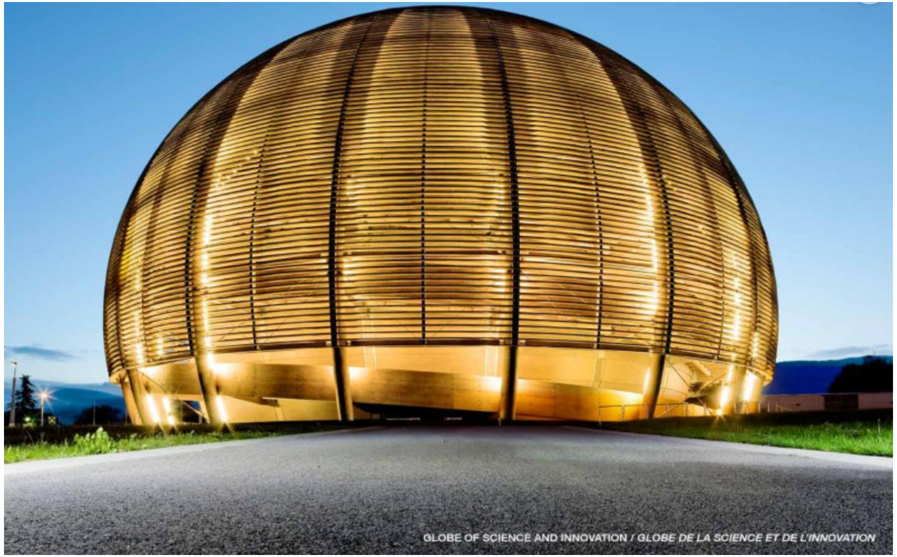
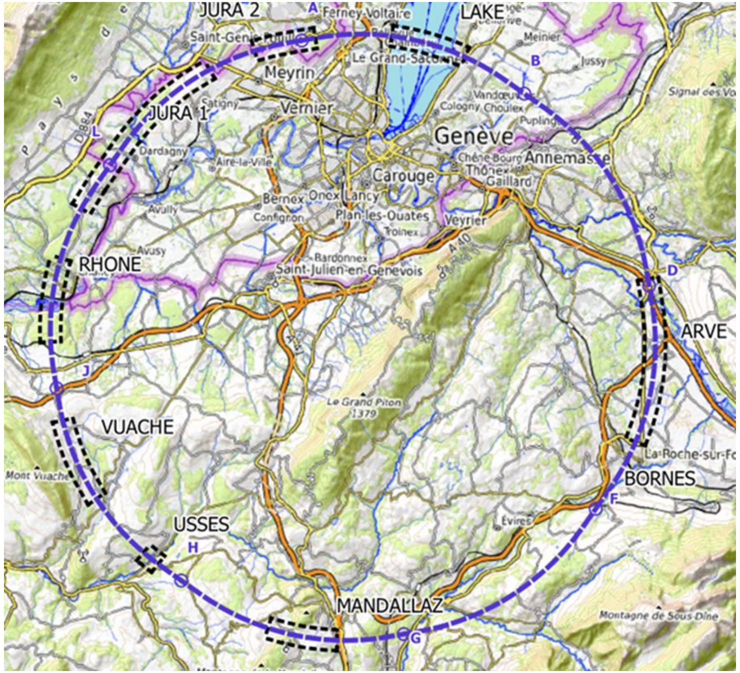
CERN

# FUTURE CIRCULAR COLLIDER

# Booster and Collider challenges for septa and separators



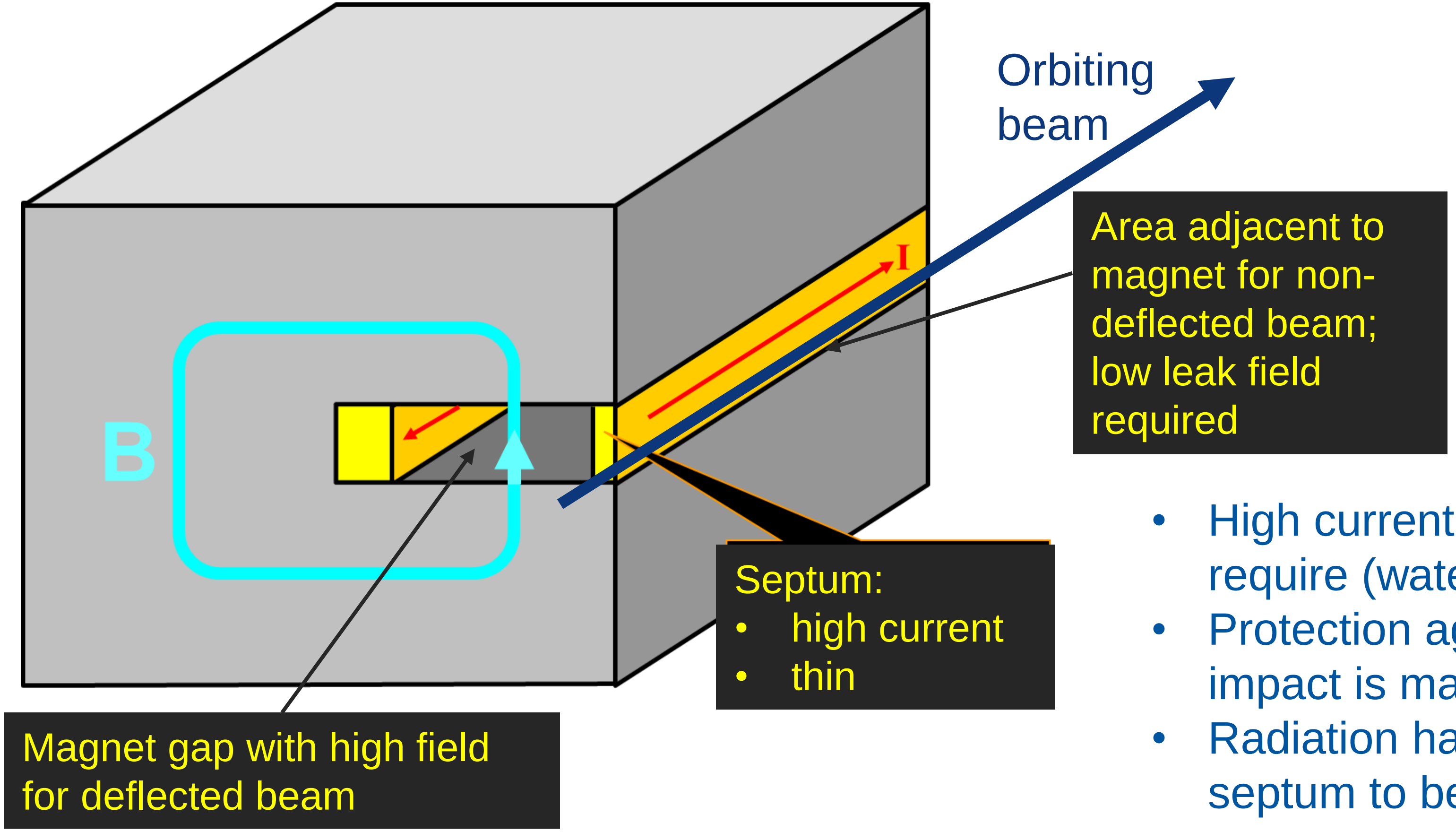

J. Borburgh, CERN, Geneva, Switzerland

with valuable input from W. Bartmann, B. Balhan, C. Bracco, C. Baud, Y. Dutheil, G. Favia, J. Plett, S. Yue

# Outline

- Introduction
- Booster septa
- Collider septa
- Collider EM separators
- Outlook and summary

# What is a septum and what are its main challenges for FCC?

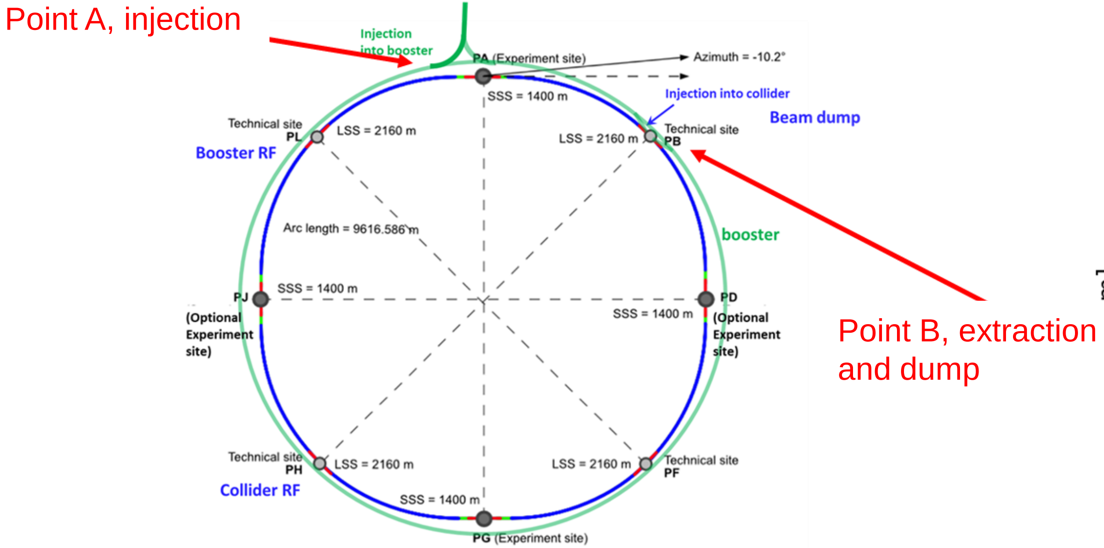



- High current densities require (water) cooling.
- Protection against beam impact is mandatory.
- Radiation hardness of septum to be assured.

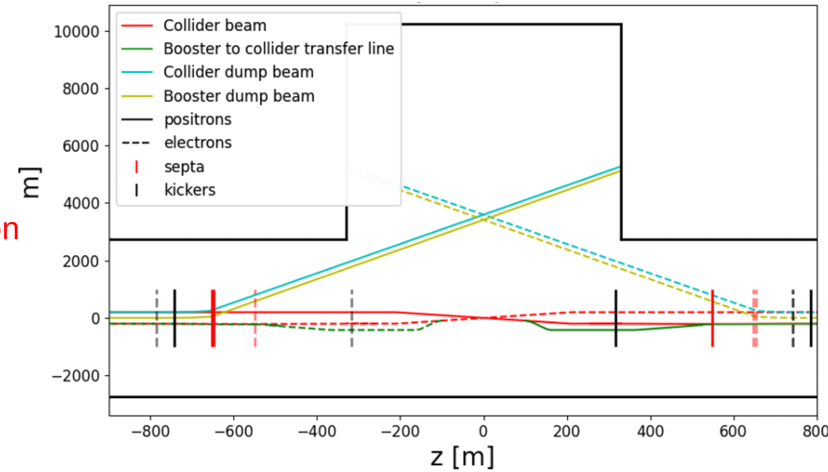
# Booster

See talks: Sen Yue, Tuesday
Wolfgang Bartmann, Thursday

- Injection into the Booster, will be done near point A of the FCC.
- The present baseline foresees injection will be from the top (vertical injection), using a kicker and septum magnets for each beam.
- For extraction towards the collider and towards the dump, septa magnets are located in point B.




Point B houses many booster and collider injection and extraction elements



# Booster, point A, injection septa

| Element | # elements | Allocated length [m] | Required length [m] | Baseline topology |
|---|---|---|---|---|
| e- injection septum | 2 | 6 | 5 | Eddy current septum, under vacuum |
| e+ injection septum | 2 | 6 | 5 | Eddy current septum, under vacuum |

For kicker requirements, see next talk by Giorgia Favia.

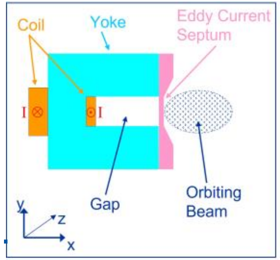
# Booster, point B, extraction elements

See talk Sen Yue, Tuesday

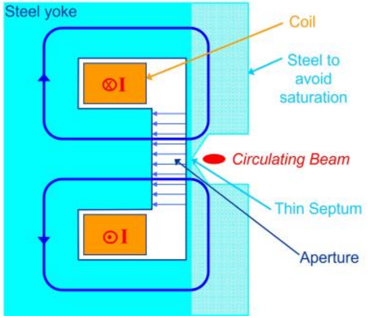
| Element | # elements | Allocated length [m] | Baseline topology |
|---|---|---|---|
| e+ dump septa | 5 | 9 | Slowly ramped DC septum, outside vacuum |
| e- extraction septa | 1 | 9 | Pulsed, outside vacuum septum |
| e+ extraction septa | 1 | 9 | Pulsed, outside vacuum septum |
| e- dump septa | 5 | 9 | Slowly ramped DC septum, outside vacuum |

# Booster injection septa

- For each mode, injection takes place at constant beam energy.
- More sustainable and robust solution: eddy current septa [1]. Each beam uses 2 septa magnets, reducing total power consumption < 1 kW.
  - Powering assumption: repetition rate of 100 Hz, half sine pulse width of < 300 µs.
  - Can draw upon existing CERN eddy current septa technology.
  - Outstanding main challenges:
    - **Power converter**: repetition rate and stability.
    - **Injection protection elements**: need masks upstream to protect against mis-steered beams.
    - **Orbiting beam shielding**: need beam impedance screen that also serves as magnetic screen.
    - Under vacuum, laminated magnet: **impact of vacuum requirements** on magnet.

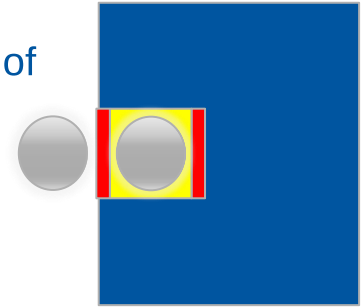



- Alternative to investigate:
  - Lambertson septum [2].
  - Requires a 2-plane injection (kicker horizontally, septum in the vertical pla
  - May yield a more robust and, possibly, a more sustainable solution.

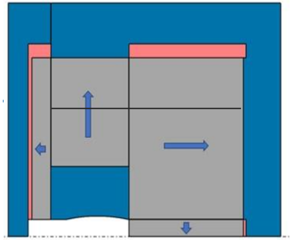


# Booster extraction septa

- For each mode, extraction takes place at constant energy.
- Pulsed outside vacuum septum with thin-walled vacuum chambers [3]:
  - Pulse length relatively long (5 ms half sine) to allow > 304 µs flat top
  - Should implement edge cooling for septum blade to improve robustness in case of beam impact on upstream diluter/mask.
  - Leak field requirements relaxed, in particular after the extraction.
  - To be verified:
    - If the **impact of the metal vacuum chambers on the field** homogeneity is acceptable.
    - **Diluter/mask requirements** for equipment protection mandatory.
    - **GFR requirements**, critical for beam

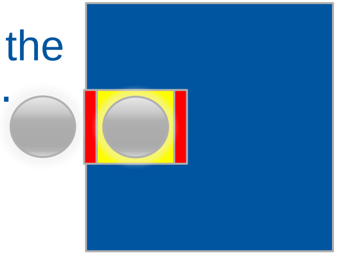


- Alternatively, a permanent-magnet (PM) [4] based solution will be investigated:
  - Power consumption reduction.
  - Significantly improves reliability, and availability w.r.t. machine protection.
  - A few topologies exist: need to verify if septum thickness requirement can be met.
  - Reduces civil engineering space requirements, due to absence of power converters.
  - Between FCC mode changes, the number of installed PM septa should be adjusted to obtain the required deflection angle.

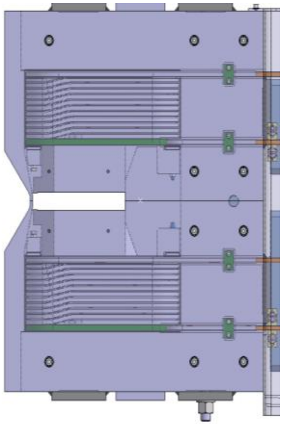


# Booster dump septa

- Leak field requirements more stringent than for extraction septa.
- Field homogeneity in Good Field Region (GFR) relaxed.
- The proposed topology is a slowly ramped DC septum, to be able to have the current corresponding to actual beam energy at any given moment in time.
- Baseline foresees an outside vacuum magnet,
  using a 1 mm thin vacuum chamber made of stainless steel or Inconel.
- To be verified:
  - If ramp rate is slow enough for the vacuum chamber to have negligible effect on the **field quality during the ramp**.
  - If the **presence of cooling water channels in septum** could be an issue in case of beam impact on upstream diluter/spoiler.

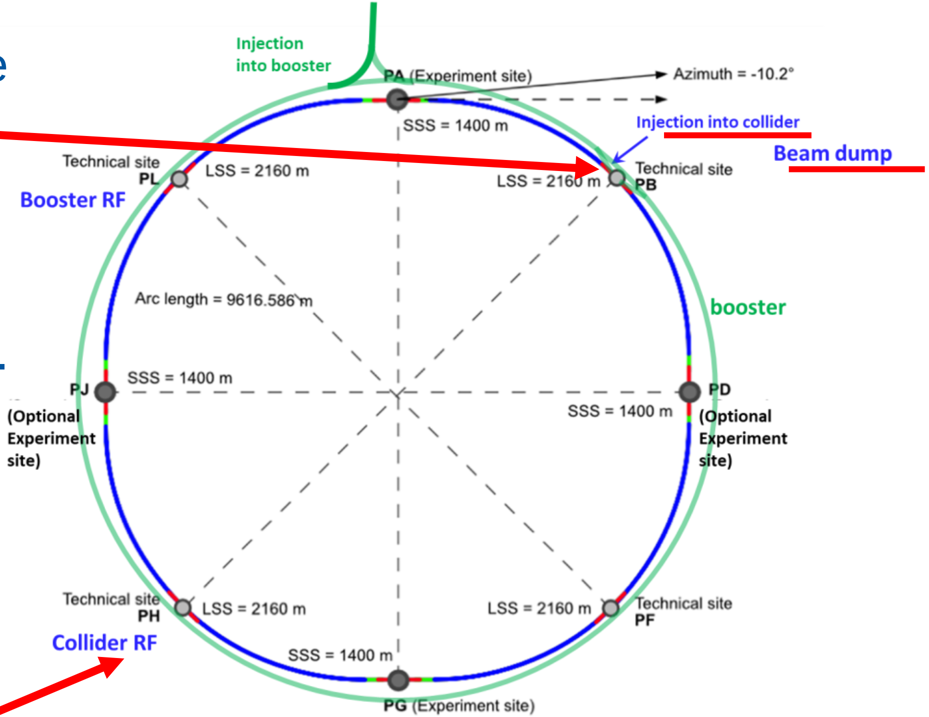


- Alternative: Low power DC septum [5] topology still to be investigated:
- Will be more robust w.r.t. equipment protection
- To be verified:
  - If it can be ramped sufficiently fast to follow energy ramp.
  - If required septum thickness can be achieved.
  - Integration: significantly larger cross section outside vacuum DC septum.



# Collider

- Injection into the Collider, will be done at point B of the FCC.
- Injection is done in the horizontal plane using a septum for each beam, and a common kicker for both beams.
- The horizontal (in-plane) extraction towards the dump, kickers and septa are also located in point B.
- The RF is located in point H, where EM separators will be needed.



# Collider injection and extraction elements

See talk Sen Yue, Tuesday

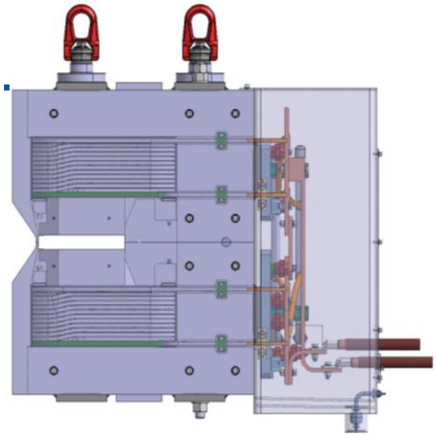
| Element | # elements | Allocated length [m] | Baseline topology |
|---|---|---|---|
| e+ dump septa | 4 | 8 | Outside vacuum, Low power DC septum |
| e- thin injection septum | 1 | 1.2 | Under vacuum, direct drive septum |
| e- thick injection septa | 5 | 6 | Under vacuum, direct drive septum |
| e+ thick injection septa | 5 | 6 | Under vacuum, direct drive septum |
| e+ thin injection septum | 1 | 1.2 | Under vacuum, direct drive septum |
| e- dump septa | 4 | 8 | Outside vacuum, Low power DC septum |

# Collider injection septa

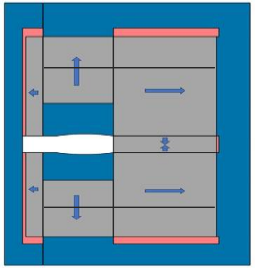
- Used for top-up injection. See talk Yann Dutheil, Tuesday
- Main challenges w.r.t. Booster extraction septa:
  - required septum thickness is very thin: 2.8 mm
  - Leak field needs to be lower, due to top-up injection scheme
- Baseline topology proposed is a pulsed direct drive magnetic septum, under vacuum.
- Presently no remote positioning system is planned, but it may be possible to adjust the septum position between FCC mode changes.
- To be verified:
  - **Vacuum requirements**
  - **GFR requirements**
  - Impact on design of **beam impedance requirements**
  - **Equipment protection** from mis-steered beams

# Collider dump septa

- Collider dump septa run at constant energy in each mode.
- Leak field requirements still to be defined, but due to the DC operation, these are less critical.
- Field homogeneity in Good Field Region (GFR) relaxed.



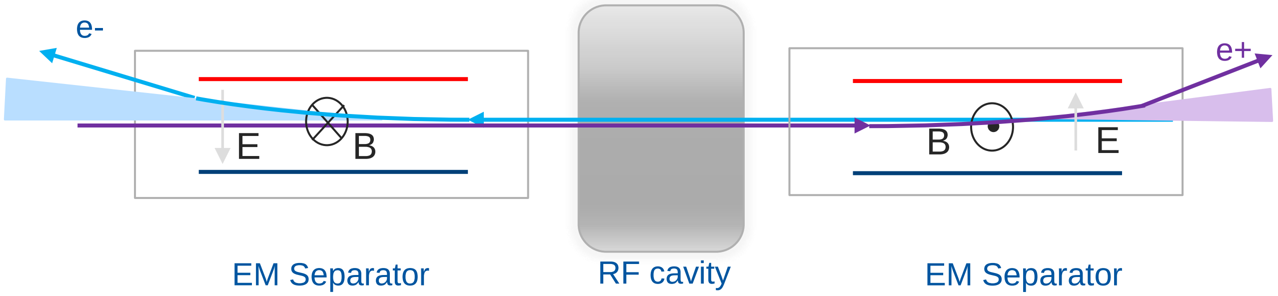
The proposed Low Power septum topology will allow to monitor the current sufficiently in time for beam / equipment protection.

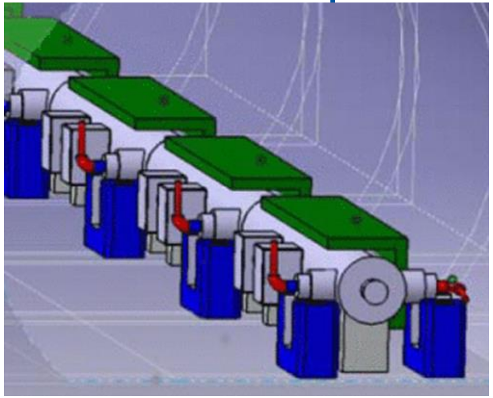


Still to investigate the possibility to use a Permanent Magnet topology, to improve availability, reliability and sustainability.

# Collider: Electric-Magnetic (EM) separator

- Installed upstream and downstream of RF section in ttbar mode in point H.
- Used to assure both beams pass through centre of RF cavities, while avoiding synchrotron light hits the cavities.
- Magnetic field is cancelled by the electric field before entering the cavity, while adding up for particles the cavities.
- The 2 families of 10 EM separators [6] will be powered in series (magnet) and parallel (separator), limiting the power converter footprint.

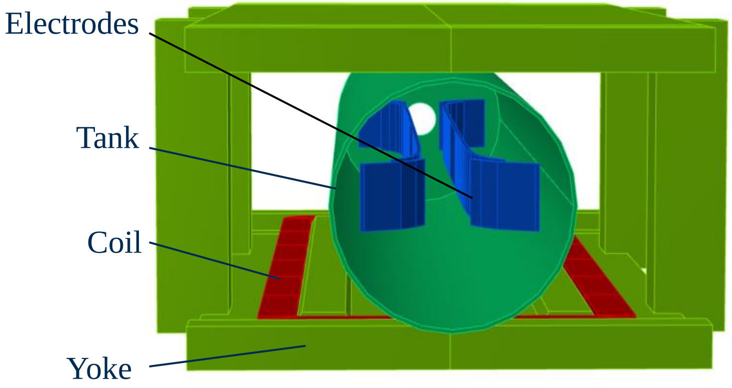


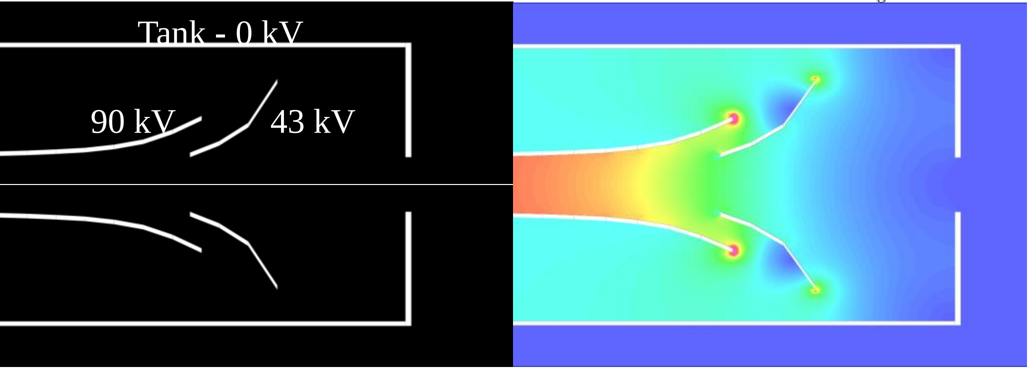
# EM Separator challenges

- B and E **longitudinal field matching**; the acceptable deviation still to be defined.
- **Beam impedance** preservation and management of image currents
- **Heat deposition** by the beams **on** the HV **electrodes**.
- **Synchrotron light on** the HV **electrodes** → Definition of requirements for dedicated masks to be clarified.

# EM Separator Simulations



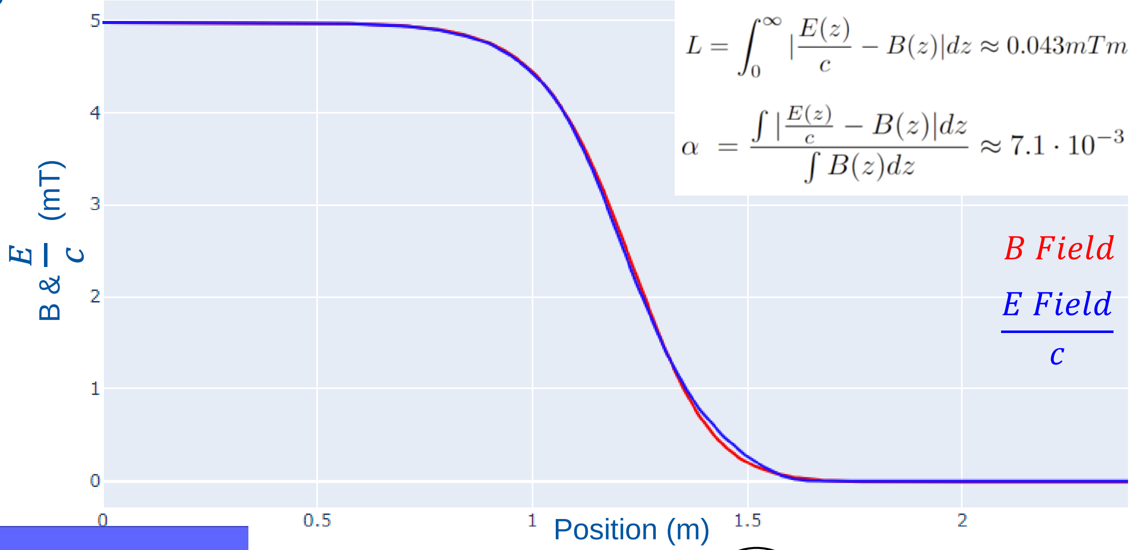

EM Separator

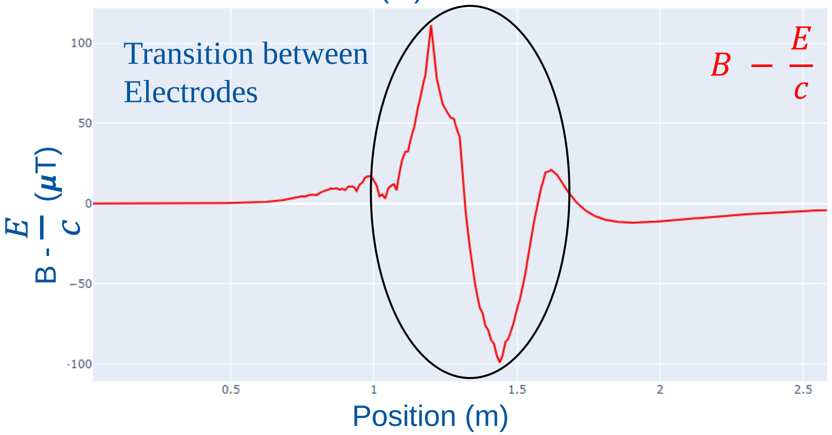



2D longitudinal cross section of Electrodes

Magnet yoke 2.8m, vacuum tank 3.2 m.

## Longitudinal E and B field Matching



# Outlook

For feasibility study, the following items need still to be studied:

- Confirm septa topology choice after evaluation of equipment protection equipment feasibility and performance.
- Impact of beam impedance requirements on septa design.
- Feasibility of Low Power septum for Booster dump extraction.
- Feasibility of PM septa for Booster extraction and collider dump.
- In depth EM separator feasibility, w.r.t. E and B field matching as well as spark rate requirements.

# Conclusion

- Some proposed septum topologies proposed may be at the forefront of present technology, but all baseline proposals are sufficiently mature to be deployed for FCC-ee.
- Devices still needing significant development are the Electro-Magnetic separator and the Permanent Magnet septa.
- Integration of the power converters and control electronics appears feasible, but for the fast pulsed devices a max. cable length (~ 100 m) between power converter and magnet needs to be respected.
- The allocated space in the lattice is sufficient for the presented hardware baseline designs.
- The equipment protection (masks, spoilers etc.) will require detailed study and (additional) space in the lattice upstream of the septa.

# References


1. T. Helseth et al., “FEASIBILITY STUDY FOR THE NOVEL CERN PS FAST EXTRACTION SEPTUM”, IPAC 2021
2. S. Bidon et al., “STEEL SEPTUM MAGNETS FOR THE  LHC BEAM INJECTION AND EXTRACTION”, EPAC 2002
3. J. Borburgh et al., “Design and construction of the LEIR extraction septum”, MT19, Genova, Italy, 2006
4. T. Kawakubo et al., “ Permanent Magnet generating high and variable septum magnetic field and its deterioration by radiation”, EPAC 2004
5. H. Yamaguchi et al., “DC SEPTUM MAGNET WITH LOW CURRENT DENSITY FOR THE SYNCHROTRON LIGHT SOURCE”, IPAC 2023
6. O. Napoli et al., “Technical Challenges for the Head-On Collisions and Extraction  at the ILC”, PAC2007, Albuquerque (USA)

# Back-up slides

# Booster injection septum

- Under vacuum magnets.
- Fixed position of septum blade to be able to reach alignment tolerances.

**Table 2** Principal parameters of Booster injection electromagnetic eddy current septa

| Parameter | value | unit |
|---|---|---|
| Max physical length per unit | 3000 | mm |
| Particle energy | 20 | GeV |
| Deflection angle | 4.5 | mRad |
| Integrated magnetic field | 0.3 | T.m |
| Beam size (15 $\sigma$ and 300 m beta function) | 4.5 | mm |
| Septum position w.r.t. orbiting beam centre | 12 | mm |
| Equivalent magnetic length | 2000 | mm |
| Beam stay clear area (H x V) | 15 x 15 | mm |
| Apparent septum thickness | 10 | mm |
| Gap height ($\perp$ to deflection) | 16 | mm |
| Gap width (in plane of deflection) | 26 | mm |
| Pulse length (full sine) | 500 | $\mu$s |
| Repetition rate | 200 | Hz |
| Lamination thickness | 0.35 | mm |
| Relative integrated leak field | $\leq 10^{-3}$ | |
| GFR (H x V) | tbd | mm |
| GFR precision | tbd | % |
| Number of coil turns | 1 | |
| Nominal magnet current (peak) | 1.95 | kA |
| RMS current | 604 | A |
| Nominal voltage on magnet | 61 | V |
| Electrical resistance magnet | 0.75 | $m\Omega$ |
| Electrical inductance magnet | 2.4 | $\mu H$ |
| Relative flat top stability | $5.10^{-4}$ | |
| Power dissipation / unit | 130 | W |
| Water cooling flow rate (dP 5 bar) driven coil | 6 | l/min |
| Static vacuum | $\leq 10^{-9}$ (tbc.) | mbar |
| Number of units (electrons / positron) | 2/2 | |

# Booster extraction septum

- Outside vacuum magnets.

**Table 3** Principal parameters of Booster Extraction pulsed outside vacuum septum

| Parameter | value | unit |
|---|---|---|
| Max physical length per unit | 3000 | mm |
| Particle energy | 182.5 | GeV |
| Deflection angle | 2 | mrad |
| Integrated magnetic field | 0.811 | T.m |
| Beam size (15 $\sigma$ and 300 m beta function) | xyz | mm |
| Septum position w.r.t. orbiting beam centre | x | mm |
| Equivalent magnetic length | 1500 | mm |
| Beam stay clear area (H x V) | 10 x 10 | mm |
| Apparent septum thickness | 10 | mm |
| Septum conductor thickness | 6 | mm |
| Gap height ($\perp$ to deflection) | 14 | mm |
| Gap width (in plane of deflection) | 20 | mm |
| Pulse length (full sine) | 5 | ms |
| Repetition rate | 0.03 | Hz |
| Lamination thickness | 0.35 | mm |
| Relative integrated leak field | $\leq 10^{-3}$ | |
| GFR (H x V) | tbd | mm |
| GFR precision | tbd | % |
| Number of coil turns | 1 | |
| Nominal magnet current (peak) | 9.1 | kA |
| Electrical resistance magnet | 0.7 | $m\Omega$ |
| Electrical inductance magnet | 7.7 | $\mu H$ |
| Relative flat top stability | tbc | |
| Power dissipation / unit | 10 | W |
| Number of units (electrons / positron) | 1/1 | |

# Booster dump septa

- Outside vacuum magnet.
- Fixed position of septum blade to be able to reach alignment tolerances.
- High power consumption, but manageable due to repetitive cycling of the magnet (and accelerator).
- Energy overshoot in Z mode not yet taken into account in table 4.

**Table 4** Principal parameters of Booster dump septa

| Parameter | Z mode | t tbar mode | |
|---|---|---|---|
| Particle energy | 45.5 | 182.5 | GeV |
| Total max physical length | 20 | | m |
| Proposed physical length per magnet | 1.8 | | m |
| Equivalent magnetic length per magnet | 1.5 | | m |
| Apparent septum thickness | 25 | | mm |
| Septum conductor width | 10 | | mm |
| Magnetic screen thickness | 1 | | mm |
| Gap height (⊥ to deflection) | 20 | | mm |
| Gap width (in plane of deflection) | 23 | | mm |
| Deflection angle per magnet | 1.7 | | mrad |
| Number of coil turns | 2 | | |
| Magnet inductance | 11 | | $\mu H$ |
| Water cooling flow rate (dP = 8 bar) | 14 | | l/m |
| Beam stay clear area (H x V) | 20 × 10 | | mm |
| Normalised integrated leak field | $10^{-3}$ | | |
| GFR (H x V) | tbd | | |
| GFR precision | 0.5 | | % |
| Integrated magnetic field | 0.30 | 1.22 | T.m |
| Rise/Fall time | 0.3 | 2.4 | s |
| Flat top length | 0.5 | 1 | s |
| Flat bottom length | 2.2 | 30 | s |
| Peak current | 1.4 | 5.5 | kA |
| Flat bottom current | 715 | 0 | A |
| RMS current | 4 | kA | |
| Repetition rate | 0.3 | Hz | |
| Peak current | 1.6 | 6.5 | kA |
| RMS current | 1.2 | 3.9 | kA |
| Power dissipation / unit | 1.2 | 16.1 | kW |
| Number of units (electrons / positrons) | 3/3 | | |

# Collider injection septa

- Present design foreseen conventional direct drive septum.
- Injection protection equipment (diluter) mandatory.

**Table 5** Principal parameters of Collider injection electromagnetic septa

| Parameter | thin | thick | unit |
|---|---|---|---|
| Particle energy | 45 - 182.5 | | GeV |
| Total available physical space on beam line | 3000 | 7000 | mm |
| Proposed physical length per magnet | 1200 | 1200 | mm |
| Deflection angle per magnet | 0.1 | 0.2 | mrad |
| Integrated magnetic field | 0.061 | 0.122 | T.m |
| Septum position w.r.t. orbiting beam centre | x | x | mm |
| Equivalent magnetic length | 1000 | 1000 | mm |
| Beam stay clear area (H x V) | $20 \times 10$ | $20 \times 10$ | mm |
| Apparent septum thickness | 2.8 | 10 | mm |
| Septum conductor width | 2 | 9 | mm |
| Magnetic screen thickness | 0.5 | 0.5 | mm |
| Gap height ($\perp$ to deflection) | 15 | 15 | mm |
| Gap width (in plane of deflection) | 21 | 23 | mm |
| Flat top length | $\geq 300$ | $\geq 300$ | $\mu s$ |
| Repetition rate | 0.3 | 0.3 | Hz |
| Pulse width | 5 | 5 | ms |
| Relative integrated leak field | $10^{-2}$ | $10^{-3}$ | |
| GFR (H x V) | tbd | tbd | mm |
| GFR precision | 0.5 | 0.5 | % |
| Nominal magnet current | 0.74 | 1.5 | kA |
| Number of coil turns | 1 | 1 | |
| Magnet inductance | 2.2 | 3.1 | $\mu H$ |
| Power dissipation / unit | 5 | 5 | W |
| Water cooling flow rate (dP = 5 bar) | 1 | $\geq 1$ | l/min |
| number of units (electrons / positron) | 1/1 | 5/5 | |

# Collider dump septa

- Low current density DC septum:
  - Large coils
  - Low power dissipation
  - Large device cross section
  - Large weight

**Table 6** Principal parameters of collider dump septa

| Parameter | value | unit |
|---|---|---|
| Max physical length in total on beam line | 20 | m |
| Particle energy | 45.5 - 182.5 | GeV |
| Physical length per unit | 2 | m |
| Deflection angle | 2.5 | mrad |
| Integrated magnetic field | 1.22 | T.m |
| Beam stay clear area (H x V) | $20 \times 10$ | mm |
| Equivalent magnetic length | 1800 | mm |
| Apparent septum thickness | 29 | mm |
| Gap height ($\perp$ to deflection) | 20 | mm |
| Gap width (in plane of deflection) | 26 | mm |
| Relative integrated leak field | $\leq 10^{-3}$ | |
| GFR (H x V) | tbd | mm |
| GFR precision | tbd | % |
| Number of coil turns | 72 | |
| Nominal magnet current | 160 | A, DC |
| Power dissipation / unit | 1 | kW |
| Water cooling flow rate (dP 5 bar) driven coil | tbd | l/min |
| Number of units (electrons / positron) | 2/2 | |

# E-M Separator

- Concept design parameters in table 6.
- Matching of E and B field will be done using Machine Learning; collaboration being set up.
- Integration in collider still pre-mature, due to uncertainty of device dimensions.

**Table 7** Principal parameters of each E-M separator module

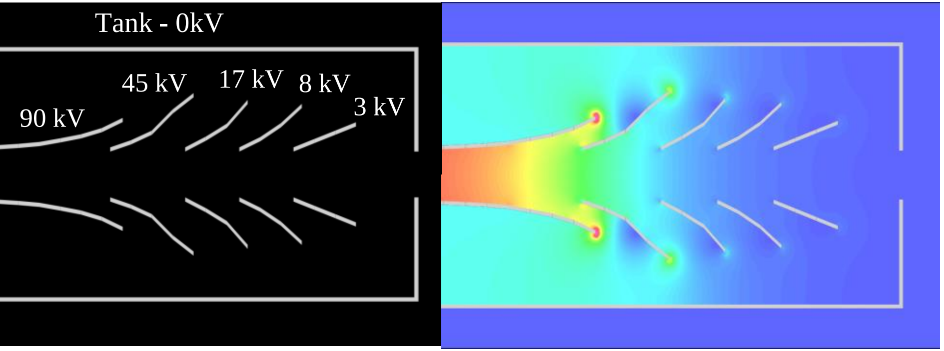
| Parameter | Value | unit |
|---|---|---|
| Active length | 2500 | mm |
| Particle energy | 182.5 | GeV |
| Deflection angle | 40 | $\mu$ rad |
| Beam acceptance (entry, exit flanges) | 60 | mm |
| GFR (H x V) | X x Y | mm |
| GFR precision | tbc | % |
| E and B profile overlap error | tbc | % |
| Magnetic field | 4.9 | mT |
| Electric field | 1.46 | MV/m |
| Electrode aperture | $\pm$ 60 | mm |
| Magnetic gap height | 450 | mm |
| Potential difference | $\pm$ 87.6 | kV |
| Magnet current | 87 | A |
| Number of coils | 2 | |
| Number of turns per coil | 10 | |
| Electrical resistance at the magnet terminals | 27 | $m\Omega$ |
| Total cooling water flow (dP 6 bar) | 2.3 | l/min. |
| Power dissipation | 204 | W |
| Good field region (x) | $\pm$ 15 | mm |
| Good field region (y) | $\pm$ 10 | mm |
| # of families x # units | 2 x 10 | |

# EM Separator - 18 Electrodes

Version 1

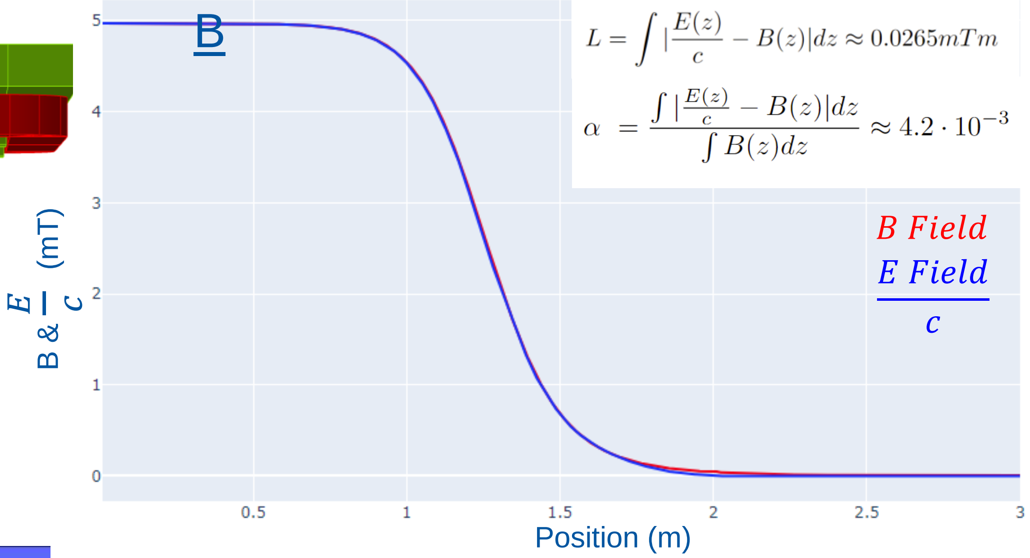
Version 2

This version of the dipole magnet (Version 2) has a magnetic field that decays more slowly along the longitudinal axis. Therefore, more electrodes are needed to match this longitudinal decay – but this also allows for better accuracy




2D longitudinal cross section of Electrodes

## Longitudinal Matching of E and B




$$L = \int \left|\frac{E(z)}{c} - B(z)\right| dz \approx 0.0265 mTm$$

$$\alpha = \frac{\int \left|\frac{E(z)}{c} - B(z)\right| dz}{\int B(z) dz} \approx 4.2 \cdot 10^{-3}$$