LHC Status

by Helmut Burkhardt / CERN BE/ABP for the LHC team

- introduction
- current LHC status
- recent bunch train commissioning
- luminosity optimisation & normalisation
- schedule and next steps this year
- 2011 and beyond

LHC Physics Workshop 2010, Hamburg, 01/10/2010

Accelerators at the Energy Frontier

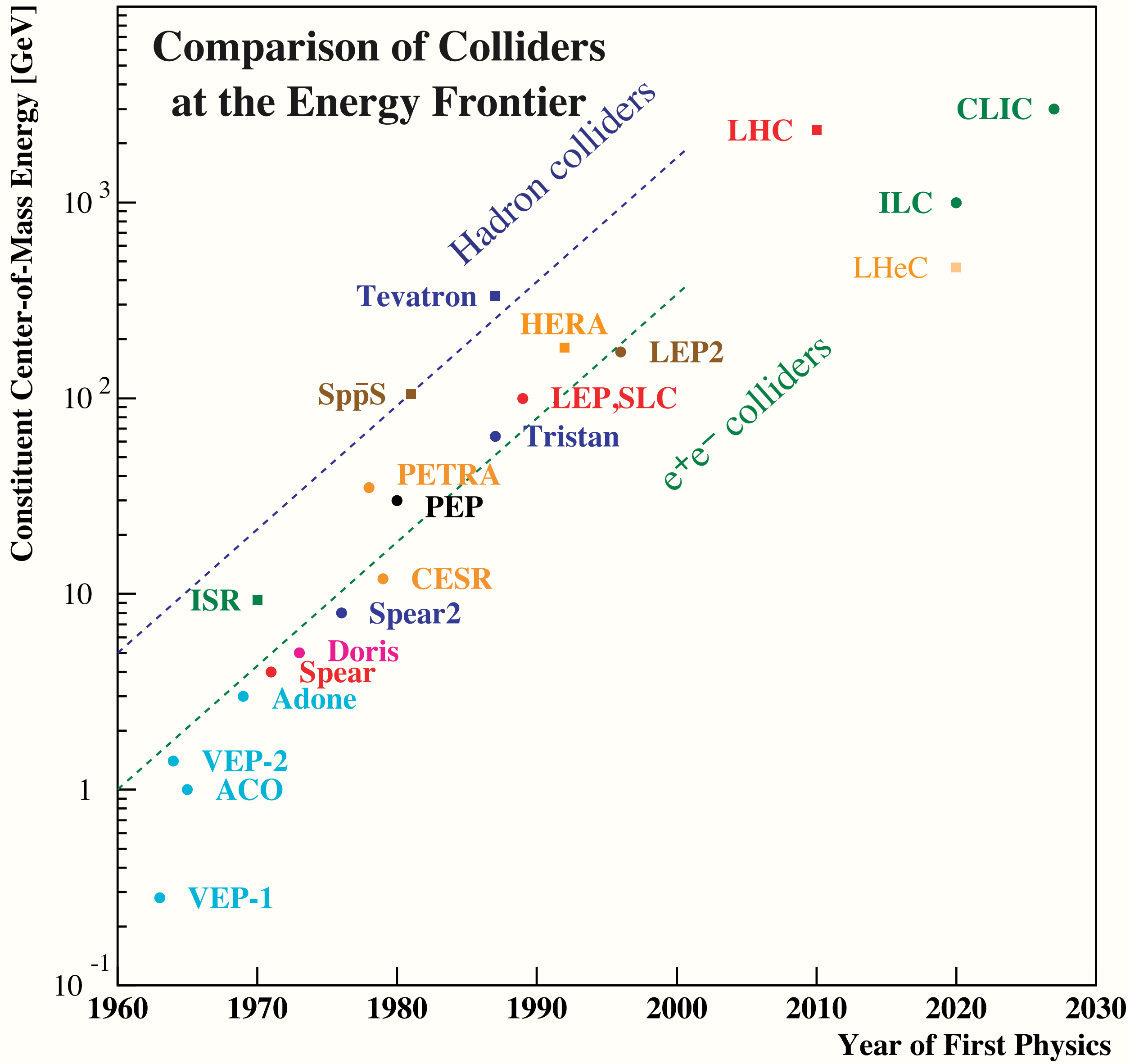
Livingston plot

Exponential growth of E_{cm} in time

Starting in 60's with e^+e^- at about 1GeV

Factor 4 every 10 y

$pp, p\bar{p}$: E_{cm} / 6 still 5 × above e^+e^- at same time



$pp, p\bar{p}$: discovery

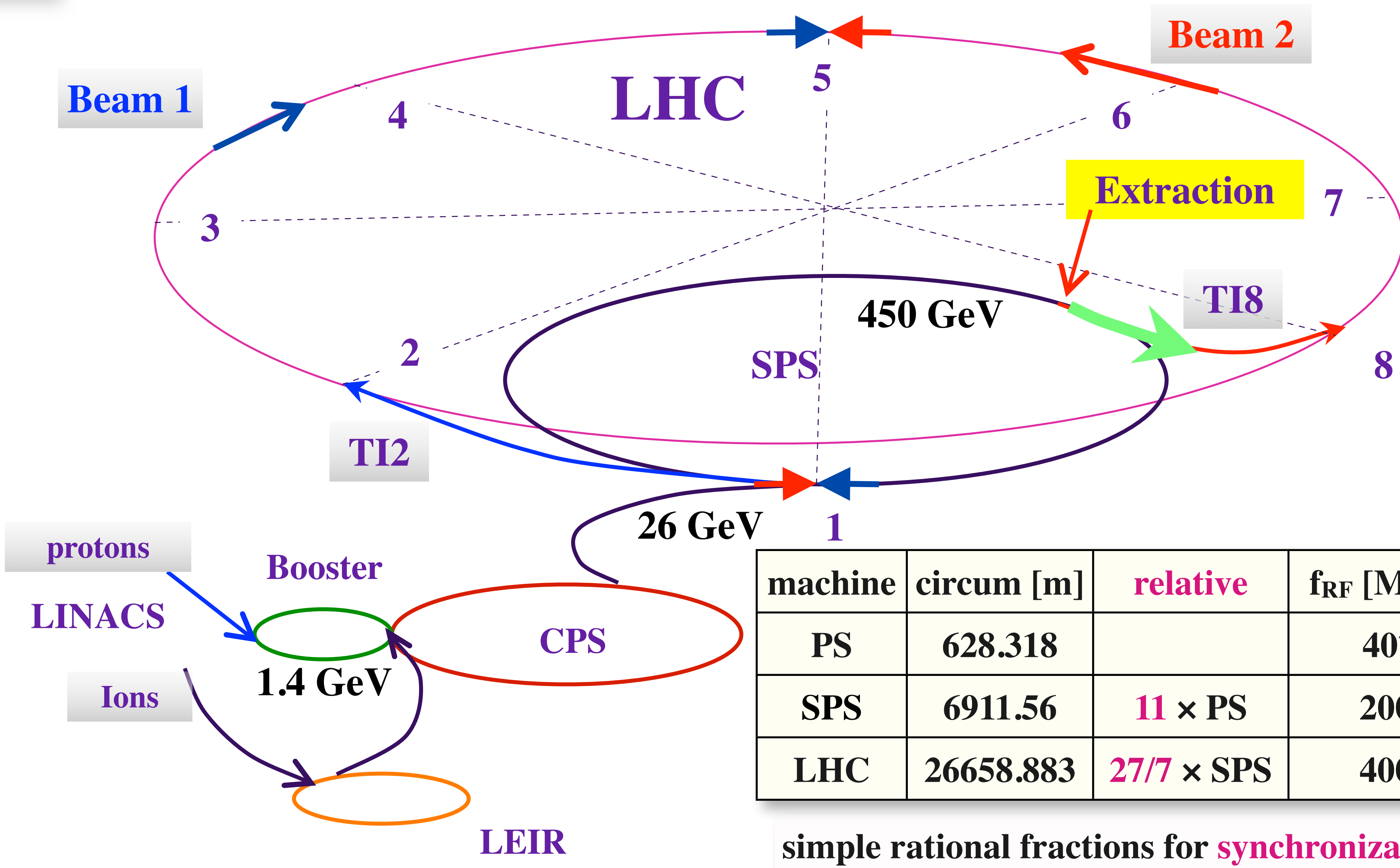
e^+e^- : precision

both required machines

\+ ep : hadron structure, QCD
HERA, LHeC

The LHC is a big step forward
Excellent potential for major discoveries

The CERN accelerator complex : injectors and transfer



machine	circum [m]	relative	f_{RF} [MHz]
PS	628.318		40†
SPS	6911.56	11 × PS	200
LHC	26658.883	27/7 × SPS	400

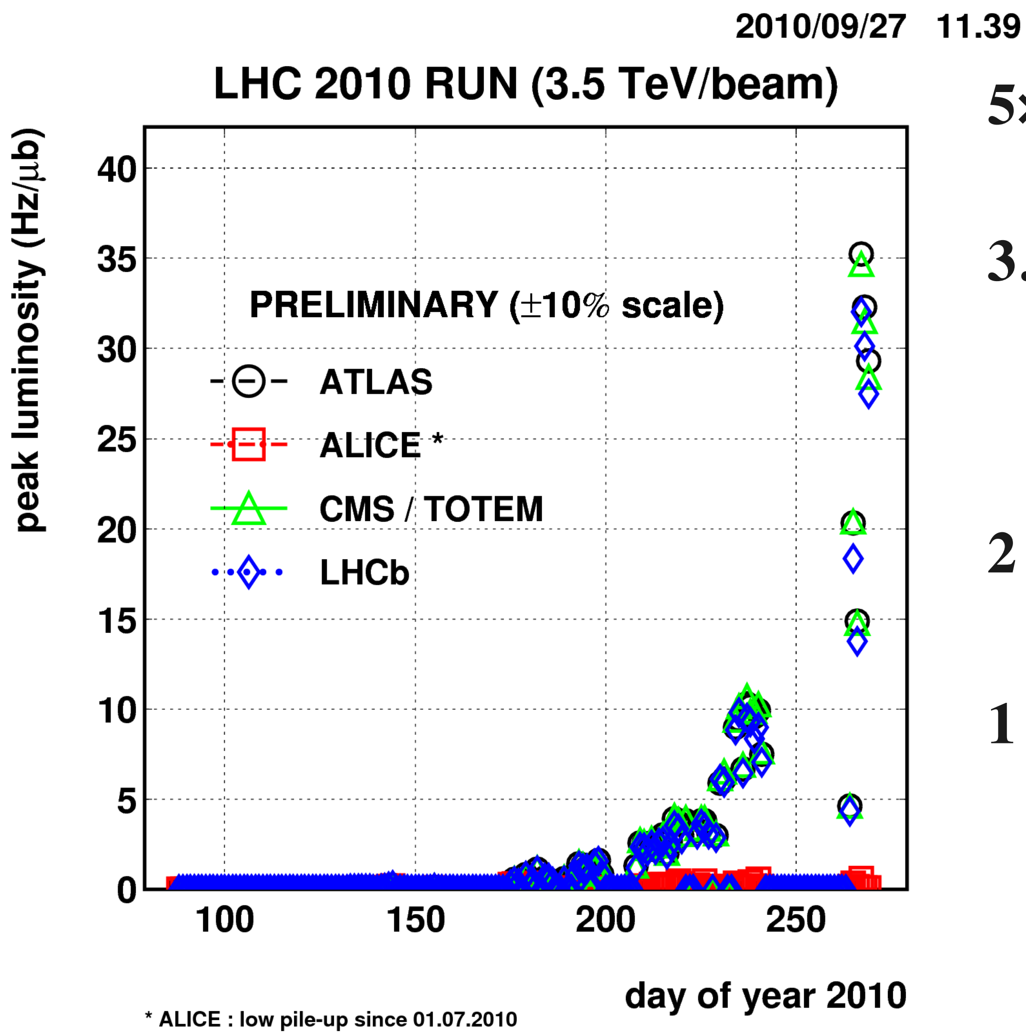
simple rational fractions for synchronization
based on a single frequency generator at
injection; 25 ns : multiple of 40 MHz

†at PS extraction with h=84 for nominal 25 ns

Beam parameters determined by injectors
size of protons decreases with energy : area $\sigma^2 \propto 1 / E$
Beam size largest at injection, using the full aperture

Peak luminosity

increase, mostly from increase in the number of bunches, now ~ 100



5×10^{31} cm^{-2}s^{-1} yesterday

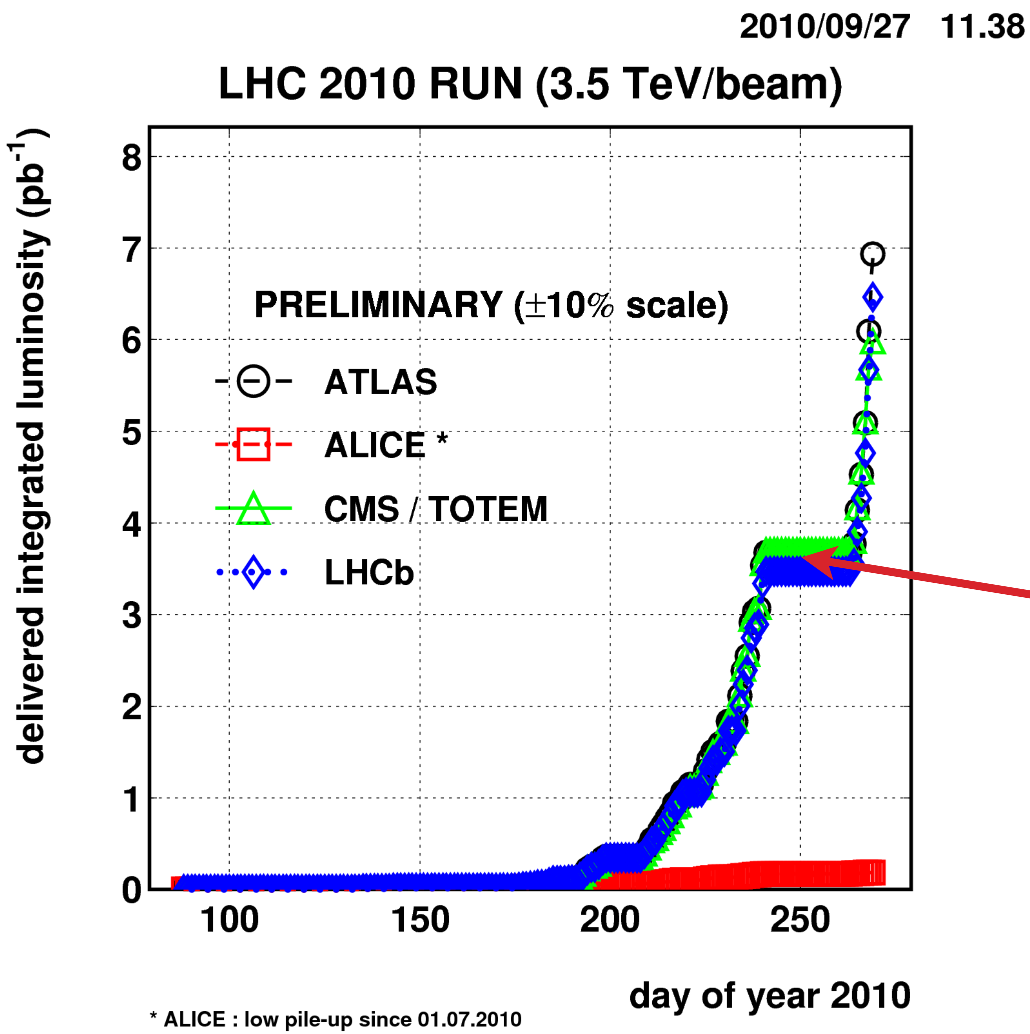
3.5×10^{31} cm^{-2}s^{-1} last weekend

2×10^{31} cm^{-2}s^{-1} last week

1×10^{31} cm^{-2}s^{-1} end August

LHC status - luminosity performance

2010 : first year of high energy operation
mostly commissioning to safely increase the intensity and luminosity + physics

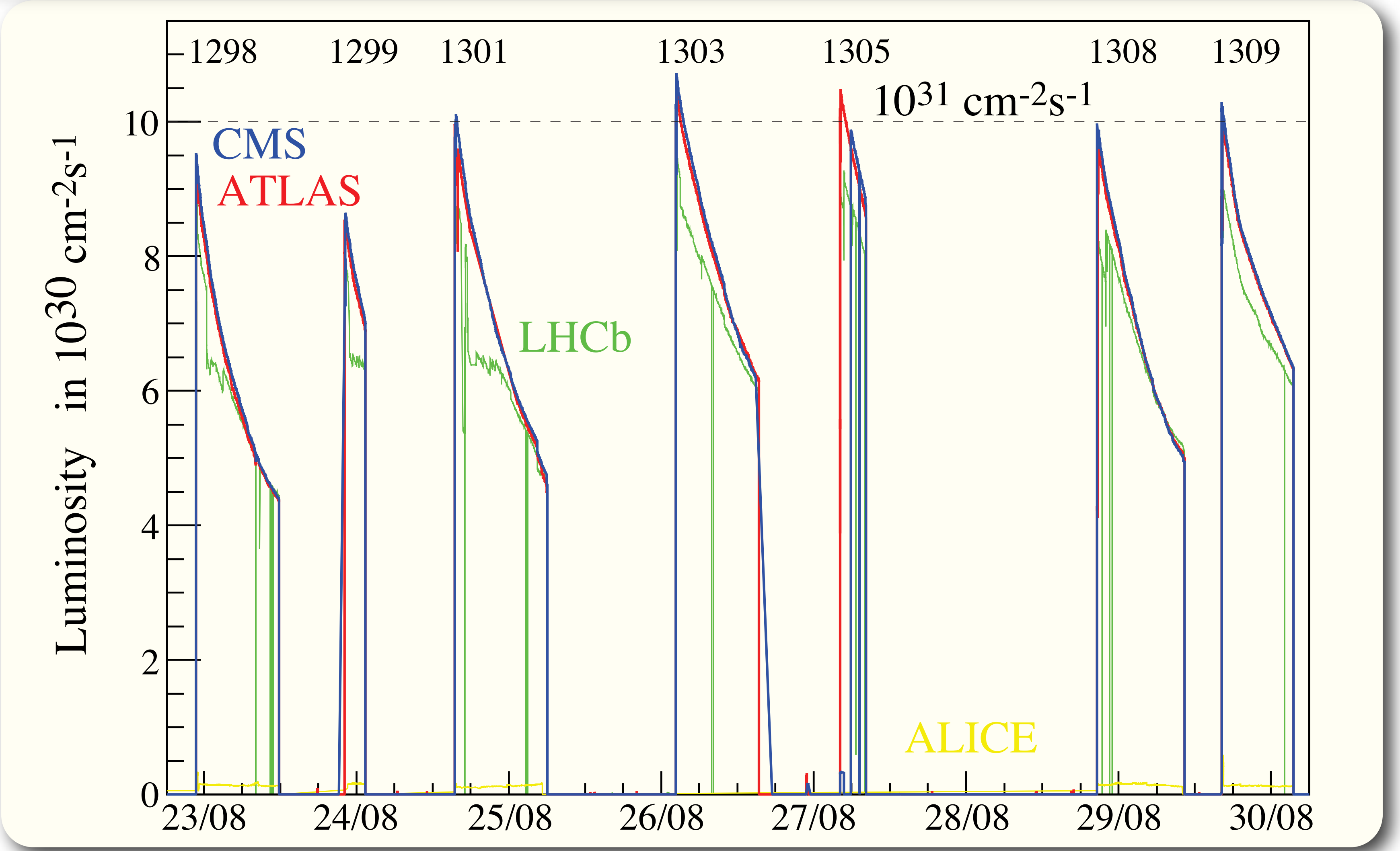


over 7 pb^{-1} each in ATLAS and CMS beginning of this week
+1 pb^{-1} each fill

1 week stop
+ bunch train commissioning

by request :
LHCb small,
ALICE major decrease in luminosity to avoid pile-up

Luminosity production week end of August



Excellent performance in stable physics period in August

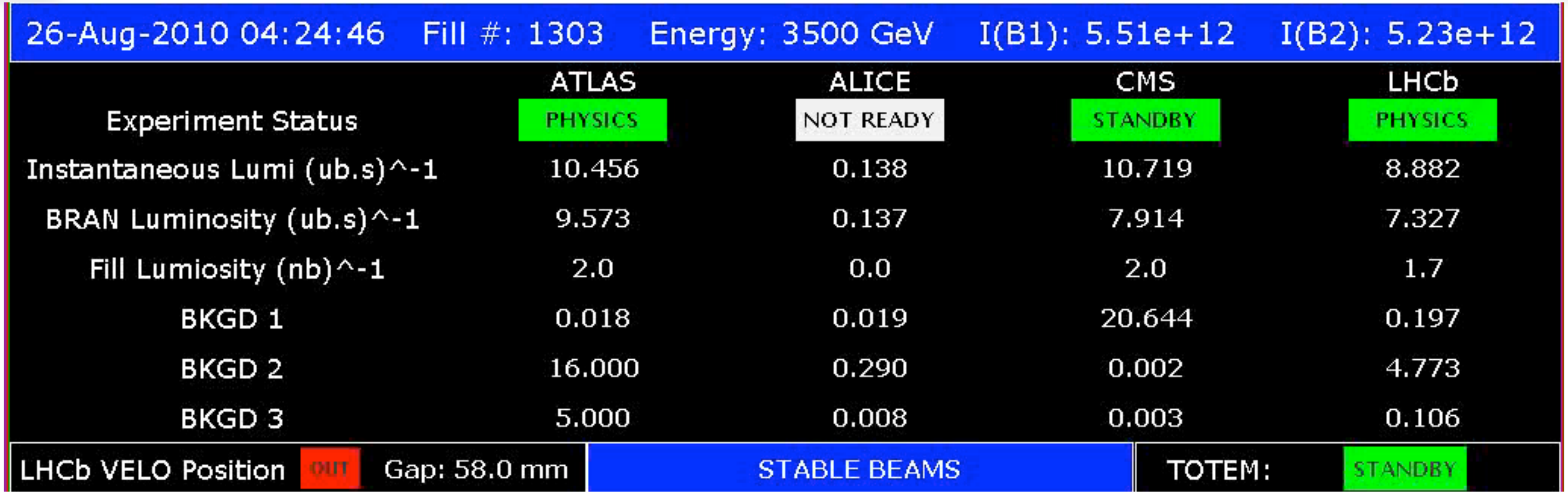
Then as planned technical stop in the 1st September week

followed by a major commissioning step :

full commissioning of bunch trains, ± 170 μrad crossing angles in injection + ramp

which is the nominal configuration for full LHC intensity with factor 10 increase planned for the rest of this years run ----> more details on this in the following

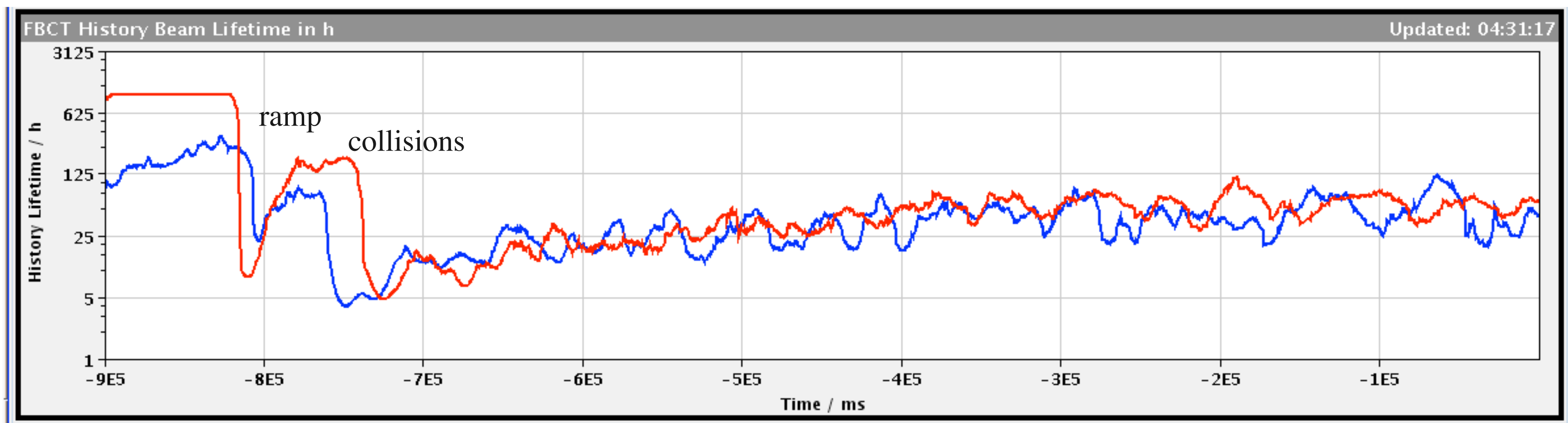
Fill 1303, end of August, L = 1e31 $cm^{-2}s^{-1}$



26-Aug-2010 04:24:46 Fill #: 1303 Energy: 3500 GeV I(B1): 5.51e+12 I(B2): 5.23e+12

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	NOT READY	STANDBY	PHYSICS
Instantaneous Lumi (ub.s)^-1	10.456	0.138	10.719	8.882
BRAN Luminosity (ub.s)^-1	9.573	0.137	7.914	7.327
Fill Lumiosity (nb)^-1	2.0	0.0	2.0	1.7
BKGD 1	0.018	0.019	20.644	0.197
BKGD 2	16.000	0.290	0.002	4.773
BKGD 3	5.000	0.008	0.003	0.106

LHCb VELO Position OUT Gap: 58.0 mm STABLE BEAMS TOTEM: STANDBY



Factors left to go to nominal : #bunches 2808/36 = 78 ; β* 3.5/0.55 = 6.4; E_b 7/3.5 = 2
together 1000 which gets us to 1.e34 $cm^{-2}s^{-1}$

Fill 1381 yesterday

30-Sep-2010 02:27:38 Fill #: 1381 Energy: 3500 GeV I(B1): 1.55e+13 I(B2): 1.56e+13	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	STANDBY	STANDBY	PHYSICS
Instantaneous Lumi (ub.s)^-1	48.706	0.000	48.535	45.034
BRAN Luminosity (ub.s)^-1	41.219	0.883	49.887	43.331
Fill Luminosity (nb)^-1	5.5	--	5.2	4.6

peak luminosity $L \approx 5e31\ cm^{-2}s^{-1}$ already within factor 2 of this years goal of $1.e32cm^{-2}s^{-1}$

Factors left to go to nominal : #bunches 2808/140 = 20 ; β^* 3.5/0.55 = 6.4; E_b 7/3.5 = 2

together 257 $257 \times 4.9e31 = 1.3e34\ cm^{-2}s^{-1}$

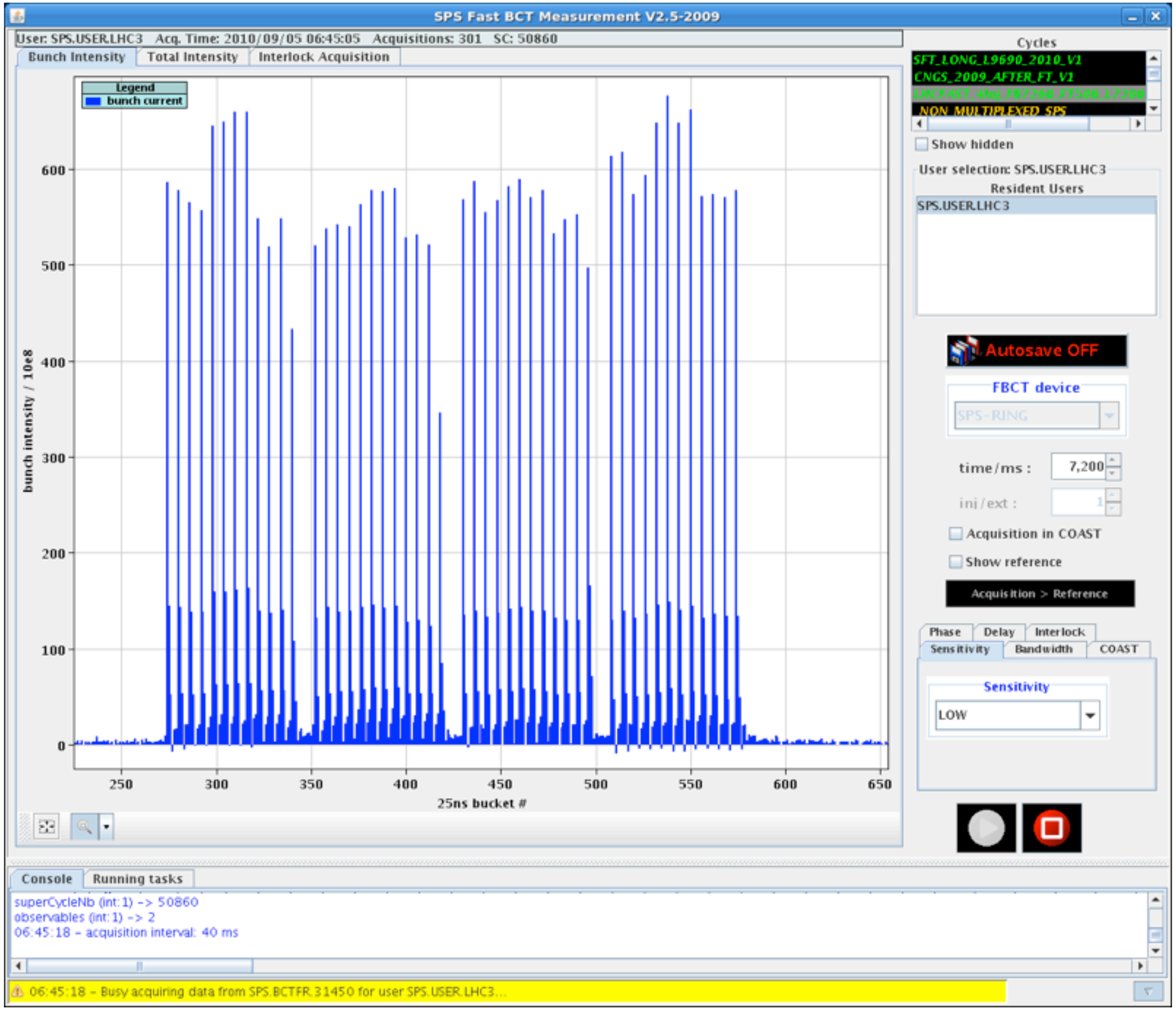
Very well corrected machine. Example closed orbit deviation measured around the ring

r.m.s

H 0.11 mm

V 0.07 mm

Bunch trains in the SPS before injection into the LHC



SPS ready to inject (3 or) 4 batches

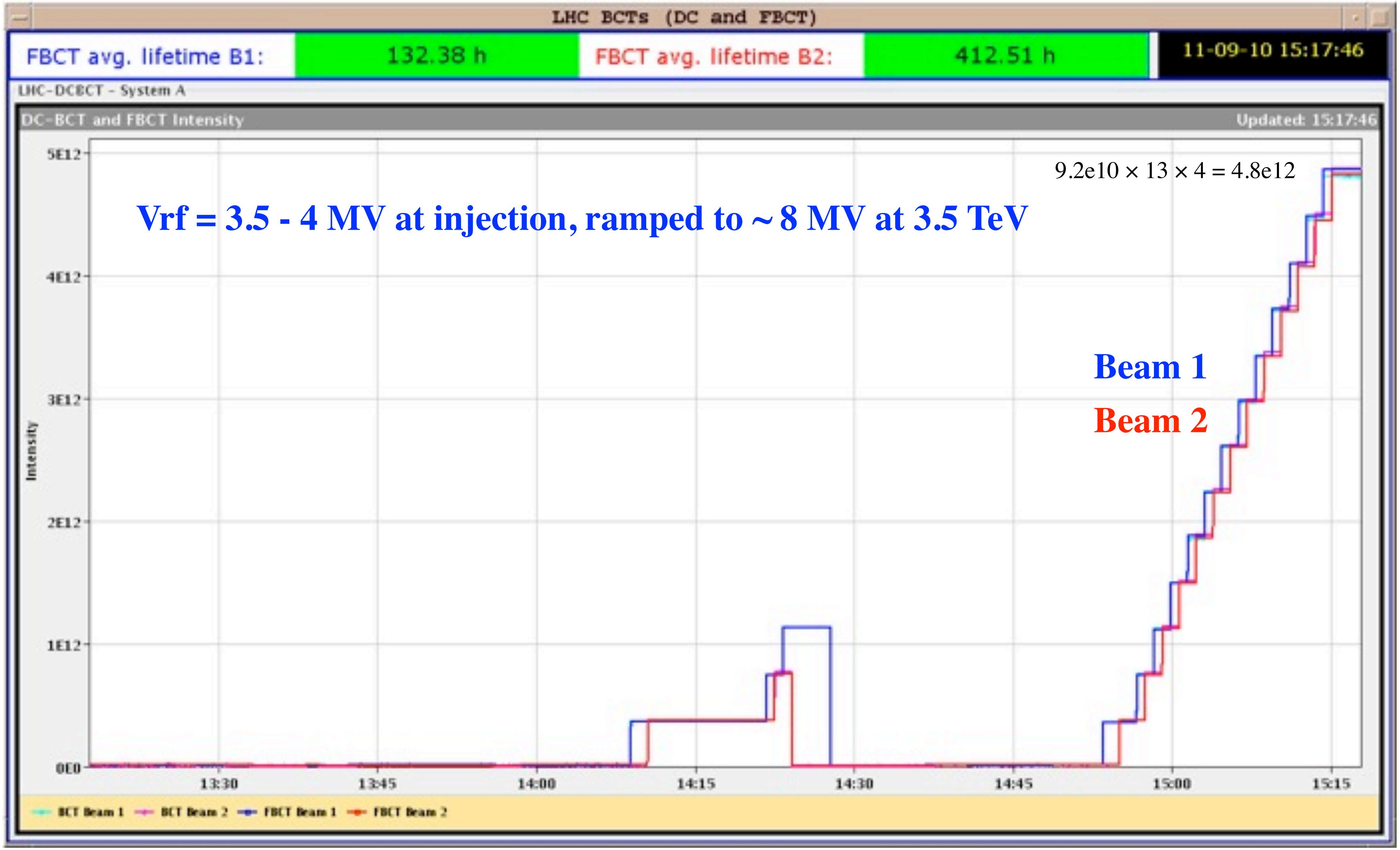
here each batch with 12 bunches spaced by 150 ns   as one of the options these days

nominal LHC is 72 bunches per batch spaced by 25 ns

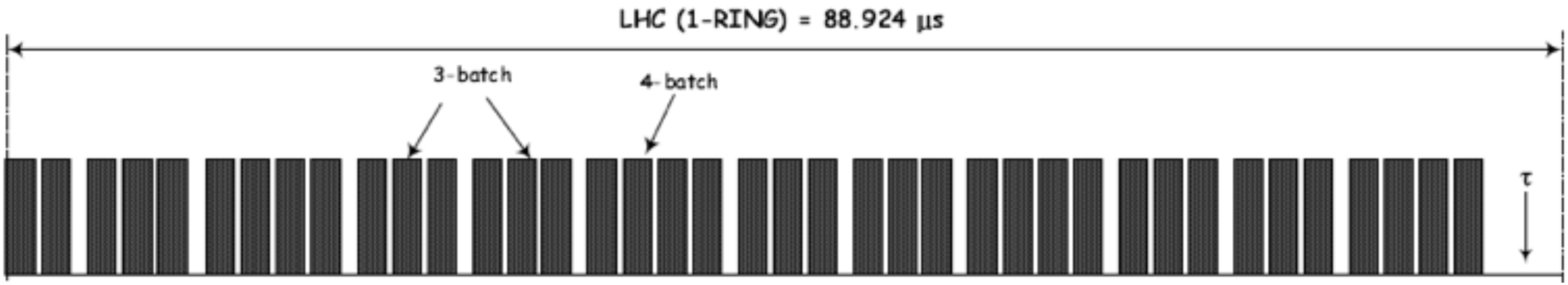
Bunch trains injected into the LHC

LHC 10/09/2010 after RF adjust at injection :

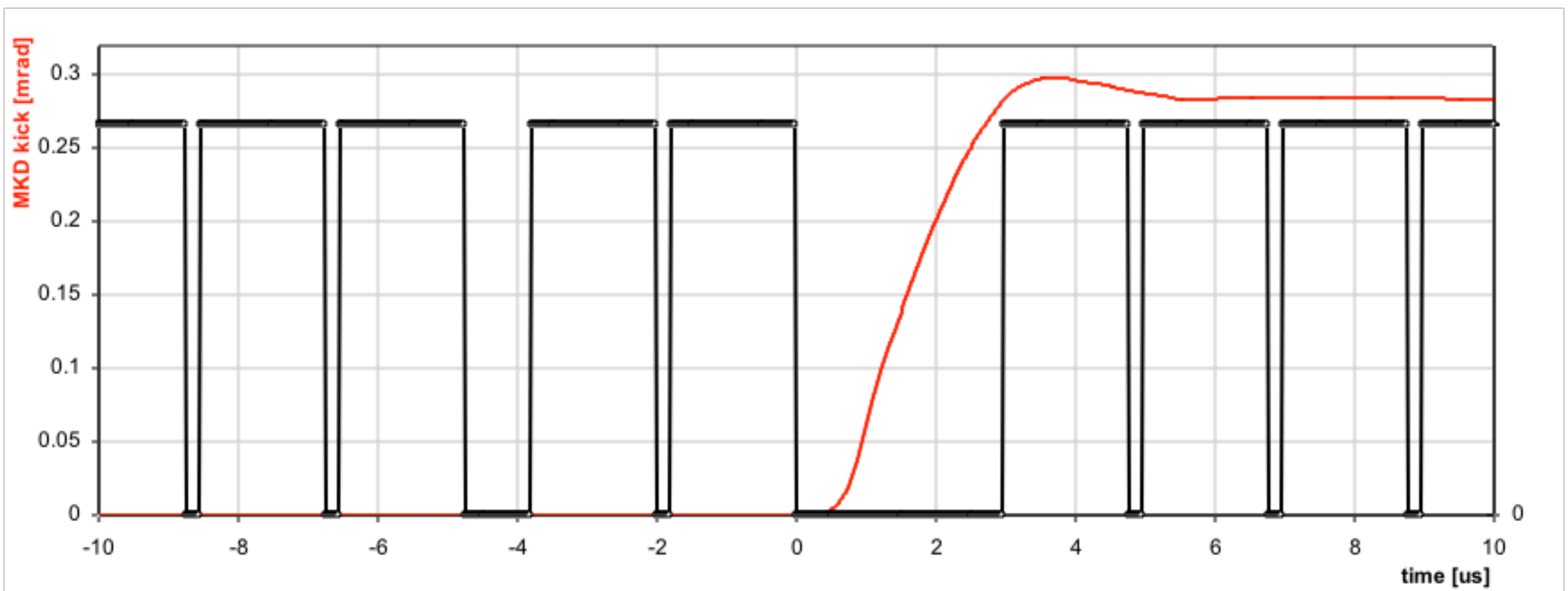
Complete injection sequence of 13×4 bunches per beam was executed and went smoothly with very little uncaptured beam. This week : 8 bunch inj. + studies 16 bunch injection



Batches in the LHC and abort gap



dump trigger **Extraction kicker MKD deflection**



Current LHC status

LHC :
End of 2009 first collisions, mostly at injection energy 2x450 GeV

2010 : commissioning and first year of operation with collisions at high energy;

- **already 3.5 pb^{-1} delivered** per high L experiment
- **main LHC challenge : damage potential,**
- **enormous stored energy :** nominal is 10 GJ in magnets, 362 MJ in beam
- currently 2.5 GJ in magnets, 10 MJ in beam going up to 20 MJ end of 2010 run
- Now (30/09/10) 150ns_152b_140_16_140_8bpi11inj 152 bunches of which 140 colliding in 1,5,8

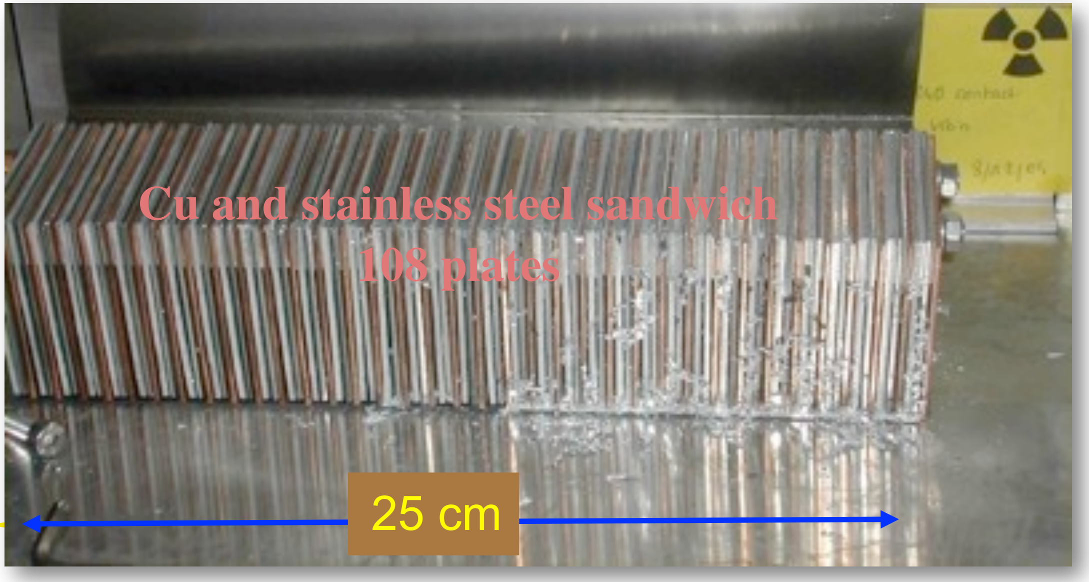
	LHC design	now
Momentum at collision, TeV/c	7	3.5
Luminosity, $cm^{-2}s^{-1}$	1.0E+34	3.5E+31
Dipole field at top energy, T	8.33	4.17
Number of bunches, each beam	2808	50 --> 500
Particles / bunch	1.15E+11	1E+11 (up to 1.3E+11)
Typical beam size in ring, µm	200 – 300	300-500
Beam size at IP, µm	17	59

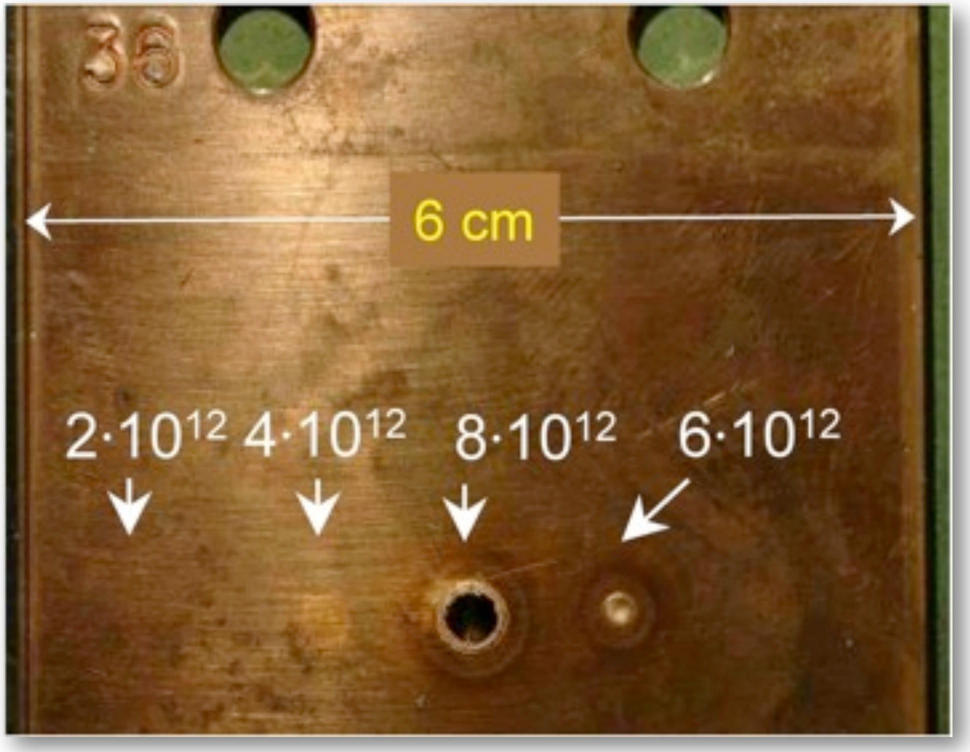
Damage potential : confirmed in controlled SPS experiment

controlled experiment with beam extracted from SPS at 450 GeV in a single turn, with perpendicular impact on Cu + stainless steel target

450 GeV protons

r.m.s. beam sizes $\sigma_{x/y} \approx 1$ mm





SPS results confirmed :

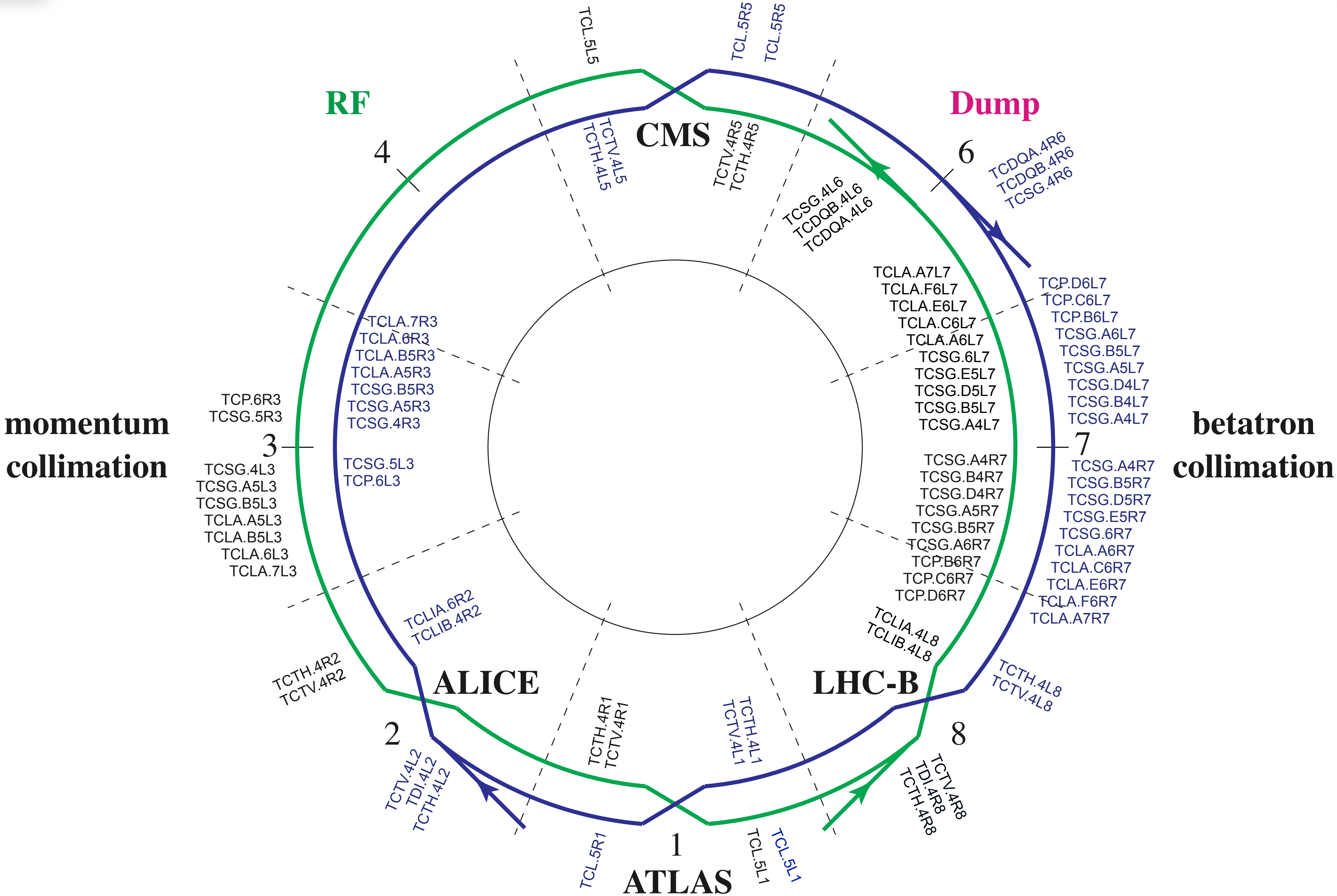
8×10^{12} clear damage

2×10^{12} below damage limit

for details see V. Kain et al., PAC 2005 RPPE018

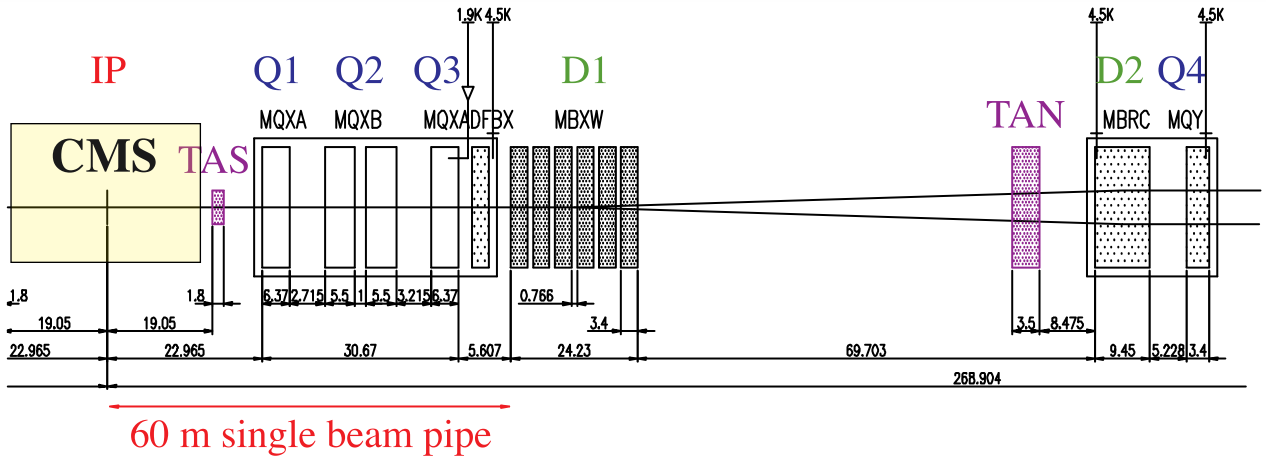
For comparison, the LHC nominal at 7 TeV :
$2808 \times 1.15\times10^{11} = 3.2\times10^{14}$ p/beam
at $< \sigma_{x/y} > \approx 0.2$ mm
over 3 orders of magnitude above damage level for perpendicular impact

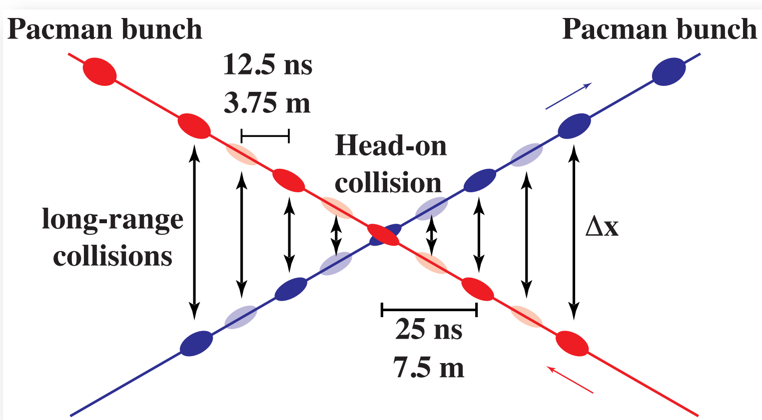
Layout of the LHC



94 collimators (phase 1)

Crossing angle





without crossing angle limited to 156 bunches
Crossing angle needed for bunch spacing
< 2 × 60m or < 400 ns
avoid encounters closer than ~ 6 σ
Angle scales with σ or 1/√β* and 1/√E_b
2×15 parasitic crossings ± 58m from IP at 7.5 – 13 σ

E_b [TeV]	β* [m]	angle [μrad]	
0.45	10, 11	± 170 μrad	injection+ramp
3.5	3.5	± 100 μrad	current phys.
7.0	0.55	± 142.5 μrad	nominal phys

commissioned now

started 1&5 end of June, **now all IPs,** 120μrad IP2

Filling pattern and collisions

Reference numbers, nominal LHC
f_{RF} = 400.7896 MHz
λ_{RF} = 0.748 m or 2.4951 ns
35 640 RF buckets
Bunches spaced by multiples of 25 ns or 10 buckets, allowing for a maximum of 3564 bunches

Gaps required for kicker timing with
a 119 bunch abort gap ~ 3 μs
Inject batches of
2, 3 or 4 x 72 bunches
1 batch = 72 bunches
total 39×72 = **2808 bunches**

A full LHC turn is 88.9244 μs

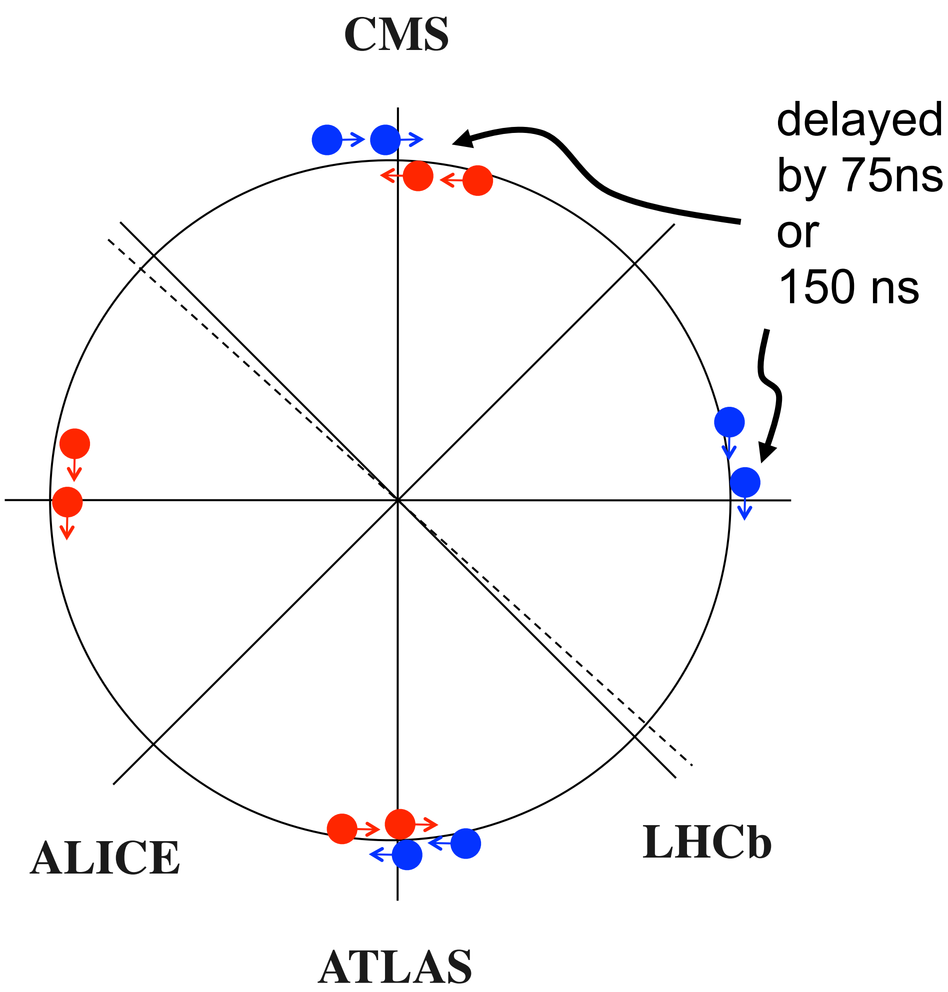
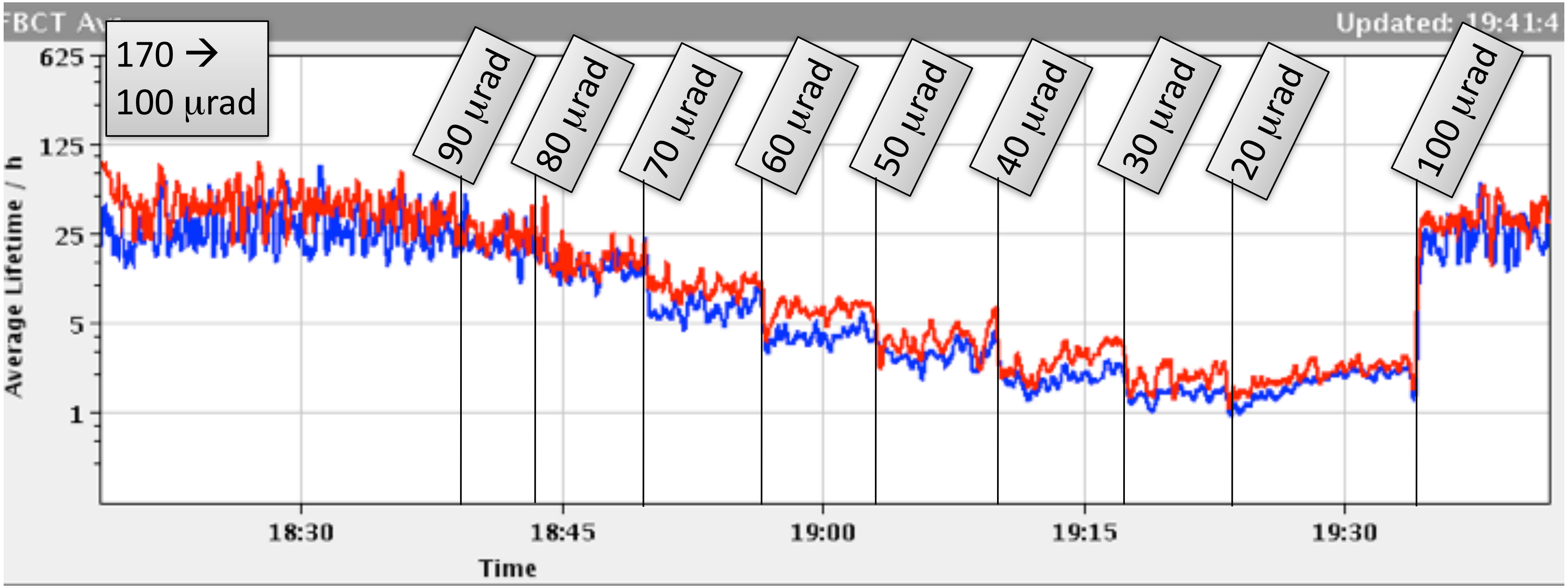


Illustration of collisions from few bunches as relevant for current operation

Recent news from the bunch train / crossing angle commissioning

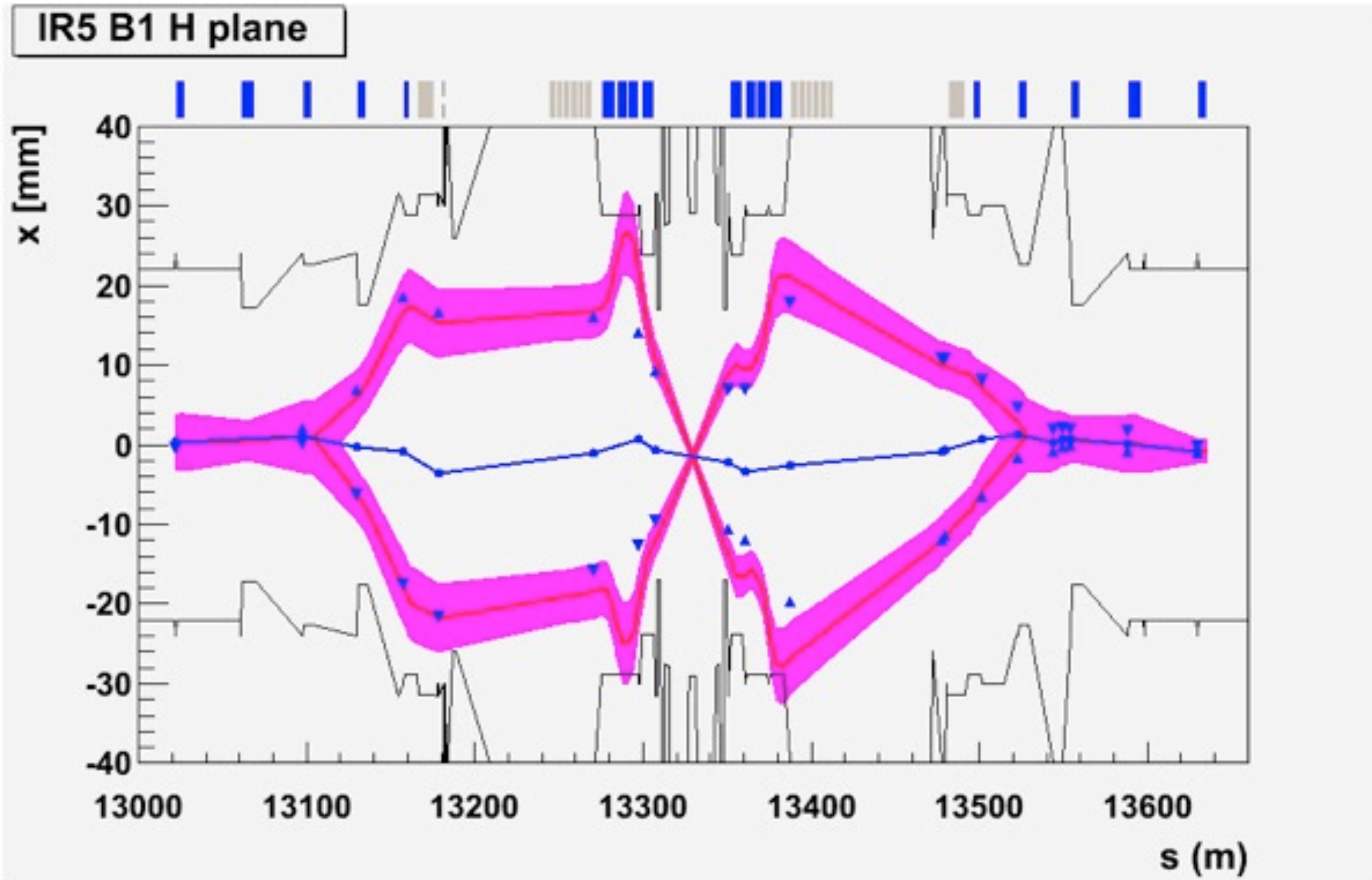
3 batches of 8 bunches each, spacing 150 ns ➔ up to 6 LR interactions per bunch



10/9/2010 Werner Herr et al.

Good news from beam-beam studies :
excellent lifetime with nominal 170 µrad crossing angle at injection
lifetime started to drop at 90 µrad
100 µrad crossing angle as in physics could still be acceptable – allowing potentially to keep the crossing angle constant through the cycle for this year

Going to operation with crossing angles potentially dangerous -- beam getting much closer to aperture limits just next to the experiments !



Aperture and losses were measured at injection with the crossing angle on Friday 10 Sept.

Measurements of aperture with crossing angle at injection

Emittance blow-up method

Loss at Q4 higher than at TCP

Loss at Q4 about same as TCP

Loss at Q4 lower than at TCP

Looking here at IR4 were aperture is expected to be tighest "n1=7" measured significantly more "n1=10–12"

11/9/2010 R.A. et al.

News from bunch train / crossing angle commissioning

Conclusion from aperture studies 9-12 Sept. with crossing angles at injection :

- **Plenty of aperture at triplets: > 13 σ (n1 > 10)**
- Can open tertiary collimators, from 8.5 to 13 σ at injection.
- Can provide 6σ margin to injection and dump protection to fulfill the machine protection and dump requirements.
- **Can stay with 170 μrad crossing angle at injection**
- **100 μrad would currently simplify operations** but may reduce flexibility in future
- **decided to go for 170 μrad (S. Myers, meeting Sat. morning, 11/09/2010)**
- **and to open up tertiary collimators at injection from 8.5 to 13 σ**

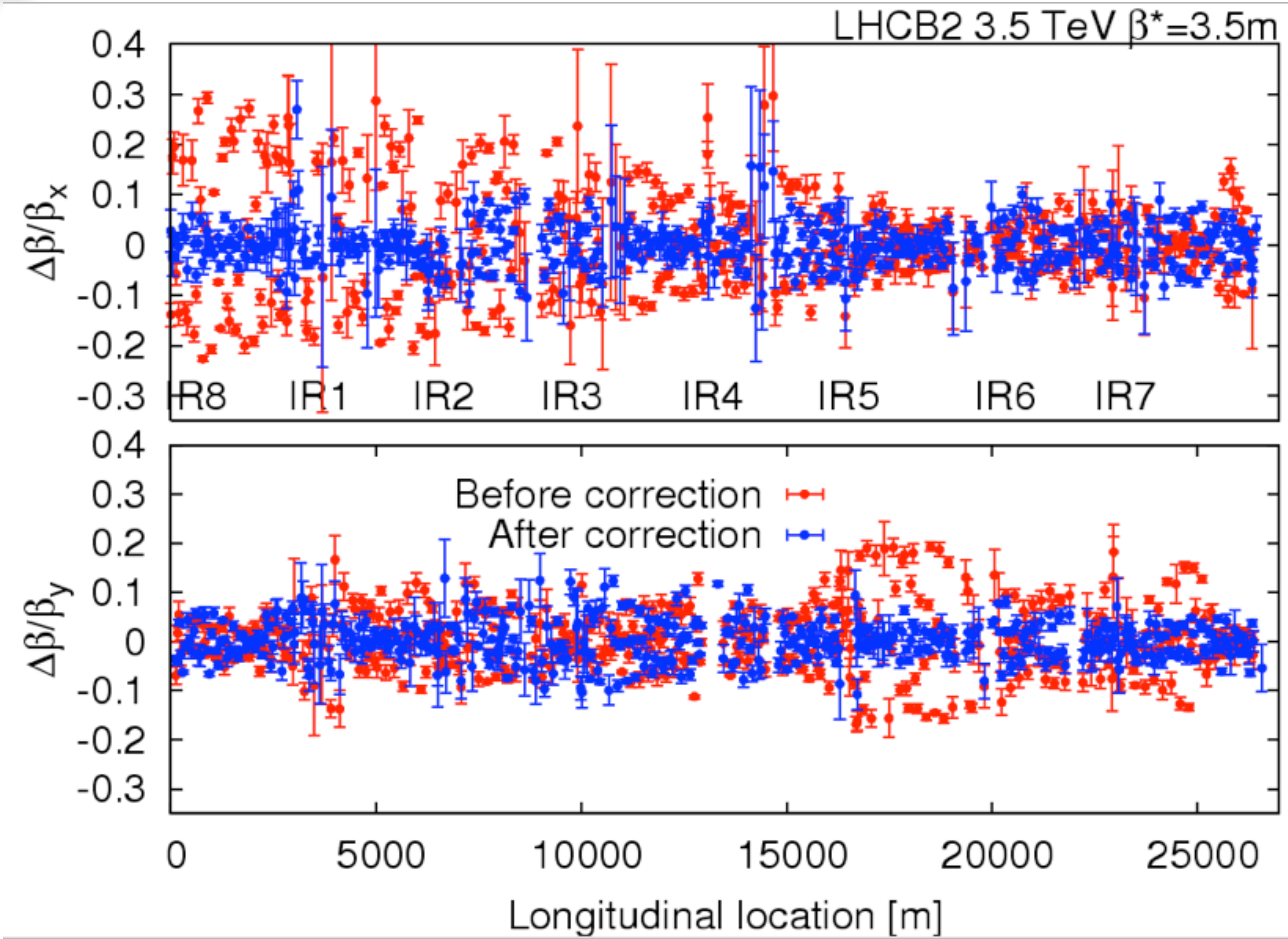
- **subject to further tests with beam - including asynchronous dump**

In addition to these major changes there are other recent changes / improvements :

- **Increased ramp speed 10A/s**
- **Injection steering, transfer lines, collimators re-adjusted**
- **energy matching and RF adjusts : smother ramp, allow for higher V_{rf} in coast**

  3.5-4 MV injection, from 5.5 MV to now ~ 8 MV (max. ~12 MV in 2010) at top energy
- **β-beating corrected, for the first time globally with many quadrupoles →**

β-beating measured and corrected



Rogelio Thomas et al.

Performance estimate

An estimate from M. Lamont July 2010

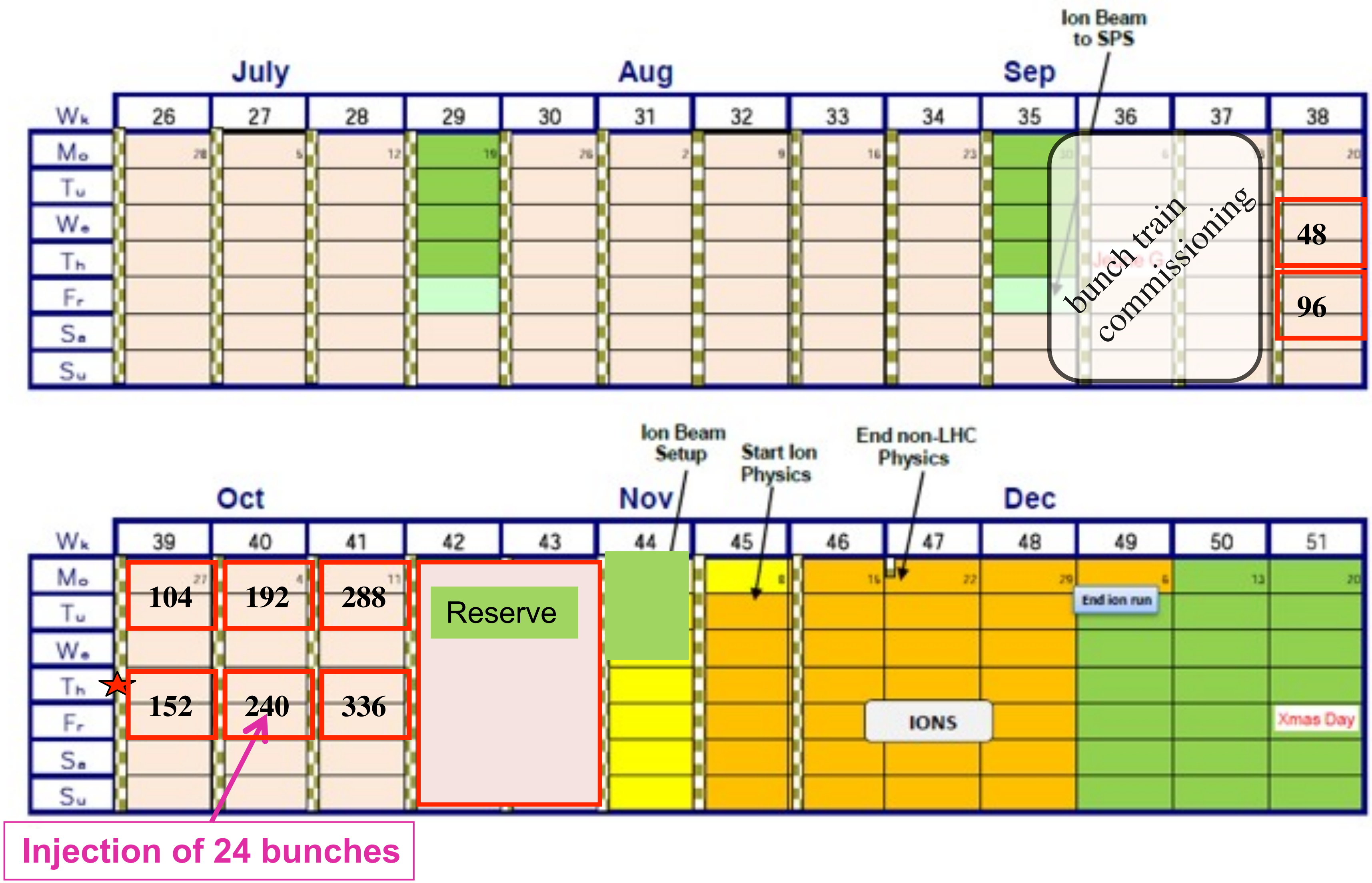
Table 2: Projected intensity increases and associated performance in 2010 with around nominal bunch intensity (1.1×10^{11}). All numbers approximate.

N_b	N_c	I_{tot}	Energy per beam [MJ]	Peak Luminosity [$cm^{-2}s^{-1}$]	Days	Int. Lumi [pb^{-1}]	Approx. date	
3	1	3×10^{11}	0.2	2.5×10^{29}	5	0.03	W4 June	
4	2	4×10^{11}	0.2	5.1×10^{29}	5	0.07	W1 July	
8	4	8×10^{11}	0.4	1.0×10^{30}	5	0.13	W2 July	
20	10	2×10^{12}	1.1	2.5×10^{30}	10	0.6	W3/4 July	
24	16	2.4×10^{12}	1.5	4.9×10^{30}	20	1.7	August	← exceeded by factor 2
48	32	4.8×10^{12}	3.0	9.8×10^{30}	10	1.7	September	
96	96	9.6×10^{12}	5.9	2.9×10^{31}	10	5.1	September	
144	144	1.4×10^{13}	8.9	4.4×10^{31}	10	7.6	October	
192	192	1.9×10^{13}	11.8	5.9×10^{31}	10	10.1	October	
240	240	2.4×10^{13}	14.8	7.3×10^{31}	10	12.7	November	

currently in very active phase of commissioning for a strong increase in intensity
with excellent rapid progress – but not much too time for production
very hard to predict, max. 8 days in November for protons
not excluded we do better than the above estimate (by factor 2-3 ??)

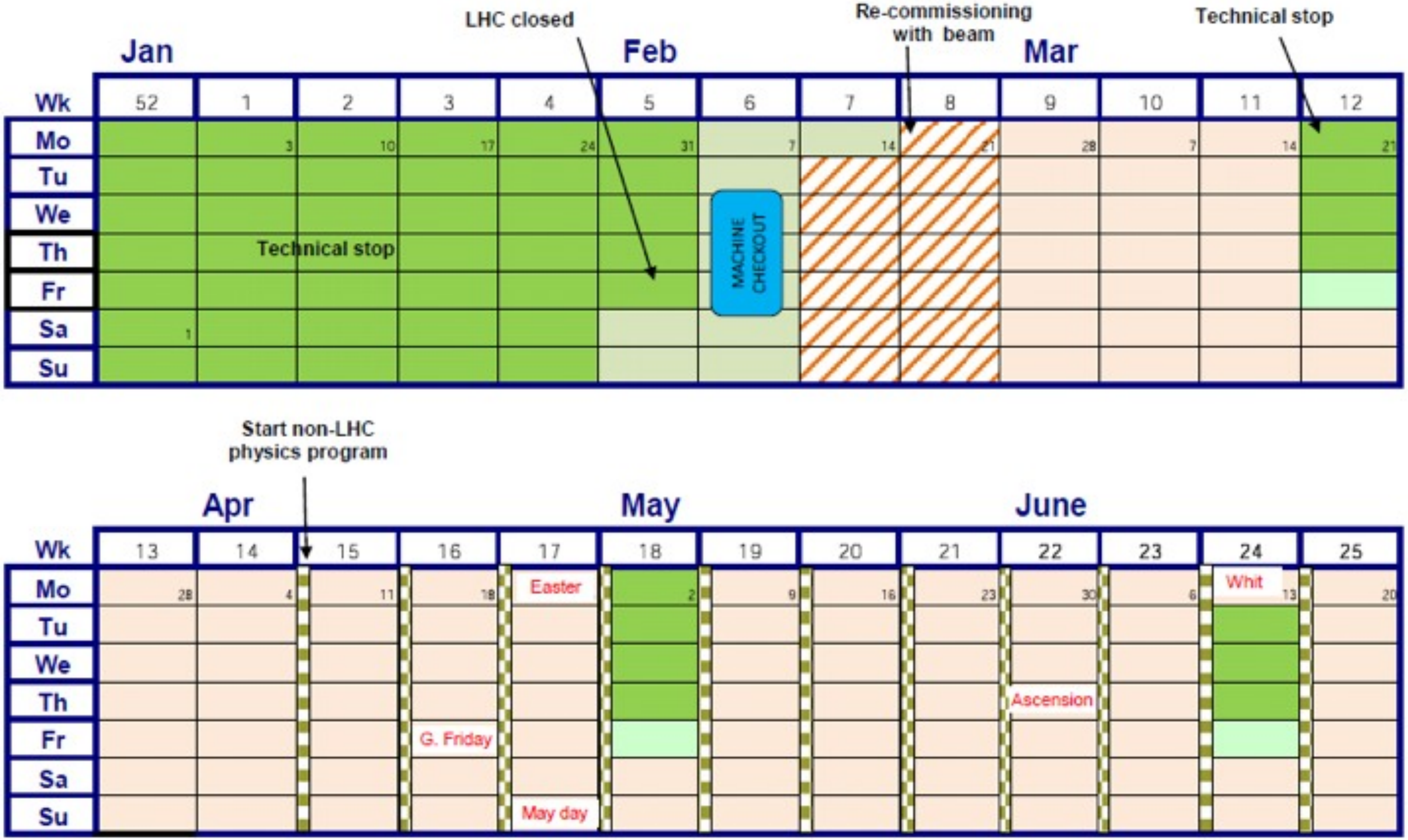
End of 2010 schedule

Ambitious schedule : increase #bunches, 2 steps every week, to get to L = 1.e32 cm^{-2}s^{-1}



based on Steve Myers LHCC 22/09/2010, minor update after M.L. presentation LMC#70 29/09/2010

2011 Q1&2


LHC closed
Re-commissioning with beam
Technical stop
Jan
Feb
Mar
Wk
52
1
2
3
4
5
6
7
8
9
10
11
12
Mo
Tu
We
Th
Fr
Sa
Su
Technical stop
MACHINE CHECKOUT
Start non-LHC physics program
Apr
May
June
13
14
15
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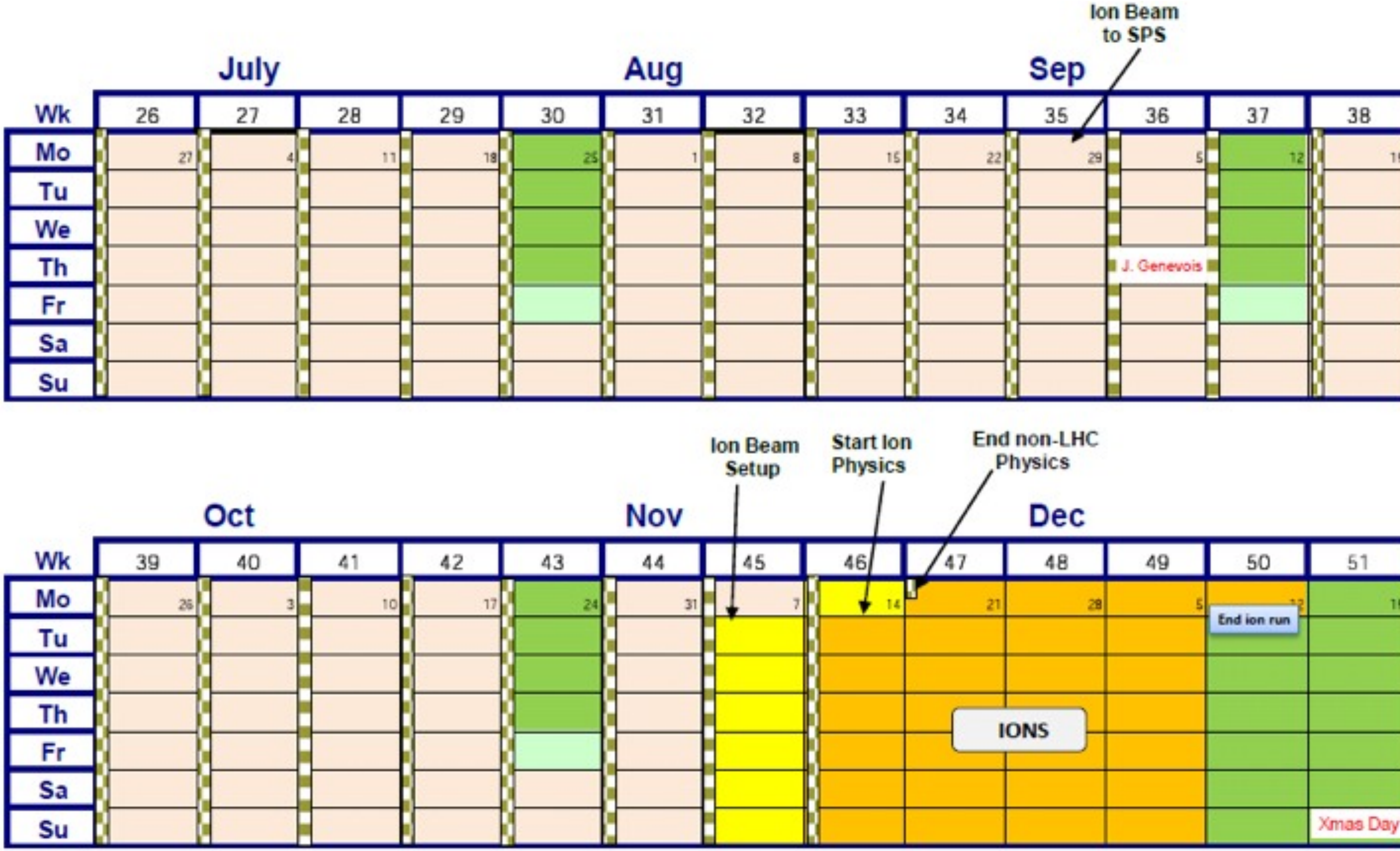
Easter
Whit
Ascension
G. Friday
May day

2011 Q3&4


Ion Beam to SPS
July
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Tu
We
Th
Fr
Sa
Su
J. Genevois
Ion Beam Setup
Start Ion Physics
End non-LHC Physics
Oct
Nov
Dec
Wk
39
40
41
42
43
44
45
46
47
48
49
50
51
Mo
Tu
We
Th
Fr
Sa
Su
End ion run
IONS
Xmas Day

2011 – 3.5 TeV

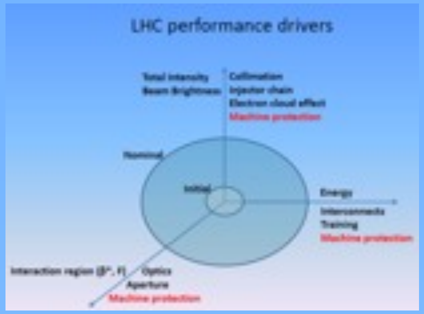
- Restart 4th February
- 9 months protons, 4 weeks ions
- Integrated luminosity target driven – 1 fb^{-1}
- Need to run flat out above 1e32 $cm^{-2}s^{-1}$

Table 4: Possible 2011 ball-park scenarios with 1.1×10^{11} protons per bunch.

N_b	β^* [m]	Energy per beam [MJ]	Peak Luminosity [$cm^{-2}s^{-1}$]	Int. Lumi per month [pb^{-1}]
432	3.5	27	1.3×10^{32}	61
432	2.5	27	1.8×10^{32}	85
796	3.5	49	2.4×10^{32}	113
796	2.5	49	3.4×10^{32}	157

Getting to nominal (dates indicative)

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

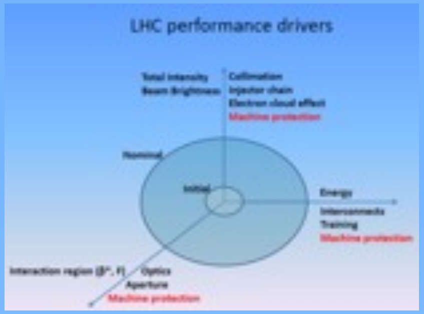


2010	2011	2012	2013	2014	2015	2016
Energy 3.5TeV		Splices, Collimators in IR3	Increase Beam Energy to 7TeV			
β^* of 2m			Decrease β^* to 0.55m			
20% of I_{nom}			Increase k_b to 2808			
Initial			Nominal			
2 10^{32}			10^{34}			
1 fb^{-1}			≤ 50 fb^{-1}/yr			

R. Bailey Aug.2010

Overall strategy beyond 2016 (dates indicative)

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



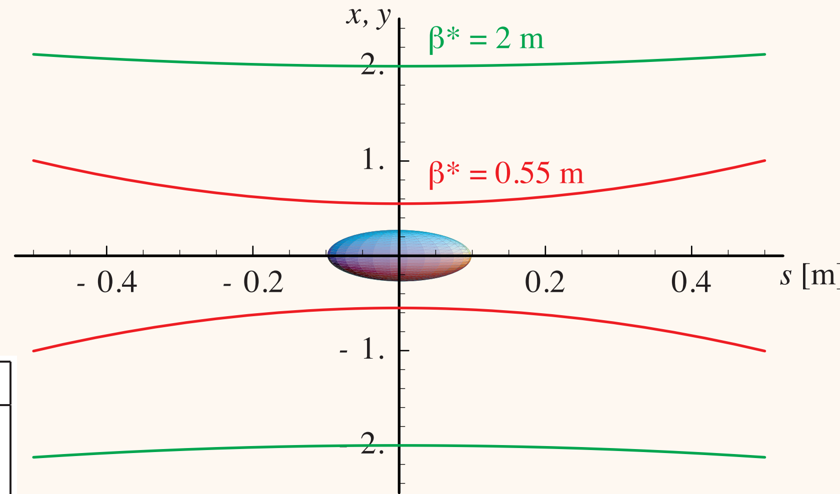
2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	etc.
														Increase Beam Energy to 16.5 TeV					
				New interaction region (β^* to 0.2m, luminosity leveling)															
Increase beam brightness																			
Ultimate				HL-LHC										HE-LHC					
2.3 10^{34}				5 10^{34}										2 10^{34}					
≤ 100 fb^{-1}/yr				≤ 200 fb^{-1}/yr										≤ 100 fb^{-1}/yr					

R. Bailey Aug.2010

Luminosity reduction; hourglass effect and crossing angle

Hourglass effect. Relevant when β* is decreased close to the bunch length σ_z
Define $r = \beta^* / \sigma_z$. Luminosity gets reduced. For round beams the factor is

$$H(r) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{e^{-s^2}}{1 + s^2/r^2}\, ds = \sqrt{\pi}\, r\, e^{r^2}\, \mathrm{Erfc}(r)$$



LHC nominal
σ_z = 7.55 cm
or 1 ns for 4σ ; 16 MV
currently ~ 1.2 ns, 12 MV

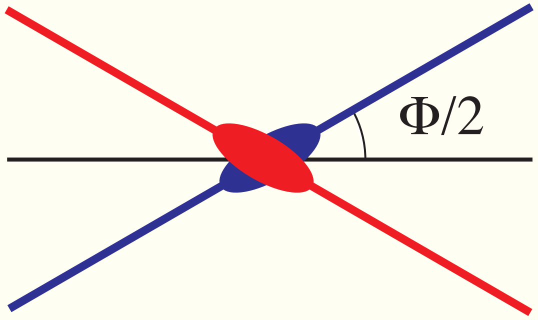
β^*	r	$H(r)$
10.	132.	0.999972
2.	26.5	0.999289
1.	13.2	0.997174
0.55	7.28	0.990833

negligible effect for β* > 2m and still small for nominal β*

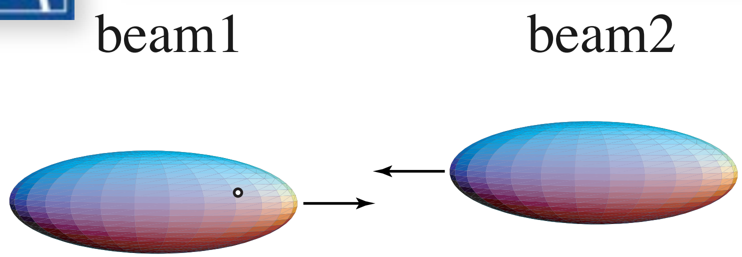
Factor from crossing angle in one plane (x) : $$S = \frac{1}{\sqrt{1 + \left(\frac{\sigma_z}{\sigma_x} \tan\frac{\Phi}{2}\right)^2}}$$

σ_x [μm]	σ_z [mm]	$\Phi/2$	S	
59.3	0.0755	100	0.992	3.5 TeV, $\beta^* = 3.5$ m, July 2010
16.6	0.0755	142.5	0.840	7 TeV, $\beta^* = 0.55$ m, nominal

small effect



Beam-beam effects

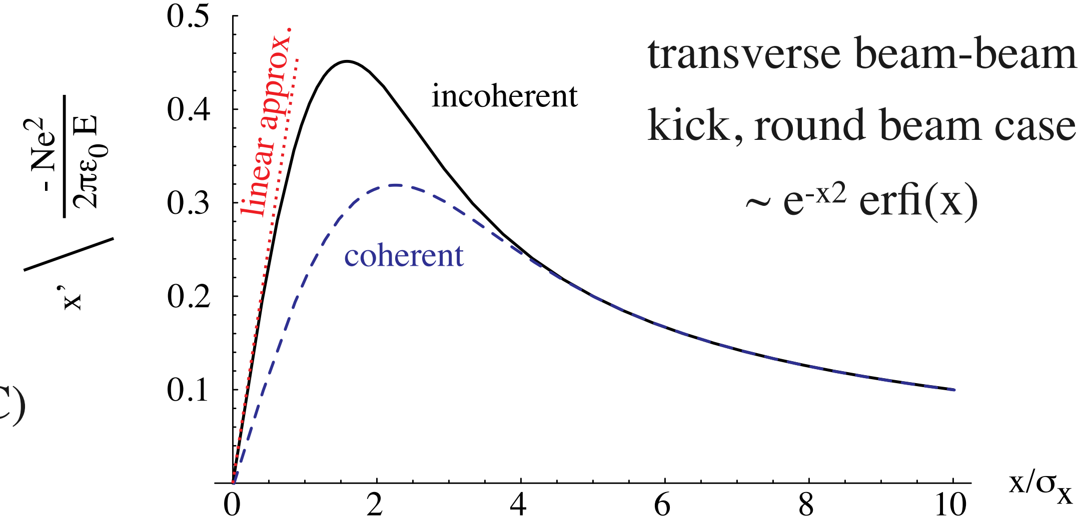


for small x approx. linear kick x' ∝ x

like quadrupole but **same in both planes**,

defocusing if beam1, 2 have same charge (LHC)

and focusing for opposite charge (e+e-, $\mathbf{p\bar{p}}$)



separation in σ

tune shift from linear kick $\Delta Q_x = -\frac{\beta_x}{4\pi}\frac{\Delta x'}{x}$

this maximum tune shift - effective for particles at the bunch centre - is used to quantify the beam-beam effect.

N = bunch population,

r_c = classical particle (e, p) radius

$$\xi_{x,y} = \frac{r_c \; N \, \beta^*_{x,y}}{2\pi \, \gamma \, \sigma_{x,y} \, (\sigma_x + \sigma_y)}$$

LEP

$\xi_{x,y}$ ~ .03 -.08

LHC round beams, const ε_N $\quad \sigma_{x,y} = \sqrt{\beta_{x,y} \, \epsilon_N / \gamma}$

$$\xi = \frac{r_c \, N}{4\pi \, \epsilon_N}$$

N	ξ
5×10^9	0.000163
4×10^{10}	0.00130
1.15×10^{11}	0.00374

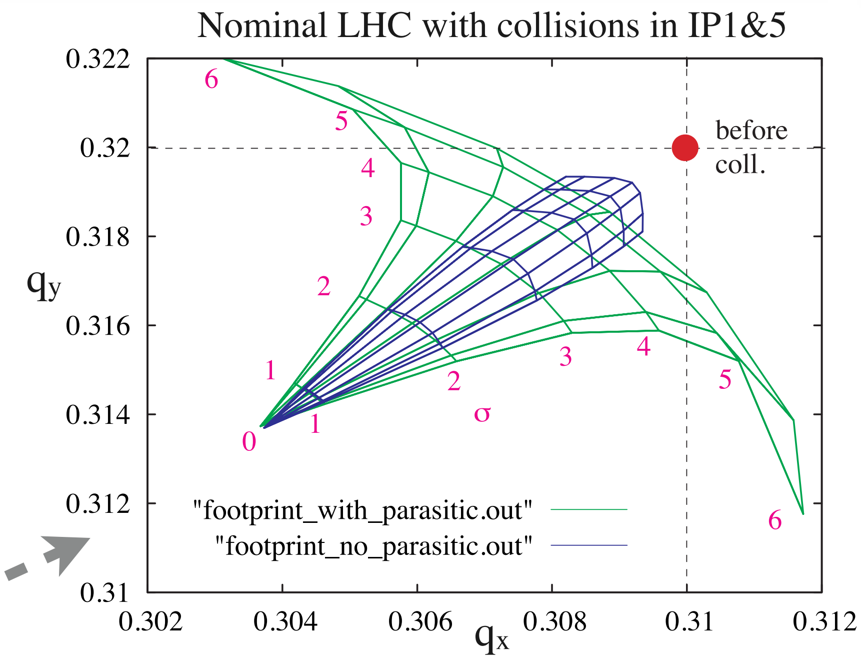
at the design emittance $\varepsilon_N = 3.75$ μm

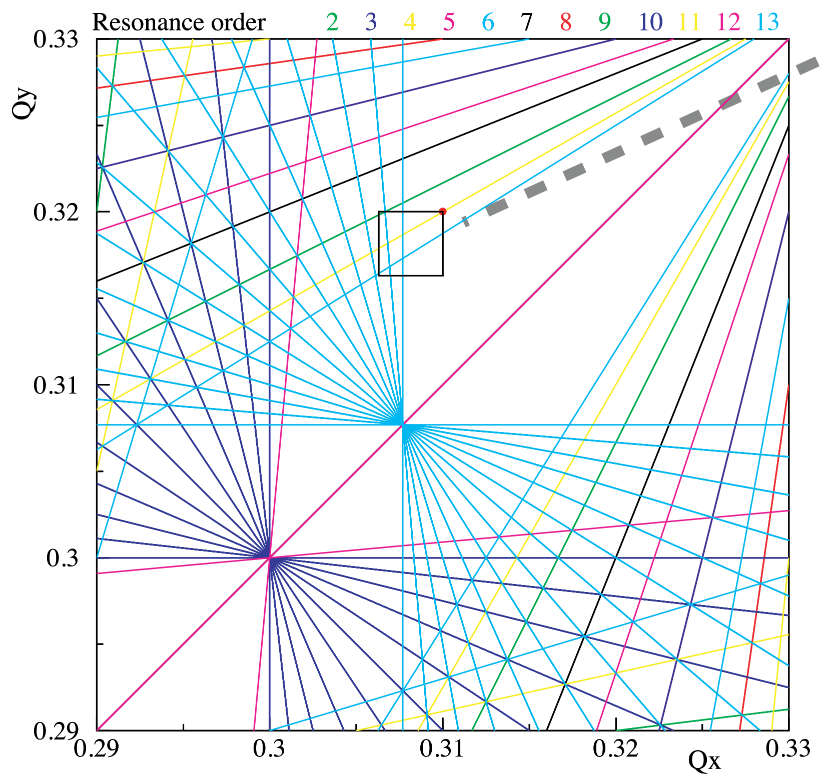
already exceeded by factor 1.5 with

N = 1.e11 ; $\varepsilon_N = 2.2$ μm ; $\xi \approx 0.0056$

Beam-beam footprint and tune diagram

Parasitic beam-beam effects. Can be completely avoided up to 156 bunches.
Then gradually becoming an issue. Gain first experience on this in the 2009 / 2010 run
Nominal, IP1/5 : each 30 parasitic collisions ~ 9σ
Parasitic b.b. effects reduce with fewer bunches or increased crossing angle



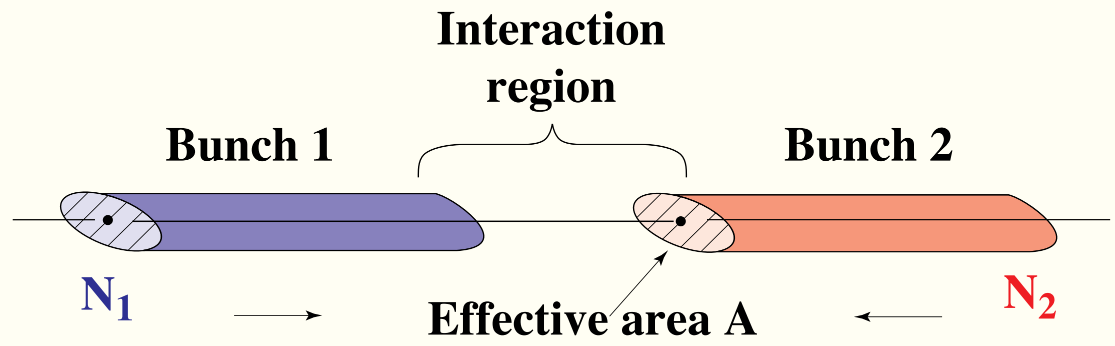


Some ref.
W. Herr, M. Zorzano LHC Project Report 462 ; Tatiana Pieloni thesis
Figures above from S. M. White, H. Burkhardt, S. Fartoukh, T. Pieloni, *Optimization of the LHC Separation Bumps Including Beam-Beam Effects WE6PFP018,* PAC'09

Absolute Luminosity Normalization

Luminosity from bunch crossings at frequency $f = f_{rev}\, n_b$

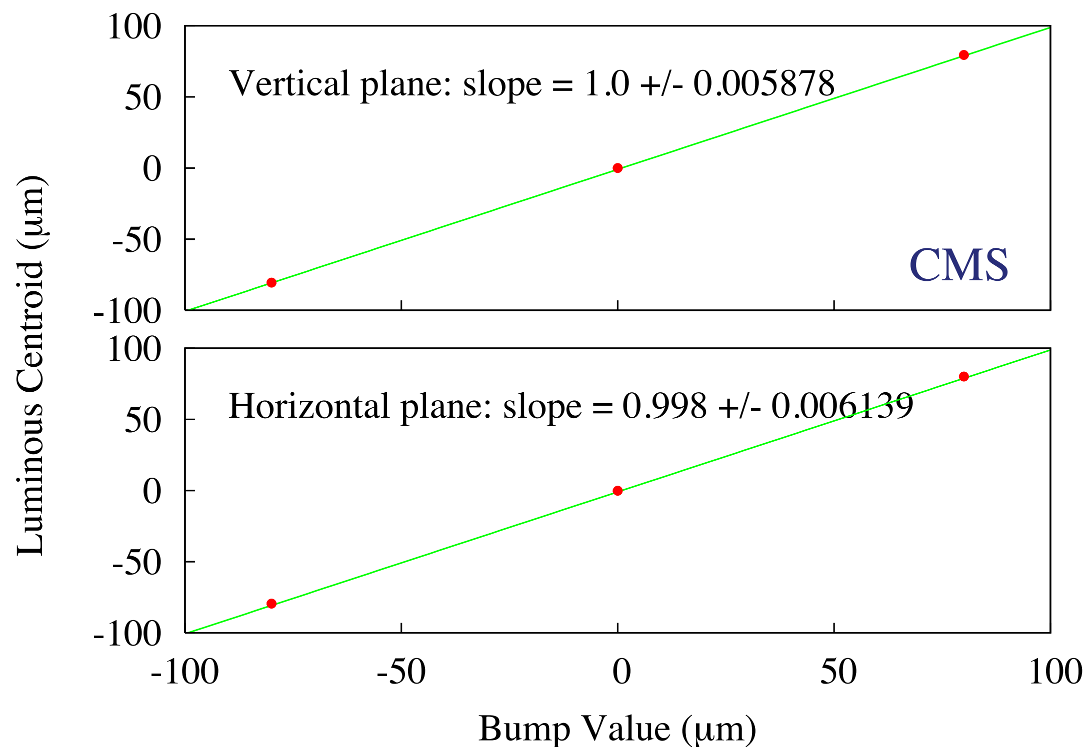
$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$



for Gaussian bunches with rms sizes $\sigma_x\, \sigma_y$ $\quad \mathbf{A} = 4\,\pi\,\sigma_x\,\sigma_y$

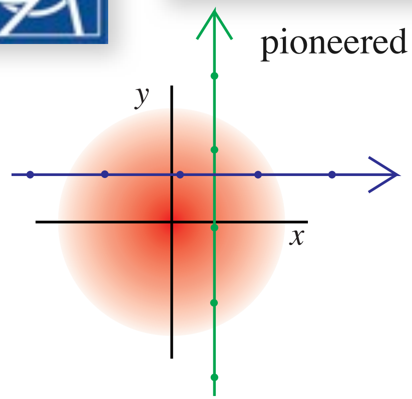
The overlap area is directly measured in separation scans , pioneered by Simon Van der Meer @ ISR

length scale calibrated displacing both beams using the vertex information from detectors



Luminosity scans and absolute luminosity

pioneered by Van der Meer @ ISR;   proposed for the LHC by Grafstrom + myself; LHC Report 1019; May 2007

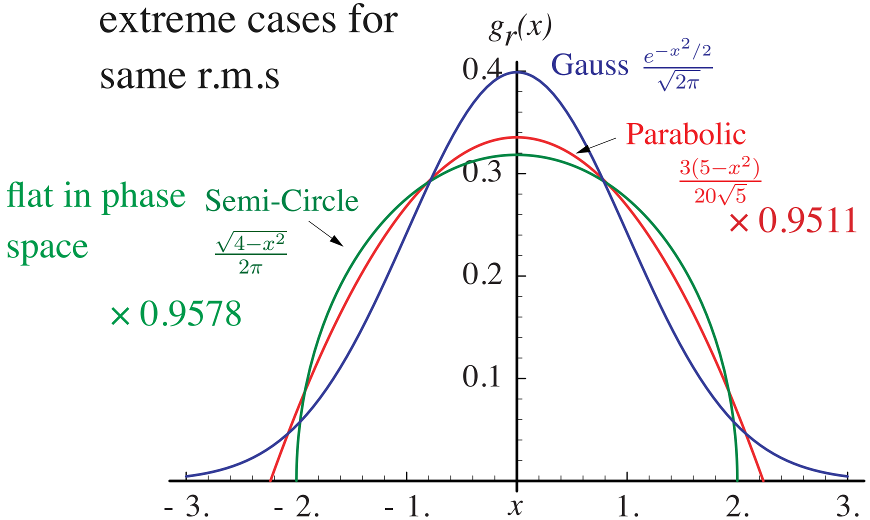


Orthogonal x, y scans to determine $\sigma_{x,y}$*

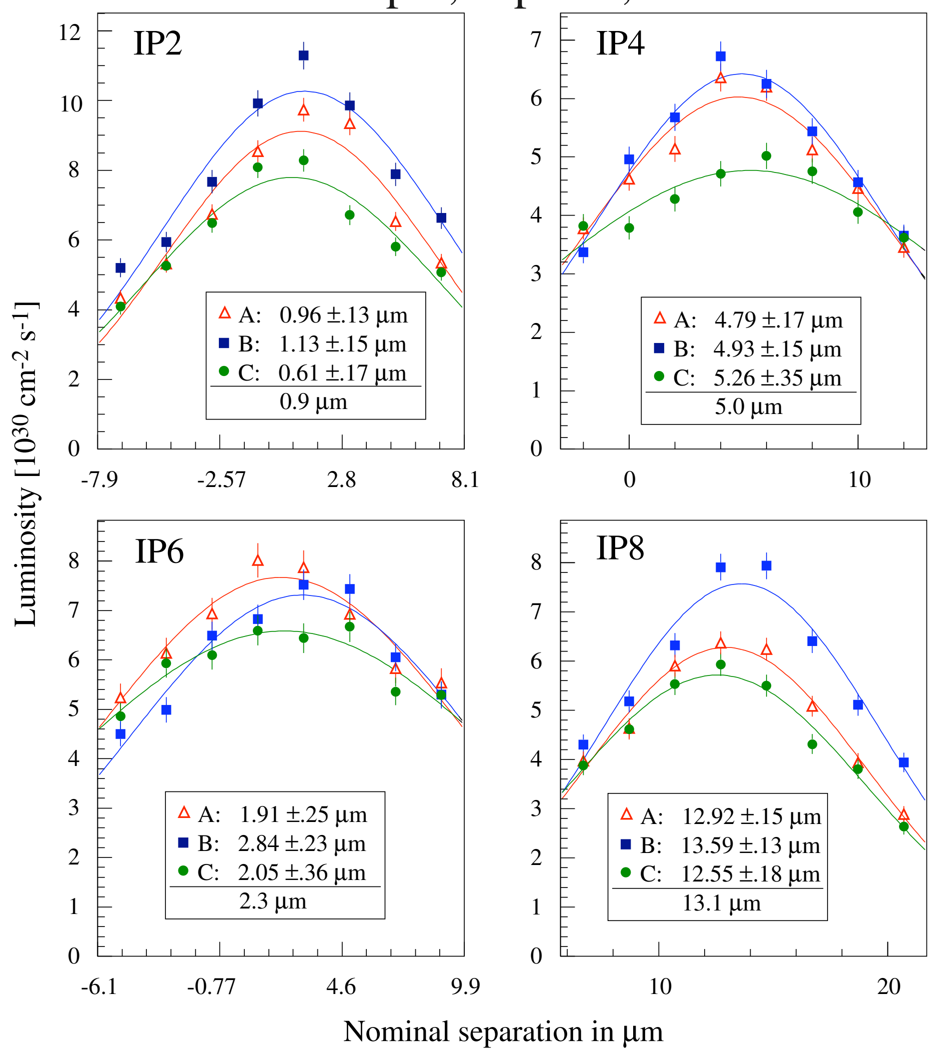
$$\mathcal{L} = \frac{N_1 N_2 f}{4\pi\, \sigma_x\, \sigma_y}$$

$$\frac{\mathcal{L}}{\mathcal{L}_0} = \exp\left[-\left(\frac{\delta x}{2\sigma_x}\right)^2 - \left(\frac{\delta y}{2\sigma_y}\right)^2\right]$$ gaussian beams

Beam shape :
extreme cases for
same r.m.s



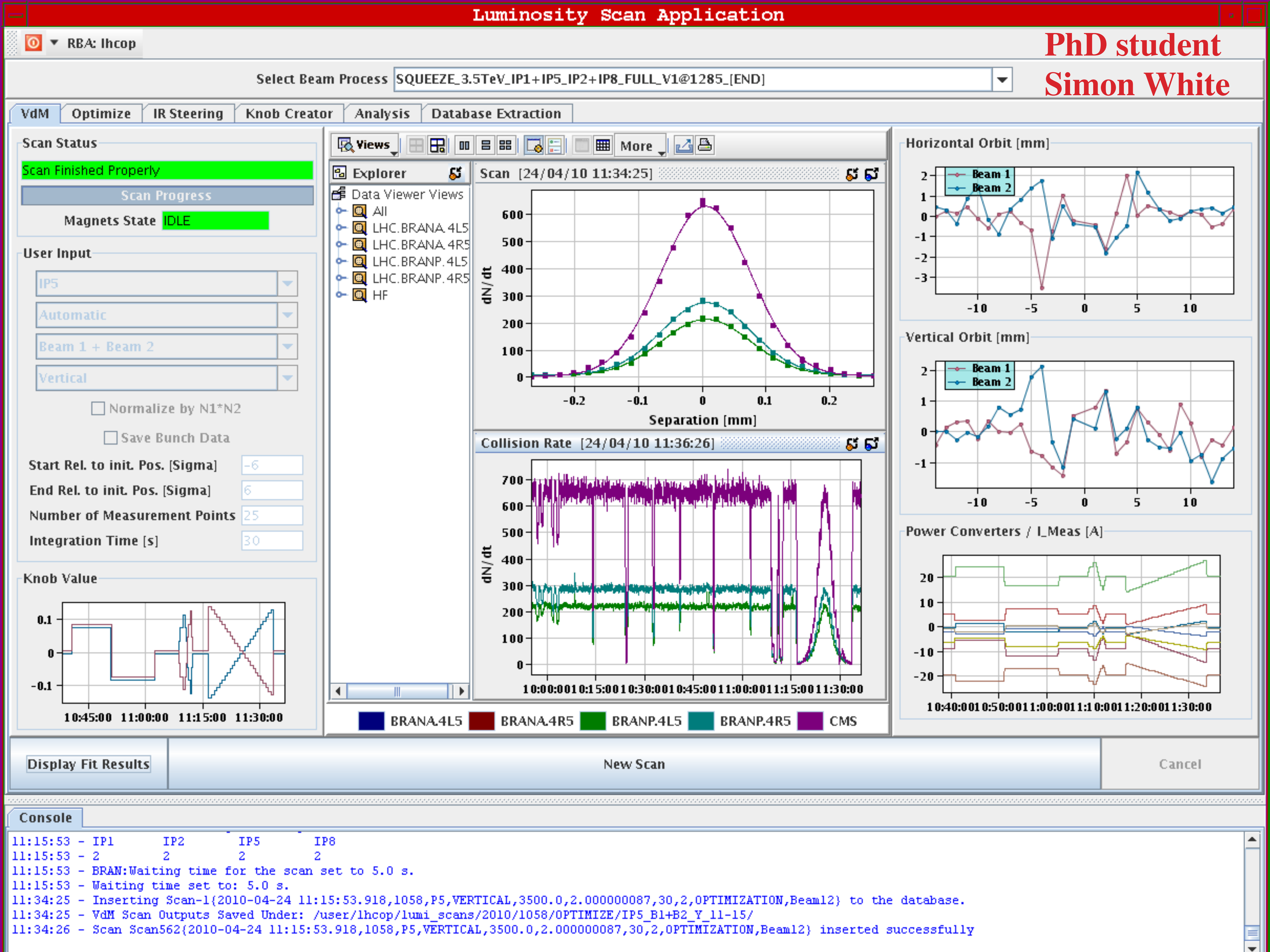
LEP example, V-plane, 3 bunches



Realistic beam shapes are close to Gaussian and precisely measured in the scan ;
can be complemented by vertex distribution and beam-gas measurements

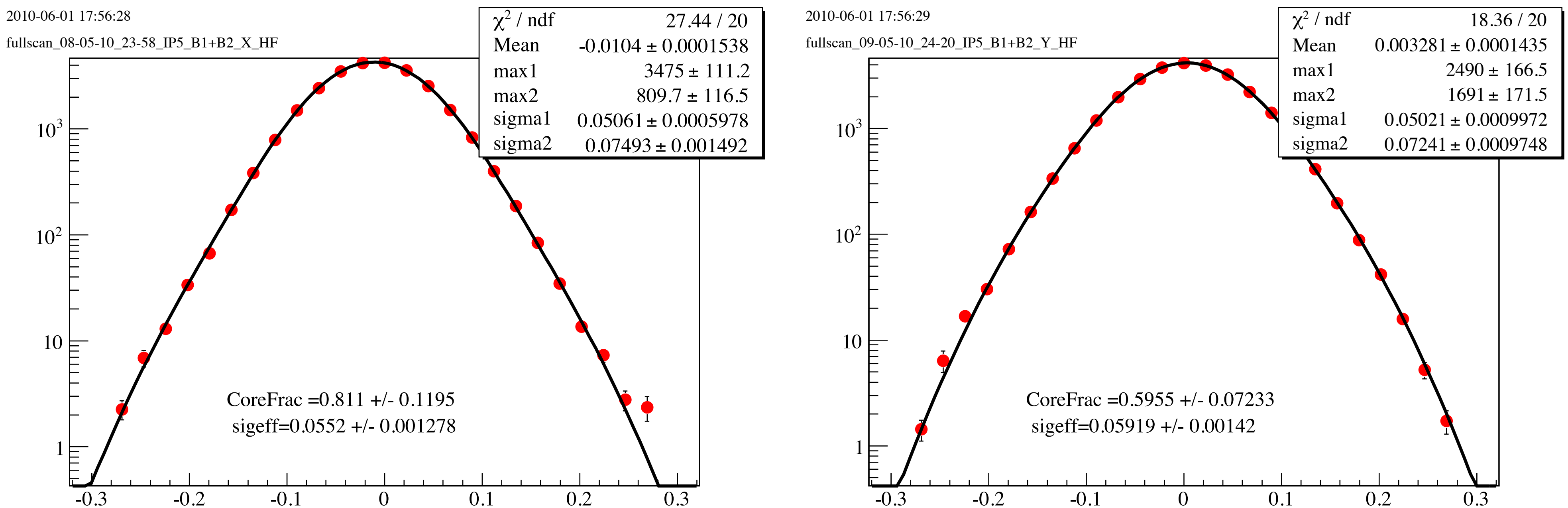
H.B., R. Schmidt, *Intensity and Luminosity after Beam Scraping*, CERN-AB-2004-032

Tails measured by extended scans. Limited by aperture. Also possible to measure / reduce with scraping


Luminosity Scan Application
RBA: lhcop
PhD student
Simon White
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
IP5
Automatic
Beam 1 + Beam 2
Vertical
Normalize by N1*N2
Save Bunch Data
Start Rel. to init. Pos. [Sigma]
-6
End Rel. to init. Pos. [Sigma]
6
Number of Measurement Points
25
Integration Time [s]
30
Knob Value
Views
More
Explorer
Data Viewer Views
All
LHC.BRANA.4L5
LHC.BRANA.4R5
LHC.BRANP.4L5
LHC.BRANP.4R5
HF
Scan [24/04/10 11:34:25]
dN/dt
Separation [mm]
Collision Rate [24/04/10 11:36:26]
BRANA.4L5
BRANA.4R5
BRANP.4L5
BRANP.4R5
CMS
Horizontal Orbit [mm]
Beam 1
Beam 2
Vertical Orbit [mm]
Power Converters / I_Meas [A]
Display Fit Results
New Scan
Cancel
Console
11:15:53 - IP1 IP2 IP5 IP8
11:15:53 - 2 2 2 2
11:15:53 - BRAN:Waiting time for the scan set to 5.0 s.
11:15:53 - Waiting time set to: 5.0 s.
11:34:25 - Inserting Scan-1{2010-04-24 11:15:53.918,1058,P5,VERTICAL,3500.0,2.000000087,30,2,OPTIMIZATION,Beam12} to the database.
11:34:25 - VdM Scan Outputs Saved Under: /user/lhcop/lumi_scans/2010/1058/OPTIMIZE/IP5_B1+B2_Y_11-15/
11:34:26 - Scan Scan562{2010-04-24 11:15:53.918,1058,P5,VERTICAL,3500.0,2.000000087,30,2,OPTIMIZATION,Beam12} inserted successfully

First extended scans : beams very clean

Example for illustration from online data sent by CMS to the CCC
Showing a scan by ±3 nominal σ for CMS in LHC fill 1089
2e10 protons / bunch; single colliding pair



Beam shape very well described by a double gaussian. Low background.
No extended tails.

Offline analysis done by the experiments – in close contacts with us :
Working groups LBS + LPC, BCNWG on intensity measurement

Overall uncertainty from very first scans ~ 11%, dominated by the uncertainty in the intensity determination

Luminosity scans - which precision could be reached ?

- the first experience from the scans (~ two per experiment) done so far was very promising
  two different types of uncertainties
- intensity "N1 × N2"; 3-4 % from BCT specification JJ. Gras et al. Beam Instrum. group
- luminous region "$\sigma_x \times \sigma_y$"; very clean nearly Gaussian beams,
- we can hope to get down to 5% in the second round of calibration scans scheduled now
  using the current LHC beam setup – with fewer bunches (~10), moderate bunch intensity
  (≤ 8e10, matched for good BCT precision); ATLAS + CMS calibration in same fill
  increase #points in the length scale calibration

Is there an interest to push this further ? -- Recent answer : Yes !!

What might be the ultimate precision ? → Lumi workshop in Jan 10. week 2011

What about 1% as for the ISR ? G. Carboni et al., Nucl. Phys. B 254 (1985) 697; K. Potter CAS'92

Would certainly require much more work and probably extra instruments

One idea exotic -- other ideas welcome

Intensity normalisation by proton counting (for example with diamond detectors) when slowly scraped off :

40 MHz × 100 sec = 4×10^9 protons

Further information, bibliography - with authors from the machine

Documentation of details in forthcoming PhD thesis :

Simon White, Determination of the Absolute Luminosity in the LHC;

thesis defense Paris XI, Orsay 11/10/2010

Yngve Levinsen, Study of LHC Experimental Conditions and Machine Induced Detector Backgrounds; Autumn 2011

H.B. and Per Grafstrom; Absolute Luminosity from Machine Parameters, LHC Report 1019 May 2007

IPAC2010 proceedings :

First Luminosity Scans in the LHC, MOPEC014

Beam-gas Loss Rates in the LHC, TUPEB072

Dependence of Background Rates on Beam Separation in the LHC, TUPEB073

Characterization of Interaction-Point Beam Parameters .. in the ATLAS Detector at the LHC, MOPEC008

Concluding remarks

The LHC performs very well in the early physics operation

Single beam parameters (intensity, b.b. tune shift) reached nominal parameters

The increase in single bunch intensities was rather fast and smooth

Potential limitations : beam-beam effects and now the aperture in the presence of crossing angles – less critical then conservative estimates

Next : increase the number of bunches - mostly a challenge for beam-protection including beam-dump and collimation

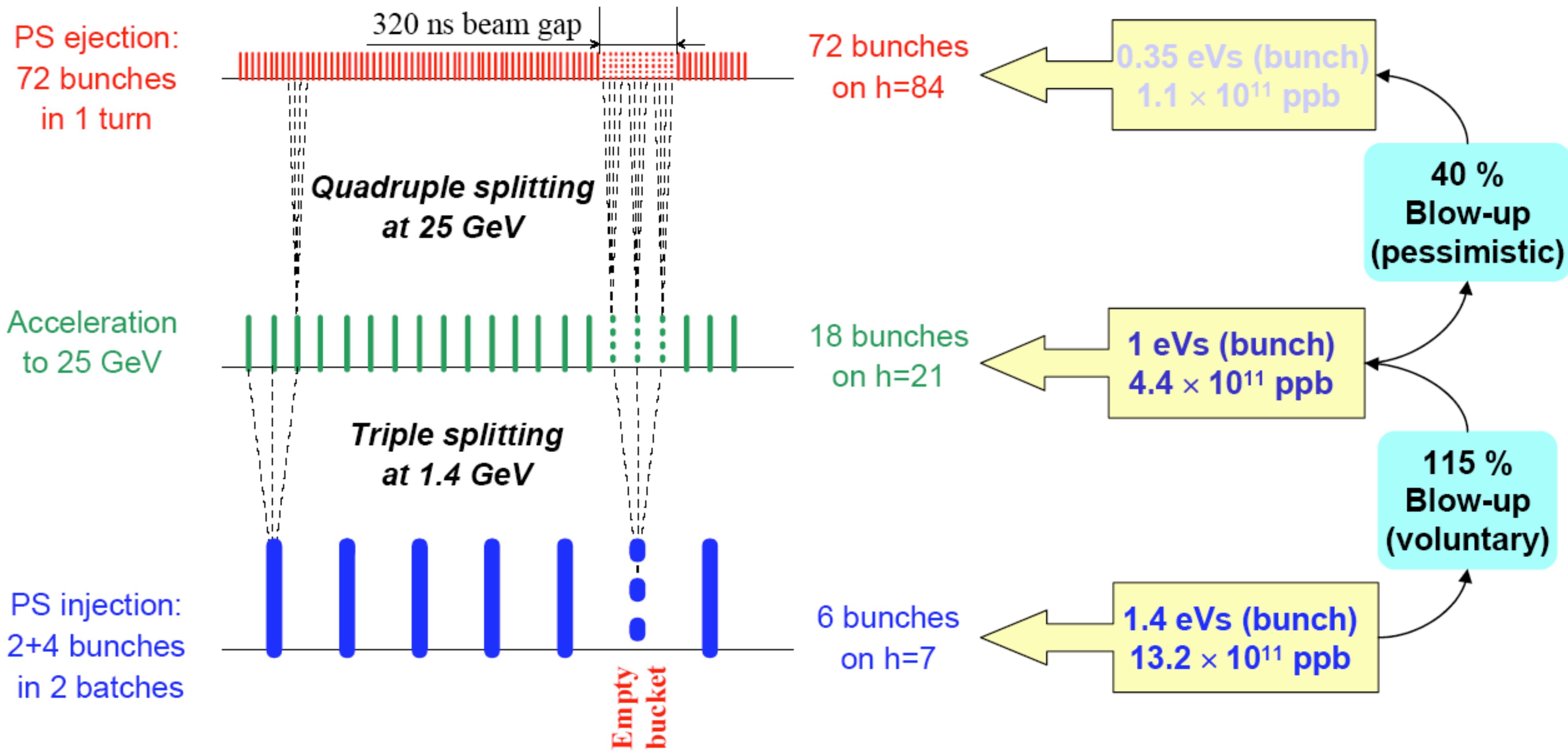
but also : improved and tighter control of many parameters and tolerances, decrease differences between beams and bunches; identify and reduce any sources of blow up pick-up and vibrations

Optimization tools : lumi scans, tunes (and b1, b2 tune split), minimize optics errors like beta beating, transverse damper, ...

Backup Slides

Nominal 25 ns batch, PS

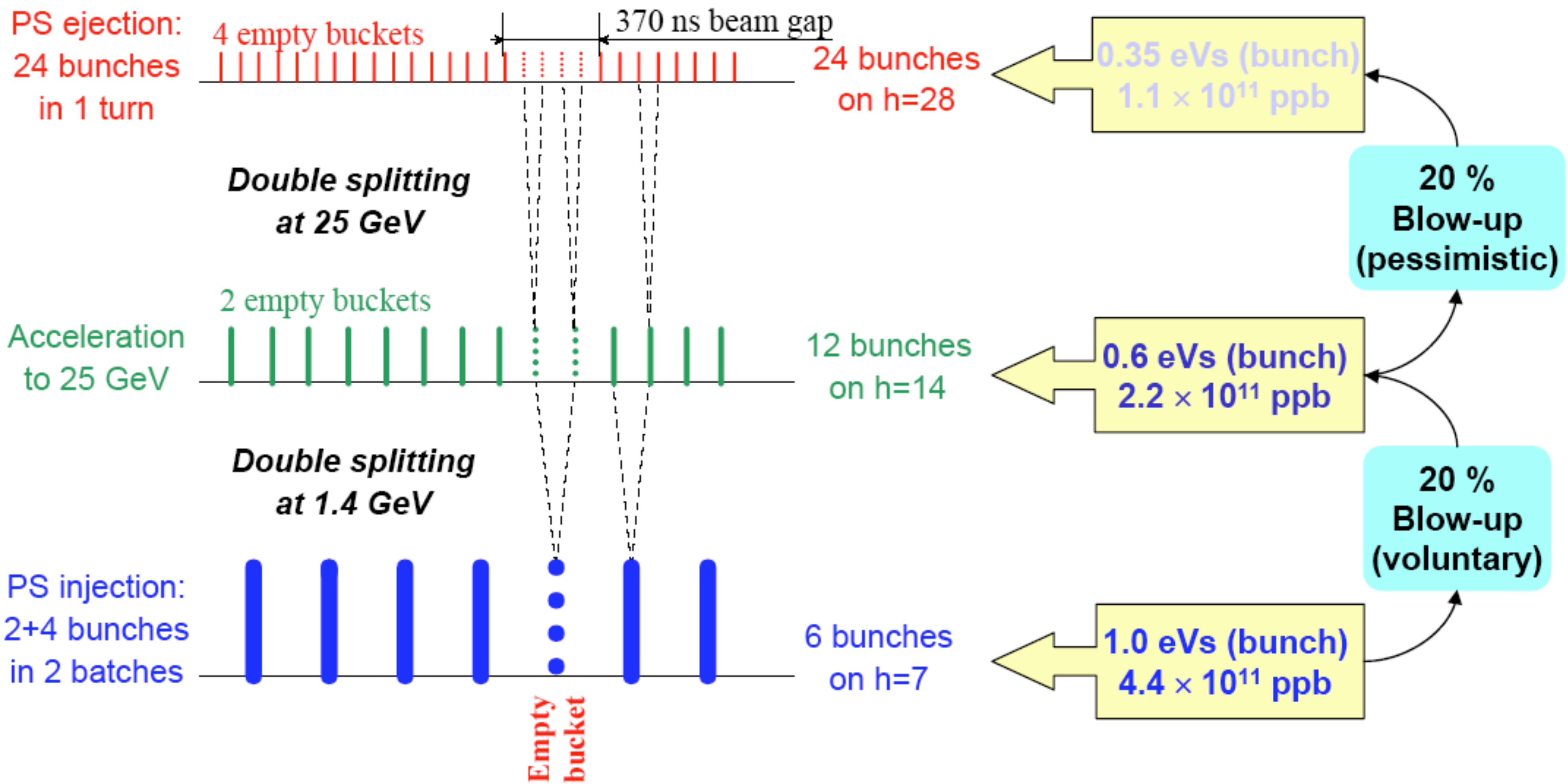
Batches (or bunch trains) of up to 72 bunches with 25 ns spacing are made in the PS from 6 bunches from Booster, using splitting in 2 steps $6 \times 3 = 18$ $18 \times 4 = 72$



from R. Garoby, Chamonix 2003

75 ns batch, PS

Batches of up to 24 bunches with 75 ns spacing are made in the PS from 6 bunches, double splitting in 2 steps   6 × 2 = 12   12 × 2 = 24



Compared to 25 ns : starting from much less intense 6 bunches, less blowup in splitting, resulting in similar long. emittance

from R. Garoby, Chamonix 2003

Beam-beam kick

Gaussian beams of elliptical cross section, beam-beam deflection angle and kicks using Basetti-Erskine function f_{BS}

$$\theta_{0\pm} = \frac{N_{\mp} e^2}{2\pi\,\epsilon_0\; E_{\pm}\;(\sigma_{x\mp} + \sigma_{y\mp})} = \frac{2 N_{\mp} r_c}{\gamma_{\pm}\;(\sigma_{x\mp} + \sigma_{y\mp})}$$

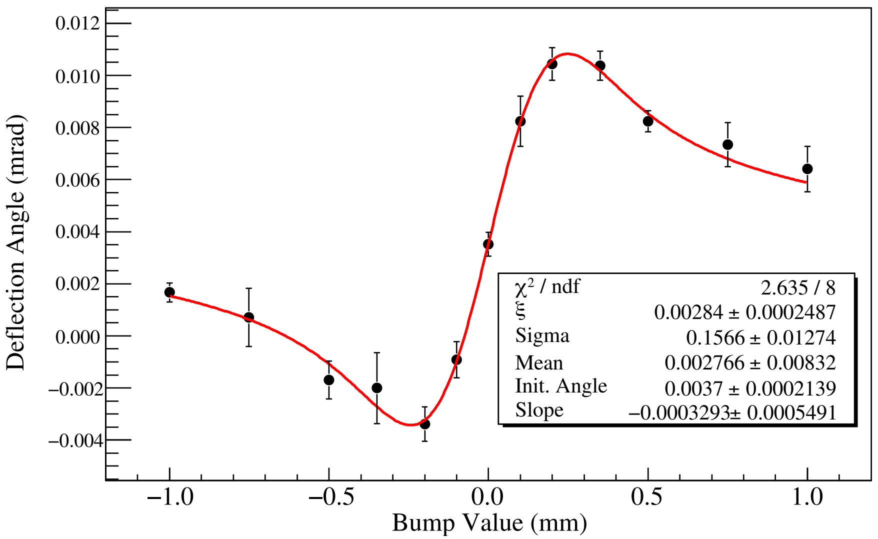
$$\Delta x'_{\pm} - i\Delta y'_{\pm} = -\theta_{0\pm}\; f_{\mathrm{BS}}(x_{\pm} - \overline{x}_{\mp}, y_{\pm} - \overline{y}_{\mp}; \sigma_x^{\mp}, \sigma_y^{\mp})$$

Round gaussian beams, $\sigma_x = \sigma_y = \sigma_r$ ~ the case of the LHC

$$\theta_0 = \frac{N e^2}{2\pi\,\epsilon_0\; E\;(\sigma_x + \sigma_y)} = \frac{N e^2}{2\pi\,\epsilon_0\; E\; 2\,\sigma_r} = \frac{N r_c}{\gamma\,\sigma_r}$$

$$\Delta r' = -\frac{N\,e^2}{2\pi\epsilon_0\,E}\,\frac{1 - \exp\frac{-r^2}{2\sigma_r^2}}{r} = -2\,\sigma_r\;\theta_0\;\frac{1 - \exp\frac{-r^2}{2\sigma_r^2}}{r}$$

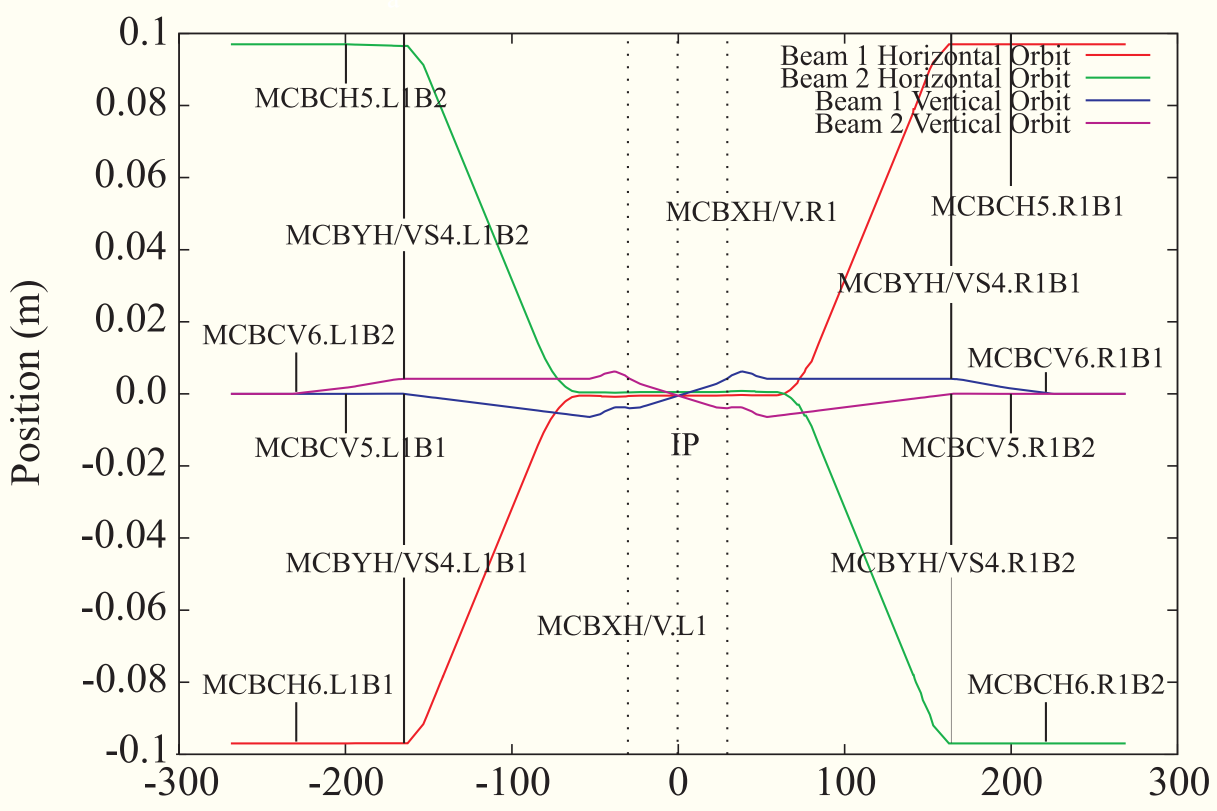
60 µrad LEP2, measurable, deflection scans
1.4 µrad for nominal LHC parameters
visible in RHIC :



A. Drees, S. White, et al. IPAC 2010

IR-bumps

two types of magnetic separation bumps :
parallel separation to avoid collisions in beam preparation, off in physics
crossing angle to avoid parasitic collisions, always required for > 156 bunches
IR1 : horizontal separation and vertical crossing angle
IR5 : vertical separation and horizontal crossing angle



courtesy Simon White

orbit corrector magnets used in the IP bumps

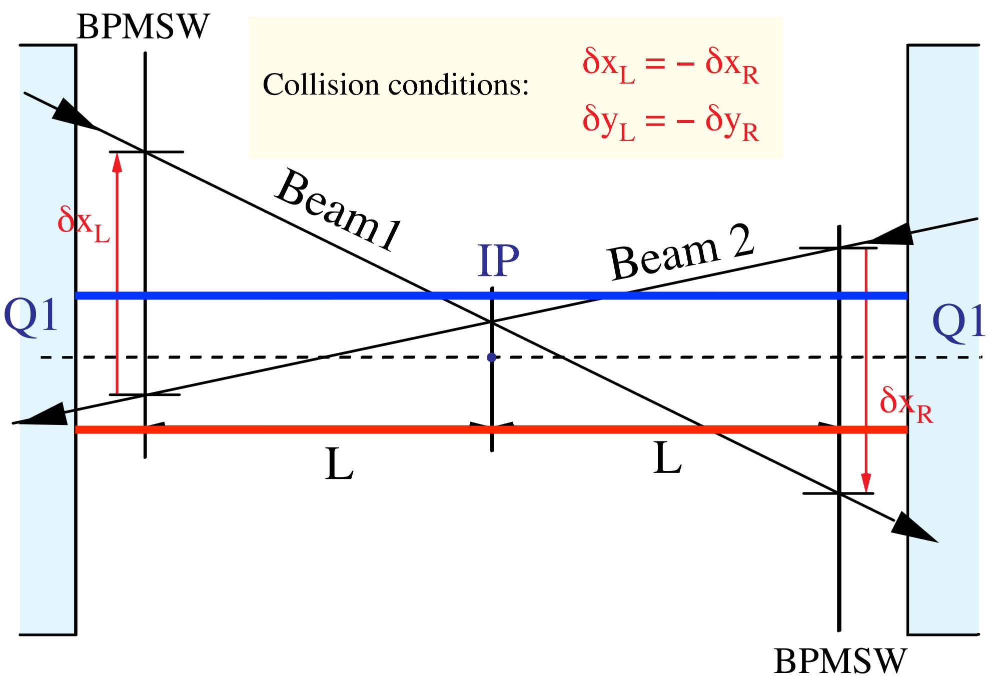
MCBX in triplet - important for crossing angle and aperture at injection

collapse bump by combination of MCBC, MCBY and MCBX
or ramp down MCBX first

Separation scans, optimization with MCBC, MCBY on one beam

Get LHC beams colliding : BPM resolution

adjust orbits such, that the beam 1 and 2 difference left/right of the IP is the same
beams must then collide. This is independent of mechanical offsets and crossing angles



nominal beam sizes at the IP			
	450GeV	3.5 TeV	5 TeV
β* [m]	σ* [μm]	σ* [μm]	σ* [μm]
11	293	105	88.0
3	153	54.9	45.9
2	125	44.8	37.5
1	88.4	31.7	26.5

$\frac{\delta x}{\sigma_x}$	$\frac{\delta y}{\sigma_y}$	$\mathcal{L}/\mathcal{L}_0$
0	0	1.0000
0.1	0	0.9975
0.2	0	0.9901
0.3	0	0.9778
0.4	0	0.9608
0.5	0	0.9394
0.5	0.5	0.8825
1	0	0.7788
1	1	0.6065
2	0	0.3679
2	2	0.1353

measured with special (beam-) directional strip-line couplers BPMSW, at about L = 21 m left and right of the IP in front of Q1 in each IR. Resolution each plane $\delta_{\mathrm{IP}} = \sigma_{\mathrm{BPM}}$

Expected resolution for small separation and 0 crossing angle ; in each plane.

~ 50 μm using selected, paired electronics ; otherwise ~ 100 - 200 μm
beam 1 and beam 2 have separate electronics

~ 10 μm with extra BPMWF button pick-ups. Installed in 1&5, for large bunch spacing, EDMS doc 976179

Low β insertion ; LHC

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

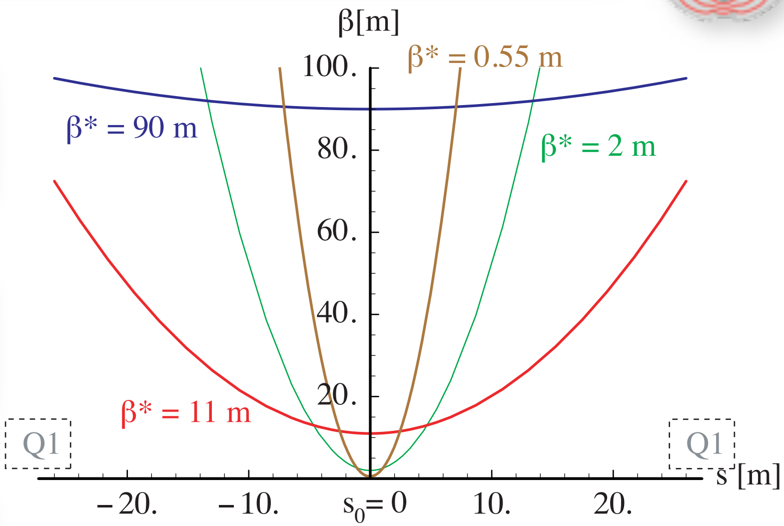
$$\beta(s) = \beta^* + \frac{(s - s_0)^2}{\beta^*}$$

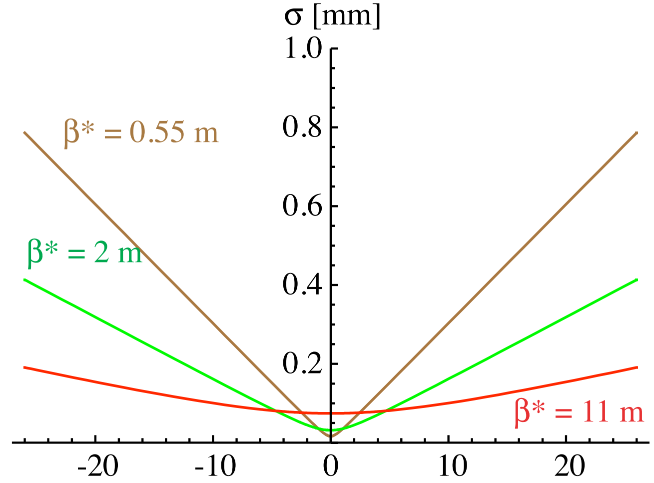
the beam size of a beam of emittance ε in a dispersion free region is

$$\sigma = \sqrt{\beta\,\varepsilon}$$

and the angular beam size divergence

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





the beam size increases about linearly from the IP to the first quadrupole, by a factor s / β* (for s >> β*)

--> aperture limit for low β*

LHC triplet aperture currently 70 mm (50 mm with screen)

upgrade studies --> 130 mm aperture, NbTi

for the nominal emittance

$\varepsilon_N = 3.75\ \mu m$, $\varepsilon_N = \varepsilon\,\beta\,\gamma$

$\varepsilon = 0.503$ nm at 7 TeV

Early Heavy Ion Run Parameters

John Jowett

		Early (2010/11)	Nominal
$\sqrt{s}$ per nucleon	TeV	2.76	5.5
Initial Luminosity (L_0)	$cm^{-2}s^{-1}$	1.25×10^{25}	10^{27}
Number of bunches		62	592
Bunch spacing	ns	1350	99.8
β^*	m	2	0.5
Pb ions/bunch		7×10^{7}	7×10^{7}
Transverse norm. emittance	µm	1.5	1.5
Luminosity half life (1,2,3 expts.)	h	τ_{IBS}=7-30	8, 4.5, 3

Initial interaction rate: 100 Hz (10 Hz central collisions *b* = 0 – 5 fm)

$\sim 10^8$ interaction/10^6s (~1 month)

Summary of Luminosity progress

calculated

Event	TeV	OEF	β*	Nb	Ib	Itot	MJ	Nc	Peak luminosity	Date
1	3.5	0.2	10	2	1.00E+10	2.0E+10	0.0113	1	8.9E+26	30 March 2010
2	3.5	0.2	10	2	2.00E+10	4.0E+10	0.0226	1	3.6E+27	02 April 2010
3	3.5	0.2	2	2	2.00E+10	4.0E+10	0.0226	1	1.8E+28	10 April 2010
4	3.5	0.2	2	4	2.00E+10	8.0E+10	0.0452	2	3.6E+28	19 April 2010
5	3.5	0.2	2	6	2.00E+10	1.2E+11	0.0678	4	7.1E+28	15 May 2010
6	3.5	0.2	2	13	2.60E+10	3.4E+11	0.1910	8	2.4E+29	22 May 2010
7	3.5	0.2	3.5	3	1.10E+11	3.3E+11	0.1865	2	6.1E+29	26 June 2010
8	3.5	0.2	3.5	6	1.00E+11	6.0E+11	0.3391	4	1.0E+30	02 July 2010
9	3.5	0.2	3.5	8	9.00E+10	7.2E+11	0.4069	6	1.2E+30	12 July 2010
10	3.5	0.2	3.5	13	9.00E+10	1.2E+12	0.6612	8	1.6E+30	15 July 2010
11	3.5	0.2	3.5	25	1.00E+11	2.5E+12	1.4129	16	4.1E+30	30 July 2010
12	3.5	0.2	3.5	48	1.00E+11	4.8E+12	2.7127	36	9.1E+30	19 August 2010

Maximum reached is 10.7×10^{30} $cm^{-2}s^{-1}$