RADSAGA

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JYVÄSKYLÄN YLIOPISTO
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Board and system level testing in other RADSAGA facilities and beyond

Daniel Söderström

RADSAGA System Level Test Review

CERN, November 11-13, 2019

Outline

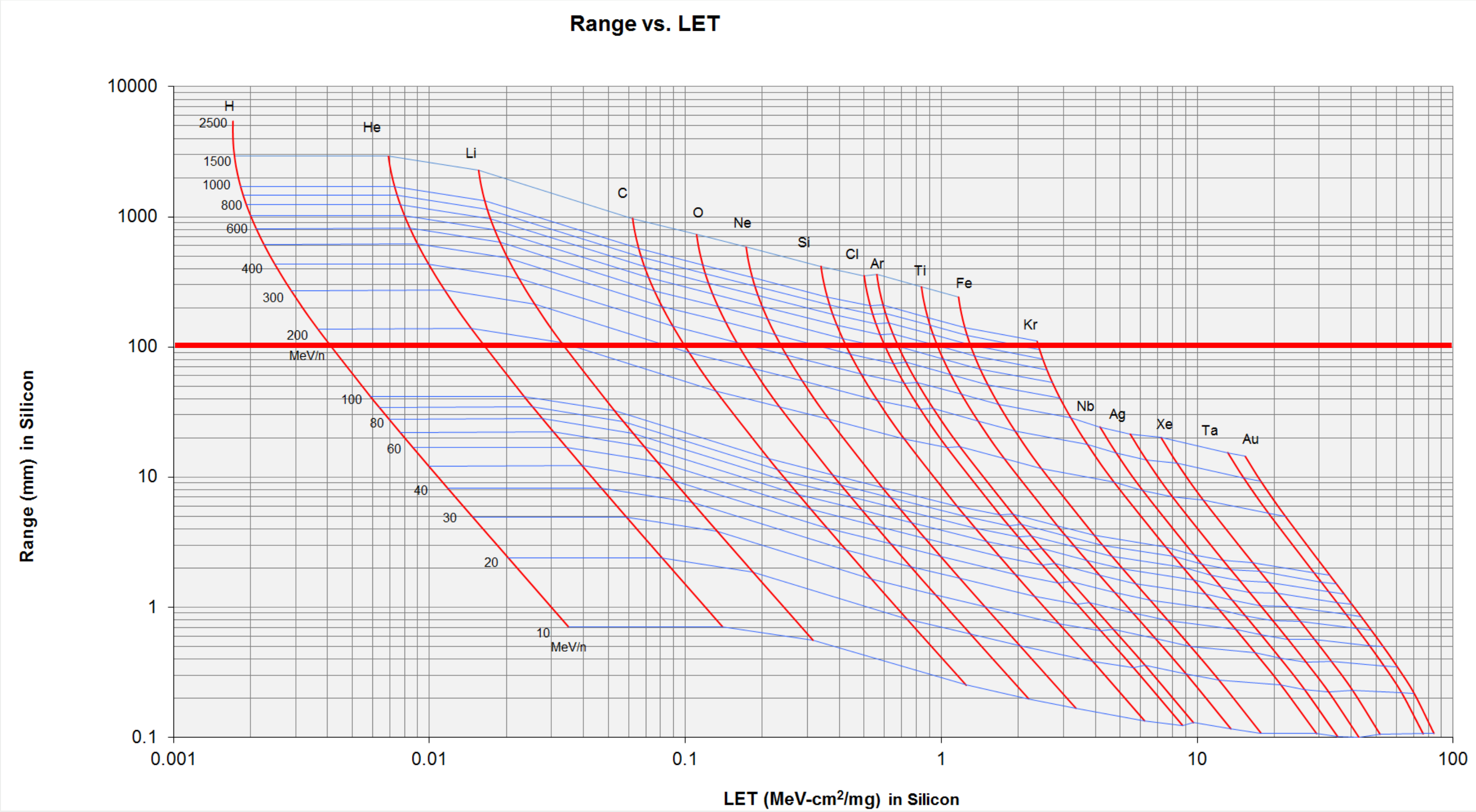
- Facility requirements for system level tests
- Example facilities
  - Heavy ions
  - Protons
  - Neutrons
- Summary

Facility requirements for system level tests

- High beam penetration
  - High energies
  - Projectile properties
- Large beam size
  - Large irradiation area
  - Dependent on system and test mode

Penetration of particles

- Ions
- For 10 cm range:
  - / 200 MeV H
  - / 400 MeV/n O
  - / 600 MeV/n Ar
  - / 900 MeV/n Kr

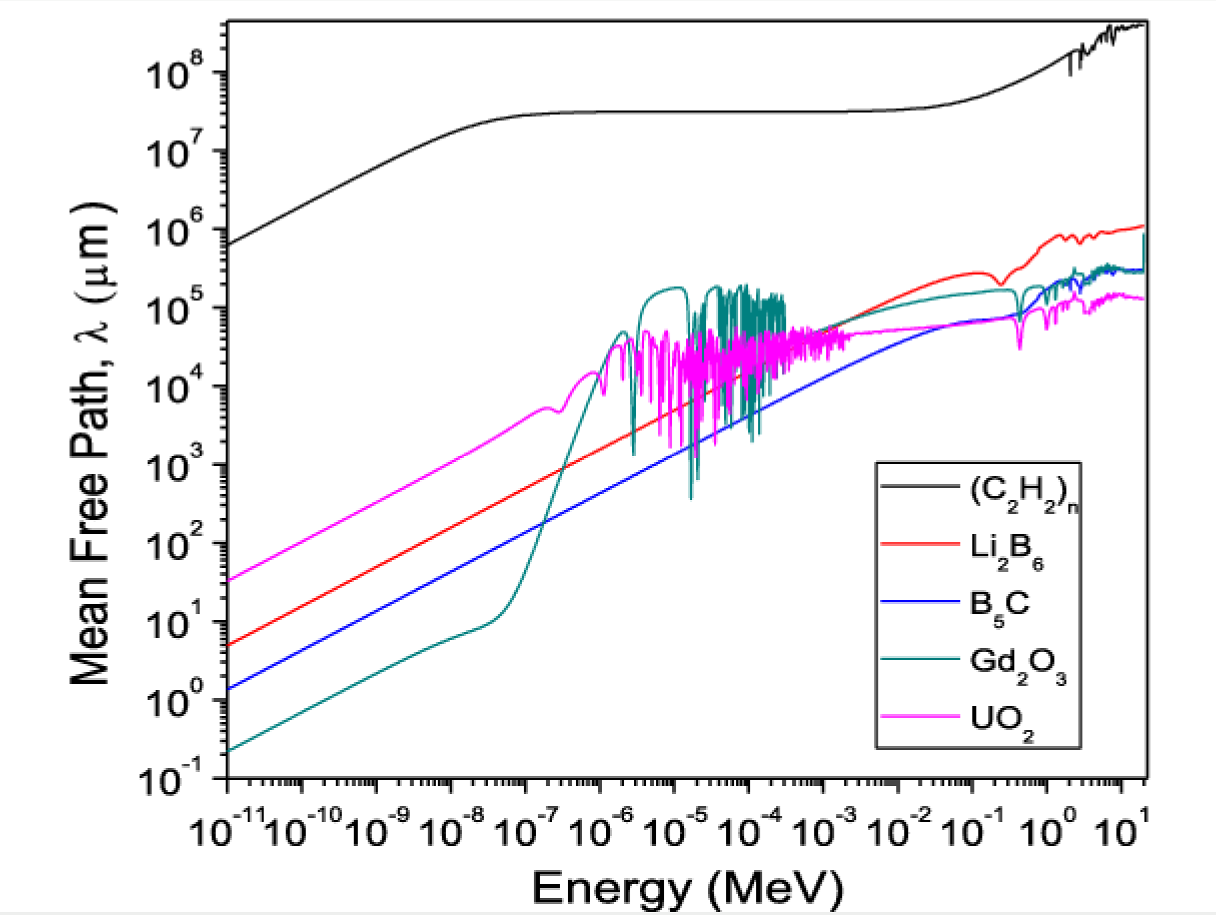


At very high energies, the particle range becomes limited by the inelastic interaction length.

https://www.bnl.gov/nsrl/userguide/let-range-plots.php

Penetration of particles

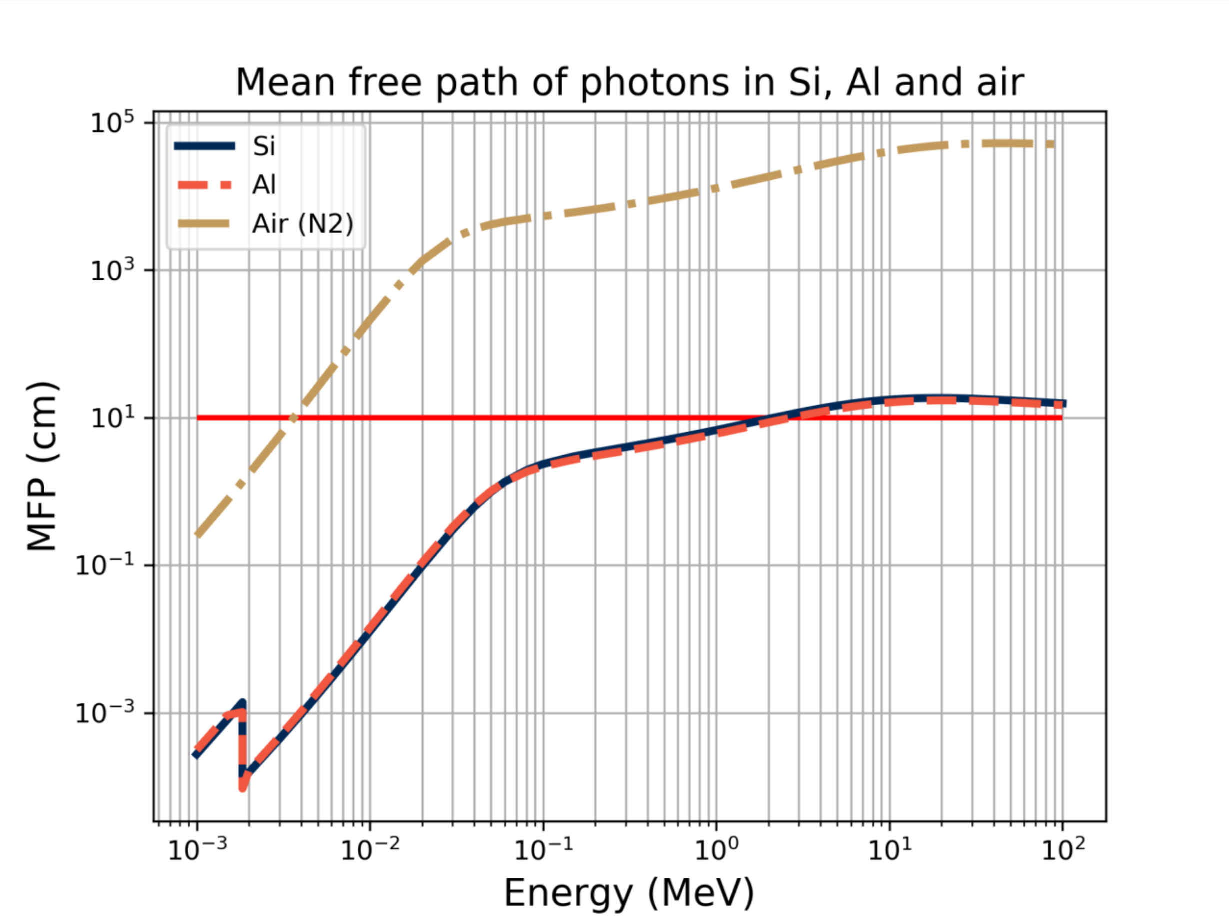
- Neutrons
  - Thermal: ~9 cm MFP in Si
  - 10 MeV: ~25 cm in water
  - Differs greatly with material, but generally long range



A. N. Caruso, The physics of solid-state neutron detector materials and geometries, Journal of physics. Condensed matter: an Institute of Physics journal, 2010, vol. 22 44, p. 443201

Penetration of particles

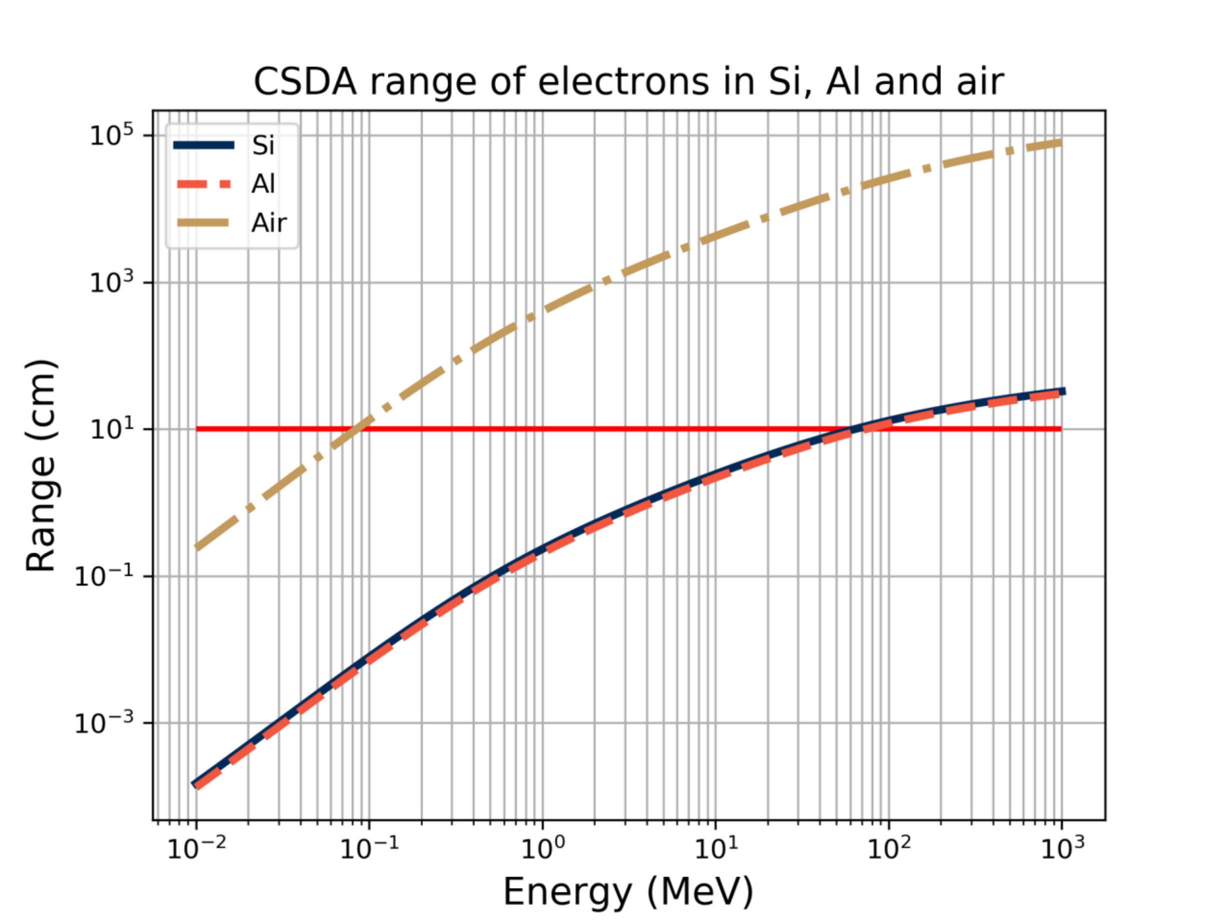
- Gammas
- ^{60}Co γ in Si: ~10 cm MFP
  - $I(x) = I_0 e^{-\mu x}$
  - $MFP = \frac{1}{\rho\mu}$
  - (with suitable units)



Data from https://www.nist.gov/pml/xcom-photon-cross-sections-database

Penetration of particles

- Electrons
- Even if electrons are stopped, brems-strahlung is present
- About 10 cm range in Si for 100 MeV electrons



Data from https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

Beam sizes – Heavy-ion facilities

Heavy-ion facility	Beam size	Max energy (MeV/u)	Compliance with ESCC 25100	Cost of test per hour (ballpark)
NSRL	60x60 cm^2 (typ. 20x20)	1500	Yes	~$5700
RADEF	5x5 cm^2 (3x3 in air)	16.3	Yes	~800 €
TAMU	4.5 cm diameter	40	Yes	~$1000
KVI	3x3 cm^2	90	Yes	-
UCL	2.5 cm diameter	9.3	Yes	~800 €
GANIL	Few cm diameter, sweeping beam	60	Yes	-
LBNL	Few cm diameter	30	Yes	~$1600
GSI	1 cm diameter	2000	Yes	-

Beam sizes – Proton facilities

Proton facility	Beam size	Max energy (MeV)	Compliance with ESCC 25100
NSRL	60x60 cm^2 (typ. 20x20 cm^2)	2500	Yes
KVI	12 cm diameter	184	Almost*
RADEF	10 cm diameter	55	Almost*
PSI PIF	9 cm diameter	230	Yes
LBNL BASE	8 cm diameter	55	Almost*
UCL	8 cm diameter	62	Almost*
TRIUMF PIF	7.5x7.5 cm^2	480	Yes
TAMU	4.5 cm diameter	45	Almost*
GSI	1 cm diameter	4500	Yes

*Protons should be delivered in the energy range 20-200 MeV

Beam sizes

- Bigger fields
  - Point sources, ^{60}Co
  - CHARM
  - Reactors

Image from *Research Nuclear Reactor TAPIRO information sheet,* ENEA. 40 cm diameter Grand Horizontal irradiation channel. It has also the Grand Vertical Channel with 80-90 cm diameter.

NSRL – NASA Space Radiation Laboratory

Located in USA at Brookhaven National Laboratory

Much used for radiobiology testing

High-energy heavy ions and protons

Large beam size

Ion species

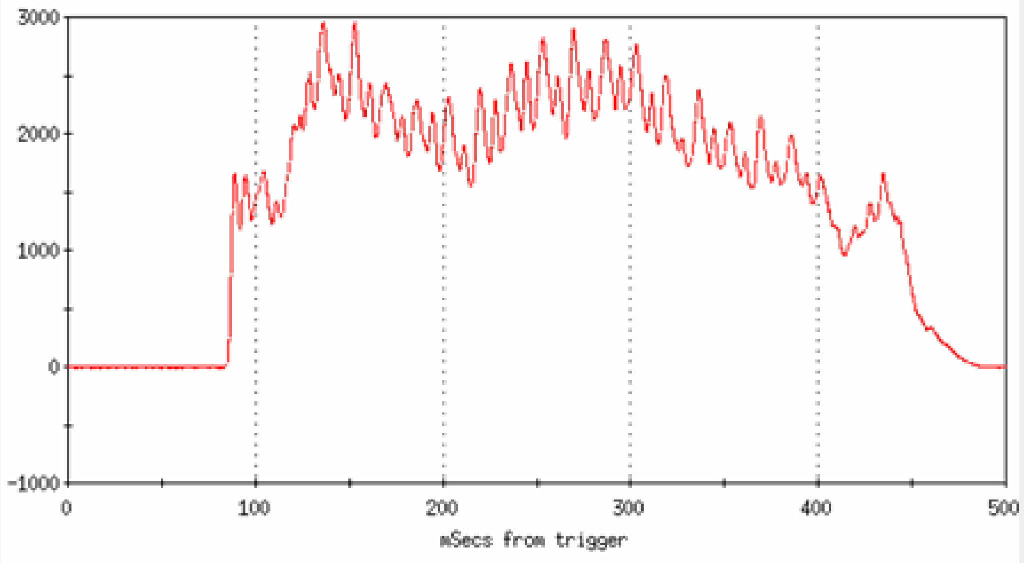
- Many ions from BNL booster
  - Almost any ion possible, table present used ions so far
- Switching time 1.5 – 2 minutes
  - (When pre-tuned for the new energy)
- Fluxes 10^6-10^{11} ions per spill

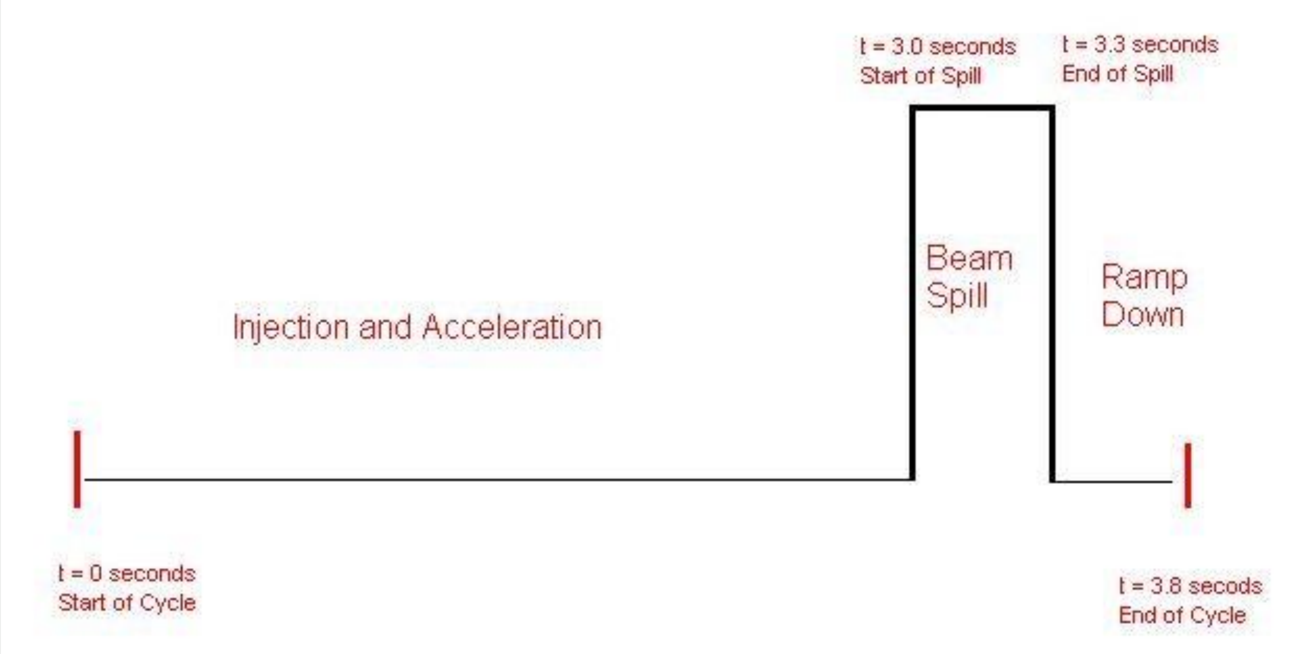
https://www.bnl.gov/nsrl/userguide/beam-ion-species-and-energies.php

Ion Species [1]	Max Energy [2] (MeV/n)	LET in Si at Max Energy [6] (MeV/(mg/cm ^{2}))	Peak LET in Si (MeV/(mg/cm ^{2}))	Range in Si (mm)	Max Flux [3] (ions/spill)
H^1	2500	0.00171	0.51	5470	$2.2x10^{11}$
He^3	1500	0.006679	1.5	2220	0.3×10^{10}
He^4	1500	0.006919	1.5	2960	0.3×10^{10}
Li^7	1500	0.01557	2.3	2274	$4x10^9$
C^{12}	1500	0.06227	5.2	972	$1.2x10^{10}$
O^{16}	1500	0.1107	7.3	729	$0.4x10^{10}$
Ne^{20}	1500	0.173	9	583	$1.2x10^{10}$
Si^{28}	1500	0.339	14	417	$0.3x10^{10}$
Cl^{35}	1500	0.4999	17.4	353	$0.2x10^{10}$
Ar^{40}	1500	0.5605	18.7	360	$0.02x10^{10}$
Ti^{48}	1500	0.8372	24.2	289	$0.08x10^{10}$
Fe^{56}	1470	1.171	29.3	235	$0.2x10^{10}$
Kr^{84}	721	2.54	41	70.5	$2.0x10^7$
Zr^{91}	300	4.58	48.5	15.6	1×10^6
Nb^{93}	300	4.8	47.4	15.4	1×10^6
Xe^{132}	589	6.1	69.2	36.6	$5.0x10^7$
Ta^{181}	475	11.7	87.5	21.1	$5.0x10^7$
Au^{197}	400	15.0	94.2	14.9	$1.0x10^8$
Sequential Field	Various	Various	Various	Various	Various
Solar Particle Event	Various	Various	Various	Various	Various
GCR Simulation	Various	Various	Various	Various	Various

Time structure

- Spills and microstructure
- 300 ms every 2.8 - 6.6 s





https://www.bnl.gov/nsrl/userguide/time-structure-in-beam.php

Beam size and monitoring

- Large field size
  - Typically 20 x 20 cm^2
  - Up to 60 x 60 cm^2
- Uniformity typically ± 3 %
- Monitoring
  - Digital beam imager
  - Large ion chamber for high flux
  - Plastic scintillators for low flux

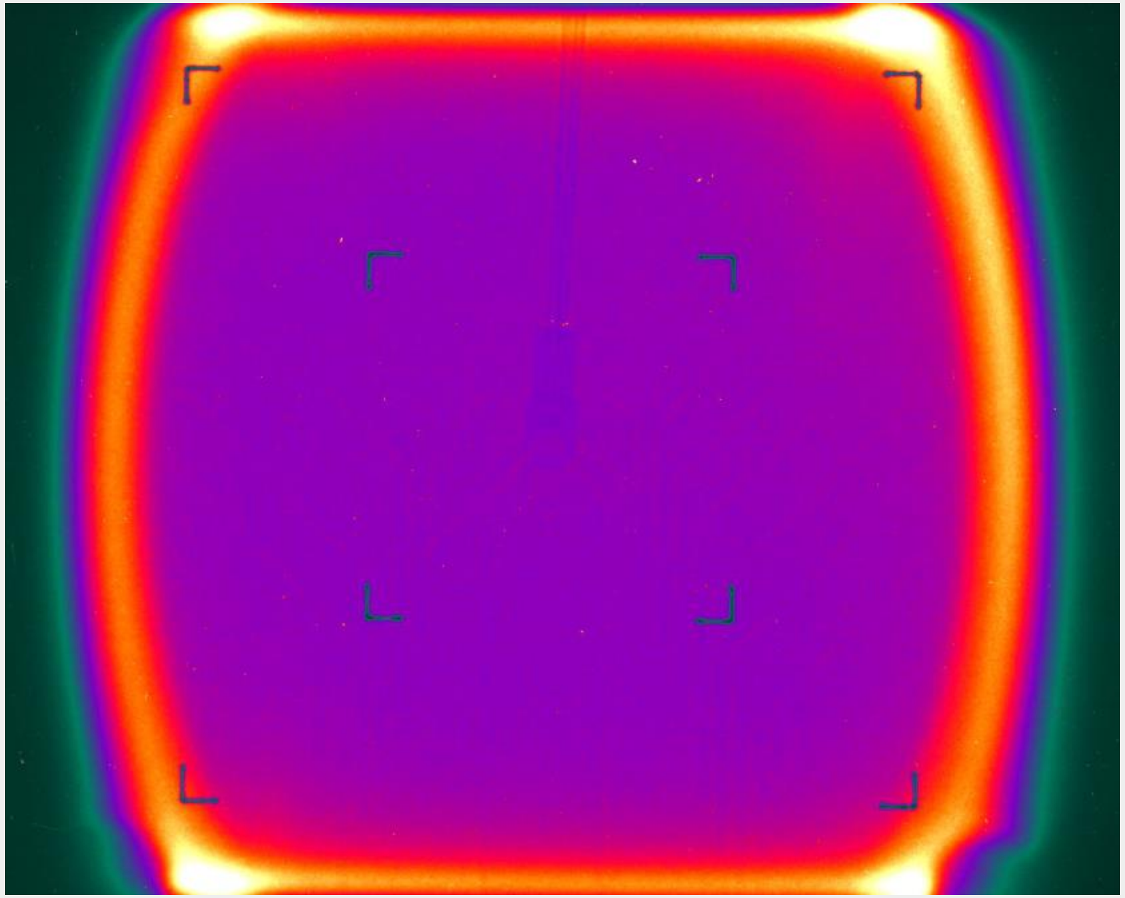


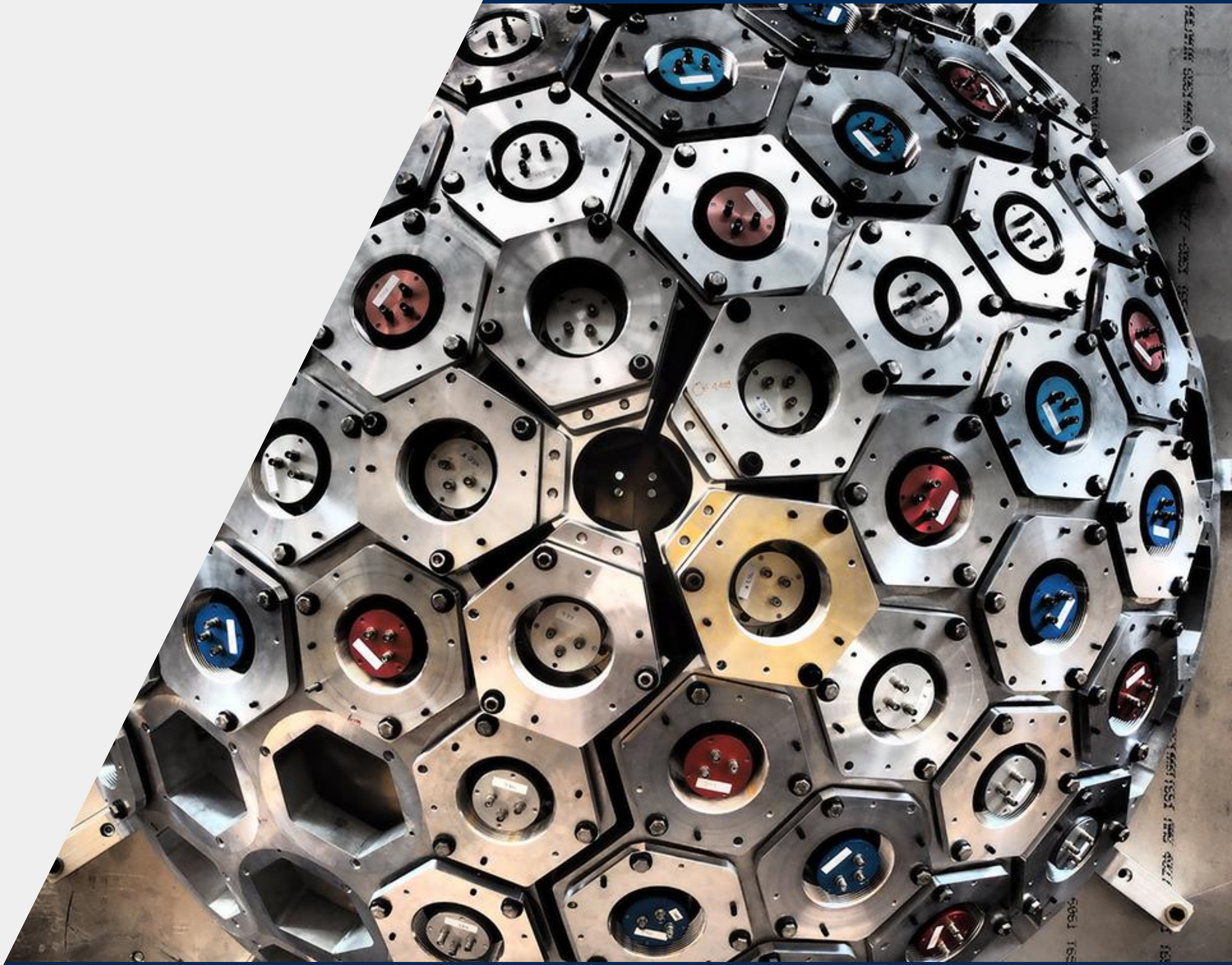
Image and info from presentation *Introduction to NSRL – Heavy Ion Facilities Comparison LBNL/TAMU/NSRL*, Michael Sivertz, NSRL
https://www.bnl.gov/nsrl/userguide/beam-uniformity-and-profile.php

TRIUMF

Located in Vancouver, Canada

Protons (PIF)

Neutrons (NIF)

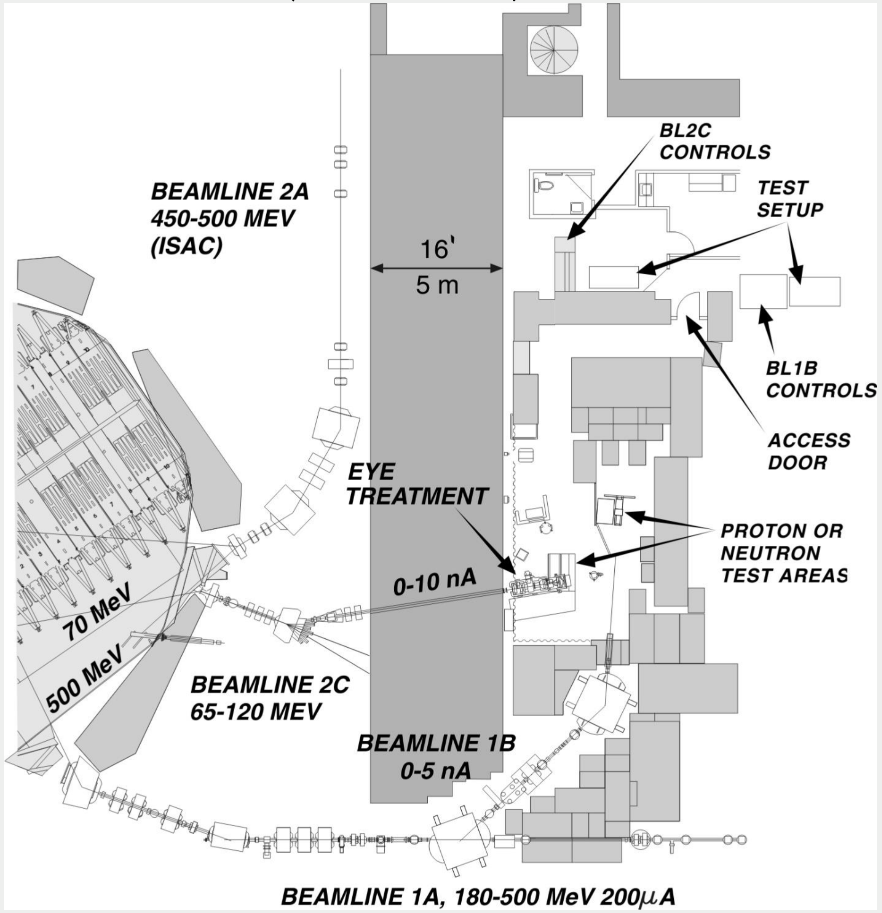


Proton Irradiation Facility, PIF

A 480 MeV proton has 58 cm range in Si (SRIM2013)

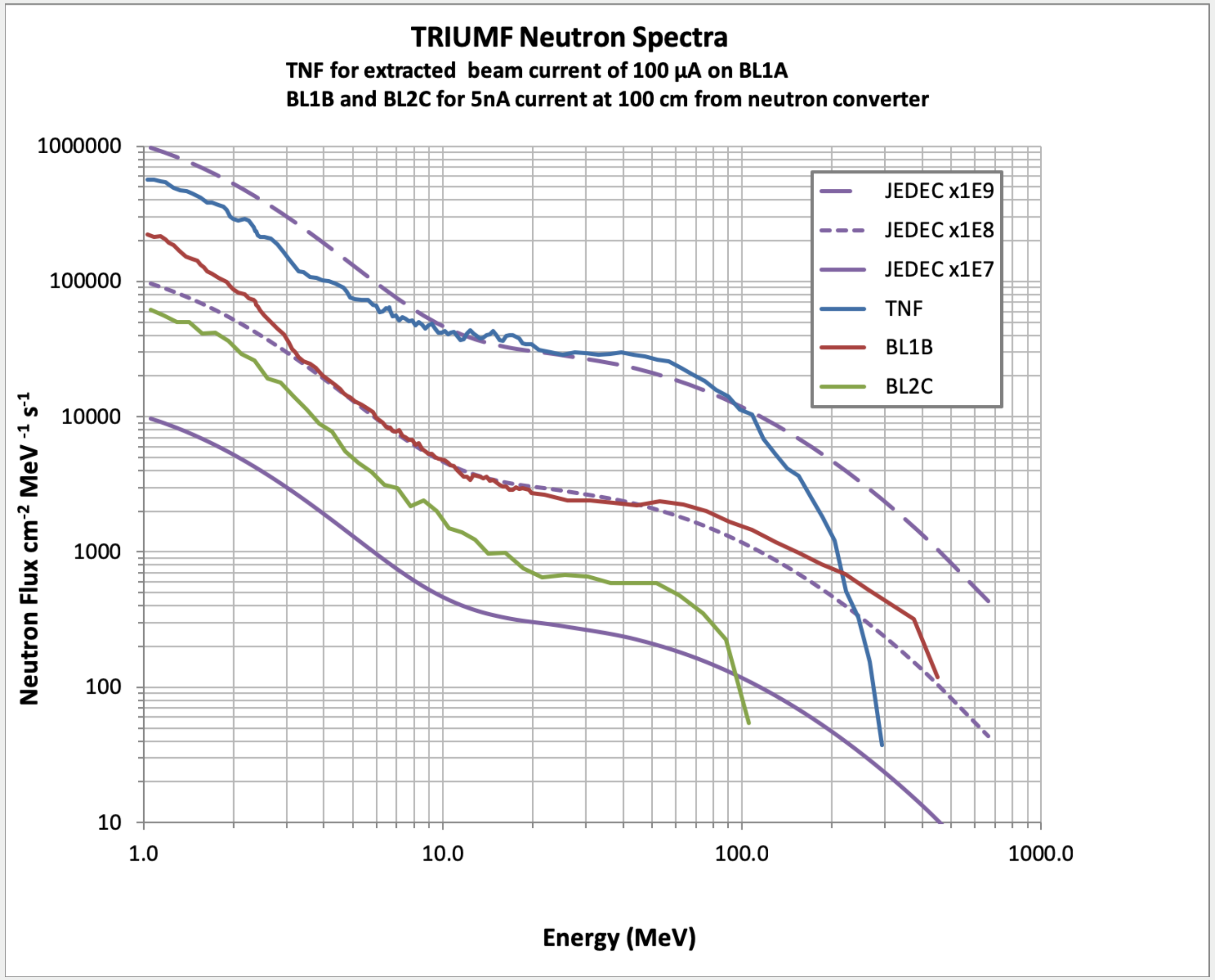
	BL1B protons	BL2C protons
Standard Test Energies	350 or 480 MeV (480 MeV preferred) Some other energies with a degrader	**63 or 105 MeV** Other energies available with a degrader or by changing the cyclotron extraction energy
Extracted Intensity	0.1 to 3 nA	**0.1 to 7 nA**
Flux (protons/cm²/s)	Standard location: 10^5 to 4×10^7 (10^2 possible) Upstream location: 7×10^8 max	Standard location: **10^5 to 1×10^8** (10^2 possible) Upstream location: 2×10^9 max
Spot Size	Standard location: **3x3 cm to 7.5x7.5 cm** Upstream location: 1 to 2 cm diameter	Standard location: **1x1 cm to 5x5 cm or 7.5 cm diameter** Upstream location: 0.5 to 2 cm diameter
Spot Homogeneity	Standard location: **+/- 5%** Upstream location: +/- 10%	Standard location: **+/- 5%** Upstream location: +/- 10%
Dose Rate	Standard location: **10 to 20 mGy/s** (1 to 2 rads/s) Upstream location: up to 500 mGy/s (50 rads/s)	Standard location: **50 to 100 mGy/s** (5 to 10 rads/s) Upstream location: up to 1000 mGy/s (100 rads/s)
Beam Counting and Monitoring System	**Ion Chamber or Scintillator**	**Ion Chamber, Scintillator, or Faraday Cup**
Device-Positioning System	**Remote-controlled X-Y platform with laser alignment**	**Remote-controlled X-Y platform with laser alignment**
Access Conditions	**20 m cable length to Control Area**	**20 m cable length to Control Area**

https://www.triumf.ca/pif-beam-specifications



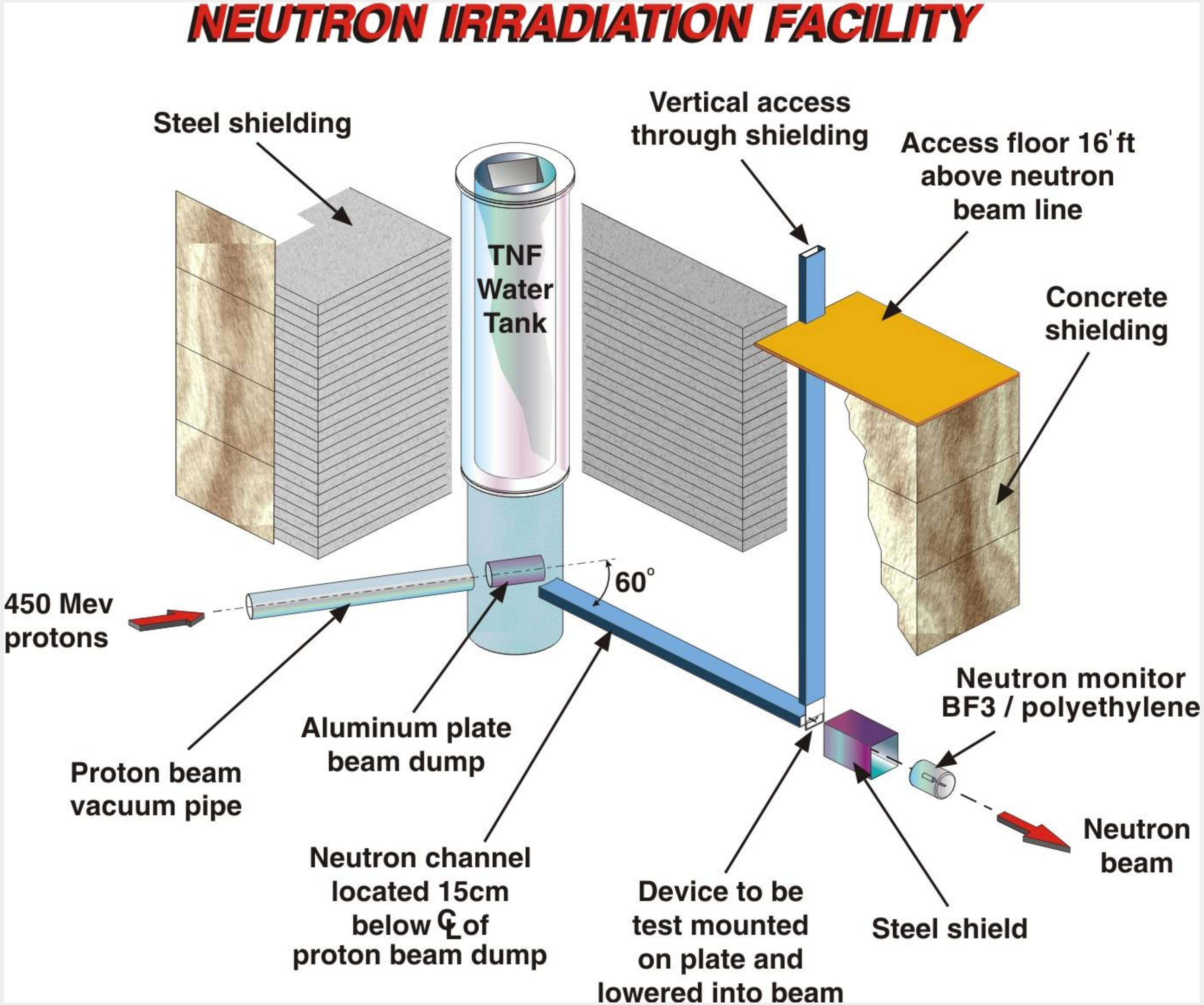
Neutron Irradiation Facility, NIF

- Spallation neutrons
- TNF
  - / TRIUMF Neutron Facility
  - / Target down BL1A
- BL1B and BL2C
  - / Targets in PIF



https://www.triumf.ca/nif-beam-specifications

NIF, TNF area



https://www.triumf.ca/neutron-irradiation-facility

NIF, TNF area

- High flux but limited space
  - / Fixed beamspot size, 5 cm x 15 cm (vertical x horizontal)
  - / Narrow access channel, 15 cm in beam direction x 27 cm perpendicular to beam
  - / Typical flux of >10 MeV neutrons: ~3×10^6 $n/cm^2/s$

NIF, BL1B area

- Large area for setting up and testing equipment in PIF
- Ability to change beam size and flux
  - Flux of >10 MeV neutrons: 10^3 to 10^5 n/cm^2/s
  - Circular beamspot, 5 to 75 cm diameter
- Collimated protons available at the same location (PIF) to confirm errors from a specific sensitive chip.
- Variety of stands and support tables with vertical positioning capability.

NIF Beam data

Systems can be irradiated

	TNF neutrons	BL1B neutrons	BL2C neutrons
Energy	Thermal to 400 MeV	1/E spectrum to 480 MeV	1/E spectrum to 120 MeV
Flux (neutrons/cm²/s)	2×10^6 to 3×10^6 above 10 MeV. 5×10^5 thermal energies	10^3 to 5×10^5 above 10 MeV	10^3 to 5×10^4 above 10 MeV
Spot Size	5x12 cm	5 to 75 cm diameter	30 to 150 cm diameter
Spot Homogeneity	+/- 10%	+/- 10%	+/- 10%
Beam Counting and Monitoring System	BF_3 Counter and Activation Foils	BF_3 Counter and Activation Foils	BF_3 Counter and Activation Foils
Device-Positioning System	Movable Trolley with positive stop	Remote-controlled X-Y platform with laser alignment	Remote-controlled X-Y platform with laser alignment
Access Conditions	6 m cable length to Control Area	20 m cable length to Control Area	20 m cable length to Control Area

https://www.triumf.ca/nif-beam-specifications

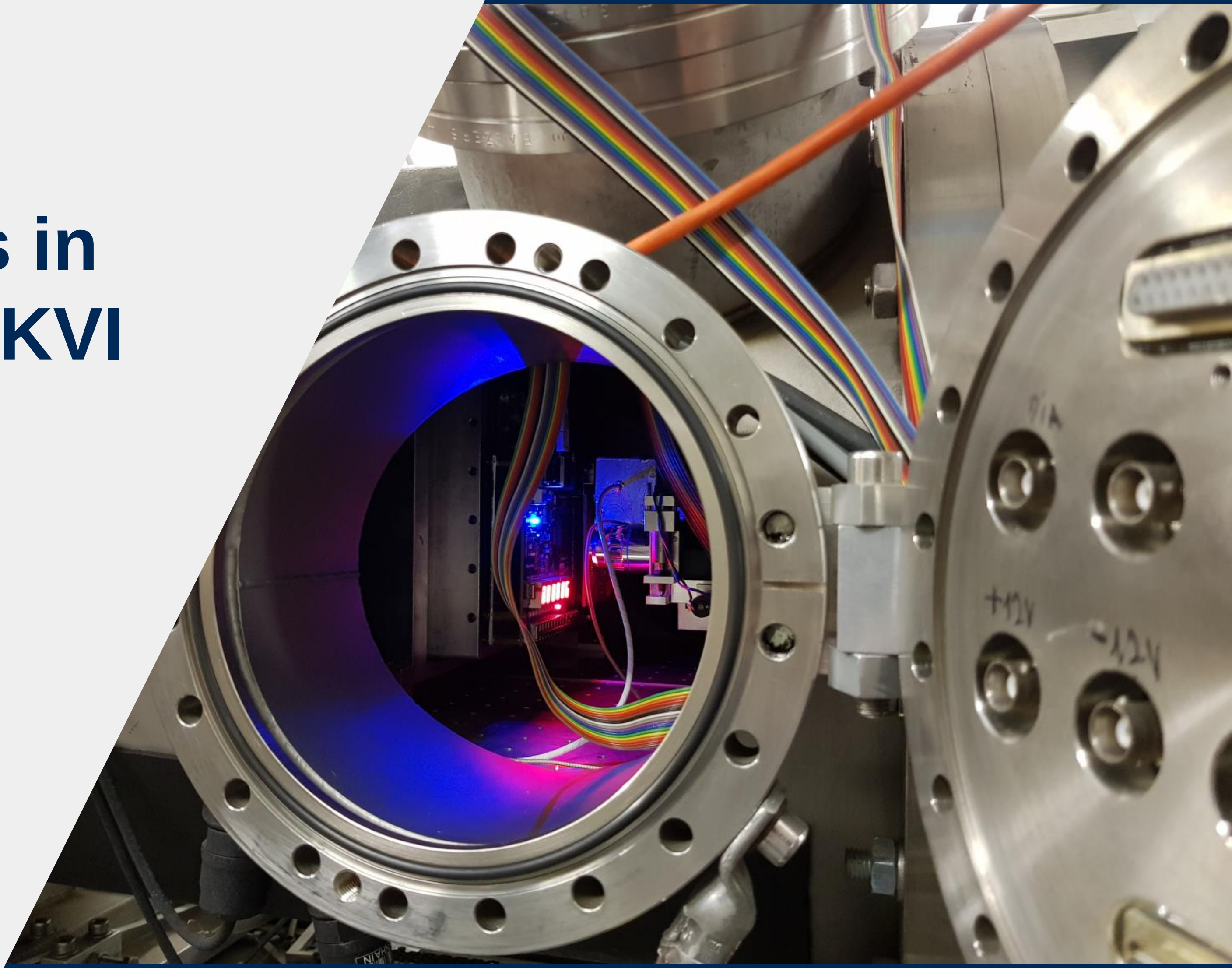
High energy accelerators in Europe: GANIL, GSI and KVI

European high-energy heavy-ion beams

GANIL – Caen, France

GSI – Darmstadt, Germany

KVI – Groningen, Netherlands



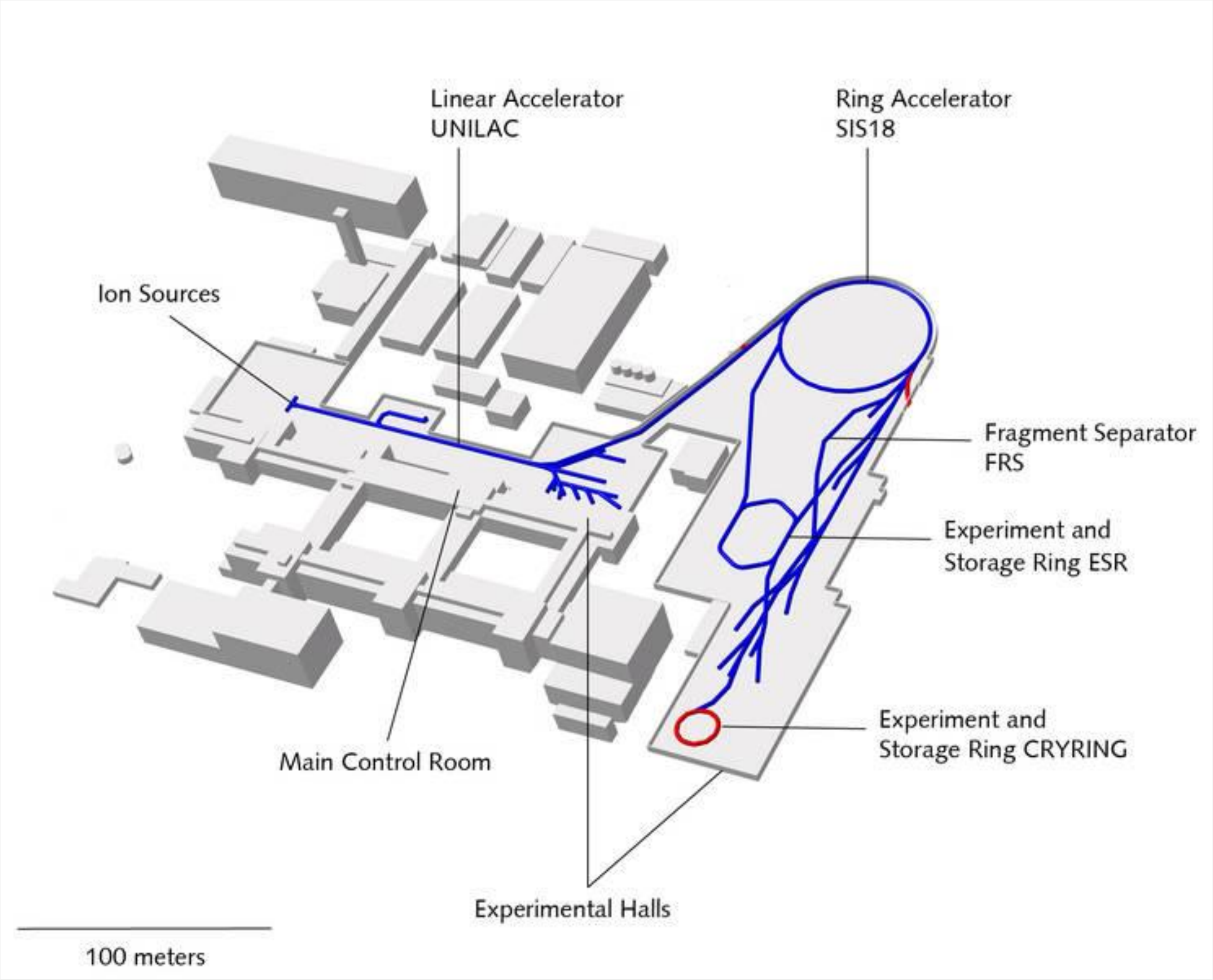
GANIL

- Small beam that can be swept over a region
  - Can cover 4x50 cm^2
- Energies up to 60 MeV/u for ^{86}Kr
  - 1223 µm range in Si
- Might not be able to cover whole system
- Not able to penetrate packaged components
- One ion per campaign

GSI SIS18 beam

System possible to irradiate.
High beam penetration.

- Energies up to 2 GeV/u
  - From p to U
  - Lower for heavier elements
- Beam size 1 cm diameter
  - Beam sweeping 20x20 cm^2
- Not commonly used for electronics testing
- One ion per campaign



https://www.gsi.de/en/researchaccelerators/accelerator_facility.htm

KVI

- Energies up to 90 MeV/u
  - He, C, O, Ne
- Up to 30 MeV/u
  - O, Ne, Ar, Kr, Xe
- Beam size 3x3 cm^2
- cm range in Si for 90 MeV/u, and mm range for 30 MeV/u

AGOR cyclotron https://www.rug.nl/kvi-cart/research/facilities/agor/agorfirm/

Small part of system possible to irradiate. Some beam penetration.

European high-energy proton irradiation facilities

KVI continuation

PIF at PSI – Villigen, Switzerland

Proton beams

- PIF and KVI provide high energies
- UCL and RADEF have only lower energies available

	PIF	KVI	UCL	RADEF
Energy (MeV)	6 – 230	10 - 184	10 - 62	0.4 – 55
Beam size (cm diameter)	9	12	8	10
Max. range in Si (mm, SRIM2013)	176	120	18	14
Flux ($p/cm^2/s$)	$< 2x10^9$	$< 10^9$	$< 5x10^8$	$< 3x10^8$

Proton system level testing information: S. M. Guertin, *Board Level Proton Testing Book of Knowledge for NASA Electronic Parts and Packaging Program*

Summary

- Facilities where irradiation of whole 3D structures is possible are scarce
- Testing systems at other facilities would require some imagination, but is possible
- Testing with many particle types possible
  - Neutrons provide high penetration
  - NSRL heavy ion testing facility for 3D systems

Thank you for your attention!

- Daniel Söderström
  - daniel.p.soderstrom@jyu.fi

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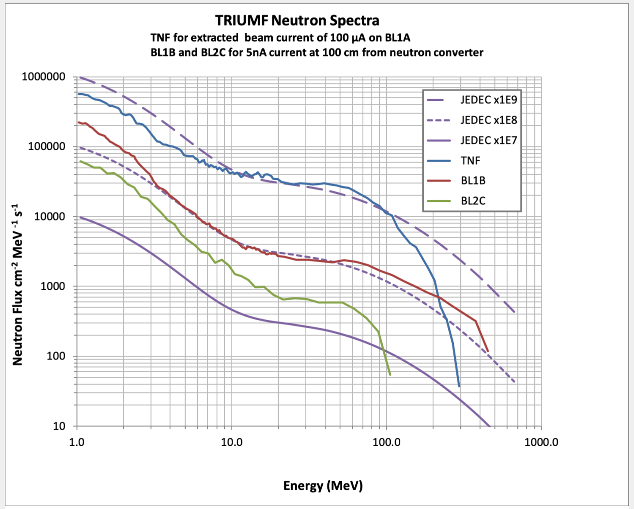
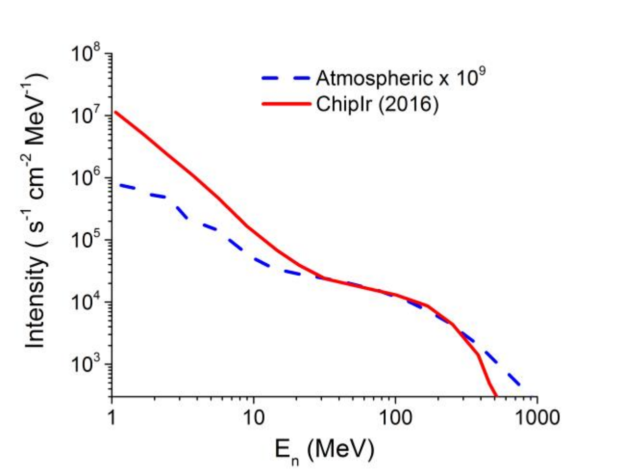
Bonus and old slides

NIF vs ChipIr





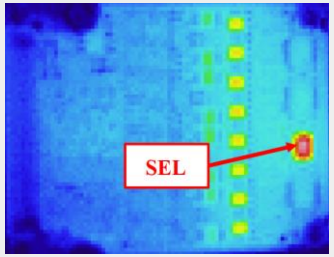
	TNF neutrons	BL1B neutrons	BL2C neutrons	ChipIr
Energy	Thermal to 400 MeV	1/E spectrum to 480 MeV	1/E spectrum to 120 MeV	(1/E) spectrum to 800 MeV
Flux (neutrons/cm²/s)	$2x10^6$ to $3x10^6$ above 10 MeV $5x10^5$ thermal energies	10^3 to $5x10^5$ above 10 MeV	10^3 to $5x10^4$ above 10 MeV	10^7 above 10 MeV
Spot Size	5x12 cm	4 to 60 cm diameter	30 to 150 cm diameter	Up to 70x70 mm^2 (Planned up to 1 m^2 for future)
Spot Homogeneity	+/- 10%	+/- 10%	+/- 10%	
Beam Counting and Monitoring System	BF_3 Counter and Activation Foils	BF_3 Counter and Activation Foils	BF_3 Counter and Activation Foils	
Device-Positioning System	Movable Trolley with positive stop	Remote-controlled X-Y platform with laser alignment	Remote-controlled X-Y platform with laser alignment	
Access Conditions	6 m cable length to Control Area	20 m cable length to Control Area	20 m cable length to Control Area	

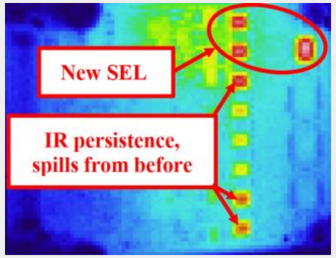
Electronic systems testing example

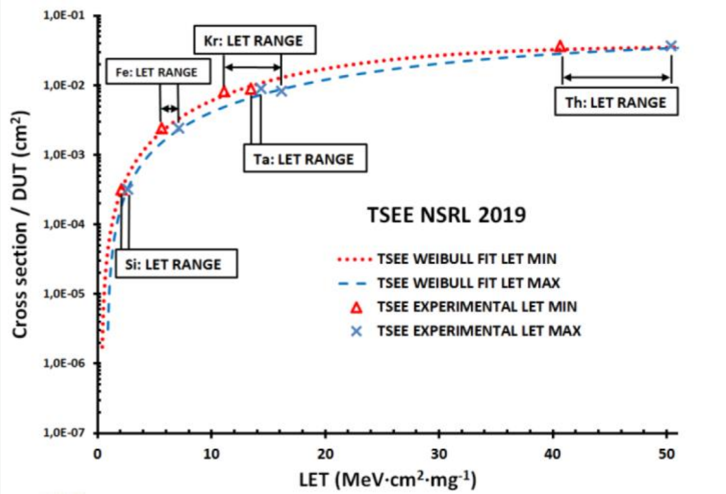
- A. de Bibikoff et al. RADECS 2019
- Irradiation of one PCB with components on both sides
- Considerations for SEL in system
  - IR camera to detect SEL
- Considerations for LET span of ion through the system

Electronic systems testing example

- A. de Bibikoff et al.
- Irradiation of one PCB with components on both sides
- Considerations for SEL in system – IR camera
- Considerations for LET span of ion through the system







A. de Bibikoff, Method for System-level testing of COTS electronic board under High Energy Heavy Ions, RADECS 2019

CERN facilities

CHARM already discussed

IRRAD – high-energy protons

Gamma ray facilities

Sometimes very high-energy ions

CHARM and IRRAD

- 24 GeV protons from PS in spills
- Sometimes 5-6 GeV/n ions
- Beam sizes
  - CHARM about 10x10 cm^2
  - IRRAD up to about a cm diameter

LANSCE

Los Alamos Neutron Science Center

Proton linac and neutron spallation targets

Industrial research at the Weapons Neutron Research facility (WNR)

Neutrons at LANSCE

- Electronic systems and ICs testing at the Irradiation of Chips and Electronic (ICE) Houses (ICE-I and ICE-II)
- 800 MeV protons on a tungsten spallation target
- Atmospheric neutron spectrum up to about 600 MeV
  - At ICE-II, se image
  - At ICE-I, lower energies

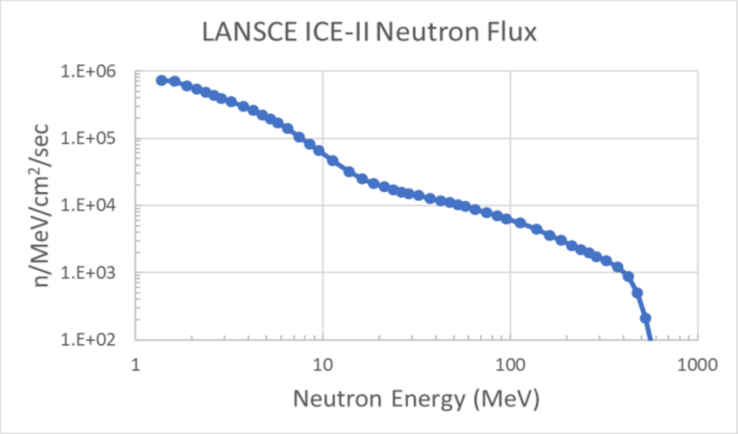
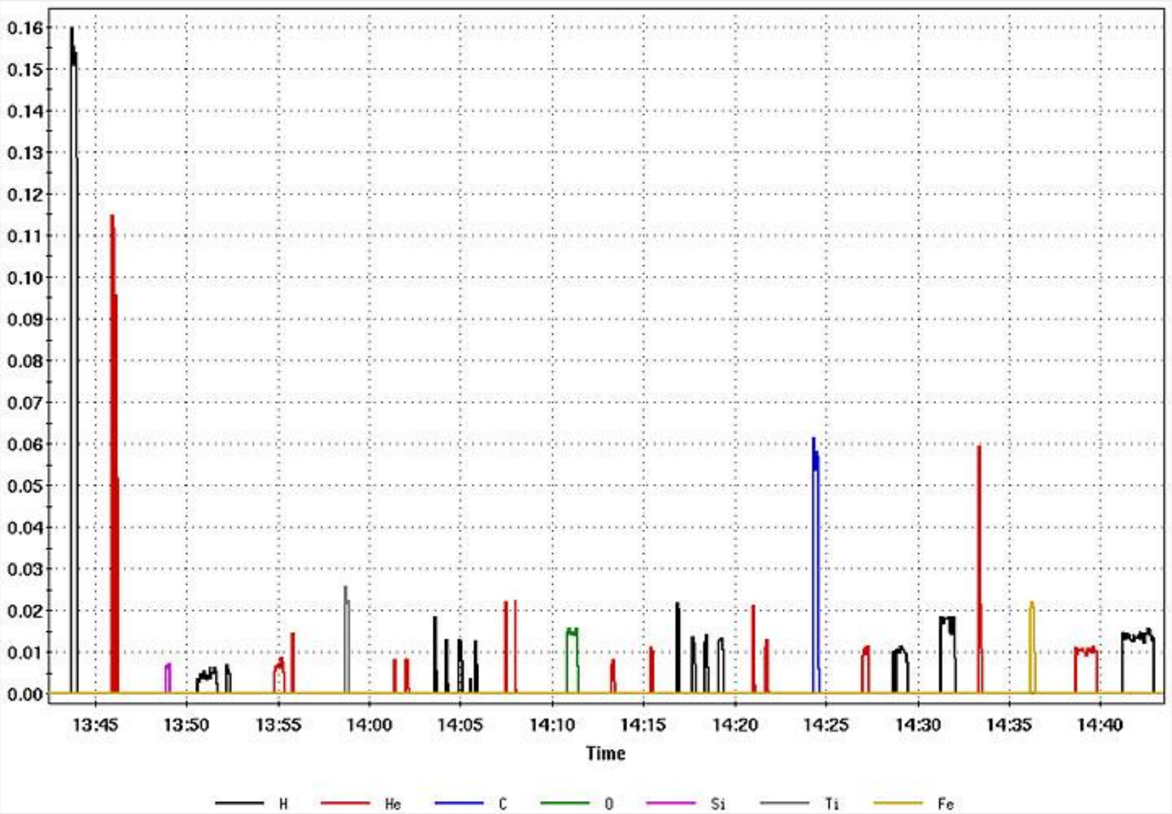


Figure 1 Neutron Spectrum for the ICE-II flight path (30R) at LANSCE/WNR

Los Alamos High-Energy Neutron Testing Handbook, Steve Wender, LANL

Radiobiology

- Facility used mainly for radiobiology, e.g. how astronauts are affected by space radiation
- Different irradiation routines
  - / E.g. GCR simulation



https://www.bnl.gov/nsrl/userguide/GCRSim.php

Proton Irradiation Facility, PIF

	BL1B protons	BL2C protons
Standard Test Energies	350 or 480 MeV (480 MeV preferred) Some other energies with a degrader	**63 or 105 MeV** Other energies available with a degrader or by changing the cyclotron extraction energy
Extracted Intensity	**0.1 to 3 nA**	**0.1 to 7 nA**
Flux (protons/cm²/s)	Standard location: **10^5 to $4x10^7$** (10^2 possible) Upstream location: $7x10^8$ max	Standard location: **10^5 to $1x10^8$** (10^2 possible) Upstream location: $2x10^9$ max
Spot Size	Standard location: **3x3 cm to 7.5x7.5 cm** Upstream location: 1 to 2 cm diameter	Standard location: **1x1 cm to 5x5 cm or 7.5 cm diameter** Upstream location: 0.5 to 2 cm diameter
Spot Homogeneity	Standard location: **+/- 5%** Upstream location: +/- 10%	Standard location: **+/- 5%** Upstream location: +/- 10%
Dose Rate	Standard location: **10 to 20 mGy/s** (1 to 2 rads/s) Upstream location: up to 500 mGy/s (50 rads/s)	Standard location: **50 to 100 mGy/s** (5 to 10 rads/s) Upstream location: up to 1000 mGy/s (100 rads/s)
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https://www.triumf.ca/pif-beam-specifications

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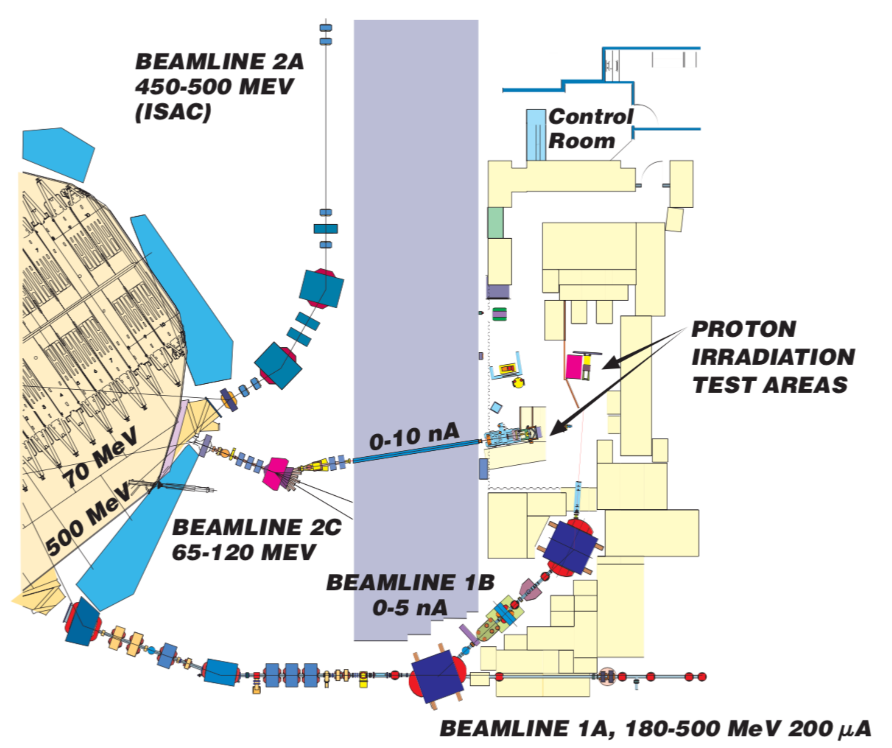

https://www.triumf.ca/proton-irradiation-facility

NIF, BL1B area

- Irradiation in the PIF area