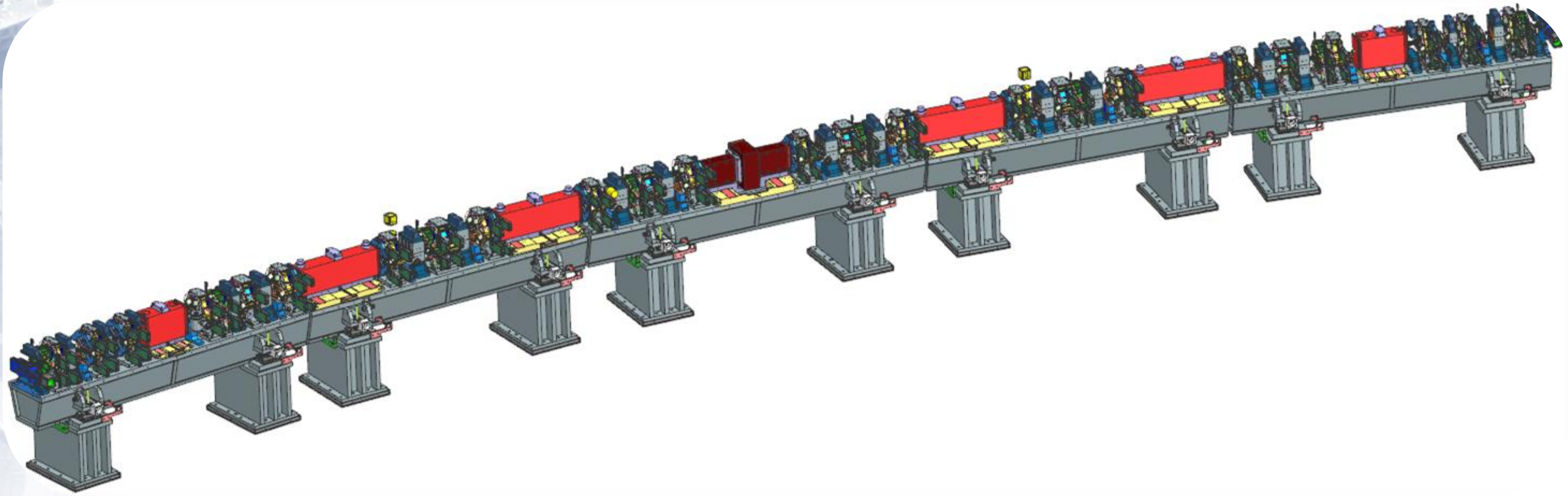
12th International Workshop on
Radiation Safety at Synchrotron Radiation Sources
24-27 June 2025

Challenges in Radiation Safety associated with SOLEIL II Upgrade project

J-B. Pruvost, P. Berkvens



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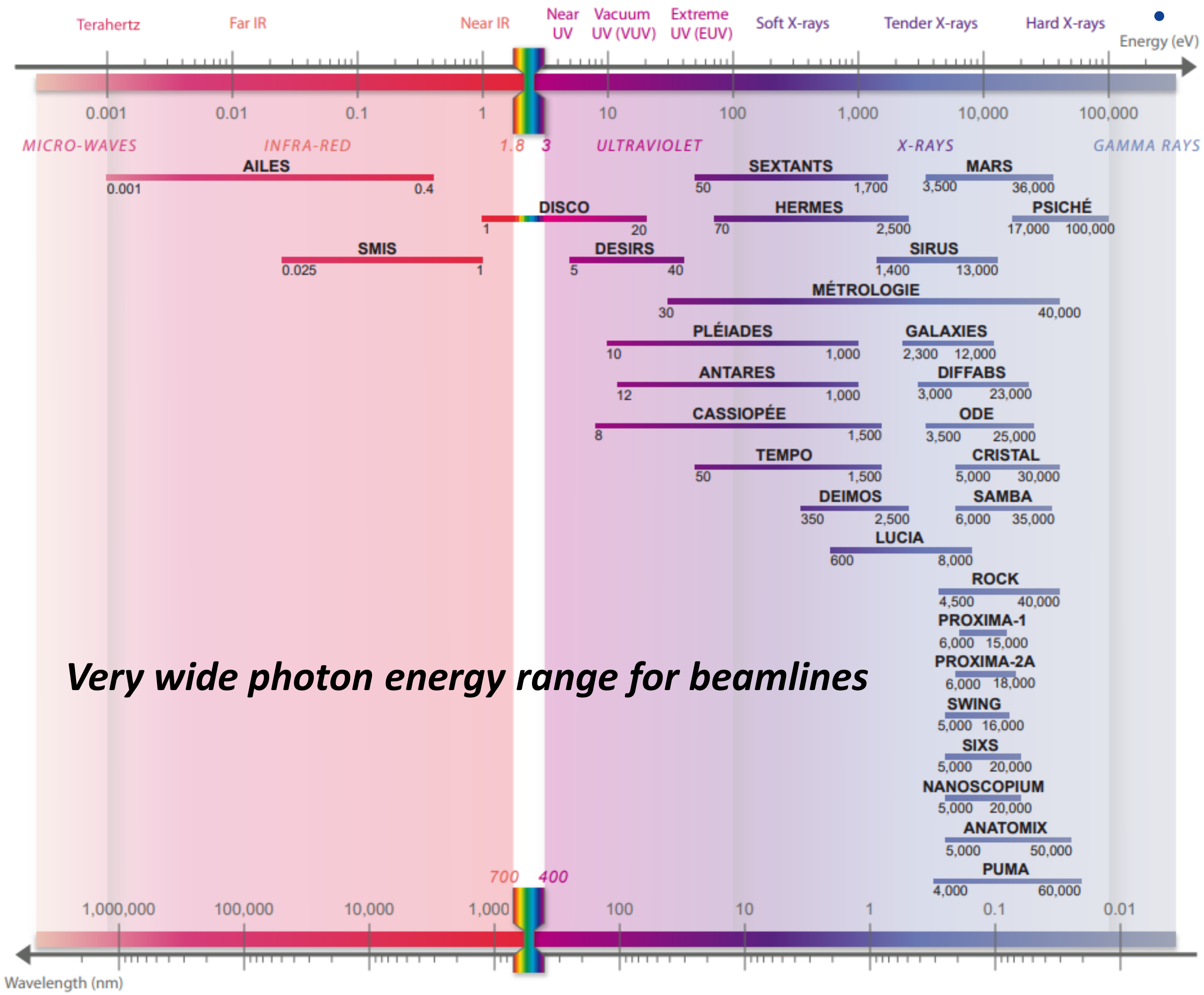
OUTLINE

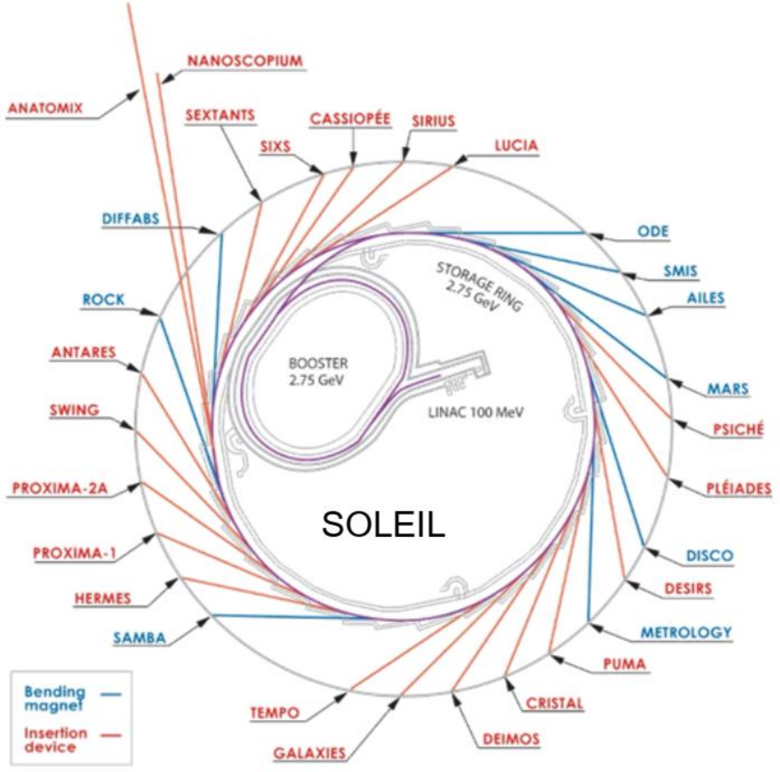
- SOLEIL II Ambitious upgrade project towards 4th generation light source
- General Radiation Safety Policy at Synchrotron SOLEIL
- Radiation safety Assessment Program
- Preliminary shielding results for SOLEIL II storage ring
- Permanent magnet exposure concerns

Synchrotron SOLEIL Main Parameters

- 1 LINAC, 3 Hz, 110 MeV, up to 10 nC (LPM) – 16 m ;
- 1 BOOSTER, 3 Hz, 110 MeV → 2.75 GeV – 156 m ;
- 1 STORAGE RING, 2.75 GeV, 500 mA and top-up operation – 354 m ;
- 16 DBA cells
- 24 straight sections
- On-axis injection, 2 cryo-modules of 2x supra-conducting RF cavities @352MHz
- 29 beamlines (2x IR, 7 BM, 20 ID) with very large photon Energy range
- ~4800 users per year



Very wide photon energy range for beamlines



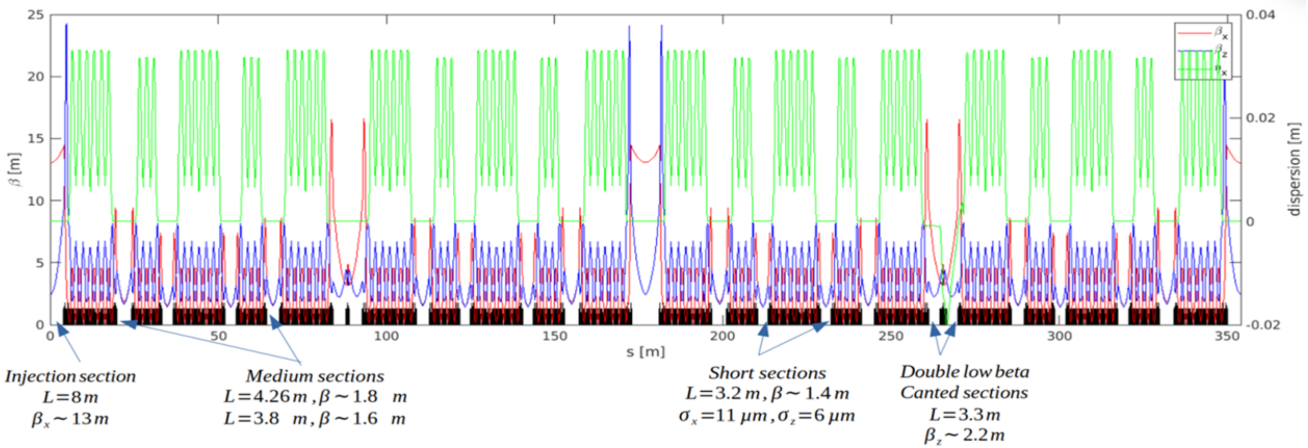
A New Storage Ring for SOLEIL II

Upgrade Project of the SOLEIL Accelerator Complex, SRN, 2023
https://doi.org/10.1080/08940886.2023.2186661
A brief introduction to the Synchrotron SOLEIL and its upgrade programme. *Eur. Phys. J. Plus* **139**, 80 (2024). https://doi.org/10.1140/epjp/s13360-024-04872-2

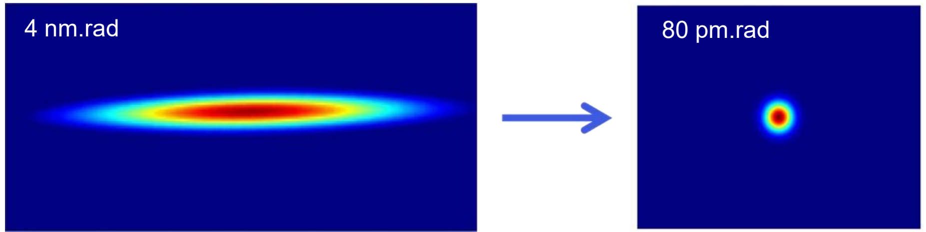
Rebuilt a complete new storage ring based on Multi Bend Achromat scheme

→ **Non-standard MBA HOA Lattice: 12x 7BA + 8x 4BA**

- ✓ Natural equilibrium emittance: **85 pm.rad**
- ✓ Low β functions in medium and short straight sections
- ✓ 20 straight sections
- ✓ 8 super-bends (1.7 & 3 T)



3rd generation SOLEIL → **4th generation SOLEII II**



Parameters*	SOLEIL	SOLEIL II
Energy [GeV]	**2.75**	**2.75**
Circumference [m]	354.10	353.97
Maximum Beam Current [mA]	**500**	**500**
Lattice Type	**DBA**	**7BA-4BA**
Cell Number	24	20
Natural Emittance [pm.rad] Round beam (100% coupling)	**3 900** **-**	**83** **53**
Energy Spread	1.02 E-3	0.91 E-3
Total Beam Lifetime [h]	16	3 / 6-8 (w/ HC)
Natural RMS Bunch Length [ps]	16.1	8.6
Transverse Damping Times, $\tau_x/\tau_y/\tau_s$ [ms]	6.9 / 6.9 / 3.5	7.8 / 14.3/ 12.4
Momentum Compaction Factor	4.2 E-4	1.06 E-4
Energy Loss per Turn [keV]	917	453
Overall RF Voltage [MV]	2.6	1.8
RF Frequency [MHz]	352.20	352.33
RF Power into the Beam [kW]	575	245
Synchrotron Frequency [kHz]	4.2	1.8

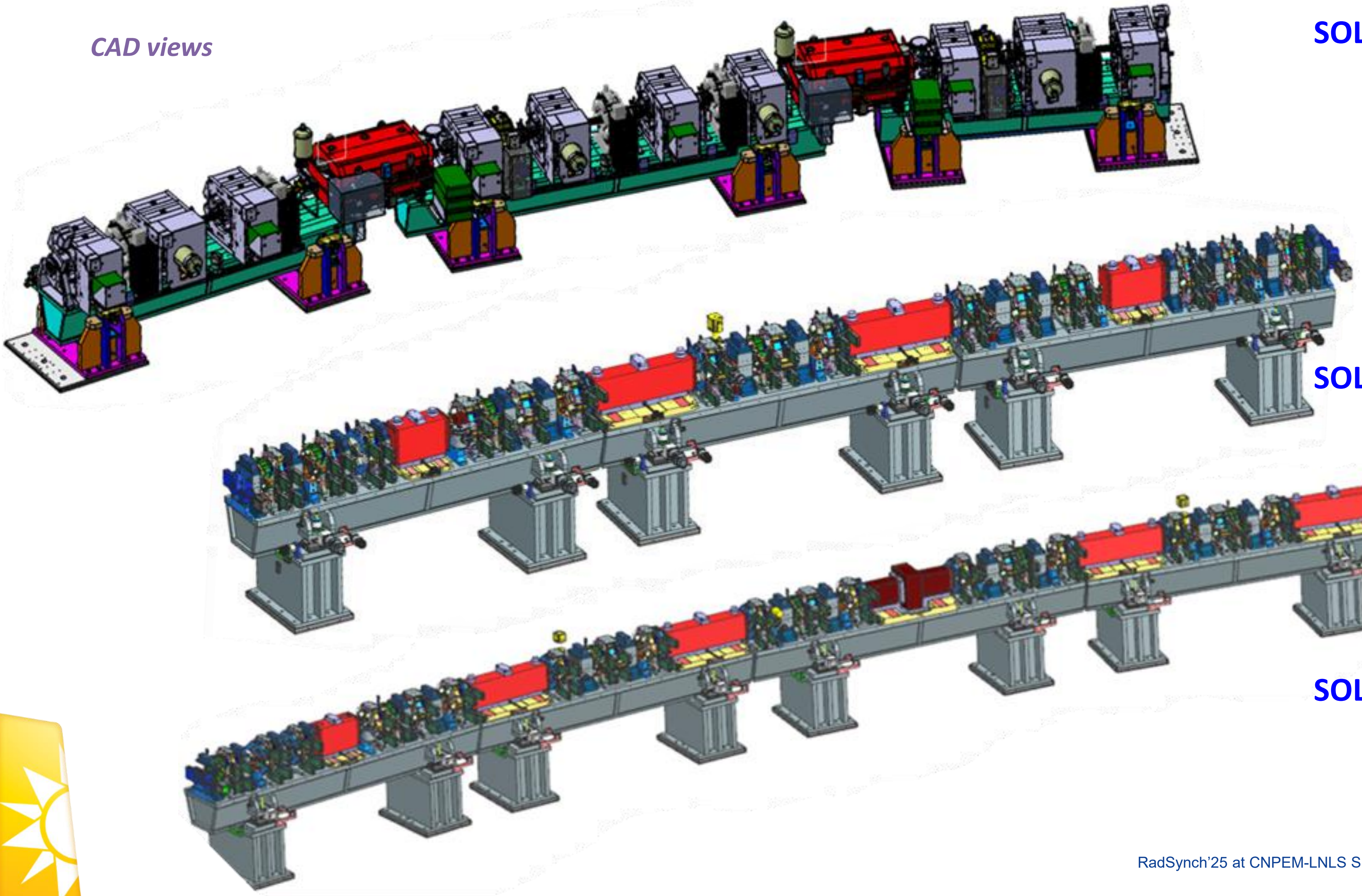
Parameters without insertion devices nor harmonic cavity

SOLEIL II Storage Ring Upgrade Project

- **Extensive use of Permanent Magnets (Sm_2Co_{17}) for all dipoles and quadrupoles**
- **Strong miniaturization of the vacuum pipes and magnet yokes**
- **Off axis injection scheme thanks to High performance Multi-pole Injection Kicker (MiK) developped at SOLEIL**
- **4 « hot » fondamental RF cavities + 2 passive harmonic cavities to stretch beam bunches length and enhance stability and beam lifetime**
- **Very large Photon Energy spectrum for Beamlines (from far IR to hard X-rays)**
- **Strong limit conditions:**
  - Re-use of the present storage ring shielding
  - Maintain top-up operation at 500 mA with best beam stability as for SOLEIL's
  - ***Preserving most current Beamline positions (at least for almost all IDs)***
    - Unvariant axis: 2 long beamlines (NANOSCOPIUM & ANATOMIX)
    - Specific Material beamline dedicated to radioactive samples (MARS)
  - As low impact as possible for BL on bending magnet source
    - Source point axis deviation < 1° to minimize relocation and realignment of the BL
  - As much Beamlines as possible ready for the restart including 6 relocated BL
- **Energy savings (~ -1.5 GWh/year)**
- **Plus new low-emittance Booster, upgraded Linac Energy (150MeV), Innovative Insertion devices**

SOLEIL II Storage Ring Upgrade Project

CAD views



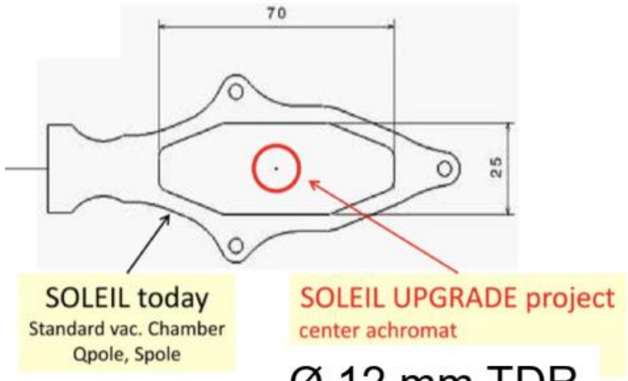
SOLEIL - Double Bend Achromate

SOLEIL II - 4 Bends Achromate

SOLEIL II - 7 Bends Achromate

SOLEIL II Storage Ring Upgrade Project

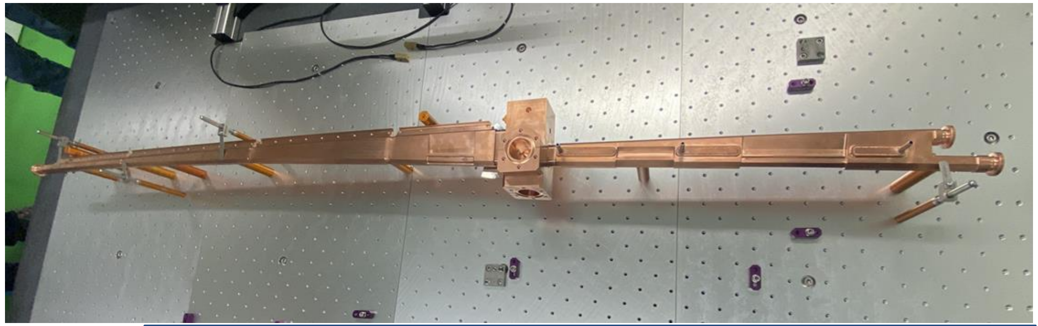
- Huge miniaturization of almost all componants

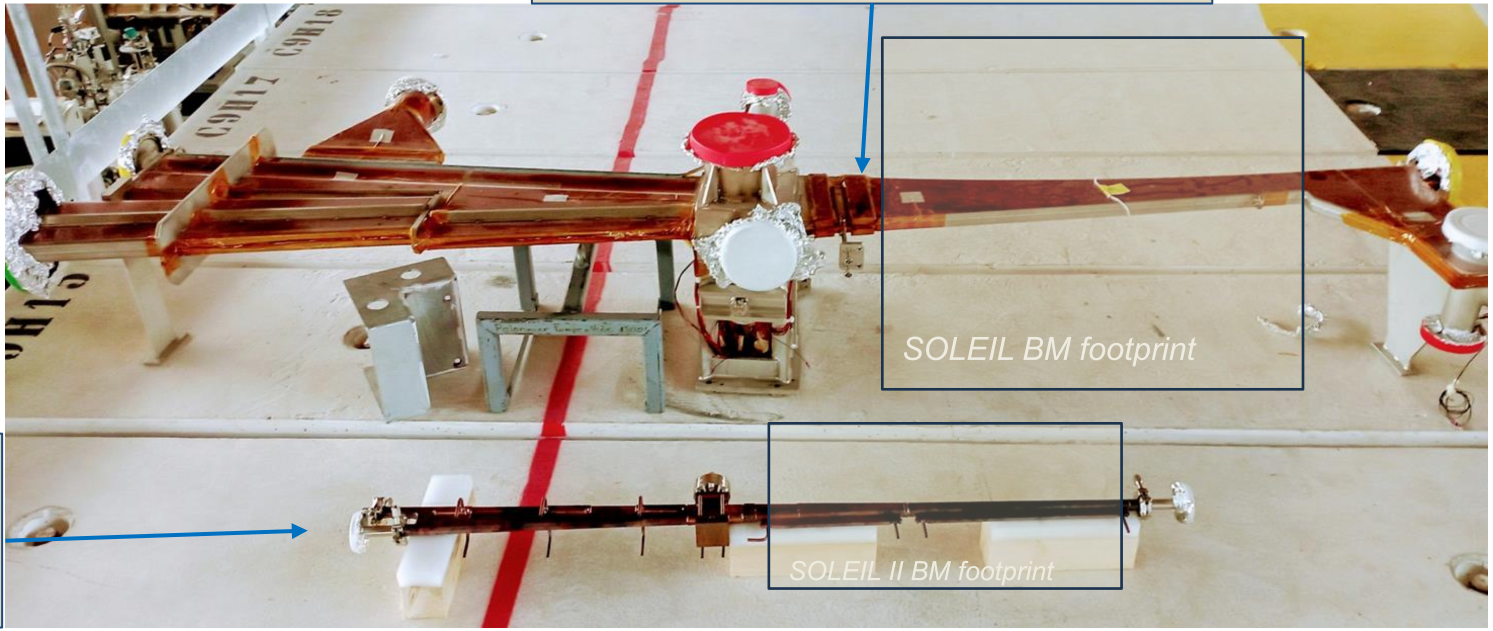


Ø 12 mm TDR

- Full NEG-coated narrow Vacuum Chamber

Dipole Arc Vacuum chamber
SOLEIL → *2005*
[SS316LN]

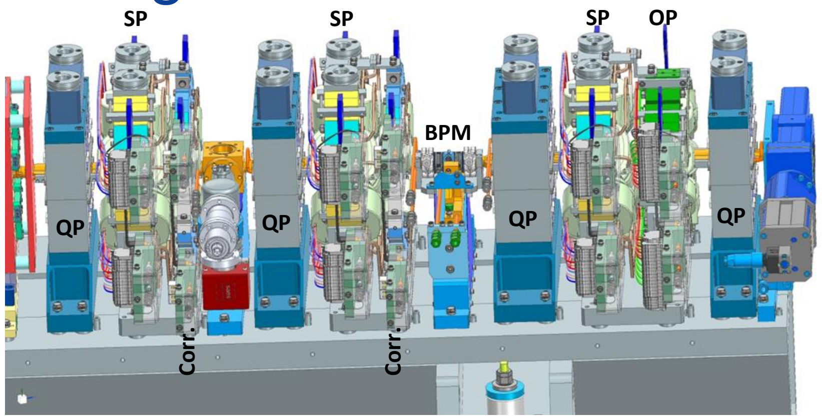




Dipole Arc Vacuum chamber prototype
SOLEIL II - *2024*
[Full copper / OFS+CuCrZr]

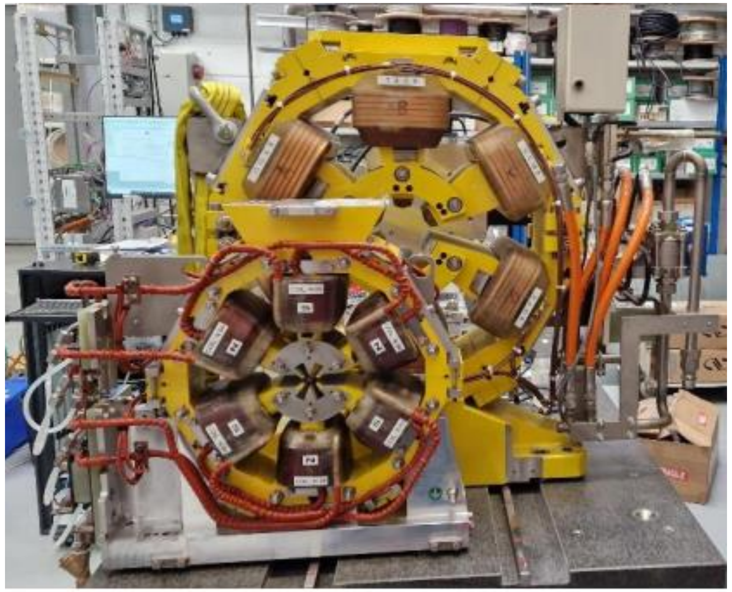
SOLEIL II Storage Ring Upgrade Project

- Magnets



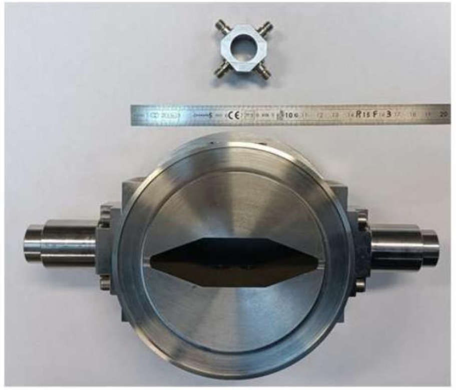
Very tight mecanical integration – matching section example

Permanent magnet quadrupole prototype (top) for SOLEILII and Electromagnet quadrupole for SOLEIL

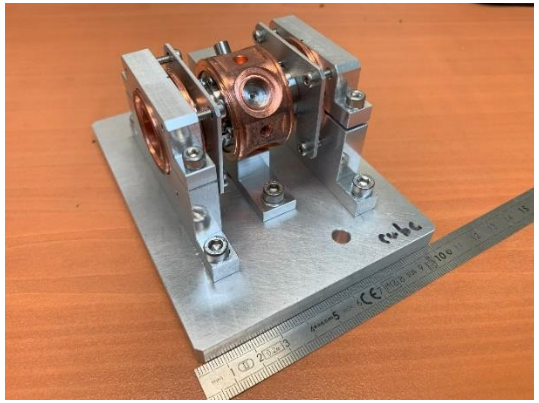


Sextupole SOLEIL/SOLEIL II

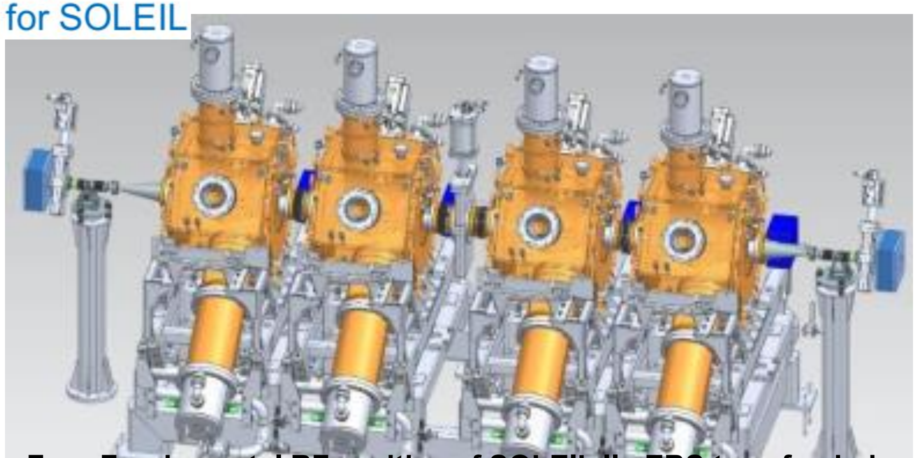
- BPMs



BPM prototypes for SOLEIL (bottom) and SOLEIL II (top)



SOLEIL II BPM prototype realized with bellows (SS316L with copper coating)



Four Fondamental RF cavities of SOLEIL II - EBS type feeded by 4x 200 kW upgraded SSPA towers assembly

GENERAL SCHEDULE

→ **Synchrotron shutdown + restart + commissioning: 24 months**
→ **Return of scientific users: October 2030**

Shutdown

2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035

CDR
(Avant-Projet Sommaire)

TDR
(Avant-Projet Détaillé)

PHASE 1: CONSTRUCTION

- Shutdown and dismantling of whole booster and storage rings
- Start and commissioning of new Booster and new Storage Ring
- Adaptation and restart of Beamlines
- Support labs modernization
- Instrumentation R&D Program

PHASE 2: TOWARDS FULL PERFORMANCE

- Complete Beamlines modernization
- Development of Support Laboratories
- Instrumentation R&D Program
- Innovative Analysing Technics Development

GENERAL RADIATION SAFETY POLICY AT SYNCHROTRON SOLEIL

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SOLEIL GENERAL RADIATION PROTECTION POLICY

- MAIN GENERAL RULE:
  - **All SOLEIL's staff members and all scientific users are considered as non-radiation exposed workers.**
- GENERAL BULK SHIELDING AROUND ACCELERATORS ARE DESIGNED AS:
  - **There is no radiation area accessible by workers (staff or users) during operation or shutdown period.**
- Around Accelerator tunnels or Beamline hutches, Area ambient equivalent dose must remain below 80 μSv per month. (French Regulation Area delimitation criteria)
- Individual annual effective dose strictly below 1 mSv for SOLEIL staff. (French Regulation Individual Exposition Limit for non exposed workers)
- Accelerator Radiation Safety System (ARSS - fully redundant & hardwire technology) controls tunnel access, accelerator permits and radiation level outside tunnels
- Integrated ambient equivalent dose by radiation monitors (gamma & neutron) should be lower than 2 μSv within 4 hours period.

RADIATION SAFETY ASSESSMENT

RADIATION PROTECTION ASSESSMENT PROGRAM FOR SOLEIL II

- Present Storage Ring shielding fully compatible with SOLEIL II Lattice
  - Touschek beam lifetime and losses (natural @500mA ~ 3h)
  - Gas scatering beam lifetime and losses (@500mA ~ 60h)
  - Collimation needed? Collimators and/or additional shielding to design?
- Injection scheme for Storage Ring filling and top-up?
  - SR shielding concerns? Injection cell or elsewhere?
- How to handle safely beam stops/trips? Intentional or not?
  - Collimators, scrapers?
  - Beam dump?
- Radiation damage to Permanent Magnets
  - Exposure evaluation
  - Irradiation tests
- Induced activity assessment
  - Residual dose rates
  - Tunnel access controls needed during shutdowns?

EXTENSIVE USE OF FLUKA* MONTE CARLO CODE

- For a detailed 3D model of exisiting tunnel shielding and main components of the future machine (beam pipes, magnets, guirders, ID jaws, etc…)
- Using FLUKA capabilities to implement magnetic fields and sampling beam losses distribution and phase space distribution provided by machine physics group. (user routines)
- For Effective and Ambient Dose Rate evaluation outside tunnel shielding
- For Induced activity calculation and Residual Ambient Dose Rate evaluation inside tunnel in the vicinity of accelerator equipments
- For neutron fluence calculation and Permanent Magnets exposure evaluation
- To evaluate Energy and Power density deposited into collimators and/or beam stop specific chamber

**FLUKA-CERN distributions: 4-4.0 and 4-5.0*

FIRST RADIATION SHIELDING ASSESSMENT RESULTS

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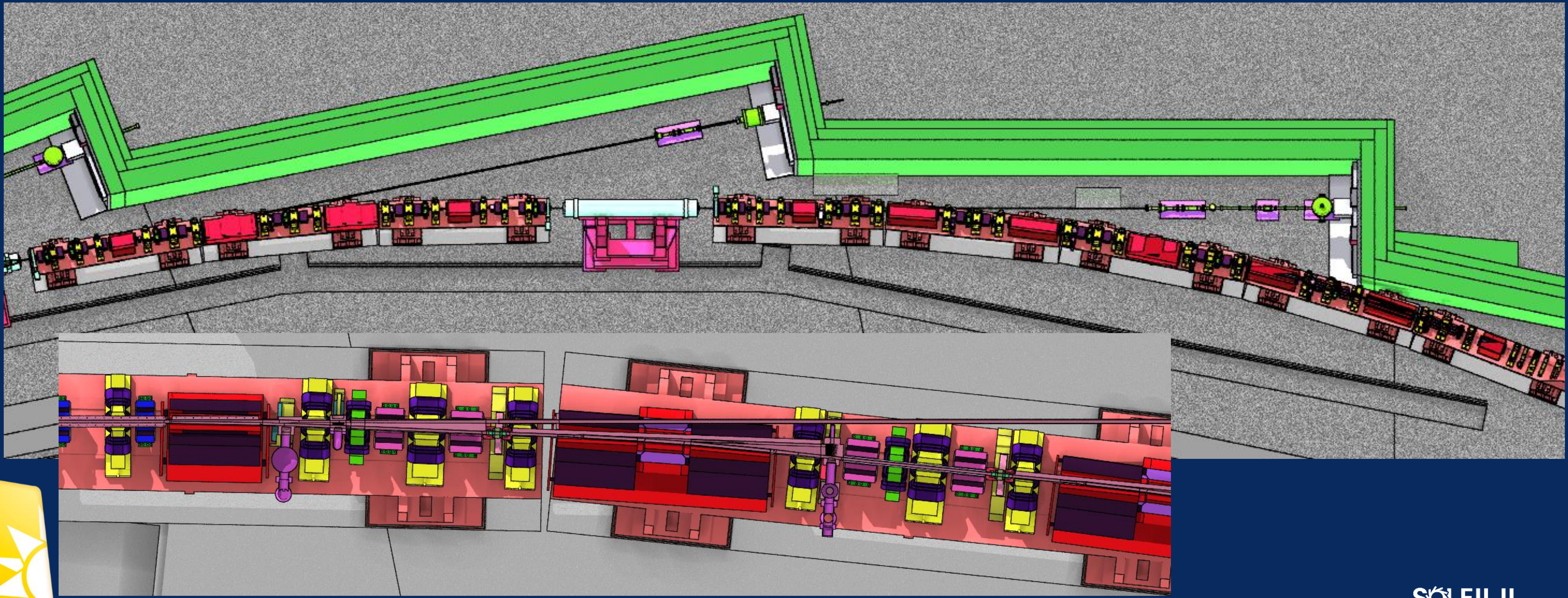
FLUKA MODEL FOR LATTICE VERSION V3588

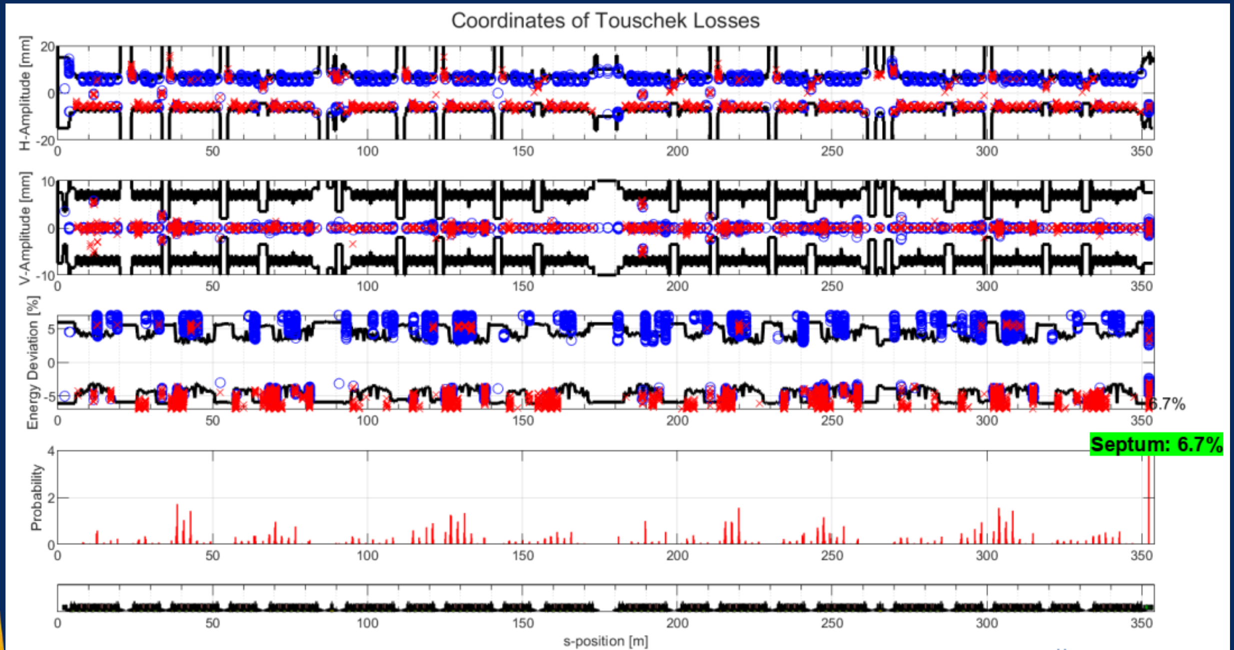
- Refined FLUKA model of V3588 Lattice including prototype beam pipe and both beam losses distribution and phase space for Touschek electron losses obtained with phase 1 undulators effects and corrected errors



MAIN ASSUMPTIONS FOR FLUKA CALCULATIONS

We assumed conservative assumptions as follow:

- Touschek beam life time of 3 hours for prompt radiation assessment (>6h foreseen w/HC)
- For integrated neutron fluence assessment;
  - First 5 years of operation with 3 hours beam lifetime;
  - Next 20 years of operation with 6 hours beam lifetime;
  - Corresponding total beam losses in storage ring of ~38 mC for approx. 6000 h/yr
- Storage Ring zone selected as ‘Standard’: C07-C08 cells
- Beam losses reproduced as accuratly as possible from machine physics group simulations

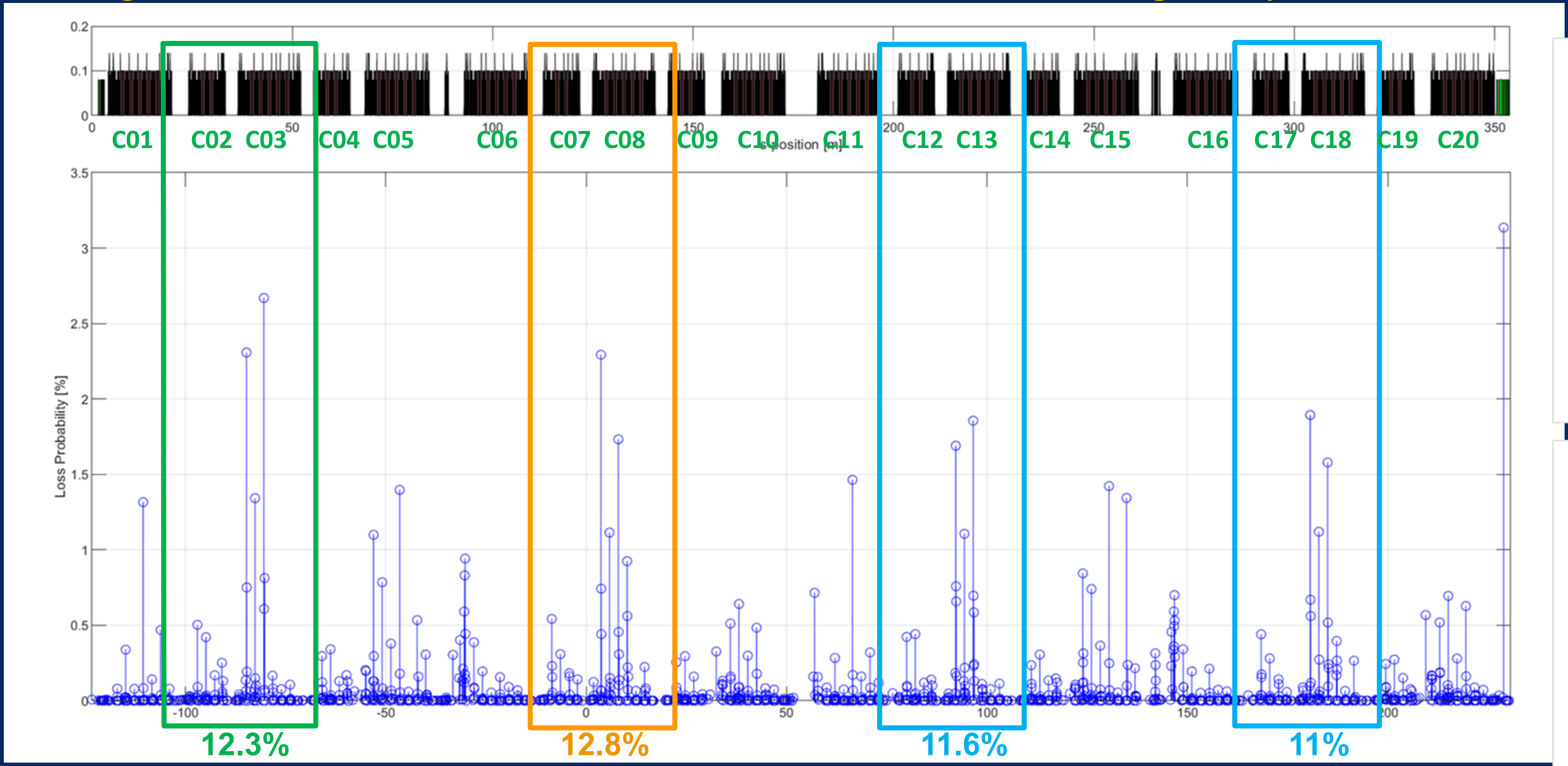


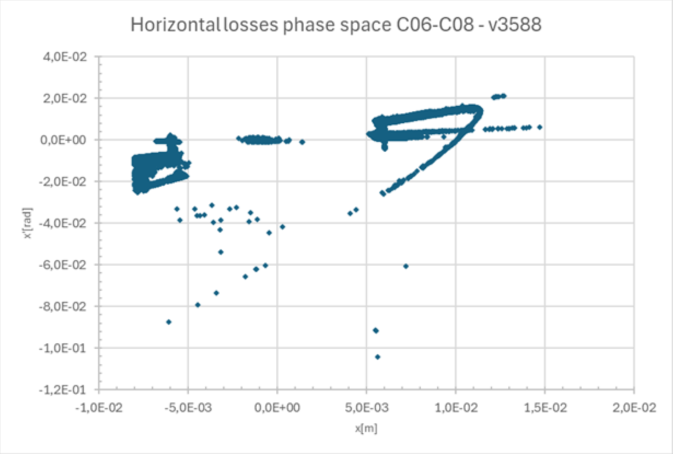
- Losses occur for 99% of the cases in the horizontal plane (no coupling, no errors, no IDs except their gaps)
- Very limited lost stay clear: the narrow chamber acting as a distributed collimator
- Very short-range losses (80% in less than 1 turn; 90% in less than 4 turns)
- From left, magnetic and alignment errors after correction added, as coupling and multipole effects, all phase 1 IDs effects after correction added

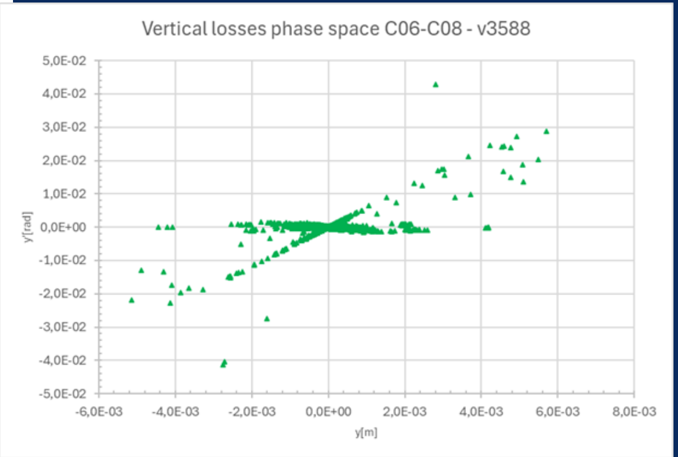
RP ASSESSMENT OF BEAM LOSSES FOR V3588

Highest cumulated beam losses in 4BA-7BA cells: C07-C08 - ~4% more than in C02-C03

Highest beam losses occures in first half of 7BA arcs – highest peak in C03 ~11% more than C08







A possible mitigation of these losses distribution is identified and, to be investigated in terms of efficiency, is the installation of 1 vertical collimator in the injection cell and possibly another 1 in cell C06 to reduce the losses in $Nd_2Fe_{14}B$ ID Magnets

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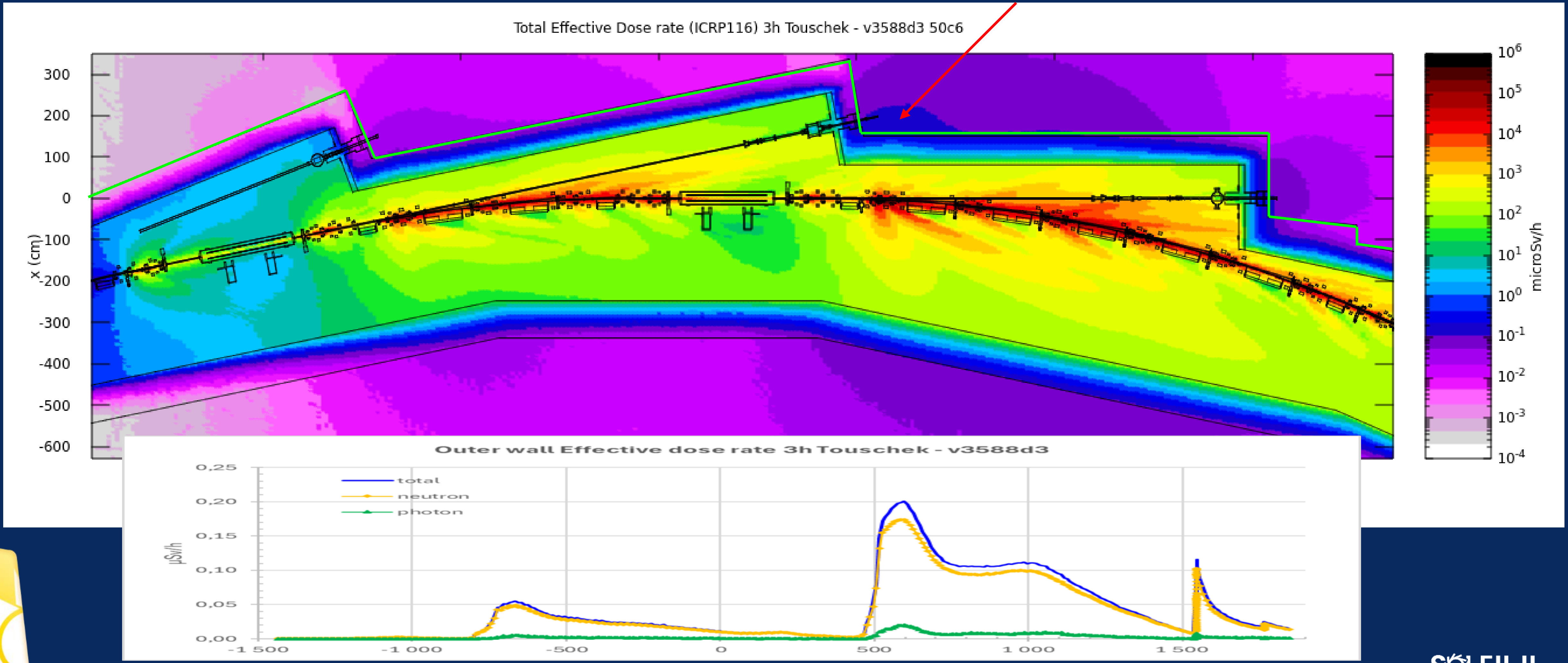
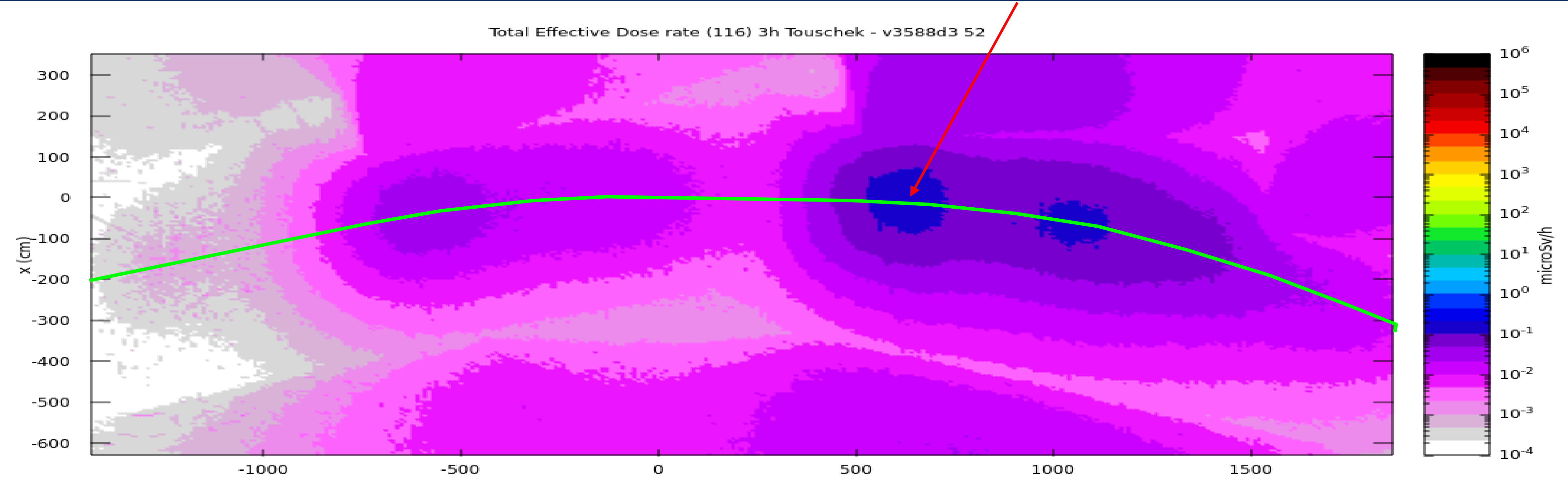
RP ASSESSMENT OF BEAM LOSSES FOR V3588 LATTICE

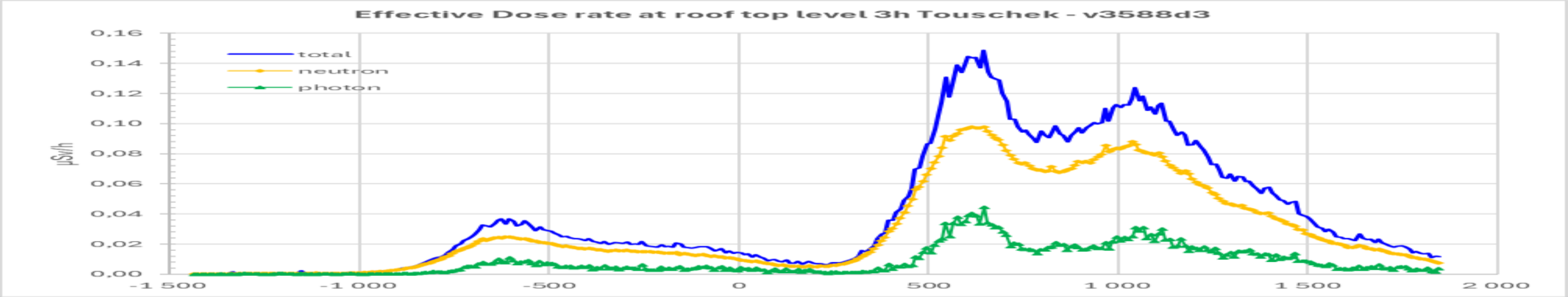
- Results behind walls are in agreement with regulation limit for non radiation hazard zone delimitation: Maximum Effective dose rate below 0.50 µSv/h (max = 0.20 µSv/h in C08 – port wall)



RP ASSESSMENT OF BEAM LOSSES FOR V3588 LATTICE

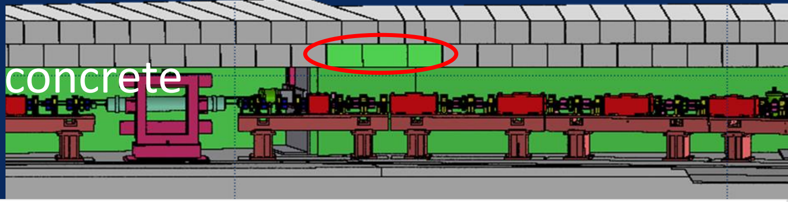
- Results above roof top are in agreement with regulation limit for non-radiation hazard zone delimitation: Maximum Effective dose rate below 0.50 µSv/h (max = 0.148 µSv/h in C08)

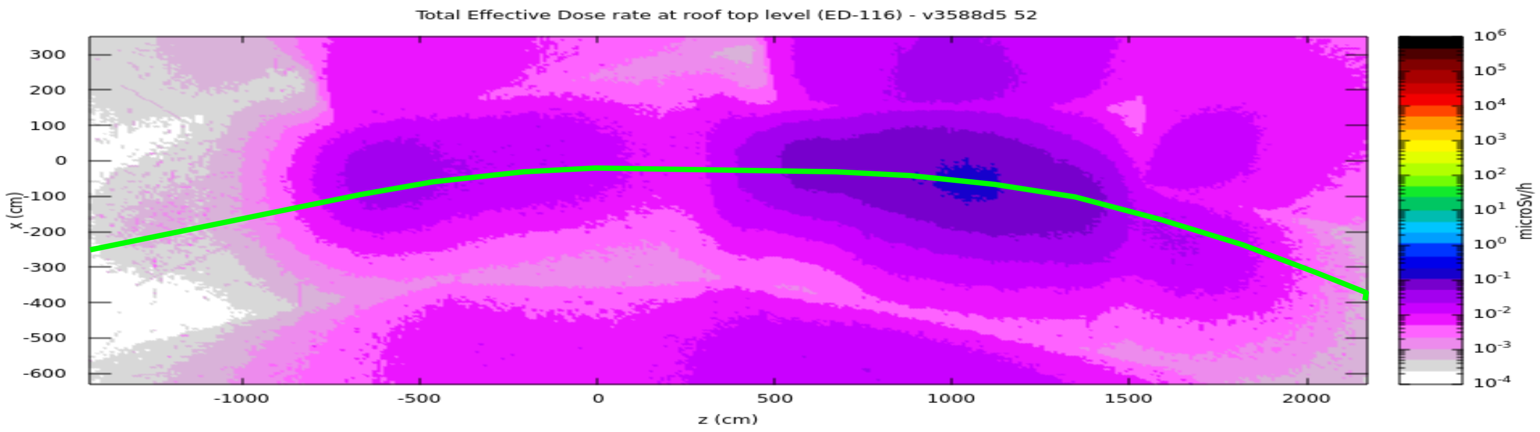


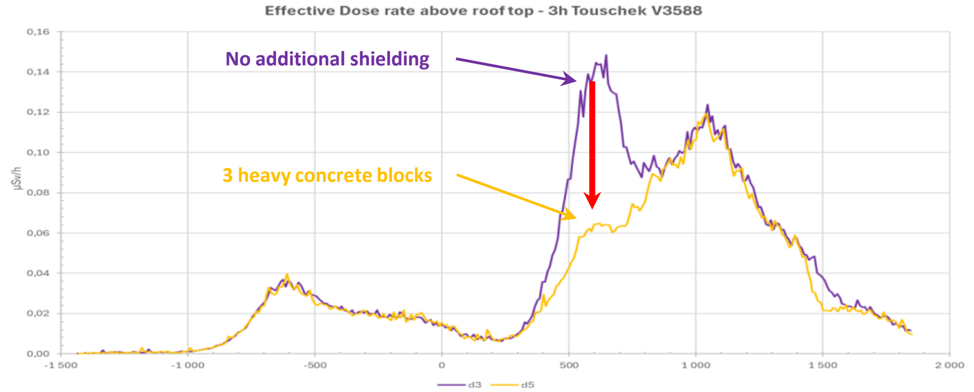


RP ASSESSMENT OF BEAM LOSSES FOR V3588 LATTICE

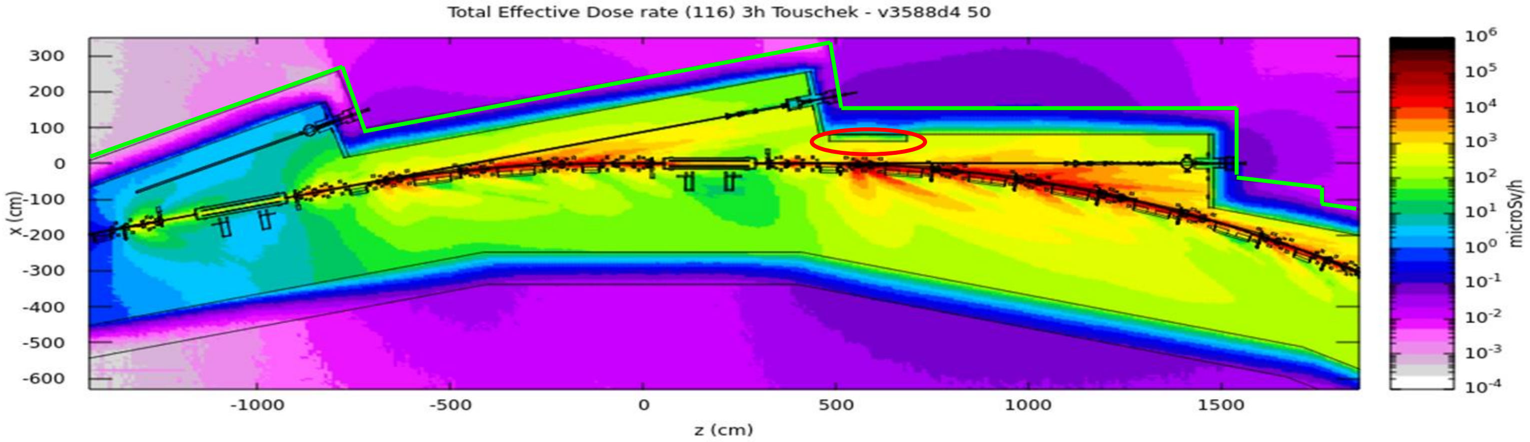
- Assessment of efficiency and margin gained with the use of local additional shielding at critical point positions
  - 3x – 1st layer – roof concrete blocs in heavy concrete instead of ordinary concrete

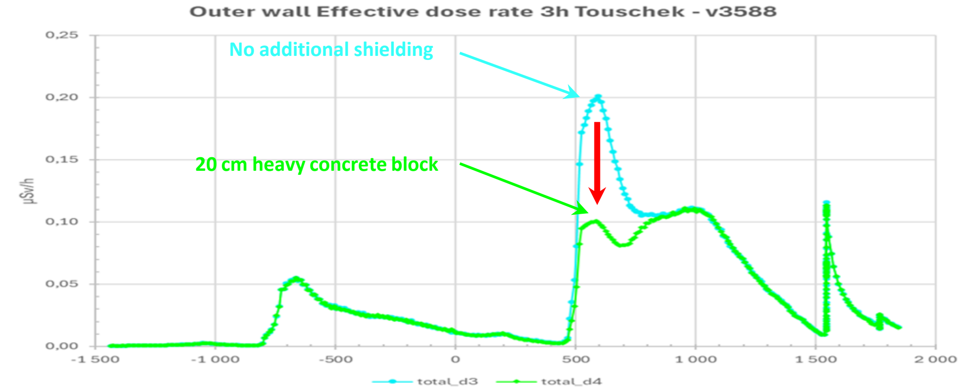






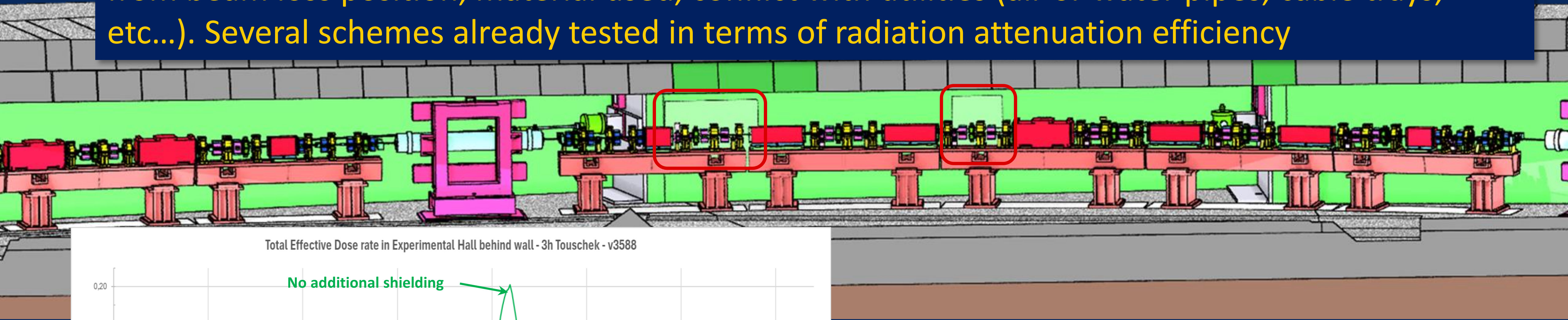
  - Additional 20cm thick heavy concrete screen along beam axis

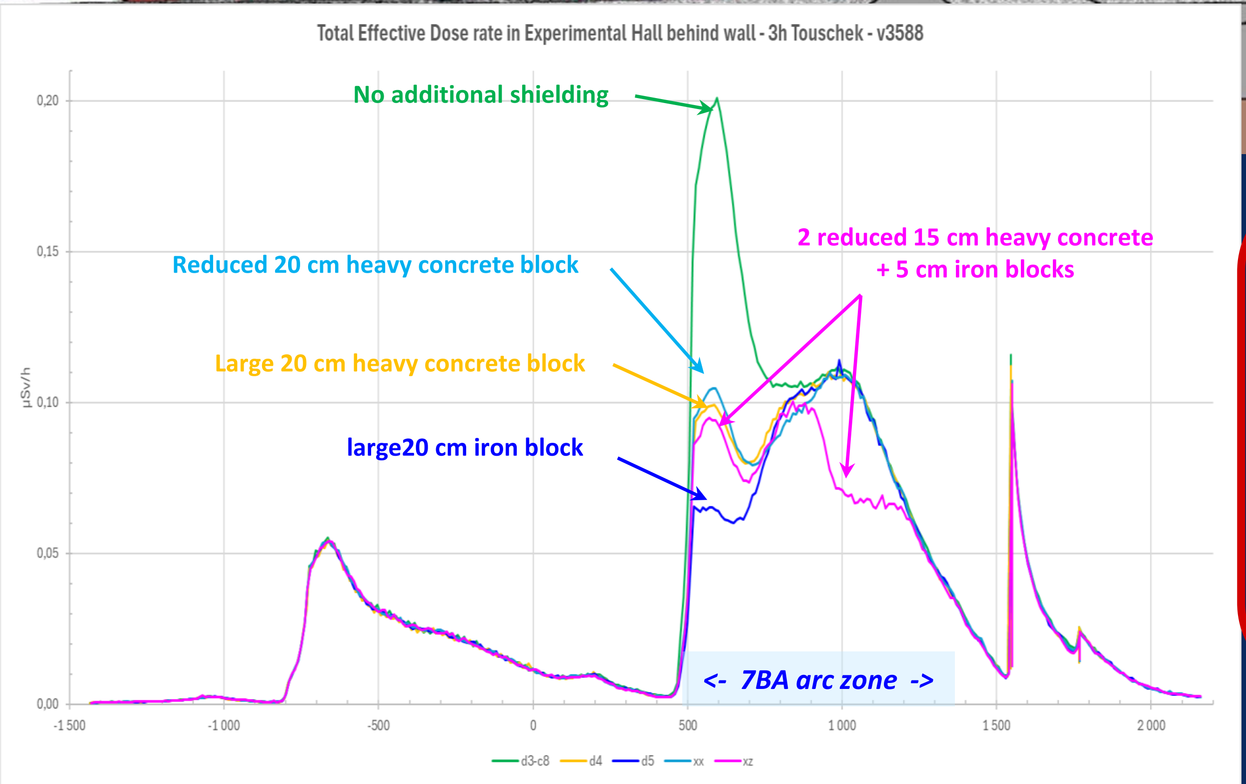




RP ASSESSMENT OF BEAM LOSSES FOR V3588 LATTICE

Local shielding optimization to be done with respect to available room at critical points, distance from beam loss position, material used, conflict with utilities (air or water pipes, cable trays, etc…). Several schemes already tested in terms of radiation attenuation efficiency





These additional local shieldings, combined with the foreseen gain in terms of beam lifetime thanks to the HC, should be necessary and essential arguments to support our case and to face up ASNR requirements for SOLEIL II authorization clearance.

PERMANENT MAGNETS EXPOSURE AND DAMAGE RISKS

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Sm_2Co_{17} Permanent magnet exposure for 25 years of operation

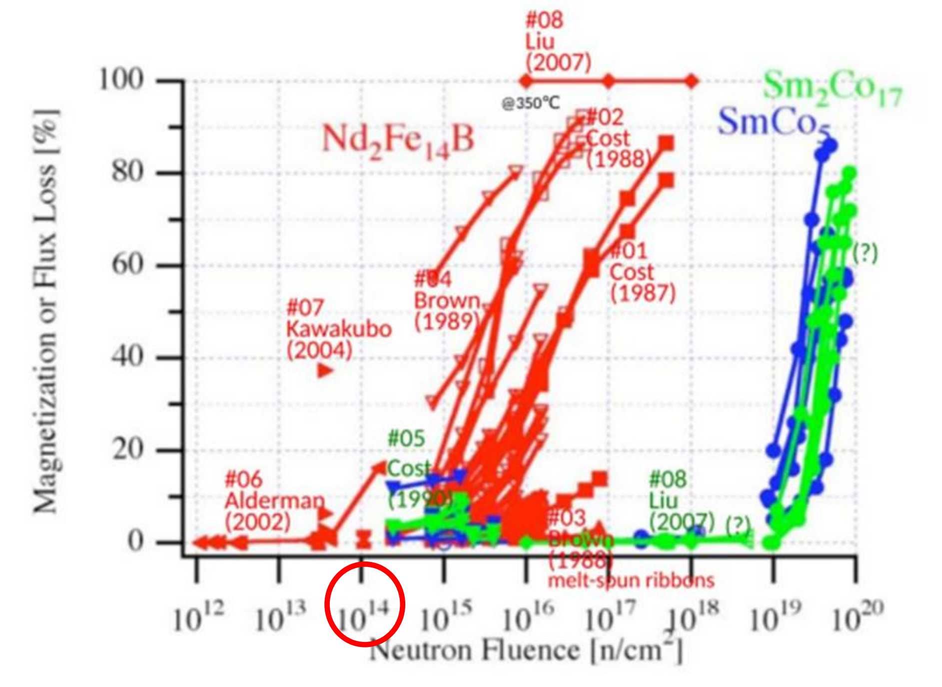
For 500 mA with worst case 3 h beam lifetime within first 5 years operation and then, 6 h beam lifetime within further 20 years of operation

6300 h of operation per year.

(e.g. cumulative charge into SR of 37 mC / 25 yrs)

Referring to neutron fluence exposition from FLUKA:

- Most exposed PMs are on axis QP/RB magnets
  => up to **7 .10^{12} n/cm^2**
- Highest exposure level of PMs for short DP
  => **2 .10^{11} n/cm^2**
- Highest exposure level of PMs for long DP
  => **5 .10^{11} n/cm^2**

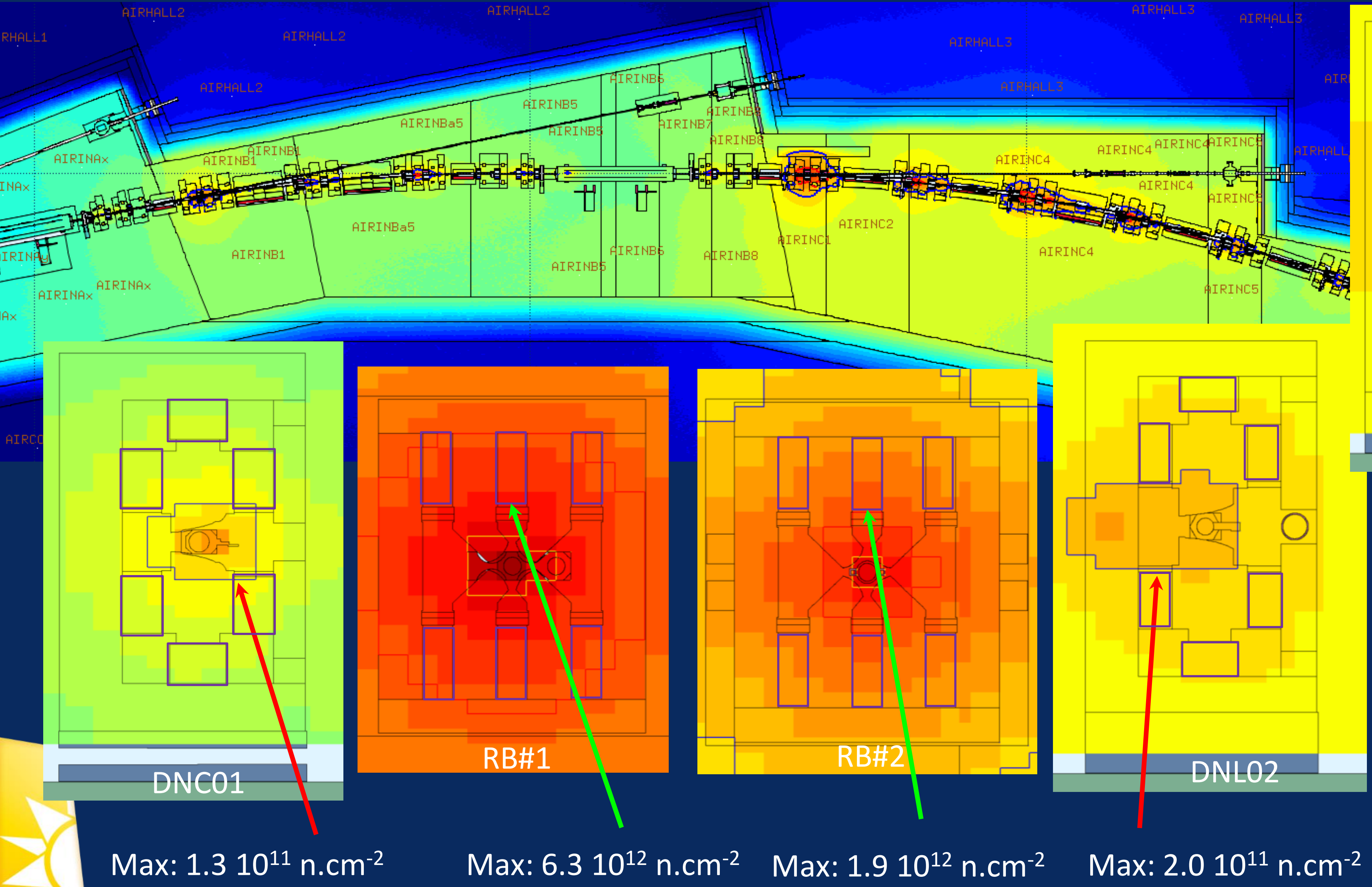


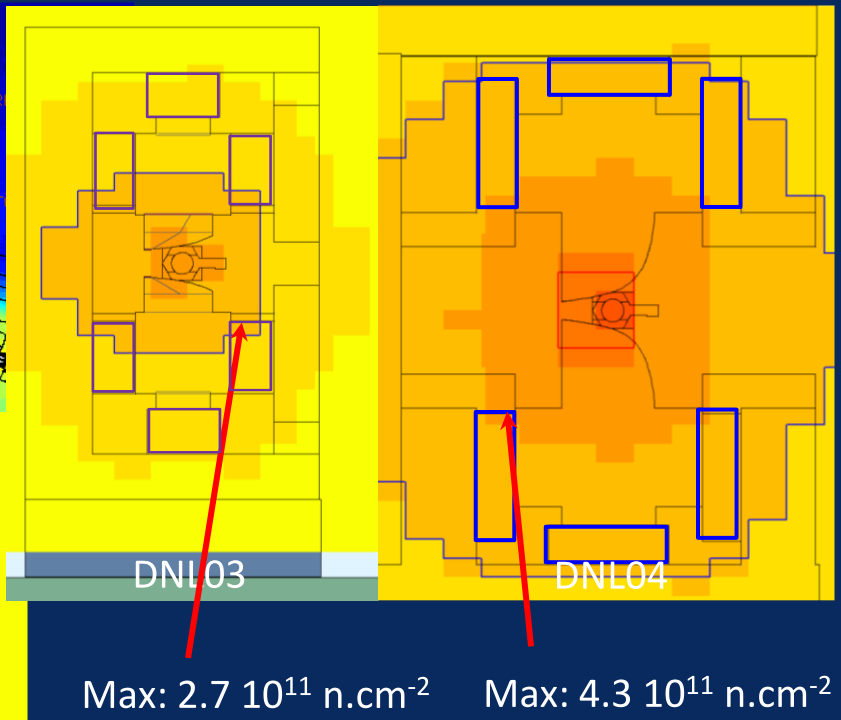
Demagnetisation as a function of neutron fluence in various experiments.
Plot originally shown in EPAC'2006 paper "65 MeV Neutron Irradiation of Nd-Fe-B Permanent Magnets" by X.-M. Maréchal et al (THPCH135) and updated in CLIC – Note – 1079 by Ben Shepherd.

- ***Seems significantly lower than the apparent damage threshold for Sm_2Co_{17} magnet grade of 10^{14} n/cm^2.***

PM NEUTRON EXPOSURE ASSESSMENT – FLUKA RESULTS

- Neutron fluence exposure of most exposed permanent magnets in 7BA arc.





Magnet damage threshold for Sm_2Co_{17}: 10^{14} n.cm^{-2}

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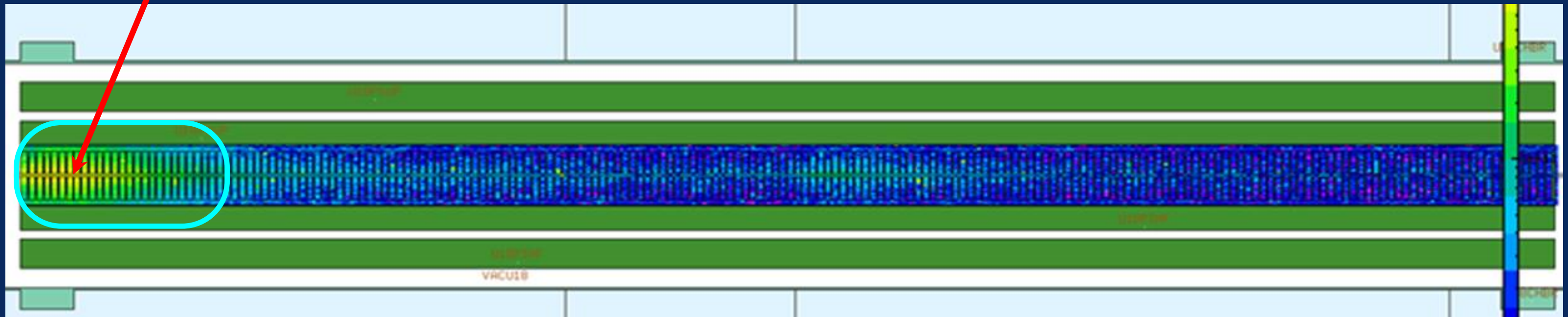
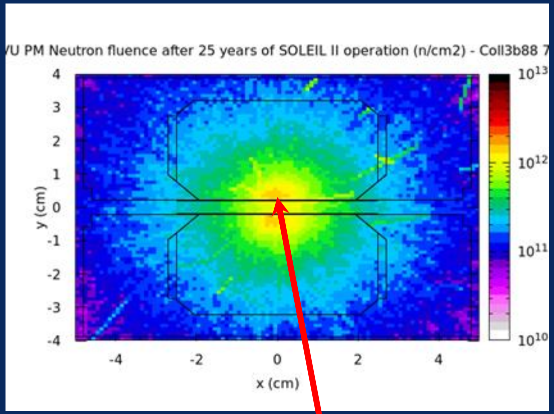
PM NEUTRON EXPOSURE ASSESSMENT – FLUKA RESULTS

- Neutron fluence exposure of most exposed permanent magnets in in-vacuum ID

Maximum neutron fluence averaged in a whole PM volume: 9.6 $.10^{11}$ n/cm^2



Most exposed PM in IVU18 are at the entrance of the ID (~20 first raws)



Neutron fluence distribution particularly heterogeneous
Maximum neutron fluence almost at impinging beam position up to 2 $.10^{12}$ n/cm^2

Magnet damage threshold for $Nd_2Fe_{14}B$: 10^{12} n.cm^{-2}

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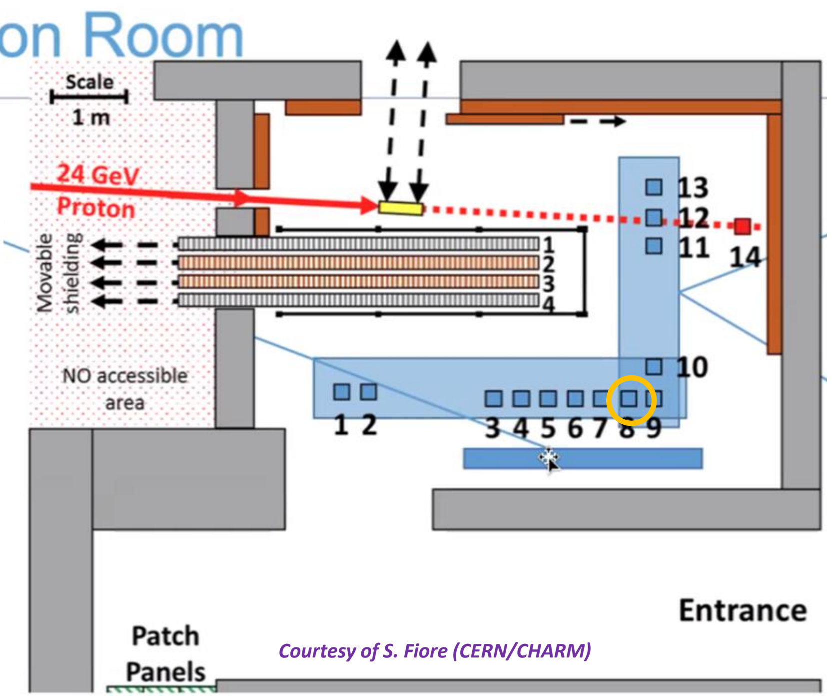
PERMANENT MAGNETS IRRADIATION TESTS AT CHARM FACILITY

- PMs Demagnetization vs neutron fluence exposure experiments



Courtesy of S. Fiore (CERN/CHARM)

The **CERN Highly-Accelerated Mixed Field Facility (CHARM)** at CERN is a facility for testing radiation effects on electronics. The proton beam is obtained in spills with an intensity of approximately 5×10^{11} protons and a duration of around 350 ms from the Proton Synchrotron (PS) of the CERN accelerator complex and has a momentum of 24 GeV/c. The spill is repeated around three times during a super-cycle of 45 seconds.

Data from CERN-ACC-NOTE-2017-0059 (A. Infantino et al.)

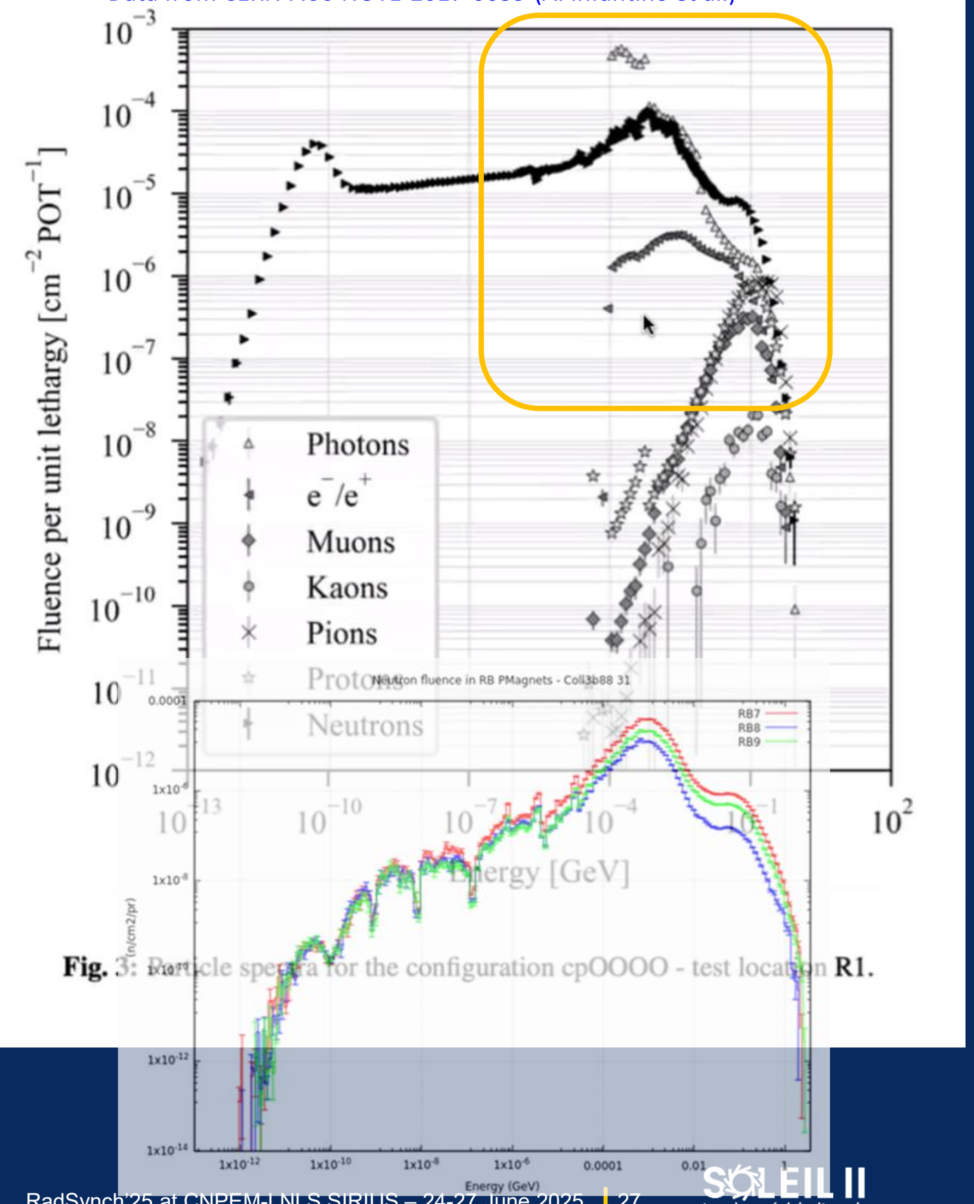
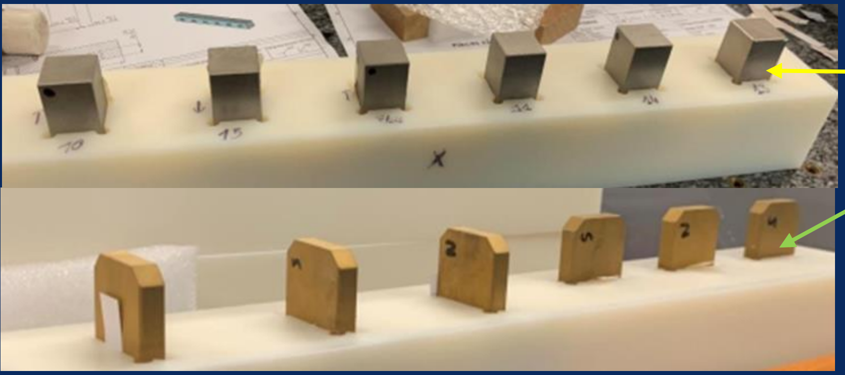


Fig. 3: Particle spectra for the configuration cpOOOO - test location R1.

1 week irradiation session to reproduce almost 25 years of SOLEIL II operation

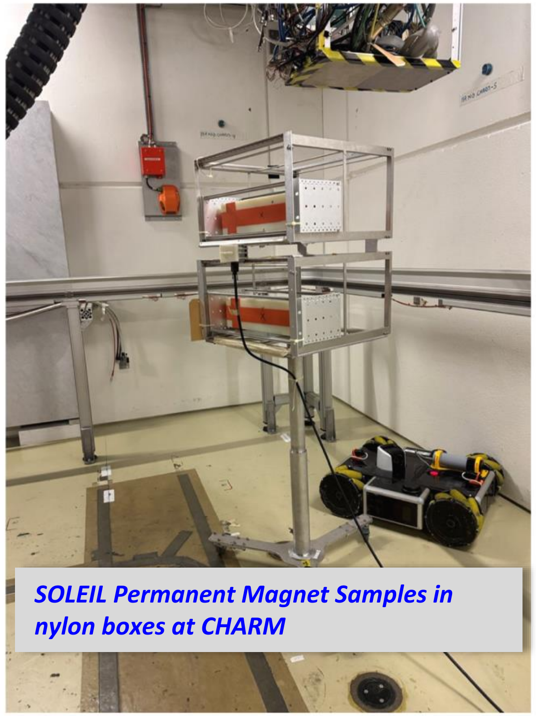
1st Irradiation in November 2024 just before winter shutdown

PERMANENT MAGNETS IRRADIATION TESTS AT CHARM FACILITY



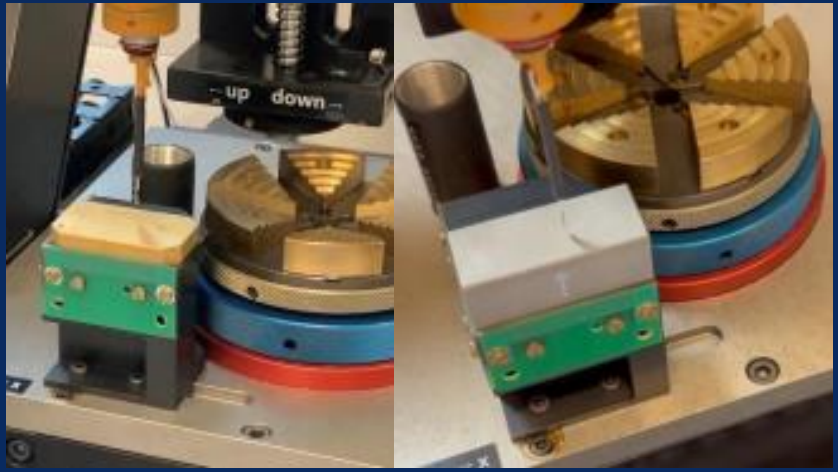
2 sets of Permanent Magnets irradiated at CHARM for each PM grade
Sm_2Co_{17}
and
$Nd_2Fe_{14}B$

Nylon boxes with the permanent magnets set with different field orientations (N/S & // or ⊥)



SOLEIL Permanent Magnet Samples in nylon boxes at CHARM

- The 2 boxes were irradiated at 1.9 10^{12} Si 1MeVEqn (Electronic radiation damage quantity measured at sample position)
- This level corresponds to ~ 5 10^{12} n/cm^2 neutron fluence



All Magnets have been measured on a 2D Hall probe scanner before and after irradiation.
Both faces of the magnets have been characterized

- For *Sm_2Co_{17}* magnets, No Significant variation of the field was measured. Reproductivity of the bench is about +/-0.1%
- For *$Nd_2Fe_{14}B$* magnets, the measured field has decreased by ~2%

CONCLUSION

- Even with a thoroughly reduced beam lifetime in the SOLEIL II SR wrt to present SOLEIL performance, detailed FLUKA simulation results are showing that the upgrade 7BA-4BA Lattice for SOLEIL II seems compatible with present SR tunnel shielding
- Significant margin is foreseen with both the HC performance on beam lifetime and possible use of local shieldings.
- These two points should be mandatory to argue and to obtain from ASNR (French Nuclear Regulation Authority) SOLEIL II operation authorization
- Lot of work still to be addressed for SOLEIL II RP assessment about injection, beam trips, induced activity and corresponding residual dose rates
- Permanent Magnets exposure evaluation by FLUKA MC calculations, completed with irradiation tests and measurements at CHARM Facility, seems satisfactory to secure demagnetization hazard for Sm_2Co_{17} Lattice Magnets (DP, QP, RB). Further measurements already scheduled to confirm these former results and to complete this study, specially for more radio-sensitive ID PMs as $Nd_2Fe_{14}B$.

THANK YOU FOR YOUR ATTENTION

SOLEIL SYNCHROTRON

SOLEIL II
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BACK-UP SLIDES

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