Principals of fast injection and extraction

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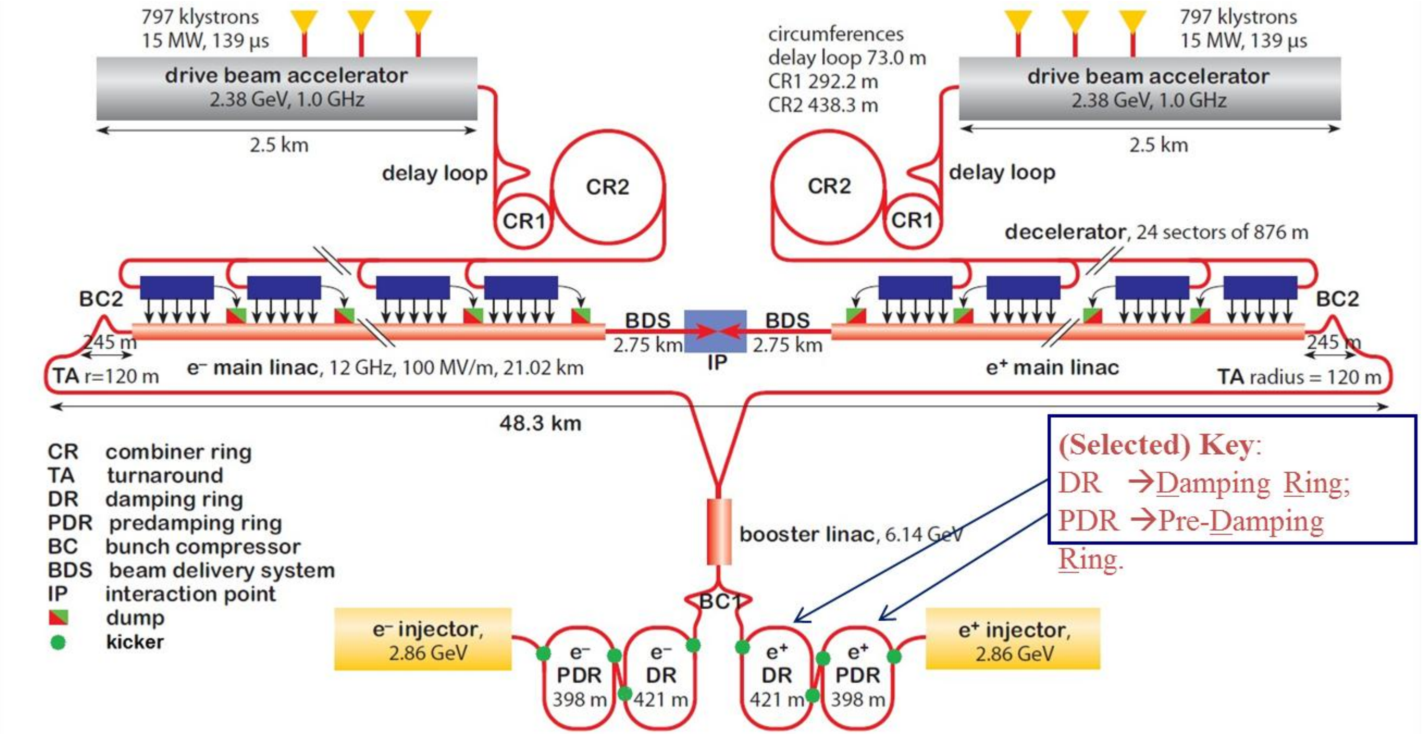
Why do we need injection and extraction systems?

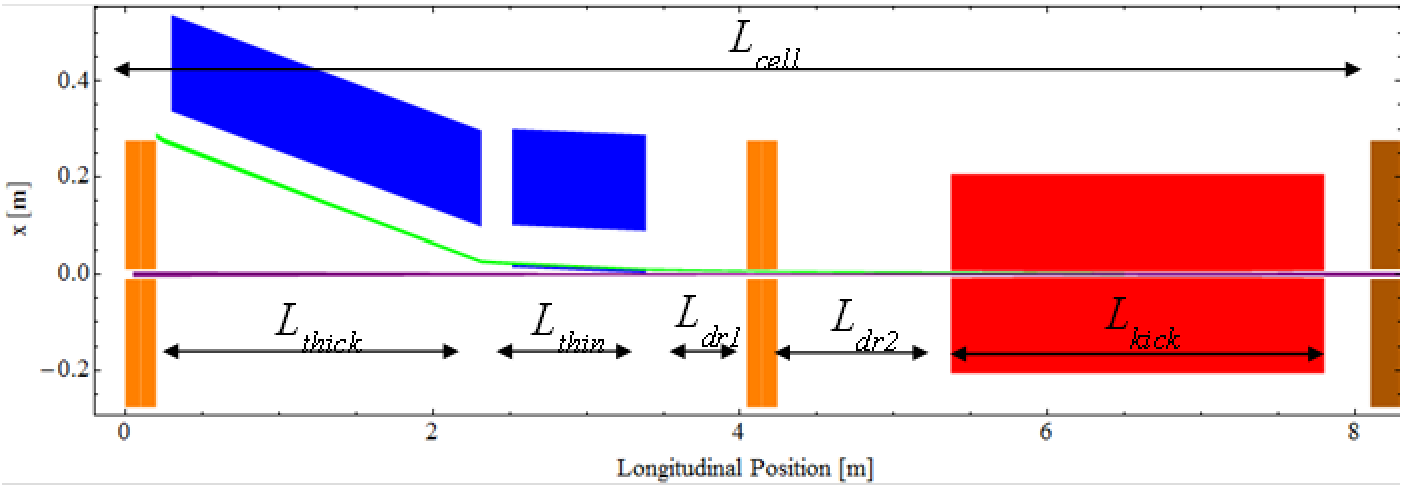
- All modern accelerators consist of multiple stages
  - Particle source
  - Linac
  - Damping/storage rings
  - …
- Need to get beam from one stage to the next
  - Injection and extraction systems
  - Beam transported along beam transfer lines

Example: CLIC main beam



Each green dot represents the location of an injection or extraction system for the CLIC main beam line.

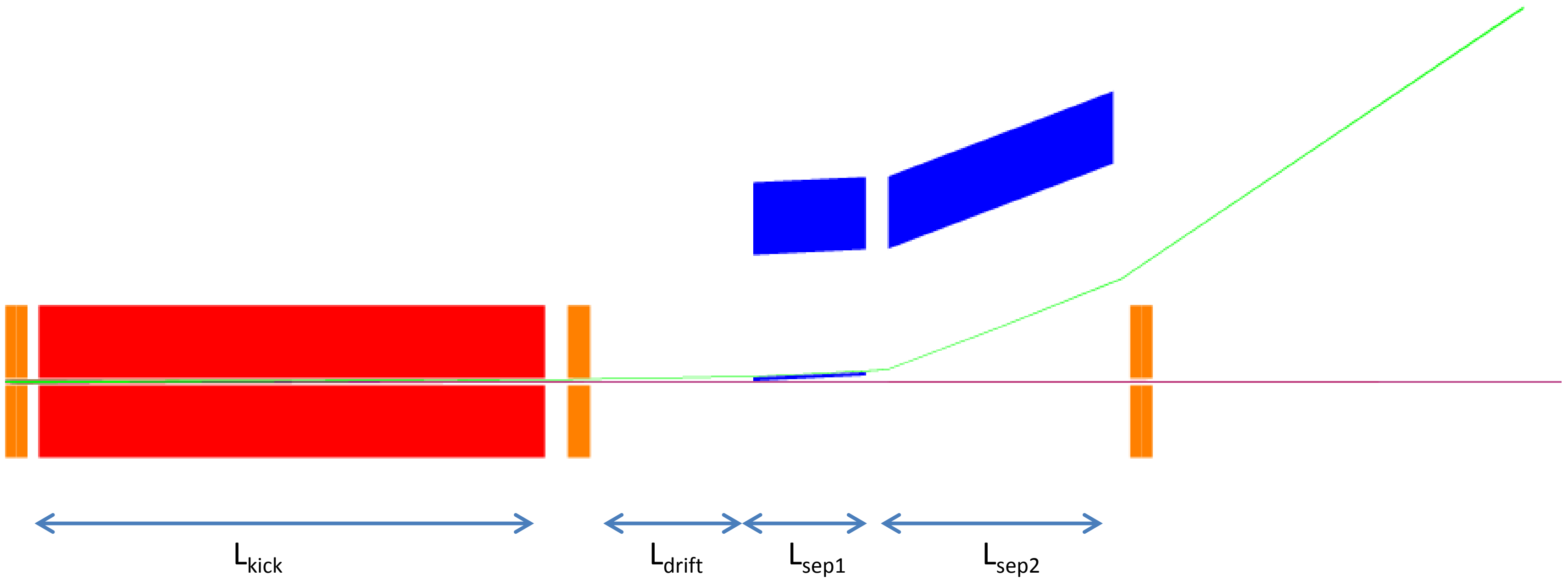
Fundamental principal: Injection



Injected beam (green) travels along the injection transfer line.
Septum magnets (blue) are used to reduce the angle of the injected beam.
Defocussing quadrupole (middle) further reduces the angle of the beam.
The kicker (red) does the final change to the injected beam angle.

At the end of the kicker the position and angle of the injected beam are the same as for the stored beam (purple).

Fundamental principal: Extraction



Extracted beam (green) is deflected off the nominal orbit by the kicker (red).
Defocussing quadrupole (middle) increases beam deflection.
Septum magnets (blue) give large deflection to the extracted beam.

Extracted beam is then transported along the extraction beam transfer line to the next stage of the machine.

Kicker and septum magnets

- Kickers
  - Can be switched on and off very fast
    - < 1 revolution of damping ring
  - Can only deliver relatively small deflection angles
- Septum magnets
  - Very low magnetic field observed by stored beam
  - High magnetic field observed by extracted beam
  - Can deliver large deflection angles
  - Very slow response times
    - Typically operated in DC mode or < ~100Hz
- Kicker and septum magnets don't affect stored beam
  - (to 1st order…)

Design of injection and extraction systems [1]

- Injection
  - Reflect order of elements and treat as extraction
    - Injection beam parameters not yet known
  - Injected beam must match stored beam
    - Prevents beam instability
- Injection and extraction
  - Systems must be optimised over a large number of parameters…
  - Aperture requirements are typically for a 5σ beam (+ errors)

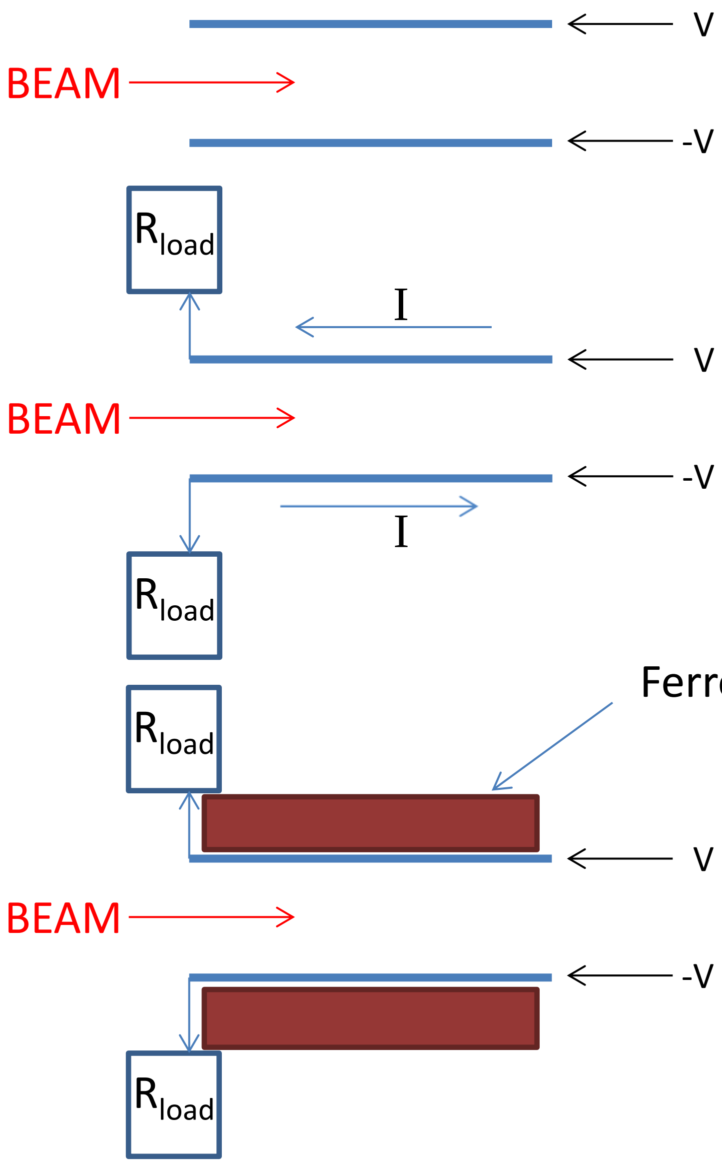
Design of injection and extraction systems [2]

- Local constraints
  - ≤ ½(kicker aperture) @ end of kicker
  - ≤ ½(quad aperture) @ defocussing quad
  - ≥ thin septum thickness @ thin septum
  - ≥ thick septum thickness @ thick septum
  - ≥ outer quadrupole radius @ final quad
  - β_x, β_y, α_x, α_y, D_x matched @ start of cell
  - β_x, β_y, α_x, α_y, D_x matched @ end of cell

Design of injection and extraction systems [3]

- Global constraints
  - Horizontal and vertical tunes matched
  - Chromaticity matched
  - Rematch optics in damping ring
    - Changes when matching tunes
- Physical constraints
  - Injection and extraction cells must be symmetrical
    - Kickers and septum magnets need to fit in both cells
  - Minimise cell length
    - Minimises beam instability through collective effects

Types of kicker



Electrostatic kicker

- Each strip pulsed with equal and opposite charge
- No termination so no current flow

Only electric field

Electromagnetic kicker

- Each strip pulsed with equal and opposite charge
- Terminated to ground, so current flow

Electric and magnetic fields

Ferrite loaded kicker

- Same as electromagnetic kicker but surrounded by ferrous material (e.g. steel)
- Produces much stronger magnetic field

Types of kicker: Electrostatic stripline

- Each stripline is charged to equal and opposite potentials
  - No termination at other end of kicker; hence electrostatic
  - Particles accelerated transversely over potential gradient:

Initial momentum

$$P_i = \begin{pmatrix} 0 \\ 0 \\ p_z \end{pmatrix}$$

Final momentum

$$P_f = \begin{pmatrix} p_{kick} \\ 0 \\ p_z \end{pmatrix}$$

$$F = \frac{dp}{dt} = \mathrm{qE} = -\mathrm{q}\frac{dV}{dx}$$

$$\therefore p_{kick} = -q\frac{V\Delta t}{d}$$

$$\Delta t = \frac{L_{kick}}{\beta c}$$

For a static homogeneous field

$$\therefore P_f = \begin{pmatrix} -\dfrac{qVL_{kick}}{d\beta c} \\ 0 \\ p_z \end{pmatrix}$$

$$\theta_{kick} = \tan^{-1}\left(\frac{qVL_{kick}}{d\beta p_z c}\right)$$

Types of kicker: Electromagnetic stripline [1]

- Each stripline is charged to equal and opposite potentials
  - Charged from DOWNSTREAM end of kicker
    - Otherwise electric and magnetic components of kick cancel each other!
  - Termination resistors at upstream end of each stripline

Electric component is same as before
Magnetic field perpendicular to electric field and particle momentum

Let's consider the kick in the rest frame of the particles…
Lorentz transformations of an electromagnetic field:

$$\overline{E'} = \gamma\left(\overline{E} - \overline{\beta} \times \overline{B}\right) - \frac{\gamma^2}{\gamma + 1}\overline{\beta}\left(\overline{\beta} \cdot \overline{E}\right) = \gamma\left(\overline{E} - \overline{\beta} \times \overline{B}\right)$$

$$\overline{B'} = \gamma\left(\overline{B} + \overline{\beta} \times \overline{E}\right) - \frac{\gamma^2}{\gamma + 1}\overline{\beta}\left(\overline{\beta} \cdot \overline{B}\right) = \gamma\left(\overline{B} + \overline{\beta} \times \overline{E}\right)$$

$$\overline{E} = \begin{pmatrix} E \\ 0 \\ 0 \end{pmatrix} \qquad \overline{B} = \begin{pmatrix} 0 \\ B \\ 0 \end{pmatrix} \qquad \overline{\beta} = \begin{pmatrix} 0 \\ 0 \\ \beta \end{pmatrix}$$

Types of kicker: Electromagnetic stripline [2]

$$\overline{E'} = \gamma \begin{pmatrix} E + \beta B \\ 0 \\ 0 \end{pmatrix} \qquad \overline{B'} = \gamma \begin{pmatrix} 0 \\ B - \beta E \\ 0 \end{pmatrix}$$

$$F' = q\left[\overline{E'} + \overline{v} \times \overline{B'}\right] = \frac{p_{kick}}{\Delta t'}$$

$$\Delta t' = \frac{\Delta t}{\gamma} = \frac{L_{kick}}{\gamma \beta c}$$

$$F' = \gamma q (1 + \beta^2) E$$

$$\theta_{kick} = \tan^{-1}\left((1 + \beta^2) \frac{qVL_{kick}}{d\beta pc} \right)$$

$\theta_B \approx \beta^2 \theta_E$ (for small kicks)

In ultra-relativistic limit (β=1), it is clear that the electric and magnetic kicks are equal.

This kicker design can deliver up to twice the kick as an electrostatic kicker for the same voltage and design.

However it is

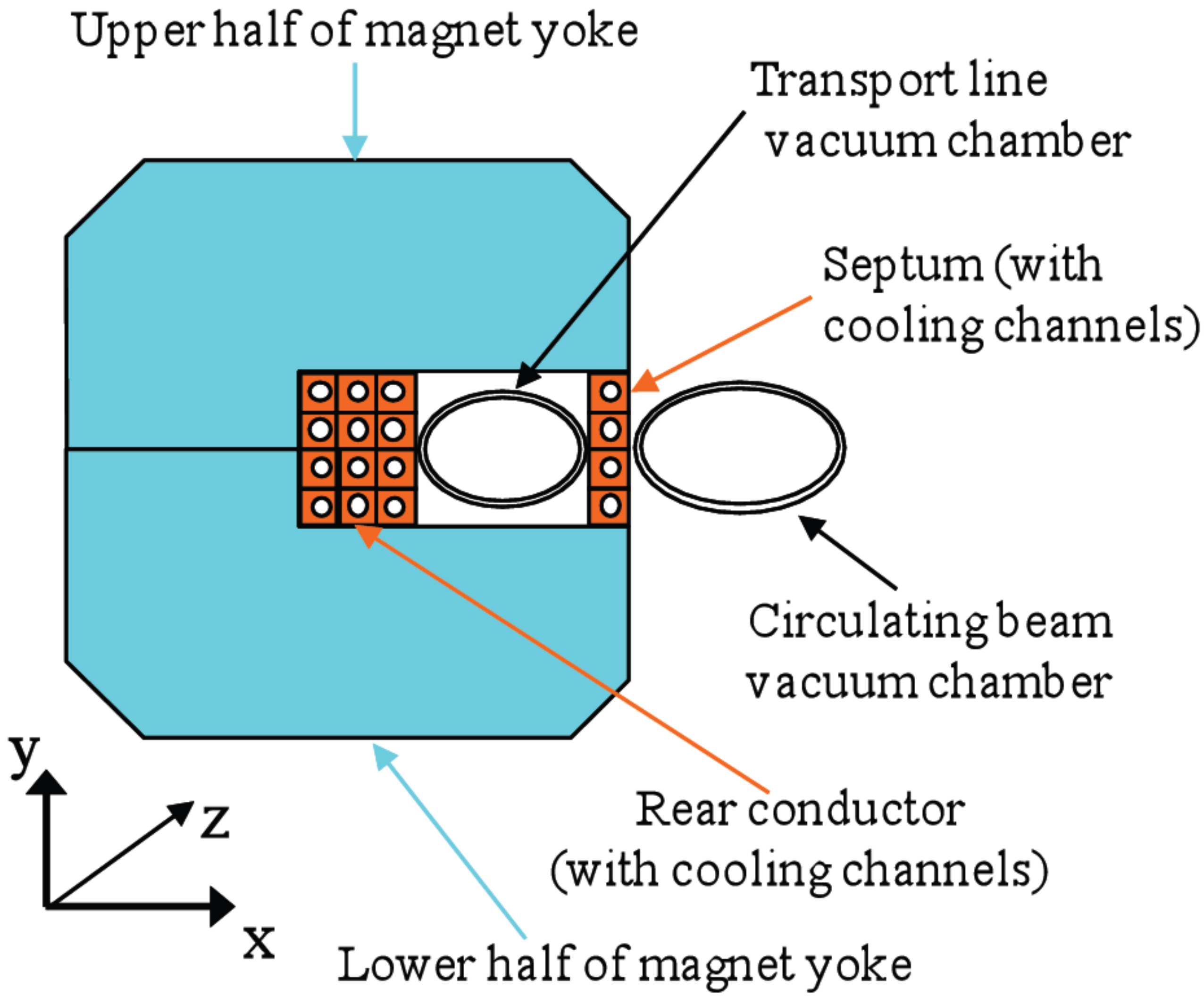
Types of kicker: Ferrite loaded kicker

- Similar to electromagnetic kicker, but surrounded by ferrous material (e.g. steel)
  - Can deliver much larger kicks than other 2 designs
    - ~10 time larger
  - Slower reaching steady state
  - Stored beam induces Eddy currents; this causes heating
    - Cooling can be a problem
  - Kick depends on relative permeability, μ_r , of the material
    - Magnetic kick becomes: $\theta_B = \mu_r \beta^2 \theta_E$ (assuming linear magnetisation)
    - Total kick becomes: $\theta_{kick} = \tan^{-1}\left((1 + \mu_r \beta^2)\frac{qVL_{kick}}{d\beta pc}\right)$
  - Magnetic field takes time to stabilise

Septum magnets

- 2 main types of septa:
  - Electrostatic septum
    - Septum thickness typically ≤100μm
  - Magnetic septum
    - Septum thickness typically 2 – 20 mm
    - Can be DC or pulsed (typically < ~100Hz)
    - Many different designs, but concept is the same

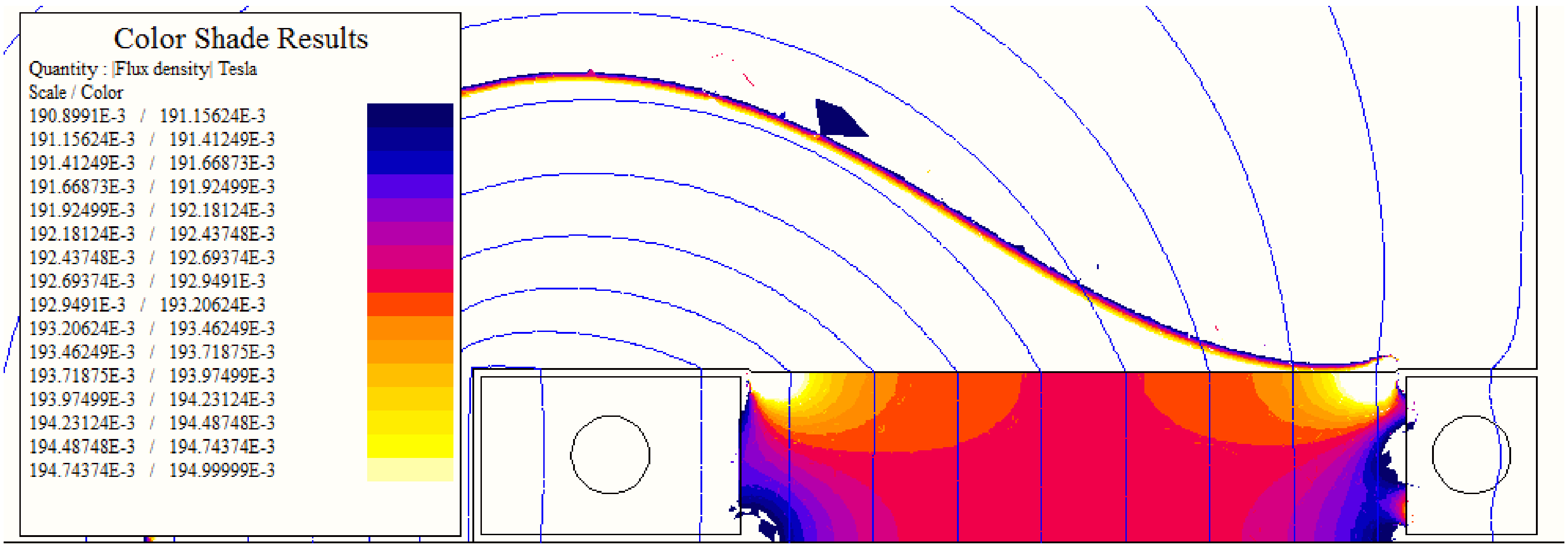
Basic diagram of septum magnet



Septum magnet: design challenges

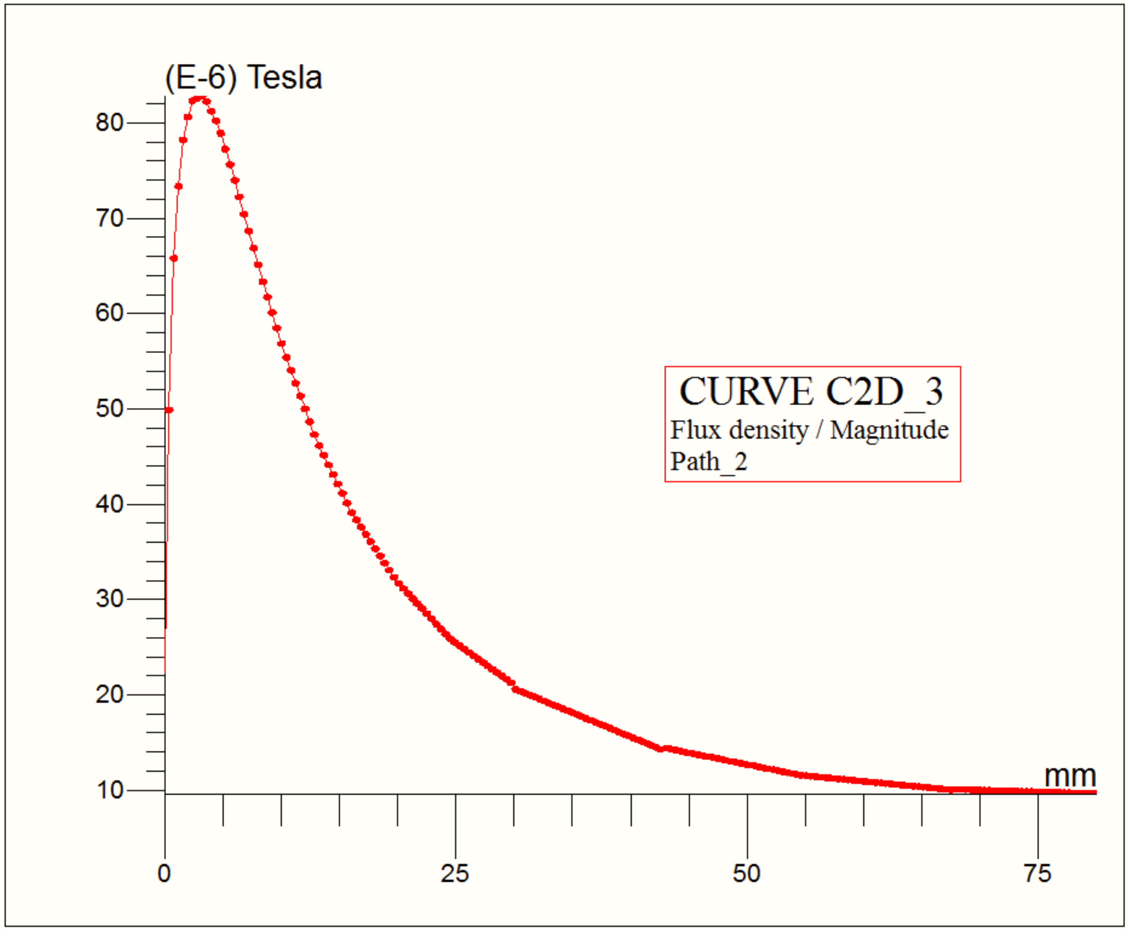
- Low leakage field
  - In the "zero-field" region there will be some residual field
    - High-order multipole fields experienced by stored beam
    - Can cause beam instability and reduce dynamic aperture
- Good field homogeneity in field region
  - Reduces beam jitter on injected or extracted beam
    - Can lead to luminosity loss, emittance growth and beam instabilities

CLIC damping ring septum
Field homogeneity



For good field region, homogeneity ~±1x10^{-4}
Need 2x10^{-5} so still optimisation to be done…

CLIC damping ring septum
Leakage field



Multipole term	Value
Dipole	2.23×10^{-5}
Quadrupole	9.64×10^{-6}
Sextupole	5.38×10^{-6}
Octopole	3.49×10^{-6}
Decapole	2.44×10^{-6}
Dodecapole	1.81×10^{-6}

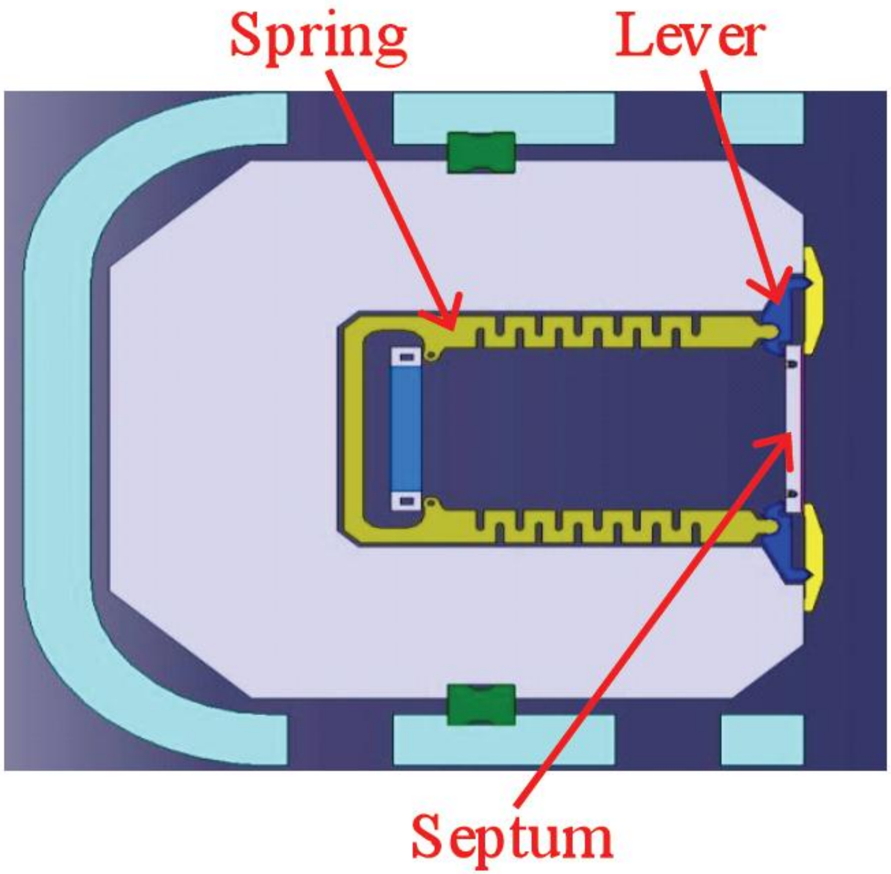
Practical issues: cooling

- Magnet coil and cooling pipes all inside septum
  - Cooling water flow rate limited
    - Too fast will damage septum magnet
  - Higher magnetic field needs more current
    - This means more current density in septum
    - Needs more cooling pipes; further increase current density…
      - This means more leakage field
      - This also means less field homogeneity
    - This sets limit on field strength for a given design

Forces on kickers and pulsed septa

- Force typically ~10kN when beam passes
  - Huge stresses can damage kickers and septa
    - Metal fatigue
    - Warping the conductors and aperture
  - Special damping springs used to stabilise

Septum magnet damping springs



Homework

Use MADX to design a simple extraction system for the following sequence:

Match kqf and kqd to obtain a periodic lattice with $\beta_x = 10, \beta_y = 39.6229, \alpha_x = 0, \alpha_y = 0$ at the start and end of the cell.

Assume a 5σ beam envelope for aperture calculations and a horizontal normalised emittance of 10^{-7}m.rad. Assume a septum thickness of 10mm and an outer quadrupole radius of 250mm. Match kick.k and sept.k to extract this beam.

```
Extraction_cell: sequence, L=10.00;
qf: quadrupole, L=0.1, K1:=kqf, at=0.05;
extkick:  hkicker, L=4.4, kick:=kick.k, at=2.5;
qd: quadrupole, L=0.1, K1:=kqd, at=4.95;
qd: quadrupole, L=0.1, K1:=kqd, at=5.05;
extsept:  hkicker, L=2.1, kick:=sept.k, at=8.65;
qf: quadrupole, L=0.1, K1:=kqf, at=9.95;
end.ext, at=10.00;
endsequence;
```

Assume the kicker is an electrostatic kicker, if the aperture is 25mm, and you are using 2.5GeV electrons, what is the voltage across the kicker?

For further information you can read the following papers:

Kickers: http://arxiv.org/ftp/arxiv/papers/1103/1103.1583.pdf
Septum magnets: http://arxiv.org/ftp/arxiv/papers/1103/1103.1062.pdf

These papers deal with the kickers and septum magnets in a lot more depth that I can during this lecture.