# LHC Design Report - Volume I

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12 Vacuum system
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13 Beam Diagnostics and Instrumentation
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   Responsible : Schmickler H.

14 Control System
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15 Machine Interlock System
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   Responsible : Schmidt R.

16 Injection System
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17 Beam Dumping System
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18 Beam Cleaning and Collimation System
   Editorial linkman : Myers S.
   Responsible : Assmann R.

19 Interface with and Requirements from the Experiments
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(Keywords)

01 Introduction

Editorial linkman : Myers S.
Responsible Evans L.

02 Beam Parameters and Definition

Editorial linkman : Brüning O.
Responsible Brüning O.

2.01 Glossary

Definition of sector and octants
Beam1 and beam2; upstream and downstream
LHC filling pattern and PS and SPS batches
Units and definitions for main beam parameters

03 Layout and Performance

Editorial linkman : Brüning O.
Responsible Brüning O.

3.01 Performance

Nominal luminosity and summary of the nominal LHC beam parameters
Crossing angle
Summary of expected luminosity beam lifetime and turn around time (this will only be a short summary of the main parameters with reference to the chapters where more detailed information can be found)

3.02 Lattice layout

Geometry: the LHC position in the LEP tunnel and its implication to the design
Modular design approach: arc cells, dispersion suppressor (individual powering of the quadrupoles), matching sections and triplet layout (including D1/D2)

Functional description of the arc correction circuits:
  Combined MB, QF and QD powering of beam1 and beam2
  Summary of the spool piece and lattice correction circuits

Functional description of all insertions:
  Luminosity insertions with beam crossing and low beta -> IR1 and IR5
  Combined luminosity and injection insertions -> IR2 and IR8
  RF insertion
  Beam dump
  Beam cleaning (betatron and momentum cleaning)

3.03 References
Optics and Single Particle Dynamics

4.01 Arc optics
Nominal 90 degrees lattice with tune split in horizontal and vertical plane
(required for coupling correction and dynamic aperture)

4.02 Insertion Optics:
The high luminosity insertions: IR1 and IR5
The combined luminosity and injection insertions: IR2 and IR8
The RF insertion
The beam dump insertion
The betatron cleaning insertion
The momentum cleaning insertion

Each of the above sub-section will address the following key points:
- summary of the main optics constraints (constant phase advance over IR, DS aperture etc)
- nominal optics and crossing angle for beam1 and beam2
- tuneability
- mechanical acceptance

4.03 Mechanical acceptance
Definition of the halo shape for a two (three) stage collimation system
(summary of LHC Project NOTE 111)
Summary of all contributions and tolerances for the aperture analysis
(beta-beat, spurious dispersion, injection oscillations, mechanical tol. etc.)
Difference in the horizontal / vertical and radial apertures (na and nr)

4.04 Beam and machine parameter tolerances for operation
Specification of the operational tolerances for orbit, tune, coupling, chromaticity,
tune spread and beta beat (-> accessible area in tune diagram)
Specification of the maximum acceptable magnet alignment tolerances (orbit and feed down errors)

4.05 Field quality specification
Summary of the main dipole field quality specification and the available corrector strength
Summary of the main quadrupole field quality specification
Summary of the triplet and the D1/D2 field quality specification
4.06 Special optics solutions
Alignment optics for the luminosity insertions
Resonance free lattice and limits for the arc tune split

4.07 Dynamic aperture
Justification for a 100000 turn DA of 12 sigma for a machine that has a mechanical aperture of 6 sigma (collimator jaws) (reduction factor of 2 in the DA)
DA for the specified field error tolerances at injection (-> justification for a tune split of 5 units)
DA for the injection optics with long-range beam-beam interactions (-> justification for 10 sigma beam separation)
DA for the squeezed optics with triplet field errors and long-range beam-beam at top energy (-> specification of the maximum acceptable crossing angle)

4.08 References

05 Collective Effects

Editorial linkman : Brüning O.
Responsible : Ruggiero Fr.

5.01 Impedance budget
Overview of components (pumping slots, collimator jaws, RF tanks etc)
Inductance

5.02 Single beam instability mechanisms
Short summary of key mechanisms and related threshold currents
(Resistive wall, general multi bunch, microwave, head tail instability etc)

5.03 Cures against instabilities
Tune spread: Landau damping octupoles and beam-beam
Transverse feedback system
RF voltage program

5.04 Electron cloud
Heat load
Beam stability
Emittance growth
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(Keywords)

5.05 Emittance growth
Intra beam scattering
Toucheck effect
Rest gas scattering
Emittance growth due to feedback in presence of tune spread

5.06 Synchrotron radiation
Emittance damping
Heat load
Gas and electron desorption

5.07 Heat load summary
Summary of total budget
Sort description of heat load coming from particles leaving the IP

5.08 Beam-Beam
Tune spread (head-on and long range)
Budget from past experience (SPS and Tevatron)
Pacman bunches
Coherent beam-beam instabilities

5.09 References

06 The RF Systems (& Longitudinal Beam Feedback)

Editorial linkman: Collier P.
Responsible: Linnecar T.

6.01 Introduction
Recalling main beam parameters and longitudinal beam parameters in the flat bottom, ramping and in coast influencing the RF manipulations necessary and the design of the RF system (and transverse feedback system).

6.02 Discussion of particularities: one RF system per ring, choice of SC,
Capture/accelerating systems (staging of latter), 1 Klystron /cavity, why no separate longitudinal FB etc.
Results of simulations and calculations - emittance, impedance, power, losses etc. Main RF system parameters.
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(Keywords)

6.03 Main 400MHz RF system
specification
cavities and ancillaries
power amplifiers
HT system and protection

6.04 Staged 200 MHz capture system -
specification
cavities
power amplifiers
HT system and protection

6.05 Beam control
specification
cavity feedbacks and servo controls
main beam control systems
synchronization system
techniques used - implementation

6.06 Beam control
specification
cavity feedbacks and servo controls
main beam control systems
synchronization system
techniques used - implementation

6.07 Equipment Controls
Equipment level: PLCs, layout, interlocking, protection, etc.
front ends
analogue acquisition
post mortem

6.08 Layout in tunnel and cavern
e.g. impact of ACS move into UX45, radiation(Wall),
LLRF siting. Vacuum, Cryo etc. etc plus safety issues

07 Main Magnets in the Arcs

Editorial linkman : Lebrun P. Ostojic R.
Responsible Rossi L.
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(Keywords)

7.01 Overview

7.02 Cryodipoles

7.2.1. Dipole cold mass
- Superconducting cable
- Collared coils
- Magnetic yoke
- He II heat exchanger tube
- Helium enclosure
- Cold bores
- Spool correctors
- Protection diodes
- Instrumentation
- Production QA and steering

7.2.2. Cryostat
- Vacuum vessel
- Radiation shield and MLI
- Support posts
- Cryomagnet assembly

7.2.3. Cryodipole performance
- Equipment and procedures for cold tests
- Power tests
- Magnetic measurements

7.03 Short Straight Sections

7.3.1 Quadrupole cold mass
- Superconducting cable
- Collared coils
- Magnetic yoke
- Helium II heat exchanger tube
- Helium enclosure
- Cold bores
- Corrector magnets
- Protection diodes
- Instrumentation
- Production QA and steering

7.3.2. SSS cryostat
- Vacuum vessel
- Radiation shield and MLI
- Support posts
- Vacuum barrier
- Technical service module
- SSS assembly

7.3.3. SS performance
- Equipment and procedures for cold tests
- Power tests
- Magnetic measurements

7.04 Reference Magnet System (RMS)

(I do not like the phrase "multipole factory")
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(Keywords)

7.05 Interconnections

7.5.1. Electrical
7.5.2. Hydraulic/cryogenic
7.5.3. Vacuum
7.5.4. Thermal insulation
7.5.4. QA for interconnections

08 Insertion magnets

Editorial linkman : Lebrun P. Ostojic R.
Responsible Siegel N.

8.01 Overview

8.02 Dispersion suppressors

a. MB in the dispersion suppressors
b. Dispersion suppressor quadrupoles in the experimental, dump and RF insertions insertions
c. Dispersion suppressor quadrupoles in the cleaning insertions IR3/7
d. Cold testing and performance of the magnets

8.03 Matching sections

a. Superconducting matching quadrupoles
   i. Standard stand-alone cryo-magnets (magnet and cold mass design, cryostat design, interfaces, performance)
   ii. Special stand-alone cryo-magnets
      a. Q6 in the injection and extraction areas
      b. Q4-D2 cryo-magnet string
      c. Q7 cryo-magnet at end-of-arc
b. Resistive matching quadrupoles in IR3 and IR7

8.04 Separation dipoles

a. Superconducting separation dipoles in the experimental and RF insertions: design and performance
b. Resistive separation dipoles in the cleaning insertions

8.05 Low-beta triplets

a. Low-beta quadrupoles: design and performance
b. Cryostat design and interconnects
c. Electrical feedboxes DFBX

8.06 Orbit and multipole correctors in the Insertions

8.07 Compensator dipoles in ALICE and LHCb experiments
8.08 Specific installation requirements
   a. Interface of low-beta triplets with experiments
   b. Alignment of low-beta triplets (alignment galleries, specific equipment, performance)
   c. Radiation protection of the insertion magnets (TAS, TAN)

09 Powering and protection

9.01 Overview

9.02 Powering circuits

9.03 Powering equipment
   a. Current leads
   b. Electrical feedboxes
   c. Busbar systems
   d. SC links

9.04 Protection equipment
   a. Quench detectors
   b. Quench heater power supplies
   c. Energy extraction systems
   d. Controllers, supervision

9.05 Operational aspects and reliability

10 Power Converter System

10.01 Introduction and design constraints
    Environmental considerations, space restrictions, underground, sectorisation
    Performance requirements plus parameter table per circuit type
## Overview of system
Design considerations
Overall system description
Table of power converter types with characteristics

### Equipment subsystems
Brief description of each type of voltage source
DCCTs
ADCs
PC Control system

### Specific requirements placed on other systems and interfaces to them
AC power requirements
Cooling requirements
Controls, Postmortem and logging
Interlocks and quench protection
EMC

### Operational aspects
System reliability
Expected fault frequencies
Radiation tolerance
Maintenance issues

### Scheduling, installation and commissioning
Subsystem construction, integration ..
Installation
Hardware commissioning without beam

### References

### NB:
Assumes sectorisation and basic powering configuration is dealt with in chapter 9, "powering and protection,………").
Deals with all Power Converters of the Machine, including Experiments, Klystron, undulators, but excludes Power Converters for QPS, which are dealt with in chapter 9.
Does not cover the beam transfer lines.
11 Cryogenics

11.01 Overview

11.02 Functions, constraints, architecture

11.03 Heat loads and temperature levels
Static & dynamic heat loads, dependence on beam parameters, basic thermal design features of cryostat/cryoline.

11.04 Operating modes
From the point of view of cryogenics, including transient modes such as cooldown, warmup, quench recovery.

11.05 Arc magnet cooling scheme
From principles to standard cell flow-scheme, cryogenic sectorization

11.06 Cryogenic distribution
QRL, QUI, local lines

11.07 Cryogenic plants
11.7.1. 4.5 K refrigerators
Cycle, compressor station, cold box, purifiers, LN2 subcoolers

11.7.2. 1.8 K refrigeration units
Cycle, warm compressor station, cold compressors, cold box.

11.08 Instrumentation

11.09 Process control

11.10 Cryogen storage and management
11.10.1. Helium
Management, gas storage, gas ring line, "virtual” or liquid storage

11.10.2. Liquid nitrogen
Usage for cooldown, purification
Supply logistics, buffer storage, transfer
12 Vacuum system

12.01 Overview

12.02 Beam vacuum system in the arcs
   a. Beam screen: design and performance
   b. Interconnection elements

12.03 Beam vacuum system in the insertions
   a. Beam screens (1.9 K magnets, 4.5K magnets)
   b. Cold-warm transitions
   c. Interconnection elements
   d. Warm chambers (magnets, field-free regions)
   e. Sectorization

12.04 Beam vacuum system in the experiments

12.05 Insulation vacuum systems
   a. Cryo-magnets in the arc and insertions
   b. Cryogenic distribution line

12.06 Vacuum controls

12.07 Operational aspects

13 Beam Diagnostics and Instrumentation

[For each instrument/monitor discuss the:
   a) beam requirements,
   b) the hardware implementation,
   c) the anticipated performance, calibration issues etc.]

13.01 Beam Position Monitors

Arc monitors, straight section monitors, warm monitors, directional couplers, alignment of monitors and calibration
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13.02 Beam Current transformers
Ring systems: DC and bunch-by-bunch monitors
Beam dump extraction channel systems

13.03 Beam loss system
Arc monitors
Critical section monitors (BLMS) - installed close to aperture limits, low-beta
Collimator monitors - fast and slow (BLMC)
Optimisation of monitor position for maximum coverage of losses
Calibration and thresholds

13.04 Transverse Profile Measurement
Screens in the ring and in the dump extraction lines
Wire scanners,
Synchrotron light monitors (inc Detector, wiggler magnets, power supplies etc)
Ionization profile monitors,
Conversion to emittance and cross-calibration of emittance measurement devices.

13.05 Longitudinal Profile Measurement
High sensitivity monitor for monitoring the beam dump gap, debunched beam fraction, ghosts and tails.

13.06 Luminosity Monitors
TAN Type

13.07 Tune, Chromaticity and Betatron Coupling
Pickups: High sensitivity, resonant, head-tail
Q-kicker Kickers (magnets, pulse generators & transmission lines)

13.08 Aperture and non-linear measurements
Pickups?
Aperture Kickers (magnets, pulse generators & transmission lines)

13.09 Other Baseline Instruments/Systems
K-modulation system
Dedicated BPM's: Damper, IP timing, radial loop control, dump septum aperture control …
High frequency pickup
Quadrupole pickup (for betatron matching)
Schottky system
Beam synchronous timing
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13.10 Non-Baseline, Staged or Proposed Instruments

AC Dipole.
Long-range beam-beam compensator

13.11 Beam Feedback Systems

Tune, Chromaticity, Orbit, Coupling, Energy

14 Control System

Editorial linkman : Poole J.
Responsible Frammery B.

14.01 Introduction

What the control system is - machine, industrial systems, slow controls …
What the controls Group is responsible for and what is delivered by other Groups
Interfaces to the rest of CERN, the world- hardware and software

14.02 Hardware

General architecture
Details

14.03 Software

Architecture
Functionality
Development process

14.04 Data Management

General principles
Development process

14.05 Security ??

15 Machine Interlock System

Editorial linkman : Collier P.
Responsible Schmidt R.
15.01 Introduction
The need for the machine protection / machine interlock system
The challenge of operation with very high stored beam and magnet energy
Basic philosophy of machine interlock system power abort, beam abort etc.

15.02 Interface with other systems
The glue between the systems for protection is the machine interlock system
- Beam dump system
- Some part of beam instrumentation (beam loss monitors, a small subset of beam position monitors, beam current monitors, abort gap monitors)
- Quench protection system
- To some extent, collimation and cleaning systems
- Protection devices in other systems (for example, in the RF, in the vacuum, …)
For other systems the required protection in case of failure had also an important impact on the system design (for example for the power converters)

15.03 System Reaction Times vs. fault Scenarios
Possible fault scenarios and system reaction times …
Counter measures … such as D1 problem

15.04 Powering Interlocks
The power abort philosophy
System layout
Powering sectors & sub-sectors
Power interlock controller system
Interfaces to other systems

15.05 Beam Interlocks
The beam abort philosophy
System layout (includes beam permit loops)
The beam interlock controller
Interfaces to other systems

15.06 Other Protection Devices
Anything not included in the above and not adequately treated in other chapters (from a machine protection point of view). This should include energy tracking, transfer line collimators and other additional elements.
16 Injection System

16.01 System and parameters
- Beam characteristics (pilot and nominal). *Briefly or not at all since covered in general parameters*
- Operational assumptions (injection schemes, intensities)
- System overview and design considerations
- Overall system parameters

16.02 Reliability and fault cases
- Acceptable (design) fault cases and associated parameters
- Expected fault frequencies

16.03 Equipment subsystems
- TCDI collimators
- MSI septa (magnets, powering, controls, surveillance, special vacuum chambers)
- MKI kickers (magnets, generators, transmission lines, controls)
- TDI diluter
- TCDD shielding
- TCL collimators
- Vacuum (subsystems, sectorisation, bakeout, beamlines)
- Beam Instrumentation (BPMs, BLMs, BTVs)
- Electronics and controls (accessibility, interventions)
- Alignment issues

16.04 Interfaces to other systems
- SPS machine and Transfer Lines (fill sequencing, injection and extraction inhibits)
- PO (MSI powering)
- RF (injection synchronisation)
- Controls system (settings, alarms, timing, postmortem and logging)
- Integration (physical layout and installation sequencing)
- Collimators (interdependence of settings with LHC collimation system)
- Machine protection (beam permit)

16.05 Radiation protection
- Activation and dose levels
- Monitoring
- Test conditions (special precautions, sectorisation)
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16.06  Performance and operational aspects
Trajectories
Apertures (circulating and injected beams)
Interlocks
Postmortem and logging (internal, external)
Spare
Procedures for component replacements (kickers, septa, protection devices)
Modes of operation for TDI (limits, assumptions)

16.07  Specific requirements placed on other machine systems
Collimators (loading for MKI fault case)
Beam dumping system (direct link to avoid 'deadlock' case)

16.08  Scheduling, installation and commissioning
Subsystem construction
Installation
Hardware commissioning without beam
Reliability tests without beam

16.09  References

17  Beam Dumping System

Editorial linkman : Proudlock P.
Responsible  Goddard B.

17.01  System and parameters
Beam characteristics (nominal and worst-case). Briefly or not at all since covered in general parameters.
Operational assumptions (dump trigger frequency, intensities)
System overview and design considerations
Overall system parameters

17.02  Reliability and fault cases
System reliability
Availability considerations
Acceptable (design) fault cases and associated parameters
Unacceptable (beyond design) fault cases
Expected fault frequencies
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17.03 Equipment subsystems

MKD kickers (magnets, generators, controls)
MKB kickers (magnets, generators, controls)
MSD septa (magnets, powering, controls, surveillance)
TCDS diluter
TCDQ diluter
TDE dump (core, shielding)
Vacuum (subsystems, TD beamlines, exit window)
Beam Instrumentation (BPMs, BLMs, BTVs)
Electronics and controls
Alignment issues

17.04 Interfaces to other systems

Machine Protection (BIC)
PO (MSD powering, Beam Energy meter)
RF (Revolution frequency and abort gap synchronisation)
Controls system (settings, alarms, timing, postmortem and logging)
Safety (fire detection, access)
Integration (physical layout and installation sequencing)
Collimators (interdependence of settings with TCDQ)

17.05 Radiation protection

Activation and dose levels
Containment issues (ventilation, N2 flushing, environmental impact)
Monitoring

17.06 Performance and operational aspects

Trajectories
Apertures (circulating and extracted beams)
Interlocks
Postmortem and logging (internal, external)
Limitations on LHC operation (staged MKB installation and TDE cooling)
Spare
Procedures for component replacements (kickers, septa, TDE core)

17.07 Specific requirements placed on other machine systems

RF (abort gap cleaning)
BDI (beam position interlock, abort gap density monitor)
Collimators (impact following asynchronous dump)
LHC magnets (Q4 current tolerance, D1 trips, MSD short circuit surveillance)
Localised orbit feedback
17.08 Scheduling, installation and commissioning

Subsystem construction
Installation
System tests
Reliability tests without beam

17.09 References

18 Beam Cleaning and Collimation System

Editorial linkman: Myers S.
Responsible: Assmann R.

18.01 Summary of functions

i) Cleaning of beam halo to avoid quenches
ii) Tuning of experimental backgrounds due to beam halo
iii) Passive protection
iv) Scraping and special studies

18.02 Basic definitions and notation

i) Cleaning efficiency
ii) Notation in normalized phase space

18.03 Design constraints

i) Proton/ion intensity and allowable loss rate in operation (lifetime)
ii) Cleaning efficiency from quench thresholds
iii) Acceptable extension of halo (aperture, beta*, ...)
iv) Maximum impedance from collimators
v) Proton shock impact from irregular dumps
vi) Vacuum constraints (bake-out, local e-cloud, ...)
vii) Available space in cleaning insertions
viii) Handling and maintenance (radioactivity, limits on personnel exposure, ...)
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18.04 The overall LHC collimation system
i) Separate betatron and momentum cleaning
ii) Two-stage cleaning system with additional absorbers
iii) Number of devices and phase advance rules
iv) Beta functions in the cleaning insertions (required gaps)
v) Minimal allowable settings for other absorbers
vi) Extension to a three-stage system for 7 TeV
vii) Predicted cleaning efficiency
viii) Basic operational tolerances
ix) Mechanical tolerances for collimator jaws
x) Required DOF’s in collimator movement
xi) Constraints on operational freedom (allowable perturbations, ...)
xi) Abort gap cleaning

18.05 Collimator materials
i) Overview on possible materials - Advantages and disadvantages
ii) Energy deposition in materials
iii) Damage and fatigue analysis for proton/ion shock impact
iv) Vacuum considerations (out-gassing, dust, ...)
v) Radiation impact analysis
vi) Choice of best material (robustness, impedance, vacuum, ...)

18.06 Mechanical layout
i) Basic scheme for the LHC collimator
ii) Heat maps in the collimator
iii) Estimates of deformations during normal operation
iv) Moving mechanism (reliable and accurate motors, ...)
v) Vacuum pumping, clearing electrodes, solenoids, ...
vi) Reliability and maintenance (activation, required cooling period before access, estimated frequency of access, easy or remote handling, detection and localization of errors, number of spares, ...)

18.07 Required instrumentation for collimation set-up and tuning
i) Beam loss monitoring for beam-based optimization of settings (required dynamical range, sampling, ...)
ii) BPM’s for local orbit stabilization (sampling, required performance, errors due to shower impacts, ...)
iii) Determination of the local beta function
iv) Instrumentation in the collimator tank (temperature sensor, charge measurement, fail-safe determination of collimator gap, halo measurement with crystals, ...)
v) Background signals from the experiments
18.08  Constraints on commissioning and operation of the LHCg

i) Conditions for initial set-up of the collimation system (tuning with "safe" beams, low activation allowing easier access, ...)
ii) Increase of intensity and decrease of collimator gap (cleaning efficiency, background, damage risk, ...)
iii) Strategy for handling collimator impedance through the LHC cycle (collimator gaps, beta squeeze, octupoles, ...)
iv) Required sequence of collimator adjustments in relation to overall LHC cycle (injection, ramp, squeeze, collision)
v) Daily fine tuning of efficiency and background conditions
vi) Possible operational impact due to collimator maintenance

19  Interface with and Requirements from the Experiments

19.01  Introduction
what experiments are where

19.02  Requirements

Highest possible time integrated Luminosity for ATLAS & CMS
Early commissioning preferences such as smallest possible number of interactions per bunch crossing
Heavy Ion (Pb)operation for ALICE, ATLAS & CMS
Medium Luminosity (2 x 10**32 cm-2.s-1) for LHCb with very clean conditions
Low Luminosity proton running for ALICE. (4 sigma separated beams)
Special High beta* runs for TOTEM (36 half intensity, small emittance bunches)
Background conditions

19.03  Interface

Data exchange (Timing signals, Luminosity, bunch currents & background, logging of machine conditions - vacuum etc.) - giving information concerning both directions (to and from the machine)
Beampipes for experiments (40m of beampipe between low-beta quadrupoles), design, interface

20  Parameters, commissioning and operation

20
Heavy ion (Pb-Pb) collisions were included in the LHC conceptual design study right from the beginning and are scheduled for one year after the start-up with protons. While the major hardware systems appear compatible with ion operation, a closer look reveals several phenomena specific for heavy ions with potentially serious consequences on some systems.

The most important ones are:
(i) Pb ion losses generated by electro-magnetic interactions during collisions, which in turn may lead to magnet quenching;
(ii) Pb losses, IBS, etc and their impact on the luminosity lifetime;
(iii) desorption of gas molecules by lost Pb ions impinging on the beam screen and potential impact on LHC vacuum conditions;
(iv) collimation of Pb ions - are ions behaving the same way as protons?
(v) limitations due to the performance of beam instrumentation and feedback loops;
(vi) minimization of the ion crossing angle in ALICE. A diagram showing the small working area determined by various limitations reveals the small margin to commission the nominal Pb beam; an "early" scheme, albeit yielding lower luminosity, is proposed which enables running-in and early physics with relaxed parameters and more margin. A comprehensive parameter list of Pb ions in the LHC for both schemes, including Pb beam characteristics required from the injectors, is presented.