# A Transparent Injection Scheme for Diamond-II


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# Talk Outline

Introduction to Diamond-II:

- Requirements for injection
- Injection schemes and layout

Single bunch injection with fast stripline kickers:

- 'Aperture-sharing' vs. 'Kick-and-cancel' injection
- Injection simulations (transparency, collective effects, error sensitivity)

Hardware overview:

- Diamond-II injection magnet specifications
- Design status / prototyping on Diamond

Conclusions

# Diamond-II Lattice

Modified Hybrid 6-Bend Achromat (M-H6BA) for low emittance

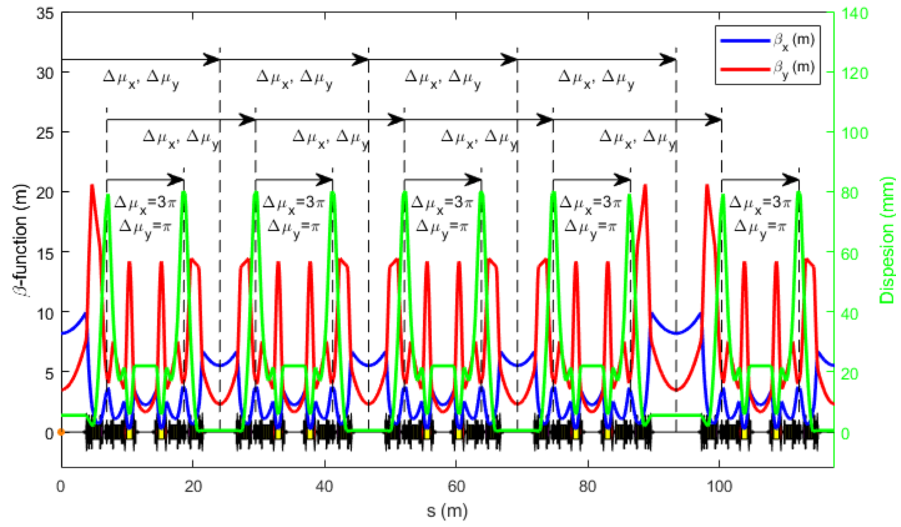
Number of insertion straights increased from 24 to 48

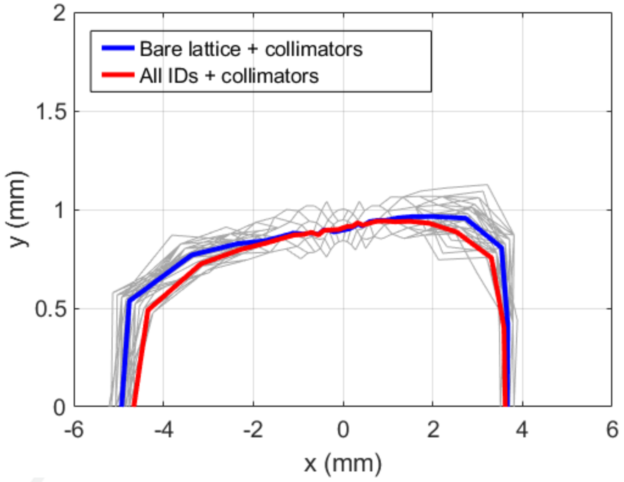
- Long straights: 7.54 m
- Standard straights: 5.06 m
- Mid straights: 2.92 m

Off-axis injection for beam accumulation

'-I' transformer plus const. cell phase for nonlinear dynamics

Passive SC harmonic cavity for lifetime / beam stability / IBS




| Parameter | Units | Diamond | Diamond-II |
|---|---|---|---|
| **Energy** | **GeV** | **3.0** | **3.5** |
| Circumference | m | 560.6 | 560.560944 |
| Harmonic Number | - | 936 | 934 |
| RF Frequency | MHz | 499.654 | 499.511 |
| Positive Bending Angle | deg | 360.0 | 374.4 |
| Reverse Bending Angle | deg | 0.0 | 14.4 |
| Total Bending Angle | deg | 360.0 | 388.8 |
| Betatron Tunes | - | [27.21, 12.36] | [54.14, 20.24] |
| Natural Chromaticity | - | [-79.0, -35.6] | [-68.2, -89.1] |
| Corrected Chromaticity | - | [1.7, 2.2] | [2.6, 2.6] |
| Mom. Compaction Factor | $\times 10^{-4}$ | 1.70 | 1.03 |
| **Natural Emittance** | **pm.rad** | **2729** | **162** |
| Energy Spread | % | 0.096 | 0.094 |
| Energy Loss per Turn | MeV | 1.01 | 0.724 |
| Natural Bunch Length | ps | 11.4@2.4 MV | 12.4@1.4 MV |
| Horizontal Damping Partition | - | 1.00 | 1.88 |
| Horizontal Damping Time | ms | 11.1 | 9.4 |
| Vertical Damping Time | ms | 11.2 | 18.1 |
| Longitudinal Damping Time | ms | 5.6 | 16.1 |

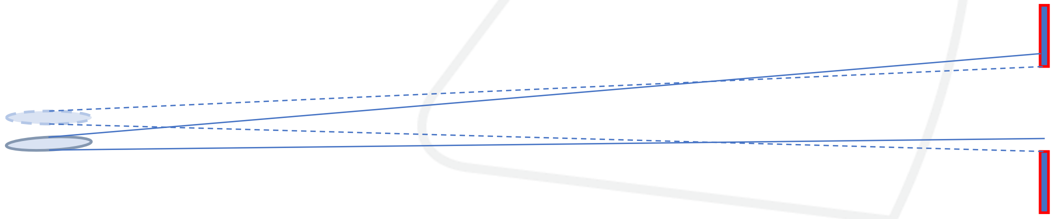
# Injection Requirements

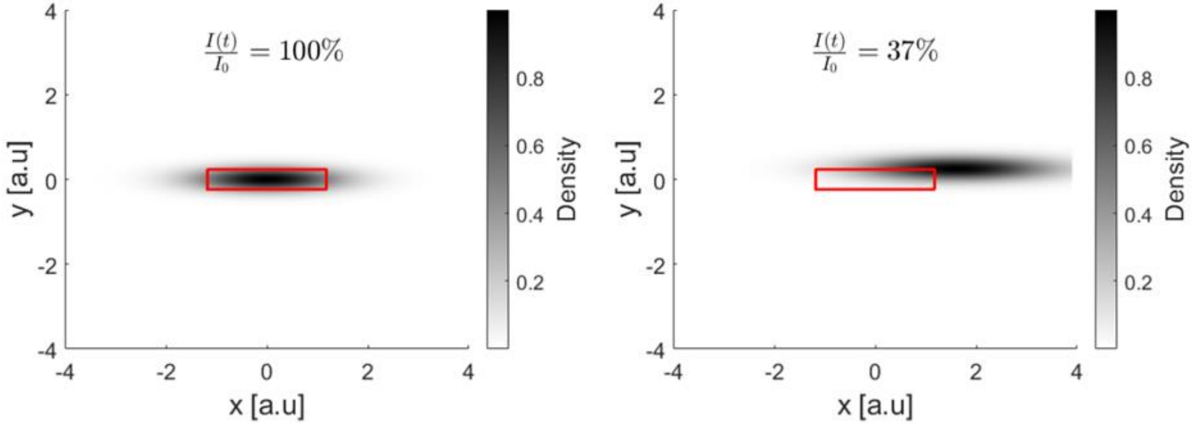
<u>Injection requirements:</u>

1) Off-axis accumulation (minimises requirements on injector; avoids beam dump?; improved reliability?)
2) Matched to available dynamic aperture / momentum acceptance (new booster required)
3) Minimise filling time after beam trip
4) Use proven technology where possible to minimise risk
5) Transparent top-up injection during user time (key requirement from users!)

<u>Transparency figure of merit (FoM):</u>

*"**Intensity integrated over 100 µs through 2D FWHM slit** 45 m downstream from source point **must remain above 99% of nominal** at all times at all beamlines"*





# Injection Schemes

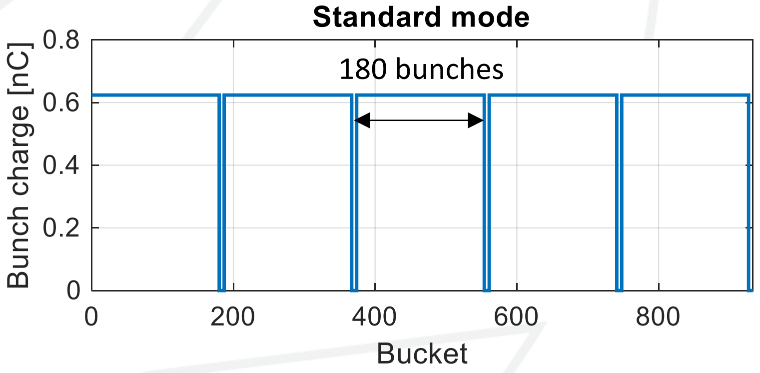
Diamond-II will operate two different injection schemes:

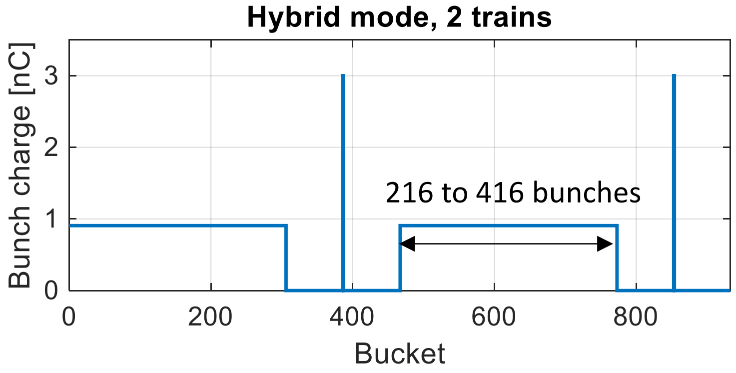
1) <u>PM thick septum + pulsed thin septum + standard four kicker bump (single or multi-bunch)</u>

- Robust, proven concept
- Can be adjusted for different stages during commissioning:
    - ➢ Stage 1: single shot, on-axis injection (first turns => first stored beam)
    - ➢ Stage 2: off-axis accumulation with non-closed bump (improved capture efficiency)
    - ➢ Stage 3: off-axis accumulation with closed orbit bump (improved transparency)

2) <u>PM thick septum + pulsed thin septum + fast stripline kickers (single bunch only)</u>

- Frequent top-up injection using single-bunch injection (transparent to users: 1 bunch in 900 kicked)





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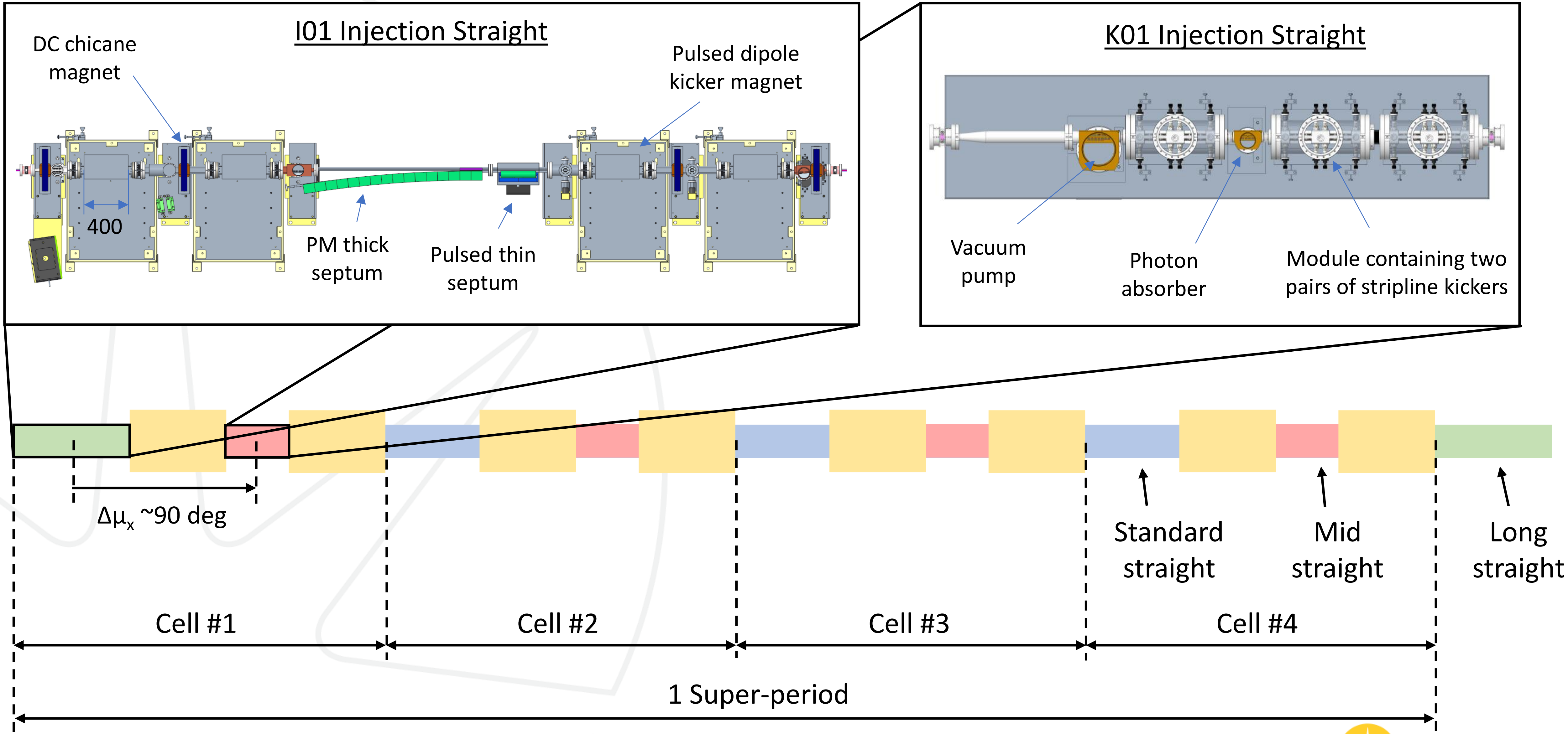
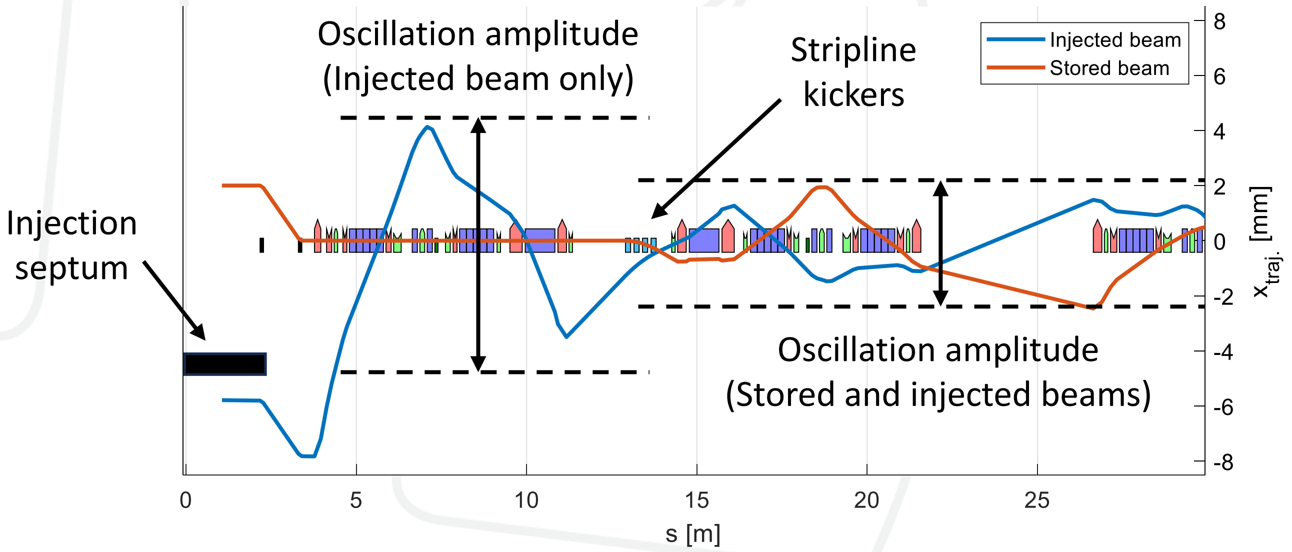
# Injection Layout

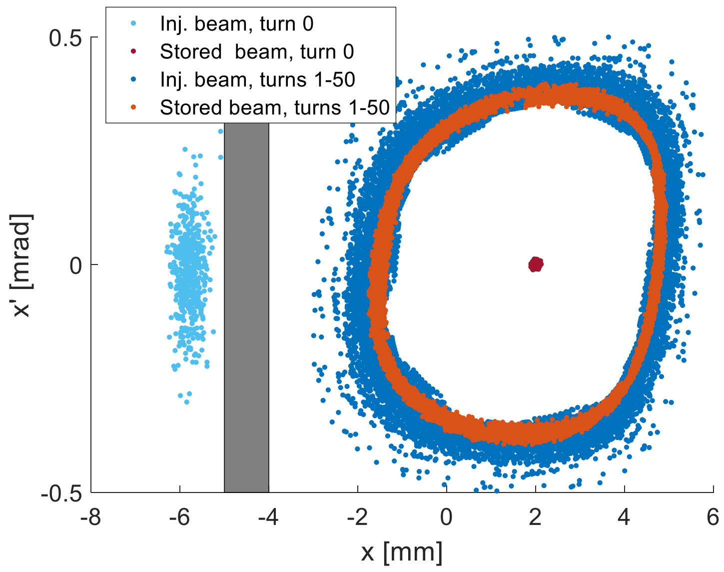


# Single-Bunch 'Aperture-Sharing' Injection

An aperture-sharing injection scheme was assumed during the Technical Design Report (TDR) phase:

- Four-kicker bump is switched off, leaving injected bunch ~8 mm offset from on-axis stored beam
- Injected bunch oscillates at large amplitude until it reaches the first mid-straight (K01)
- Stripline kickers reduce oscillation amplitude for injected bunch but cause stored bunch to oscillate at similar amplitude (i.e. initial injected bunch amplitude is shared between stored and injected bunches)



# Single-Bunch 'Aperture-Sharing' Injection

Issues with aperture sharing:

- Impact on overall brightness from stored bunch oscillations
  - ➢ Particular problem for hybrid bunch / timing mode users
  - ➢ Bunches before and after target bunch could also be kicked if pulse duration > 3 ns
- Transverse wakefields generated by stored bunch affecting injected bunch
- Interaction of multi-bunch feedback with off-axis bunches

Alternative: Implement a 'kick-and-cancel' double kick for the stored bunch

1) Give the stored bunch a pre-kick *n* turns before injection such that there is close to 180 degrees phase advance at injection
2) Injected bunch arrives as before:
   - ➢ stripline kicker still reduces injected bunch oscillation amplitude by ~factor 2
   - ➢ stored bunch is kicked back on-axis rather than being made to oscillate



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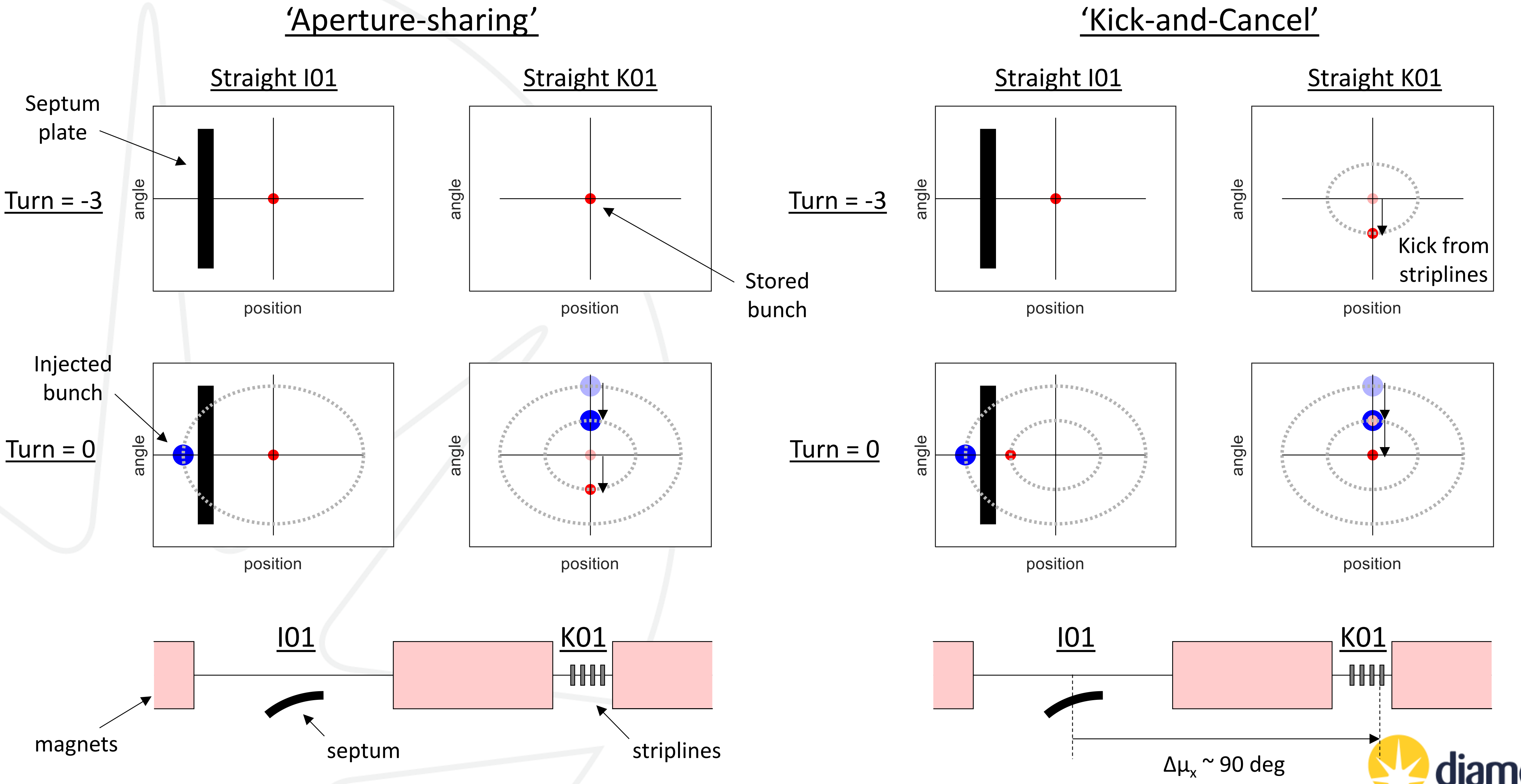
# Single Bunch 'Kick-and-Cancel' Injection

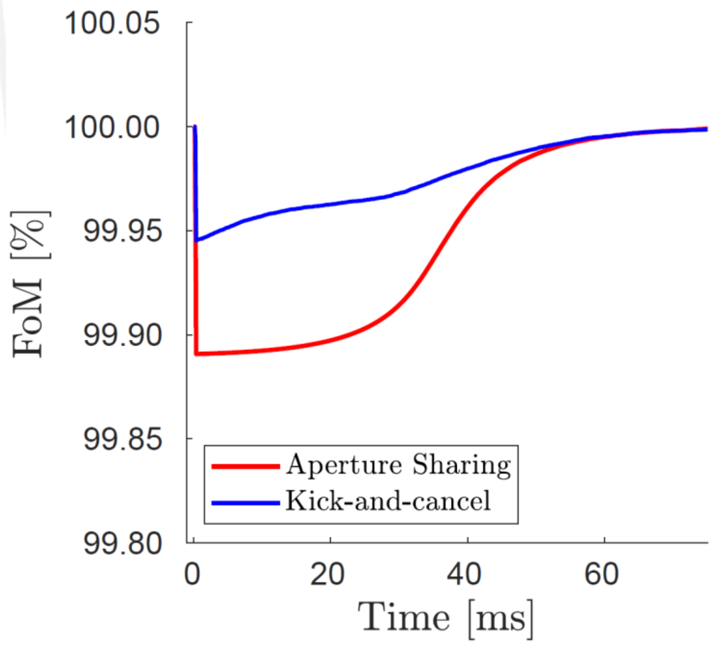


# Brightness Comparison

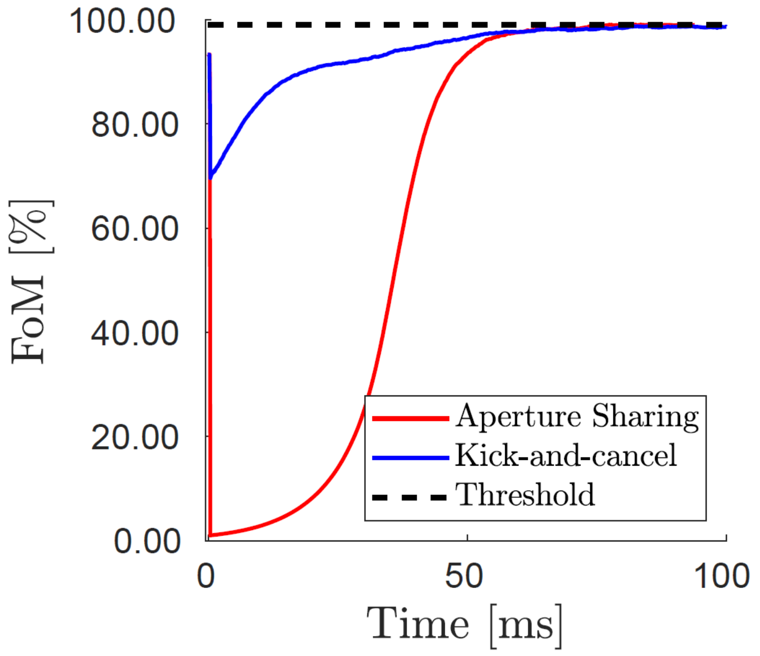
Improved transparency:

- Target >99% flux through BL aperture
- Stored bunch back on axis after second kick
- Only injected bunch continues to oscillate

<u>Brightness Impact for Stored Beam</u>
(300 mA, 900 bunches)




<u>Brightness Impact for Target Bunch</u>
(3 nC, single bunch)



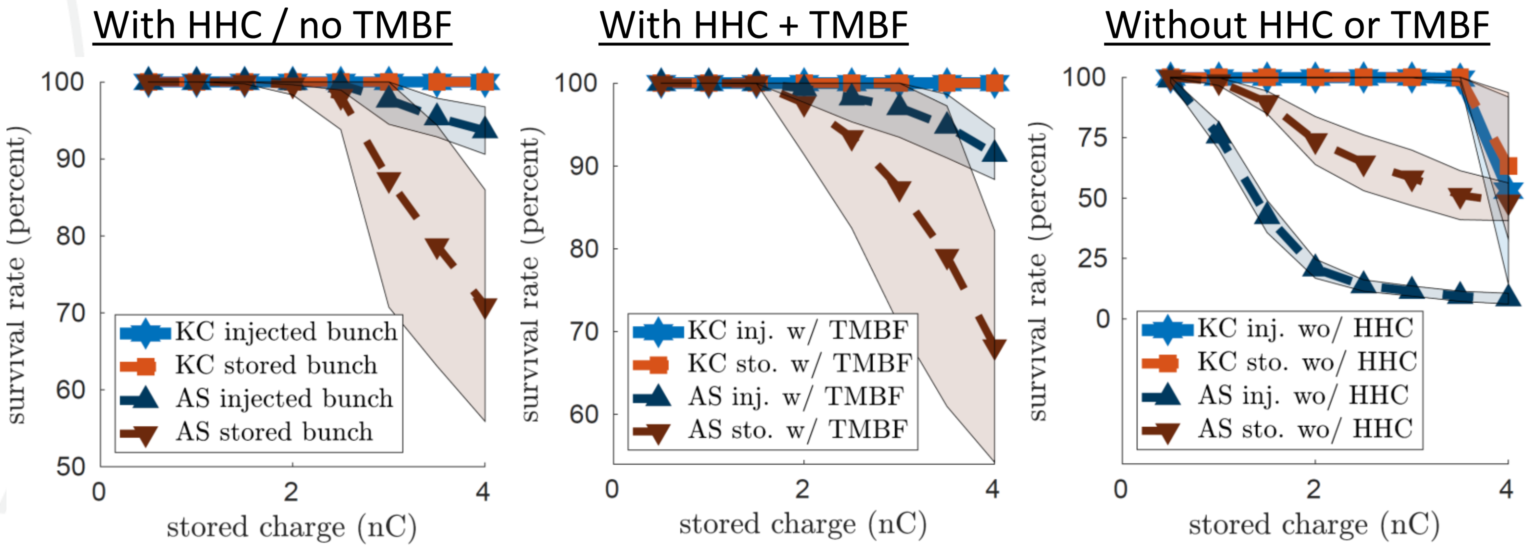
# Collective Effects

Injection efficiency calculated as a function of stored bunch charge including harmonic cavity (flat potential):

- Impedance elements (resistive wall, cavity HOMs and short-range geometric)
- Element-by-element tracking including physical apertures, IDs and field/alignment errors
- Injected bunch charge = 0.1 nC
- Macroparticle charge = 0.1 pC (i.e. 3 nC stored = 30,000 macroparticles)
- Track stored bunch for 12K turns to reach equilibrium, add injected bunch and fire striplines, track for a further 3K turns

K&C lowers wakefield effects:

- Stored bunch is on-axis
- Can accumulate to higher charges
- More tolerant:
  - Smaller interaction with TMBF
  - Does not need harmonic cavity

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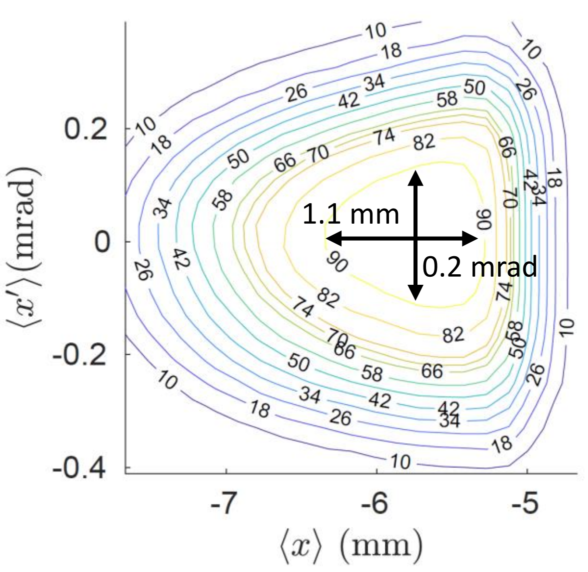
# Tolerance Studies

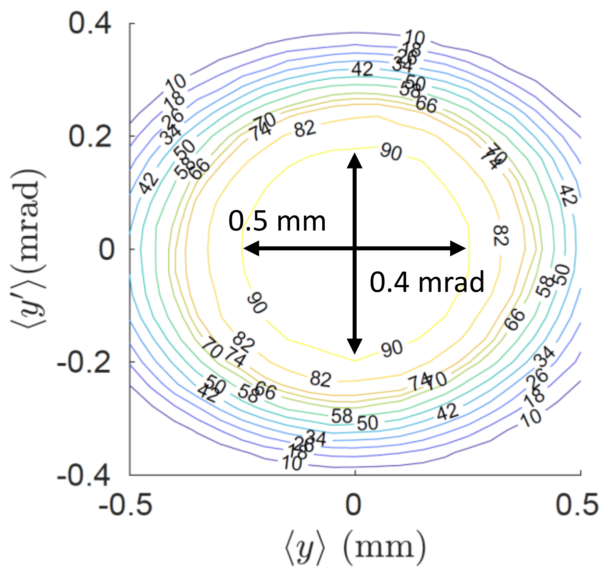
The sensitivity of injection efficiency to injected beam trajectory errors with stripline kickers has been studied using AT2 lattices at the end of Simulated Commissioning*:

- Commissioning procedure applied, including field and alignment errors, IDs, HHC and closed collimators
- Injection efficiency determined as a function of injected beam offsets for 40 lattices
- Only considers injected beam (no collective effects) – applies to both aperture sharing and kick and cancel

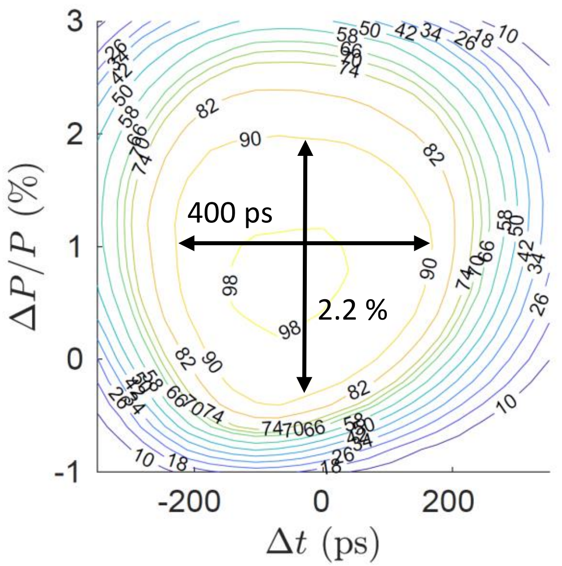
Horizontal phase space




Vertical phase space




Longitudinal phase space

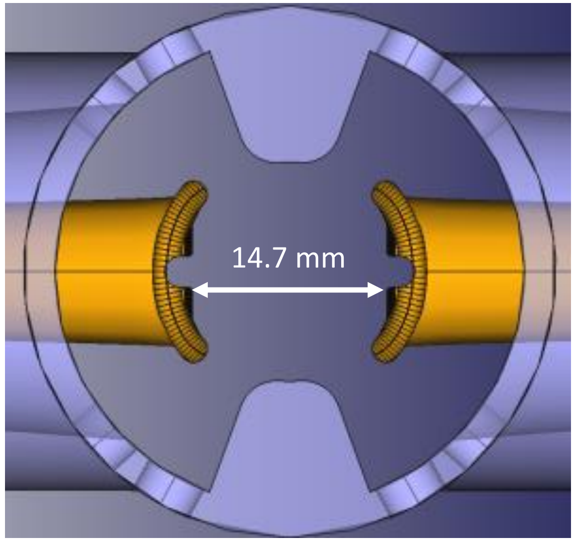



*T. Hellert, et al., PRAB 25, 110701, (2022)*

# Stripline Kickers

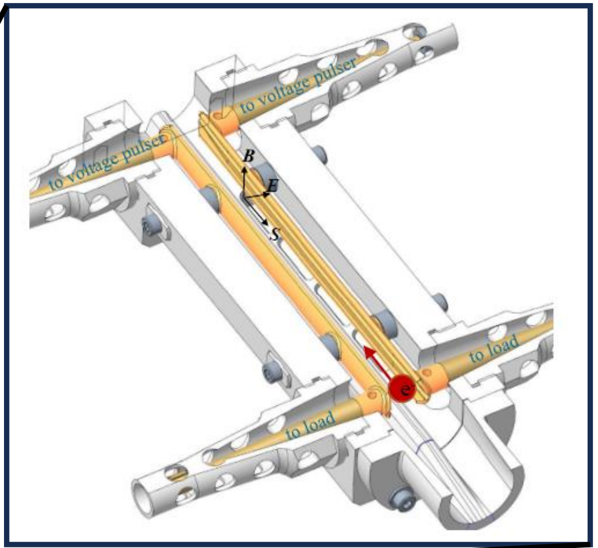
Six sets of striplines are required, grouped in three separate modules:

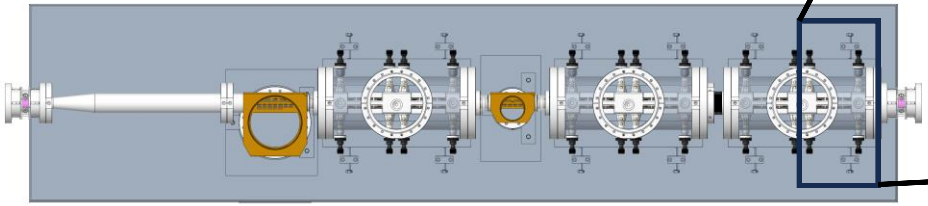
| Parameter | Units | Value |
|---|---|---|
| Length | mm | 150 |
| Full gap | mm | 14.7 |
| Bend angle per stripline | µrad | >156 |




Evolution of D-II MBF stripline design + SLS 2.0 solution:

- Double skin vacuum tank (Large outer chamber, internal pipe with pumping grills)
- Flat central section to improve field uniformity
- End tapers optimised to minimise field roll-off and reflections
- Rounded edges and maximise spacing to avoid arcing
- Cut-outs for synchrotron radiation



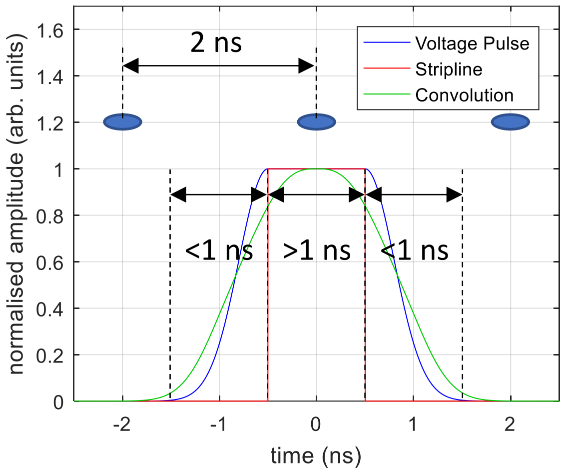
# Stripline Power Supplies

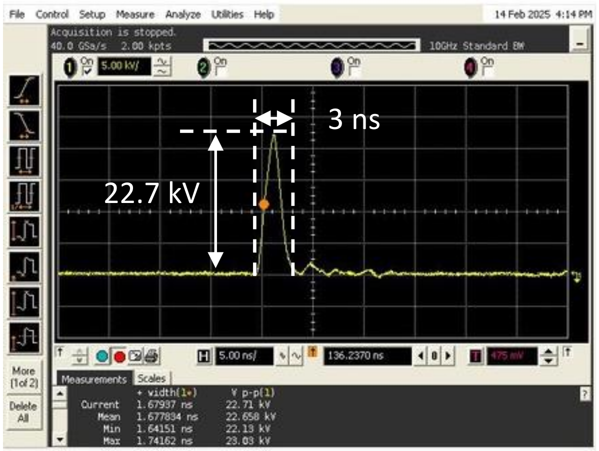
To ensure only a single bunch is kicked, require:

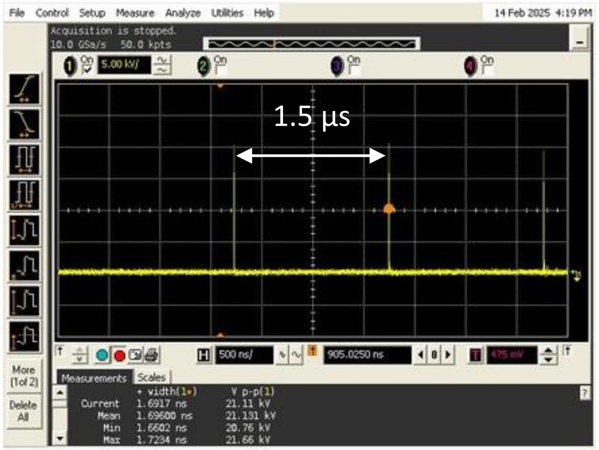
$$\tau_{pulse} < \frac{2}{f_{RF}} - \frac{2L_{strip}}{c} = 3\ ns$$

Prototype pulser developed by Kentech Ltd.

- Stage 1: +2.5kV, <15 ns, 4 pulses/cycle
- Stage 2: ±4 kV, <4 ns, >10 pulses/cycle
- Stage 3: ±20 kV, <4 ns, >10 pulses/cycle




Specification

Amplitude adjustment: 5:1 (best effort for 10:1)

Post-pulse noise: <±5% for 15 ns, <±2% thereafter (over 2:1 tuning range)

Amplitude / timing jitter: <±5% / <±0.1 ns

| # Striplines | Nominal bend angle | Nominal Stripline Voltage | Power Supply Peak Voltage* |
|---|---|---|---|
| All 6 operational | 124 µrad | 11.7 kV | 15.9 kV |
| 5 out of 6 (#6 failed) | 156 µrad | 14.7 kV | 20.0 kV |

*includes increase to account for 12% cable losses and +20% contingency for tuning



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# Prototype Stripline

Prototype striplines under development to validate D-II design choices and test individual components:

- Rotated by 90 degrees
- Larger apertures to suit Diamond injection
- Single-skin vacuum chamber

<u>Stage 1</u> – Lab tests (Feb 2025)

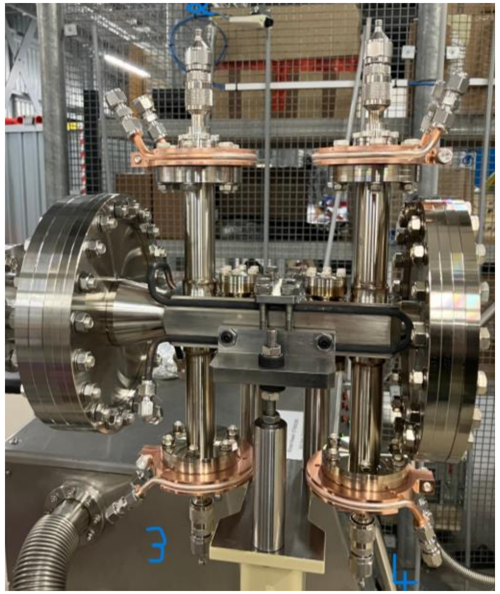
- S-parameter measurements validated simulations
- Pulser / cabling / feed-throughs successfully tested

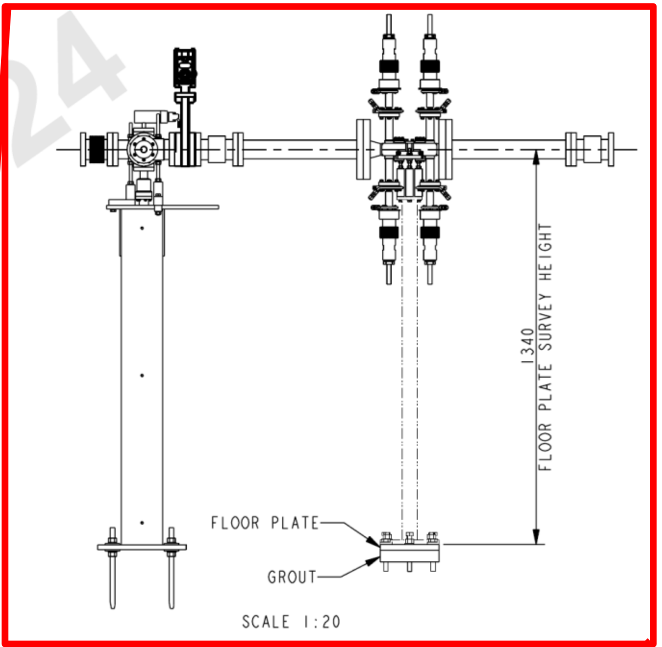
<u>Stage 2</u> – BTS tests (Spring 2025)

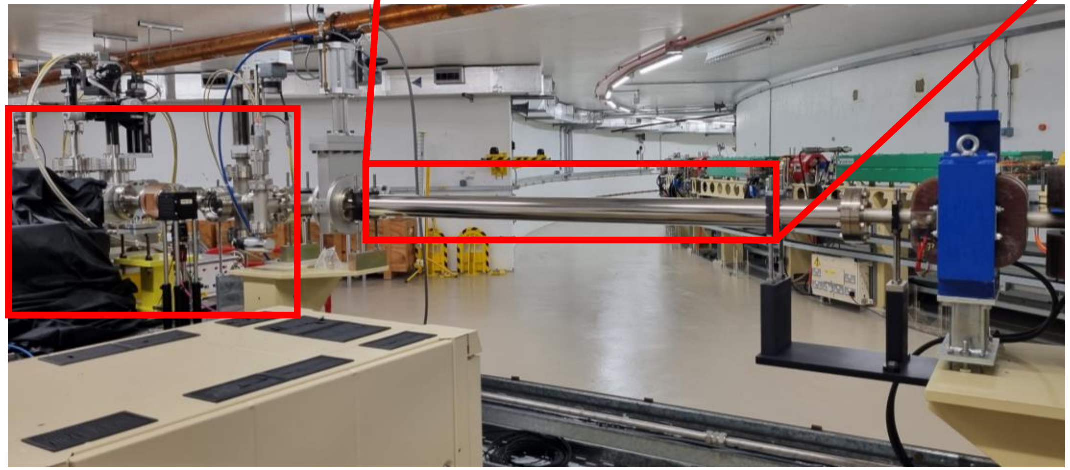
- Kick amplitude and field quality

<u>Stage 3</u> – Storage Ring tests (Summer 2025)

- Kick and cancel operation
- Impedance and beam dynamics





<u>BTS Test Stand</u>



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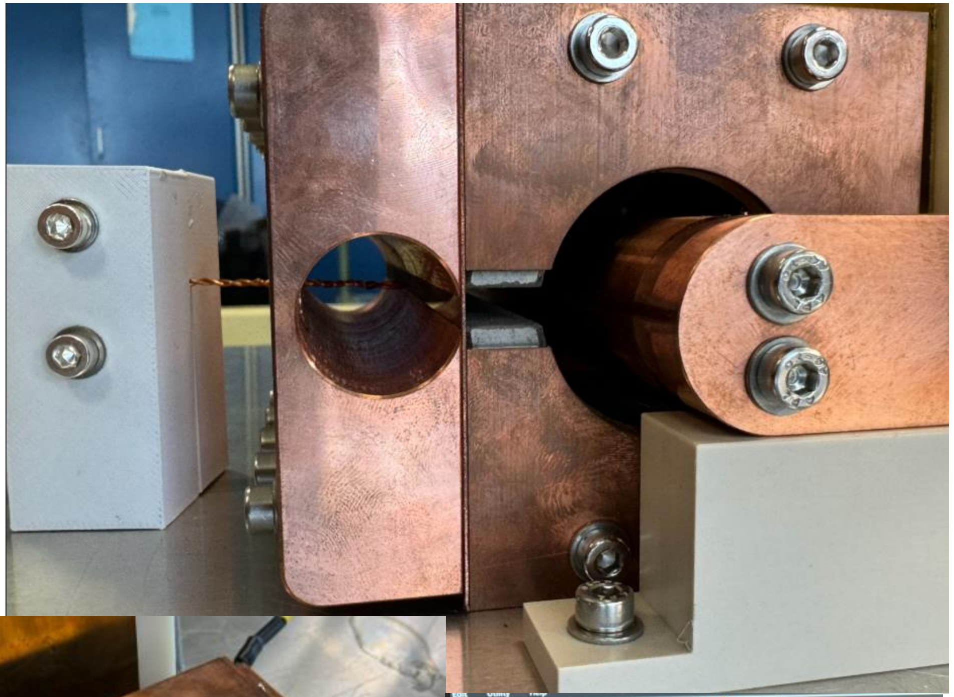
# Pulsed Thin Septum Magnet

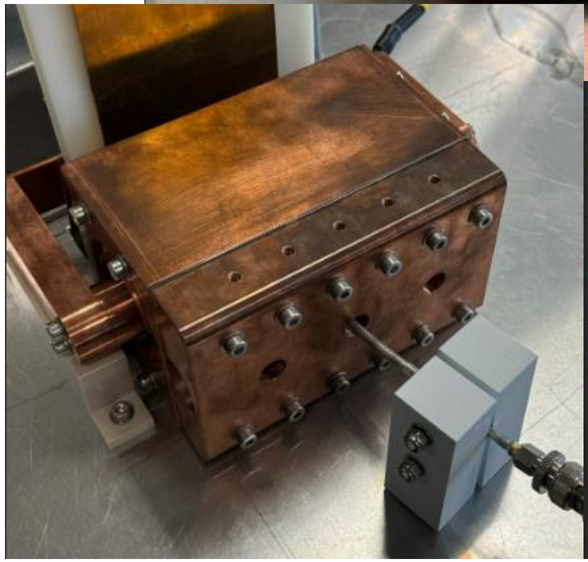
Thin electromagnetic septum (1 mm, in-vacuum)

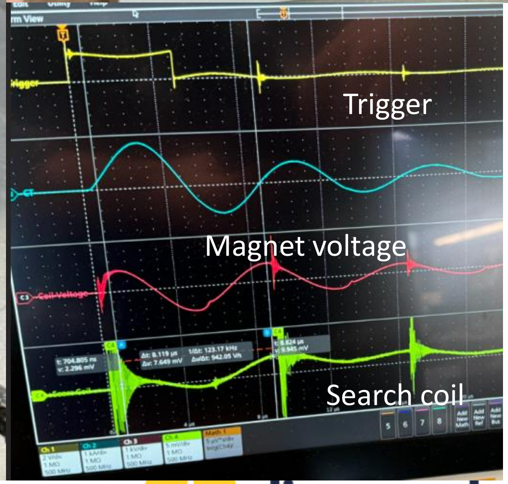
- 0.6 T, 400 mm long, 10 μsec full sine, iron powder core
- Targeting 10 μTm integrated leakage field for transparency

Prototype mock-up

- 120 mm long, full cross-section
- Tested shielding configuration examples:
  - 0.5 mm copper
  - 0.5 mm copper + 0.1 mm iron layers
  - 0.5 mm copper + 0.05 mm mumetal layers
  - 0.5 mm copper + 0.05 mm nanocrystalline layers
- Issues with power supply output (repurposed kicker PS)
  - noise in the measurements
  - clean full-sine pulse not possible
- Believe end leakage might be dominating, even in the centre of the magnet (no end shielding in mock-up)



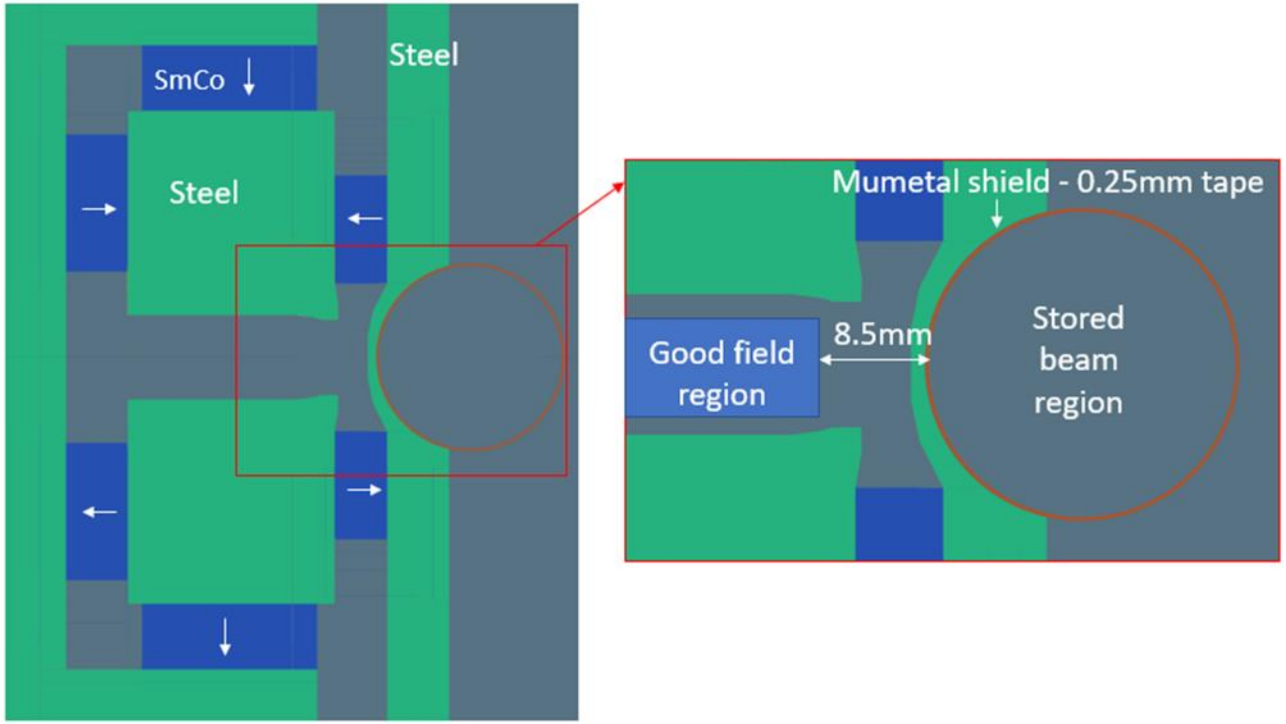


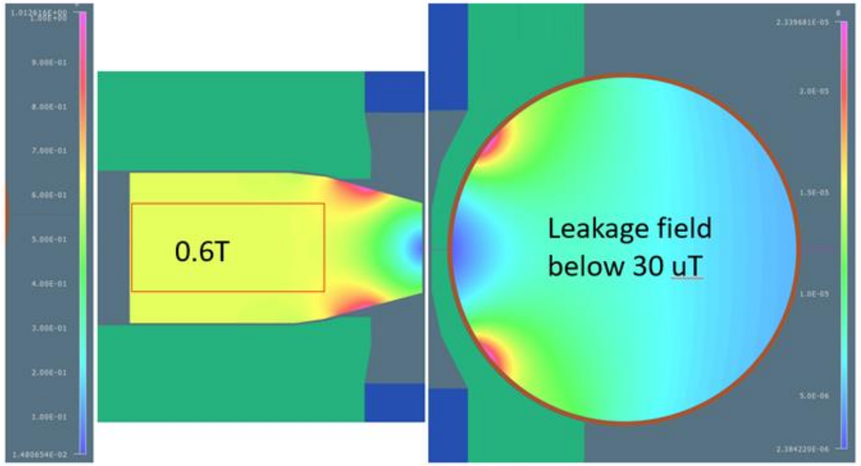


# Permanent Magnet Main Septum

<u>Thick PM septum (8.5 mm, out-of-vacuum)</u>

- PM septum reduces shot-to-shot jitter for injected beam position and angle
- Static leakage field eliminates disturbance during top-up
- Different strength modules to optimise shielding close to the stored beam (0.6 T end module, up to 1.5 T further away from the beam)
- Integrated (DC) leakage field: aiming <100 µTm
- Field tuning mechanisms under study:
    - ➢ Extra corrector in transfer line
    - ➢ DC EM module to replace 1T PM module
    - ➢ Mechanical shunts also possible but difficult to implement




Field uniformity and leakage in the end module (different scales)



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# Conclusions

Two injection schemes developed for Diamond-II

Updated 'classic' four-kicker bump scheme for commissioning and beam refills:

- Flexible, adjustable
- Can be single or multi-bunch injection (reduces fill-time and/or number of injection shots per cycle)
- Risk minimization: maintains fallback options; robust, proven technology

Transparent injection during top-up using single-bunch 'kick-and-cancel' injection:

- Only 1 bunch in 900 is kicked
- Can be installed / tested / developed separately from basic injection scheme
- Upgrade path for injection into potential future 'high-brightness' lattices

Several key technologies under development:

- In-vacuum eddy current thin septum
- PM out-of-vacuum thick septum magnet
- 150 mm striplines
- Few nanosecond pulsers from industry

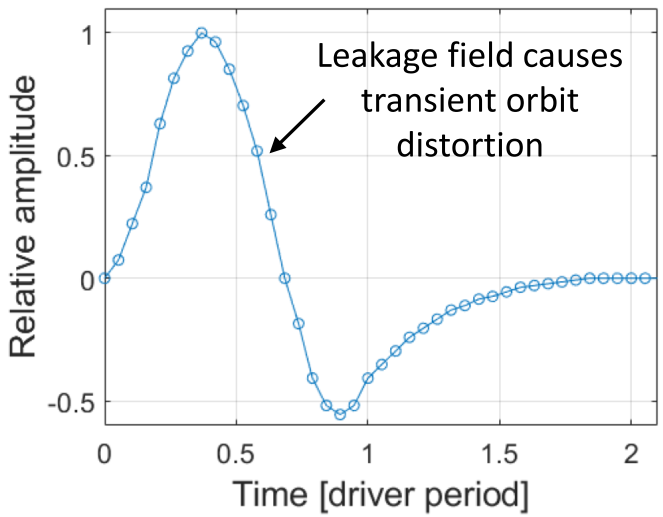
| Stage | Scheme | Mode |
|---|---|---|
| Commissioning | 4-kicker bump | Multi/single bunch |
| User mode - refill | 4-kicker bump | Multi/single bunch |
| User mode - top up | Kick-and-cancel injection | Single-bunch |
| Future brightness upgrade? | Kick-and-aperture-share | Single-bunch |

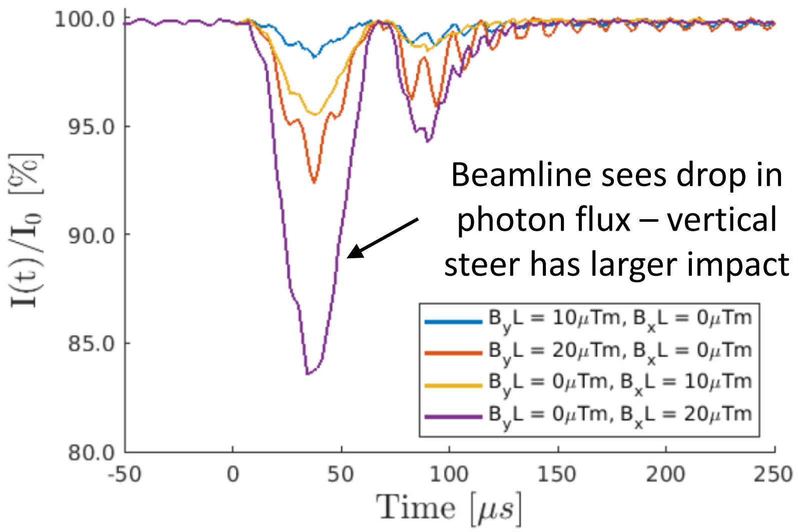
# Extra Slides

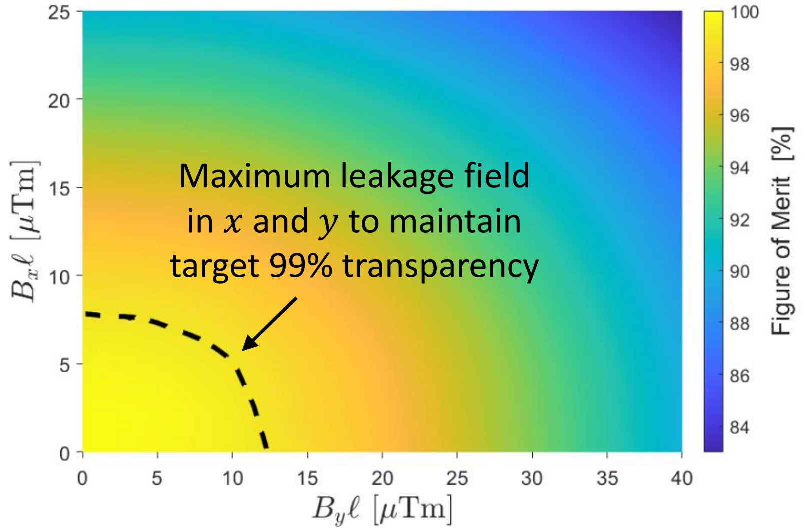
# Septum Leakage Field

Leakage field from the pulsed septum magnet can affect injection transparency:

- Impact studied during TDR phase assuming generic 100 us full sine pulse (SLS septum pulse shape assumed)
- Impact on any given beamline depends on local $\beta$ and phase advance between septum and source point
- Could add a compensation magnet to counter the leakage field, if required
- Leakage field depends on shield material and pulse duration $f$: $B_y(x) = B_y(0)e^{-x/\delta}$, $\delta = 1/\sqrt{\pi\mu\sigma f}$
  - ➢ Minimum septum pulse duration is defined by multi-bunch injection requirements
  - ➢ D-II plans for 180 bunch trains (360 ns) in multi-bunch injection (pulse duration irrelevant for SB inj.)



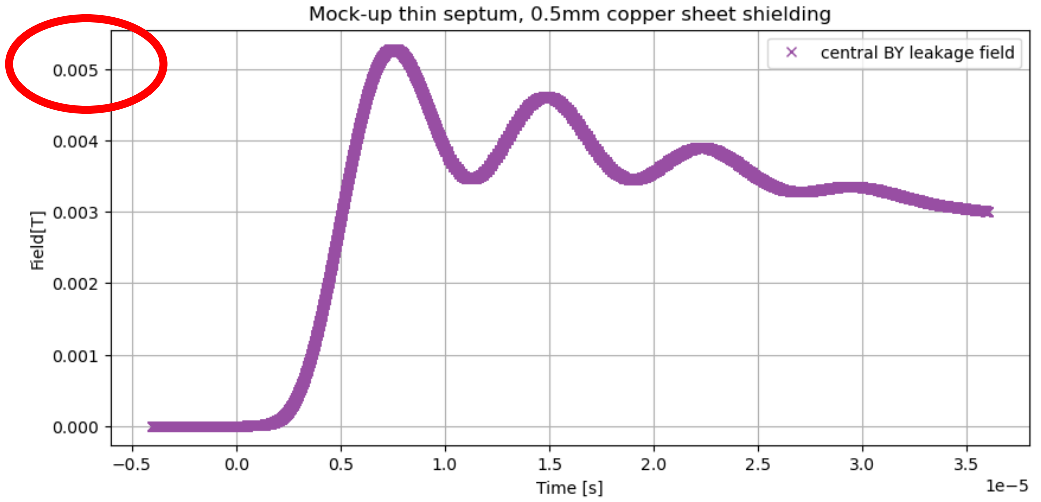



# Pulsed Thin Septum Magnet

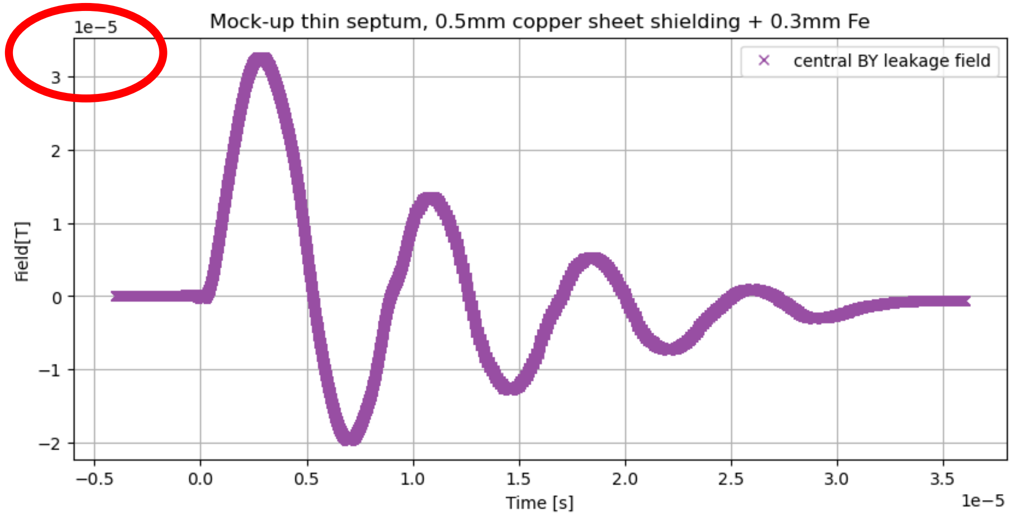
<u>Copper shielding only</u>

- Visible phase shift of the peak leakage field (matching opera predictions)
- Leakage dominated by field penetrating the copper septum blade




<u>Copper plus Iron shielding</u>

- No phase shift of the peak field (as expected)
- Leakage dominated by field penetraing openings/ends?




<u>No improvements with different other materials/layers:</u>

- Shielding with other materials did not match simulations
- All materials provided similar levels of shielding
- No improvement from increasing stacking layers



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