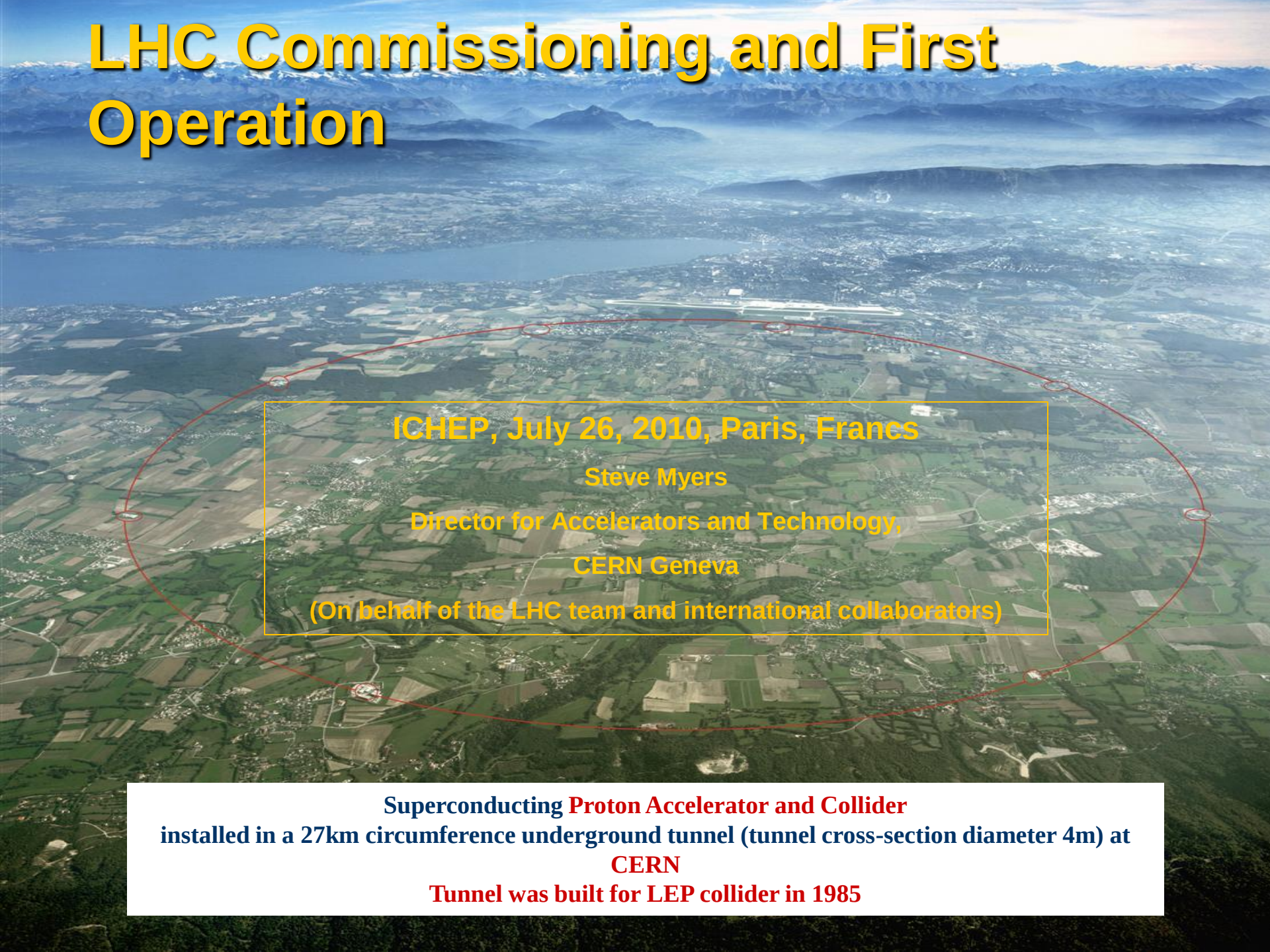
LHC Commissioning and First Operation



ICHEP, July 26, 2010, Paris, Francs

Steve Myers

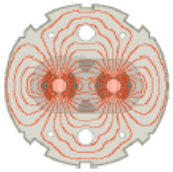
Director for Accelerators and Technology,

CERN Geneva

(On behalf of the LHC team and international collaborators)

Superconducting **Proton Accelerator and Collider**
installed in a 27km circumference underground tunnel (tunnel cross-section diameter 4m) at **CERN**
Tunnel was built for LEP collider in 1985

LHC: Some Technical Challenges

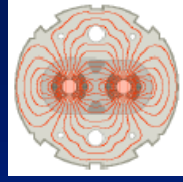


Circumference (km)	26.7	100-150m underground
Number of superconducting twin-bore Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K) (cryogenics system)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	$2.2.10^{-6}$ loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current 1MJ melts 1.5kg Cu
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

Topics

- The Past 21 months (reminder)
- The Present (status)
- The Future
  - Short term
  - Medium term
  - Long term

Incident of September 19th 2008



A very impressive start-up with beam on September 10, 2008

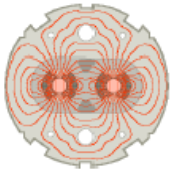
During a few days period without beam

Making the last step of dipole circuit in sector 34, to 9.3kA

At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole

Electrical arc developed which punctured the helium enclosure

Summary LHC Commissioning (1)

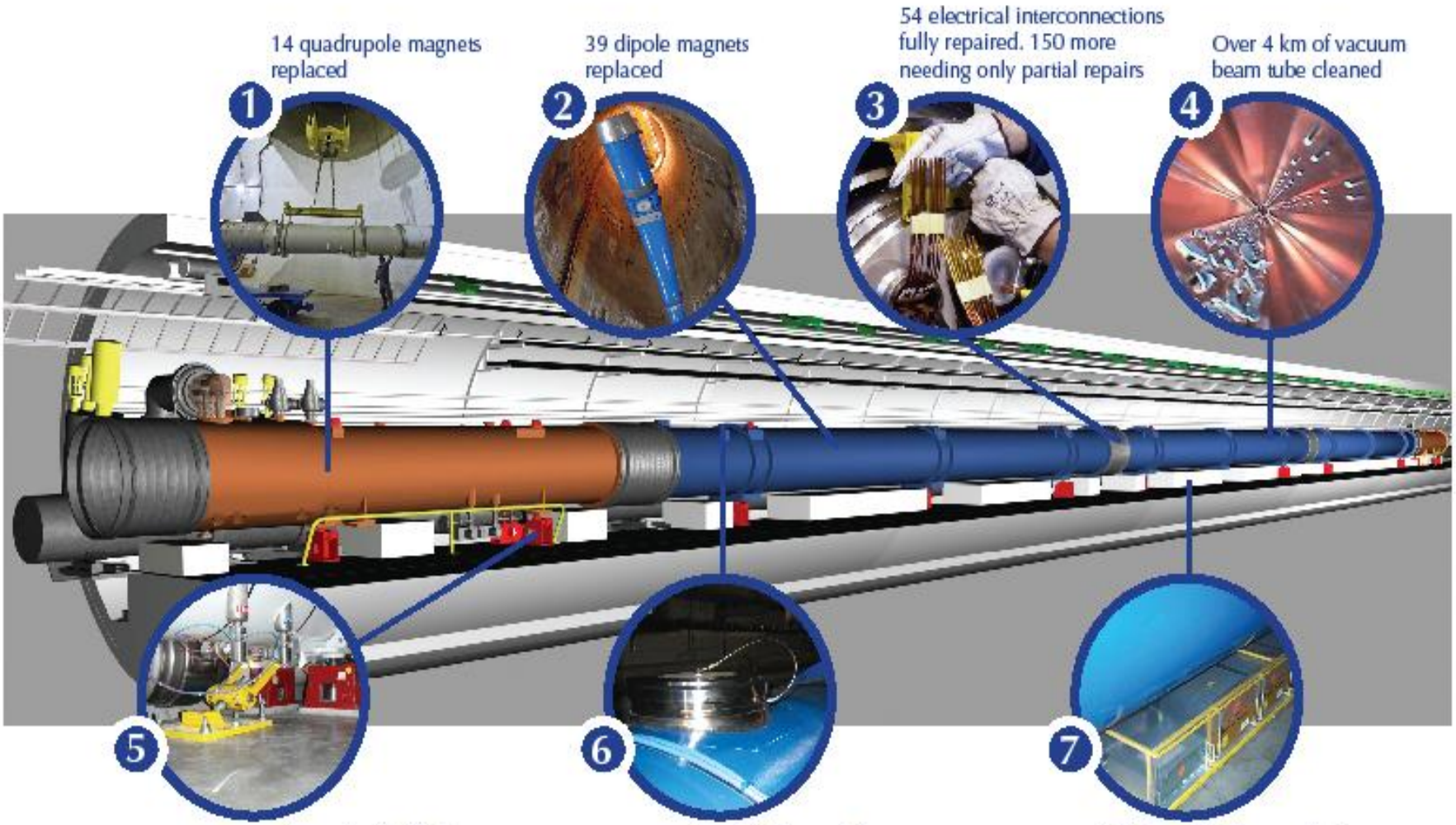


2008

- 2008
  - Accelerator complete
  - Ring cold and under vacuum
- September 10th 2008
  - First beams around
- September 19th 2008
  - The incident
- 2008 – 2009
  - 14 months of major repairs and consolidation
  - New Quench Protection System for online monitoring and protection of all joints.

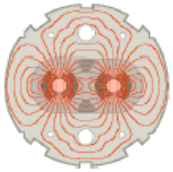
Phase 1 +2

The LHC repairs in detail



+ 8 cryogenics!

Summary of LHC Commissioning (2)

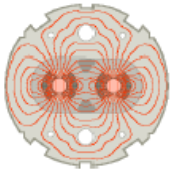


2009

- November 20th 2009
  - First beams around again
- November 29th 2009
  - Both beams accelerated to 1.18 TeV simultaneously
- December 8th 2009
  - 2x2 accelerated to 1.18 TeV LHC - highest energy collider
  - First collisions at 2.36 TeV cm!
- December 14th 2009
  - Stable 2x2 at 1.18 TeV
  - Collisions in all four experiments

Limited to 2 kA in main circuits (1.18 TeV) during deployment and testing of new Quench Protection System

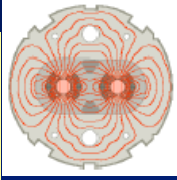
Decided Scenario 2010-2011



Following the technical discussions in Chamonix (Jan 2010) the CERN management and the LHC experiments decided

- Run at 3.5 TeV/beam up to a integrated luminosity of around $1fb^{-1}$.
- Then consolidate the whole machine for 7TeV/beam (during a shutdown in 2012)
- From 2013 onwards LHC will be capable of maximum energies and luminosities

Why do we limit the beam energy to 3.5TeV in 2010-2011?



All the work we have done since November 2008 makes us certain that a repeat of September 19 can NEVER happen.

The offending connector in this incident had an estimated resistance of 220nΩ. We have measured all 10,000 inter-magnet connectors and the maximum resistance we have seen is 2.8nΩ.

BUT in April 2009, we have uncovered a different possible failure scenario which could under certain circumstances produce an electric arc in the "copper stabilizers" of the magnet interconnects

OP Vistars - Mozilla Firefox

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http://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php?usr=LHC1

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CERN - AB - OP eLogbook - Vi... | CERN - AB - OP eLogbook - Vi... | CERN - AB - OP eLogbook - Vi... | CERN - AB - OP eLogbook - Vi... | OP Vistars

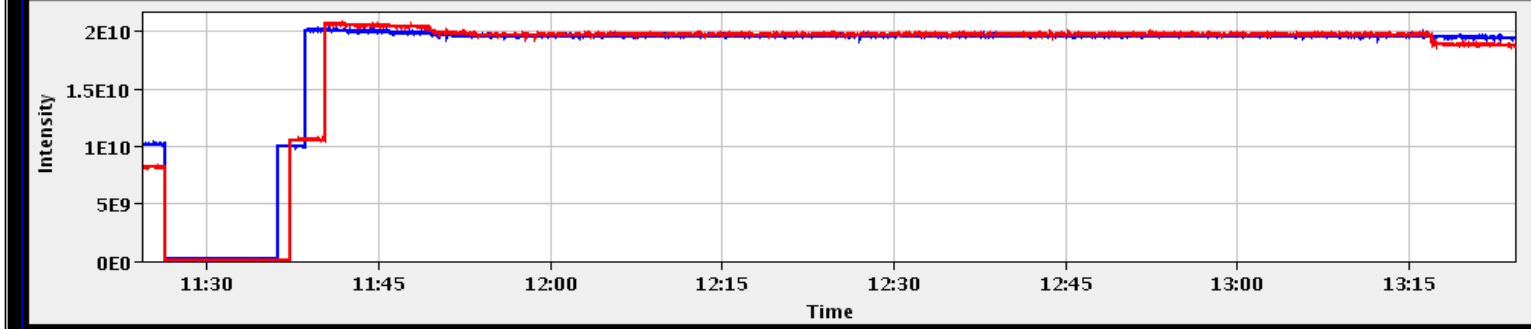
LHC1 — OP Vistars

LHC Page1	Fill: 1005	E: 3500 GeV	30-03-2010 13:24:16

PROTON PHYSICS: STABLE BEAMS

Energy:	3500 GeV	I(B1):	1.88e+10	I(B2):	1.68e+10

FBCT Intensity — Updated: 13:24:16



First Collisions at 3.5TeV/beam

Comments 30-03-2010 13:22:57 :

Stable beams!

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

LHC Operation in CCC : 77600, 70480 — PM Status B1: ENABLED — PM Status B2: ENABLED

Done

Summary of Luminosity Evolution 2010

Event	β*	Nb	Ib	Itot	MJ	MJ Factor	Nc	Peak luminosity	Date
1	10	2	1.00E+10	2.0E+10	0.0113	0.0000	1	8.9E+26	30 March 2010
2	10	2	2.00E+10	4.0E+10	0.0226	2.0000	1	3.6E+27	02 April 2010
3	2	2	2.00E+10	4.0E+10	0.0226	1.0000	1	1.8E+28	10 April 2010
4	2	4	2.00E+10	8.0E+10	0.0452	2.0000	2	3.6E+28	19 April 2010
5	2	6	2.00E+10	1.2E+11	0.0678	1.5000	4	7.1E+28	15 May 2010
6	2	13	2.60E+10	3.4E+11	0.1910	2.8167	8	2.4E+29	22 May 2010
7	3.5	3	1.10E+11	3.3E+11	0.1865	0.9763	2	6.1E+29	26 June 2010
8	3.5	6	1.00E+11	6.0E+11	0.3391	1.8182	4	1.0E+30	02 July 2010
9	3.5	8	9.00E+10	7.2E+11	0.4069	1.2000	6	1.2E+30	12 July 2010
10	3.5	13	9.00E+10	1.2E+12	0.6612	1.6250	8	1.6E+30	15 July 2010

Easter: A very good 48 hour period!

Event	β*	Nb	Ib	Itot	MJ	MJ Factor	Nc	Peak luminosity	Date
1	10	2	1.00E+10	2.0E+10	0.0113	0.0000	1	8.9E+26	30 March 2010
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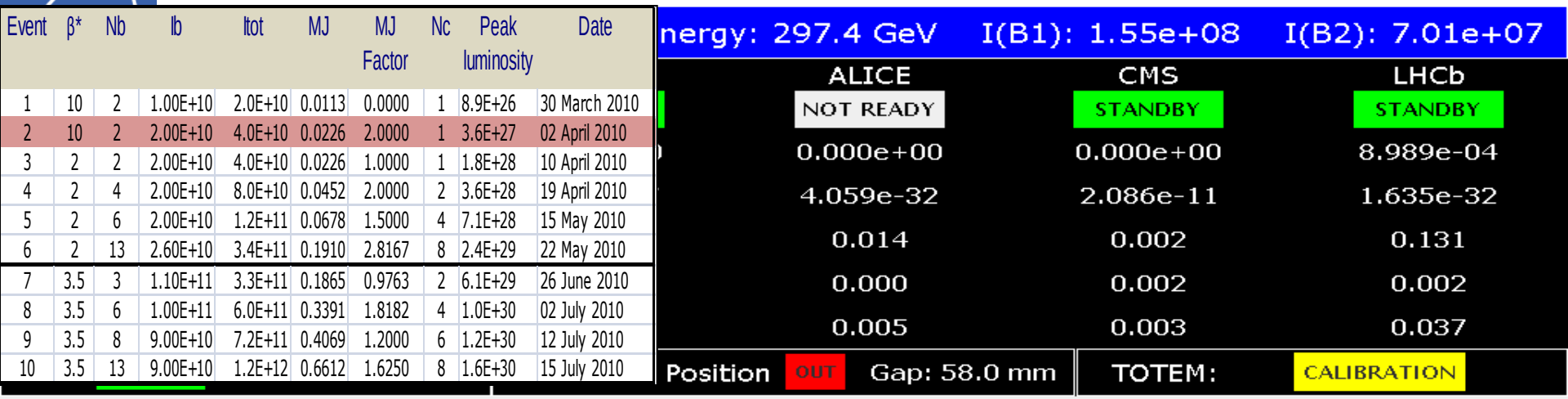

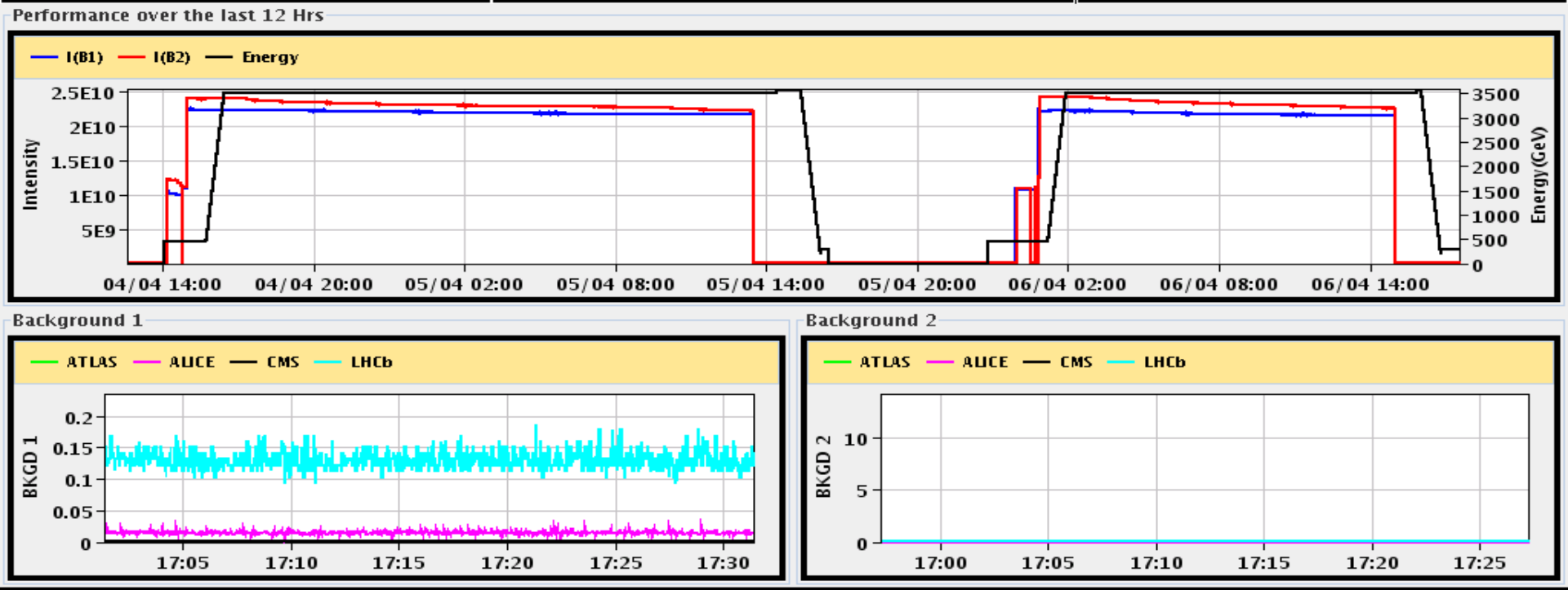

10th April IP1 and 5, beta squeeze

- Raw (online) lumi plots on 10 apr 2010, during the squeeze to 2m in IP1 and IP5
- Factor gained (raw numbers):
  - ~4.5 in Pt5 (after min scan)
  - ~4 in Pt1
- Not corrected for lumi decay over the ~5h of squeeze and mini scans

Event	β*	Nb	Ib	Itot	MJ	MJ Factor	Nc	Peak luminosity	Date
1	10	2	1.00E+10	2.0E+10	0.0113	0.0000	1	8.9E+26	30 March 2010
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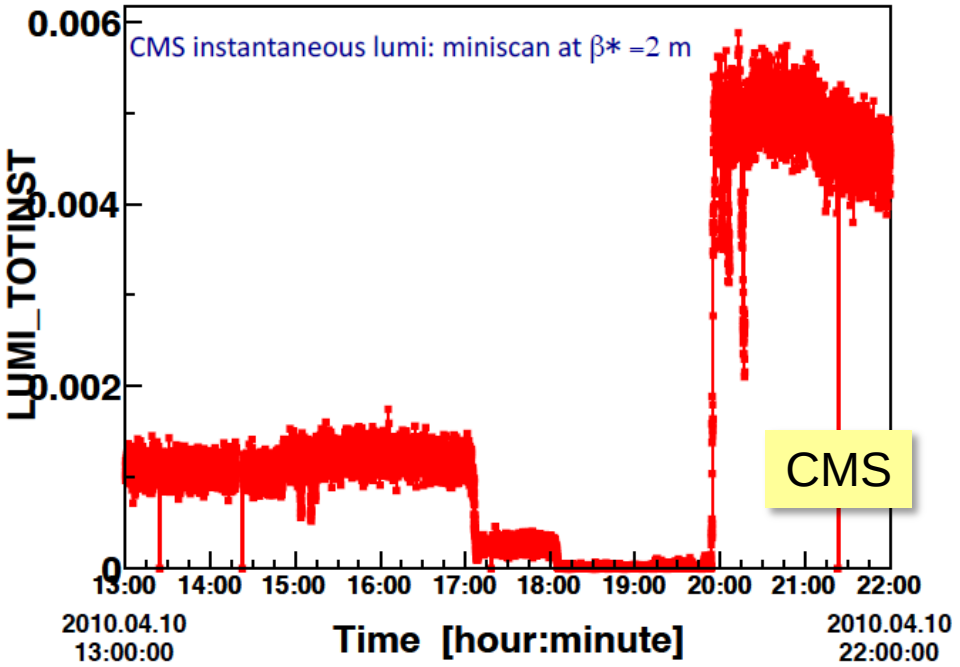
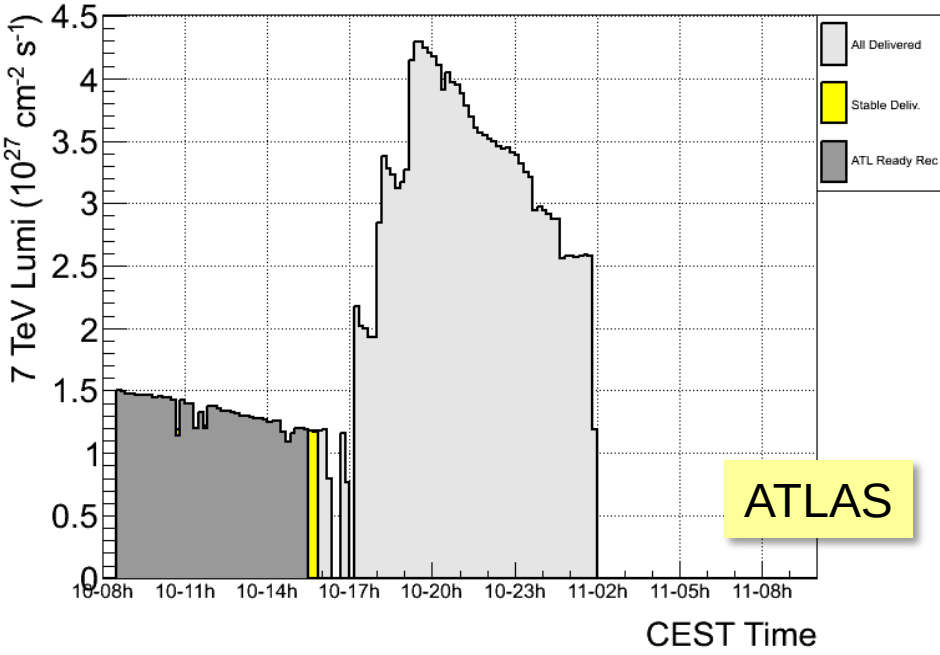
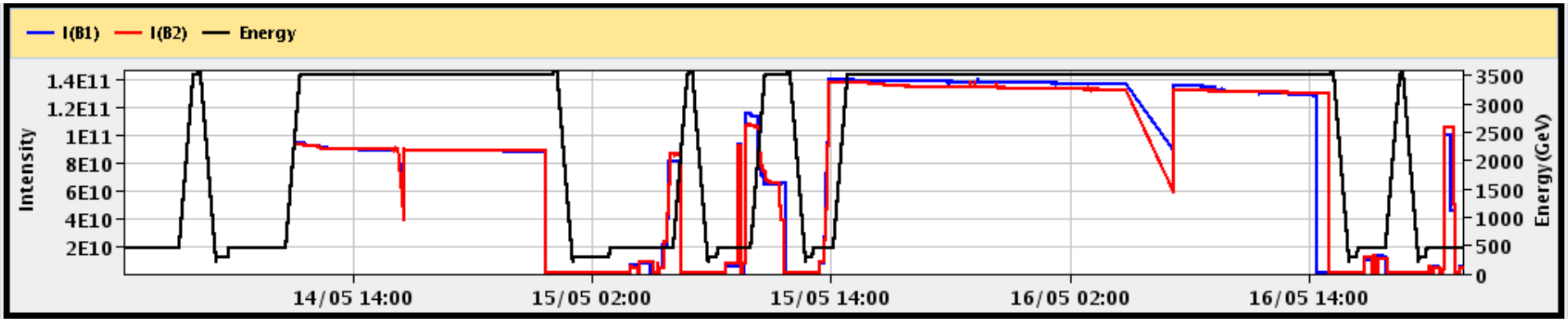




Pushing Number of 2e10 Bunches

2 x 2e10 ➔ **4 x 2e10** **6 x 2e10** per beam



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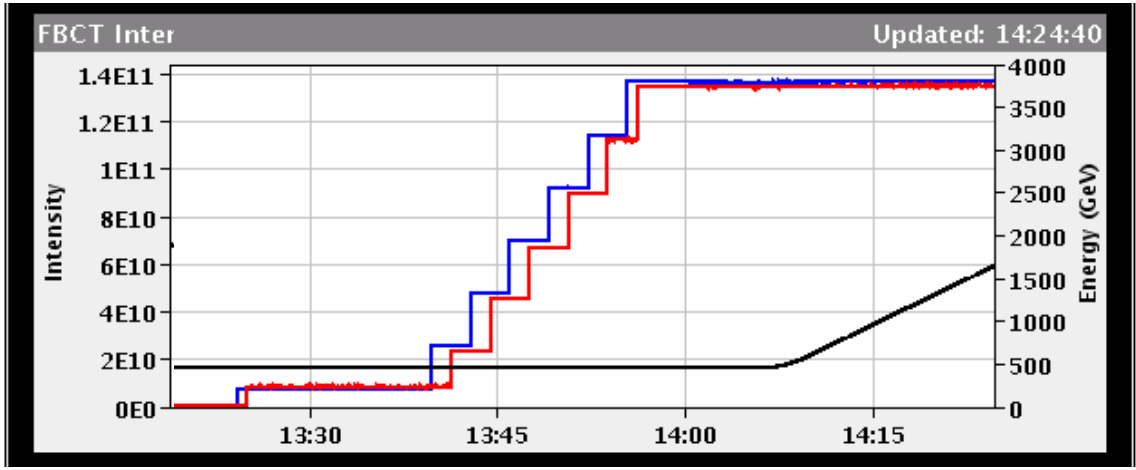
10	3.5	13	9.00E+10	1.2E+12	0.6612	1.6250	8	1.6E+30	15 July 2010

48 hours



13 bunches: $3x10^{29}$!!

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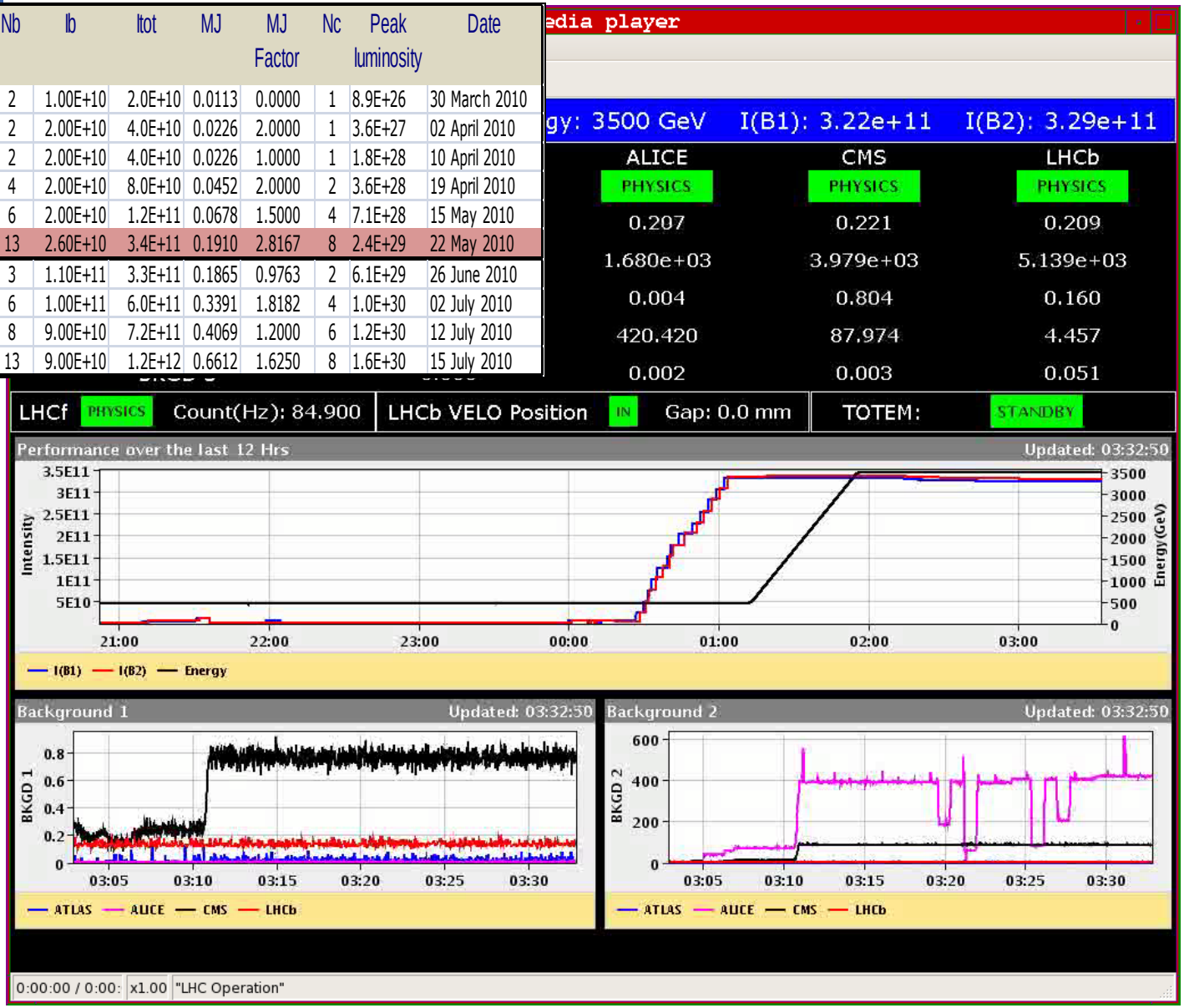


LHC Design Bunch Intensity: Thursday 15.4.2010

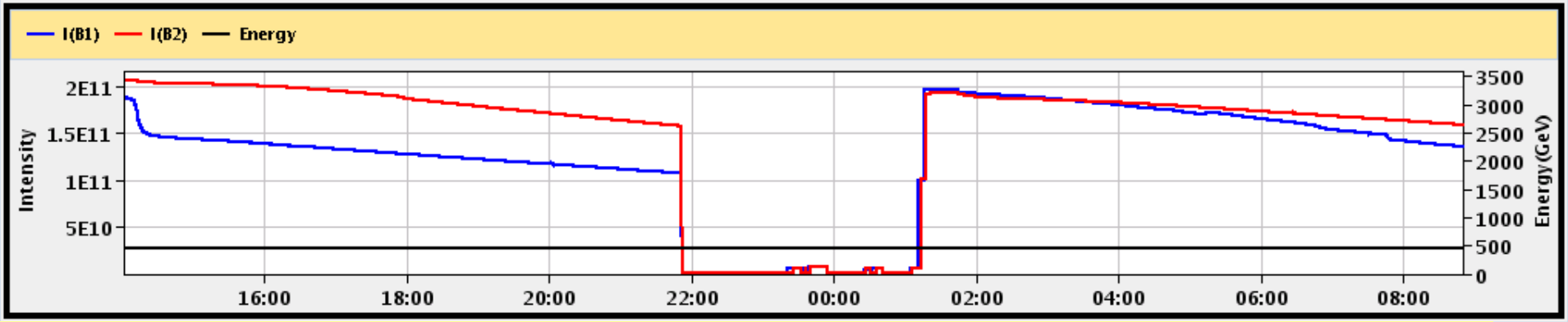
- Higher intensity
  - Over-injection working well
  - Over-injected 1.1E11, with collimators at nominal 4.5 sigma settings.
  - Emittance at 1E11: 2.5 um H, 2,3 um V.

03-May-2010 08:49:21 Fill #: 1069 Energy: 450.1 GeV I(B1): 1.35e+11 I(B2): 1.59e+11

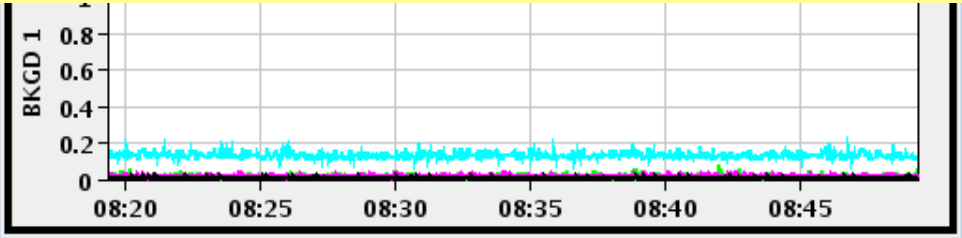
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Luminosity	4.080e-03	2.376e-03	3.276e-03	2.314e-03
BRAN Count Rate	0.000e+00	0.000e+00	5.000e+00	1.000e+00
BKGD 1	0.015	0.013	0.010	0.122
BKGD 2	0.000	5.000	0.774	0.850
BKGD 3	0.000	0.005	0.003	0.047

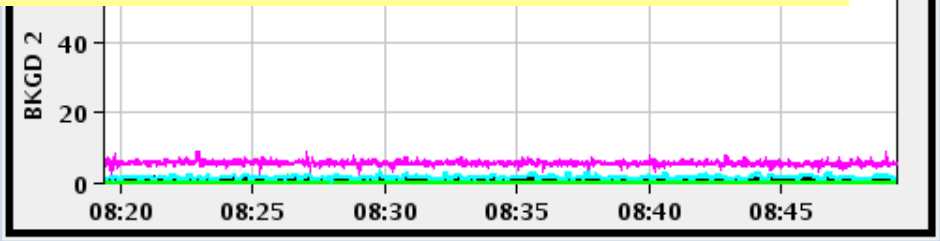
LHCf PHYSICS Count(Hz): 0.000 | LHCb VELO Position IN Gap: 20.0 mm | TOTEM: STANDBY

Performance over the last 12 Hrs



3rd May: Stable beams at design current per bunch at 450GeV
Much easier than anticipated!!



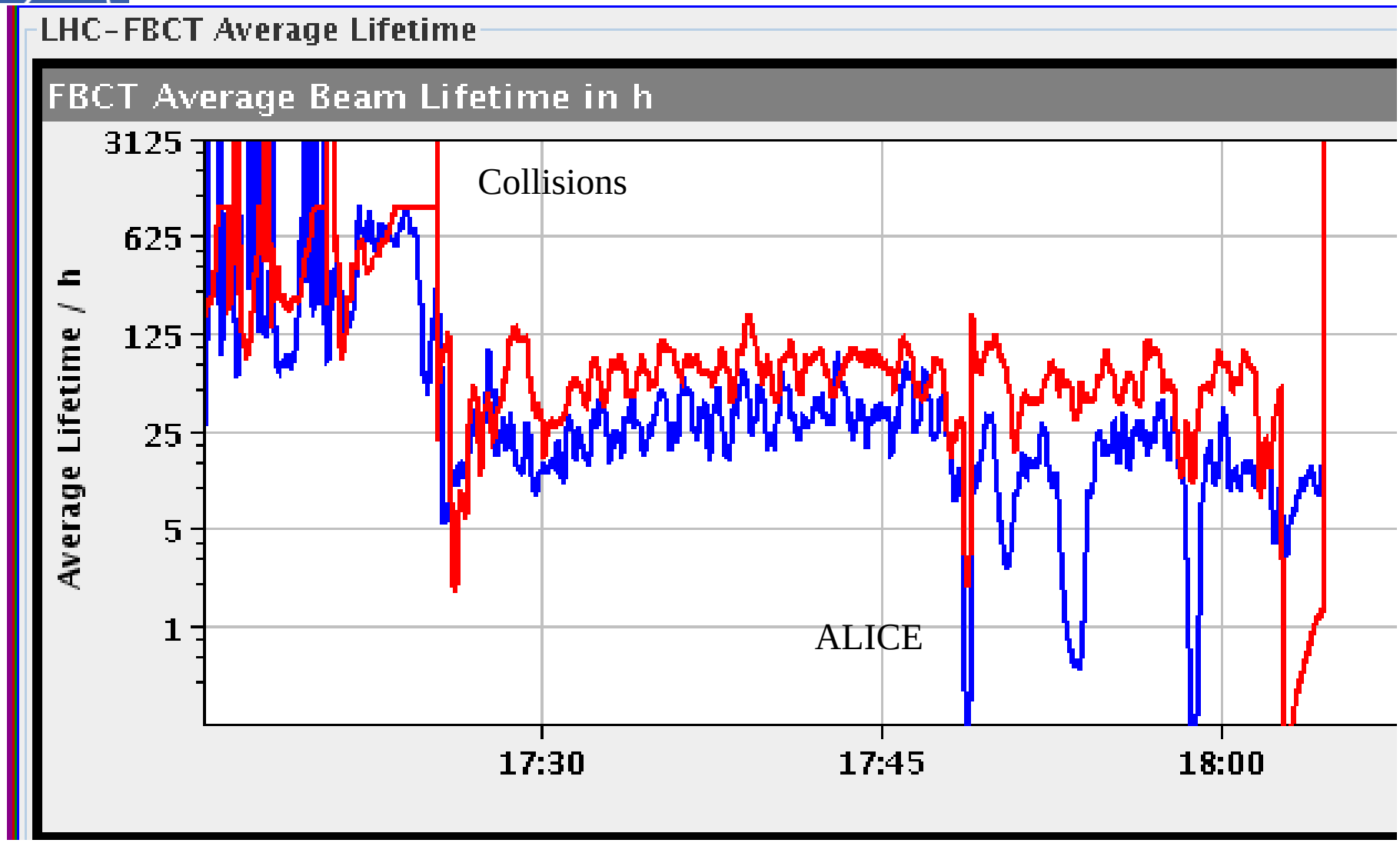


Preparation for design intensities at 3.5TeV/beam

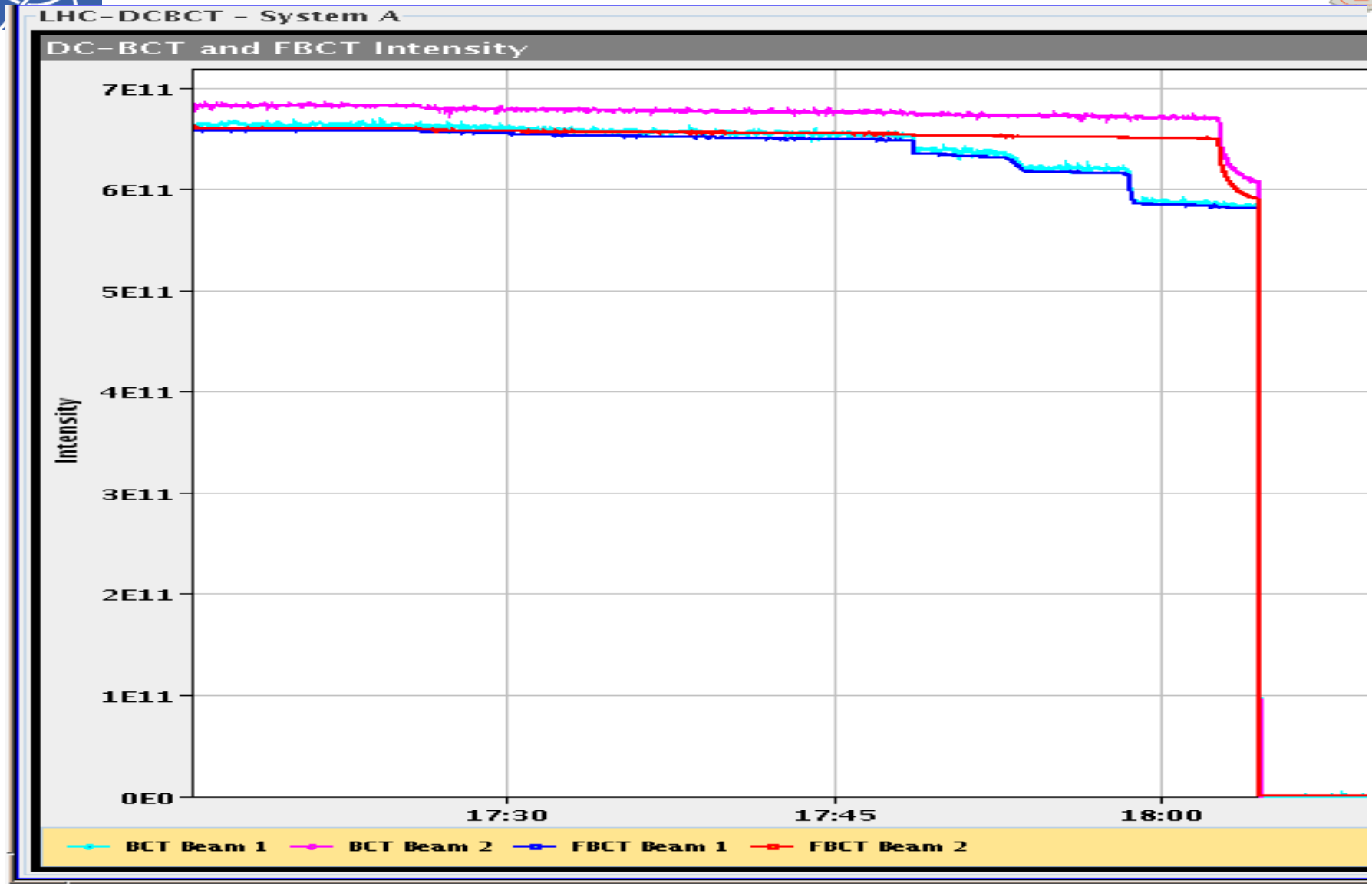
- From 3rd May until 9 June, machine time shared between physics and machine studies.
  - Physics with ~2×10^{10} protons/bunch
  - Machine studies to develop 1×10^{11} protons per bunch

Following discussions with the 4 spokespersons and the physics coordinator, a decision was unanimously made on 9 June to concentrate on "Machine studies to develop 1×10^{11} protons per bunch" until it was operational. This meant postponing physics data taking for around 2-3 weeks.

Not as easy as we anticipated after the 450GeV runs



Beam Intensity Losses



Getting to Stable beams at ~1.1x10^{11}.

- Set up for high intensity
  - Collimators (loss maps)
  - Injection tuning
  - Beam dump set up

} This part was anticipated as needed

Not anticipated following collisions at 450 GeV

- Instabilities in Collision at 3.5TeV/beam
  - Collimator closer to beam → increased beam impedance → transverse stability limit reduced
  - Peak current increased → transverse instabilities
    - Cure: longitudinal emittance increase in the SPS and during the ramp in LHC
    - Cure: transverse feedback system
  - Transverse beam size too small → beam-beam
    - Cure: emittance increase in the SPS
    - Cure: emittance control during the ramp in the LHC
    - Cure: better equalization of emittances between beams 1 and 2

26th June: 5x10^29 with 3 bunches/beam; 10^11/b

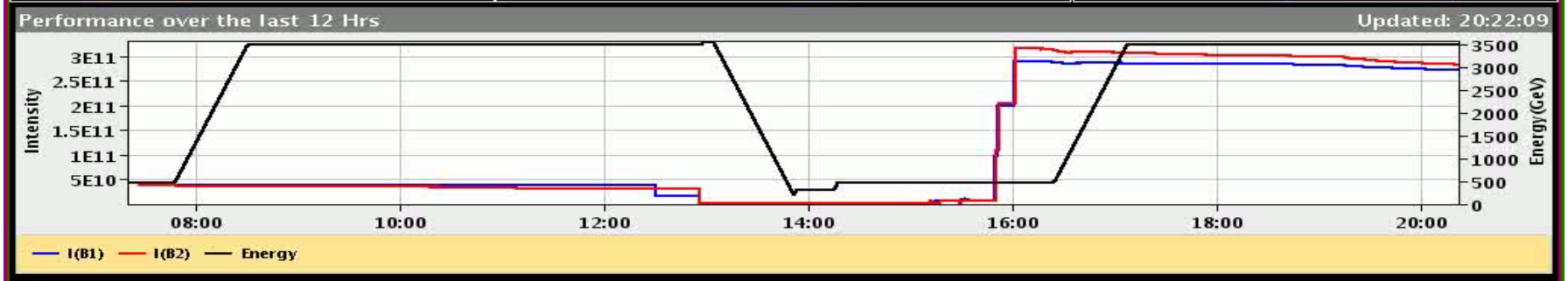
VLC media player

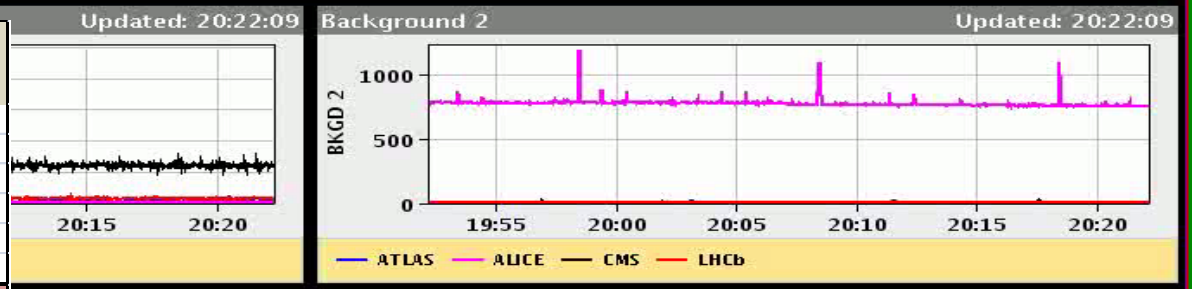
File View Settings Audio Video Navigation Help

26-Jun-2010 20:22:09 Fill #: 1182 Energy: 3500 GeV I(B1): 2.73e+11 I(B2): 2.84e+11

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi (ub.s)^-1	0.500	0.275	0.516	0.444
BRAN Count Rate (Hz)	5.395e+03	3.675e+03	7.550e+03	8.960e+03
BKGD 1	0.022	0.014	1.178	0.131
BKGD 2	3.000	755.420	0.002	1.238
BKGD 3	0.000	0.006	0.003	0.054

LHCf PHYSICS Count(Hz): 565.500 | LHCb VELO Position OUT Gap: 58.0 mm | TOTEM: CALIBRATION





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5	2	6	2.00E+10	1.2E+11	0.0678	1.5000	4	7.1E+28	15 May 2010
6	2	13	2.60E+10	3.4E+11	0.1910	2.8167	8	2.4E+29	22 May 2010
7	3.5	3	1.10E+11	3.3E+11	0.1865	0.9763	2	6.1E+29	26 June 2010
8	3.5	6	1.00E+11	6.0E+11	0.3391	1.8182	4	1.0E+30	02 July 2010
9	3.5	8	9.00E+10	7.2E+11	0.4069	1.2000	6	1.2E+30	12 July 2010
10	3.5	13	9.00E+10	1.2E+12	0.6612	1.6250	8	1.6E+30	15 July 2010

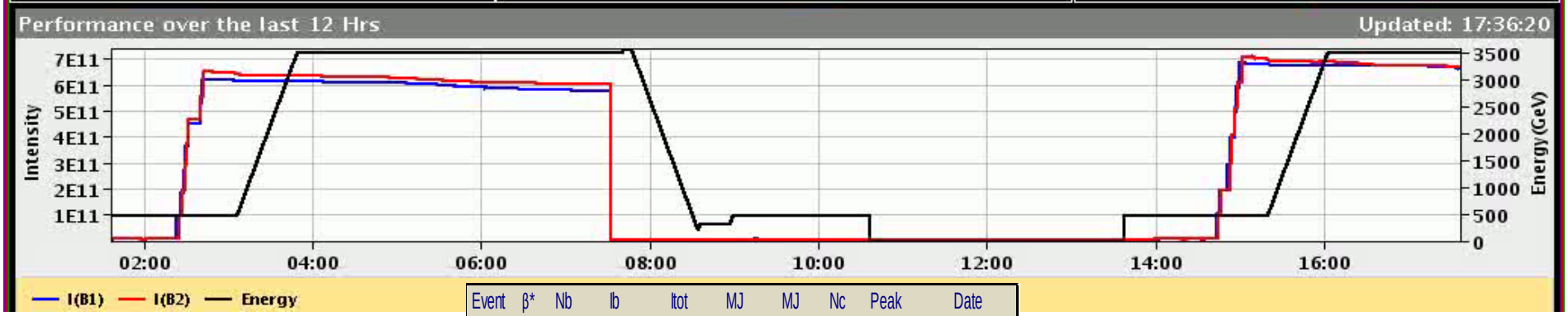
New Record Lumi > 1e30 cm-2 s-1

02-Jul-2010 17:36:21 Fill #: 1192 Energy: 3500 GeV I(B1): 6.65e+11 I(B2): 6.70e+11

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi (ub.s)^-1	1.054	0.004	1.172	1.047
BRAN Count Rate (Hz)	1.098e+04	3.100e+01	1.657e+04	2.124e+04

2nd July: Colliding 6 bunches per beam; 10^{11}/b

LHCf MOVING Count(Hz): 0.114 | LHCb VELO Position OUT Gap: 58.0 mm | TOTEM: STANDBY



Emittances before ra nces meas during the ramp
B1 H: 2.5 .2
B1 V: 2.5 .1
B2 H: 2.5
B2 V: 3.0 (measure n .3 .9

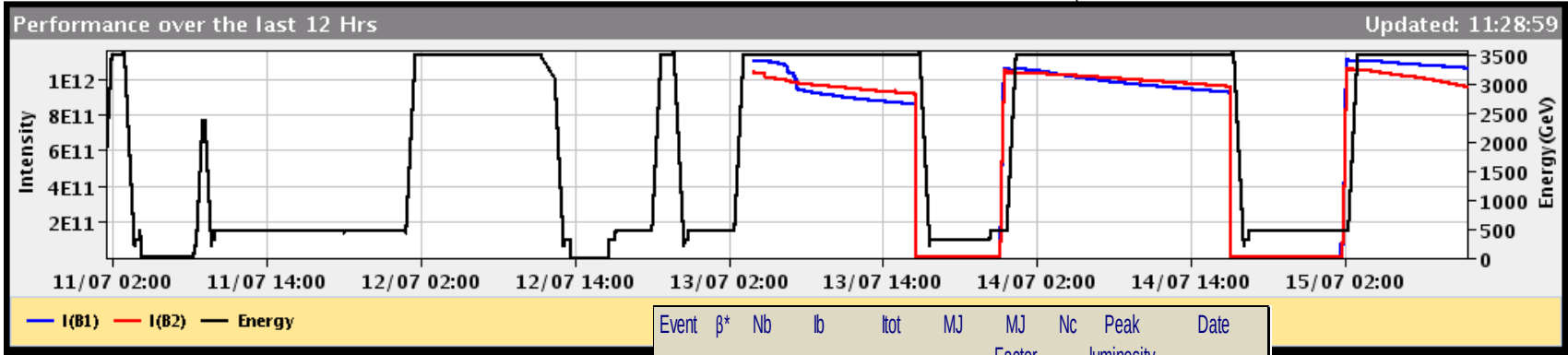
Event	β*	Nb	Ib	Itot	MJ	MJ Factor	Nc	Peak luminosity	Date
1	10	2	1.00E+10	2.0E+10	0.0113	0.0000	1	8.9E+26	30 March 2010
2	10	2	2.00E+10	4.0E+10	0.0226	2.0000	1	3.6E+27	02 April 2010
3	2	2	2.00E+10	4.0E+10	0.0226	1.0000	1	1.8E+28	10 April 2010
4	2	4	2.00E+10	8.0E+10	0.0452	2.0000	2	3.6E+28	19 April 2010
5	2	6	2.00E+10	1.2E+11	0.0678	1.5000	4	7.1E+28	15 May 2010
6	2	13	2.60E+10	3.4E+11	0.1910	2.8167	8	2.4E+29	22 May 2010
7	3.5	3	1.10E+11	3.3E+11	0.1865	0.9763	2	6.1E+29	26 June 2010
8	3.5	6	1.00E+11	6.0E+11	0.3391	1.8182	4	1.0E+30	02 July 2010
9	3.5	8	9.00E+10	7.2E+11	0.4069	1.2000	6	1.2E+30	12 July 2010
10	3.5	13	9.00E+10	1.2E+12	0.6612	1.6250	8	1.6E+30	15 July 2010

Good periods !

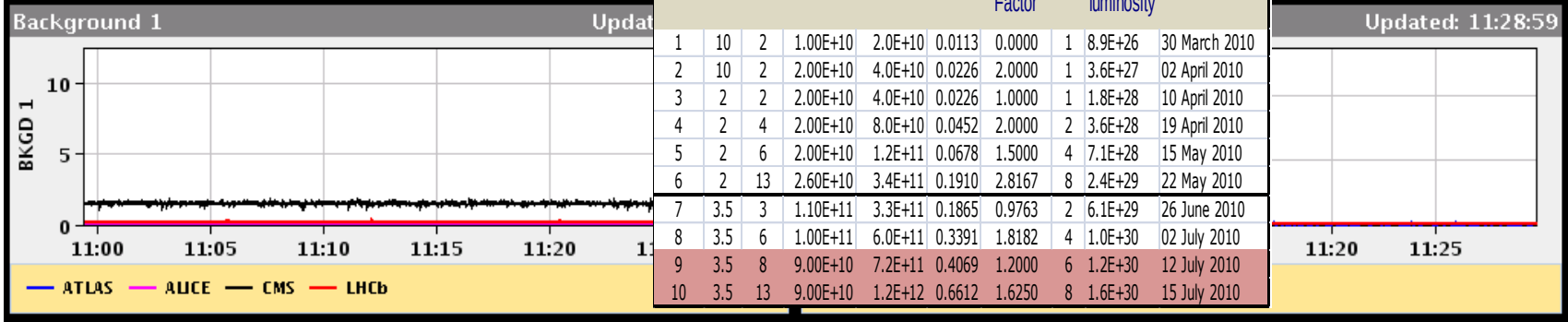
15-Jul-2010 11:29:49 Fill #: 1226 Energy: 3500 GeV I(B1): 1.06e+12 I(B2): 9.56e+11

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous Lumi (ub.s)^-1	0.763	0.109	0.772	0.816
BRAN Count Rate (Hz)	8.195e+03	9.410e+02	1.245e+04	1.615e+04
BKGD 1	0.006	0.026	1.428	0.160
BKGD 2	2.000	0.232	0.002	0.002
BKGD 3	0.000	0.008	0.003	0.069

LHCf PHYSICS Count(Hz): 0.000 | LHCb VELO Position IN Gap: -0.0 mm | TOTEM: PHYSICS



Event	β*	Nb	Ib	Itot	MJ	MJ Factor	Nc	Peak luminosity	Date
1	10	2	1.00E+10	2.0E+10	0.0113	0.0000	1	8.9E+26	30 March 2010
2	10	2	2.00E+10	4.0E+10	0.0226	2.0000	1	3.6E+27	02 April 2010
3	2	2	2.00E+10	4.0E+10	0.0226	1.0000	1	1.8E+28	10 April 2010
4	2	4	2.00E+10	8.0E+10	0.0452	2.0000	2	3.6E+28	19 April 2010
5	2	6	2.00E+10	1.2E+11	0.0678	1.5000	4	7.1E+28	15 May 2010
6	2	13	2.60E+10	3.4E+11	0.1910	2.8167	8	2.4E+29	22 May 2010
7	3.5	3	1.10E+11	3.3E+11	0.1865	0.9763	2	6.1E+29	26 June 2010
8	3.5	6	1.00E+11	6.0E+11	0.3391	1.8182	4	1.0E+30	02 July 2010
9	3.5	8	9.00E+10	7.2E+11	0.4069	1.2000	6	1.2E+30	12 July 2010
10	3.5	13	9.00E+10	1.2E+12	0.6612	1.6250	8	1.6E+30	15 July 2010



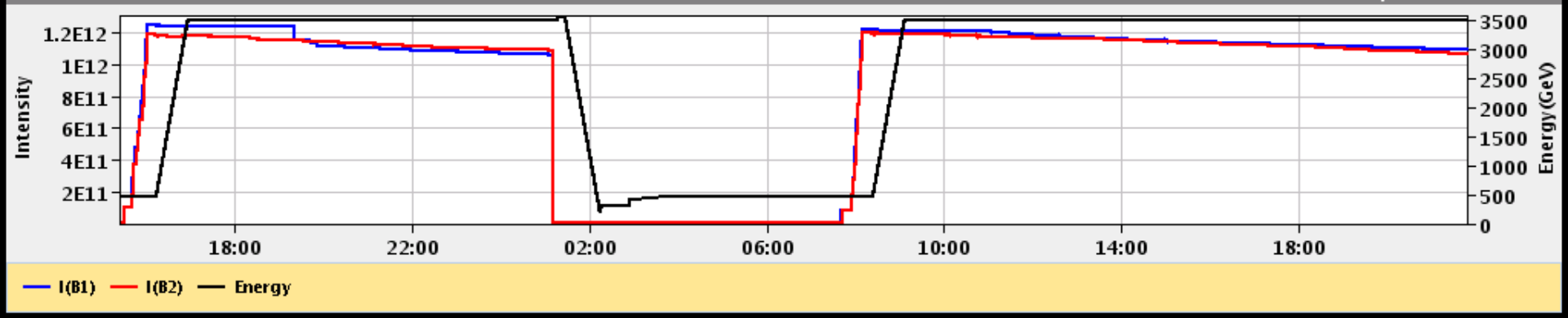
18-Jul-2010 21:47:06 Fill #: 1233 Energy: 3500 GeV I(B1): 1.09e+12 I(B2): 1.06e+12

Event	β*	Nb	Ib	Itot	MJ	MJ Factor	Nc	Peak luminosity	Date
1	10	2	1.00E+10	2.0E+10	0.0113	0.0000	1	8.9E+26	30 March 2010
2	10	2	2.00E+10	4.0E+10	0.0226	2.0000	1	3.6E+27	02 April 2010
3	2	2	2.00E+10	4.0E+10	0.0226	1.0000	1	1.8E+28	10 April 2010
4	2	4	2.00E+10	8.0E+10	0.0452	2.0000	2	3.6E+28	19 April 2010
5	2	6	2.00E+10	1.2E+11	0.0678	1.5000	4	7.1E+28	15 May 2010
6	2	13	2.60E+10	3.4E+11	0.1910	2.8167	8	2.4E+29	22 May 2010
7	3.5	3	1.10E+11	3.3E+11	0.1865	0.9763	2	6.1E+29	26 June 2010
8	3.5	6	1.00E+11	6.0E+11	0.3391	1.8182	4	1.0E+30	02 July 2010
9	3.5	8	9.00E+10	7.2E+11	0.4069	1.2000	6	1.2E+30	12 July 2010
10	3.5	13	9.00E+10	1.2E+12	0.6612	1.6250	8	1.6E+30	15 July 2010

	ATLAS	ALICE	CMS	LHCb
	HYSICS	PHYSICS	STANDBY	NOT_READY
	.930	0.063	0.944	0.905
	15e+03	5.430e+02	1.471e+04	1.847e+04
	.008	0.013	1.714	0.160
	.000	0.134	0.002	3.602
	.000	0.007	0.003	0.066

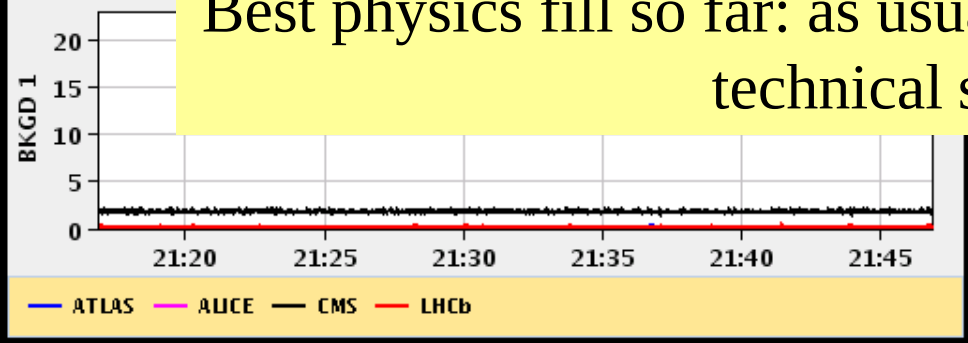
LHCf PHYSICS Count(Hz): 195.200 | LHCb VELO Position IN Gap: 0.0 mm | TOTEM: STANDBY

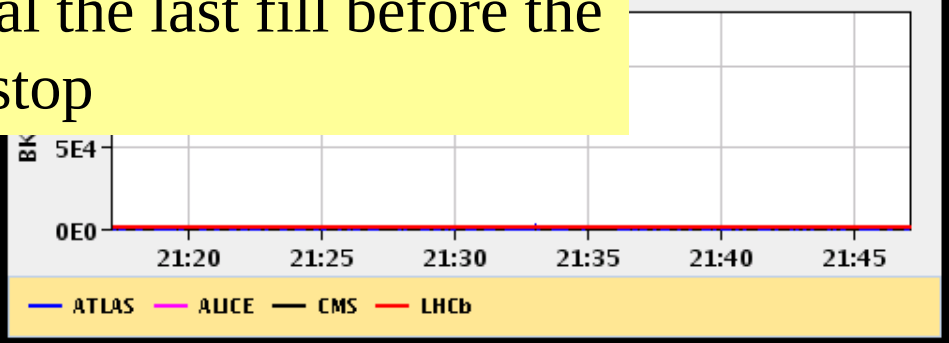
Performance over the last 12 Hrs Updated: 21:46:23



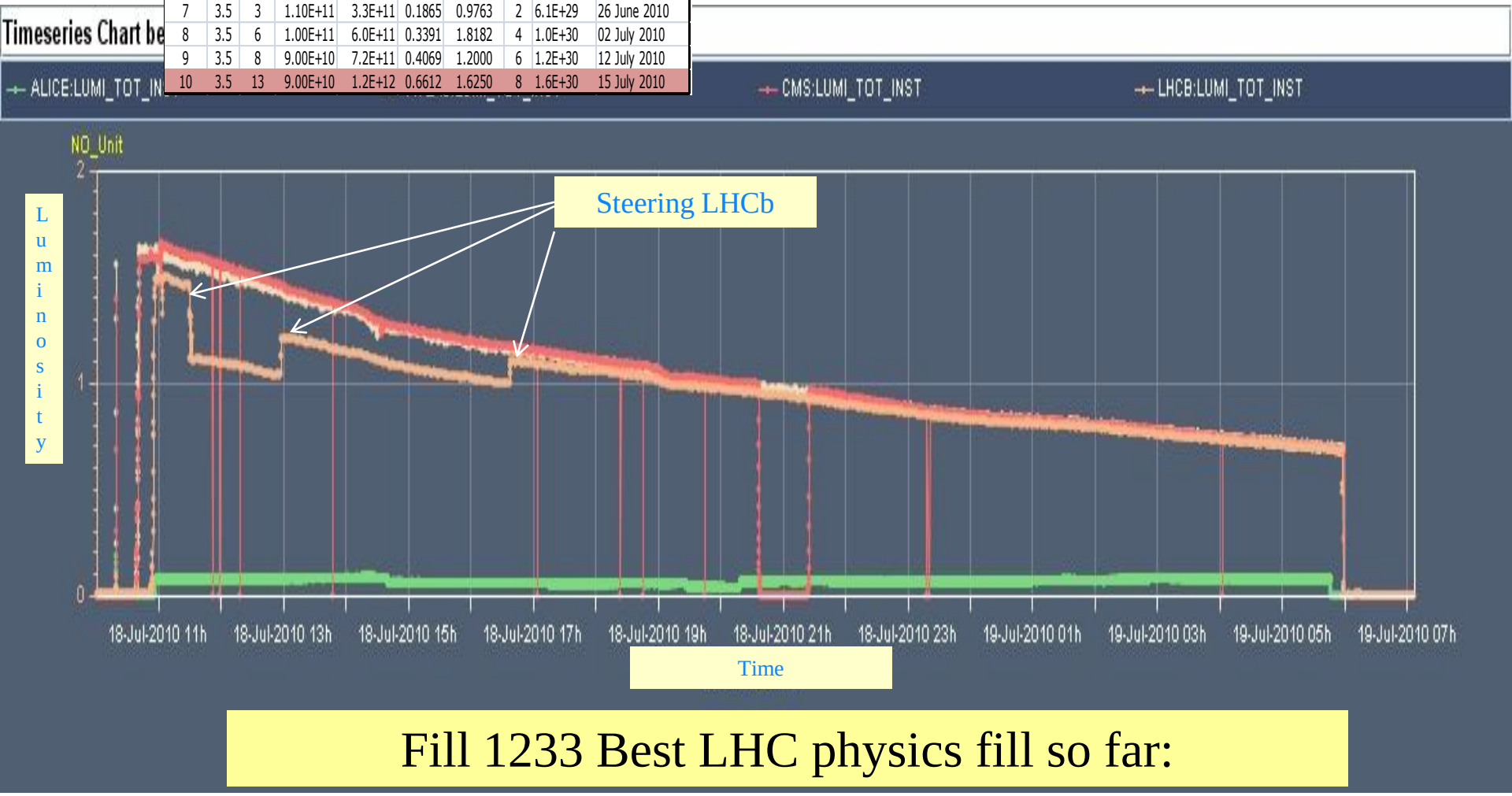
Background Updated: 21:46:35

Best physics fill so far: as usual the last fill before the technical stop





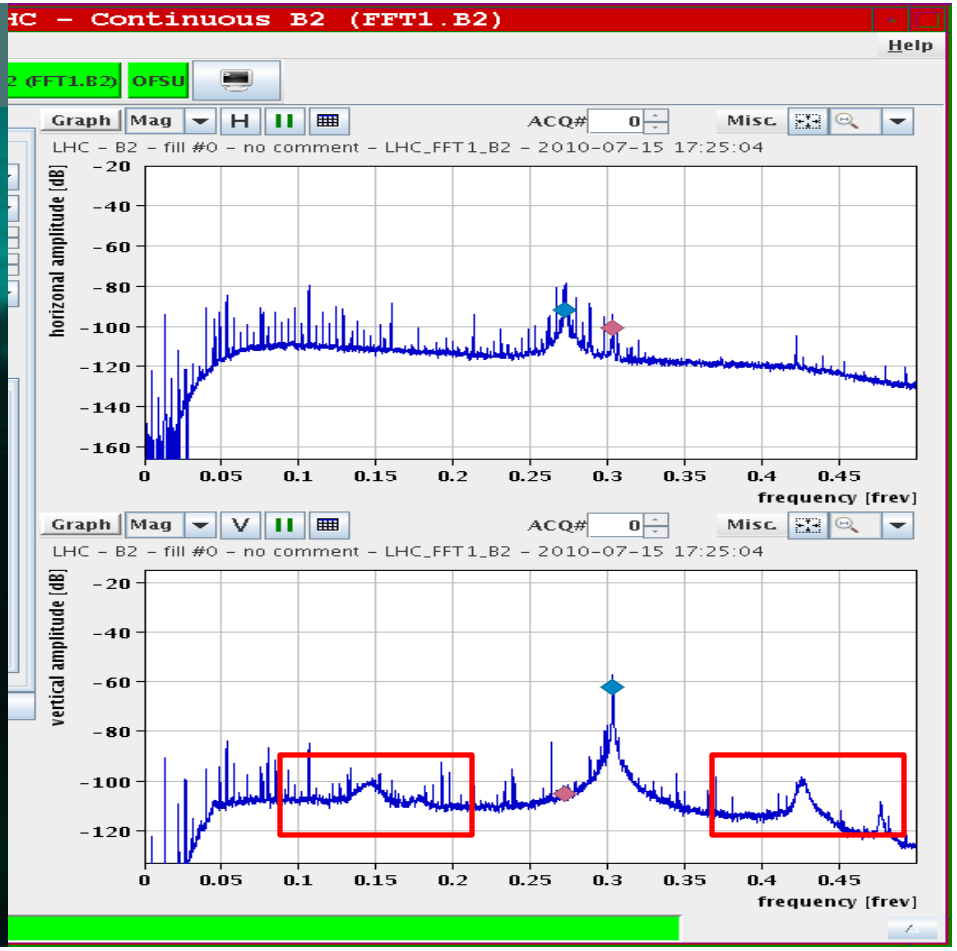
Event	β*	Nb	Ib	Itot	MJ	MJ Factor	Nc	Peak luminosity	Date
1	10	2	1.00E+10	2.0E+10	0.0113	0.0000	1	8.9E+26	30 March 2010
2	10	2	2.00E+10	4.0E+10	0.0226	2.0000	1	3.6E+27	02 April 2010
3	2	2	2.00E+10	4.0E+10	0.0226	1.0000	1	1.8E+28	10 April 2010
4	2	4	2.00E+10	8.0E+10	0.0452	2.0000	2	3.6E+28	19 April 2010
5	2	6	2.00E+10	1.2E+11	0.0678	1.5000	4	7.1E+28	15 May 2010
6	2	13	2.60E+10	3.4E+11	0.1910	2.8167	8	2.4E+29	22 May 2010
7	3.5	3	1.10E+11	3.3E+11	0.1865	0.9763	2	6.1E+29	26 June 2010
8	3.5	6	1.00E+11	6.0E+11	0.3391	1.8182	4	1.0E+30	02 July 2010
9	3.5	8	9.00E+10	7.2E+11	0.4069	1.2000	6	1.2E+30	12 July 2010
10	3.5	13	9.00E+10	1.2E+12	0.6612	1.6250	8	1.6E+30	15 July 2010



Fill 1233 Best LHC physics fill so far:

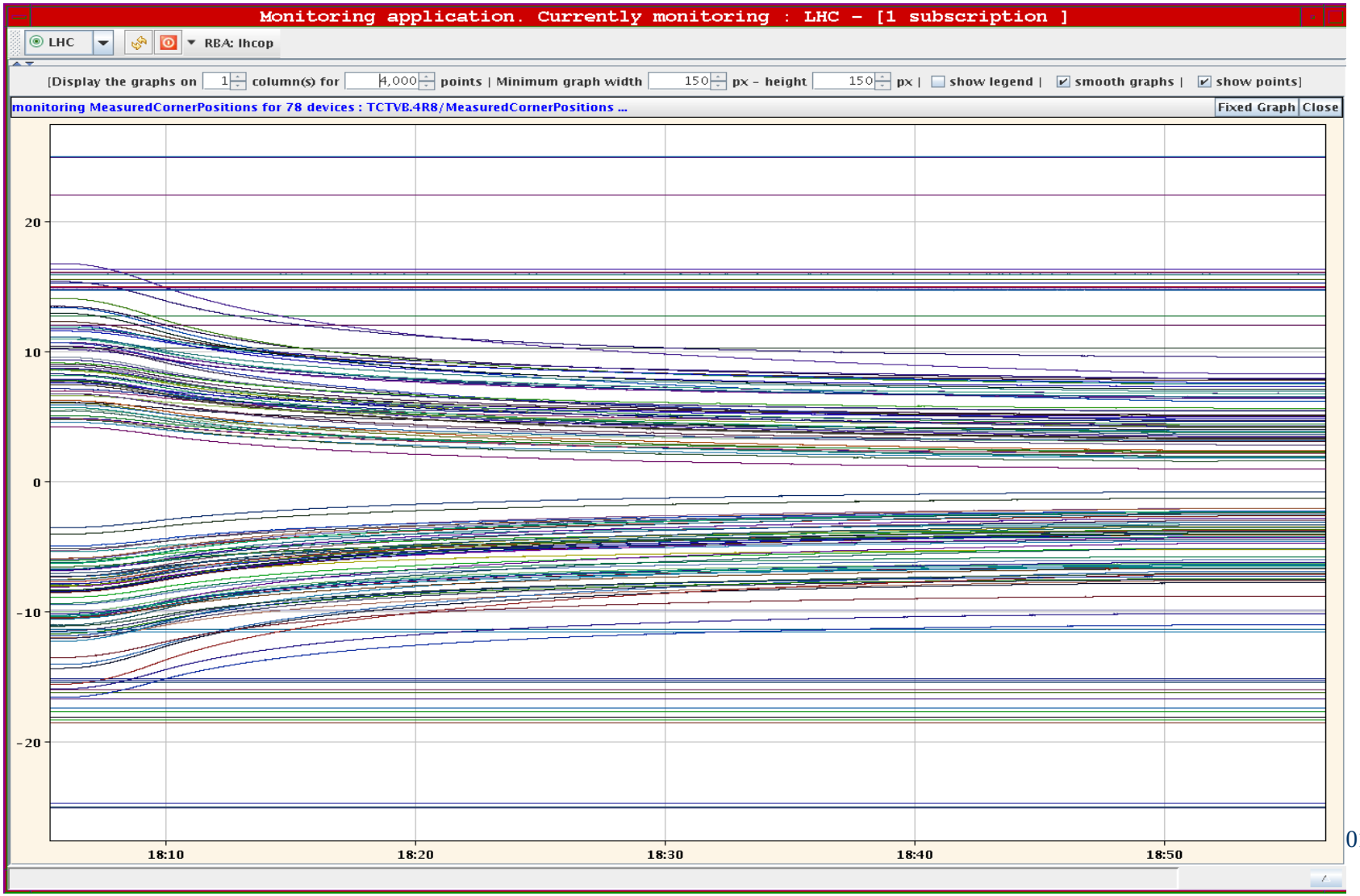
Some Accelerator Physics issues: The Hump

The Hump



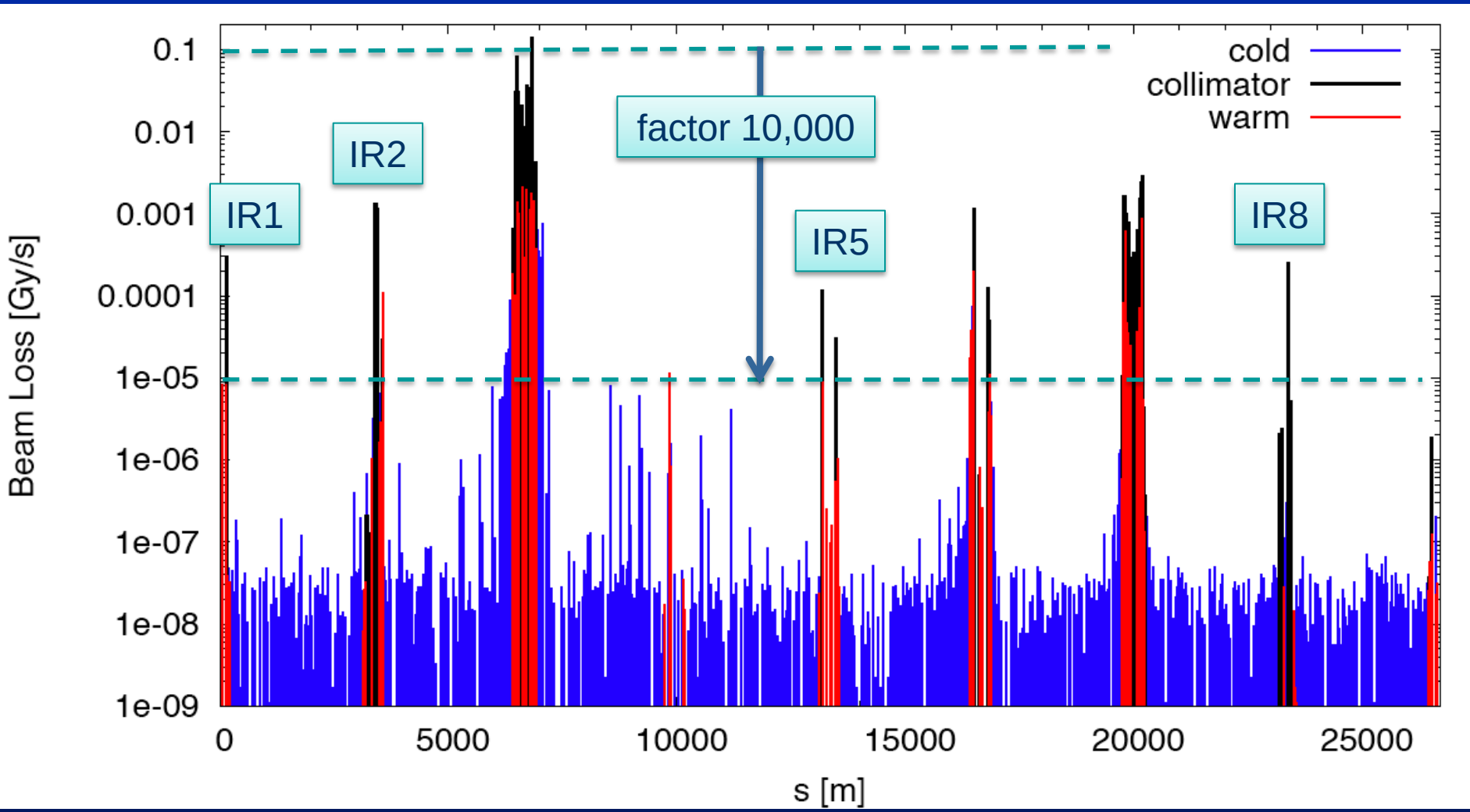
Cure: transverse feedback system

Closing Collimators During Ramp increases the transverse impedance

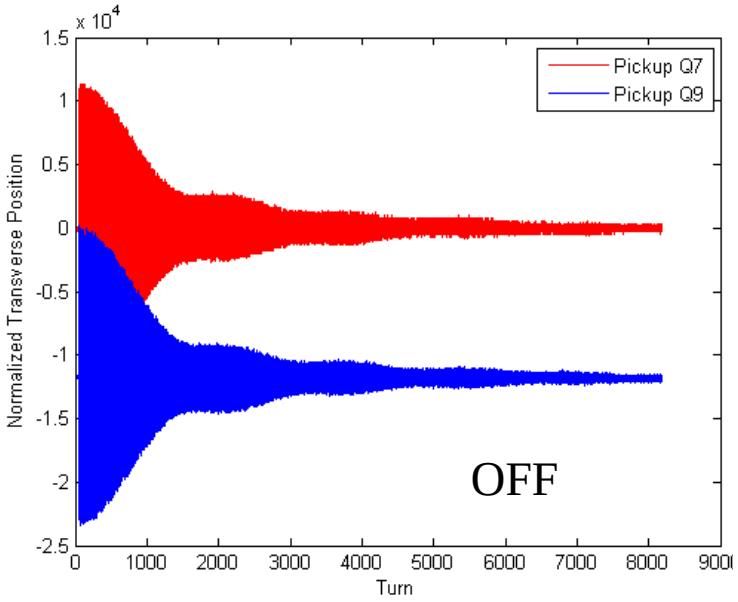


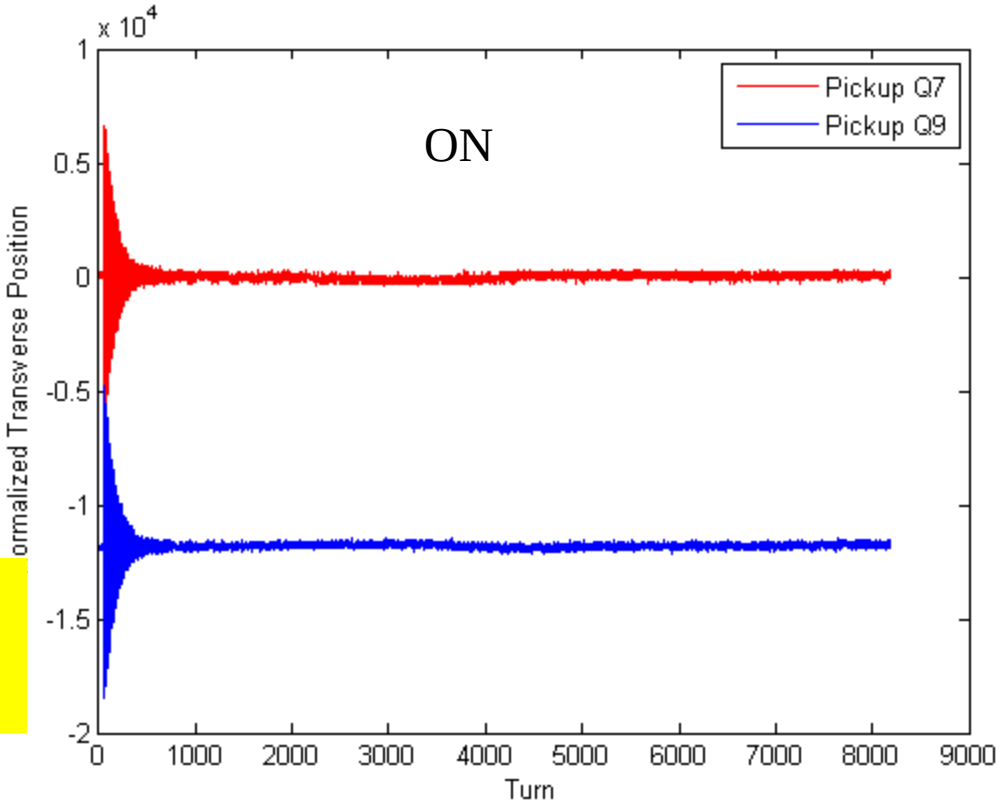
Qualification: Off-momentum collimation

Loss map for off-momentum error. All OK. See expected low leakage to experimental IR's. OK for stable beams from coll.



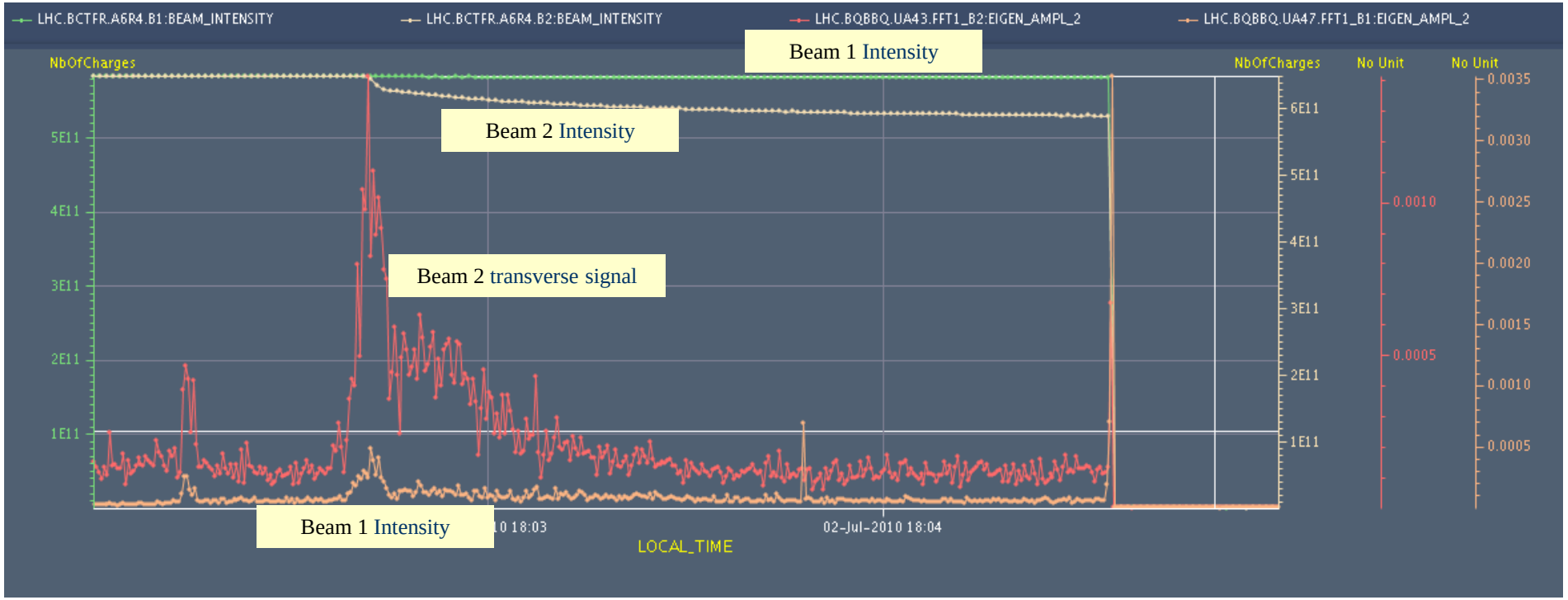
Transverse Damper: Damping Beam Excitations





Transverse Damper will stabilize against the Hump

Tune: Coherent Excitation

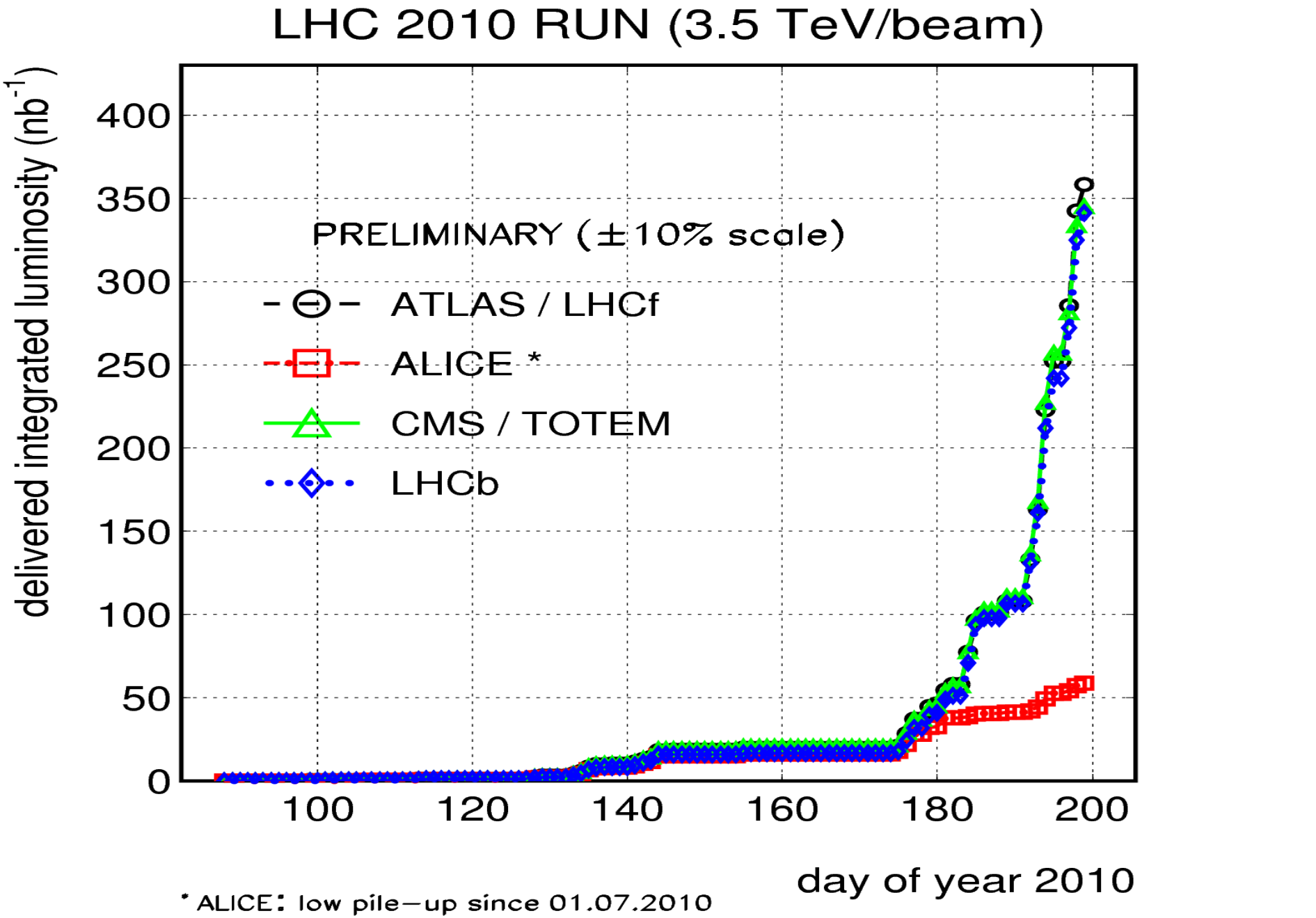


Transverse Damper will stabilize against these coherent instabilities

Summary of Luminosity Evolution

Event	β*	Nb	Ib	Itot	MJ	MJ Factor	Nc	Peak luminosity	Date
1	10	2	1.00E+10	2.0E+10	0.0113	0.0000	1	8.9E+26	30 March 2010
2	10	2	2.00E+10	4.0E+10	0.0226	2.0000	1	3.6E+27	02 April 2010
3	2	2	2.00E+10	4.0E+10	0.0226	1.0000	1	1.8E+28	10 April 2010
4	2	4	2.00E+10	8.0E+10	0.0452	2.0000	2	3.6E+28	19 April 2010
5	2	6	2.00E+10	1.2E+11	0.0678	1.5000	4	7.1E+28	15 May 2010
6	2	13	2.60E+10	3.4E+11	0.1910	2.8167	8	2.4E+29	22 May 2010
7	3.5	3	1.10E+11	3.3E+11	0.1865	0.9763	2	6.1E+29	26 June 2010
8	3.5	6	1.00E+11	6.0E+11	0.3391	1.8182	4	1.0E+30	02 July 2010
9	3.5	8	9.00E+10	7.2E+11	0.4069	1.2000	6	1.2E+30	12 July 2010
10	3.5	13	9.00E+10	1.2E+12	0.6612	1.6250	8	1.6E+30	15 July 2010

2010/07/19 11.54



Short term Objectives

Integrated luminosity of $\geq 1 fb^{-1}$ by the end of 2011

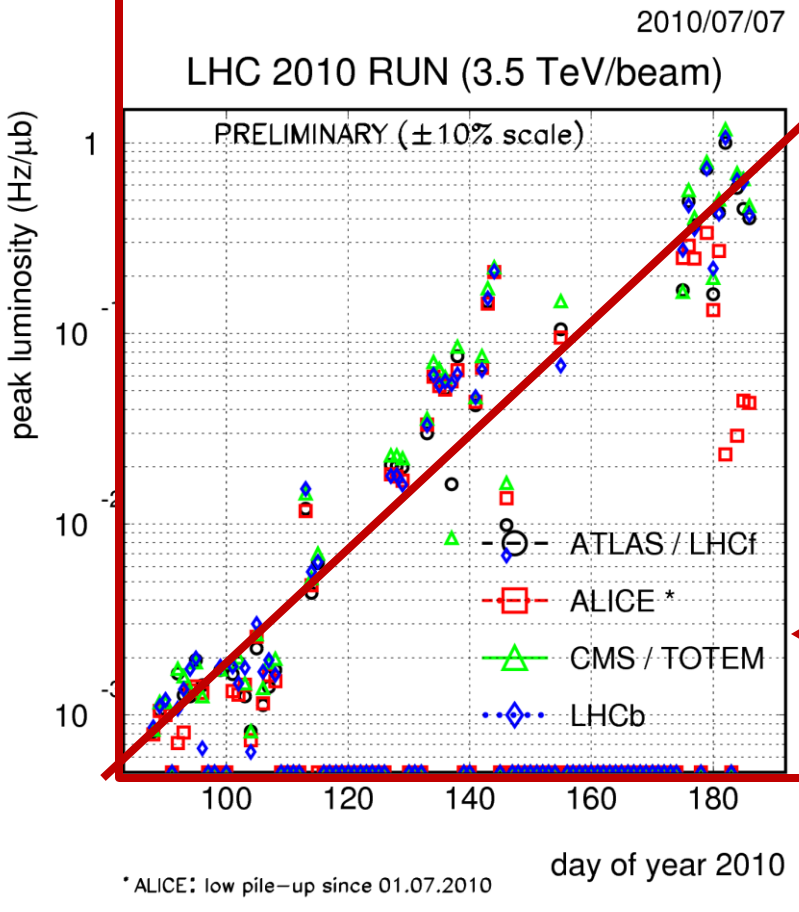
- requires a peak luminosity of $\geq 1 \times 10^{32}$ $cm^{-2}s^{-1}$ during 2011
- → must reach ~1 $\times 10^{32}$ $cm^{-2}s^{-1}$ during 2010

Peak lumi (in STABLE BEAMS)

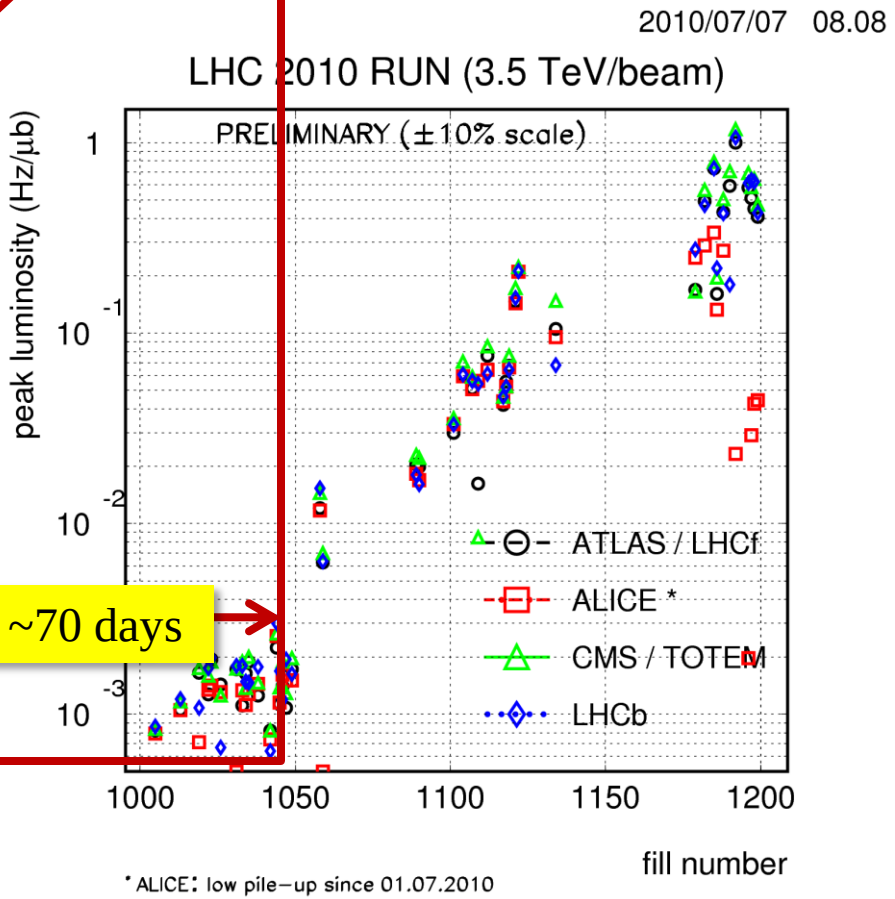
1e32 !!

(modulo some possible luminometers down time...)

Fills 1005-1199



~70 days



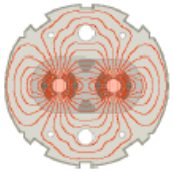
Longer Term Objectives

Integrated luminosity of $\geq 3000 fb^{-1}$ by the end of the LHC life

- requires a peak luminosity of $\geq 5 \times 10^{34}$ $cm^{-2}s^{-1}$ during 2021-2030

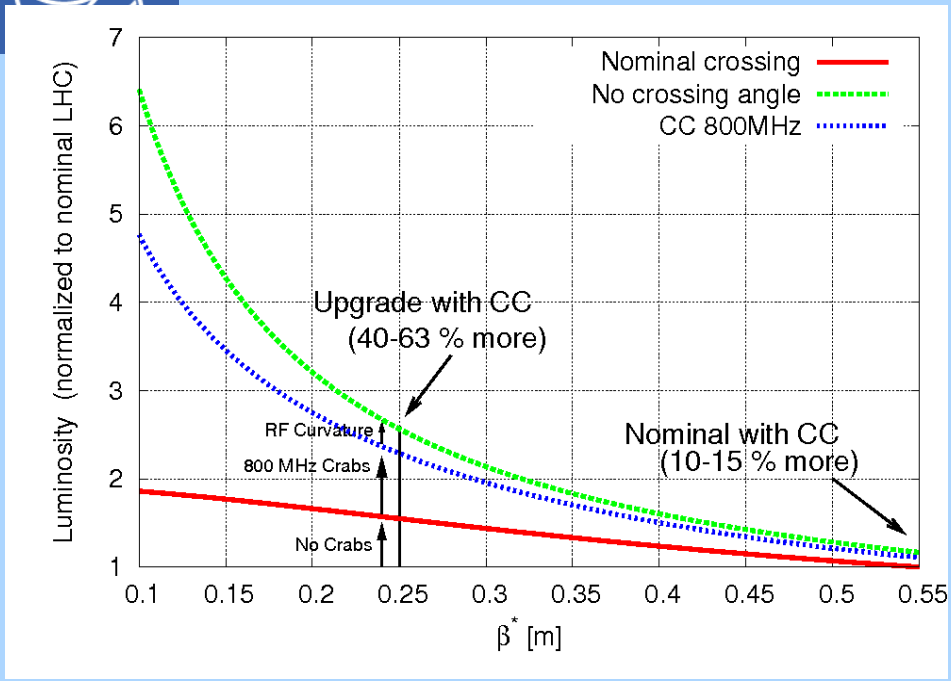
- → integrated yearly luminosity of around 250-300fb^{-1}

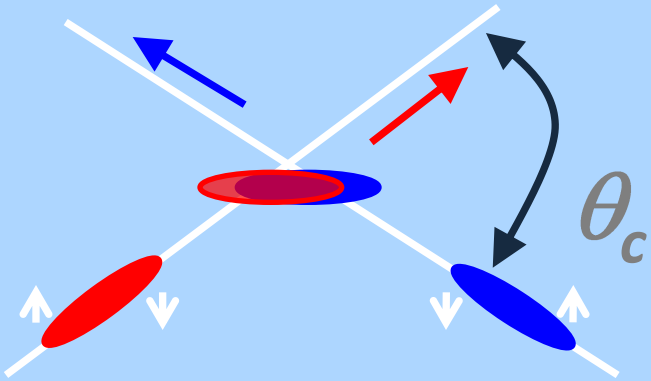
New studies under way (HL-LHC)

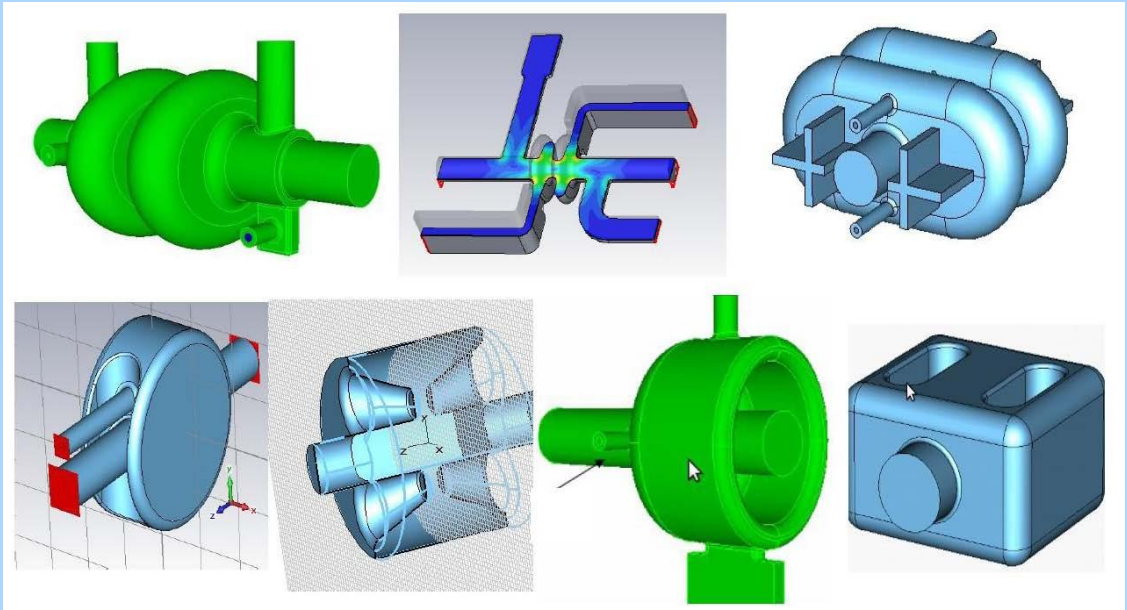


- **High Gradient/Large Aperture Quads, with B_{peak} 13-15 T.** (Nb_3Sn)
  - Higher field quadrupoles translate in **higher gradient/shorter length** or larger aperture/same length or a mix.
  - **US-LARP engaged to produce proof by 2013.**
  - β^* as small as 22 cm are possible with a **factor ~2.5** in luminosity by itself, **if coupled with a mechanism to compensate the geometrical reduction**
- **Crab Cavities**: this is the best candidate for exploiting small β^*
  - However it should be underlined that today Crab Cavities are not validated for LHC , not even conceptually: **the issue of machine protection will be addressed with priority**
- **SC links** to replace at the surface elecronic equipment today in the tunnel and exposed to high radiation
- **New Cryoplants** in IP1 & IP5: for power AND to make independent Arc- IR:
- Upgrades in the injector chain (LINAC4, PS Booster, PS, SPS)

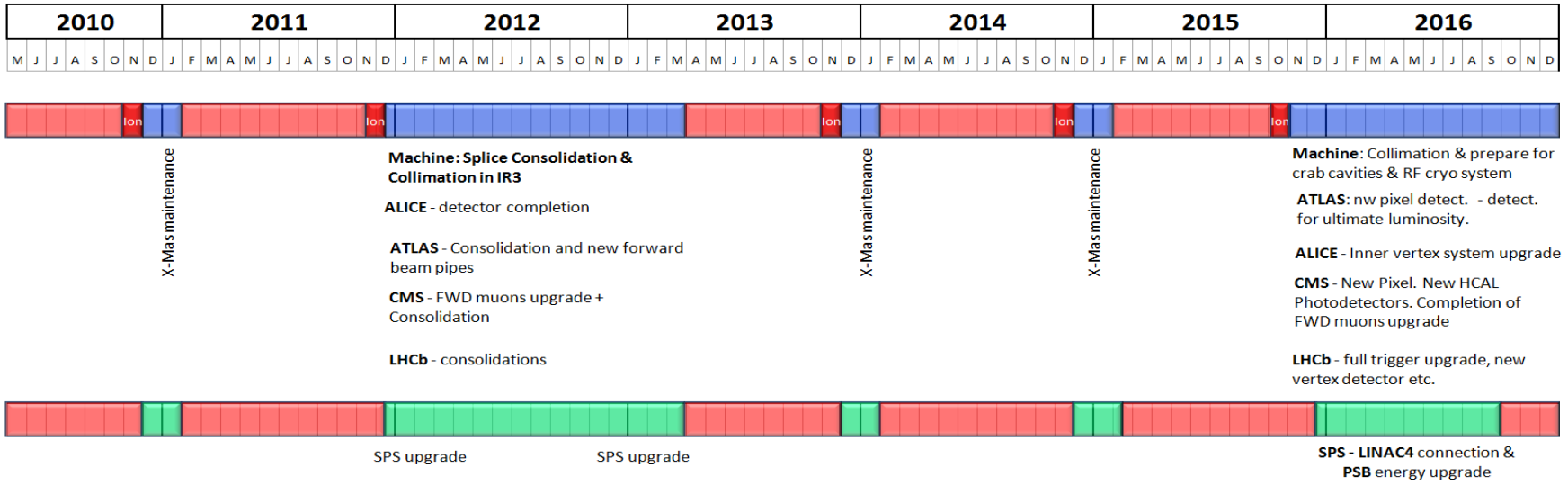
Crab cavities for exploiting low β*

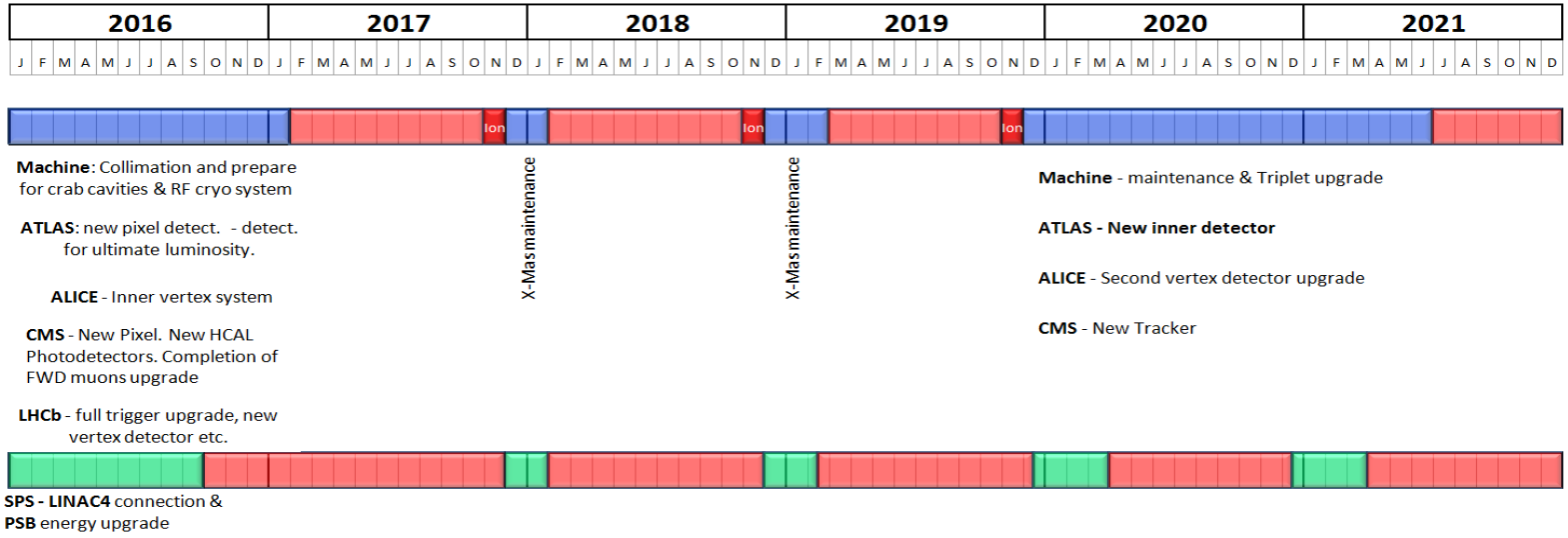




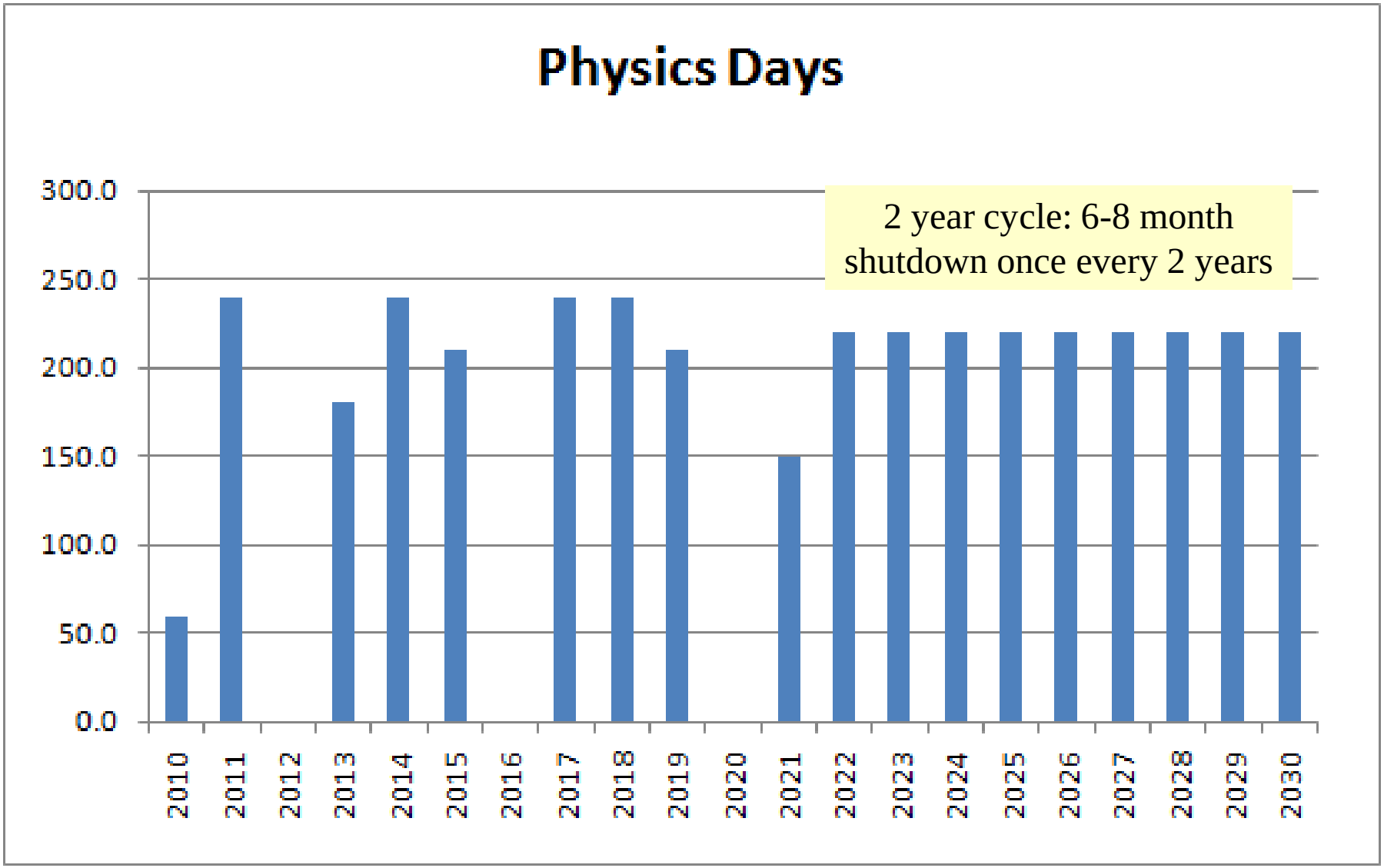


The 10 year technical Plan

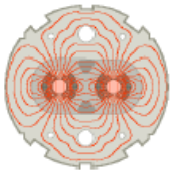




The 20 year physics plan



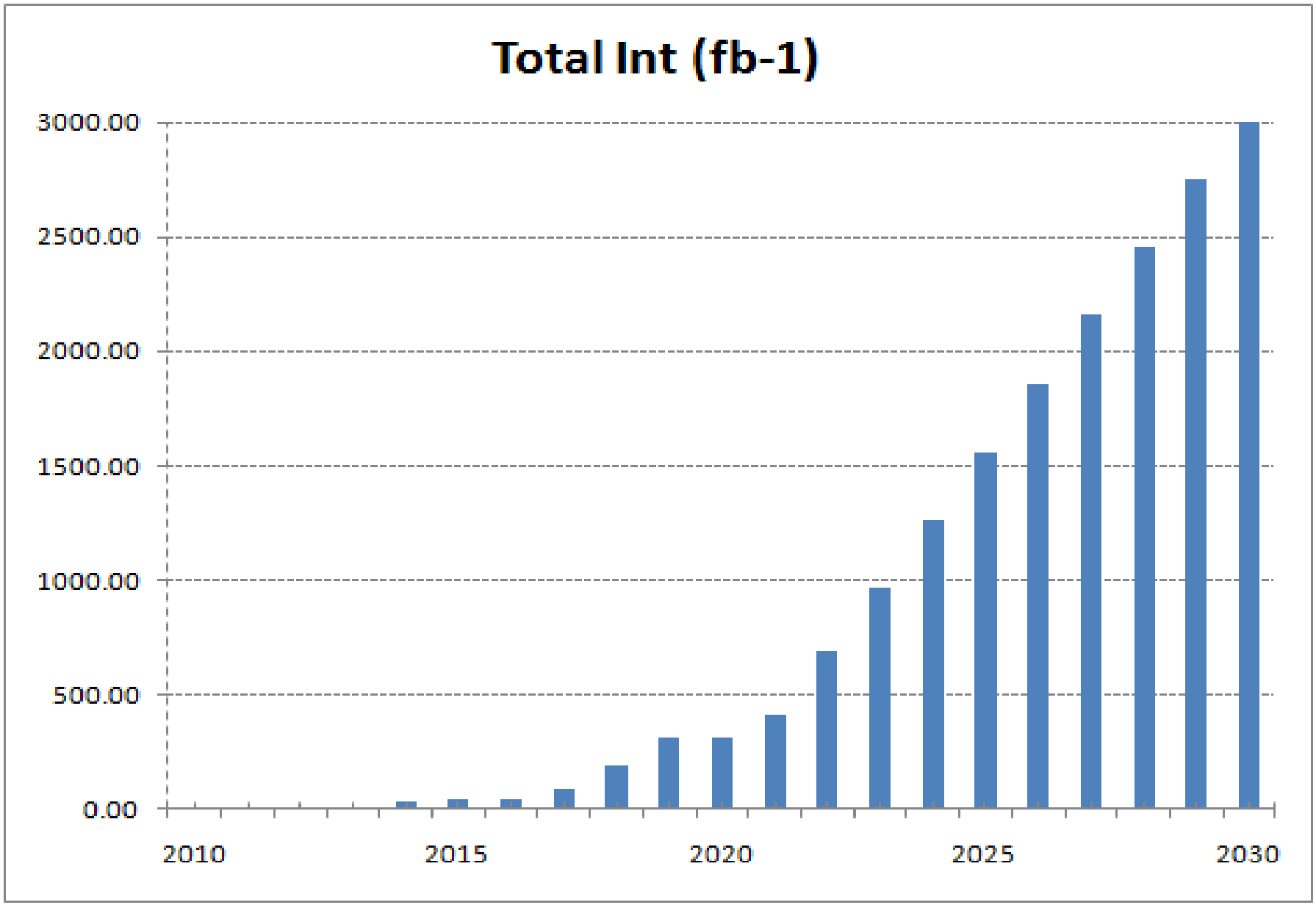
Preliminary Luminosity Predictions



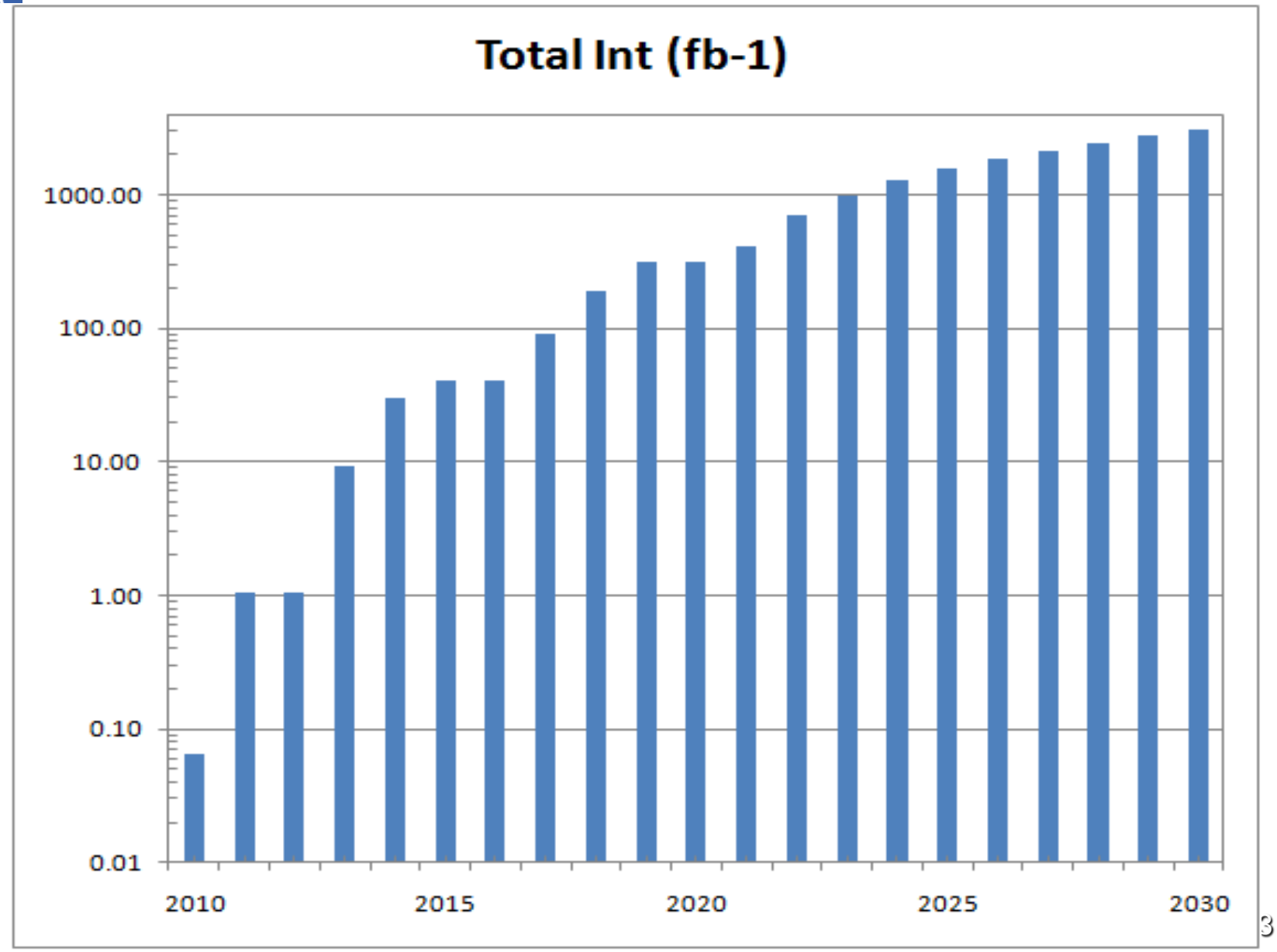
Year	TeV	OEF	β*	Nb	Ib	Itot	MJ	Peak luminosity	Pile up	ph	ysics	Integrated (fb-1/year)	Total Int (fb-1)
2010	3.50	0.20	2.00	796	8.0E+10	6.4E+13	36.0	1.886E+32				0.1	0.07
2011	3.50	0.25	2.00	796	8.0E+10	6.4E+13	36.0	1.886E				0.98	1.04
2012												0.0	1.0
2013	6.50	0.20	0.55	796	1.15E+11	9.2E+13	96				180.0	8.2	9.2
2014	7.00	0.20	0.55	1404	1.15E+11	1.6E+14					240.0	20.7	30.0
2015	7.00	0.20	0.55	2808	1.15E+11	3.2E+				172.8	210.0	36.3	66.3
2016											0.0	0.0	66.3
2017	7.00	0.25	0.55	2808	1.15E+				000	216.0	240.0	51.8	118.1
2018	7.00	0.28	0.55	2808	1.				32.3251	411.6	240.0	98.8	216.9
2019	7.00	0.30	0.55	28				+34	41.5198	566.4	210.0	118.9	335.8
2020											0.0	0.0	335.8
2021	7.00	0.20	0				.6	4.006E+34	76.1197	692.3	150.0	103.8	439.7
2022	7.00	0.27					571.3	5.390E+34	102.4060	1257.3	220.0	276.6	716.3
2023	7.00					+14	571.3	5.390E+34	102.4060	1257.3	220.0	276.6	992.9
2024	7.0					.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	1290.0
2025						5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	1587.1
2026	7.0				.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	1884.2
2027	7.00			08	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	2181.3
2028	7.00			2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	2478.4
2029	7.00	0.2	.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	2775.5
2030	7.00	0.29	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	3072.6

Very preliminary with large error bars

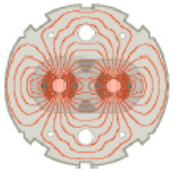
Preliminary Long Term Predictions



Preliminary Long Term Predictions



Very Long Term Objectives: Higher Energy LHC



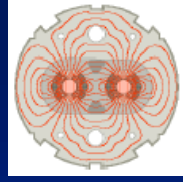
Preliminary HE-LHC - parame

	nor	HE-LHC
beam energy [TeV]		16.5
dipole field [T]		20
dipole coil aperture [mm]		40-45
#bunches / beam		1404
bunch population [10^{11}]		1.29
initial transverse normalized	3.75	3.75 (x), 1.84 (y)
number of IPs contributi	3	2
maximum total beam	0.01	0.01
IP beta function	0.55	1.0 (x), 0.43 (y)
full crossing	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored b	362	479
SR po	3.6	62.3
longitud damping time [h]	12.9	0.98
events per	19	76
peak luminos [10^{34} cm^{-2}s^{-1}]	1.0	2.0
beam lifetime [h]	46	13
integrated luminosity over 10 h [fb^{-1}]		

Very preliminary with large error bars

HE-LHC – main issues and R&D

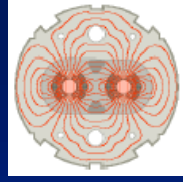
- ***high-field 20-T dipole*** *magnets based on Nb_3Sn, Nb_3Al, and HTS*
- ***high-gradient quadrupole magnets*** *for arc and IR*
- ***fast cycling SC magnets*** *for 1-TeV injector*
- ***emittance control*** *in regime of strong SR damping and IBS*
- *cryogenic handling of* ***SR heat load*** *(first analysis; looks manageable)*
- *dynamic* ***vacuum***



Acknowledgements

The work summarized here is the result of work carried out by hundreds if not thousands of scientists, engineers and technicians both employed by CERN and **very importantly by the many institutes which collaborate with CERN.**

It is a great personal pleasure to acknowledge the incredible contributions and dedication of such a wonderful team.



Thank you for your attention