CERN

Kickers, Septa and Protection Elements

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Content

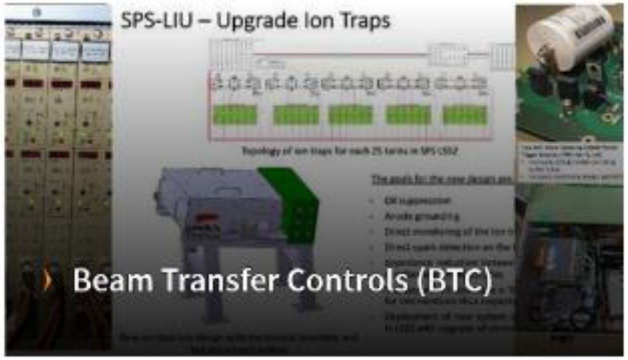
- Introduction and Reminder
- Beam Transfer Hardware
  - Kickers
  - Septa
  - Protection Devices

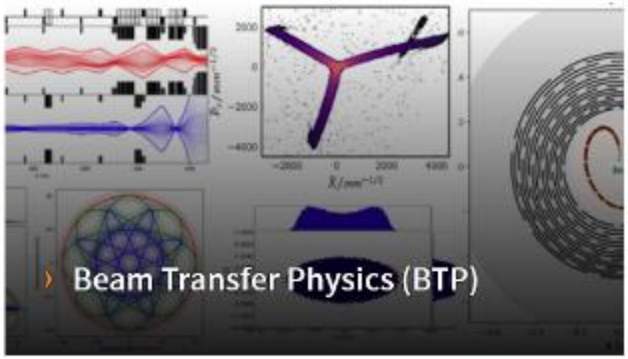
Introduction and Reminder

Accelerator Beam Transfer Group

Over **100 operational kicker and septa** modules at CERN - designed, constructed and operated by:

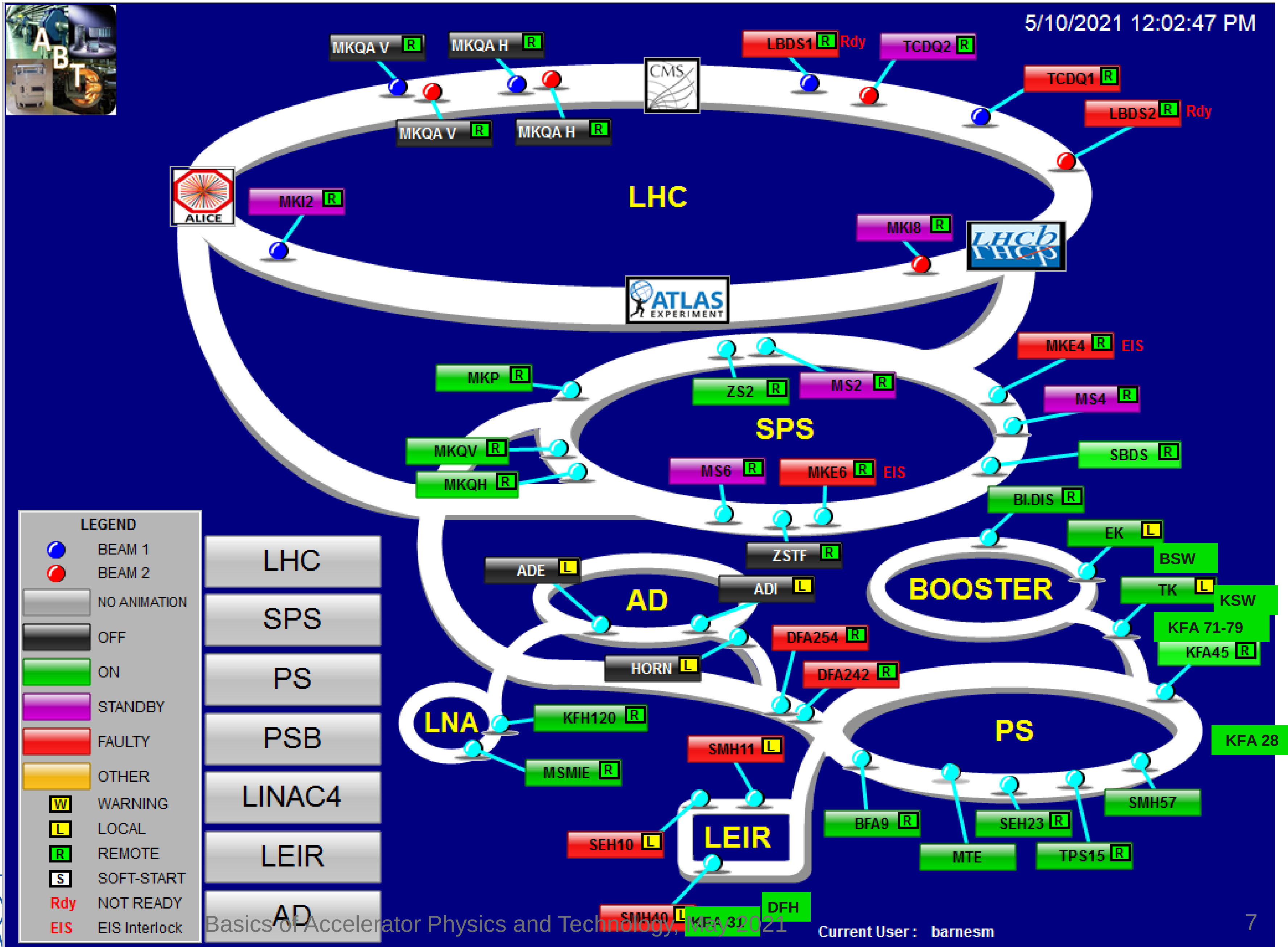
SY-ABT





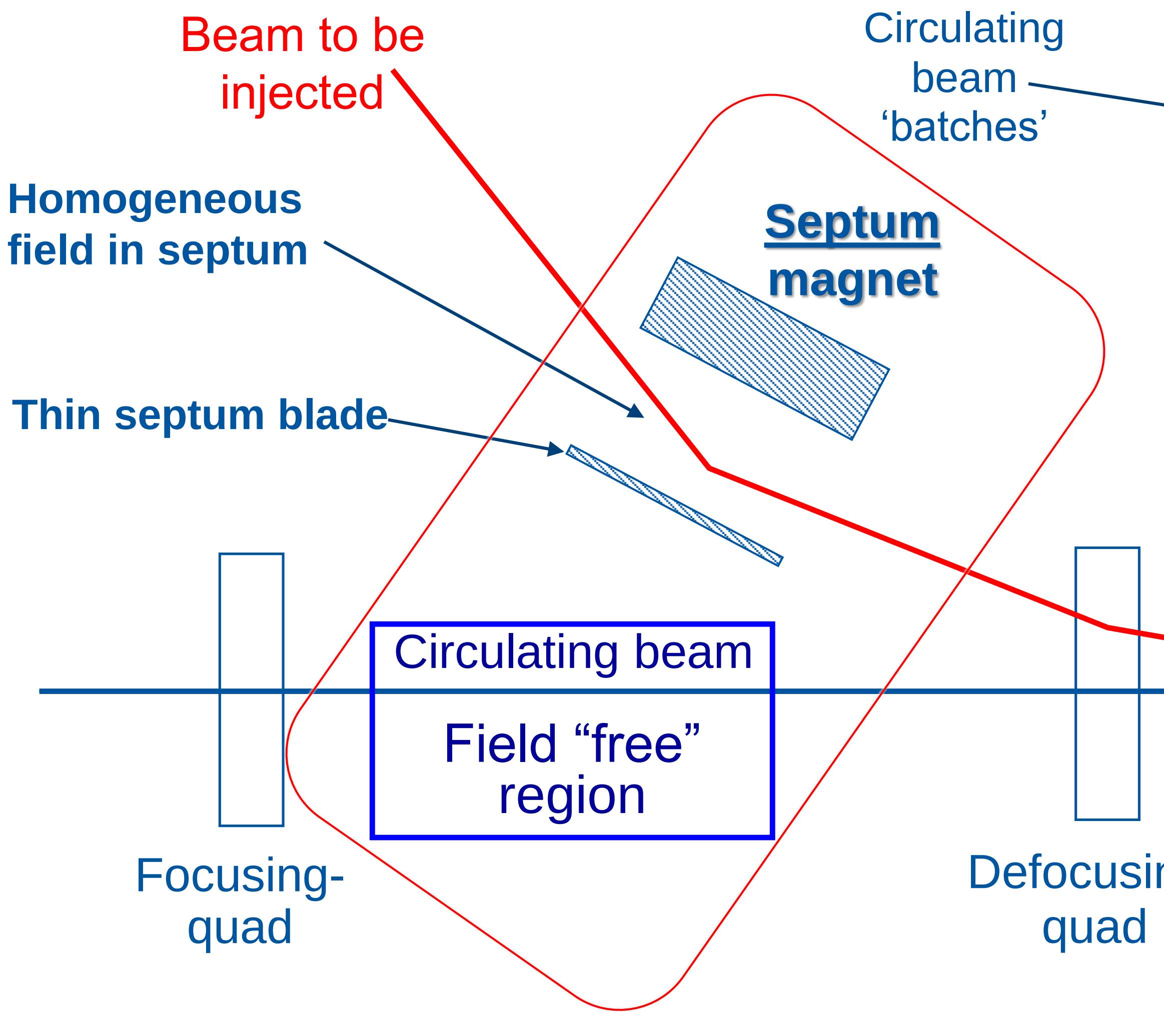
To address operational issues, TE-ABT has a kicker system Piquet outside working hours.

BT systems distributed over the complete CERN accelerator chain:

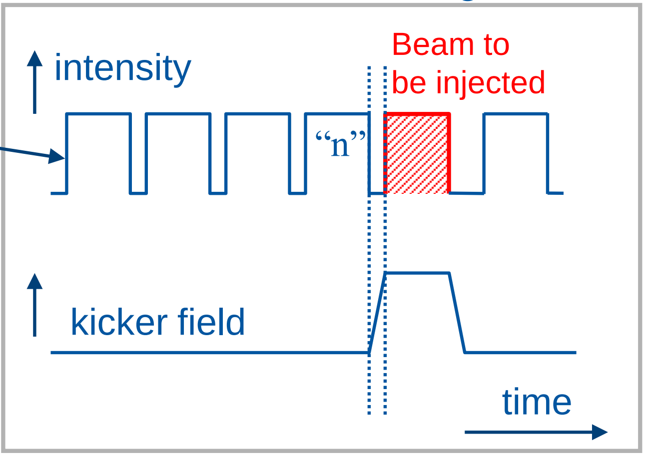


Reminder: injection, extraction

Beam injection, extraction, dump:



'boxcar' stacking



Kicker field: fast rise/fall, good flat-top, high precision timing

For more details see lecture on "Injection, Extraction and Beam Transfer" by Y. Dutheil

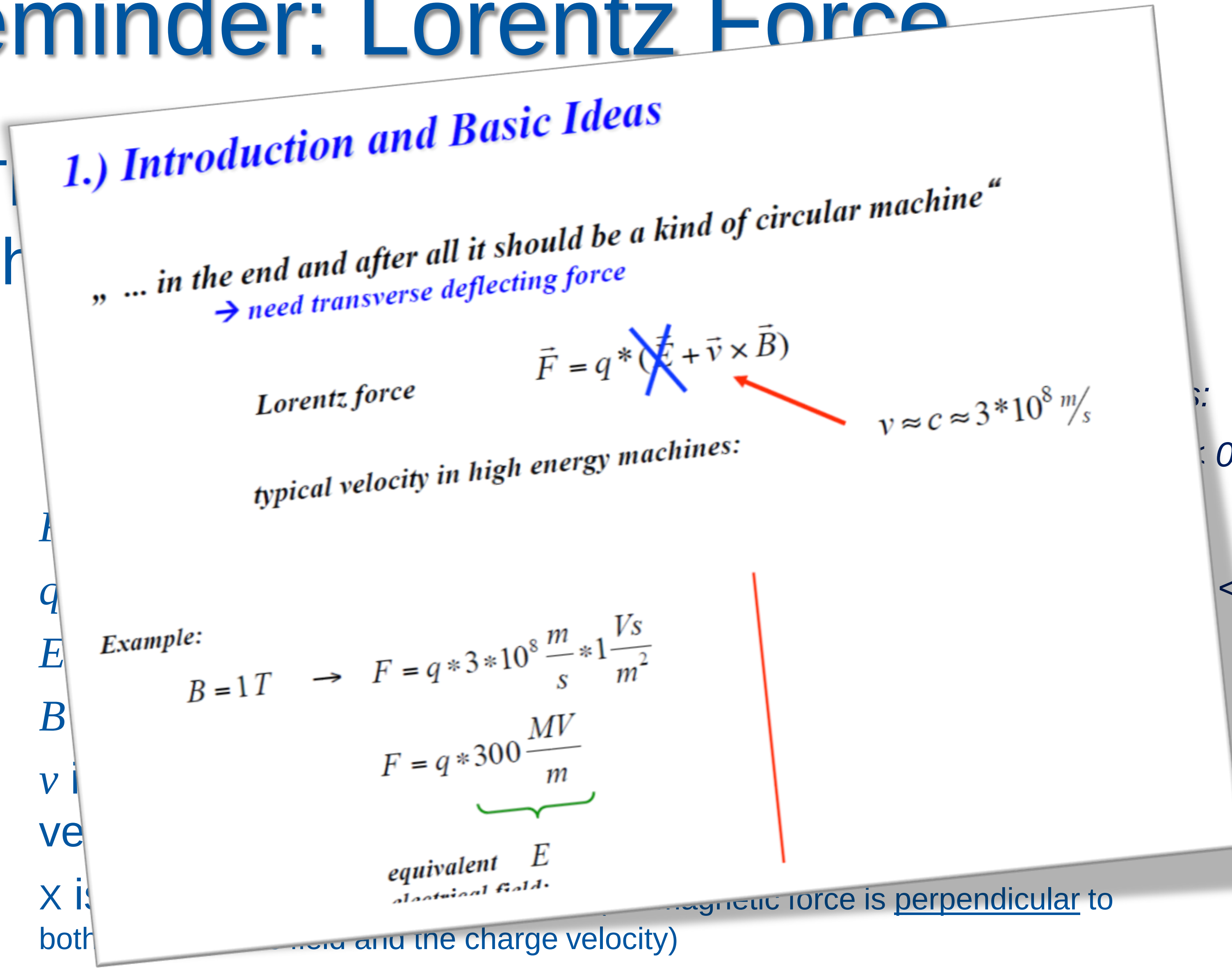
Reminder: Lorentz Force

- Th…
  ch…

…s:

… < 0.3T

- F …
- q … … $< 15\,\frac{MV}{m}$
- E …
- B …
- v i… ve…
- x is … agnetic force is perpendicular to both … field and the charge velocity)



1.) Introduction and Basic Ideas

„ … in the end and after all it should be a kind of circular machine"

→ need transverse deflecting force

Lorentz force $\vec{F} = q * (\vec{E} + \vec{v} \times \vec{B})$

typical velocity in high energy machines: $v \approx c \approx 3 * 10^8\ m/s$

Example:

$B = 1T \rightarrow F = q * 3 * 10^8 \frac{m}{s} * 1 \frac{Vs}{m^2}$

$F = q * 300 \frac{MV}{m}$

equivalent E

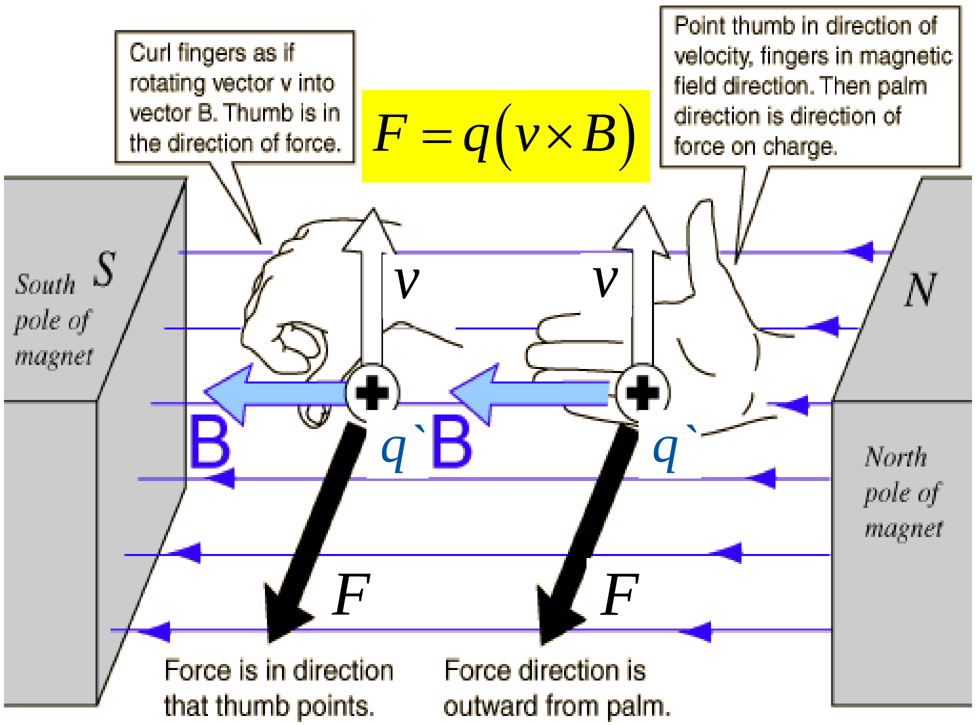
electrical field:

For more information see lecture on "Transverse Beam Dynamics I" by B. Holzer

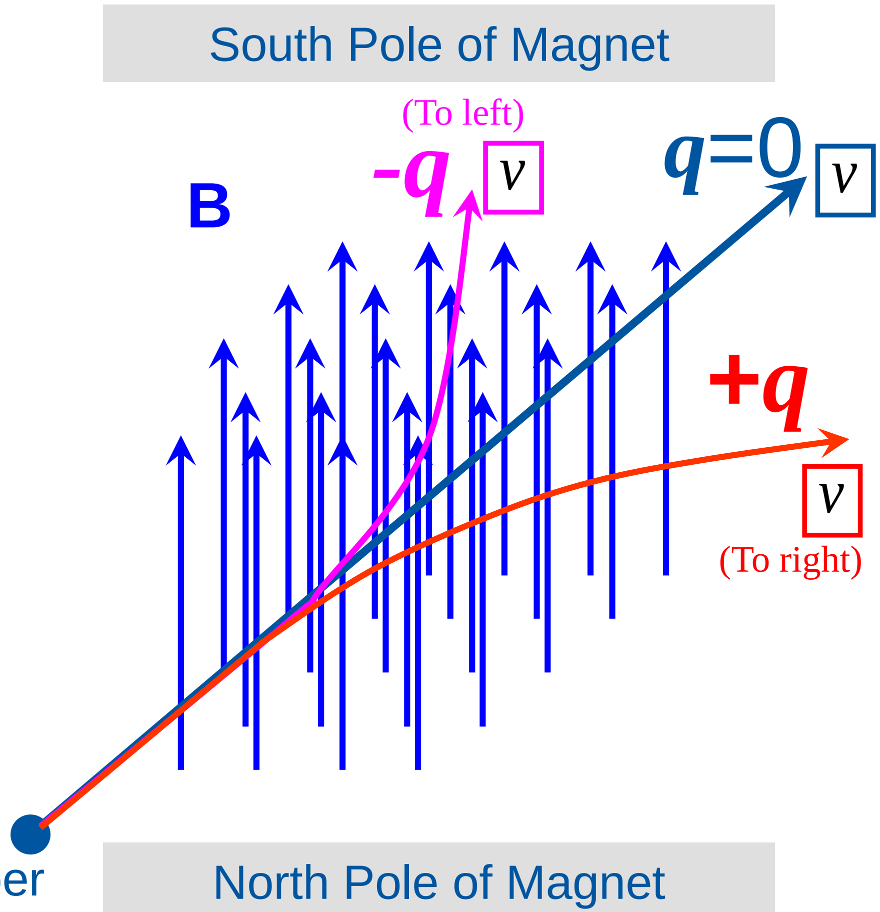
Reminder: Deflection in a Magnetic Field

Magnetic force is perpendicular to both the magnetic field and the charge velocity:

Right-Hand Rule



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

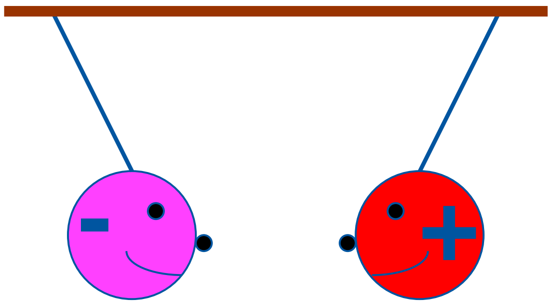


Charge moving into plane of paper

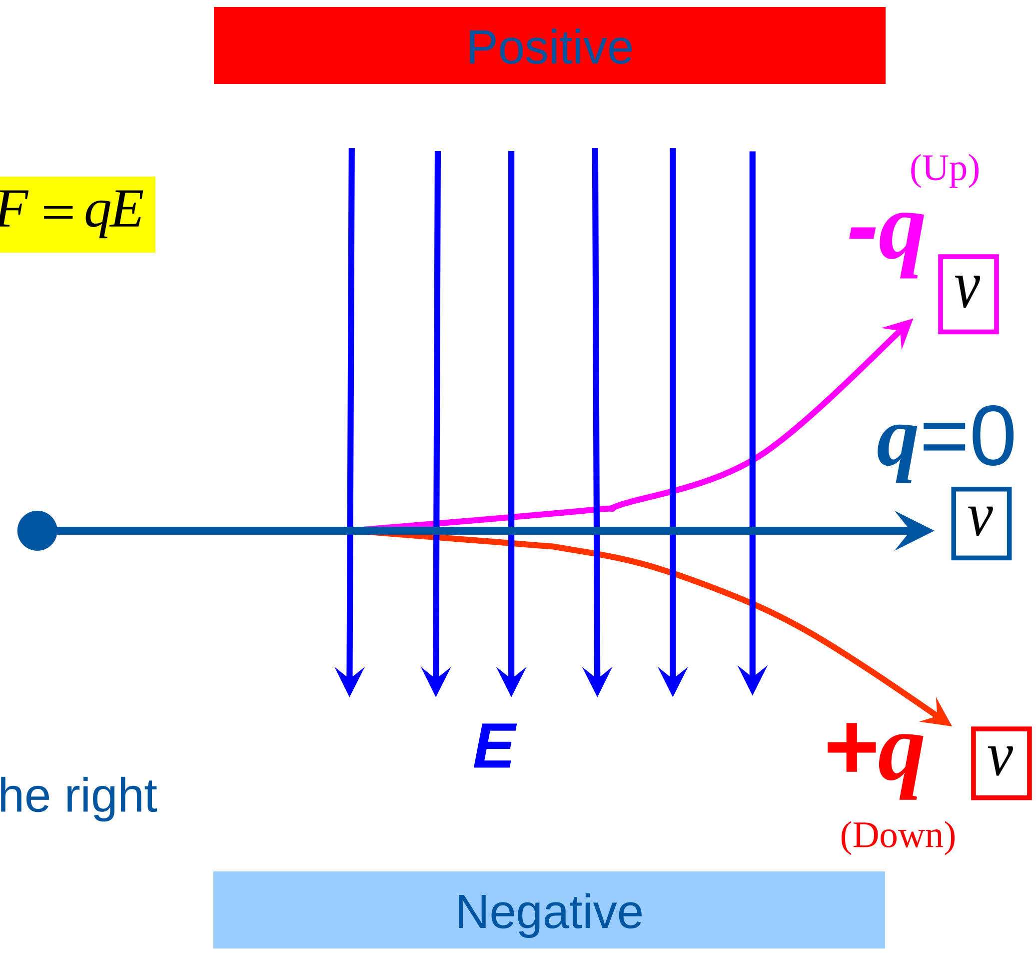
For more information see lecture “Normal-conducting Magnets” by T. Zickler

Reminder: Deflection in an Electric Field

Opposites Attract !



$F = qE$



Charge moving from the left to the right

Fast Pulsed Systems for Accelerator Beam Transfer

Use:

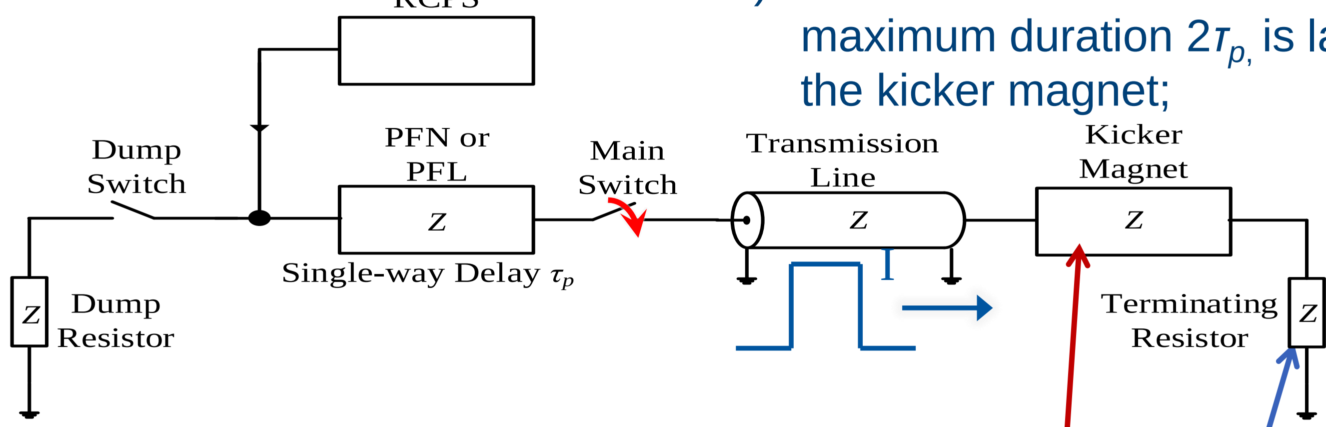
- **Beam injection, extraction, dump**
- **Tune measurements**
- **Beam chopping**

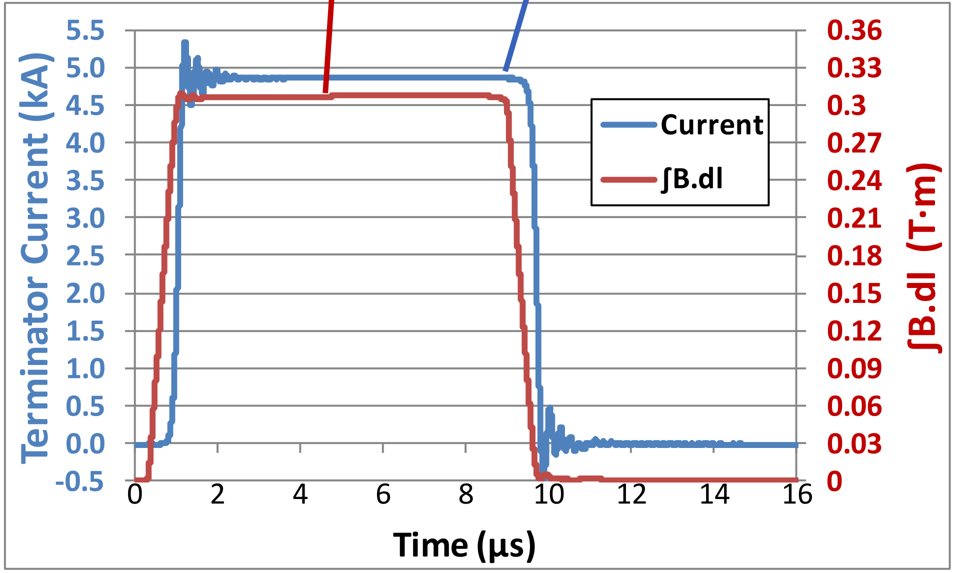
Typical kicker system topology

Line Type Modulator:

RCPS = Resonant Charging Power Supply
PFN/L = Pulse Forming Network/Line

1) Charge PFN/PFL from RCPS (few ms before the kicker is required);
2) Turn-on main switch: a current pulse, of maximum duration $2\tau_p$, is launched towards the kicker magnet;





Kicker Magnets

Kicker magnet options

- *Basic Concepts*
  - In vacuum magnet
  - Outside vacuum magnet
  - Lumped inductance kicker
  - Transmission line kicker

- *Operational modes*
  - Terminated
  - Short circuited

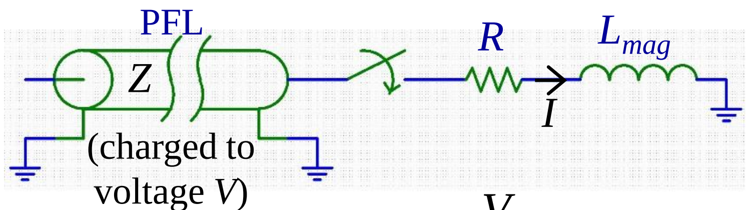
Inside versus outside vacuum

- Outside Vacuum
  - Magnet built around vacuum chamber
  - Magnet easier to build
  - HV insulation can be an issue
  - Complex vacuum chamber necessary:
    - to isolate beam vacuum
    - let transient field pass -> ceramic + metallization
    - consumes aperture!

- Inside Vacuum
  - Magnet inside vacuum tank
  - Feedthroughs for all services necessary (HV, cooling, signals)
  - Materials need to be vacuum compatible
    - “Bake-able” design
  - Vacuum <u>can</u> also improve HV insulation

Lumped Inductance vs. Transmission Line Kicker

"Lumped inductance"



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

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

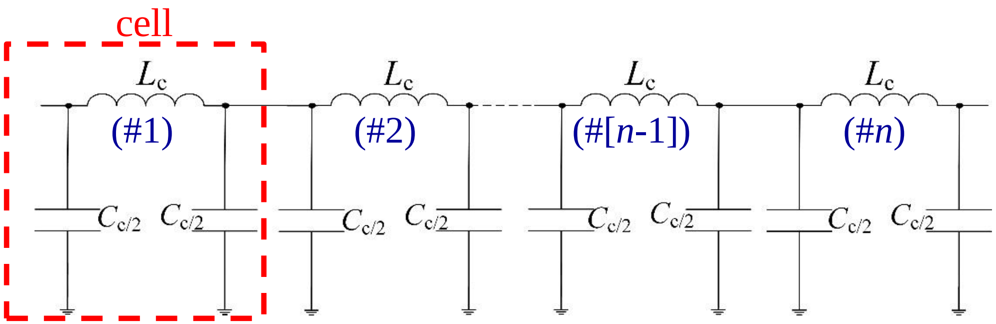
If R=Z: $\tau = \frac{L_{mag}}{2 \cdot Z}$

- 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:



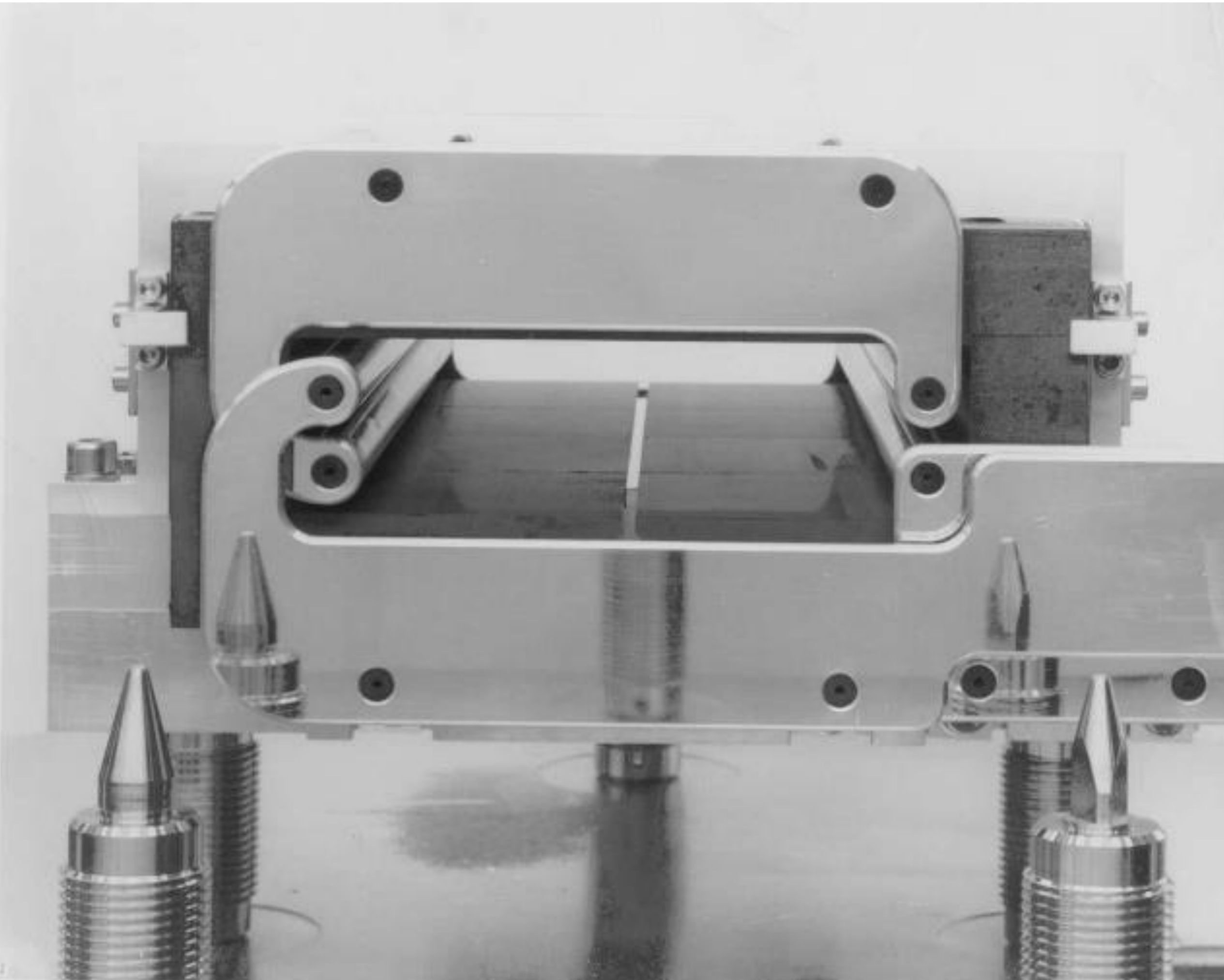
$$Z = \sqrt{\left(L_c / C_c\right)} \qquad L_{mag} = n \cdot L_c$$

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

- 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

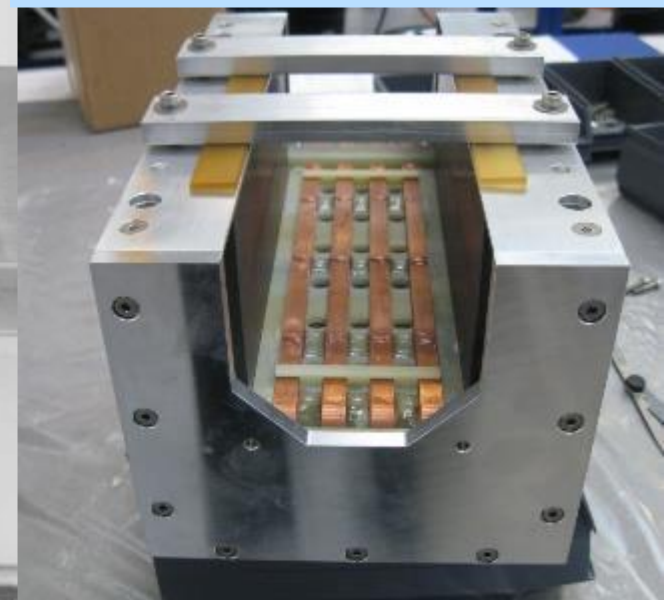
Lumped Inductance Magnets



- Used for "slower" systems
- "Simple" and "robust"

At CERN:

- Currents up to 18.5 kA
- Voltages up to 40 kV

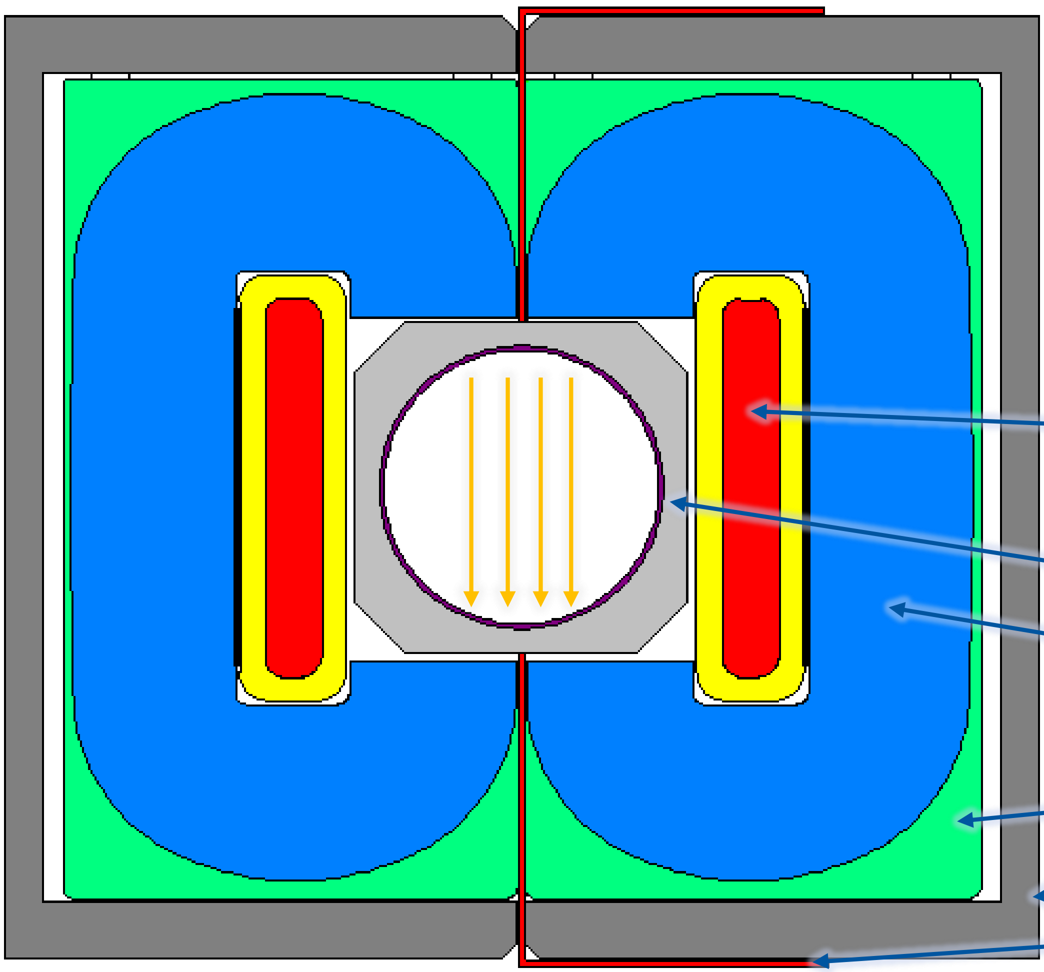


LHC extraction kickers “MKD”

- **15 magnets provide a total horizontal deflection of 0.28 mrad (0.3 T peak field)**
- **Operated at 18.5 kA / 30 kV**
- **Safety and reliability were major system design factors.**

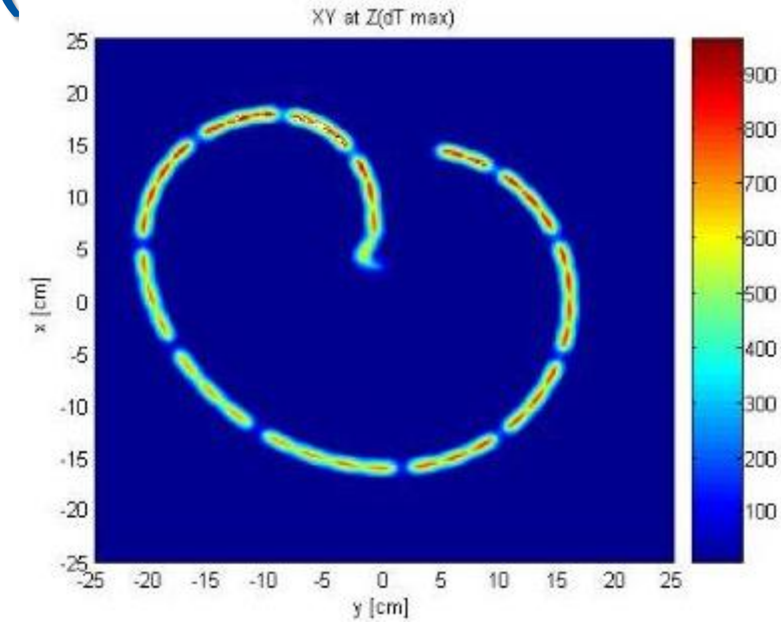
LHC extraction kicker magnet - MKD

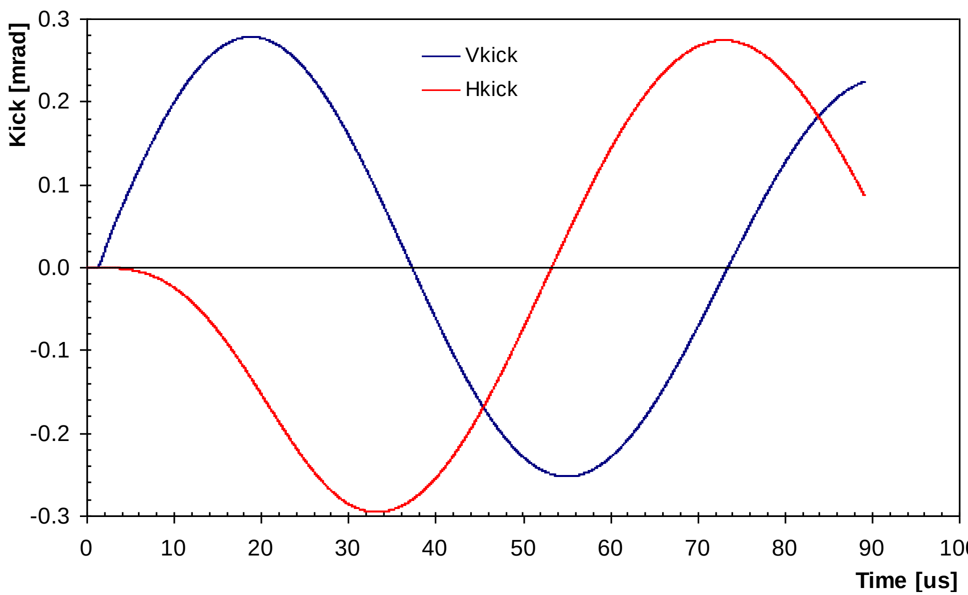
Magnets are built around a metallized ceramic vacuum chamber

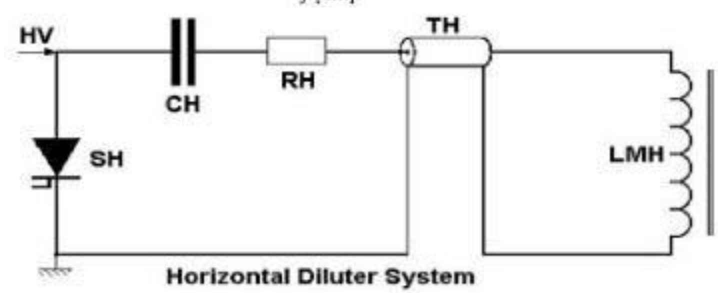


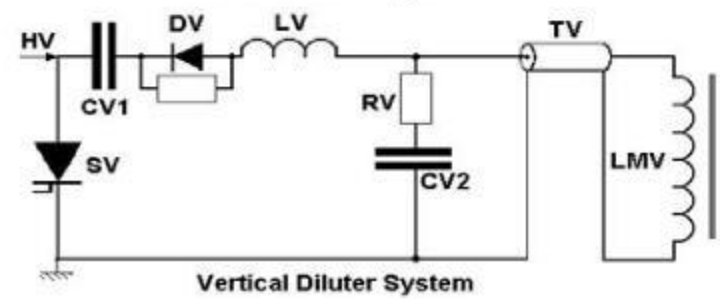
LHC dilution kickers (MKB)

- 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 FHCT stack per generator)
    - 27 kV and 24 kA per generator;
    - Semiconductor switch excites an L-C oscillation;



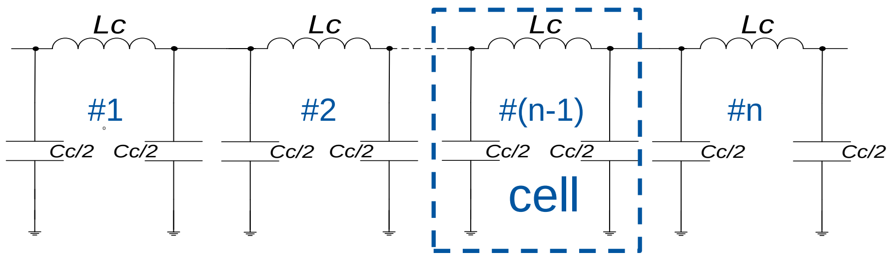


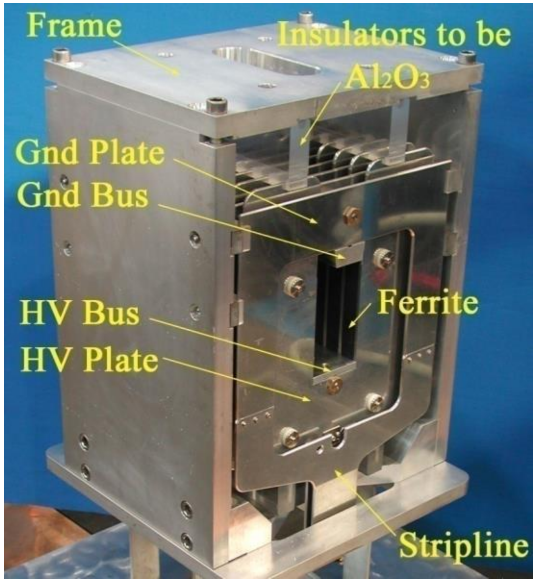


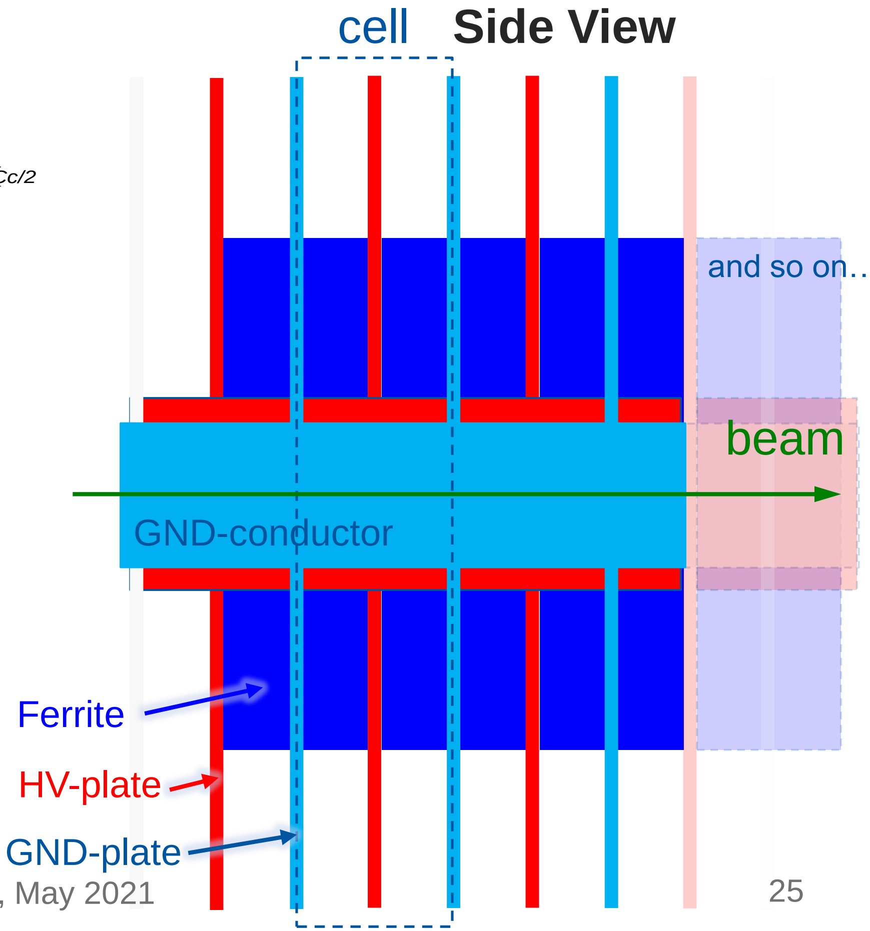


Magnets – Transmission Line Kicker

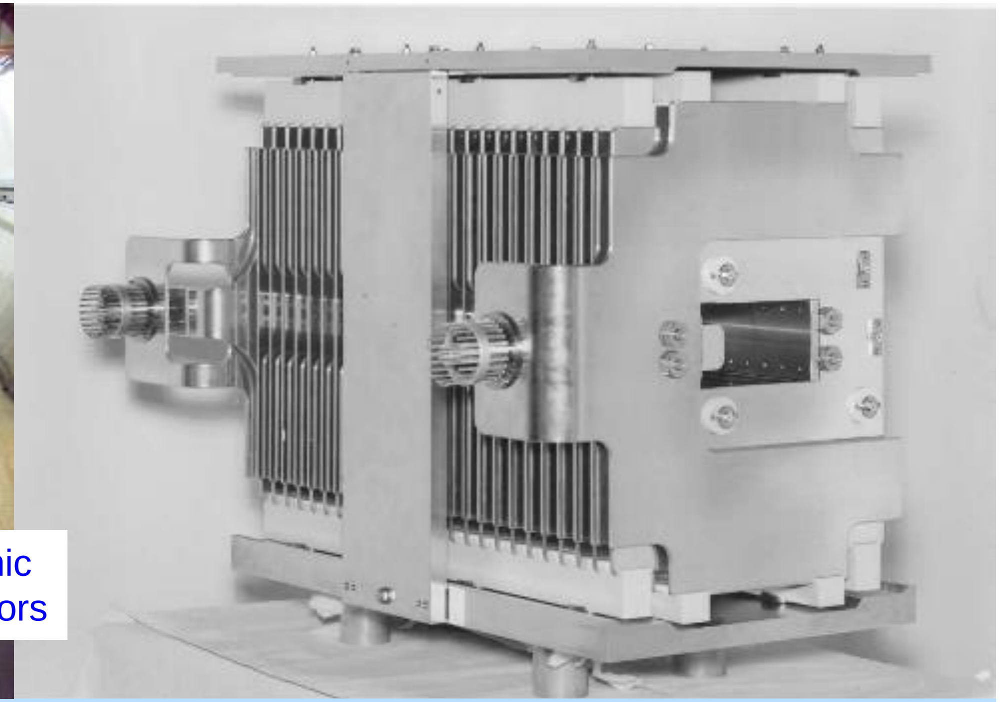
- Fast kicker magnets are generally **ferrite loaded** transmission lines:
  - Kicker magnets consist of many, relatively short, cells to approximate a “broadband” transmission line
  - Ferrite C-cores are sandwiched between HV plates
  - Grounded plates are interleaved to form a capacitor to ground







Transmission Line Kickers

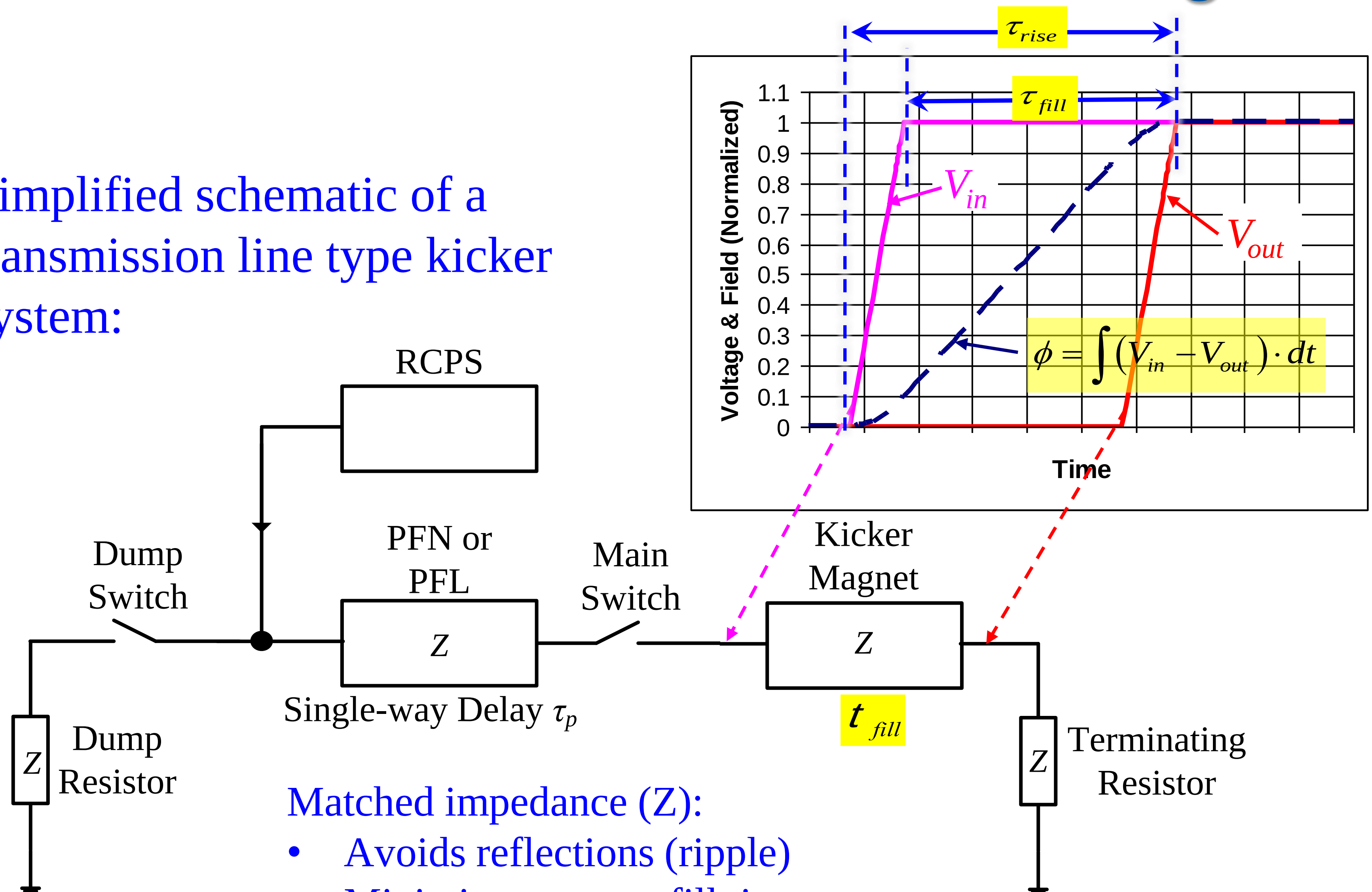


At CERN:

- Used for “fast” systems (30ns-800ns range for field rise time)
- Currents up to 5 kA
- Voltages up to 80 kV

Pulse transmission in a kicker magnet

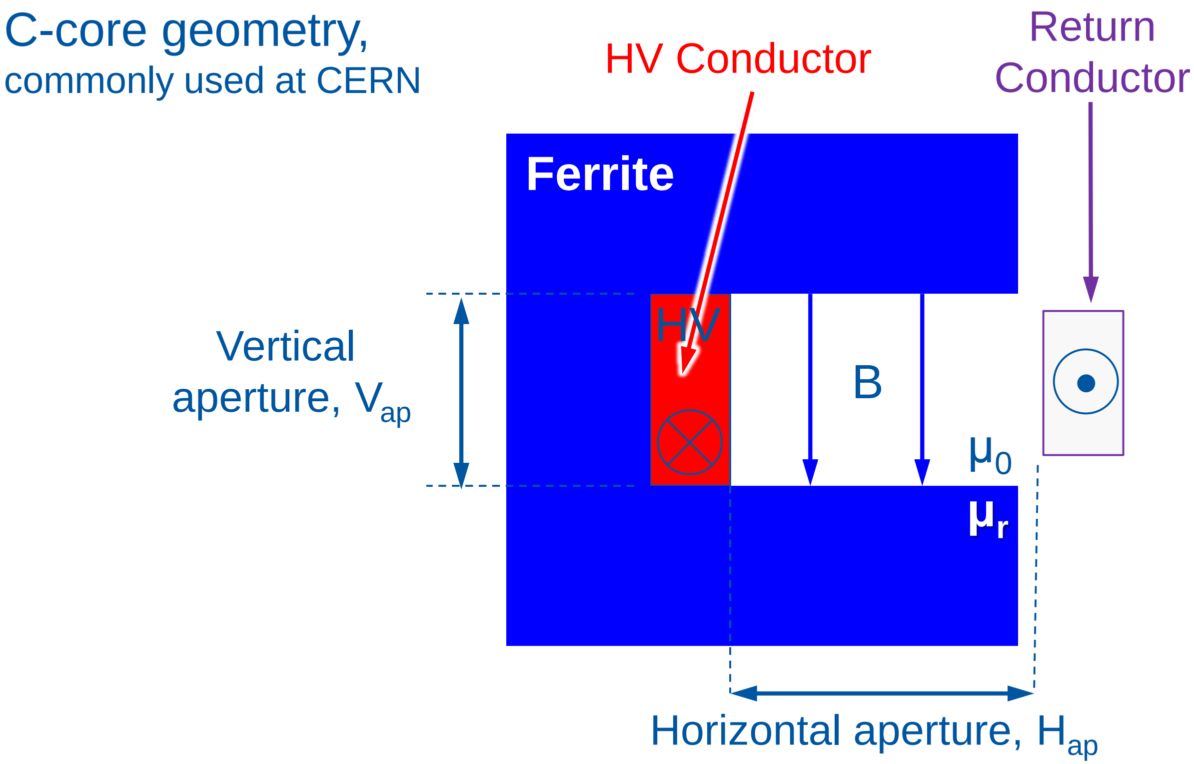
Simplified schematic of a transmission line type kicker system:



Matched impedance (Z):

- Avoids reflections (ripple)
- Minimizes magnet fill time

Basic Magnetic Circuit Parameters



Magnetic field

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

Magnet inductance

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

- Dimensions H_{ap} and V_{ap} basically determined by beam parameters at kicker location.
- Ferrite ($\mu_r \approx 1000$) reinforces magnetic circuit and uniformity of the field in the gap.
- For fast rise times the inductance must be minimised:
  - typically, the number of turns (N) = 1.
  - Kicker systems are often split into several short units.

For more information on magnets see lecture “Normal-conducting Magnets” by T. Zickler

Simplified Kicker Design Process

"Given" Design Parameters

Deflection Angle → $\theta_{B,x} \approx \left[\frac{0.3 \cdot l_m}{p}\right] \cdot |B_y|$

Beam momentum

Apertures

Available Beam Line Length

Magnet / Module design:

Inductance/m length (N=1) $L' = \mu_0 \frac{H_{ap}}{V_{ap}}$

Total Inductance $L_t = \mu_0 \frac{H_{ap}}{V_{ap}} l_m$

Split "Magnet" into *n* modules? $\tau_{fill} = \left(L_t / Z\right) / n$

B-field $B = \frac{\mu_0}{V_{ap}} I$

Current $I = \frac{U}{Z}$

Technology Limits:

- Max. voltage hold off
- Max. current
- Switch limits
- Cables
- etc.

Cell design:

Cell Inductance $L_c = \frac{L_m}{n_c}$ ← no. of cells

Cell Capacitance $C_c = \frac{L_c}{{Z_0}^2}$

Feasibility aspect:

- Capacitance
- Mech. Apertures
- Voltage hold off

Cell Cut Off Freq. $\omega_{0c} \approx \frac{2}{\sqrt{L_c C_c}}$

Needs to be high enough to not attenuate the rising or falling edges too much.

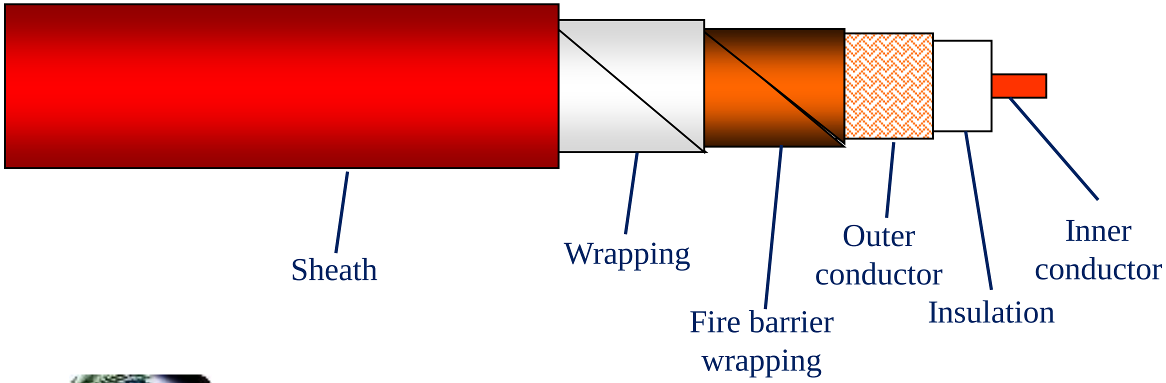
High Voltage Coaxial Cables for Kicker Systems

Transition from SF6 gas filled coaxial cables to RG220 (PS KFA-79)

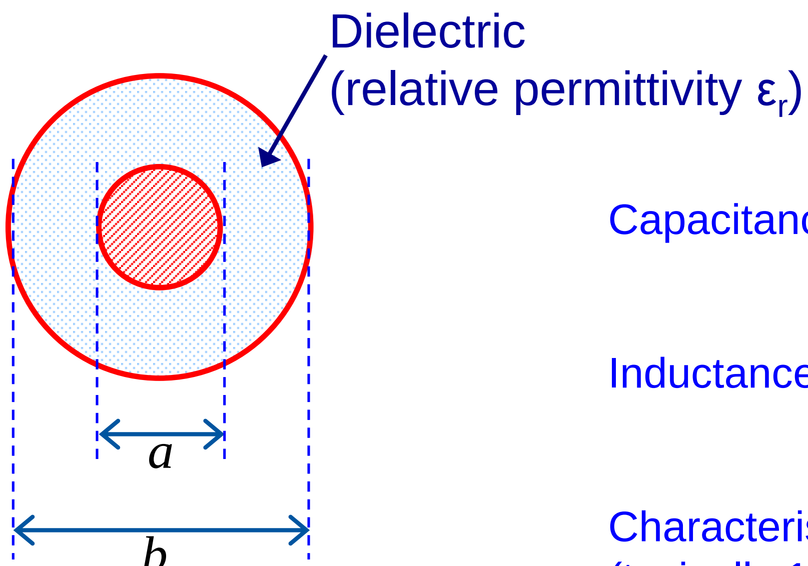
Coaxial Cables

Coaxial cables play a major role in kicker systems!

- Need to **transmit fast pulses & high currents**.
- Cables can be also used as **pulse forming lines (PFLs).**
- Should **not attenuate** or distort the pulse (attenuation < ~5.7dB/km for RG220 and <3dB/km for SF6 filled - both at 10 MHz).
- Need to **insulate high voltage** (conventional 40kV, SF6 80 kV)
- Precise **characteristic impedance** over complete length - mandatory! Otherwise issues with reflections.
- Need to be **radiation and fire resistant**, acceptable bending radius etc.



Coaxial Cables



Cross-section of coaxial cable

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

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

Characteristic Impedance (Ω): (typically 15Ω to 50Ω). $Z_0 = \sqrt{\dfrac{L}{C}}$

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

Maximum electric field (V/m), in dielectric, at voltage *U*: $E = \dfrac{U}{\frac{a}{2} \cdot \ln\left(b/a\right)}$

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 Generators

FHCT stack with trigger transformer

MKD (LHC Dump):

- 15 Pulse generators in gallery parallel to LHC tunnel.
- Connected to the magnets via ~30 m of 8 parallel transmission cables.

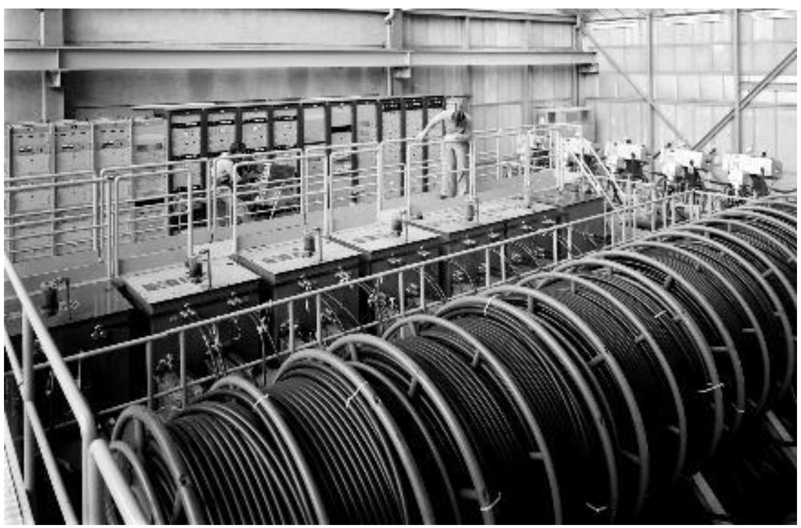
Pulse Generators

- For **energy storage** and pulse forming lines (**PFL**) or artificial pulse forming networks (**PFN**) can be used.
- A **power switch** is needed to switch the charged "energy storage" to the load. Spark gaps (not anymore at CERN), thyratrons, ignitrons, solid state switches, etc. are frequently used.
- The pulse generator requires a lot of other important equipment (e.g. slow controls, timing, cooling etc.) - not discussed further in this lecture.

PFL/PFN

Pulse Forming Line (PFL)

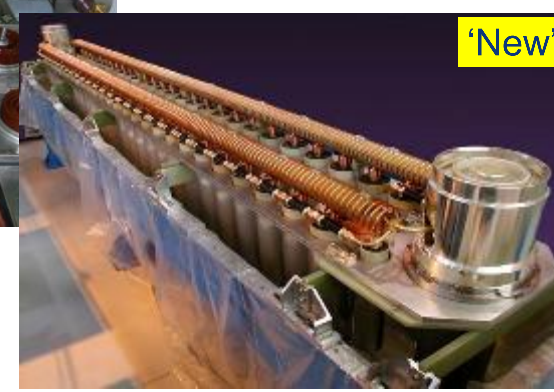
- Low-loss coaxial cable
- Fast and ripple-free pulses
- Attenuation & droop becomes problematic for pulses > 3 μs
- Above 40 kV SF6 pressurized PE tape cables are used at CERN
- Bulky: 3 μs pulse ⇨ 300 m of cable



Reels of PFL used at the PS complex (as old as the photograph!)

Pulse Forming Network (PFN)

- Artificial coaxial cable made of lumped elements
- For low droop and long pulses > 3 μs
- Old systems: each cell individually adjustable. Adjustment of pulse flat-top difficult and time consuming.
- New systems: precision design and manufacture with adjustment at ends only.



Switches

Thyratrons

- Deuterium gas thyratrons are still commonly used.
- Hold off >80kV and switch up to 6kA.
- Fast switching ~30ns (~150kA/μs).
- Erratic turn-on: use with ‘RCPS’ to reduce voltage hold-off time.

Power semiconductor switches

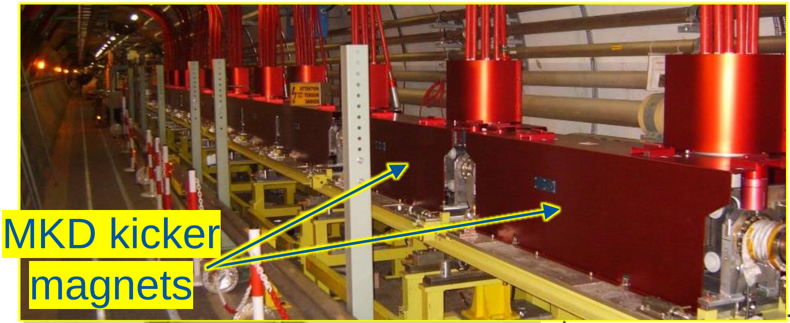
- Various types (MOSFET, IGBT, GTO’s…) used at CERN.
- Suitable for scenarios where erratic turn-on is not allowed:
  - LHC beam dump generators at required voltage throughout operation (e.g. >10h) ready to safely abort beam at any moment.
- Series/parallel “stacking” used.
- Hold off up to 30kV and switch up to 18.5kA (LHC MKD).
- Slower than thyratron: ~32kA/μs achieved.

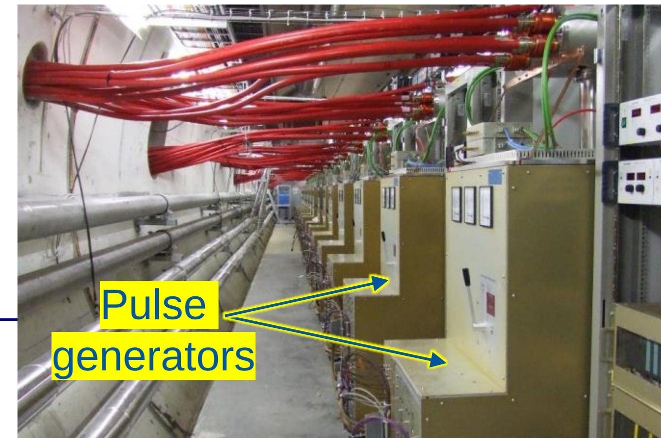
~ 340 mm

Extraction kickers (MKD)

Function: safely extract beam from LHC towards 'dump block'.
Stored energy per LHC beam is up to 360 MJ = twice the kinetic energy of a Boeing 737 MAX8 at landing [~70 t at 250 km/h].!

- Rise time of 3.0 μs
- Fixed deflection angle of 0.28 mrad (for 450 GeV to 7 TeV): hence **voltage α beam energy**

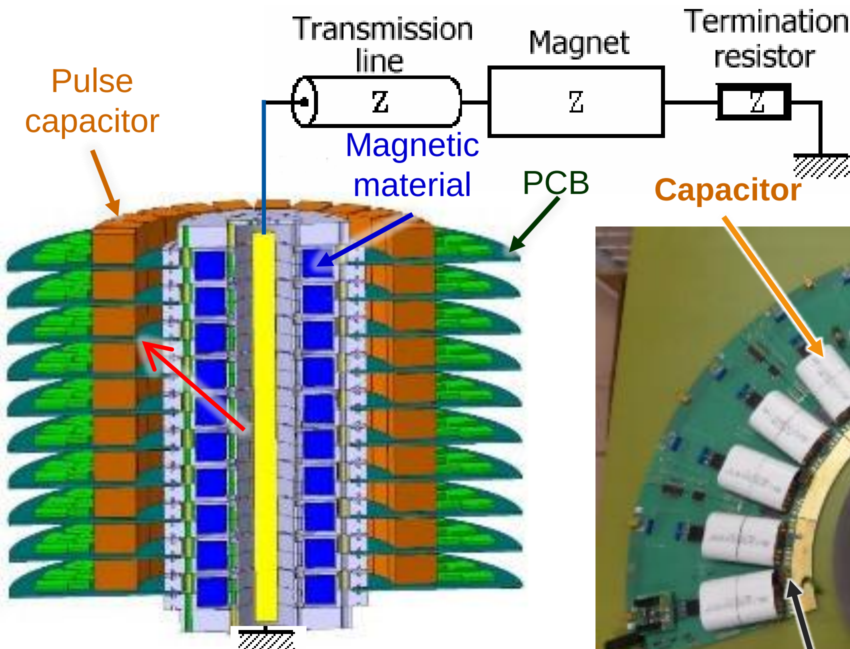




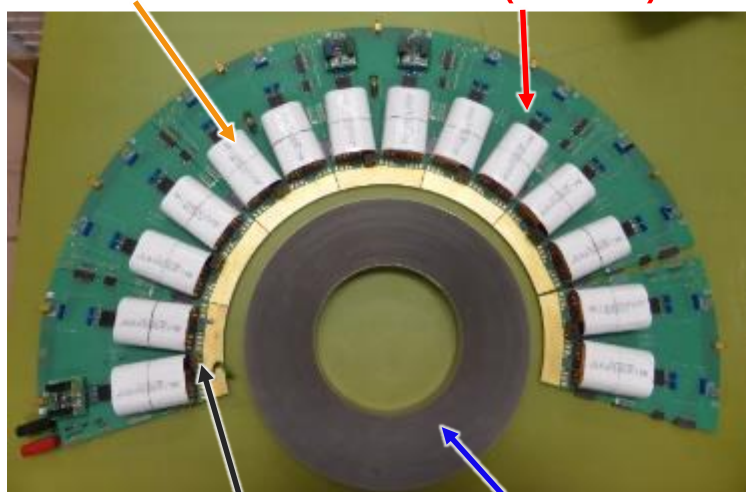
MKD generator parameters:
- Voltage: 1.7 kV – 27 kV;
- Current: 1.3 kA – 18.5 kA;
- Magnet current flat top: 91 μs;
- Maximum di/dt: 32 kA/μs (~1/5th of a thyratron).

Inductive adder

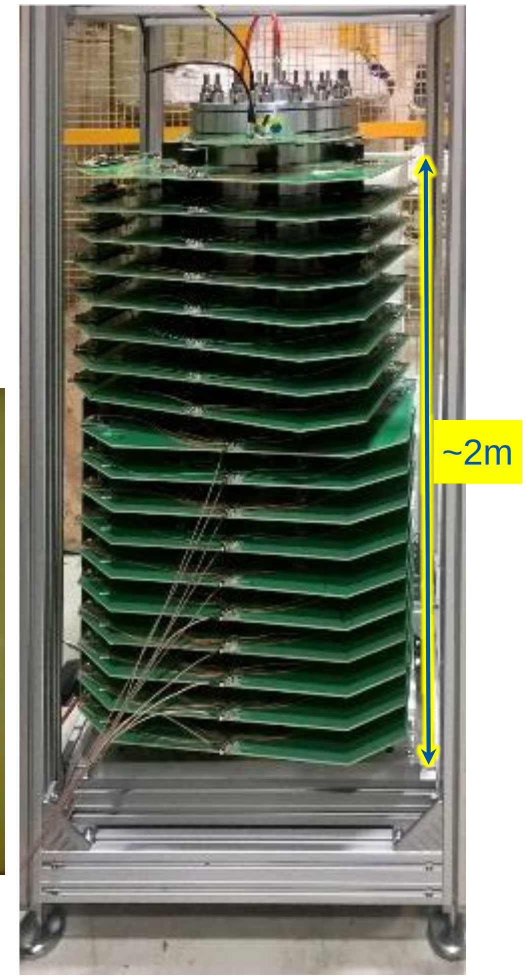
- Turn-on AND Turn-off Capability (MOSFETs or IGBTs) – hence PFN/PFL is NOT required: <u>energy stored in capacitors</u>;
- Excellent scalability for current and voltage;
- Polarity of output pulse easily changed;
- Output pulse can be <u>modulated</u> ⇨ high precision;
- But… pulse length is generally limited by magnetic material.



- *‘n’* low voltage, primary, layers
- *‘x’* parallel branches per layer
- Magnetic coupling



Inductive adder tested with beam at ALBA (Spain)



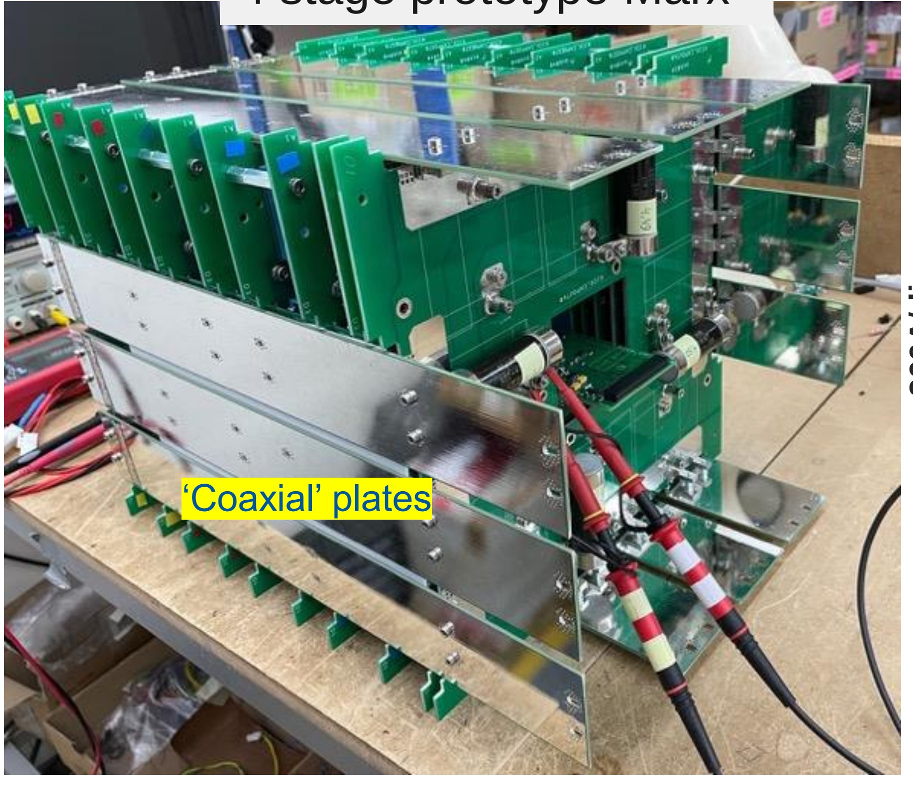
Developed for CLIC and FCC. Now developed for possible use in PS.

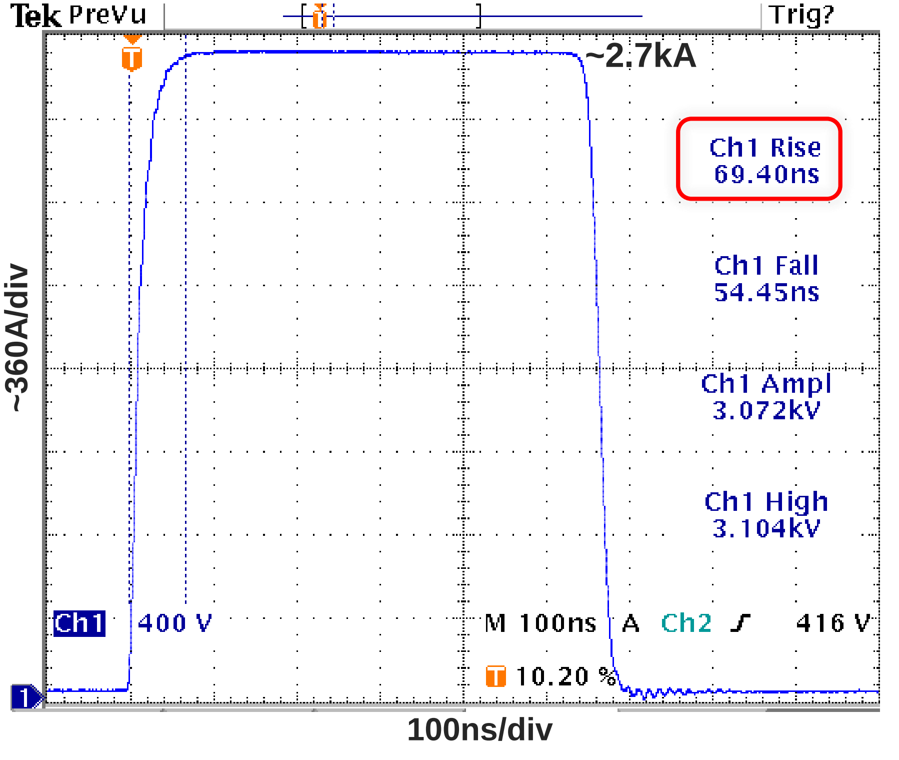
Semiconductor based Marx generator

Collaboration with Instituto Superior de Engenharia de Lisboa (ISEL) and EPS, Portugal:

- No magnetic material on output ⇨ long duration pulse capability;
- Prototype with up to 36 parallel SiC MOSFETs per stage;
- Return 'coaxial' plates to reduce inductance;
- Initially targeting: 16 kV, 2.6 kA, 75 ns rise and fall (0.5% to 99.5%).

4 stage prototype Marx





Beam Coupling Impedance

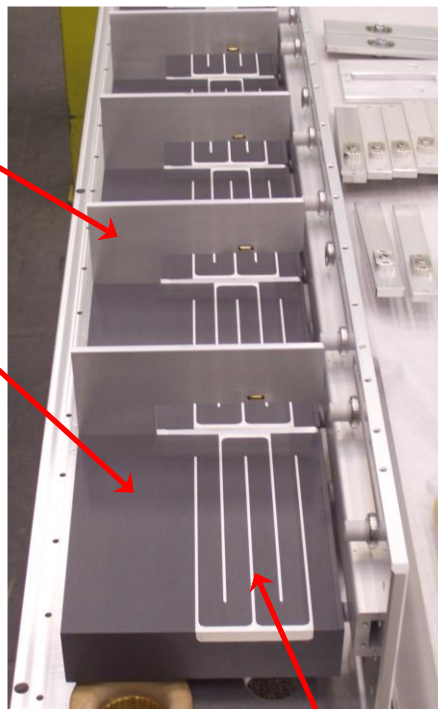
Beam can result in **considerable** heating of ferrite yoke.

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

- High voltages issues due to fast changing magnetic field $\left(U = {d\phi}/{dt}\right)$

HV Plate

Ferrite



MKE Kicker: serigraphy on ferrite

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

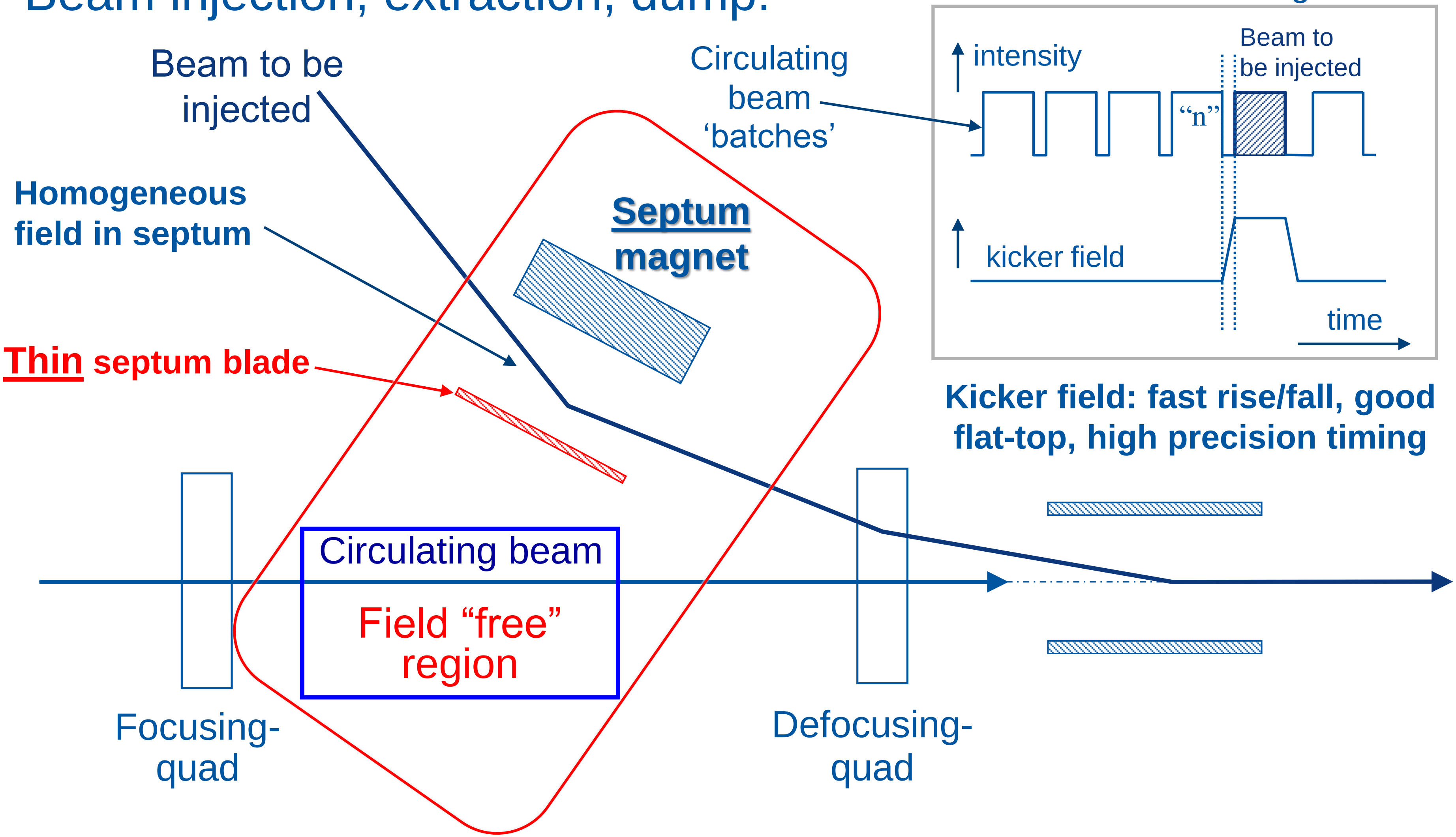
Septa

LHC beam dump
septa (MSD)

Reminder: injection, extraction

Beam injection, extraction, dump:

'boxcar' stacking

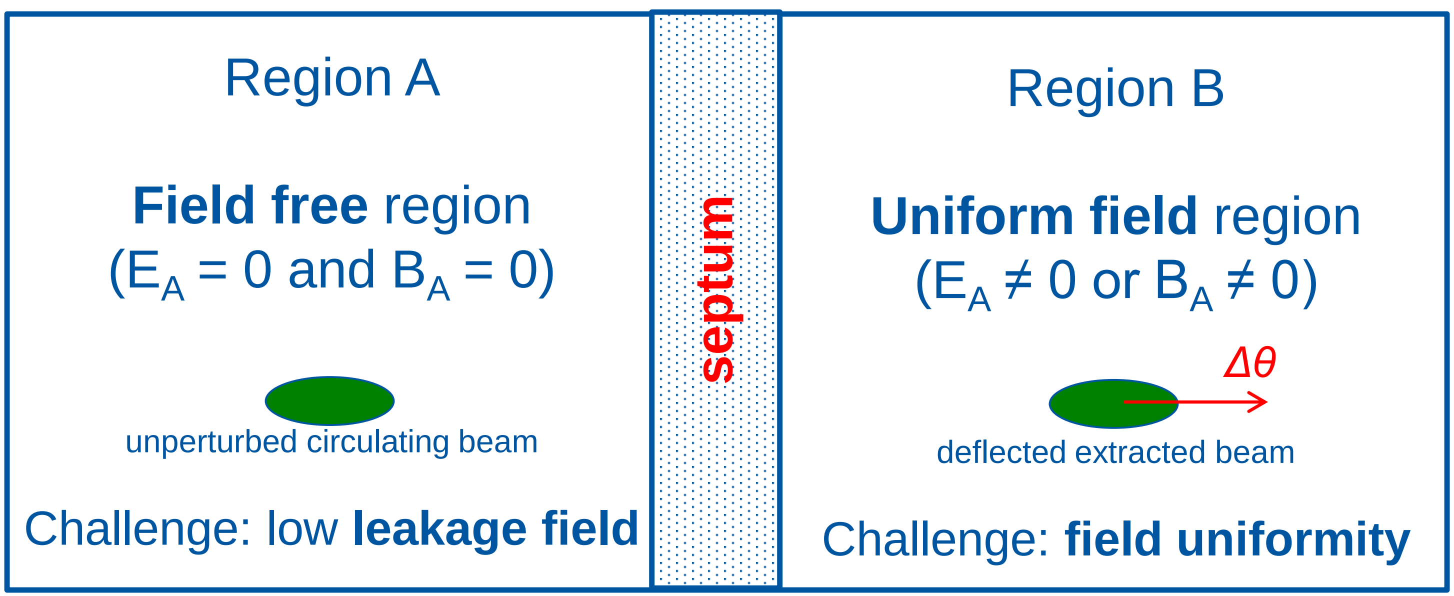


Kicker field: fast rise/fall, good flat-top, high precision timing

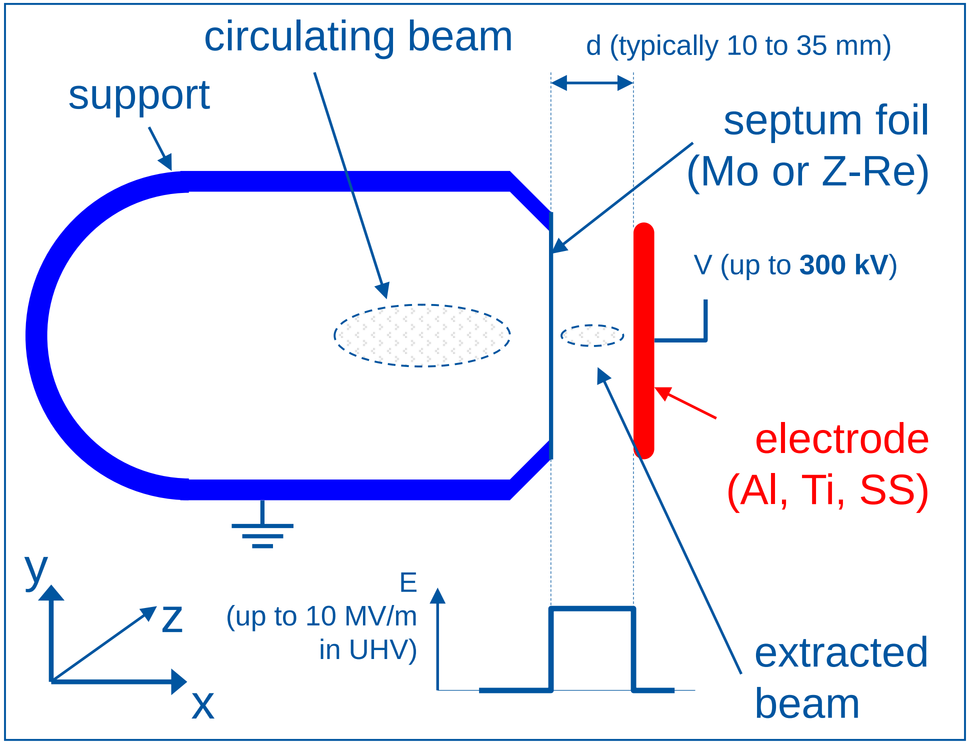
For more details see lecture on "Injection, Extraction and Beam Transfer" by Y. Dutheil

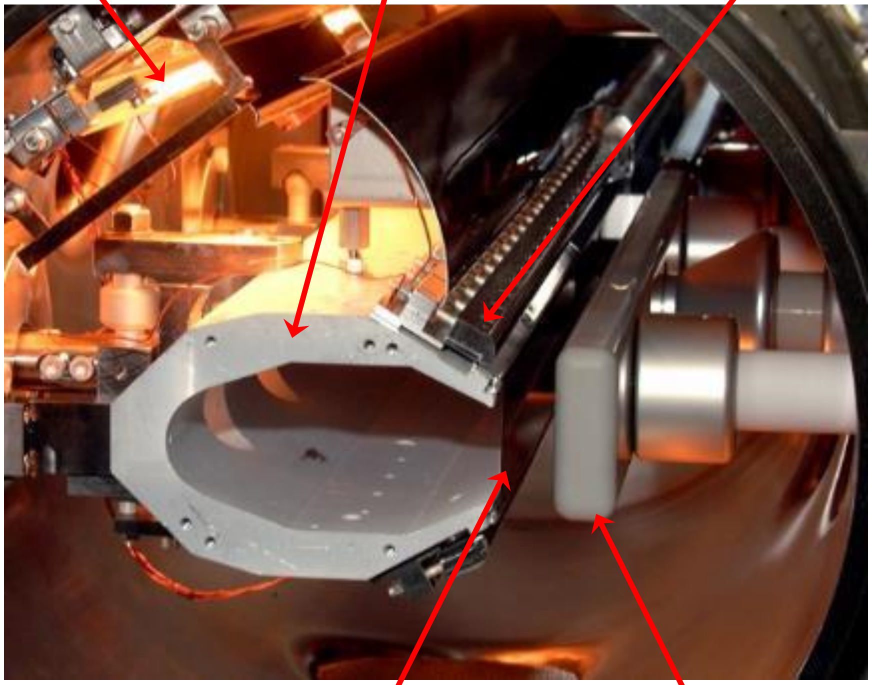
Septa

- Two main types:
  - **Electrostatic septa (DC)** → “weak” field, “thin” septum
  - **Magnetic septa** (DC and pulsed): → “strong” field, “thick” septum
    - Direct drive septum
    - Eddy current septum (pulsed only)
    - Lambertson septum (deflection parallel to septum)



Electrostatic foil septum





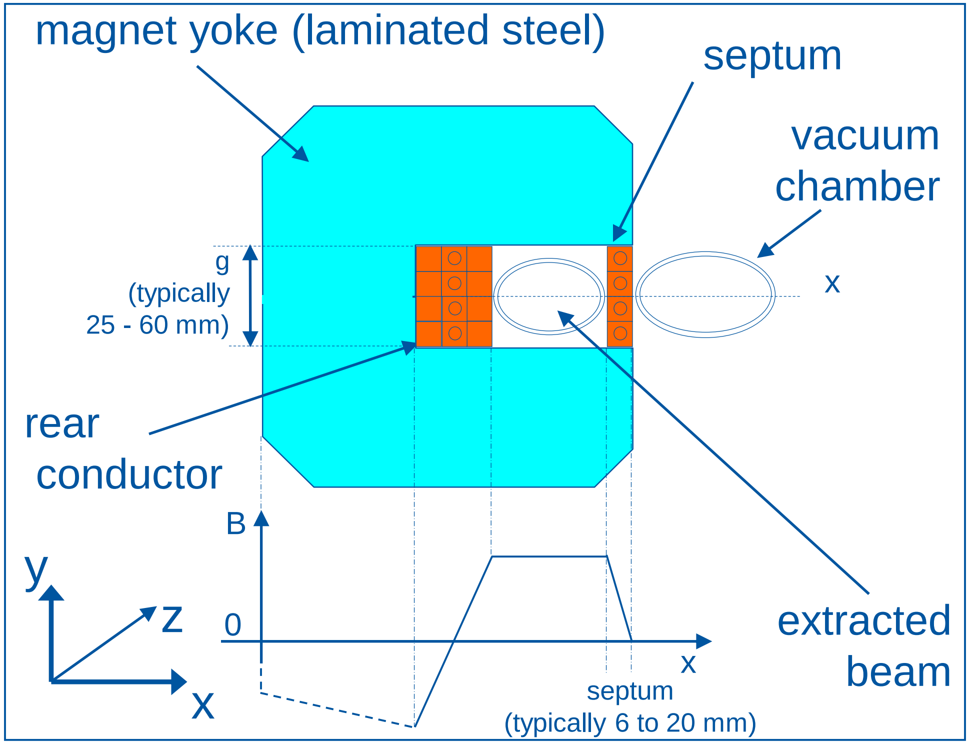
- **Thin septum ~0.1 mm** needed for high extraction efficiency:
  - Foils or stretched wire arrays provide thinner septa
- Challenges include **conditioning and preparation of HV surfaces**, vacuum in range of 10^{-9} – 10^{-12} mbar and **in-vacuum precision position alignment**

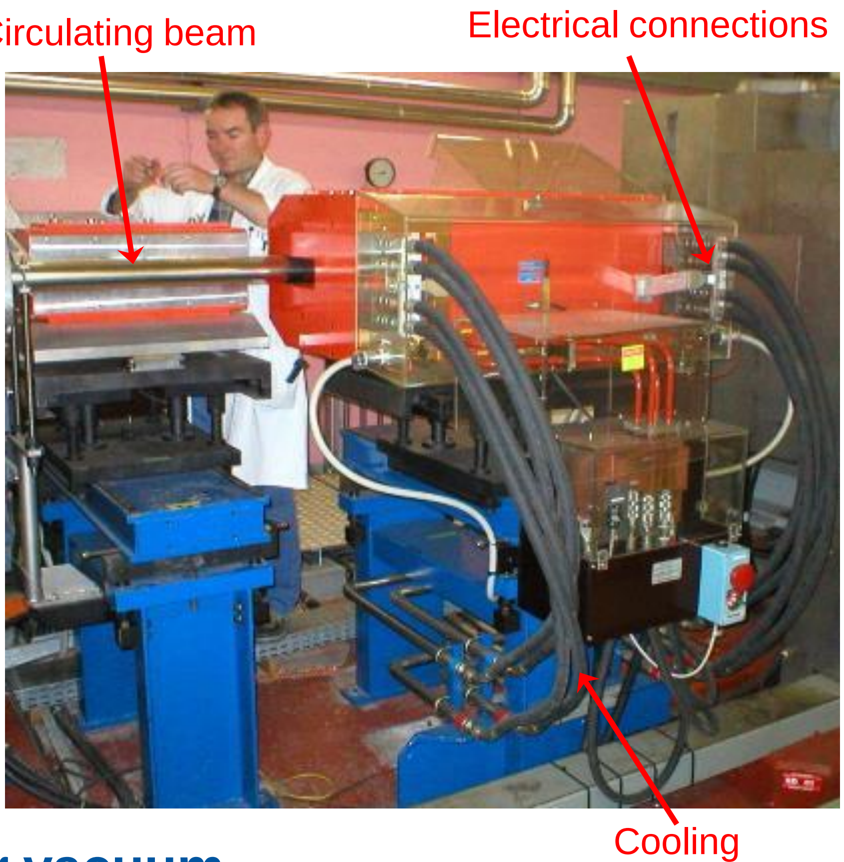
Electrostatic wire septum

At **SPS LSS2** we slow-extract 400 GeV protons using approximately **15 m of septum** split into 5 separate vacuum tanks, each over 3 m long.

Alignment of the 60 - 100 μm wire array over 15 m is challenging!

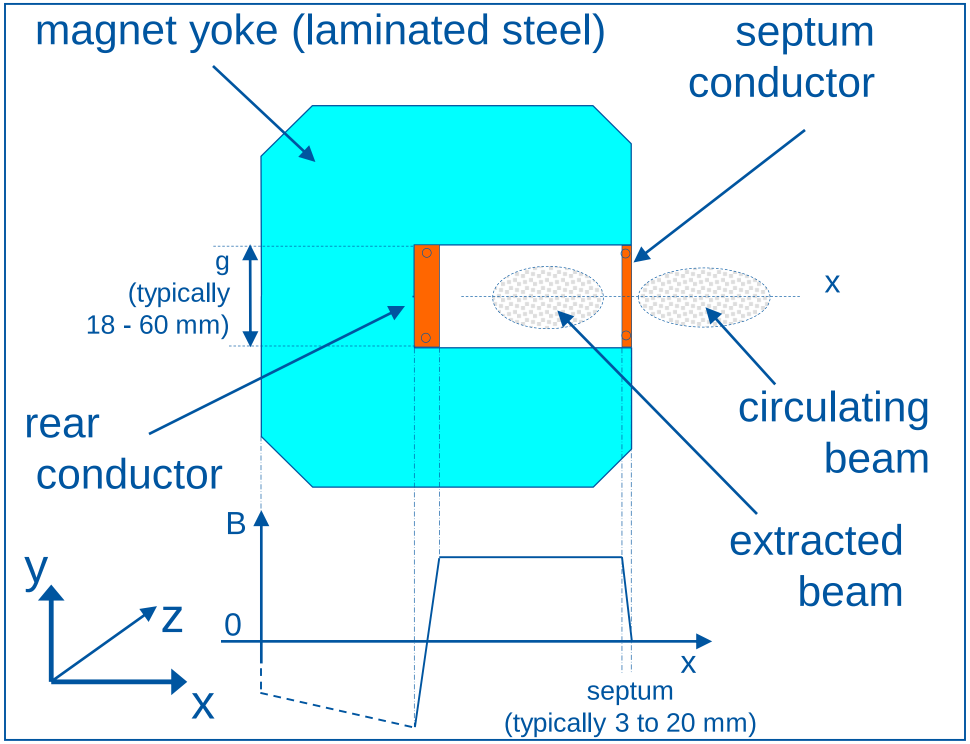
DC direct drive magnetic septum

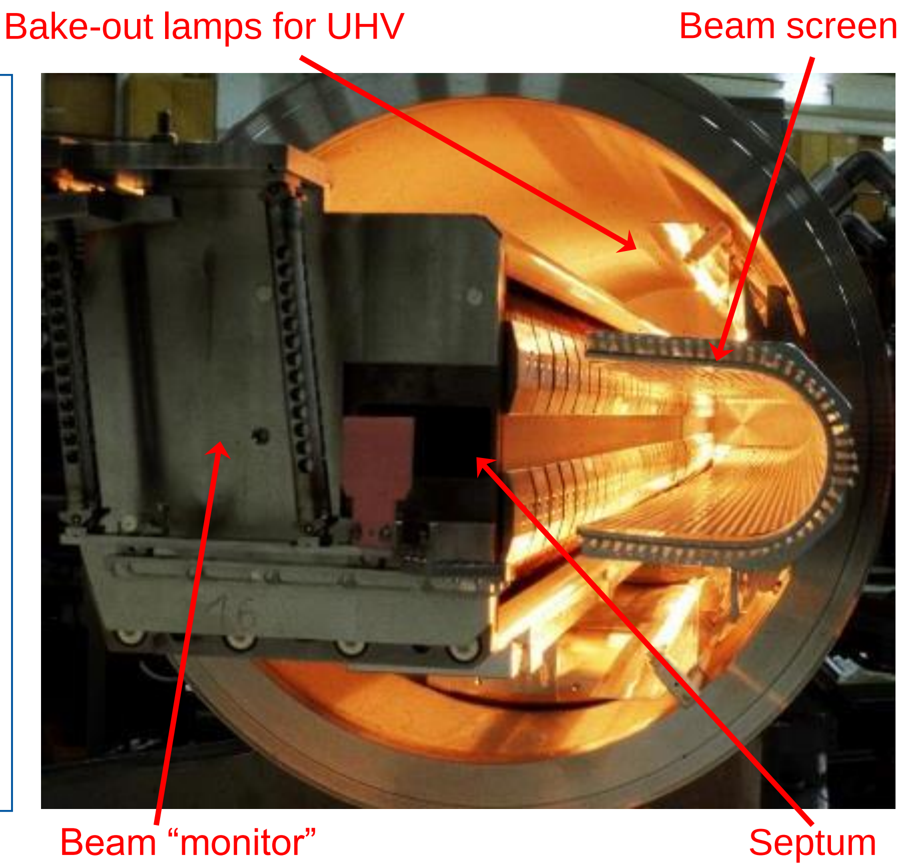




- **Continuously powered, rarely under vacuum**
- Multi-turn coil to reduce current needed but **cooling** still an issue:
  - Cooling water circuits flow rate typically at 12 – 60 l/min
  - Current can range from 0.5 to 4 kA and power consumption up to **100 kW**!

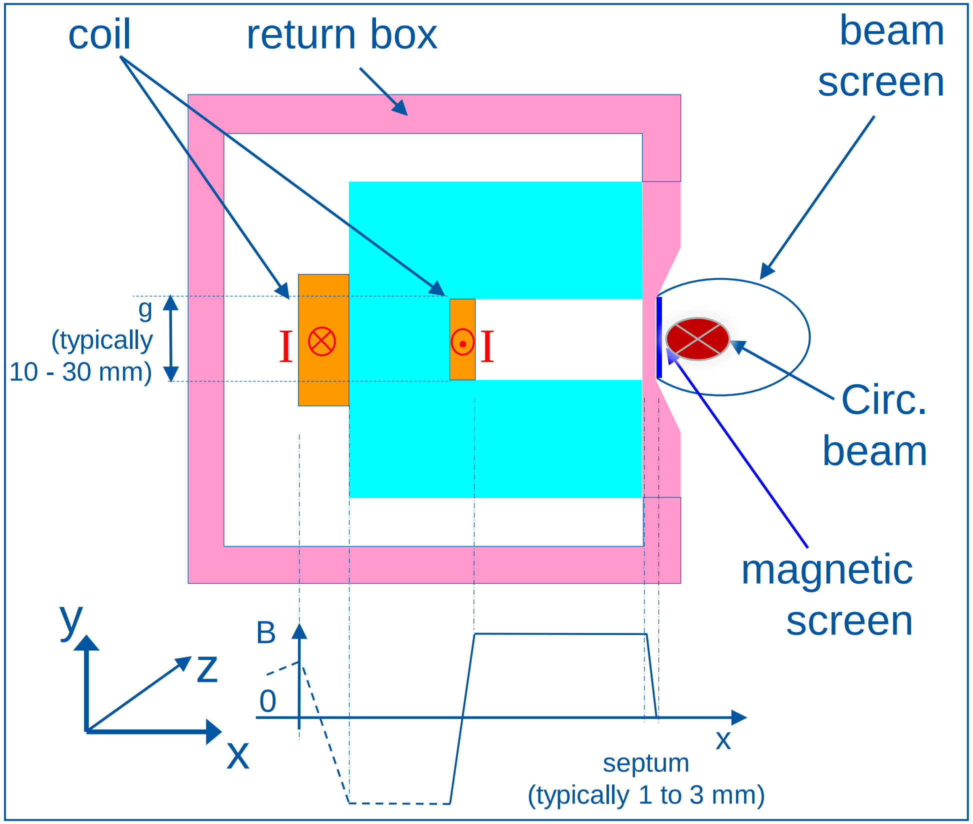
Direct drive pulsed magnetic septum





- **Pulsed current** allows for **thinner septum**
- Usually in vacuum, to minimise distance between circulated and extracted beam even more
- **Single-turn coil** to minimise inductance, bake-out up to 200 °C (~10^{-9} mbar)
- **Pulsed by capacitor discharge** (7 – 40 kA), Cooling water flow rate from 1 – 80 l/min

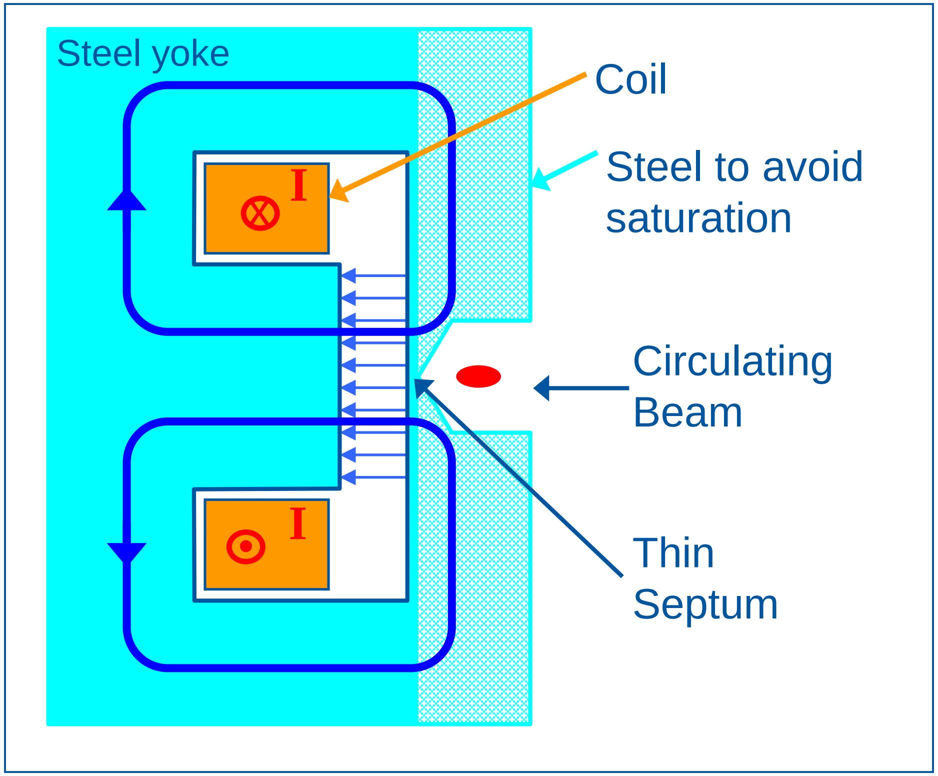
Eddy current septum



- Coil removed from septum and placed behind C-core yoke:
  - Coil dimension **not critical**
  - **Very thin septum blade**
- Magnetic field **pulse induces eddy currents** in septum blade
- Eddy currents **shield** the circulating beam from magnetic field
- Return box and **magnetic screen reduce fringe field** seen by circulating beam

- In or out of vacuum, single-turn coil
- Pulsed by capacitor discharge (~10 kA fast pulsed with ~ 50 μs oscillation period)
  - Cooling water flow rate from 1 – 10 l/min

Lambertson septum



- Magnetic **field in gap orthogonal** to previous examples of septa:
  - Lambertson deflects beam orthogonal to kicker: dual plane injection/extraction
- Rugged design: **conductors safely hidden** away from the beam
- Thin steel yoke between aperture and circulating beam – however extra steel required to avoid saturation, magnetic shielding often added

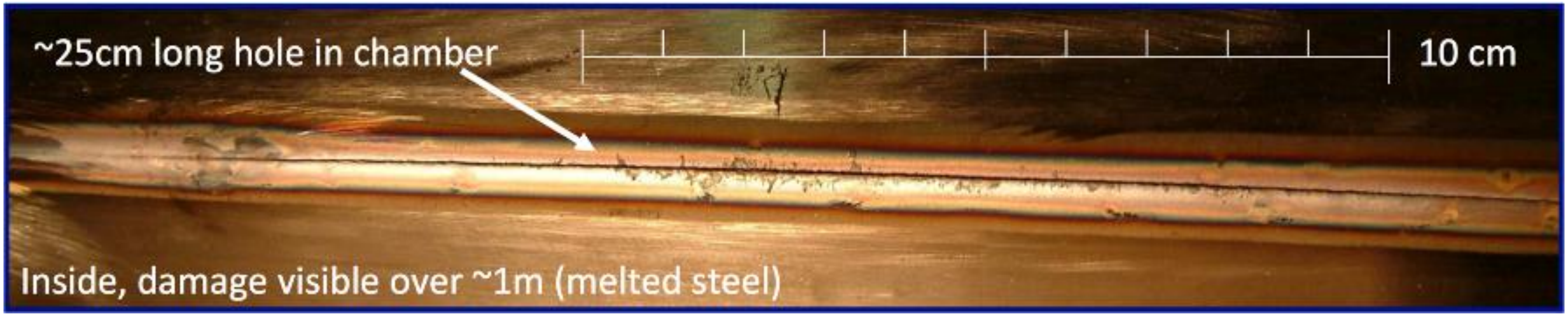
Summary Septa

- **Specialized asymmetric devices** to deflect injected and extracted batches in close vicinity of the circulating beam.
- **Electrostatic** and **magnetic** variants.
- Usually **normal conducting** (at least at CERN) but superconducting septa exist as well.
- **Challenging** in terms of **mechanical** and **electrical engineering** as well as during maintenance due to **UHV** and **radiation** environment.

Beam Transfer Protection Devices

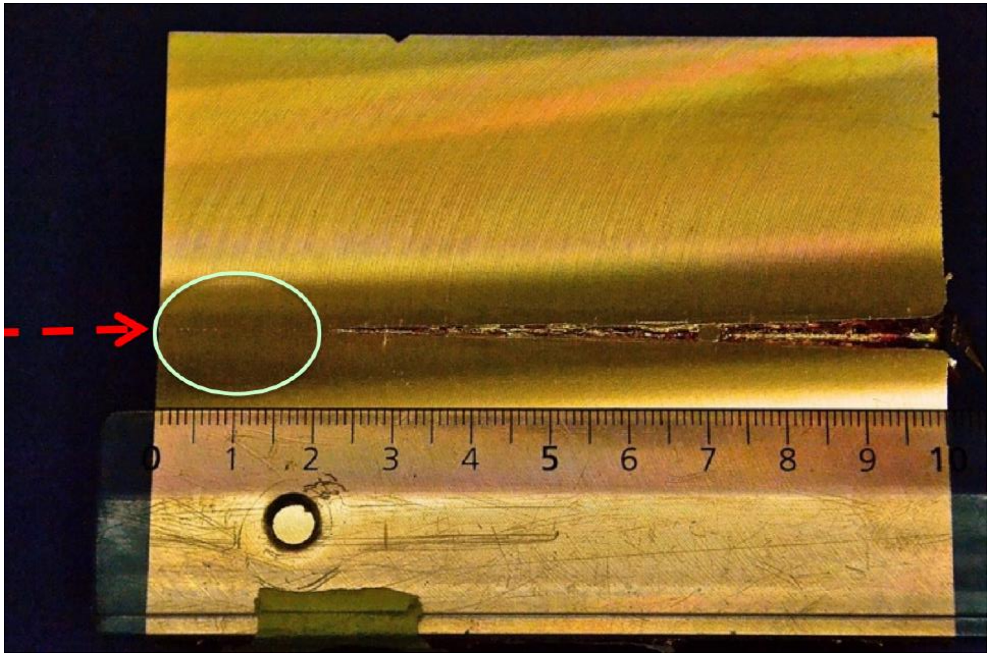
Protection devices

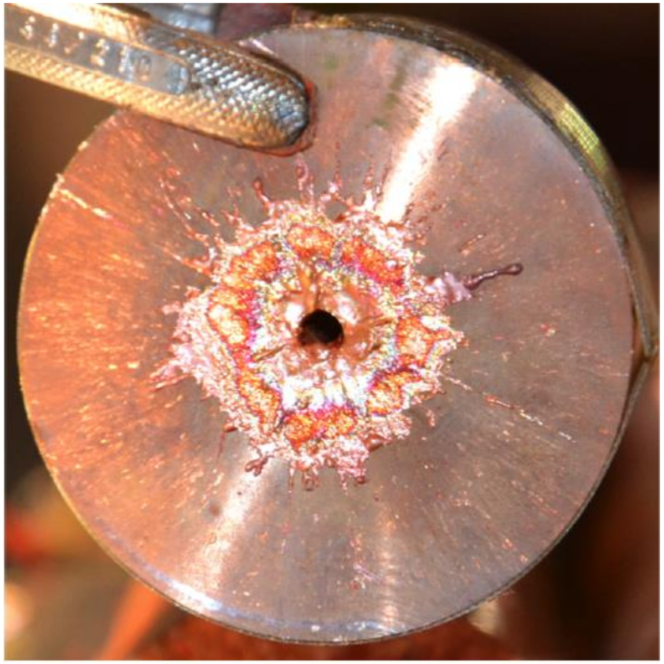
- Beam Transfer (BT) Protection devices **protect valuable equipment** and also increase machine availability.
- Wasn't such a concern in the early days. Getting crucial these days, even at relatively low energies, due to **record beam intensities and high brightness beams**. Nominal LHC beam can easily penetrate several meters of massive copper.
- **Active and passive protection devices** needed (e.g. Beam Interlock System (BIS) and absorbers).
- BT-Absorbers and dumps (with associated beam instrumentation) are also convenient for **commissioning** and (low intensity) beam **setup.** These devices also need to be **validated**.
- In 2004 an extraction septum power supply failure and directed 3.4×10^{13} protons, at 450 GeV, into the transfer line (TL) vacuum chamber (2.5 MJ beam energy).



Damage Studies

- Important to understand failure scenarios and material properties (**damage limits**).
- Simulation of **failure scenarios** (MAD-X) and **impact** (FLUKA).
- Validation of simulations by experiments e.g. at CERN's HiRadMat facility.





http://www.cern.ch/hiradmat/

Protection devices

- When beam **parameters exceed damage limit**: critical beam transfer systems need redundancy and multiple layers of protection:
  - **“Fail-Safe” design**
  - **Active protection** systems (e.g. BIS, not covered in this talk)
  - **Passive protection** devices are the last layer of security
    - Passive protection devices are **designed to dilute and absorb beam energy** safely

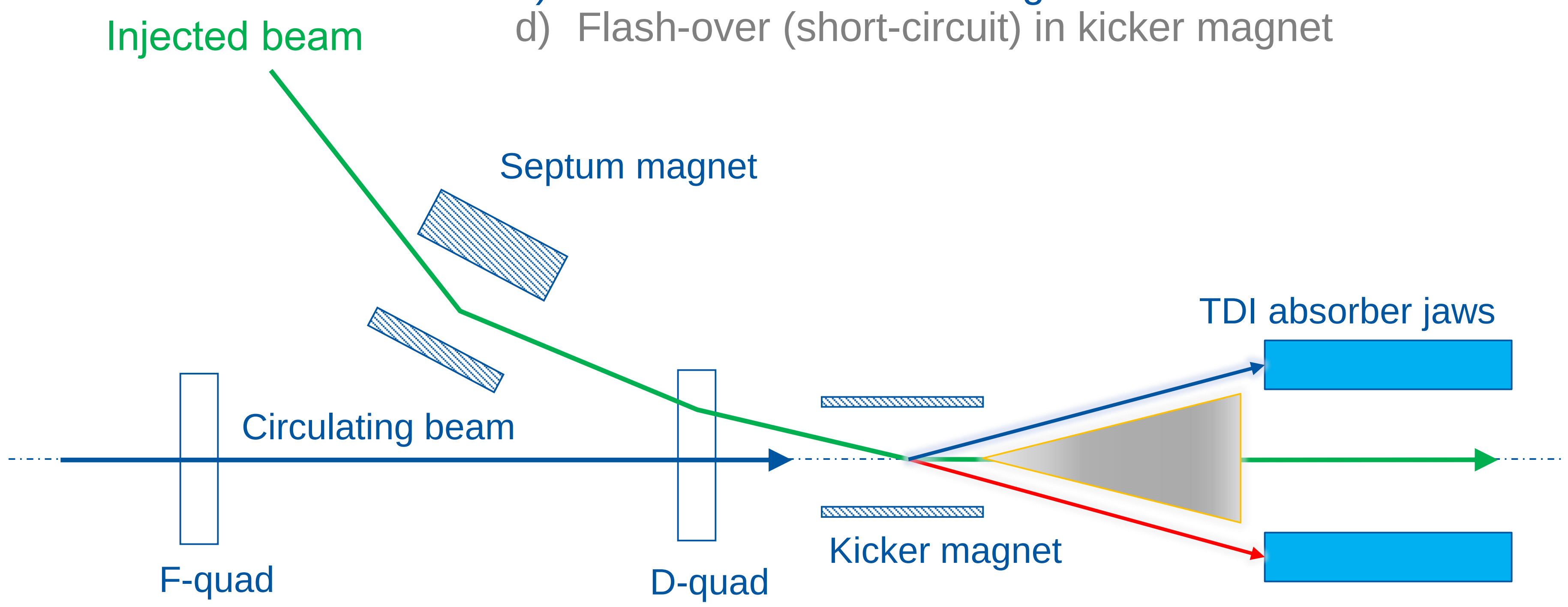
- **Failures** associated with beam transfer equipment are typically **<u>very fast</u>** and difficult to catch, for example:
  - **No turn-on** of kicker: injection protection
  - **Erratic** turn-on of kicker: circulating beam swept over aperture
  - **Flash-over** (short-circuit) in kicker: wrong kick angle
  - **Wrong timing** or particles in abort gap
  - **Transfer line failure:** steering beam into aperture limitation of downstream machine

See talk from Markus Zerlauth: “Machine Protection”

Example: Injection protection

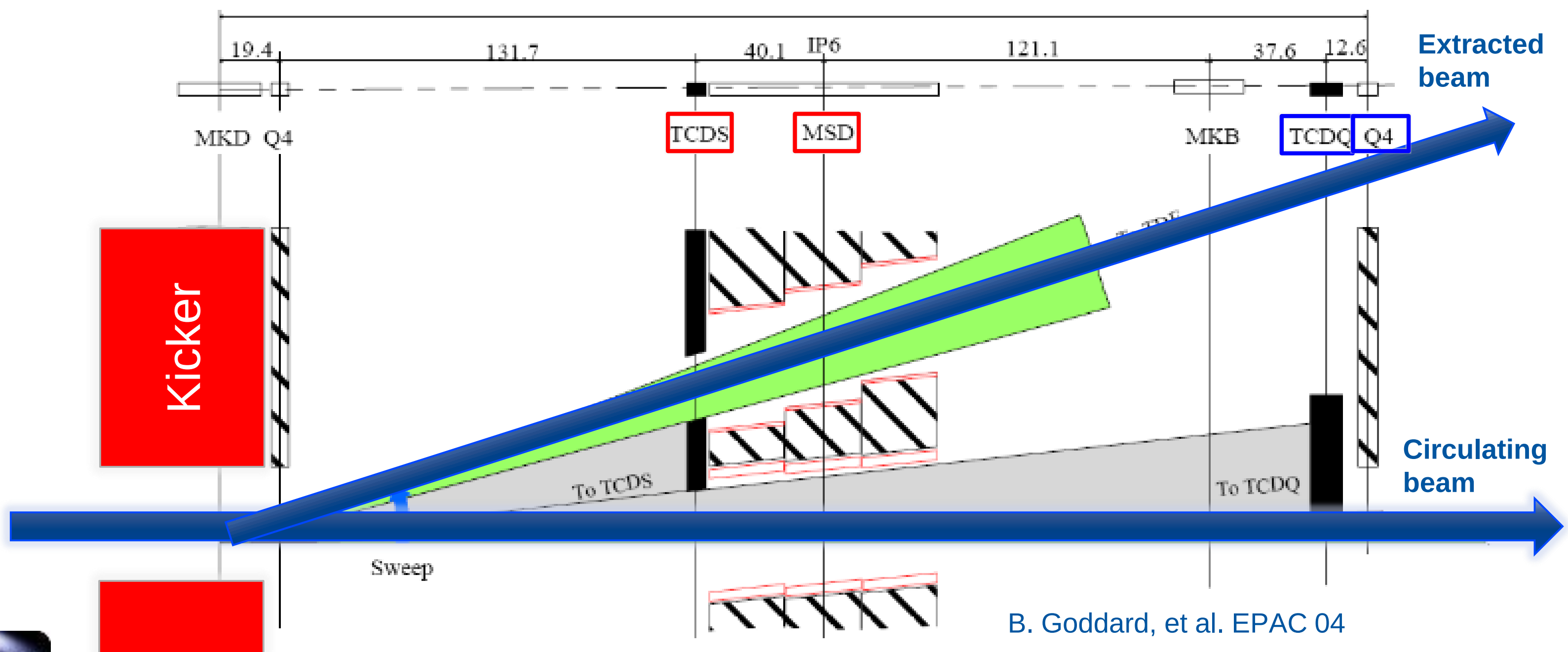
Dedicated injection dump (TDI) to protect against fast failures of the injection kicker system.

a) Normal injection process
b) No turn-on: beam steered onto absorber
c) Erratic turn-on: circulating beam steered onto absorber
d) Flash-over (short-circuit) in kicker magnet



Example: LHC Extraction protection

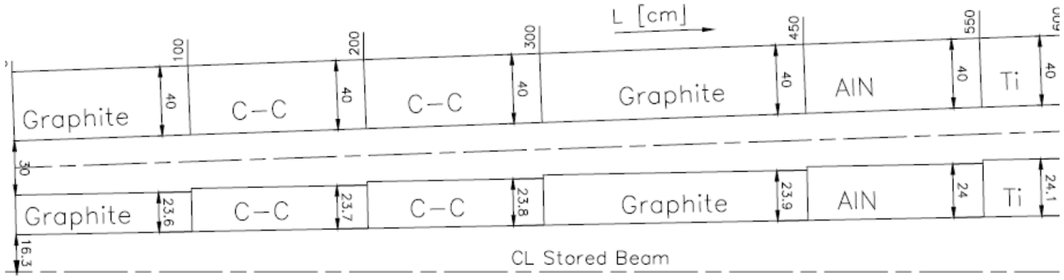
- **360 MJ stored energy** per beam to be safely extracted. **Reliability** and **machine protection** is a major concern.
- **Kickers** are (typically) turned-on in a particle free 3 µs long **abort gap:** next arriving beam is then deflected into the dump line.
- **Absorbers** in front of septa (TCDS) and Q4 (TCDQ).
- **Abort Gap Keeper** and **Abort Gap Cleaning**.
- Sophisticated **Beam Interlock System**. (e.g. Surveillance of orbit, BLMs, MB current, Septa, Kicker, Access etc. over 10,000 devices connected)



B. Goddard, et al. EPAC 04

LHC Extraction: Passive Protection Devices

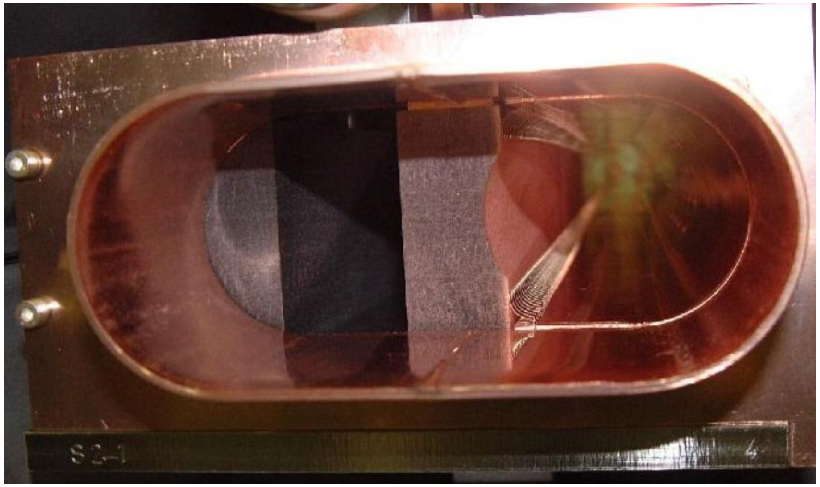
TCDS

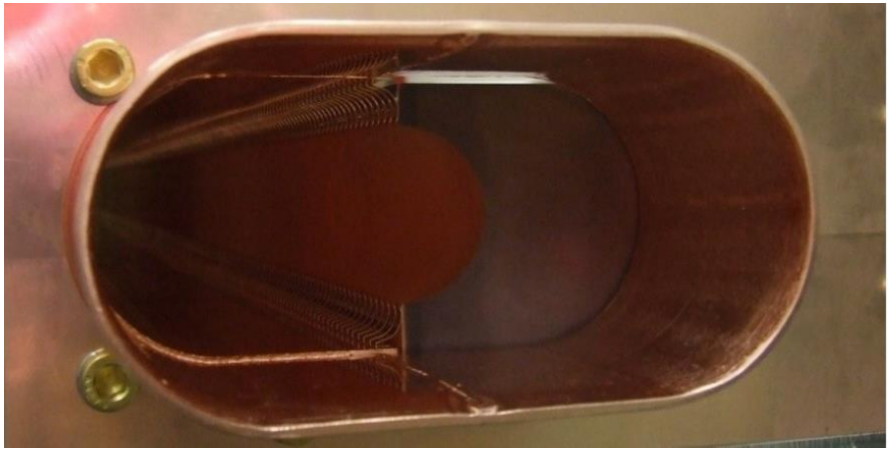


Sandwich construction.

TCDQ

Movable jaws (follows beam energy)





Summary BT-Protection Devices

- **Dedicated absorbers** for Transfer Line, injection and extraction protection are used **when beam parameters exceed damage limit**.

- Designed to **dilute and absorb beam energy** safely.

- Premise is however to **reduce critical failure** cases **by design**.

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Thanks for your attention!

Questions?

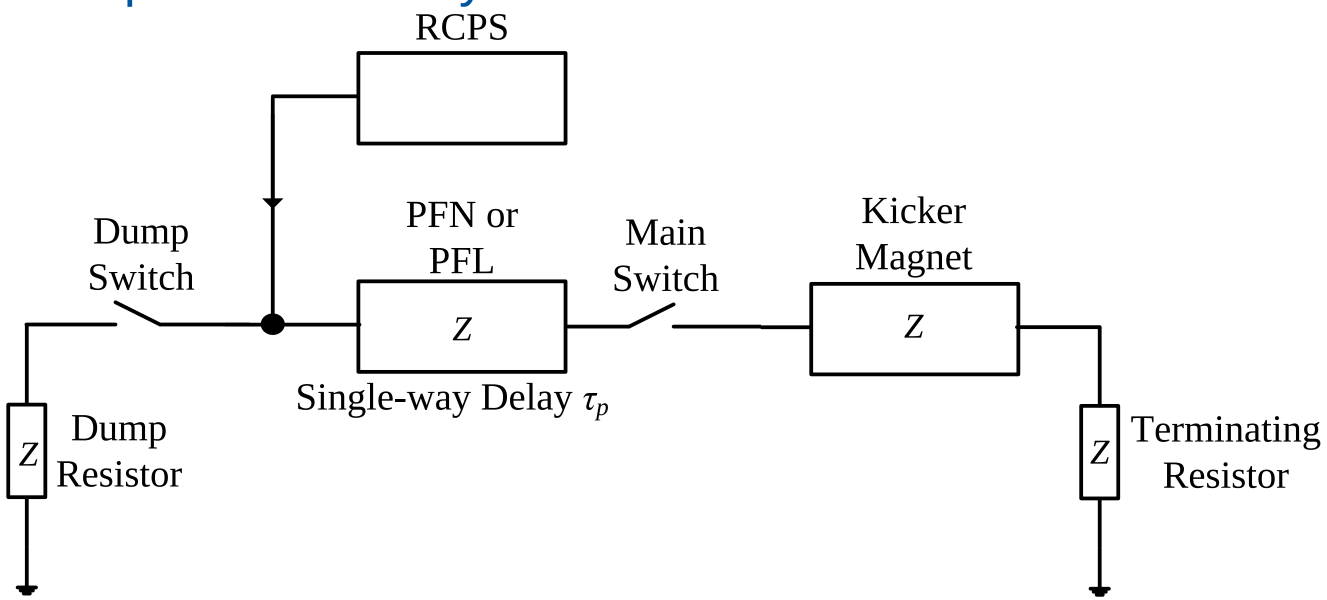
If you have questions later on: feel free to ask them by email!

Spare Slides

Pulse Transmission

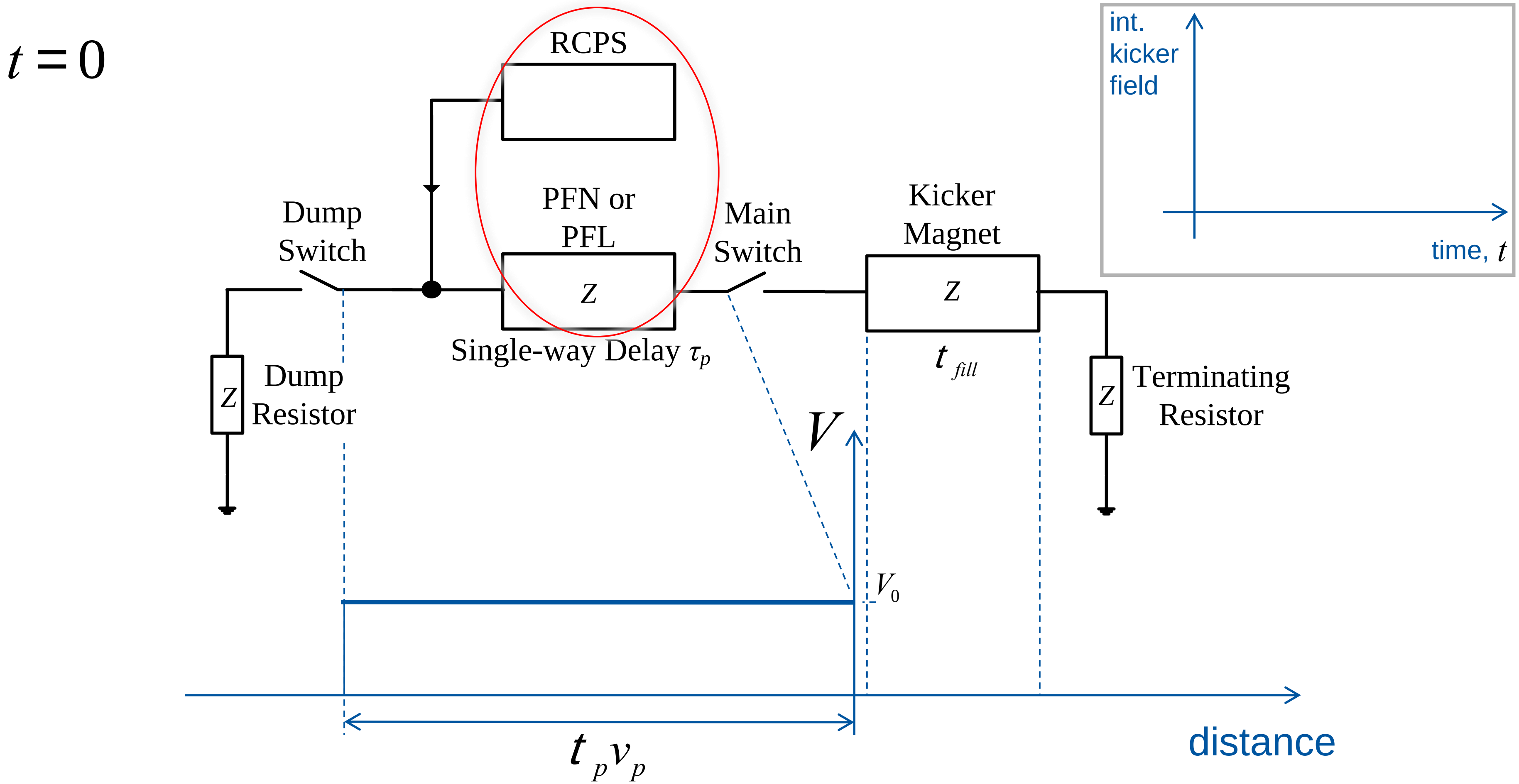
Pulse Transmission

- Simplified kicker system schematic:



What happens when we pulse the system?…

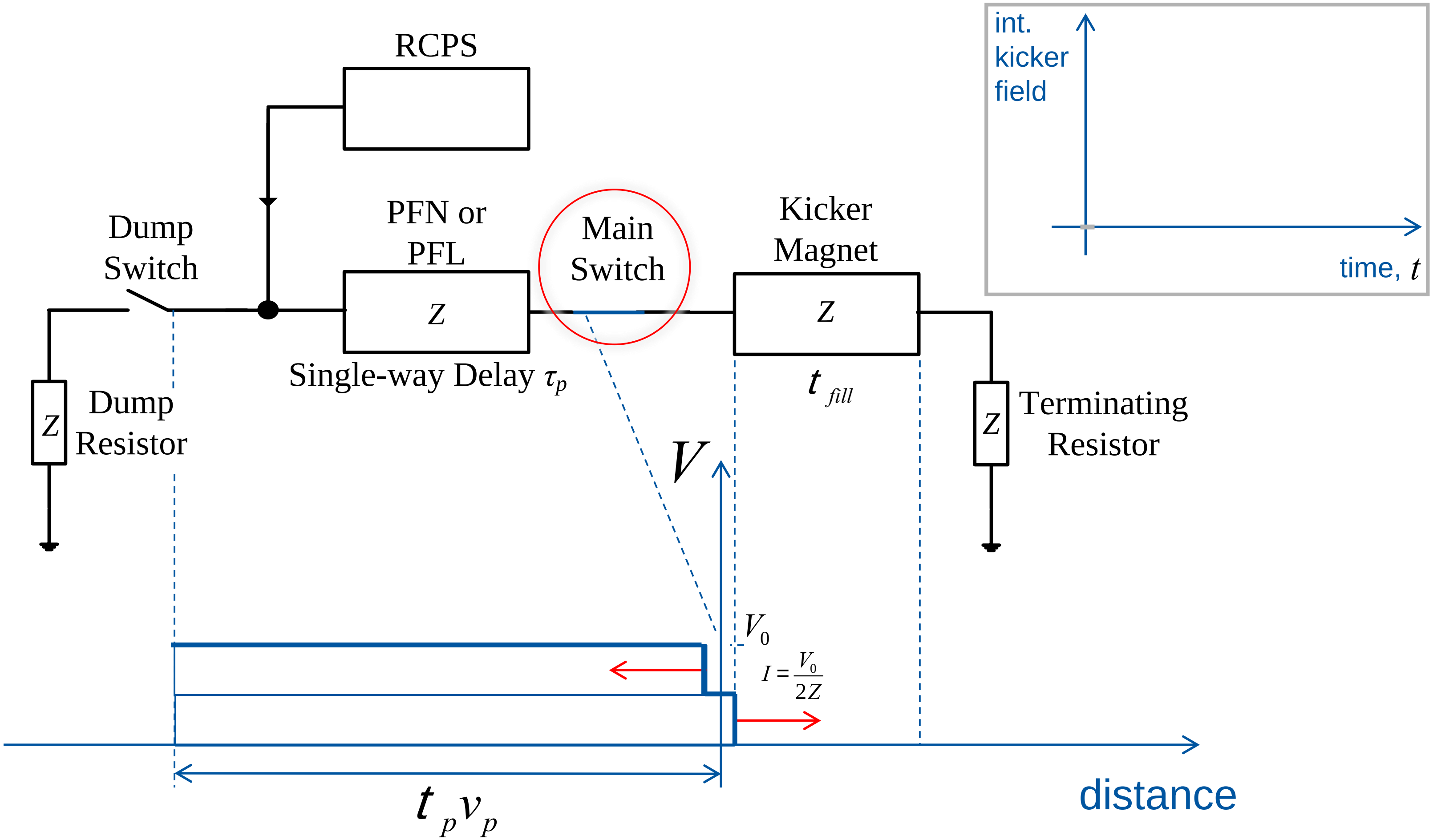
Simplified kicker system schematic



- Pulse forming network or line (PFL/PFN) charged to voltage V_0 by the resonant charging power supply (RCPS)
  - RCPS is de-coupled from the charging system by a diode stack

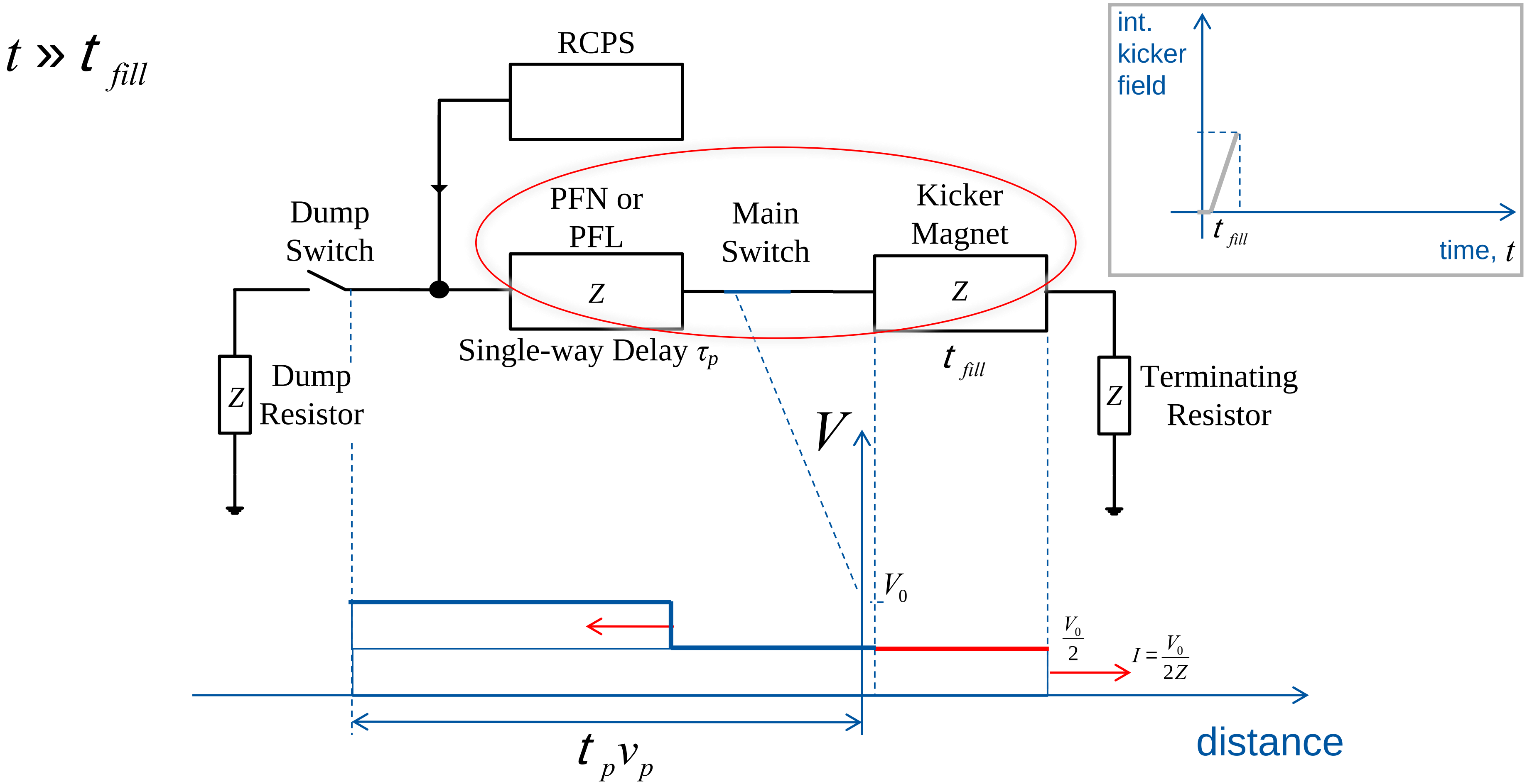
Simplified kicker system schematic

$t \gg 0$



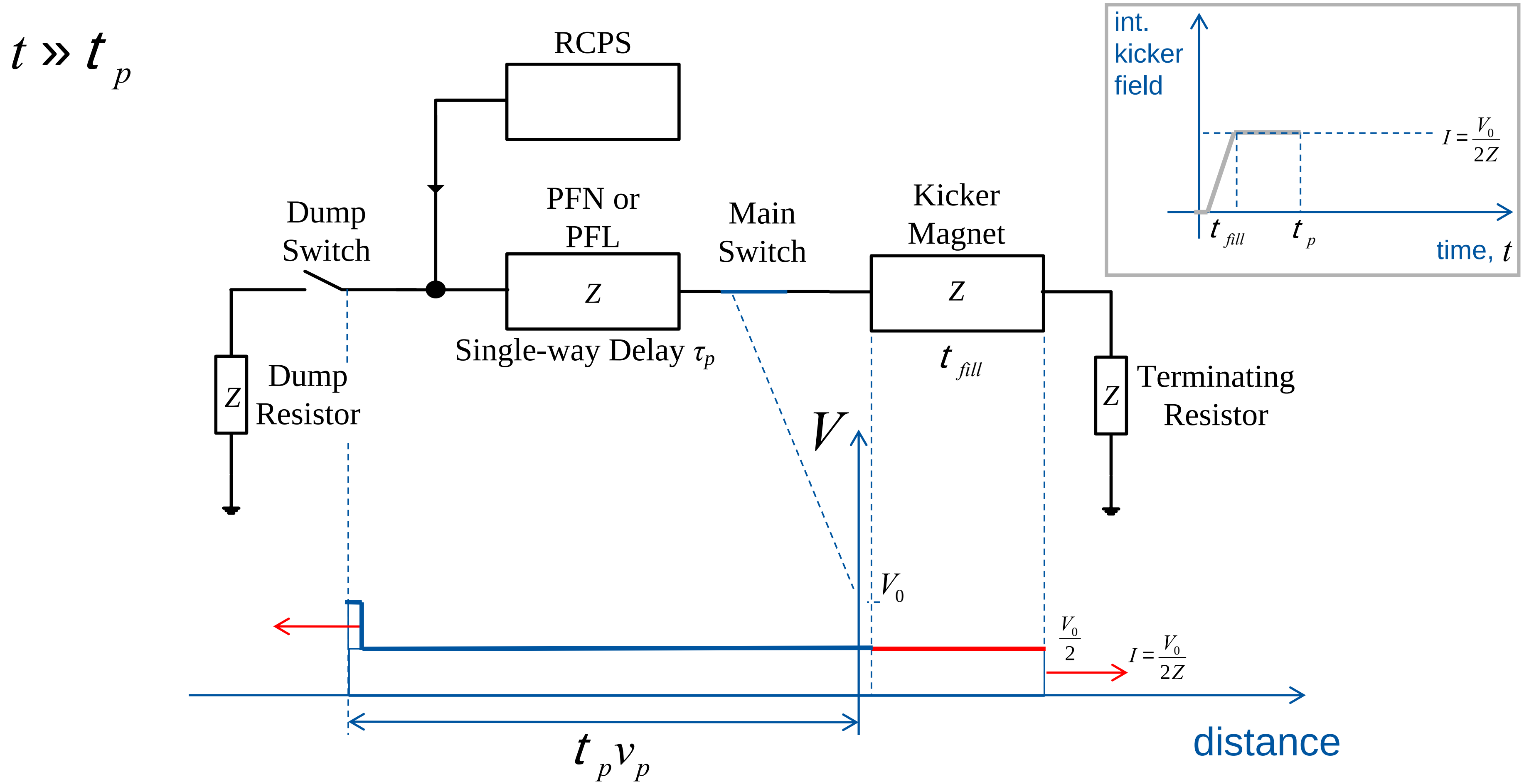
- At $t = 0$, main switch is closed and current starts to flow into the kicker

Simplified kicker system schematic



- At $t = \tau_{fill}$, the voltage pulse of magnitude $V_0/2$ has propagated through the kicker and nominal field achieved with a current $V_0/2Z$
  - Typically, $\tau_p >> \tau_{fill}$ (schematic for illustration purposes)

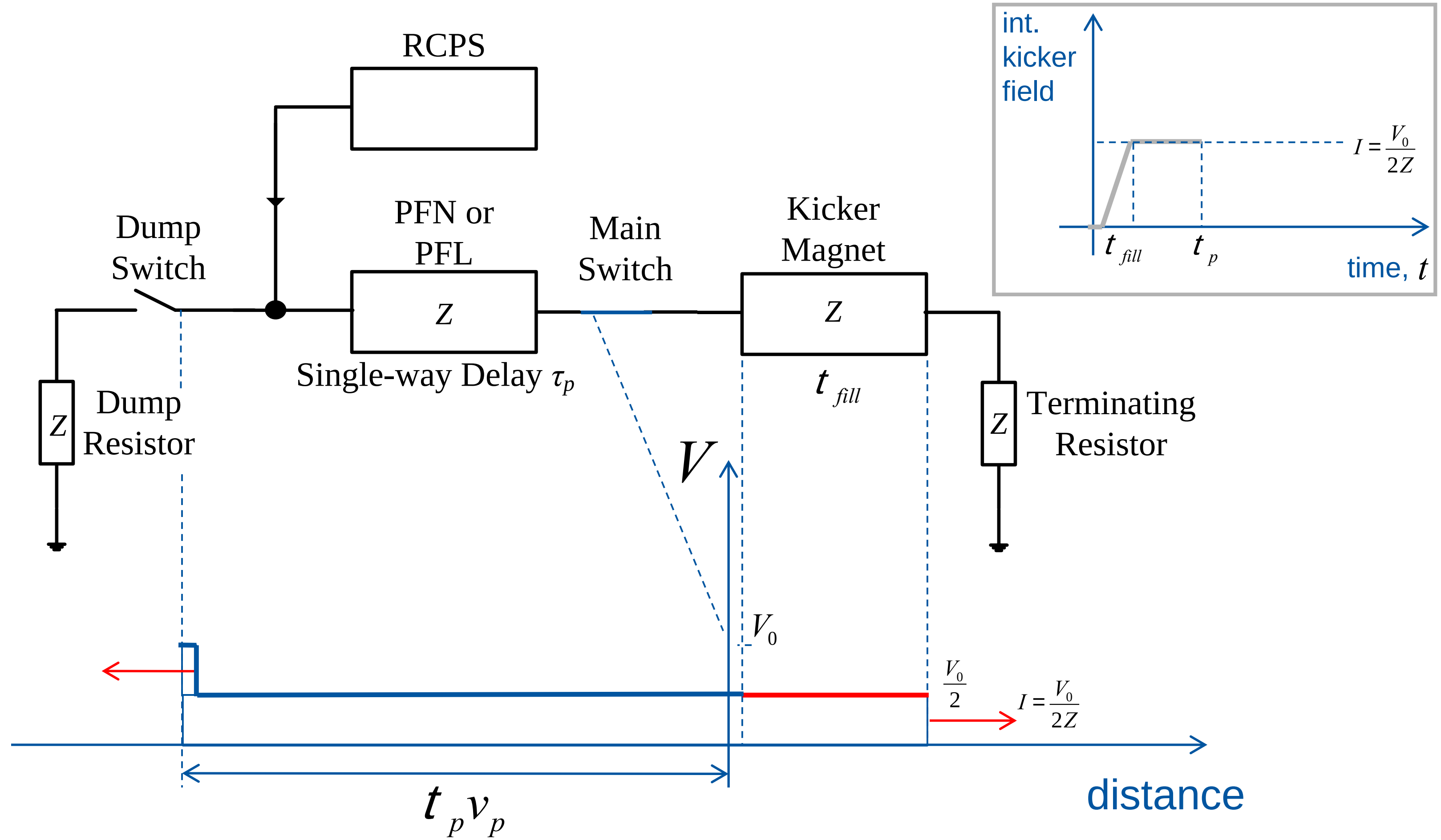
Simplified kicker system schematic



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

Simplified kicker system schematic

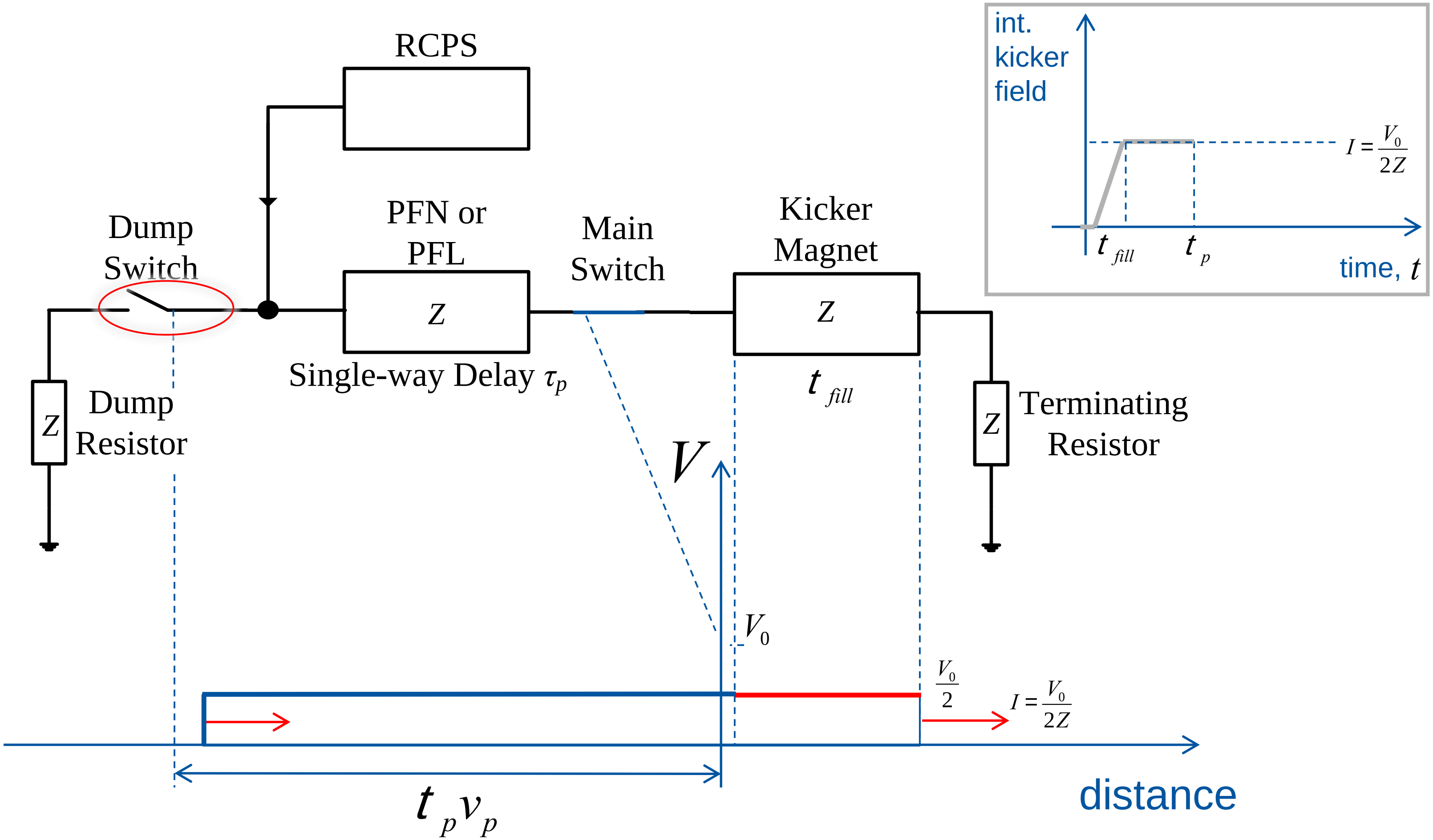
$t \gg t_p$



- PFN continues to discharge energy into kicker magnet and matched terminating resistor
- At $t \approx \tau_p$ the negative pulse reflects off the open end of the circuit (dump switch) and back towards the kicker

Simplified kicker system schematic

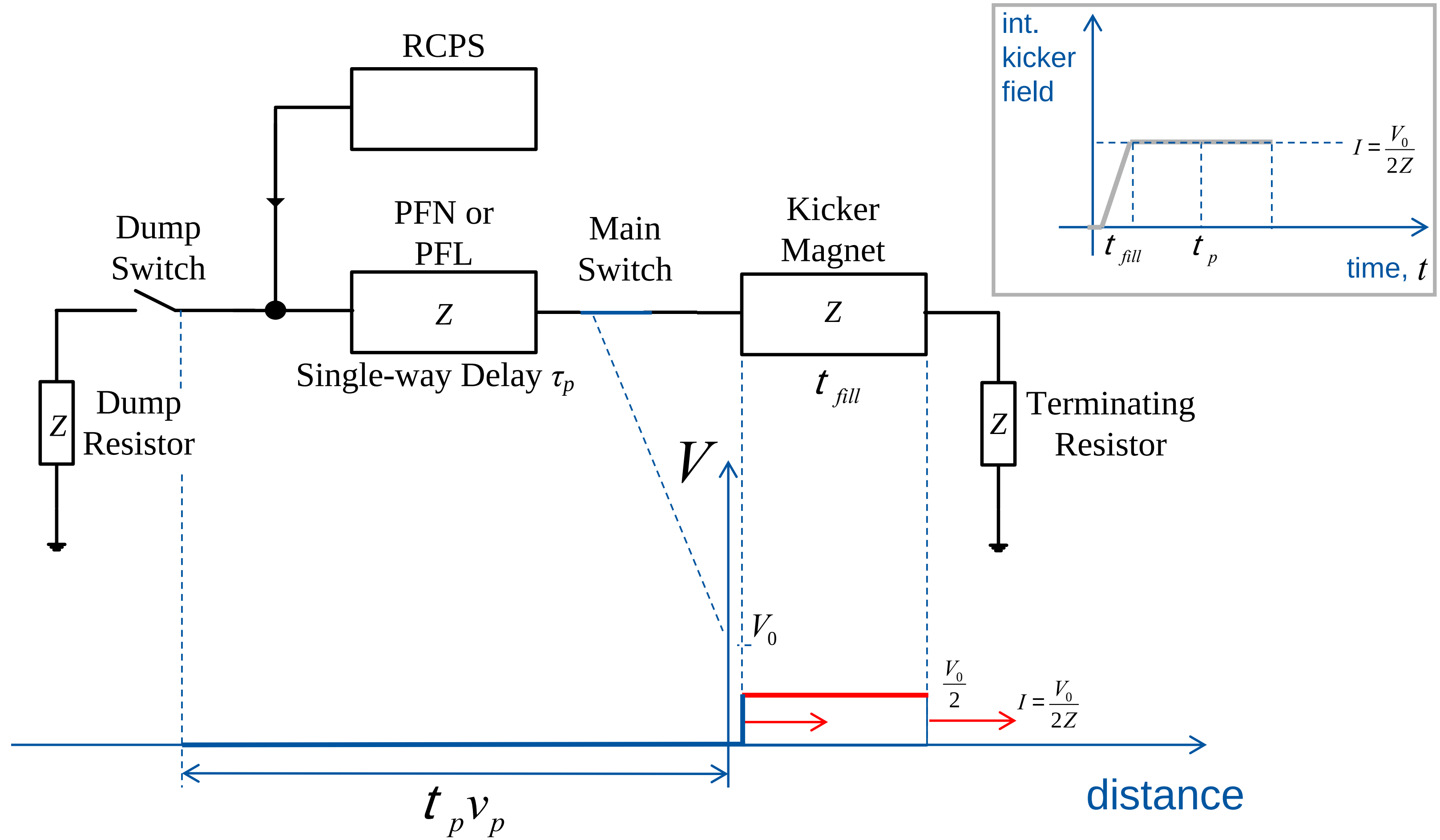
$t \gg t_p$



- Dump switch is open, hence PFN continues to discharge energy only into magnet and matched terminating resistor.

Simplified kicker system schematic

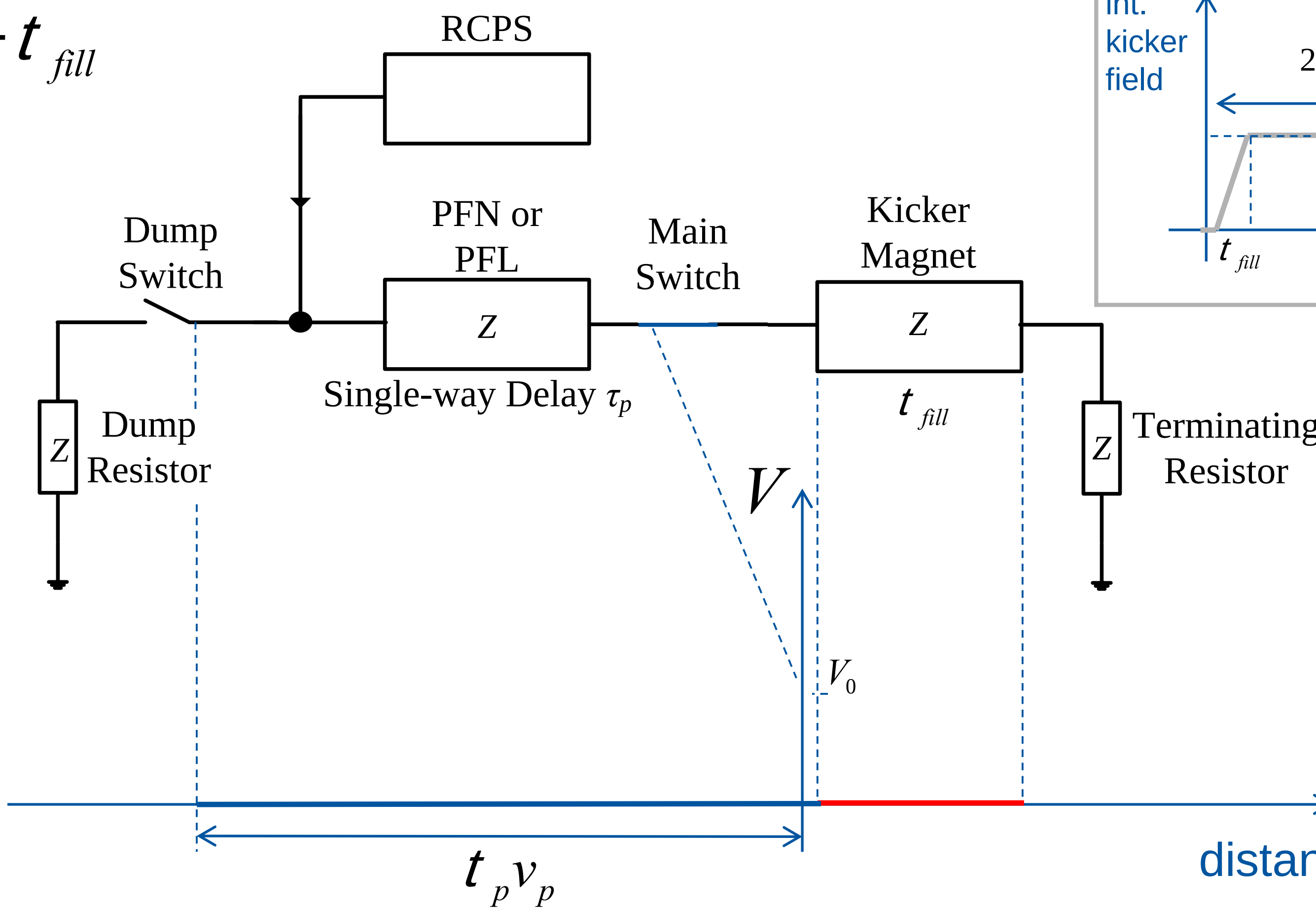
t » $2t_p$

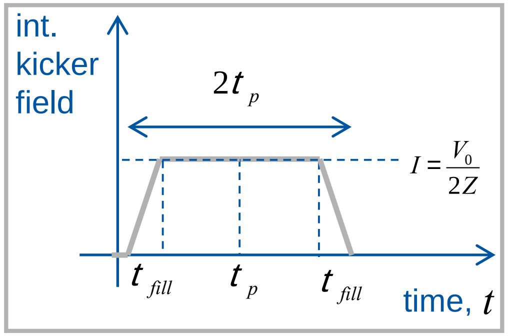


- At $t \approx 2\tau_p$ the reflected pulse from the open dump switch arrives at the kicker and field starts to famm.

Simplified kicker system schematic

$$t = 2t_p + t_{fill}$$





- Pulse reduced to zero. All energy from PFN/PFL has been dissipated.
- Kicker pulse length can be changed by adjusting the relative timing of dump and main switches. e.g. if the dump and main switches are fired simultaneously the pulse length in the magnet will be halved and energy shared on dump and terminating resistors.

Pulse Transmission: Reflections

- Reflection coefficient:
  - Ratio of reflected wave to incident wave

$$\Gamma = \frac{E^-}{E^+} \quad \Rightarrow \quad \Gamma = \frac{Z_{Load} - Z_{Source}}{Z_L + Z_S}$$

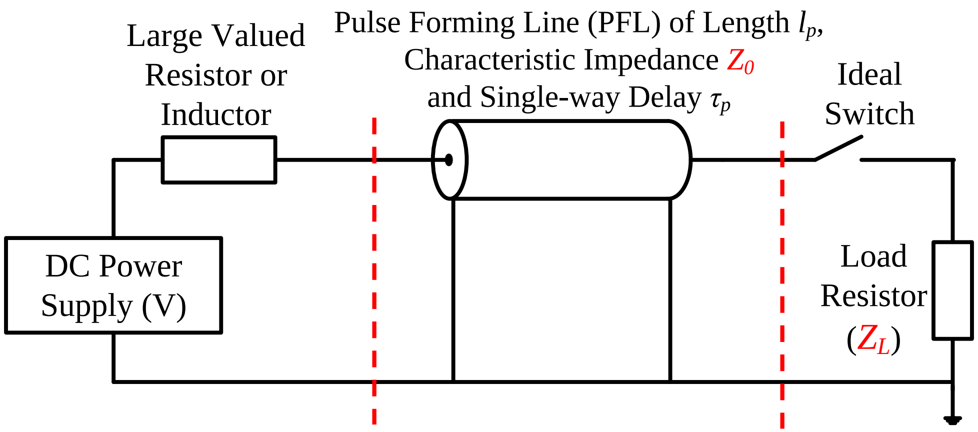
- 50 Ω load $\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S} = \frac{50-50}{50+50} = 0$

- SC load $\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S} = \frac{0-Z_S}{0+Z_S} = -1$

- Open load $\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S} = \frac{\infty-Z_S}{\infty+Z_S} = 1$

Load Voltage

- A simplified pulse forming circuit pre-charged to voltage U:



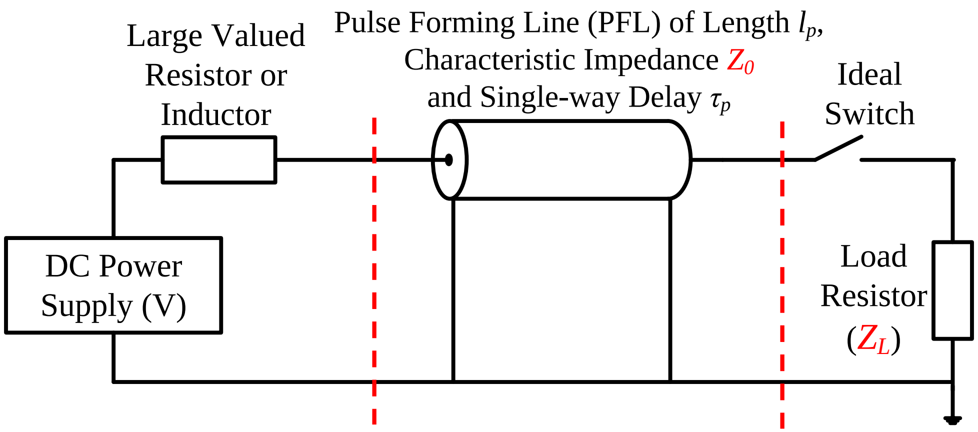
- When the switch is turned on the voltage is divided as: $$U_L = U \cdot \left(\frac{Z_L}{Z_0 + Z_L} \right) = \alpha V$$

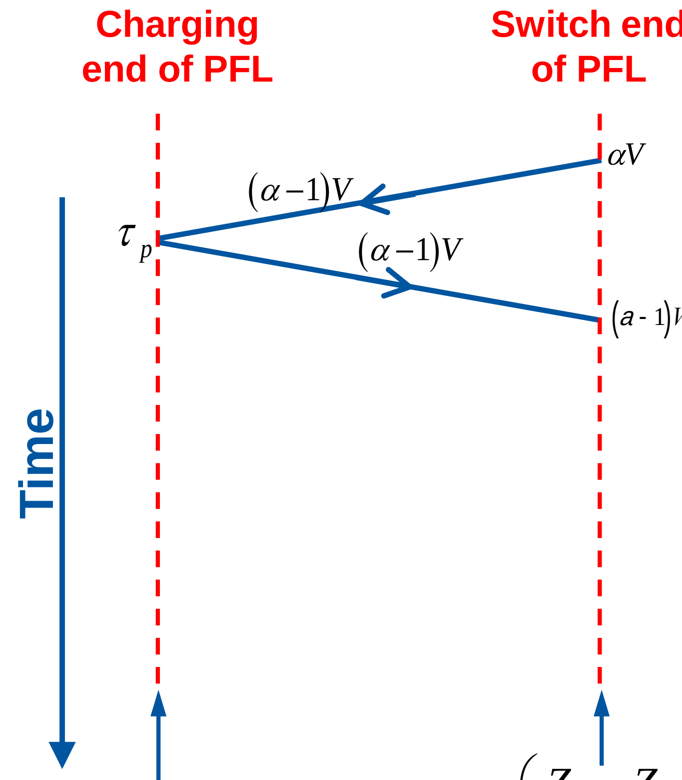
- In the matched case: $Z_0 = Z_L$ $\qquad \alpha = \frac{1}{2}$

- Hence PFL charging voltage is twice the required voltage!

Reflections

- A simplified pulse forming circuit pre-charged to voltage U:





G=1

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

for matched case:

$\Gamma = 0$

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

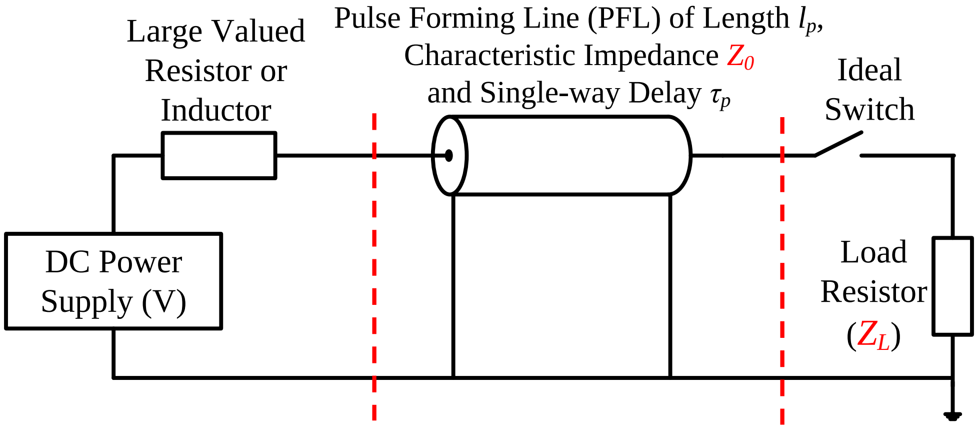
$$V_L = V \cdot \left(\frac{Z_L}{Z_0 + Z_L}\right) = \alpha V$$

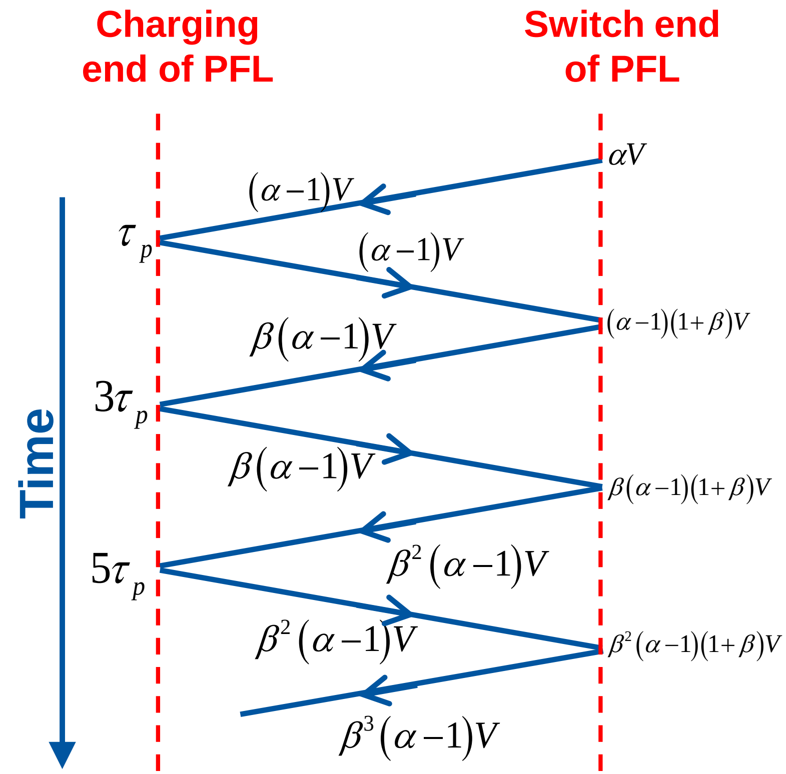
- In the matched case:

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

Reflections

- A simplified pulse forming circuit:





Match impedances to avoid reflections!

- When the switch is fired the voltage is divided as:

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

- In the matched case:

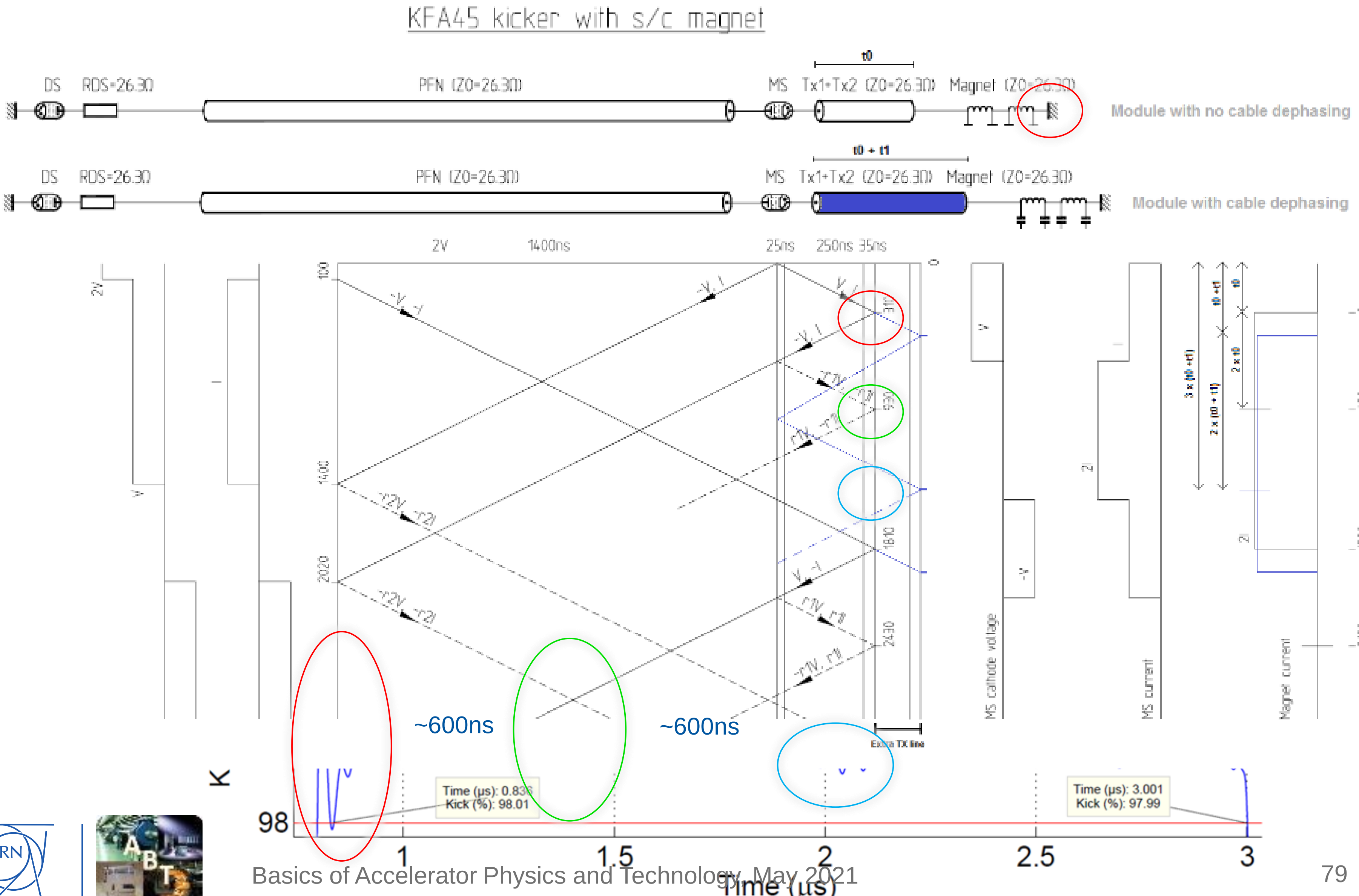
$$Z_0 = Z_L \qquad a = \frac{1}{2}, \; b = 0$$

In general (mis-matched):

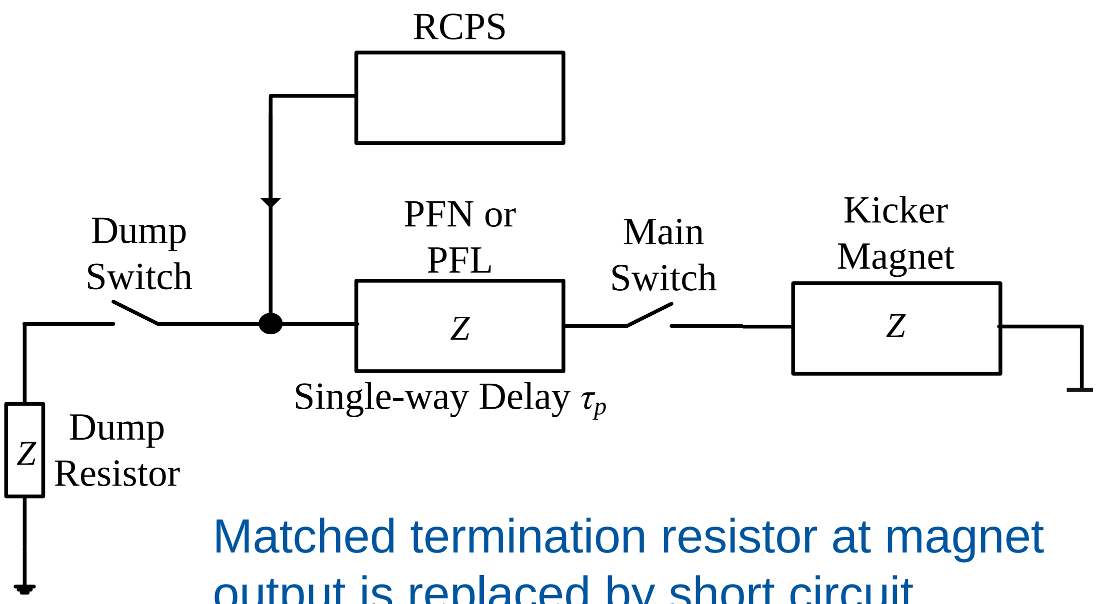
G=1

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

Reflections: Example KFA-45



Terminated vs. Short Circuited (SC) mode



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

- At SC point:
  - Voltage =0 (incoming and reflected waves cancel)
  - Current doubles $I_{sc} = V\left(\frac{1-\Gamma}{Z}\right)$
- Magnet kick strength doubles but also the reflected wave needs to travel through the kicker again -> 'fill time' doubles as well.
- Any system mismatch will create reflections!