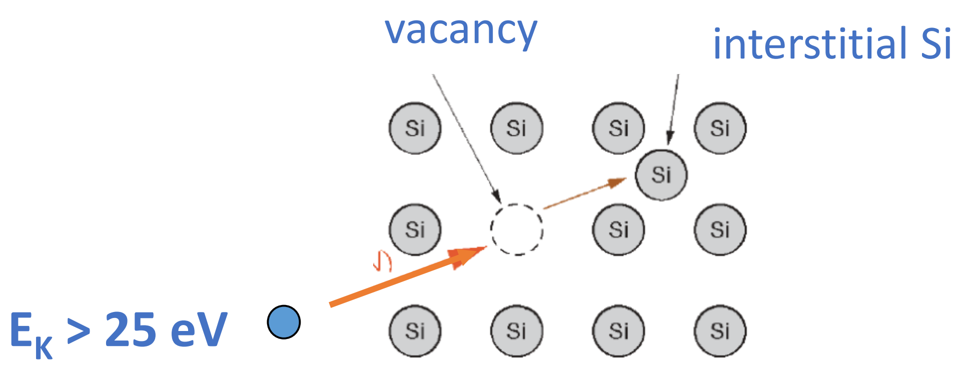
Irradiation to extreme neutron fluences

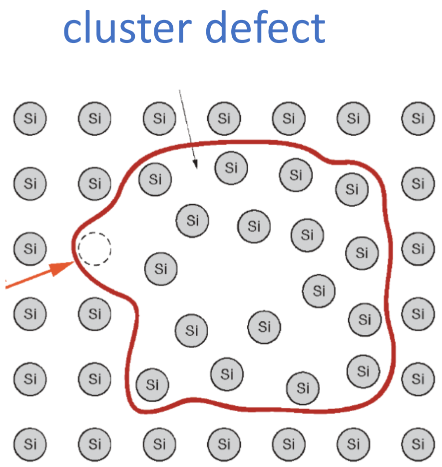
WP4 – Highlight presentation

Igor Mandić, Jožef Stefan Institute, Ljubljana Slovenia

Radiation damage

- detectors for tracking of charged particles in particle physics
- main radiation problem for Si detectors (and similarly for other semiconductors) is displacement damage:
  - particle knocks Si atom from the crystal lattice
  - knocked Si can displace neighboring atoms – cluster defect



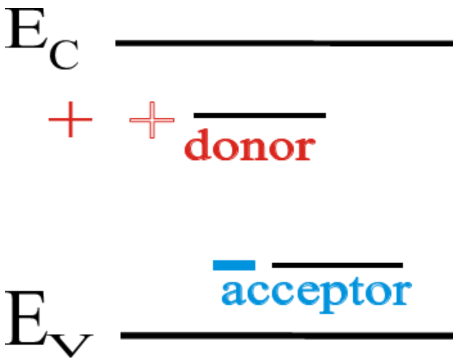


➔ **localized energy levels in the energy band gap**

Radiation damage

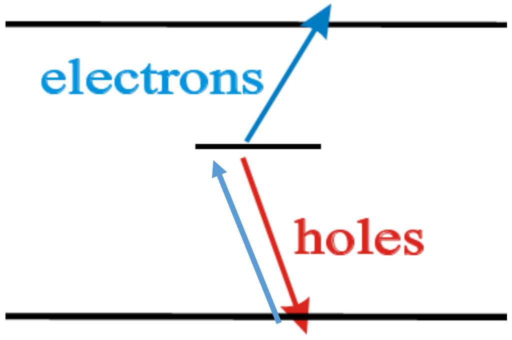
- density of localized energy levels proportional to fluence $\boldsymbol{\Phi}$

$N_{eff} = g_c \cdot \Phi + \ldots$



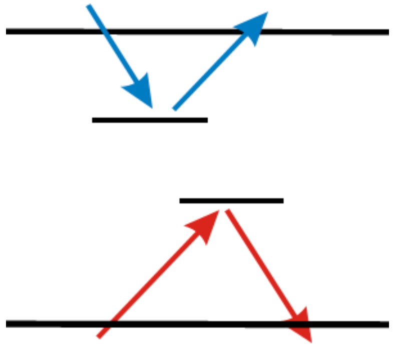
- Increased effective space charge concentration
  ➔ **increase of full depletion voltage**

$I = \alpha \cdot \Phi \cdot V$



- increased rate of thermal generation of charge carriers
  ➔ **increased detector current**

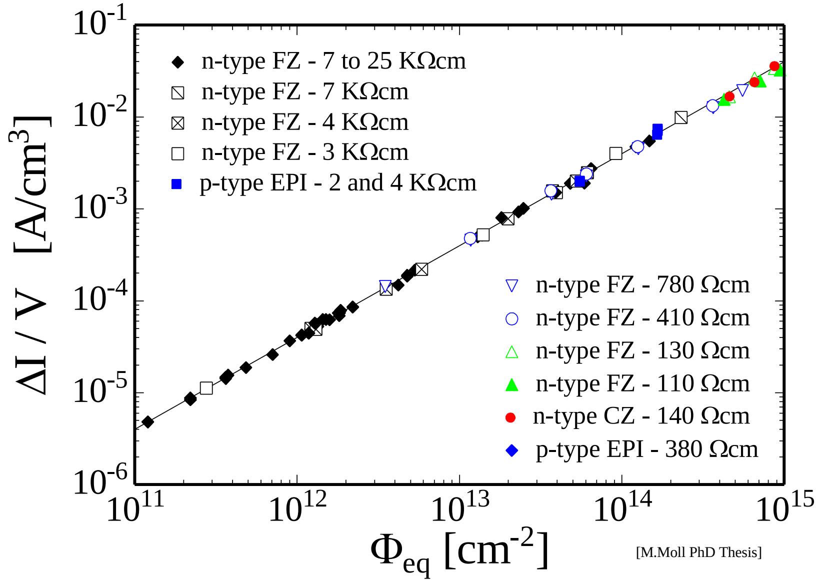
$1/\tau = \beta \cdot \Phi$



- increased charge carrier trapping probability
  ➔ **lower signal**

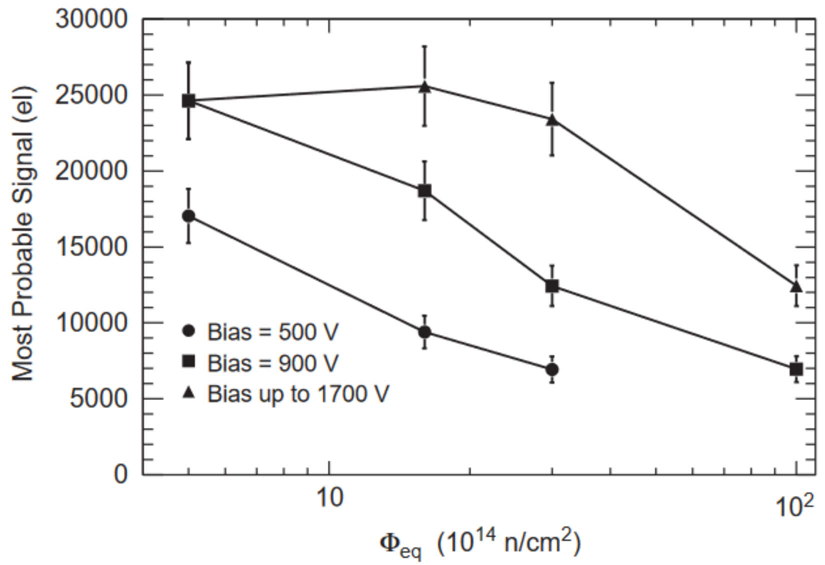
- displacement damage proportional to Non Ionizing Energy Loss (NIEL) of irradiation particles
- amount of NIEL expressed in units of equivalent fluence of 1 MeV neutrons in Si (Φ_{eq})
  ➔ **but:** effects on detector performance depend on particle type, not only on Φ_{eq}
  ➔ Φ_{eq} is still a useful unit when different radiation sources are used

Leakage current increases with fluence
➔ detectors must be cooled



M. Moll, PHD thesis, DESY-THESIS-1999-040

Charge collection efficiency drops with increasing fluence
➔ must operate at higher bias voltage to compensate



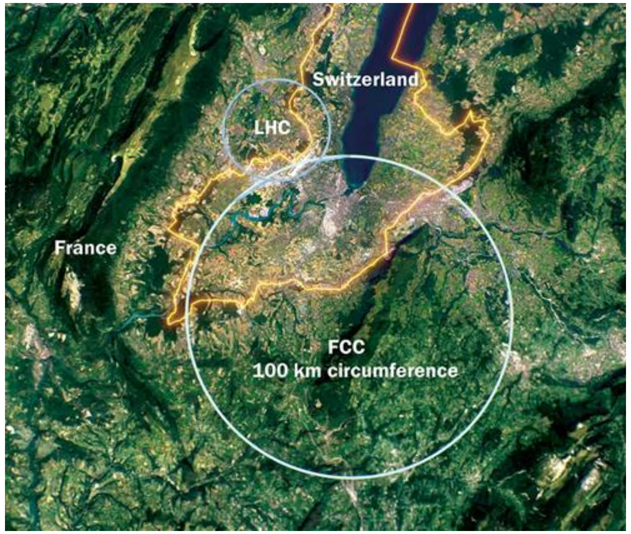
I. Mandić et al., Nucl. Instr. And Meth. A 603 (2009) 263-267

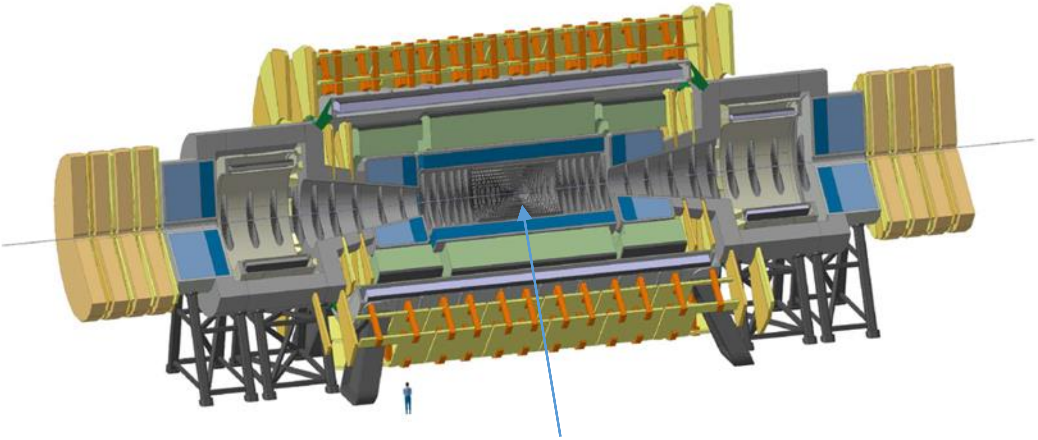
- we know how to build and operate tracking detectors up to radiation levels exceeding $\boldsymbol{\Phi_{eq}}$ **~ 10^{16} n_{eq}/cm^2**

➔ maximum radiation levels for tracking detectors at High Luminosity LHC (**HL-LHC**)

What is “extreme” fluence

- **F**uture **C**ircular **C**ollider **FCC – 100 km ring near CERN**
  - start as an **electron-positron** Higgs factory
    ➔ radiation levels not higher than HL-LHC
  - later stage: **proton-proton** collider at the highest achievable energy”: FCC-hh (10.1140/epjst/e2019-900087-0)
    ➔ radiation damage will be one of the major problems
    - **FCC-hh** maximal fluences beyond **10^{17} n_{eq}/cm^2** might even go up to **10^{18} n_{eq}/cm^2** in the tracker
      ➔fluences above 10^{17} n_{eq}/cm^2 are the present extreme





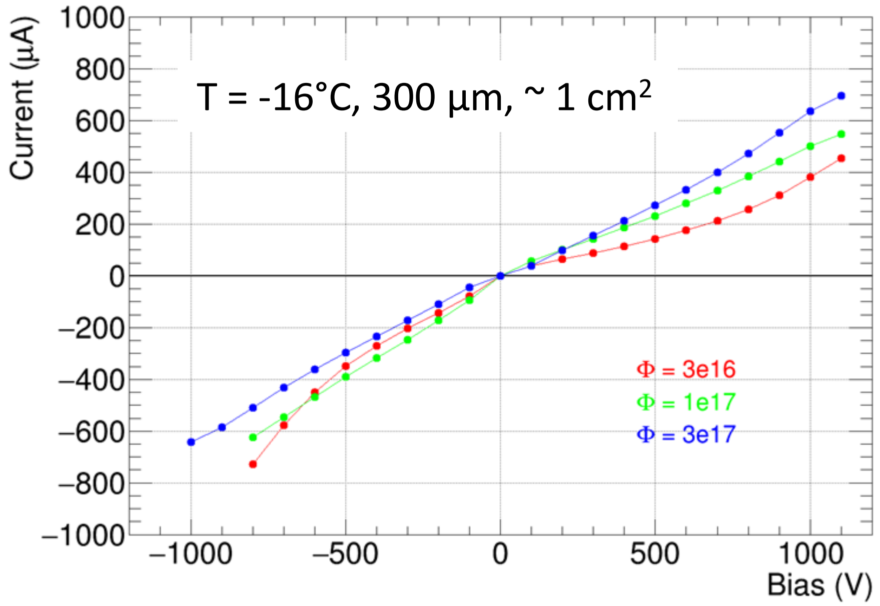
- at L_{int} = 30 ab^{-1} vertex detector at r = 2.5 cm: $\boldsymbol{\Phi_{eq}}$ **~ 6·10^{17} n_{eq}/cm^2**

Detector performance at 1e17 and beyond

- extrapolations from low fluences don't give much hope for standard detectors at extreme fluences:
  - current: 2 mA/cm^2 (2 W/cm^2 @ 1 kV) for 300 µm thick detector @ -20°C
  - full depletion voltage ≈ 100 kV
  - trapping τ_{eff} ≈ 20 ps, collected charge maybe 400 electrons at high bias voltage

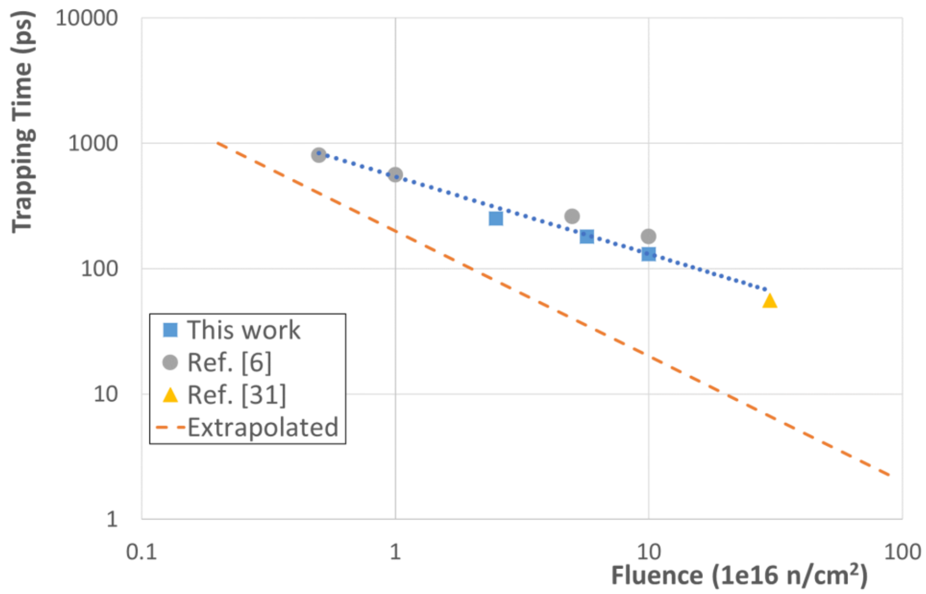
- Initial results indicate that linear extrapolations don't work

Current increase smaller



M. Mikuž et al., PSD13

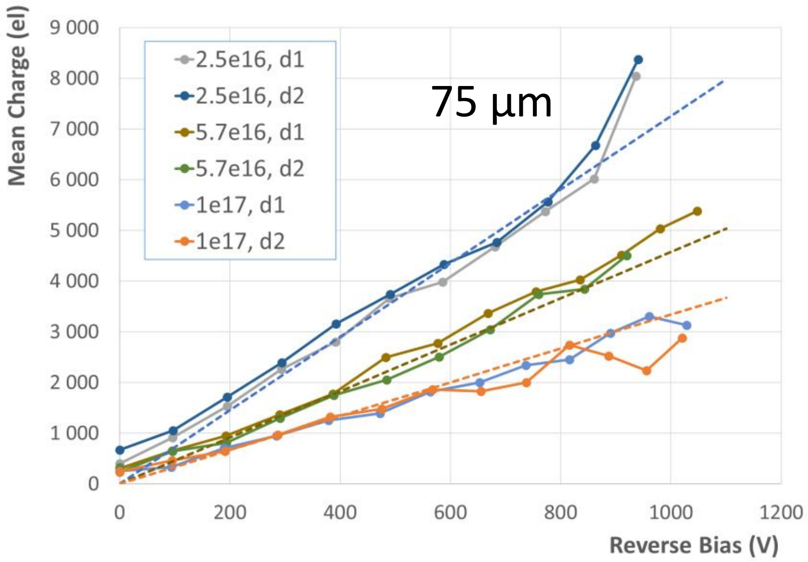
Trapping probability much smaller than expected



I. Mandić et al., **2020 JINST 15 P11018**

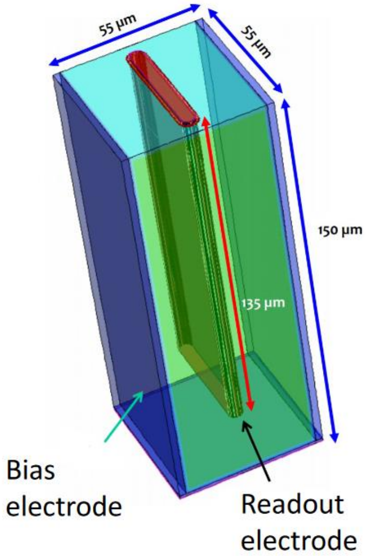
Detector performance at 1e17 and beyond

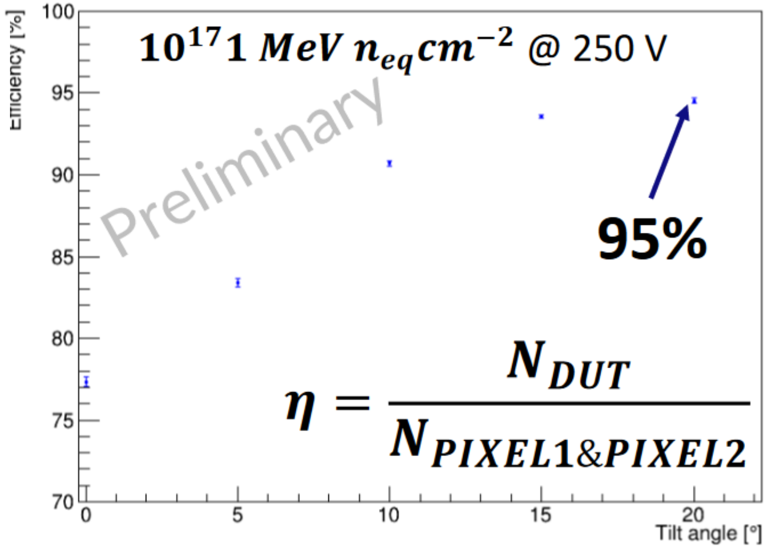
- thin detectors → more charge



[I. Mandić et al., 2020 JINST 15 P11018]

- 3D trench pixel detector at 1e17 n/cm^2 ➔ high efficiency in the test beam!





[A. Lampis, 16th Pisa Meeting 2024]

Detector performance at 1e17 and beyond

- some initial and promising results, but still many questions:

  - impact ionization?
  - carrier mobility at high fluence?
  - performance of wide band-gap materials , SiC, GaN, diamond?
  - …….
  - …….

➔ FCC-hh in distant future but many years of studies needed to develop detectors

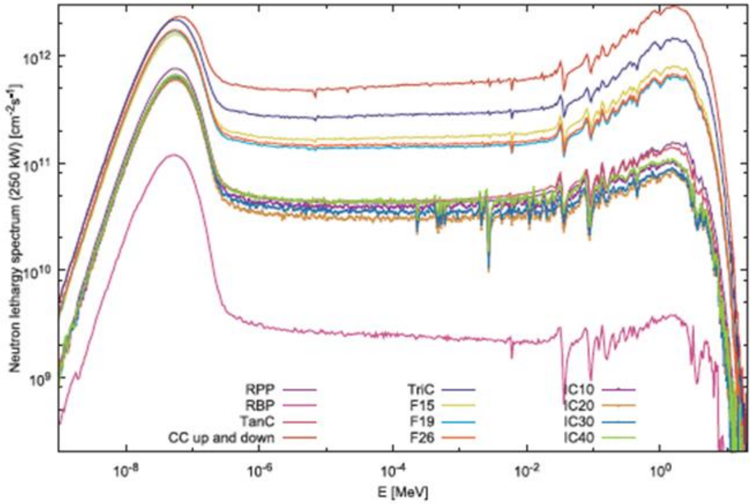
- better start now (development of detectors for HL-LHC was going on for 20 years)
- EURO-LABS has started:
  ➔ TA for irradiations to extreme fluences in the TRIGA reactor part of WP4 program

TRIGA Mark II reactor in Ljubljana

- well known irradiation facility
  - ➔ used for radiation hardness studies of solid state detectors for particle physics experiments for ~ 30 years
  - ➔ several thousands of samples for tracking detector development irradiated

➔ **WP4 – Transnational access to Research Infrastructures for HEP Detectors** https://web.infn.it/EURO-LABS/wp4-ta-for-detectors/

- neutron spectra in different irradiation channels

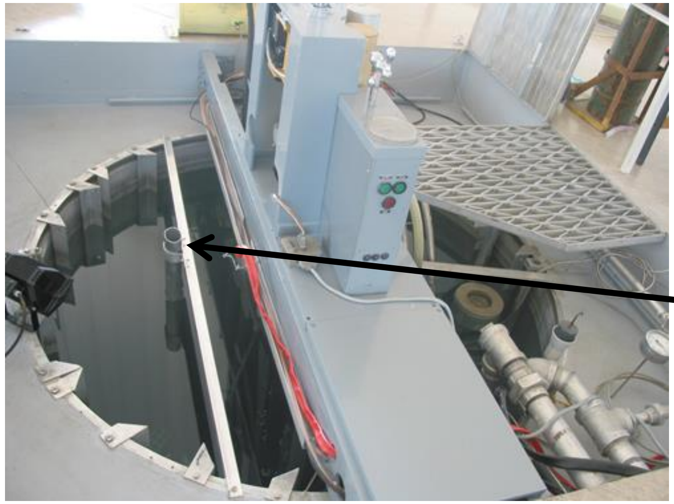


K. Ambrožič et al., *Applied Radiation and Isotopes* 130 (2017) 483-488

More info about irradiation channels: https://ric.ijs.si/en/info-za-uporabnike/lastnosti-obsevalnih-kanalov

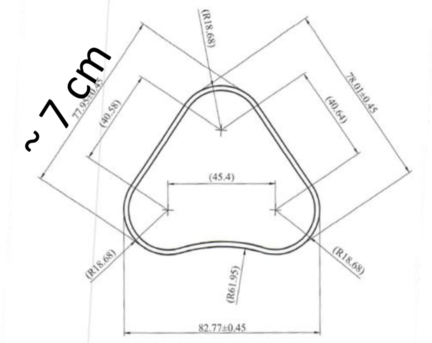
TRIGA Mark II reactor

- samples are inserted to the core through vertical channels from the reactor platform



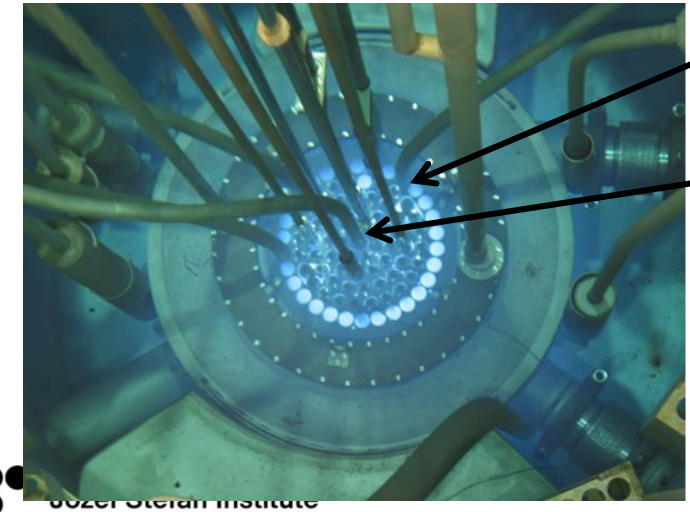
TIC channel

φ_{max} = **3.7 ·10^{12} n$_{eq}$cm^{-2} s^{-1}**



TIC channel shape

- core (under ~ 5 m of water)



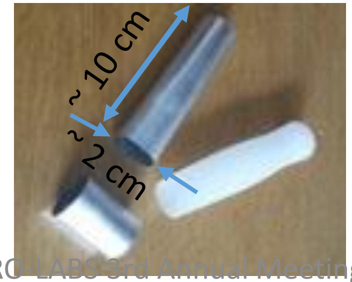
Chanel F19

φ_{max} = **1.6·10^{12} n$_{eq}$cm^{-2}s^{-1}**

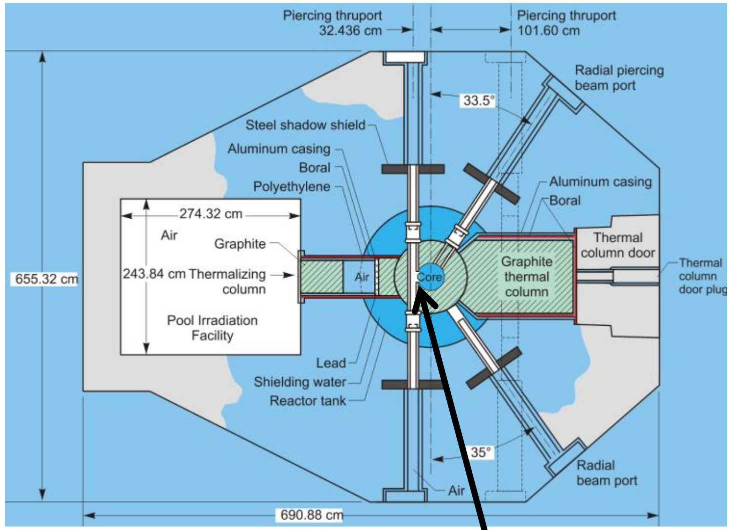
Central channel → highest flux

φ_{max} = **6 .7·10^{12} n$_{eq}$cm^{-2}s^{-1}**

Irradiation containers



- horizontal channel for larger objects
- φ_{max} = **4.8 ·10^{11} n$_{eq}$cm^{-2}s^{-1}**



- sample inserted next to the core from the side

Irradiation at TRIGA reactor

- **HL-LHC**, fluneces up to nx10^{16} n_{eq}/cm^2
  - typical irradiation few tens of minutes
  - usually several fluences requested, irradiation campaign for individual user few hours

    ➔ about 2000 irradiations were done in the last 10 years
  - still many irradiations in this fluence range going on, supported by EURO-LABS

- **FCC$_{hh}$ – up to 10^{18} n_{eq}/cm^2**

➔ **10^{18} n_{eq}/cm^2** reached in **40 hours** in the Central Channel (CC) (flux 6.7e12 $n_{eq}/cm^2/s$)

➔ reactor operates in usual working hours: one week of reactor time needed for single irradiation campaign

➔ reactor used by many users → only few (two, three) irradiations to 10^{18} n_{eq}/cm^2 possible per year

➔ **collect samples from several users and irradiate together**

Irradiation to Extreme Fluences

- a week (40 h) of reactor time for extreme fluences was booked from **19th to 23rd of August 2024**

  ➔ **irradiation campaign advertised to the DRD3 collaboration**

- use three irradiation channels in parallel
  - in 40 hours following fluences are reached
    - in CC: 1e18 n_{eq}/cm^2
    - in TIC: 5.2e17 n_{eq}/cm^2
    - in F19: 2.3e17 n_{eq}/cm^2

- samples from various groups joined together

  ➔ **only one container can be irradiated up to 1e18 in 40 hours**

2.4 cm diameter
10 cm long

- **small samples!** to fit into cylinder with diameter 2.4 cm, 10 cm long

- only bare chips (no PCBs, connectors etc…)

Irradiation to Extreme Fluences

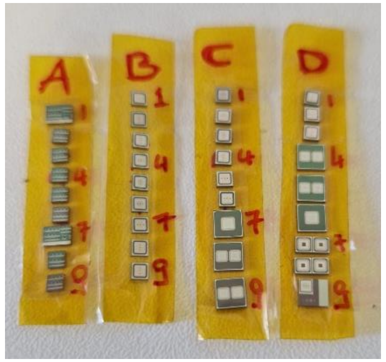
Received samples from 12 groups:

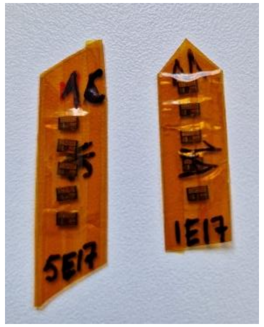
	Group	Sample	Fluences (x1e17)		
			2.3	5	10
1	Carlton, Canada	GaN	x		x
2	IMECAS, China	Si (3D)	x	x	x
3	Vilnius	SiGe, Si, Sapphire	x	x	x
4	Helsinki	CdTe, AIN	x		
5	CERN	Si, SiC	x	x	x
6	Heidelberg	Si			x
7	Cagliari	Si (3D)		x	x
8	Vienna	SiC			x
9	RD50-CMOS	Si (CMOS)			x
10	Torino	Si (LGAD)	x	x	x
11	ATLAS strips	Si (Planar)	x	x	x
12	Hamburg	Si blocks	x	x	x

Irradiation to Extreme Fluences

- not much experience with 40 hours irradiation (G. Gorine et al., IEEE TNS, VOL. 65, 2018, p1583)
- 40 hours in CC: 1e18 n_{eq}/cm^2 neutrons + ~ 10 MGy TID from gamma rays

- samples wrapped in kapton (plastic zip bags not ok)





- wrap also in aluminium foil if kapton packages fall apart

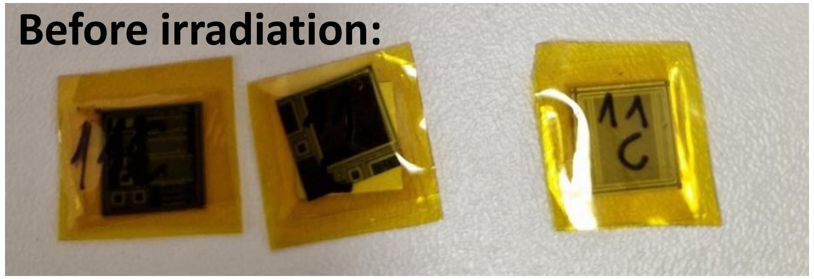
Samples for 1e18 → into container C

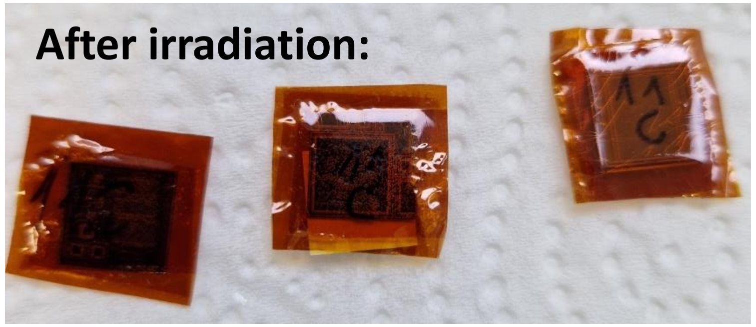
- worries before irradiation:
  - will marks be visible after 1e18 and 10 MGy?
    ➔ colleagues from CERN IRRAD said yes, they have experience with 10 MGy
  - radioactivity → when will it be possible to send samples back to labs?

Irradiation to Extreme Fluences

- irradiation from Monday to Friday (19-23/8/2024)
- containers lifted out of irradiation channels Monday (26th)
  ➔ radioactivity: ~ mSv/h at ~ 1 m
- store in the "hot chamber" for another 3 weeks

- open the containers end of September:
  - 1e18 samples → marks well visible:





- kapton brittle
- glue falls off

} slightly radioactive
➔ unwrap with care

➔ beginning of October 2024: radioactivity of all but one set **below the exemption level!**
➔ finished sending samples back to labs last week

Summary

- at future hadron colliders particle detectors will be exposed to radiation levels up to 10^{18} n/cm^2
  - present detectors can't survive such high radiation levels

- large number of irradiation tests will be needed to develop detectors for such environment

- irradiations to high fluences are a challenge
  - irradiation time
  - sample preparation
  - radioactivity and shipments of irradiated samples

- first joint irradiation campaign to extreme fluences at TRIGA reactor supported by EURO-LABS
  - lot of useful experience on how to organize such irraidation
  - various types of samples irradiated
    - hope for interesting results in presentations and publications (with acknowledgment to EURO-LABS)

- next irradiation to extreme fluences planned for 2025
  - expecting samples from many institutes developing detectors for extreme fluences