Collisions at top energy, luminosity determination and optimisation

- **Parameters, LHC 7 TeV un-squeezed and squeezed**
- **getting collisions; BPM resolution and required precision, request to reduce the uncertainty; comments on longitudinal position, β* and waist measurements**
- **comment on bunch by bunch variations**
- **beam-beam effect**
- **separation scans**
- **absolute Luminosity from machine parameters**
- **communication with experiments : Lumi & BKG**

Related presentations

- **Injection scenarios, alternative filling schemes** 14/02/2007 LHCCWG
- **LHC Machine : Luminosity Monitoring and Measurement** 26/01/2007 Joint LHC Machine - Experiments Workshops, Luminosity Monitoring and Measurement
- **presentations on squeeze by Massimo, Ralph and Mike** 29/11/2006 LHCCWG
- **Machine Background and the Exchange of Data during LHC Commissioning and Operation** 09/10/2006 LEADE
- **Background in Commissioning and Operation** 29/09/2006 LHC Machine Induced Background Working Group
- **Background in Commissioning and Operation** 26/09/2006 LEMIC
- **Bringing Beams Into Collision** 06/09/2006 LHCCWG
- **Luminosity monitor and LHC operation** 10/03/2006 **TAN integration workshop**

Parameter Range

and single **bunch luminosities** as relevant for lumi / separation scan statistics

Event rates for σ = 10 mb, which is about the cross section with high energy neutrons in the BRAN

ϵ_N μm	ϵ nm	p GeV/c	β^* m	σ^* μm	N_p	L $cm^{-2}s^{-1}$	$\dot{N} = L\sigma$ Hz	$\frac{\dot{N}}{f_{rev}}$	ξ
3.75	7.82	450	11	293.3	5×10^9	2.60×10^{25}	0.26	0.000023	0.000 16
3.75	7.82	450	11	293.3	4×10^{10}	1.66×10^{27}	16.64	0.0015	0.001 30
2.5	5.21	450	11	239.4	4×10^{10}	2.49×10^{27}	24.94	0.0022	0.001 95
3.75	7.82	450	11	293.3	1.15×10^{11}	1.37×10^{28}	138	0.0122	0.003 74
3.75	0.503	7000	11	95.14	5×10^9	4.00×10^{26}	4.00	0.00036	0.000 16
3.75	0.503	7000	11	95.14	9×10^{10}	1.30×10^{29}	1296	0.115	0.002 93
3.75	0.503	7000	2	31.71	1.15×10^{11}	1.11×10^{30}	11087	0.986	0.003 74
3.75	0.503	7000	0.55	16.63	1.15×10^{11}	3.54×10^{30}	35400	3.15	0.003 74

Commissioning is planned with 43 - 156 bunches. No crossing angle

Nominal longitudinal LHC beam parameters V4.0 , LHC design report (frf = 400.8 MHz) :

V_{rf} = 8 MV σ_E / E = 4.716e-4 σ_Z = 11.24 cm σ_T = 0.375 ns 450 GeV

V_{rf} = 16 MV σ_E / E = 1.129e-4 σ_Z = 7.55 cm σ_T = 0.252 ns 7 TeV

Get beams colliding

Luminosity with separation

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

$\frac{\delta x}{\sigma_x}$	$\frac{\delta y}{\sigma_y}$	$\frac{\mathcal{L}}{\mathcal{L}_0}$
0	0	1
1/2	0	0.9394
1/2	1/2	0.8825
1	0	0.7788
1	1	0.6065
2	0	0.3679
2	2	0.1353

Procedure and requirements :

- **End of ramp / squeeze, beams separated**
- **Turn off separation, based on BPM information**

required, roughly (values for x and y or radius, √2 better in each plane)

$\delta_r < 2\ \sigma$ to see collisions

$\delta_r < 0.5\ \sigma$ to optimise luminosity and equalise between experiments

or in each plane x,y: $\delta_{x,y} < 1.4\ \sigma$ and $\delta_{x,y} < 0.35\ \sigma$

this implies at 7 TeV for nominal emittances :

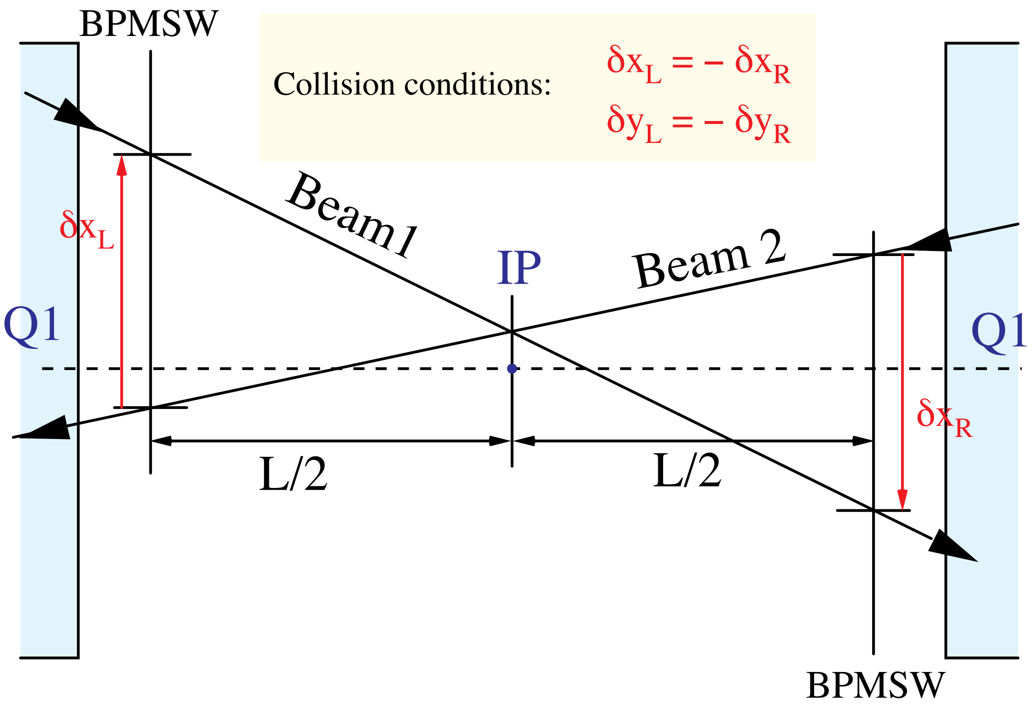
un-squeezed, β^*= 11 m : $\delta_{x,y} <$ 133 μm and $\delta_{x,y} <$ 33 μm

squeezed to β^*= 2 m : $\delta_{x,y} <$ 44 μm and $\delta_{x,y} <$ 11 μm

squeezed to β^*= 0.55 m : $\delta_{x,y} <$ 23 μm and $\delta_{x,y} <$ 6 μm

Get beams colliding : BPM resolution, based on S. Fartoukh LCC 3/2001

Adjust orbits such, that the beam 1 and 2 difference left/right of the IP is the same.
measured with special (beam) directional stripline couplers BPMSW at about 21 m L/R from IP in front of Q1. There are 2 each in IR1 (Atlas), IR2 (Alice), IR5 (CMS) and IR8 (LHCb)
Beams must then collide. This is independent of mechanical offsets and crossing angles.



when both planes (x, y) are considered together

$$\delta_{\rm IP} = \sqrt{\left(\frac{\delta x_L + \delta x_R}{2}\right)^2 + \left(\frac{\delta y_L + \delta y_R}{2}\right)^2} = \sqrt{2}\,\sigma_{\rm BPM}$$

or simply **σ_{BPM} in each plane**

expected resolution for small separation and 0 crossing angle, each plane :
initially ~ 100 - 200 µm later (after k - modulation) **~ 50 µm**
mainly limited by electronics which is separate for b1 and b2

Request for improved BPM resolution

~ 100 - 200 μm BPM resolution should be (just about) sufficient to get beams close enough to see some collisions for un-squeezed beams at 7 TeV.

Request for an improved BPM system at the IP. Anyway needed for high-β Totem/Atlas (assume 5 and 10 μm resolution in their TDRs).

For operation with 0 crossing angle and a limited number of bunches, it should be possible to eliminate offsets using (non-directional) button pickups and electronics for beam1 and beam2, aiming for $\sigma_{BPM} = 10\ \mu m$ resolution needed for high-β which would also assure close to optimal collisions without need for frequent scanning.

Prelim. discussion with Rhodri : **appears to imply the design, construction and installation of a new combined pick-up system : stripline for normal operation with crossing angle and many bunches and button to measure the zero crossing angle angle and adjust collisions in early operation.**
Approve soon, to allow for installation before the zone gets too irradiated - and to be able to profit for early-physics !

Longitudinal position

Once we are in stable physics, this will be monitored precisely by the experiments.

In principle not too critical in commissioning. First collisions will be without crossing angle and with rather large β^* (11 m). Even few ns resolution could be sufficient together with information from the experiments.

How to adjust in commissioning before experiments observe collisions ?

How to detect offsets later ? - no collisions with crossing angle and offset !

From preliminary discussion with Rhodri:

Could be made possible by the development of a new electronics card for the BPM system, which using the existing infrastructure could give relative beam arrival measurements with sub ns resolution.

Comments on β* and waist measurements

see also Rogelio Tomas in LHCCWG#8 on β-beating/correction and Jörg Wenninger LHCCWG#9 on response matrix analysis

here : local β measurement , applied to β* at the IP

Principle :
a change of the quadrupole gradient Δk of a quadrupole at the beta function β_Q results in a tune shift of

$$\Delta Q = \frac{\Delta k \ \beta_Q}{4\pi}$$

β^* and β_Q at distance l from the IP
LHC $l = 26.15$ m from IP to centre of Q1

$$\beta_Q = \beta^* + \frac{\ell^2}{\beta^*}$$

numerical values for the LHC

β^* m	β_Q m	kqx 1/ m	ΔQ from $\Delta k = 10^{-5}$/m
11	73.165	$8.576824107 \times 10^{-3}$	0.00157
2	343.911	$8.730196766 \times 10^{-3}$	0.0082

measure with PLL

Waist position

- was an issue in LEP in 1991 to optimise and **equalise** luminosities between experiments. Assure β* has the minimum at the IP. Steps of ±2e-4 in Qs0 strength resulted in 0.8 cm waist shift.

  LEP had typically $\sigma_z = 1.2$ cm, $\beta_y^* = 0.05$ m ($\beta_x^* = 1.25$ m). Distance IP to centre of 1st quad: 4.7 m

  What about the LHC ? All (length and β's) scaled up by 5 - 10 compared to LEP

- **LHC $\sigma_z = 7.55$ cm, $\beta_x = 0.55$ m, distance IP to centre of 1st quad 26.15 m**

  Quick check with mad : add same $\Delta k = 1.e\text{-}5/\text{m}$ to triplet strength left and right. Moves waist position by about 10 cm at $\beta^* = 0.55$ m with about 3% relative increase of β at the IP.

  Should not be critical in commissioning. β varies only by 0.8 % over a length of ± 1 m from the IP for $\beta^* = 11$ m.

Comment on bunch by bunch variations

Our initially ~ 43, 54, 108, 156 and later ~ 2000 bunches will have a spread in intensity and emittance

What is acceptable ?
Aim for < 10% in intensity and ~ 20% in emittance
Discussed with W. Herr, to be studied further.
Seems to match about what is feasible from injectors (G. Arduini).
If not ? Anything foreseen to equalise bunches ? - check with scrapers.

Measurements :
For optimising collisions and total integrated luminosity it is sufficient to take the sum from individual bunches.

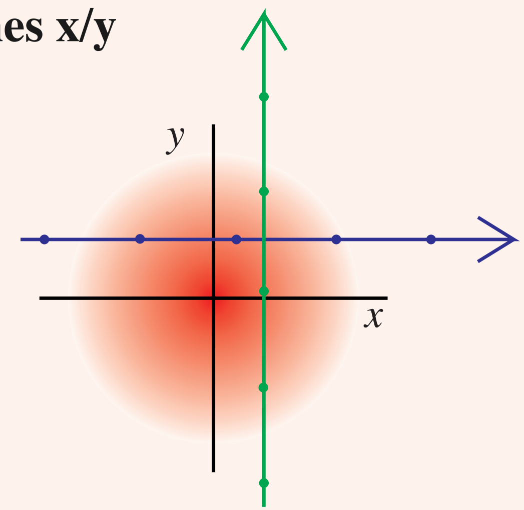
For a full analysis and optimisation of lifetime, background and stability, measurements should be able to distinguish between bunches, for quantities like current, beam size (emittance), tune and luminosity

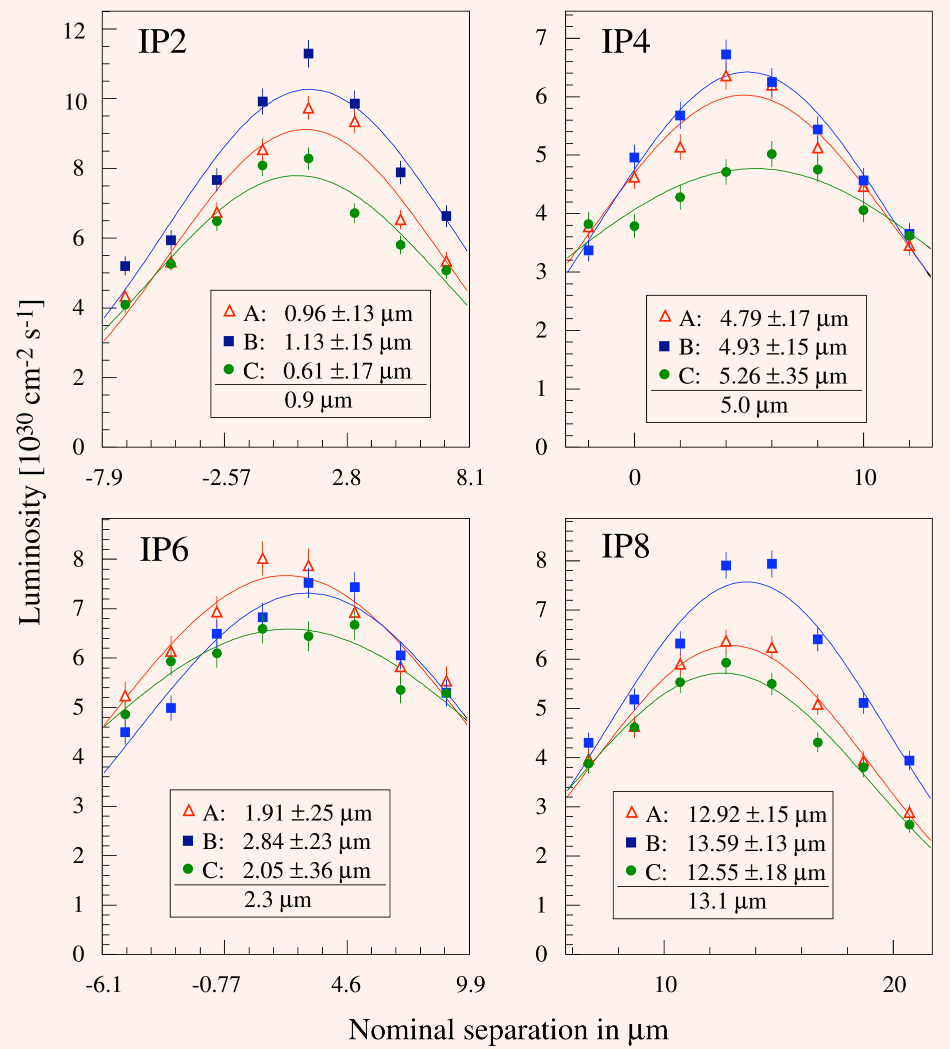
Separation Scan (pioneered by Van der Meer @ ISR)

LEP example:
vertical separation scans using LEP luminosity detectors in operation with 4 bunch trains of each 3 bunches
Time: about 5 min / IP

should be faster in the LHC
but needed in two planes x/y

Commissioning :
simple, orthogonal
x / y scan





different from LEP, the effect of one beam on the other is really small in LHC (negligible dynamic β effects)

Separation scans in the LHC should allow for reliable beam size measurements at the IPs.

Precise separation measurement : bump (and BPM) calibration (response matrix analysis)

Possible alternative : Optimise using beam-beam interaction

head-on b.b. tune shift

$$\xi_x = \frac{r_c\, N\, \beta_x^*}{2\pi\,\gamma\,\sigma_x\,(\sigma_x + \sigma_y)} \qquad \xi_y = \frac{r_c\, N\, \beta_y^*}{2\pi\,\gamma\,\sigma_y\,(\sigma_x + \sigma_y)}$$

calculated, using the classical particle radius, here for the proton $r_c = r_p = 1.5347 \times 10^{-18}\ \mathrm{m}$

In the LHC we have by design round beams with $\sigma = \sigma_x = \sigma_y,\ \beta^* = \beta_x^* = \beta_y^*$

so that

$$\xi = \frac{r_c\, N\, \beta^*}{4\pi\,\gamma\,\sigma^2}$$

in terms of the normalised emittance $\sigma = \sqrt{\beta\epsilon_N/\gamma}$ we get simply

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

numerically

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

independent of beam energy and β*
just a function of bunch intensity
which does not vary too much.

This is of the same order as the natural tune spread, $\delta Q/Q \approx 10^{-3}$ from $\delta p/p = 4.7 \times 10^{-4}$, $Q' = 2$
and should be observable. Was used successfully to optimise Luminosity in other machines :
Beam-beam transfer function, ISR, Hemery, Hofmann, JP Koutchouk et al. at PAC 1981
“Tune coupling” with excitation was used in HERA to steer collisions, S. Herb, Lauterberg 1992

Luminosity from Machine Parameters

$$\mathcal{L} = \frac{N^2 \, f_{\rm rev} \, n_b}{4\pi\sigma^{*2}}$$

For head-on collisions of round beams and
N particles / bunch for n_b bunches
Gives **absolute** luminosity
Accuracy : knowledge of effective beam sizes (overlap integral) at IP

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

Reduction by crossing angle. θ_c is the full crossing angle, nominally ~ 300 mrad

Not an issue for commissioning.

~ 1% or still rather negligible for 7 TeV, β^* = 11 m
only really significant (~ 20%) at 7 TeV squeezed.
σ_z is the r.m.s bunch length, 7.55 cm at 7 TeV

We expect to be able to predict absolute luminosities for head-on collisions based on beam intensities and dimensions, to maybe initially 20-30 % and potentially much better if a special effort is made.
Planned : LHC Machine luminosity determination - subject of a PhD thesis.

Experimental conditions

Experiments need good, or at least acceptable running conditions.
The goal is to optimise the accepted, integrated luminosity by the experiments ⇛→

good or at least acceptable background conditions.
efficient communication ; when can experiments turn on ?

Technically prepared (LEADE) and more recently followed up within LHC Background WG and LEMIC with proposal for normalised BKG1/2 figures of merit.

Summary on TV-screen status page
as for other CERN accelerators using the AB/CO teletext services **http://hpslweb.cern.ch/teletext.html**

proposed LHC status page in mode with collisions

	111	CERN AB	31-11-07	12:20:26	
LHC	Run 1234	data of	31-11-07	12:20:16	

— ** STABLE BEAMS ** —

E = 0.450 TeV	Beam	In Coast	0.5 h	
Beams	Beam 1	Beam 2		
#bun	43	43		
Nprot(t)	1.71e12	1.73e12		
tau(t) h	121	140		

Luminosities	ATLAS	ALICE	CMS	LHC-B
L(t) 1e28 cm-2s-1	5.23	6.23	7.13	1.21
/L(t) nb-1	0.78	0.68	0.78	0.12
BKG 1	1.20	0.52	0.90	0.33
BKG 2	0.85	0.82	0.50	0.60

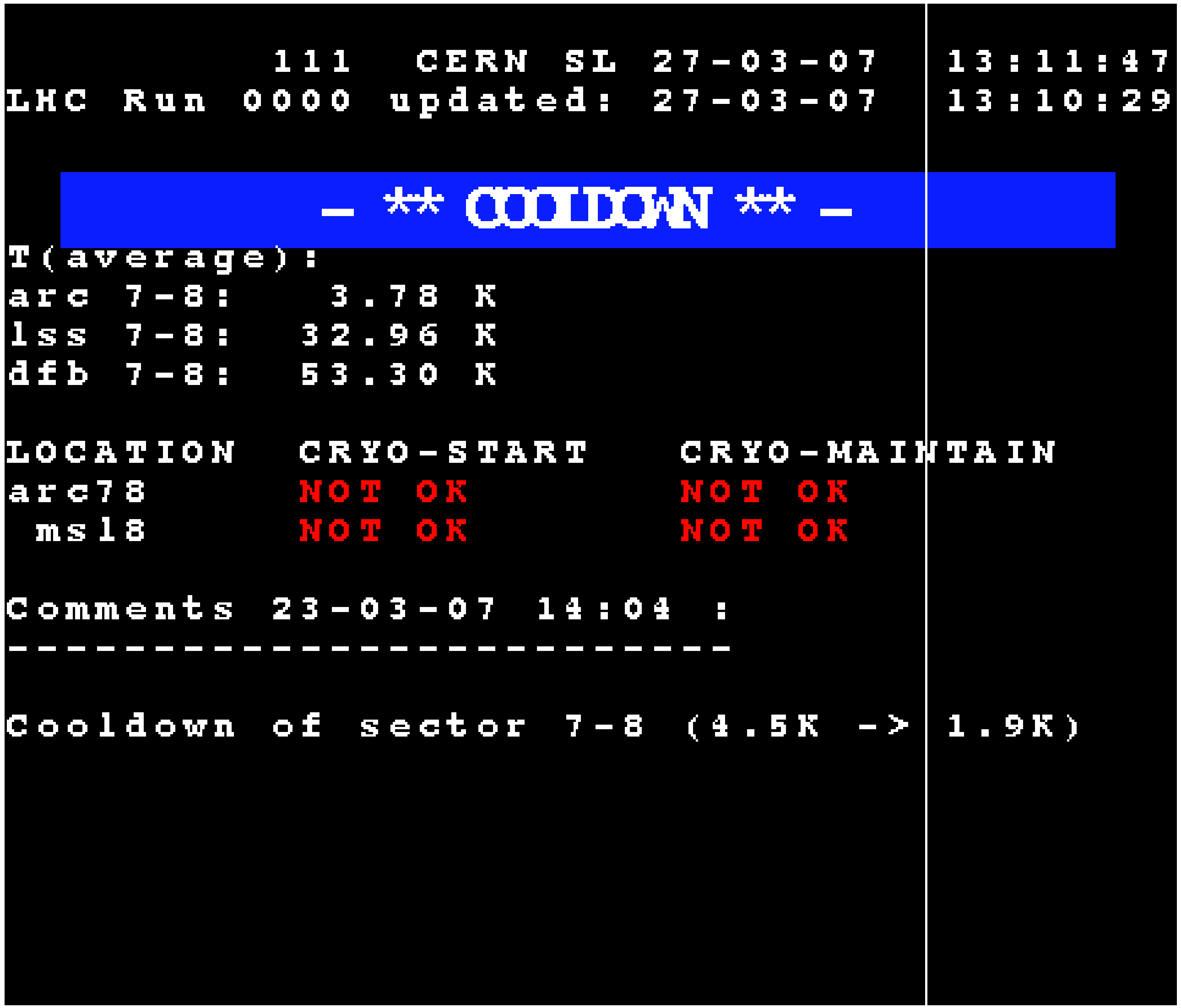
Comments 31-11-07 11:40:26

COLLIMATORS in coarse settings

Separation Scan in IR1/Atlas

A first implementation, by Markus Albert

see http://hpslweb.cern.ch/frame/java/1.1/view111-java.html



Layout and data for other modes remains to be defined

For feedback contact Markus, Mike (or me)

Conclusion

- **getting collisions and optimise (integrated) luminosity at 7 TeV is our "main commissioning objective"**
- **we could profit a lot from an improved BPM resolution, needed anyway later for high β ➟ Recommend to implement this a.s.a.p ; also add a card to allow the determination of the longitudinal position**
- **use LHC luminosity monitor BRAN to centre collisions and measure beam sizes at the IP : possibility to predict absolute luminosities and make sure IP1&5 get equal sharing.**
- **maximise the accepted integrated luminosity by experiments : importance of low or at least tolerable backgrounds and efficient communication between experiments and machine.**