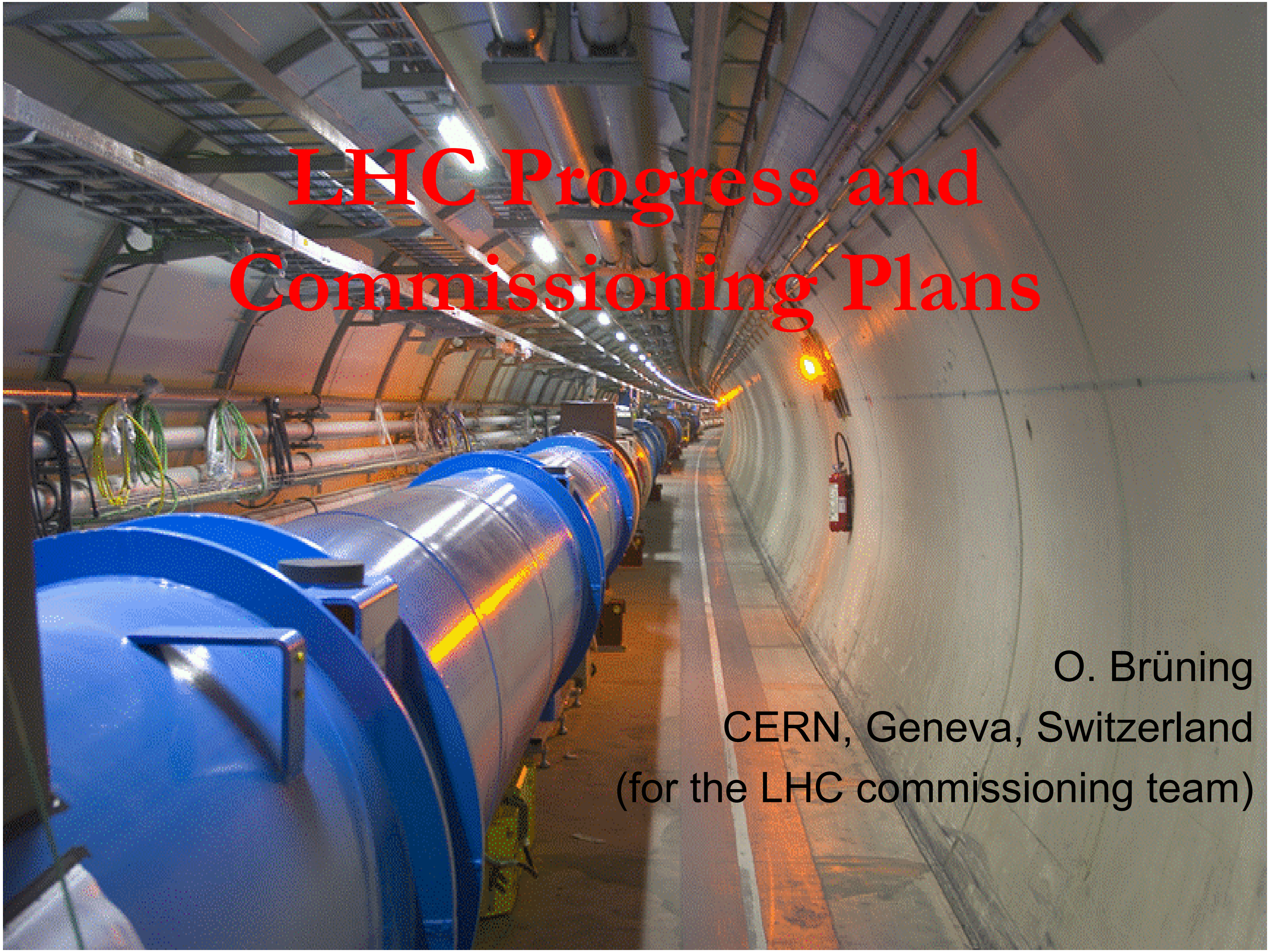
LHC Progress and Commissioning Plans



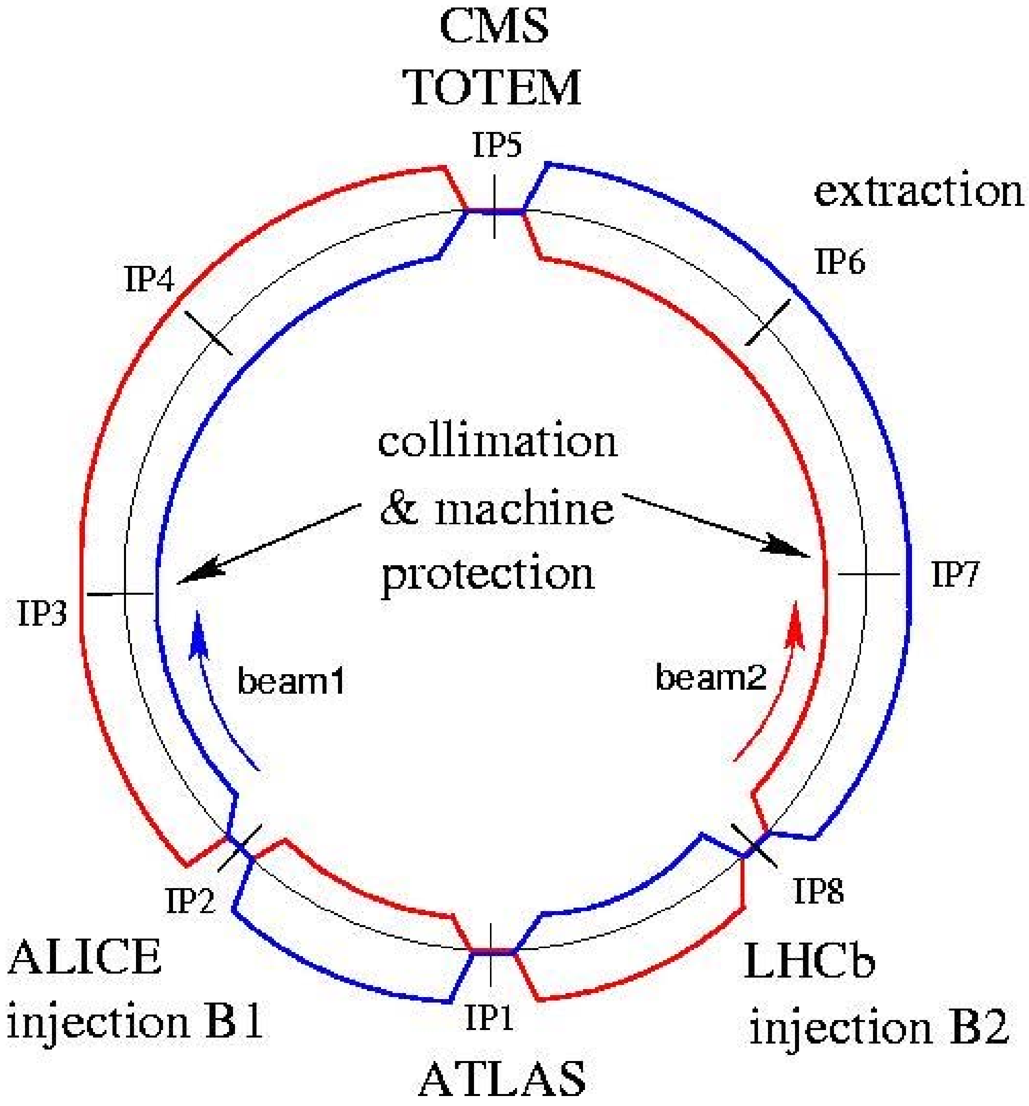
O. Brüning
CERN, Geneva, Switzerland
(for the LHC commissioning team)

Contents

- LHC layout overview and main parameters
- Project status
- Main challenges for the commissioning
- Commissioning plan

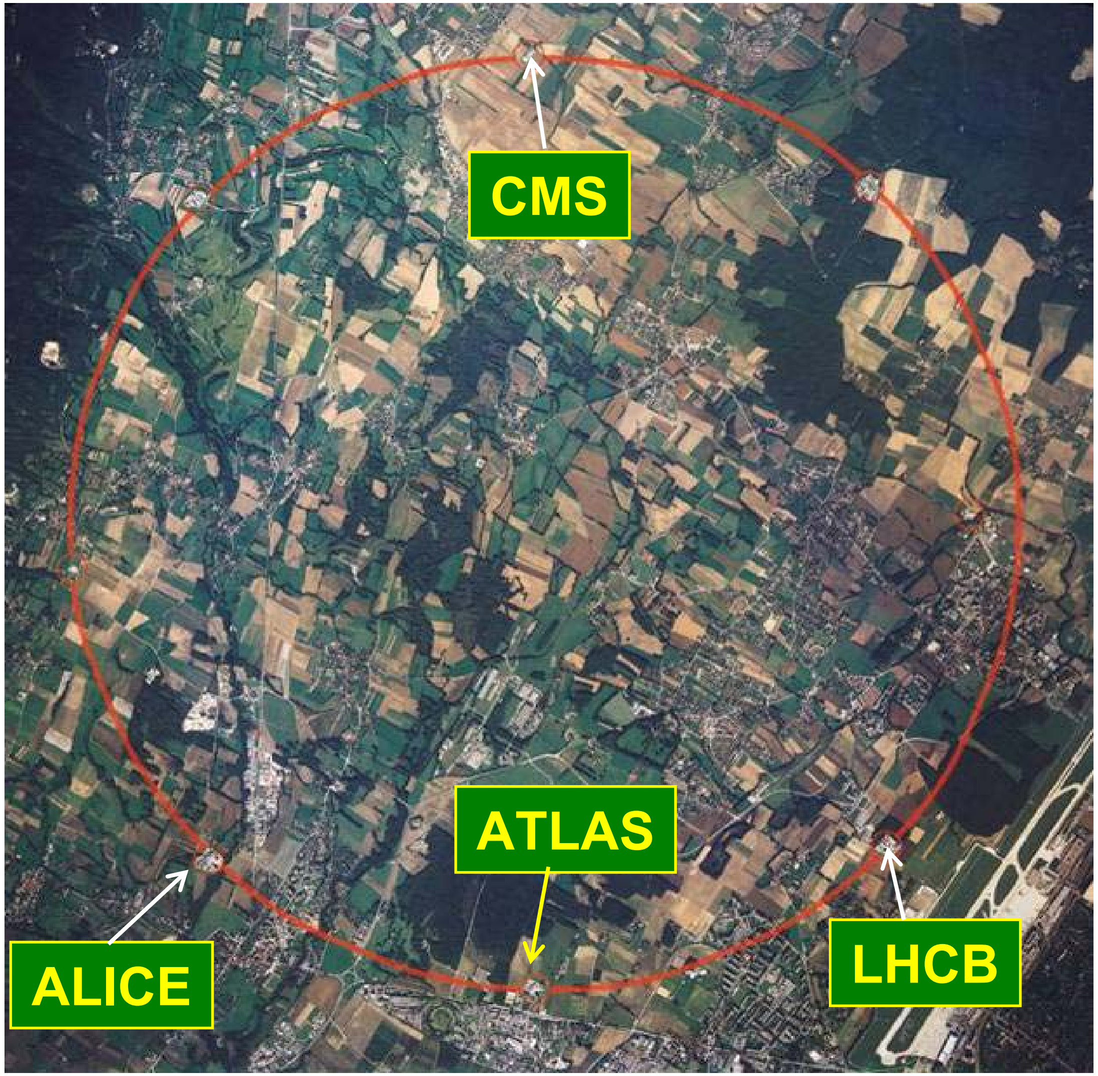
LHC Layout and Main Parameters

- 2-in-1 magnet design
  p-p & Pb-Pb collisions
- 7 TeV p-beam energy
  ➔ > 1 TeV CM energy
  ➔ Higgs discovery
- 2 high L experiments with
  $L = 10^{34}\ cm^{-2}\ sec^{-1}$
  ➔ 2808 bunches / beam
  with 1.15 10^{11} ppb
- 2 low L experiments:
  ALICE (Pb-Pb) & LHCb



LHC Layout and Main Parameters

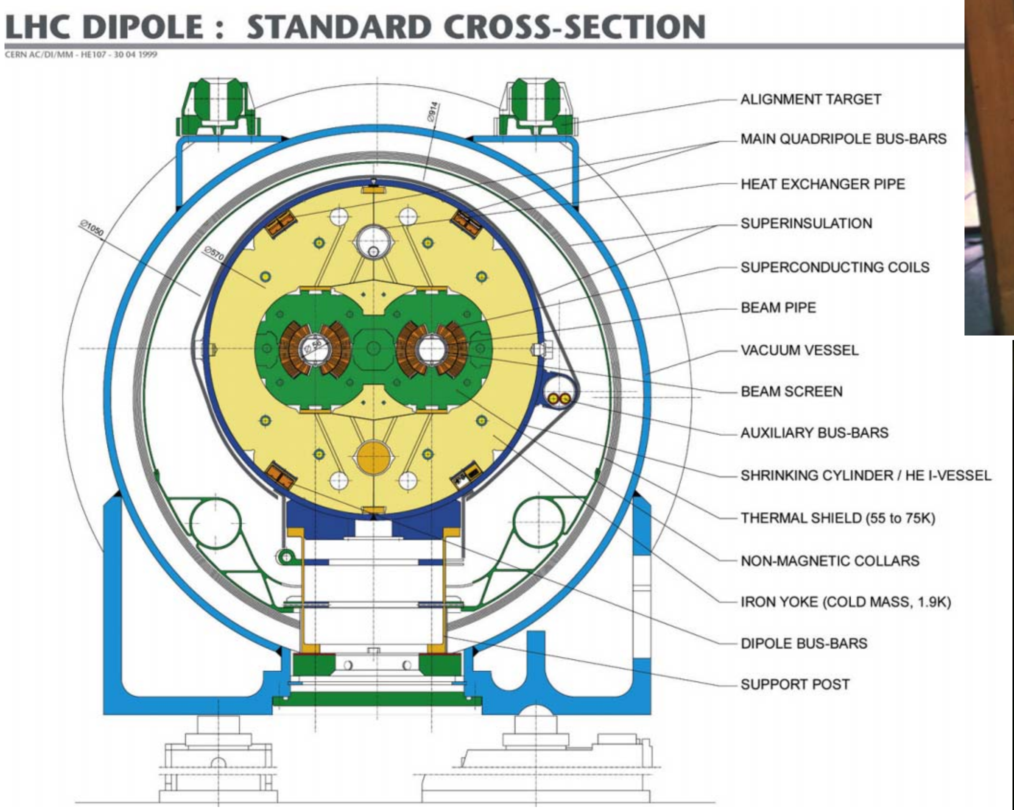
- built in old LEP tunnel
  - ➔8.4 T dipole magnets
  - ➔ 10 GJ EM energy
  - ➔ powering in 8 sectors
- 2808 bunches per beam with 1.15 10^{11} ppb
  - ➔360 MJ / beam
  - ➔crossing angle & long range beam-beam
- Combined experiment/ injection regions

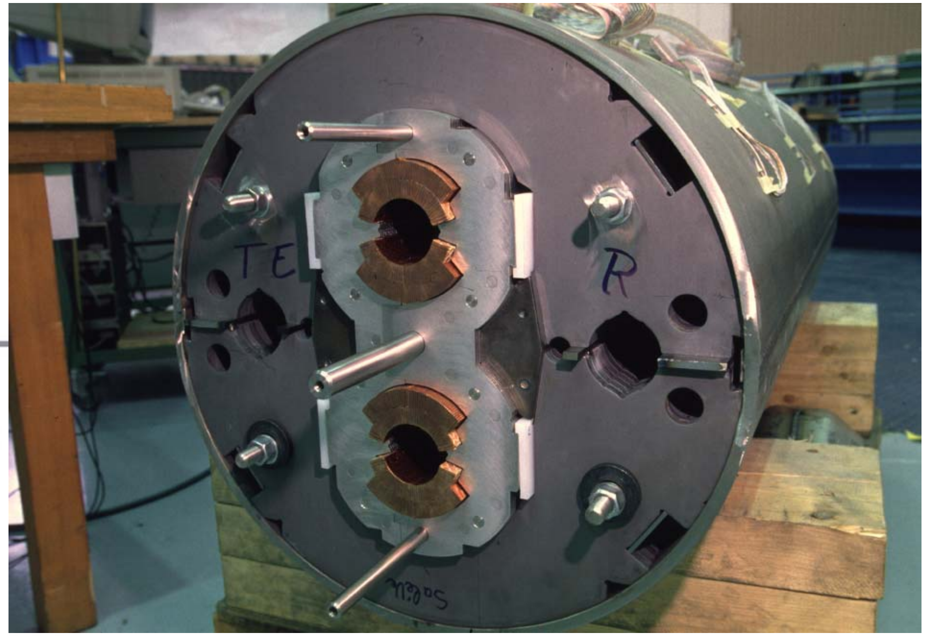


[A. Koschik et al, TUPLS014] [A. Koschik et al, WEPCH043]

LHC Layout and Main Parameters

- 2-in-1 dipole magnet design
  8.4 T, 15 m long, 30 Ton





Project Status

- Main dipole (MB) production and installation (1232)

  -almost all MB have been delivered to CERN (November 2006)
  -all MB will have passed cold test by end of 2006
  -3/4 have been prepared for installation and slot assigned
  -almost 50% have been installed in the tunnel
  installation is expected to progress at rate of 18 MB / week

- Main quadrupole (MQ) production and installation (392)

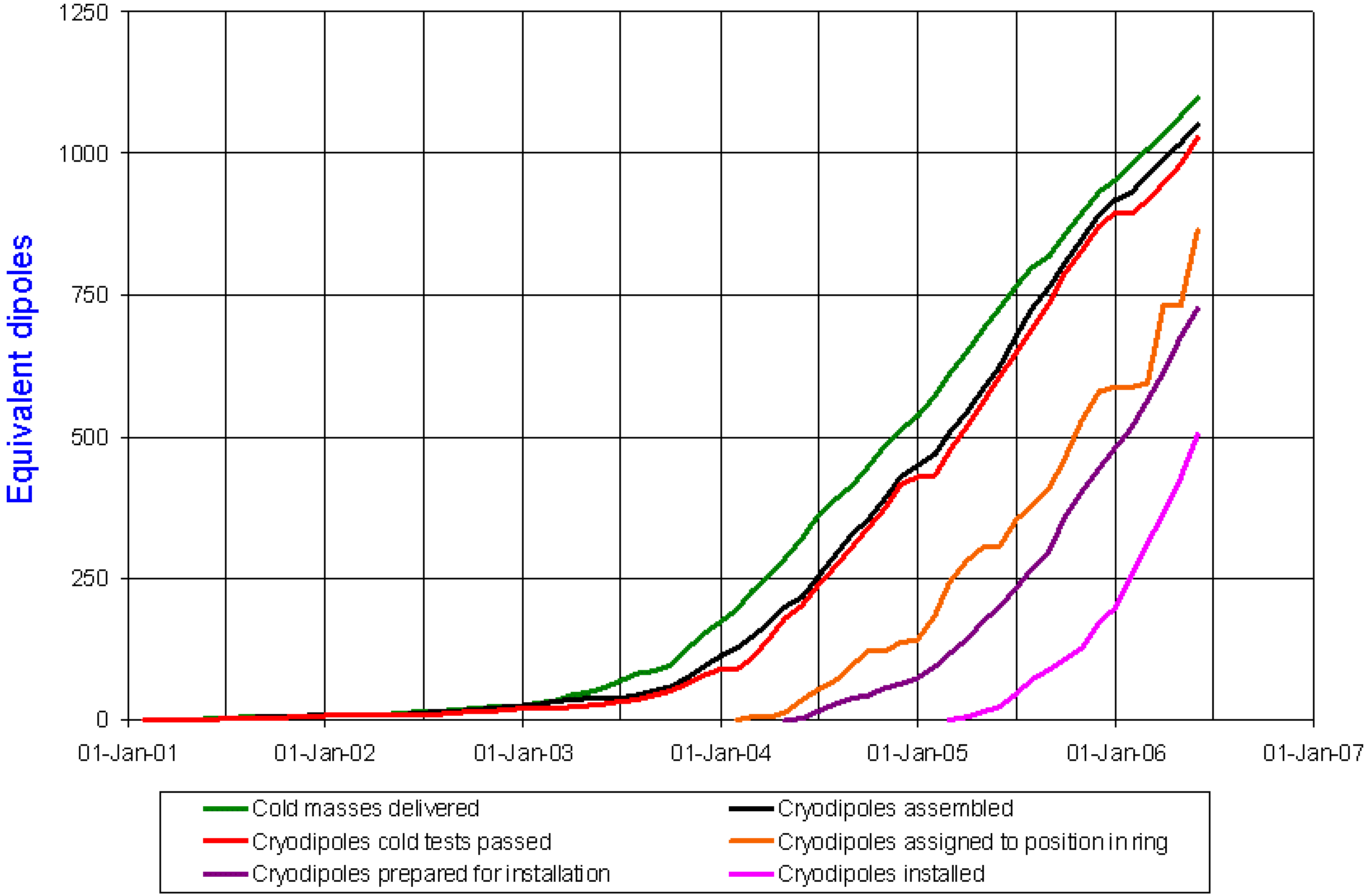
  -almost all MQ have been delivered to CERN
  -1/3 of the assemblies have been installed in the tunnel
  -2/3 have been slot assigned
  installation is expected to progress at rate of 6 assemblies / week

➔ closure of machine in March 2007, interconnect and pressure test August 2007

LHC Progress Dashboard

Accelerator Technology Department

Cryodipole overview

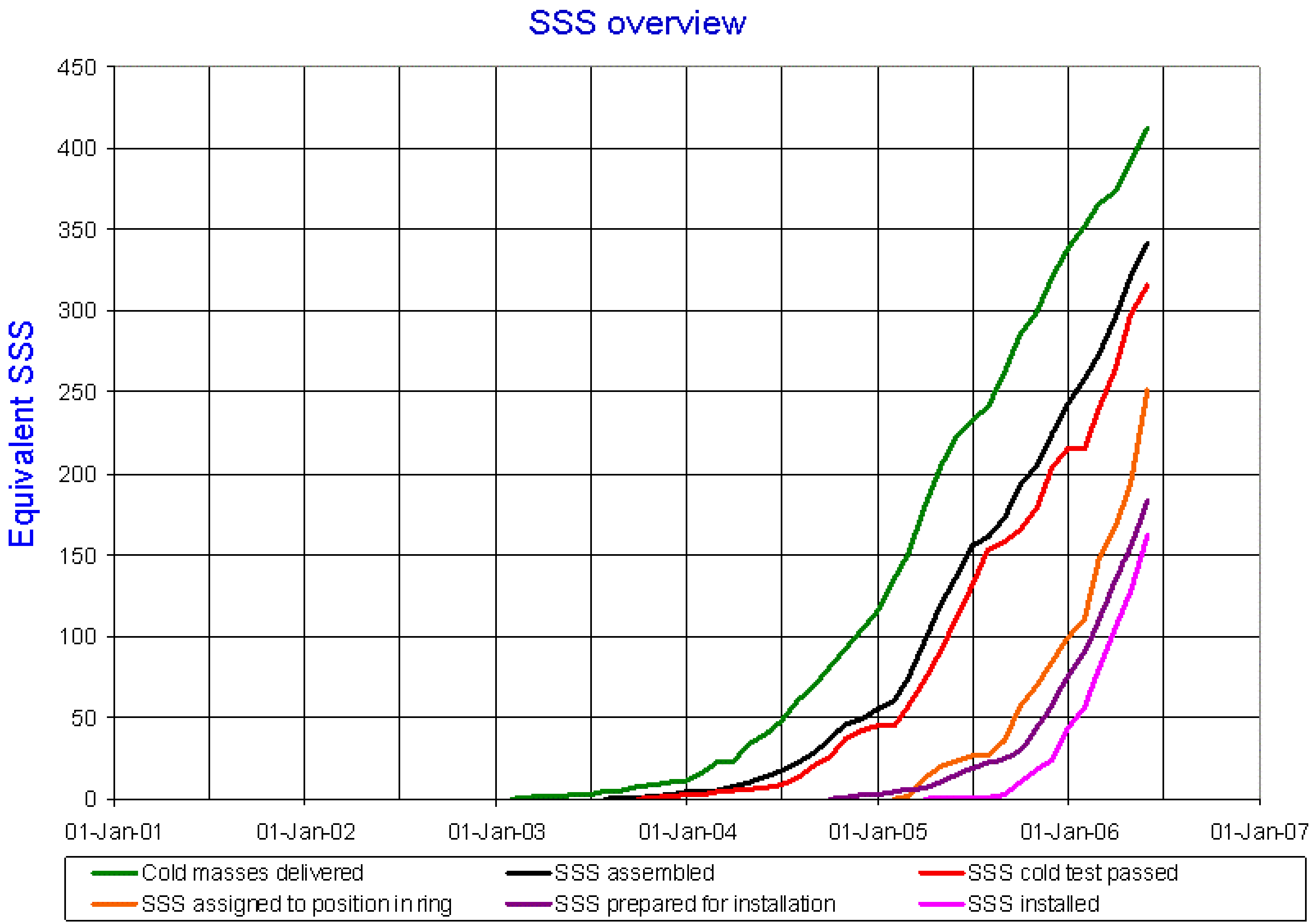


Updated 31 May 2006

Data provided by D. Tommasini AT-MAS, L. Bottura AT-MTM

LHC Progress Dashboard

Accelerator Technology Department



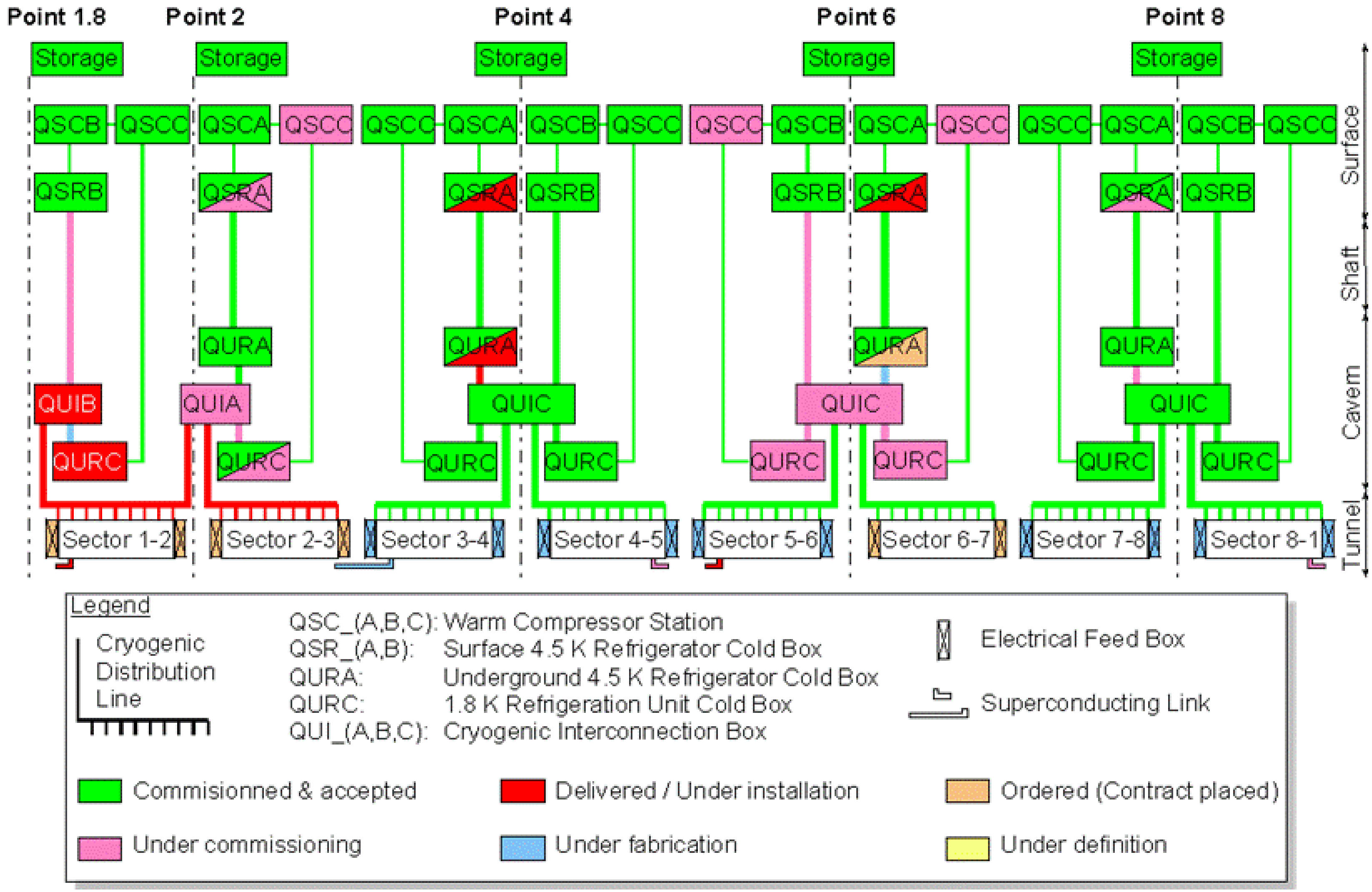
Updated 31 May 2006

Data provided by M. Modena AT-MAS, L. Bottura AT-MTM

LHC Progress Dashboard

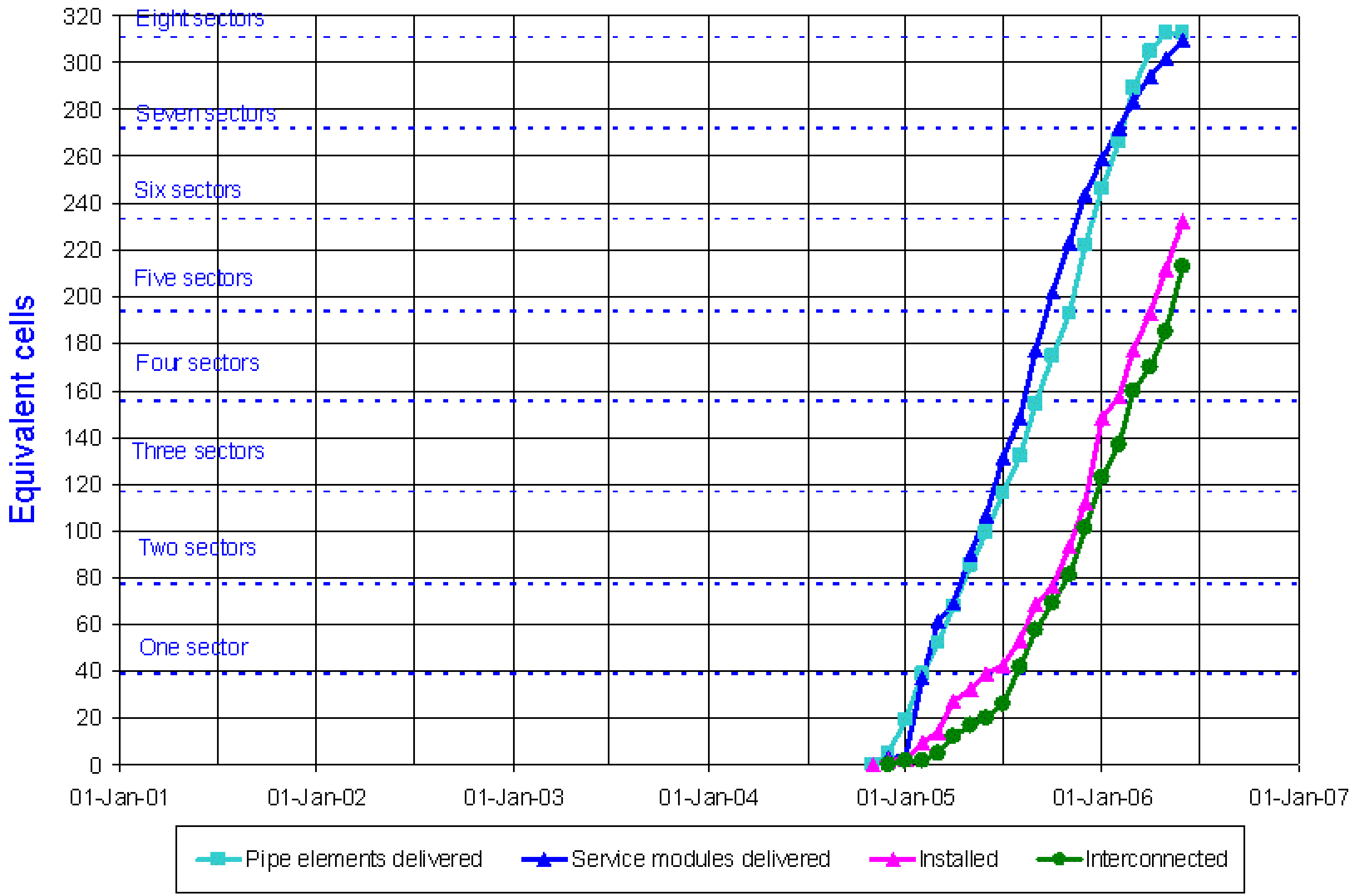
Accelerator Technology Department

Cryogenics overview



LHC Progress Dashboard

Cryogenic distribution line



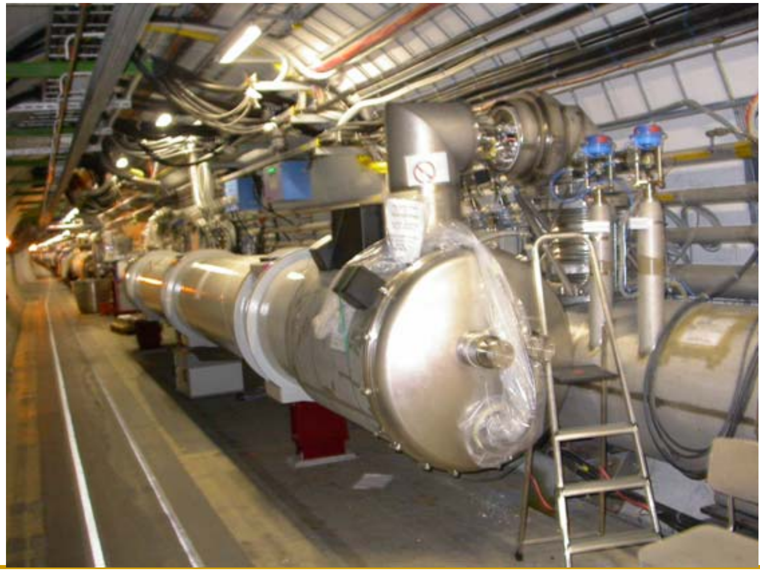
Updated 31 May 2006

Data provided by G. Riddone AT-ACR

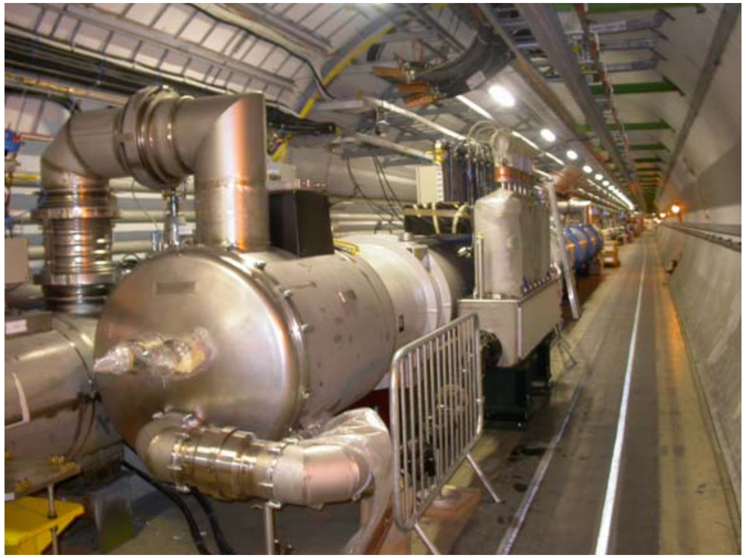
LHC Installation

cryogenic distribution in 12

superconducting link



Q6 with cryogenic connection in IR8

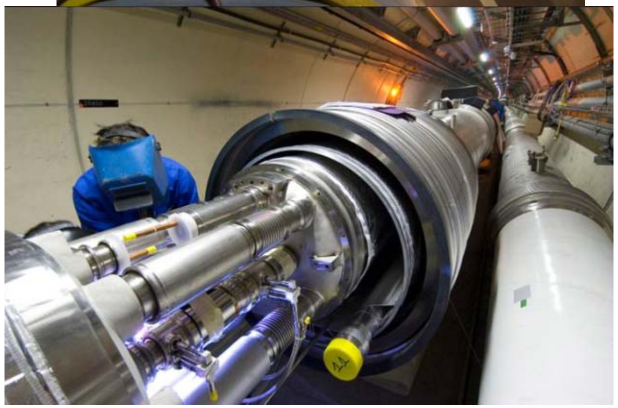
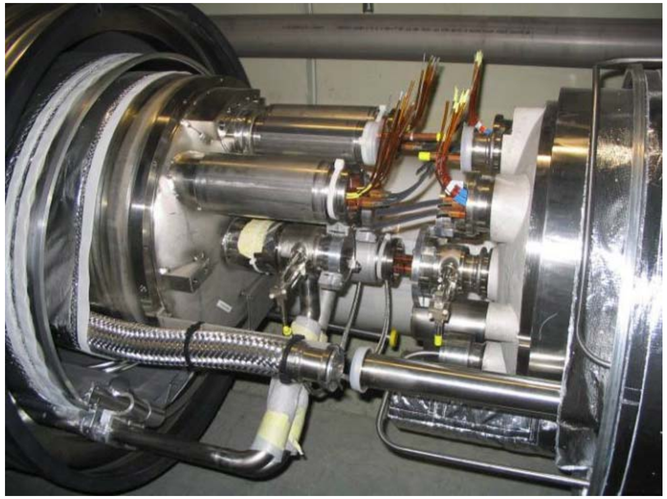


electrical distribution in IR8

LHC Installation





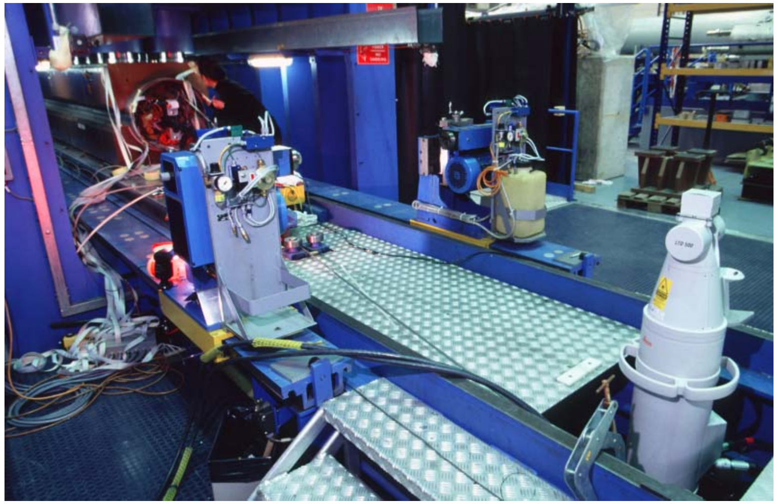



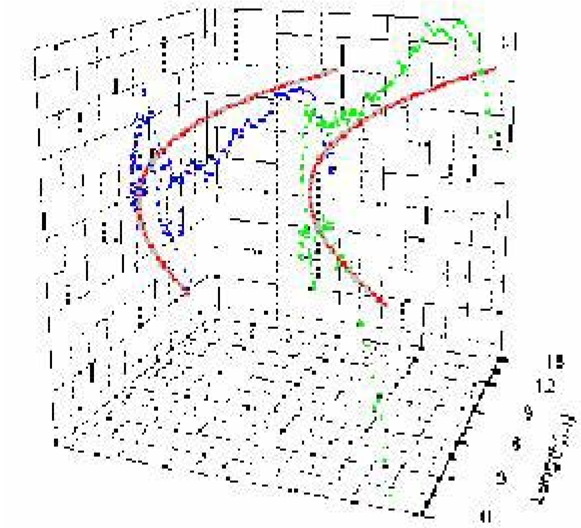
Main Challenges for the Operation

- Mechanical aperture
- Polarity errors
- Global magnet field quality & corrector circuit powering
- Collimation efficiency
- Beam power and machine protection
- Collective effects and impedance
- Triplet aperture and beam-beam
- Electron cloud effect

Mechanical Aperture

- all magnets are geometrically measured





➔ classification & slot compatibility for installation at critical locations

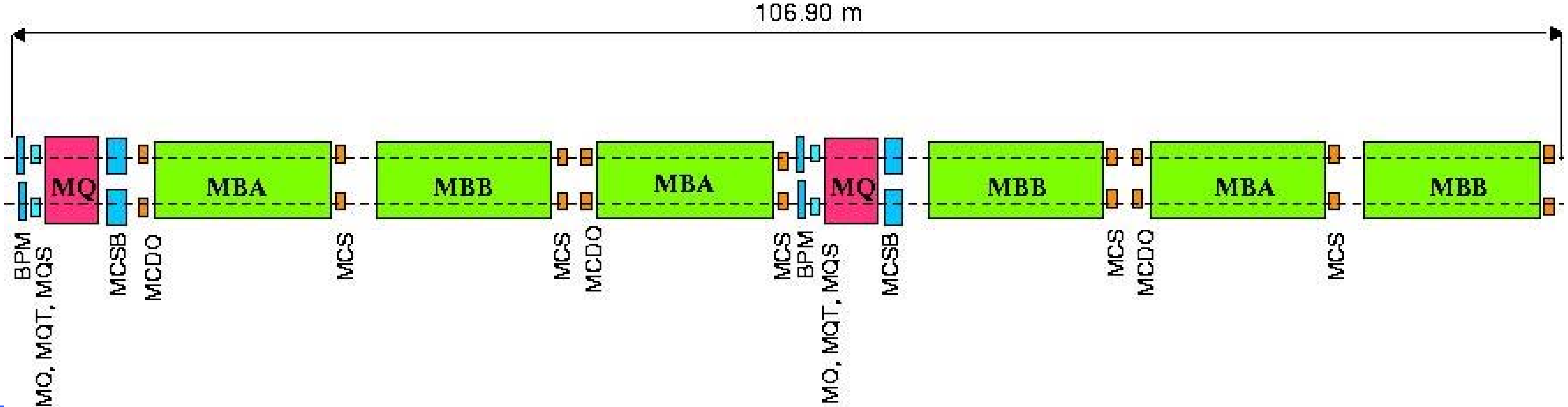
- microwave reflectrometer:

➔ detection of obstacles

[T. Kroyer et al, WEPLS141]

Polarity Errors

- the LHC features 112 circuits / beam (+ orbit correctors)



- all magnet circuits are tested before and during installation

[D. Bozzini et al, WEPLS099]

- adjustments during operation

➔ non-destructive beam instrumentation

[P. Cameron et al, THPCH105]

Global Magnetic Field Quality

- field quality measurement before installation:

  -all magnets are measured warm at industry ➔ monitoring

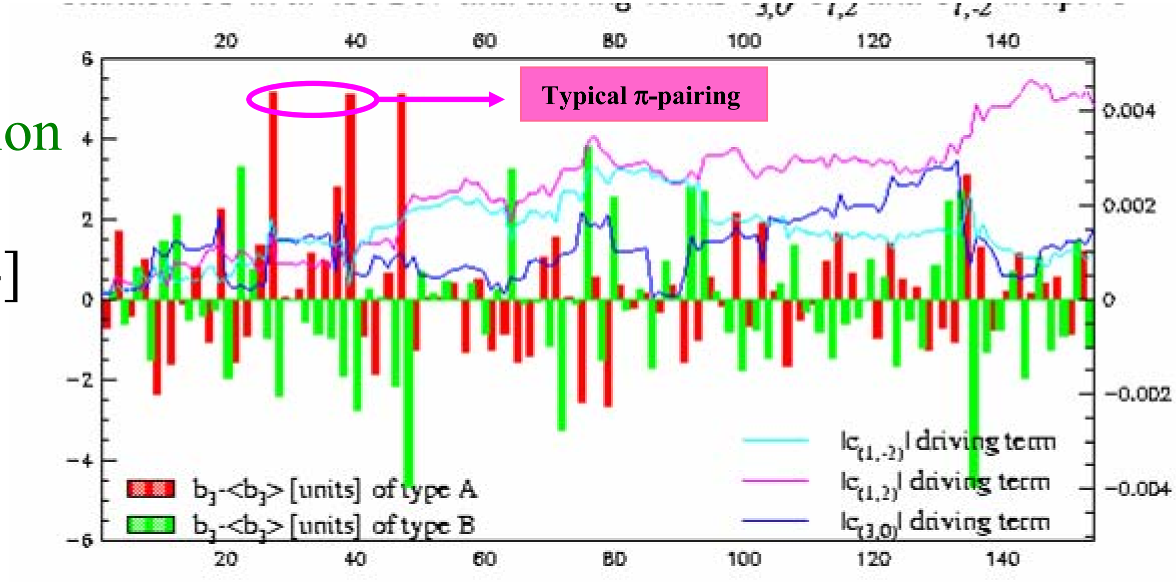
  -all magnets are cold tested ➔ electrical integrity & quench

  -a subset undergoes cold measurements ➔ warm-cold correlation

➔ ‘sorting’ during installation

Sector 78 V1

[S. Fartoukh, EPAC 2004]



-a smaller subset is subject to ‘extended’ measurements

➔field quality modeling during operation ➔ corrector powering!

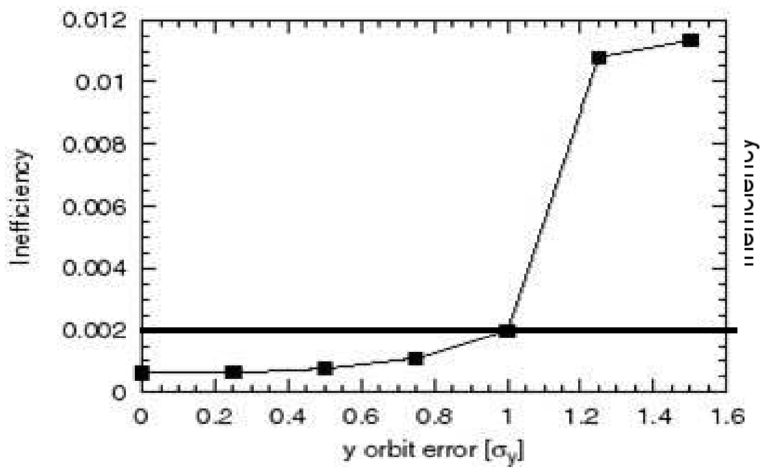
[N. Sammut et al, WEPLS104] [G. Rijk, WEPLS100]

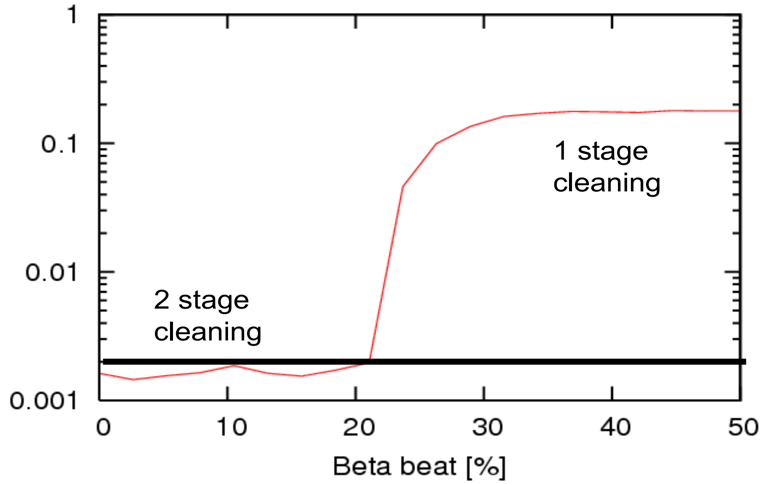
Collimation Efficiency

- Machine operation requires high collimation efficiency:

Collimation inefficiency := #p above 10 σ / # p on primary
➔design value of 2 10^{-3} ➔ below 0.2 h / 2 h are acceptable
➔2 stage collimation system with ca 100 collimators!

- Effect of machine imperfections:



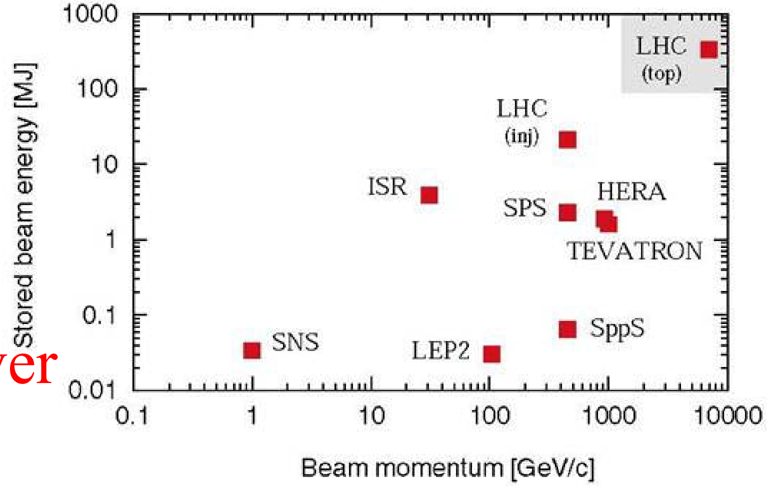


➔ requires good optic and orbit control!➔ feedback loops

[R.Assmann, TUODFI01] [C.Bracco et al, TUPLS018][G Robert-Demolaize TUPLS019]
[S. Redaelli, TUPLS130 and TUPLS131]

Beam Power and Machine Protection

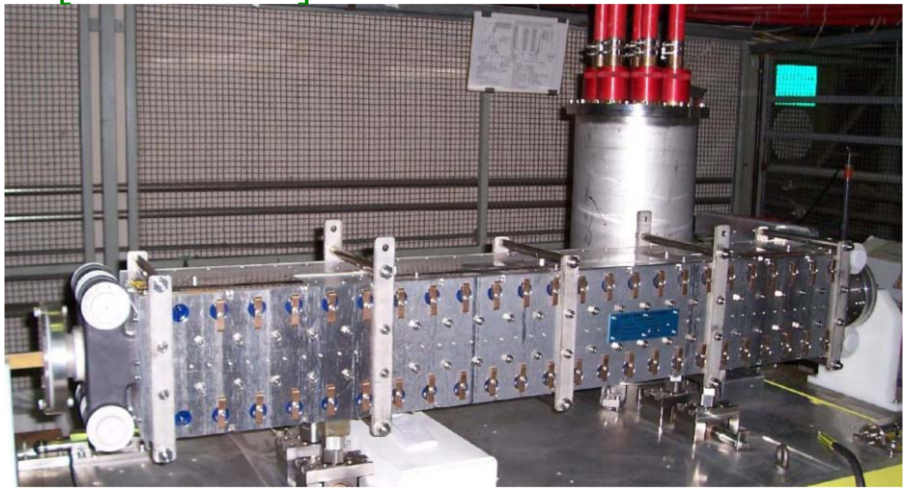
[R. Assmann]



Unprecedented beam power:

- ➔ potential equipment damage in case of failures during operation
- ➔ in case of failure the beam must never reach sensitive equipment!

[B. Goddard]



Machine Protection System

- ➔ Beam Los Monitors
- ➔ Quench protection system
- ➔ Beam Interlock System
- ➔ reliable Beam Dump system (15)
- ➔ dedicated absorbers in case of asynchronous dump

[R. Filippini et al, WEPLS140] [B. Goddard et al, MOPLS008] [B. Goddard et al, TUPLS013]

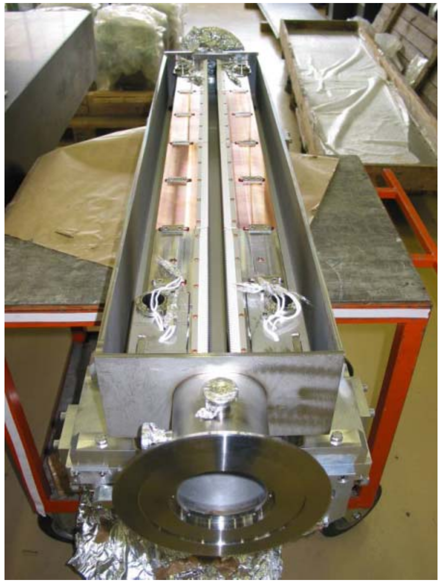
Beam Power and Machine Protection

- Unprecedented beam power:

  ➔ all absorbers and the collimation system must be designed to survive an asynchronous beam dump!
  (total of up to 136 collimators & absorbers)

- Robust collimator jaw design

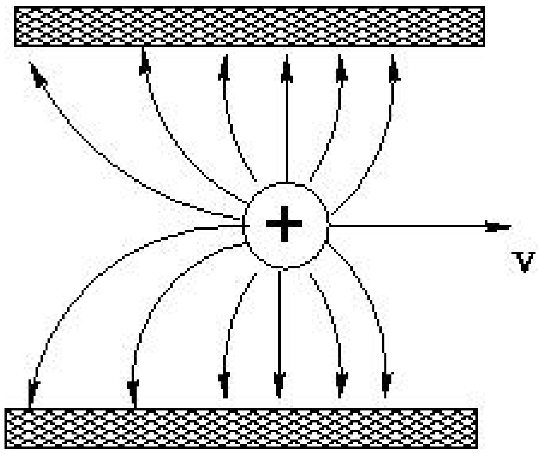
  ➔ fiber reinforced graphite jaws are more robust than Cu jaws
  ➔ fiber reinforced graphite has a higher impedance and electrical resistivity



[R. Assmann, TUODFI01] [F. Zimmermann et al, THPCH061]

Collective Effects & Impedance

- resistive wall impedance:
  ➔ image charges trail behind due to resistivity of surrounding materials
  ➔ Wake fields drive beam instabilities
  ➔ effect increases with decreasing gap opening of the collimator jaws



➔ impedance of Graphite jaws either limits the minimum collimator opening ➔ limit for β* or the maximum beam current

[F. Zimmermann et al, THPCH061]

- phased collimation system for the LHC:

  ➔ Phase 1: graphite jaws for robustness during commissioning
  ➔ Phase 2: nominal performance (low impedance, non-linear or feedback)

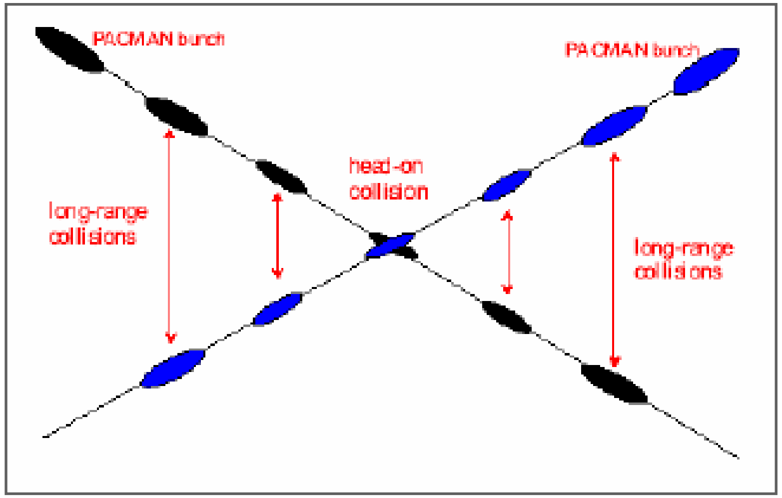
[R. Assmann, TUODFI01][J. Resta MOPCH091][A. Faus-Golfe WEXFI03]

Triplet Aperture and Beam-Beam

- long range beam-beam:

Operation with 2808 bunches features approximately 30 unwanted collision points per Interaction Region (IR).

➔ Operation requires crossing angle



- non-linear fields and additional focusing due to beam-beam

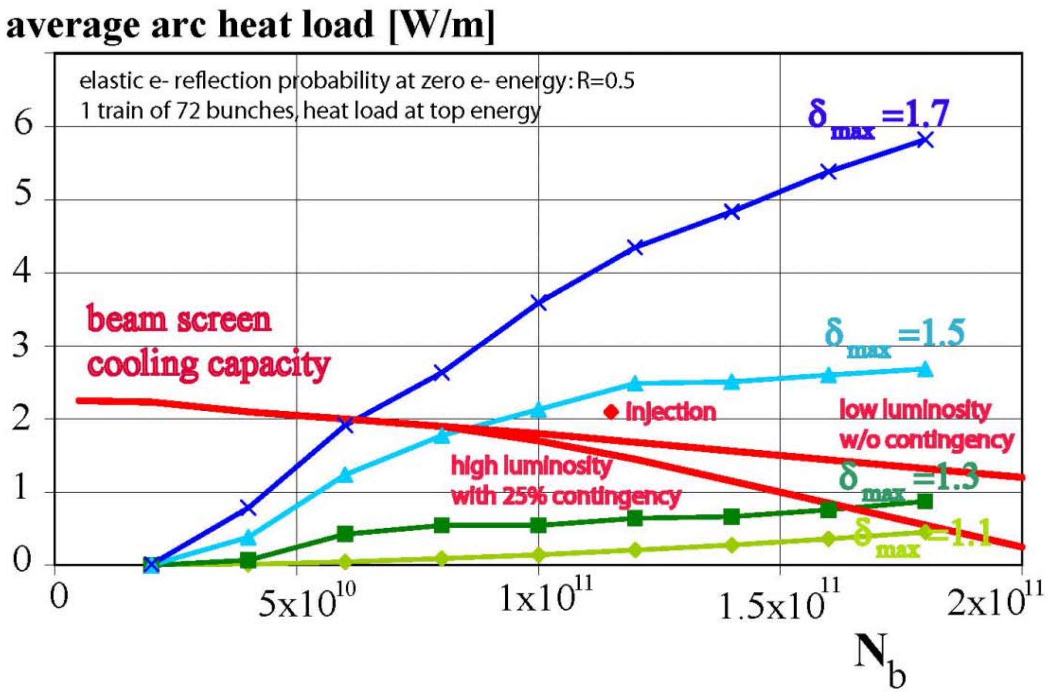
efficient operation requires large beam separation at unwanted collision points ➔ separation of 9 σ is at the limit of the triplet aperture for nominal β* values! ➔ margins can be introduced by operating with fewer bunches, lower bunch intensities, larger β* values (or larger triplet apertures ➔ upgrade studies)

[T. Pieloni, WEPCH095] [U. Dorda WEPCH138]

Electron Cloud Effect

- Synchrotron light releases electrons from beam screen:

  ➔ electrons get accelerated by p-beam ➔ impact on beam screen
  ➔ generation of secondary electrons ➔ e-cloud
  ➔ heating, instabilities and emittance growth



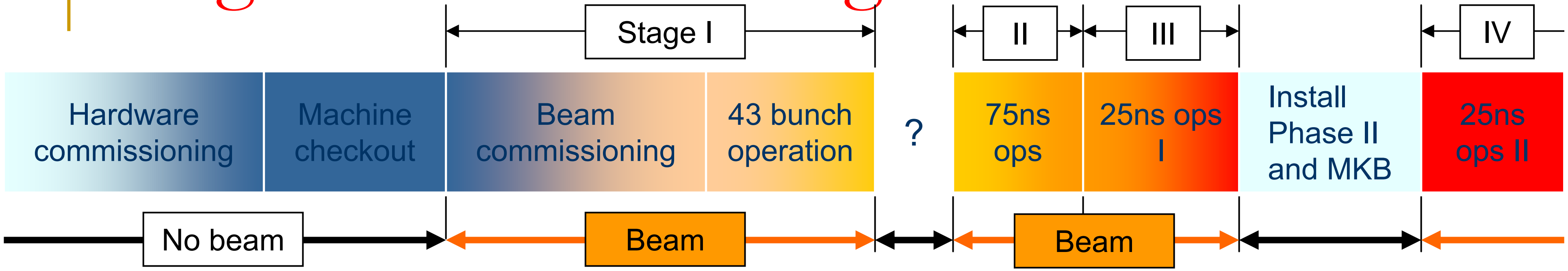
[E. Benedetto, THPCH018]

➔ effect disappears for low bunch currents or large bunch spacing

➔ secondary emission yield decreases during operation (beam scrubbing)

[F. Zimmermann]

Staged Commissioning Plan for Protons



I. Pilot physics run
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)

II. 75ns operation
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle

III. 25ns operation I
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal

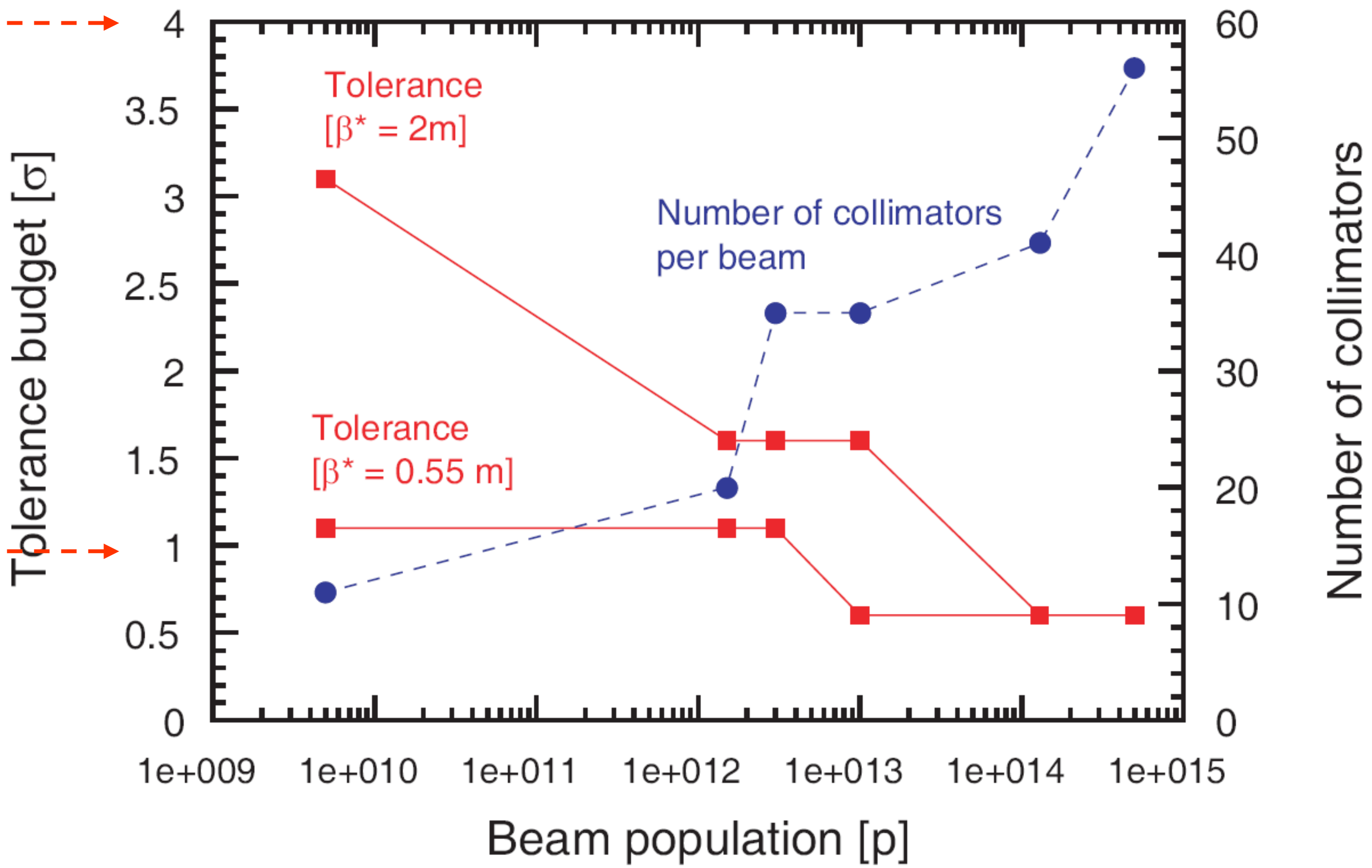
IV. 25ns operation II
- Push towards nominal performance

[R. Bailey et al, MOPLS005]

Staged Commissioning: Tolerances@7TeV

0.8 mm at a typical collimator

0.2 mm at a typical collimator



[R. Assmann]

Summary

- Mechanical aperture
- Polarity errors
- Global magnet field quality & corrector circuit powering

} careful analysis and definition of procedures during installation
→ optimization in Stage I

- Collimation efficiency — optimization during Stage I
- Beam power and machine protection — from Stage I to Stage II
- Collective effects and impedance — only at Stage III
- Triplet aperture and beam-beam — only > Stage III
- Electron cloud effect — only at Stage IV

Stage I physics run

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

$$Eventrate / Cross = \frac{L\sigma_{TOT}}{k_b f}$$

Protons/beam ≲ 10^{13} (LEP beam currents)

- Start as simple as possible
- Change 1 parameter (k_b N $\beta^*_{1,5}$) at a time

Parameters			Beam levels		Rates in 1 and 5		Rates in 2	
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}	18	$1\ 10^{10}$	10^{-2}	10^{27}	<< 1	$1.8\ 10^{27}$	<< 1
43	10^{10}	18	$4.3\ 10^{11}$	0.5	$4.2\ 10^{28}$	<< 1	$7.7\ 10^{28}$	<< 1
43	$4\ 10^{10}$	18	$1.7\ 10^{12}$	2	$6.8\ 10^{29}$	<< 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

Stored energy/beam ≲ 10MJ (SPS fixed target beam)

Stage II physics run

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

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

$$Eventrate/Cross = \frac{L \sigma_{TOT}}{k_b f}$$

- Relaxed crossing angle (250 μrad)
- Start un-squeezed
- Then go to where we were in stage I

Protons/beam ≈ few 10^{13}

Stored energy/beam ≤ 100MJ

Parameters			Beam levels		Rates in 1 and 5		Rates in 2 and 8	
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
936	$4\ 10^{10}$	18	$3.7\ 10^{13}$	42	$1.5\ 10^{31}$	<< 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	$4\ 10^{10}$	1	$3.7\ 10^{13}$	42	$2.5\ 10^{32}$	1.4	$2.6\ 10^{31}$	0.15
936	$9\ 10^{10}$	1	$8.4\ 10^{13}$	94	$1.2\ 10^{33}$	7	$1.3\ 10^{32}$	0.76

Stage III physics run

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

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

$$Eventrate/Cross = \frac{L\sigma_{TOT}}{k_b f}$$

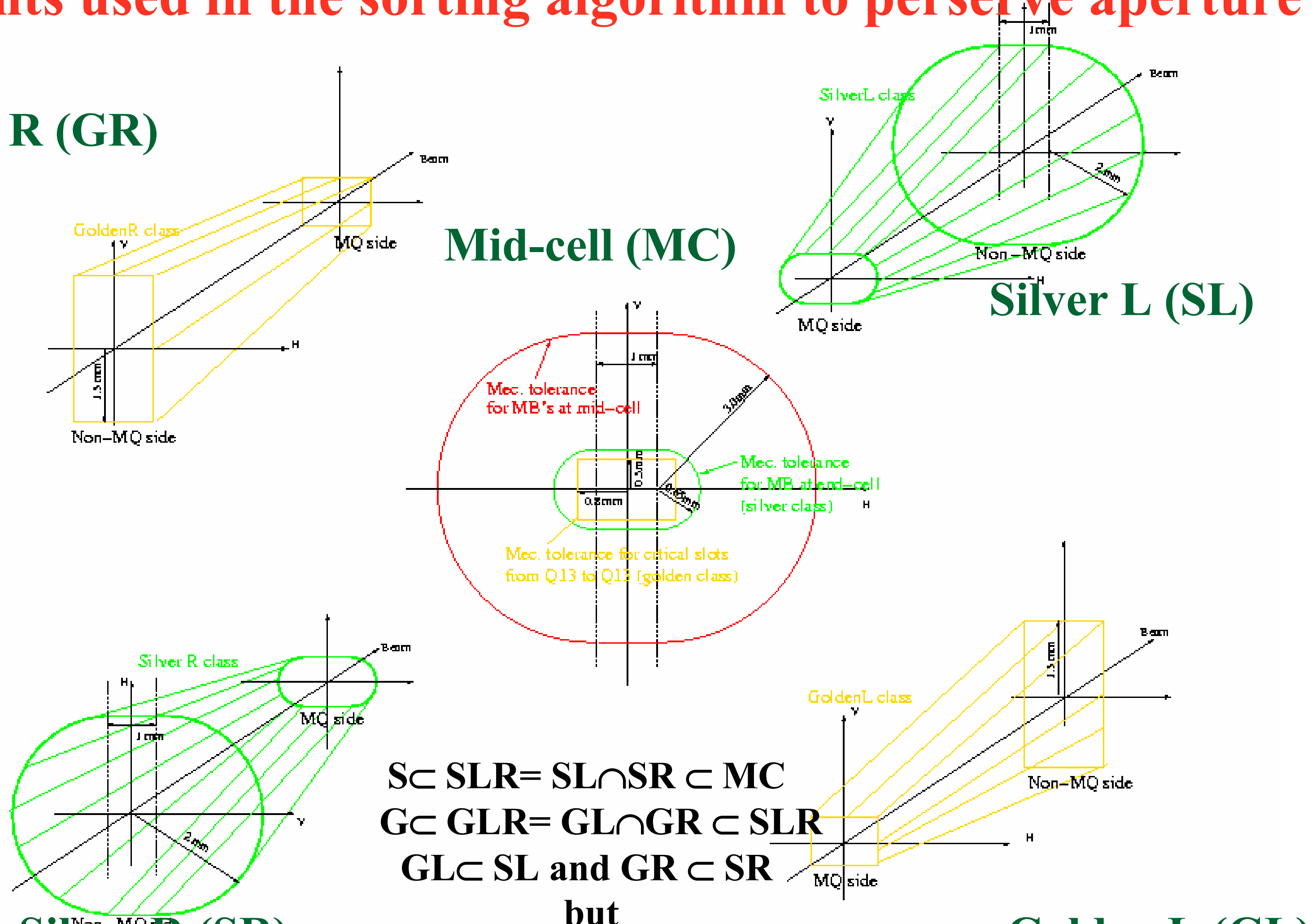
- Nominal crossing angle (285 μrad)
- Start un-squeezed
- Go to where we were in stage II

Protons/beam ≈ 10^{14}

Stored energy/beam ≥ 100MJ

Parameters			Beam levels		Rates in 1 and 5		Rates in 2 and 8	
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
2808	$4\ 10^{10}$	18	$1.1\ 10^{14}$	126	$4.4\ 10^{31}$	<< 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	$5\ 10^{10}$	2	$1.4\ 10^{14}$	157	$5.9\ 10^{32}$	1.1	$1.2\ 10^{32}$	0.24
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
Nominal			$3.2\ 10^{14}$	362	10^{34}	19	$6.5\ 10^{32}$	1.2

Five geometry sub-classes for the LHC main dipoles and their variants used in the sorting algorithm to perserve aperture



$S \subset SLR = SL \cap SR \subset MC$

$G \subset GLR = GL \cap GR \subset SLR$

$GL \subset SL$ and $GR \subset SR$

but

$GL \not\subset S$ and $GR \not\subset S$

Global Magnetic Field Quality

field quality measurement before installation:

- -all magnets are measured warm at industry ➔ monitoring
- -all magnets are cold tested ➔ electrical integrity & quench
- -a subset undergoes cold measurements
  - ➔ warm-cold correlation
  - ➔ 'sorting' during installation [S. Fartoukh, EPAC 2004]
- -a smaller subset are subject to 'extended' measurements
  - ➔ field quality modeling during operation ➔ corrector powering!

Identity Card of Cryodipole **HCLBBR_000-IN003416**

Cold performance	
1st Quench (T)	8.58
2nd Quench (T)	-
Maximum Reached Field (T)	9
Number of Quenches to 9T	1
Number of Cooldowns	1
First Quench After Last Cd (T)	-
Cold Tests Class	G

ok
warning1
warning2
off limits

Advancement	
Arrival at CERN	2005-11-24
Connection to Test Bench	2005-11-30
Performance Assent	2005-12-12
MEB Approval	2006-05-16
Data Extraction	2006-05-12
Last Modified On	

Deviation from Geometric Axis		
Measurement @ WP08-19		
(mm)	V1	V2
α georef (mrad)	-.367	
δx upstream	-.302	-.24
δz upstream	-.162	-.081
δx downstream	.014	.068
δz downstream	-.173	-.28
δx min	-.316	-.252
δz max	.415	.419
δx max	.456	.301
δz min	-.352	-.342
δx average	.016	-.016
δz average	0	0
r upstream	.342	.253
r downstream	.174	.288
r body	.415	.419
Position of correctors		
(mm)	V1	V2
MCS-δx	-.066	-.142
MCS-δz	.037	.03
MCO-δx		
MCO-δz		
MCD-δx		
MCD-δz		

Magnetic Field (Extrapolated to Cold)									
	Aperture 1 (V1)					Aperture 2 (V2)			
	760A	EOL	EOR	11850A		760A	EOL	EOR	11850A
TF	10.109	10.111	N/A	10.051	Tm/kA	10.113	10.115	N/A	10.055
ML	14.303	14.303	N/A	14.304	m	14.303	14.303	N/A	14.304
FD	N/A	N/A	N/A	N/A	mrad	N/A	N/A	N/A	N/A
b1	-12.81	-11.33	N/A	-16.12	units	-8.94	-7.45	N/A	-12.23
b2	0.86	0.86	N/A	-0.61	units	-0.95	-0.95	N/A	0.51
b3	-5.16	-3.31	N/A	2.03	units	-5.94	-4.10	N/A	1.25
b4	-0.07	-0.06	N/A	0.13	units	-0.03	-0.03	N/A	-0.23
b5	0.51	0.20	N/A	-0.70	units	0.44	0.13	N/A	-0.77
b6	-0.03	-0.03	N/A	-0.03	units	-0.04	0.00	N/A	0.00
b7	0.64	0.66	N/A	0.95	units	0.66	0.68	N/A	0.97
b8	-0.03	-0.03	N/A	-0.02	units	0.01	0.01	N/A	0.00
b9	0.57	0.55	N/A	0.34	units	0.56	0.53	N/A	0.32
b10	0.00	0.00	N/A	0.00	units	0.00	0.00	N/A	0.00
b11	0.67	0.67	N/A	0.64	units	0.67	0.67	N/A	0.64
a2	1.57	1.54	N/A	1.60	units	1.77	1.80	N/A	1.74
a3	0.25	0.28	N/A	0.24	units	0.36	0.38	N/A	0.34
a4	-0.40	-0.41	N/A	-0.41	units	0.29	0.30	N/A	0.30
a5	0.08	0.08	N/A	0.08	units	0.14	0.14	N/A	0.14
a6	0.03	0.03	N/A	0.03	units	0.12	0.12	N/A	0.12
a7	-0.02	-0.03	N/A	-0.03	units	-0.03	-0.04	N/A	-0.04
a8	-0.01	-0.01	N/A	-0.01	units	-0.01	-0.01	N/A	-0.01
a9	-0.05	-0.05	N/A	-0.04	units	-0.07	-0.07	N/A	-0.06
a10	0.00	0.00	N/A	0.00	units	0.00	0.00	N/A	0.00
a11	-0.08	-0.08	N/A	-0.08	units	-0.11	-0.11	N/A	-0.11

Important Specificities
No remaining non-conformities
Dispositions of the Magnet Evaluation Board
Assigned to the slot LBBRA.13L7 (sector 67)

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