Kicker Systems - Part 2 - Hardware: Existing and Future

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Contributions from:
Overview of Presentation

Part 1:
- What is a kicker system?
- Importance of pulse shape
- Deflection due to Electric and Magnetic fields
- Major design options
- Pulse transmission in a kicker system
- Main components of a kicker system and examples of hardware

Part 2:
- Hardware: Issues & “Solutions”
- LHC Dump System
- Exotic Kicker Systems
- Possible Future Machines
Thyratron Turn-On (1)

Typically a three-gap thyratron is used (can hold-off 80 kV). Once triggered:

a) ‘Gap K’ turns on first;
b) ~40ns later ‘Gap C’ turns on;
c) ~40ns later ‘Gap A’ turns on ⇒ current pulse rising edge.

Due to parasitic capacitances:
‘Gap K’ and ‘Gap C’ turn-on result in ‘displacement current’ before the main current-rise.
Thyratron Turn-On (2)

Without DISI: transmission line ($\tau_\chi$) is impedance matched to kicker magnet ⇒ no reflection ($\Gamma=0 \Rightarrow V_R=0$).

With DISI: DISI is initially a high-impedance c.f. transmission line ($\tau_\chi$) ⇒ reflection ($\Gamma=+1 \Rightarrow V_R=V_I$).
With a Dump Switch:
- Fall not much faster than no dump/clipper;
- + Dissipates remaining PFN energy in dump resistor;
- + Reduce duration of field pulse, e.g. in the case of a main-switch erratic (not shown);
  - BUT: no influence on field until single-way delay of PFN and transmission line after triggering dump switch.
Clipper Switch (1)

Without a Clipper Switch (or dump):
- Relatively slow fall-time of field (2-way delay of PFN ⇒ relatively high attenuation & dispersion);
- No means of rapidly discharging PFN, other than via the main switch;
- No means of reducing length of field pulse in magnet, e.g., in the case of a main switch erratic.

Note: dump replaced by inverse diode

Diagram:
- RCPS
- PFN
- Main Switch
- Transmission Line
- Kicker Magnet
- Terminating Resistor
- Dump Resistor
- Inverse Diode

Graph:
- Normalized Field (%)
- Elapsed Time (μs)

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With a Clipper Switch:

- Relatively fast fall-time of field;
- Faster than a dump-switch (DS: 1-way delay of PFN ⇒ cut-of frequency, attenuation & dispersion);
- Dissipates remaining PFN energy in dump resistor;
- Permits rapid discharge of PFN, other than via the main switch.
With a Clipper Switch:
- Relatively fast fall-time of field;
  - Faster than a dump switch;
- + Dissipates remaining PFN energy in dump resistor;
- + Permits rapid discharge of PFN, other than via the main switch;
- + Rapidly reduce duration of field pulse, e.g. in the case of a main-switch erratic;
  - Note: unlike dump switch, clipper action is NOT delayed by single-way delay of PFN

![Diagram of CERN SPS “Pre-2016” MKE4 System]

![Graph showing normalized field over elapsed time with different clipper settings]
Need for Beam Transfer Protection

• Beam Transfer Protection devices **protect valuable equipment** and also increase machine availability (see talks by Chiara & Annika);

• Critical beam transfer systems need redundancy and multiple layers of protection:
  – “Fail-Safe” design
  – **Active protection** systems
  – **Passive protection** devices form the last layer of security

• **Failures** associated with beam transfer equipment are typically very fast and difficult to catch.
  – In 2004 an extraction septum power supply failure directed $3.4 \times 10^{13}$ protons at 450 GeV into the transfer line vacuum chamber (2.5 MJ beam energy):

![Image of a 25 cm long hole in chamber with damage visible over ~1m (melted steel)]
Dedicated injection dump (TDI) to protect against fast failures of the injection kicker system.

a) Normal injection process
b) No turn-on: injected beam steered onto absorber
c) Erratic (slides 11-12) turn-on / mistiming: circulating beam steered onto absorber
d) Flash-over (short-circuit) in kicker magnet (slides 13-15): e.g. in one LHC injection kicker magnet ⇒ 75% to 125% of nominal system deflection
Active Protection – Real Case

- Beam Energy Tracking System (BETS) measures PFN voltage of MKI system – in case of incorrect voltage, extraction from SPS is inhibited;
- In the event of an MKI Erratic (self-triggered) turn-on of a main switch: the other 3 main-switches and four dump switches are triggered, e.g. on 2/9/2016 (876 circulating bunches of which ~210 miskicked):

1) Erratic of a main switch during resonant charging of PFN (70%)
2) Circulating batch grazes on lower TDI jaw
3) Other 3 main switches & 4 dump switches turned on
4) ~70% of nominal deflection
5) Some circulating bunches graze on lower TDI jaw during fall time
Minimizing Erratic Turn-Ons

- Erratic turn-on is a statistical event;
- Erratic rate is dependent upon, amongst other things, time for which high voltage is applied to the thyratron switch;
- **Minimize duration of high-voltage, and thus erratic rate, by fast resonant charging of PFN/PFL;**
- Only one erratic, while preparing for LHC injection, during 2016 and none during 2015.
Example of Flashover in a Kicker Magnet (1)

- Flashover 30% into one magnet:
  - Current doubles at short-circuit;
    - $30\% \times 2 \Rightarrow 60\%$ of normal deflection from this magnet;
    - $25\% \times 3 + 60%/4 \Rightarrow 90\%$ of total, normal, system deflection.

Four kicker magnets, each terminated with a TMR (not shown).
Four kicker magnets, each terminated with a TMR (not shown).

- Flashover 60% into one magnet:
  - Current doubles at short-circuit;
    - \(60\% \times 2 \Rightarrow 120\%\) of normal deflection from this magnet;
    - \(25\% \times 3 + 120%/4 \Rightarrow 105\%\) of total, normal, system deflection.
Flashover 100% into one magnet:
- Current doubles at short-circuit;
  - $100\% \times 2 \Rightarrow 200\%$ of normal deflection from this magnet;
  - $25\% \times 3 + 200%/4 \Rightarrow 125\%$ of total, normal, system deflection.
Minimizing Flashover with Beam

- At design stage, ensure adequately low electric field (proper clearances, avoid sharp corners, ….);
- Properly high voltage condition magnets after assembly – see next slide;
- Beware of pressure rise during operation (Paschen curve);
- Verify/recondition LHC injection magnets, with high voltage, before injection, (SoftStart) – see next slide.

![Example Paschen curve - Air](chart.png)

Breakdown Voltage (kV) vs. Pressure × Gap (Torr·cm)
MKI magnet flashovers in the LHC:

- **2016 / 2015:**
  - 4 / 5 during “SoftStarts” (~80% of pulses)
  - 3 / 0 with beam (~20% of pulses)

- In 2016, disproportionate number of flashovers with high-intensity beam: shows deconditioning effect of LHC beam.

- Flashovers in LHC already reduced by a short (re-)conditioning (SoftStart) following dump of beam.
Beam Induced Heating

- **Injected beam**
- **Circulating beam**
- **Kicker magnet** (installed in circulating beam)
- **Quad**
- **Screen**
- **Ferrite**

Above the Curie Temperature the ferrite temporarily loses its permeability.
Example of Beam Induced Heating

LHC injection kicker magnets: high intensity physics fills, July 2016:

![Graph showing measured temperature and total beam induced power loss.](image)

- **Note:** very long thermal time-constants for both heating and cooling.
Kicker magnets are generally in vacuum tanks, hence thermal energy (e.g. in ferrite yoke) can be challenging to extract:

- Difficult to directly cool – because yoke is at pulsed high voltage;
- No convection;
- Cooling generally by radiation and thermal conduction.

The CERN SPS extraction kicker magnets have relatively long cells (~240mm) and can be indirectly cooled:

In general it is better to avoid, if possible, heat deposition in the kicker magnet ferrite yoke.
Need to reduce real impedance seen by beam:
- e.g. install an alumina tube between beam and ferrite;
- metallize alumina tube on inner surface to screen ferrite yoke from beam:

BUT:
- Eddy currents, during field rise and fall, are induced in metallization.
- A sheet-resistance of >~20kΩ/□ is required so that field rise-time is not unduly increased – but this sheet-resistance is too high to shield the ferrite from beam…..
Reduction of Beam Induced Heating (2)

- E.g. alumina tube (~3m) with slots on its inner wall;
- Screen conductors installed in slots;
  - Connected to beam pipe at far end of alumina tube;
  - Capacitively coupled, through dielectric of alumina tube, at near end.
- Eddy currents, induced during field rise and fall, do not unduly influence the field.

**BUT…**

Beam screen conductors within aperture – requires a larger aperture ($V_{ap}$):

$$B_y \approx \mu_0 \left( \frac{N \cdot I}{V_{ap}} \right)$$

- Hence higher current in kicker magnet, for a given magnet length;
- Hence higher PFN voltage, for a given impedance.
High voltage is transiently induced on the screen conductors – which can introduce flashover problems…..

From Faraday’s Law:

\[ V = -A \left( \frac{dB_x}{dt} \right) \]
Beam Coupling Impedance Reduction (2)

For existing kicker magnets, where beam coupling impedance must be reduced and the available aperture cannot be decreased:

- Serigraphy of ferrites (painted stripes) ⇒ negligible loss of aperture;
- Not as efficient, electromagnetically, as the screen conductors – but still good.
Terminating the output of a kicker magnet with a short-circuit can influence beam coupling impedance (below ~100 MHz) and increase beam induced power deposition.

"Tail" on real impedance
Beam Coupling Impedance: Magnet Termination

Terminating the output of a kicker magnet with a short-circuit can influence beam coupling impedance (below ~100 MHz) and increase beam induced power deposition.

"Tail" on real impedance

In addition, the “open” main switch, together with a short-circuit termination and $\tau_x$, can create impedance resonances (not shown).

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Electron Cloud

The alumina tube used, to support and insulate the screen conductors for the MKIs, has a high Secondary Electron Yield (SEY) – of up to 10!
⇒ High dynamic pressure rise due to electron cloud (>1000x background pressure).

High pressure during injection ⇒ increased probability of flashover and hence mis-kicking beam (high voltage on screen conductors).
Conditioning of alumina with beam can be very slow.....
Laboratory measurements show that Cr$_2$O$_3$, applied by magnetron sputtering, greatly reduces the SEY of alumina to a maximum of ~2. In addition, the SEY further conditions to below 1.4.

Decreased SEY should greatly reduce/eliminate significant pressure rise due to Ecloud and thus improve high voltage performance.

Evidence to date is that, independent of pressure rise, Cr$_2$O$_3$ also improves high voltage performance.

Cr$_2$O$_3$ coated pieces to be installed in the SPS, for testing with beam, in the coming months.
High V oltage Connectors

High voltage (e.g. 50kV), high current (e.g. 5kA), impedance matched (coaxial), connectors are VERY challenging to make…. In addition, once a bad contact and sparking commences, the connector can rapidly deteriorate….

LHC injection kicker: high voltage, high current vacuum feedthrough
Proton Energy: 7 TeV

In order to achieve very high luminosity:

Number of bunches per beam: 2808
Number of protons per bunch: 1.25 \times 10^{11}

\[ \{ 3.5 \times 10^{14} \text{ protons / beam} \]

\textbf{Stored energy per beam: 390 MJoules}

The beam dump (8 m long graphite block) is the ONLY element of the LHC that can safely absorb all the beam !!

\textbf{Ultra-reliable beam dump systems are required}......

Kickers are turned-on in a particle free 3 \mu s long \textit{abort gap}: the following beam bunches are then deflected into a dump line.
Fast Single Turn Extraction: LHC Dump

LHC beam dump systems, 2x ~1000 m long, in LHC straight section 6:
In some kicker applications thyratron switches cannot be used; e.g. for the dump (abort) kickers in the LHC where - the generator voltage must track the beam energy and NO self-firing is allowed.

### LHC Nominal Cycle

<table>
<thead>
<tr>
<th>Event</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp down</td>
<td>≈ 18 Mins</td>
</tr>
<tr>
<td>Pre-Injection Plateau</td>
<td>15 Mins</td>
</tr>
<tr>
<td>Injection</td>
<td>≈ 15 Mins</td>
</tr>
<tr>
<td>Ramp</td>
<td>≈ 28 Mins</td>
</tr>
<tr>
<td>Squeeze</td>
<td>&lt; 5 Mins</td>
</tr>
<tr>
<td>Prepare Physics</td>
<td>≈ 10 Mins</td>
</tr>
<tr>
<td>Physics</td>
<td>10 - 20 Hrs</td>
</tr>
</tbody>
</table>

Acceleration of the beam to the required energy and subsequent physics can be for > than 10 hours!

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Requirements for Abort System (MKD)

- Function: deflect beam into extraction septum; field rise during abort gap.
- Turn-on desirable only in abort gap – i.e. synchronous turn-on;
- Asynchronous turn-on ⇒ beam swept over downstream equipment. Hence self-triggering (erratic) highly undesirable;
- **Abort system MUST turn-on when required**;

- Abort system requires 14 kicker magnets and pulse generators per beam – 15 are used.
- Health of abort system is continuously monitored and beam is dumped if anything goes out of pre-specified thresholds.

- Rise time < 2.8 μs;
- Fixed deflection angle of 0.28 mrad (for 450 GeV to 7 TeV): **Voltage ∝ beam energy**;
- Operated at up to 19 kA / 29 kV.
Semiconductor Switches for MKD

High power thyristors (semiconductor switches) allow a wide dynamic range of operation [voltage α beam energy (450 GeV to 7 TeV)].

Two parallel GTO stacks per switch (one stack can carry the required current).

**BUT:**
- Semiconductors may be influenced by ionizing radiation and neutron flow from both cosmic rays and from the LHC;
- Radiation effects may be cumulative, with relatively slow deterioration of performance, or sudden (Single Event Effect - SEE);
- For power semiconductors SEE can lead to Single Event Burnout (SEB).

**LHC MKD parameters:**
- Ten series GTO’s ($V_{DRM}=4.5$ kV);
- Voltage range: $2.1$ kV – $29$ kV (450 GeV to 7 TeV);
- Current range: $1.2$ kA – $19$ kA;
- Magnet current flat top: $\sim 93$ μs;
- Maximum $di/dt$ specification: $20$ kA/μs ($\sim 1/8$th of a thyatron).
To minimize radiation effects, 15 pulse generators in gallery parallel to LHC tunnel ⇒ connected to the magnets via ~30 m of 8 parallel transmission cables.
• Function: sweep beam in Lissajous figure on dump block
  – Separate horizontal and vertical kicker systems;
  – Sine and cosine-like current shapes over 90 µs;
  – Peak deflection angle of 0.28 mrad (for 450 GeV to 7 TeV).

• Main components
  – Kicker magnets (4 Horizontal and 6 Vertical per beam);
    • In vacuum, otherwise same technology as MKD.
  – Generators (1 per magnet and one GTO stack per generator)
    • 27 kV and 24 kA per generator;
    • CH & CV1 pre-charged;
    • Semiconductor switch excites an L-C oscillation;
    • RH & RV define damping coefficient.

See talk by Wolfgang concerning MKB failure modes
“Exotic” Kicker Systems
Double Kicker System: Concept

For extremely low ripple

Extraction with one kicker magnet:
- Would require a very uniform and stable field pulse.

Extraction with two kicker magnets:
- Two “identical” field pulses are required;
- One power supply sends the pulses to 2 “identical” kickers (kicker & anti-kicker).

- 1st kicker system for beam extraction;
- 2nd kicker system for compensation of jitter of deflection angle (ripple & droop) from 1st kicker;
- Figure shows 1st and 2nd kickers separated by a betatron phase of 2nπ: for a betatron phase of (2n−1)π the 2nd kick is in the other direction.

See talk by Verena

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Double Kicker System: Realization

Need to ensure that a bunch sees the same part of the flat-top at Kicker 1 and Kicker 2:
   •  Hence need for time-of-flight compensation.

Potential problems
   ➢ Different attenuation & dispersion of waveforms (due to beam time-of-flight);
   ➢ Unintended differences between magnetic characteristics of kicker & anti-kicker;
   ➢ Field uniformity in kicker magnets;
   ➢ Imperfections in beam-line elements/alignment between kicker & anti-kicker.
   ⇒ KEK/ATF achieved a factor of 3.3 reduction in kick jitter angle, with respect to a single kicker.
Extremely Fast Kicker System
System Overview

Schematic of Tail-Clipper

MOSFET Switch (8kV, 200A)

Note: both current flow and voltage on stripline plates/electrodes.

5V Trigger Pulse

Current in 50Ω load (2.5ns rise, 5.6kV PFL) ⇒ Field rise-time of ~3.2ns.
Deflection due to BOTH magnetic and electric field:

**Deflection due to Electric Field:**

- **Strip-line at positive voltage**
  
  Beam (e⁻)
  
  $F_e$
  
  (e⁻)
  
  $+V$

- **Strip-line at negative voltage**

**Deflection due to Magnetic Field:**

- **Striplines fed from beam downstream end**

  Beam (e⁻)

  $F_m$

  (e⁻)

  $-V$

**Note:** $F_e = F_m$ for the tail clipper.
Possible Future Machines
High-Luminosity LHC is the #1 priority and will increase number of collisions by a factor of 10 from 2024. Then... ??

Many challenges:
- Technological demands;
- Reliability (time to access);
- Redundancy;
- ....

Goal of the FCC and CLIC studies:
- examine feasibility of various machines
- evaluate their costs.

FCC: 2 x 50 TeV beam, 16 - 20 T dipoles for 10 - 12 km bending radius

CLIC: 48 km long linear accelerator, with a lot of RF klystrons and modulators

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Inductive adder (CLIC)

- Turn-on AND Turn-off Capability – hence PFN/PFL is NOT required: instead **Capacitors** are used to store energy;
- Excellent scalability;
- Output pulse can be modulated (next slide);
- Prototype under design: 12.5 kV, ~300 A, 1µs, **required flat-top stability ±0.02 % !!**

- **BUT:** pulse length is limited by saturation of magnetic material….
Compensation of Droop and Ripple

\[ V_{\text{load}} = V_{\text{cv}} + V_{\text{mod}} \]

- **Compensation of droop**
- **Slope due to voltage droop of capacitors**
- **“Constant” voltage layers of Inductive Adder (have capacitors)**
- **Modulation layers**

Graph showing:
- Measured, compensated (modulated), output pulse (100 averages)
- ±1.0 V (±0.04%)
- 900 ns

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CLIC Damping Ring (DR) specifications: Field inhomogeneity:

- ±0.1% (±1000 ppm) for DR injection (over 3.5 mm radius);
- ±0.01% (±100 ppm) for DR extraction (over 1 mm radius).

Theoretically field homogeneity achieved – striplines installed at ALBA (ES) for measurements.
CERN collaboration with Instituto Superior de Engenharia de Lisboa (ISEL), Portugal, to develop a high repetition-rate, semiconductor based, Marx generator.

### Specifications of this Marx generator include:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage rise/fall time</td>
<td>µs</td>
<td>0.1</td>
</tr>
<tr>
<td>Field flattop duration</td>
<td>µs</td>
<td>0.5 to 100</td>
</tr>
<tr>
<td>Output load</td>
<td>pF</td>
<td>150</td>
</tr>
<tr>
<td>Output voltage</td>
<td>kV</td>
<td>up to 10</td>
</tr>
<tr>
<td>Normal rep-rate</td>
<td>kHz</td>
<td>up to 1</td>
</tr>
</tbody>
</table>

10.5 kV, 1 kHz operation:
Solid-State Marx Generator (1)

Electrical circuit first described by Erwin Otto Marx in 1924 – until recently the Marx did not use semiconductor switches.

**Concept: generate a high-voltage pulse from a low-voltage DC supply.**

The circuit operates by **charging capacitors in parallel**, then subsequently connecting them in series to generate a high-voltage output pulse.

**STEP 1**

1a) All the odd numbered MOSFETs/IGBTs (i.e. M1, M3, M5, …) are off.

1b) The capacitors (C1, C2 , … C5) are charged in parallel, from Vdc, by turning-on all the even numbered MOSFETs/IGBTs (i.e. M2, M4, M6, …) [Vmarx ≈ 0 V]:

![Diagram of the Marx generator](image-url)
The circuit operates by charging capacitors in parallel, then subsequently connecting them in series to generate a high-voltage output pulse.

**STEP 2**

2a) Capacitors $C_1$, $C_2$, … $C_5$ have been charged to $V_{dc}$ in step (1b). All the even numbered MOSFETs/IGBTs (i.e. $M_2$, $M_4$, $M_6$, …) are then turned off.

2b) All the odd numbered MOSFETs/IGBTs (i.e. $M_1$, $M_3$, $M_5$, …) are then turned on, to connect the capacitors in series. $V_{\text{MARX}} \approx 5 \cdot V_{dc}$
Application of New Technology to CERN Kickers

- 45 year old system, in CERN PS, that utilizes a PFL (coaxial cable), pressurized with SF6, pre-charged to 80 kV;
- PFL is aging and is expected to need replacement soon;
- System requires ~1 km of cable – now very difficult / impossible to source;
- Specifications include: 46 ns (96 ns) field rise (fall) time, 2.6 μs pulse length.

Alternative pulse generator design is required.
Pulse generator could be low source impedance to allow reduced “PFL” voltage, e.g.:
- Inductive adder (ongoing R&D at CERN);
- Solid-state Marx generator (collaboration commenced with ISEL and EPS, Portugal).

High reliability is an important requirement for the design.
High Burst-Rate Power Modulator

Required for CLIC:
a) ~700 kHz burst rate (for ~100 pulses) @ 50 Hz;
b) 10 kV, 200 A pulses – **low droop**;
c) “Collaboration” ongoing with **SLAC**.

Series switches ⇒ BIG capacitor. Hence a **variant of the typical inductive adder** topology (magnetic material) and full bridge inverter;
• Cells produce alternating positive and negative polarity pulses, but load output is single polarity;
• Flux alternates direction in the core, resetting cores magnetic state;
• “Low” voltage prototype demonstrated basic concept.

**Diagram:**

- **Q1, Q2, Q3, Q4**
- **Cell 1, Cell 2**
- **DC in**
- **To load**

**Graph:**

- **BH curve:**
- **Timebase:** 1 µs/div
- **Label:** Primary Current & Flux, Load Voltage, pri v 1, pri v 2
- **Measurement:**
  - \(\Delta V/\Delta N = 2.057 \mu s\)
  - \(\Delta I^* / \Delta N = 52.0 \text{ mV/ps}\)
- **Angle:** 60.6°
High energy beam to be injected into FCC. Hence important to avoid damage to downstream equipment (see talk by Chiara):

- **Reliable** kicker system is needed to avoid miskicking beam;
- A staggered transfer of batches with a reduced number of bunches is envisaged:
  - ~2 μs pulse duration, Field rise/fall time (0.5% - 99.5%), repetition rate up to 115 Hz.
- **Generator**: semiconductor switches foreseen (e.g. Inductive Adder or Marx generator):
  - R&D into both options has commenced;
- Magnet: R&D has commenced.
Stored energy per beam: **8.5 GJ**

Extreme **reliability** required….

- To minimize generator pre-fire
- Highly **segmented** dump system envisaged to allow for:
  - several missing modules
  - reduces impact of pre-trigger / erratic’s etc.
  - avoid asynchronous dump (i.e. synchronize timing with abort gap)
- **Ongoing R&D.**
Thank you for your attention.
Kicker System Bibliography – Part 2 (1)

Kicker System Bibliography – Part 2 (2)

Due to the close bunch spacing of 25 ns, in the LHC, a significant number of electrons can accumulate in the LHC beam pipe as a result of a combination of processes.

These seed electrons are accelerated by the beam electric field, can impact on the other side of the vacuum chamber and, if the secondary emission yield (SEY) is greater than unity, can create a large number of secondaries.

If the traversal time of the electron across the vacuum chamber is comparable to the time interval between two bunches, a resonance condition is established and the number of electrons grows exponentially (beam induced multipacting).

The STAIRCASE Bumper consists of 1 generator supplying two magnets:

- RCPS’s charge PFLs of same step;
- Each step can have a different PFL voltage;
- All steps are charged synchronously;
- PFLs are discharged by sequential triggering of thyatrons (starting at magnet end);
- A wave pattern is generated corresponding to PFL voltage.
Deflection due to ELECTRIC field between parallel plates:

\[
\Gamma = \frac{qE}{m_0c} = \frac{qV}{m_0c^2}
\]

50 Ω coaxial cable. 
~213ns single way delay per reel.

\[V/2 \text{ reflected} \]

\[\Gamma = 1 \]

\[\Gamma = -1 \]

\[+V/2 \text{ reflected} \]

\[-V/2 \]

\[\text{SWITCH} \]

\[\text{OPEN CIRCUIT} \]

(Pulse Doubling)

\[\text{SHORT CIRCUIT} \]

(Polarity Reversal)

\[\text{PULSE ADDITION}\]

1 MHz Chopper CW – Bidirectional Deflection
The current waveform consists of 4 main periods:

- **A**: SW1 & SW2 on, SW3 off;
- **B**: SW1 off, SW2 on, SW3 cycled on & off;
- **C**: SW2 & SW3 turned-off;
- **D**: SW1, SW2 & SW3 off.

Capability:
- Rise and fall times ~10’s of μs;
- Flat-top: 0 to DC.
Bi-Directional Kicker Magnet: Concept (1)

Concept:
1) Deflect beam in one-direction (e.g. up) to extract beam;
2) Deflect beam in opposite direction (e.g. down) to dump beam.

Potential issues
- Kicker magnet is charged to high voltage, together with PFLs – hence insulation must be adequate;
- Abort functionality is delayed by propagation delay $t_d$ (delay of PFL#2) after switch AB is turned-on.
Bi-Directional Kicker Magnet: Concept (2)

**Concept:**
1) Deflect beam in one-direction (e.g. up) to extract beam;
2) Deflect beam in opposite direction (e.g. down) to dump beam.

Abort/dump functionality is NOT delayed by PFL.

**Potential issues**
- Kicker magnet is charged to high voltage, together with PFLs – hence insulation must be adequate;
- For a fast field rise, two PFLs and four switches are required;
- Switches should be not be triggered by fast rates of change of voltage (e.g. triggering of FE#1 and FE#2, should not cause an erratic of AB#2).
## Example Parameters for Kickers in the CERN Complex

<table>
<thead>
<tr>
<th>Kicker Location</th>
<th>Max. Beam Energy (GeV)</th>
<th># Magnets</th>
<th>Gap Height $[V_{ap}]$ (mm)</th>
<th>Current (kA)</th>
<th>Impedance ($\Omega$)</th>
<th>Rise Time (ns)</th>
<th>Total Deflection (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTF3 TC</td>
<td>0.2</td>
<td>4</td>
<td>40</td>
<td>0.056</td>
<td>50</td>
<td>~4</td>
<td>1.2</td>
</tr>
<tr>
<td>PS Inj.</td>
<td>2.14</td>
<td>4</td>
<td>53</td>
<td>1.52</td>
<td>26.3</td>
<td>42</td>
<td>4.2</td>
</tr>
<tr>
<td>SPS Inj.</td>
<td>13/26</td>
<td>16</td>
<td>54 to 61</td>
<td>1.47/1.96</td>
<td>16.67/12.5</td>
<td>115/200</td>
<td>3.92</td>
</tr>
<tr>
<td>SPS Ext.</td>
<td>450</td>
<td>3 or 4</td>
<td>32 to 35</td>
<td>3.1 to 3.3</td>
<td>10</td>
<td>~6000 to 8000</td>
<td>~0.4 to 0.5</td>
</tr>
<tr>
<td>LHC Inj.</td>
<td>450</td>
<td>4 (x2)</td>
<td>54</td>
<td>5.12</td>
<td>5</td>
<td>~800</td>
<td>0.82</td>
</tr>
<tr>
<td>LHC Abort</td>
<td>7000</td>
<td>15 (x2)</td>
<td>73</td>
<td>1.3 to 18.5</td>
<td>1.5 (not T-line)</td>
<td>2700</td>
<td>0.275</td>
</tr>
</tbody>
</table>
An Opera2D model of the PFN for the LHC Injection was used to predict self-inductance and mutual-inductance as a function of frequency.

Subsequently a circuit model of the inductance characteristic was fitted to the Opera2D predictions to permit realistic Pspice simulations.
Magnet Design Tools (1)

Design tools such as Opera2D and Opera3D (Elektra) are used for the kicker magnet design. Opera2D (AC) allows for eddy currents: it is used to predict magnetic field and central cell inductance, as well as to optimize the geometry of ferrite and busbars. Opera2D (static) can be used to predict electric field. Elektra is used for predicting end cell inductance and fringe fields.

Example prediction (Opera3D): total horizontal deflection uniformity.

Note: sum of deflections due to magnetic and electric fields

<table>
<thead>
<tr>
<th>Deflection Uniformity</th>
<th>Percentage area of specified aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>±1%</td>
<td>73.5%</td>
</tr>
<tr>
<td>±2%</td>
<td>86.1%</td>
</tr>
<tr>
<td>±3%</td>
<td>90.4%</td>
</tr>
</tbody>
</table>

\[ \theta_{\text{Horizontal}} = \theta_{B,x} + \theta_{E,x} \]
Capacitance to ground of an HV plate is influenced by insulators and nearby ground planes:

- Ground plate;
- Magnet frame;
- Ground conductor.

Software such as Coulomb, a 3D code from Integrated Engineering Software, can be used to accurately predict capacitance of a cell of a kicker magnet.
Sophisticated time-domain simulations of the transient response of kicker magnets are carried out with PSpice circuit analysis software. Simulations must model both physical components and parasitic elements. Complex models can include more than 10,000 circuit components to accurately model a kicker system.

Equivalent circuit for a 7 turn MKI PFN cell [damping circuit values for MS end cell in parentheses]:

- DC $\rightarrow$ 200Hz
- 200Hz $\rightarrow$ 5kHz
- 5kHz $\rightarrow$ 10MHz

**Grover Lower Limit (1766nH): solid conductor**

**Grover "Upper" Limit#1 (2208nH): solid conductor**

**Grover "Upper" Limit#2 (2147nH): tubular conductor**

Effect of Screen Shielding: Skin & Proximity Effect

- 40kHz
- 63kHz
- 25kHz
Sophisticated software such as CST (Computer Simulation Technology) can be used to model and predict beam coupling impedance, and beam based power deposition in various solids in the model of the kicker magnet.

Power loss distribution for post-LS1 MKI design
ppb=1.15e11, Nb=2808, bl=1ns

Upstream Rings
Downstream Rings
Ferrite Yoke

# Solid
Power Loss per Solid (W)
To reduce influence of switch erratic:
• Use 2 fully rated GTO switch stacks;
• Sw2 must hold voltage in case of Sw1 erratic and vice-versa.

Advantages in case of an erratic:
• Capacitor remains charged (could still be triggered if intelligent logic identifies the need for it !!)
• Little current through magnet (but see below)

Disadvantages:
• Still voltage over 2nd switch (voltage sharing) and full voltage pulse during 1st switch erratic
  • High dU/dt for 2nd switch in case of erratic firing of 1st switch
  • Impact of adapted snubber circuit on magnet current
• Higher probability of missing module (compared to LBDS)