Capabilities of the n_TOF spallation facility at CERN for electronics testing

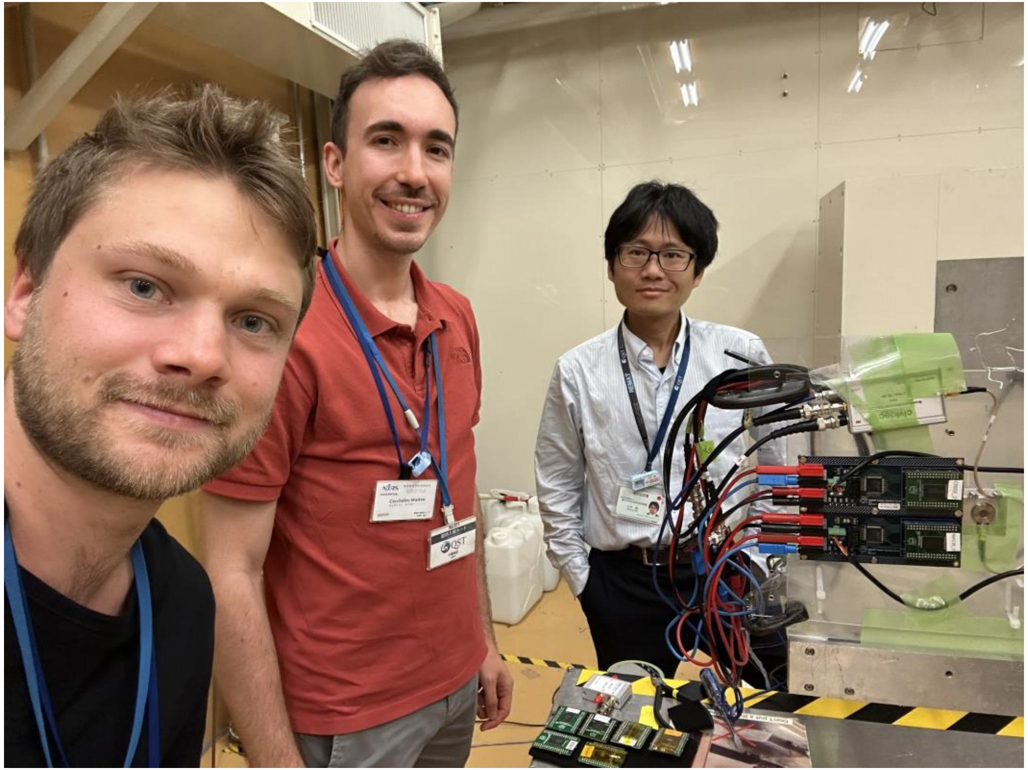
Matteo Cecchetto, Rubén García Alía

GB-RADNEXT Workshop

12 June 2024

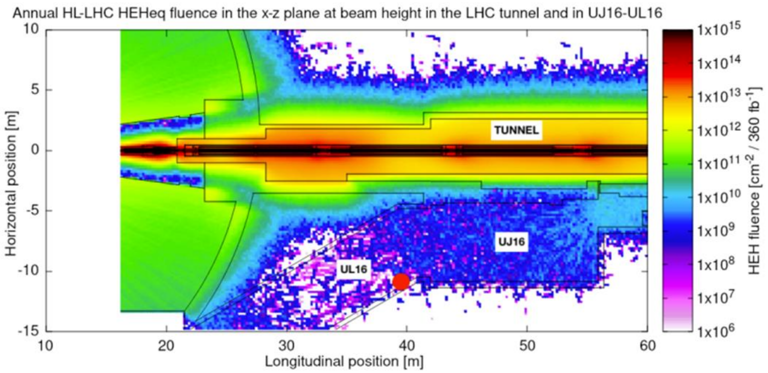
https://indico.cern.ch/event/1353707/

Matteo is not here today, but kindly prepared most slides



Radiation to Electronics activity at CERN

- High-energy accelerators are subject to **beam losses** and hence generate prompt radiation in their vicinity
- Part of the accelerator equipment needs to be installed near the machine itself, and is therefore subject to a complex and challenging **radiation environment**
- Such equipment is critical for the successful operation of the accelerator, and uses microelectronic components which are **sensitive to radiation**



Expected HL-LHC radiation levels around the ATLAS interaction point (IP1), as simulated in FLUKA

FLUKA

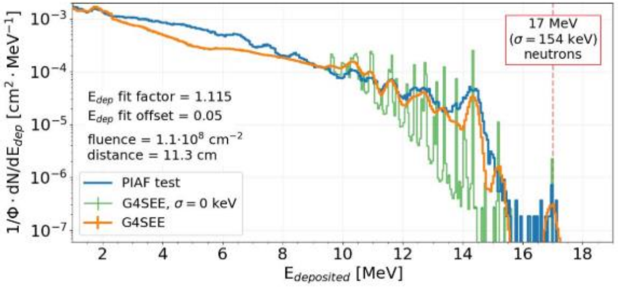
Tens of thousands of electronic boards in the LHC (and millions of individual components), all capable of negatively affecting its operation through radiation effects

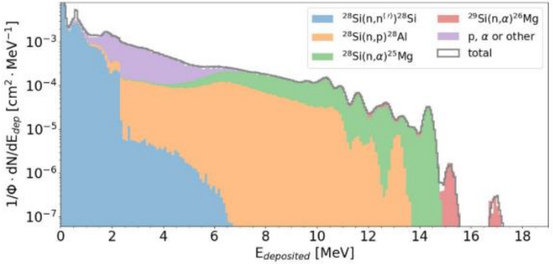
Neutron activities within CERN's Radiation to Electronics team

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 69, NO. 3, MARCH 2022 273

G4SEE: A Geant4-Based Single Event Effect Simulation Toolkit and Its Validation Through Monoenergetic Neutron Measurements

Dávid Lucsányi, Rubén García Alía, *Member, IEEE*, Kacper Biłko, Matteo Cecchetto, Salvatore Fiore, *Member, IEEE*, and Elisa Pirovano

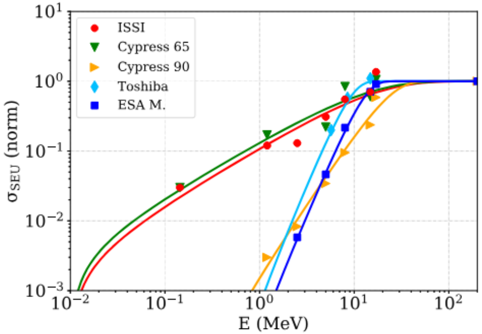


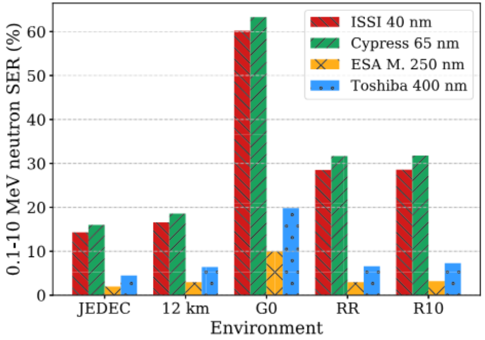


IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 68, NO. 5, MAY 2021 873

0.1–10 MeV Neutron Soft Error Rate in Accelerator and Atmospheric Environments

Matteo Cecchetto, Rubén García Alía, *Member, IEEE*, Frédéric Wrobel, Andrea Coronetti, *Student Member, IEEE*, Kacper Bilko, David Lucsanyi, Salvatore Fiore, *Member, IEEE*, Giulia Bazzano, Elisa Pirovano, and Ralf Nolte



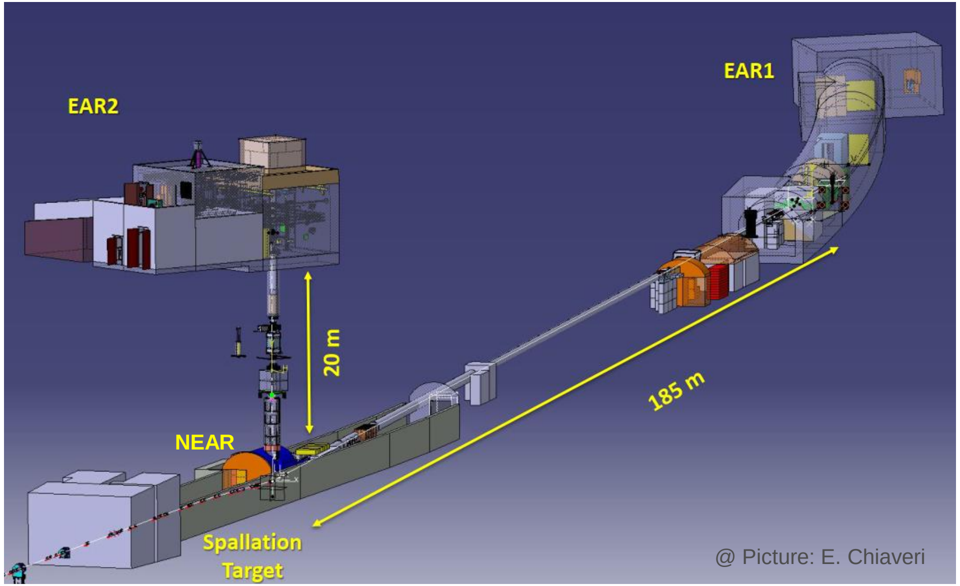


Outline

- NEAR station at n_TOF
- Characterization through simulations and measurements
- NEAR comparison to CHARM and other facilities
- Overview on EAR1 and EAR2 experimental areas
- TOF in the literature

The neutron time of flight facility (n_TOF) at CERN

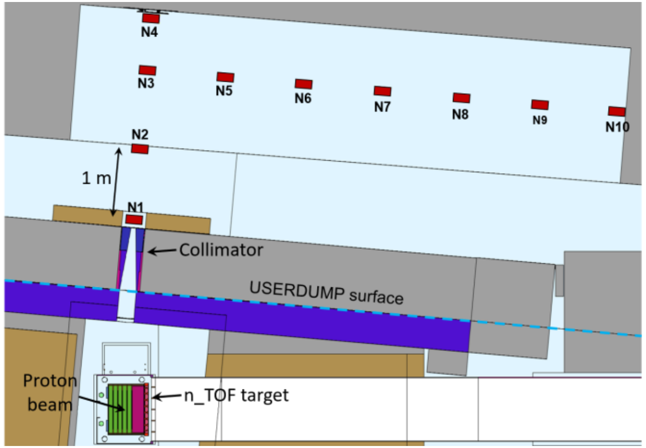
- N_TOF is a spallation neutron source employed for very accurate cross section measurements, radioactive isotopes, etc. via the time-of-flight technique.
- Neutrons are produced by the interaction of 20 GeV protons on pure lead target.
- Three experimental areas: **EAR1** (185 m from the target), **EAR2** (20 m above the target) and **NEAR** (next to the target, built in 2021 and focus of this study).
- Pulsed proton beam (6 ns duration, cycle of 6 pulses every 1.2 s + 30 s cool-down).



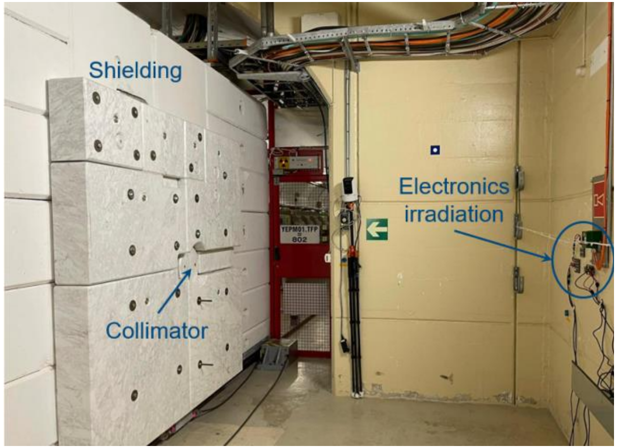
NEAR at n_TOF

NEAR is dubdivided in two main areas:

- Inside the target shielding → high dose levels (on the order of MGy) to study radiation damage in materials.
- Outside the shielding → experimental area for electronics irradiation.



Top view of the NEAR geometry in FLUKA with ten test positions N1-N4 are of major interest because they are situated in front of the collimator.

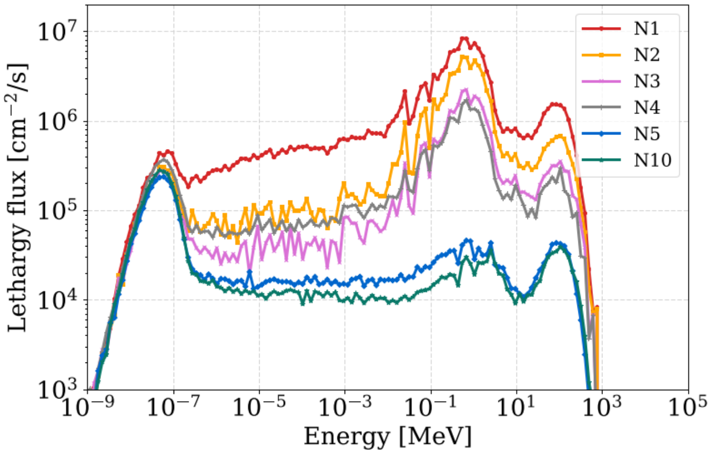


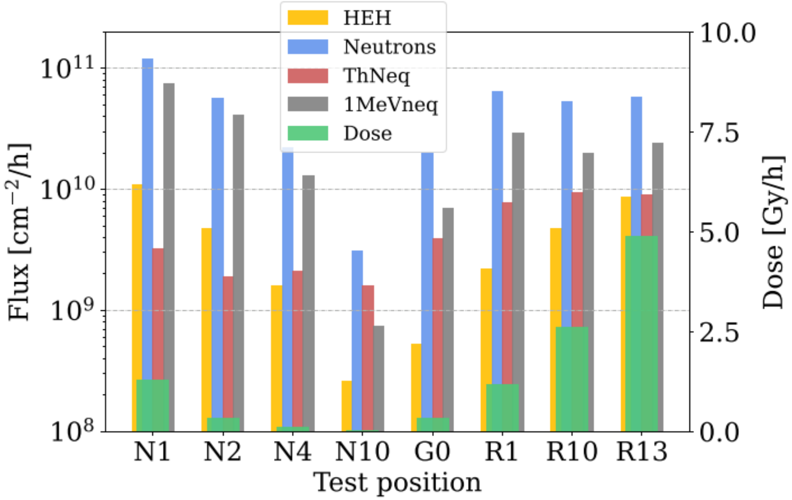
Photograph of the NEAR station for irradiation of electronics. On the left the concrete and marble shielding, beyond which the lead target is installed.

NEAR (N4) characterization through simulations

- N4 is located in front of the collimator, 5 m from the target.
- The neutron spectrum ranges from thermals up to 830 MeV.
- Typical fluxes in N4:

Flux	ThNeq	> 10MeV	> 20MeV	Total
[n/cm^2/s]	6.4×10^5	4.2×10^5	3.5×10^5	5.9×10^6



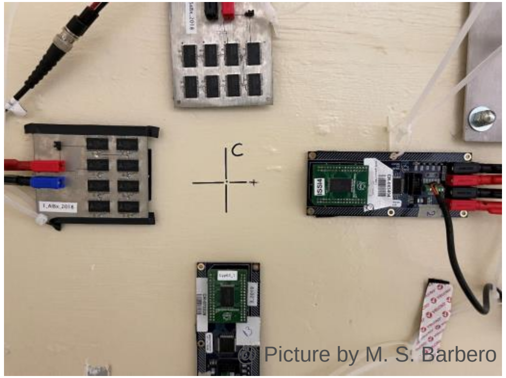


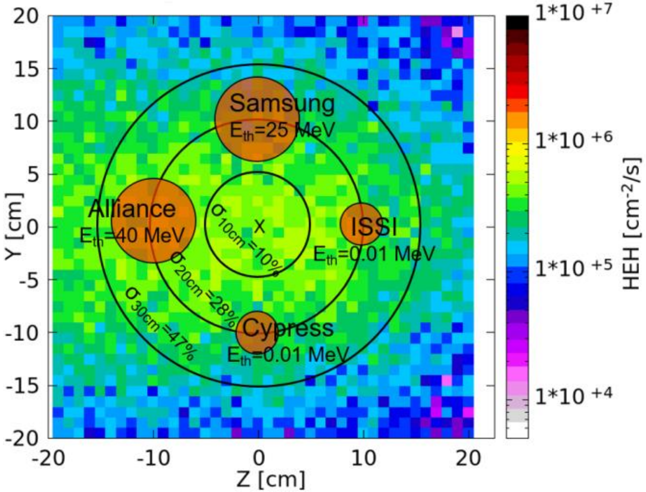
Simulated fluxes at NEAR (N1, N2, N4, N10) and at the CHARM (G0, R1, R10, R13) facility at CERN (see next slides)

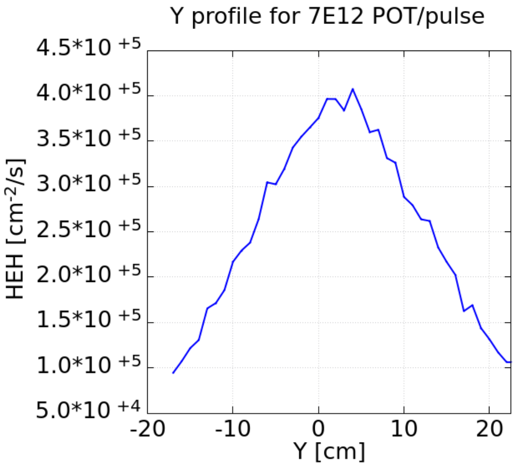
*M. Cecchetto et al., “Electronics Irradiation with Neutrons at the NEAR Station of the n_TOF Spallation Source at CERN,” IEEE TNS link

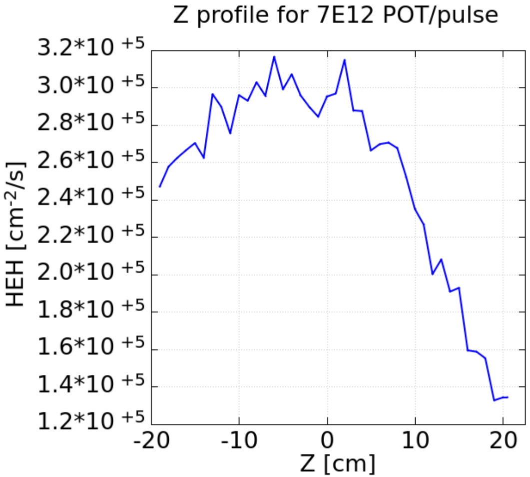
NEAR – Homogeneity and profile

- SRAM memories (measuring SEU and SEL) and RPL dosimeters (dose) were installed in N4 to indirectly measure the neutron fluence and the dose.
- The map shows the simulated neutron flux >20 MeV.



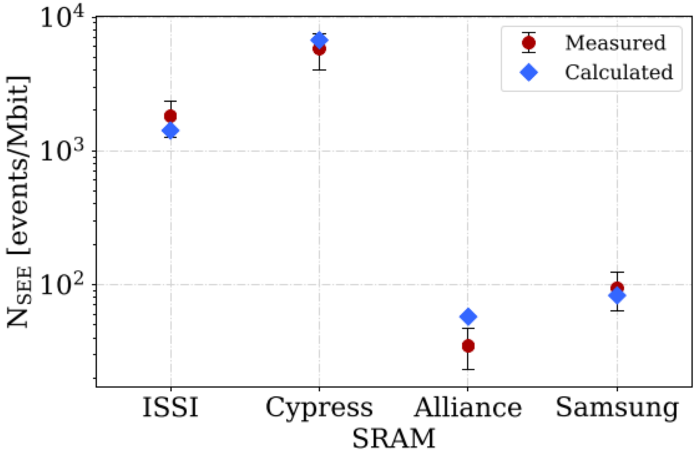






NEAR N4 – SRAM and RPL characterization

- The SRAMs' response as a function of the neutron energy was well-known
- Good agreement of SRAM and RPL measurements with FLUKA simulations, therefore, confirming the neutron fluence and dose.



	RPL-0	RPL-A	RPL-I	RPL-S	RPL-C
Sim. Dose [Gy]	278	256	193	178	132
Meas. Dose [Gy]	211	198	192	183	164
Difference [%]	-24	-23	-1	3	24

*M. Cecchetto et al., "Electronics Irradiation with Neutrons at the NEAR Station of the n_TOF Spallation Source at CERN," IEEE TNS link

Mixed-field – CHARM facility at CERN

- CHARM provides a mixed-field (mainly hadrons: neutrons, protons, pions but also electrons and photons) though a combination of **target** and **shielding**.
- Representative of the multitude of spectra found in the LHC accelerator and other environments (space, atmospheric, etc.).

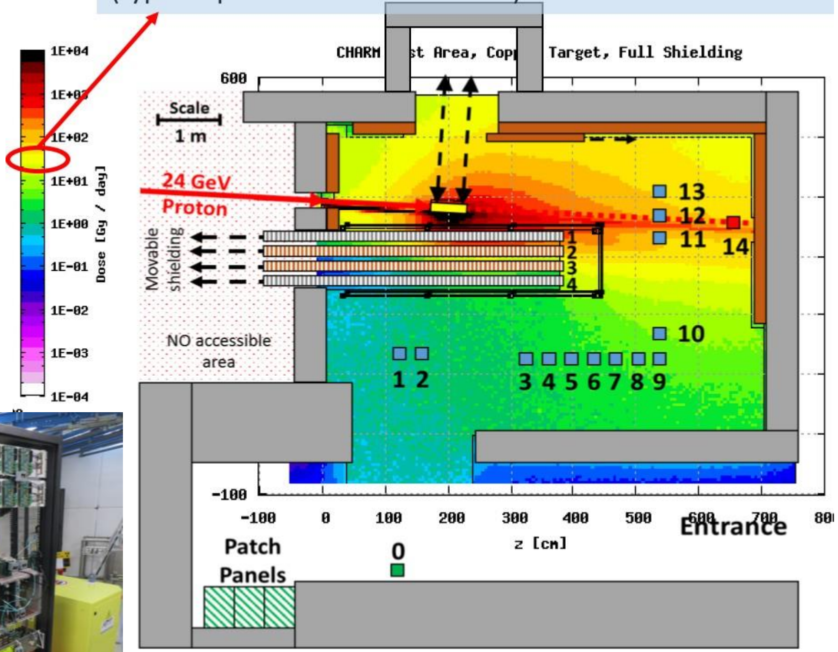
24 GeV protons impact the target

A mixed radiation field is produced

System level testing for TID, SEEs and DD:

- Essential for CERN RHA assurance approach for Commercial Off The Shelf (COTS) components.

With 40 Gy/day it is possible to achieve 200 Gy in 1 week (typical qualification limit for TID)

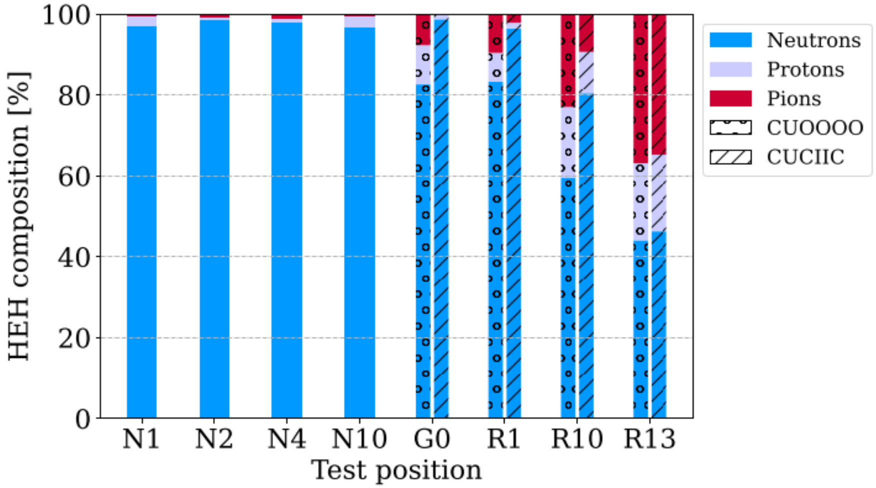


Dose map FLUKA simulation, top view

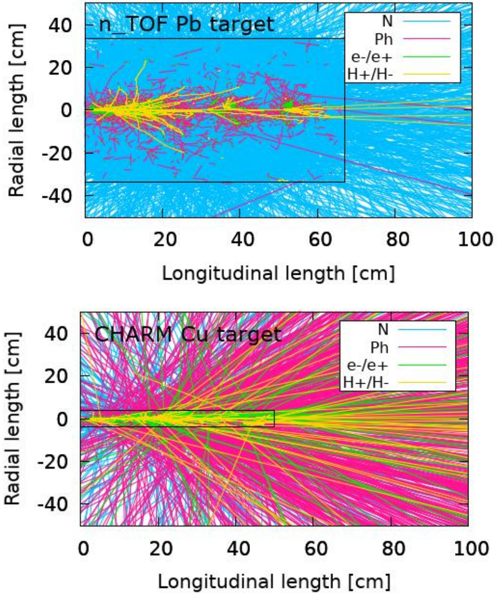
NEAR (n_TOF) – CHARM comparison

- NEAR: 20 GeV protons on lead target → neutrons
- CHARM: 24 GeV protons on *copper target → neutrons, protons, pions

*typically



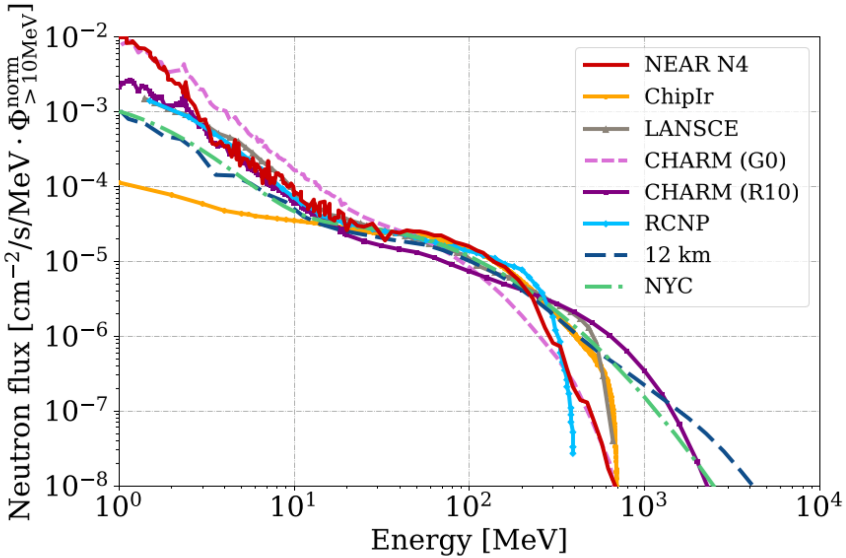
HEH (>20 MeV) particle composition (neutrons, protons, pions) for test positions at NEAR (N1, N2, N4, N10) and CHARM (G0, R1, R10, R13), the latter configured with copper target and no shielding (CUOOOO) and full shielding (CUCIIC)



Production of neutrons (N), photons (Ph), electrons/positrons (e-/e+) and charged hadrons (H+/H-) in the n_TOF (top picture) and CHARM(bottom picture) targets.

NEAR comparison to other facilities

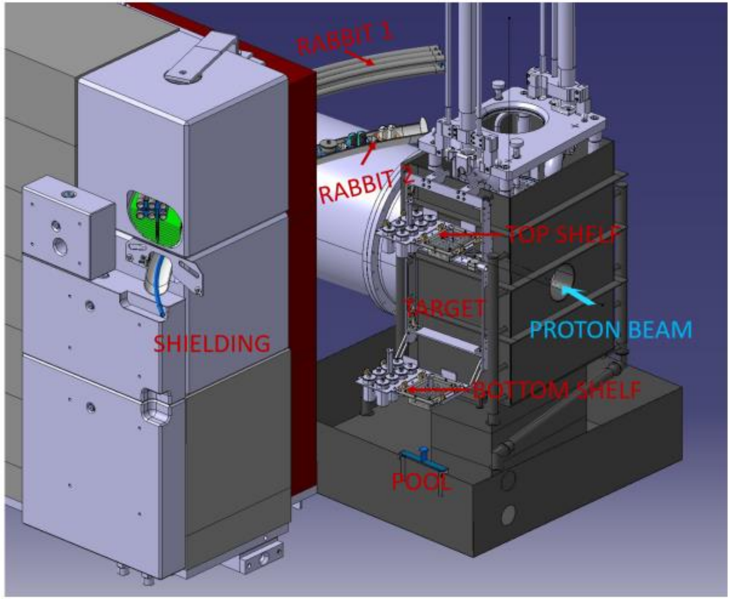
- n_TOF (NEAR) neutron spectrum compared to that of other **spallation facilities**, ground level (**JESD89A**, New York City), and **avionic environments** (12 km altitude above Geneva).
- NEAR spectrum is very similar to that at **RCNP** and compatible with the typical shape of spallation sources.

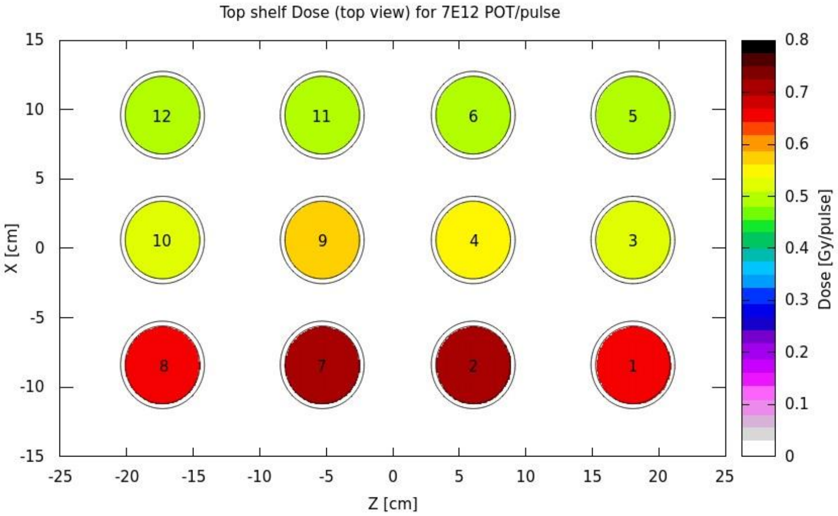


Normalization: the integral above 10 MeV of each curve is the same.

NEAR - Irradiation of materials

- The area inside the target's shielding is designed for high dose material irradiation (MGy/year).
- Not only electronics is affected by the dose! Samples can be installed on shelves or pipes very close to the target to study the **dose damage** in materials such as cables, grease, etc.

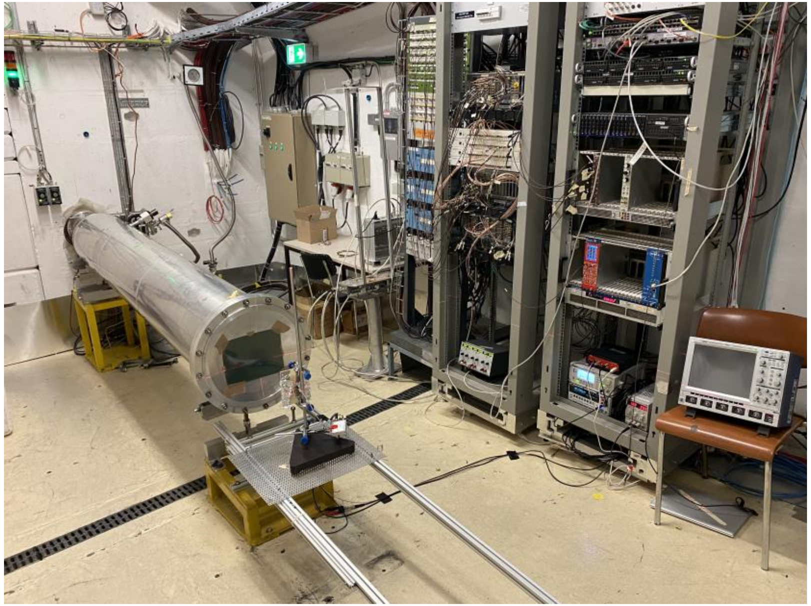




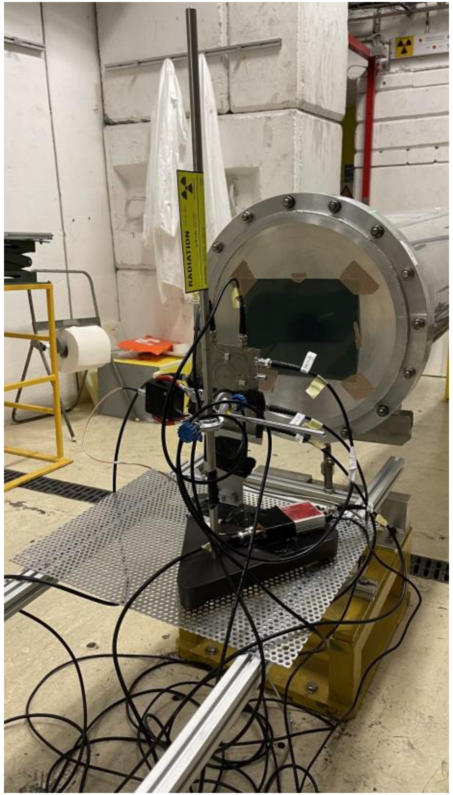
More info: M. Ferrari et al., "Design development and implementation of the NEAR area and its neutron irradiation station at the n_TOF facility at CERN,"

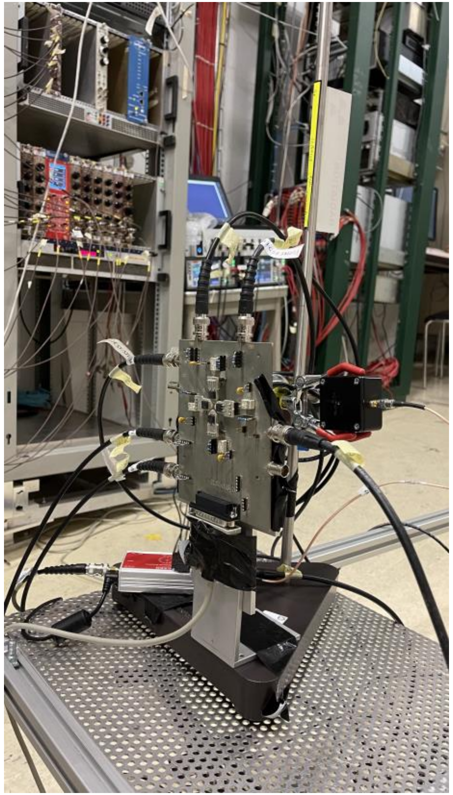
Experimental Area 1 (EAR1) - Neutron Escape Line (NEL)

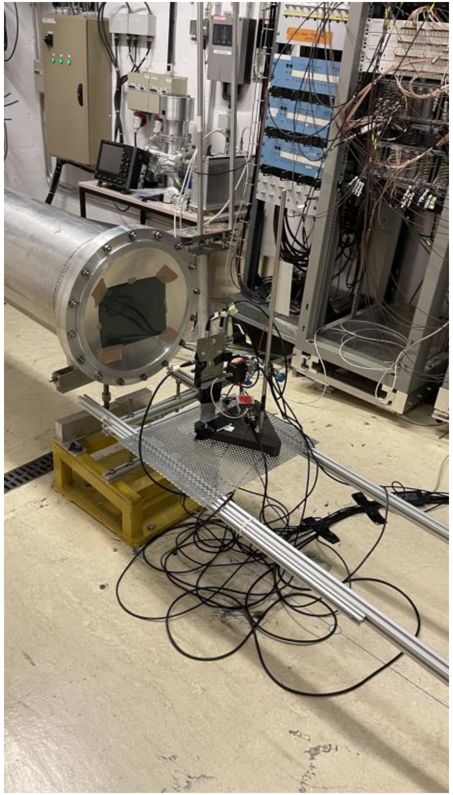
- NEL is located 196 m from the n_TOF target.
- Spectrum within a radius of 1-10 cm, depending on the collimator.
- The flux >10 MeV is 10^3 n/cm^2/s, the lowest among experimental areas.
- Energies up to 12 GeV!



SEE time-of-flight testing at EAR1/NEL







SEE time-of-flight testing at EAR1/NEL

Main objective:

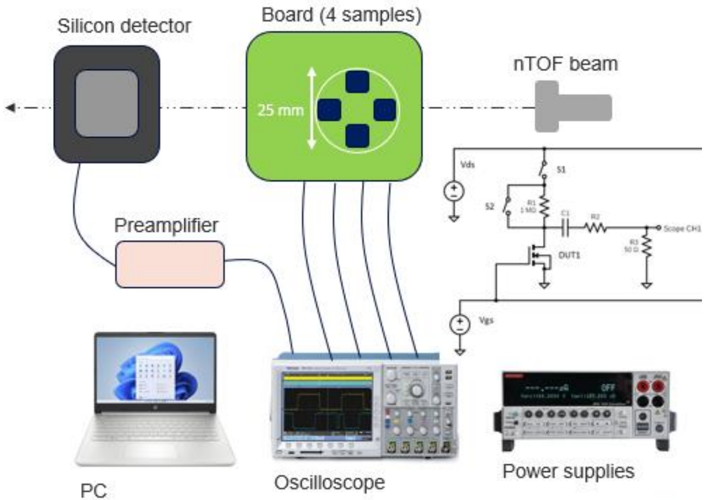
- Proof of concept of neutron SEB testing with time-of-flight measurement.
- Previously at LANSCE (US), neutron TOF for power MOSFETs: *J. M. Prittset al., "Energy-Dependent Single-Event Effects in Power MOSFETs from a Broad-Spectrum Neutron Beam," 2020.*

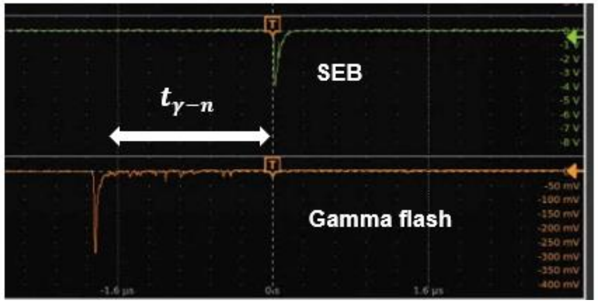
Experimental setup:

- Non-destructive SEB setup. Drain voltage sampled via decoupling capacitor.
- Silicon diode samples gamma flash to trigger acquisition and provide time difference between photon and neutron. Placed behind MOSFETs.

Test conditions:

- DUT: STD10NF10 - 110V bias to maximise cross-section – 4 samples.
- 1 MΩ shunt resistor, 100 pF decoupling capacitor + 1 kΩ resistor.
- Neutron beam 2.5 cm wide. Alignment challenges expected due to DUTs size.
- Total numbers: 1.6e18 POT, 2.3e5 pulses, 16 days, 6.6e9 n/cm^2 (>10 MeV)





SEE time-of-flight testing at EAR1/NEL

$$E_k = m_n c^2 \left[\frac{1}{\sqrt{1 - \left(\frac{L}{tc}\right)^2}} - 1 \right]$$

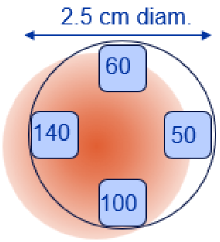
$$L \approx 200\ m \quad t = \frac{L}{c} + t_{\gamma-n}$$

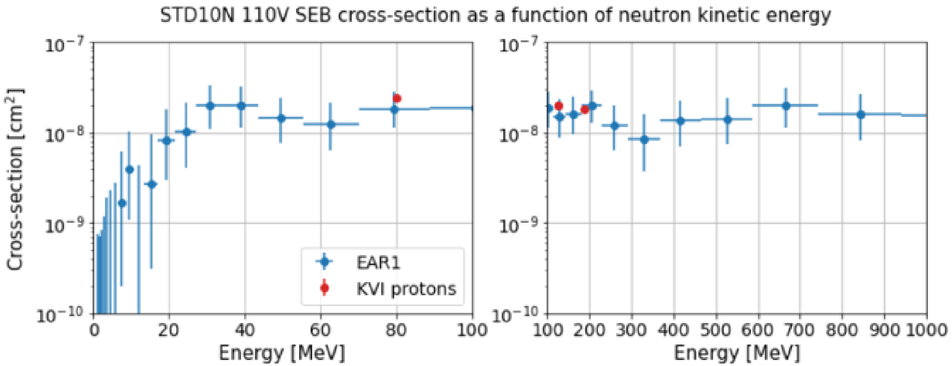
Data post-processing:

- Use kinetic energy definition formula to corelate with neutron time of flight (gamma flight time + delay between flash and SEB).
- Neutron flux per pulse obtained from FLUKA simulations, depending on beam line configuration (different collimators).

Results:

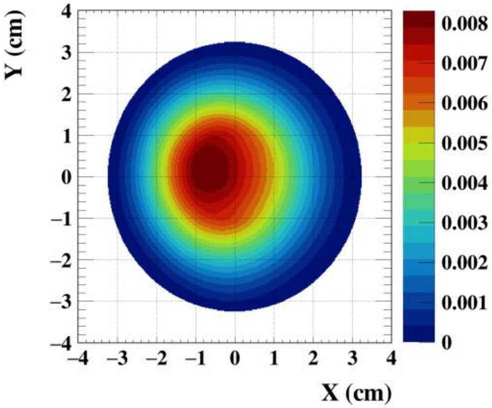
- Despite low statistics, threshold found at ∽10 MeV, reaching saturation at ∽ 40 MeV.
- Good agreement with KVI high energy protons thanks to the upgraded FLUKA simulations by M. Cecchetto and the nTOF team.





Experimental Area 2 (EAR2)

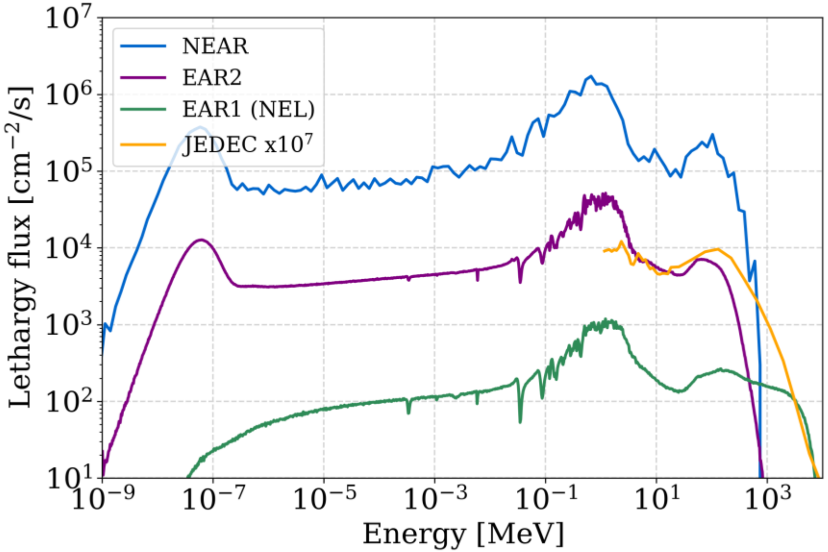
- EAR2 is located 20 m above the n_TOF target.
- Spectrum within a radius of 1 cm, where good homogeneity (20%) is present.
- Hence, EAR2 can be used to irradiate a small sample, while at NEAR larger devices could be irradiated with good homogeneity.



@ Simulation by J. A. Pavon Rodriguez

Experimental Area Comparison

- NEAR and EAR2 present similar spectra, however, fluxes at NEAR are more than one order of magnitude larger, hence more suitable for SEE testing considering also the larger beam size.
- EAR2 and EAR1 → possible TOF measurements (not possible at NEAR).
- EAR1 can reach up to high energies, which would permit to study whether energies above 1 GeV can have some impact, however the flux is very little and testing may require several weeks.



Location	Phi>10MeV	Phi>20MeV	Phitot
	[cm-2/s]	[cm-2/s]	[cm-2/s]
EAR2 20m	2.9E+04	2.4E+04	3.7E+05
EAR1 NEL 196m	1.1E+03	9.8E+02	5.1E+03
NEAR N4	5.2E+05	4.5E+05	6.1E+06

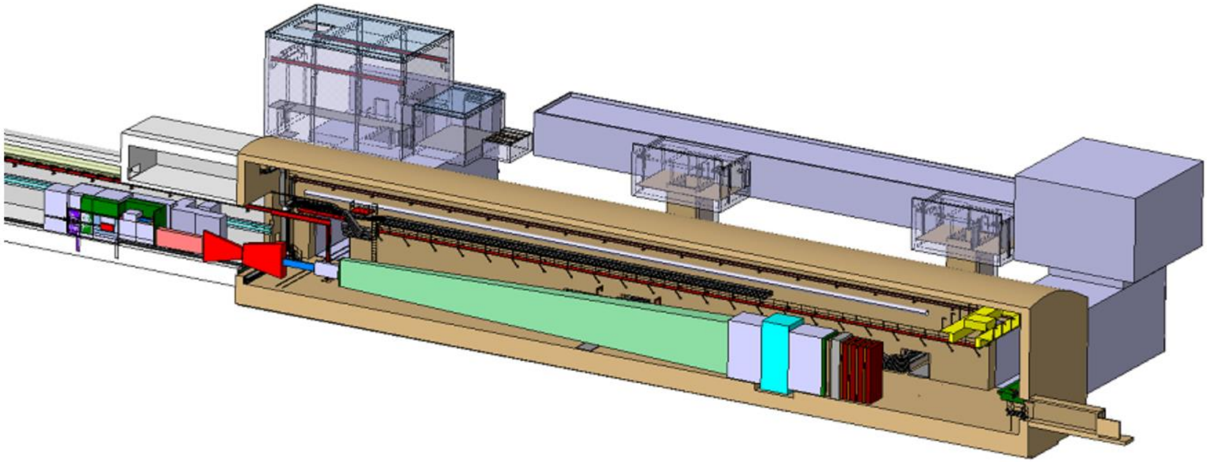
Conclusions

- The NEAR station at n_TOF showed to be suitable for SEE testing of components and systems with neutron spectra ranging from **thermals** up to **830 MeV**.
- Appropriate for **atmospheric** and **soft spectra accelerator** applications.
- Flux (>10 MeV) composed of neutrons (>98%) up to **$5.2x10^{5}$ cm^{-2}/s** (N4, larger if closer to the collimator), compatible with fluxes at CHARM, the reference facility for electronics qualification at CERN.
- **FLUKA** simulations of neutron fluence and dose benchmarked with the response of well-calibrated SRAM and RPL measurements with very good agreement.
- Interest of EAR1-NEL and EAR2 for TOF SEE measurements with spectra up to **12 GeV** → if this is of interest to the radiation effects community, we could conside putting together a Letter of Interest addressed to the nTOF collaboration
- Currently, NEAR, EAR1 and EAR2 are not a user facility and should therefore be considered as an **experimental area** for potential R&D applications.

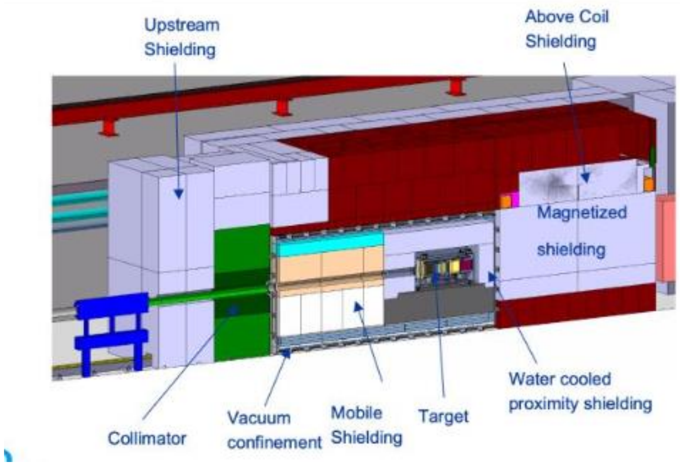
Looking further ahead…

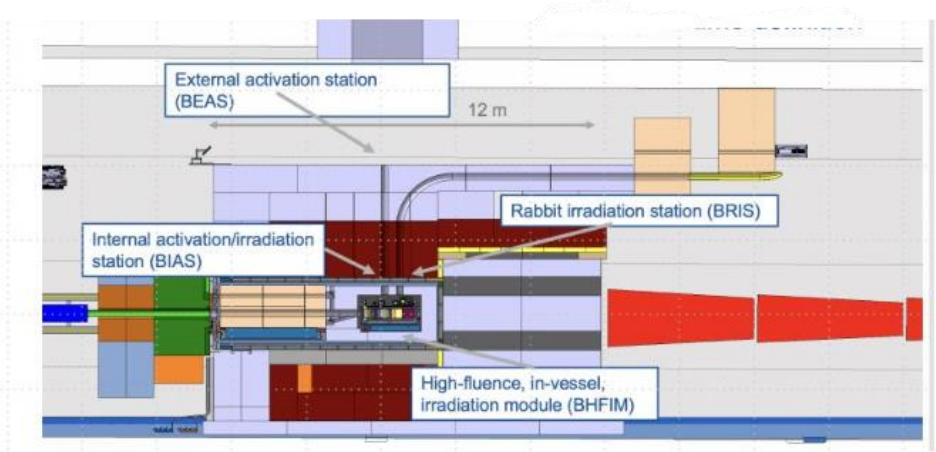
SHiP - Search for Hidden Particles

SHiP and the associated SPS Beam Dump Facility is a new general-purpose experiment in preparation at the SPS to search for "hidden" particles as predicted by a large number of models of Hidden Sectors that are capable of explaining for instance dark matter, neutrino oscillations, and the origin of the baryon asymmetry in the Universe. The experiment is design to search for any type of feebly interacting long-lived particles, among which are found e.g. heavy neutral leptons, dark photons , dark scalars, axion-like particles, and light supersymmetric particles - sgoldstinos, etc, as well as different types of Light Dark Matter.The high intensity of the SPS and in particular the large production of charm mesons and photons with the 400 GeV proton beam allow a comprehensive search at the MeV-GeV scale over many orders of magnitude in coupling. The detector incorporates two complementary apparatuses aimed at searching for hidden particles through both visible decays and through scattering signatures from recoil of electrons or nuclei. Moreover, the facility is ideally suited to study the interactions of tau neutrinos.



Looking further ahead…





Shall we consider the option of an atmospheric neutron irradiation station?

Thank you for your attention!

TOF in the literature (FPGA, MOSFETs)

1) Other TOF measurements

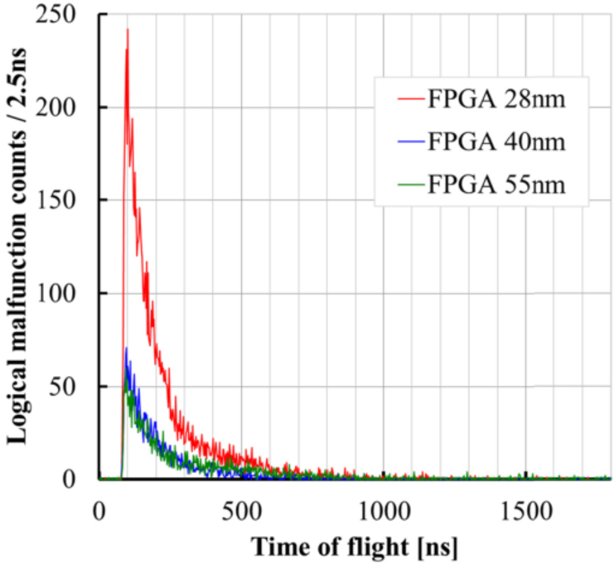
Energy-Resolved Soft-Error Rate Measurements for 1–800 MeV Neutrons by the Time-of-Flight Technique at LANSCE https://ieeexplore.ieee.org/document/9201514

RESULTS OF MEASUREMENT OF N_{CRAM}

Design rule [nm]	Neutron Fluence above 1.25 MeV [n/cm^2]	CRAM Error Counts per Mbit (N_{CRAM})
28	7.08×10^9	5.5
40	5.12×10^9	6.2
55	1.37×10^{10}	13.5

Results of measurement of NCRAM (CRAM Error count). The CRAM error counts for each DUT and the irradiated neutron fluence above 1.25 MeV are shown.

FPGA 28 nm, 12713 counts;
FPGA 40 nm, 2894 counts;
FPGA 55 nm, 3719 counts.



- LANSCE beamline distance: **20 m** (same as EAR2), pulsed proton beam repetition **1.8 us** (no TOF <1MeV)
- SEU measurements FPGA 250 MHz, 8ns: **1-800 MeV**
- To reach a fluence of 7e9 n/cm^2 >1 MeV in EAR2 (as did in LANSCE): 18 hours

2) Other TOF measurements

Energy-Resolved SEU Cross Section From 10-meV to 800-MeV Neutrons by Time-of-Flight Measurement https://ieeexplore.ieee.org/document/10045640

- Japan Proton Accelerator Research Complex (J-PARC) beamline distance: **13.7 m**
- SEU measurements FPGA: **10 meV-0.1 MeV** (up to 800 MeV with less resolution due to spill time structure)

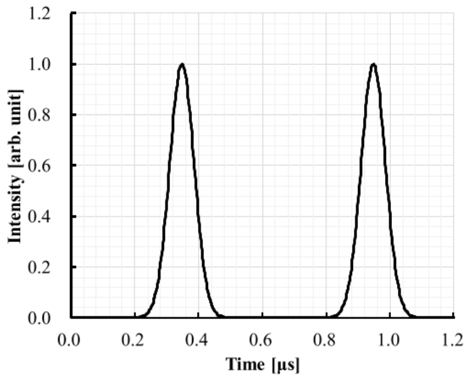


Fig. 2. Time structure of proton pulse at J-PARC (200 kW) [22]. The proton pulse of this facility is double bunch with a peak-to-peak measurement of 600 ns.

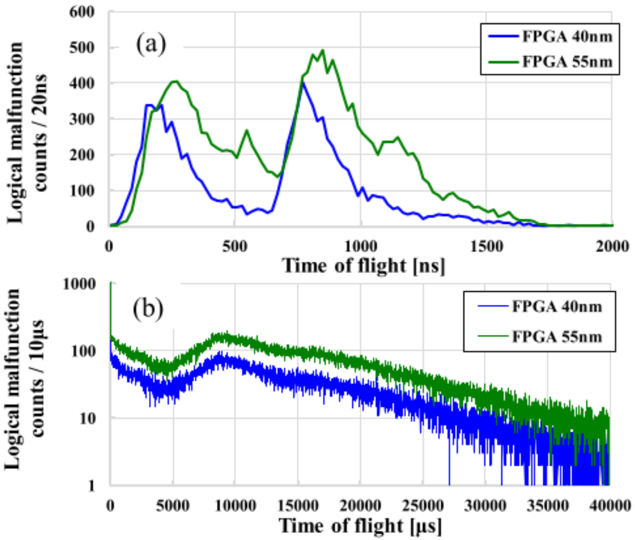


Fig. 6. Results of TOF spectra of logical malfunction counts for the two FPGAs, which were the DUTs. Time bin of (a) 20 ns and (b) 10 μs.

1 and 2) Other TOF measurements

Design rule [nm]	Number of protons irradiated to the neutron production target	Irradiation time [second]	CRAM error counts per Mbit (N_{CRAM})
40	1.16 x 10^{18}	666	37.5
55	8.81 x 10^{17}	506	30.5

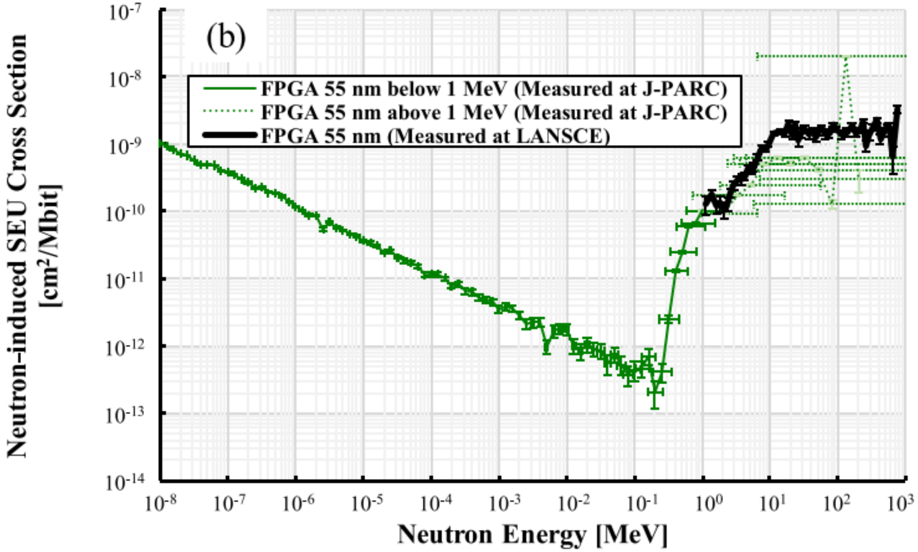


Fig. 7. SEU cross section of (a) FPGA 40 nm and (b) FPGA 55 nm. The SEU cross sections above 0.1 MeV at J-PARC are not accurate because of the double pulse (see Fig. 2).

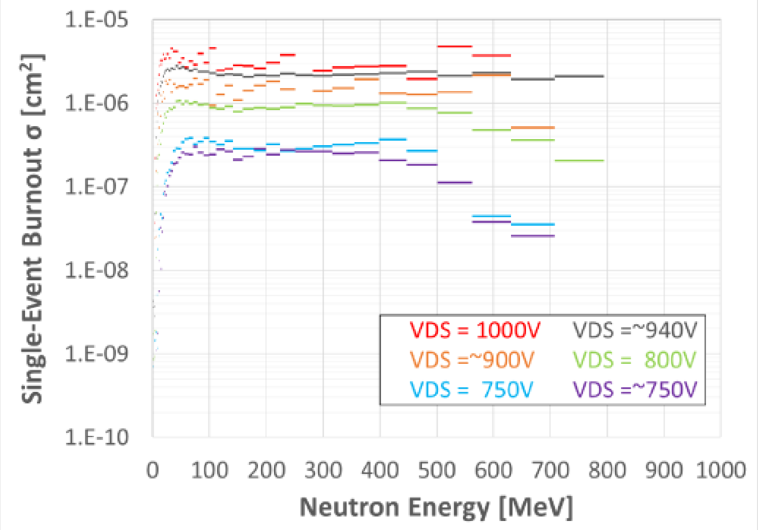
3) Other TOF measurements with Power MOSFETs

Energy-Dependent Single-Event Effects in Power MOSFETs from a Broad-Spectrum Neutron Beam
https://ieeexplore.ieee.org/document/9325839

- LANSCE (ICE-II) beamline distance: 13.8 m
- Power MOSFETs measurements
- Assumption that MOSFETS are not sensitive to neutrons below 1 MeV (due to spill separation 1.8 us)

TABLE VII
IRFBG30PBF COUNTS AND FLUENCES LISTED BY BIAS CONFIGURATION AND ENERGY RANGE

Range	V_{DS} = 1000 V		V_{DS} = 850 V		V_{DS} = 750 V	
[MeV]	#	n/cm^2	#	n/cm^2	#	n/cm^2
0-9	270	1.4E12	4070	1.0E14	9	3.7E13
10-99	1970	1.1E11	16217	8.0E12	819	2.6E12
100+	1541	8.7E10	11842	6.3E12	1009	2.1E12



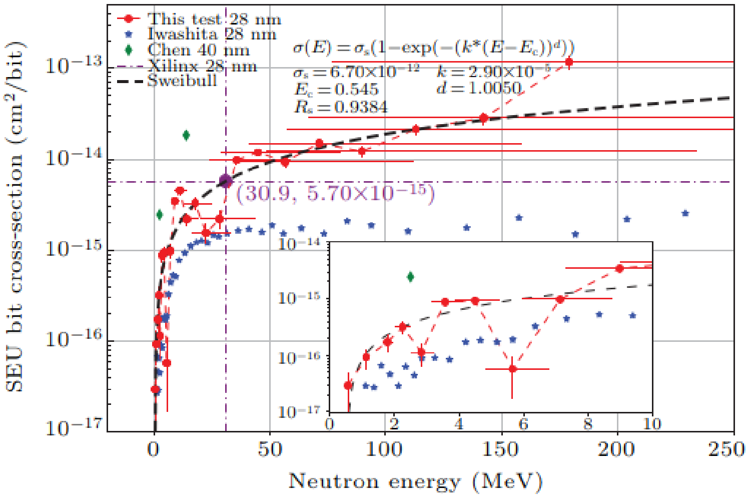
4) Other TOF measurements

Direct measurement of an energy-dependent single-event-upset cross-section with time-of-flight method at CSNS https://iopscience.iop.org/article/10.1088/1674-1056/aca603

- China Spallation Neutron Source (CSNS) beamline distance: 57.2 m
- Time structure: two spills separated 410 nm

  → limit for fast neutrons
- SEU measurements 28 nm BRAM (FPGA):

  1-800 MeV
- Resolution 200 MHz
- Test lasted 104.5 h, with 908 SEUs



Important facts for TOF measurements

- Need of **fast readout** for SEE detection depending on neutron energy.
- The **time structure** of the proton spills is very important for an accurate TOF measurement:
  - Spills must be separated enough to ensure that the slowest neutrons pass through the flight path before the next pulse arrives (**1.8 us in LANSCE, 1.2 s at n_TOF**).
  - The width of the spill should be narrow (**1 ns in LANSCE, 6 ns at n_TOF**) to ensure that produced neutrons start at almost the same time.