CERN concept for high energy, heavy ion dosimetry

20.04.2023

HEARTS WP4 Knowledge transfer meeting

https://indico.cern.ch/event/1255543/

HEARTS

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/ CERN

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under GA No 101082402.

Acknowledgements

- Eliott Johnson: CERN accelerator complex, PS operation
- Kacper Bilko: Beam transversal profile, spill and intensity analysis
- Natalia Emriskova: Si diode setup, spill analysis
- Andrea Coronetti: SRAM memories as flux monitors
- Ruben Garcia Alia: heavy ion activity@CERN coordination
- Federico Ravotti: IRRAD coordinator
- Inaki Ortega Ruiz, Federico Roncarolo, Jocelyn Tan: Beam instrumentation support

Outline

1. HEARTS WP4 context
2. CERN beam line operation, layout and existing beam instrumentation
    - Accelerator complex
    - PS operational aspects: users, beam energy and intensity
    - Transfer line infrastructure (T08 and CHARM)
    - Beam instrumentation overview
    - Data visualisation and logging
3. CERN diode system for dosimetry: experience with VHE ion beams, status and plans
4. Summary and outlook

HEARTS WP4 Context

- **WP4 objectives**: Streamlined and efficient **access** to the accelerator facility, especially for industrial partners, requires a precise **standardisation of the beam instrumentation** in terms of beam **delivery, online monitoring**, **target station remote controlling and dosimetry**. In this WP, we will define and calibrate the beam delivery sensors at GSI and CERN for both shielding material and microelectronics. Dosimetry activity will include both monoenergetic ions and the full GCR spectrum characterisation.

HEARTS WP4 Context

- **Task 4.1:** Knowledge transfer between CERN and GSI (CERN, GSI, M1-12)
- **Task 4.2:** Calibration of beam instrumentation for VHE ion beam extraction (CERN, M1-24)
- **Task 4.6:** Intercomparison between CERN and GSI (CERN, GSI, M24-48)

- **D4.1 (M12):** Beam instrumentation for high-energy low intensity heavy ion beam characterization
- **D4.2 (M24):** Calibrated CERN beam instrumentation documented and installed in the accelerator

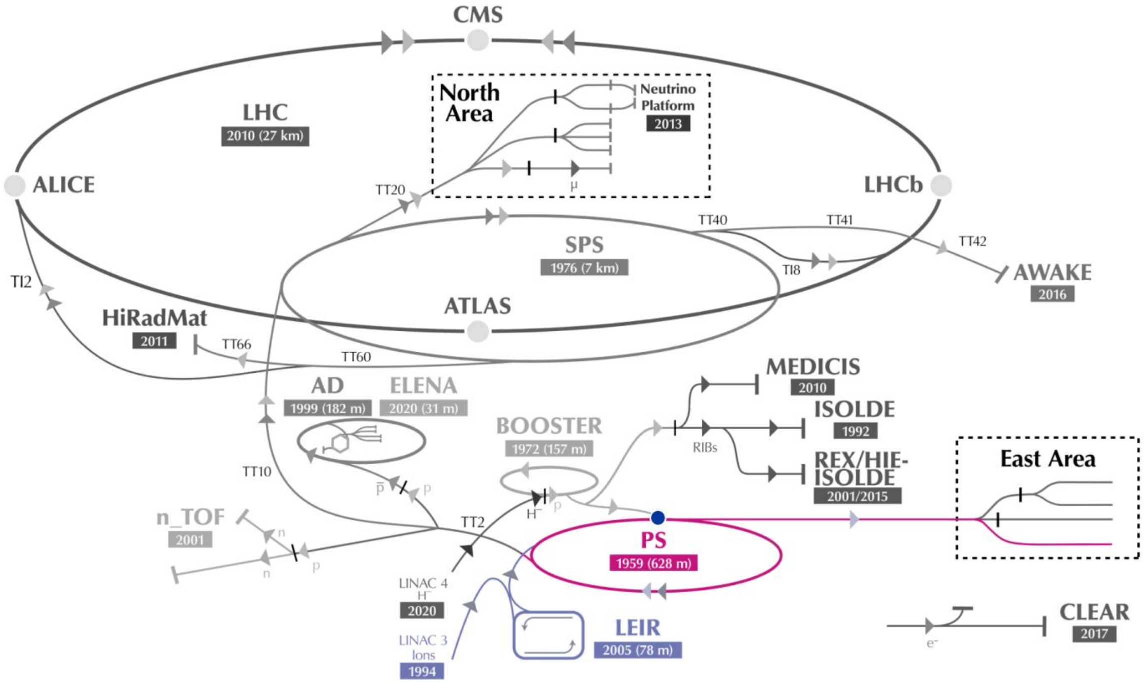
- **M12**: CERN beam instrumentation and dosimetry installed and running

CERN beam line operation, layout and existing beam instrumentation

- Accurately measuring the beam profile and intensity/flux during irradiation is essential in order to perform quantitative radiation effects measurements
- Fortunately, the T8 line in the PS East Area is well equipment with “standard” CERN beam instrumentation
- However, these instruments are tailored to and calibrated against high intensity proton beams, as opposed to low intensity ion beams
- Considerable efforts need to be made to complement and calibrate these standard beam instruments → **HEARTS WP4**

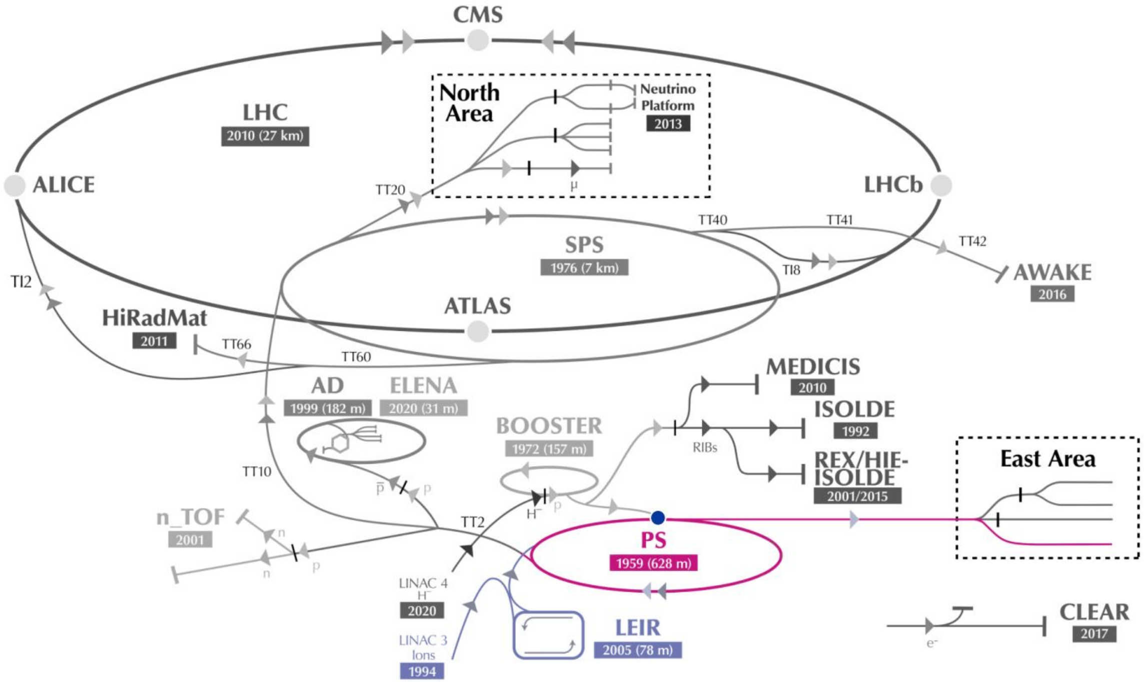
CERN beam line operation, layout and existing beam instrumentation

- HEARTS will only be active in the colored part of the accelerator complex
- However, beams are extracted from the Proton Synchrotron for many other beam lines and accelerators (=”users”)!



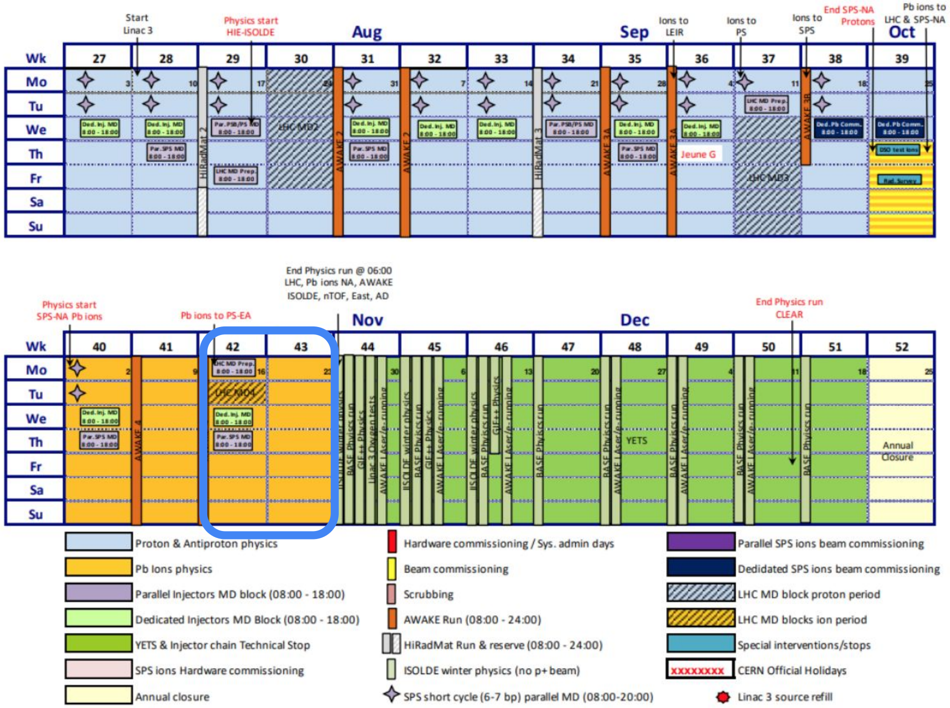
CERN beam line operation, layout and existing beam instrumentation

- The PS beam can be setup in “supercycles”, composed of cycles attributed to individual users, allowing parallel operation.
- Machine reproducibility is a challenge though! Careful programming of supercycle is required
- Generally, each user has attributed a combination of **beam particle, energy** and **destination**
- Extraction intensity can be varied for the same user profile (see later)



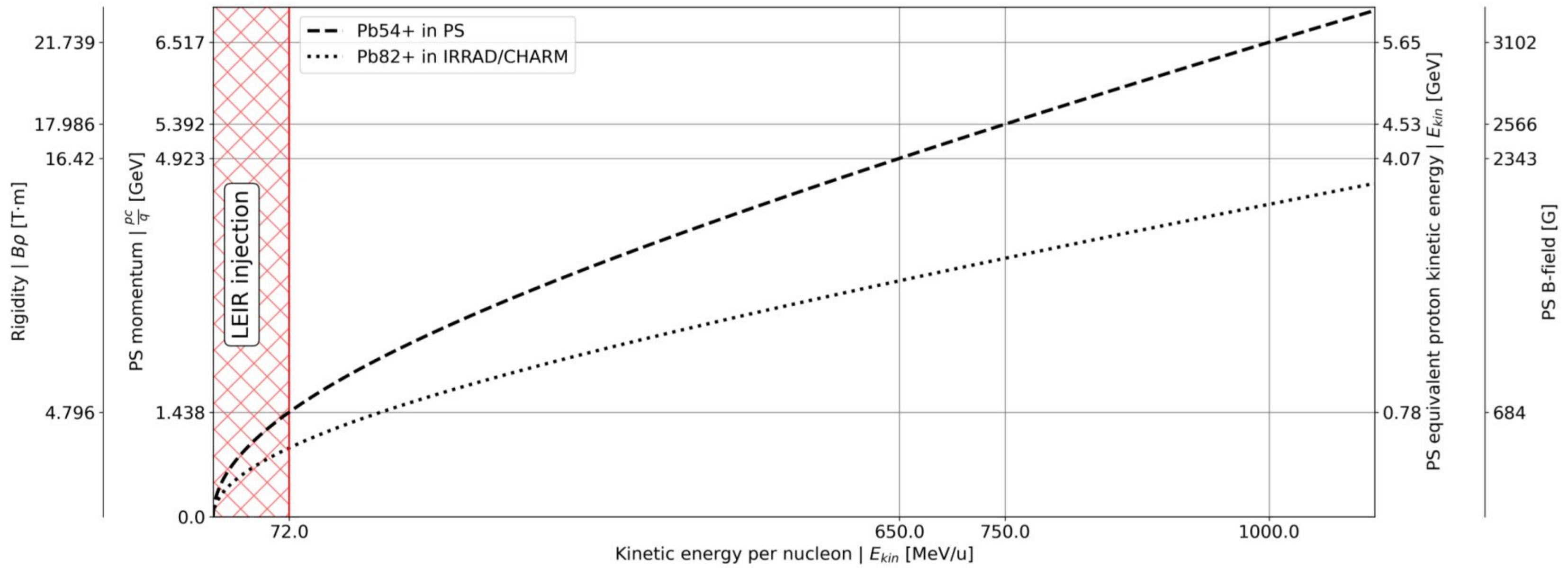
CERN beam line operation, layout and existing beam instrumentation

- 2023 injector schedule: two weeks of Pb ions in PS East Area between October 16th and 29th.



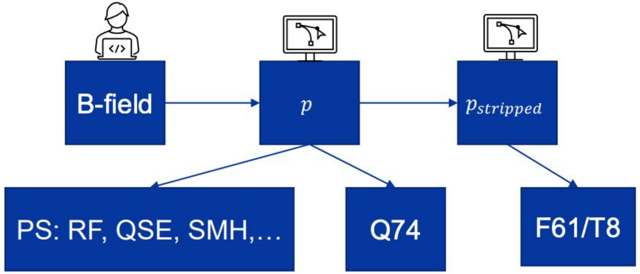
CERN beam line operation, layout and existing beam instrumentation

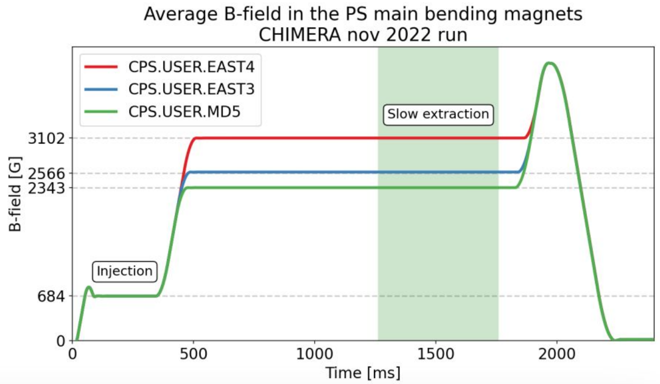
- PS and extraction lines used in general for protons, not ions!



CERN beam line operation, layout and existing beam instrumentation

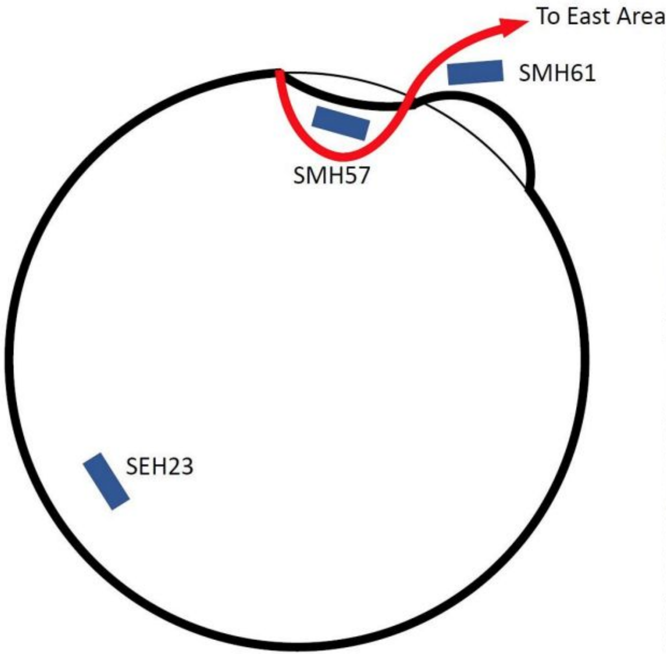
E_{kin} [MeV/nucleon]	$\frac{pc}{54}$ [GeV]	$\frac{pc}{82}$ [GeV]	PS B-field [G]	USER
1000	6.517	4.292	3102	CPS.USER.EAST4
750	5.392	3.551	2566	CPS.USER.EAST3
650	4.923	3.242	2343	CPS.USER.MD5

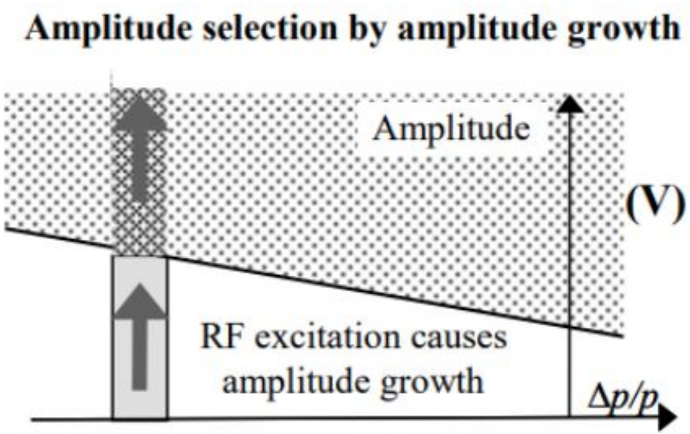




- Continuous energy requires automatic scaling which has been achieved for the energy range we are interested in (100s MeV/n - 1 GeV/n)
- Direct mapping of PS magnet strengths to T08 magnet strengths
- Script: ramp beam energy removes need for several users

CERN beam line operation, layout and existing beam instrumentation



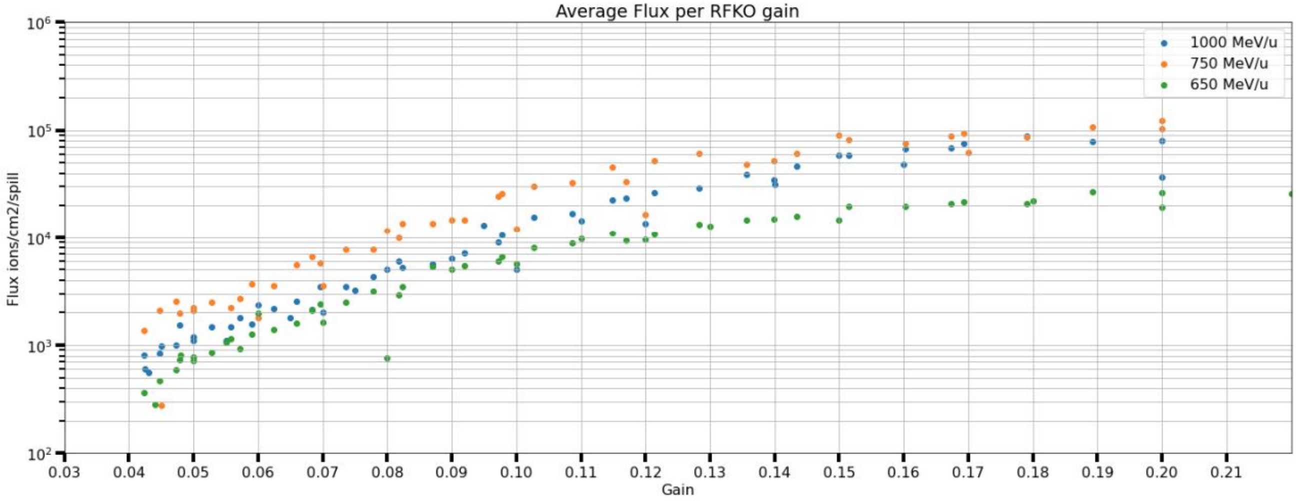


RF Knock Out extraction technique

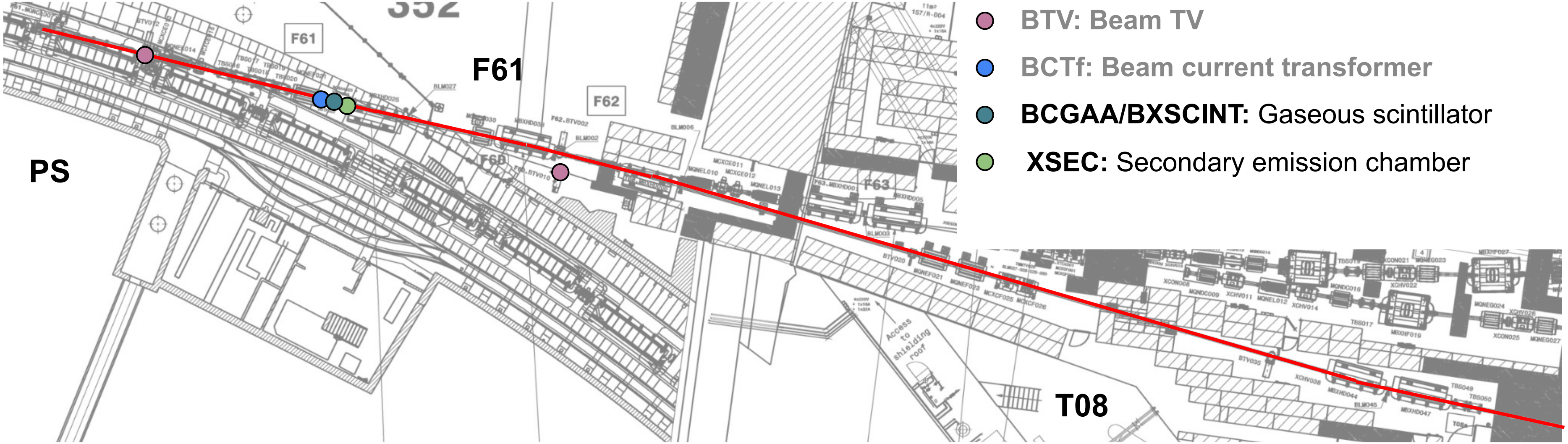
- Constant extracted beam optics
- RF Excitation with transverse damper
- No bunch rotation (small dp/p)
- More stable at different energy
- Easier control of the beam intensity

CERN beam line operation, layout and existing beam instrumentation

- Single variable to change intensity = voltage gain on transverse feedback system (TFB) plates. This allows an **easy control** of the intensity.
- Calibration with diode allows to convert from XSEC amplitude to ions/spill (see later)

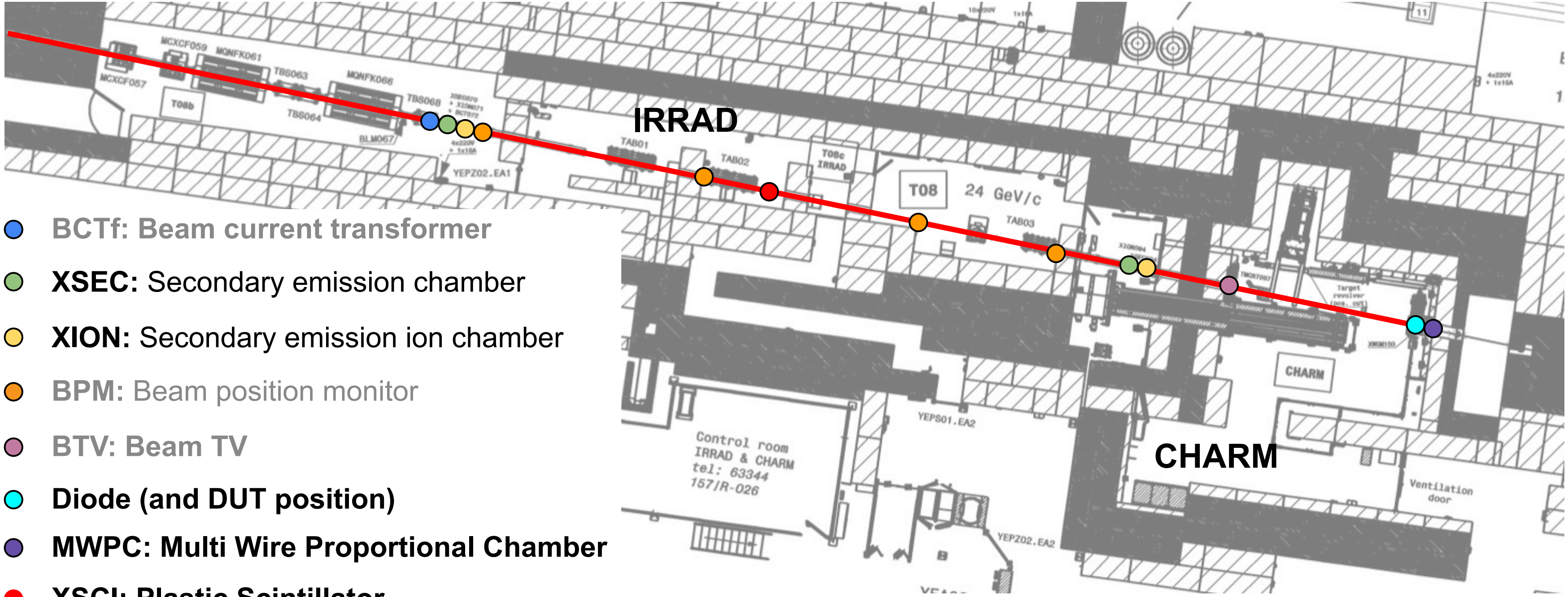


CERN beam line operation, layout and existing beam instrumentation



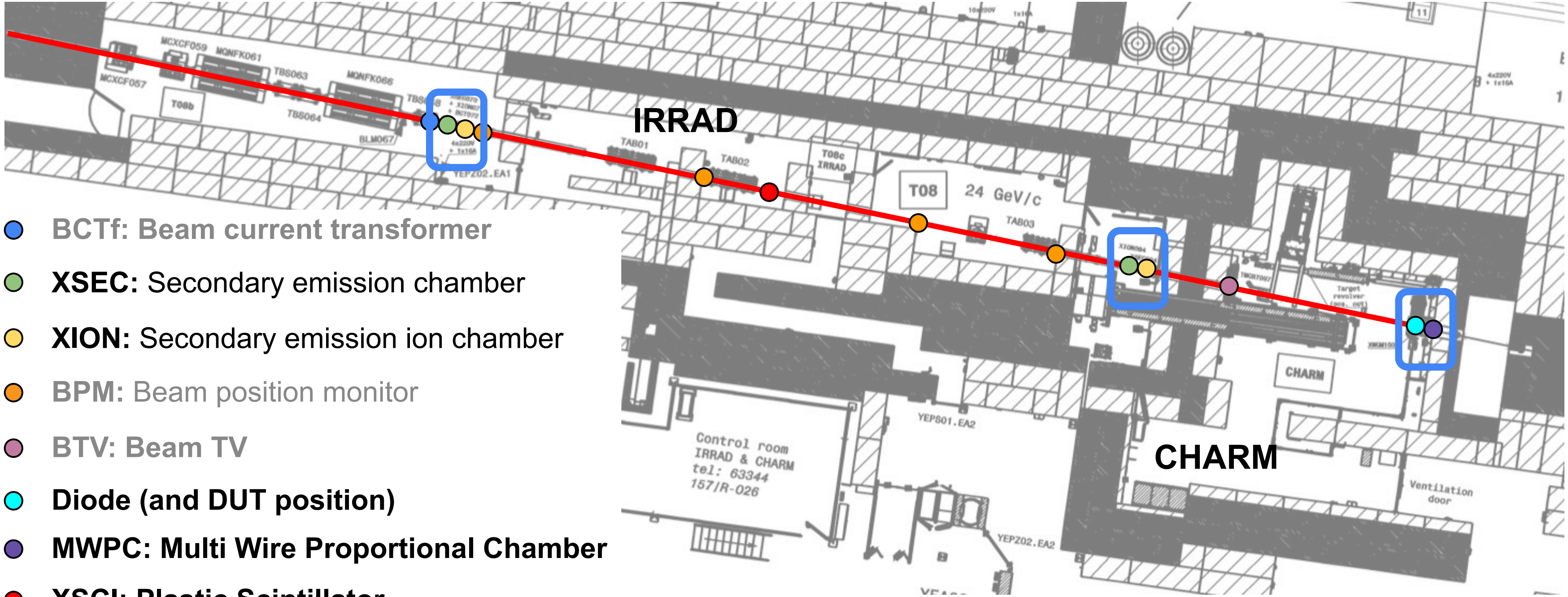
- BTV: Beam TV
- BCTf: Beam current transformer
- **BCGAA/BXSCINT:** Gaseous scintillator
- **XSEC:** Secondary emission chamber

CERN beam line operation, layout and existing beam instrumentation



- **BCTf: Beam current transformer**
- **XSEC:** Secondary emission chamber
- **XION:** Secondary emission ion chamber
- **BPM:** Beam position monitor
- **BTV: Beam TV**
- **Diode (and DUT position)**
- **MWPC: Multi Wire Proportional Chamber**
- **XSCI: Plastic Scintillator**

CERN beam line operation, layout and existing beam instrumentation



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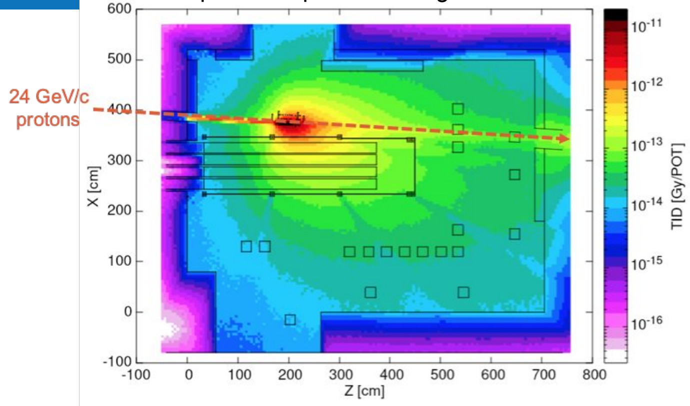
CERN beam line operation, layout and existing beam instrumentation

- **CHARM = CERN High-energy AcceleRator Mixed field**
- Radiation test facility at CERN used to qualify components and systems mainly for Large Hadron Collider (LHC) accelerator applications.
- The radiation field is generated through the interaction of a 24 GeV/c proton beam from the PS with a metallic target.
- The mixed-field environment resembles that present in the vicinity of a high-energy accelerator and can be adapted to the application conditions by selecting different test configurations/locations.
- Infrastructure for electronics testing is present
- Heavy ion beam extracted from the PS sent to CHARM in-beam position, i.e. no target
- Improved user integration and service is a key objective, also related to this is RP aspect: running at low fluxes will allow us to be more flexible for setup and installations in CHARM

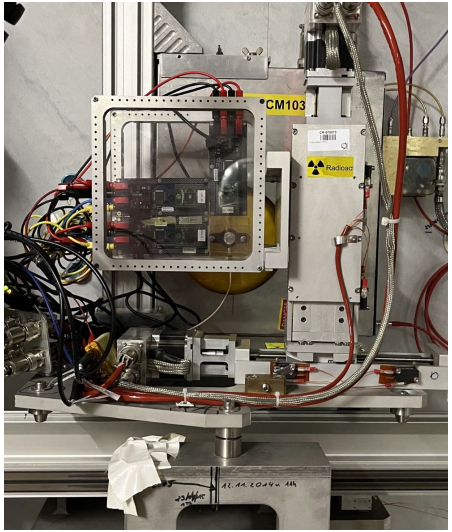
Courtesy D. Prelipcean
https://ieeexplore.ieee.org/document/9762483

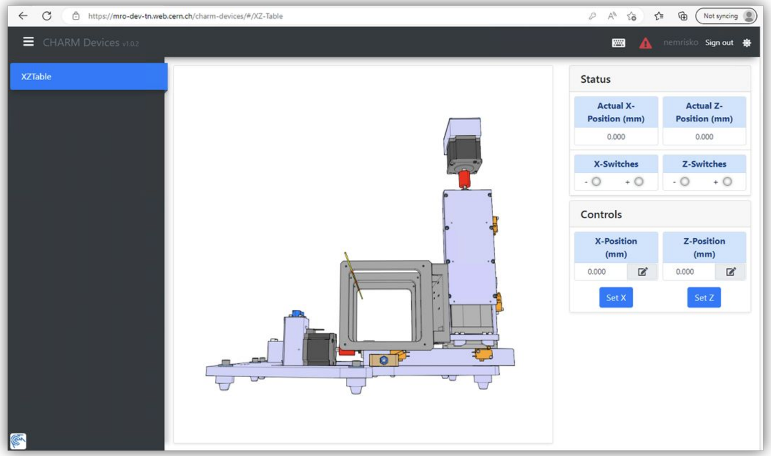


CERN beam line operation, layout and existing beam instrumentation

- **Our “target station” in CHARM -> support to place devices under test**

“MONTRAC” allows test setup (3 frames) to be placed outside of radiation zone, moved in on rail

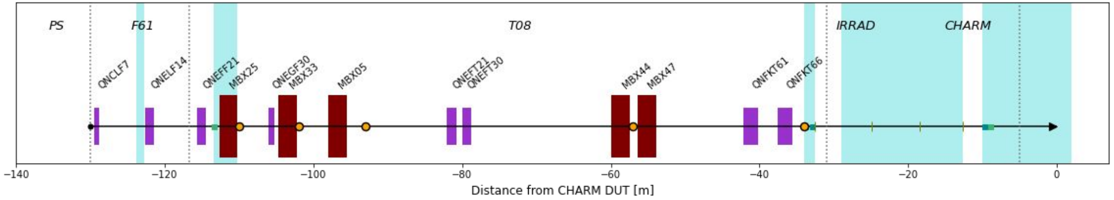


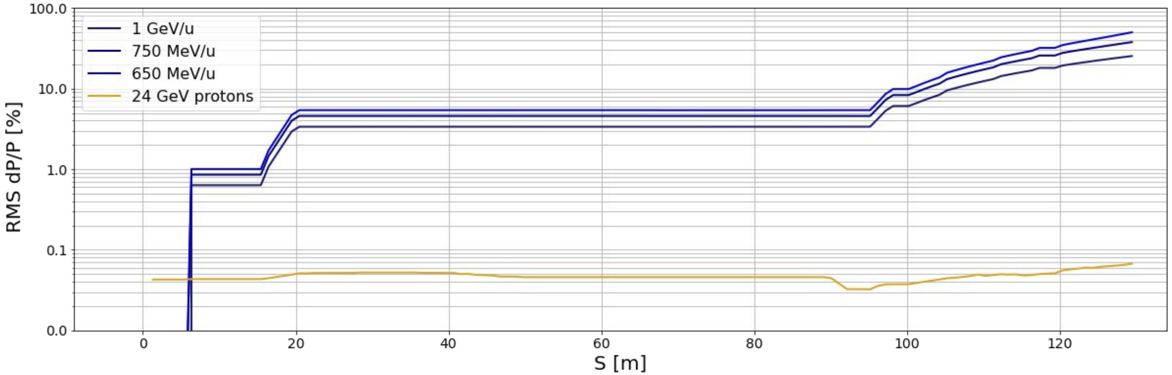


Remote control of XY translation table

CERN beam line operation, layout and existing beam instrumentation

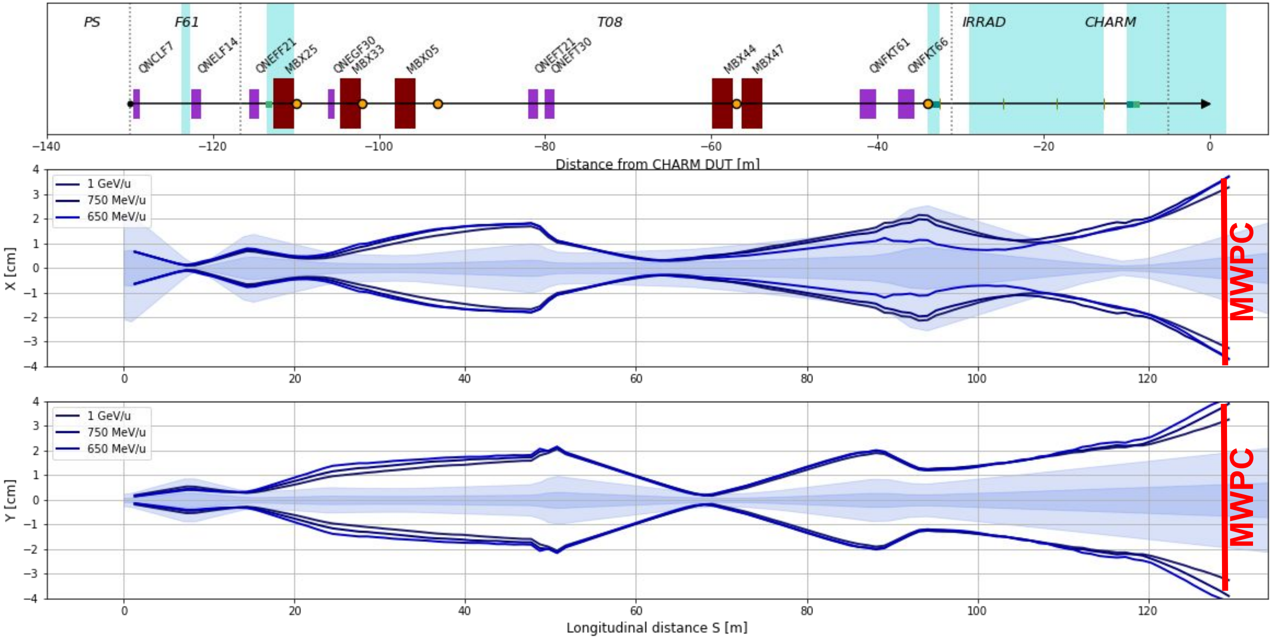
- Effect of beam line: energy straggling! Beam is significantly degraded by the time it reaches DUT position





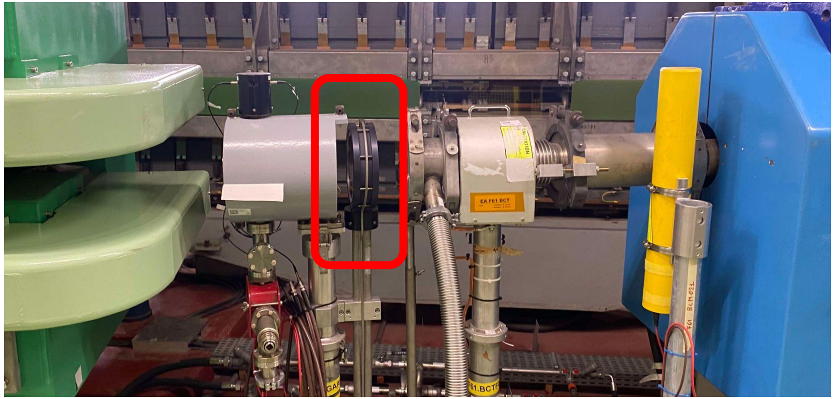
CERN beam line operation, layout and existing beam instrumentation

- Effect of beam line: beam size blow-up by scattering in air, vacuum windows, beam instrumentation
- We require a **uniform** beam for testing: further defocusing the beam and then using a mask

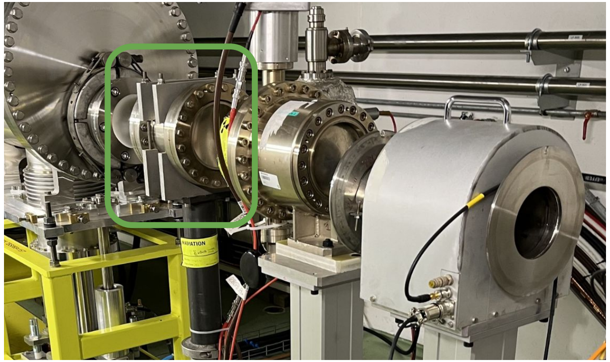


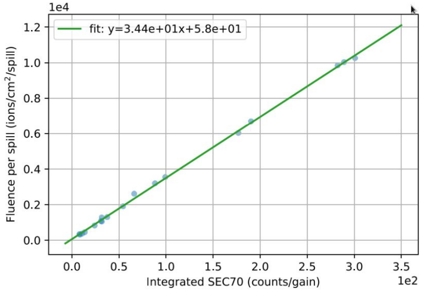
CERN beam line operation, layout and existing beam instrumentation

- **Liquid/gaseous scintillator detector (BCGAA/BXSCINT)**
  - collecting beam-induced ionisation photons with Nitrogen gas. The electric signal generated by a photomultiplier (PM) is amplified and sampled
  - Variable voltage
  - 0.5ms timing resolution
  - Measures full beam coming through
  - Location: upstream of first T08 dipole



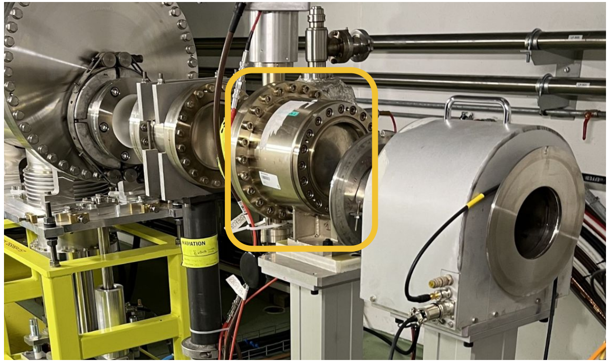
CERN beam line operation, layout and existing beam instrumentation

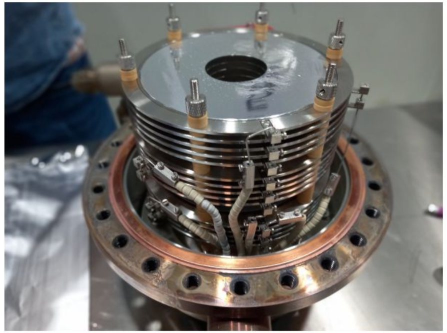




- **Secondary emission chamber (XSEC)**
  - electron emission from the surfaces of thin metal foils hit by charged particles
  - stack of plain (targets) and polarised hollow thin metal films in vacuum: secondary electrons collected by polarised electrodes are proportional to the total number of incoming particles (variable gain)
  - 20 ms timing resolution
  - Calibration with bunched beams is required
  - Locations: F61, upstream of IRRAD, upstream of CHARM
  - **XSEC and XIONs are very good instruments for measuring the (relative) beam intensity over large ranges**

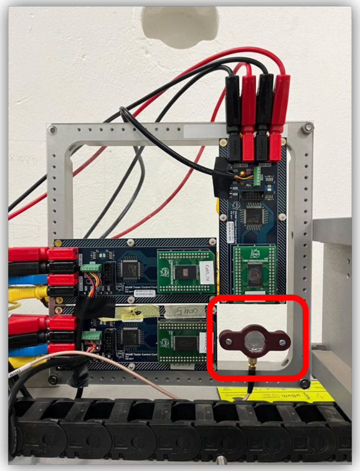
CERN beam line operation, layout and existing beam instrumentation





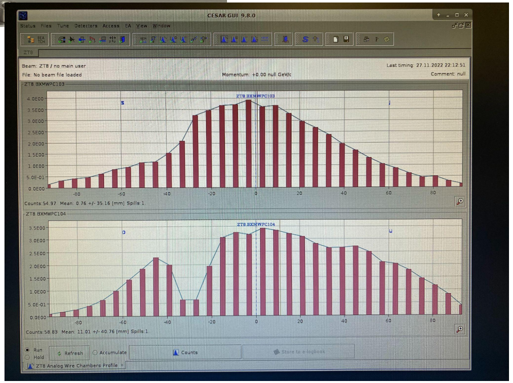
- **Argon ionization chamber (XION)**
  - Same principle as XSEC but specifically designed for ion beams -> more sensitive! (variable gain)
  - Filled with Argon gas, slightly above atmospheric pressure
  - 20 ms timing resolution
  - Calibration with bunched beams is required
  - Locations: Upstream of IRRAD, upstream of CHARM
  - **XSEC and XIONs are very good instruments for measuring the (relative) beam intensity over large ranges**

CERN beam line operation, layout and existing beam instrumentation



- **Si diode**
  - 300um thick with an exposed active surface area of $0.5cm^2$
  - Placed at the DUT position to register on event-by-event basis, measuring deposited energy and localized particle flux
  - 2-3 ms timing resolution for full spill time profile measurements, down to 10 ns resolution for single particle measurements (flux)
  - We will stick to the diode working principle but are considering more suitable architectures
  - More on the diode setup later …

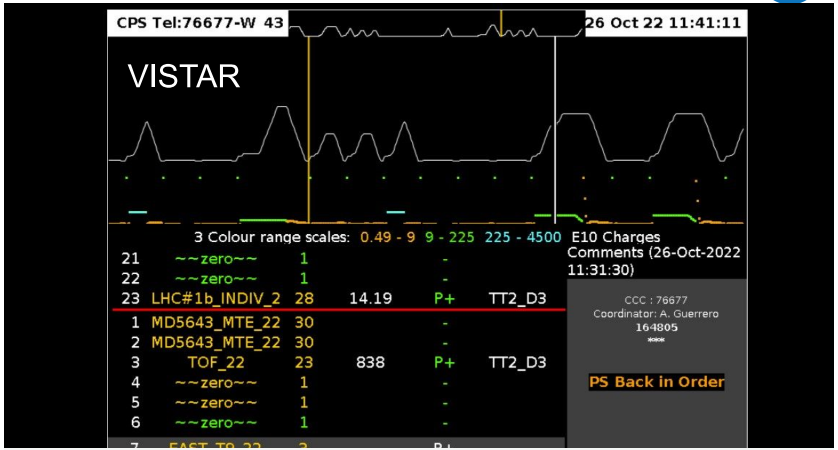
CERN beam line operation, layout and existing beam instrumentation



- **Multi Wire Proportional Chamber (MWPC)**
  - Set of 32 x 32 (in each plane), 40 µm stretched W wires with 1 mm spacing, placed between aluminum foils in a housing containing an equal mix of CO_2 and Ar gas. A high voltage is applied between the foils (cathode) and the wires (anode) which collect ionisation-induced electrons amplified by avalanche effect.
  - Variable voltage, is in principle also sensitive to the lowest intensities tested for (1.8 kV instead of 100V for standard proton operation)
  - 20 cm diameter
  - Timing resolution: per spill

CERN beam line operation, layout and existing beam instrumentation

- **Visualisation (VISTAR)**
  - Real time visualisation of beam information (user, intensity, particle type and destination) during operation
- **Live dashboard**
  - During November 2022 HI run, a dashboard was created to supply external users with real-time beam information (energy, flux, fluence)
- **Data logging**
  - In general, data from different instruments are logged in CERNs accelerator Logging System (NXCALS) and can be extracted using e.g. Timber GUI or self-made python script



CERN beam line operation, layout and existing beam instrumentation

- **Measuring beam intensity using XSEC/XION/Si diode**
- The XSEC and XIONs are very good instruments for measuring the (relative) beam intensity over large ranges
- Absolute calibration for proton beams in the T8 line, two methods are typically applied:
  - Using Al foil activation → cross section for heavy ions not known!
  - Calibration against absolute intensity measurement using fast beam current transformers → only possible with fast extraction!
- Therefore, absolute flux measurements were performed through counts on Si diode of known sensitive surface at the beam center, i.e. DUT position.
- This method allows retrieving the fluence (per spill) or flux (per second) at the centre of the beam at the DUT position

CERN beam line operation, layout and existing beam instrumentation

- **Measuring beam intensity using XSEC/XION/Si diode**
- SEC response might be energy dependent, cross-calibration needs to be performed for each extracted energy.
- Two main limitations:
  - Si diode active surface area is partially covered (~30%) by a stainless steel case

    → mitigated by placing a “collimator”, covering the case and exposing only active area (see later)

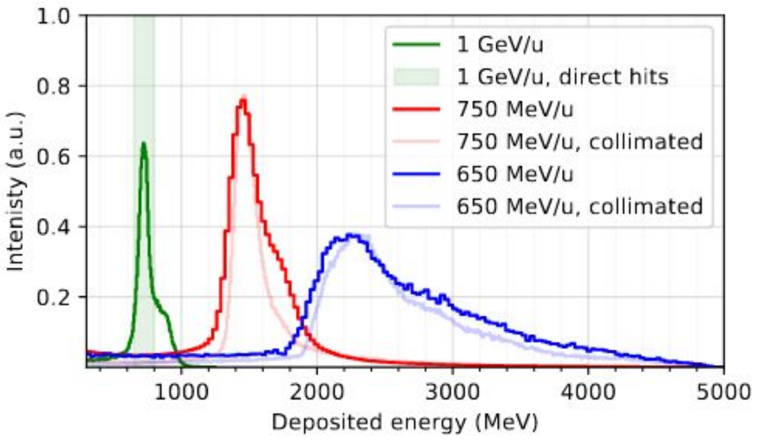
  - Dead time in the acquisition chain causes buffer saturation at high intensities

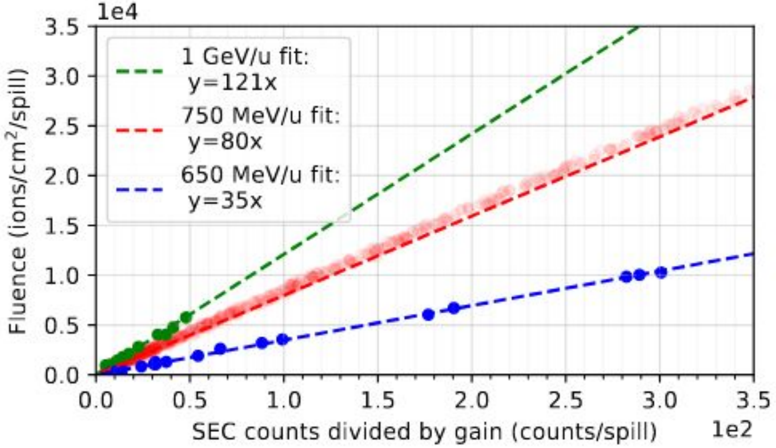
    → mitigated by optimisation of the digitizer settings

    - *increase of detection threshold*
    - *Possible future improvements: real-time processing of events instead of storing full pulses by digitizer firmware change and/or data link enhancement*

CERN beam line operation, layout and existing beam instrumentation

- **Measuring beam intensity using XSEC/XION/Si diode**
- relative beam intensity can be accurately measured with the XSEC and XION in a very large intensity range, absolute beam intensity is measured by counting ions with Si diode of known surface



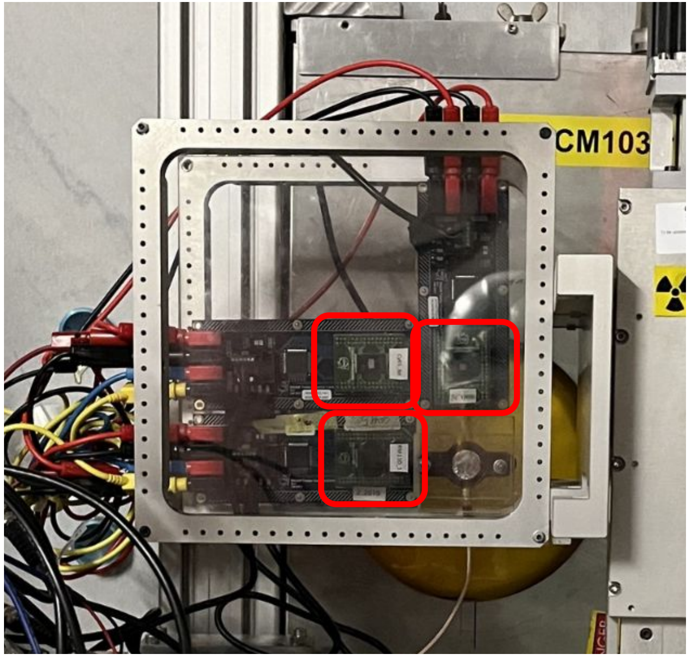


CERN beam line operation, layout and existing beam instrumentation

- **Verification of utilized approach using SRAMs**
- Flux measurements are possible for ISSI and Cypress memories straight from the SEU cross-section IF the LET is known (from simulation)

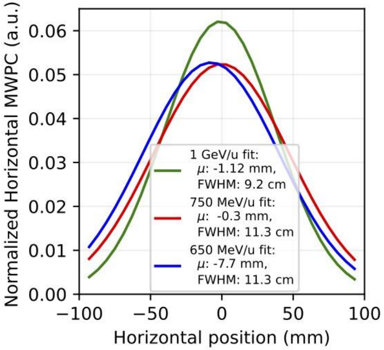
Run	Flux dashboard (ions/cm2/spill)	Flux Cypress (ions/cm2/spill)	Ratio Cypress/dash
650 MeV/n low flux	450	468	**1.04**
650 MeV/n high flux	16825	13532	**0.80**
750 MeV/n	38788	31680	**0.82**
1000 MeV/n	1295	1418	**1.09**

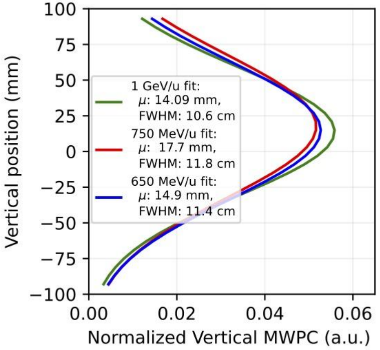
Run	Flux dashboard (ions/cm2/spill)	Flux ISSI (ions/cm2/spill)	Ratio ISSI/dash
650 MeV/n low flux	465	417	**0.90**
650 MeV/n high flux	18558	12056	**0.65**
750 MeV/n	38500	32905	**0.86**
1000 MeV/n	1181	1436	**1.22**

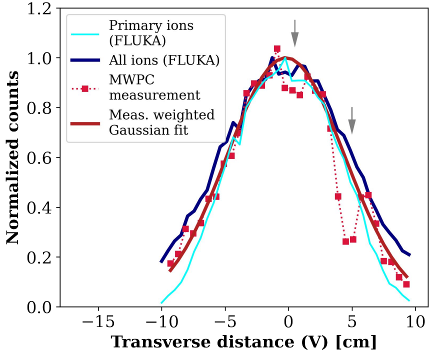


CERN beam line operation, layout and existing beam instrumentation

- **Measuring beam profile using MWPC**
- Instrument allows for measuring horizontal and vertical 1D projections of the beam very close to DUT position (0.5m)
- Gaussian beam size remains fairly similar in range of energies used for electronics testing in both horizontal and vertical plane.
- Considerable effort will be needed to make beam homogeneous, for this the MWPC will be a critical instrument

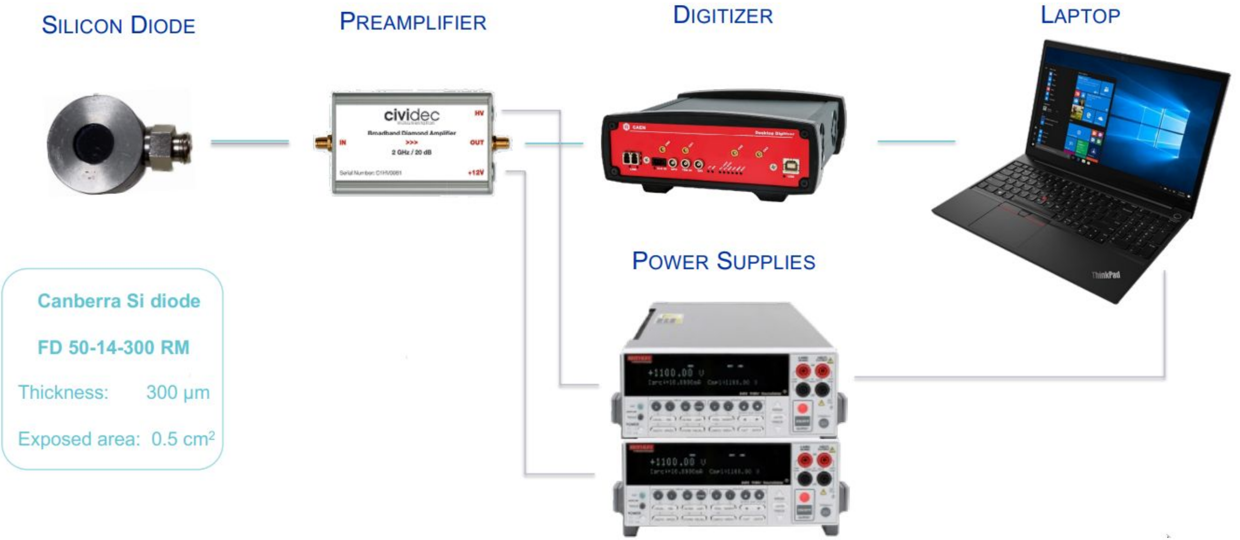




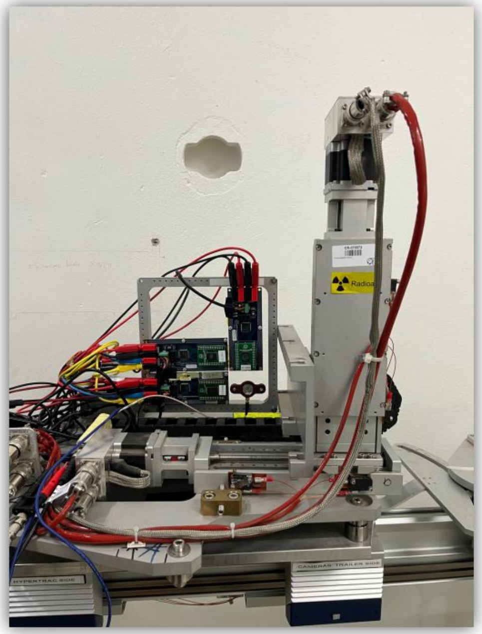


CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **Diode setup**
  - Chosen for it's relatively simple setup and representativeness in understanding the physical basis of radiation effects in electronics

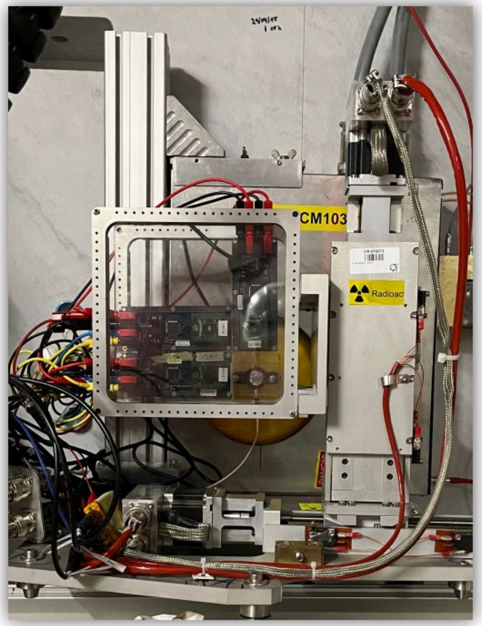


CERN diode system for dosimetry: experience with VHE ion beams, status and plans



Diode and SRAMs on a movable table on the CHARM Montrac conveyer.

The Montrac conveyor connected to the patch panel with a cable chain.

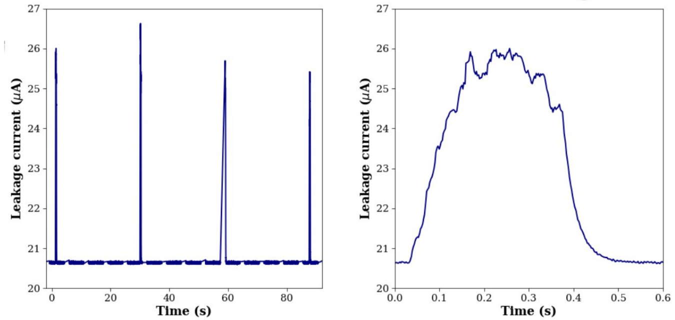


Devices in place in-beam position in CHARM, diode centered to the beam.

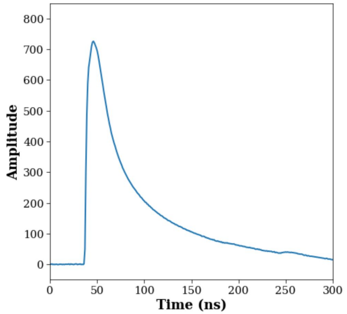
CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **Diode acquisition**
  - leakage current: use as a **spill** monitor → low frequency (still 10 times higher than XSEC) measurement of the spill time profile (Max. sampling: 2 ms)
  - single pulses: generated charge in 300um Si layer on an event-by-event basis
    - Use as a **flux** monitor by counting events (10 ns resolution)
    - Use as a beam **energy** spectrometer by integrating pulses and converting to deposited energy

Leakage current

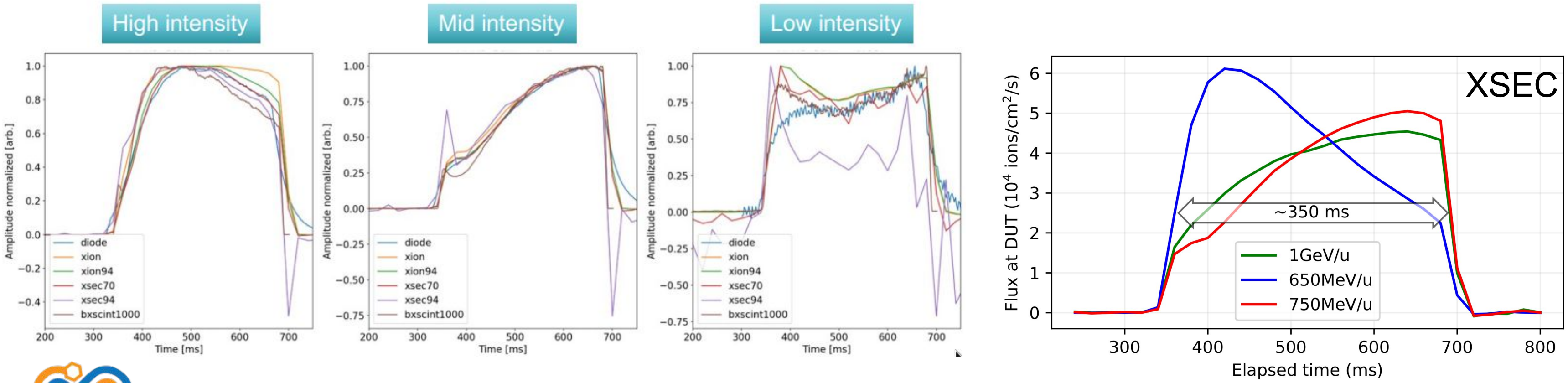


Single pulse



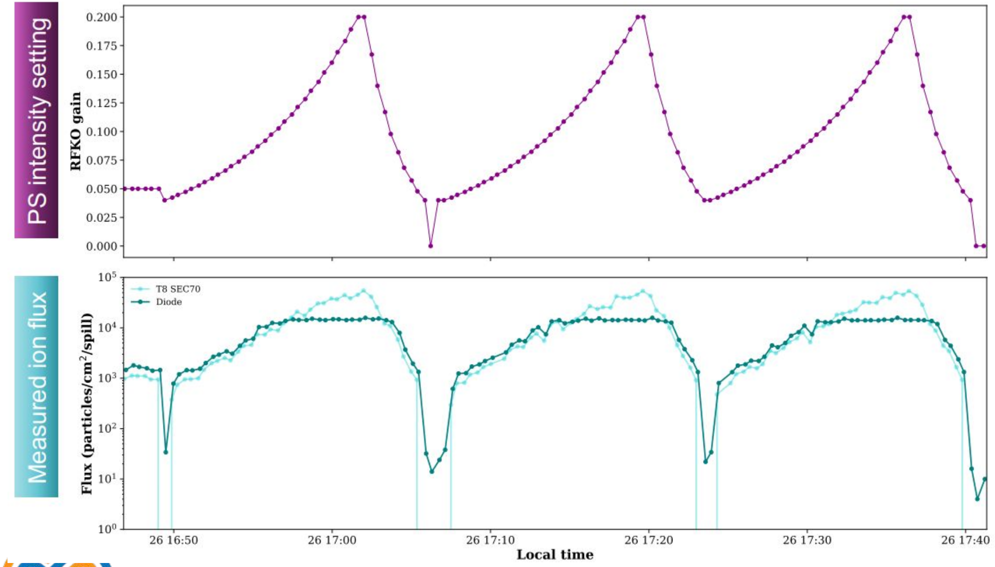
CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **Diode as a spill monitor**
  - Excellent agreement between the diode spill time profile and the exact same spills measured by standard 5 different T8 beam instruments, i.e., secondary emission chambers (SECs) and ionization chambers (XION) for various intensities and extracted energies



CERN diode system for dosimetry: experience with VHE ion beams, status and plans

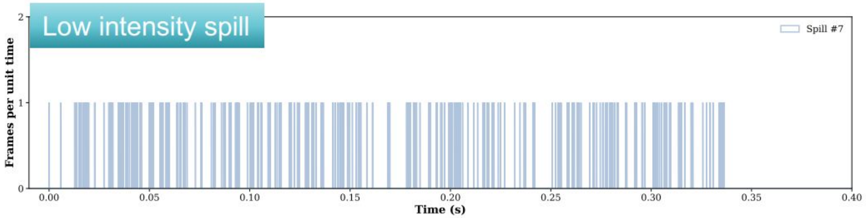
- **Diode as a flux monitor**

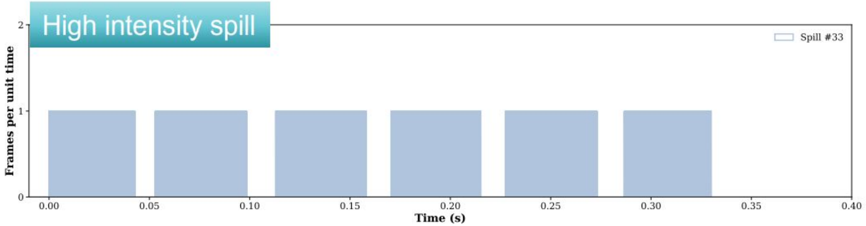


- Setting the RFKO gain ⟶ easy change of the ion beam intensity
- Measured ion flux follows the RFKO gain, variation over 2 orders of magnitude achieved
- Diode flux profile similar to the flux profile measured by a secondary emission chamber (SEC70)
- Diode can measure even a very low flux, but saturates at high intensity (> 10^4 particles/cm^2/spill).

CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **Diode as a flux monitor**





- **High intensity ⟶ high rate ⟶ dead time** in the data acquisition chain due to the data transfer through USB2.0 limited to 30 MB/s.
- How to address this limitation:
  - Increased detection threshold
  - Using a smaller diode
  - Shorter acquisition window
  - Digitizer upgrade to do online processing and to store only relevant quantities instead of full pulses.
  - Improved data link

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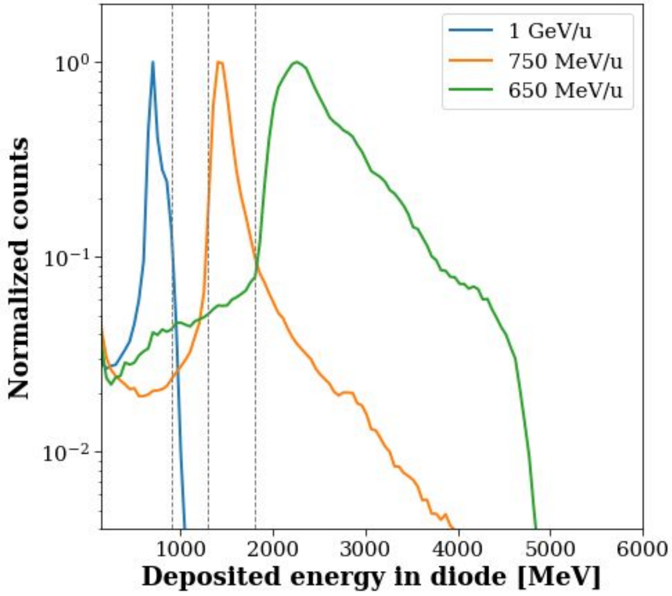
- **Diode as a beam energy spectrometer**



- Typical use of silicon diodes: measurement of the event-by-event energy deposition spectra which show distinct peaks for each extracted energy.
- This allows to verify the LET of the beam.
- Integral of each single-event pulse

  ⟶ charge deposited in the diode

  ⟶ proportional to deposited energy

- Lower extracted beam energy

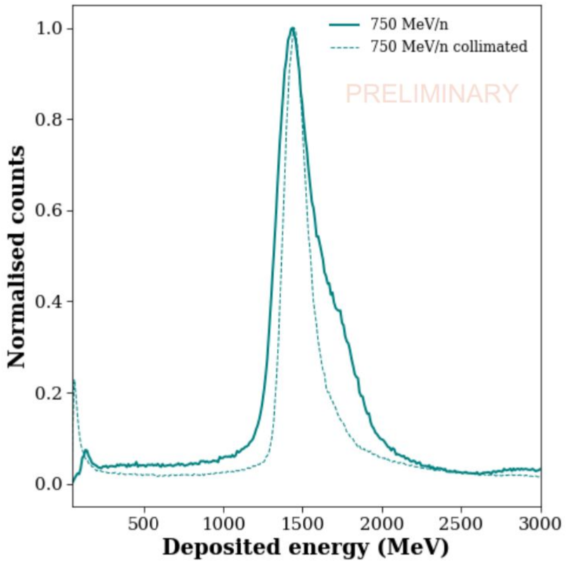
  ⟶ higher energy deposited in the diode

  ⟶ higher LET

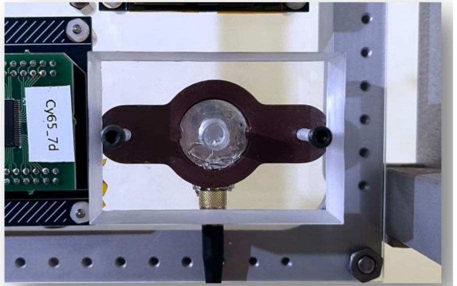
- Can be compared to simulation heavy ion transport through the T08 beam line
- Energy deposition measurement with diode is not an absolute and/or repeatable way of characterizing beam energy
  - Uncertainty on calculated energy values arriving to DUT
  - Cable attenuation, uncertainty on preamp gain, attenuator
  - Logging errors (manual for the moment)

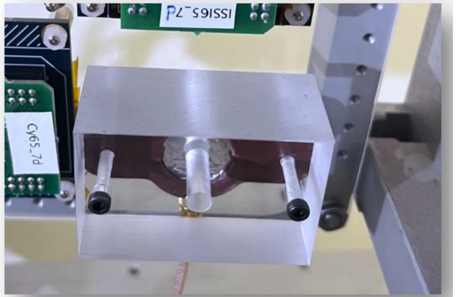
CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **Diode case "collimator"**



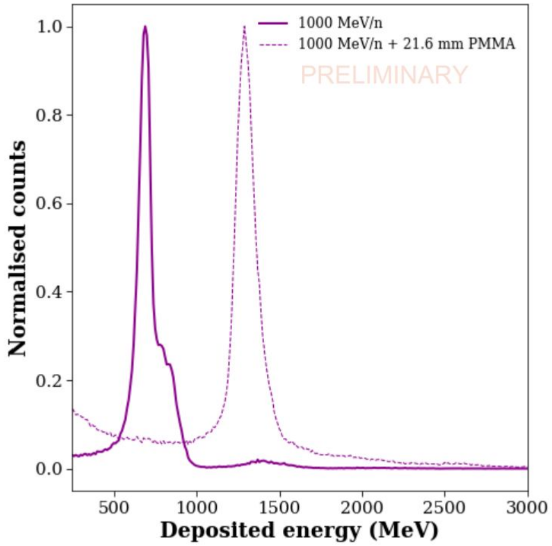
- The currently used diode is enclosed in a stainless steel case.
- A small part of the the sensitive volume under the cover can detect particles passing through the case. The exact case geometry and composition is proprietary information!
- Tests with 3 cm and 6 cm thick PMMA collimators used to quantify this effect.
- E.g. 750 MeV/n beam with a 3 cm collimator results in a narrower energy spectrum.
- We are currently investigating if a caseless diode could be more advantageous.



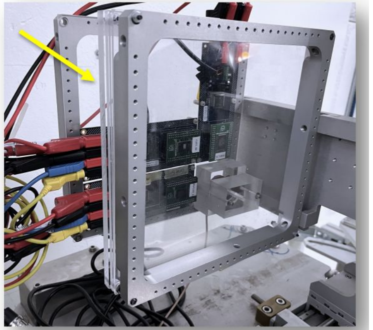


CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **Use of PMMA degraders**



- Reaching even higher LETs requires a decrease in the beam energy.
- Difficult to propagate a very low energy beam through the whole T8 beam line.
- Degraders ⟶ decrease beam energy locally at the end of the transfer line.
- Tests with PMMA degraders of 1.5, 7.2 and 21.6 mm carried out.
- 1 GeV/n beam crossing 21.6 mm of PMMA deposits about twice as much energy in the diode ⟶ higher LET!



CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **FLUKA simulations of energy degradation**, inherent to T08 beam line

USER	Kinetic energy/ nucleon [GeV/u]	Surface LET in Si [MeVcm^2/ mg] (SRIM)
EAST4	**1**	*12*
EAST3	**0.75**	*12.5*
MD5	**0.65**	*13*

→

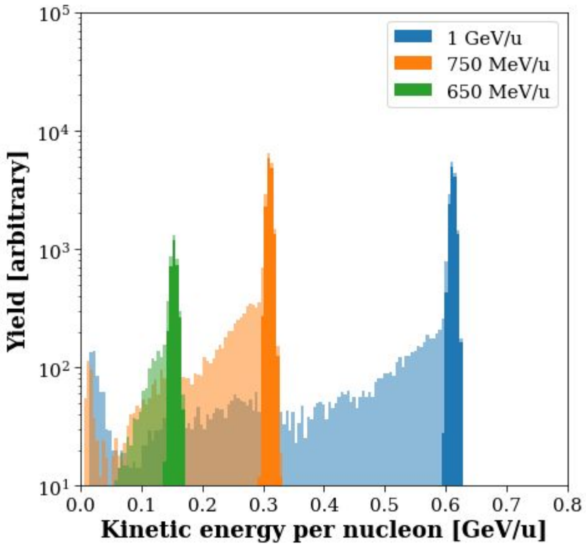
Kinetic energy @DUT [GeV/u] + Primary ion spread (FLUKA)	Surface LET in Si [MeVcm^2/ mg] (SRIM)	Range in Si [mm] (SRIM)	Range in PMMA [mm] (SRIM)	Energy deposition in 300um of Si [MeV]
0.6 ± 0.02	***13***	35	55	900
0.3 ± 0.02	***18***	10	15	1300
0.15 ± 0.02	***25***	3	5	1800

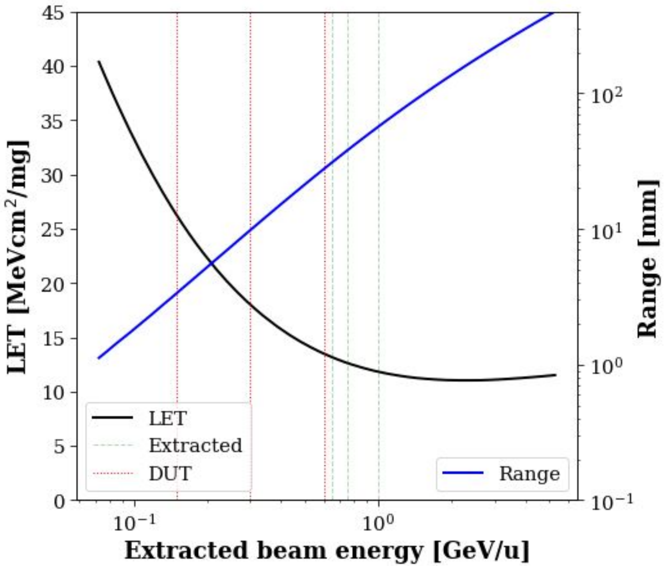
Range for all energies is large enough to cross 300um of Si

LET [MeVcm^2/mg] x 0.03cm x 2330 mg/cm^3

CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **FLUKA simulations of energy degradation**, inherent to T08 beam line





	Primary/ Total ions
650 MeV/u	0.63
750 MeV/u	0.63
1 GeV/u	0.65

Summary and outlook

- Activities in WP4
    - feed directly into WP7: Upgrade of CHARM beam line at CERN for VHE ion testing
    - rely on simulation work done in WP3: Monte Carlo Simulations

- The CERN PS-T08 beam line infrastructure has standard beam instrumentation at its disposal
    - Generally used for proton operation but also usable for heavy ions
    - Requires re-calibration and cross checks to meet dosimetry requirements within HEARTS

- Experimental campaigns in 2022 have allowed to verify beam instrumentation adequacy to provide:
    - Beam intensity based on SEC/XION + diode calibration
    - Beam profile at DUT location using MWPC, could potentially also be complemented by the diode
    - Beam energy and LET using Si diode, based on event-by-event spectrum + FLUKA simulation to extract LET

- Open challenges for which HEARTS WP4 task are essential:
    - Improve the accuracy of intensity/flux tuning and improving machine reproducibility
    - Achieve an optimized routine for intensity/flux calibration and measurements
    - Improve tunability and homogeneity of beam shape by an increase of the slow extracted spill duration and intensity homogeneity (spill quality) within spills
    - Open questions regarding diode setup (calibration, signal attenuation by cables) will be addressed, improvements are under discussion (caseless diode, use of bias-T)

This project has received funding from the European Union’s Horizon Europe Research and Innovation programme under GA No 101082402.

HEARTS

EXTRA SLIDES

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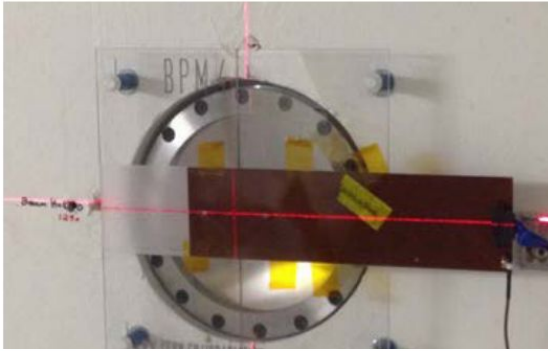
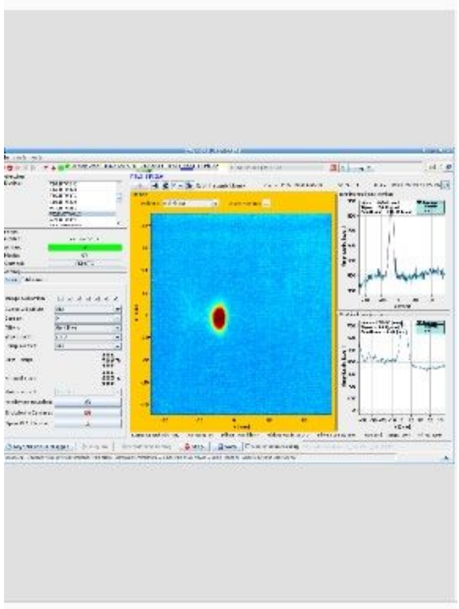
CERN beam line operation, layout and existing beam instrumentation



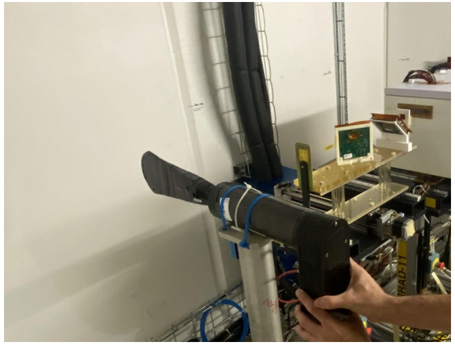
- **IRRAD Beam position Monitor (BPM)**
  - 39 Cu pixels measuring 4x4mm^2 on kapton layer, overall 700 um thick
  - Covering 36 mm × 27 mm on the beam transversal plane (not enough for large ion beams!)
  - On 4 locations in IRRAD
  - Timing profile only given by BPM1 (and only central pad)
  - Limited response for electronics testing ion fluxes
  - New, improved 40mm x 30 mm Al/Kapton BPM prototypes are being tested, also optimized for use in heavy ion beams.

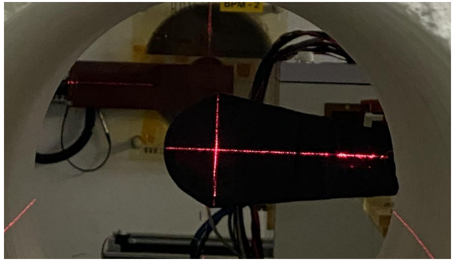
CERN beam line operation, layout and existing beam instrumentation



- **Beam TV (BTV)**
  - Intercepting (and destructing!) the beam with chromium-doped alumina screens and observing the emitted fluorescence with radiation hard cameras.
  - Full beam coverage
  - Used for beam steering
  - Upstream of F61 beam dump + near the target in CHARM

CERN beam line operation, layout and existing beam instrumentation

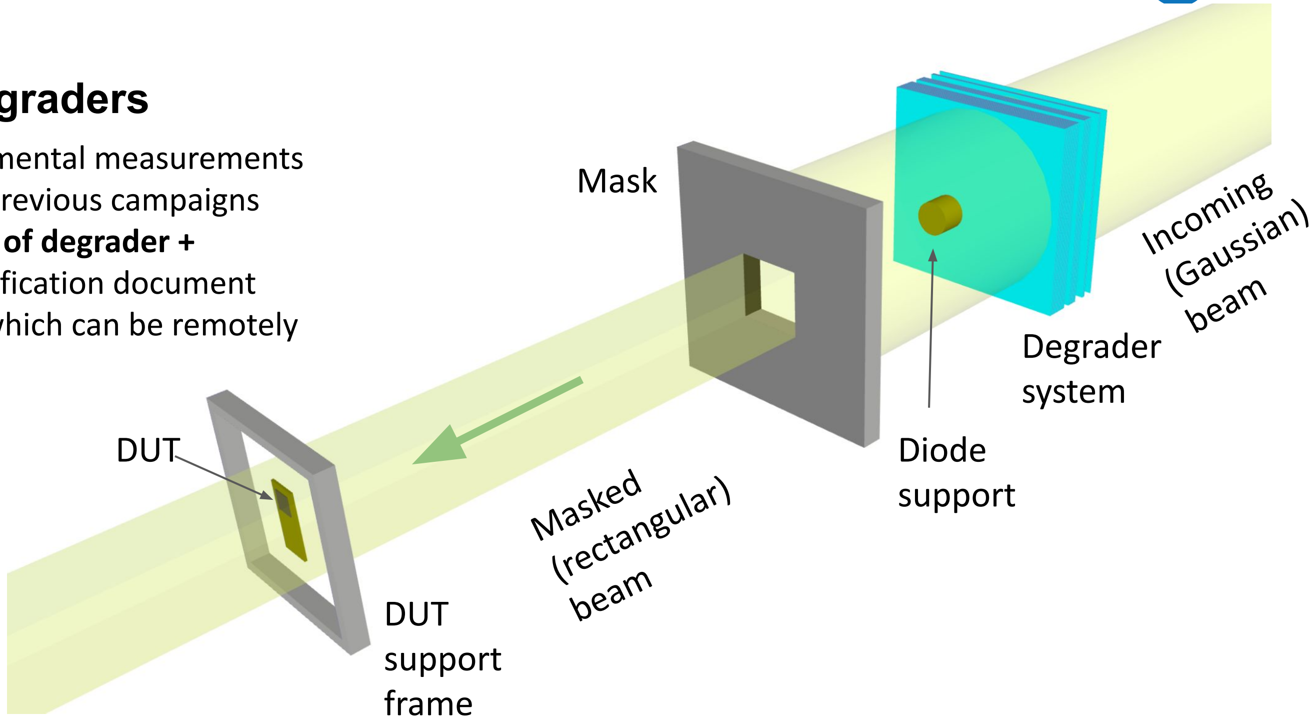




- **Plastic Scintillator (XSCI)**
  - PMMA doped with PVT, fluorescent light yield proportional to deposited energy is collected by fishtail light guide and amplified by PMT
  - Full beam coverage
  - Placed in IRRAD, close to BPM2
  - Used as R&D device, troubleshooting and analysis still ongoing.
  - Timing? Comparable to diode? TBC

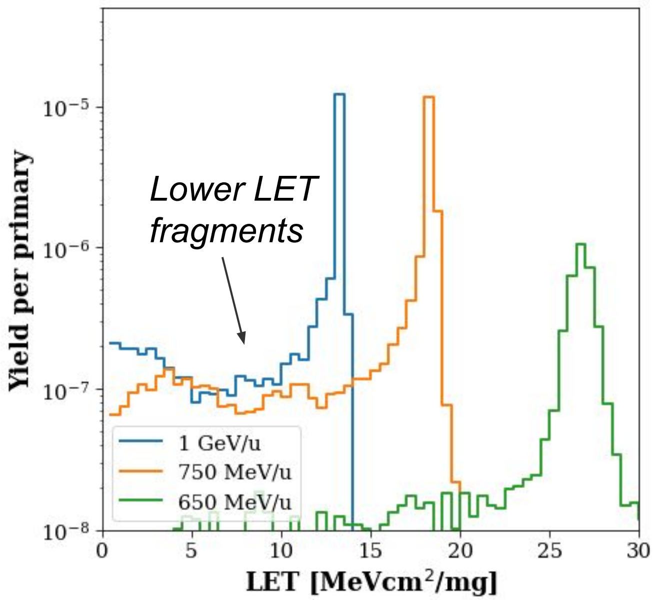
CERN diode system for dosimetry: experience with VHE ion beams, status and plans

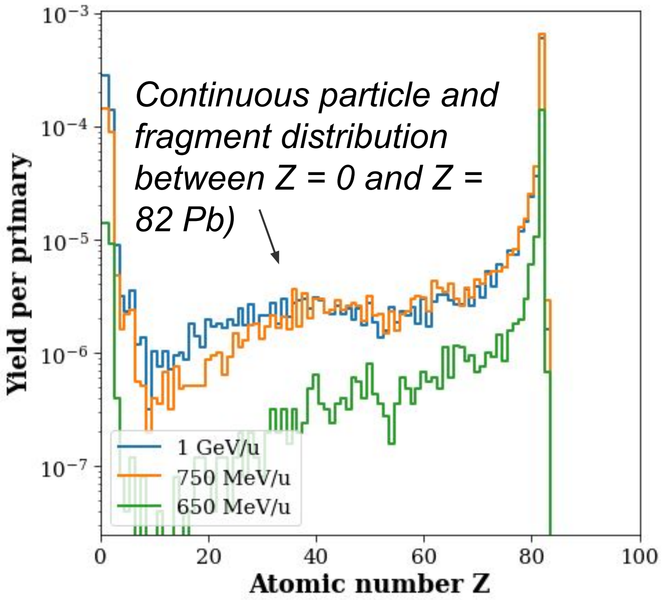
- **Use of PMMA degraders**
- Simulation work, experimental measurements + lessons learned from previous campaigns directly feed into **design of degrader + collimator system** (specification document ready to be circulated) which can be remotely controlled.



CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **FLUKA simulations of energy degradation**, inherent to T08 beam line



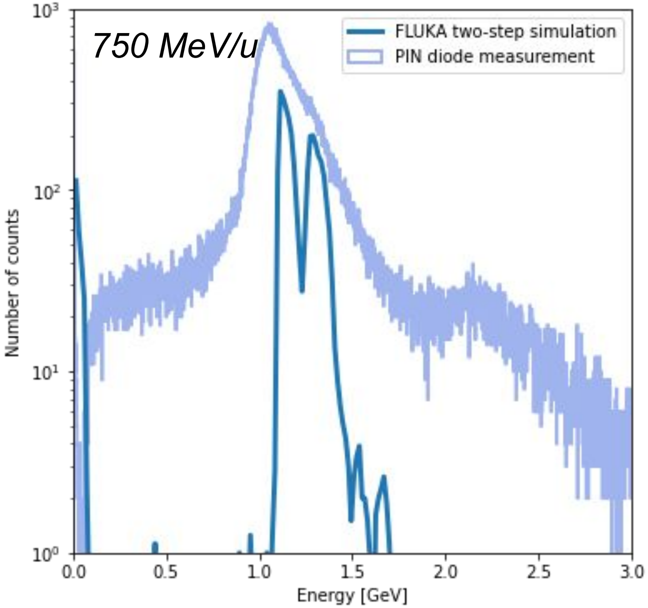


CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **FLUKA simulations of energy degradation**, inherent to T08 beam line

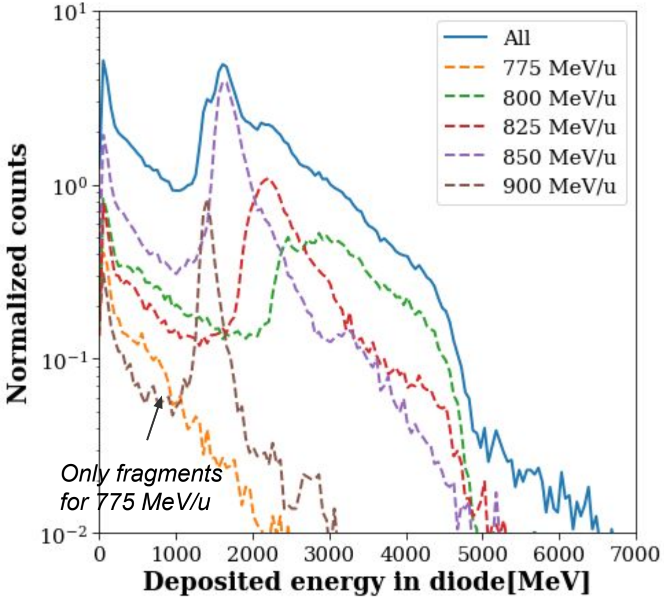
- Work-in-progress: **two-step** FLUKA simulation
  - Step 1: Calculate beam distribution at DUT position
  - Step 2: More in-depth characterization of diode energy deposition spectrum disentangling different particles and energies

- Convolution of the simulated energy deposition distribution with a spread in the energy response could give a very good agreement.

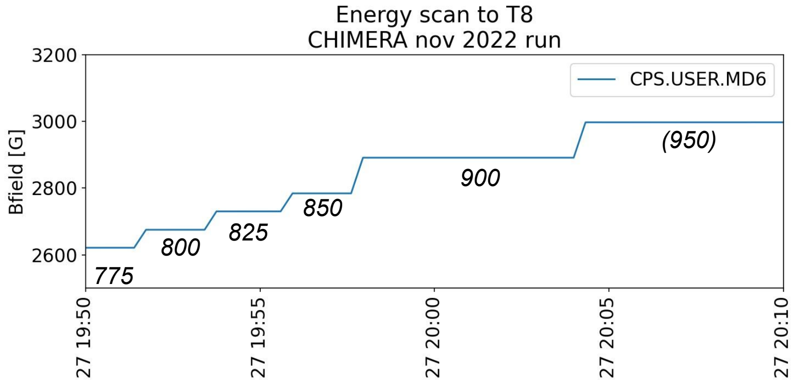


CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **Energy scan**

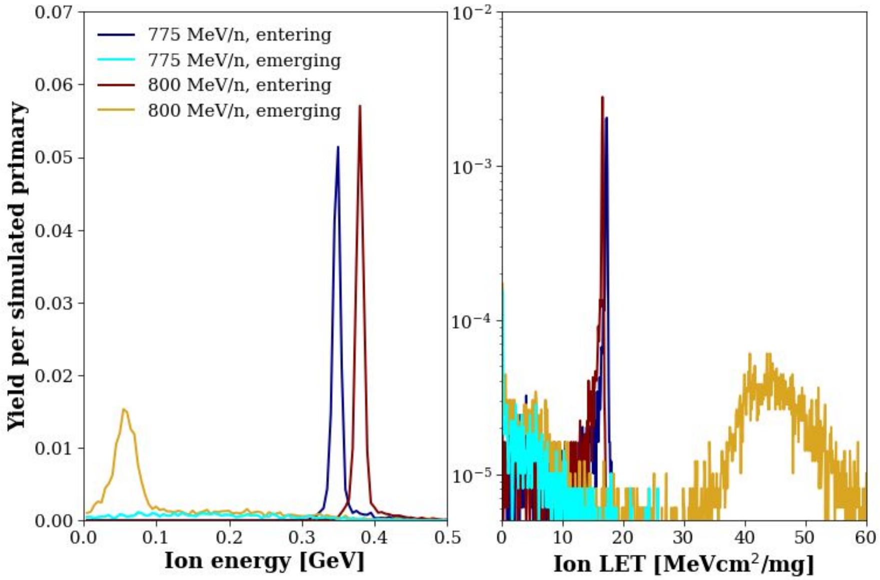


- **Scan of energies including 21.6mm PMMA degrader**
- Range in PMMA of 750 MeV/u Pb ions, degraded to 300 MeV/u: 15 mm
- Thickness of degrader indicates (degraded) beam energy with 25 MeV/u resolution



CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **Energy scan**



- **FLUKA simulations** to confirm energy scan measurements with diode.

CERN diode system for dosimetry: experience with VHE ion beams, status and plans

- **Benchmark experiments** carried out in GSI, April '22