The LHC as a Nucleus-Nucleus Collider

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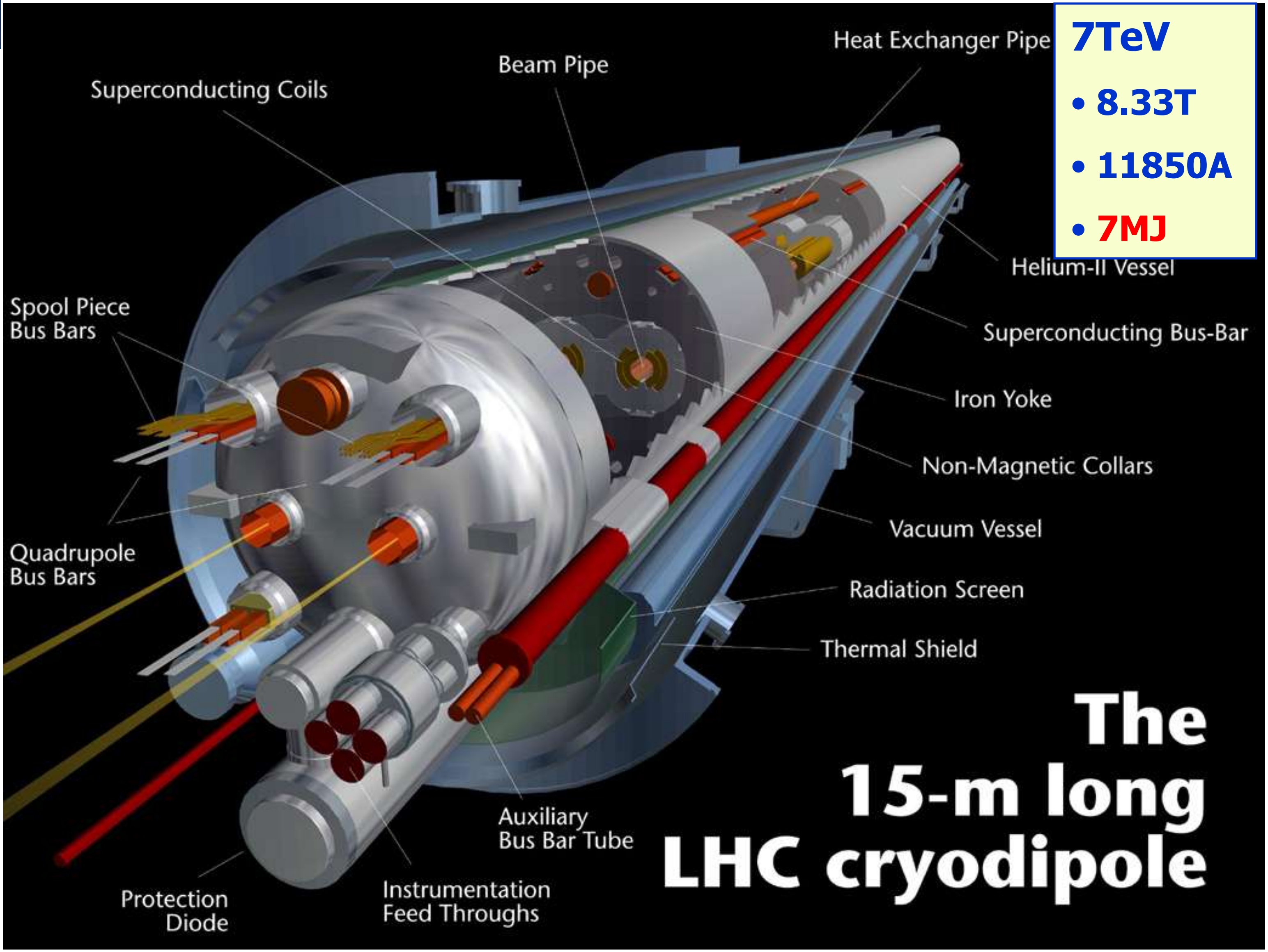
LHC Status Summary

Status of the LHC

- We are almost at the end of the long road from the first public “Feasibility Study of a Large Hadron Collider in the LEP Tunnel” (1984) to colliding protons and heavy nuclei in the LHC.
- Enormous efforts made in recent years to minimise slippage of the schedule.
- Solutions to engineering setbacks have been found and implemented
  - Main cryogenic line (QRL)
  - Low-beta (“triplet”) quadrupoles
  - Plug-in modules for vacuum interconnects
- Installation of the collider’s hardware is complete.
- Hardware, then beam, commissioning will soon be fully under way.

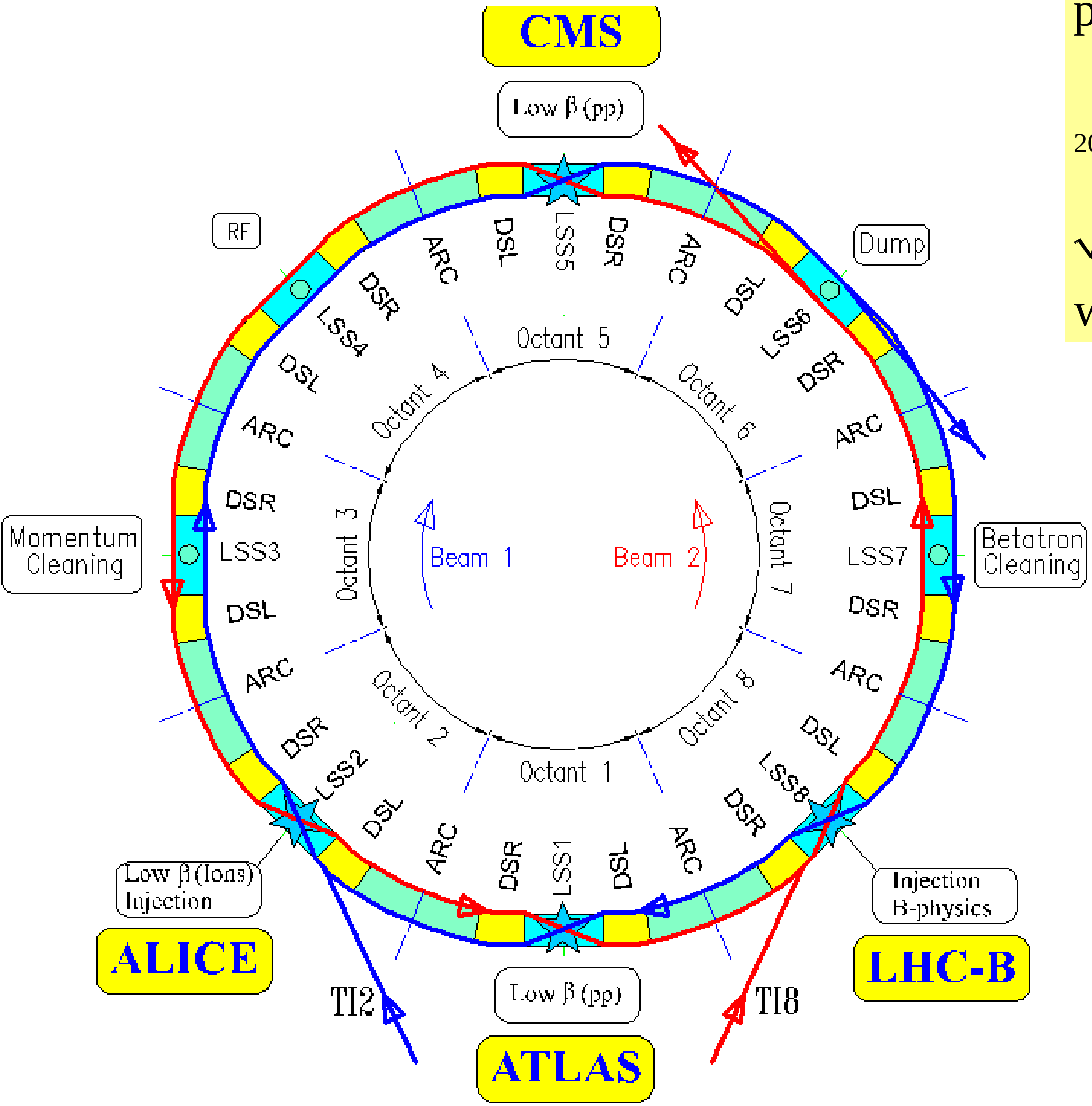
1232 dipole magnets operating at 1.9K



7TeV
- 8.33T
- 11850A
- 7MJ

The most prominent of a host of technological developments.

Schematic LHC

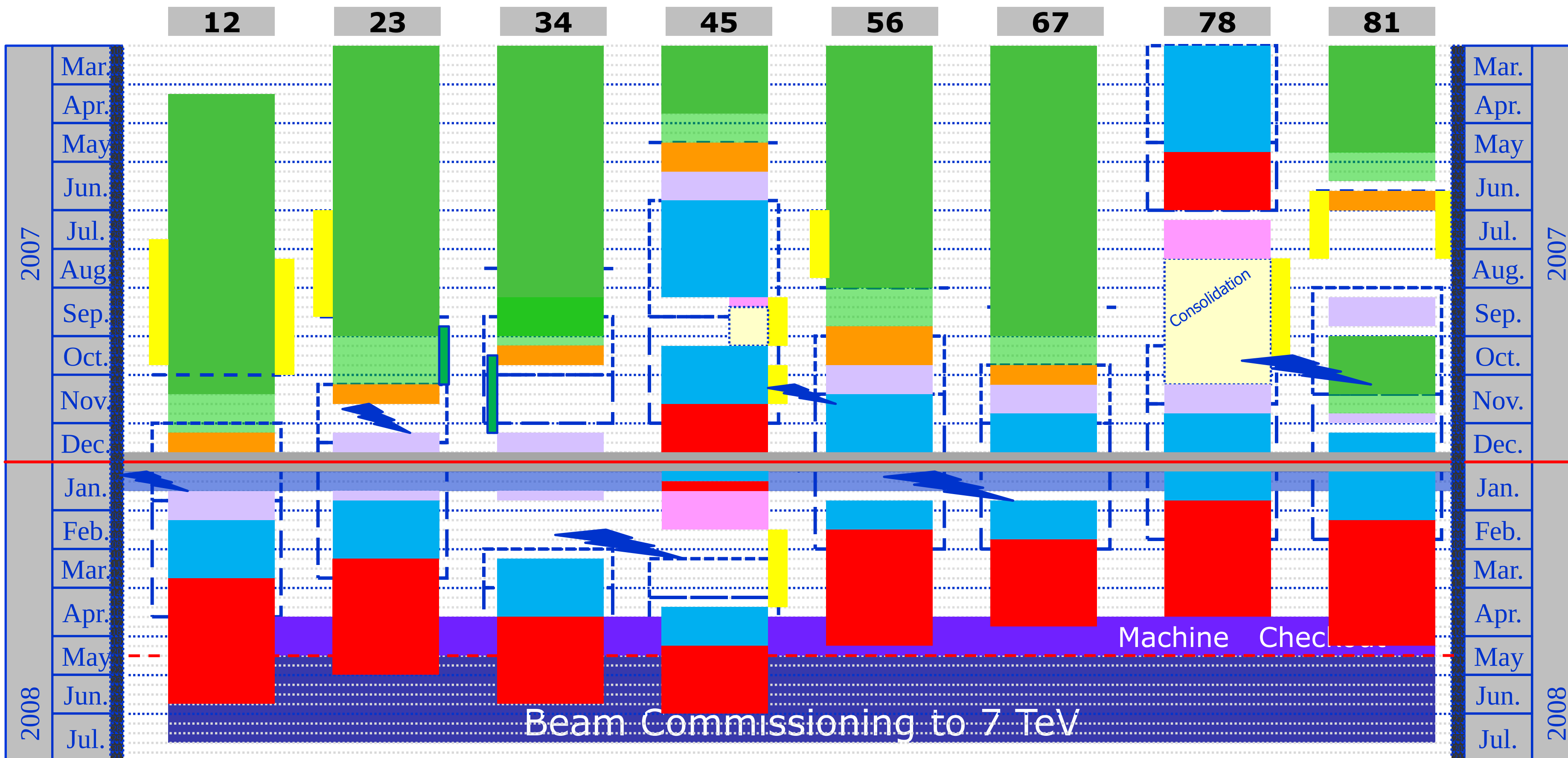


p-p collisions at $\sqrt{s} = 14$ TeV

$^{208}Pb^{82+}$-$^{208}Pb^{82+}$ collisions at $\sqrt{s} = 1.15$ PeV $= 5.5\, A$ TeV with nominal dipole field.

- 4 large experiments
  - ALICE
  - ATLAS
  - CMS
  - LHC-b

Master Schedule (published 8 Oct 2007)



General schedule Baseline rev. 4.0

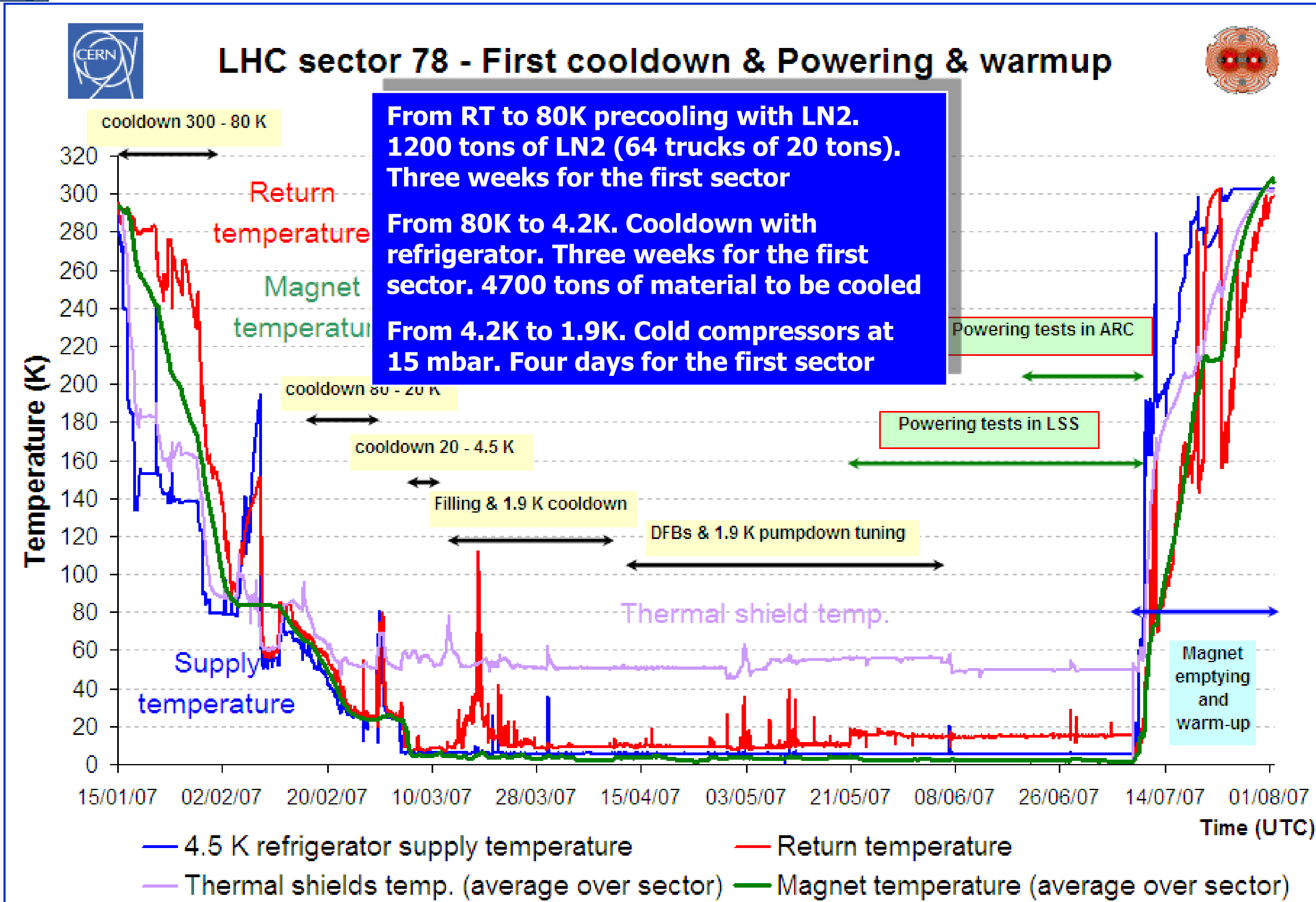
- Global pressure test &Consolidation (dotted line)
- Cool-down (dotted box)
- Powering Tests (dashed box)

- Interconnection of the continuous cryostat
- Leak tests of the last sub-sectors
- Inner Triplets repairs & interconnections
- Global pressure test &Consolidation
- Flushing
- Cool-down
- Warm up
- Powering Tests

Current outlook

- Expect whole machine to be cold by beginning of June
  - 2-3 weeks behind published schedule
  - Technically feasible but "success-oriented", i.e., sensitive to any major new problem
- Then start commissioning with proton beams to achieve injection, RF capture, good lifetime on the injection plateau
  - Hard to predict time necessary, should not be rushed …
  - 75 ns bunch spacing (for LHC-b) asap
- Real luminosity will depend on ability to protect machine
  - must gain experience with collimation, etc.

Commissioning of sector 78 (no triplet)



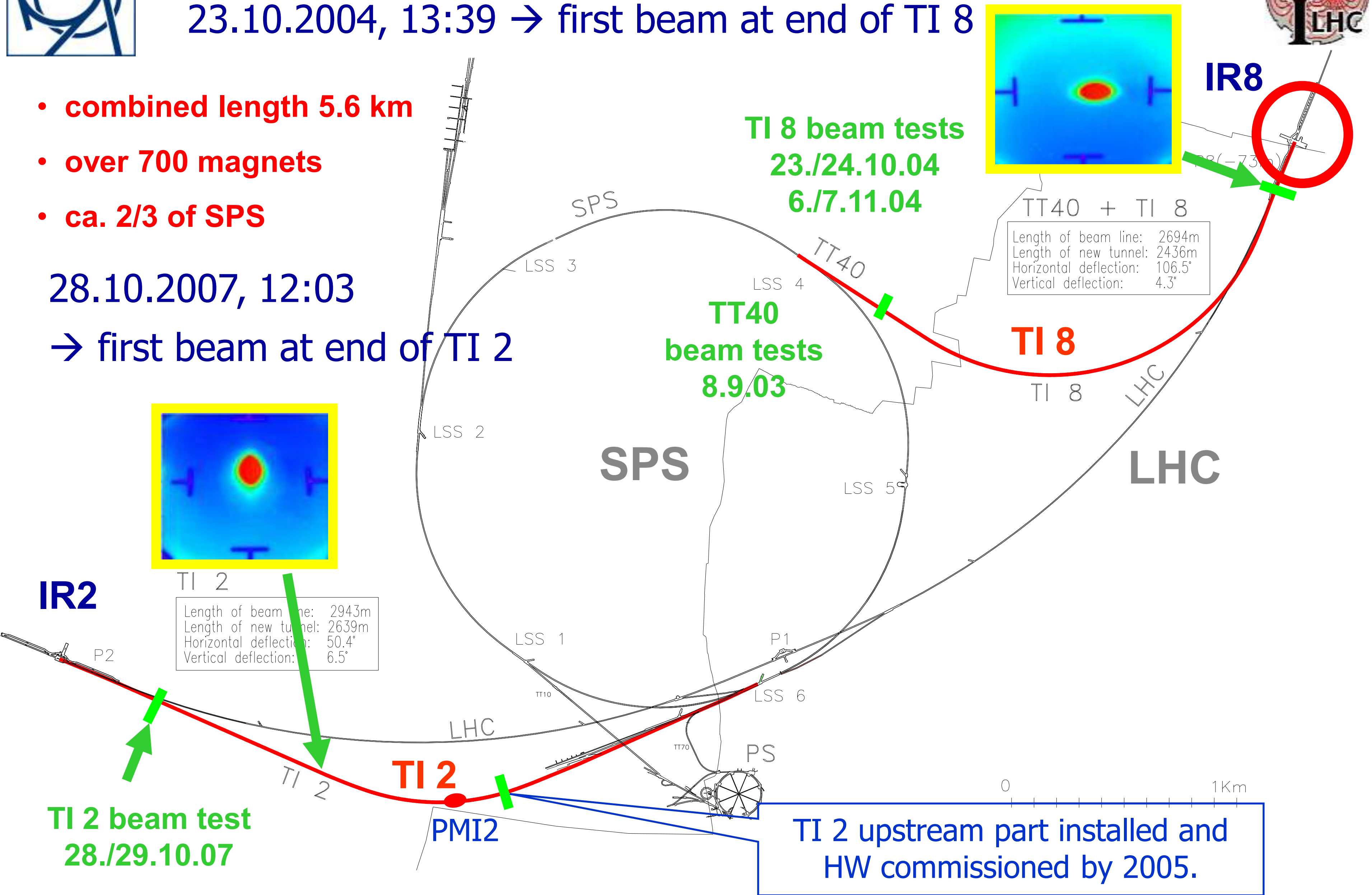
LHC proton injection - overview

23.10.2004, 13:39 → first beam at end of TI 8

- **combined length 5.6 km**
- **over 700 magnets**
- **ca. 2/3 of SPS**

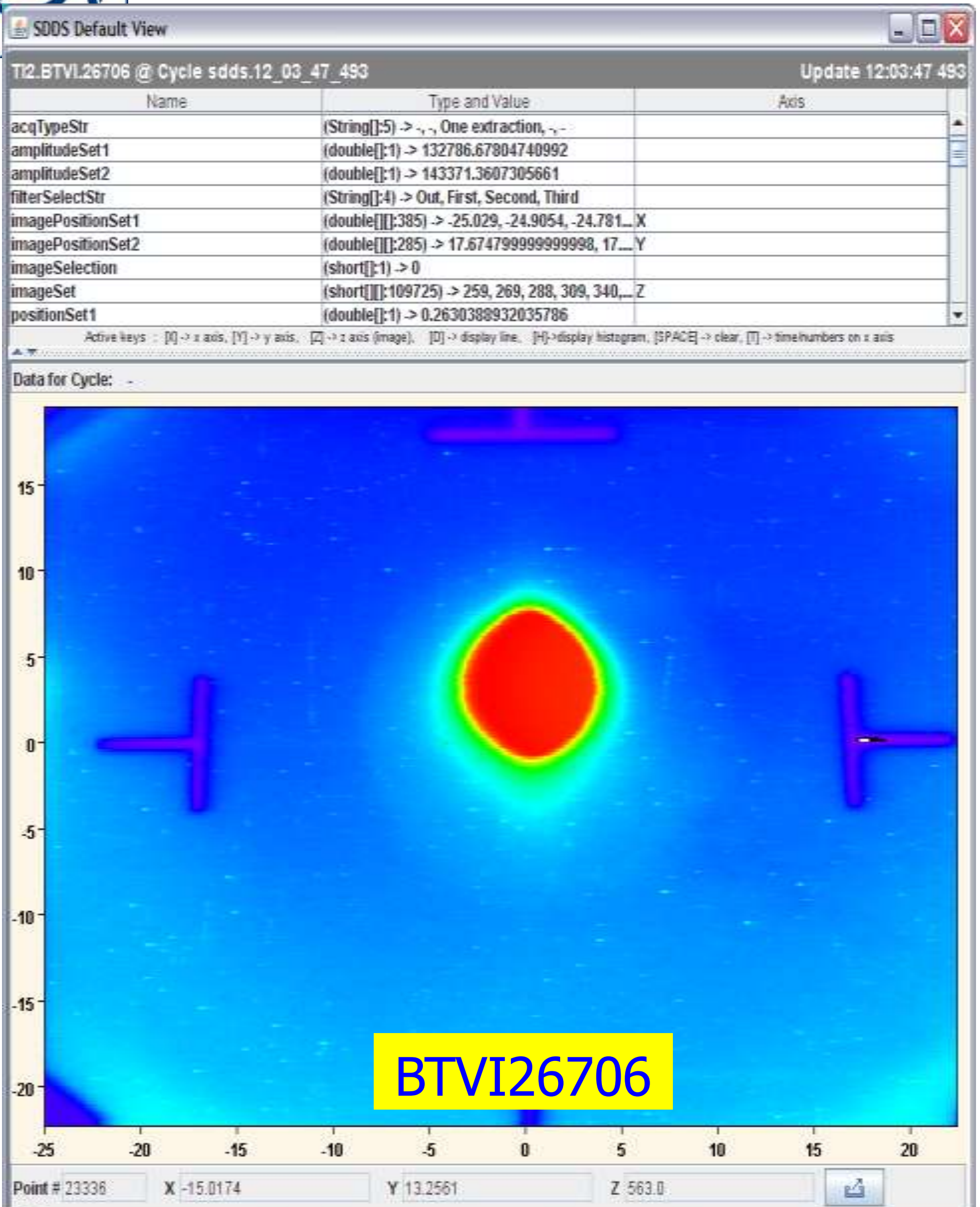
28.10.2007, 12:03

→ first beam at end of TI 2



Courtesy of V. Mertens

Proton beam in TI2 at 12:03:47 on 28 Oct 2007



First shot straight down the line.

This BTV screen is the last in the part of TI2 which could be explored with beam on 28 October 2007. It is located some 70 m after the lowest point in TI2, and some 700 m away from the temporary dump, which in turn is placed at some 50 m from the end of the TI2 tunnel, to avoid irradiating the LHC area..

The proton beam for $L = 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ is ready.

Courtesy of V. Mertens

Commissioning the LHC with proton beams

Luminosity

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

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

- **Parameters in luminosity**
  - Number of particles per bunch — N
  - Number of bunches per beam — k_b
  - Relativistic factor — γ
  - Normalised emittance — ε_n
  - Beta function at the IP — β^*
  - Crossing angle factor — F
    - Full crossing angle — θ_c
    - Bunch length — σ_z
    - Transverse beam size at the IP — σ^*

Equal amplitude functions:

$\beta_x^*=\beta_y^*=\beta^*$,

Geometric and normalised emittance:

$$\varepsilon_x^*=\varepsilon_y^*=\varepsilon^*=\frac{\varepsilon_n}{\sqrt{\gamma^2-1}}$$

$\Rightarrow$ Round beams at IP:

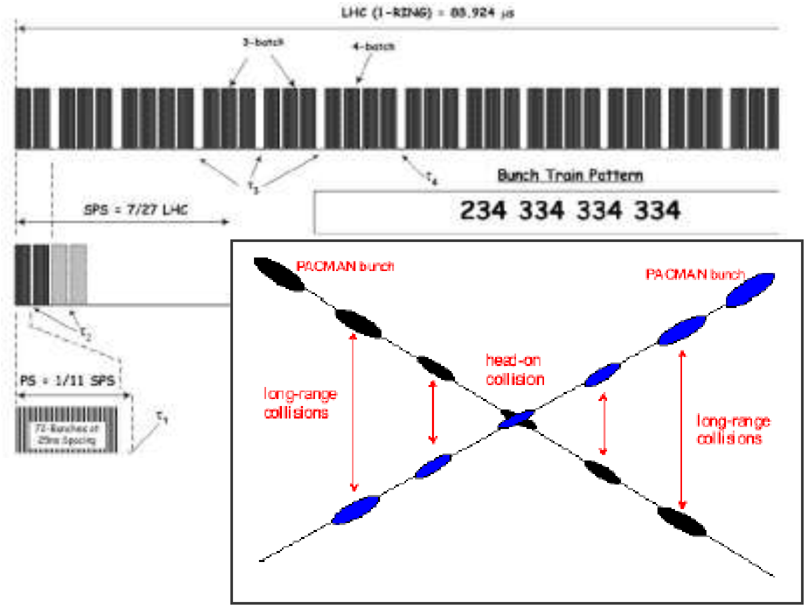
$$\sigma_x^*=\sigma_y^*=\sigma^*\approx\sqrt{\frac{\beta^*\varepsilon_n}{\gamma}}$$

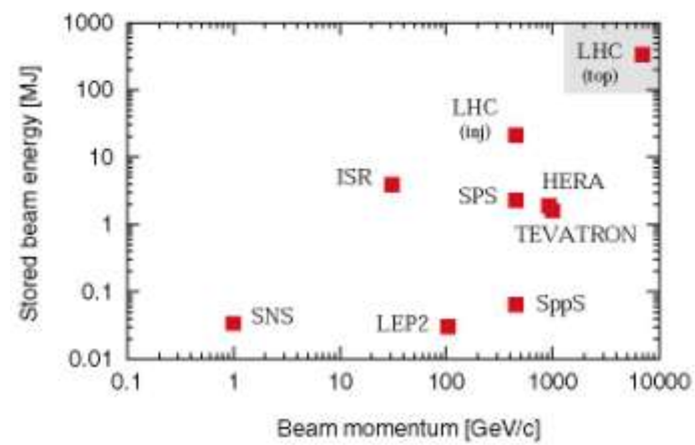
(N.B. LHC uses RMS emittances.)

Nominal p-p luminosity

Nominal settings	
Beam energy (TeV)	7.0
Number of particles per bunch	$1.15\ 10^{11}$
Number of bunches per beam	2808
Crossing angle (μrad)	285
Norm transverse emittance (μm rad)	3.75
Bunch length (cm)	7.55
Beta function at IP 1, 2, 5, 8 (m)	0.55,10,0.55,10

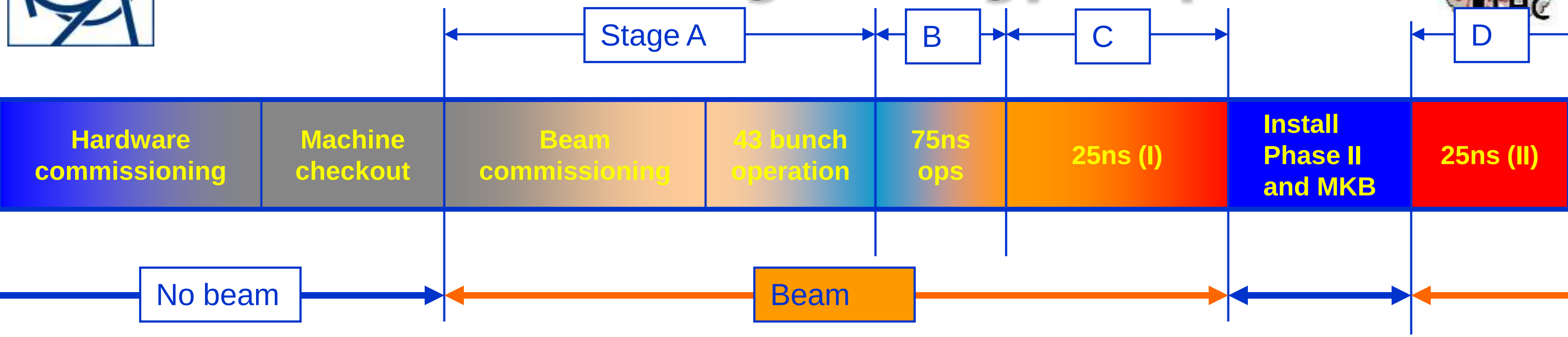
Related parameters	
Luminosity in IP 1 & 5 ($cm^{-2}\ s^{-1}$)	10^{34}
Luminosity in IP 2 & 8 ($cm^{-2}\ s^{-1}$)	$\sim 5\ 10^{32}$
Transverse beam size at IP 1 & 5 (μm)	16.7
Transverse beam size at IP 2 & 8 (μm)	70.9
Stored energy per beam (MJ)	362





Requires Phase II collimation

Commissioning strategy for protons



I. Pilot physics run
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

II. 75ns operation
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

III. 25ns operation I
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} cm^{-2} s^{-1}

IV. 25ns operation II
- Push towards nominal performance

–Complexity
–Beam power
–Losses ($\sim 1/\beta^*$)
–Pileup
minimised by optimising
$N,\ k_b,\ \beta^*$ (squeeze)

Stage A p-p physics run

- Start as simple as possible
- Change 1 parameter (k_b N $\beta^*_{1\,,\,5}$) at a time
- All values for
  - nominal emittance
  - 7TeV
  - 10m β* in point 2 (luminosity looks fine)

$$\text{Events/Crossing} = \frac{L\sigma_{TOT}}{k_b\, f}$$

Protons/beam <10^{13}

Stored energy/beam <10MJ

(c.f. SPS fixed target beam)

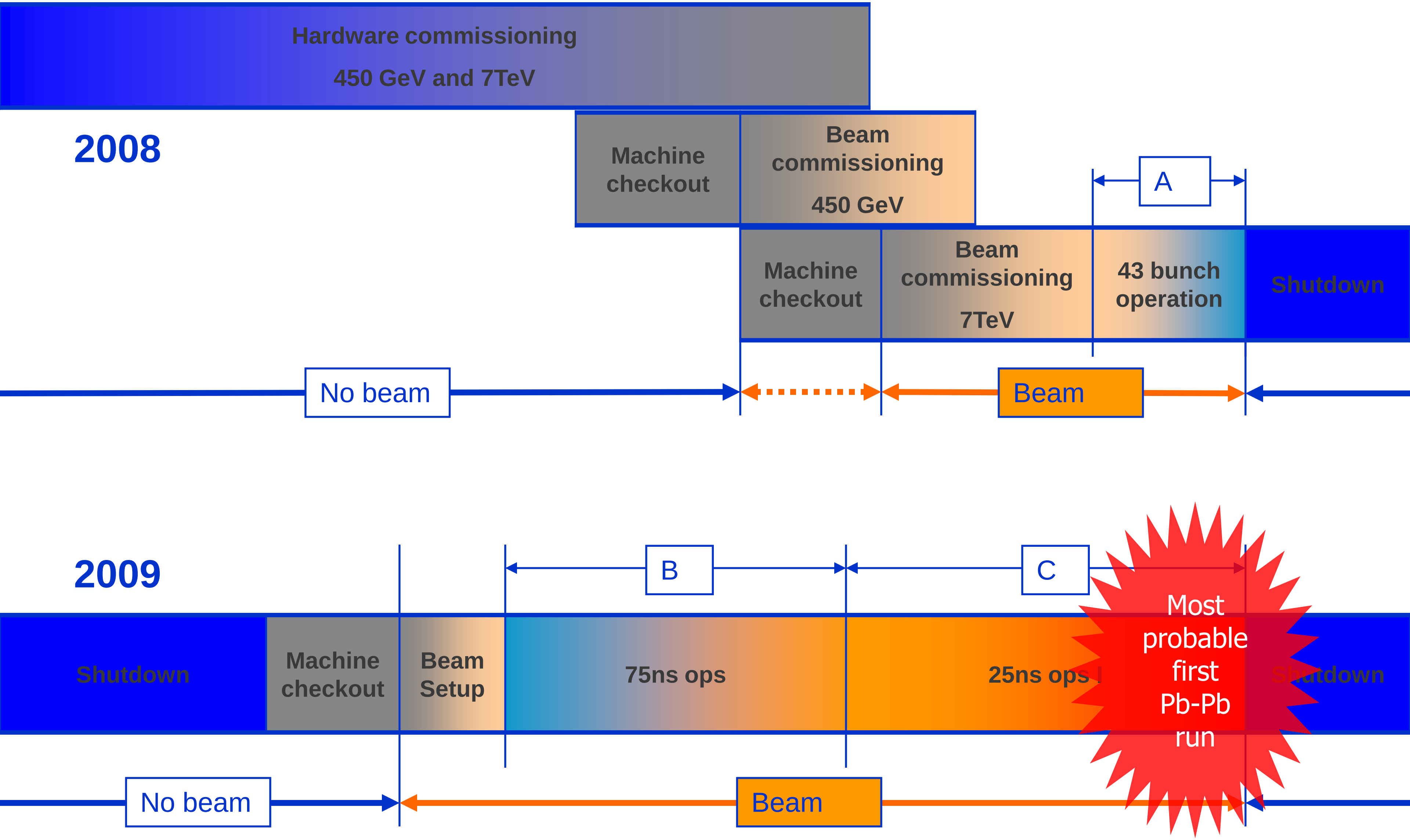
Parameters			Beam levels		Rates in ATLAS or CMS		Rates in ALICE	
k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
1	10^{10}	11	1 10^{10}	10^{-2}	1.6 10^{27}	<< 1	1.8 10^{27}	<< 1
43	10^{10}	11	4.3 10^{11}	0.5	7.0 10^{28}	<< 1	7.7 10^{28}	<< 1
43	4 10^{10}	11	1.7 10^{12}	2	1.1 10^{30}	<< 1	1.2 10^{30}	0.15
43	4 10^{10}	2	1.7 10^{12}	2	6.1 10^{30}	0.76	1.2 10^{30}	0.15
156	4 10^{10}	2	6.2 10^{12}	7	2.2 10^{31}	0.76	4.4 10^{30}	0.15
156	9 10^{10}	2	1.4 10^{13}	16	1.1 10^{32}	3.9	2.2 10^{31}	0.77

Evolution through p-p stages A,B,C

All values for nominal emittance, 7 TeV, β^*=10 m in points 2 and 8

Parameters			Beam levels		ATLAS, CMS		ALICE (LHC-b)	
k_b	N	β^* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
43	$4\ 10^{10}$	11	$1.7\ 10^{12}$	2	$1.1\ 10^{30}$	<< 1	$1.2\ 10^{30}$	0.15
43	$4\ 10^{10}$	2	$1.7\ 10^{12}$	2	$6.1\ 10^{30}$	0.76	$1.2\ 10^{30}$	0.15
156	$4\ 10^{10}$	2	$6.2\ 10^{12}$	7	$2.2\ 10^{31}$	0.76	$4.4\ 10^{30}$	0.15
156	$9\ 10^{10}$	2	$1.4\ 10^{13}$	16	$1.1\ 10^{32}$	3.9	$2.2\ 10^{31}$	0.77
936	$4\ 10^{10}$	11	$3.7\ 10^{13}$	42	$2.4\ 10^{31}$	<< 1	$2.6\ 10^{31}$	0.15
936	$4\ 10^{10}$	2	$3.7\ 10^{13}$	42	$1.3\ 10^{32}$	0.73	$2.6\ 10^{31}$	0.15
936	$6\ 10^{10}$	2	$5.6\ 10^{13}$	63	$2.9\ 10^{32}$	1.6	$6.0\ 10^{31}$	0.34
936	$9\ 10^{10}$	1	$8.4\ 10^{13}$	94	$1.2\ 10^{33}$	7	$1.3\ 10^{32}$	0.76
2808	$4\ 10^{10}$	11	$1.1\ 10^{14}$	126	$7.2\ 10^{31}$	<< 1	$7.9\ 10^{31}$	0.15
2808	$4\ 10^{10}$	2	$1.1\ 10^{14}$	126	$3.8\ 10^{32}$	0.72	$7.9\ 10^{31}$	0.15
2808	$5\ 10^{10}$	1	$1.4\ 10^{14}$	157	$1.1\ 10^{33}$	2.1	$1.2\ 10^{32}$	0.24
2808	$5\ 10^{10}$	0.55	$1.4\ 10^{14}$	157	$1.9\ 10^{33}$	3.6	$1.2\ 10^{32}$	0.24

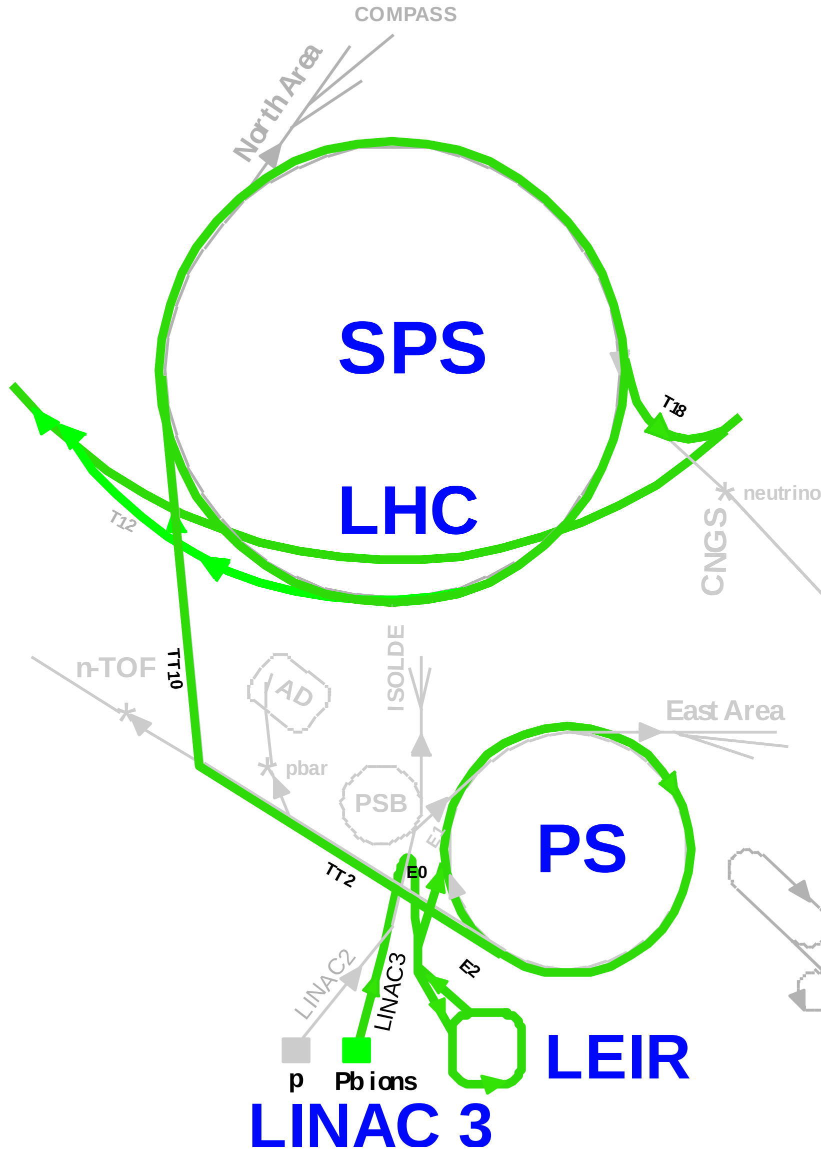
Staged commissioning plan for protons



Ion Injector Chain for LHC

LHC Ion Injector Chain

- ECR ion source (2005)
  - Provide highest possible intensity of Pb^{29+}
- RFQ + Linac 3
  - Adapt to LEIR injection energy
  - strip to Pb^{54+}
- LEIR (2005)
  - Accumulate and cool Linac3 beam
  - Prepare bunch structure for PS
- PS (2006)
  - Define LHC bunch structure
  - Strip to Pb^{82+}
- SPS (2007)
  - Define filling scheme of LHC



Ion Injector Chain – key facts

- Beam required for LHC is much more demanding than SPS fixed target ion beams
  - Required new electron cooler ring LEIR and many other changes and upgrades (bulk of cost of I-LHC project)
- Two sets of LHC beam parameters correspond to different modes of operations of injectors
  - "Early beam": 10 times fewer bunches in LHC but *same bunch intensity*, simplifies injectors but provides useful initial luminosity
  - "Nominal beam": full 592 bunches in LHC, more complicated injector operations
- See elsewhere for full information

LHC Pb Injector Chain: Key Parameters for luminosity 10^{27} cm^{-2} s^{-1}

	ECR Source →	Linac 3 → (4)	LEIR →	PS → (13,12,8)	SPS → (12)	LHC
Output energy	**2.5 KeV/n**	**4.2 MeV/n**	**72.2 MeV/n**	**5.9 GeV/n**	**177 GeV/n**	**2.76 TeV/n**
^{208}Pb charge state	**27+**	**27+ → 54+**	**54+**	**54+ → 82+**	**82+**	**82+**
Output Bρ [Tm]		2.28 → 1.14	4.80	86.7 → 57.1	1500	23350
bunches/ring			2 (1/8 of PS)	4 (or 4x2)[4]	52,48,32	592
ions/pulse	$9\ 10^9$	$1.15\ 10^9$ [1])	$9\ 10^8$	$4.8\ 10^8$	$\leq 4.7\ 10^9$	$4.1\ 10^{10}$
ions/LHC bunch	**$9\ 10^9$**	**$1.15\ 10^9$**	**$2.25\ 10^8$**	**$1.2\ 10^8$**	**$9\ 10^7$**	**$7\ 10^7$**
bunch spacing [ns]				100 (or 95/5)[4]	100	100
ε*(nor. rms) [μm][2]	**~0.10**	**0.25**	**0.7**	**1.0**	**1.2**	**1.5**
Repetition time [s]	0.2-0.4	0.2-0.4	3.6	3.6	~50	**~10'fill/ring**
ε_{long} per LHC bunch[3]			0.025 eVs/n	0.05	0.4	1 eVs/n
total bunch length [ns]			200	3.9	1.65	1

Stripping foil (dotted line)

[1]50 eμA_e x 200 μs Linac3 output after stripping

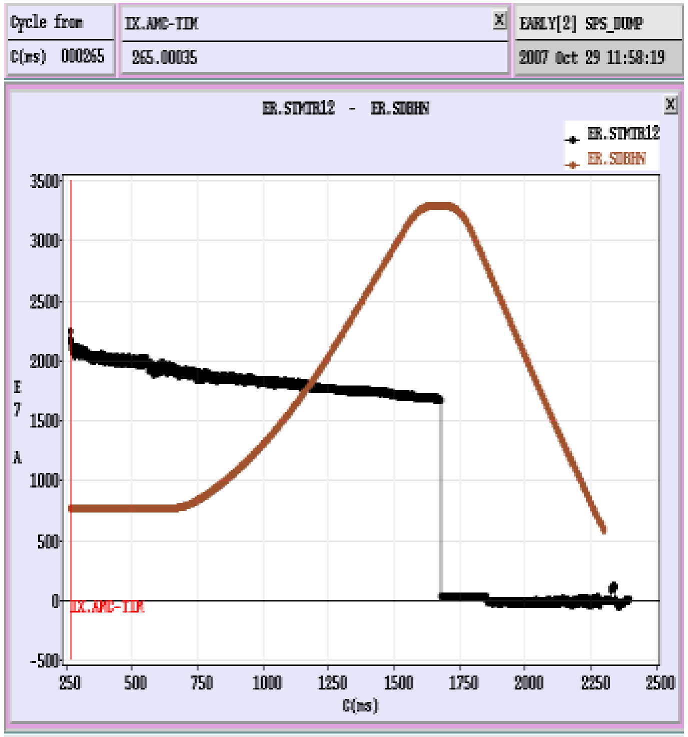
[2] Same physical emittance as protons,

$$\varepsilon^* \equiv \varepsilon_n = \sqrt{\gamma^2 - 1}\,\varepsilon_{x,y}$$ is invariant in ramp.

Injector Chain Status Summary (1)

- **Source + Linac3**
  - Intensity OK for Early Scheme (record = 31 eμA of Pb^{54+} out of the linac)
  - More stability/reliability required for Nominal Scheme will be supplied by upgrade of source generator to 18 GHz
  - Numerous other improvements implemented or coming.

- **LEIR**
  - Early beam obtained, reliable
  - Reproducible



Injector Chain Status Summary (2)

- LEIR for Nominal
  - Progress but some concerns about intensity loss
- Requires substantial development time in 2009

- PS + transfer lines
  - Early scheme now OK (much effort)
  - No development towards Nominal possible in 2007
  - Requires development time in 2009

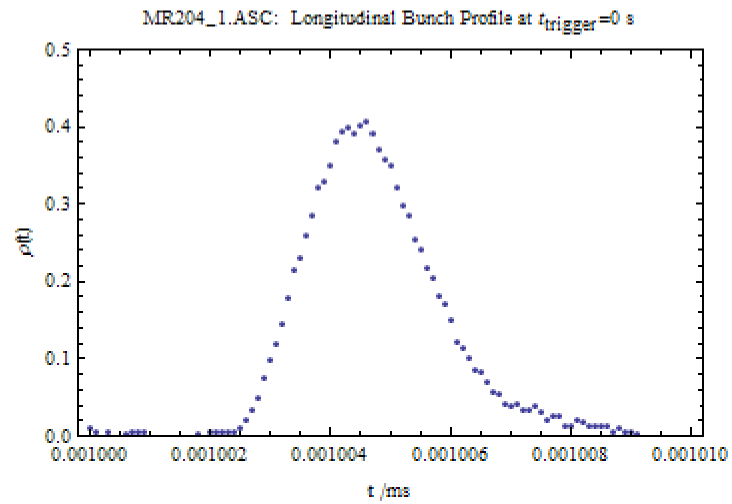
N.B. LHC ion injectors will not be operated in 2008

- Resources all devoted to p-p for LHC

Injector Chain Status Summary (3) SPS

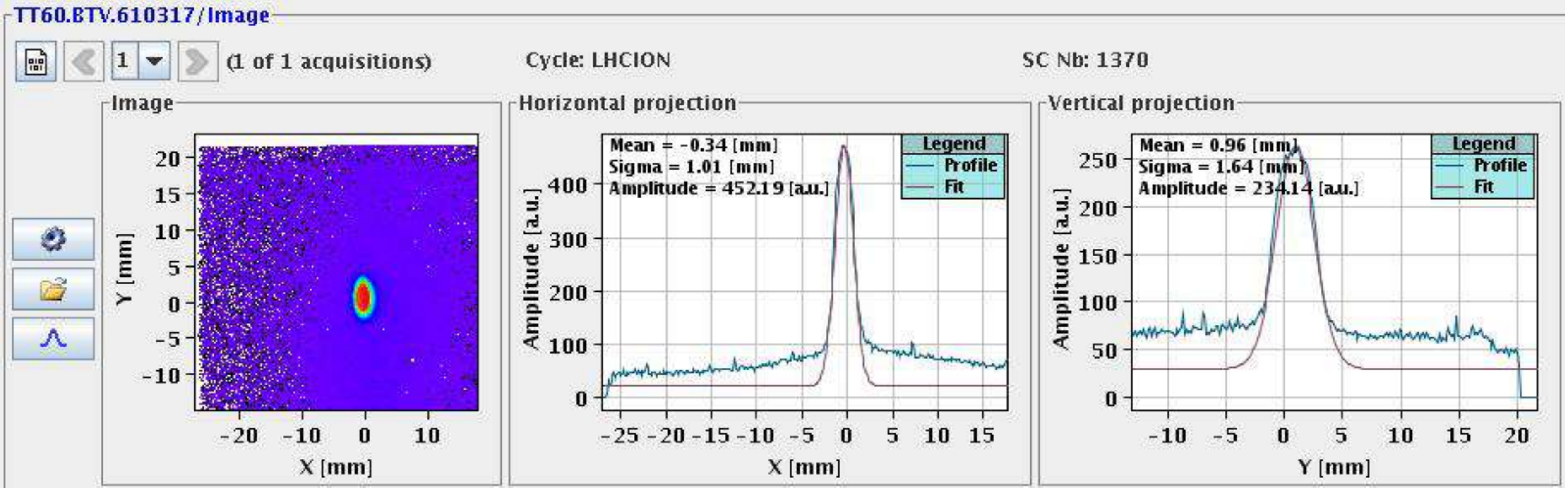
- First commissioning of LHC Pb beam late 2007
  - Time lost due to mishaps, RF hardware
- Early beam mostly commissioned and extracted
  - See next slide
- Crystal collimation test (H8 beamline) had to be dropped
- Development time required in 2009!

At injection energy, bunch typically loses half intensity in 2 min (real time of movie), c.f. Nominal injection plateau 47 s.



May still improve. Otherwise considering new filling scheme to shorten this plateau (75ns spacing in LHC).

First beam of lead nuclei ejected from SPS towards LHC



- TI2 line set up for protons worked first time (same magnetic rigidity)
- No synchronization of extracted beam (yet)
- (*) Extracted intensity was ~20% of design due to vacuum leak in PS, but 90% design intensity had been accelerated 2 weeks before

Parameter	Design	Achieved	Unit
N	3.6	0.7 (*)	10^8 ions
ε_H	6 10^{-3}	6 10^{-3}	π.mm.mrad
ε_V	6 10^{-3}	6 10^{-3}	π.mm.mrad
ε^*_H	1.2	1.2	μm
ε^*_V	1.2	1.2	μm

Pb-Pb Collisions in the LHC

- **The LHC will collide lead nuclei at centre-of-mass energies of 5.5 TeV per colliding nucleon pair.**
- **This leap to 28 times beyond what is presently accessible will open up a new regime, not only in the experimental study of nuclear matter, but also in the beam physics of hadron colliders.**

Nominal vs. Early Ion Beam: Key Parameters

Parameter	Units	Nominal	Early Beam
Energy per nucleon	TeV/n	2.76	2.76
Initial Luminosity L_0	$cm^{-2}\ s^{-1}$	$1\ 10^{27}$	$5\ 10^{25}$
No. bunches/bunch harmonic		592/891	62/66
Bunch spacing	ns	99.8	1350
β^*	m	0.5 (same as p)	1.0
Number of Pb ions/bunch		**$7\ 10^7$**	**$7\ 10^7$**
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	H	8, 4.5, 3	14, 7.5, 5.5

Nominal scheme parameters

		Injection	Collision
Beam parameters			
Lead ion energy	[GeV]	36900	574000
Lead ion energy/nucleon	[GeV]	177.4	2759.
Relativistic "gamma" factor		190.5	2963.5
Number of ions per bunch		$7. \times 10^7$	
Number of bunches		592	
Transverse normalized emittance	[μm]	1.4^a	1.5
Peak RF voltage (400 MHz system)	[MV]	8	16
Synchrotron frequency	[Hz]	63.7	23.0
RF bucket half-height		1.04×10^{-3}	3.56×10^{-4}
Longitudinal emittance (4σ)	[eV s/charge]	0.7	2.5^b
RF bucket filling factor		0.472	0.316
RMS bunch length[c]	[cm]	9.97	7.94
Circulating beam current	[mA]	6.12	
Stored energy per beam	[MJ]	0.245	3.81
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2	[m]	10.0	0.5
RMS beam size at IP2	μm	280.6	15.9
Geometric luminosity reduction factor F[d]		-	1
Peak luminosity at IP2	[$cm^{-2}sec^{-1}$]	-	$1. \times 10^{27}$

Nominal scheme, lifetime parameters

		Injection	Collision
Interaction data			
Total cross section	[mb]	-	514000
Beam current lifetime (due to beam-beam)[a]	[h]	-	11.2
Intra Beam Scattering			
RMS beam size in arc	[mm]	1.19	0.3
RMS energy spread $\delta E/E_0$	$[10^{-4}]$	3.9	1.10
RMS bunch length	[cm]	9.97	7.94
Longitudinal emittance growth time	[hour]	3	7.7
Horizontal emittance growth time[b]	[hour]	6.5	13
Synchrotron Radiation			
Power loss per ion	[W]	3.5×10^{-14}	2.0×10^{-9}
Power loss per metre in main bends	$[\mathrm{Wm}^{-1}]$	8×10^{-8}	0.005
Synchrotron radiation power per ring	[W]	1.4×10^{-3}	83.9
Energy loss per ion per turn	[eV]	19.2	1.12×10^{6}
Critical photon energy	[eV]	7.3×10^{-4}	2.77
Longitudinal emittance damping time	[hour]	23749	6.3
Transverse emittance damping time	[hour]	47498	12.6
Variation of longitudinal damping partition number[c]		230	230
Initial beam and luminosity lifetimes			
Beam current lifetime (due to residual gas scattering)[d]	[hour]	?	?
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 11.2
Luminosity lifetime[e]	[hour]	-	< 5.6

Early scheme Parameters

		Injection	Collision
Beam parameters			
Number of bunches		62	
Circulating beam current	[mA]	0.641	
Stored energy per beam	[MJ]	0.0248	0.386
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2	[m]	10.0	1.0
RMS beam size at IP2 [e]	[μm]	280.6	22.5
Peak luminosity at IP2	[$\mathrm{cm}^{-2}\mathrm{sec}^{-1}$]	-	5.4×10^{25}
Interaction data			
Beam current lifetime (due to beam-beam)[a]	[h]	-	21.8
Synchrotron Radiation			
Power loss per metre in main bends	[Wm^{-1}]	8.5×10^{-9}	5.0×10^{-4}
Synchrotron radiation power per ring	[W]	1.5×10^{-4}	8.8
Initial beam and luminosity lifetimes			
Beam current lifetime (beam-beam, residual gas)	[hour]	-	< 21.8
Luminosity lifetime (as in Table 21.3)	[hour]	-	< 11.2

Only show parameters that are different from nominal scheme

Nuclear Beam Physics

- Ultraperipheral and hadronic interactions of highly-charged beam nuclei will cause beam losses
  - Bound-free pair production (BFPP) at the IP, direct limit on luminosity
  - Collimation inefficiency, direct limit on beam current
  - Direct luminosity burn-off of beam intensity by BFPP and electromagnetic dissociation (EMD) processes dominates luminosity decay

Pair Production in Heavy Ion Collisions

Racah formula (1937) for free pair production in heavy-ion collisions

$$Z_1 + Z_2 \to Z_1 + e^- + e^+ + Z_2$$

$$\sigma_{PP} = \frac{Z_1^{\,2} Z_2^{\,2} \alpha^2 r_e^2}{\pi}\left[\frac{224}{27}\log\left(2\gamma_{CM}\right)^3 + \cdots\right] \approx \begin{cases} 1.7\times 10^4 \text{b for Au-Au RHIC} \\ 2.\times 10^4 \text{b for Pb-Pb LHC} \end{cases}$$

Cross section for Bound-Free Pair Production (BFPP) (several authors)

$$Z_1 + Z_2 \to Z_1 + e^-_{1s_{1/2},\ldots} + e^+ + Z_2$$

has very different dependence on ion charges (and energy)

$$\sigma_{PP} \propto Z_1^{\,5} Z_2^{\,2}\left(A \log \gamma_{CM} + B\right)$$

$$\propto Z^7\left[A\log\gamma_{CM} + B\right] \text{ for } Z_1 = Z_2$$

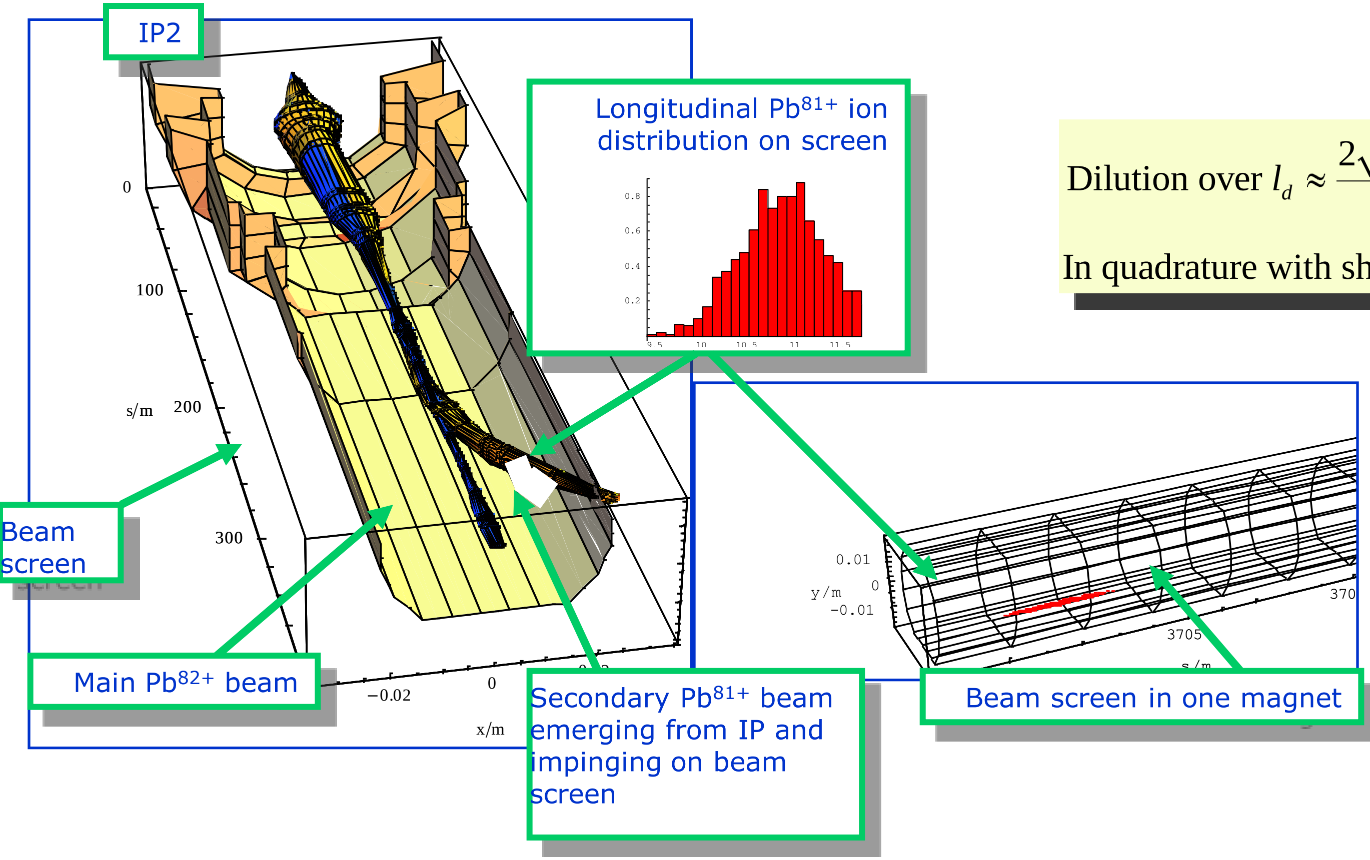
$$\approx \begin{cases} 0.2 \text{ b for Cu-Cu RHIC} \\ 114 \text{ b for Au-Au RHIC} \\ 281 \text{ b for Pb-Pb LHC} \end{cases}$$

We use BFPP values from Meier et al, Phys. Rev. A, **63**, 032713 (2001), includes detailed calculations for Pb-Pb at LHC energy

BFPP can limit luminosity in heavy-ion colliders, S. Klein, NIM A **459** (2001) 51

Luminosity Limit from BFPP in LHC

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + e^{+}$$



Dilution over $l_d \approx \dfrac{2\sqrt{\varepsilon\beta_x + D_x^{\,2}\sigma_\delta^{\,2}}}{D'(s)\delta_p} \approx 1.4\ \mathrm{m}$,

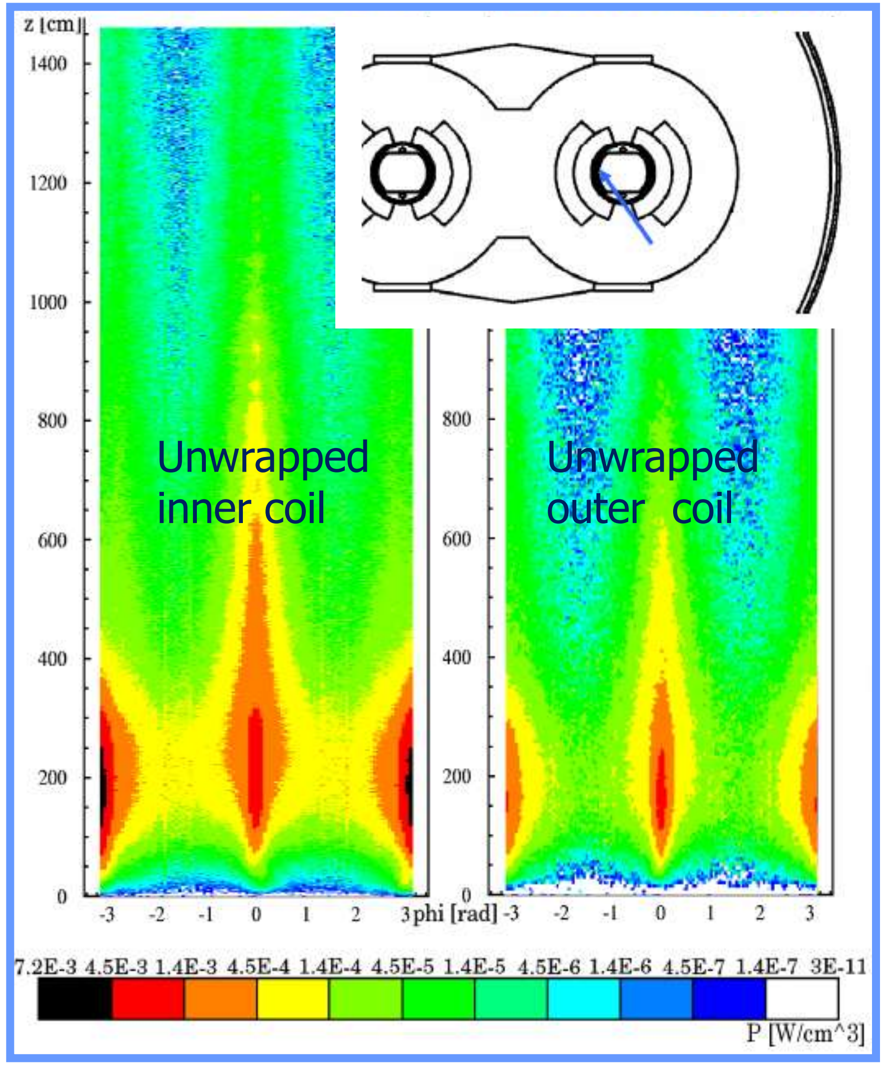
In quadrature with shower length 1 m $\rightarrow \quad \approx 1.7$ m

Distinct EMD process (similar rates) does not form spot on beam pipe

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \xrightarrow{\mathrm{GDR}} ^{208}\mathrm{Pb}^{82+} + ^{207}\mathrm{Pb}^{82+} + n$$

Consequences for the LHC

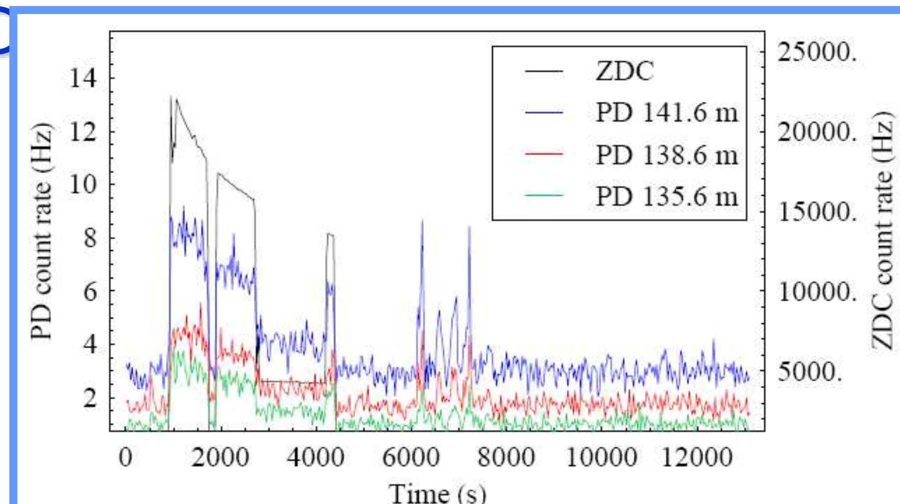
- 281 kHz loss rate at nominal *L*
- 25 W heating power in dispersion suppressor dipole magnet
- Detailed Monte-Carlo of hadronic shower: heavy-ion interactions with matter in FLUKA
- Revised estimates of quench limit (thermodynamics of liquid He and heat transfer) suggest magnets are not likely to quench due to BFPP beam losses
- However, quench still possible within estimated uncertainties
  - Quench limit, Monte Carlo, BFPP cross section, …
- Additional beam loss monitors installed around IPs to monitor these losses in LHC operation, can redistribute them to some extent



Test of LHC methodology at RHIC

- Parasitic measurement during RHIC Cu-Cu run
  - Loss monitors setup as for LHC
  - Just visible signal!
- Compared predictions and shower calculations as for LHC
  - Reasonable agreement
- *R. Bruce et al, Phys. Rev. Letters 99:144801, 2007*
- We still need to benchmark quench limit (in LHC!)

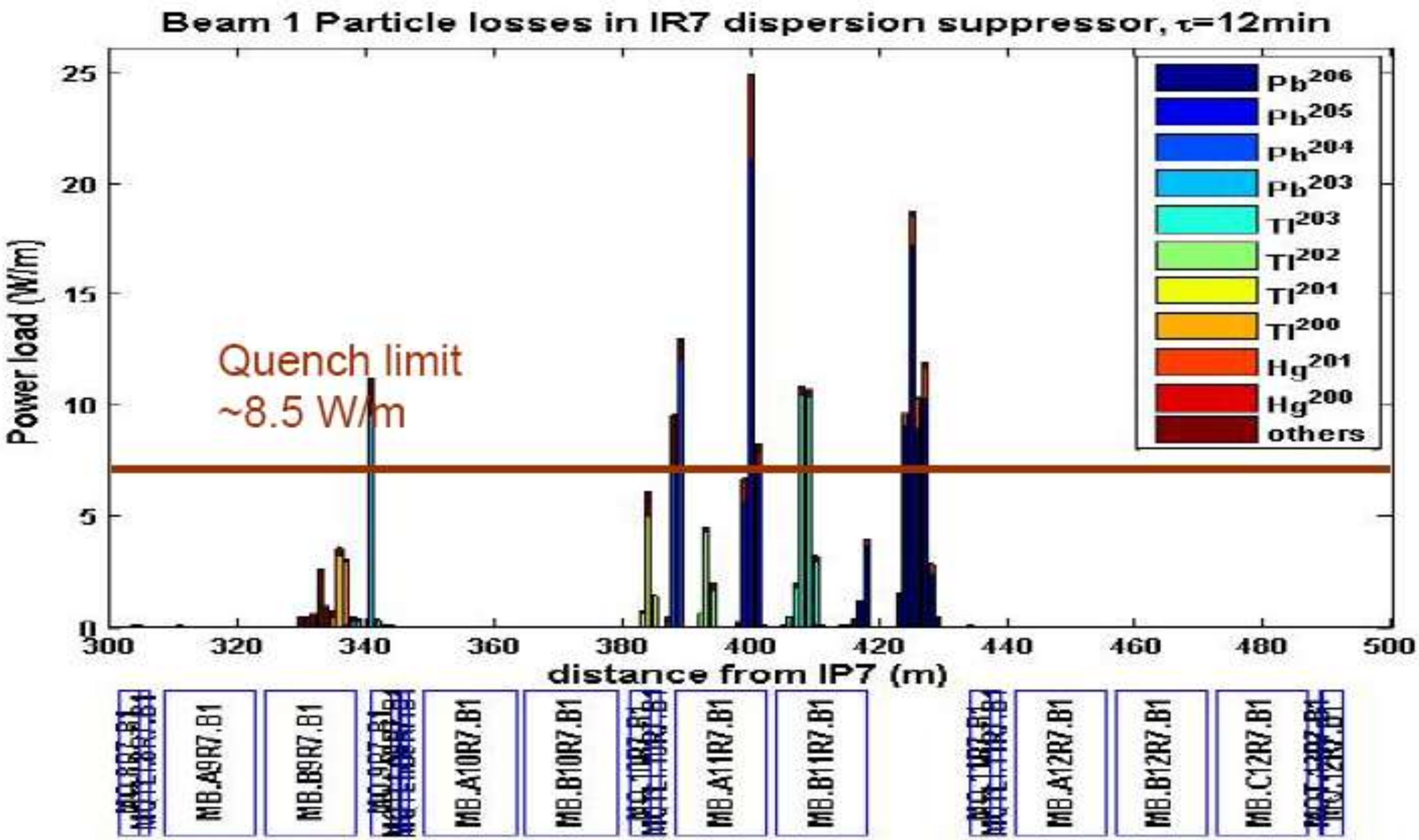
View towards PHENIX



Ion Collimation in LHC

- Collimation system essential to protect machine from particles that would be lost causing magnet quenches or damage
- Principle of collimation for protons:
  - Particles at large amplitudes undergo multiple Coulomb scattering in sufficiently long primary collimator (carbon), deviating their trajectories onto properly placed secondary collimators which absorb them in hadronic showers
- Ions undergo nuclear fragmentation or EMD before scattering enough
  - Machine acts as spectrometer: isotopes lost in other locations, including SC magnets
  - Secondary collimators ineffective

LHC Collimation Example



Loss map after IR7 (betatron cleaning section).
Collision optics, standard collimator settings.
Special simulation, requires much nuclear physics input, etc.
Used to locate additional beam loss monitors for ion runs.

Courtesy G. Bellodi

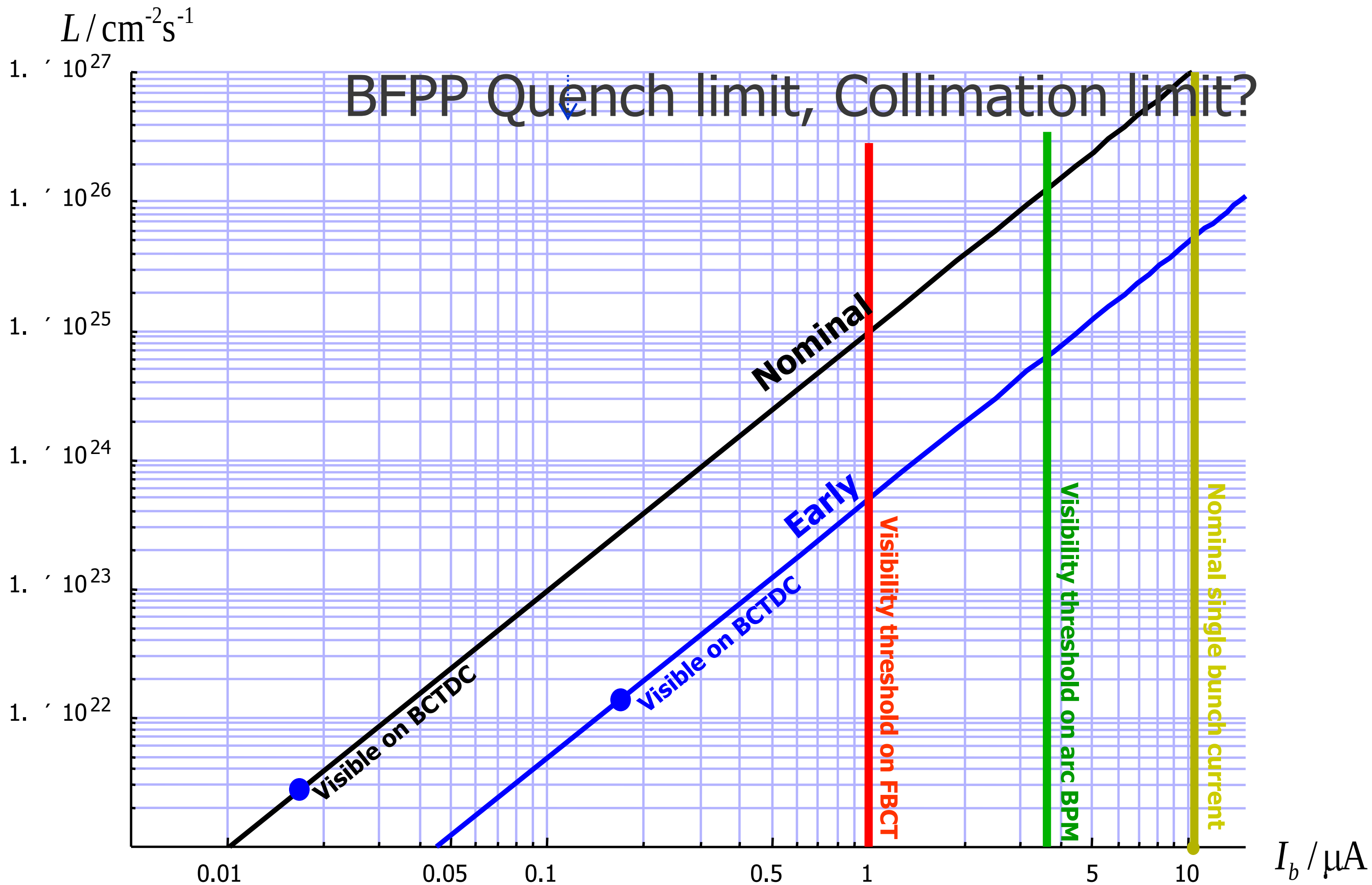
Remarks on Ion Collimation

- Probably the major limit for LHC ion luminosity
- Nevertheless:
  - Conventional (1996) quench limit (tolerable heat deposition in superconducting magnet coils) now appears pessimistic
  - This is a soft limit: losses only get to this level if, for some reason, the *single-beam (not including collisional) losses* reach a level corresponding to a lifetime of 12 min.
- Simulations benchmarked with real beams
  - LHC collimator in SPS (2007) - good agreement
  - Earlier data from RHIC - consistent
- Phase II Collimation upgrade needed for p-p
  - Looking at what can be included for ions
  - New ideas: crystals, magnetic collimation, optics changes, high-Z primary collimators, …

Other limits on performance

- Total bunch charge is near lower limits of visibility on beam instrumentation, particularly the beam position monitors
  - Must always(!) inject close to nominal bunch current
  - Rely on ionization profile monitors more than with protons
- Intra-beam scattering (IBS, multiple Coulomb scattering within bunches) is significant but less so than at RHIC where it dominates luminosity decay
- Vacuum effects (losses, emittance growth, electron cloud …) should not be significant

Operational parameter space with lead ions



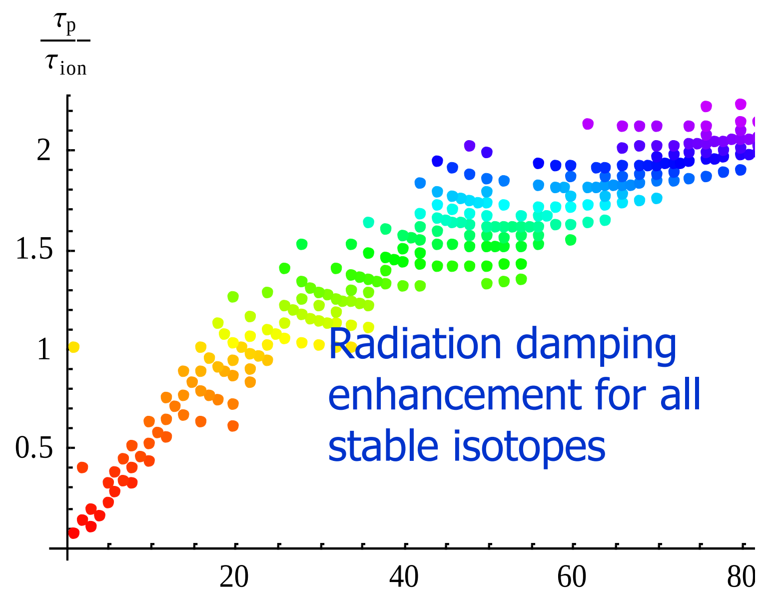
Thresholds for visibility on BPMs and BCTs.

Synchrotron Radiation

- Nuclear charge radiate *coherently* at relevant wavelengths (~ nm)
- Scaling with respect to protons *in same ring, same magnetic field*
  - Radiation damping for Pb is twice as fast as for protons
    - Many very soft photons
    - Critical energy in visible spectrum
- This is fast enough to overcome IBS at full intensity

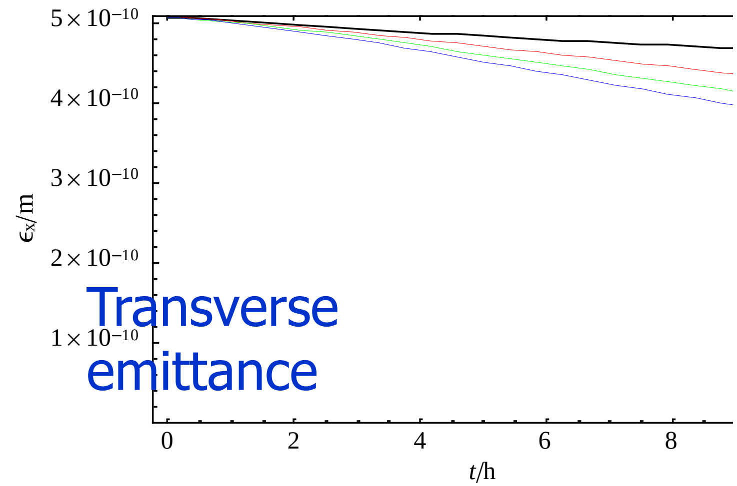
$$\frac{U_{\rm ion}}{U_{\rm p}} \simeq \frac{Z^6}{A^4} \simeq 162, \qquad \frac{u^c_{\rm ion}}{u^c_{\rm p}} \simeq \frac{Z^3}{A^3} \simeq 0.061,$$

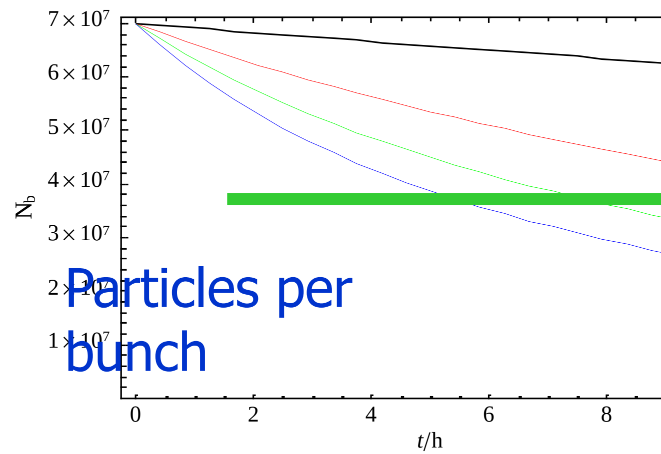
$$\frac{N_{\rm ion}}{N_{\rm p}} \simeq \frac{Z^3}{A} \simeq 2651, \qquad \frac{\tau_{\rm ion}}{\tau_{\rm p}} \simeq \frac{A^4}{Z^5} \simeq 0.5$$



Lead is (almost) best, deuteron is worst.

Luminosity evolution: Nominal scheme

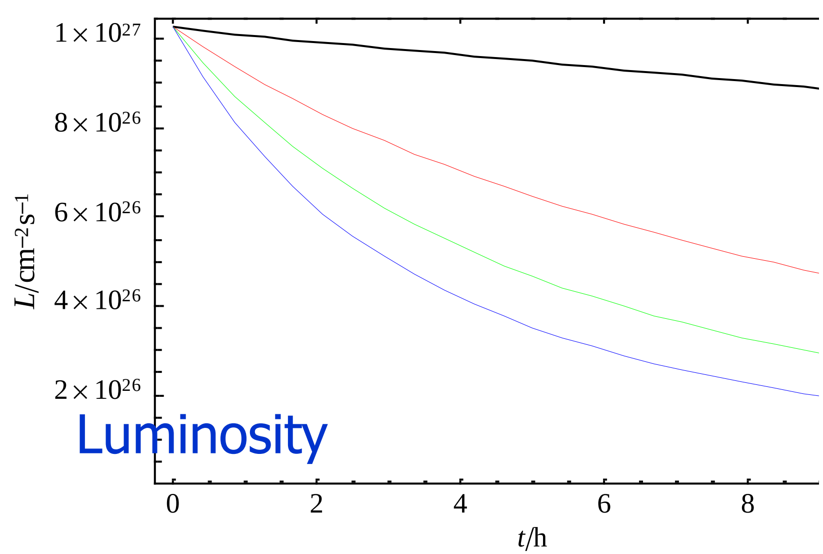




BPM visibility threshold

No. of experiments: $n_{exp} = 0, 1, 2, 3$

An "ideal" fill, starting from design parameters giving nominal luminosity.



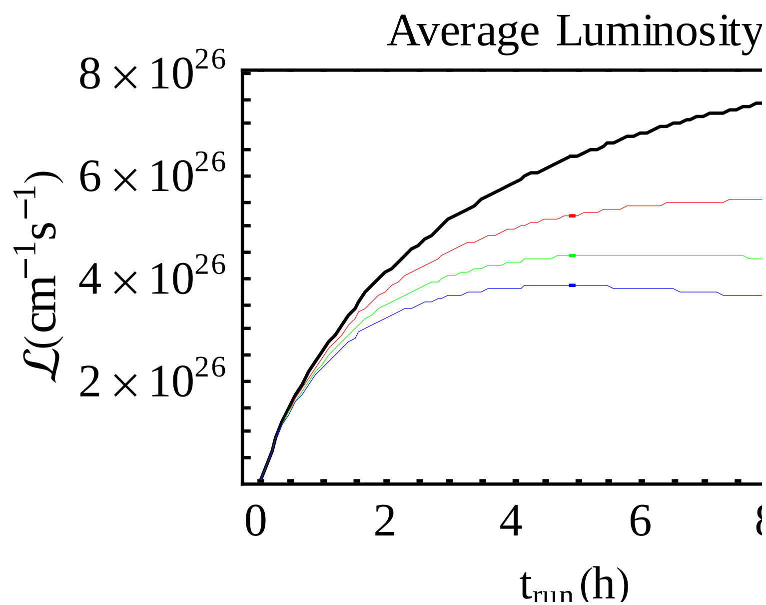
Increasing number of experiments reduces beam and luminosity lifetime.

Example: average luminosity

Average luminosity depends strongly on time taken to dump, recycle, refill, ramp and re-tune machine for collisions.

Average luminosity with 3h turn-around time, in ideal fills starting from nominal initial luminosity.

Maximum of curve gives optimum fill length.



No. of experiments: $n_{exp} = 0, 1, 2, 3$

Beams will probably be dumped to maximise average *L* **before** BPM visibility threshold is reached.

Commissioning Pb-Pb in the LHC Main Rings

- Basic principle: *Make the absolute minimum of changes to the working p-p configuration*
  - Magnetically identical transfer, injection, ramp, squeeze of IP1, IP5
  - Same beam sizes
  - Different RF frequency swing,
  - Add squeeze of IP2 for ALICE
- Requirements
  - LHC works reasonably well with protons
  - Ion injector chain ready with Early Beam (lead time!)
- After Early scheme push up number of bunches towards Nominal
  - always maximising bunch current

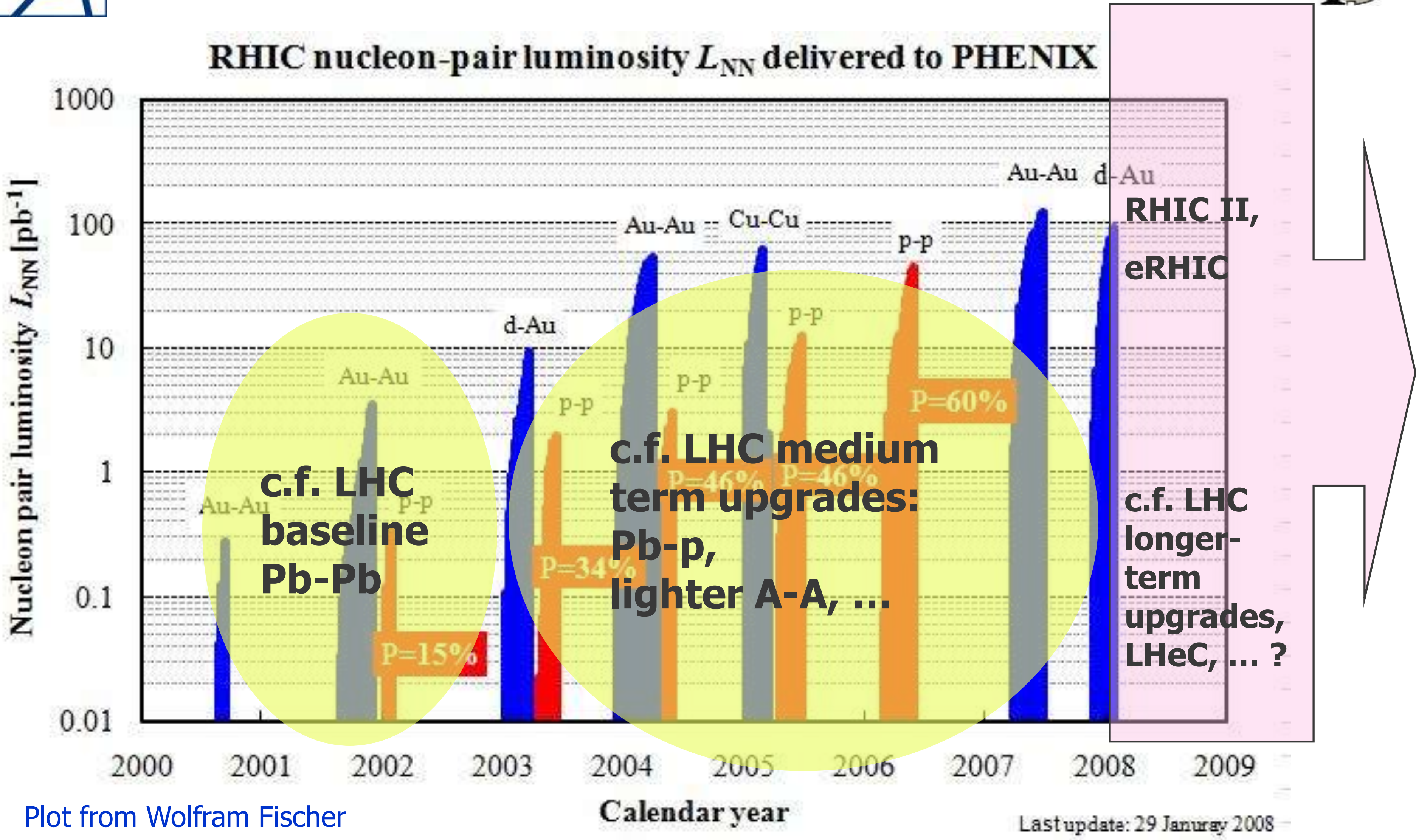
How long will it take?

- This will be a *hot-switch*, done when the LHC is already operational with protons
  - *Not* a start-up from shutdown
- Previous experience of species-switch:
  - RHIC several times, typically from ions to p-p, with 1 week setup + 1 week performance"ramp-up"
    - More complicated optics changes than LHC (injection is below transition with ions, above with protons)
    - Protons are polarized
  - Done a few times with CERN ISR, late 1970s
    - Went very quickly (< 1 day), because magnetically identical
    - LHC closer to ISR than RHIC from this point of view

Beyond Baseline Pb-Pb Collisions

- Further stages not yet scheduled within CERN programme:
  - p-Pb: preliminary study made (2005)
    - Injectors can do it.
    - Concerns about different revolution frequencies, moving beam-beam encounters, in LHC (2 in 1 magnet) but effects seem weak enough
  - Lighter ions
    - Resources concentrated elsewhere so far.
    - Will take time and detailed scheduling together with other upgrades to LHC.

RHIC programme as a model for LHC?



Plot from Wolfram Fischer

Summary

- The LHC is on track for first proton beams in summer 2008
  – Schedule remains sensitive to mishaps
- First Pb-Pb run expected at end 2009
  – very sensitive to time and resources available for ion injectors in 2009
  – "competition" for LHC beam time with p-p
- Pb-Pb luminosity limited by new beam physics
  – Understanding improving, tested
  – Measures taken to monitor and alleviate
  – Number of active experiments
- Programme beyond baseline Pb-Pb to be established and studied

Acknowledgements

- This talk sketched some aspects of the work of many people, over many years, in “Ions for LHC” and “LHC” Projects, in CERN and many collaborating institutes around the world.

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