Septa II

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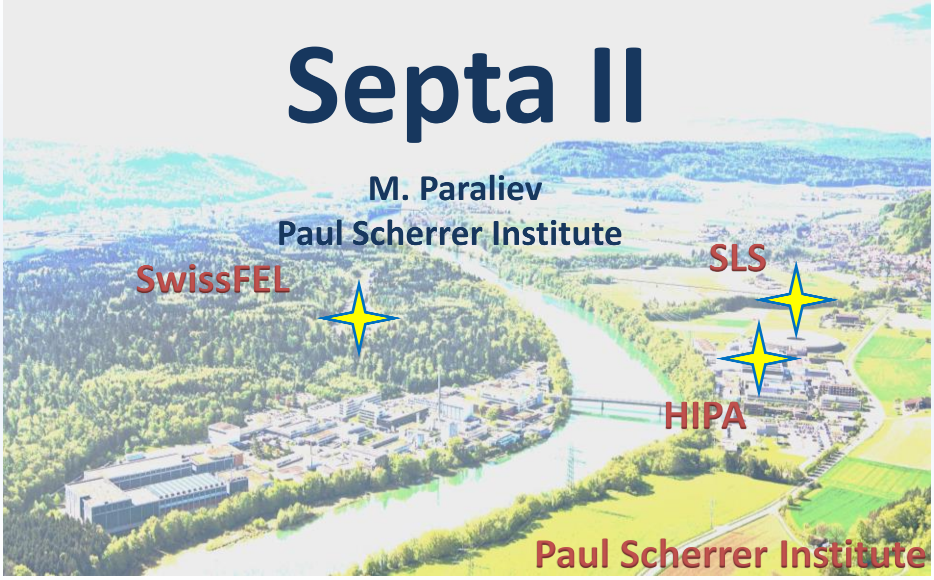
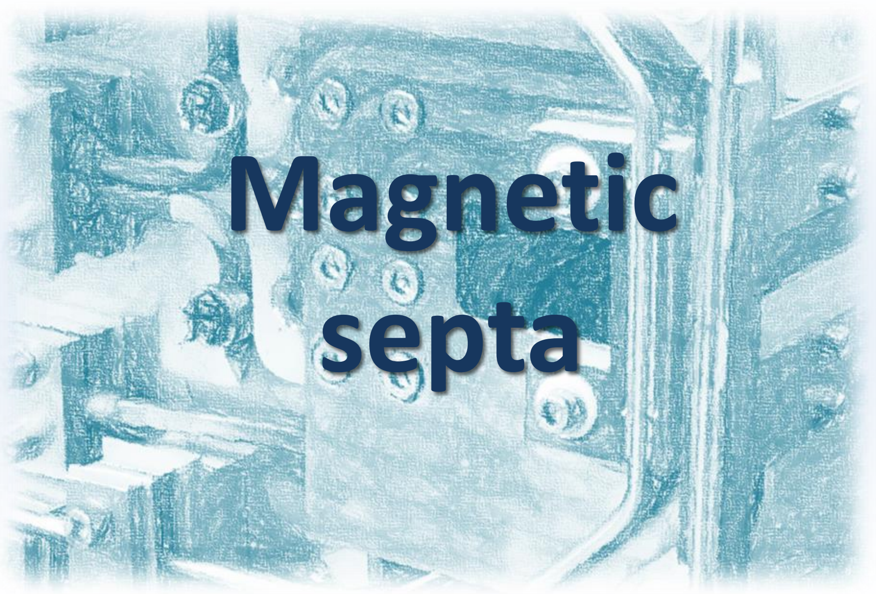


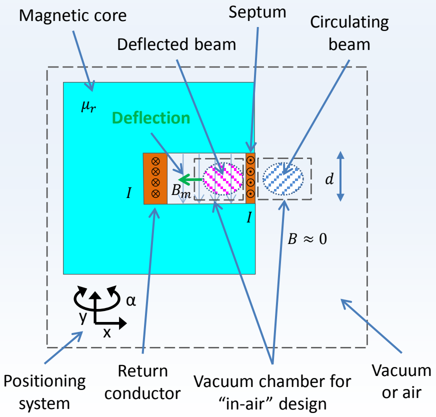
Presentation overview



Magnetic septa

Basic scheme

The deflected beam goes through homogeneous magnetic field that is established between to magnetic poles. The circulating (straight) beam passes next to main magnetic circuit “seeing” as less as possible magnetic field. Often magnetic screening techniques are used to shield the straight beam.



$$B_m \approx \frac{\mu_0 \cdot N \cdot I}{d}$$

Follows from Hopkinson’s law (analogous to Ohm’s low), for $\mu_r \gg 1$

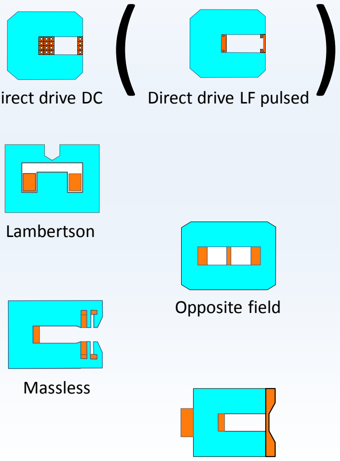
Where:

B_m – magnetic flux density [T]
μ_0 – vacuum permeability [H/m]
μ_r – core relative permeability [-]
N – number of turns [-]
I – current [A]
d – gap [m]

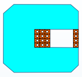
Types of magnetic septa

Classification according to magnetic field variation in time. Basically each type can be "in-vacuum" or "in-air design"

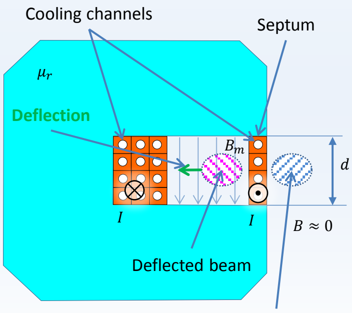
- Magnetic septa
  - DC and low frequency pulsed septa
    - Direct drive
    - Lambertson
    - Opposite field
    - Massless
  - Eddy current septa



Direct drive DC septum


Direct drive DC septum

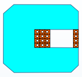
Direct drive DC septum or "C" type active septum magnet is a type of a window frame magnet with one of the legs removed. The septum is used as one of the magnet conductors and the return conductor is inside the magnetic core[17].



Direct drive DC septum

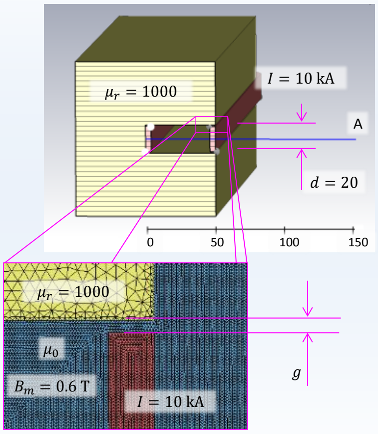
- Due to the magnet geometry the field quality in the gap is good
- Simple design and driving
- The septum carries the full magnet's current
- The septum is relatively ***thick*** due to the incorporated cooling channels
- The leakage field outside the gap is relatively strong
- The DC operation means that the circulating beam will be disturbed at each turn
- Additional magnetic screening could improve the performance in the cost of even thicker effective septum

Gap field and leakage



Direct drive DC septum

Static magnetic field simulation



Simplified static model of the magnet and the meshing in the gap region

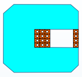
- ➢ Static simulations do not require large amount of computing power and are relatively quick
- ➢ Mesh density could be high, covering the fine details of the magnet's geometry

Parametric study over the gap *g* between septum and magnetic core.

Main field and leakage field (along line A) are simulated for different values of *g*

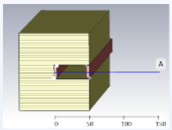
Simulation parameters: current 10 kA, magnetic gap 20 mm, septum thickness 4 mm and magnetic core relative permeability 1000

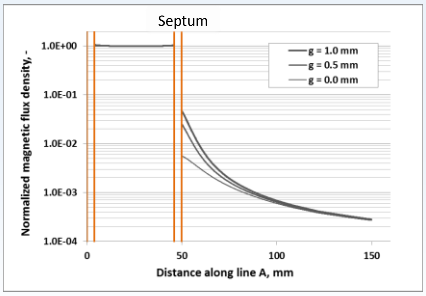
Gap field and leakage



Direct drive DC septum

Static magnetic field simulation – parametric study





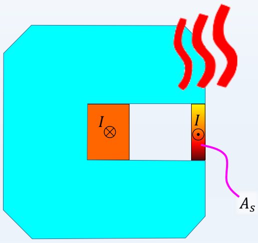
Absolute value of normalized magnetic flux density along line A

- ➢ Main field does not change significantly with changing gap *g*
- ➢ Leakage field depends strongly on gap *g*
- ➢ Reducing *g* to zero is practically difficult due to conductor electrical insulation
- ➢ Even with g = 0, leakage field is relatively strong(~0.5% of main field)
- ➢ Additional measures are needed for further reduction of the leakage field (magnetic screening, more complex septum shape)

Thermal loading

Septum current density and Joule heating

Direct drive DC septum



⚠

Using the parameters in the previous example we get:

Septum current density **125 A/mm²**

Dissipated power in the septum conductor per meter **21 kW/m**

Current density J [A/mm²]

$$J = \frac{I}{A_s}$$

Dissipated power in the septum P [W]

$$P = I^2 R$$

Dissipated power in Cu septum per meter P_{Cu} [W/m]

$$P_{\mathrm{Cu}} \approx 1.68 \cdot 10^{-2} \frac{I^2}{A_s}$$

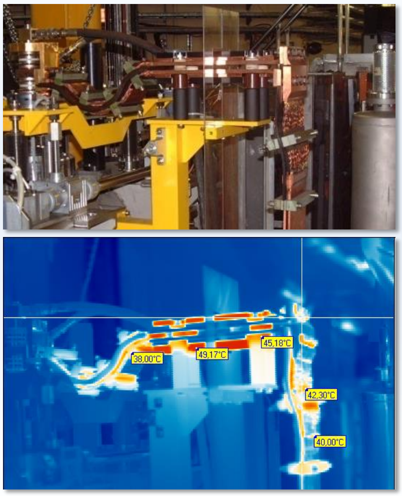
Where:

I – septum current [A]
A_s – septum conductor cross section [mm²]
R – septum resistance [Ω]

Thermal loading

Thermal loading can cause problems not only in the magnet

Direct drive DC septum



Courtesy of CERN, M. Hourican

- Magnet conductors, terminals and cables operate in elevated temperatures

Resistance temperature dependence (for non cryogenic temperatures)

$$R = R_0[1 + \alpha(T - T_o)]$$

Where:

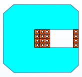
R – conductor resistance [Ω]
R_0 – initial conductor resistance [Ω]
T – conductor temperature [°C]
T_0 – initial conductor temperature [°C]
α – resistivity thermal coefficient [°C^{-1}]

- Current regulation might be required

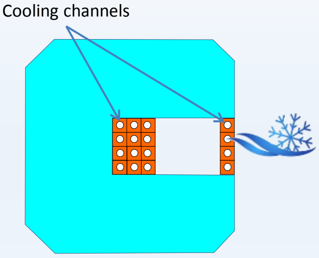
⚠ Bear in mind that copper wire operating 50°C above its initial temperature has **20% more resistance**

Cooling

To avoid overheating, magnet conductors have channels for fluid cooling.



Direct drive DC septum



Using the parameters in the previous example we get:

Required cooling water flow rate for 40°C temperature difference per meter **0.13 kg/s.m** or **7.5 l/min.m**

- Adequate fluid flow rate must be provided to remove the power dissipated in the septum

Removed power P_r [W]

$$P_r = \dot{m} c_p (T_{Out} - T_{In})$$

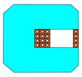
Where:

$\dot{m}$ – fluid mass flow rate[kg/s]
c_p – specific heat capacity [J/kg.K] or [J/kg.°C]
T_{Out} – fluid input temperature [°C]
T_{In} – fluid output temperature [°C]

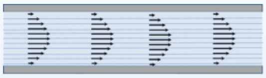
- Often deionized water is used as cooling fluid
- Cooling interlock is necessary otherwise the septum could turn into a **giant fuse**

Laminar vs turbulent flow

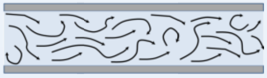
Cooling fluid dynamics and Reynolds flow criterion



Direct drive DC septum



Laminar flow (Re < 2000)



Turbulent flow (Re > 4000)

Using the parameters in the previous example we get:

For 4 cooling channels with diameter 3 mm and surface roughness 10 µm

Reynolds number 28500 (definitively turbulent flow)

Water pressure drop per meter

1 bar

- Turbulent fluid flow is more efficient in heat removal

Reynolds number Re [-]

$$Re = \frac{\rho v D}{\mu}$$

Pressure drop Δp [Pa] per meter

$$\Delta p = f_{\mathrm{D}} \frac{\rho v^2}{2D}$$

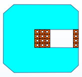
Where:

ρ – fluid density [kg/m^3]
v – mean velocity of fluid [m/s]
D – pipe inside diameter [m]
μ – dynamic viscosity of fluid [kg/m.s]
f_{D} – Darcy friction factor [-]

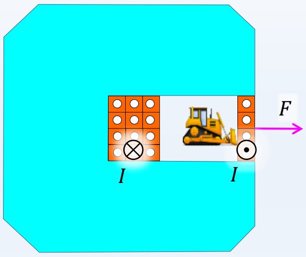
- High flow rate might cause erosion and vibration

Magnetic force

Mechanical force due to magnetic field interaction



Direct drive DC septum



Septum mechanical force per meter length F [N/m]

$$F = \frac{\mathrm{BI}}{2}$$

Where:

B – magnetic flux density [T]
I – septum current [A]

- ➢ The septum (and the return conductor) should be adequately attached in order to withstand the repulsive magnetic force (without excessive displacement)

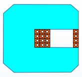
⚠

Using the parameters in the previous example we get:

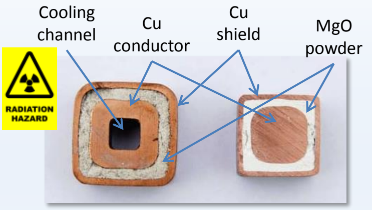
The septum will be pushed out of the magnet's gap with force per meter as high as
3 kN/m or 320 kg/m

Insulation

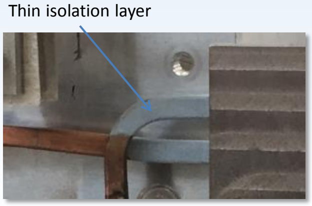
Due to high levels of radiation special measures have to be taken to ensure reliable radiation hard insulation[6, 23].



Direct drive DC septum



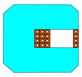
Magnesium oxide powder insulated conductors



Ceramics deposition

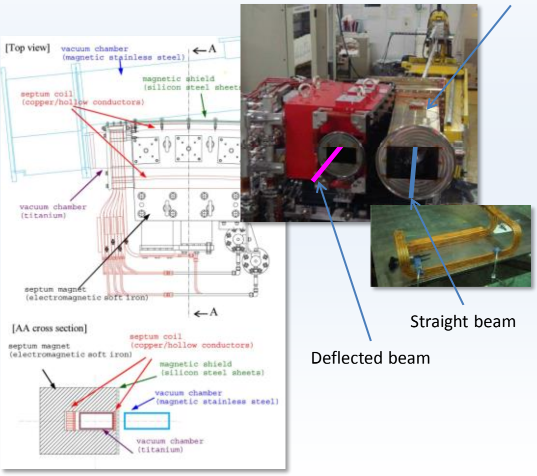
- ➢ High radiation levels damage organic materials and they are not suitable for conductor insulators
- ➢ 7 MGy per week limits lifetime of a regular epoxy magnet coil to < 2 weeks[6]
- ➢ Buck (powder) inorganic materials like magnesium oxide (MgO) are used to provide adequate insulation
- ➢ Deposited ceramic layer is another alternative for radiation hard insulation but it is vulnerable to mechanical damage

Example I



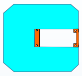
Direct drive DC septum

Construction and technical data of direct drive DC septum ISEP2 (RCS, J-PARC)[9, 24, 25]



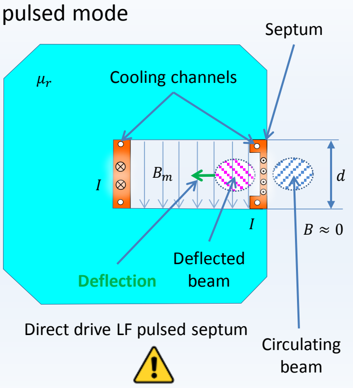
- ➢ "In-air" design
- ➢ Field length : 650 mm
- ➢ Gap height: 140 mm
- ➢ Gap width: 348 mm
- ➢ Beam momentum: 181 MeV/c
- ➢ Deflection angle: 90.8 mrad
- ➢ Septum thickness: 45 mm
- ➢ Current: 6 kA
- ➢ Magnetic flux density: 0.475 T
- ➢ Magnetic st. steel screen

Direct drive LF pulsed septum



Direct drive LF pulsed septum

To reduce average heat dissipation direct drive septa operate in pulsed mode



Direct drive LF pulsed septum

⚠

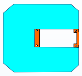
High currents produce large forces and strong dynamic mechanical stress.

For a septum operating at 1 T with 30 kA pulse maximum force per meter could be as large as **15 kN/m or 1500 kg/m**

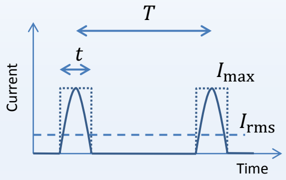
- ➢ Average heat dissipation is reduced due to the low duty cycle
- ➢ Power consumption and cooling requirement are reduced
- ➢ Septum conductor can be thinner (edge cooling)
- ➢ The leakage field outside the dap is relatively strong (like in direct drive DC septa)
- ➢ Circulating beam is less disturbed (during the pulse only)
- ➢ Eddy currents effects have to be taken in account (core lamination)
- ➢ Dynamic stress in septum
- ➢ Measures against mechanical vibrations

Average dissipation

Pulsed septa can benefit from low duty cycle



Direct drive LF
pulsed septum



Pulsed operation

For short pulses there is no effective heat transfer and the case should be treated as the pulses deposit the heat instantaneously

Duty cycle of the septum δ [-]

$$\delta = \frac{t}{T}$$

Rms current of a rectangular pulse $I_{\mathrm{rms\ sq}}$ [A]

$$I_{\mathrm{rms}\ sq} = I_{\max}\sqrt{\delta}$$

Rms current of half-sine pulse $I_{\mathrm{rms\ 1/2sine}}$ [A]

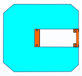
$$I_{\mathrm{rms\ 1/2sine}} = I_{\max}\sqrt{\frac{\delta}{2}}$$

Where:

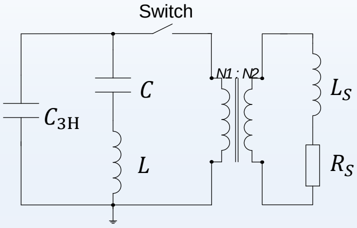
t – pulse duration [s]
T – period of repetition frequency [s]
$I_{\max}$ – maximum current [A]
I_{rms} – rms current [A]

Septa pulsed supplies

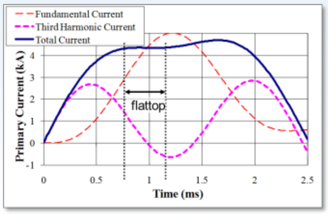
Pulsed operation requires more complex power supplies



Direct drive LF
pulsed septum



Simplified circuit of septum pulsed supply



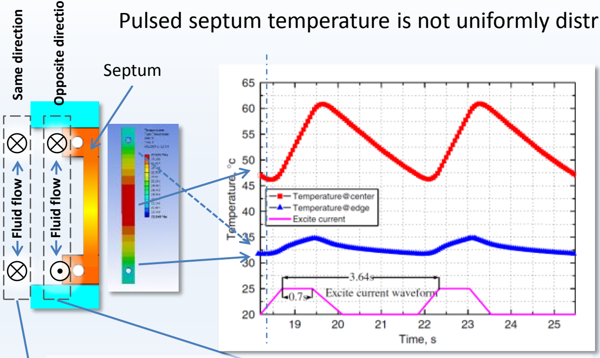
Current waveforms

- Capacitors are accurately charged to the required voltage
- Third harmonic circuit ($C_{3\mathrm{H}}$) could be used to improve the flat-top of the pulse. (fundamental and third harmonic current add together to form more flat-top waveform)
- Additional active regulation circuit could be used to improve further stability of the flat-top current
- Step-down transformer could be used to provide the required high current. Typically the transformation ratio is in the range 4:1 to 50:1

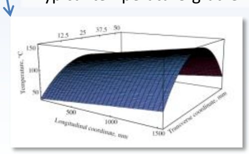
Pulsed septum heating

Pulsed septum temperature is not uniformly distributed[10]

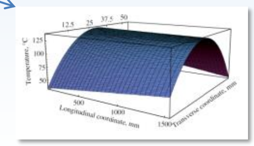
Direct drive LF pulsed septum



Typical temperature gradient and temperature variation of a septum



Cooling fluid in the same direction



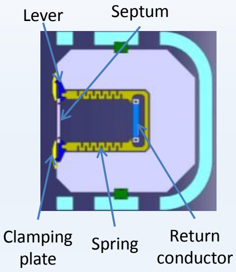
Cooling fluid in opposite direction

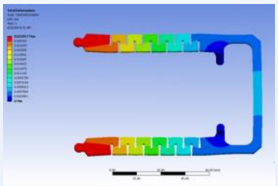
- "Edge cooling" allows thinner septum
- Dynamic temperature gradient across the septum conductor (thermal resistance)
- Non-uniform longitudinal cooling due to cooling fluid temperature change
- Cooling fluid flowing in opposite direction helps to reduce longitudinal temperature difference

Mechanical damping

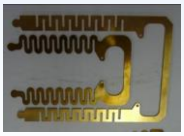
Series of clamping plates and springs hold the septum in the gap[21]

Direct drive LF pulsed septum



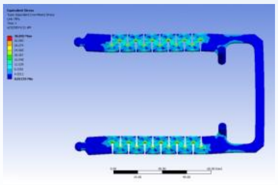


Spring deformation



BeCu spring absorbers

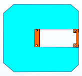
Courtesy of CERN, M. Hourican



Spring stress values

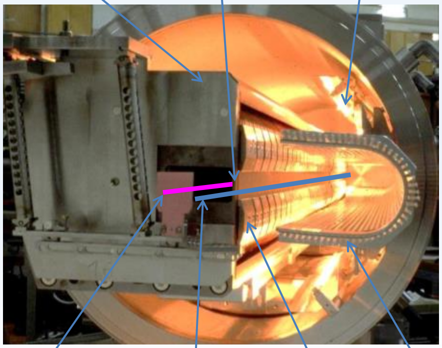
- Pulsed electromagnetic force between septum conductors launches mechanical shockwave known as "hammering"
- Beryllium copper (BeCu) springs are inserted at regular intervals to absorb the mechanical vibrations
- The spring is in contact with the septum via a lever which is clamped in a slot in the magnet yoke

Example II



Direct drive LF pulsed septum

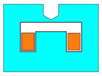
Construction and technical data of “in-vacuum” direct drive LF pulsed septum PESMH16 (PS, CERN)[21, 22]



Courtesy of CERN Septa Section

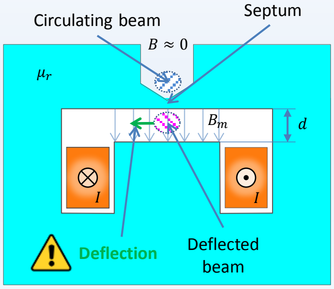
- In situ bake-out 200°C
- Vacuum: 10^{-9} mbar
- Field length : 2180 mm
- Gap height: 30 mm
- Gap width: 65 mm
- Beam momentum: 25.1 GeV/c
- Deflection angle: 30 mrad
- Septum thickness: 3 mm
- Current: 28.5 kA (half sine 3.5 ms)
- Magnetic flux density: 1.2 T
- Beam screen: perforated st. steel
- Cooling water flow rate: 1.2 L/min

Lambertson septum



Lambertson septum

Due to magnetic circuit symmetry the circulating beam area has very low leakage field



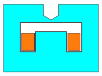
Lambertson septum

- Thin septum
- Low stray fields
- More complex geometry
- Could be DC or LF pulsed
- **Deflection perpendicular to beam displacement** ⚠

(In shown example:)

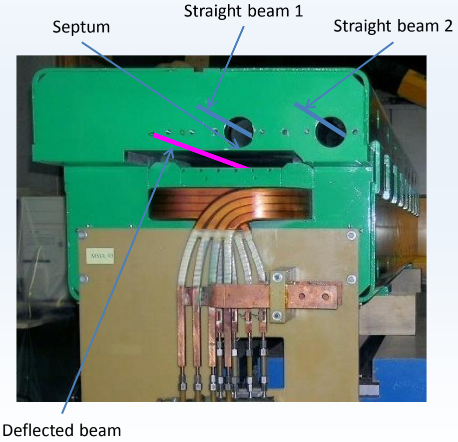
Kicker magnet is used to deflect the beam vertically (Down) and then the Lambertson septum deflects the beam horizontally (To the left)

Example III



Lambertson septum

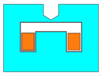
Construction and technical data of "in-air" Lambertson septum MSIA (LHC, CERN)[13, 26]



Courtesy of CERN Septa Section

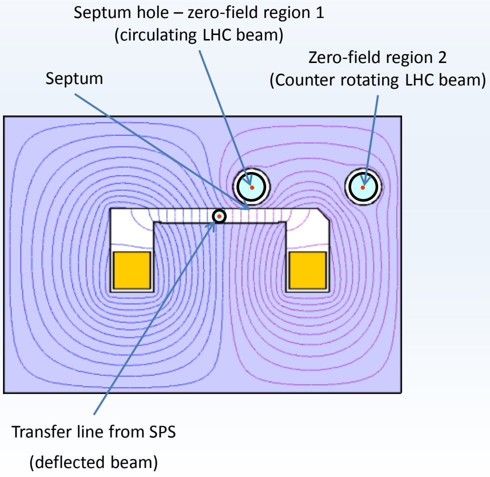
- Vacuum: 10^{-7} mbar
- Field length : 3650 mm
- Gap height: 25 mm
- Gap width: 230 mm
- Beam momentum: 450 GeV/c
- Deflection angle: 1.846 mrad
- Septum thickness: 6 mm
- Current: 950 A x 16 turns
- Magnetic flux density: 0.76 T
- Cooling water flow rate: 7.9 L/min
- Dissipated power: 10.6 kW

Example III



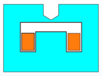
Lambertson septum

Design specifics of MSIA (LHC, CERN)[13, 26]



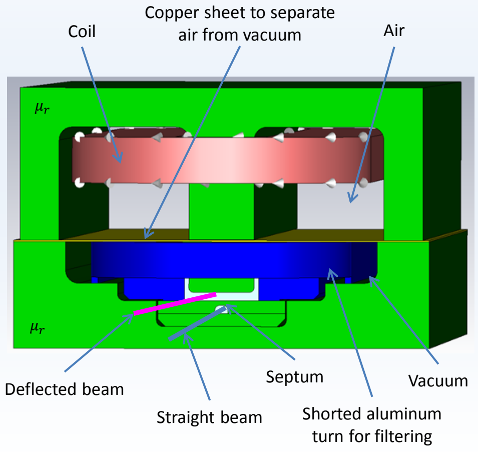
- "In-air" design
- Two zero-field regions for circulating beam and for counter rotating beam
- Mu metal chambers (thickness: 0.9 mm, 0.8 T saturation) for additional screening
- Chamber is copper coated (0.4 mm) to improve beam impedance
- Vacuum chamber is NEG coated
- In-situ bake-out 200°C
- Top yoke side (with zero-field regions) extends 175 mm on each side to screen the fringe fields

Example IV



Lambertson septum

Construction and technical data of "half-in-vacuum" Lambertson septum* for SwissFEL switchyard (PSI)[5]

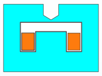


- Vacuum: 10^{-7} mbar
- Field length : 760 mm
- Gap height: 6.8 mm
- Gap width: 61 mm
- Beam momentum: 3.15 GeV/c
- Deflection angle: 35 mrad
- Septum thickness: 2.5 mm
- Current: 100 A x 41 turns
- Magnetic flux density: 0.51 T
- Dissipated power: 0.4 kW

---

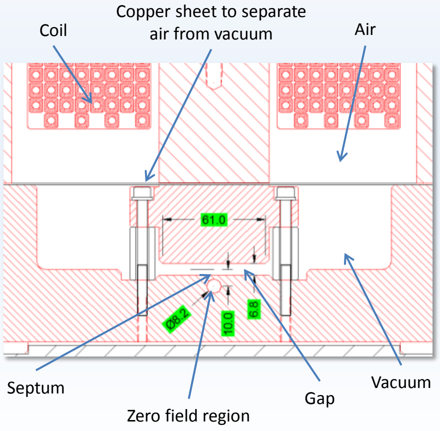
*Under construction!

Example IV



Lambertson septum

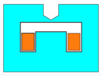
Design specifics of Lambertson septum for SwissFEL switchyard



- "Half-in-vacuum" design
- Small vacuum volume
- Coil on the air side
- Thin septum
- Small aperture - Ø8.2 mm
- Small gap - 6.8 mm
- High stability <10 ppm
- Shorted turn for electrical filtering
- Bottom yoke side (with zero-field region) extends 150 mm on each side to screen the fringe fields

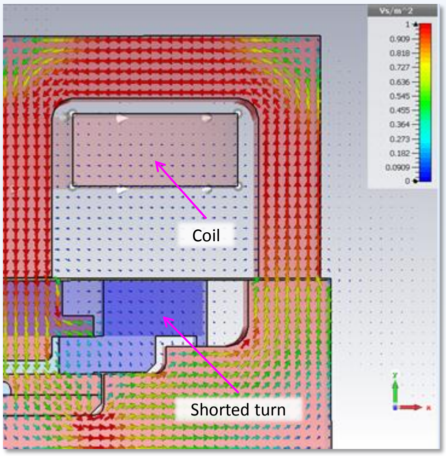
Example IV

Field low pass filter with built-in shorted turn

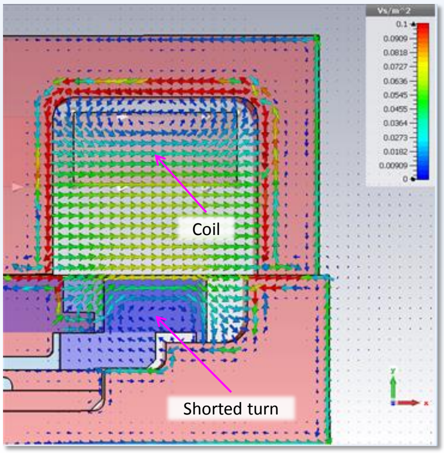


Lambertson septum

B Field @0.001Hz

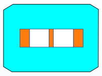


B Field @50Hz

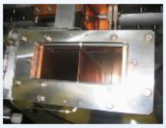


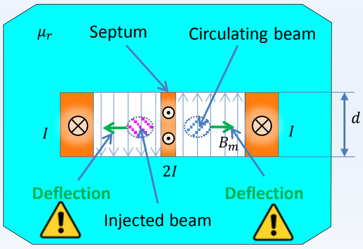
Opposite field septum

Instead of zero-field region the opposite field septum has a region with magnetic field in the opposite direction[11]



Opposite field septum



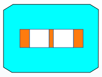


Opposite field septum

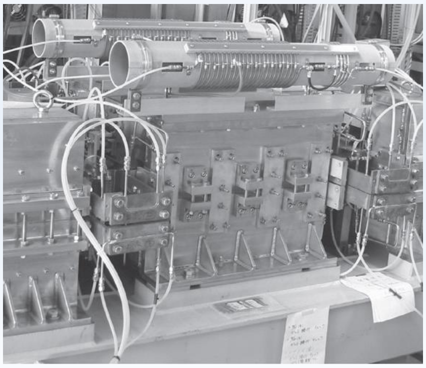
- ➢ Electromagnetic forces cancel out
- ➢ Large aperture
- ➢ Thin septum
- ➢ No need of field-free region
- ➢ More complex geometry
- ➢ Could be DC or LF pulsed
- ➢ **Both beams are deflected** ⚠

Example V

Technical data of opposite field injection septum for J-PARC (KEK)[7]



Opposite field septum

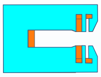


Opposite field septum at KEK

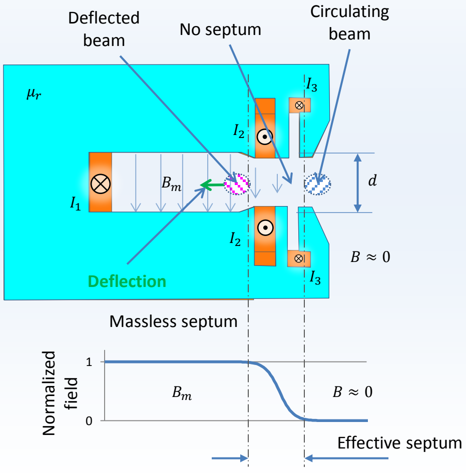
- Field length : 700 mm
- Gap height: 120 mm
- Gap width: 150 mm / 400 mm
- Beam momentum: 3 GeV/c
- Deflection angle: 68 mrad
- Septum thickness: 8 mm
- Current: 48 kA x 2 (half sine 2.5 ms)
- Magnetic flux density: 0.6 T

Massless septum

Magnetic field is shaped using system of currents and magnetic paths[16, 8]



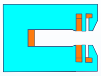
Massless septum



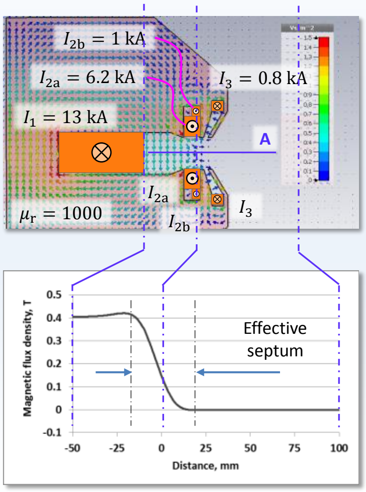
- DC or pulsed
- No physical septum, no beam interaction
- Complex design
- Currents are adjusted to cancel the dipole leakage field
- Slow field transition (thick effective septum)
- Operating in transition gradient might compromise machine optics

Example VI

Technical data of massless septum* NSRF (Kyoto)[16]



Massless septum



Magnetic flux density along line **A**

- Gap height: 30 mm
- Gap width: 50 mm
- Effective septum thickness: 40 mm
- Currents in the range of 0.8 to 13 kA
- Magnetic flux density: 0.4 T

Field transition or effective septum thickness is in order of the gap height.

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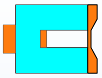
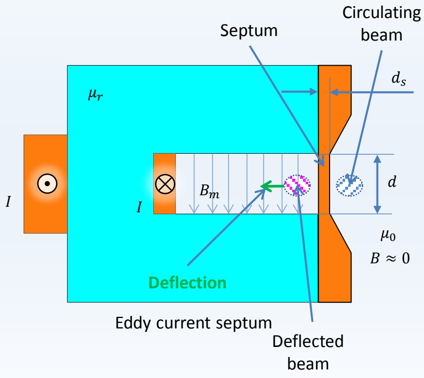
*Proposed design!

Eddy current septum

Eddy currents in the septum conductor cancel the changing magnetic field (eddy currents screening)

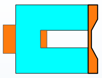


Eddy current septum



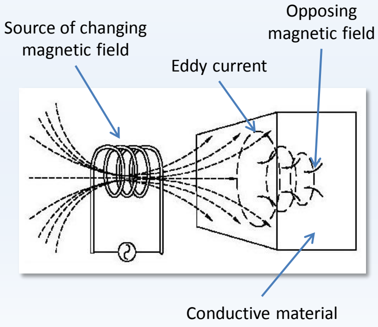
- Thin septum
- Eddy currents dissipate power as well (edge cooling might be necessary)
- Doesn’t work for DC magnets
- Low leakage fields
- Maximum of the leakage field appears after certain delay
- More complex pulsed power supplies (short pulses)
- Low inductance magnets (single turn)
- Combined with thin mu-metal screening brings the ratio main field to leakage field to >1000:1

AC magnetic field penetration



Eddy current septum

Eddy currents always flow in such direction that their magnetic field opposes the change of the magnetic field that produces them (Lenz's law)



Skin depth (field penetration) δ [m] – distance after the AC current is reduced 63%.

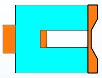
$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \sigma}}$$

Where:

f – magnetic field frequency [Hz]
μ_0 – vacuum permeability [H/m]
μ_r – relative permeability [-]
σ – material conductivity [S/m]

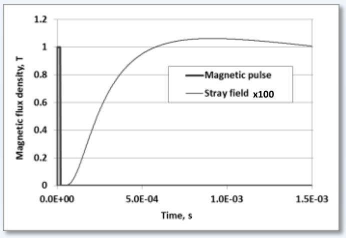
- High frequencies penetrate less
- High conductivity materials screen better
- Penetration in magnetic materials is smaller

Pulsed magnetic field penetration



Eddy current septum

Pulsed magnetic field through septum[15, 20, 27]



Stray field in time[20]
($d_s = 5$ mm, $\sigma = 5.8 \cdot 10^7$ S/m,
$\mu = 4\pi 10^{-7}$ H/m, $B_0 = 1$ T, $\tau = 20$ µs
and $\lambda_c = 5$ mm)

Time delay of stray field maximum t_m [s]

$$t_m = \frac{1}{2} {d_s}^2 \sigma \mu$$

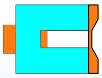
Maximum stray field B_m [T]

$$B_m = B_0 \frac{2\sqrt{2}\tau}{d_s \sigma \mu \lambda_c \sqrt{\pi e}}$$

Where:

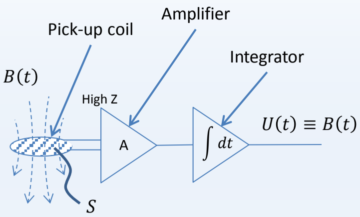
d_s – septum thickness [m]
σ – septum conductivity [S/m]
μ – septum permeability [H/m]
B_0 – amplitude of main field [T]
τ – pulse width [s]
λ_c – characteristic length of stray field decay [m]

Measurement of pulsed magnetic fields



Eddy current septum

Faraday's law of induction gives a practical way of measuring changing magnetic fields



If magnetic flux density does not change within the area of the pick-up coil the output voltage $U(t)$ is directly proportional to the magnetic flux density $B(t)$.

Low noise and **low offset** amplifier/integrator could give very high field sensitivity.

Modern scopes' built-in numeric integration function can be used for rough field measurements.

Faraday's law of induction

Electromotive force ε [V]

$$\varepsilon = -N\frac{d\Phi}{dt}$$

Magnetic flux Φ [Wb]

$$\Phi = \iint_S B dS$$

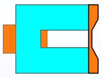
For constant magnetic flux density B in the area S, magnetic flux is simply:

$$\Phi(t) = B(t)S$$

Where:

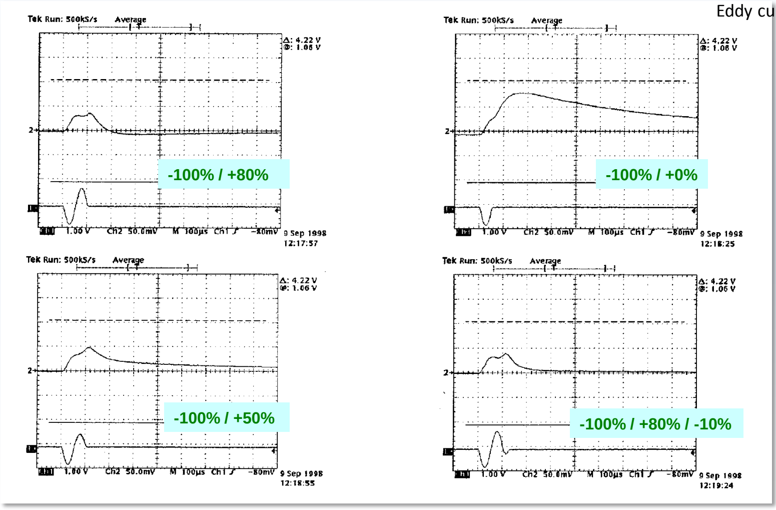
B – magnetic flux density [T]
t – time [s]
S – surface of the pick-up coil [m^2]
N – number of turns of the pick-up coil [-]

Magnetic pulse waveform form

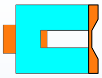


Eddy current septum

What is the best magnetic pulse waveform?

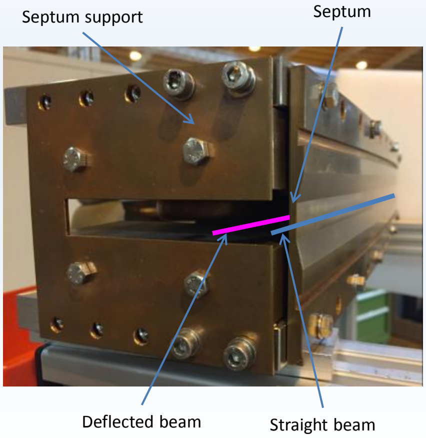


Example VII



Eddy current septum

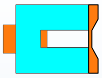
Construction and technical data of “in-vacuum” eddy current septum for SLS (PSI)[12]



- Vacuum: 10^{-7} mbar
- Field length : 600 mm
- Gap height: 6 mm
- Gap width: 20 mm
- Beam momentum: 2.4 GeV/c
- Deflection angle: 70 mrad
- Septum thickness: 2.5 mm
- Current: 4.3 kA (full sine 0.16 ms)
- Magnetic flux density: 0.9 T
- Eddy currents septum extends 50 mm on each side of the magnet to screen the fringe fields

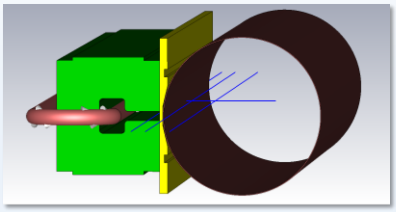
---

Example VII

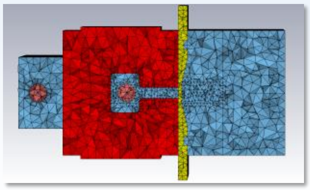


Eddy current septum

Magnetic field simulations



Magnetic model (Low frequency solver)

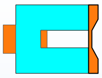


Meshing

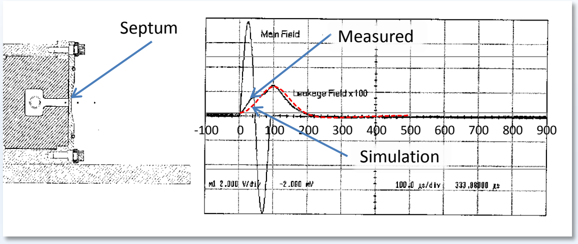
- 3D numerical magnetic simulations in time domain are computer resources demanding (**simulation could take days!**) ⚠
- With 3D models it is easy to have too many mesh points that are out of the computer configuartion capabilities or to make the simulation last too long
- Use vacuum “solids” to control mesh density
- Use benchmark examples / measurements to verify the results credibility

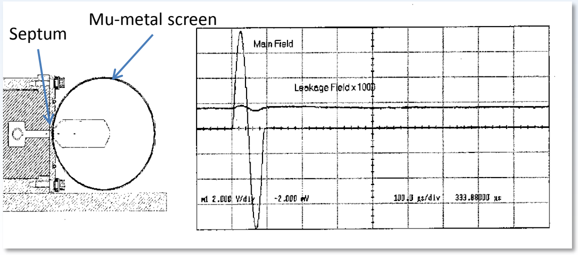
Example VII

Leakage field measurements with and without mu-metal screen[12]



Eddy current septum





- Leakage field is reduced below 0.01%
- Leakage field only varies by 2:1 over entire horizontal volume
- With mu-metal screen, integral leakage dominated by screen end effect (integral leakage <1e-6 is possible)

Things can go wrong

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

Courtesy of CERN, M. Hourican

Things can go wrong

Septum conductor fatigue failure

Courtesy of CERN, M. Hourican

Things can go wrong

Cooling water speed too high. Excessive cavitation and erosion.

Courtesy of CERN, M. Barnes

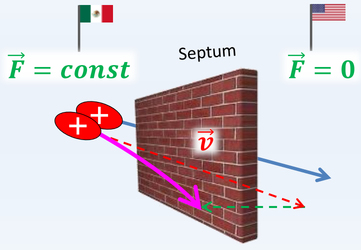
Practical considerations

- ☐ High mechanical and thermal stress – adequate support, damping and cooling
- ☐ The maximum leakage field of eddy current septum is delayed
- ☐ Good field region – pole geometry (shims etc.) to optimize the field homogeneity
- ☐ Leakage dipole field – magnetic shielding (make sure material doesn't saturate)
- ☐ Beam impedance – proper screening
- ☐ Cooling – turbulent flow removes heat more efficiently (erosion and vibration issues)
- ☐ Insulators degradation – use radiation hard isolation materials
- ☐ Alignment – remote positioning systems
- ☐ Good vacuum – bake-out capabilities, vacuum conductivity, NEG coatings
- ☐ Machine protection (system failure, operator mistakes)
- ☐ Avoid brazed joints in vacuum as much as possible
- ☐ Vacuum (cold) welding – use silver-plated bolts in steel threads
- ☐ Activation – maintenance limitations

What to remember

Septum is a ***wall****!*

… but a good one! :)



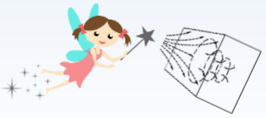
Electrostatic

Thin but weak!

Magnetic

Thick but strong!

Magnetic eddy current



Best choice if possible!

old greek dictum of wisdom:
if you are clever, you use magnetic fields in an accelerator wherever it is possible.
Dr. Bernhard Holzer

When possible choose…

… ***magnetic****!*

Acknowledgments

Special thanks to
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Special thanks to
Dr. Sladana Dordevic (PSI)
for helping with the field simulations

Thank you for your attention

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