Status and plans for the startup of the LHC machine

Plus some beam alignment questions

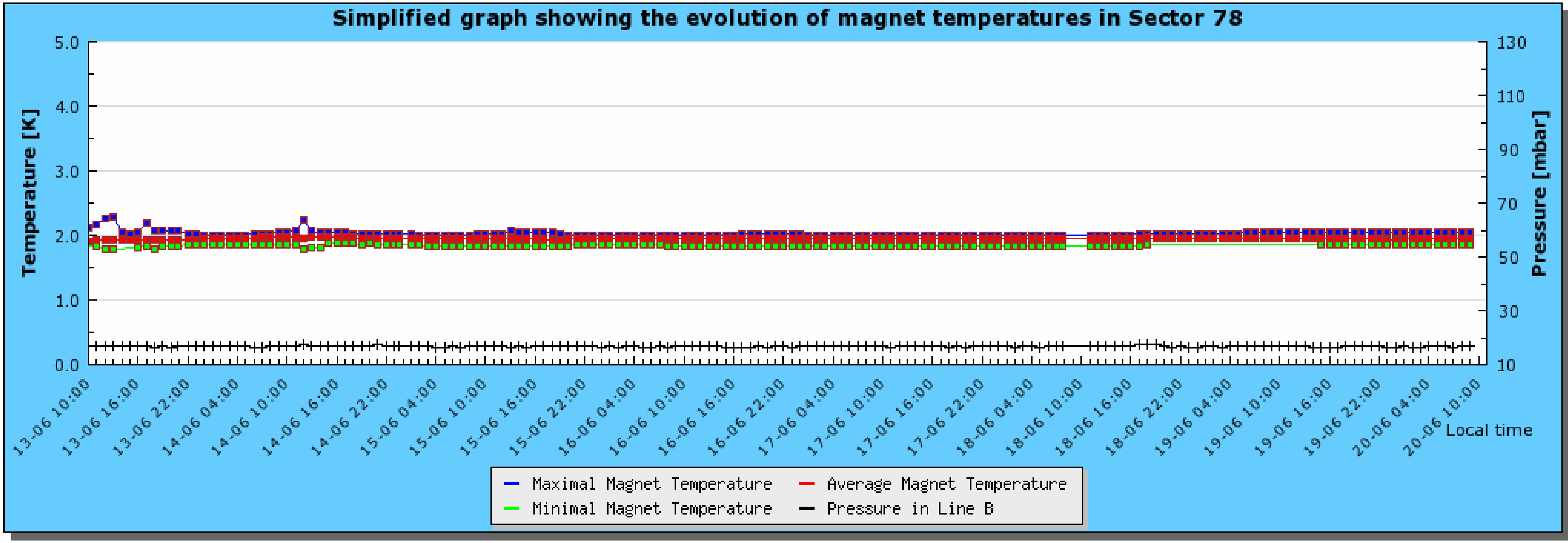
Mike Lamont AB/OP

Schedule slides c/o Lyn Evans (MAC 14/6/07)

Status: Installation & equipment commissioning

- **Procurement problems** of remaining components (DFBs, collimators) now settled
- Good progress of **installation and interconnection work**, proceeding at high pace in tunnel
- Numerous **non-conformities** intercepted by QA program, but resulting in added work and time
- Technical solutions found for **inner triplet problems**, but repair of already installed magnets will induce significant delays
- **Commissioning of first sectors** can proceed by isolating faulty triplets, but will have to be re-done with repaired triplets (needing additional warm-up/cooldown cycles)
- **First sector cooled down to nominal temperature and operated with superfluid helium**; teething problems with cold compressor operation have now been fixed.
- **Power tests** now proceeding.

Sector 78



Simplified graph showing the evolution of magnet temperatures in Sector 78
Temperature [K]
Pressure [mbar]
5.0
4.0
3.0
2.0
1.0
0.0
130
110
90
70
50
30
10
13-06 10:00
13-06 16:00
13-06 22:00
14-06 04:00
14-06 10:00
14-06 16:00
14-06 22:00
15-06 04:00
15-06 10:00
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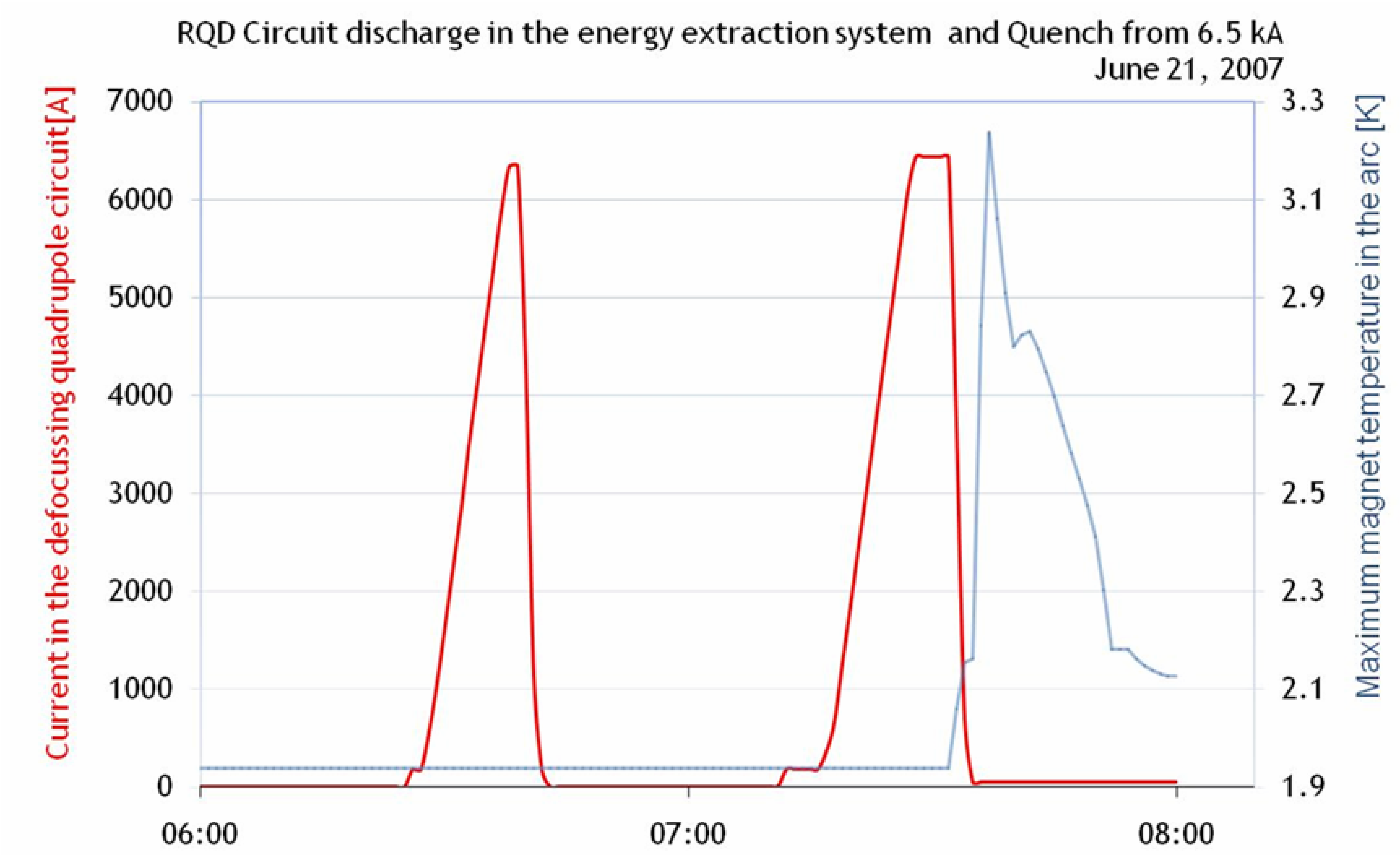
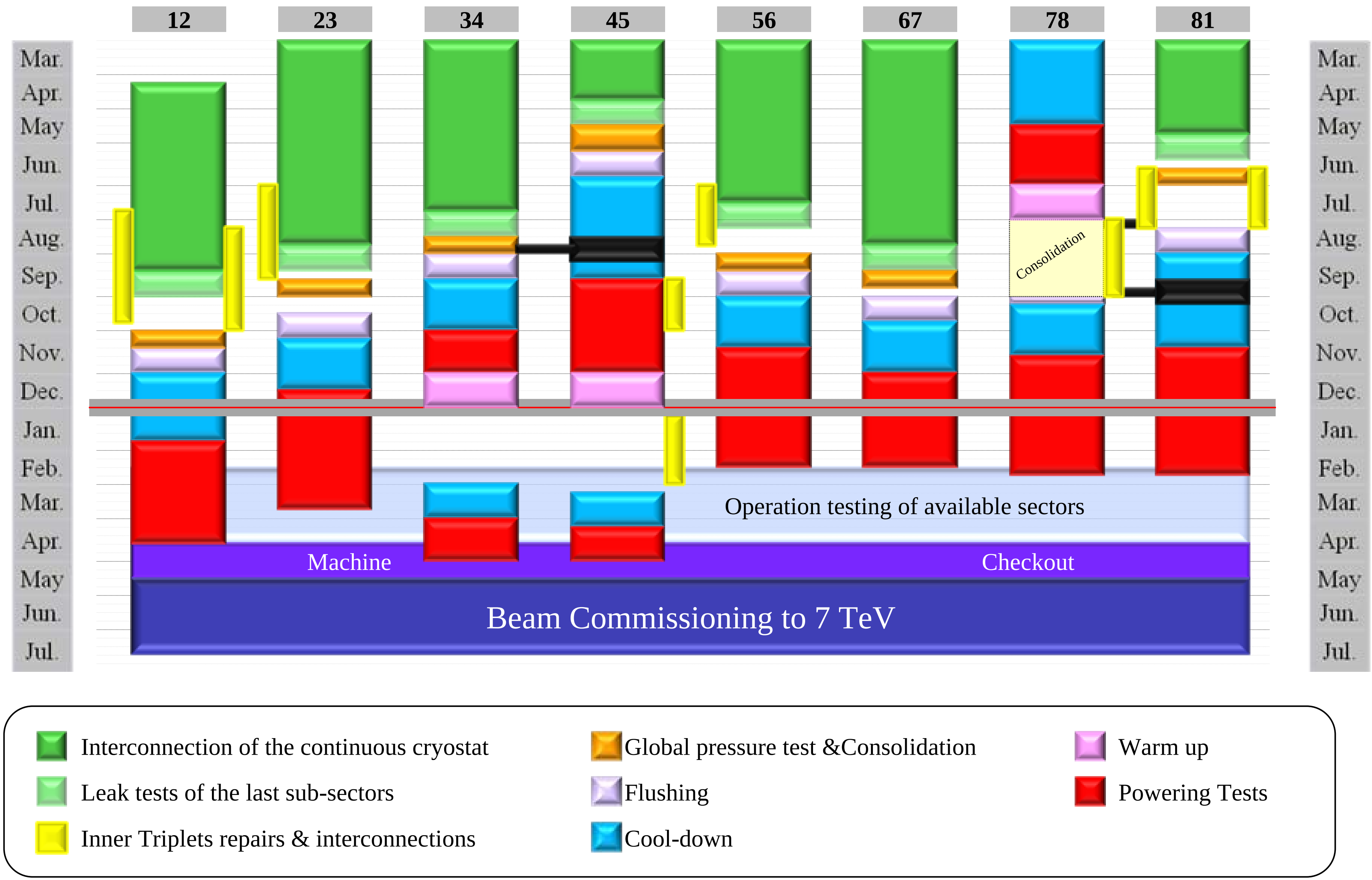
18-06 10:00
18-06 16:00
18-06 22:00
19-06 04:00
19-06 10:00
19-06 16:00
19-06 22:00
20-06 04:00
20-06 10:00
Local time
Maximal Magnet Temperature
Average Magnet Temperature
Minimal Magnet Temperature
Pressure in Line B

Sector 78



End hardware commissioning 6th July for warm-up

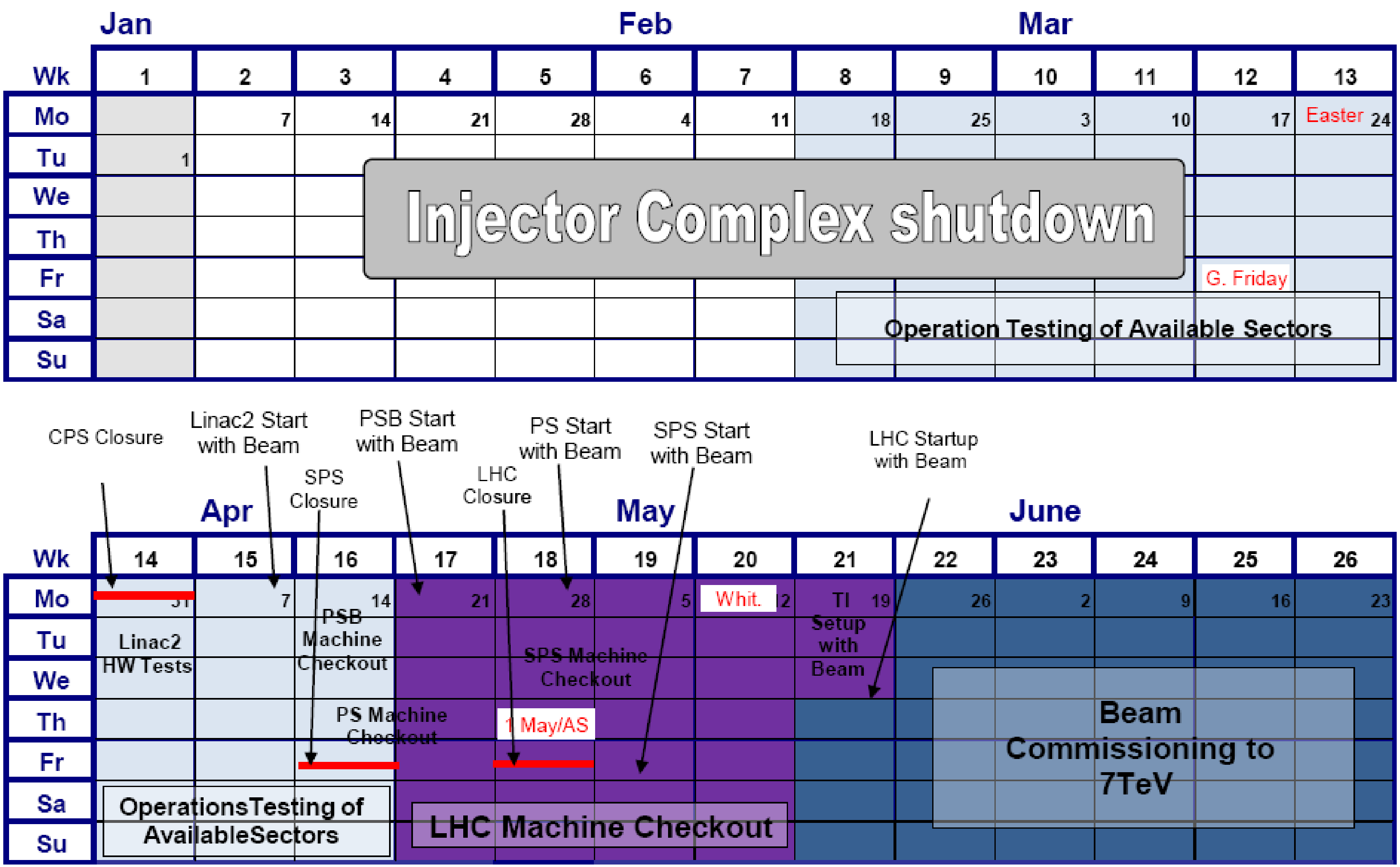
LHC Schedule – 2007/2008



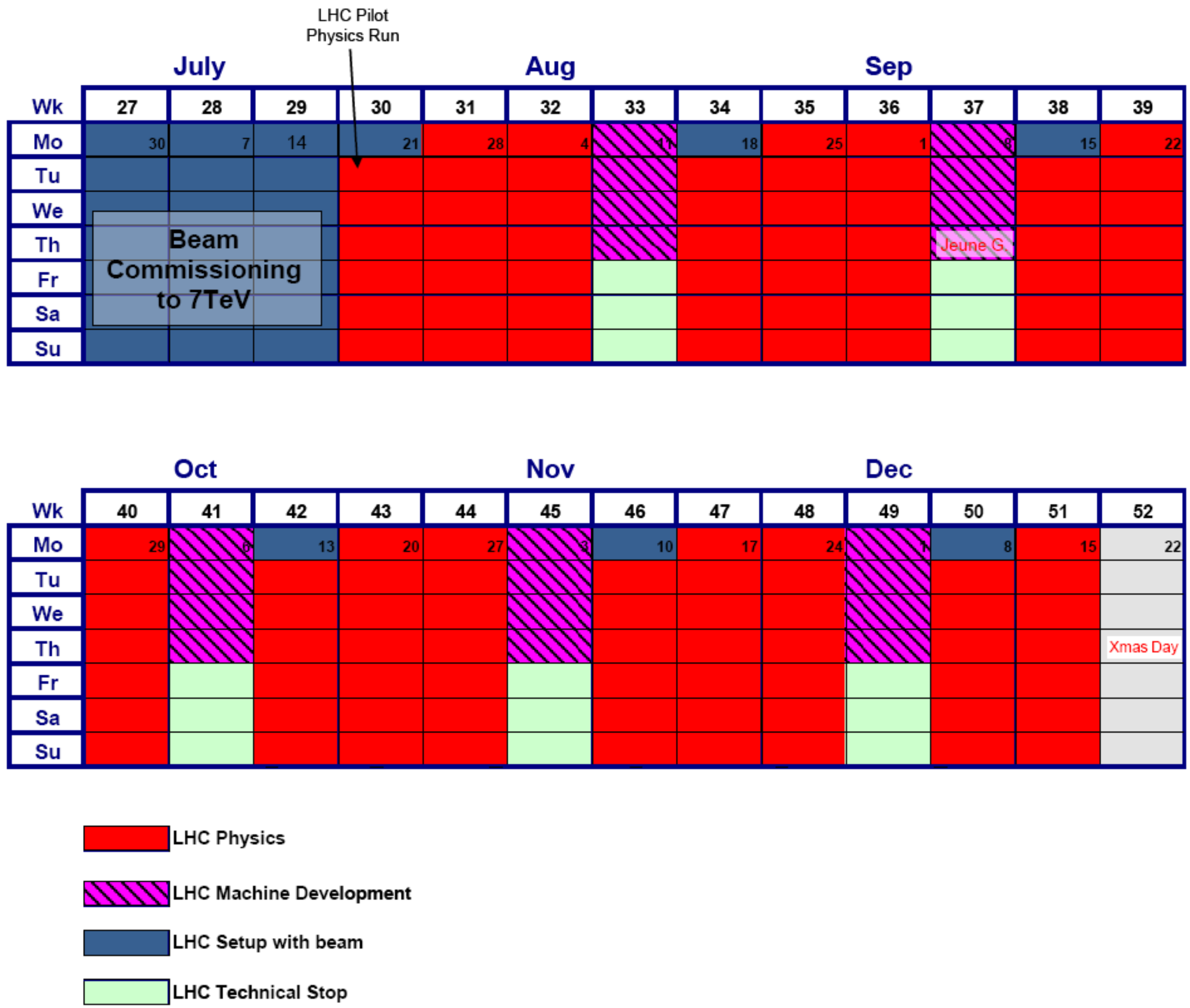
General co-ordination schedule - Milestones

	Pressure test	Cool-down		Powering tests	
Sector 12	27-28 Oct. 07	03 Dec. 07	25 Jan. 08	28 Jan.08	18 Apr.08
Sector 23	15 -16 Sep.07	05 Nov. 07	14 Dec.07	17 Dec. 07	21 Mar. 08
Sector 34	11-12 Aug. 07	17 Sep. 07	26 Oct. 07	29 Oct. 07	30 Nov. 07
		03 Mar. 08	28 Mar. 08	31 Mar. 08	02 May 08
Sector 45	Done	25 Jun. 07	14 Sep. 07	17 Sep. 07	30 Nov. 07
		10 Mar. 08	04 Apr. 08	07 Apr. 08	02 May 08
Sector 56	18 - 19 Aug. 07	01 Oct. 07	09 Nov. 07	12 Nov. 07	15 Feb.08
Sector 67	25-26 Sep. 07	22 Oct. 07	30 Nov. 07	03 Dec. 07	15 Feb.08
Sector 78	Done	Done		Started	29 Jun. 07
		08 Oct. 07	16 Nov. 07	19 Nov. 07	22 Feb. 08
Sector 81	16-17 Jun. 07	27 Aug. 07	09 Nov. 07	12 Nov. 07	22 Feb. 08

2008 LHC Accelerator schedule



2008 LHC Accelerator schedule



General Schedule

- **Engineering run** originally foreseen at end 2007 now precluded by delays in installation and equipment commissioning.
- **450 GeV operation** now part of normal setting up procedure for beam commissioning to high-energy
- **General schedule** reassessed, accounting for inner triplet repairs and their impact on sector commissioning
  - **All technical systems commissioned to 7 TeV operation, and machine closed April 2008**
  - **Beam commissioning starts May 2008**
  - **First collisions at 14 TeV com July 2008**
  - **Pilot run pushed to 156 bunches for reaching 10^{32} $cm^{-2}s^{-1}$ by end 2008**
- No provision in success-oriented schedule for major mishaps, e.g. additional warm-up/cool-down of sector

Commissioning Plans

Commissioning stages

STAGE A
INITIAL COMMISSIONING
43 x 43 -> 156 x 156 3×10^{10} per bunch
Zero to partial squeeze

STAGE B
75 ns OPERATION
3-4 x 10^{10} per bunch
Partial squeeze

STAGE C
25 ns OPERATION
3-4 x 10^{10} per bunch
Partial to near full squeeze

LONG SHUTDOWN

STAGE D
25 ns OPERATION
push to nominal per bunch
Partial to full squeeze

- Establish colliding beams as quickly as possible
- Safely
- Without compromising further progress

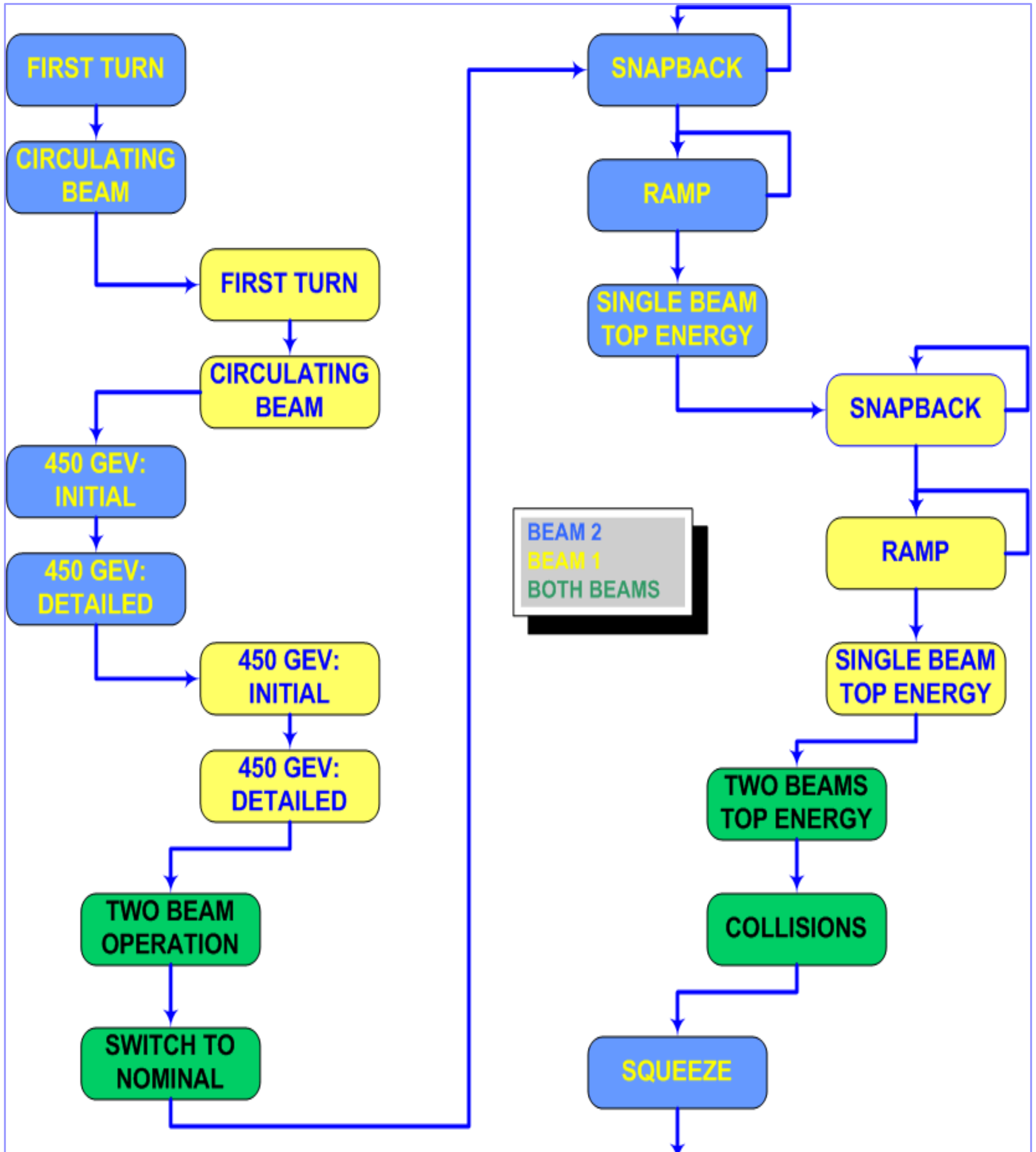
- Initial optics:
  - β^*= 11 m in IR 1 & 5
  - β^*= 10 m in IR 2 & 8
- Crossing angles off
  - 1, 12, 43, 156 bunches per beam
  - No parasitic encounters - no long range beam-beam
  - Larger aperture in IRs

Phase A: Beam

- Start with Pilot Beam:
  - Single bunch, 5 to 10 x 10^9 protons
- Intermediate single:
  - 3 to 4 x 10^{10} ppb
- 4 bunches etc. pushing towards…
- 43 (and possibly 156) bunches
  - 3 to 4 x 10^{10} ppb **(3.1 mA - 2 MJ)**

- Good for Instrumentation (bunch spacing), RF, vacuum…
- Relatively safe beam
  - Reduced demands on beam dump system, Collimation & Machine protection

Stage A: Commissioning Phases



Have to commission:

Hardware: RF, beam Dump, Collimators, Kickers etc

Instrumentation: BPMs, BLMs, BCT, Beam size, luminosity etc.

Controls

Machine Protection

Measure optics, energy, aperture etc. etc. etc.

Procedures: Injection, snapback, ramp, squeeze, recover etc.

Details available…

Beam commissioning to 7 TeV collisions

		Rings	Total [days]
1	**Injection and first turn**	**2**	**4**
2	**Circulating beam**	**2**	**3**
3	**450 GeV - initial**	**2**	**4**
4	**450 GeV - detailed**	**2**	**5**
5	**450 GeV - two beams**	**1**	**1**
6	**Snapback - single beam**	**2**	**3**
7	**Ramp - single beam**	**2**	**6**
8	**Ramp - both beams**	**1**	**2**
9	7 TeV - setup for physics	**1**	**2**
10	Physics un-squeezed	**1**	**-**
	TOTAL TO FIRST COLLISIONS		**30**
11	Commission squeeze	**2**	**6**
12	Increase Intensity	**2**	**6**
13	Set-up physics - partially squeezed.	**1**	**2**
14	Pilot physics run		

Stage A: First collisions

- Approx 30 days of beam time to establish first collisions
  - Un-squeezed
  - Low intensity
- Approx 2 months elapsed time
  - Given optimistic machine availability
- Continued commissioning thereafter
  - Increase intensity
  - Squeeze

Stage A - Luminosities

- 1 to N to 43 to 156 bunches per beam
- N bunches displaced in one beam for LHCb
- Pushing gradually one or all of:
  - Bunches per beam
  - Squeeze
  - Bunch intensity

IP 1 & 5

Bunches	β^*	I_b	Luminosity	Event rate
1 x 1	18	10^{10}	10^{27}	Low
43 x 43	18	3×10^{10}	3.8×10^{29}	0.05
43 x 43	4	3×10^{10}	1.7×10^{30}	0.21
43 x 43	2	4×10^{10}	6.1×10^{30}	0.76
156 x 156	4	4×10^{10}	1.1×10^{31}	0.38
156 x 156	4	9×10^{10}	5.6×10^{31}	1.9
156 x 156	2	9×10^{10}	1.1×10^{32}	3.9

Stage B – 75ns

- Parameter tolerances:
  - Tightened up. Optics/beta beating under control
- Commission crossing angles.
  - Injection, ramp and squeeze
  - long range beam-beam, effect on dynamic aperture,
- Need for feedback
  - orbit plus adequate control of tune and chromaticity through snapback.
- Lifetime and background optimization in physics
  - with a crossing angle and reduced aperture needs to be mastered.
- Bunch train bunch-to-bunch variations, implications for beam instrumentation.
- Emittance conservation through the cycle

Plus Machine Protection with increased intensity

Won't happen overnight

Issues

Vacuum

- Will start with warm vacuum chambers baked and NEG activated, both in the experimental region and in the LSS.
  - The static pressure after this is expected to be of order 10^{-11} mbar (as already achieved in ALICE).
- Cold sections will be simply cooled
- Followed by conditioning with beam:
  - **Dynamic vacuum:** increase beam current $\rightarrow$induced multipacting $\rightarrow$ lower secondary electron emissions.
  - Things get a bit worse.
- After conditioning things will improve.

Vacuum

	Stage 1	Stage 2	Nominal
Months of operation	4	7	7
Days of operation	100	175	175
Bunches	1/43/156	936/2808	2808
Protons/bunch	10^{10}-9 10^{10}	10^{10}-9 10^{10}	1.1 10^{10}
Protons	10^{10}-1.4 10^{13}	(3.7–9.8) 10^{13}	3.2 10^{14}
Current (mA)	0.02 - 25	70 - 80	582
Average current (mA)	8	140	582

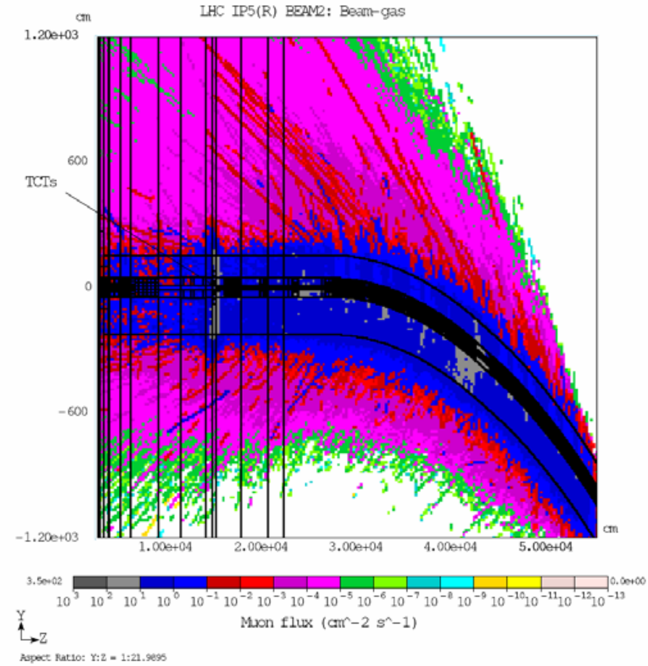
$\mathbf{n}_b$	**43**	**156**	**2808**
Start-up	1.8×10^{12}	5.7×10^{12}	4.3×10^{13}
Nominal	4.2×10^{11}	6.3×10^{11}	5.3×10^{12}

Table 3: Average H_2 equivalent residual gas density, [mol/m^3] in the IR1 & 5 at the machine start-up and at nominal operation after the machine conditioning with the beam of different intensity.

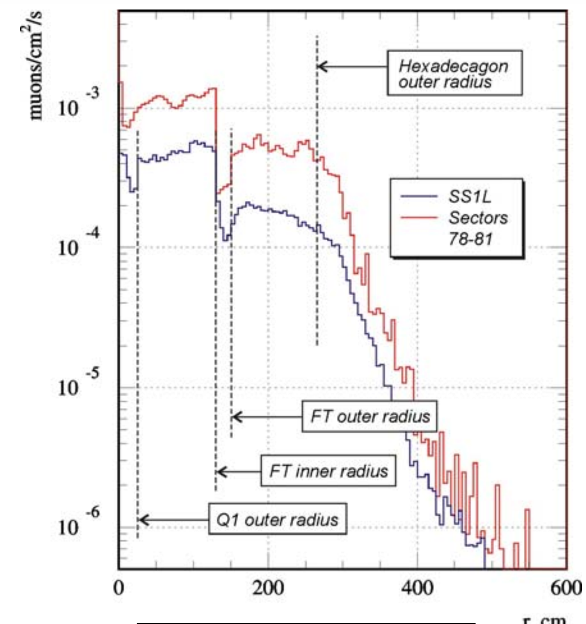
Residual gas density estimations in LHC Insertion Regions IR1 and IR5 and the experimental regions of ATLAS and CMS for different beam operations.
Adriana Rossi LPR 783

Background (briefly!)

Nikolai Mokhov



- Residual gas within experiments
  - Baked out etc. – low rates
- Residual gas in adjacent straight sections
  - See Adriana Rossi
- Gas pressure in adjacent cold sectors
  - Residual gas pressures expected in the cold arcs ≥ 20 times those in the cold sections of the LSS
  - Elastic scattering into IRs
  - Muons →



- Inefficiency of cleaning in IR7 & IR3
  - Tertiary halo on tertiary collimators
  - Not an issue initially

See: M. Huhtinen, V. Talanov, G. Corti, N. Mokhov et al

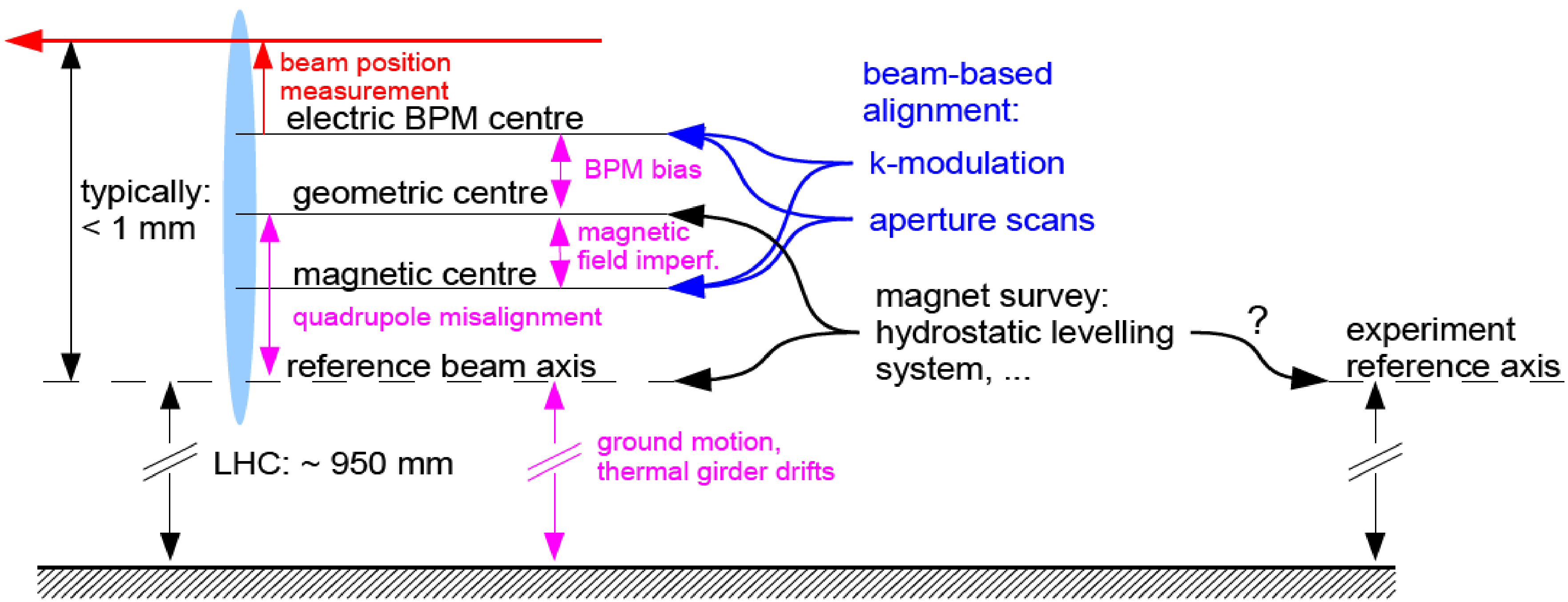
G. Corti, V. Talanov

Transverse crossing point etc.

A lot of subtleties here – so just some pointers

Alignment Reference System Definition

- Beam stability analysis depends on the choice of reference system:
  - beam position measurements (different for B1 & B2!)
  - magnetic quadrupole centre (minimising feed-down effects)
  - geometric quadrupole centre (maintaining aperture constraints)
  - external reference
- Some definitions:



not to scale!

Final Focus Stability, Ralph.Steinhagen@CERN.ch, 2007-06-24

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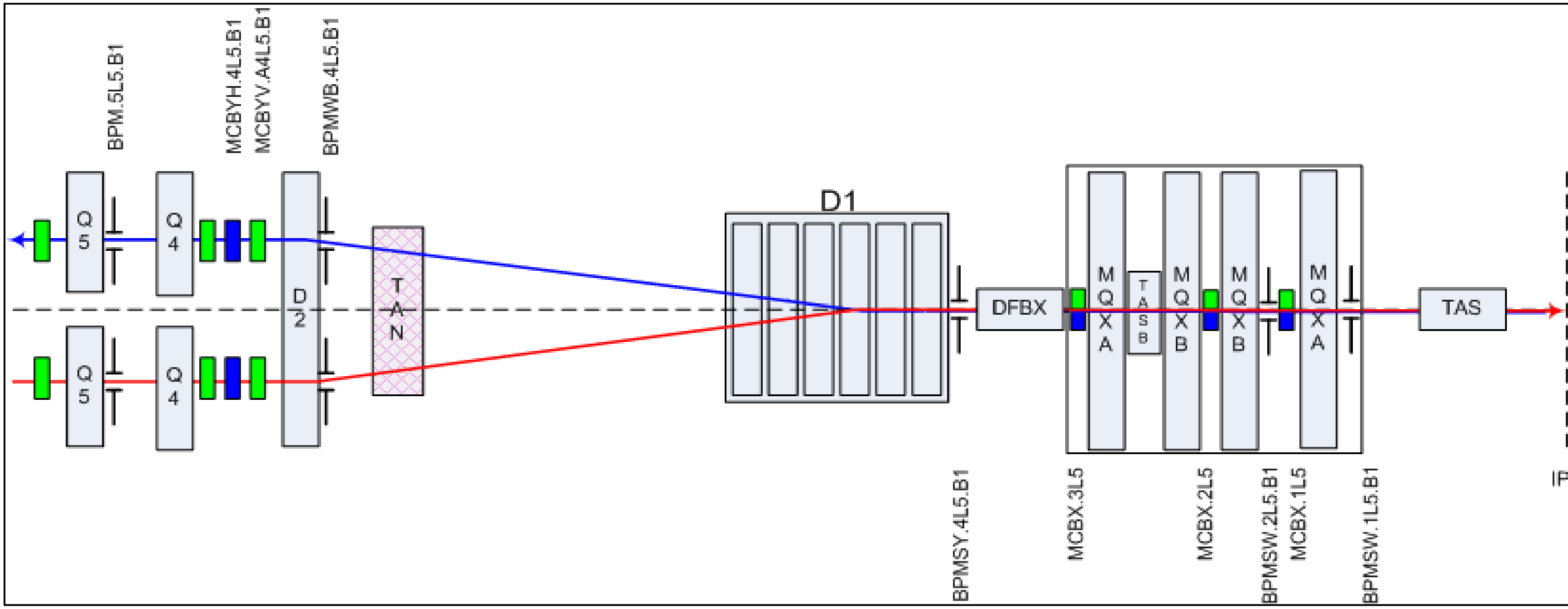
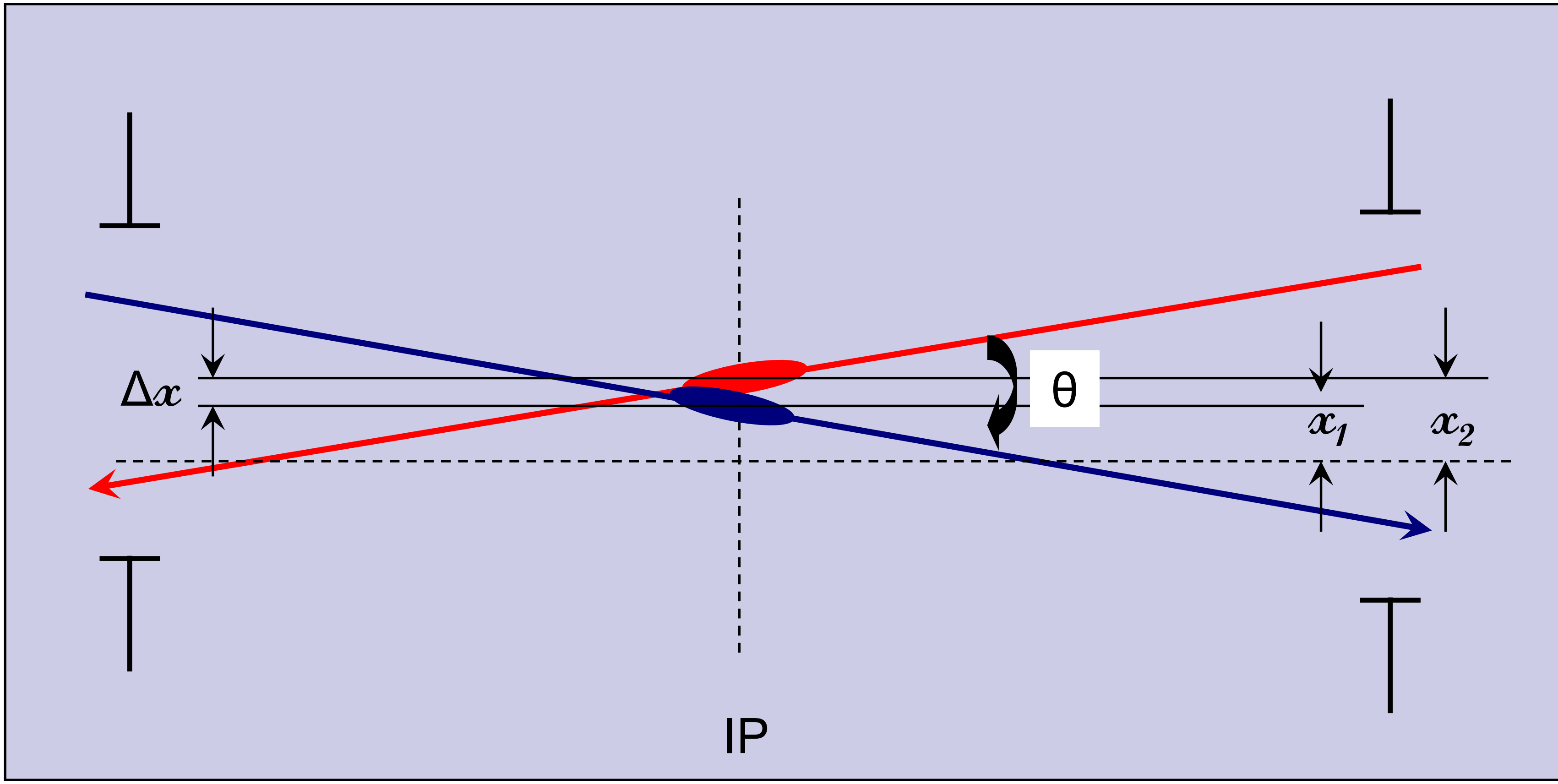
Transverse vertex position



- Inner triplet BPMs
  - Directional strip-line couplers
  - Capable of distinguishing between counter rotating beams in the same beam pipe.
  - Have one either side at about 21 m from IP in front of Q1
    - extrapolate straight through IP

BPMSW



In both planes

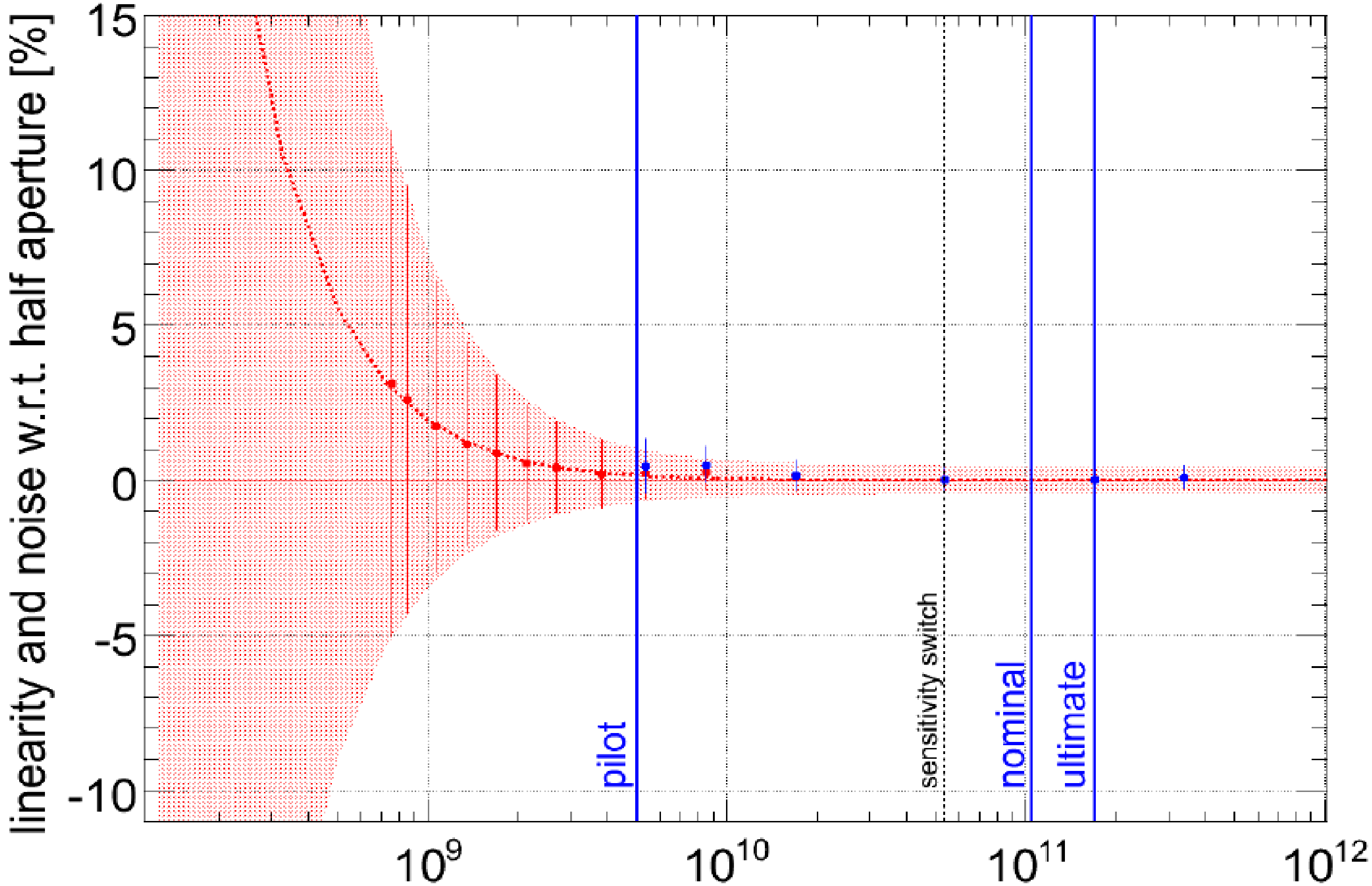
BPM errors

- Beam Position Measurement:
  - electrical BPM bias: 100 μm r.m.s.
  - electrical BPM centre w.r.t. geometric quad. centre: 200 μm r.m.s.
    - after aperture scan: < 50-100 μm r.m.s.
  - electrical BPM centre w.r.t. geometric quad. centre: 200 μm r.m.s.
    - after k-modulation: < 50 (5?) μm
- Survey group targets for magnet alignment:
  - 0.2 mm r.m.s. globally
  - 0.1 mm r.m.s. as an average over 10 neighbouring magnets
  - N.B. Orbit FB: working assumption: 0.5 mm r.m.s.

From threading the first pilot to 43x43 bunches

- 43x43 operation: max. intensity $4 \cdot 10^{10}$ protons/bunch

→ No gain-switching: BPMs will always operate at 'high' sensitivity

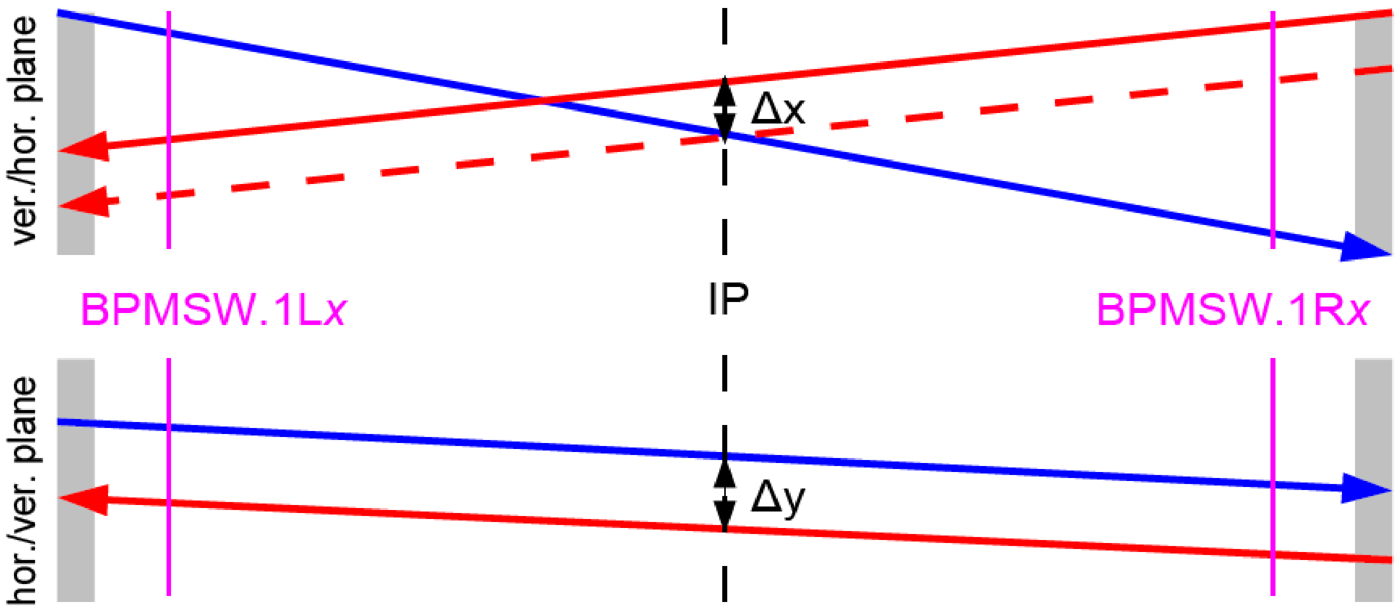


noise/error: ~ $(n_b)^{-1.5}$, half-aperture ≈ 22 mm
switch at: ~$5.3 \cdot 10^{-10}$ protons/bunch

Luminosity stability

$$L = L_0 \cdot e^{-\frac{1}{4}\left[\left(\frac{\Delta x}{\sigma_x}\right)^2 + \left(\frac{\Delta y}{\sigma_y}\right)^2\right]} \cdot F_{crossing} \cdot F_{hour\ glass} \cdot \ldots$$

- Effective beam overlap:



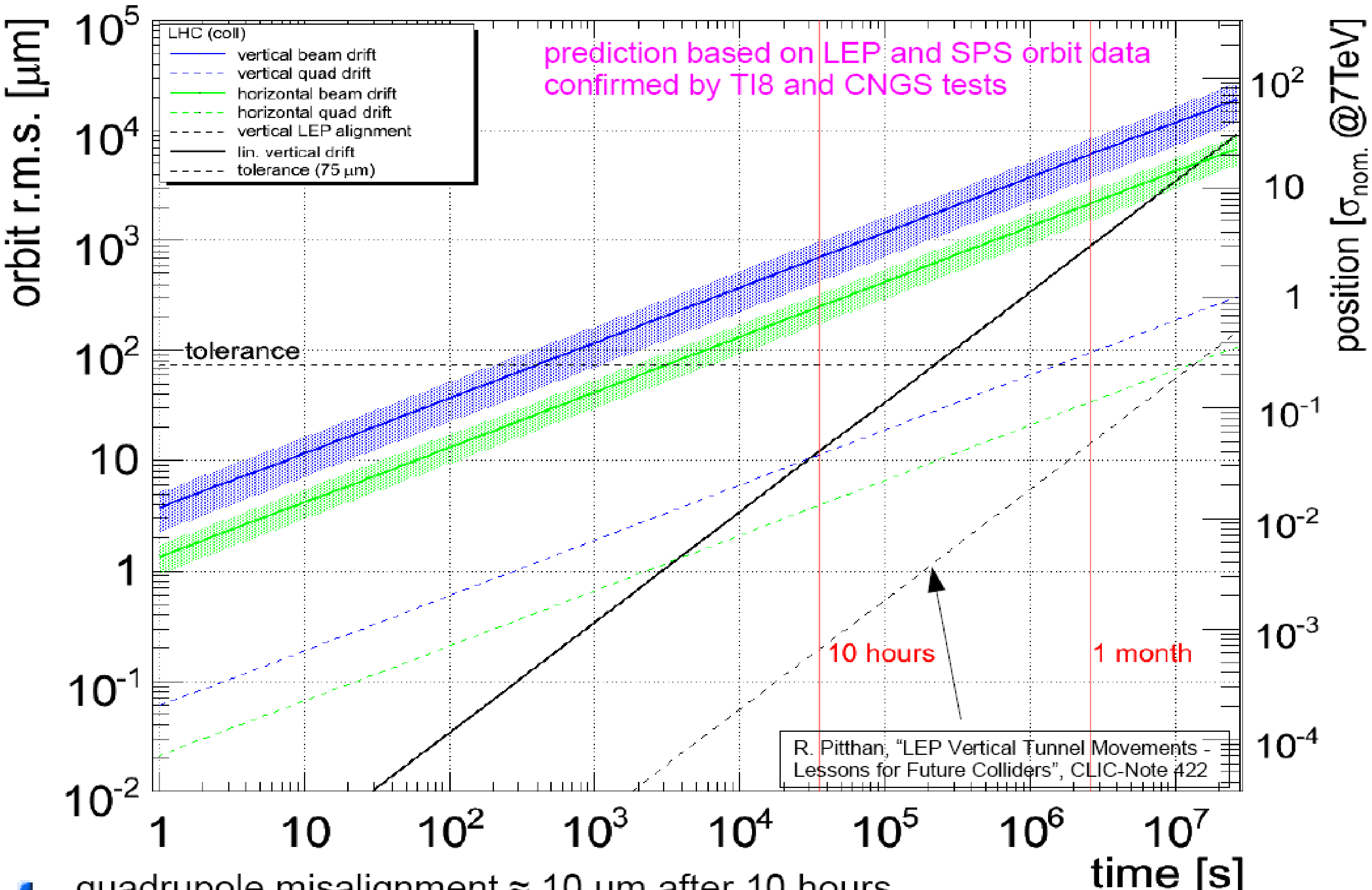
$\Delta x/\Delta y$ [σ]	L/L_0 [%]
0	100
0.5	≈ 94
1	≈ 79
2	≈ 37
3	≈ 11
4	≈ 2

- geometric optics: beam overlap at IP ↔ beam position stability at BPMSW
  - nominal: $\sigma^* \approx 15$ µm, e.g. 1σ overlap at IP → 15 µm stability at BPMSW
- N.B. nom. crossing angle “guarantees” one plane overlap (long. shift « 20 µm)

Extra high resolution pick-ups?

- 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 σ_{BPM} = 10 μm resolution
- Implies design, construction and installation of a new combined pick-up system :
  - Strip-line for normal operation with crossing angle and many bunches
  - Button to measure the zero crossing angle angle and adjust collisions in early operation etc.
  - Would also be useful for VdMSs

Ground motion



Final Focus Stability, Ralph.Steinhagen@CERN.ch, 2007-06-24

- quadrupole misalignment ≈ 10 μm after 10 hours
  → closed orbit drifts (coll. optics) ≈ 1-3 σ

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Thermal Expansion of Girders

- Mechanism: Orbit feedback intrinsically aligns with respect to the BPMs that are either attached to the quadrupoles or have similar girders
- Thermal expansion, steel $\alpha_{steel} \approx 10\text{-}17 \cdot 10^{-6}\,K^{-1}$ (BS:970, DIN18800):

$$\Delta x = x_0 \cdot \alpha \cdot \Delta T$$

- Systematic shift of beam reference system with respect to non-moving external reference (e.g. potentially collimators):
  - Cryo-Magnets: $x_0 \geq (340 \pm 20)$ mm → $\Delta x \approx 3.4 - 5.8$ µm/°C
  - Warm equipment: $x_0 \approx 950$ mm → $\Delta x \approx 9.5 – 16$ µm/°C
- The inlet temperature is stabilised to about ±1°C
  - temperature changes shouldn't pose a problem for even IRs

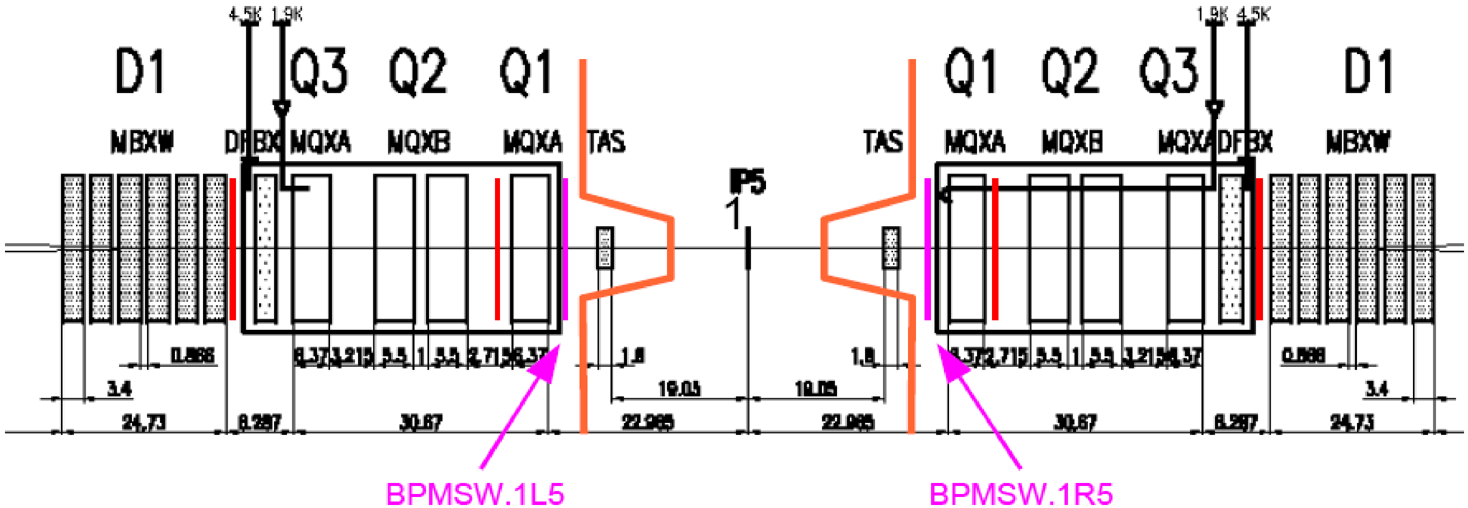
Thermal Expansion of Girders - IRs

- Left-Right temperature gradient:

tunnel air:
$T_1 \approx 23 \pm 6$ °C

cavern:
$T_3 \approx 23 \pm 6$ °C (?)

tunnel right:
$T_2 \approx 23 \pm 6$ °C



- $T_1 \neq T_2 \neq T_3$
  - powering of arc equipment (CODs, ...) → dyn. heat-load asymmetry
  - IR4 (RF, BI) → IP5 ← IR6 (beam extraction)
- Working assumption: $\Delta T = |T_2 - T_1| \approx \pm$ 1...2 °C → $\Delta x_{thermal} \approx$ 16-32 μm

Transverse beam size at IP

- The further we squeeze, the smaller the beam size at the IP, and thus the smaller the beam movement to luminosity resolution.

beta*	Nominal beam size at IP (μm)
17	92
11	74
9	67
5	50
1	22
0.55	17

- Emittance variation/blow-up a definite possibility
  - Fill-to-fill, bunch-to-bunch…
- Transverse beam size from one of:
  - Synchrotron Light Monitor, Rest Gas Monitor or Wire Scanner plus optics measurements - difficult
- Van der Meer scans

RHIC

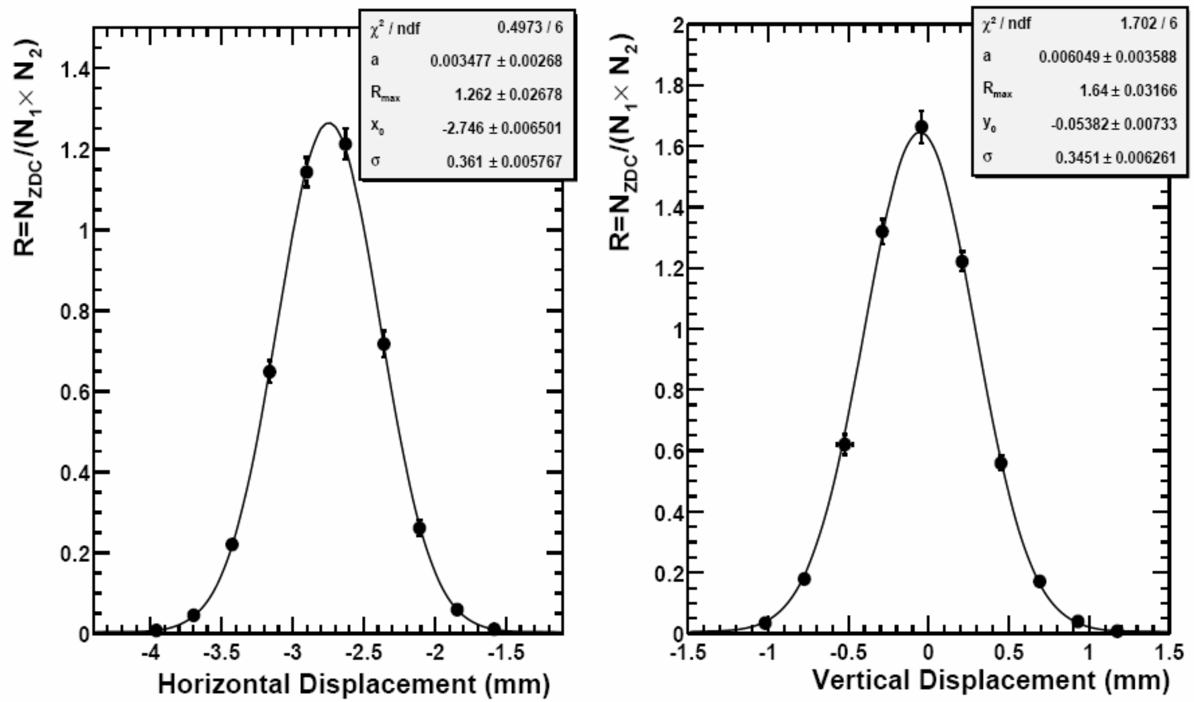


Figure 2.4: The R $(= N_{ZDC}/(N_1 N_2))$ vs. the measured beam horizontal (left) and vertical (right) position and fit with a Gaussian function $R = a + R_{max}\exp[-(x - x_0)^2/2\sigma^2]$.

Figure 2.4 shows the calculated $N_{ZDC}/(N_1 N_2)$ (in unit of 10^{-18}Hz) vs. the beam horizontal and vertical positions and fit with a Gaussian function plus a constant representing any possible background. From the fit, we can extrapolate the beam profiles $\sigma_{Vx} = 361 \pm 6$ μm and $\sigma_{Vy} = 345 \pm 6$ μm.

Alignment Optics

- Special optics without triplet powering have been designed
- Beam trajectory in the IR without quadrupoles can be used as a reference for triplet alignment.
  - Aim to avoid orbit distortions
  - Optics errors

Longitudinal crossing point

- RMS bunch length at 7 TeV = 7.55 cm, 16 MV
- No longitudinal feedback during commissioning:
  - Injection errors not compensated for second and subsequent injections
  - (Anyway for nominal beams there is planned blow-up with RF noise during the ramp (IBS))
- Re-phasing (coarse and fine) at top of ramp
  - Adjustment of collision point to very high precision
  - Fully reproducible from fill to fill
    - LEP: One RF system – two beams
    - LHC: Two independent RF systems that can be adjusted as desired

Conclusions 1/3

- Beam commissioning
  - Should start May 2008
  - 2 months to get first collisions
  - First collisions - low intensity, un-squeezed.
  - We will be careful.

- Phase A
  - No crossing angle
  - Gradual increase in current - up to 156 bunches/beam
  - Pilot physics: un-squeezed to partial squeeze
  - $\leq 10^{32}$ $cm^{-2}s^{-1}$

- Collimation
  - Phase 1 scheme will be in place
  - Full and appropriate machine protection will be pursued.

http://cern.ch/lhccwg/

Conclusions 2/3

- "How well do you (we) know the beamline at the interaction point?"
  - without beam-based alignment: $\Delta x \approx$ 300-600 µm r.m.s.
    - for details: LHC Collimation WG Meeting #79
  - with beam-based alignment: $\Delta x \approx$ 5 µm r.m.s.
    - after k-modulation, Lumi-scans ("guess")

Conclusions 3/3

- "Will it change within a run or to the next run/fill?" - **Yes**
  - stability without orbit feedback but "perfect" feed-forward of last cycle
    - $\Delta x \approx 300 – 600\ \mu m$ r.m.s.
    - for details: LHC Collimation WG Meeting #79
  - stability with orbit feedback:
    - w.r.t. geometric cold quad. centre: $\Delta x \approx 5\text{-}7\ \mu m$ r.m.s.
      - assumes nominal FB operation
    - w.r.t. geometric warm quad. centre: $\Delta x \approx 20\text{-}30\ \mu m$ r.m.s.
      - limited by thermal gradients
  - w.r.t. ext. reference (e.g. CMS detector): $\Delta x \approx 30\text{-}50\ \mu m$ r.m.s.
    - limited by ground motion and thermal drifts
  - Numbers assume perfect fill-to-fill beam parameters reproducibility
  - does not include long-term BPM stability – to be verified

Particular thanks to Ralph Steinhagen