FCC-hh Injection and Extraction
Kicker Topologies
and Solid State Generators

T. Kramer, CERN TE/ABT
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Acknowledgements
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B. Goddard, J. Holma, A. Lechner, J. Rodziewicz, V. Senaj, T. Stadlbauer, D. Woog
Outline of presentation

Injection
- Requirements
- Magnet
- Inductive Adder and Marx Generator

Extraction
- Redefined requirements
- Segmented kicker system

Dilution
- Considerations on dilution pattern
- Kickers and generators

CERN TE-ABT
FCC-hh Beam Transfer Systems
TE Special Technologies WP 3

Slides to be seen in context with the presentations of this morning (W. Bartmann, B. Goddard and F. Cerutti).
Injection Kicker System Requirements

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic Energy</td>
<td>TeV</td>
<td>3.3</td>
</tr>
<tr>
<td>Available system length</td>
<td>m</td>
<td>150</td>
</tr>
<tr>
<td>Deflection angle</td>
<td>mrad</td>
<td>0.3</td>
</tr>
<tr>
<td>Field rise/fall time (0.5 % - 99.5 %)</td>
<td>ns</td>
<td>280</td>
</tr>
<tr>
<td>Field flattop duration</td>
<td>µs</td>
<td>2.25</td>
</tr>
<tr>
<td>Field flattop ripple</td>
<td>%</td>
<td>± 0.5</td>
</tr>
<tr>
<td>System impedance</td>
<td>Ω</td>
<td>5 ?</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>Hz</td>
<td>up to 115</td>
</tr>
</tbody>
</table>

- Focused studies on **3.3 TeV** injection energy (lower energy variants are less demanding to design).

- **3.3 TeV pulse duration** is limited to **2.25 µs** for machine protection reasons.

- Final system impedance depends on system optimization outcome.
Injection Kicker Magnet

- **Delay line type** magnet (will be initially based on the LHC injection kicker design).
- System will be **much shorter** than the available length of 150 m.
- Inside vacuum.
- Optimized beam screen.

**Additional magnet requirements**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet filling time</td>
<td>ns</td>
<td>( \leq 200 )</td>
</tr>
<tr>
<td>Magnet current</td>
<td>kA</td>
<td>2.6</td>
</tr>
<tr>
<td>Magnet voltage</td>
<td>kV</td>
<td>13</td>
</tr>
</tbody>
</table>
Injection Generator: Inductive Adder

• Design ongoing, impedance and dielectric evaluated (oil), magnetic cores specified.
• Characterization of components started.
• Assembly of prototype planned for 2017.
• Prototyping will profit from CLIC high precision developments.
• Successful development will have benefits for the CERN accelerator complex.

Additional generator requirements:

<table>
<thead>
<tr>
<th>Generator current</th>
<th>kA</th>
<th>2.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage range</td>
<td>kV</td>
<td>1.3 to 13</td>
</tr>
<tr>
<td>Output pulse rise time (0.5%-99.5%)</td>
<td>ns</td>
<td>80</td>
</tr>
</tbody>
</table>
Injection Generator: Inductive Adder

- Energy stored in distributed capacitors.
- Capacitors are partially discharged via SiC MOSFET switches in parallel branches.
- Several layers add up to the required output voltage.

Advantages:
- **Modularity**: the same module design can be used for different voltage/current specifications;
- **Short rise and fall times** can be achieved;
- Output pulse **voltage can be modulated** -> very good flat top quality.
- Switches and control electronics are referenced to ground.

Disadvantages:
- Output transformer limits maximum **pulse length** to typically ~3 μs;

Poster: “Inductive Adder Type Solid-State Pulse Modulator Development for Kicker Systems of the Future Circular Collider” by D. Woog et al.
Injection: Marx Generator

Alternative solution for longer flat top requirement.

- Capacitors **charged in parallel**, and **discharged in series** ⇒ high voltage output.
- **No output transformer** ⇒ maximum pulse length limited by droop of capacitor voltage.
- **Modularity**: the same design can be used for different voltage specifications.
- Switches and control electronics are **not referenced to ground**.
- Fail safe circuits to be investigated.
- **No modulation layer**.
- **Proposal** to develop a high power Marx Generator, under Portugal 2020 programme, for replacing thyratrons and PFN/PFL has been submitted.

Poster: “Marx Generator Solid-State Pulse Modulator Application to Kicker Systems of the Future Circular Collider” by M.J. Barnes et al.
Extraction Kicker System

- Part of a safety critical system: Up to 8.5 GJ to be safely extracted and dumped.
- **Extraction** Kickers & Generators
- **Horizontal Dilution** Kickers & Generators
- **Vertical Dilution** Kickers & Generators

<table>
<thead>
<tr>
<th>Unit</th>
<th>Extraction</th>
<th>Dilution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic Energy</td>
<td>TeV</td>
<td>3.3 to 50</td>
</tr>
<tr>
<td>Available length</td>
<td>m</td>
<td>130</td>
</tr>
<tr>
<td>Deflection angle</td>
<td>mrad</td>
<td>0.13</td>
</tr>
<tr>
<td>Field rise time (0.5-90%)</td>
<td>µs</td>
<td>1</td>
</tr>
<tr>
<td>Field flattop duration</td>
<td>µs</td>
<td>≥ 333</td>
</tr>
<tr>
<td>Magnet current</td>
<td>kA</td>
<td>0.5 to 8</td>
</tr>
<tr>
<td>Output voltage range</td>
<td>kV</td>
<td>~10</td>
</tr>
</tbody>
</table>

- Initially challenging requirements. BT-Optics team developed very beneficial layout!
- Started with ultra high current considerations (tr=10µs).
- Evolved to a fast but **segmented system** for machine protection and feasibility reasons.
Extraction Kicker Magnet

Preliminary Design Concept:

- Based on (robust) LHC extraction kicker design.
- Outside vacuum (ceramic chamber).
- Segmented system (300 units per beam):
  - Allows for low inductance and fast rise time
  - Impact of one unit on beam $< 1\sigma$
  - 10 “Hot spares” included (increases system availability)

- With the help of the developed beam optics we succeeded to achieve reasonable design values!

Parameters (per module):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Modules</td>
<td>300</td>
</tr>
<tr>
<td>$B.dl [T.m]$</td>
<td>0.076</td>
</tr>
<tr>
<td>$k [\mu rad]$</td>
<td>0.517</td>
</tr>
<tr>
<td>$B [T]$</td>
<td>0.25</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>300</td>
</tr>
<tr>
<td>Inductance [$\mu H$]</td>
<td>0.38</td>
</tr>
<tr>
<td>Current [kA]</td>
<td>7.3</td>
</tr>
<tr>
<td>Voltage [kV]</td>
<td>10 *</td>
</tr>
<tr>
<td>Aperture (h/v) [mm]</td>
<td>36/36</td>
</tr>
</tbody>
</table>

* assuming additional circuit inductance (1$\mu H$)
Extraction Kicker Generator

- One generator per Magnet (10 kV / 7.3kA / 1µs system rise time)
- Challenge: Compensation stage to be designed for 330 µs.
  - Long flat top needs some thought (compensation circuits).
- Possibly using **GTO switch** technology:
  - long “on” state duration (330µs) – segmented system (lower current helps a lot vs. very high current concept)
  - Promising developments within the “wide band gap” sector.
  - Direct laser triggering being investigated.
- Again **reasonable** basic design values achieved but:
  - Reliability will be extremely important!
  - Radiation effects will be a serious issue which needs to be addressed.
  - Controls and trigger (re-trigger) interface will be challenging.

Poster: “Prospects for laser triggering of large arrays of semiconductor switches” by Janusz Rodziewicz

Talk: “Controls architecture challenges for beam dump kickers” by P. Van Trappen, Thursday
Dilution Kicker System

- Dump **pattern crucial** for survival of dump block!
- **No crossing**, 1.8 mm minimum bunch separation.
- **Spiral** seems to be the only good solution.
- **Painting inwards** to ease hardware design.
- Resulting dump radius of ~600 mm!

- Same **radiation concerns** as for extraction!
- Horiz. and vertical system could use the **same generator design**.
  - Vertical generators would be triggered at 90 degree of horizontal sine wave (= 5µs @50kHz).
  - Ok for scheduled dump but for asynchronous events only the horiz. dilution is available immediately. (First 5 µs of beam would be painted on a horizontal line before the spiral starts.) Impact to be checked.

Talk: “Absorber for beam dumping ” by A. Lechner et al.

Poster: “FCC Dump Pattern Studies” by D. Barna (Wigner Institut)
Dilution Kicker Magnets

- Unexpectedly the most challenging system!
- **Highest B.dl to deliver** and aperture of the vertical system increases with length.
- Introduced **2 vert. magnet types**.
- **Quad** after horiz. kickers for “over focusing” under study.
- **Short magnets** to allow for 3-turn coil and higher dilution frequency.
- **High number** of magnets: Impact of missing (or misbehaving) unit lower (to be optimized).

### Table: Kicker Magnets

<table>
<thead>
<tr>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.dl</td>
<td>Tm</td>
</tr>
<tr>
<td>Leverage arm</td>
<td>m</td>
</tr>
<tr>
<td>Angle</td>
<td>mrad</td>
</tr>
<tr>
<td>Max. deflection</td>
<td>m</td>
</tr>
<tr>
<td>Design frequency</td>
<td>kHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit</th>
<th>Horiz. Vert.1 Vert. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. B-field</td>
<td>T 0.85 0.5 0.4</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>m 0.85 0.9 0.9</td>
</tr>
<tr>
<td>Horiz. aperture</td>
<td>mm 62 81 104</td>
</tr>
<tr>
<td>Vertical aperture</td>
<td>mm 40 58 81</td>
</tr>
</tbody>
</table>

Horizontal: 48 magnets, 54 m
Vertical 1: 39 magnets, 43 m
Vertical 2: 48 magnets, 54 m

Total length: ~150 m
Dilution Kicker Generators

<table>
<thead>
<tr>
<th>Magnet Inductance [µH]*</th>
<th>I [kA]*</th>
<th>U [kV] **</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Vertical 1</td>
<td>4.8</td>
<td>10.8</td>
</tr>
<tr>
<td>Vertical 2</td>
<td>4.4</td>
<td>11</td>
</tr>
</tbody>
</table>

* For magnet with three turn coil.
** 1µH considered for additional circuit Inductance.

- Reasonable main capacitance: 1.8 µF
- Amplitude decay needs to be improved to avoid getting higher density towards the centre.
Summary/Outlook

- **Three challenging kickers systems** in FCC-hh (Injection, extraction, dilution).
- Development of **semiconductor generators** will also have a benefit for the CERN accelerator complex.
- **A segmented extraction system** topology has been developed.
- Since the basic ideas have settled, interfaces to **reliability engineering, risk assessment and machine protection** need to be addressed next.
- **Radiation hard design** needs to be studied.
- Several **international collaborations** on kicker technologies established/proposed.
- Initially **challenging basic design requirements** have been translated together with all collaborators and the TE-ABT team into a **feasible design draft**
  no technology show stopper identified yet!
- Nevertheless: the big challenge will be the **system safety and reliability**!!

Discussions on the presented topics are very welcome!
Grazie per l’attenzione!
Thank you for your attention!