LHC Status

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Status of the LHC

Early beam operation

Strategy and progress so far

Examples of what we do

Prospects

Instantaneous luminosity

$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f\gamma}{4\pi\varepsilon_n\beta^*} F$$

"Thus, to achieve high luminosity, all one has to do is make (lots of) high population bunches of low emittance to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible." PDG 2005, chapter 25

- Nearly all the parameters are variable (and not independent)
  - Number of bunches per beam k_b — Total Intensity
  - Number of particles per bunch N — Beam Brightness
  - Normalised emittance ε_n — Beam Brightness
  - Relativistic factor (E/m_0) γ — Energy
  - Beta function at the IP β^* — Interaction Region
  - Crossing angle factor F — Interaction Region
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*

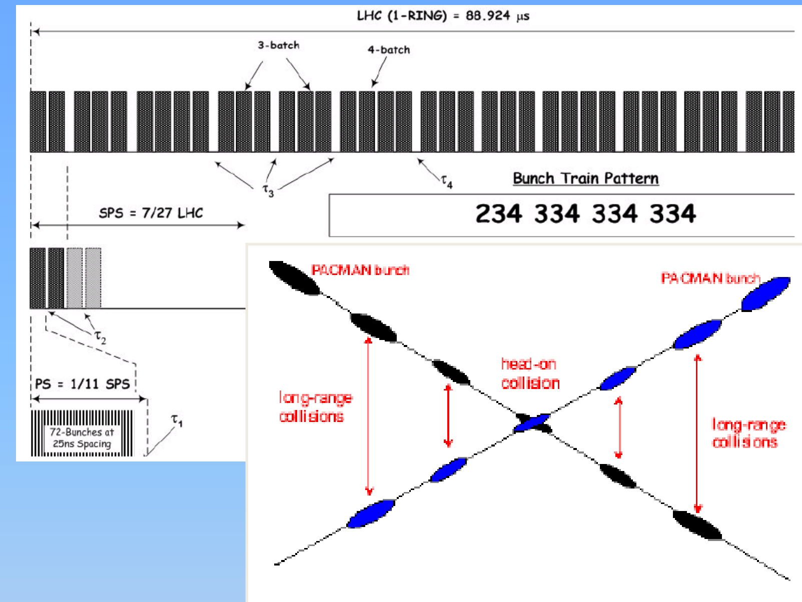
$$F = 1 \Big/ \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

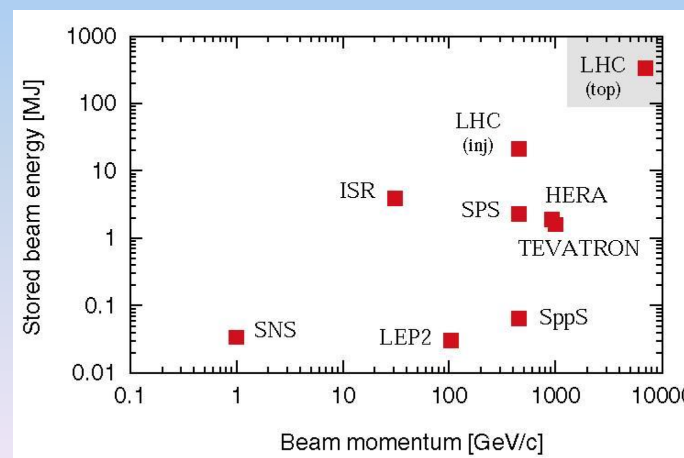
LHC nominal performance

Nominal settings	
Beam energy (TeV)	7.0
Number of particles per bunch	$1.15\ 10^{11}$
Number of bunches per beam	2808
Crossing angle (μrad)	285
Norm transverse emittance (μm rad)	3.75
Bunch length (cm)	7.55
Beta function at IP 1, 2, 5, 8 (m)	0.55,10,0.55,10

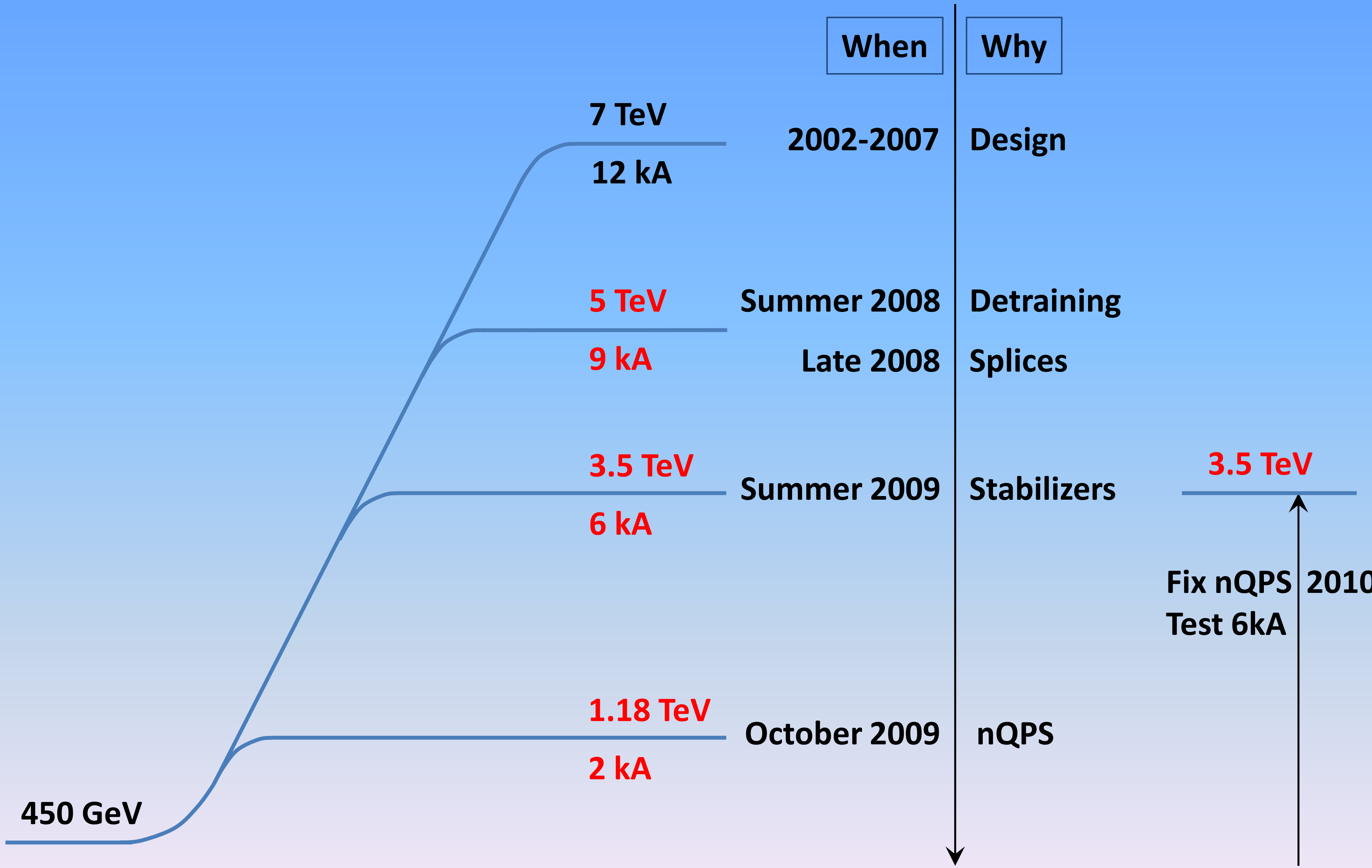
Derived parameters	
Luminosity in IP 1 & 5 ($cm^{-2}\ s^{-1}$)	10^{34}
Luminosity in IP 2 & 8 ($cm^{-2}\ s^{-1}$)*	$\sim 5\ 10^{32}$
Transverse beam size at IP 1 & 5 (μm)	16.7
Transverse beam size at IP 2 & 8 (μm)	70.9
Stored energy per beam (MJ)	362

* Luminosity in IP 2 and 8 optimized as needed





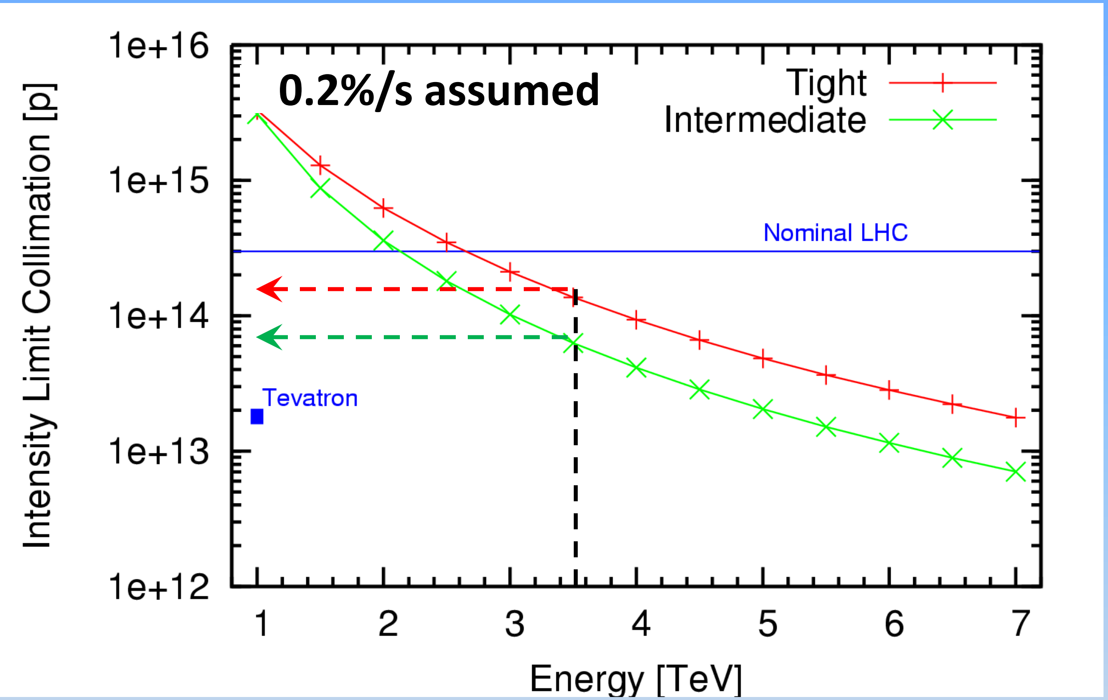
Evolution of target energy during commissioning



LHC Intensity limits 2010 2011

- Collimation system conceived as a staged system

- First stage to allow 40% of nominal intensity at 7TeV
  - Under certain assumptions
    - LHC lifetimes and loss rates
    - 0.1%/s assumed (0.2h lifetime)
    - Ideal cleaning
  - Imperfections bring this down
    - Deformed jaws
    - Tilt & offset & gap errors
    - Machine alignment
  - Machine stability
    - Tight settings a challenge early
    - Intermediate settings make use of aperture to relax tolerances

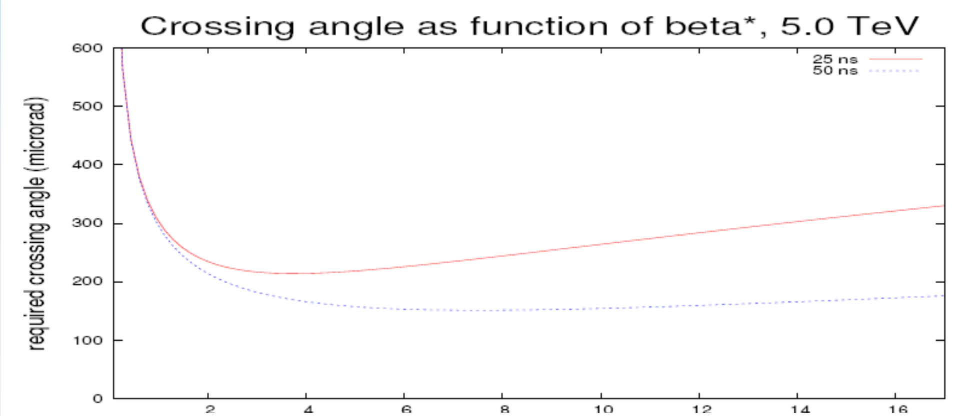


Fix I_{max} to 6 10^{13} protons per beam at 3.5TeV (about 20% nominal intensity)

30MJ stored beam energy

β* and F in 2010 2011

- Lower energy means bigger beams $\varepsilon_n = \varepsilon\gamma$ $\sigma = \sqrt{\varepsilon\beta}$
  - Less aperture margin around the IP
  - Higher β* helps in this
- > 150 bunches requires crossing angle
  - Requires more aperture
  - Higher β* again helps
- Targets for 3.5TeV
  - 2m no crossing angle
  - 3m with crossing angle



Operation with β^* between 1 m and 4 m very promising

Early beam operation

2009			2010			2011		
Repair of Sector 34	1.18 TeV	nQPS 6kA	3.5 TeV $I_{safe} < I < 0.2\ I_{nom}$ β* > 2 m	Ions		3.5 TeV $\sim 0.2\ I_{nom}$ β* ~ 2 m	Ions	
No Beam	B		Beam			Beam		

- Energy limited to 3.5 TeV
- 2010
  - Intensity carefully increased to collimation limit
  - β* pushed as low as possible
  - Target luminosity 10^{32} $cm^{-2}s^{-1}$
- 2011
  - Run at established limits
  - Target integrated luminosity 1 fb^{-1}

Energy	TeV	3.50	3.50	3.50	3.50
Bunch intensity	1.E+10	10.0	10.0	10.0	10.0
Bunches per beam		4	24	432	792
Emittance	μm	3.75	3.75	3.75	3.75
β*	m	3.50	3.50	3.50	3.50
Luminosity 1 and 5	cm-2 s-1	1.0E+30	6.1E+30	1.1E+32	2.0E+32
Total inel X section	cm2	6.0E-26	6.0E-26	6.0E-26	6.0E-26
Event rate	Hz	6.1E+04	3.7E+05	6.5E+06	1.2E+07
Event rate / Xing	Hz	1.4	1.4	1.3	1.3
Protons		4.0E+11	2.4E+12	4.3E+13	7.9E+13
% nominal		0.1	0.7	13.4	24.5
Current	mA	0.7	4.3	77.7	142.5
Stored energy	MJ	0.2	1.3	24.2	44.4
Beam size 1 and 5	um	59.3	59.3	59.3	59.3

40% efficiency for physics → 10^6 seconds collisions per month

10^6 seconds @ <L> of 10^{32} cm^{-2} s^{-1} → 100 pb^{-1}

Status of the LHC

Early beam operation

Strategy and progress so far

Examples of what we do

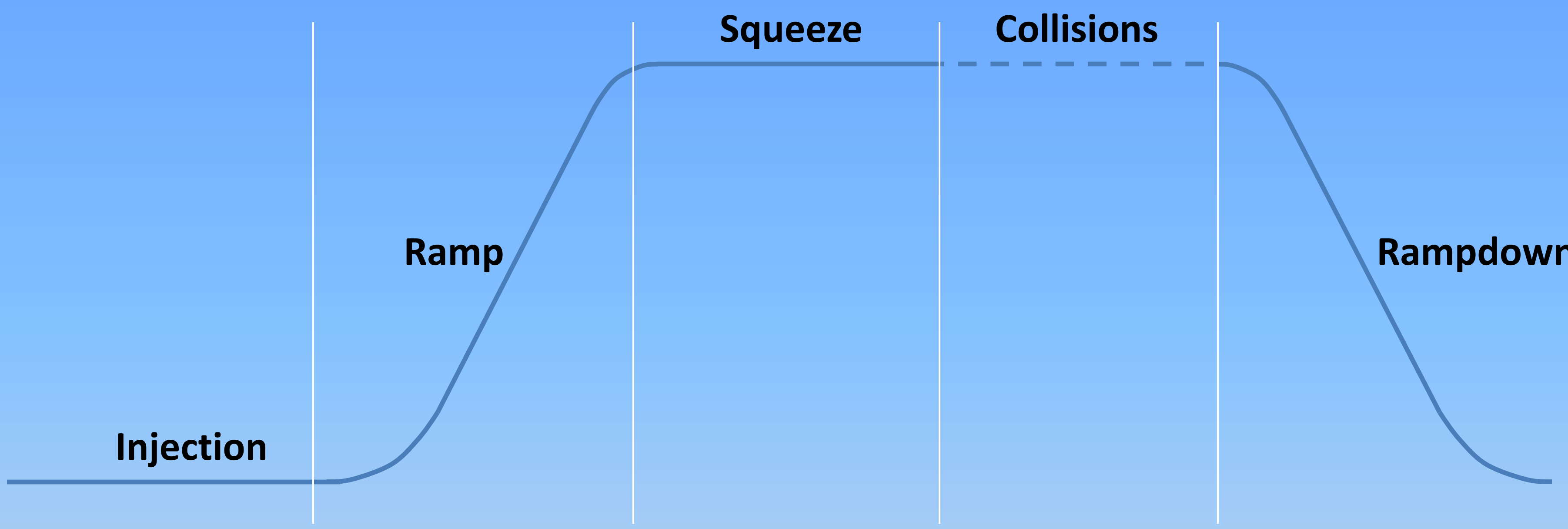
Prospects

Commissioning strategy

- At whatever energy
  - Correct everything we can with safe beams
  - Then establish references
  - Then set up protection devices
  - Then increase intensity incrementally
    - Low bunch currents, increase k_b
    - Increase bunch current
    - High bunch current, low k_b, same total current
    - Nominal bunch currents, increase k_b
    - Once k_b > 50 or so, need bunch trains
  - At each stage, re-qualify machine protection systems

Some numbers			
What	**Limit**		**Comment**
Pilot	**Single bunch of 5 10^9 protons**		**Quench limit**
Safe beam	**10^{12} protons at 450 GeV**		**Damage limit**
	Energy	**Safe beam**	**Scales with $1/E^{1.7}$**
	0.45	**1.00E+12**	
	1.18	**1.94E+11**	
	3.5	**3.06E+10**	
	7	**9.41E+09**	

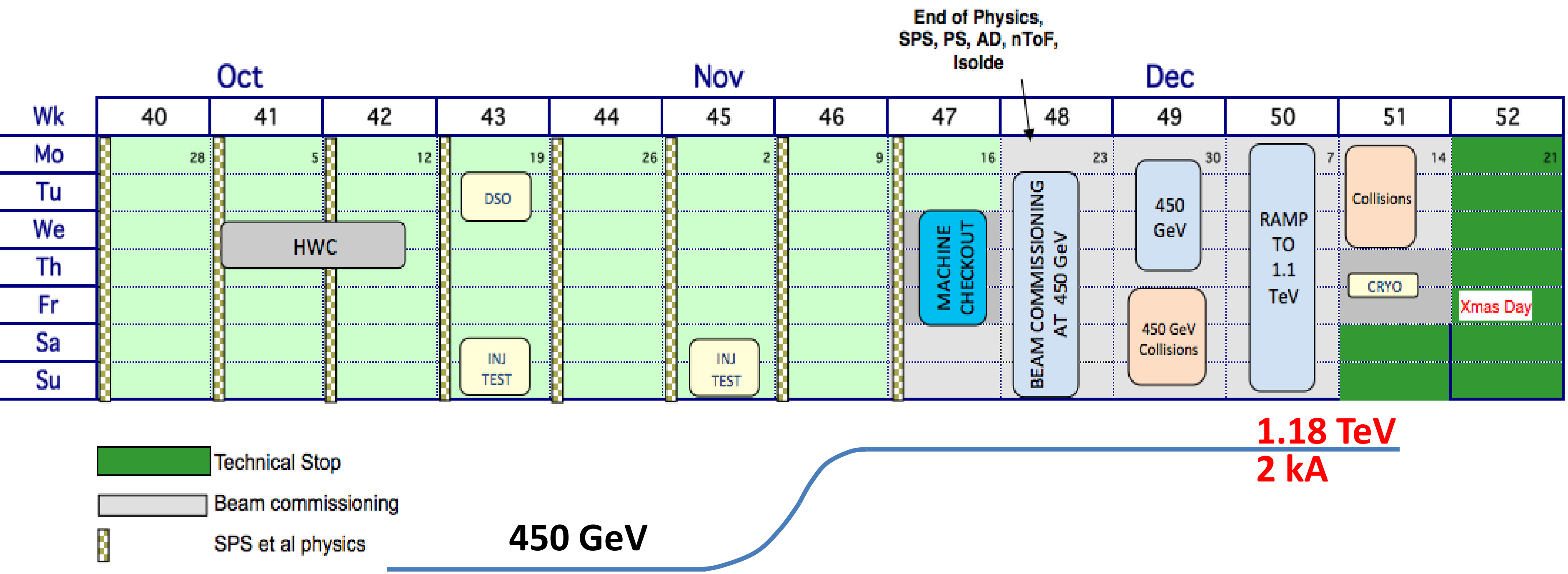
The operational cycle



Injection	Ramp	Squeeze	Collisions	Rampdown
Many schemes Injection channel	Dynamic effects Feedbacks	Optics Collimators	Beam steering Beam-beam	Ramp rates Reproducibility

← All through the cycle →
Beam dump Collimations system Protection devices

Targets with beam 2009



AIMS

450 GeV collisions
10^6 events

Ramp to 1.18 TeV
Collisions at 1.18 TeV

Do this with SAFE BEAMS

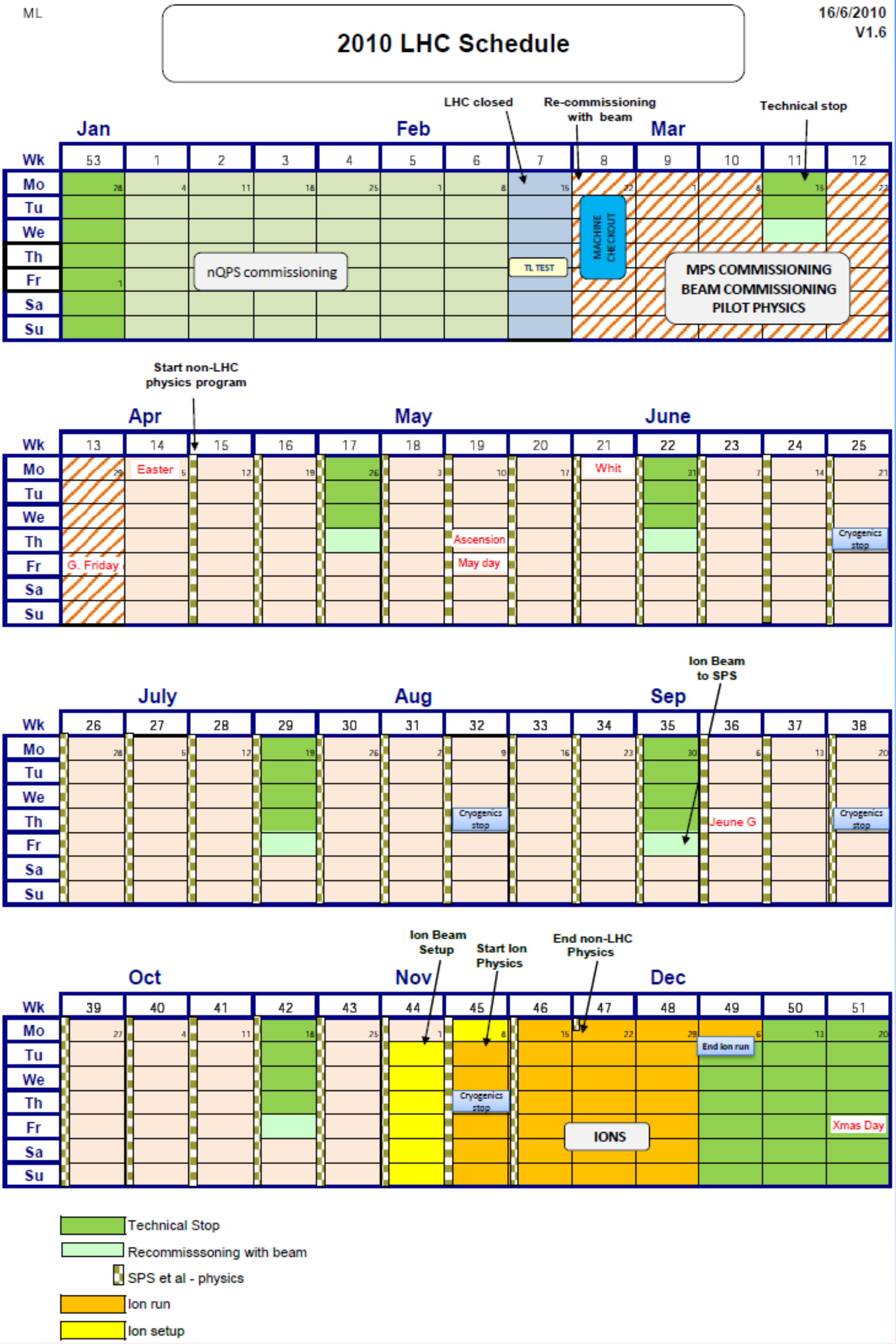
10^{12} at 450 GeV → 2 10^{11} at 1.18 TeV

LIMITS

2 on 2 with 5 10^{10} per bunch at 1.18 TeV
4 on 4 with 2 10^{10} per bunch at 1.18 TeV

Milestones reached 2009

Date	Day	Achieved
Nov 20	1	Each beam circulating. Key beam instrumentation working.
Nov 23	4	First collisions at 450 GeV. First ramp (reached 560 GeV).
Nov 26	7	Magnetic cycling established (reproducibility).
Nov 27	8	Energy matching done.
Nov 29	10	Ramp to 1.18 TeV.
Nov 30	11	Experiment solenoids on.
Dec 04	15	Aperture measurement campaign finished. LHCb and ALICE dipoles on.
Dec 05	16	Machine protection (Injection, Beam dump, Collimators) ready for safe operation with pilots.
Dec 06	17	First collisions with STABLE BEAMS, 4 on 4 pilots at 450 GeV, rates around 1Hz.
Dec 08	19	Ramp colliding bunches to 1.18 TeV
Dec 11	22	Collisions with STABLE BEAMS, 4 on 4 at 450 GeV, > 10^{10} per bunch, rates around 10Hz.
Dec 13	24	Ramp 2 bunches per beam to 1.18 TeV. Collisions for 90mins.
Dec 14	25	Collisions with STABLE BEAMS, 16 on 16 at 450 GeV, > 10^{10} per bunch, rates around 50Hz.
Dec 16	27	Ramp 4 on 4 to 1.18 TeV. Squeeze to 7 m. Collisions.



2010

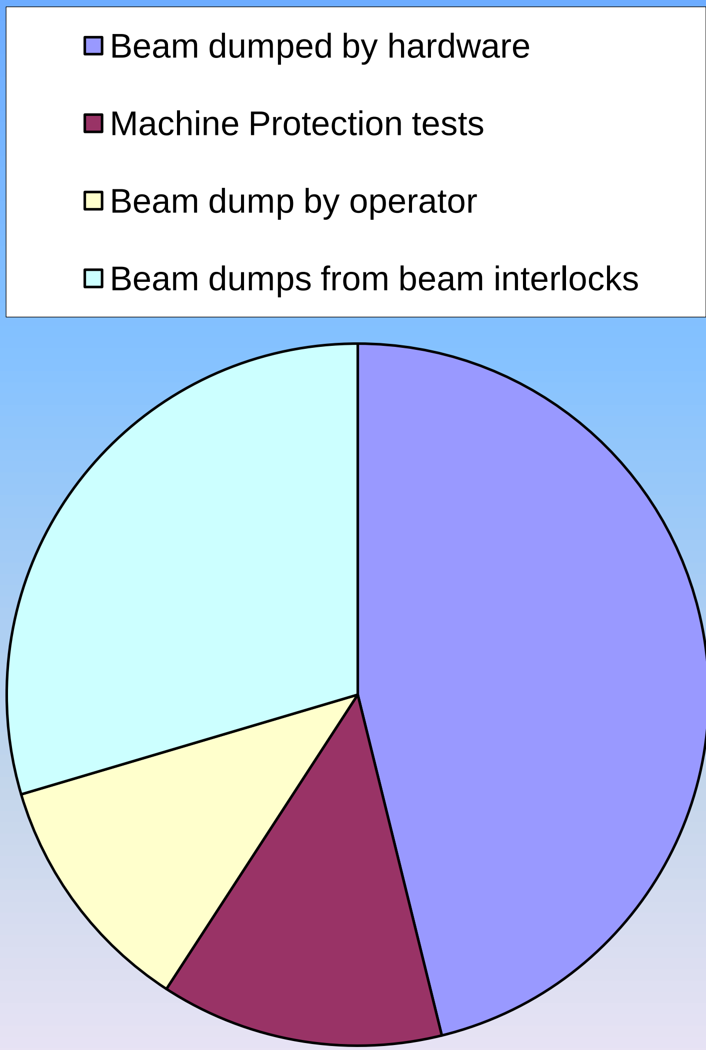
Hardware commissioning for 3.5 TeV
Ramp beams to 3.5 TeV
Machine protection systems qualified
Colliding safe stable beams (2 on 2 pilots)

Squeeze to 2m
Low bunch currents, increase k_b
Machine protection systems qualified
13 on 13 low intensity bunches at 2m

High bunch currents, low k_b
Increase k_b
Machine protection systems qualified
25 on 25 high intensity bunches at 3.5m (Aug)

Ions (early scheme, max 62 bunches per beam)
Same magnetic machine as for protons
1 week to switch
4 weeks ion run

Beam dump analysis end July (169 dumps)



Beam dumps by hardware	
Triggers by QPS	10
False beam dump by Beam Dump System	9
Collimator positions not correct	10
Problem with cryogenics	9
Power converter faults	10
Electrical Network	10
Operational error	9
False beam dump by Beam Loss monitors	3
Triggers by vacuum system	2
False beam dump by SIS	1
Controls system problem	1
RF faults	1
False beam dump by Beam Interlock System	1
Experiments hardware	2

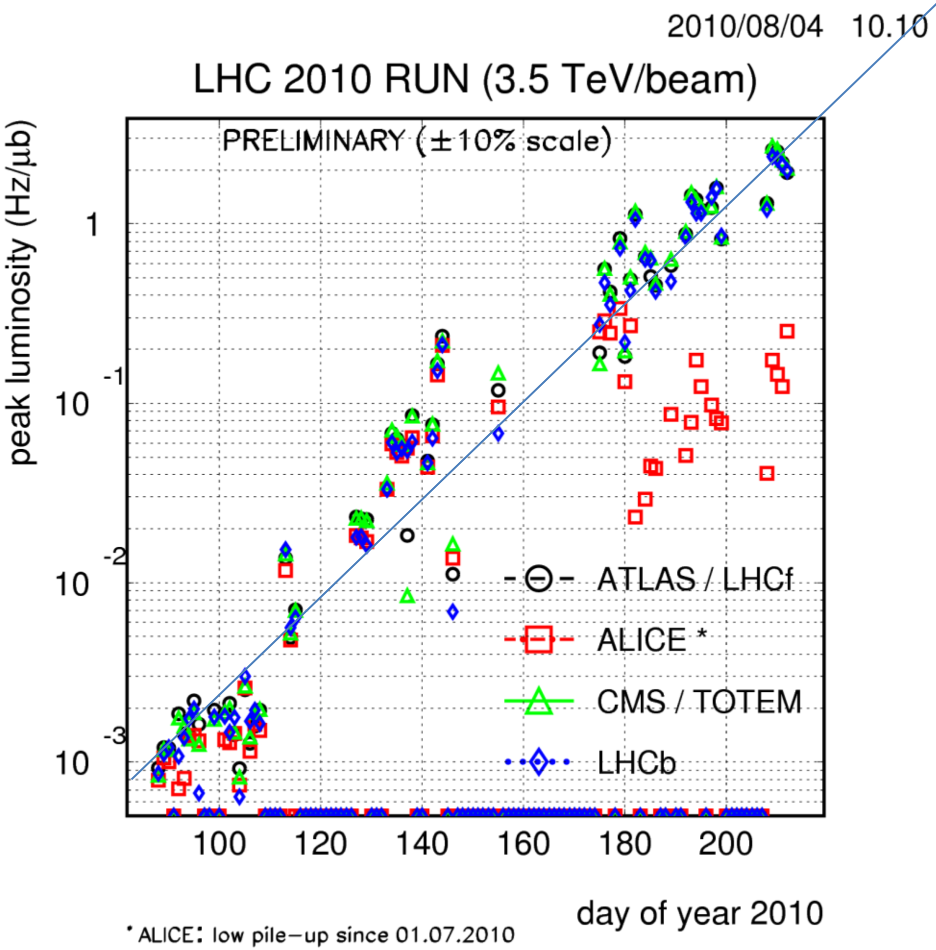
Beam dumps from beam interlocks	
Orbit outside tolerances	17
Beam loss	13
Feedback	11
Collimator adjustement	6
Experiments BCM	3

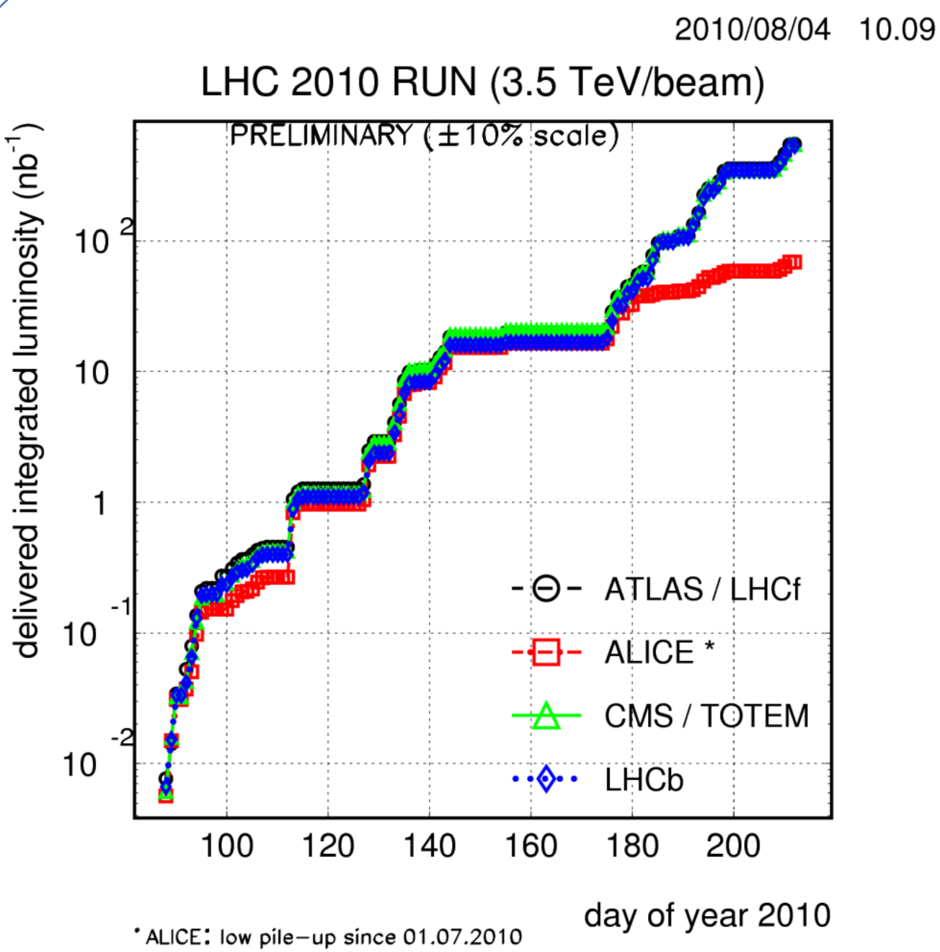
Milestones reached 2010 (early August)

Date	Day	Achieved	
Feb 28	1	Restart with beam.	
Mar 12	13	Ramp to 1.18 TeV.	
Mar 19	20	Ramp to 3.5 TeV.	
Mar 30	31	First collisions at 7 TeV centre of mass.	Luminosity ~ $2\ 10^{27}\ cm^{-2}\ s^{-1}$
Apr 01	33	Start squeeze commissioning.	Regular physics runs 2 on 2 bunches of 10^{10} Un-squeezed 1 colliding pairs per experiment Rates around 100Hz
Apr 07	39	Squeeze to 2 m in points 1 and 5.	
Apr 09	41	Single nominal bunch of 1.1 1011 stable at 450GeV.	
Apr 13	45	Squeeze to 2 m in point 8.	
Apr 16	48	Squeeze to 2m in point 2.	
April 24	54	First stable beams at 7 TeV, 3 on 3, squeeze to 2m.	Luminosity ~ $2\ 10^{28} cm^{-2}\ s^{-1}$
May		Increase bunch intensity to $2\ 10^{10}$, Increase k_b.	Regular physics runs
May 24		13 on 13, 8 colliding pairs per experiment.	Luminosity ~ $3\ 10^{29} cm^{-2}\ s^{-1}$
June		Increase bunch intensity to nominal, squeeze to 3.5m.	No physics !
June 25		First stable beams at 7 TeV, 3 on 3 nominal bunch.	Luminosity ~ $5\ 10^{29} cm^{-2}\ s^{-1}$
July 15		13 on 13, 8 colliding pairs per experiment, $9\ 10^{10}$ / bunch	Luminosity ~ $1.5\ 10^{30} cm^{-2}\ s^{-1}$
July 30		25 on 25, 16 colliding pairs per experiment, $9\ 10^{10}$ / bunch	Luminosity ~ $3\ 10^{30} cm^{-2}\ s^{-1}$
Aug		Stable running period to consolidate operation and MP	1.3 MJ per beam !

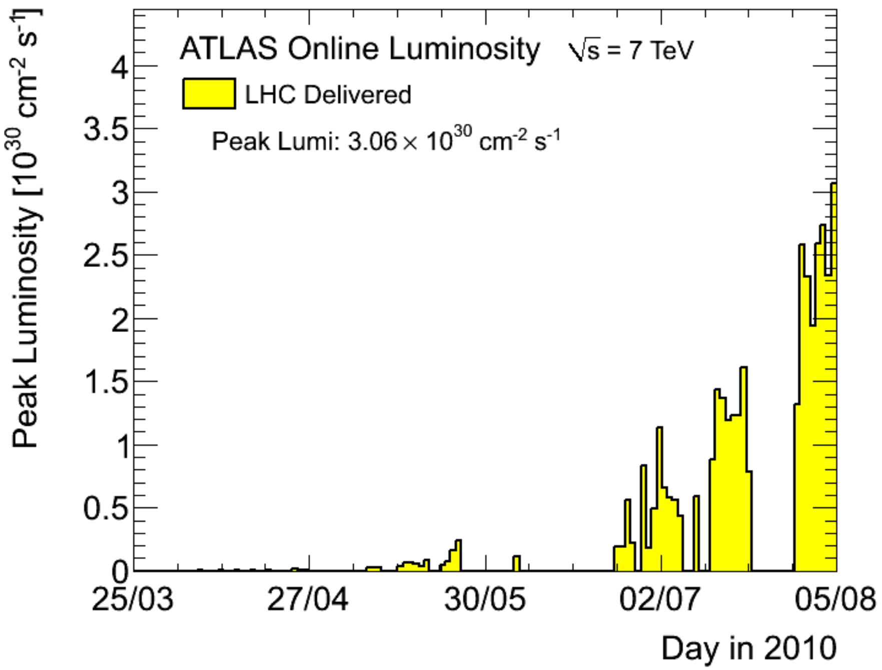
Luminosity (early August)

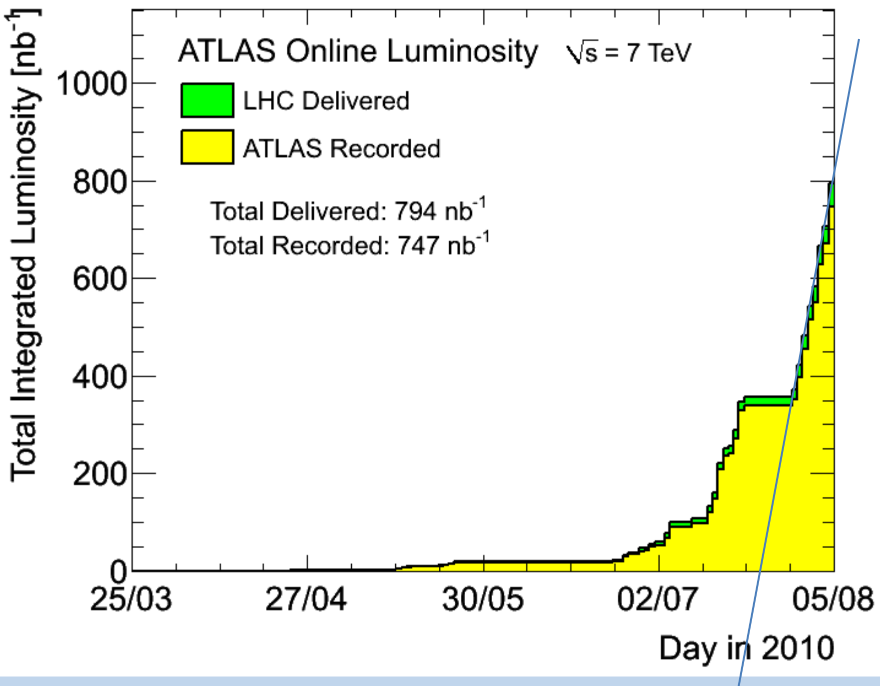
3 orders of magnitude in ~120 days





Latest from ATLAS





60nb^{-1} per day

$<\mathcal{L}>$ ~1.5 10^{30}

40% efficiency

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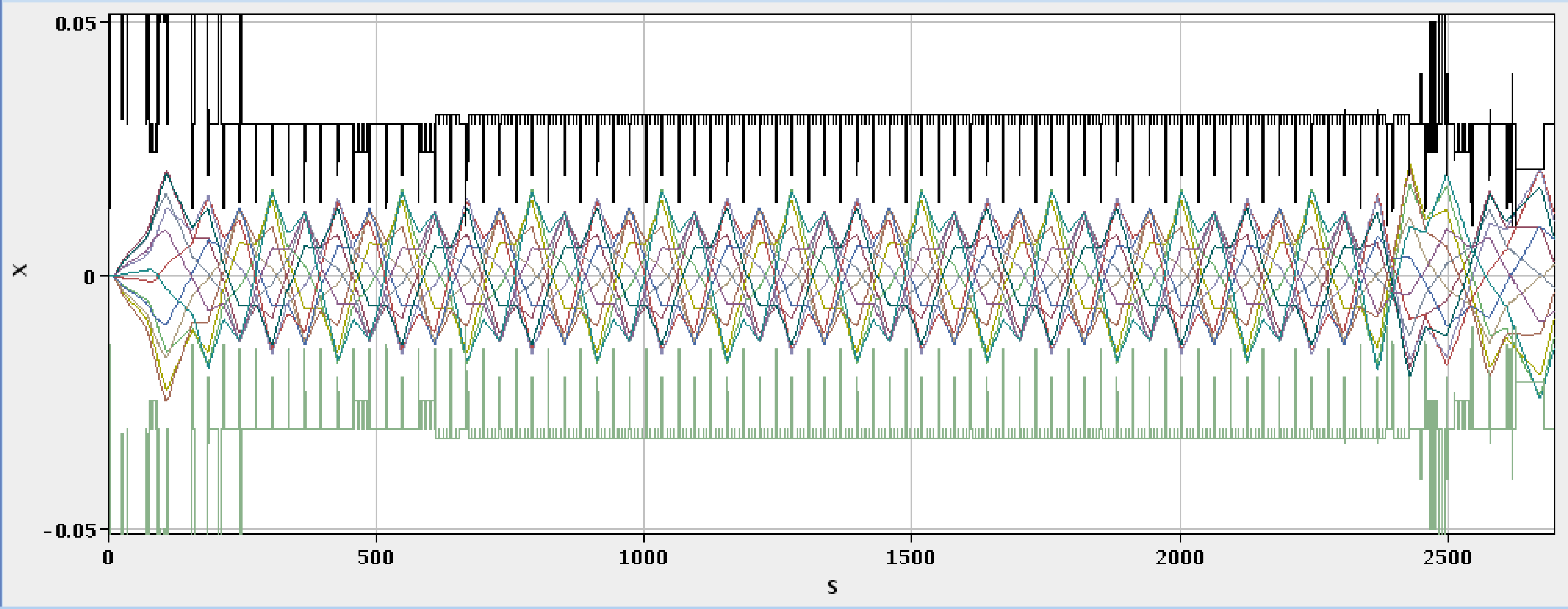
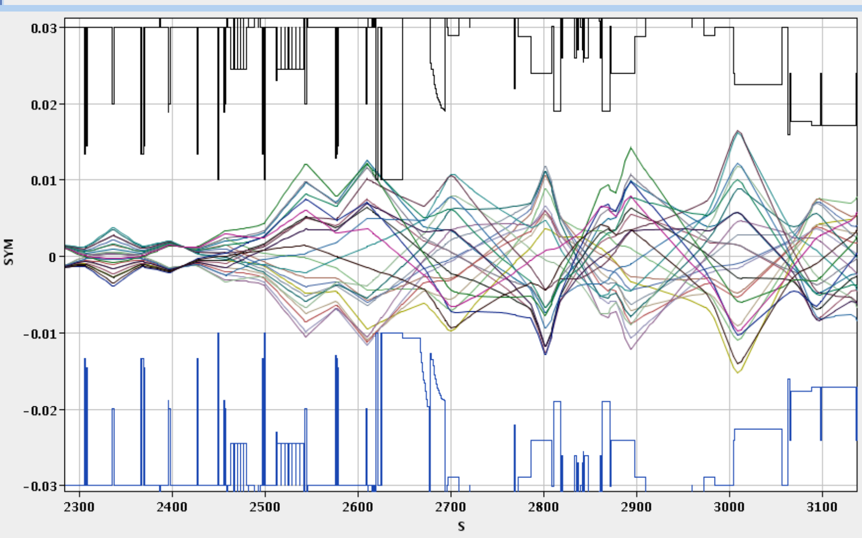
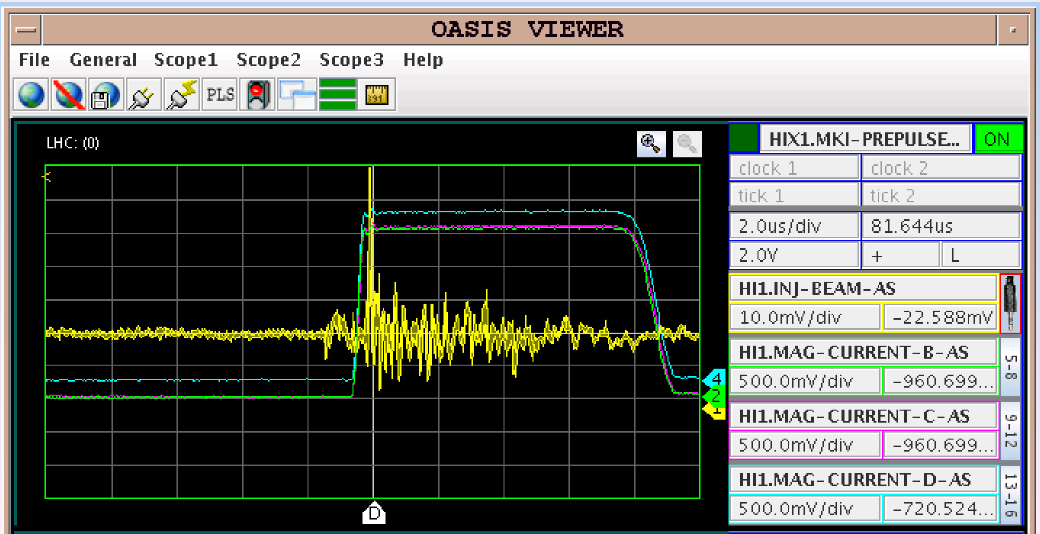
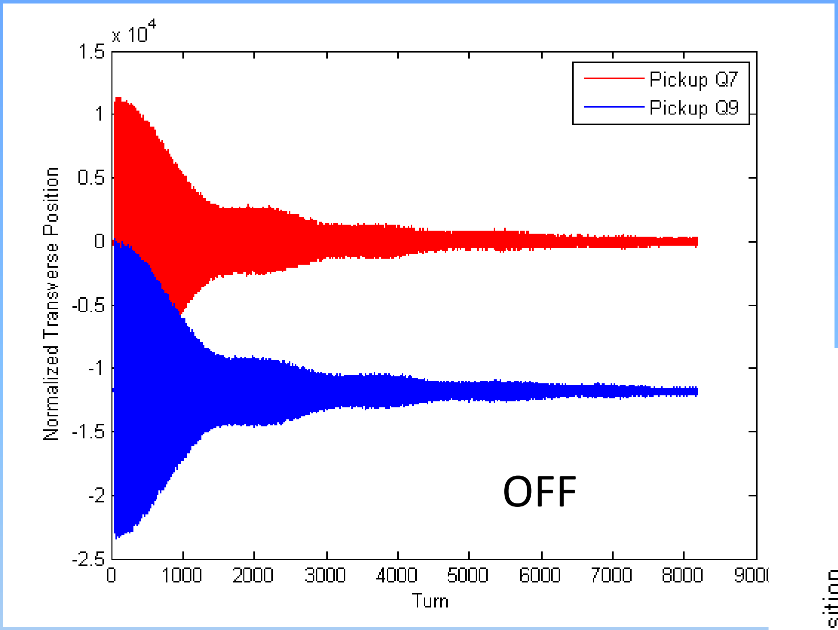
Beam transfer and Injection

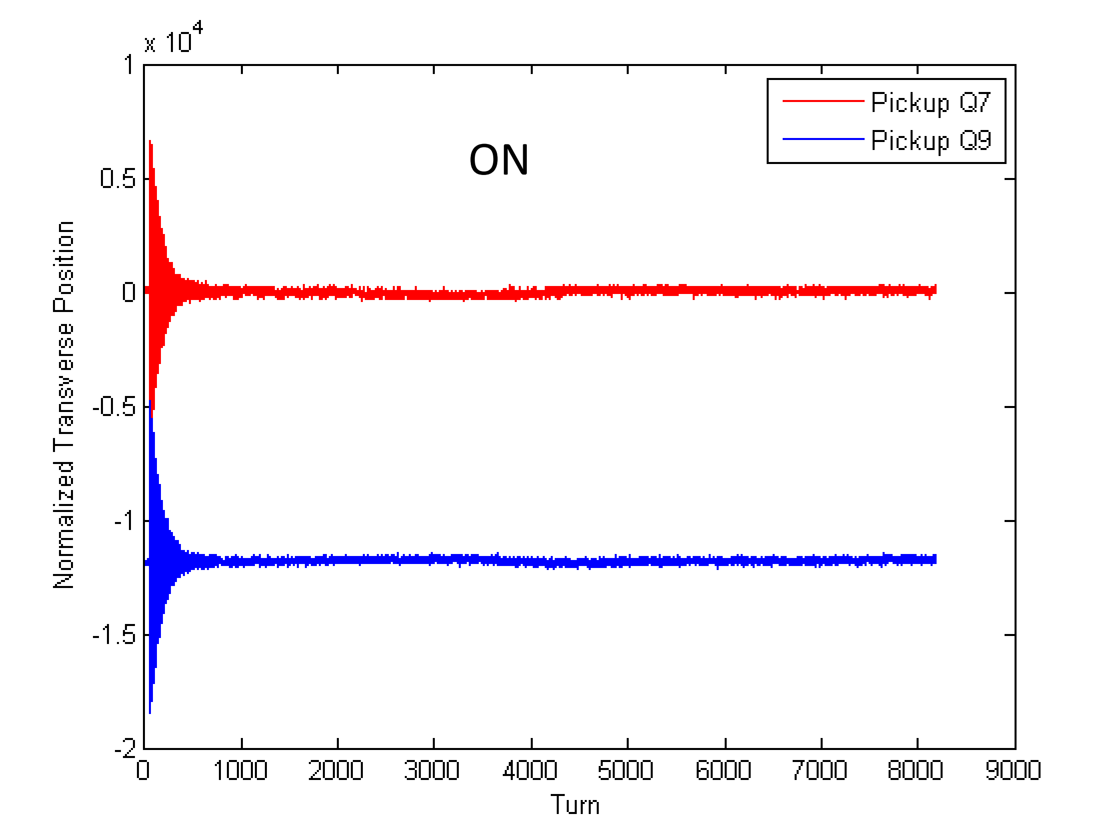






Injection oscillations

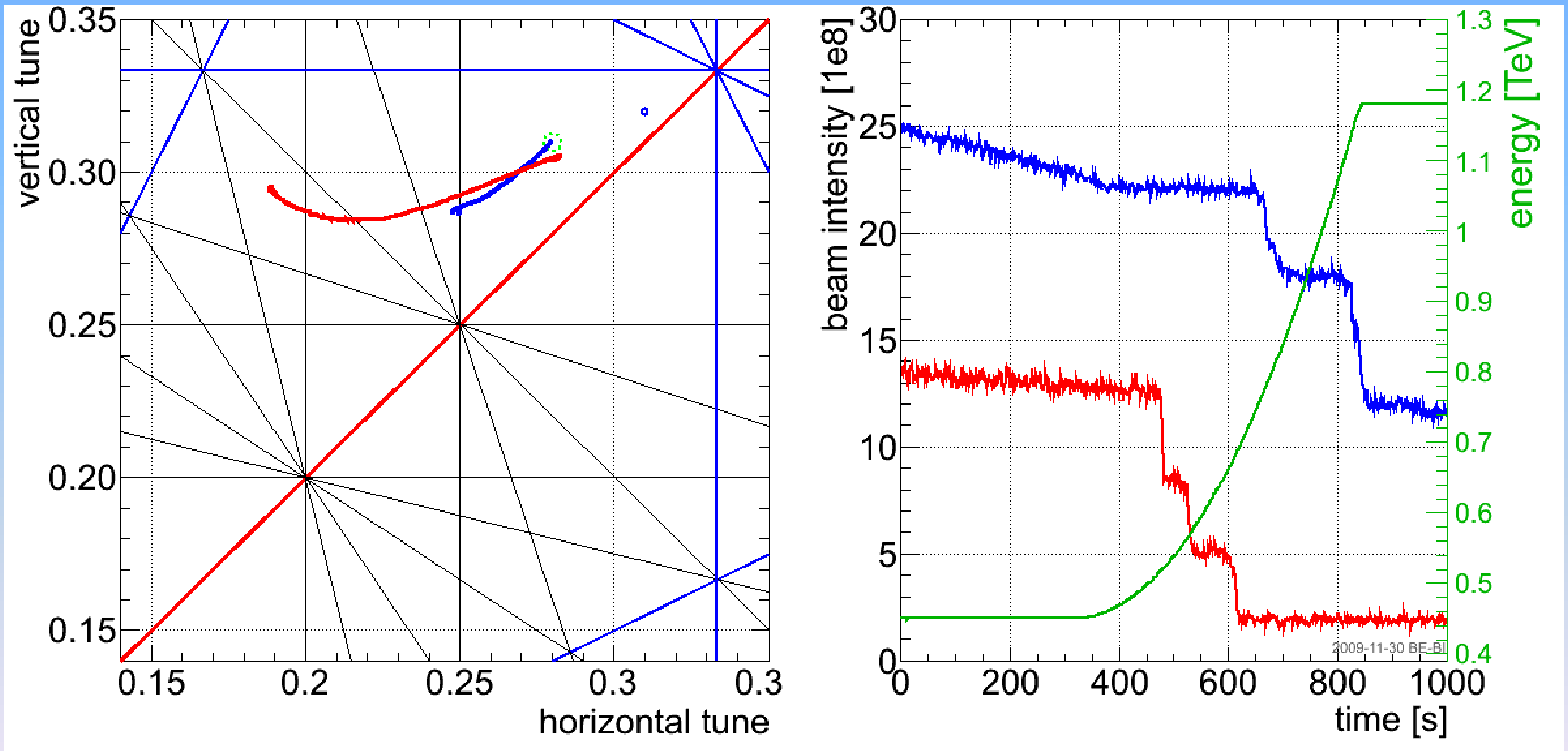




Transverse damper - Crucial device to keep emittance growth under control!

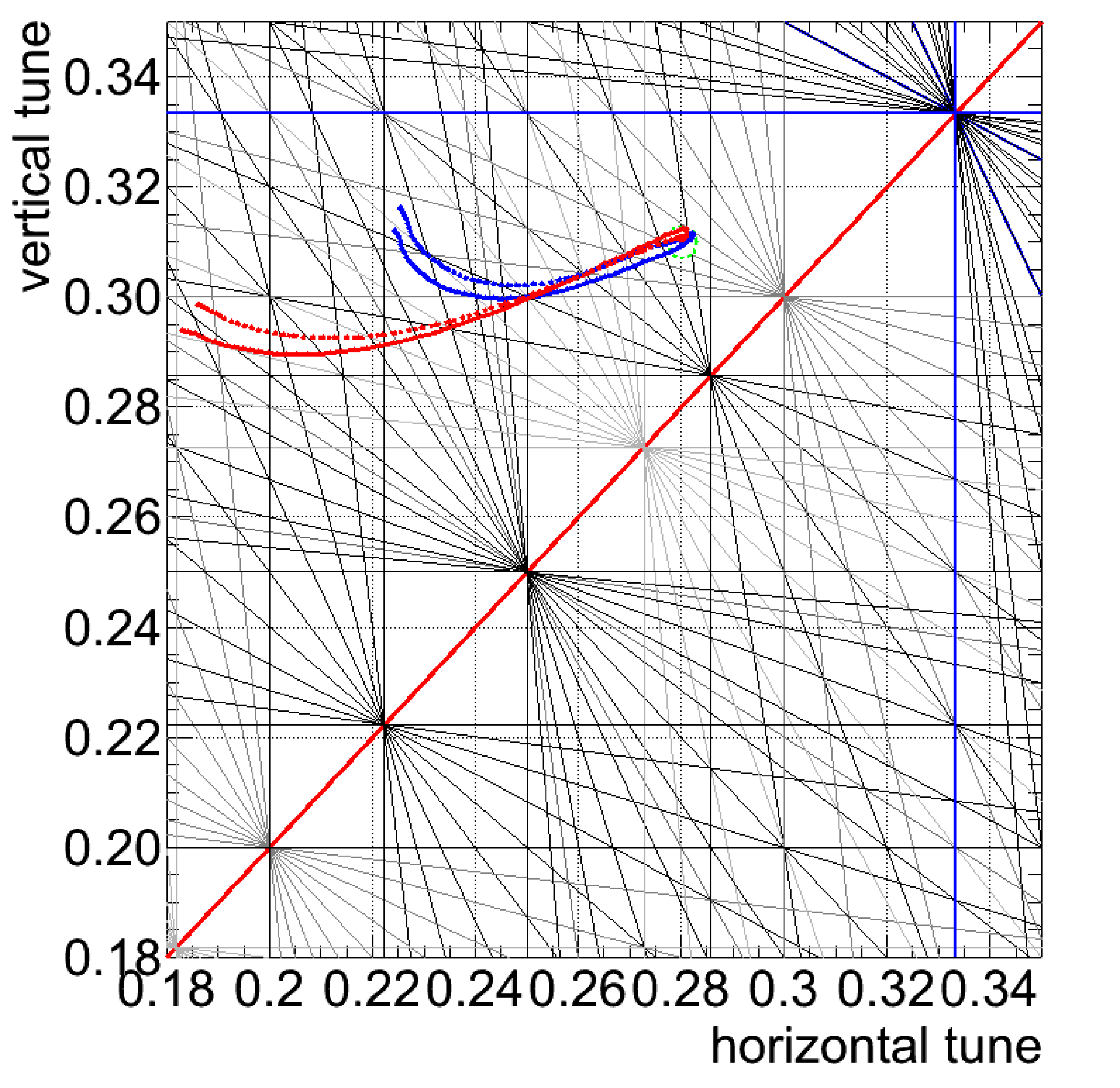
Ramp - Tunes

Tune excursions during the ramp → Losses on resonances

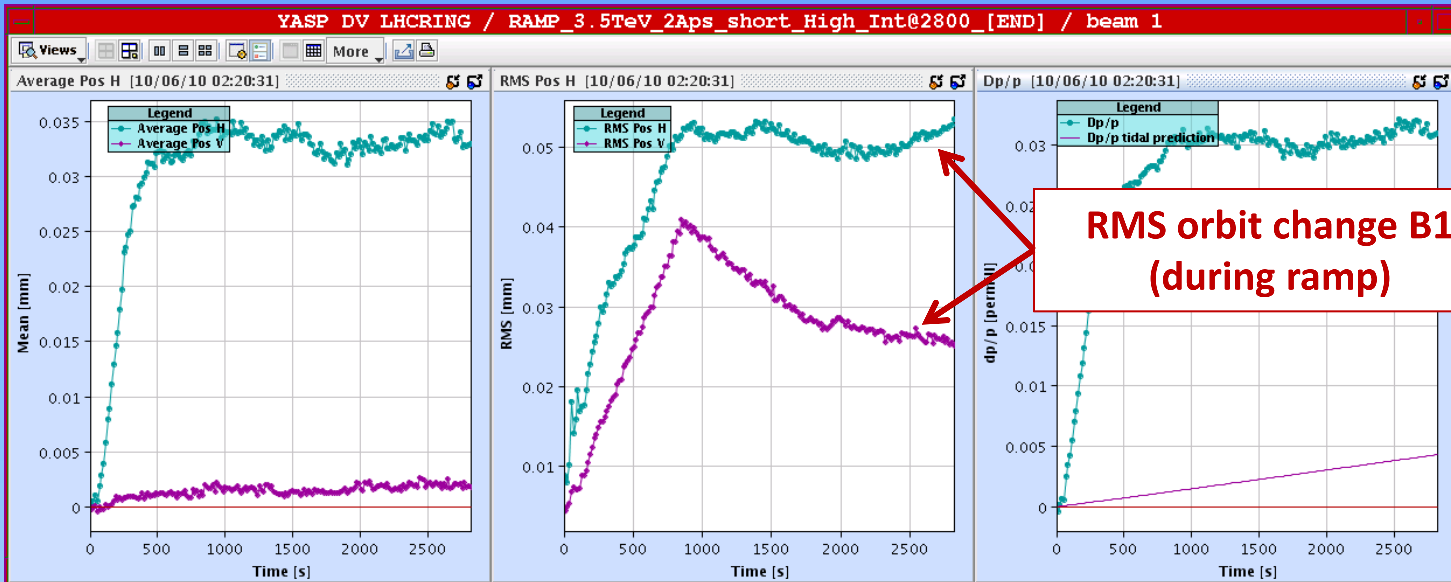


Ramp – Tune feedback

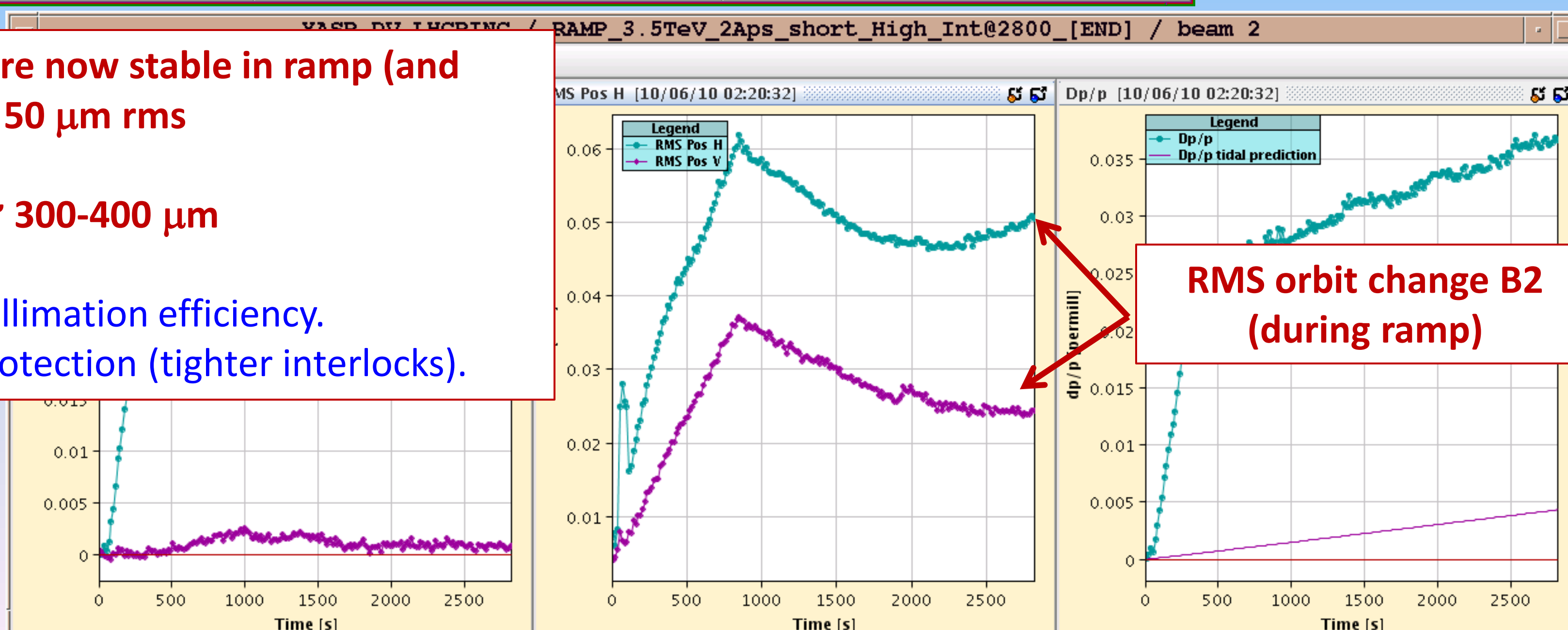
Feedback employed early. Reconstructed tune excursions



Ramp - Orbit feedback



RMS orbit change B1 (during ramp)



The orbits are now stable in ramp (and squeeze) to 50 μm rms

Previously ~ 300-400 μm

>> Better collimation efficiency.
>> Better protection (tighter interlocks).

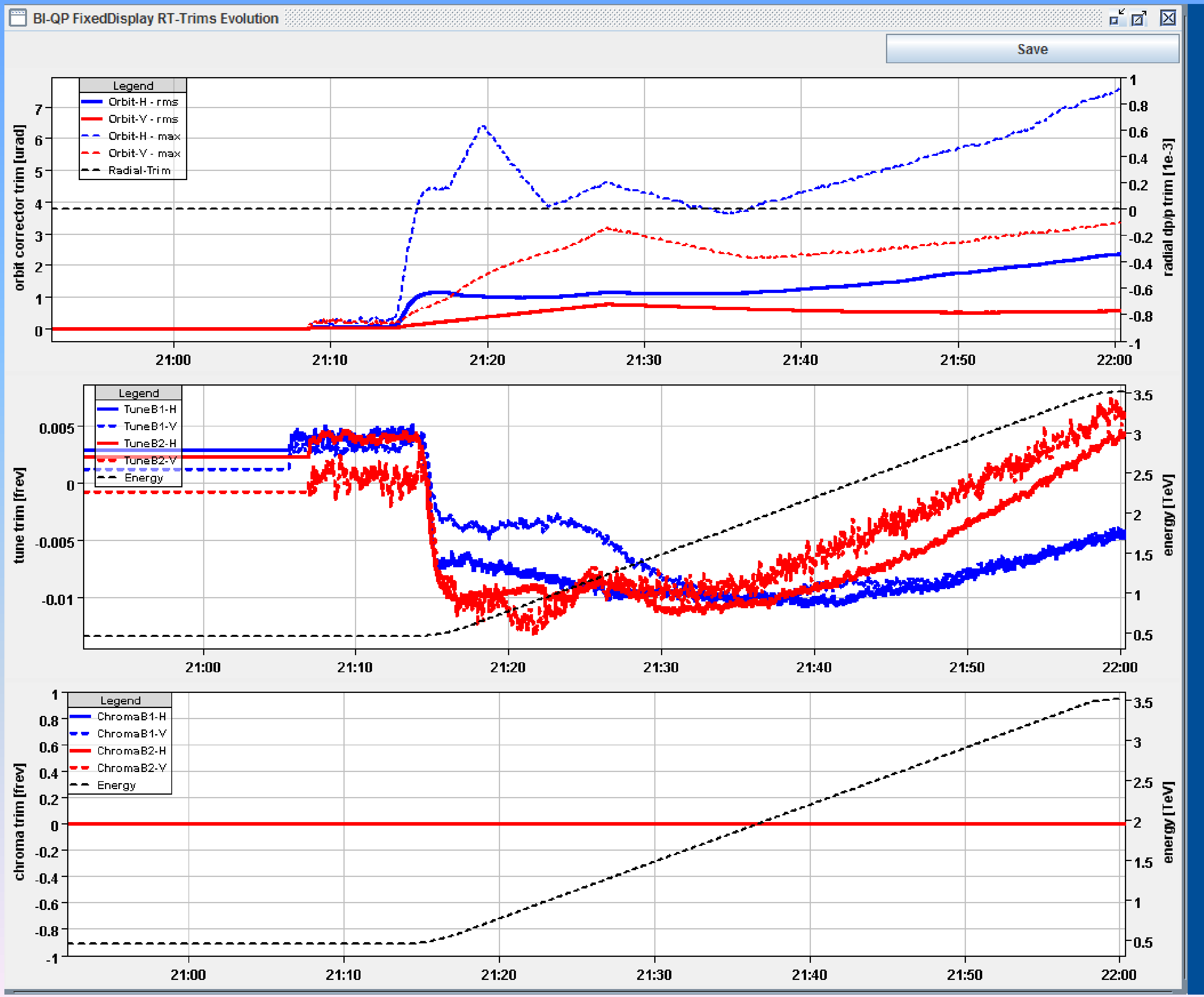
RMS orbit change B2 (during ramp)

Feedbacks essential for ramp of high currents

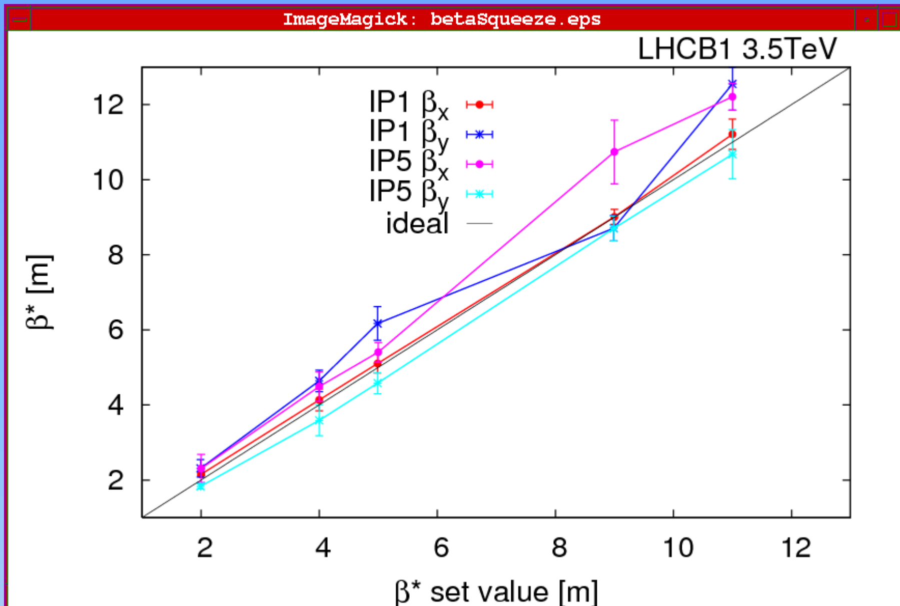
Orbit

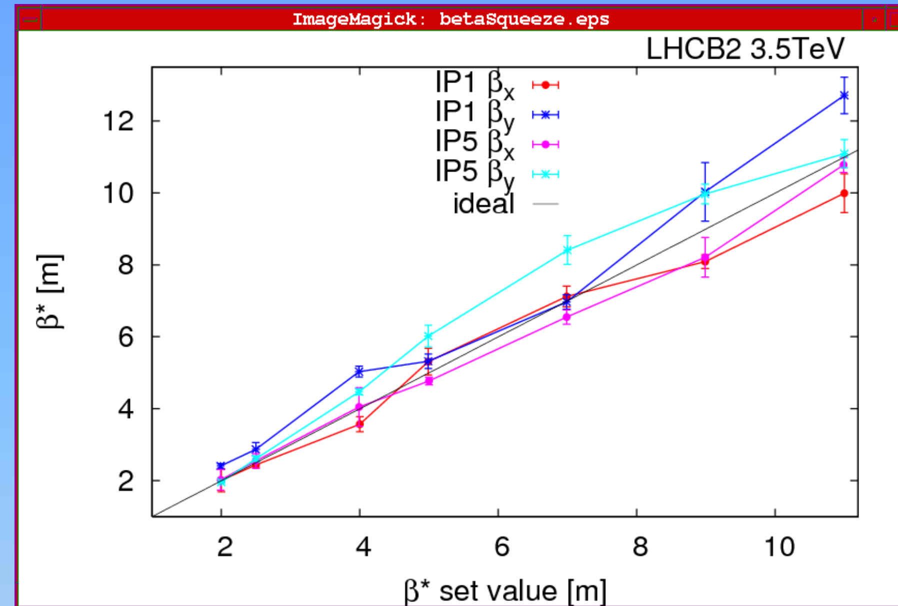
Tune

Q' (soon)



Squeeze in points 1 and 5



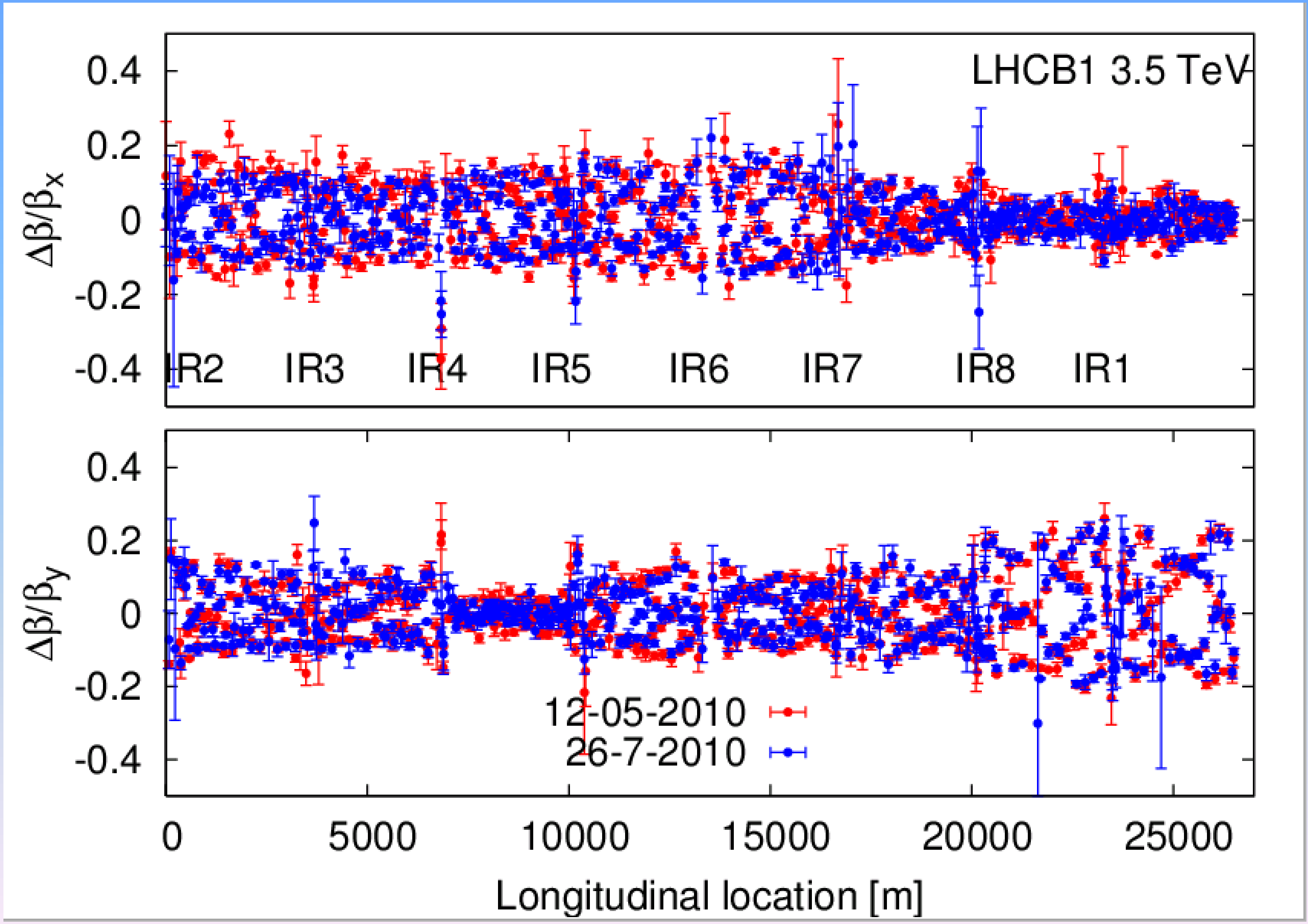


Measured β^*s at 3.5m

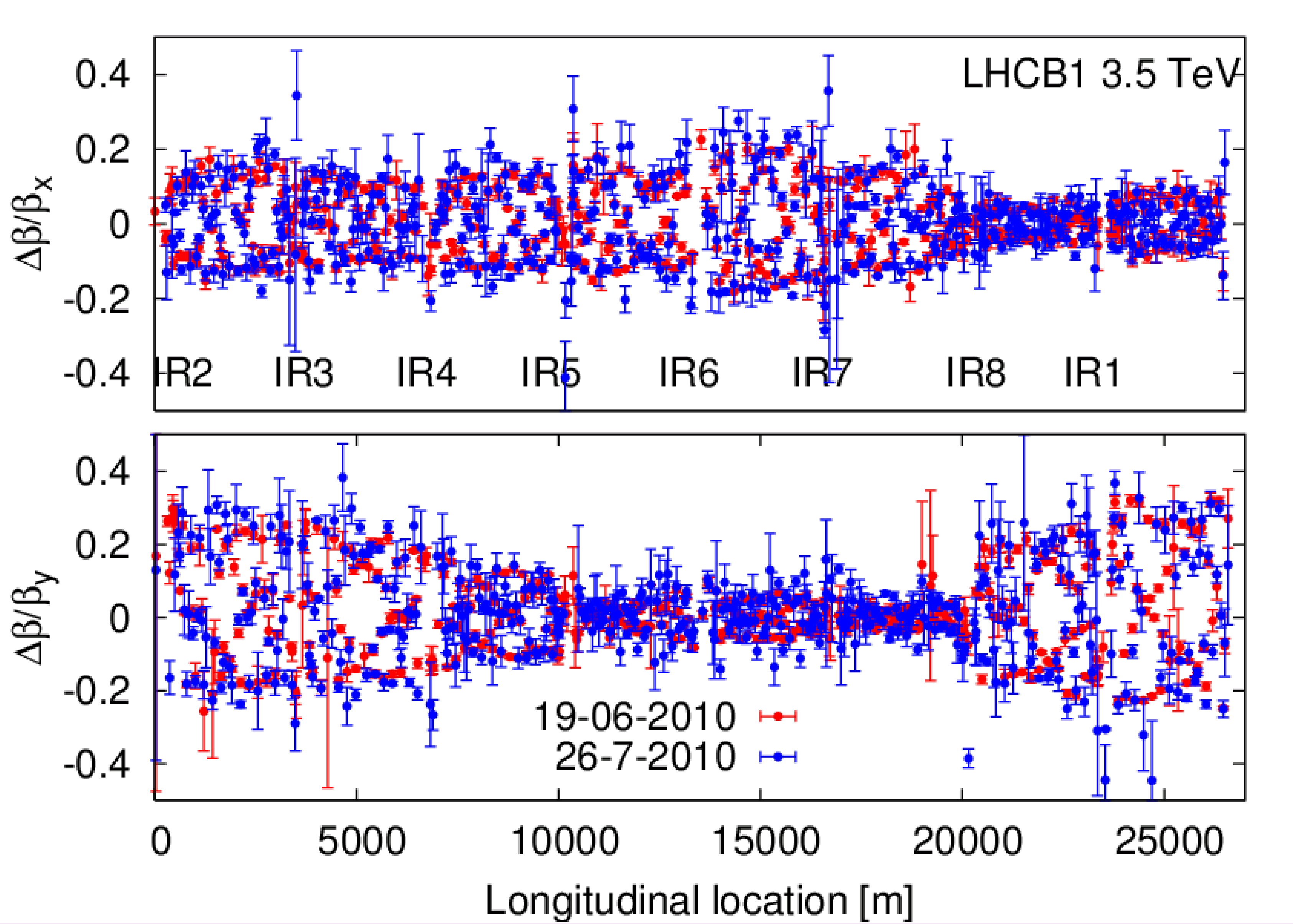
	Beam 1		Beam 2	
IP	β^*_x	β^*_y	β^*_x	β^*_y
IP1	3.27±0.01	3.8±0.3	3.5±0.2	3.8±0.4
IP2	3.45±0.09	2.6±0.2	3.3±0.3	4.2±0.1
IP5	3.70±2	3.4±0.3	3.7±0.4	3.9±0.4
IP8	3.42±0.14	3.9±0.7	3.6±0.2	3.1±0.5

Important mismatch in IP2 β_y

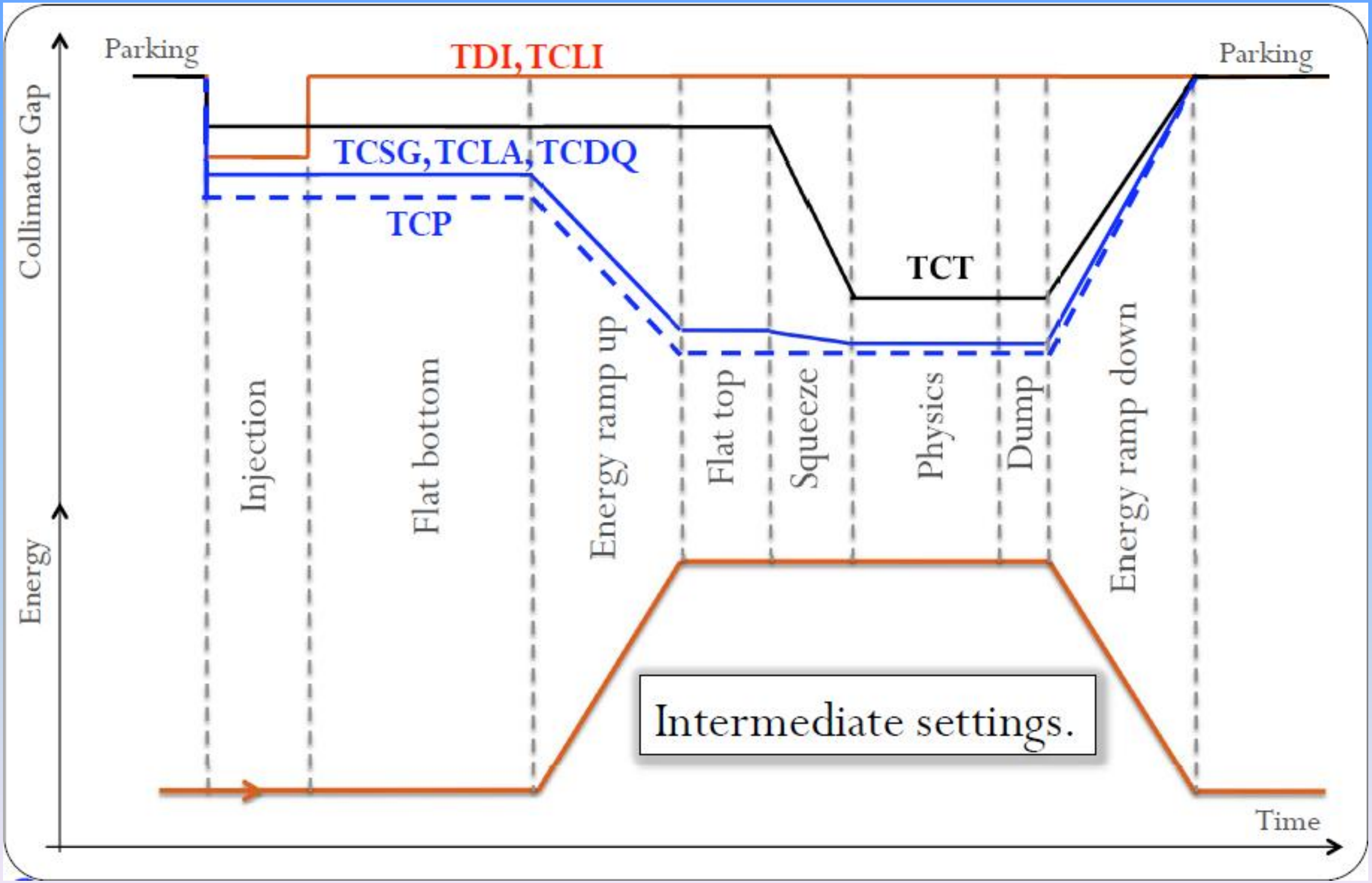
Beta-beat B1 on flat top (10/11 m) - reproducible



Beta-beat B1 at 3.5 m - reproducible



Collimation system

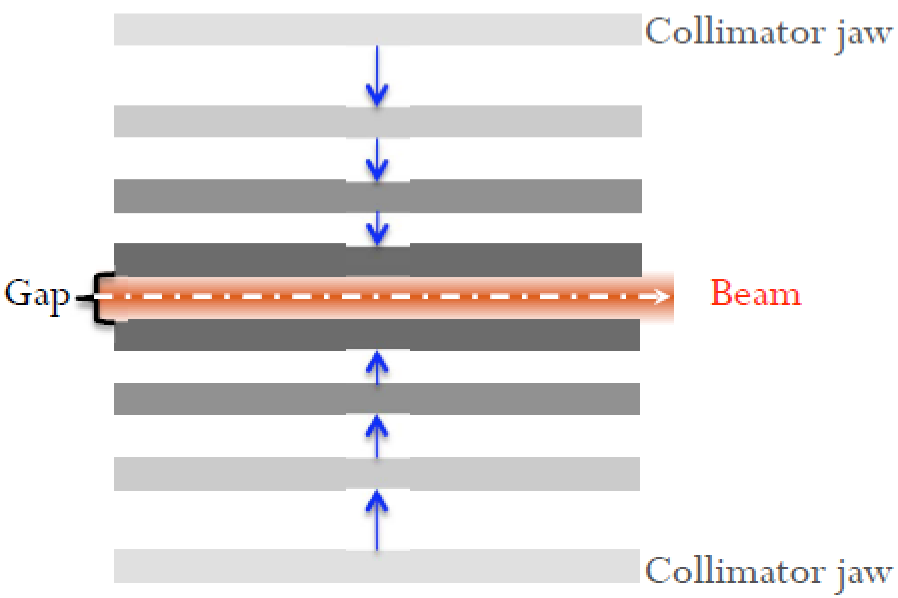


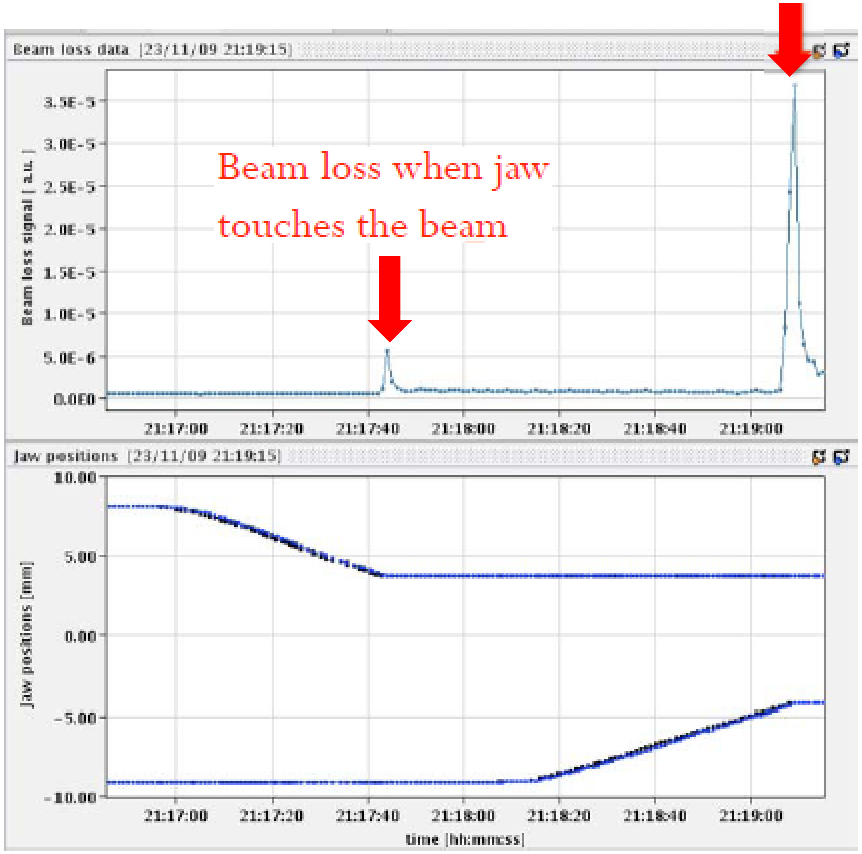
Collimation system commissioning

Collimation system is for beam cleaning and passive protection

Each collimator has to be positioned using beam based alignment

Beam based alignment:



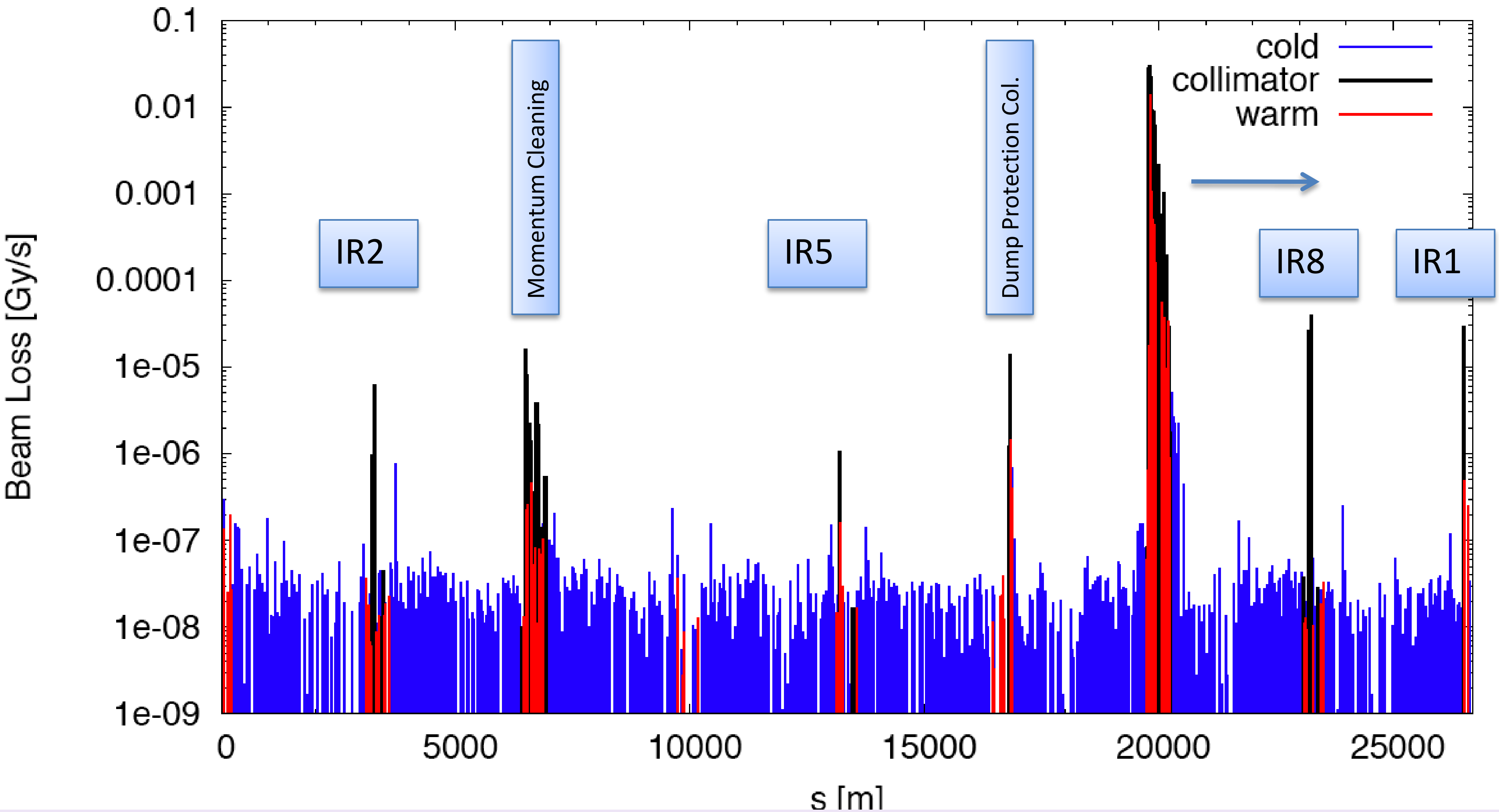


Gap => Beam centre

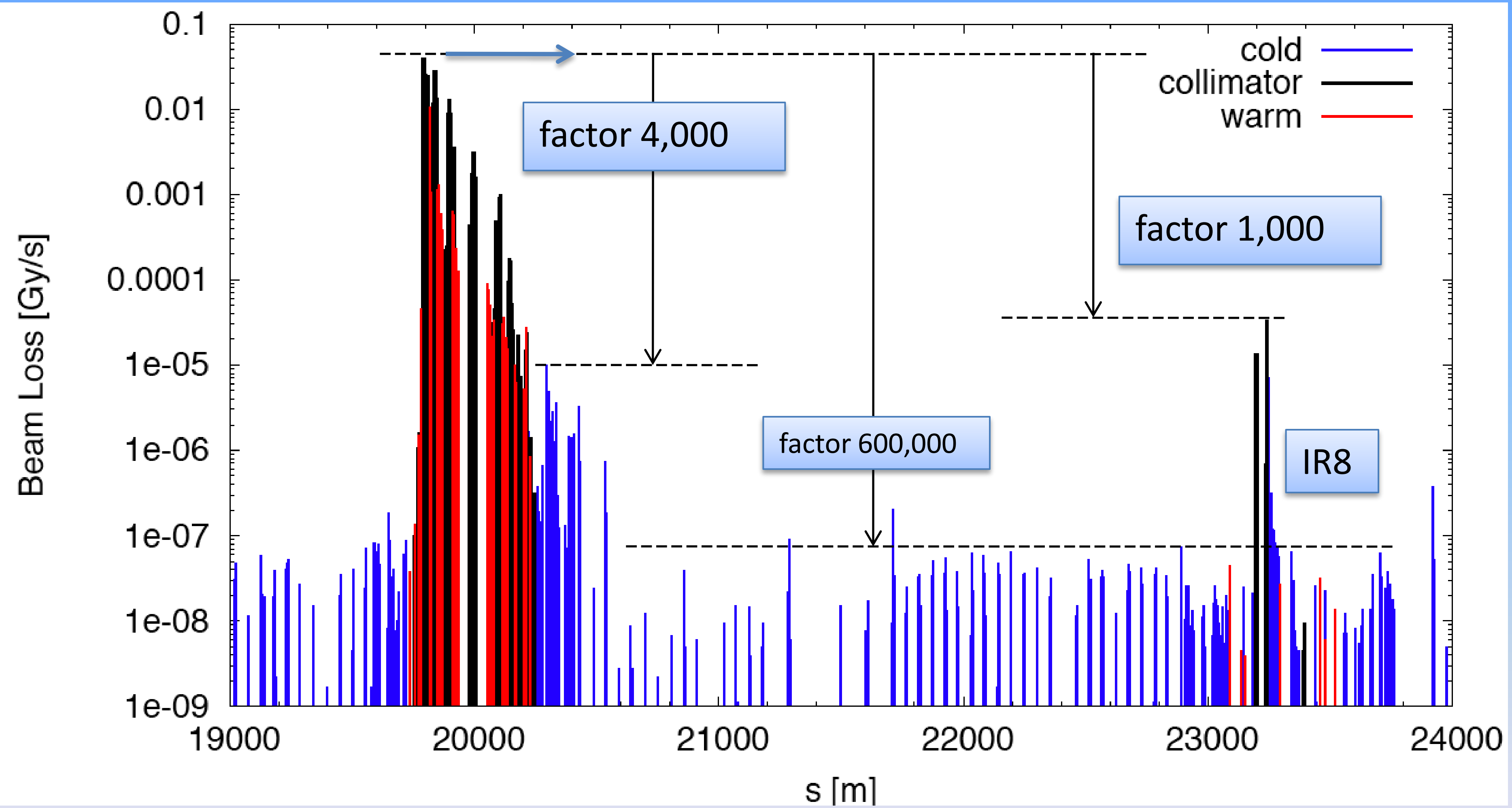
Beam size => Nominal settings

Collimation system efficiency

Provoked vertical beam loss on beam 1, 2m optics

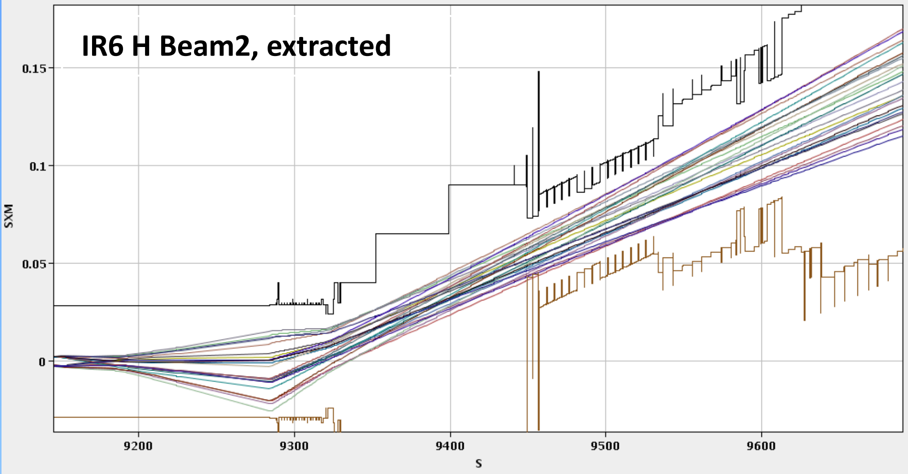


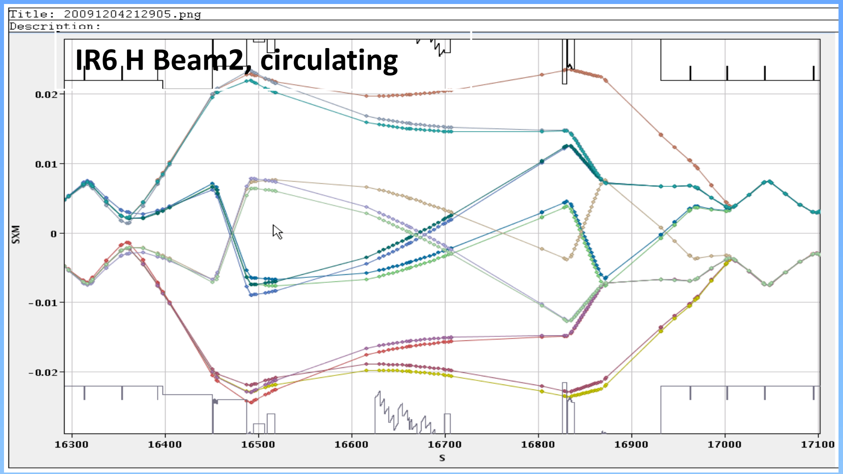
Zoom around betatron cleaning



➔ OK for stable beams from collimation

Beam dump


IR6 H Beam2, extracted
SXM
0.15
0.1
0.05
0
9200
9300
9400
9500
9600
S


Title: 20091204212905.png
Description:
IR6 H Beam2, circulating
SXM
0.02
0.01
0
-0.01
-0.02
16300
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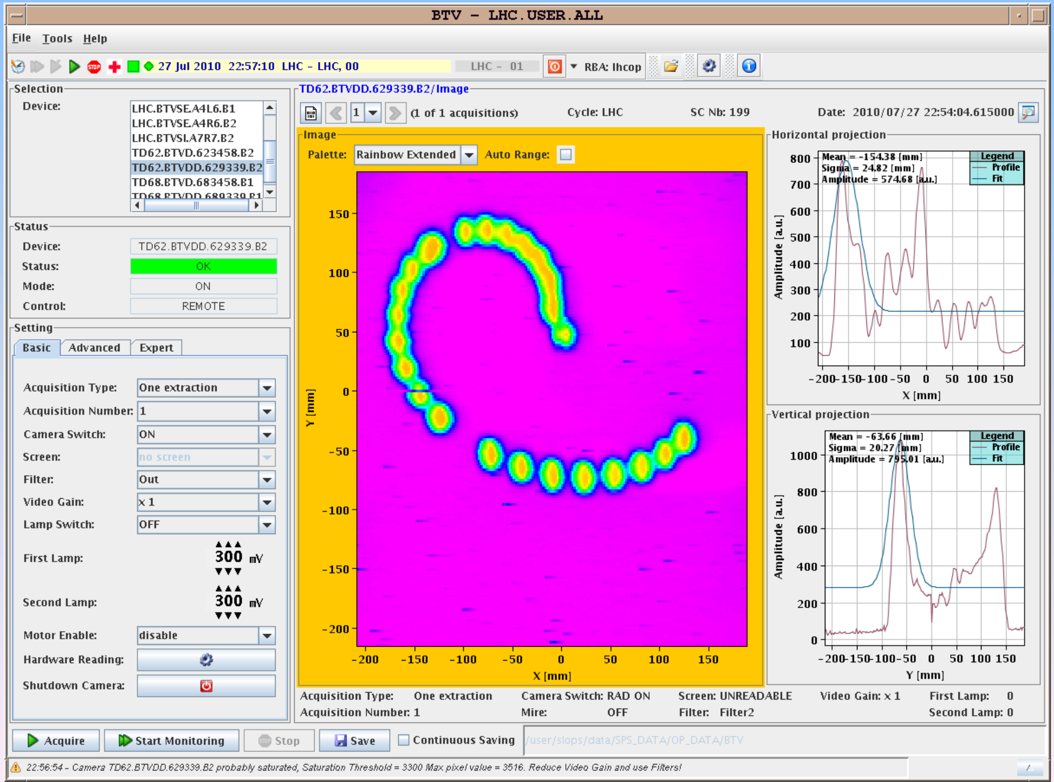
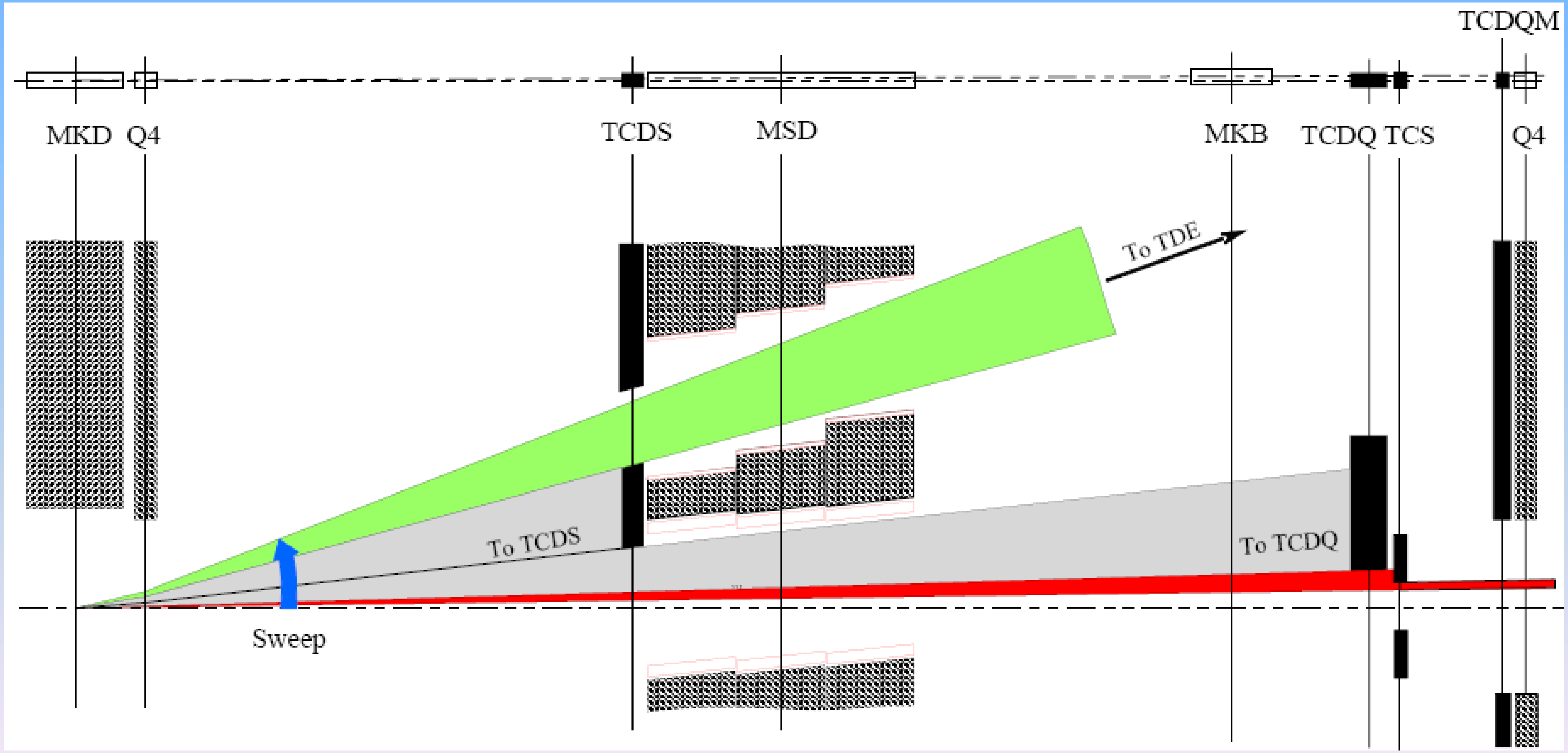
16600
16700
16800
16900
17000
17100
S


BTV – LHC.USER.ALL
File Tools Help
27 Jul 2010 22:57:10 LHC - LHC, 00
LHC - 01
RBA: lhcop
Selection
Device:
LHC.BTVSE.A4L6.B1
LHC.BTVSE.A4R6.B2
LHC.BTVSI.A7R7.B2
TD62.BTVD.623458.B2
TD62.BTVDD.629339.B2
TD68.BTVD.683458.B1
Status
Device: TD62.BTVDD.629339.B2
Status: OK
Mode: ON
Control: REMOTE
Setting
Basic Advanced Expert
Acquisition Type: One extraction
Acquisition Number: 1
Camera Switch: ON
Screen: no screen
Filter: Out
Video Gain: x 1
Lamp Switch: OFF
First Lamp: 300 mV
Second Lamp: 300 mV
Motor Enable: disable
Hardware Reading:
Shutdown Camera:
TD62.BTVDD.629339.B2/Image
(1 of 1 acquisitions)
Cycle: LHC
SC Nb: 199
Date: 2010/07/27 22:54:04.615000
Image
Palette: Rainbow Extended
Auto Range:
Y [mm]
X [mm]
Horizontal projection
Mean = -154.38 [mm]
Sigma = 24.82 [mm]
Amplitude = 574.68 [a.u.]
Legend
Profile
Fit
Amplitude [a.u.]
X [mm]
Vertical projection
Mean = -63.66 [mm]
Sigma = 20.27 [mm]
Amplitude = 795.01 [a.u.]
Legend
Profile
Fit
Amplitude [a.u.]
Y [mm]
Acquisition Type: One extraction
Acquisition Number: 1
Camera Switch: RAD ON
Mire: OFF
Screen: UNREADABLE
Filter: Filter2
Video Gain: x 1
First Lamp: 0
Second Lamp: 0
Acquire
Start Monitoring
Stop
Save
Continuous Saving
/user/slops/data/SPS_DATA/OP_DATA/BTV
22:56:54 - Camera TD62.BTVDD.629339.B2 probably saturated, Saturation Threshold = 3300 Max pixel value = 3516. Reduce Video Gain and use Filters!

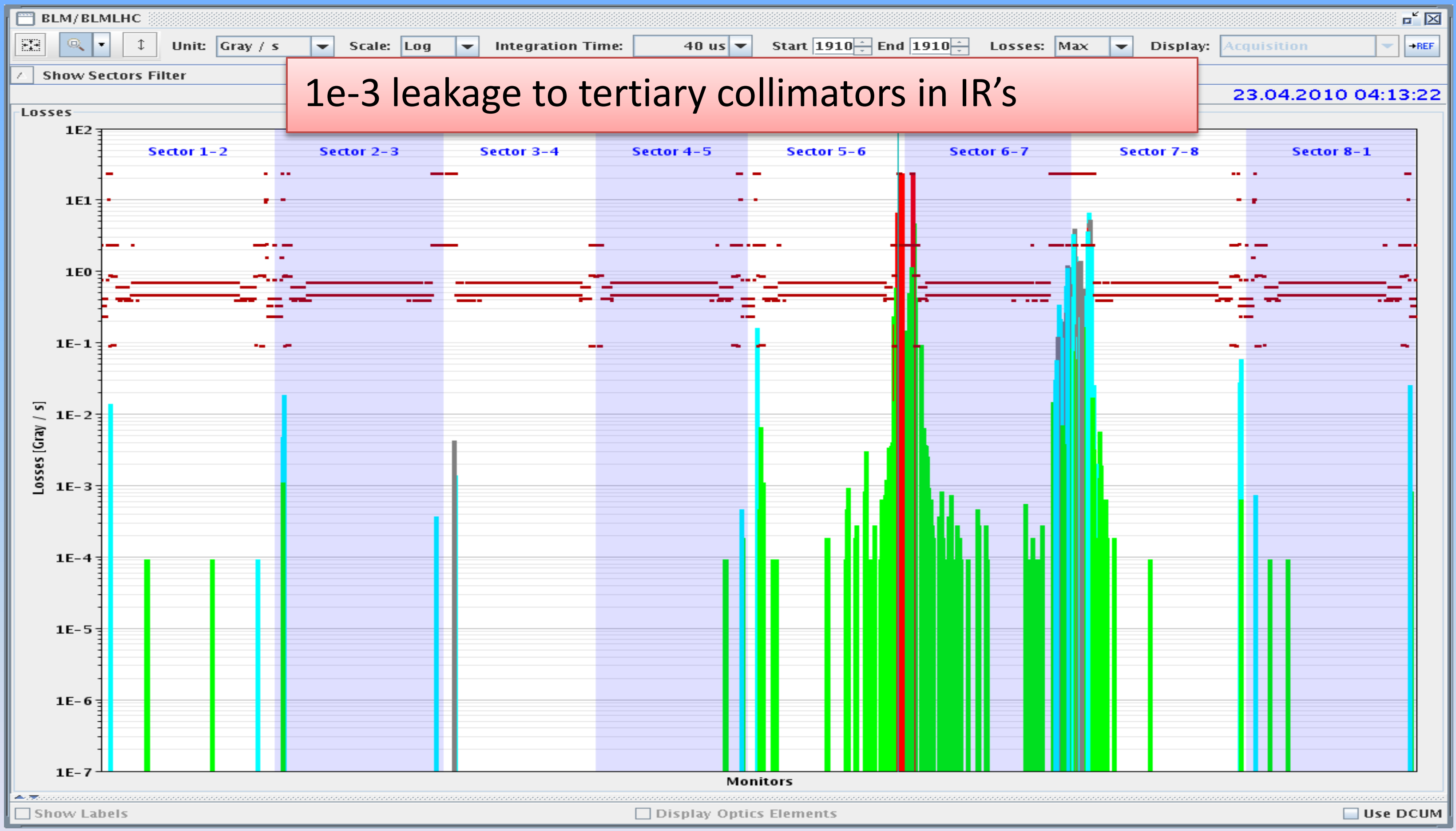
Beam dump protection systems

Protection devices to catch beam in abort gap



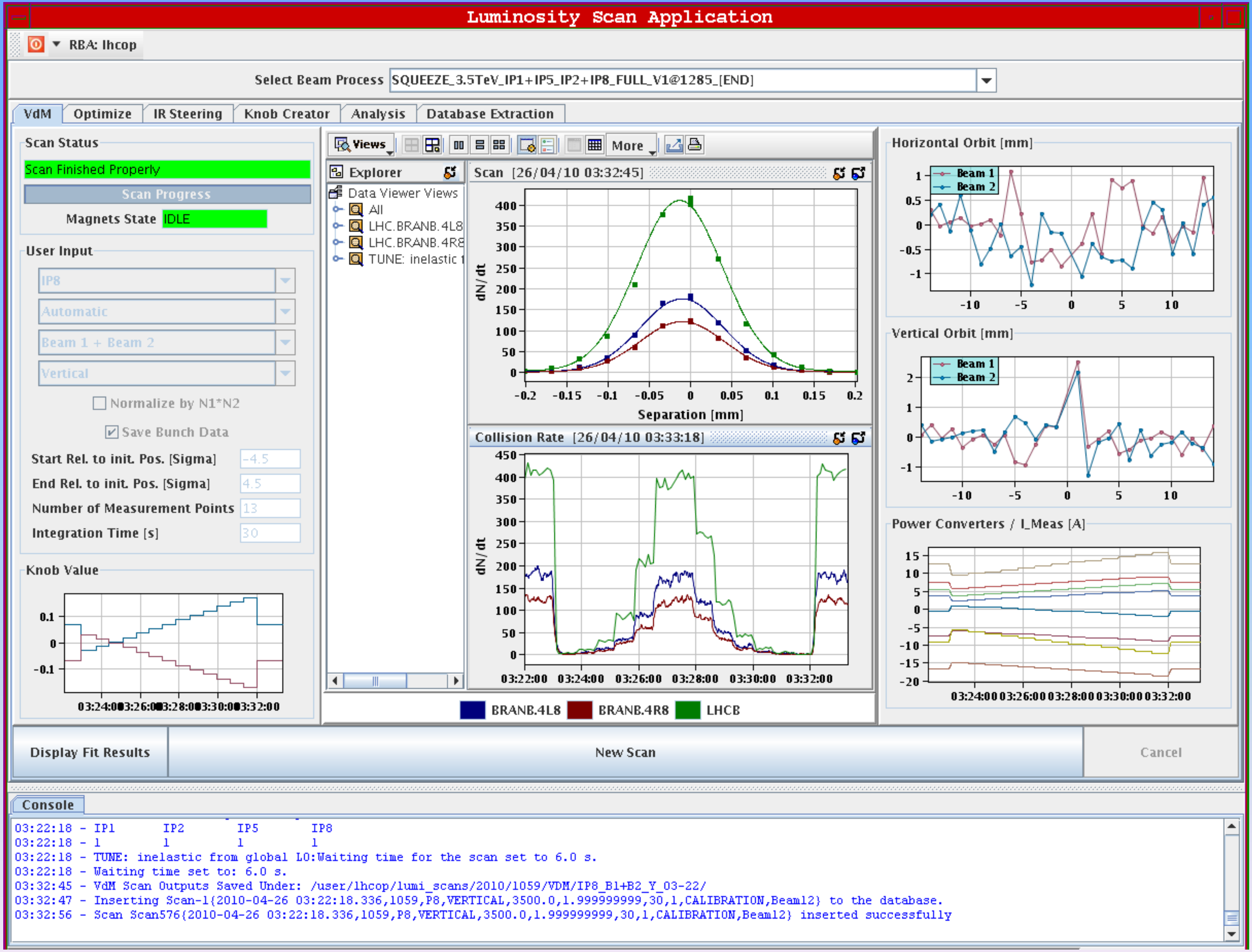
Beam dump protection systems efficiency

Provoked asynchronous beam dump



➔ OK for stable beams from beam dump

Collisions

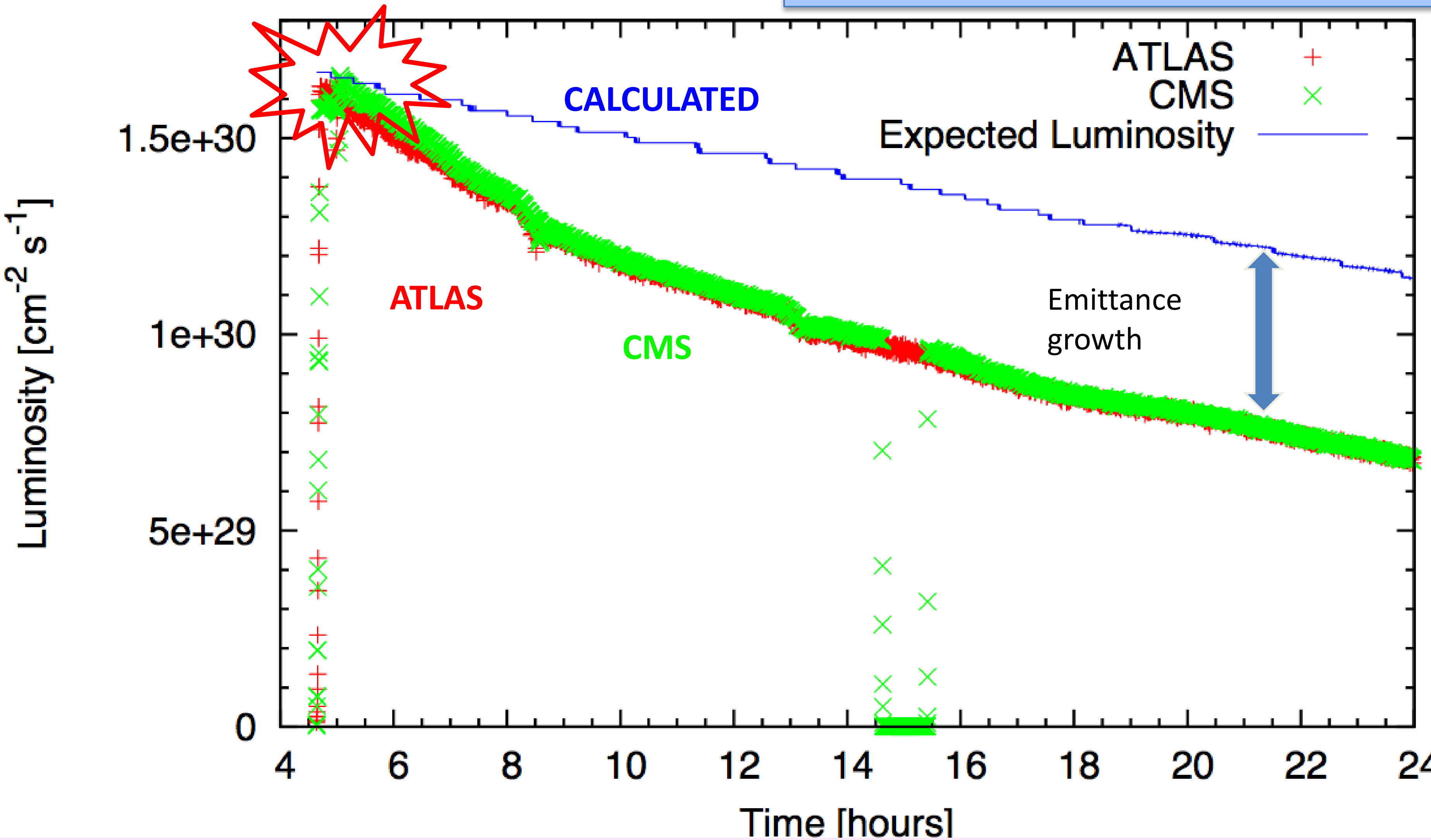


Luminosity Scan Application
RBA: lhcop
Select Beam Process SQUEEZE_3.5TeV_IP1+IP5_IP2+IP8_FULL_V1@1285_[END]
VdM
Optimize
IR Steering
Knob Creator
Analysis
Database Extraction
Scan Status
Scan Finished Properly
Scan Progress
Magnets State IDLE
User Input
IP8
Automatic
Beam 1 + Beam 2
Vertical
Normalize by N1*N2
Save Bunch Data
Start Rel. to init. Pos. [Sigma] -4.5
End Rel. to init. Pos. [Sigma] 4.5
Number of Measurement Points 13
Integration Time [s] 30
Knob Value
Explorer
Data Viewer Views
All
LHC.BRANB.4L8
LHC.BRANB.4R8
TUNE: inelastic
Scan [26/04/10 03:32:45]
dN/dt
Separation [mm]
Collision Rate [26/04/10 03:33:18]
BRANB.4L8
BRANB.4R8
LHCB
Horizontal Orbit [mm]
Beam 1
Beam 2
Vertical Orbit [mm]
Power Converters / I_Meas [A]
Display Fit Results
New Scan
Cancel
Console
03:22:18 - IP1 IP2 IP5 IP8
03:22:18 - 1 1 1 1
03:22:18 - TUNE: inelastic from global L0:Waiting time for the scan set to 6.0 s.
03:22:18 - Waiting time set to: 6.0 s.
03:32:45 - VdM Scan Outputs Saved Under: /user/lhcop/lumi_scans/2010/1059/VDM/IP8_B1+B2_Y_03-22/
03:32:47 - Inserting Scan-1{2010-04-26 03:22:18.336,1059,P8,VERTICAL,3500.0,1.999999999,30,1,CALIBRATION,Beam12} to the database.
03:32:56 - Scan Scan576{2010-04-26 03:22:18.336,1059,P8,VERTICAL,3500.0,1.999999999,30,1,CALIBRATION,Beam12} inserted successfully

Collisions – emittance blow up

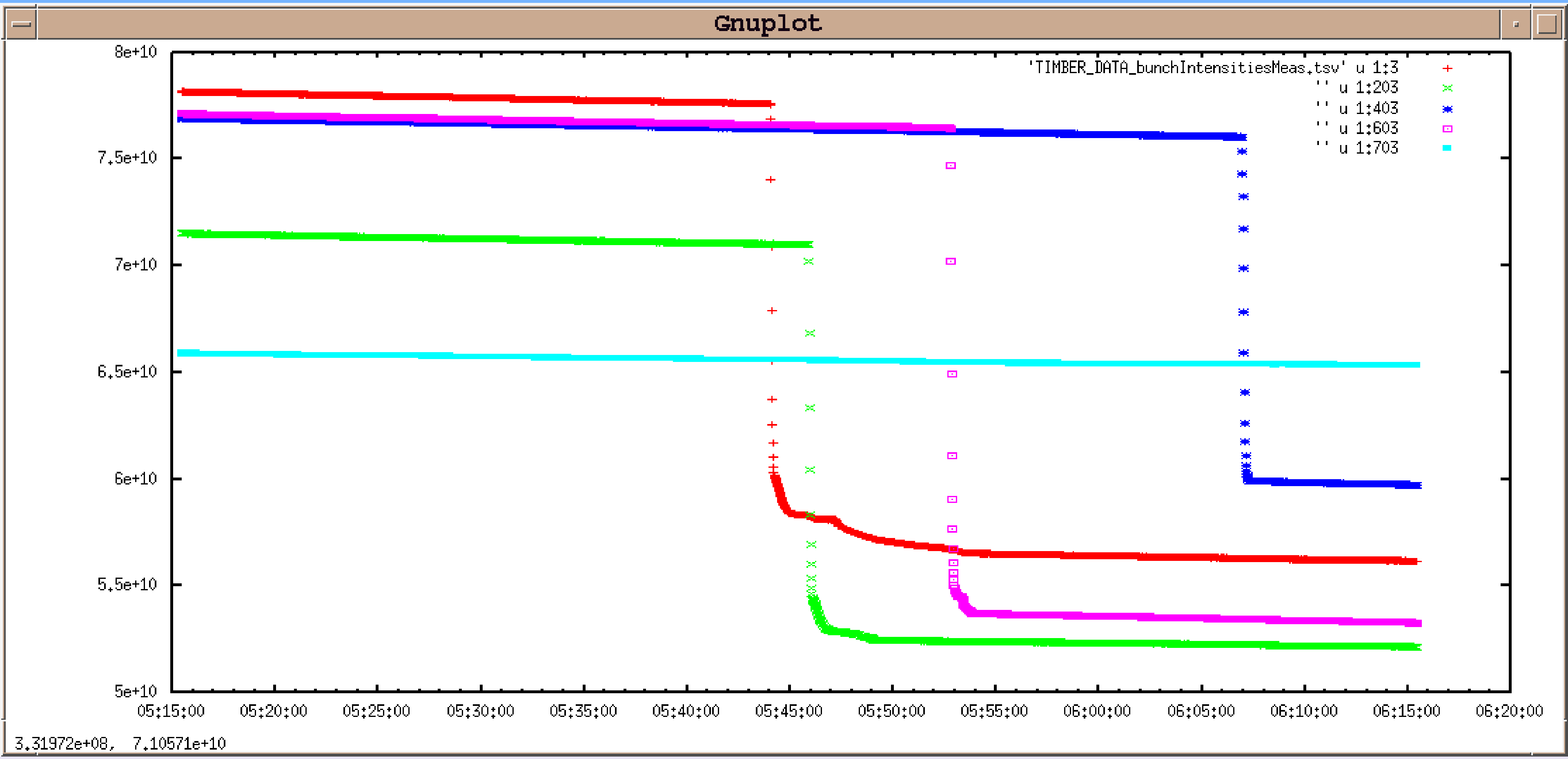
Machine parameters very well controlled!

calculated with measured bunch intensity, nominal $\gamma\varepsilon$ = 3.75 μm and β^*=3.5m

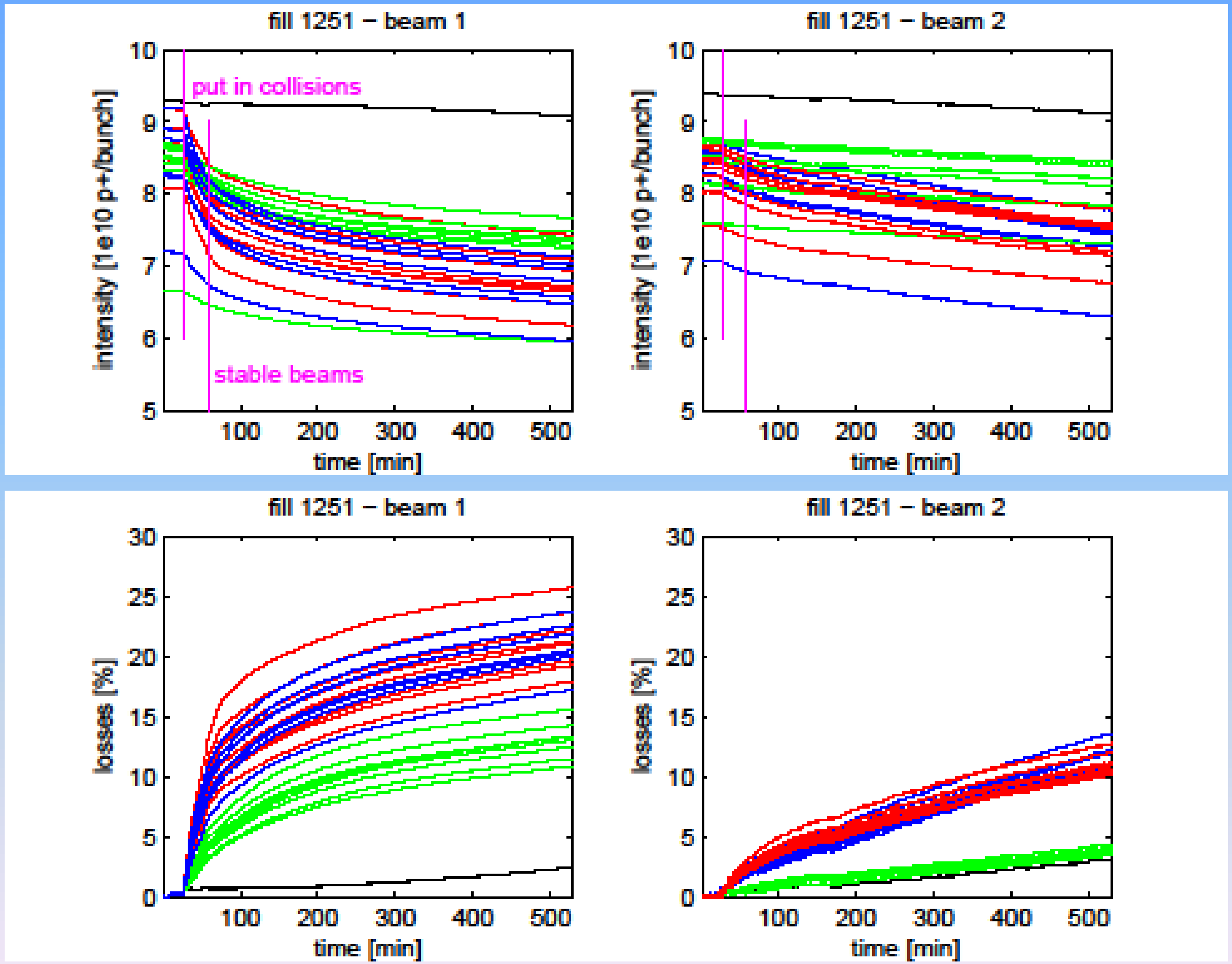


Collisions – beam-beam effects

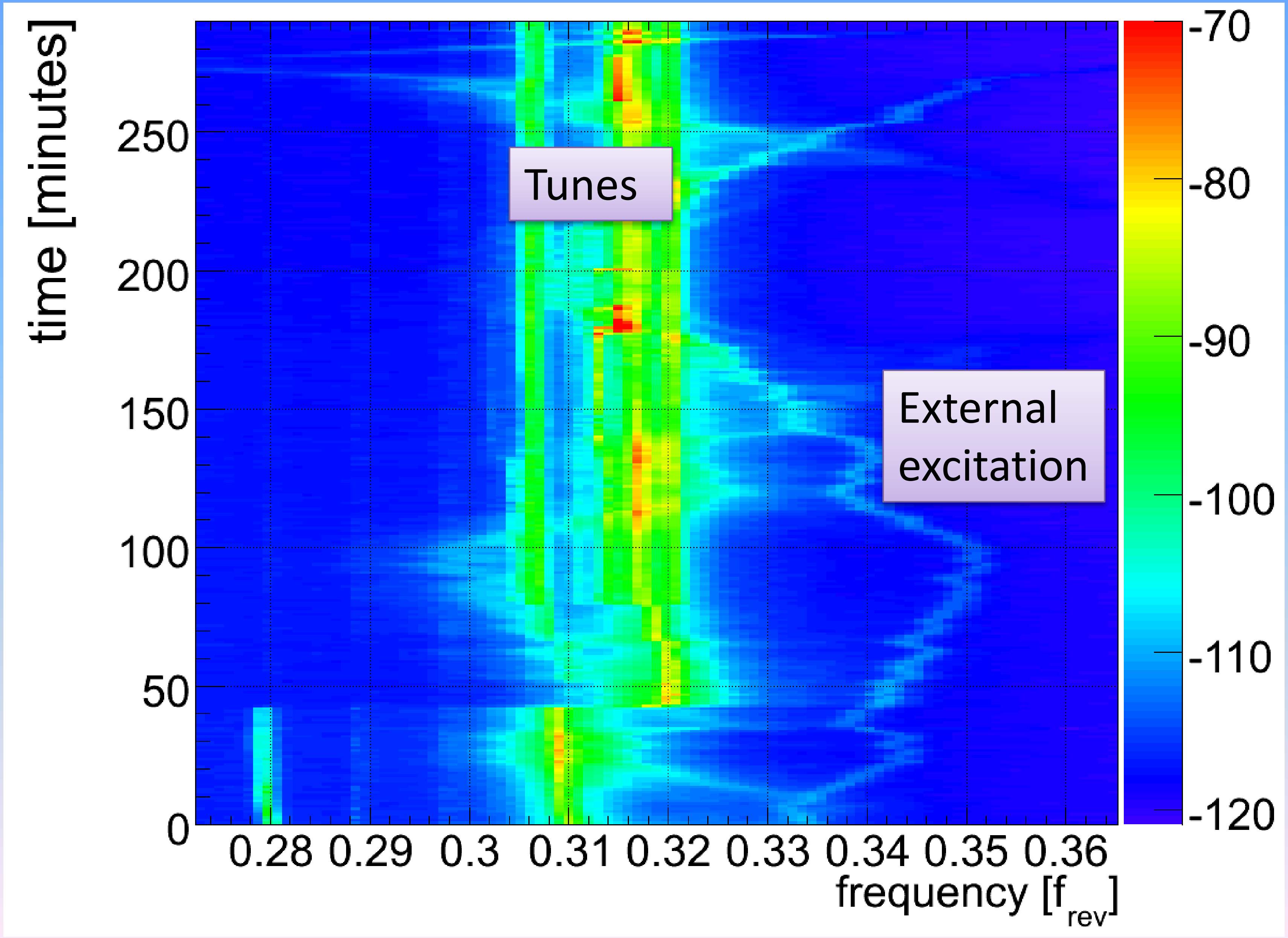
Losses only in first 4 bunches, from bucket 1 onwards



Collisions – behaviour of different beams / bunches



Unwanted excitation - source still unknown



Status of the LHC

Early beam operation

Strategy and progress so far

Examples of what we do

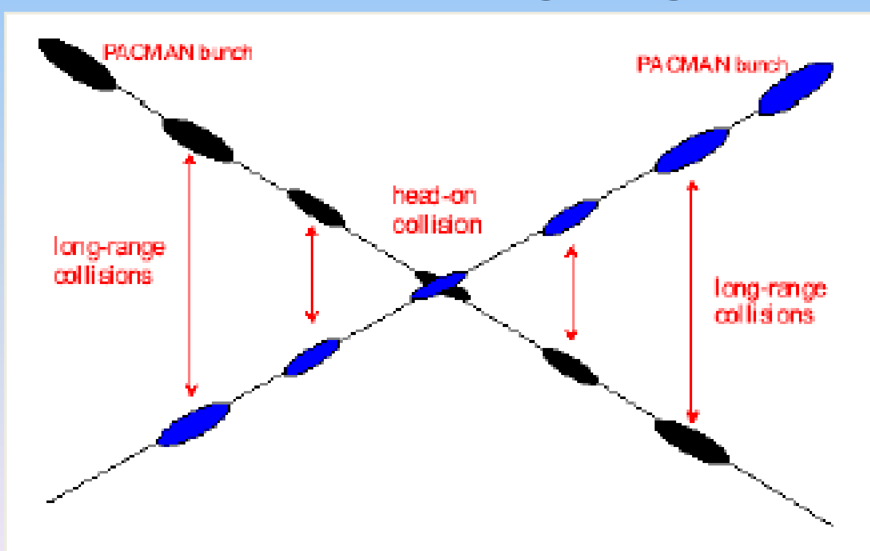
Prospects

Reminder of road map

- Progress to date based on widely spaced (2.5 μs) bunches (not efficiently used)

We are here

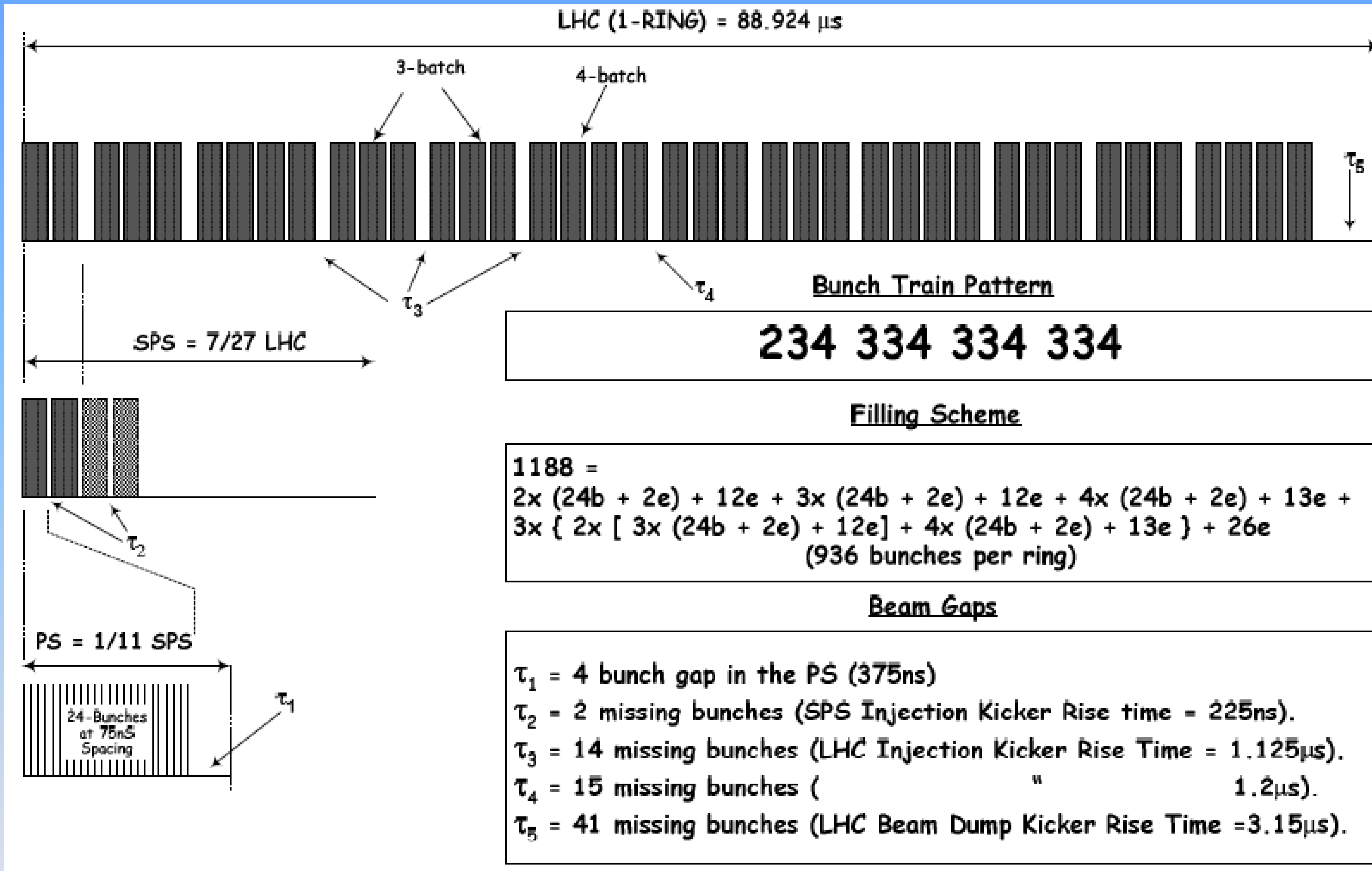
- Need bunch trains to go to (much) higher k_b
- Need crossing angle



Energy	TeV	3.50	3.50	3.50	3.50
Bunch intensity	1.E+10	10.0	10.0	10.0	10.0
Bunches per beam		4	16 (25)	432	792
Emittance	μm	3.75	3.75	3.75	3.75
β*	m	3.50	3.50	3.50	3.50
Luminosity 1 and 5	cm-2 s-1	1.0E+30	4.0E+30	1.1E+32	2.0E+32
Total inel X section	cm2	6.0E-26	6.0E-26	6.0E-26	6.0E-26
Event rate	Hz	6.1E+04	2.4E+05	6.5E+06	1.2E+07
Event rate / Xing	Hz	1.4	1.3	1.3	1.3
Protons		4.0E+11	2.4E+12	4.3E+13	7.9E+13
% nominal		0.1	0.7	13.4	24.5
Current	mA	0.7	4.3	77.7	142.5
Stored energy	MJ	0.2	1.3	24.2	44.4
Beam size 1 and 5	um	59.3	59.3	59.3	59.3

Want to be here

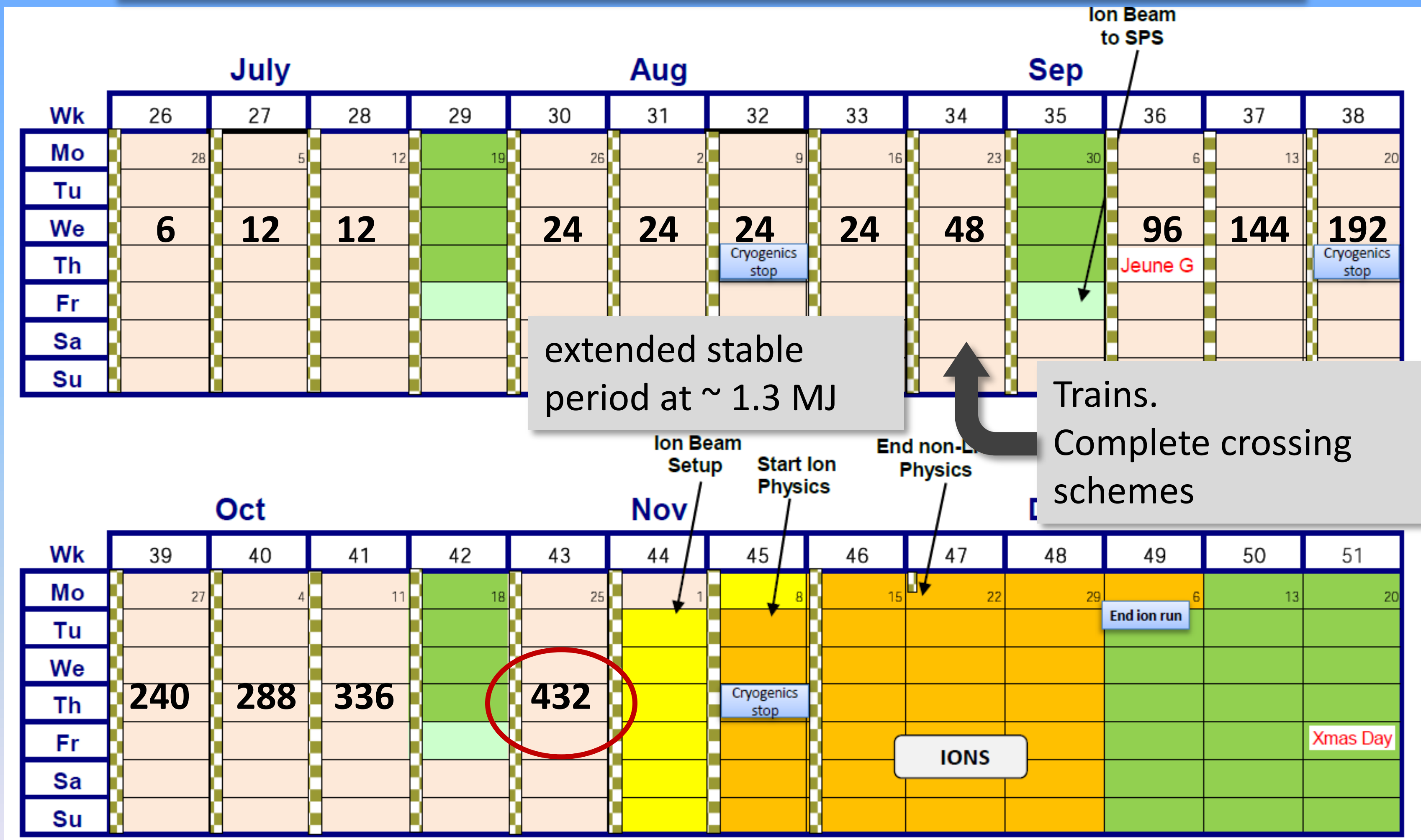
75ns scheme (might use 150ns)



24 bunches per batch injected into the SPS. 1 2 3 or 4 batches

Possible evolution with ~ 10^{10} per bunch

Assume constant β* = 3.5 m , assume we aim for 1e32 end 2010



Summary early August 2010

- Limited in 2010 and 2011 to
    - 3.5 TeV per beam
    - 20% intensity
    - $\beta^* > 2$ m
- Started with safe beams
    - Qualified machine protection systems
- First collisions at 7 TeV March 30
    - Squeeze and incremental increase of intensity thereafter
- 3 orders of magnitude $\mathcal{L}$ improvement in 4 months
    - Highest Luminosity so far ~ 3 $10^{30} cm^{-2} s^{-1}$
- Factor 30 more to go to be ready for 2011 campaign