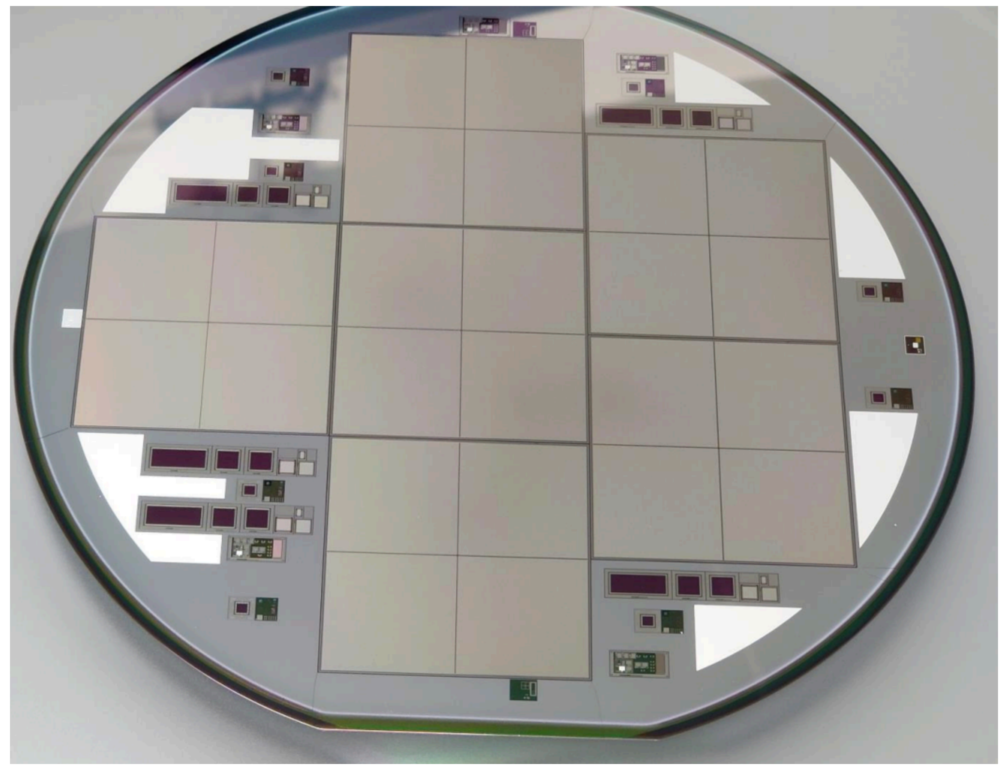
Irradiations

Disclaimer: When it comes to irradiations, I'm very much an 'end user'



"It's a very user-friendly model."

Outline

Today's lecture will cover:

- The motivation for irradiation
- Ionising and non-ionising radiation
- Radiation damage and consequences
- Examples of some irradiation facilities
- Testing of irradiated parts

Next lecture on Friday will cover:

- Single event effects
- Low dose rate irradiations
- Decomissioning
- PEPT: an example of irradiations for industrial applications

Why do we need irradiation facilities?

- Many of you will be involved in developing or working with apparatus that will be deployed in environments with radiation

- Unless the devices you are using are low cost and easy to replace, it will be necessary to design them such that they can survive radiation damage and continue to perform to specification up to the end of their required lifetime

- Irradiation facilities allow us to take instrumentation and expose it to a radiation field in a controlled (and usually accelerated) way, taking the instrument to its end of life state

- We can then measure the irradiated device to test its performance at end of life and adjust or approve designs accordingly

- There is also a use for irradiations from an operational point of view, i.e. how does my device perform when the unwanted effects of radiation are disturbing the measurements in ‘real time’ -> single event effects / upsets / transients

Why do we need irradiation facilities?

- There are also additional uses for irradiation facilities that are perhaps less familiar:
    - Sterilisation of medical products without removal of packaging
    - Production of isotopes for medicine and industry
    - Irradiations for automotive and aeronautical parts where low dose rates (cosmic rays) over long time scales can be a contributing factor to reliability

Facilties worldwide: https://irradiation-facilities.web.cern.ch/#googlemaps

Recap

- Please see Karol’s slides given as part of this lecture series for a great deal more detail on this topic:
    - https://indico.cern.ch/event/1277888/timetable/#13-interaction-of-particles-wi
    - https://indico.cern.ch/event/1277888/timetable/#14-interaction-of-particles-wi
- The same goes for the talks by Laura on radiation damage which is also relevant to this talk:
    - https://indico.cern.ch/event/1277888/timetable/#16-radiation-damage-1
    - https://indico.cern.ch/event/1277888/timetable/#17-radiation-damage-2
- I will recap some of their material here since it is very relevant to this topic…

Ionising and non-ionising radiation

Phil Allport

Ions (alpha particles, fission fragments, also protons etc. in nuclear physics)

Straight tracks

Electrons (beta particles) (+ve and -ve)

Highly scattered tracks

Charged: directly ionising,

along track of particle

Neutrons

Interact only with nuclei: to give ion tracks

Photons: gamma-rays and X-rays

Interact with atoms/electrons: to give electron tracks

Uncharged: indirectly ionising,

along tracks of secondary radiation following interactions

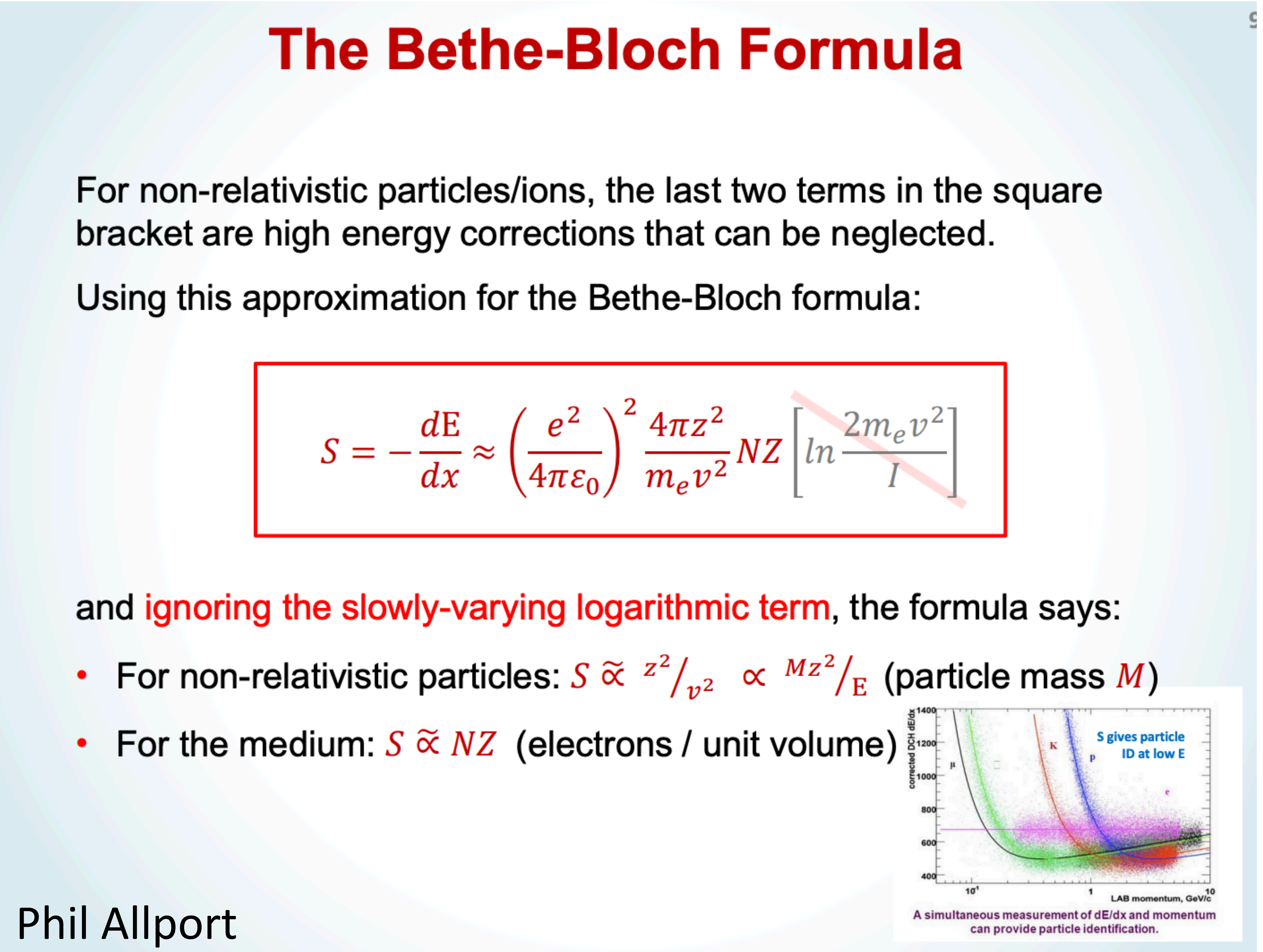
The radiation source chosen depends on the damage mechanism required for the application or study

Ions and neutrons principally chosen for non-ionising energy loss effects

Photons principally for their ionising dose

UNIVERSITY OF LIVERPOOL

Ionising radiation



The Bethe-Bloch Formula

For non-relativistic particles/ions, the last two terms in the square bracket are high energy corrections that can be neglected.

Using this approximation for the Bethe-Bloch formula:

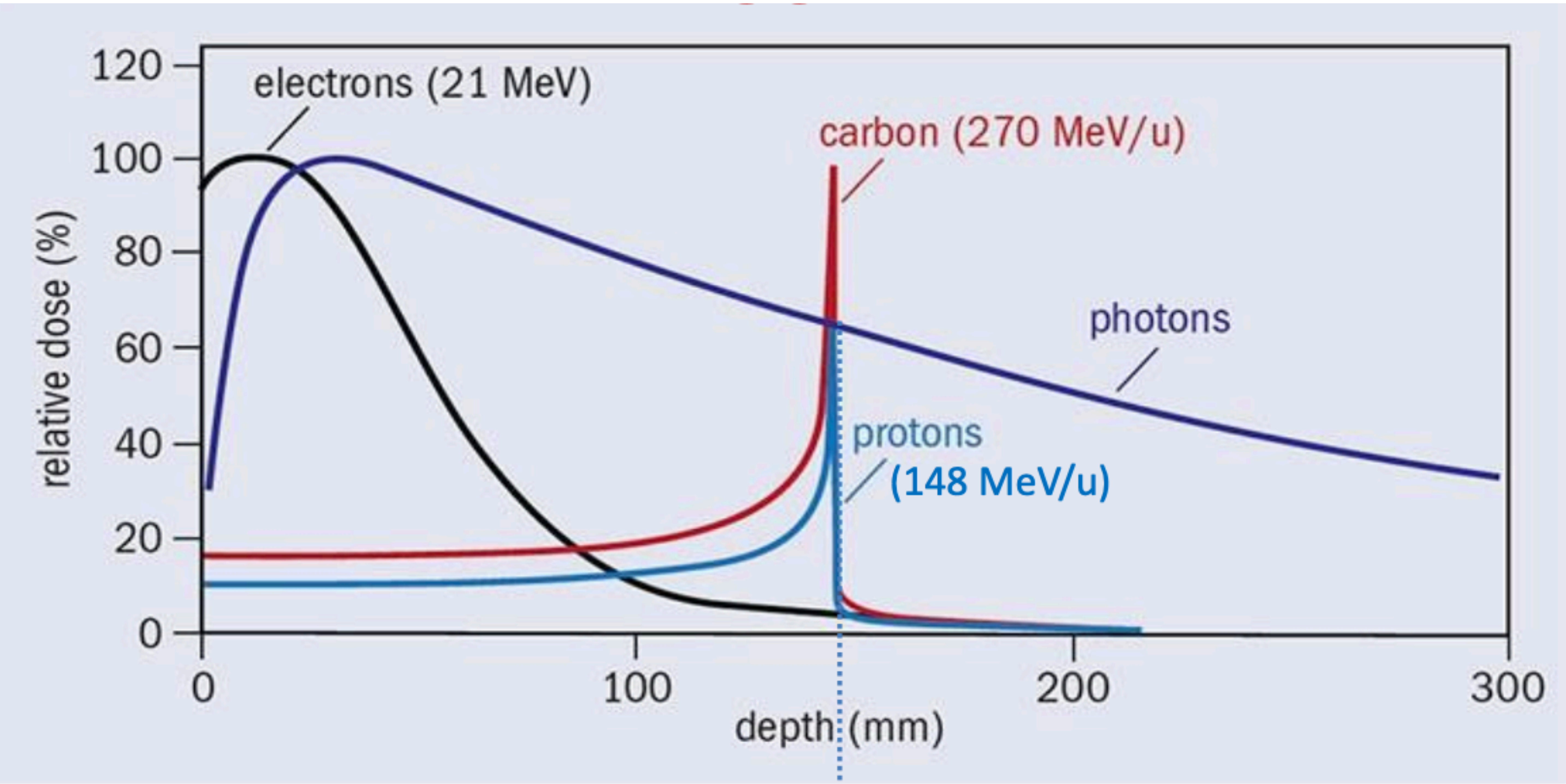
$$\boxed{S = -\frac{dE}{dx} \approx \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{4\pi z^2}{m_e v^2} NZ \left[\cancel{ln\frac{2m_e v^2}{I}}\right]}$$

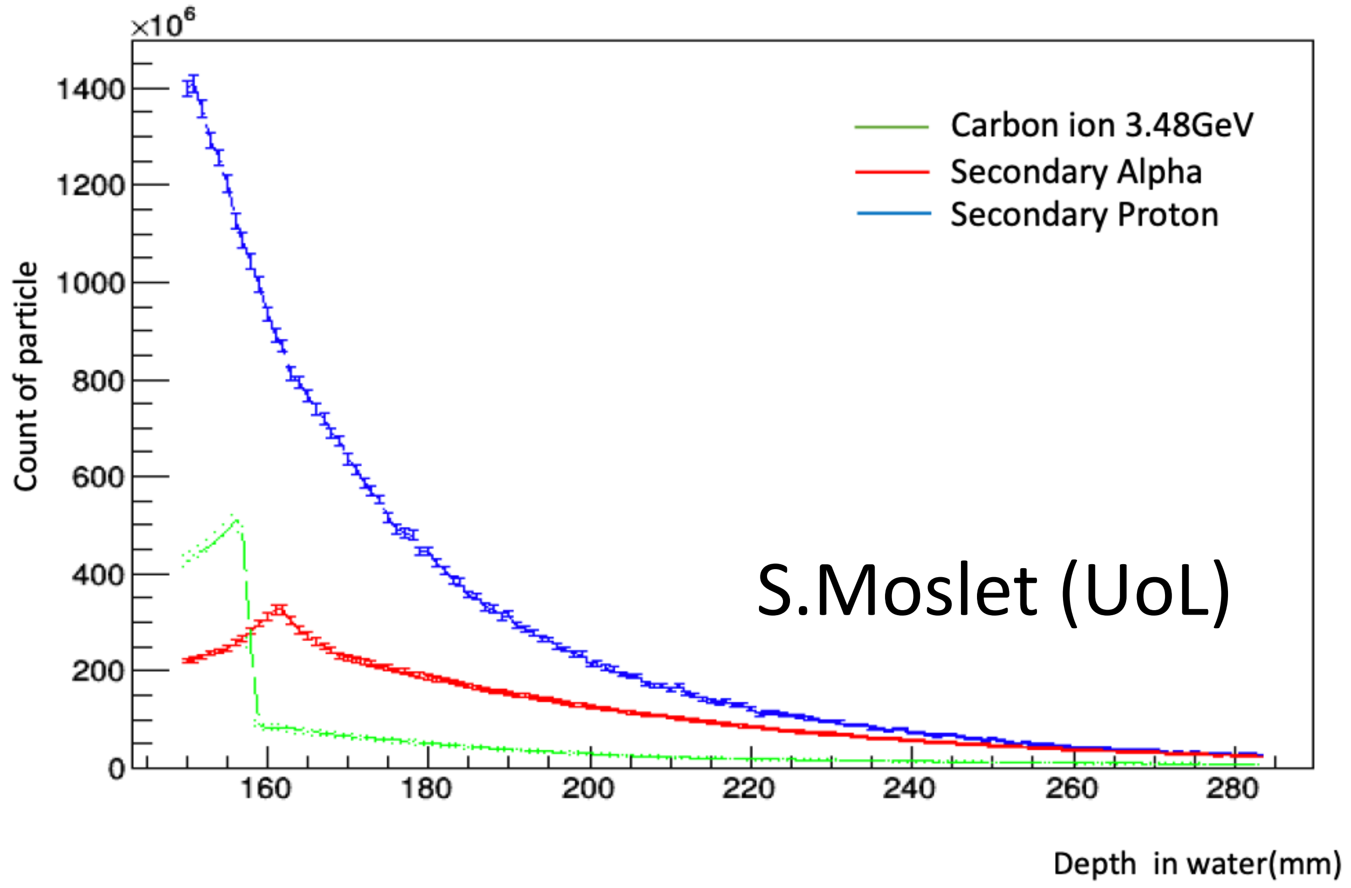
and ignoring the slowly-varying logarithmic term, the formula says:

- For non-relativistic particles: $S \mathrel{\overset{\sim}{\propto}} {}^{z^2}/_{v^2} \propto {}^{Mz^2}/_{E}$ (particle mass M)
- For the medium: $S \mathrel{\overset{\sim}{\propto}} NZ$ (electrons / unit volume)

A simultaneous measurement of dE/dx and momentum can provide particle identification.

Phil Allport





S.Moslet (UoL)

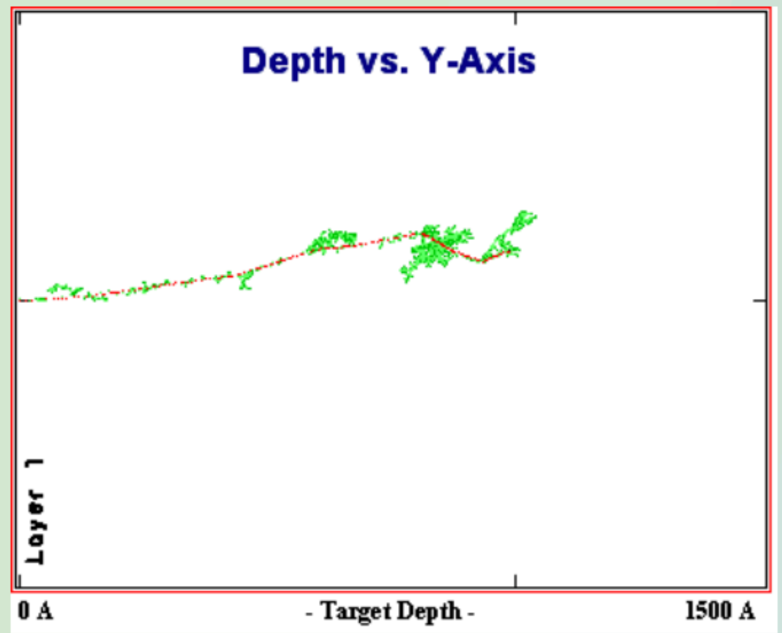
- ○ Increased electron density -> increased stopping power (dE/dx) -> increased total ionising dose (TID)
- ○ Non-ionising energy loss (NIEL) also occurs particularly with (heavier) ions (see next slide and this plot ->)

Non-Ionising radiation

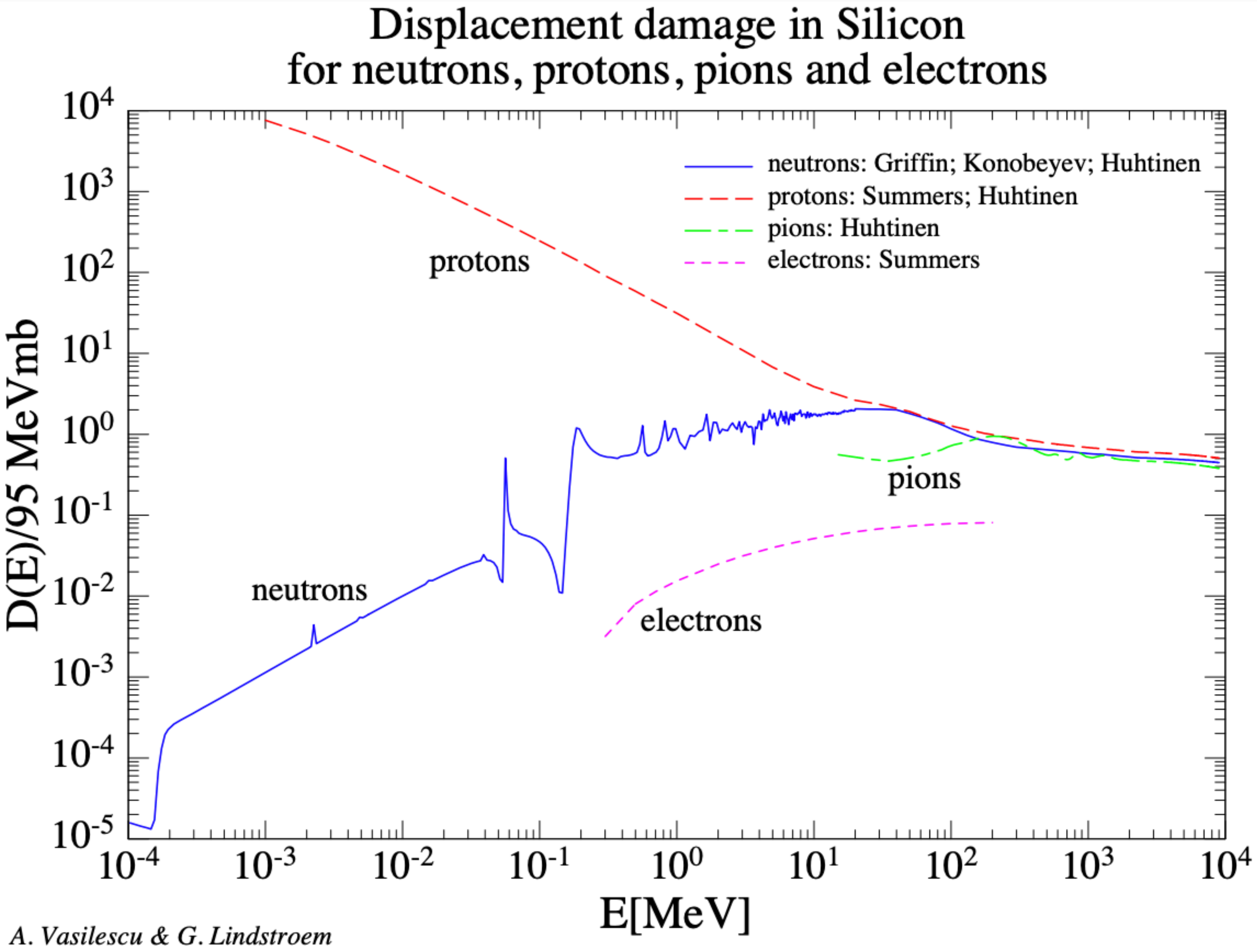
Damage to the crystal lattice in silicon caused by nuclear interactions (see Laura's radiation damage lecture for more detail)

Damage normalised to the damage caused by 1 MeV neutrons -> 1 MeV neq/cm^2 unit

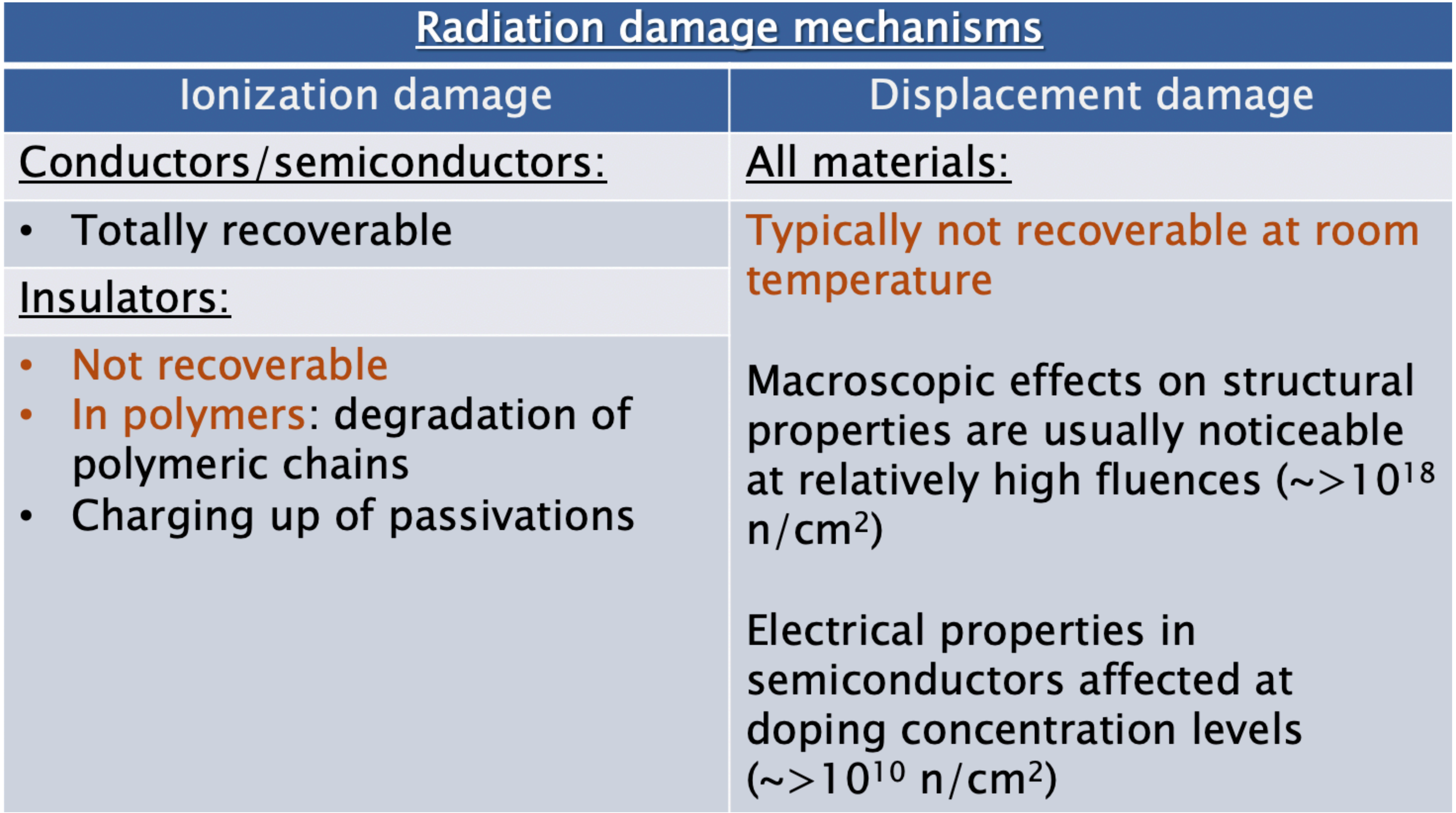
Conversion is done via determination of hardness factors (see comparison slide later on)



TRIM simulation of damage created by a 50 keV Si ion: each track has about 700 vacancies (G. Davies (WODEAN collaboration) RD50 Workshop Ljubljana 2008



Radiation damage mechanisms



Radiation damage mechanisms

Ionization damage	Displacement damage
Conductors/semiconductors:	All materials:
• Totally recoverable	Typically not recoverable at room temperature Macroscopic effects on structural properties are usually noticeable at relatively high fluences (~>10^{18} n/cm^2) Electrical properties in semiconductors affected at doping concentration levels (~>10^{10} n/cm^2)
Insulators:	
• Not recoverable • In polymers: degradation of polymeric chains • Charging up of passivations	

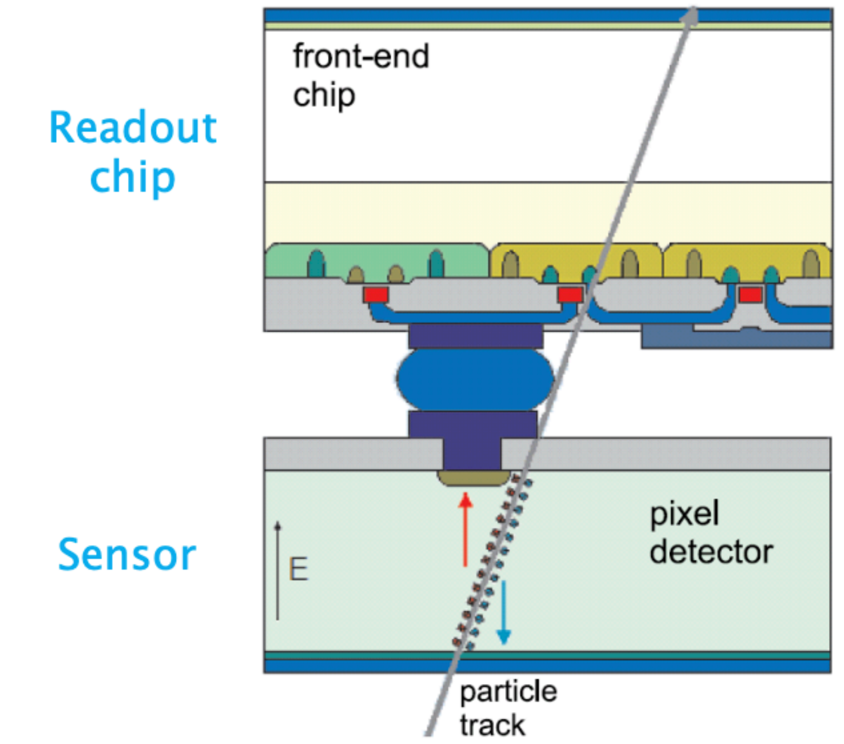
Radiation damage in electronics

For solid state detectors e.g. silicon, radiation damage has three main effects:

- Increased leakage current -> increased shot noise -> (increased) cooling required
- Charge trapping -> lower signal / charge multiplication
- Change of doping concentration -> reduction in Vdep -> increased bias voltages required

For sensors, which typically contain very little by way of electronics, users are usually interested in radiation damage in the 'bulk' of the device. For electronic components and e.g. CMOS detectors which have circuitry embedded within them, the Total ionising dose (TID) is also of interest due to the charge build up in Si-SiO2 interfaces

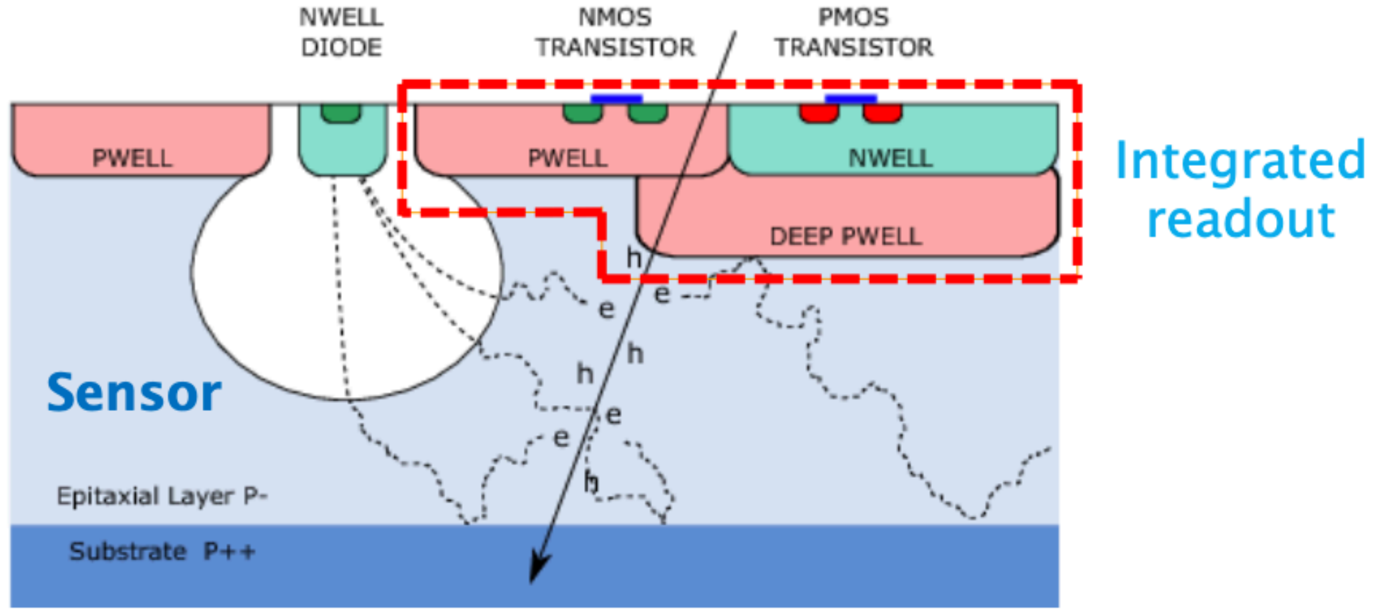
Pixels - Hybrid



TID

NIEL

Pixels - Monolithic



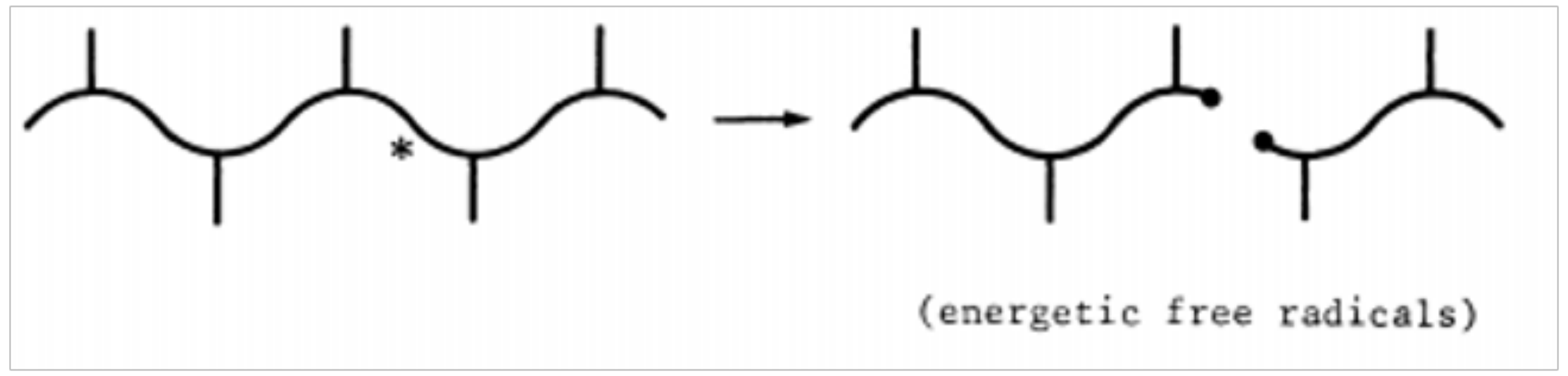
ALICE ITS2 ALPIDE detector, sketch of the cross-section of one pixel

Radiation damage in polymers

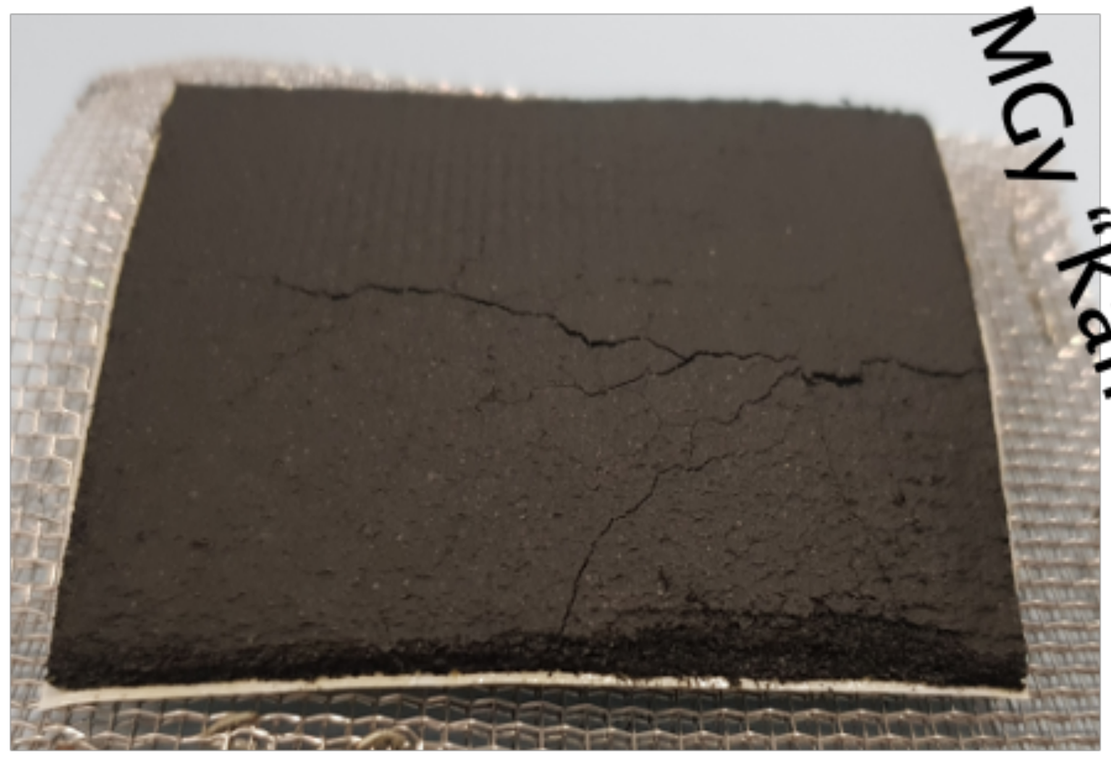
- Radiation causes polymers chain to break
- Depending from the polymer characteristics, the chain can either:

Scission :

The polymer softens and loses cohesion (depolymerization), typical for Teflon, polycarbonate etc.



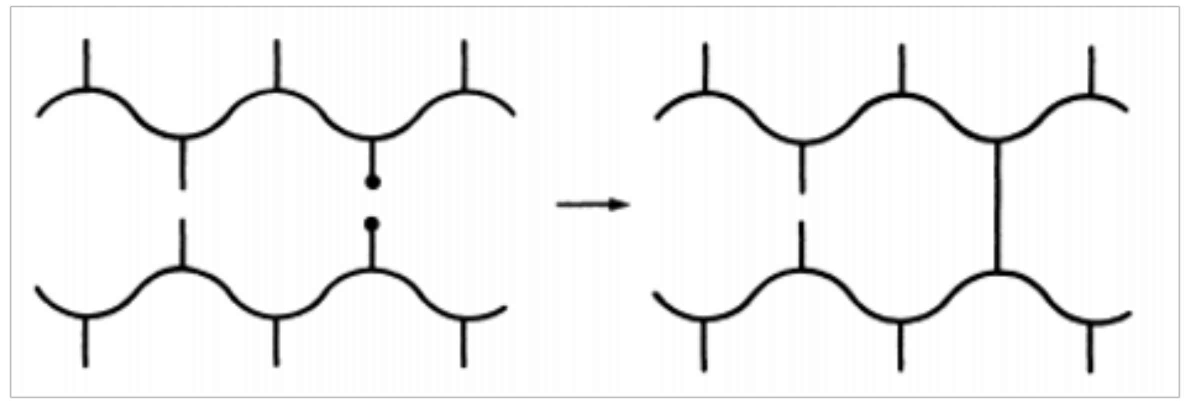
N. Pacifico



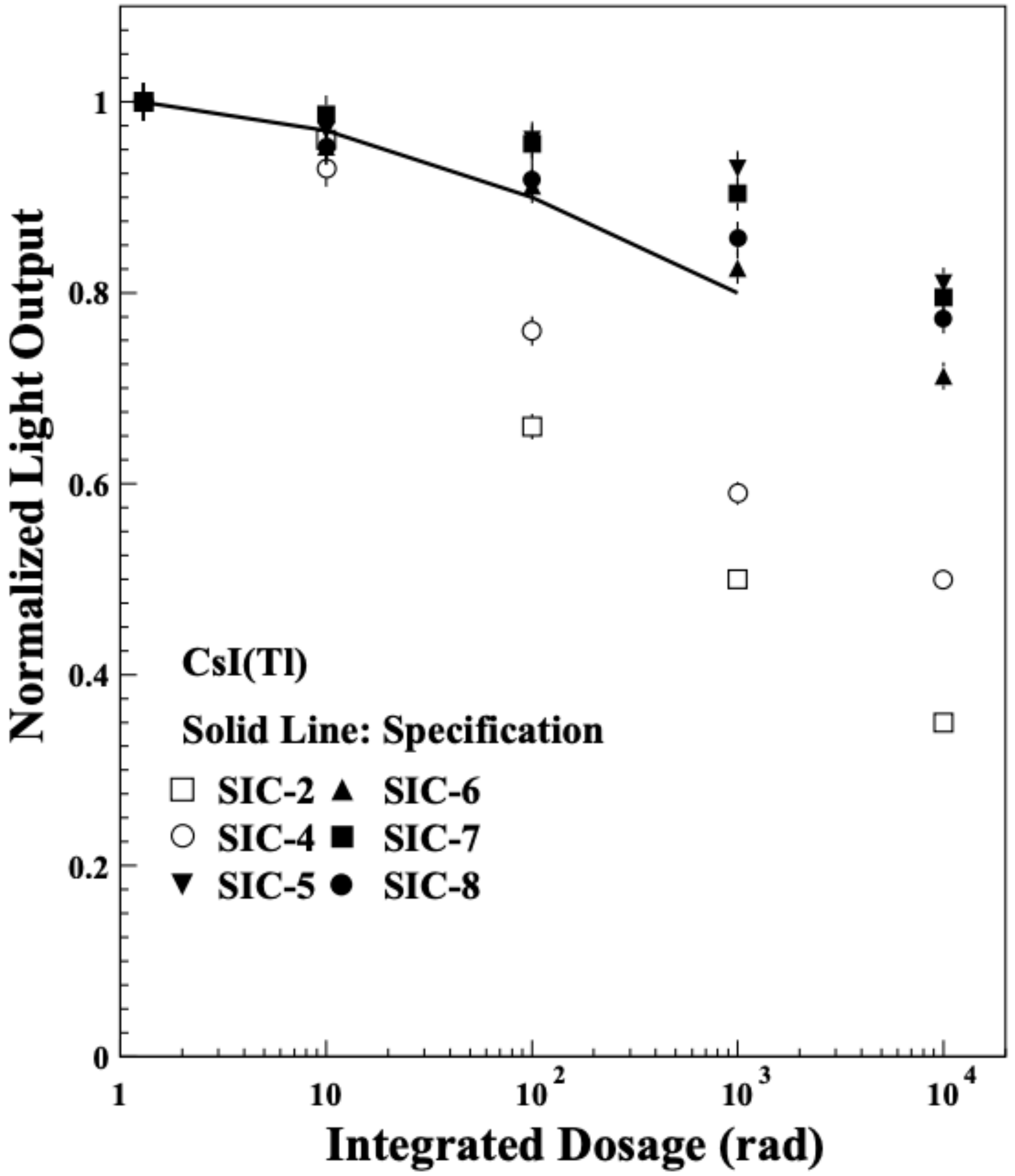
1 MGy "Kaiflex" sheet

Recombine into longer chains (cross-link):

The polymer becomes rigid and brittle (e.g. rubbers)



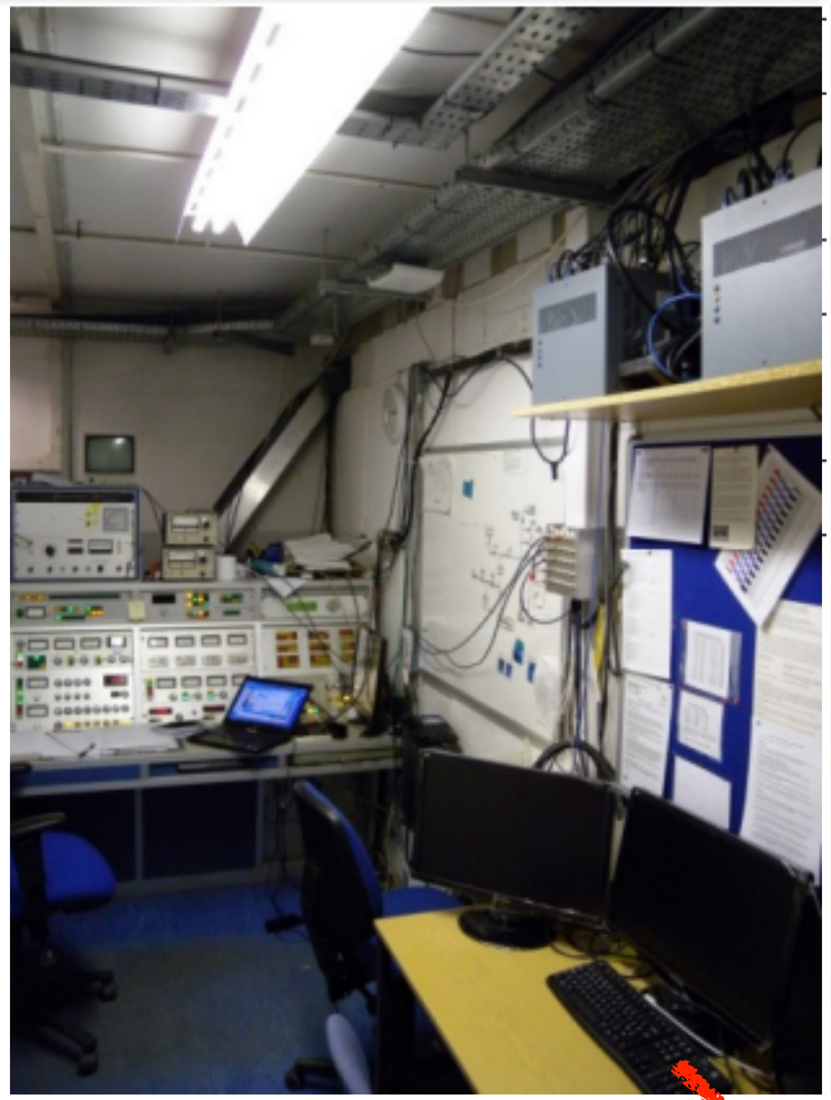
(more details on CERN-70-05)

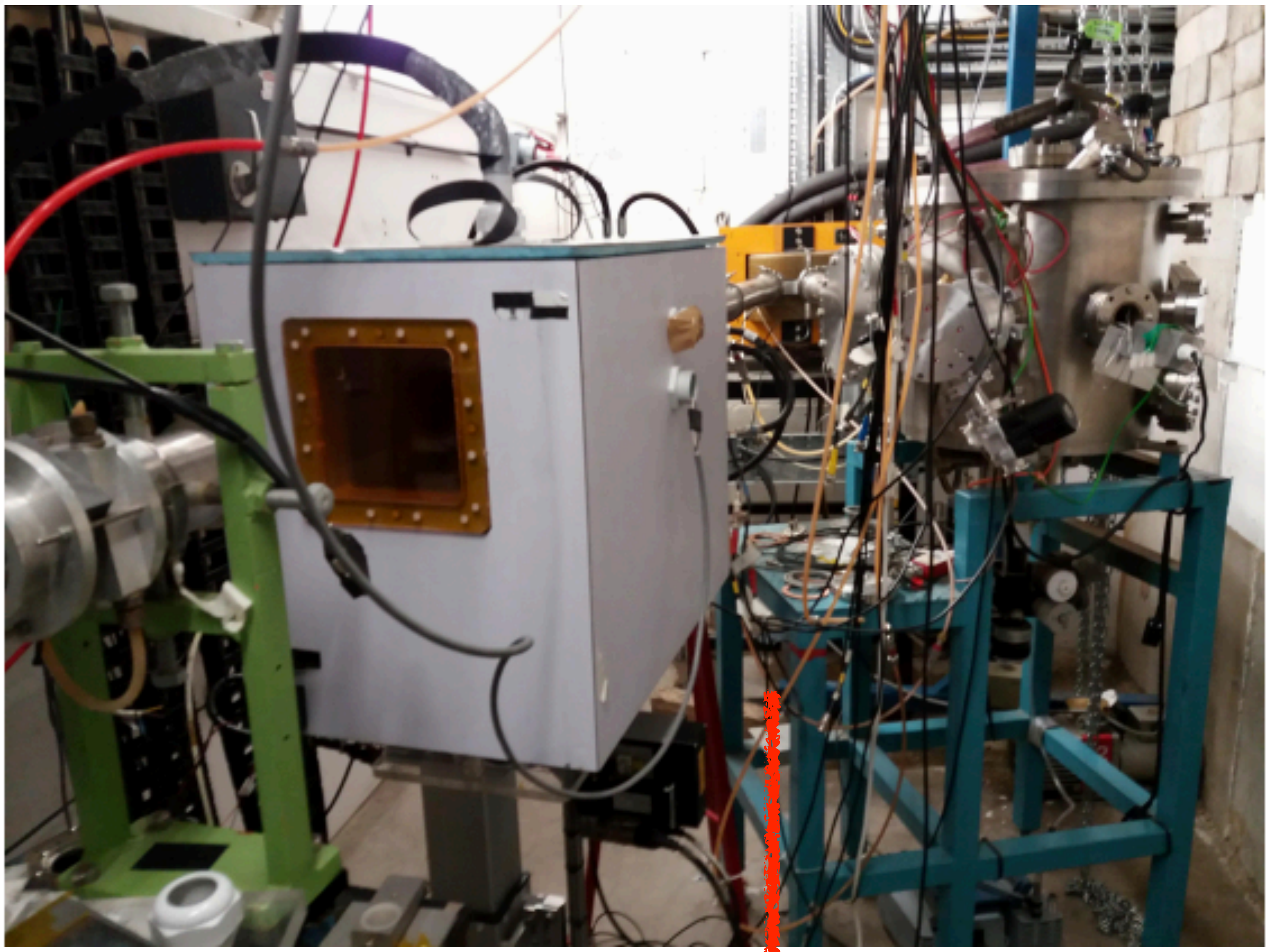


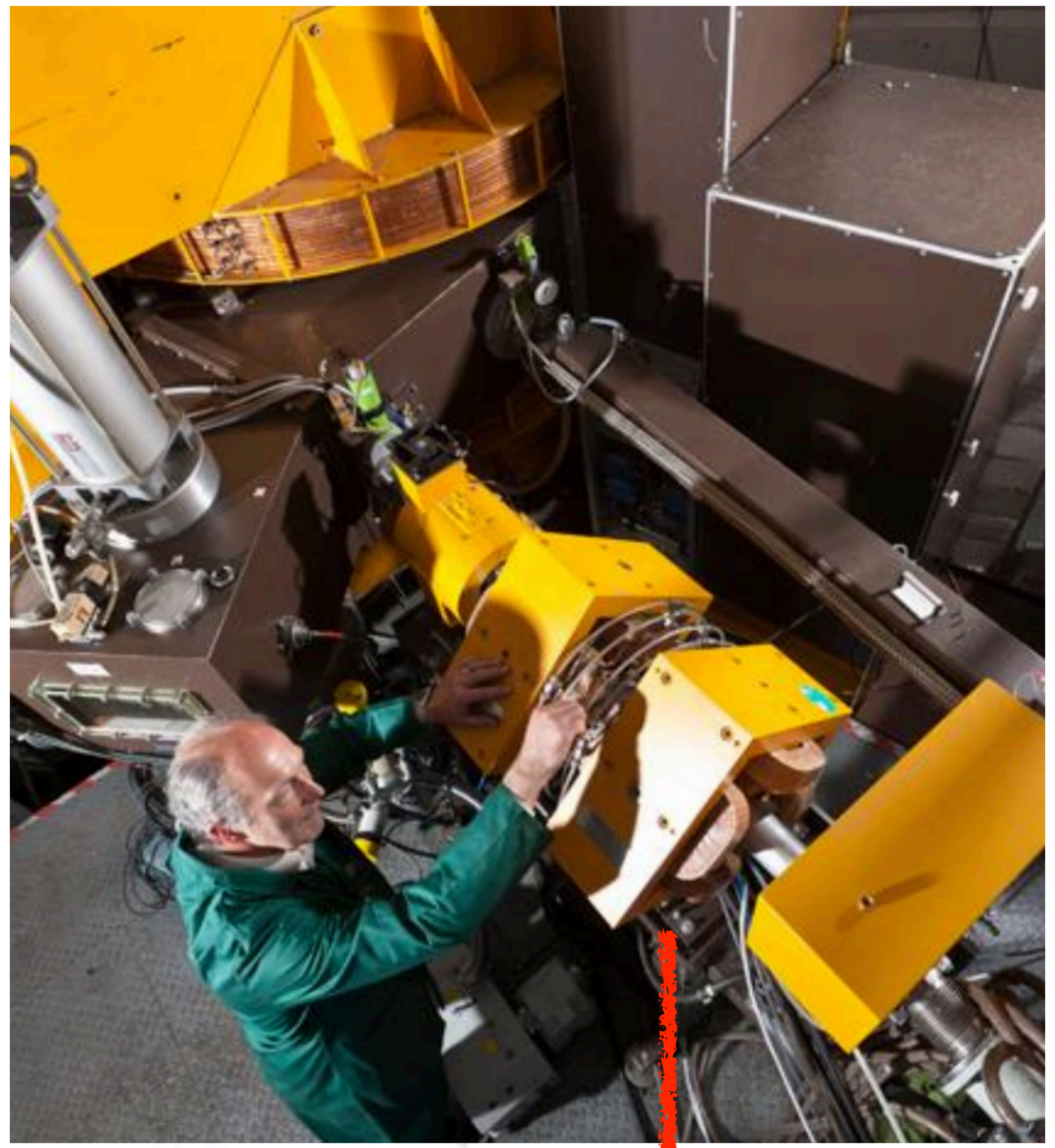
https://cds.cern.ch/record/686978

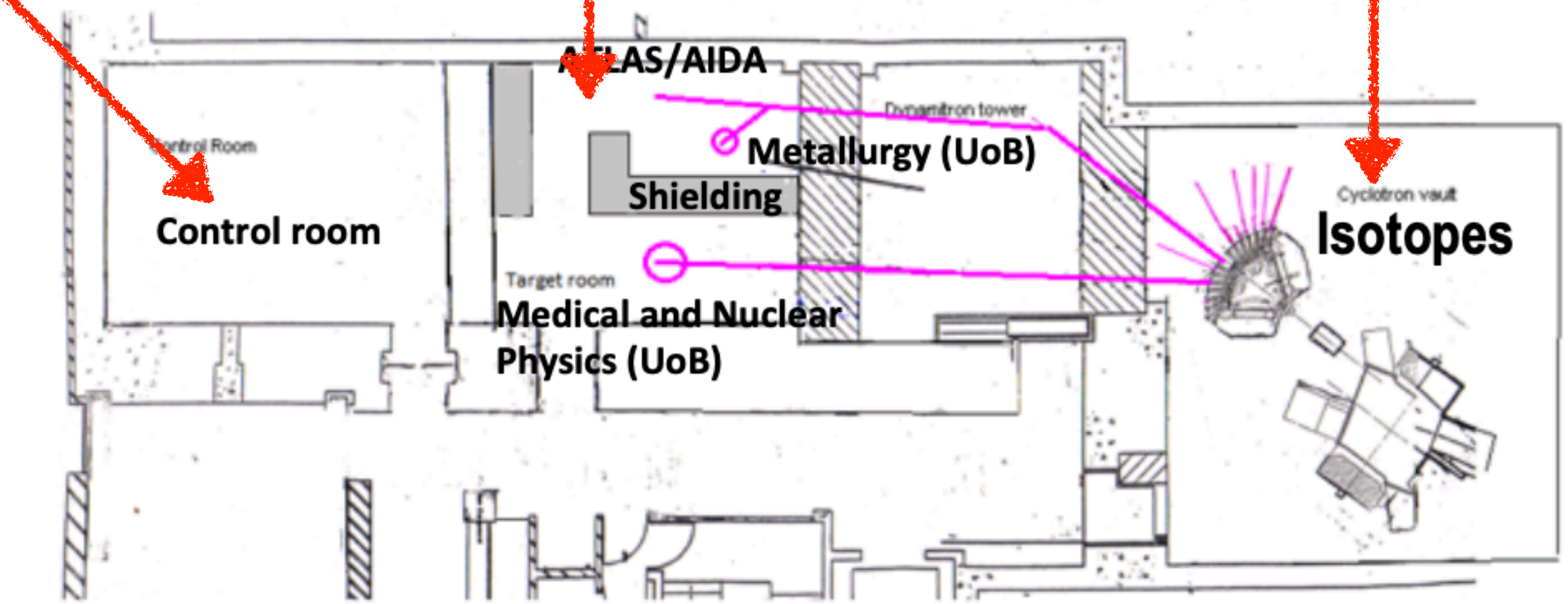
Birmingham MC40 proton irradiation facility, UK

- Provides: p, d, ^{3}He, and ^{4}He ~continuous beams
- Second beam-line into specially shielded area (2013)
  - high dose-rate damage studies
- Proton current: up to 2μA
- Beam spot: ~10×10 mm^2
- Flux: up to 10^{13} protons/s/cm^2
- Typical beam parameters:
  - Energy: 27 MeV
  - Current: 0.1-0.5μA









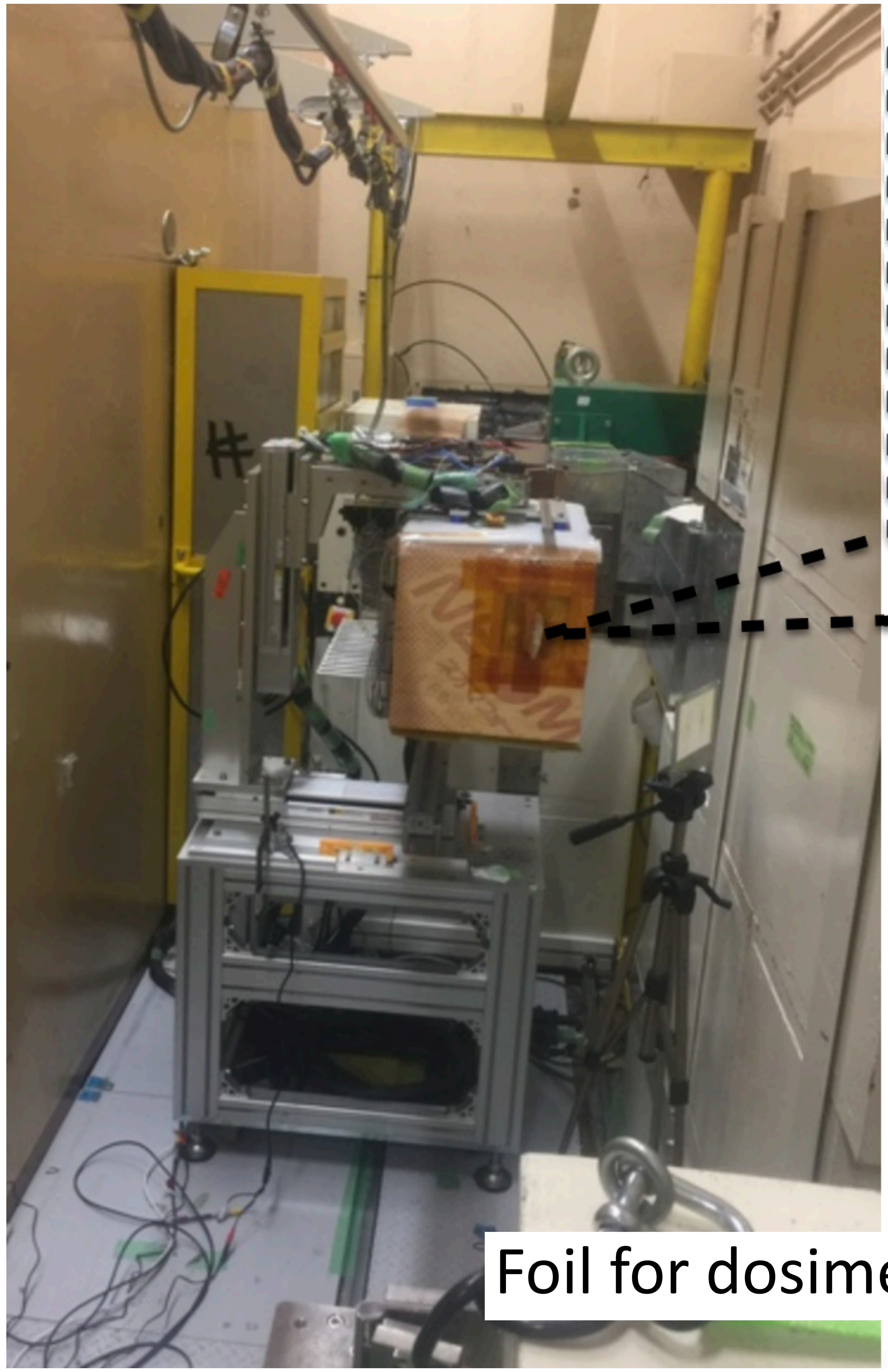
10^{15} 1MeV-n_{eq} cm^{-2} in 80s at 1μA
Fluence strip sensors need to withstand at HL-LHC (3000 fb^{-1})

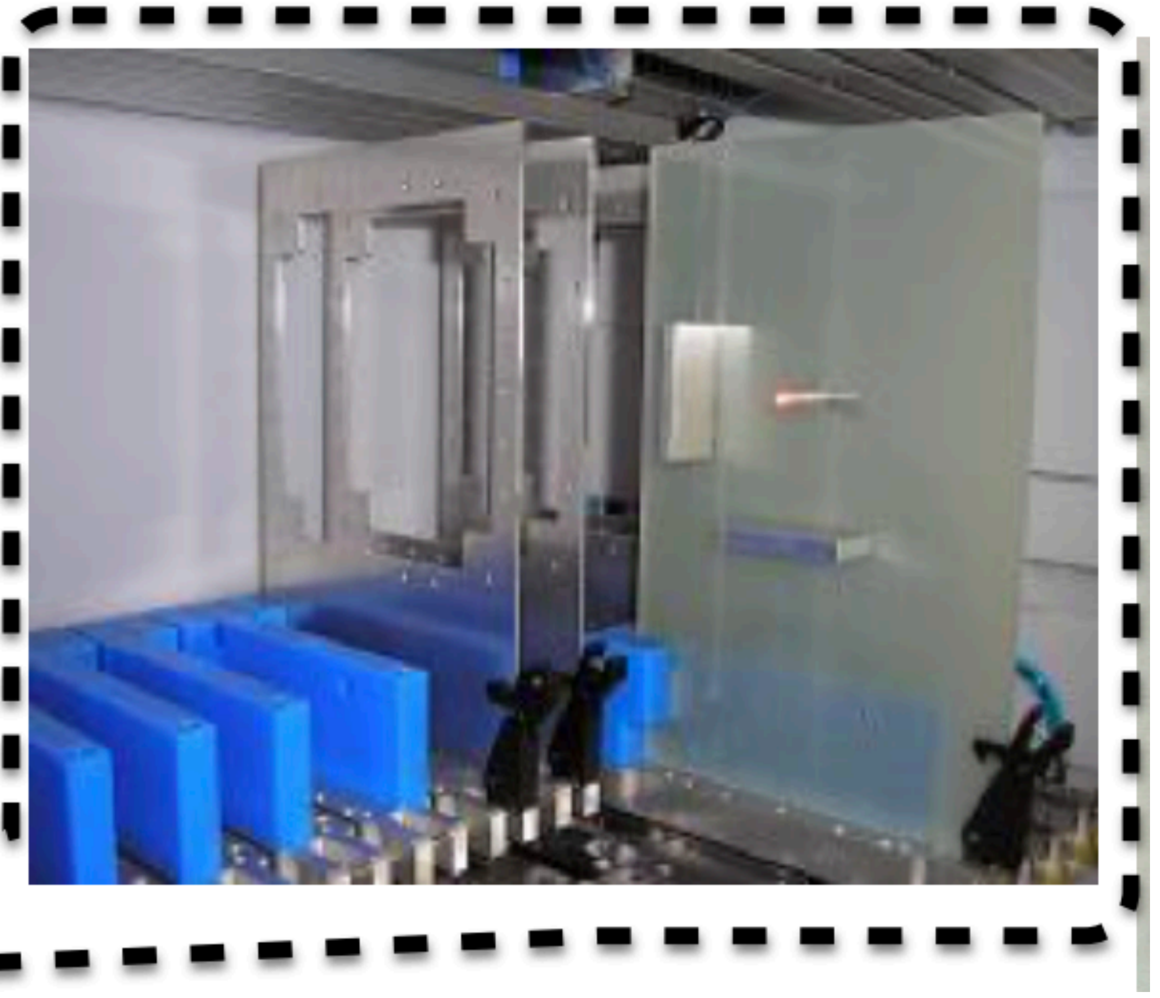
K. Nikolopoulos /RD50 Workshop, 3 June 2020

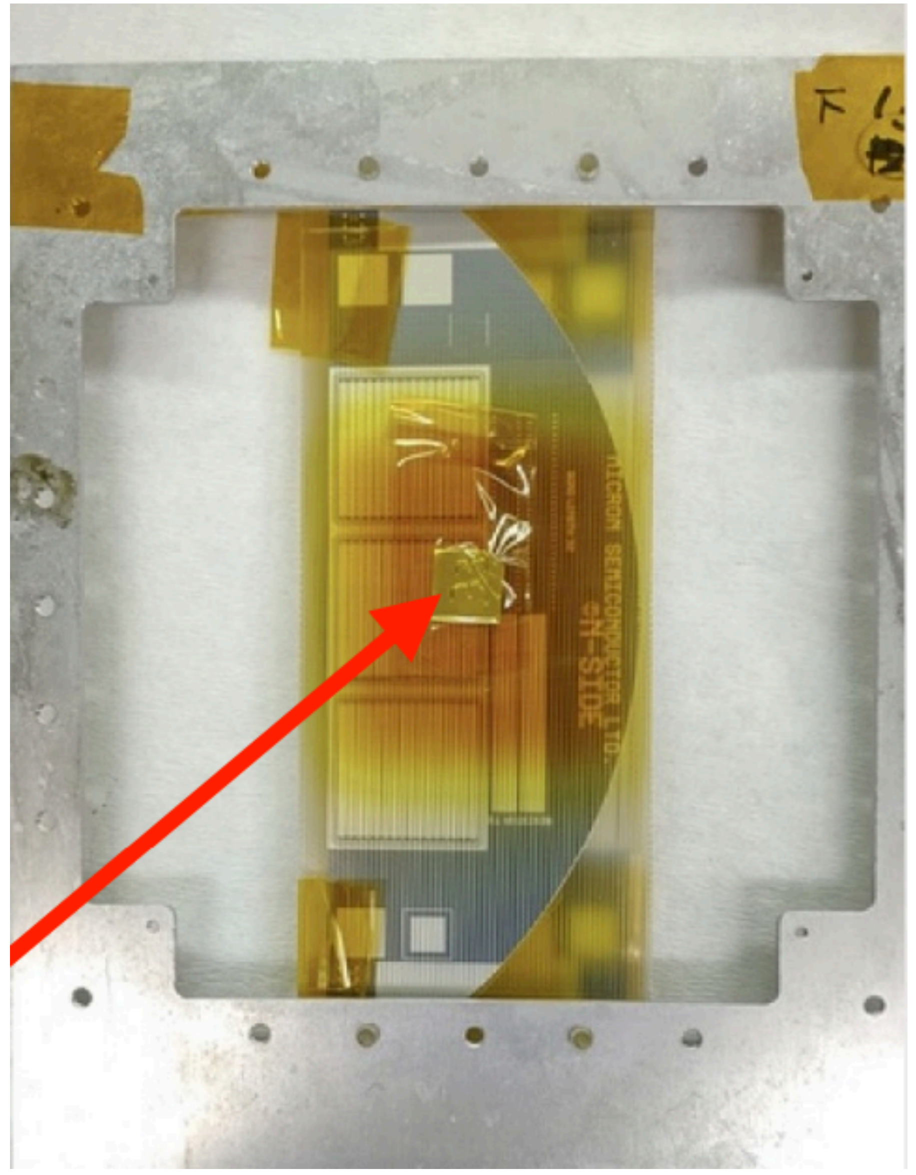
CYRIC proton irradiation facility, Japan

- Target 1x1016 neq/cm2 and 7 MGy
- Dose has monitored with the activation of Al film placed in front/rear of samples.
- Front : 95% and 91% within ~5 % uncertainty.
- Sample cooled down to -15C with flowing vaporized liquid nitrogen (monitored in box).

	CYRIC (Jan 2014)
P+ Energy	70 MeV
Beam Current	10-1000 nA
Time	6h @ 600nA for $3\text{x}10^{15}$ neq/cm^2
Scan speed	20 mm/s
Temperature	-5-20°C (Chiller+dry N$_2$)



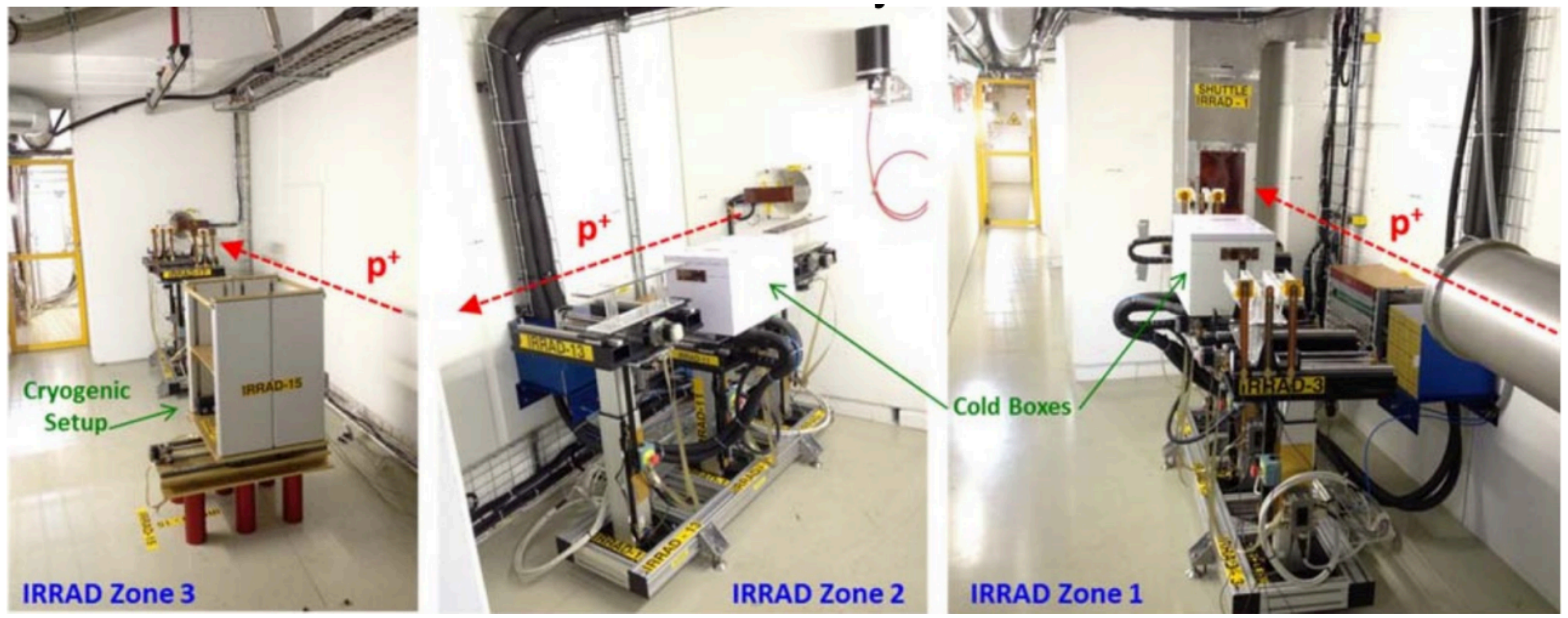


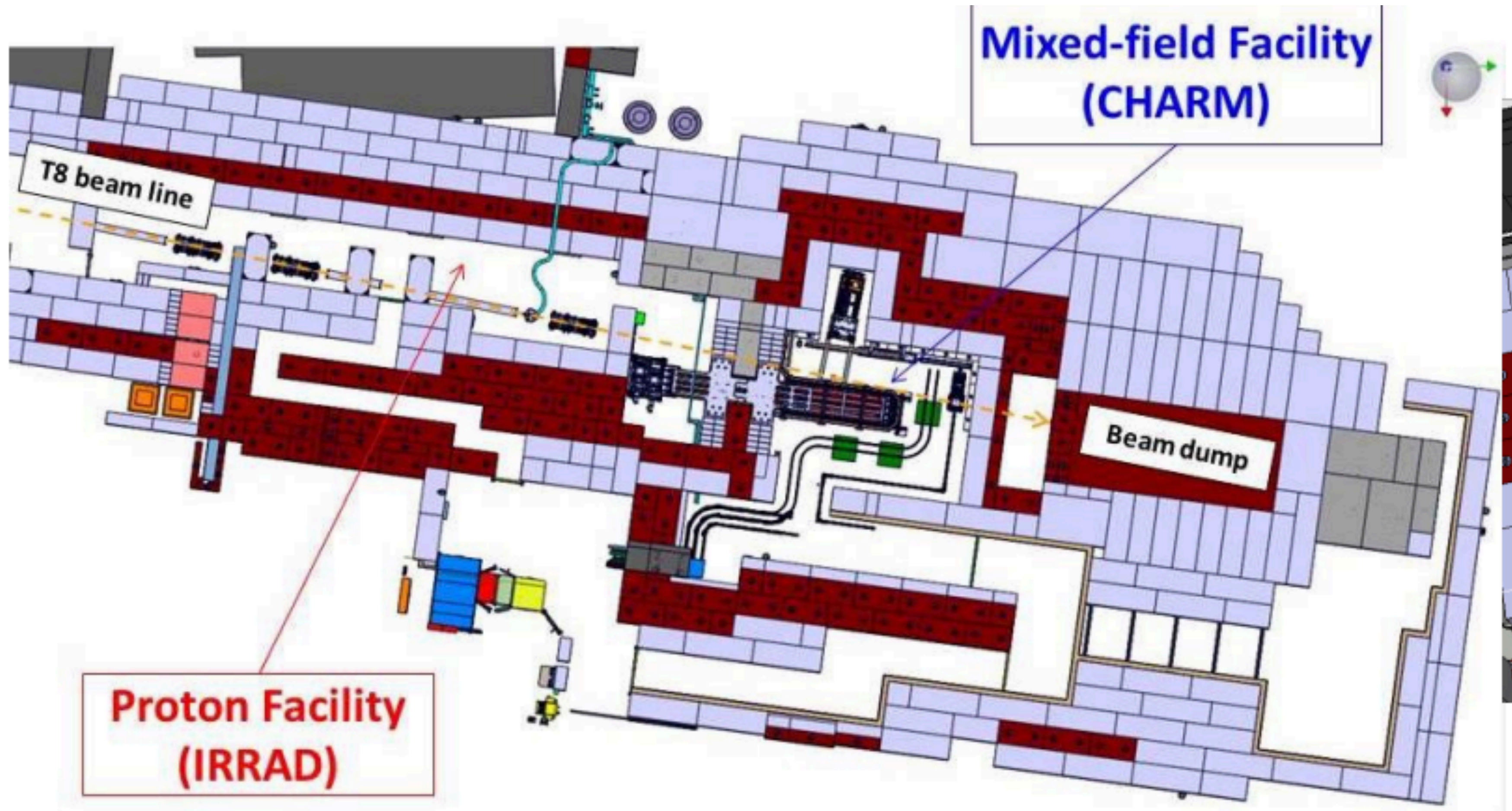


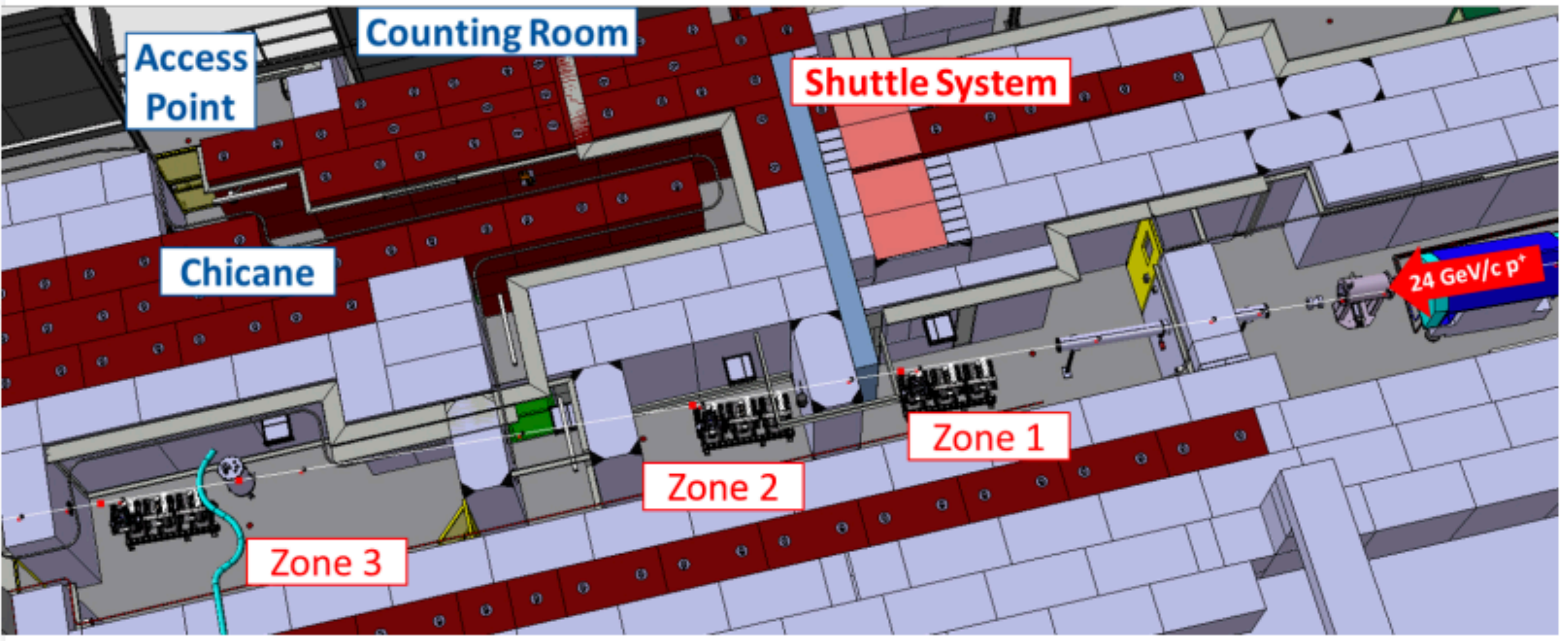
Foil for dosimetry

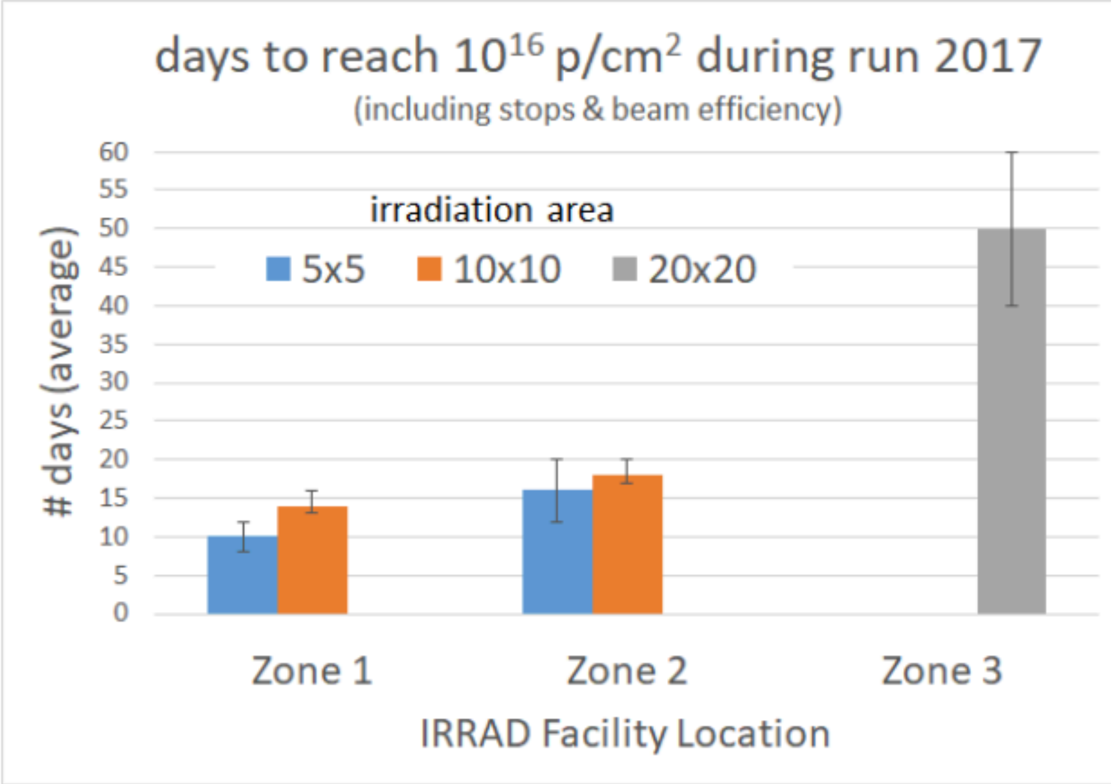
Proton irradiations at the SPS, CERN

- CERN Irradiation facility provided with protons from the Proton Synchrotron
- Beam momentum: 24 GeV/c
- Beam dimensions standard size: ~12x12 mm^2 (FWHM)
  - spot size from ~6x6 mm^2 to ~20x20 mm^2 (FWHM)
- Beam intensity: ~5×10^{11} protons/spill on cycles of 30-37 s
  - Typically: 3 spills per CPS
- ~0.7-1 x 10^{14} p cm^{-2} h^{-1} (on 5x5 mm^2 sample)









TRIGA neutron irradiation facility

- Built in 1966 (General Atomics)
- 250 kW maximum power, can be lowered to few W
- Flux scales with power
- Maximum total flux is 4x1012 cm-2s-1
- Several in core and ex core irradiation channels
- Maximum uninterrupted irradiation time is 16 hours
- Small tube - irradiations in standard containers (diameter 24 mm)
- Elliptic large tube (axes 7 x 5cm)
- TID is about 1 kGray for 10^14 neqcm-2
- Flux is 1.69 10^12 n cm-2 s-1 in small tube (10^16 in 100 min)
- Flux is 3.05 10^12 n cm-2 s-1 in large tube
- Temperature increase to about 45°C during irradiation
- About 100 irradiations per year
- http://www-f9.ijs.si/~mandic/ReacSetup.html

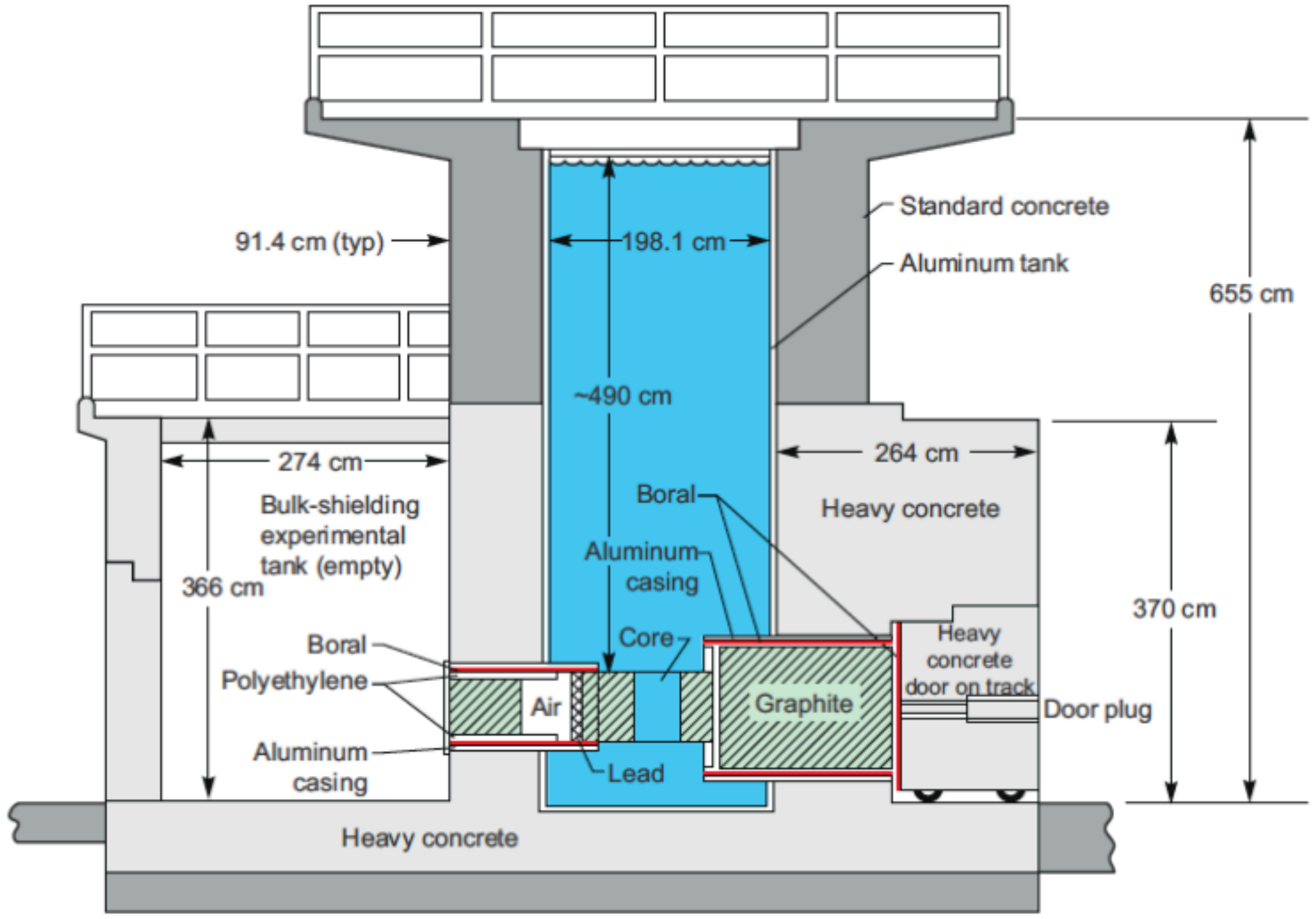
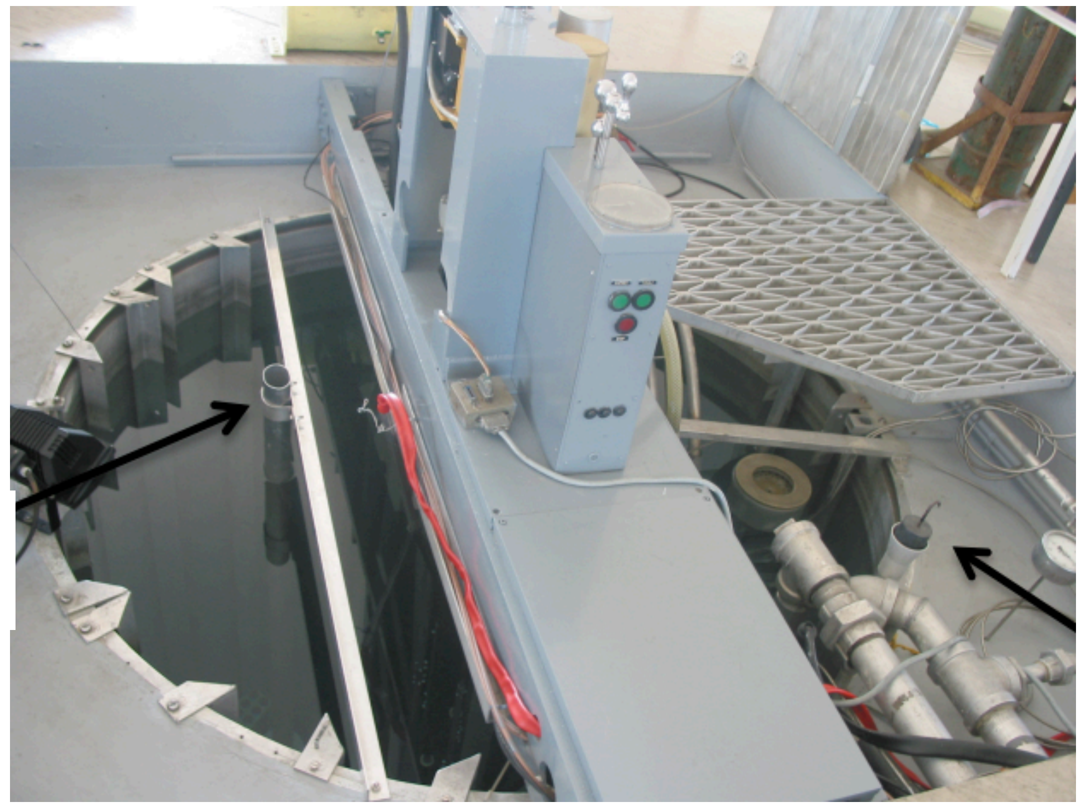
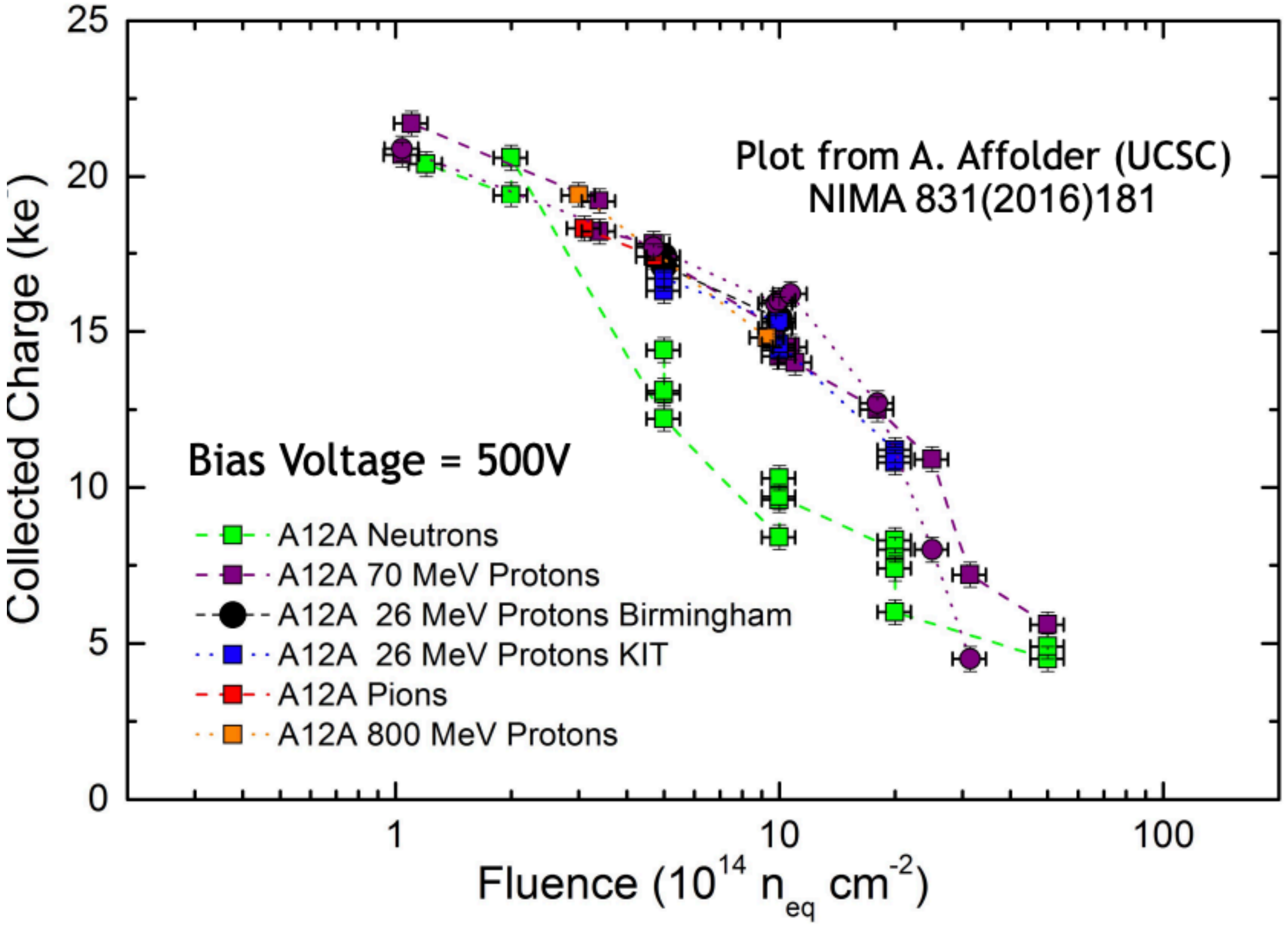


Fig. 1. TRIGA reactor at JSI, side view (Jeraj and Ravnik, 1999).



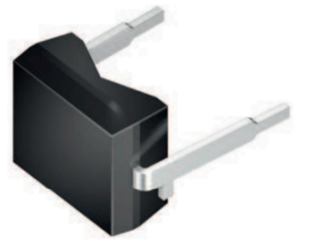
large tube

Comparison of facilities for hadron irradiation



Silicon sensor: BPW34F

- BPW34F diode was chosen for this study
  - silicon p-i-n photodiode with daylight blocking filter
  - produced by OSRAM Opto-Semiconductors
  - commercially available
  - extensively studied
- For comparison, measurements at CERN also performed with Float Zone pad diodes



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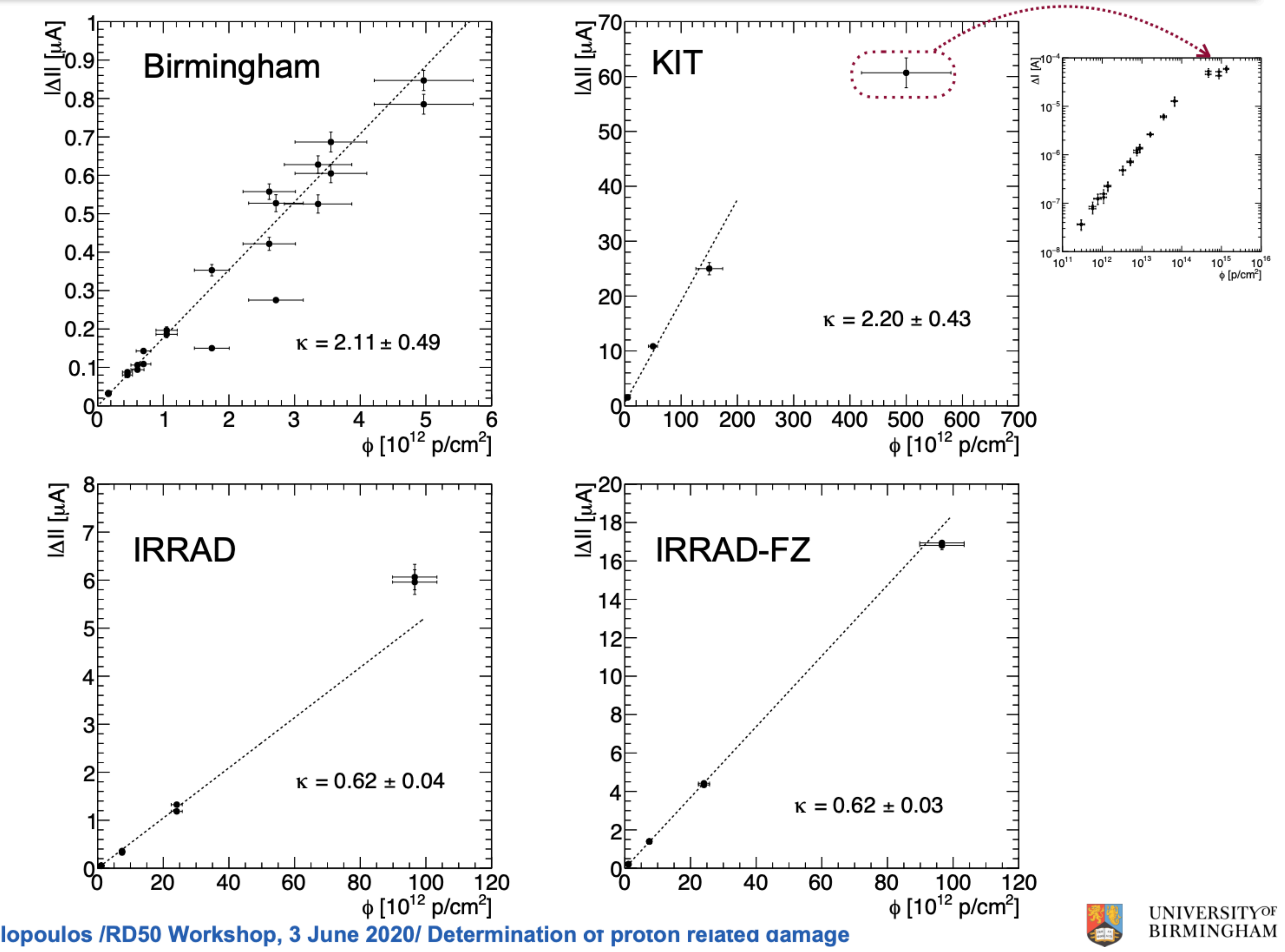
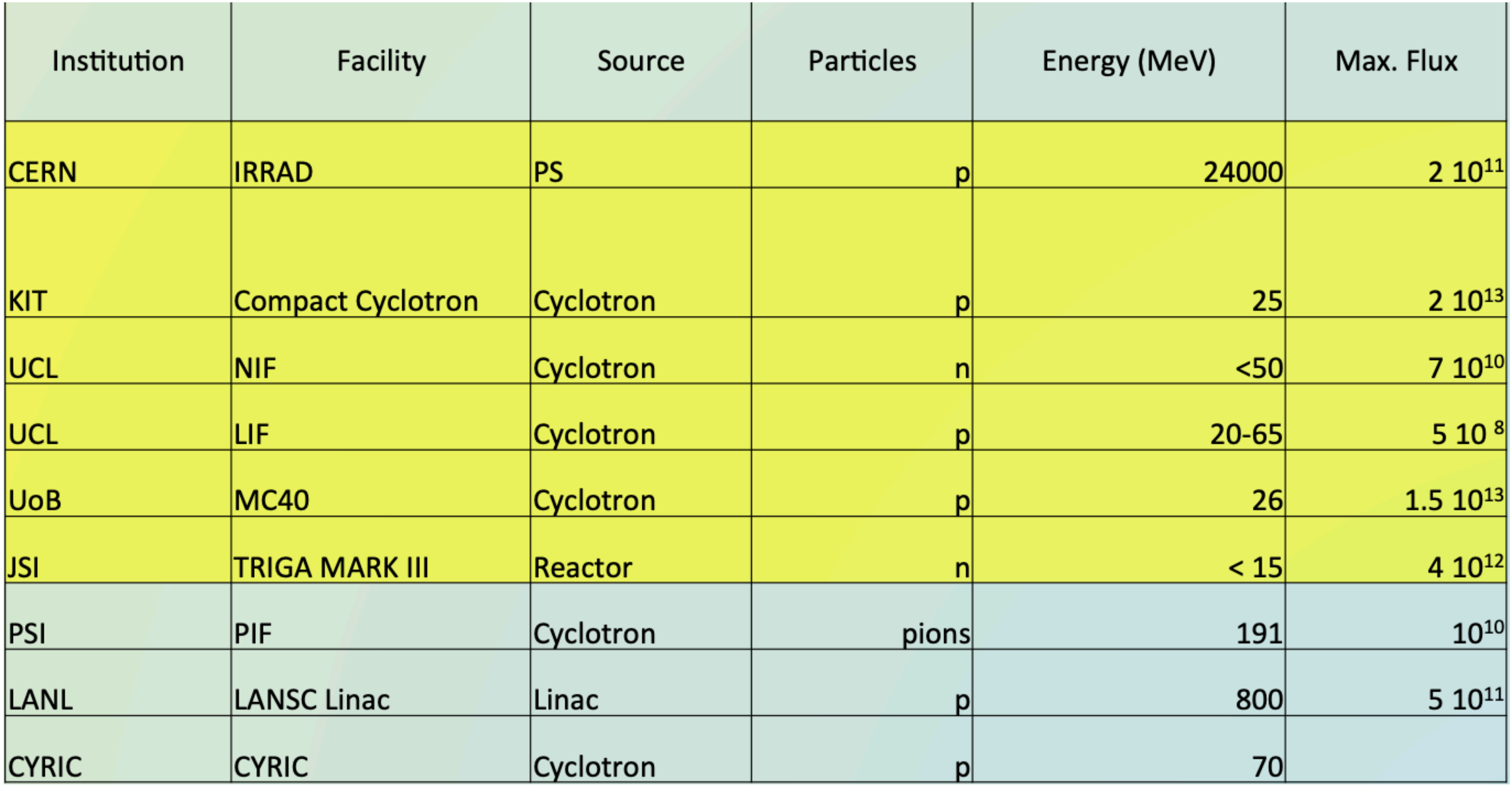
Hardness factors



K. Nikolopoulos /RD50 Workshop, 3 June 2020/ Determination of proton related damage

UNIVERSITY OF BIRMINGHAM

Comparison of facilities for hadron irradiation



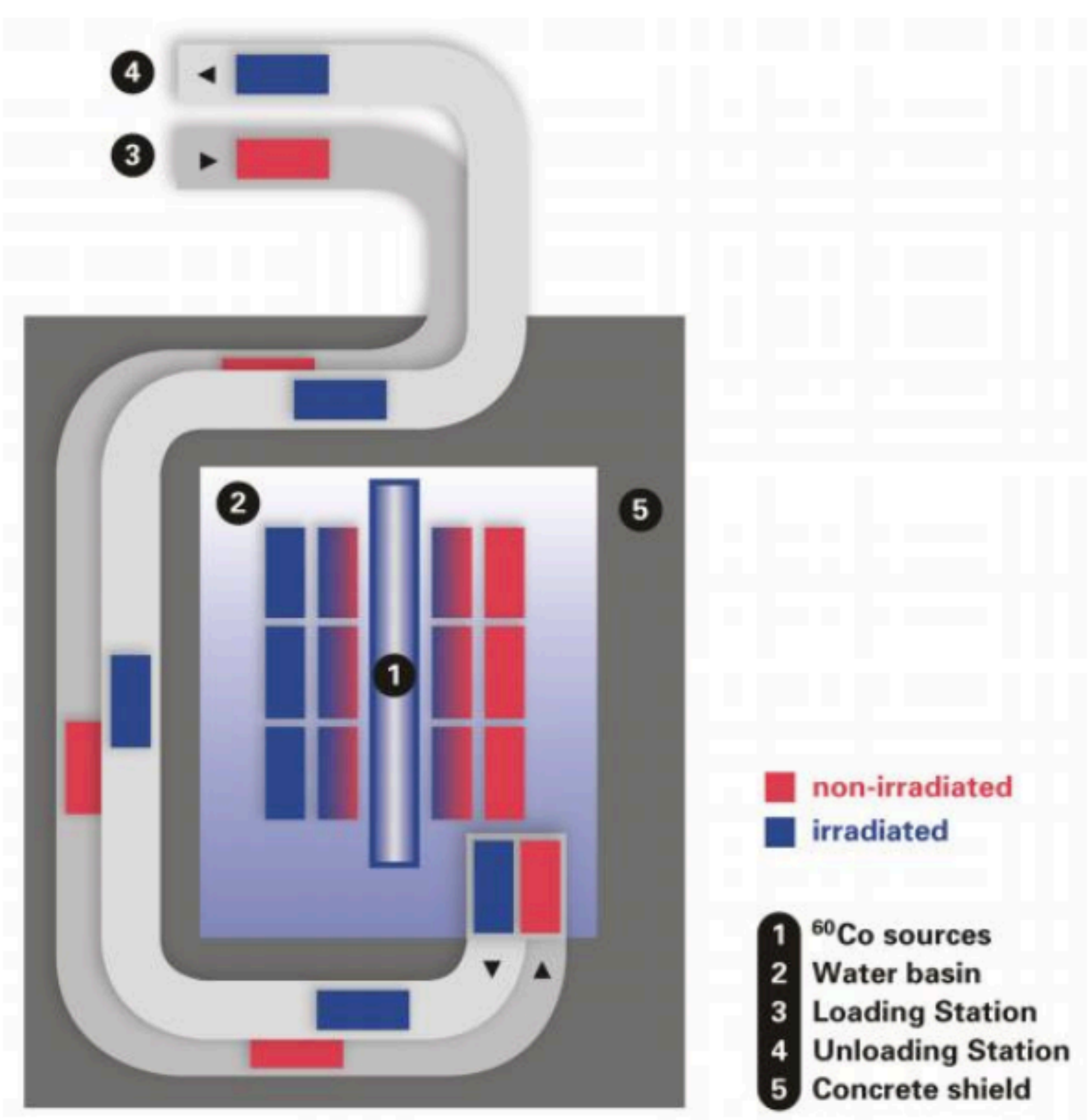
Institution	Facility	Source	Particles	Energy (MeV)	Max. Flux	Cost
CERN	IRRAD	PS	p	24000	$2\ 10^{11}$	
KIT	Compact Cyclotron	Cyclotron	p	25	$2\ 10^{13}$	
UCL	NIF	Cyclotron	n	<50	$7\ 10^{10}$	
UCL	LIF	Cyclotron	p	20-65	$5\ 10^{8}$	
UoB	MC40	Cyclotron	p	26	$1.5\ 10^{13}$	~£0.5k - 1k / day
JSI	TRIGA MARK III	Reactor	n	< 15	$4\ 10^{12}$	
PSI	PIF	Cyclotron	pions	191	10^{10}	
LANL	LANSC Linac	Linac	p	800	$5\ 10^{11}$	
CYRIC	CYRIC	Cyclotron	p	70		

Gamma irradiation facilities

Beta-Gamma Services GmbH – Germany

Two irradiation options:

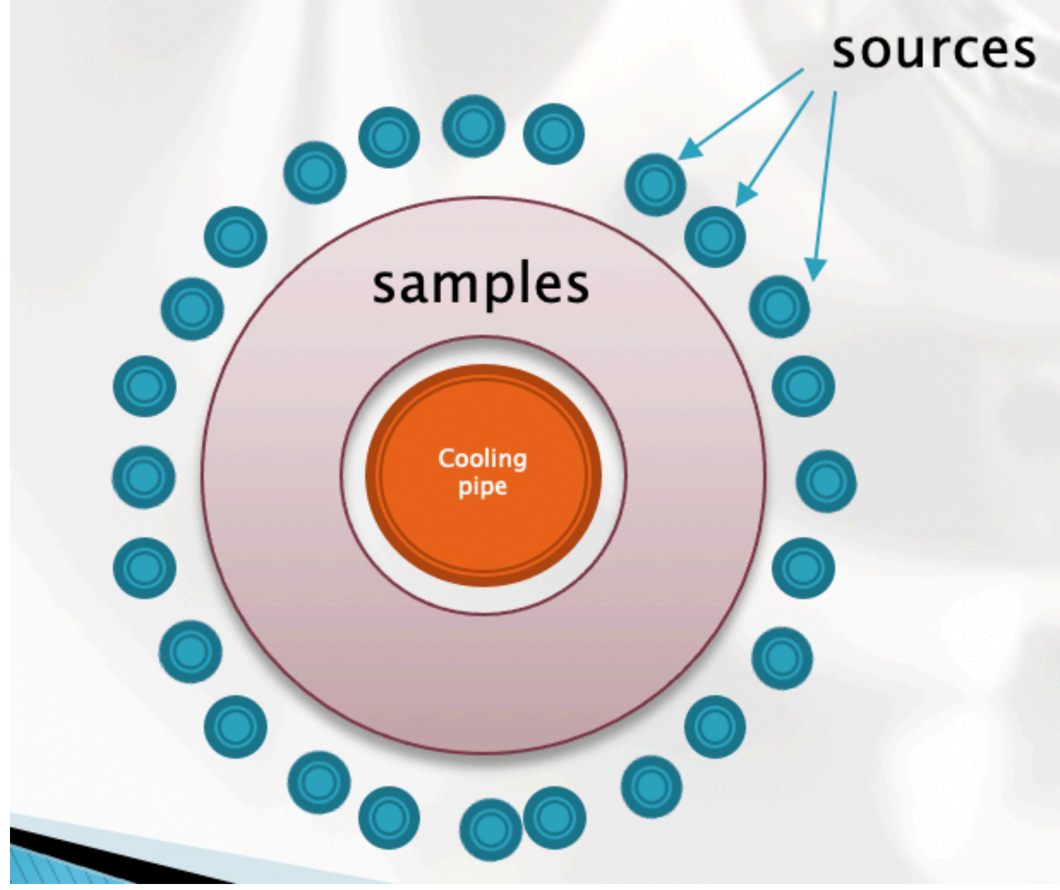
- BGS high-dose irradiation box (30 kGy/h);
- BGS Pallet-circulator (10 kGy/h);

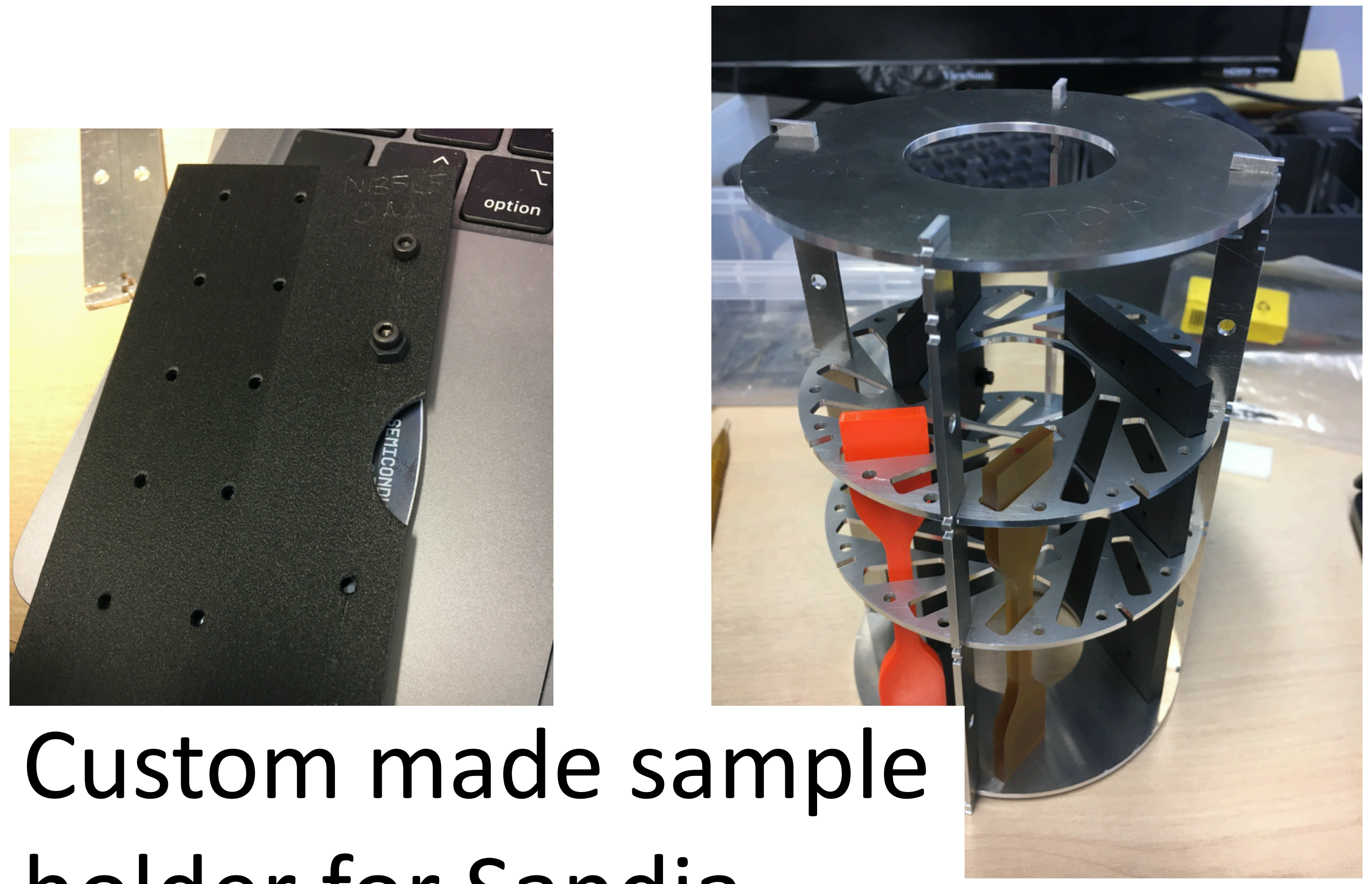


BGS sample trolley

Sandia - NM, USA

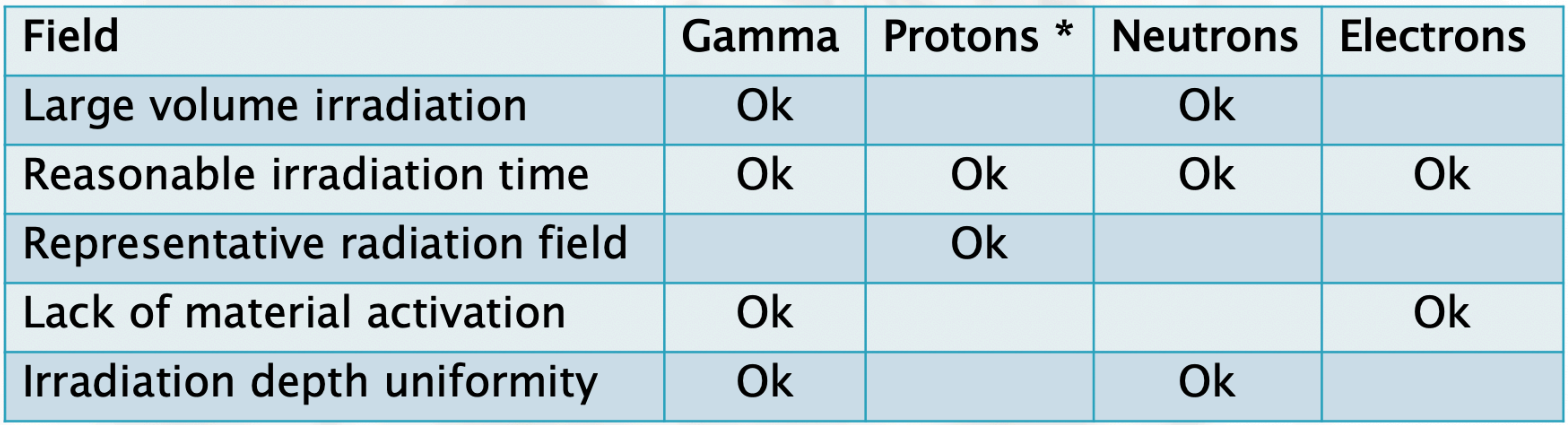
- Irradiation rate: > 50 Gy/h
- Active cooling of the samples with forced air flow from the center
- Chamber shape most suitable for irradiating standardised samples (Lap joints, double cantilever beams, dogbones, etc.)
- Dim: OD ~ 110, ID ~ 40, h ~ 350 mm
- Produce sample holders to maximise sample uniformity and space usage





Custom made sample holder for Sandia

Choice of irradiation facility



Field	Gamma	Protons *	Neutrons	Electrons
Large volume irradiation	Ok		Ok	
Reasonable irradiation time	Ok	Ok	Ok	Ok
Representative radiation field		Ok		
Lack of material activation	Ok			Ok
Irradiation depth uniformity	Ok		Ok	

N. Pacifico

Main factors: damage mechanism of interest (TID or NIEL), availability, cost, volume/area

Often guided by what is available as much as what is most suitable

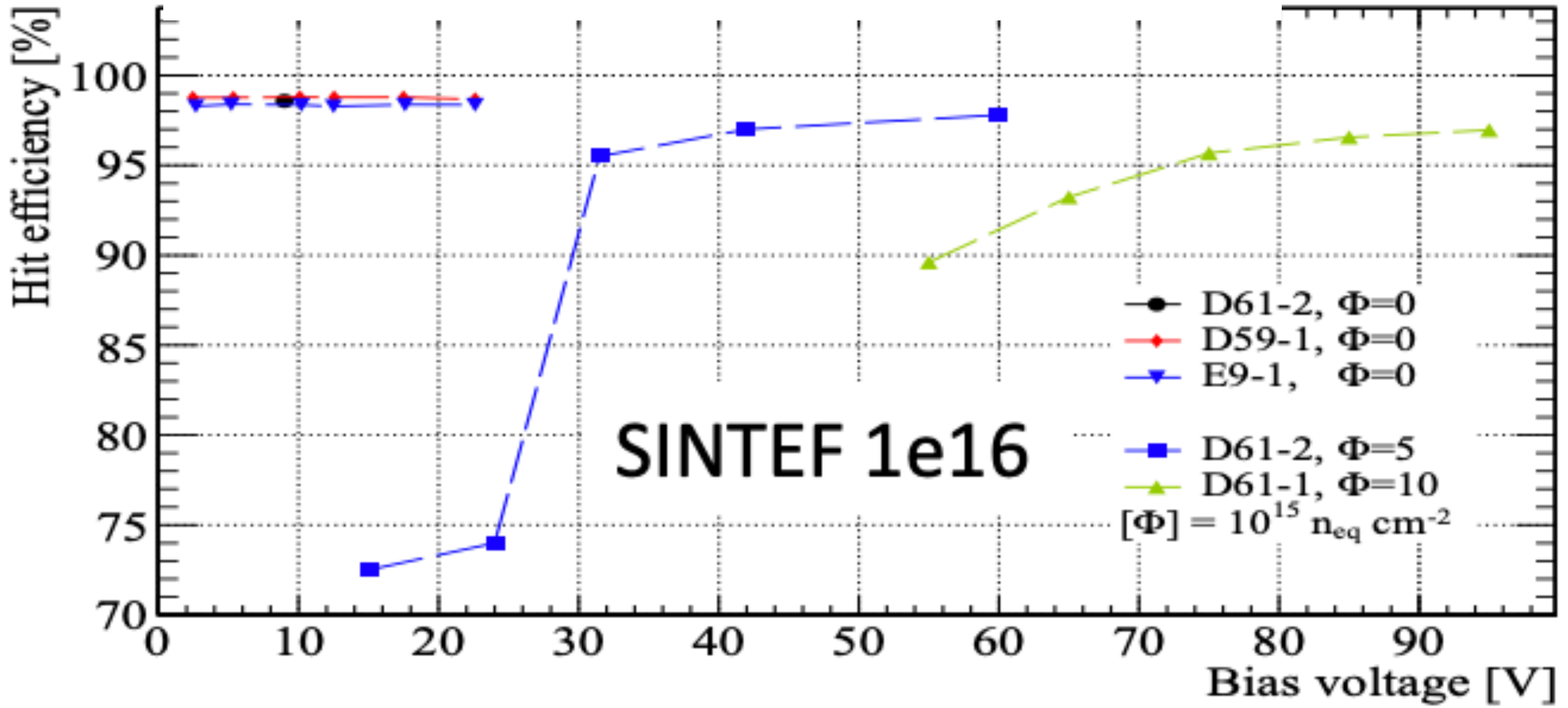
Testing irradiated parts

Testing irradiated parts can take different forms depending on the device and application, will only cover the following three inter-related categories:

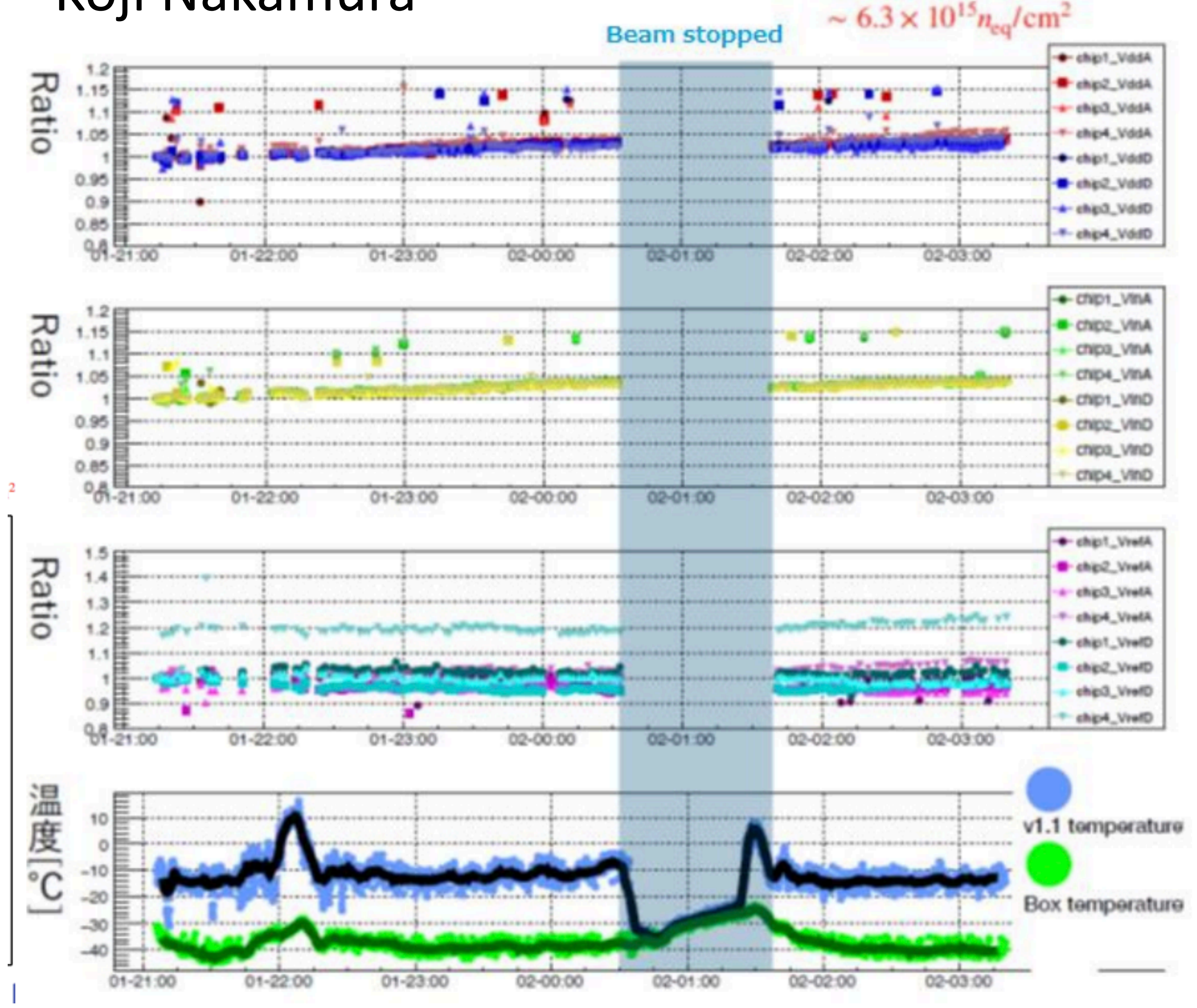
- Electrical testing : IV’s and readout
- Mechanical tests
- Thermal tests

Testing irradiated parts - electrical tests

3D sensor efficiency vs bias

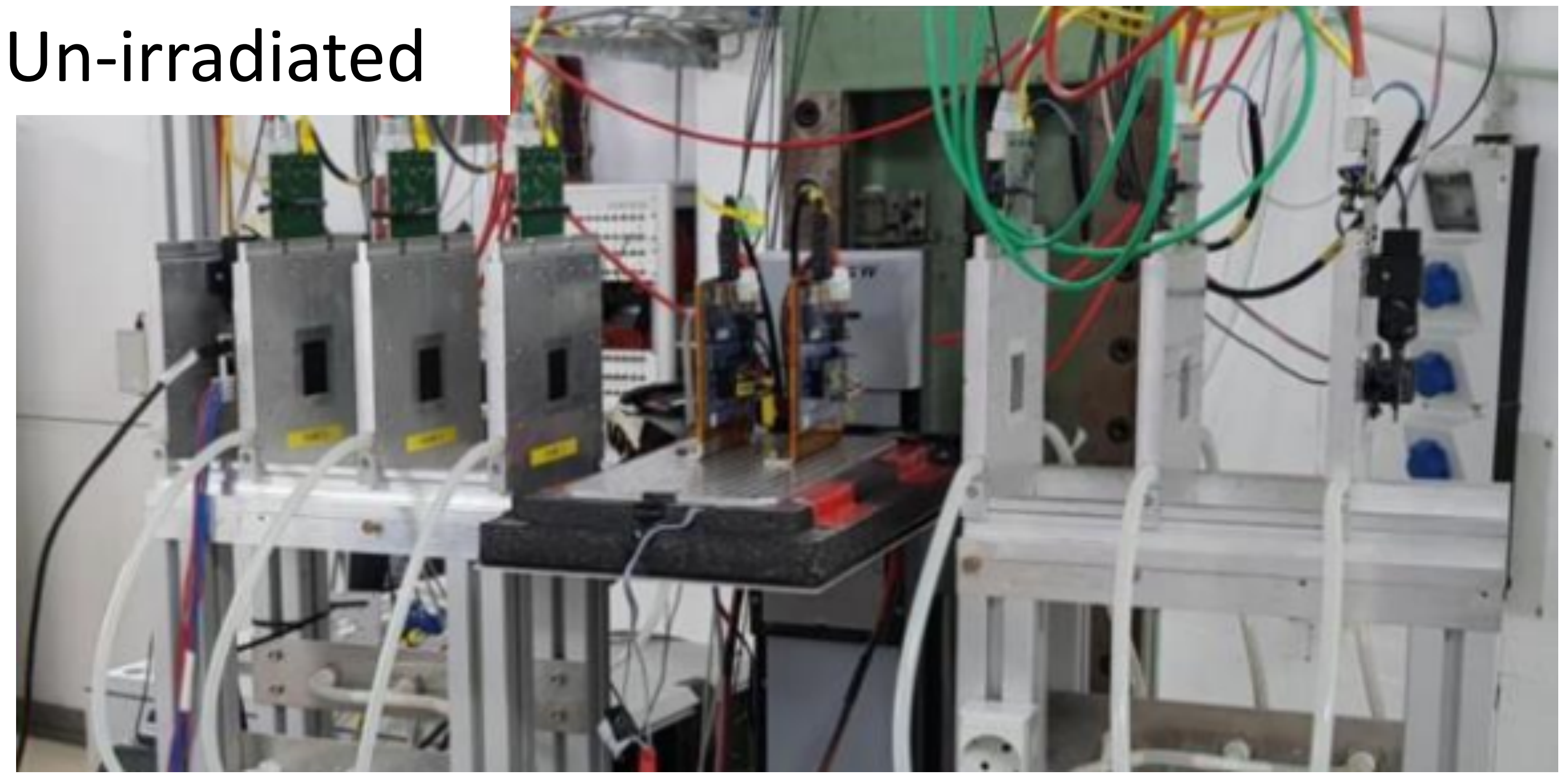


Koji Nakamura

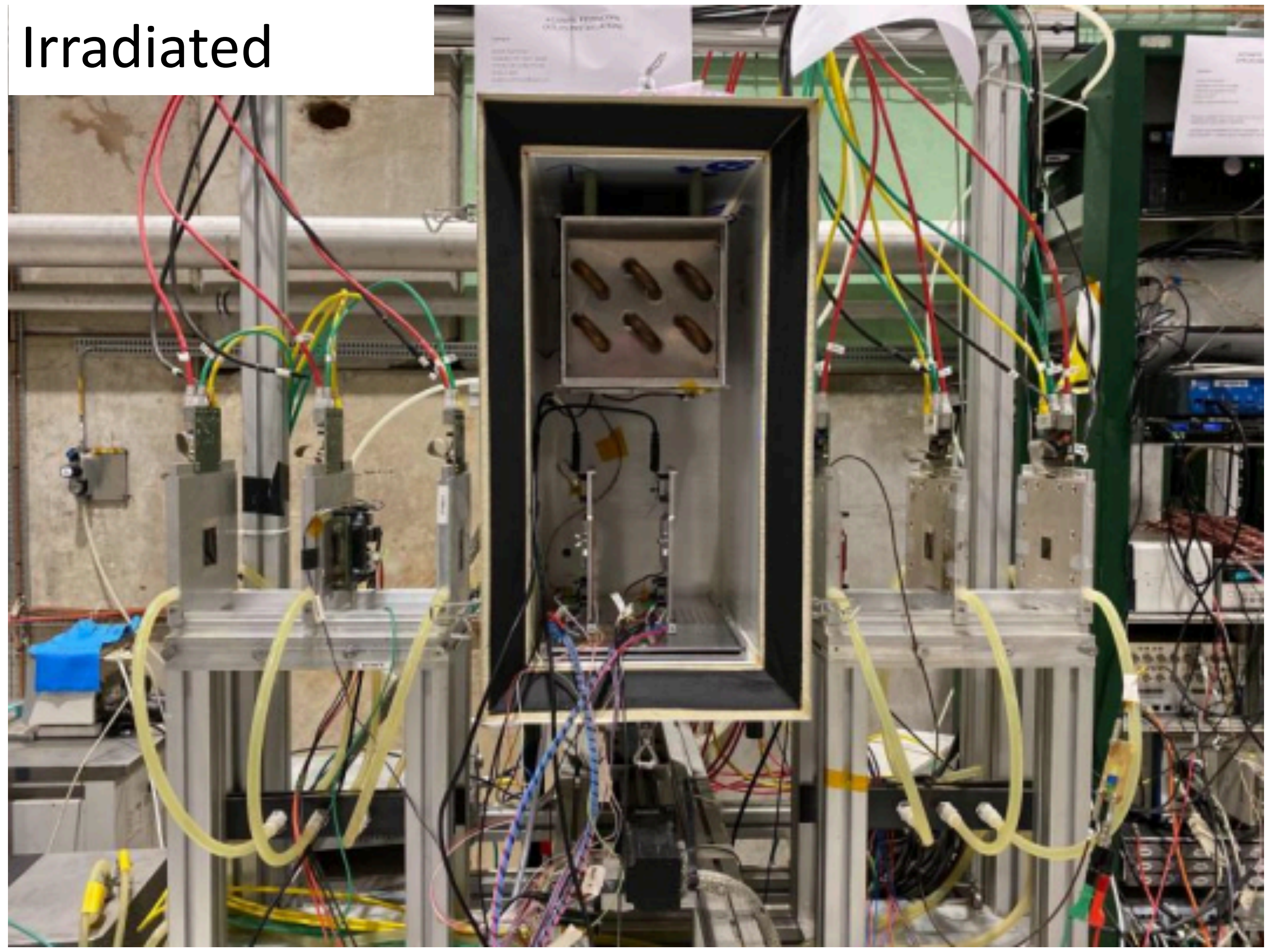


ITkPix v1.1 LDO voltage/temp/RO frequency vs irradiation time

Un-irradiated

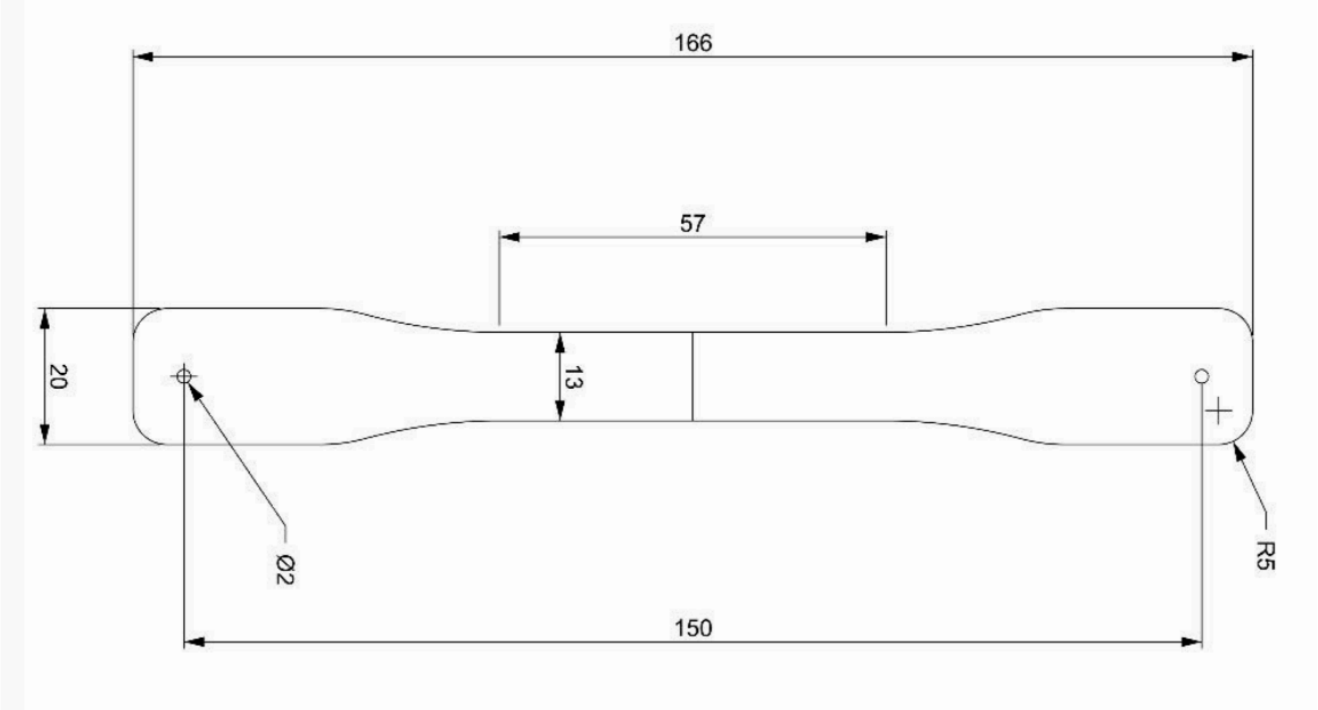


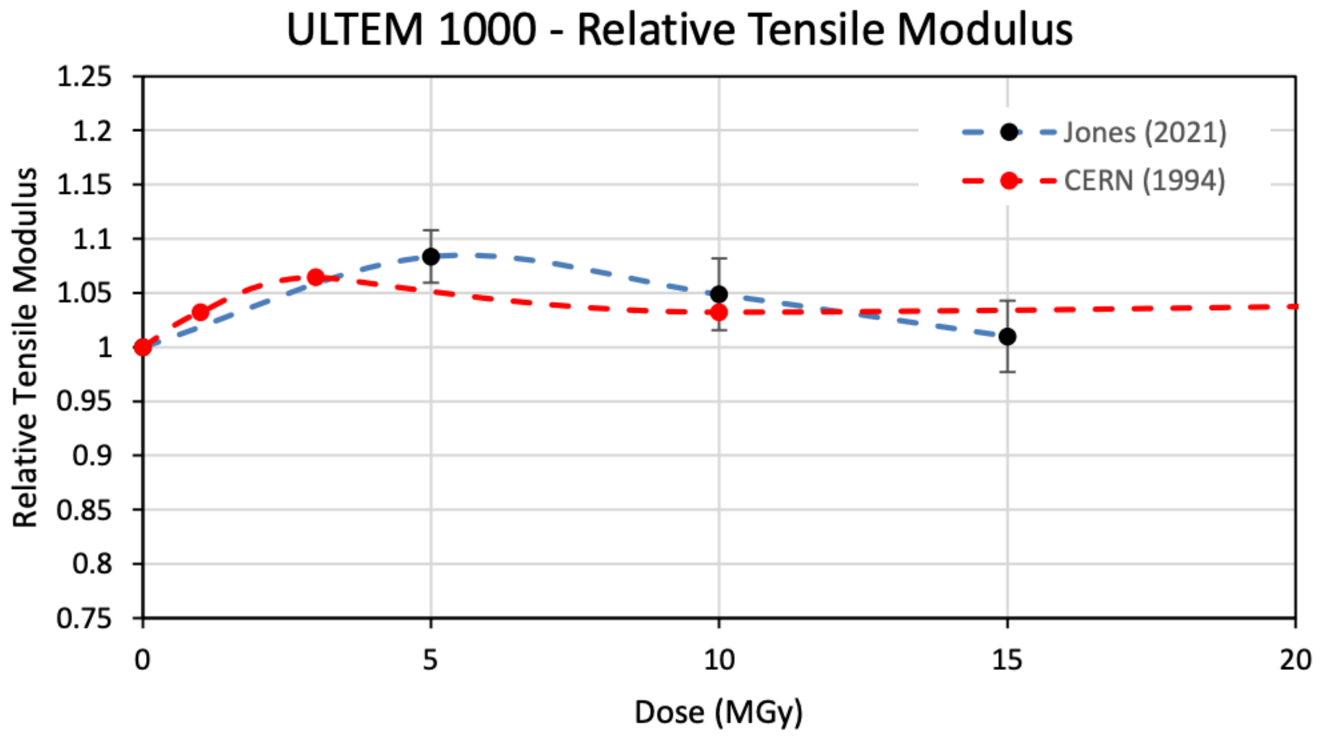
Irradiated

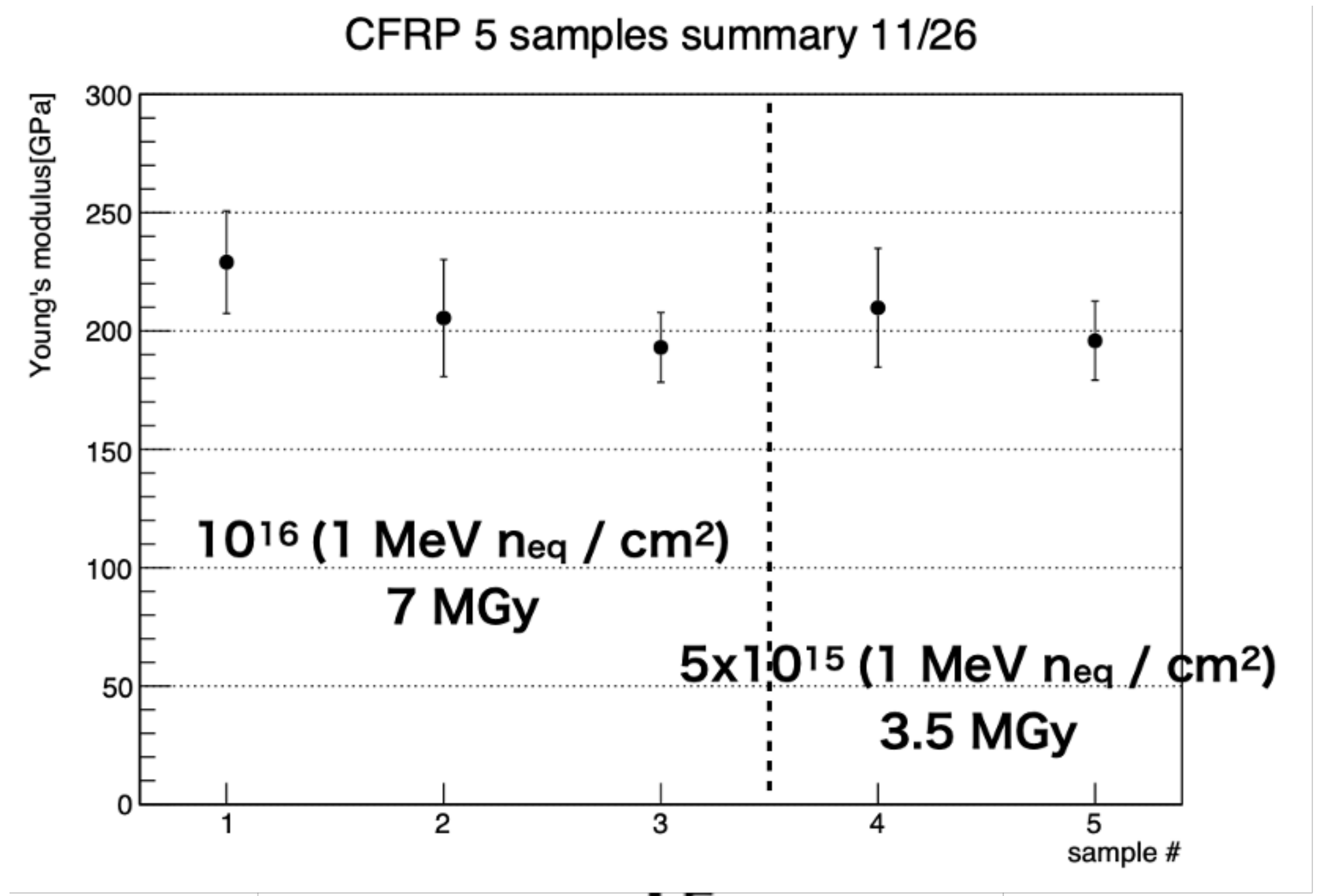


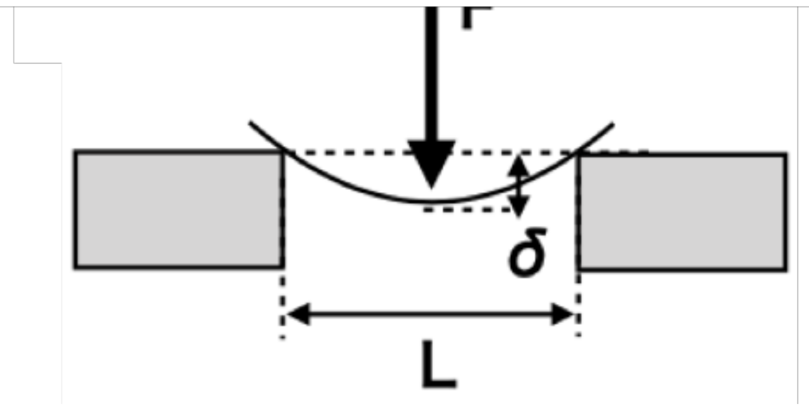
Testing irradiated parts - mechanical tests

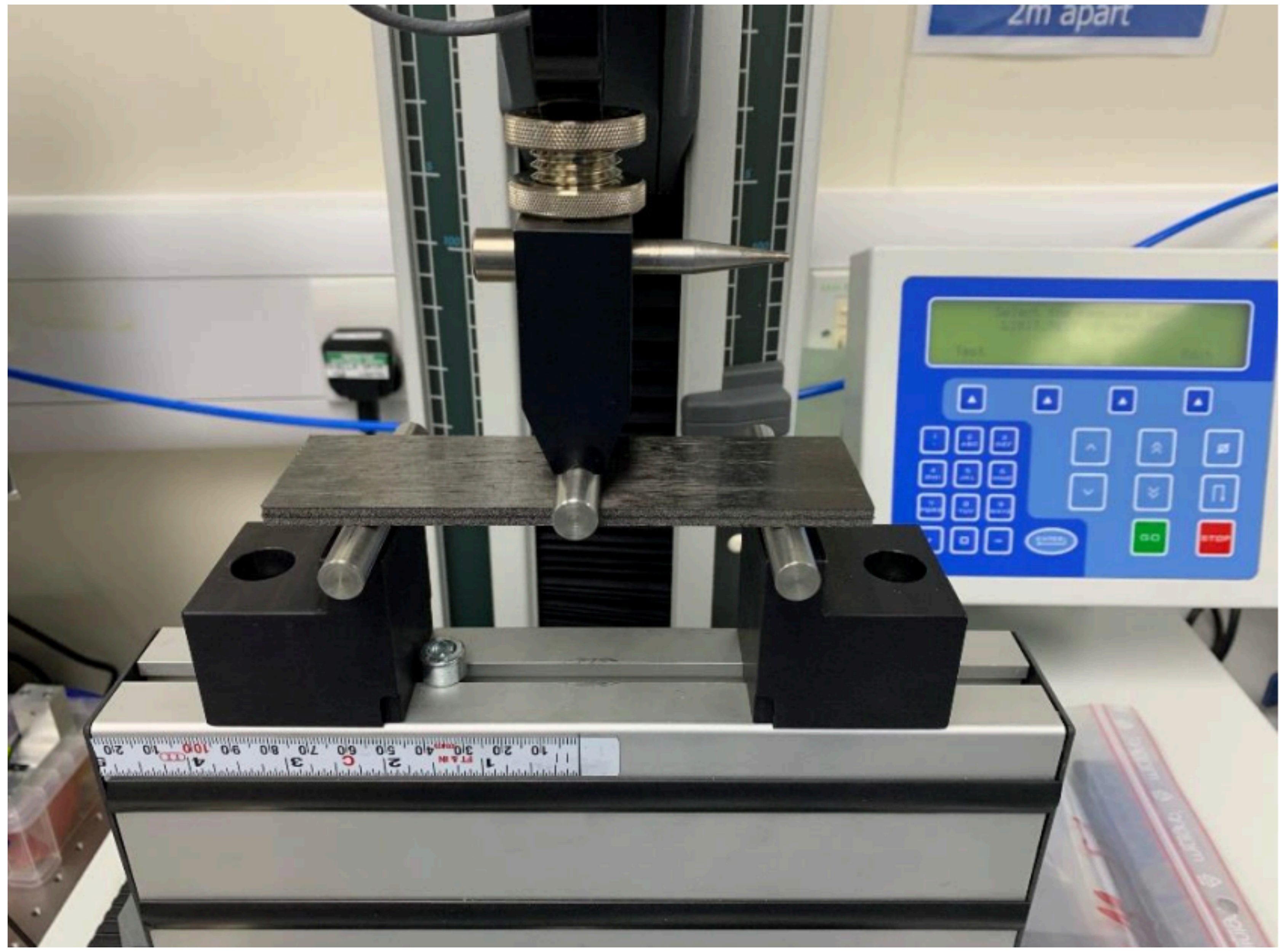
- Testing of irradiated CFRP structures and ULTEM ‘dogbone’ samples for ATLAS upgrade
- Pixel modules will be held on ‘local supports made from carbon foam and CFRP ‘skin’ glued together
- Parts were irradiated with gamma rays and mechanical pull tests and 3 point bending tests were carried out
- Dogbone samples irradiated and their mass, modulus and dimensions checked before and after irradiation





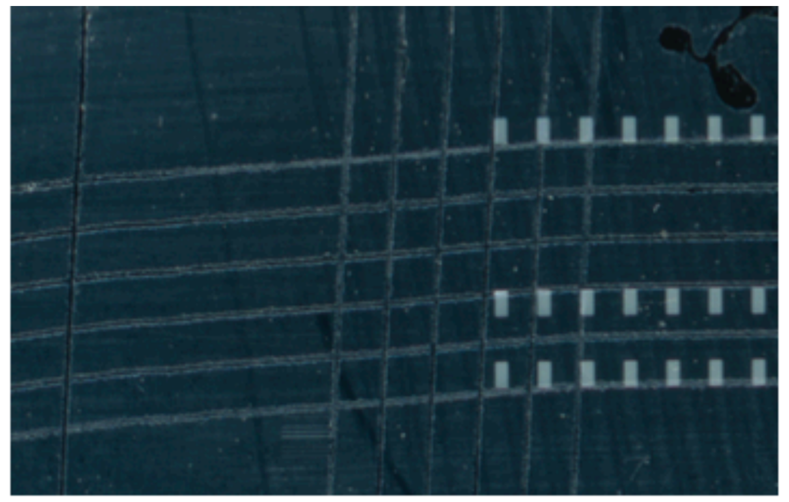




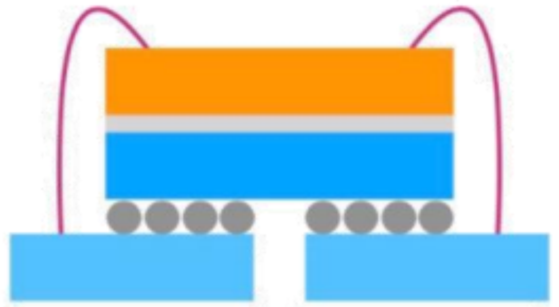


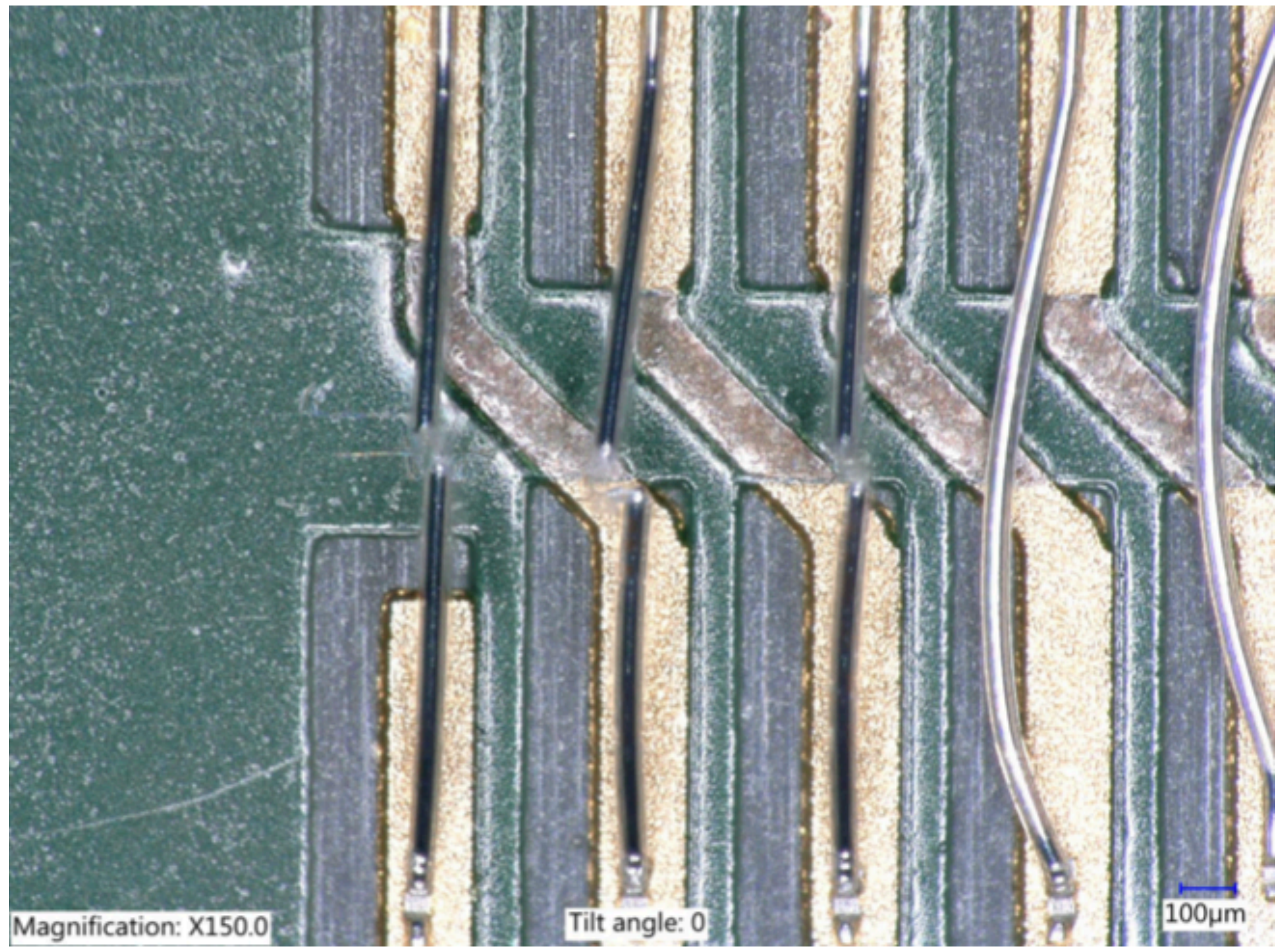
Testing irradiated parts - mechanical tests

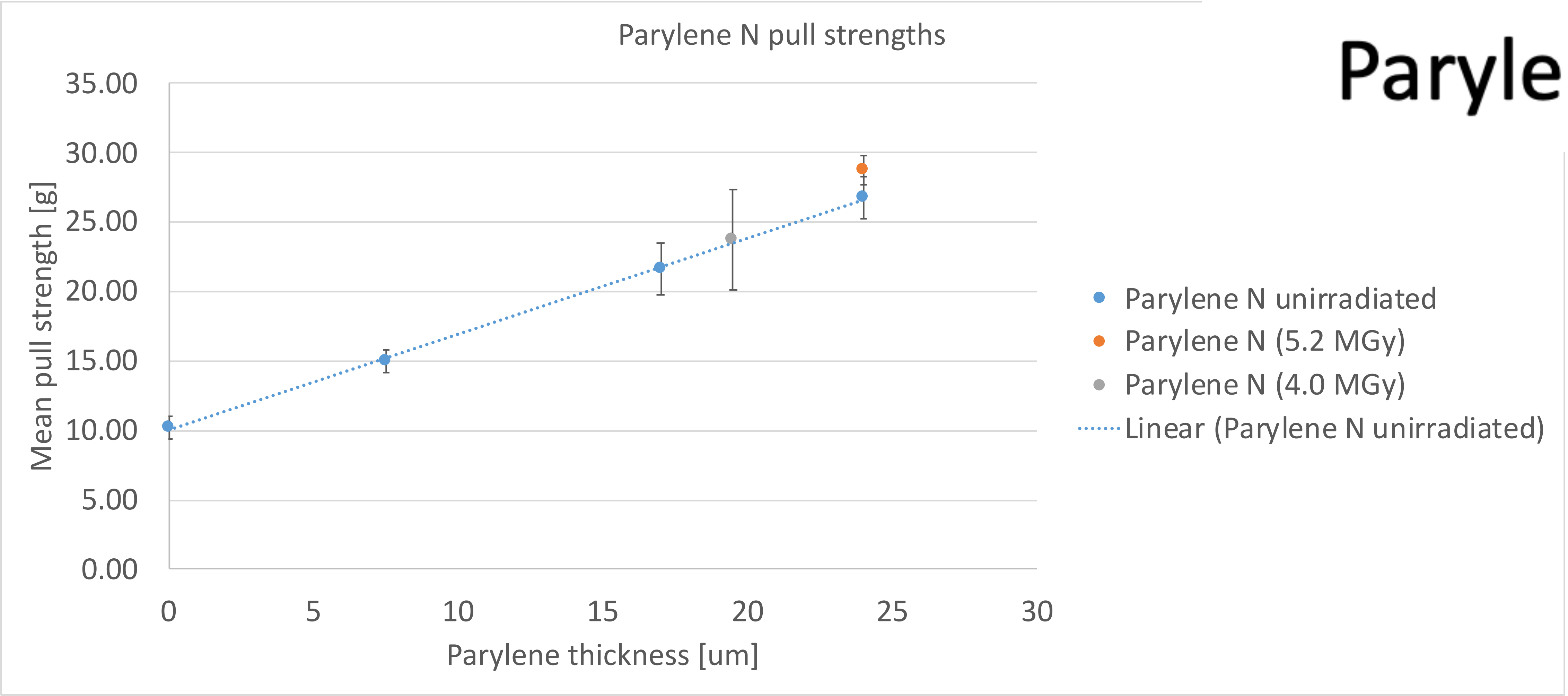
- Parylene CVD layer deposited on ATLAS ITk pixel modules
- Wire bond pull testing after irradiation of parylene coated aluminium wires to test for brittleness of coating
- ISO 2409 cross cut test to check for adhesion after irradiation

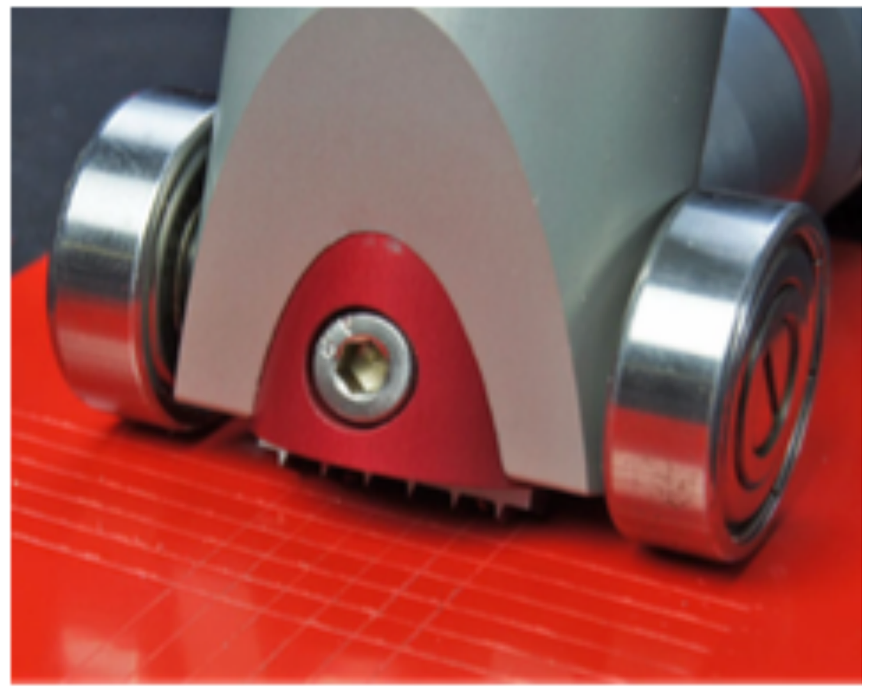


Parylene N, 5 MGy

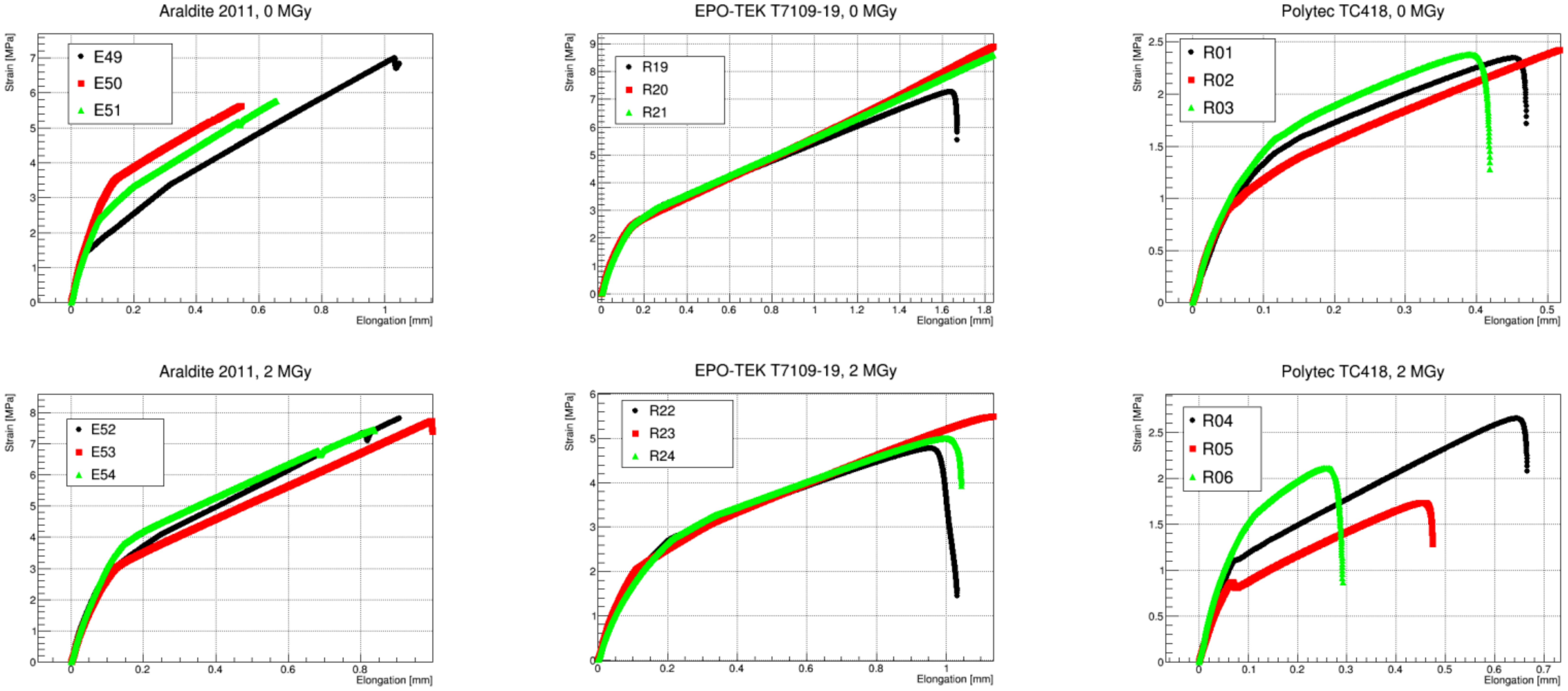




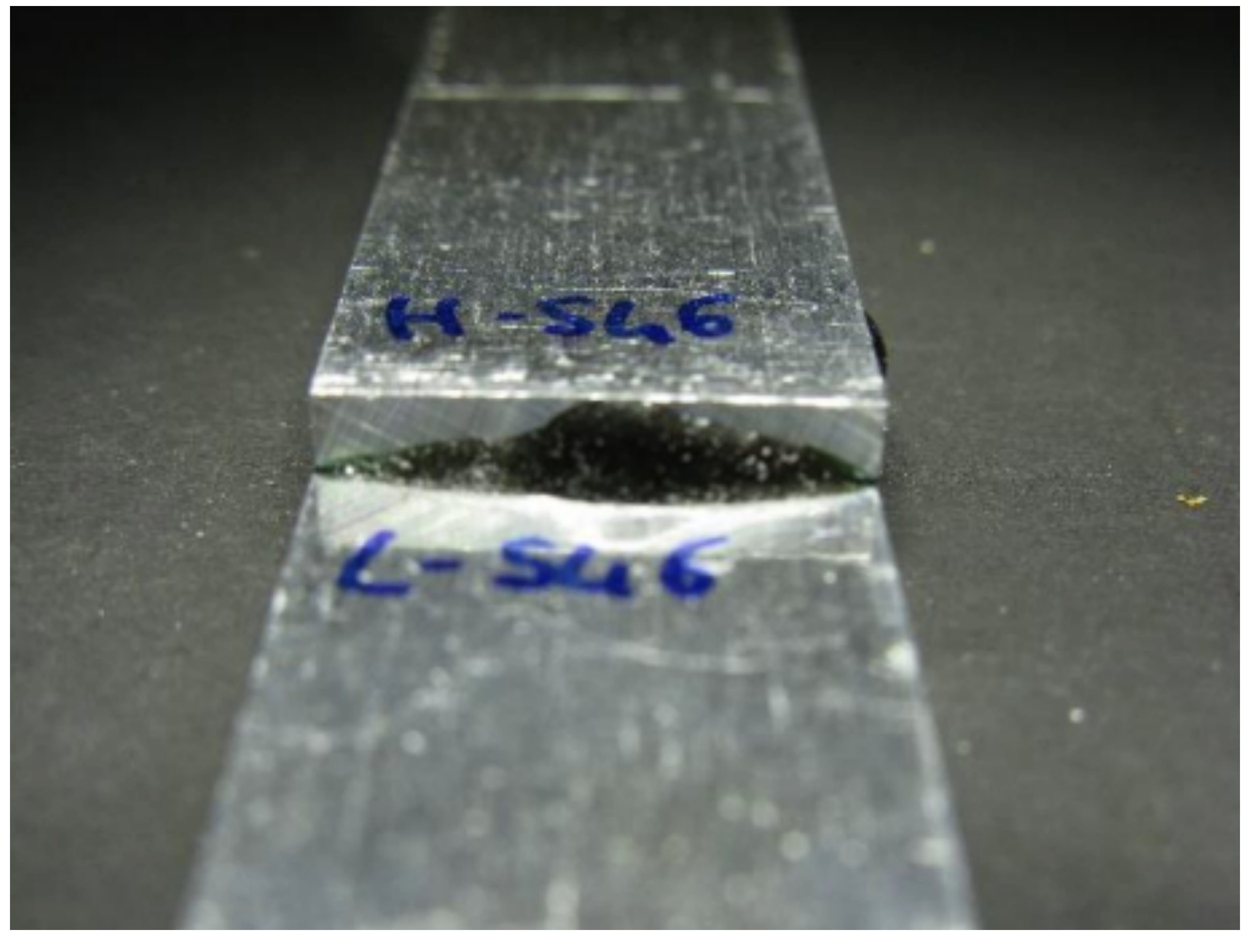


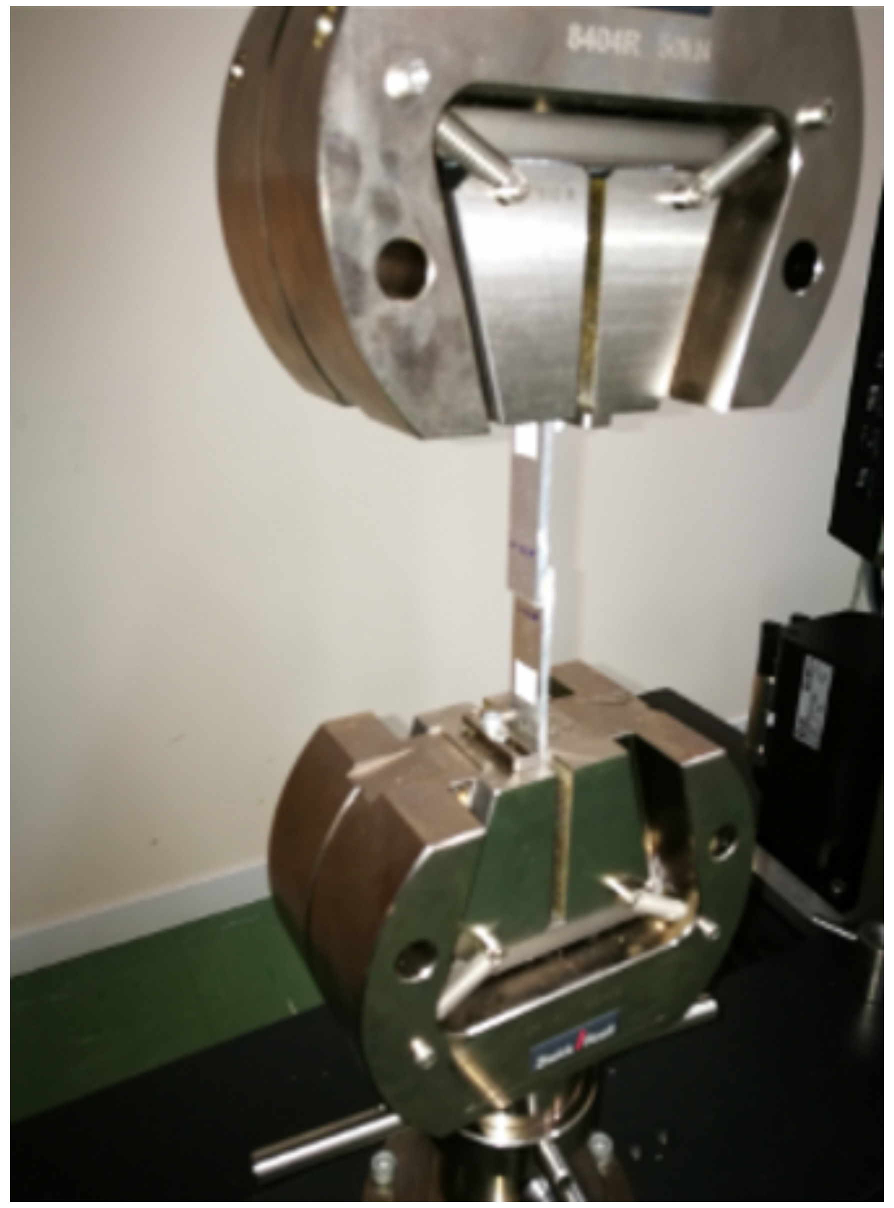


Testing irradiated parts - mechanical tests



TC 418: Manufacturing non uniformities





Lap-shear tests can be used to test adhesives
A mechanical pull tests is applied and the failure can be observed
Failure in the bulk of the glue joint, or failure at the interface

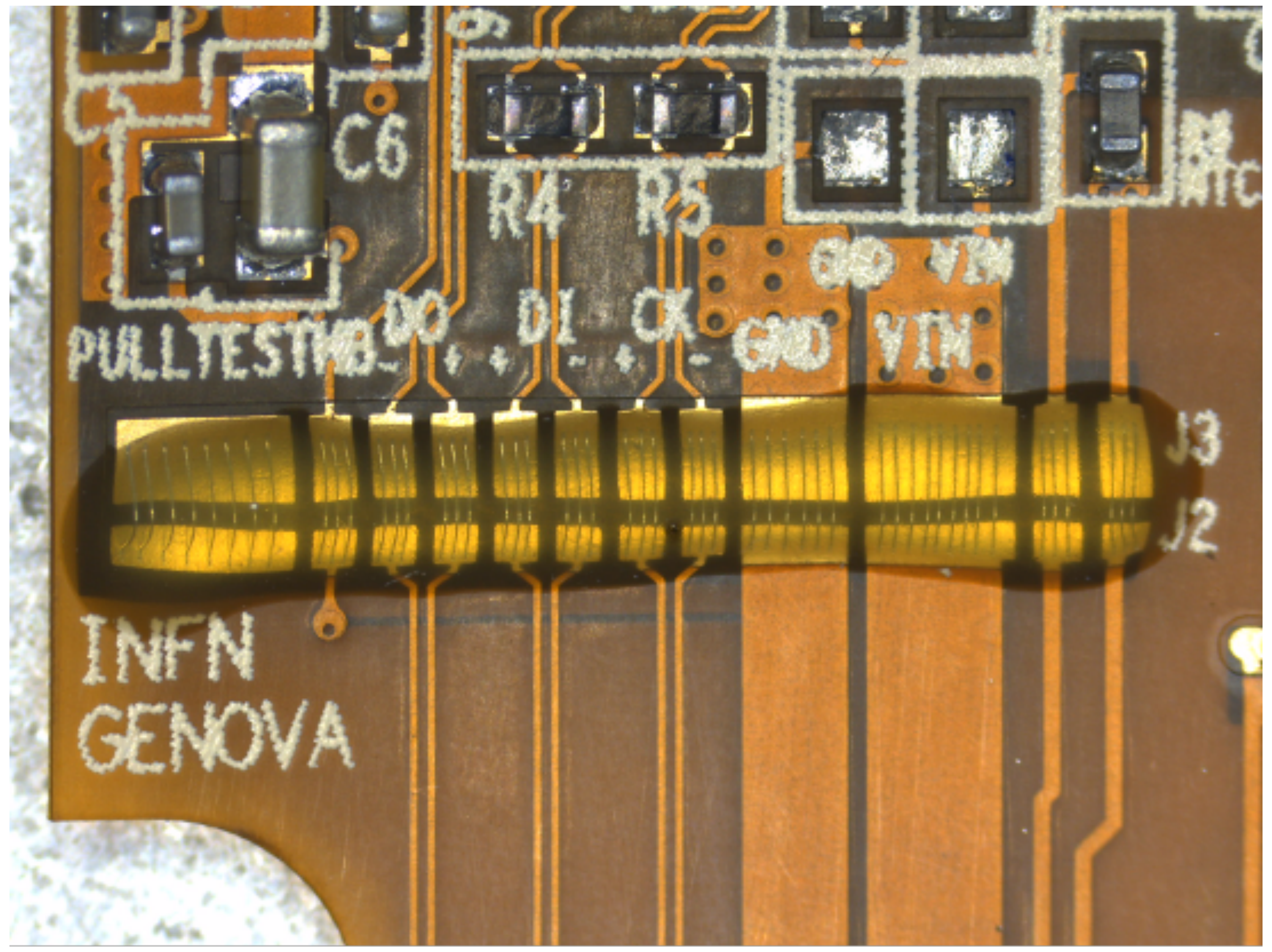
Testing irradiated parts - thermal tests

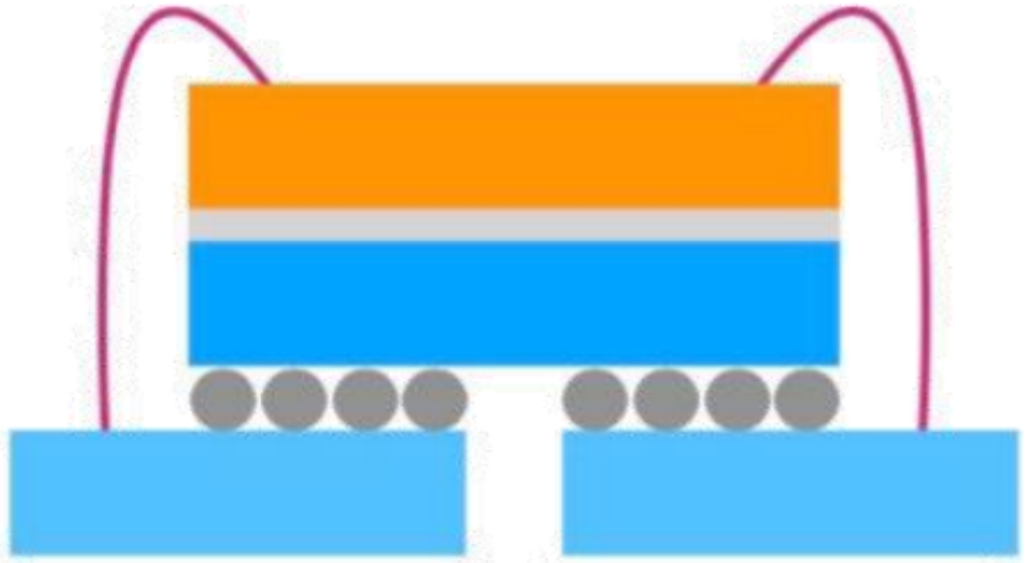
- Testing of irradiated structures often includes thermal cycling from low to high temperature and vice versa
- This allows the parts to be mechanically stressing emulating further the conditions they would see in a real experiment
- After irradiation materials can become more brittle and thermal cycling can cause cracking to occur more quickly especially if there is a CTE mismatch between materials that are in close proximity
- This can cause encapsulants added to protect delicate features like wire bonds, to have the opposite effect and pull wire bonds off

shock chamber

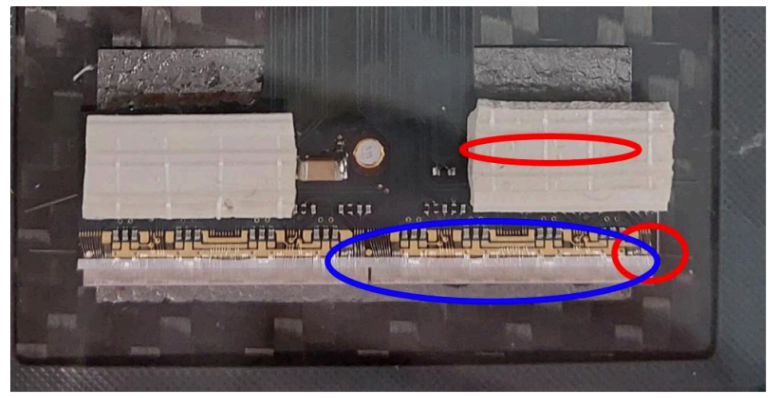
air flow chiller

climate chamber

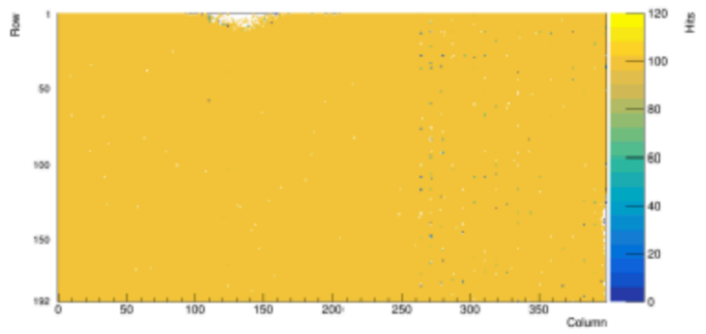




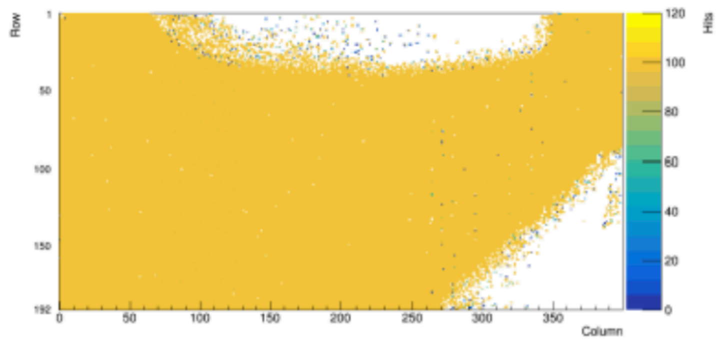
- Up to 1000 cycles at -55 to +60°C
- Vendor B: significant bump delamination after 50..150 cycles, increasing



150 cycles



500 cycles



Bump bond delimitation seen in ATLAS/CMS Pixel devices (RD53A), Jörn Grosse-Knetter

Summary

- Irradiations remain one of the main tools for testing instrumentation deployed in HEP, NP, Medical physics and many industrial and space applications

- Understanding of the environment of you experiment and the probably failure modes of your devices will help with the choice of irradiation. Sometimes combining different irradiations fields with realistic environmental effects e.g. temperature, humidity etc will be necessary to reveal certain failure modes

- Many facilities exist, but waiting times can be long and access limited (or expensive), collaborating with others and maximising the number of samples irradiated without compromising the results may be important