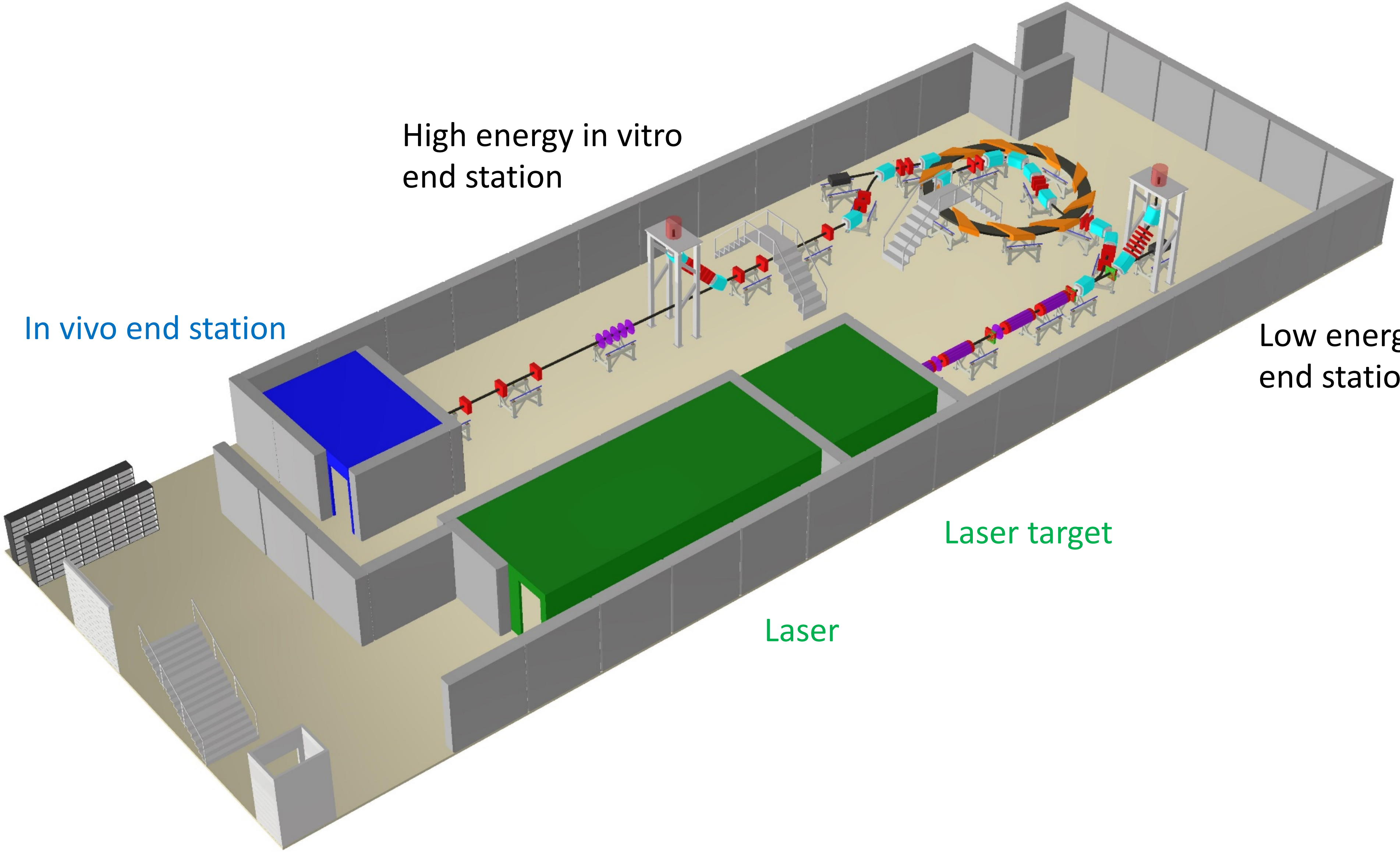
Instrumentation for LhARA

John Matheson
Rutherford Appleton Laboratory

- Layout of the facility
- Stage 1 end station
    - SciWire
    - Thin ceramic monitors
- SmartPhantom
- Dosimetry
- Laser instrumentation
- Stage 1 beamline Instrumentation
- FFA Instrumentation
- Research Plan

(Not including instrumentation beyond the interaction of the proton beam, e.g. secondary particles and photons)

Layout of the facility – Overall



High energy in vitro end station

In vivo end station

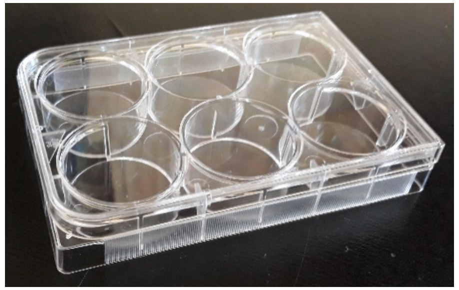
Low energy in vitro end station

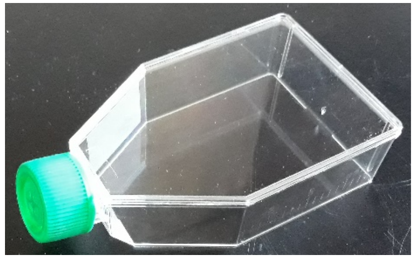
Laser target

Laser

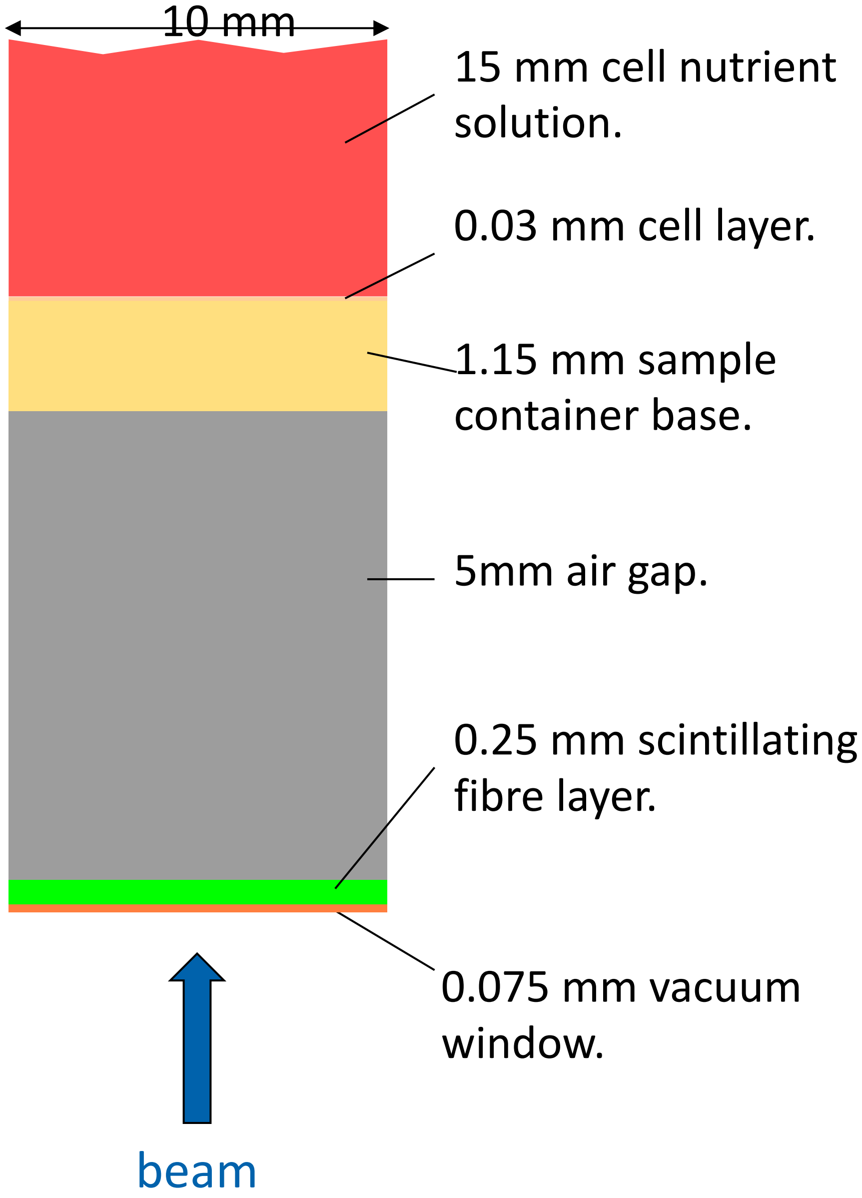
Stage 1 end station

- Material budget determines required beam energy.
  - More material increases cost of laser.
  - Consider cell sample containers.



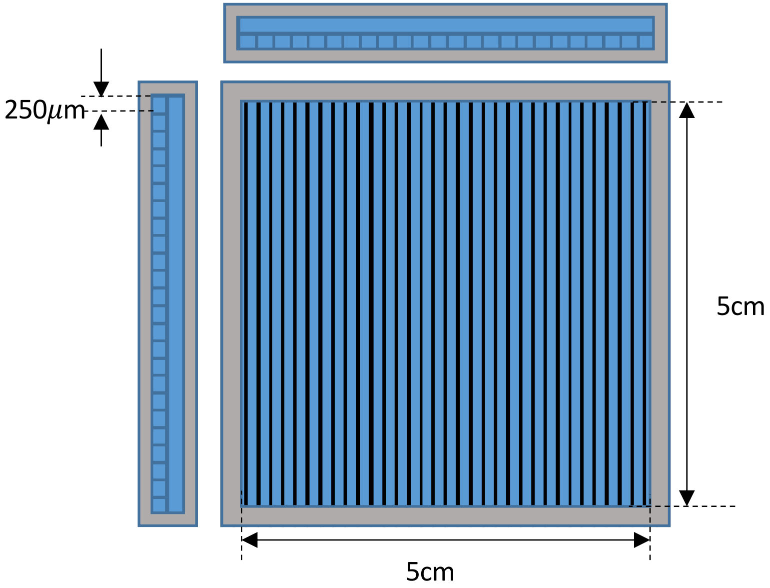


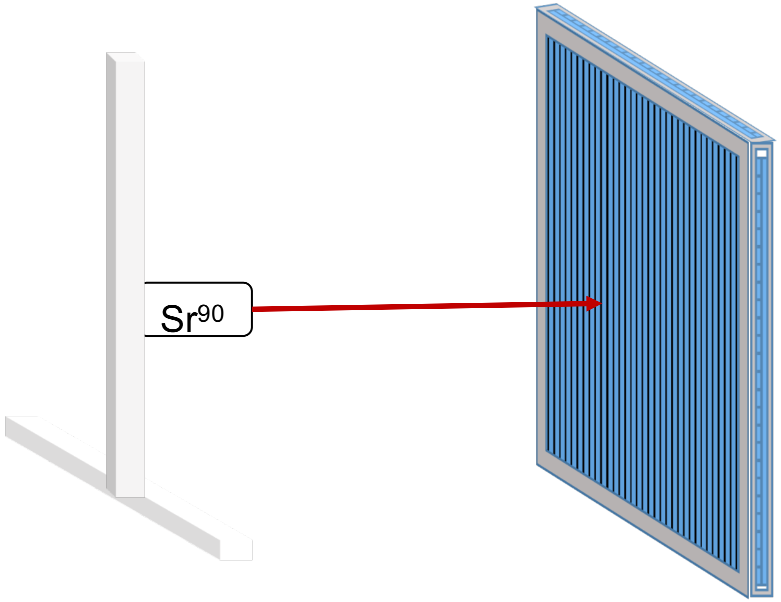
- Energy deposition and dose calculation very important for the design of the end station.
  - Want the Bragg peak in the cell layer.
  - Ensure efficient delivery of dose to the cells (i.e. minimize the time needed to irradiate a sample).
  - Dose verification.



SciWire - Scintillating Fibre Detector

- STFC Impact Acceleration Account grant to develop scintillating fibre detector for low-energy ion beams.
  - Energy measurement.
  - Intensity profile.
- Plane made of fibres arranged in two layers perpendicular to each other.
  - Detector consists of multiple planes.
  - Scintillation light from all planes is read out from one side for each orientation.





- Step a Sr^{90} source across face of the detector, positioning the source at the centre of a pair of x and y fibres.
- Measure position resolution and cross-talk.
- Further tests with the laser driven ion beam.
- Possibility of dose profiling.

Thin ceramic monitors

Since 1994, Silson Ltd has been supplying ultra-thin membranes and related lithographic products to Corporations, Universities and Government Research Laboratories throughout the world. Products are extensively used within the x-ray and e-beam communities but additionally Silson is now able to offer a MEMS prototyping service.

Standard silicon nitride membrane windows

The standard range of Silson silicon nitride membrane windows consist of square silicon nitride membranes in square silicon supporting frames. The standard frame sizes are: 5.0, 7.5 and 10.0 mm.

The default frame thickness is 200 µm but we are also able to offer the full range of membrane thicknesses on 381, 525 and now 100 µm thick substrate stock. The standard membrane sizes are: 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 mm

The maximum membrane size within a 5.0 mm frame is 1.5 mm and the maximum for a 7.5 mm frame is 3.0 mm. Otherwise, the full range of membrane sizes is available within each of the standard frame sizes. The following range of standard membrane thicknesses is available: 30, 50, 75, 100, 150, 200, 500 and 1000 nm.

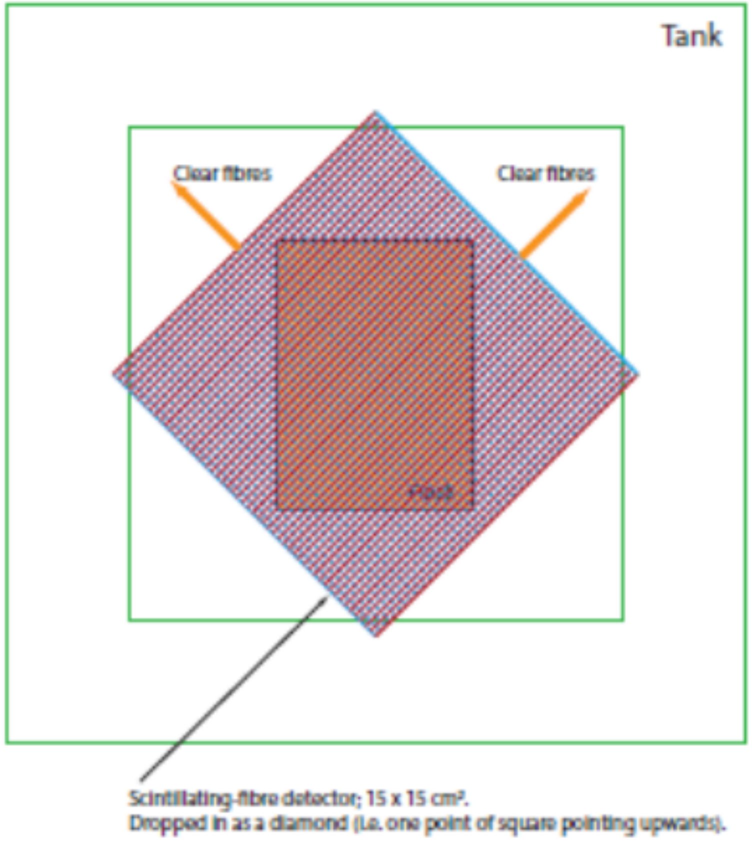
If your preferred design is not covered by the above permutations then we may able to help you with one of our other products.

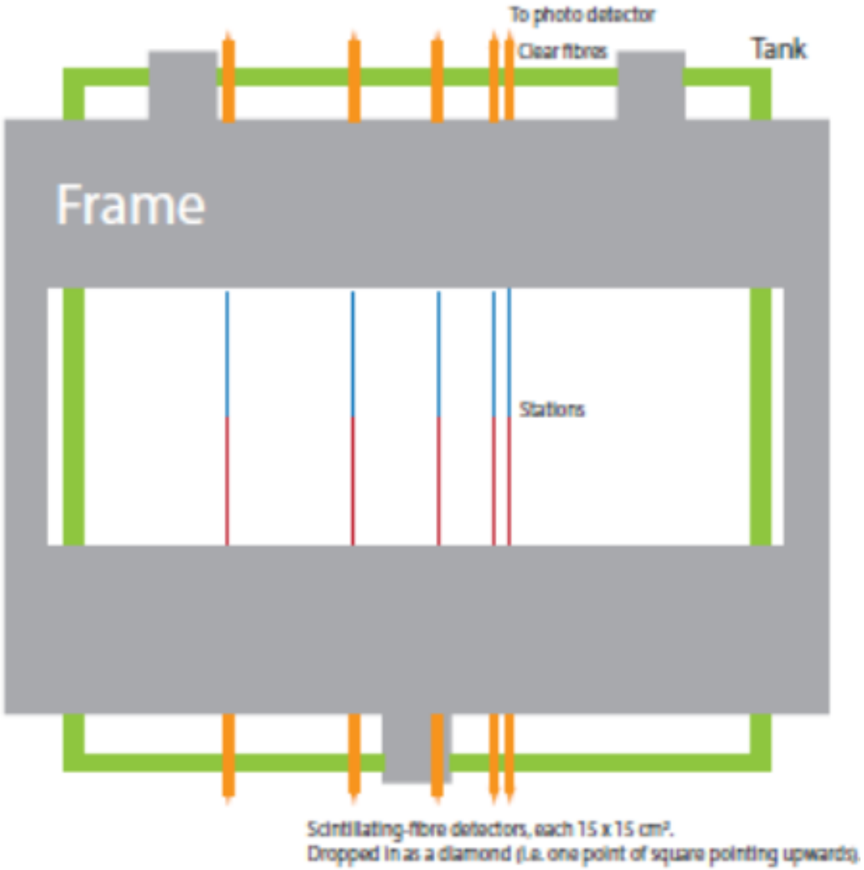
Use the standard product finder to see if your preferred permutation is available. go

- AlN or SiN membrane 50-150 micron
- Chemically etched and metal electrodes deposited
- Beam induces currents on the electrodes
- Needs some work to define diameter, thickness, mechanics, electrode geometry, readout
- Available from industry (Silson, Ametek/HSFoils)

Thanks to Alex Howard

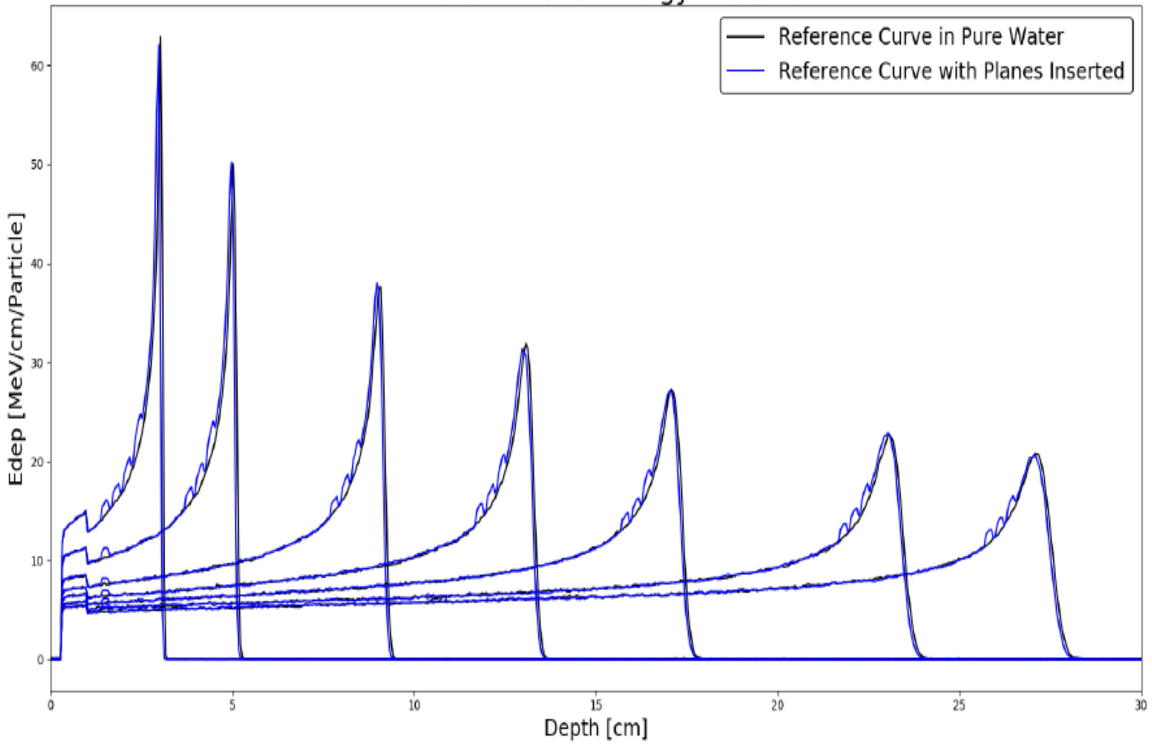
SmartPhantom Concept

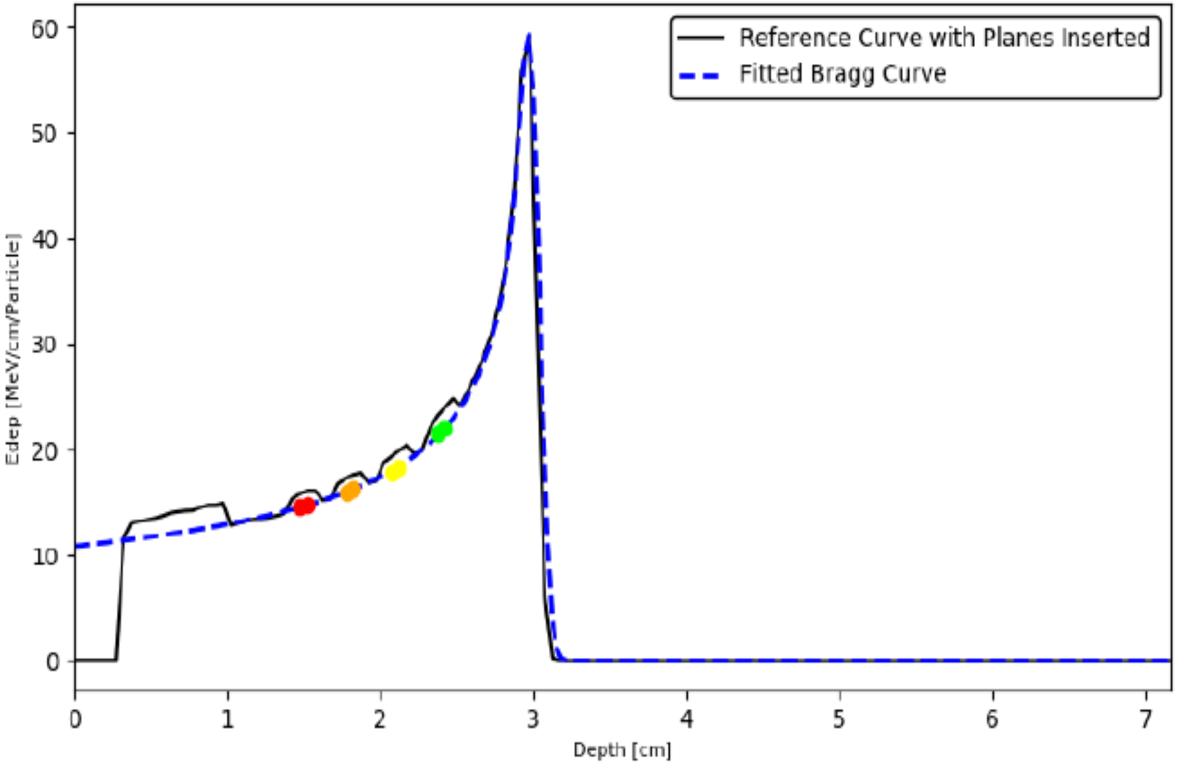




- Water phantom with scintillating fibre planes
- 250 um scint fibre Saint-Gobain BCF-10
- 250 um clear fibre
- Readout 1: bundle coupled to CMOS camera
- Readout 2: OptoDiode ODD-B1, Texas Instuments LMP7712, Analog Devices AD7779

SmartPhantom simulations


Different Mono-Energy Protons


62.4 MeV Protons (0.5% Energy spread)
Measurements Corrected to PureWater

Thanks to H.T. Lau

SmartPhantom simulations

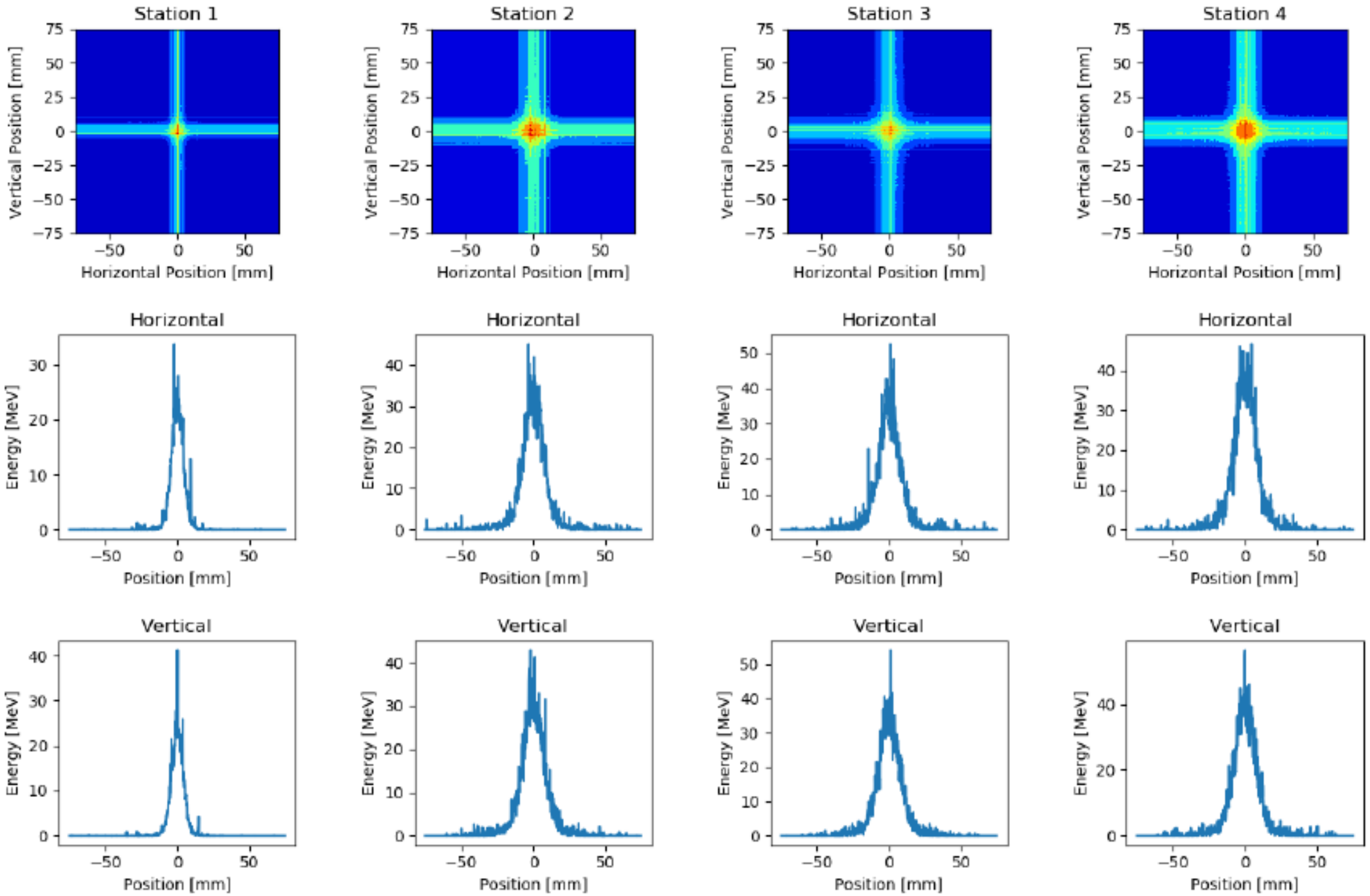
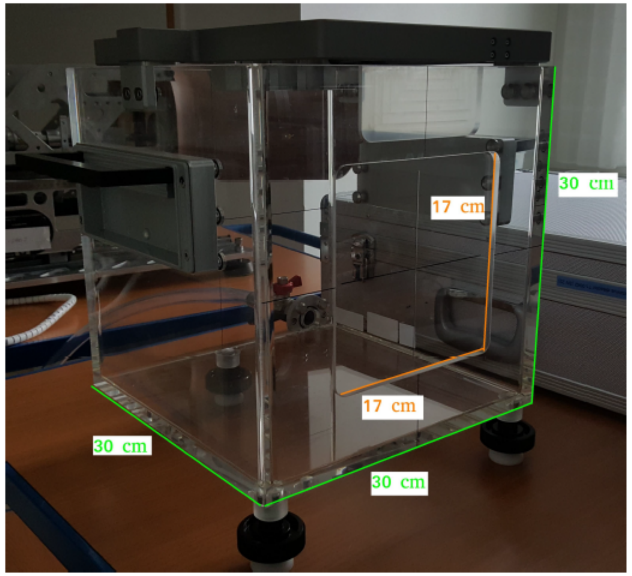
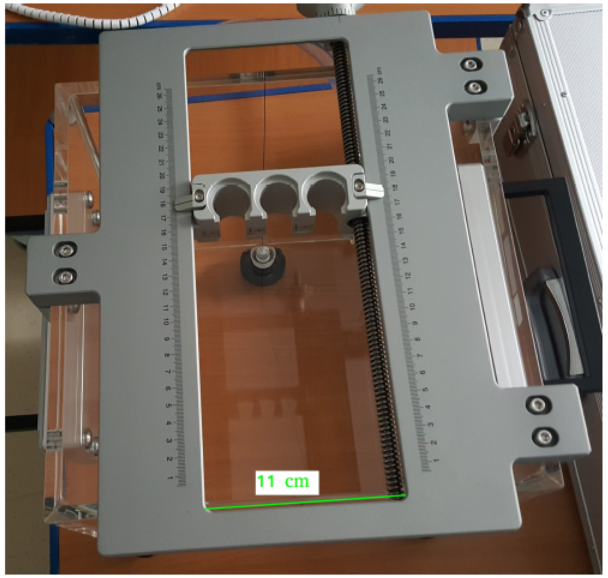


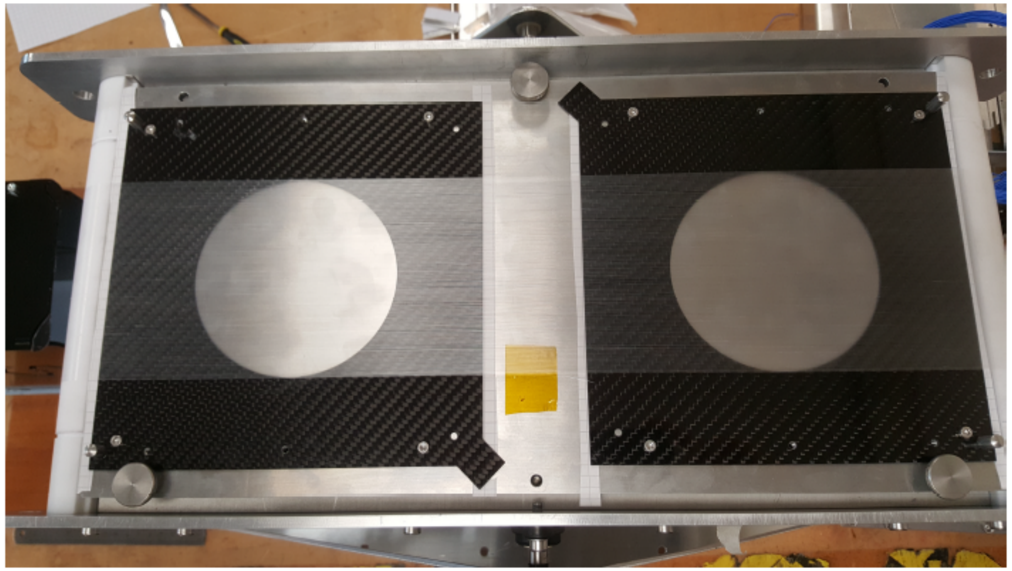
Figure: (Simulation) Example of beam profile measurements from four stations.

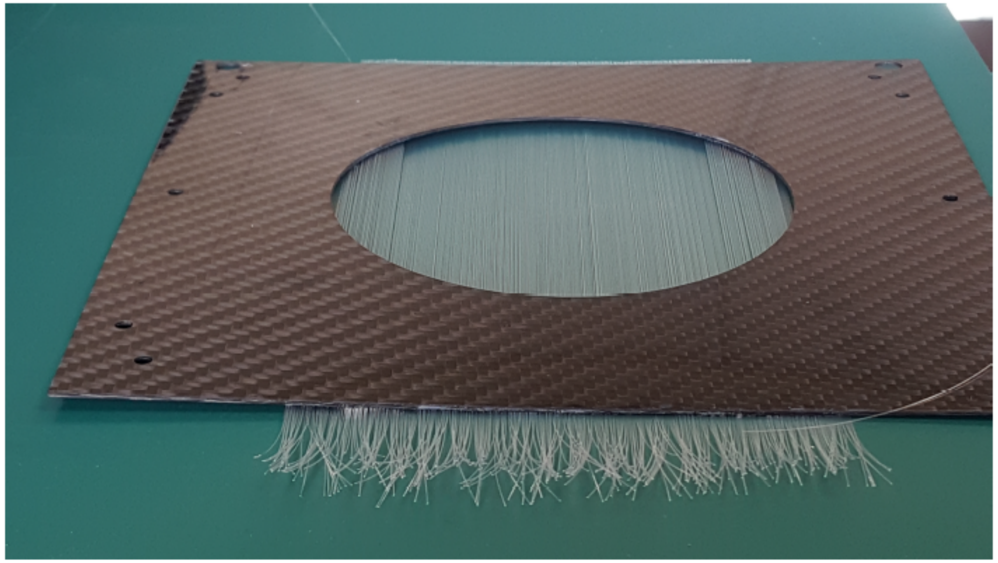
SmartPhantom Prototyping





- SmartPhantom water tank
- Support for planes and phials
- Planes on fibre winding jig
- Finished plane prototype
- To be beam tested at MedAustron





SmartPhantom Next steps

- SmartPhantom is being simulated in GEANT4
- Simulations will be used to develop analysis scripts, to fit the data and find the position of the Bragg peak
- Then calculate beam profile, LET and dose delivered in real time.
- Derive these parameters from measurements taken shot by shot, not purely from Monte Carlo simulations.
- Collaboration with the Technical University of Vienna
- Test first prototypes of the SmartPhantom at MedAustron (Austrian national facility for research into proton and carbon-ion radiotherapy)

Dosimetry

- Aim to have online dosimetry pulse by pulse
- Based on SciWire, SmartPhantom
- How to calibrate against a standard ?
- May use:
  - Nuclear track detectors (NTDs) or radiochromic films (RCFs)
    - CR39 plastic (chemical etch)
    - Al_2O_3:C,Mg crystals (fluorescence microscopy)
- Or:
  - Radiochromic films (RCFs)
    - Gafchromic – monomer microcrystals, polymerised by radiation (scanner)

- Significant dose under-response in some Gafchromic film types, with increasing LET in the vicinity of the Bragg peak. We will enlist help from NPL to characterise suitable NTDs and RCFs in known beams.

Laser instrumentation

- Ti:Sapphire laser emitting at 800nm
- 1J of energy per 30fs pulses
- Repetition rate of 10Hz
- Laser to be supplied as a turn-key unit
- The laser focal spot will be characterised using a camera-based system and high speed wavefront measurements
- The techniques to be used are well understood and it is intended to buy the necessary equipment from commercial vendors

Example Instrumentation at PSI Proscan

250 MeV cyclotron:

- Space for instrumentation in a cyclotron is very limited
- RF fields inside the machine are problematic
- One probe is available, inserted radially and with 2 interchangeable heads
- One head measures total beam current
- One head uses scintillating screen & CCD camera => beam profile and position
- For initial setup of the cyclotron, test foils were placed in the beam

Beamlines:

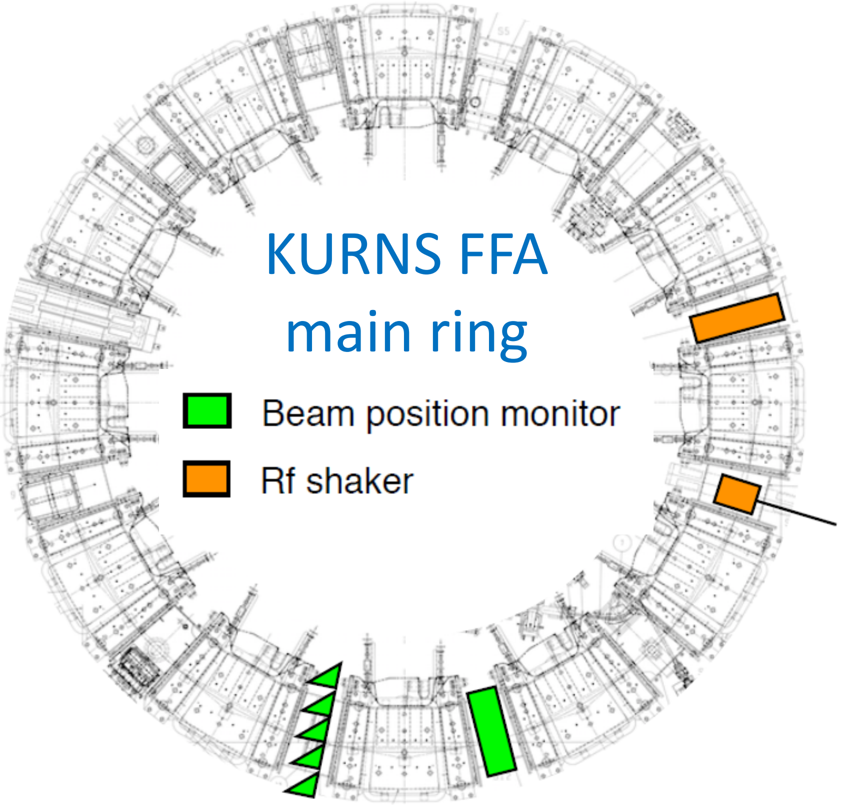
- Beam current and profile are measured by ionisation chambers
- Full-area electrodes => beam current
- Segmented electrodes => beam profile.
- Chambers may be mounted on pneumatic actuators
- High beam current => use SEM
- Position and Halo Monitor:
  - ionisation chamber with open bore
  - intercepts beam halo => position & transverse dimensions
- Beam profile - fluorescent screen & camera (destructive)
- Beam loss monitors - downstream of bending magnets
- Multi-layer Faraday cups (destructive) - absolute beam current & Bragg peak (in copper).

- Placement of monitors needs input from machine designers

DAQ

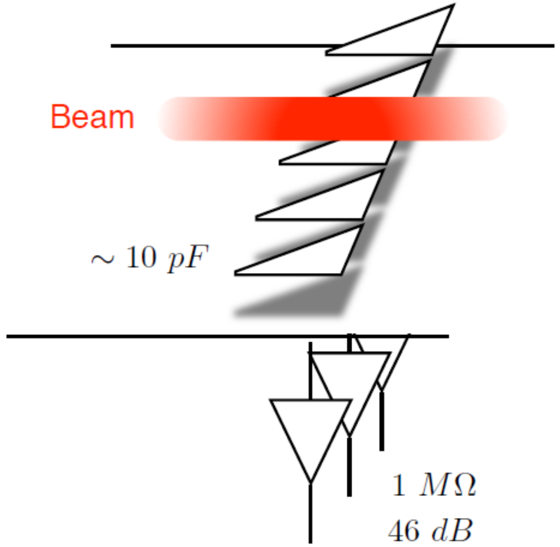
- Electronics with wide dynamic range
- FPGAs => fast fitting and pattern recognition of beam profiles
- Store calibration, apply corrections in real time.
- Find beam centre from non-Gaussian/asymmetric profile

FFA Instrumentation



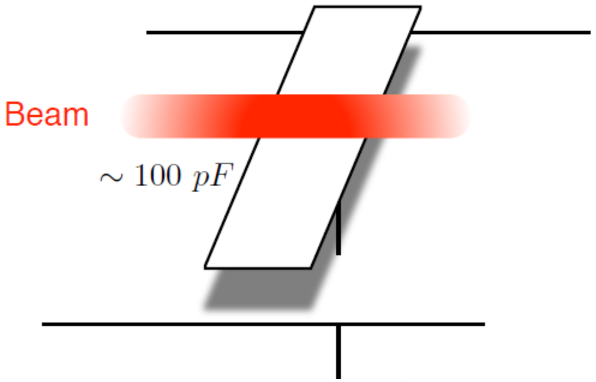
for horizontal position pickup

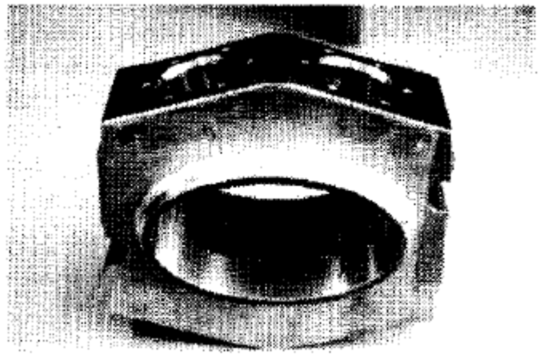
Triangular electrodes



for vertical position pickup

Wide electrode





- LhARA FFA based on RACCAM, 10 cells
- Beam position measured at injection and extraction septa
- Position measurement at least every second cell

Beam pickups will require calibration

KURNS = Institute for Integrated Radiation and Nuclear Science, Kyoto University

Research Plan

Low energy beam Conventional diagnostics
- Beam position – capacitive button pickups
- Beam current - BCT
- Beam current and energy - multi-layer Faraday cups (destructive)
- Emittance - slit-grid/slit scanners or pepper-pot emittance monitors

Low energy beam diagnostics
- SciWire - online beam profile measurement
- Thin ceramic monitors - online beam profile measurement

High energy beam diagnostics
- Develop beam position measurement for the FFA
- Investigate conventional diagnostics for beam current, position and profile measurement in the transfer lines
- Bunch length is important in the transfer line to the in vivo end station
- Emittance measurements by conventional instruments

Fast feedback and controls
- Initial R&D for the fast feedback system will focus on Stage 1
- Depends on details of the low energy beam instrumentation
- Development of an automated system for tuning the beam
- Monte Carlo simulation of the LhARA beam line in firmware
- Later extend to include Stage 2

Online dosimetry and dose profile
- Development of SciWire - dose profile at low energy end station
- Development of thin ceramic monitors - dose profile at low energy end station
- Development of SmartPhantom - online dose measurements in the high energy end stations

Absolute dosimetry at ultra-high dose rates
- Characterisation of nonlinear response of film detectors at high dose rates
- Investigate use of films for calibrating the online dose monitors

Spare Slides

Ion Instrumentation – Ceri Brenner

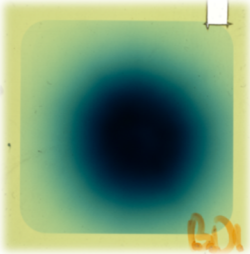
Requirements

- In-situ measurement of:
    - Ion energies
    - Ion species distribution
    - Beam profile
    - Fluence / Conversion Efficiency

- EMP Resistance
- High repetition rate operation
- Robust – radiation and laser damage
- Calibrated and Characterised
- Minimal user intervention

Established detectors

- **Radiochromic Film**
- **CR-39 Track detectors**
- **Image Plate**

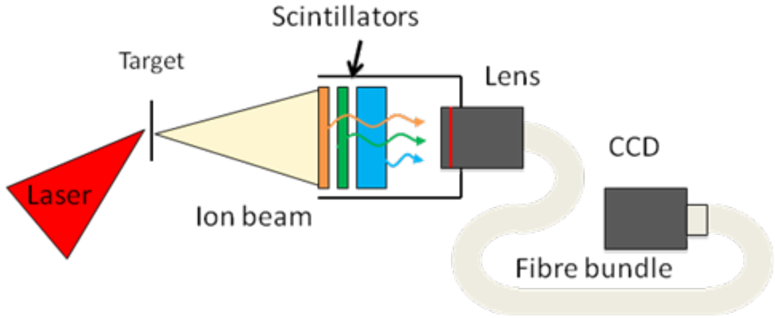


In-situ detectors

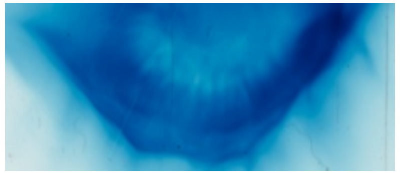
- **MCPs**
- **Scintillators**
- **Phosphor screens**
- **TOF detectors**

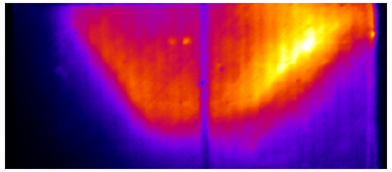
Ion Instrumentation

Beam profiler



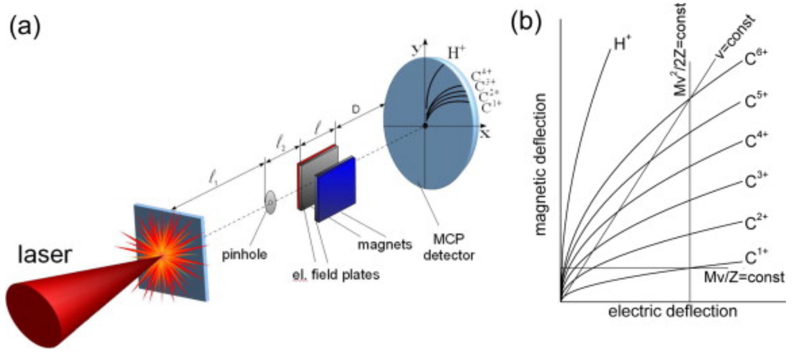
- 2D ion beam profiler
- Organic scintillator detectors
- 3 spectral channels


RCF


Scintillator

J.S. Green et al. *Proc. SPIE* **8079** (2011)

Thomson Parabola

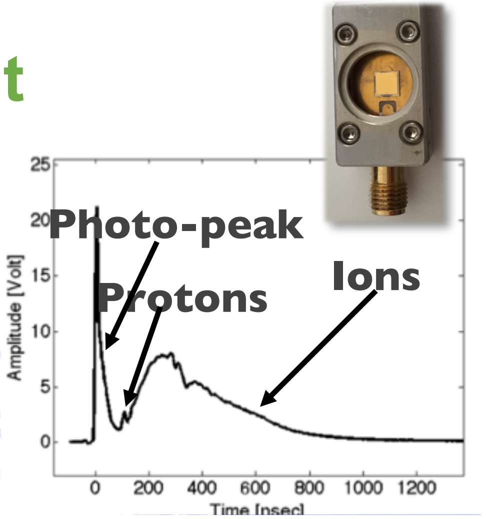


- 1D Multi-species ion spectrometer
- MCP or Scintillator detector

P. Bolton et al. Phys. Med. **30** (2014)

Time of Flight

- Diamond / SiC detectors
- 80-350 ps time resolution

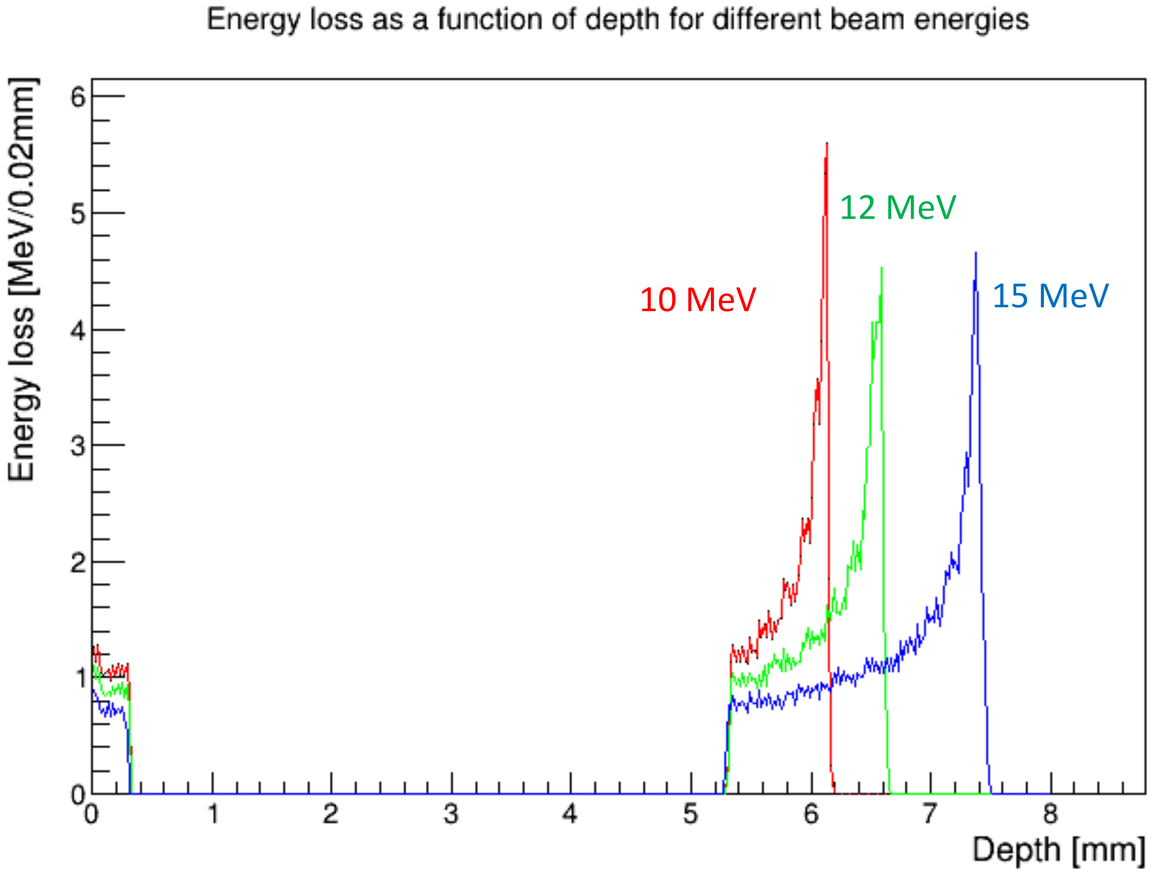


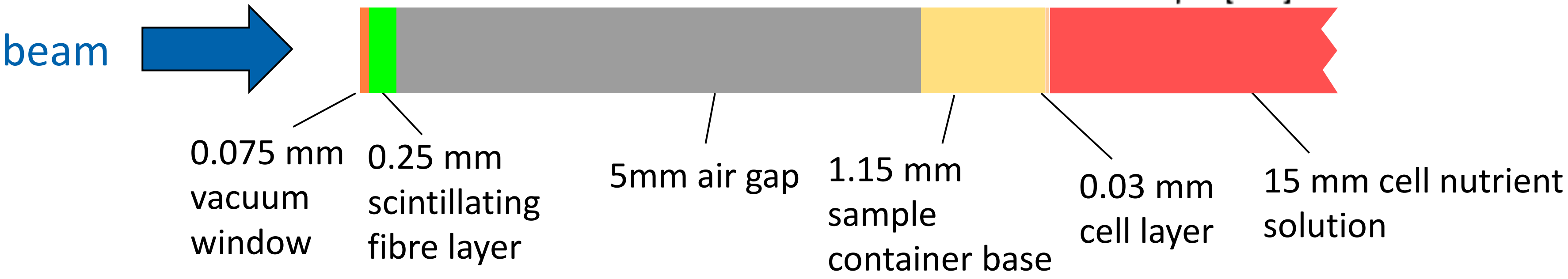
V. Scuderi et al. *J. Inst* **12** (2017)

Ceri Brenner

Stage 1 end station

- Energy loss in the end station using the beam tracked from after the capture section.





Instrumentation in other FFAs

US neutrino factory FFA

- 1 x 4-button BPM per quadrupole magnet
- (OTR) foils
- phase probes for beam-RF comparison
- wall-current monitor
- wire scanners
- integrating current toroid or Faraday cup
- transverse deflection cavity & fluorescent screen (bunch shape)
- Extraction line has dispersive region => momentum
- “pepper-pot” emittance monitor

EMMA (Daresbury Laboratory)

- 42 F-D cells with 81 BPMs
- BPM:
    - 4-button pickup
    - 2 front end modules
    - VME module – ADCs + 4000 turns memory

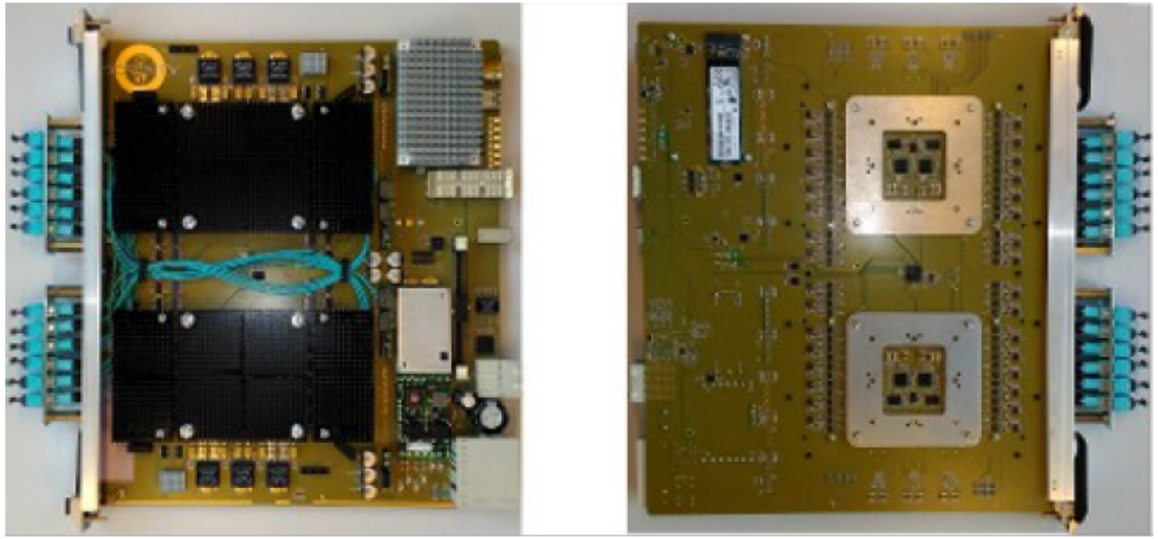
Fast feedback controls and monitoring

PROSCAN facility at PSI

- Signals from beam instruments digitised and fed back to the machine control system (MCS)
- BPM currents fed to LogIV unit (logarithmic transimpedance amplifier and ADC)
- LogIV outputs digitised signals, accessible via the VME backplane
- Digitised signals read by a VPC digital back end electronics module, which contains 2 FPGAs
- System FPGA runs the common firmware
- User FPGA implements the local storage and processing algorithms
- RAM provided for lookup tables
- User FPGA is used to calculate quantities derived from raw pickup data, such as total beam current, beam vertical position, beam horizontal position, beam sizes, etc.
- Limits can be set on parameters which can be used in an interlock system, via fast optical data links.
- BPM data is sampled at 5kHz and fed back to the MCS for applying beam corrections

SERENITY

- V1.1: 72 x 2 firefly links can run at up to 28Gbps/link
- V1.2: 120 x 2 firefly links, less (6) interconnection between FGPAs
- 2 Daughter Card sites (custom FPGA)
- Carrier card with service FPGA and CPU + ZYNQ option (v1.2)
- ATCA, but adaptable form factor (e.g. rack/pizza box)



Alex Howard

Proton Tomography

Note that other approaches to this include proton tomography, as researched by the PRaVDA collaboration, who have built a prototype silicon tracker for proton tomography: http://www.pravda.uk.com/index.php/78-pgeneral/71-phone. See also Burker et al. (Vienna Conference on Instrumentation 2019) – developing a similar detector system to PRaVDA, in this case for ion tomography.

Secondary particles

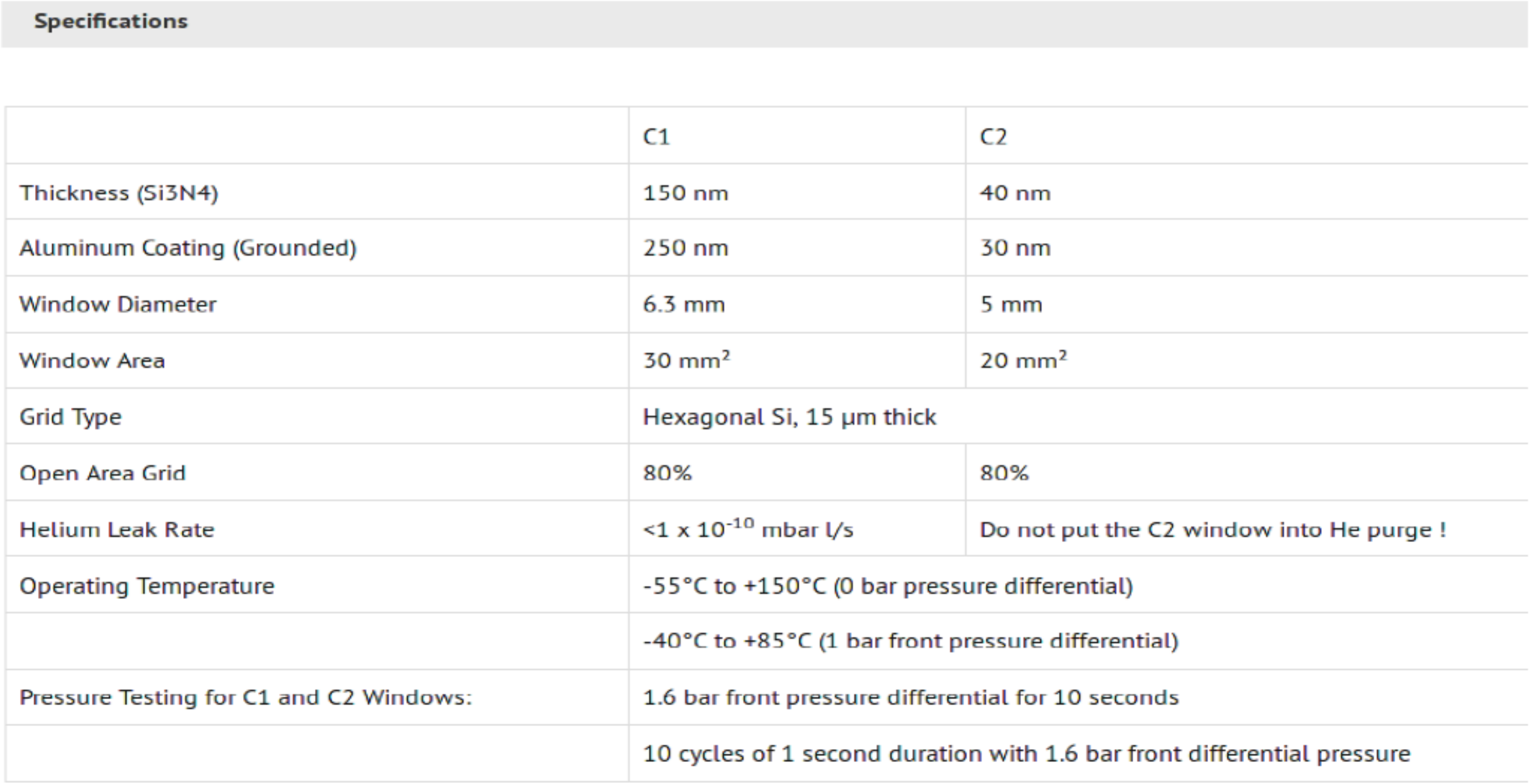
In proton radiotherapy, secondary neutrons from the proton interaction lead to unwanted dose in healthy tissue. Gioscio et al. (Vienna 2019) have built a prototype 250 micron scintillating plastic fibre tracker with a SPAD array (from LFoundry).

Thin Ceramic monitors (Silson)

- Have put 14.0 mm membranes into 17.5 mm frames and 19.0 mm into 23.5 mm
  - Depending on how they will be mounted you may need a wider frame.
- Can also mount membranes into free-issue mounts or we can design a mount to meet your requirements
  - Usually mount with low out-gassing epoxy.
- 1 atmosphere window at 10.0 mm the membrane needs to be 1000 nm thick
  - At 50 nm it's down to 0.5 mm
- You can make windows from arrays of membranes but the transmission is then poor because of all the supporting ribs and if you make the ribs too narrow it is the ribs which break, e.g.:
  - a 100 nm thick, 10.0 mm membrane in a 14.0 mm frame is GBP 120.00.
  - a 50 nm thick, 10.0 mm membrane in a 17.5 mm frame is GBP 270.00.
  - lower yield per wafer by area:
    - the membrane is thinner, they break more - lower success per wafer.
- Metallisation increases prices by ~50%

Thin Ceramic monitors (Ametek)

- Etched Si_3N_4 with outside support frame
- Very thin free standing (I believe), can withstand 1 bar
- Formerly hsfoils in Finland, now ametek



Specifications

	C1	C2
Thickness (Si3N4)	150 nm	40 nm
Aluminum Coating (Grounded)	250 nm	30 nm
Window Diameter	6.3 mm	5 mm
Window Area	30 mm^2	20 mm^2
Grid Type	Hexagonal Si, 15 µm thick	
Open Area Grid	80%	80%
Helium Leak Rate	<1 x 10^{-10} mbar l/s	Do not put the C2 window into He purge !
Operating Temperature	-55°C to +150°C (0 bar pressure differential)	
	-40°C to +85°C (1 bar front pressure differential)	
Pressure Testing for C1 and C2 Windows:	1.6 bar front pressure differential for 10 seconds	
	10 cycles of 1 second duration with 1.6 bar front differential pressure	

Alex Howard