
WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

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Machine Interlock and Beam Abort System for SLS 2.0

9th Low Emittance Rings Workshop at CERN, Geneva, February 16th , 2024

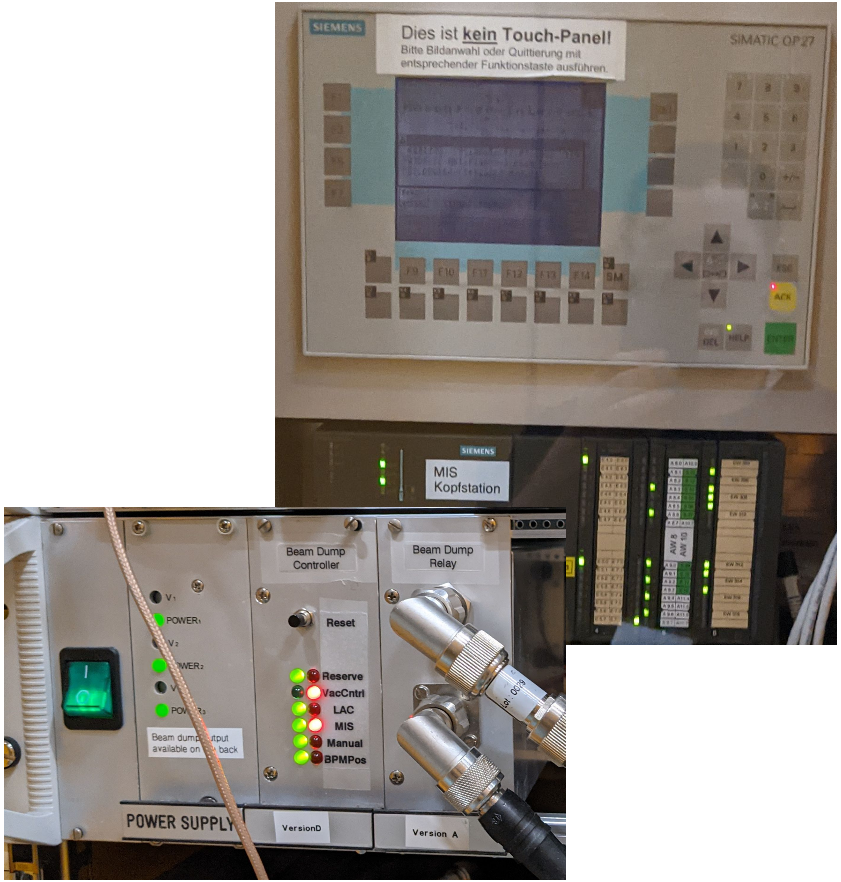
Outline

1. **Introduction**
   1.1. The SLS Beam Abort System
   1.2. The SLS 2.0 Beam Abort System
2. **Interlock Systems**
   2.1. Overview Schematic
   2.2. Machine Interlock System (MIS)
3. **Beam Abort System**
   3.1. Dedicated Dump
   3.2. Energy Deposition
   3.3. Loss Distribution
4. **Losses**
   4.1. Continuous Loss Distribution
   4.2. Overall Loss Distribution
   4.3. Risk for Permanent Magnets
5. **Conclusion**

Introduction: The SLS Beam Abort System

- Concept
  - RF phase inversion
  - Decelerate beam
  - Dispersive orbit
  - Distributed losses at restrictive apertures
    - Septum blade
    - High-dispersion TBA-arcs

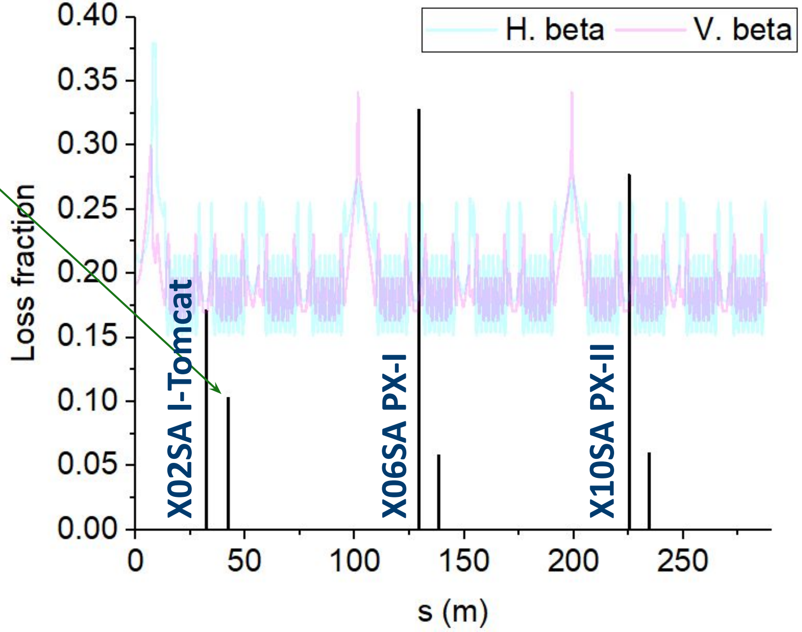
- SLS machine protection main aspects
  - Synchrotron radiation
  - Beam loading



Introduction: The SLS 2.0 Beam Abort System

Tracking simulations for RF phase inversion show

- Loss localization at **IVU** & **SC superbend** (Arc **1**, **2**, **6**, **10**)
- Fragile, 1 mm copper vacuum chamber
  - ➔ **RF phase inversion beam dump not applicable**
- Coasting beams lost after 300 turns (RF trips)
- Decelerated beams lost in 100 turns (PSYS interlocks)
  - ➔ **Beam dump delay < 100 µs required**
  - ➔ **Fast beam dump controller bypassing slow PLCs**



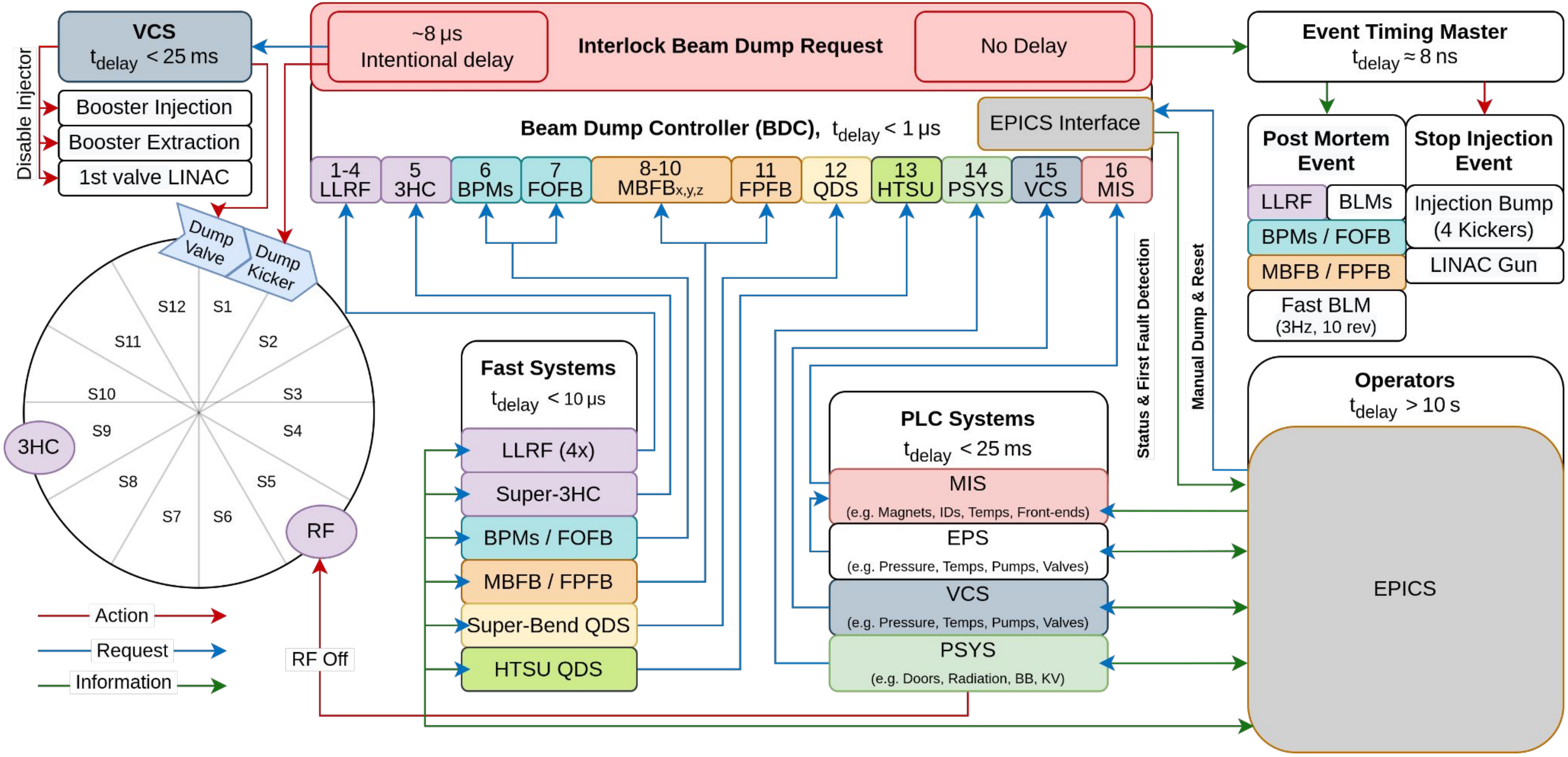
Longitudinal distribution of beam loss after RF phase inversion

Destructive potential of stored beam

- 400mA @ 2.7GeV (from 2.4 GeV) = 1 kJ beam energy
- Emittance 157 pm (from 5500 pm)
- APS tungsten scraper experiments (2 kJ)
- SPring-8 Injection chamber vacuum leak with low-emittance optics (4 kJ)
  - ➔ **Dedicated kicker and dump for “bunch painting”**
  - ➔ **Stored beam itself becomes machine protection aspect like synchrotron radiation and beam loading**

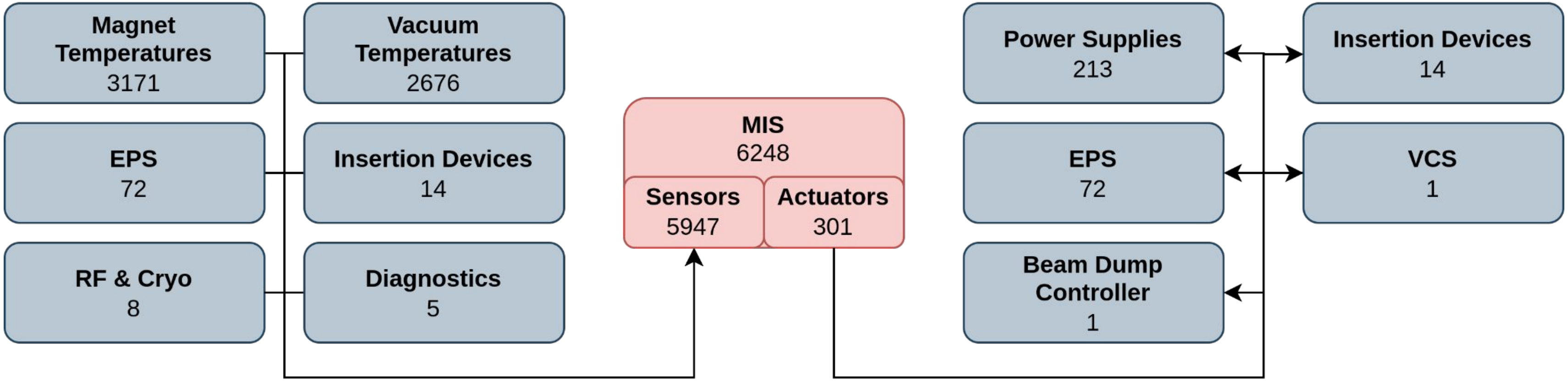
Courtesy of M. Aiba

Interlock Systems: Overview Schematic



→ **For fast systems the total delay time from failure detection until completion of the interlock beam dump must be less than 100 µs**

Interlock Systems: Machine Interlock System

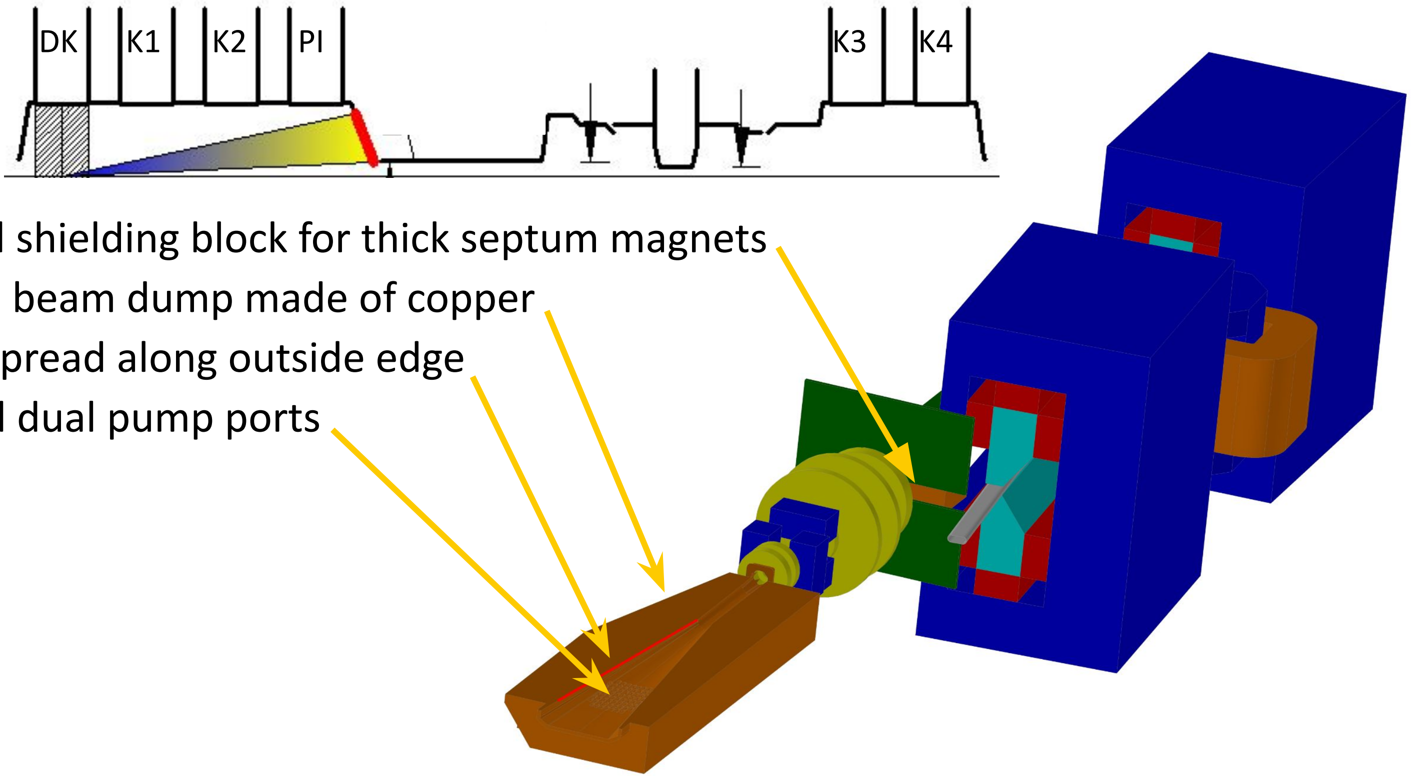


The **M**achine **I**nterlock **S**ystem (MIS)

- Monitors the sensors and provides beam permits to the actuators
- Storage ring sensor signals in the tunnel are combined via profinet for each sector
- Extrapolating from experience with the SLS MIS, 90 dumps / year are expected during user operation

Beam Abort System: Dedicated Dump

The dedicated beam dump is located upstream of the thick septum in the injection straight



- Additional shielding block for thick septum magnets
- Dedicated beam dump made of copper
- Bunches spread along outside edge
- Integrated dual pump ports

Courtesy of M. Paraliev

Beam Abort System: Energy Deposition

Beam Parameters	
E	$2.7\,\mathrm{GeV}$
σ_x	$35\,\mu\mathrm{m}$
σ_y	$11\,\mu\mathrm{m}$

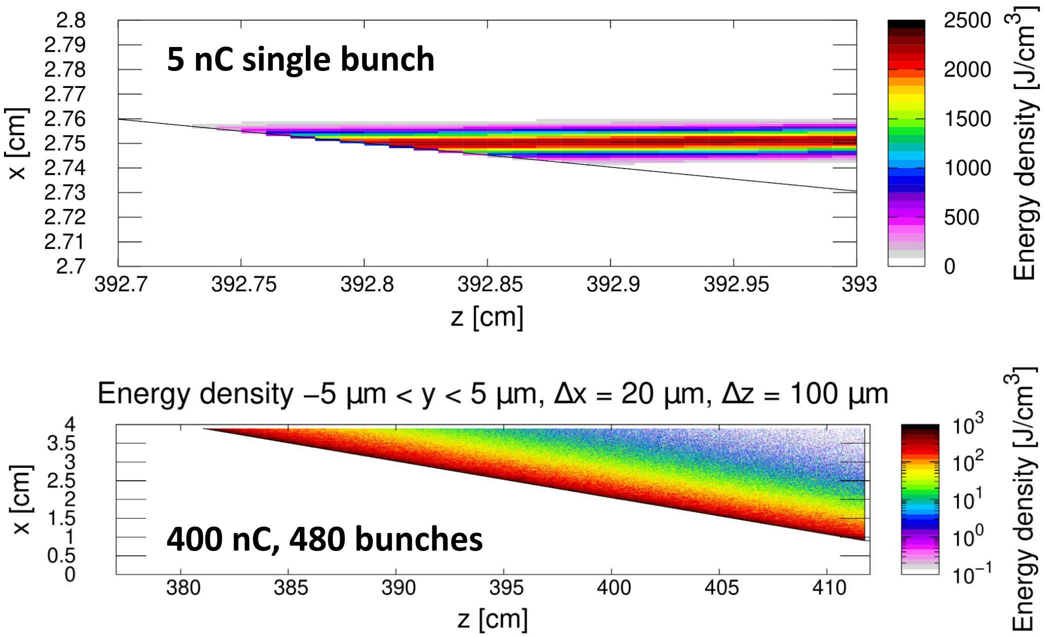
→ Dump kicker pulse spreads bunches over **331 mm** on the beam dump

	FLUKA	**Formula*** [1]
5 nC single Bunch	~ 2300 J/cm^3	~ 3530 J/cm^3
400 mA stored	~ 1000 J/cm^3	~ 588 J/cm^3

*Angle of incidence and super-imposition of multiple bunches and their particle showers not taken into account

→ No heat diffusion (<1 µs)

→ Neglecting heat of melting 3.6 kJ/cm^3 is limit

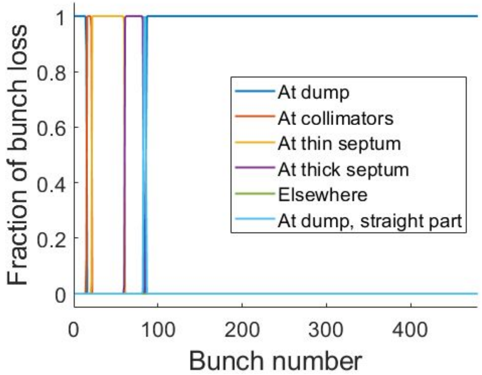


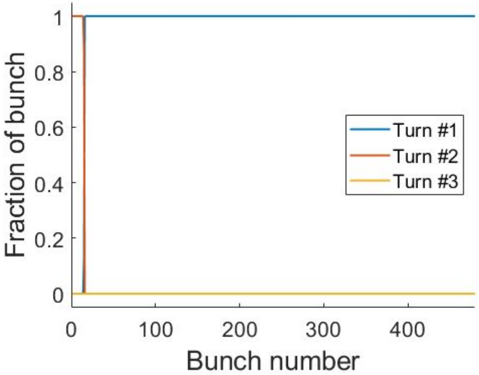
[1] M. Borland, J. Dooling, R. Lindberg, V. Sajaev, A. Xiao, “*Using Decoherence to Prevent Damage to the Swap-Out Dump for the APS Upgrade”*, in Proceedings of 9th IPAC, 2018, Vancouver, BC, Canada

Courtesy of M. I. Besana

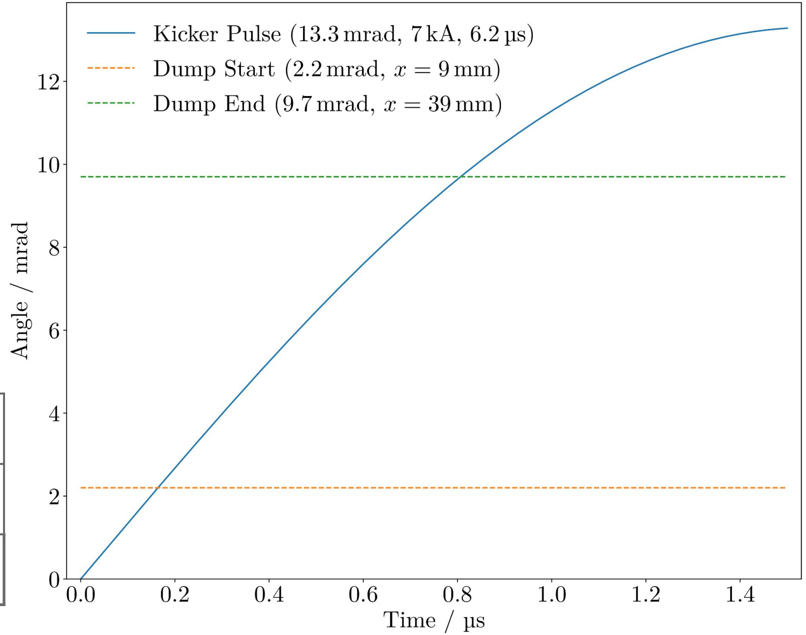
Beam Abort System: Loss Distribution

→ Interlock beam dump loss distribution remains unchanged for horizontal or vertical orbit distortions of 500 µm peak to peak.





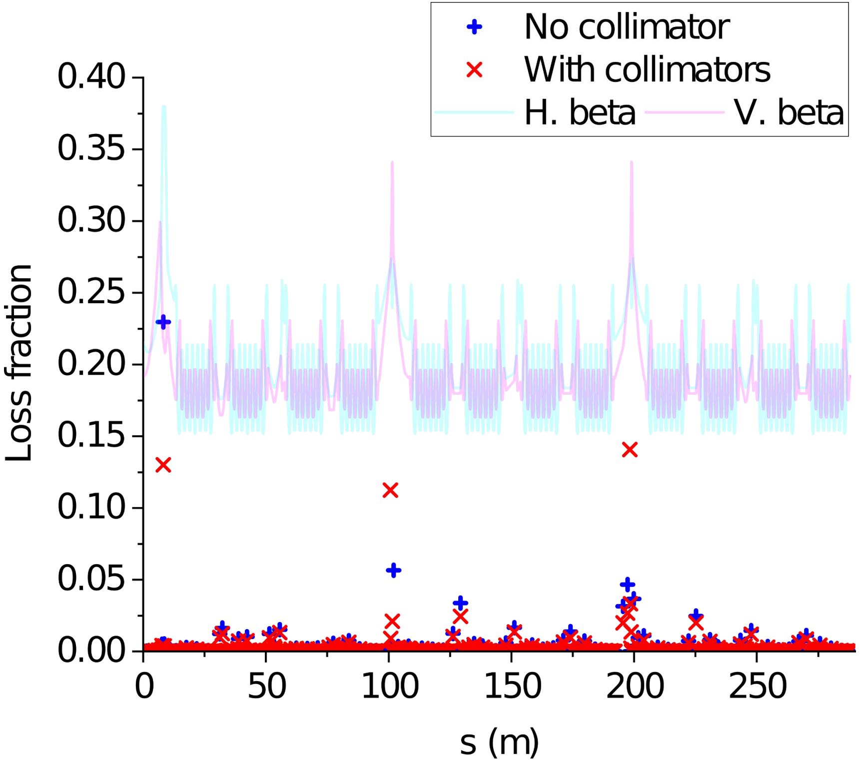
Orbit Distortion	**Collimators**	**Thin septum**	**Thick septum**	**Dump**	**Elsewhere**
Horizontal	1.2 ± 0.5 %	8.1 ± 0.1 %	4.3 ± 0.2 %	86.3 ± 0.5 %	0.0 ± 0.0 %
Vertical	1.3 ± 0.0 %	8.1 ± 0.0 %	4.4 ± 0.0 %	86.2 ± 0.0 %	0.0 ± 0.0 %



Courtesy of J. Kallestrup

Losses: Continuous Loss Distribution

Inklusive loss map (Touschek, Bremss, Gas) for user operation with / without horizontal and vertical collimators at 5L and 9L



- Total Lifetime of 8 hours
  - With SC 3HC (2.6 x bunch lengthening)
  - Touschek scattering (Lifetime ~11.7 hours)
  - Gas scattering (Lifetime ~35 hours)
  - Bremsstrahlung (Lifetime ~90 hours)

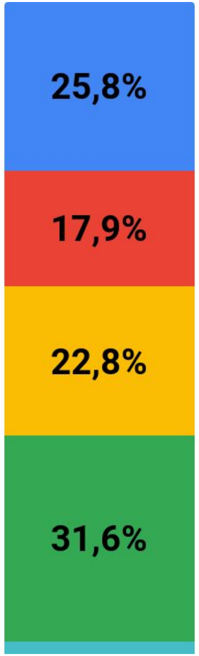
- Loss of 1200 mA per day
  - Due to finite beam lifetime
  - Stored beam of 400 mA
  - Frequent-refill Top-Up Scheme every 3 min

Courtesy of M. Aiba

Losses: Overall Loss Distribution

	Dump *	Lifetime	Total
Lost beams per year	~ 210	~ 846	~ 1058
Lost charge per year	36 µC	338 µC	422 µC
Collimators 9L	**< 1 %**	**17.4 %**	**13,9 %**
Collimators 5L	**< 1 %**	**12.1 %**	**9,7 %**
Thin Septum Blade **Outer Thin Septum**	**< 1 %** **8 %**	**13.4 %** **< 1 %**	**12,3 %**
At Beam Dump	**86 %**	**< 1 %**	**17,1 %**
At Thick Septum	**5 %**	**< 1 %**	**1 %**
Elsewhere	**< 1 %**	**57 %**	**45,7%**

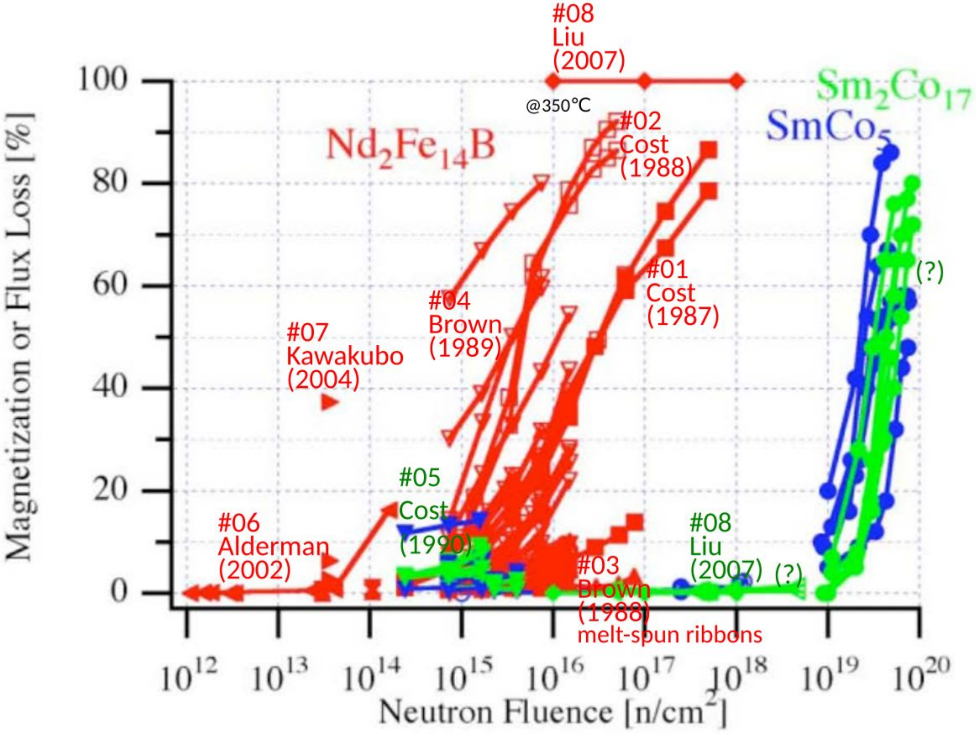
* = ~90 interlock beam dumps
+ ~70 beam dumps after/before user operation
+ ~50 during machine development



Beam loss distribution between the hotspots excluding the fraction lost “elsewhere”

Losses: Risk for Permanent Magnets

- Defining a safe / tolerable neutron fluence limit for permanent magnets is difficult
- Radiation damage demagnetization mechanisms complex with many variables
- Conservative limit following this plot (we use NdFeB)
  - ➢ **10^{12} n/cm^2**



Demagnetisation as a function of neutron fluence in various experiments.

Plot originally shown in EPAC’2006 paper “65 MeV Neutron Irradiation of Nd-Fe-B Permanent Magnets” by X.-M. Maréchal et al (THPCH135) and updated in CLIC – Note – 1079 by Ben Shepherd.

Losses: Risk for Permanent Magnets

Conservative Loss Approximation (Lifetime = 8 h, Beam Current = 400 mA, top up every 3 min)

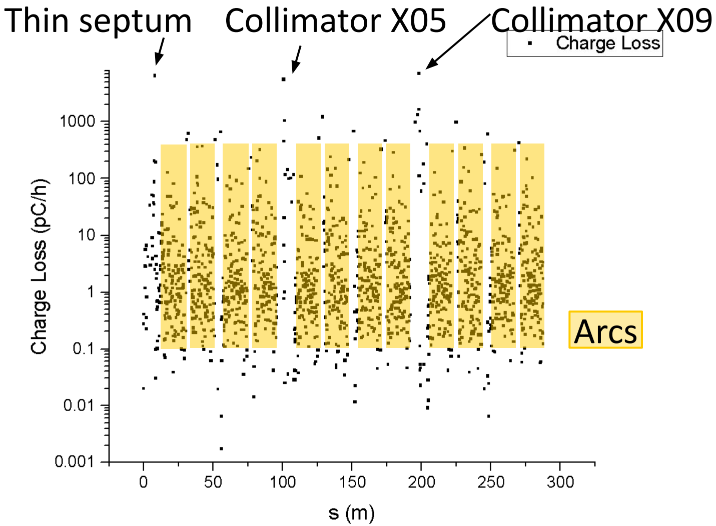
→ 1200 nC lost per day = 7.5e12 electrons per day = `8.6e7 electrons per s`

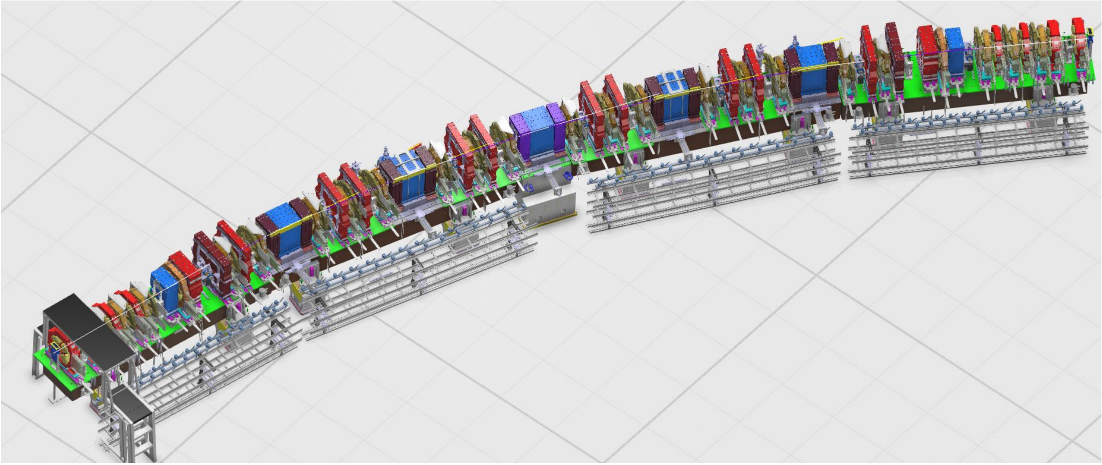
→ 57 % lost at non-hotspots = `4.9e7 electrons per s`

→ assume even distribution to each arc (1/12) = `4.1e6 electrons per s`

→ assume even distribution to each bend (1/7) = `5.8e5 electrons per s`

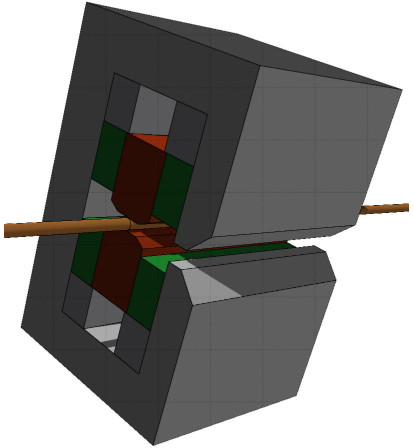
→ add 4e5 electrons per s from collimators = **`9.8e5 electrons per s`**





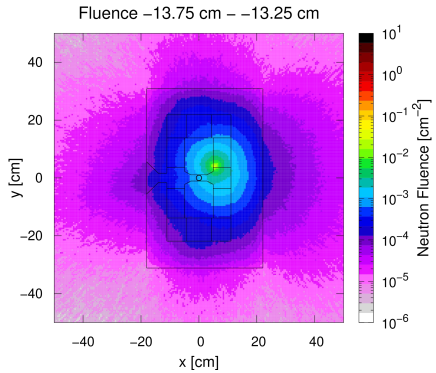
Courtesy of M. Aiba and R. Ganter

Losses: Risk for Permanent Magnets



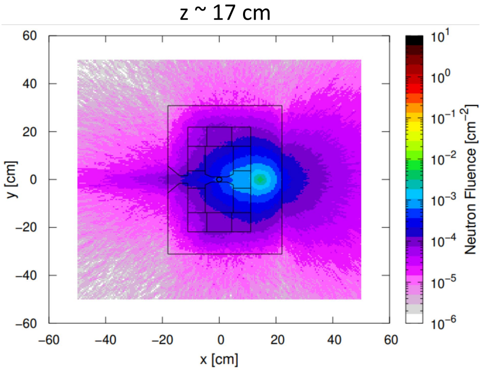
Unrealistic Case

Vertical losses aimed at PM block from short distance.
→**0.7 m** upstream of BN center
→**y'= 62 mrad**



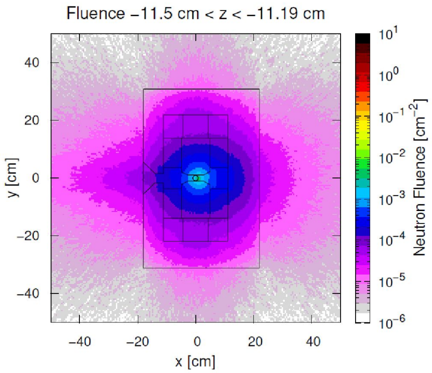
Bad Case

Horizontal losses aimed at magnet from short distance.
→ **0.5 m** upstream of BN center
→ **x'= 200 mrad**



Slightly More Realistic Case

Horizontal losses localized directly at start of PM block.
→ **0.2 m** upstream of BN center
→ **x' = 200 µrad**



	Unrealistic Case	Bad Case	Slightly More Realistic Case
Neutrons / cm^2 on PM block in 20 years	2.5e13	6.2e11	2.2e+11
1e12 neutrons / cm^2 reached after	0.8 years	32.2 years	92.1 years

Courtesy of M. I. Besana

Summary

Machine protection architecture for SLS 2.0 compared to predecessor

- Substantially faster
- More sophisticated interlock beam dump procedure
- Better post mortem diagnostics

Losses for the SLS 2.0 compared to predecessor

- More concentrated loss regions due to
  - Low dispersion arcs MBA design
  - Use of collimators in storage ring

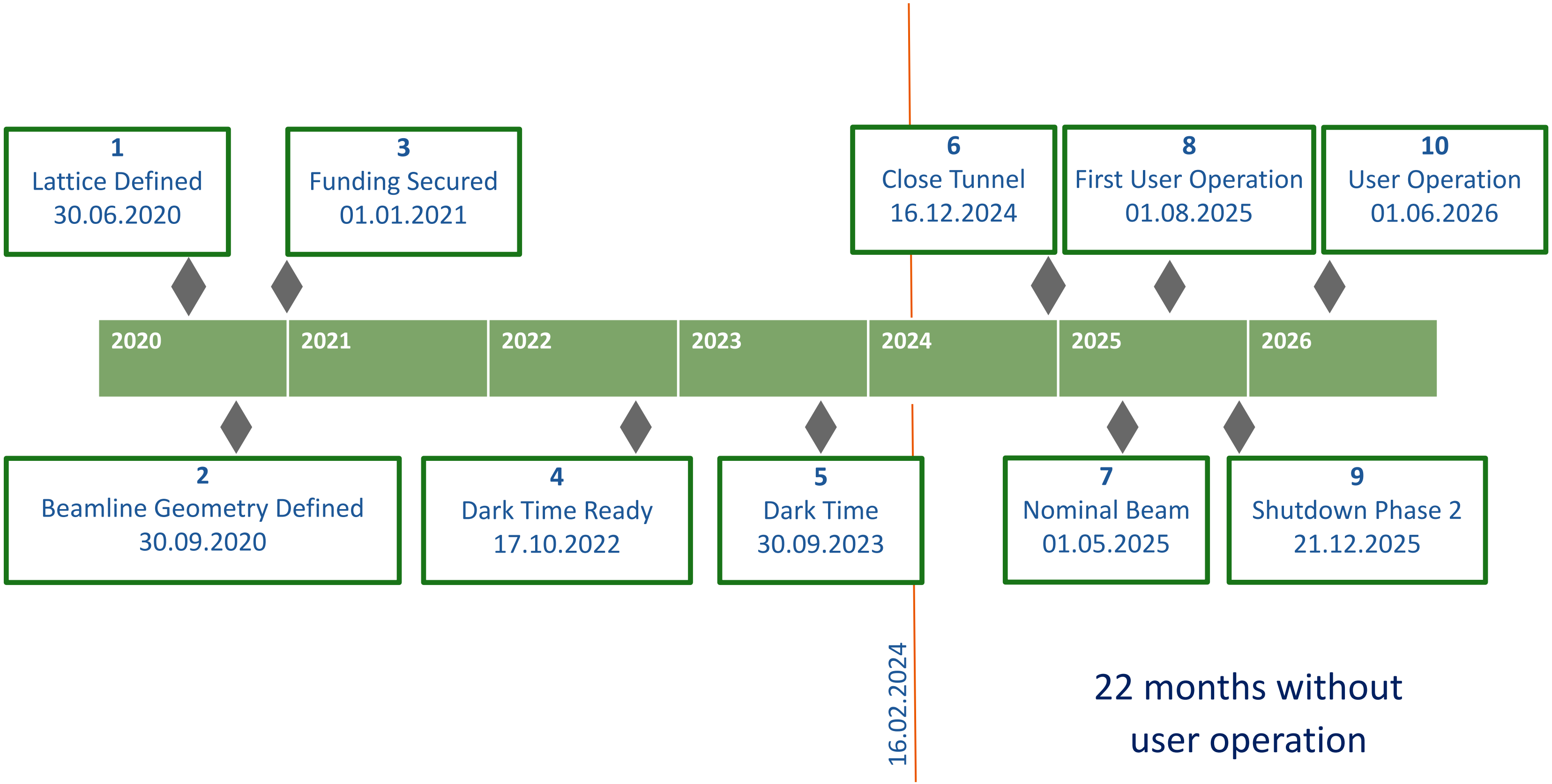
➢ **No critical degradation to permanent magnets over lifetime of accelerator**

Thank you for your attention

And many thanks to my colleagues

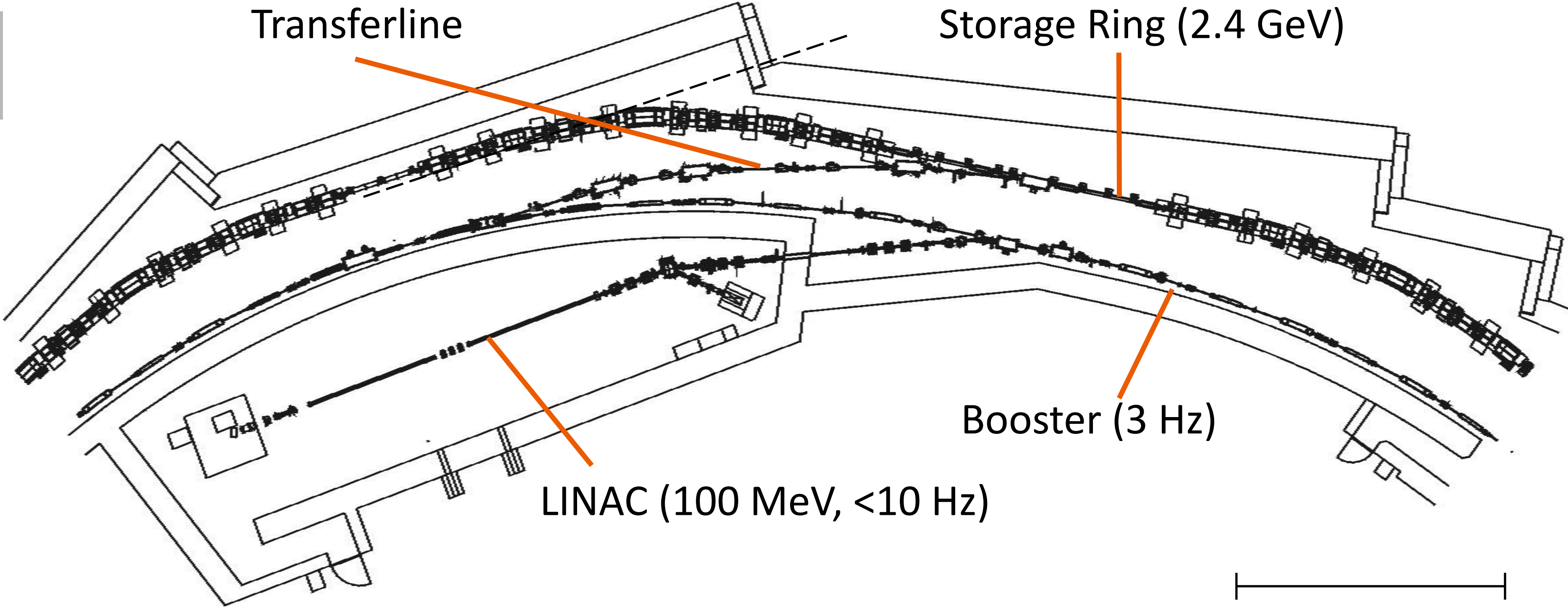
- Masamitsu Aiba
- Maria Ilaria Besana
- Romain Ganter
- Jonas Kallestrup
- Martin Paraliev

SLS 2.0 - Milestones

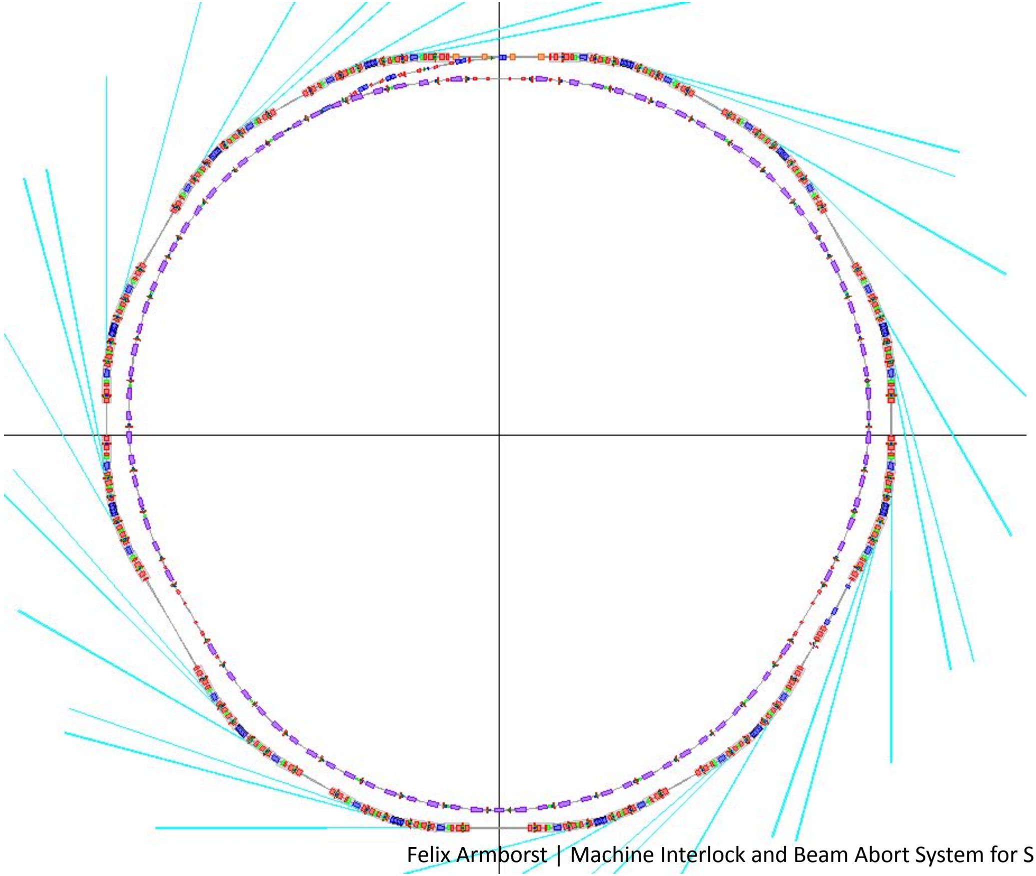


22 months without
user operation

Swiss Light Source - SLS

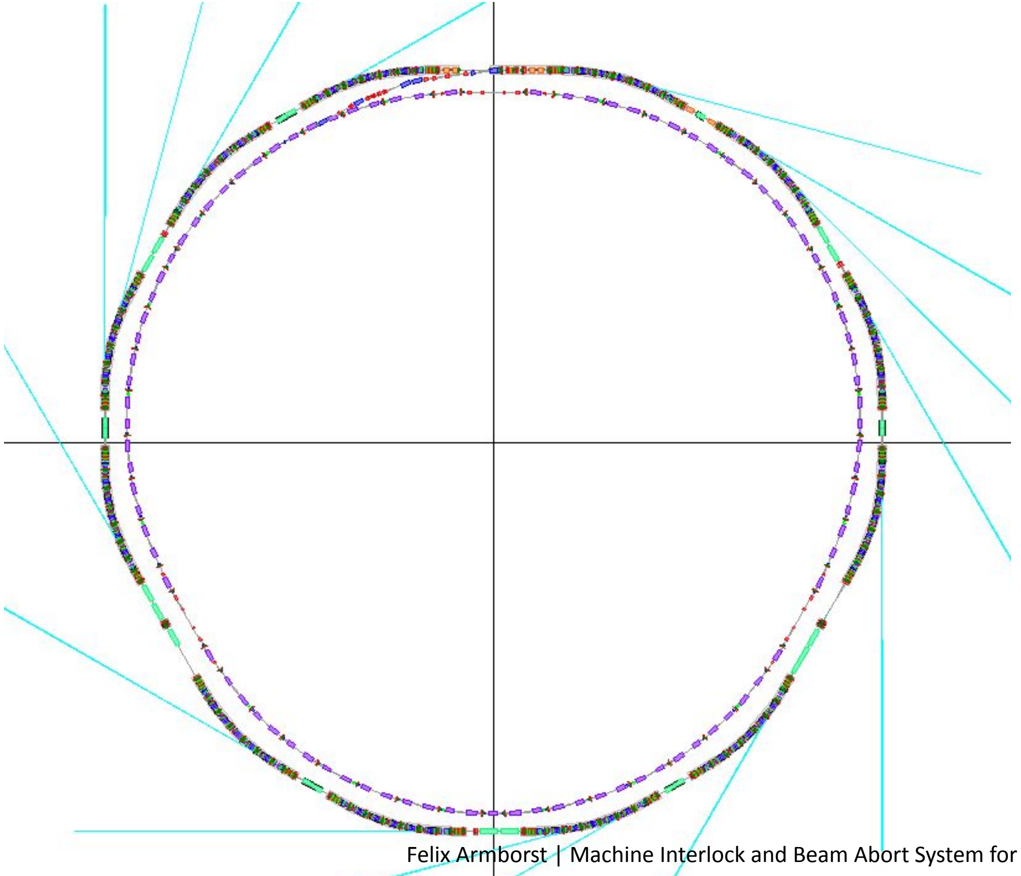


Swiss Light Source - **SLS**



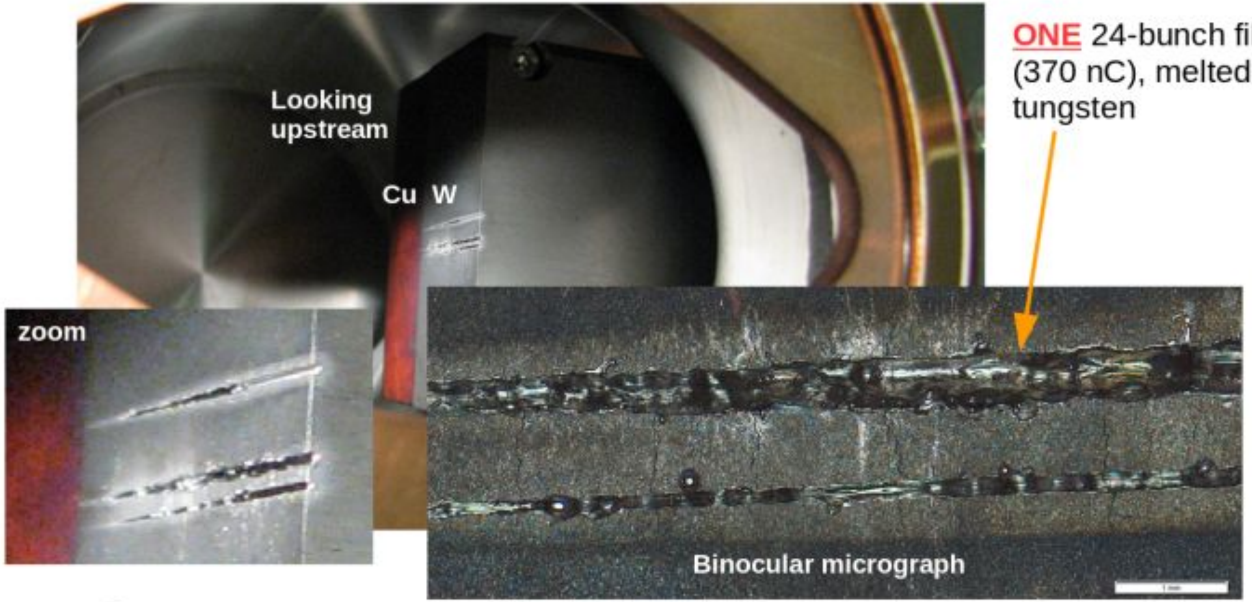
- Circumference **288 m**
- Straights
  - ○ **3** × Long
  - ○ **3** × Medium
  - ○ **6** × Short
  - ○ Total Length ~ **80 m**
- Beam Current **400 mA**
- Beam Energy 2.41 GeV
- Emittance 5.5 nm

Swiss Light Source - Upgrade Project **SLS 2.0**



- **Maintained**
  - Circumference **288 m**
  - Straights
    - **3** × Long
    - **3** × Medium
    - **6** × Short
    - Total Length **~80 m**
  - Beam Current **400 mA**
- **Almost Maintained**
  - Source Point Positions |shifts| < **70 mm**
- **Improved**
  - Emittance **157 pm** (from 5500 pm)
  - Energy **2.7 GeV** (from 2.41 GeV)

SLS 2.0 Interlock Beam Dump - Requirements



ONE 24-bunch fill (370 nC), melted tungsten

Tracking

- Un
  - ➔
- RF
  - ➔
  - ➔

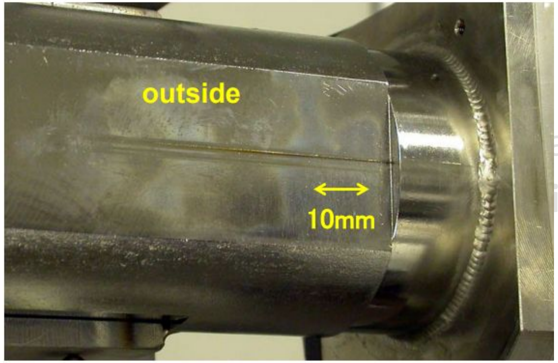
Destruct

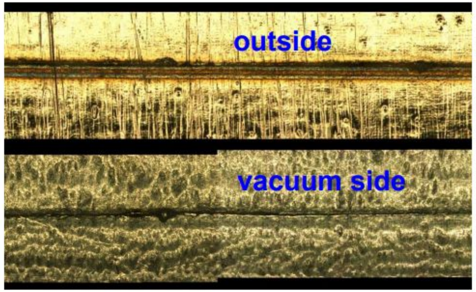
- Em
- 40(
- **APS tungsten scraper experiments (2 kJ) [1, 2]**
- SPring-8 Injection chamber vacuum leak with low-emittance optics (4 kJ)
  - ➔ Controlled beam dump with dedicated kicker, dump and “bunch painting”

[1] J. Dooling & M. Borland, *Energy Deposition in the APS-U swap-out dump and discussion of whole beam loss*, Technical Workshop on Injection and Injection Systems, August 28-30, 2017, Berlin, Germany

[2] *Advanced Photon Source Upgrade Project*, Final Design Report, May, 2019, Chapter 2: Accelerator Upgrade, 2-2.9 Beam Dumps and Collimation, 2-2.9.4 Whole-beam dump, P.42

SLS 2.0 Interlock Beam Dump - Requirements





Tracking simulations show

- Unfortunate loss loca and SC superbend
  - ➔ **RF phase invers icable**
- RF trip causes beam l
  - ➔ **Beam dump de**
  - ➔ **Fast beam dum systems required**

Destructive potential of stc

- Emittance 157 pm (fr
- 400mA @ 2.7GeV (fr
- APS tungsten scraper
- **SPring-8 Injection chamber vacuum leak with low-emittance optics (4 kJ) [3]**
  - ➔ Controlled beam dump with dedicated kicker, dump and "bunch painting"

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[3] H. Tanaka et al., *Top-Up Operation of SPring-8 Storage Ring with Low-Emittance Optics,* Proceedings of EPAC 2006, Edinburgh, Scotland, THPLS034

Introduction: The SLS 2.0 Beam Abort System

- SLS interlock beam dump concept
  - RF phase inversion
  - Decelerate beam
  - Dispersive orbit
  - Distributed losses at restrictive apertures
    - Thin septum
    - High-dispersion TBA-arcs

- Machine protection main aspects
  - Synchrotron radiation
  - Beam loading

- SLS 2.0 interlock beam dump concept
  - Fast Beam Dump Controller
    - Bypass slow PLC systems
  - Dedicated Dump Kicker
    - Bunch painting
  - Dedicated Beam Dump
    - Localized losses

- Machine protection main aspects
  - Synchrotron radiation
  - Beam loading
  - **Stored beam**

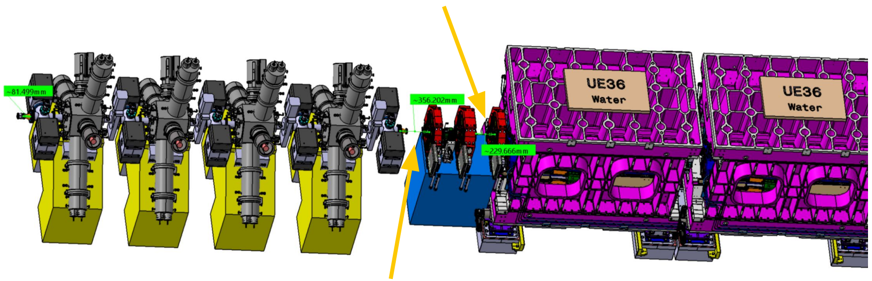
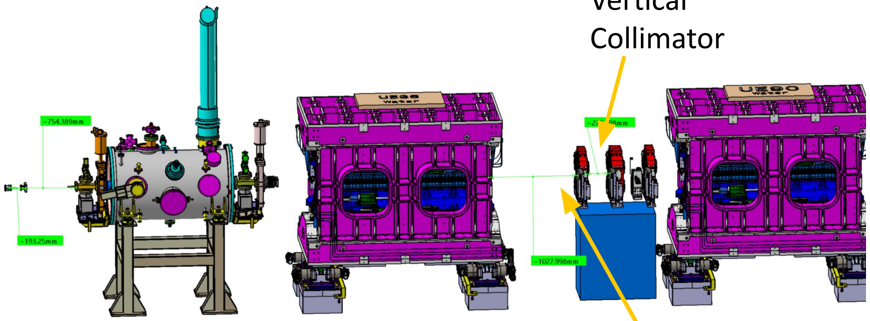
Losses: Collimation Concept

- Main tasks
  - Catch mis-injected beams
  - Mitigate hot spots from
    - gas scattering at small gap and high beta undulators
    - Touschek scattering in arcs
  - Protect
    - IDs
    - RF
- Collimation efficiency
  - 42.9 % overall including thin septum aperture
    - Short range losses dominate for Touschek- and Gas-Scattering
    - No space for collimator in dispersive region

Machine Protection: Collimation

Collimator Positioning

- No space in dispersive regions in arc sections
- Use long straights 5L and 9L with each
  - 2 hor. Collimators, aperture equivalent to the Injection septum
  - 2 ver. Collimators, aperture equivalent to 4-mm **full** undulator gap
  - Design based on simplified & smaller ESRF-EBS collimators

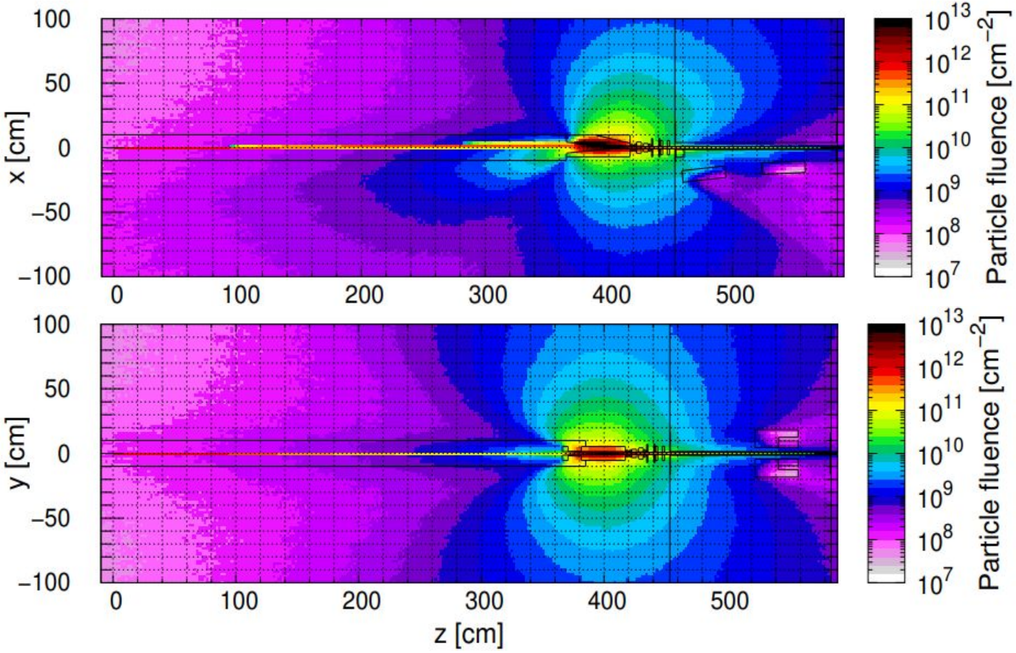
Collimators in 5L	Collimators in 9L
Vertical Collimator  Horizontal Collimator	Vertical Collimator  Horizontal Collimator

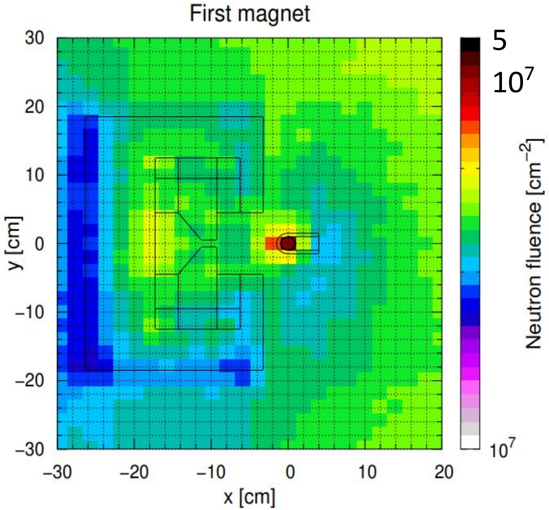
Courtesy of R. Ganter

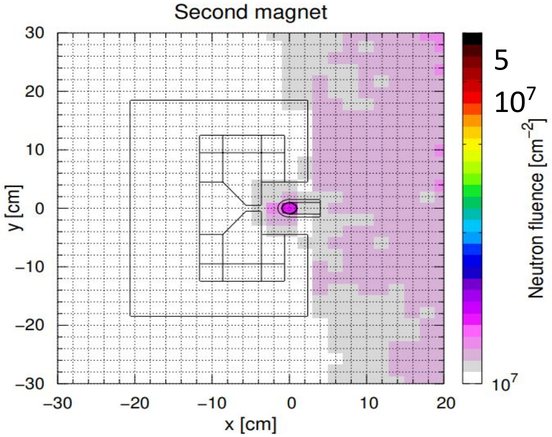
Radiation Protection: Interlock Beam Dump

Dose on thick septum permanent magnets

- $10^7 << 10^{15}$ neutrons / cm^2
- Total average dose < 0.1 Gy





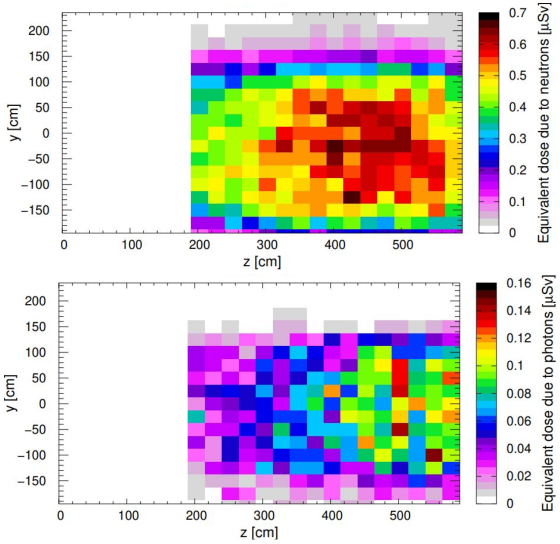


Courtesy of M. I. Besana

Radiation Protection: Interlock Beam Dump

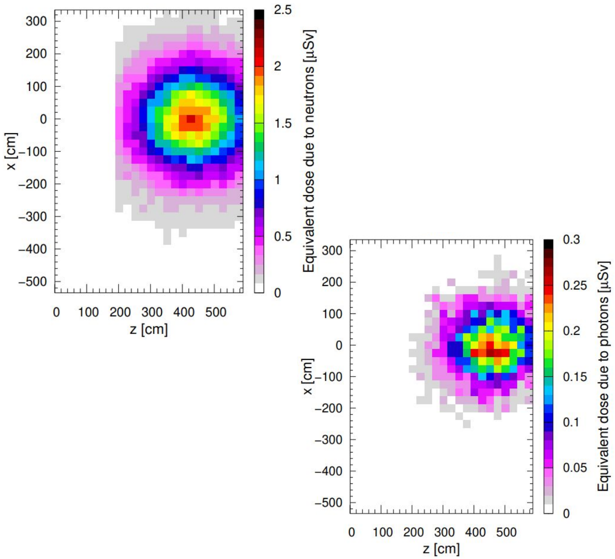
Dose outside Tunnel

Inner Wall



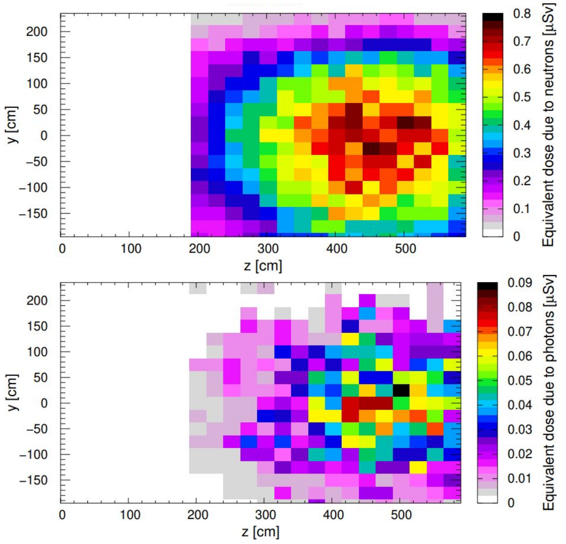
∑ < 1 µSv/dump

Roof



∑ < 3 µSv/dump

Outer Wall



∑ < 1 µSv/dump

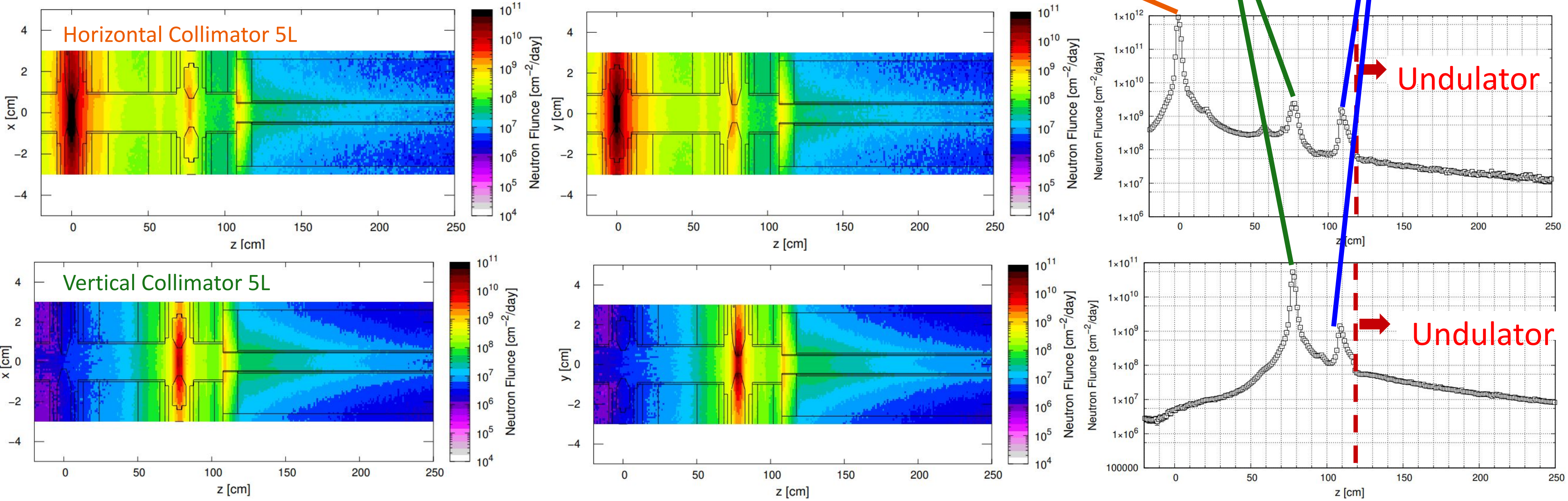
- Dose outside SLS bunker dominated by neutron contribution. Total escaping energy ~1%. No shielding yet.
- **Limit** outside inner and outer wall: **20 µSv/week**

Courtesy of M. I. Besana

Radiation Protection: Collimation

Collimators in X05L - Dose on Downstream UE36

- Total daily fluence ~10^8 neutrons/cm^2
- Considered threshold for demagnetization ~10^{12} neutrons/cm^2
- **Possible operation for more than 20 years**



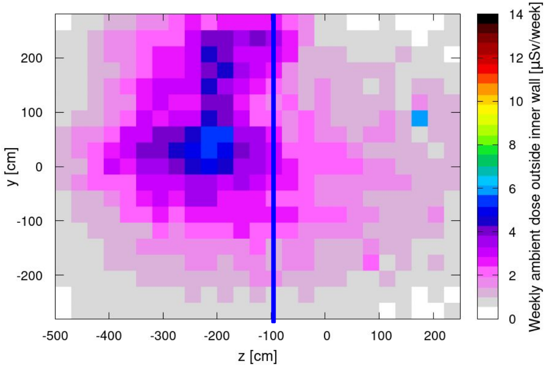
Courtesy of M. I. Besana

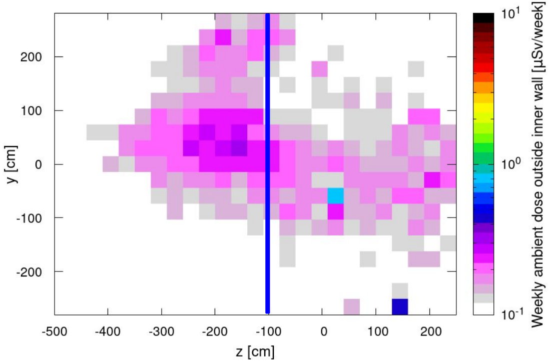
Radiation Protection: Collimation

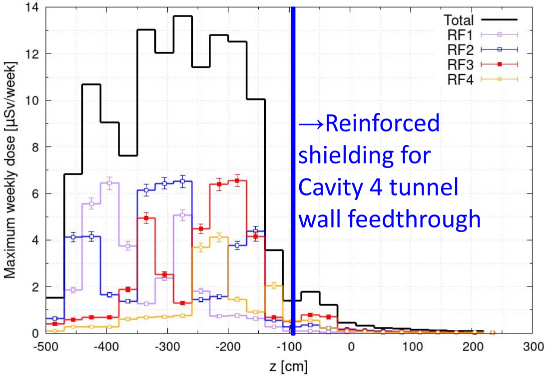
Collimators in X05L - Dose Outside Tunnel

Horizontal Collimator | **Vertical Collimator** | **RF**

Inner Wall
∑ < 20
µSv/week

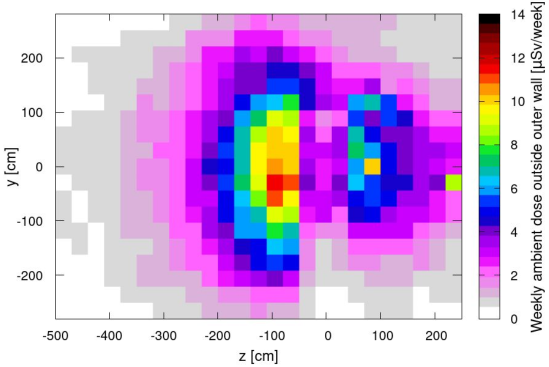


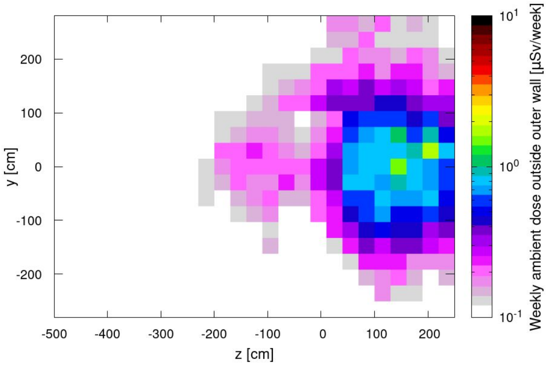


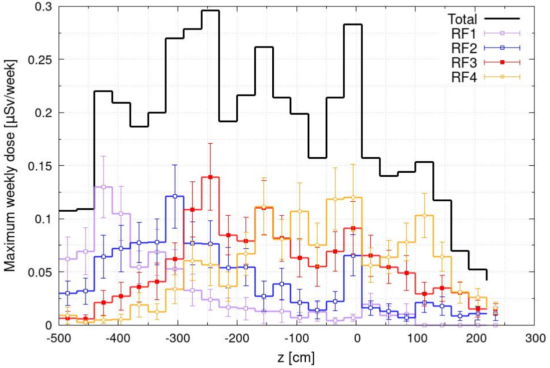


→Reinforced shielding for Cavity 4 tunnel wall feedthrough

Outer Wall
∑ < 13
µSv/week
(Inside hutch)



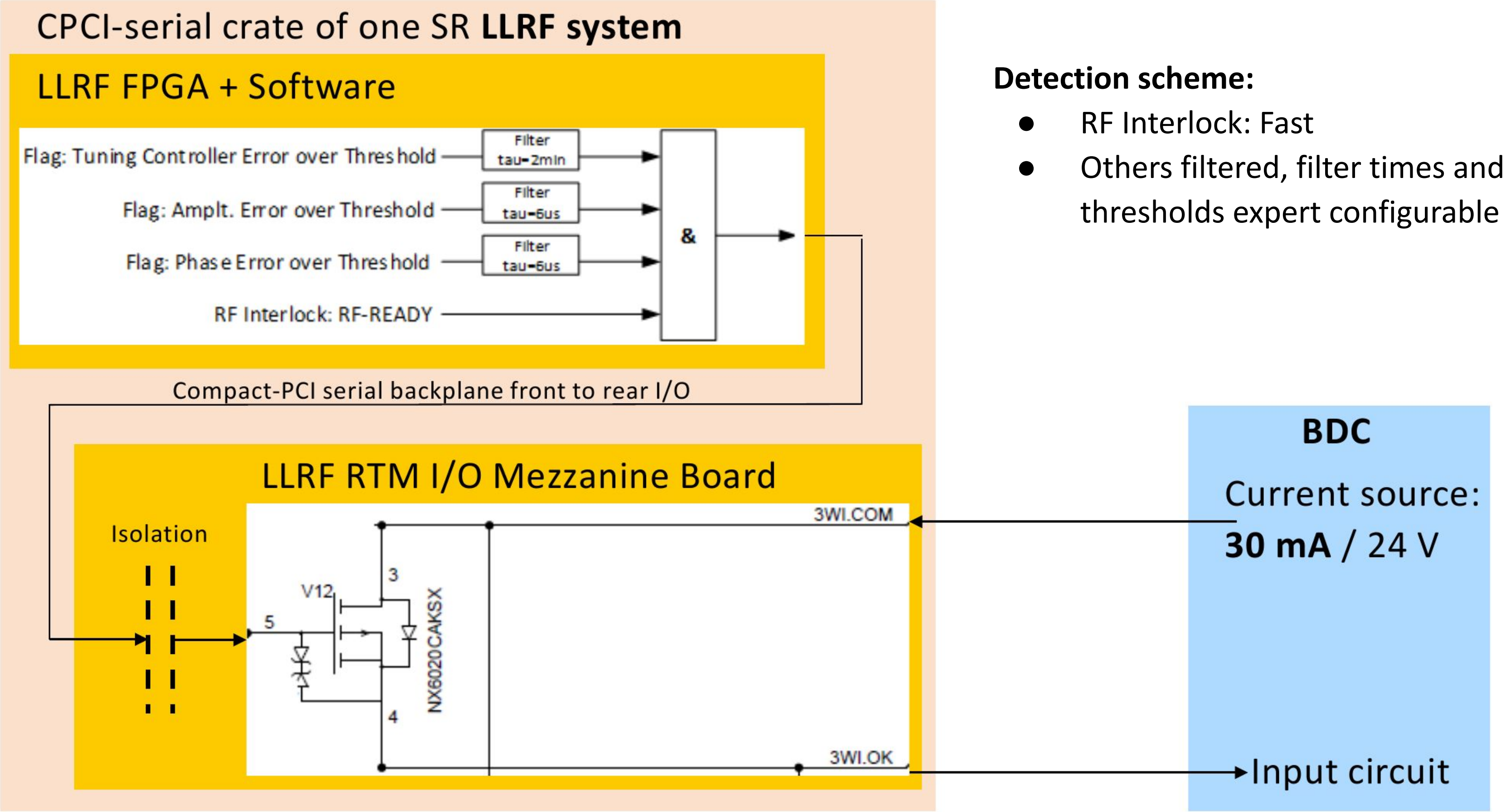




- Dose on tunnel roof varies with construction but ∑ **< 1 µSv/hour** (Limit is ~10 µSv/hour).
- RF cavity assumption (14 µSv/week) based on maximum from measurements fluctuating by factor 3.

Courtesy of M. I. Besana

Beam Dump Controller - LLRF Input



CPCI-serial crate of one SR **LLRF system**

LLRF FPGA + Software

Flag: Tuning Controller Error over Threshold → Filter tau=2min

Flag: Amplt. Error over Threshold → Filter tau=6us

Flag: Phase Error over Threshold → Filter tau=6us

RF Interlock: RF-READY

&

Compact-PCI serial backplane front to rear I/O

LLRF RTM I/O Mezzanine Board

Isolation

BDC

Current source:

30 mA / 24 V

Input circuit

Detection scheme:

- RF Interlock: Fast
- Others filtered, filter times and thresholds expert configurable

Courtesy of R. Kalt

Beam Dump Controller - Orbit Monitoring

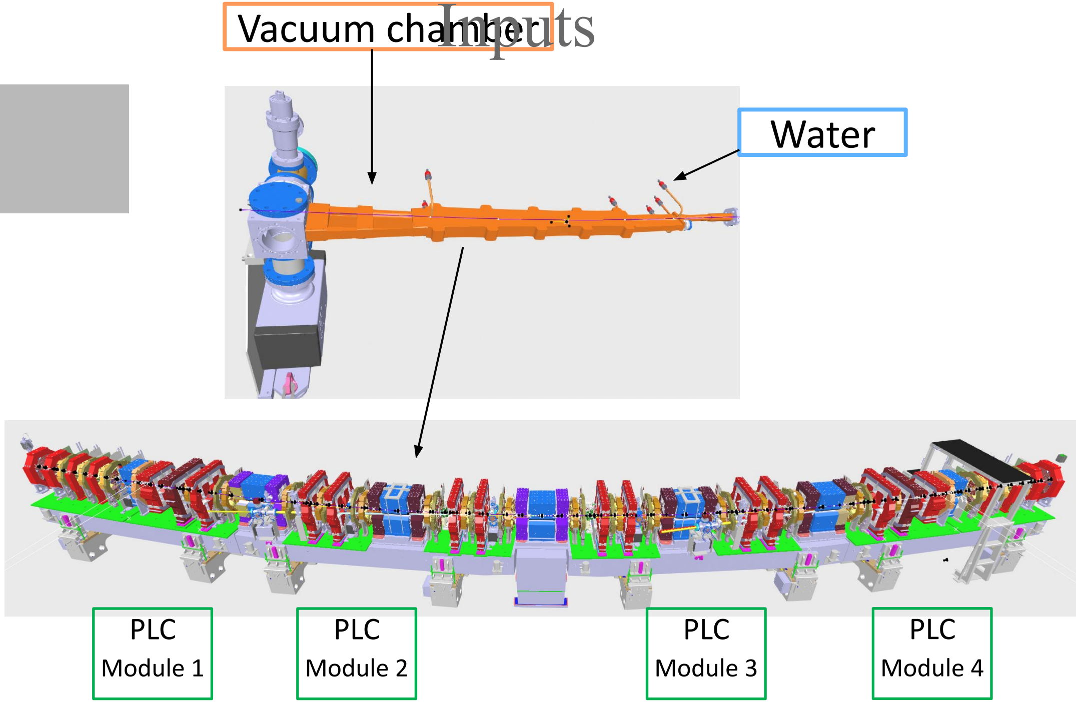
Bad situations

- **RF trip (e.g., arc detected)**
  - Coasting Beam lost after 300 µs in 2-3 turns
- **Failure of superconducting superbend**
  - 60 mrad, decay in ~ca. 30 s → 2 µrad / ms
  - Critical limit at ~1 % → 0.6 mrad → reached after 300 ms

Catching corresponding orbit errors

- **With only new SLS 2.0 DBPM3**
  - 20 kHz → 100us → 0.2 uRad << 0.6 mRad
  - 1 MHz → 2us → 4 nRad << 0.6 mRad
- **With mix of old BPM and new DBPM3**
  - 4 kHz sampling rate, 1 kHz bandwidth, 1 ms → 2µrad
    - too slow for RF trip !

Machine Interlock System - Vacuum Temperature Inputs



Vacuum chamber

Water

PLC Module 1

PLC Module 2

PLC Module 3

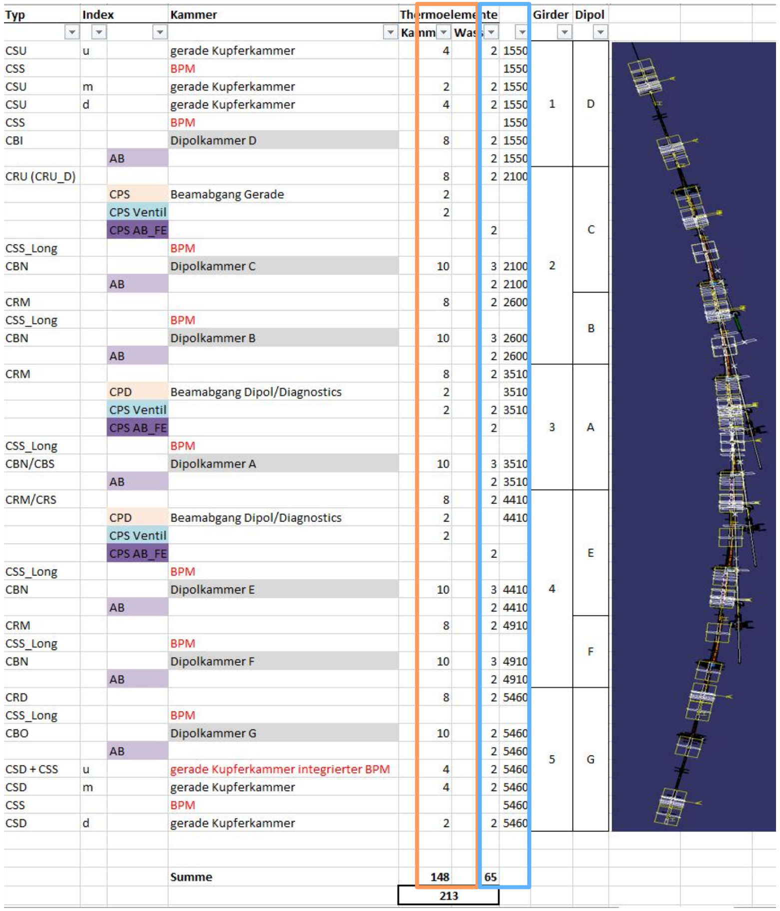
PLC Module 4

Chambers:

EPICS HIGH	55°C
EPICS HIHI	60°C
Interlock	70°C

Water

EPICS HIGH	35°C
EPICS HIHI	40°C
Interlock	50°C

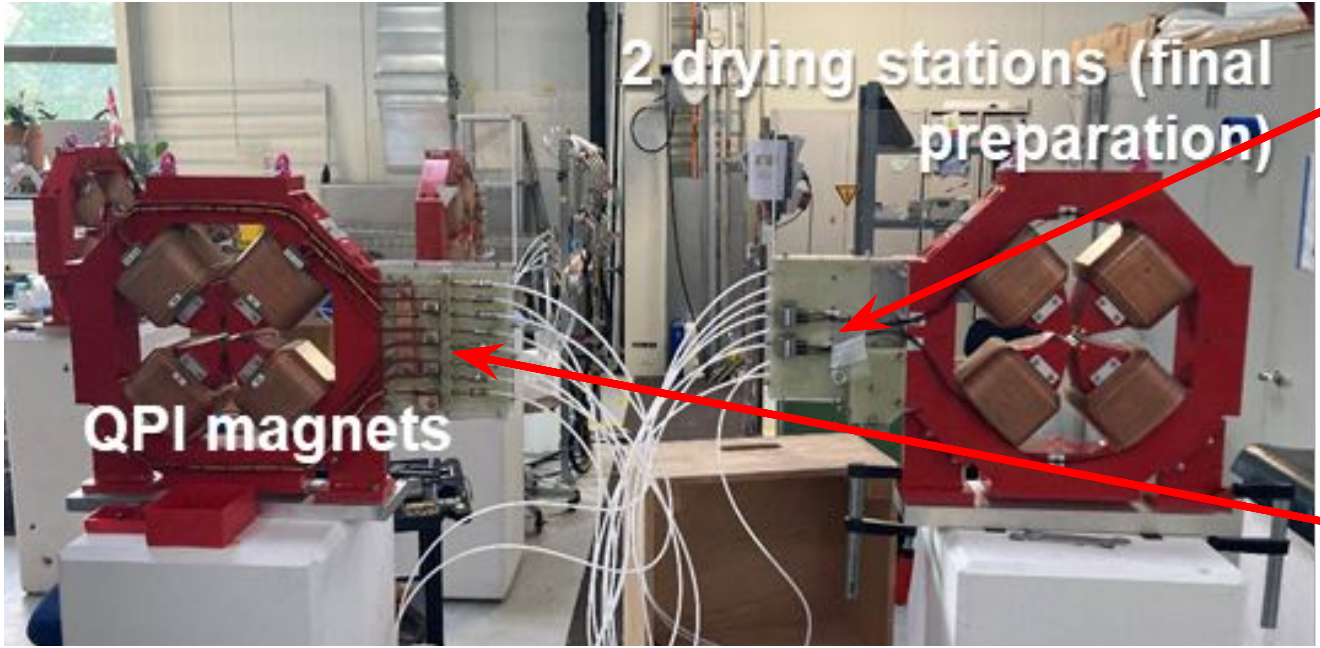


Typ	Index		Kammer	Thermoelemente			Girder	Dipol
				Kamm	Was			
CSU	u		gerade Kupferkammer	4	2	1550	1	D
CSS			BPM			1550		
CSU	m		gerade Kupferkammer	2	2	1550		
CSU	d		gerade Kupferkammer	4	2	1550		
CSS			BPM			1550		
CBI			Dipolkammer D	8	2	1550		
		AB			2	1550		
CRU (CRU_D)				8	2	2100	2	C
		CPS	Beamabgang Gerade	2				
		CPS Ventil		2				
		CPS AB_FE			2			
CSS_Long			BPM					
CBN			Dipolkammer C	10	3	2100		
		AB			2	2100		
CRM				8	2	2600		B
CSS_Long			BPM					
CBN			Dipolkammer B	10	3	2600		
		AB			2	2600		
CRM				8	2	3510	3	A
		CPD	Beamabgang Dipol/Diagnostics	2		3510		
		CPS Ventil		2	2	3510		
		CPS AB_FE			2			
CSS_Long			BPM					
CBN/CBS			Dipolkammer A	10	3	3510		
		AB			2	3510		
CRM/CRS				8	2	4410	4	E
		CPD	Beamabgang Dipol/Diagnostics	2		4410		
		CPS Ventil		2				
		CPS AB_FE			2			
CSS_Long			BPM					
CBN			Dipolkammer E	10	3	4410		
		AB			2	4410		
CRM				8	2	4910		F
CSS_Long			BPM					
CBN			Dipolkammer F	10	3	4910		
		AB			2	4910		
CRD				8	2	5460	5	G
CSS_Long			BPM					
CBO			Dipolkammer G	10	2	5460		
		AB			2	5460		
CSD + CSS	u		gerade Kupferkammer integrierter BPM	4	2	5460		
CSD	m		gerade Kupferkammer	4	2	5460		
CSS			BPM			5460		
CSD	d		gerade Kupferkammer	2	2	5460		
			Summe	**148**	**65**			
				213				

Courtesy of R. Ganter

Machine Interlock System - Magnet Temperature Inputs

- **Concept:** PT-100 Temperature sensors are cast into the coils
- Each sensor is individually wired to and monitored by the MIS
- Front and rear view:

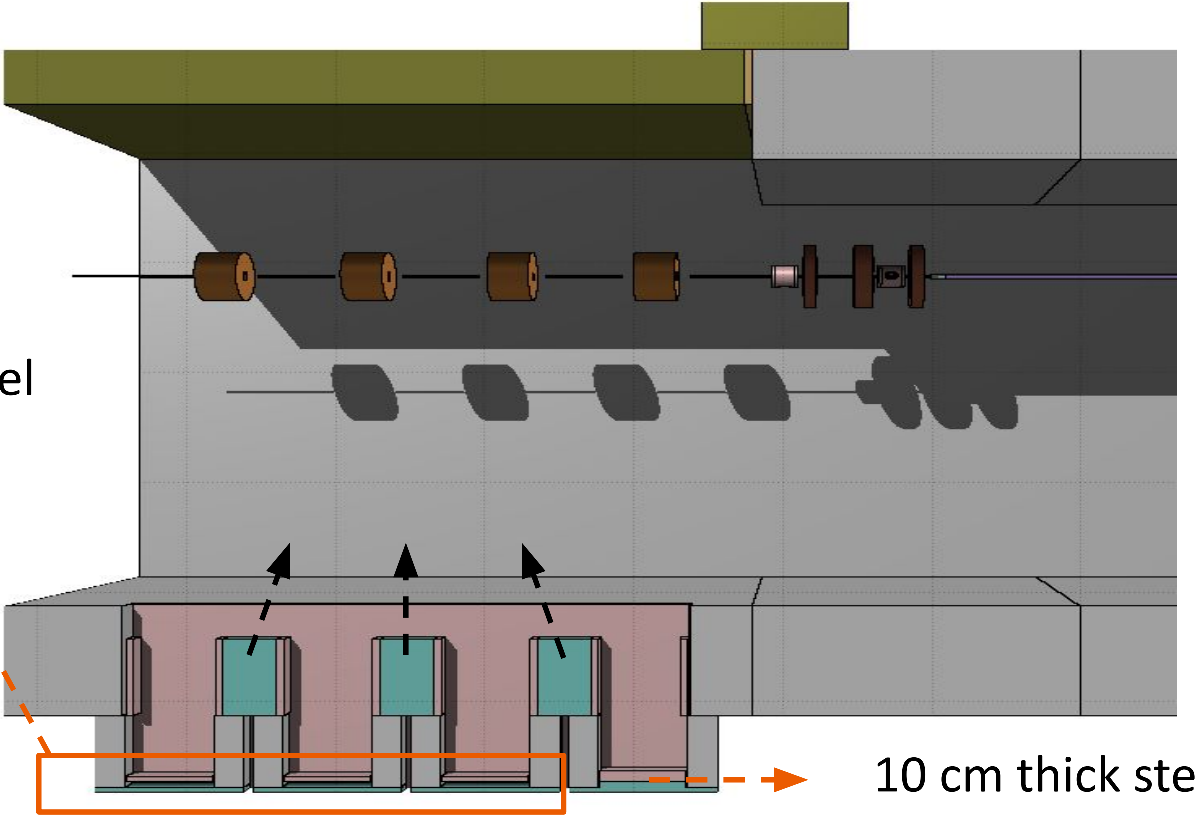


Temperature sensor interface

PS and cooling interface

Courtesy of A. Gabard

RF Shielding



5 cm thick steel

+

5 cm thick polyethylene

10 cm thick steel +

10 cm thick polyethylene

Courtesy of M. I. Besana