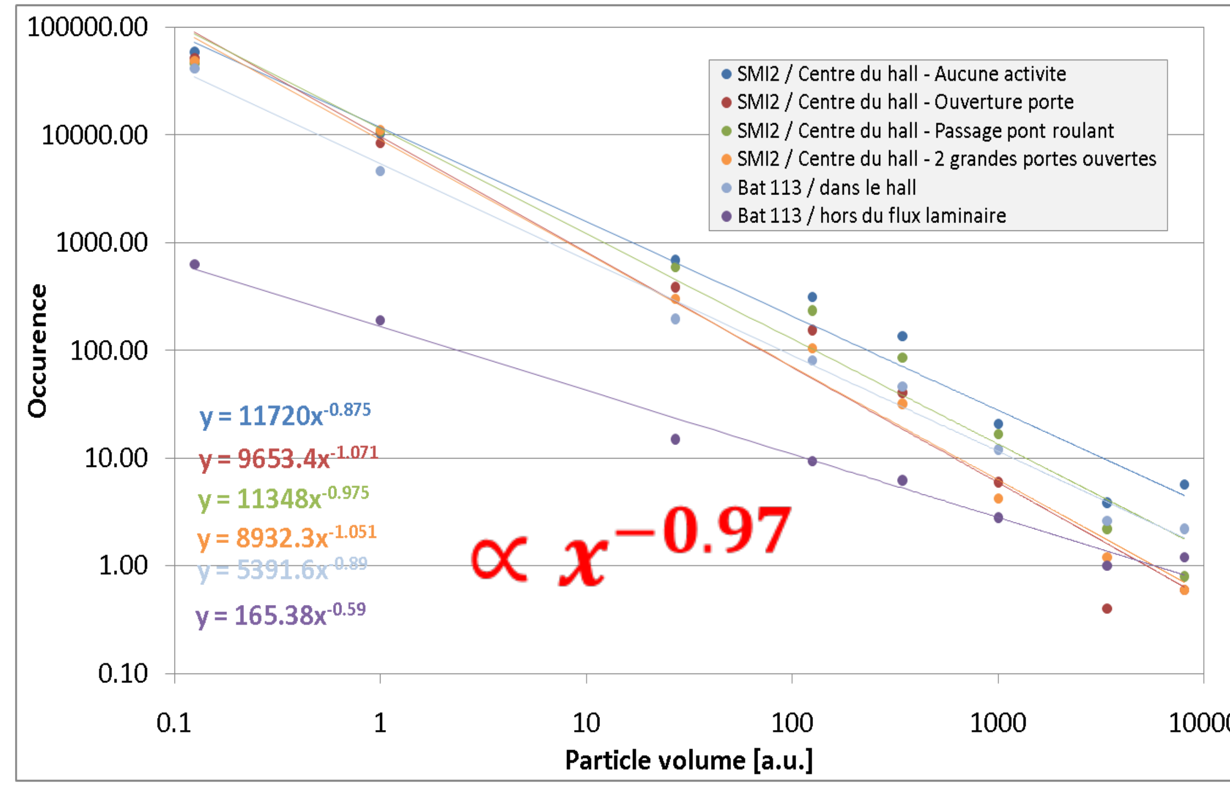
Beam Dump: UFO at Injection Kickers in Pt. 2, at **450 GeV.**

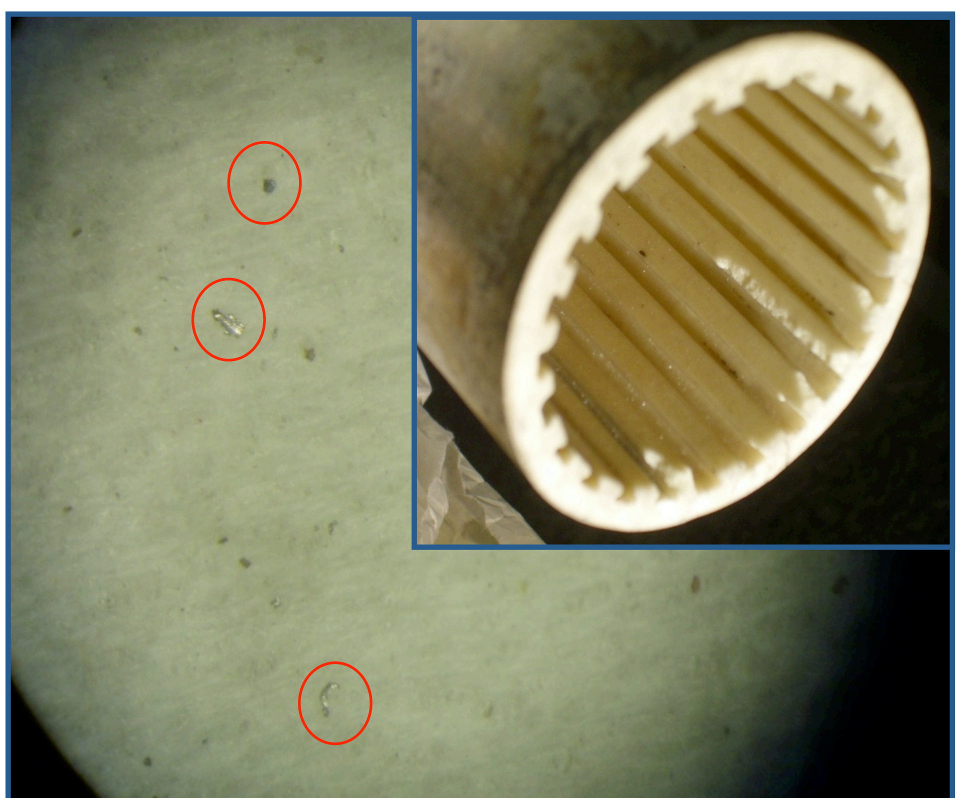




Are UFOs just Dust?







Dust particle distribution in ceramic test beam tube

... may not be representative of the LHC.

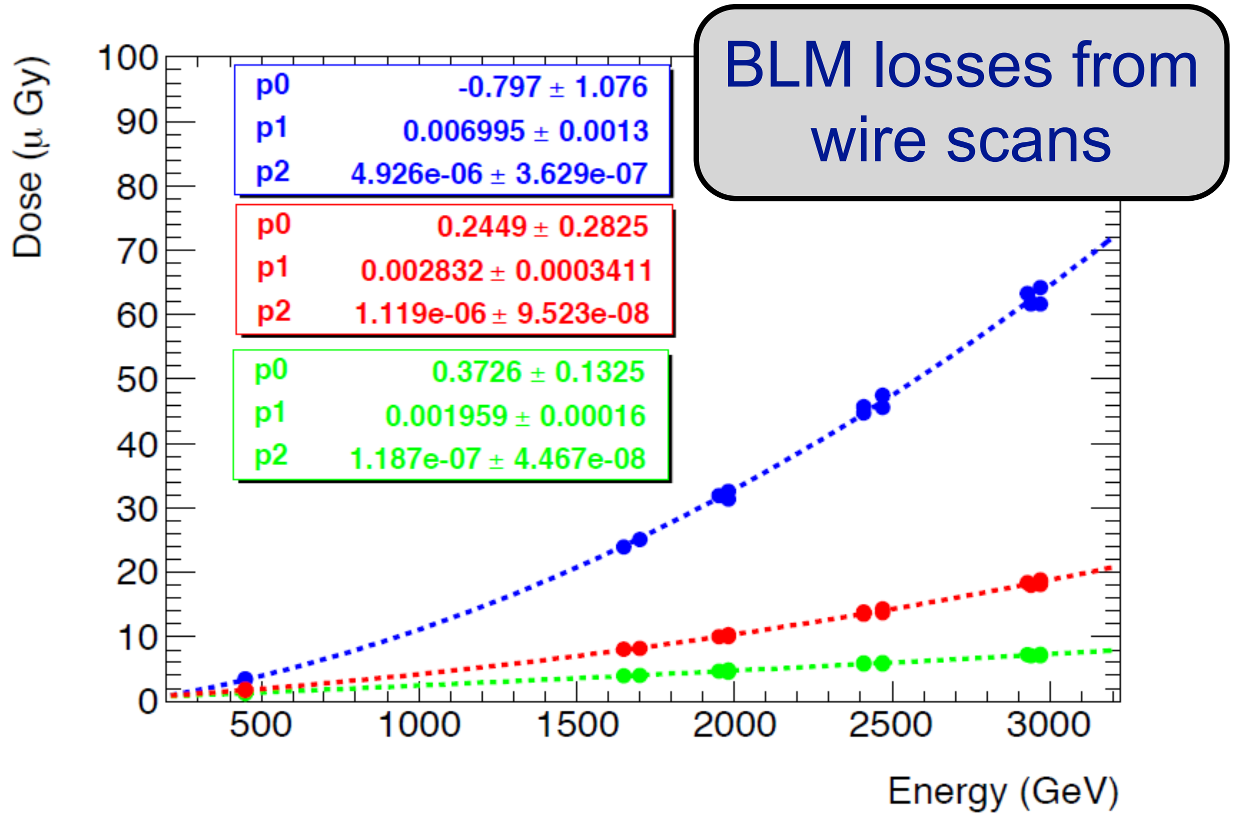
Measured 1/x distribution of dust particles seen in vacuum test stand could explain UFO distribution.

UFOs: Implications for Higher Energies

- UFO amplitude: At 7 TeV about **3 times higher** than at 3.5TeV.

- Beam Loss Monitor thresholds:

  Arc thresholds at 7 TeV are a **factor 5 smaller** than at 3.5 TeV.



- UFO rate:
  - Observations suggest no dependency with energy

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- Beam Loss Monitor thresholds:
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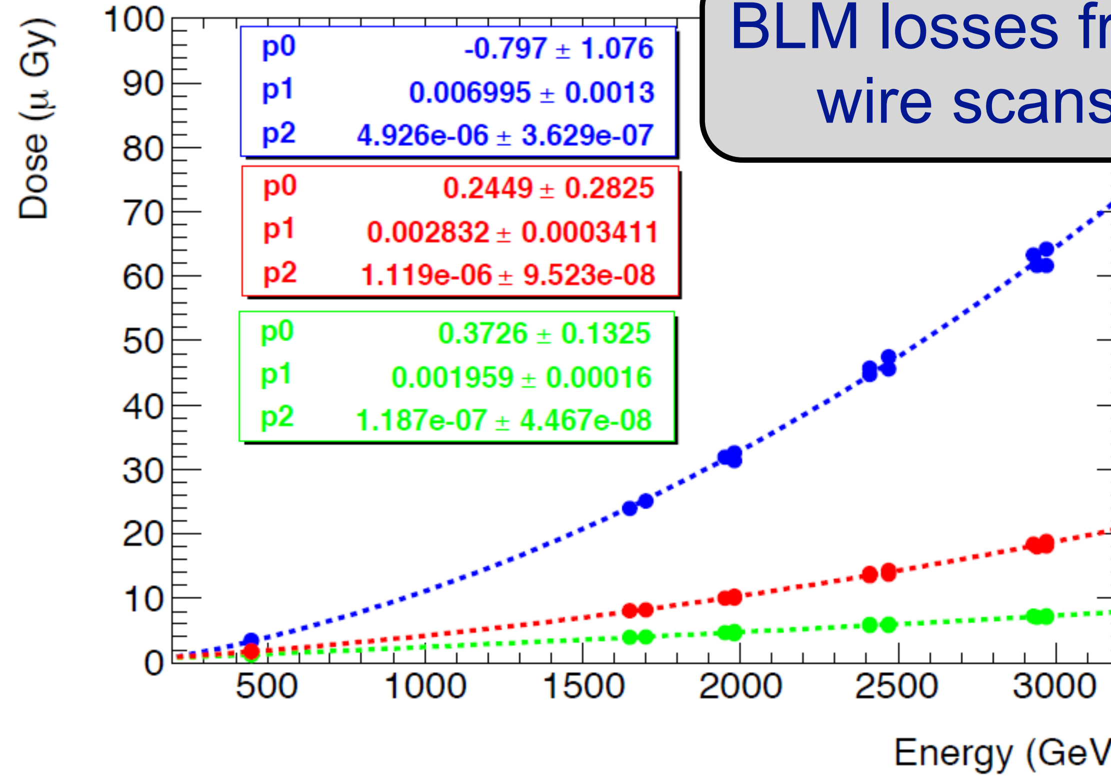
BLM losses from wire scans



- UFO rate:
  - Observations suggest no dependency with energy

Arc UFO beam dump Estimates: Scaling from 3.5 TeV to 7 TeV

2 beam dumps @ 3.5TeV => 82 dumps by arc UFOs@ 7TeV

Radiation Levels: Measured & Expected

Weekly Report

Radiation levels in the LHC (R2E-related)

Week 26 (27.06.2011 00:00h - 03.07.2011 23:59h)

Comments:
- Locations with cumulated fluences <1E6 HEH/cm2 are those where the RadMons counts (@5V & @3V) are statistically not relevant
- RadMon readings in shielded areas are <u>strongly</u> affected by the thermal neutron component
- If more than one detector exists for an area, the highest level is taken into consideration
- BLM dose takes detailed offset correction into account (BE/BI)
- W25: physics + MD week. 27th and 28th June were the last two days with lumi fills. Afterwards the week was dedicated to machine developments. Some losses expected but significantly lower than a normal physics fill.
- UJ14/16 show highest values for shielded areas, US85 > 1E7 , UJ56 ... > several SEE failures during the week

Uncertainties:
Tunnel locations - factor of 2x
Shielded areas - factor of 3x

Lumi/week	ATLAS (μb^{-1})	ATLAS (peak) ($Hz*\mu b^{-1}$)	CMS (μb^{-1})	CMS (peak) ($Hz*\mu b^{-1}$)	ALICE (μb^{-1})	LHCb(μb^{-1})
	109.5	1262.2	106.7	1243.7	0.3	42.7

	shielded areas		tunnel		
RRs	HEH (cm-2/w26)	HEH (cm-2/2011)	HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
13	<1.0E+6	2.1E+06	3.5E+06	8.8E+07	<10
17	<1.0E+6	2.2E+06	3.5E+06	6.7E+07	<10
53	<1.0E+6	2.9E+06	5.2E+06	9.7E+07	<10
57	<1.0E+6	2.4E+06	<1.0E+6	8.5E+07	<10
73	<1.0E+6	2.6E+06	<1.0E+6	<1.0E+6	<10
77	<1.0E+6	4.3E+06	5.2E+06	1.1E+08	<10
	shielded areas		*tunnel*		
UJs	HEH (cm-2/w26)	HEH (cm-2/2011)	HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
14 (13, tun)	3.3E+06	5.7E+07	9.8E+09	3.8E+10	<10
16 (17, tun)	2.3E+06	4.0E+07	7.7E+08	5.2E+10	<10
22	N/A	N/A	5.2E+07	1.1E+09	<10
23	<1.0E+6	<1.0E+6	8.6E+06	1.5E+08	<10
32	N/A	N/A	<1.0E+6	<1.0E+6	1402
33	<1.0E+6	<1.0E+6	<1.0E+6	<1.0E+6	N/A
56	<1.0E+6	9.3E+06	9.8E+08	1.6E+10	<10
76	<1.0E+6	<1.0E+6	8.8E+08	8.8E+09	<10
87	<1.0E+6	1.1E+06	1.3E+08	2.4E+09	<10
88	N/A	N/A	1.5E+08	8.6E+08	<10
	shielded areas		*tunnel/side*		
REs	HEH (cm-2/w26)	HEH (cm-2/2011)	HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
28	<1.0E+6	<1.0E+6	<1.0E+6	1.3E+07	<10
32	<1.0E+6	<1.0E+6	<1.0E+6	<1.0E+6	1402
38	<1.0E+6	<1.0E+6	<1.0E+6	2.8E+07	<10
62	<1.0E+6	<1.0E+6	1.3E+06	2.0E+07	<10
68	<1.0E+6	<1.0E+6	1.3E+06	2.8E+07	<10
78	<1.0E+6	<1.0E+6	1.3E+06	2.4E+07	<10
	cavern US85		*cavern UX85*		
US85/UX85	HEH (cm-2/w26)	HEH (cm-2/2011)	HEH (cm-2/w26)	HEH (cm-2/2011)	
	<1.0E+6	1.6E+07	3.3E+06	8.3E+07	
			tunnel		
			HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
R34	N/A		3.0E+09	1.9E+10	<10
R74/76	N/A		3.9E+09	4.6E+10	<10
R771	N/A		8.8E+09	8.1E+10	<10
	shielded areas (UA)		*tunnel (RA)*		
	HEH (cm-2/w26)	HEH (cm-2/2011)	HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
P2 right (27)	<1.0E+6	<1.0E+6	8.9E+07	6.5E+08	<10
P2 left (23)	<1.0E+6	<1.0E+6	2.3E+08	2.6E+09	<10
P8 right (87)	<1.0E+6	<1.0E+6	5.4E+08	7.1E+10	<10
P8 left (83)	<1.0E+6	1.6E+06	N/A	N/A	<10

Additional points of interest (losses observed in 'unusual' locations)

	tunnel			*shielded areas*	
	HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)	HEH (cm-2/w26)	HEH (cm-2/2011)
RB44/46	2.2E+07	1.6E+09	N/A	N/A	N/A
UXC55	1.7E+08	2.7E+09	N/A	N/A	N/A
8R5	2.6E+08	4.1E+09	<10	N/A	N/A
9R5	5.5E+07	8.8E+08	<10	N/A	N/A
11R5	7.4E+07	1.1E+09	<10	N/A	N/A
UPS54	N/A	N/A	<10	2.7E+06	4.3E+07
11L1	7.6E+07	1.1E+09	<10	N/A	N/A
8L1	2.0E+09	3.3E+10	<10	N/A	N/A
ARC/DS					
18R7	4.5E+06	9.5E+07	<10		

Radiation Levels: Measured & Expected

Weekly Report → **Detailed Analysis**

Radiation leve

Week 26 (27.06.

Comments:
- Locations with cumulated fluences <1E6 HEH are statistically not relevant
- RadMon readings in shielded areas are stron
- If more than one detector exists for an area,
- BLM dose takes detailed offset correction int
- W25: physics + MD week. 27th and 28th June machine developments. Some losses expected
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Uncertainties: Tunnel locations - factor of 2x; Shielded areas - factor of 3x

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57	<1.0E+6	2.4E+06	<1.0E+6	8.5E+07	<10
73	<1.0E+6	2.6E+06	<1.0E+6	<1.0E+6	<10
77	<1.0E+6	4.3E+06	5.2E+06	1.1E+08	<10
	shielded areas		*tunnel*		
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32	N/A	N/A	<1.0E+6	<1.0E+6	1402
33	<1.0E+6	<1.0E+6	<1.0E+6	<1.0E+6	N/A
56	<1.0E+6	9.3E+06	9.8E+08	1.6E+10	<10
76	<1.0E+6	<1.0E+6	8.8E+08	8.8E+09	<10
87	<1.0E+6	1.1E+06	1.3E+08	2.4E+09	<10
88	N/A	N/A	1.5E+08	8.6E+08	<10
	shielded areas		*tunnel/side*		
REs	HEH (cm-2/w26)	HEH (cm-2/2011)	HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
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			tunnel		
			HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
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UJs	*shielded areas*		*tunnel*		
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Radiation Levels: Measured & Expected

Weekly Report → **Detailed Analysis** → **Comparison & Extrapolation**

Radiation leve

Week 26 (27.06.

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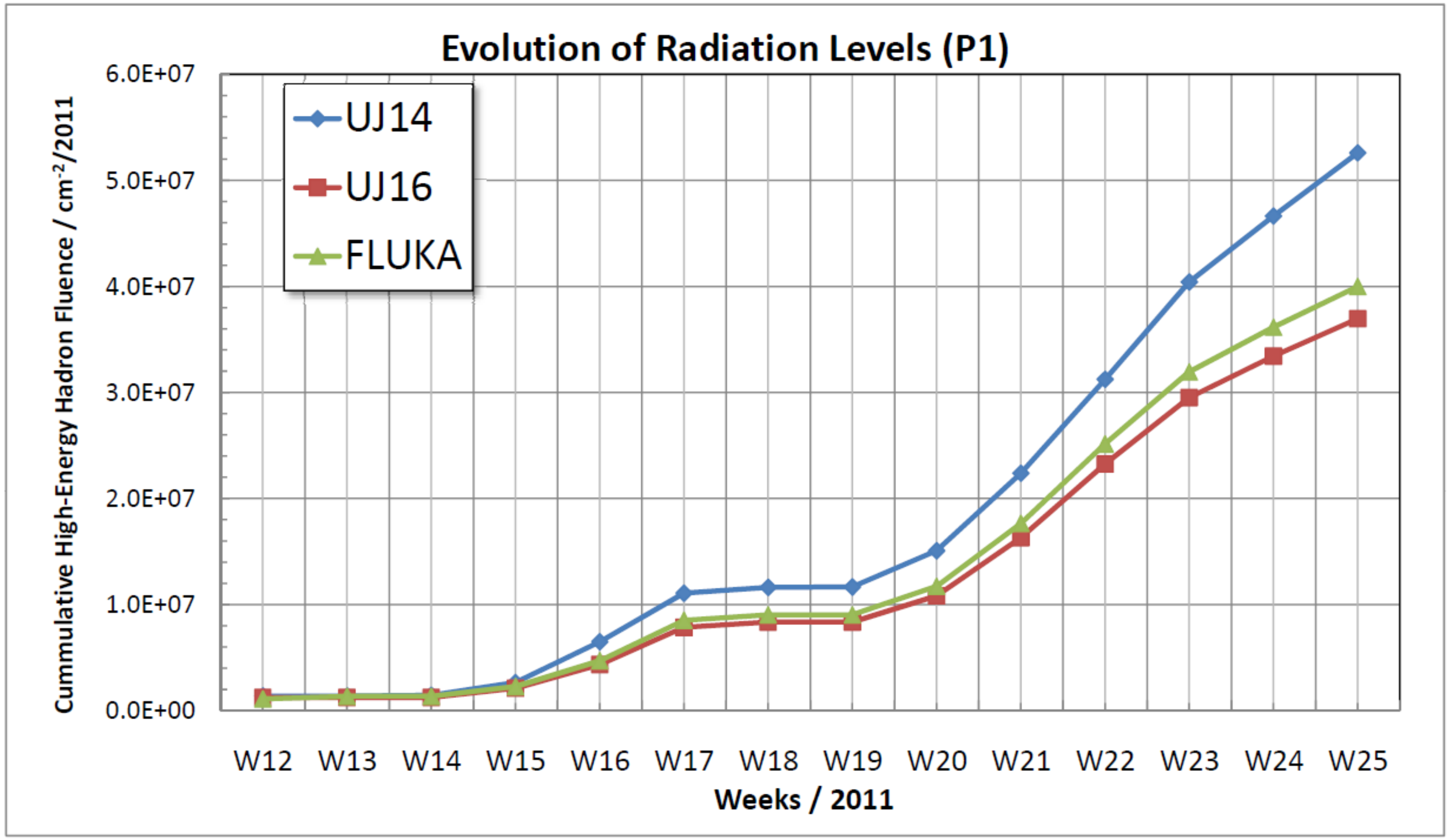
32	N/A	N/A	<1.0E+6	<1.0E+6	1402
33	<1.0E+6	<1.0E+6	<1.0E+6	<1.0E+6	N/A
56	<1.0E+6	9.3E+06	9.8E+08	1.6E+10	<10
76	<1.0E+6	<1.0E+6	8.8E+08	8.8E+09	<10
87	<1.0E+6	1.1E+06	1.3E+08	2.4E+09	<10
88	N/A	N/A	1.5E+08	8.6E+08	<10
REs	**shielded areas**		**tunnel/side**		
	HEH (cm-2/w26)	HEH (cm-2/2011)	HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
28	<1.0E+6	<1.0E+6	<1.0E+6	1.3E+07	<10
32	<1.0E+6	<1.0E+6	<1.0E+6	<1.0E+6	1402
38	<1.0E+6	<1.0E+6	<1.0E+6	2.8E+07	<10
62	<1.0E+6	<1.0E+6	1.3E+06	2.0E+07	<10
68	<1.0E+6	<1.0E+6	1.3E+06	2.8E+07	<10
78	<1.0E+6	<1.0E+6	1.3E+06	2.4E+07	<10
US85/UX85	**cavern US85**		**cavern UX85**		
	HEH (cm-2/w26)	HEH (cm-2/2011)	HEH (cm-2/w26)	HEH (cm-2/2011)	
	<1.0E+6	1.6E+07	3.3E+06	8.3E+07	
			tunnel		
			HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
R34	N/A		3.0E+09	1.9E+10	<10
R74/76	N/A		3.9E+09	4.6E+10	<10
R771	N/A		8.8E+09	8.1E+10	<10
	shielded areas (UA)		**tunnel (RA)**		
	HEH (cm-2/w26)	HEH (cm-2/2011)	HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
P2 right (27)	<1.0E+6	<1.0E+6	8.9E+07	6.5E+08	<10
P2 left (23)	<1.0E+6	<1.0E+6	2.3E+08	2.6E+09	<10
P8 right (87)	<1.0E+6	<1.0E+6	5.4E+08	7.1E+10	<10
P8 left (83)	<1.0E+6	1.6E+06	N/A	N/A	<10

Additional points of interest (losses observed in 'unusual' locations)

	tunnel			shielded areas	
	HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)	HEH (cm-2/w26)	HEH (cm-2/2011)
RB44/46	2.2E+07	1.6E+09	N/A	N/A	N/A
UXC55	1.7E+08	2.7E+09	N/A	N/A	N/A
8R5	2.6E+08	4.1E+09	<10	N/A	N/A
9R5	5.5E+07	8.8E+08	<10	N/A	N/A
11R5	7.4E+07	1.1E+09	<10	N/A	N/A
UPS54	N/A	N/A	<10	2.7E+06	4.3E+07
11L1	7.6E+07	1.1E+09	<10	N/A	N/A
8L1	2.0E+09	3.3E+10	<10	N/A	N/A
ARC/DS					
18R7	4.5E+06	9.5E+07	<10		

UJs	shielded areas		tunnel		
	HEH (cm-2/w26)	HEH (cm-2/2011)	HEH (cm-2/w26)	HEH (cm-2/2011)	BLM dose (mGy/week)
14 (13, tun)	3.3E+06	5.7E+07	9.8E+09	3.8E+10	<10
16 (17, tun)	2.3E+06	4.0E+07	7.7E+08	5.2E+10	<10



Radiation Levels: Measured & Expected

Weekly Report

Radiation leve
Week 26 (27.06.

Comments:
- Locations with cumulated fluences <1E6 HEH are statistically not relevant
- RadMon readings in shielded areas are stron
- If more than one detector exists for an area,
- BLM dose takes detailed offset correction int
- W25: physics + MD week. 27th and 28th June machine developments. Some losses expected
- UJ14/16 show highest values for shielded are

Uncertainties: Tunnel locations - factor of 2x; Shielded areas - factor of 3x

	ATLAS (μb^{-1})	ATLAS (peak) ($Hz{*}\mu b^{-1}$)	CMS (μb^{-1})	CMS (peak) ($Hz{*}\mu b^{-1}$)	ALICE (μb^{-1})	LHCb(μb^{-1})
Lumi/week	109.5	1262.2	106.7	1243.7	0.3	42.7

RRs	shielded areas HEH (cm-2/w26)	shielded areas HEH (cm-2/2011)	tunnel HEH (cm-2/w26)	tunnel HEH (cm-2/2011)	tunnel BLM dose (mGy/week)
13	<1.0E+6	2.1E+06	3.5E+06	8.8E+07	<10
17	<1.0E+6	2.2E+06	3.5E+06	6.7E+07	<10
53	<1.0E+6	2.9E+06	5.2E+06	9.7E+07	<10
57	<1.0E+6	2.4E+06	<1.0E+6	8.5E+07	<10
73	<1.0E+6	2.6E+06	<1.0E+6	<1.0E+6	<10
77	<1.0E+6	4.3E+06	5.2E+06	1.1E+08	<10

UJs	shielded areas HEH (cm-2/w26)	shielded areas HEH (cm-2/2011)	tunnel HEH (cm-2/w26)	tunnel HEH (cm-2/2011)	tunnel BLM dose (mGy/week)
14 (13, tun)	3.3E+06	5.7E+07	9.8E+09	3.8E+10	<10
16 (17, tun)	2.3E+06	4.0E+07	7.7E+08	5.2E+10	<10
22	N/A	N/A	5.2E+07	1.1E+09	<10
23	<1.0E+6	<1.0E+6	8.6E+06	1.5E+08	<10
32	N/A	N/A	<1.0E+6	<1.0E+6	1402
33	<1.0E+6	<1.0E+6	<1.0E+6	<1.0E+6	N/A
56	<1.0E+6	9.3E+06	9.8E+08	1.6E+10	<10
76	<1.0E+6	<1.0E+6	8.8E+08	8.8E+09	<10
87	<1.0E+6	1.1E+06	1.3E+08	2.4E+09	<10
88	N/A	N/A	1.5E+08	8.6E+08	<10

REs	shielded areas HEH (cm-2/w26)	shielded areas HEH (cm-2/2011)	tunnel/side HEH (cm-2/w26)	tunnel/side HEH (cm-2/2011)	tunnel/side BLM dose (mGy/week)
28	<1.0E+6	<1.0E+6	<1.0E+6	1.3E+07	<10
32	<1.0E+6	<1.0E+6	<1.0E+6	<1.0E+6	1402
38	<1.0E+6	<1.0E+6	<1.0E+6	2.8E+07	<10
62	<1.0E+6	<1.0E+6	1.3E+06	2.0E+07	<10
68	<1.0E+6	<1.0E+6	1.3E+06	2.8E+07	<10
78	<1.0E+6	<1.0E+6	1.3E+06	2.4E+07	<10

US85/UX85	cavern US85 HEH (cm-2/w26)	cavern US85 HEH (cm-2/2011)	cavern UX85 HEH (cm-2/w26)	cavern UX85 HEH (cm-2/2011)
	<1.0E+6	1.6E+07	3.3E+06	8.3E+07

		tunnel HEH (cm-2/w26)	tunnel HEH (cm-2/2011)	tunnel BLM dose (mGy/week)
R34	N/A	3.0E+09	1.9E+10	<10
R74/76	N/A	3.9E+09	4.6E+10	<10
R771	N/A	8.8E+09	8.1E+10	<10

	shielded areas (UA) HEH (cm-2/w26)	shielded areas (UA) HEH (cm-2/2011)	tunnel (RA) HEH (cm-2/w26)	tunnel (RA) HEH (cm-2/2011)	tunnel (RA) BLM dose (mGy/week)
P2 right (27)	<1.0E+6	<1.0E+6	8.9E+07	6.5E+08	<10
P2 left (23)	<1.0E+6	<1.0E+6	2.3E+08	2.6E+09	<10
P8 right (87)	<1.0E+6	<1.0E+6	5.4E+08	7.1E+10	<10
P8 left (83)	<1.0E+6	1.6E+06	N/A	N/A	<10

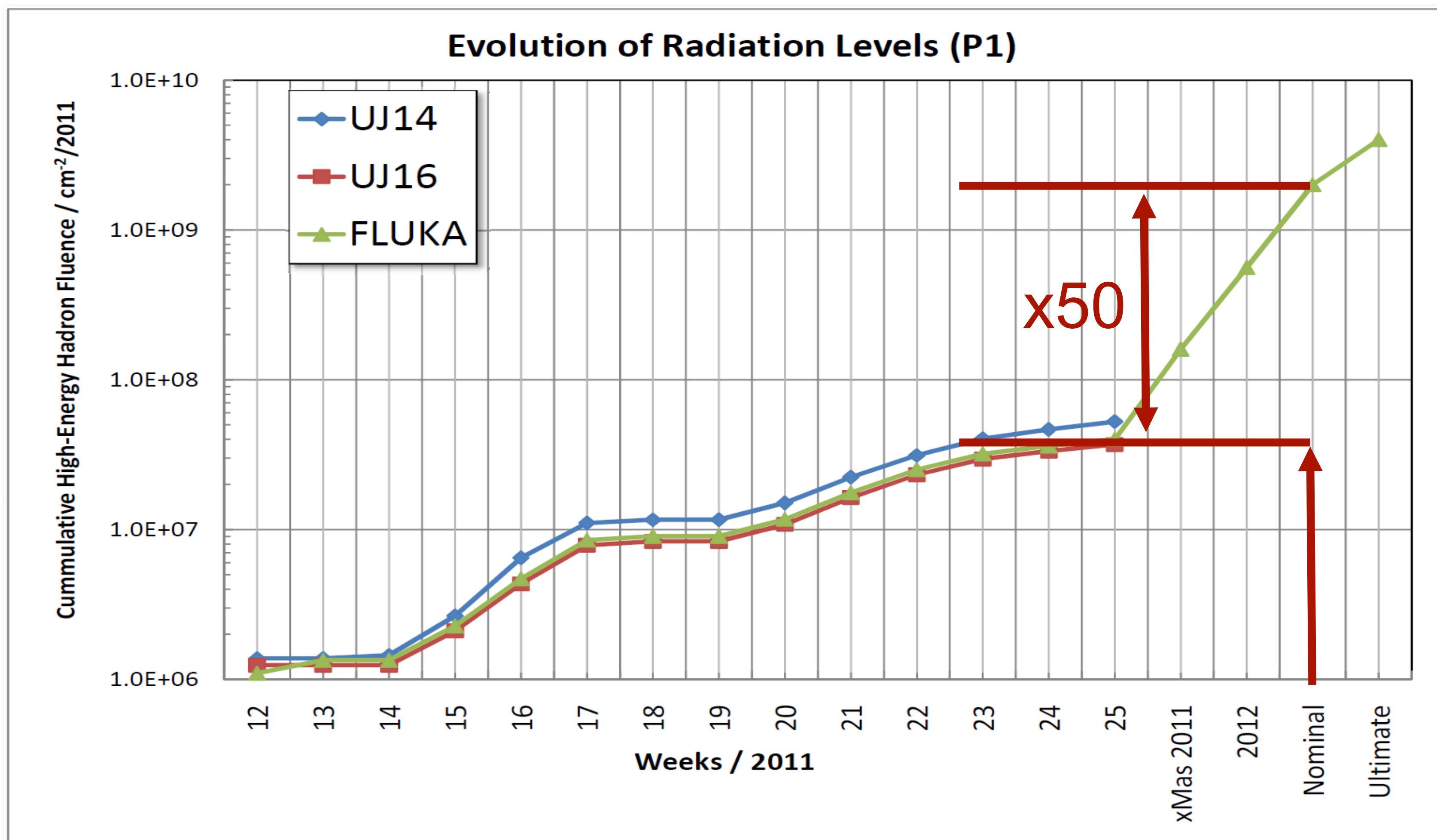
Additional points of interest (losses observed in 'unusual' locations)

	tunnel HEH (cm-2/w26)	tunnel HEH (cm-2/2011)	tunnel BLM dose (mGy/week)	shielded areas HEH (cm-2/w26)	shielded areas HEH (cm-2/2011)
RB44/46	2.2E+07	1.6E+09	N/A	N/A	N/A
UXC55	1.7E+08	2.7E+09	N/A	N/A	N/A
8R5	2.6E+08	4.1E+09	<10	N/A	N/A
9R5	5.5E+07	8.8E+08	<10	N/A	N/A
11R5	7.4E+07	1.1E+09	<10	N/A	N/A
UPS54	N/A	N/A	<10	2.7E+06	4.3E+07
11L1	7.6E+07	1.1E+09	<10	N/A	N/A
8L1	2.0E+09	3.3E+10	<10	N/A	N/A
ARC/DS					
18R7	4.5E+06	9.5E+07	<10		

Detailed Analysis

UJs	shielded areas HEH (cm-2/w26)	shielded areas HEH (cm-2/2011)	tunnel HEH (cm-2/w26)	tunnel HEH (cm-2/2011)	tunnel BLM dose (mGy/week)
14 (13, tun)	3.3E+06	5.7E+07	9.8E+09	3.8E+10	<10
16 (17, tun)	2.3E+06	4.0E+07	7.7E+08	5.2E+10	<10

Comparison & Extrapolation



Radiation and Single Event Upsets

Radiation can cause single event upsets that lead to **equipment failure** and **beam downtime**

Equipment	Locations	# of Failures		Consequence	Mitigation	Comments
		Conf	Likely			
Collimation Control	**UJ14/16/56**	2	2	Dump	Relocation Shielding	Details
Cryogenics Control	**UJ14/16/56/76**	4	2	Dump	Relocation Shielding	Details
Cryogenics WorldFip	**TI2, RR53**	2		Dump	Software Update	Details
Biometry	**UJ14/16**		2	Delay	Relocation	
Cryogenics PLCs	**US85**	3	1	Dump	Relocation	Details
Cryogenics Power Converter	**US85**	2		Dump	Relocation	
Power Converters auxilliary power supply	**UJ14/43 RR17 UA87**	4	1	Dump	Relocation Shielding Re-Design	Details
Power Converters Other	**several**	several		Dump	Relocation Shielding Re-Design	confirmed after H4IRRAD tests
UPS	**UJ56/US85**		2	Dump	Relocation	
QPS Control	**UJ14/16**	1	1	Dump	Re-Design	Details
QPS ISO-150	**Tunnel, UJ14/16, RR53**	38		some: Dump	Firmware Re-Design	23 cases transparent to operation after firmware update
uFIP	**Tunnel, UJ14**	1	1		Re-Design	Details
WIC	**TI8**	1		Dump	Relocation (done)	Details
Power Converters 60A	**Tunnel**		?		Re-Design	analysis is ongoing (H4IRRAD)
Valve Controllers	**US85**	?			Replacement	under investigation

Radiation and Single Event Upsets

Radiation can cause single event upsets that lead to **equipment failure** and **beam downtime**

up to Wk 26	# of Failures				
	Conf	Likely	Grand Total	Dump	Transparent
Total:	58	12	70		
Shielded Area.:	21	12	33	33	
Tunnel:	37		37	12	25

Power Converters auxilliary power supply	**UJ14/43 RR17 UA87**	4	1	Dump	Relocation Shielding Re-Design	Details
Power Converters Other	**several**	several		Dump	Relocation Shielding Re-Design	confirmed after H4IRRAD tests
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QPS Control	**UJ14/16**	1	1	Dump	Re-Design	Details
QPS ISO-150	**Tunnel, UJ14/16, RR53**	38		some: Dump	Firmware Re-Design	23 cases transparent to operation after firmware update
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WIC	**TI8**	1		Dump	Relocation (done)	Details
Power Converters 60A	**Tunnel**		?		Re-Design	analysis is ongoing (H4IRRAD)
Valve Controllers	**US85**	?			Replacement	under investigation

Radiation and Single Event Upsets

Radiation can cause single event upsets that lead to **equipment failure** and **beam downtime**

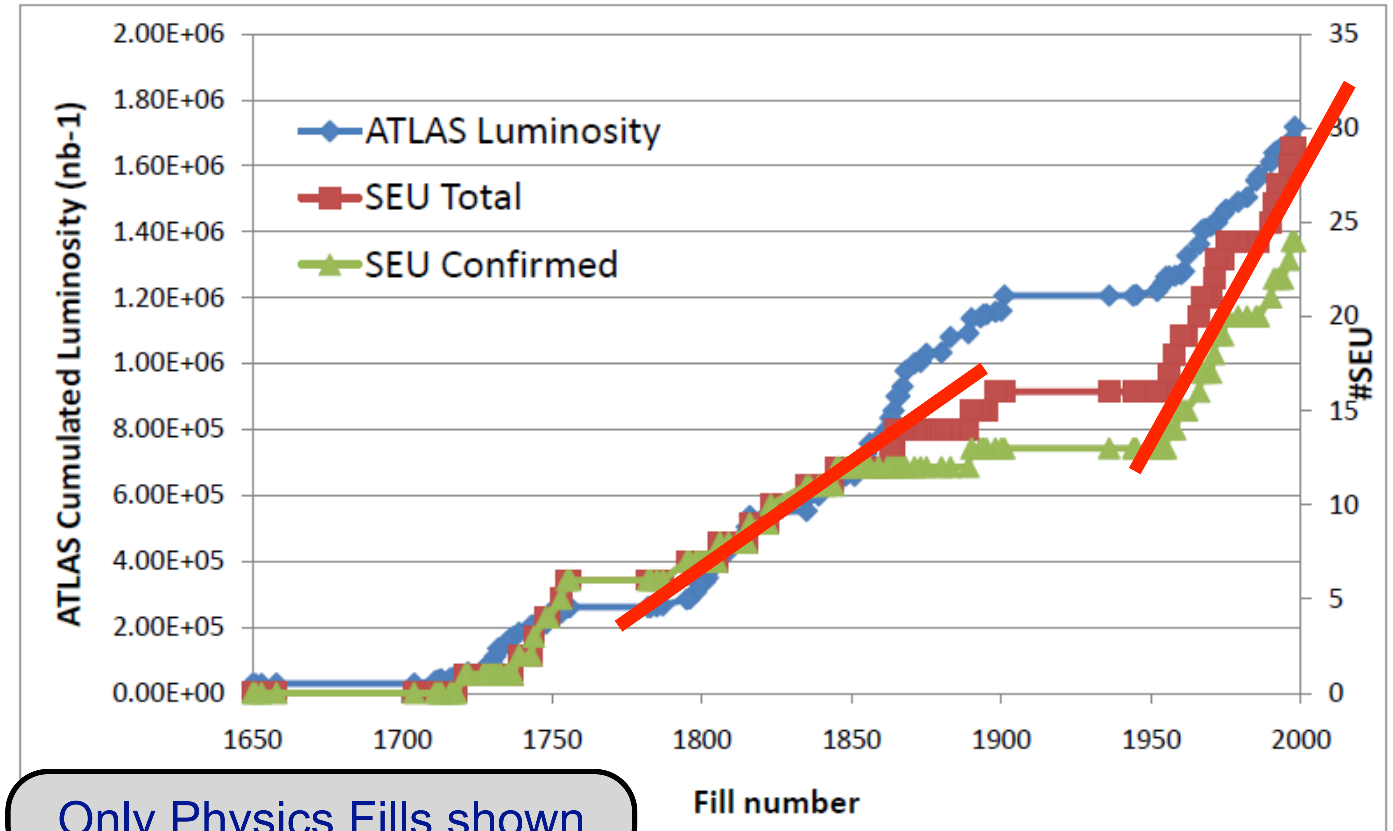
up to Wk 26

	# of Failures				
	Conf	Likely	Grand Total		
Total:	58	12	70	Dump	Transparent
Shielded Area.:	21	12	33	33	
Tunnel:	37		37	12	25

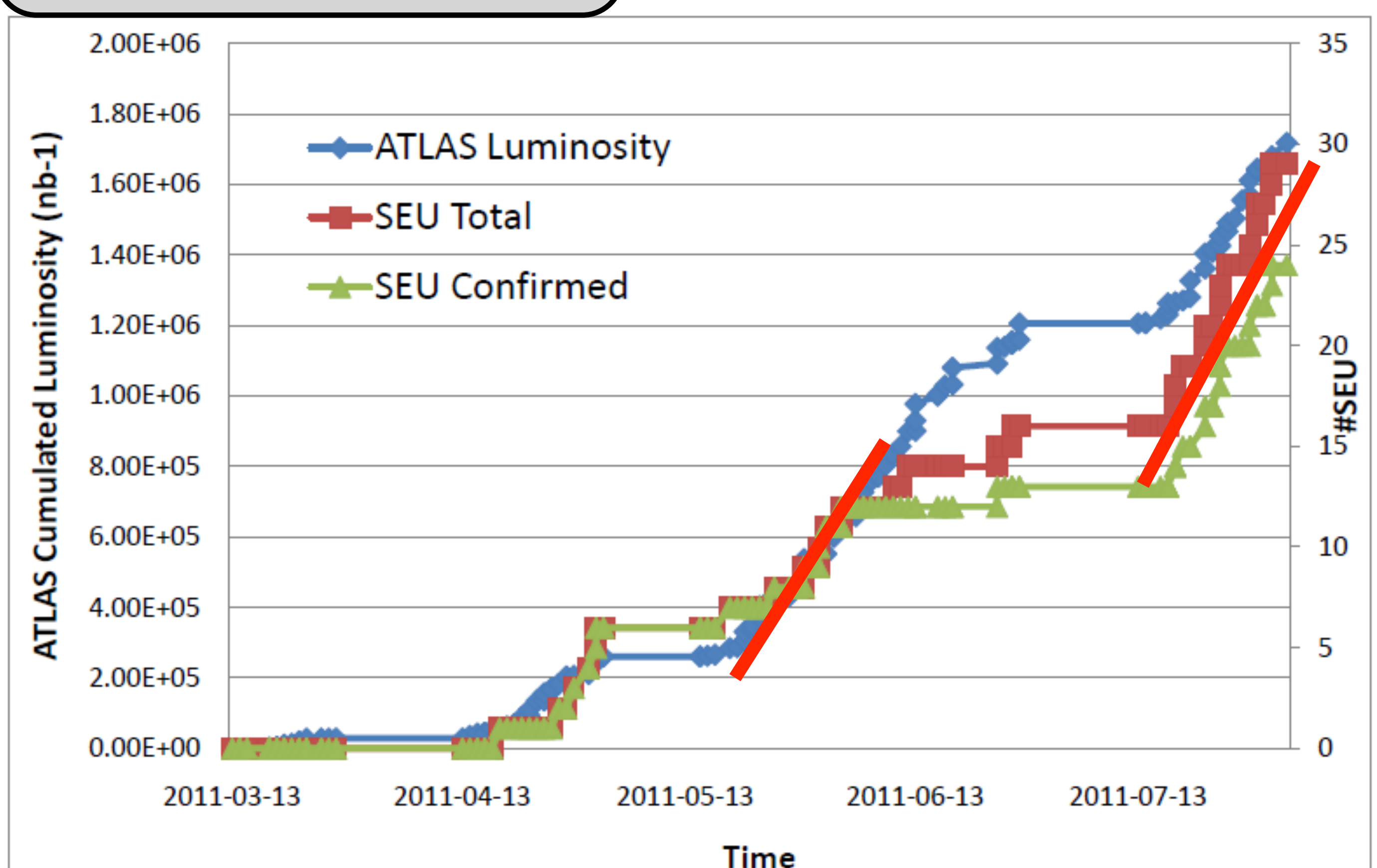
- SEUs that lead to a beam dump can result in significant recovery time: eg cryogenics recovery can be **24hrs++**
- Concern: How to Scale SEUs to Nominal Operation?
  - Luminosity: P1/5 (x50), P8: (x3-5)
  - Energy: P1/5/7/8: (x1.5)
  - Intensity: P7(Collimation): Losses & Distribution (x ???)
  - Beam-Gas: P1/5/7/8 + ARC @25ns & Scrubbing (x ???)

Valve Controllers	US85	?			Replacement	under investigation

SEUs: Failures & Correlations



Only Physics Fills shown



- Short fills with higher luminosity
  - 'more' likely to have SEUs ending the fill since some other failure modes depend rather on time?

- **In terms of SEU time the failures reflect the cumulative luminosity**

- With mitigations to date, expect **~10** SEU failures for remainder of 2011 run

What Can be Done

RELOCATION

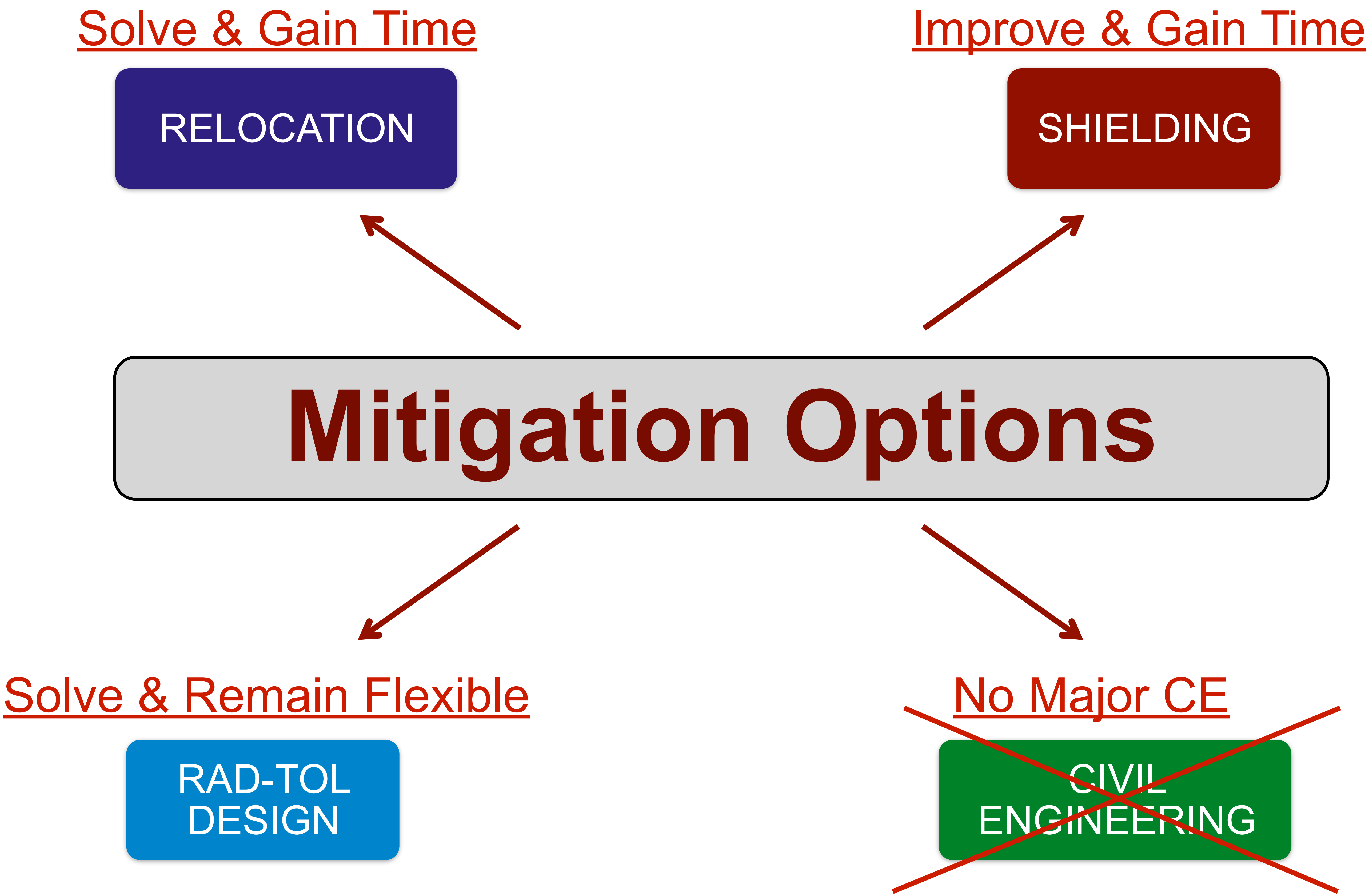
SHIELDING

Mitigation Options

RAD-TOL DESIGN

CIVIL ENGINEERING

What Can be Done



Performed Mitigations

- Shielding:
  - P6 (RA63/UA63 and RA67/UA67) (gain ~factor 5-10)
  - UJ22/23/76/88/87 (gain ~factor 10)
  - RR77/73 (gain ~factor 10)
  - US85 Safe-Room (gain ~factor 10)
- Relocations:
  - Fire-Control Racks UJ56/76, US85 (safe)
  - RTU relocated from safe room in UJ56/76 (safe)
  - Cryo-relocations/valve replacement in UX85 (safe)
  - UPS from UJ76 (safe)
  - Fire-Detectors: US85, other points prepared (safe)
  - PLCs from US85 (safe)
- Replacements & Upgrades:
  - QPS Firmware Upgrade (ISO150 failures) (transparent)
  - US85 24V Power Supply -> replaced by old model (more robust)

R2E (Radiation 2 Electronics) RoadMap

- 2011 Operation shows:
  - failures will continue to occur **but not limit luminosity reach**
  - Identifies the most critical equipment
  - Evolution of radiation levels compared with expectations
- 2011/12 Christmas Break (and Technical Stops):
  - **Relocation** of most critical elements
  - Additional shielding of most critical areas
- 2012 Operation:
  - **Aim is that SEEs will not limit LHC performance**
- Next long-shutdown:
  - Relocation & Shielding for all critical areas

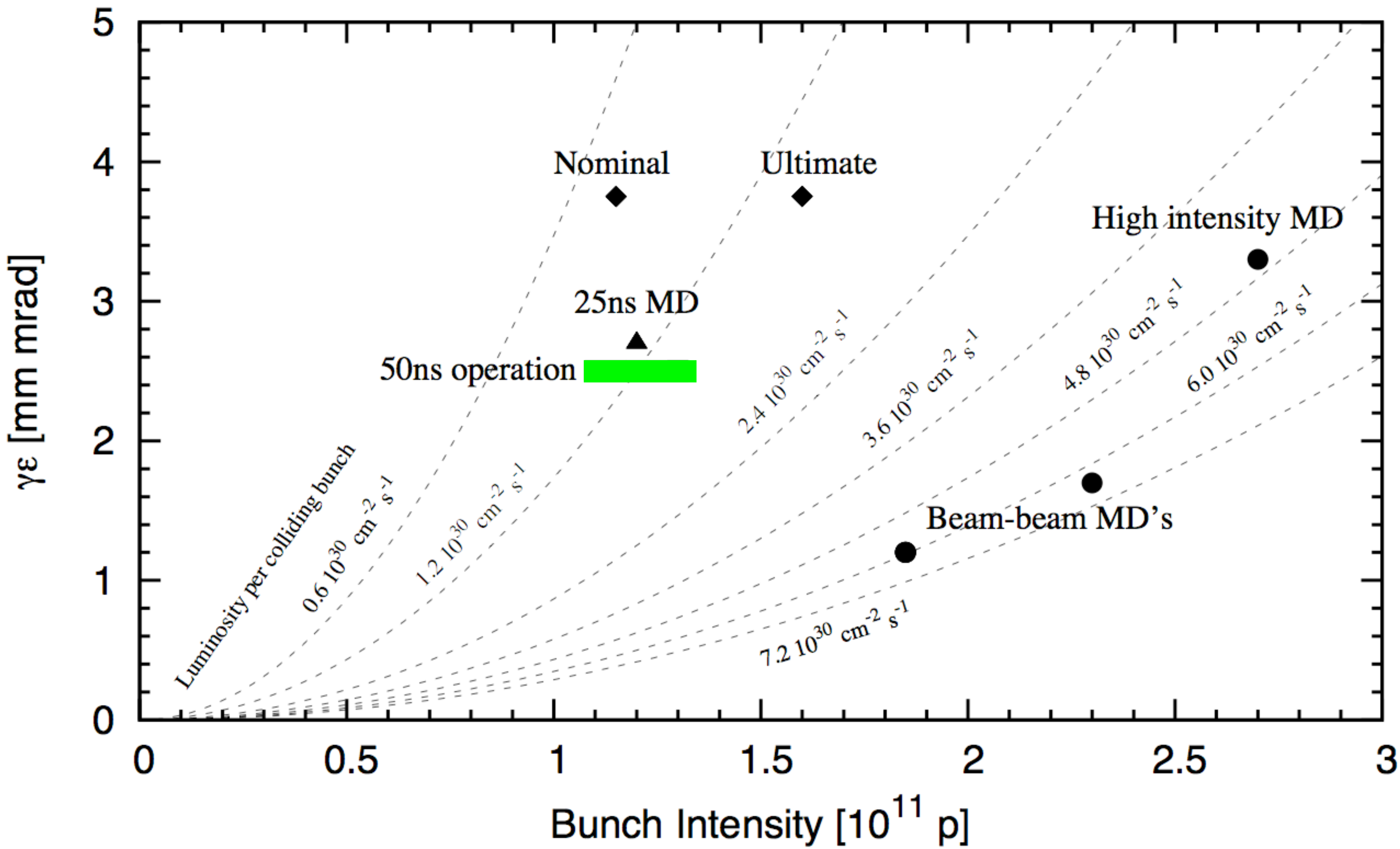
Long shut down R2E Mitigation work is in parallel to the Splice Consolidation program for the Magnet inter-connects

- What is the LHC
- LHC performance to date
- What holds us back
  - Electron Cloud
  - Beam Induced Heating
  - UFOs
  - Implications of Radiation to Electronics and single event upsets
- Outlook: where we think we can improve (2011 & 2012)

LHC Machine Development: Whats next ...

- Machine Development
  - 22 days allocated in 2011.
- MD website
  - http://www.cern.ch/lhc-md
- Investigate luminosity reach
- MD3 (end of August):
  - **β* =1m for 50ns**
    - factor 1.5 in luminosity
  - explore 25ns beams setup

Machine Development: Exploring the LHC

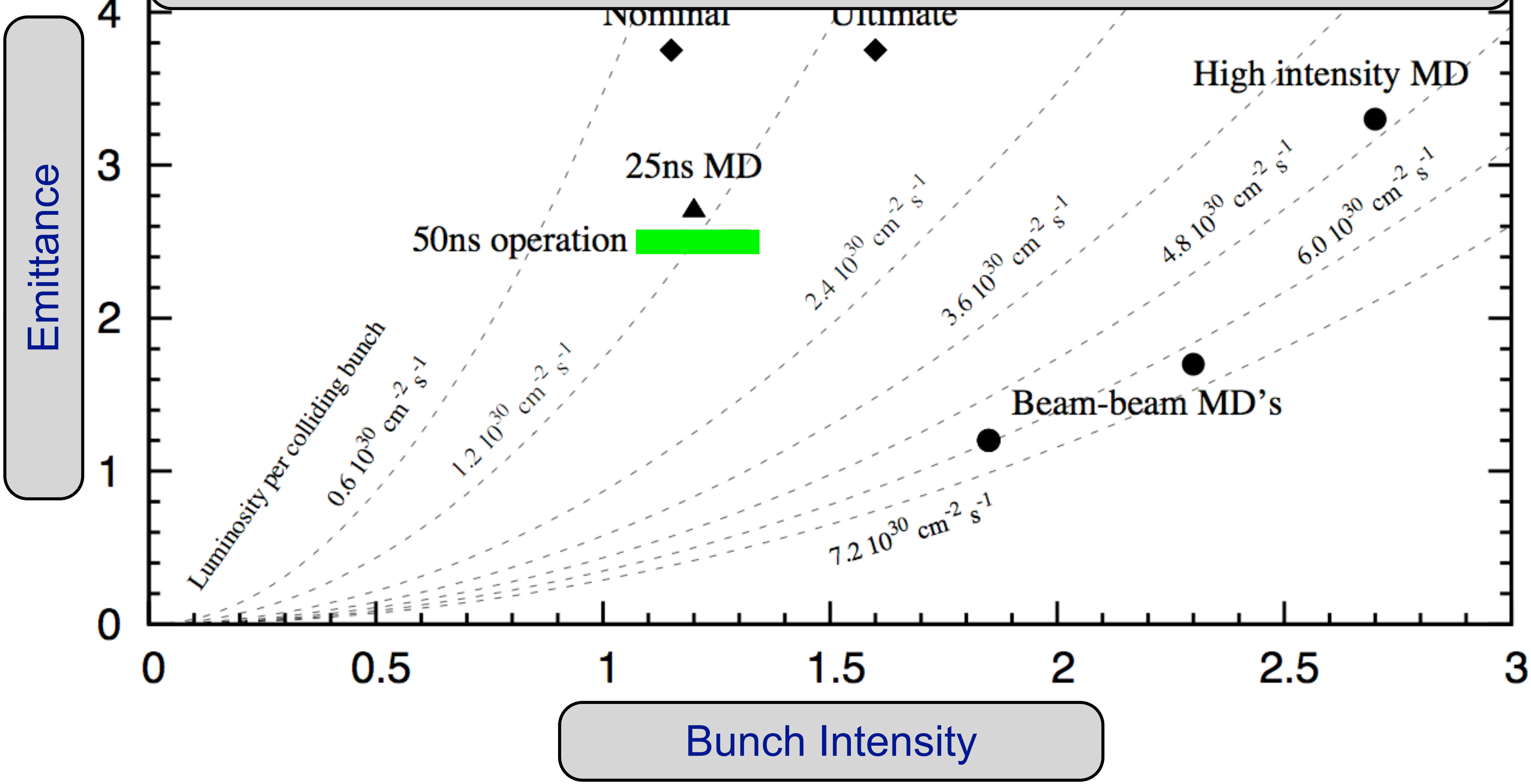


Machine Development: Exploring the LHC

Iso-lumi lines: luminosity per colliding bunch in (E= 3.5 TeV, ß*= 1.5m)

➔ Eg: peak luminosity:

$1318 \times 1.2 \times 10^{30} = 1.58 \times 10^{33}$ $cm^{-2}s^{-1}$ = 1.58 Hz/pb

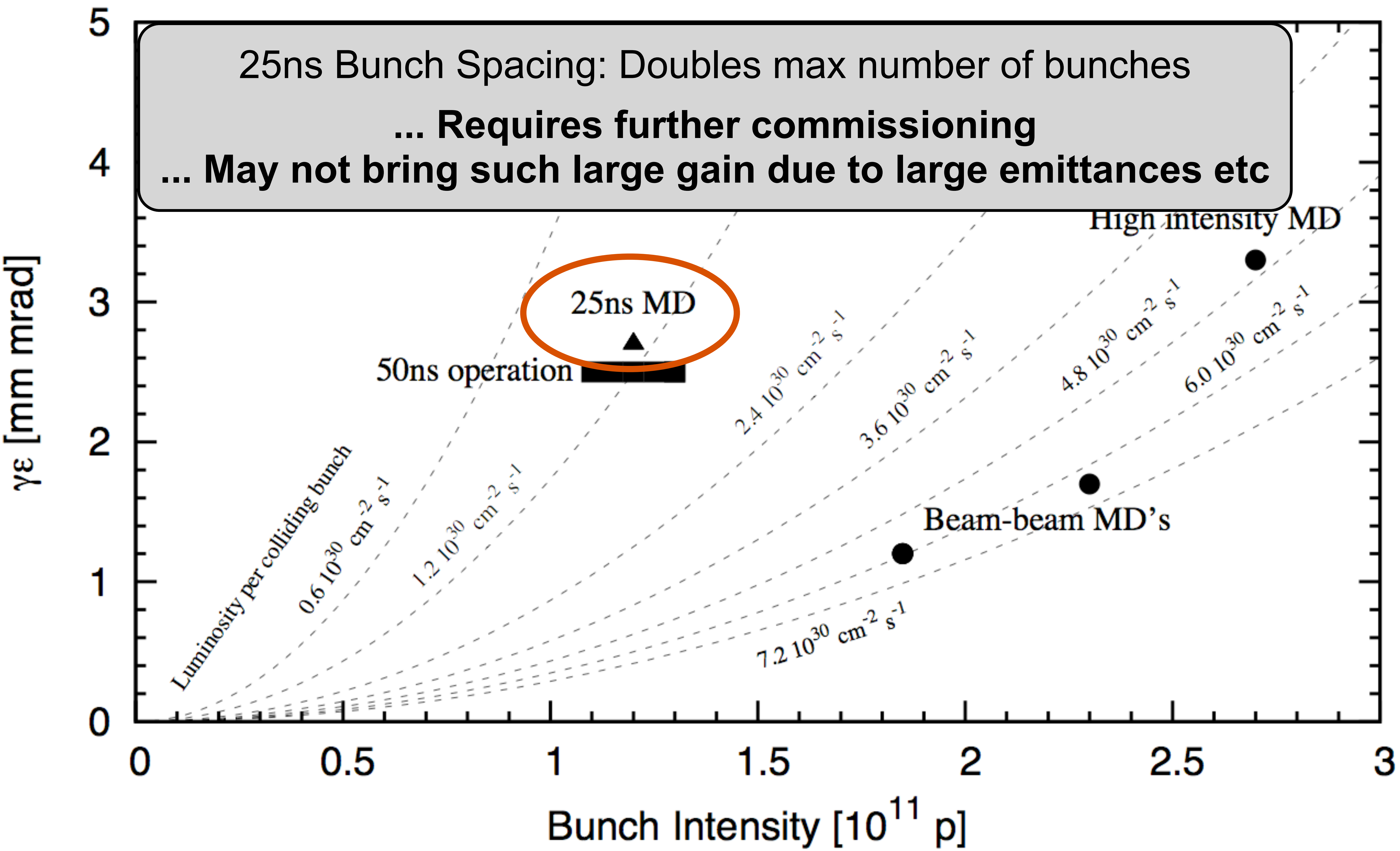


MDs: Bunch Intensity and Emittance

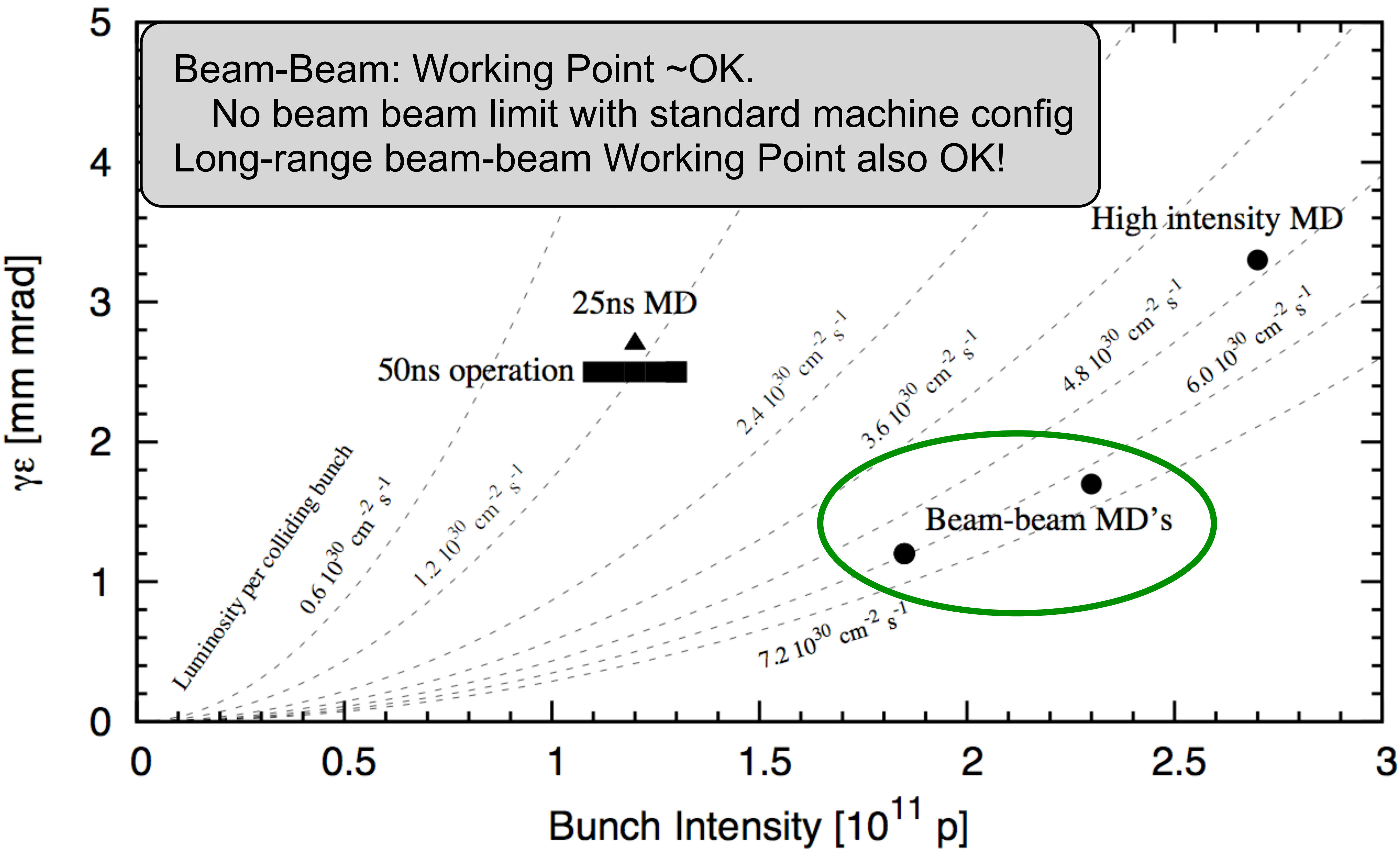
25ns Bunch Spacing: Doubles max number of bunches

... Requires further commissioning

... May not bring such large gain due to large emittances etc



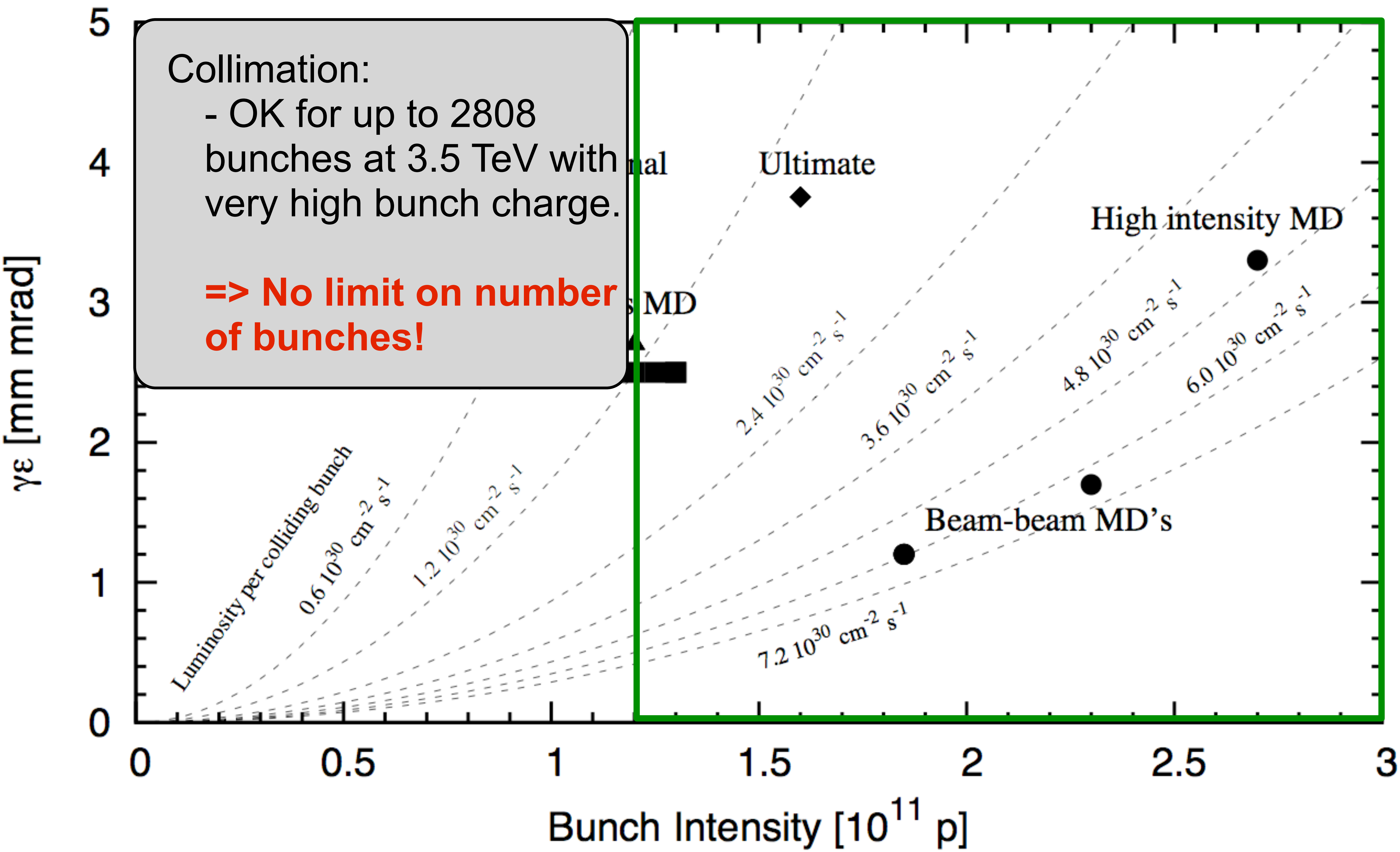
MD: Bunch Intensity and Emittance



MD Results: Bunch Intensity and Emittance

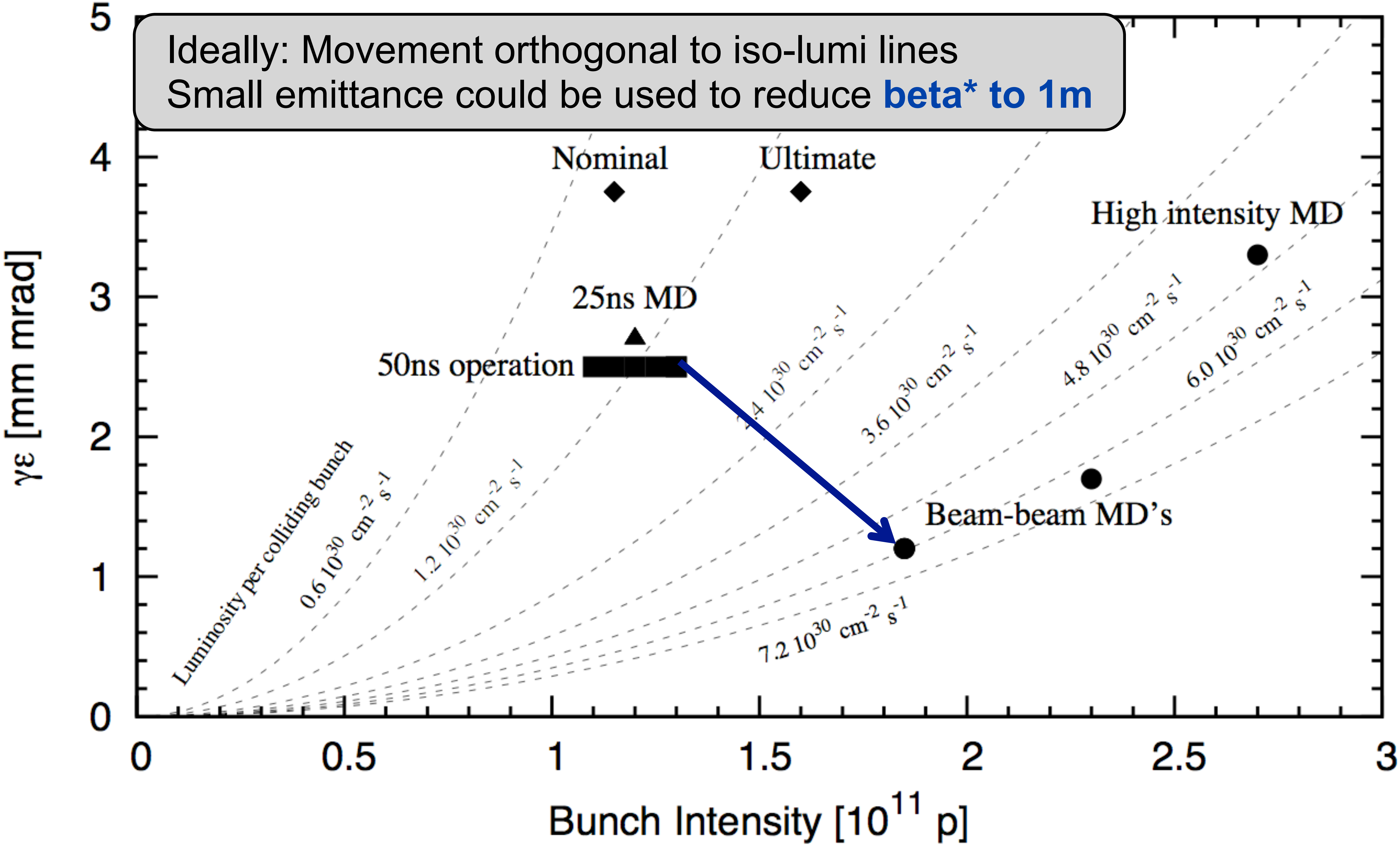
Collimation:
- OK for up to 2808 bunches at 3.5 TeV with very high bunch charge.

=> No limit on number of bunches!

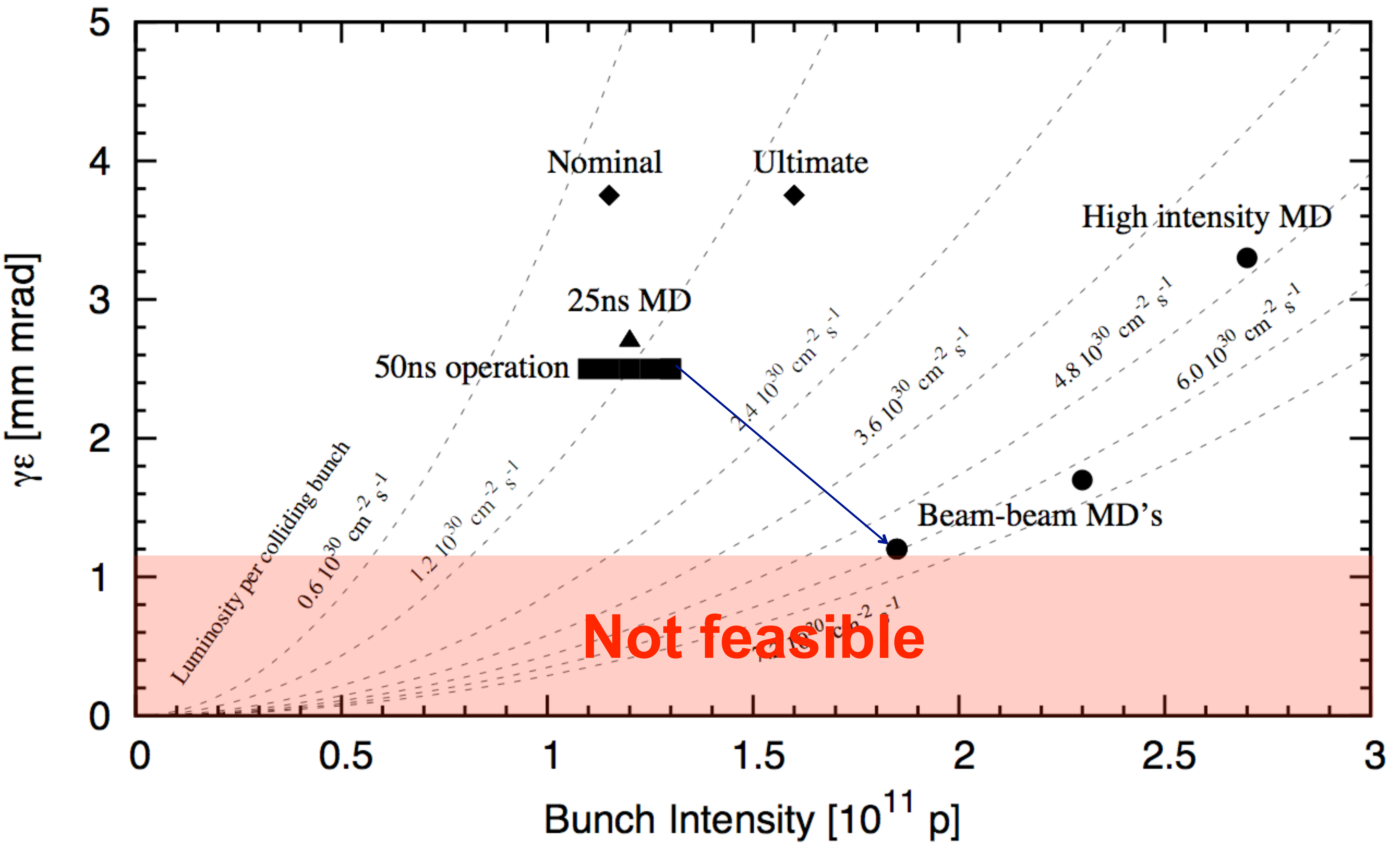


Optimal performance improvement

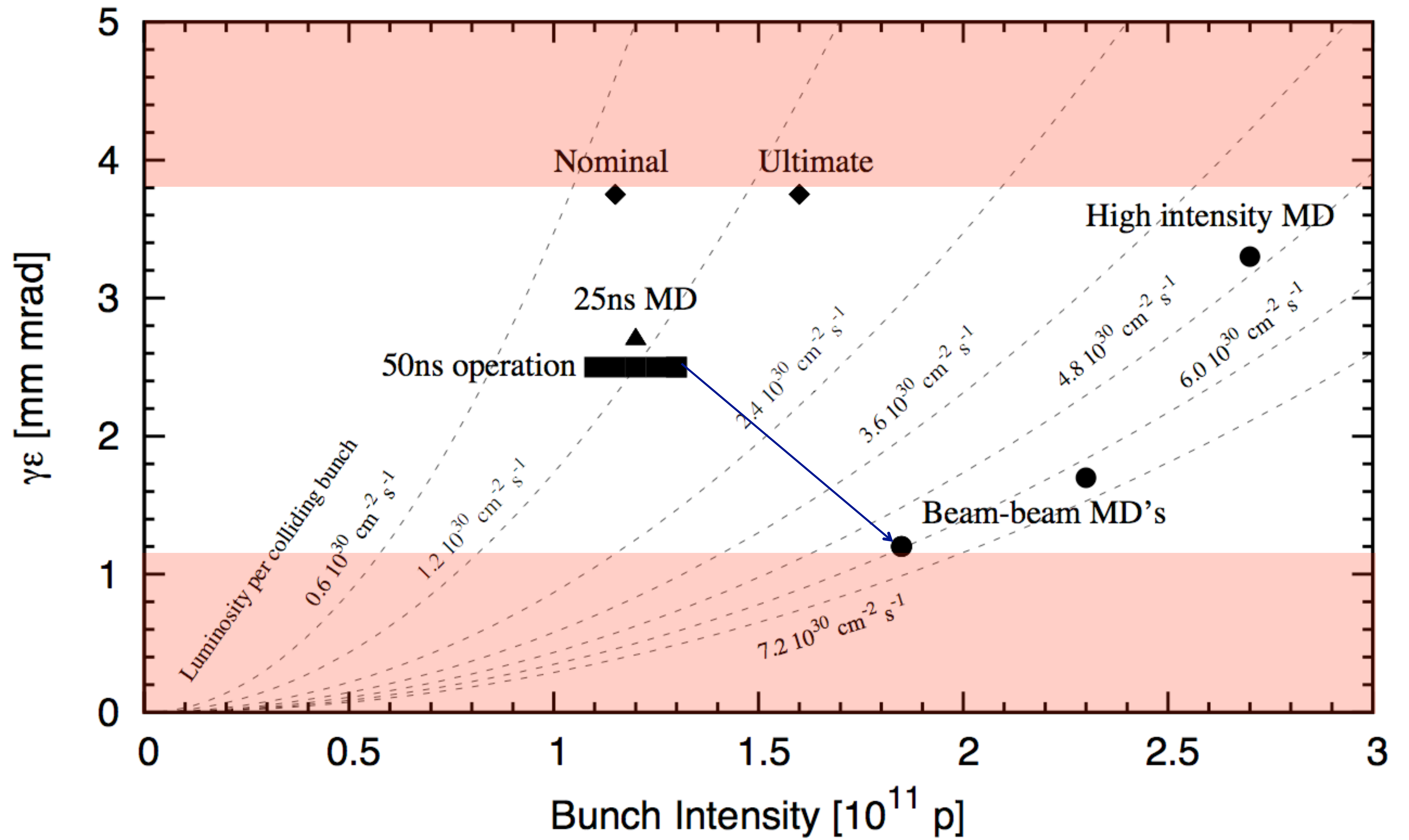
Ideally: Movement orthogonal to iso-lumi lines
Small emittance could be used to reduce **beta* to 1m**



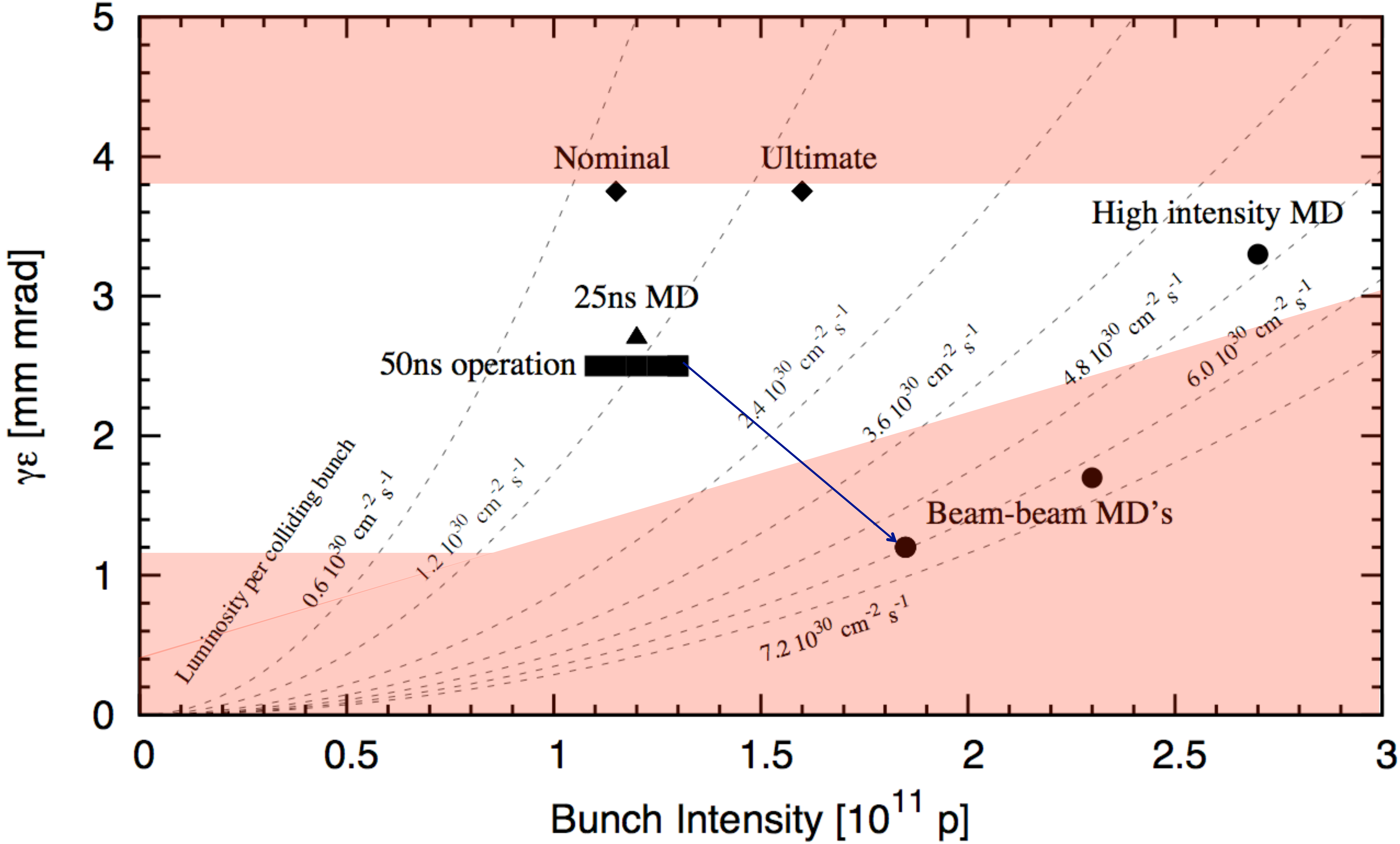
Assume 1.2 mm mrad minimum emittance



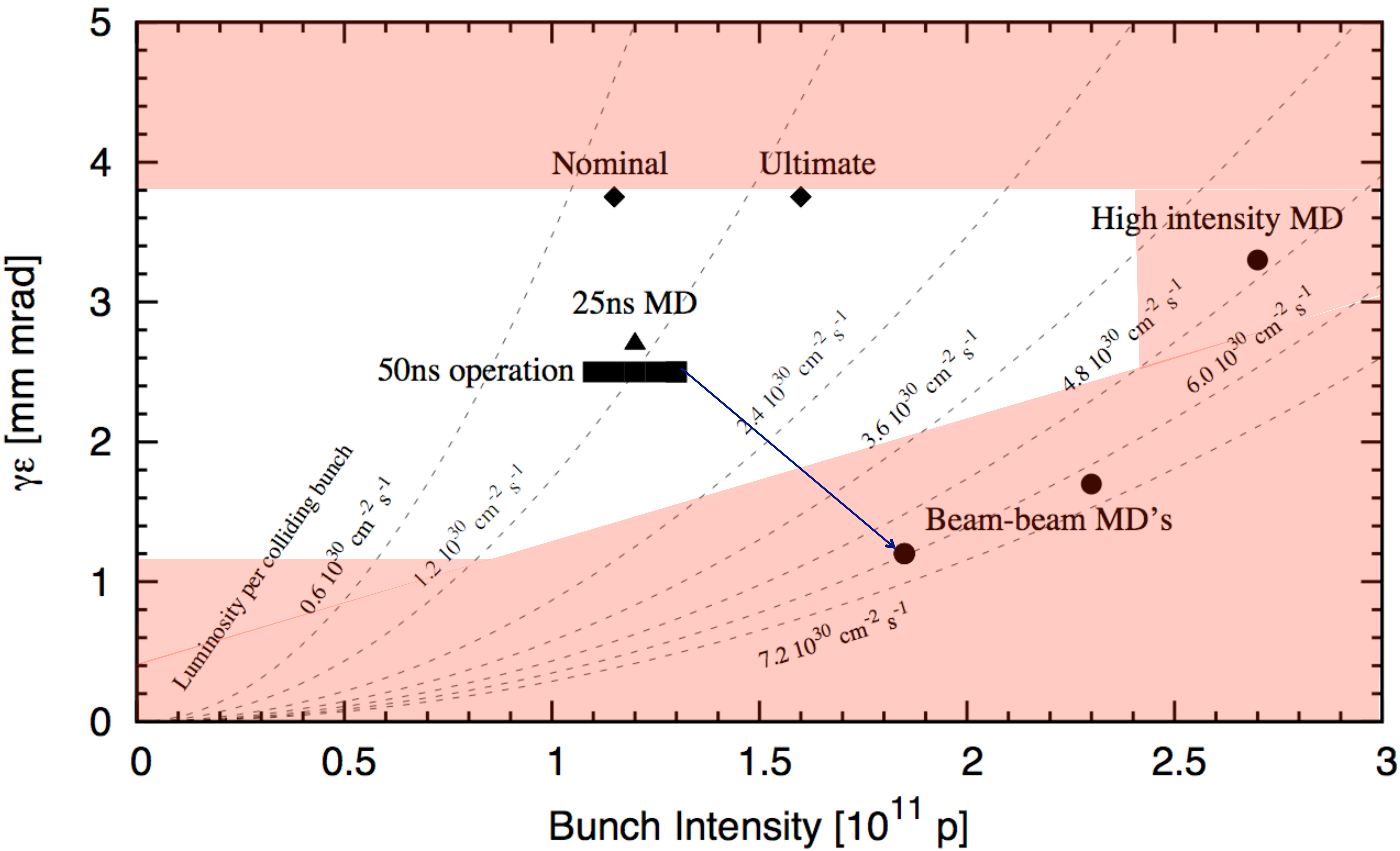
Injection limit on high emittance



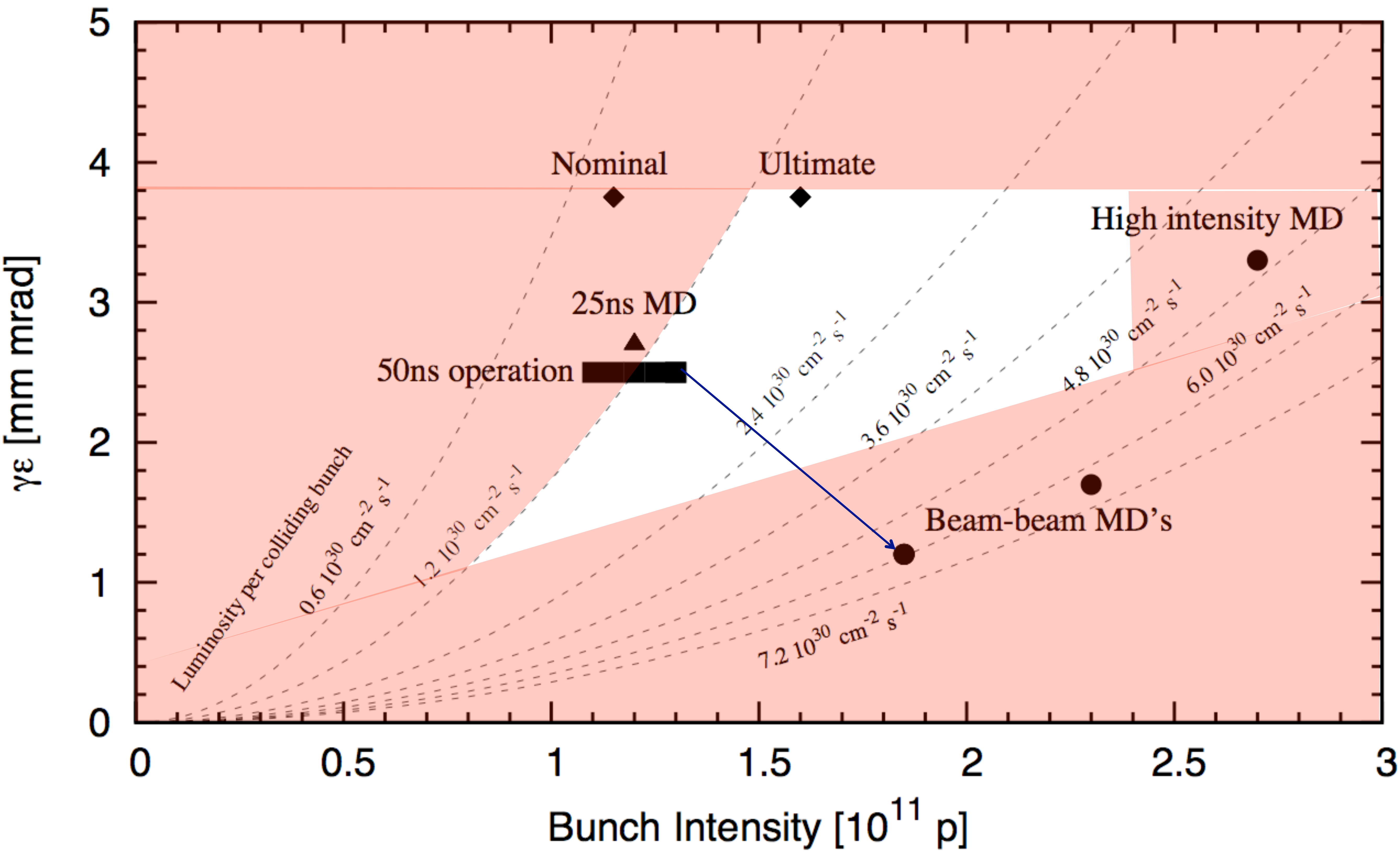
Beam Dump (TCDQ) Robustness



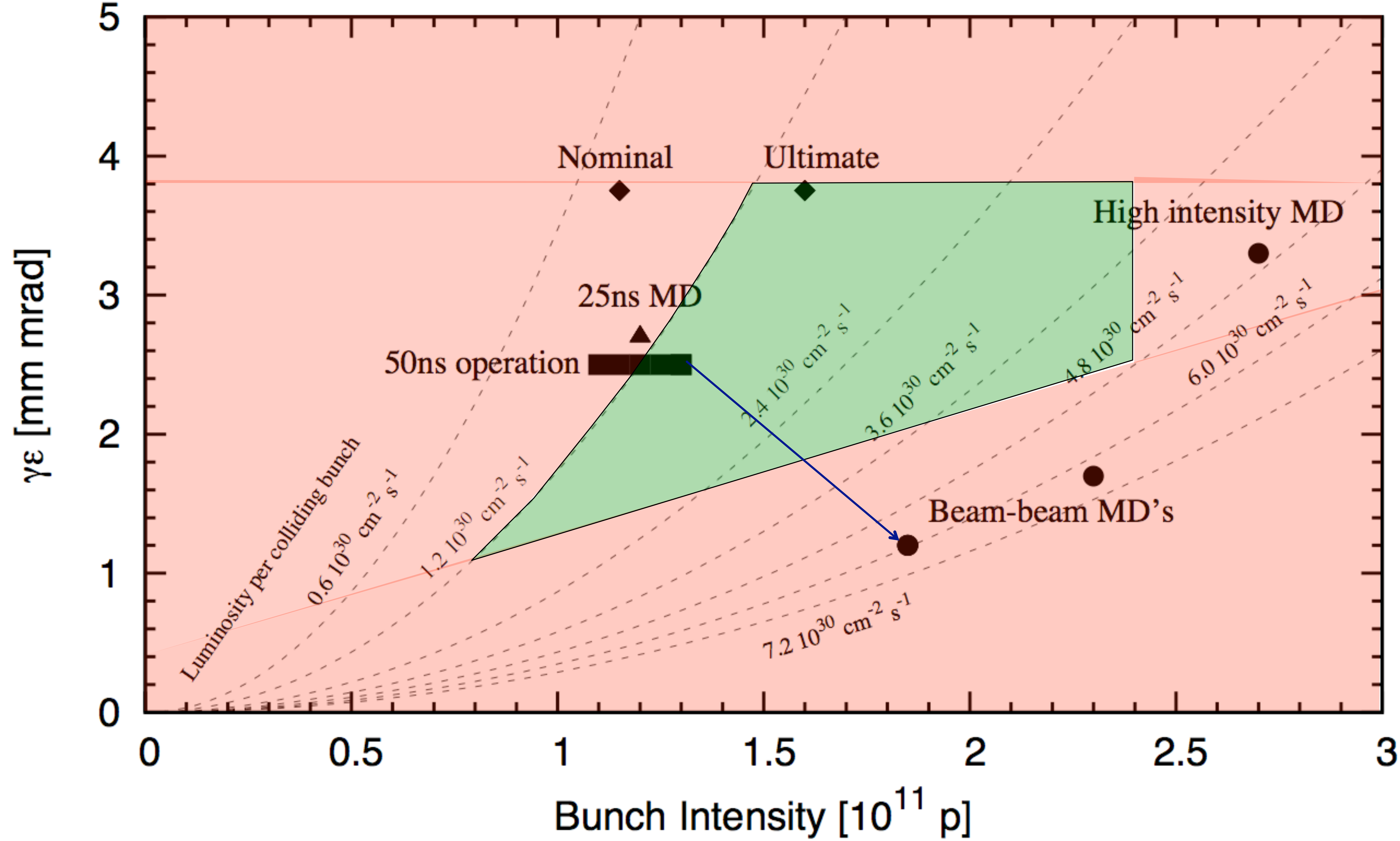
Intensity Limit for Smallish Emittance



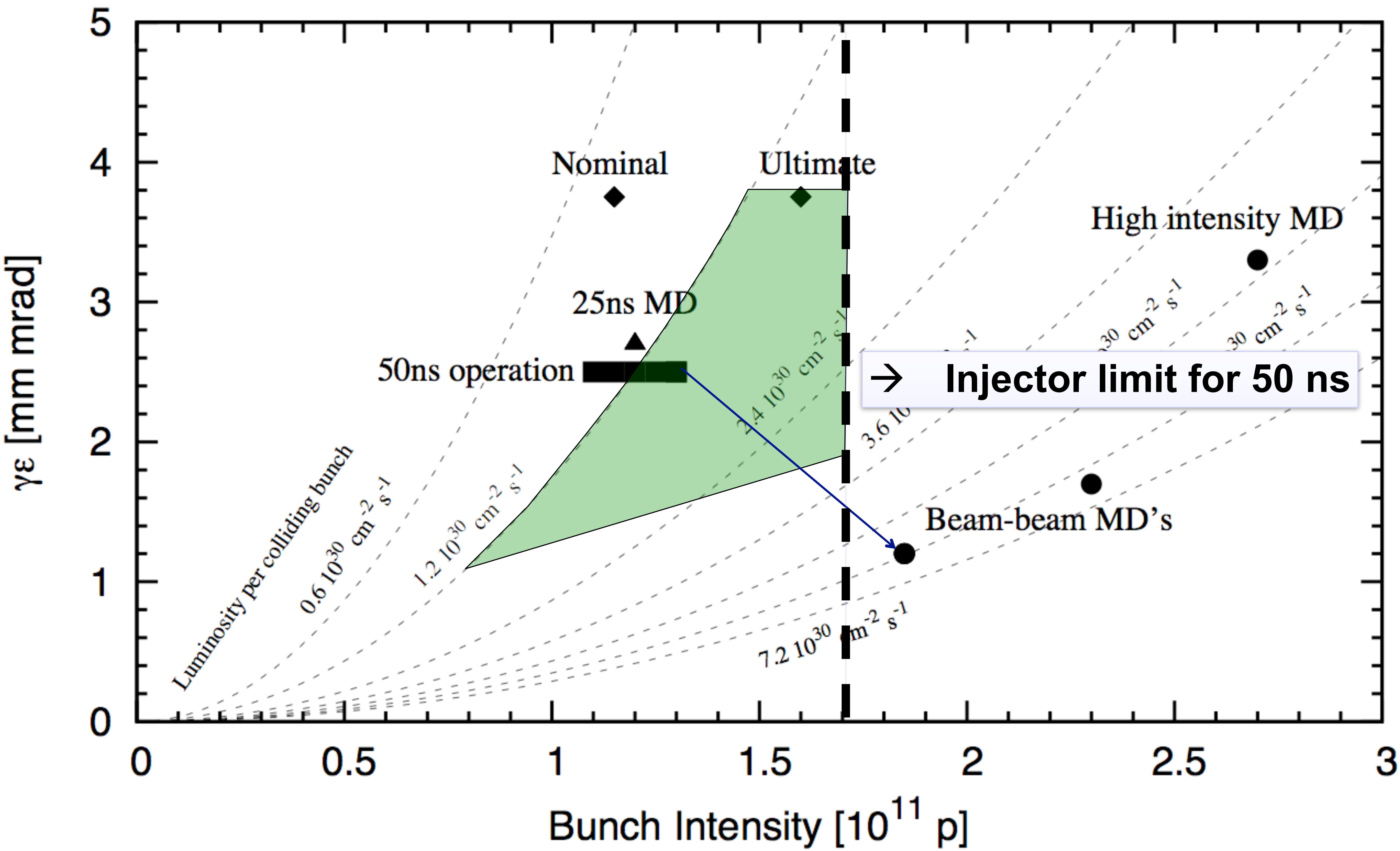
Exclude Region with Lower Luminosity



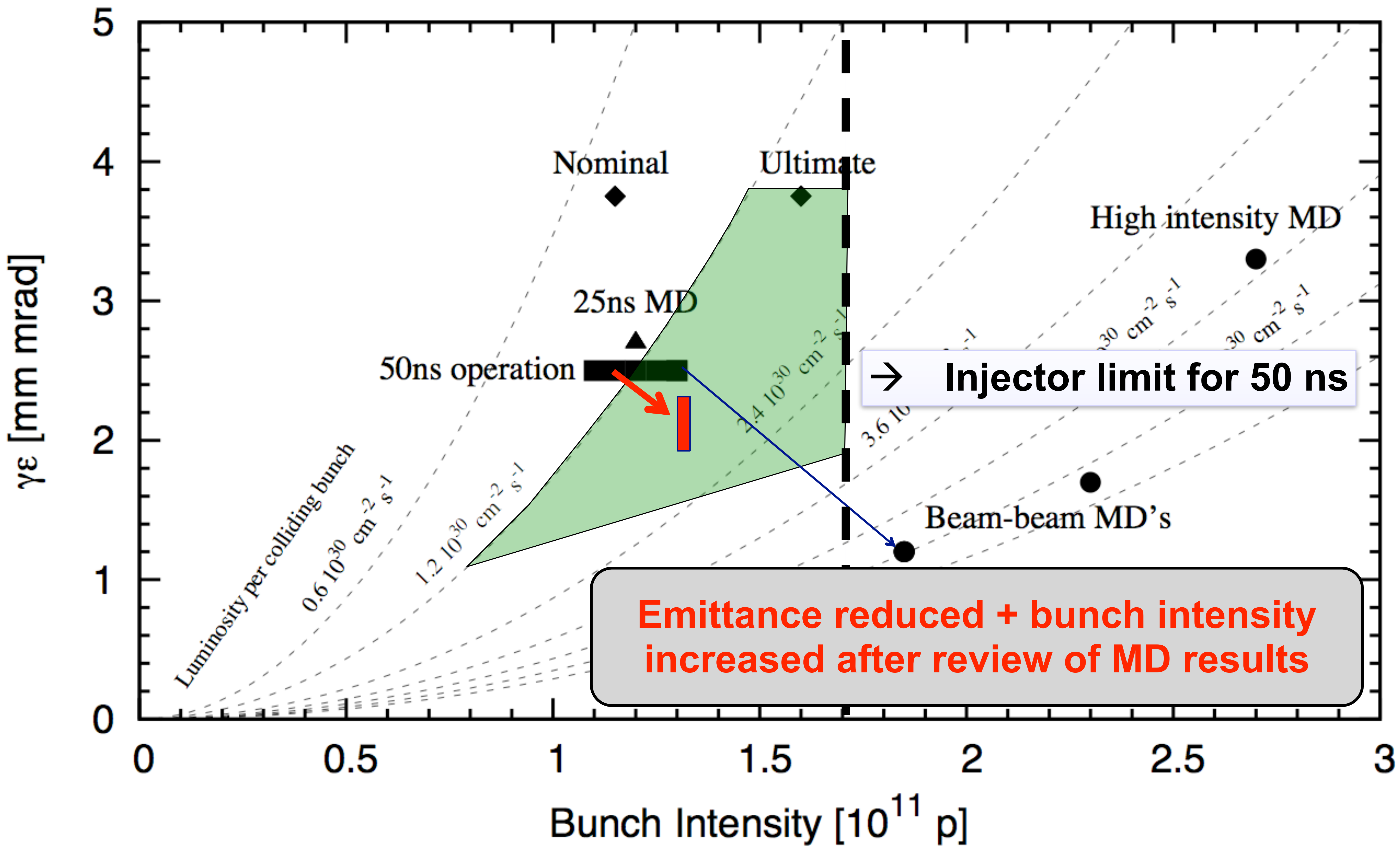
Room for Improvements



Room for Improvements (with injector limit)



Room for Improvements (with injector limit)

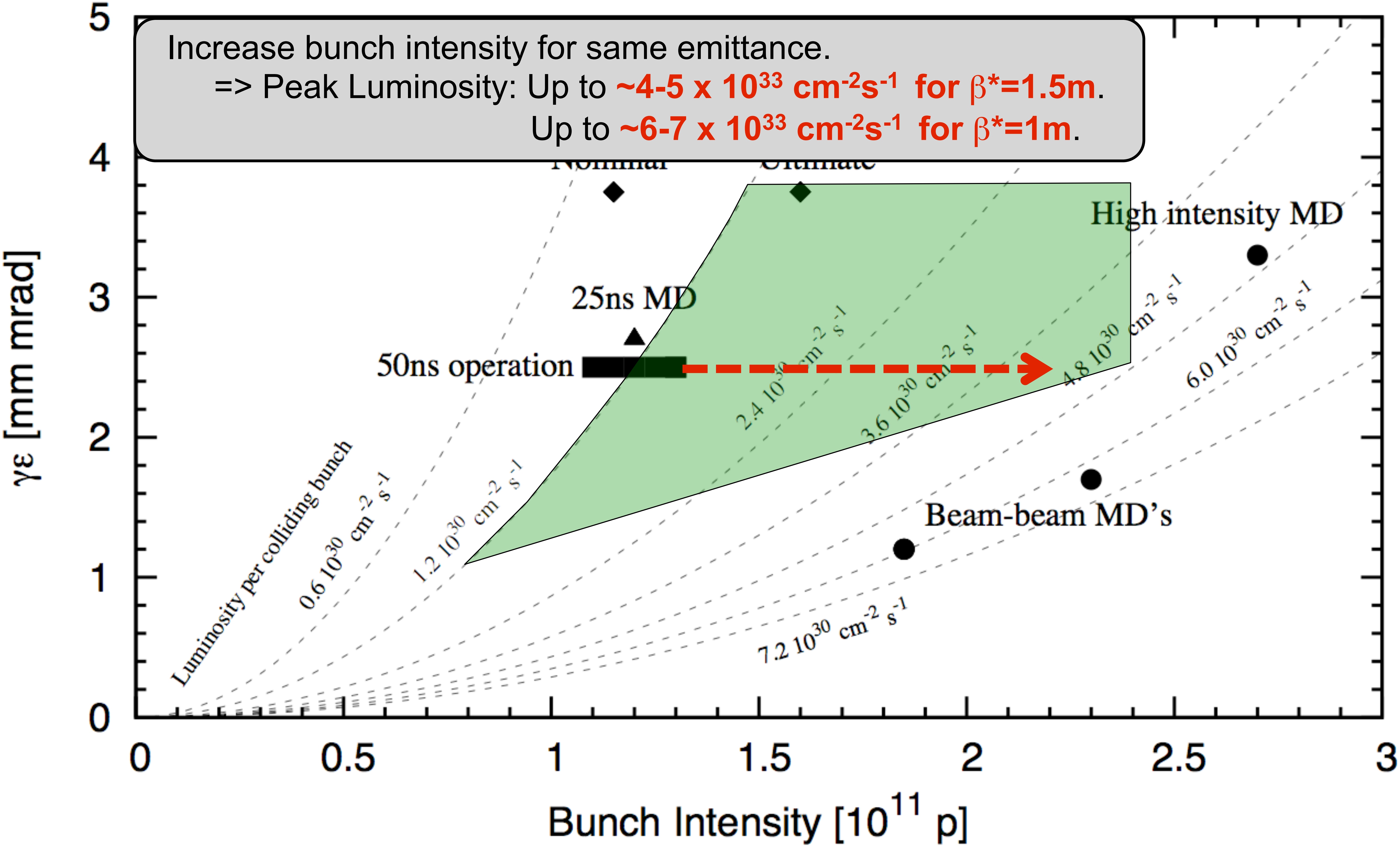


LHC MDs: Conclusion to Date

Increase bunch intensity for same emittance.

=> Peak Luminosity: Up to **~4-5 x 10^{33} $cm^{-2}s^{-1}$ for β^*=1.5m**.

Up to **~6-7 x 10^{33} $cm^{-2}s^{-1}$ for β^*=1m**.



MD Achievements in numbers

- High bunch intensity in LHC: N_p = 2.7×10^{11} p/bunch
  excellent beam lifetime $\gamma\varepsilon$ ≈ 3.3 μm
- Colliding beam @ 450 GeV: **N_p = 2.3×10^{11} p/bunch**
  twice nominal intensity, half nominal emittance, head-on & parallel separation OK **$\gamma\varepsilon$ ≈ 1.7 μm**
- Long-range beam-beam for 50ns: **$\alpha_c/2$ = 48 μrad** for $\tau \approx 15$ h
  crossing angle can be more than halved
- Short bunch spacing → 25ns: N_{bunch} = 216
  24b trains, vacuum ~OK, heat load ~OK, N_p = 1.2×10^{11} p/bunch
  instabilities, better than 50ns at same stage $\gamma\varepsilon$ ≈ 2.7 μm first batches
- Injection: $\gamma\varepsilon$ ≈ 3.5 μm OK for injection
- Tune working point: Q_x/Q_y = 0.47/0.47
  more space in tune diagram for BB footprint
- ATS optics: β^* = 0.3 m

Lumi Reach for remainder of 2011

	Adiabatic	Max Lumi Improvement factor	Lost Physics Time (Days)	Risk/ Reversibility	Pileup	Cumulative improvement factor	
						50 ns	25 ns
bunch Intensity	Yes	2	0	0	higher	Yes	No
Emittance	Yes	1.35	0	0	higher	Yes	No
Beta* = 1m	No	1.5	3	>0	higher	Yes	Yes
Beta* = 1.5m	No	1	3	0	higher	Yes	Yes
25ns	No	1.9	10	>0	same	No	Yes
			Luminosity Improvement Factor			4.1	2.9
			Pile Up			28	10
			Relative Integrated Luminosity Factor			3.42	2.06
			Luminosity Improvement Factor			2.7	1.9
			Pile Up			19	7
			Relative Integrated Luminosity Factor			2.32	1.38
			Est. Integrated Lumi if stay as we are			**~1.0 fb^{-1}**	

<u>Luminosity comparison wrt:</u>

1380 bunches, 1.1E11 av bunch intensity, emittance = 2.7um, beta* = 1.5, Peak Lumi = 1.2E33

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Plan of attack

- **Continue with 50ns**
- Operate with **Beta* =1m** and **emittance < 2um**
- **Increase bunch intensity** (max 1.55e11)

Luminosity comparison wrt:
1380 bunches, 1.1E11 av bunch intensity, emittance = 2.7um, beta* = 1.5, Peak Lumi = 1.2E33

LHC Outlook ... till end of 2012

- Proton Physics data-taking until end of 2012
  - 50ns or 25 ns
    - 50ns with Beta* = 1m should give better delivered luminosity
    - Peak Luminosity better with 50ns due to better beams from the injectors.
    - Very high intensity operation at 50ns may need beam scrubbing with 25ns
  - Beam energy
    - After copper stabilizer resistances measurements during the Christmas stop, re-evaluate maximum energy for 2012 (Chamonix 2012)
- Ions Phyiscs
  - Lead-lead for 4-5 weeks at end of 2011
    - increase number of bunches and luminosity wrt 2010
  - Feasibility Test end 2011 for protons-lead (possibly 2012)
  - Possibility of protons-lead in 2012. Otherwise stay with lead-lead.

Summary

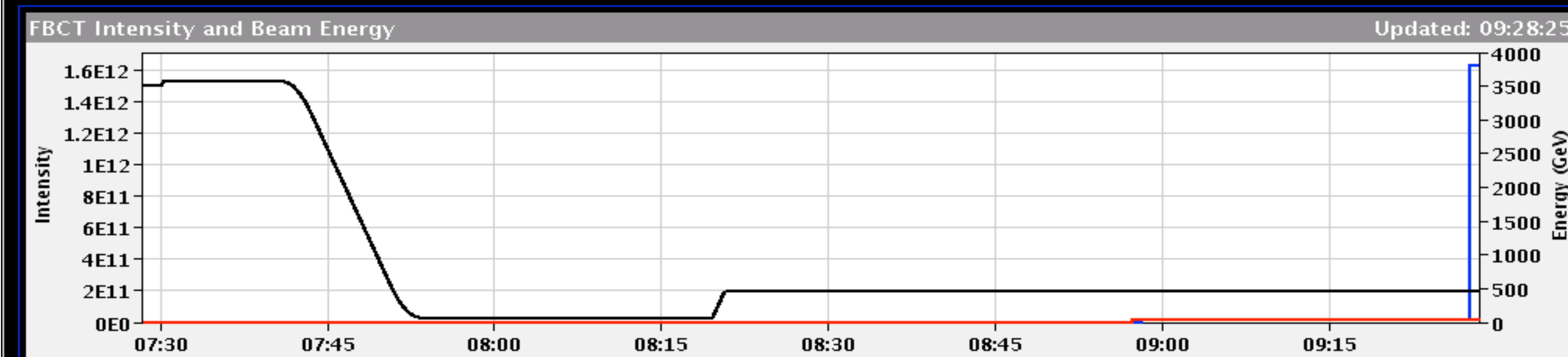
- **Beam Intensity, peak and Integrated luminosity are still going up**
- Successfully implemented luminosity calibration + leveling for LHCb
- Reached 2011 target integrated luminosity, with ~16 wks remaining
- Several issues being addressed that effect delivered luminosity progress (intensity, beam instabilities , ß*, emittance, electron cloud)
- Questions on energy, 25ns operation and schedule for 2012 to be addressed in “Chamonix 2012” (Jan 2012)
- Machine Protection issues are foremost in LHC operation
  - We currently operate with ~110MJ of stored energy
- The LHC is an immensely interesting environment, and we are looking forward to **delivering a lot of luminosity** both before both and after the 2011/2012 break (ie before the 2013 long shutdown).

LHC Page1	Fill: 2082	E: 450 GeV	07-09-2011 09:28:25

PROTON PHYSICS: INJECTION PHYSICS BEAM

BCT TI2:	0.00e+00	I(B1):	1.65e+12	BCT TI8:	0.00e+00	I(B2):	9.38e+09

TED TI2 position:	BEAM	TDI P2 gaps/mm	up: 10.91	down: 8.59
TED TI8 position:	BEAM	TDI P8 gaps/mm	up: 9.58	down: 8.90



Comments 07-09-2011 08:39:11 :

Asynch test and loss maps completed

Next fill for physics, 264b
(possible need of inj studies, though)

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

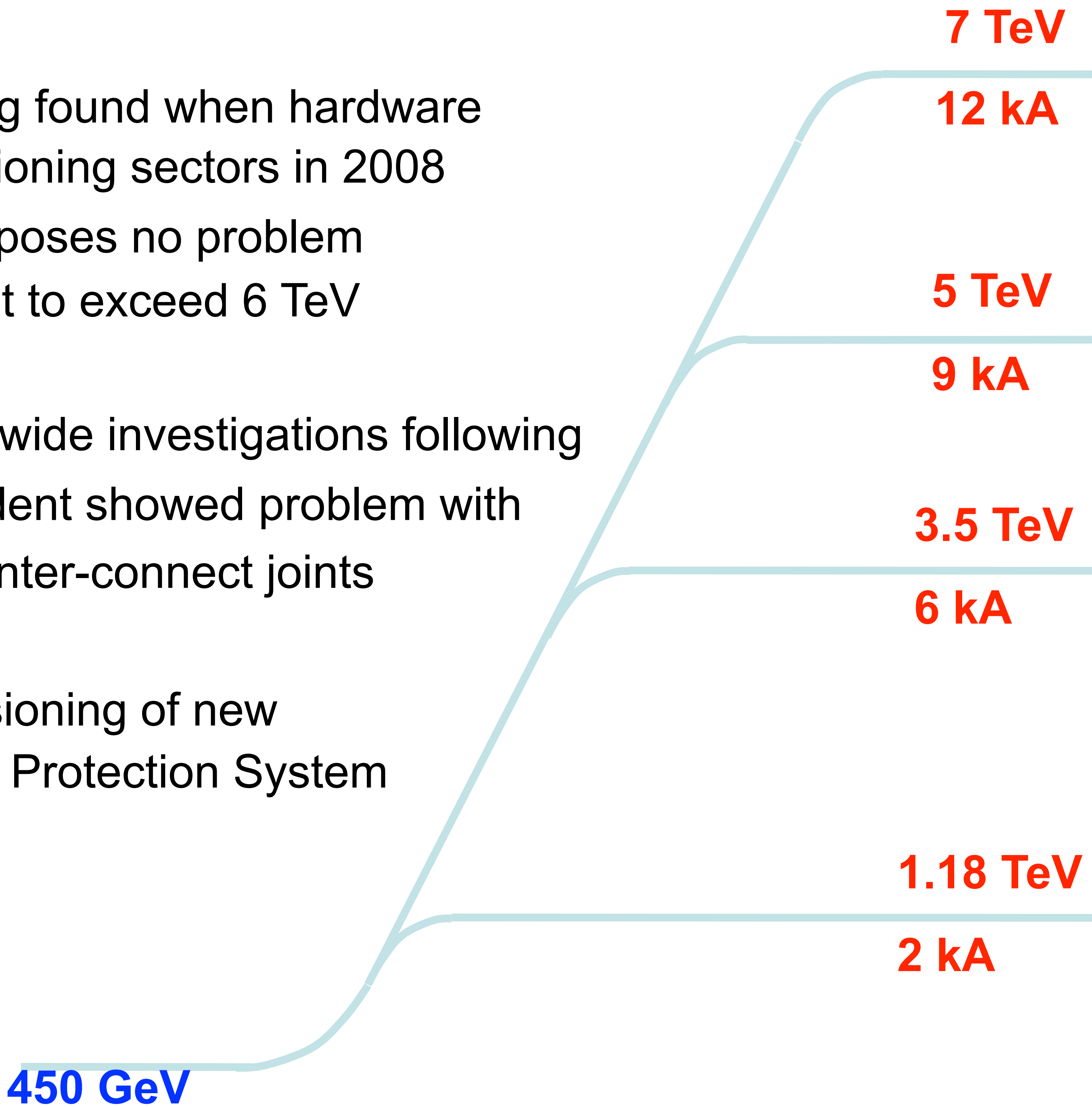
AFS: 50ns_264b+1small_250_25_216_36bpi9inj

PM Status B1 ENABLED PM Status B2 ENABLED

Spare slides

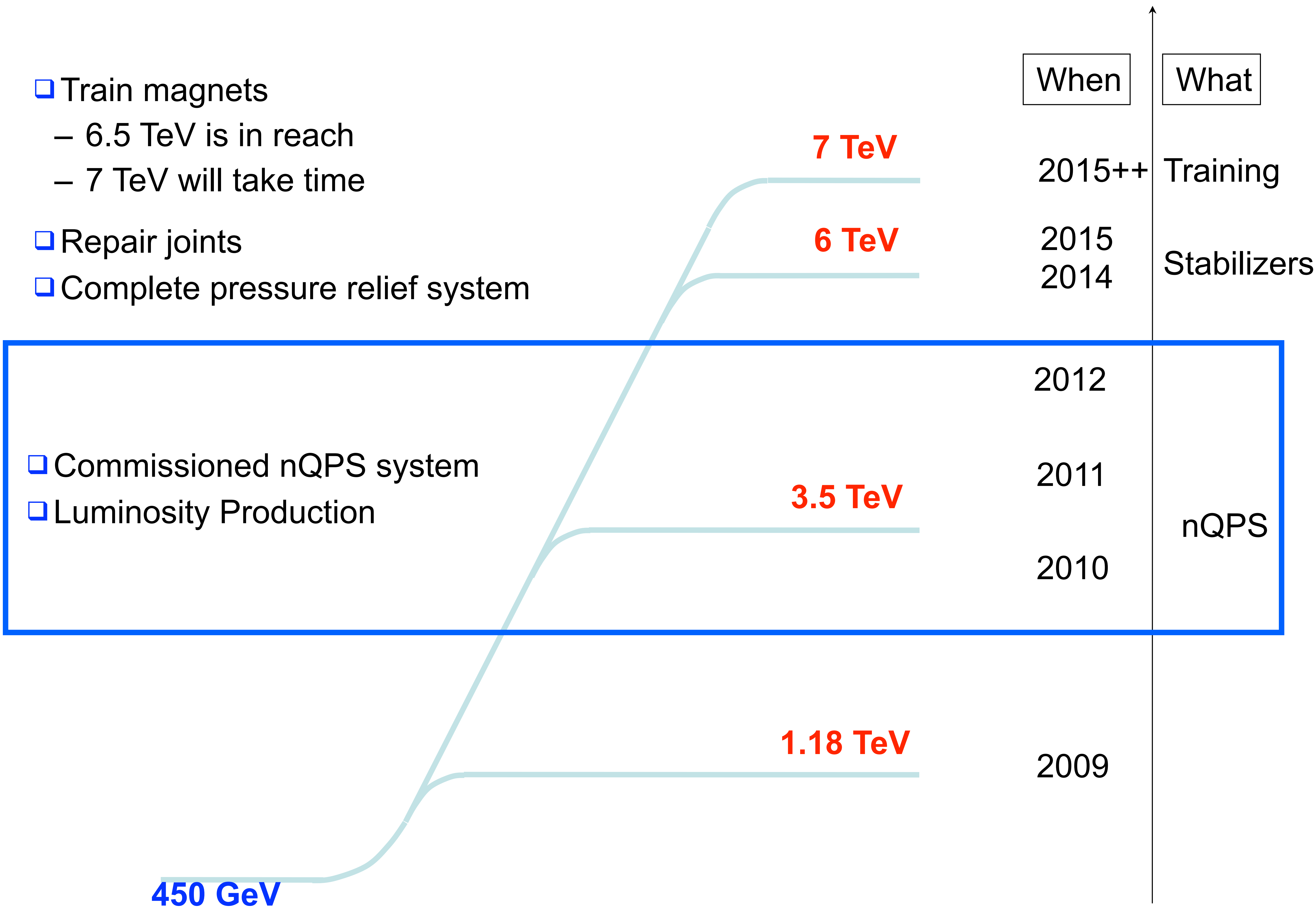
LHC target energy: the way down

- All main magnets commissioned for 7TeV operation before installation
- Detraining found when hardware commissioning sectors in 2008
  - 5 TeV poses no problem
  - Difficult to exceed 6 TeV
- Machine wide investigations following S34 incident showed problem with magnet inter-connect joints
- Commissioning of new Quench Protection System (nQPS)



When	Why
2002-2007	Design
Summer 2008	Detraining
Late 2008 Spring 2009	Joints
Nov. 2009	nQPS

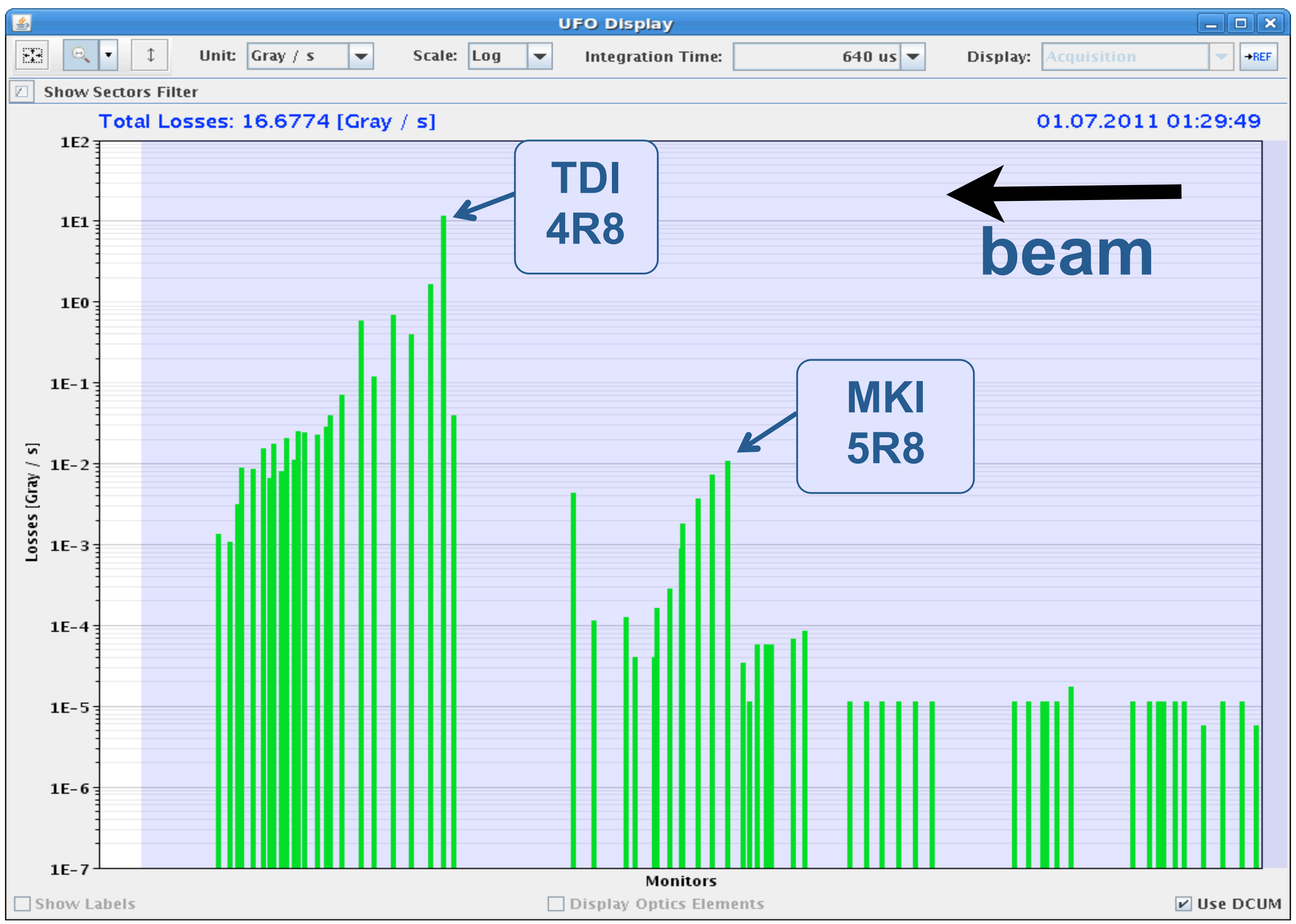
LHC target energy: the way up

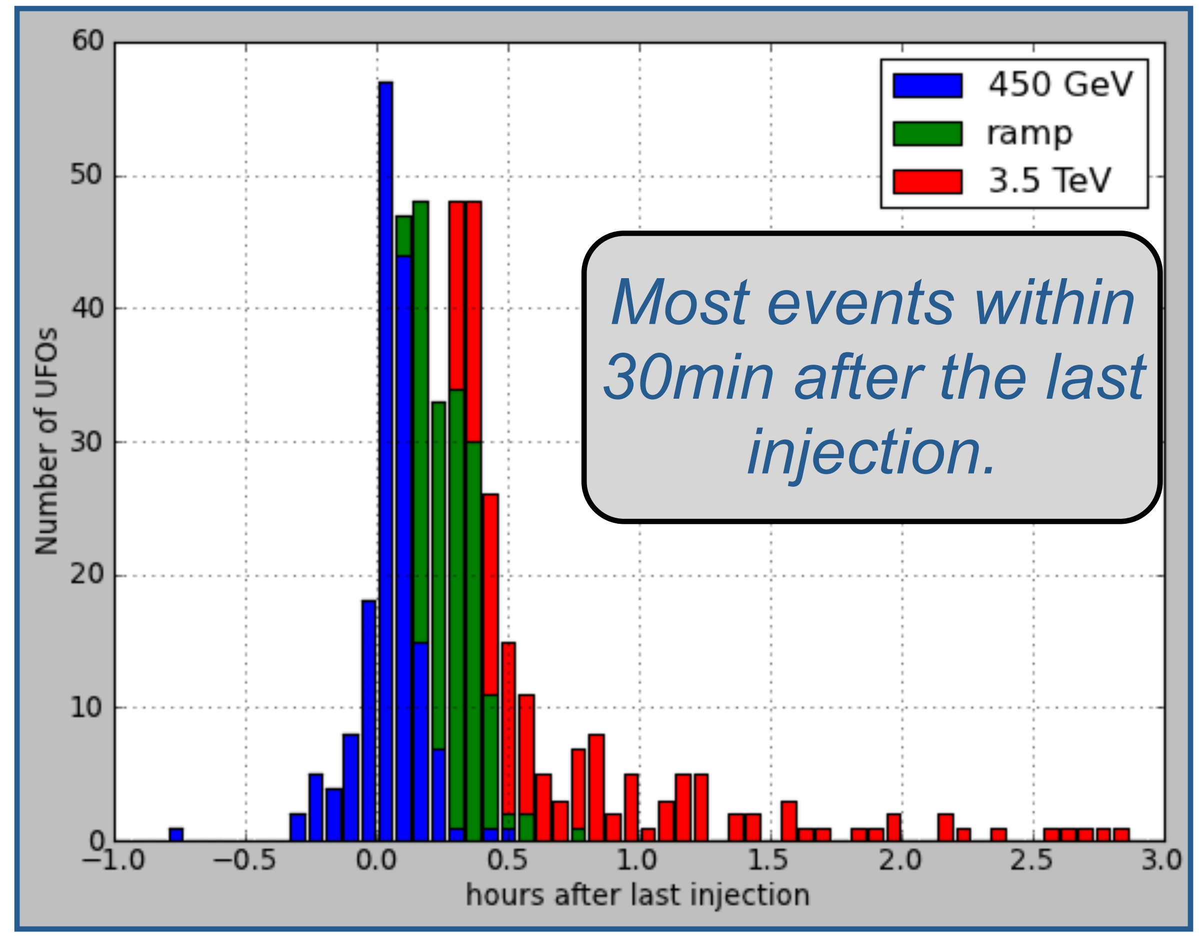


UFOs not just in the ARCs

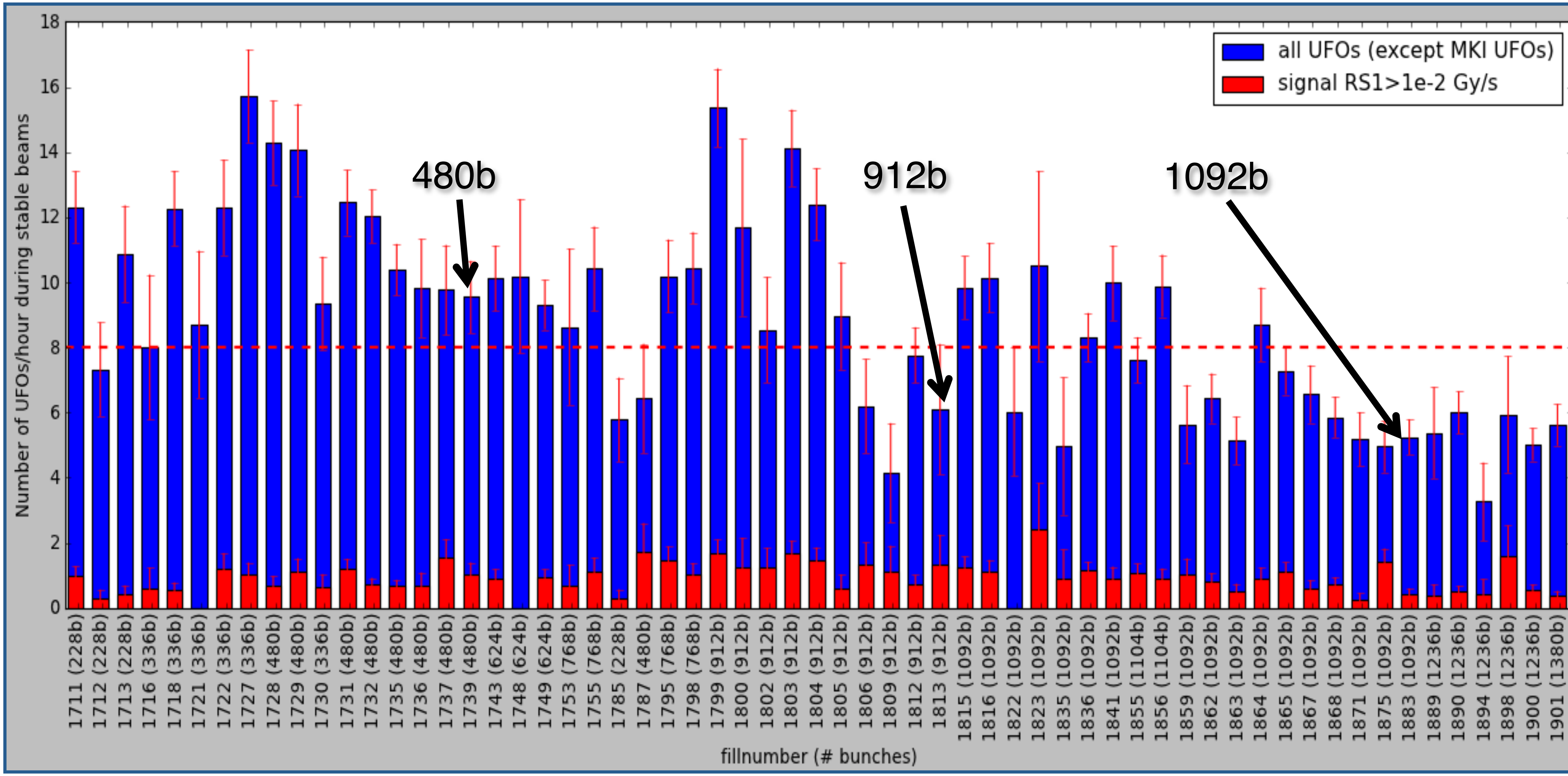
13 beam dumps due to UFOs around injection kicker magnets (MKIs)

In total **≈1500 UFOs around MKIs**





UFO rate

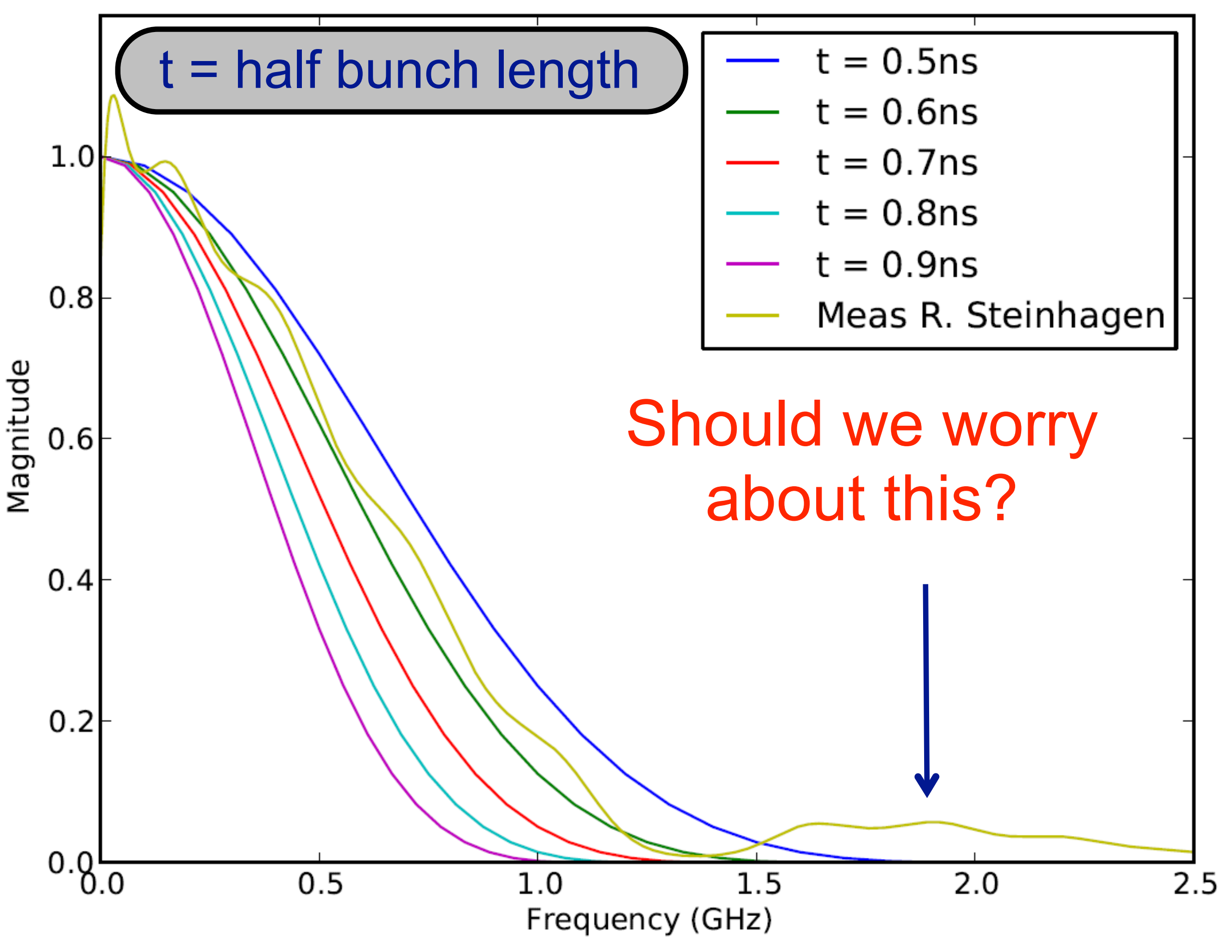


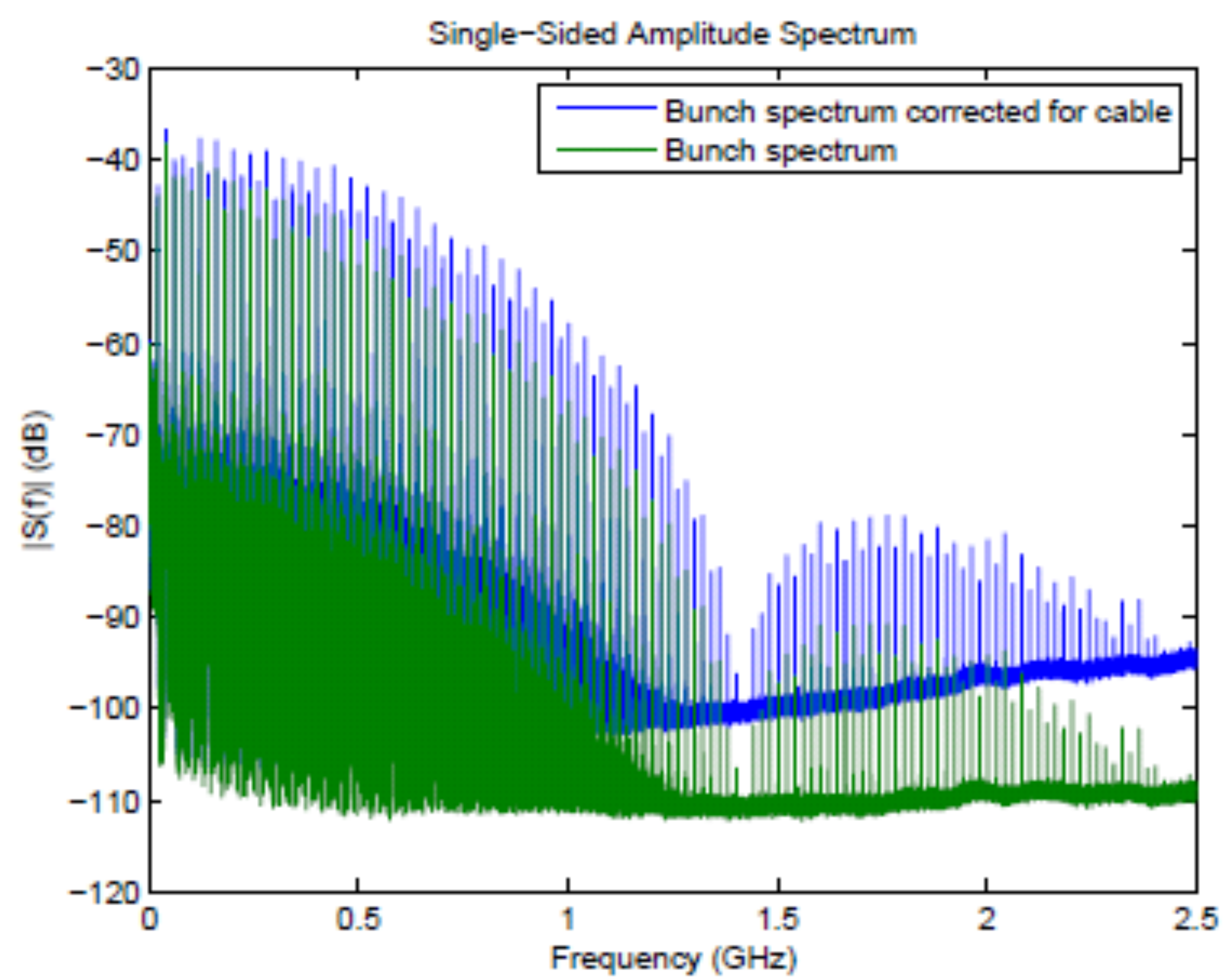
On average now ~6 UFOs/hour.
Is there a conditioning effect?

2301 candidate UFOs (excluding MKI UFOs) during stable beams in fills with at least 1 hour stable beams.
all UFOs: Signal RS05 > 2·10^{-4} Gy/s.
Data scaled with 1.85 (detection efficiency from reference data)

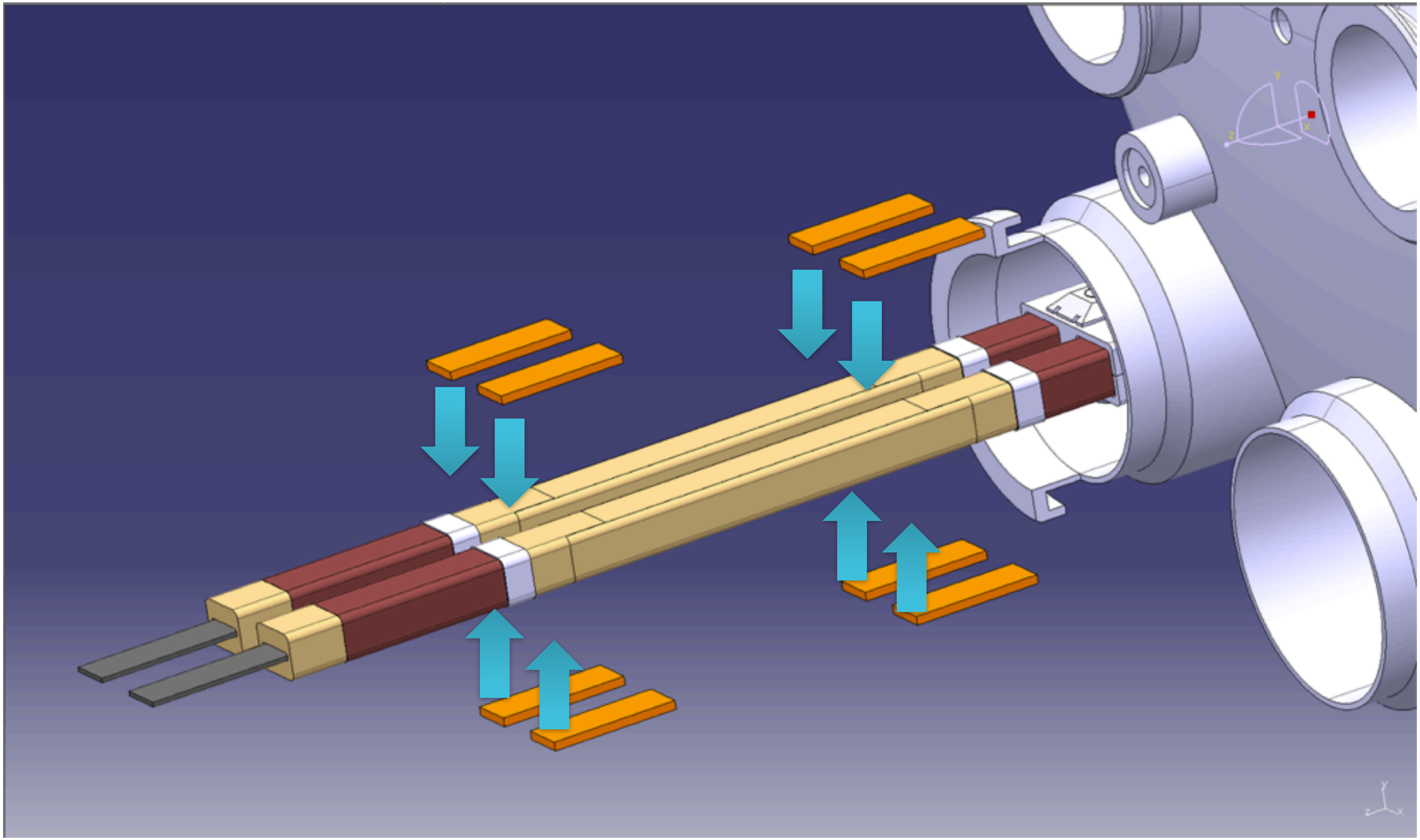
Measured and Calculated Power Spectra

- Beam Frequency Spectrum: simulation agrees with measurement below 1.2GHz for bunch length of ~ 1.2ns
- **Beam impedance indicates higher order modes above 1GHz**
- Significant power at 1.6 GHz.
  - 35 dB below 400 MHz component(factor of 3000 in power)



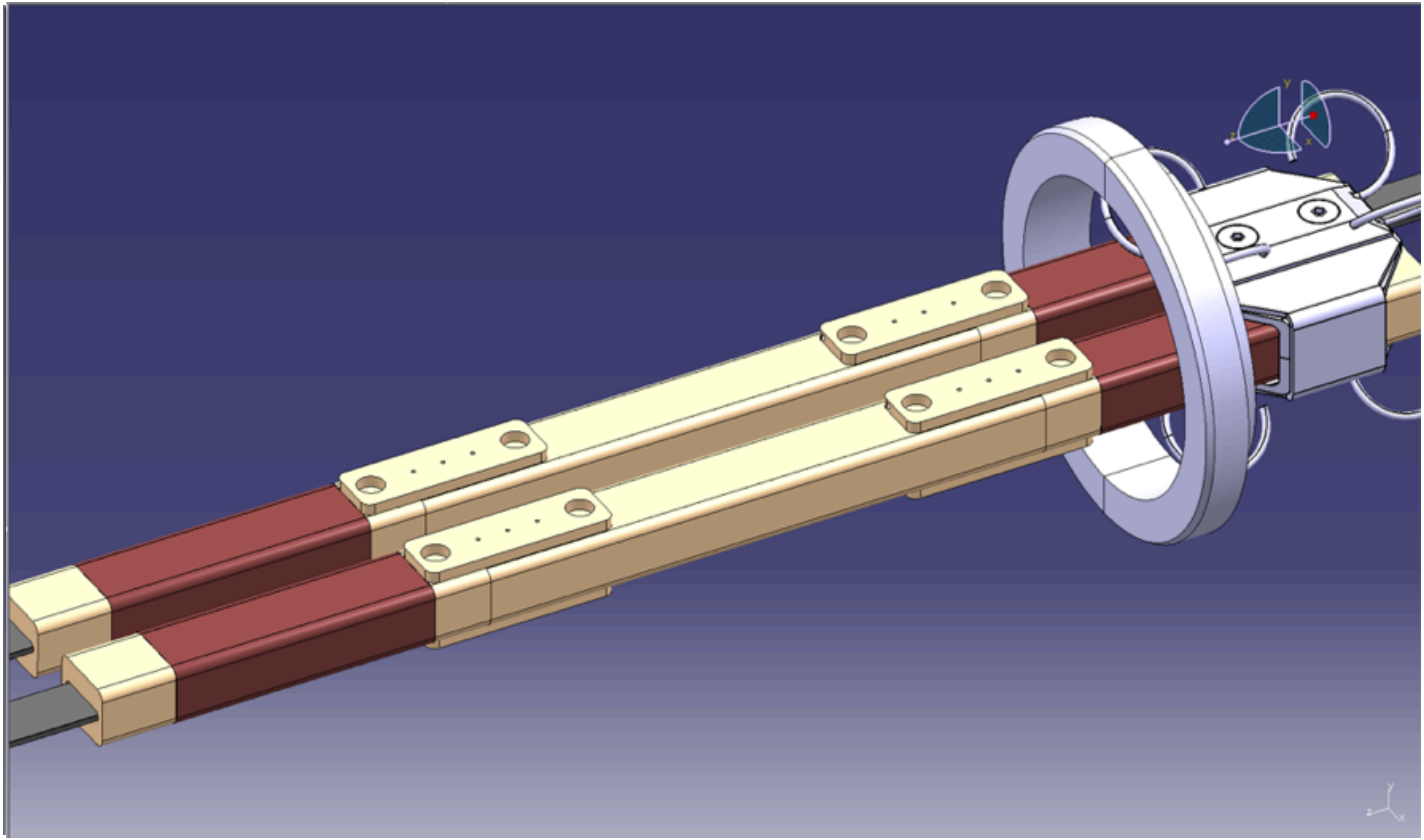


LHC MB circuit splice consolidation proposal



Phase I
Surfacing of bus bar and installation of redundant shunts by soldering

LHC MB circuit splice consolidation proposal



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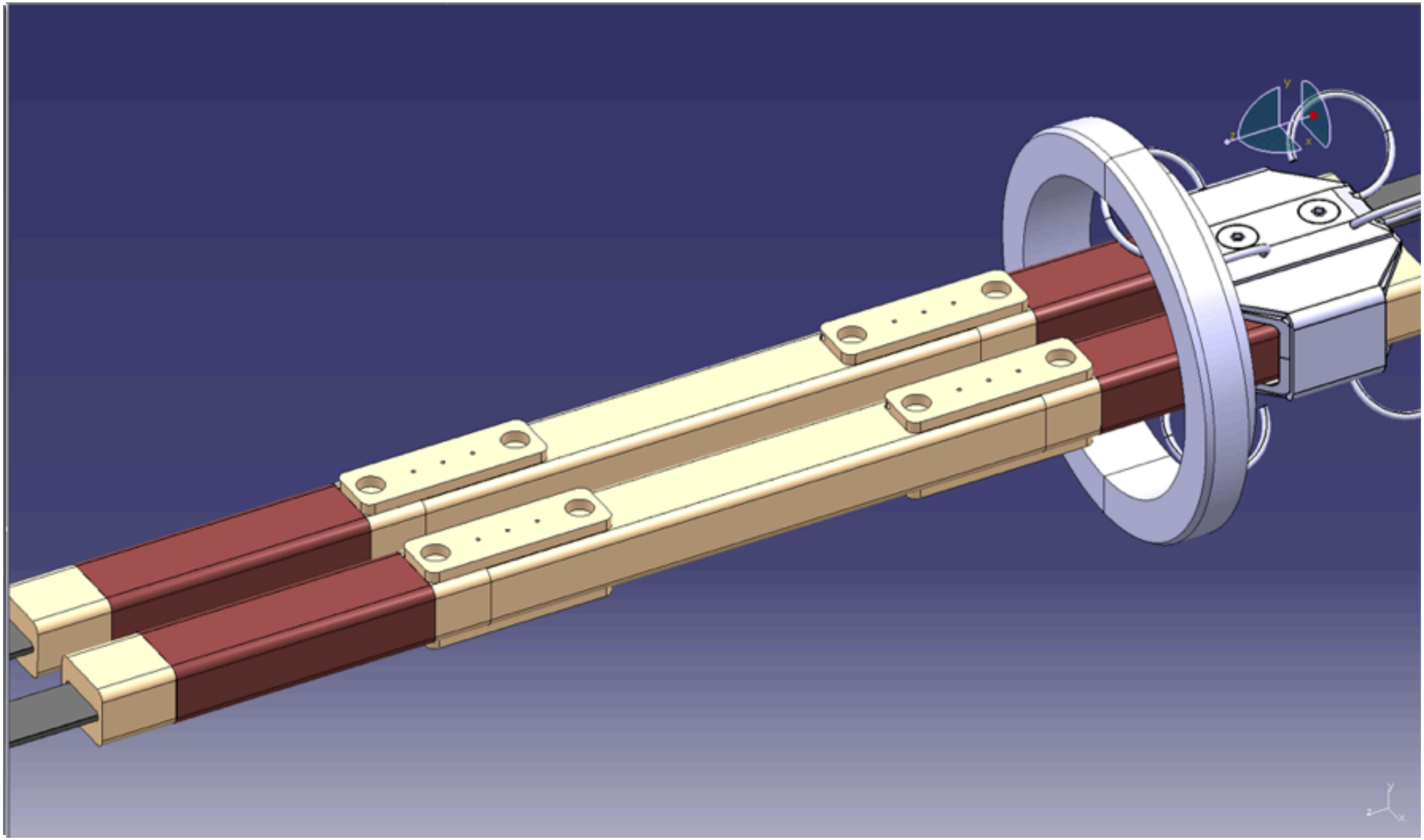

Phase II
Application of clamp and reinforcement of nearby bus bar insulation

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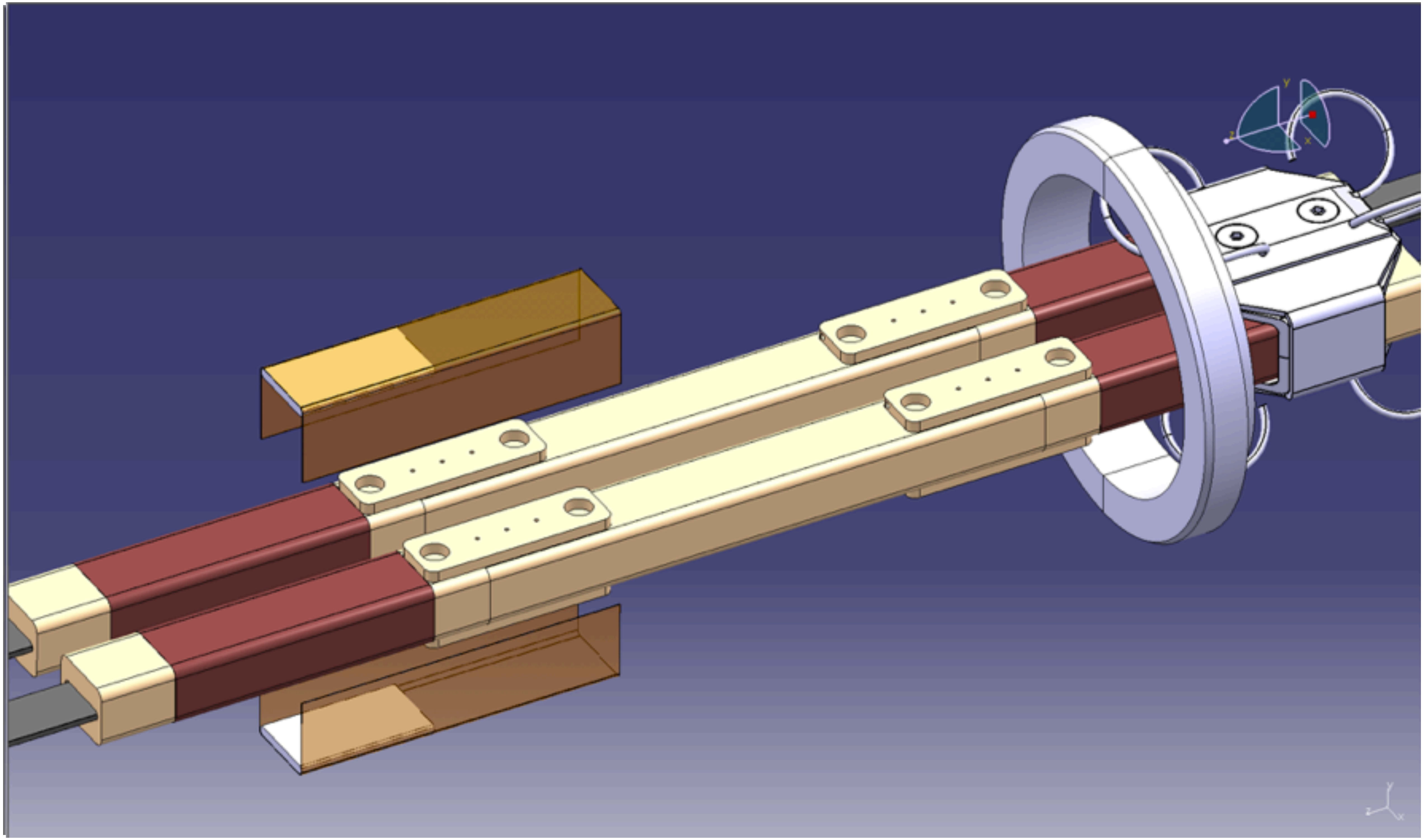

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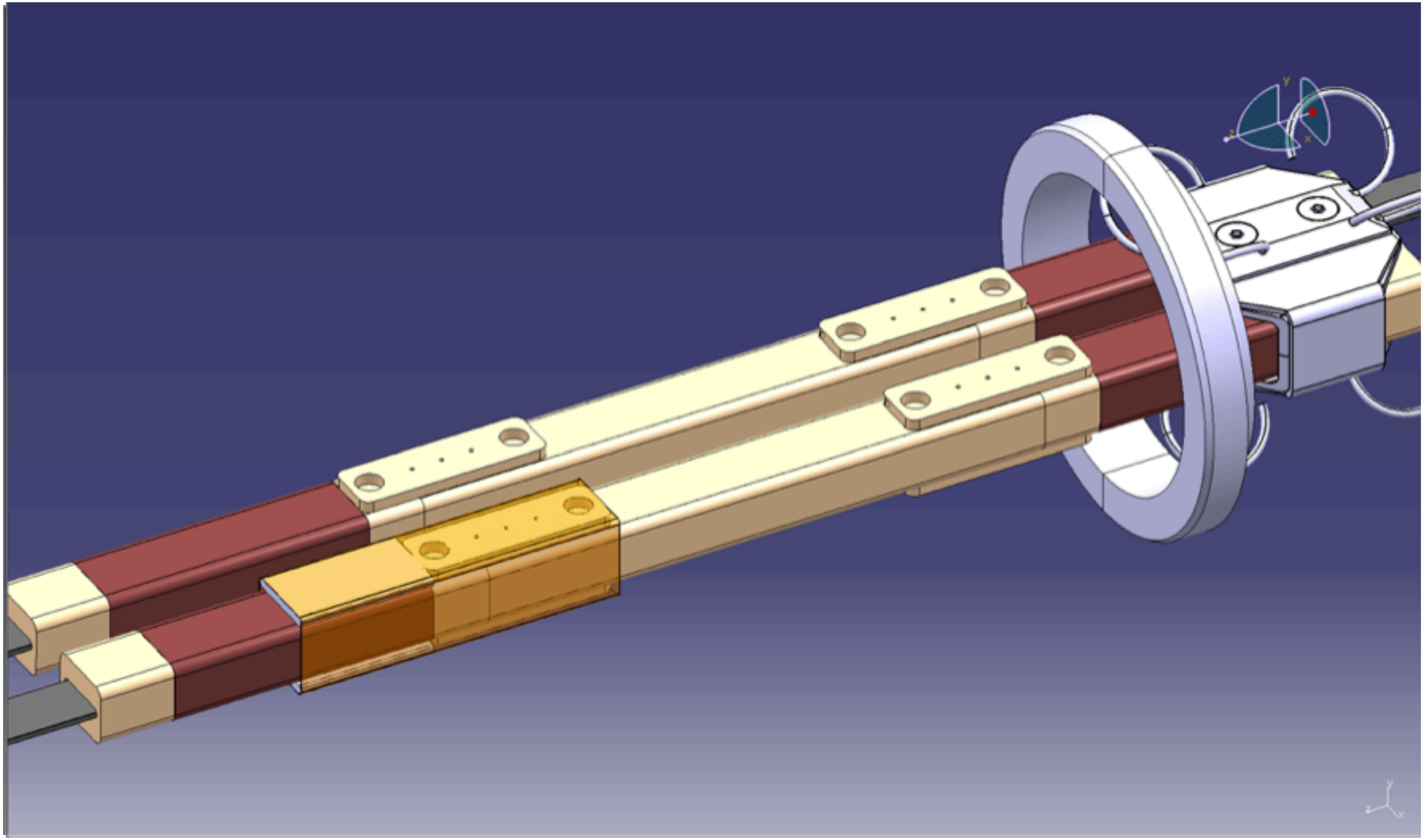

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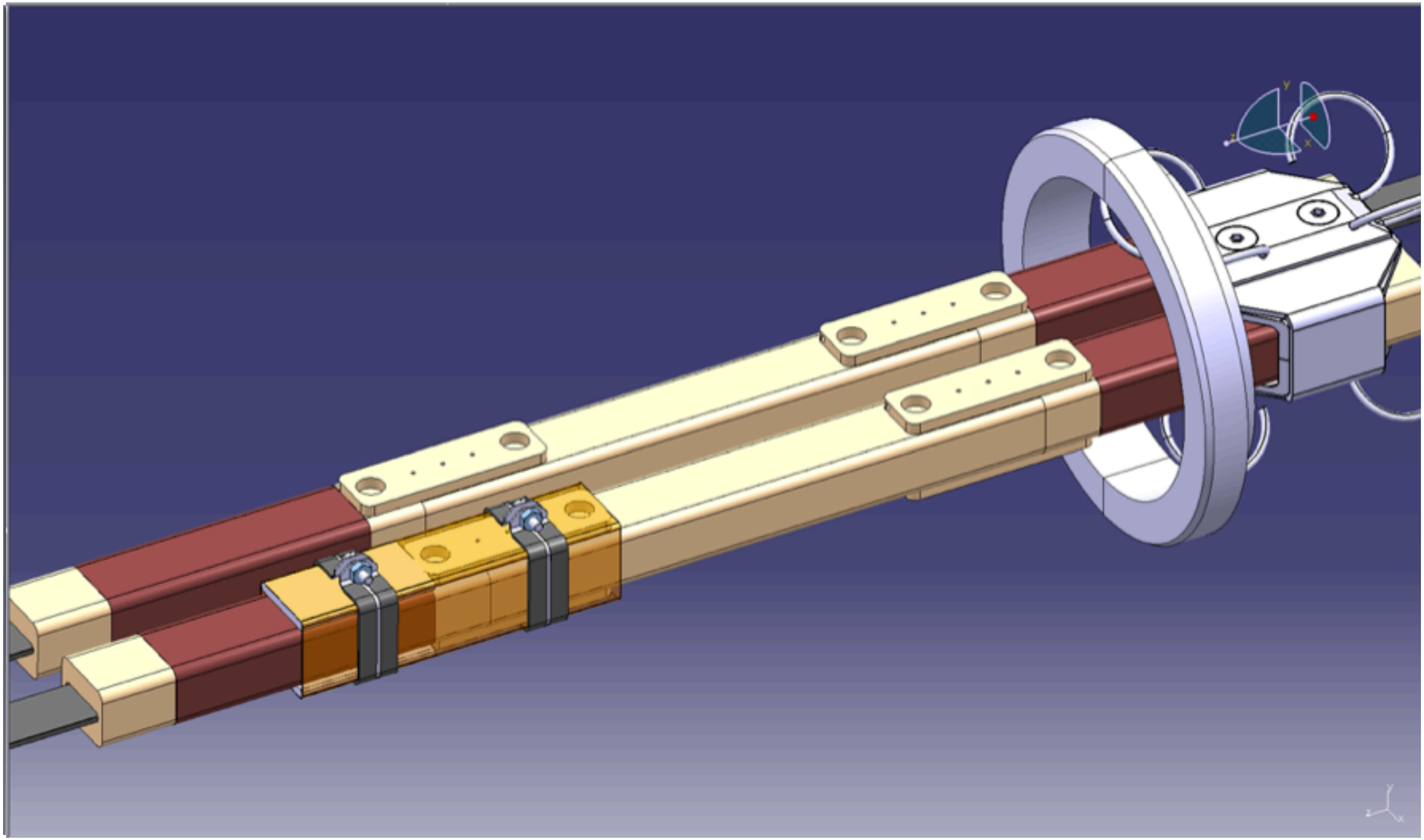

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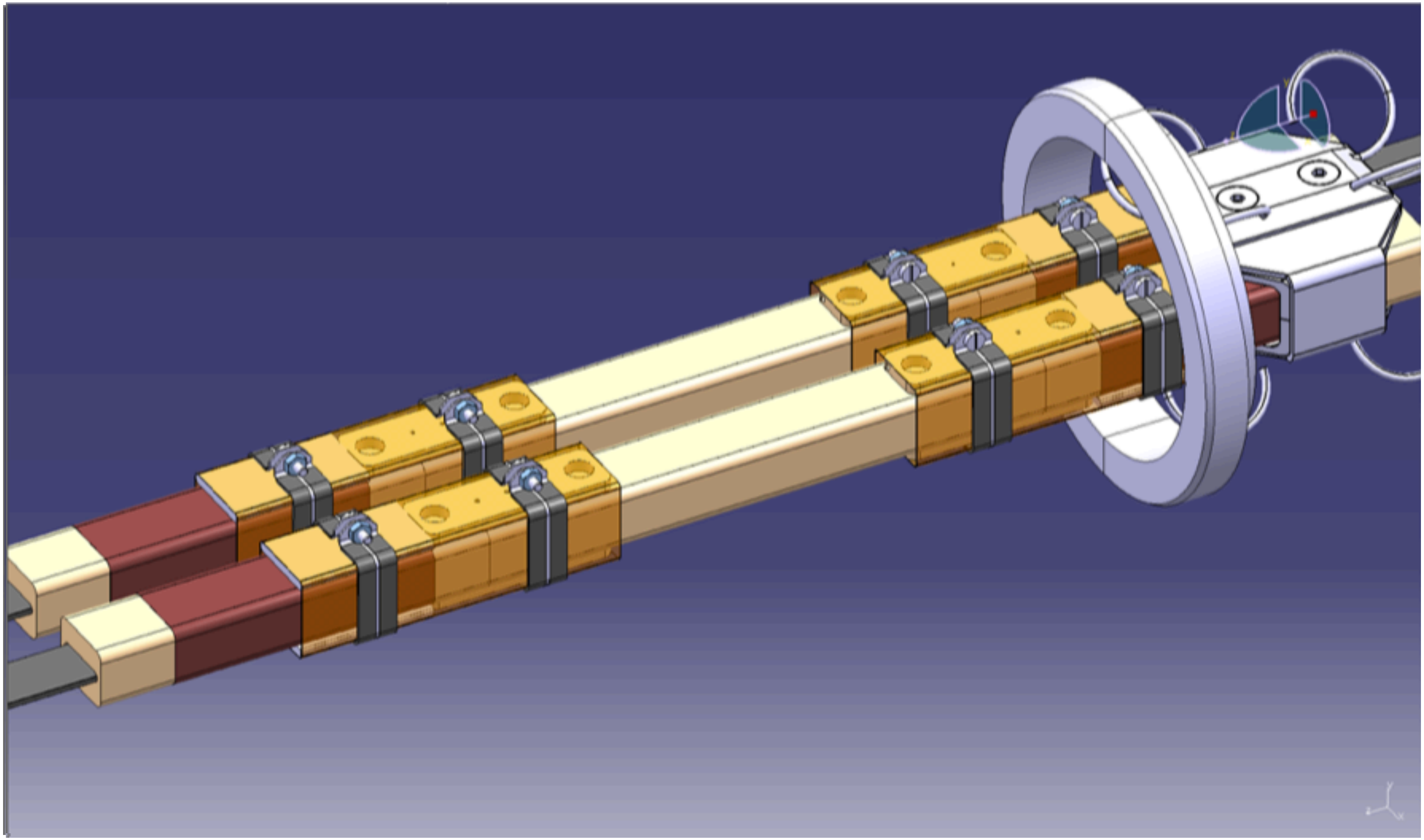

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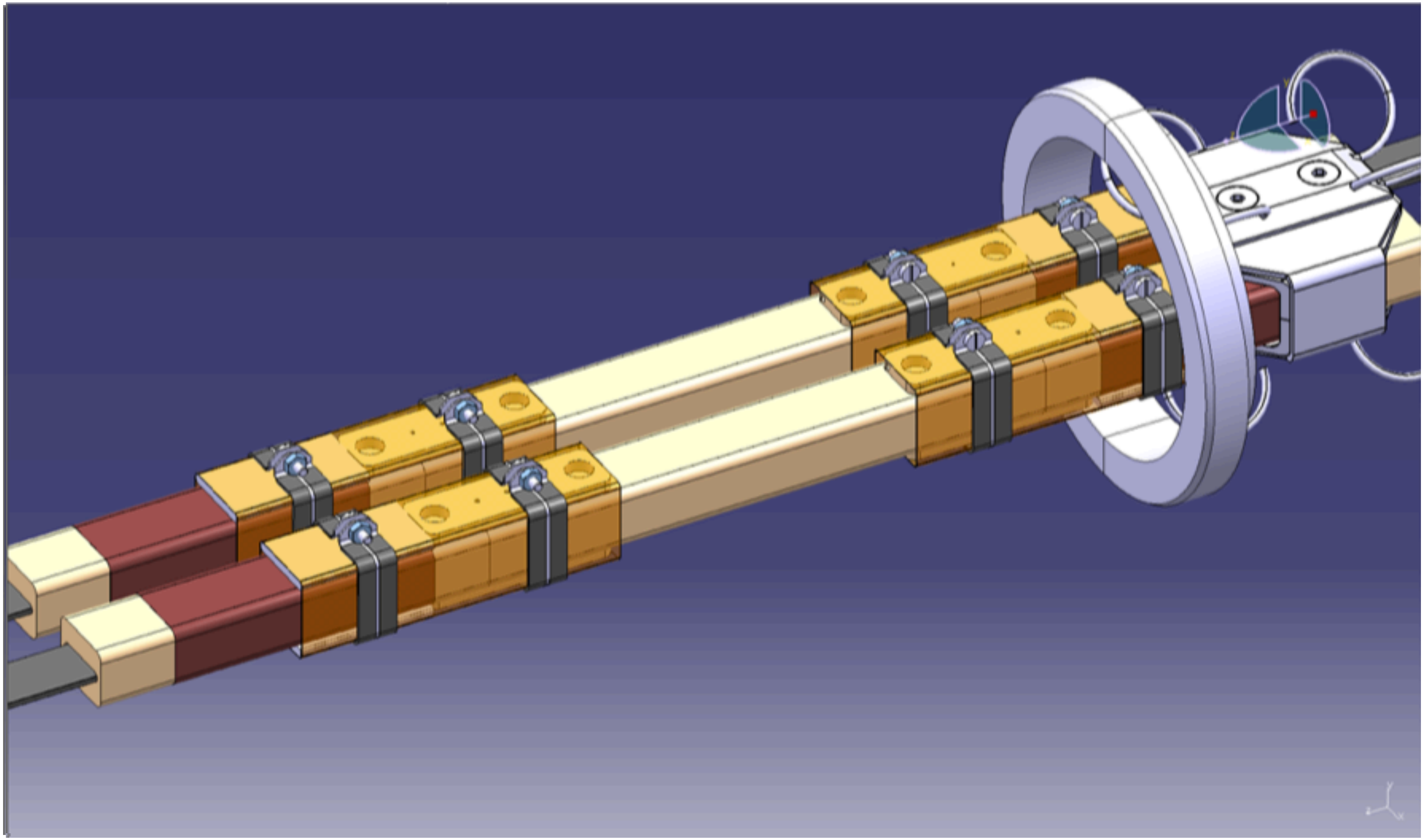
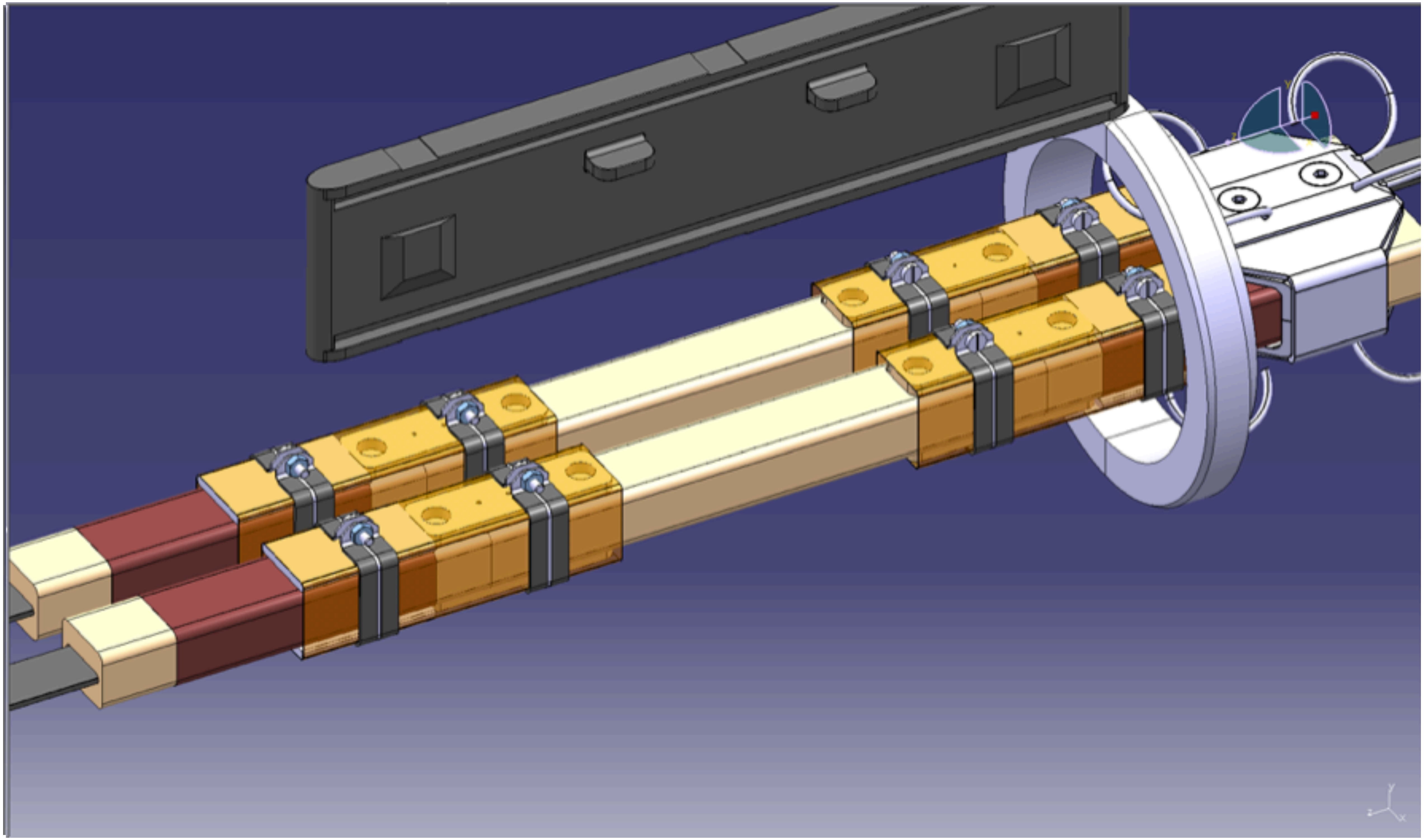


Phase III
Insulation between bus bar and to ground, Lorentz force clamping

LHC MB circuit splice consolidation proposal



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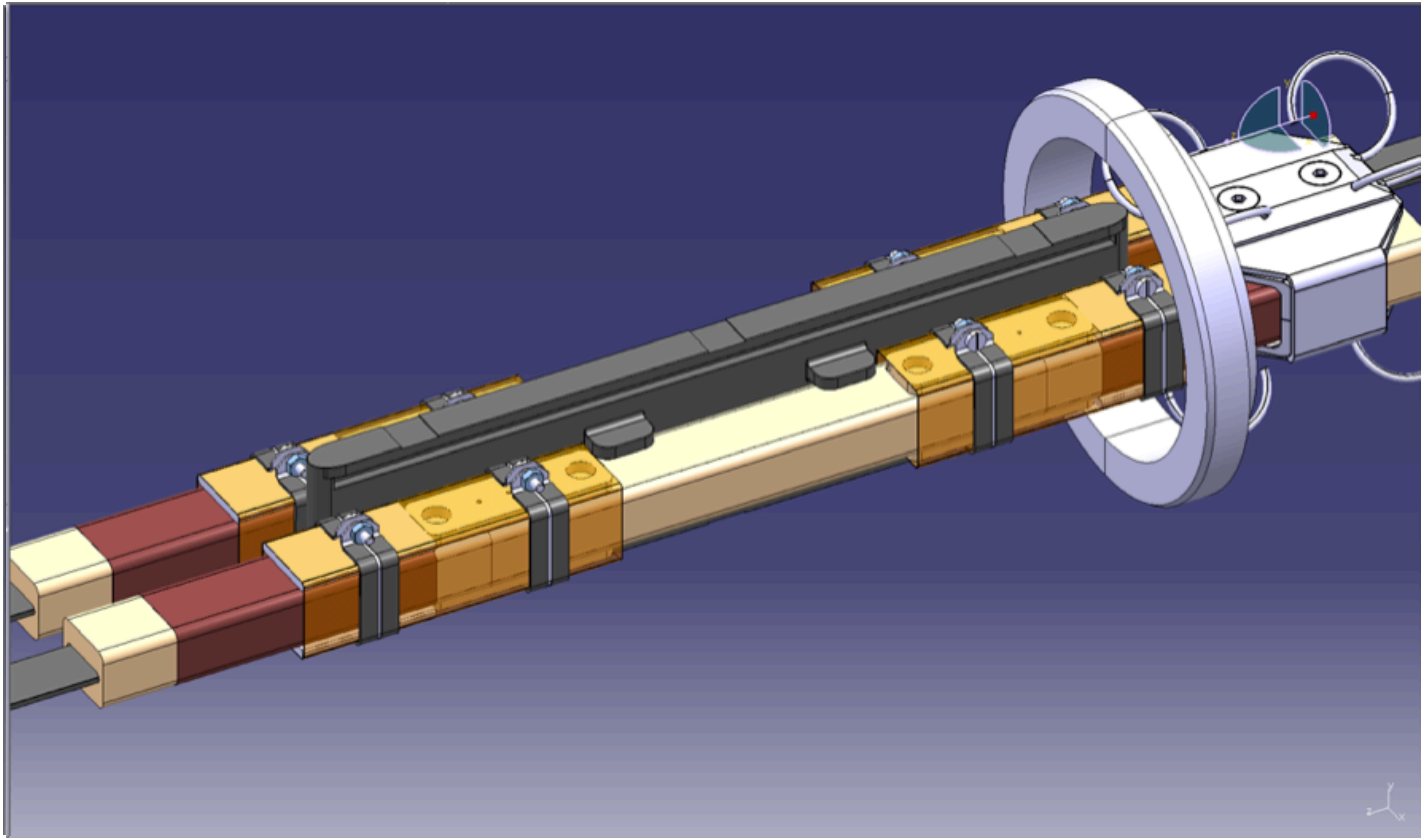

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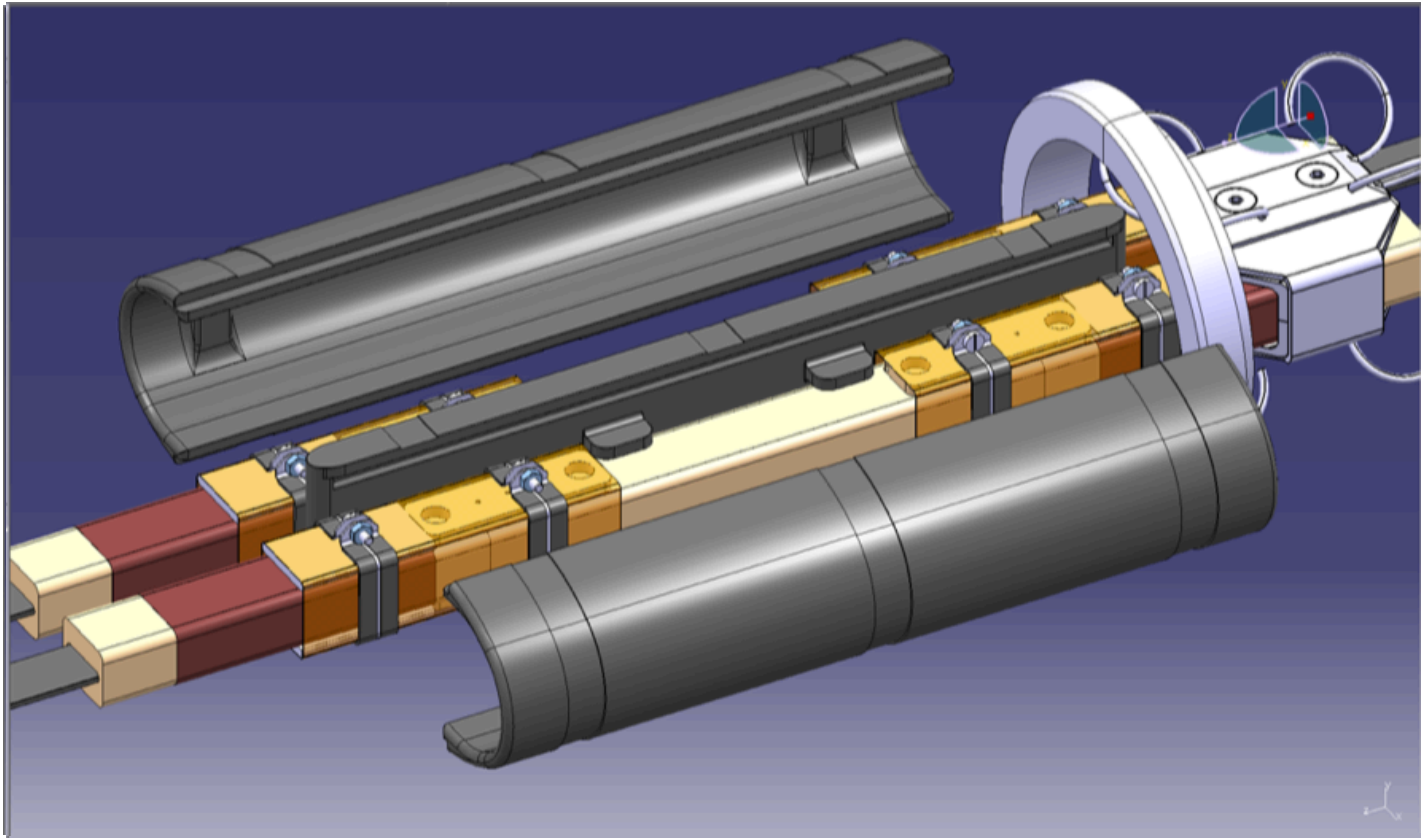

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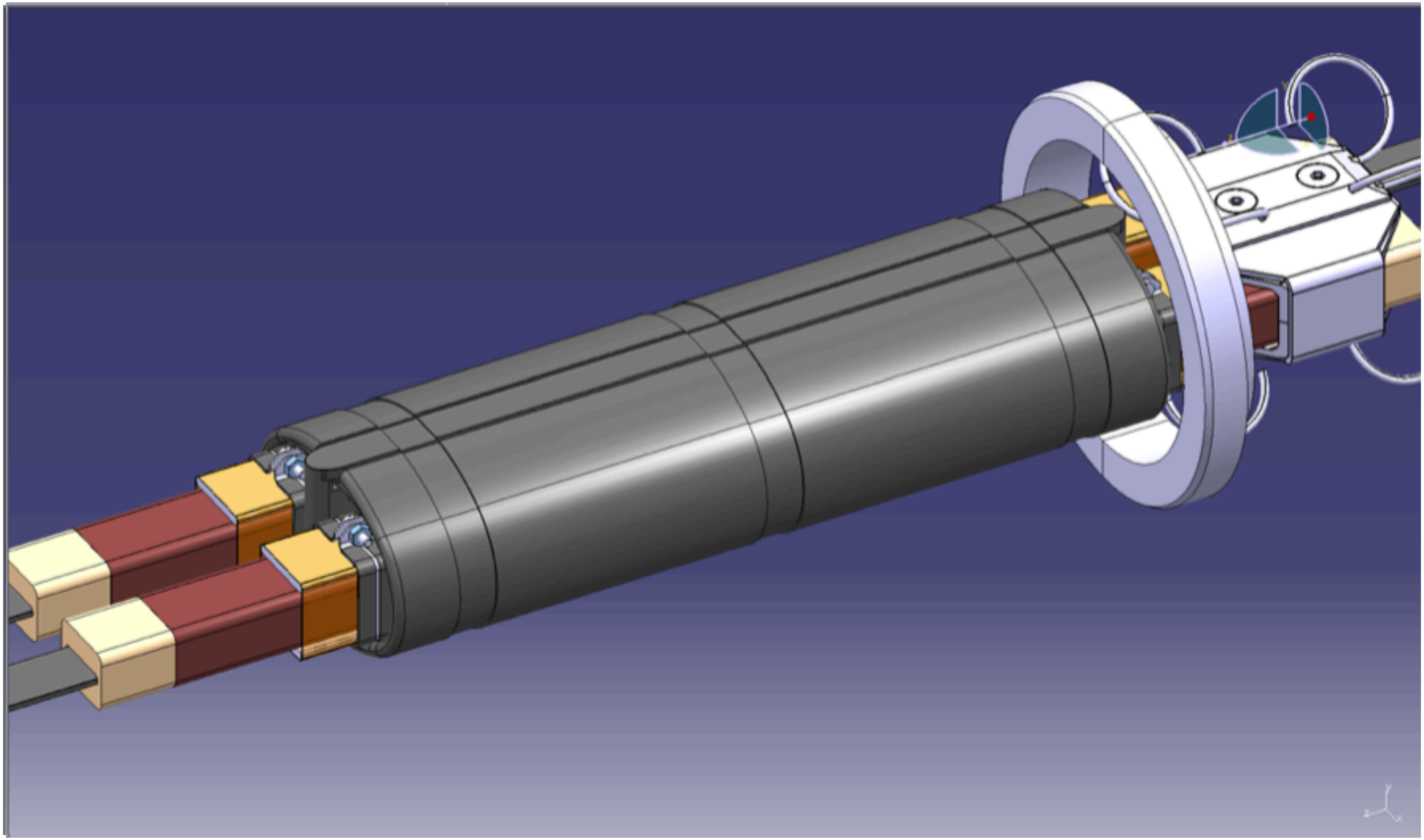

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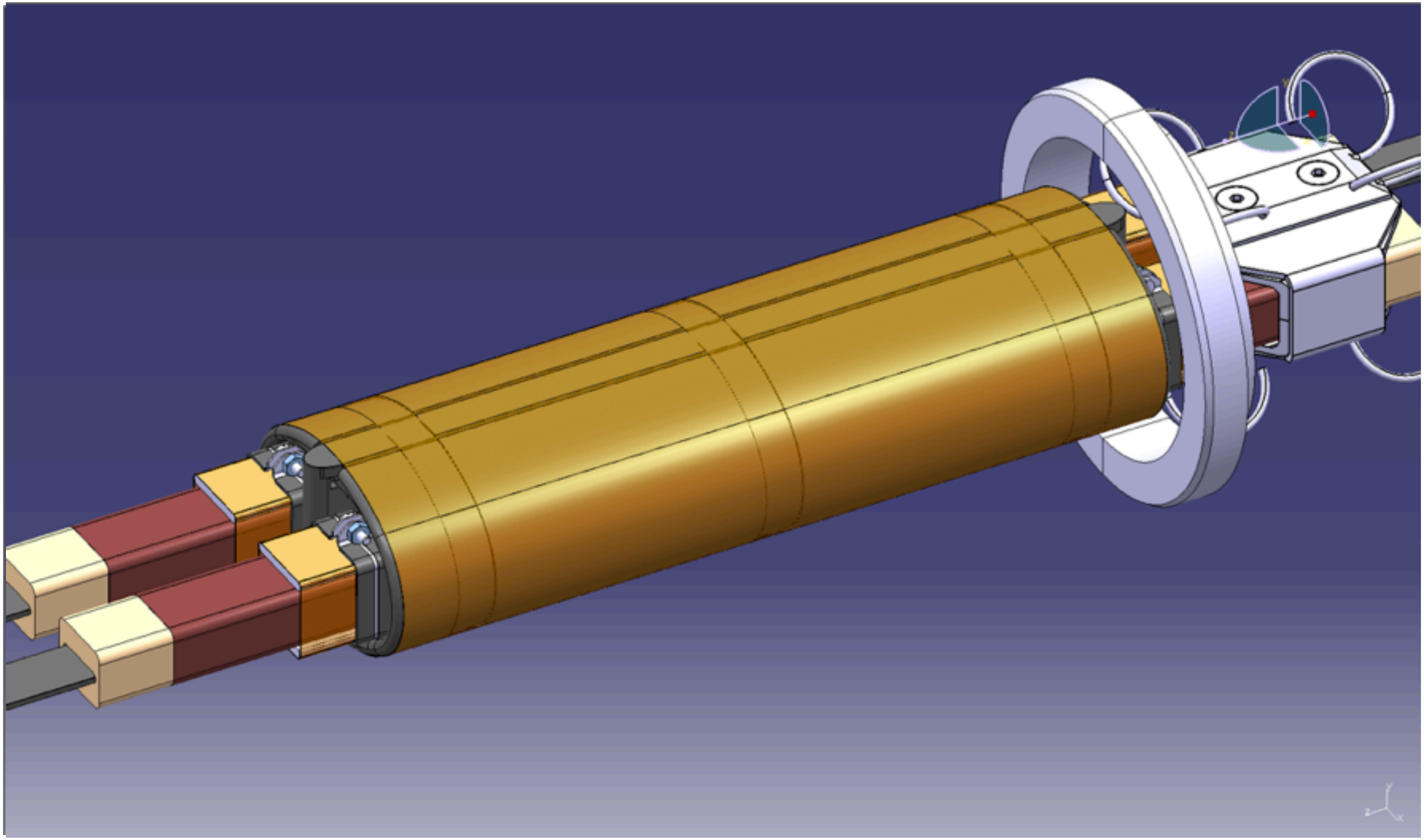

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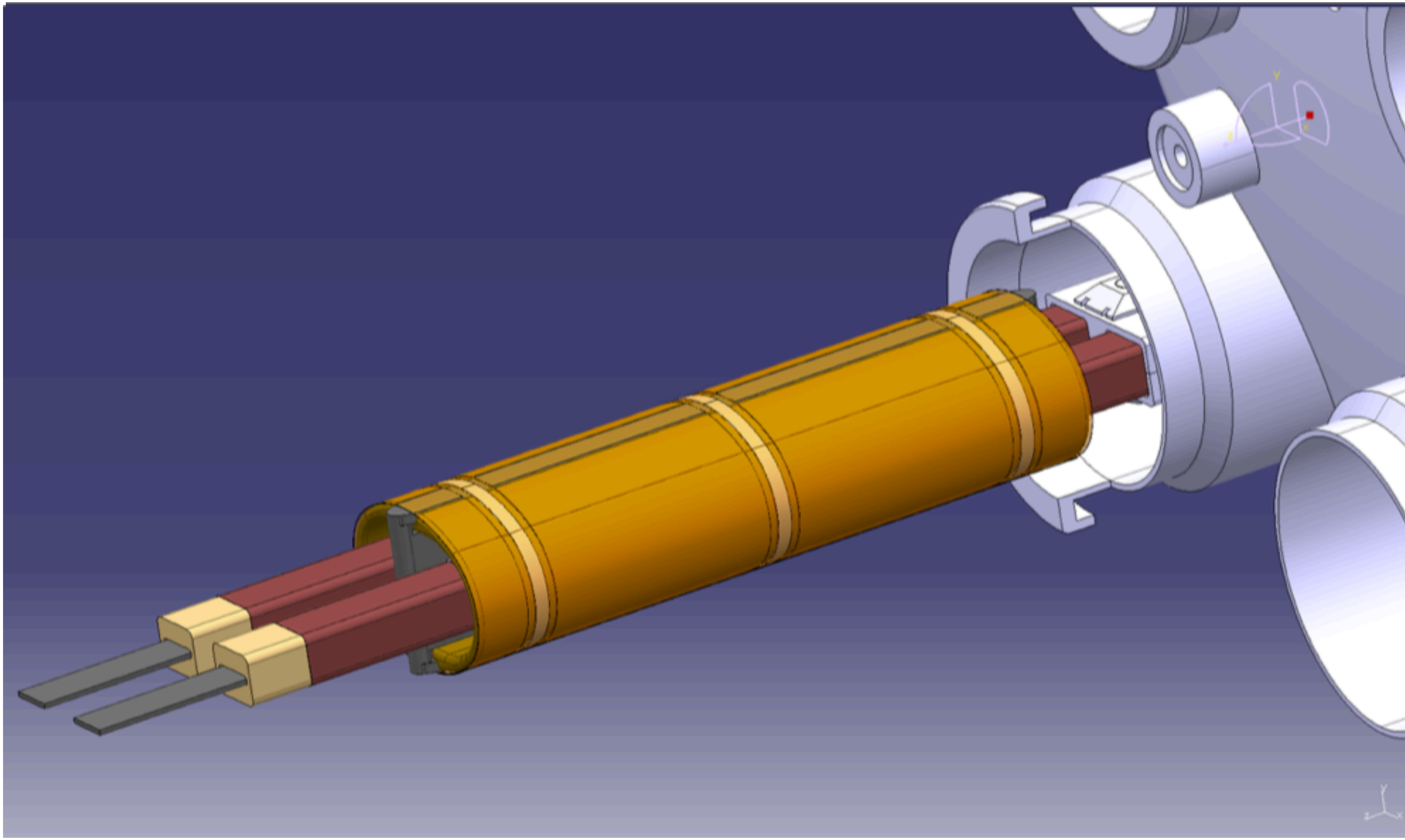

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