TRIUMF

Beam Safety Shut-Off System for TRIUMF's ARIEL e-Linac based on Cherenkov Fiber

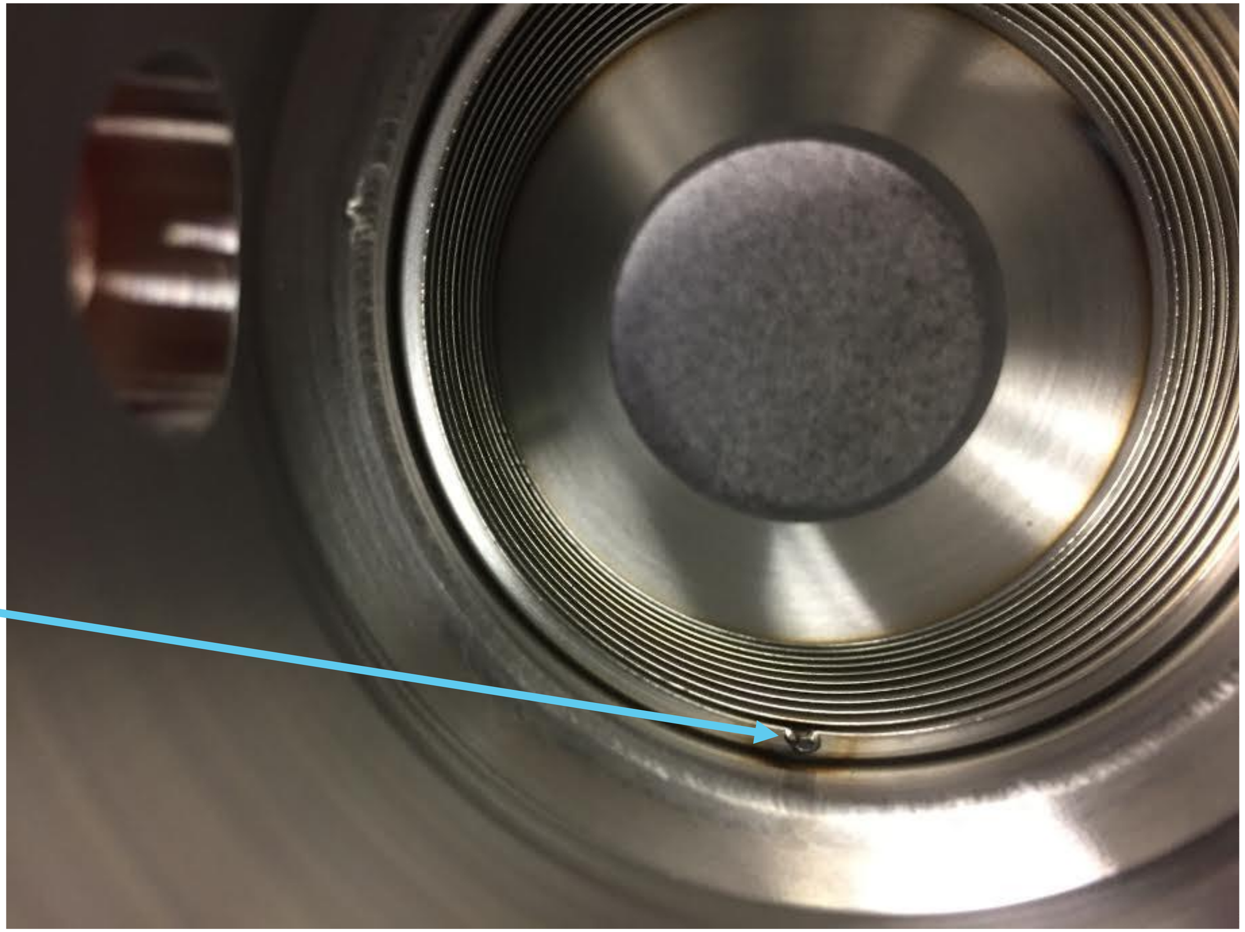
Richard Hermann

TRIUMF Accelerator Development Group

2025-02-11

Machine Protection System

- Beam Safety Shut-Off System
  - There to detect beam malfunction and **stop it in < 10 µs**

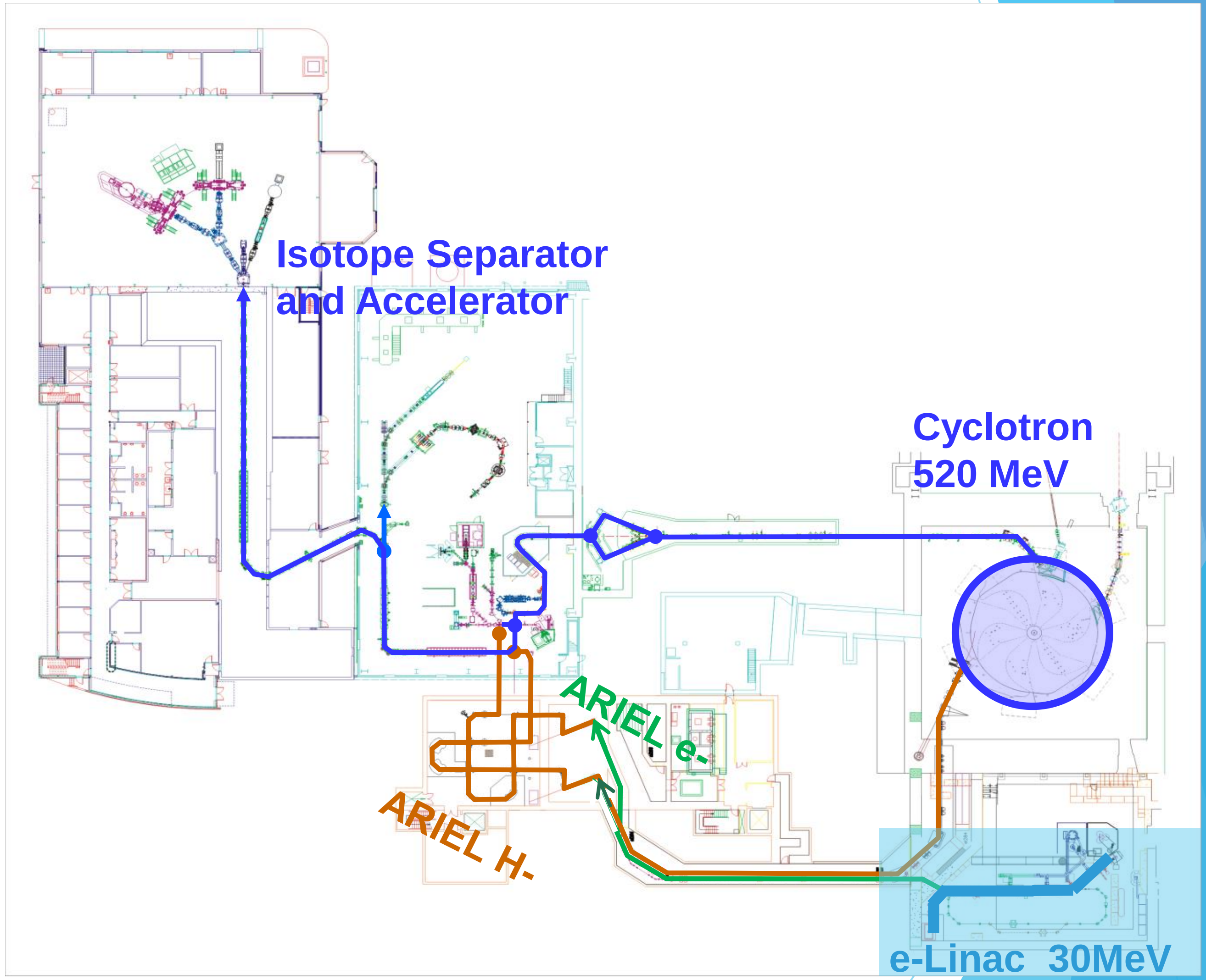


200 W beam (660 uA, 300 keV) went through a bellow and vented the entire beamline

Machine Protection System

- Beam Safety Shut-Off System
  - There to detect beam malfunction and **stop it in < 10 µs**

- for TRIUMF's ARIEL e-Linac
  - TRIUMF: Canada's particle accelerator center
    TRI-University Meson Facility
  - ARIEL: Advanced Rare Isotope Laboratory
  - e-Linac: Electron Linear accelerator



WNPPC 2025

Machine Protection System

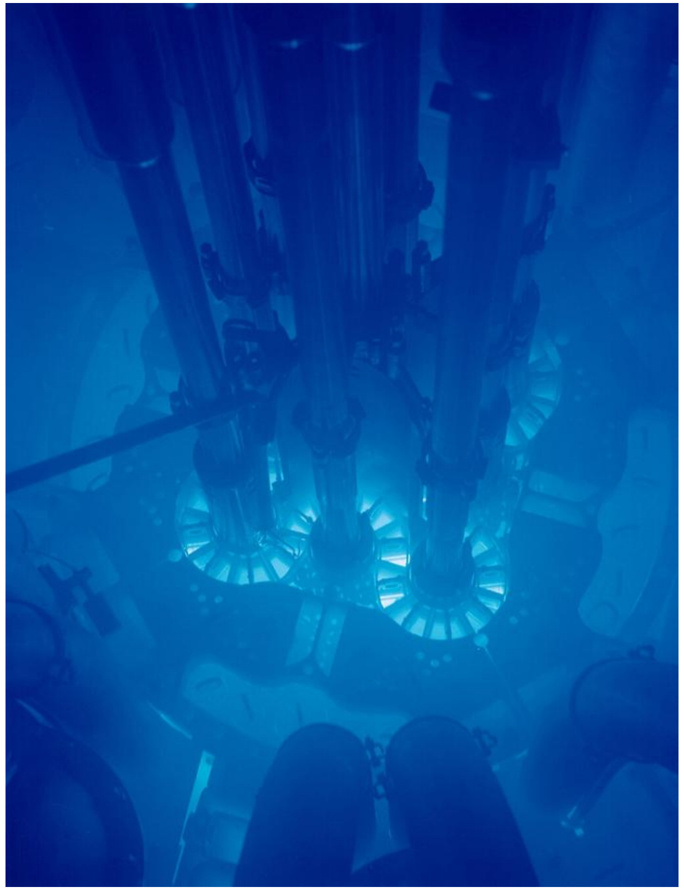
TRIUMF

WNPPC 2025

- Beam Safety Shut-Off System
  - There to detect beam malfunction
    and **stop it in < 10 μs**

- for TRIUMF's ARIEL e-Linac
  - TRIUMF: Canada's particle accelerator center
    TRI-University Meson Facility
  - ARIEL: Advanced Rare Isotope Laboratory
  - e-Linac: Electron Linear accelerator

- based on Cherenkov Fiber
  - optical fiber emitting Cherenkov radiation (photons)
    if particles travel faster than light in the material

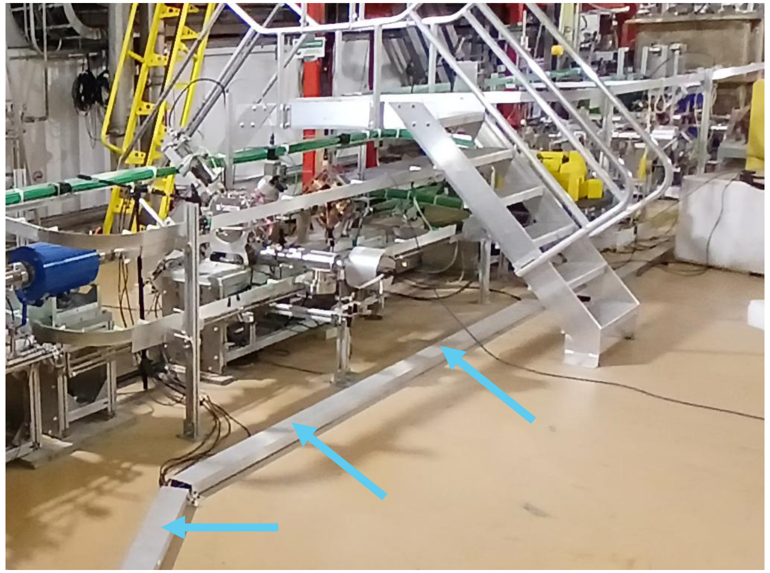


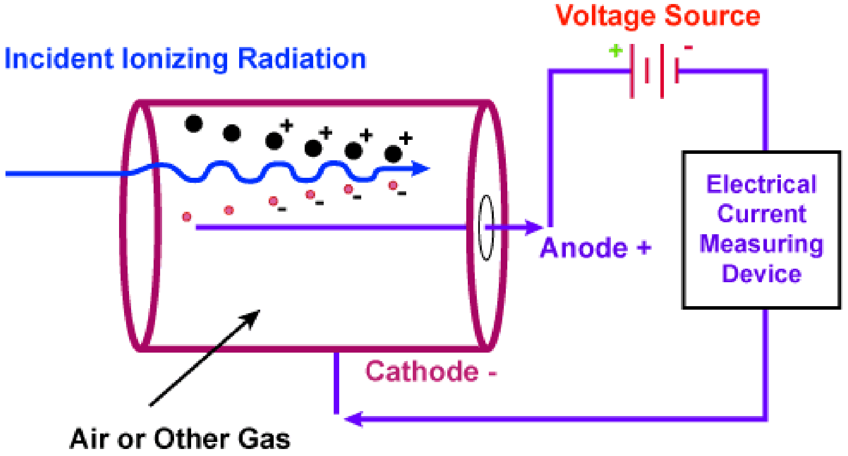
Cherenkov radiation - Wikipedia
Advanced test reactor
Idaho National Laboratory

Beam Loss Monitors

- Long Ionization Chamber (LIC)

  + Variable continuous coverage (1.5m, 2m, 3m)
  + Robust, proven technology (Response of 1m: 22 μC/Gy)
  - Bulky
  - Slowest response
  - Maintenance intensive



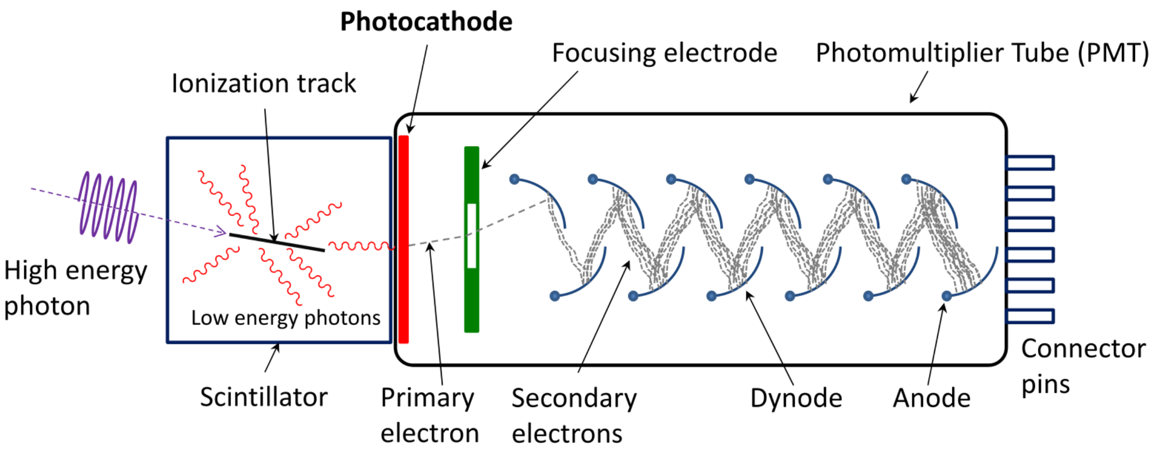


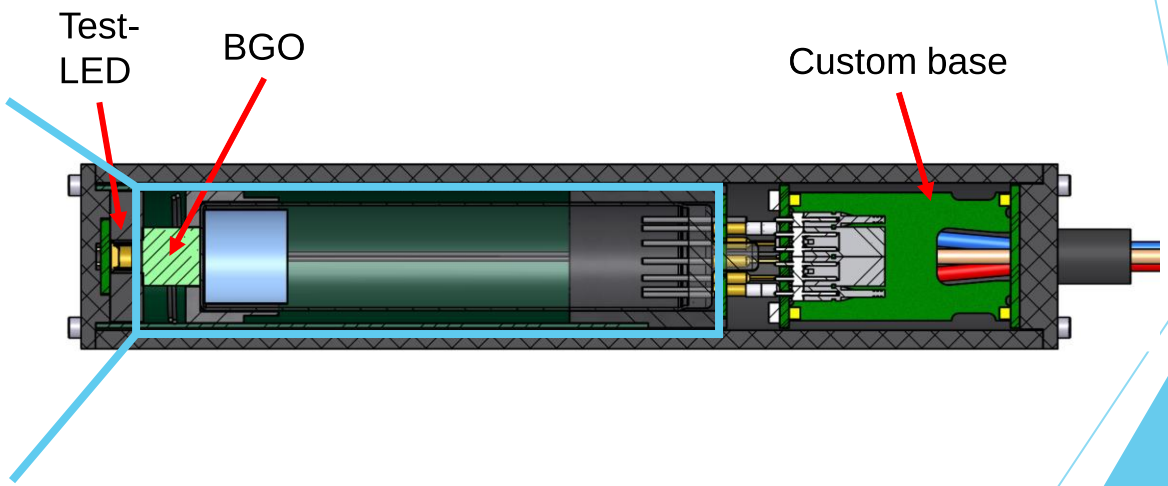
https://electricalvoice.com/ionization-chamber-working/

Beam Loss Monitors

- $Bi_4Ge_3O_{12}$ scintillator coupled to Photo-multiplier tube

+ High sensitivity/precision	(~35 µC/Gy) for chronic beam loss
+ Fast response	(readout is limit)
- Very local information	(multiple needed → costly)
- Electronics close to beam	(aging)
- Long cables necessary	(= capacitor, signal degradation)



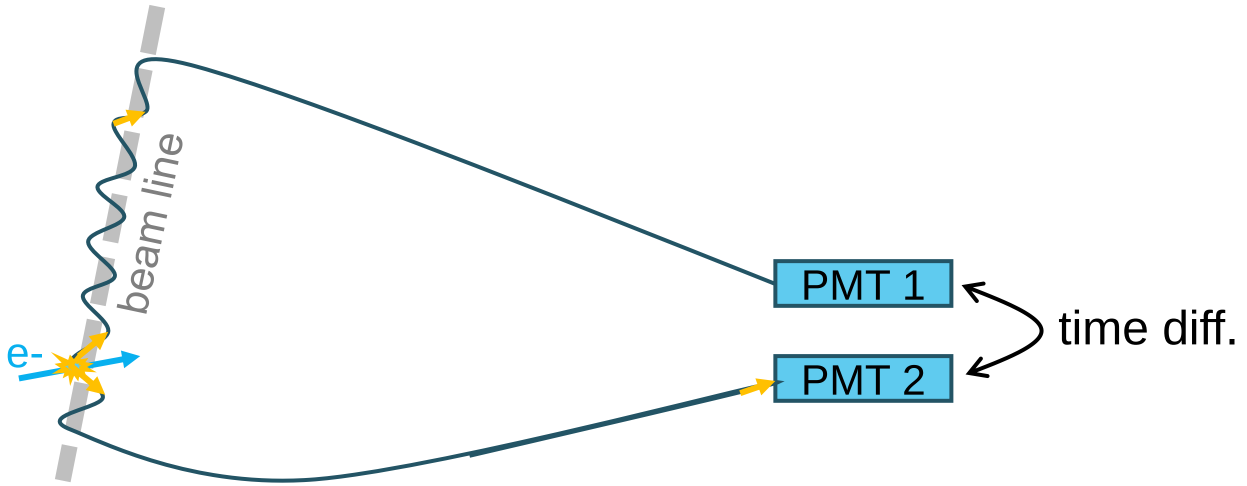


https://instrumentationtools.com/scintillation-counter-principle/

Beam Loss Monitors

- Cherenkov Fiber with PMTs

  - + High flexibility (*complete* beamline, close to beam)
  - + Fast response (readout is limit)
  - + Simple (only two channels)
  - + Electronics outside of hall (easy development/exchange)
  - - Lower sensitivity (x2-x3 smaller then LIC)
  - - Signal loss (attenuation)

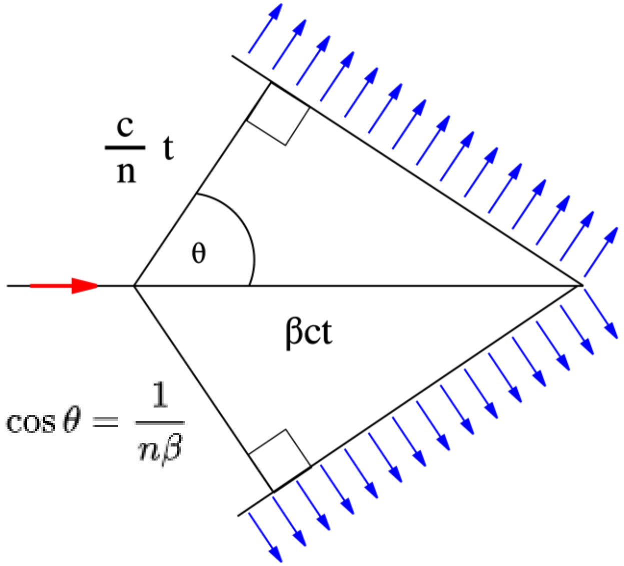


Cherenkov Fiber Principle

- Like a SONIC BOOM in aircrafts.

- If a charged particle passes through a medium with a speed larger than the phase velocity of light in that medium then photons are emitted.

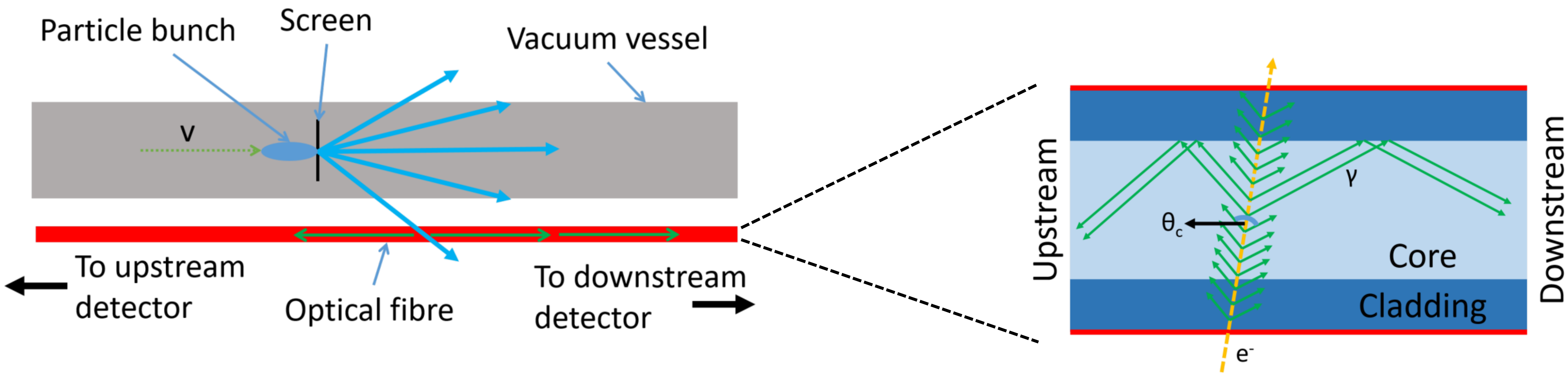
$$\frac{c}{n} < v_p < c$$

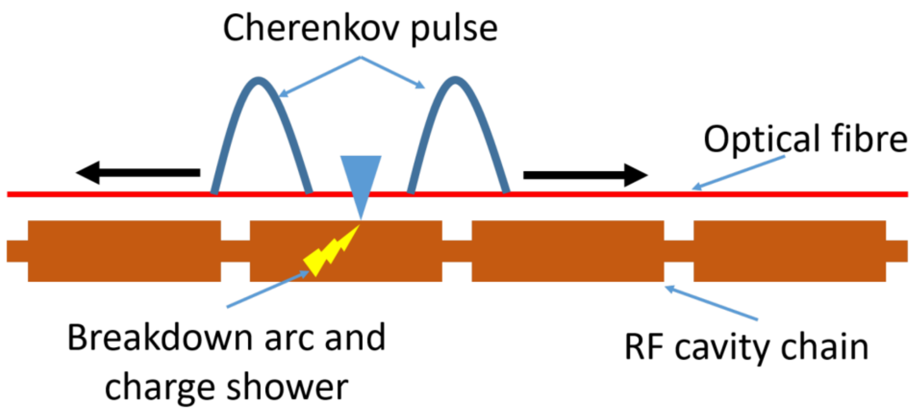


- wavelength of Cherenkov radiation: particle’s speed (β=v/c) and refractive index (n) of the material **not** on the entry angle

BEAM LOSS POSITION MONITOR USING CERENKOV RADIATION, DIPAC 2005 proceedings, M. Koerfer

Cherenkov Fiber Principle

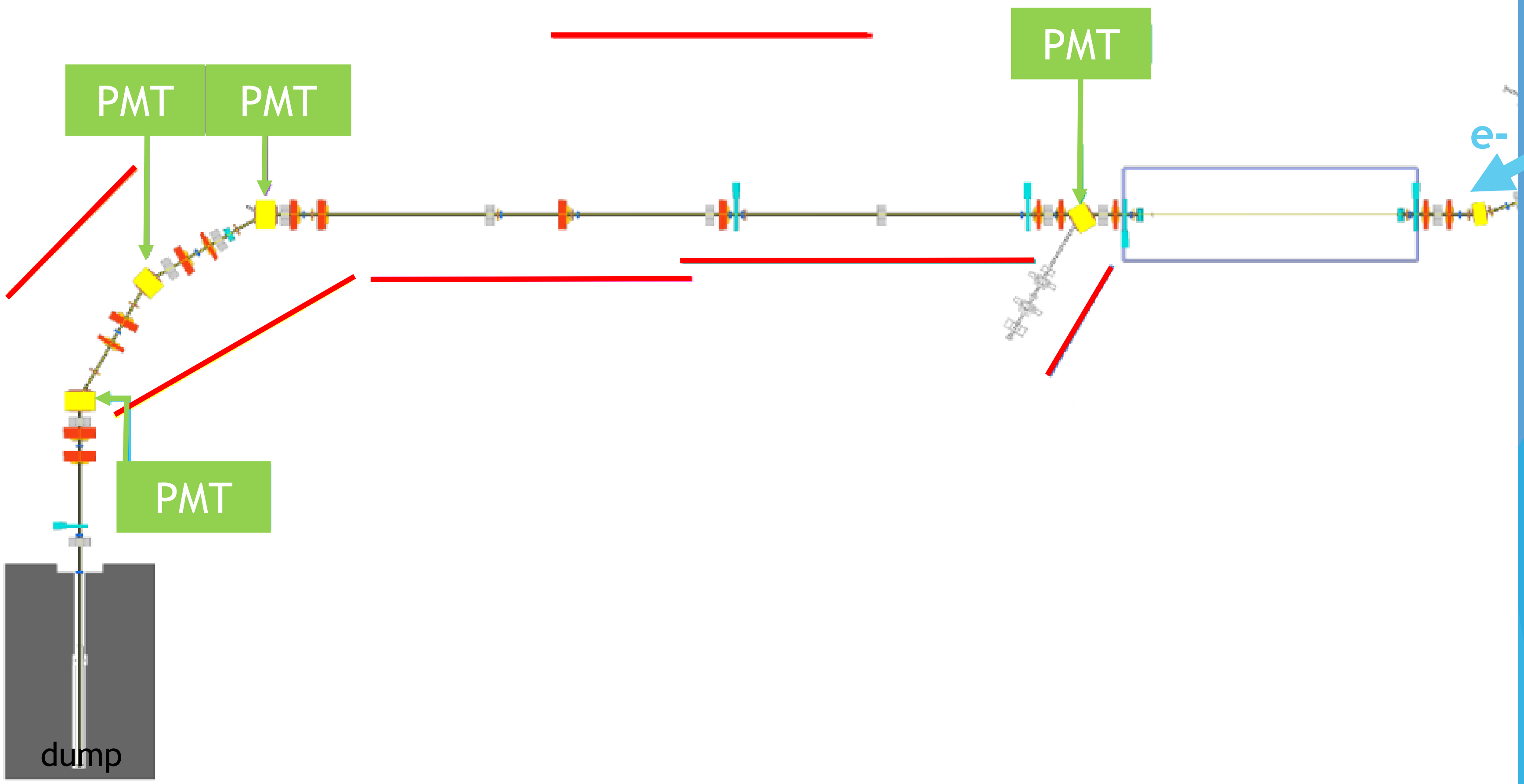




Cherenkov Radiation in Optical Fibres as a Versatile Machine Protection System in Particle Accelerators, 16.02.2023, *J. Wolfenden* et al., *Sensors 2023*, https://doi.org/10.3390/s23042248

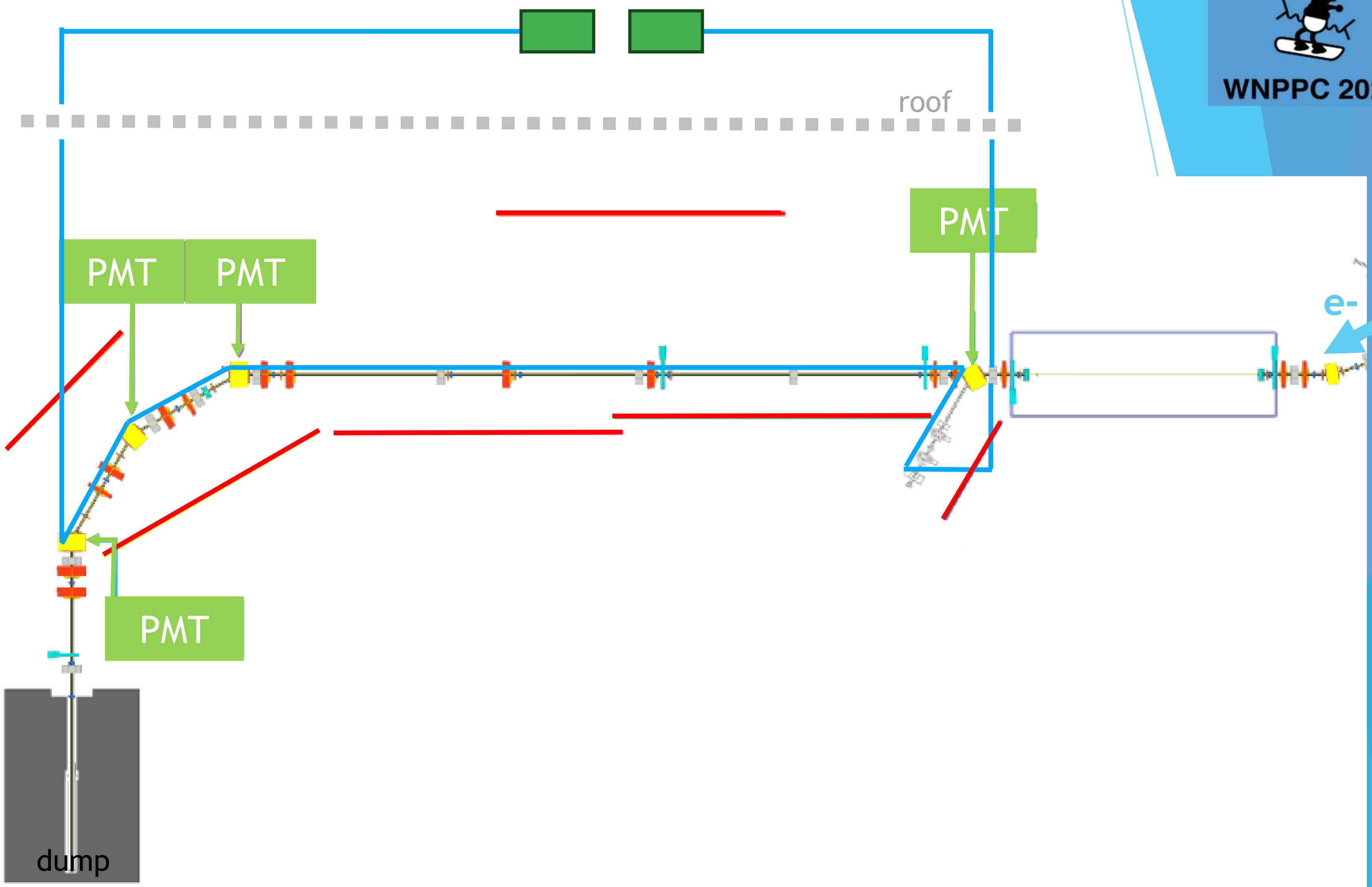
e-Linac Machine Protection Systems

- Existing beam loss monitors:
  - LICs
  - BGOs & PMTs



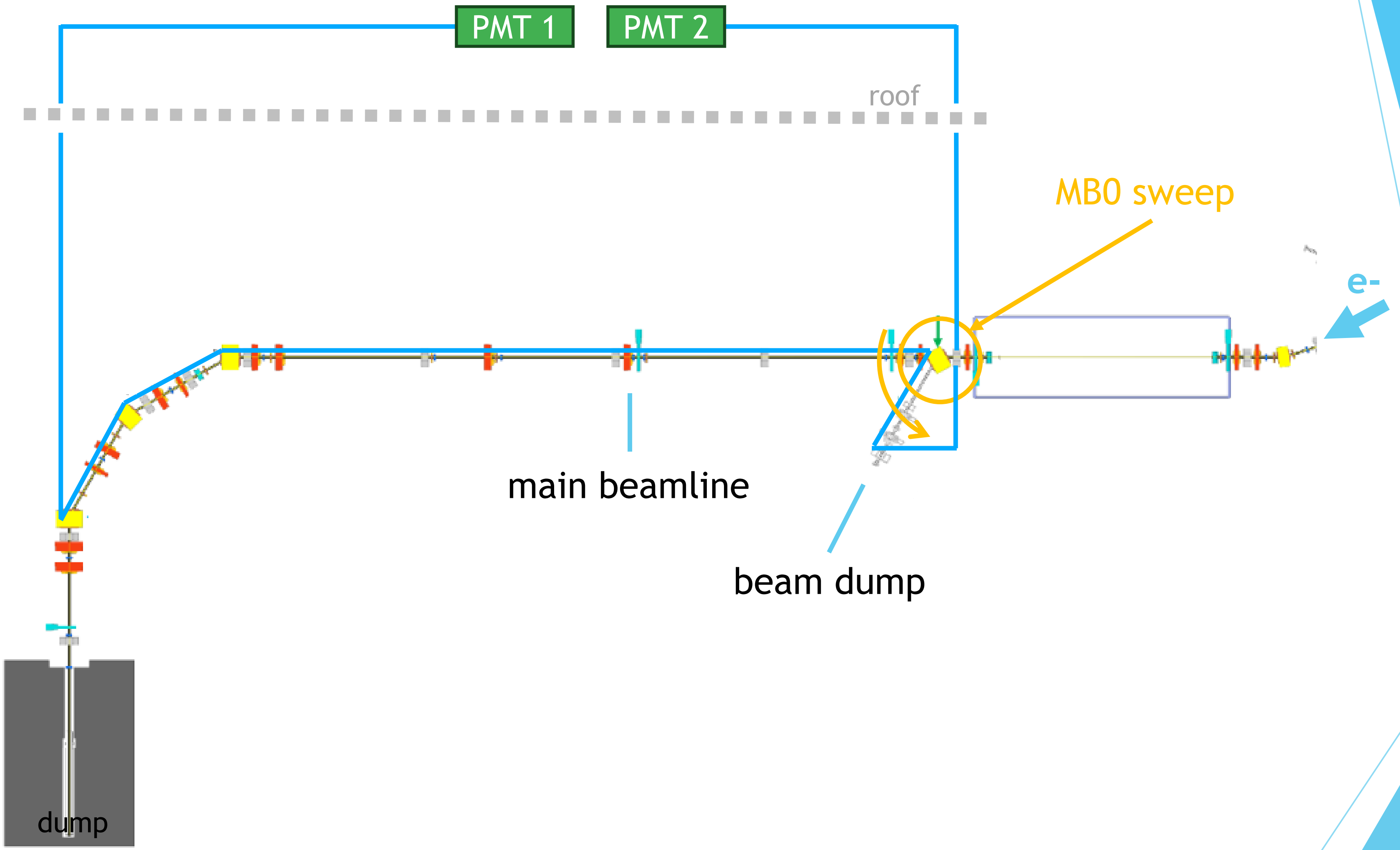
e-Linac Machine Protection Systems

- Existing beam loss monitors:
  - LICs
  - BGOs & PMTs
- Cherenkov Fiber:
  - 1x 100m Fiber + 2x PMT



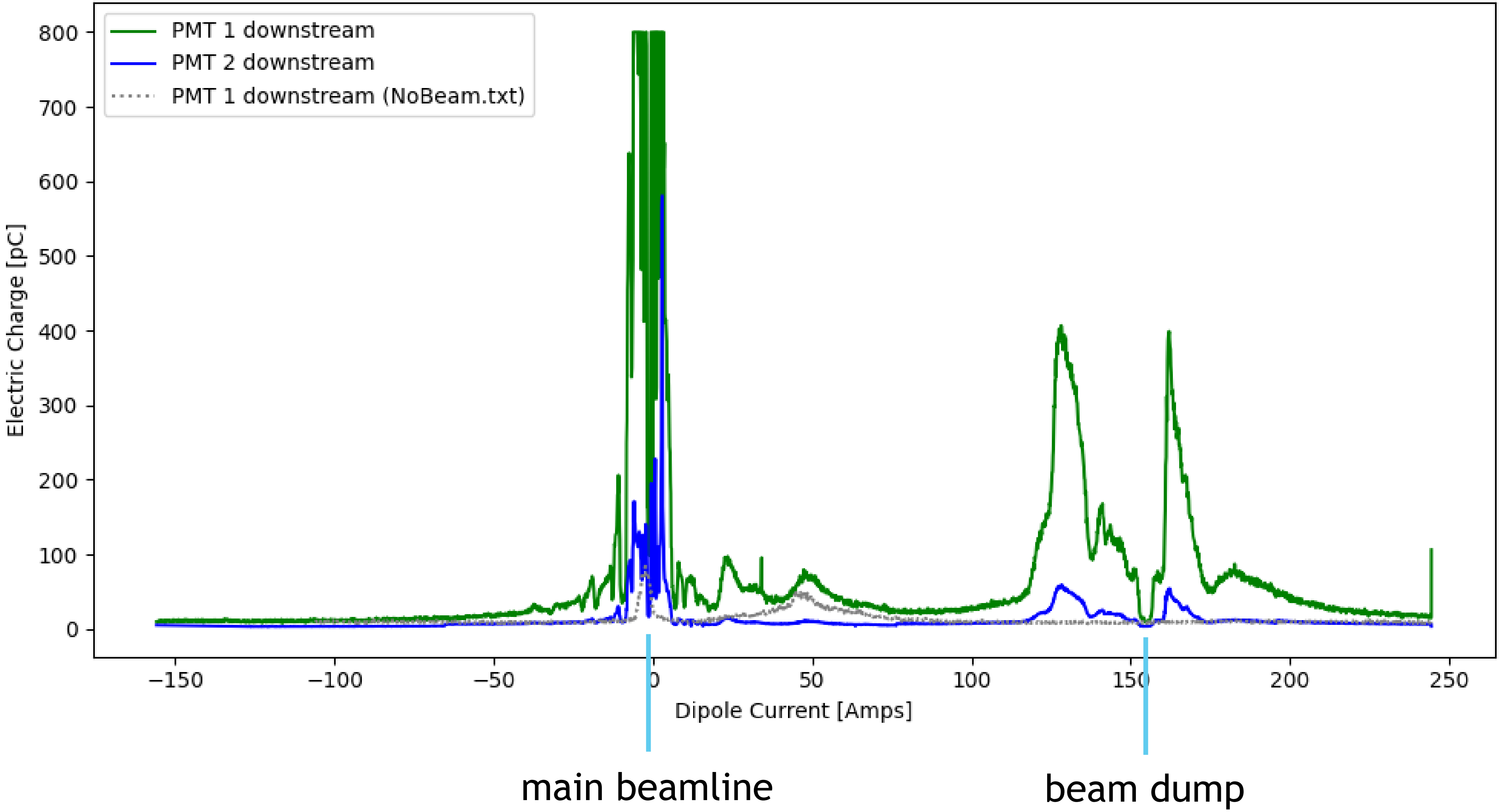
Results so far?

- Sweep Measurement



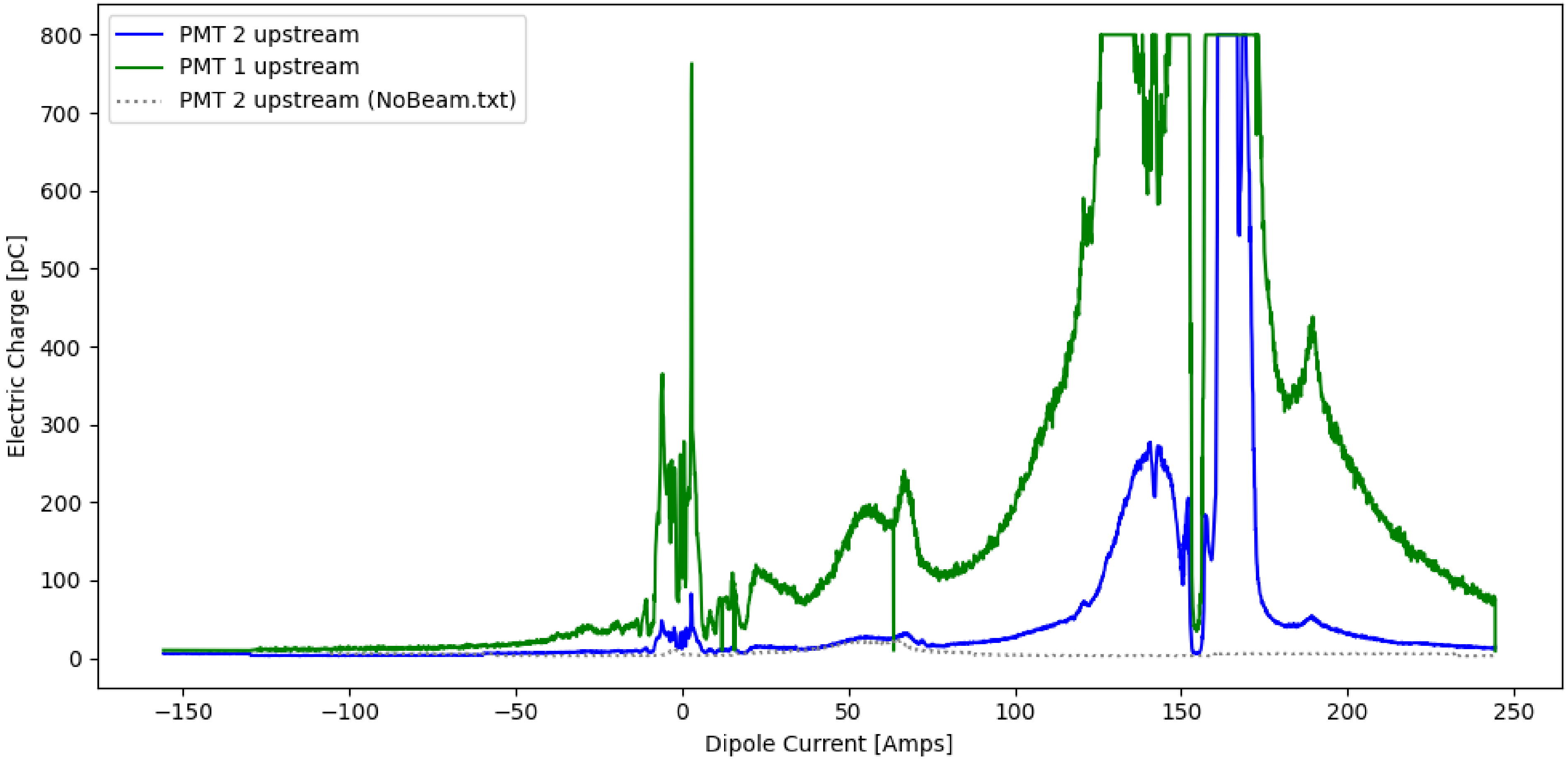
Sweep Measurement

- Shut off: as simple as setting an electric charge threshold (basically plug&play)



Sweep Measurement

- Shut off: as simple as setting an electric charge threshold (basically plug&play)



- Signal is different up- and downstream (as expected)

Conclusion

- Proof of Concept (=could work already) ✓

- Advantages of Cherenkov Fiber over current system (LICs or BGO&PMTs):
  - Adjustable: just a fiber, hardly any space consumption, can be fed through magnets or placed very close.
  - Scalable: one system with two PMTs for whole beamline
  - Cost effective: only two channels necessary
  - Less complex: great for development, change/test electronics on the fly

- Up next:
  - Proof and improve time delay measurement for **position measurement**
  - Better materials: replace old PMT, change to double cladding fiber, implement RedPitaya
  - Extra fiber with windings only close to Cryo to subtract background
  - Test if protons give distinguishable signal to electrons

TRIUMF

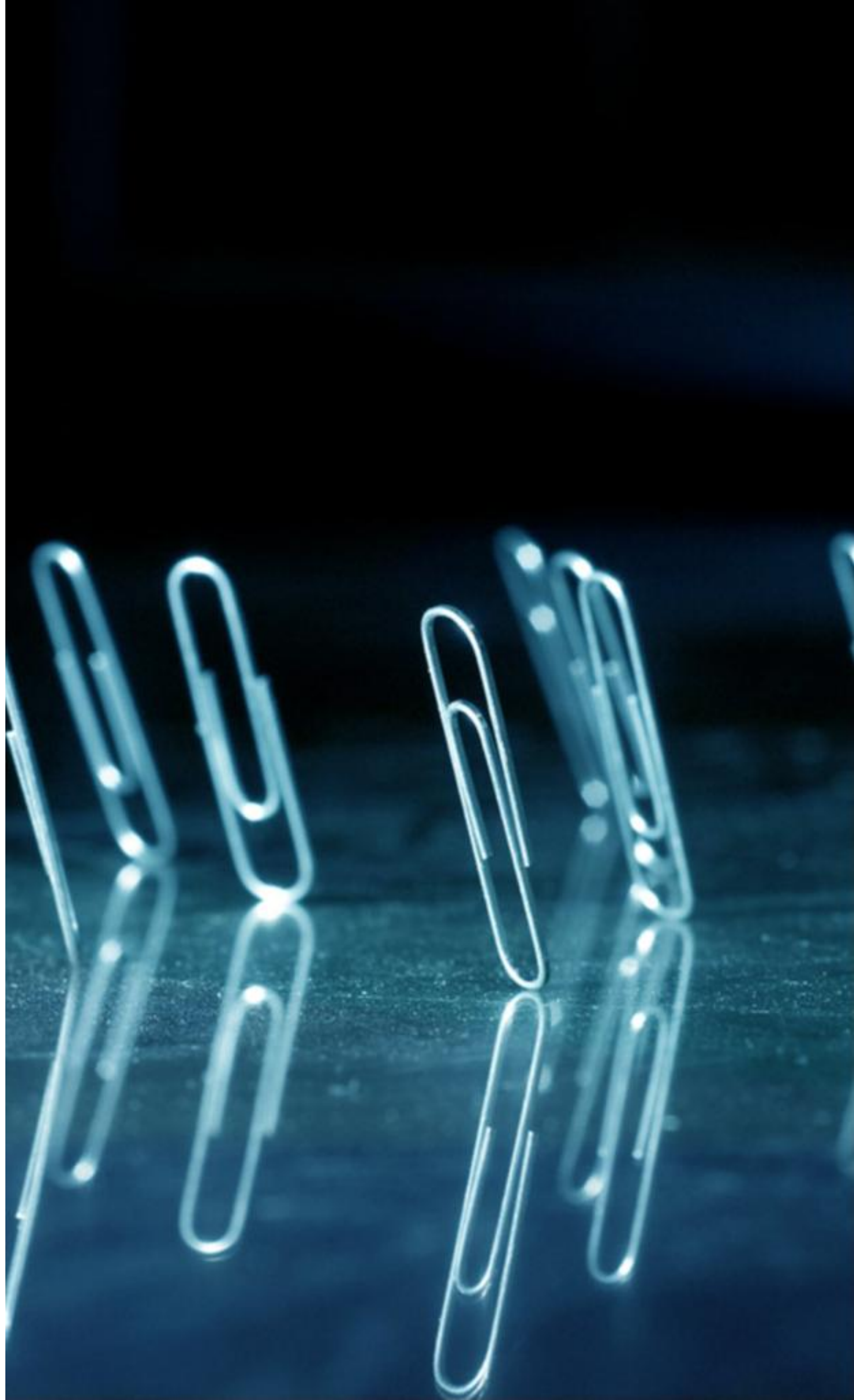
Thank you
Merci

Contact: *Richard Hermann*

rhermann2@triumf.ca

www.triumf.ca

Follow us **@TRIUMFLab**

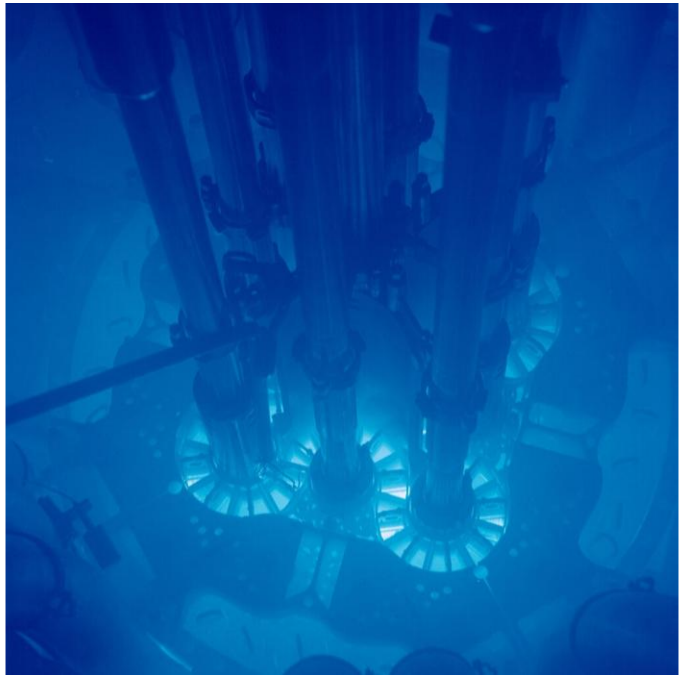


Appendix

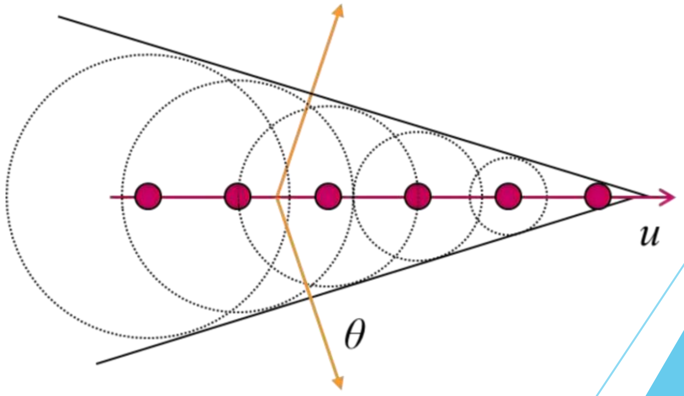
- Extra Slides

Machine Protection System

- Beam Safety Shut-Off System
  - There to detect beam malfunction and **stop it in < 10 μs**
- for TRIUMF's ARIEL e-Linac
  - TRIUMF: Canada's particle accelerator center
    TRI-University Meson Facility
  - ARIEL: Advanced Rare Isotope Laboratory
  - e-Linac: Electron Linear accelerator
- based on Cherenkov Fiber
  - optical fiber emitting Cherenkov radiation (photons) if particles travel faster than light in the material



Cherenkov radiation - Wikipedia
Advanced test reactor
Idaho National Laboratory



Stanford 2014, lecture H. Alaeian

Comparison

	Advantages	Disadvantages
LIC	Proven technology, sensitive, robust	Slowest response, bulky, maintenance-intensive Individual channels – more expensive
BGO&PMT	Fast response, flexible, high precision, very sensitive	very local information, many needed → costly, electronics close to beam (aging), long cables necessary – basically large capacitor, degradation of signal, Individual channels – more expensive
Cherenkov	Fast, flexible, simple, suitable for large setups, accessibility to hall, test different pmts on the fly, great for development, …, cheaper as for two channel	lower sensitivity, signal loss

Individual channels
More expensive, …

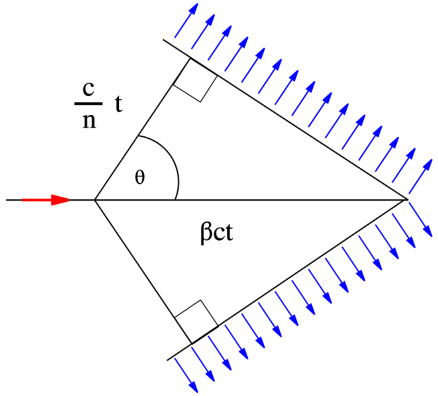
Cherenkov Fiber Principle

- Like a 

 in aircrafts.

- If a charged particle passes through a medium with a speed larger than the phase velocity of light in that medium then photons are emitted

$$\frac{c}{n} < v_p < c$$



$$\cos\theta = \frac{1}{n\beta}$$

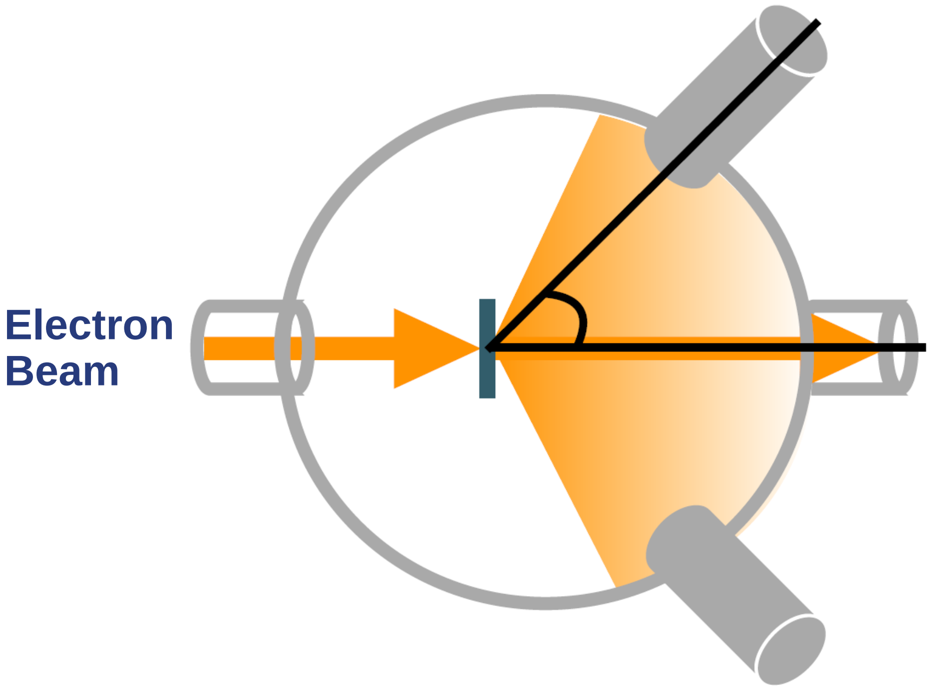
- wavelength of Cherenkov radiation: particle's speed (β=v/c) and refractive index (n) of the material **not** on the entry angle
  - → Emitted spectral range remains unchanged
  - → Spatial and directional distribution of the emitted photons can vary with the angle.
  - → May be used to distinguish different particles via the different emission spectra (e.g. protons and electrons)

$$\frac{d^2E}{dx\,d\omega} = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right)$$

BEAM LOSS POSITION MONITOR USING CERENKOV RADIATION, DIPAC 2005 proceedings, M. Koerfer

e-Linac use cases (high intensity electron beam)

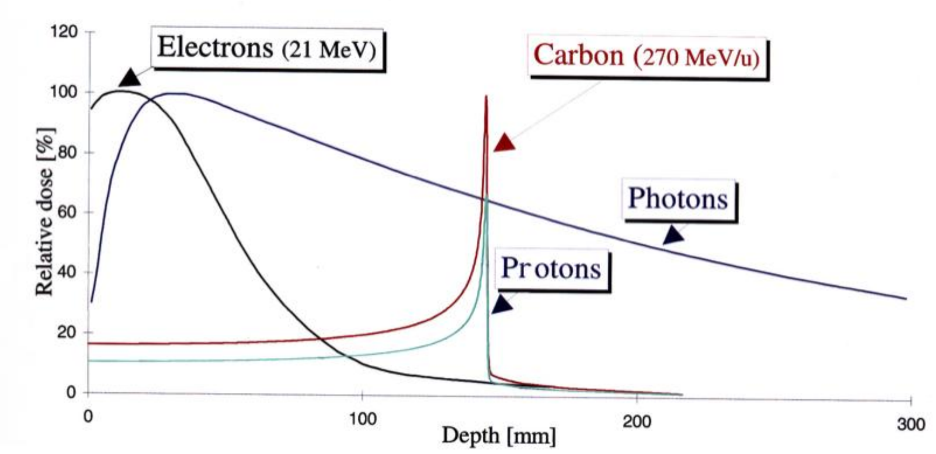
- DarkLight
  - ATOMKI experiment with Beryllium 8 observed hypothetical X17 Boson (mass 17 MeV/c2)
  - Electrons on thin target (Tantalum, C12-foil, Be8) shall create γ and X17
  - Min. 30MeV, 300uA, 10kW, **1000h cw**
- FLASH
- THz



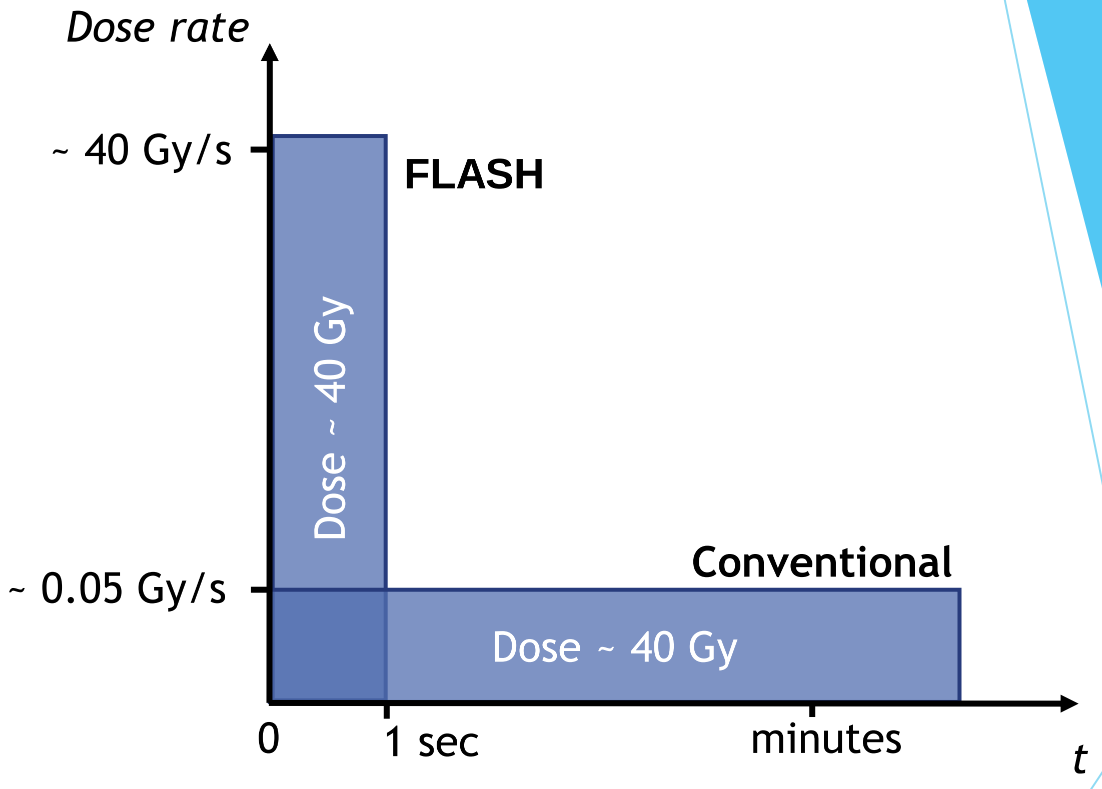
K. Pachal: "The DarkLight experiment at TRIUMF and the hunt for a new boson"

e-Linac use cases (high intensity electron beam)

- DarkLight
- FLASH
  - Ultra high dose rate (UHDR) radiotherapy
  - Reduced damage in healthy tissue (L.Egoriti 2022)
  - Higher patient security (movement)
- THz



https://www.quantumdiaries.org/.../bragg-peak-3/

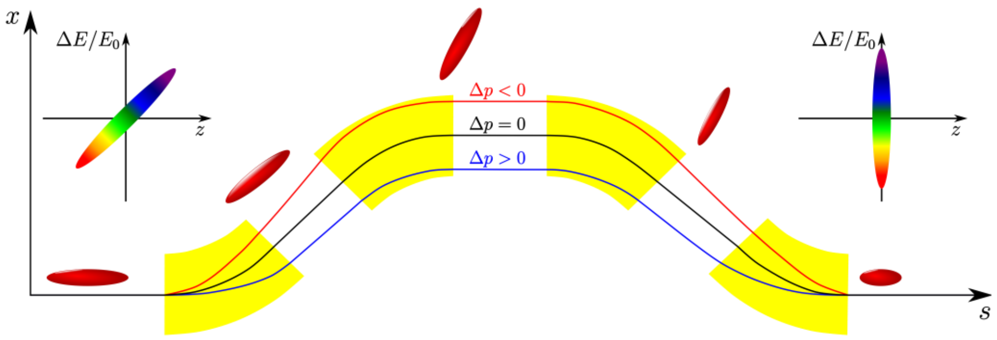


S. D. Rädel, "Status and Future Perspective of the TRIUMF E-Linac", 2019

e-Linac use cases (high intensity electron beam)

- DarkLight
- FLASH
- THz
  - Sub mm high charge electron bunches (THz wavelengths are 100µm – 1mm)
  - Extents the Spectroscopy range
  - For now, used for beam tuning
  - Pre-requisite for energy recovery

Bunch compressor for high intensity

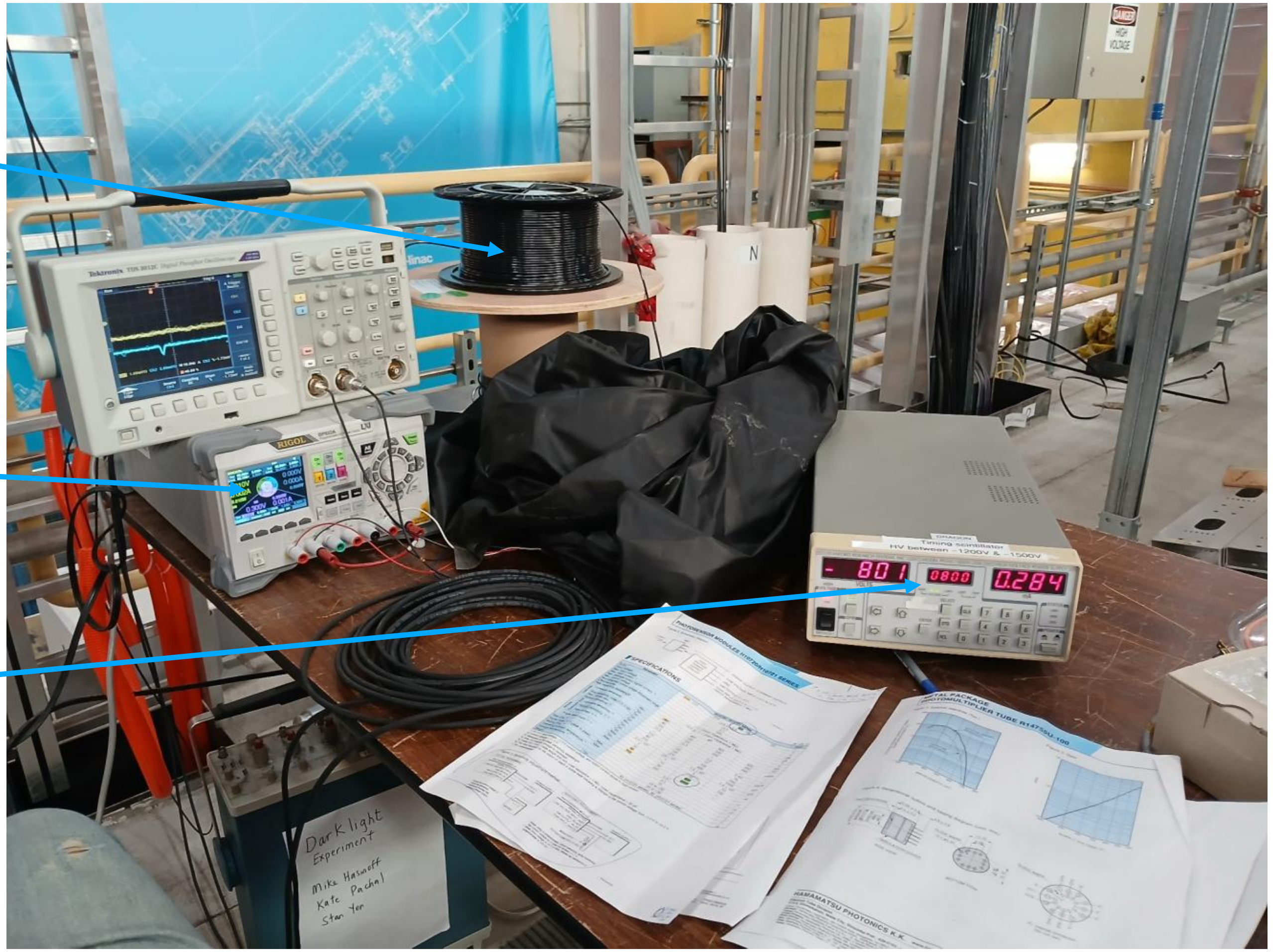


S. D. Rädel, "Status and Future Perspective of the TRIUMF E-Linac", 2019

Pathway

Setup

- Quartz-fiber
- PMTs:
  - "New" (designed 2016)
    H10720 series
    ~0.7V with 5V bias
  - "Old" (designed 2000)
    R14755U-100
    ~800V



2024-12-05 Results

TRIUMF

WNPPC 2025

- Viewscreen in the beam upstream EABT:VS1
- Signal for both channels, even with visible time shift
- → ~300ns