LHC INJECTOR UPGRADES: BEAM TRANSFER ASPECTS

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INTRODUCTION

The various mooted upgrades of the CERN accelerator complex up to and including the LHC will necessitate substantial modifications to the Beam Transfer systems, comprising extraction elements, transfer lines, injection elements and beam dumps. A general overview of the present performance reach, technological challenges and areas for study of the Beam Transfer systems is given, focussing mainly on the kicker systems and highlighting areas which are expected to be most relevant to the different CERN upgrade proposals.

IMPLICATIONS OF THE INJECTION UPGRADES FOR BEAM TRANSFER

An upgrade of the LHC and its injector chain [1] will imply major changes to the CERN complex, Fig. 1. Such an upgrade programme will also have a major impact on the beam transfer systems currently in place, and will require a significant programme of design, prototyping and construction of new beam transfer systems.

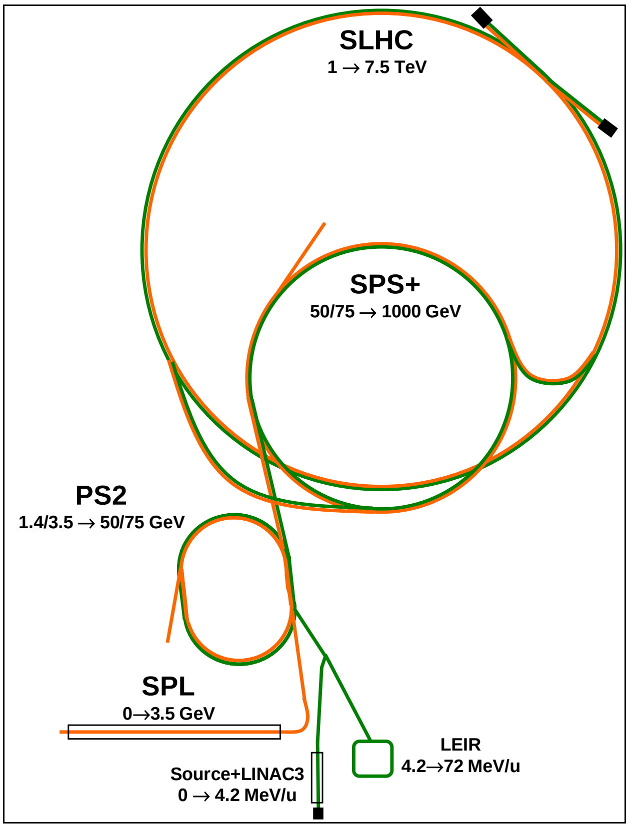

Figure 1. Schematic of future upgraded configuration of the main elements of the CERN complex [1] assumed for this paper.

The present discussion focuses on some of the requirements at the higher energies, from PS2 to SLHC, for which Table 1 lists some of the major areas in which upgrades or new systems will be required.

Table 1: Margin Specifications

	PS2	**SPS+**	**SLHC**
Injection	1.4 GeV: fast (ions) 3.5 GeV: fast (if RCS) *or* 3.5 GeV: H^- (if SPL)	50-75 GeV: fast	1 TeV: fast
Extraction	50-75 GeV: fast, slow (3rd integer), CT (MTE)	1 TeV: fast, slow?	7.5 TeV: fast
Transfer	1.4 - 3.5 GeV (from PS/RCS/SPL) 50 – 75 GeV to EA?	50-75 GeV (from PS2) 1 TeV TT20/TT41?	1 TeV TI 2/8
Beam dump	1.4 - 75 GeV: ~1.5 MJ	0.05 - 1 TeV: ~14 MJ	1 - 7.5 TeV: ~1100 MJ

EQUIPMENT SYSTEMS AND TECHNOLOGICAL LIMITATIONS

The specialised technical systems for beam transfer include:

- Kicker magnets
- Septum magnets
- Active beam dilution systems
- Passive protection (absorber) elements
- Beam dump blocks
- Beam transfer lines

There are a number of areas in which technological concerns or limitations are expected to present serious challenges, which are described in varying degrees of detail in the following sections.

Injection systems

Concerning the various injection systems the high energy (3.5 GeV) H^- injection system in PS2 will present particular challenges, in particular in the control of the beam losses and the design of a stripping system at such high energies. More details are given in the subsequent section on the PS2.

The upgrade of the SPS injection system to 50 GeV will require an increase in the rise time of the injection kickers and the construction of new magnets – and finally the upgrade of the SLHC injection system to 1 TeV will also require major changes to the installed hardware, again with a probable increase in the rise time from the present value of 1 µs.

Extraction

Many new or upgraded extraction systems are needed, in addition to those dedicated to beam dumping, see below. For the PS2, multiple systems are required, in as compact a configuration as possible, and subject to the limitations imposed by the extraction element technology. More details are given in the subsequent section on the PS2.

For the SPS+, the energy for the fast extraction for transfer to the LHC will increase to 1 TeV, which poses problems to achieve the required ∫B.dl. The existing type of kicker magnet systems can operate in short-circuit mode to give twice the kick (at twice the rise time). However the extraction septa concepts will require major modifications to enable the beams to be extracted from the SPS, and it is possible that dedicated insertions will be needed in the extraction straights to accommodate the very long (~40 m) sequence of septa which will be needed.

Beam dumping

The LHC beam dumping system [2] will require a factor of about 2 increase in the dilution for the SLHC beam. This dilution factor can be attained by doubling the frequency of the MKB dilution kicker systems and increasing the damping, which will produce a spiral sweep with an acceptable maximum temperature rise in the beam dump block, Fig. 2; this will reduce the system strength and so the number of installed kickers will need to be increased. To avoid local temperature peaks in the resulting sweep requires an increase in the reaction time of about a quarter of an LHC turn, to allow the kicker fields to reach the required value before the beam sweep starts.

Another area which will require development is machine protection for beam in the extraction gap in the SPS+ and SLHC; at the present intensities and energies the technological limitations impose the use of long, low density absorbers, and these are presently at the edge of the performance reach [3].

The high beam power for PS2 and SPS+ also has an impact on the choice of beam dump design, with a balance between the radiation and “co-habitation” issues for internal dumps and the issues associated with aperture and extraction system design for external dumps.

Transfer lines

For the 1 TeV transfer from SPS+ to LHC, the existing TI 2 and TI 8 lines [4] will need to be upgraded with superconducting magnets. The new lines will need SC dipoles of about 4.0 T, with beam apertures of ~50 x 20 mm (H x V). The tunnels have a slope of up to 3.8 % and kinks, Fig. 3, which may be an issue for the cryogenics of the magnets – in addition the tunnels are small (3.0 m) diameter which may pose difficulties for integration of cryostats, feed boxes and cryogenic feed lines.

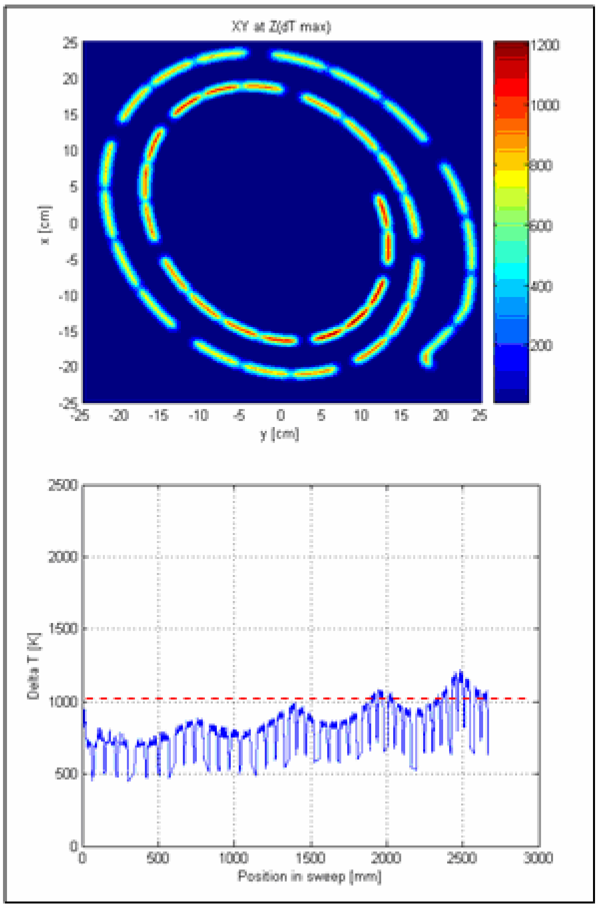

Figure 2. Possible sweep (top) and energy deposition profiles for SLHC beam, with factor 2 increase in sweep speed and hence dilution.

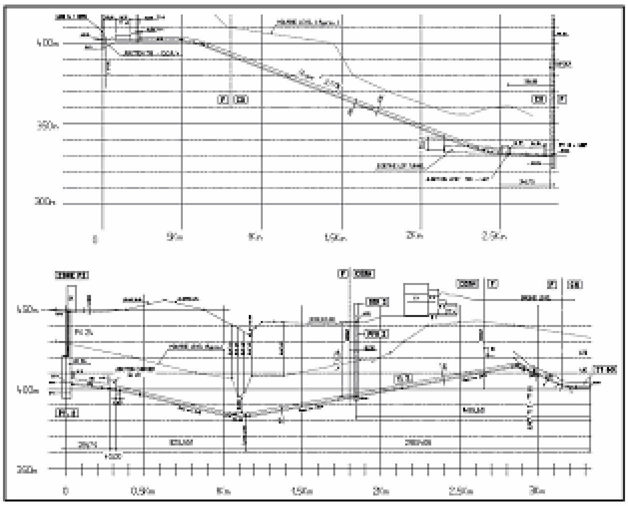

Figure 3. Profiles of the existing SPS to LHC transfer lines TI 2 (top) and TI 8.

Another area of concern for these transfer lines will be the machine protection systems [5] (including the LHC injection), since the passive protection systems will need to be significantly upgraded to withstand the 14 MJ beam energy.

Kicker impedance and parameters

The impedance of kicker magnets is already a significant contribution to the SPS machine impedance, and the longitudinal impedance leads to beam induced heating of the kicker ferrites [6]. Above 125 ºC the magnets looses kick strength as the ferrite passes the Curie temperature.

Issues actively being addressed include cooling of kicker ferrites (applied to installed extraction kicker magnets), impedance reduction, Fig. 4, (stripes, coated ceramic chambers, inserts) and configuring the system with fewer installed kickers (by operating in short-circuit which leads to larger kick for a given voltage, at the cost of a proportionately larger rise time).

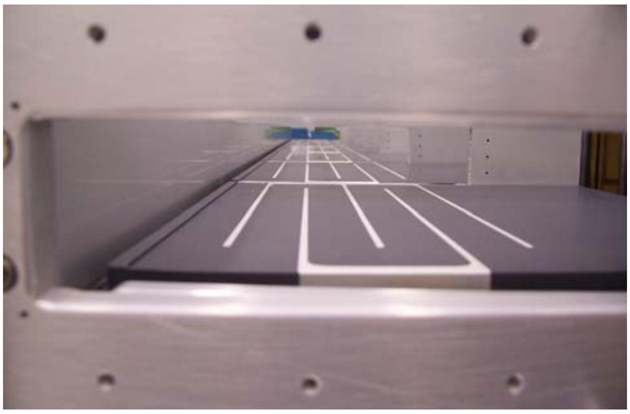

Figure 4. Metallic stripes applied to SPS extraction kicker ferrites, for impedance reduction purposes.

DETAILS OF PS2 STUDIES

The replacement of the existing PS with a modern, reliable, flexible and robust synchrotron has been identified as an important part of the future upgrade programme of the CERN accelerator complex, both to allow efficient and reliable exploitation of the SPS and LHC machines, and to provide extra potential for LHC performance upgrades [7]. Main design goals include low radiological impact, significantly improved performance for LHC and SPS FT beams, flexibility for possible future applications and upgrades, very high reliability and availability and compatibility with staged upgrade programme and with the ongoing LHC exploitation. More details of these issues can be found in [8].

The 'basic' parameters of the machine are the circumference, the injection and extraction energies, the dipole field, the aperture, the transition energy and the lattice type. A separated function machine is assumed, with a circumference of 1160 m (twice that of the existing PS) and an initial parameter set for the preliminary conceptual studies as given in Table 2. It is to be noted that the injection energy is assumed to be 3.5 GeV, but that 1.4 to 5 GeV may be required to be able to accept heavy ions from the LEIR machine, which has a 1.4 GeV proton equivalent extraction energy, and eventually for the high brightness LHC beam at 5 GeV. The extraction energy range is assumed to be 50 GeV: depending on the eventual choice of normal or superconducting magnet technology, which could affect the energy reach, this could increase to around 75 GeV.

Table 2. Basic PS2 design parameters

Injection energy	GeV	3.5
Extraction energy	GeV	50
Circumference	m	1256.6
Injection B.ρ.	T.m.	14.5
Extraction B.ρ.	T.m.	169.9
Maximum beta function	m	35
Revolution period at injection	μs	4.289
Revolution period at extraction	μs	4.192
Beam intensity	p+	1.4×10^{14}
Cycle period	s	2.4

Beam Transfer Requirements

In order to meet the beam transport requirements for the different beams and clients, and also to ensure that the limitations on beam losses and activation are respected, it is assumed that the following systems are required:

Injection

- Fast single-turn injection of ions at 1.4 GeV, for LHC beams, and of protons at 3.5 GeV, for LHC beams, PS2 FT beams and SPS FT beams;
- Multi-turn H^- injection of protons at 3.5 GeV, for PS2 FT beams and SPS FT beams.

Extraction

- Fast single-turn extraction of protons and ions at 50 GeV, for LHC beams;
- Slow 3rd integer resonant extraction of protons at 50 GeV, for PS2 FT beams;
- Low-loss 5-turn continuous transfer of protons and ions at 50 GeV.

Beam dumps

- A fast single-turn 'emergency' beam dump;
- Beam dump blocks in transfer lines, for setting-up.

Beam transfer lines

- The injection line able to accept 1.4 GeV ion beams and 3.5 GeV proton beams;
- A line to the SPS, for 50 GeV protons and ions;
- Extraction lines to experimental areas, for 50 GeV protons.

Basic Assumptions

Layout and lattice

In addition to the basic PS2 design parameters listed above a number of assumptions have been made, in order to allow a first conceptual definition of the various beam transfer systems and quantitative estimates to be made concerning deflection angles, apertures, numbers of extraction elements and installed lengths. The main assumption concerns the lattice, and in particular the long straight sections available for injection and extraction. For simplicity and ease of generating a simple test lattice, the conceptual systems presented here have been evaluated on the basis of the following assumptions:

- regular FODO cell structure in the injection and extraction regions;
- phase advance of ≈90° per cell;
- β-functions in the range 6-33 m;
- 21 m cell length;
- 7 m 'free' drift per half-cell available to accommodate beam transfer elements (which could be increased to about 8.5 m if absolutely required);
- local dispersion function matched in these regions to $|D_x| < 0.5$ m.

Acceptance and aperture requirements

The kicker and septum apertures/elements are kept outside a canonical half-aperture of 50 mm at a beta of 33 m, which corresponds to about 300 π.mm.mrad geometric acceptance in the horizontal plane. In the vertical plane the acceptance is assumed to be defined by the main dipole full aperture of 80 mm at a β of 33 m, which gives a geometrical acceptance of about 200 π.mm.mrad.

Lattice quadrupoles

To provide enough aperture in the injection and extraction regions, it is assumed that the design will use enlarged quadrupoles where needed (denoted QFE and QDE). These are assumed to have 85 mm good field regions, compared to 50 mm for the regular quadrupoles. In addition, it is proposed that the extraction trajectories can be via openings in these quadrupole coils as is the case for the SPS, with the beam experiencing only linear fields in this case [9].

To estimate the injection and extraction angles required, the lattice quadrupole yokes are assumed to be 700×700 mm for standard types, and 900×900 mm for enlarged types. The enlarged types are assumed to be 20 % longer that the regular types.

Beam characteristics

The H/V circulating beam emittances are assumed to be 15 and 8 π.mm.mrad, respectively. From the SPL, the H^- beam emittance is assumed to be 1 π.mm.mrad. With a beam intensity of 10^{14} p+, the stored beam energy is of the order of 1.2 MJ.

Injection systems

Fast single-turn p+/ion injection

A classical single-turn type injection system (orbit bump, septum, fast kicker) with variable kick length is needed from the very beginning, when PS2 will operate with the present injectors, and will in any case always be needed for ion operation. The lattice requirements are for 2 half-cells, with one QDE in the centre.

Multi-turn H^- injection

An H^- charge exchange injection system will be needed if the PSB is replaced with ~3.5 GeV Superconducting LINAC. The injection system will consist of a septum, similar or identical to that described above, short special dipoles, the stripping foil, and a system of fast orbit bumpers in the PS2 machine for phase-space painting during the injection process (≤100 turns i.e. ≤500 μs). For the initial PS2 parameters this gives about 5 kW of unstripped H^0/H^- to be dumped. For beam loss management reasons, it is assumed that this will need an external dump, which imposes the use of secondary stripping foils, an extraction septum and a short transport line. The design of this system is expected to be difficult: in the SNS, the H^- injection system at 1.3 GeV takes up one of the four long straights, a total of 32 m in the lattice [10]. The issues here for the layout are the maximum dipole field the H^- beam can traverse, to avoid magnetic stripping (SNS: <0.3 T for 1 GeV), together with the maximum allowed beam loss rate.

The lattice requirements are assumed to be 3 half-cells, with one QFE and one QDE in the centre.

Extraction systems

Fast single turn extraction

A classical fast extraction system (orbit bump, septum, fast kicker) with variable kick length is needed as principal extraction system. The system has to be designed for variable extraction energies up to 50 GeV, i.e. a maximum magnetic rigidity of $B\rho = 170$ Tm. The fast extraction uses a closed orbit bump to move close to the septum, then one a fast kicker system to extract the beam.

3rd integer resonant (slow) extraction

A slow extraction system for physics from the PS2 is also needed. This system will require multipole magnets an orbit bump, electrostatic and magnetic septa. The system should allow for extraction spills of around one second. The system has to be designed for variable extraction energies up to 50 GeV, i.e. a maximum magnetic rigidity of $B\rho = 170$ Tm. The extraction is assumed to be based on a classical 1/3 integer scheme [9], using an electrostatic and several DC magnetic septa.

Low-loss 5 turn continuous transfer (MTE)

A continuous transfer extraction is considered, based on non-linear fields to allow beam to be captured in stable islands to produce a physical separation at the entrance of the extraction septum [11]. Extraction then takes place over 5 turns at a quarter-integer tune. In addition to the extraction septa, two sets of kicker magnets are required, the first to produce a closed bump for five turns, and the second the extract the central island on the 5th turn.

Overall lattice implications

In the preliminary version studied with all extraction systems in one straight, a total of 9 half-cells are required, in addition to some short bumper magnets slightly further out in the lattice. If the slow extraction is made in a separate system in another straight, the total space is still 9 half-cells, with 6 needed for the joint fast/CT extractions and 3 for the slow.

Beam dump systems

Emergency dump

A beam dump system will be required to safely dispose of the 1.5 MJ of beam energy. Either an internal dump or an external dump could be envisaged. An external dump resembles the fast extraction channel described above, with the difference that the aperture must be large enough to accept the beam at injection energy. This imposes difficult constraints for the extraction septa, including much larger gaps and energy tracking of the beam. An internal dump is easier and more compact.

Transfer line dumps

A series of dumps will be required for the transfer lines, to enable setting up of the injection and extraction systems and of the lines themselves, and for personnel protection reasons when accessing downstream accelerator zones.

Summary of equipment requirements and parameters

The exercise has allowed tentative estimates to be made of the equipment parameters, in order to provide some basis for an evaluation of feasibility and to indicate areas in which optimisation is required.

Injection kicker

- Request about 100 ns rise/fall time;
- Need about 7 mrad deflection (120 mm offset with average beta of 25 m and sinΦ of 0.7), determined by the QDE good field region, the beam size and the septum width;
- 16.6 Ω system operating at maximum of 65 kV to give ~100 ns rise time and 0.101 Tm, in 4.5 m installed length.

Injection septum

- Need about 200 mrad (2 m lever arm, 400 mm deflection to miss adjacent quad);
- Septum width about 22 mm;
- With the aperture available this can be a 3 m long out-of-vacuum magnet, with 16 turn coil and slowly pulsed.

Thick magnetic septum (extraction magnet)

- Need about 25 mrad (5 m lever arm, 125 mm additional deflection needed to extract the beam out through a suitable quadrupole coil window);
- Septum width about 30 mm;
- Can probably make this outside vacuum with several turns (assumed 12);
- Limit is 1.5 T in gap (saturation).

Intermediate magnetic septum

- Need about 13 mrad (2 m lever arm, 25 mm additional opening at MS3);
- Septum width about 15 mm;
- Technological limit is ~40 A/mm^2 current density in septum coil (0.9 T).

Thin magnetic septum

- Need about 2.5 mrad (4 m lever arm, 10 mm additional opening at MS2);
- Septum width about 5 mm;
- Limit is ~40 A/mm^2 current density in septum coil (0.18 T).

Electrostatic septum

- Need about 1.2 mrad to give 12 mm opening at MS1 (assuming 15 m average beta and sinΦ ~0.7);
- Septum width assumed to be 0.1 mm;
- Technological limit is field in gap (maximum of about 10 MV/m).

Extraction and bump kickers

- Need about 1.6 mrad to give 16 mm opening at MS1 (assuming 15 m average beta and sinΦ ~0.7);
- Rise time assumed to be 150 ns – determined basically by inductance of the magnet $L = \mu_o$ w.l/h;
- Characteristic system impedance assumed to be 10 Ω.
- Technological limit is 65 kV switch voltage.

Slow extraction bumper magnets

- Need about 1.6 mrad to give 25 mm bump at ES/MS1 (assuming 15 m average beta and sinΦ ~0.7);
- Classical many-turn short dipoles – assume 0.3 m magnetic length;
- Some enlarged H^- aperture versions will be needed;
- Technological limit is 1.5 T field in gap (saturation).

Transfer line systems

The detailed requirements of the transfer lines will clearly depend on the choice of experimental area, orientation and injection/extraction types. Assuming that part of the existing TT2/TT10 line could be used to transfer for 3.5 (1.3) GeV beams into PS2, one issue is the acceptance of this line, designed for higher energy. Another important question which affects the positioning of the PS2 machine is the length of 50 GeV transfer line needed for matching into the SPS – the PS2 optics with beta-functions of about 35 m needs matching into the SPS with beta-functions of about 110 m – in addition it is probable that this line will accommodate a final stripping foil for converting the partially stripped Pb ions to Pb^{82+}. In this case a low-beta insertion will be needed to minimise transverse emittance blow-up.

Overall space and layout implications

The total space required in the lattice for the beam transfer systems depends on the injection and extraction energy of the machine, the number of injection and extraction lines plus the layout with regard to beamline orientation. The basic requirements detailed above amount to about 14 half-cells – however, this number can change depending on which systems are combined where, since in general the septa and kicker are advantageously located near QF elements. In the preliminary version studied a total of 13 half-cells are required for the two injection systems and the extraction system without slow extraction, with several unused half-cells scattered through the straight. Overall, it seems a reasonable assumption that about 14-18 half-cells will be needed, of the order of 150 - 200 m of straight section.

Discussion of scaling from 50 to 75 GeV

Extraction and bump kickers

The space required at 75 GeV increases to about 9.5 m (from 7.0 m). This could be a problem with the initial parameters, as the length required for the kicker module will not fit in a single half-cell – this system is already close to the limit for the 50 GeV version. Here the requirements on the very fast rise time (150 ns) mean that the system has to have a very low inductance and therefore a relatively high characteristic impendence ($Z \propto \sqrt{L}$). This reduces the strength of the magnet for a given applied voltage. Improvements could be obtained by:

- Reducing the characteristic impedance to 8.3 or 7.1 Ω would mean 7.2 m magnetic or 5.4 m magnetic length (but rise time would increase at least 200 ns);
- Reducing vertical AND horizontal gap to maintain the inductance and hence the rise time for a given current, while increasing the field. Just reducing the vertical gap does not work, as this increases the magnet inductance & hence rise time;
- Reducing the required subsystem deflection by extracting first across an ES during the CT extraction and using both the bump and extraction kicker systems for the fast extraction.

Magnetic extraction septa

- Thick extraction magnet version: space required at 75 GeV goes to about 4.7 m (from 3.5 m);
- Intermediate version: space required at 75 GeV goes to about 4.2 m (from 3.5m);
- Thin version: space required at 75 GeV goes to about 4.2 m (from 3.5 m).

Electrostatic septum

- Space required at 75 GeV goes to about 9.5 m (from 7.0 m at 50 GeV). This is above the limit for one half-cell, and could pose a problem as it will not be possible to distribute this element in two half-cells.

Slow extraction bumper magnets

- Space required at 75 GeV stays at about 0.4 m.

CONCLUSION AND FUTURE WORK

A first study has been made of some aspects of the beam transfer issues associated with a possible upgrade of the CERN injection complex, in particular for the PS2 accelerator. This has given some idea of the implications of the chosen parameters for the equipment, and of the possible problems and limitations which may be encountered. Particularly challenging aspects for PS2 appear to be the H^- injection at 3.5 or even 5 GeV, the very fast rise times requested for the fast/CT extraction kickers, especially if a 75 GeV extraction energy is required, and the length of electrostatic septum needed for the slow extraction, again if 75 GeV extracted is needed.

There are several possible directions of R&D which could help overcome some of the limitations identified above. A detailed breakdown of the possibilities and the potential gains is beyond the scope of this note; a preliminary list of topics and sub-topics is given below.

- Impedance and shielding;
  - Ceramic chamber coatings, surface treatments, geometries, effect on rise times;
  - Ferrite surface treatments, stripes;
- Switch technology: fast solid state high current thyristor devices;
- High Voltage technology: flashover under vacuum (magnets, connectors, ceramic chambers);
- Magnetic materials;
  - High saturation ferrites;
  - High Currie-temperature vacuum-compatible ferrites;
  - Ultra-thin laminations, tape-wound cores;
- Coil technology: in-vacuum insulation;
- “New” beam transfer concepts: C-type extraction kickers;
- Beam intercepting protection devices;
  - Materials and geometries for increased robustness;
  - Consumable/single-use devices.

The potential solutions sometimes involve contradictory requirements, which furthermore have to take into account various design considerations such as bakeout, vacuum quality, etc. These complications and inter-dependencies mean that that the research and development efforts should be made in parallel and in a coordinated way, and towards well-defined goals.

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