LHC status, commissioning plans and a brief overview of upgrade issues

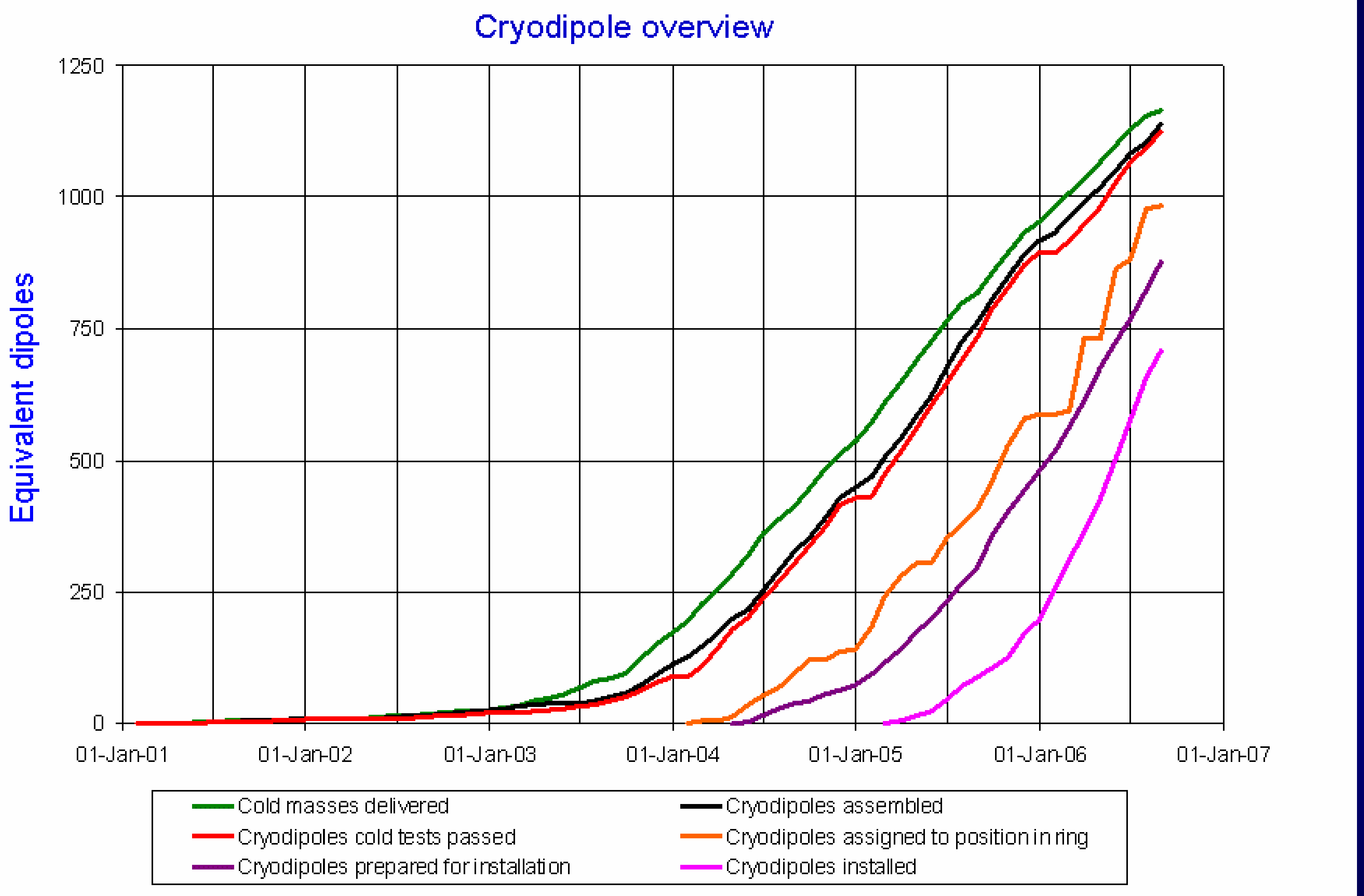
Mike Lamont

Installation

Sector	In progress	Next
1-2	QRL installation	Finish October 2006
2-3	QRL consolidation	Magnet installation
3-4	Magnets in place, quench protection/cryo instrumentation	Interconnects
4-5	Most magnets in place	Finish interconnects
5-6	Most magnets in place	Interconnects
6-7	Magnet installation	All magnets in Feb. 07
7-8	Most magnets in place, interconnects	Cool-down November 06
8-1	All magnets in place, interconnects	Finish interconnects Cool-down - start 07

Note: Cryogenic supply lines (QRL) – solved problem

Dipoles



Updated 31 Aug 2006 Data provided by D. Tommasini AT-MAS, L. Bottura AT-MTM

Magnets

5 September, the 1000th cryo-magnet was installed in the LHC tunnel in the arc between point 3 and point 4.

1000 out of 1746

(1232 dipoles)

Last one due in in March 2007

Interconnects

Joining everything up – 1700 times

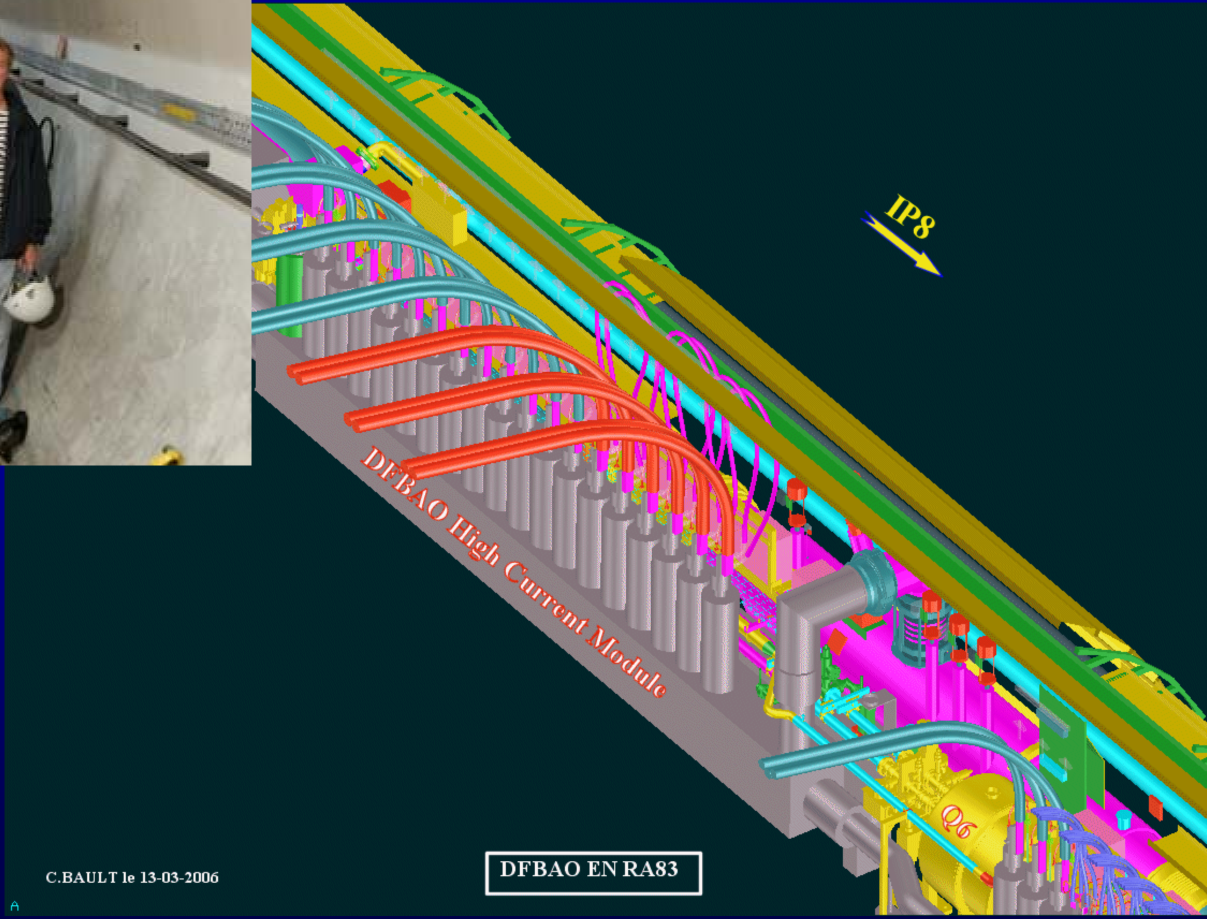
- Vacuum, bellows, RF contacts plus leak checks
- Cryogenics, thermal shield, heat exchanger
- Bus bars
  - superconducting splices x 10,000   (induction welding)
- Corrector circuit
  - splices x 50,000 (ultrasonic welding)

Huge, painstaking & industrialised

Clearly on the critical path

DFBs

Responsible for feeding the room temperature cables into the cold mass.

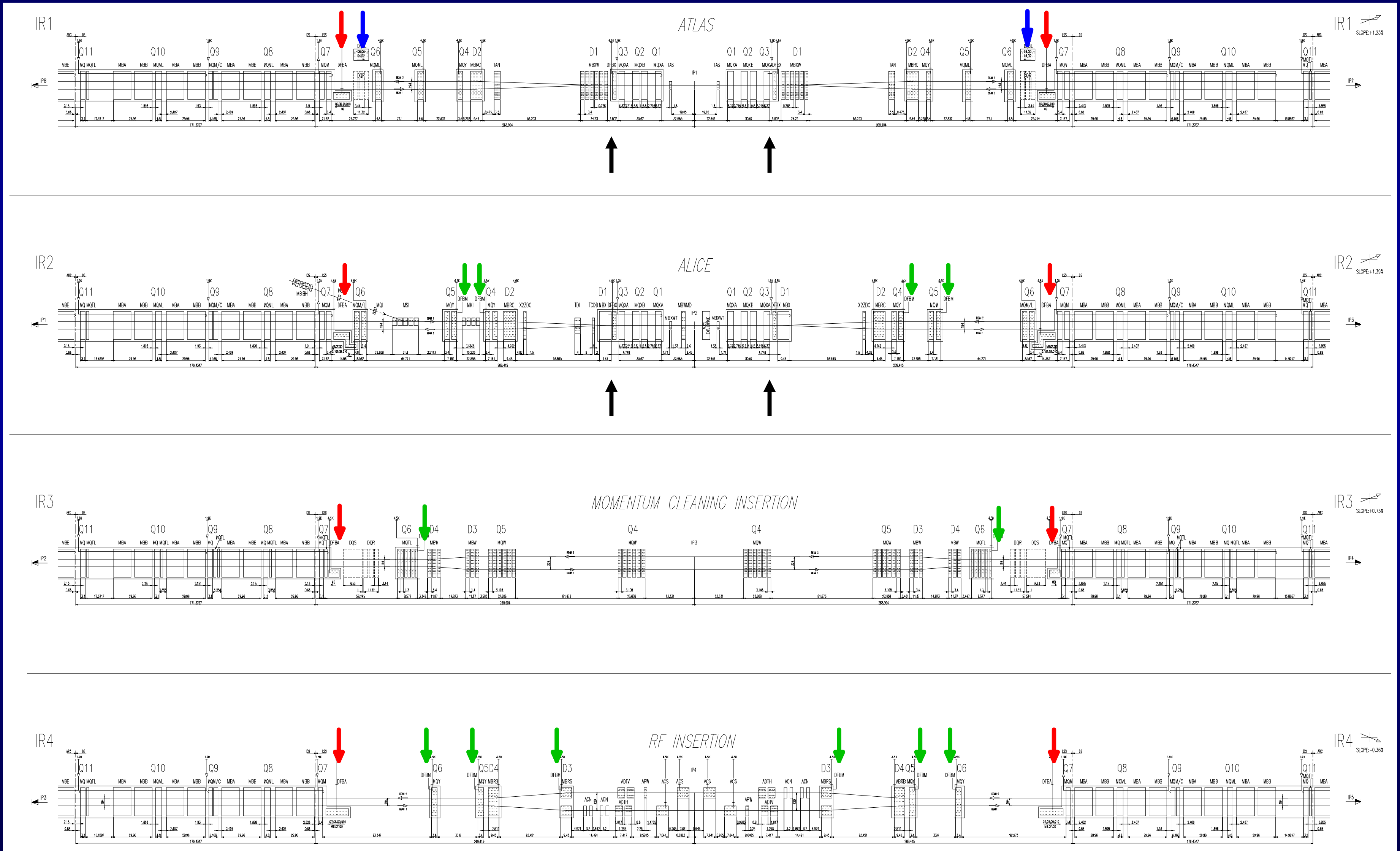


- DFBA - arcs
- DFBM - quads
- DFBL - links
- DFBX – triplets

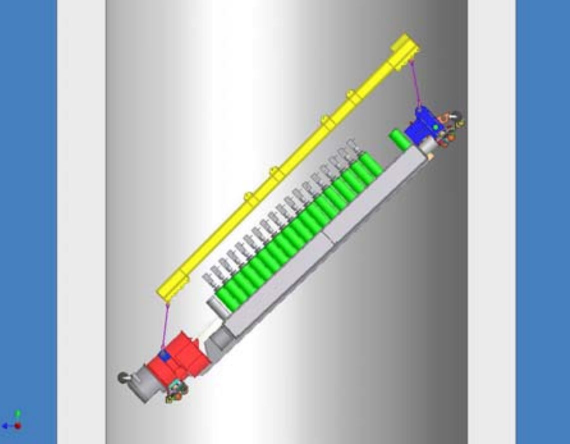
52 total

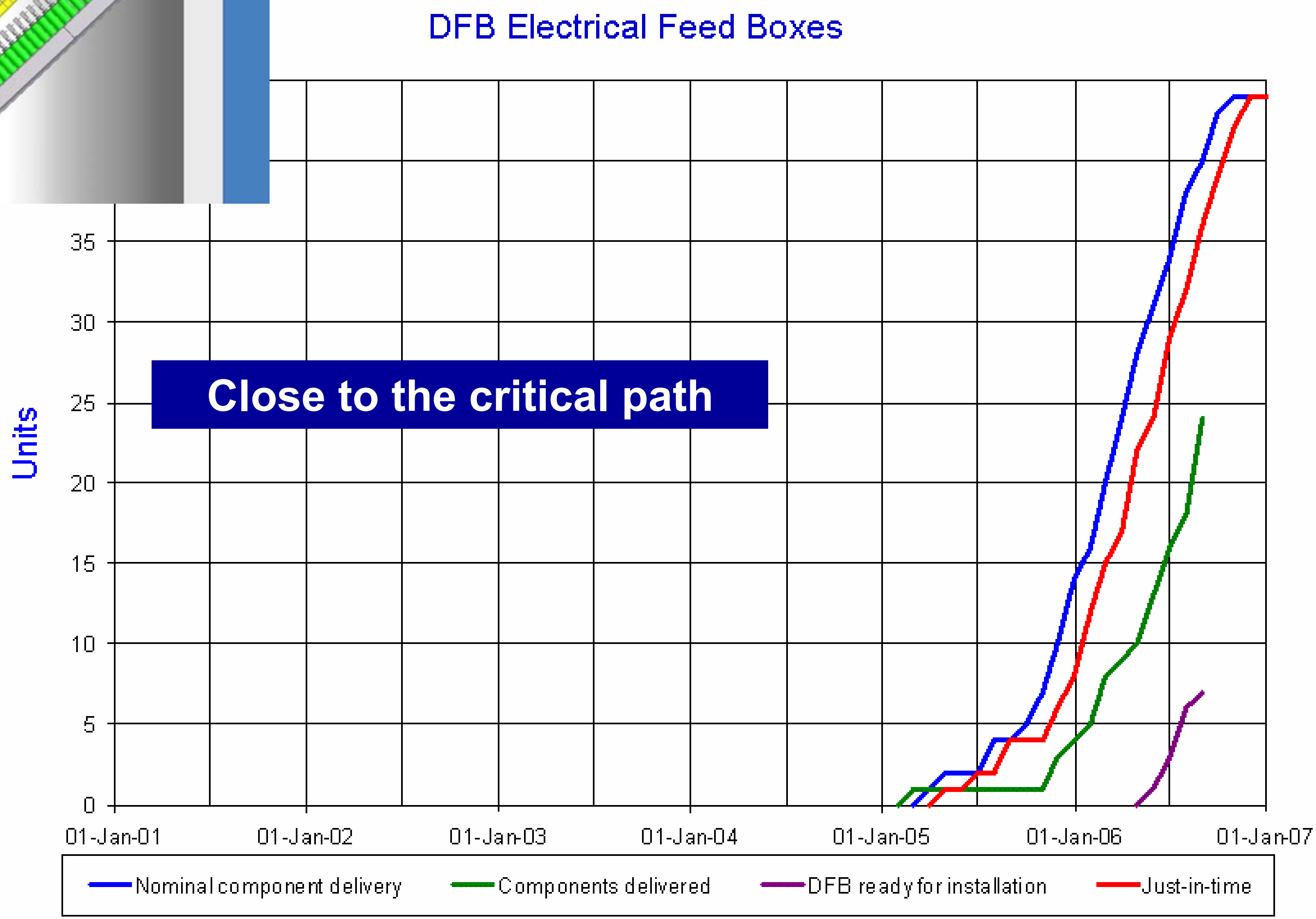
DFBs

Have to be in position before cool-down



DFBs

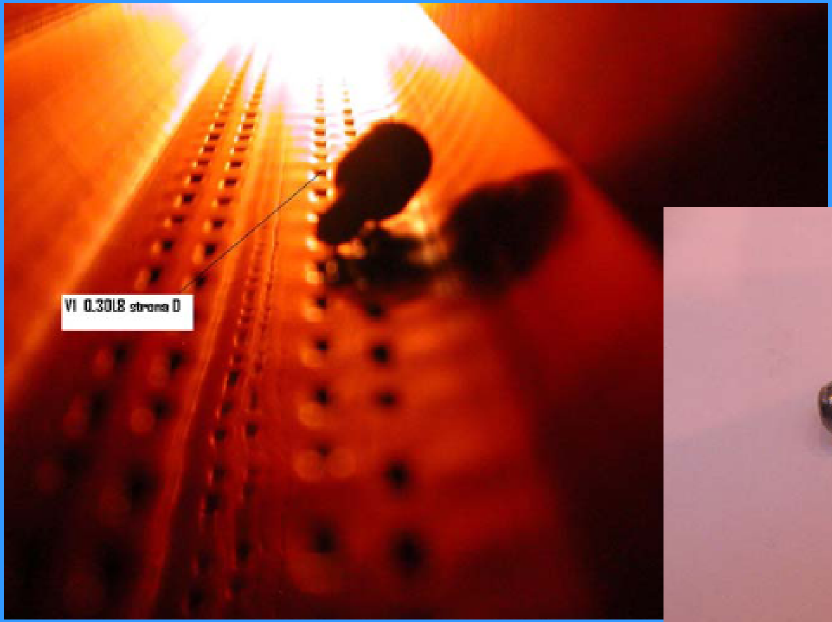




Updated 31 Aug 2006 Data provided by A. Perin AT-ACR

Miscellaneous

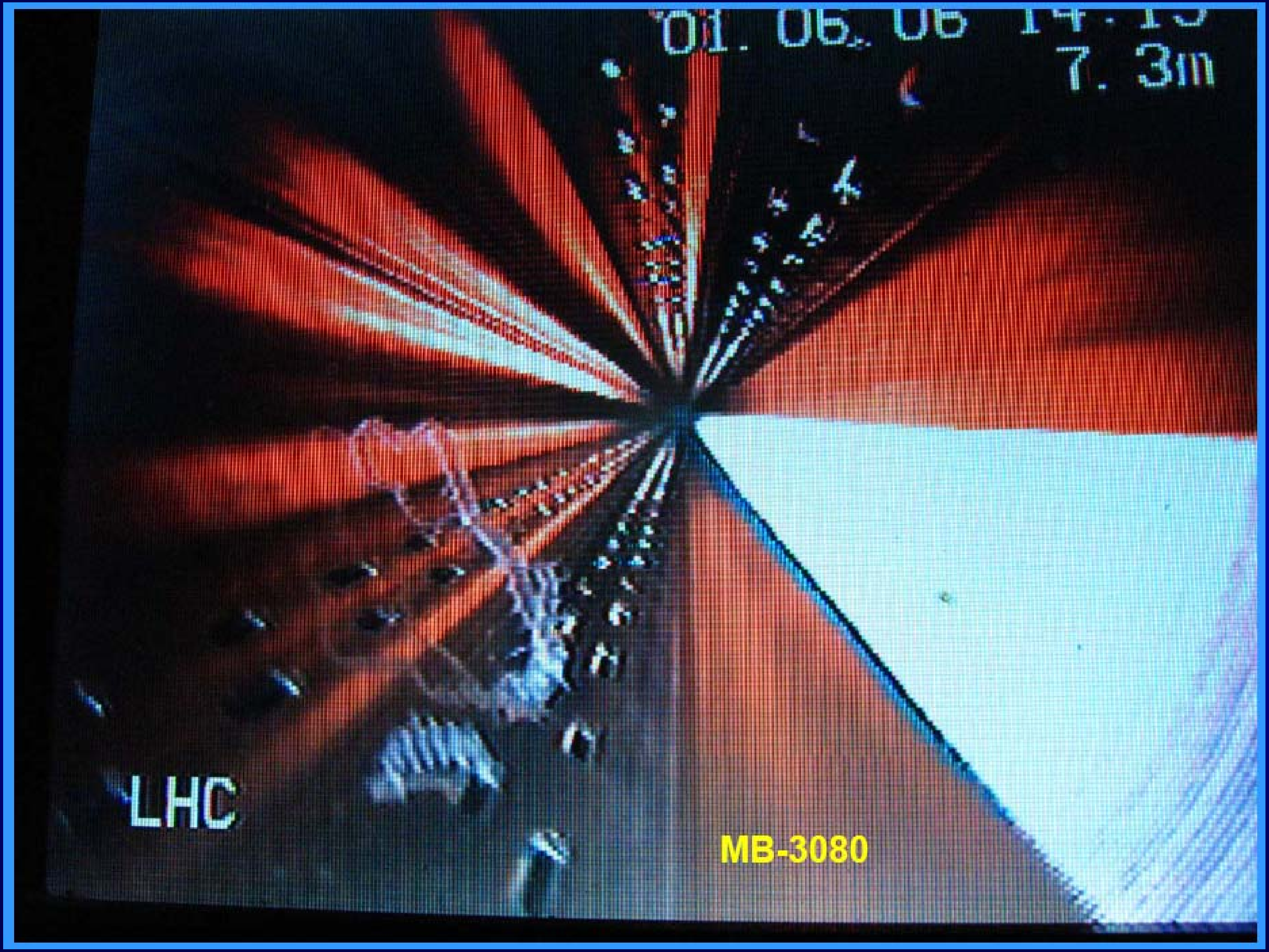
MQ.30L8, 31.01.2006



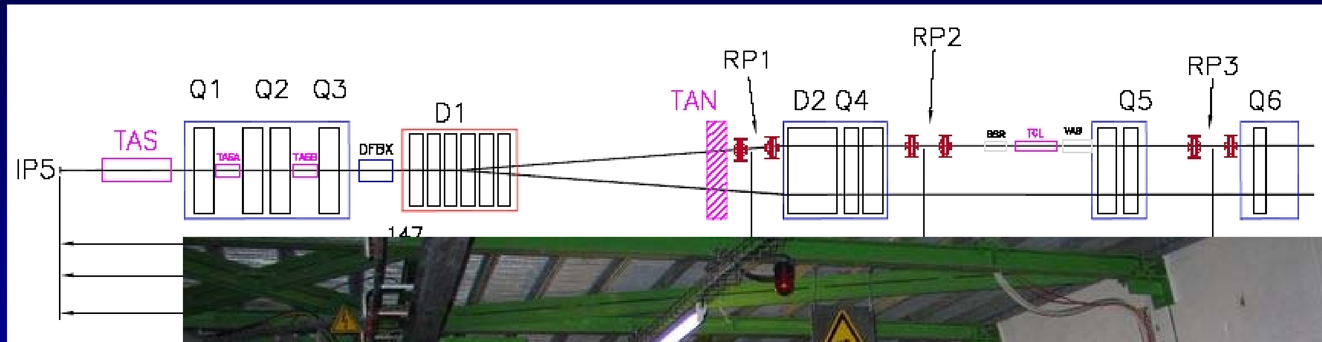
echo -22 dB

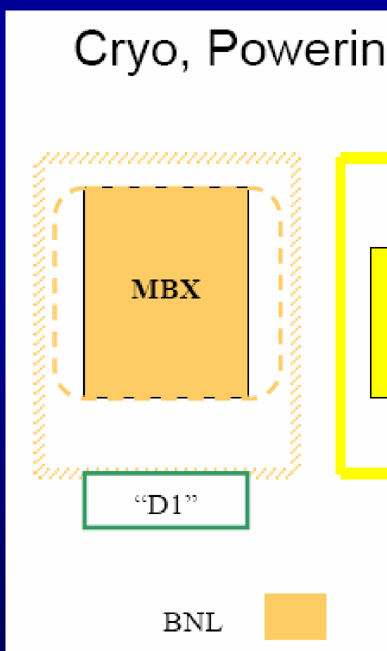
Potential aperture restrictions

Bits and bobs



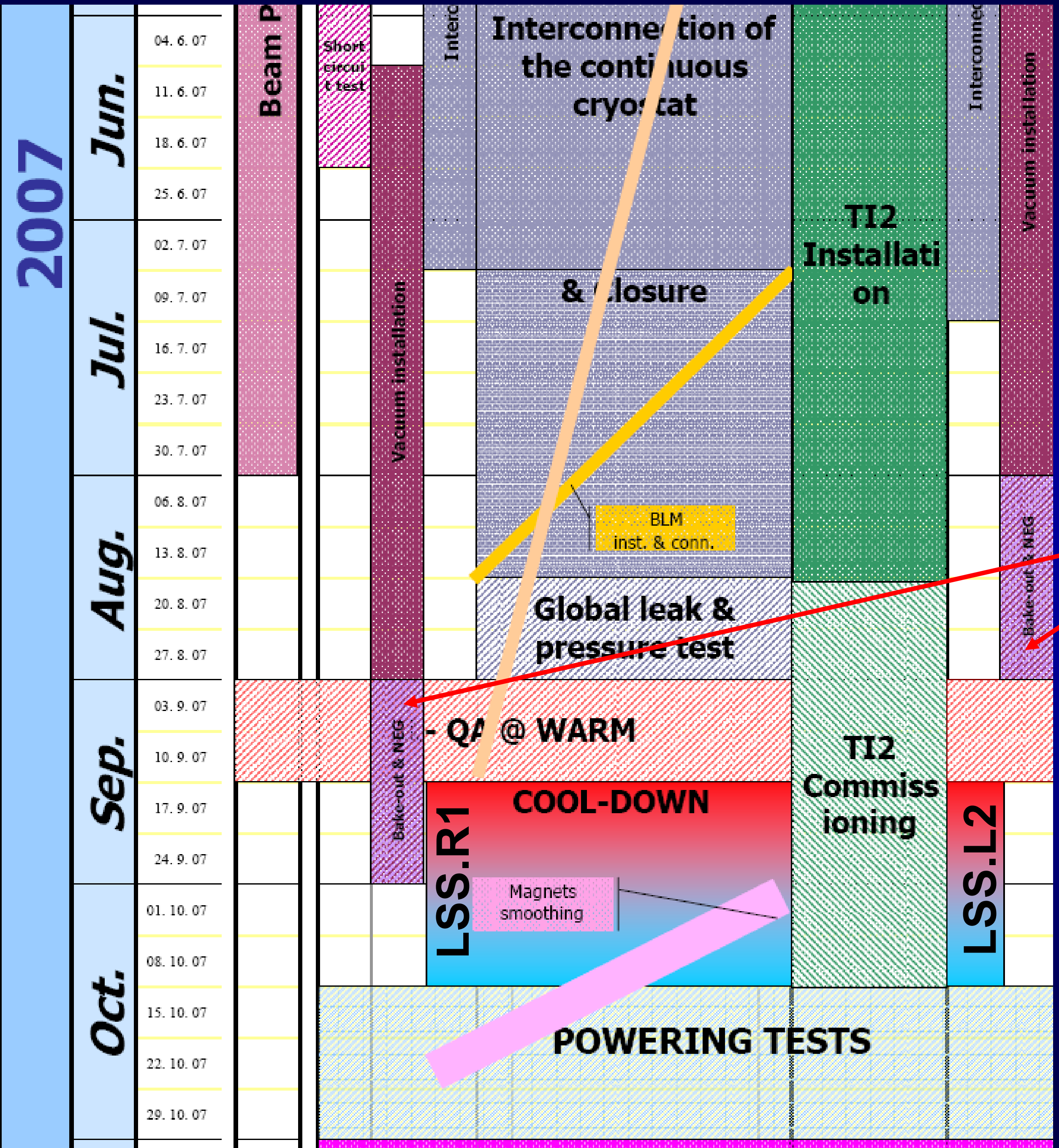
LSSs


IP5
TAS
Q1
Q2
Q3
D1
DFBX
TAN
RP1
RP2
D2 Q4
Q5
RP3
Q6


Cryo, Powerin
MBX
"D1"
BNL


Fermilab
COTE I.P

⇐ ATLAS SECTOR 1-2 ALICE ⇒



NB Bake-out

Arc dependency

Installation - remarks

It is a huge job

- QRL problem solved
- Magnet installation proceeding well

- Interconnects – work in progress
- DFBs – just in time (plus some other stuff…)

- A lot still to do, plus the challenges of hardware commissioning:

- First sector to start cool-down in November

- Powering test to still to come
  - Quench protection, quenches, energy extraction, cold leaks, DFB commissioning at cold, interlocks etc. etc.

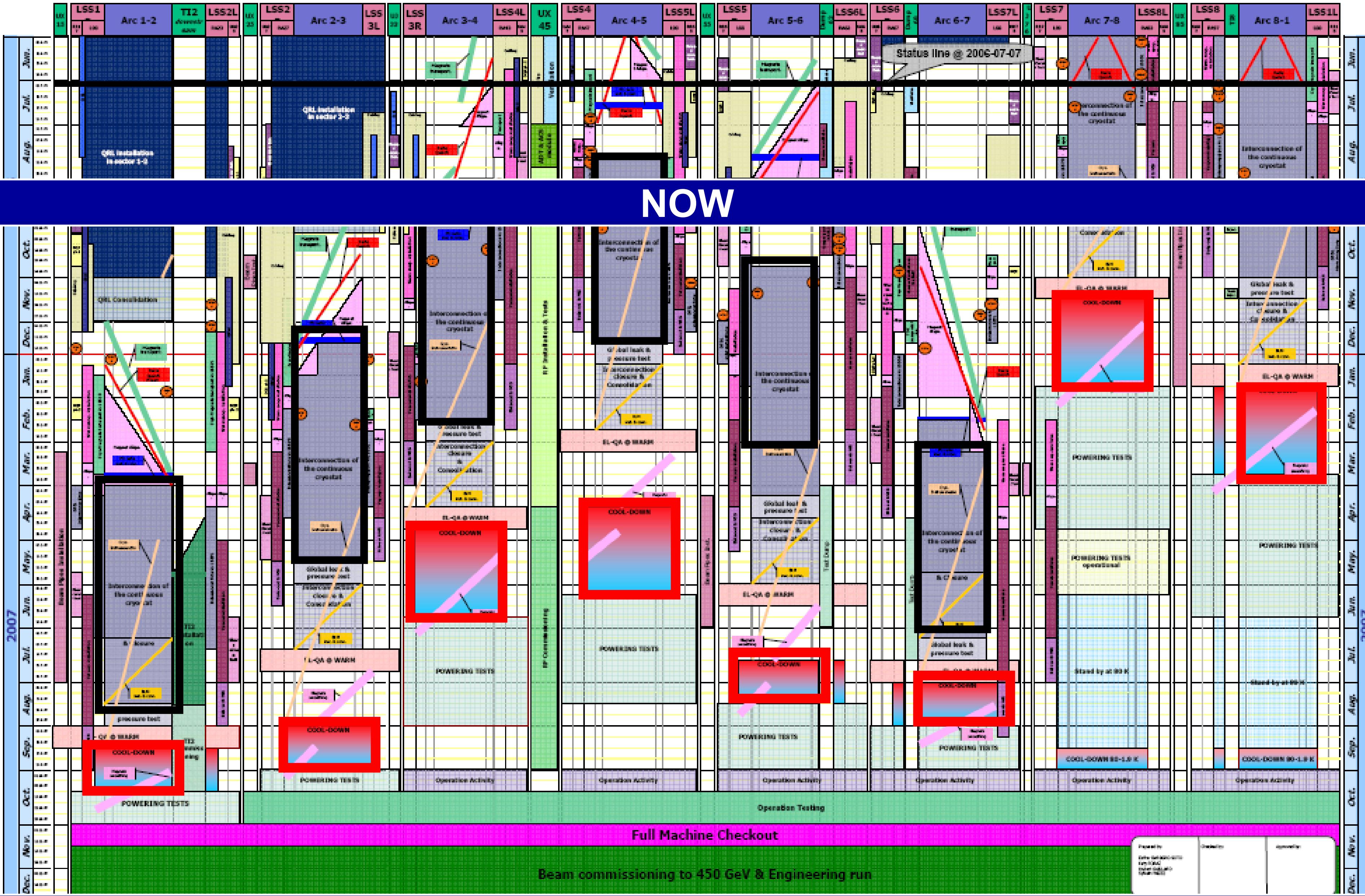
And that's before we even mention beam.

Challenges will include:

- High beam energy – demands on machine protection system
- Very low tolerance to beam loss (quenches)
- Which implies tight constraints on key beam parameters
- Dynamic characteristics of the magnets (persistent currents etc.)

LHC Construction and Installation

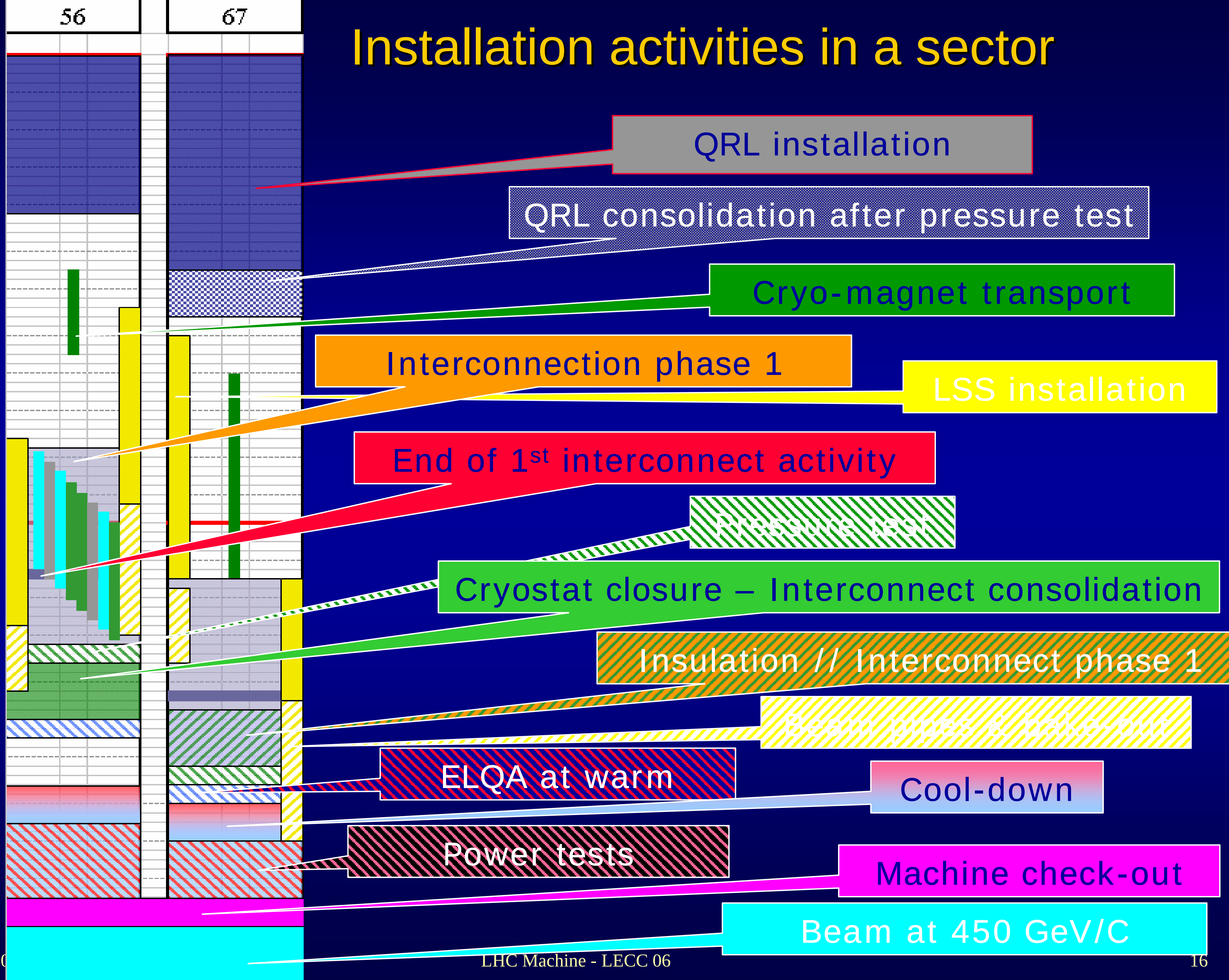
General Co-ordination Schedule



NOW

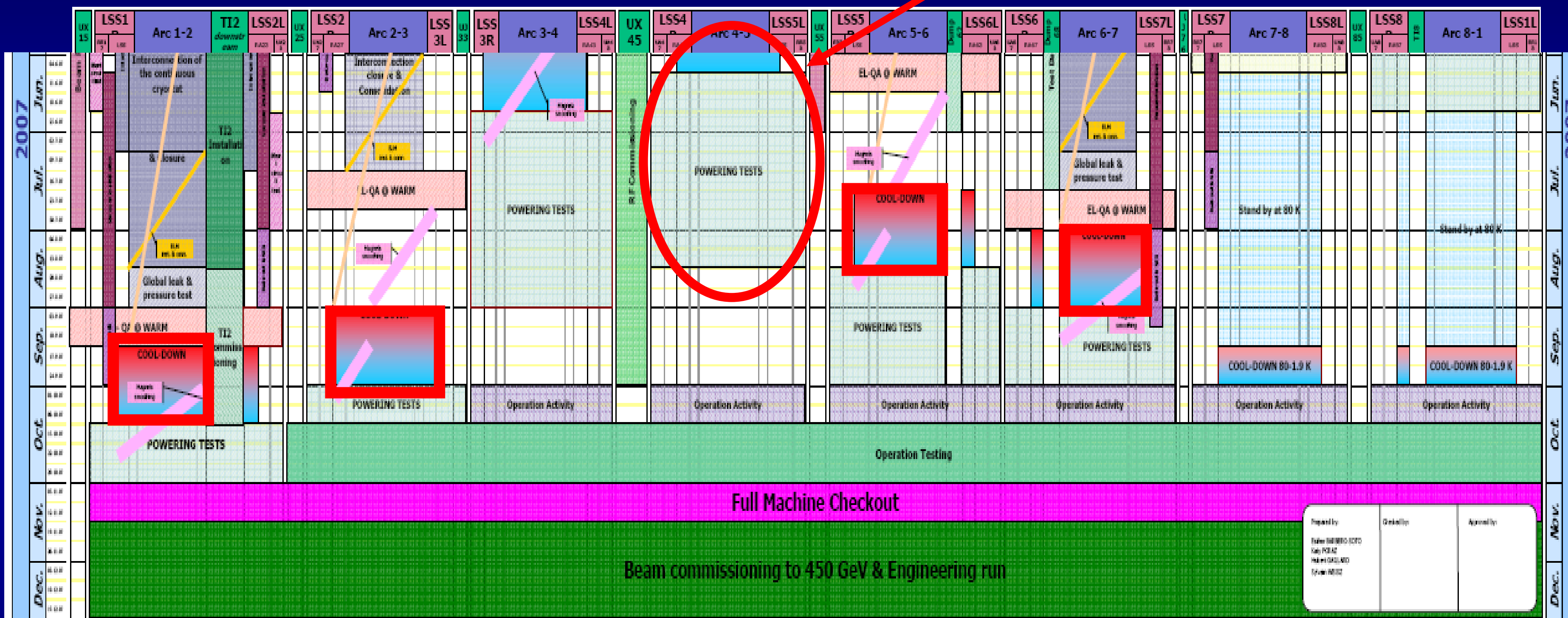
XMAS 2007

Installation activities in a sector

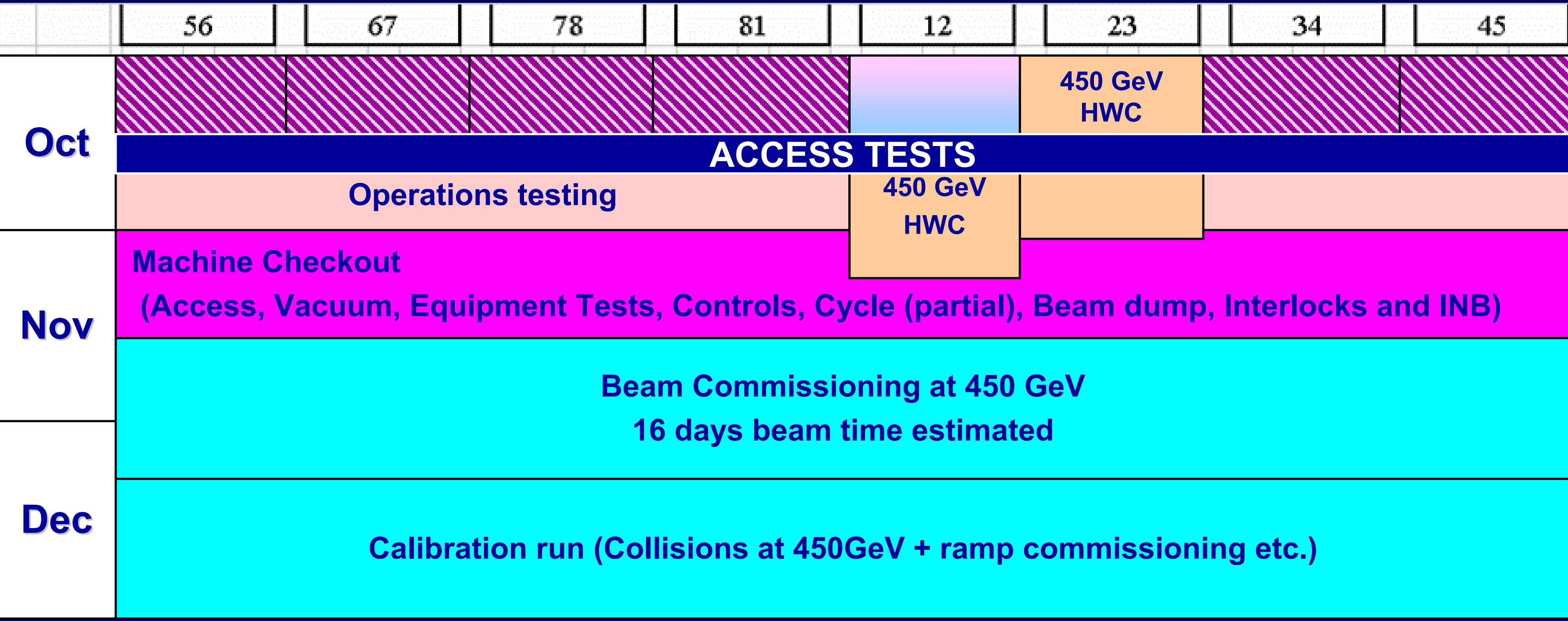


End 2007

Hardware Commissioning qualification of circuits to 7 TeV – not trivial



End 2007



Sectors 5-6, 6-7, 1-2 & 2-3:

- baseline commissioning of main circuits to 1.1 TeV
- minimal circuit set

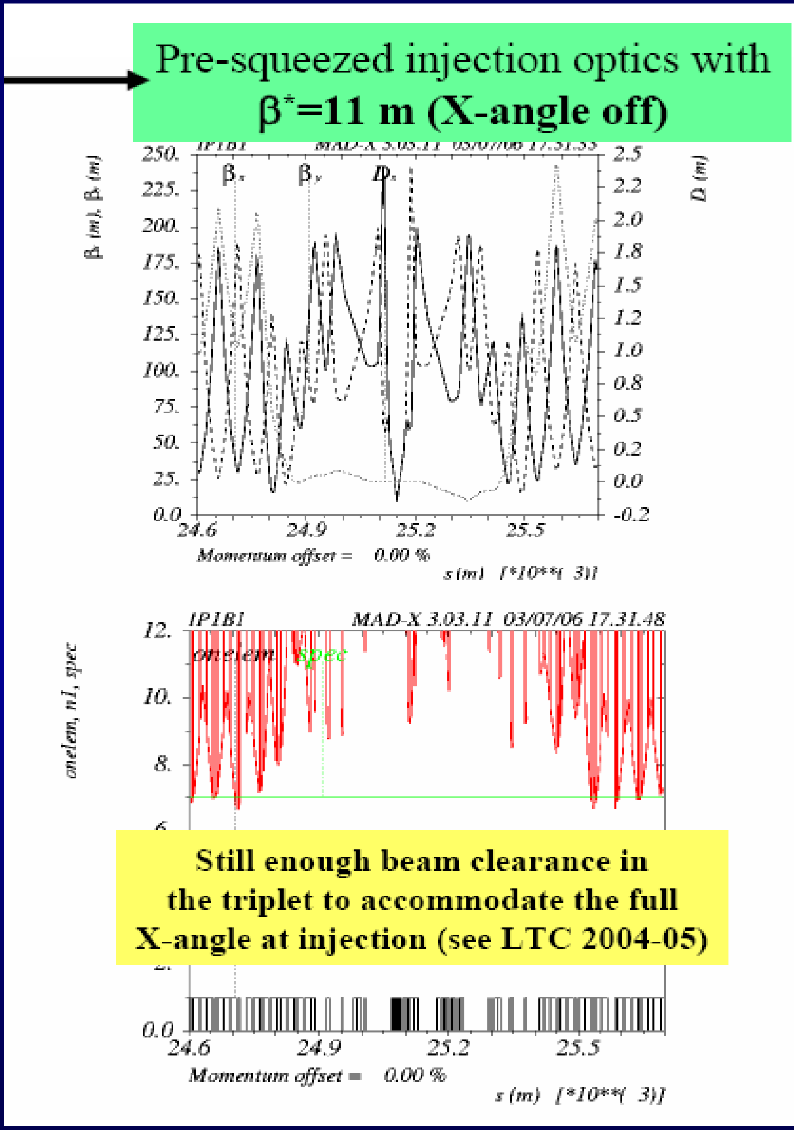
450 GeV – Calibration Run

- **Operations' aims:**
  - Commission essential safety systems
  - Commission essential beam instrumentation
  - Commission essential hardware systems
  - Perform beam based measurements to check:
    - Polarities
    - Aperture
    - Field characteristics
  - Establish collisions
  - Provide stable two beam operation at 450 GeV
  - Interleave collisions with further machine development, in particular, the ramp.

Should provide a firm platform for eventual commissioning to 7 TeV and provide adequate lead time for problem resolution.

Machine Configuration

- **Optics:**
  - β*= 11 m in IR 1 & 5 (no squeeze)
  - β*= 10 m in IR 2 & 8
  - Limited by triplet aperture
- **Crossing angles off**
  - 1, 12, 43, 156 bunches per beam
- **Separation bumps - two beam operation**
- **Shift bunches for LHCb**
  - 4 out of 43 bunches, or 24 bunches out of 156
- **Solenoids & Exp. Dipoles etc.**
  - off (to start with)



450 GeV Beam Commissioning: Phases

	Phase	Main Objectives
1	First turn	End TI2, TI8, injection region, BPMs, BLMs, thread first turn, polarity checks
2	Establish circulating beam	Closed orbit, chromaticity, energy matching, tune, RF capture
3	Initial commissioning	RF, control & correction, transverse diagnostics, linear optics checks, BLMs, beam dump, machine protection
4a	Measurements	Beta beating, aperture, field quality checks, transfer functions
4b	System commissioning	RF, transverse feedback, BLMs to MPS, tune PLL, collimators and absorbers
5a	Two beam operations	Parallel injection, separation bumps, instrumentation and control
5b	Collisions	Establish collisions, luminosity monitors, collimation, solenoids
6	Increase intensity	Collimators, LFB, multi-batch injection

Beam

- **Pilot Beam**
  - **Single bunch, 5 - 10 x 10^9 protons, reduced emittance**
- **Pilot++**
  - **Single bunch 3 to 4 x 10^{10} protons**
- **4, 12 bunches etc. pushing towards…**
- **43,156 bunches**
  - **3 to 4 x 10^{10} ppb**

	Bunches	Bunch Intensity [10^{10} p]	Total intensity [10^{14} p]	Fraction of nominal
One pilot	**1**	**0.5**	**0.00005**	**1.6 10^{-5}**
12 Nominal	**12**	**10.0**	**0.01**	**3.7 10^{-4}**
43	**43**	**4.0**	**0.017**	**5.3 10^{-3}**
156 - I	**156**	**4.0**	**0.062**	**0.019**
156 - II	156	10.0	0.156	0.048
75 ns	936	4.0	0.37	0.12
25 ns - 1	2808	4.0	1.1	0.35
Nominal	2808	11.5	3.2	1.0

Time

	Phase	Beam time [days]	Beam
1	First turn	4	1 x Pilot
2	Establish circulating beam	3	1 x Pilot
3	450 GeV – initial	3	1 x Pilot++
4a	450 GeV - consolidation	1-2	1 x Pilot++
4b	450 GeV – system commissioning	2-3	1 x Pilot++
5a	2 beam operations	1	2 x Pilot++
5b	Collisions	1-2	$2 \times 1 \times 10^{11} \rightarrow$
		16 days	

Given an operational efficiency of 60%, this gives an elapsed time of about 26 days. ***CAVAET: MACHINE AVAILABILITY***

Some opportunities for parallel development and parasitic studies…

450 GeV - Performance

			Reasonable	Maximum
k_b	43	43	156	156
i_b (10^{10})	2	4	4	10
β^* (m)	11	11	11	11
intensity per beam	$8.6\ 10^{11}$	$1.7\ 10^{12}$	$6.2\ 10^{12}$	$1.6\ 10^{13}$
beam energy (MJ)	.06	.12	.45	1.1
Luminosity ($cm^{-2}s^{-1}$)	$2\ 10^{28}$	$7.2\ 10^{28}$	$2.6\ 10^{29}$	$1.6\ 10^{30}$
event rate [1] (kHz)	0.4	2.8	10.3	64
W rate [2] (per 24h)	0.5	3	11	70
Z rate [3] (per 24h)	0.05	0.3	1.1	7

Several days

1. Assuming 450GeV inelastic cross section 40 mb
2. Assuming 450GeV cross section $W \rightarrow l\nu$ 1 nb
3. Assuming 450GeV cross section $Z \rightarrow ll$ 100 pb

Calibration Run 2007

- 6 weeks beam time
- 3 weeks beam commissioning
  - Essentially single beam, low intensity for the most part
- 3 weeks collisions
  - Single bunch initially, with staged increase to 156 x 4 x 10^{10} (+)
  - Luminosities: 1.3 10^{28} to 2.6 10^{29} $cm^{-2}s^{-1}$ (+)
  - Interleafed with low intensity single beam MD
    - Initial ramping tests to 1.1 TeV etc.

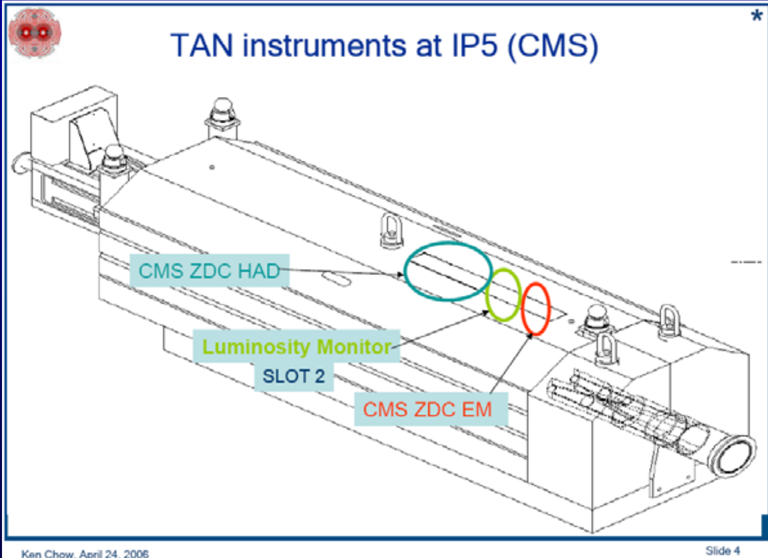
Beam spot – transverse

- **Bigger beams at 450 GeV**
  - 290 μm at $\beta^* = 11$ m.
  - 277 μm at $\beta^* = 10$ m.
- **2 challenges:**
  - **Colliding the beams**: should be able to get them within 150 μm using BPMs
  - **Orbit stability:** feedback to be commissioned
- **Vertex position**
  - Transverse: 1 mm run-to-run, 3 mm long term
  - Absolute position: approx. ± 400 μm from BPMs

Transverse beam size from one of:
Synchrotron Light Monitor, Rest Gas Monitor or Wire Scanner
plus optics measurements

Relative Luminosity Measurement

- **Low luminosity will be straining bounds of machine luminosity monitors (LBL ionization chambers - BRAN)**
  - **Low event rates of high energy neutrons in BRAN**
  - **Background, Signal/Noise**
- **Initial collisions with single bunch 1.1 x 10^{11} to give BRAN something to see.**
- **Other ideas:**
  - **Beam-beam coupling signal from high sensitivity BPM**
  - **Schottky**
  - **Scintillators [machine]**



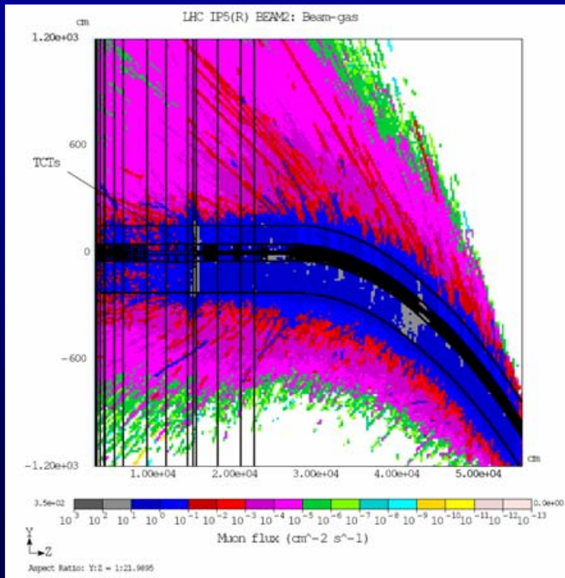
Background

Beam gas interactions and beam halo muon/hadron rates

- Residual gas within experiments
  - Baked out – low rates
- Residual gas in LSSs
- Gas pressure in adjacent cold sectors
  - Relative high pressures, elastic scattering

- Inefficiency of cleaning in IR7 & IR3

Nikolai Mokhov



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

Vacuum – 450 GeV

	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}	([illegible].7–9.8) 10^{13}	3.2 10^{14}
Current (mA)	0.02 - 25	70 - 80	582
Average current (mA)	8	140	582

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.

A. Rossi LPR 783

The 450 GeV run will be stage 0.

No conditioning, minimal pump-down time in some sectors. Static vacuum.

Potentially some LSSs un-baked - no NEG activation. Experiments should be baked.

Vacuum life time shall be greater than 35 h and 50 h for 2007 and 2008 respectively cf 100 h nominal

Halo

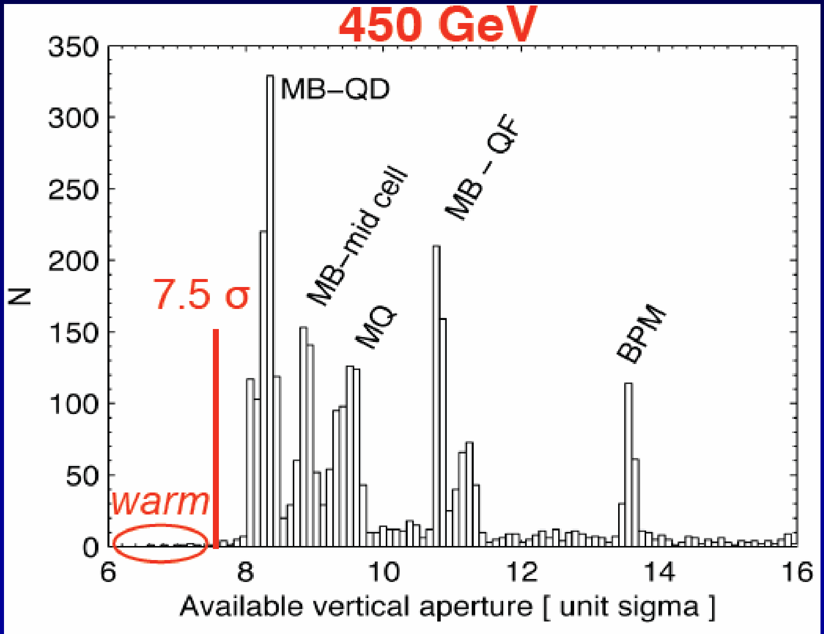
- Scrape in the SPS, collimate in the transfer lines
- Expect halo generation from
  - RF noise
  - Intra Beam Scattering
  - Optics mismatch
  - Beam-gas
  - Poor parameter control (tune, chromaticity), poor lifetime, stream particles to aperture limit

- Nominally this is cleaned by the collimation system with the resulting tertiary halo potentially finding its way to the experiments insertion – and the tertiary collimators

Vadim Talanov & team plan detailed studies, given scenario of collimator operation at the 450 GeV start-up (loss maps etc.)

450 GeV: Collimation I

- Lower intensity
- Lower energy
- Bigger beams
- Un-squeezed
- Aperture limitation is the arcs & DS



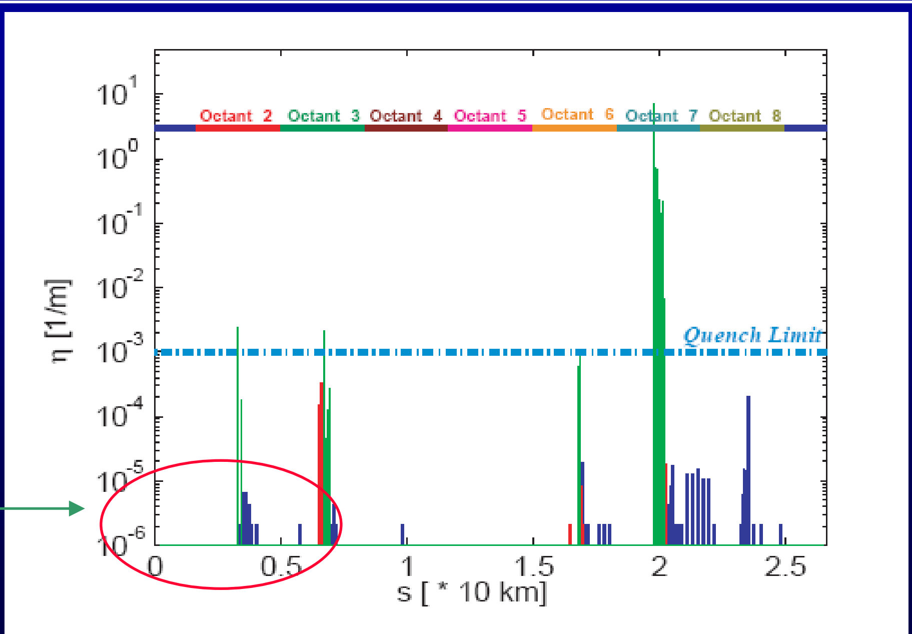
- **With low beam intensity:**
  - Primary collimators: 6σ
  - Secondary collimators: out
  - Tertiary collimators: out
  - Absorbers: out
  - TCDQ: 10σ
  - TDI: out

450 GeV: Collimation II

- **With an optimistic beam intensity we might see:**
  - Primary collimators: 5.7σ
  - Secondary collimators at 6.7σ
  - Tertiary collimators: out
  - Absorbers: out
  - TCDQ: 9σ
  - TDI: 6.8σ

Un-squeezed – tertiary collimators out – aperture limit in the arcs – would expect low halo losses in IRs

TDI – IP2
(out after inj.)



Who knows…

	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/c	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	5.21
/L(t) nb-1	0.78	0.68	0.78	0.52
BKG 1	1.20	0.52	0.90	0.43
BKG 2	0.85	0.82	0.50	0.80

Comments 31-11-07 11:40:26

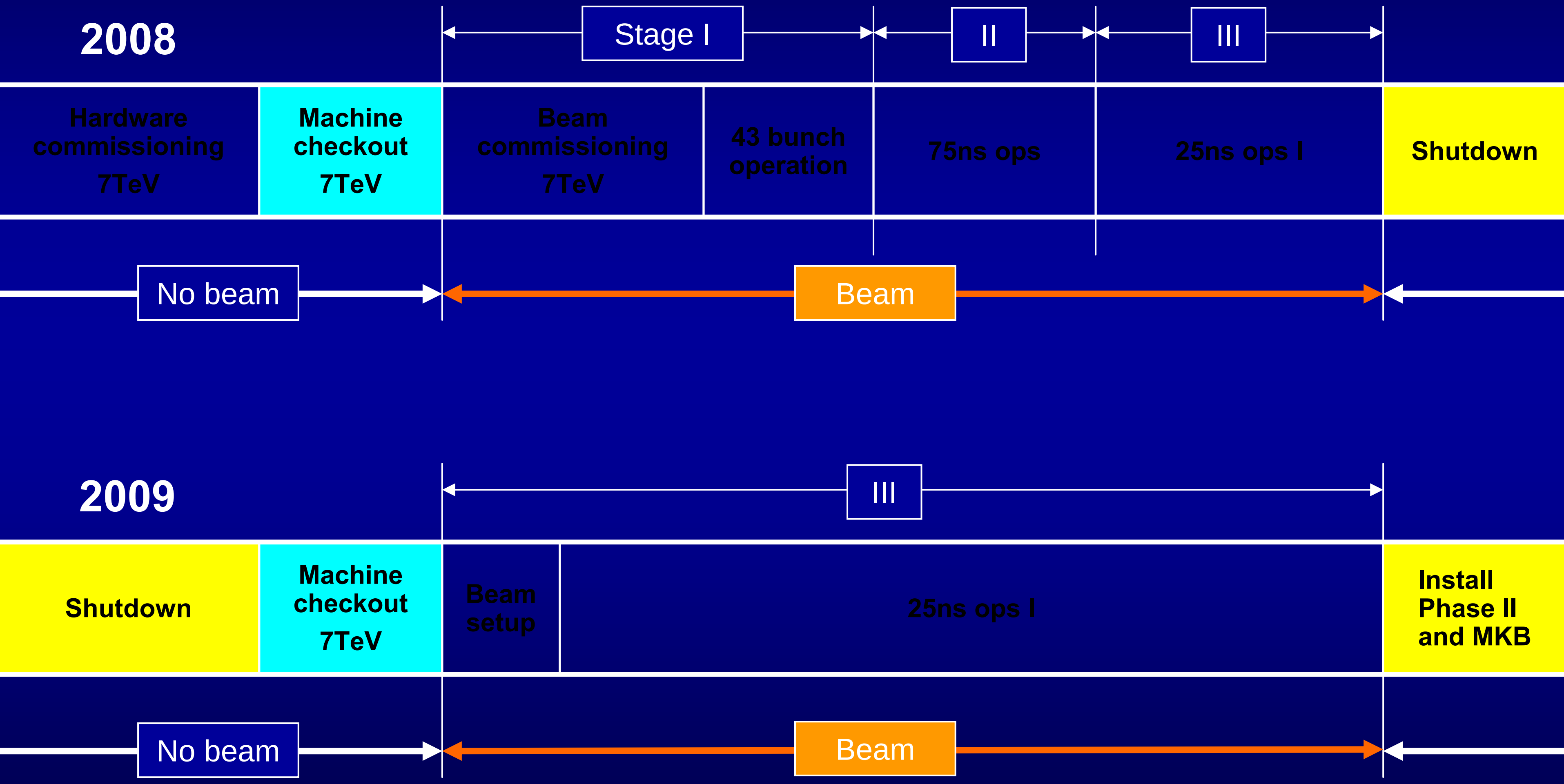
COLLIMATORS in coarse settings

Separation Scan in IR1/Atlas

Helmut Burkhardt

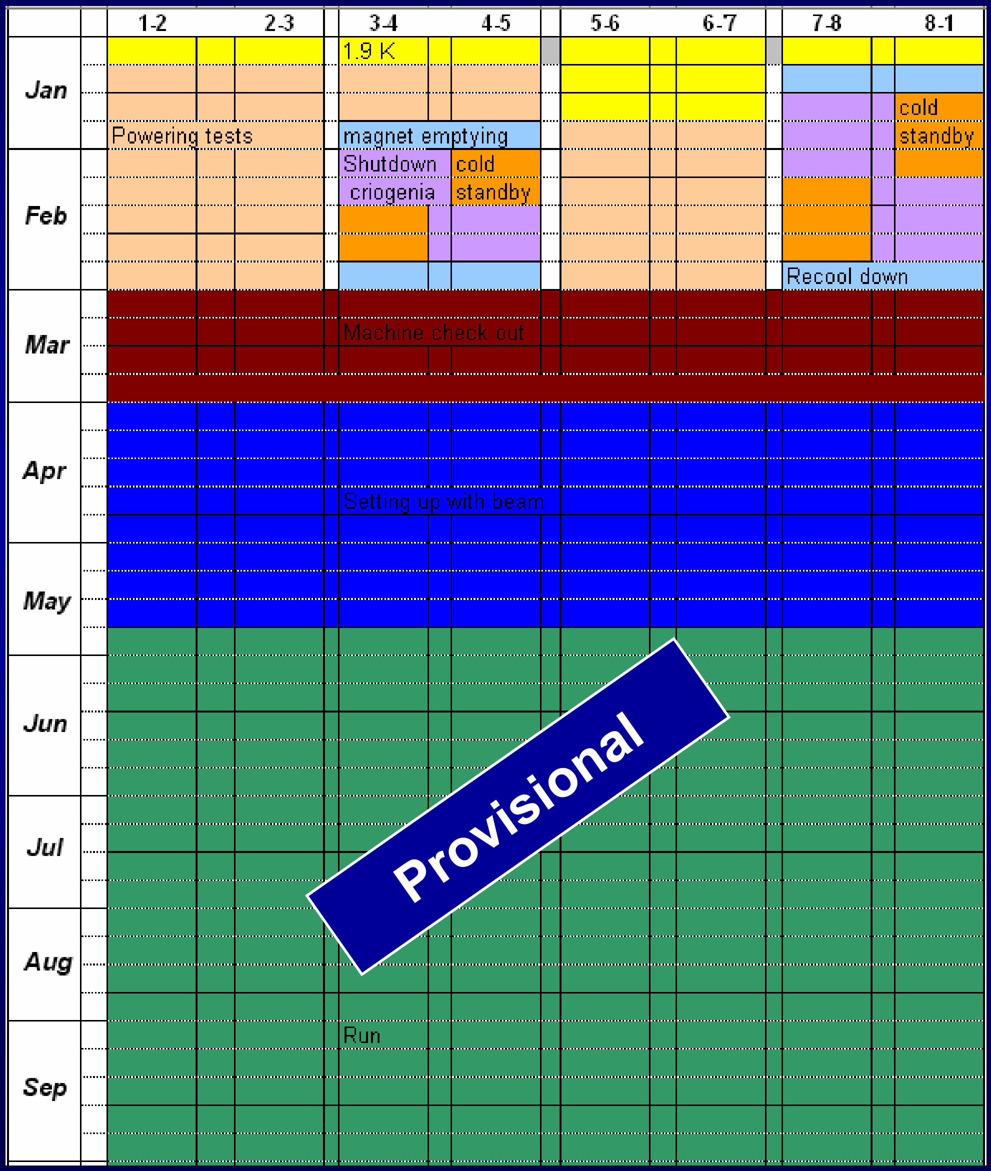
2008
(briefly)

Staged commissioning plan for protons@7TeV



2008

Should look something like…



Hardware commissioning to 7 TeV

Machine Checkout ≈ 1 month

Commissioning with beam ≈ 2 months

Pilot Physics ≈ 1 month

Beam Commissioning: usual stuff..

First turn
- Commission injection region
- Instrumentation
- Threading

PILOT — RING 1 RING2

Establish circulating beam
- Circulating low intensity beam

PILOT — RING 1 RING2

450 GeV Initial
- Polarities and aperture checked.
- Basic optics checks performed.
- First pass commissioning of BI performed.
- Phase 1 of machine protection system commissioning performed. .
- Beam Dump commissioned with beam

SINGLE INTERMEDIATE — RING 1 RING2

450 GeV Detailed
- Well-adjusted beam parameters, detailed optics checks
- Fully functioning beam instrumentation.
- Machine protection as required for ramp
- RF - beam control loops operational and adjusted

SINGLE INTERMEDIATE ++ — RING 1 RING2

Two beam operation
- 2 beams, well-adjusted beam parameters,
- beam instrumentation, cross talk etc.

Switch to nominal
- 2 beams, well-adjusted beam parameters,
- beam instrumentation, cross talk etc.

Snapback
- Single beam, good transmission through snapback
- Requisite measurements (orbit, tune, chromaticity)

PILOT++ — RING 1 RING2

Ramp Single Beam
- Single beam, good transmission to top energy
- Commission beam dump in ramp
- Stops in ramp - measurements
- RF

PILOT++ — RING 1 RING2

Two beams to top energy
- Two beams, good transmission to top energy
- Measurements

43 x 43 — COLLIDE

Squeeze
- Single beam - step through squeeze
- Parameter control, measurements

SINGLE INTERMEDIATE — RING 1 RING2

Full commissioning to 7 TeV

		Rings	Total [days] both rings
1	Injection and first turn	2	6
2	Circulating beam	2	3
3	450 GeV - initial	2	5
4	450 GeV - detailed	2	12
5	450 GeV - two beams	1	2
6	Snapback - single beam	2	4
7	Ramp - single beam	2	8
8	Ramp - both beams	1	3
9	7 TeV - setup for physics	1	2
10	Physics un-squeezed	1	-
	TOTAL to first collisions		45
11	Commission squeeze	2	6
12	Increase Intensity	2	6
13	Set-up physics - partially squeezed.	1	2
14	Pilot physics run		

Should benefit from 450 GeV run

Given 450 GeV run and reasonable machine availability might expect first 7 TeV collisions in around 2 months

RHIC 2000:
- First beam April 3rd
- First successful ramp: June 1st
- First collisions June 12th

7 TeV commissioning

- **Around 2 months elapsed time to establish first collisions**
  - Mostly pilot++, low intensity, single beam, alternate rings
  - No crossing angle
  - No squeeze: β^* = 17 – 10 – 17 – 10 m.
- **Stage 1 vacuum conditions**
  - Experiments & LSSs should be baked out
  - Other LSSs potentially not
  - Full details: LHC project note 783
- **Collimation during initial commissioning**
  - Minimal collimation scheme under discussion, probably primary & secondary with no tertiary/absorbers
  - Again, un-squeezed, expect low halo loss in experiments
- **First collisions**
  - Single bunch
  - Un-squeezed
- **Pilot physics**

Pilot physics

Sub-phase	Bunches	Bun. Int.	beta*	Luminosity	Time	Int lumi
First Collisions	1 x 1	4×10^{10}	17 m	1.6×10^{28}	12 hours	0.6 nb^{-1}
Repeat ramp - same conditions	-	-	-	-	2 days @ 50%	1.2 nb^{-1}
Multi-bunch at injection & through ramp - collimation	-	-	-	-	2 days	-
Physics	12 x 12	3×10^{10}	17 m	1.1×10^{29}	2 days @ 50% in physics	6 nb^{-1}
Physics	43 x 43	3×10^{10}	17 m	4.0×10^{29}	2 days @ 50% in physics	30 nb^{-1}
Commission squeeze – single beam then two beams, IR1, IR5	-	-	-	-	2 days	-
Measurements squeezed	-	-	-	-	1 day	-
Physics	43 x 43	3×10^{10}	10 m	7×10^{29}	3 days - 6 hr t.a. - 70% eff.	75 nb^{-1}
Commission squeeze to 2m collimation etc.	-	-	-	-	3 days	-
Physics	43 x 43	3×10^{10}	2 m	3.4×10^{30}	3 days - 6 hr t.a. - 70% eff.	0.36 pb^{-1}
Commission 156 x 156	-	-	-	-	1 day	
Physics	156 x 156	2×10^{10}	2 m	5.5×10^{30}	2 days - 6 hr t.a. - 70% eff.	0.39 pb^{-1}
Physics	156 x 156	3×10^{10}	2 m	1.2×10^{31}	5 days - 5 hr t.a. - 70% eff.	2.3 pb^{-1}
					28 days total	

Leading into 75 ns running

Conclusions

- **450 GeV calibration run**
  - 3 weeks single beam machine commissioning
  - Low beam current but potentially interesting vacuum conditions
  - Minimal collimation scheme
  - 3 weeks collisions with the hope to push over 10^{29} $cm^{-2}s^{-1}$
  - Detailed BG studies planned

- **7 TeV**
  - 6-8 weeks single/two beam machine commissioning
  - Low beam current but potentially interesting vacuum conditions
  - Un-squeezed initially, with minimal collimation
  - Still work to do after first collisions – pilot physics
  - Detailed BG studies already performed and on-going

http://cern.ch/lhc-commissioning/

LHC Upgrade

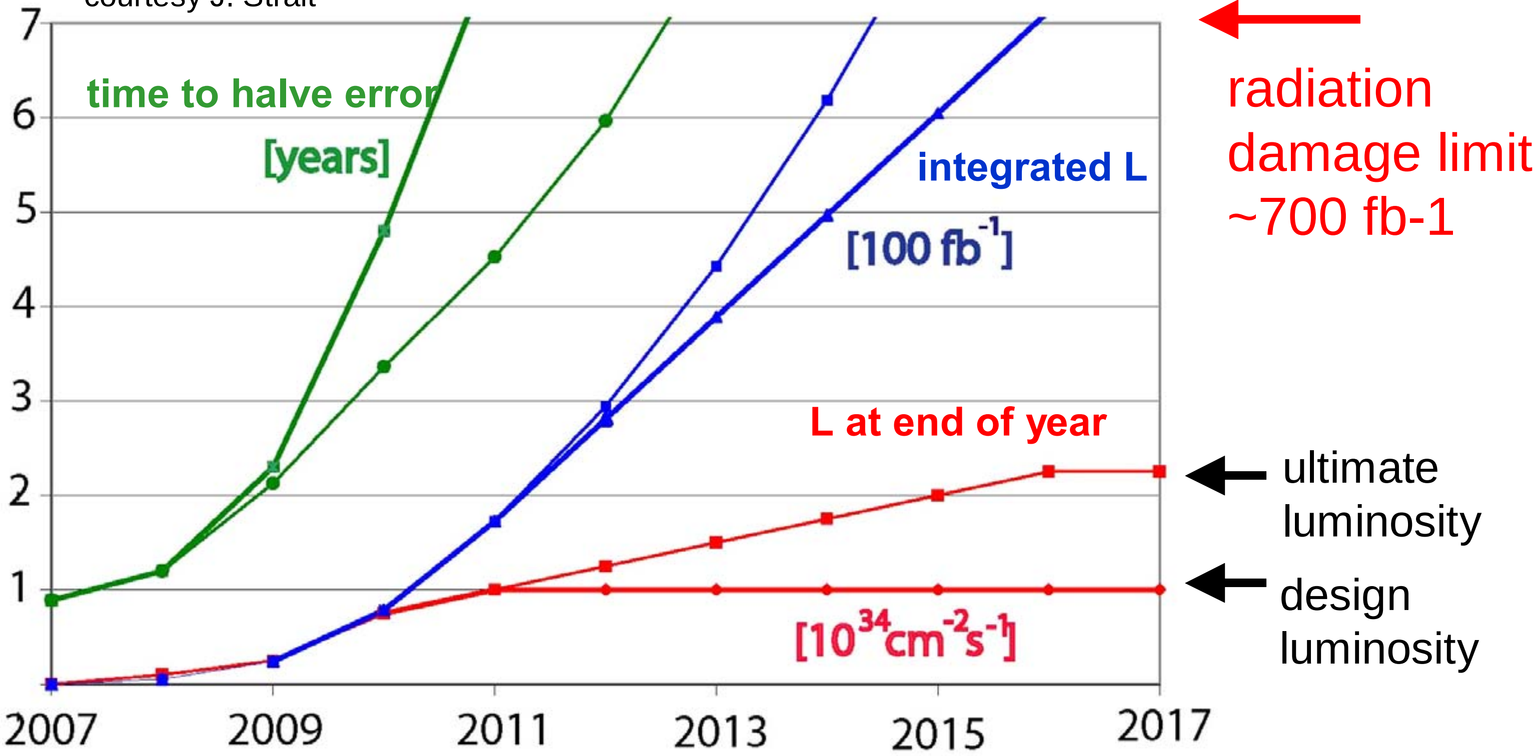
Brief Overview

Acknowledgments:

Walter Scandale, Francesco Ruggiero

time scale of an LHC upgrade

courtesy J. Strait



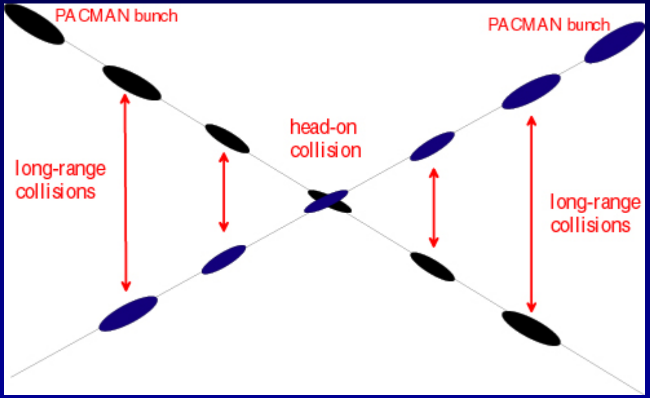
(1) ***life expectancy of LHC IR quadrupole magnets*** is estimated to be <10 years due to high radiation doses

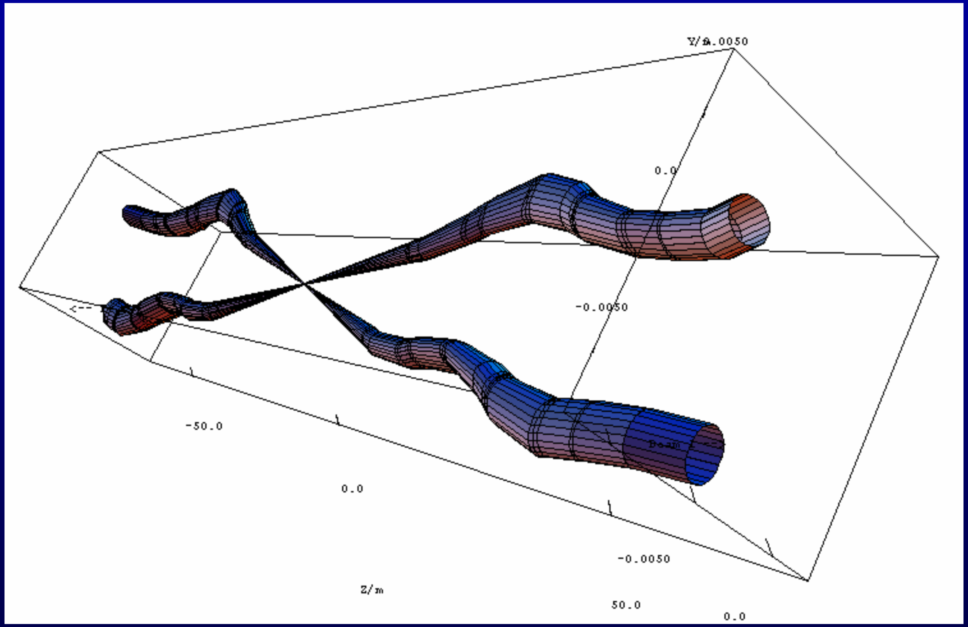
(2) the ***statistical error halving time*** will exceed 5 years by 2011-2012

(3) therefore, it is reasonable to plan a ***machine luminosity upgrade based on new low-β IR magnets before ~2014***

Basic Issues

- Head-on beam-beam
- Long-range beam-beam
- Crossing angle
  - Larger – reduces luminosity
  - Larger – eats aperture
- β* - beam size at IP
  - Smaller the β* - larger the beam size in the triplets - aperture



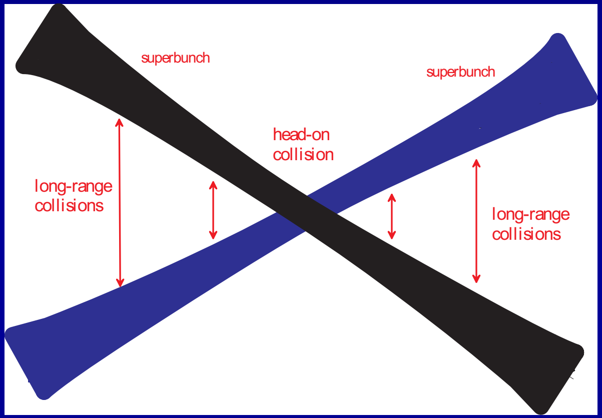


$$\sigma^* = \sqrt{\beta^* \varepsilon}$$

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

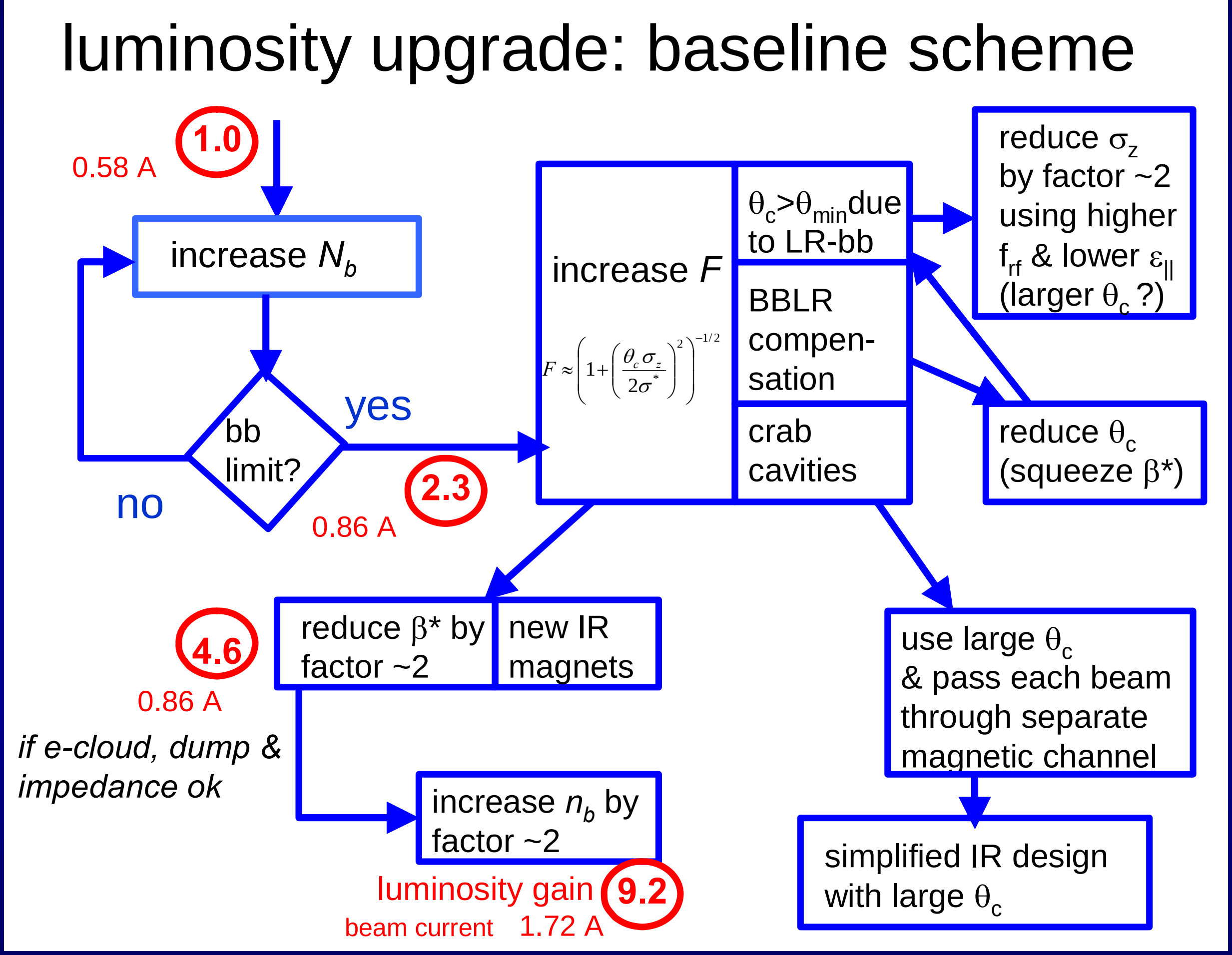
Some Options

- **More beam**
  - Increase bunch intensity (➔ upgrade injectors)
  - Increase number of bunches - reduce bunch spacing to 12.5 ns (or 10 ns or…) - see Andy Butterworth later this week
  - Super bunches



- **Increase F**
  - Redesign insertions
  - Crab cavities
- **Fight the long range beam-beam**
  - Wires
- **Squeeze harder**
  - New magnets

Options


luminosity upgrade: baseline scheme
1.0
0.58 A
increase N_b
bb limit?
yes
no
2.3
0.86 A
increase F
$F \approx \left(1+\left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2\right)^{-1/2}$
$\theta_c > \theta_{min}$ due to LR-bb
BBLR compen-sation
crab cavities
reduce σ_z by factor ~2 using higher f_{rf} & lower $\varepsilon_{||}$ (larger θ_c ?)
reduce θ_c (squeeze β^*)
4.6
0.86 A
if e-cloud, dump & impedance ok
reduce β^* by factor ~2
new IR magnets
increase n_b by factor ~2
luminosity gain
9.2
beam current 1.72 A
use large θ_c & pass each beam through separate magnetic channel
simplified IR design with large θ_c

IR upgrade

<u>goal:</u> reduce β* by at least a factor 2

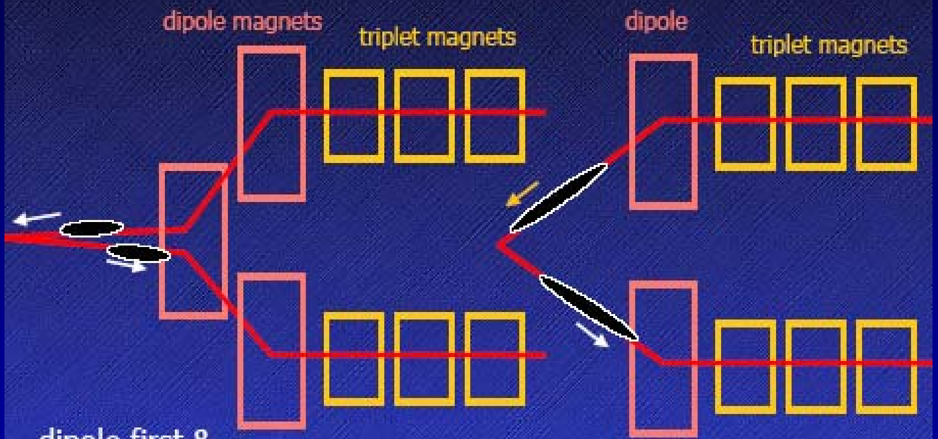
<u>options:</u> NbTi 'cheap' upgrade, NbTi(Ta), Nb_3Sn
new quadrupoles
new separation dipoles

<u>factors driving IR design:</u>

maximize magnet aperture
minimize distance to IR

- minimize β*
- minimize effect of LR collisions
- large radiation power directed towards the IRs
- accommodate crab cavities and/or beam-beam compensators. Local Q' compensation scheme?
- compatibility with upgrade path

alternative IR schemes

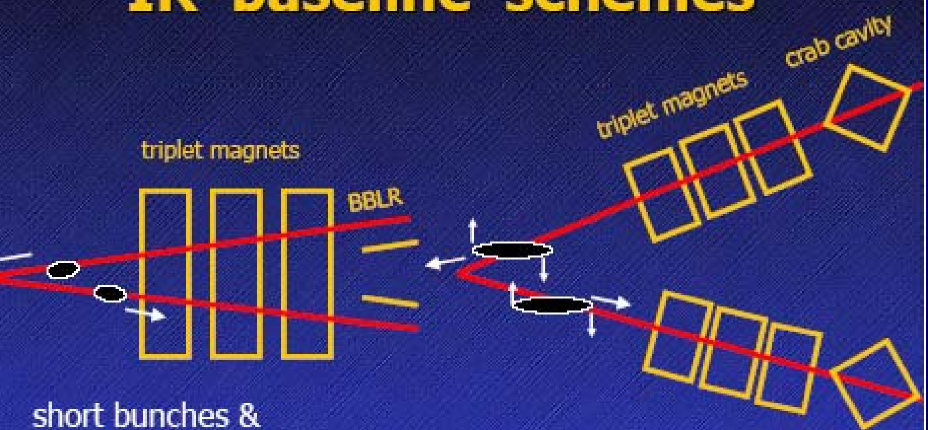


dipole first &
small crossing angle

reduced # LR collisions
collision debris hit D1

dipole first &
large crossing angle &
long bunches or crab cavities

IR 'baseline' schemes

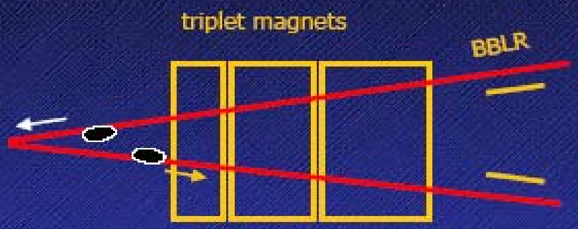


short bunches &
minimum crossing angle &
BBLR

crab cavities &
large crossing angle

'cheap' IR upgrade

in case we need to double LHC luminosity earlier than foreseen



short bunches &
minimum crossing angle &
BBLR

each quadrupole individually optimized (length & aperture)
IP-quad distance reduced from 23 to 22 m
NbTi, β=0.25 m possible*

Expected factors for the LHC luminosity upgrade

The peak LHC luminosity can be multiplied by:

- factor 2.3 from nominal to ultimate beam intensity (0.58 $\Rightarrow$ 0.86 A)
- factor 2 (or more?) from new low-beta insertions with β^* = 0.25 m

Major hardware upgrades (LHC main ring and injectors) are needed to exceed ultimate beam intensity. The peak luminosity can be increased by:

- factor 2 if we can double the number of bunches (maybe impossible due to electron cloud effects) or increase bunch intensity and bunch length

Increasing the LHC injection energy to 1 TeV would potentially yield:

- factor ~2 in peak luminosity (2 x bunch intensity and 2 x emittance)
- factor 1.4 in integrated luminosity from shorter $T_{turnaround}$~5 h

thus ensuring L~10^{35} cm^{-2} s^{-1} and $\int Ldt$ ~ 9 x nominal ~ 600/(fb*year)

Various LHC upgrade options

parameter	symbol	nominal	ultimate	shorter bunch	longer bunch
no of bunches	n_b	2808	2808	5616	936
proton per bunch	N_b [10^{11}]	1.15	1.7	1.7	6.0
bunch spacing	Δt_{sep} [ns]	25	25	12.5	75
average current	I [A]	0.58	0.86	1.72	1.0
normalized emittance	ε_n [µm]	3.75	3.75	3.75	3.75
longit. profile		Gaussian	Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	3.78	14.4
ß* at IP1&IP5	$ß^*$ [m]	0.55	0.50	0.25	0.25
full crossing angle	θ_c [µrad]	285	315	445	430
Piwinski parameter	$\theta_c \sigma_z/(2\sigma^*)$	0.64	0.75	0.75	2.8
peak luminosity	L [10^{34} cm^{-2} s^{-1}]	1.0	2.3	9.2	8.9
events per crossing		19	44	88	510
luminous region length	σ_{lum} [mm]	44.9	42.8	21.8	36.2

Upgrades - summary

- Baseline scenario includes:
  - a reduction of β^* to 0.25 m,
  - an increased crossing angle
  - and a new bunch-shortening RF system.
- Corresponding peak luminosity with ultimate beam intensity is 4.6 x 10^{34} cm^{-2} s^{-1} at two IP's.
  - Electron cloud effects and/or cryogenic heat loads may exclude the possibility to double the number of bunches.
- R&D ongoing
  - Magnets, crab cavities, LRBB compensation etc. etc.
- Several LHC IR upgrade options are currently being explored
- Major conference here in Valencia in 3 weeks (CARE – HHH)