CERN

Kicker Systems - Part 2 - Hardware: Existing and Future

M.J. Barnes
CERN TE/ABT

Contributions from:

A. Adraktas, W. Bartmann, C. Belver-Aguilar, E. Carlier, A. Chmielinska, H. Day, L. Ducimetière, B. Goddard, J. Holma, T. Kramer, J. Rodziewicz, V. Senaj, L. Sermeus, M. Taborelli, L. Vega Cid, V. Vlachodimitropoulos, W. Weterings, D. Woog

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

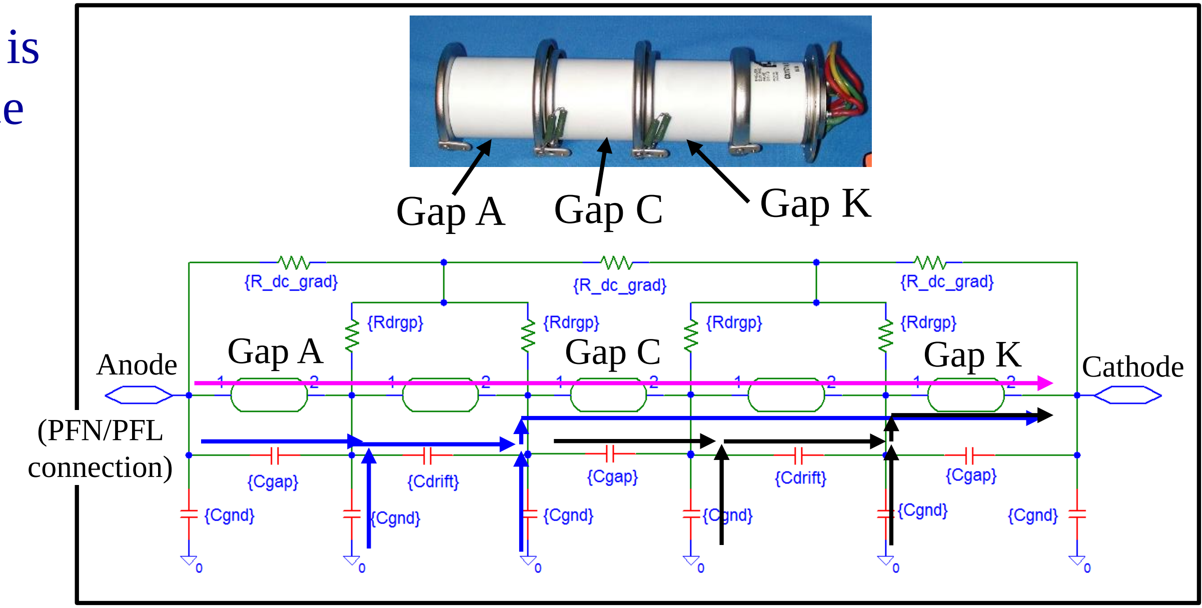
Thyratron Turn-On (1)

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

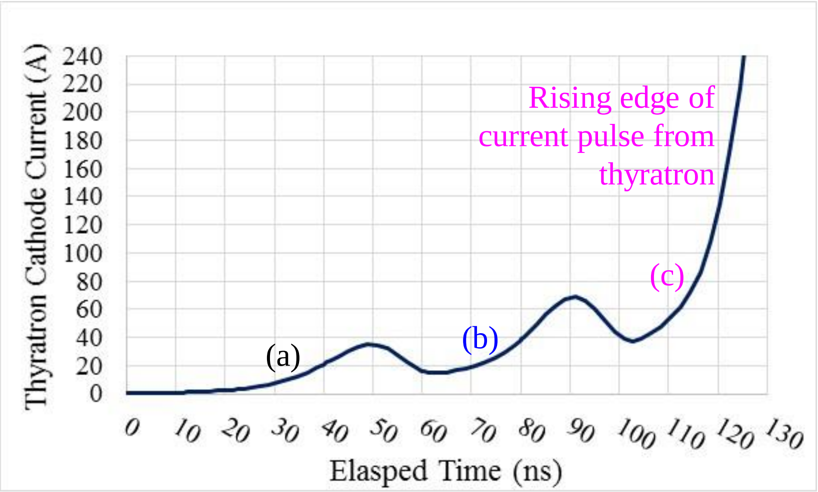
a) ‘Gap K’ turns on first;

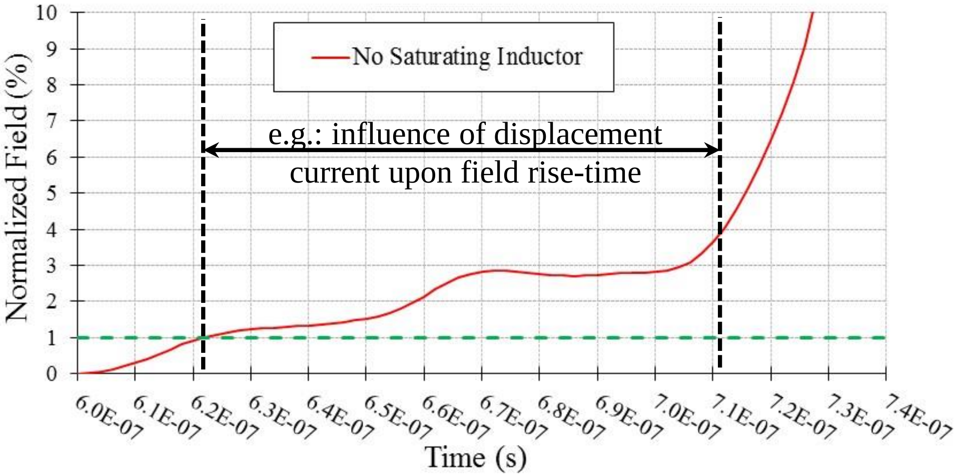
b) ~40ns later ‘Gap C’ turns on;

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.

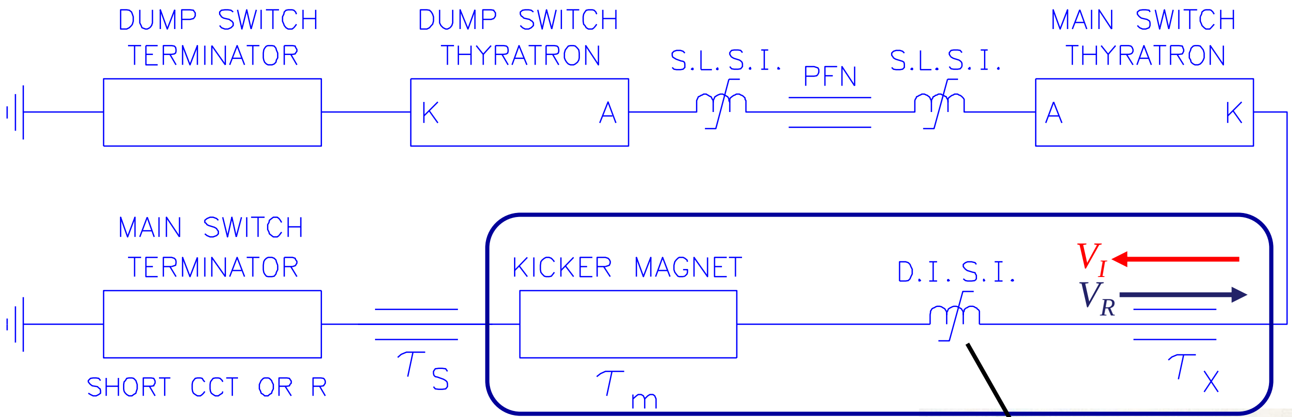


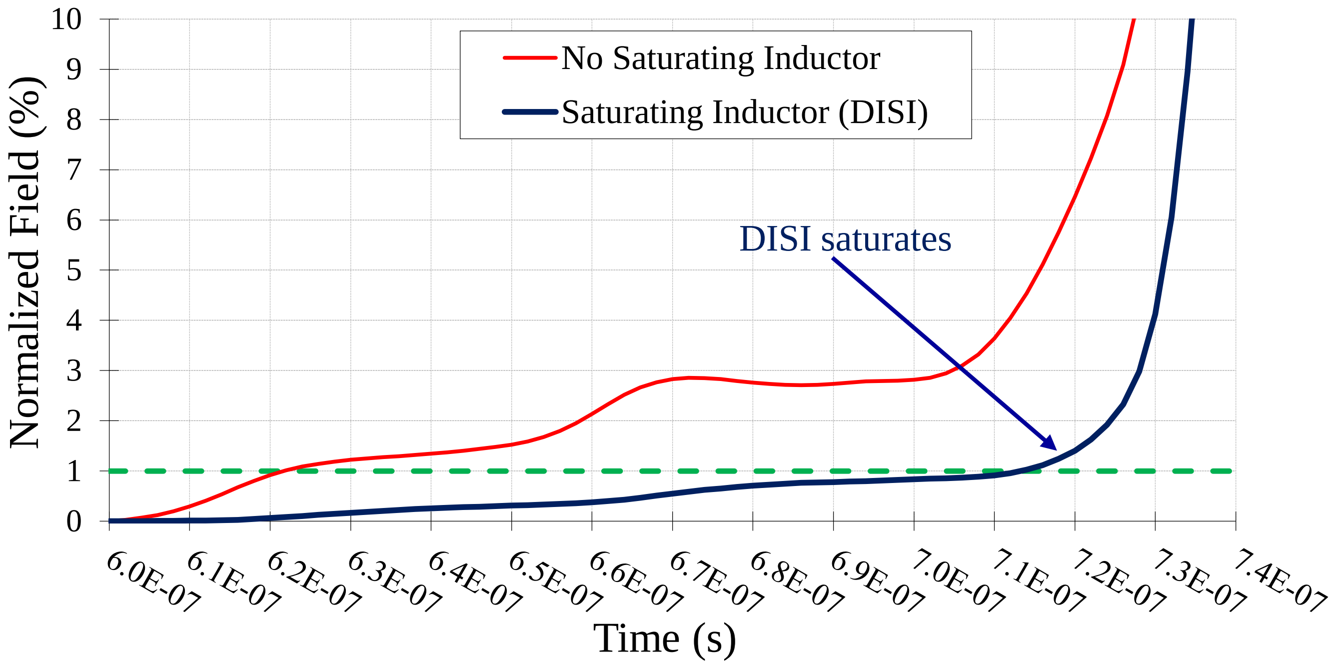


Thyratron Turn-On (2)

Without DISI: transmission line (τ_x) is impedance matched to kicker magnet ⇨ no reflection (Γ=0 ⇨ V_R=0).

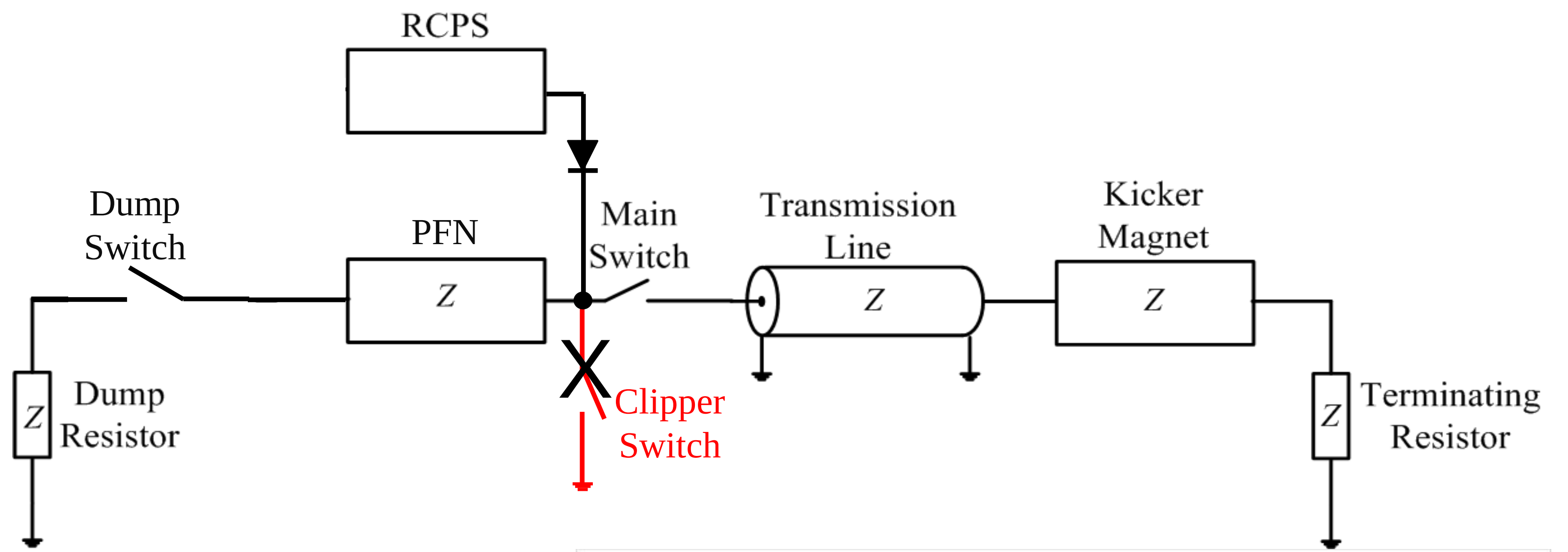
With DISI: DISI is initially a high-impedance c.f. transmission line (τ_x) ⇨ reflection (Γ=+1 ⇨ V_R=V_I).





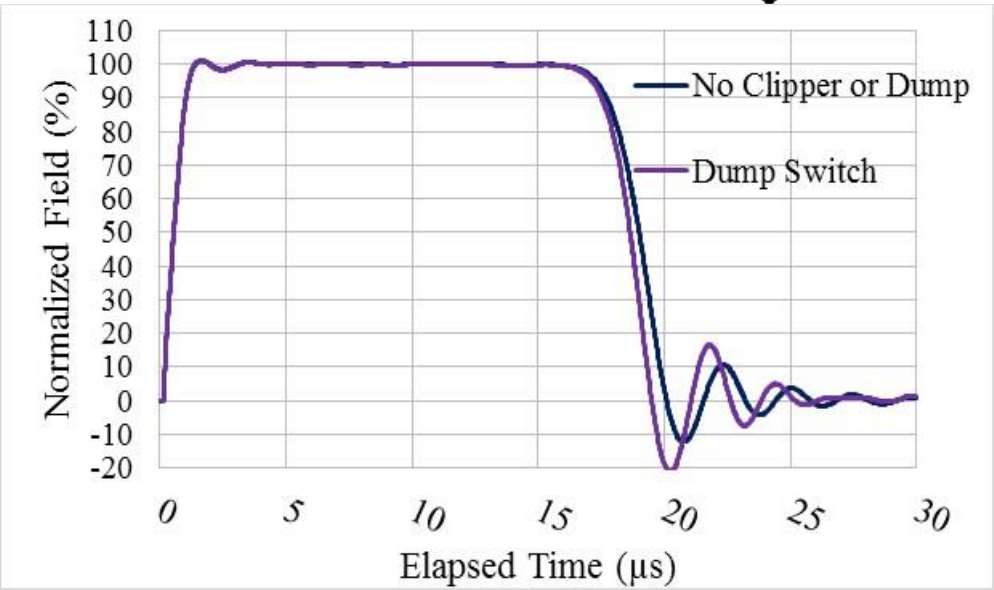
DISI: ferrite rings

Dump Switch

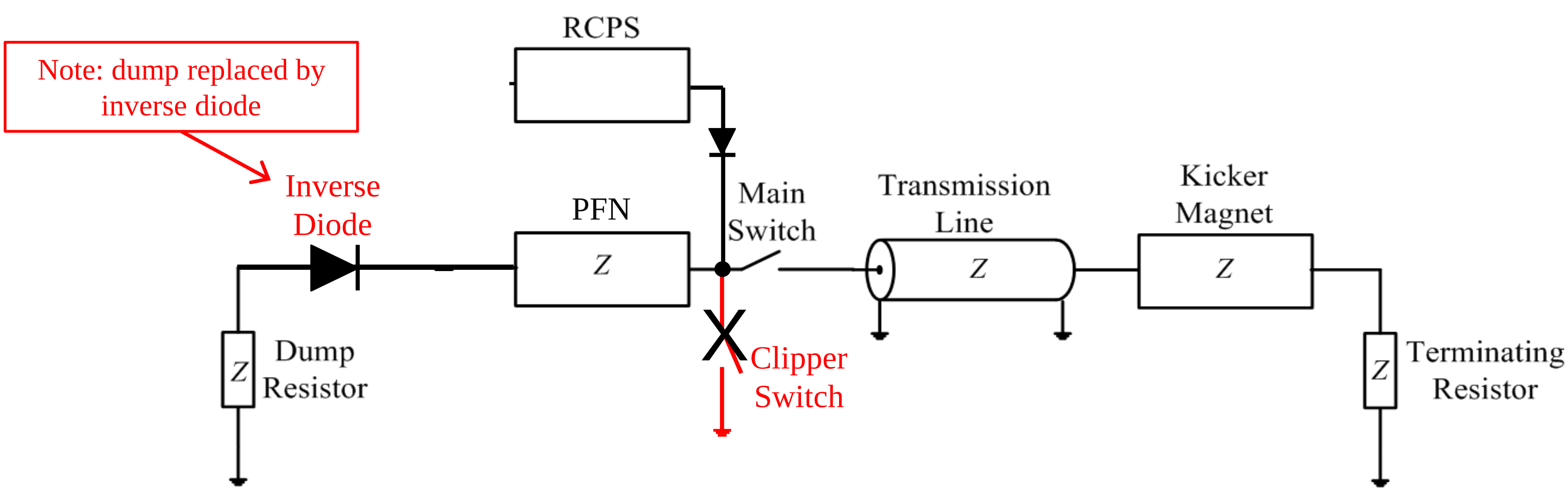


With a Dump Switch:

- 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.**

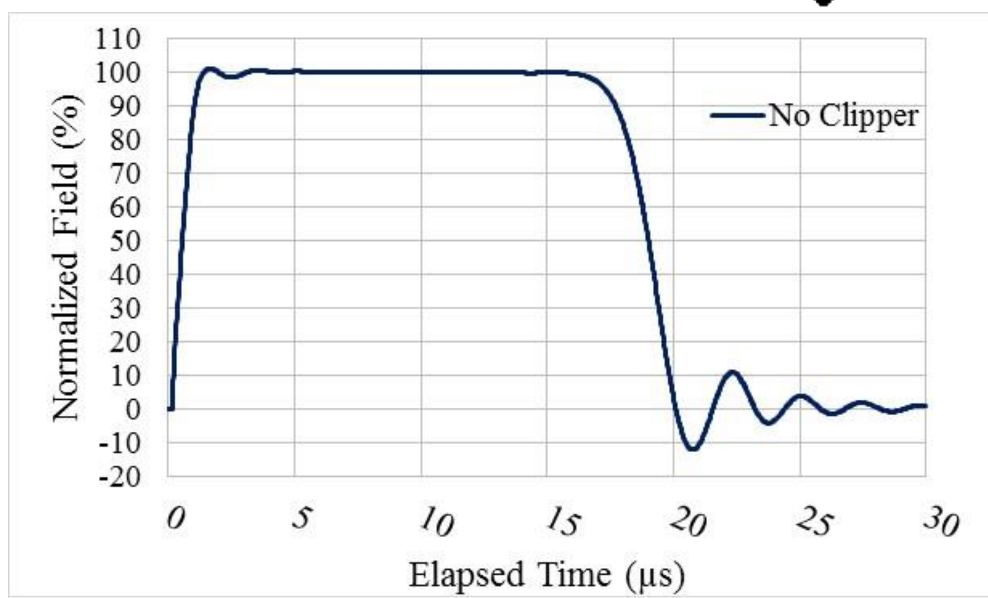


Clipper Switch (1)



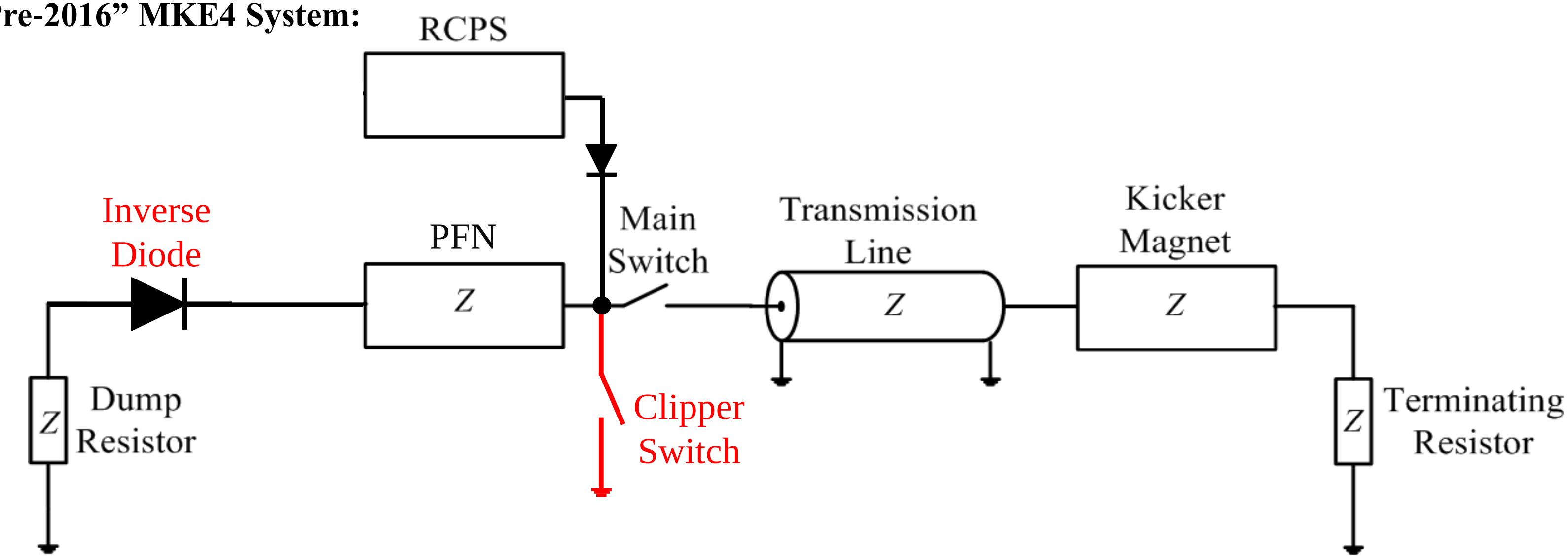
Without a Clipper Switch (or dump):

- 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.



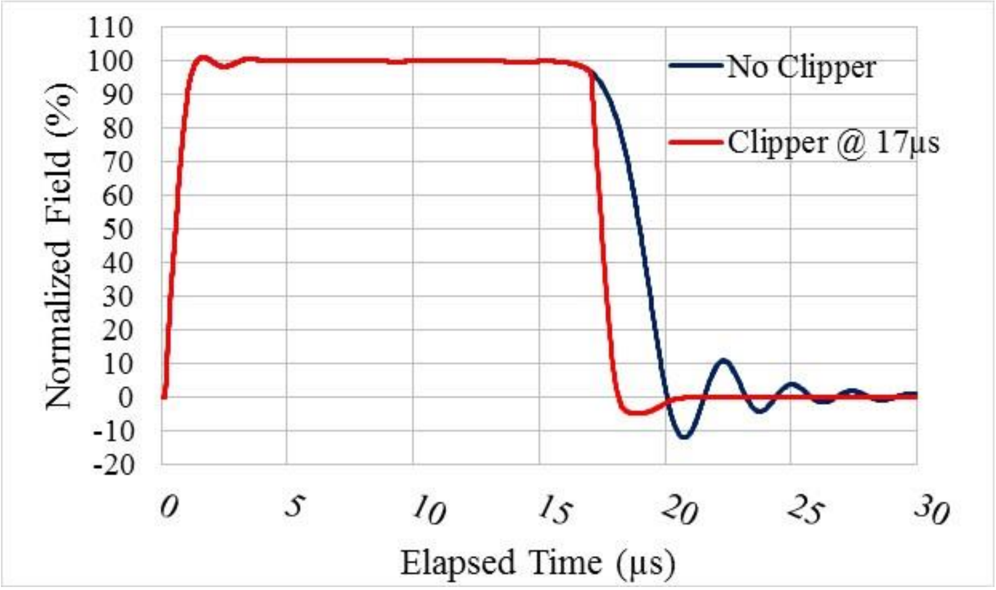
Clipper Switch (2)

CERN SPS "Pre-2016" MKE4 System:



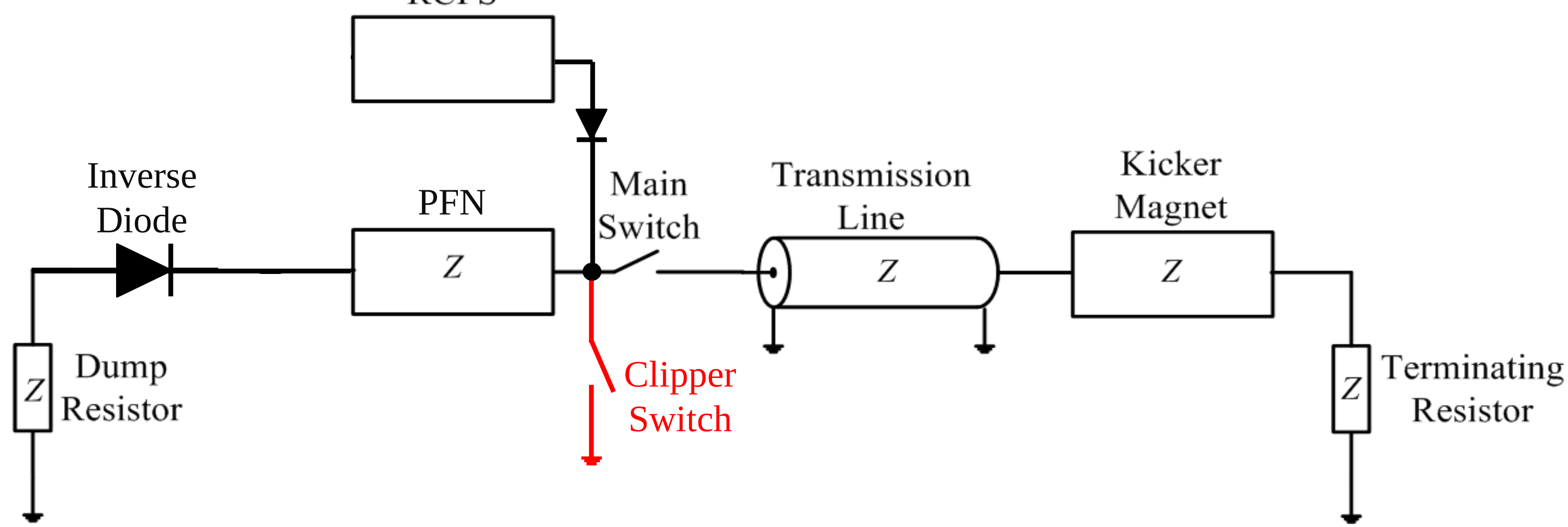
With a Clipper Switch:

- **+ 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, <u>other than via the main switch</u>.



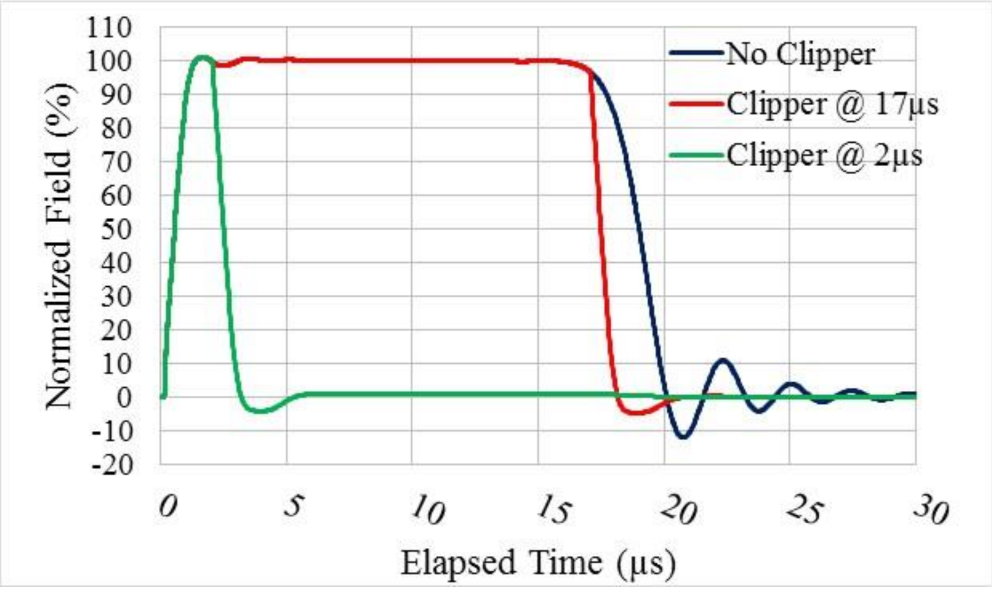
Clipper Switch (3)

CERN SPS "Pre-2016" MKE4 System:



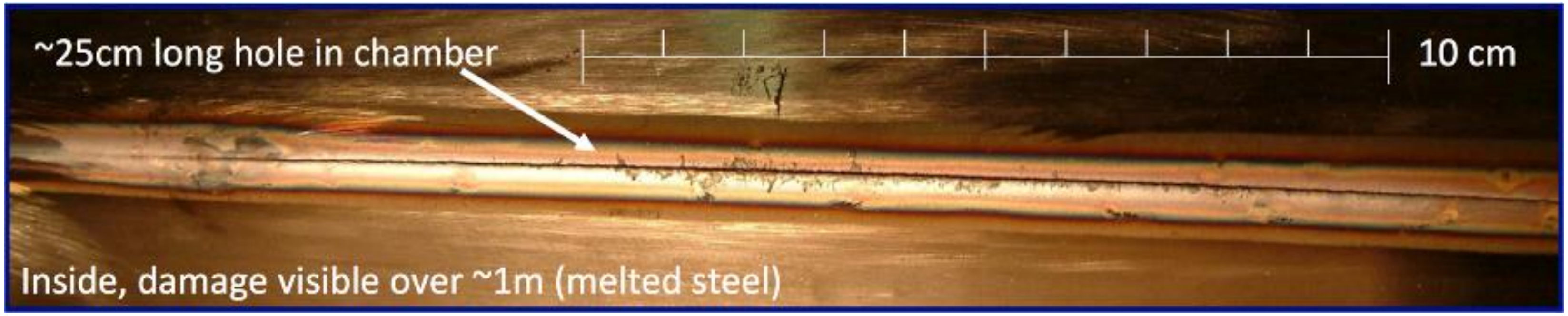
With a Clipper Switch:

- 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**



Need for Beam Transfer Protection

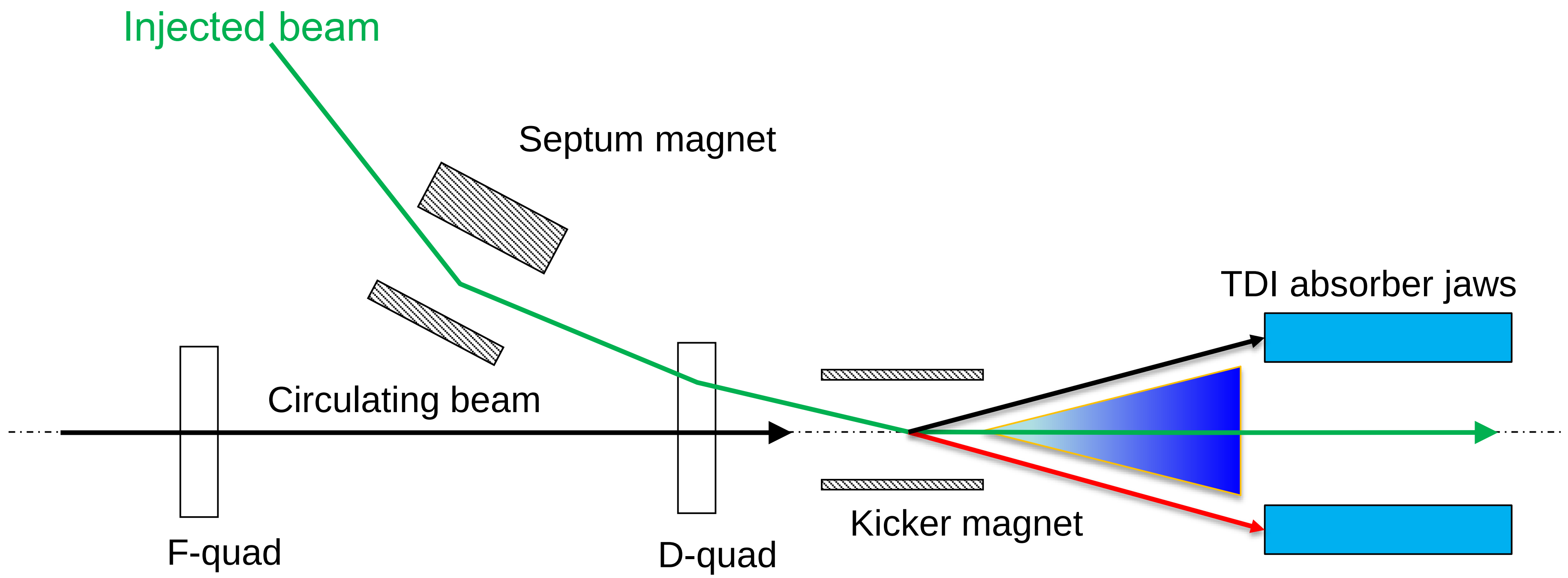
- Beam Transfer Protection devices **protect valuable equipment** and also increase machine availability (see talks by Chiara & Annika);
- Critical beam transfer systems need redundancy and multiple layers of protection:
  - **"Fail-Safe" design**
  - **Active protection** systems
  - **Passive protection** 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 3.4×10^{13} protons at 450 GeV into the transfer line vacuum chamber (2.5 MJ beam energy):



Example: Injection Protection Hardware

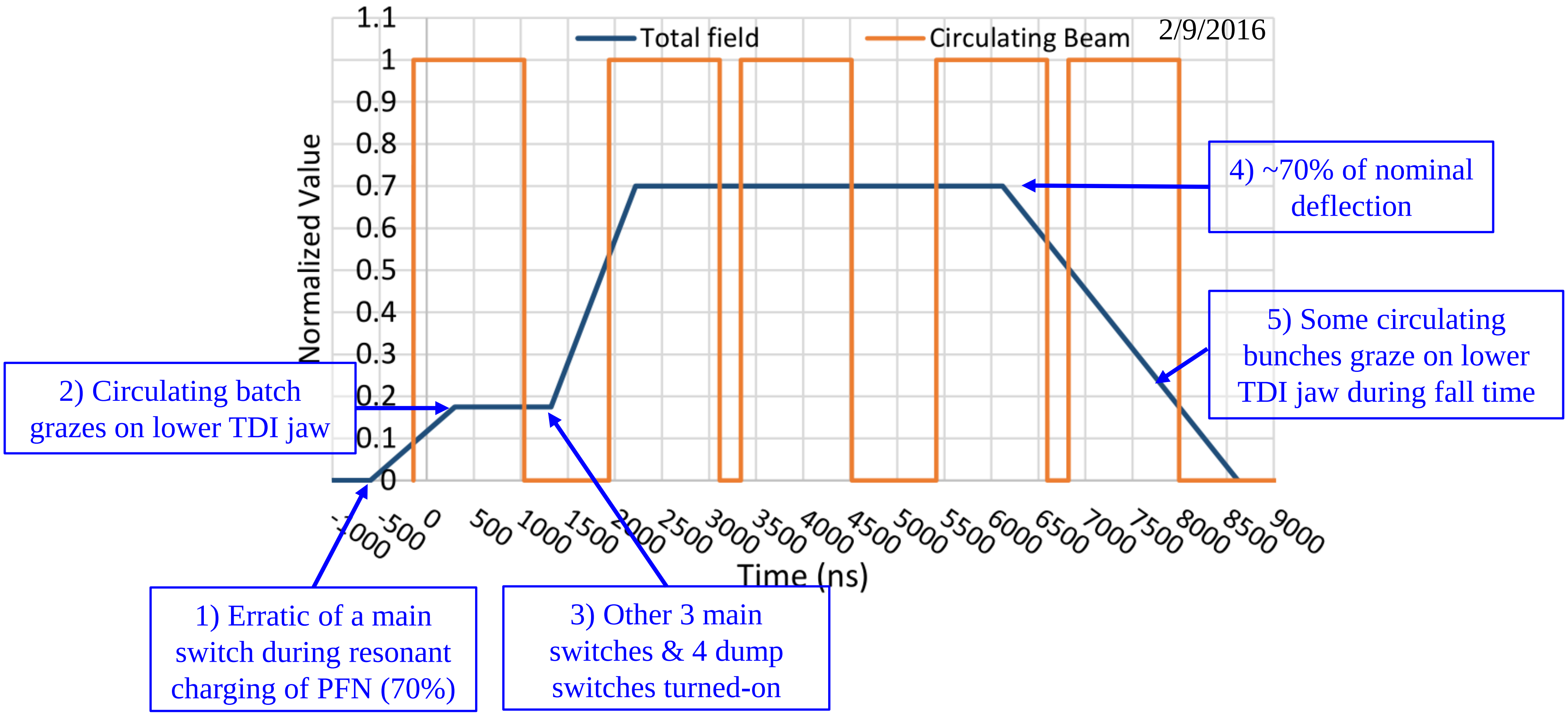
Dedicated injection dump (TDI) to protect against **fast** failures of the injection kicker system.

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

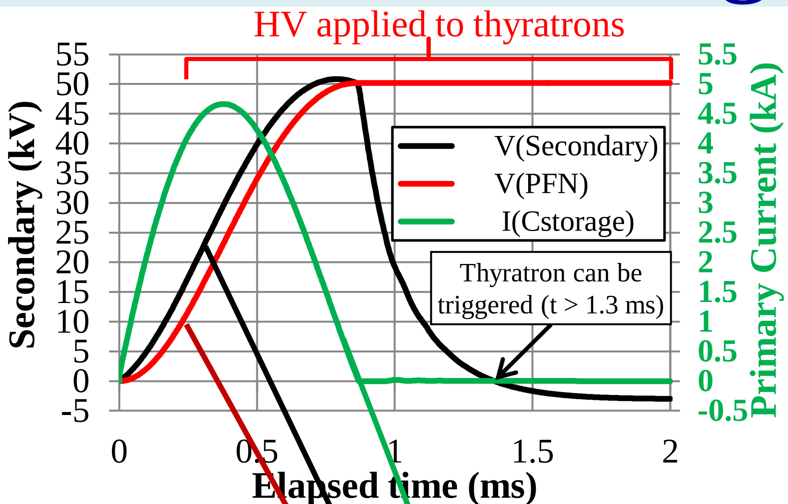


Active Protection – Real Case

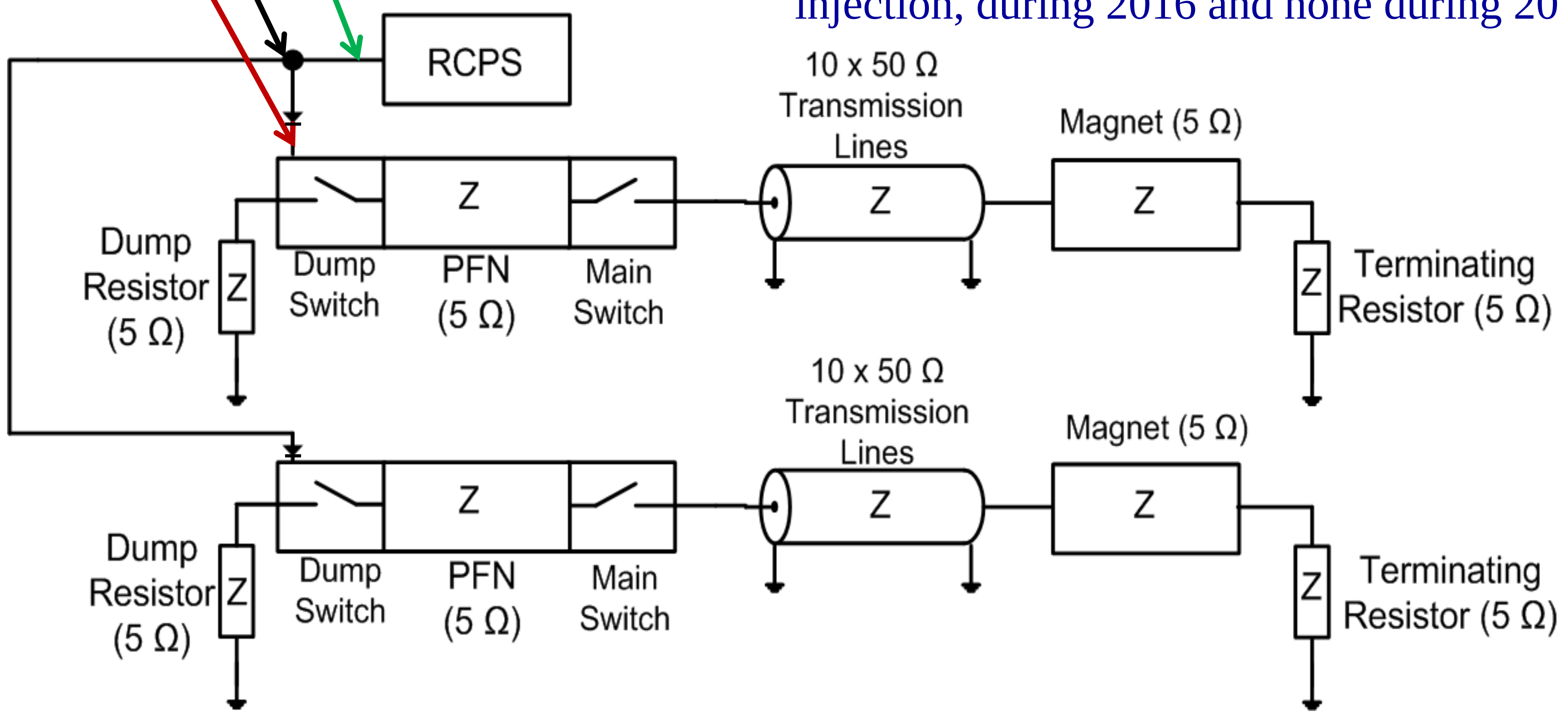
- Beam Energy Tracking System (BETS) measures PFN voltage of MKI system – in case of incorrect voltage, extraction from SPS is inhibited;
- In the event of an MKI Erratic (self-triggered) turn-on of a main switch: the other 3 main-switches and four dump switches are triggered, e.g. on 2/9/2016 (876 circulating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



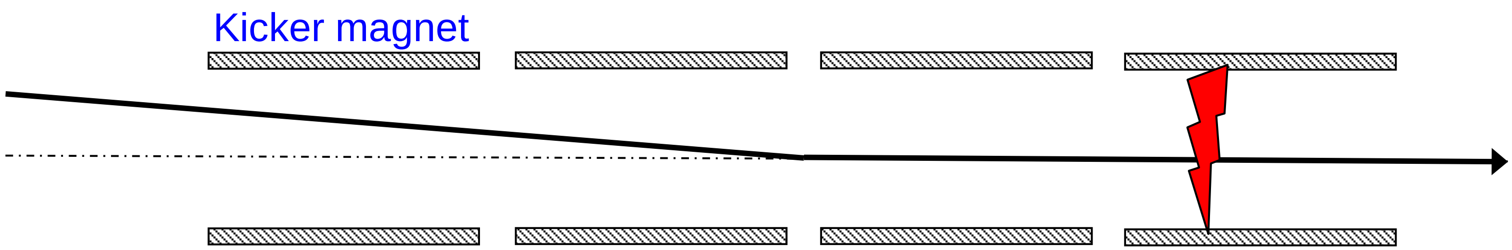
Minimizing Erratic Turn-Ons



- 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.

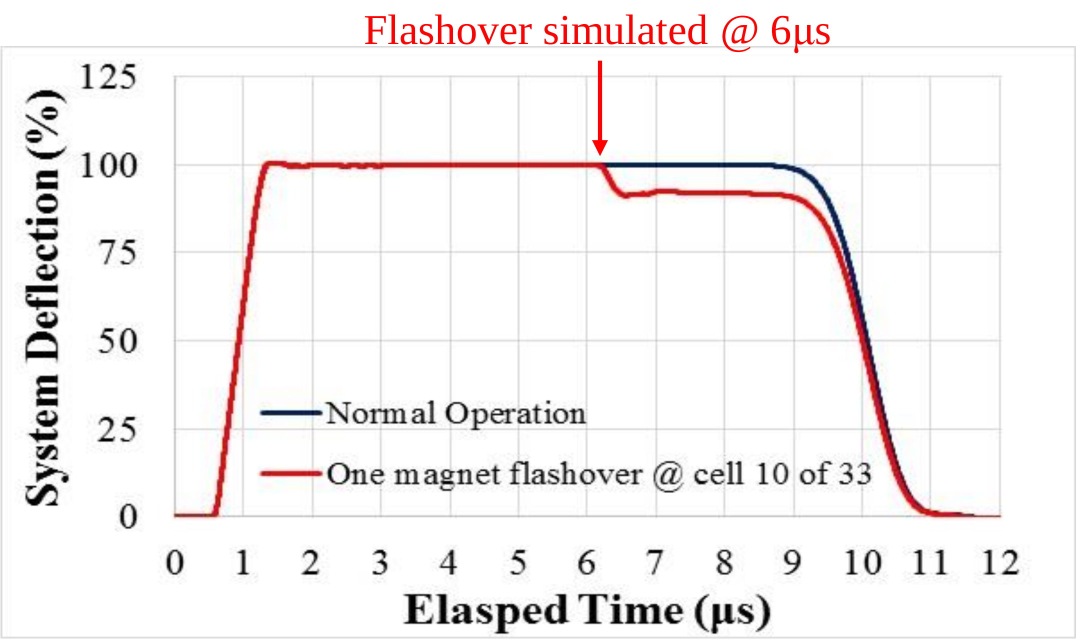


Example of Flashover in a Kicker Magnet (1)

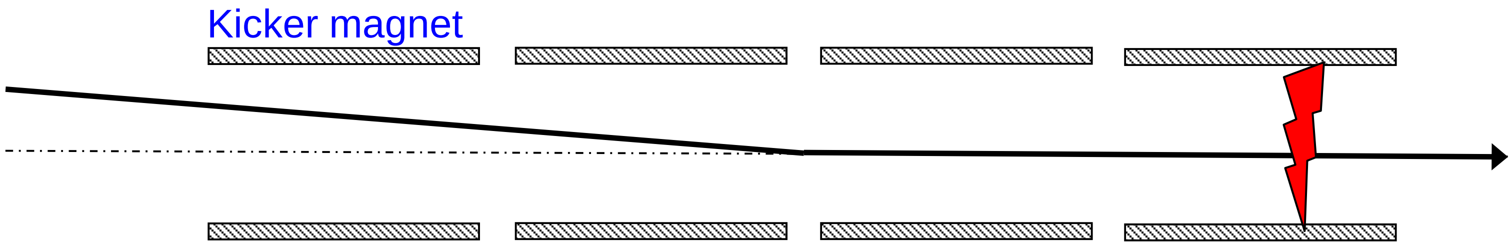


Four kicker magnets, each terminated with a TMR (not shown).

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

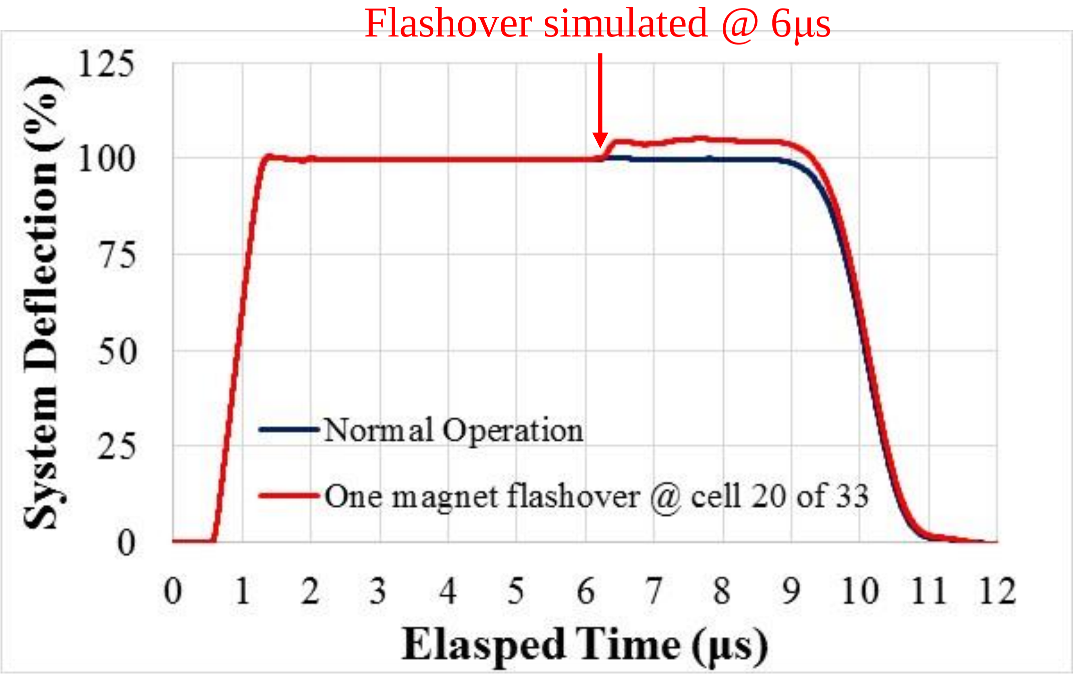


Example of Flashover in a Kicker Magnet (2)

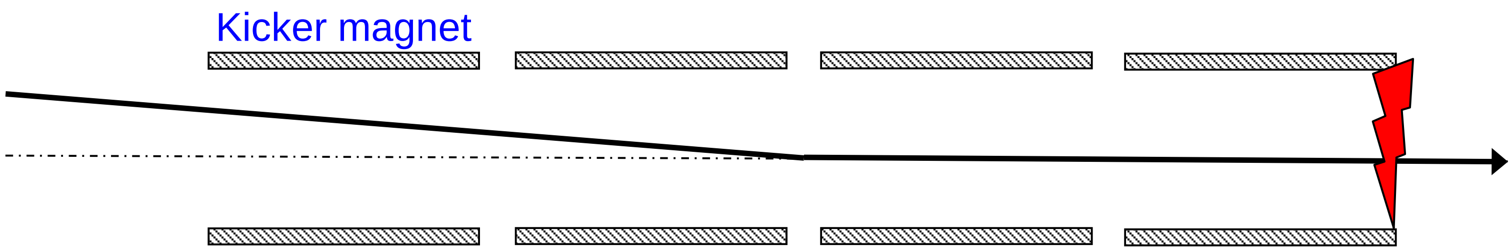


Four kicker magnets, each terminated with a TMR (not shown).

- Flashover 60% into one magnet:
- Current doubles at short-circuit;
  - 60% × 2 ⇨ 120% of normal deflection from this magnet;
  - 25% × 3 + 120%/4 ⇨ 105% of total, normal, system deflection.

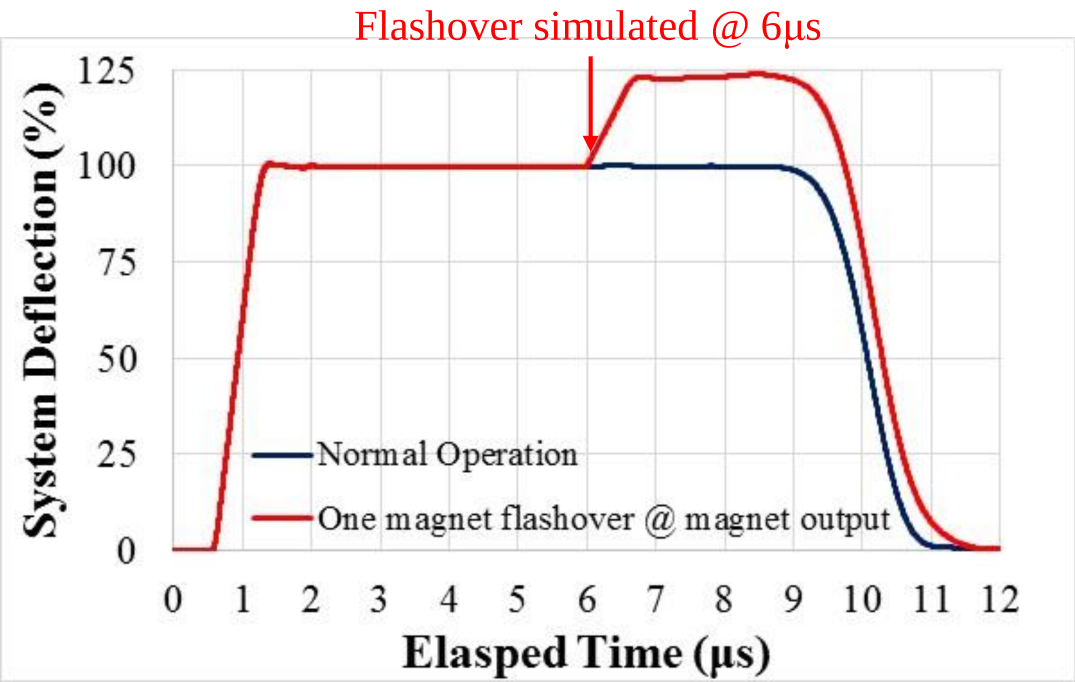


Example of Flashover in a Kicker Magnet (3)



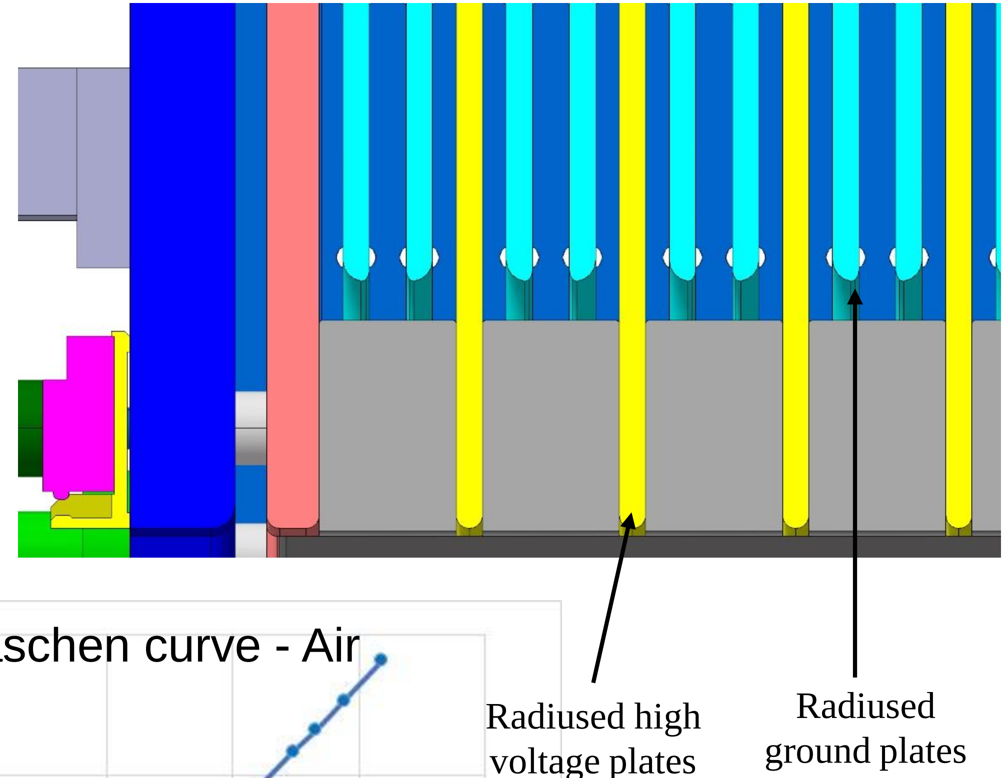
Four kicker magnets, each terminated with a TMR (not shown).

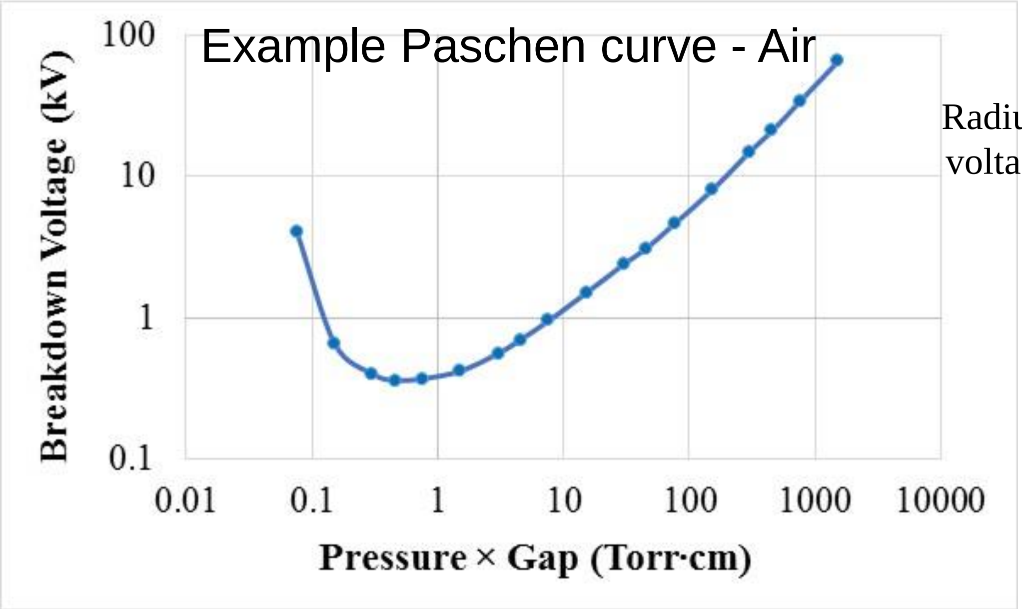
- Flashover 100% into one magnet:
- Current doubles at short-circuit;
  - 100% × 2 ⇨ 200% of normal deflection from this magnet;
  - 25% × 3 + 200%/4 ⇨ 125% of total, normal, system deflection.



Minimizing Flashover with Beam

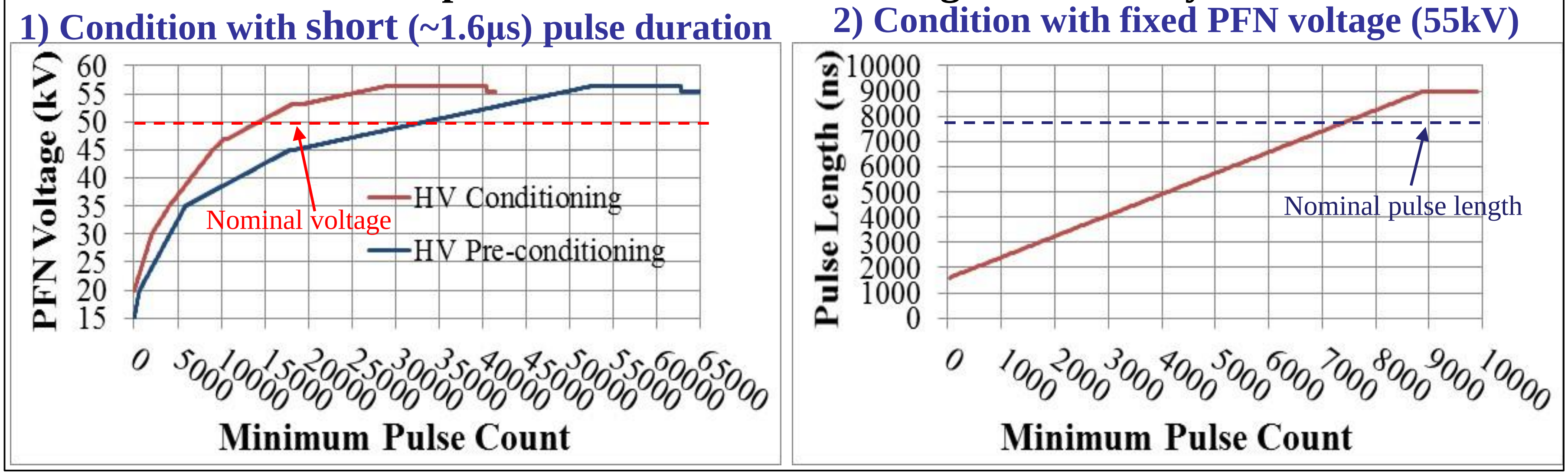
- At design stage, ensure adequately low electric field (proper clearances, avoid sharp corners, ….);
- Properly high voltage condition magnets after assembly – see next slide;
- Beware of pressure rise during operation (Paschen curve);
- Verify/recondition LHC injection magnets, with high voltage, before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





Minimizing Flashover in a Kicker Magnet

Computer controlled conditioning in laboratory

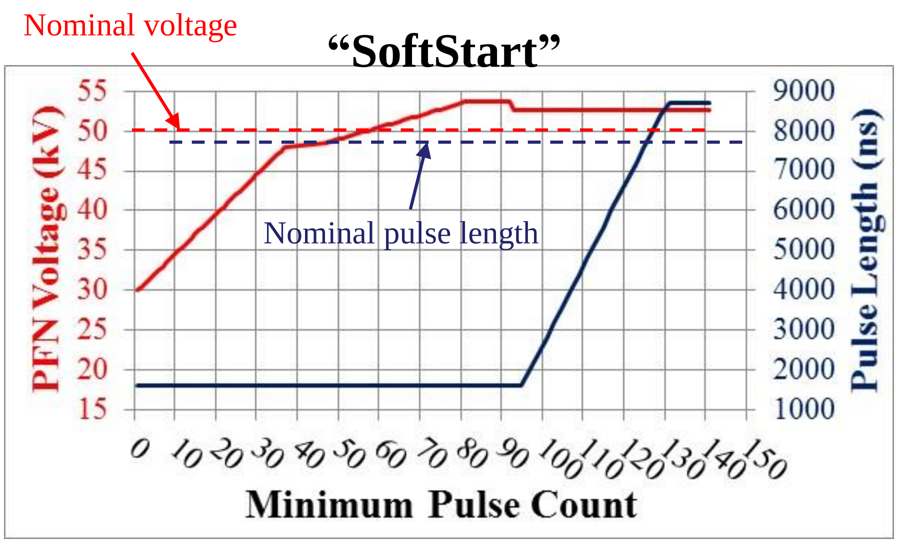


MKI magnet flashovers in the LHC:

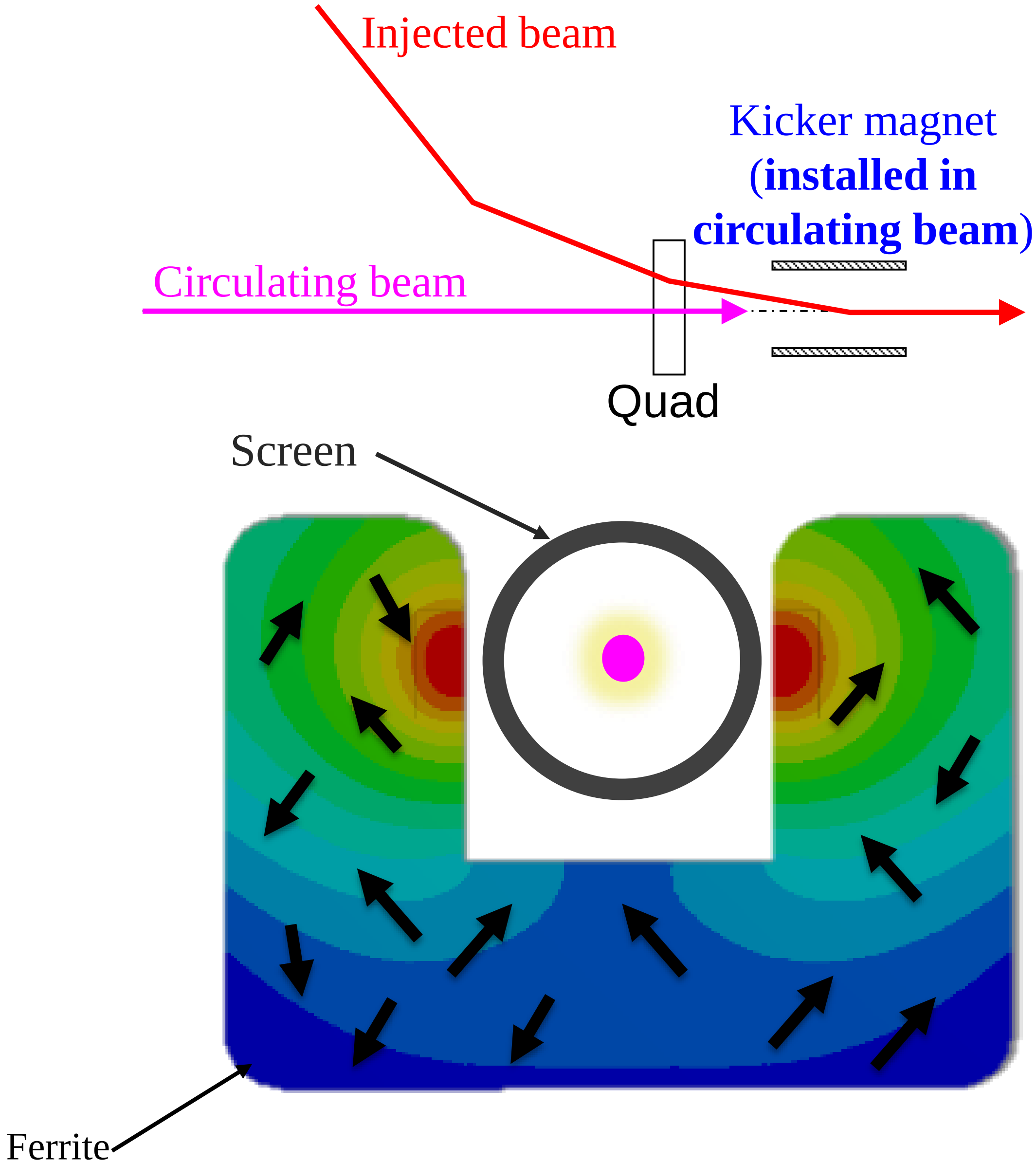
- 2016 / 2015:
  - **4** / 5 during "SoftStarts" (**~80% of pulses**)
  - **3** / 0 with beam (**~20% of pulses**)

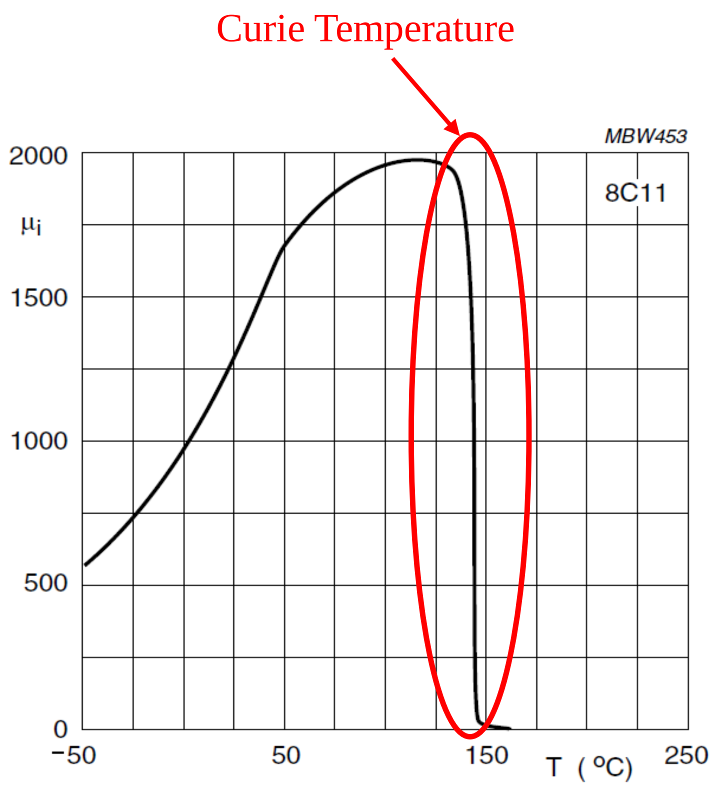
⇨ In 2016, disproportionate number of flashovers with high-intensity beam: shows deconditioning effect of LHC beam.

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



Beam Induced Heating

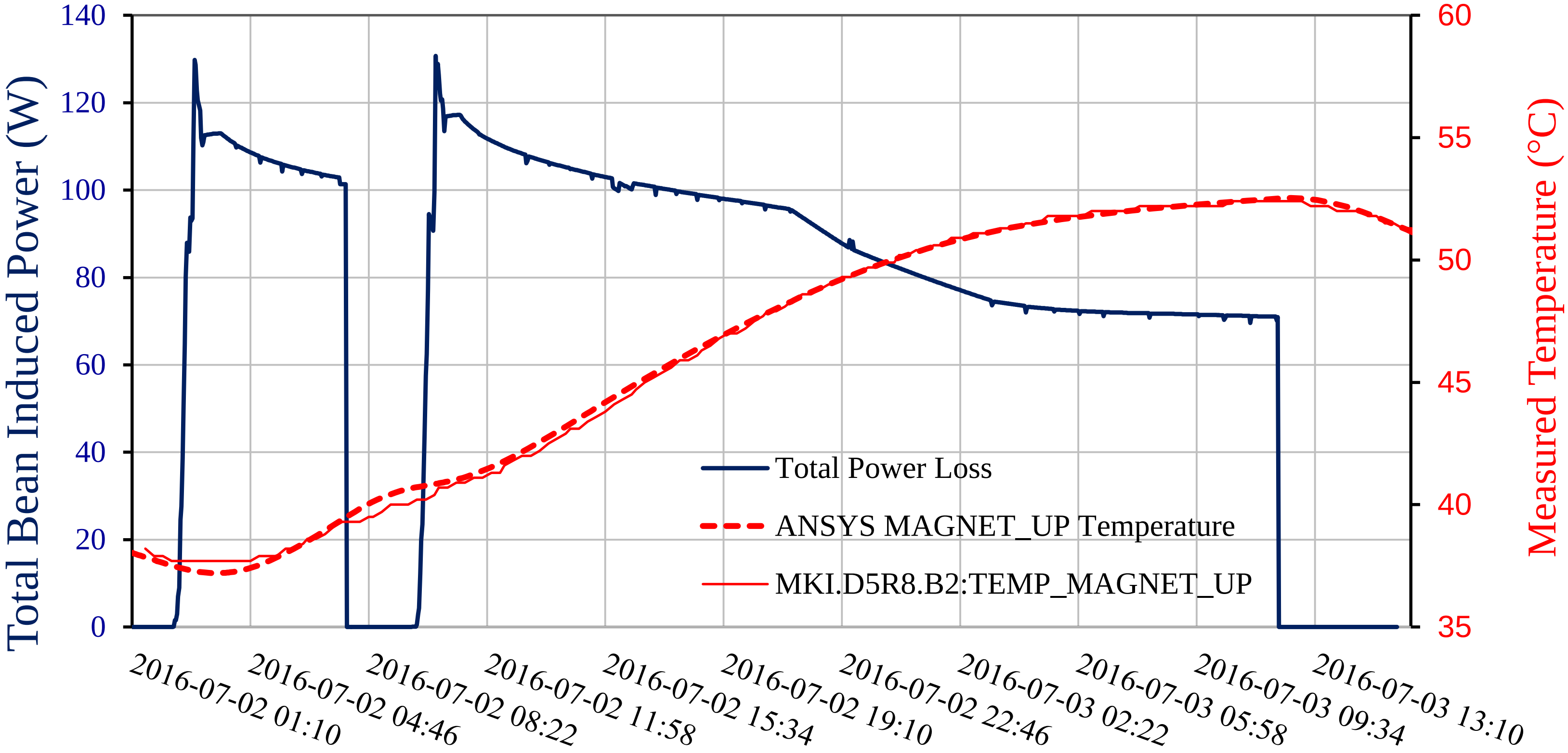




Above the Curie Temperature the ferrite temporarily looses its permeability.

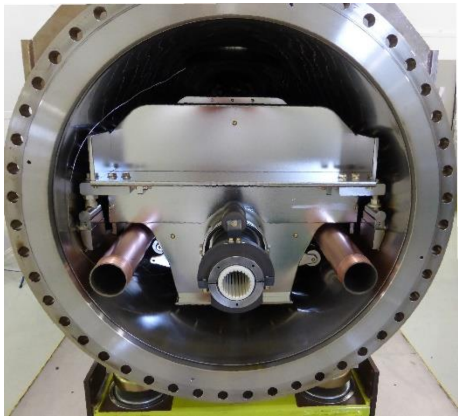
Example of Beam Induced Heating

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



Note: very long thermal time-constants for both heating and cooling.

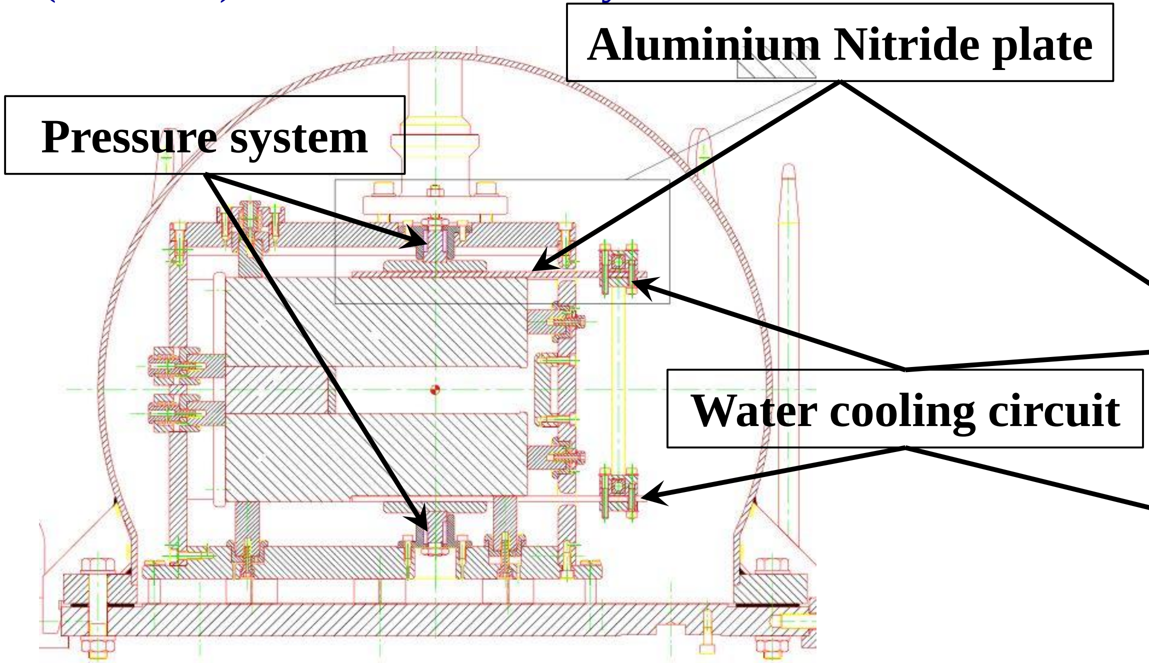
Heat Extraction from Kicker Magnets

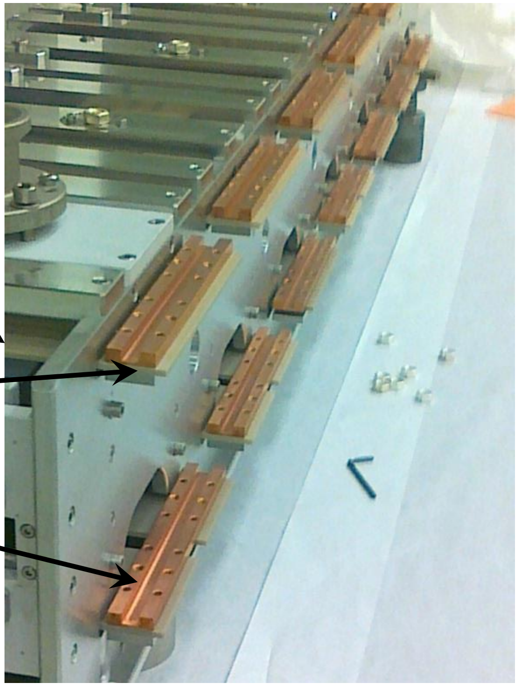


Kicker magnets are generally in vacuum tanks, hence thermal energy (e.g. in ferrite yoke) can be challenging to extract:

- 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:



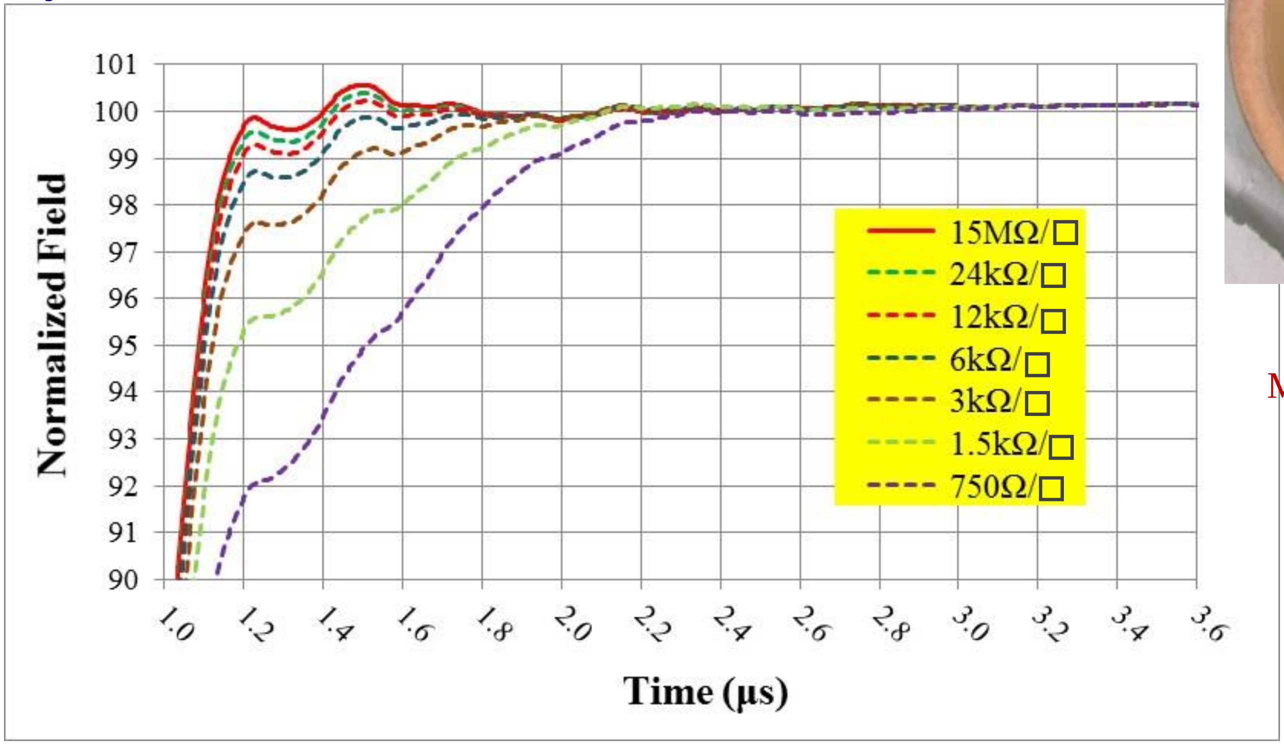


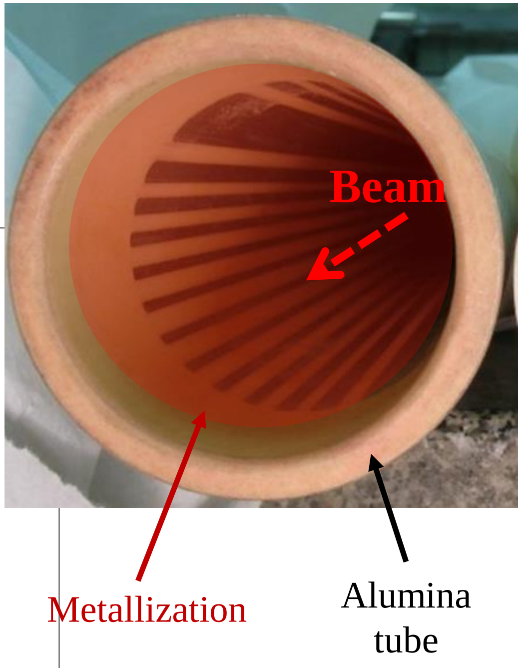
In general it is better to avoid, if possible, heat deposition in the kicker magnet ferrite yoke.

Reduction of Beam Induced Heating (1)

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 to high to shield the ferrite from beam…..

Reduction of Beam Induced Heating (2)

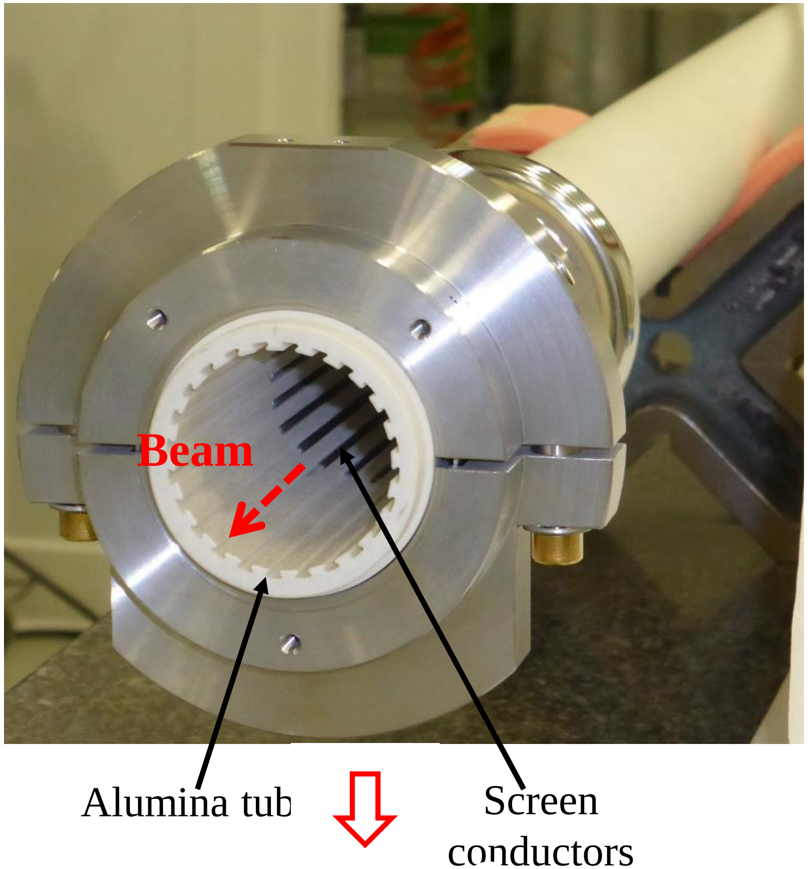
- E.g. alumina tube (~3m) with slots on its inner wall;
- Screen conductors installed in slots;
  - Connected to beam pipe at far end of alumina tube;
  - Capacitively coupled, through dielectric of alumina tube, at near end.
- Eddy currents, induced during field rise and fall, do not unduly influence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

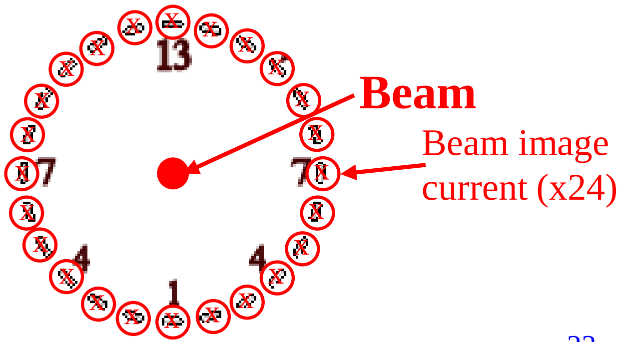
BUT….

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

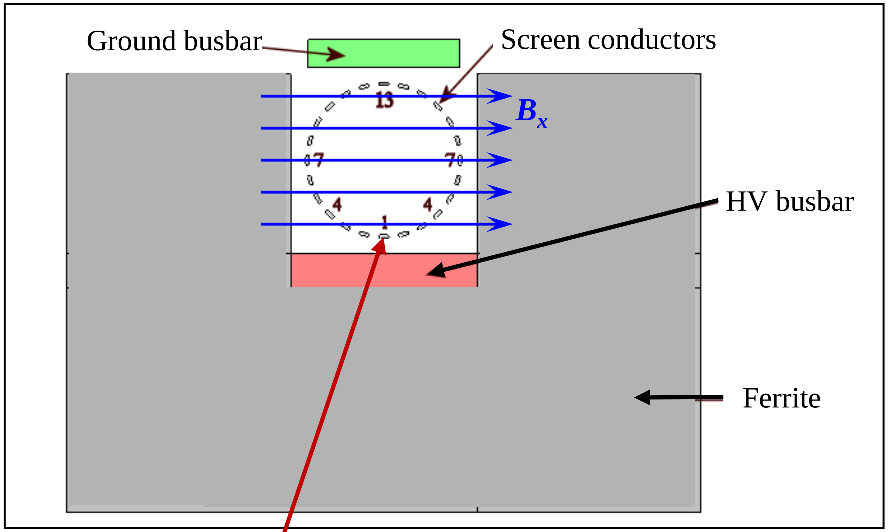
$$B_y \cong \mu_0 \left(\frac{N \cdot I}{V_{ap}} \right)$$

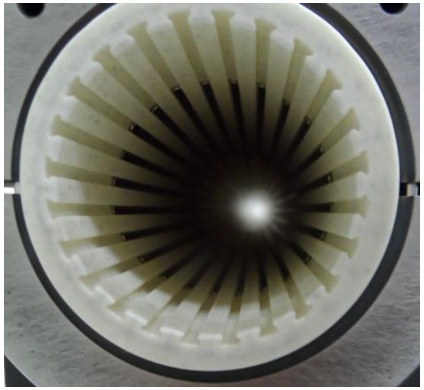
- Hence higher current in kicker magnet, for a given magnet length;
- Hence higher PFN voltage, for a given impedance.





Beam Coupling Impedance Reduction (1)

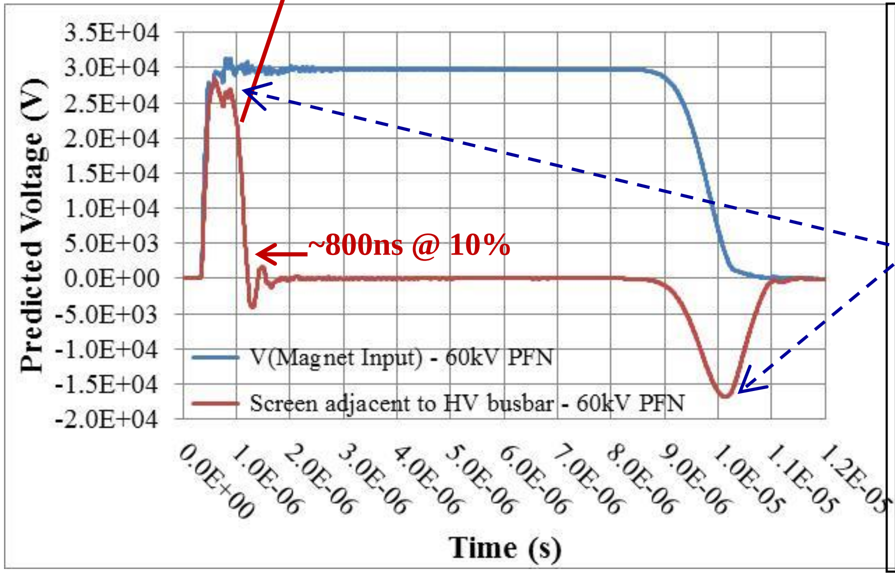


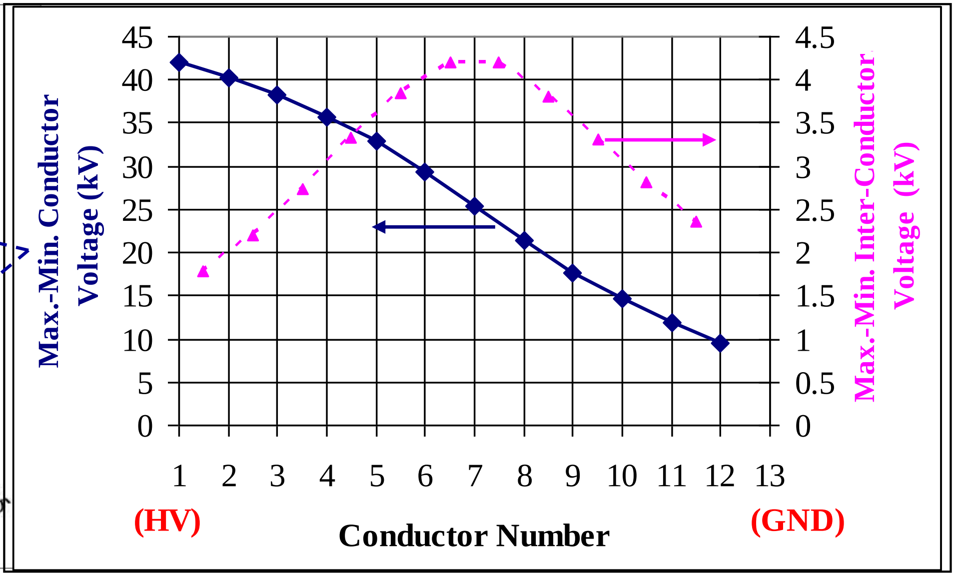


From Faraday's Law:

$$V = -A\left(\frac{dB_x}{dt}\right)$$

High voltage is transiently induced on the screen conductors – which can introduce flashover problems…..

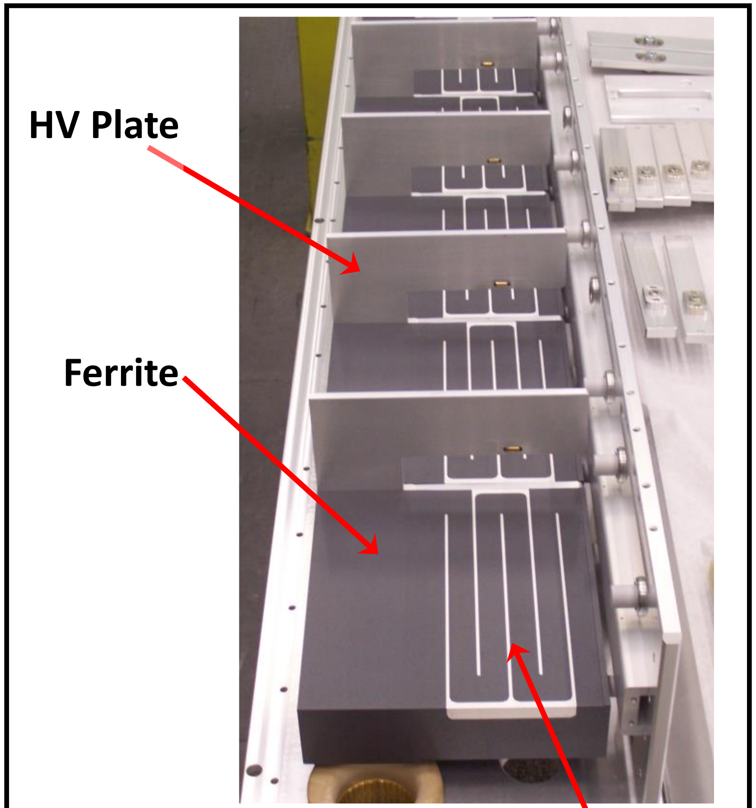




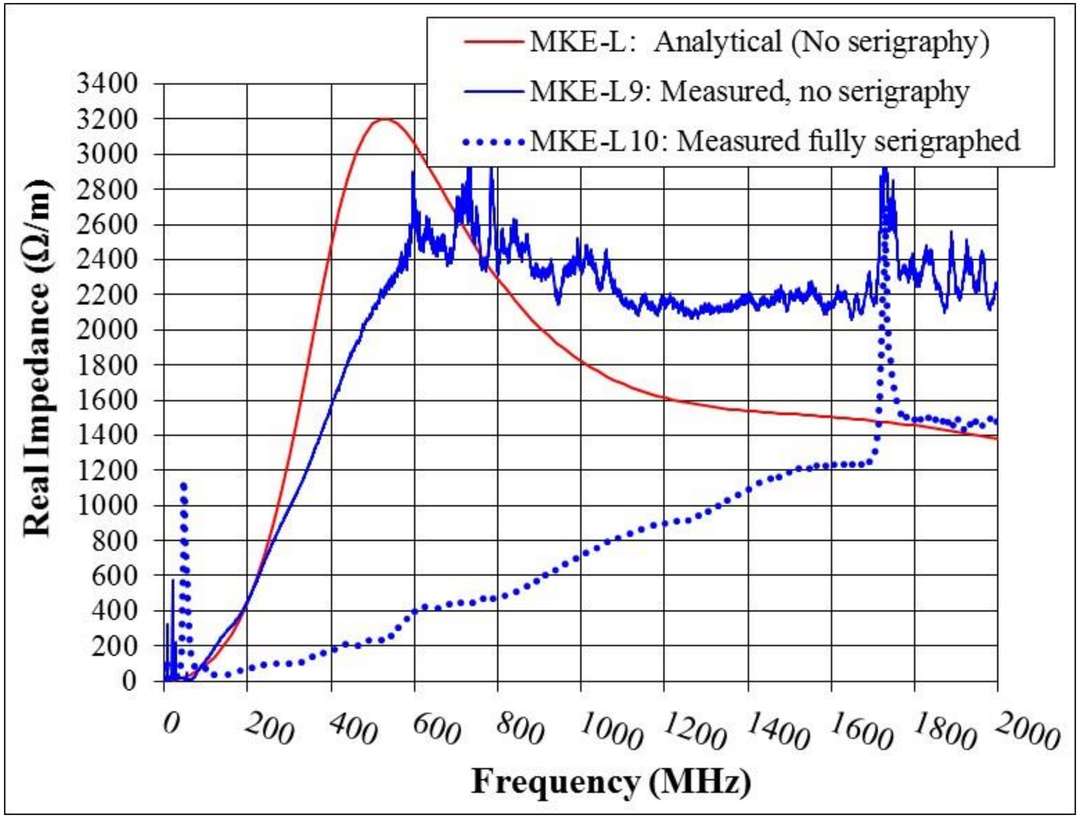
Beam Coupling Impedance Reduction (2)

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

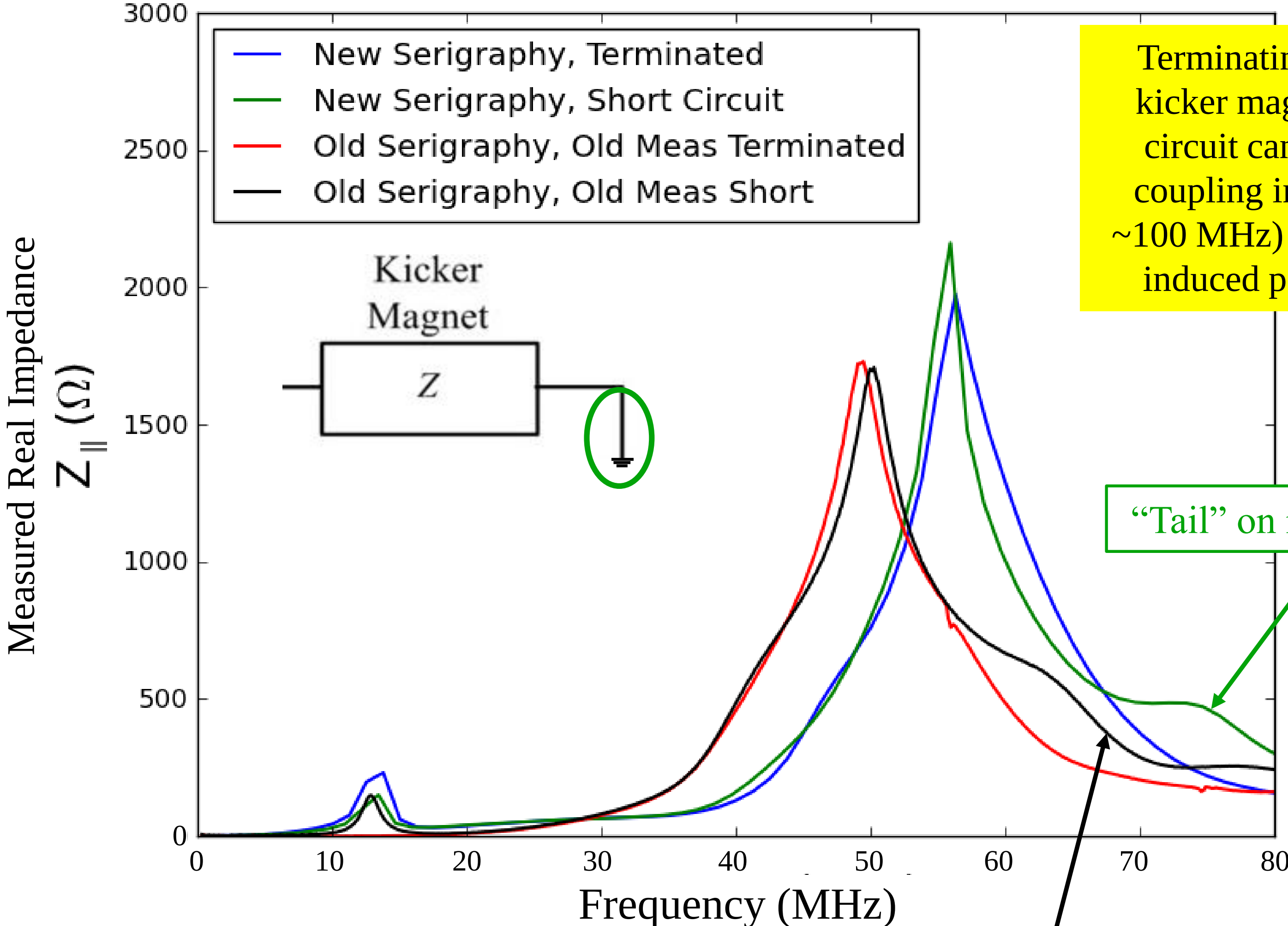
- Serigraphy of ferrites (painted stripes) ⇨ negligible loss of aperture;
- Not as efficient, electromagnetically, as the screen conductors – but still good.



MKE Kicker: serigraphy on ferrite



Beam Coupling Impedance: Magnet Termination

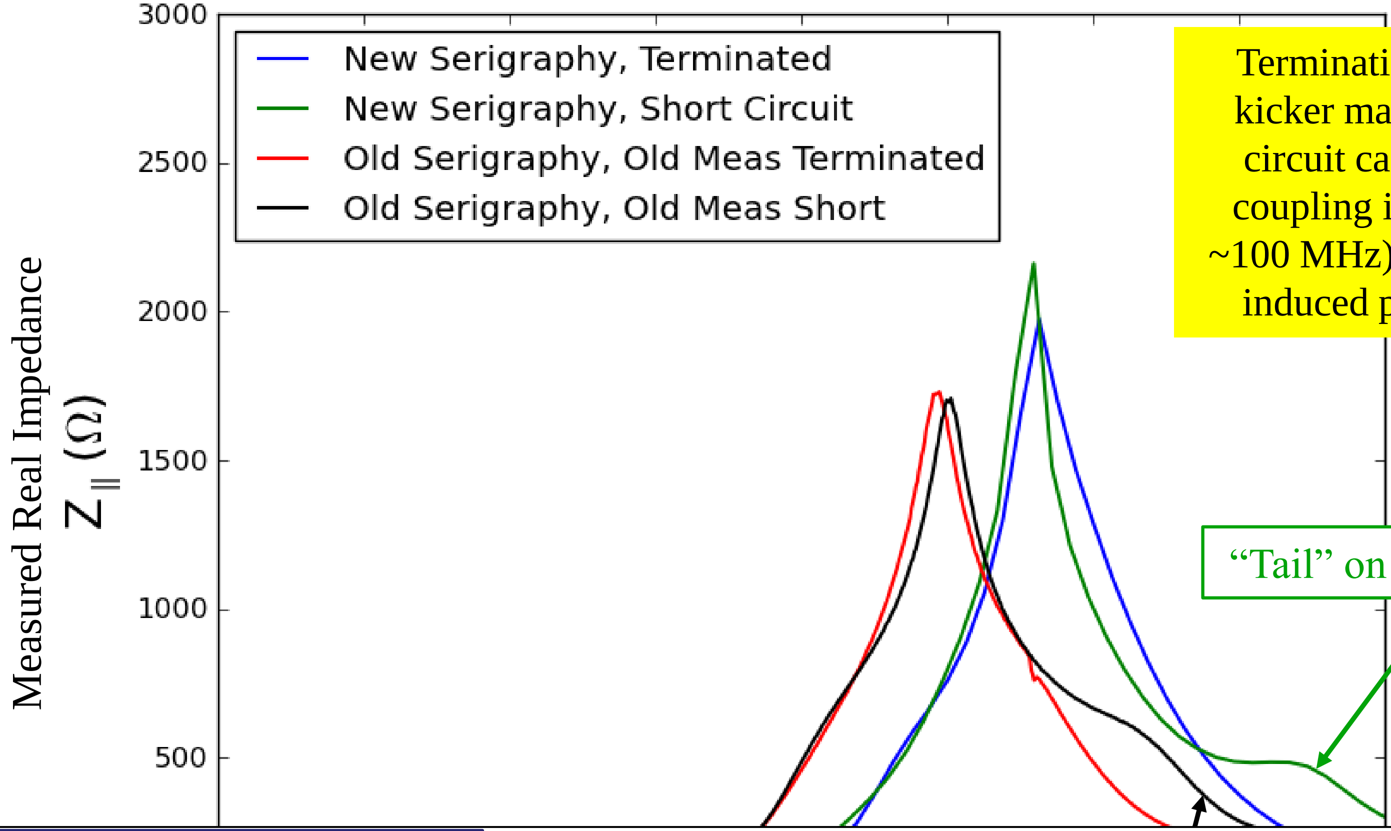


Terminating the output of a kicker magnet with a short-circuit can influence beam coupling impedance (below ~100 MHz) and increase beam induced power deposition.

"Tail" on real impedance

"Tail" on real impedance

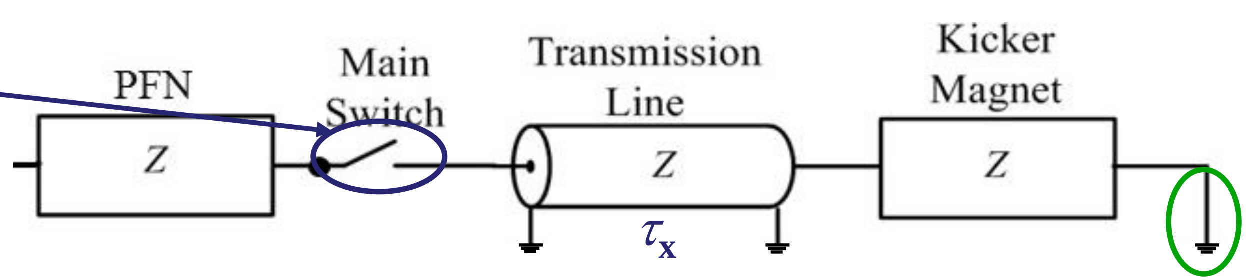
Beam Coupling Impedance: Magnet Termination



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.

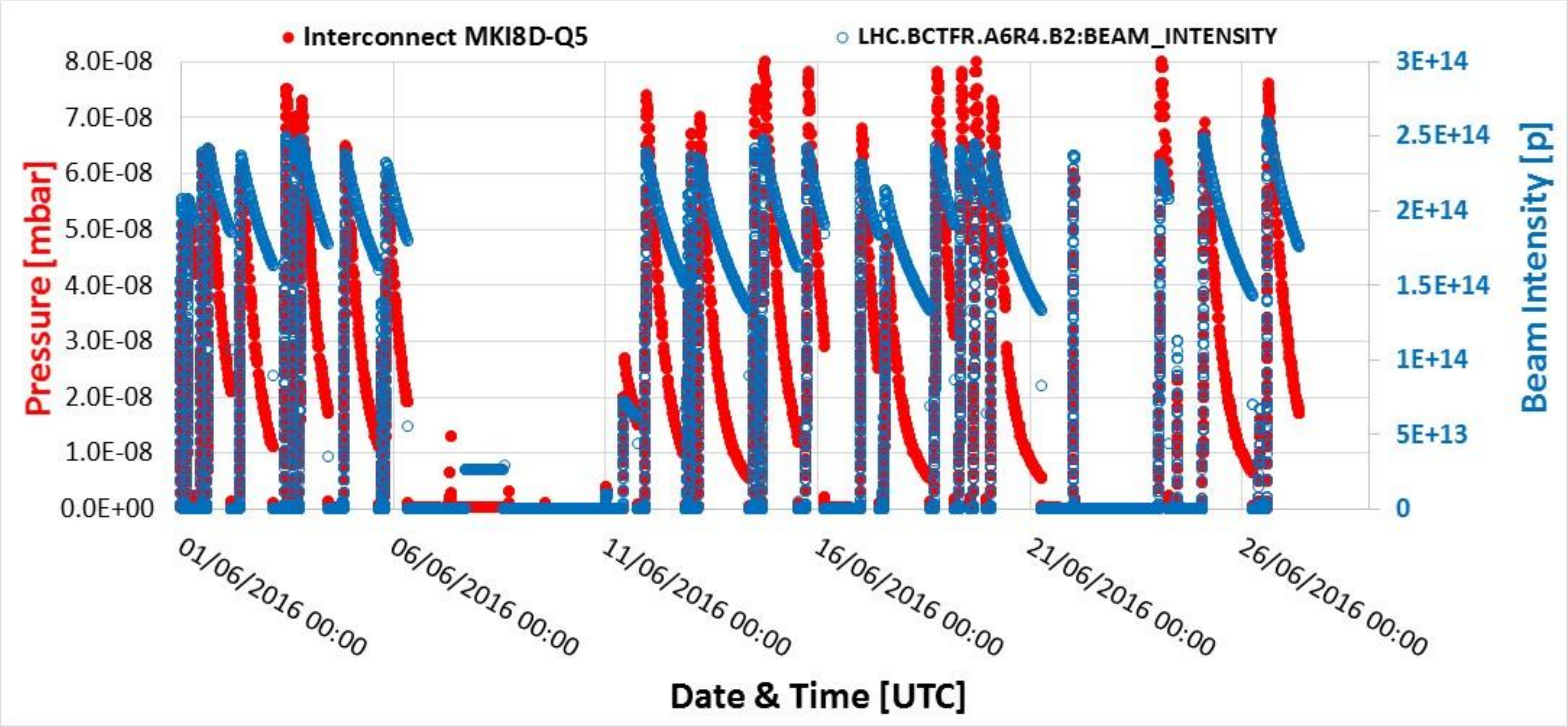
"Tail" on real impedance

In addition, the "open" main switch, together with a short-circuit termination and τ_x, can create impedance resonances (not shown).



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).

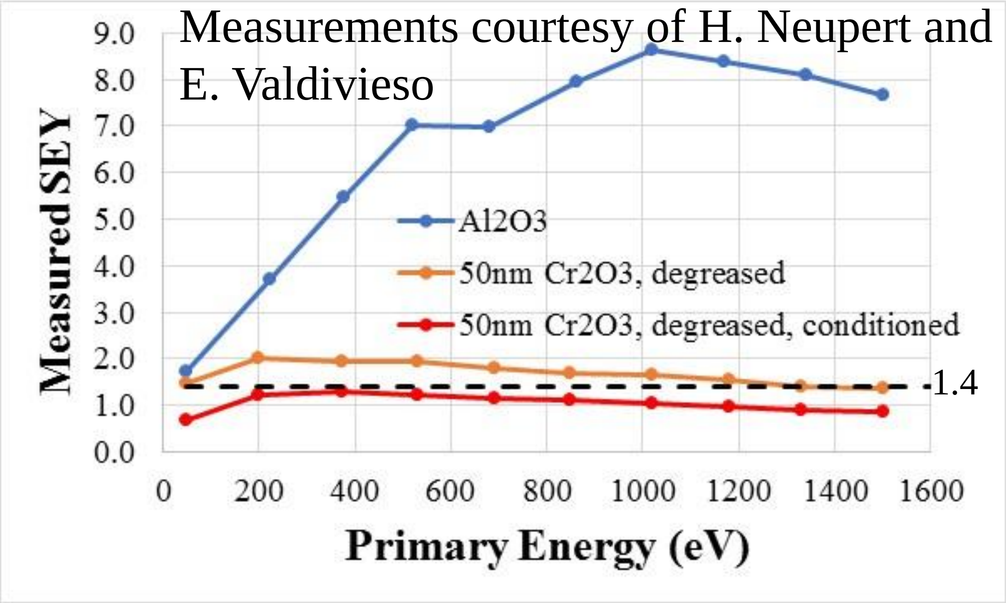


High pressure during injection ⇨ increased probability of flashover and hence mis-kicking beam (high voltage on screen conductors).
Conditioning of alumina with beam can be **very** slow…..

Electron Cloud – Promising Solution

Laboratory measurements show that Cr_2O_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.

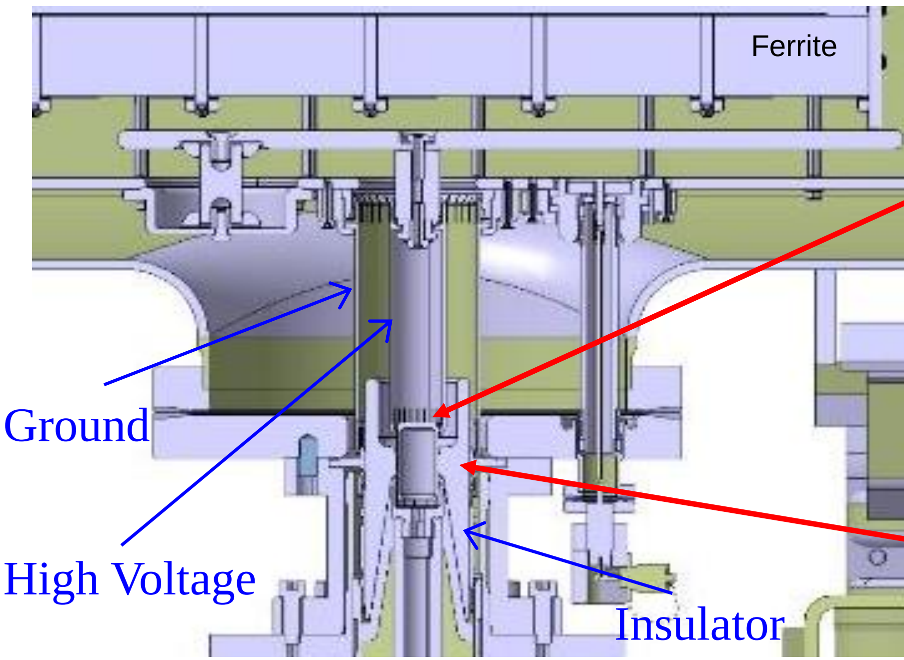


Evidence to date is that, independent of pressure rise, Cr_2O_3 also improves high voltage performance.

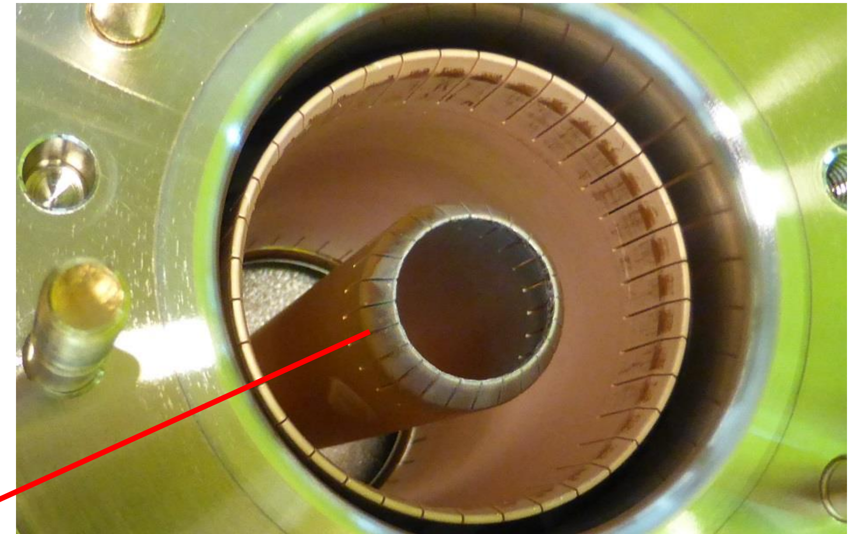
Cr_2O_3 coated pieces to be installed in the SPS, for testing with beam, in the coming months.

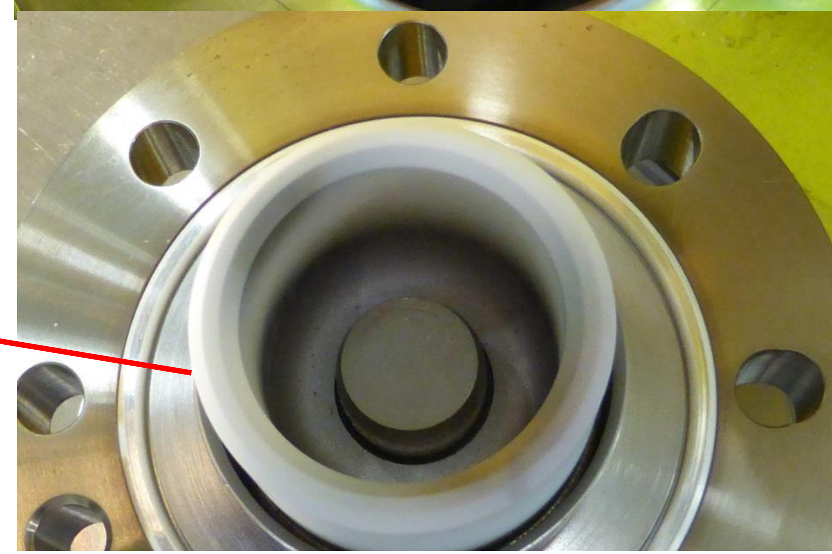
High Voltage Connectors

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





Energy Stored in the LHC Beams

Stored beam energy: Proton Energy • Number of Bunches • Number of protons per bunch

Proton Energy: 7 TeV

In order to achieve very high luminosity:

Number of bunches per beam: 2808

Number of protons per bunch: 1.25×10^{11}

$\Big\}$ 3.5×10^{14} protons / beam

Stored energy per beam: <u>390 MJoules</u>

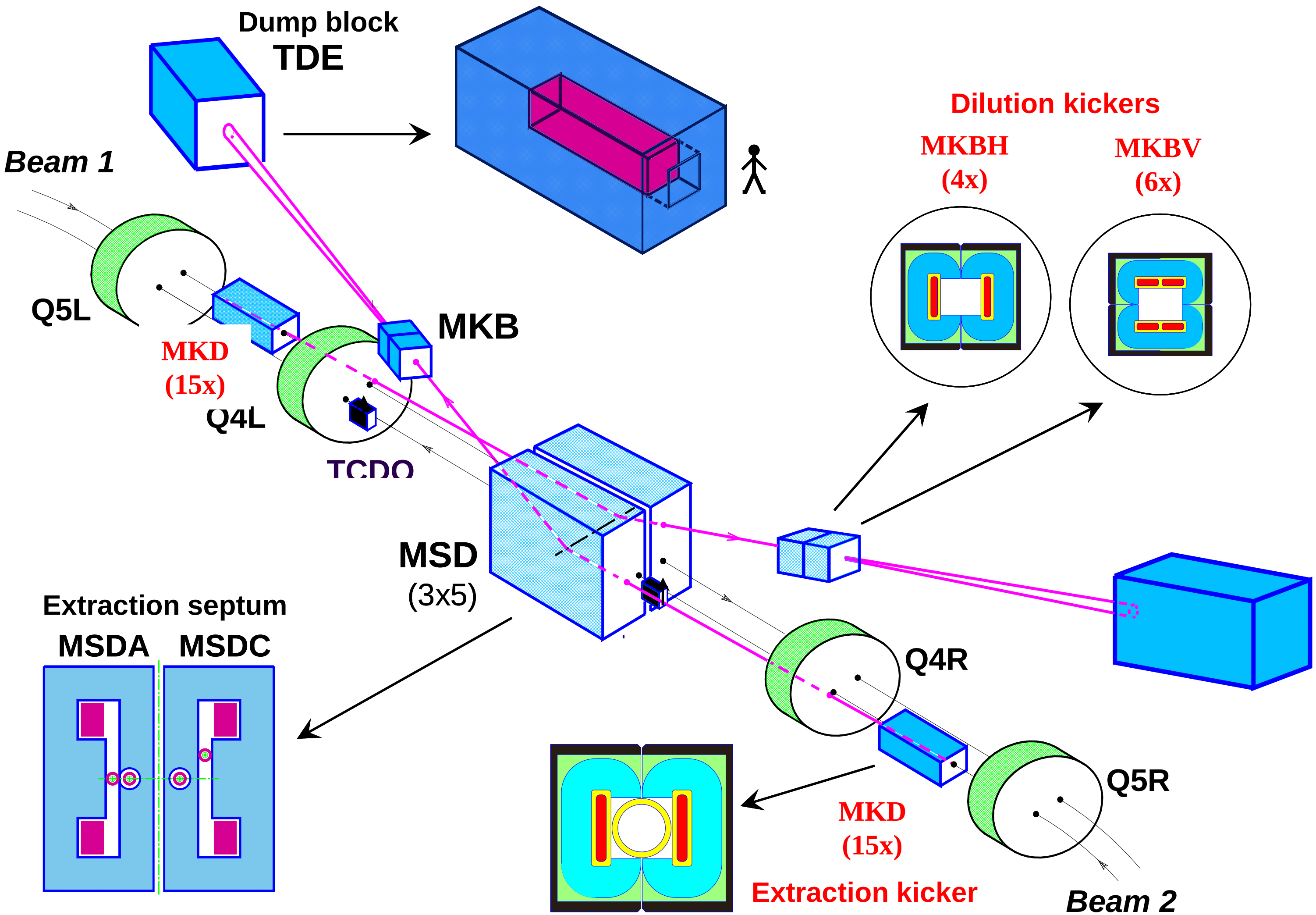
The beam dump (8 m long graphite block) is the ONLY element of the LHC that can safely absorb all the beam !!

Ultra-reliable beam dump systems are required…….

Kickers are turned-on in a particle free 3 μs long *abort gap*: the following beam bunches are then deflected into a dump line.

Fast Single Turn Extraction: LHC Dump

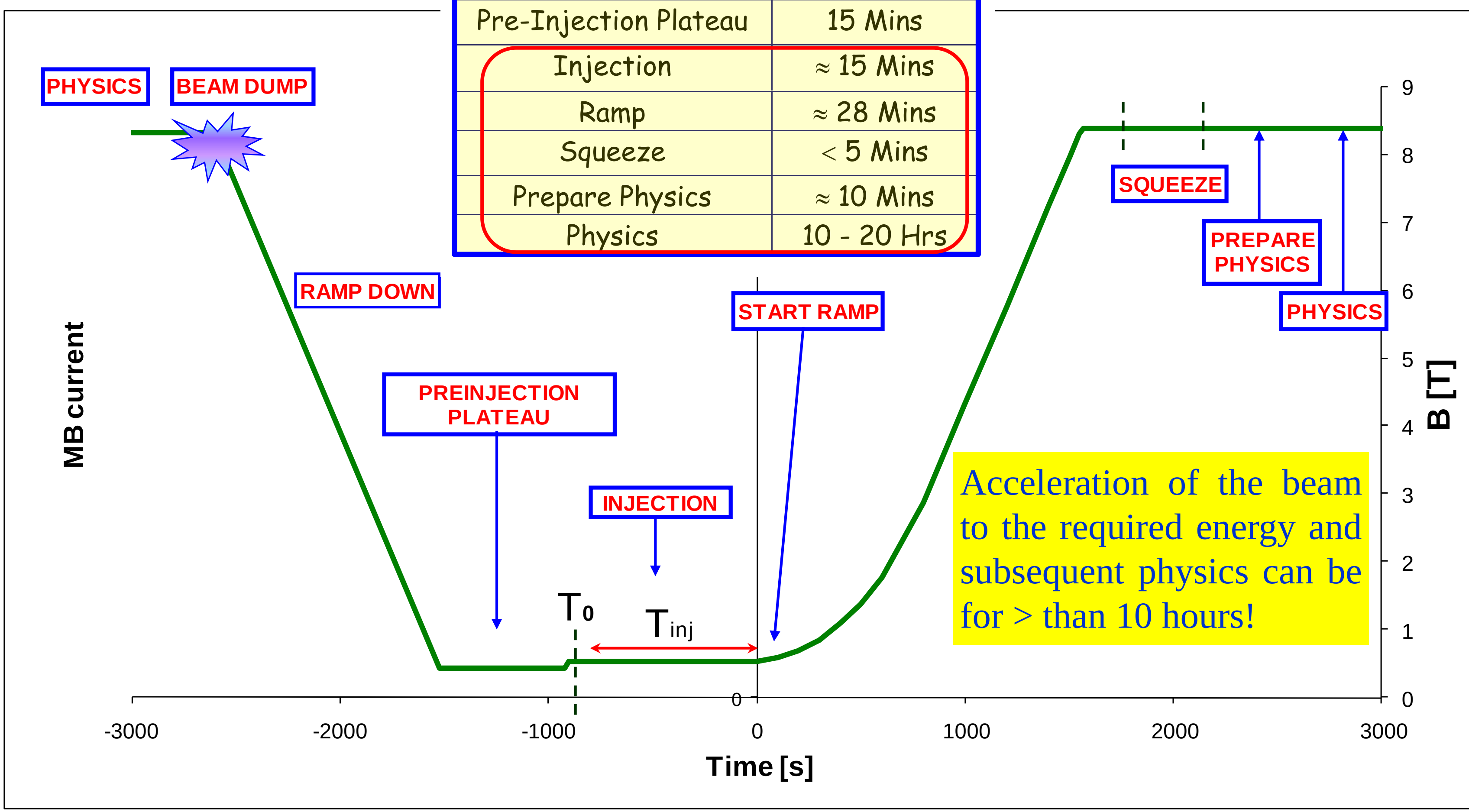
LHC beam dump systems, 2x ~1000 m long, in LHC straight section 6:



LHC Nominal Cycle

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**.

Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs



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 α 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).

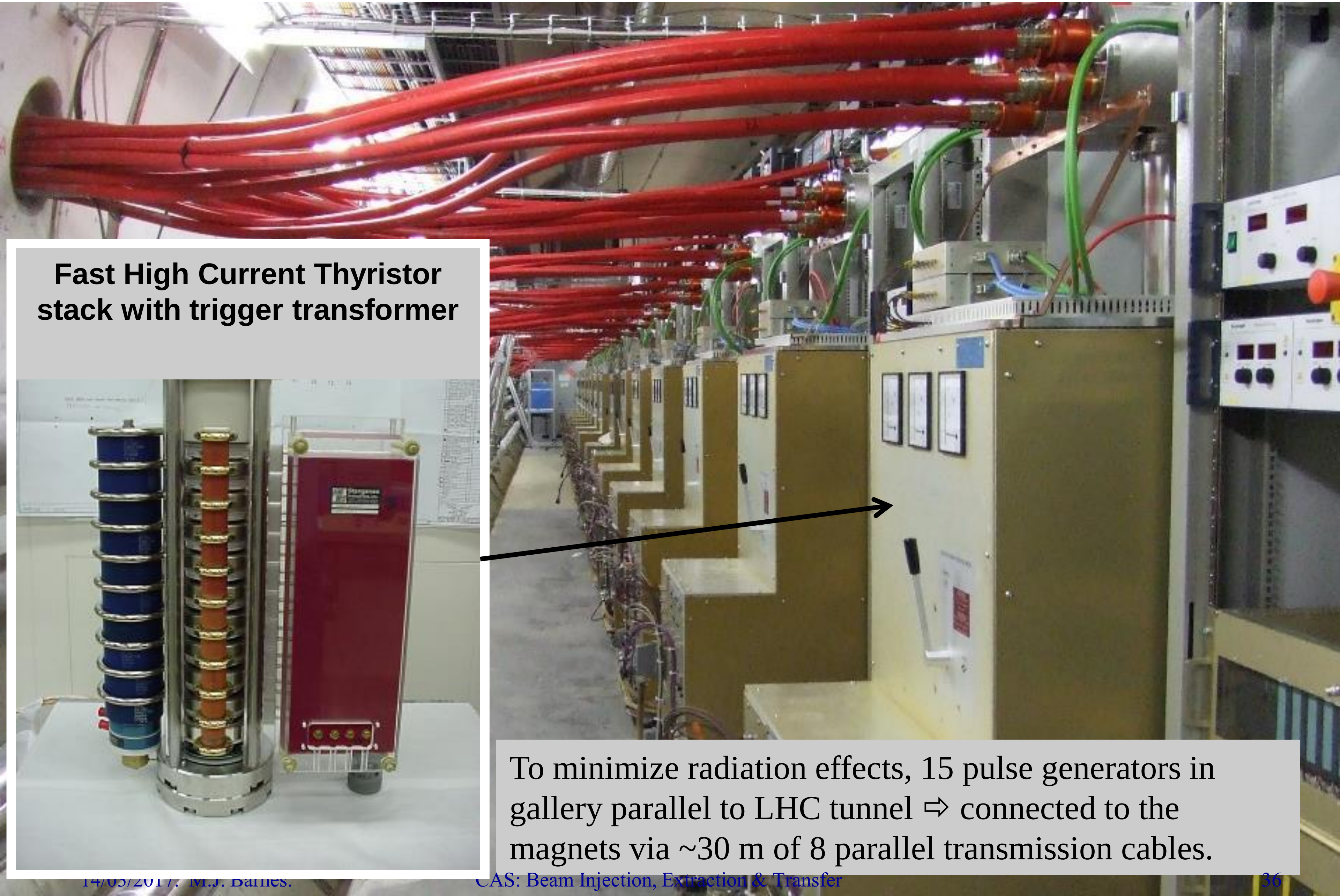
BUT:

- 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: ~93 μs;
- Maximum di/dt specification: 20 kA/μs (~1/8th of a thyratron).

MKD Pulse Generators

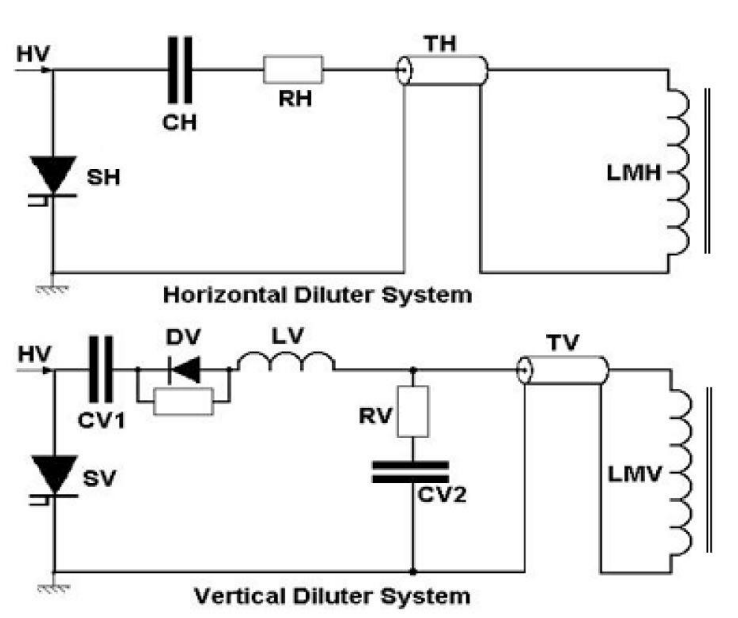


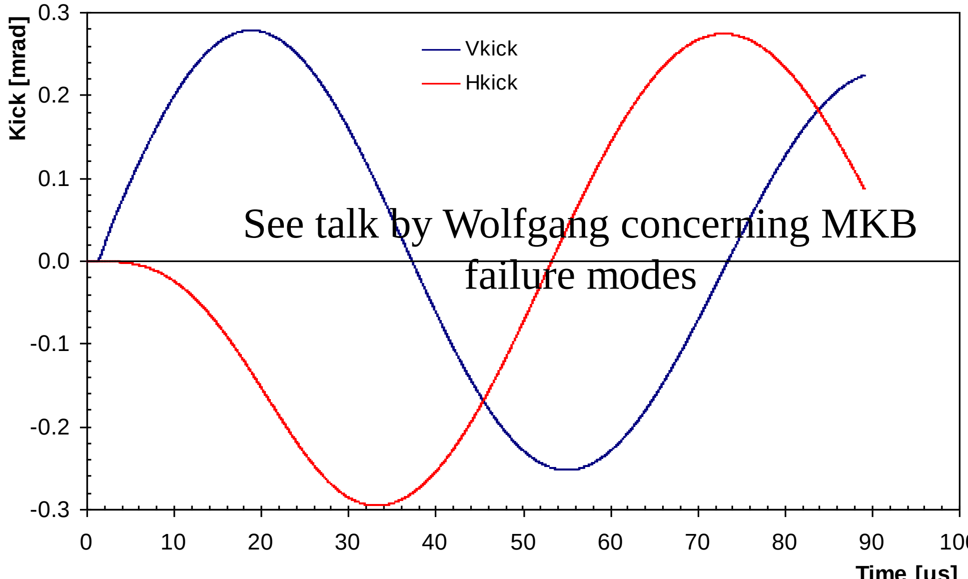
Fast High Current Thyristor stack with trigger transformer

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.

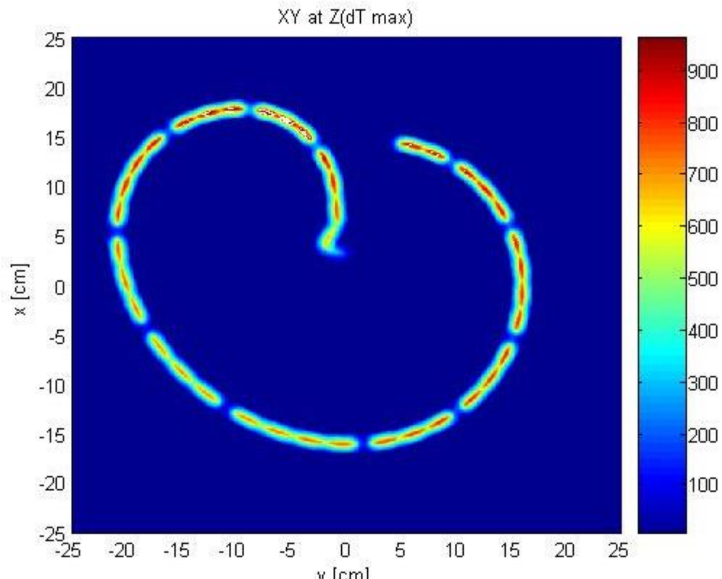
Dilution kickers (MKB)

- 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



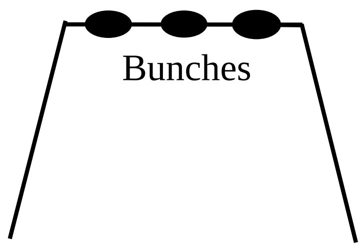
“Exotic” Kicker Systems

Double Kicker System: Concept

For ***extremely*** low ripple

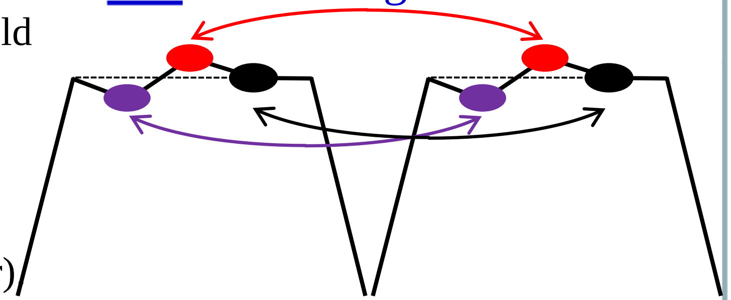
Extraction with **one** kicker magnet:

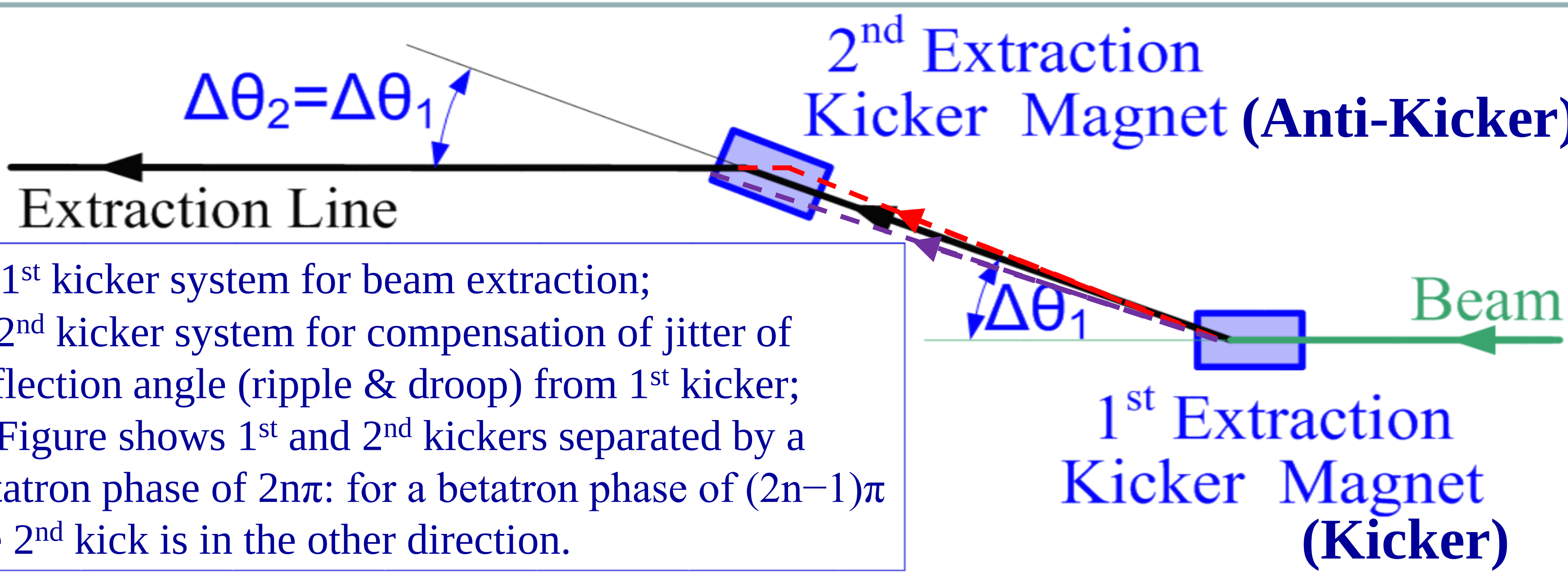
- Would require a very uniform and stable field pulse.



Extraction with **two** kicker magnets:

- Two "identical" field pulses are required;
- One power supply sends the pulses to 2 "identical" kickers (kicker & anti-kicker)

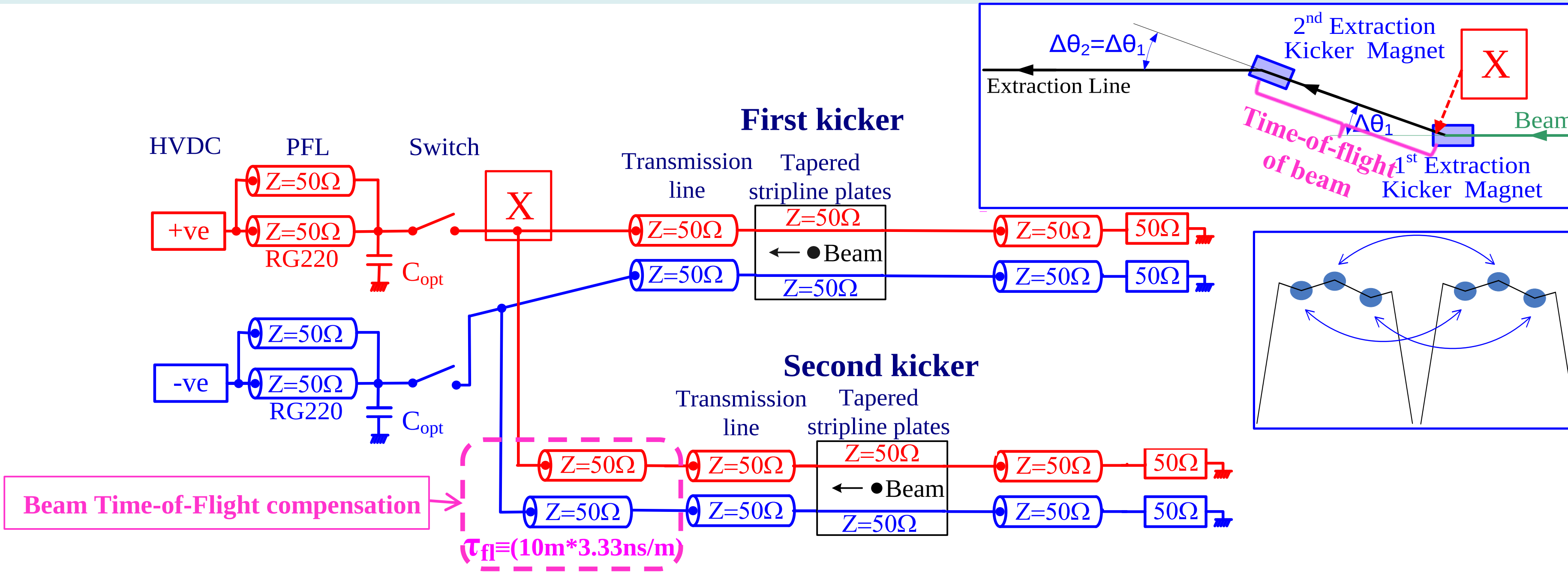




- 1st kicker system for beam extraction;
- 2nd kicker system for compensation of jitter of deflection angle (ripple & droop) from 1st kicker;
- Figure shows 1st and 2nd kickers separated by a betatron phase of $2n\pi$: for a betatron phase of $(2n-1)\pi$ the 2nd kick is in the other direction.

See talk by Verena

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

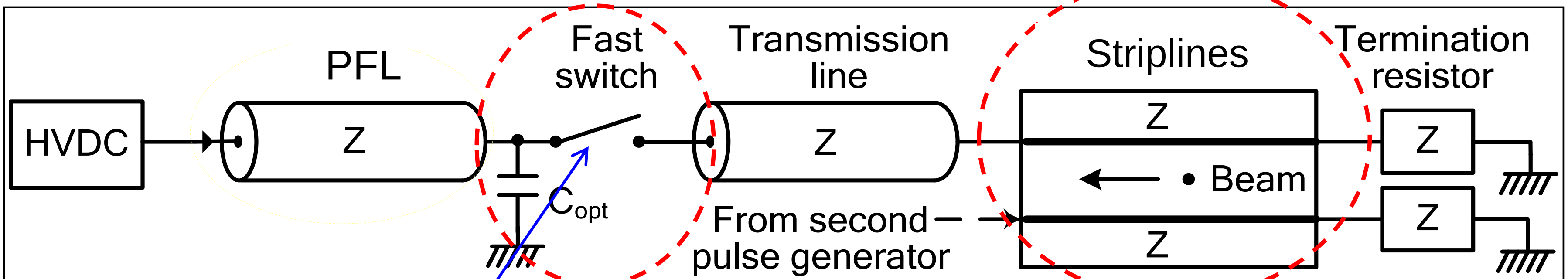
- ➢ Different attenuation & dispersion of waveforms (due to beam time-of-flight);
- ➢ Unintended differences between magnetic characteristics of kicker & anti-kicker;
- ➢ Field uniformity in kicker magnets;
- ➢ Imperfections in beam-line elements/alignment between kicker & anti-kicker.

⇨ **KEK/ATF achieved a factor of 3.3 reduction in kick jitter angle**, with respect to a single kicker.

Extremely Fast Kicker System

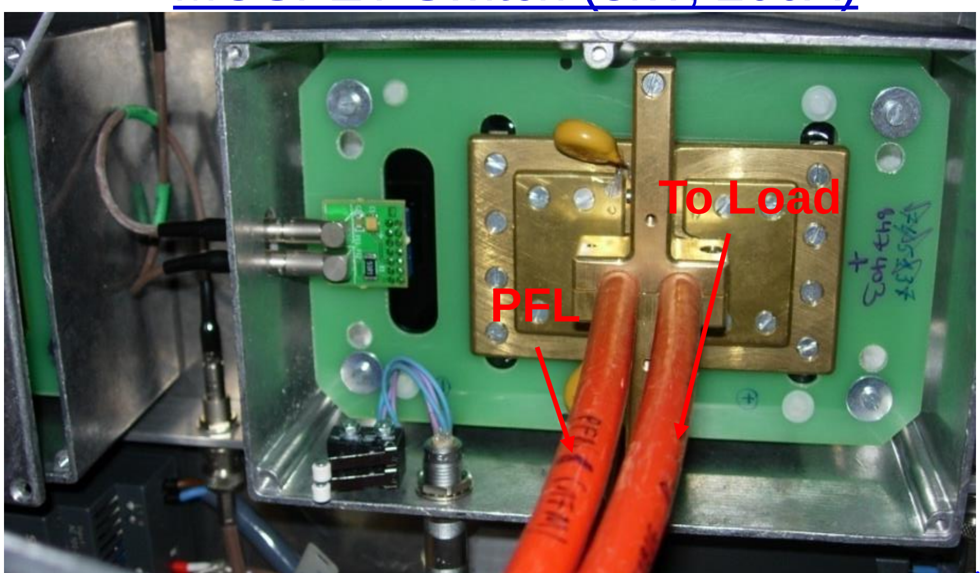
System Overview

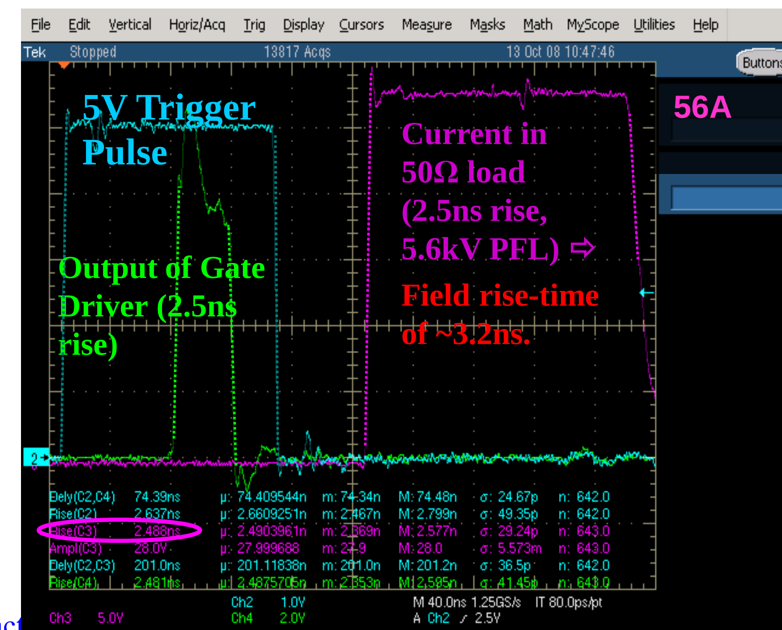
Schematic of Tail-Clipper



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

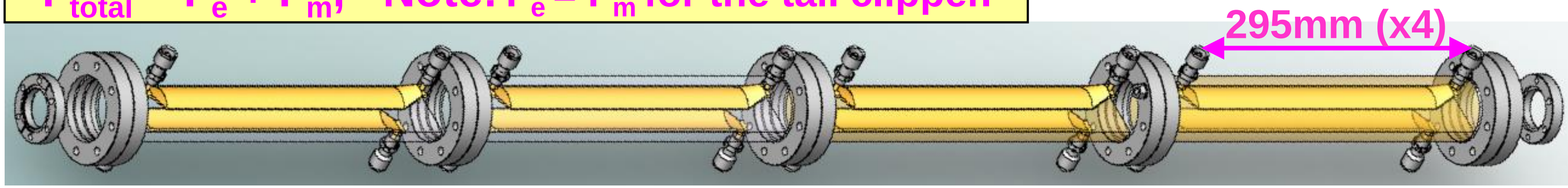
MOSFET Switch (8kV, 200A)





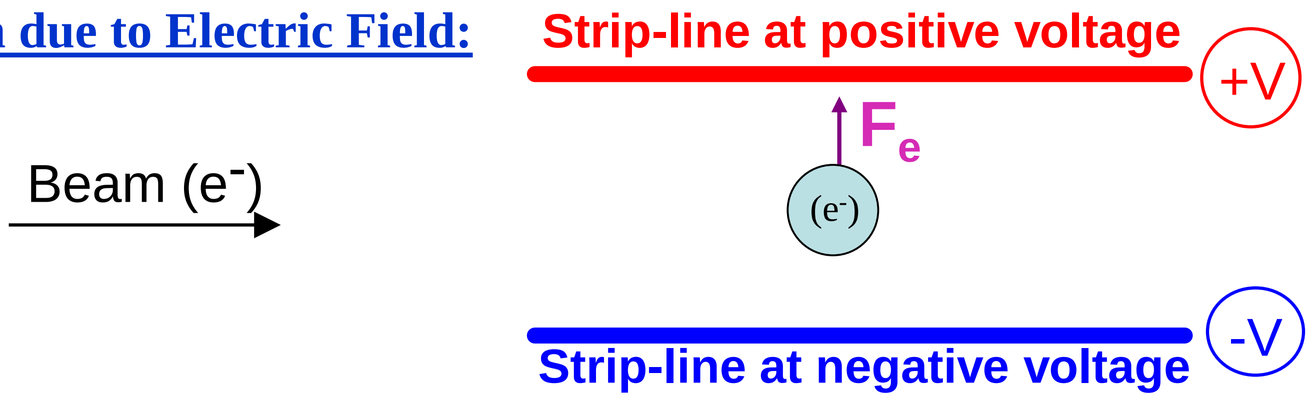
CTF3 Tail Clipper: Striplines

$F_{total} = F_e + F_m$, **Note:** $F_e = F_m$ **for the tail clipper.**

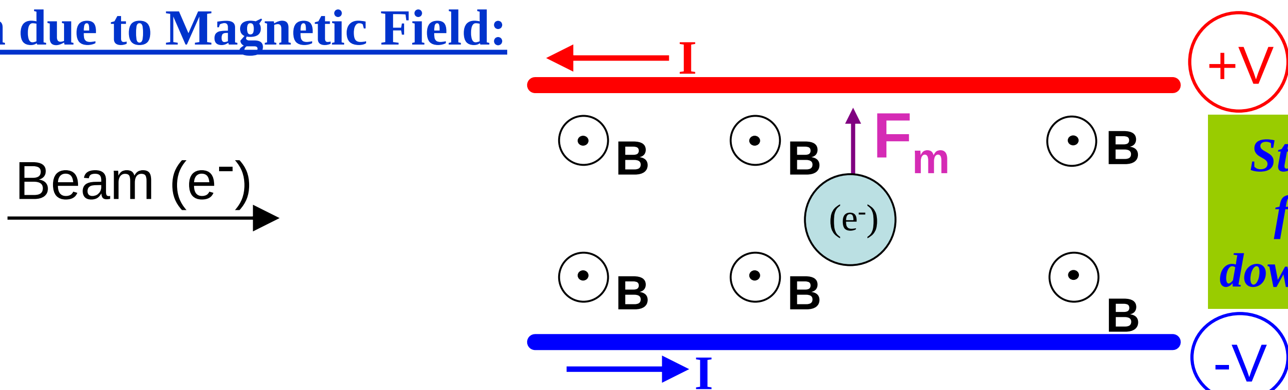


Deflection due to BOTH magnetic and electric field:

Deflection due to Electric Field:



Deflection due to Magnetic Field:

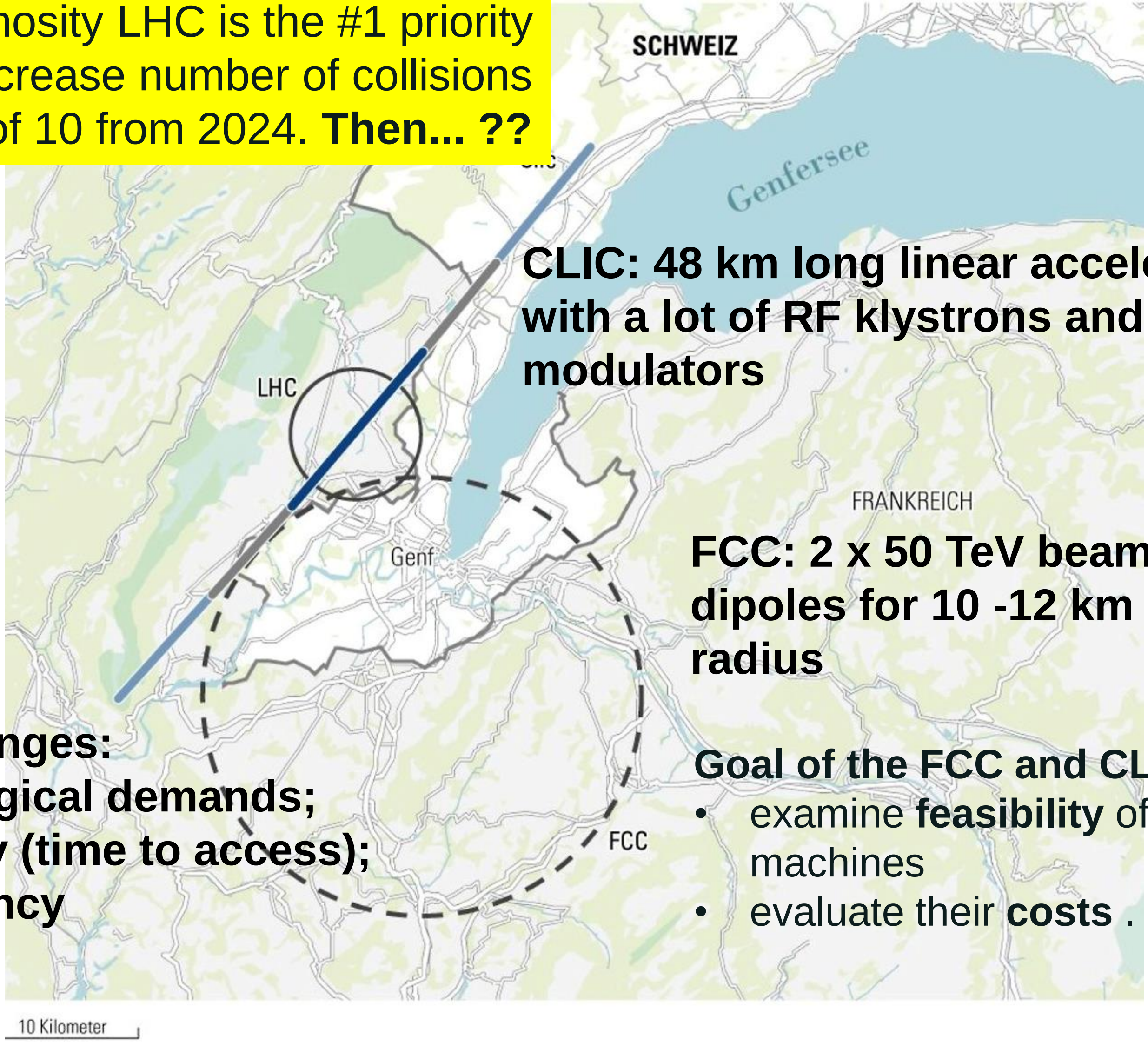


Striplines fed from beam downstream end

Possible Future Machines

HL-LHC then CLIC or a FCC at CERN?

High-Luminosity LHC is the #1 priority and will increase number of collisions by a factor of 10 from 2024. **Then... ??**



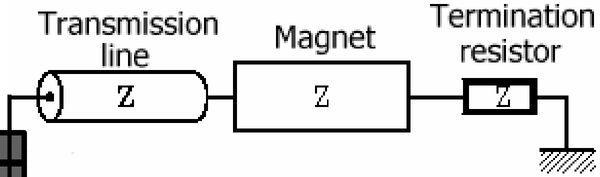
CLIC: 48 km long linear accelerator, with a lot of RF klystrons and modulators

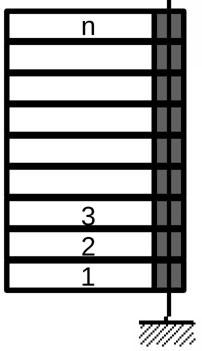
FCC: 2 x 50 TeV beam, 16 - 20 T dipoles for 10 -12 km bending radius

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

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

Inductive adder (CLIC)

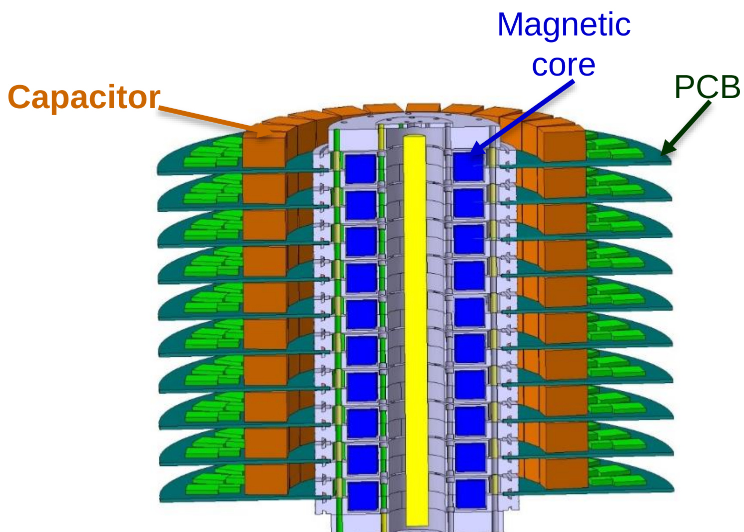




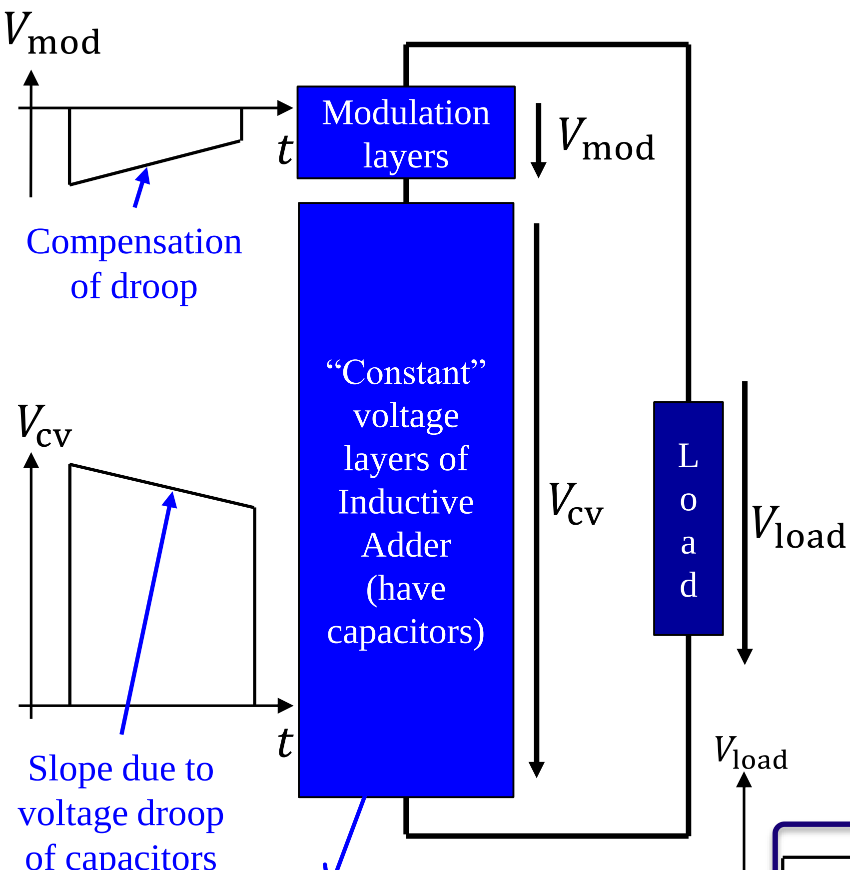
- n x low voltage layers
- Turn on/off: MOSFETs or IGBTs
- Magnetic coupling

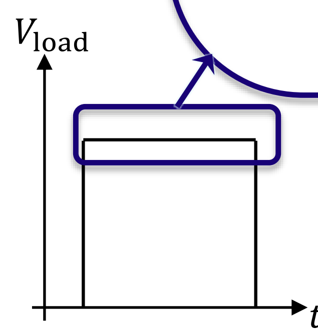
- Turn-on AND Turn-off Capability – hence PFN/PFL is NOT required: instead **Capacitors** are used to store energy;
- Excellent scalability;
- Output pulse can be modulated (next slide);
- Prototype under design: 12.5 kV, ~300 A, 1μs, **required flat-top stability ±0.02 % !!**

- **BUT: pulse length is limited by saturation of magnetic material….**

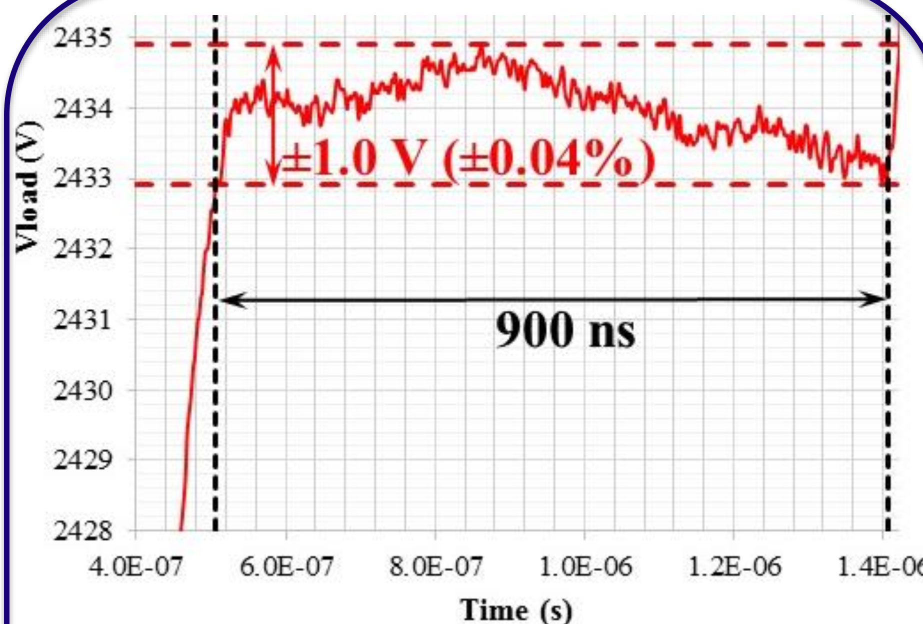


Compensation of Droop and Ripple

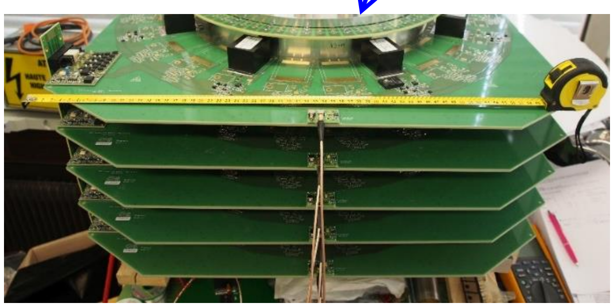




$$V_{load} = V_{cv} + V_{mod}$$



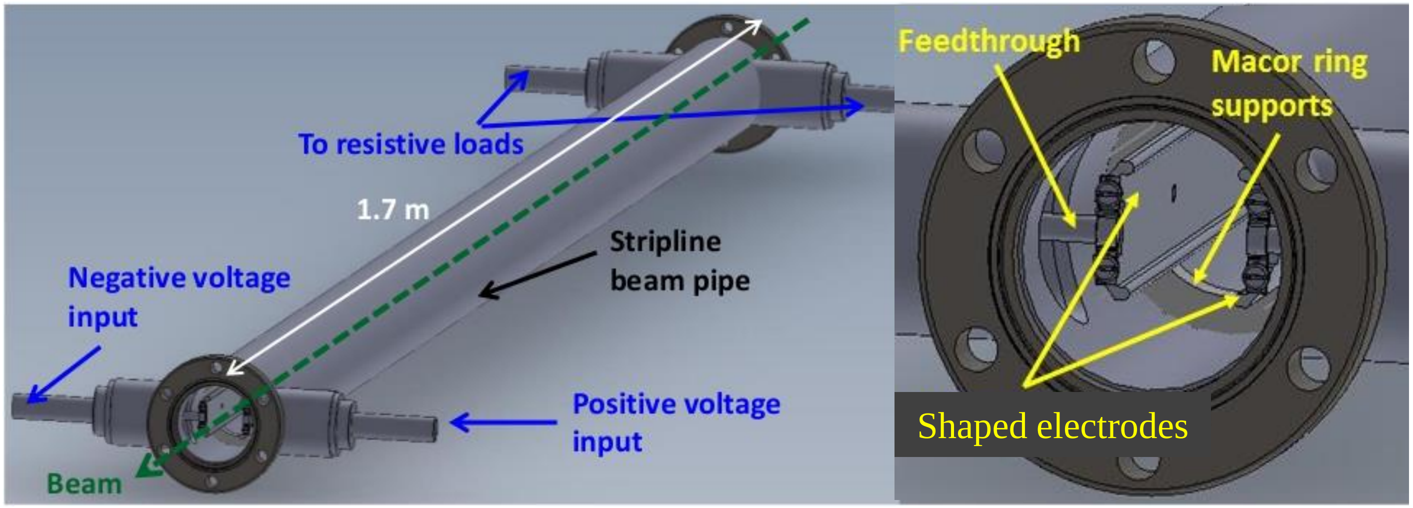
Measured, compensated (modulated), output pulse (100 averages)

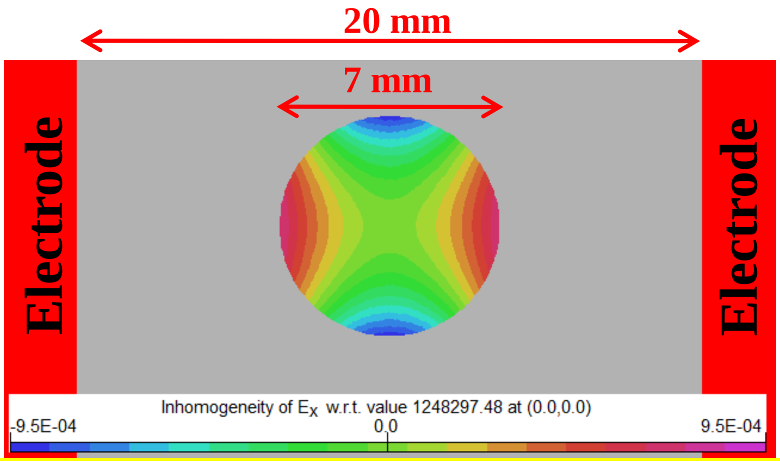


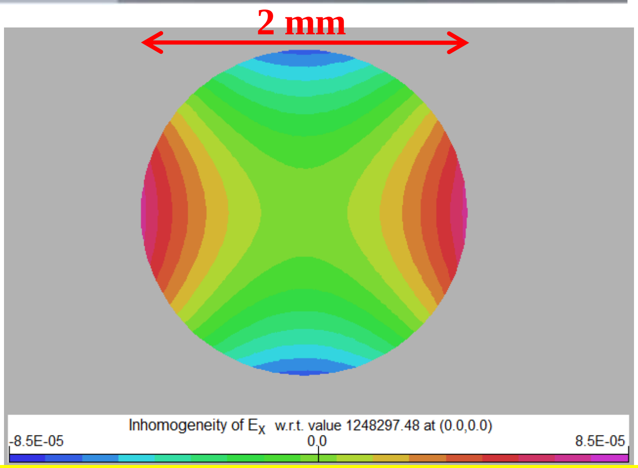
Stripline Design: Field Homogeneity

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).







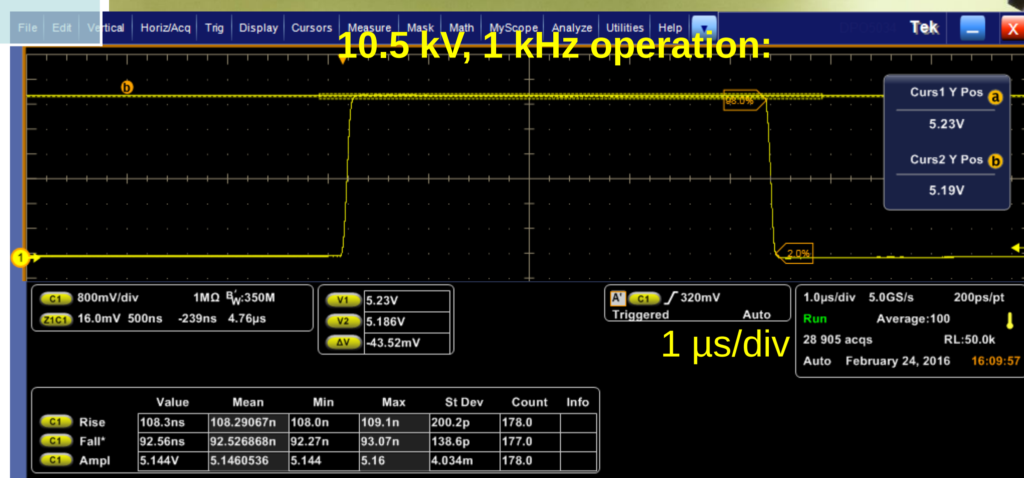
Theoretically field homogeneity achieved – striplines installed at ALBA (ES) for measurements.

Solid-State Marx Generator

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:

Output voltage rise/fall time	µs	0.1
Field flattop duration	µs	0.5 to 100
Output load	pF	150
Output voltage	kV	up to 10
Normal rep-rate	kHz	up to 1



Solid-State Marx Generator (1)

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

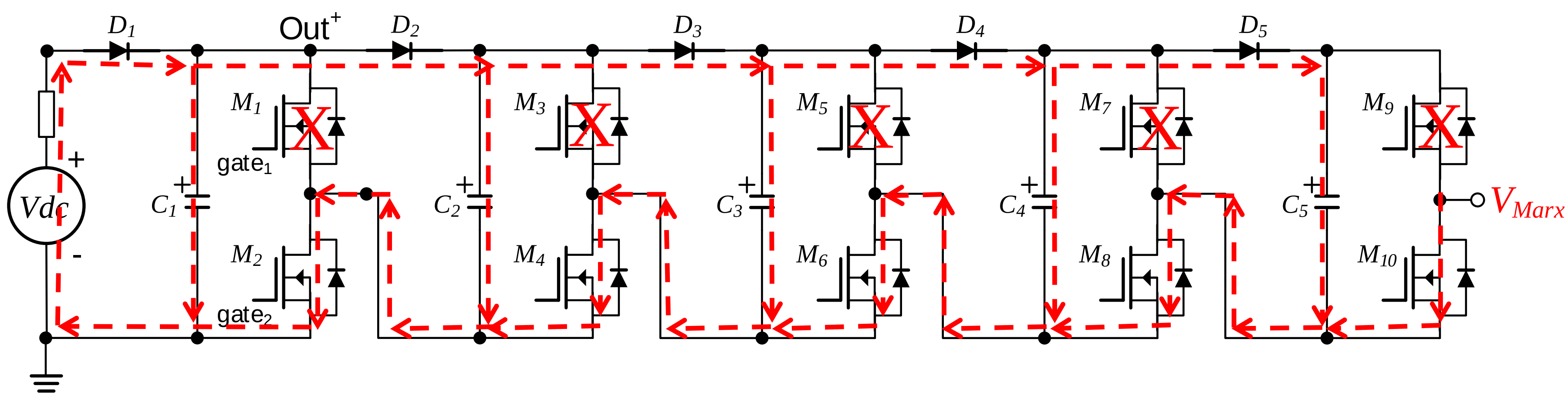
Concept: generate a high-voltage pulse from a low-voltage DC supply.

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]:



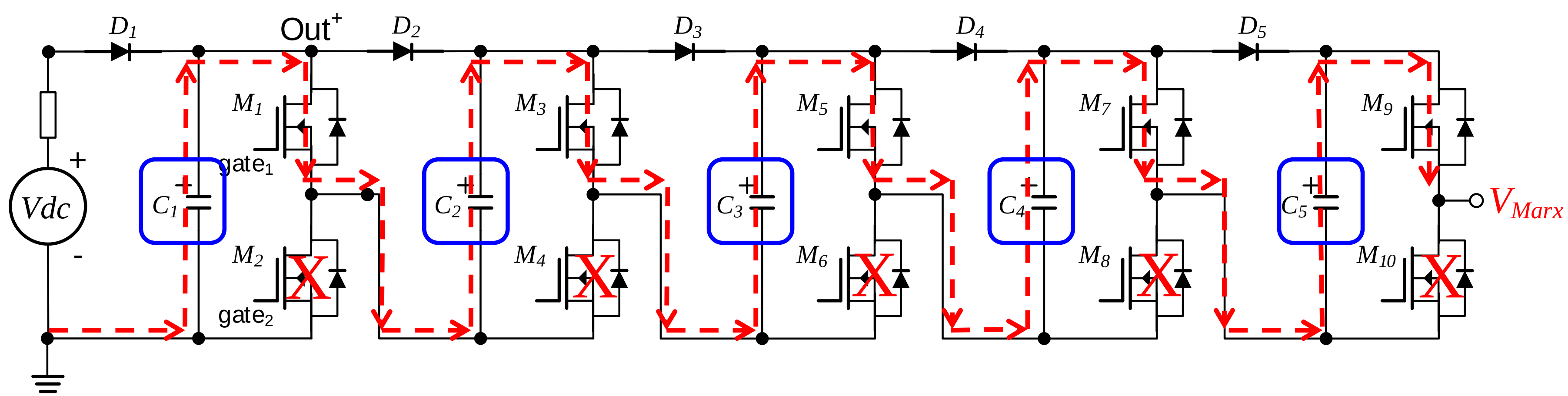
Solid-State Marx Generator (2)

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

STEP 2

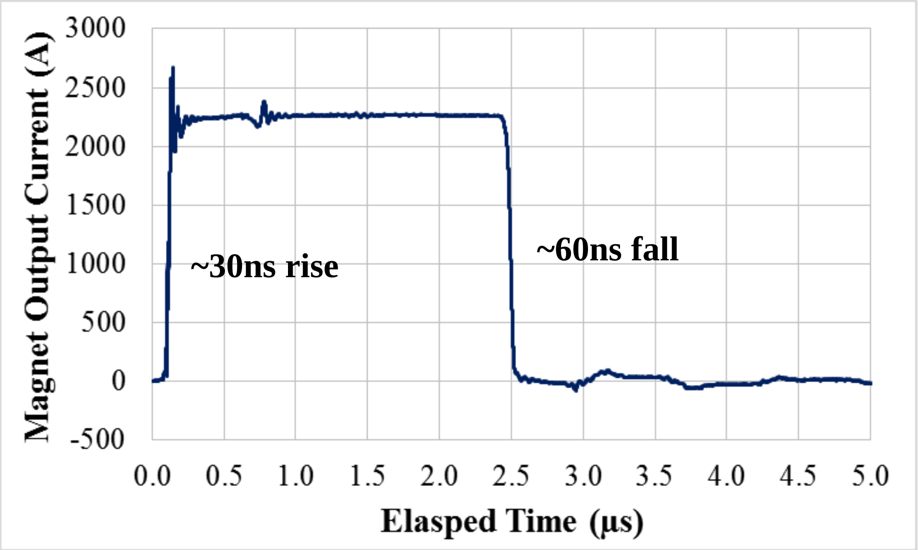
2a) Capacitors C_1, C_2 , … C_5 have been charged to V_{dc} in step (1b). All the even numbered MOSFETs/IGBTs (i.e. M_2, M_4, M_6, …) are then turned off.

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. $V_{MARX} \approx 5 \cdot V_{dc}$



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.

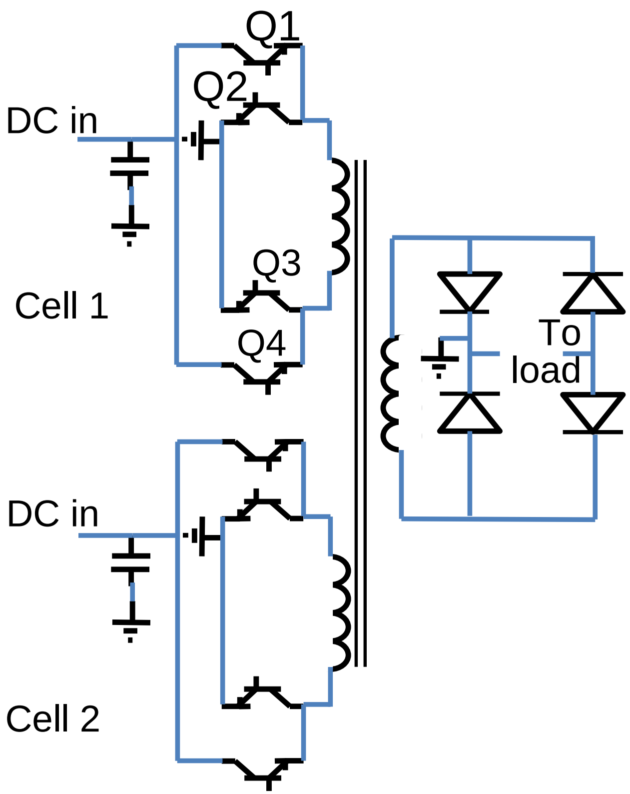
High Burst-Rate Power Modulator

Required for CLIC:

a) ~700 kHz burst rate (for ~100 pulses) @ 50 Hz;

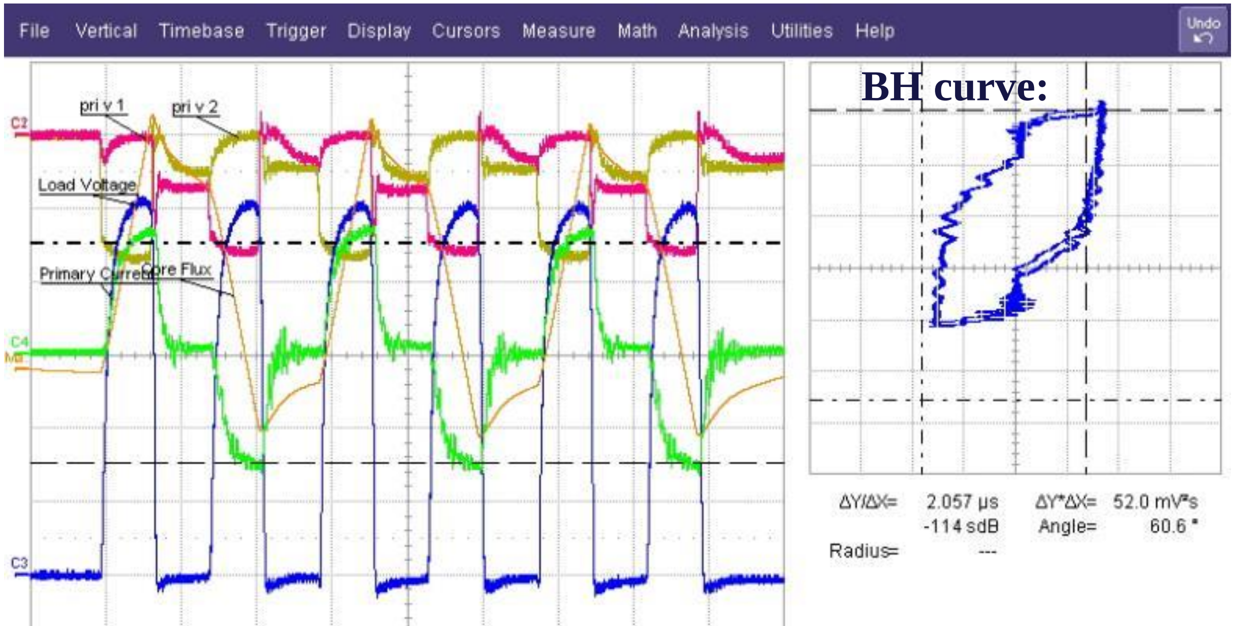
b) 10 kV, 200 A pulses – **low droop**;

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.



1 µs/div

FCC Injection Kicker

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.

FCC Extraction Kicker

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.

Questions ?

Thank you for your attention.

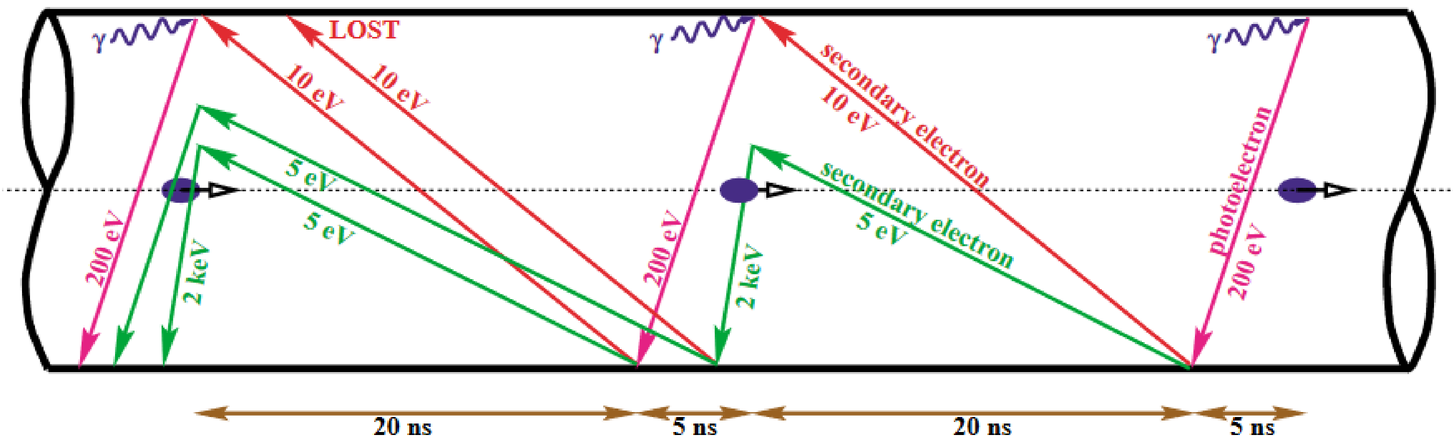
Kicker System Bibliography – Part 2 (1)

- J. Bonthond, et. al., “Dual Branch High Voltage Pulse Generator for the Beam Extraction of the Large Hadron Collider”, 2002 Power Modulator Symposium, Hollywood, USA, 30 June-3 July 2002, pp114-117.
- Eds. O. Brüning, L. Rossi, "The High Luminosity Large Hadron Collider: The New Machine for Illuminating the Mysteries of the Universe", Advanced Series on Direction in High Energy Physics – Vol. 24, (2015).
- C. Belver-Aguilar et. al., “Stripline Design for the Extraction Kicker of Compact Linear Collider Damping Rings”, Physical Review Special Topics: Accelerators and Beams, 17, 071003 (2014).
- J. Holma, M.J. Barnes, “The Prototype Inductive Adder with Droop Compensation for the CLIC Kicker Systems”, IEEE Transactions on Plasma Science, Vol. 42, No. 10, October 2014, pp2899-2908.
- R.B. Armenta (UVic.), et. al., “Electromagnetic Modeling of the AGS A10 Injection Kicker Magnet”, IEEE Trans. on Applied Superconductivity, Vol. 16, No. 2, June 2006, pp293-296.
- M.J. Barnes, G.D. Wait (TRIUMF), Y. Shirakabe, Y. Mori (KEK), “Conceptual Design of a Bipolar Kicker Magnet for J-PARC-Kamioka Neutrino Project”, IEEE Trans. On Applied Superconductivity, Vol. 14, Issue 2, June 2004, pp465-468.
- W. Zhang, et. al., “An Overview of High Voltage Dielectric Material for Travelling Wave Kicker Magnet Application”, proc. of 25th International Power Modulator Conf. and High Voltage Workshop, Hollywood, USA, June 30-July 3, 2002, pp674-678.
- M.J. Barnes, G.D. Wait, “Solid State Switch Alternatives for Klystron Modulators” (invited), 1995 Modulator/Klystron Workshop, Stanford, USA, Oct. 9-11, 1995.
- G.D. Wait, M.J. Barnes, “Thyratron Lifetimes: A Brief Review” (invited), 1995 Modulator/Klystron Workshop, Stanford, USA, Oct. 9-11, 1995
- H. Day, M.J. Barnes, L. Ducimetière, L. Vega Cid, W. Weterings, “Current and Future Beam Thermal Behaviour of the LHC Injection Kicker Magnet”, proc. of 7th International Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 8-13, 2016, THPMW031.
- L.S. Stoel, M.J. Barnes, W. Bartmann, F. Burkart, B. Goddard, W. Herr, T. Kramer, A. Milanese, G. Rumolo, E. Shaposhnikova, “High Energy Booster Options for a Future Circular Collider at CERN”, proc. of 7th International Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 8-13, 2016, MOPOY007.
- L.S. Stoel, et. al., “High Energy Booster Options for a Future Circular Collider at CERN”, proc. of 7th International Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 8-13, 2016, MOPOY007.

Kicker System Bibliography – Part 2 (2)

- T. Kramer, et. al., “Considerations for the Injection and Extraction Kicker Systems of a 100 TeV centre-of-mass FCC-hh Collider”, proc. of 7th International Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 8-13, 2016, THPOR049.
- C. Belver-Aguilar, M.J. Barnes, L. Ducimetière, “Review on the effects of characteristic impedance mismatching in a stripline kicker”, proc. of 7th International Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 8-13, 2016, THPMW034.
- M.J. Barnes, et. al., “Operational Experience of the Upgraded LHC Injection Kicker Magnets”, proc. of 7th International Particle Accelerator Conf. (IPAC’16), Busan, Korea, May 8-13, 2016, THPMW033.
- M.J. Barnes, L. Ducimetière, J. Holma, T. Kramer, A. Fowler, “Inductive Adders for Replacing Thyratron Based Modulators at CERN”, Published in: Power Electronics and Applications (EPE'15 ECCE-Europe), 2015 17th European Conference, 8-10 Sept. 2015.
- H. Day, M.J. Barnes, L. Feliciano, “Impedance Studies of the LHC Injection Kicker Magnets for HL-LHC”, proc. of 6th International Particle Accelerator Conf. (IPAC’15), Virginia, May 3-8, 2015, MOPJE038.
- A. Lechneret, et. al., “Protection of Superconducting Magnets in Case of Accidental Beam Losses during HL-LHC Injection”, proc. of 6th International Particle Accelerator Conf. (IPAC’15), Virginia, May 3-8, 2015, TUPTY049.
- T. Kramer, et. al., “Considerations for the Beam Dump System of a 100 TeV Centre-of-mass FCC hh Collider”, proc. of 6th International Particle Accelerator Conf. (IPAC’15), Virginia, May 3-8, 2015, TUPTY050.
- W. Bartmann, et. al., “Beam Transfer to the FCC-hh Collider from a 3.3 TeV Booster in the LHC Tunnel”, proc. of 6th International Particle Accelerator Conf. (IPAC’15), Virginia, May 3-8, 2015, THPF089.
- T. Baer et al., “UFOs: Observations, Statistics and Extrapolations”, proc. of 2012 Evian workshop on LHC beam operation, Evian, 17th to 20th December 2012.
- Y. Papaphilippou, et. al., “Conceptual Design of the CLIC damping rings”, proc. of 3rd International Particle Accelerator Conf. (IPAC’12), New Orleans, May 21-26, 2012, p1368-1370.
- G.D. Wait, M.J. Barnes, K.D. Metzmacher, L. Sermeus, “The Application of Saturating Inductors for Improving the Performance of the CERN PS Kicker Systems”, proc. of 17th Particle Accelerator Conf. (PAC’97), Vancouver, Canada, May 12-16, 1997, pp1328-1330
- G.D. Wait, M.J. Barnes, “Measurements on a FET Based 1 MHz, 10 kV Pulse Generator”, proc. of 10th International Pulsed Power Conf., Albuquerque, USA, July 10-13, 1995, pp1341-1346.

Electron Cloud



Schematic of electron cloud build-up mechanism in LHC (courtesy of F. Ruggiero).

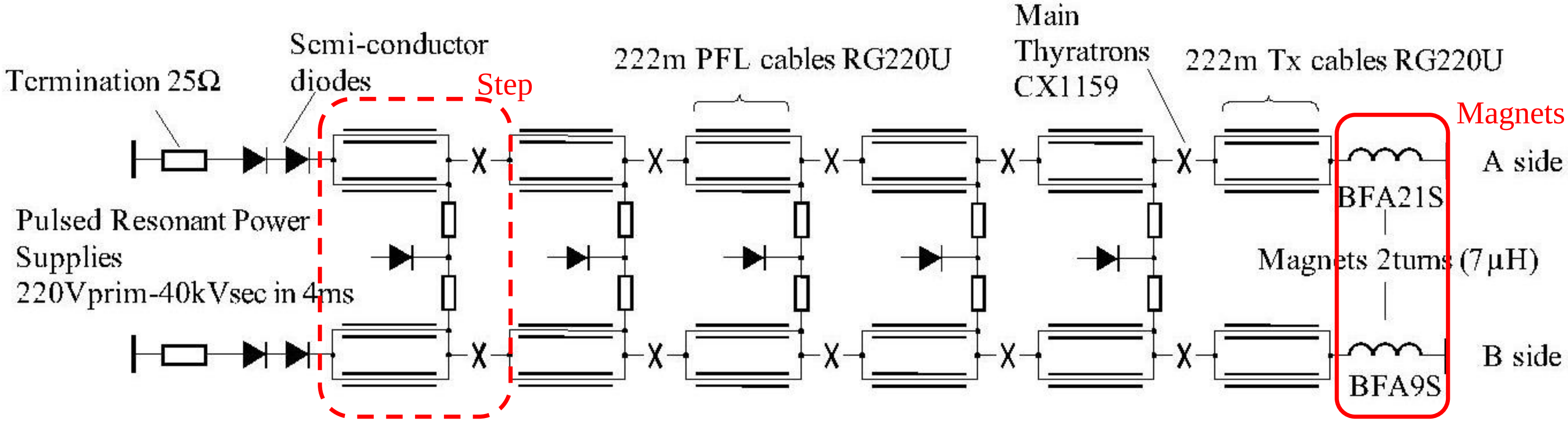
- Due to the close bunch spacing of 25 ns, in the LHC, a significant number of electrons can accumulate in the LHC beam pipe as a result of a combination of processes.
- These seed electrons are accelerated by the beam electric field, can impact on the other side of the vacuum chamber and, if the secondary 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).

Courtesy of E. BENEDETTO, “Emittance growth induced by electron cloud in proton storage rings”, PhD Thesis, April 2006..

CERN PS Staircase Generator

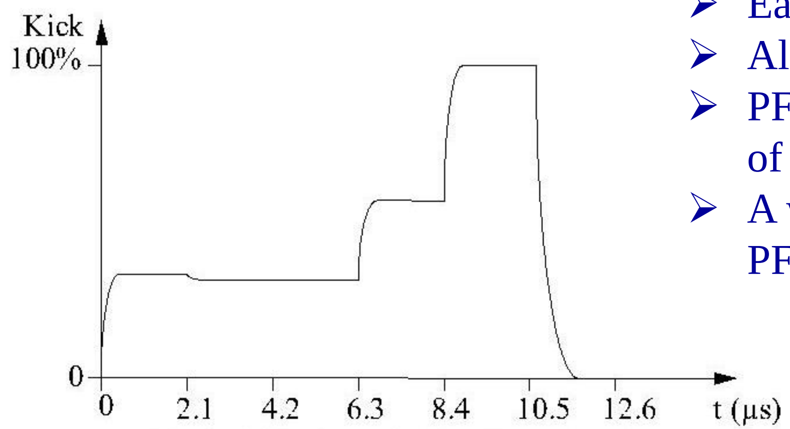
Continuous Transfer Normal Staircase Generator

a)



The STAIRCASE Bumper consists of 1 generator supplying two magnets

b)

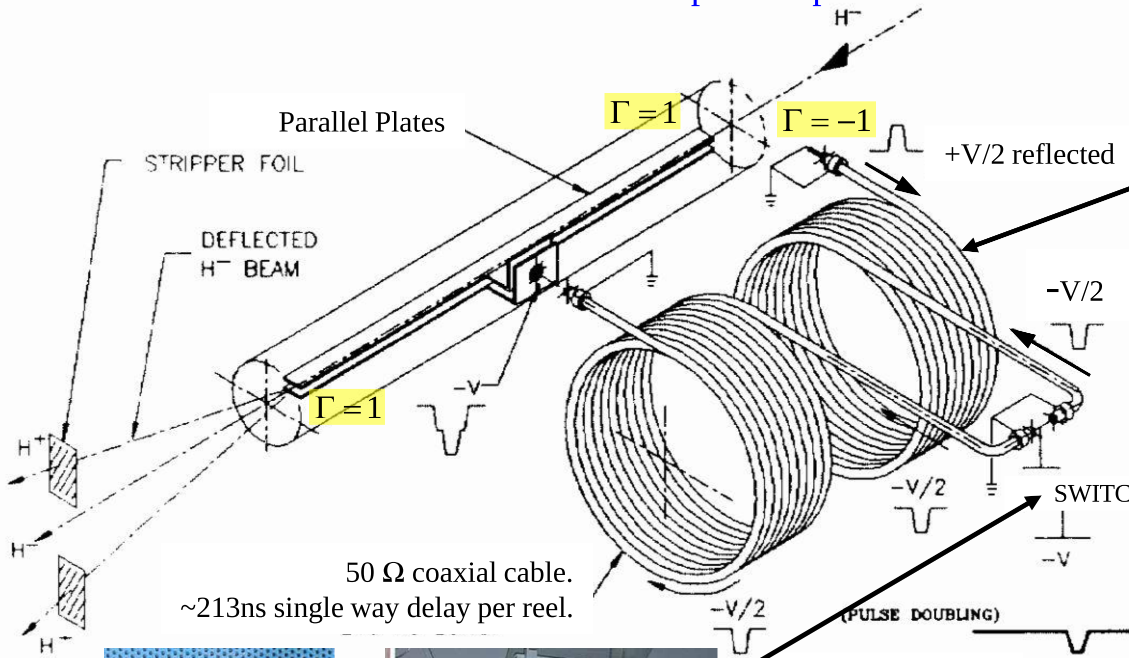


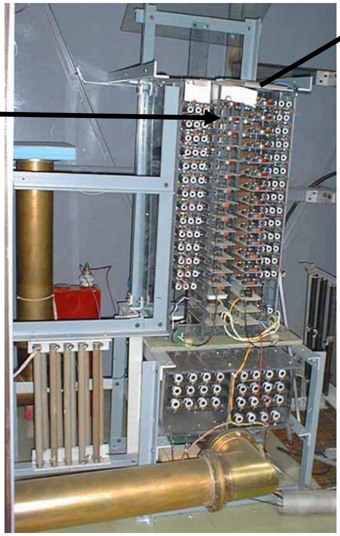
Typical "Staircase" Waveforms A and B

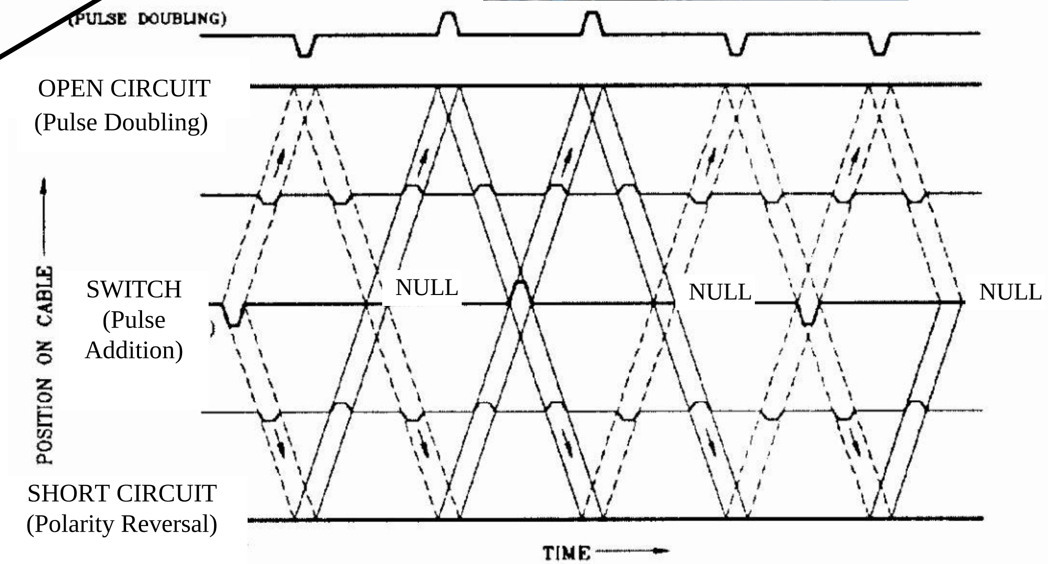
- RCPS's charge PFLs of same step;
- Each step can have a different PFL voltage;
- All steps are charged synchronously;
- PFLs are discharged by sequential triggering of thyratrons (starting at magnet end);
- A wave pattern is generated corresponding to PFL voltage.

1 MHz Chopper CW – Bidirectional Deflection

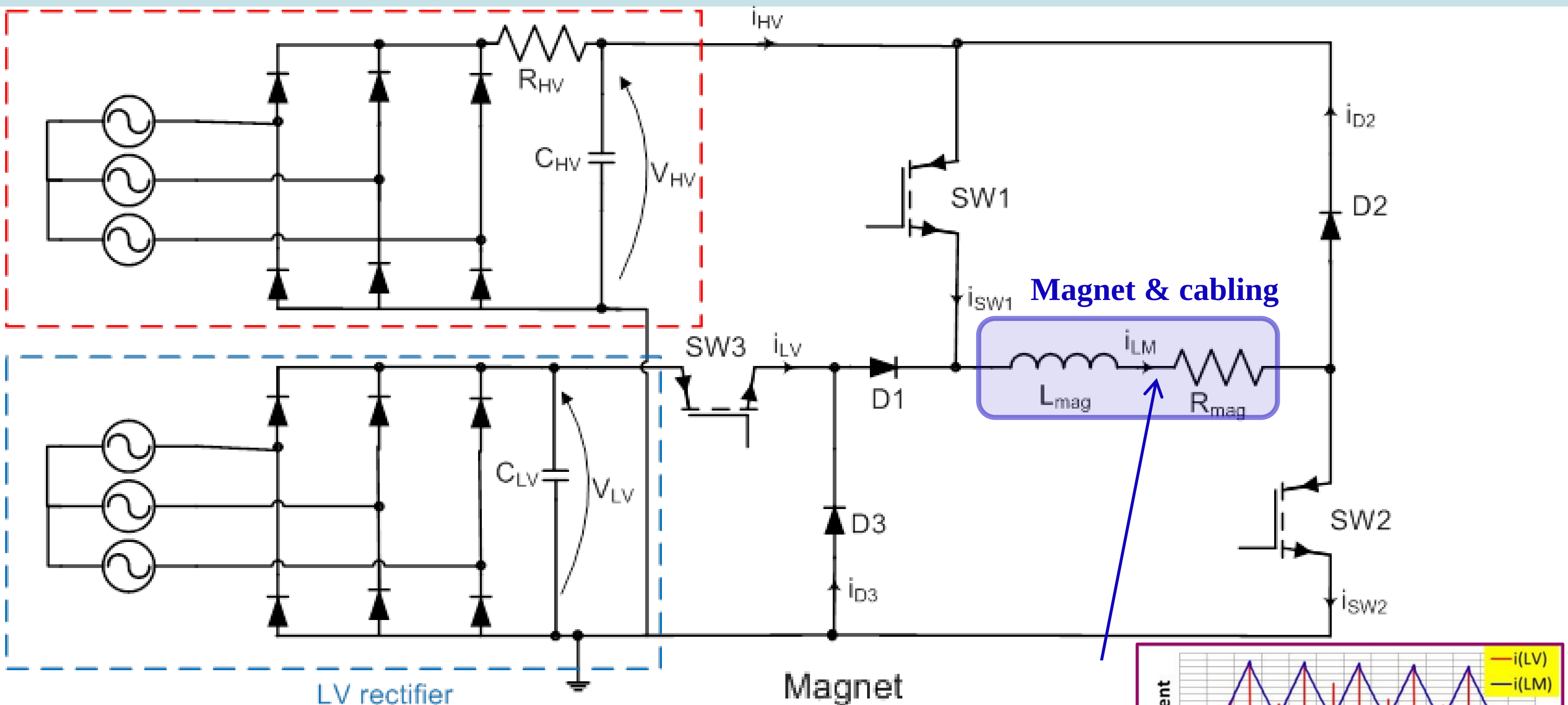
Deflection due to ELECTRIC field between parallel plates:





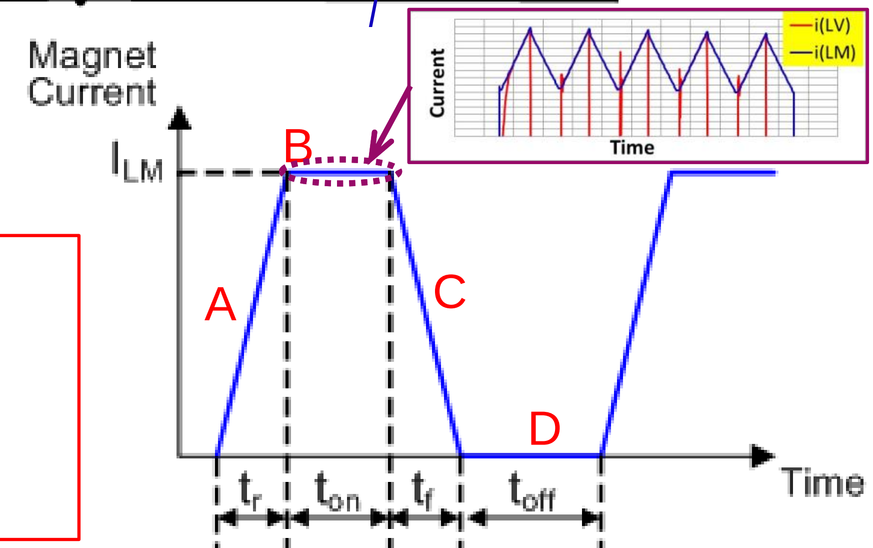


"Long-pulse" magnet power supply



Capability:

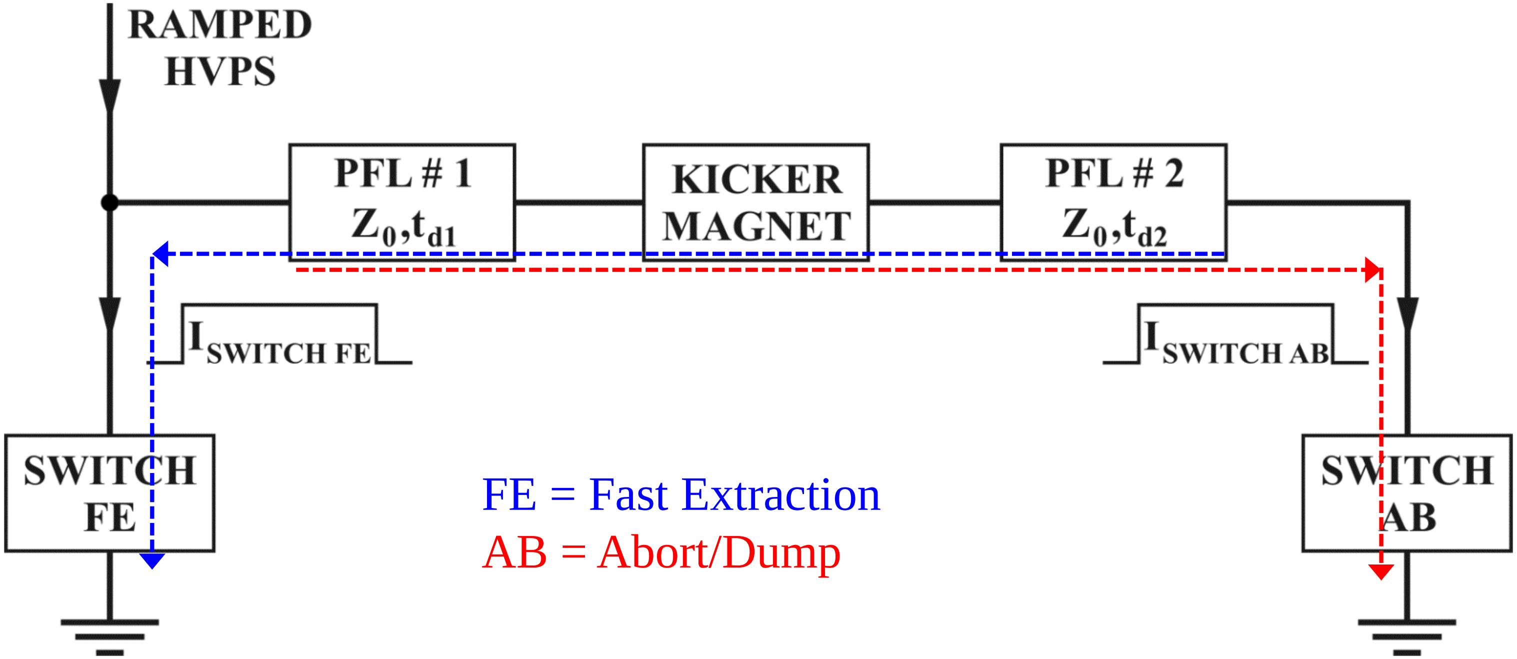
- Rise and fall times ~10's of μs;
- Flat-top: 0 to DC.



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.

Bi-Directional Kicker Magnet: Concept (1)



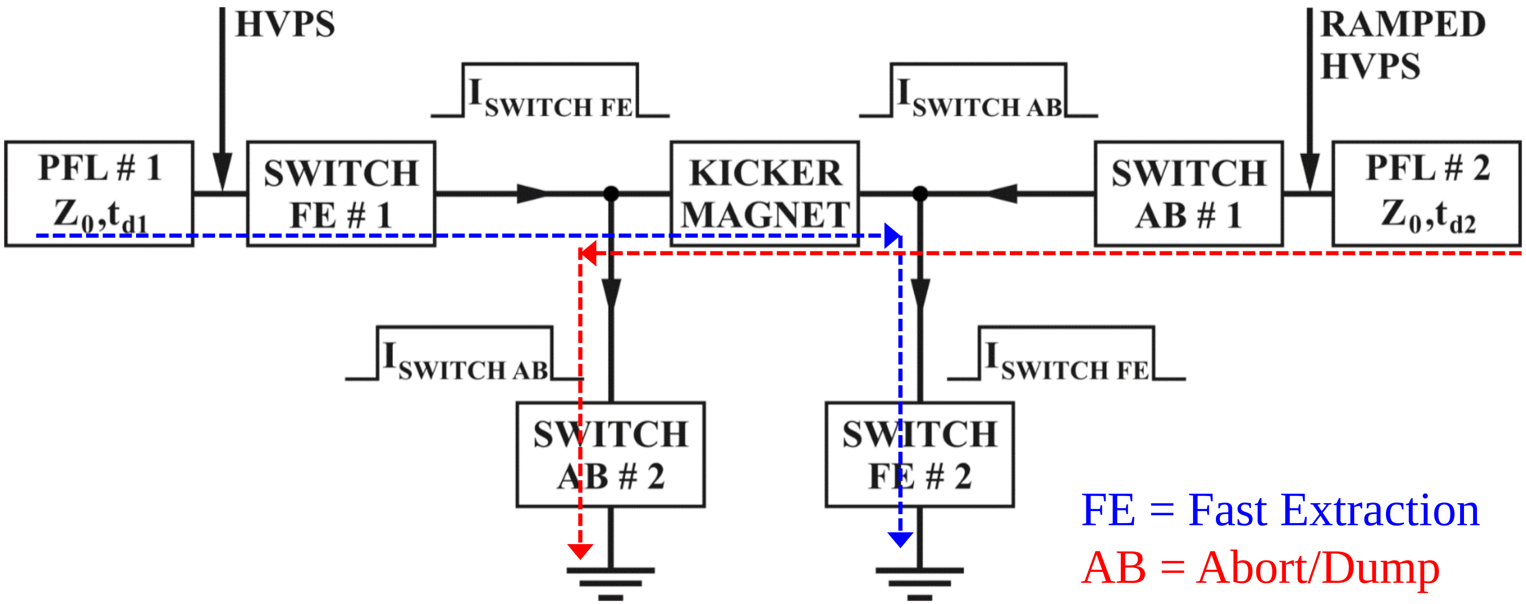
Concept:

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

<u>Potential issues</u>

- ➢ Kicker magnet is charged to high voltage, together with PFLs – hence insulation must be adequate;
- ➢ Abort functionality is delayed by propagation delay t_{d2} (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

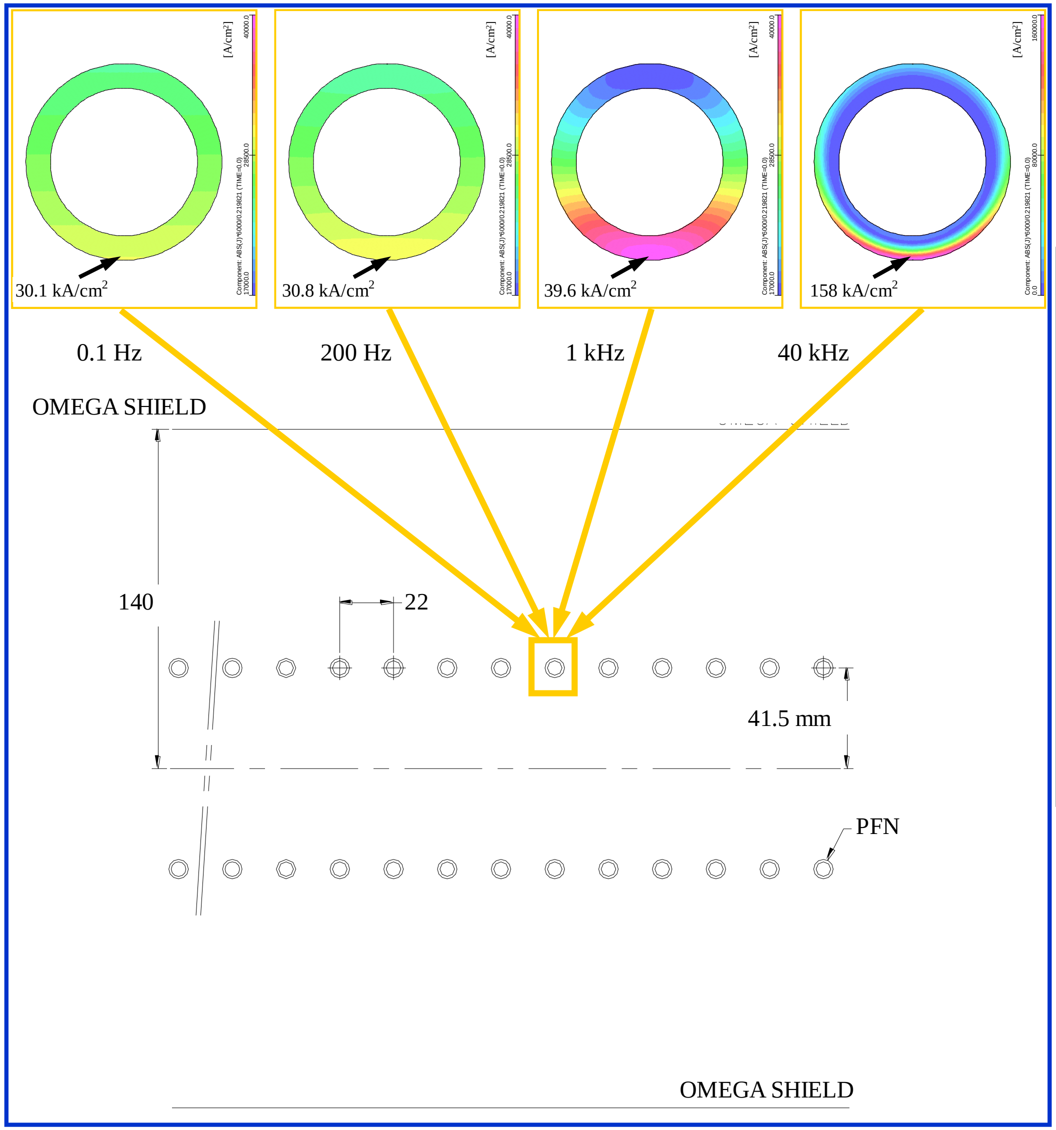
- Kicker magnet is charged to high voltage, together with PFLs – hence insulation must be adequate;
- For a fast field rise, two PFLs and four switches are required;
- Switches should be not be triggered by fast rates of change of voltage (e.g. triggering of FE#1 and FE#2, should not cause an erratic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

Example Parameters for Kickers in the CERN Complex

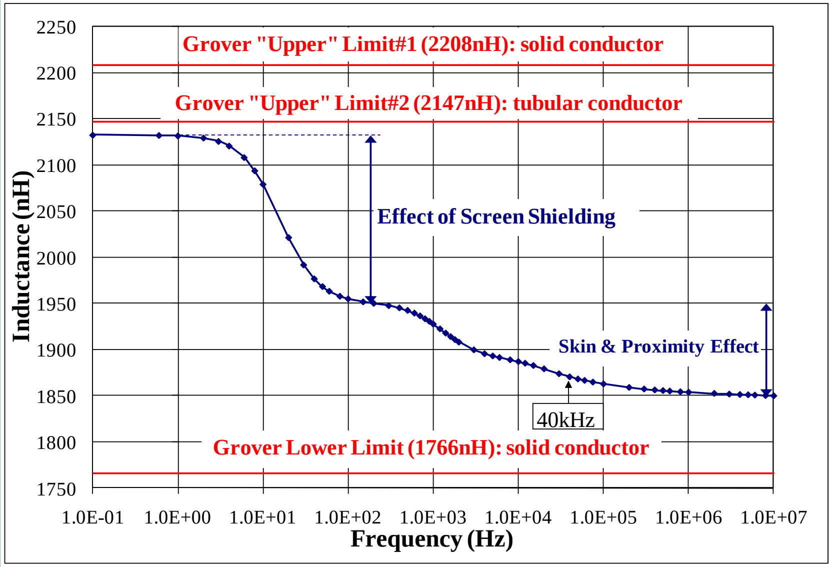
Kicker Location	Max. Beam Energy (GeV)	# Magnets	Gap Height [V_{ap}] (mm)	Current (kA)	Impedance (Ω)	Rise Time (ns)	Total Deflection (mrad)
CTF3 TC	0.2	4	40	0.056	50	~4	1.2
PS Inj.	2.14	4	53	1.52	26.3	42	4.2
SPS Inj.	13/26	16	54 to 61	1.47/1.96	16.67/12.5	115/200	3.92
SPS Ext.	450	3 or 4	32 to 35	3.1 to 3.3	10	~6000 to 8000	~0.4 to 0.5
LHC Inj.	450	4 (x2)	54	5.12	5	~800	0.82
LHC Abort	7000	15 (x2)	73	1.3 to 18.5	1.5 (not T-line)	2700	0.275

PFN Modelling – Opera2D

Opera2D Prediction for Current Distribution in PFN Coil



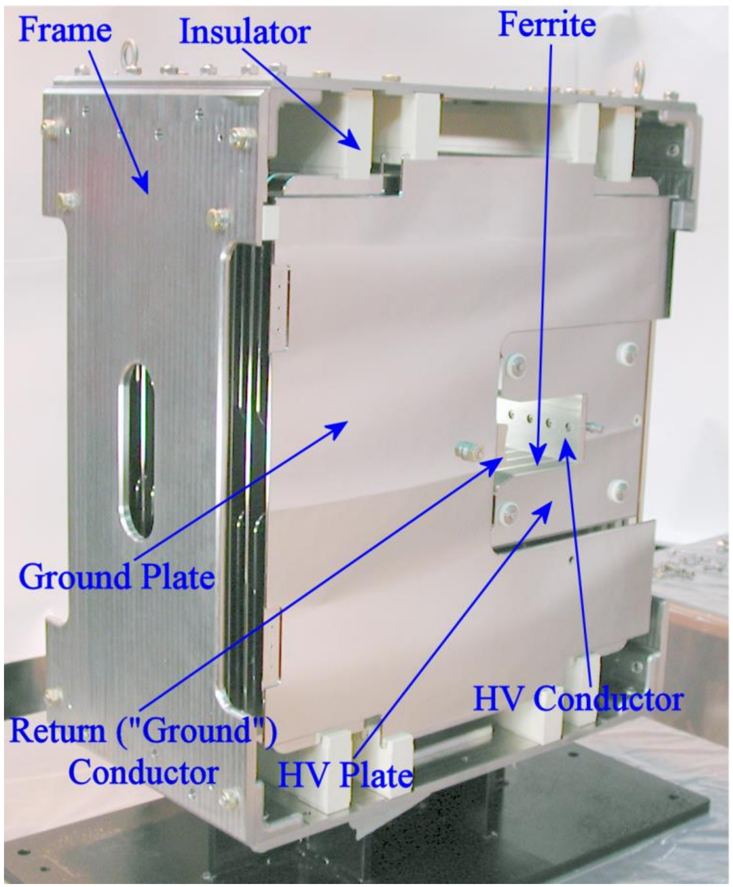
An Opera2D model of the PFN for the LHC Injection was used to predict self-inductance and mutual-inductance as a function of frequency.



Subsequently a circuit model of the inductance characteristic was fitted to the Opera2D predictions to permit realistic Pspice simulations.

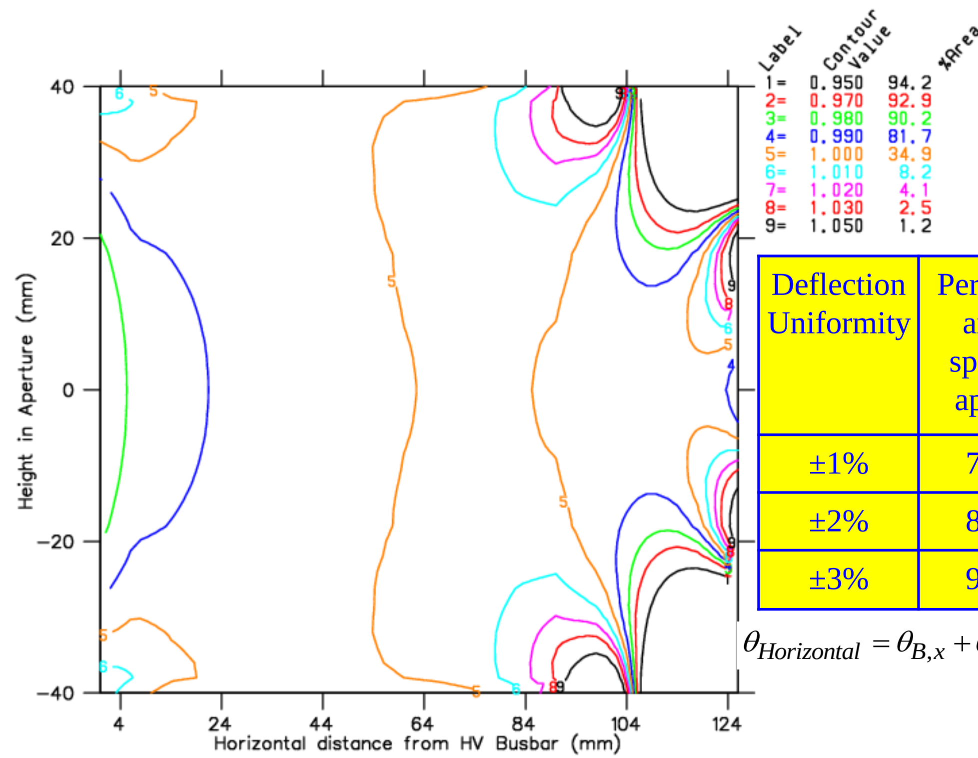
Magnet Design Tools (1)

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



Deflection Uniformity	Percentage area of specified aperture
±1%	73.5%
±2%	86.1%
±3%	90.4%

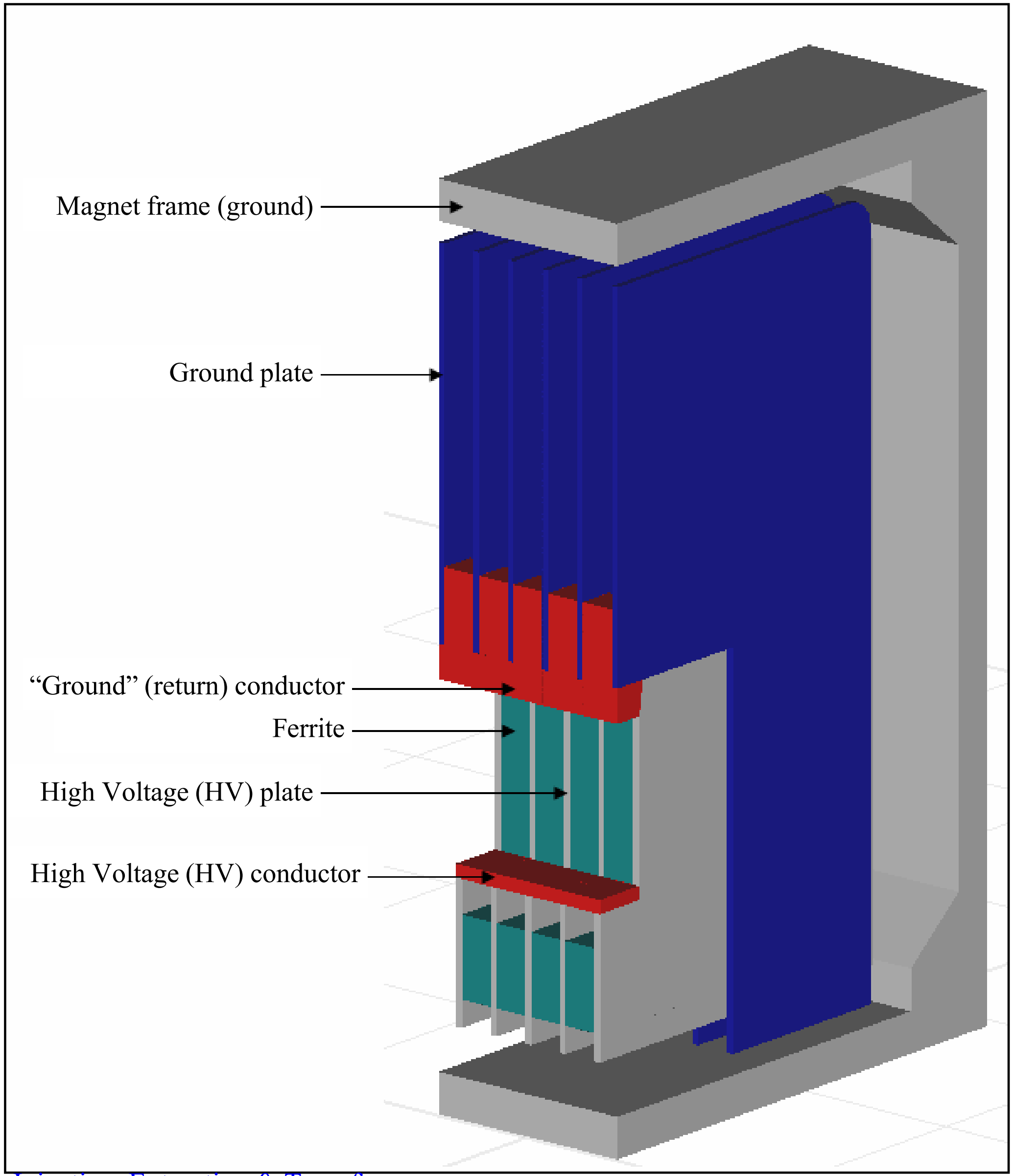
$$\theta_{Horizontal} = \theta_{B,x} + \theta_{E,x}$$

Magnet Design Tools (2)

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.

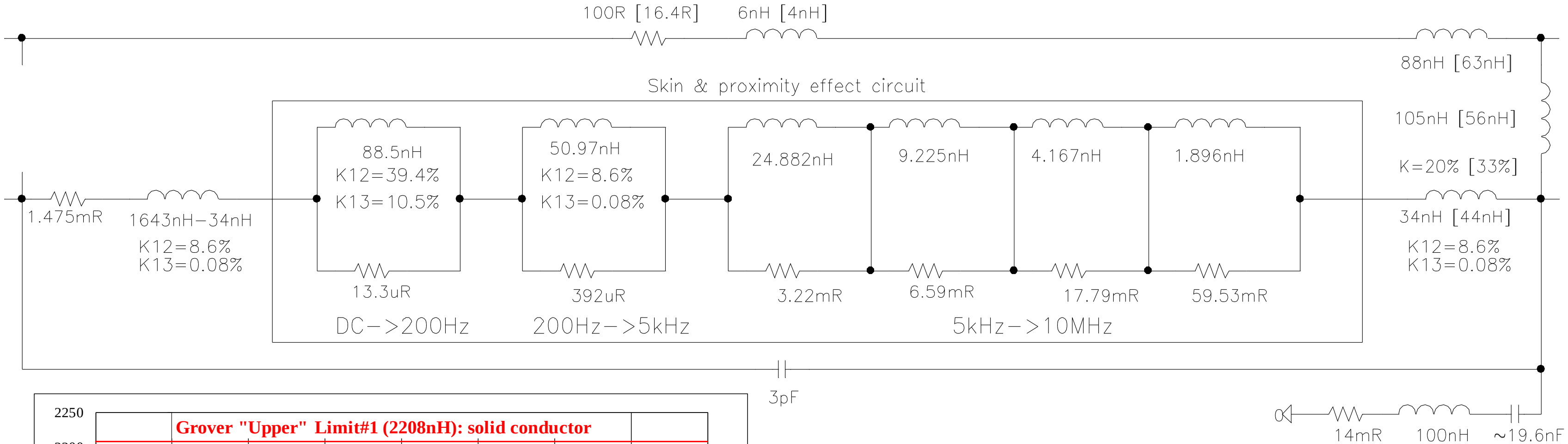


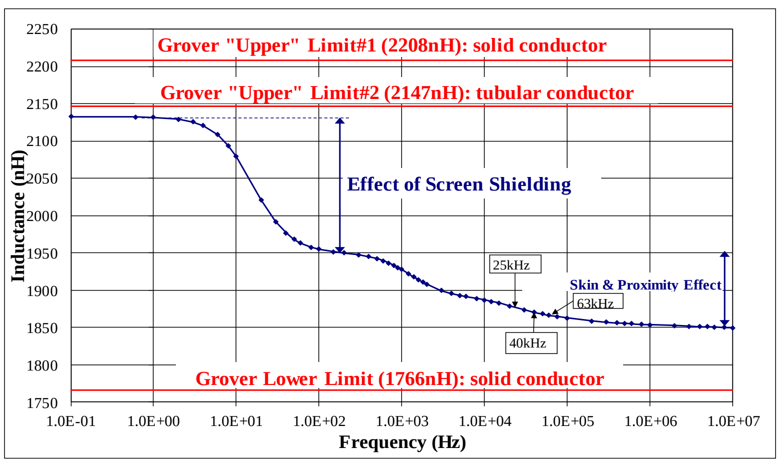
Circuit Modelling

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.

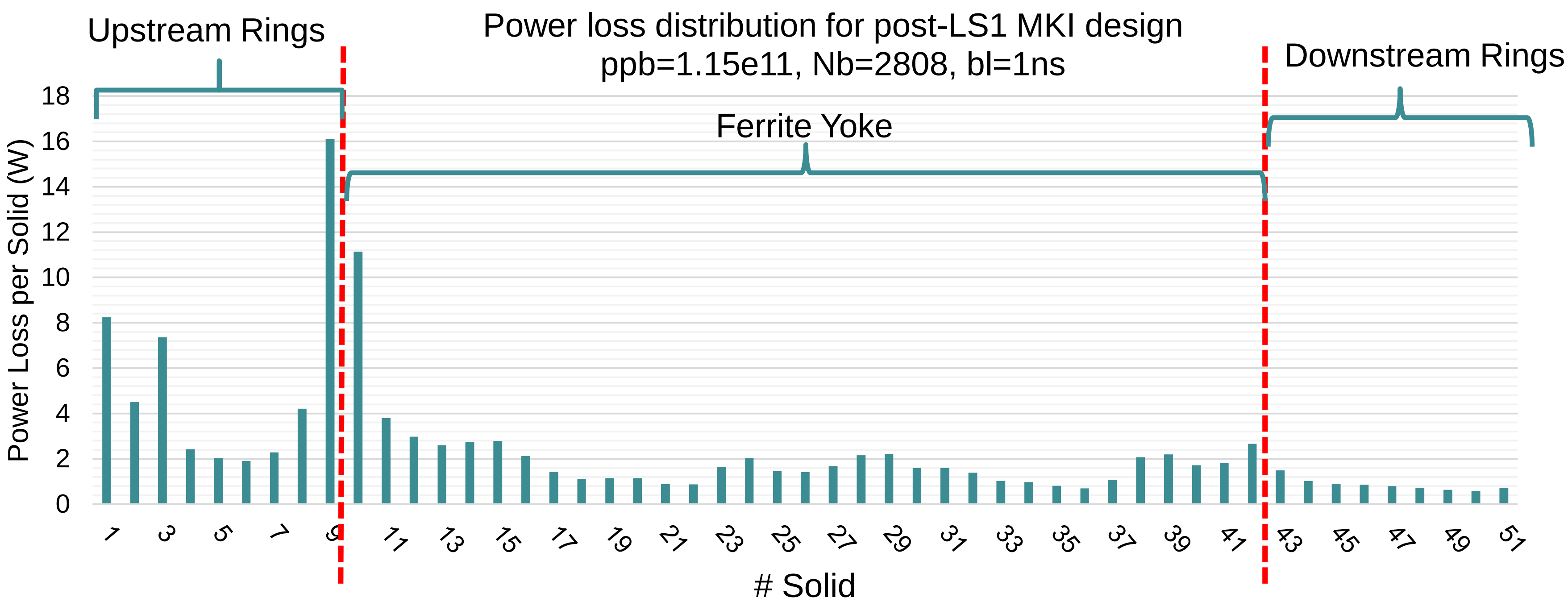
Equivalent circuit for a 7 turn MKI PFN cell [damping circuit values for MS end cell in parentheses]:



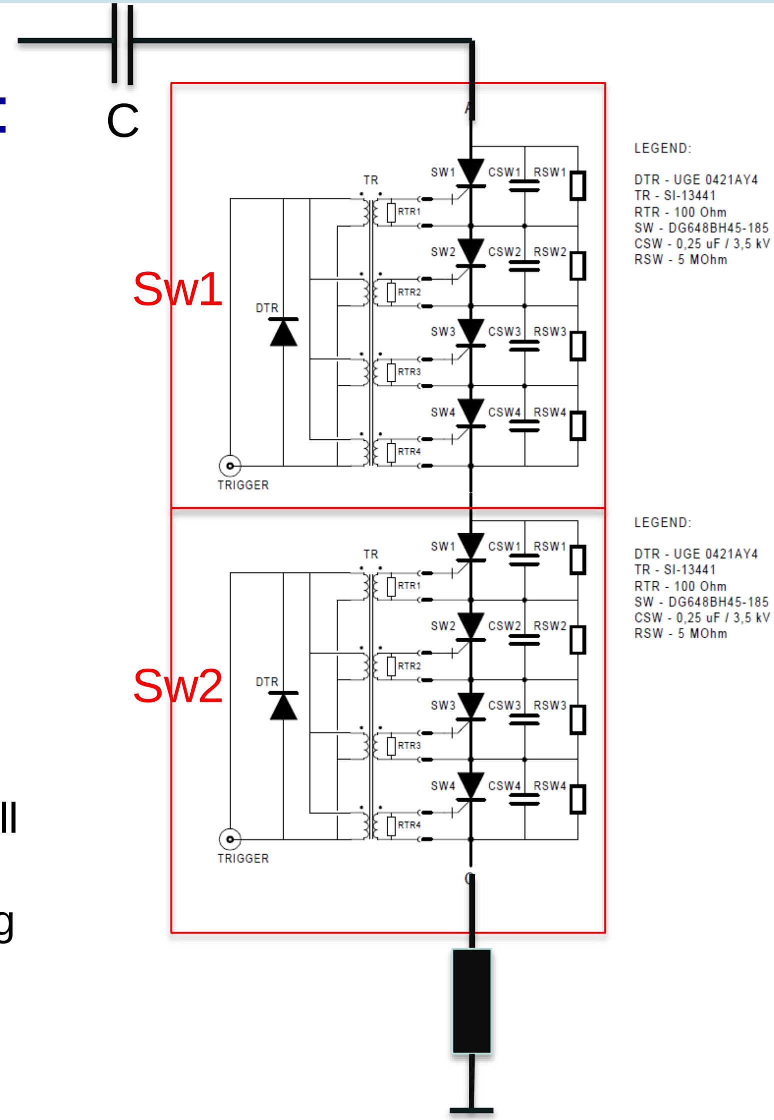


Beam Impedance Modelling

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.



Series Switch



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)