# OTHER SCENARIOS FOR A PARTIAL UPGRADE OF THE INJECTOR COMPLEX

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*Abstract*

Other partial upgrade options than the proposed scenario consisting of the construction of a 4GeV SPL and PS2, together with substantial SPS upgrades, are investigated. Based on the observation that, after the PS main magnets are believed to be this study concentrates on options for a new injector for the existing PS.

## INTRODUCTION

### *Motivations for SPL, PS2 and SPS Upgrade*

The "standard" LHC injector upgrade path, consisting of SPL, PS2 and SPS upgrades, is based on consistent set of arguments [1,2]:

- One of the main arguments brought up to support the construction of PS2 was the impression that the PS magnets come close to the end of their life-time and thus the need for a fast replacement of this machine. The maximum energy of PS2 should be significantly higher than the one of the present PS to mitigate some of the limitations like TMCI. This requires either to increase the magnetic field of the magnets or to increase the circumference, the solution adopted for the PS2 study.
- The replacement of the PS by a longer machine implies that the present Booster cannot be kept temporarily, but must be replaced by a new injector providing higher energies to avoid a reduction of the performance of the whole complex. A 4 GeV kinetic energy SPL has been adopted as proposed PS2 injector with the argument that it offers many options for physics after the LHC era at a modest price increase compared to a rapid cycling synchrotron RCS.
- Finally, extensive upgrades of the SPS, which will be the main performance limitation of the complex with Linac4, are required to make use of the performance possible with SPL and PS2.

### *Scope of this Study*

Latest investigations have shown that after a successful renovation program, the status of the PS main magnets allows operating them for a long duration comparable with the requirements for LHC, provided appropriate continued maintenance is carried out. Moreover, the present main limitation of the SPS for LHC beams is the electron cloud effect, which would even be increased with the increased injection energy envisaged with PS2. Only after curing the electron cloud effect, the SPS could profit from a higher injection energy increasing the TMCI threshold.

These two observations motivate studies on an upgraded LHC injector complex comprising the existing PS. This study concentrates on options for new PS injectors for the existing PS. It is assumed that a Linac4 extension to the energy required for the new injector, possibly improvements of the PS to cure intensity limitations other than direct space charge detuning and an SPS upgrade will be implemented as well.

Other possible alternative upgrade scenarios like replacing the PS by a superconducting machine of the same circumference or starting a renovation of the injector complex by replacing the SPS with a new machine have not been considered due to lack of study time.

## REQUIREMENTS AND ASSUMPTIONS

### *Assumptions on LHC Requirements and maximum direct space charge tune shifts*

For the moment, no clear scenario, but several proposals exist for a phase two upgrade of the LHC aiming at a luminosity around $10^{35}$ cm$^{-2}$s$^{-1}$. Thus, several sets of beam parameters with rather different requirements, in terms of beam brightness, exist for the injector complex. Finally, for this study, requirements assumed are similar to the ones for the PS2 study, since this allows a direct comparison:

- $N = 4.0^{11}$ protons per LHC bunch spaced by 25 ns within transverse emittances of $\varepsilon_T^* = 2.5$ µm corresponding to a beam brilliance of $N/\varepsilon_T^* = 1.6\ 10^{11}$ µm$^{-1}$. Note that this brilliance is compatible with most LHC "small emittance schemes" requiring smaller intensities as well.
- The maximum tolerable direct space charge tune shift at PS injection is $\Delta Q_{PS}$=-0.3. In case of new injector synchrotrons with shorter acceleration times, larger maximum tolerable tune shifts of $\Delta Q_{INJ}$=-0.35 and $\Delta Q_{INJ}$=-0.45 have been assumed.
- Bunching factors: For the PS and fast cycling injector synchrotrons, the bunching factor has been estimated assuming that 70% of the RF bucket are filled by the beam. Note that for the PS injection flat bottom, this procedure yields a bunching of $B_f = 0.425$.

Note that, for this report, more pessimistic bunching factors, but larger maximum direct space charge tune shifts than for the PS2 study have been assumed. Altogether, similar injection energies as function of requirements are obtained for both cases.

### *Implications for the PS*

It is assumed that the performance of the PS for LHC type beams is limited by direct space charge effects and that other effects like instabilities are not a concern or can be cured by appropriate measures. The minimum injection energy as a function of beam brightness is plotted in Fig. 1. To fulfil the assumed requirements, the PS injection energy (kinetic) has to be raised to about 2.5 GeV. For comparison, the data underlying the preparation of the PS complex for LHC in the 90'ies are highlighted as well: the brightness of ultimate LHC beams* requires a minimum injection energy of about 1.4 GeV, i.e. the one chosen at that time.

Injecting into the PS above transition energy could be envisaged in principle in order to cure losses and problems associated with transition crossing. However, this option is not investigated here, since then the PS injection (kinetic) energy would have to be raised to 5 or 6 GeV implying higher cost and, in case of a new PS injector ring efforts to avoid transition crossing in this new machine.

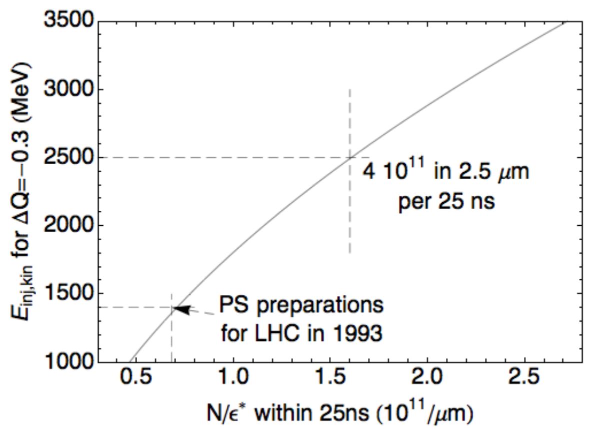



Figure1: PS injection (kinetic) energy required as function of beam brightness.

## SPL AS PS INJECTOR

A Superconducting Proton Linac (LP-SPL) with a lower energy than the version proposed for PS2 could provide $H^-$ injected directly into the existing PS. The length of such a LP-SPL solution has been interpolated from Fig. 5 in reference [3] to about 300 m in addition to Linac4 to reach 2.5 GeV. A possible limitation of such a solution is Lorentz stripping in the transfer line, in particular, if this SPL is constructed as prolongation of Linac4 at the location proposed for PS2. Loss rates due to Lorentz stripping computed with empirical formulas given in [4] are plotted in Fig. 2. Assuming an average particle flux rate of $10^{13}$ $H^-$ per second, a maximum heat deposition of 1 W/m, the peak magnetic field in a bending section should remain below 0.214 T. Assuming an maximum average bending field of about 0.15 T gives an minimum average radius of transfer line of about 75 m. A possible geometry of a 2.5 GeV SPL located as an extension of Linac4 and the transfer line to the PS is shown in Fig. 3.

* At that time it has been assumed that the transfer up to collisions in LHC will be loss free and that the Booster with Linac2 can provide the required brilliance with the initial scheme filling eight PS buckets with eight PSB bunches with transfers.

An SPL as PS injector allows, in principle, replacing the low frequency "10 MHz" PS RF system by a tunable 40 MHz system (as proposed and studied for PS2) to generate LHC bunch trains already at injection. Such a 40 MHz RF system would simplify the PS operation for LHC beams, because the RF gymnastics applied at present to generate the LHC bunch patterns are not required any more, but may be incompatible with the generation of many other physics beams delivered by the PS.

The implementation of a new $H^-$ charge exchange injection would have to be studied and designed and, may well turn out to be a challenge.

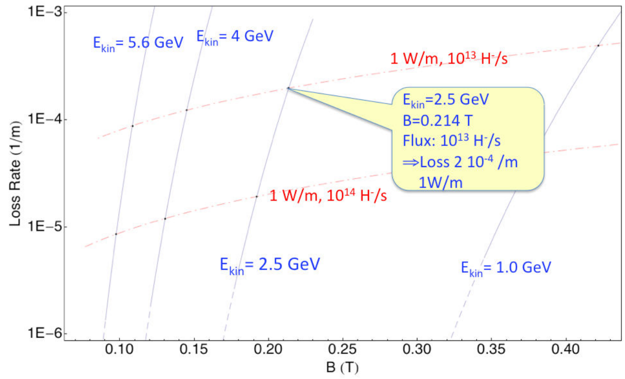



Figure 2: Loss rates due to Lorentz stripping using formulas given in ref. [4]. The dot-dashed lines connect points with constant 1 W/m energy deposition and for a particle flux with $10^{13}$ and $10^{14}$ $H^-$ second.

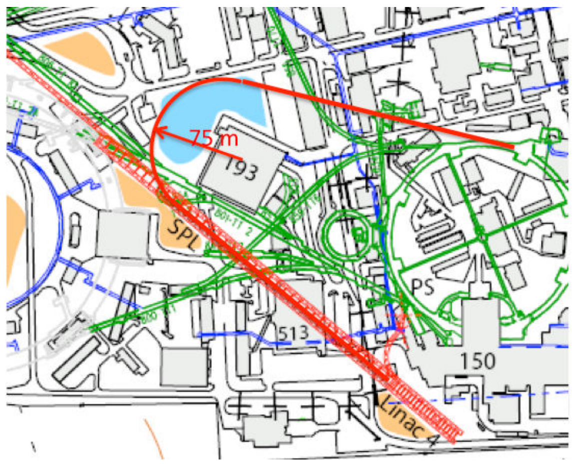



Figure 3: Possible geometry of a 2.5 GeV SPL injecting into the PS.

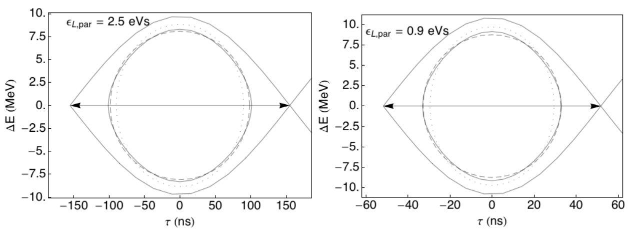
## OPTIONS FOR A NEW PS INJECTOR RING

### *General Considerations on new PS Injector Rings*

For the case of a new PS injector ring, the required LHC beam structure at ejection has to be generated by RF gymnastics (various double and triple splittings and bunch compression) similar to the ones applied at present. Thus the following restriction apply for the harmonic number of the PS $h_{PS}$ at injection of LHC bunch trains:

- The PS harmonic number $h_{PS}$ must be a multiple of the factor 7.
- The maximum harmonic number is assumed to be $h_{PS} = 21$. This corresponds to a bunch spacing of 100 ns and a PS injection kicker rise time† of less than 40 ns, i.e. even a bit less than the one available at present with a lower strength.

The longitudinal emittance at PS injection for 25 ns LHC trains is at present limited by the Booster RF system, but not the by the RF voltage available in the PS. In rapid cycling synchrotrons, larger longitudinal emittances require larger RF voltages and, thus, lead to smaller synchronous phase and larger bunching factors. Thus, longitudinal emittances per bunch of $\varepsilon_l = 2.5$ eVs and $\varepsilon_l = 0.9$ eVs are assumed for transfer with PS harmonic number $h_{PS} = 7$ and $h_{PS} = 21$, respectively. Resulting RF buckets and bunches after transfer into the PS are plotted in Fig. 4.




$h_{PS} = 7$, $V_{RF} = 14$ kV　　　$h_{PS} = 21$, $V_{RF} = 51$ kV

Figure 4: RF bucket and bunch after PS injection on a 2.5 GeV plateau.

## *Rapid Cycling Synchrotron (RCS) with $h_{RCS} = 1$*

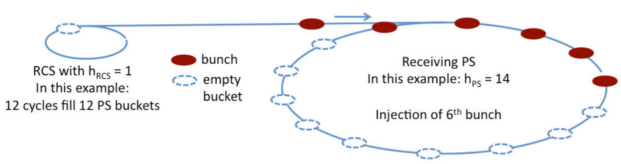



Figure 5: Example for filling the PS with an RCS with harmonic number $h_{RCS} = 1$.

The principle of a Rapid Cycling Synchrotron with harmonic number $h_{RCS}$=1 is depicted in Fig. 4. In this example, 12 out of 14 PS buckets are filled for LHC operation. Since every RCS cycle generates only one bunch, the distance between bunches in the receiving PS is not given be the geometry of the two machines.

The advantage of filling the PS with many shots is that the RCS intensity per transfer and, thus, the required beam brightness, are lowered. On the other hand, PS filling time tends to increase and, thus, an RCS should pulse with a high repetition rate in particular for a PS operating with a large harmonic number.

Table 1: Main parameter of a RCS with harmonic number $h_{RCS} = 1$ filling 6 out of 7 PS buckets for the generation of LHC bunch trains.

| | | | | | |
|---|---|---|---|---|---|
| N in 2.5μm ($10^{11}$) | | | 4.0 | | 8.5 |
| $E_{kin,ej}$ (MeV) | | | 2500 | | 4000 |
| $(B\rho)_{ej}$ /R (T) | | | 0.44 | | 0.65 |
| $f_{RF,ej}$ (MHz) | | | 1.84 | | 1.87 |
| $\varepsilon_{long}$ (eVs) | 2.5 | 2.5 | 1.3 | 2.5 | 2.5 |
| ΔQ | -0.35 | -0.45 | -0.35 | -0.35 | -0.35 |
| $T_{acc}$ (ms) | 50 | 50 | 50 | 25 | 50 |
| $E_{kin,inj}$ (MeV) | 675 | 510 | 840 | 760 | 1550 |
| $(B\rho)_{inj}$ /R (T) | 0.175 | 0.147 | 0.201 | 0.188 | 0.308 |
| $f_{RF,inj}$ (MHz) | 1.55 | 1.45 | 1.62 | 1.59 | 1.77 |
| $B_{f,inf}$ | 0.279 | 0.289 | 0.219 | 0.246 | 02.16 |
| $V_{RF}$ (kV) | 52 | 62 | 31 | 77 | 44 |
| $\phi_s$ (degree) | 24 | 22 | 37 | 31 | 37 |
| $f_{s,inj}$ (kHz) | 2.40 | 3.11 | 1.51 | 2.64 | 1.07 |

Table 2: Main parameter of a RCS with harmonic number $h_{RCS} = 1$ filling 12 out of 14 PS buckets for LHC buckets for the generation of LHC bunch trains.

| | | | | | |
|---|---|---|---|---|---|
| N in 2.5μm ($10^{11}$) | | | 4.0 | | 8.5 |
| $E_{kin,ej}$ (MeV) | | | 2500 | | 4000 |
| $(B\rho)_{ej}$ /R (T) | | | 0.44 | | 0.65 |
| $f_{RF,ej}$ (MHz) | | | 1.84 | | 1.87 |
| $\varepsilon_{long}$ (eVs) | 1.25 | 1.25 | 0.65 | 1.25 | 1.25 |
| ΔQ | -0.35 | -0.45 | -0.35 | -0.35 | -0.35 |
| $T_{acc}$ (ms) | 50 | 50 | 50 | 25 | 50 |
| $E_{kin,inj}$ (MeV) | 385 | 270 | 505 | 445 | 1010 |
| $(B\rho)_{inj}$ /R (T) | 0.124 | 0.102 | 0.146 | 0.135 | 0.228 |
| $f_{RF,inj}$ (MHz) | 1.34 | 1.21 | 1.45 | 1.40 | 1.67 |
| $B_{f,inf}$ | 0.239 | 0.247 | 0.184 | 0.209 | 0.186 |
| $V_{RF}$ (kV) | 46 | 52 | 33 | 76 | 47 |
| $\phi_s$ (degree) | 32 | 30 | 45 | 39 | 44 |
| $f_{s,inj}$ (kHz) | 2.95 | 3.60 | 1.99 | 3.38 | 1.52 |

Main machine parameters for an RCS with $h_{RCS}$=1, a circumference which is one forth of the PS‡, $1/\gamma_{tr}^2 = 0$ and for a single harmonic RF system§ are given Tabs. 1 and 2 for filling six out of seven PS buckets and 12 out of 14 PS buckets, respectively. Despite gaining from a large number of transfers, the required injection energies are large, because fast acceleration leads to large synchronous angles and, thus, small bunching factors. In consequence,

† The creation of additional gaps in the LHC bunch train for the PS injection kicker is ruled out.

‡ The circumference can be easily adjusted since the circumference ratio is not fixed by the harmonic numbers, but can be any "simple" rational number

§ In principle, a second harmonic RF system for bunch flattening could increase the bunching factor and, thus, decrease the required RCS injection energy. However, this has not been considered due to the large voltages required.

the typical magnetic field swings are small. With the full RF voltage, bunches arrive at the ejection plateau with too short bunch lengths even for the $h_{PS} = 14$ case. It has to be verified that the bunch length can be adjusted simply by reducing the RF voltage during the last part of the cycle or by other RF manipulations.

### *Rapid Cycling Synchrotron (RCS) for "geometric PS filling"*

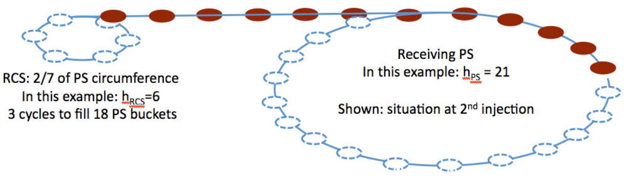



Figure 6: Example for "geometric filling of the PS" with an RCS with harmonic number larger than one $h_{RCS} > 1$.

The principle of "geometric" PS filling with a Rapid Cycling Synchrotron is depicted in Fig. 6. The harmonic number of the RCS is larger than one (6 in the example shown, but other harmonics are possible) and, thus, the distance between extracted bunches has to match the spacing between PS buckets. The advantage of harmonic numbers larger than one in the RCS is that the bunching factor tends to increase for fixed total longitudinal emittances; the RF voltage increases and the synchronous phase decreases. Still, the required injection energies are higher than with a $h_{RCS} = 1$ RCS, but on the other hand less transfers are needed speeding up PS filling.

Ruling out special RF gymnastics generating an irregular bunch pattern in the RCS to adapt the bunch spacing (similar to the procedures applied with the present Booster for the generation of LHC bunch trains with single batch Booster to PS transfers [5]), the circumference ratio between the two machines is determined by the harmonic numbers. A natural choice is an RCS with 2/7 of the PS circumference[**]. This allows harmonic numbers $h_{RCS} = 2$ and $h_{PS} = 7$ or $h_{RCS} = 6$ and $h_{PS} = 21$ (as sketched in Fig. 6) in the RCS and the PS. Three transfers are required to fill the PS for the generation of LHC bunch trains with RF gymnastics analogous to the ones applied at present.

Main machine parameters of an RCS for "geometric PS filling", a circumference which is 2/7 of the PS, $1/\gamma_{tr}^2 = 0$ and for a single harmonic RF system are given Tabs. 3 and 4 for harmonic numbers $h_{RCS} = 2$ and $h_{RCS} = 6$, respectively. As expected, the required injection energies are even larger than for the $h_{RCS} = 1$ case. The larger harmonic number $h_{RCS} = 6$ leads as expected to larger RF voltages, but the decrease of the required injection energy is small.

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[**] An RCS with 1/3 of the PS circumference with harmonic numbers $h_{RCS} = 7$ and $h_{PS} = 21$ are another possible option allowing filling the whole PS circumference with three transfers for other beam than LHC.

Table 3: Main parameter of a RCS with $h_{RCS} = 2$ for "geometric filling" of 6 out of $h_{PS} = 7$ PS buckets with three transfers for the generation of LHC bunch trains.

| | | | | | |
|---|---|---|---|---|---|
| N in 2.5μm ($10^{11}$) | 4.0 | | | | 8.5 |
| $E_{kin,ej}$ (MeV) | 2500 | | | | 4000 |
| $(B\rho)_{ej}$ /R (T) | 0.39 | | | | 0.57 |
| $f_{RF,ej}$ (MHz) | 3.21 | | | | 3.28 |
| $\varepsilon_{long}$ (eVs) | 2.5 | 2.5 | 1.3 | 2.5 | 2.5 |
| ΔQ | -0.35 | -0.45 | -0.35 | -0.35 | -0.35 |
| $T_{acc}$ (ms) | 50 | 50 | 50 | 100 | 50 |
| $E_{kin,inj}$ (MeV) | 1070 | 840 | 1250 | 990 | 2190 |
| $(B\rho)_{inj}$ /R (T) | 0.207 | 0.177 | 0.231 | 0.197 | 0.348 |
| $f_{RF,inj}$ (MHz) | 2.95 | 2.84 | 3.02 | 2.92 | 3.19 |
| $B_{f,inf}$ | 0.333 | 0.340 | 0.273 | 0.361 | 0.269 |
| $V_{RF}$ (kV) | 79 | 102 | 38 | 64 | 51 |
| $\phi_s$ (degree) | 13 | 12 | 25 | 8.7 | 26 |
| $f_{s,inj}$ (kHz) | 2.7 | 3.7 | 1.6 | 2.6 | 1.1 |

Table 4: Main parameter of a RCS with $h_{RCS} = 6$ for "geometric filling" of 18 out of $h_{PS} = 21$ PS buckets with three transfers for the generation of LHC bunch trains.

| | | | | | |
|---|---|---|---|---|---|
| N in 2.5μm ($10^{11}$) | 4.0 | | | | 8.5 |
| $E_{kin,ej}$ (MeV) | 2500 | | | | 4000 |
| $(B\rho)_{ej}$ /R (T) | 0.39 | | | | 0.57 |
| $f_{RF,ej}$ (MHz) | 9.64 | | | | 9.84 |
| $\varepsilon_{long}$ (eVs) | 0.9 | 0.9 | 0.45 | 0.9 | 0.9 |
| ΔQ | -0.35 | -0.45 | -0.35 | -0.35 | -0.35 |
| $T_{acc}$ (ms) | 50 | 50 | 50 | 100 | 50 |
| $E_{kin,inj}$ (MeV) | 950 | 750 | 1080 | 910 | 1910 |
| $(B\rho)_{inj}$ /R (T) | 0.191 | 0.164 | 0.209 | 0.186 | 0.315 |
| $f_{RF,inj}$ (MHz) | 8.70 | 8.33 | 8.87 | 8.64 | 9.46 |
| $B_{f,inf}$ | 0.380 | 0.385 | 0.327 | 0.398 | 0.326 |
| $V_{RF}$ (kV) | 196 | 259 | 72 | 175 | 103 |
| $\phi_s$ (degree) | 5.8 | 5.0 | 14.5 | 3.3 | 14.6 |
| $f_{s,inj}$ (kHz) | 8.2 | 11.2 | 4.5 | 8.0 | 3.2 |

### *"SuperBooster" SB as PS Injector*

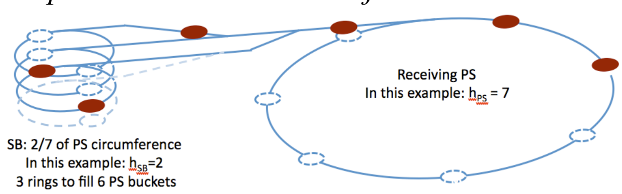


Figure 7: Example for PS filling with a "SuperBooster", i.e. several superimposed synchrotrons with moderate cycle times.

Another option for a new PS injector is stack of superimposed synchrotrons similar to the existing Booster, but with higher maximum energy. This could be obtained easily with a machine with a size similar to the present Booster, but a larger bending magnet-filling factor and a higher maximum magnetic field.

A natural choice for the generation of LHC bunch trains is to operate three superimposed rings with harmonic numbers $h_{SB} = 2$ and $h_{PS} = 7$ in this SuperBooster and the PS; this avoids special gymnastics in the SuperBooster similar to the ones required for the generation of LHC bunch trains with the present Booster and single batch PSB to PS transfer [5]. Note that this scheme with three such superimposed rings is designed to fill six out of seven buckets and, thus, it is not easily possible to fill the entire PS circumference for high intensity beams with one transfer††. Solutions to overcome this limitation are the construction of a forth ring (producing only one bunch) or to lower the PS harmonics and to adjust the bunch spacing in this SuperBooster by adding first harmonic RF component.

In case of a slowly cycling SuperBooster, the beam is accelerated with smaller RF voltages and smaller synchronous angles. A double harmonic RF system for bunch flattening and, extrapolating from the present Booster, a bunching factor of $B_f = 0.55$ is assumed. Then an injection energy of 680 MeV and 530 MeV is required‡‡ assuming a maximum direct space charge tune shift of $\Delta Q = -0.35$ or $\Delta Q = -0.45$, respectively.

## *FFAG as new PS Injector*

The magnetic field swing of possible PS injector synchrotrons, appropriate to obtain the assumed beam brightness required for the LHC, is relatively small. Furthermore, for RCS options and, in particular for an RCS with harmonic number $h_{RCS} = 1$, high repetition rates are of interest to keep the PS filling time at an acceptable level. With these observations, a Fixed Field Alternate Gradient (FFAG) accelerator appears as possibly interesting option. However, the in general large transverse acceptances of FFAGs are not of interest for the generation of small emittance LHC type beams.

FFAGs have gained renewed interest during the last years for different applications and different approaches to design the magnetic field have been proposed. This makes the question whether one of the various FFAG types [6] may be an attractive solution as PS injector not easier.

FFAG have a magnetic field, which is not ramped, but remains fixed during acceleration and, thus, have many similarities and analogies with cyclotrons. The advantage is that complications associated with rapid cycling magnetic structures are not present and the acceleration time is limited only by the RF system. However, the beam position varies during acceleration requiring large aperture magnets and RF cavities.

Within this study, it has not been possible to design an FFAG as PS injector. Thus, to roughly estimate how such an FFAG could look like, selected proposed designs based on normal conducting magnets§§ are scaled to reach the energy required for the PS:

- Fig. 8 shows a so-called "scaling FFAG" proposed for medical applications [7]. In case of scaling FFAG, the magnetic field increases proportional to the radius to the power of a "field index", which should be large for strong horizontal focusing and, thus, small orbit variations with energy. Vertical focusing is obtained by azimuthal variations of the magnetic field (in some proposals even with sections bending the beam outwards) and, possibly spiralling structures. The intention of scaling FFAGs is to keep the focusing structure and, thus, the working point, constant during acceleration. If the geometry of the example in Fig. 8 is scaled up by a factor 5.6, one obtains roughly the required energy swing 440 MeV to 2500 MeV. However, with such a scaled up version, transition would have to be crossed [9] and the aperture width becomes almost 4 m. The pole rotation angle and the "field index" can be increased [9] to raise the transition energy to above the ejection energy and to reduce the orbit excursion to about 0.8 m. However, non-linearities experienced by the beam increase.
- Fig. 8 sketches a so-called non-linear non-scaling FFAG proposed as proton driver for high beam power application [8] and with an energy swing similar to what would be required for a new PS injector. In case of nonscaling FFAGs, the idea to keep the focusing structure constant during acceleration is abandoned to gain more flexibility to increase horizontal (and vertical) focusing for reduced orbit variations and to avoid sections bending outwards. Non-scaling linear FFAGs have only dipolar and quadrupolar field components; the working point moves during acceleration often even over integer resonances. The example sketched in Fig. 8 is a non-scaling non-linear FFAG, where additional non-linearities have been added to keep the tunes fixed throughout acceleration.

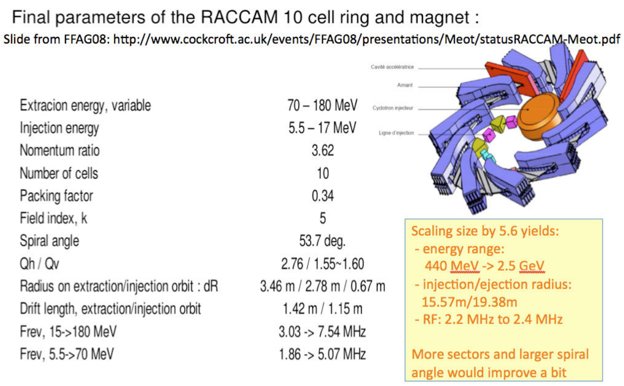


Figure 8: Scaling FFAG proposed (see e.g. ref [7]) for medical applications.

††Another option avoiding this problem, but requiring faster kickers, would be three superimposed SuperBooster rings with one third of the PS circumference operating with $h_{SB} = 7$ and $h_{PS} = 21$.

‡‡A SuperBooster (operated with harmonic hSB = 1) with double batch PS filling for LHC beams would allow reducing the required injection energy, but as well lengthen PS filling and, thus, has not been considered as new injector.

§§A superconducting magnetic structure could, in principle, be envisaged, since the magnetic field is nit ramped, and would reduce the size and the apertures required..

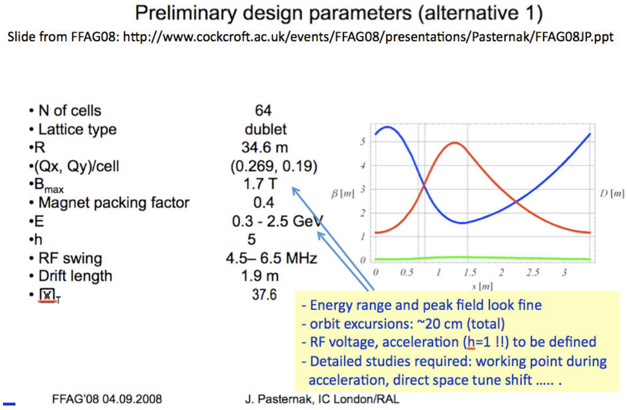


Figure 9: Non-linear non-scaling FFAG proposed in ref. [8] to generate a high power proton beam.

For any FFAG type (ruling out strong variations of the working point moving across many resonances), a compromise between magnet non-linearities, which have to be acceptable for beam dynamics aspects in particular for high intensity beams, and orbit excursions has to be found. To assess the feasibility of an FFAG as PS injector, limitations due to direct space charge effects have to be investigated for such a machine with strong non-linearities and technical solutions e.g. for the implementation of an $H^-$ charge exchange injection and large aperture RF system have to be found.

## CONCLUSIONS AND OUTLOOK

Possible PS injectors have been enumerated and basic parameters have been estimated. Requirements for future LHC beams similar to the ones underlying the PS2 study have been assumed and led to the conclusion that the PS injection energy should be raised to about 2.5 GeV. However, for the moment different LHC upgrade scenarios with rather different beam requirements exist. Thus, the required beam brightness and, in consequence, PS injection energy could become smaller than assumed here. Furthermore, it has been assumed that direct space charge effects are limiting the machine performances and, thus, that other potential limitations like instabilities and, in particular, the limitations at low energy in the SPS are cured by appropriate actions.

Options investigated for a new PS injectors comprise: (i) an SPL type solution accelerating $H^-$ ions to the required 2.5 GeV and implying that a technical solution to implement a charge exchange injection must be found, (ii) rapid cycling synchrotrons operated with $h_{RCS} = 1$ or "geometric PS filling, (iii) a stack of several accelerators similar to the present PSB, but with a higher maximum energy and (iv) FFAGs.

Injection energies in possible new PS injector rings are rather high in the range of slightly below 0.5 GeV and above 1.0 GeV depending on the option chosen. In case of fast cycling machines, the bunching factors are reduced due to a large synchronous angle and since only a single harmonic RF system has been assumed. Even for a "superbooster" solution, the required injection energy is high since for a new injector, double batch PS filling has been ruled out.

For the moment, only basic parameters of possible PS injectors have been estimated. Even the feasibility of certain options, like e.g. FFAGs, is not guaranteed. For a fair comparison, the feasibility and cost has to be estimated for the different options. Furthermore, possible additional limitations like instabilities and impact on other beams than the one required for LHC are required.

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