



Injection and extraction in the collider

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With thanks to Y. Dutheil, W. Bartmann, J. Borburgh, M. Hofer, P. Hunchak, M. Aiba, A. Krainer, A. Lechner

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Outline

Injection into the collider ring

- Conventional injection vs. Multipole Kicker Injection (MKI)
- On-axis and off-axis injection
- Kicker and septa technology considerations

Extraction from the collider ring

- Extraction from the collider and transfer to the beam dump
- The extraction line should defocus the beam enough to not damage the spoiler and achieve sufficient separation between the beam dump and the collider ring



Top-up injection strategies

At highest energies, the beam lifetime is less than one hour requiring top-up injection to achieve high integrated luminosity

Off-axis vs. on-axis injection

Liouville's theorem: Under conservative forces, the density of the particles in phase-space stays constant [1] \therefore you cannot inject into this phase-space.

Instead, injected beams are separated in *betatron* or *synchrotron* phase-space, and merge via *synchrotron radiation damping*.

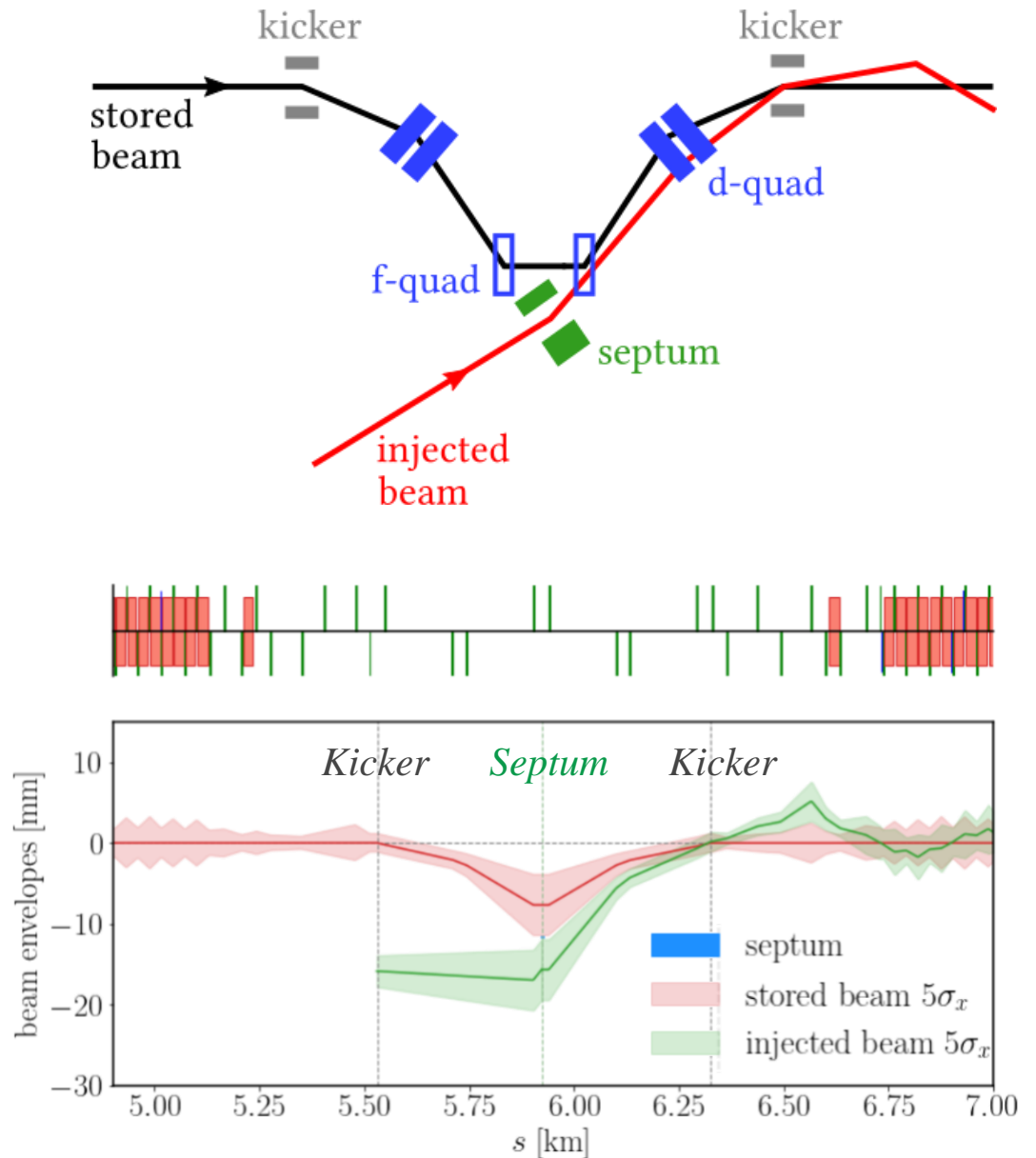
- **Off-axis:** separation in betatron phase-space - injected with a **transverse offset**.
- **On-axis:** separation in longitudinal phase-space - injected with **longitudinal offset** onto off-momentum closed orbit. This requires there to be dispersion at the septum for separation of beams in energy.

Booster placement: the options of side-by-side or stacked placement will be studied in terms of how this affects injection. In either case, injection should be horizontal because of the larger horizontal aperture.

[1] H. Wiedemann, *Particle Accelerator Physics I—Basic Principles and Linear Beam Dynamics* (1993).

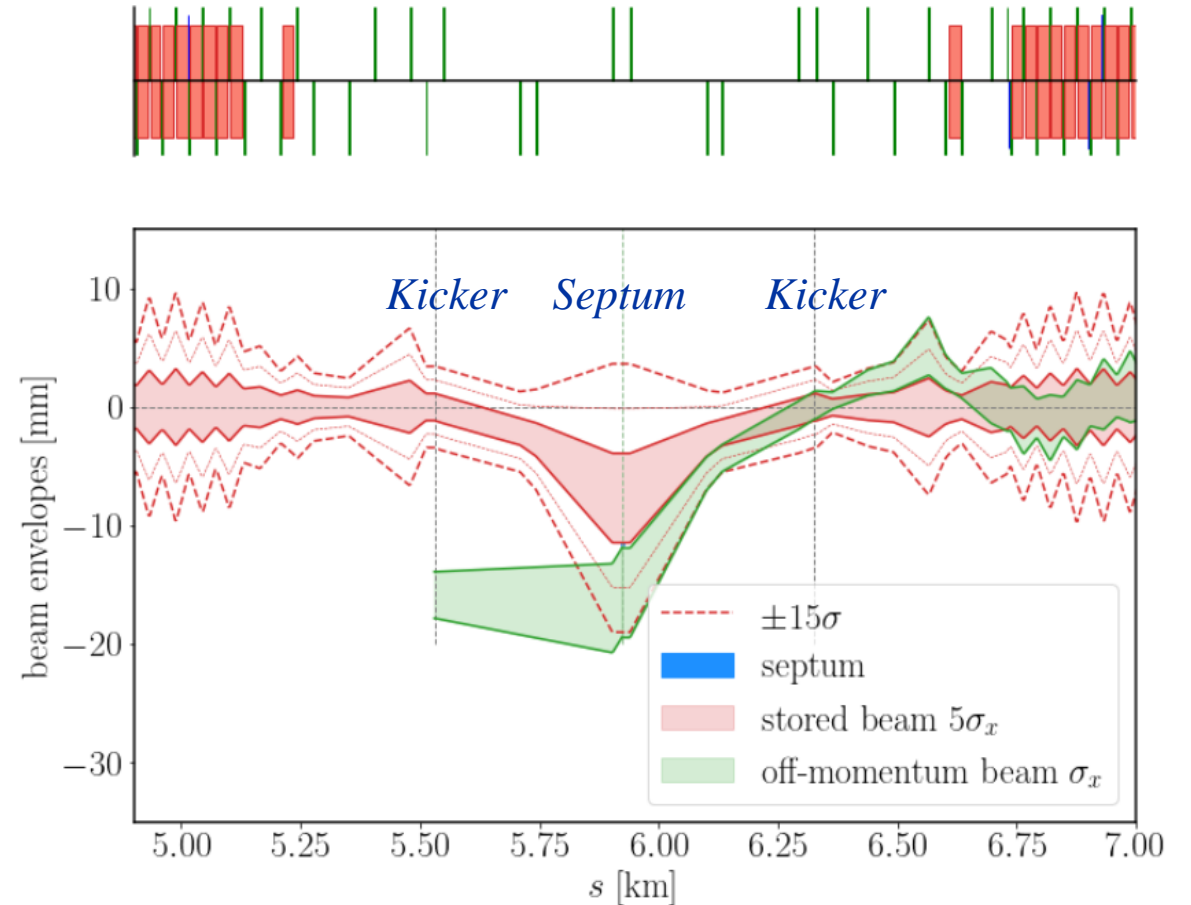
Conventional injection

- Uses a dynamic orbit bump (dipole kickers) to bring the beam into the high-field region of the septum.
- Requires a thin septum ($\sim 200 \mu\text{m}$) such as an electrostatic wire septum.
- **Machine protection:** consider failure of the kicker and consequent impact on the wire septum, also consider beam deposition if the orbit bump is not correctly closed.
- **Kicker:** feasible with current technology.
- **Septum:** consider the rate of sparking in this atmosphere.



Conventional injection (off-axis)

- Separation between the two beams at the septum of $> 5\sigma_i + S + 5\sigma_s$, and bump amplitude of $10\sigma_i + S$.
- 200 μm septum-width means the beam-beam separation is $\therefore 10.3\sigma$, as $\sigma_x = 0.75$ mm.
- Kicker deflection: 12.5 μrad .
- Septum deflection: 65 μrad , achievable with two 3 m modules with $E = 2 \frac{\text{MV}}{\text{m}}$.
- Bump amplitude: 7.6 mm. Injected beam offset at septum: 15.7 mm.



Electrostatic septum

Electrostatic septum with wires under tension separating the high-field and field-free regions. High-field between the wires and cathode.

Such a thin septum requires a dedicated positioning system for alignment.

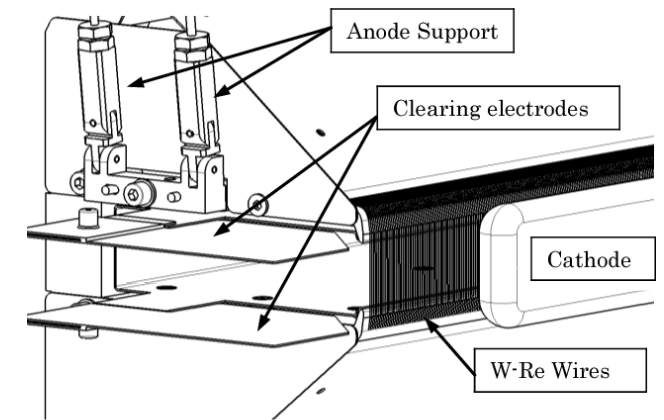


Fig. 1. ZS electrostatic septum used for SPS slow extraction

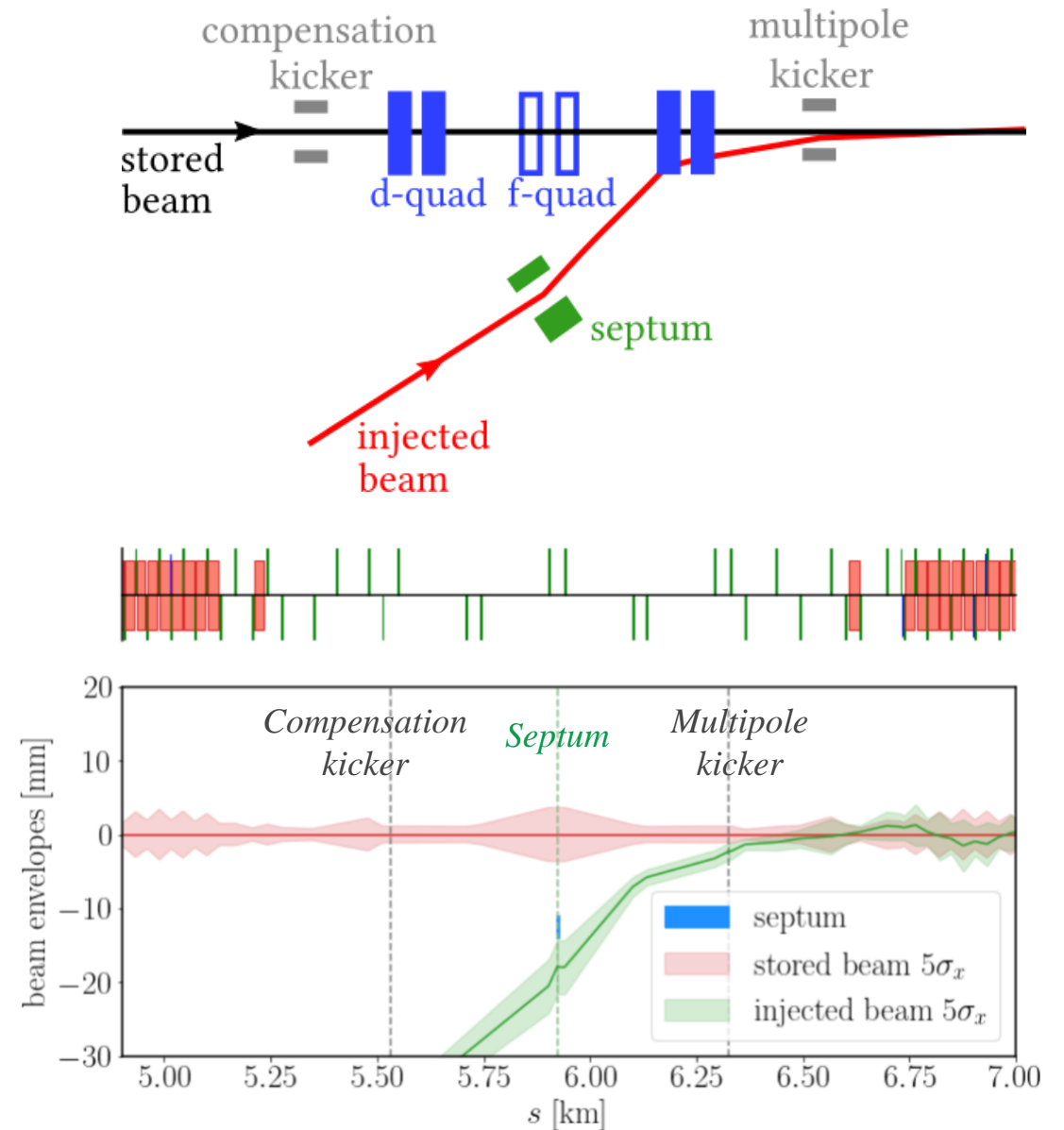
[2]

“J. Borburgh (SY-ABT-SE) will start R&D in 2022 to look into the effect of X-rays on electrostatic septa sparking rates as a function of voltage

- **How often will it spark?** Quantify SR hitting septum wires and the e -cloud around septum. Ions produced by ionising residual gas can cause breakdown as in the SPS ZS septa.
- **How damaging would sparking be?** Damage to HV components, equipment and vacuum.
- **What to do in case of sparking?** SPS has spark detection system [3].
- **How to minimise sparking?** Lower voltage, ion trap, improve vacuum levels.

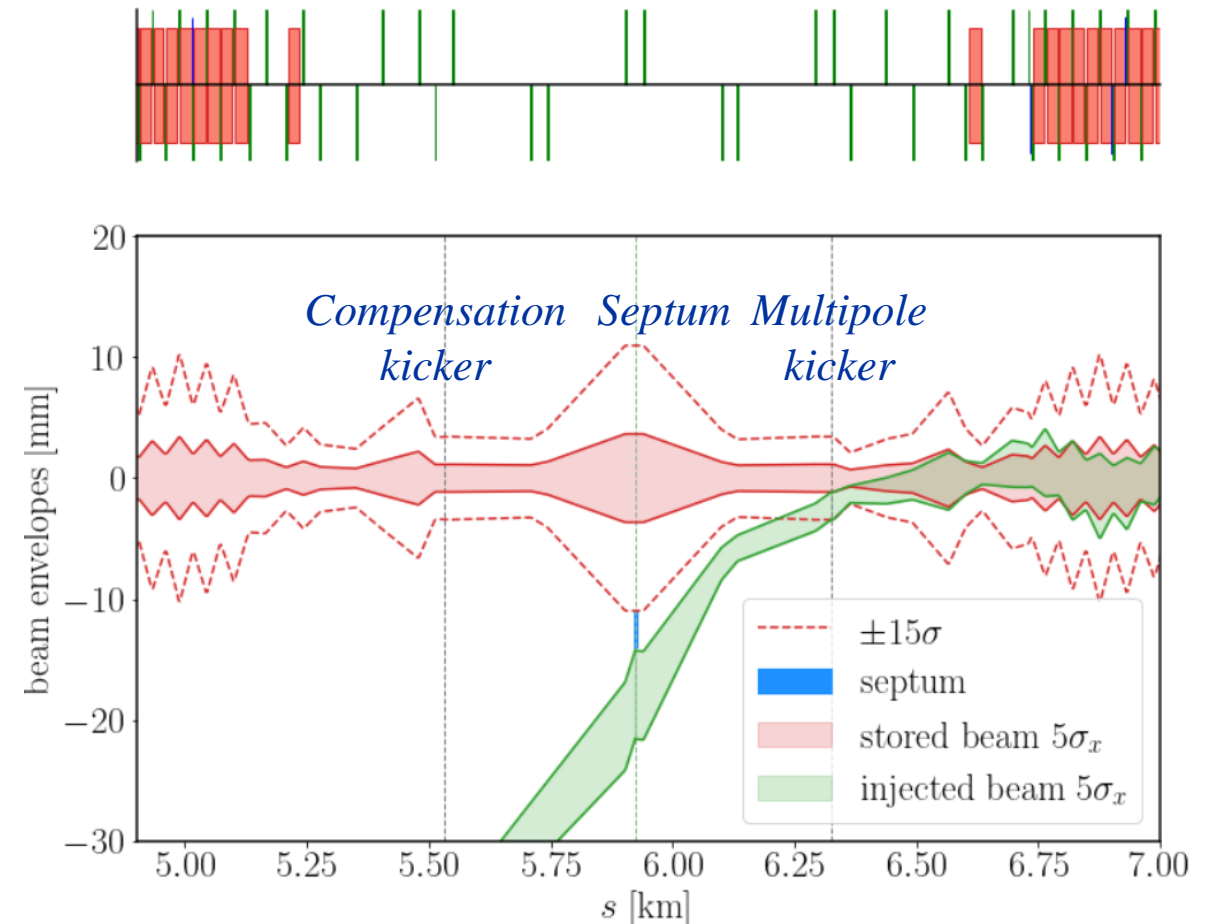
Multipole kicker injection

- Multipole kicker has, ideally, zero field for the stored beam and constant field for the injected beam (i.e. step-function).
- Compensation kicker to compensate the perturbation to the stored beam distribution.
- **Septum:** a thicker magnetic eddy septum (blade e.g. 3 mm) or electrostatic septum.
- **Kicker:** the order of disturbance goes with the order of the multipole kicker used. Here, we consider octupole fields.



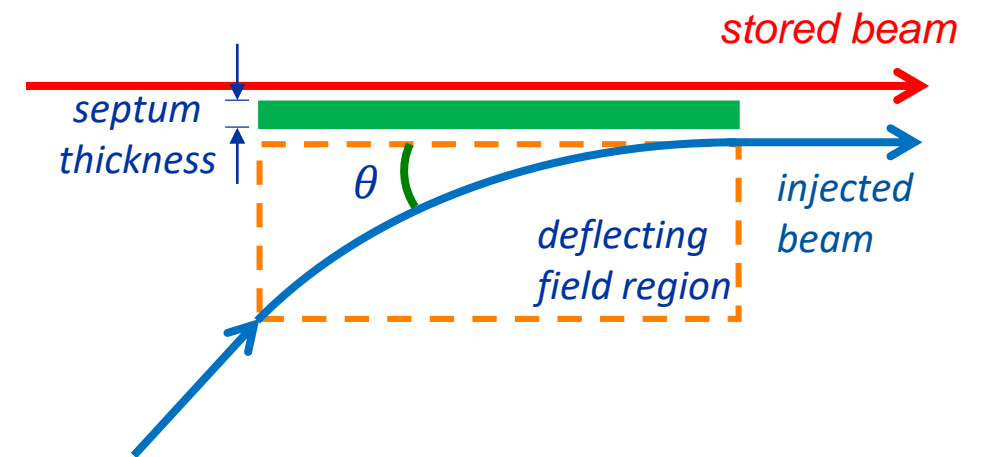
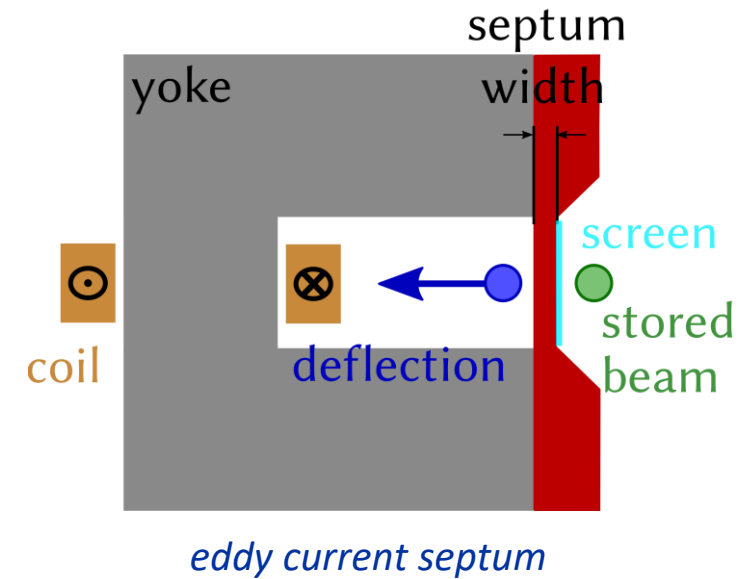
MKI (off-axis)

- Separation of beams at septum $> 5\sigma_s + 10\sigma_s + S + 5\sigma_i$, to account for betatron oscillations of injected beam.
- Tracking studies of the disturbance to the stored and injected beams to be presented by P. Hunchak (following talk).
- **MKI deflection:** 29 μrad .
- **Septum deflection:** 100 μrad ; septum thickness: 3 mm.
- **Machine protection:** absorbers for failure of kicker or septum. Less risk for stored beam than conventional injection.



Magnetic eddy septa

- If the magnetic field changes inside of a solid conductor, eddy currents will be induced to oppose the magnetic field change. These septa use the eddy currents to shield the leakage field.
- Eddy current magnitude depends on the frequency of change of the magnetic field.
- Leakage fields can be down to 0.01%, this may require mu-metal shielding.
- The coil is typically single-turn, to minimise inductance.



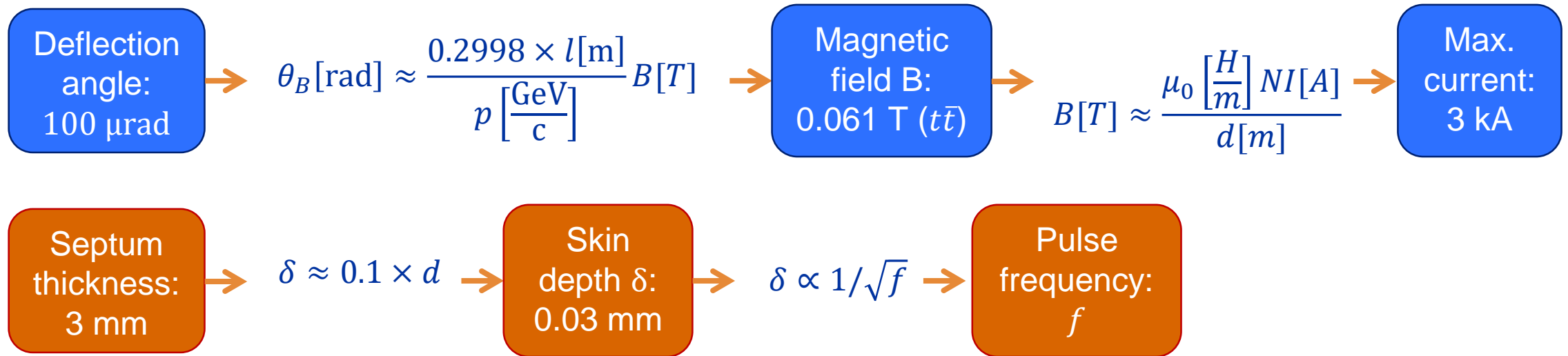
Magnetic eddy septum

- Leakage field, do we need mu-metal shielding?
- Gap width and deflecting field region required.
- Powering: half-sine, full-sine. Pulse frequency, duration.
- Is edge-cooling required?
- Consider mechanical and thermal stresses.

Preliminary still under study

Parameter	Value
Deflection	100 μ rad
Field (Z , $t\bar{t}$)	0.015/0.061 T
Max. current	3 kA
Septum thickness	3 mm
Gap height	6 cm

Design process



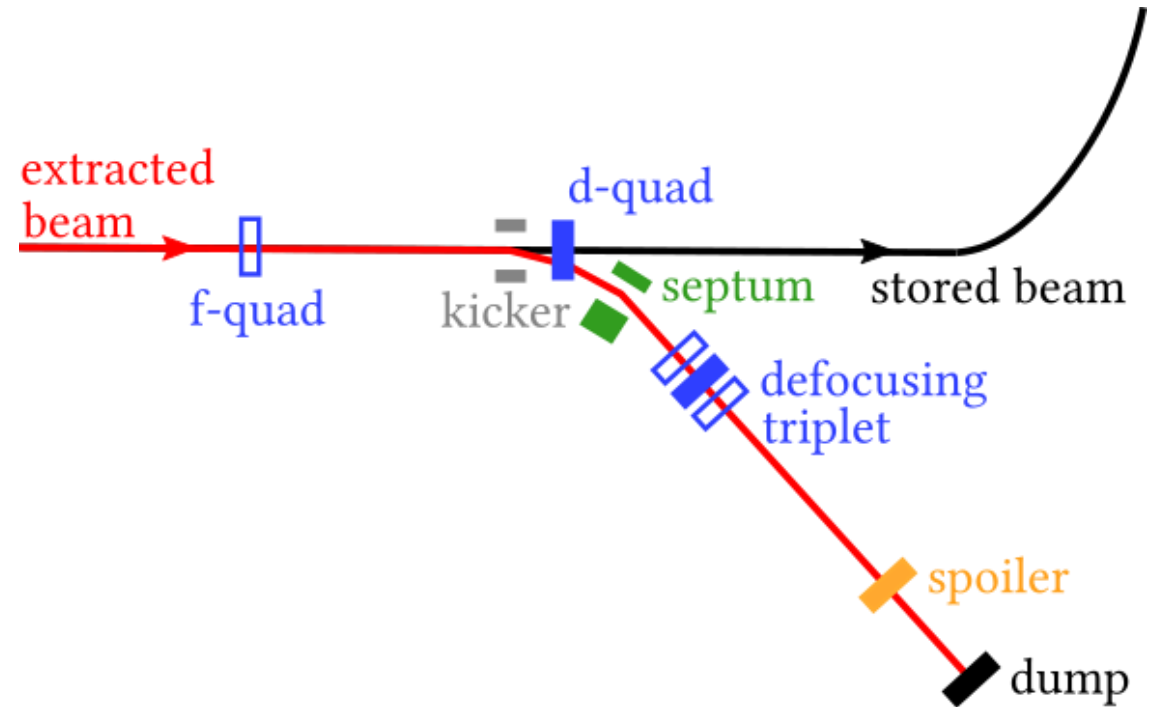


Extraction from the collider ring

Extraction from the collider

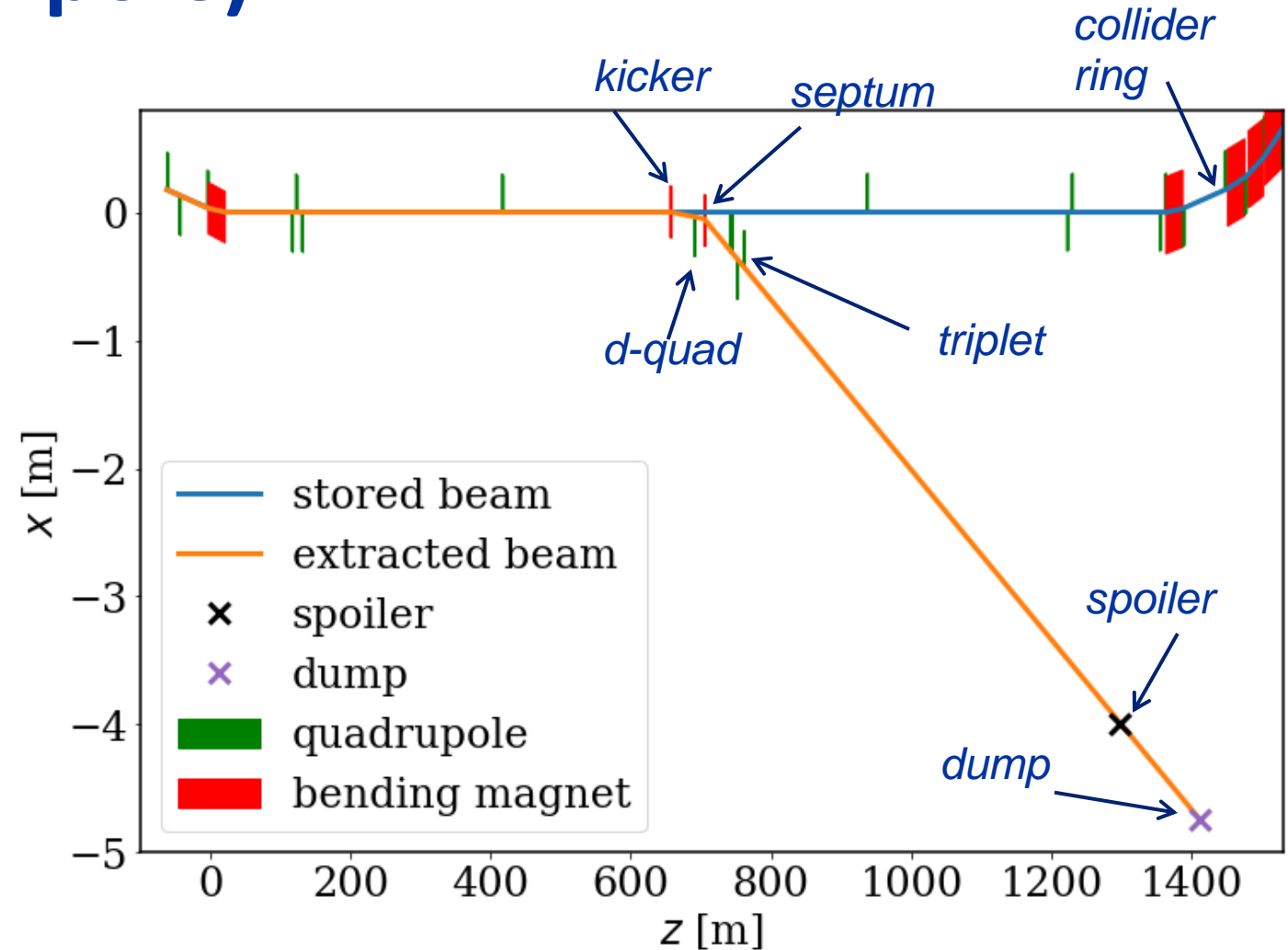
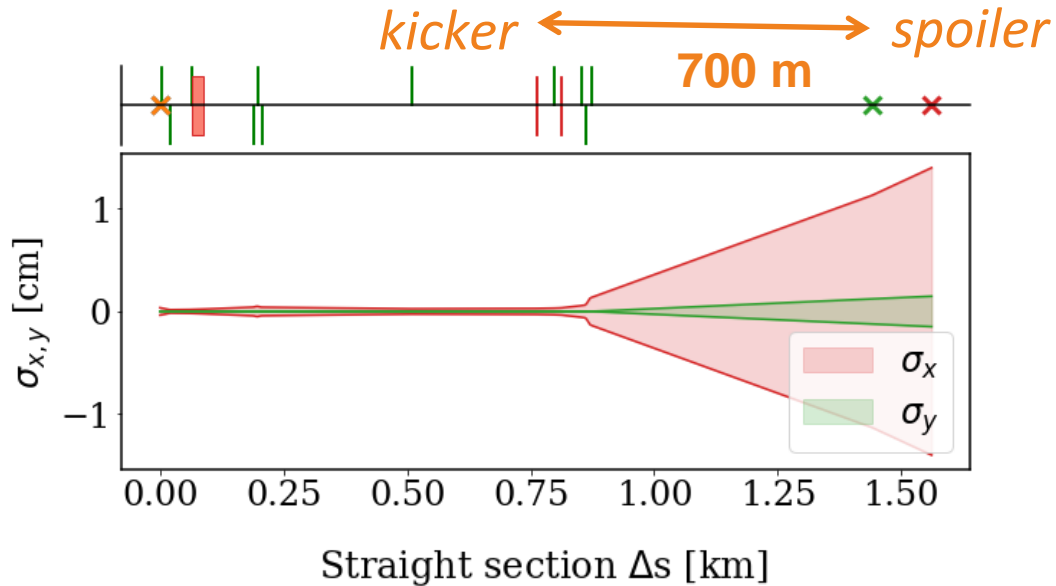
- Extraction with kicker and septum separated, ideally, with a defocusing quadrupole.
- At Z-pole, **20.6 MJ** of stored energy/beam.
- Beam-dump-to-collider separation of **5-10 m** for sufficient protection from radiation.
- Beam is defocused with the triplet, propagates for 100s of metres and passes through a spoiler to further dilute the beam.
- Alternatives considered: horizontal vs. vertical extraction, septum-less extraction, among other configurations.

Potential extraction configuration for the end of LSS



Horizontal extraction (Z-pole)

- Horizontal kicker and septum.
- At spoiler $\sigma_{x,y} = 11.3 \times 1.2$ mm.
- Kicker deflection 1 mrad, septum deflection 5 mrad. Beam-beam separation at septum 5 cm.



Kicker and septum

Kicker and septum parameters below are achievable with current technology (taking CDR beam params).

Magnet	Length [m]	Field	1σ (x/y) [mm]
Kicker	3	0.05 T	0.29/0.023
Septum (DC)	3	0.25 T	0.35/0.023
Q1	3	4.2 Tm ⁻¹	0.50/0.024
Q2	3	-3.3 Tm ⁻¹	0.14/0.038
Q3	3	4.2 Tm ⁻¹	11.1/1.2

Preliminary still under study

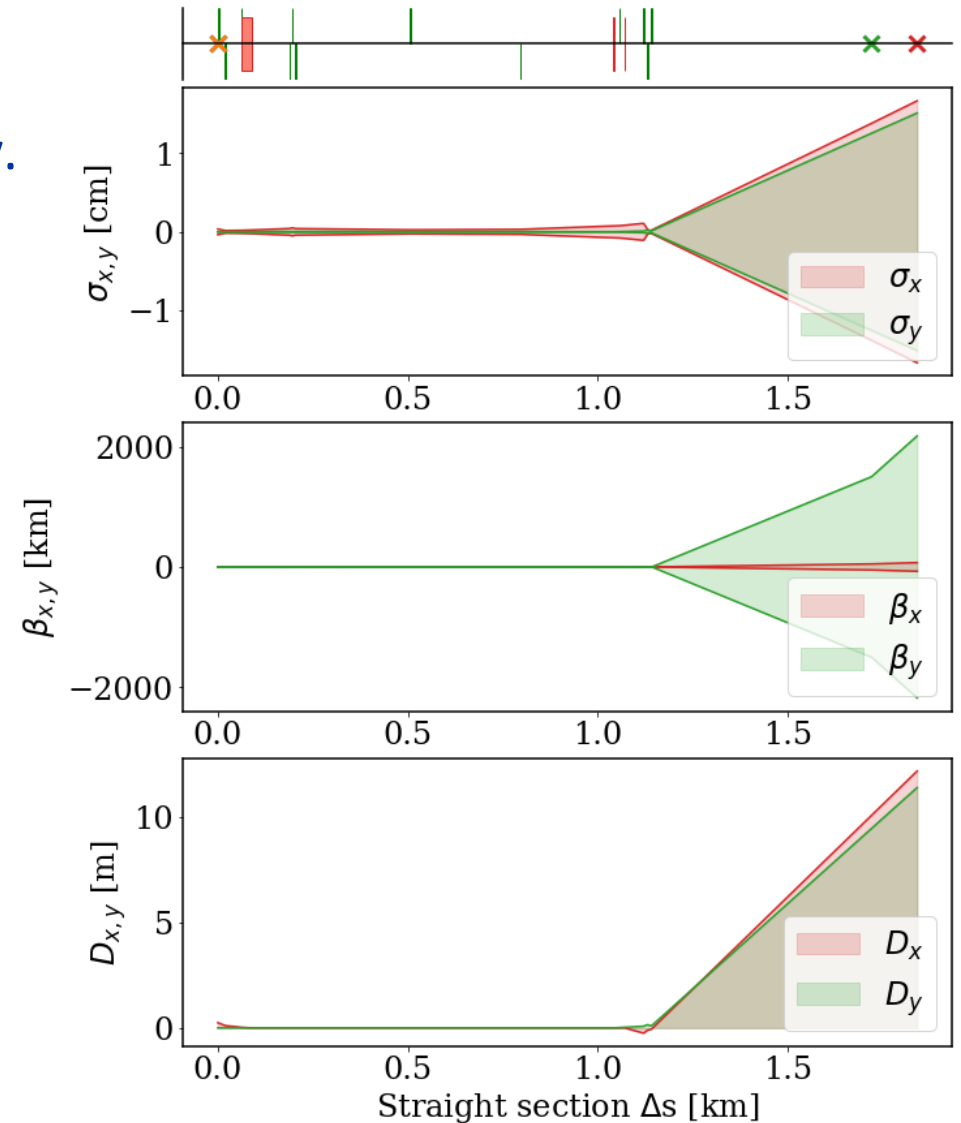
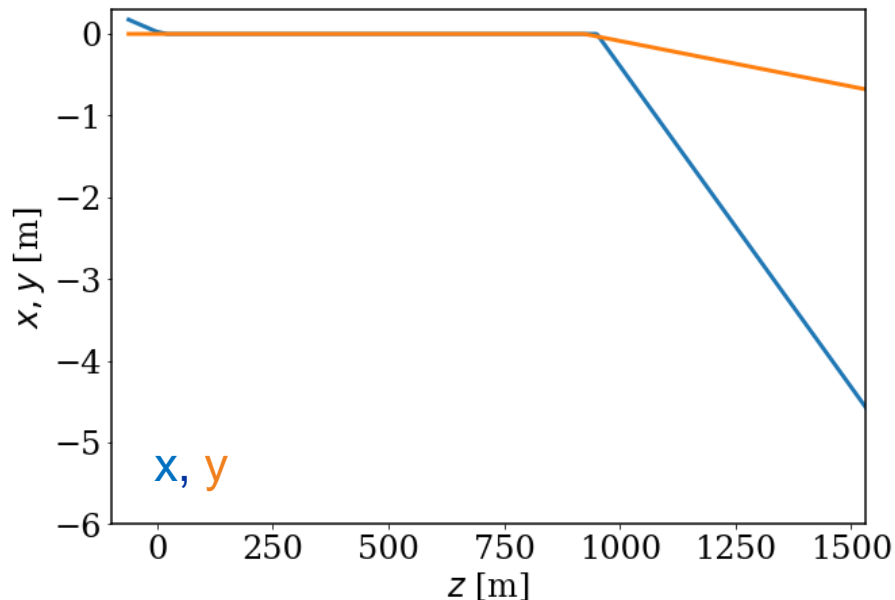
Kicker rise time 3 μ s (within abort gap) and flat-top (to cover entire ring ~ 300 μ s).

Machine protection

- Without the defocusing triplet, the beam would damage the spoiler, $1\sigma_{x,y} = 5 \text{ mm} \times 0.03 \text{ mm}$.
- As is the case for the LHC, we could implement current-change monitors to detect variations of order 10^{-3} in the triplet to trigger a beam dump.
- For a $\pm 2\%$ change in any of the quadrupoles in the triplet, the beam size could reduce to $10.7 \times 1.1 \text{ mm}$.

Vertical-kicker extraction

- Kicker to extract **vertically**, septum to deflect **horizontally**.
- Offers more flexibility for the placement of extraction, in terms of the availability of defocusing quadrupoles.
- Vertical dispersion, from the kicker, also helps with increasing the vertical beam size at the spoiler.



Conclusions

Injection

We will consider four strategies for top-up injection, with studies so far focusing on off-axis injection. We will study conventional and multipole kicker injection, with both off-axis and on-axis injection.

SY-ABT will offer expertise for kicker and septum technologies.

Also, to be considered is how the booster-collider placement impacts the injection.

Extraction

Designs for the extraction line and extraction devices are progressing, in collaboration with A. Krainer for the beam requirements at the spoiler/dump.

We have shown a kicker-septum configuration for extracting the beam, with a defocusing triplet to blow up the beam before the spoiler. This satisfies the beam size requirements at the spoiler and requirements on the separation between the beam dump and collider ring.



Thank you for listening

Frequency of magnetic field change

The higher the magnetic field change rate is, the thinner the septum need be.

Typically powered by half or full sine wave current

Frequency of magnetic field change dependent on the septum thickness.

Skin depth for eddy currents typically between 10%-20% of the septum width [\[1\]](#),

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

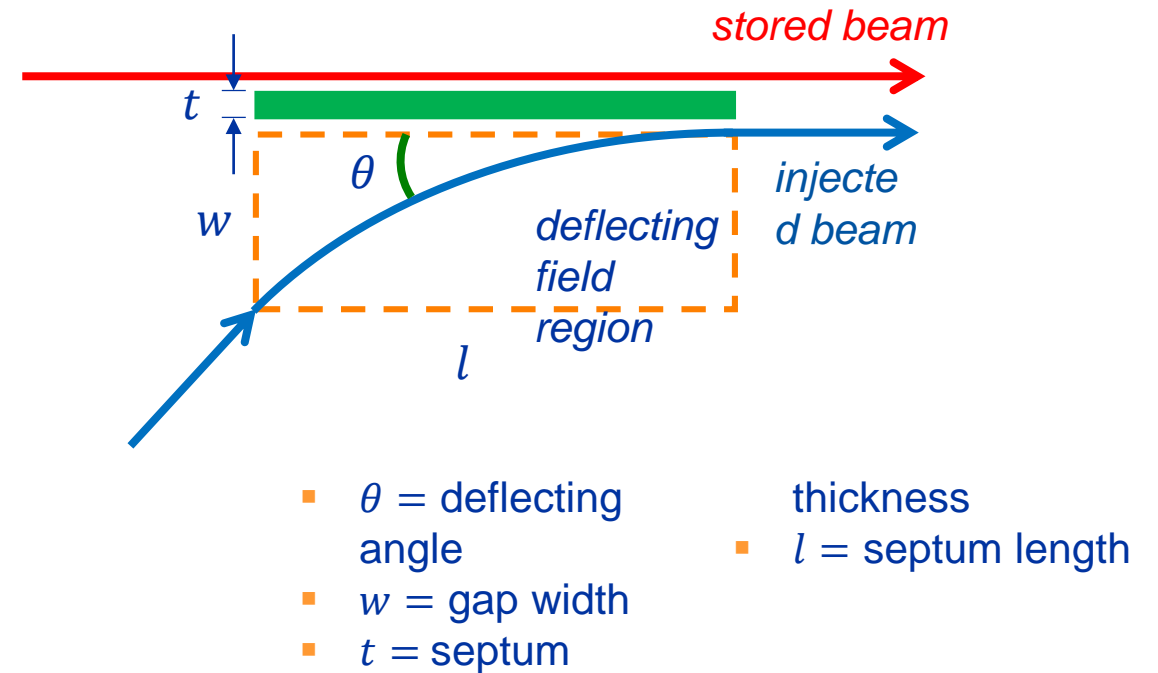
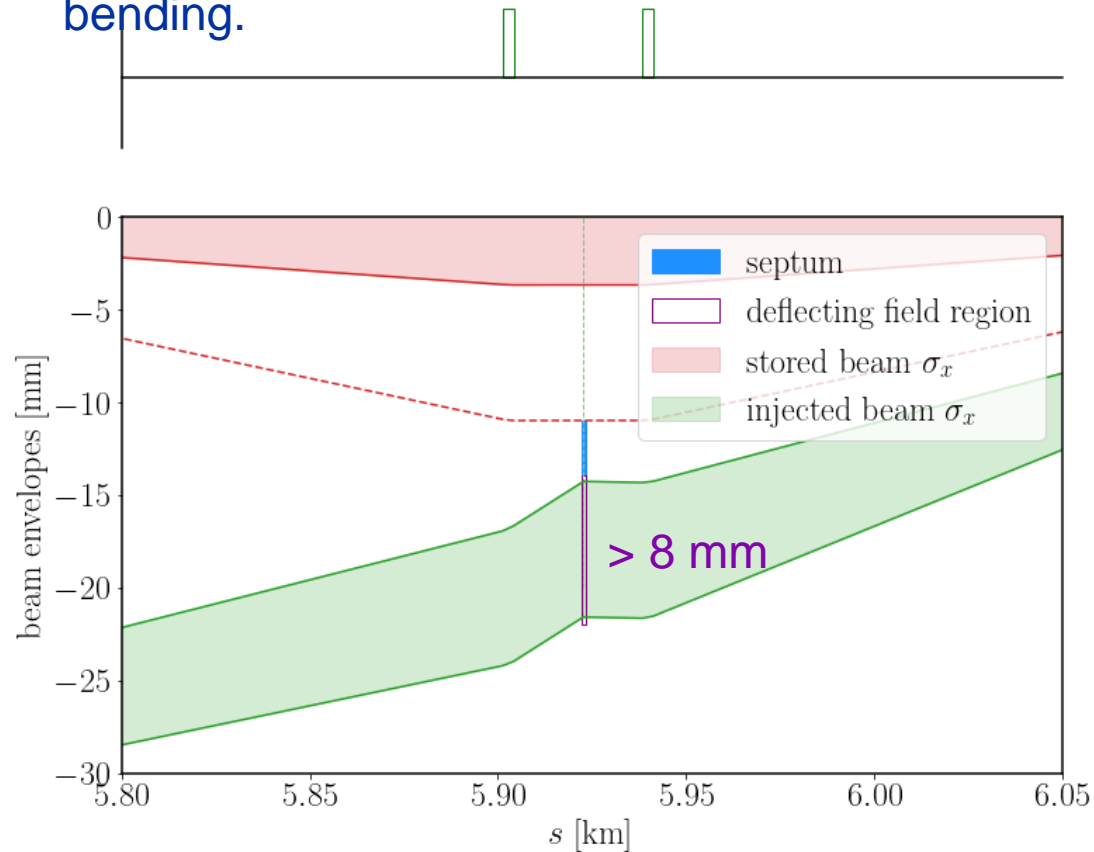
Where f is the magnetic field frequency [Hz], $\mu_{0,r}$ are the vacuum [H/m] and relative permeabilities and σ is the material conductivity [S/m] [\[2\]](#).

Determine desired pulse frequency and duration.

E.g [LINAC4](#) copper septum blade: 9 kHz; this corresponds to a skin-depth of ~0.7 mm

Gap width & deflecting field region

Must include beam envelopes and start and end of septum and beam trajectory from bending.



Gap width 10-30 mm is common for Eddy Septa.
[CAS 2018]

Leakage field

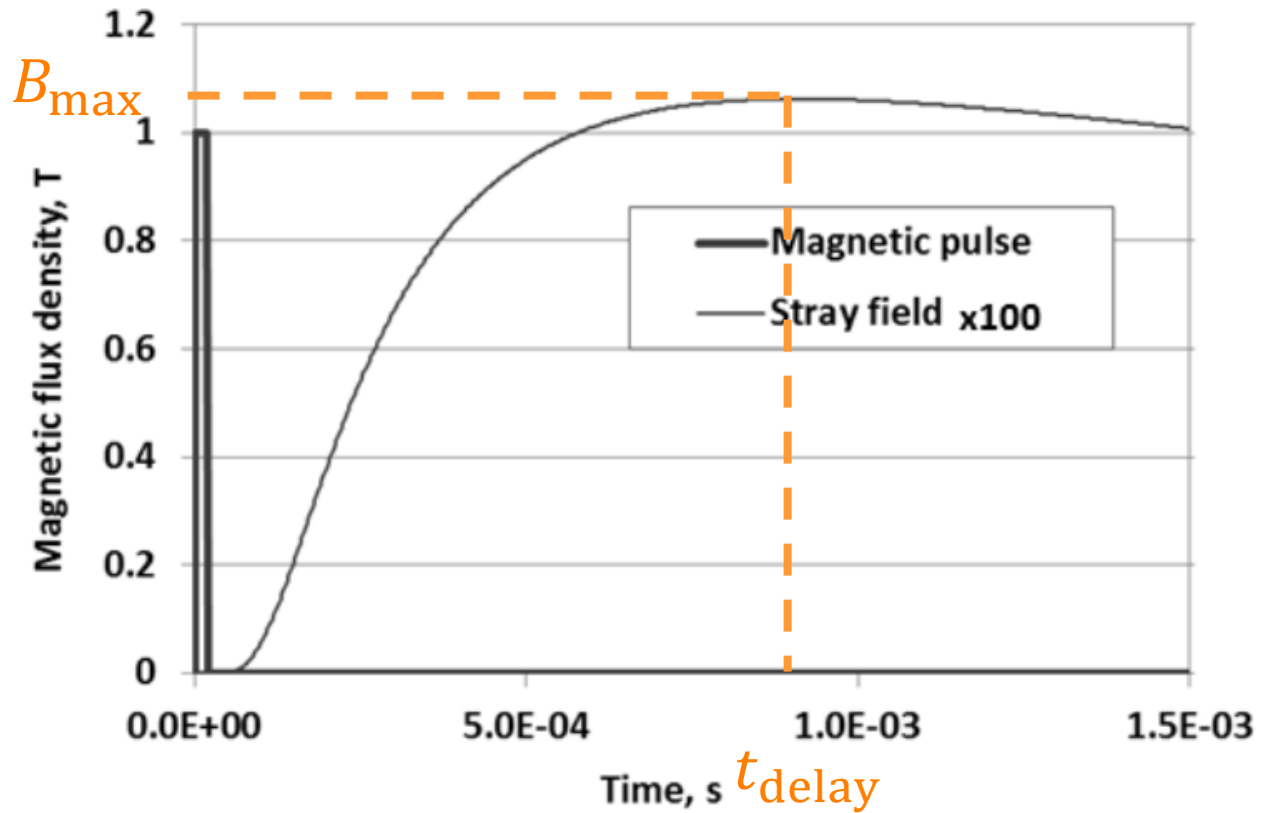
Primarily low-frequency components that leak through. *Example stray field time structure*
Need to study frequency components of the main field.

Maximum leakage field has delay, several tir

t_{delay}

B_{max}

d_s = septum thickness, σ =conductivity, μ =permeability
 λ_c =characteristic length of stray field delay.



Higher order considerations

Need to determine if there are any key parameters likely to be show-stoppers.

Pulsed power supply needs.

Additional magnetic shielding, e.g mu metal?, study saturation of the material. Shield thickness in addition to septum thickness.

Pole geometry to be designed to optimise field homogeneity.

Beam impedance.

Vacuum level.

Edge cooling may be needed.

Septum mechanical and thermal stress - pressure on the coil in the aperture.

Wire septa

$$\theta_E [\text{rad}] \approx \frac{E [\text{V/m}] l_{eff} [\text{m}]}{10^9 \beta p \left[\frac{\text{GeV}}{c} \right]} \rightarrow \frac{E [\text{V/m}] l_{eff} [\text{m}]}{182.5 \times 10^9}$$

In the CDR, wire septum deflection over two modules, each of length 3 m:

- $65 [\mu\text{rad}] \approx \frac{E \left[\frac{\text{MV}}{\text{m}} \right] (2 \times 3) [\text{m}]}{10^9 \beta \times 182.5 \left[\frac{\text{GeV}}{c} \right]}$, so that $E = 2 \frac{\text{MV}}{\text{m}}$

Comment on kicker from [Aiba, et al., 2018. NIM A, 880, pp.98-106.]:

- The required bump height is 6.6 mm achieved with a deflection angle of $21 \mu\text{rad}$. The corresponding integrated field of the kicker is then $\sim 0.012 \text{ Tm}$ for 175 GeV beam, which is feasible using conventional kicker technology (for example, magnetic length of 0.4 m and field of 0.03 T).