Injection Hardware Challenges of Low Emittance Rings – SLS 2.0 Injection Elements

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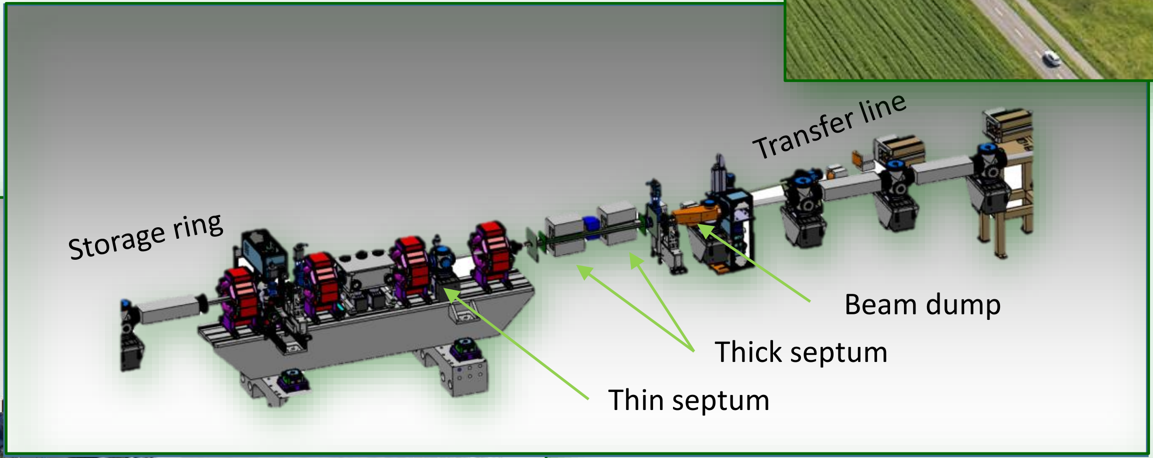
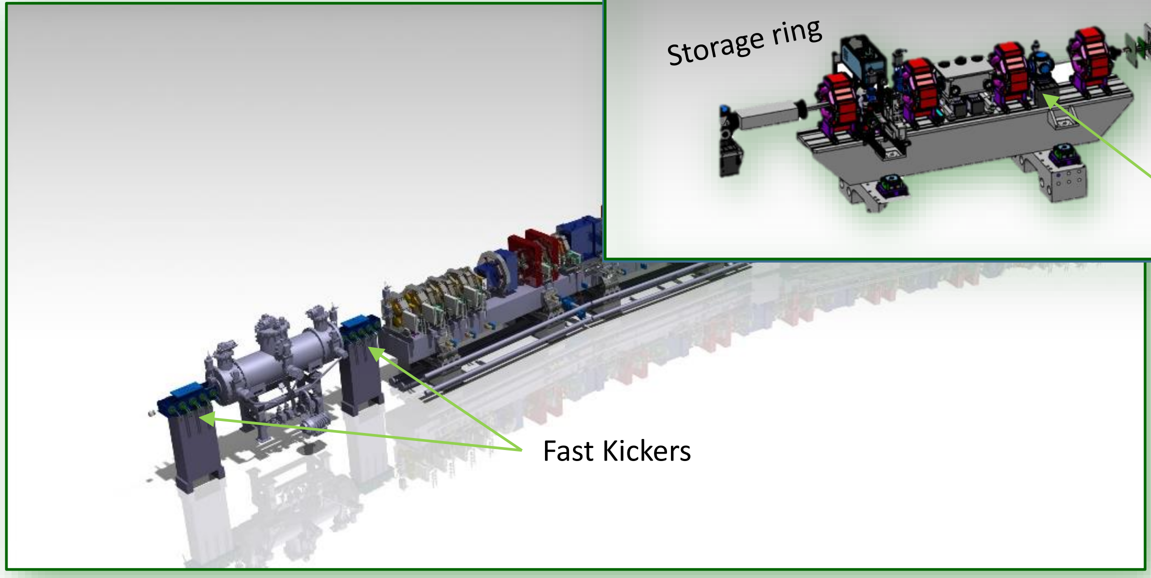


Injection straight



Straight two

Why is it Necessary to Upgrade Injection Hardware?

Injection in small dynamic aperture

Due to the new SLS 2.0 low emittance lattice the beam acceptance of the machine is reduced. A thin septum should make the conventional 4-kicker bump injection possible [1].

→ **Improved septa**

Top-up injection transparency

Advanced injection modes like fast injection and on-axis injection will improve further top-up injection transparency [2].

→ **Fast injection elements**

Beam dump

Due to the much smaller dispersion in the arcs (compared to SLS 1) an RF phase inversion-based beam dump might not be acceptable, causing beam loss and irradiation of sensitive devices like superconducting superbends and in-vacuum undulators. To avoid deterioration or damage, a dedicated beam dump magnet should deflect the beam towards well shielded beam dump.

→ **Dedicated beam dump**

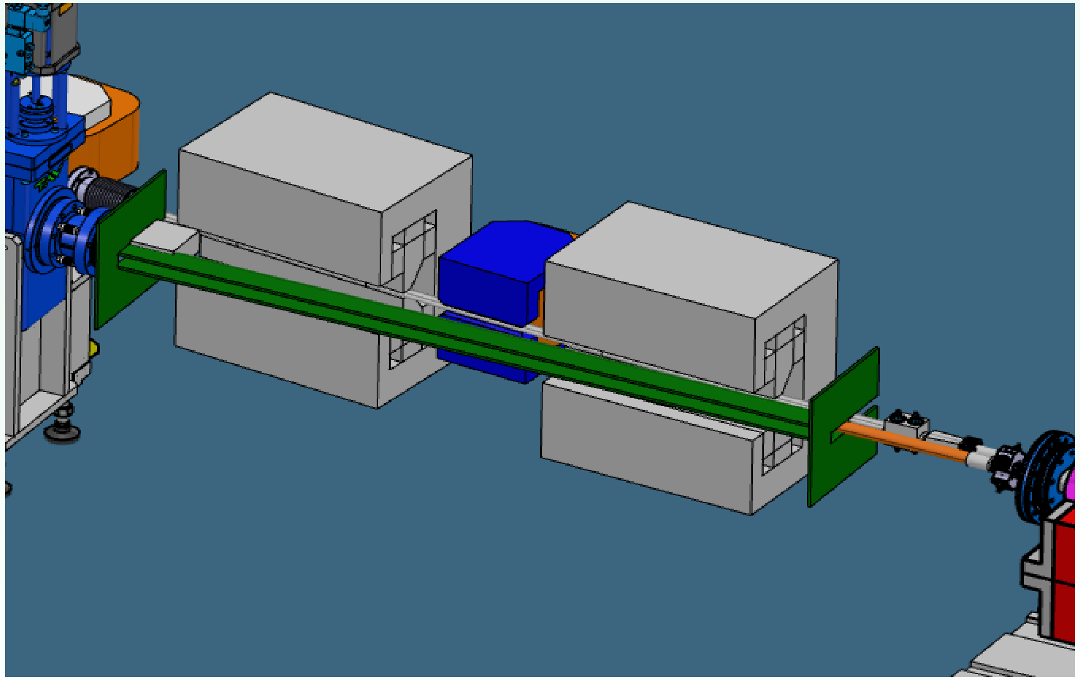
SLS 2.0 Permanent Magnet-based Thick Septum

Permanent magnet-based septum will ensure the necessary stability and deflection of the injected beam benefiting from practically maintenance-free device. Advance magnetic materials like CoFe high magnetic saturation alloys make possible to screen the dipole field in the stored beam region.

- Split septum design with and electrical corrector in the middle
- Soft magnetic material sandwich-shielding for the stored beam

Thick Septum Specification

Parameter	Thick Septum
Gap, mm	10
Magnet length, m	2x 0.35
Bending angle, mrad	120@2.7 GeV
Field integral, T.m	1.1
Gap field. T	1.57
Permanent magnets' type	Sm_2Co_{17}
Target zero-field integral, µT.m	50
Shielding coefficient, -	>20000
Temperature stability, ppt/K	0.1

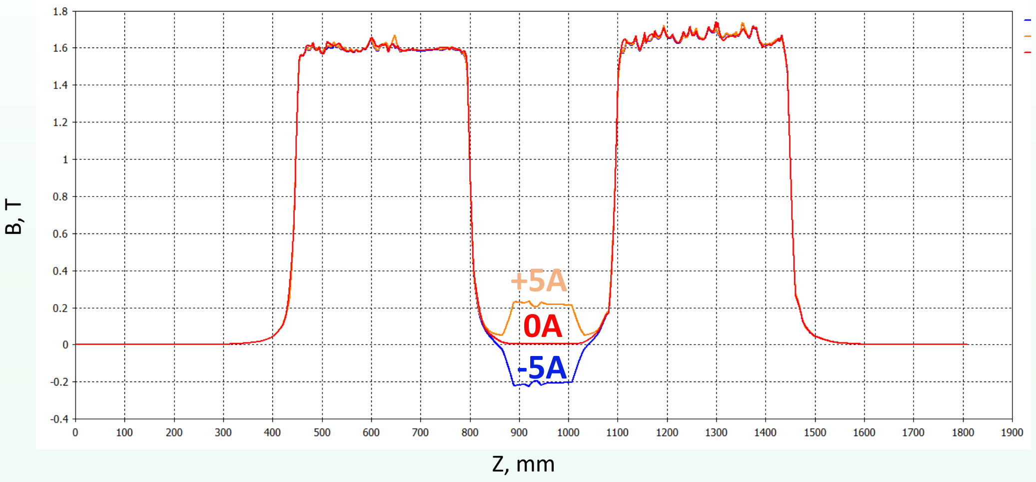


Thick septum 3D model

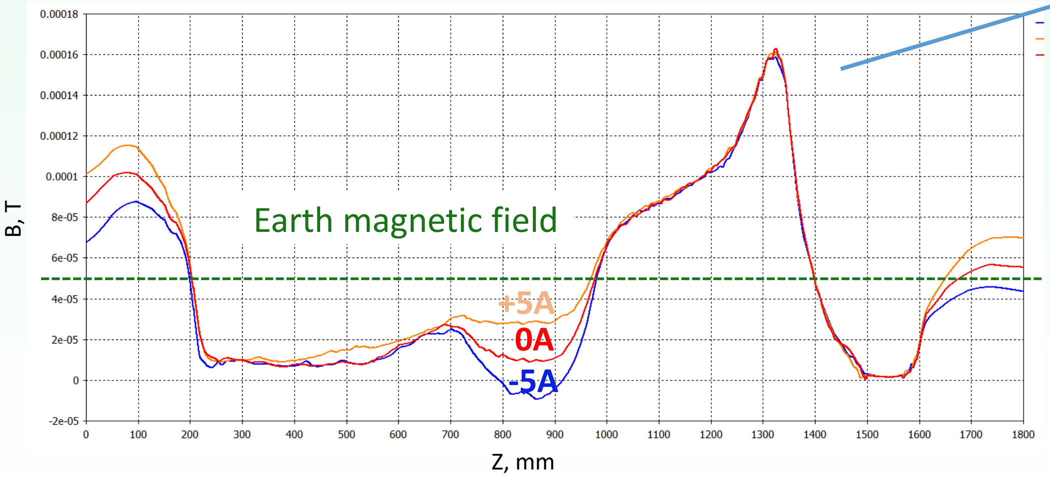
SLS 2.0 PM-based Thick Septum

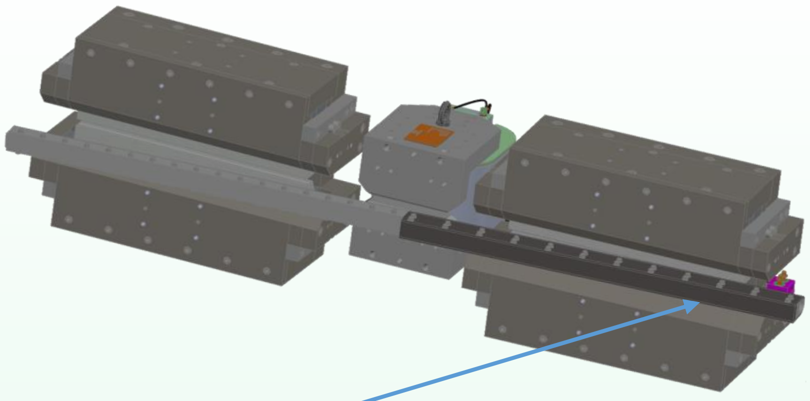
Combine magnetic performance

Main field



Leakage field



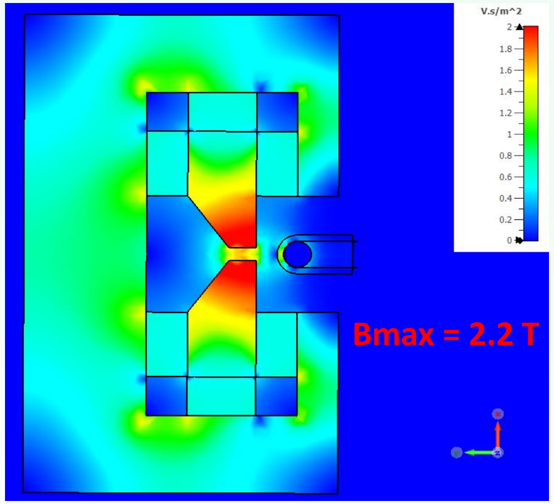


Field Integral
(for given corrector setting):

+5 A: 1.22 T.m (2.7%)
0 A: 1.19 T.m
-5 A: 1.15 T.m (-3.1%)

Leakage field Integral
(for given corrector setting):

+5 A: 94 μT.m
0 A: 84 μT.m
-5 A: 76 μT.m



Magnetic simulation
Smallest distance between beams ~35 mm.
Air gap is important.

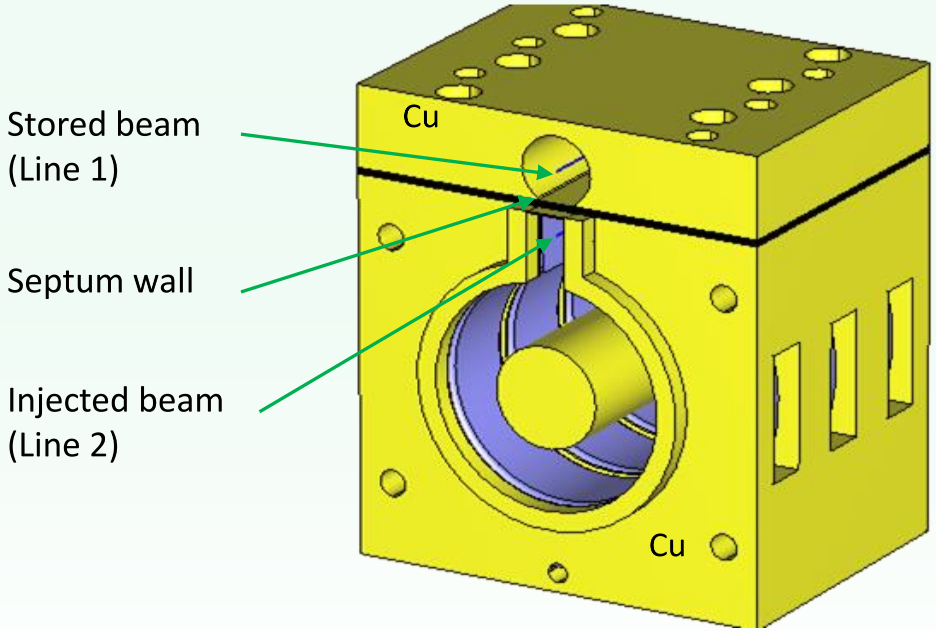
SLS 2.0 Thin Septum

Very thin eddy current septum should ensure inserting the injected beam very close to the stored beam with preferably no disturbance.

Thin Septum Specification

Parameter	Thin Septum
Septum thickness, mm	1.0
Magnet length, m	0.3
Gap, mm	6.0
Magnet length, m	0.3
Bending angle, mrad	15@2.7 GeV
Field integral, T.m	0.135
Gap field. T	0.45@2.7 kA
Pulse length (period), µs	12.5 (full sine)
Maximum zero-field integral, µT.m	2.37
Shielding coefficient, -	>50000
Stability, ppt	1.2

- Distance between injected and stored beam only 3 mm.
- Very thin septum wall - 1 mm
- Good magnetic screening



Three sections of SLS 2 thin septum prototype 3D CST® magnetic model

Eddy current septum numerical simulations

Powder cores are chosen for the magnetic circuit to cover the frequency and the filed strength requirements.

3D electromagnetic numerical simulations were used to optimize the screening of the thin septum.

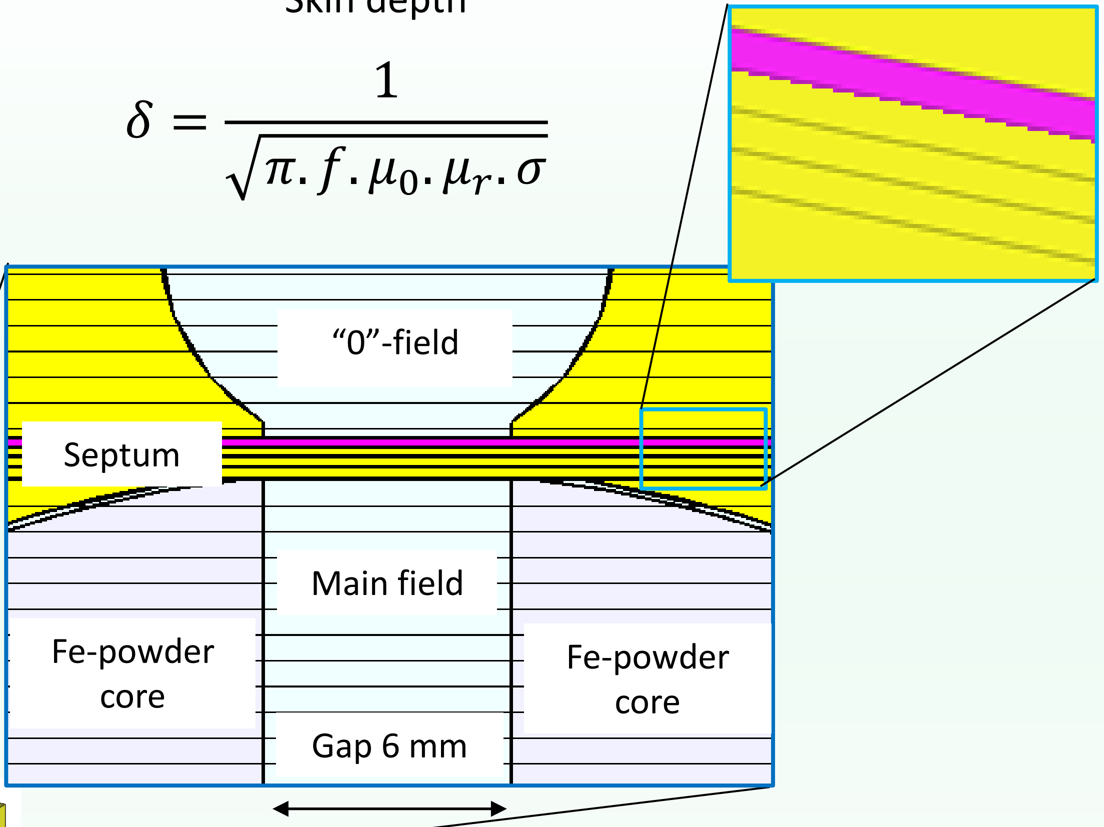
The credibility of the simulation results depends a lot on the correct material model. Choosing the proper material model parameters proved itself difficult since this information is usually not readily available.

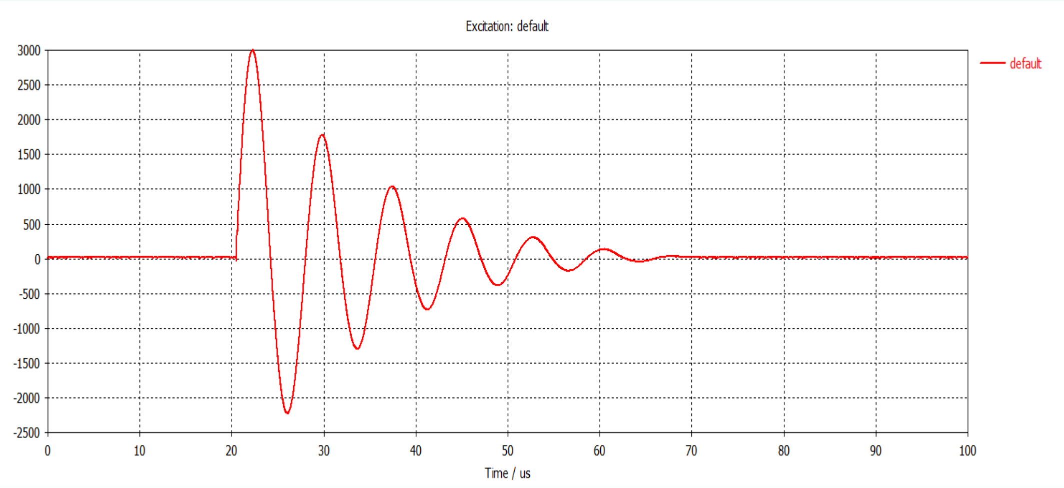
Skin depth

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

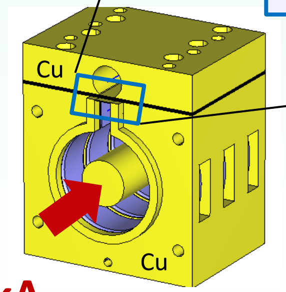
Legend:

Septum’s 4-layers





Excitation pulse



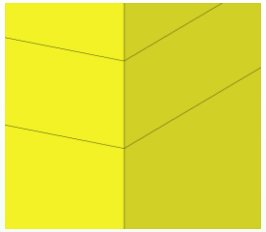
Ip = 3 kA

Electromagnetic model of the thin septum
Courtesy of S. Dordevic

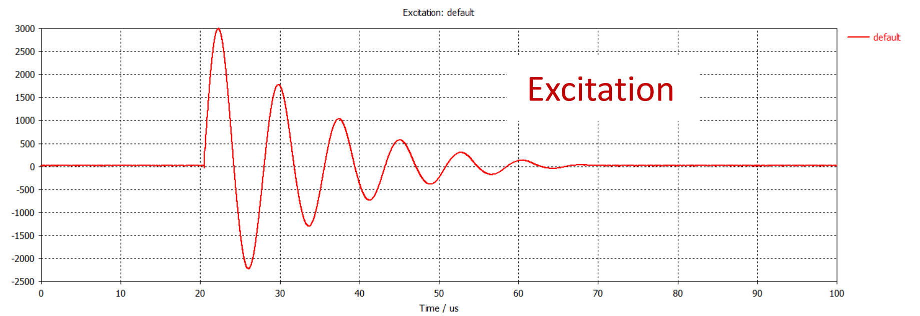
Conductivity limitation

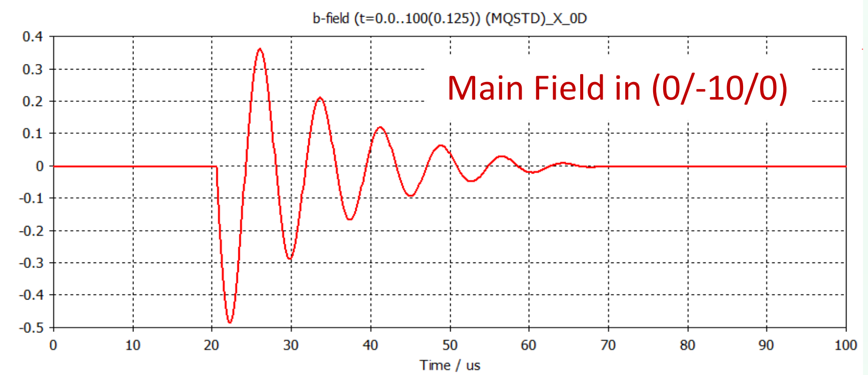
One mm of cooper does not provide the required screening. No other engineering material (at room temperature) could provide much better conductivity. (Silver is only ~6% more conductive and will not give significant skin depth reduction.)

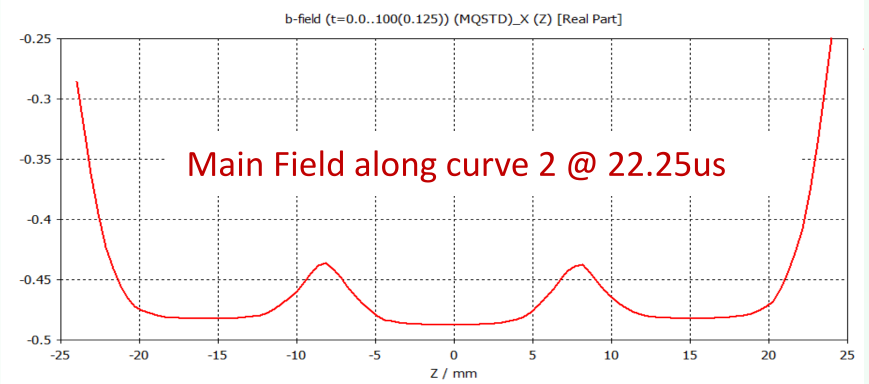
Legend

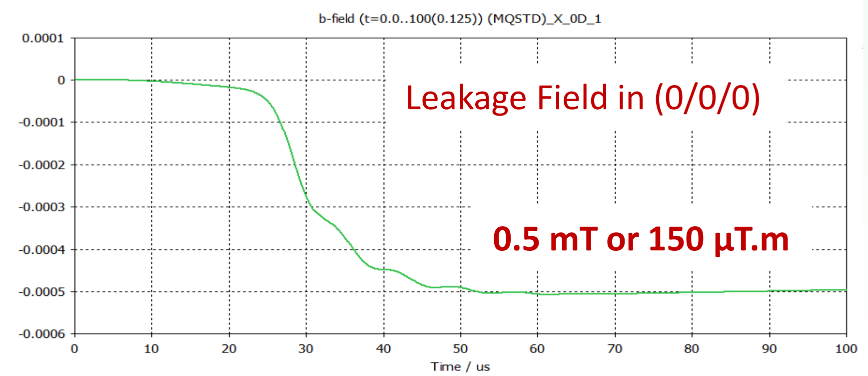


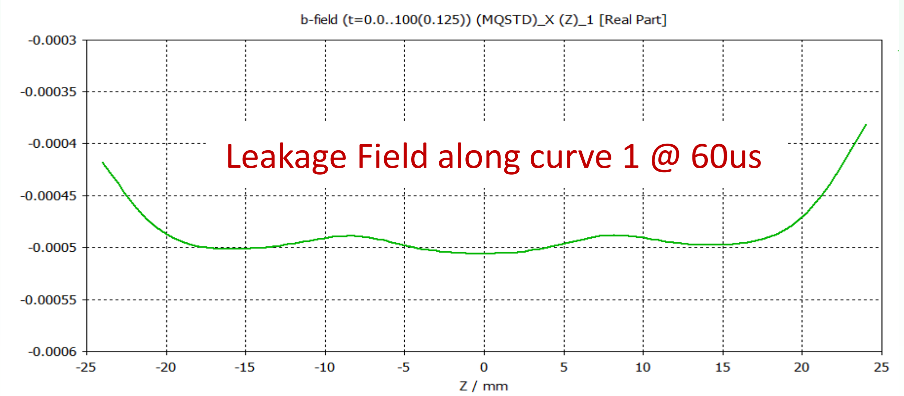
Copper, thickness 1mm





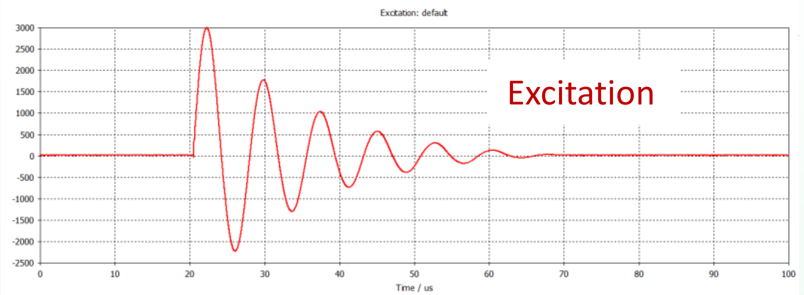


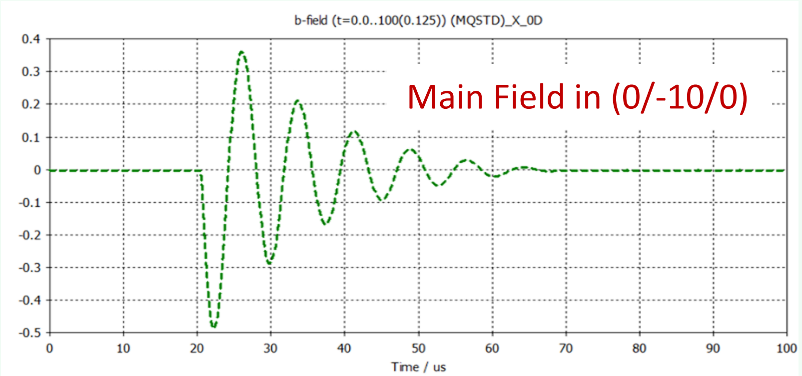


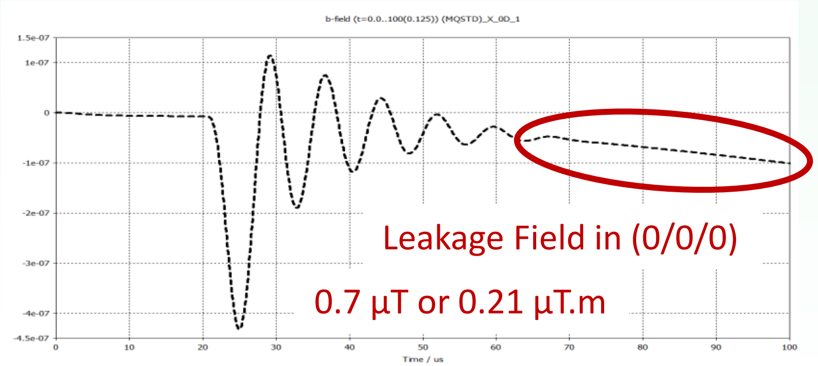


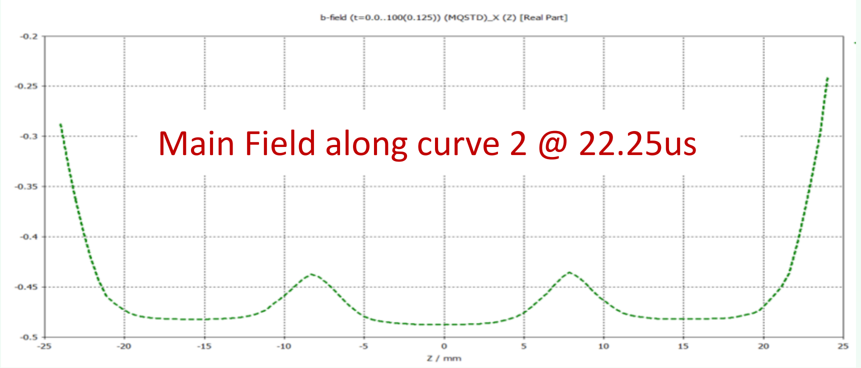
Going beyond cooper

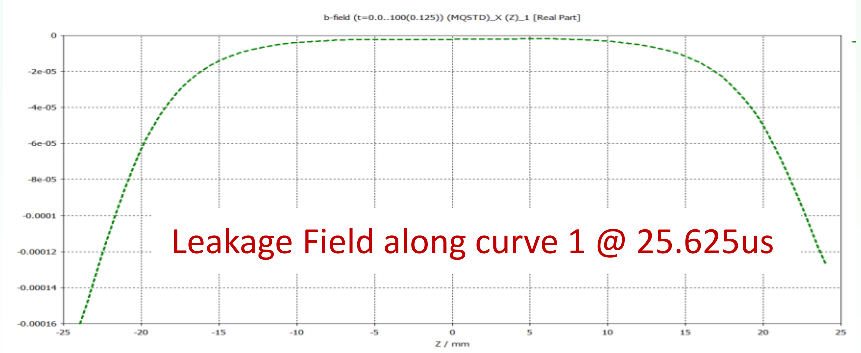
Cooper sheet screens the majority of the field. Adding high-μ soft magnetic material we can beat copper in the frequency range where it has available significantly large relative permeability. This compensates its lower conductivity and overall reduces the skin depth.



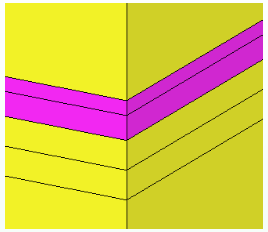








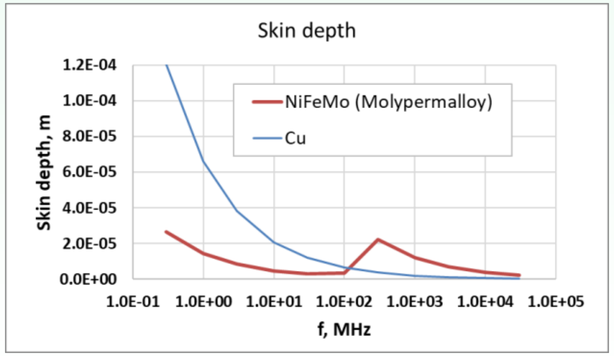
Legend



μ-metal, thickness 0.15mm
μ-metal, thickness 0.25mm
Copper, thickness 0.3mm
Copper, thickness 0.3mm

Skin depth

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



Story is a bit more complicated

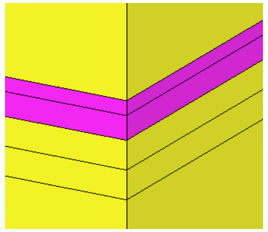
Eddy current barrier is not magnetic field "insulator"!

The field propagates slowly through the septum structure and its maximum can appear much later.

(Electromagnetic wave travels very slowly through the material $c = 1/\sqrt{\mu\epsilon}$)

Legend

µ-metal, thickness 0.15mm
µ-metal, thickness 0.25mm
Copper, thickness 0.3mm
Copper, thickness 0.3mm

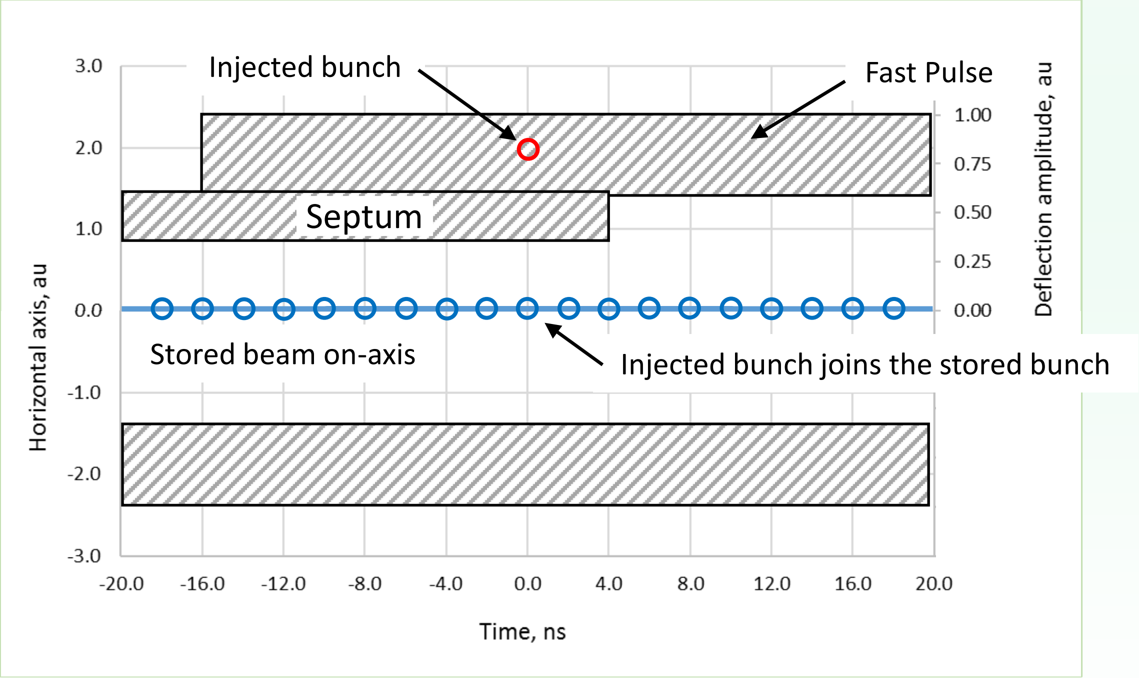


Leakage Field in (0/0/0)

SLS 2.0 Advanced Injection Schemes

"Fast" injection scheme, aperture sharing

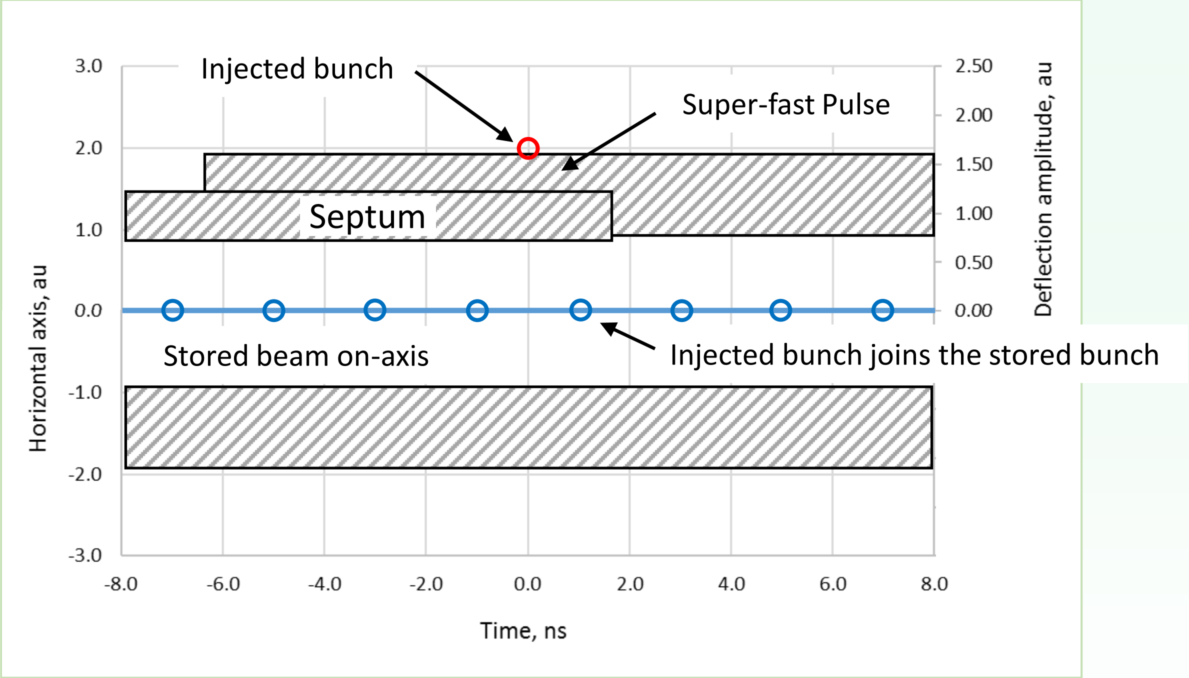
A portion of the stored beam (15 bunches in the illustration) and the *injected* bunch are deflected with a short kicker pulse (20..30 ns) to fit in the machine aperture. With decaying ***Betatron oscillation*** they come back on axis.



Simplified illustration of "Fast" injection scheme with aperture sharing (off-axis injection)

"Super-fast" injection scheme, on-axis

A very short kicker pulse (<2 ns) puts an off-momentum injected bunch on-axis *without significantly disturbing* the adjacent stored bunches. With decaying ***Synchrotron oscillation*** the injected bunch joins a stored one.

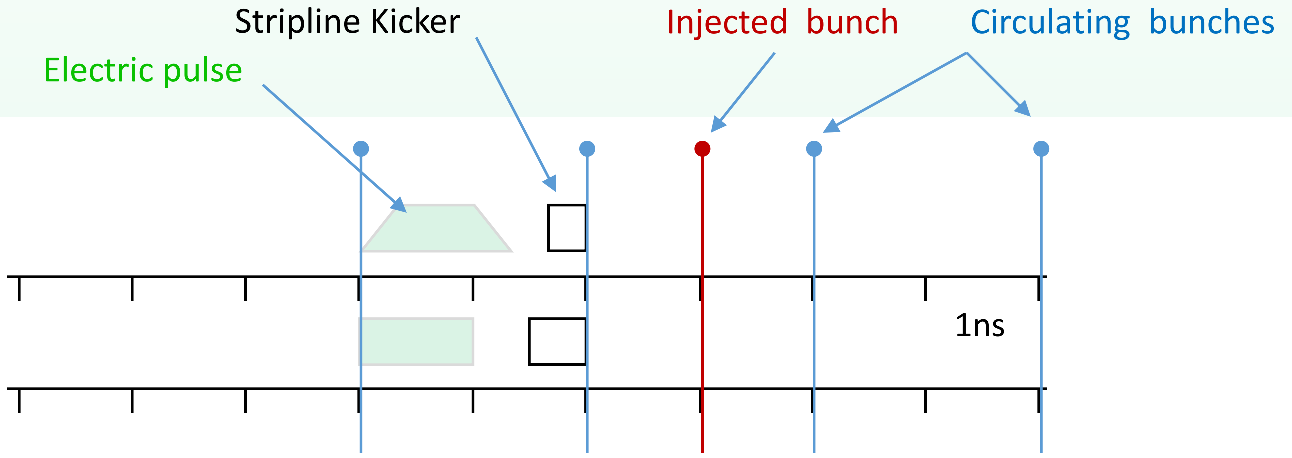


Simplified illustration of "Super-fast" on-axis injection scheme

Anatomy of the deflection with stripline kickers

- Nanosecond-long deflections require stripline (TEM) kickers -> Small deflection angles

- In order to add magnetic and electric deflection the electric pulses and the particle beam should **counterpropagate** (down-steam excitation).



0.66/1.32 ns pulse,
0.33 ns kicker (10 cm)

1.0 ns pulse,
0.5 ns kicker (15 cm)

Time representation of a rectangular and trapezoidal pulse to inject between two bunches in 500 MHz storage ring.

Conditions for an efficient use the kicker and not disturbing adjacent bunches:

1. Pulse full-amplitude length ≥ 2x Kicker electrical length
2. Pulse total length + 2x Kicker electrical length ≤ bunches separation

Ideal: a rectangular pulse, 1 ns long and TEM kicker with 0.5 ns electrical length.

SLS 2.0 Fast Kicker requirements and single section prototype construction

Given and machine related

Parameter	Fast	Super-fast
Beam momentum	2.7 GeV/c	
SR bunch spacing	2 ns	
Injection repetition rate	3 Hz	
Injection type	Horizontal	
Number of defl. SR bunches (off-axis)	<15	1..3
Number of defl. SR bunches (on-axis)	NA	0..2
Deflection angle (off-axis)	>0.35 mrad	
Deflection angle (on-axis)	NA	1.0 mrad
Horizontal aperture on axis	±5 mm	
Active kicker length	800 mm	

Derived and chosen kicker parameters

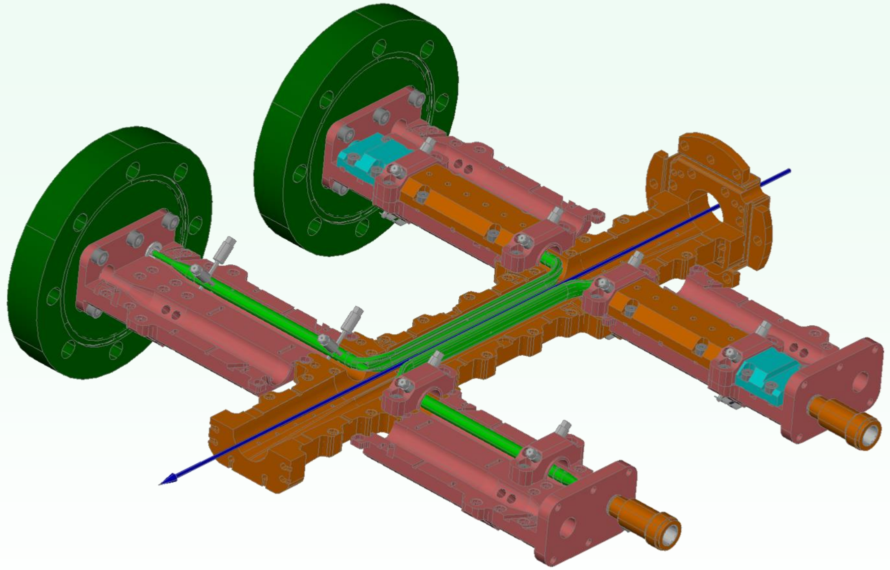
Parameter	Fast	Super-fast
Deflection type	Electromagnetic (TEM)	
Kicker type	Stripline (vacuum)	
Kicker section length	100 mm	
Number of sections	8	
Maximum deflection	0.5 mrad	1.0 mrad
Magnetic field	2.8 mT	5.7 mT
Electric field	0.9 MV/m	1.7 MV/m
Electrode voltage	±4.3 kV	±8.5 kV
Electrode current	±85 A	±170 A
Excitation pulse length	<30 ns	~2 ns
Odd / Even el. impedance	2x 50.0 Ω / 2x 56.0 Ω	

The technology is not matured yet – to mitigate the risks we divided the development in two phaces – **Fast** and **Superfast**.

Design of the kicker should be suitable for both phases - only the excitation pulses will be different.

Design goals:

- **As low excitation voltage as possible**
- **Broad bandwidth impedance matching**

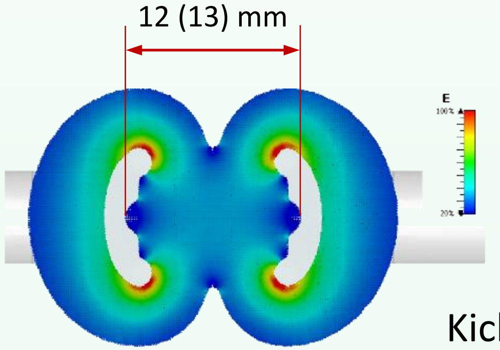


Kicker prototype interior

SLS 2.0 Fast Kicker prototype – Electrical Characteristics

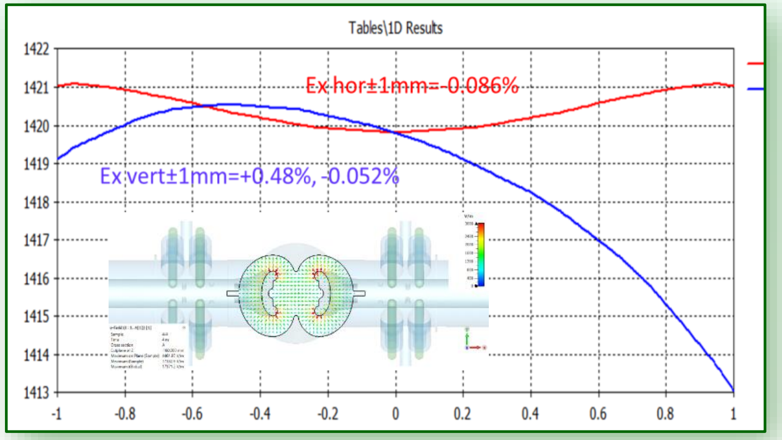
Blades

The kicker electrodes were optimized to provide the necessary field and electrical impedance maximizing the clear aperture on axis. Care was taken to avoid excessive surface electric field.



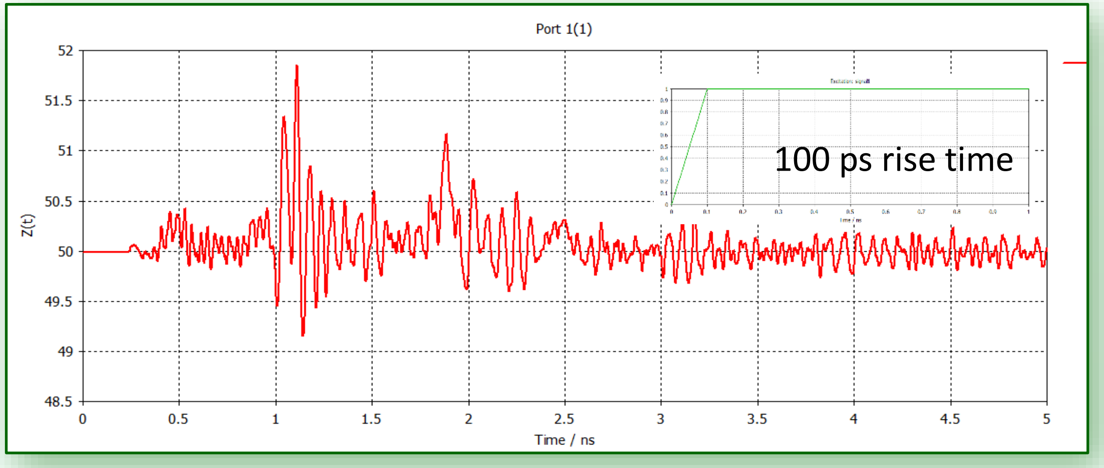
Kicker blades' cross section

Matched blades with increased beam space at the center

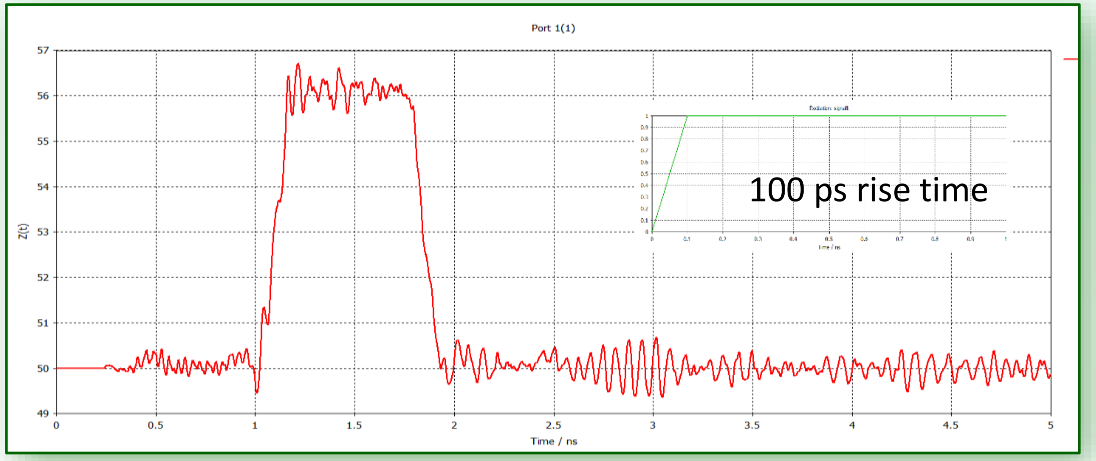


Synthetic time domain reflectometry

Differential mode 100.1 Ω (Odd impedance 50.1 Ω)

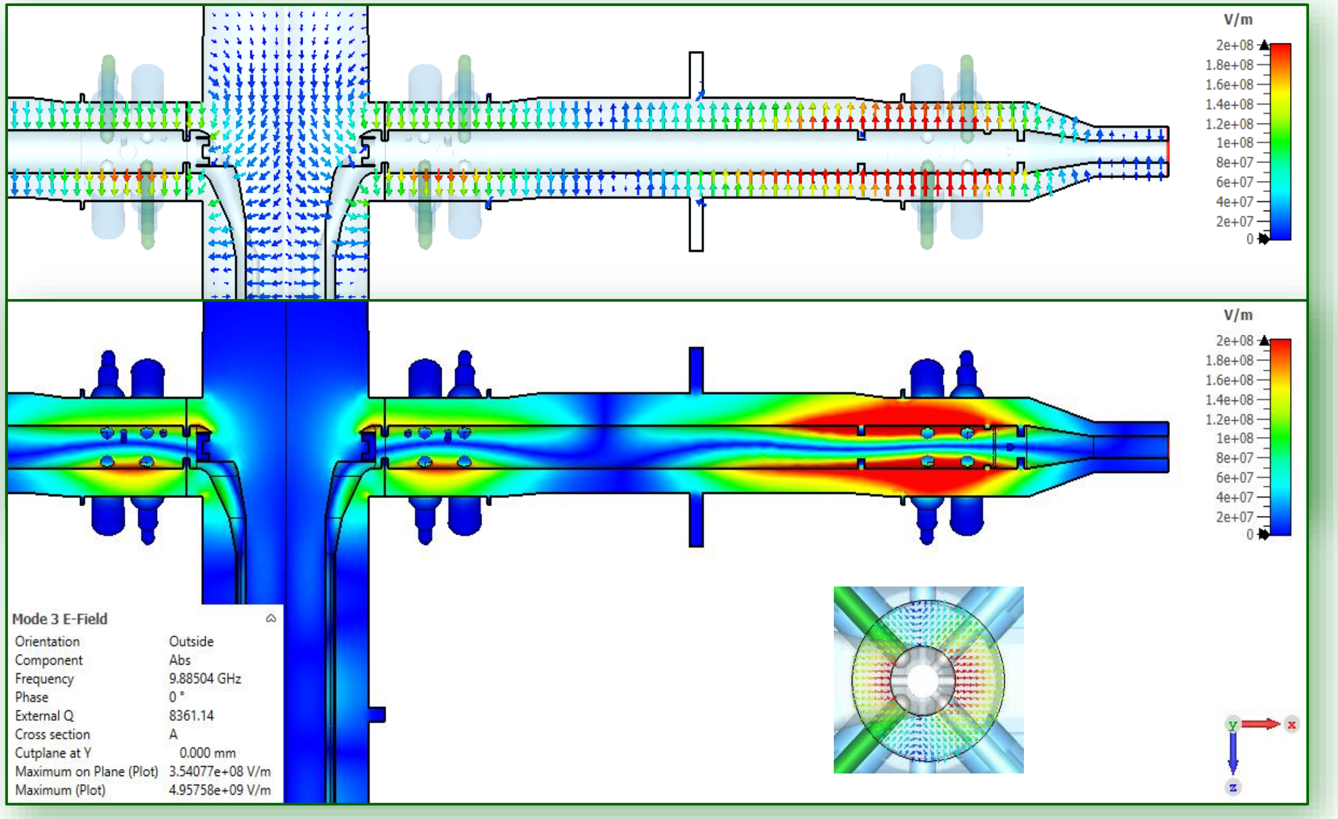


Common mode 28.0 Ω (Even impedance 56.0 Ω)



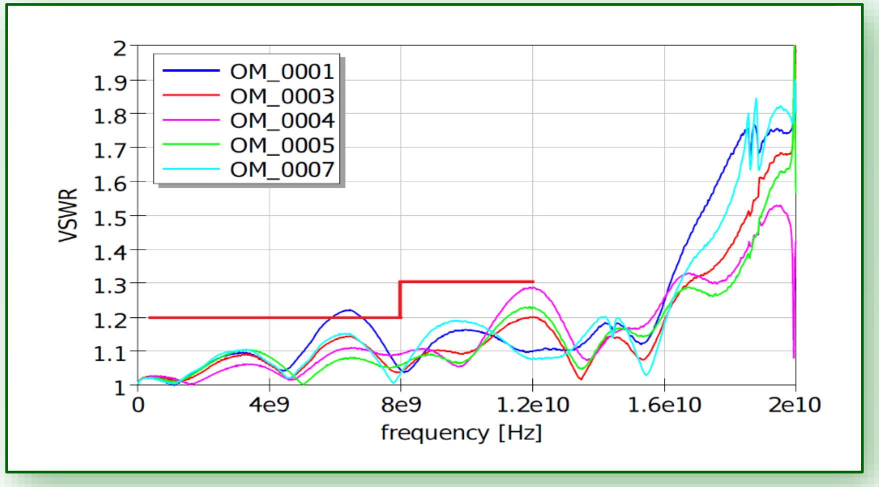
SLS 2.0 Fast Kicker Prototype – Electrical Characteristics

Coaxial line asymmetry and vacuum feedthrough



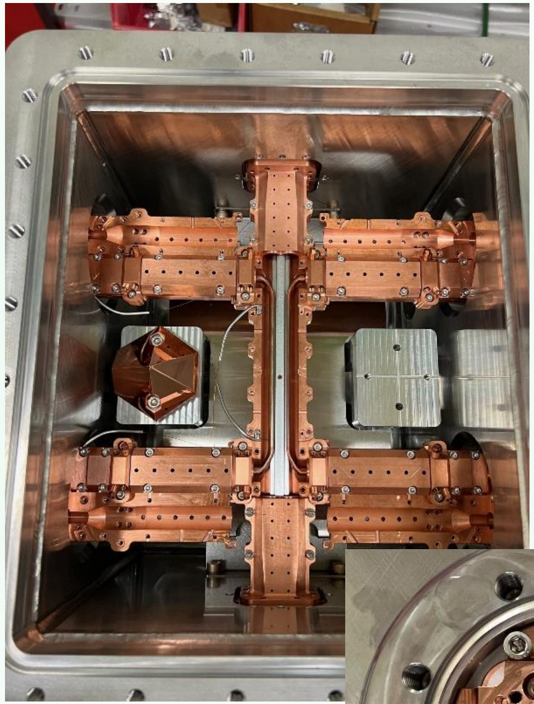
Example of one trapped mode in the coaxial transmission line

Orient microwave feedthrough.

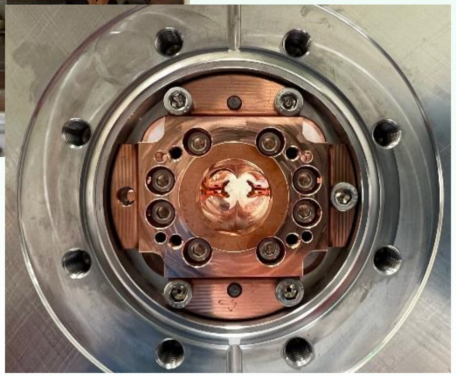


Measured voltage standing wave ratio of OM feedthroughs

SLS 2.0 Fast Kicker prototype – construction and measurements

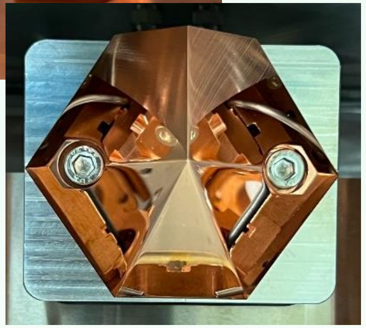


Kicker prototype in the chamber



Side view of the blades

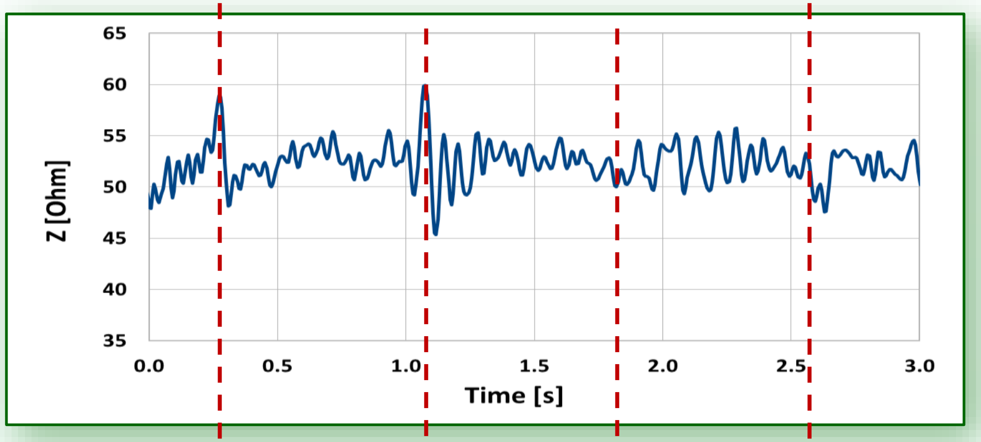
Blade transition and coaxial feeding line suspension



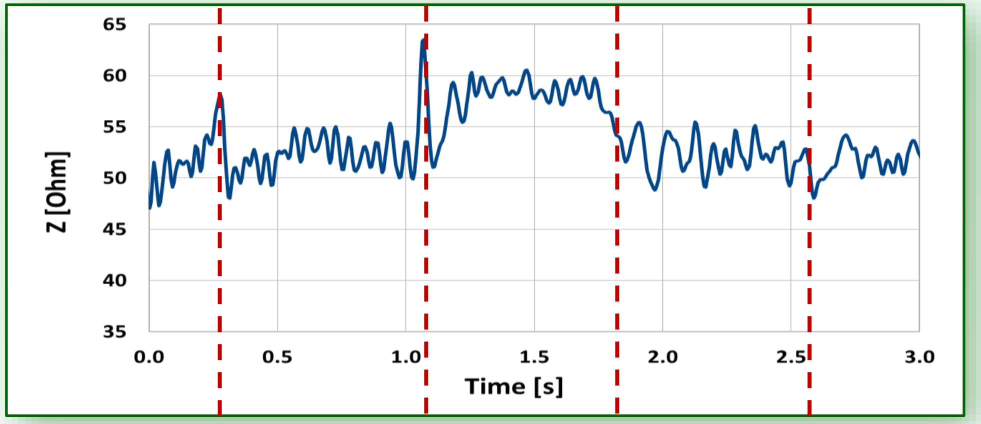
Infrared mirror for remote blades temperature monitoring

Time domain reflectometry (2-port)

Odd impedance



Even impedance



Feedthrough

Blade transition

Blade transition

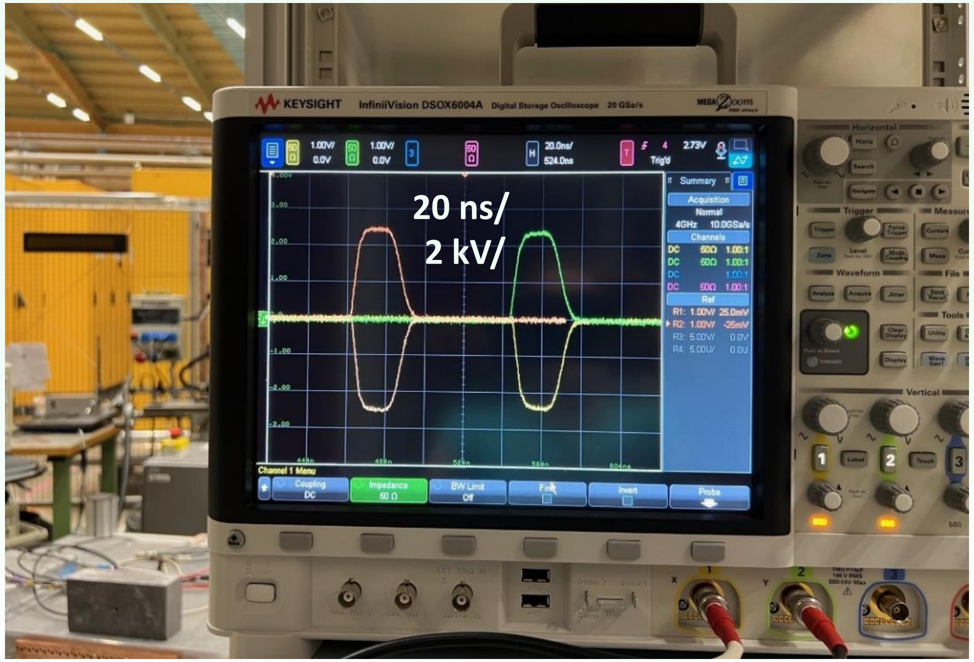
Feedthrough

SLS 2.0 Fast Kicker prototype – HV pulses test

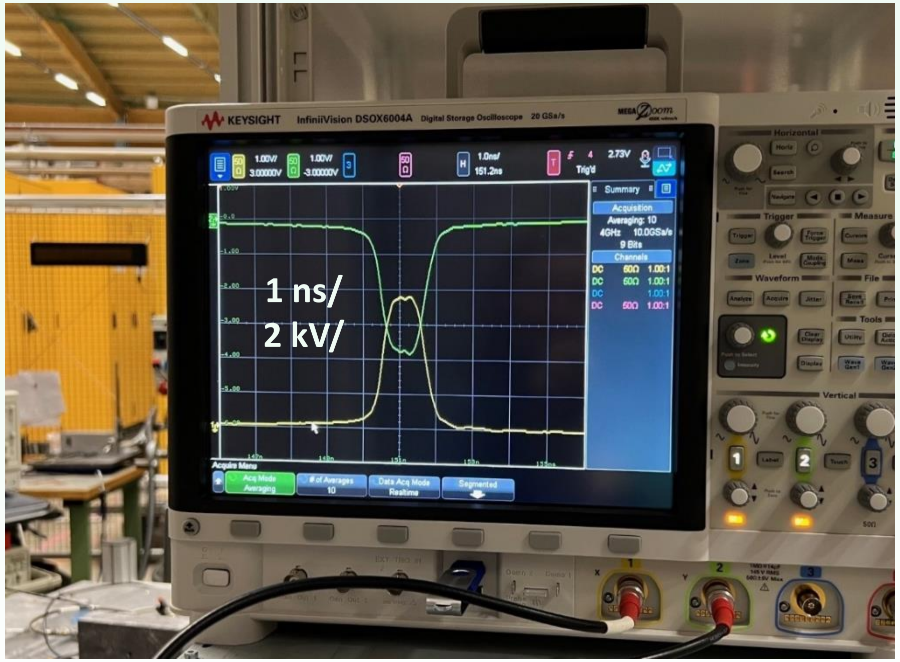
No HV breakdowns were observed applying the fast excitation pulses (in air – vacuum isolation performance should be even better).

Storage ring test is planed in March. The test outcome, especially the thermal performance, is expected to provide crucial information for the design of the final SLS 2.0 fast kickers.

No good solution yet for kicker termination – a broad bandwidth attenuator that withstands high CW power (100 to 200 W) and super high single pulse peak power (0.5 to 2 MW)



“Fast” pulses (30 ns) through the kicker prototype



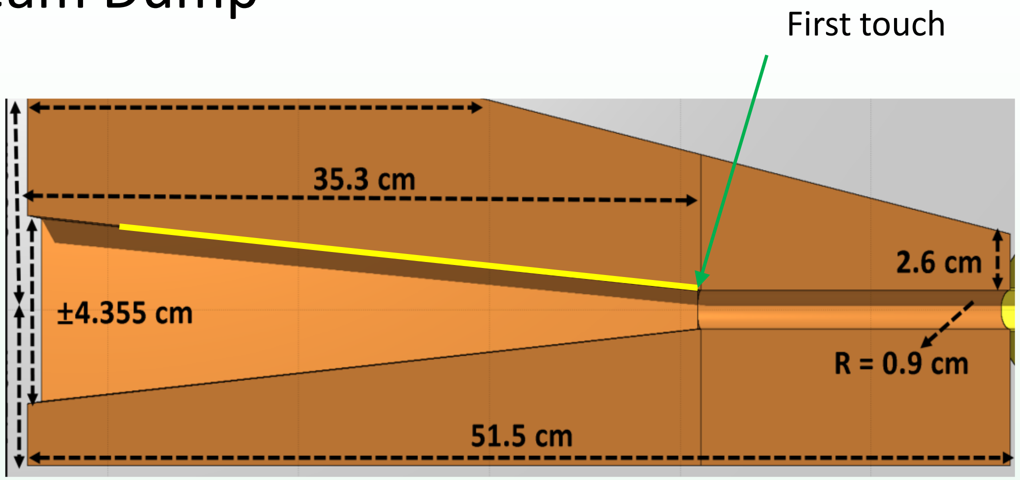
“Superfast” pulses (1.5 ns) through the kicker prototype

SLS 2.0 Dedicated Beam Dump

A dedicated beam dump magnet will be used to remove the beam in an orderly way. The beam energy ~1 kJ will be deposited at a dedicated beam dump out of copper.

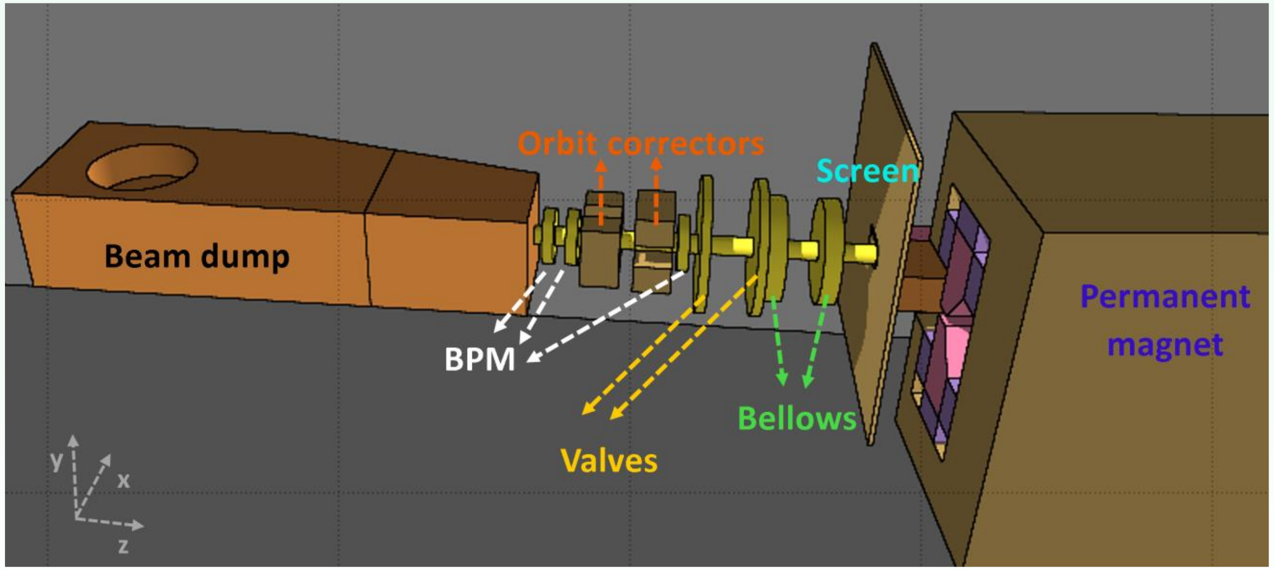
The beam train is spread over a large distance to avoid local material damage.

The design is such that the copper block is one wire-eroded thick monolithic piece (can not be disassembled) to give local attenuation for the potential surface activation.

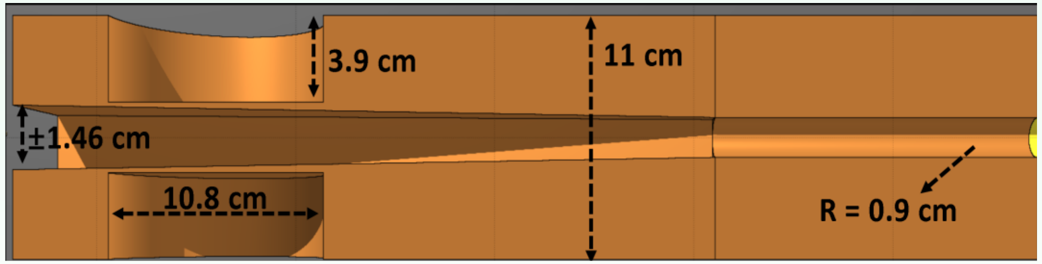


Beam dump – top view.

The yellow line indicates the beam dump surface



Beam dump region as modelled in FLUKA.

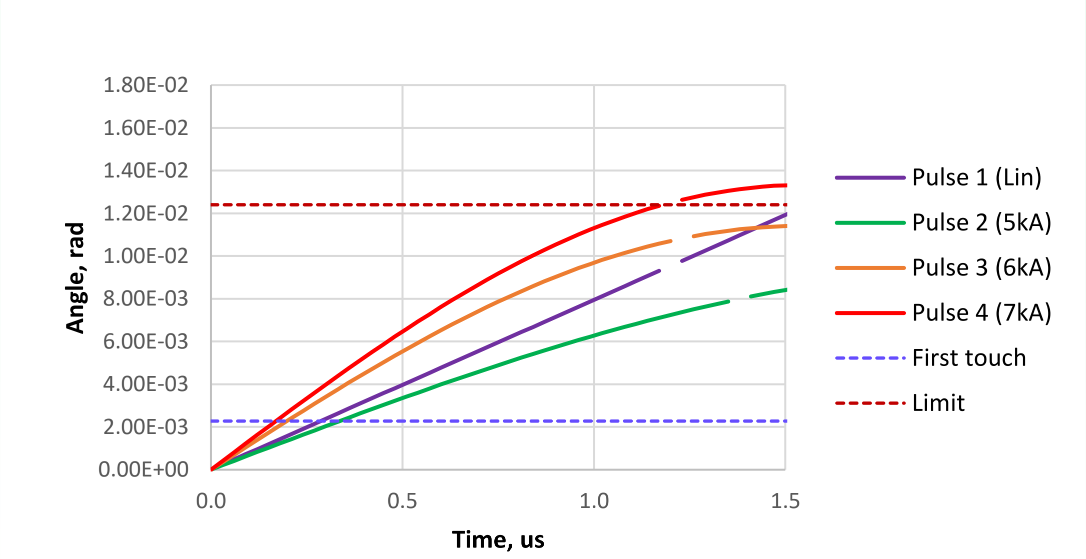


Beam dump – side view

Courtesy of I. Besana

SLS 2.0 Beam Dump deflection

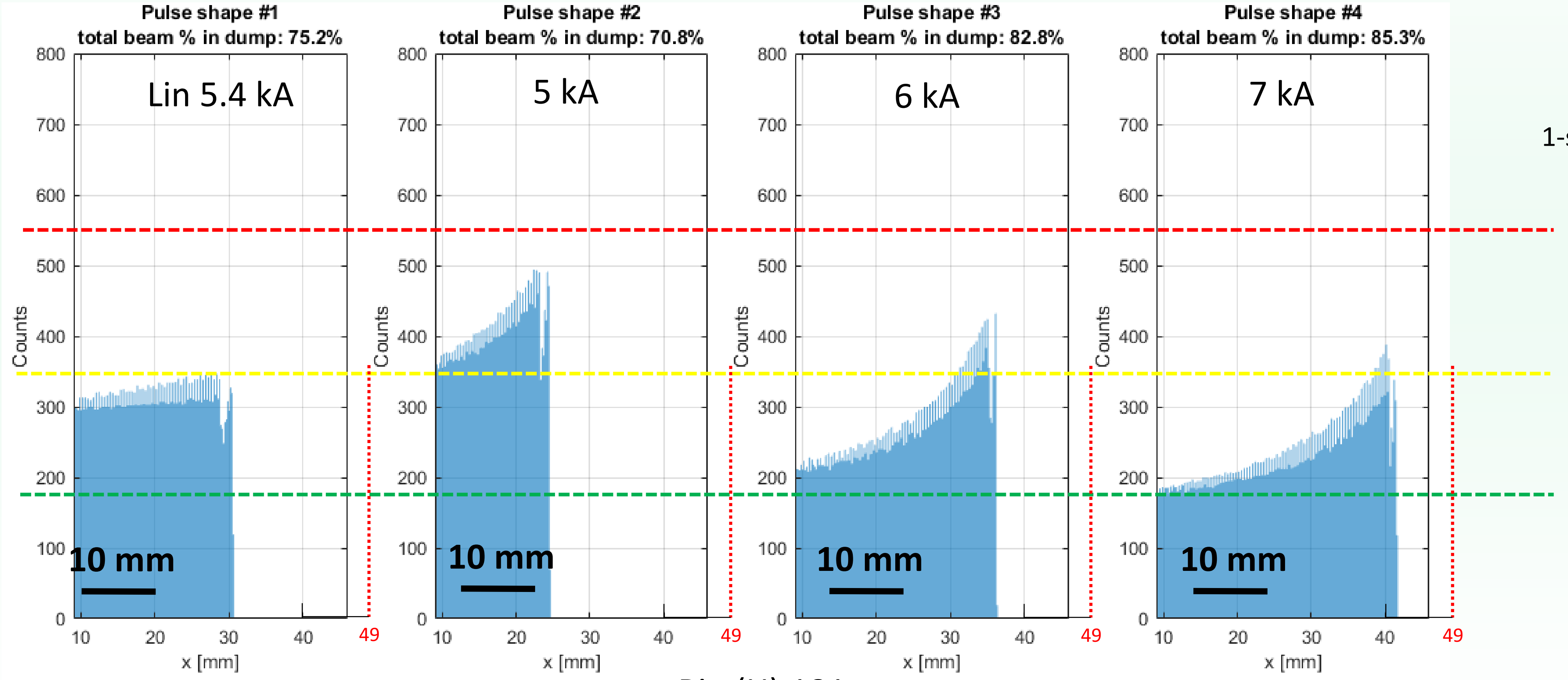
		At dump	At dump [-]	At thin septum	At thin septum [-]	At thick septum	At thick septum [-]	At collimator	At collimator [-]	Elsewhere
Lin 5.4 kA	New pulse shape 1	76.3%	366	13.7%	66	7.8%	37	2.2%	11	0%
5 kA	New pulse shape 2	72.1%	346	16.1%	77	9.3%	45	2.5%	12	0%
6 kA	New pulse shape 3	83.5%	401	9.5%	46	5.4%	26	1.5%	7	0%
7 kA	New pulse shape 4	86%	413	8.1%	39	4.7%	23	1.3%	6	0%



Pulse shape 1 (Lin 5.4 kA, 1.3 us)
Pulse shape 2 (5 kA, 8.8 us)
Pulse shape 3 (6 kA, 6.7 us)
Pulse shape 4 (7 kA, 6.2 us)

Stored train spread for different dump magnet currents

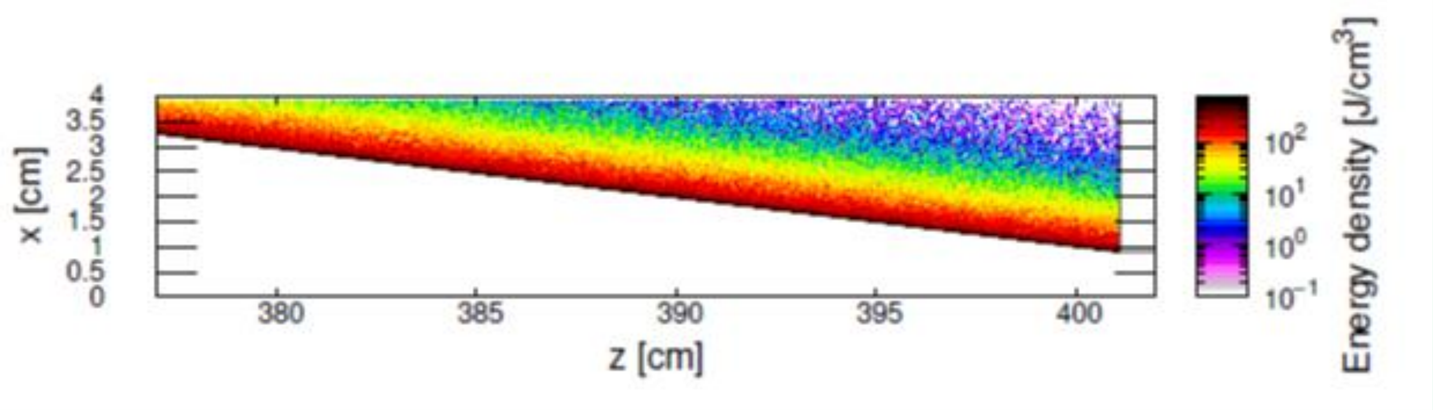
Currents are relatively high due to the large magnetic gap (~40 mm) defined by the choice to use an in-air magnet and a ceramic chamber identical with those of the storage ring kickers (and pingers).



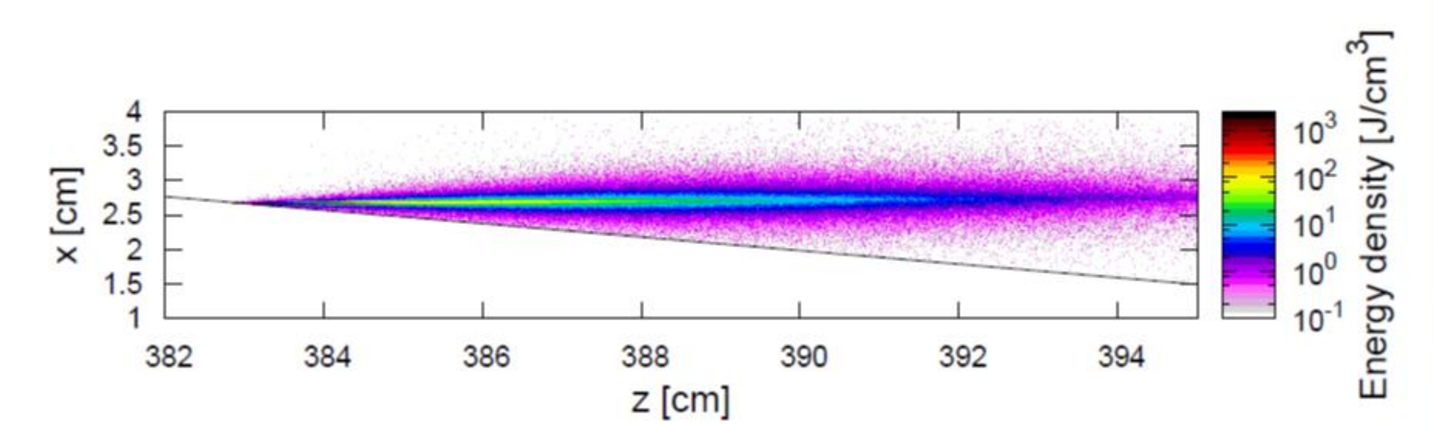
Bin (H) 181 um

Courtesy of J. Kallestrup

Deposited energy

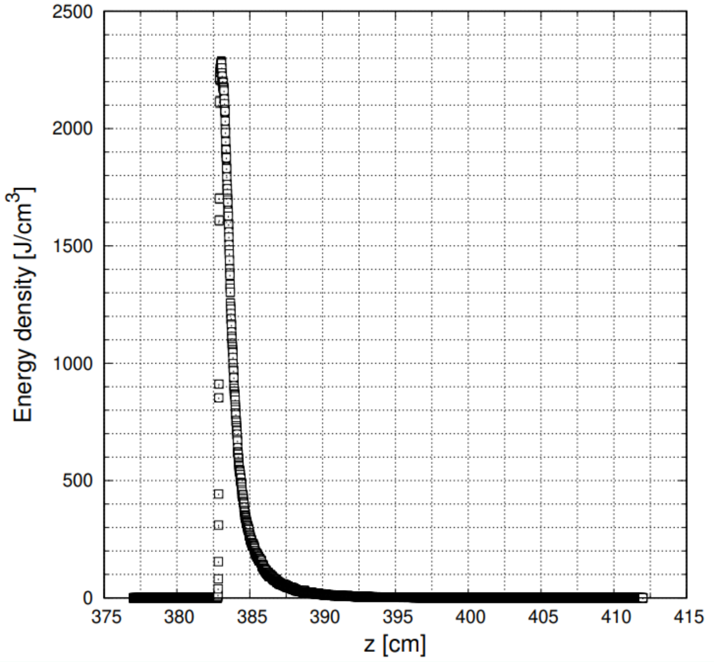


Energy deposition by dumping the entire bunch train
(regularly filed machine)



Energy deposition by a single bunch 5 nC (camshaft bunch)

Energy density lower than 2500 J/cm^3
- no material damage is expected

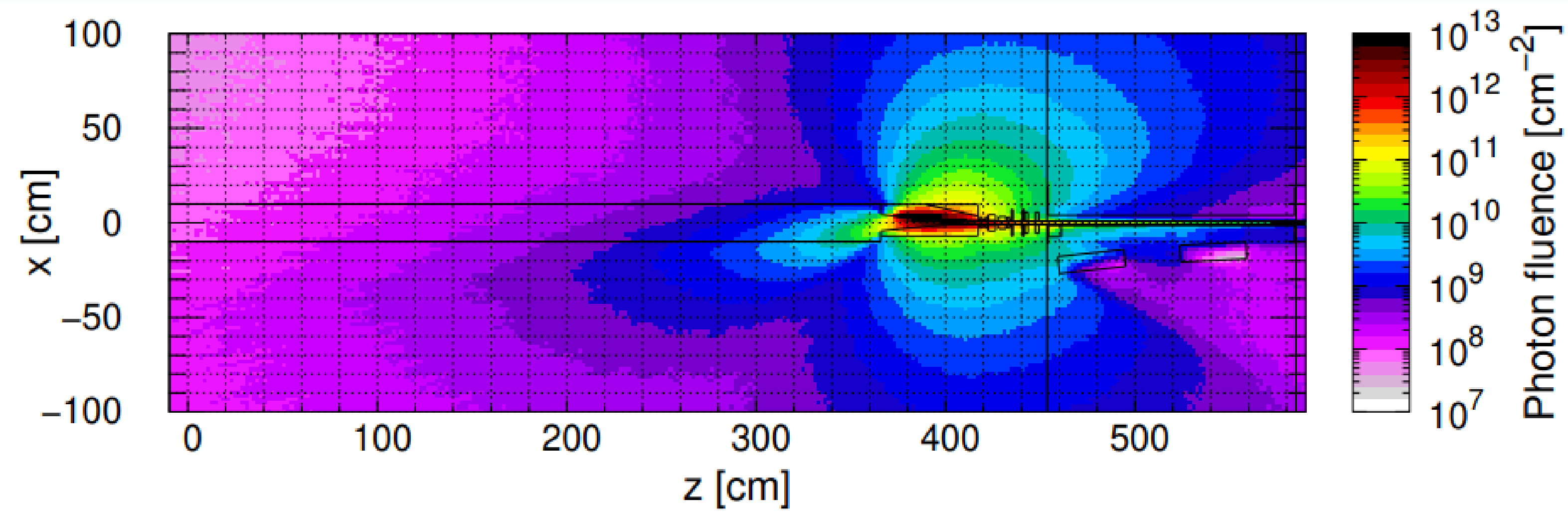


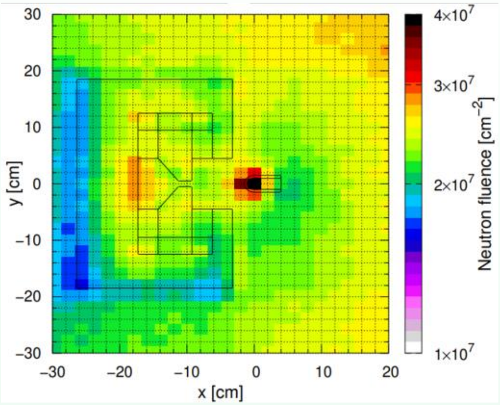
Energy deposition vs dept of ingle
bunch 5 nC (camshaft bunch)

Courtesy of I. Besana

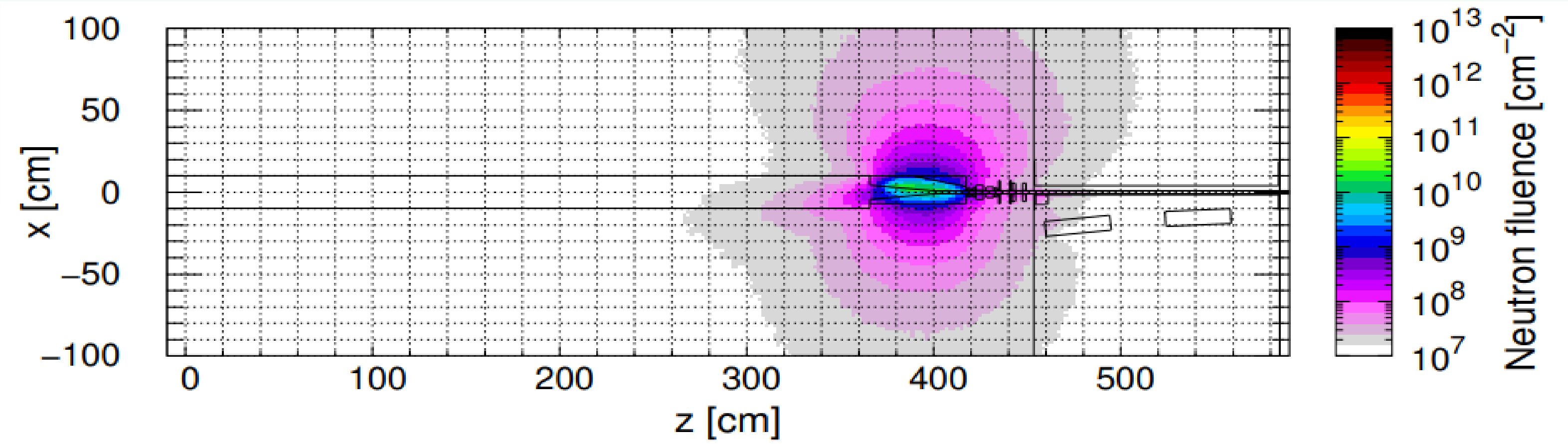
Beam dump related radiation (horizontal plane)

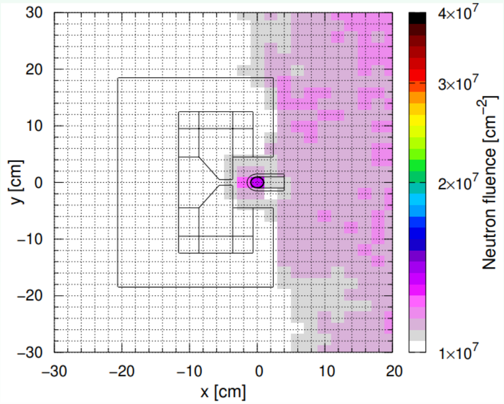
Radiation levels should not cause permanent magnets' magnetic field degradation.





Neutron fluence at first (upper graph) and second (lower graph) permanent magnet-based septum dipole





Courtesy of I. Besana

Conclusions and discussion

Thick septum

Rare-earth permanent magnets dipoles combined with high-saturation soft magnetic screen give a good alternative to pulsed septa. **Nevertheless, the magnetic screening requires larger beam separation.**

Thin septum

Combination of copper and µ-metal sheets can provide very good eddy current screening with total septum thickness down to 1 mm.

Eddy current screen is not a magnetic "insulator". Leakage field maximum could appear after ms. **Simulation and measurement of the leakage field is challenging.**

Stripline kicker

Fast kickers open new perspectives for more transparent top-up injection. A fast kicker prototype is developed based on two key principles: **as low excitation voltage as possible and efficient broad bandwidth matching**. A beam test is planed for March.

Together with the kicker construction, **a reliable generation of fast (ns) kV pulses and their termination are still very problematic.**

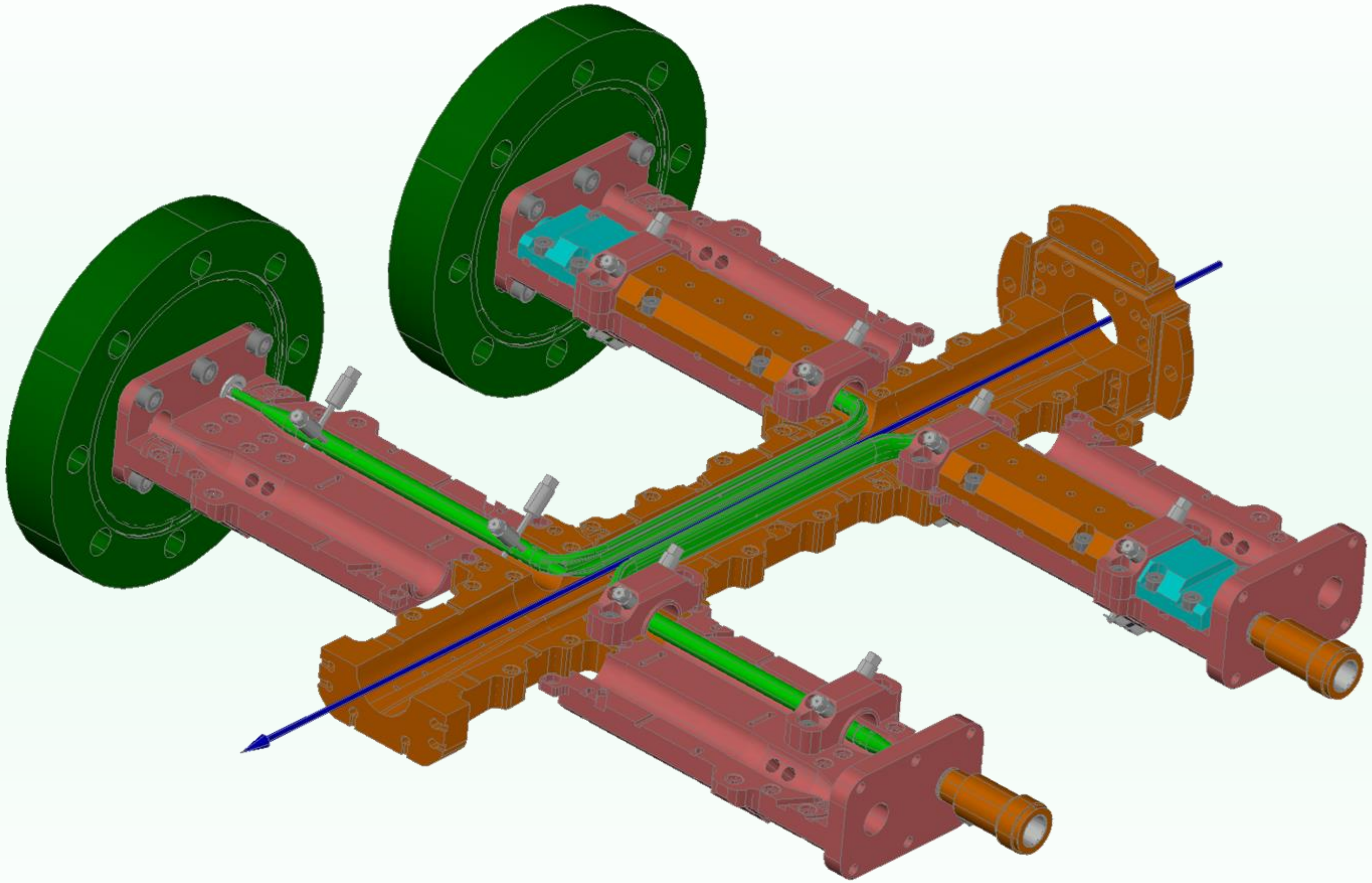
Beam dump

First slope of 7 kA sine wave is sufficient to deflect and spread the beam over the beam dump surface. Only about 5% of the bunches are lost on the second turn.

Almost 95% of the total energy is deposited on the beam dump and the peak power density is below 2.5 kJ/cm^3. **The copper is expected to withstand these energy density values without damage.**

The maximum neutron fluence at the septum dipoles is 3×10^7 neutrons/cm^2 per dump event and **it is not expected to degrade the magnets.**

Beam dump magnet is still to be designed.



Thank you for your attention

[1] A. Streun, “SLS-2 Conceptual Design Report”, 2017

[2] A. Streun, “SLS 2.0, The Upgrade of the Swiss Light Source”, IPAC2022, Bangkok, Thailand, 2022

[3] F. Armborst et al., “SLS 2.0 Machine Protection”, IPAC 2023, Venice, Italy, 2023