Injector Upgrade – Discussion and Synthesis

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Abstract

We summarize the discussion on merits and drawbacks of various options for the injector upgrade, brought up at the second-to-last day of the LUMI06 workshop, notably the comparison of a normal-conducting and super-conducting PS successor (PS2 and PS2+), items related to the SPS, and aspects of space-charge compensation.

1 INTRODUCTION

The discussion focused on the PS upgrade and here successively addressed the following points:

- construction cost,
- exploitation cost,
- potential for SPS,
- potential for a super-conducting SPS upgrade,
- potential for ions,
- potential for neutrino physics,
- operation risk,
- operation flexibility,
- transfer lines,
- SPS injection system,
- the possible motivation for higher extraction energy, and
- the choice between normal-conducting and super-conducting magnets.

We also address SPS items and space-charge compensation using an electron lens.

2 CONSTRUCTION AND EXPLOITATION COST

P. Spiller explained that the GSI FAIR project chose a superferric ring for SIS100 in view of vacuum requirements (advantage of a cold beam pipe), higher field, less weight & mass, smaller operational cost, and rather low ac losses. P. Lebrun pointed out that one should look at the full system, including protection elements. T. Taylor highlighted that the power consumption was the decisive argument for the GSI. P. Spiller added that the FAIR beam lines will also be ramped, and use the same type of magnet as the new rings.

W. Scandale and F. Zimmermann commented that the PS upgrade needs to be complemented by other flanking measures, e.g., in the SPS. T. Taylor agreed, stressing that the present PS will likely run for another 10 years and requires consolidation, which is already ongoing, whereas the most stringent intensity bottlenecks are in the SPS. R. Garoby suggested that a better beam from the upgraded PS could help in understanding the limits of the SPS. An accumulator ring in the ISR tunnel was proposed by T. Taylor as a possible alternative. O. Bruning, agreeing that the PS needs a thourough consolidation, e.g., for the CNGS beam, stressed that radiation requirements require a deeper tunnel for the PS2.

E. Shaposhnikova recommended choosing the best injection energy into the SPS. R. Assmann commented that the expected better accelerator lifetime of the upgraded PS2, as compared to that of the present renovated PS, would still need to be demonstrated. R. Garoby replied that the new PS2 will be built for higher energy. The smaller aperture of the new PS2 was identified as a potential problem by R. Assmann. However, Michael Benedikt defended the proposed aperture [1], considering it as sufficient, even if smaller than in the present PS.

P. Spiller and F. Zimmermann discussed whether the new PS2 should have a stronger or weaker focusing than the present PS. P. Spiller then asked for the vacuum requirements in the PS2. W. Scandale replied that the required vacuum pressure lies between 10^{-9} and 10^{-8} mbar, which M. Benedikt considered to be easy to obtain. P. Spiller remarked that a bake-out system may be needed for these pressure levels.

It was commented that the ions will be injected into a PS upgrade at a much lower energy than the proton beams. F. Zimmermann observed that there had been no convincing demonstration for the need of a higher PS extraction energy, except in conjunction with a super-conducting SPS upgrade (SPS+) and a later LHC energy doubler.

G. Arduini suggested performing simulations with larger longitudinal emittance for the SPS. E. Shaposhnikova and R. Garoby responded that the past simulations had been optimized for each energy, and that the longitudinal emittance was defined by the TMCI (transverse mode coupling instability) requirements. F. Zimmermann proposed the addition of clearing electrodes for PS(2) and SPS, in order to suppress the electron-cloud build up.

3 POTENTIAL FOR SPS

G. Arduini commented that the upgraded PS would have a clear potential for the SPS, which needs to be optimized.

W. Scandale emphasized that SPS modifications will be needed in order that the LHC can already profit from the new potential of the upgraded PS.

4 POTENTIAL FOR SPS+

For the SPS+, the PS2(+) is essential, and the superconducting version more effective, as pointed out by W. Scandale. F. Zimmermann remarked that the electron-cloud heat load could be a problem in the SPS+ and PS2(+), as had been hinted at in two presentations [2, 3]. Answering to a question, W. Scandale described the SPS+ energy sweep factor as 10–15, accelerating from 50 GeV to 800 GeV (n.c. version) or from 75 GeV to 1 TeV (s.c. version), so that the LHC injection energy would be approximately doubled. A superferric alternative to the SPS upgrade, based on pipetron magnets in the LHC tunnel, had been discussed at another workshop [4] held shortly before LUMI'06, but it was rejected.

The ultimate aim is injecting into a higher energy LHC. The consequences of this aim for the PS2(+) need to be examined. J.-P. Koutchouk and W. Scandale commented that the PS2+ would keep all options open for the future, whereas with the n.c. PS2 a 3rd injector ring may be needed eventually.

R. Garoby mentioned the question of cost. R. Schmidt asked whether one would really consider a 500 GeV ring in the SPS tunnel, or not rather a VLHC Low Energy Ring in the LHC tunnel. He considered as manageable the coexistence of such rings with the experiments. A bypass around an experiment should not be a showstopper and it would save the money for new SPS-LHC transfer lines.

S. Peggs commented that the injector upgrade must bring more than a factor of 2 improvement to be worth doing. R. Garoby noticed that if we build a new deeper tunnel for the PS2, we might as well double the beam energy. O. Bruning and P. Lebrun assisted him, in saying that a new tunnel is mandatory because of radiation levels and to avoid an extended shutdown. The radiation levels are related to losses occurring in multiturn extraction. Space-charge effects may also make a significant contribution.

A somewhat controversial question was whether one can intercept lost particles locally, or whether they are spread over most of the machine. Also, for beam energies of 14–26 GeV, any large local losses require extensive and dedicated shielding. P. Spiller asked why the losses cannot be controlled. V. Shiltsev responded that this was impossible, based on FNAL experience.

T. Linnecar summarized the conclusions of this discussion as that we cannot make an energy decision now. There are several open issues such as electron cloud. The physics at the LHC will also be decisive. It is interesting to notice that for both PS2 and PS2+ collective effects may determine the optimum energy swing.

5 POTENTIAL FOR IONS

R. Garoby underlined the minimum requirement, which is that ions should have a way through the cascaded machine. E. Shaposhnikova reminded us that the present ion injection in the PS occurs below transition. With PS2 or PS2+ the energy of the extracted ions will be above the SPS transition energy. Swing issues influence the trade off between normal and superconducting magnets.

W. Scandale and P. Lebrun pointed out two major problems of the s.c. approach, i.e., the dynamic range of the s.c. magnets and the lack of manpower. P. Spiller posed a generic question on the beam lifetime, the vacuum gas composition etc. Ions in the PS2 were deemed to be crucial; the ions would preferably be fully stripped. No lifetime issues were observed in the present machines. D. Tommasini commented that the dynamic range is an issue even for n.c. magnets.

A dedicated upgrade for ions is not envisioned for cost reasons, as explained by R. Garoby.

A homework yet to be done is quantifying the performance we may hope to offer with ions in the future. M. Benedikt specified that the n.c. PS2 dipole magnets would have a field of 800 G for ion injection. This, he thinks, is OK and will enable ion operation. Both M. Benedikt and R. Garoby stressed that only the bare minimum will be guaranteed for ions in future PS upgrades.

6 POTENTIAL FOR NEUTRINOS

Beta beams should not be considered here, according W. Scandale. As far as other uses of the PS2 beam are concerned, the LUMI'06 presentation by A. Blondel [5] demonstrated that neutrino physics provides no argument for raising the beam energy. A study of the SPS with new injector reveals that the real limitation is in the SPS.

R. Garoby stated that a high power source in front of the PS is already interesting for neutrinos. He added that there is no direct concern for the old or new PS.

It was perhaps R. Schmidt who mentioned that the PS2 should not forbid the acceleration of radioactive ions. R. Assmann strongly suggested that possible implications for collimation be looked at early on, underlining that the radioactive ions will be rather different from the stable ions of the LHC. P. Spiller commented that it might be better to consider beta beams from the beginning in the design so as to prevent unacceptable uncontrolled distributed ion losses later on. He thought the s.c. option would not be possible if beta beams are not taken into account from the start. J.-P. Kouchouk suggested that the new injectors be designed for maximum flexibility.

7 OPERATION RISK

There was an unanimous consensus that a normal conducting ring is preferred in regard to operation risk.

8 OPERATION FLEXIBILITY

The s.c. ring appears less flexible. One or two weeks would be needed for its cool-down or warm-up. The risk can be reduced by a conservative magnet design. D. Tommasini asked for the frequency of beam losses in the present PS. G. Arduini responded that the beam is lost a few times per day at present, since the PS has no beam dumping system. Frequent changes of the operating cycle could be error prone, in particular for a s.c. machine.

The new ring would follow a construction principle different from the present PS. The performance and flexibility are only a question of layout. The target requirements are still to be defined.

The superferric design entails much less risk than other s.c. magnets, as has been pointed out by D. Tommasini. It was repeated by several participants that a conservative magnet design is crucial for the s.c. magnets. P. Spiller remarked that the high-current 4-T nuclotron cable from Dubna is safer than older cables. It reaches two times the nominal FAIR current. A hollow-type nuclotron cable is used for the cos-theta magnets.

R. Assmann recommended not to be afraid of quenches. R. Garoby viewed the reliability of the PS2 as much more important than that of the LHC; the lower the beam energy the higher a reliability must be achieved. Nevertheless the risk can be minimized. To this end, PS2+ requires an extremely conservative magnet design.

The striking feature was observed that, concerning the penalty of a s.c. ring design with respect to a normal conducting one, CERN reaches the opposite conclusion to the GSI. P. Lebrun suggested that it would be better to use cold vacuum chambers if one wanted to have a cold chamber, and not cold magnets.

D. Tommasini stated that a higher-energy PS2+ could not be superferric. However, in general, if we need a higher beam energy, normal-conducting magnets imply a larger ring, superconducting magnets a smaller one.

J.-P. Koutchouk recommended to produce a quantitative estimate of beam loss based on the SPS experience, the SPS having a beam dump, and then use the SPS loss behavior to draw conclusions for the PS2+ s.c. option. P. Spiller asked why the losses should be distributed all around the machine and not concentrated at the collimators. He emphasized that the magnets should not define the machine acceptance, and that good orbit correction is important. V. Shiltsev reported that distributed losses are the everyday experience at the Tevatron booster, which is a rapid cycling synchrotron operating at 30 Hz. Simulations predict more than 90% collimation efficiency. In reality, 50% of the losses are spread around the ring. Similar observations were made at CERN. Based on this experience, the goal may be to design for optimum efficiency but be prepared for the worst case. W. Scandale concluded that this question is a controversial issue.

It was also noticed that a more compact (s.c.) ring would automatically have less space-charge limitations. In any case, the imortance of space-charge effects will be reduced already by a higher injection momentum of 3.5–4 GeV/c. M. Benedikt commented that substantial longitudinal space is needed for the beam transfer. P. Lebrun added that resources and schedule are an important factor in the decision. For the n.c. option only a paper study is necessary, whereas for the s.c. version real R&D effort is required, which could perhaps be realized in collaboration with GSI.

9 TRANSFER LINES

Transfer lines will connect the PS2 or PS2+ to the injectors and to the SPS. Possibly these transfer lines could be s.c., as they are at FAIR, but there is no strong argument. T. Taylor proposed building the PS2 first, leaving some space in order to later add a s.c. PS2+ in the same tunnel. However, this was not considered by the majority to be a likely or even attractive scenario.

10 SPS INJECTION SYSTEM

More space will be needed for higher-energy injection.

11 SPS ITEMS

E. Shaposhnikova raised the question whether higher injection energy is beneficial or a “show-stopper”. The worrisome predictions, in particular those for the electron cloud by G. Rumolo [2] and M. Furman [3], should be verified.

It appears that in most upgrade paths technological solutions for the electron cloud need to be found. Recently, F. Caspers proposed a new type of quasi-continuous clearing electrode based on a double layer of enamal coating. Protoypes are illustrated in Fig. 1. G. Arduini commented that electrodes did not help in the SPS. The reason should be understood, e.g., have they been too short or too weak? Technological solutions to the electron-cloud problem will be addressed at a forthcoming mini-workshop [6].

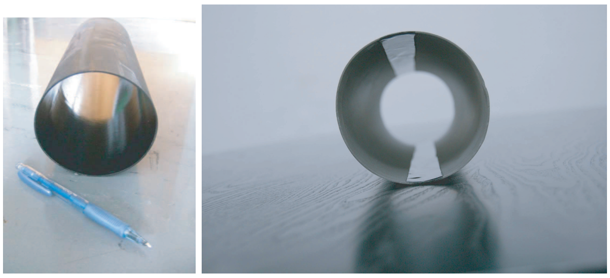

Figure 1: Prototype enamel-based clearing electrodes. Left: single enamel layer coated on a stainless steel tube with the same thermal expansion coefficient after heating test; right: conducting enamel strips on top of an insulating enamel coating. (Courtesy F. Caspers, and Eisenwerke Dueker, Laufach, Germany)

12 SPACE CHARGE COMPENSATION

Figure 2 shows a schematic of an upgraded LHC using electron lenses for head-on beam-beam compensation, as proposed by V. Shiltsev [7]. The arrangement couples at least 4 beams, and it may prove challenging to control the resulting coherent and incoherent beam-beam interactions.

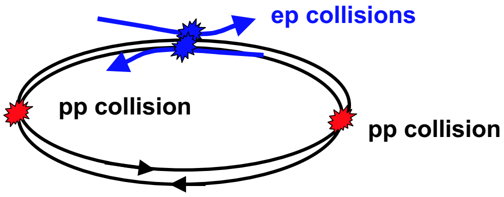

Figure 2: Schematic of LHC head-on beam-beam compensation with two proton beams and two electron lenses, coupled to each other.

A simpler system would be obtained when using a single electron lens for space-charge compensation of a single beam to raise the beam intensity, e.g., at the PS, PS booster, or PS2, as illustrated in Fig. 3.

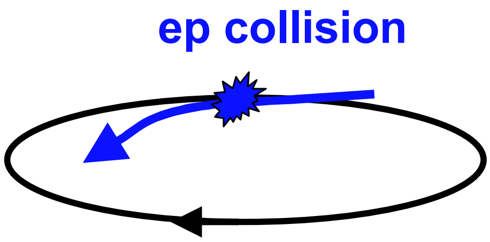

Figure 3: Schematic of electron-lens space-charge compensation in the PS or PS booster.

The main idea of the compensation would be to reduce the incoherent tune spread due to the nonlinear space-charge force. The tune shift with amplitude can be fully compensated, if the electron-beam shape is matched to that of the proton beam. Resonance driving terms may be excited, however, since the electron lens(es) will be localized in one or few regions of the ring. For compensation to be most effective the electron and proton beam should move in opposite directions (different from a cooler), a configuration which minimizes the electron current needed.

The advantages of space-charge compensation over beam-beam compensation are the reduced number of coupled beams, the potentially lower electron-beam current and lower electron density, and an easier electron profile control for larger beam sizes.

If successful, such scheme could have a huge payoff, either simplifying the injector upgrade or completely changing its philosophy.

After the workshop this idea turned out to be not new: In 2000 a similar proposal of space-charge compensation with an electron lens had already been made for the FNAL booster (“Bell review”). A subsequent paper study by A. Burov, G.W. Foster, and V. Shiltsev surveyed space-charge limits in many existing facilities, and concluded that the observed space-charge limits appear to be due to coherent tune shifts(s), and not to the incoherent space-charge effect [8]. From this it was estimated that at most a factor 2 in intensity could be gained.

Indeed, numerous other ways of compensating space-charge effects were addressed, e.g., by ions, in many past Russian studies, as early as 1956 [9]. It is also worth commemorating the experience at the DCI where a compensation of the beam-beam forces by colliding 4 beams spectacularly failed, and the beam currents were limited by violent beam-beam instabilities. A theoretical explanation of this failure was provided by Ya. Derbenev [10].

13 CONCLUSIONS

The LUMI’06 workshop endorsed an injector upgrade path based on SPL and PS2. The normal-conducting PS2 has clear advantages compared with a super-conducting PS2+, in regard to reliability, flexibility. required R&D, electron cloud, etc. The only drawback appears be a reduced potential for a later SPS+ upgrade, thereby complicating an ultimate LHC energy upgrade. Regardless, in order to draw benefit from an upgraded PS for the LHC, supplementary measures will be needed in the SPS, including a re-configuration of the injection region and injection kickers, new transfer lines, impedance reduction, and countermeasures against the electron cloud.

Any successful demonstration of space-charge compensation in proton boosters, e.g., one based on electron lenses, might change the picture of the injector upgrade.

14 REFERENCES

[1] M. Benedikt, “PS2: Basic Considerations and Optics,” to be published in Proc. CARE-HHH-APD LUMI-06 workshop, Valencia, 16–20 October 2006.

[2] G. Rumolo, “SPS Performance with PS2,” to be published in Proc. CARE-HHH-APD LUMI-06 workshop, Valencia, 16–20 October 2006.

[3] M.A. Furman, “E-Cloud in PS2, PS+, and SPS+,” to be published in Proc. CARE-HHH-APD LUMI-06 workshop, Valencia, 16–20 October 2006.

[4] CARE-HHH-AMT LER — Workshop on the Low Energy Ring study, CERN, Geneva, 11–12 October 2006; web site *http://ler06.web.cern.ch/LER06/*.

[5] A. Blondel, “Physics Potential of PS2 and PS+,” to be published in Proc. CARE-HHH-APD LUMI-06 workshop, Valencia, 16–20 October 2006.

[6] Joint CARE-HHH and EUROTeV mini-workshop on “Electron Cloud Clearing (ECL2), CERN, 1-2 March 2007; web site *http://care-hhh.web.cern.ch/CARE-HHH/ECL2*.

[7] V.D. Shiltsev, “LHC Electron Lenses,” to be published in Proc. CARE-HHH-APD LUMI-06 workshop, Valencia, 16–20 October 2006.

[8] A.V. Burov, G.W. Foster, V.D. Shiltsev, "Space-Charge Compensation in Proton Boosters," PAC 2001 Chicago (2001) p. 2896.

[9] G.I. Budker, "Relativistic Stabilized Electron Beam," CERN Symposium on High Energy Accelerators and Meson Physics (1956).

[10] Ya. S. Derbenev, "Collective Instability of Compensated Colliding Beams," IYF-70-72 and SLAC-TRANS-0151 (1972).