FCC injection kicker magnet design, impedance and heating aspects

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Acknowledgements:

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Outline

- Parameters of injection system
- Pulse generators
- Kicker magnets
  - Electrical impedance
  - Beam coupling impedance
  - FCC beam spectrum
  - Measured electromagnetic properties of ferrite
  - Beam induced power deposition
  - Ongoing R&D
Parameters of Injection System

<table>
<thead>
<tr>
<th>Hardware parameter</th>
<th>Unit</th>
<th>Kicker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection</td>
<td>mrad</td>
<td>0.18</td>
</tr>
<tr>
<td>Integrated field</td>
<td>T\cdot m</td>
<td>2.0</td>
</tr>
<tr>
<td>Total magnet length</td>
<td>m</td>
<td>40</td>
</tr>
<tr>
<td>Good field region (h/v)</td>
<td>mm</td>
<td>32/32</td>
</tr>
<tr>
<td>Field rise time</td>
<td>µs</td>
<td>0.43</td>
</tr>
<tr>
<td>Flattop length</td>
<td>µs</td>
<td>2.0</td>
</tr>
<tr>
<td>Flattop stability</td>
<td>%</td>
<td>±0.5</td>
</tr>
</tbody>
</table>

- Injection kicker system must be highly reliable;
- The baseline injection energy for the FCC-hh is 3.3 TeV;
- For machine protection reasons, a maximum of 80-100 bunches can be accepted by the injection protection system and hence safely transferred into FCC at a time;
- Each ring will be filled with 130 batches of 80 bunches (separated by 25 ns) ⇒ 2 µs pulse;
- Injection kicker magnets are installed in the circulating beam.
Injection kicker system – pulse generators

• Many kicker systems today use thyratron (gas tube) switches and pulse forming networks/lines;
  – Long-term availability of thyratrons is a real concern;
  – Thyratrons can exhibit unwanted, spontaneous, turn-on.
• Solid-state technology and topologies such as the Inductive Adder or Marx Generator permit series and parallel connection of power semiconductors to achieve high pulsed power:
  + Scalable, reliable, modular, maintainability, …. 

Oral presentation: “Marx prototype pulse generator design and initial results”, M. Barnes, 11/04/2018, 09:30.
The injection region has a FODO lattice with a half-cell length of 150m, to provide space for a normal-conducting septum, vacuum equipment and protection devices.

A length of **120m** is available for injection kickers: however it is desirable to utilize a shorter kicker system length for both beam impedance and beam stability reasons:

- However the length must be **consistent with the ability of the pulse generator to supply the required current**;
- In the present design, the kicker magnet system will be reduced to **~40m** and moved to the end of the half-cell, with a phase advance of 90° in both planes, to the internal dump.
Injection system – kicker magnets (2)

To achieve a fast field rise time with low ripple, a transmission line type kicker magnet, as used for injection into the LHC, has been chosen;

The number of \( \pi \) (L-C) cells, per magnet, has been optimized to be 20:

Twenty cells gives a good compromise between complexity of the magnet and the required cut-off frequency of each cell;

The yoke of the kicker magnet will use a NiZn ferrite;

The characteristic impedance \( (Z) \) of the kicker magnet is given approximately by:

\[
Z = \sqrt{\frac{L_c}{C_c}} ,
\]
The electrical impedance of the FCC injection kicker magnet has been optimized together with the inductive adder operational requirements.

An inductive adder uses magnetic cores. To limit the size, cost and propagation delay through the adder, the output voltage must be kept at a reasonably low value.

Hence the kicker system must have low characteristic impedance, but consistent with rise time requirements;

A characteristic impedance of $6.25\Omega$ has been chosen: in comparison with a lower impedance (e.g. $5\Omega$), $6.25\Omega$ gives a larger gap of the secondary insulation - significantly reducing the electrical field in this region.
Injection kicker magnets – beam coupling impedance

- In the transverse and longitudinal planes, the imaginary and real parts of the beam coupling impedance might critically affect beam stability.
- The real part of the longitudinal beam impedance determines energy loss of beam particles and thus the beam induced heating.
- The power deposition in a kicker magnet may provoke temperature rise of the ferrite yoke beyond the Curie point.
- The power deposition induced by a beam composed of $n$ bunches, each populated by $N_b$ protons, travelling through the structure of longitudinal impedance of $Z_l$ is:

$$\Delta P = 2q^2 n^2 f_0^2 N_b^2 \sum_{p=1}^{\infty} \hat{\lambda}_{beam}(pf_0)^2 \Re[Z_l(pf_0)]$$

where $q$ is proton charge, $f_0$ is the revolution frequency, $p$ is an integer and $\hat{\lambda}_{beam}$ is the Fourier transform of the normalized beam charge distribution.
FCC beam spectrum

Bunch spacing: 25 ns, Bunch length: 0.08 m

Filling pattern: \((80b+4e) \times 130 + 10\mu s\) (gap, including pilots) \(\Rightarrow\) 10,400 bunches, \(\sim 80\%\) filling

Fundamental harmonics: \(f_{h0}=40\) MHz
Side-band harmonics: \(f_{h1}=0.439\) MHz, \(f_{h2}=0.00303\) MHz
Injection kicker magnets – beam induced power

Analytical approach (Tsutsui model):

- Valid for an unshielded ferrite kicker magnet and for an ultra-relativistic beam.
- The model does not take into account the C-shape of the magnet yoke, but has been shown to be in good agreement with results of impedance measurements.

Longitudinal impedance (@25°C) and beam spectrum:

Nominal aperture is 32x32 mm. A beam screen is necessary ⇒ aperture size of ~48x48 mm.

<table>
<thead>
<tr>
<th>Aperture (mm)</th>
<th>Power Deposition (W/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>202</td>
</tr>
<tr>
<td>48</td>
<td>301</td>
</tr>
</tbody>
</table>
Injection kicker magnets – transverse impedance

From the Tsutsui model, the transverse impedance of injection kicker magnets is very large, and needs to be significantly reduced (to be studied):

![Graph showing impedance vs. frequency for injection kicker magnets]
Ferrite – measured electromagnetic properties

Ferrites with various Curie temps. ($T_C$), @ 25°C:

CMD10B ($T_C \geq 190°C$) is a 50/50 blend of CMD5005 ($T_C \geq 125°C$) & CMD10 ($T_C \geq 250°C$)

CMD5005 at various “measured” temperatures:

- For $T_{Meas}$ increasing to ~125°C, initial permeability increases.
- For $T_{Meas}$ increasing, initial permeability decreases.

Note: from datasheet, CMD5005 $\approx 8C11$

Note: actual ferrite temperature < measured
Kicker magnet – ongoing R&D

CST simulations of both longitudinal and transverse beam coupling impedance.

Compare predicted impedance for beam screens consisting of:

✓ straight conductors (e.g. 24 parallel, as per the LHC injection kicker beam screen):

✓ helix serigraphy (e.g. 24 parallel – only one shown):
Conclusion and Outlook

- Length of injection kicker systems significantly reduced – greatly reducing contribution to beam coupling impedance;
- Characteristic impedance of injection kicker system has been optimized (6.25 Ω) together with the number of cells per magnet;
- Main harmonics and side harmonics of FCC spectrum have been analyzed;
- Beam coupling impedance has been determined analytically, without a beam screen:
  - A beam screen is necessary to limit beam induced heating;
  - Transverse impedance is high and needs to be significantly reduced.
- CST simulation of various beam screens has commenced.
Thank you for your attention !!

Questions ?
Bibliography

- Injection and extraction insertions and dump lines (F. Burkart, FCC Week 2017).
- Beam transfer technology challenges, including dump and dilution system design (W. Bartmann, FCC Week 2017).
- LHC at 3.3 HEB (W. Bartmann, FCC Week 2017).
- New design concepts for suppressing erratic triggering of solid state switch stacks (P. Van Trappen et al, FCCWeek 2017).