Injection & Extraction Magnets II: Kickers

M.J. Barnes
CERN TE/ABT

Acknowledgements:

L. Ducimetière, T. Fowler, V. Senaj, L. Sermeus, B. Goddard, J. Uythoven

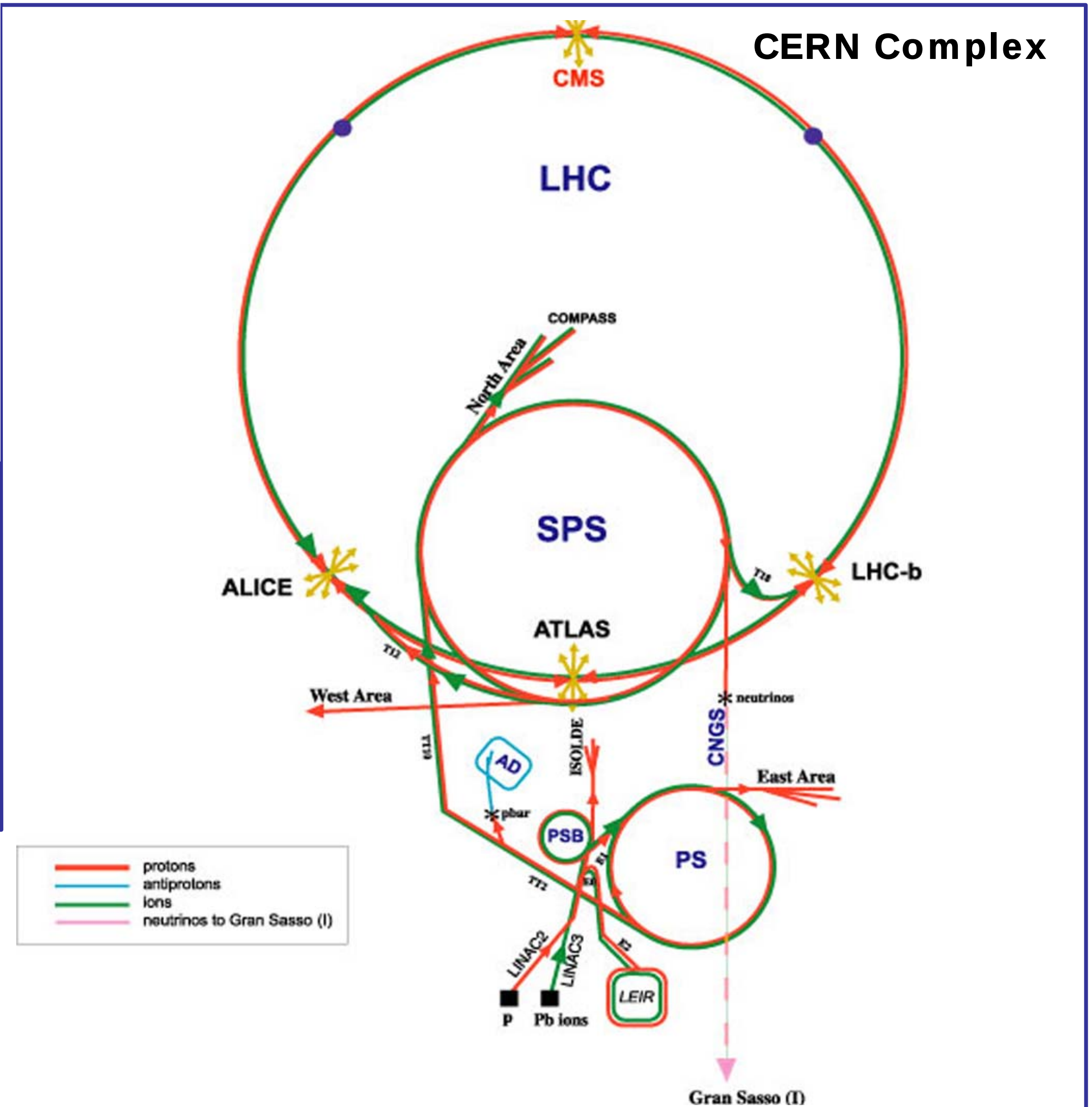
Overview of Presentation

- Role of a kicker system:
  - Beam Injection, Extraction & Dump
- Main sub-systems (“components”) of a kicker system;
  - Purpose and description of each main “component”
  - Major design options
  - Design aids
- Examples of different kicker equipment and some typical waveforms

Injection, Extraction and Transfer

- An accelerator stage has limited dynamic range.
- Chain of stages needed to reach high energy
- Periodic re-filling of storage (collider) rings, like LHC
- External experiments, like CNGS

Beam transfer (into, out of, and between machines) is necessary.



LHC:	Large Hadron Collider
SPS:	Super Proton Synchrotron
AD:	Antiproton Decelerator
ISOLDE:	Isotope Separator Online Device
PSB:	Proton Synchrotron Booster
PS:	Proton Synchrotron
LINAC:	LINear Accelerator
LEIR:	Low Energy Ring
CNGS:	CERN Neutrino to Gran Sasso

Introduction

- What do we mean by injection?
  - Inject a particle beam into a circular accelerator or accumulator ring, at the appropriate time.
    - minimize beam loss
    - place the injected particles onto the correct trajectory, with the correct phase-space parameters
- What do we mean by extraction?
  - Extract the particles from an accelerator to a transfer line or a beam dump, at the appropriate time;
    - minimize beam loss
    - place the extracted particles onto the correct trajectory, with the correct phase-space parameters
- Both processes are important for performance of an accelerator complex.

Special Elements

A combination of septa and kickers are frequently used – both are required for some schemes;

Kicker magnet: pulsed dipole magnet with very fast rise and/or fall time (typically 50 ns $\rightarrow$ 1 μs).

Septum magnet: pulsed or DC dipole magnet with thin (2-20mm) septum between zero field and high field region.

Electrostatic septum: DC electrostatic device with very thin (~100 μm) septum between zero field and high field region.

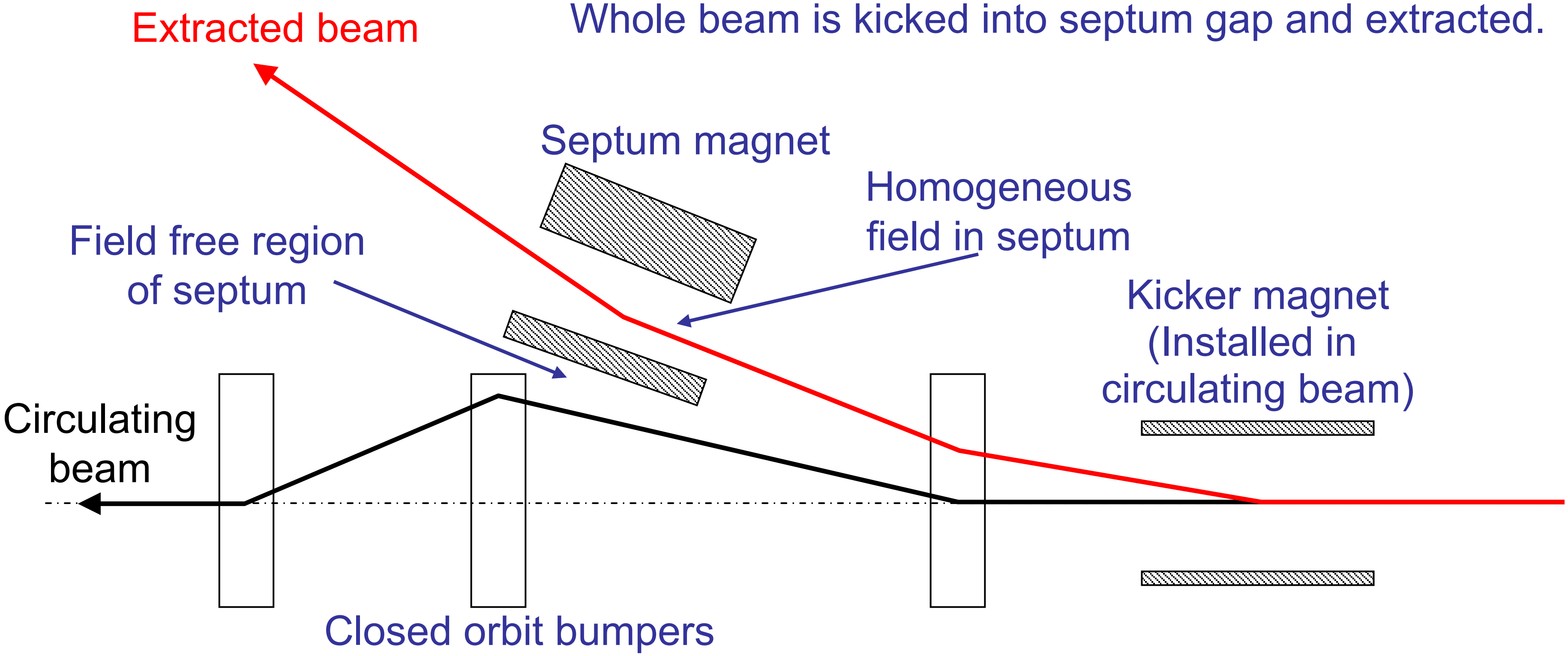
Example Parameters for Septa and Kickers in the CERN Complex

Septum Location	Max. Beam Energy (GeV)	Gap Height (mm)	Max. Current (kA)	Magnetic Flux Density (T)	Deflection (mrad)
LEIR/AD/CTF (13 systems)	Various	25 to 100	1 DC to 40 pulsed	0.5 to 1.6	up to 130
PS Booster (6 systems)	1.4	25 to 60	28 pulsed	0.1 to 0.6	up to 80
PS complex (8 systems)	26	20 to 77	2.5 DC to 33 pulsed	0.2 to 1.2	up to 55
SPS Ext.	450	20	24 slow pulsed	1.5	up to 13.5

Kicker Location	Max. Beam Energy (GeV)	# Magnets	Gap Height [V_{ap}] (mm)	Current (kA)	Impedance (Ω)	Rise Time (ns)	Total Deflection (mrad)
CTF3	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. (MKE4)	450	5	32 to 35	2.56	10	1100	0.48
LHC Inj.	450	4	54	5.12	5	900	0.82
LHC Abort	7000	15	73	1.3 to 18.5	1.5 (not T-line)	2700	0.275

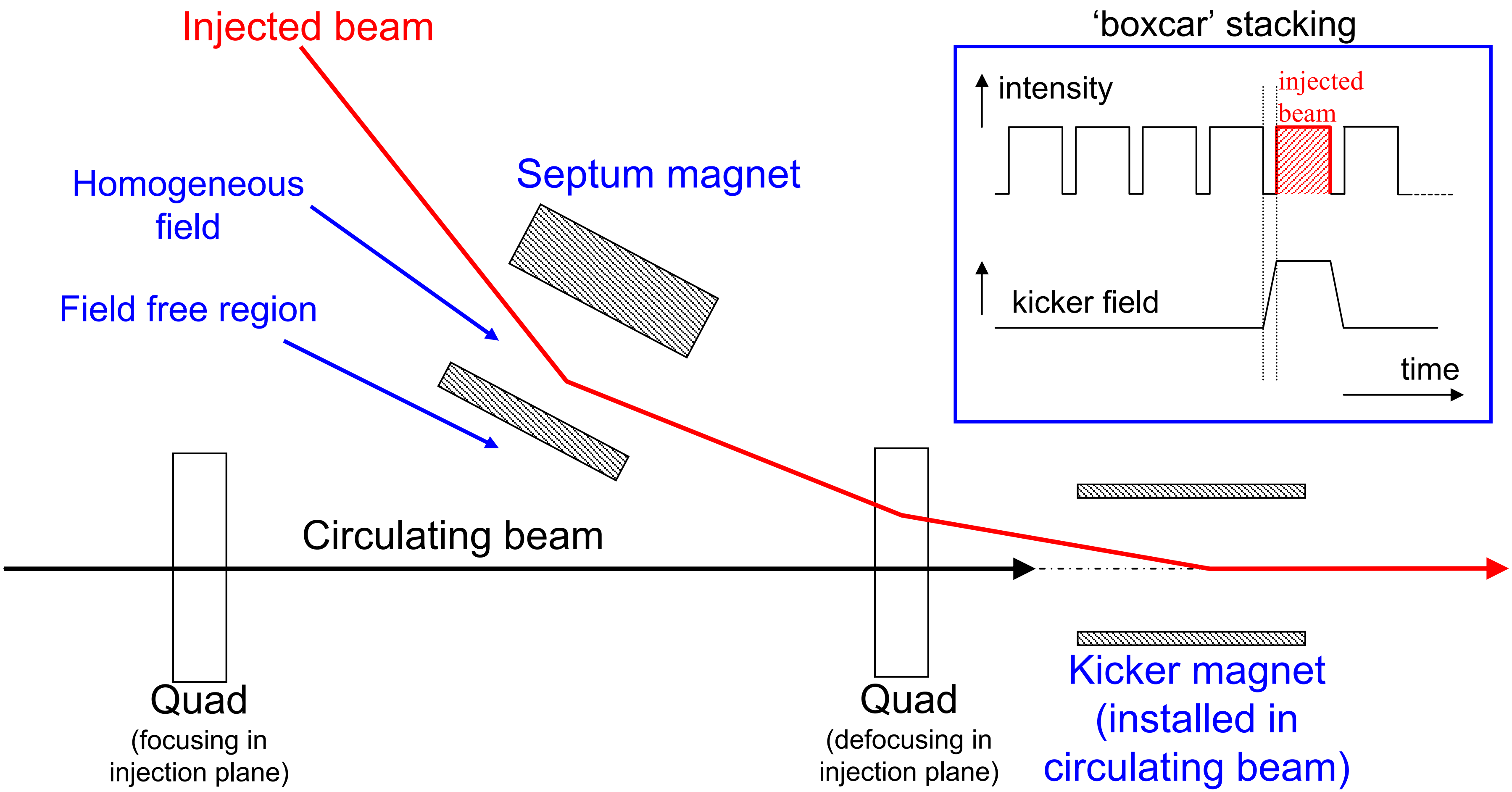
Fast Single-Turn Extraction: Same Plane

Whole beam is kicked into septum gap and extracted.



- **Kicker** deflects the entire beam into the septum in a single turn (time selection [separation] of beam to be extracted);
- **Septum** deflects the entire kicked beam into the transfer line (space separation of circulating and extracted beam).

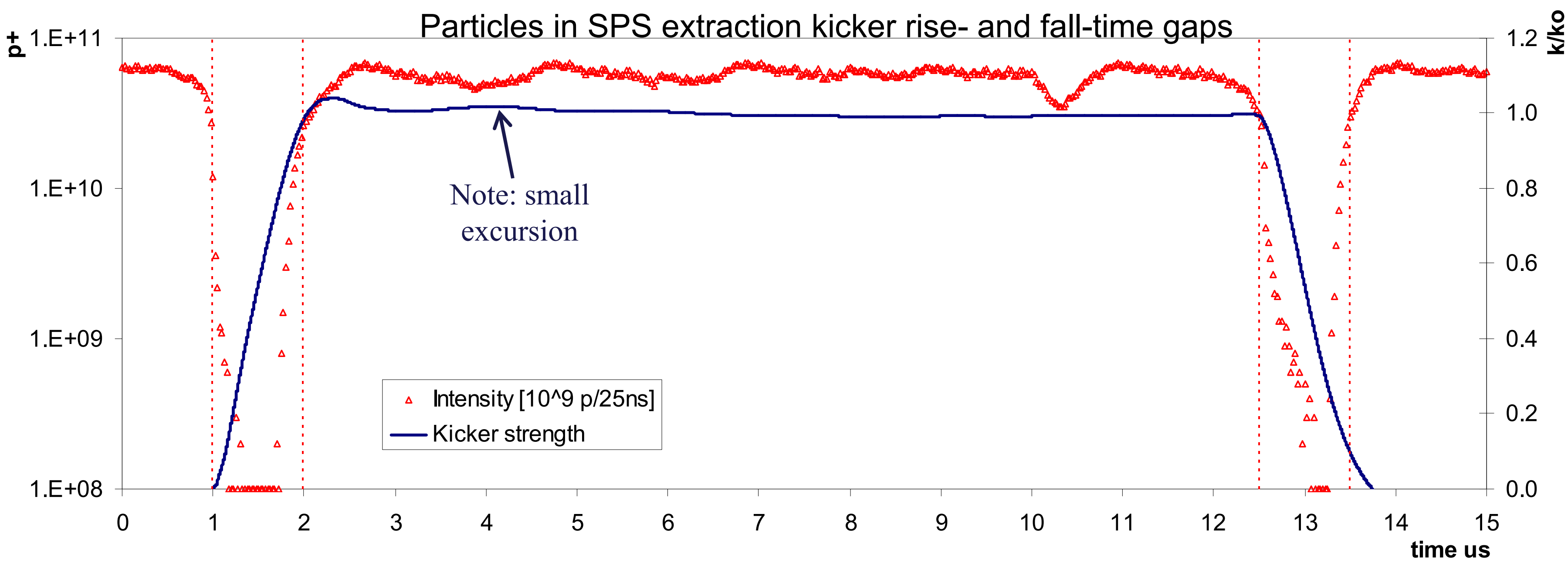
Fast Single-Turn Injection: Same Plane



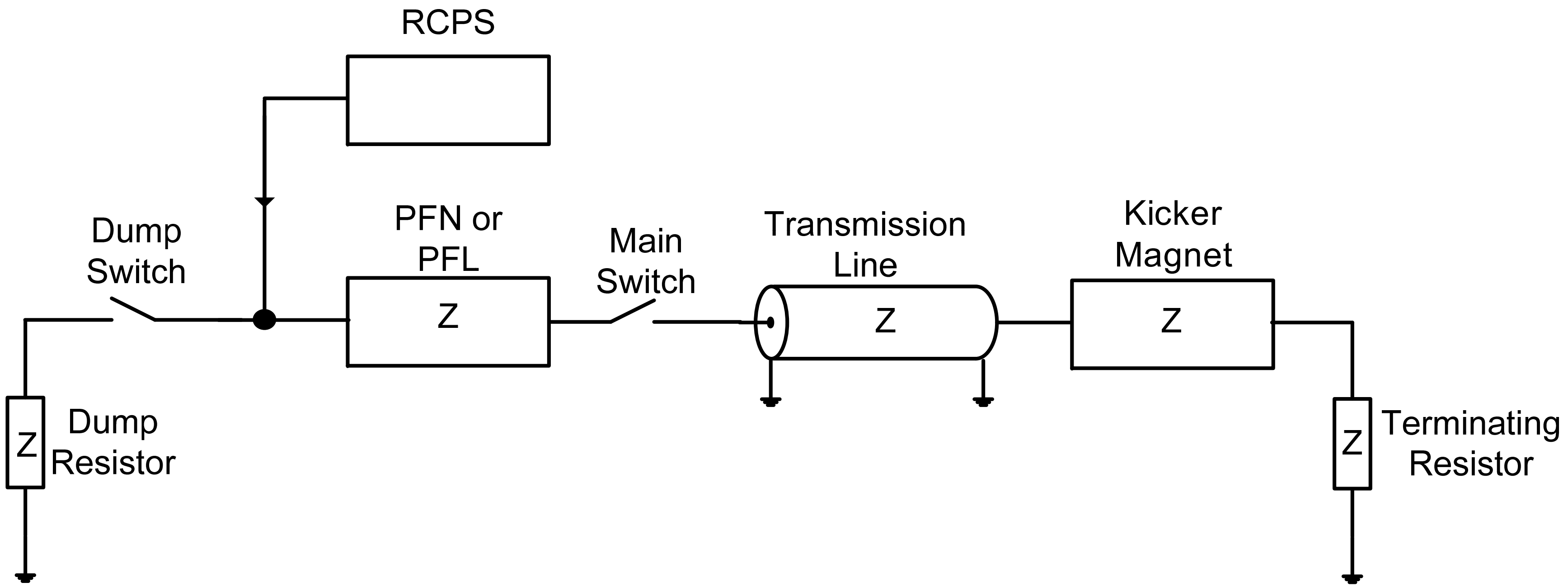
- **Septum** deflects the beam onto the closed orbit at the centre of the kicker
- **Kicker** compensates for the remaining angle
- Septum and kicker either side of **quad** to minimize kicker strength

Fast Single Turn Injection/Extraction (e.g. CERN SPS)

- The kicker magnetic field must rise/fall within the time period between the beam bunches. In addition, the magnetic field must not significantly deviate from the flat top of the pulse or from zero between pulses (i.e. very small ripple/excursions).
  - Typical field rise/fall times range from 10's to 100's of nanoseconds and pulse widths range from 10's of nanoseconds to 10's of microseconds;
- If a kicker exhibits a time-varying structure in the pulse field shape this can translate into small offsets with respect to the closed orbit (betatron oscillations).
- **A fast, low ripple, kicker system is required !**



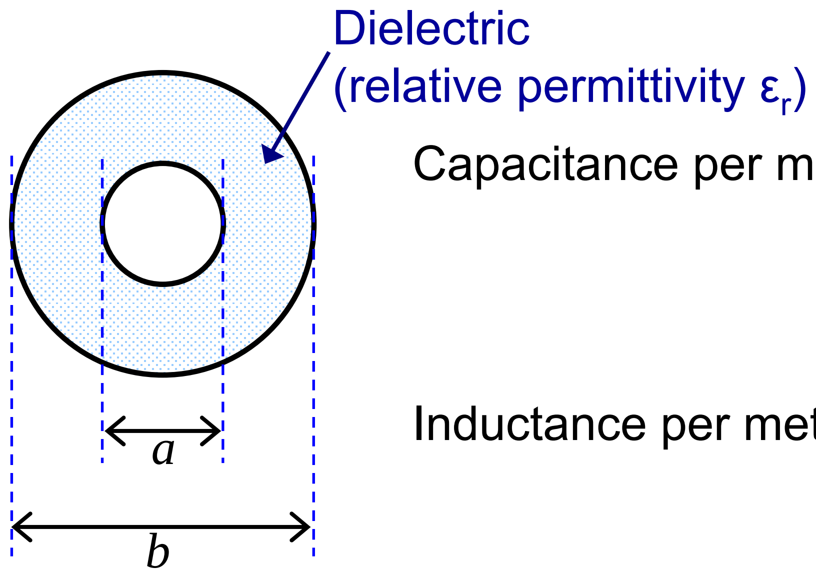
Simplified Schematic of a Kicker System



Main sub-systems ("components") of kicker system;

- **RCPS** = Resonant Charging Power Supply;
- **PFL** = Pulse Forming Line (coaxial cable) or PFN = Pulse Forming Network (lumped elements);
- Fast high power **switch(es)**;
- **Transmission line(s)** [coaxial cable(s)];
- **Kicker Magnet**;
- **Terminators** (resistive).

Characteristic Impedance of Coaxial Cable



Cross-section of coaxial cable

Capacitance per metre length (F/m): $C = \left(\frac{2\pi\varepsilon_0\varepsilon_r}{Ln\left(b/a\right)} \right)$

Inductance per metre length (H/m): $L = 2 \cdot 10^{-7} \cdot Ln\left(\frac{b}{a}\right)$

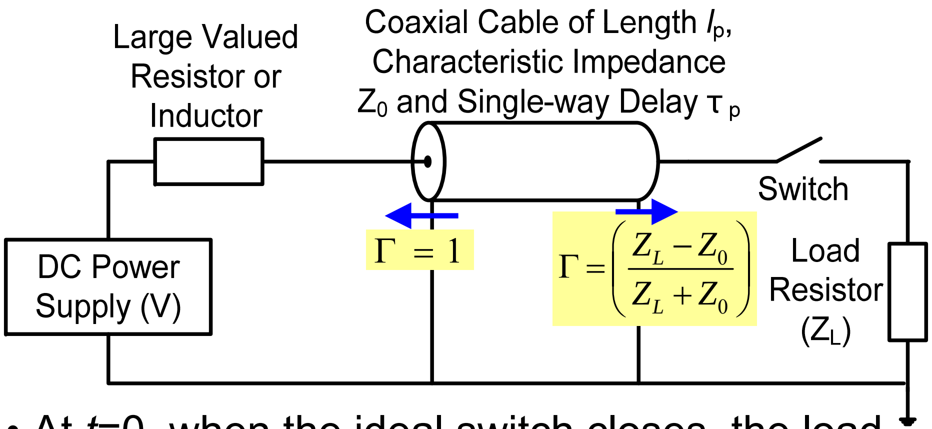
Characteristic Impedance (Ω): $Z_0 = \sqrt{\frac{L}{C}}$
(typically 20 Ω to 50 Ω).

Delay per metre length: $\tau = \sqrt{L \cdot C}$
(~5 ns/m for polyethylene dielectric cable).

Where:

a is the outer diameter of the inner conductor (m);
b is the inner diameter of the outer conductor (m);
ε_0 is the permittivity of free space (8.854×10^{-12} F/m).

Pulse Forming Circuit: General Case



• At t=0, when the ideal switch closes, the load potential (V_L) is given by:

$$V_L = V \cdot \left(\frac{Z_L}{Z_0 + Z_L}\right) = \alpha V$$

A voltage pulse of "$(\alpha-1)V$" propagates from the load end of the line towards the charging end.

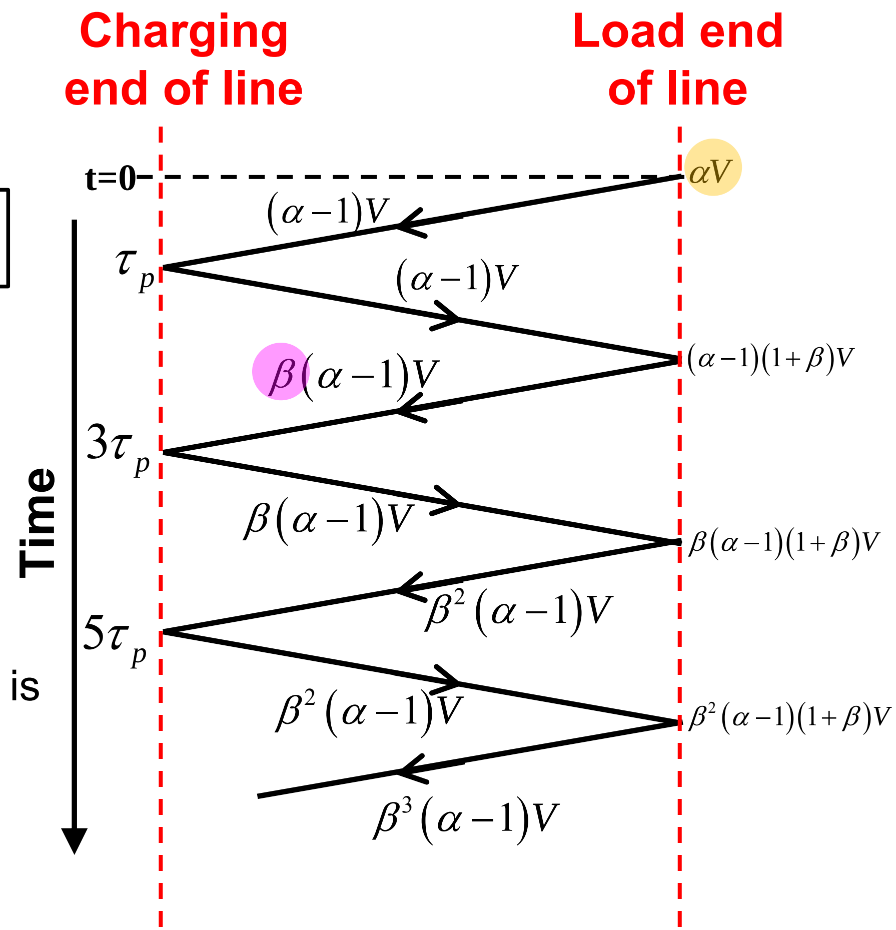
• At the charging end the reflection coefficient (Γ) is +1 and hence "$(\alpha-1)V$" is reflected back towards the load end of the line.

• At the load end of the line:

$$\Gamma = \left(\frac{Z_L - Z_0}{Z_L + Z_0}\right) = \beta \text{ say.}$$

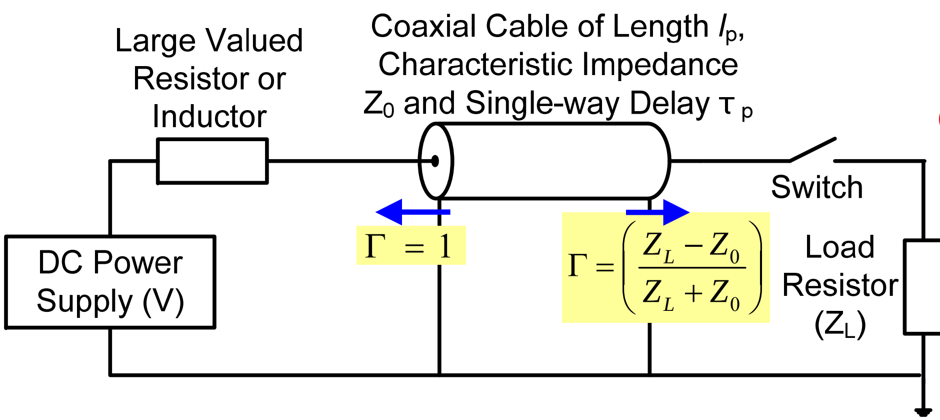
and hence "$\beta(\alpha-1)V$" is reflected back towards the charging end of the line.

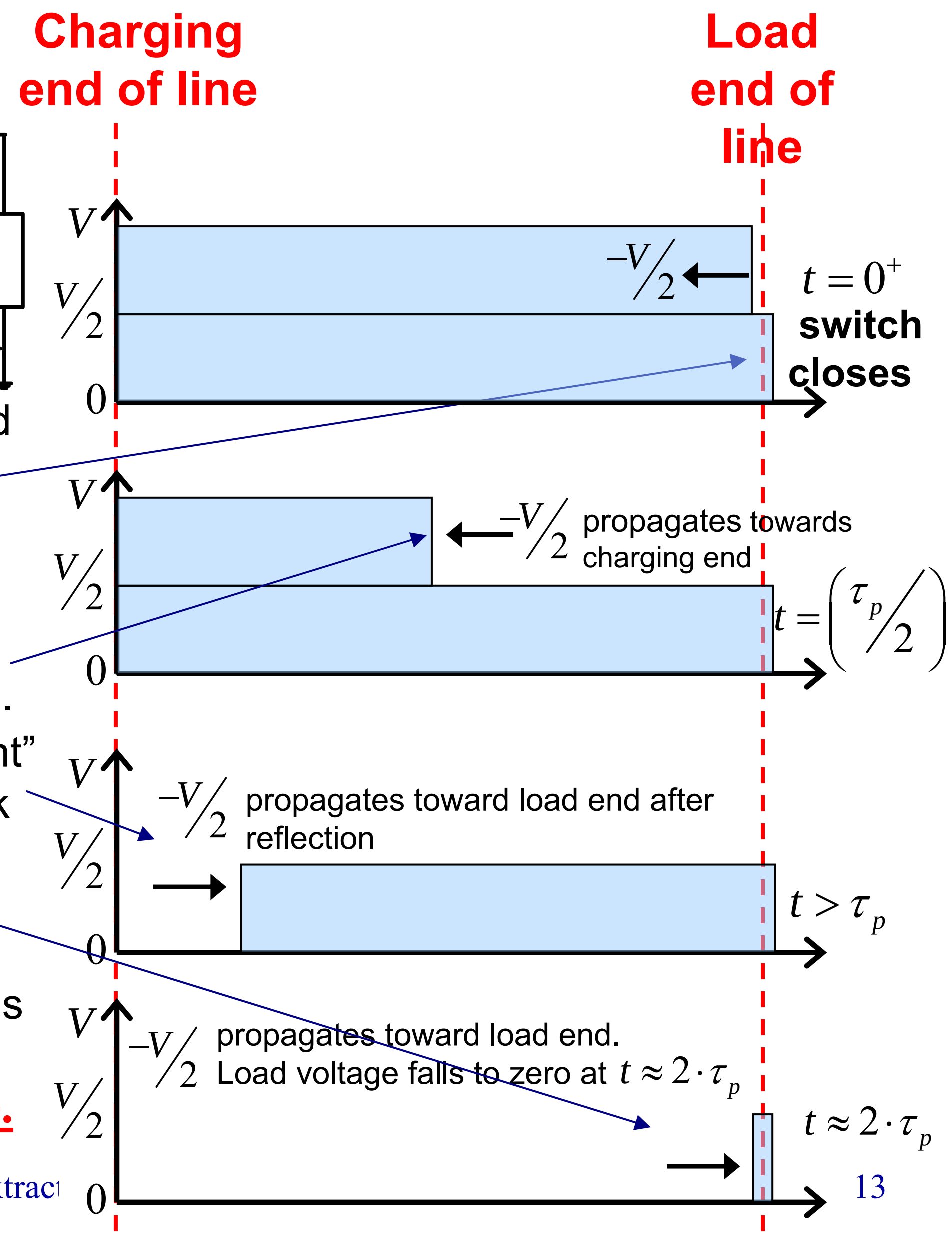
• Etc.



Impedances need to be matched to avoid reflections !, (i.e. $Z_L=Z_0$ ⇨ $\beta=0$)

Pulse Forming Circuit: Matched Load ($Z_L=Z_0$)





- At t=0, when the ideal switch closes, the load potential (V_L) is given by (Note: $Z_L=Z_0$):

$$V_L = V\cdot\left(\frac{Z_0}{Z_0+Z_0}\right) = \frac{V}{2}$$

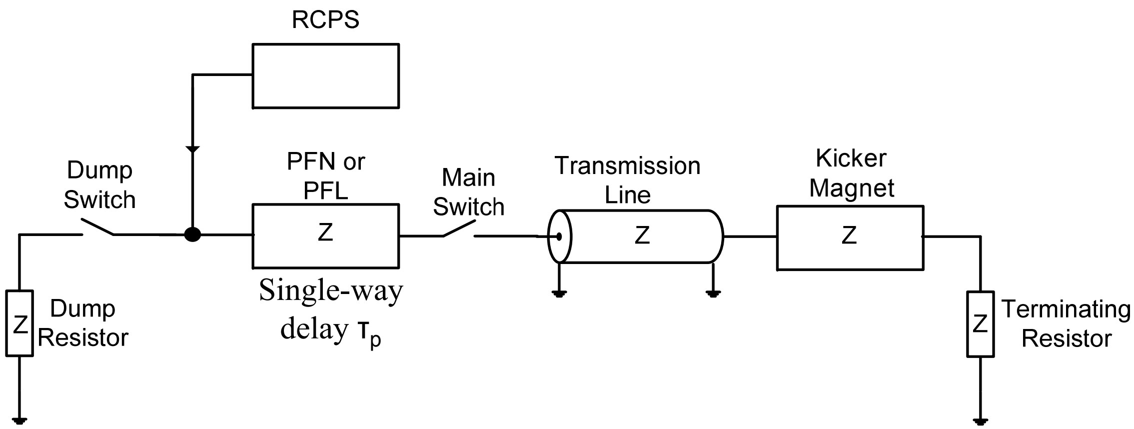
A voltage pulse of $-V/2$ propagates from the load end of the line towards the charging end.

- At the charging end the “reflection coefficient” (Γ) is +1 and hence the $-V/2$ is reflected back towards the load end of the line.
- At the load end of the line: $\Gamma = \left(\frac{Z_L - Z_0}{Z_L + Z_0}\right) = 0$

and hence no voltage is reflected back towards the charging end of the line.

Note: PFN voltage is twice the load voltage.

Overview of Kicker System

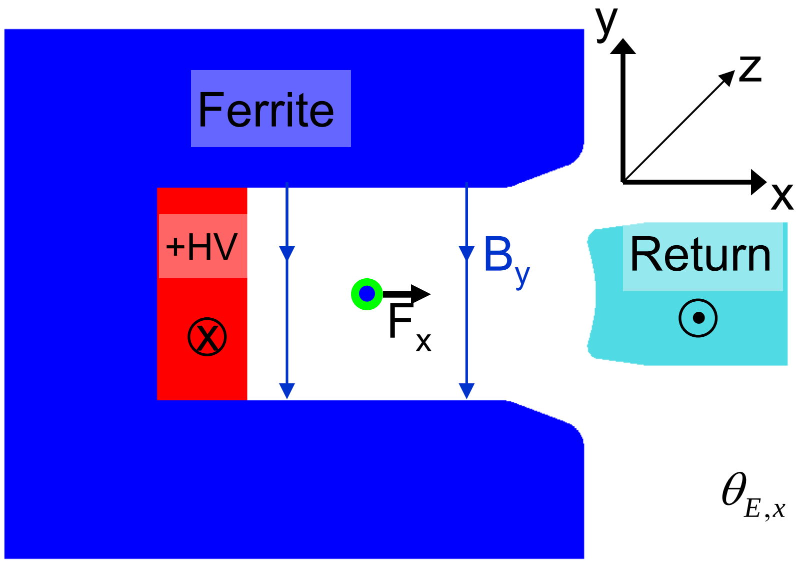


- Typically matched impedances;
- PFL = Pulse Forming Line (coaxial cable);
- PFN = Pulse Forming Network (lumped elements);
- RCPS = Resonant Charging Power Supply;
- Floating switch(es).

<u>Typical circuit operation:</u>

- PFN/PFL is charged to a voltage *V* by the RCPS*;*
- Main Switch closes and, for a matched system, a pulse of magnitude (*V/2)* is launched, through the transmission line, towards the magnet;
- Once the current pulse reaches the (matched) terminating resistor full-field has been established in the kicker magnet;
  - Note: if the magnet termination is a short-circuit, magnet current is doubled but the required “fill-time” of the magnet is doubled too (slide 20);
- The length of the pulse in the magnet can be controlled in length, between 0 and $2\tau_p$, by adjusting the timing of the Dump Switch relative to the Main Switch.
  - Note: the Dump Switch may be an inverse diode: the diode will “automatically” conduct if the PFN voltage reverses, but there is no control over pulse-length.

Angular Deflection Due To Magnetic and Electric Fields



Key:
- Proton beam moving out of plane of paper;
- ⊗ Current flow into plane of paper;
- ⊙ Current flow out of plane of paper;

$$\theta_{B,x} = \left[\frac{0.3}{p}\right] \cdot \int_{z_0}^{z_1} |B_y| dz = \left[\frac{0.3 \cdot l_{eff}}{p}\right] \cdot |B_y|$$

$$\theta_{E,x} = \tan^{-1}\left[\frac{1}{(p \cdot 10^9) \cdot \beta} \cdot \int_{z_0}^{z_1} |E_x| dz\right] = \tan^{-1}\left[\frac{|E_x| \cdot l_{eff}}{(p \cdot 10^9) \cdot \beta}\right]$$

$$\theta_x = \theta_{B,x} \pm \theta_{E,x}$$

Where:
- p is beam momentum (GeV/c);
- β is a unit-less quantity that specifies the fraction of the speed of light at which the particles travel;
- l_{eff} is the effective length of the magnet (usually different from the mechanical length, due to fringe fields at the ends of the magnet).

Electrical Parameters for a Magnetic Kicker

Usually 1 for a kicker magnet

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

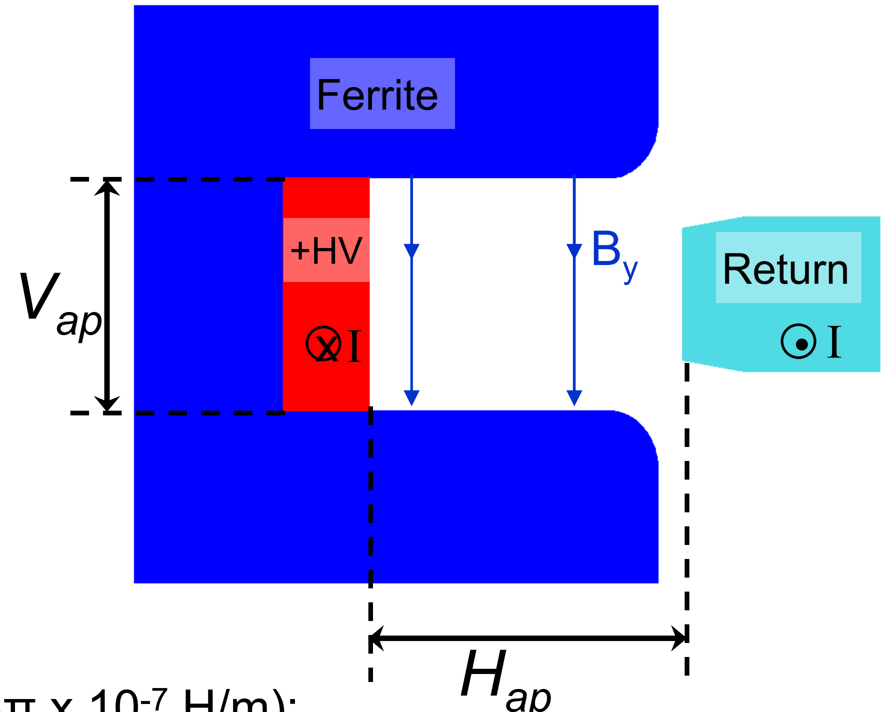
Minimum value set by beam parameters

Hence: “I” determines B_y

Eddy-currents and proximity effect result in current flow on inside surface of both conductors. Hence inductance is given by:

Minimum value set by beam parameters

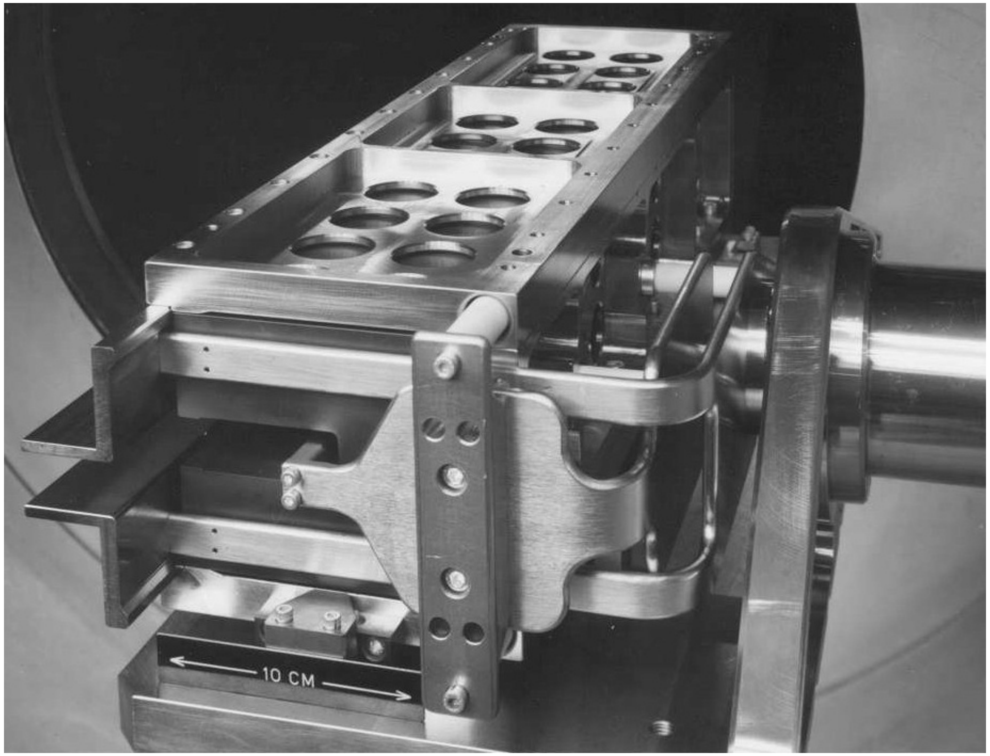
$$L_{m/m} \cong \mu_0 \left(\frac{N^2 \cdot H_{ap}}{V_{ap}} \right)$$



Where:

- μ_0 is permeability of free space ($4\pi \times 10^{-7}$ H/m);
- N is the number of turns;
- I is current (A);
- H_{ap} is the distance between the inner edges of the HV and return conductors (m);
- V_{ap} is the distance between the inner “legs” of the ferrite (m);
- $L_{m/m}$ is inductance per metre length of the kicker magnet (H/m).

Example of a 1960's Kicker Magnet



The original (~1960's) "plunging" kicker magnets were hydraulically operated: the aperture was too small for the kicker to be in the beam-line during circulating-beam.

Developments leading to higher current pulses permitted larger apertures: kicker magnets developed later at CERN were not hydraulically operated.

Kicker Magnet Design Options

Since kicker magnets generally need to be fast they usually only have a single turn coil: a multi-turn coil is only used for, slower, lumped inductance kicker magnets.

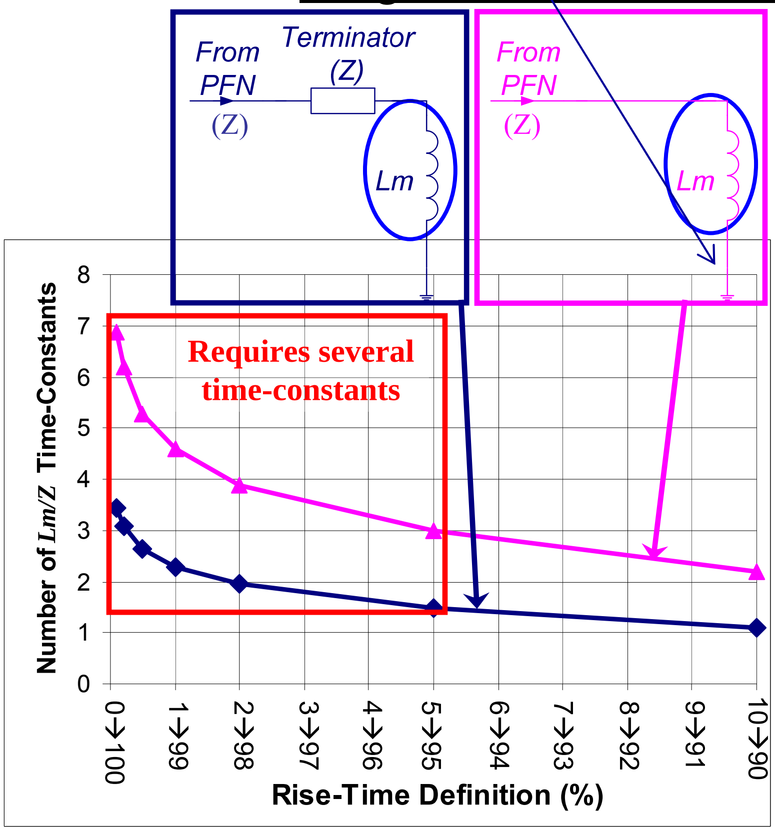
<u>Design options for kicker magnets</u>:

1. Type: “lumped inductance” or “transmission line” (with specific characteristic impedance (Z)) ?;
2. Machine vacuum: install in or external to machine vacuum?;
3. Aperture: window frame, closed C-core or open C-core ?;
4. Termination: matched impedance or short-circuited ?.

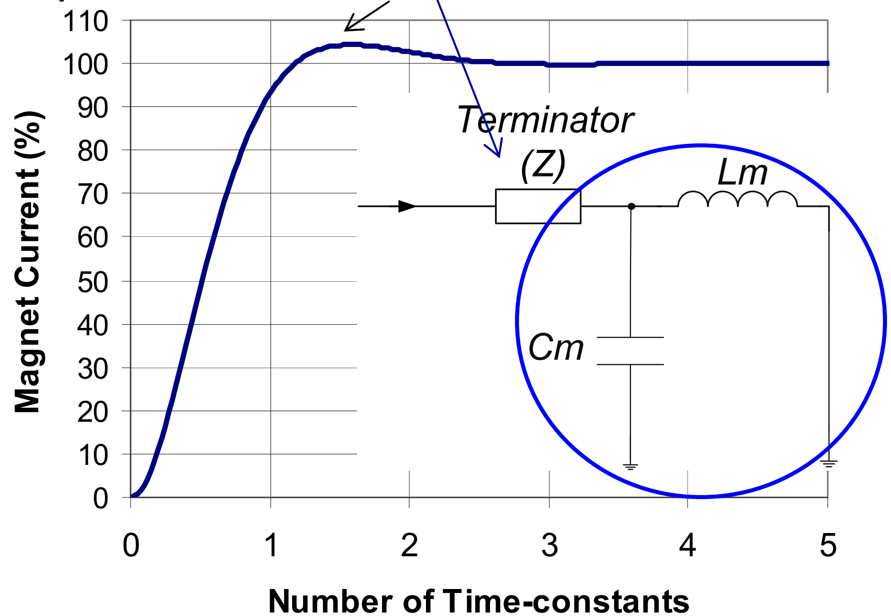
Lumped Inductance Kicker Magnets

Although a lumped-type magnet has a simple structure, in most cases it cannot be applied to a fast kicker system because of its impedance mismatch and its slow response. The lumped inductance kicker is generally useable only when a rise time above a few hundreds of ns is required. The termination is generally either in series with the magnet input or else the magnet is short-circuited. In both cases the magnet only sees (bipolar) voltage during pulse rise & fall. With a short-circuit termination, magnet current is doubled.

<u>Magnet current rise for a step input voltage</u>:

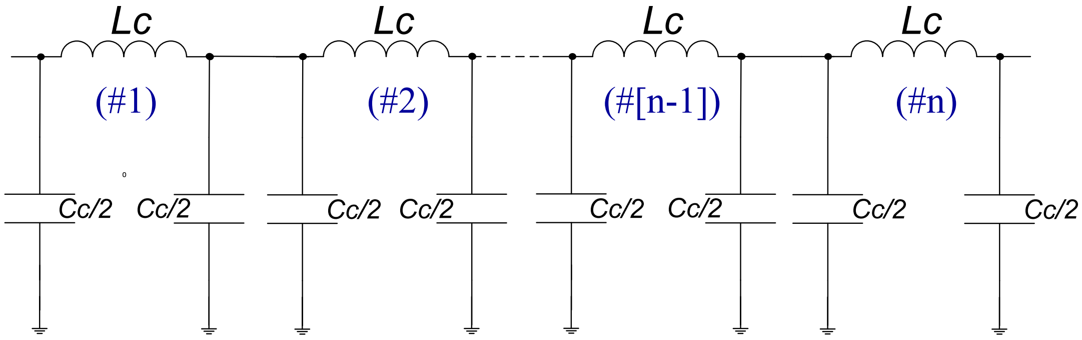


A capacitor (*Cm*) can be added to a lumped inductance magnet, but this can provoke some overshoot:



Transmission Line Kicker Magnet

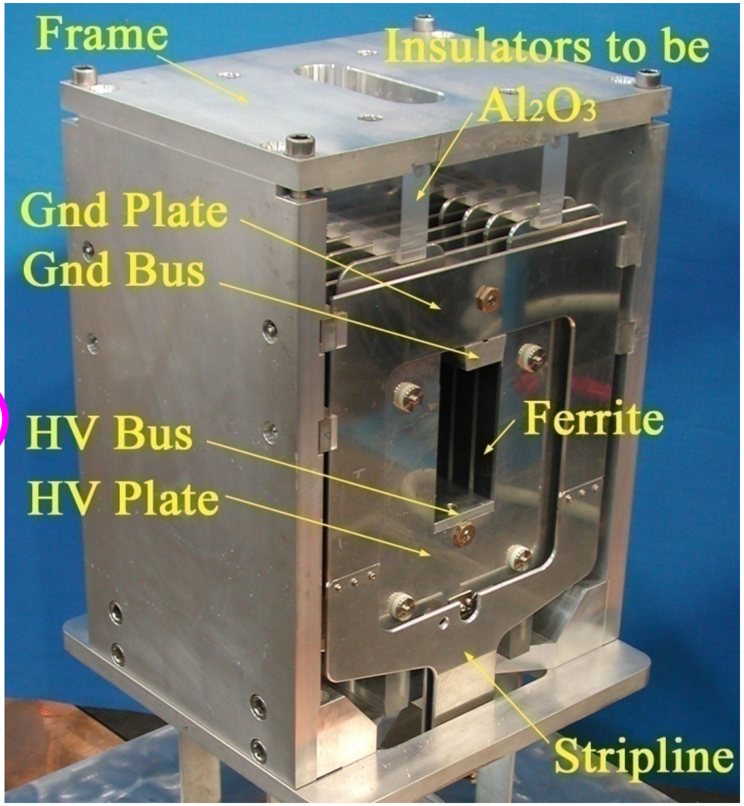
- Consists of few to many "cells" to approximate a broadband coaxial cable;



$$Z = \sqrt{\frac{Lc}{Cc}}$$

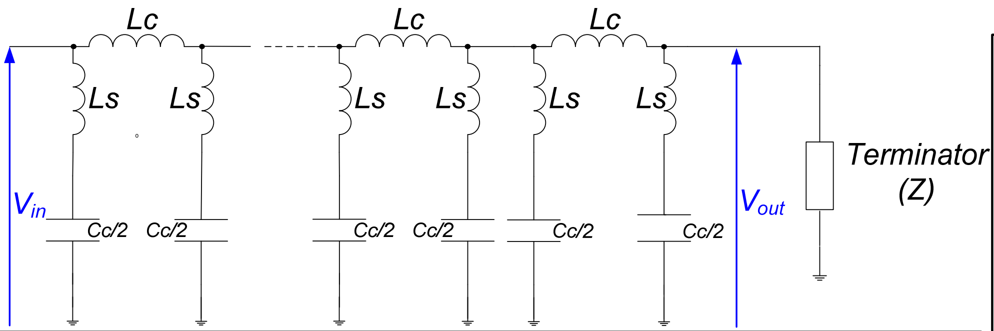
For a given cell length, *Lc* is fixed by aperture dimensions.

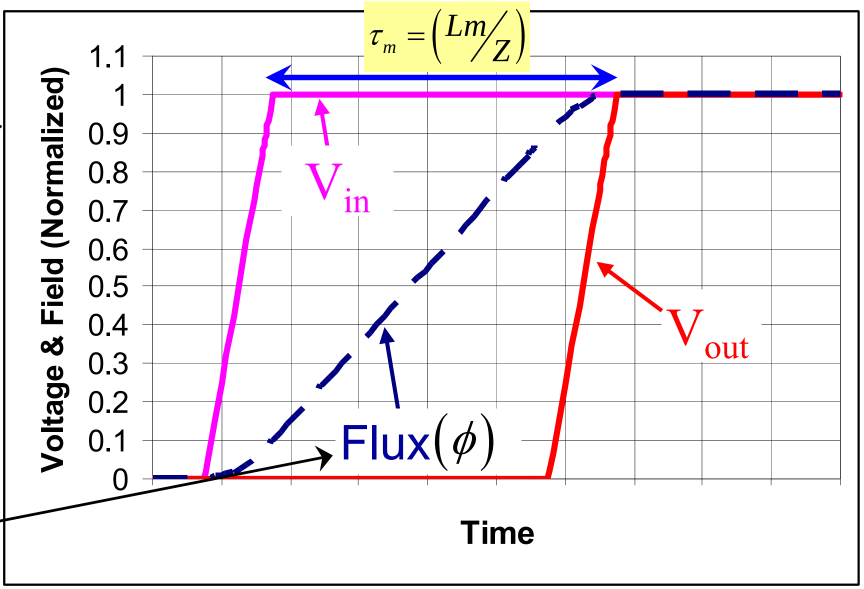
$$\tau_m = n \cdot \sqrt{Lc \cdot Cc} = n \cdot \left(Lc/Z \right) = Lm/Z$$



- Ferrite C-cores are sandwiched between high voltage (HV) capacitance plates;
- Plates connected to ground are interleaved between the HV plates;
- One C-core, together with its ground and HV capacitance plates, is termed a cell. Each cell conceptually begins and ends in the middle of the HV capacitance plates;
- The "filling time" (τ_m) is the delay required for the pulse to travel through the "*n*" magnet cells.

Transmission Line Kicker Magnet





For a magnet terminated with a matched resistor: **field rise** time starts with the beginning of the voltage pulse at the entrance of the magnet and ends with the end of the same pulse at the output. **Field rise** is given by the sum of the voltage rise time and the magnet filling time$\left(= Lm/Z \right)$:

$$\phi = \int \left(V_{in} - V_{out} \right) dt$$

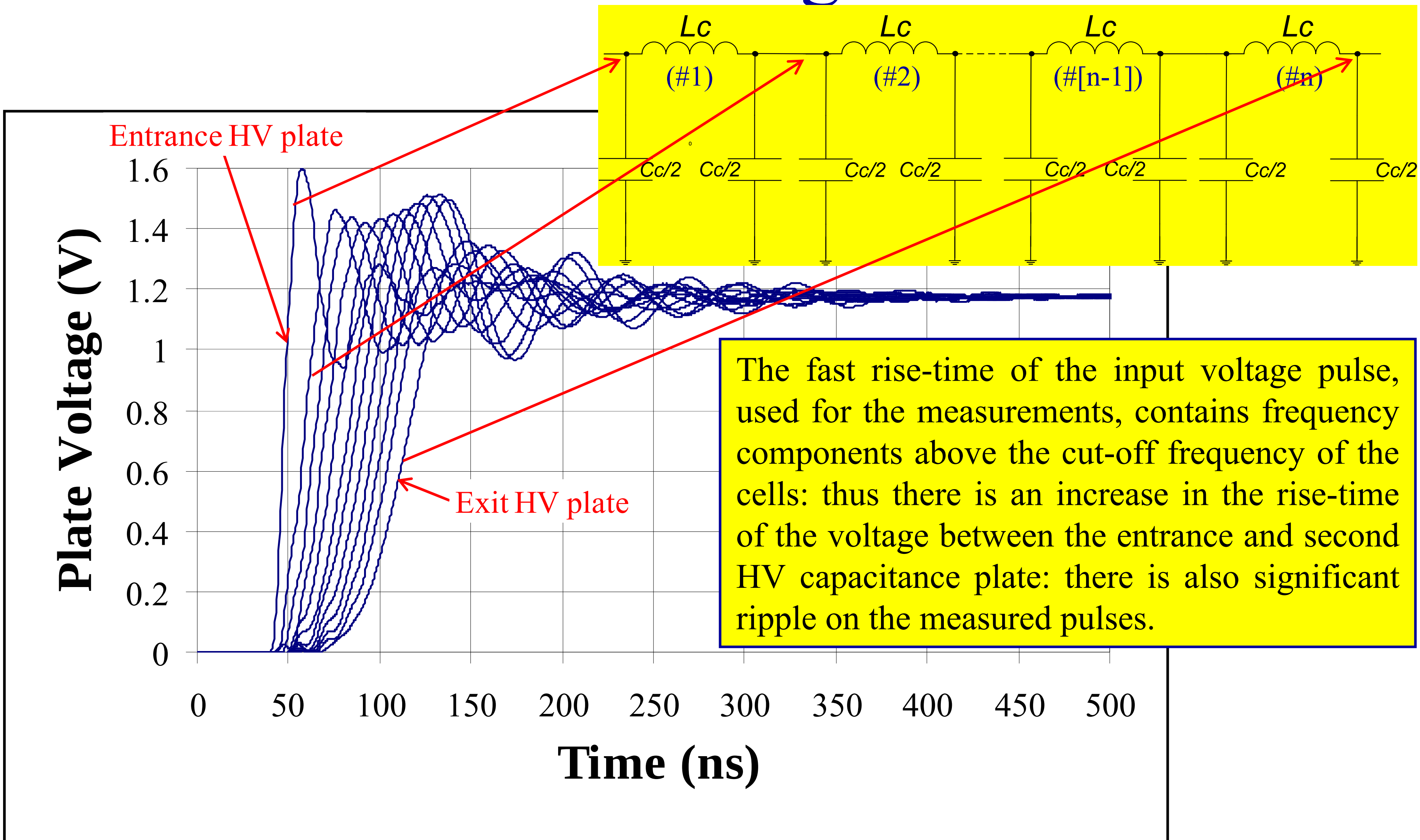
The field builds up until the end of the voltage rise at the output of the magnet. Hence it is important that the pulse does not degrade while travelling through the magnet. Thus the magnet cut-off frequency is a key parameter, especially with field rise times below ~100 ns. Cut-off frequency (f_c) depends on series inductance (Ls) associated with the cell capacitor (Cc):

$$f_c = \frac{1}{\pi \cdot \sqrt{\left(Lc + 4Ls \right) \cdot Cc}}$$

Thus, Ls should be kept as low as possible and the cell size small. However cells cannot be too small (voltage breakdown & cost).

Transmission line kicker magnets have much faster field rise time than equivalent lumped magnets. However, design and construction is more complicated and costly.

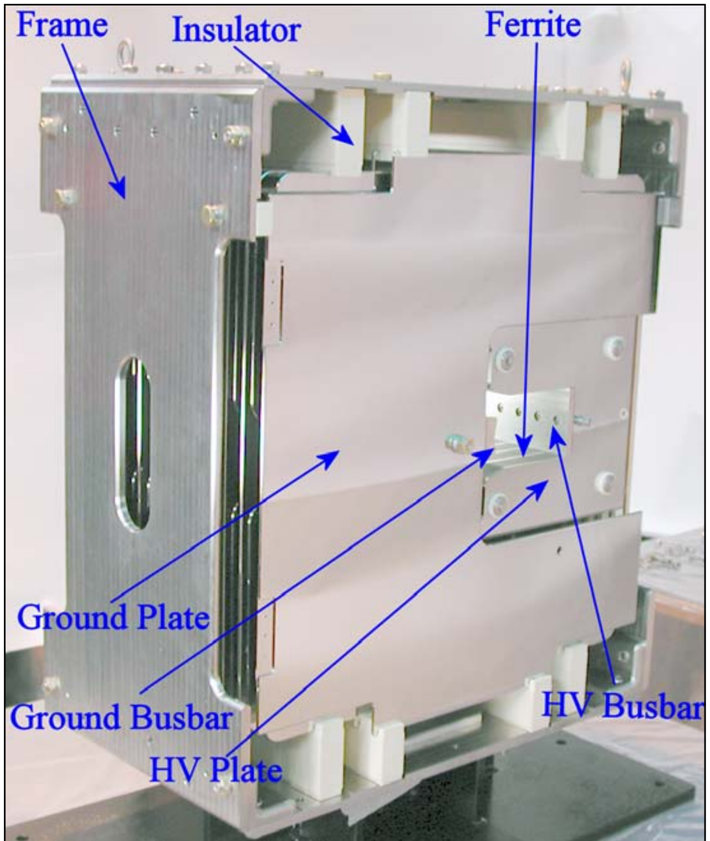
LV Measurements on a Transmission Line Kicker Magnet



The fast rise-time of the input voltage pulse, used for the measurements, contains frequency components above the cut-off frequency of the cells: thus there is an increase in the rise-time of the voltage between the entrance and second HV capacitance plate: there is also significant ripple on the measured pulses.

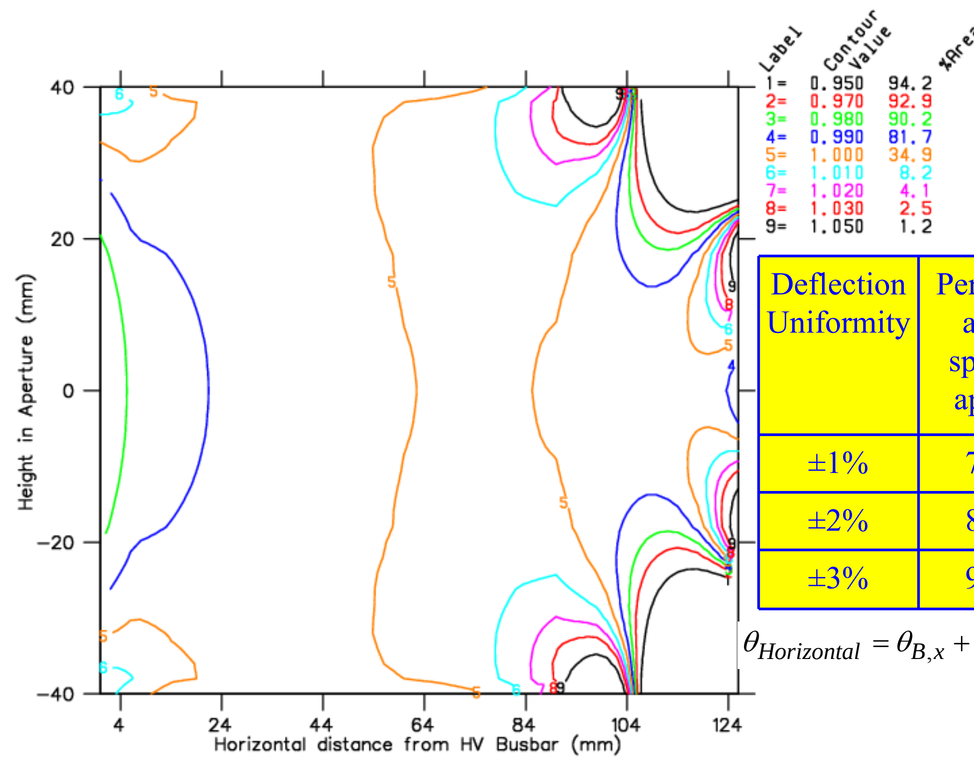
Magnet Design Tools (1)

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%

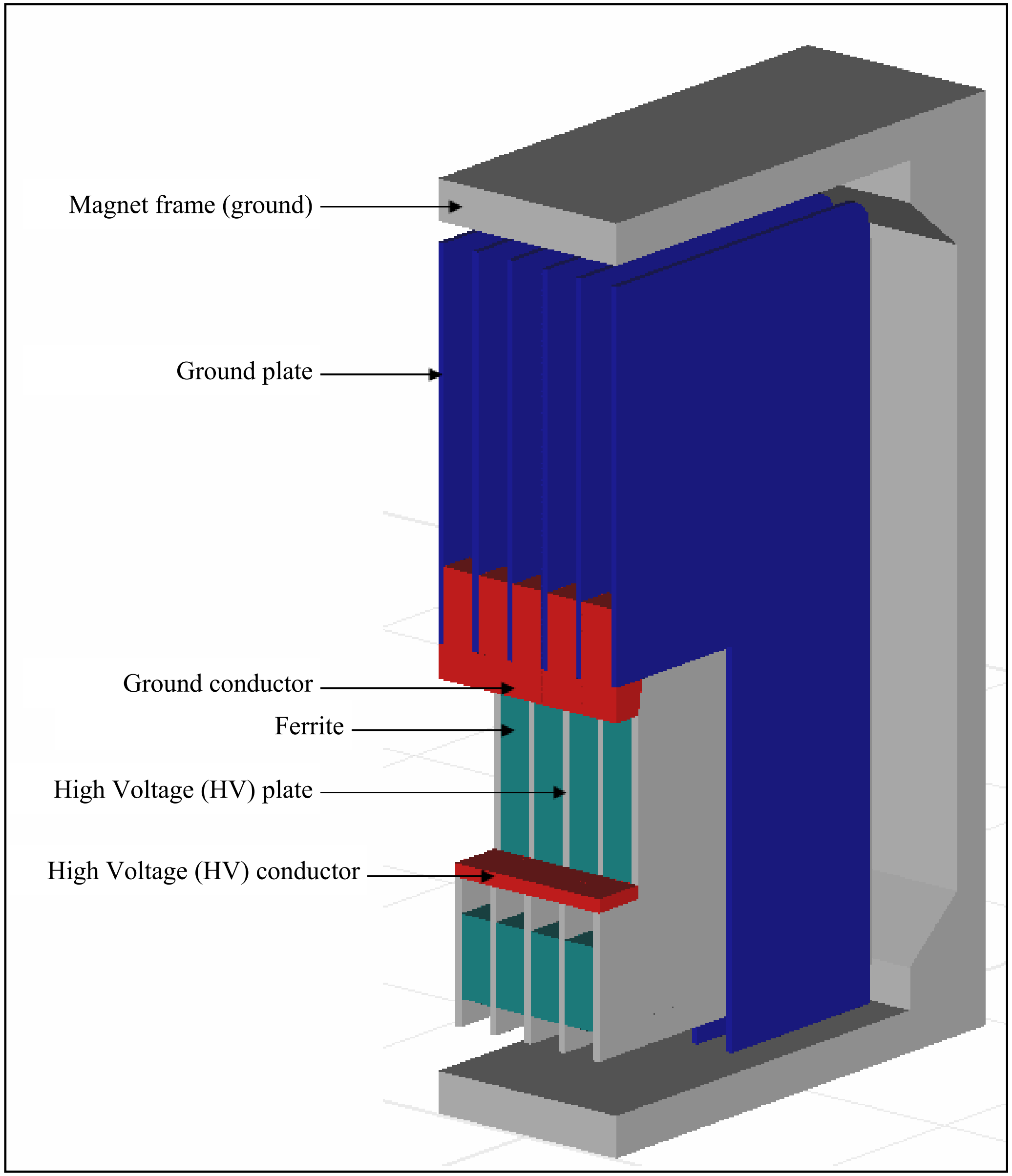
$$\theta_{Horizontal} = \theta_{B,x} + \theta_{E,x}$$

Magnet Design Tools (2)

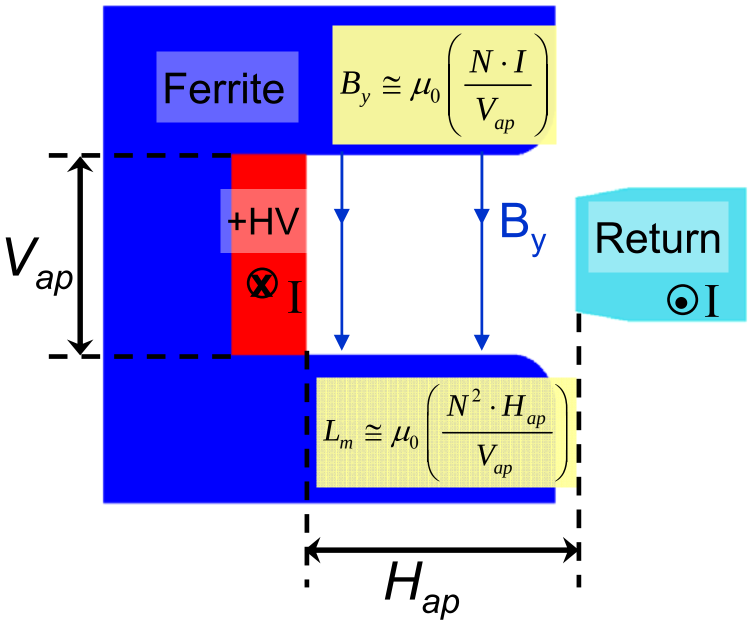
Capacitance to ground of an HV plate is influenced by insulators and nearby ground planes:

- 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.



Installing Kicker Magnets in Machine Vacuum



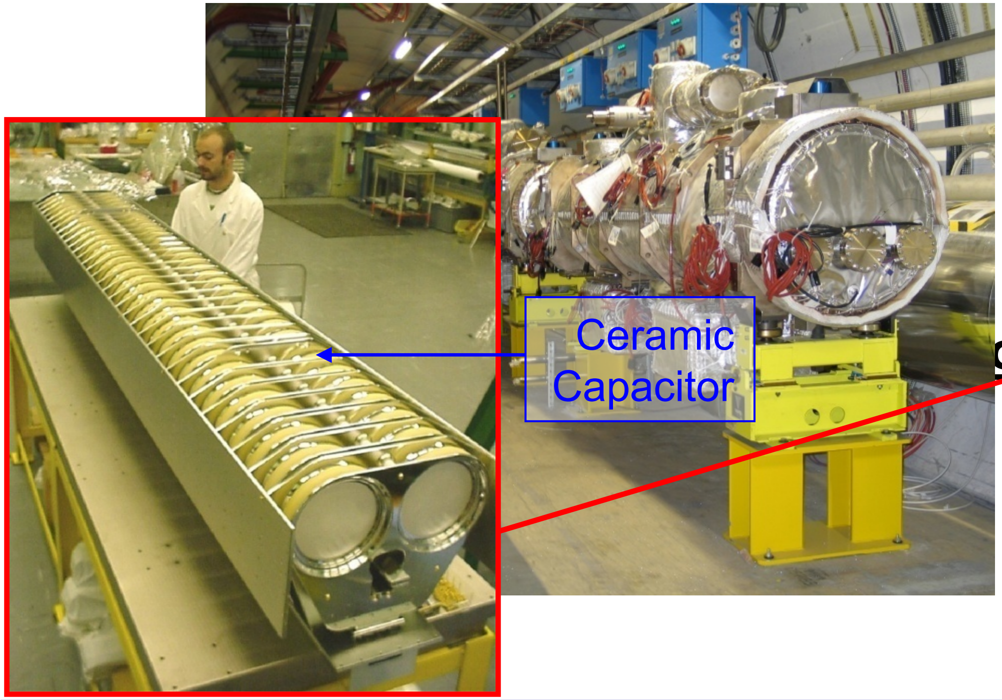
Disadvantages:

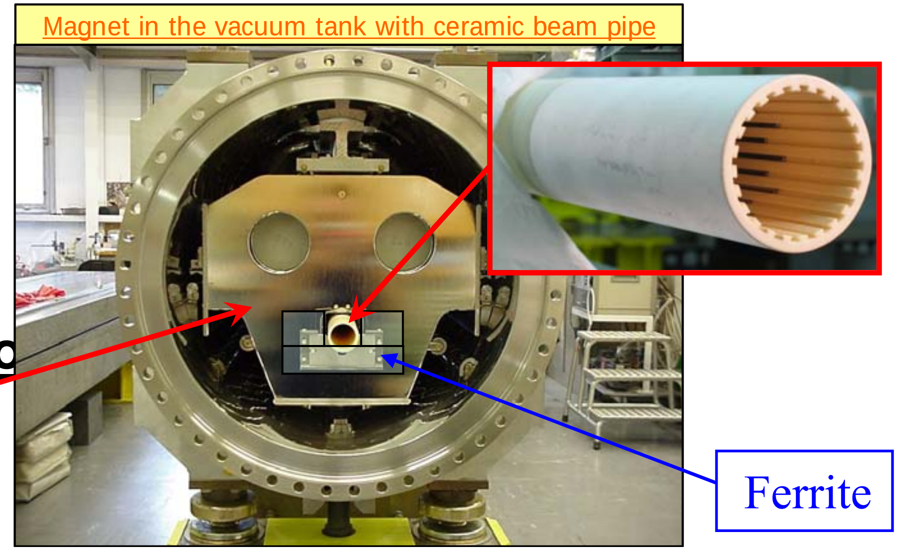
- Costly to construct (vacuum tank, pumping, bake-out);
- Coupling impedance to beam may be an issue (a beam screen, in the kickers aperture, may be required in any case) – slide 29.

Advantages:

- Aperture dimensions are minimized;
- Therefore number of magnets and/or voltage and current are minimized for a given kick and rise-time;
- Machine vacuum is a reliable dielectric (70kV/cm OK) – generally "recovers" after a flashover, whereas a solid dielectric, outside vacuum, may not recover.

Transmission Line Kicker Magnet





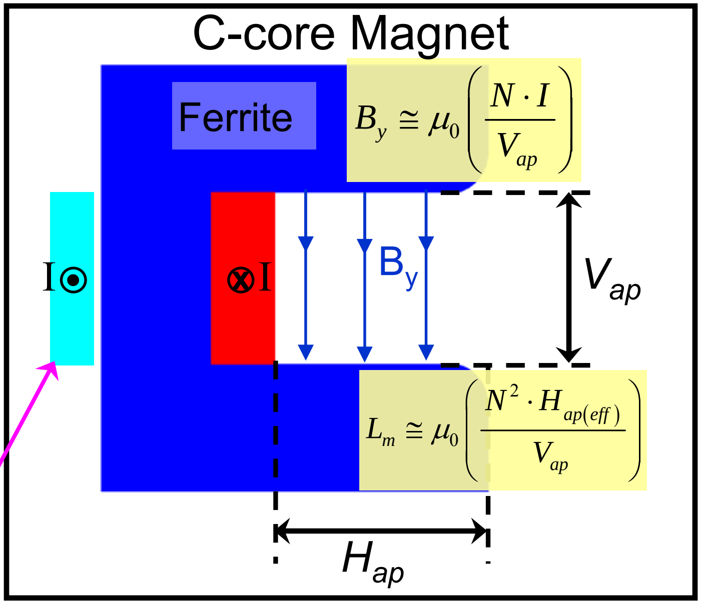
- Transmission line magnets are usually installed in a vacuum chamber to withstand high voltage between the capacitor plates;
- In this case, a vacuum enclosure with expensive feedthroughs is necessary;
- Careful bake-out is required to control out-gassing from the ferrite core and therefore beam loss.

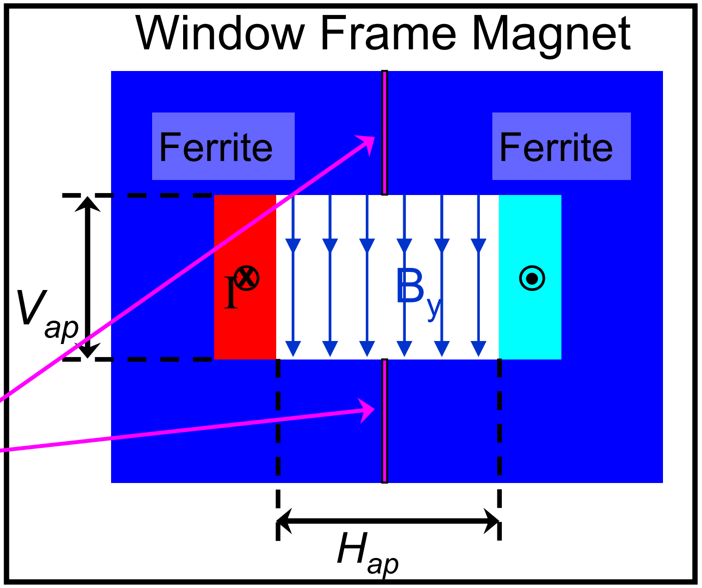
LHC Injection Kicker

- Vertical deflection (force downwards);
- Baked out to 300°C;
- 2.7m long magnet;
- 33 cells;
- Lc=101 nH, Cc=4.04 nF (per cell values);
- 5Ω characteristic impedance;
- Magnet fill-time ≈ 680ns;
- 38 mm ID ceramic pipe (for beam screening) in 54 x 54 mm aperture of kicker.

Kicker Magnet Magnetic Circuit

- Normally a magnetic circuit is used which contains magnetic material: without magnetic material the effective value of V_{ap} is greatly increased, therefore requiring more current to achieve the required field. In addition, magnetic material improves field uniformity.
- NiZn Ferrite is usually used, with $\mu_r \approx 1000$:
  - Field rise can track current rise to within ~1ns;
  - Has low remnant field;
  - Has low out-gassing rate, after bake-out.
- Sometimes the return conductor is behind the yoke (for beam gymnastic reasons) – this increases Lc by about 10%.
- To reduce filling time by a factor of two FNAL and KEK use a window frame topology:
  - It can be considered as two symmetrical C-magnets energized independently.
  - Requires two generators to achieve the reduced filling time.
  - Conducting "shields" are used between the two ferrite C-cores to reduce beam coupling impedance.





Transmission Line Kicker Magnet Termination

When space is at a premium, a short circuit termination has the advantage of doubling kick (for a given system impedance): in addition, a short circuit termination reduces the time during which the kicker magnet is exposed to high voltage. However disadvantages include:

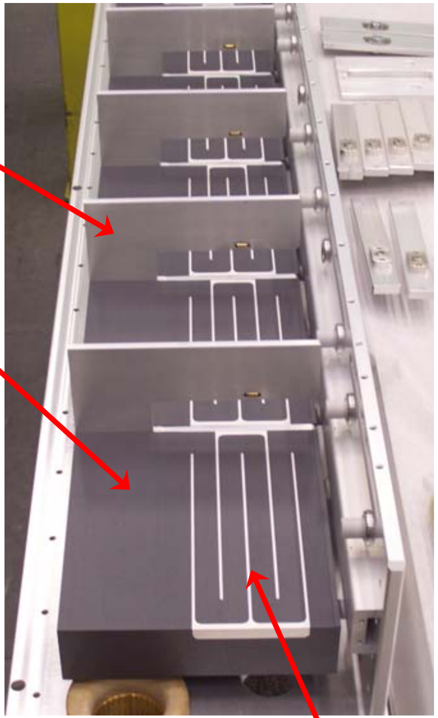
- fill-time of the kicker magnet is doubled;
- magnet experiences voltage of both polarities;
- if the dump-switch is used to control pulse length it must be bidirectional (unidirectional dump-switch, acting as an inverse diode, is suitable for a fixed length pulse);
- beam can be affected (resonances, below magnet cut-off frequency, with kicker circuitry).

Beam Coupling Impedance Reduction (1)

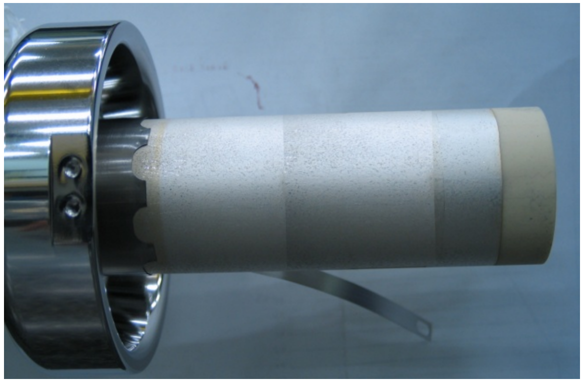
In order to reduce beam coupling impedance the ferrite must be shielded from the beam, by providing <u>a path for beam image current</u>. However the design must ensure that eddy-currents, induced by the fast rising field, do not unduly increase field rise-time.

HV Plate

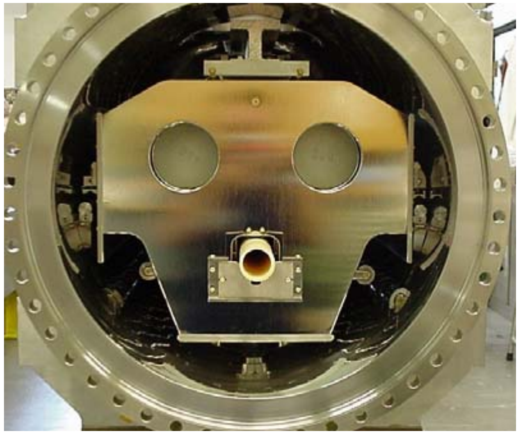
Ferrite



MKE Kicker: serigraphy on ferrite

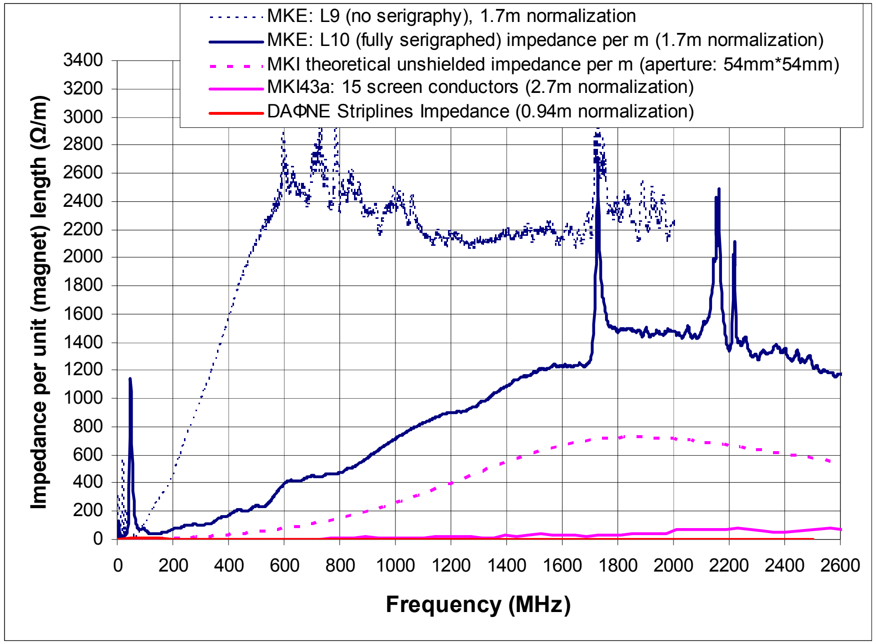


"beam-screen" of LHC Injection Kicker: ceramic tube with conductors in slots



Beam Coupling Impedance Reduction (2)

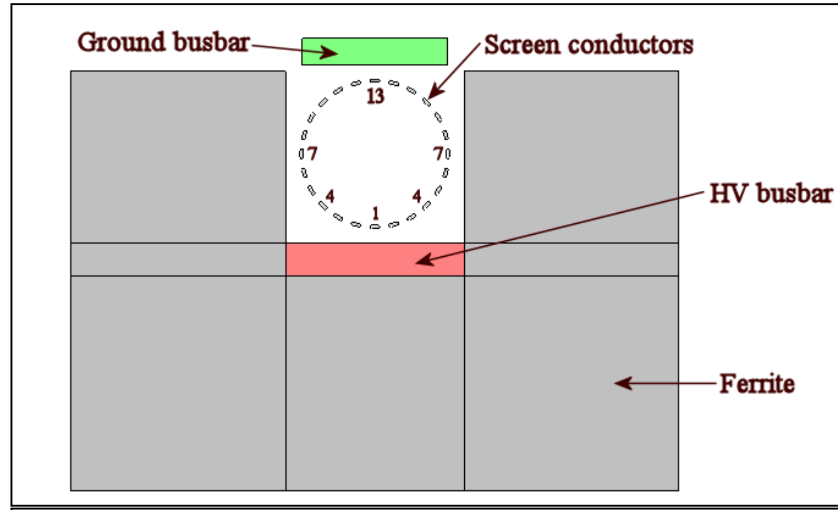
Longitudinal Beam Coupling Impedance

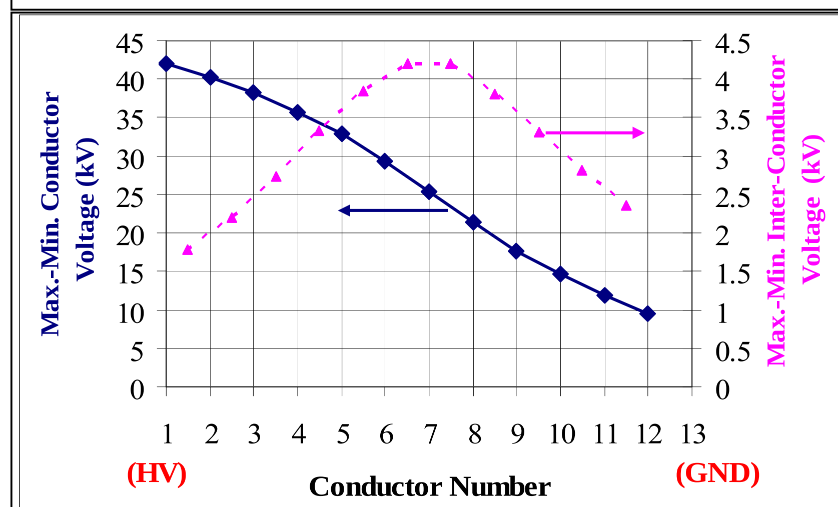


Longitudinal beam coupling impedance is significantly reduced by:

- Serigraphy of ferrites (painted stripes) – with negligible loss of aperture;
- Beam screen conductors within aperture – up to 15 mm loss of aperture;
- Striplines instead of ferrite loaded magnet – not feasible for large kick in limited length.

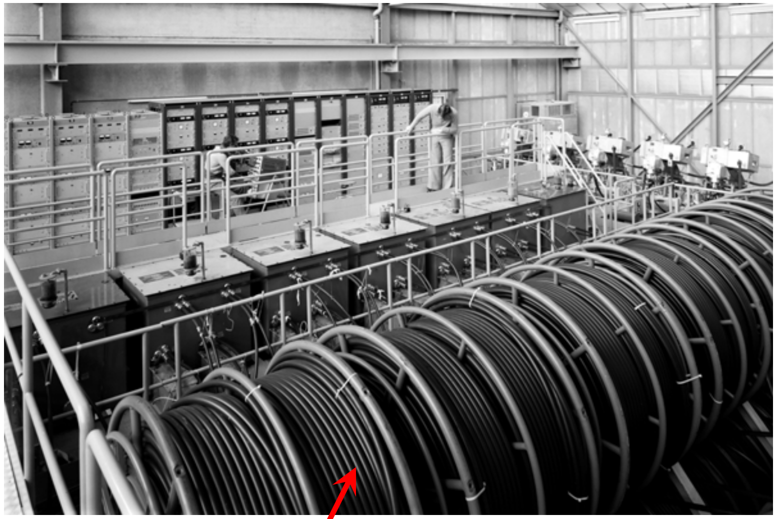
An electromagnetic model of the (LHC Injection) screen conductors, in the magnet aperture, permits self and mutual inductance to be derived and an accurate PSpice model of the kicker magnet.





Pulse Forming Line (PFL)

- Simplest configuration is a PFL charged to **twice the required pulse voltage**;
- PFL (cable) gives fast and ripple free pulses, but low attenuation is essential (especially with longer pulses) to keep droop and "cable tail" within specification;
- Attenuation is adversely affected by the use of semiconductor layers to improve voltage rating;
- Hence, for PFL voltages above 50kV, SF6 pressurized PE tape cables are used.



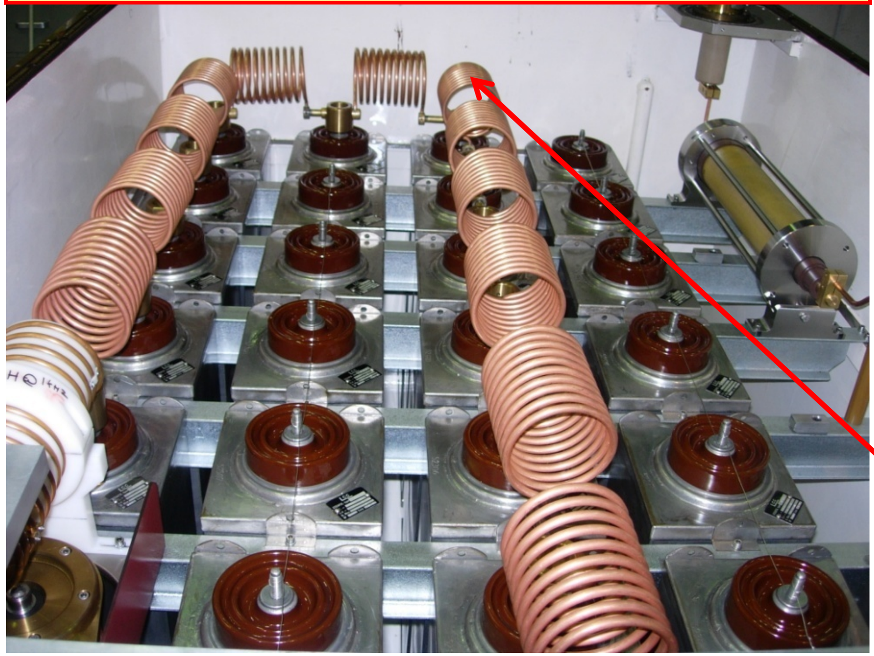
Reels of PFL

PFL becomes costly, bulky and the droop becomes significant (e.g. ~1%) for pulses exceeding about 3μs width.

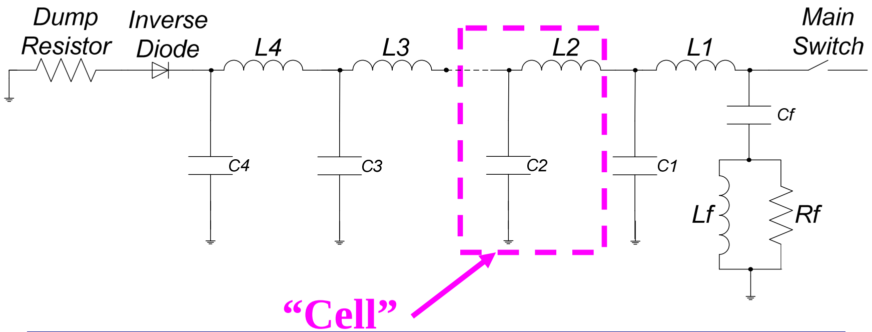
Pulse Forming Network (PFN) – CERN SPS

	LSS4 -- LHC (for protons)	LSS4 -- CNGS	LSS6 -- LHC (for protons)
Energy [GeV]	450	400	450
Total System Deflection angle [mrad]	0.48	0.54	0.48
# MKE-L (large [35 mm] aperture) magnets	3	3	3
# MKE-S (small [32 mm] aperture) magnets	2	2	2
Individual magnet length [m]	1.674	1.674	1.674
2 – 98% Rise Time (μs)		<1.1	
Induction Field MKE-L [mT]	82.6	82.8	82.6
Induction field MKE-S [mT]	90.4	90.5	90.4
|Flattop ripple (overshoot)|	< 1%	< 2%	< 1%
98 – 2% Fall Time [μs]		<1.1	
System impedance (Ω)	10 (terminated)	10 (terminated)	10 (short-circuit)

A PFN is an artificial coaxial cable made of lumped elements.



Schematic for an SPS Extraction PFN:

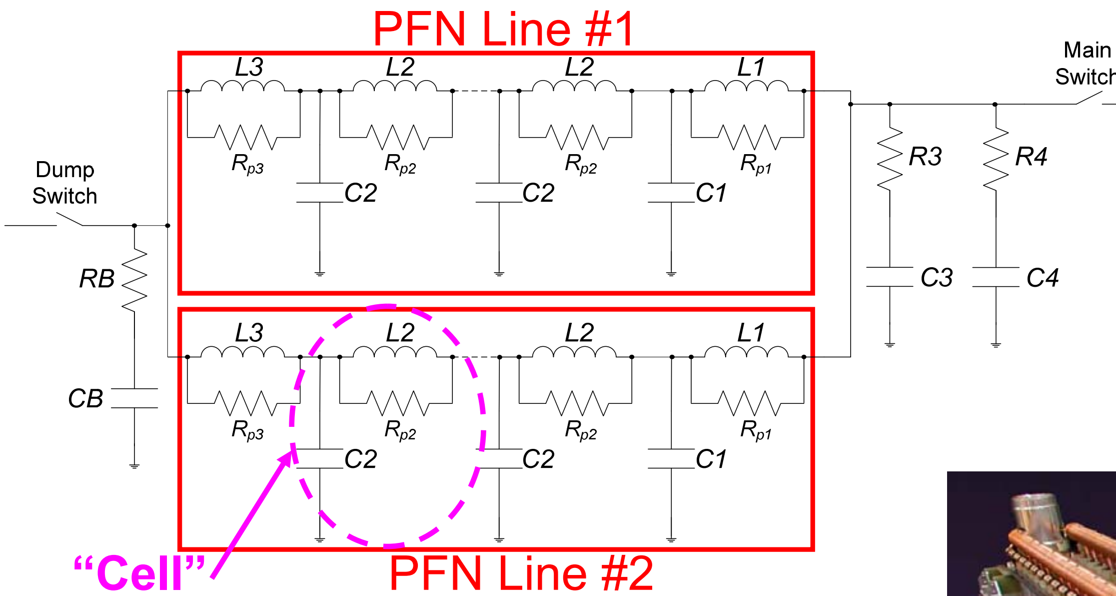


CERN SPS Extraction PFN (MKE4):

- Nominal PFN Voltage = 50 kV for CNGS and 51.2 kV for LHC;
- 17 cells individually “adjustable”;
- PFN has “corners” therefore mutual inductance between inductances is NOT well defined;
- Adjusting the pulse flattop is difficult and time-consuming.

Pulse Forming Network (PFN) – CERN MKI

Schematic for an LHC Injection PFN:

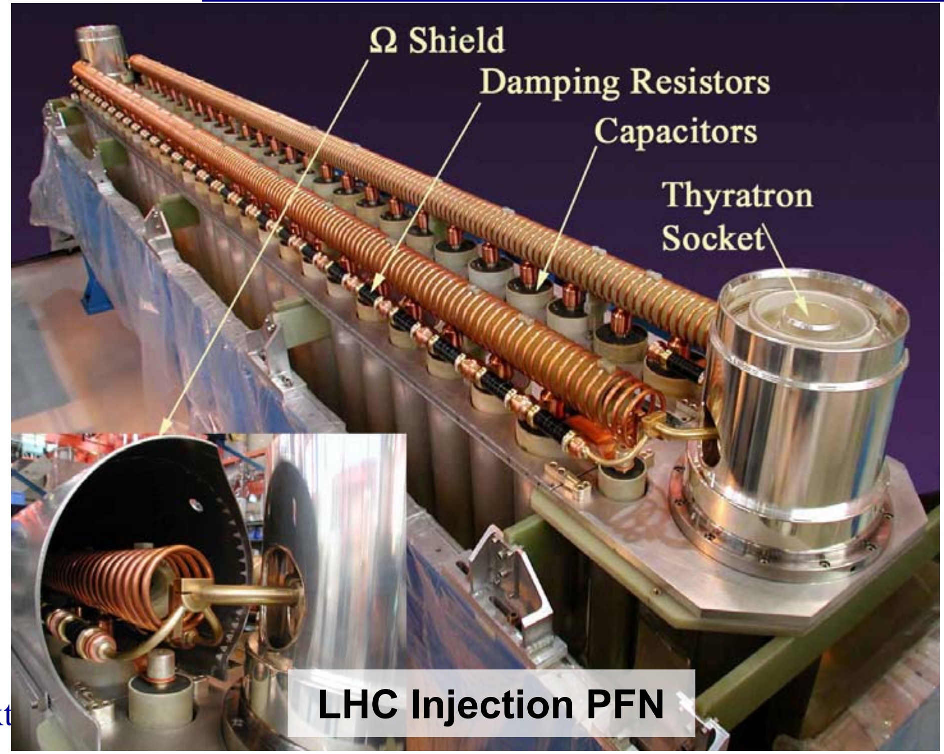


LHC Injection PFN:

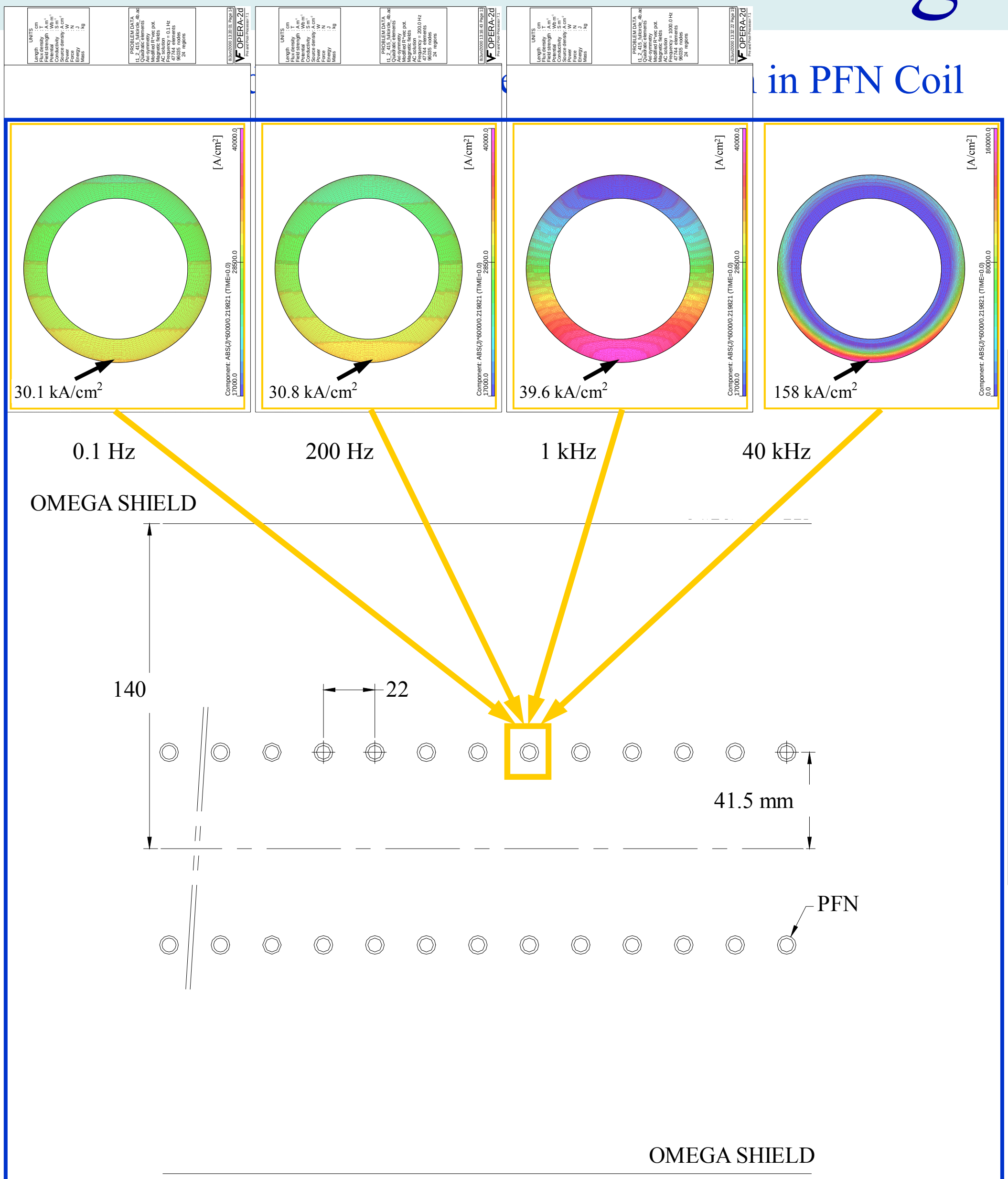
- 5Ω system (two parallel 10Ω "lines");
- Nominal PFN Voltage = 54kV;
- Single continuous coil per 10Ω line, 4.356 m long, with 198 turns and a pitch of 22 mm;
- Copper tube wound on a rigid fibreglass coil former.
  - The 26 central cells of the coils are not adjustable and therefore defined with high precision.

System Parameters:

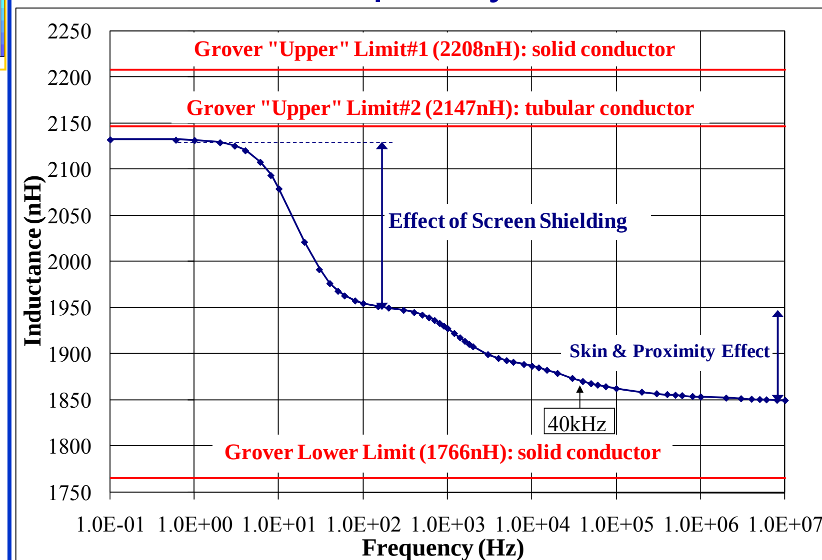
- **Field flat top duration ≤ 7.86μs**;
- **Field flat top ripple < ±0.5%;**
- Field rise-time 0.5% to 99.5% = 0.9μs;
- Kick strength per magnet = 0.325 T·m;
- Nominal PFN Voltage = 54kV;
- Nominal Magnet Current = 5.4kA.



PFN Modelling – Opera2D

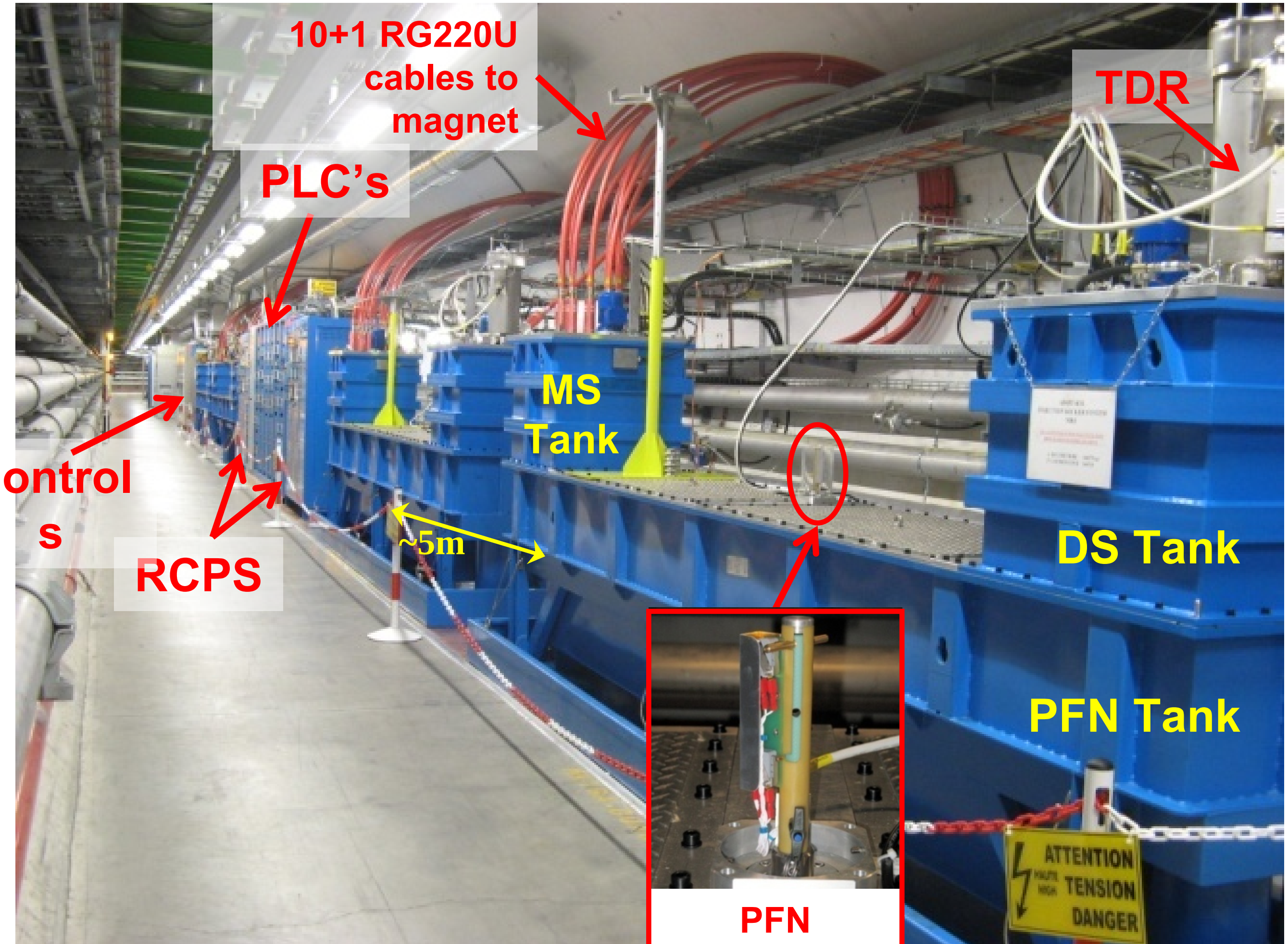


An Opera2D model of the PFN for the LHC Injection was used to predict self-inductance and mutual-inductance as a function of frequency.



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

LHC Injection PFN's, Switch Tanks & RCPS's



- 4 kicker magnets per injection point;
- 1 PFN for each kicker magnet;
- 1 RCPS per 2 PFN's.

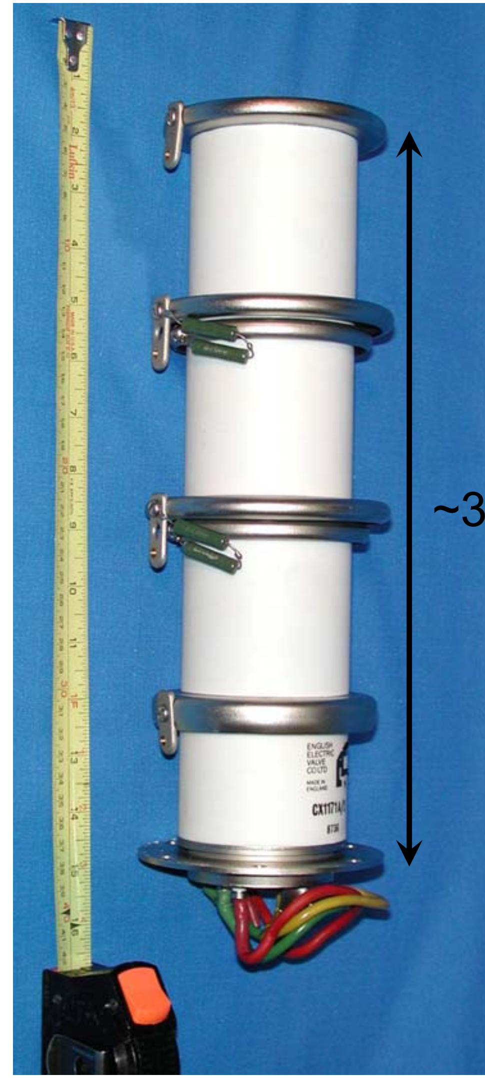
Thyratron Switches

In general deuterium thyratrons are used as the power switch.

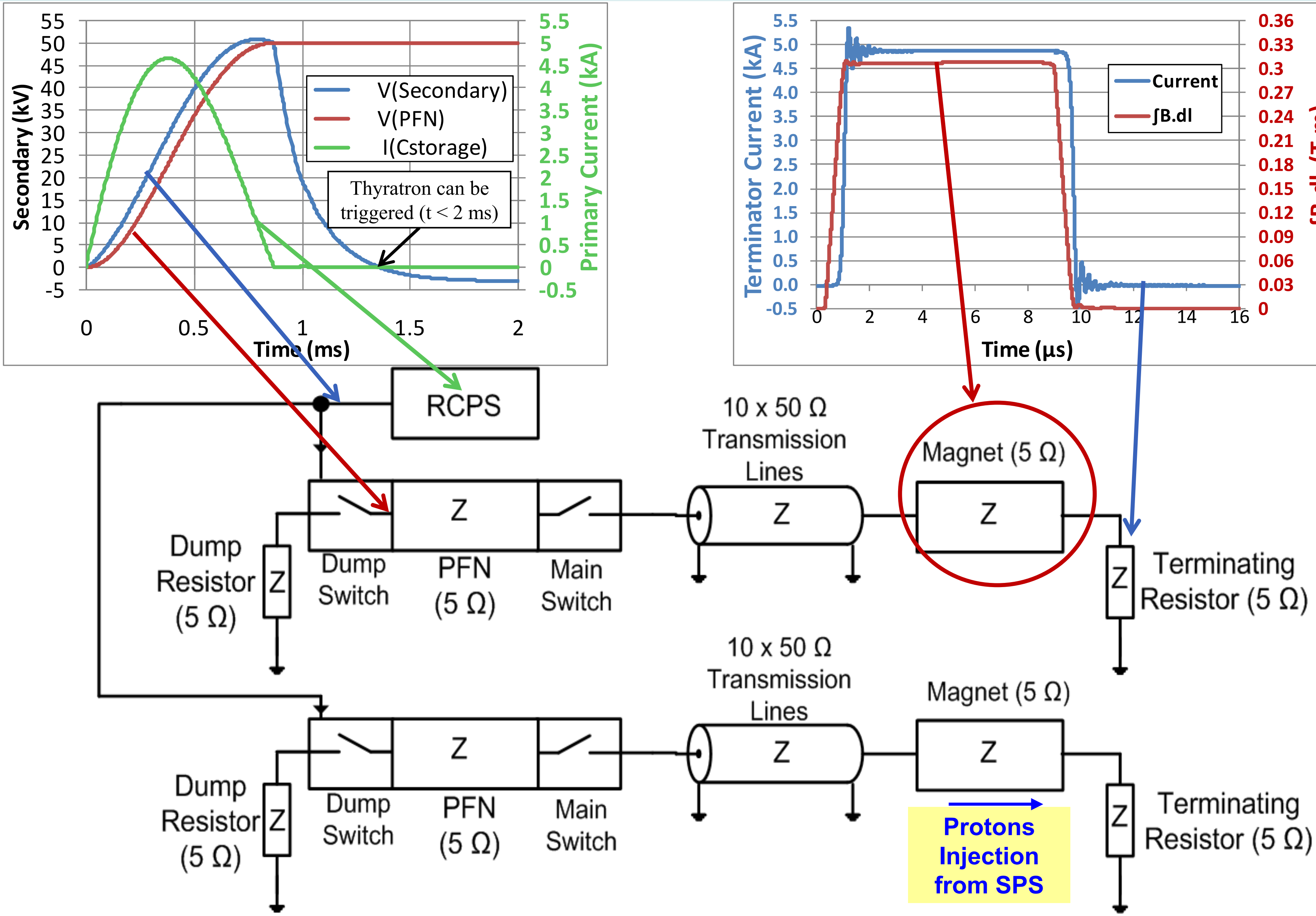
Three-gap thyratrons can hold-off 80kV and switch 6kA of current with a 30ns rise-time (10% to 90%) [~150kA/μs].

BUT: care must be taken, e.g. …..

- Coaxial housings for low inductance;
- Adequate insulation to the housing;
- Erratic turn-on (turn-on without a trigger being applied): reduced significantly by **<u>“fast” (~ms)</u>** charging-then-discharging of the PFN/PFL;
- Appropriate thyratron for anticipated short-circuit and fault conditions.

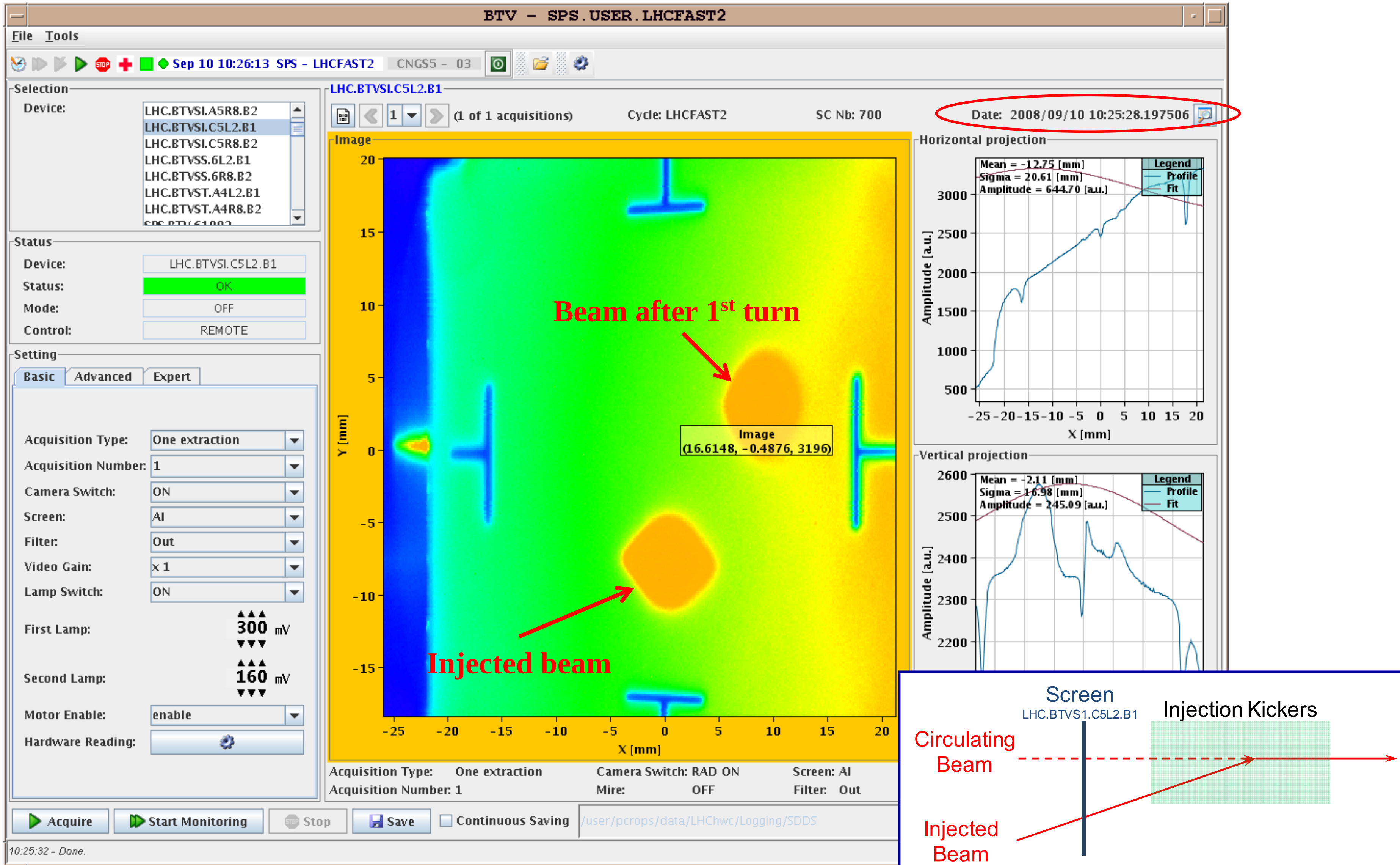


Schematic of an LHC Injection System



First Turn of Beam Injected into LHC

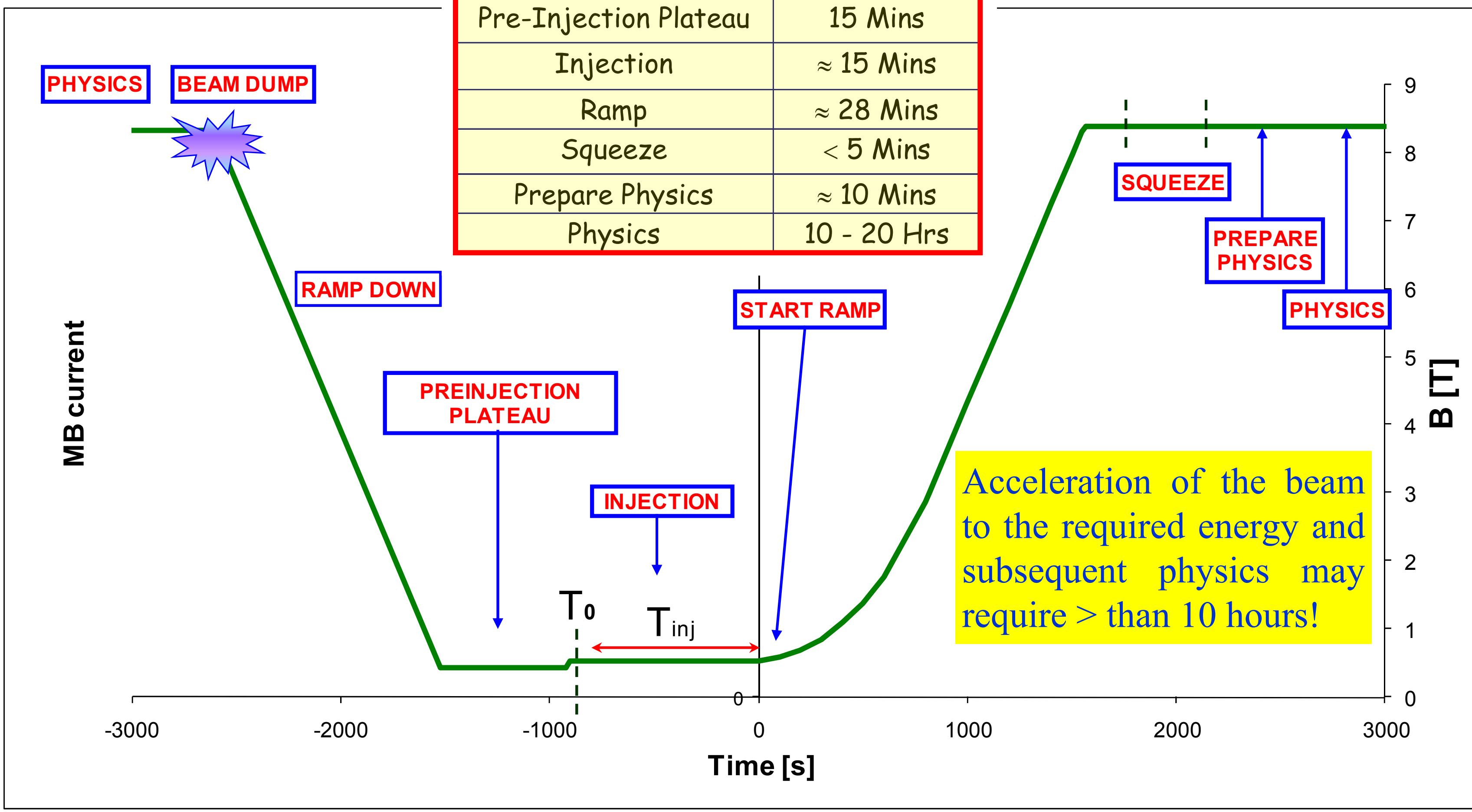
Just to demonstrate that the LHC Injection Kickers, at Point 2, work……



LHC Nominal Cycle

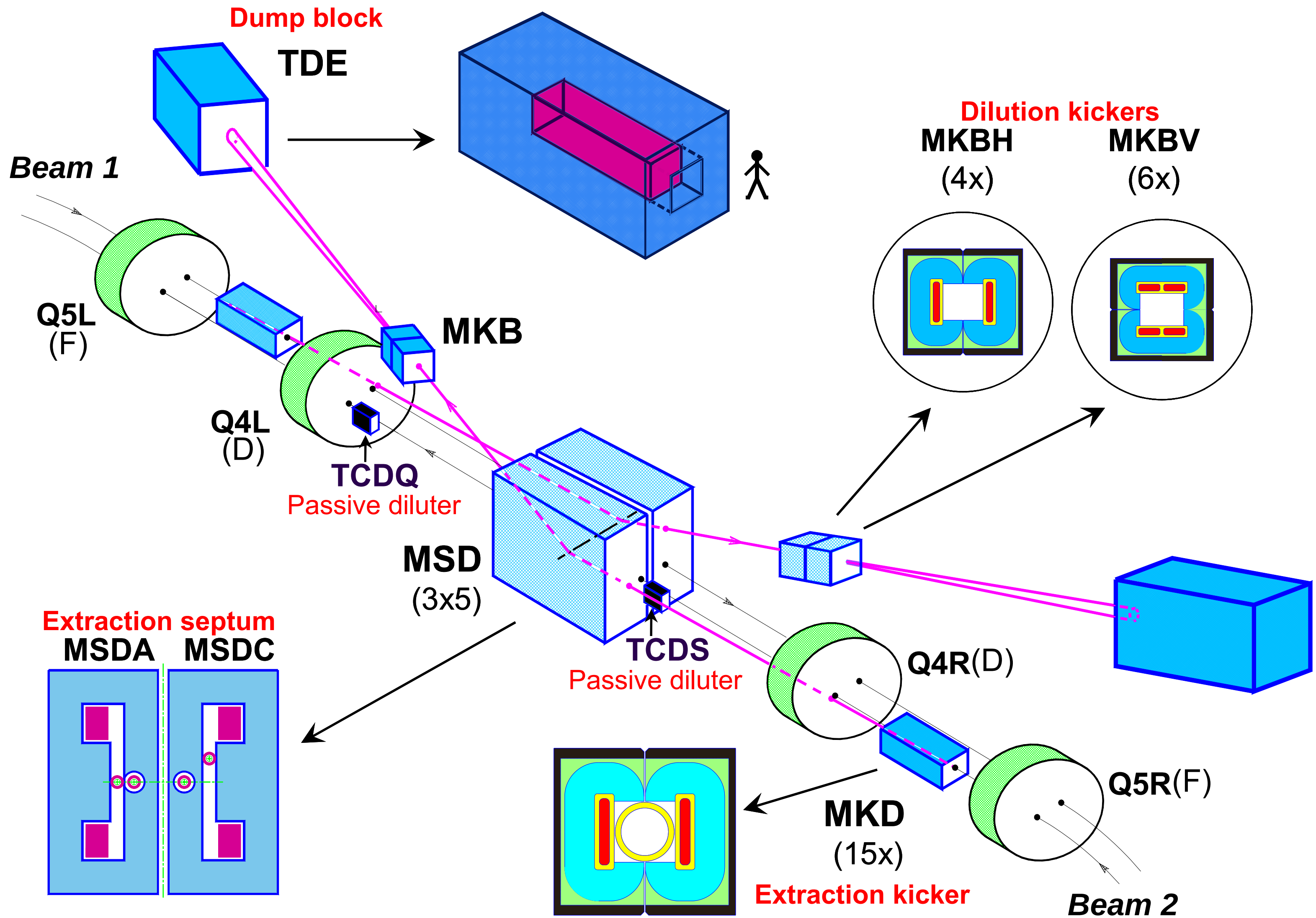
In some applications thyratron switches cannot be used; e.g. for the dump (abort) kickers in the LHC where **the generator voltage must track the beam energy and NO self-firing is allowed**.

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



Fast Single Turn Extraction: LHC Dump

- LHC beam dump systems – 2x ~1000 m long - occupy LHC straight section 6:



Semiconductor Switches II

For the <u>dump (abort) kickers in the LHC,</u> where the generator voltage must track the beam energy, and no self-firing is allowed, high power semiconductor switches are used (rise-time ≥ 1μs). The semiconductor switches also allow a wide dynamic range of operation.

Maintenance is significantly reduced with a semiconductor switch.

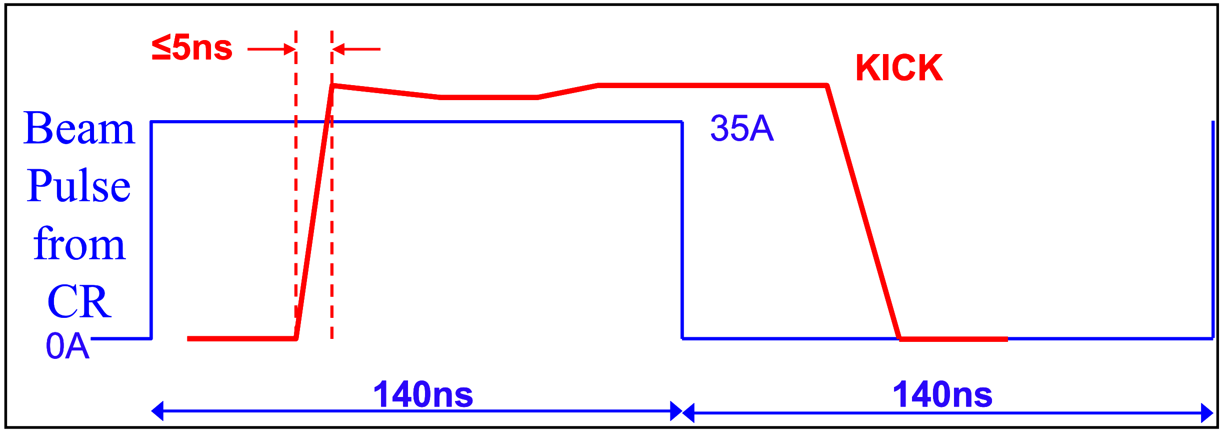
<u>LHC dump parameters</u>:

- Ten series GTO's (V_{DRM}=4.5kV);
- Voltage range: 2.2kV – 30kV (450 GeV to 7 TeV);
- Current range: 1.3kA – 18.5kA;
- Magnet current flat top: 95μs;
- Maximum di/dt: ~~18kA/μs~~ 32kA/μs (~~~1/8th~~ 1/5th of a thyratron).


GTO die damaged during testing at high di/dt

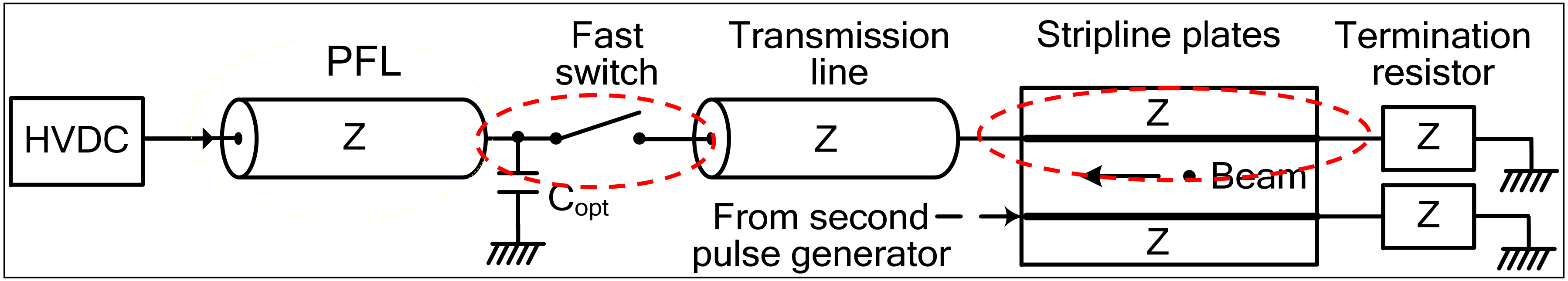
CTF3 Tail Clipper: Overview

Beam Pulse



The beam pulse extracted from the Combiner Ring (CR) is 35 A and 140 ns. **The tail-clipper must have a fast field rise-time, of 5ns or less**, to minimize uncontrolled beam loss. The flatness of the kick pulse is not important as deflected beam is to be thrown away.

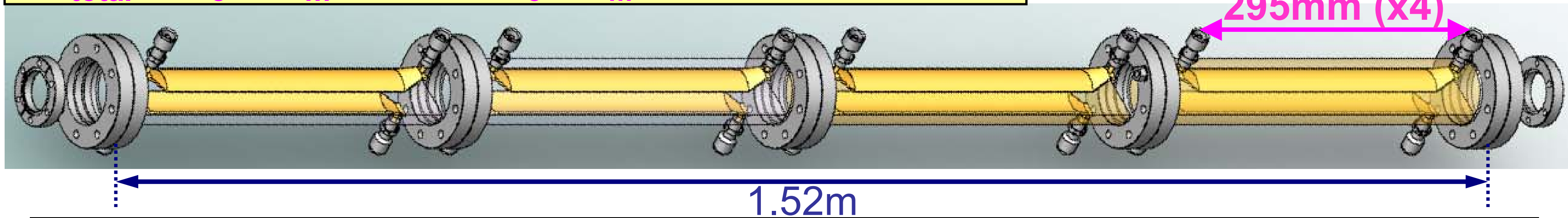
Schematic of Tail-Clipper



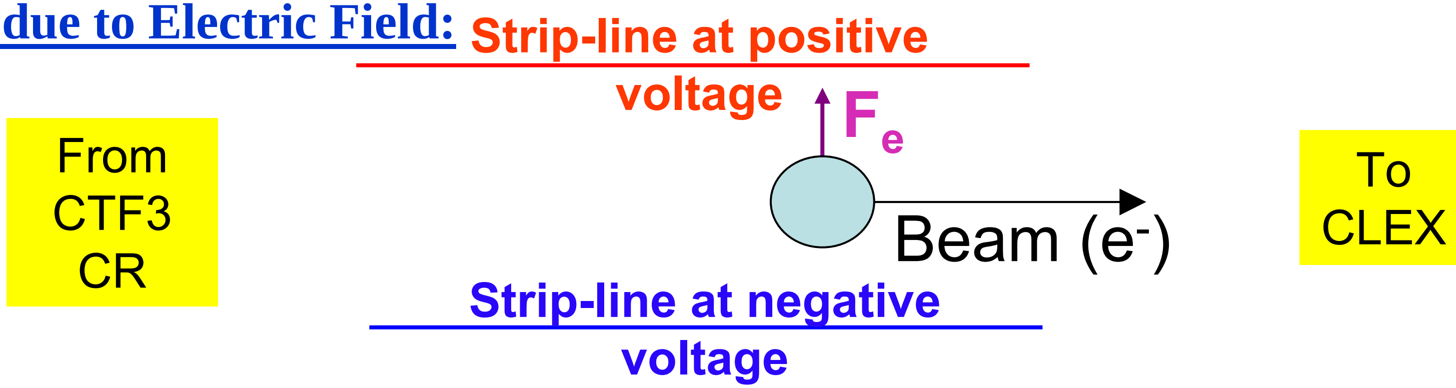
Each (of 8) pulse generator is composed of a 50Ω (Z) PFL, a fast semiconductor (Behlke) switch, 50 Ω stripline plates (no magnetic material) and a matched terminating resistor.

CTF3 Tail Clipper: Striplines I

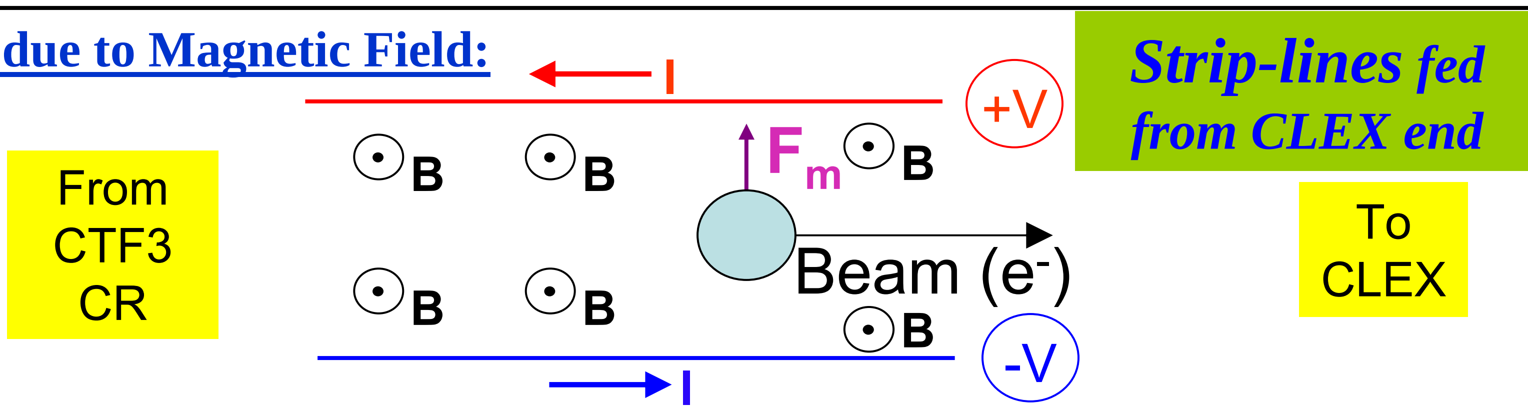
$F_{total} = F_e + F_m$, Note: $F_e = F_m$ for the tail clipper.



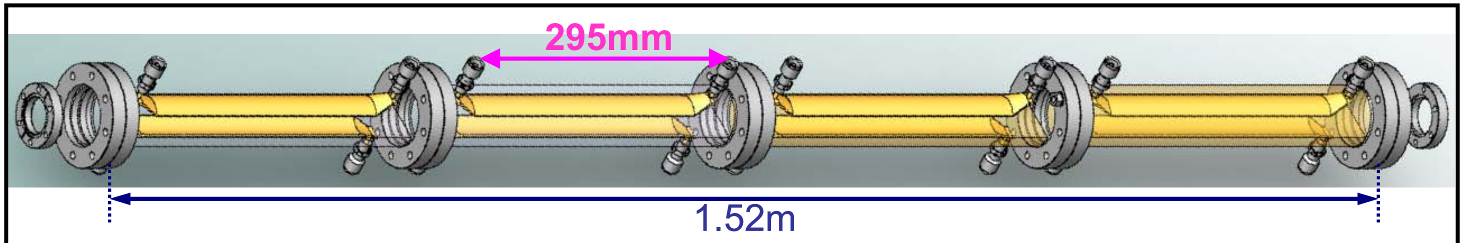
Deflection due to Electric Field:

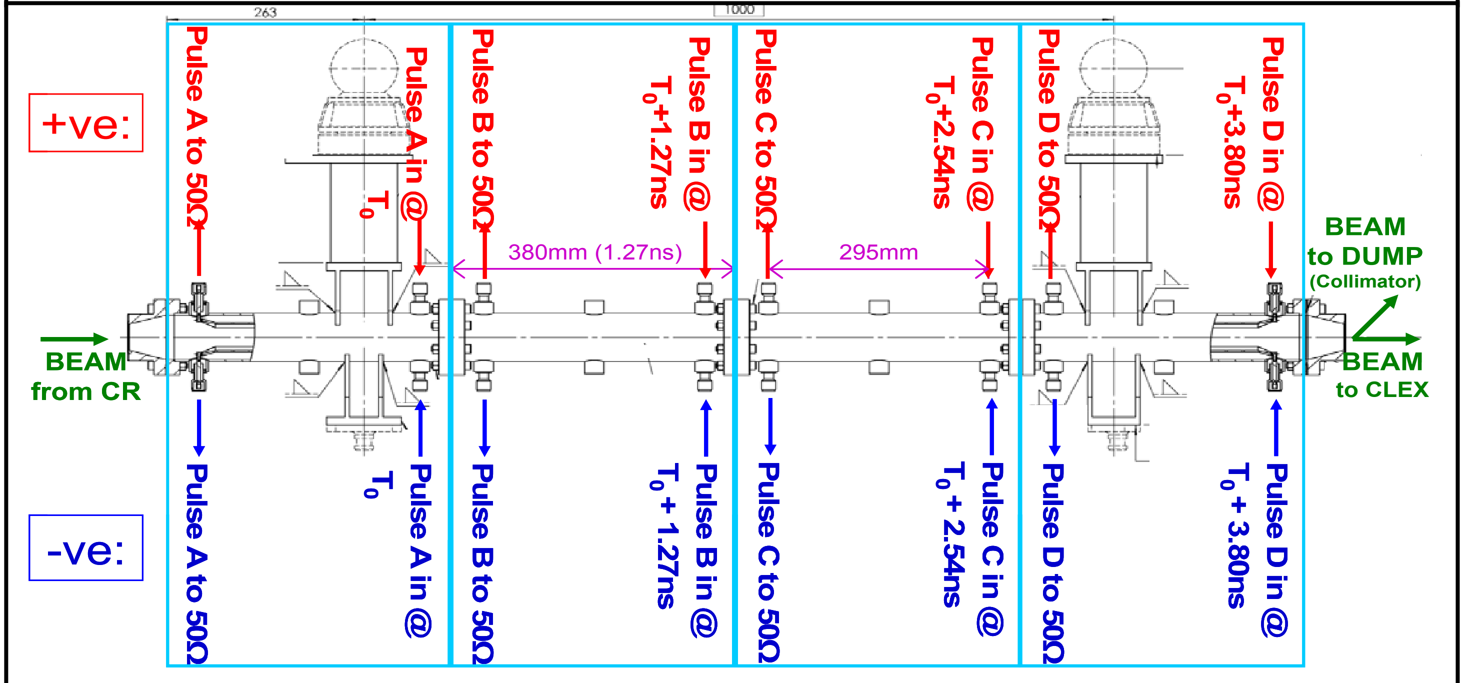


Deflection due to Magnetic Field:



CTF3 Tail Clipper: Striplines II



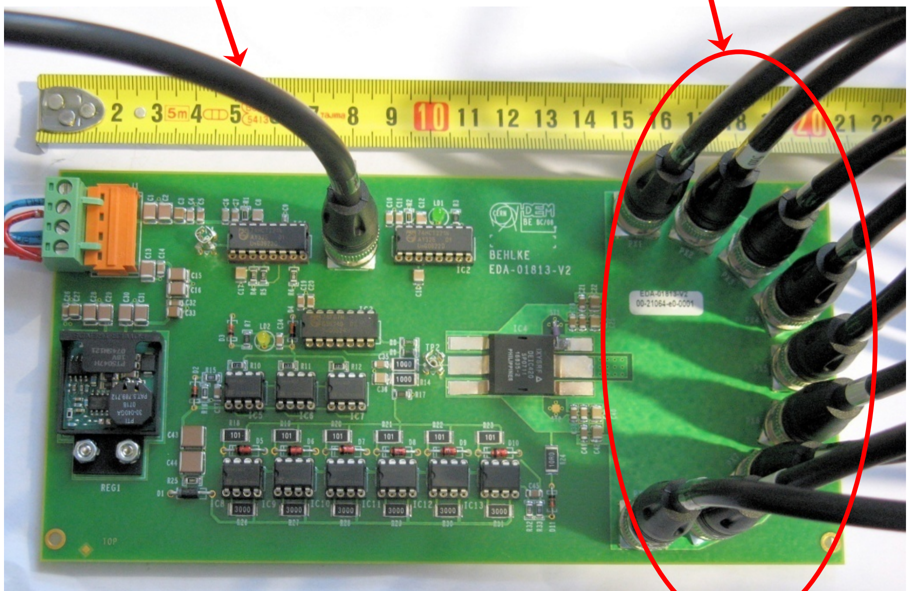


- Four sets of striplines with each section energized a time delay 1.27 ns (0.38 m/*c*) after the previous section.
- Smooth transition from coaxial feedthru to stripline.
- Tapered electrodes preserve 50 Ω characteristic impedance.

CTF3 Tail-Clipper Hardware

Input Trigger (5V)

9 Parallel 50Ω Outputs



[Gate Driver PCB](#)

(9 Parallel 50Ω Outputs [to drive 8 Behlke Switches])

Note: Behlke switch contains series connected, fast turn-on, MOSFETs.

Peaking Capacitor

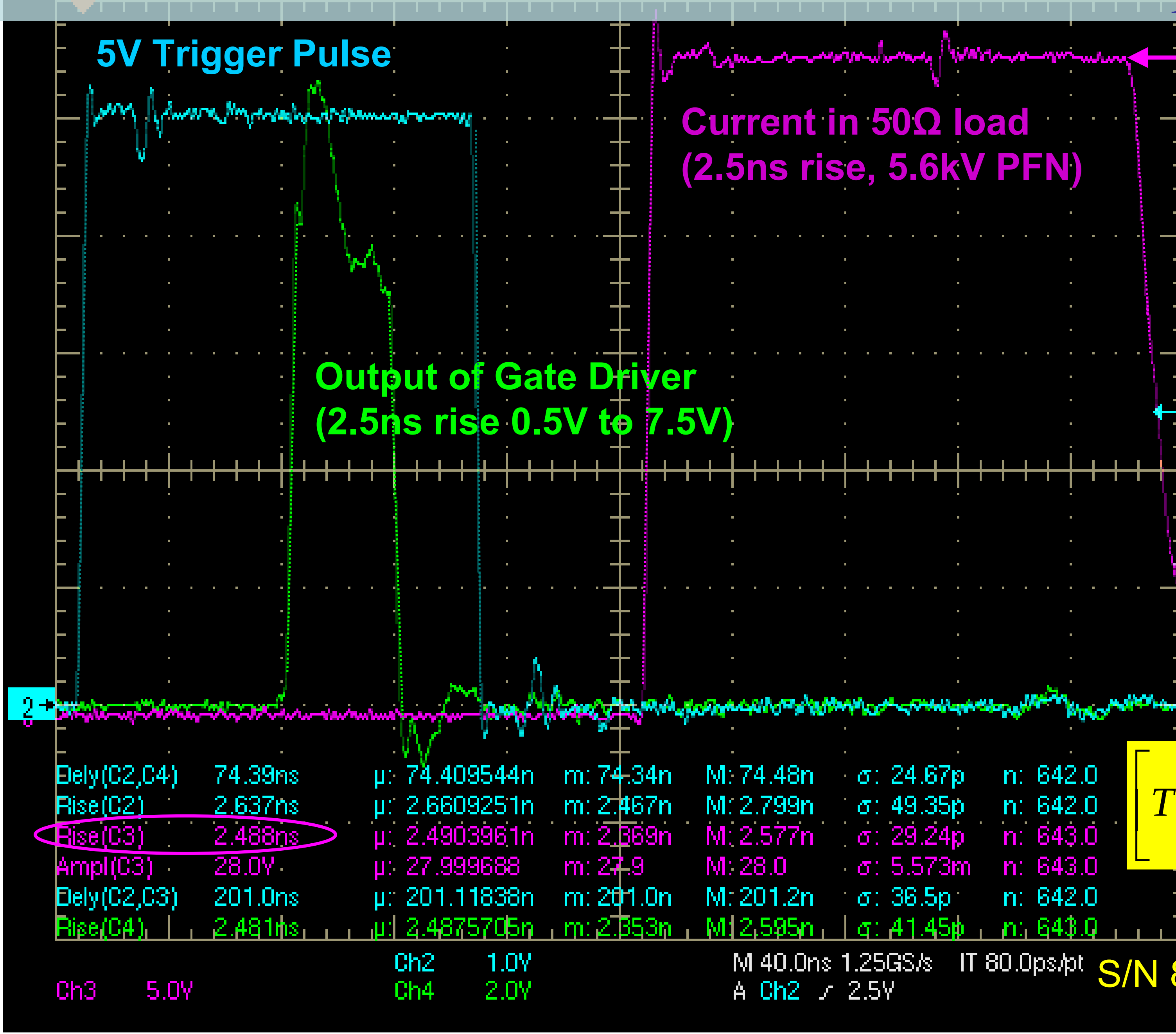
10V Trigger from Gate Driver PCB

To Load

PFN

Behlke Switch (8kV, 200A): Very Low Inductance Connections

Measured Waveforms: Normal Operation



56A
(53A [40A] reqd. for 3 [4] sets of striplines).

Field rise-time of ~4.0ns [~3.2ns] predicted using PSpice (with t_d of 1.27ns), 0.25% to 99.75%, with measured current waveform, for 56A.

$$\left[T_{field} \approx T_r + \left(\frac{0.38}{c} \right) \right]$$

S/N 847409; 5x10pF

Bibliography for Kickers

- D. Fiander, K.D. Metzmacher, P.D. Pearce, “Kickers and Septa at the PS complex, CERN”, Prepared for KAON PDS Magnet Design Workshop, Vancouver, Canada, 3-5 Oct 1988, pp71-79.
- M.J. Barnes, G.D. Wait, I.M. Wilson, “Comparison of Field Quality in Lumped Inductance versus Transmission Line Kicker Magnets”, EPAC 1994, pp2547-2549.
- G. Kotzian, M. Barnes, L. Ducimetière, B. Goddard, W. Höfle, “Emittance Growth at LHC Injection from SPS and LHC”, LHC Project Report 1116.
- J. N. Weaver et al., “Design, Analysis and Measurement of Very Fast Kicker Magnets at SLAC,” Proc of 1989 PAC, Chicago, pp. 411–413.
- L. Ducimetière, N. Garrel, M.J. Barnes, G.D. Wait, “The LHC Injection Kicker Magnet”, Proc. of PAC 2003, Portland, USA, pp1162-1164.
- L. Ducimetière, “Advances of Transmission Line Kicker Magnets”, Proc. of 2005 PAC, Knoxville, pp235-239.
- W. Zhang, J. Sandberg, J. Tuozzolo, R. Cassel, L. Ducimetière, C. Jensen, M.J. Barnes, G.D. Wait, J. Wang, “An Overview of High Voltage Dielectric Material for Travelling Wave Kicker Magnet Application”, proc. of 25th International Power Modulator Conference and High Voltage Workshop, California, June 30-July 3, 2002, pp674-678.
- J. Bonthond, J.H. Dieperink, L. Ducimetière, U. Jansson, E. Vossenberg, “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.
- M.J. Barnes, T. Fowler, G. Ravida, H. Nakajima, “Design & Testing of the Modulator for the CTF3 Tail Clipper Kicker”, Proc. of 2nd Euro-Asian Pulsed Power Conference, 22-26 September 2008, Vilnius, Lithuania.