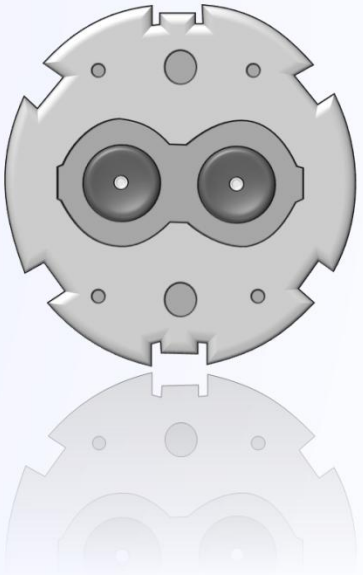
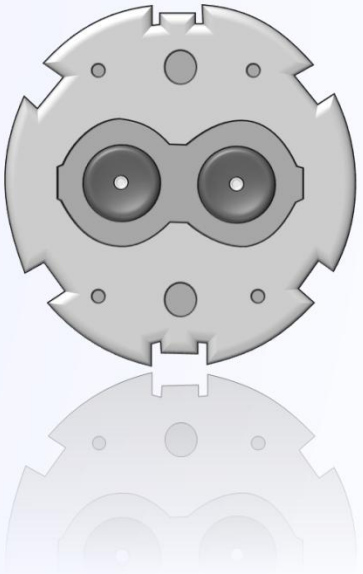


LHC Beam Operations
Past, Present and Future

K. Foraz – CERN

(Acknowledgement : R. Bailey)



LHC Beam Operation

Operation envelope

Progress with beam in 2009

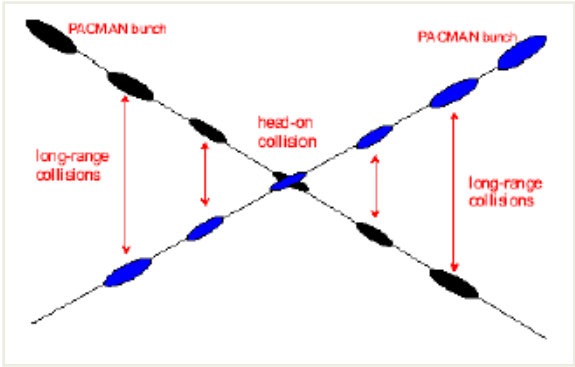
2010-2011

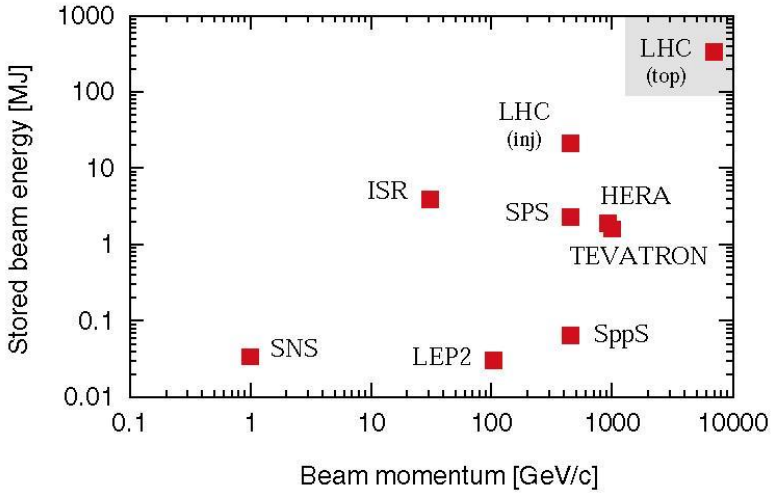
LHC nominal performance

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**





Instantaneous luminosity

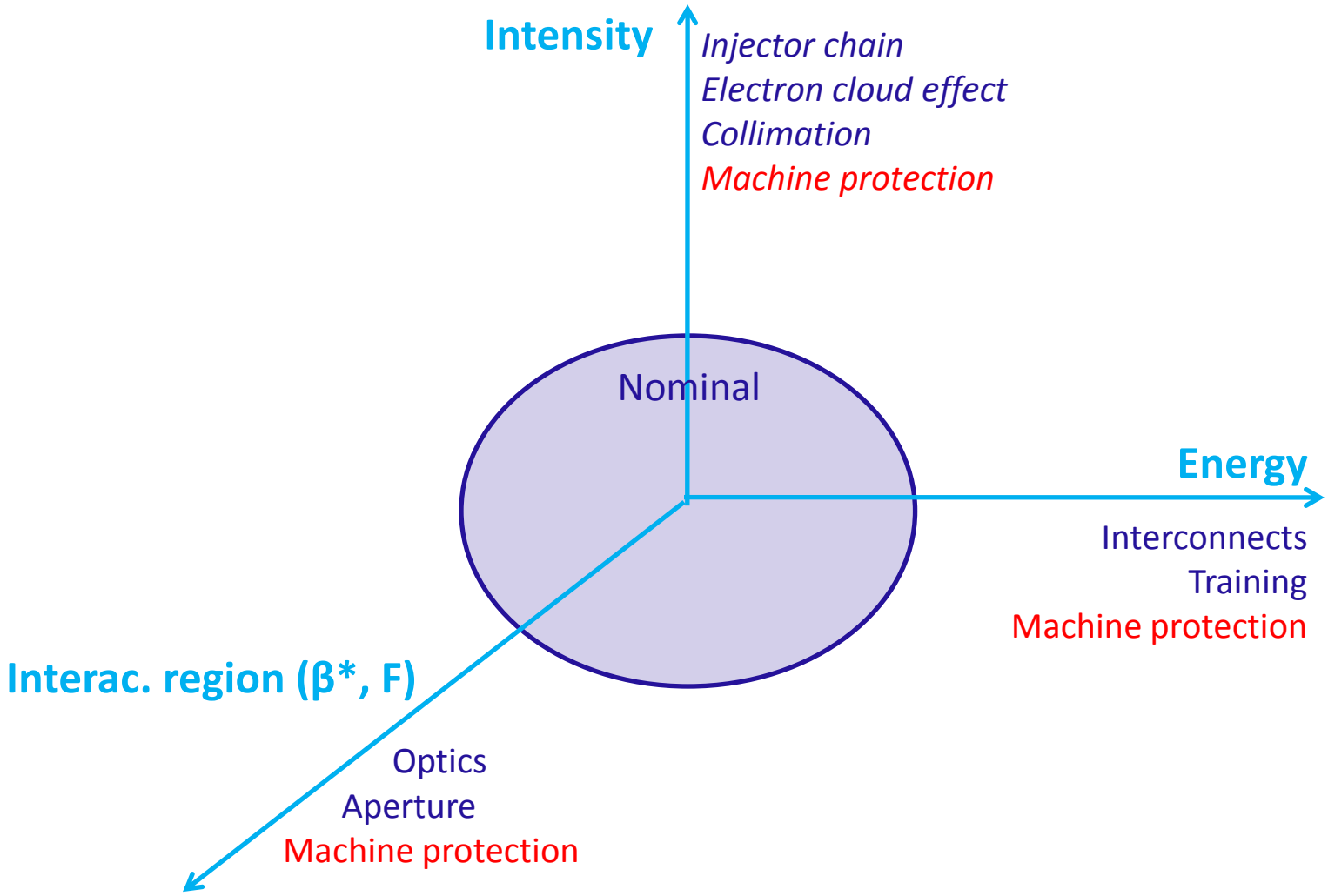
$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

"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

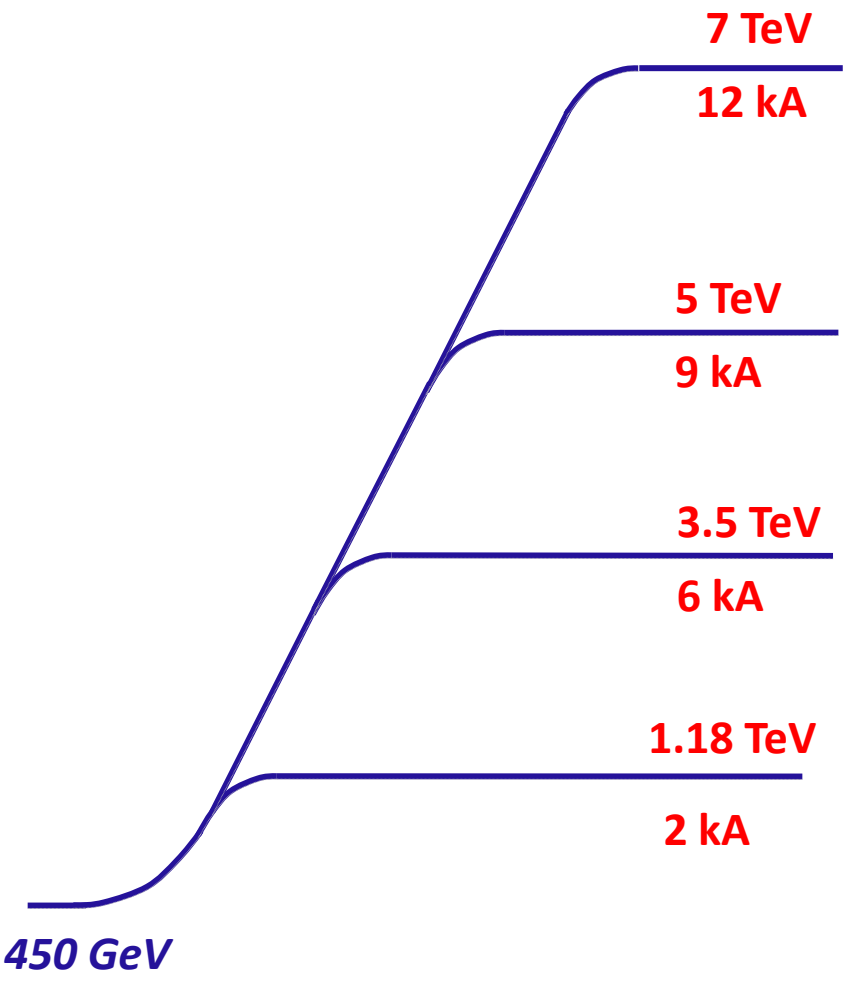
- Nearly all the parameters are variable (and not independent)
  - Number of particles per bunch N — Intensity
  - Number of bunches per beam k_b — Intensity
  - Relativistic factor (E/m_0) γ — Energy
  - Normalized emittance ε_n
  - Beta function at the IP β^* — Interaction Region
  - Crossing angle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

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

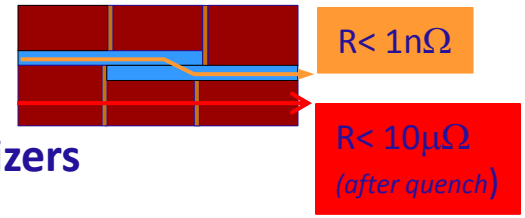
LHC performance drivers



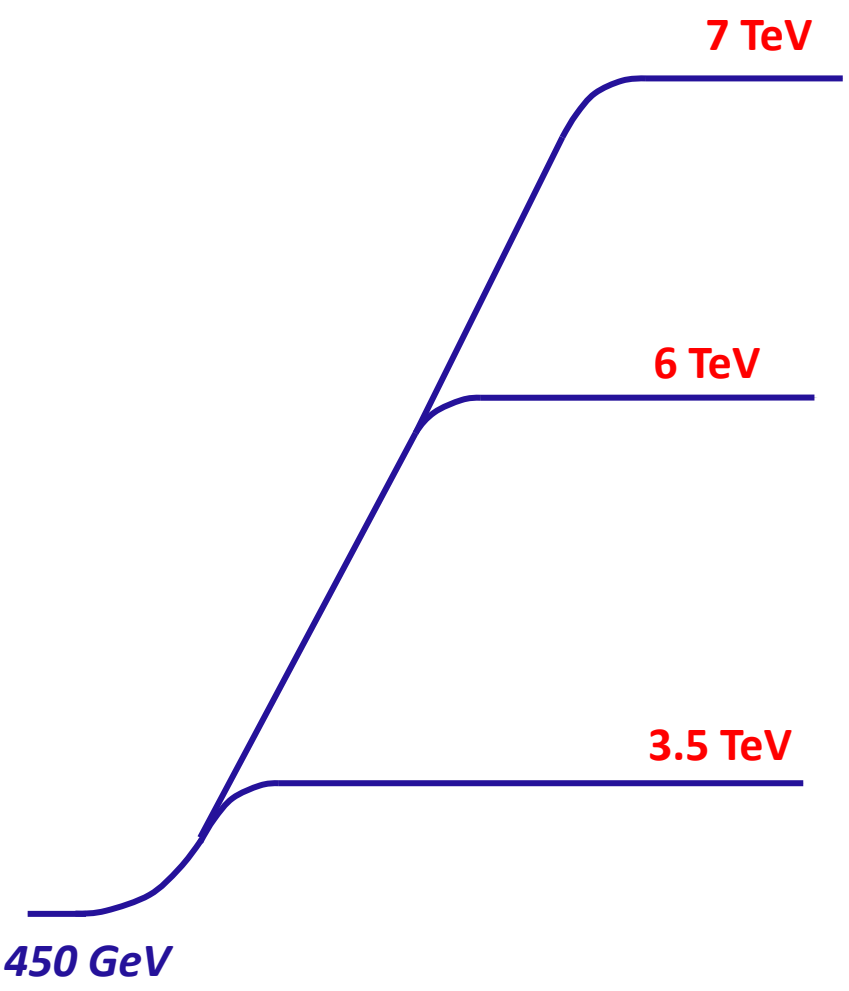
Energy : Evolution of target



When	Why
2002-2007	**Design** ….. Magnets commissioning
Summer 2008	**Detraining** …. During hardware Commissioning
Winter 2008	**Splices** …. Sept. 08 incident
Summer 2009	**Stabilizers**
Autumn 2009	**QPS connectors** Breakdown at operational voltage Connector quality



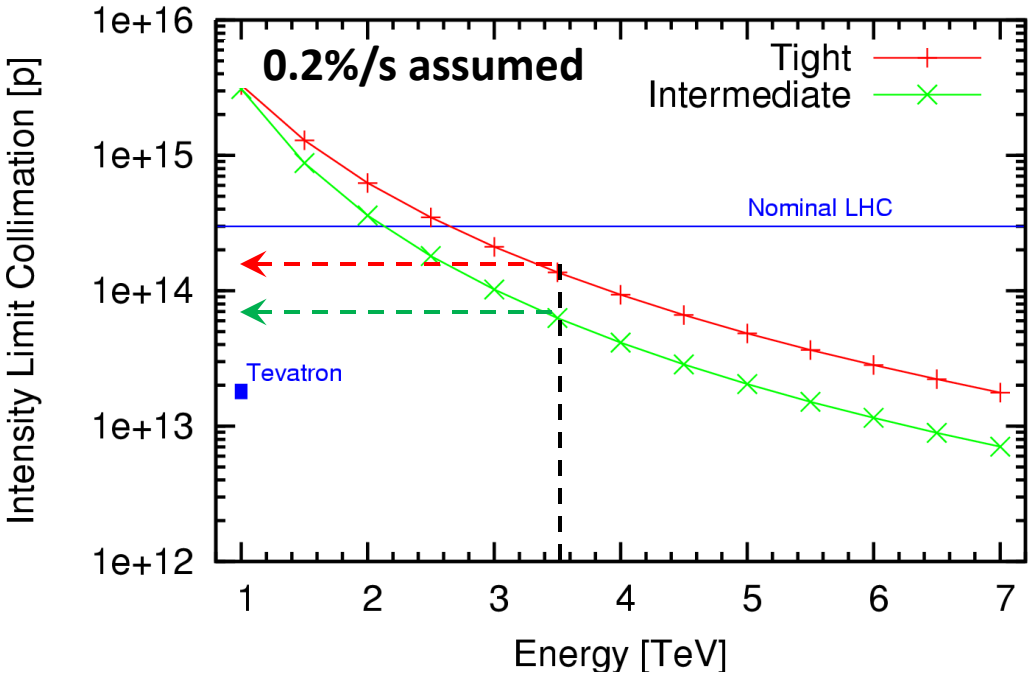
Energy: the way back



When	What
2014 ?	**Train magnets** Should be easy to get to 6TeV…. 7 TeV will take time
2013	
2012	**Long shut-down:** **Interconnections** & completion of pressure relief system
2010 – 2011	**Run @ 3.5TeV**
January 2010	**Connectors fixed** Commission nQPS system **Commission circuits to 6kA**

Intensity: limits 2010 2011

- **Collimation system** conceived as a staged system
  - First stage to allow 40% of nominal intensity at 7 TeV
- **Imperfections** bring this down
- **Machine stability and reproducibility** also play a role
- Cleaning gets easier at lower energies



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

30MJ stored beam energy

Higher intensities

- With experience assume that we can
  - Move to tight settings
  - Achieve 0.1% loss rates

- Then need to install something more
  - ➢ Proposal exists for next phase of collimation

β* and F: 2010 2011

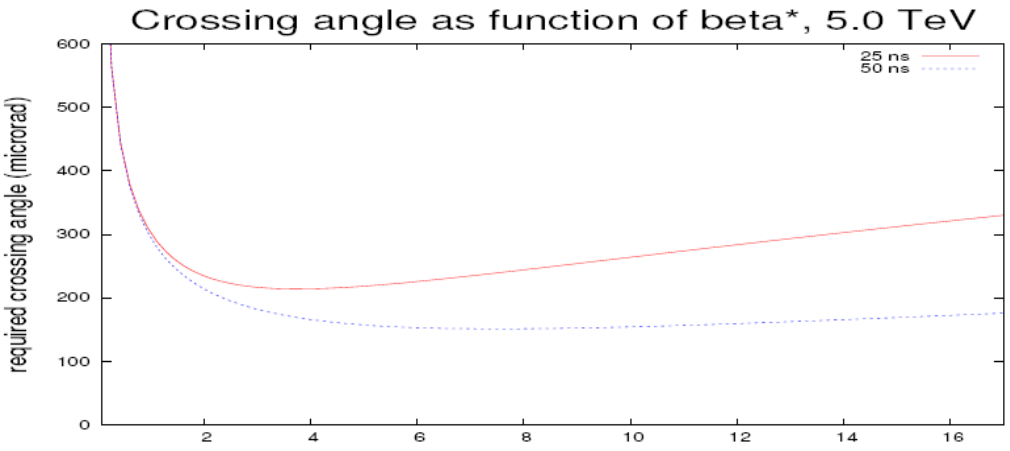
- Lower energy means bigger beams

$$\varepsilon_n = \varepsilon\gamma \qquad \sigma = \sqrt{\varepsilon\beta}$$

  - Less aperture margin
  - Higher β*

- > 150 bunches requires crossing angle
  - Requires more aperture
  - Higher β*

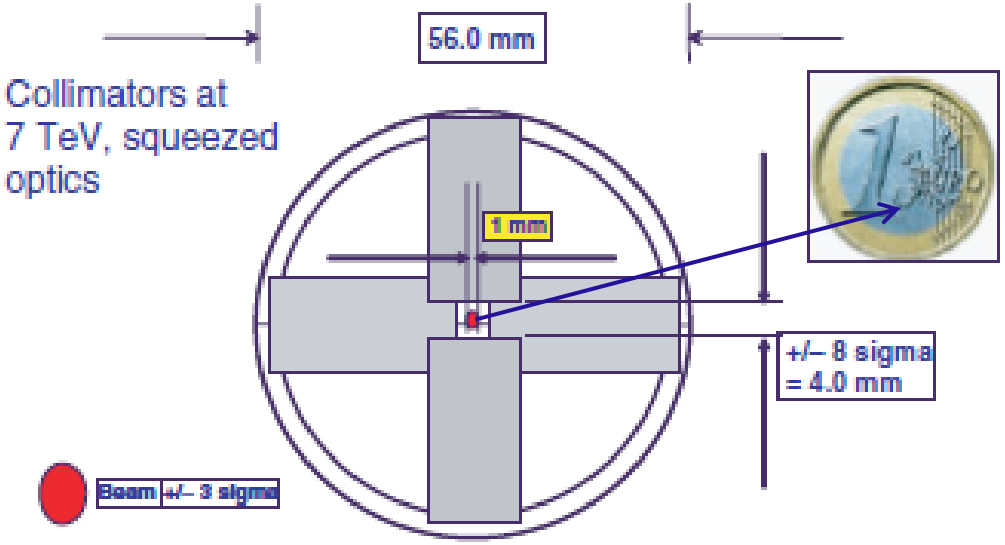
- Targets for 3.5TeV
  - 2 m no crossing angle
  - 3m with crossing angle



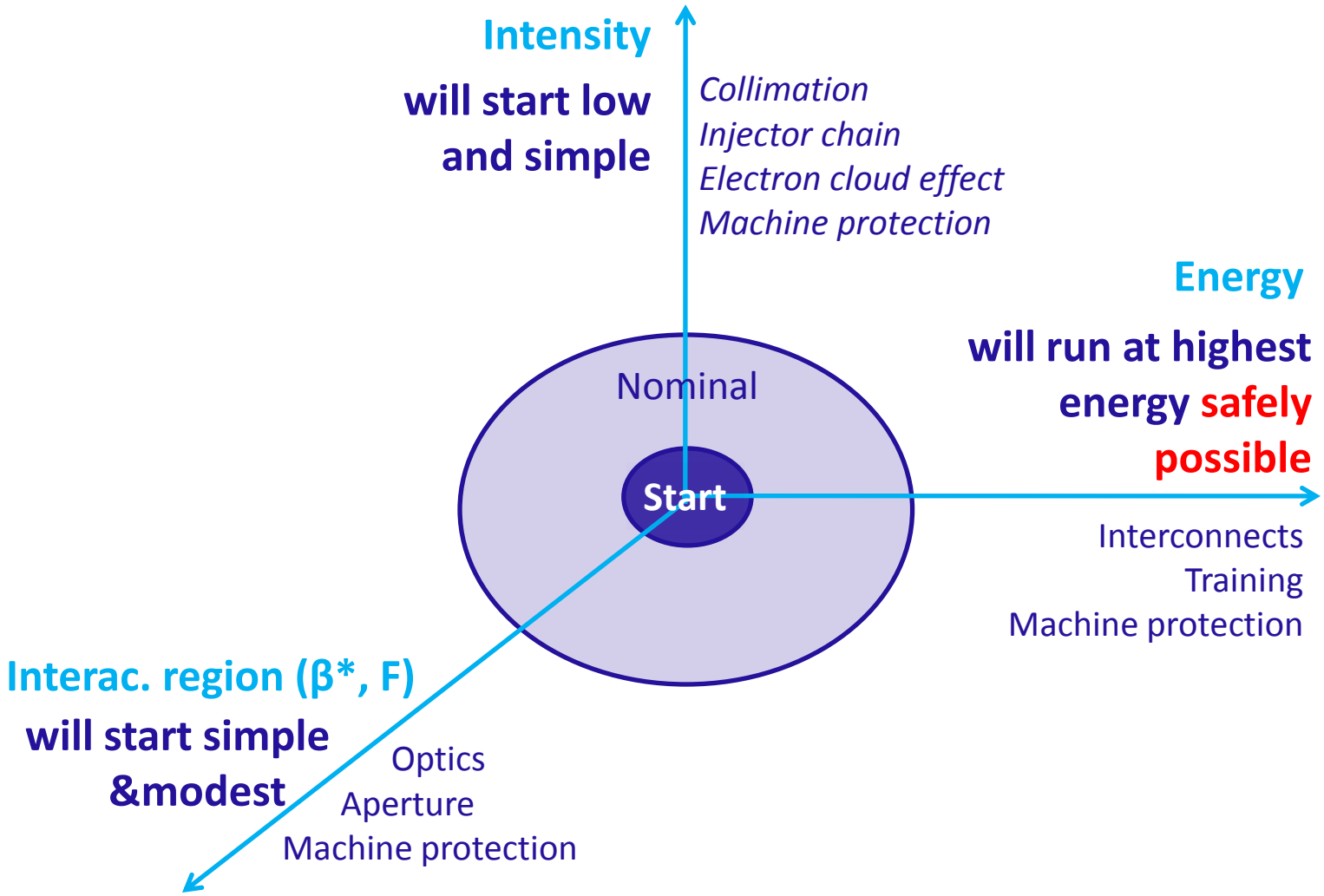
Operation with β^* between 1 m and 4 m very promising

β*: Evolution

- **As energy increases, lower β* gets easier**
- The **squeeze** is always going to be **challenging**
  - Optics
  - Collimator
- With experience, should be easier, but still …



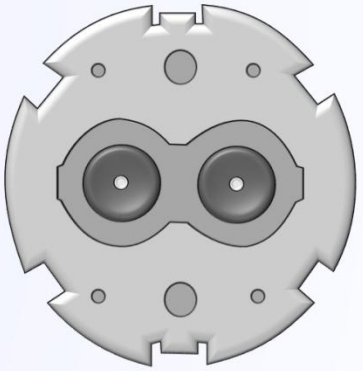
LHC performance drivers at start



Early beam operation

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

- Energy limited to 3.5 TeV by the stabilizers
- 2010
  - Intensity carefully increased to collimation limit
  - β* pushed as low as possible
- 2011
  - Run at established limits



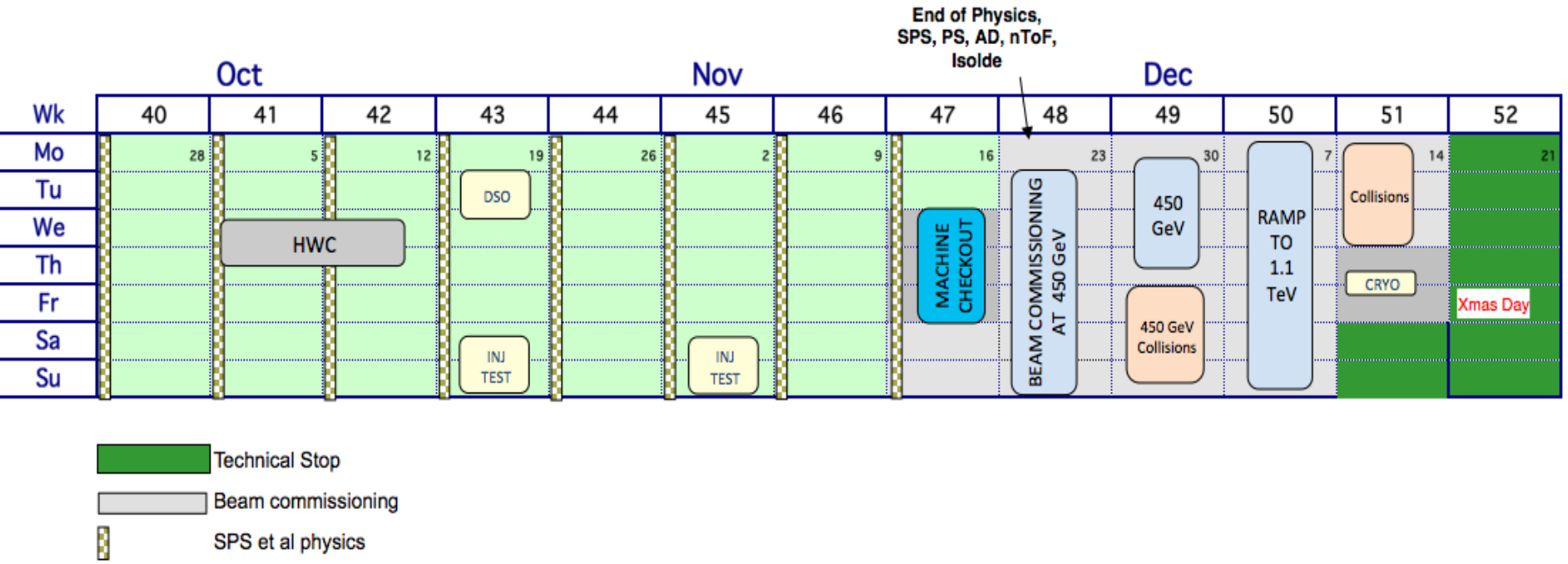
LHC Beam Operation

Operation envelope

Progress with beam in 2009

2010-2011

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

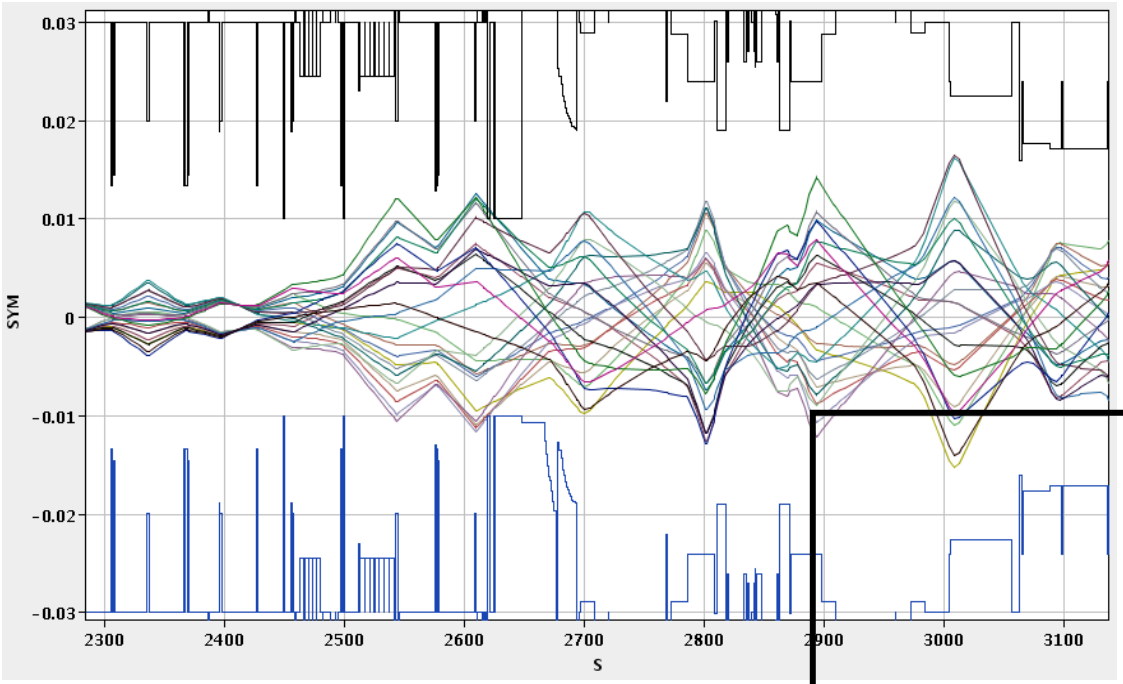
10^{12} at 450 GeV → 2 10^{11} at 1.18 TeV

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

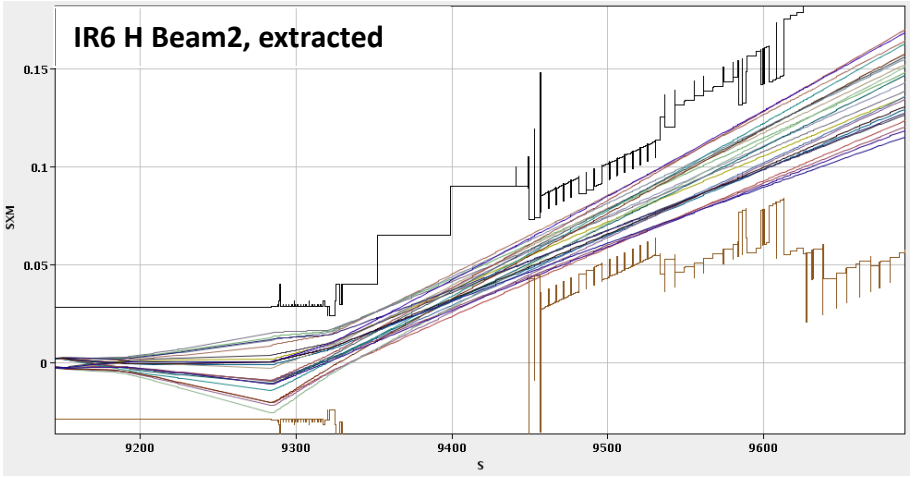
Milestones reached

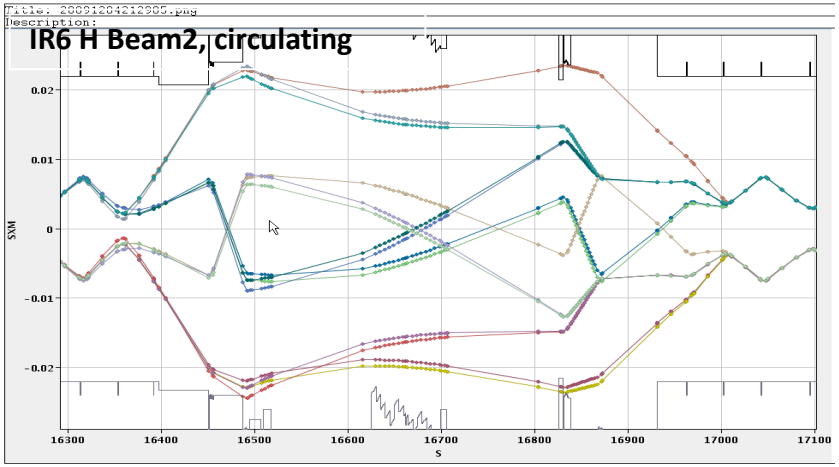
Date	Day	Achieved
Nov 20	1	Each beam circulating. Key beam instrumentation working.
Nov 23	4	First collisions at 450 GeV. First ramp (reached 560 GeV).
Nov 26	7	Magnetic cycling established (reproducibility).
Nov 27	8	Energy matching done.
Nov 29	10	Ramp to 1.18 TeV.
Nov 30	11	Experiment solenoids on.
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.

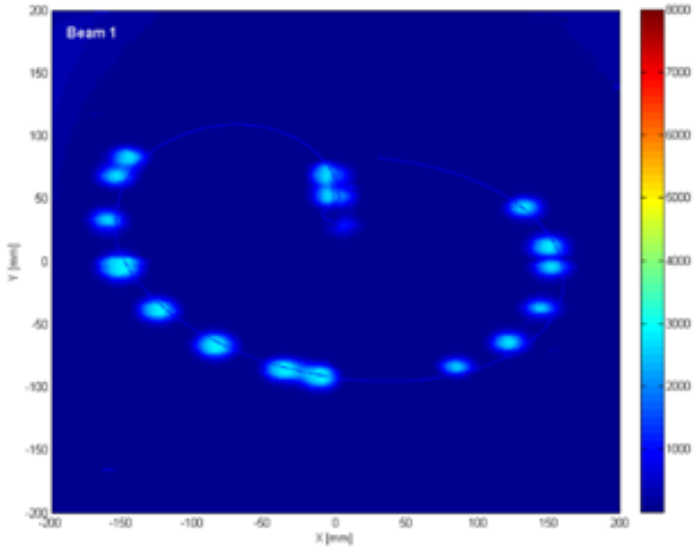
Injection

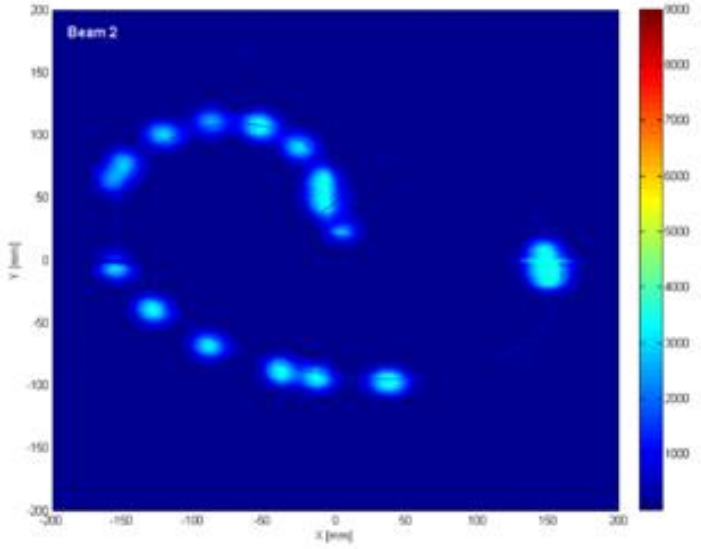

0.03
0.02
0.01
0
-0.01
-0.02
-0.03
SYM
2300
2400
2500
2600
2700
2800
2900
3000
3100
S

Beam dump

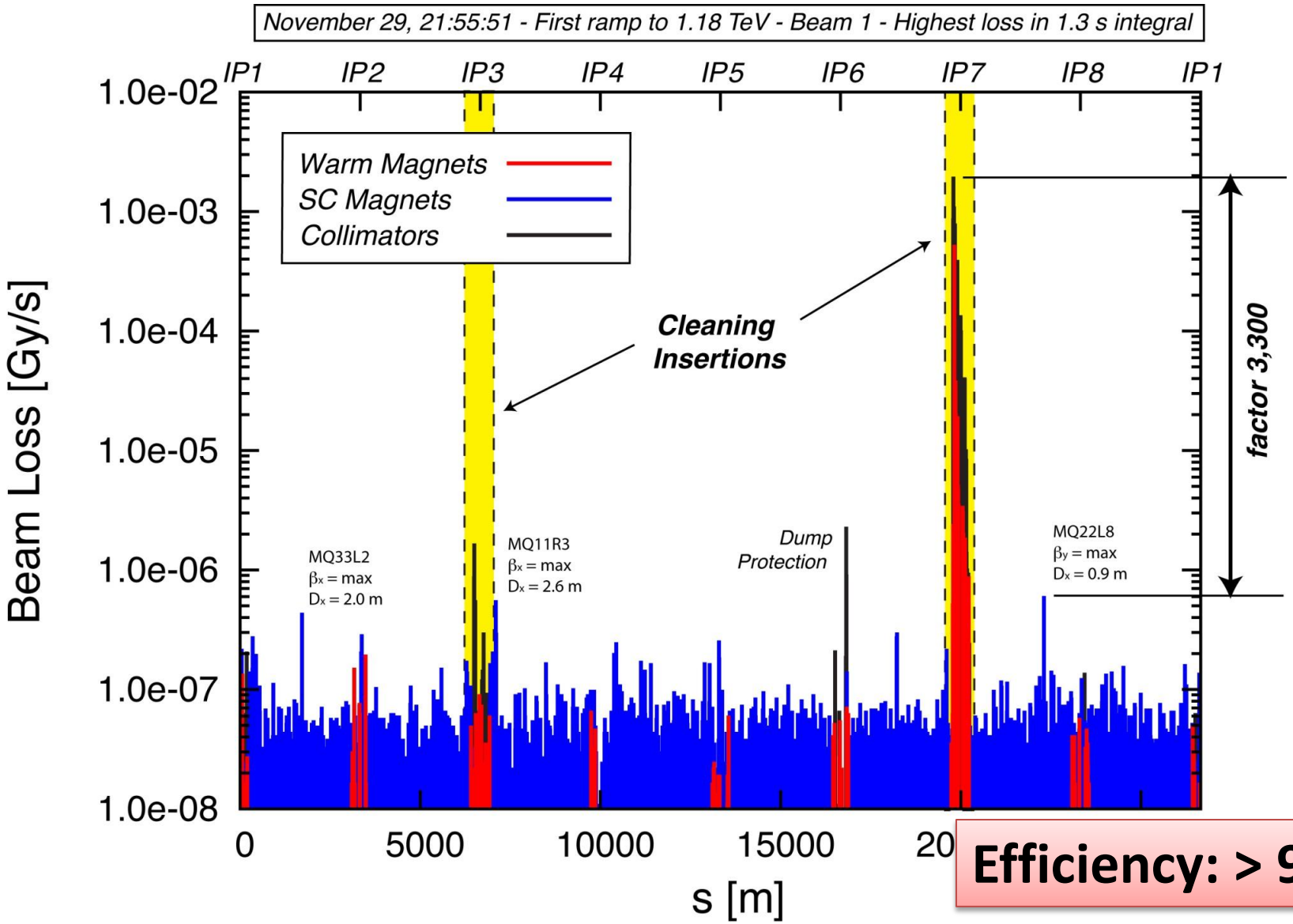

IR6 H Beam2, extracted
0.15
0.1
0.05
0
SXM
9200
9300
9400
9500
9600
S


IR6 H Beam2, circulating
0.02
0.01
0
-0.01
-0.02
SXM
16300
16400
16500
16600
16700
16800
16900
17000
17100
S


Beam 1
Y [mm]
X [mm]

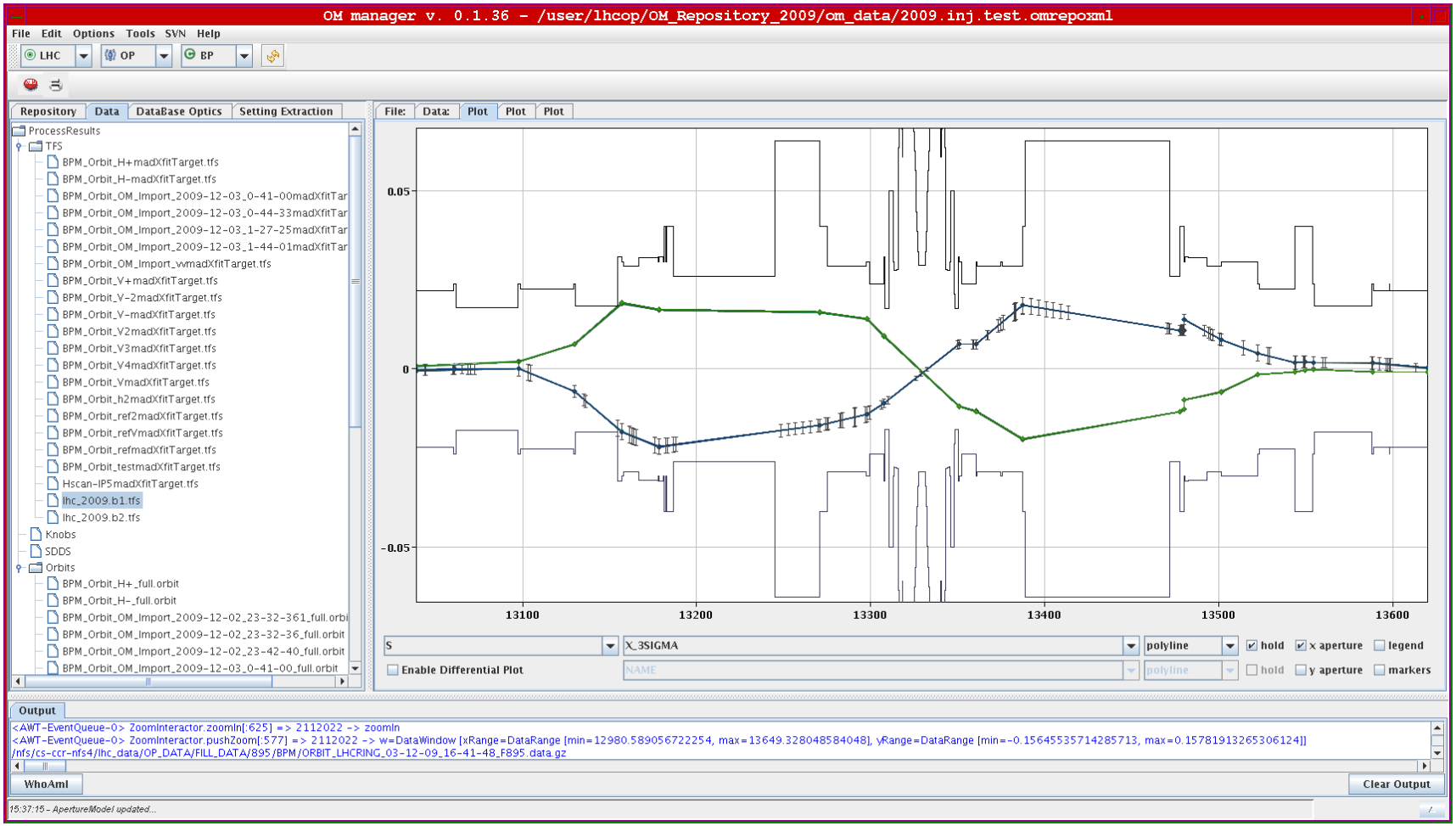

Beam 2
Y [mm]
X [mm]

Collimation after beam based set up (Ralph)

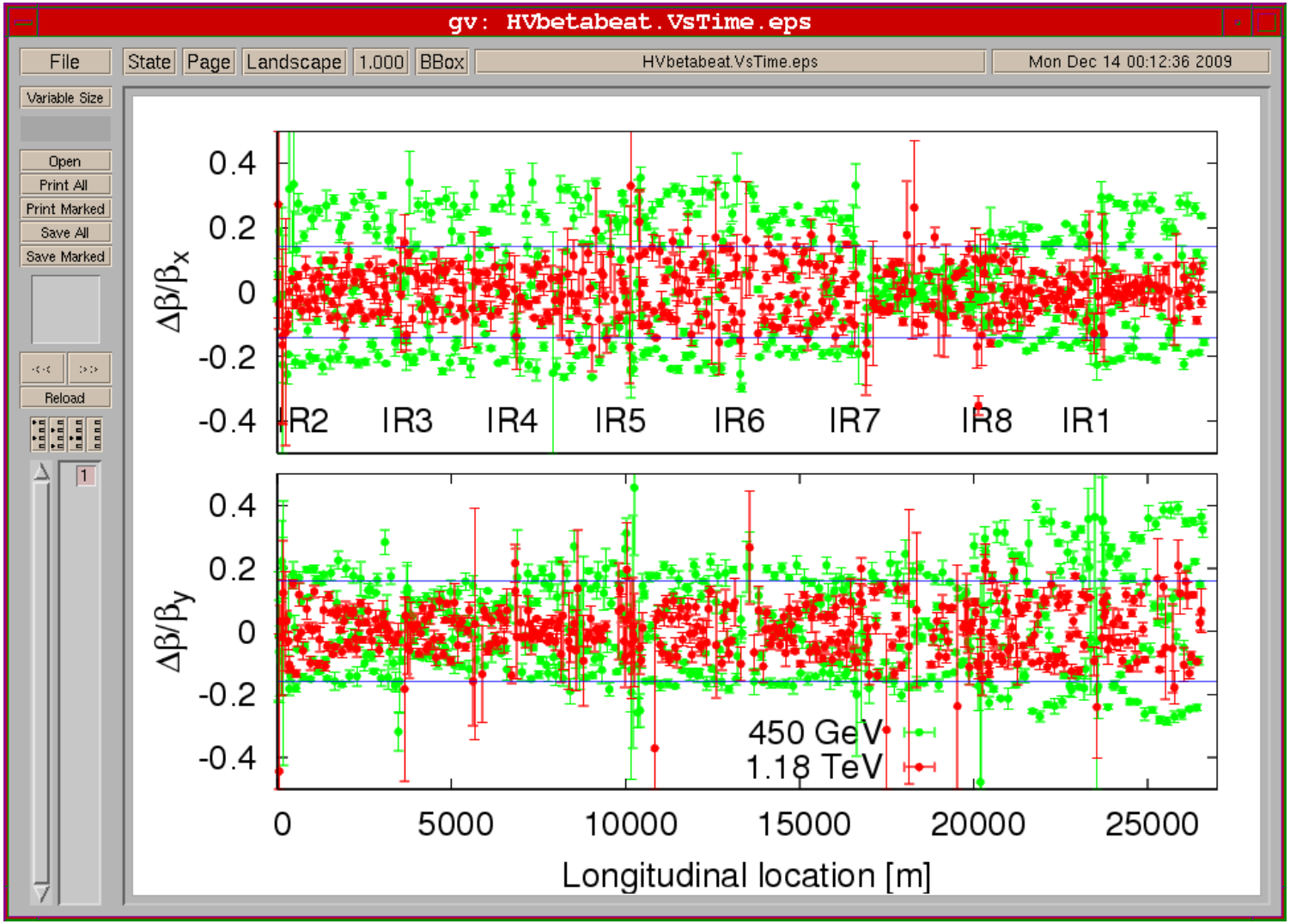


Efficiency: > 99.9%

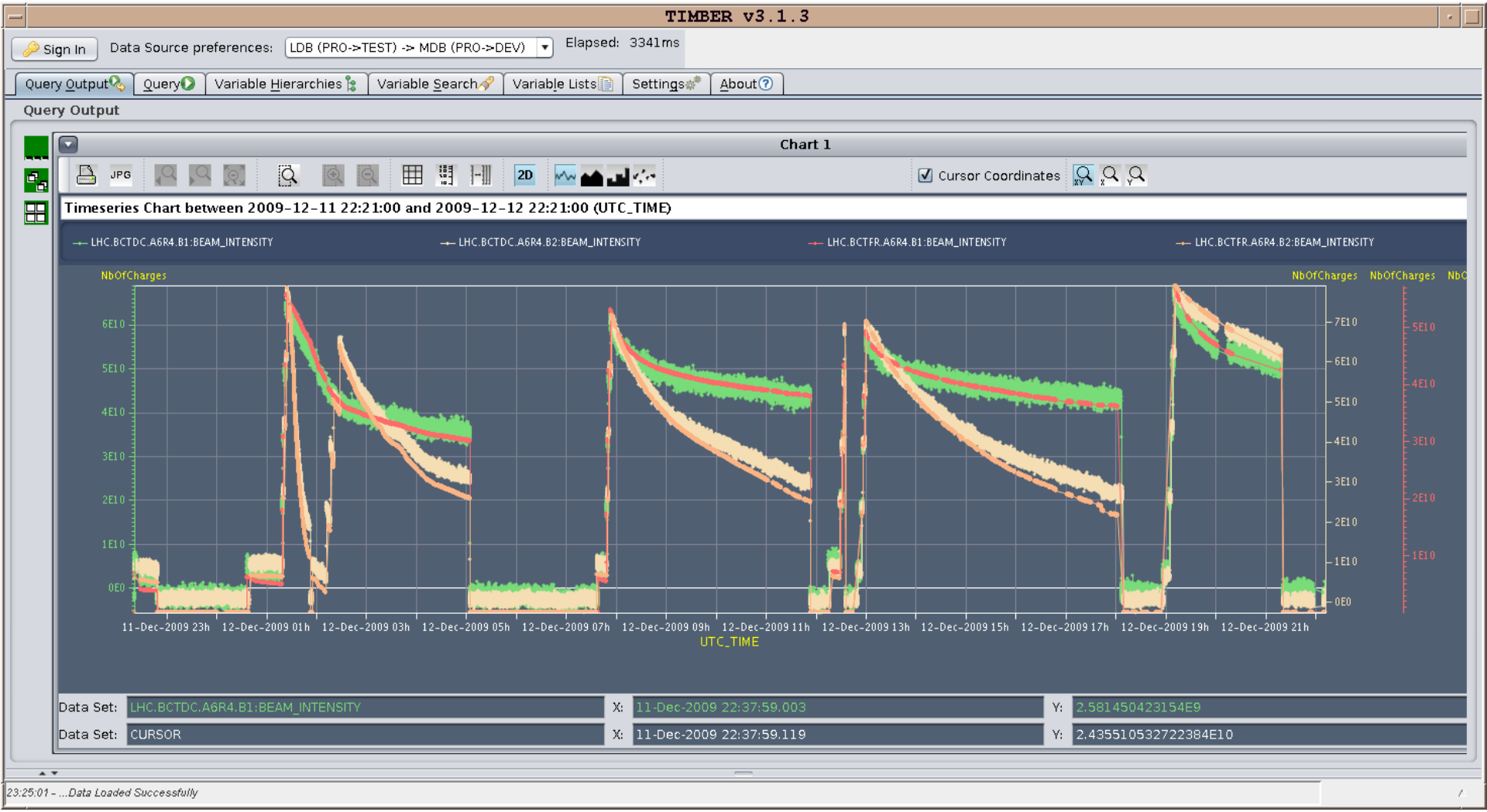
Aperture scans – IR5 H shown



Beta-beat comparison 450 GeV and 1.18 TeV



Production !


TIMBER v3.1.3
Sign In
Data Source preferences:
LDB (PRO->TEST) -> MDB (PRO->DEV)
Elapsed: 3341ms
Query Output
Query
Variable Hierarchies
Variable Search
Variable Lists
Settings
About
Query Output
Chart 1
JPG
2D
Cursor Coordinates
Timeseries Chart between 2009-12-11 22:21:00 and 2009-12-12 22:21:00 (UTC_TIME)
LHC.BCTDC.A6R4.B1:BEAM_INTENSITY
LHC.BCTDC.A6R4.B2:BEAM_INTENSITY
LHC.BCTFR.A6R4.B1:BEAM_INTENSITY
LHC.BCTFR.A6R4.B2:BEAM_INTENSITY
NbOfCharges
6E10
5E10
4E10
3E10
2E10
1E10
0E0
7E10
11-Dec-2009 23h
12-Dec-2009 01h
12-Dec-2009 03h
12-Dec-2009 05h
12-Dec-2009 07h
12-Dec-2009 09h
12-Dec-2009 11h
12-Dec-2009 13h
12-Dec-2009 15h
12-Dec-2009 17h
12-Dec-2009 19h
12-Dec-2009 21h
UTC_TIME
Data Set: LHC.BCTDC.A6R4.B1:BEAM_INTENSITY X: 11-Dec-2009 22:37:59.003 Y: 2.581450423154E9
Data Set: CURSOR X: 11-Dec-2009 22:37:59.119 Y: 2.435510532722384E10
23:25:01 - ...Data Loaded Successfully

Data recorded

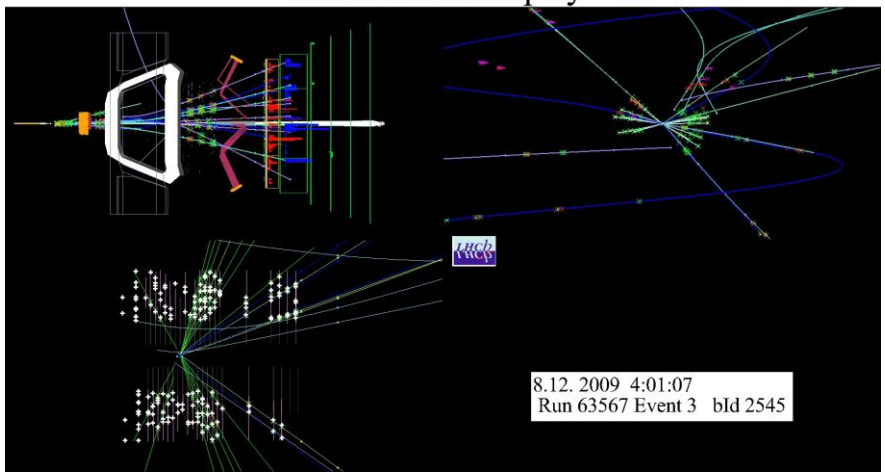
"stage"		Total hours
4x4	5e9 p/bch	16 hrs
4x4	1.5e10 p/bch	26 hrs
16x16	1e10 p/bch	1.5 hrs
		43.5 hrs

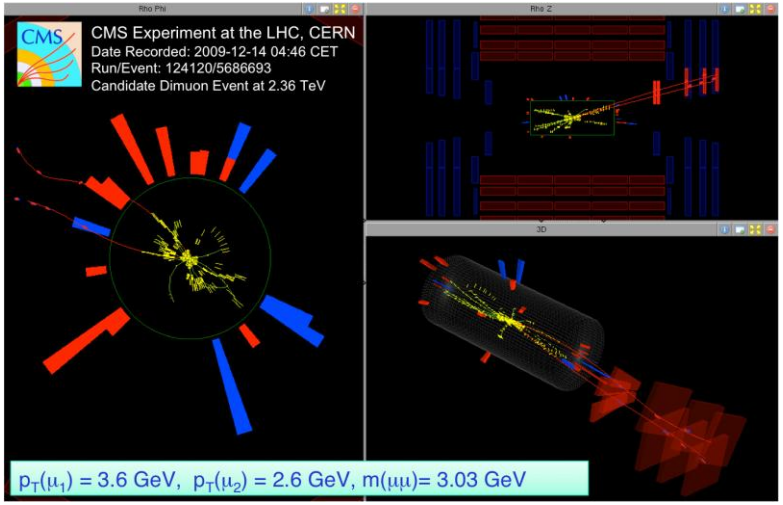
Estimated numbers of pp interactions recorded by experiments

	Not stable beams *(detectors partly on)*		Stable beams *(full detector on)*
	450GeV	**1.18 TeV**	**450 GeV**
ALICE	40k	33k	~ 400k
ATLAS	~ 320k	~ 34k	~ 540k
CMS	~ 100k	~18k	~ 410k
LHCB		~ 40k	~ 250k

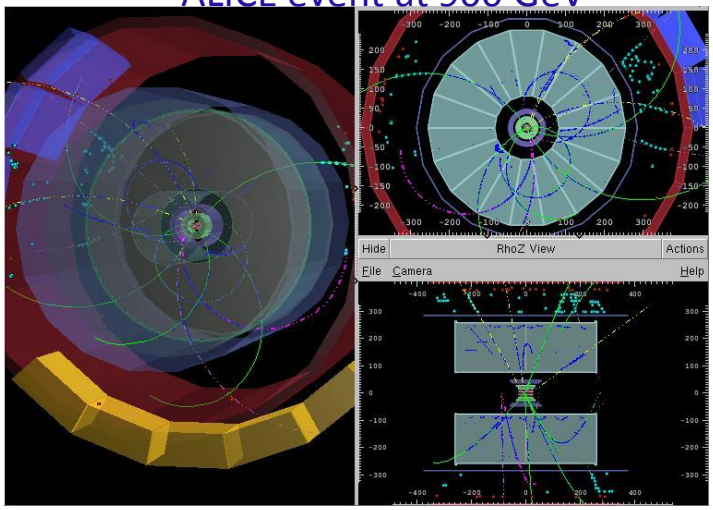
Experiments events

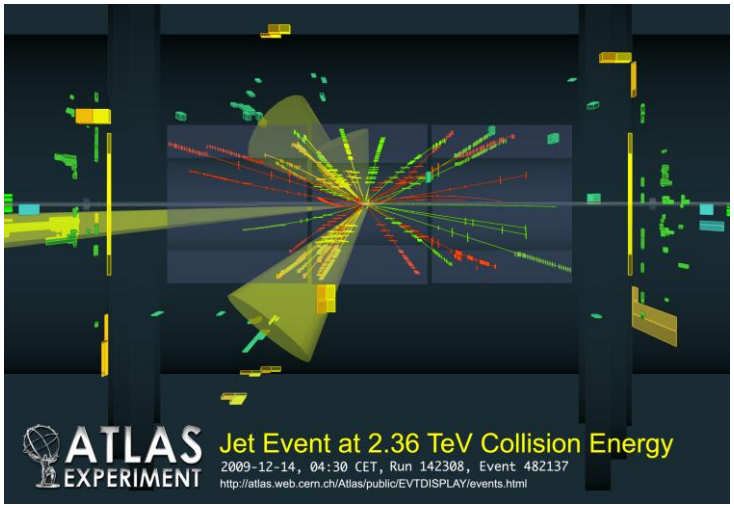
LHCb Event Display





ALICE event at 900 GeV



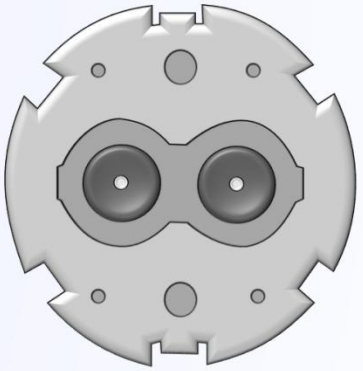


Summary of progress with beam 2009

- Excellent machine availability
- Excellent performance of all accelerator systems
- Huge amount achieved in 4 weeks
- All targets met and more

- All done with safe beams
- Minimum changes made in the interest of expediency
- Plenty to think about

- Great collaboration between machine and experiments



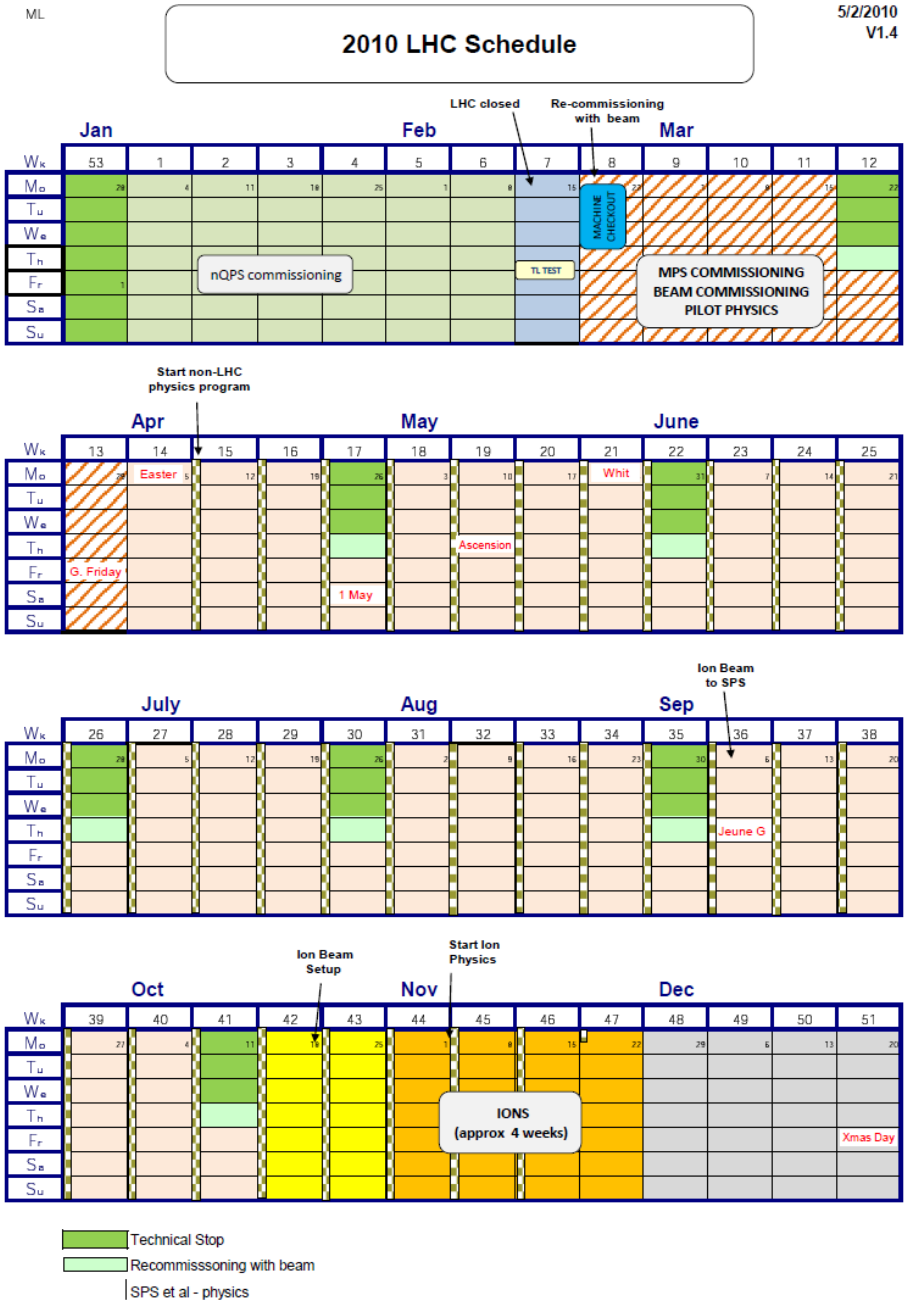
LHC Beam Operation

Operation envelope

Progress with beam in 2009

2010-2011

2010 plan



450 GeV phase 1 / Ramp to 3.5 TeV
450 GeV phase II / Ramp to 3.5 TeV
Collide / Squeeze / Collide
Colliding, safe, stable, squeezed beams

Increase intensity in steps x2
Week of running after each step
No crossing angle
43 on 43 at 2m

Increase stored energy in steps of 2MJ
Week of running after each step
Bunch trains and crossing angle
10^{32} cm^{-2} s^{-1}

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

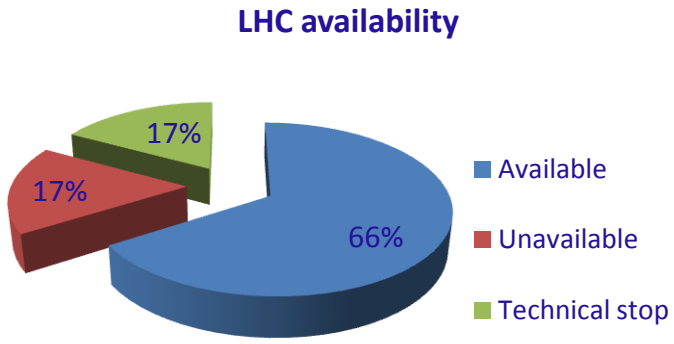
2010 strategy

- In 2009
  - We corrected Q Q' coupling orbit
  - Otherwise optics were frozen
  - Reference orbit established
  - Protection devices set up and fixed

- In 2010
  - We correct everything we can with safe beams
  - Then establish references
  - Then set up protection devices
  - Any further change will require another iteration

2010 progress with safe beams

- Some difficulties to get new QPS operational
- 450 GeV work completed to date
  - Q Q' coupling orbit measured and corrected
  - Optics (beta-beating) measured and corrected
  - Established references
  - Collimation set up
  - Injection and associated protection
  - Extraction and associated protection
  - RF
- Ramp to 3.5 TeV done last week
  - Optics
  - Collimation set-up…
- Target for first colliding stable 3.5 TeV beams March 30th



Rates in 2011

Energy	TeV	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
Month		Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Bunch intensity	1.E+10	7	9	9	9	9	9	9	9
Bunches / beam		432	432	560	720	720	720	720	720
Emittance	µm	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
β*	m	2	2	2	2	2	2	2	2
Luminosity 1 & 5	cm-2 s-1	9.2E+31	1.5E+32	2.0E+32	2.5E+32	2.5E+32	2.5E+32	2.5E+32	2.5E+32
Protons		3.0E+13	3.9E+13	5.0E+13	6.5E+13	6.5E+13	6.5E+13	6.5E+13	6.5E+13
% nominal		9.4	12.0	15.6	20.1	20.1	20.1	20.1	20.1
Current	mA	54.4	70.0	90.7	116.6	116.6	116.6	116.6	116.6
Stored energy	MJ	16.9	21.8	28.2	36.3	36.3	36.3	36.3	36.3
Beam size 1 & 5	um	44.8	44.8	44.8	44.8	44.8	44.8	44.8	44.8
Initial luminosity	cm-2s-1	9.17E+31	1.52E+32	1.97E+32	2.53E+32	2.53E+32	2.53E+32	2.53E+32	2.53E+32
Integrated/month	pb-1	52.37	86.58	112.23	144.30	144.30	144.30	144.30	144.30
Integrated	pb-1	52.37	138.95	251.18	395.48	539.78	684.07	828.37	972.66

Summary

- LHC is up and running with beam in 2009
  - Excellent performance with safe beams

- In 2010 & 2011
  - Limited in energy due to interconnects …. Fixed in 2012
  - Limited in intensity by collim. cleaning syst….. Solution proposed
  - Limited in β* because of lower energies …. target 2m

- "Prudent step-by-step approach…. LHC is not a turnkey machine…." R. Heuer

- "We can take satisfaction in what we have achieved to date, while reminding ourselves, that we are breaking new ground technologically as well as scientifically" . R. Heuer