CERN

Kicker Systems - Part 1 - Introduction and Hardware

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Overview of Presentation

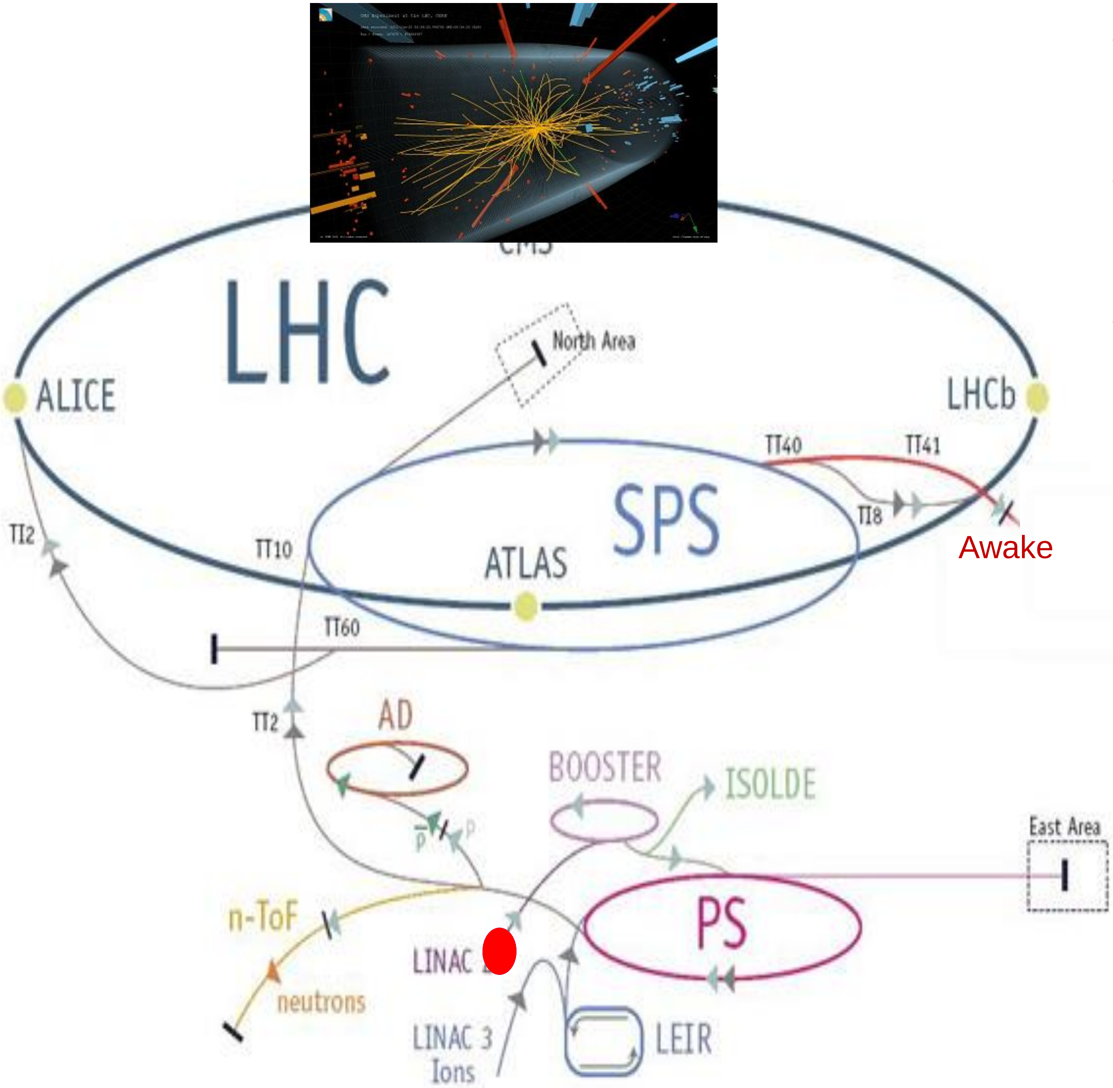
Part 1:

- 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

CERN's Particle Accelerators



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

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

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

- 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

- 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: generally, at CERN, a pulsed dipole magnet with very fast rise and/or fall time (typically 50 ns → 1 μs).

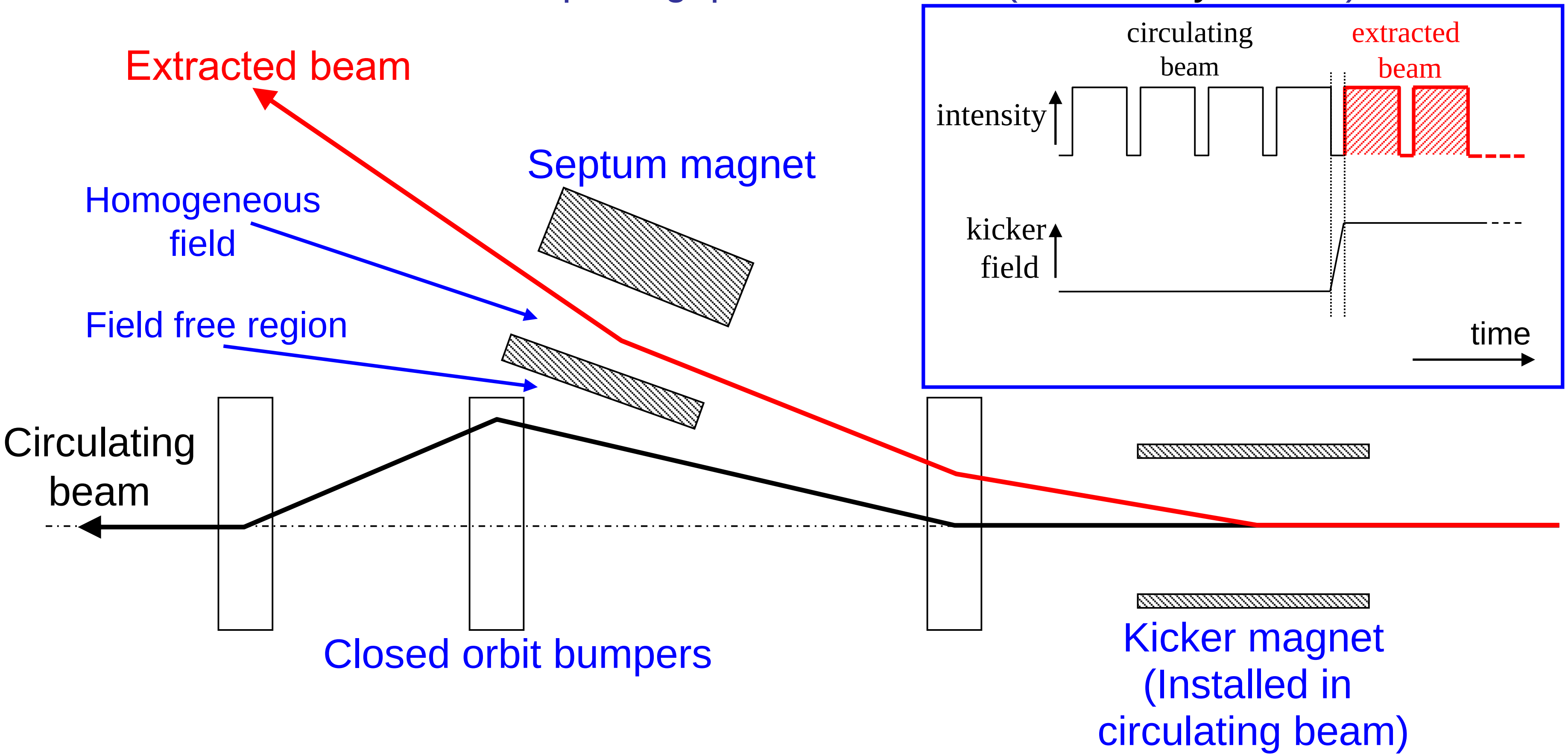
Septum magnet: pulsed or DC dipole magnet with thin (2-20mm) septum between zero field and high field region.

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

Septa discussed by Martin (Thursday)

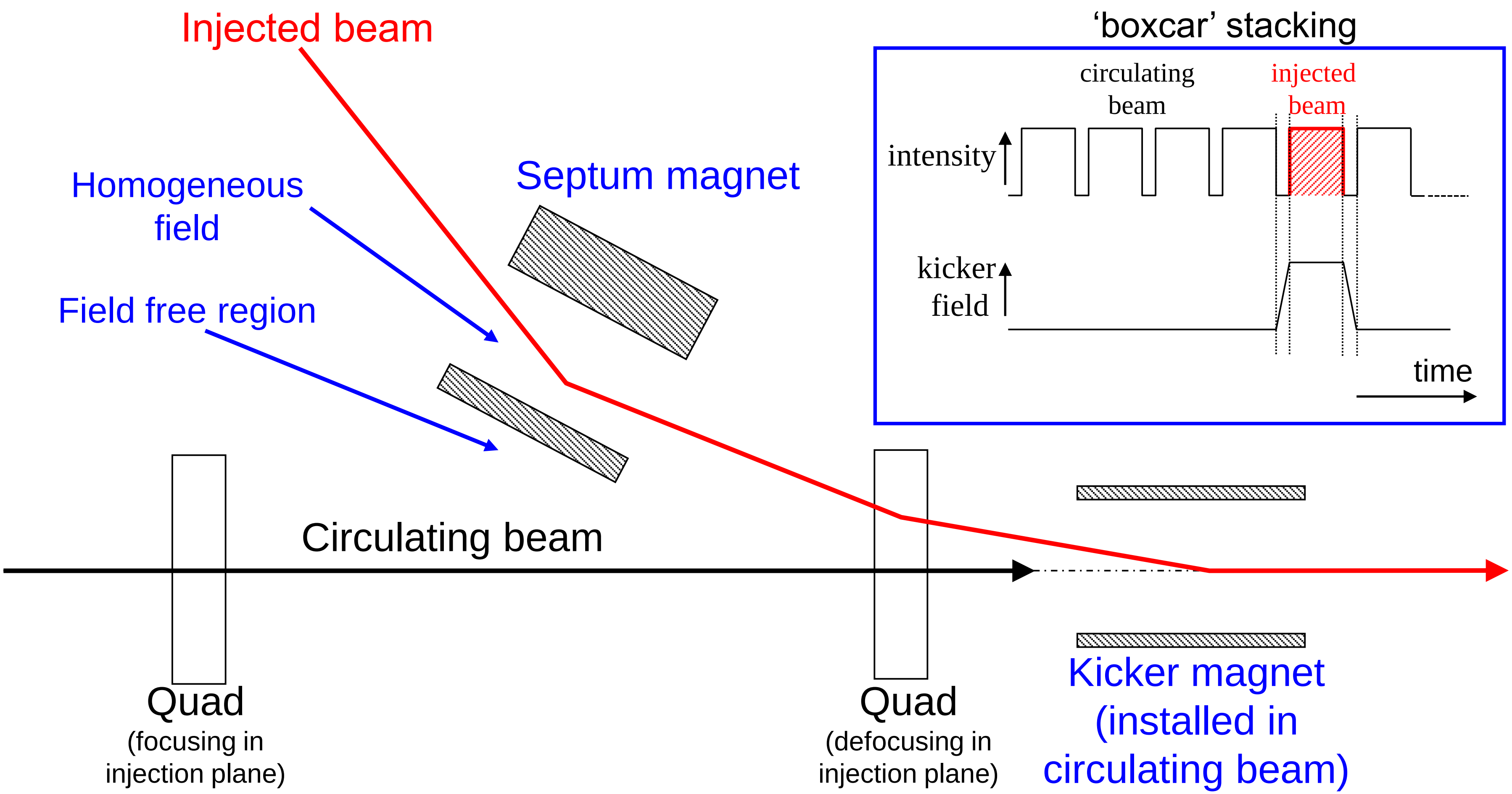
Fast Single-Turn Extraction: Same Plane

Whole beam is kicked into septum gap and extracted (see talk by Chiara).



- **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

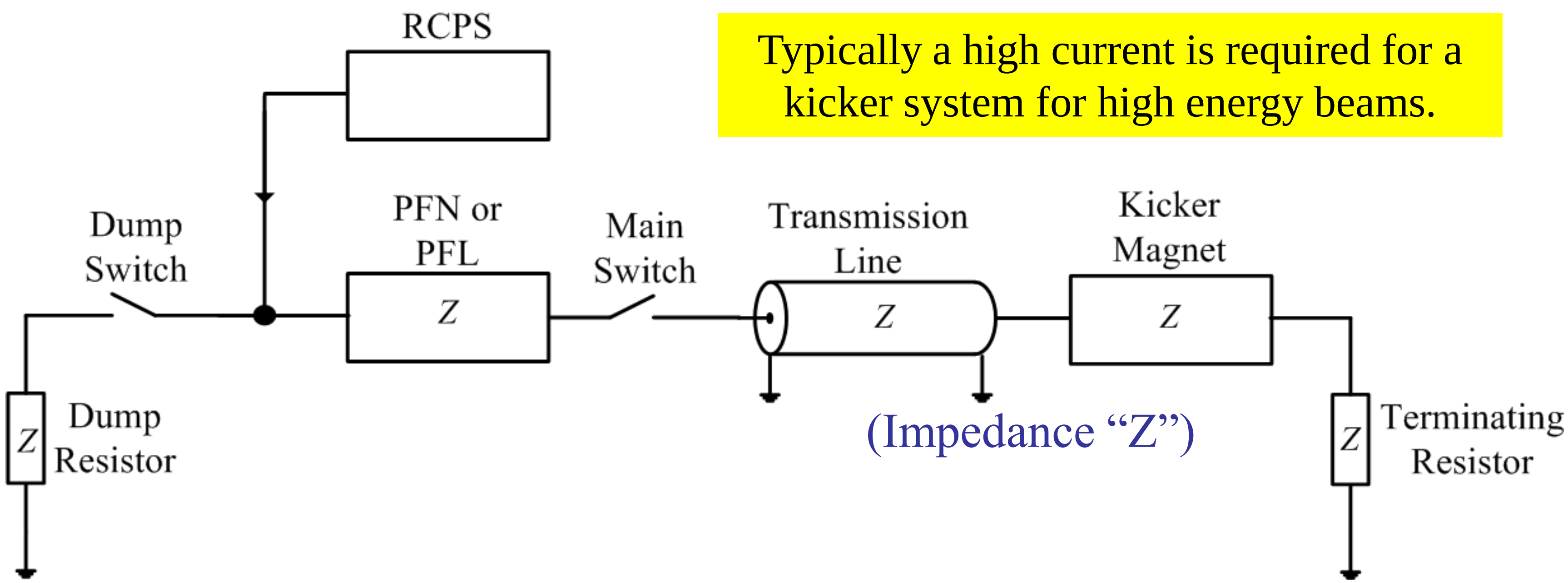


- **Septum** deflects the beam onto the closed orbit at the centre of the kicker
- **Kicker** compensates for the remaining angle

See talk by Chiara for details.

Schematic of a Modern Kicker System

Typically a high current is required for a kicker system for high energy beams.

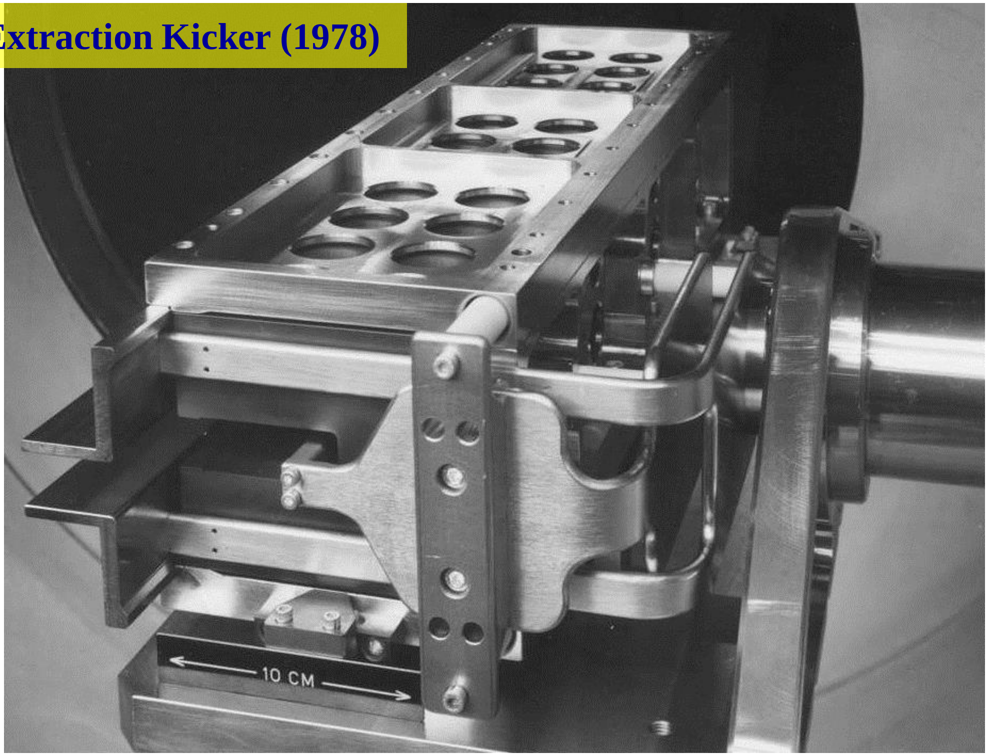


Main sub-systems ("components") of kicker system;

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

Example of a “Plunging” Kicker Magnet

CERN Antiproton Accumulator Extraction Kicker (1978)

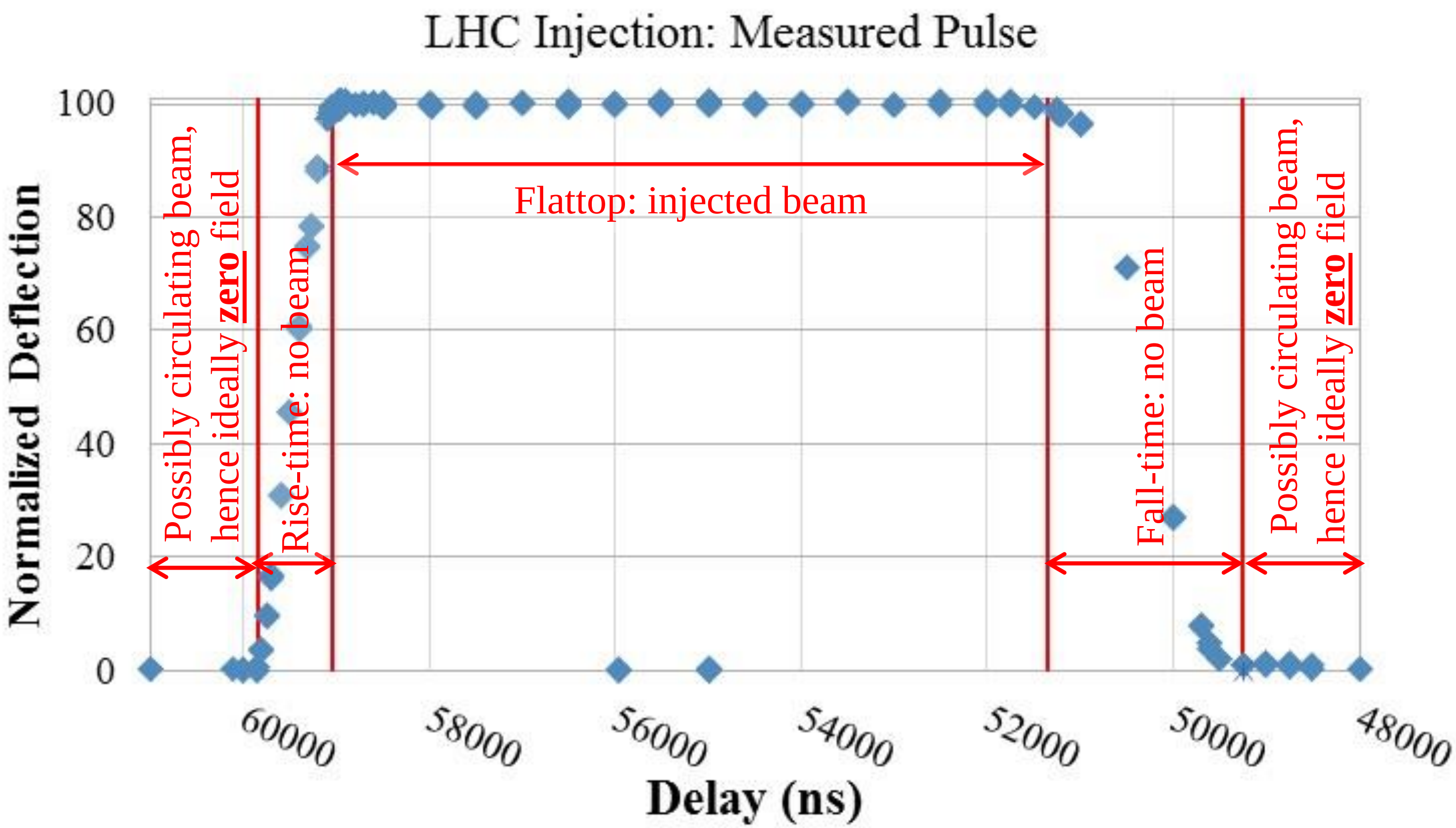


The original (~1960’s) “plunging” kicker magnets were hydraulically operated: the aperture was too small for the kicker to be in the beam-line during circulating-beam.

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

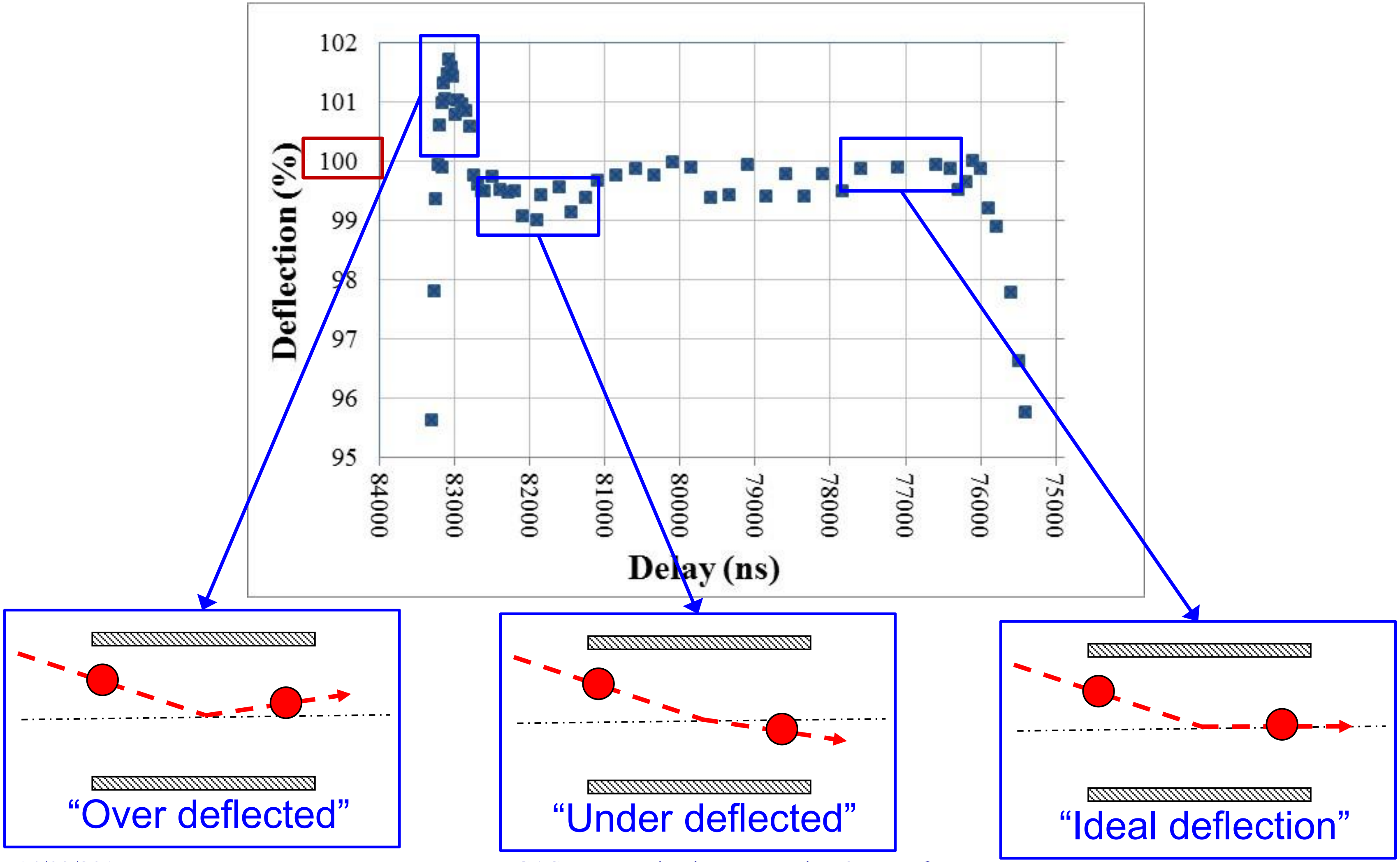
Pulse Shape for Fast Single Turn Injection

- The kicker magnetic field must rise/fall within the time period between the beam batches. 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;
- **A fast, low ripple, kicker system is required!**



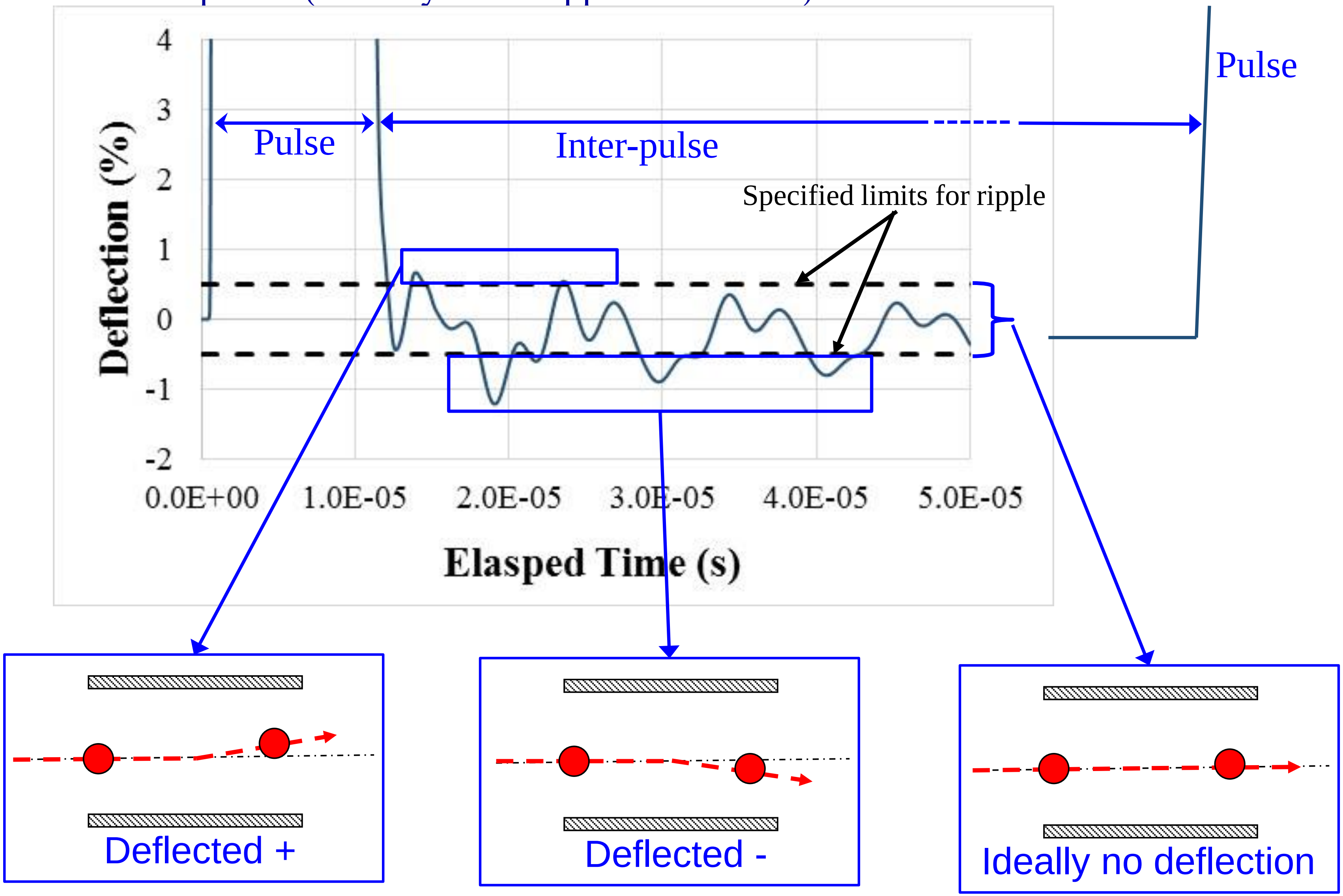
Examples of Influence of Pulse Flattop Ripple

- The magnetic field must not significantly deviate from the flat top;
- 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).



Examples of Influence of Inter-pulse Ripple

- **Circulating beam**: hence the magnetic field must not significantly deviate from zero between pulses (i.e. very small ripple/excursions).



Deflection by Electromagnetic Field: Lorentz Force

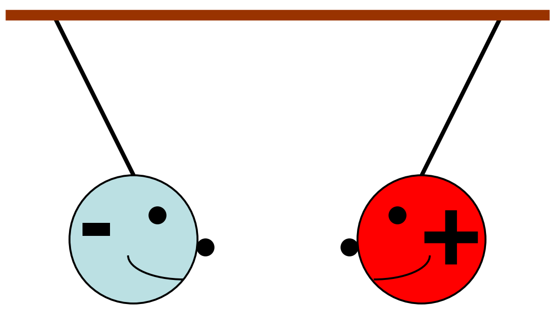
The Lorentz force is the force on a point charge due to electromagnetic fields. It is given by the following equation in terms of the electric and magnetic fields:

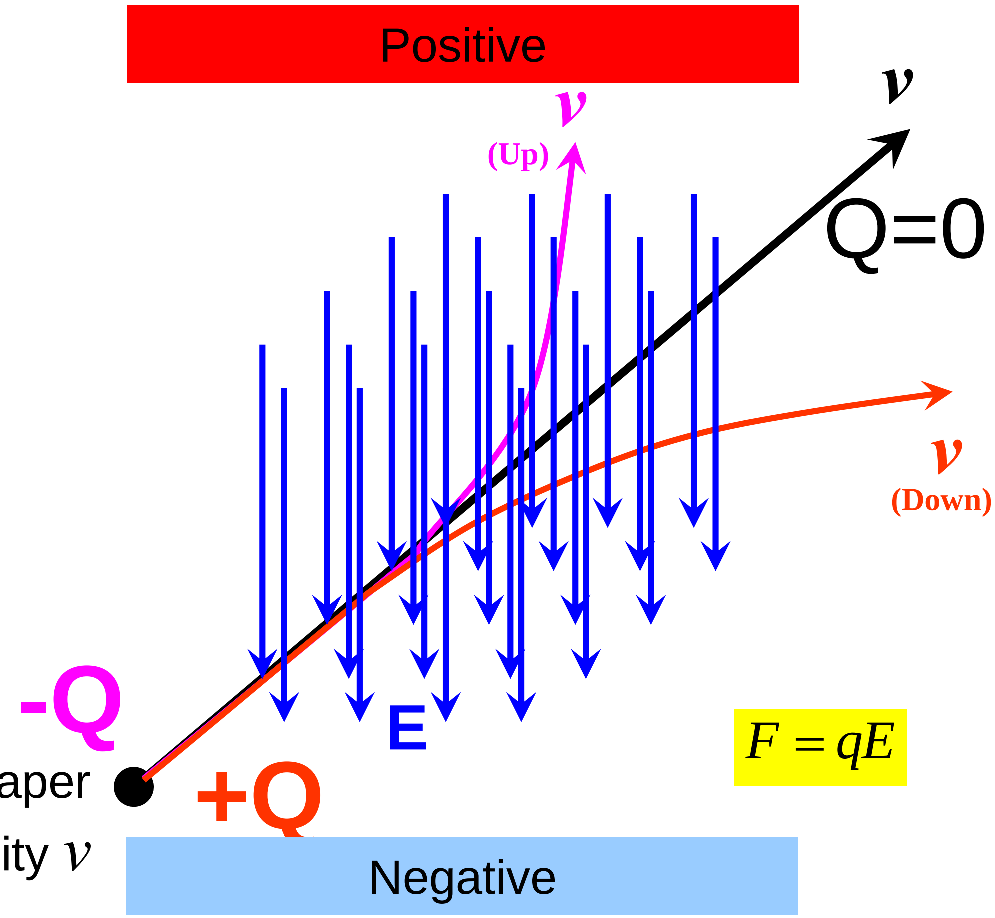
$$F = q\left[E + \left(v \times B\right)\right]$$

- F is the force (in Newton) – vector quantity;
- E is the electric field (in volts per meter) – vector quantity;
- B is the magnetic field (in Tesla) – vector quantity;
- q is the electric charge of the particle (in Coulomb)
- v is the instantaneous velocity of the particle (in meters per second) – vector quantity;
- x is the vector cross product

Deflection by an Electric Field

Opposites Attract !



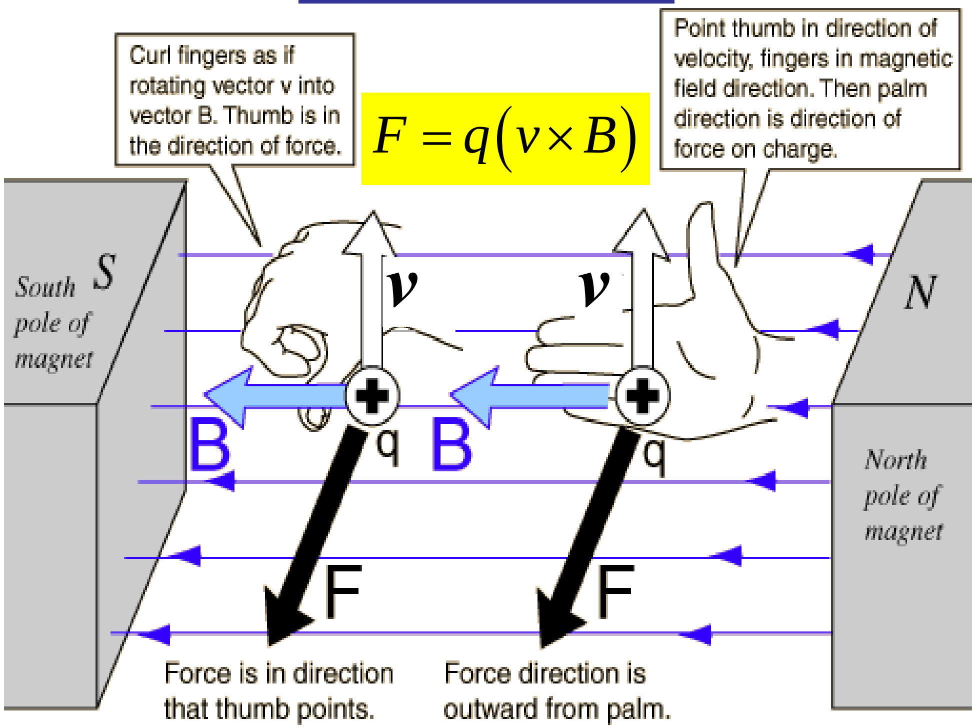


Charge moving into plane of paper at velocity v

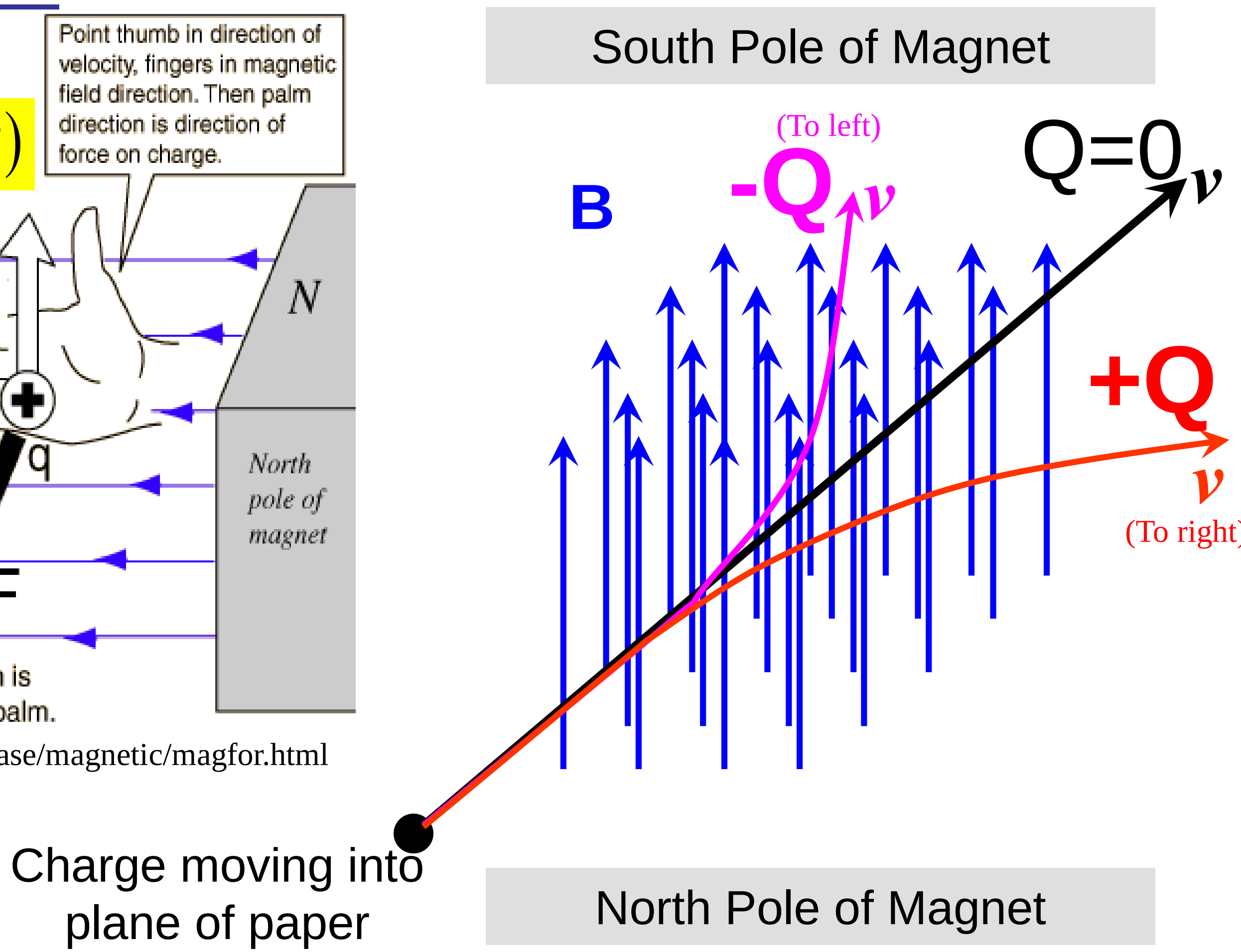
Deflection of a charged particle is either in same direction as E or in the opposite direction to E.

Example of Deflection by Force in a Magnetic Field

Right-Hand Rule

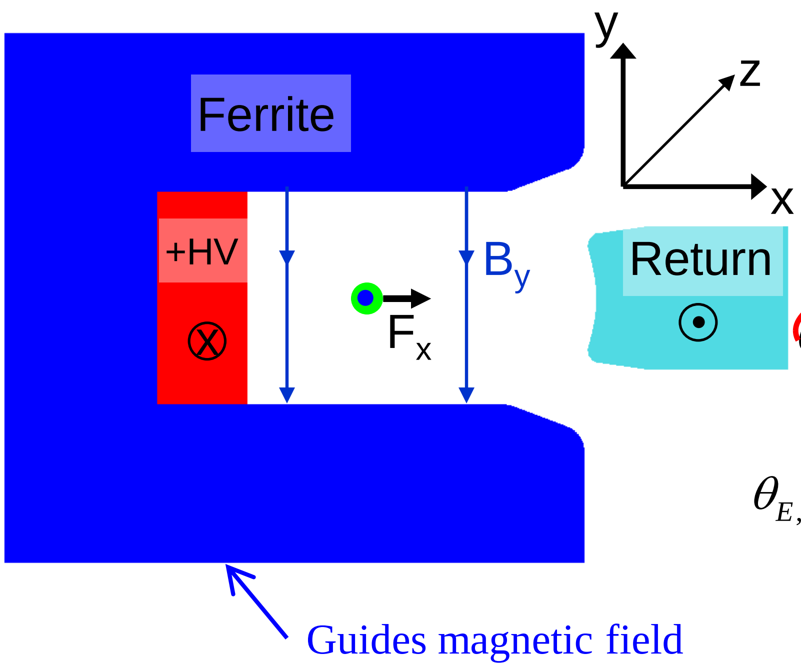


Ref: http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magfor.html



Vector F is perpendicular to the plane containing the vector B and vector *v*.

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.

$$\theta_{B,x} = \left[\frac{0.2998}{p}\right] \cdot \int_{z_0}^{z_1} |B_y| dz = \left[\frac{0.2998 \cdot l_{eff}}{p}\right] \cdot |B_y|$$

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

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

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).

Comparison of Magnetic and Electric Deflection

Consider: $$\theta_{B,x} = \theta_{E,x}$$

For small angles: $$\left[\frac{0.2998 \cdot l_{eff}}{p}\right] \cdot \left|B_y\right| = \left[\frac{\left|E_x\right| \cdot l_{eff}}{(p \cdot 10^9) \cdot \beta}\right]$$

Simplifying: $$0.2998 \cdot \left|B_y\right| = \left[\frac{\left|E_x\right|}{10^9 \cdot \beta}\right]$$

For $\beta \approx 1$, consider B_y = 0.1 T, then the electrical field to obtain the same deflection is E_x = ~30 MV/m !

Hence, in general, for kicker systems **magnetic fields are used to deflect high energy beams.**

Electrical Parameters for a Magnetic Kicker

Usually 1 for a kicker magnet

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

(neglecting saturation of ferrite)

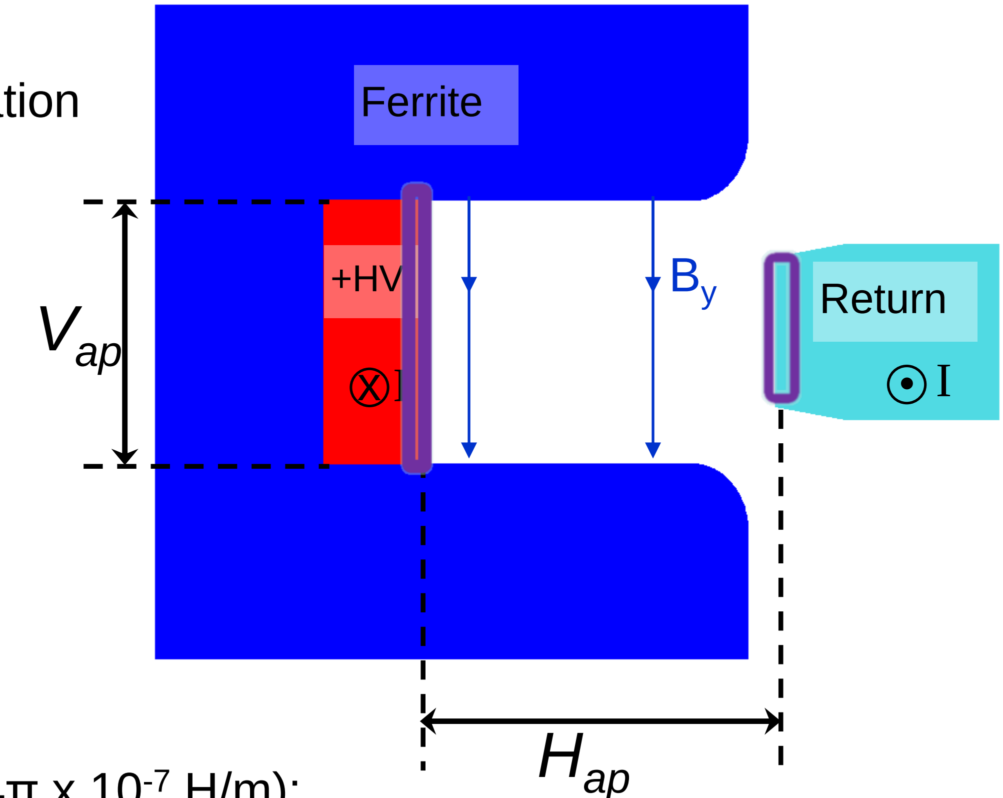
Minimum value set by beam parameters

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

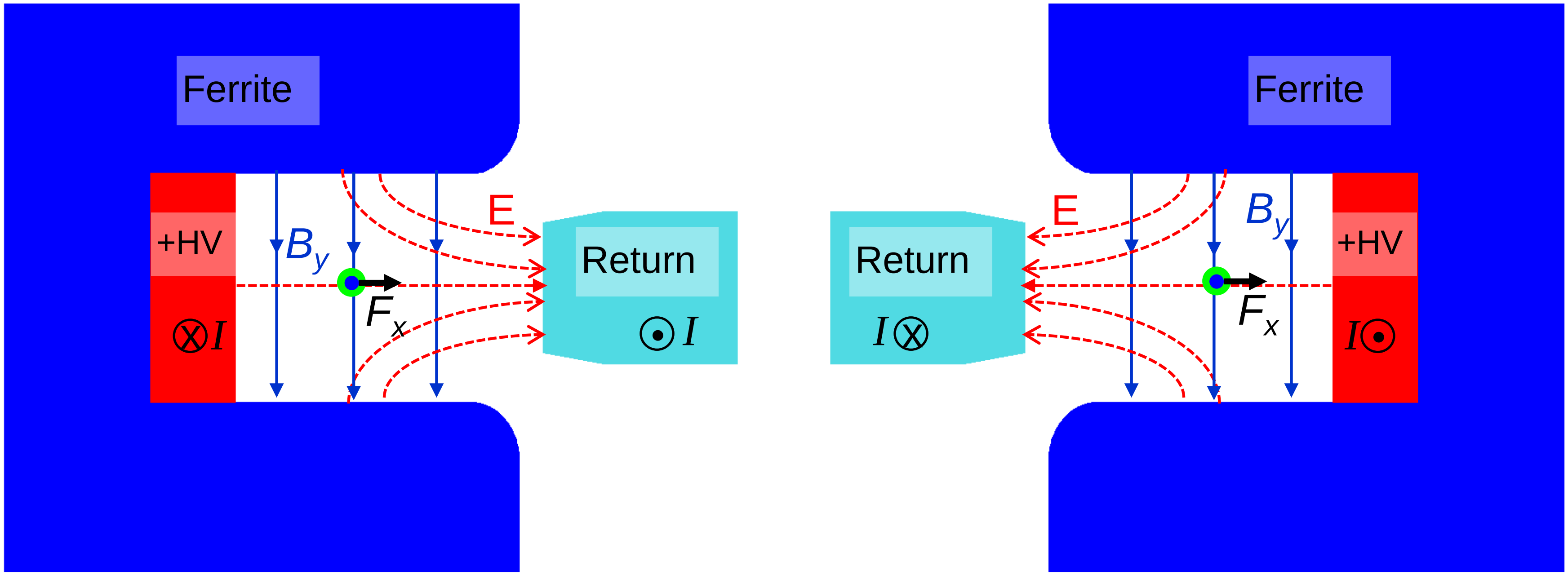
$$L_m \cong \mu_0 \left(\frac{N^2 \cdot H_{ap}}{V_{ap}} \right) \cdot l_{eff}$$



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 is the total inductance of the kicker magnet system (H/m).

Uniformity of Deflection Angle



F_x ⇨ Force due to B_y and E_x are in the same direction.

F_x ⇨ Force due to B_y and E_x are in opposite directions.

Key:

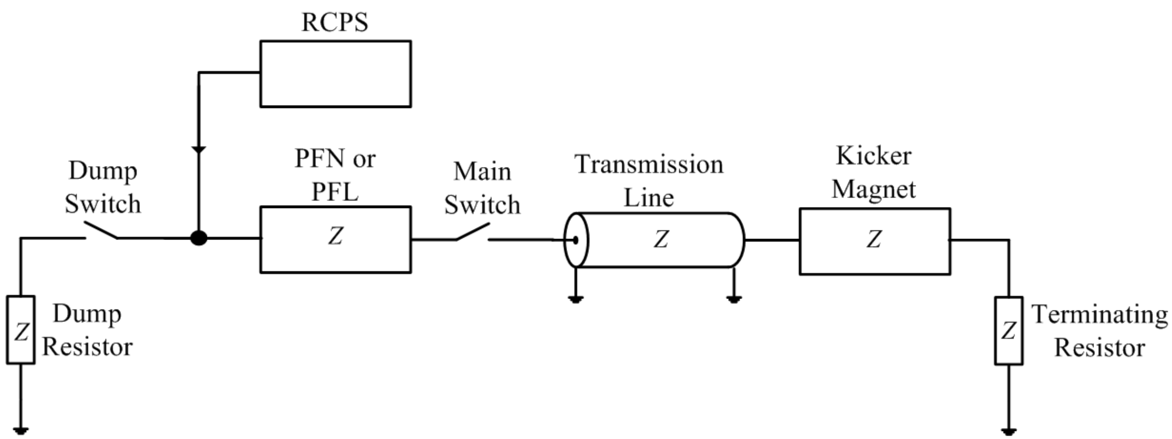
- Proton beam moving out of plane of paper;
- ⊗ Current flow into plane of paper;
- ⊙ Current flow out of plane of paper.

For a magnetic kicker, "deflection uniformity" can be influenced by electric field. Especially true for:

- ➢ relatively low flux-density;
- ➢ low β.

Shaping of return conductor and ferrite yoke can be important to achieving good deflection uniformity.

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).

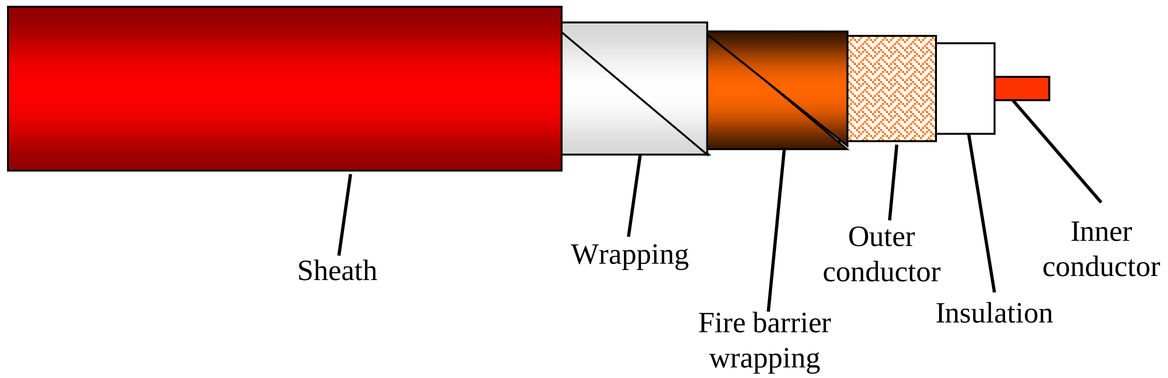
Typical circuit operation:

- 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 kicker 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 (see later slides);
- The length of the pulse in the magnet can be controlled in length 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.
  - If the Dump Switch is a switch, if the magnet is short-circuit the switch must be bi-directional.

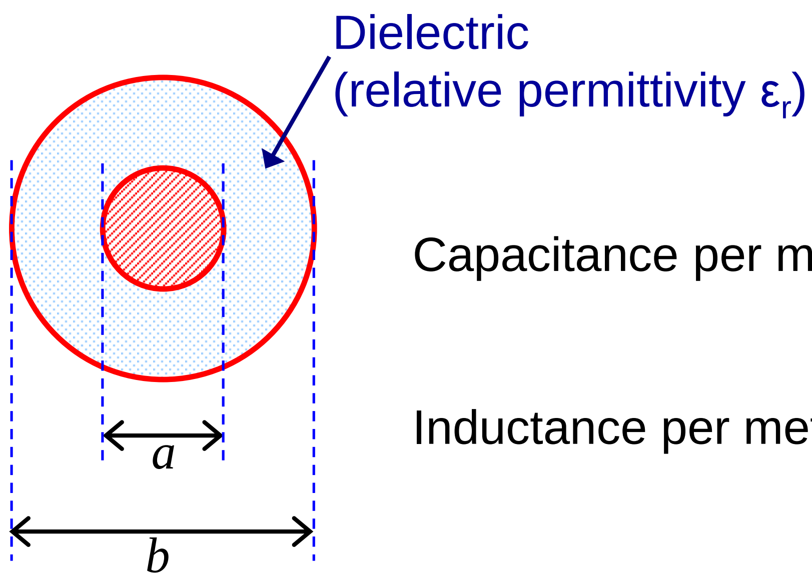
Coaxial Cables (Transmission Lines)

Coaxial cables play a major role in kicker systems!

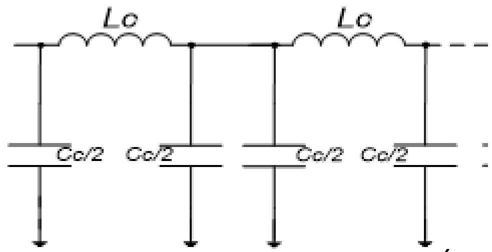
- Need to **transmit fast pulses and high currents**;
- Cables can be also used as **pulse forming line (PFL);**
- Ideally should **not attenuate** or distort the pulse
  - (RG220: attenuation < ~5.7dB/km at 10 MHz).
- Need to **insulate high voltage**
- Well matched **characteristic impedance** over complete length! Otherwise issues with reflections.
- Needs to be **radiation and fire resistant**, acceptable bending radius etc.



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): (generally 50 Ω). $$Z_0 = \sqrt{\frac{L}{C}}$$

Delay per metre length: (~5 ns/m for polyethylene dielectric cable). $$\tau = \sqrt{L\cdot C} = \frac{L}{Z_0}$$

Where:

a is the outer diameter of the inner conductor (m);

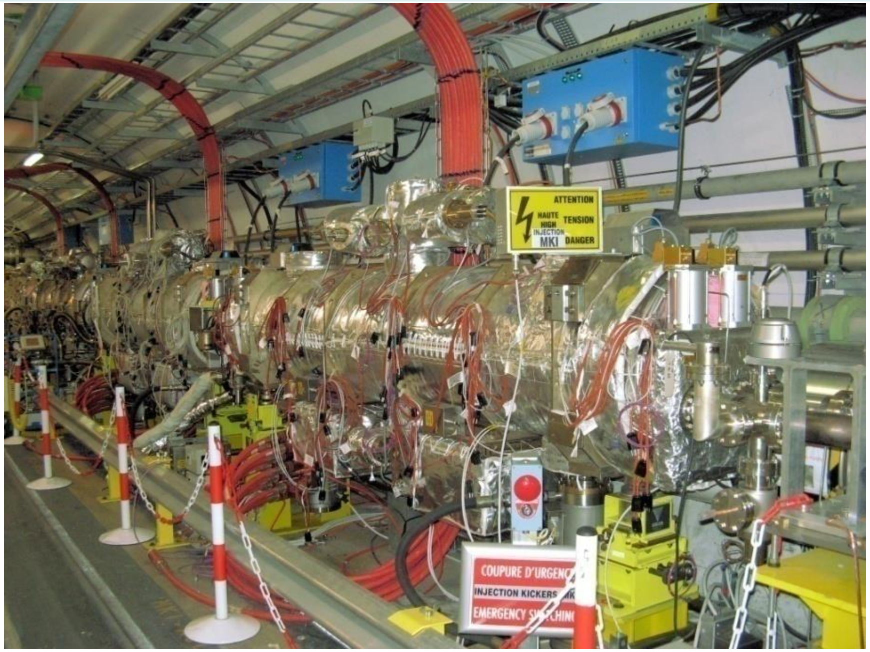
b is the inner diameter of the outer conductor (m);

ε_0 is the permittivity of free space (8.854x10^{-12} F/m).

Kicker Magnet Design Options

Kicker magnets generally need to be fast ⇨ a single turn coil;

A multi-turn coil is used for, slower, lumped inductance kicker magnets.



<u>Some design options for kicker magnets</u>:

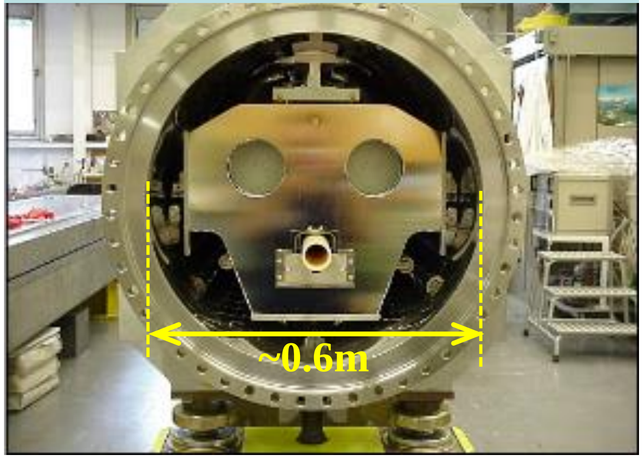
1. Machine vacuum: install in or external to machine vacuum?;
2. Type: “lumped inductance” or “transmission line” (with specific characteristic impedance (*Z*)) ?;
3. Aperture: window frame, closed C-core or open C-core ?;
4. Termination: matched impedance or short-circuited ?.

Inside Versus Outside Vacuum

- Outside Vacuum
  - Magnet built around vacuum chamber
  - Magnet easier to build
  - HV insulation can be an issue: after a flashover a solid dielectric, outside vacuum, may not recover.
  - Complex vacuum chamber necessary
    - keep beam vacuum
    - let transient field pass -> ceramic and metallization
    - increases aperture dimensions!

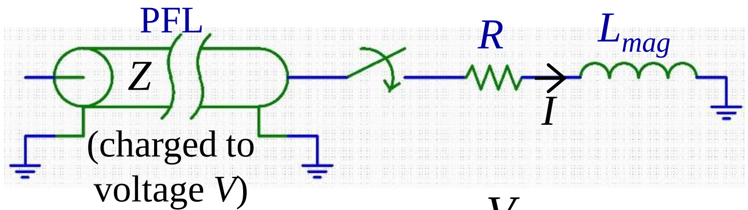
- Inside Vacuum
  - Magnet inside vacuum tank
  - Feedthroughs for all services necessary (HV, cooling, signals)
  - Materials need to be vacuum compatible
    - Preferably "bake-able" design (thermal expansion of different materials !)
  - Machine vacuum is a reliable dielectric (70 kV/cm OK) – generally "recovers" after a flashover.

MKI magnet in vacuum tank



Lumped Inductance vs. Transmission Line Kicker

"Lumped inductance"



$$I \approx \frac{V}{Z}(1 - e^{-t/\tau})$$

If R=0: $t = \dfrac{L_{mag}}{Z}$

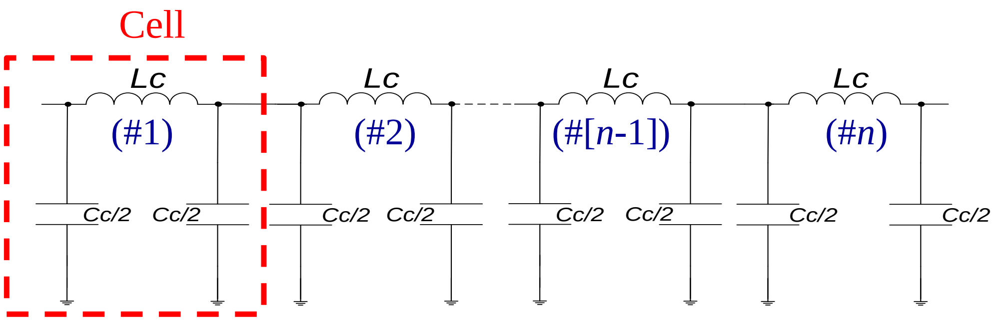
If R=Z: $\tau = \dfrac{L_{mag}}{2 \cdot Z}$

- simple magnet design;
- magnet must be nearby the generator to minimize interconnection inductance;
- generally slower: rise-times ~1μs;
- if < 1μs reflections can be significant;

- e.g. LHC MKD ~2.8 μs

"Transmission line"

Approximation of a transmission line:



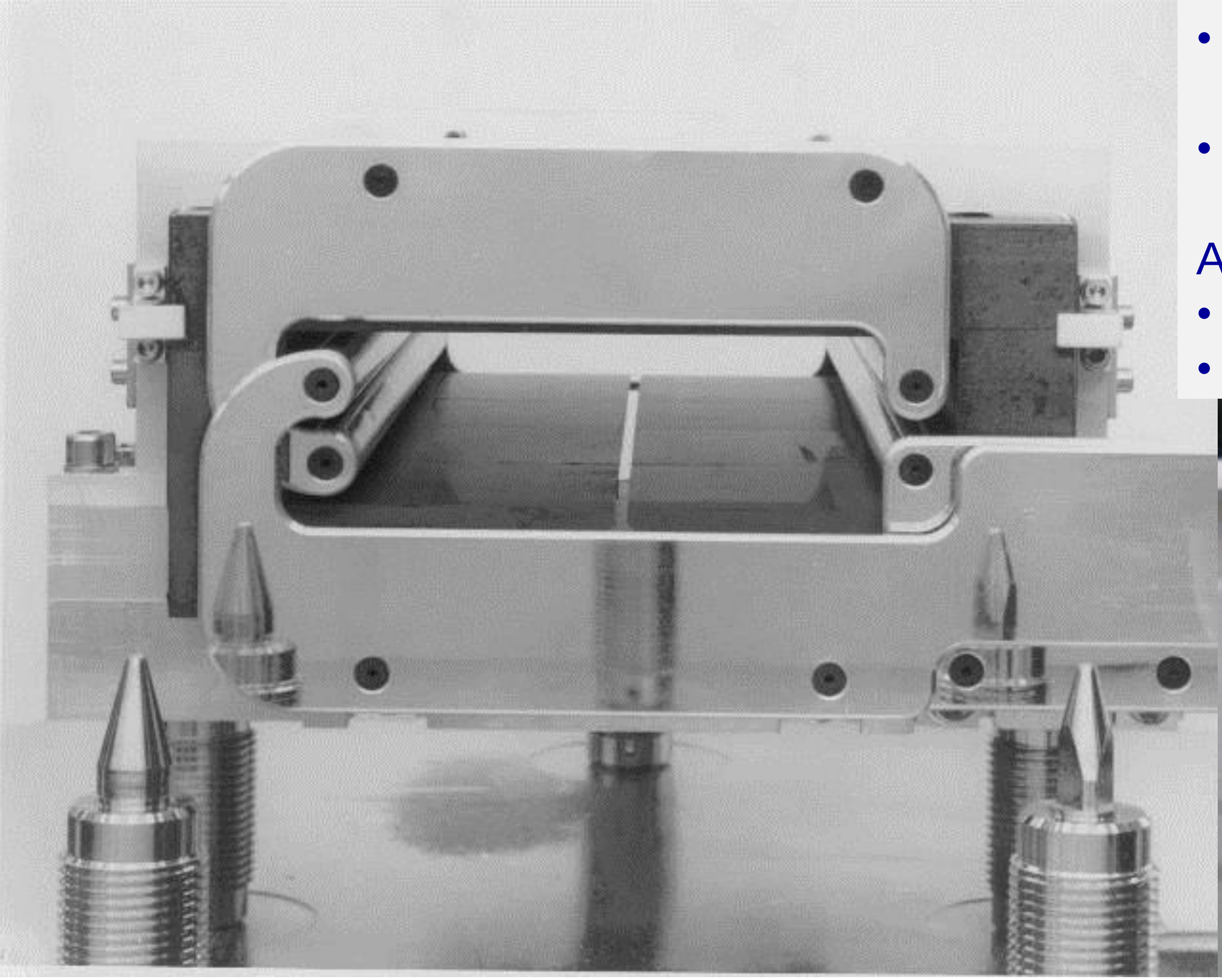
$$Z = \sqrt{\left(L_c / C_c \right)} \qquad L_{mag} = n \cdot L_c$$

$$\tau = n \cdot \sqrt{L_c \cdot C_c} = n \cdot \frac{L_c}{Z} = \frac{L_{mag}}{Z}$$

- complicated magnet design;
- impedance matching important;
- field rise-time depends on propagation time of pulse through magnet;
- fast: rise-times << 1μs possible;
- minimizes reflections;

- e.g. PS KFA-45 ~70 ns

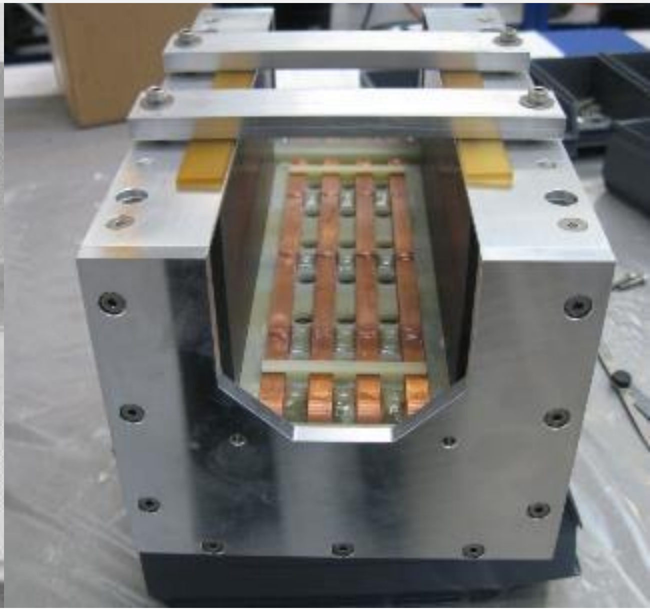
Lumped Inductance Kicker Magnet



- Used for “slower” systems (typically > ~1μs rise/fall).
- “Simple” and “robust”.

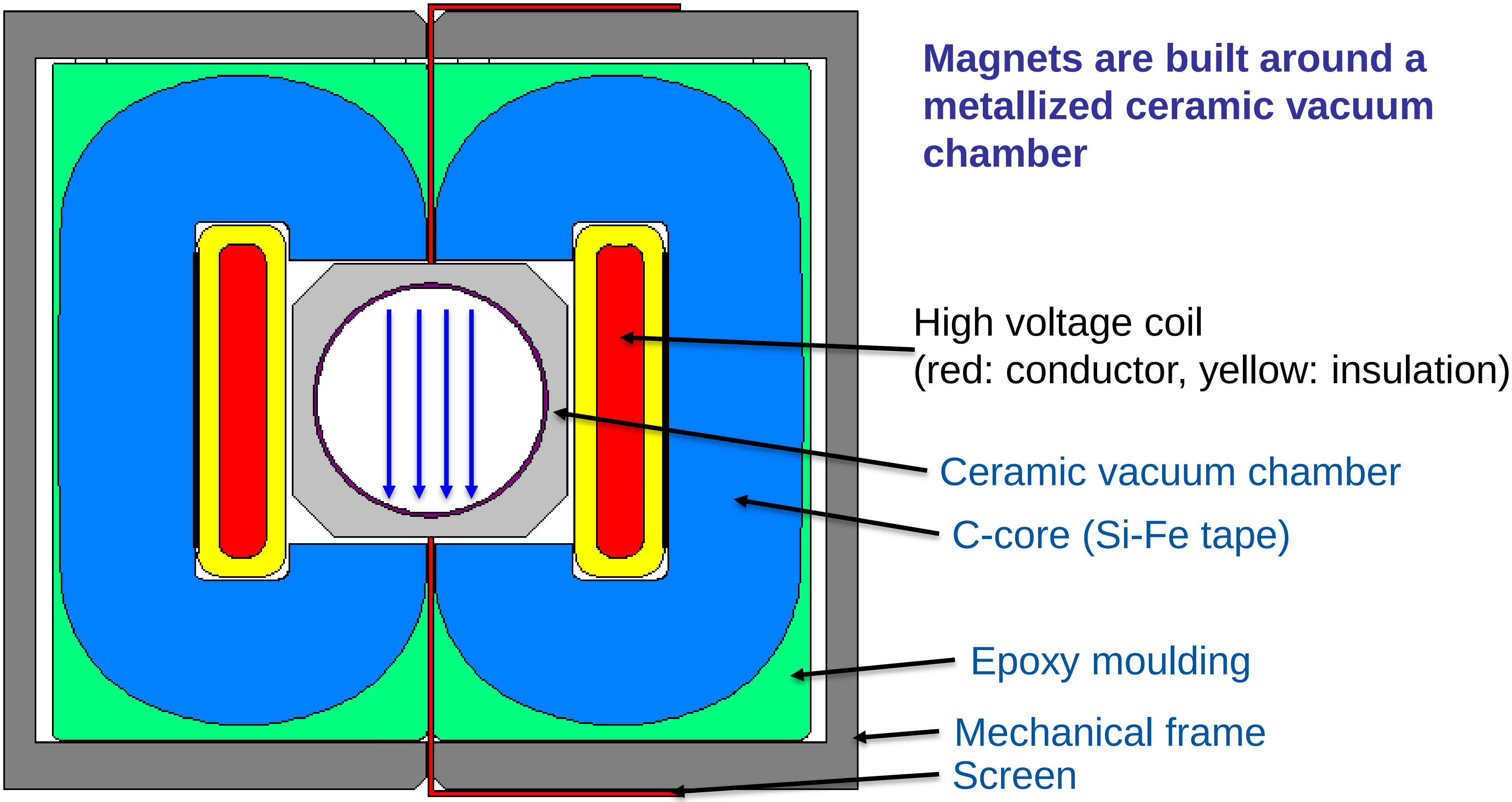
At CERN:

- Currents up to 18.5 kA
- Voltages up to 30kV



LHC Extraction Kicker Magnet - MKD

Magnets are built around a metallized ceramic vacuum chamber



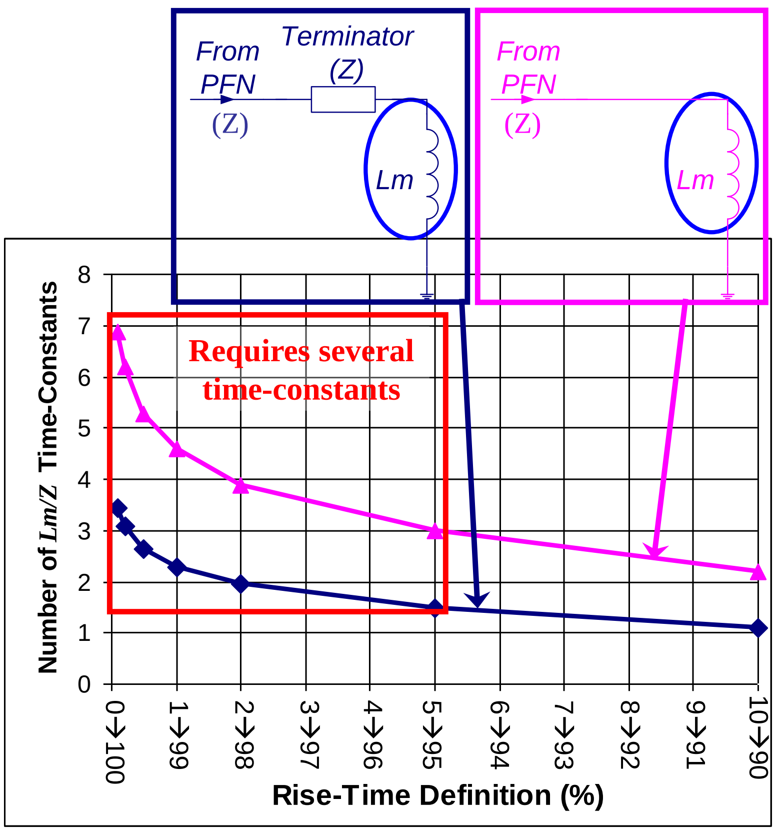
Lumped Inductance Kicker Magnets

The termination is generally either in series with the magnet input or else the magnet is short-circuited.

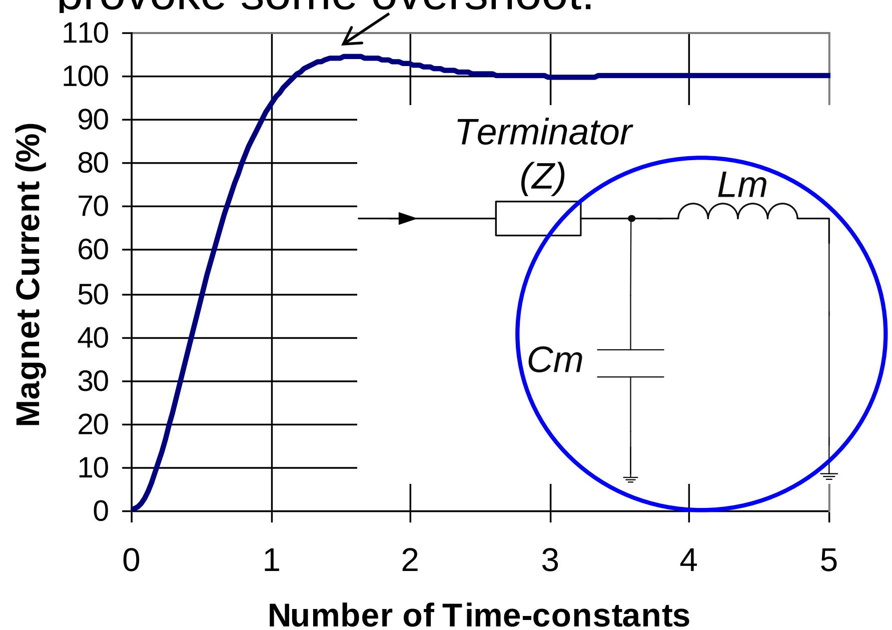
The magnet only sees (bipolar) voltage during pulse rise & fall, not during the pulse flattop ($V=L_m di/dt$).

With a short-circuit termination, magnet current is doubled.

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

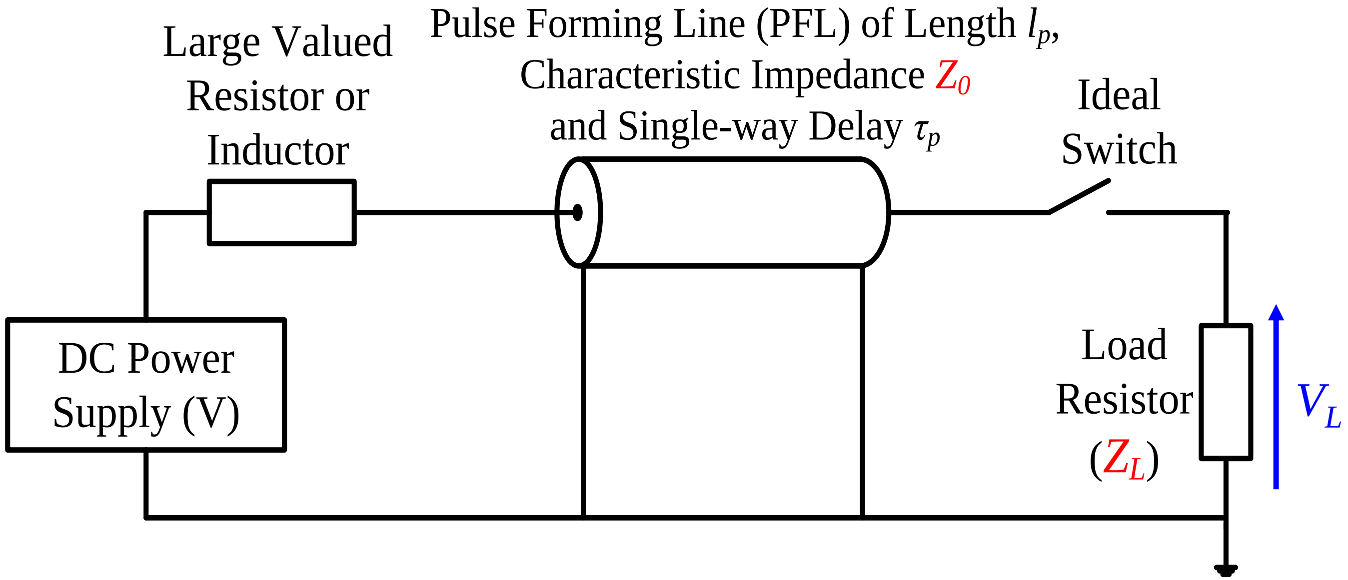


A capacitor (*Cm*) can be added to a lumped inductance magnet, but this can provoke some overshoot:



Voltage Division in a Pulse Forming Circuit

- A simplified pulse forming circuit:



- When the ideal switch is turned-on the voltage across the load resistor (V_L) is given by:

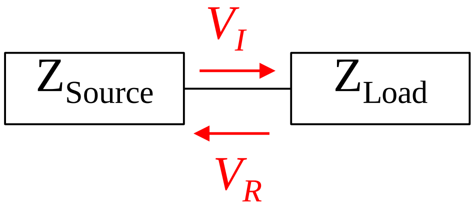
$$V_L = V \cdot \left(\frac{Z_L}{Z_0 + Z_L} \right) = \alpha V$$

- In the matched case ($Z_L = Z_0$):

$$\alpha = \frac{1}{2}$$

  - **Hence the PFL/PFN charging voltage is twice the required magnet voltage!**

Reflections in a Pulse Forming Circuit



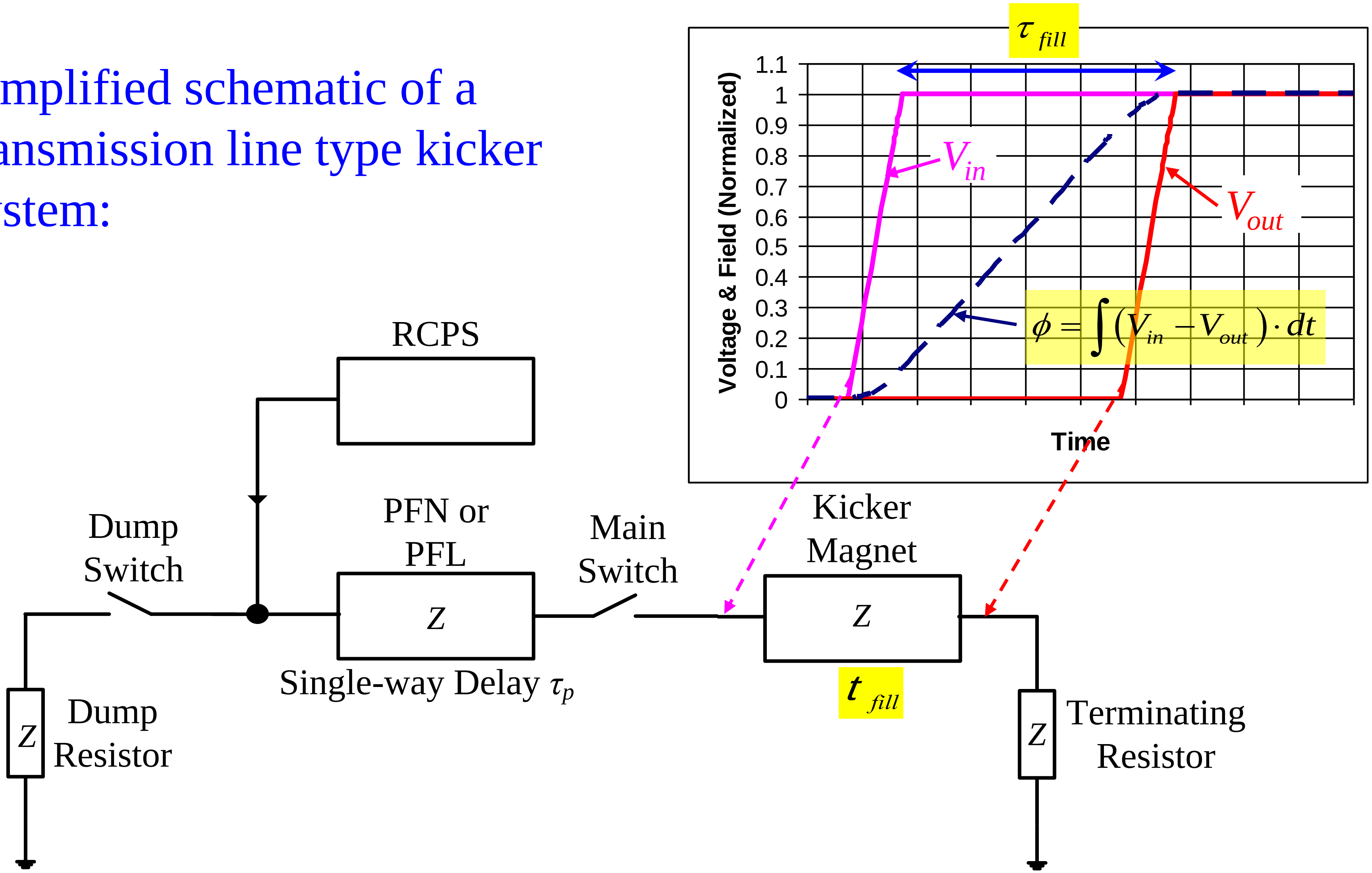
- Reflection coefficient (Γ):
  - Ratio of reflected wave (V_R) to incident wave (V_I):

$$\Gamma = \frac{V_R}{V_I} \quad \Rightarrow \quad \Gamma = \frac{Z_{Load} - Z_{Source}}{Z_{Load} + Z_{Source}}$$

  - Matched impedance (50 Ω): $\Gamma = \frac{Z_{Load} - Z_{Source}}{Z_{Load} + Z_{Source}} = \frac{50-50}{50+50} = 0$
  - Short circuit load (0 Ω): $\Gamma = \frac{Z_{Load} - Z_{Source}}{Z_{Load} + Z_{Source}} = \frac{0-50}{0+50} = -1$
  - Open circuit load (∞ Ω): $\Gamma = \frac{Z_{Load} - Z_{Source}}{Z_{Load} + Z_{Source}} = \frac{\infty-50}{\infty+50} = +1$

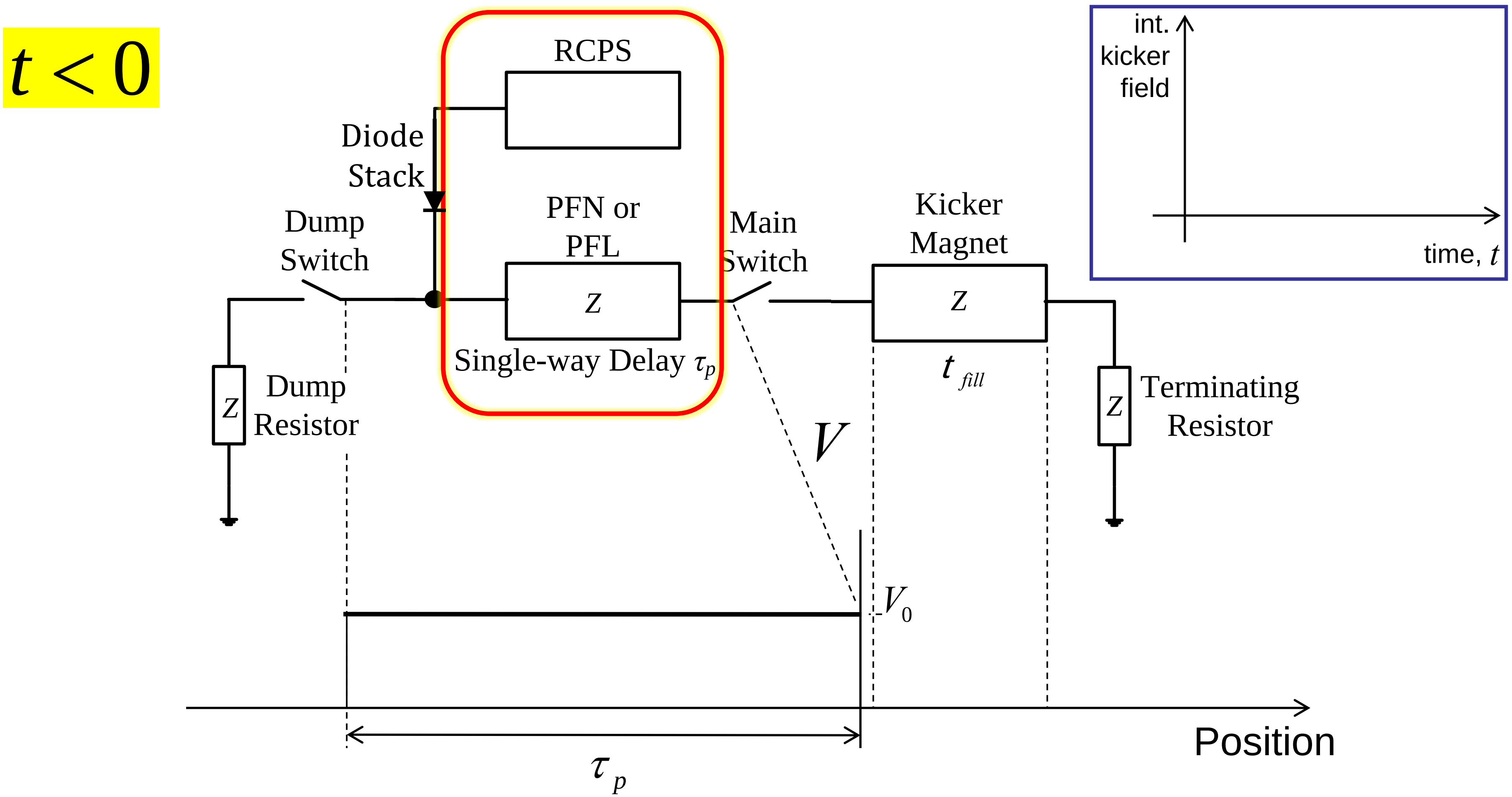
Pulse Transmission in a Kicker System

Simplified schematic of a transmission line type kicker system:



Lets see what happens when we pulse the system, but first …

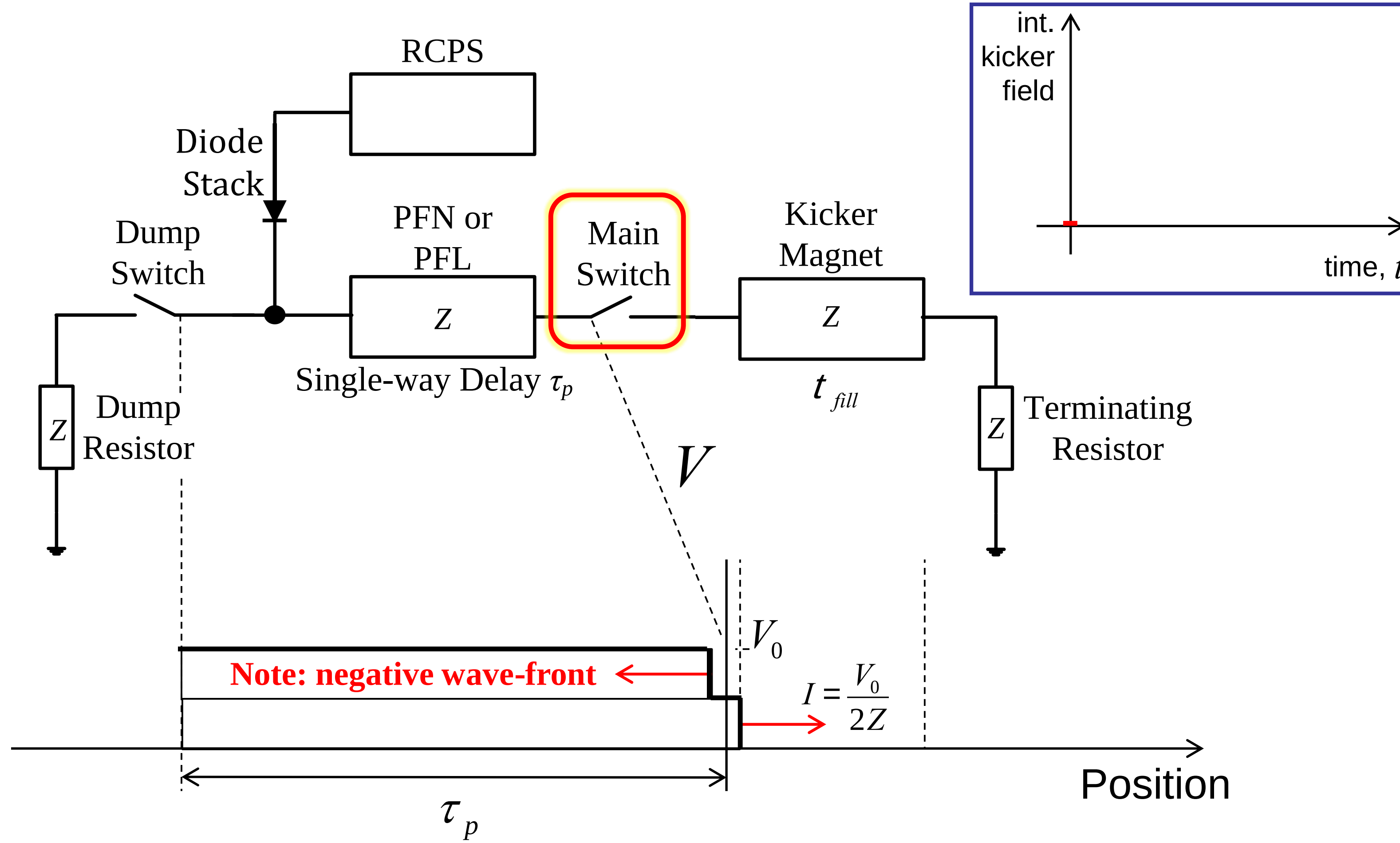
Simplified: Pulsing of a Kicker System (1)



- Pulse forming network or line (PFL/PFN) is charged to voltage V_0 by the resonant charging power supply (RCPS);
  - RCPS is de-coupled from the system through a diode stack;
  - System impedances are all matched.

Simplified: Pulsing of a Kicker System (2)

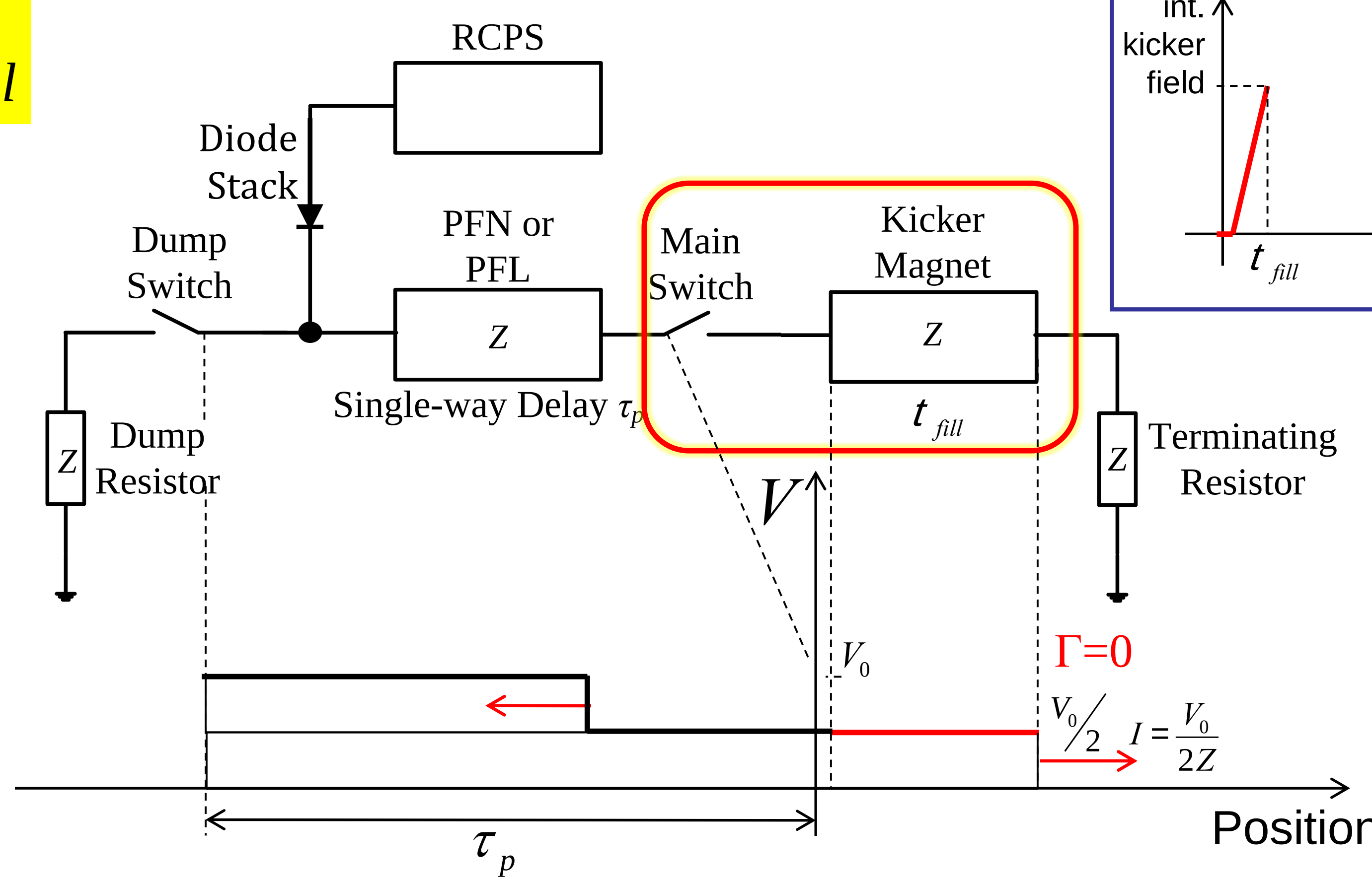
$t = 0^{+}$

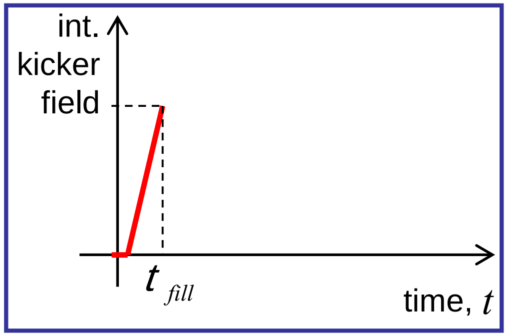


- At $t = 0^{+}$, main switch is closed, $Z_{PFL} = Z_{magnet}$ hence α=0.5 and magnet input voltage = ($V_0/2$);
- Current, $I = \left(V_0 / 2Z \right)$, starts to flow into the kicker magnet.

Simplified: Pulsing of a Kicker System (3)

$t \approx \tau_{fill}$

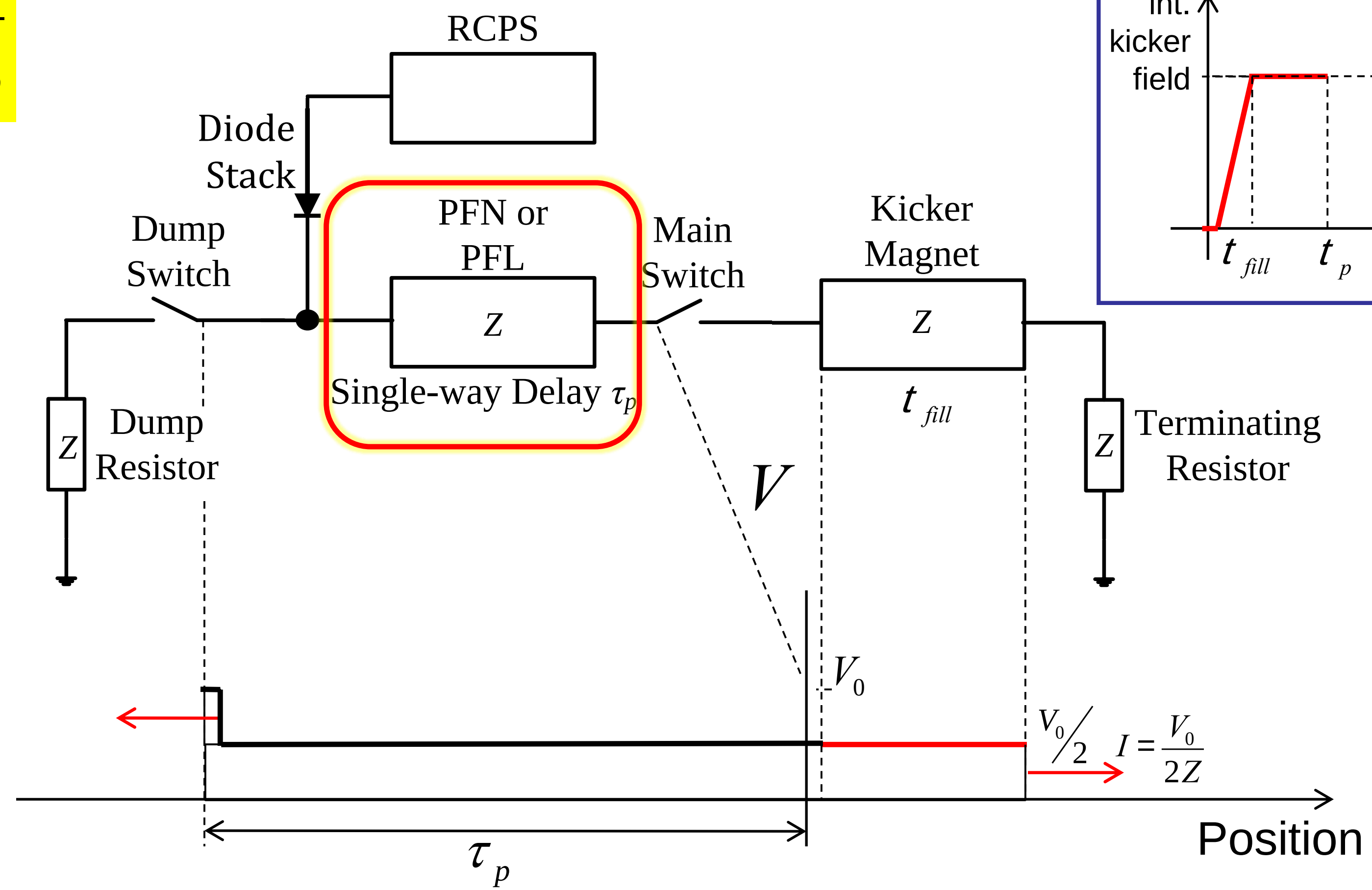


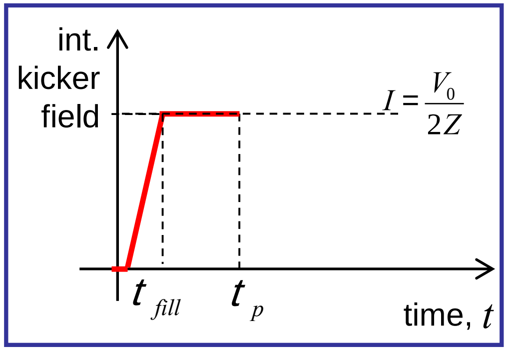


- At $t = \tau_{fill}$, the voltage wave-front of magnitude ($V_0/2$) has propagated through the kicker to the matched terminating resistor (Γ=0);
  - nominal field is achieved (current, $I = \left(V_0 / 2Z\right)$, flows throughout the kicker magnet).
  - typically $\tau_p >> \tau_{fill}$ (schematic for illustration purposes).

Simplified: Pulsing of a Kicker System (4)

$t \approx \tau_p^-$

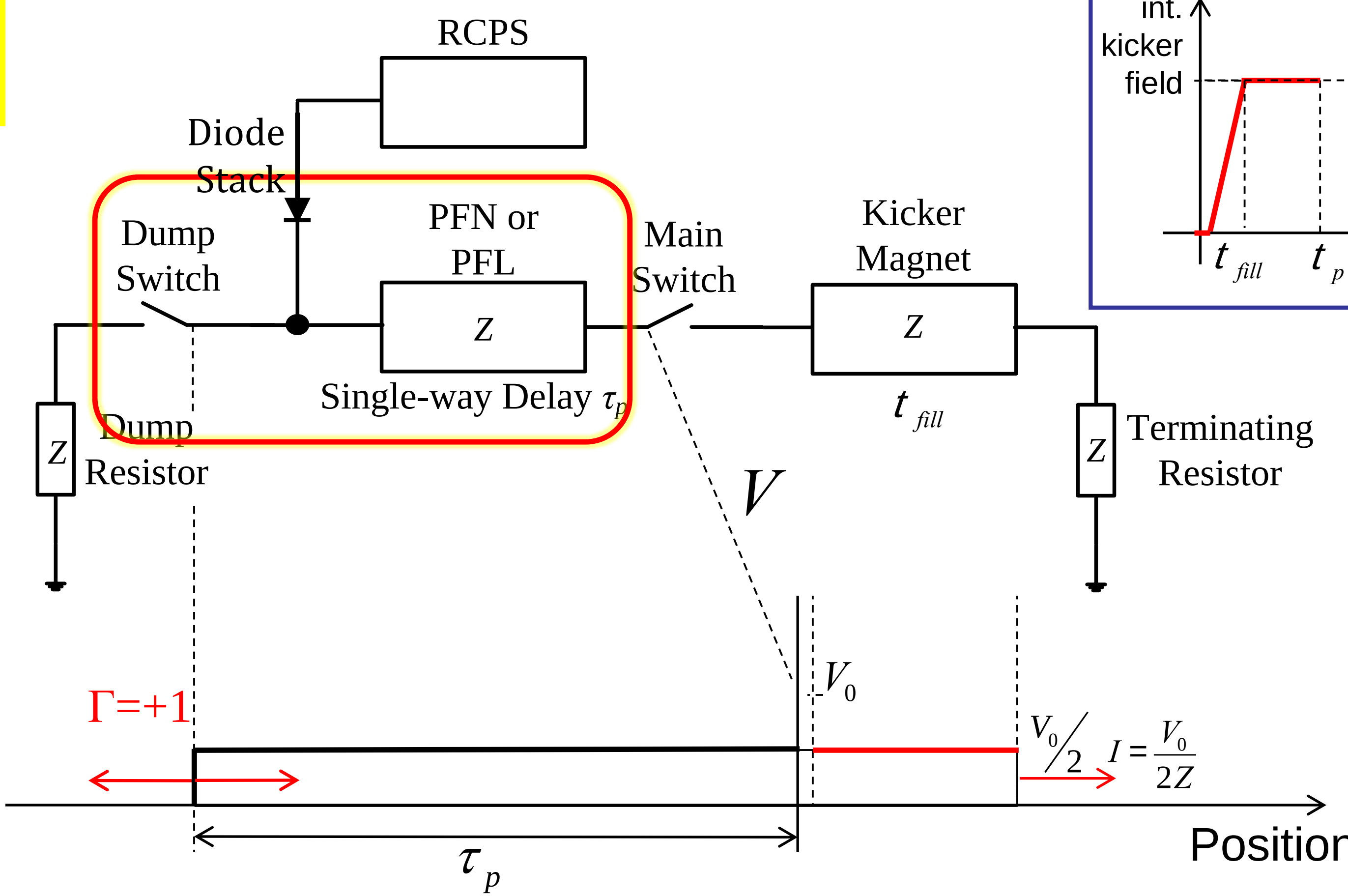


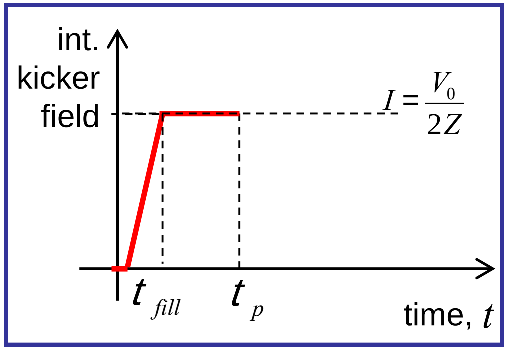


- PFN continues to discharge energy into kicker magnet and the matched terminating resistor.

Simplified: Pulsing of a Kicker System (5)

$t \approx \tau_p$

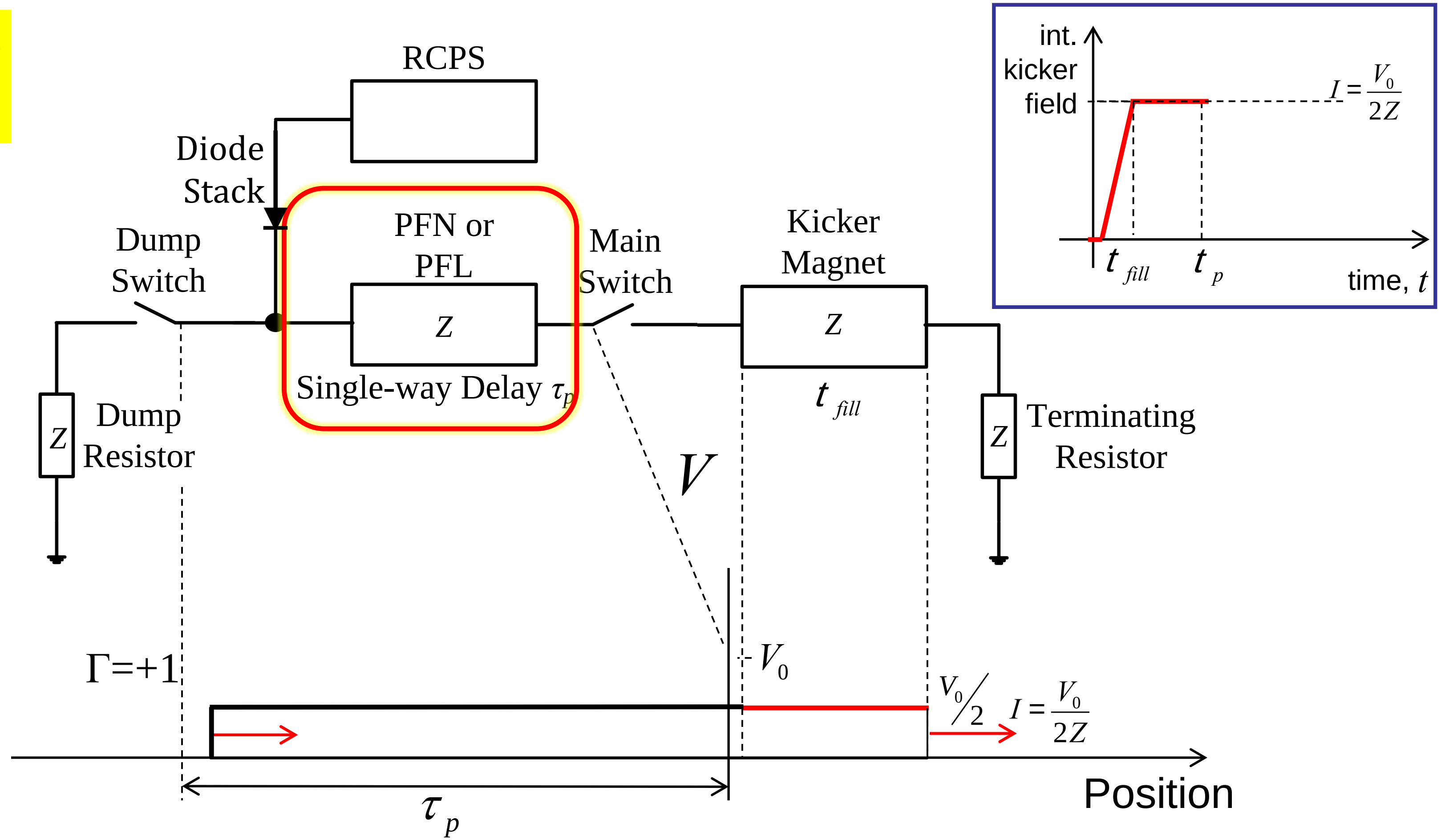




- PFN continues to discharge energy into kicker magnet and matched terminating resistor;
- If the dump switch is still open at $t \approx \tau_p$ the negative wave-front reflects (Γ=1) off the open end of the PFN/PFL and back towards the kicker

Simplified: Pulsing of a Kicker System (6)

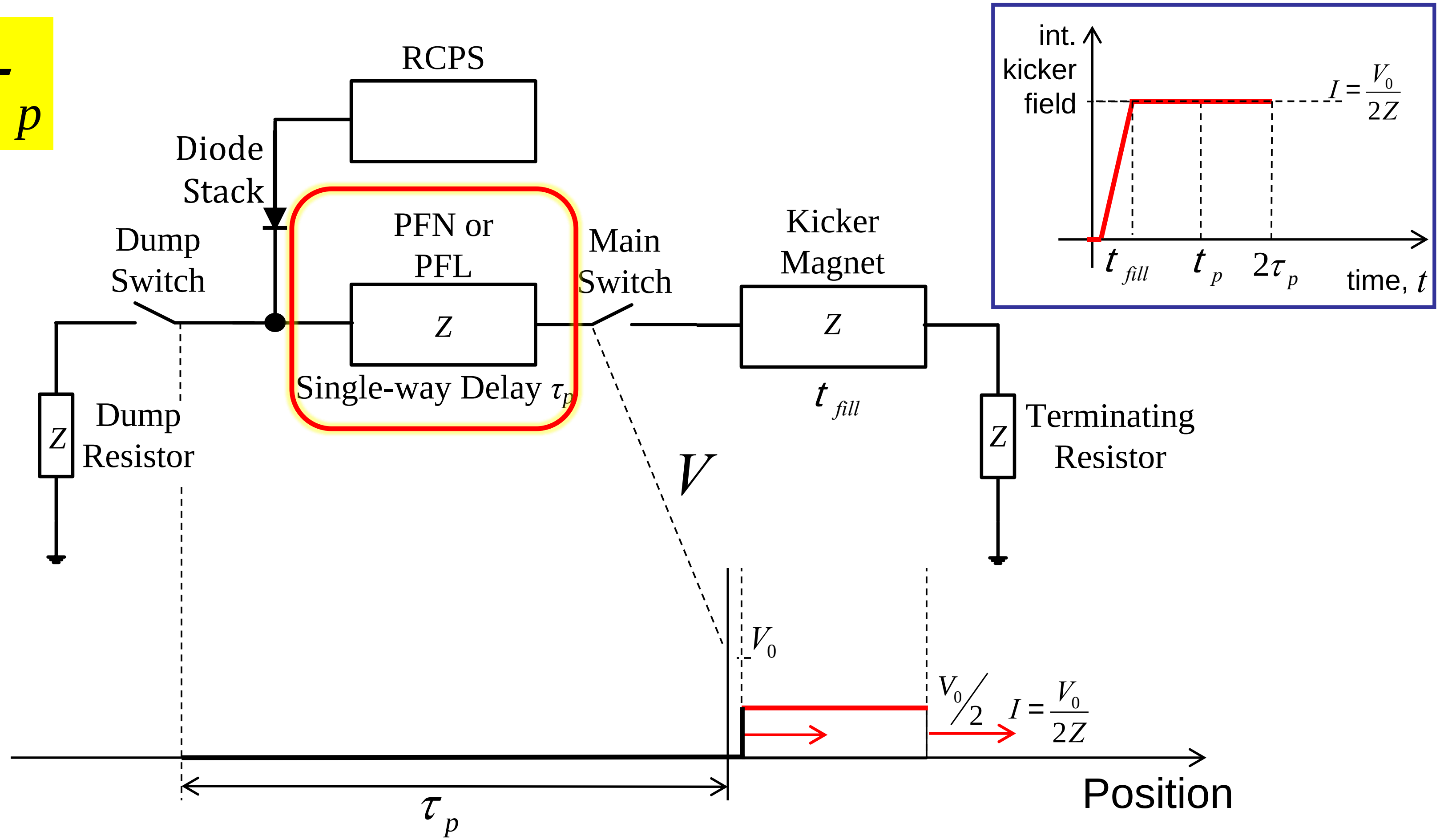
$t \approx \tau_p^+$



- PFN continues to discharge energy into matched terminating resistor;
- Voltage at the dump switch end of the PFN/PFL has now fallen to zero.

Simplified: Pulsing of a Kicker System (7)

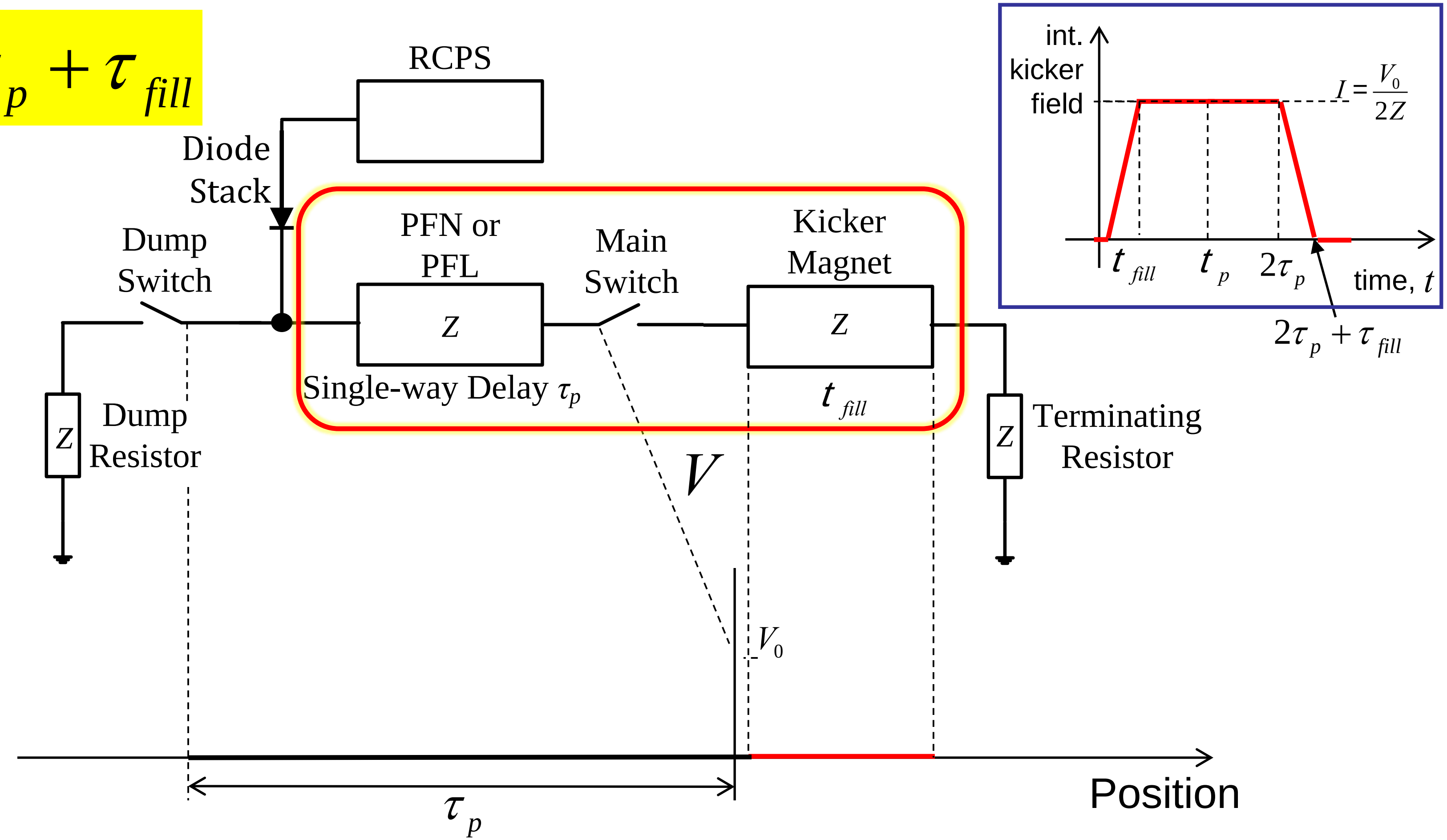
$t \approx 2\tau_p$



- At $t \approx 2\tau_p$ the negative wave-front exits the main switch end of the PFN/PFL: the PFN/PFL has been emptied of energy;
- This is the end of the flat-top field in the kicker magnet.

Simplified: Pulsing of a Kicker System (8)

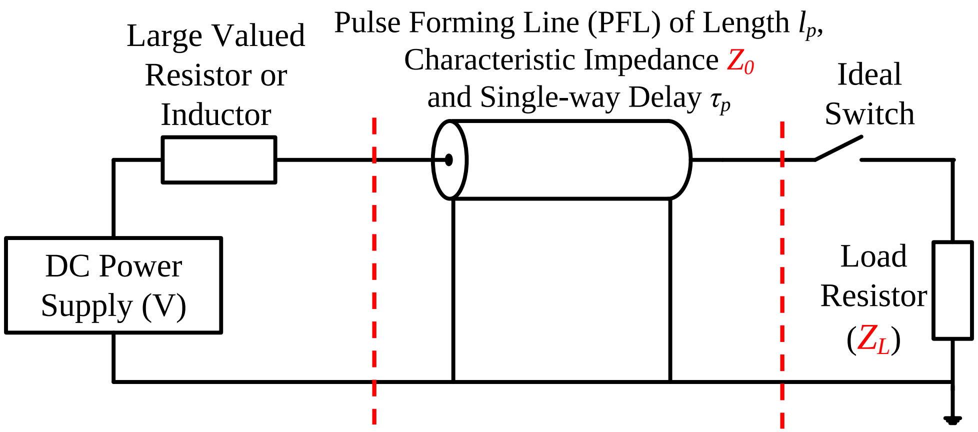
$$t \approx 2\tau_p + \tau_{fill}$$

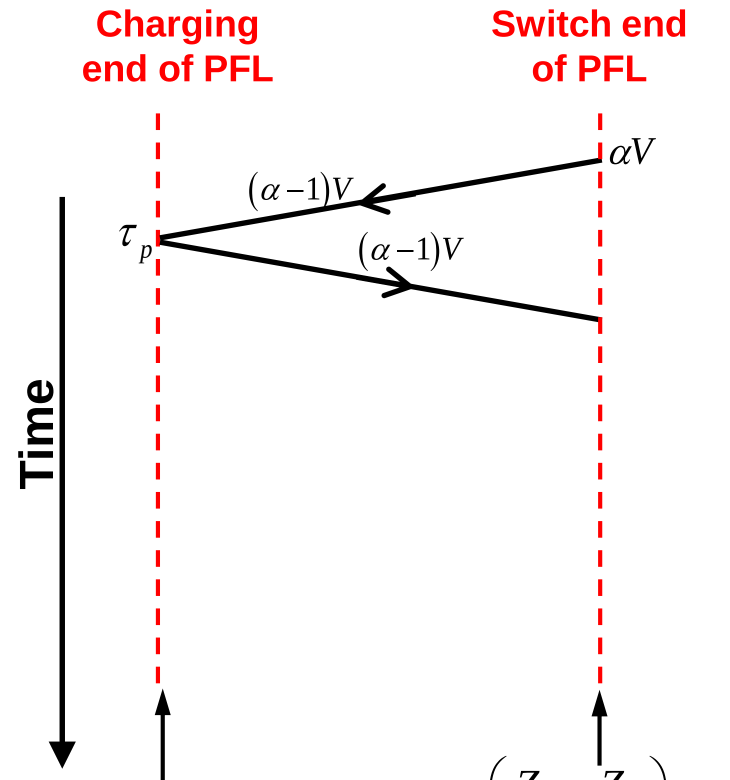


- Pulse at magnet output falls to zero (all energy has been dissipated in the terminating resistor).
- Note: kicker pulse length can be reduced by adjusting the relative timing of dump and main switches. e.g. if the dump and main switches are fired simultaneously, the pulse length will be halved and energy shared in dump and terminating resistors.

Example: Reflections in a Pulse Forming Circuit (1)

- A simplified pulse forming circuit:





G=1

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

for matched case:

$$\boxed{\Gamma\ (=\beta) = 0}$$

- When the switch is turned on the voltage is divided as:

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

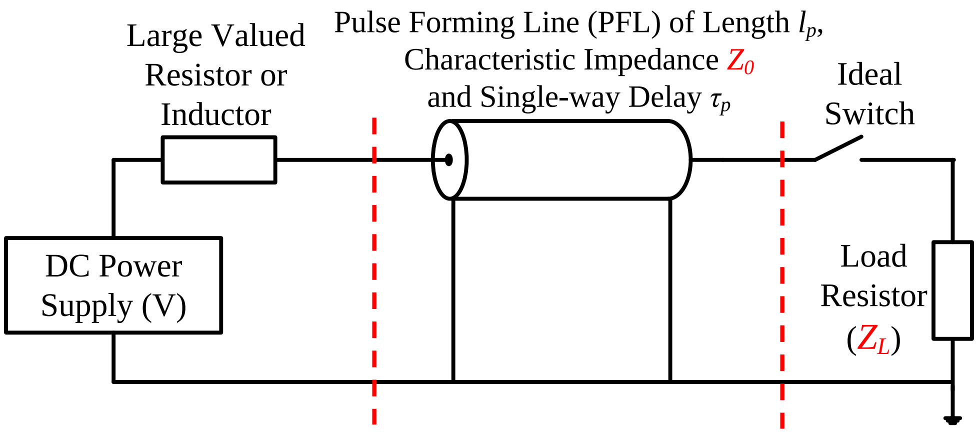
- In the matched case:

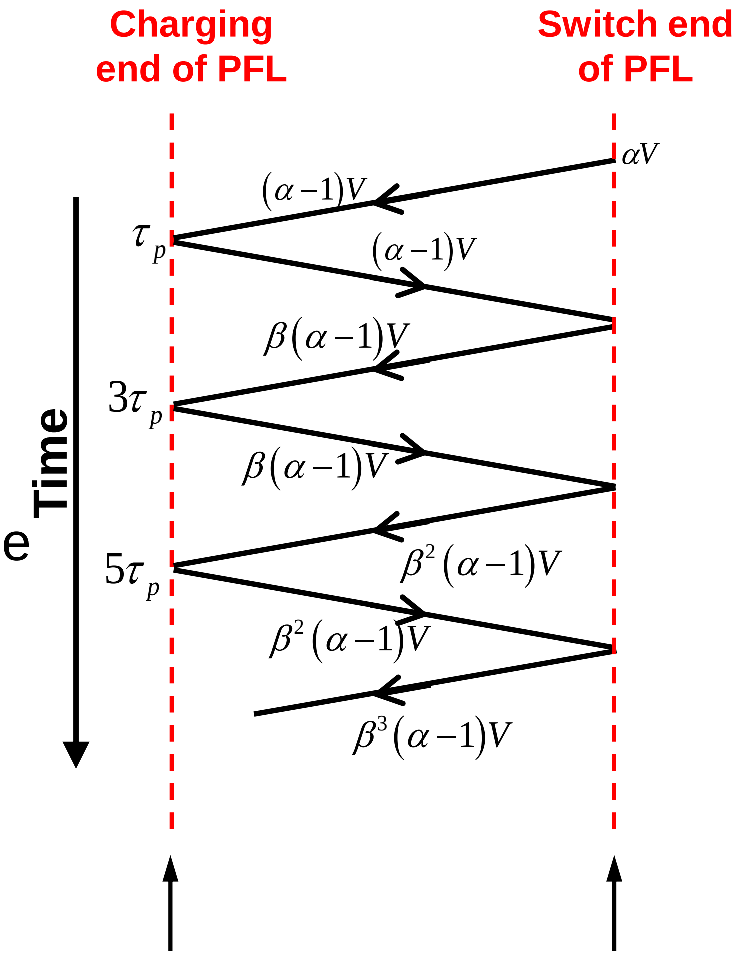
$$Z_0 = Z_L \qquad a = \frac{1}{2}, \boxed{b = 0}$$

Where β is the reflection coefficient at the RHS (switch end of PFL).

Example: Reflections in a Pulse Forming Circuit (2)

- A simplified pulse forming circuit:





G=1

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

- When the switch is turned on the voltage is divided as:

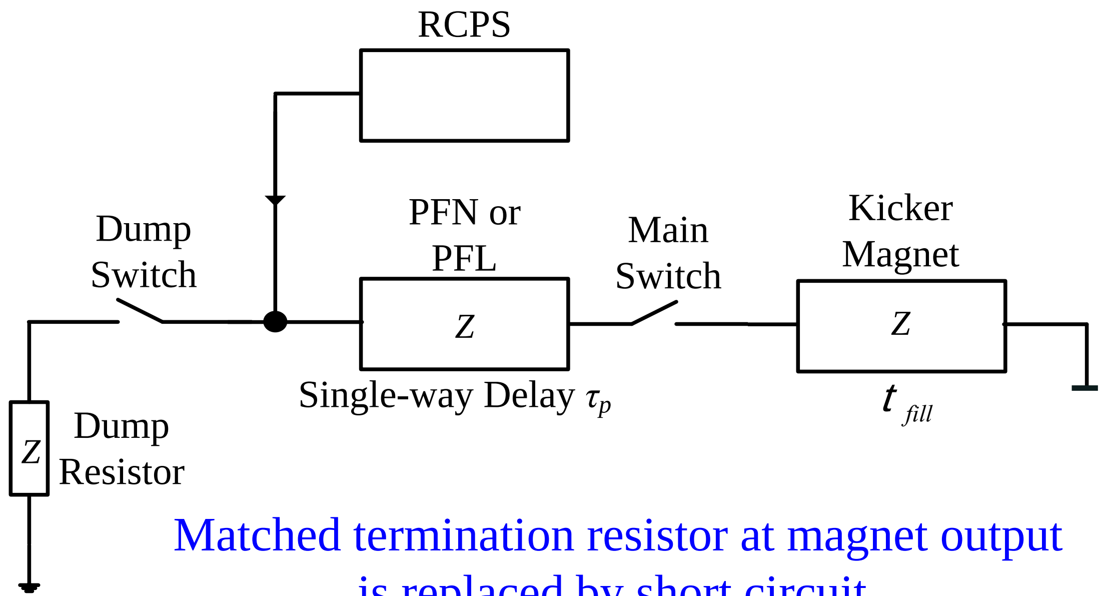
$$V_L = V \cdot \left(\frac{Z_L}{Z_0 + Z_L}\right) = \alpha V$$

- In the matched case:

$$Z_0 = Z_L \qquad a = \frac{1}{2},\ b = 0$$

Match impedances to avoid reflections!

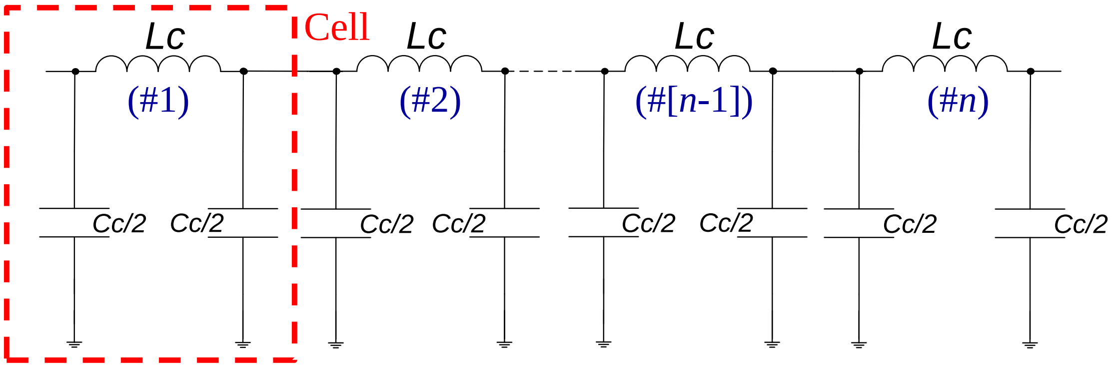
Short-circuited Magnet Output



Matched termination resistor at magnet output
is replaced by short circuit.

- At short-circuit, wave reflects $(\Gamma = -1)$:
  - Total voltage = 0 (incident and reflected waves cancel)
  - Current doubles: $I_{SC} = V \cdot \left(\dfrac{1-\Gamma}{Z}\right)$
- Magnet field doubles, for a given PFN/PFL voltage, but …
  - the reflected wave needs to travel through the magnet again -> twice the fill time.
- Any other system mismatch will create multiple reflections!

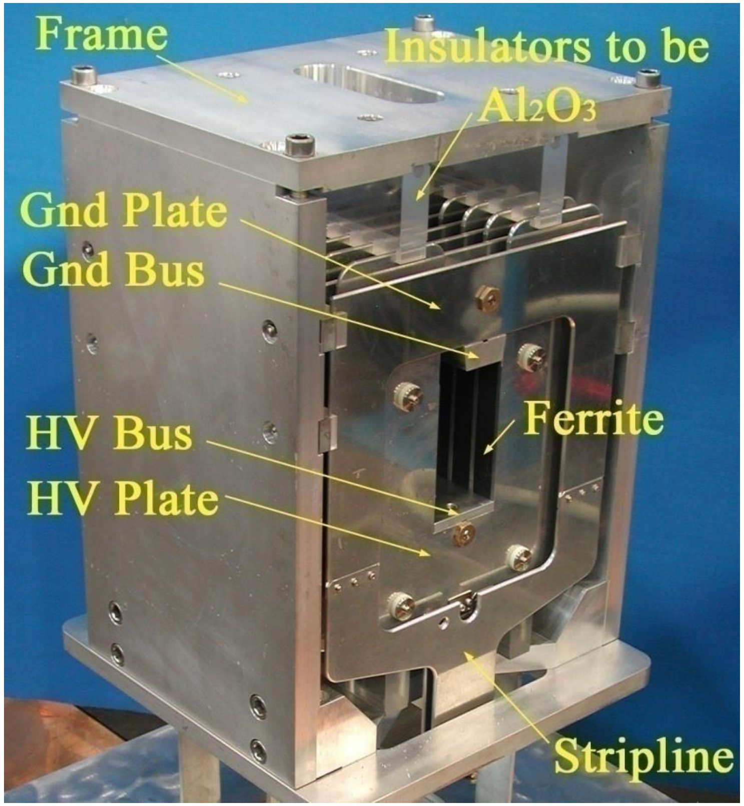
Transmission Line Kicker Magnet (1)



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

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

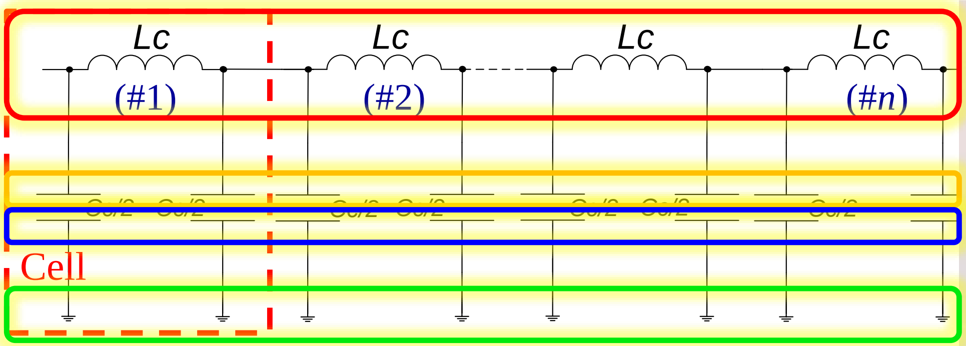
$$\tau_{fill} = n \cdot \sqrt{Lc \cdot Cc}$$

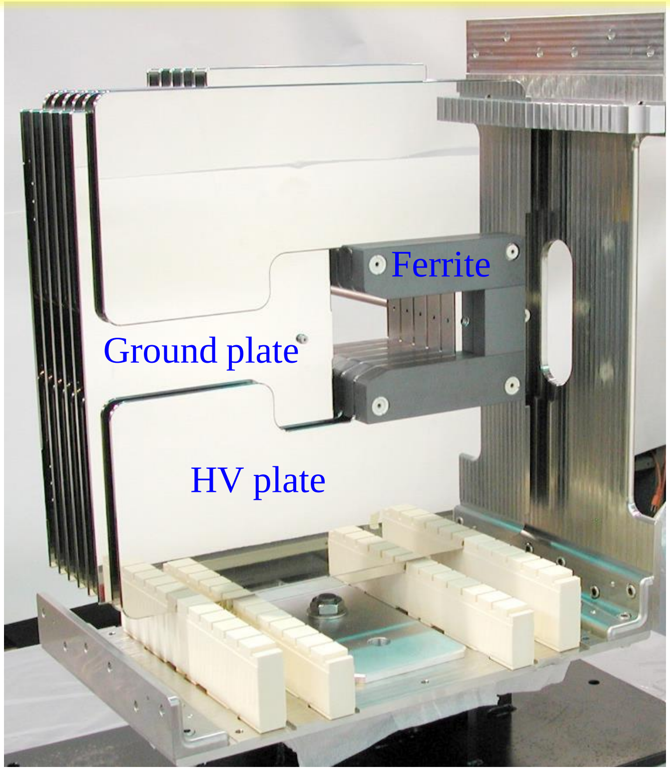


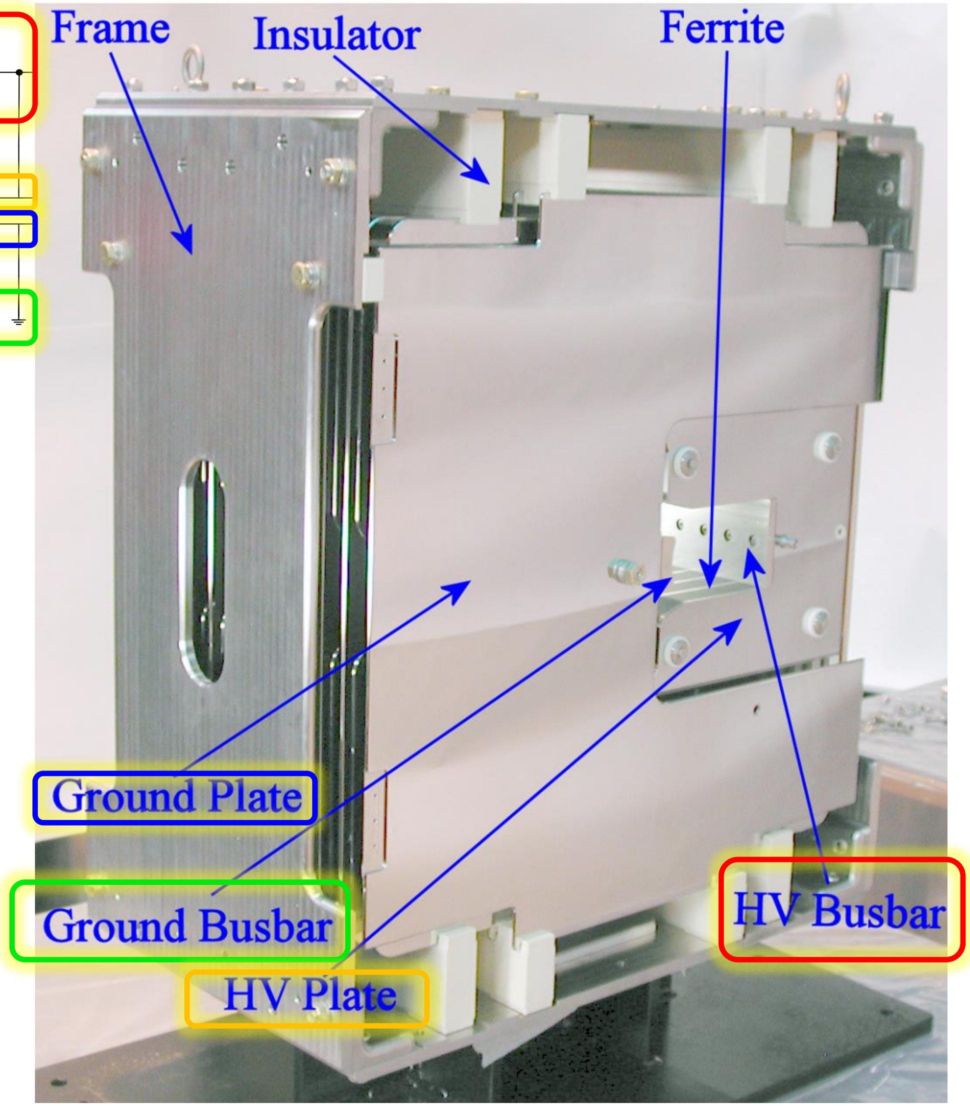
- Ferrite C-cores are sandwiched between high voltage (HV) capacitance plates;
- Plates connected to ground are interleaved between the HV plates;
- One C-core, together with its ground and HV capacitance plates, is termed a cell. Each cell conceptually begins and ends in the middle of the HV capacitance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

Transmission Line Kicker Magnet (2)

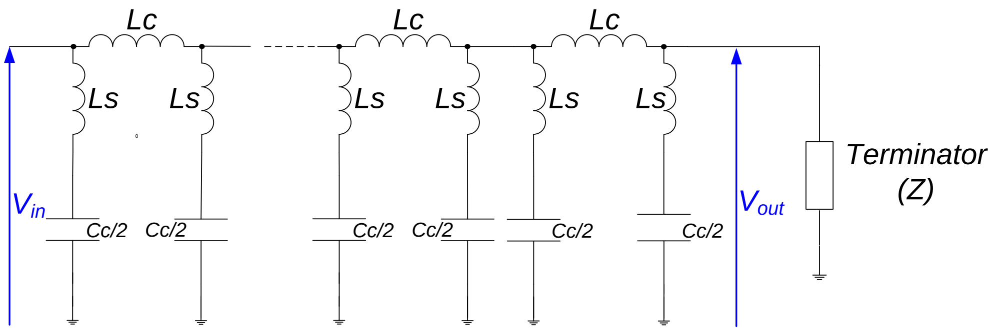
Consists of few to many “cells” to approximate a transmission line:

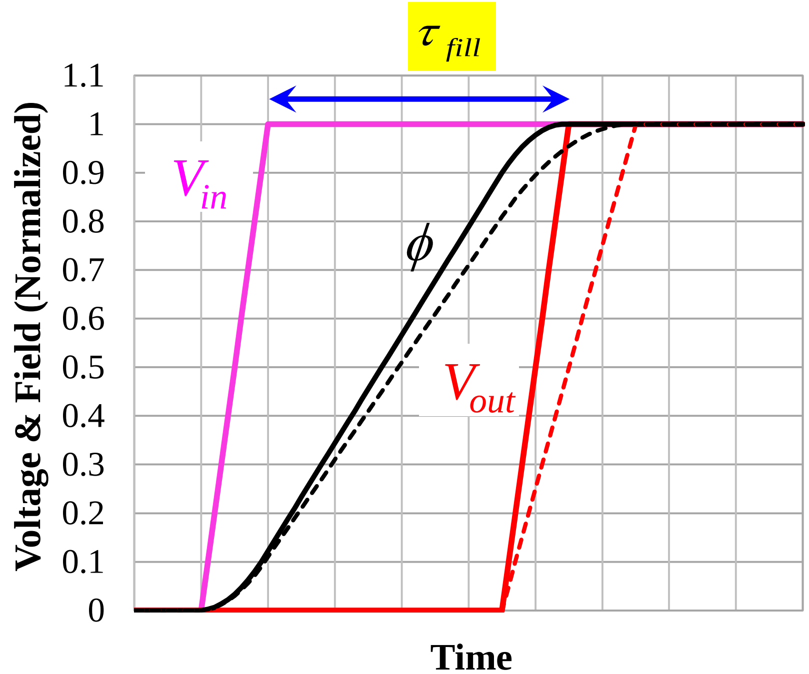






Transmission Line Kicker Magnet (3)





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.

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

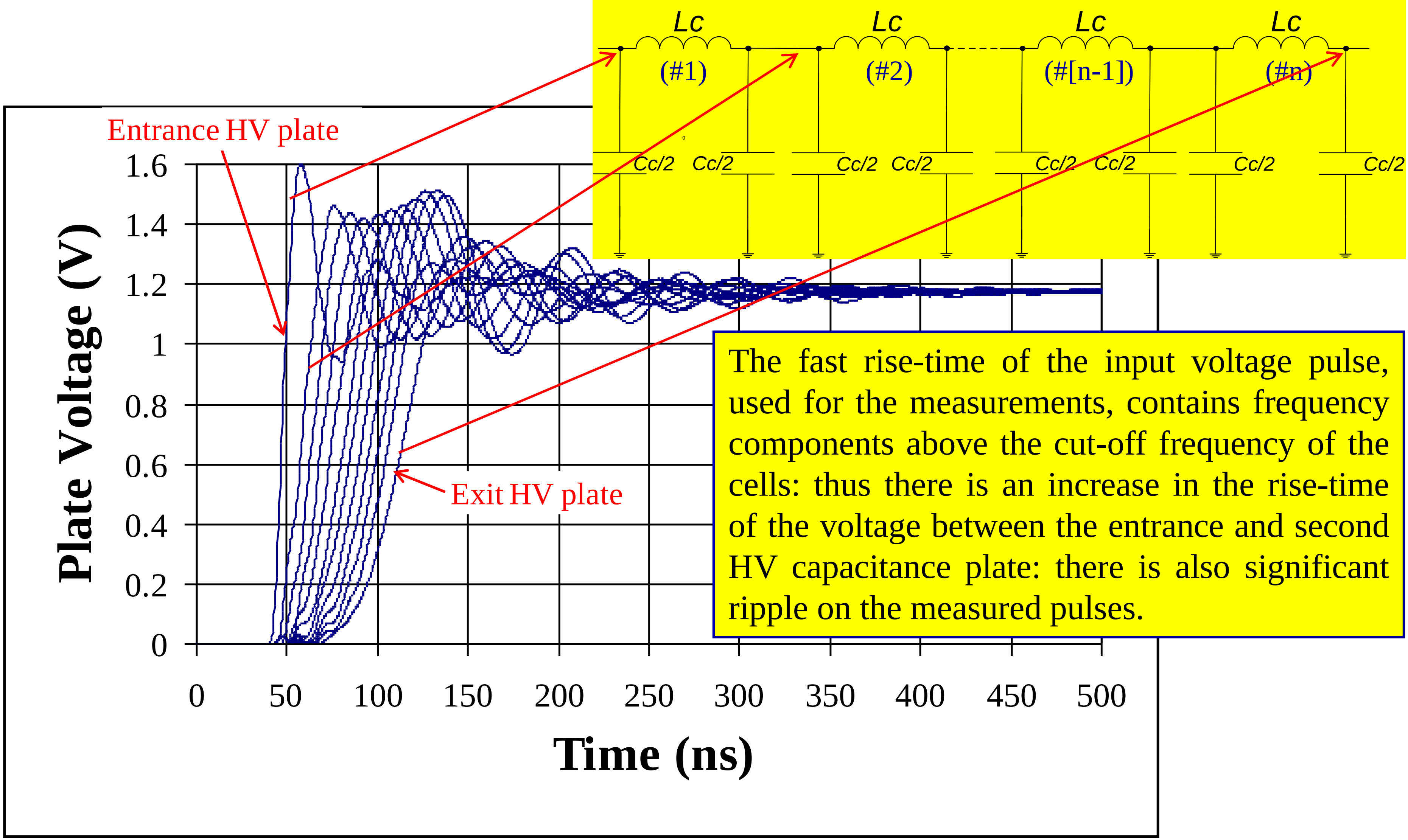
The field builds up until the end of the voltage rise at the output of the magnet. Hence it is important that the pulse does not degrade while travelling through the magnet. Thus the cut-off frequency of each cell is a key parameter, especially with field rise times below ~100 ns. Cut-off frequency (f_c)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

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

Ls should be as low as possible and the cell size reasonably small (**BUT** 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.

Low Voltage Measurements on a Transmission Line Kicker Magnet

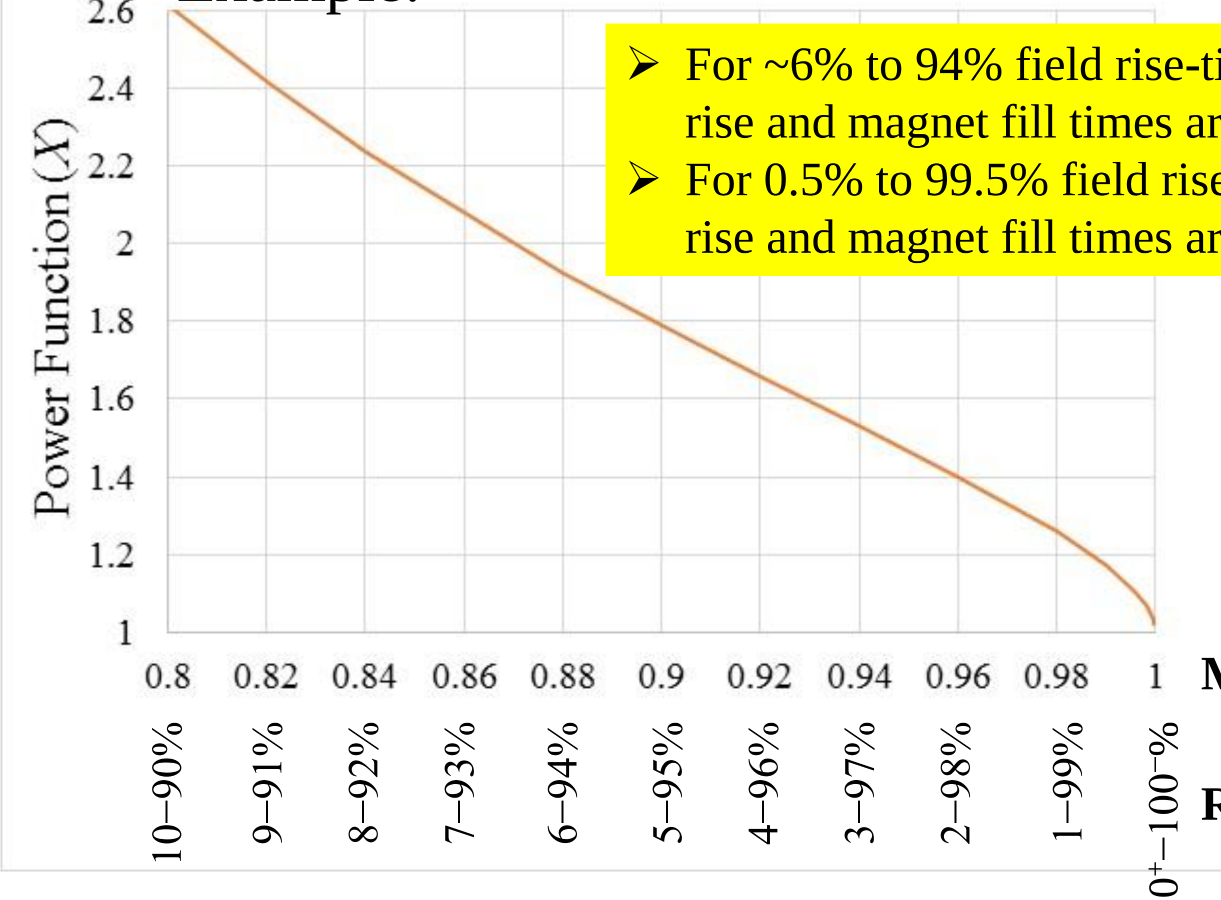


The fast rise-time of the input voltage pulse, used for the measurements, contains frequency components above the cut-off frequency of the cells: thus there is an increase in the rise-time of the voltage between the entrance and second HV capacitance plate: there is also significant ripple on the measured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

Field Rise-Time

$$\left(M\cdot\left(\text{Field rise-time}\right)\right)^{X}=\left(M\cdot\left(\text{Voltage rise-time}\right)\right)^{X}+\left(M\cdot\left(\tau_{fill}\right)\right)^{X}$$

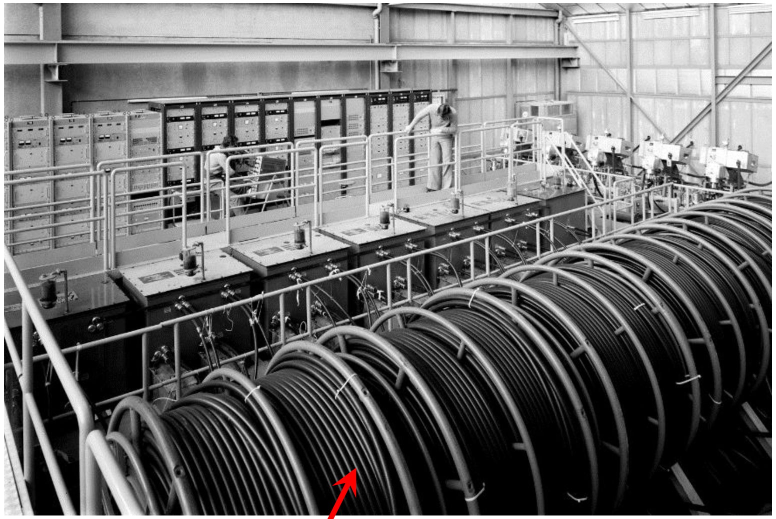
Example:



- For ~6% to 94% field rise-time definition, voltage rise and magnet fill times are added in ~quadrature;
- For 0.5% to 99.5% field rise-time definition, voltage rise and magnet fill times are added ~linearly.

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 (see next slide);
- Attenuation is adversely affected by the use of semiconductor layers to improve voltage rating;
- Hence, for PFL voltages above 50kV, SF6 pressurized polyethylene tape cables (without semiconductor layers) are used at CERN.

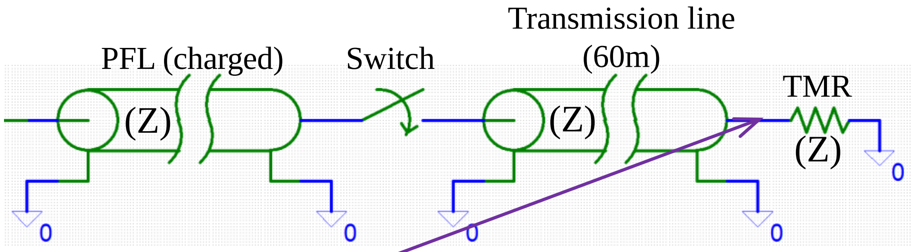


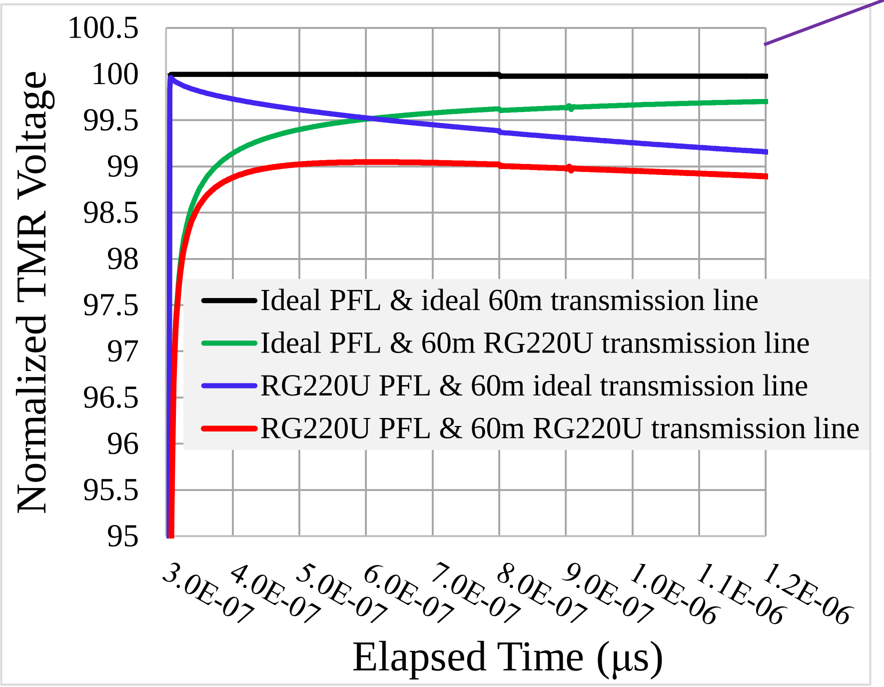
Reels of PFL

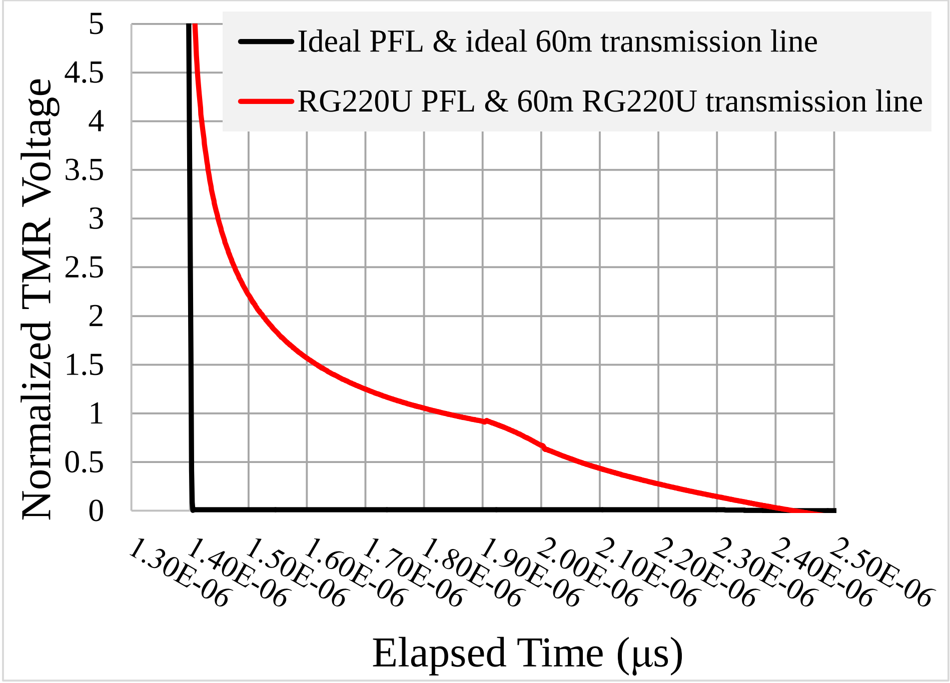
PFL becomes costly, bulky and the droop becomes significant (e.g. ~1%) for pulses exceeding about 3μs width.

PFL – Attenuation and Dispersion

- PFL (cable) gives low ripple pulses, but low attenuation is essential (especially with longer pulses) to control droop and "cable tail";
- Frequency dependent attenuation of transmission line can be used to **compensate** for PFL droop, but increased cable tail is a potential problem.



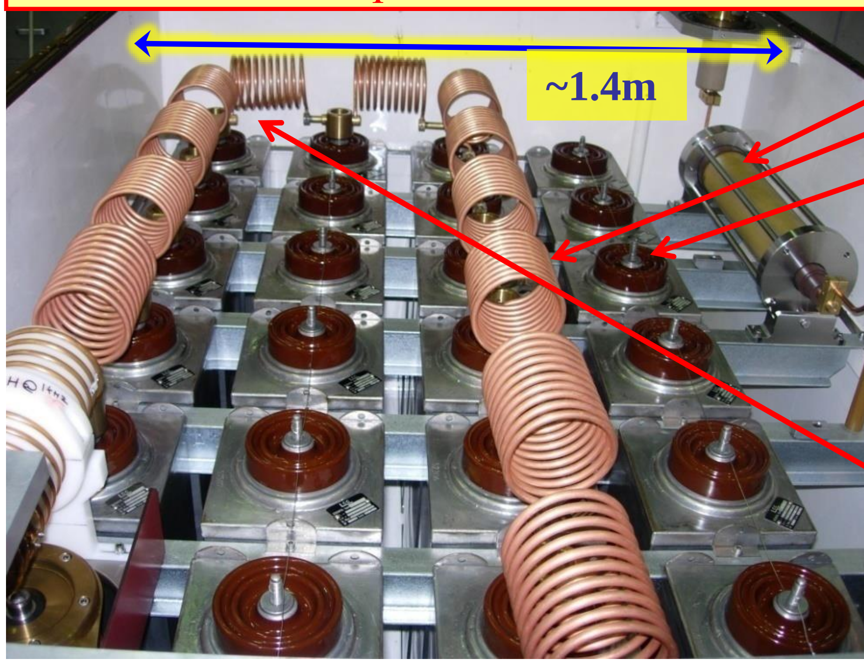




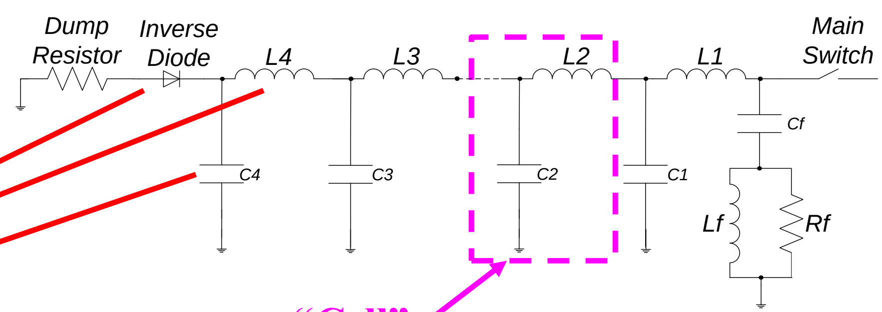
Pulse Forming Network (PFN) – CERN SPS

"Old" SPS extraction system	Proton extraction to LHC	Proton extraction to CNGS
Energy (GeV)	450	400
System deflection (mrad)	0.48	0.54
Rise & fall time (ns)		<1100
Flat-top ripple	<1%	<2%
System Impedance (Ω)	10 (terminated)	10 (terminated)
Current (A)	2560	2500

A PFN is an artificial transmission line made of lumped elements.



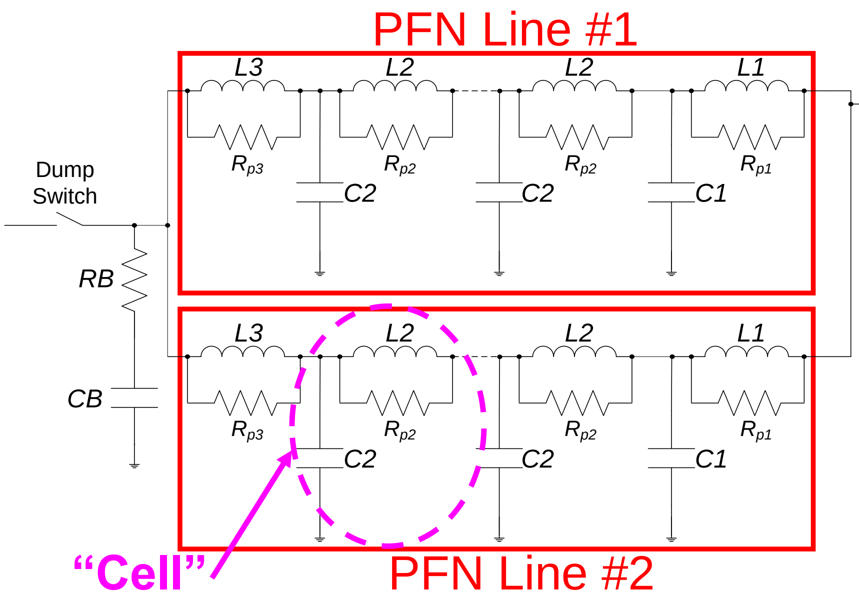
Schematic for an "Old" SPS Extraction PFN:



CERN SPS "Old" Extraction System (MKE4):
- PFN Voltage = 50 kV (CNGS) or 51.2 kV (LHC);
- Thyratron "dump" switch replaced by semiconductor diodes to reduce costs & improve lifetime & reliability;
- PFN has "corners" therefore mutual inductance between inductances is NOT well defined;
- Cells are all individually "adjustable";
- Adjusting pulse flattop is difficult & time-consuming.

Pulse Forming Network (PFN) – CERN MKI

Schematic for an LHC Injection PFN:

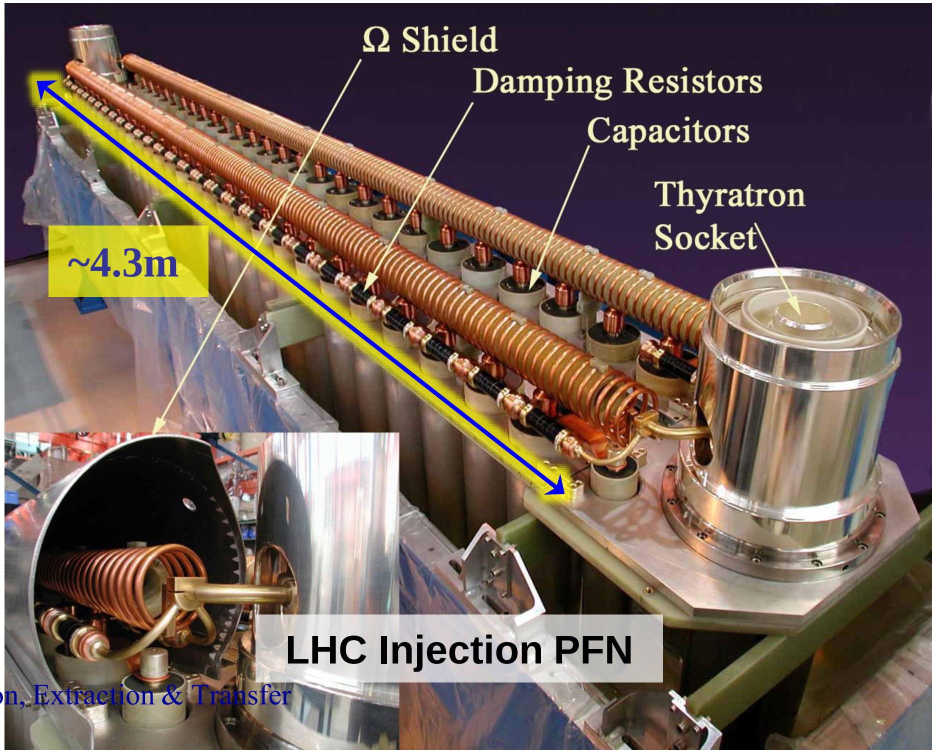


LHC Injection PFN:

- 5Ω system (two parallel 10Ω "lines");
- Nominal PFN Voltage = 54kV;
- Single continuous coil, 4.3m long, per 10Ω line (28 cells per line);
- 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.

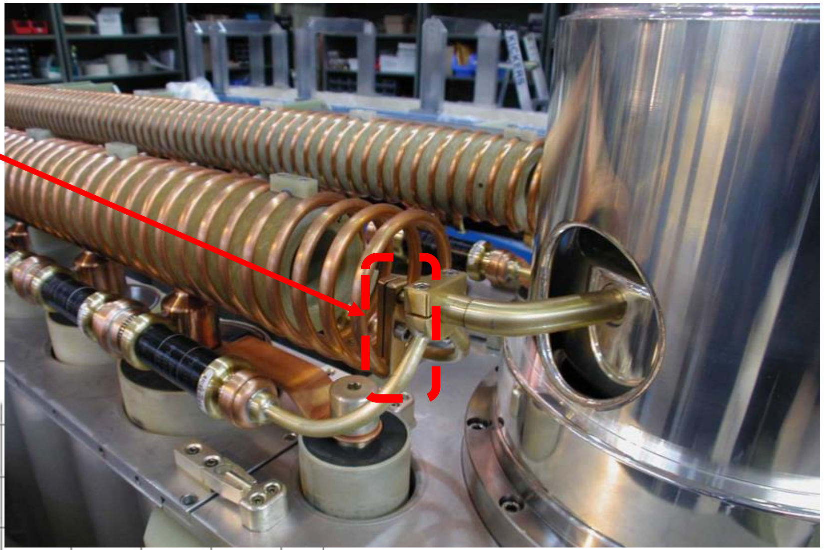
System Parameters:

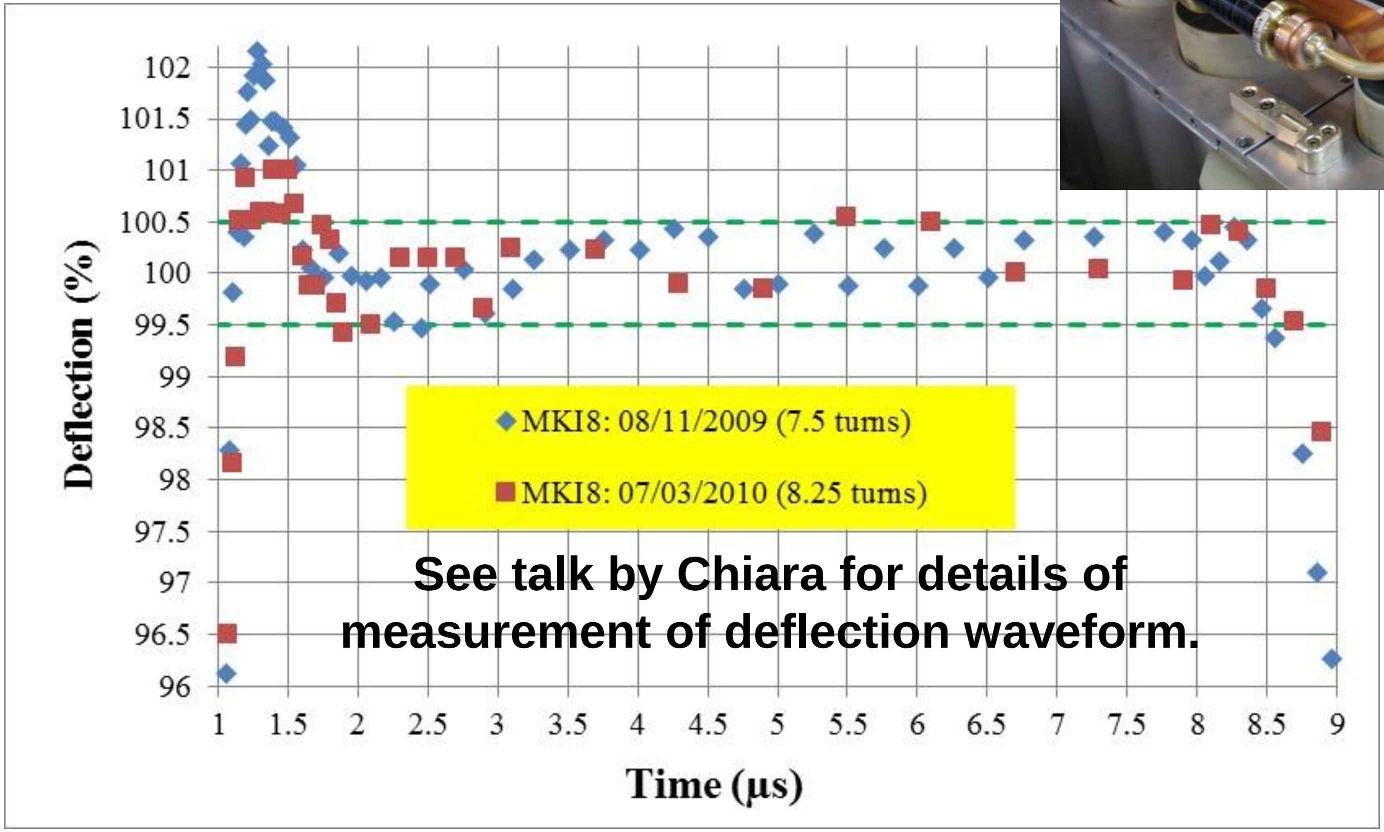
- **Field flat top duration ≤ 7.86μs**;
- **Field flat top ripple < ±0.5%;**
- Field rise-time 0.5% to 99.5% = 0.9μs;
- Kick strength per magnet = 0.325 T·m;
- Nominal PFN Voltage = 54kV;
- Nominal Magnet Current = 5.4kA.



LHC Injection Kicker Measured Flattop

Only adjustment of inductance of an LHC PFN is a wiper at each end of both coils





See talk by Chiara for details of measurement of deflection waveform.

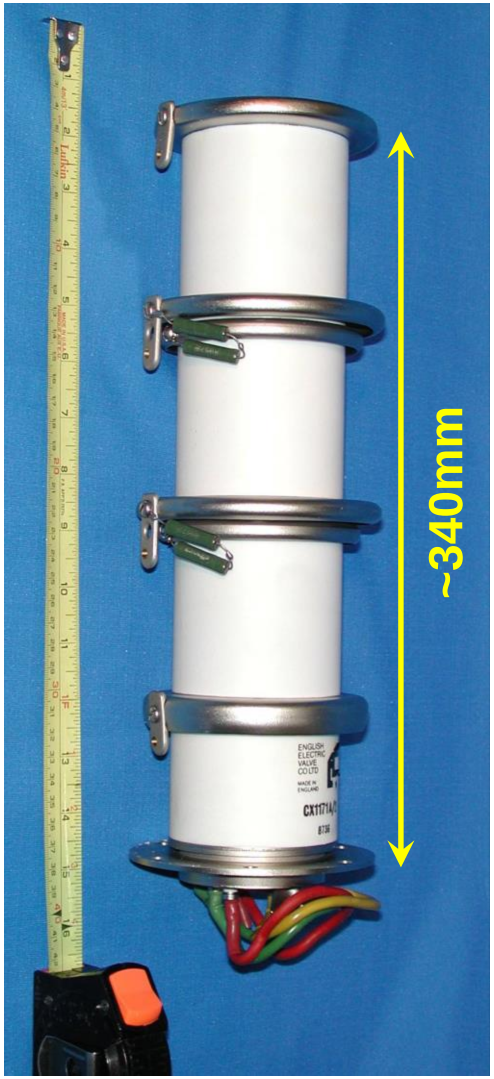
Thyratron Switches

Deuterium thyratrons are widely used as the power switch for kicker systems;

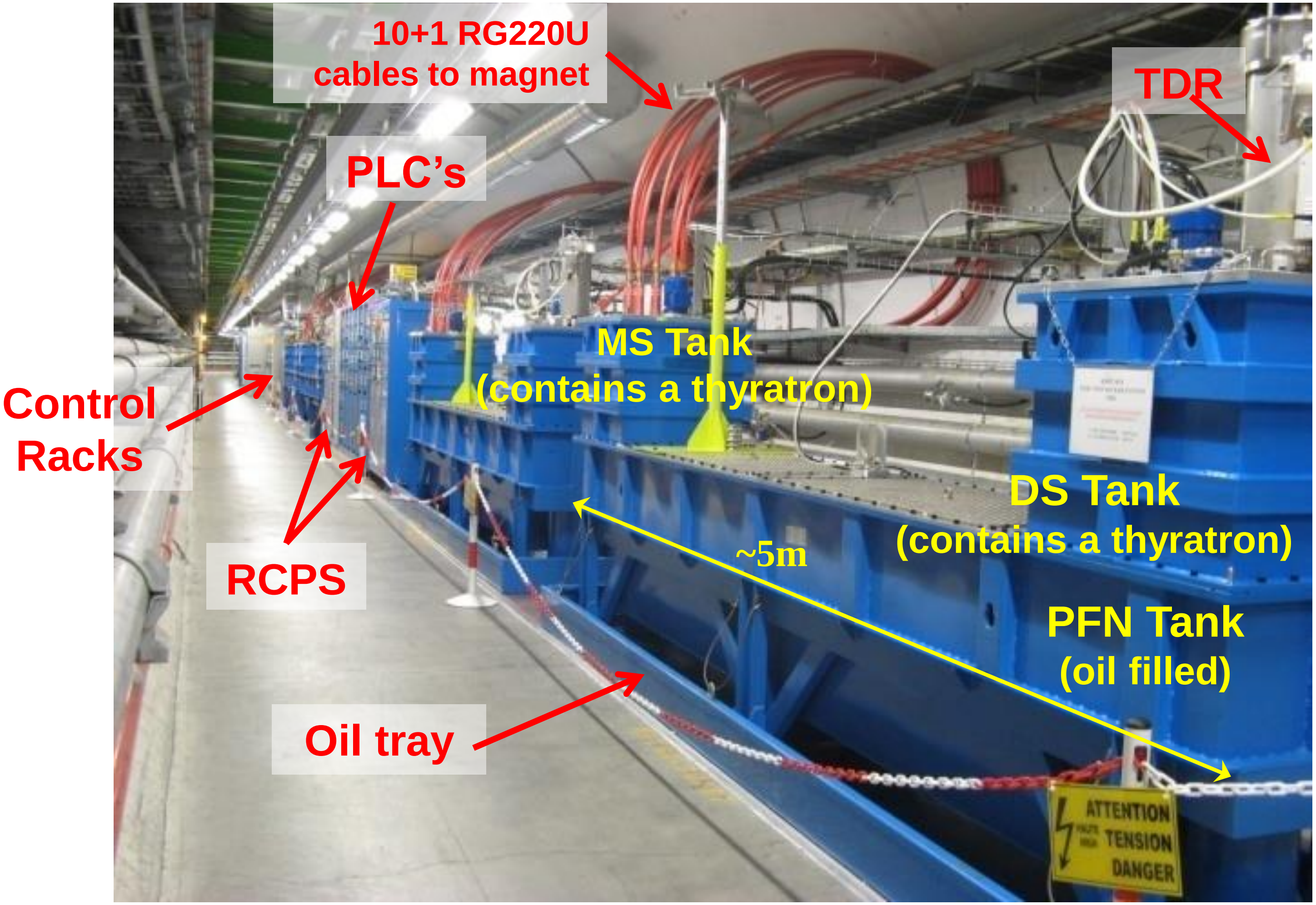
- can hold-off 80kV and switch 6kA of current;
- can switch rapidly, e.g. 30ns current rise-time (10% to 90%) [~150kA/μs];

BUT, issues include:

- *Limitations with regard to dynamic range (voltage) and repetition rate;*
- *Only a closing switch ⇨ need for PFN/PFL for energy storage;*
- *Self-triggering (turn-on without a trigger being applied) – could miskick circulating beam;*
- *Possible long-term availability ??*

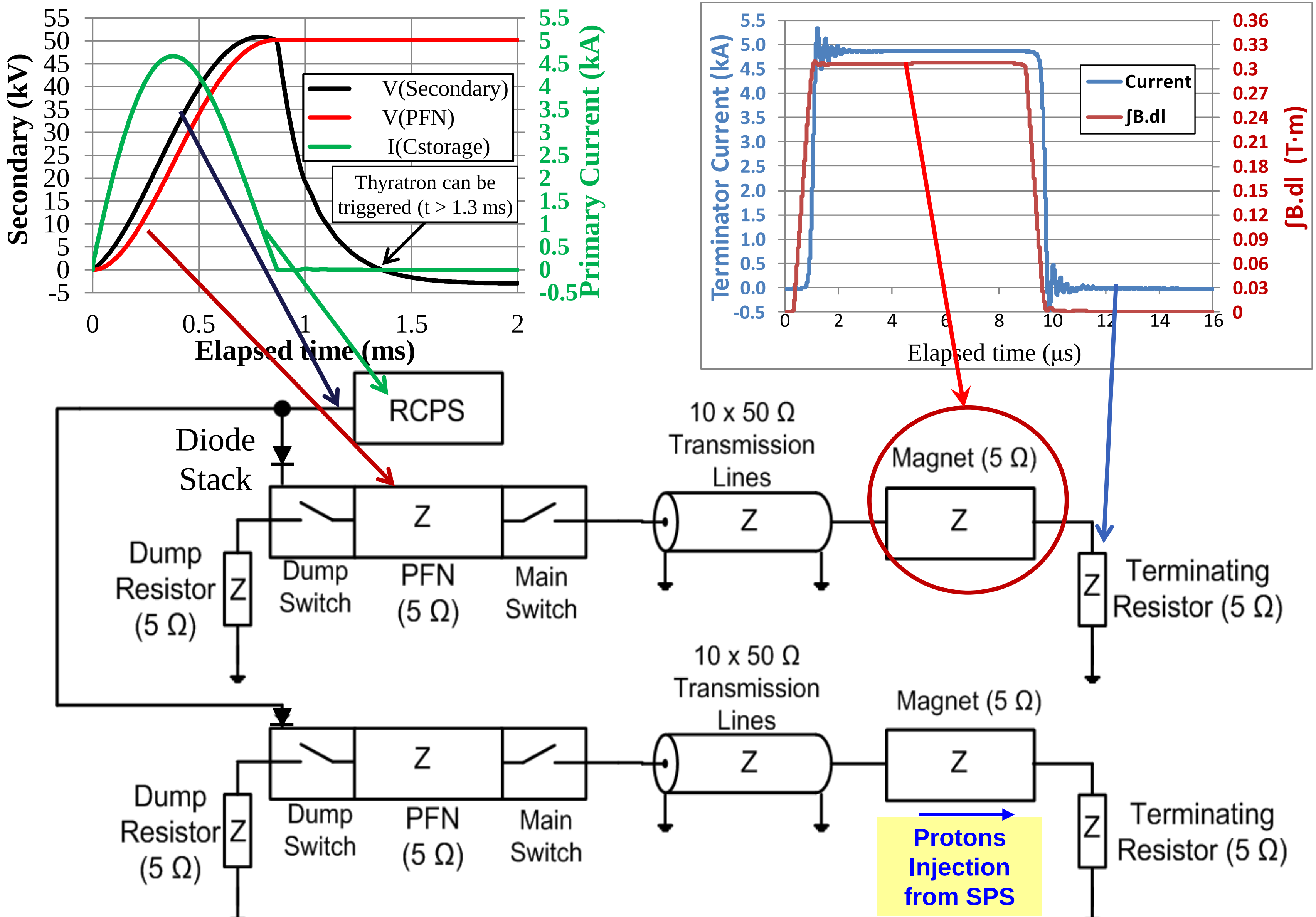


LHC Injection PFN’s, Switch Tanks & RCPS’s



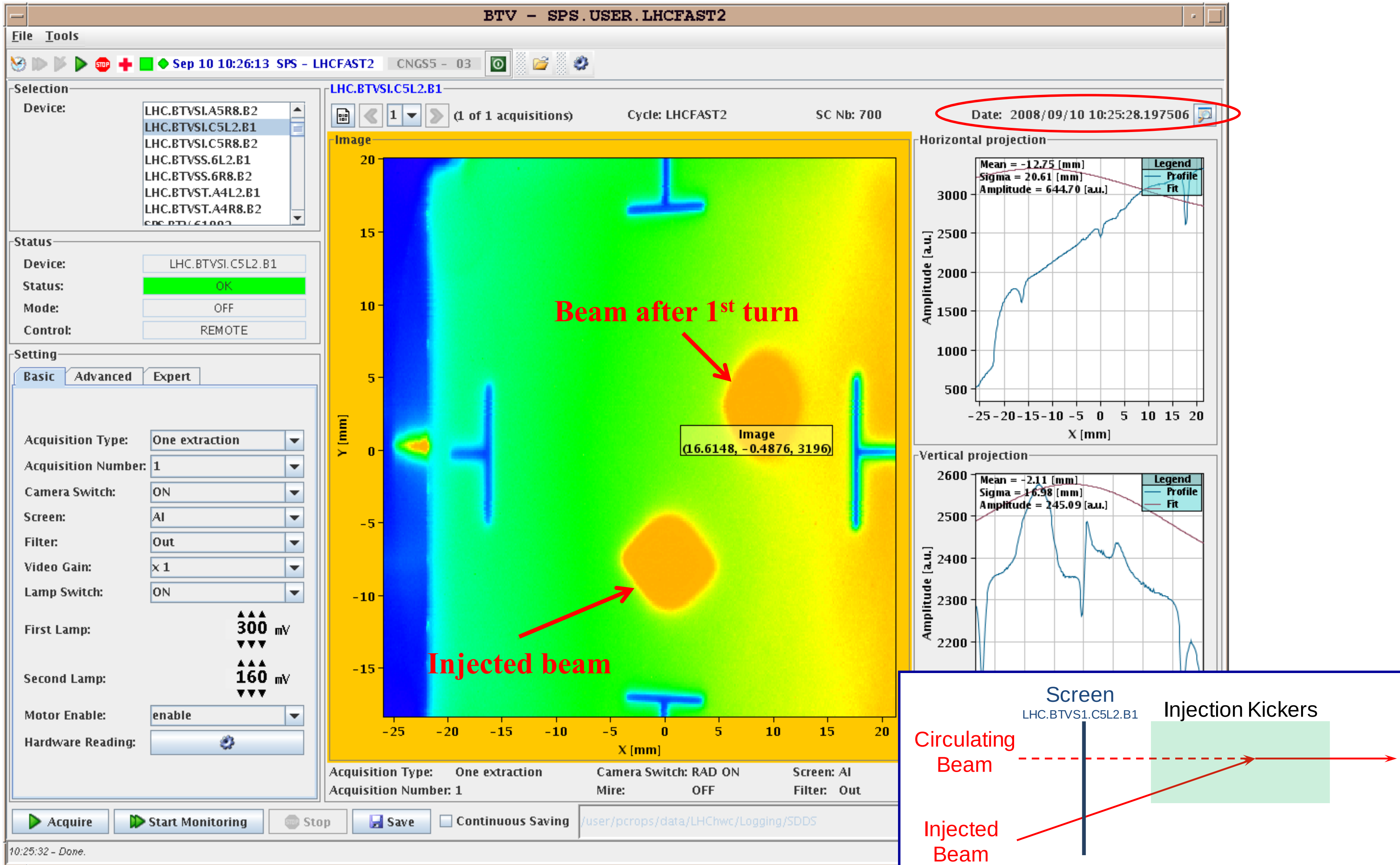
- 4 kicker magnets per injection point;
- 1 PFN for each kicker magnet;
- 1 RCPS per 2 PFN’s.

Schematic of half an LHC Injection System



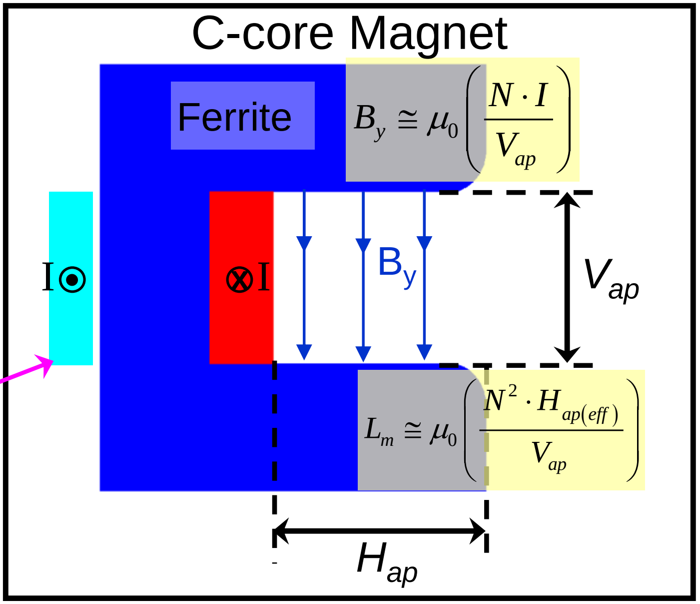
First Turn of Beam Injected into LHC (2008)

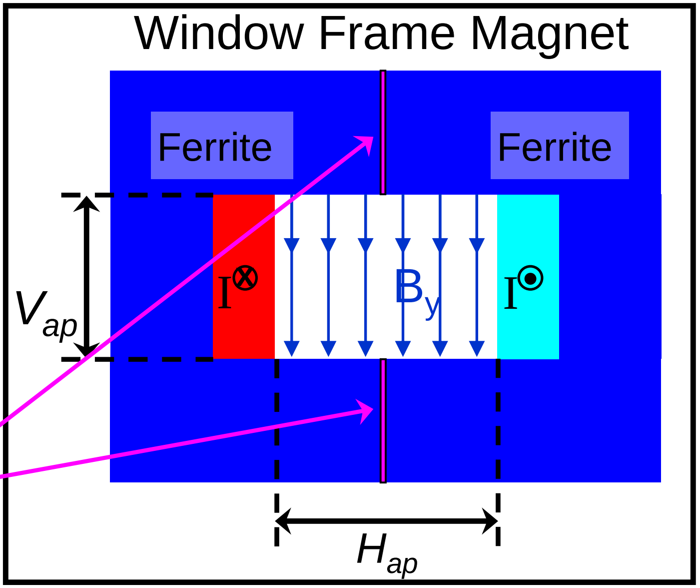
Just to demonstrate that the LHC Injection Kickers, at Point 2, work……



Kicker Magnet Magnetic Circuit

- NiZn ferrite is usually used, with $\mu_r \approx 1000$:
  - Field rise can track current rise to within ~1 ns;
  - Has low remnant field;
  - Has low out-gassing rate, after bake-out (@300°C).
- 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.
  - Transmission line magnet requires two generators, at the same end (opposite polarity), to achieve the reduced filling time.
  - Eddy current "shields" are used between the two ferrite.





Summary of Several Equations

Combining equations from earlier slides, and rearranging:

$$V_{mag-tot} = \theta_{B,x}\left[\frac{p \cdot H_{ap}}{0.2998}\right] \cdot \boxed{\left(\frac{1}{\tau_{fill}}\right)} \cdot N$$

The **required magnet voltage is inversely proportional to the required magnet fill-time** (τ_{fill}): for given parameters, shorter fill-time ⇨ increased voltage.

$$\frac{V_{mag-tot}}{N_{\text{magnets}}} = \frac{\theta_{B,x}}{N_{\text{magnets}}} \cdot \left[\frac{p \cdot H_{ap}}{0.2998}\right] \cdot \left(\frac{1}{\tau_{fill}}\right) \cdot N$$

Where:

L_m	Total magnet inductance
$V_{mag-tot}$	Total magnet voltage
N_{magnets}	Number of magnet modules

For $N=1$: $$\frac{V_{mag-tot}}{N_{\text{magnets}}} = \frac{\theta_{B,x}}{N_{\text{magnets}}} \cdot \left[\frac{p \cdot H_{ap}}{0.2998}\right] \cdot \left(\frac{1}{\tau_{fill}}\right)$$

Typically PFN voltage is less that 60kV:
e.g. for LHC injection (~0.8 mrad, 450 GeV, 54 mm, 680 ns): $V_{\text{mag-tot}}$ ⇨ 95 kV (=190 kV PFN).
Hence subdivide total length into 4 magnets.

Questions ?

Thank you for your attention.

Kicker System Bibliography – Part 1

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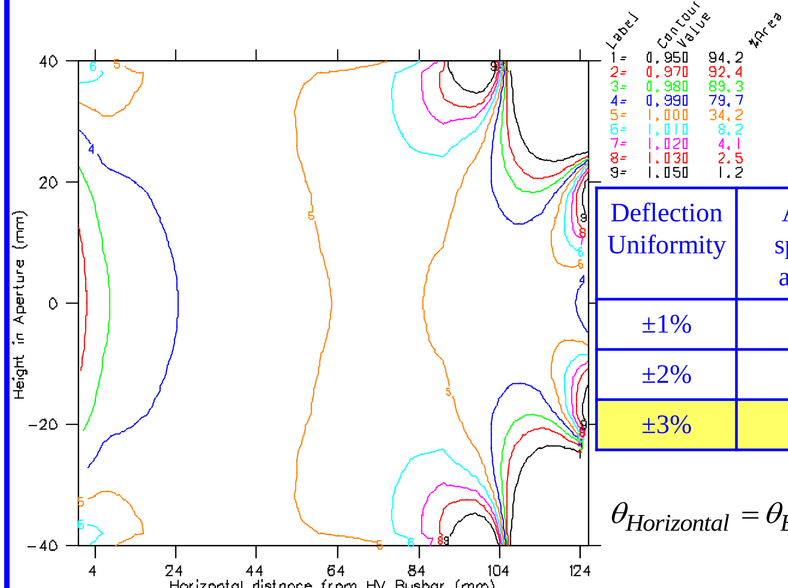
Deflection Uniformity: BNL AGS A10

β·c is smaller for Au^{77+} than for protons, the electric field deflection is larger for Au^{77+}. Since the total deflection uniformity was optimized for protons the total deflection uniformity is worse for Au^{77+}.

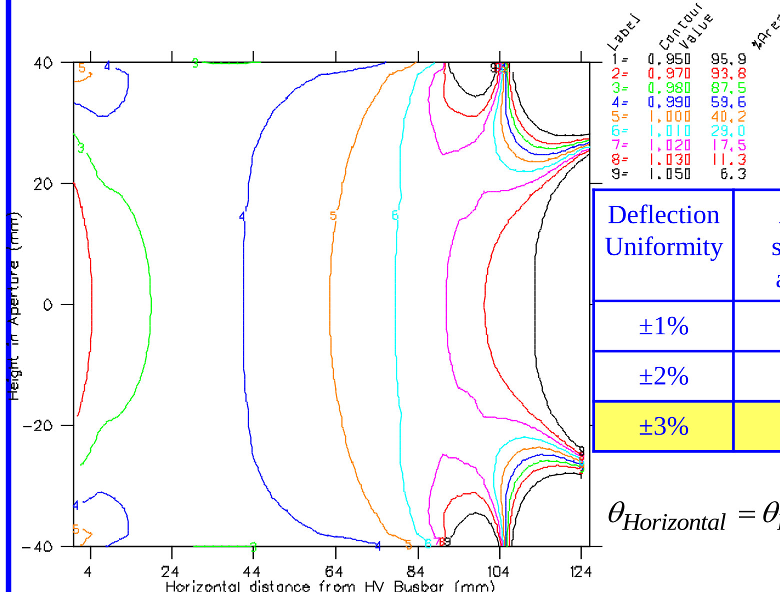
Protons: 3D model. Single kicker magnet



Deflection Uniformity	Area of specified aperture
±1%	71.5%
±2%	85.2%
±3%	89.9%

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

Au^{77+}: 3D model. Single kicker magnet



Deflection Uniformity	Area of specified aperture
±1%	30.6%
±2%	70.0%
±3%	82.5%

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

Summary of Several Equations

Combining equations from earlier slides, and rearranging:

$$\theta_{B,x} = \left[\frac{0.2998}{p}\right] \cdot B_y \cdot l_{eff} = \left[\frac{0.2998}{p}\right] \cdot \left(\frac{\mu_0}{V_{ap}}\right) N \cdot I \cdot l_{eff}$$

$$\tau = \frac{L_m}{Z_0} \cong \left(\frac{1}{Z_0}\right) \cdot \left(\frac{N \cdot H_{ap}}{V_{ap}}\right) \cdot N \cdot l_{eff} \cdot \mu_0 \qquad \text{Hence:} \quad N \cdot l_{eff} \cdot \mu_0 \cong \left(\frac{V_{ap}}{N \cdot H_{ap}}\right) \cdot \tau \cdot Z_0$$

$$V_{mag-tot} = \theta_{B,x} \left[\frac{p \cdot H_{ap}}{0.2998}\right] \cdot \boxed{\left(\frac{1}{\tau_{fill}}\right)} \cdot N$$

$$\frac{V_{mag-tot}}{N_{\text{magnets}}} = \frac{\theta_{B,x}}{N_{\text{magnets}}} \cdot \left[\frac{p \cdot H_{ap}}{0.2998}\right] \cdot \left(\frac{1}{\tau_{fill}}\right) \cdot N$$

The **required magnet voltage is inversely proportional to the required magnet fill-time** (τ_{fill}): for given parameters, shorter fill-time ⇨ increased voltage.

e.g. for LHC injection (~0.8 mrad, 450 GeV, 54 mm, 680 ns): $V_{\text{mag-tot}}$ ⇨ 95 kV (=190 kV PFN).

Hence subdivide total length into 4 magnets, .

For N=1: $$\frac{V_{mag-tot}}{N_{\text{magnets}}} = \frac{\theta_{B,x}}{N_{\text{magnets}}} \cdot \left[\frac{p \cdot H_{ap}}{0.2998}\right] \cdot \left(\frac{1}{\tau_{fill}}\right)$$

Where:

L_m	Total magnet inductance
$V_{mag-tot}$	Total magnet voltage
N_{magnets}	Number of magnet modules