Beam transfer systems at CERN’s accelerator complex.

Design, construction and operational considerations of normal conducting magnets and electrostatic deflectors in high vacuum and high radiation environments

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Lorentz force

Describes the interaction between charged particles and electromagnetic fields.

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

- \( F \) is the force vector;
- \( E \) is the electric field intensity (volt/metre);
- \( B \) is the magnetic flux density (tesla);
- \( q \) is the charge (coulomb);
- \( v \) is the particle velocity (metre/second);
- \( \times \) is the vector cross-product.

Conclusion: The vector cross-product shows that the magnetic component of the force does not change the particle energy, but only the trajectory. The electrical component acting transversely leads to a change of trajectory, and acting longitudinally leads to a change in kinetic energy. Its contribution to the change of particle energy does not depend on the particle velocity.
Right hand rule

Curl fingers as if rotating vector \( \mathbf{v} \) into vector \( \mathbf{B} \). 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.

\[
F = q(\mathbf{v} \times \mathbf{B})
\]

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

South magnetic pole

North magnetic pole
Electric component

Opposites attract!

Positive electrode

Negative electrode

\[ F = qE \]
Charged particles are kept in circular trajectories using dipole magnetic fields, which are synchronised with the accelerating (or decelerating) electric fields, in such a way, that for every increase of the particle energy, there is a corresponding increase of the bending magnetic field, such that the particle trajectory remains unchanged.
Each accelerator has a limited dynamic range;
A chain of accelerators is required in order to reach high energies;
Kicker – a fast-pulsed electromagnet giving a small initial deflection of the beam trajectory (a few mrad or less) into the high field region of the septum;

Septum – produces a magnetic field strong enough for the final deflection of the beam into the accelerator (injection), or the transfer line or fixed-target experiment (extraction), without perturbing the circulating beam.
Septum (pl. septa) is a partition separating two cavities or regions (in medicine, for example – the part between the nostrils). In a particle accelerator a septum is a device that separates two field regions:

<table>
<thead>
<tr>
<th>Region A</th>
<th>Region B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field free region</td>
<td>Region with homogenous field</td>
</tr>
<tr>
<td>$(E_A=0 \ &amp; \ B_A=0)$</td>
<td>$(E_B \neq 0 \ or \ B_B \neq 0)$</td>
</tr>
</tbody>
</table>

The important features of septa devices are the absence of field in one region (so that circulating beams are not perturbed), and the presence of a homogenous field in the other region (for the required deflection of the beam). The septum thickness should be as small as possible in order to reduce the strength of the highly complex kicker magnet.
Electrostatic septum

**Typical parameters:**
- Electrode length: 500 – 3000 mm;
- Variable gap width (d): 10 - 35 mm;
- Septum thickness: <=0.1 mm;
- Vacuum (10^{-9} to 10^{-12} mbar);
- Voltage: up to 300 kV;
- Electric field strength: 10 MV/m;
- Septum made of Mo foil or WRe wires;
- Electrode made of anodised aluminium, stainless steel or titanium for ultra-high vacuum;
- Bake-out up to 300 °C for achieving ultra-high vacuum up to 10^{-12} mbar;
Electrostatic septum

Electrode made of Peraluman® anodised with chromic acid

Foil tensioning system

Septum made of Mo foil, 0.1 mm thick
Electrostatic septum (SEH23 in PS)

- Infrared bake-out lamps
- Deflector
- Septum support acting as a Faraday’s cage for the circulating beam
Electrostatic septum (ZS in SPS)

- WRe wire septum
- Peraluman® cathode
Electrostatic septum (SEH10 in LEIR)

- High voltage feedthrough
- Vacuum vessel and flanges in 316LN stainless steel
- Remote displacement system for precise positioning of the device wrt the beam
Magnetic septum

C-shaped iron yoke

Septum conductor with high current density (up to 100 A/mm²)

Air gap/high-field region
Magnetic septum

DC powered (up to 10 kA).

Usually a multiturn coil to reduce the current.

The yoke and coil are made of two parts to allow “splitting” of the magnet for installation of the vacuum chamber.

Rarely under vacuum.
Magnetic septum (SMH61 in PS)

**Typical parameters:**
- Yoke length: 400 - 1200 mm;
- Air gap: 25 - 60 mm;
- Septum thickness: 6 - 20 mm;
- Installed outside vacuum;
- Laminated steel yoke;
- Water-cooled multi-turn coil (12 - 60 l/min);
- Rated current: 1 - 10 kA;
- Power supplied by controllable rectifier;
- Power consumption: 10 - 100 kW!
Septum vacuum chamber (SMH40 in LEIR)
Pulsed magnetic septum

- Pulsed with a half sine over 3 ms.
- Single turn coil to reduce self-inductance.
- Transformer between power converter and magnet.
- Installed under vacuum to reduce the effective septum thickness.
- Remote displacement system for precise positioning wrt the circulating beam.
- Large forces between conductors – require a special coil fixation and retention system to absorb vibrations and reduce fatigue.
Pulsed magnetic septum

Typical parameters
• Yoke length: 300 – 1200 mm;
• Air gap: 18 - 60 mm;
• Septum thickness: 3 - 20 mm;
• Vacuum levels (~10⁻⁹ mbar);
• Laminated steel yoke (0.35 - 1.5 mm);
• Water-cooled single-turn coil (1 - 80 l/min);
• Current (half sine): 7 - 40 kA;
• Powered by a capacitor discharge unit and a superposition of a 1ˢᵗ and 3ʳᵈ harmonic + active filters for increased waveform stability;

Infrared lamp for bakeout up to 200 °C
Pulsed magnetic septum (SMH42 in PS)

- Beryllium copper springs for absorbing vibrations
- Septum conductor with hard chrome plating for mechanical stability
- Silver-plated single-turn water-cooled coil
- Thermocouples
- Laminated yoke
Pulsed magnetic septum

- Insulation between return conductor and yoke of Kapton® (highly resistant to heat and radiation polyimide)

- The cooling channels are made of stainless steel pipes embedded in the bulk copper conductor

- Contact between spring and coil of Vespel® (Vacuum-compatible polyimide resistant to heat and radiation)

- Air gap
Pulsed magnetic septum

- Stainless steel cooling tubes to be embedded in the copper bulk
- 0.35 mm lamination for the magnetic yoke
- Septum conductor
- Machined grooves for the water cooling
Pulsed magnetic septum
Pulsed magnetic septum

Fully brazed coil before silver and copper plating
Pulsed magnetic septum (BESMH in PSB)
**“Lambertson” septum for LHC injection (MSI)**

1. The septum provides horizontal deflection towards the right;
2. The downstream kicker deflects vertically onto the central LHC orbit.
Protective absorbers/diluters

- Copper beam screen for the circulating beam
- Water cooling
- 3m long absorber made of carbon fibre and graphite in close proximity to the beam
Mechanical design
Electromagnetic design
Electromagnetic design
Thank You!

www.cern.ch
Extra slides – hydrodynamic tunnelling of the SPS beam into a copper target*

*HiRadMat experiment in SPS, photos courtesy F. Burkart
Extra slides – hydrodynamic tunnelling of the SPS beam into a copper target*

a)

b)

c)

*HiRadMat experiment in SPS, photos courtesy F. Burkart
Extra slides – hydrodynamic tunnelling of the SPS beam into a copper target*

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