Injection and Extraction elements

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Acknowledgement

This presentation is based on talks given earlier:

- T. Kramer, “Kickers, Septa and Protection Elements”, BASIC CAS course, 2021
- M. Barnes, “Kicker magnets I”, CAS Beam injection, extraction and transfer, Erice (I) 2017
- M. Barnes, “Kicker magnets II”, CAS Beam injection, extraction and transfer, Erice (I) 2017
- M. Barnes, “Injection & Extraction Magnets I: Septa”, CAS Magnets, Bruges (B) 2009
- M. Barnes, “Injection & Extraction Magnets I: Kickers”, CAS Magnets, Bruges (B) 2009

Outline

- **Introduction**
- **Septa**
  - Magnetic
    - Topologies
  - Electrostatic
- **Kickers**
  - Principle requirements
    - Topologies
- **Extraction protection devices**
- **Summary**

Introduction

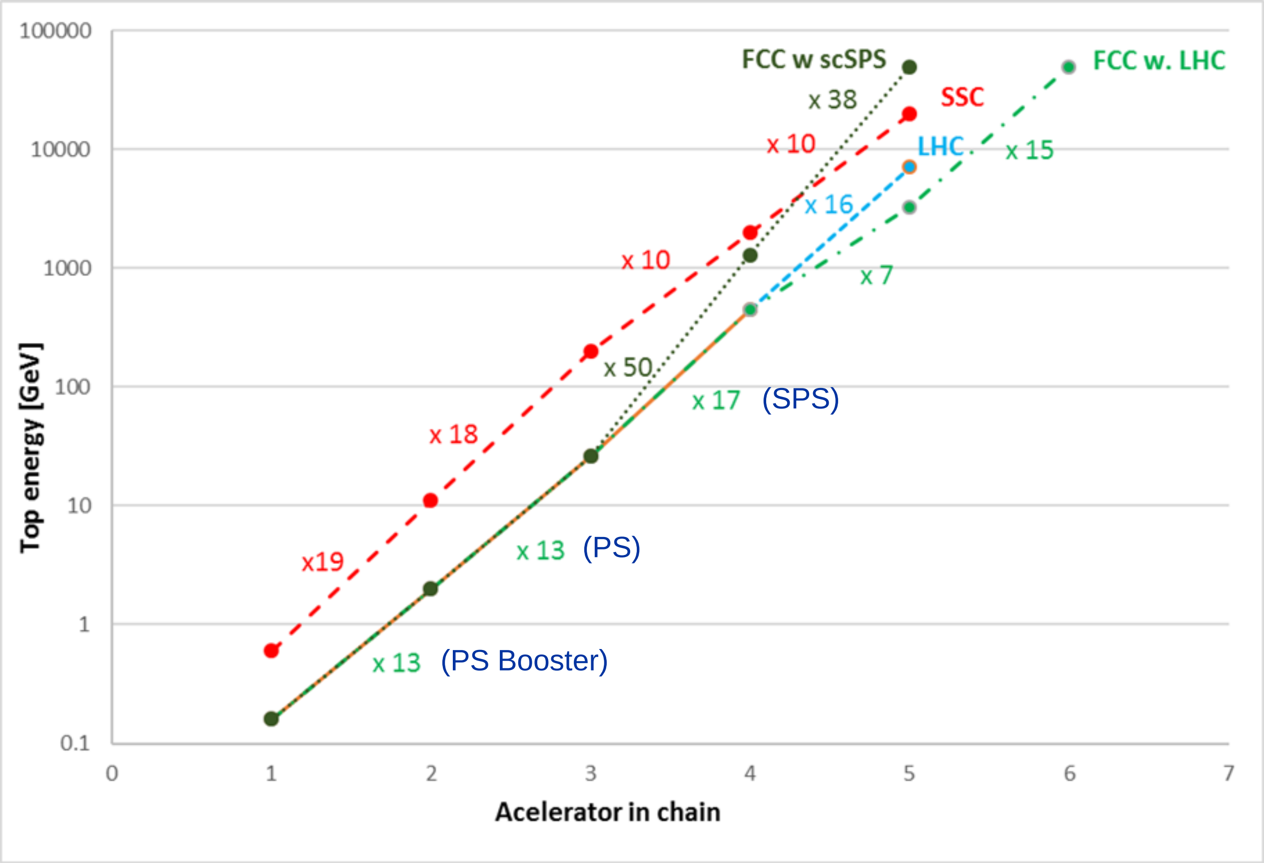
Accelerators have a limited energy range.

Synchrotrons typically accelerate by factor 10 - 20 between injection and extraction.

Beams have therefore to be injected and extracted from circular accelerators.

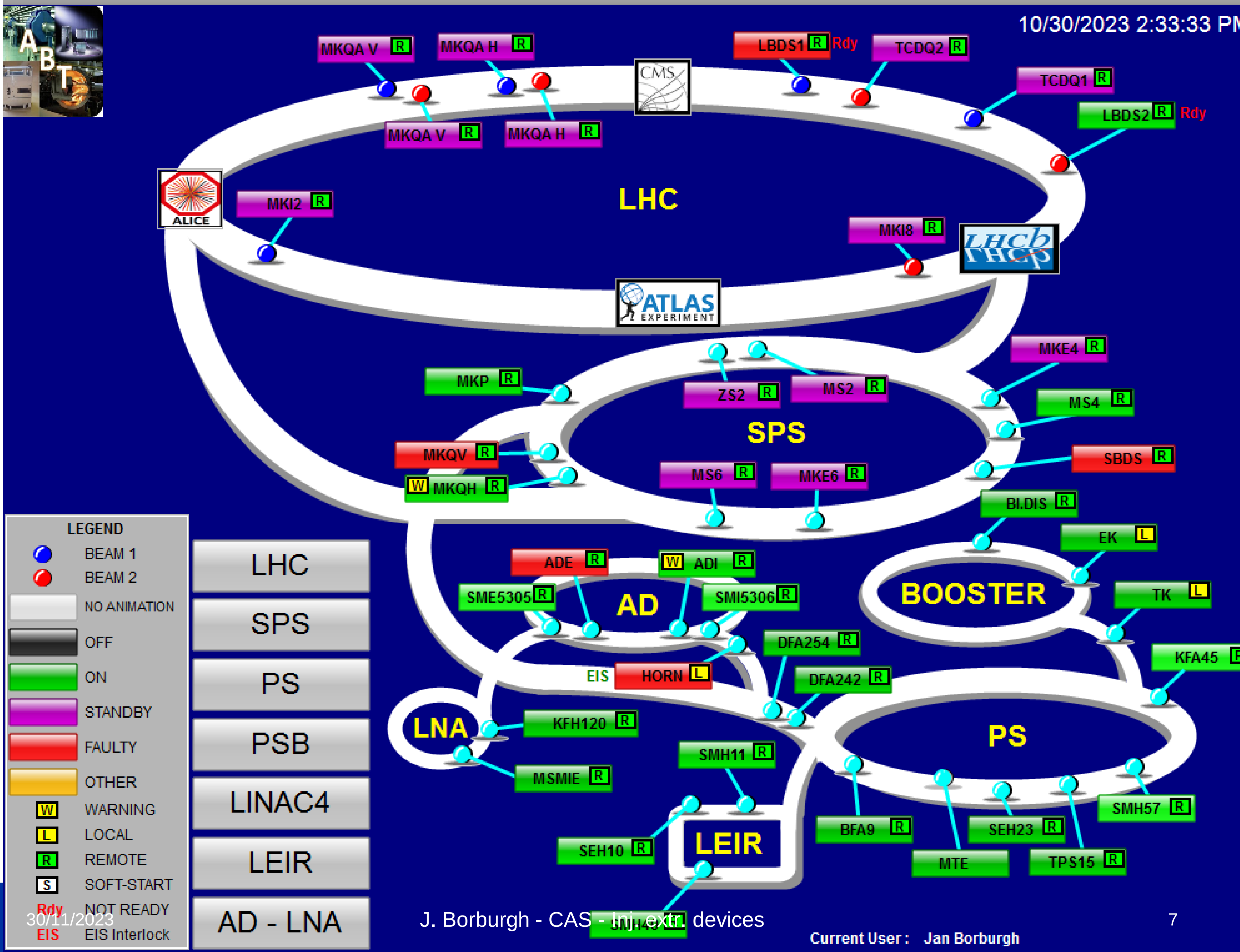
For **injection and extraction** dedicated elements are used:

- **Septa:** which provide a high field and low field area, i.e. field separated in space.
- **Kickers**: create a short-lived high field, i.e. field separation in time.
- **Beam extraction protection** devices to protect downstream equipment.



Some of the injection and extraction systems in the CERN accelerators.

At CERN, approximately 80 systems, consisting of several 100s of devices.



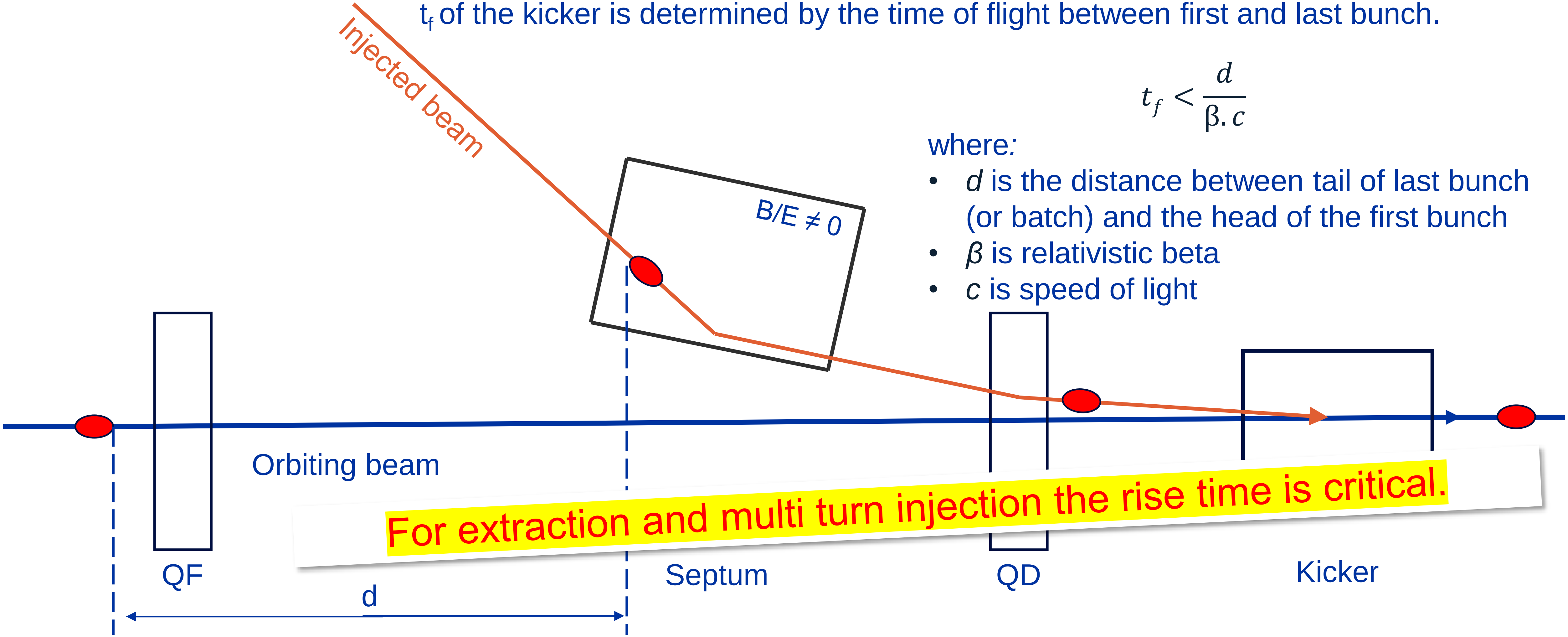
Single turn injection / extraction

For injection, the fall time (t_f) is critical, while for extraction the rise time (t_r) is critical.
t_f of the kicker is determined by the time of flight between first and last bunch.

$$t_f < \frac{d}{\beta . c}$$

where:

- *d* is the distance between tail of last bunch (or batch) and the head of the first bunch
- *β* is relativistic beta
- *c* is speed of light



Lorentz force

The Lorentz force (*F*) is the force on a charged particle due to an electromagnetic field:

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

F [N], vector quantity
q [C] electric charge of the particle
E [V/m] electric field, vector quantity
B [T] magnetic field, vector quantity
v [m/s] instant velocity of particle, vector quantity
× vector cross product (i.e. $F \perp v$ and B vectors)

Assume relativistic particle:

$v \approx 3.10^8$ m/s, **B = 1 T** is subject to same force as same particle in **E = 300 MV/m**.

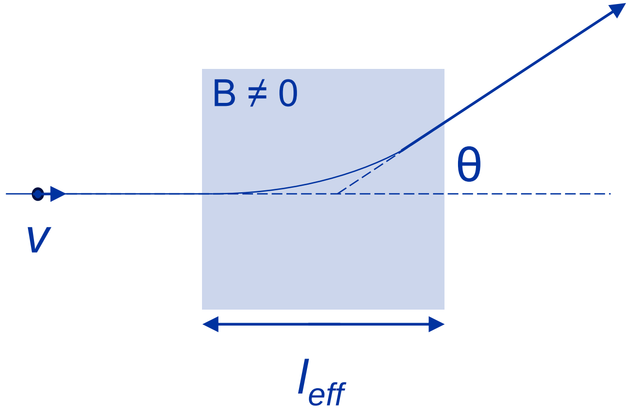
For reference:

- Ki
- Septa: B ≤ 1.5 T and E ≤ 10 MV/m.

It is much more efficient to deflect relativistic beams with a magnetic field.

Reminder: beam deflection due to a magnetic field

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



Where:

B	magnetic flux density (T);
p	beam momentum (GeV/c);
l_{eff}	effective length of the magnet (m);
θ	deflection angle due to the magnetic fi...

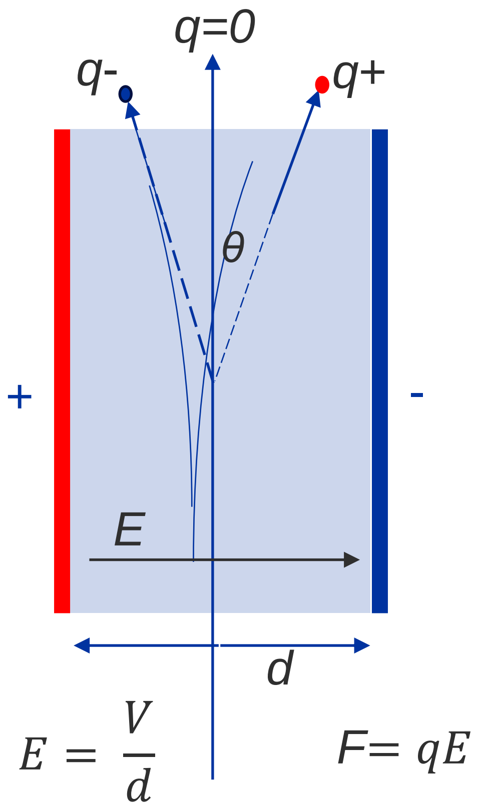
The effective lengt... ...ten different from the physical length (l_{ph}).

Unlike kickers, the magnetic length of a septum is typically shorter than its physical length

$$l_{eff} = \frac{\int_{-\infty}^{\infty} B(z).dz}{B_0}$$

Reminder: beam deflection due to an electric field

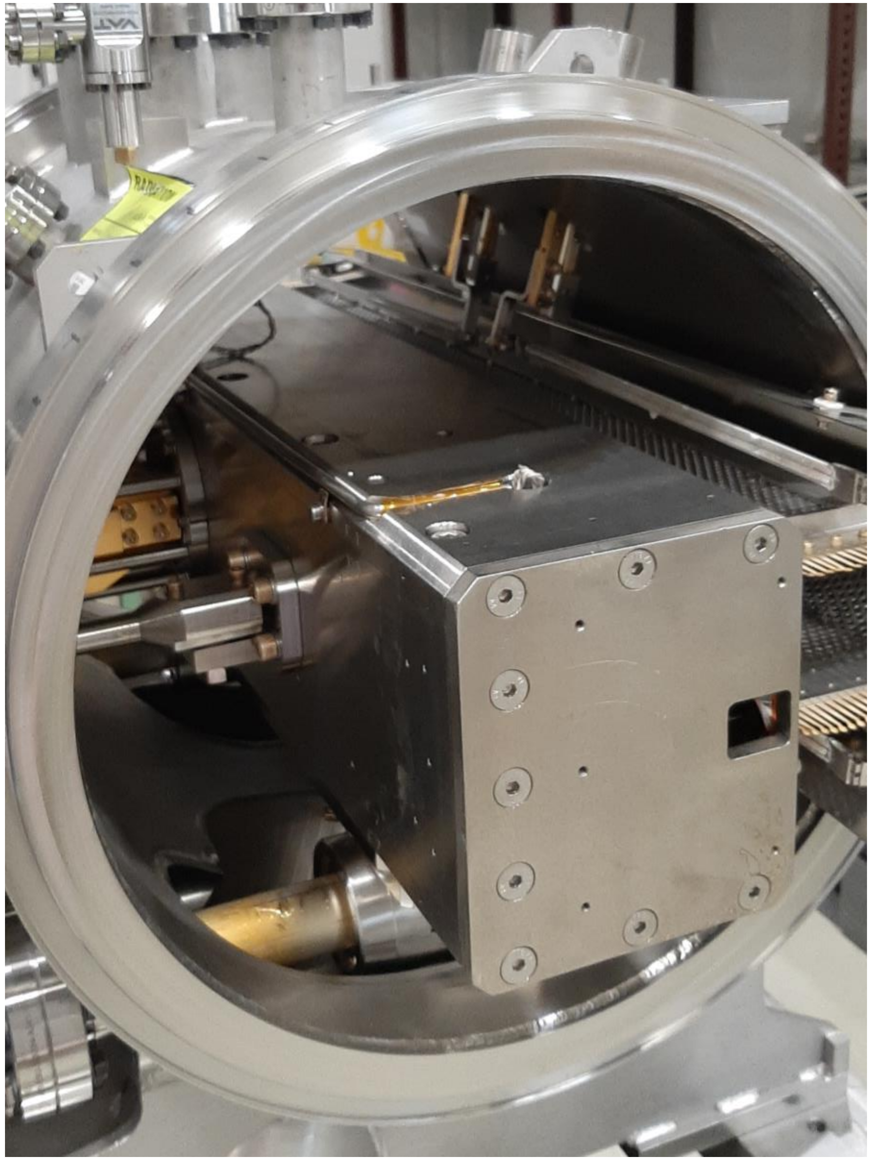
$$\theta_{E,x} = \tan^{-1}\left[\frac{1}{(p \cdot 10^9)\cdot\beta} \cdot \int_{z_0}^{z_1} |E_x|\, dz\right] = \tan^{-1}\left[\frac{|E_x| \cdot l_{eff}}{(p \cdot 10^9)\cdot\beta}\right] = \tan^{-1}\left[\frac{|V_x| \cdot l_{eff}}{d \cdot (p \cdot 10^9)\cdot\beta}\right]$$



Where:

E	electric field (V/m);
p	beam momentum (GeV/c);
β	relativistic constant;
l_{eff}	effective length of the device [m];
V	applied voltage between electrodes (V);
d	the distance between electrodes (m);
θ	deflection angle due to the electric field (rads).

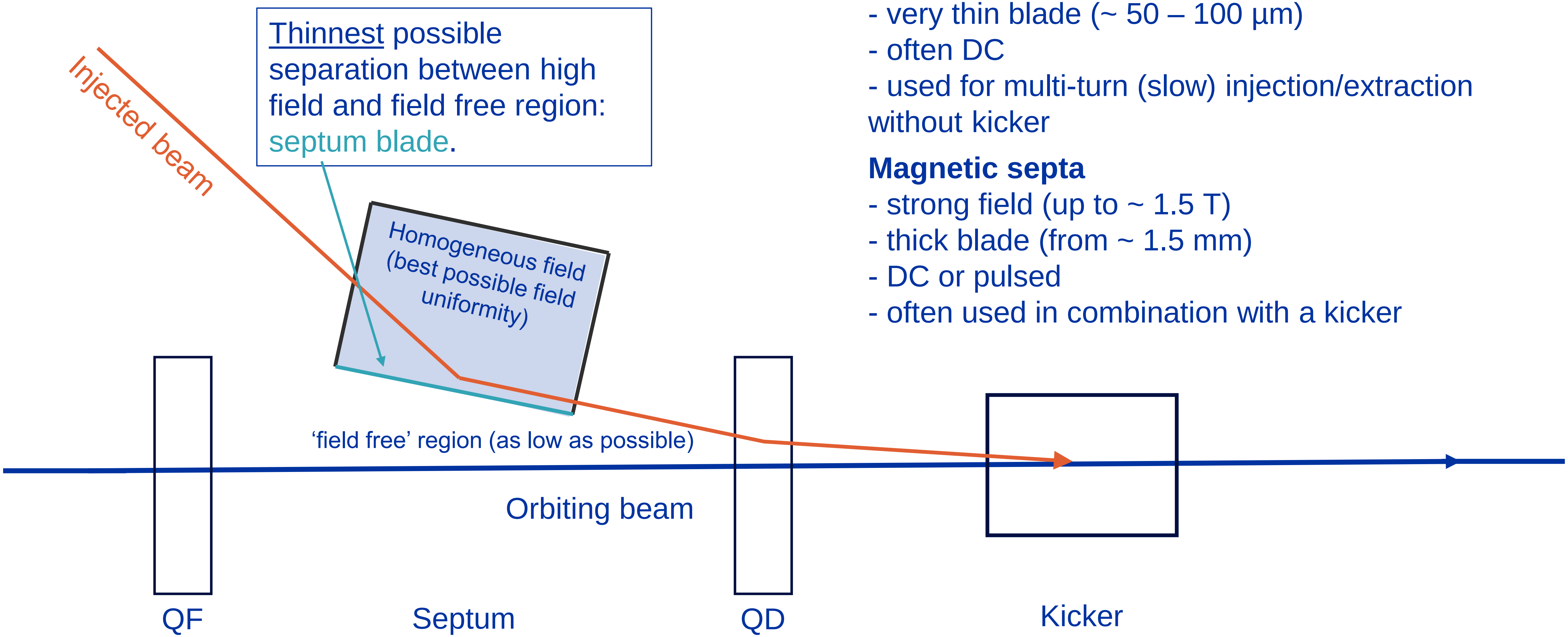
Electrostatic septa and also stripline kickers use electric fields to deflect the beam.



Magnetic Septa

Singular: septum, plural: septa.

Injection septum



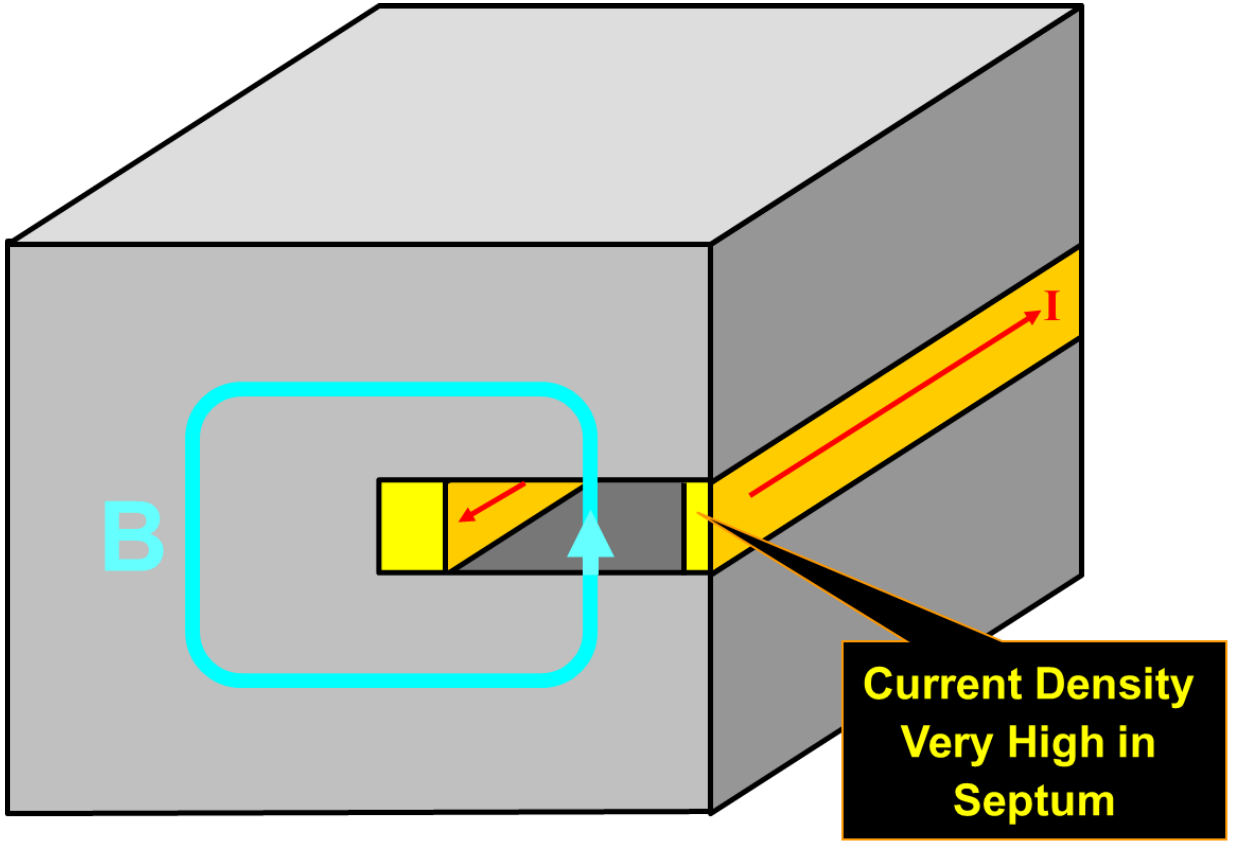
Electrostatic septa
- weak field (up to ~ 10 MV/m)
- very thin blade (~ 50 – 100 μm)
- often DC
- used for multi-turn (slow) injection/extraction without kicker

Magnetic septa
- strong field (up to ~ 1.5 T)
- thick blade (from ~ 1.5 mm)
- DC or pulsed
- often used in combination with a kicker

Magnetic Septum

Typical layout direct drive septum

- **C-shaped** magnetic **yoke**
- **Conductors on each side of the gap**; these guide the induced flux to the yoke.
- To obtain thin septum, the **current density** is pushed **very high**.
- High current density leads to increased **power dissipation**;
- **Mechanical stress** of the septum blade needs to be properly managed.
- Thermal management of coil of greatest importance.



Septum conceptual dimensioning

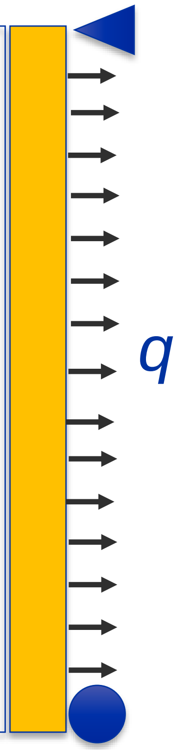
$$\oint H\,dl = nI$$

$$H_{yoke}\,lyoke + Hglg = nI$$

$$B = \mu 0 \mu_r H$$

$$\frac{B_{yoke} l_{yoke}}{\mu_0 \mu_r} + \frac{B_g l_g}{\mu_0} = nI$$

$$\mu_r \gg 1$$



So: for a 40 mm ***g*** ap,1 T ***B*** field one needs ***nI*** 3.18·10^4 A.turns

Can lead to high current densities!

Deflection $\delta = \frac{5qg^4}{384EI_m}$

with

Area moment of inertia $I_m = \frac{L.s^3}{12}$

Distributed load $q = \frac{F}{g} \approx \frac{1}{2} nIB \frac{1}{g}$

mechanical stress $\sigma_{max} = \frac{6Fg}{8Ls^2}$

with ***s*** = 5 mm copper septum thickness, the deflection of the conductor ***δ*** is 10 µm, and mechanical stress σ_{max} is ~19 Mpa.

Can lead to fatigue and vibration issues!

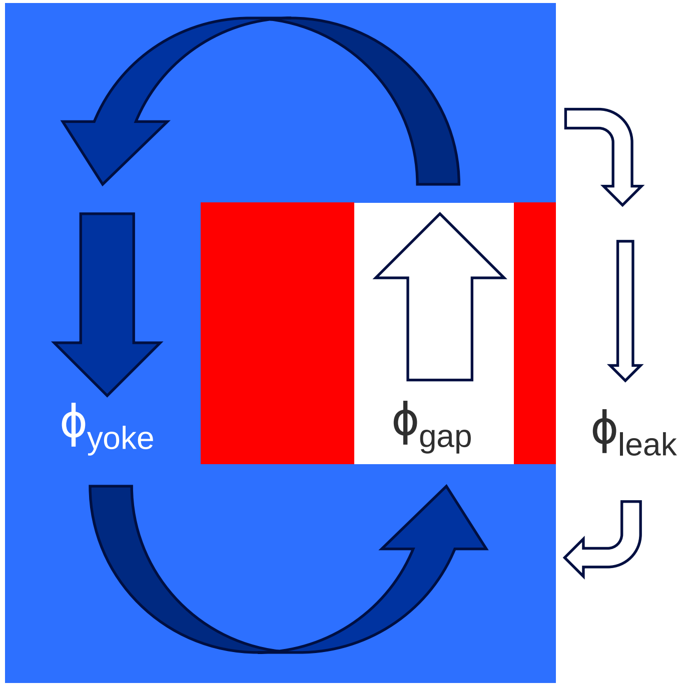
Leak field

The leak field depends on:

The **relative permeability (μ_r)** of the steel **yoke**.

- use steel with high μ_r
- avoid yoke saturation

This is the dominant factor for the leak field further from the septum (>1 gap height).



$$\phi_{gap} = \phi_{yoke} + \phi_{leak}$$

Play between the septum conductor and the yoke.

- conductor insulation and mechanical play allow field lines ‘to escape’ without passing via the yoke.
- affects predominantly the leak field closer to the yoke (< 1 gap height)

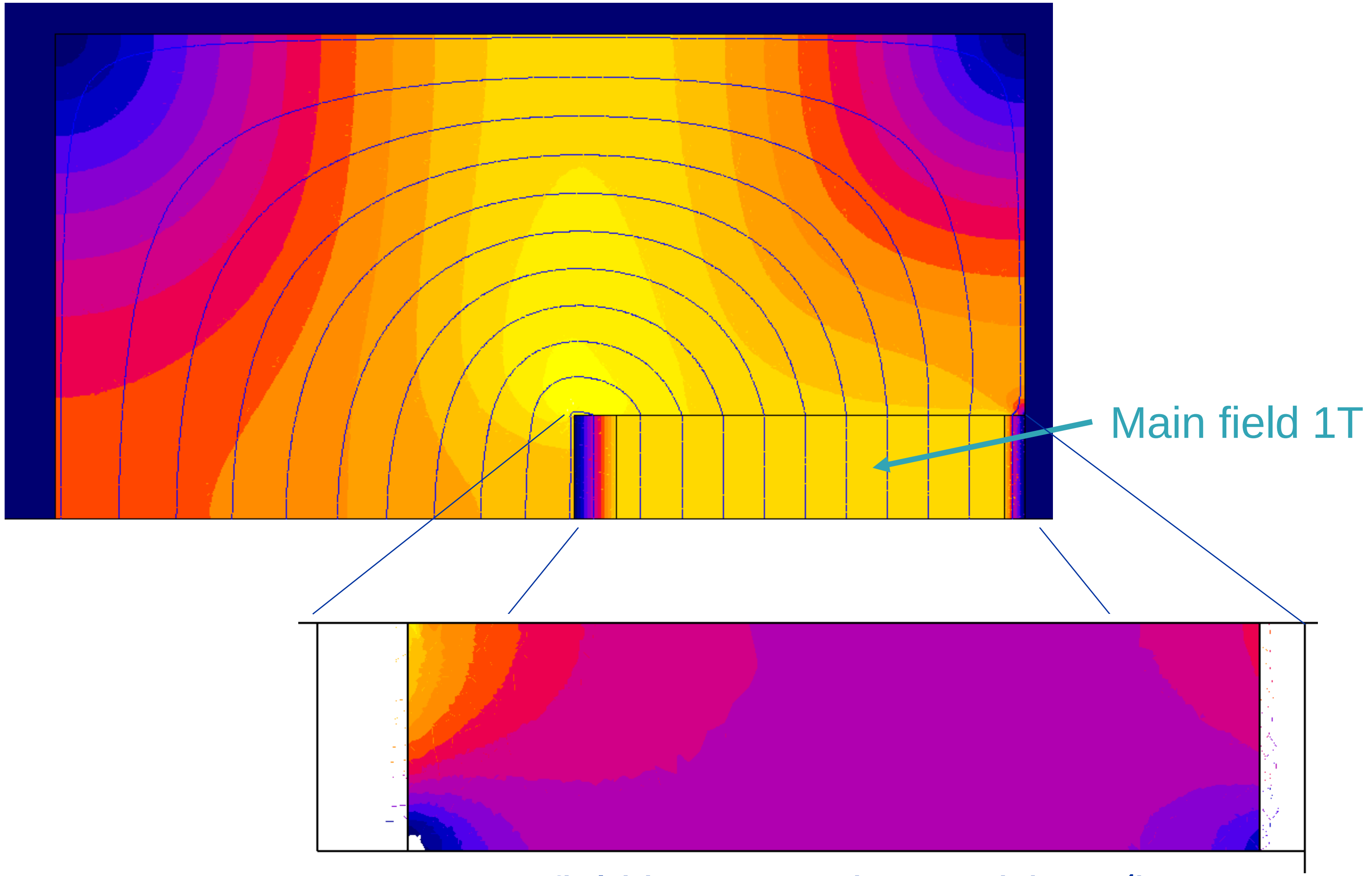
Current uniformity in the septum blade.

- due to interturn insulation and cooling channels
- affects leak field close to septum (≤ septum thickness)
- also has impact on field homogeneity inside the gap

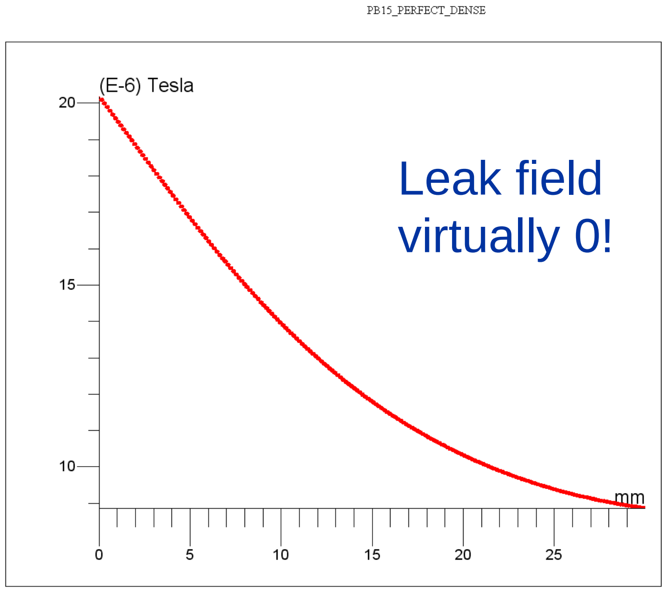
However, integral leak field is dominated by leak fields at magnet extremities!
Field clamps and shielding are effective tools.

Idealised septum magnet

no play between coil and yoke

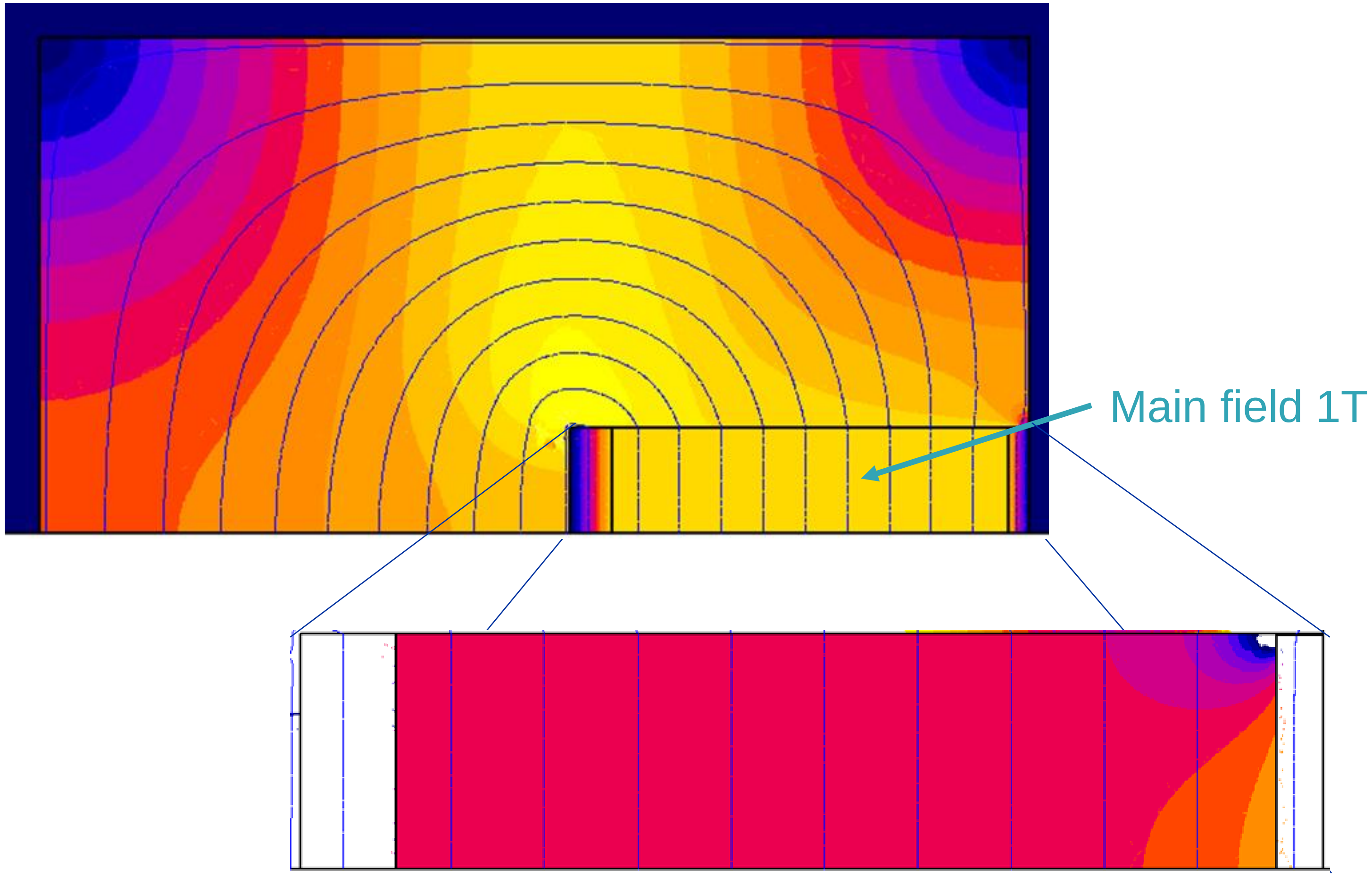


Gap field homogeneity good ($<10^{-4}$)!

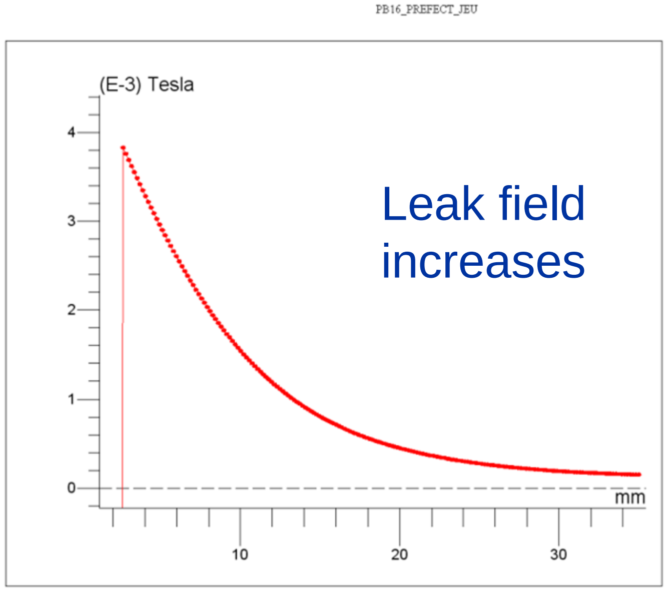


Idealised septum magnet

0.1 mm play between coil and yoke

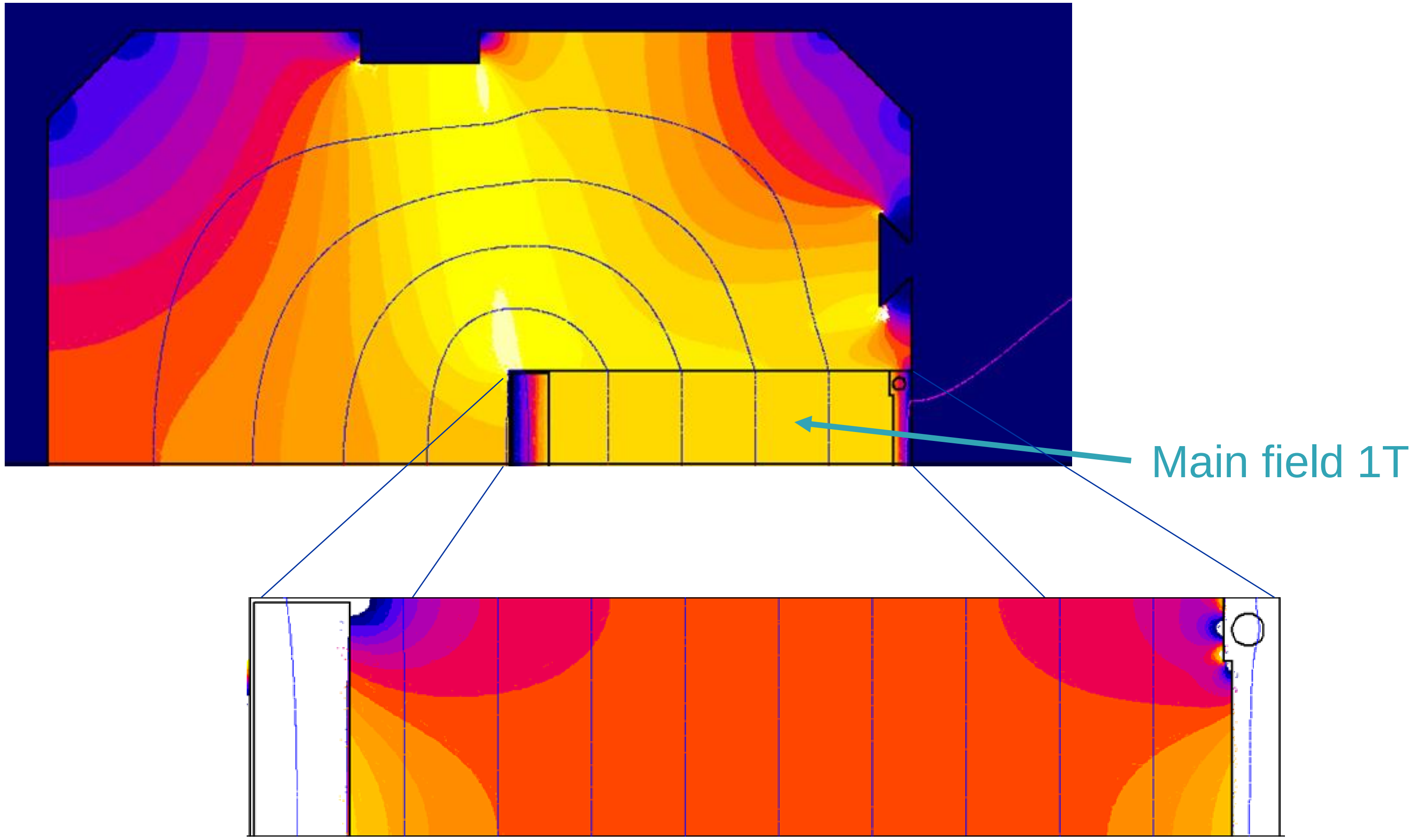


Gap field homogeneity degrades.

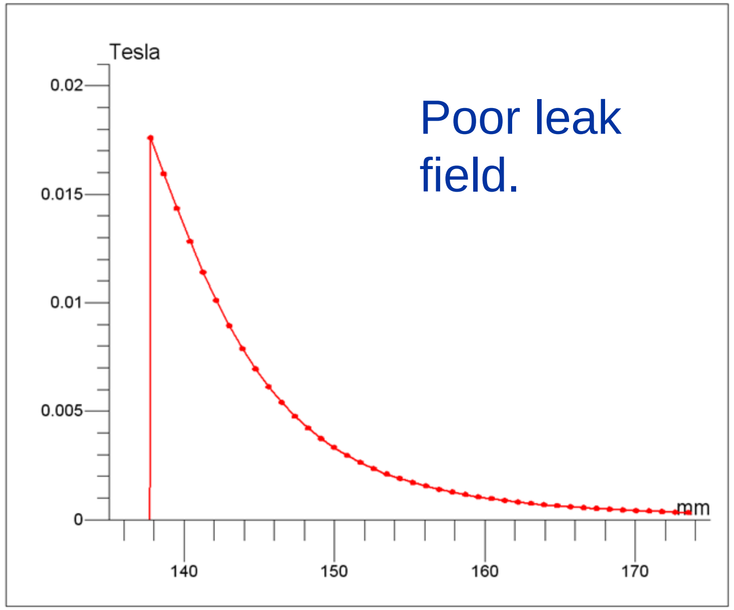


As built magnet

Including cooling channels and insulation around the coil



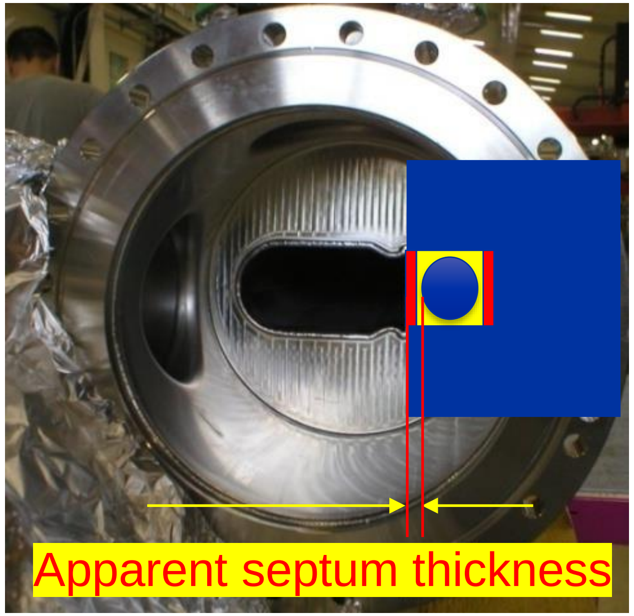
Field homogeneity in the gap: +/- 2% of B_0



Septum variants

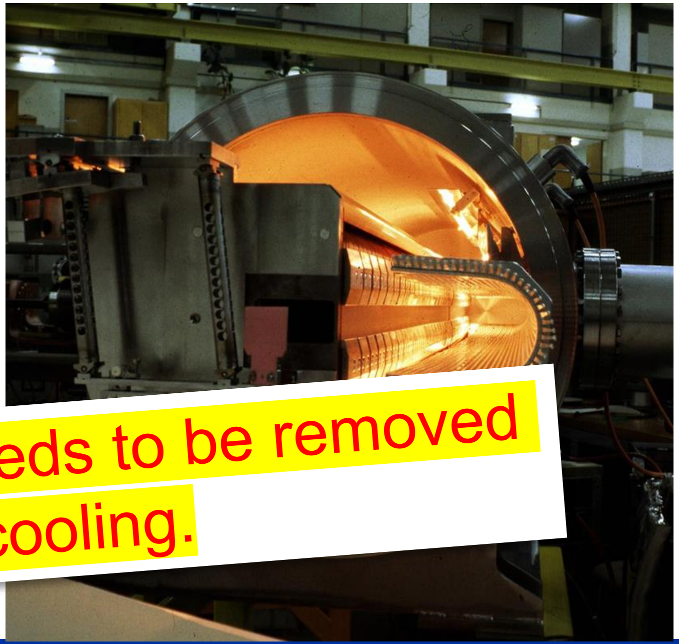
Outside vacuum

- Beam inside vacuum chambers around which the magnet is placed.
- **Apparent septum thickness** = septum blade thickness + vacuum chamber wall thickness, mechanical play and magnetic shielding
- **Multi-turn coil variants** suitable for DC applications.



Under vacuum

- Septum thickness determined by septum conductor and/or screen only → **reduced septum thickness.**
- Entire septum inside vacuum vessel; **requires careful design** and vacuum compatible materials to be used; bake-out of system to reach UHV common.
- Very suitable for **pulsed applications**.
- **Beam observation systems** are often integrated in the mechanical design.



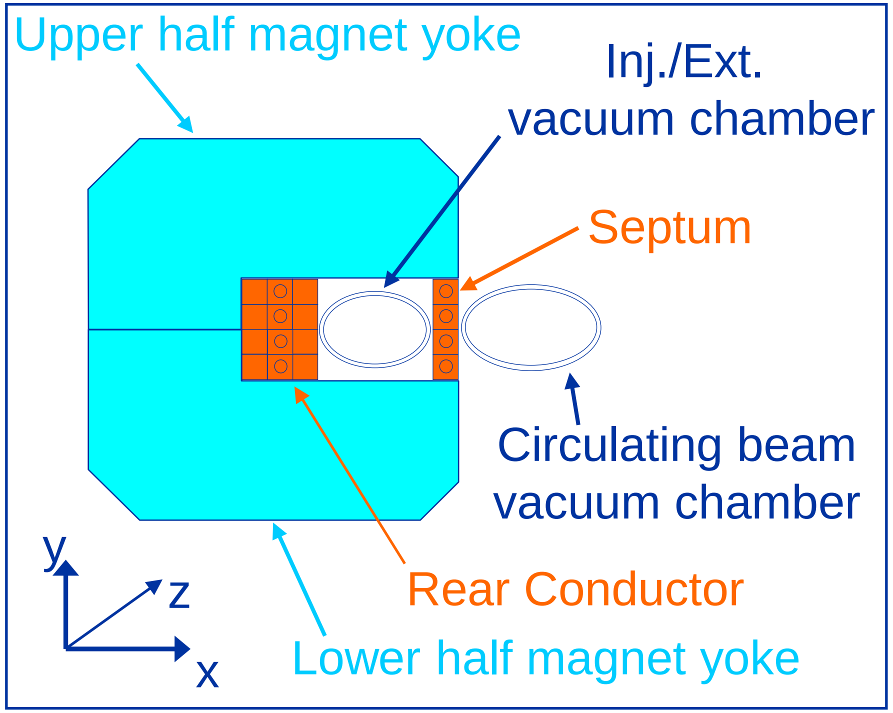
Under vacuum any heat dissipated in the magnet needs to be removed using dedicated systems, usually water cooling.

Septum magnet topologies

Many septum topologies have emerged over the years. A selection:

- **Direct drive septa**
  - **DC** magnetic **septum**
    - continuously powered with (high) current; often multiturn coils to reduce current; rarely under vacuum.
  - Under vacuum **pulsed septum**
    - Pulsed current to reduce thermal load. In return vibrations and fatigue needs to be managed.
- **Eddy current septum**
  - Powered with a short half or full sine current pulse; mechanically robust, but electrically challenging depending on gap size.
- **Lambertson septum**
  - DC or pulsed. Septum is part of yoke; coils well away from beam. Requires 2 plane injection/extraction.
- **Opposite field septum**
  - 2 adjacent gaps with opposite field. As a result: little to no mechanical force on the septum blade.
- **Massless septum**
  - No physical coil or separation in beam path. Apparent septum thickness generally ≥ 1 gap height.
- **Permanent magnet septum**
  - Still in its infancy.
- **Superconducting septa**
  - Still rare, despite some successful applications (for ex. g-2 inflector at BNL). Truncated Cosine Theta (TCT) and Superconducting Shield (SuShi) topologies nowadays being investigated for FCC.

DC Magnetic Septum [1]



- Continuously powered with a (high) current.
- Usually constructed with a multi-turn (series) coil, so as to reduce the current needed.
- The coil and the magnet yoke can be split in two, an upper and a lower part, to allow the magnet to be 'clamped' around the vacuum chamber of the injection/extraction line.
- Rarely under vacuum.

- This topology i… …the power converter drives di… …ent of the septum.

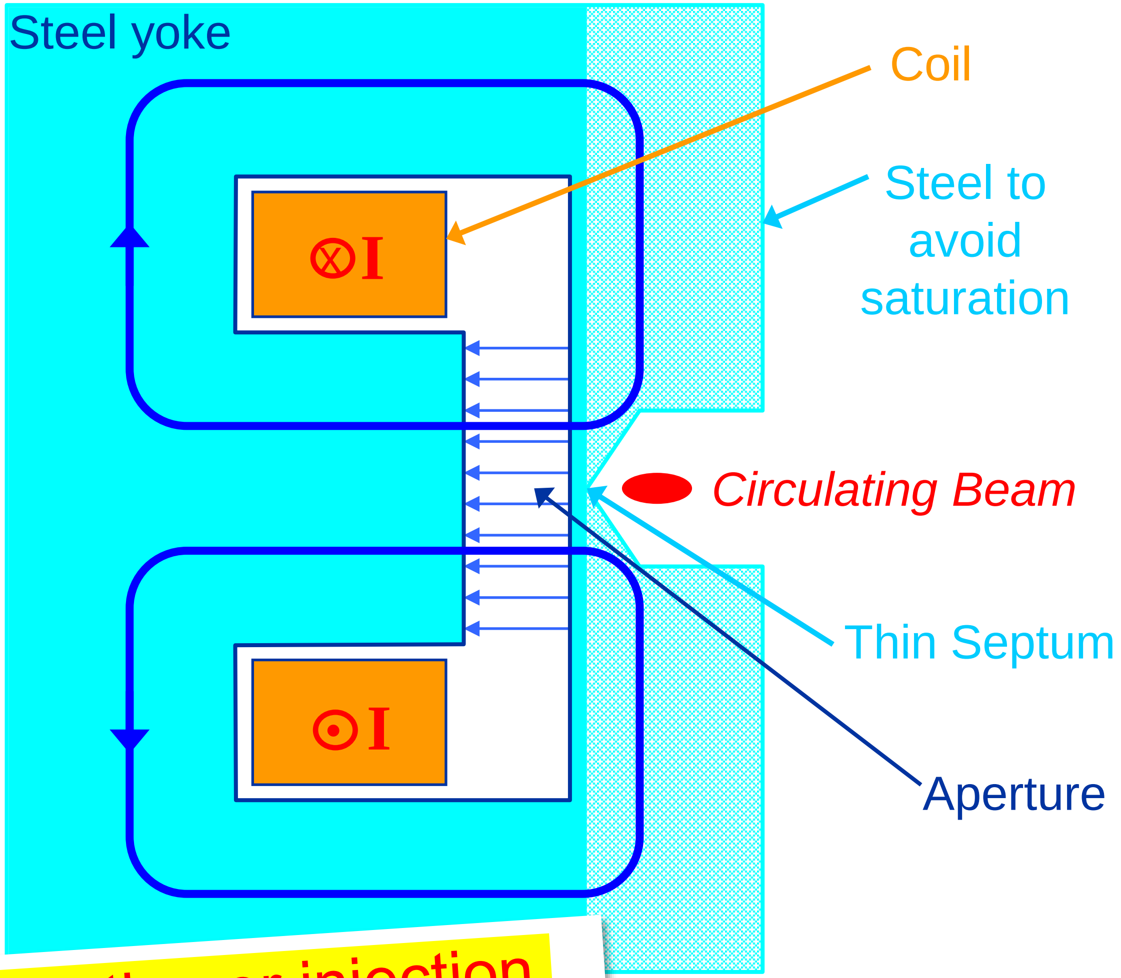
DC septa lead often to thermal challenges and high-power consumption.

- This topology can also be pulsed (typically in the ms range), which allows to simplify the cooling circuit. Pulsed variants are often single turn [2].

Lambertson Septum principle [3,4,5]

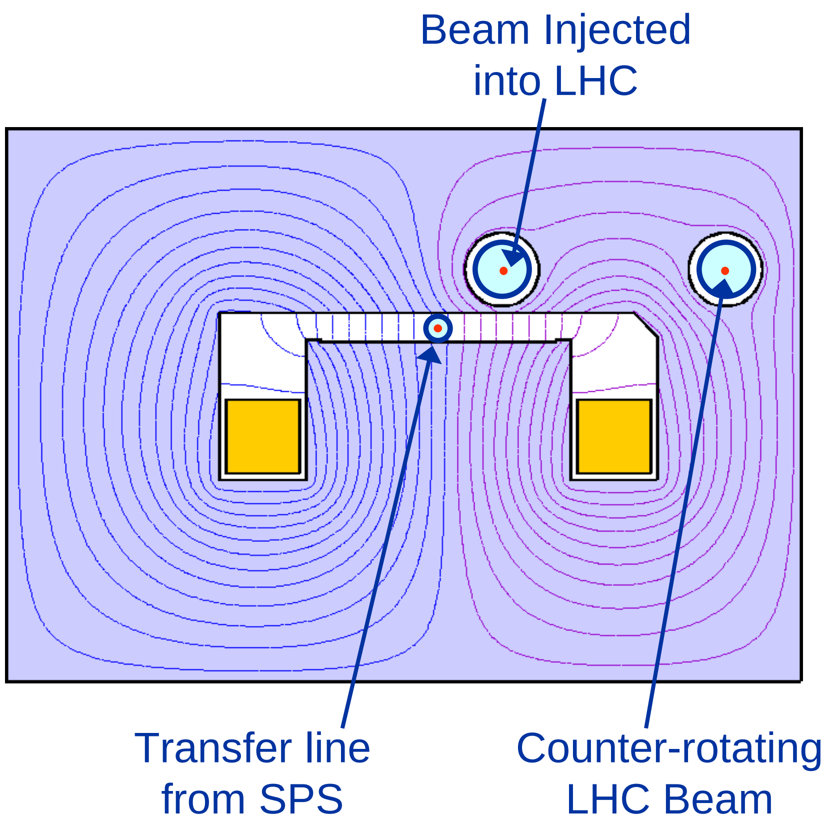
- Current: DC or pulsed;
- Conductors are enclosed in steel yoke, “well away” from beam → current density ↘
- Thin steel yoke between aperture and circulating beam – however extra steel required to avoid saturation;
- Septum, as shown, difficult to align.

- Used for injection/extraction in 2 planes (horizontal and vertical). For example for extraction: a kicker is used to deflect beam into septum aperture, and subsequently the beam is deflected perpendicular to plane of the kicker deflection.



Requires 2 plane injection or injection.

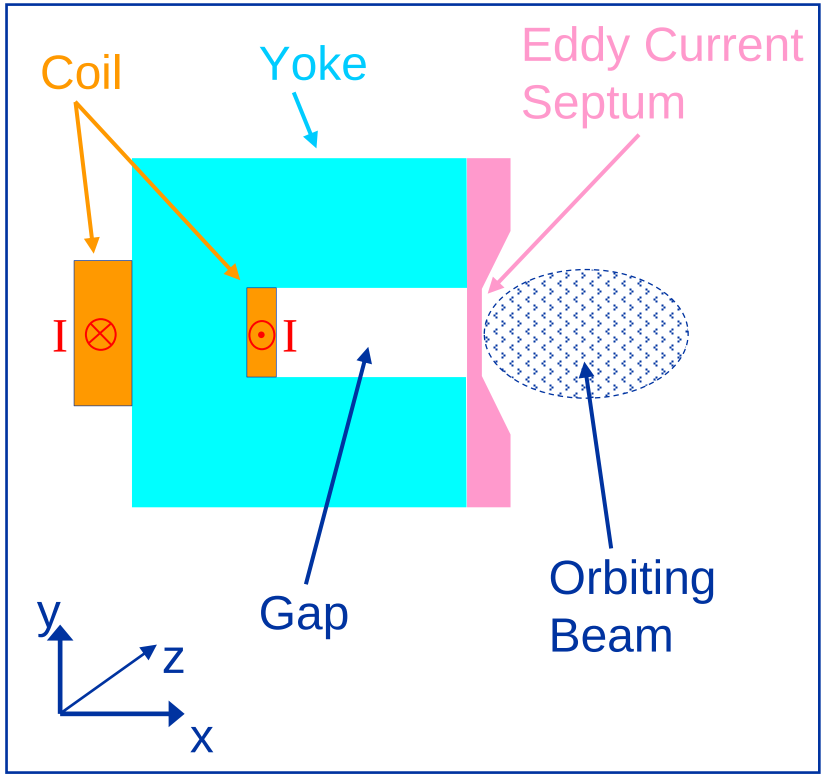
LHC injection – Lambertson Septum



1. **Septum deflects beam horizontally to the right;**
2. **Kicker deflects beam vertically onto central orbit.**
3. Note: To minimize the leak field in LHC beam-pipes, additional screen is used.

Eddy Current Septum principle [6,7,8,9,10]

See also poster Filip Malinowski @ this CAS



Powered with a half or full sine wave current with a period of typically 50 μs.

Coil is generally constructed as a single turn, so as to minimize magnet self-inductance.

The coil sits around the back leg of the C shaped yoke, and therefore coil dimensions are generally not critical.

When the magnet is pulsed, the magnetic field induces eddy currents in the septum, counteracting the fringe field created.

The septum can be made very thin, but water circuits may be needed at the edges to cool the septum.

The field in the gap as function of time follows the coil current. The electrical resistance of the septum is kept low: once the septum current is flowing, it takes quite **some time to decay**.

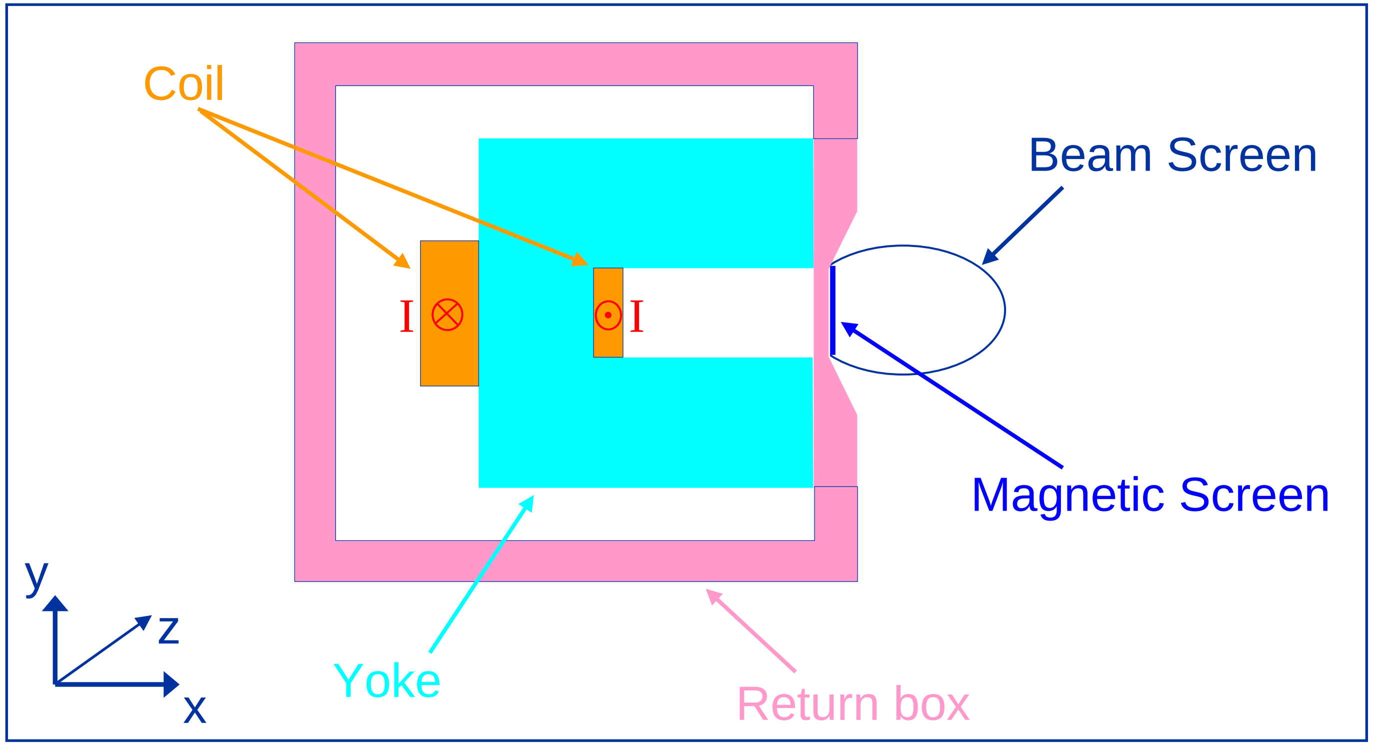
More robust than direct drive septa.

Eddy Current Septum

To reduce further the fringe field of the eddy current septum a copper box (return box) can be placed around the septum magnet.

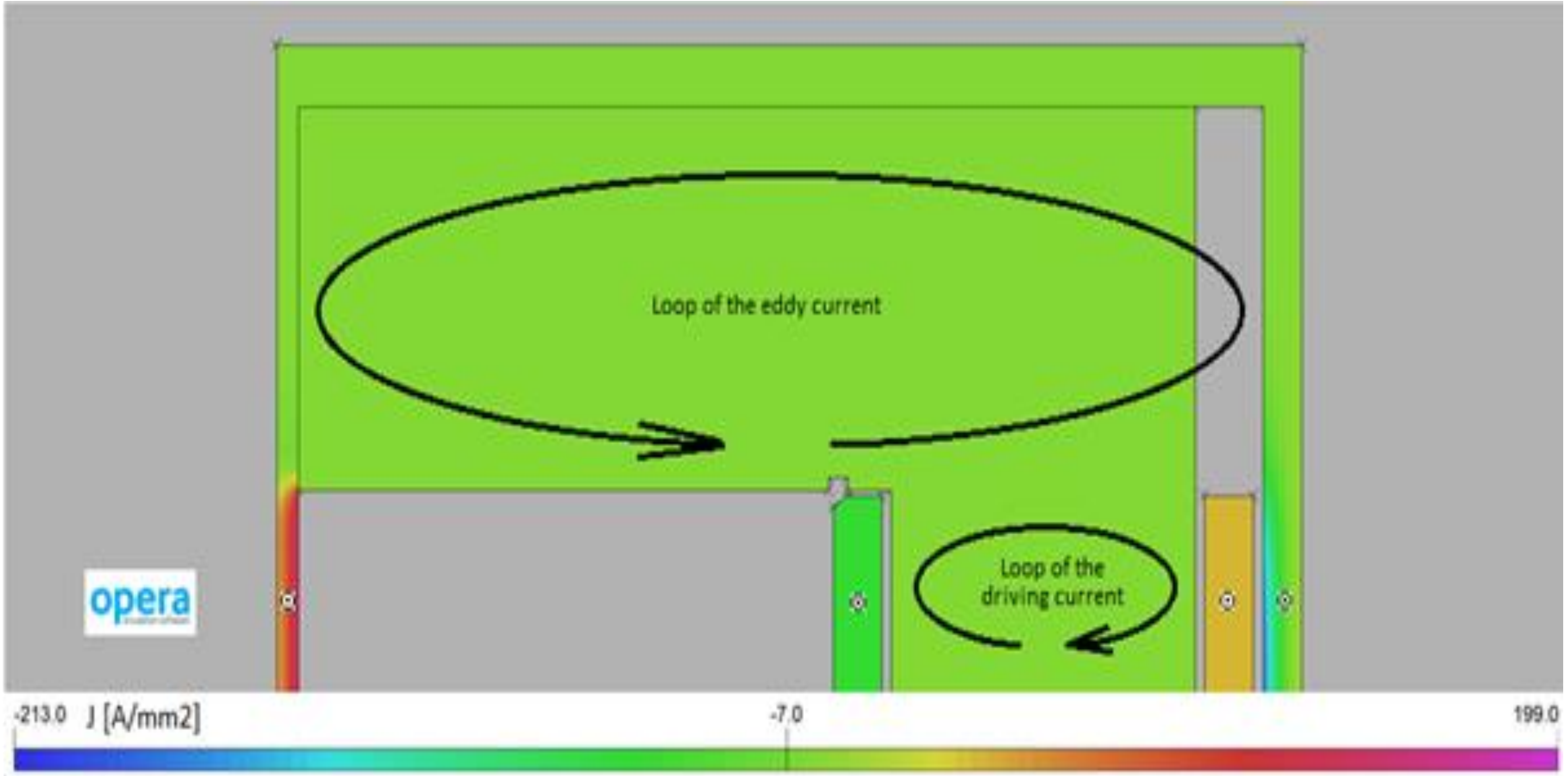
Also, a magnetic screen can be added next to the septum conductor.

These modifications permit the fringe field to be reduced to below 1/1000 of the gap field at all times and places.



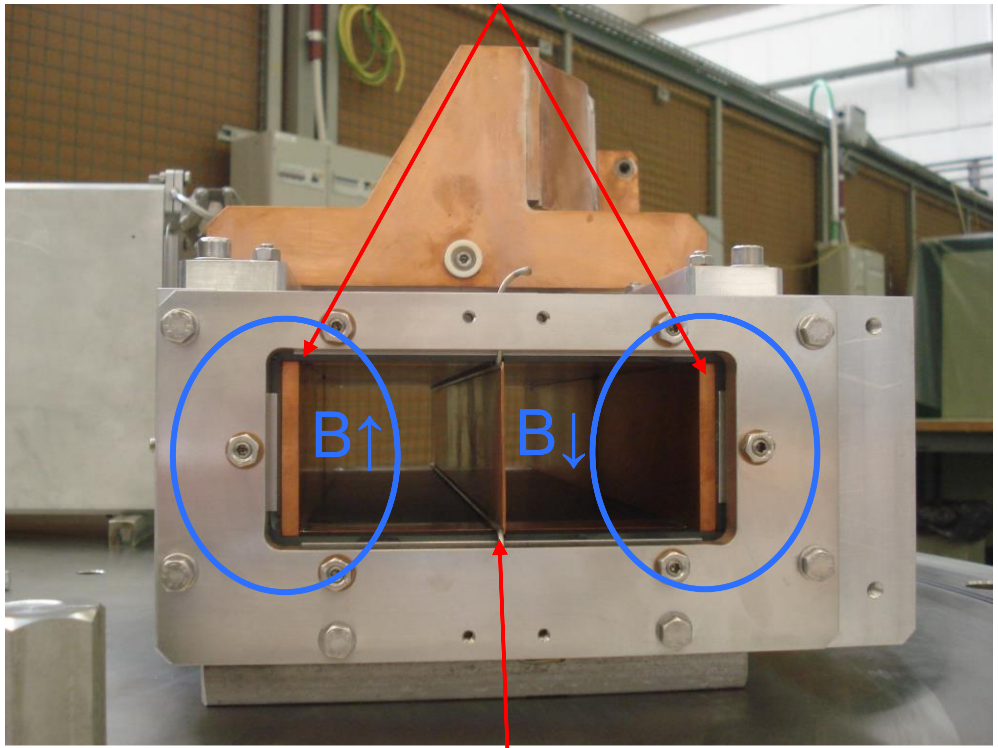
Current distribution Eddy Current septum

The current induced in the septum blade, closed via the rear of the copper shielding box.



Opposite field septum [11,12]

Return conductors



Septum blade

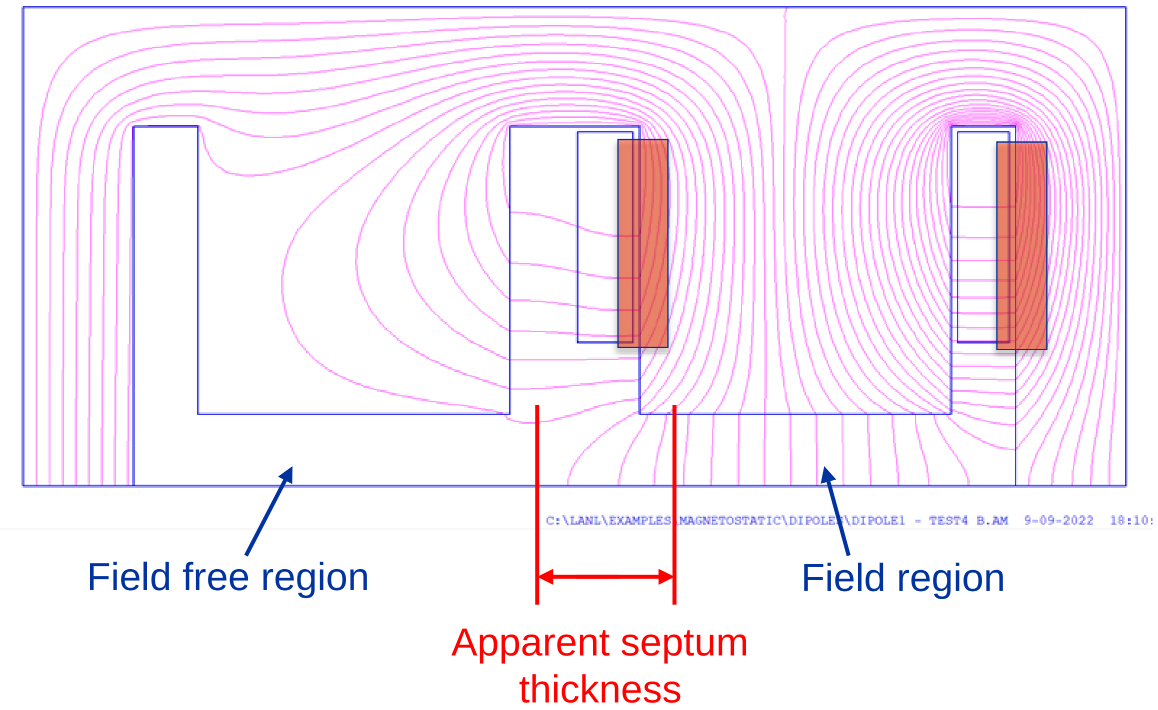
Due to the opposite fields, no mechanical force on the septum blade. Septum can be made very thin, provided high current densities are dealt with properly.

Rarely used, but can be made effective for example when 1 gap replaces part of a main dipole, and the adjacent gap serves the extraction channel.

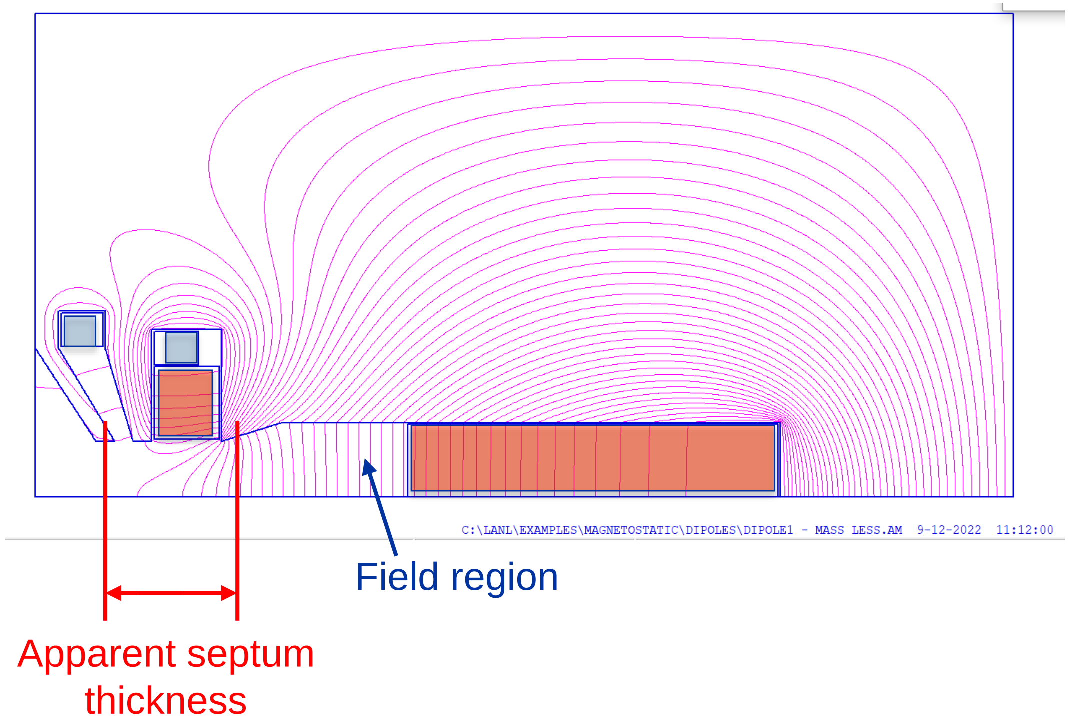
Very thin sepum blade thickness possible, due to lack of mechanical forces.

Massless septum [13,14,15]

Variant inspired by an opposite field septum.



Variant using ‘cancellation’ field coil (blue).



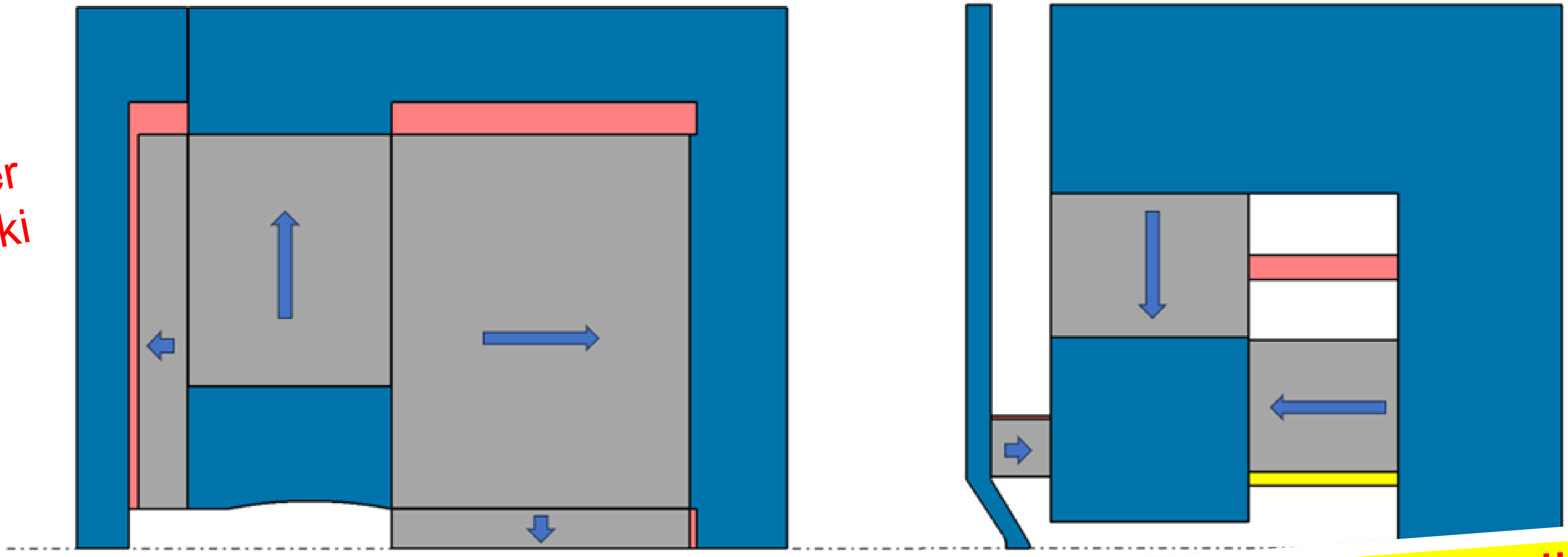
- The apparent septum width is usually larger than 1 full gap height.
- Because of the field in the septum region, it may require collimation downstream.

Little interaction with stray beam particles, hence little radioactivation.

Permanent magnet septum [16,17]

- DC septa could be favorably replaced by permanent magnet septa, **solving** their main challenge: **power consumption** and **thermal loading**.
- Their **dynamic range** (field adjustability) is **limited**.
- Relative **septum thickness** (w..r.t. the gap height) is relatively **high.**

See also poster Filip Malinowski @ this CAS



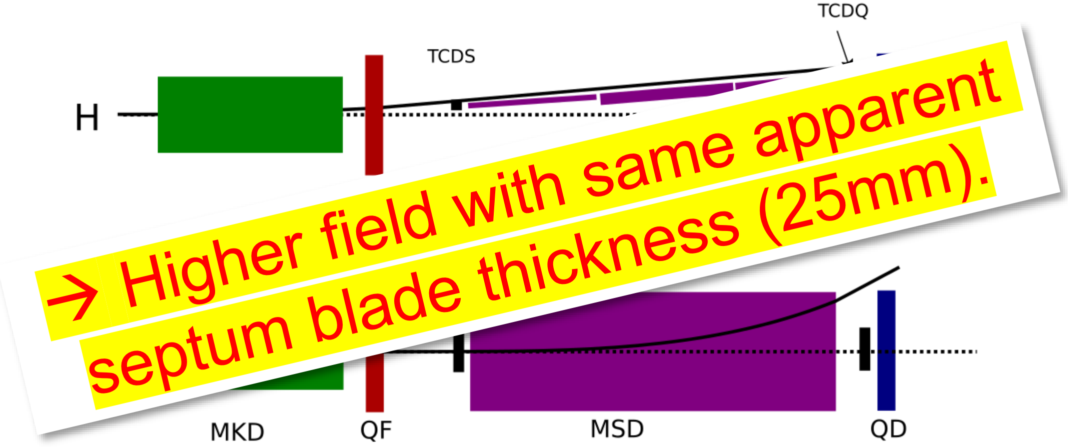
Still in its infancy; very few developments reported in literature.

Superconducting septa [18,19]

FCC extraction as a use case

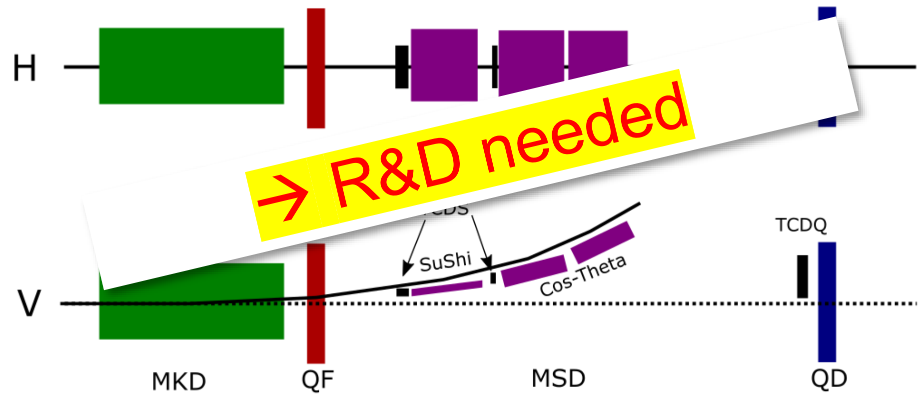
Conventional septa topologies

- **Normal conducting Lambertson septa** power consumption enormous**: 2.4 MW** [11].
- Septa topology requires double plane extraction.
- Alternatively **superferric Lambertson septa** (1.3-1.55T / ~184m with 25 mm septum blade).
- Power consumption dominated by cryo-system.

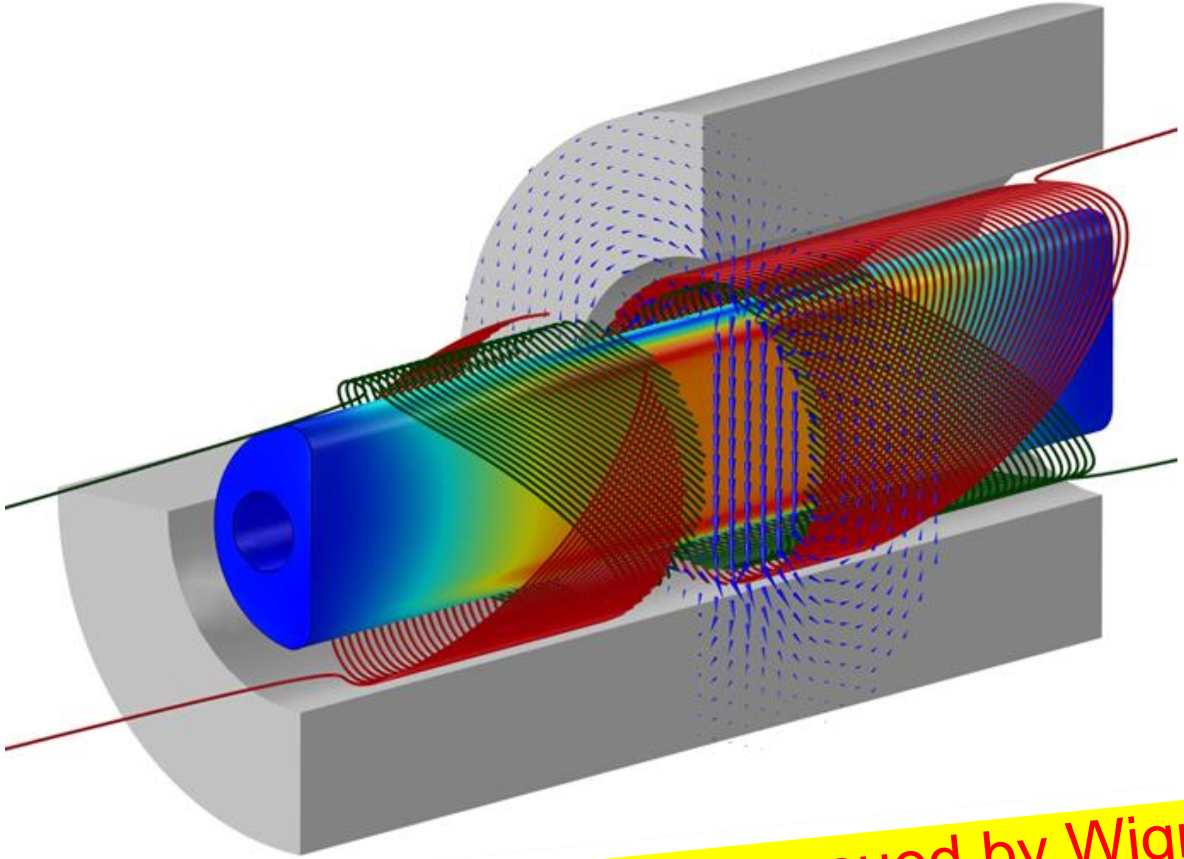


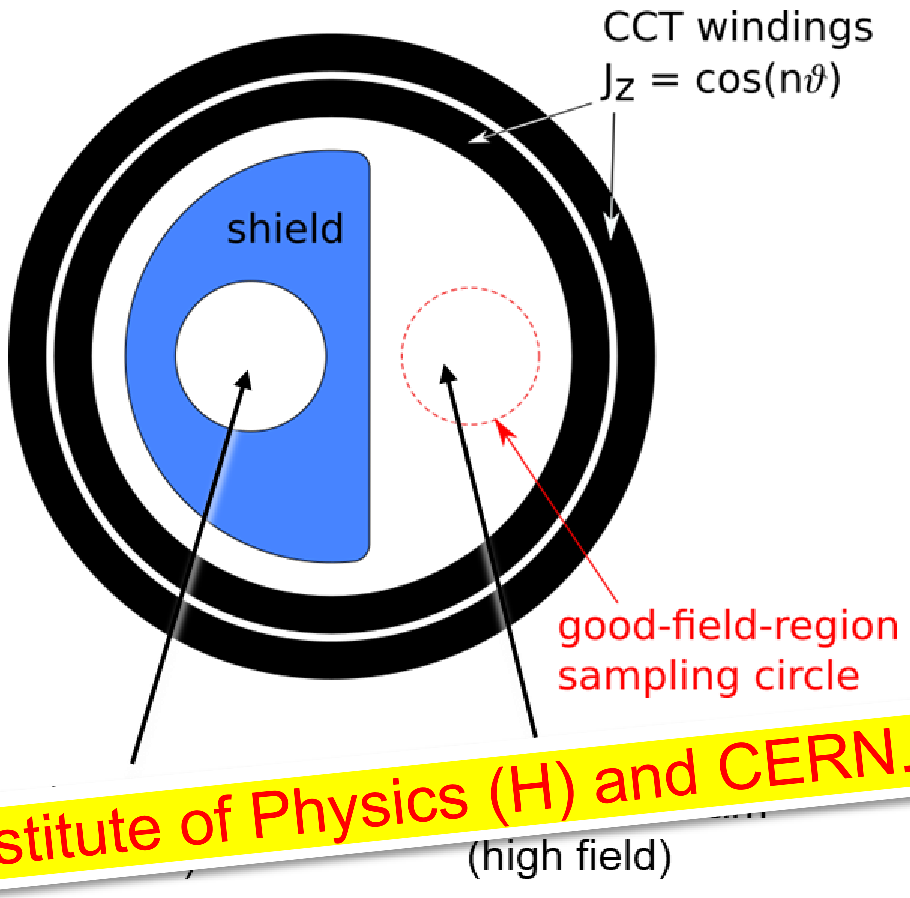
Novel septa topologies

- Based on **novel superconducting septa**: **Su**per conducting **Shi**eld (SuShi, 3.2T) and **T**runcated **C**os **T**heta (TCT, 4T). Total system length ~70m
- Septa Layout allows for single plane extraction (vertical).
- **Significantly reduced power consumption**, dominated by cryo-system.



Canted Cosine Theta (CCT) Superconducting Shield (SuShi) septum [19,20,21,22]

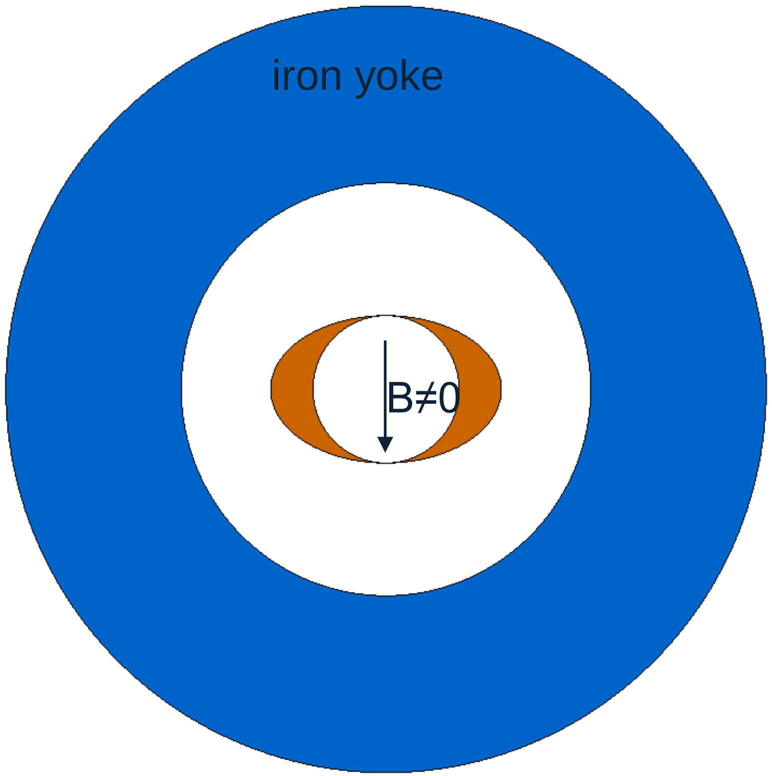


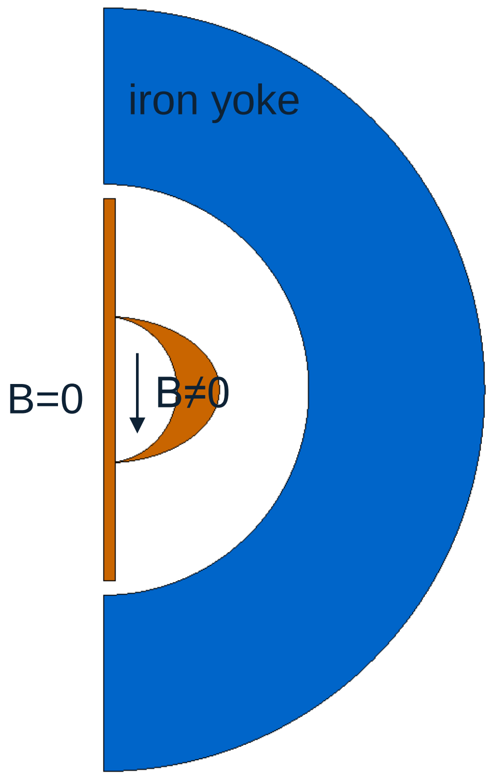


Actively being pursued by Wigner Institute of Physics (H) and CERN.

Truncated Cosine Theta septum [23]

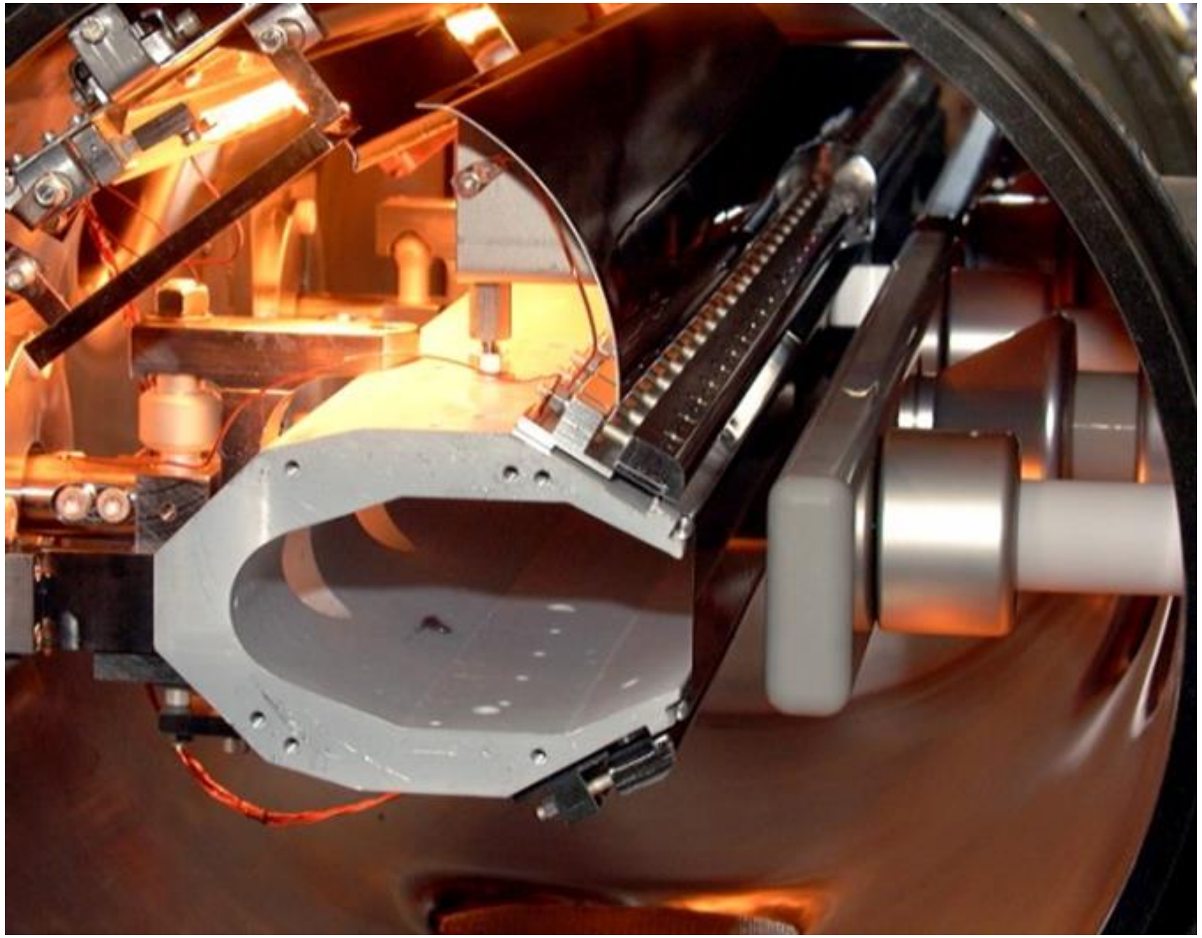
When halving the cos θ magnet and closing the beam aperture with a current wall (i.e. a superconductor), this current wall becomes a septum.



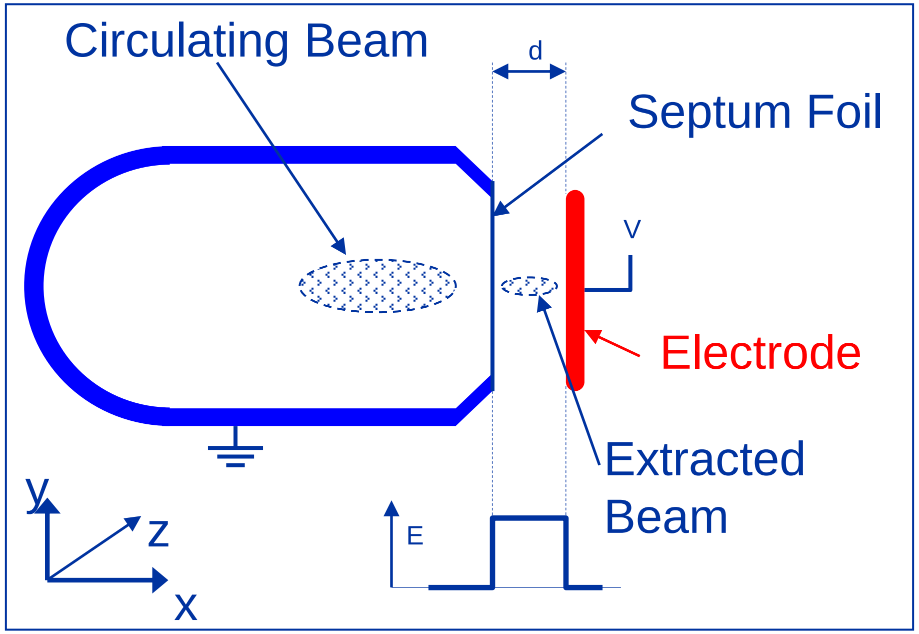


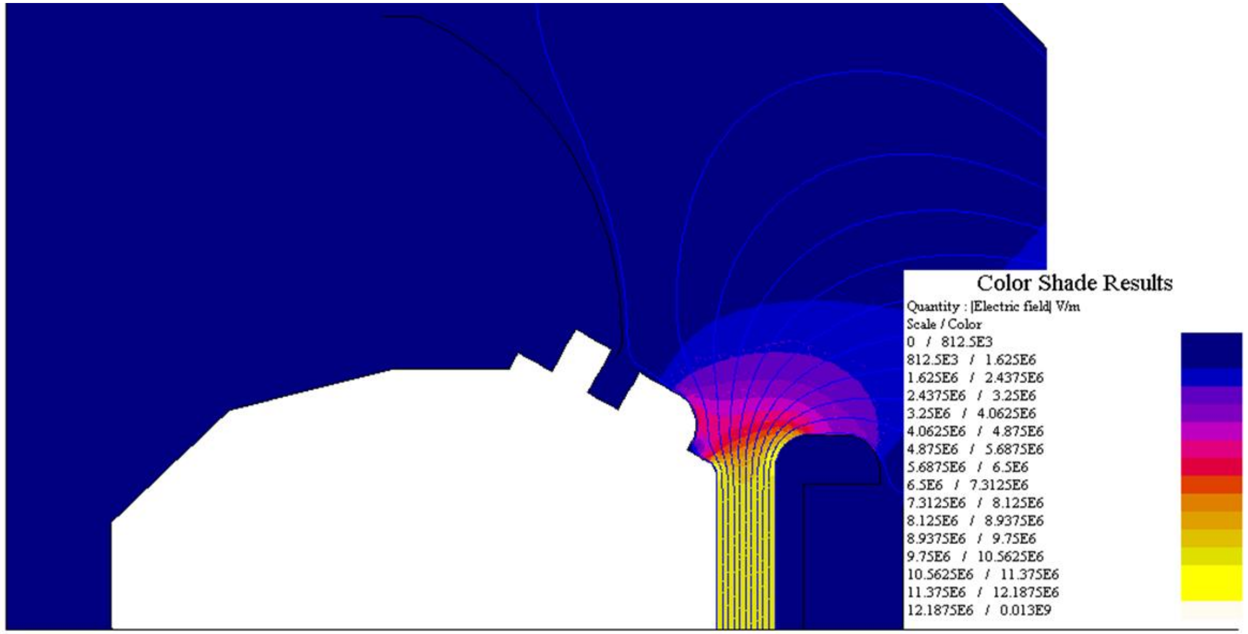
Electrostatic Septa

Singular: septum, plural: septa.



Electrostatic Septum Principle





Circulating beam passes through hollow support of septum foil (creating as such a field free region).

Extracted beam passes just on the other side of the septum (high, homogeneous, field region).

Electrostatic septa **use vacuum as an insulator** an

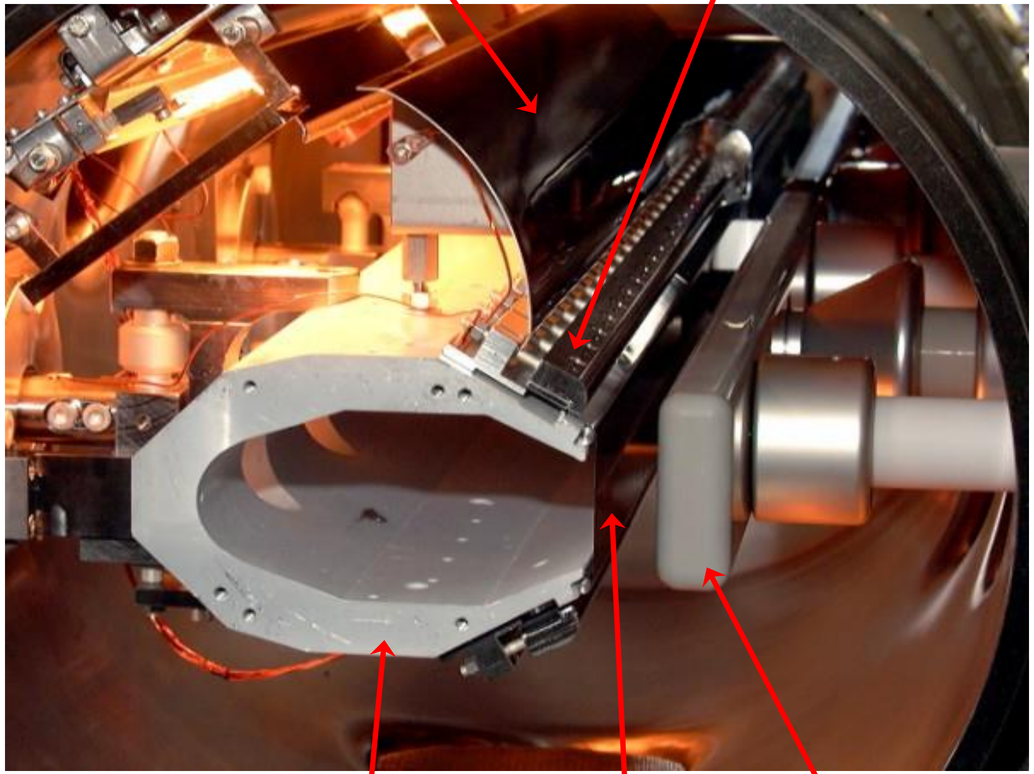
Leak field

and in practice often omitted. Simulations are a

ement.

Electrostatic septa provide a relative weak beam deflection, but the septum can be very thin (typically from 50 μm upwards).

Typical layout and parameters [24,25]

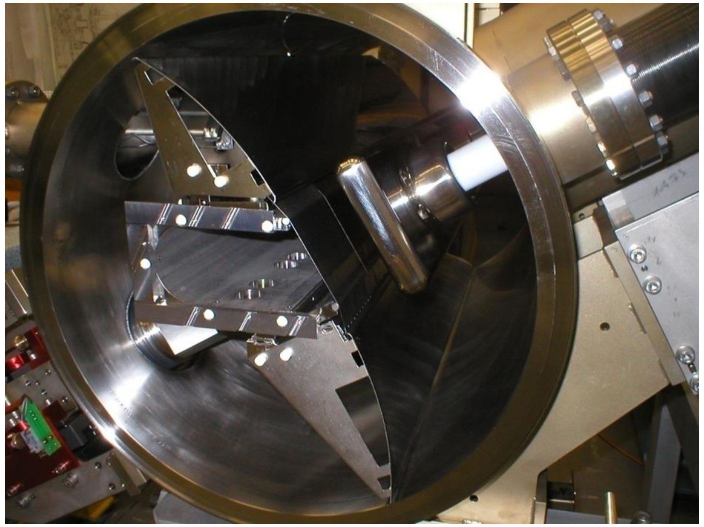


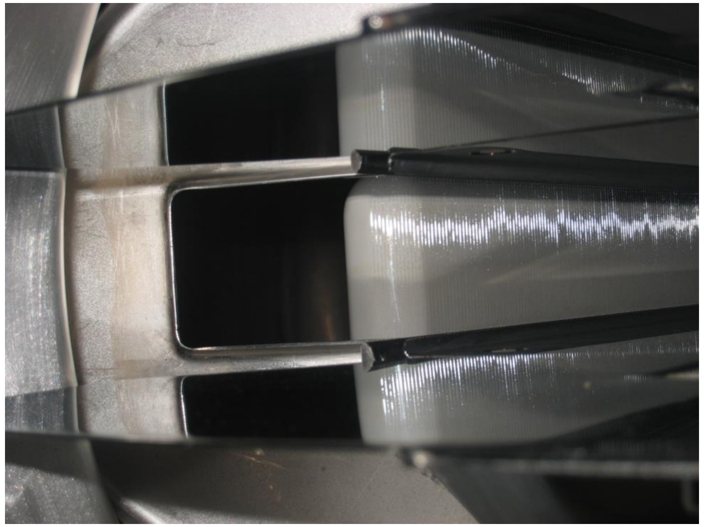
Typical technical specifications:

- Electrode **length** : 500 - 3000 mm;
- **Gap width** (typical) : 10 - 35 mm;
- **Septum thickness**: ≤ 0.1 mm;
- Vacuum (10^{-9} to 10^{-12} mbar range);
- **Operating Voltage**: up to 300 kV;
- **Electric field** strength: up to 10 MV/m;
- **Septum** Molybdenum foil or Tungsten wires;
- **HV electrode** made of stainless steel, Titanium (good for extremely low vacuum applications) or anodised aluminium;
- Bake-able up to 300 °C for vacuum in 10^{-12} mbar range;
- Power supplied by Cockcroft W [illegible] ge

Vacuum provides the insulation; cannot run at atmospheric pressure.

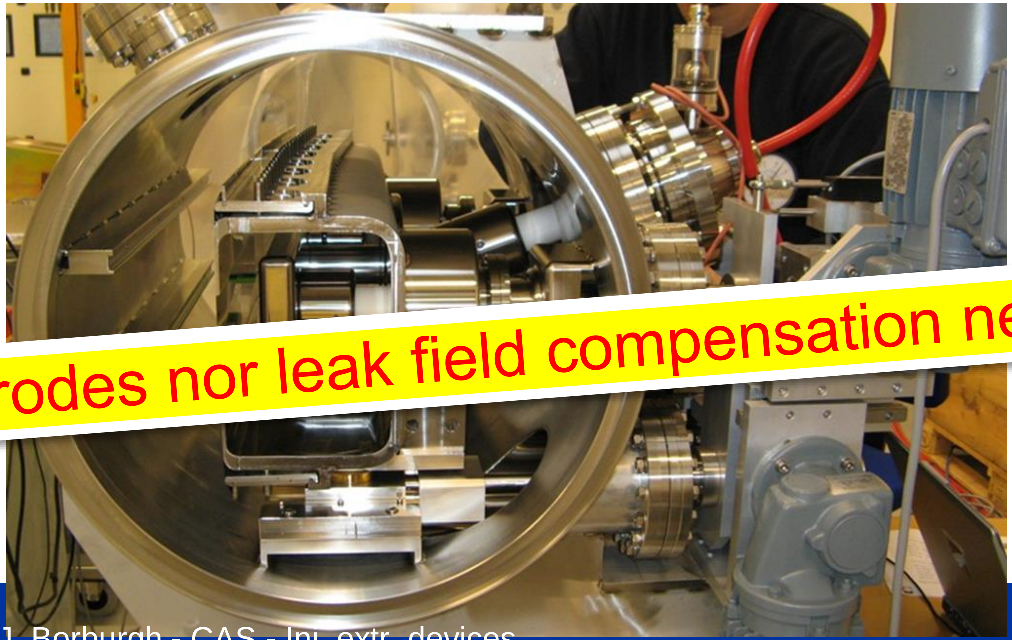
Electrostatic Septum variants and topologies





Septum variants used are:

- Foil (screens leak field very effectively)
- Ribbon (more complex fixation)
- Wire (low mass seem by beam)



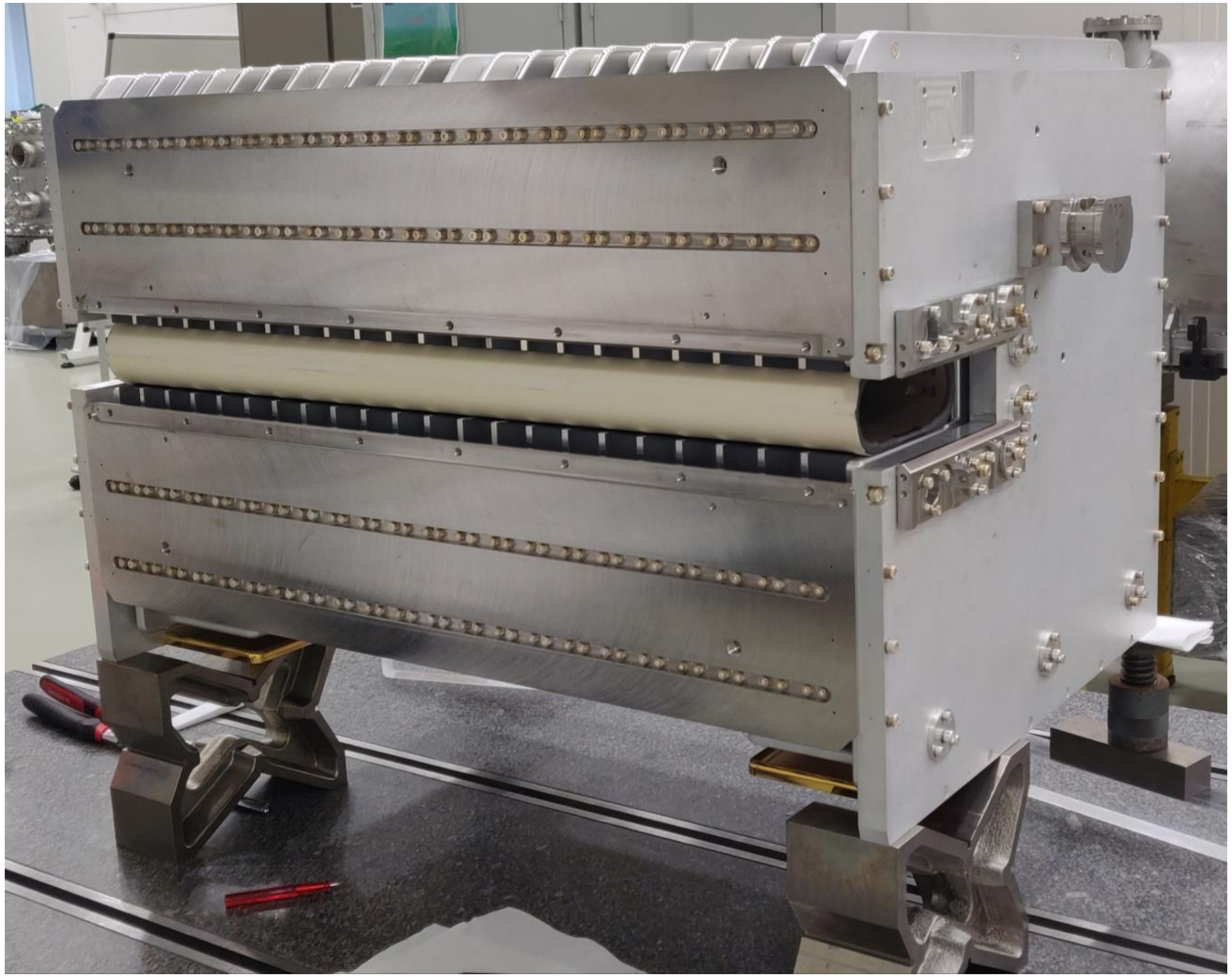
Different topologies:

- Cathode opposite anode
- Tilted electrodes, split electrodes
- Cathode inside Anode layout

Foil septa are least complex; no clearing electrodes nor leak field compensation needed.

Kicker systems

Magnets and generators [28,29]



Electrical Parameters for a Magnetic Kicker

Usually 1 for a kicker magnet

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

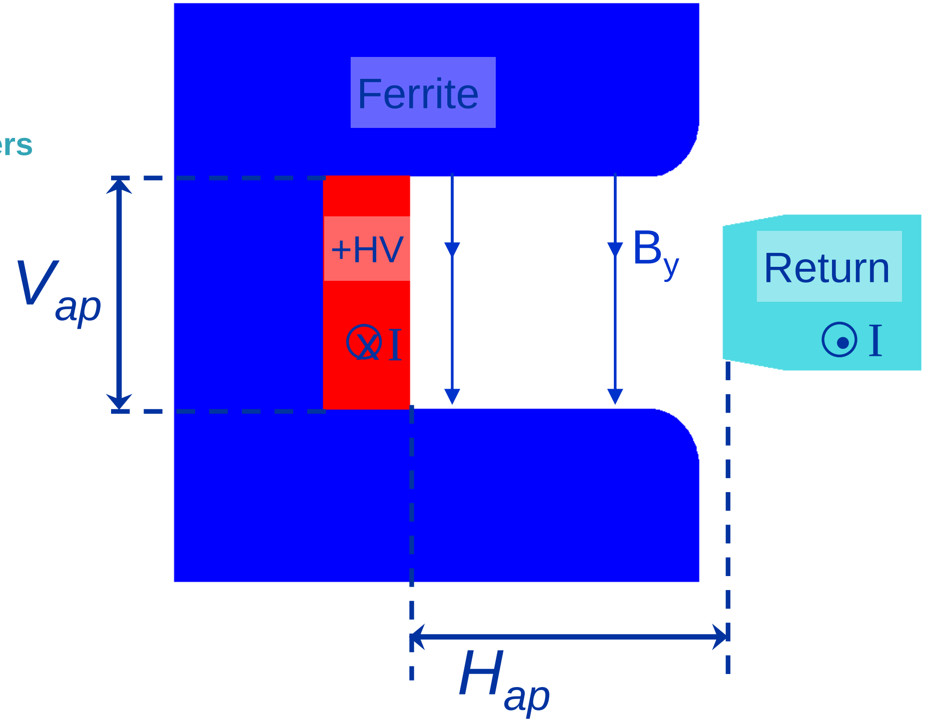
Minimum value set by beam parameters

Hence: "I" determines B_y

Eddy-currents and proximity effect result in current flow on inside surface of both conductors.

Minimum value set by beam parameters

Hence inductance is given by: $L_m \cong \mu_0 \left(\frac{N^2 \cdot H_{ap}}{V_{ap}} \right) . l$



Where
- μ_0 is permeability of free space (4π x 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
- V ...
- ... gnet (m);
- L_m is inductance of the kicker magnet (H).

To achieve fast rise and fall time, a significant voltage is needed $L_m dI/dt$

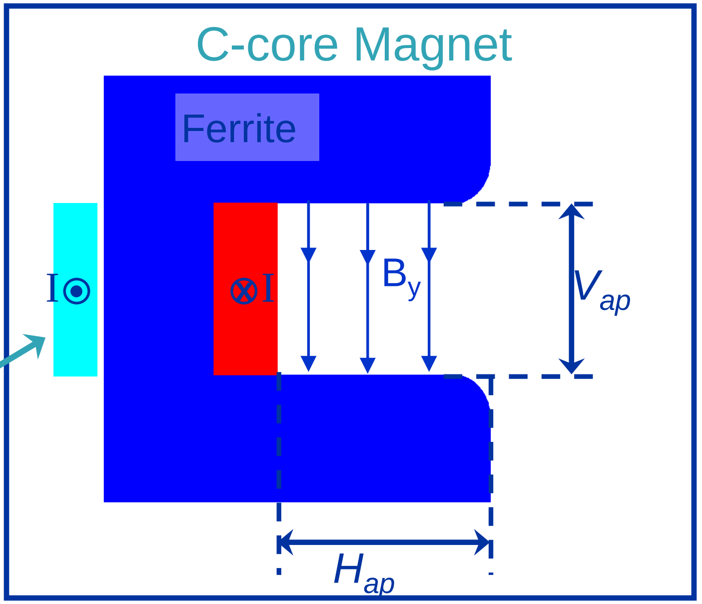
Kicker Magnet Magnetic Circuit

Most kickers use a magnetic circuit containing **magnetic material**:

- to greatly reduce the effective value of V_{ap}
- to improve the field uniformity

NiZn Ferrite is usually used, with μ_r≈1000:

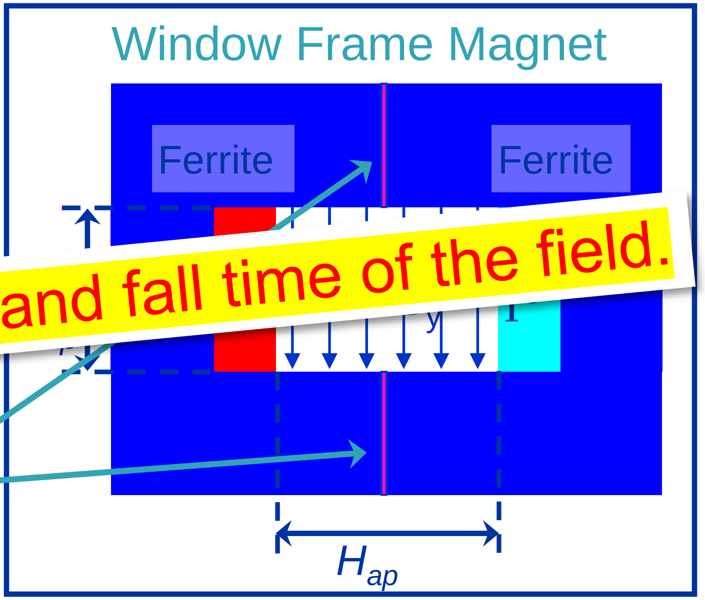
- Field rise can track current rise to within ~1ns;
- Has low remnant field;
- Has low out-gassing rate after bake-out.



Sometimes the return conductor is behind the yoke (for beam gymnastic reasons) – this increases L_m by about 10%.

To reduce filling time by a factor of two a window frame topology is used:

- It can be considered ... ...dependently.
- ... the reduced filling time.
- ...y current "shields" are used between the two ferrite C-cores to reduce beam coupling impedance.



Ferrite is the commonly used yoke material to allow fast rise and fall time of the field.

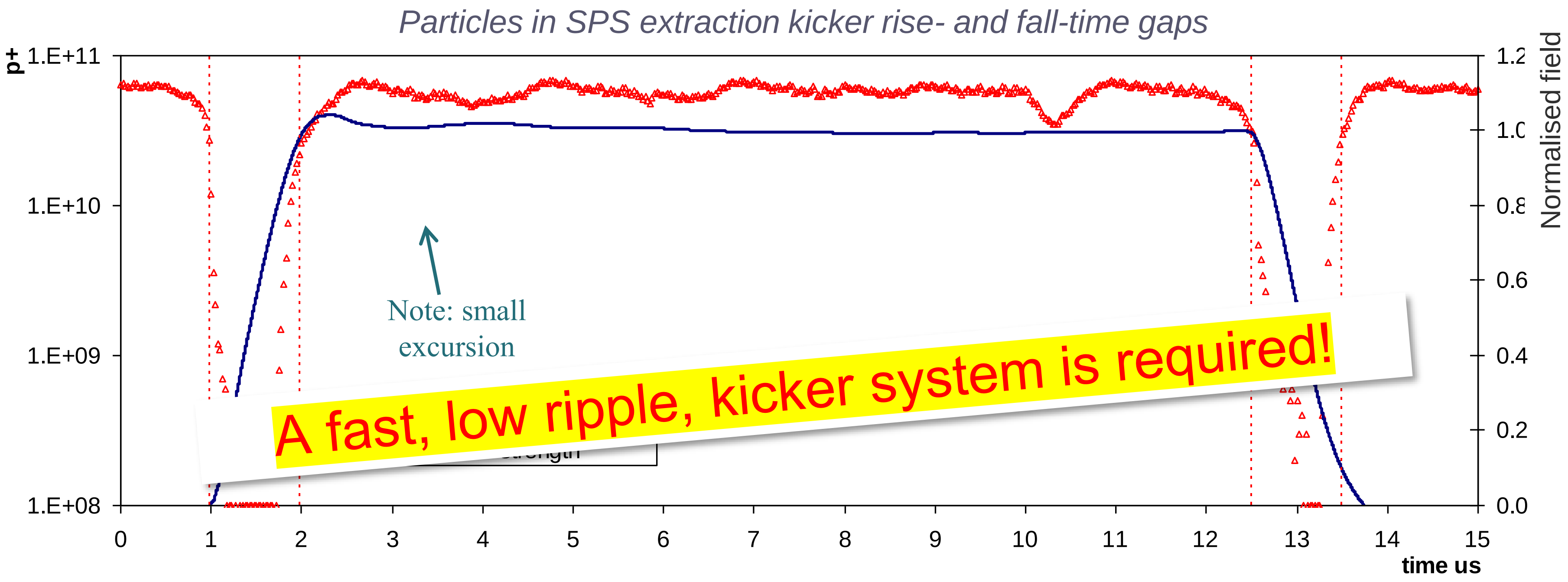
Fast Injection/Extraction kicker

The kicker magnetic field must rise/fall within the time period between the beam bunches (or batches).

Typical field rise/fall times range from 10’s of nanoseconds to microseconds and pulse width ranging from 10’s of nanoseconds to 10’s of microseconds;

If a kicker exhibits a **time-varying** structure in the pulsed field, this can **lead** to small closed orbit offsets (betatron oscillations).

A fast, low ripple, kicker system is required !



Kicker magnet topologies

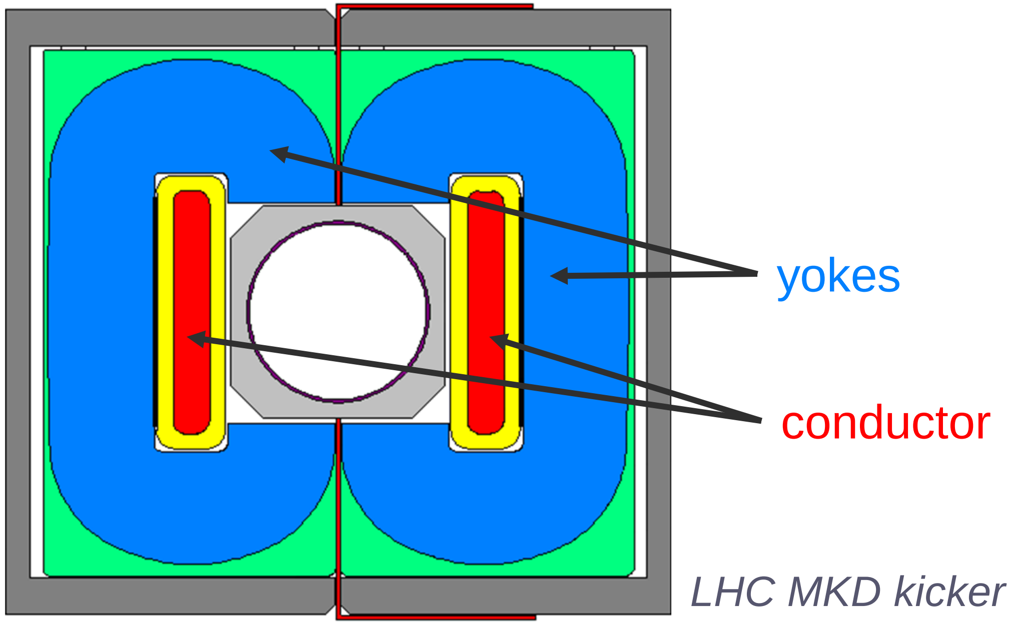
Depending required 'speed', i.e. the rise and fall time of the devices, different kicker topologies are used.

Topologies in order of their speed:

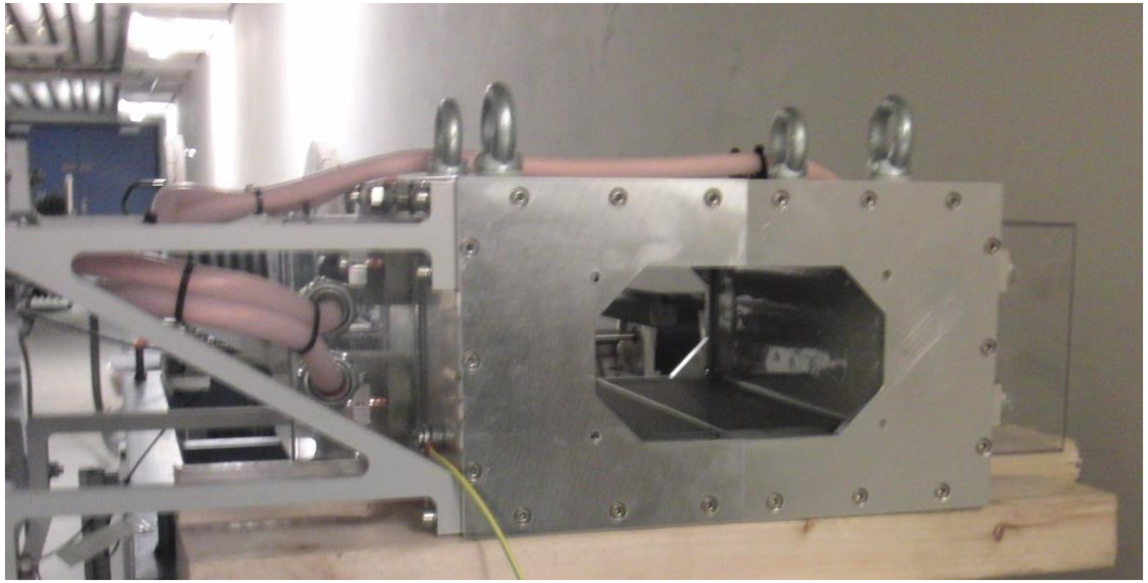
- **Lumped inductance kicker**
  - Ease of construction; often used outside vacuum; strong field (ferrite yokes < 0.3 T, but thinly laminated steel yokes < 1T). Less demanding power generator, often of the capacitor discharge type.
- **Transmission line kicker**
  - Complex kicker design: magnet inductance is distributed over cells by adding decoupling capacitors; under vacuum; medium strength (ferrite yoke < 0.3 T). Matched impedance power generator required, using a pulse forming network or pulse forming line.
- **Stripline kicker**
  - No magnetic yoke! Combines electric and magnetic field; under vacuum; weak strength; only fast pulsed. Ultra-fast, 2 completely matched impedance generators.

Lumped inductance kicker [30]

- Cost effective.
- Yoke can be made of thinly laminated steel.
- Bus-bar conductor can be insulated for High Voltage.
- Can be multi-turn coil, although mostly single turn.
- Usually not under vacuum; requires (ceramic) vacuum chamber inside the gap.



LHC MKD kicker

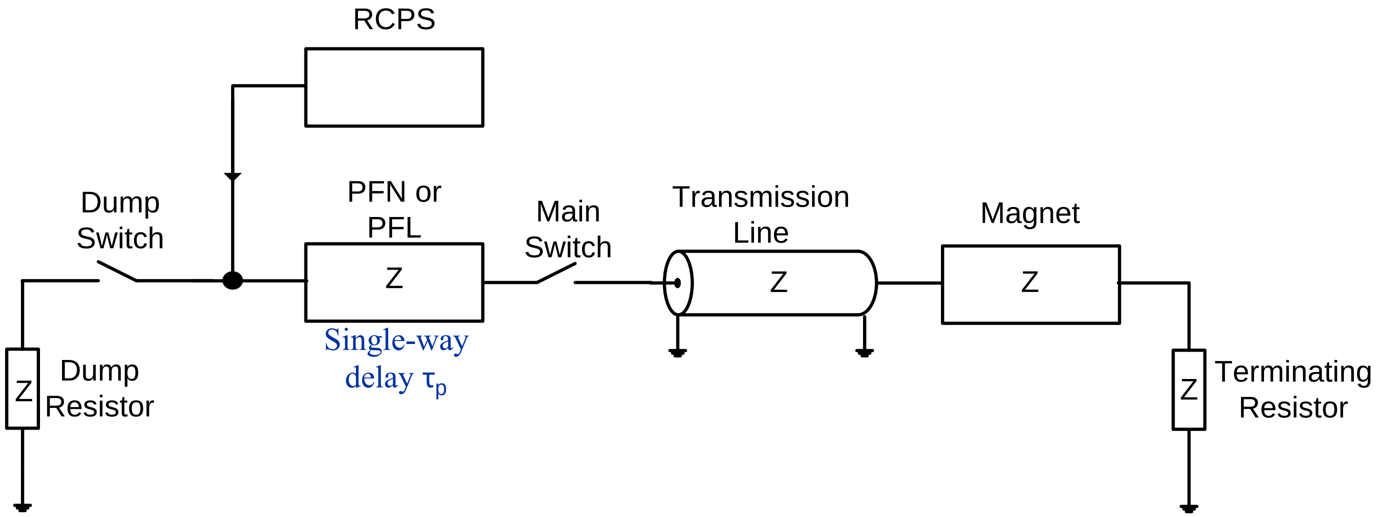


MedAustron MKI:

2 C-shaped yokes back-to-back with a non-magnetic conducting plate to decouple both halves.

t_r = 100 us
B_0 = 0.123 T
I = 1.35 kA

Overview of Transmission Line Kicker System [31,32]



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

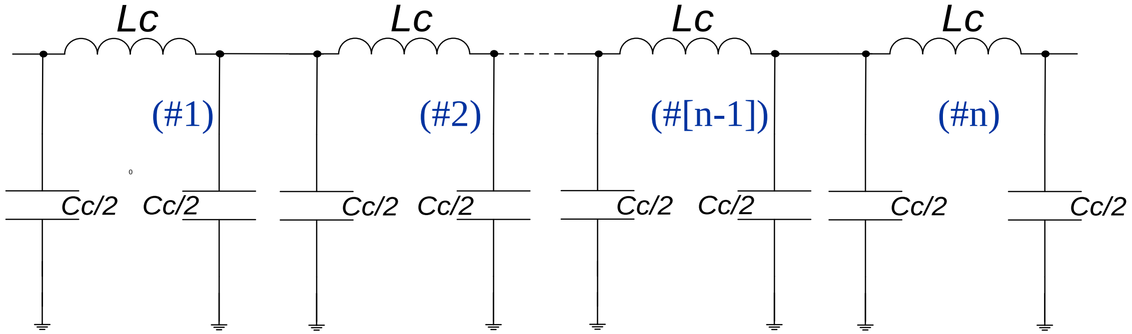
<u>Typical impedance matched circuit operation:</u>

- PFN/PFL is charged to a voltage V_p by the RCPS;
- Main Switch closes and, for a matched system, a traveling wave of magnitude … the transmission line, towards the magnet;
- Once the current pulse reaches the … full-field has been established in the kicker magnet:
- … the magnet can be controlled in length, between 0 and $2\tau_p$, by adjusting the timing … Dump Switch relative to the Main Switch.

To reduce ripple and reflections, all parts need to have same characteristic impedance.

Transmission Line Kicker Magnet

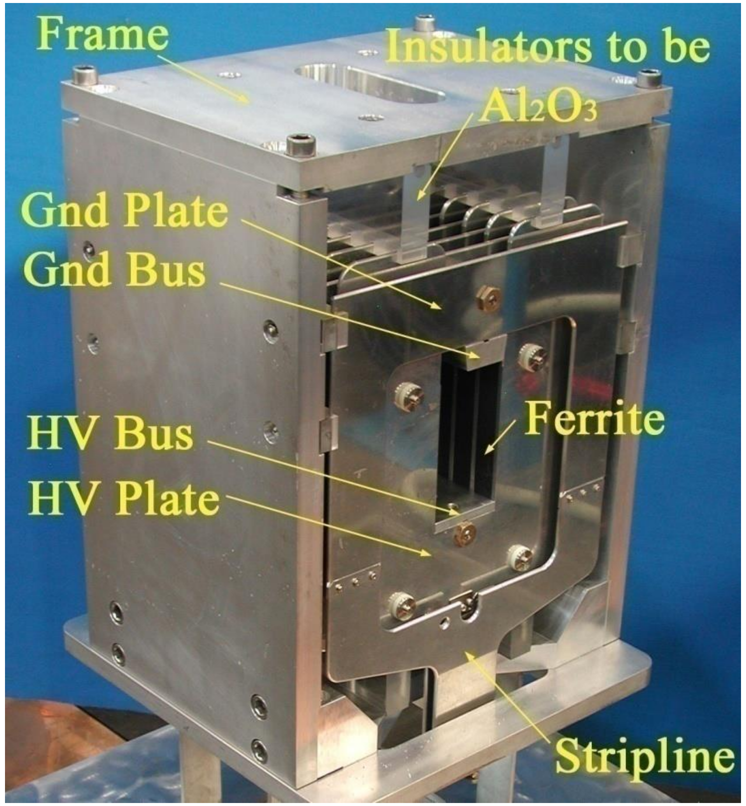
- Consists of few to many “cells” to approximate a coaxial cable;



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

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

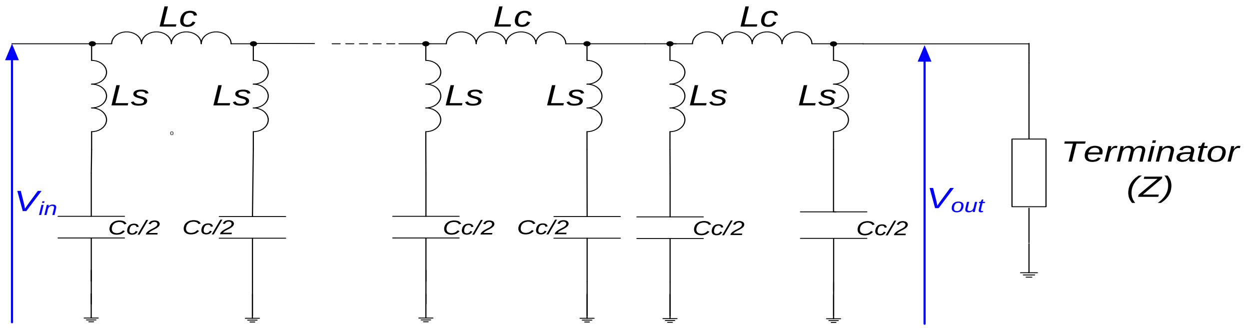
$$\tau_m = n\cdot\sqrt{Lc\cdot Cc} = n\cdot\left(Lc/Z\right) = Lm/Z$$



- Ferrite C-cores are sandwiched between high voltage (HV) capacitance plates.
- One C-core, together with its ground and HV capacitance plates, is termed a cell.
- The total inductance is split over *n* cells.
- Each cell conceptually begins and ends i...
- Th... ...identical to the circuit of an artificial transmission line.
- ... (τ_m) is the delay required for the pulse to travel through the “*n*” magnet cells.

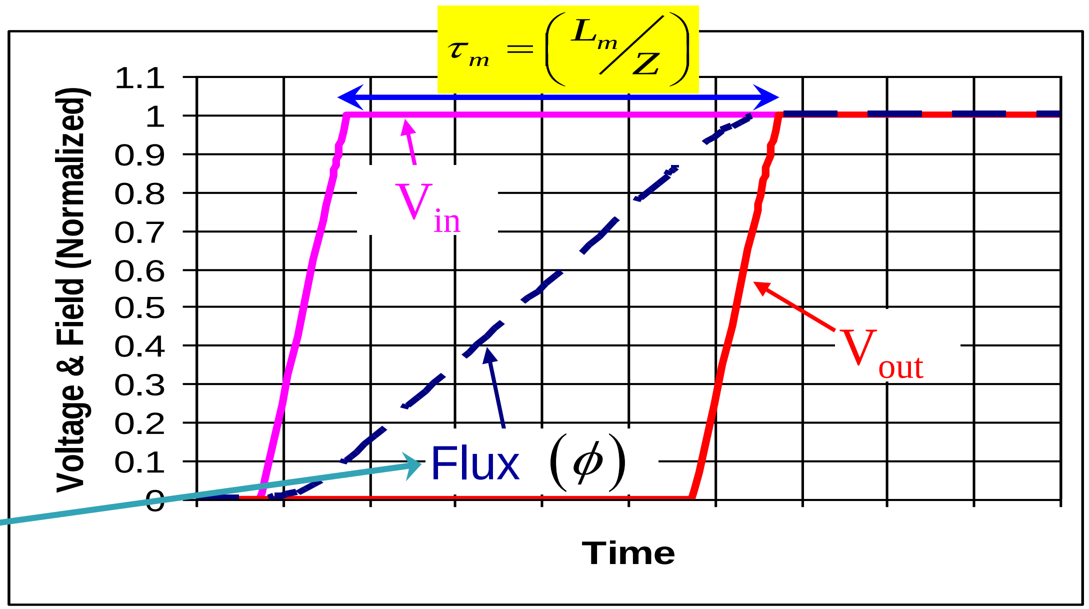
The length and number of cells has strong influence on ‘speed’ of the magnet.

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 time** is given by the sum of the pulse 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 import… degrade while travelling through the magnet. Thus the magnet cut-off fre… times below ~100 ns. Cut-off frequency (f_c) depend…

Th… as possible and the cell size small. However, cells cannot be too small (voltage breakdown & cost).

Transmission line kickers are much faster than lumped inductance kickers. However, design and construction is far more complicated and costly.

Transmission Line Kicker Magnet Termination

When space is at a premium, a **short circuit termination** has the advantage of doubling the 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** sees 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).

Short circuit termination of a kicker can double its kick strength, but it comes with draw backs.

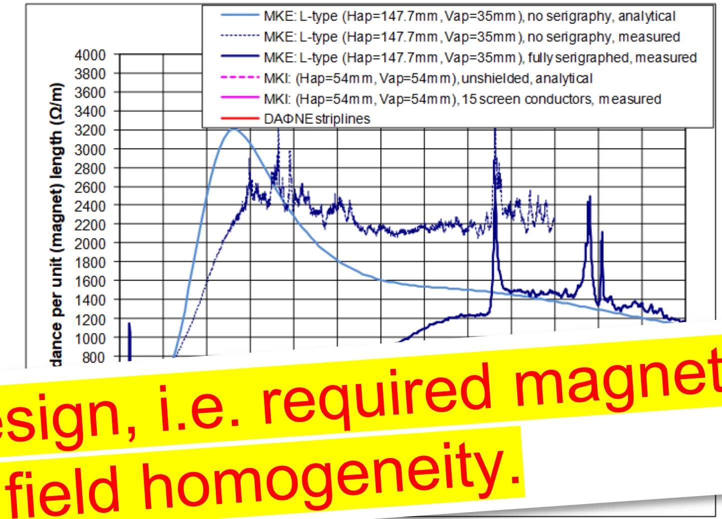
Beam impedance screening [33,34]

LHC Injection Kicker

In order to reduce beam coupling impedance, the **yoke** (ferrite) **must be shielded** from the beam by providing a path for beam image current.

<u>This can be achieved by</u>:

- inserting a beam screen inside magnet aperture (even for under vacuum kickers);
- Serigraphy on ferrites (only possible for long cells);
- Using a metalised ceramic in the aperture.



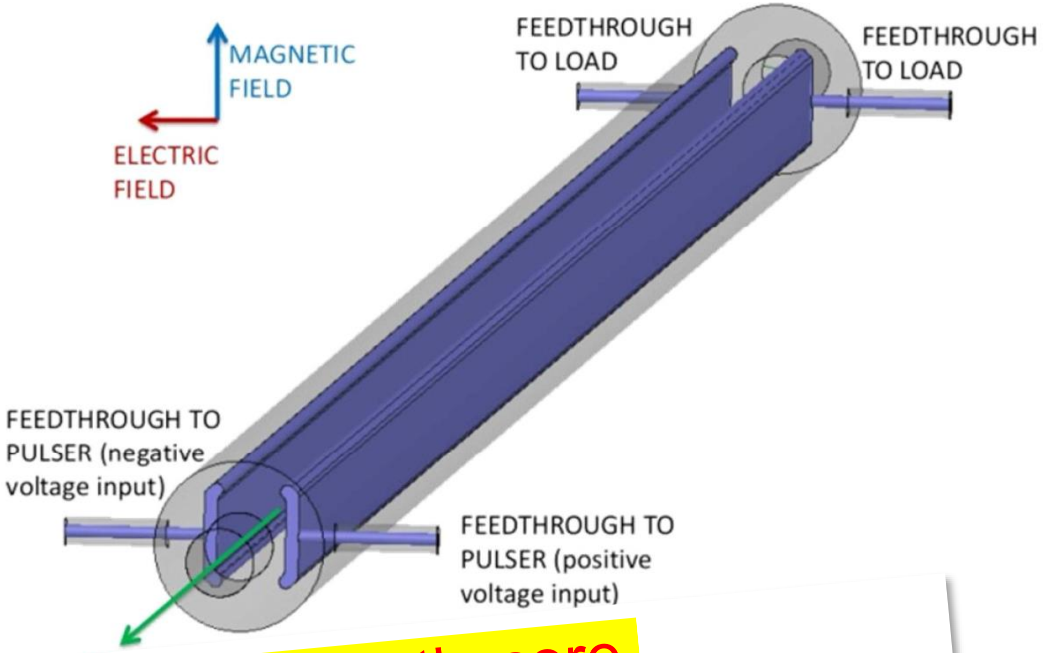
However, the desig…
i…
fi…

A screen has an impact on the magnet design, i.e. required magnet aperture, but also on the resulting field homogeneity.

SPS MKE kicker

Stripline kicker [35, 36]

- Stripline kickers combine the current in electrodes as well as the voltage differential to create a magnetic and electric field to deflect the particles.
- Low magnetic field due to the lack of a magnetic yoke.
- Very fast rise and fall times can be obtained.
- The challenge is to design a device which preserves the characteristic impedance, including near the feedthroughs.

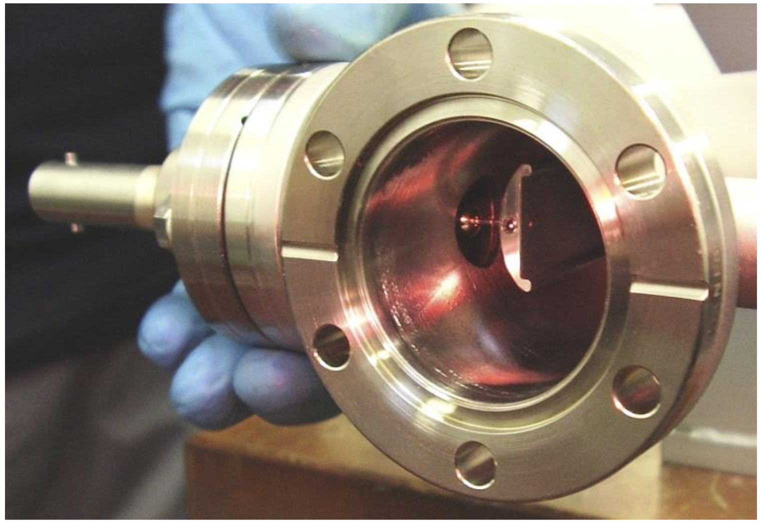


Very fast, but less powerful due the lack of a magnetic core.
Complex design to preserve the characteristic impedance.

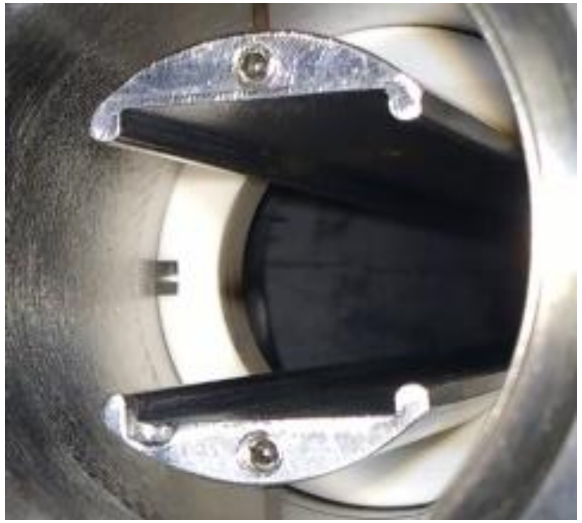
CLIC damping ring striplines

Parameter	value	unit
Nominal voltage	± 12.5	kV
Nominal current	± 306	A
Characteristic impedance	41	Ω
Magnetic field	4.2	mT
Electric field	0.63	MV/m
Gap width	20	mm
Length	1.7	m
Vacuum chamber diameter	40	mm
t_r/t_f	100	ns

As installed at ALBA Cells

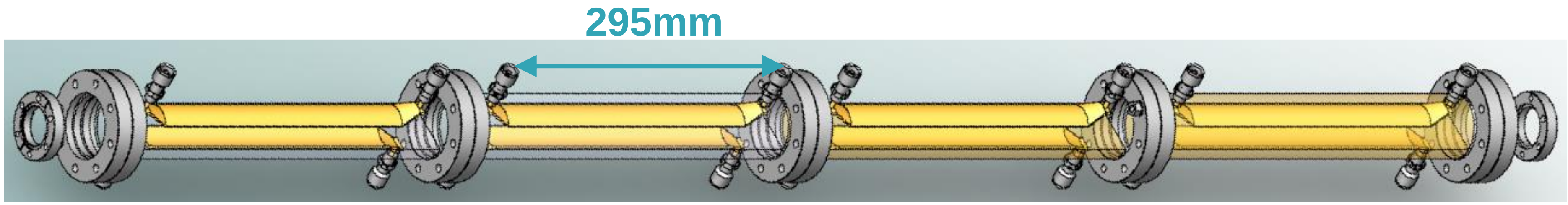


Feedthrough supporting electrode



Electrode support ring

CTF3 stripline kickers



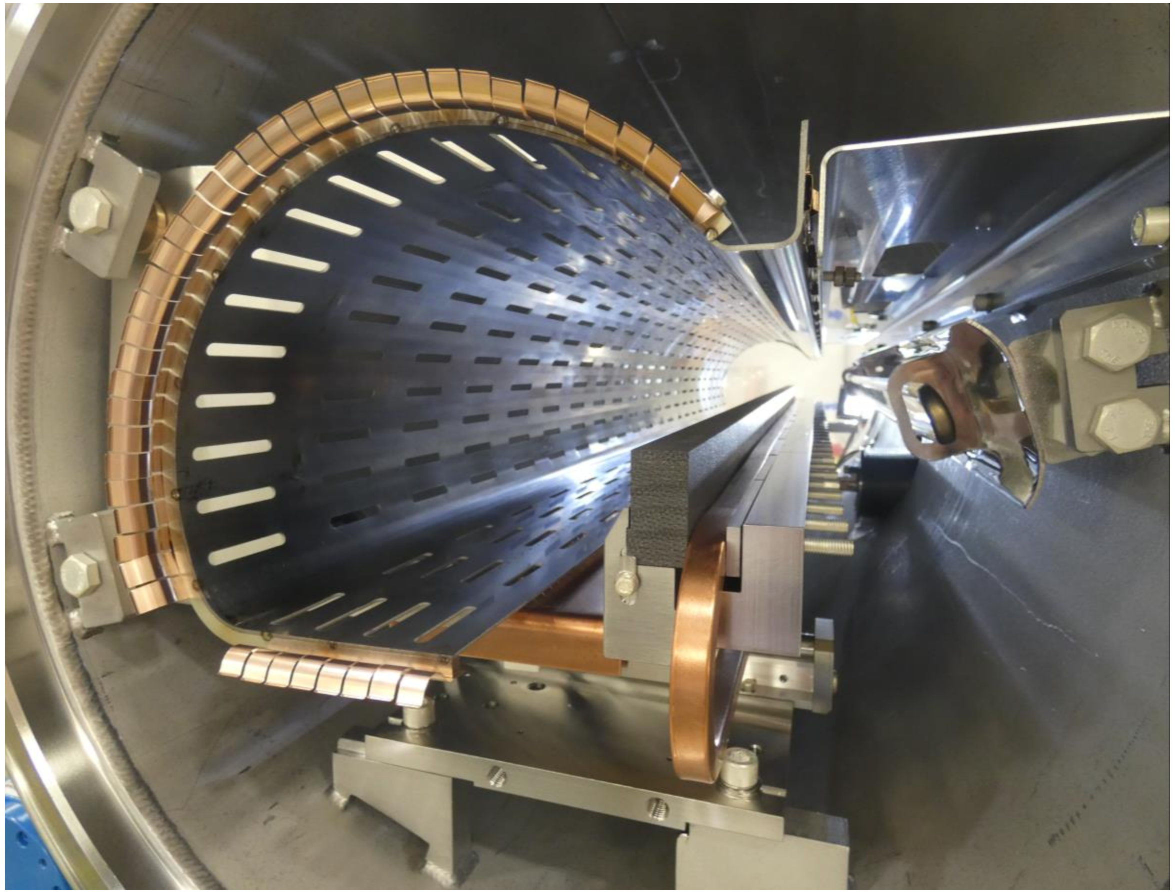
CTF3 striplines (~1.52m)

Parameter	value	unit
Nominal voltage	± 2.65	kV
Nominal current	± 53	A
Characteristic impedance	50	Ω
Magnetic field	0.43	mT
Electric field	0.13	MV/m
Gap width	40	mm
Length	1.18	M
Vacuum chamber diameter	78	mm
t_r/t_f	< 5	ns

Installed in CTF3

Machine protection

Diluters, spoilers, dummy septa



Extraction protection devices

When beam parameters exceed damage limit: critical beam transfer systems need redundancy and multiple layers of protection:

- **Active protection** systems (e.g. Beam Interlock System, BIS)
  - When a critical system fails, the BIS is responsible for initiating a beam dump: in LHC ~3h to re-establish stable beams operation.
- **Passive protection** devices are the last layer of security
  - Passive protection devices are **designed to dilute and absorb beam energy** safely

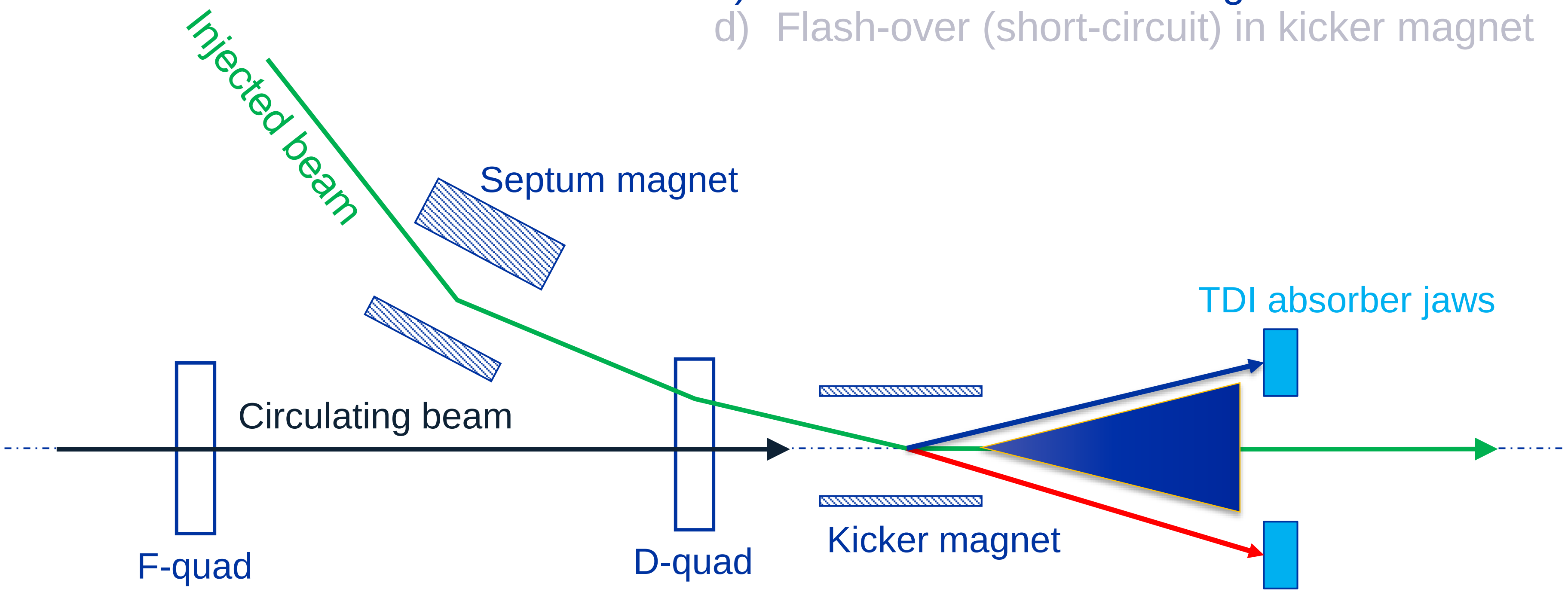
Failures associated with beam transfer equipment are typically very fast and difficult to catch, for example:

- **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

Example: LHC Injection protection

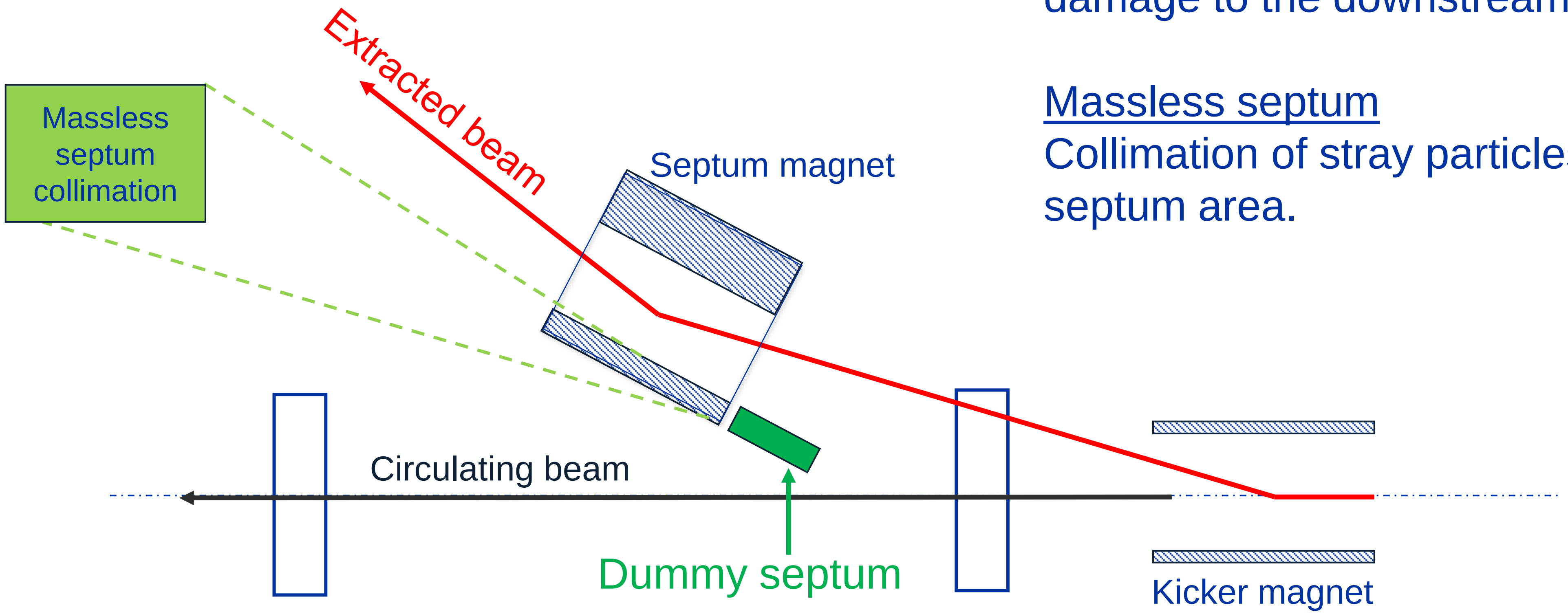
Dedicated injection dump (TDI) to protect against fast failures of the injection kicker system.

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



Extraction equipment protection

Diluters



<u>Physical septum</u>
Diluter (dummy septum) reduces beam energy density to acceptable levels to avoid permanent damage to the downstream septum.

<u>Massless septum</u>
Collimation of stray particles that transit the septum area.

Summary

Magnet Septum design dominated by mechanical constraints.

- Thermal challenges for DC septa; fatigue and vibration challenges for pulsed devices.

Electrostatic septa dominated by max. operational fields as well as mechanical tolerances to achieve a thin septum.

Kicker magnet design has a direct impact on the generator design.

- Kicker required ‘speed’ determines the kicker magnet topology.
- Beam impedance shielding should be adapted to the required kicker performance (permissible beam intensity, rise and fall time, fields quality) and needs careful study beforehand.

Extraction protection elements essential for robustness of the extraction solution retained for high energy accelerators.

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J. Holma, “A Pulse Power Modulator with Extremely Flat-top Output Pulses for the Compact Linear Collider at CERN”, PhD Thesis November 2015, https://cds.cern.ch/record/2130258

D. Woog, “Inductive Adder for the FCC Injection Kicker System. Inductive Adder für das FCC Injektionskickersystem”, PhD Thesis July 2020, https://cds.cern.ch/record/2723499

A. Chmielinska, “Optimization of the Beam Screen for the FCC Injection Kicker Magnets”, PhD Thesis 2019, http://cds.cern.ch/record/2704638

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Back-up slides

Mechanical considerations

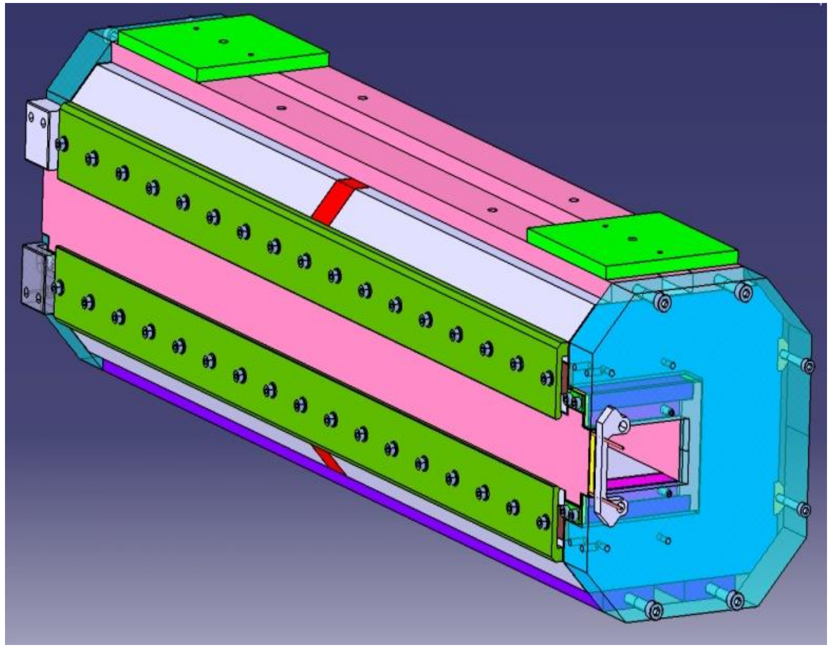
Force (F) on the on the septum blade can be approximated with (Lorentz):

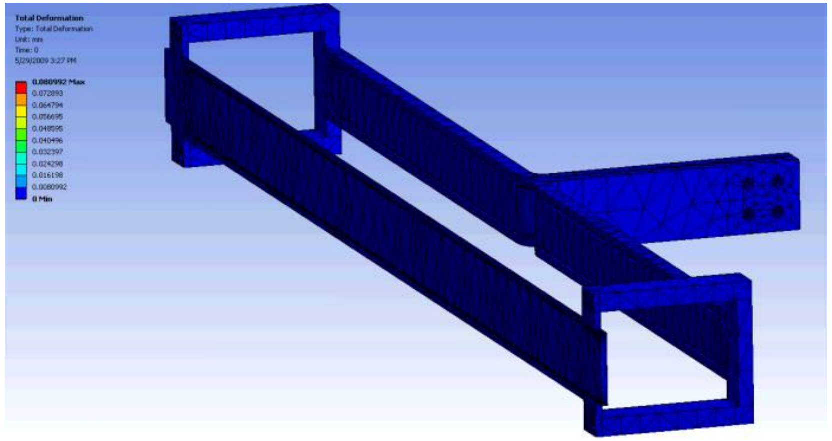
$$F=\frac{B}{2}.I.l$$

For example: 1. 10^5 N on a 40 mm tall and 5 mm thick blade of 1 metre length is being used in LEIR.

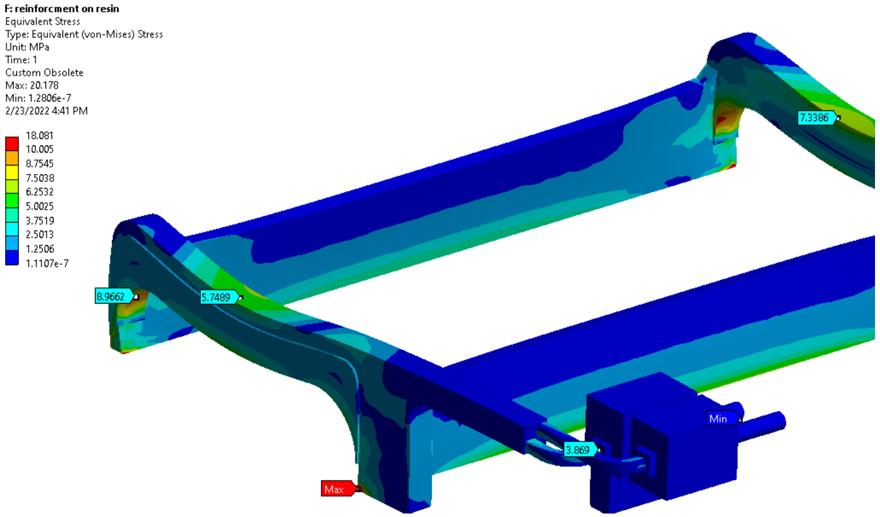
Septum can be treated as a simply supported beam, and the **maximum deflection** can be approached with the Euler-Bernoulli beam theory.

For example: 20 µm deflection of the PS extraction septum (3mm thick) at each pulse.

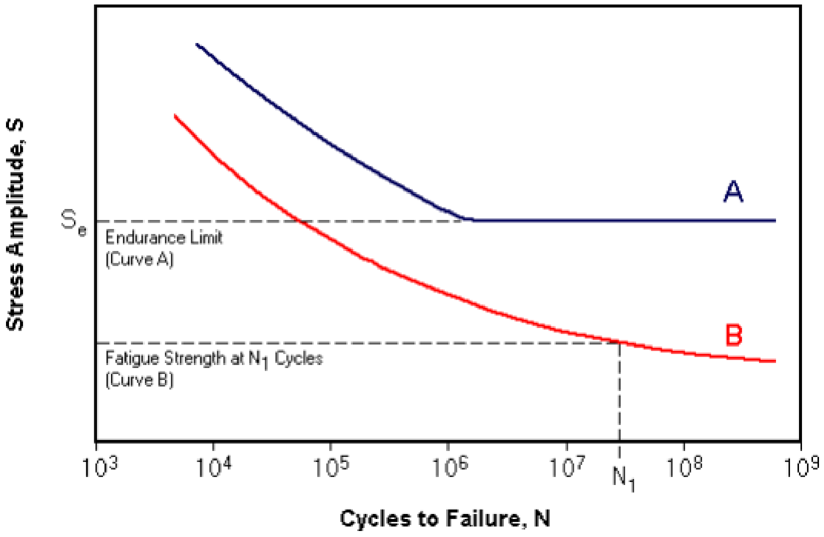




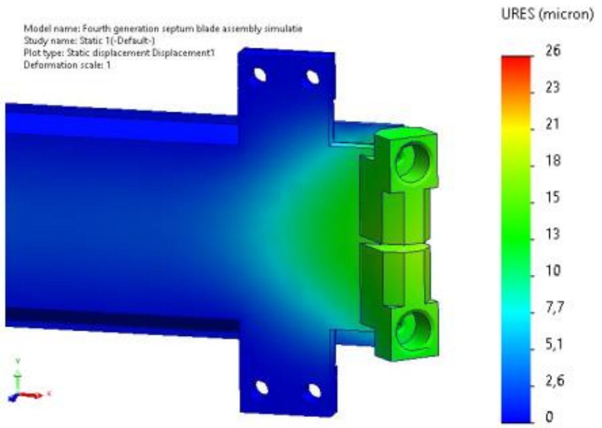
Mechanical stress + fatigue



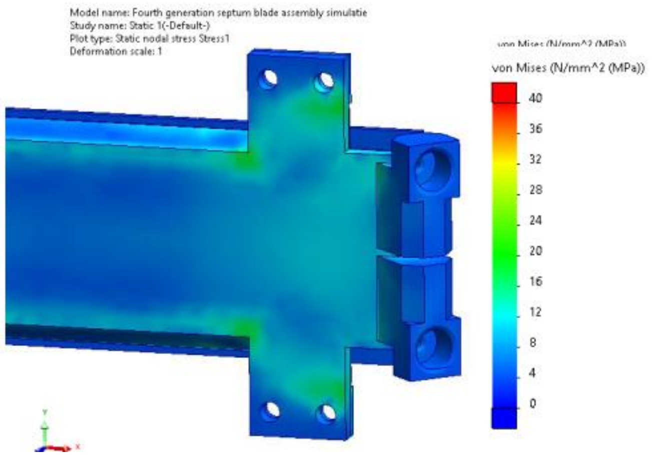
PSB, Blr.BSW1-4



Displacement



Stress



LEIR extraction SMH40

Fatigue strength is important due high amount of cycles

- Numerical prediction and optimization
- Leak testing, NDT, and qualification on test stand therefore important

For example: SPS MS septa expected lifetime is ‘only’ 10 M pulses.

Thermal magnet load

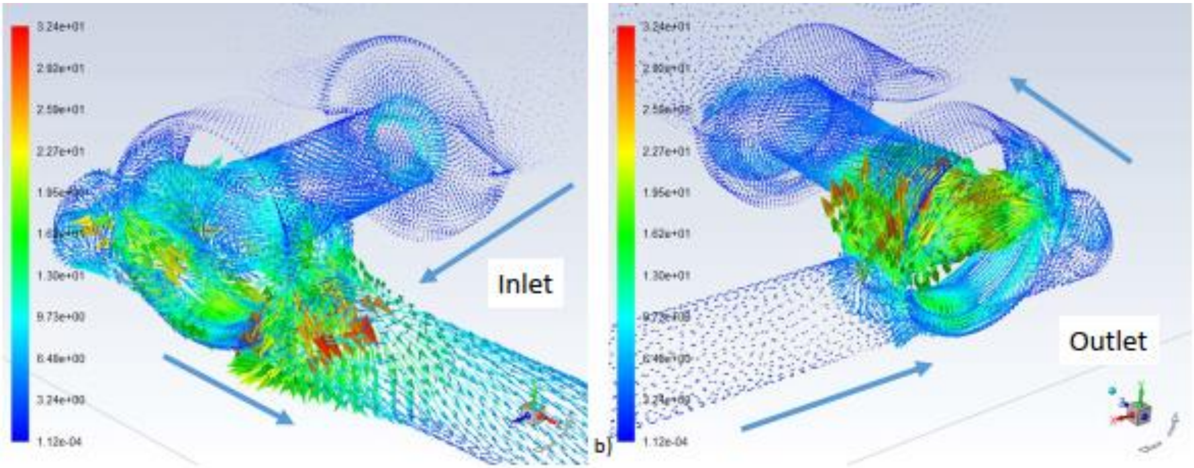
DC septa:

- Cooling for heat extraction

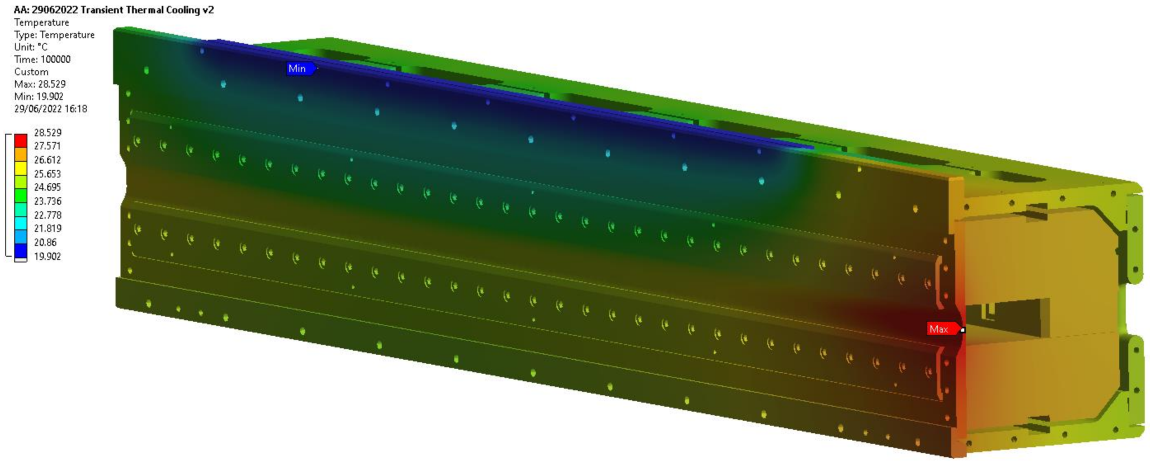
Pulsed septa:

- Electrical load variable to stabilize Temperature.

Current density and hence power dissipation is high, therefore heat extraction in a turbulent flow regime (SPS MS: 13.4 m/s).



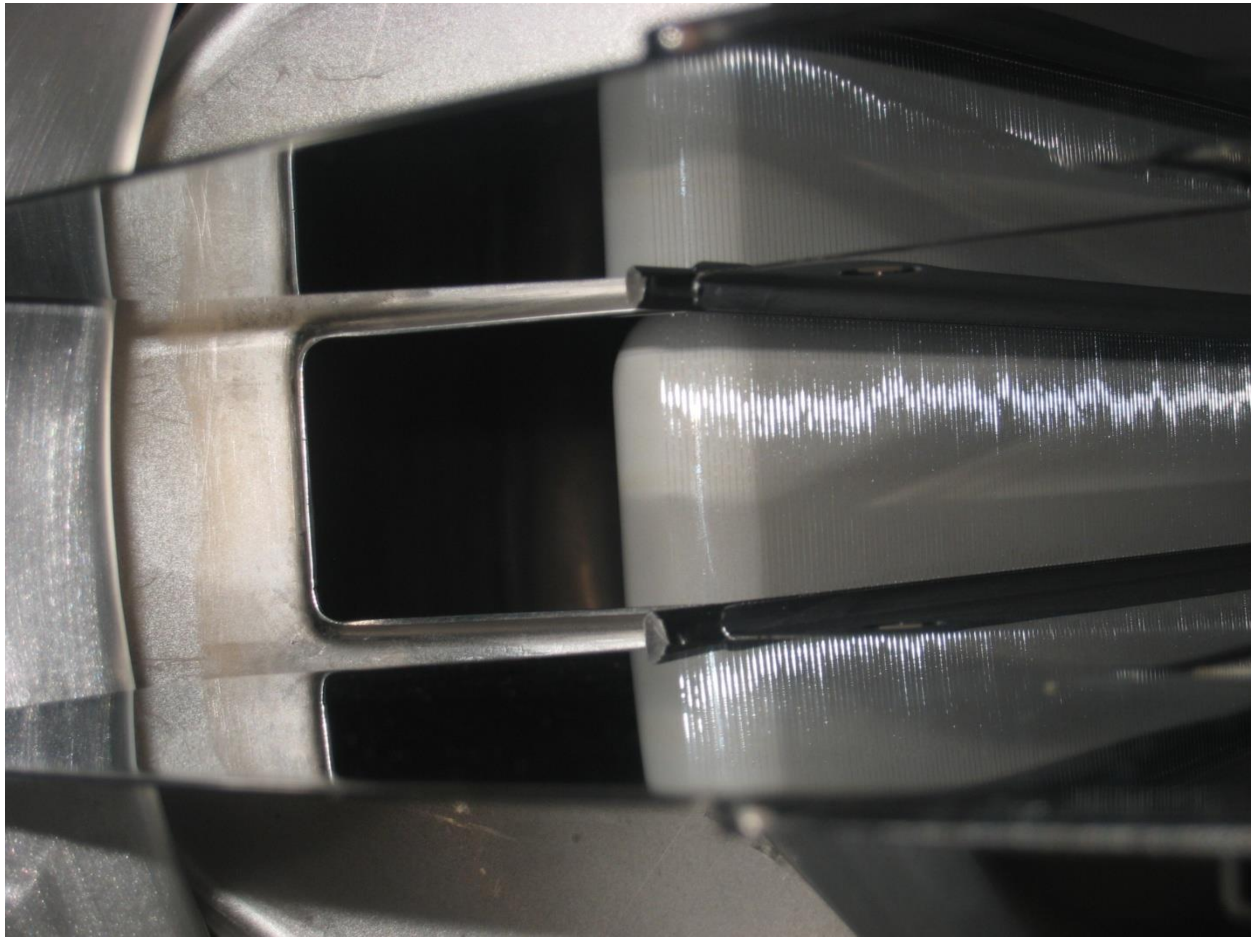
CFD modelling with aim to optimize cooling flow (SMH40)



Thermal transient model of SMH16 (PS extraction)

Wire septum [4,5,6]

- W-Re (27%) wire septum.
- Needs ion traps in circulating beam area .
- Very thin septum (60 µm).
- High operational electric field in operation possible (>10 MV/m).
- Low Z seen by the beam.



SPS ZS septum for slow extraction

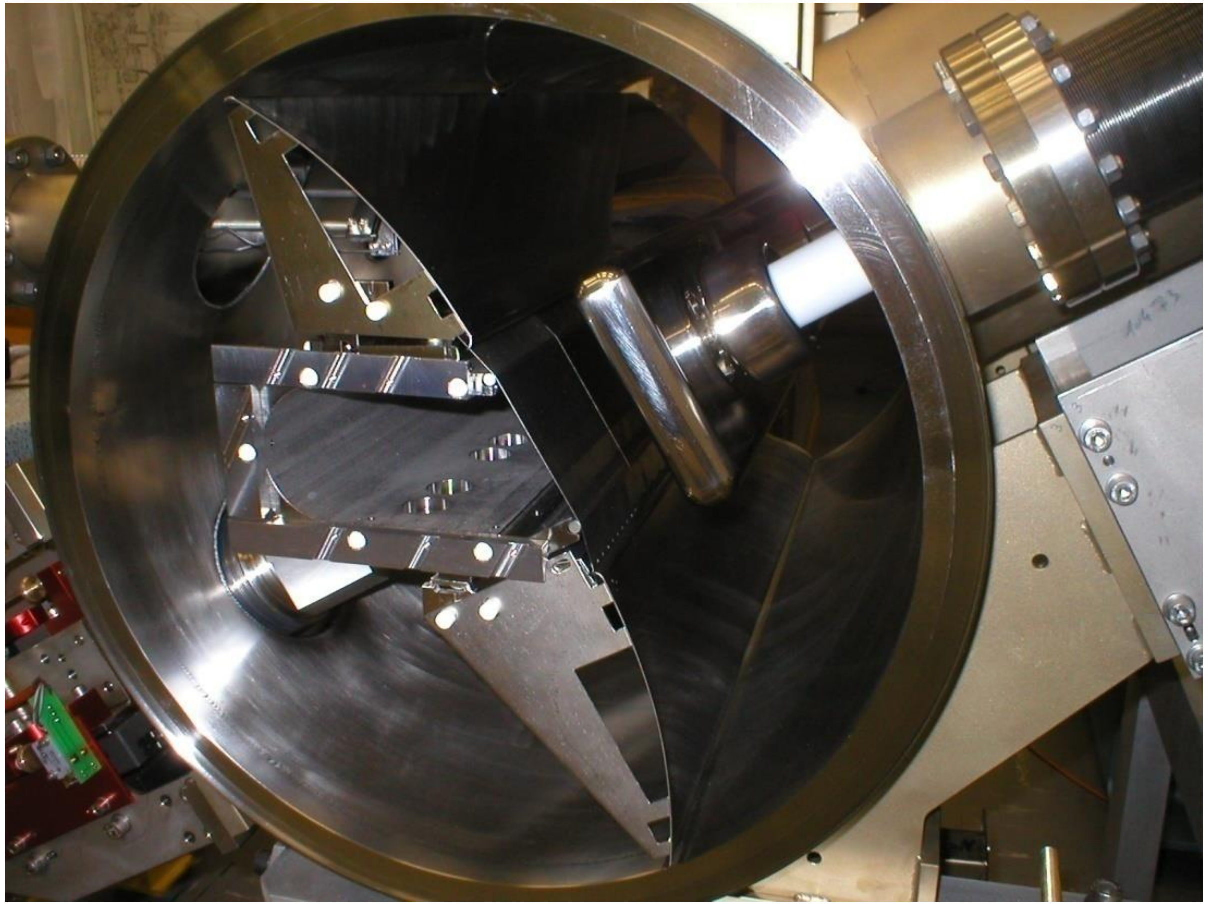
Foil septum [7,8]

Example: diagonal multi-turn injection in LEIR.

Remote displacement at 30º from horizontal plane to allow for longitudinal painting injection scheme.

Titanium cathode and deflectors to allow for high field strength whilst remaining compatible with XHV (10^{-12} mbar range).

Tall cathode, and anode deflector screens needed, to provide required good field region.

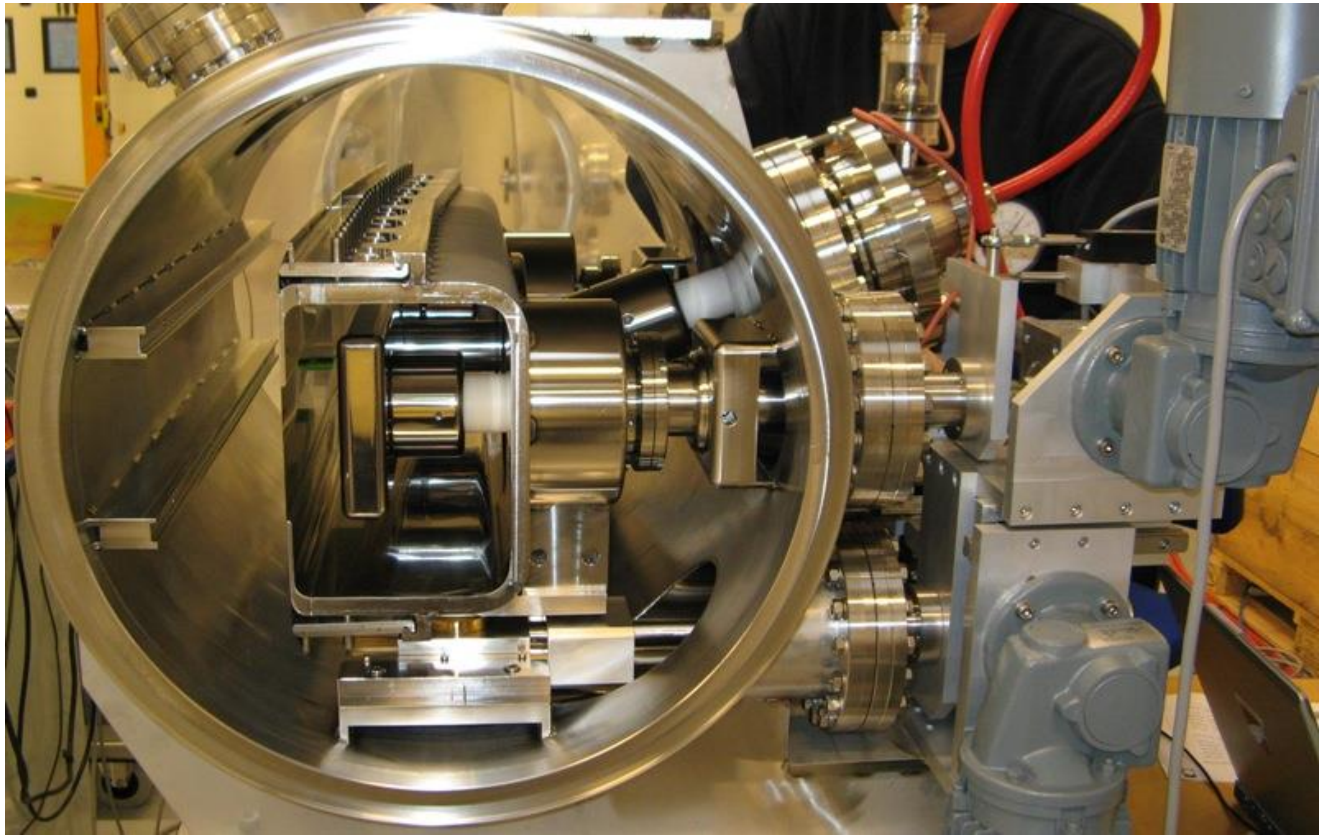


Cathode inside Anode support [9,10]

- Allows both remote displacement systems to be on the same side (free up space on orbiting beam side for other equipment.

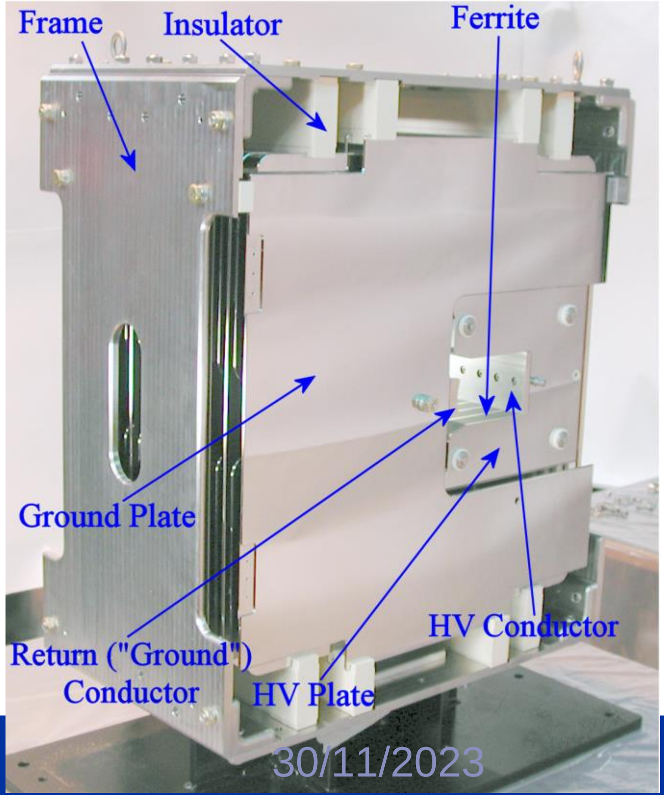
- E field for beam region is lower than max field between cathode and anode, i.e. ‘in-efficient’.

- Potentially more difficult to condition, since max. field area not easily adjustable.



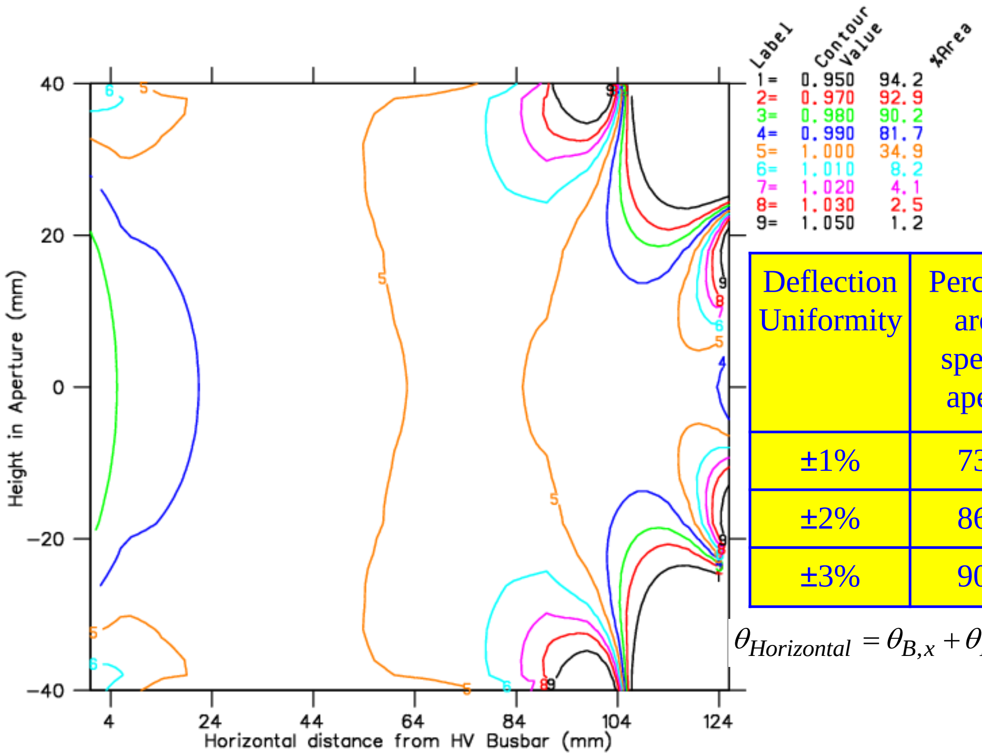
Kicker Design Tools (1)

Finite element simulation software used for the kicker magnet design. It allows for eddy current simulations, used to predict magnetic field and central cell inductance, as well as to optimize the geometry of ferrite and busbars. It is also used to predict electric fields and 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%

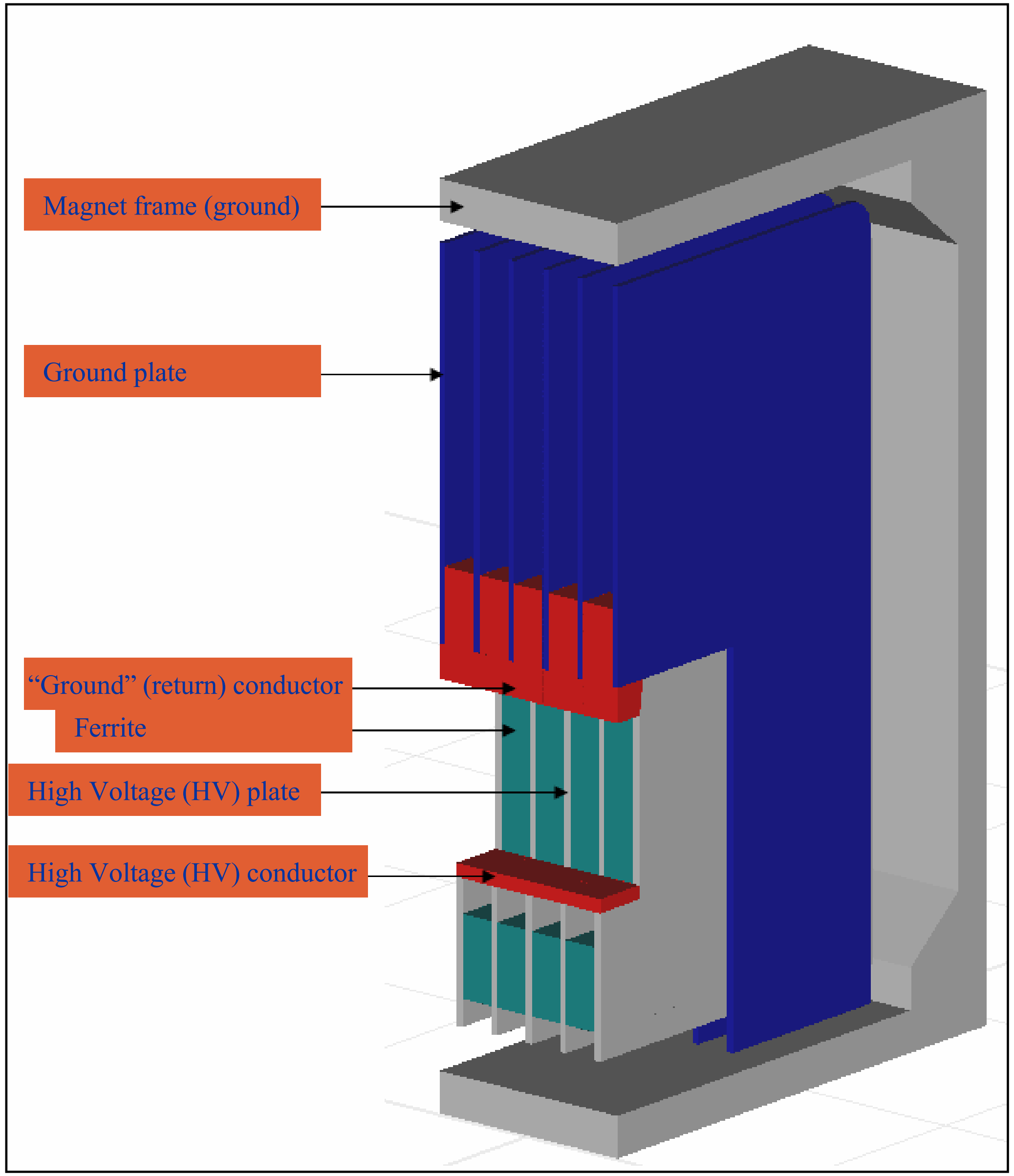
$$\theta_{Horizontal} = \theta_{B,x} + \theta_{E,x}$$

Kicker Design Tools (2)

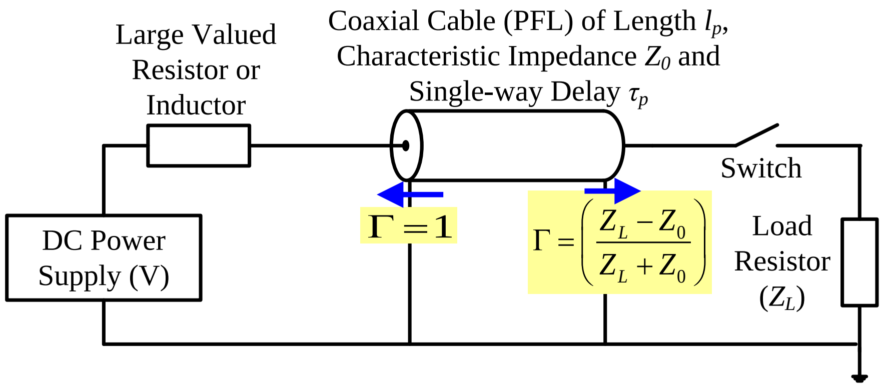
Capacitance to ground of an HV plate is influenced by insulators and nearby ground planes:

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

Finite element software can be used to accurately predict capacitance of a cell of a kicker magnet.



Pulse Forming Circuit: General Case



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

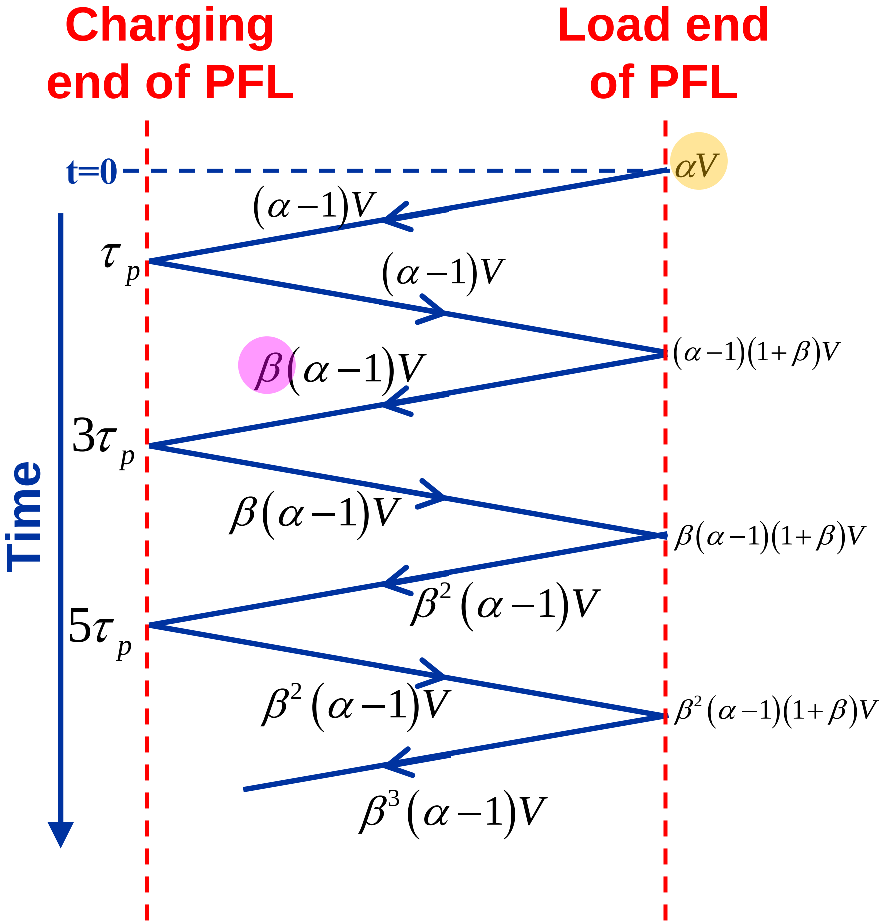
$$V_L = V \cdot \left(\frac{Z_L}{Z_0 + Z_L}\right) = \alpha V$$

A voltage pulse of “$(\alpha\text{-}1)V$” propagates from the load end of the PFL towards the charging end.

- At the charging end the reflection coefficient (Γ) is +1 and hence “$(\alpha\text{-}1)V$” is reflected back towards the load end of the PFL.
- At the load end of the PFL:

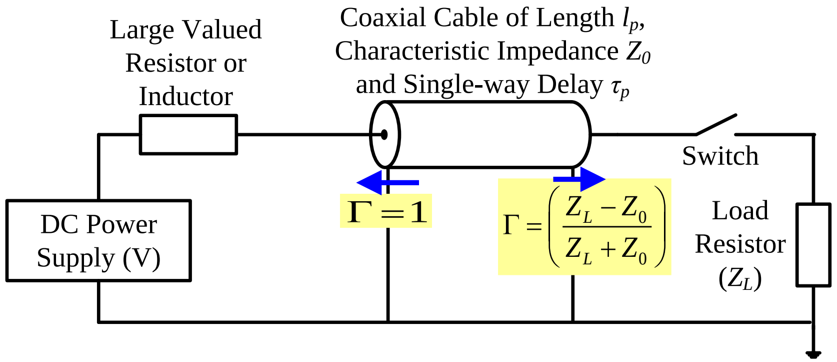
$$\Gamma = \left(\frac{Z_L - Z_0}{Z_L + Z_0}\right) = \beta \text{ say.}$$

and hence “$\beta(\alpha\text{-}1)V$” is reflected back towards the charging end of the PFL.



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

Pulse Forming Circuit: Matched Load (ZL=Z0)



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

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

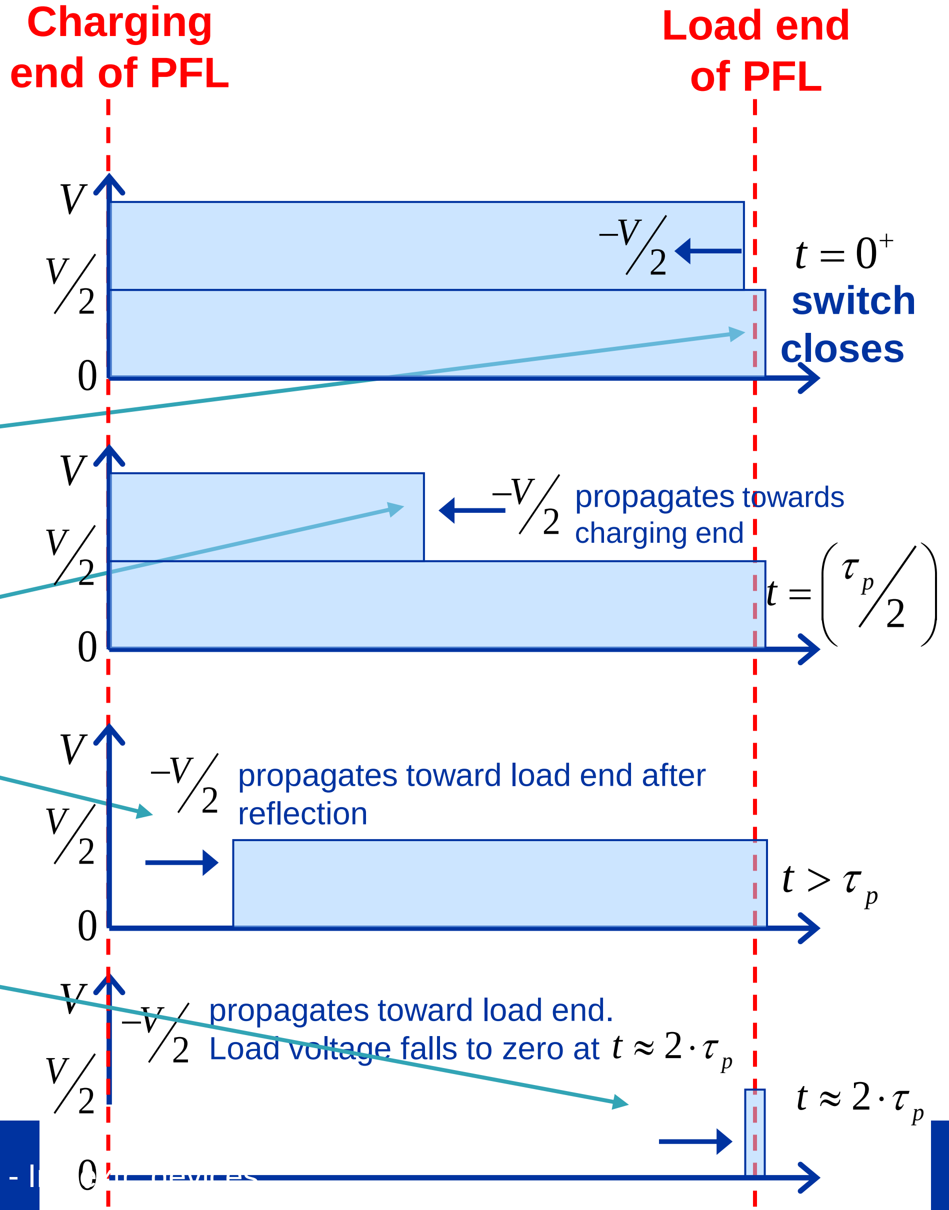
A voltage pulse of $-V/2$ propagates from the load end of the PFL towards the charging end.

• At the charging end the "reflection coefficient" (Γ) is +1 and hence the $-V/2$ is reflected back towards the load end of the PFL.

• At the load end of the PFL: $\Gamma = \left(\frac{Z_L - Z_0}{Z_L + Z_0}\right) = 0$

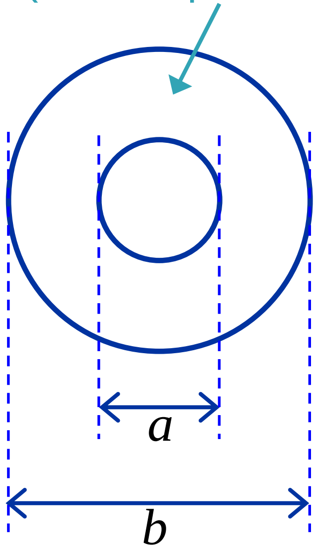
and hence no voltage is reflected back towards the charging end of the PFL.

Note: <u>PFN voltage is twice the load voltage.</u>



Characteristic Impedance of Coaxial Cable

Dielectric
(relative permittivity ε_r)



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):
(typically 20 Ω to 50 Ω). Z_0

Cable with required impedance sometimes needs to be manufactured ‘taylor made’.

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

To minimize the rise time, cable needs to be as short as possible.

a	outer Ø inner conductor (m);
b	inner Ø outer conductor (m);
ε_0	permittivity of free space (8.854x10^{-12} F/m).

Protection devices

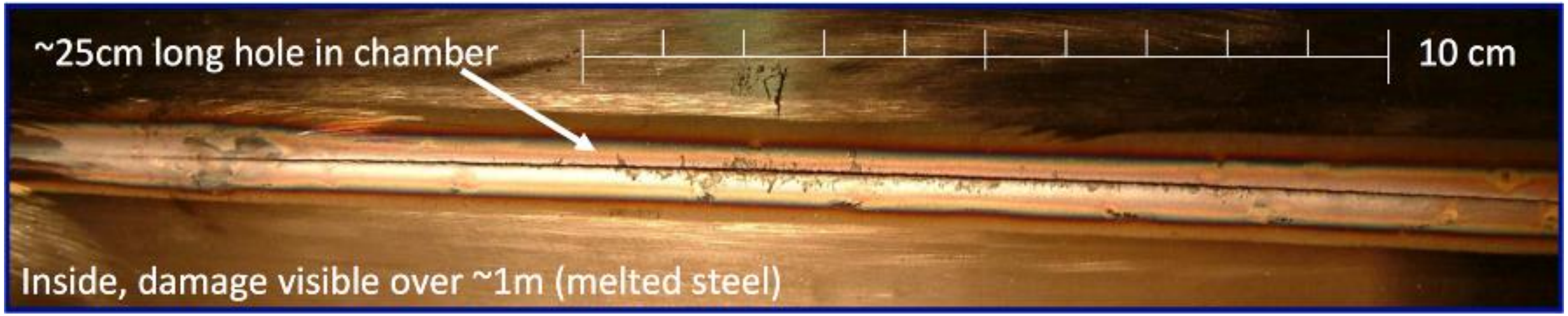
Extraction Protection devices protect valuable equipment and also increase machine availability.

- In 2004 an extraction septum power supply failure and directed $3.4x10^{13}$ protons, at 450 GeV, into the transfer line (TL) vacuum chamber (2.5 MJ beam energy).

Crucial these days:

- even at relatively low energies, due to very high beam intensities and high brightness beams.
- At high beam energies: 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).



Machine Protection [10]

Machine protection requirements are hugely important for accelerators at high energy and/or with high brightness beams. To be considered for the design are …

- Safely extract the beam – always guarantee kicker triggering and extraction line at correct field corresponding to accelerator beam energy.
- Survive asynchronous dump, i.e. when kicker would fire outside of abort gap in beam.
- Avoid asynchronous dumps.
- Avoid other failures with damage potential.
- Avoid failure imp…

This does not pretend to be an exhaustive list.
Collimation and dump design is a topic on its own.

Example: LHC Extraction protection

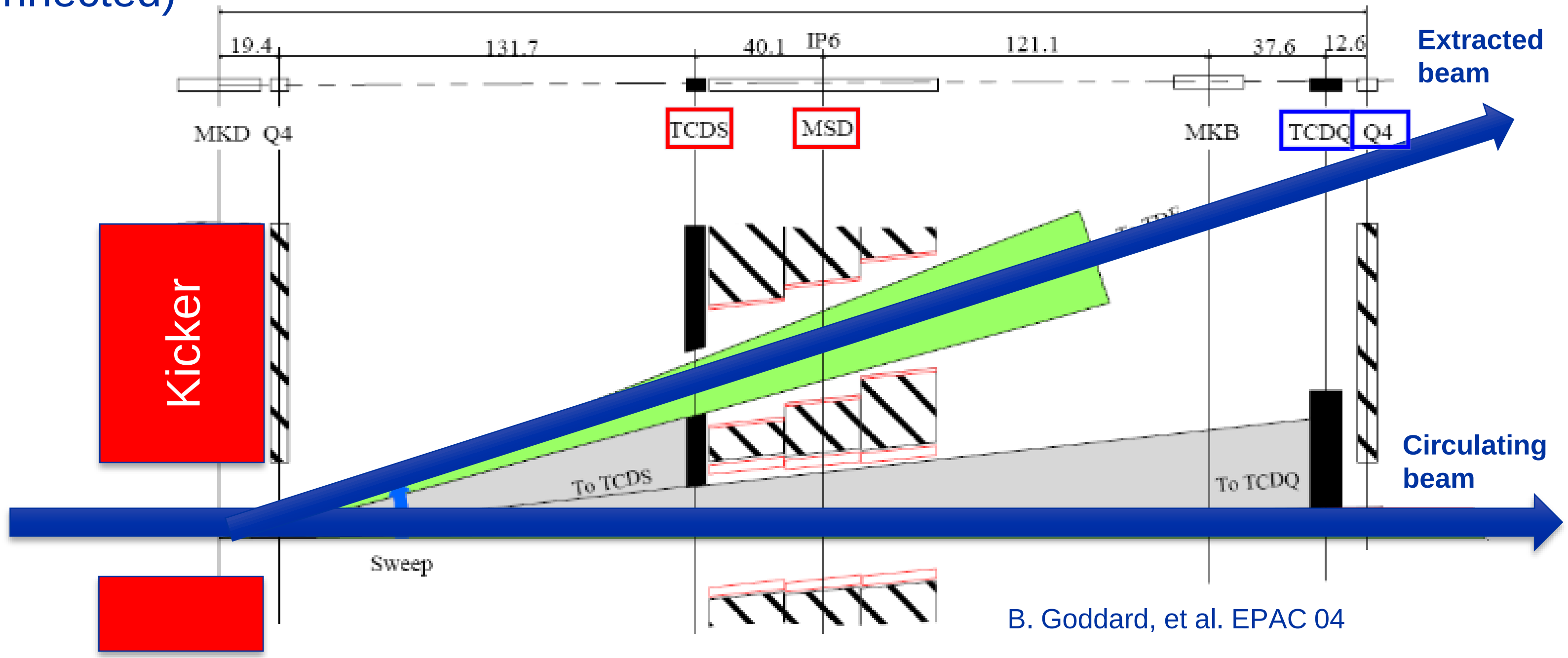
360 MJ stored energy per beam to be safely extracted. Reliability and machine protection is a major concern.

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.

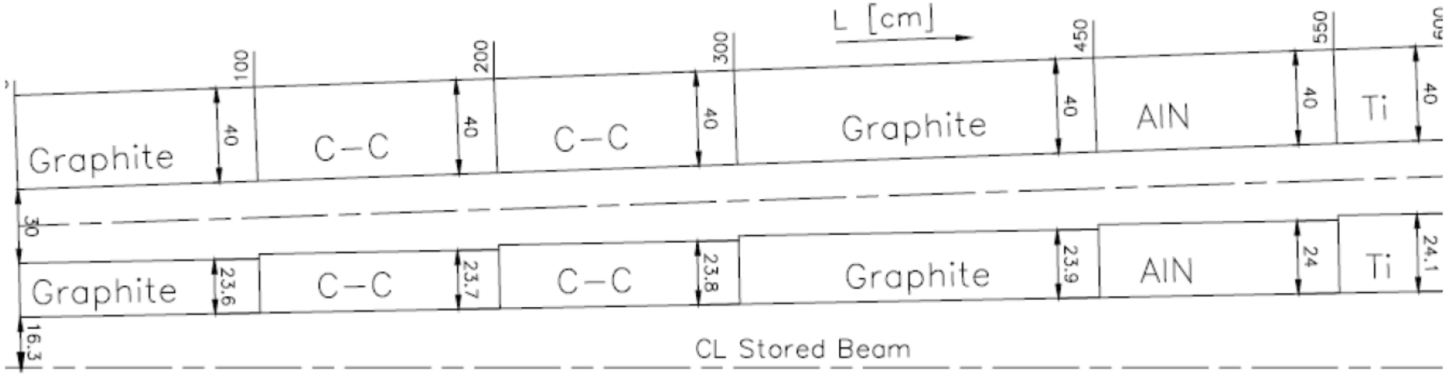
Sophisticated Beam Interlock System. (e.g. Surveillance of orbit, BLMs, MB current, Septa, Kicker, Access etc. over 10,000 devices connected)



B. Goddard, et al. EPAC 04

LHC Extraction: Passive Protection Devices

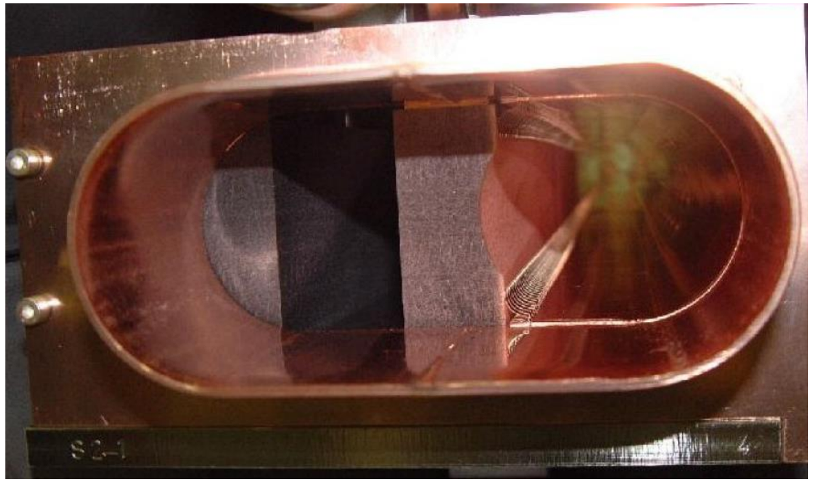
TCDS

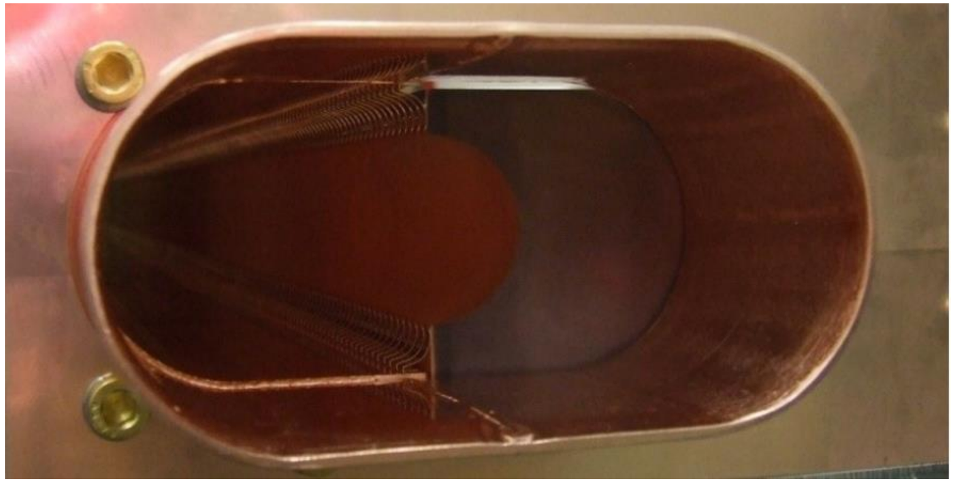


Sandwich construction.

TCDQ

Movable jaws follow the shrinking beam envelope with increasing energy.



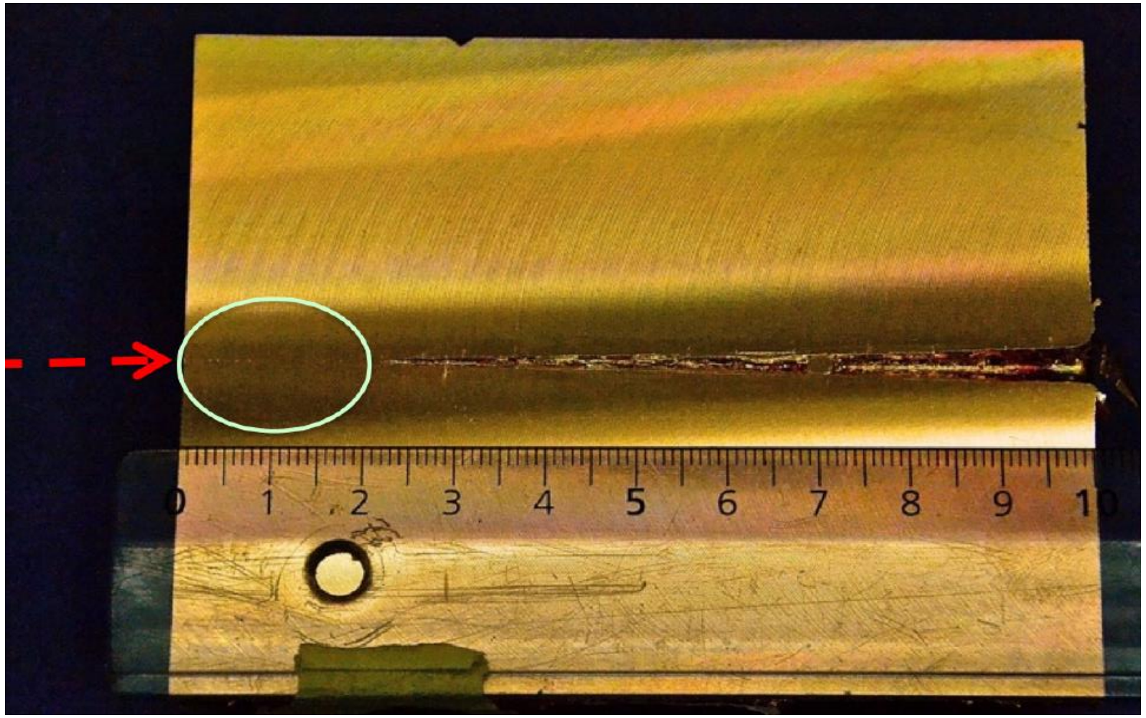


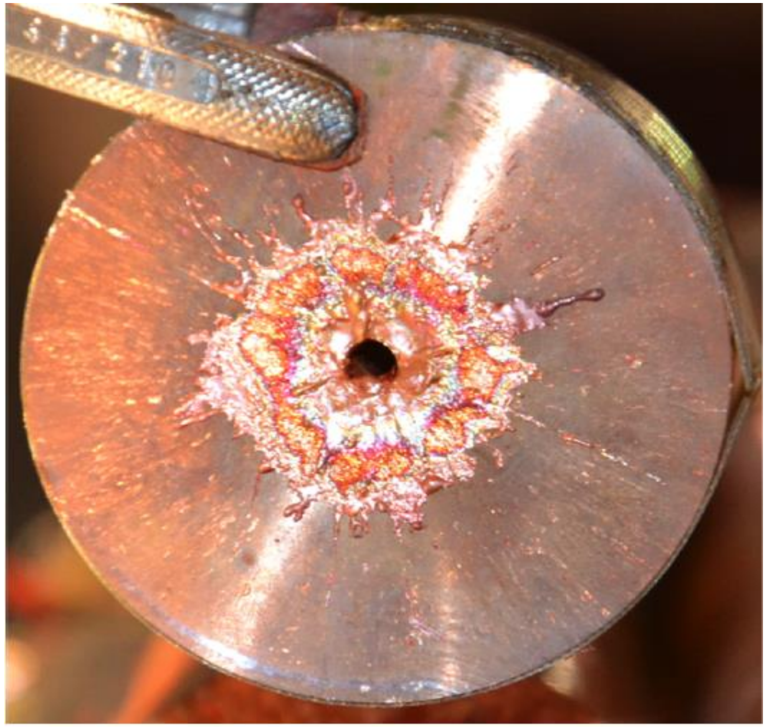
Damage Studies

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/