Considerations on a new fast extraction kicker concept for SPS

M. Barnes, B. Goddard TE/ABT

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Summary

An alternative extraction kicker concept is investigated for the SPS, based on open C-type kickers and a fast-bumper system. The beam is moved into the kicker gap some tens of ms before extraction. The concept is illustrated in detail with the LSS4 extraction from the SPS – very similar parameters and considerations apply to LSS6. A similar concept could also be conceived for injection but is more difficult due to the larger beam size. The technical issues are presented and the potential impact on the machine impedance outlined.

1. Introduction

The present SPS kicker systems are generally ferrite C-core with a return conductor closing the gap, Fig. 1a, which must provide enough aperture for the injected beam at 14 GeV. An alternative extraction kicker concept, Fig. 1b, is investigated with the idea to build an open C-type kicker and fast-bumper system, such that the beam is moved into the kicker gap shortly before extraction. In this note the concept is illustrated in detail with the LSS4 extraction from the SPS – very similar parameters and considerations apply to LSS6. A similar concept could also be conceived for injection, with a fast bump to move the beam out of the kicker aperture; however, this is much more difficult due to the larger beam size, and is not investigated here in any detail.

Figures 1a and 1b. Schematic of present (left) and alternative (right) MKE kicker cross-section, where a fast bump is used to move the beam into the gap. The vertical gap height is determined by the injected beam size for the present system, and by the extracted beam size for the alternative system.

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For a given magnet current, the kicker field is defined by the vertical gap; a smaller gap will be an advantage since more kick strength is available for a given Pulse Forming Network (PFN) voltage and system impedance. Kicker beam coupling impedance is an issue for beam stability, and having the beams present in the kicker gap for a short time only, and at high energy, could be a big advantage. Similarly, kicker heating from the real part of the beam coupling impedance will be less of an issue if the coupling impedance seen by the beam is much less for most of the accelerating cycle. In addition, since a smaller vertical gap is required (for a given current), less installed kicker length will be required, which helps reduce the overall beam coupling impedance [3]. The smaller vertical gap and single conductor of the new kickers mean that the impedance per m will, however, be significantly higher.

2. Constraints and assumptions

The constraints and assumptions used in investigating the feasibility of such a concept are listed below. These are presently first-order estimates and clearly have scope for optimisation.

- Extraction angle from kicker should be about 0.5 mrad.
- Kicker vertical and horizontal gap should provide enough aperture for extracting CNGS beam at 300 GeV, and a sufficiently good field quality for this beam.
- The aperture of the kicker tank for the injected beam should not be less than at present.
- The flat-top ripple of the kicker should be a maximum of ±1 %.
- The kicker rise- and fall-time should be 1 µs for the CNGS (can be longer for LHC, maximum 6 µs).
- The pulse-length should be enough for CNGS, i.e. 10.8 µs.
- One design is used for LSS6 and LSS4 (could even be smaller vertical aperture for LSS6).
- Optics and beam size at kicker locations
  - Maximum beta functions assumed are 100 m X, 35 m Y
  - 12/8 π.mm.mrad normalised emittance for CNGS beam
  - Dispersion at kicker location: 0.5 m
  - δp/p: 0.1 %
  - Orbit allowance: ±4 mm
  - Alignment tolerance: ±1 mm
  - Acceptance: ±5 sigma

3. Resulting kicker aperture

Using the above values the minimum horizontal half-aperture is 14.9 mm, and vertical is 9.5 mm. A minimum full aperture for a 300 GeV CNGS beam is then assumed to be 30 mm horizontal, 20 mm vertical, Fig. 2. Note that vertically this is the same as the extraction gap in the downstream MS septa, which have larger vertical beta functions (they essentially fill the half cell), although the beam only makes one pass in the septum.
4. **Kicker characteristic impedance, inductance and rise time**

For an impedance matched transmission line system we have

- \( I = \frac{U}{2Z} \)
- \( L = \mu_0 \frac{w}{h} l_m \)
- \( B = \mu_0 \frac{I}{h} \)

where \( U \) is the PFN voltage, \( L \) the inductance, \( I \) the magnet current, \( Z \) the characteristic impedance of the (matched) system, \( w, h \) and \( l_m \) are the aperture width, aperture height and magnetic length of the kicker magnet, respectively, and \( B \) the magnetic field.

The present system impedance, for the MKEs, is \( 1 \Omega \) – we assume this is kept, so that existing PFNs and generators can be re-used. The present PFN voltage, for MKE4 (a matched system), is about 50 kV giving \( I \approx 2.5 \) kA: for the existing aperture heights of 32 mm (S-type magnet) and 35 mm (L-type magnet), the central fields are approximately 98 mT and 90 mT, respectively. For the aperture shown in Fig. 2, and 2.5 kA, the central field \( B \) in the aperture would be approximately 157 mT (note: the flux-density in the back-yoke of the ferrite C-core (presently 70 mm), at the centre of the magnet, would be reduced by \( \sim 40 \% \) in comparison with the existing MKE4 kicker magnet, for a given pulse current).

Keeping the present magnet length \( l_m \) of 1.674 m, three magnets (five presently installed) then give 0.804 Tm, or 0.53 mrad deflection at 1503 Tm rigidity for 450 GeV.

The present MKE-L (\( w/h \)) is 147.7/35, so \( L \approx 9 \mu H \). Assuming that the fill-time is approximately given by \( (L/Z) \), then the present fill-time is \( \sim 0.9 \) \( \mu \)s (Note: \( L/Z \) underestimates the fill-time of the magnet as it neglects the effect of the series inductance of the magnet cell capacitance on the cell cut-off frequency). For the same magnet length, and allowing for an effective width of \( (w+h)/2 \) because of fringe fields, \( (w+h)/h \) of 50/20 gives \( \sim 5.3 \mu H \), or \( \sim 0.53 \) \( \mu \)s fill time – significantly faster than at present (\( \sim 0.9 \) \( \mu \)s ). Note that the effective width is taken as \( (w+h)/2 \) since the return conductor does not close the aperture and hence there is additional fringe field. It would be possible to either keep this rise-time margin or (probably...
better) build two longer magnets to give the same total deflection but with only 2 PFNs. For instance, two magnets each of 2.5 m long at 0.16 T gap field would have $L \approx 9 \, \mu H$, or $\sim 0.9 \, \mu s$ fill time.

5. Beam coupling impedance implications

The kicker gap height would reduce from 35 mm to 20 mm. As an illustration, for a similar design as the present MKE, reducing the gap to 20 mm would increase the real part of the longitudinal beam coupling impedance by around a factor 2, depending on the frequency, Fig. 3. However, the total installed length of MKE kickers would decrease from $\sim 13.6 \, m$ (8 magnets) to $\sim 7.8 \, m$ (4 or 5 magnets), so the net increase in real longitudinal beam coupling impedance is about a factor 1.2. It should be recalled that this increase is only for of the order of 100 ms or less, and only when the beam is at extraction energy. Similar scaling or detailed simulation would need to be made on a more realistic geometry for the longitudinal and transverse impedances, and detailed beam dynamics simulations should be made to understand whether this gives a net advantage.

![Theoretical real longitudinal beam coupling impedance, per meter length, for two different gap heights](image)

Figure 3 Theoretical real longitudinal beam coupling impedance, per meter length, for two different gap heights

If the beam coupling impedance is still too large, a possibility is to have a larger vertical aperture, increasing the number of magnets accordingly. This would either directly result in lower beam coupling impedance due to the larger gap, or more interestingly would allow space for shielding elements to be inserted, to carry the beam image current (e.g. as per LHC injection kicker magnets [4]). Alternatively the coupling impedance could be reduced by a serigraphy on the surface of the kicker, although this has some other technical concerns.

6. Extraction bump

The extraction bump should provide an offset of about 68 mm at the entrance of the kicker, with an angle matched to the beam size envelope at the kicker location. The bump, Fig. 4, must also bring the circulating beam close to the TPSG/MSE for extraction. A long extraction bump with 5 magnets is needed, Table 1.
Table 1
Horizontal bumpers

<table>
<thead>
<tr>
<th>Bumper</th>
<th>Location</th>
<th>Function</th>
<th>Strength [mrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB1</td>
<td>412</td>
<td>Adjust angle at kicker</td>
<td>-0.05</td>
</tr>
<tr>
<td>HB2</td>
<td>414</td>
<td>Produce offset at kicker</td>
<td>0.73</td>
</tr>
<tr>
<td>HB3</td>
<td>416</td>
<td>Produce offset at septum</td>
<td>0.21</td>
</tr>
<tr>
<td>HB4</td>
<td>417</td>
<td>Produce offset at septum and adjust closure</td>
<td>0.67</td>
</tr>
<tr>
<td>HB5</td>
<td>420</td>
<td>Close bump</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Figure 4 Extraction bump to move beam into the kicker gap (green). ±3 sigma envelopes for the CNGS beam are shown.

The existing MPLH magnets can reach 1.2 mrad, MPSH 0.6 mrad. Possibly HB3 and HB4 could be combined into one stronger magnet (similar to that used for slow extraction between ZS and MS).

The bump rise time should be fast enough that the time spent by the circulating beam in the kicker aperture is short compared to the rise-time of the detrimental processes at high energies (vacuum, instabilities) A rise-time of ~200 ms, comparable to existing MPSH/MPLH, would mean maybe 50 ms during which the beam is inside the kicker aperture (2000 SPS turns). The CNGS beam will be an additional 50 ms inside the kicker for the 2nd batch. The possibility of reducing the bumper rise-time could also be investigated.
6. Extraction trajectory, excursions in machine quadrupoles and injection aperture

The extraction trajectory is shown in Fig. 5. Assuming three magnets of the present MKE length, the extraction kicker strength needed is about 0.18 mrad per magnet, which should be possible with a similar maximum current to the present MKE4 operating at 52 kV (32/20 * 0.112 = 0.179), and corresponds to ~0.16 T in the aperture. The maximum excursion in QFA418 is 90 mm for the 3 sigma edge of the beam.

Because of the larger negative angle from the bump than for the present extraction this pushes the extraction septum inwards by about 2.5 mm, which reduces slightly the aperture available for the injected beam at the extraction septum. The aperture at the TPSG for the injected 14 GeV FT beam decreases from 5.49 to 5.21 sigma.

![Figure 5 Extraction trajectory (red). ±3 sigma envelopes for the CNGS beam are shown](image)

7. Other systems affected

Additional enlarged quadrupoles QFA and QDA would be needed at positions 416 and 415, respectively. Four enlarged quadrupoles in total would be needed to equip both extraction straight sections. There are only 4 spare magnets of this type in existence, one of which needs rebuilding (no tooling exists).

Apertures of other elements (correctors, pickups etc.) in the LSS between Q15 and Q17 will need to be large enough horizontally – similar to those already used in the extraction and injection regions of the SPS near the enlarged quadrupoles. This might entail the construction of some new beam instrumentation.
8. Potential issues and possible follow-up

Some potential issues with the proposed concept need some follow-up in order to prove its feasibility.

- Quantify the kicker aperture width, shim and height requirements from field quality calculations, and determine the required ferrite cross-section.
- Simulate the kicker magnet equivalent circuit, with realistic parasitics, to predict field rise-time.
- Define maximum allowable field in ferrite/aperture and required magnetic length.
- Investigate of bumper rise-times and powering.
- Simulate beam coupling impedance for new kickers compared to existing ones.
- Investigate potential impedance/stability issues for 2000 turns of beam inside kicker gap (4000 turns for the 2nd batch of CNGS double-batch extraction).

9. Installation issues and timescales

The installation work for both LSS4 and LSS6 could probably fit into one ‘normal’ length SPS shutdown, since the work essentially involves replacing two main SPS quadrupoles with enlarged magnets, replacing the MKE kicker magnets with new magnets, installing the new bumpers and BI, and the associated vacuum, cabling and infrastructure work. As in the past, the workload could be split across two shutdowns, with the preparatory works happening first (including infrastructure, cabling), and then the accelerator installation in the next stop.

Assuming a long SPS shutdown every 2 years, installation in the 2012/2013 shutdown is not possible, since a prototype kicker would need to be built before the series construction were launched – realistically the extraction systems could be designed, installed and operational from 2015 onwards at the earliest.

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References