Beam Transfer Devices: Septa

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Acknowledgements:

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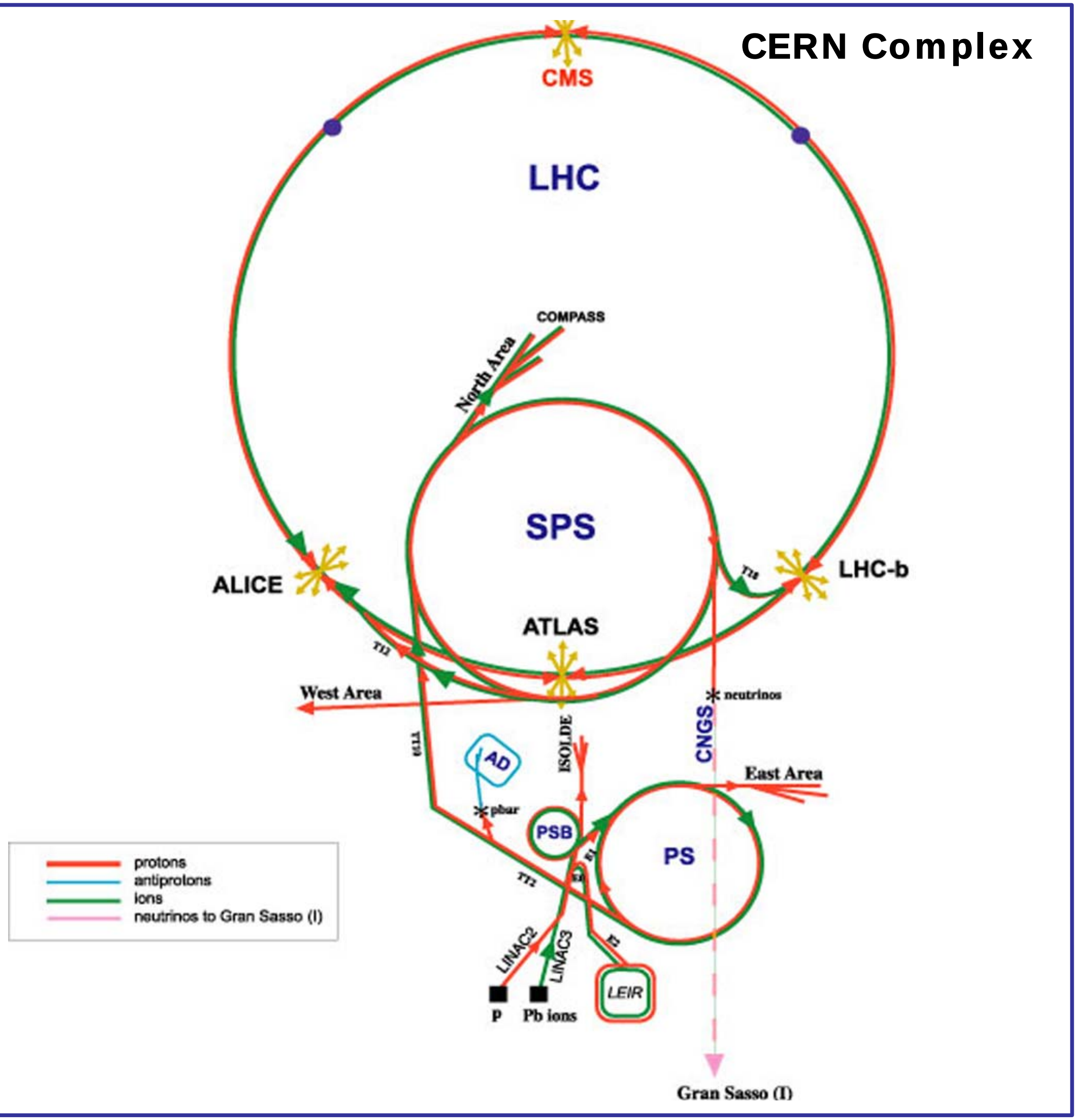
Overview of Presentation

- Role of a septum:
  - Beam Injection, Extraction and Dump.
- Main types of septa:
  - Why different varieties ?
    - Electrostatic septa
    - Magnetic Septa
- Challenges of each variety of septa
- Examples of different septa
- Useful tips !.

Injection, Extraction and Transfer

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

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



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

Introduction

- What do we mean by injection?
  - Inject a particle beam into a circular accelerator or accumulator ring, at the appropriate time.
    - minimize beam loss
    - place the injected particles onto the correct trajectory, with the correct phase-space parameters

- What do we mean by extraction?
  - Extract the particles from an accelerator to a transfer line or a beam dump, at the appropriate time;
    - minimize beam loss
    - place the extracted particles onto the correct trajectory, with the correct phase-space parameters

- Both processes are important for performance of an accelerator complex.

Injection and Extraction

- **Injection methods**
  - Single-turn (fast) hadron injection
  - Multi-turn hadron injection
  - Charge-exchange H- injection
  - Lepton injection

- **Extraction methods**
  - Single-turn (fast) extraction
  - Non-resonant multi-turn extraction
  - Resonant multi-turn (slow) extraction

Special Elements

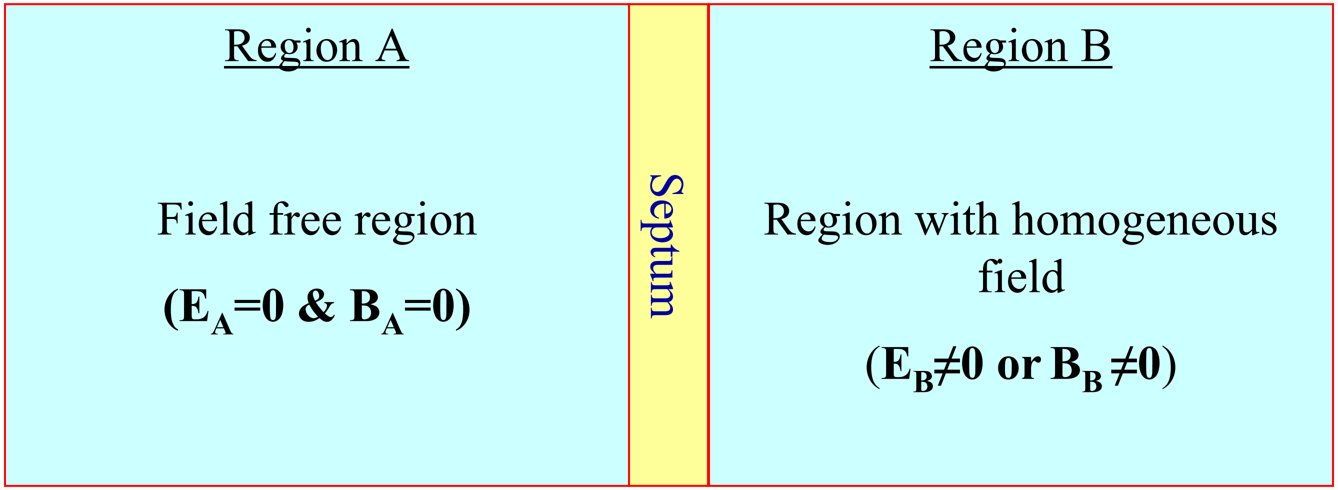
Special elements typically used for slow extraction:

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

Magnetic septum:
Pulsed or DC dipole magnet with thin (2 → 20 mm) septum between zero field and high field region.

Septum: Definition

In general: a septum (plural Septa) is a partition that separates two cavities or spaces.
In a particle-accelerator a **septum** is a device which separates two field regions:



Region A

Field free region

(E_A=0 & B_A=0)

Septum

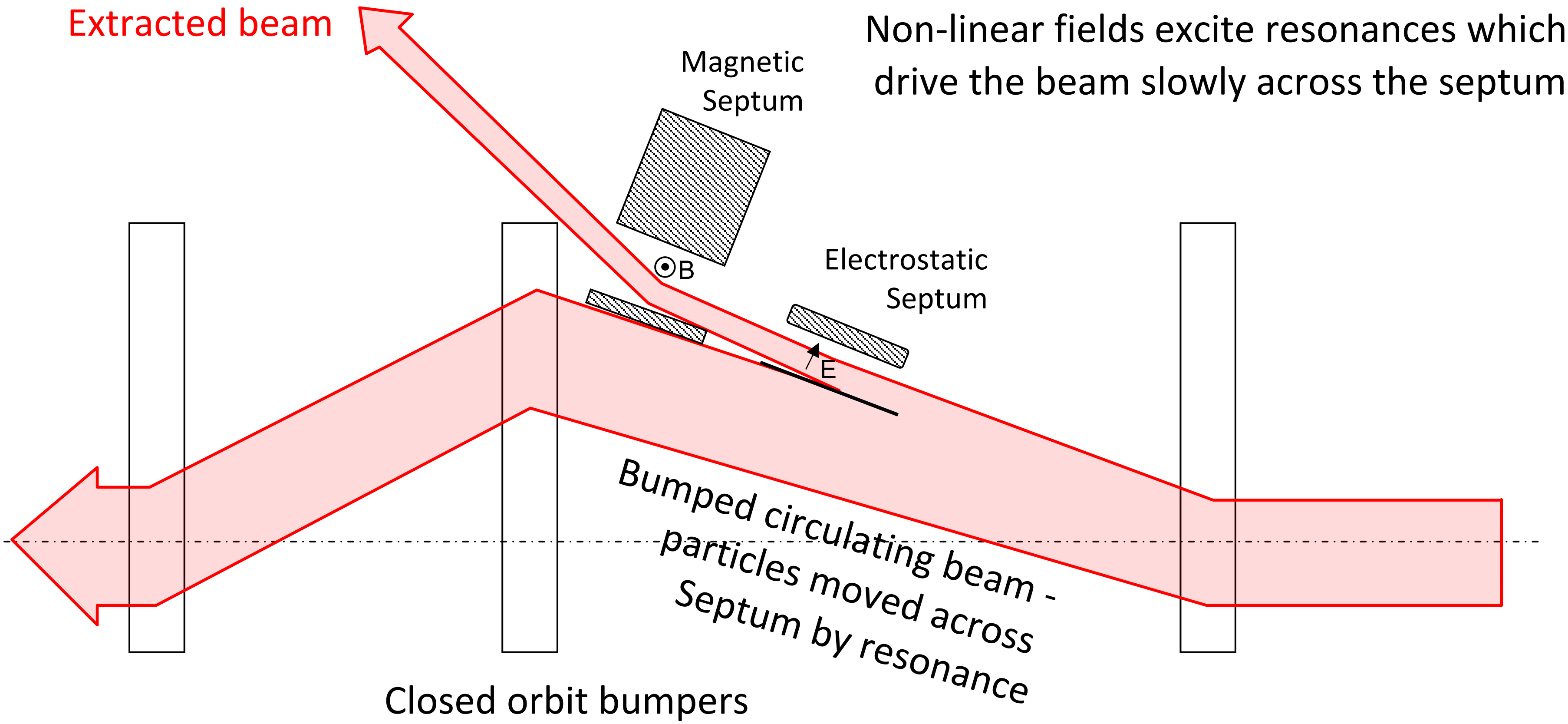
Region B

Region with homogeneous field

($E_B \neq 0$ or $B_B \neq 0$)

One of the main challenges of magnetic septa are field homogeneity in one region, for deflecting beam, and a low leakage field next to the magnet to avoid affecting the circulating beam.

Example: Resonant Multi-Turn Extraction



Non-linear fields excite resonances which drive the beam slowly across the septum.

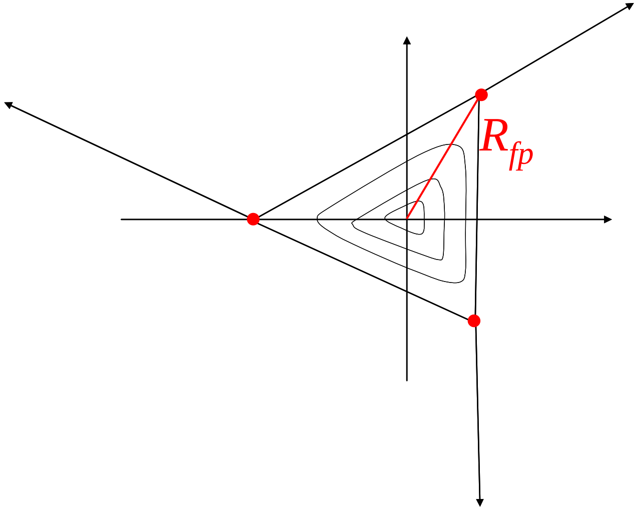
Resonant multi-turn extraction is generally used for delivering beam to experiments; the extraction process can be spread over a time-interval from ms to hours.

- Non-linear fields (slow bumpers) excite betatron resonances which drive the beam slowly across the septum ;
- Tune adjusted close to n^th order betatron resonance; (often 3^rd order).

Resonant Multi-Turn Extraction

- 3^{rd} order resonances.
  - Sextupole fields distort the circular normalised phase space particle trajectories.
  - Stable area defined, delimited by unstable Fixed Points.

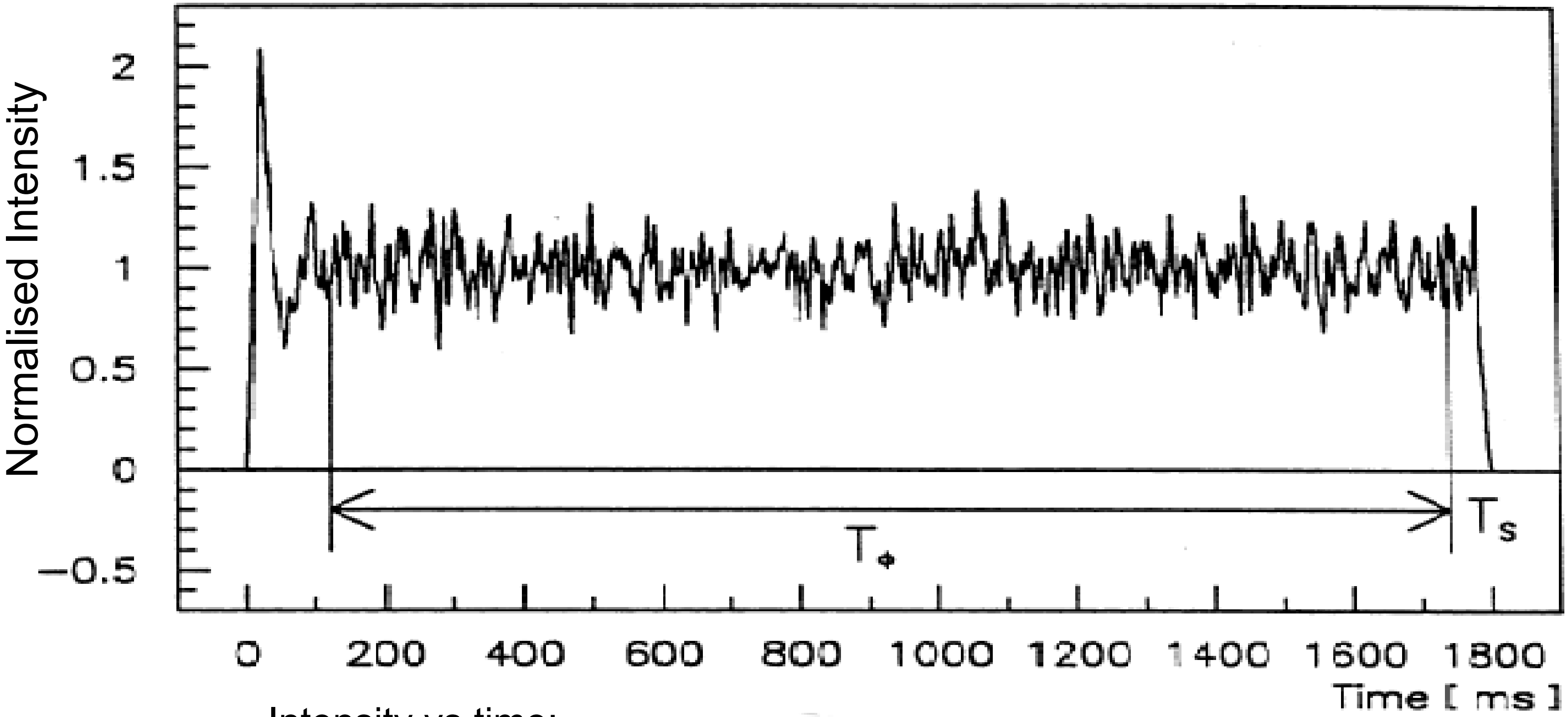
$$R_{fp}^{\ 1/2} \propto \Delta Q \cdot \frac{1}{k_2}$$



  - Sextupoles families arranged to produce suitable phase space orientation of the stable triangle at thin electrostatic septum
  - Stable area can be reduced by increasing the sextupole strength, or (easier) by approaching machine tune Q_h to resonant 1/3 integer tune
  - Reducing ΔQ with main machine quadrupoles can be augmented with a 'servo' quadrupole, which can modulate ΔQ in a servo loop, acting on a measurement of the spill intensity

Third-order Resonant Extraction

Example – SPS slow extraction at 450 GeV/c.
~3 x 10^{13} p+ extracted in a 2 s → 4 s long spill (~200,000 turns).



Intensity vs time:
~10^8 p+ extracted per turn

Main Types of Septa

- Main septa types:
  - Electrostatic Septum;
  - Direct Drive Pulsed Magnetic Septum;
  - Direct Drive DC Magnetic Septum;
  - Eddy Current Septum;
  - Lambertson Septum.

- Briefly: main challenges:
  - associated with **Magnetic septa** are not electrical but rather mechanical (cooling, support of this septum blades, radiation resistance).
  - associated with **Electrostatic septa** is surface conditioning for High Voltage.

Septa: Goals

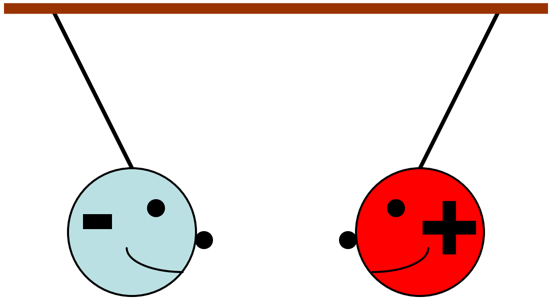
To minimize losses during the extraction, the goal is to construct a magnet with a septum **as thin as possible**.

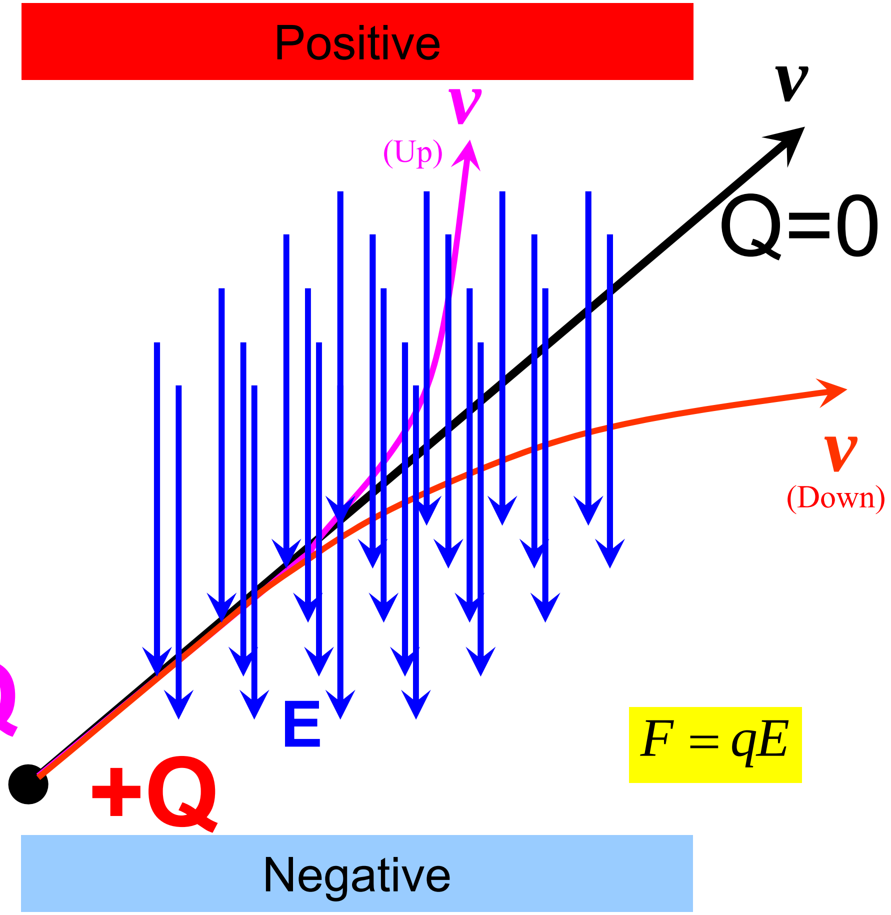
The thinnest septa are electrostatic septa: beam is deflected by accelerating beam perpendicular to initial beam direction using an electric field – to be presented first.

Thin septa help to increase extraction efficiency, but also reduce activation of equipment as well as “ease” the task of other extraction elements such as kickers and/or preceding septa.

Deflection by an Electric Field

Opposites Attract !





$$F = qE$$

Charge moving into plane of paper
at velocity v

Deflection is either in same direction as E or in the opposite direction to E.

Beam Deflection due to an Electric Field

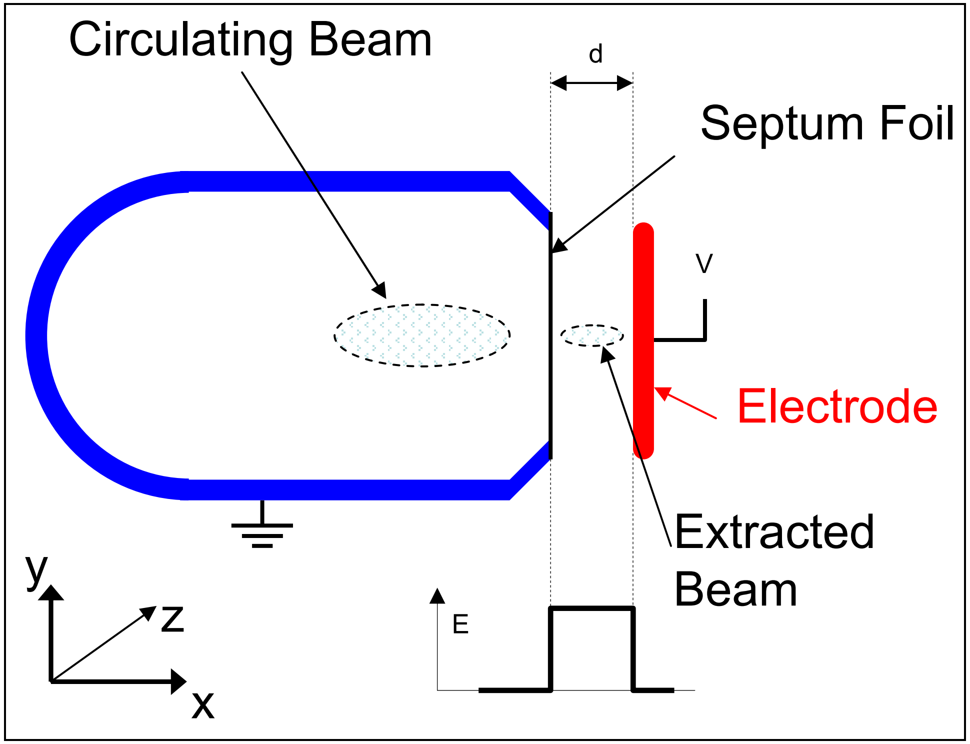
$$\theta_{E,x} = \tan^{-1}\left[\frac{1}{(p\cdot 10^{9})\cdot\beta}\cdot\int_{z_0}^{z_1}\left|E_x\right|dz\right] = \tan^{-1}\left[\frac{\left|E_x\right|\cdot l_{eff}}{(p\cdot 10^{9})\cdot\beta}\right] = \tan^{-1}\left[\frac{\left|V_x\right|\cdot l_{eff}}{d\cdot(p\cdot 10^{9})\cdot\beta}\right]$$

Usually fixed by beam considerations

Where:

- *V* is the potential difference between plates (V);
- *d* is the separation of the plates (m);
- E is electric field (V/m);
- p is beam momentum (GeV/c);
- β is a unit-less quantity that specifies the fraction of the speed of light (*c*) at which the particles travel;
- l_{eff} is the effective length of the device (usually different from the mechanical length, due to fringe fields at the ends);
- $\theta_{E,x}$ is the deflection angle due to the electric field (radians).

Electrostatic Septum: Foil (1)



Thin septum foil gives small interaction with beam.

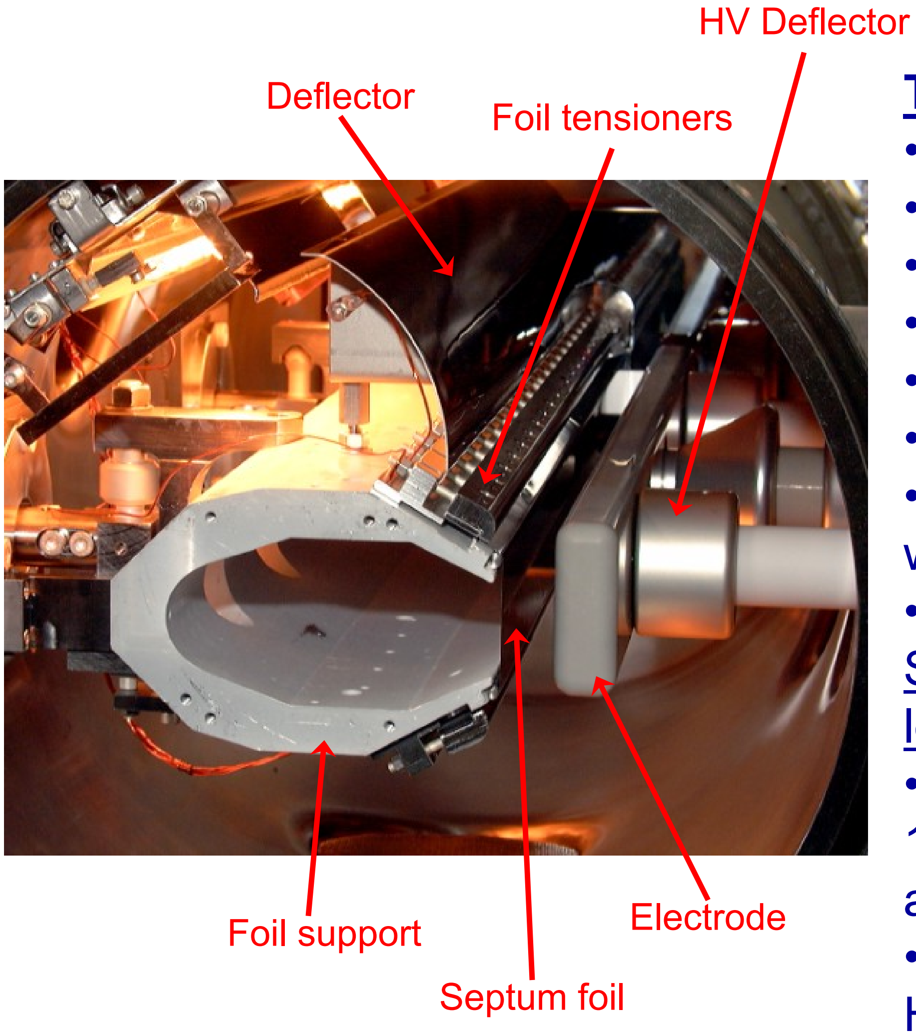
Orbiting beam passes through hollow support of septum foil (field free region).

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

Electrostatic septa generally use vacuum as an insulator, between septum and electrode, and are therefore normally in a vacuum tank.

To allow precise matching of the septum position with the circulation beam trajectory, the electrostatic septum is often fitted with a displacement system, which allows parallel and angular movement with respect to the circulating beam.

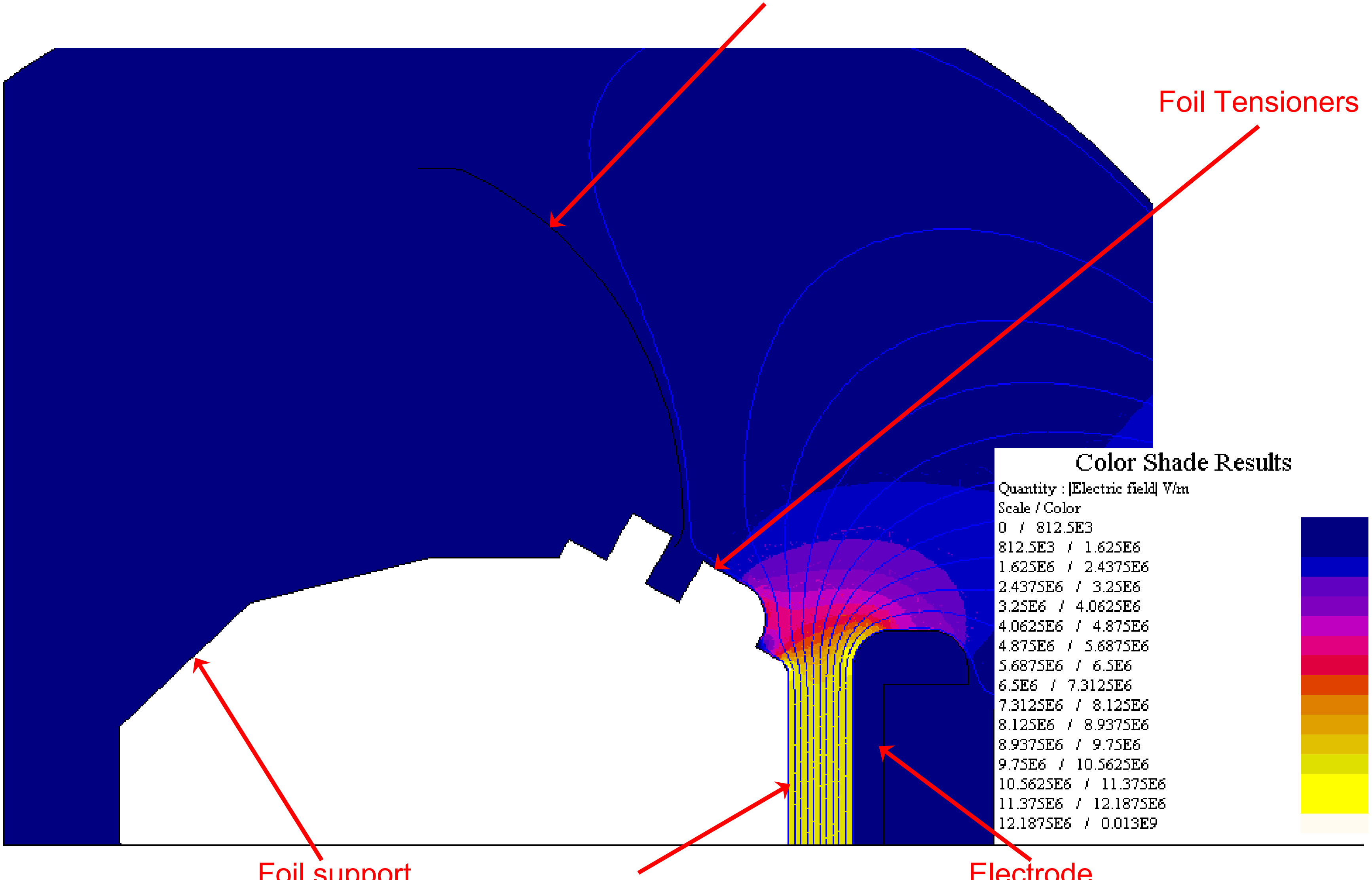
Electrostatic Septum: Foil (2)



Typical technical data:

- Electrode length : 500 - 3000 mm;
- Gap width (d) variable: 10 - 35 mm;
- Septum thickness: ≤ 100 µm;
- Vacuum (10^{-9} to 10^{-12} mbar range);
- Voltage: up to 300 kV;
- Electric field strength: up to 10 MV/m;
- Septum foil is Molybdenum (or Tungsten wires);
- Electrode made of anodised aluminium, Stainless Steel or titanium for extremely low vacuum applications;
- Bake-able up to 300°C for vacuum in 10^{-12} mbar range (not applicable to aluminium electrode);
- Power supplied by Cockroft-Walton type High Voltage (HV) generator.

Electrostatic Septum: Electric Field Plot



Deflector

Foil Tensioners

Foil support

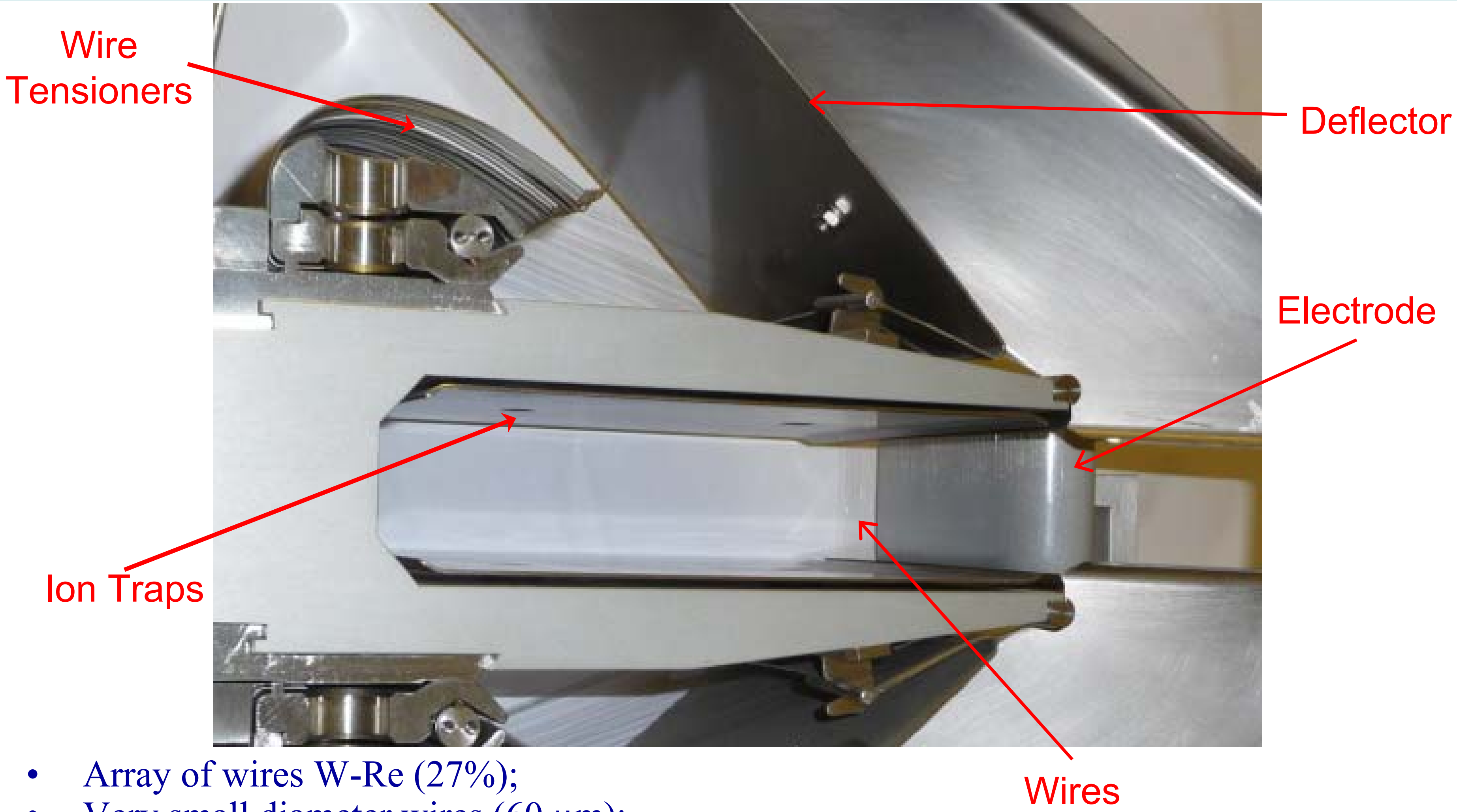
Septum foil

Electrode

Practical Considerations

- To precisely align a septum with respect to the beam a remote displacement system is implemented;
- High electric field permissible because of good vacuum;
- Bake-out systems are required for Ultra High Vacuum (UHV) applications;
- Conditioning and preparation of surfaces exposed to HV is biggest challenge.

Electrostatic Variants (1): Wire Septum



- Array of wires W-Re (27%);
- Very small diameter wires (60 μm);
- Needs ion traps in circulating beam area;
- Very high field in operation possible (>10 MV/m);
- Low atomic number seen by the beam – reduced interaction.

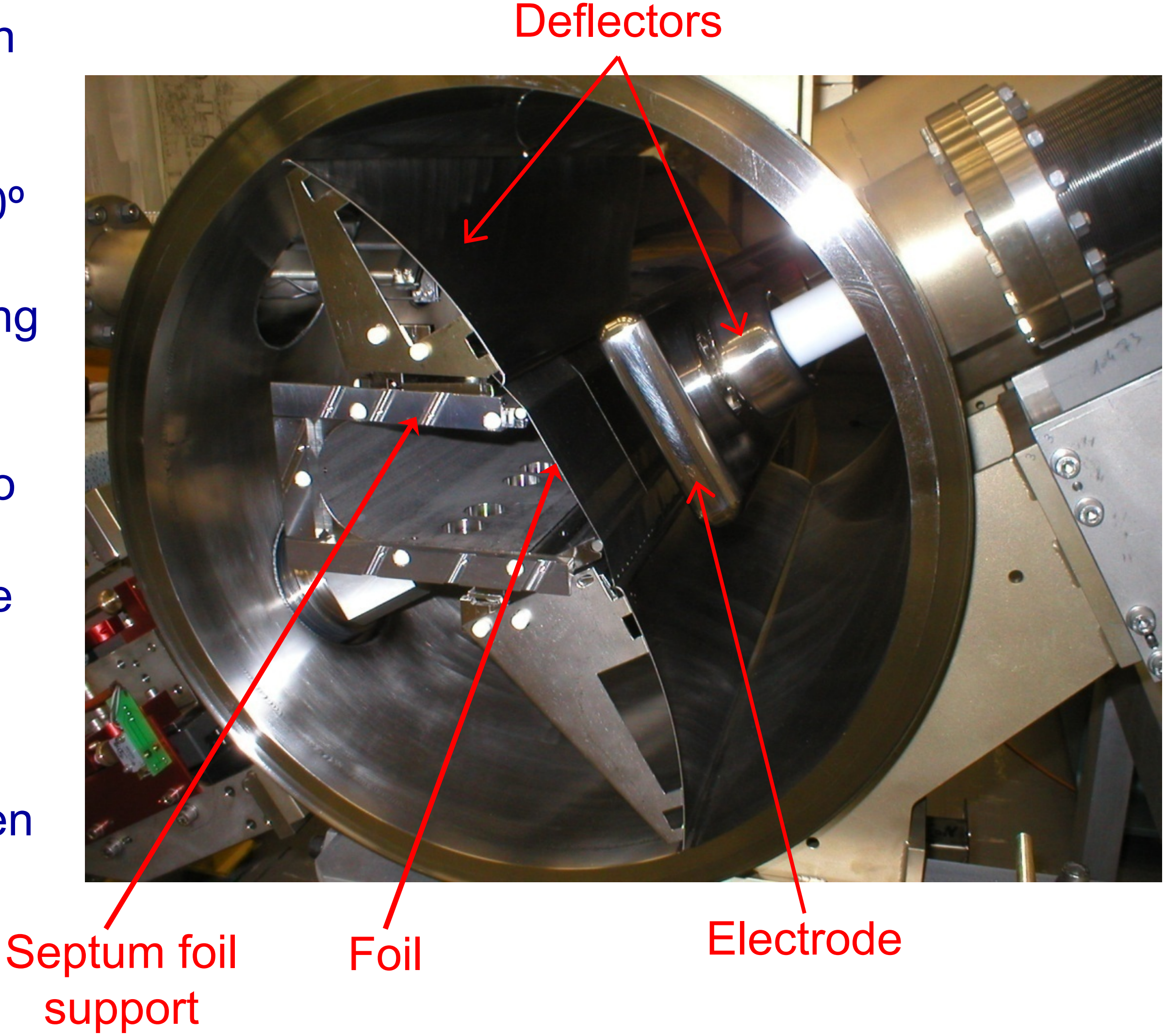
Electrostatic Variants (2): Diagonal Foil

Diagonal multi-turn injection in LEIR.

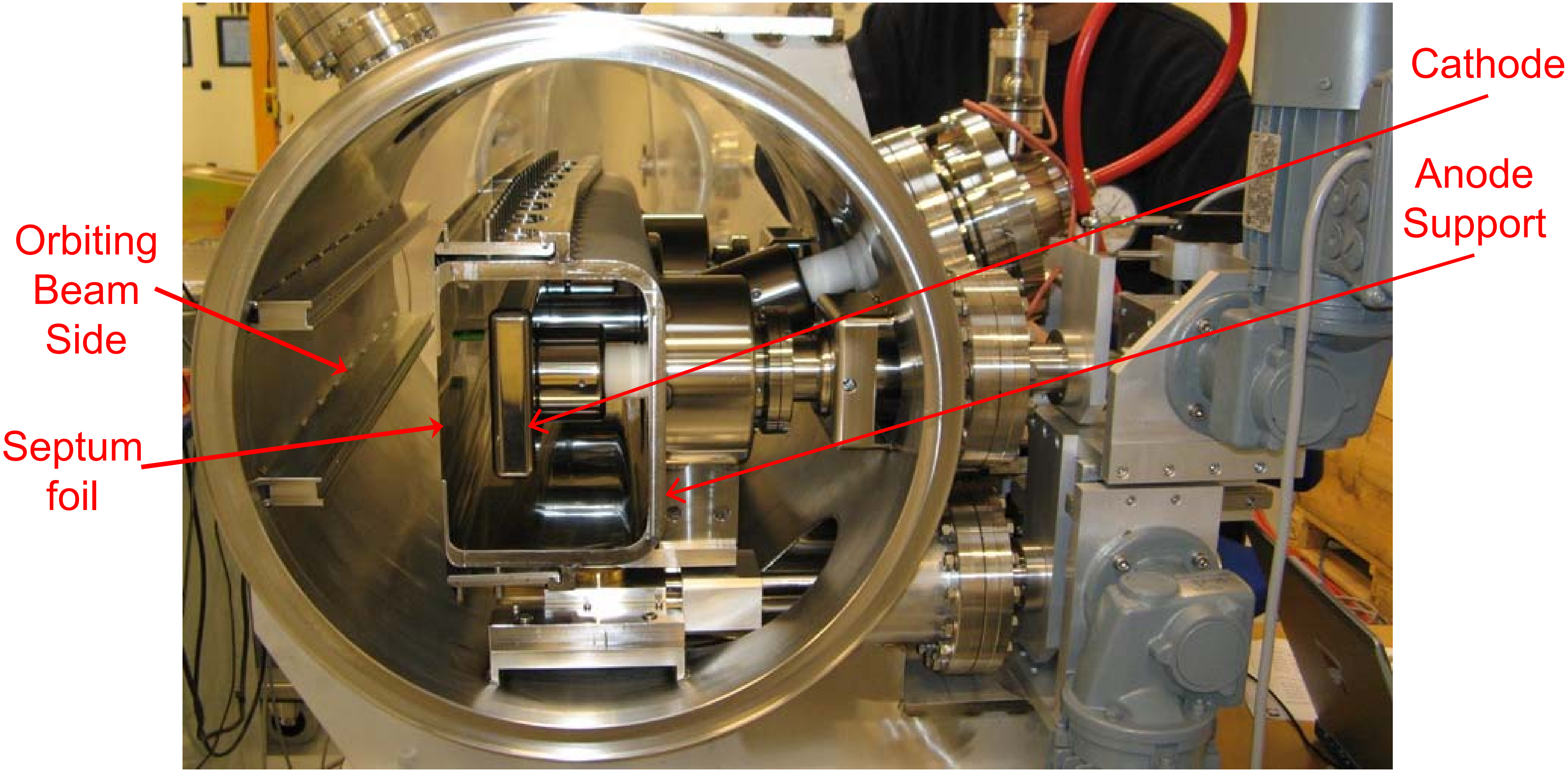
Remote displacement at 30º from horizontal plane to allow for longitudinal painting injection scheme.

Ti cathode and deflectors to allow for high field strength whilst remaining compatible with vacuum in 10^{-12} mbar range.

Wide anode deflector screen and cathode to provide required good field region.



Electrostatic Variants (3): Cathode Inside Anode Support



Cathode inside anode support to allow for both remote displacement systems to be on the same side (free up space on orbiting beam side for other equipment adjacent to tank).

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:

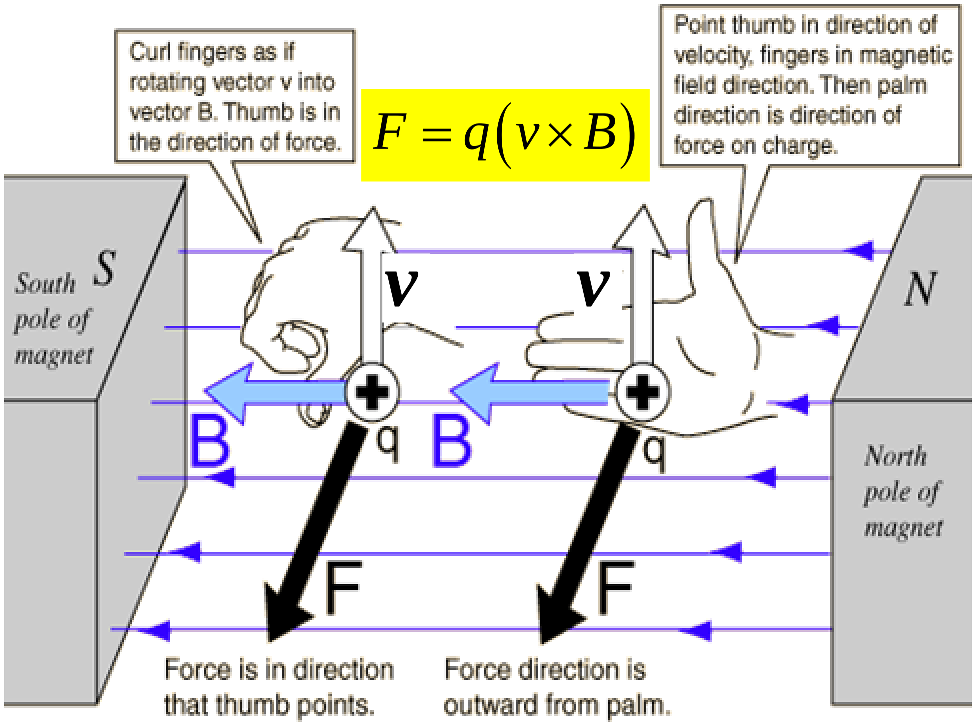
$$F = q\left[E + \left(v \times B \right) \right]$$

- 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

Example of Deflection by Force in a Magnetic Field

Right-Hand Rule

$$F = q\left(v \times B\right)$$



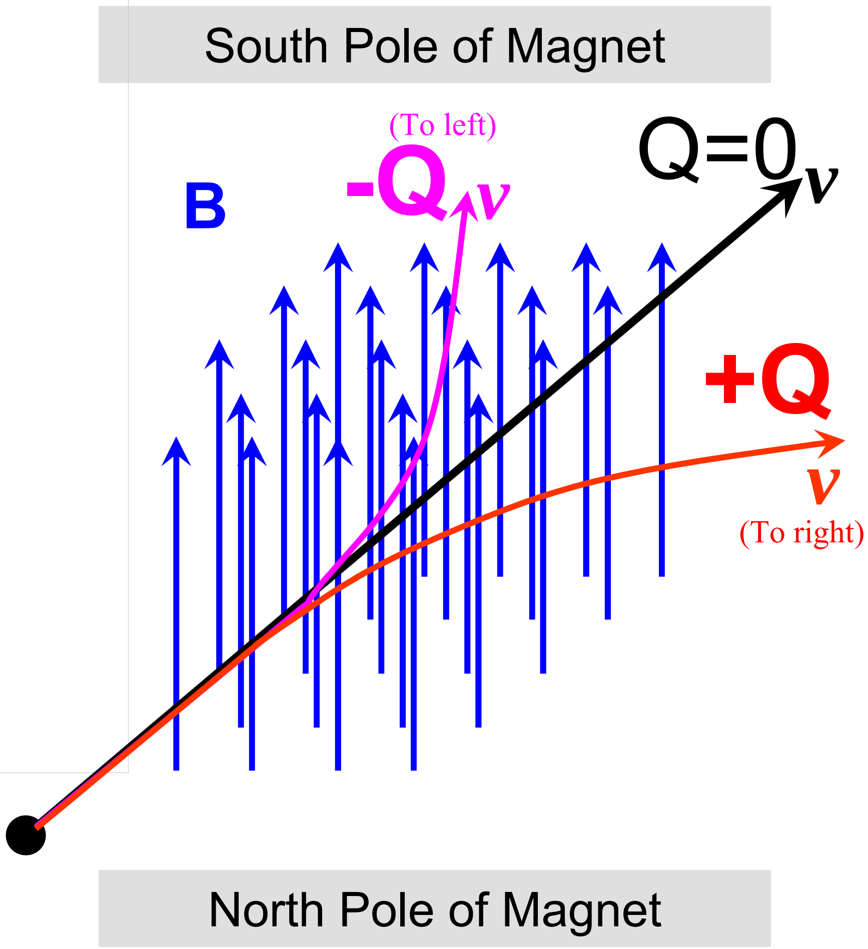
Curl fingers as if rotating vector v into vector B. Thumb is in the direction of force.

Point thumb in direction of velocity, fingers in magnetic field direction. Then palm direction is direction of force on charge.

Force is in direction that thumb points.

Force direction is outward from palm.

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



Charge moving into plane of paper

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

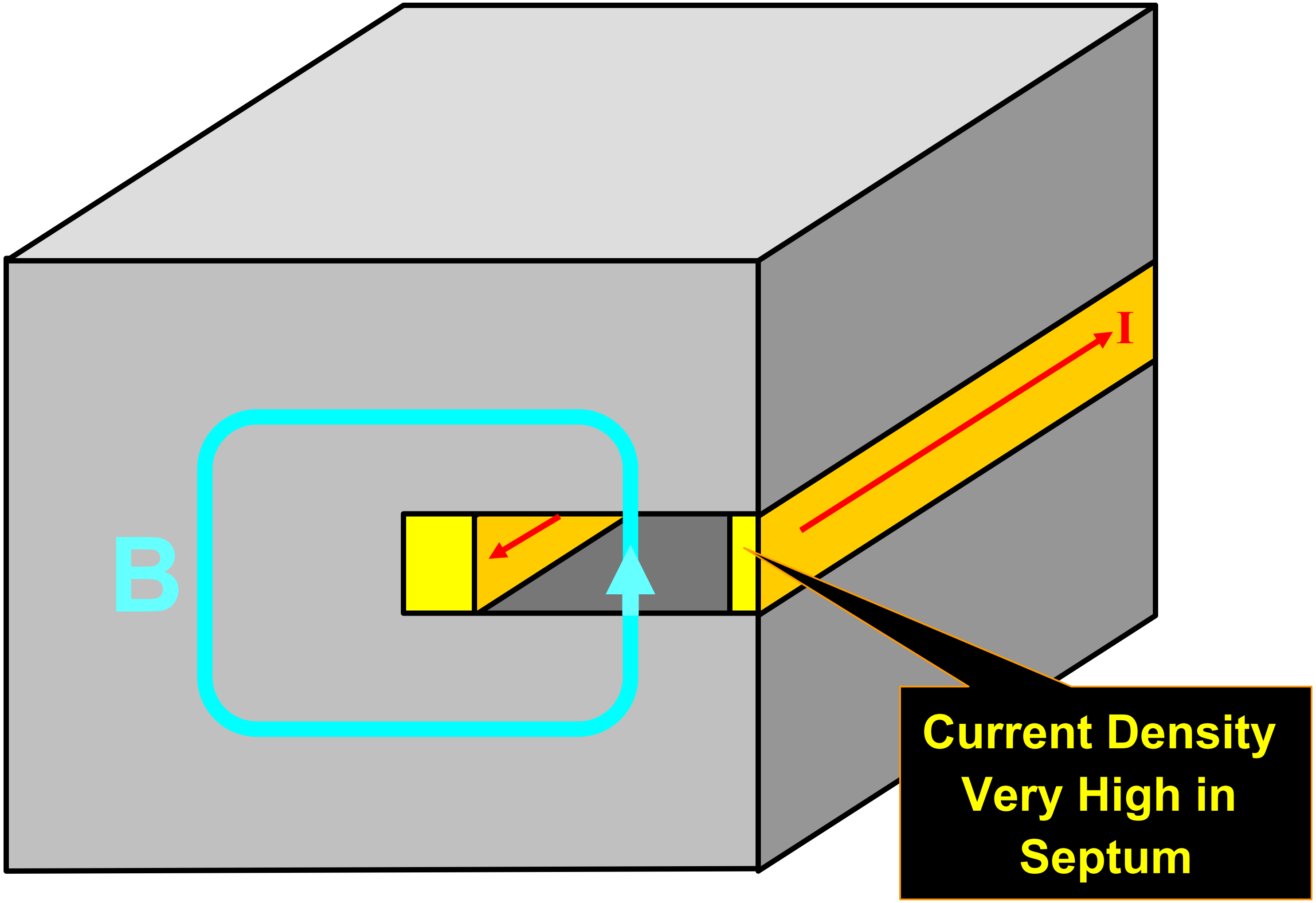
Beam Deflection due to a Magnetic Field

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

Where:

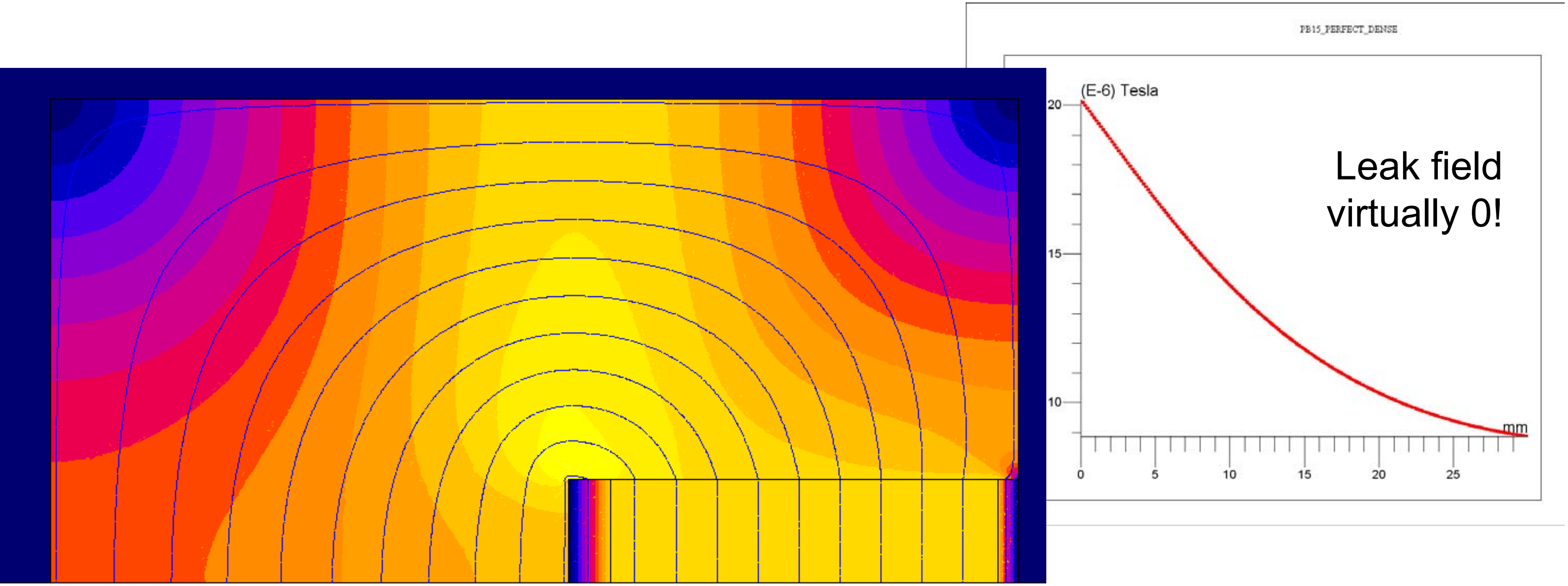
- B is the magnetic flux density (T);
- p is the beam momentum (GeV/c);
- l_{eff} is the effective length of the magnet (usually different from the mechanical length, due to fringe fields at the ends of the magnet);
- $\theta_{B,x}$ is the deflection angle due to the magnetic field (radians).

“C” Magnet → Septum Magnet



Current Density Very High in Septum

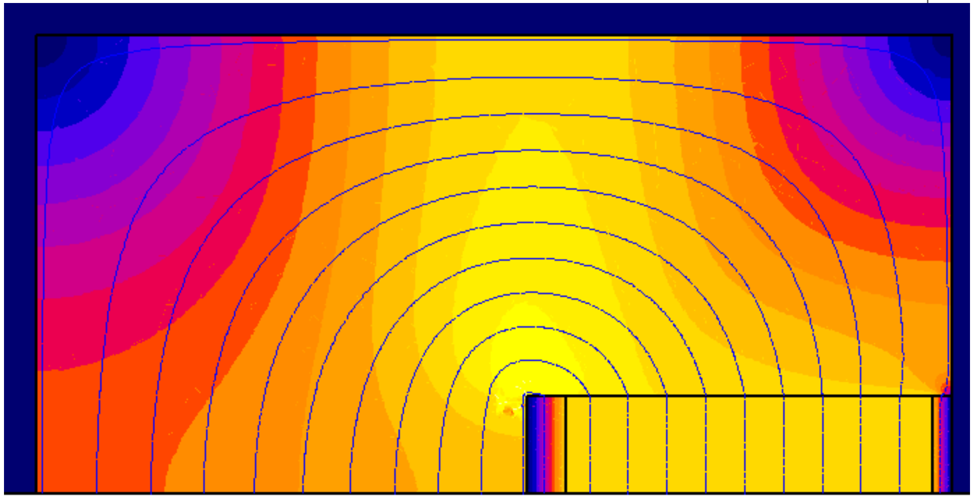
Idealised Septum Magnet: No Play Between Septum and Yoke

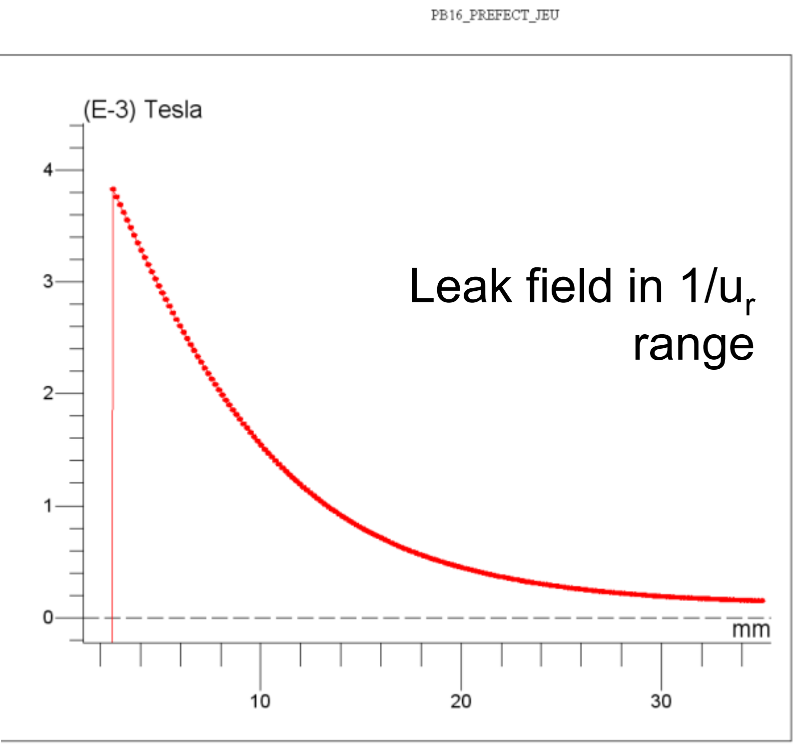


Leak field virtually 0!

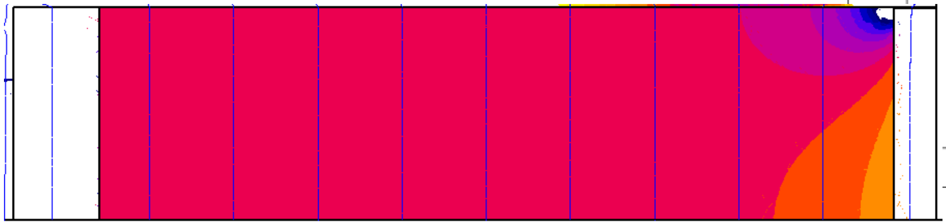
Gap field homogeneity near perfect!!!

Idealised Septum Magnet:
0.1 mm Play Between Septum and Yoke



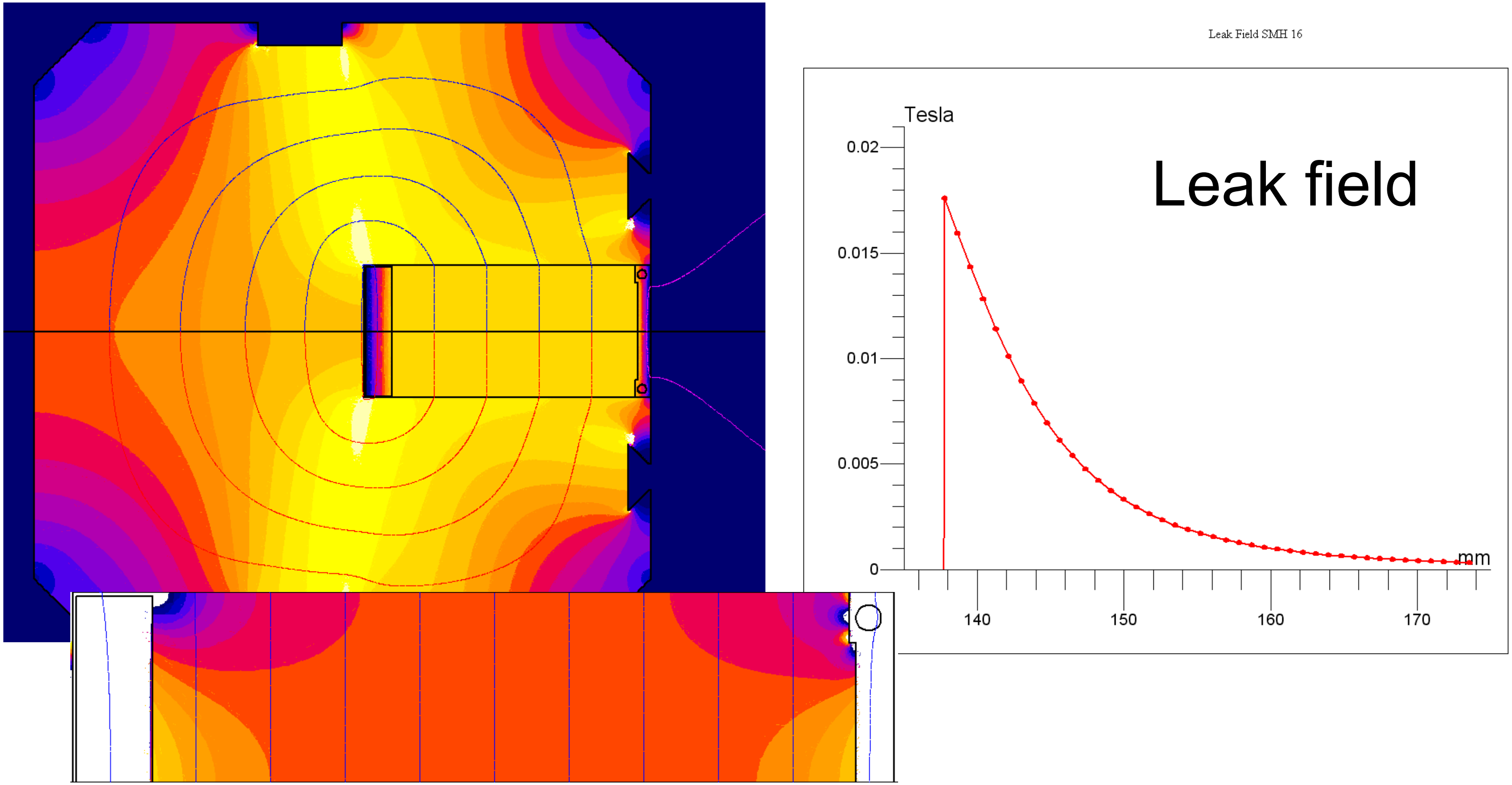


Leak field in $1/u_r$ range



Gap field homogeneity degraded by “play” between septum and yoke.

As-Built Septum Magnet: Cooling and Insulation Around Coils



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

Magnetic Septum: Thermal/Cooling Issues (1)

Small septum conductor thickness:
→ high current density
→ high thermal loads
→ high mechanical stress on the coil

septum magnet ≈ CONTROLLED FUSE !!

The flow characteristics (laminar/turbulent/mixed) in the cooling tube are dependent on the Reynolds number (Re) :

$$R_e = \left(\frac{\rho U_m D}{\mu} \right)$$

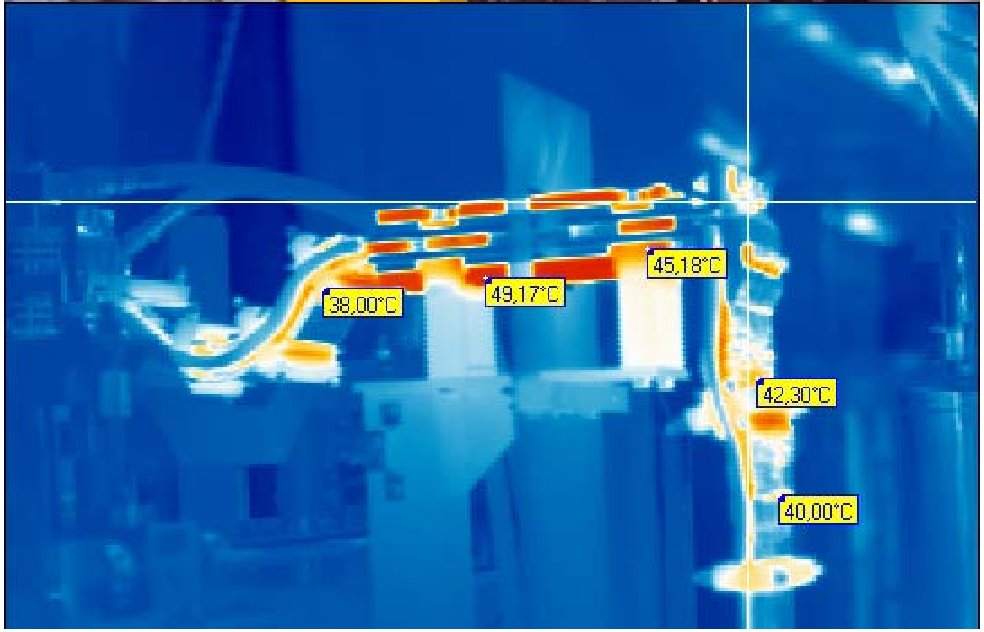
Where: ρ is density (kg·m^{-3}), U_m is mean velocity (m/s), D is diameter (m), and μ is dynamic viscosity (N·s·m^{-2}).

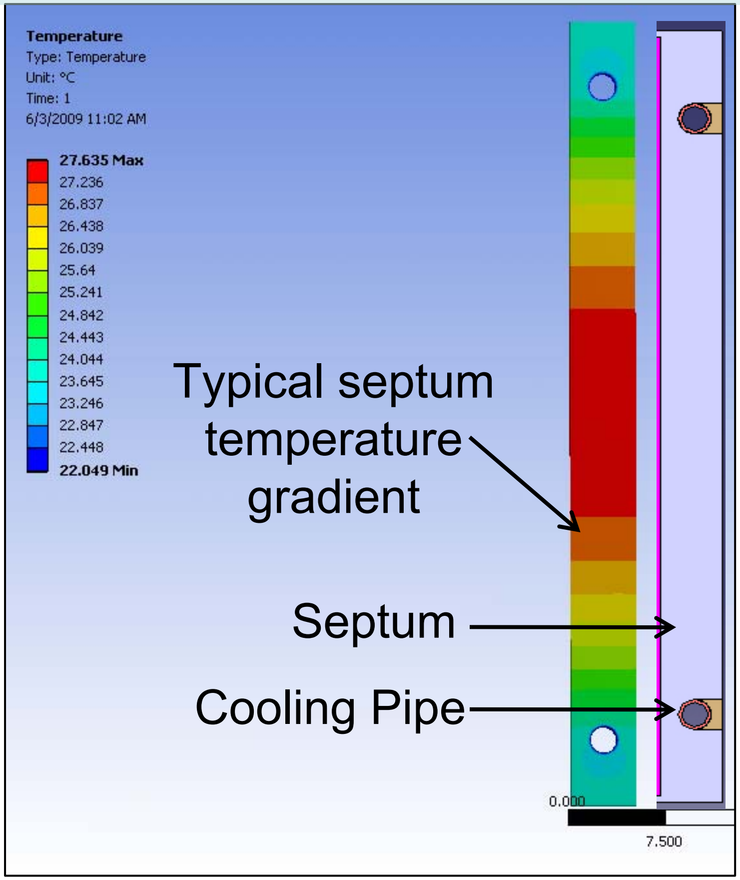
Moody friction Factor for the tube $\equiv \left(\dfrac{-(dp/dx)D}{\rho\left(U_m^2/2\right)} \right)$

To estimate the pressure drop, -dp/dx, in the cooling circuit.

Joule effect heating to be evacuated by cooling: $I^2R = mC_p(T_2-T_1)$
Where: C_p is Specific Heat Capacity and m is mass·flow-rate

Magnetic Septum: Thermal/Cooling Issues (2)





Typical septum temperature gradient

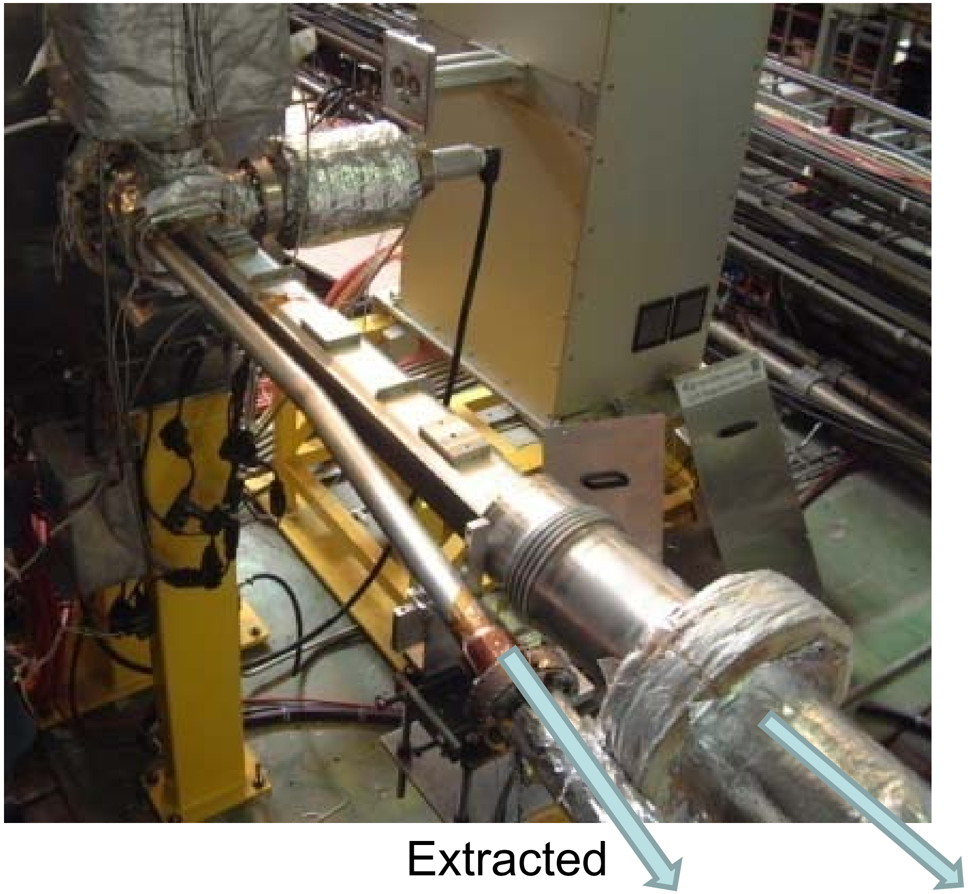
Septum

Cooling Pipe

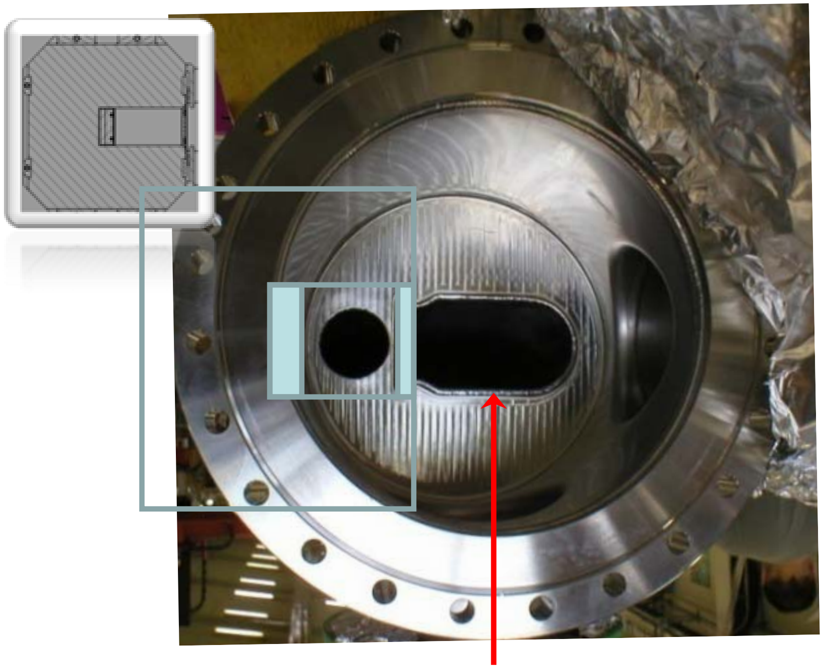
Significant increase in magnet temperature, including the power connections, can lead to load changes as seen by the power supply – so good regulation is required.

Magnetic Septum: Vacuum Considerations (1)

To reduce septum thickness, as seen by the beam (apparent septum thickness), complex, thin-walled, vacuum chambers can be used, around which septum magnet can be clamped.



Complicated (difficult to manufacture) and UHV compatible (material quality) vacuum chambers are often required for injection/extraction points.

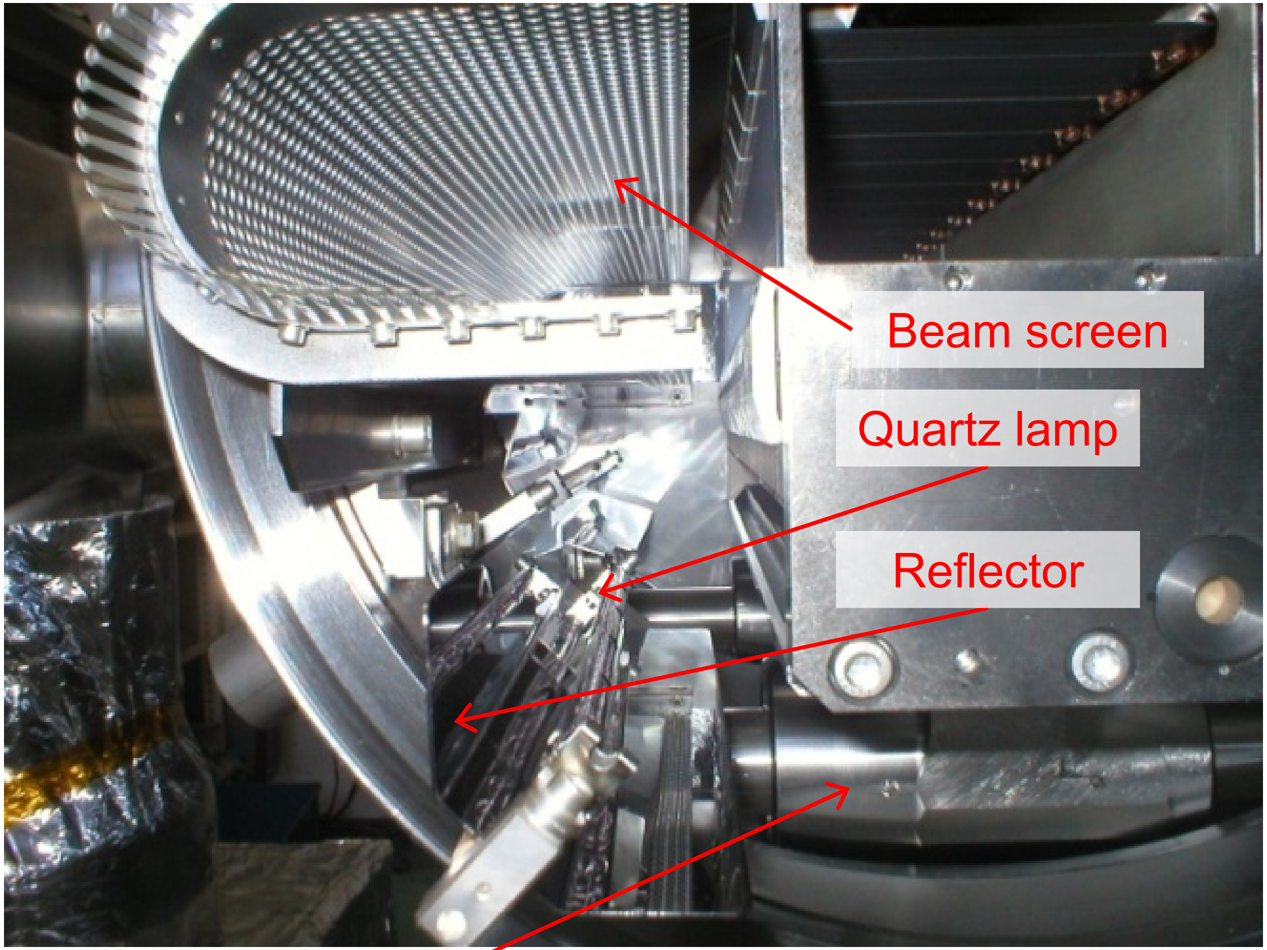


Magnetic Septum: Vacuum Considerations (2)

To reduce apparent septum thickness even further, the magnet can be put under vacuum.

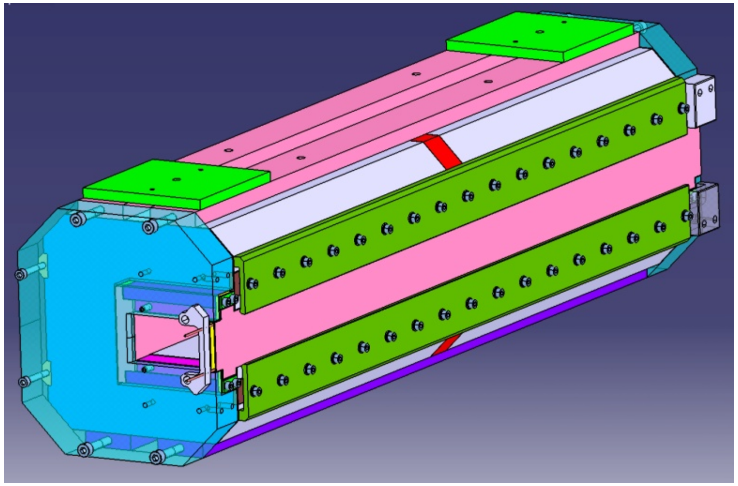
To reach UHV, pumping is required and baking may be necessary which requires all the relevant heating equipment. In this case quartz lamps, heating jackets, reflectors, ceramic insulators etc.

In some cases, where pressure is critical, NEG coating may have to be applied to the chambers which requires activation systems.



Bearing & housings (under vacuum) displacement support

Mechanical Forces for Pulsed Magnetic Septum



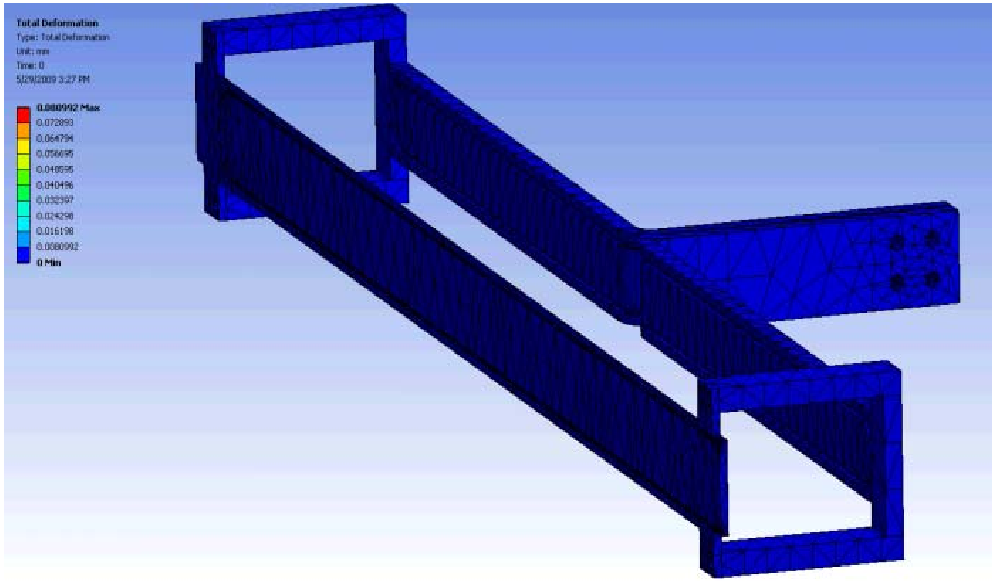
Force (F) on septum conductor: $F = \left(BIl/2 \right)$
Where: B is flux density (T), I is current (A) and
l is length (m).

Depending on the geometry, the septum can be treated as a simply supported beam,
Where:
Max. deflection = $\left(\frac{F}{l}\right)\left(\frac{5h^4}{384YJ}\right)$ on mid plane.

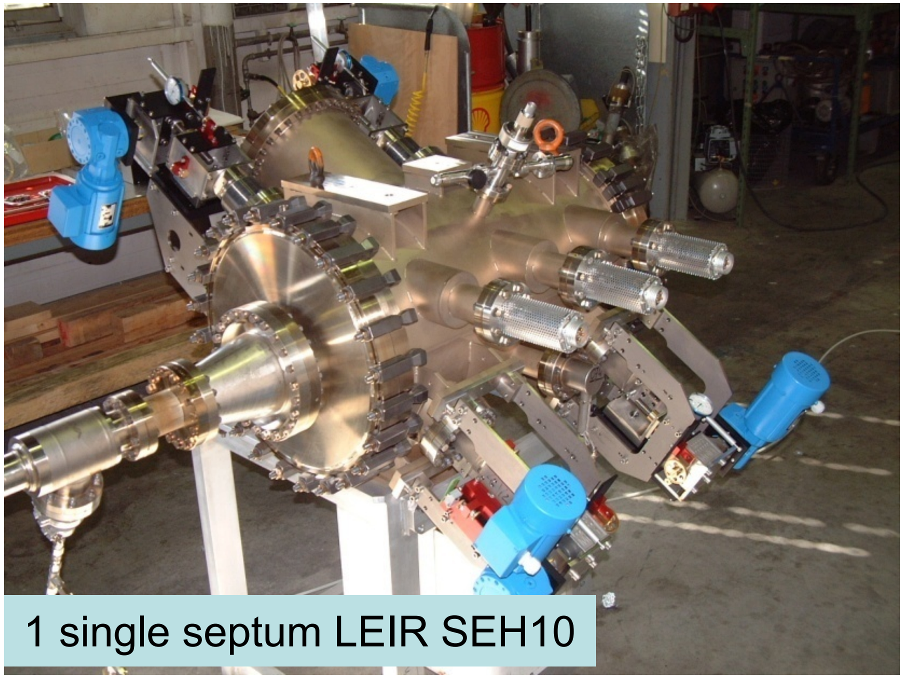
h is the height of the septum (m);
Y is the Young's modulus (N/m^2);
J is the second moment of area (m^4).

And the max. stress $\sigma = \frac{My}{J}$ (N/m^2).

Where:
M is bending moment (N·m) and;
y is distance (m) from the neutral axis.



Remote Displacement System



1 single septum LEIR SEH10

20m of SPS septa move together

The septum has to be positioned precisely (±100 μm) in relation to the orbiting beam.

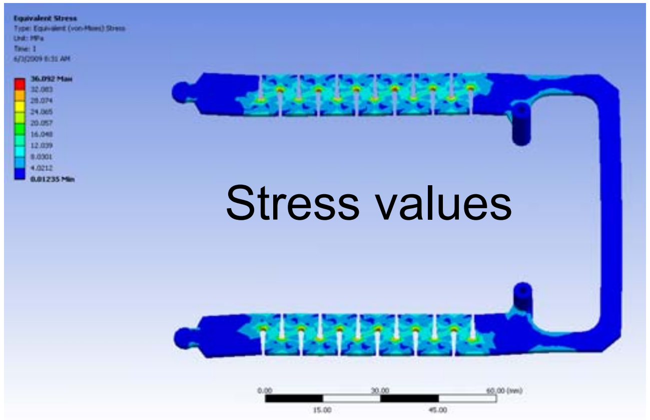
Usually implemented are:
- radial movement (typically ± 10 mm);
- angular movement (typically ± 5 mrad).

Coil Fixation for Pulsed Magnetic Septum

Damping springs are designed to absorb part of the electromechanical force during the current pulse. Damping springs are made of Beryllium copper alloy and are inserted at regular intervals along the length of the coil.

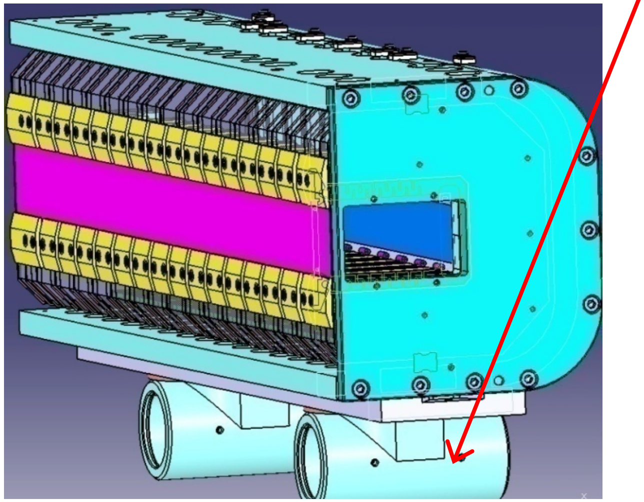
Various springs in use:

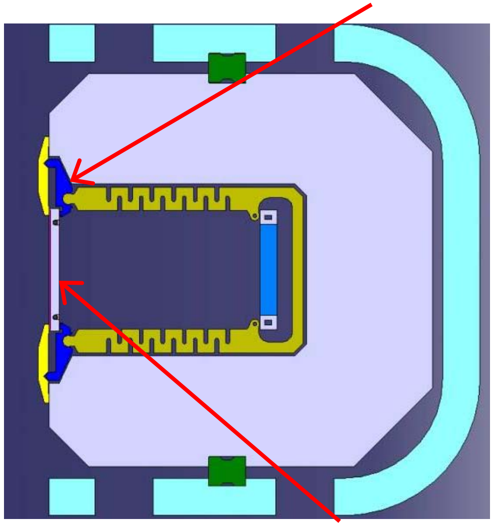
The damping spring is in contact with the septum via a lever which is clamped in a slot in the magnet yoke.



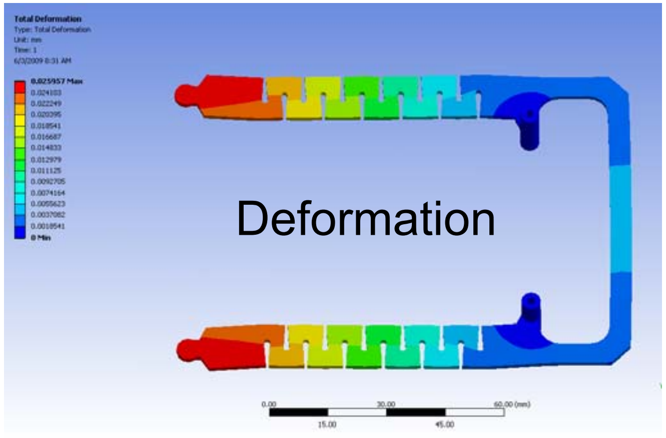
Bearing & housings displacement support

Lever





Septum



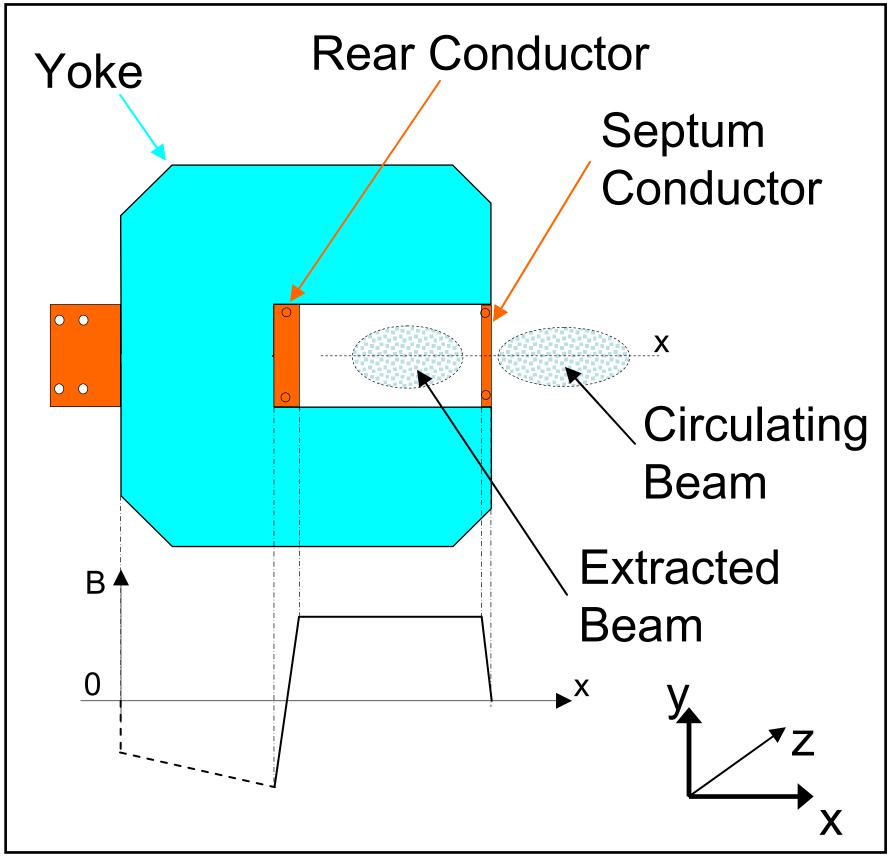
Principal Parameters for Magnetic Septa in the CERN Complex

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

Main Types of Septa

- Main types of Magnetic Septum to be briefly presented:
    - Direct Drive Pulsed Magnetic Septum;
    - Direct Drive DC Magnetic Septum;
    - Eddy Current Septum;
    - Lambertson Septum.

Direct Drive Pulsed Magnetic Septum (1)



Powered with a half sine wave current with a half period time of typically 3 ms.

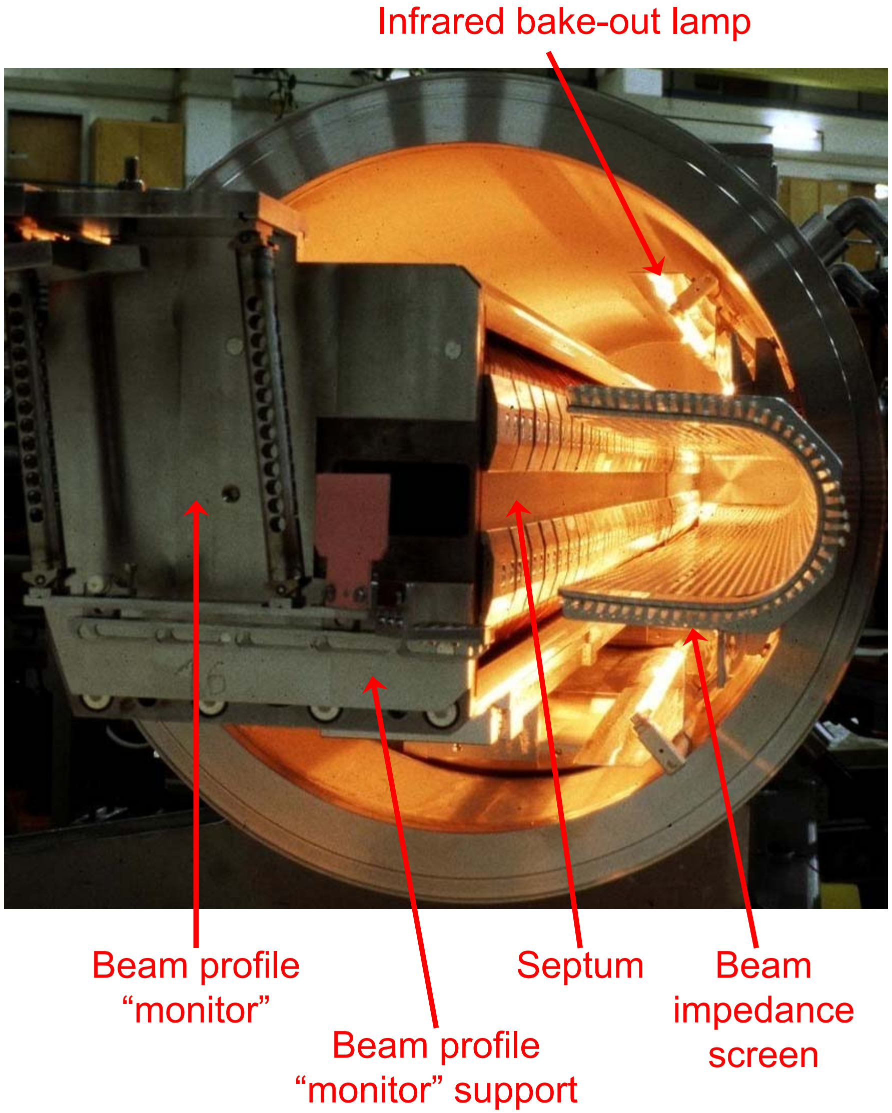
Coil is generally constructed as a single turn, so as to minimize magnet self-inductance.

A transformer is used between power supply and magnet to allow use of standard 2kV capacitors.

To allow precise matching of the septum position with the circulation beam trajectory, the magnet is also often fitted with a remote displacement system.

Often under vacuum to minimize distance between circulating and extracted beam.

Direct Drive Pulsed Magnetic Septum (2)

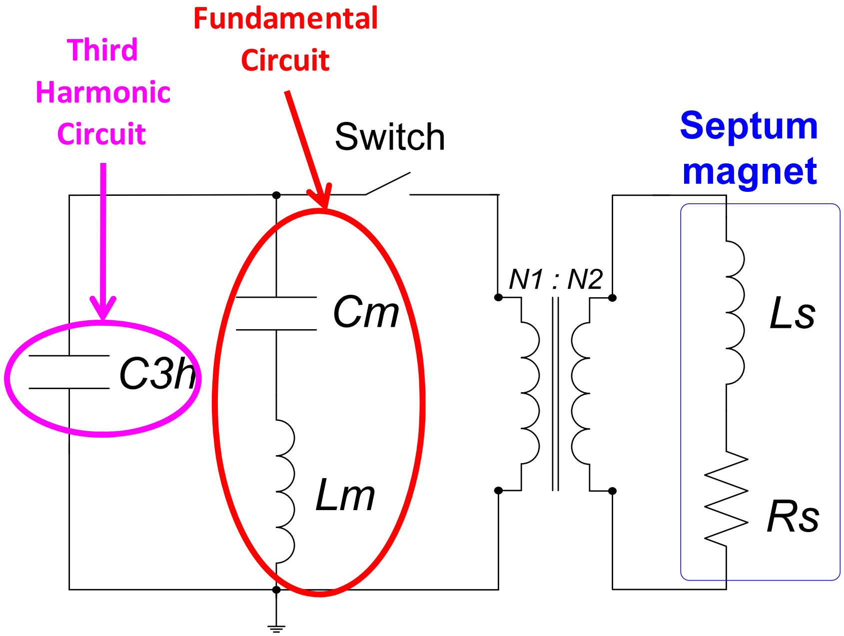


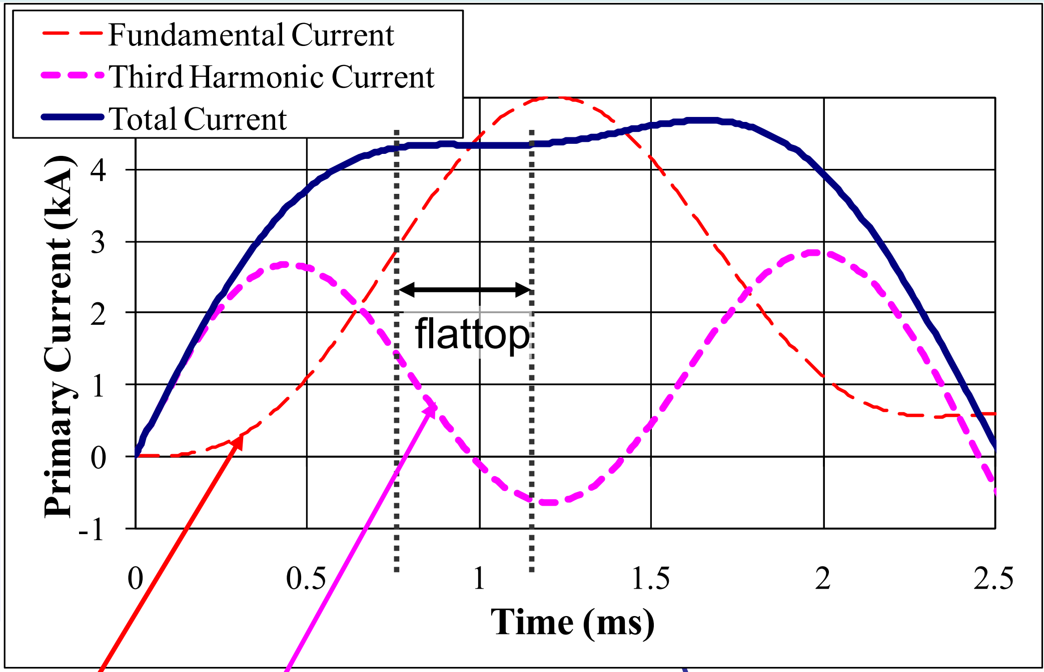
Typical technical data:

- Magnetic length per magnet yoke: 300 - 1200 mm;
- Gap height: 18 - 60 mm;
- Septum thickness: 3 - 20 mm;
- Vacuum (~10^{-9} mbar);
- Laminated steel yoke of 0.35mm - 1.5mm thick laminations;
- Single turn coil, with water cooling circuits (1 - 80 l/min.);
- Bake-able up to 200 °C;
- Current: half-sine 7 - 40 kA, half-period ~3 ms;
- Power supplied by capacitor discharge; flat top of the current improved with 3rd harmonic circuit and active filters – (rectifier circuit used for up to 6s "pulse");
- A transformer is used between power supply and magnet.

Powering Pulsed Septa

Third Harmonic Circuit:

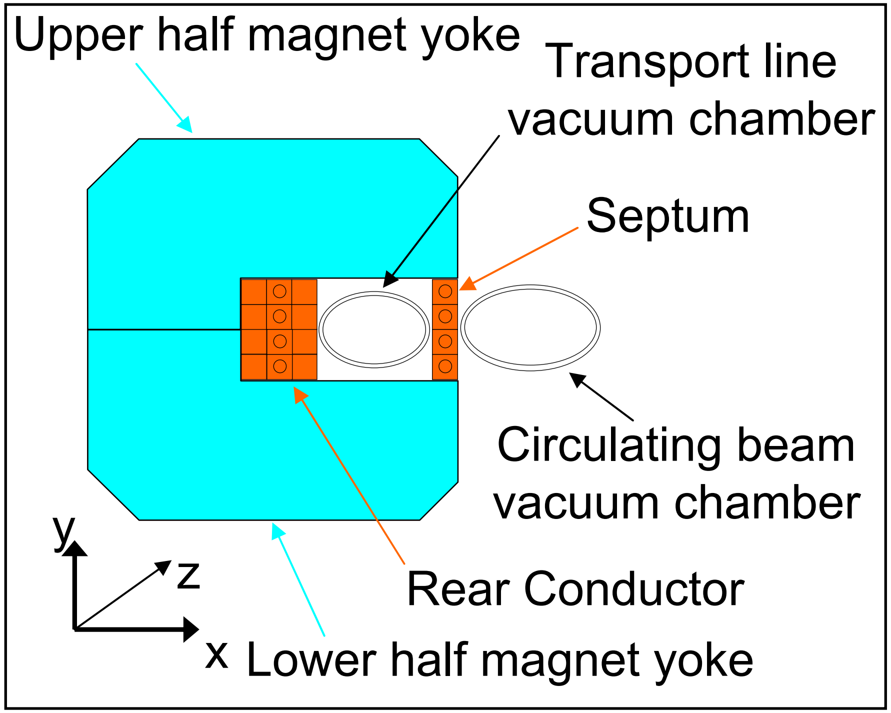




A third harmonic circuit is used to obtain a better flattop current than a basic sinusoidal discharge current:

- The capacitors are accurately charged to the required voltage;
- **The third harmonic circuit generates a current** which is superimposed upon (adds to) the **discharge current of the fundamental current**.
- A transformer is used to allow the use of standard 2kV capacitors on the primary and to give the required high current on the secondary.
- An active filter circuit (not shown) can be used to obtain a stability of flattop current of 10^{-4} over a time of 500µs.

Direct Drive DC Magnetic Septum (1)



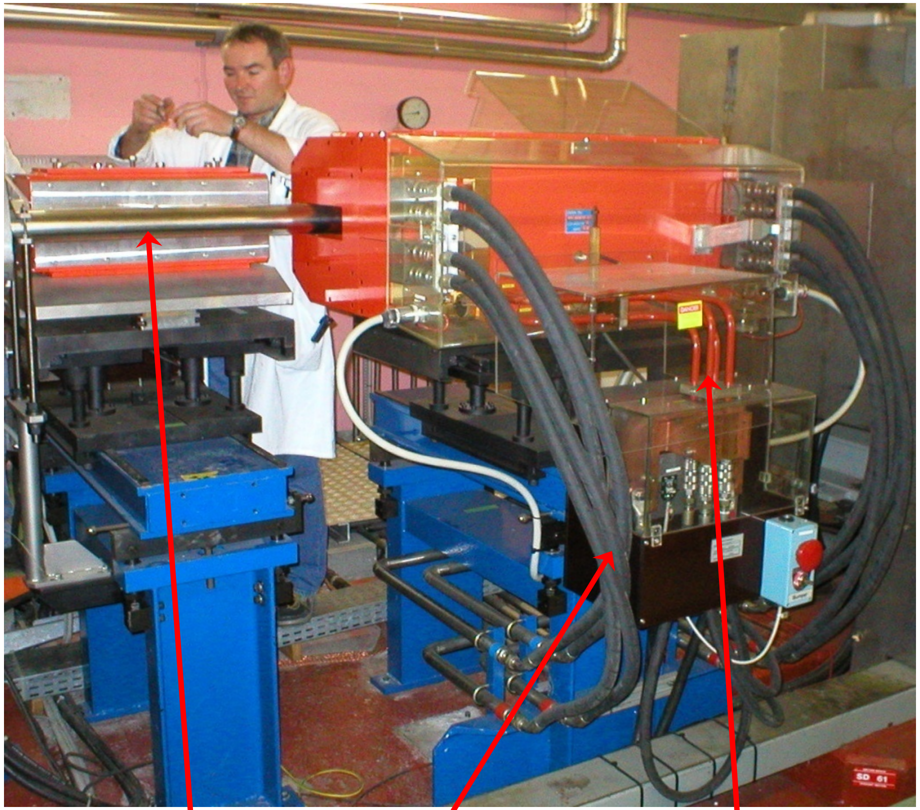
Continuously powered with a (high) current.

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' over the vacuum chamber of the extraction line.

Rarely under vacuum.

Direct Drive DC Magnetic Septum (2)



Circulating Beam

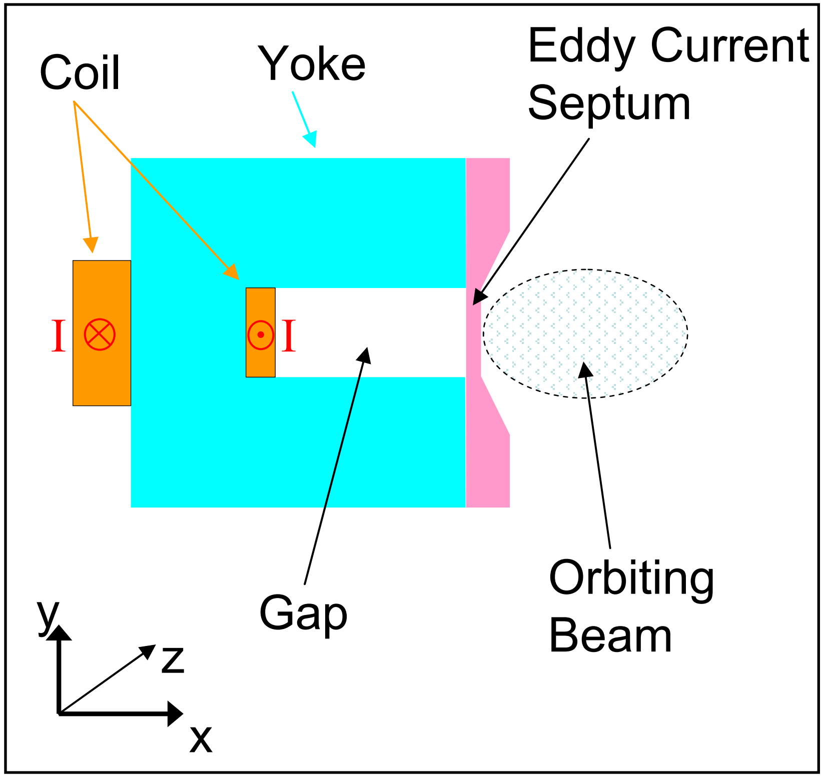
Cooling

Electrical Connections

<u>Typical technical data:</u>

- Magnetic length per magnet yoke: 400 - 1200 mm;
- Gap height: 25 - 60 mm;
- Septum thickness: 6 - 20 mm;
- Outside vacuum;
- Laminated steel yoke;
- Multi turn coil, with water cooling circuits (12 - 60 l/min.);
- Current range: 0.5– 4 kA;
- Power supplied by controllable rectifier;
- <u>Power consumption: up to 100 kW !</u>.

Eddy Current Magnetic Septum (1)



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.

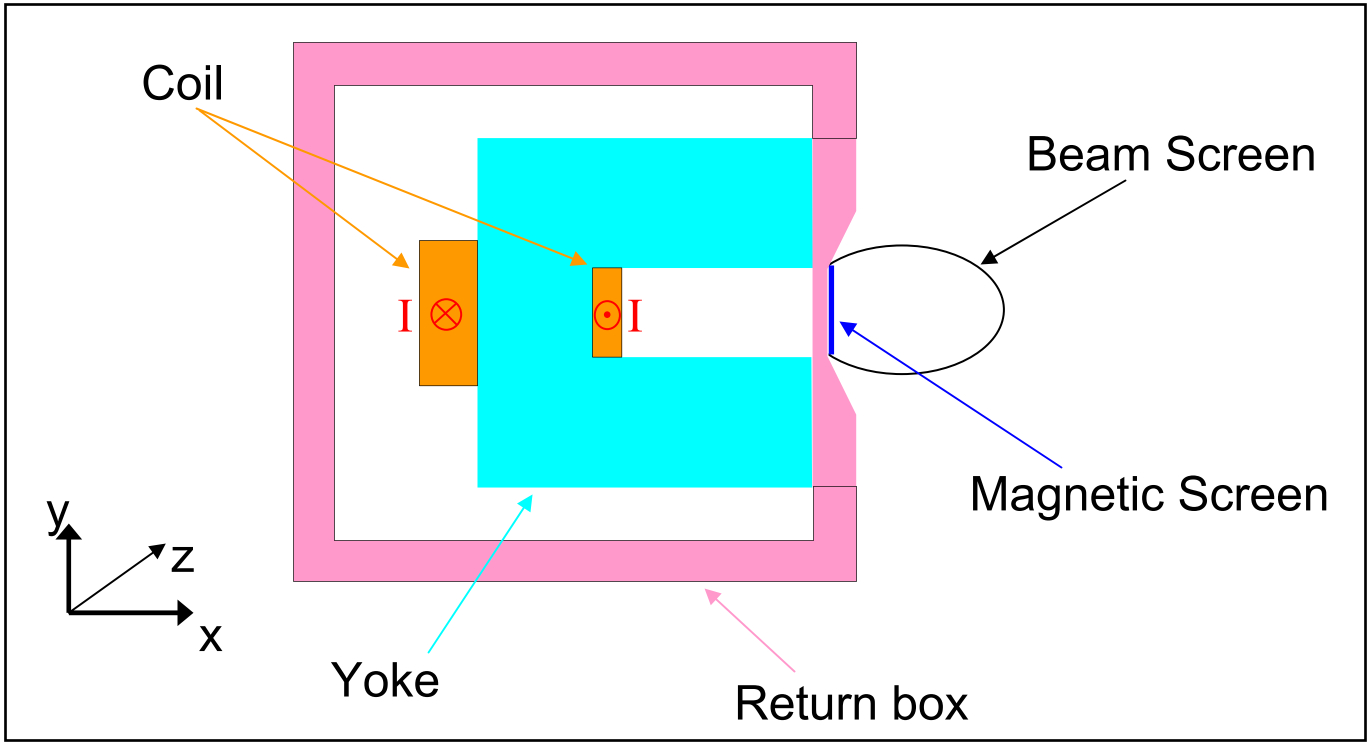
The coil sits around the back leg of the C shaped yoke, and therefore coil dimensions are generally not critical.

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.

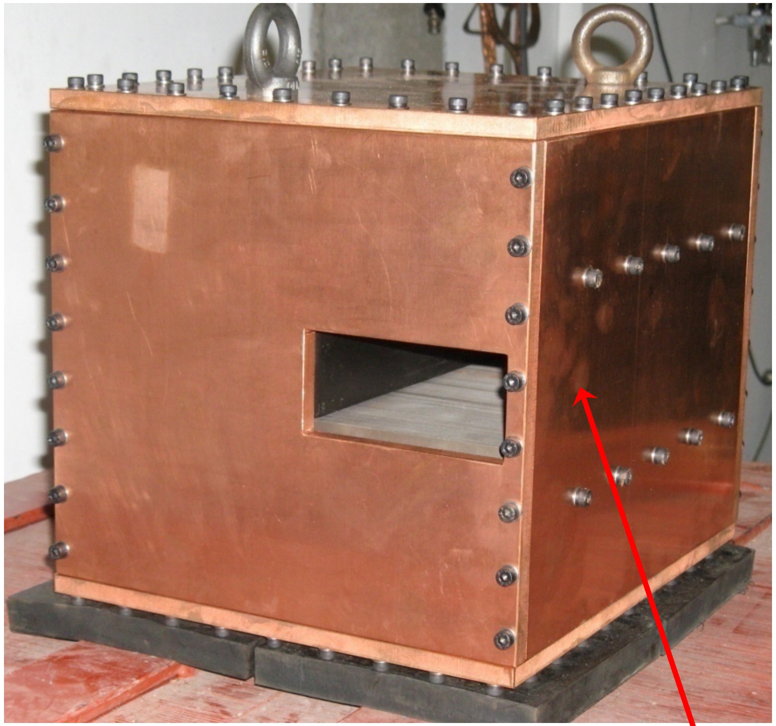
The field in the gap as function of time follows the coil current. The electrical resistance of the septum is kept low: once the septum current is flowing, it takes quite some time to decay away.

Eddy Current Magnetic Septum (2)



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 0.1% of the gap field at all times and places.

Eddy Current Magnetic Septum (3)



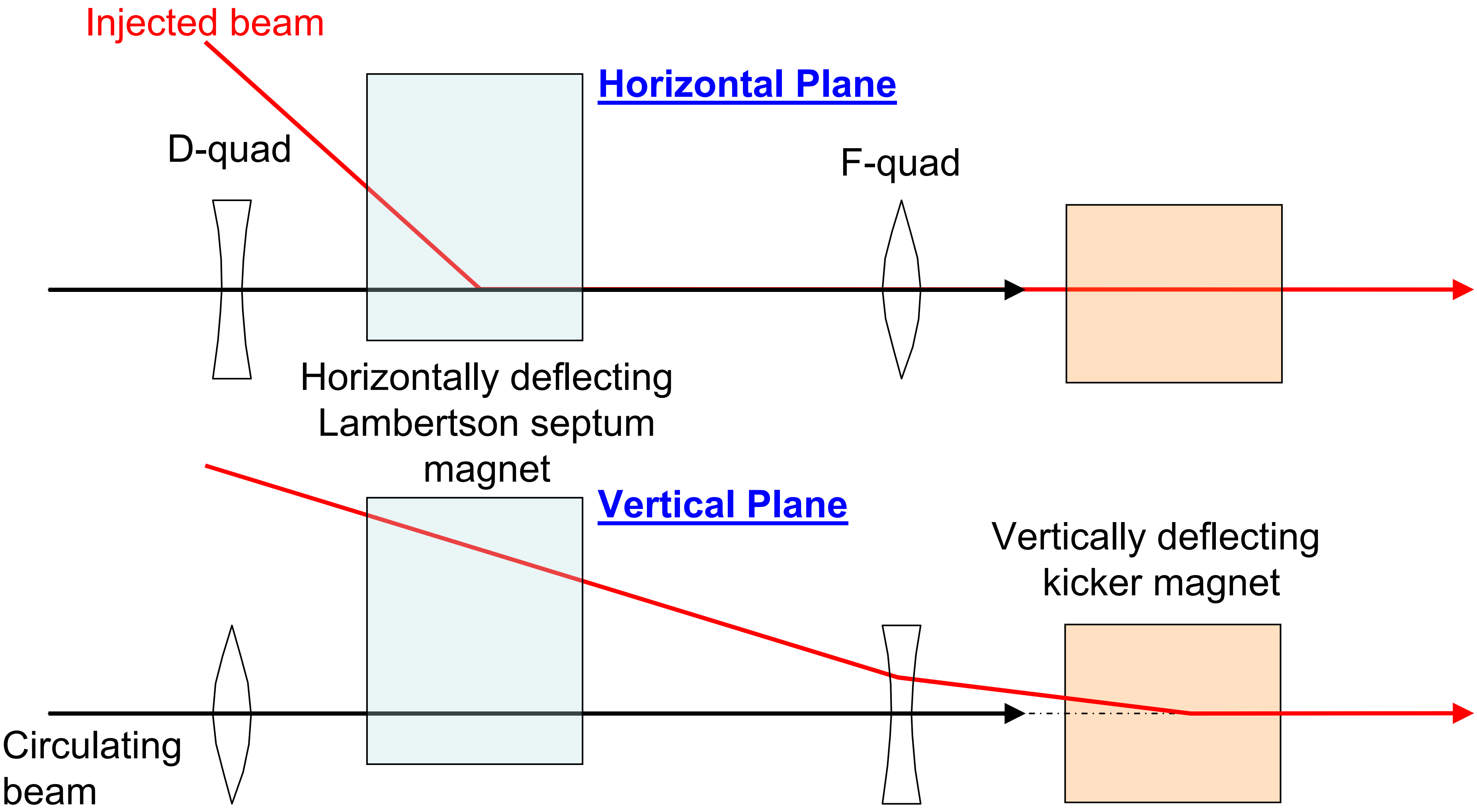
BS1 Prototype Eddy Current Septum

Septum

Typical technical data:

- Magnetic length per magnet yoke: 400 - 800 mm;
- Gap height: 10 - 30 mm;
- Septum thickness: 1 - 3 mm;
- Vacuum (~10^{-9} mbar), or out of vacuum;
- Steel yoke with 0.1 - 0.35 mm thick laminations;
- Single turn coil, with water cooling circuits (1 - 10 l/min.);
- Current: ~10 kA maximum;
- Fast pulsed : 50 μs;
- Powered with a capacitor discharge; half-sine or full sine-wave.

Single-Turn Injection – Two Plane

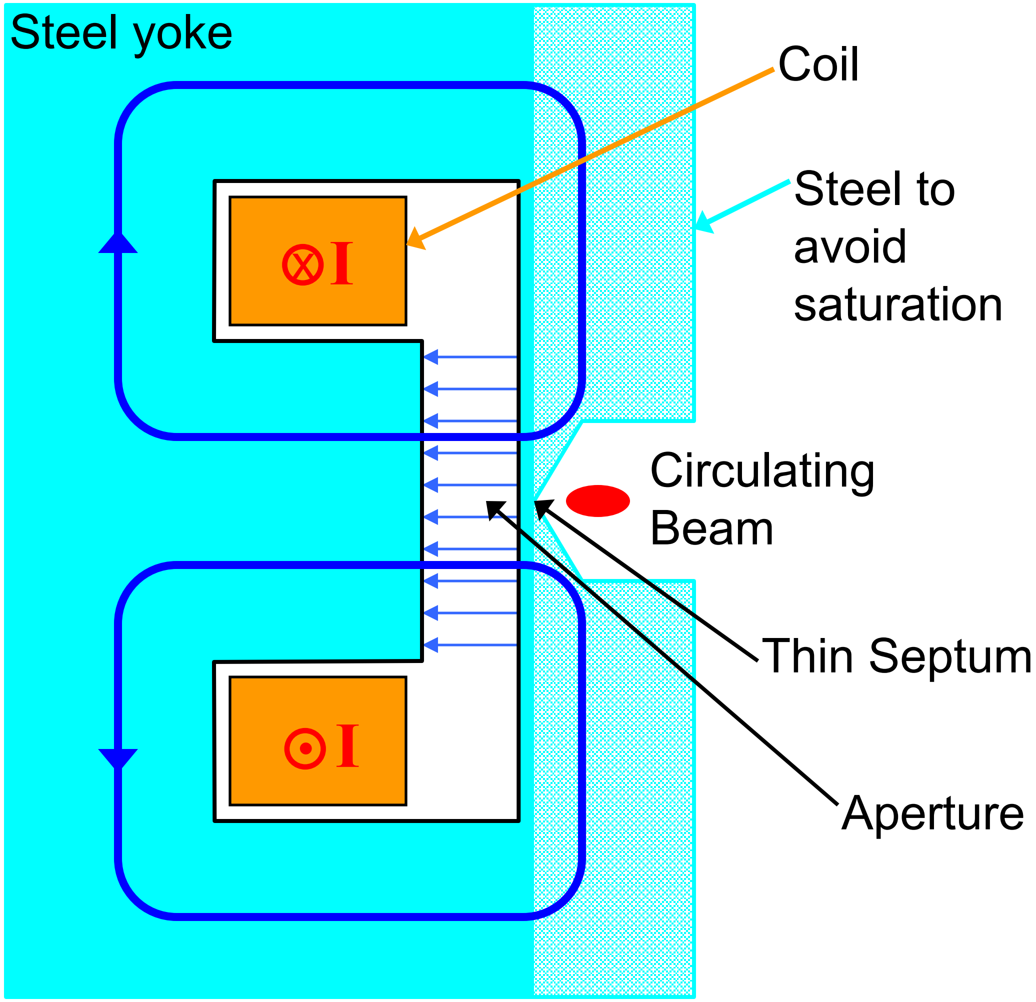


- Septum and kicker in different planes
- Allows use of iron septum – technically easier to build and more robust

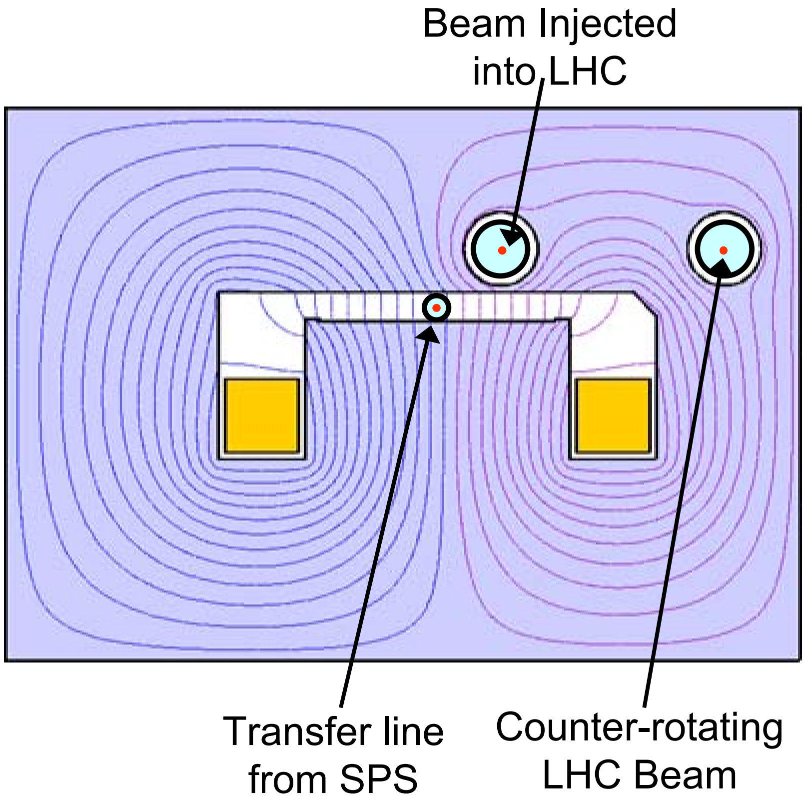
Lambertson Septum (Principle)

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

- Extraction Septum shown:
  - Use kicker to deflect beam horizontally into aperture;
  - Lambertson deflects beam vertically (orthogonal to kicker deflection).

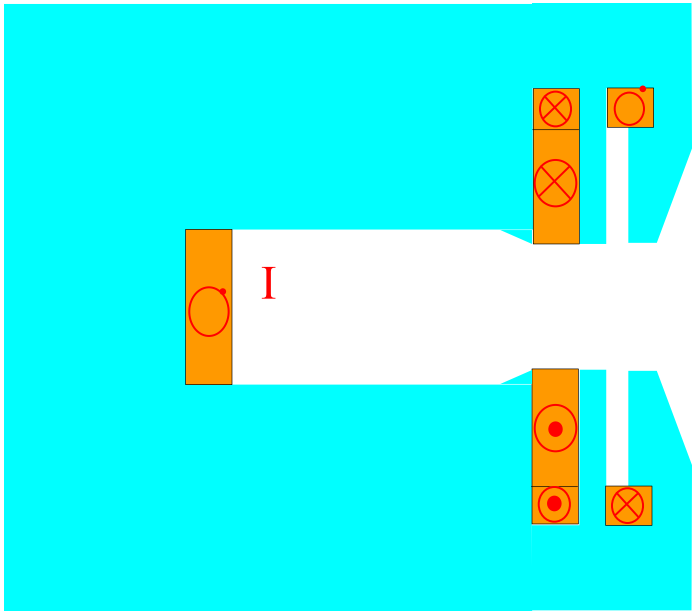


LHC Injection – Lambertson Septum



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

Massless Septum



More recent developments include massless septa: no physical separation between the field free region and homogeneous field region.

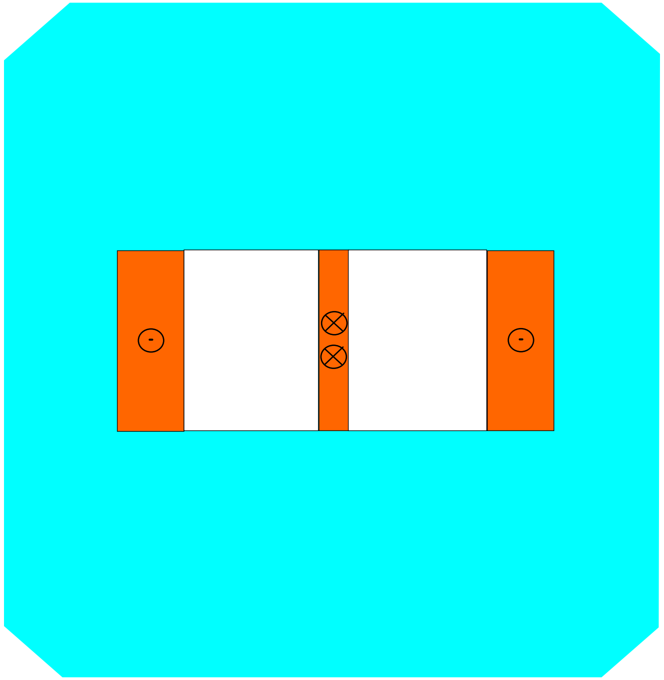
Can be obtained with a complex magnetic circuit :

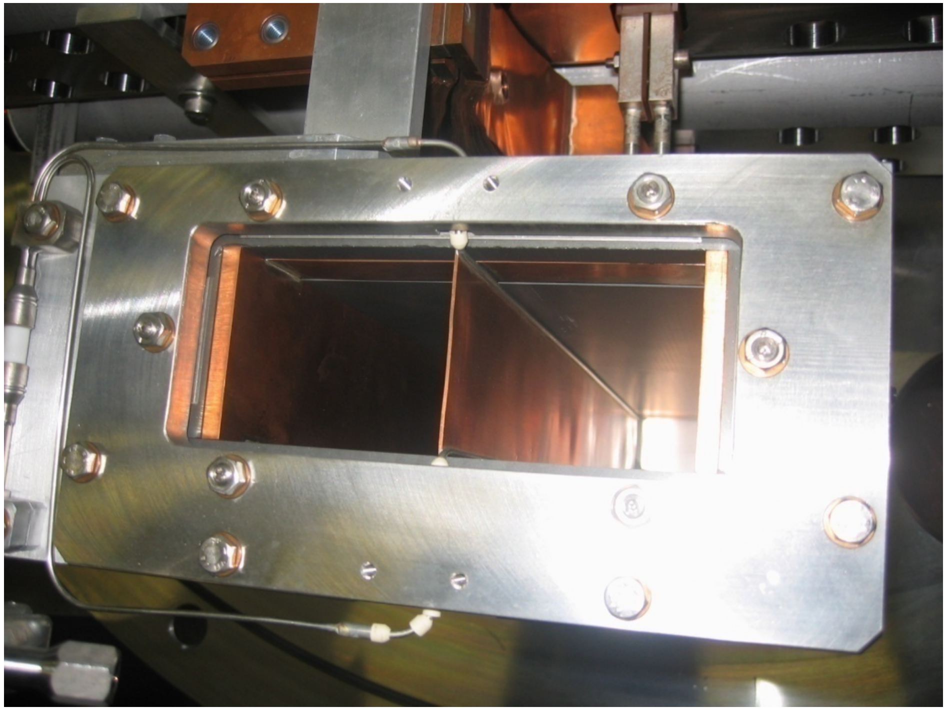
- ➢ additional coils close to septum area (pictured)
- ➢ distributed coils around field free region to cancel a dipole leak field

- Apparent septum thickness rather big (> half the gap height);
- Requires careful design and collimation of particles deflected by septum field.

Opposite Field Septum

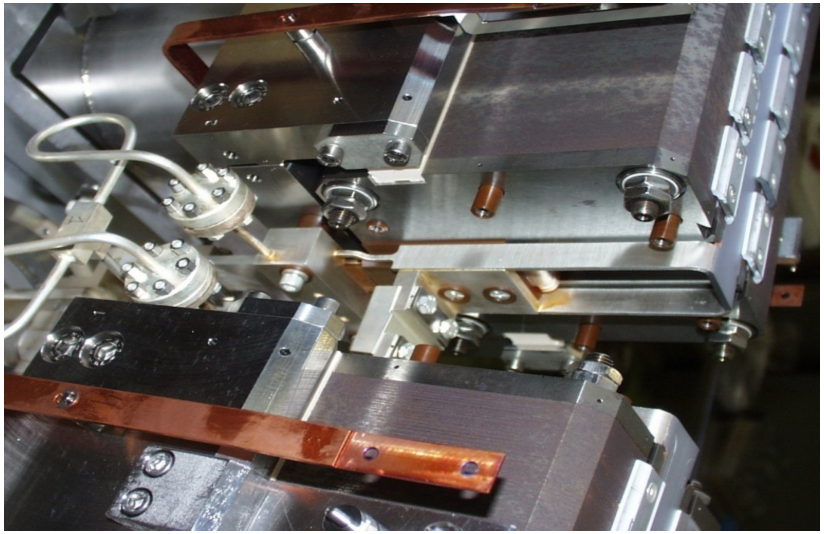
- Opposite fields in adjacent gaps yield ZERO mechanical forces on septum
- Cooling remains critical
- Orbiting beam gap needs very high field homogeneity
- Additional dipole magnets required to complete injection or extraction process





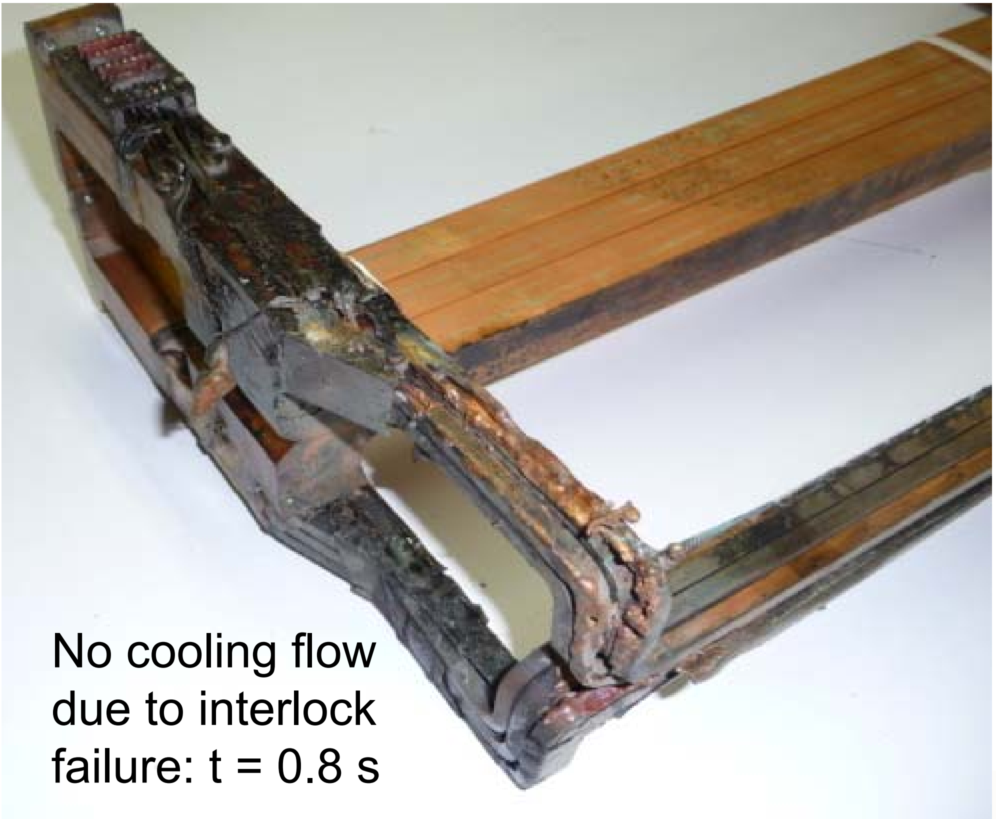
Useful Tips for Future Designers !

- Eliminate end and stray field effects as much as possible using shims and mirror plates especially in low energy machines.
- Reduce to a minimum the number of joints and brazes exposed to vacuum.
- Vibration, bakeout cycles and excessive coolant speed can lead to cooling circuit failures.
- Design for ease of access and rapid replacement in the event of failure especially for high energy machines.
- Design cooling circuit for optimum flow conditions, turbulent flow (best heat exchange), laminar flow (low erosion/cavitation).
- Ensure that the interlock system has been correctly specified and tested.
- NEVER assemble stainless steel screws in stainless steel threads: use silver plating.
- Careful choice of material for example, Vespel insulators are expensive but UHV compatible, easy to machine, self lubricating and high electrical resistance.



If you don’t design correctly then…..

This may happen to you !



No cooling flow
due to interlock
failure: t = 0.8 s

Septum Conductor
Fatigue Failure

Lamination Failure

Cooling Water speed too high.
Excessive cavitation and erosion

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