A Kick-and-Cancel Injection Scheme for Diamond-II

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Talk Outline

Introduction to Diamond-II

- Lattice details
- Requirements for injection
- Injection schemes and layout

Single bunch injection with fast stripline kickers for improved transparency during top-up

- ‘Aperture-sharing’ injection scheme
- ‘Kick-and-cancel’ injection scheme

Hardware overview

- Diamond-II injection striplines
- Pulser development
- Prototyping on Diamond

Diamond-II Lattice

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

Number of insertion straights increased from 24 to 48

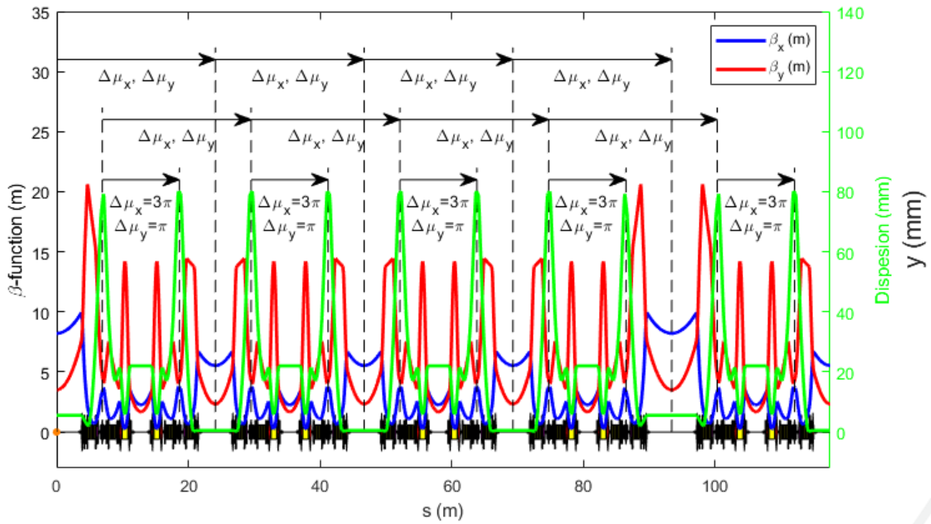
- ➢ Long straights: 7.54 m
- ➢ Standard straights: 5.06 m
- ➢ Mid straights: 2.92 m

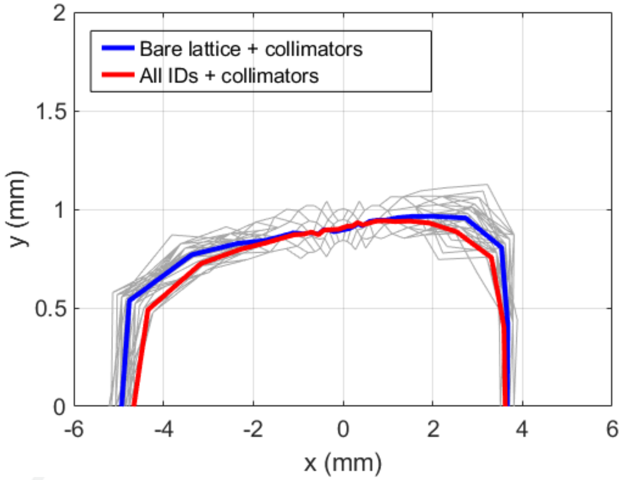
Off-axis injection for beam accumulation

'-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





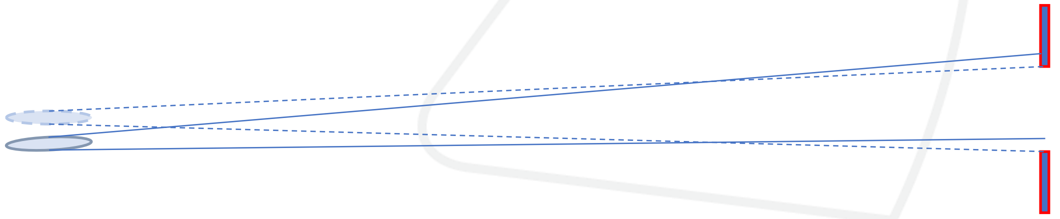
Injection Requirements

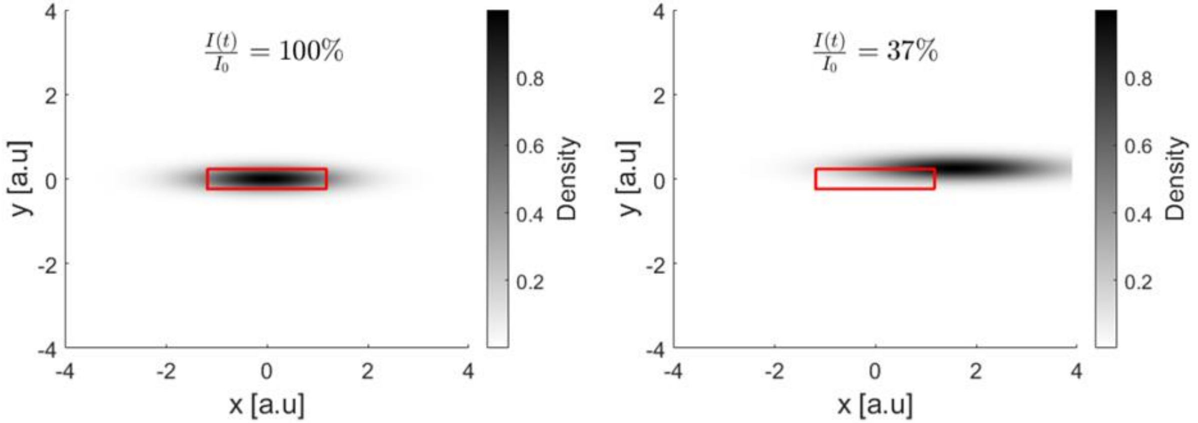
<u>Injection requirements:</u>

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"*





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Injection Schemes

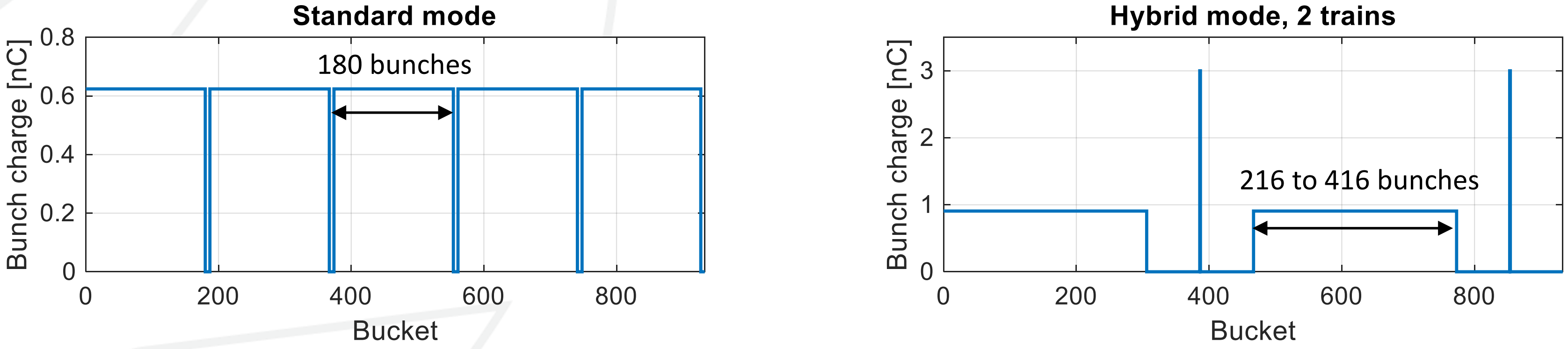
Diamond-II will operate two different injection schemes:

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

- Robust, proven technology
- 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) PM thick septum + pulsed thin septum + fast stripline kickers (single bunch only)

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



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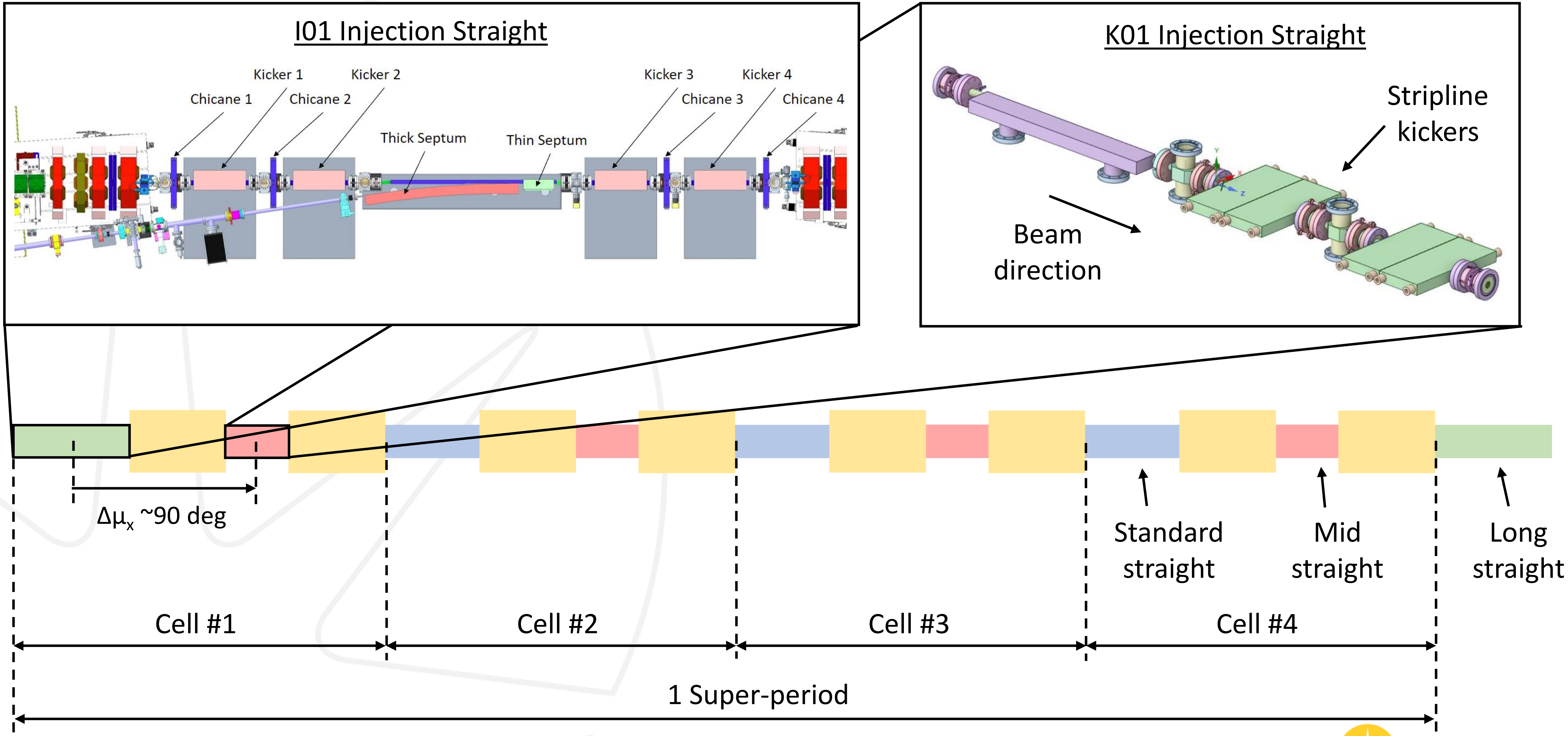
Injection Layout



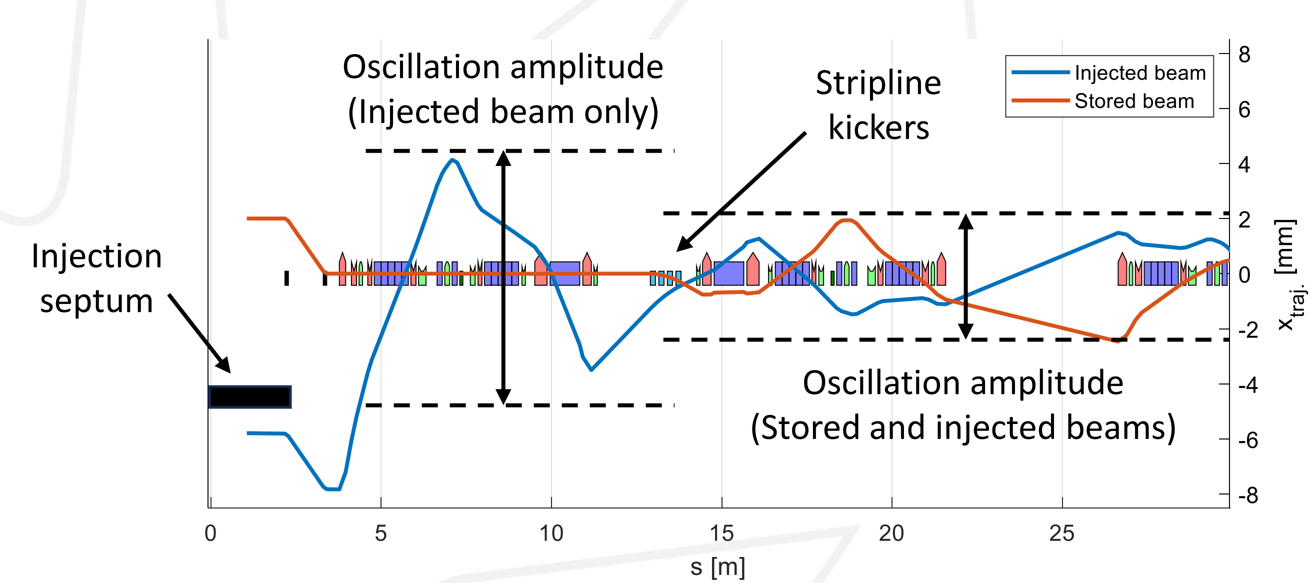
Single-Bunch 'Aperture-Sharing' Injection

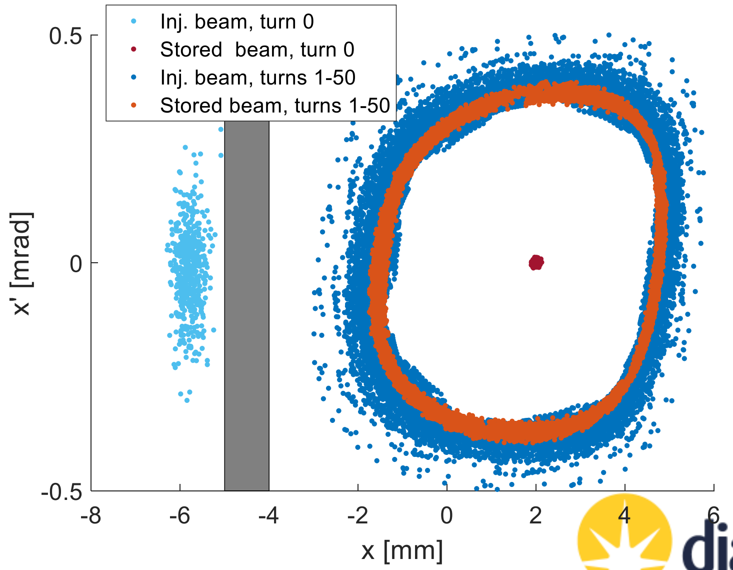
An aperture-sharing injection scheme was assumed during the Technical Design Report (TDR) phase:

- 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)

Stripline kicker and BTS optics matching parameters optimised from particle tracking:

- 175 μrad per stripline
- Pulse duration < 3 ns (zero to zero) to avoid kicking adjacent bunches ($L_{stripline}$ = 0.15 m / $\tau_{separation}$ = 2 ns)





Single-Bunch ‘Aperture-Sharing’ Injection

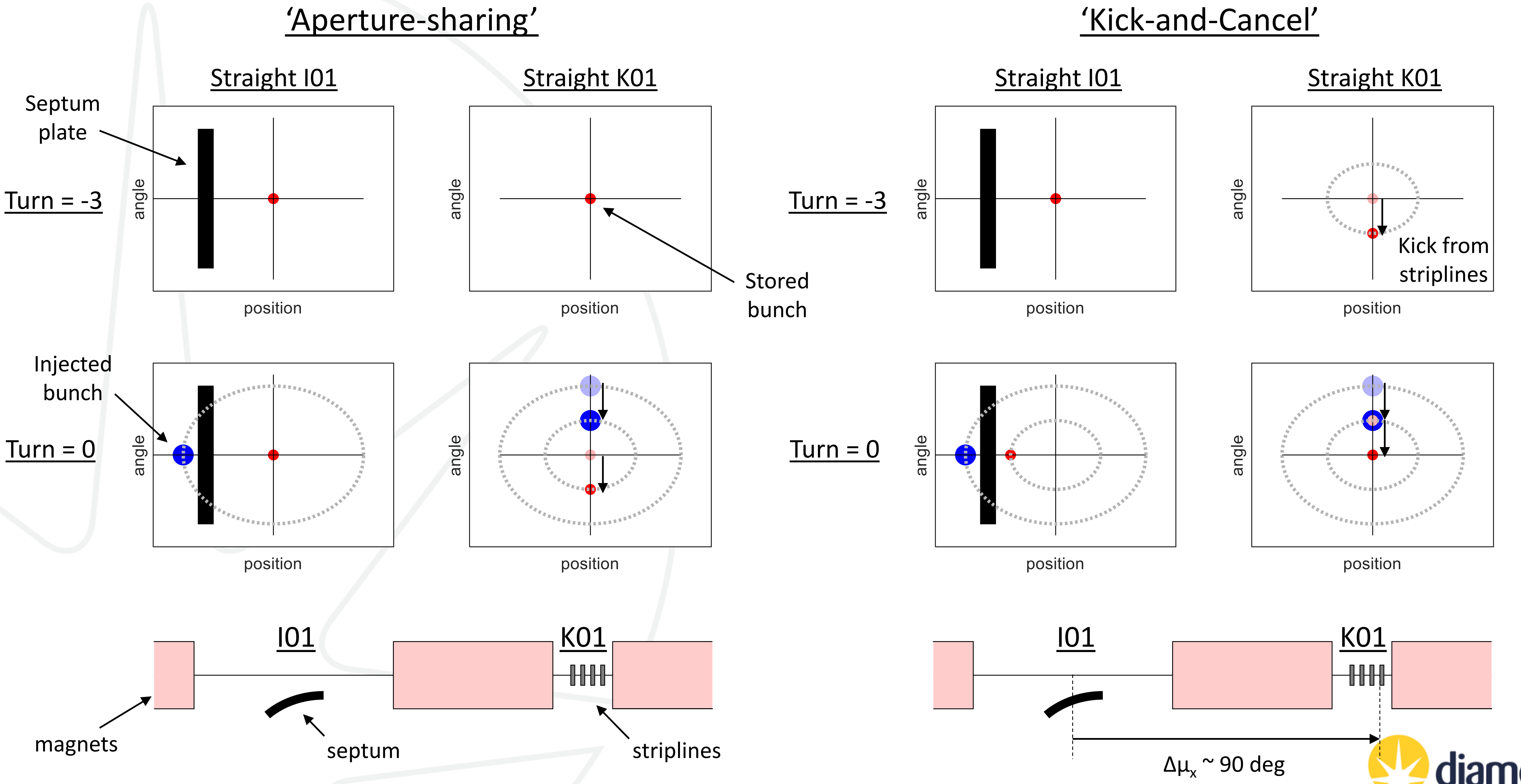
Issues with aperture sharing:

- 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

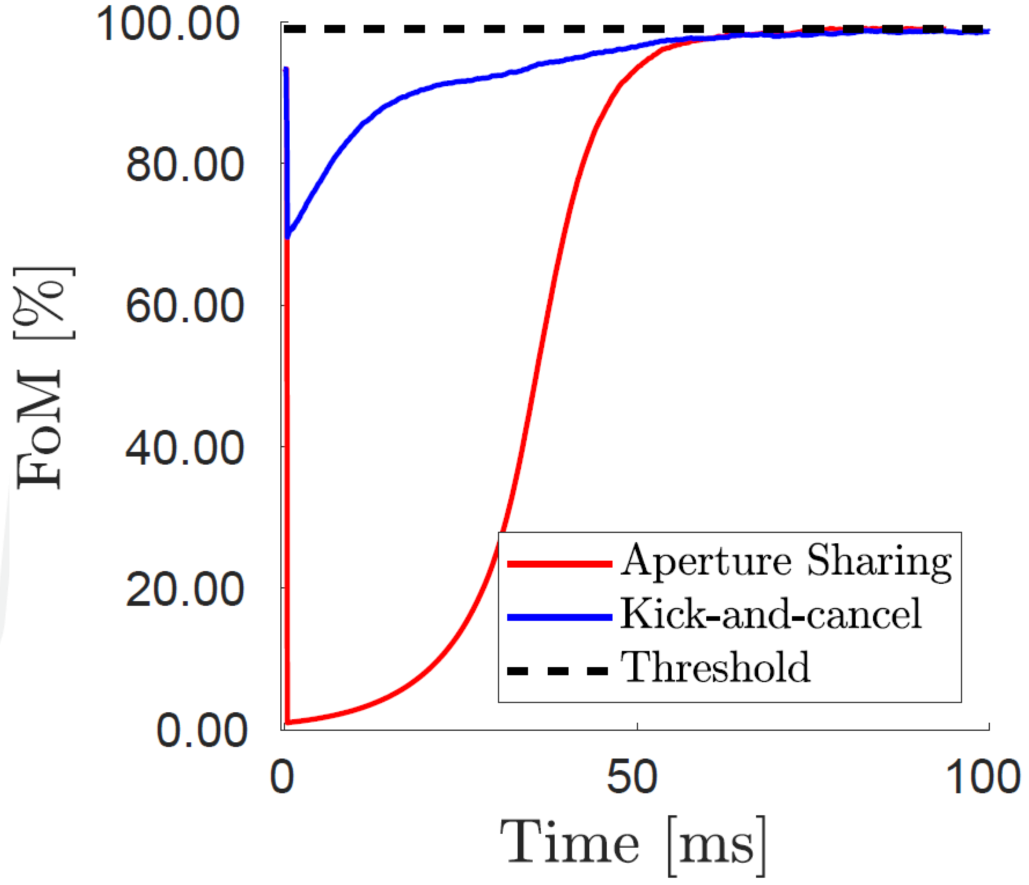
1) Give the stored bunch a pre-kick *n* turns before injection such that there is close to 180 degrees phase advance at injection
2) Injected bunch arrives as before:
    - stripline kicker still reduces injected bunch oscillation amplitude by ~factor 2
    - stored bunch is kicked back on-axis rather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

Single Bunch 'Kick-and-Cancel' Injection

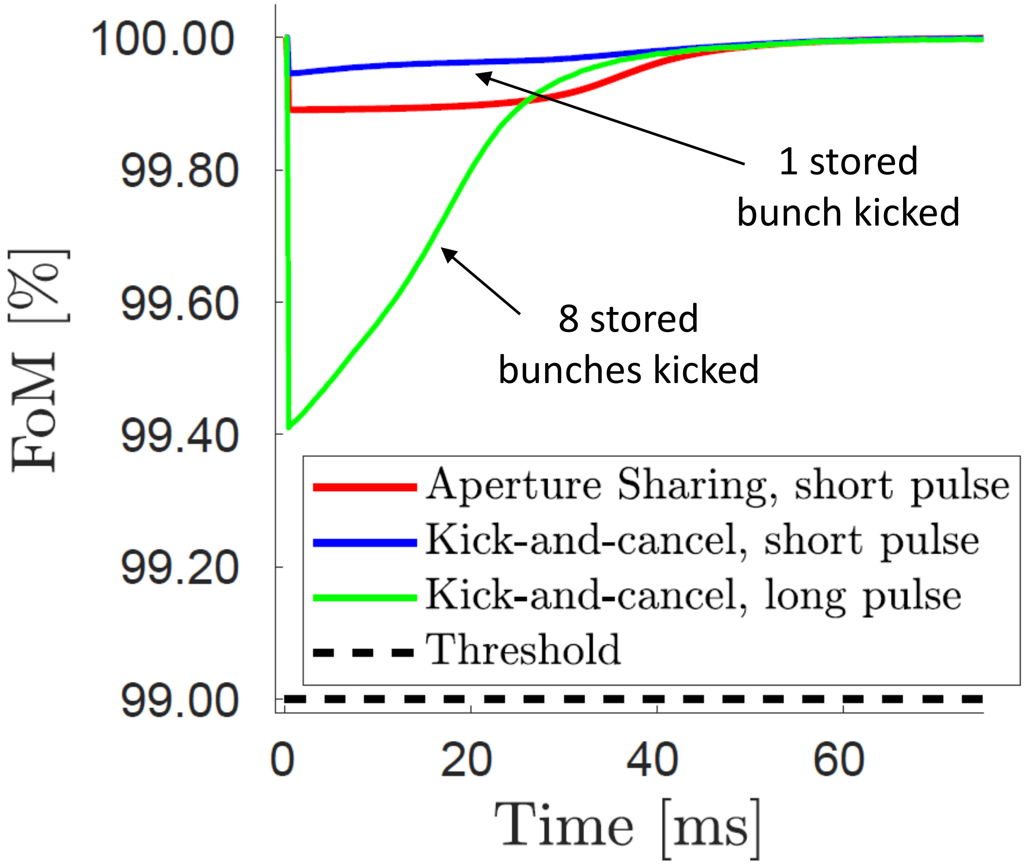


Brightness Comparison

Brightness Impact for Target Bunch
(single bunch)



Brightness Impact for Stored Beam
(900 bunches)



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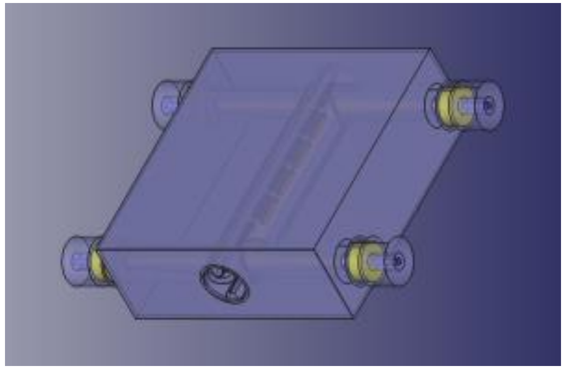
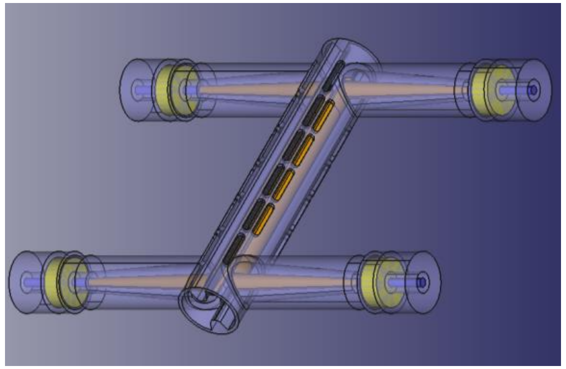
Injection Stripline Details

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

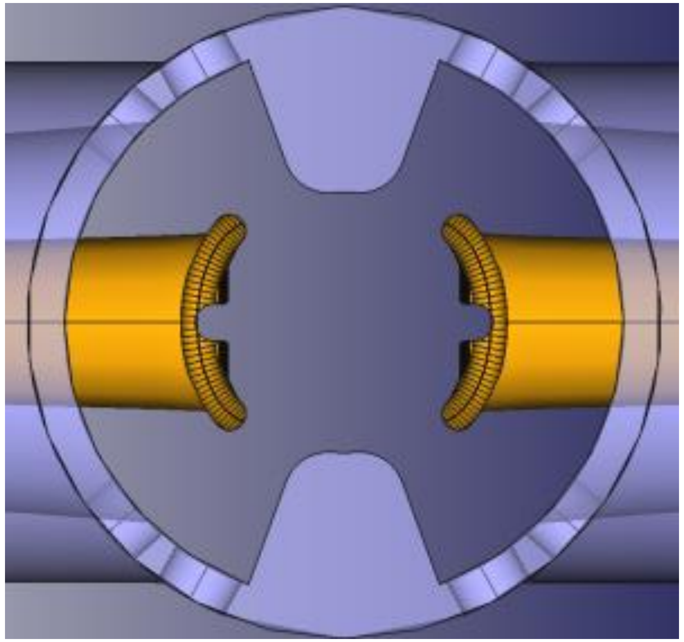
- Double skin vacuum tank
  - ➢ Large outer vacuum chamber
  - ➢ Internal beam pipe with pumping grills





Stripline details:

- 0.15 m stripline length, 0.18 m per module
- Circular arc radius 7 mm for stripline blades and vertical inserts
- Flat central section 6.2 mm from beam axis 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

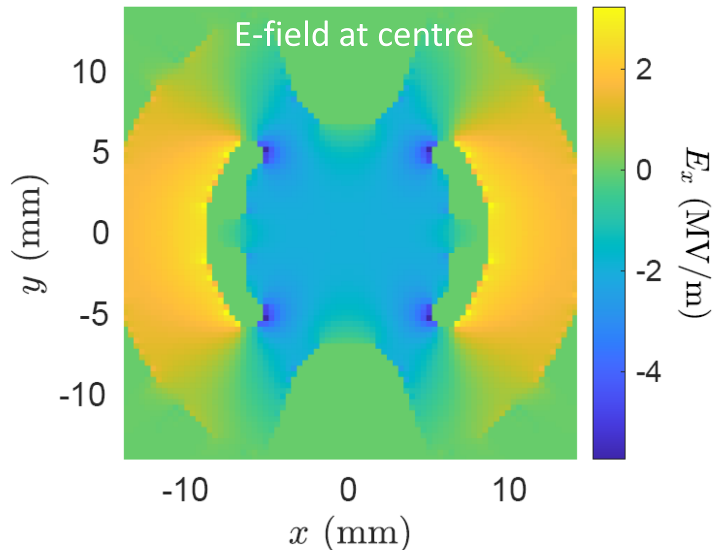


More information: *R. Fielder et al., FLS'23, Lucerne, MO4B3, Aug 2023*

Pulser Requirements

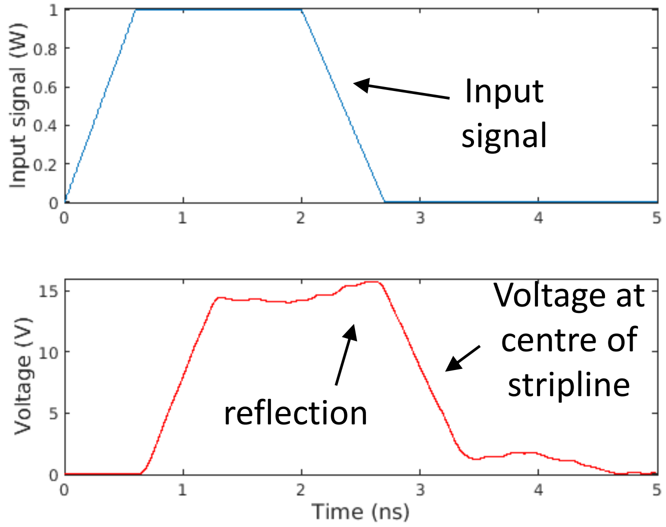
Tracking with field map

- GdfidL **E/B** fields have been converted into AT2 kickmaps
- Fields are sliced longitudinally to capture fringe fields
- Each slice is time-aligned to the bunch passage to maximise the overall bunch deflection
- Reflections in the structure are included
- Results used to verify field flatness and calculate voltage requirement for nominal bend angle (175 µrad/stripline)
- Pulser specification: ±10.5 kV to ±20.0 kV



Required Voltages for Aperture-Sharing Injection Scheme

Configuration	4 Striplines (design)	3 Striplines (reserve)
80% of Nominal	±10.5 kV	±14.1 kV
Nominal	±13.2 kV	±17.6 kV
120% of Nominal	±15.8 kV	±21.1 kV



Pulser Prototype

Prototype SiC FET pulser under development with Kentech Ltd., developed in stages.

Aim to confirm basic parameters:

- Pulse duration and amplitude tuning range
- Amplitude and timing jitter
- Burst mode (2-10 pulses per cycle with controllable delay)

Parameter	Stage 1	Stage 2	Stage 3
Peak voltage	+2.5 kV, 50 Ω load	±4 kV, 50 Ω load	±20 kV, 50 Ω load
Pulse width (5%-5%)	<=15 ns (<3 ns ultimate target)	<=4 ns (<3 ns ultimate target)	<=4 ns (<3 ns ultimate target)
Post pulse noise	<±5 % for 15 ns, <±2 % thereafter	<±5 % for 15 ns, <±2 % thereafter	TBC
Amplitude adjustment	2:1 (best effort for 5:1)	2:1 (best effort for 5:1)	TBC
Minimum re-trigger delay	1.5 µs	1.5 µs	1.5 µs
Minimum delay between pulses	1.5 µs	1.5 µs	1.5 µs
Pulse repetition frequency	1 kHz (5 Hz for Diamond-II)	1 kHz (5 Hz for Diamond-II)	1 kHz (5 Hz for Diamond-II)

Pulser Prototype

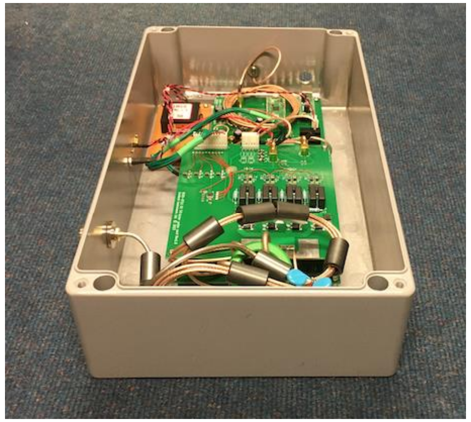
Basic design is a series / parallel array of solid-state switches

- Uses an inductive combiner
- Short-circuit and arc tolerant

Agile pulse control system updates hardware parameters after each trigger

- ~1 µs to complete
- Pulse amplitude controlled individually within the burst by switching between set of voltages
- Digital system sets the switch drive pulse width
- Embedded controller (RP2040) has a PC interface via which pulse parameters can be programmed
  - ➢ Diamond staff to implement EPICS interface in later stages

Timer detects when burst is over and the system resets for the next burst.



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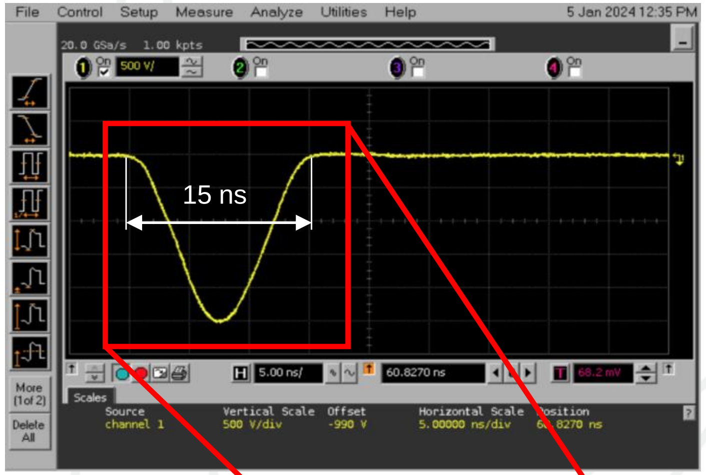
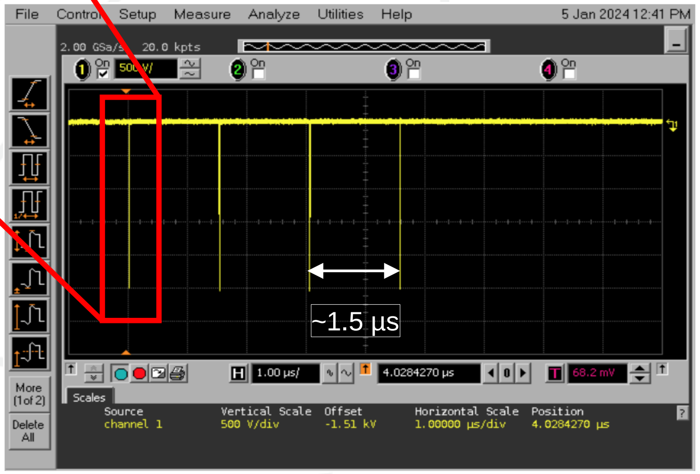
Pulser Prototype

Stage 1 Prototype

(complete)



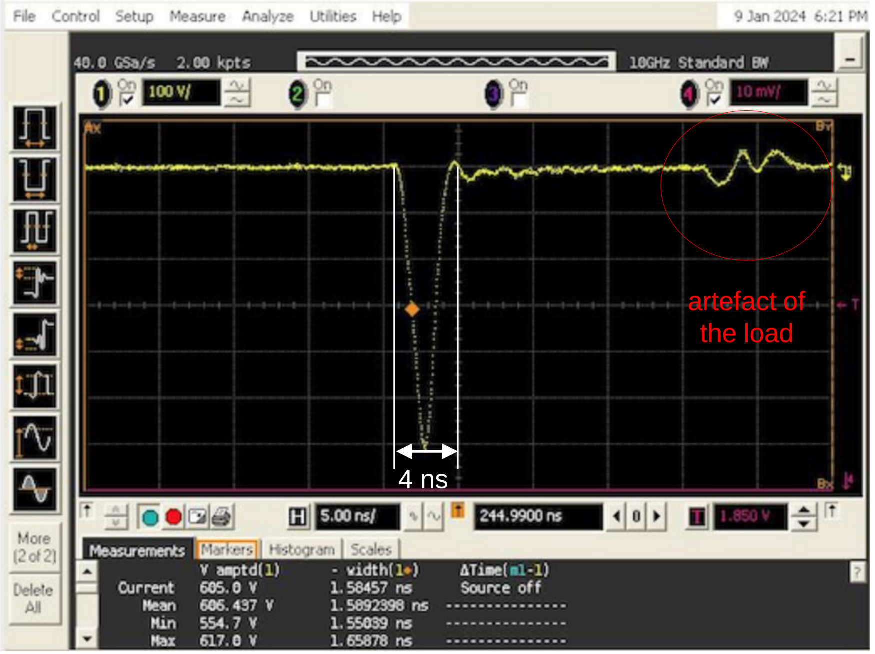
+2.5 kV into
50Ω load



Burst of 4 pulses with
1.5 µs spacing matched
in amplitude

Stage 2 Prototype

(in progress)



Modified version of the driver from a single switching device.

An array of such stages is being assembled to produce bipolar output of ±4 kV.

Attempt to reduce post-pulse noise using pulse forming network.

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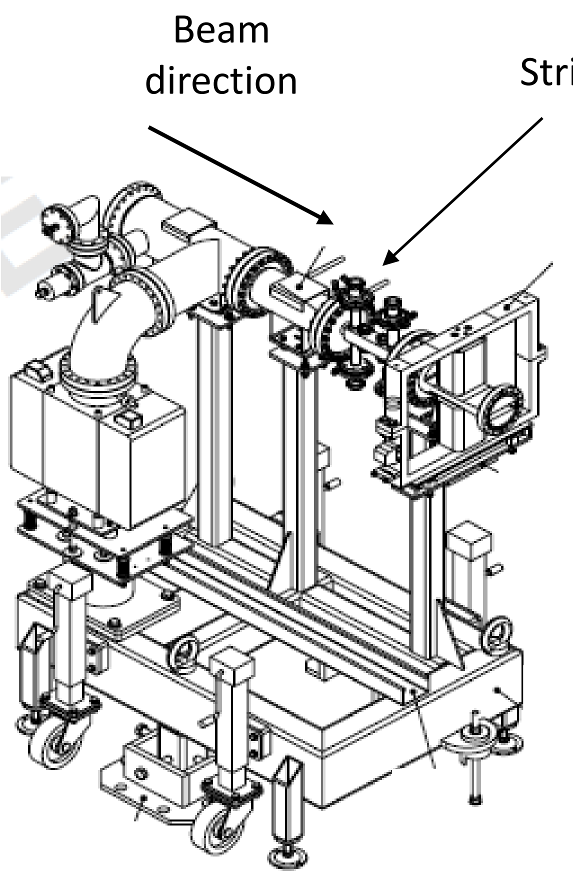
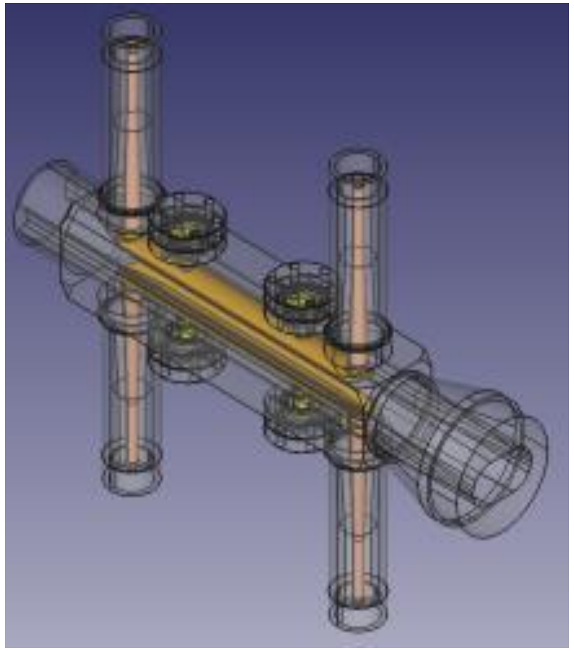
Prototype Injection Striplines in Diamond

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





Differences w.r.t. to D-II injection striplines:

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

Feed-throughs:

- Up to ±20 kV pulsed operation for D-II
- 1 GHz bandwidth for ns rise/fall times

APS-U design, supplied by Cosmotec (specified to 25 kV)

Prototyping Timeline

Plan to test components in stages:

Stage 1 – Lab tests (summer 2024)

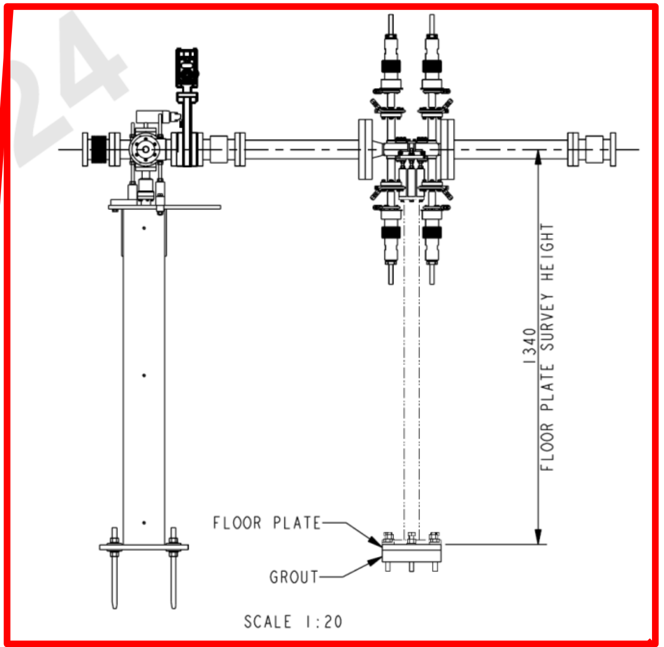
- S-parameter measurements to validate simulations
- Vacuum tests
- Pulser characterisation

Stage 2 – BTS tests (autumn 2024)

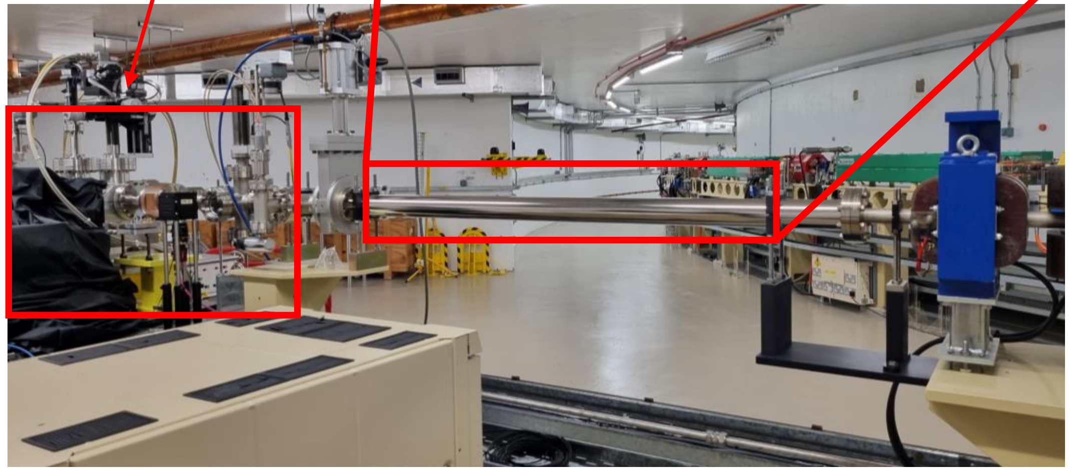
- Kick amplitude and field quality

Stage 3 – Storage Ring tests (early 2025)

- Induced heating from stored beam
- Impedance and beam dynamics



BTS Test Stand



Conclusions and Future Work

Two injection schemes developed for Diamond-II

Updated 'classic' four-kicker bump scheme for commissioning:

- Flexibility & adjustability
- 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 possible 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	
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?	Multi-kick aperture-sharing	Single-bunch

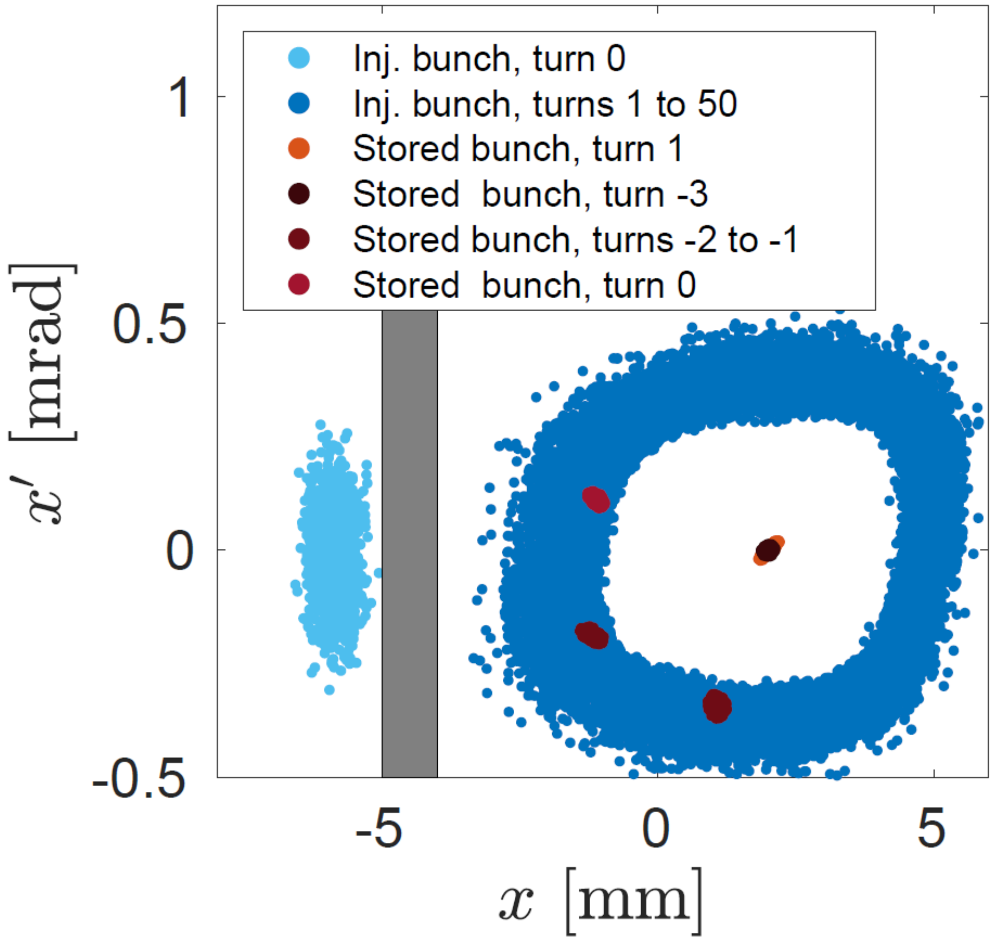
Extra Slides

‘Kick-and-Cancel’ vs. ‘Aperture-Sharing’

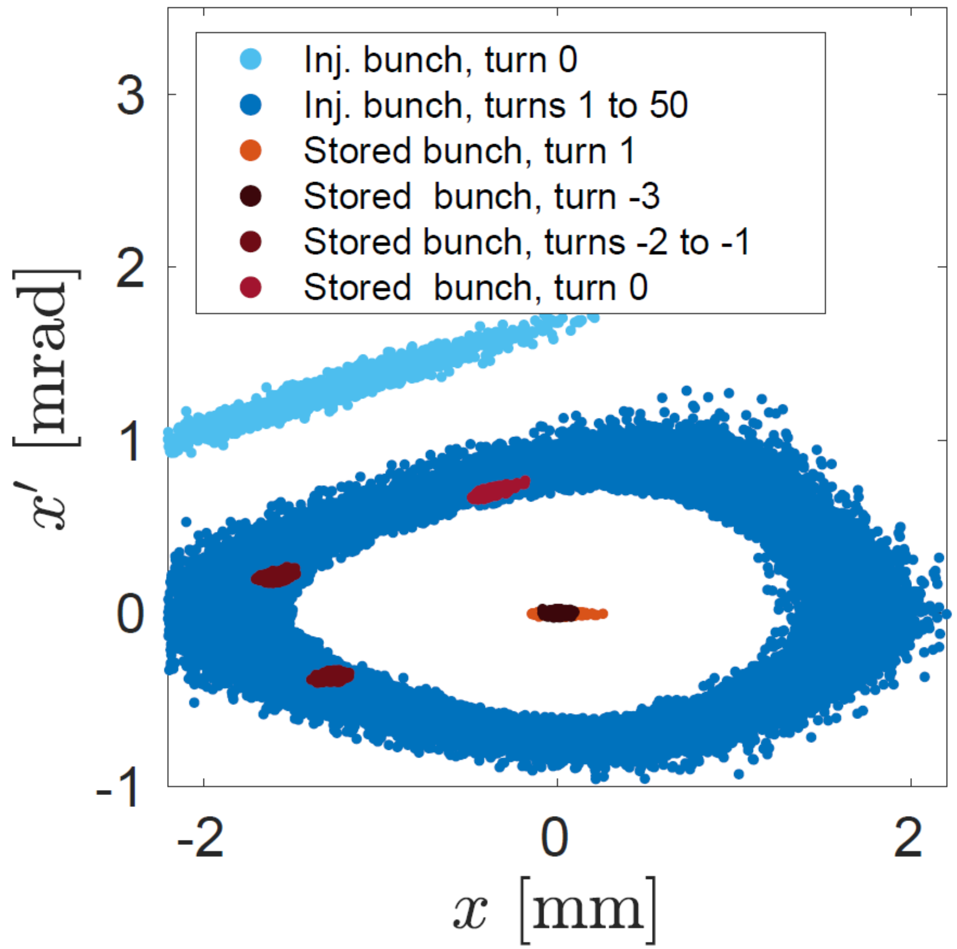
Pros	Cons
Improved overall transparency as only injected bunch continues to oscillate	Pulser needs to deliver multiple pulses
Improved transparency for hybrid bunch	Technology limit: 3 ns in multi-pulse mode challenging
Reduced transverse wakefields / interaction with TMBF as stored bunch is back on-axis	Cancellation unlikely to be perfect (stripline jitter, nominal Q_x does not give 180 deg, rise/fall bunches have diff. tunes)
Potential to operate as a hybrid scheme by combining aperture-sharing and kick-and-cancel ideas	Sensitive to decoherence for stored bunch

‘Kick-and-Cancel’ Phase Space Plots

Phase space at septum exit (I01)



Phase space at stripline entrance (K01)



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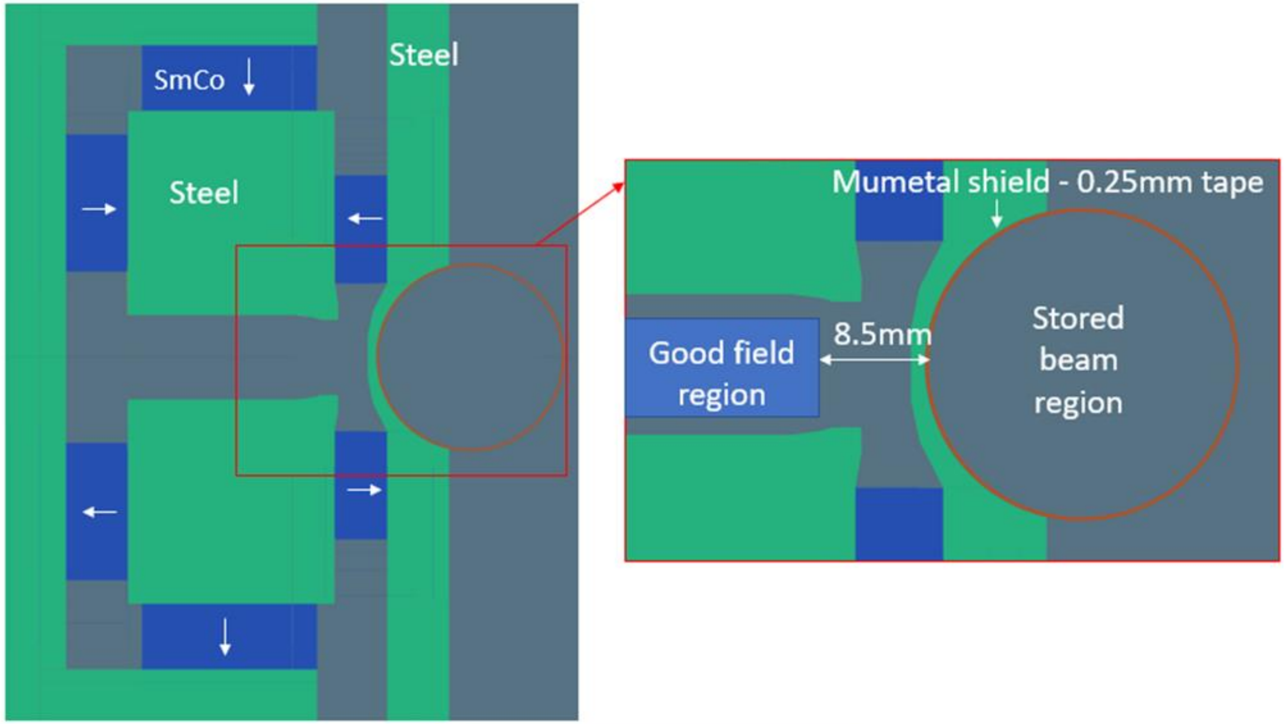
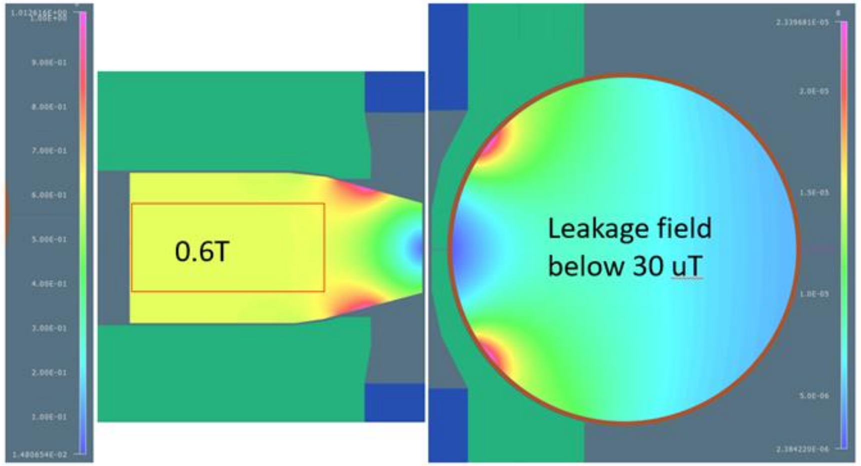
Permanent Magnet Main Septum

<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 leakage field: aiming <100 µTm
- Field tuning mechanisms under study:
  - ➢ Electromagnet?
  - ➢ Mechanical shunts?





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

Thin Septum Magnet

Thin electromagnetic septum (1 mm, in-vacuum)

- 0.6 T, 400 mm long, 10 μs full sine, 6 mm gap
- Yoke material challenging, currently working with Iron Powder cores:
    - first samples procured
    - vacuum tests and intended small scale pulsed tests
    - machining trials
- Dimensions specified to keep pulse voltage <10 kV
- Simulated saturation within material limit (soft 1.5T)
- Shielding:
    - copper plate acts as primary shield
    - Mu metal tube for circulating beam?

Thin Septum model