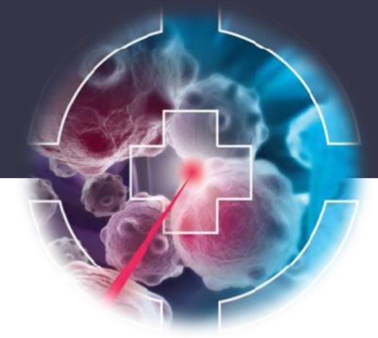
Topical Workshop on Diagnostics
for Beam and Patient Monitoring
CERN, 4-5th June 2018

Halo dose correlation in a medical accelerator

Jacinta Yap
University of Liverpool / The Cockcroft Institute

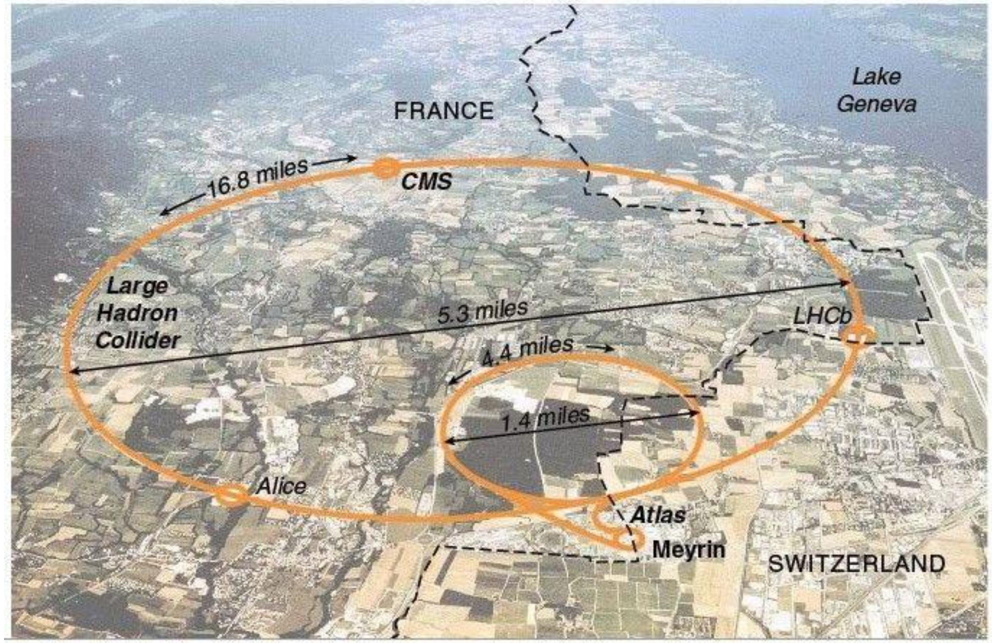
Outline



- **Project introduction**
  - Overview
- **Application: Diagnostics**
  - Beam monitoring
  - Clatterbridge Beamline
- **VELO: Standalone beam monitor**
  - Development
  - Concept / technique
- **Simulation studies**
  - Preliminary results
  - Integration of Si disc
- **Beamline studies: Emittance**
  - Beam dynamics
- **Summary**

Project Introduction

"Halo-dose Correlation in a Medical Accelerator"



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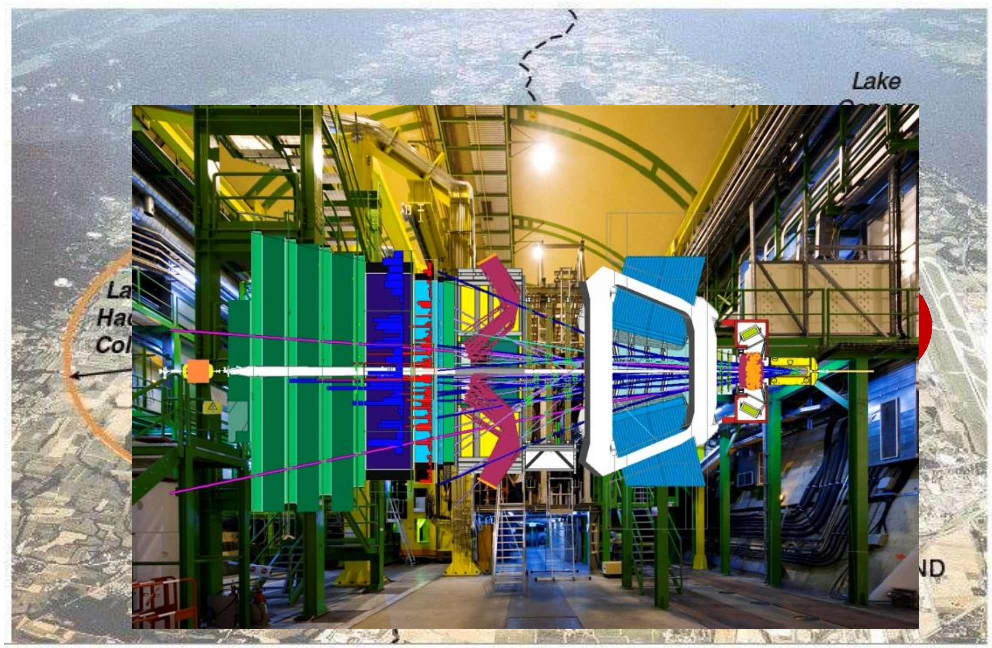

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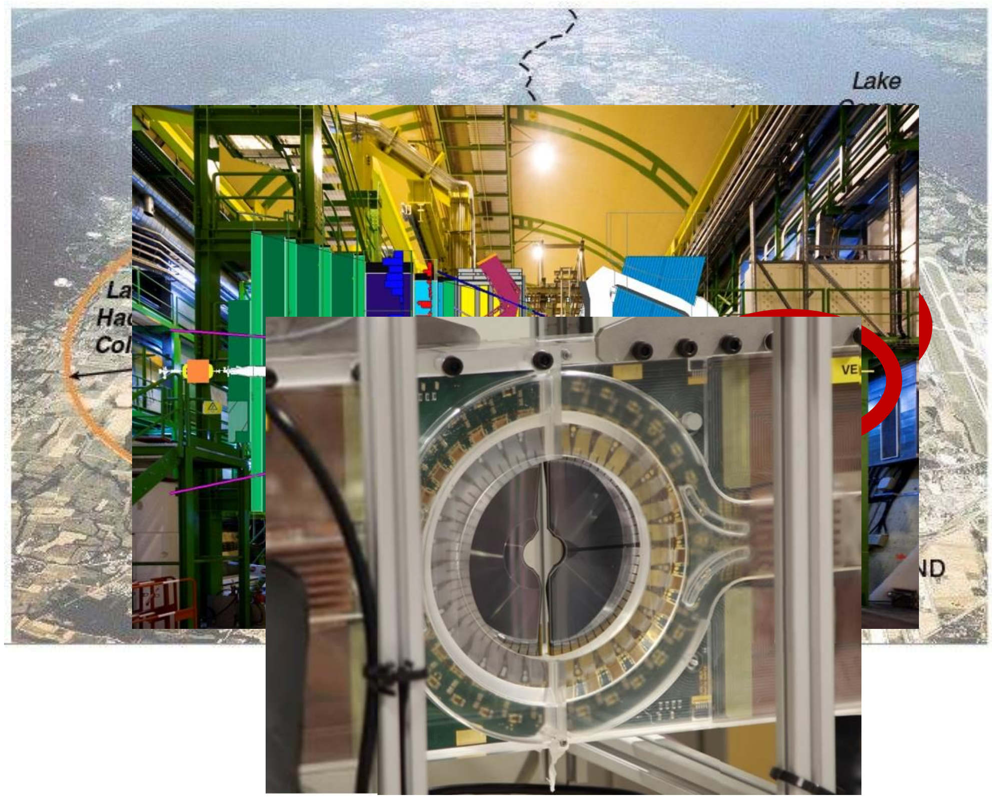


Project Introduction

“Halo-dose Correlation in a Medical Accelerator”

Project Introduction

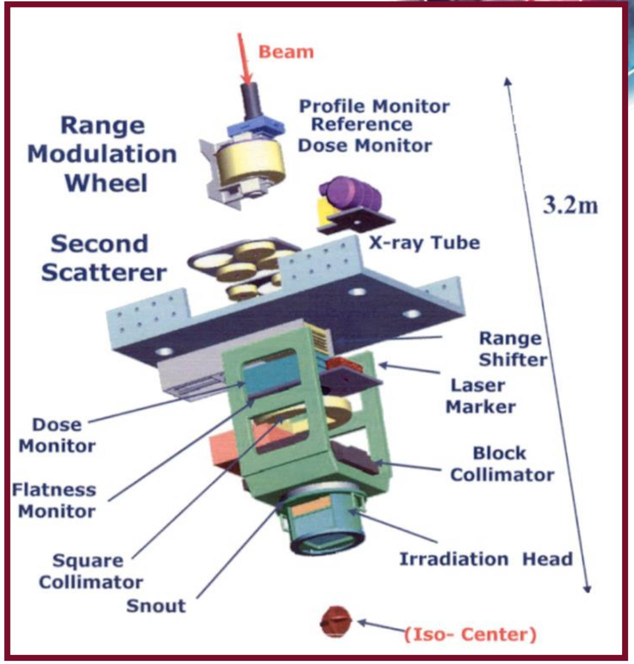
“Halo-dose Correlation in a Medical Accelerator”

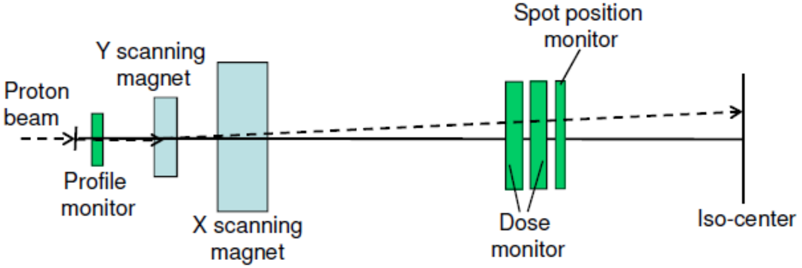
Overview

- Characterise and correlate the **beam halo to dose**
- Implementation of a beam monitor based on **LHCb VELO** technology
  - Capability as a **standalone monitor in the clinical proton beam** at Clatterbridge Cancer Centre (CCC), UK
  - Development for online use with verifiable halo maps
- Investigate integration of beam monitor in CCC
  - Beamline **optics & particle tracking** studies

Introduction – Beam monitors

- Online dose monitors
  - Gold standard: Ionisation chambers
- Treatment beam measurements:
  - Dose delivered
  - Beam intensity
  - Beam profile
  - Beam position
- Interceptive devices
  - Ionisation correction (type of gas, pressure, temperature effects..)
  - Multiple monitors required
  - Degradation of beam

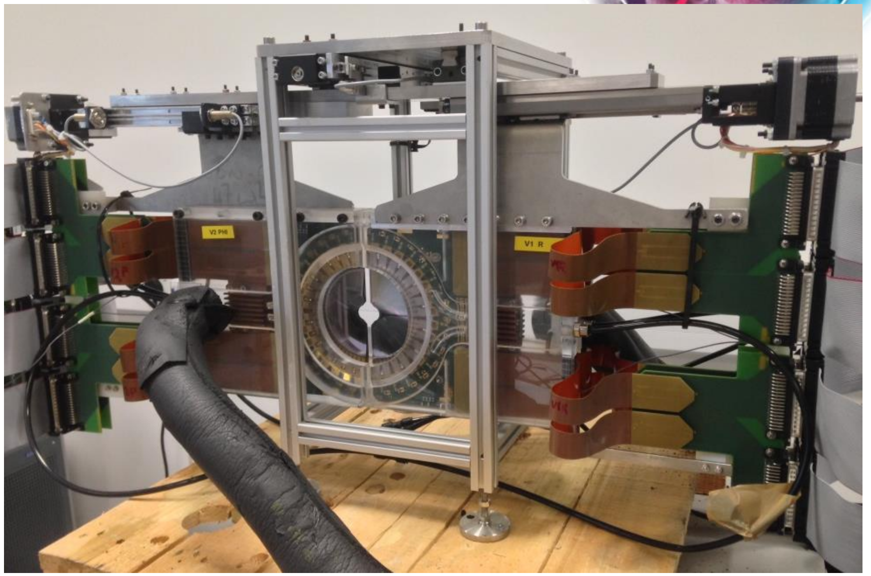




Mohan & Grosshans, Adv. Drug Deliv. Rev 109 (2017)
Zhu et al. Cancers 7 (2011)

VELO Standalone Beam Monitor

- Air flow and cooling system
  - Operation in air
  - Prevent condensation
- Electronics and readout
  - To allow individual operation without LHC signally
  - DAQ triggering
  - Compact & modified wiring
- Mobility stand
  - Precise movement
- Optimised faraday cup
  - Beam current correlated with sensor signal

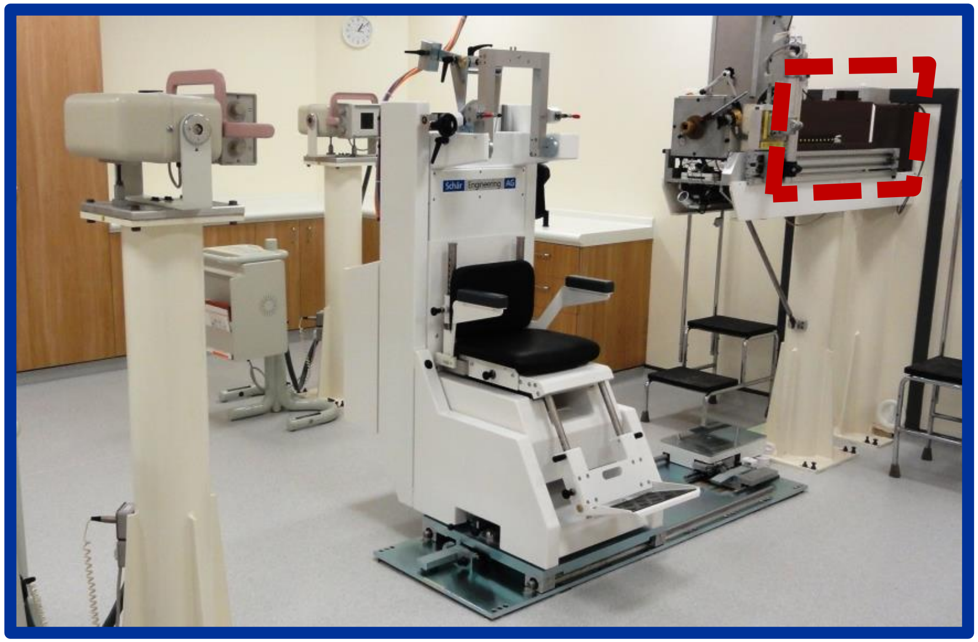


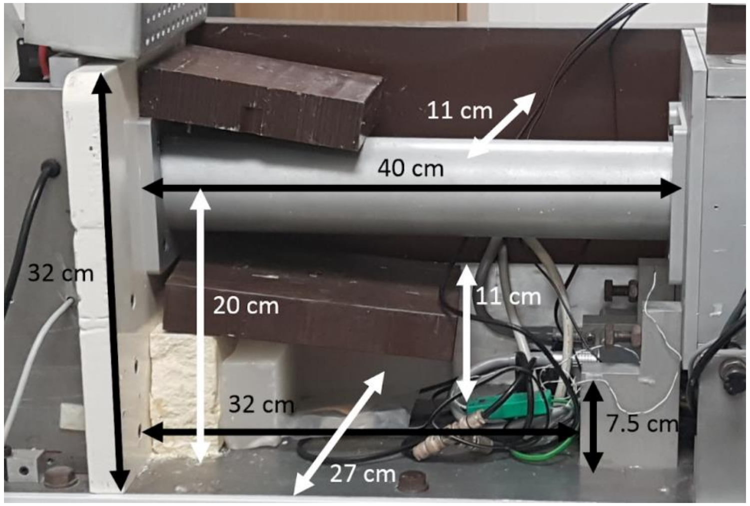
CCC Parameters	Max kinetic energy	62 MeV
	RF Frequency	25.7 MHz
	Average beam current	5 nA
	Number of ions	3.12×10^{10} /s
	Bunch length	1.37 ns

R. Schnuerer, J. S. L. Yap et al. Proceedings of IPAC (2018)

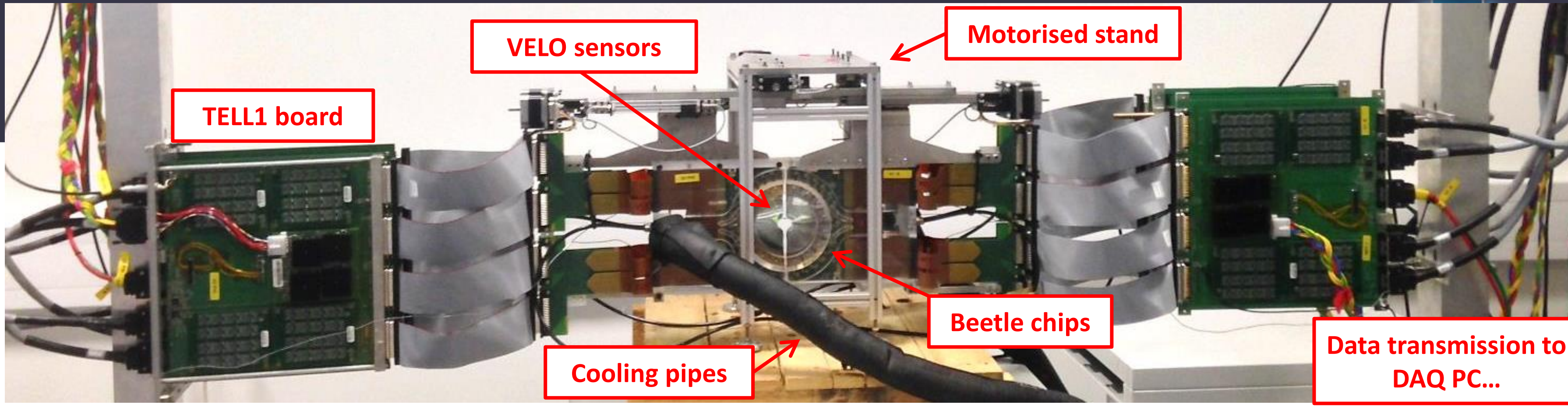
Implementation in CCC

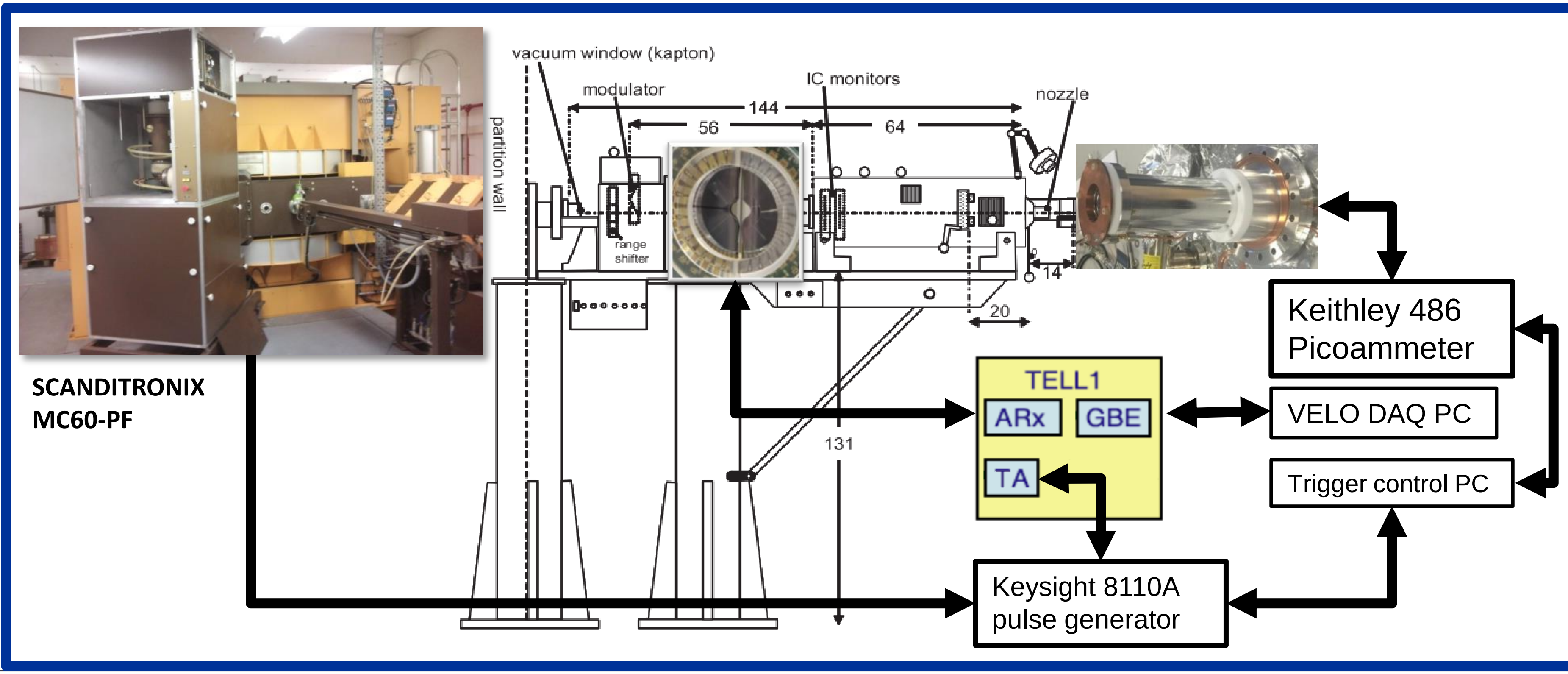
- Clatterbridge CC, UK
  - First hospital based proton therapy facility in the world
  - Ocular treatments
  - 60 MeV passively scattered protons





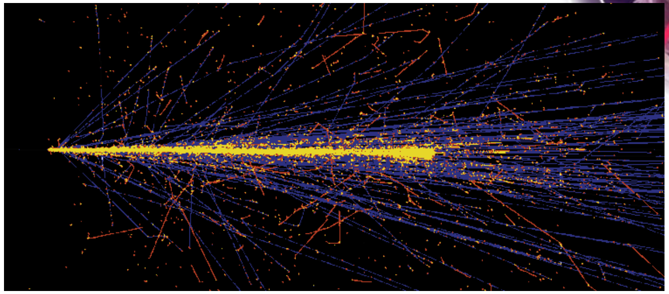
Aluminium pipe removed for integration

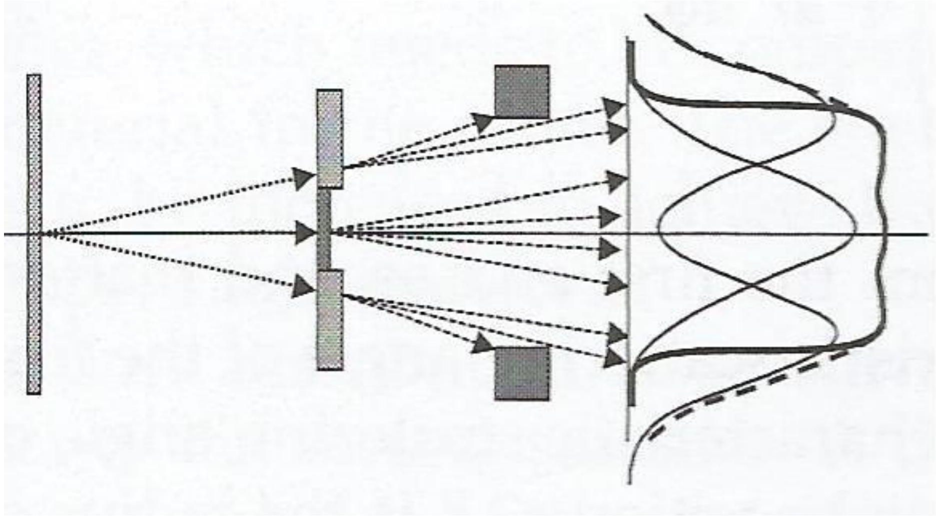

Motorised stand
VELO sensors
TELL1 board
Beetle chips
Cooling pipes
Data transmission to DAQ PC…


SCANDITRONIX MC60-PF
vacuum window (kapton)
modulator
IC monitors
nozzle
144
56
64
partition wall
range shifter
14
20
131
TELL1
ARx
GBE
TA
Keithley 486 Picoammeter
VELO DAQ PC
Trigger control PC
Keysight 8110A pulse generator

Beam halo

- Scattering foils
  - Tungsten
  - Beam shaping element
  - Broadens & flattens beam
- Halo
  - Arises due to scatter from elements & air
  - Outer edges of beam
  - Radius threshold

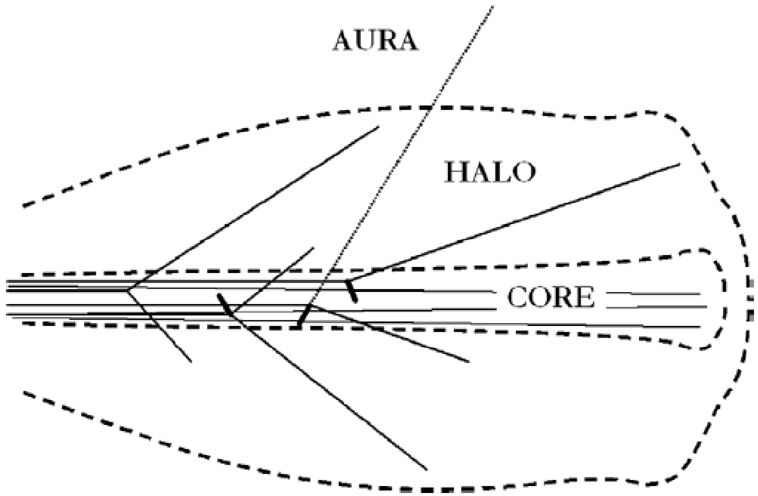




Development of beam from a double ring scattering system

Concept

- Beam halo generated from scattering components
  - Surrounding protons which are collimated prior to exit
- Correlate halo region to core of beam
  - Online monitoring of dose delivery



B. Gottschalk et. al, PIMB 60 (2015)

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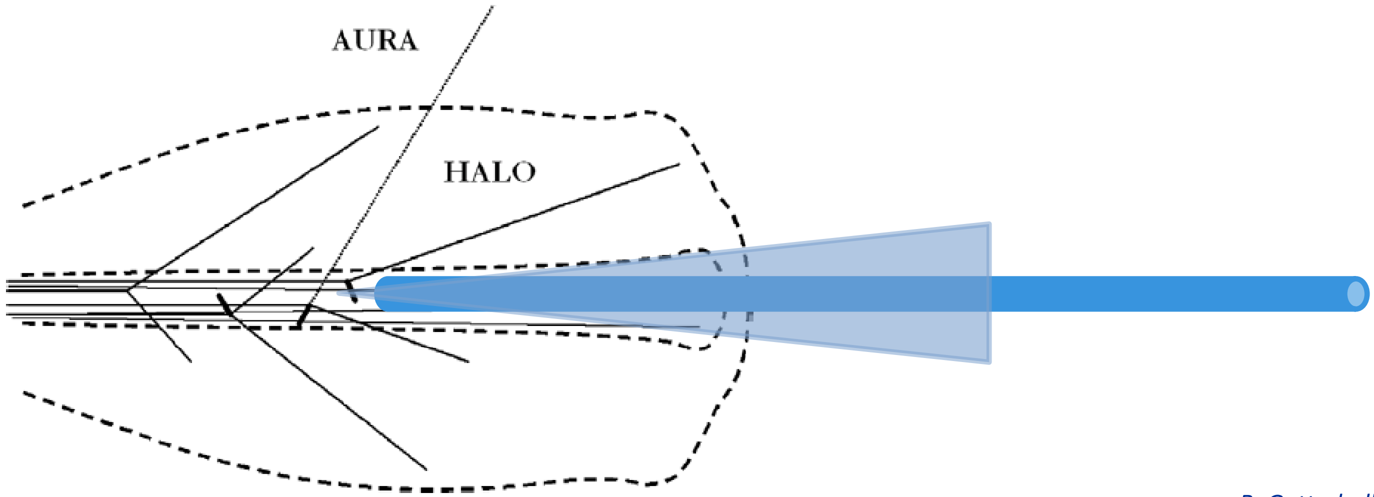

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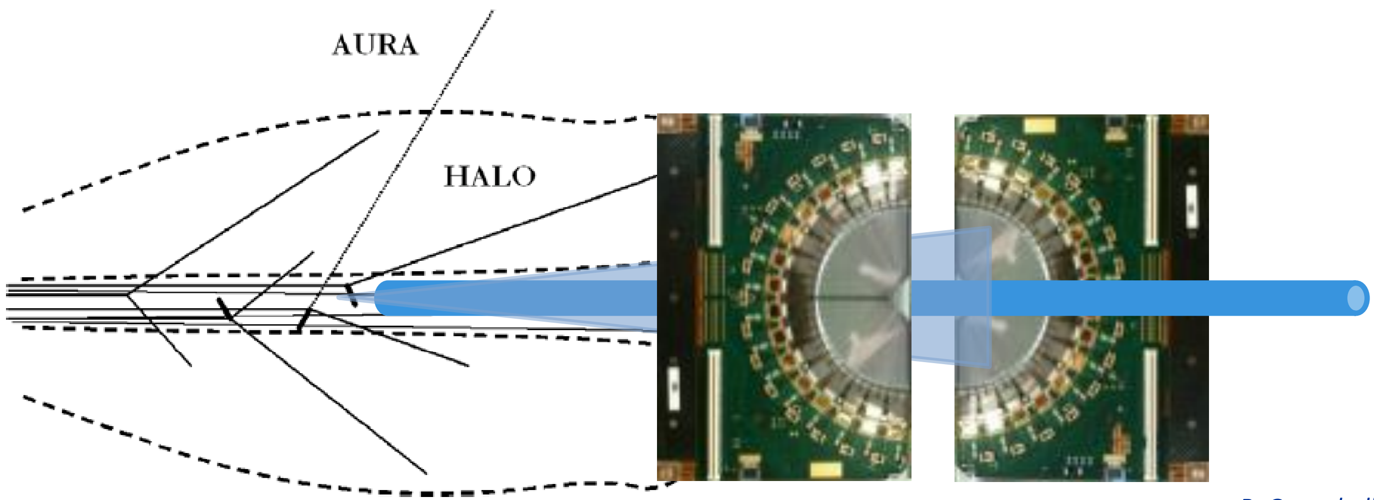

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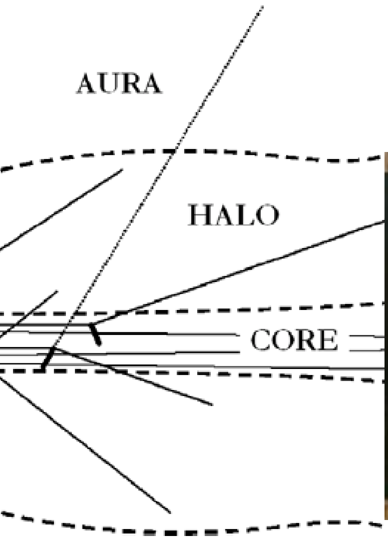
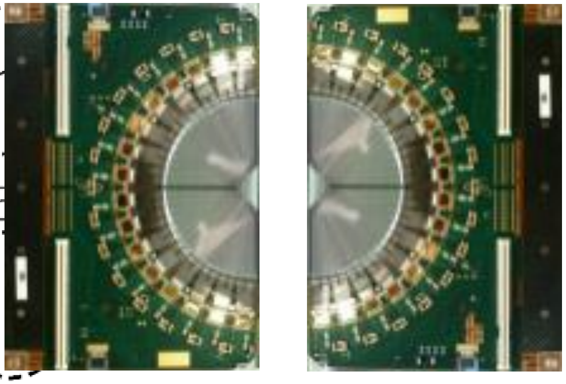
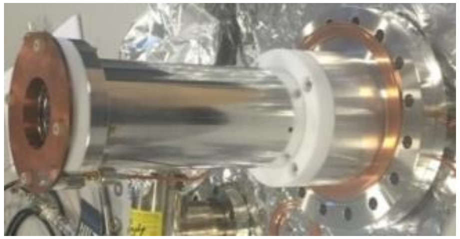
Halo dose correlation

- Correlate halo region to dose delivered
- Halo maps
  - Beam simulations, experimental data







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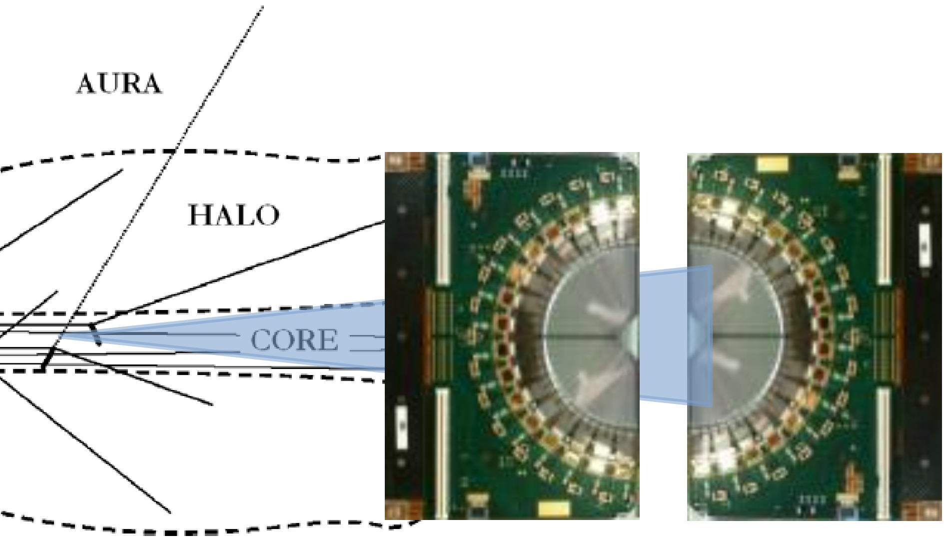

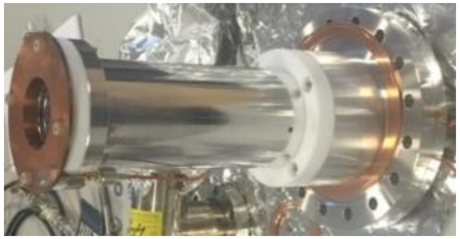

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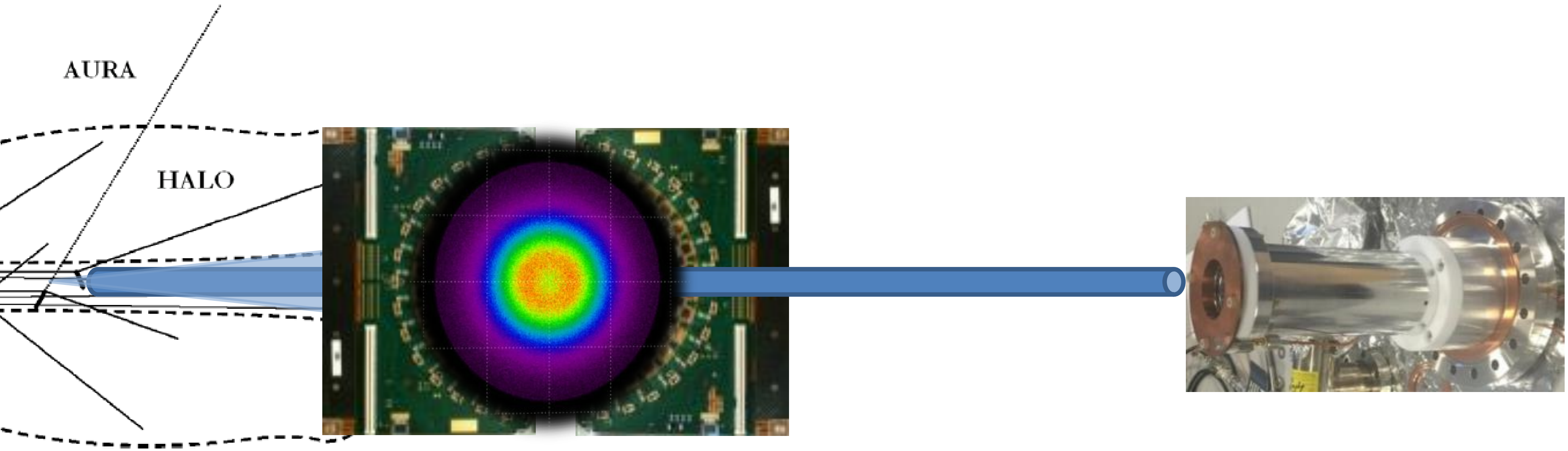

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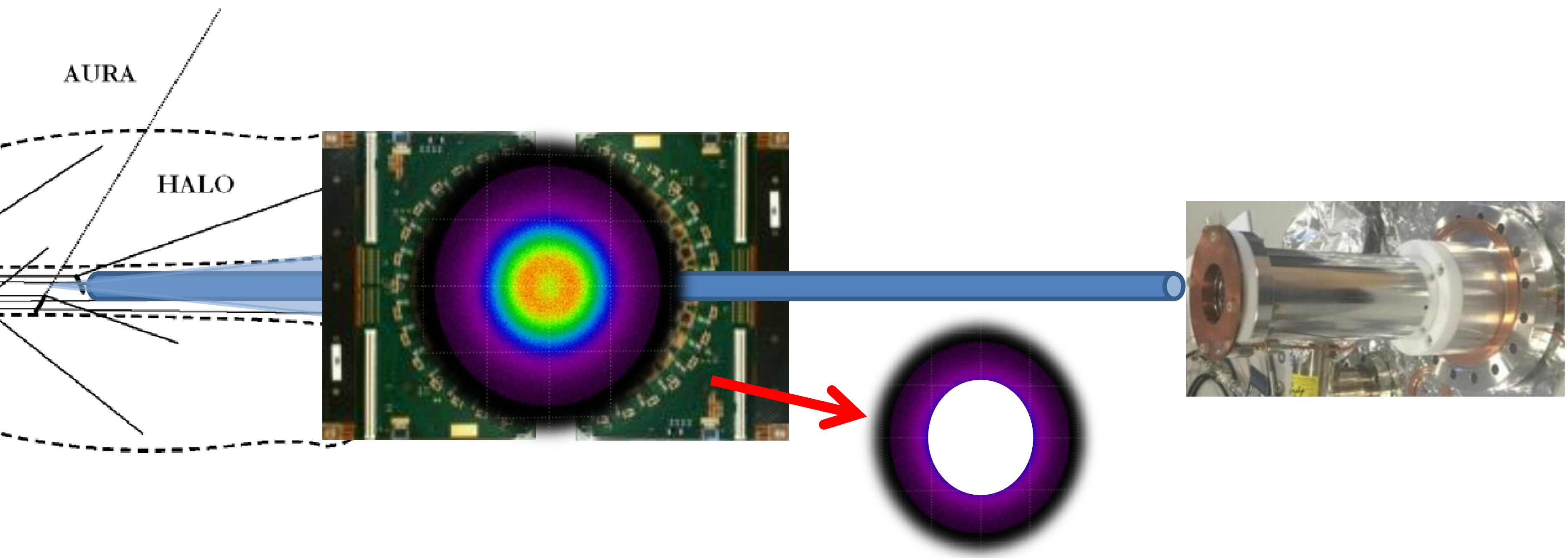

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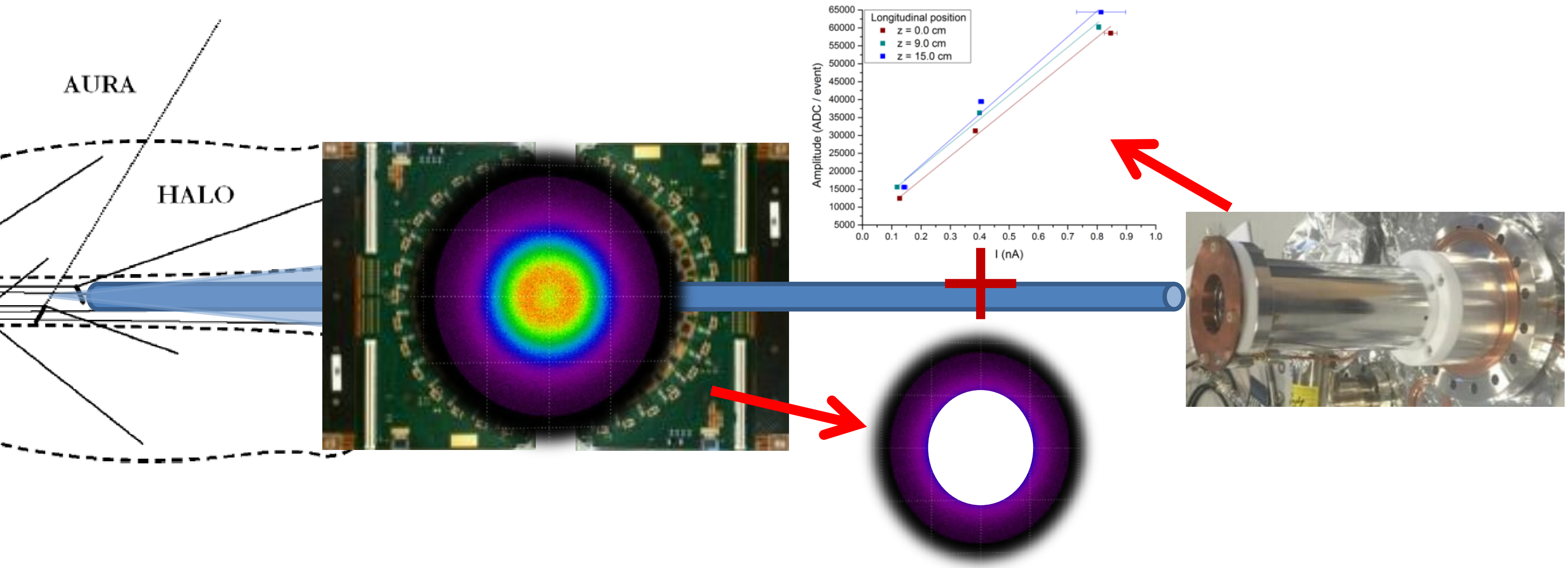

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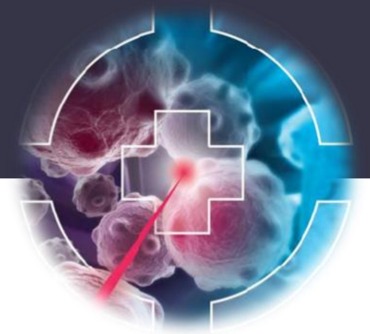

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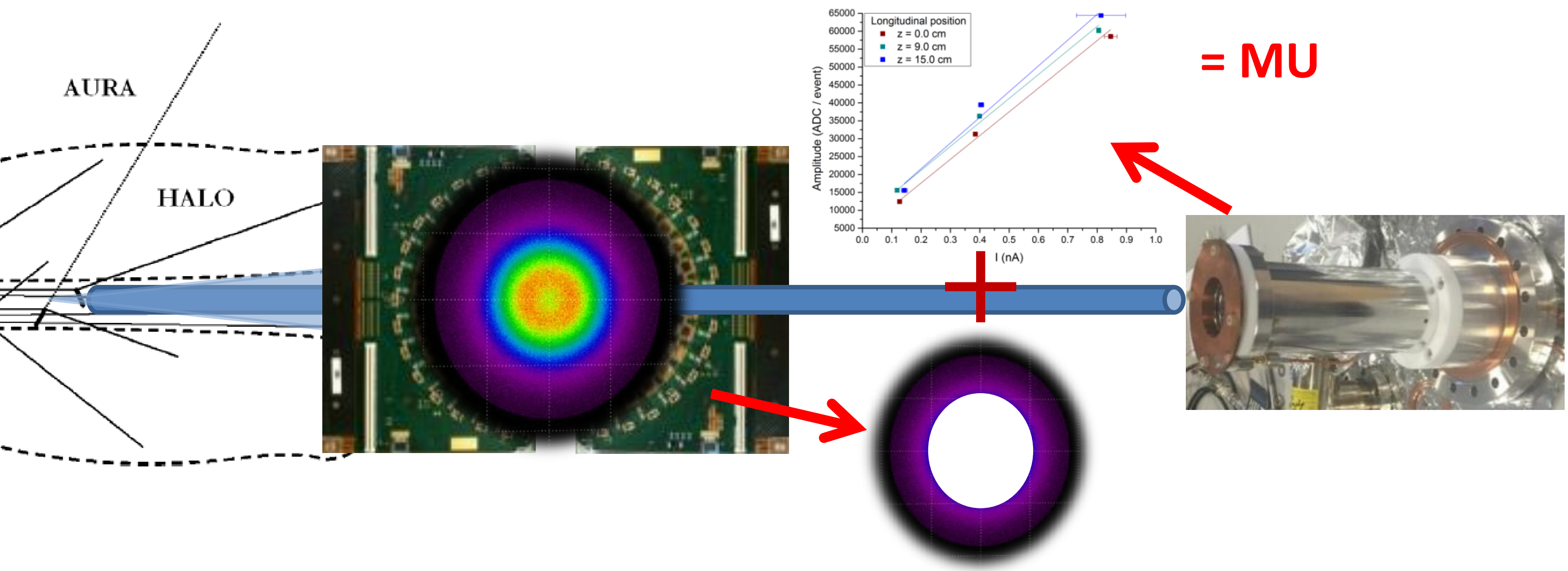
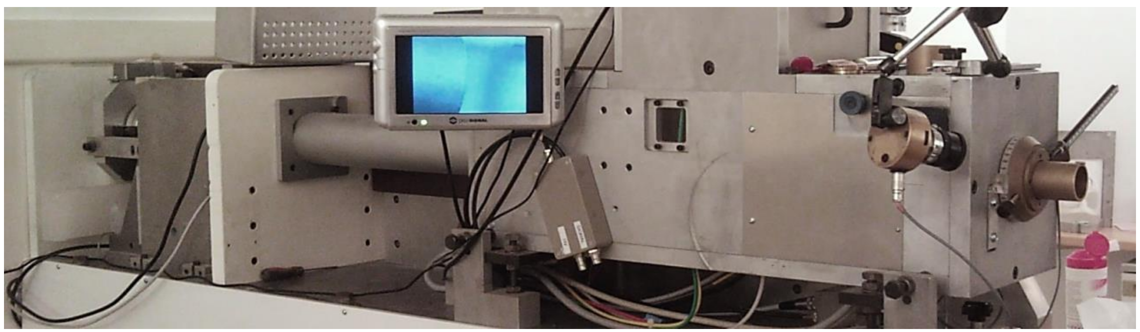
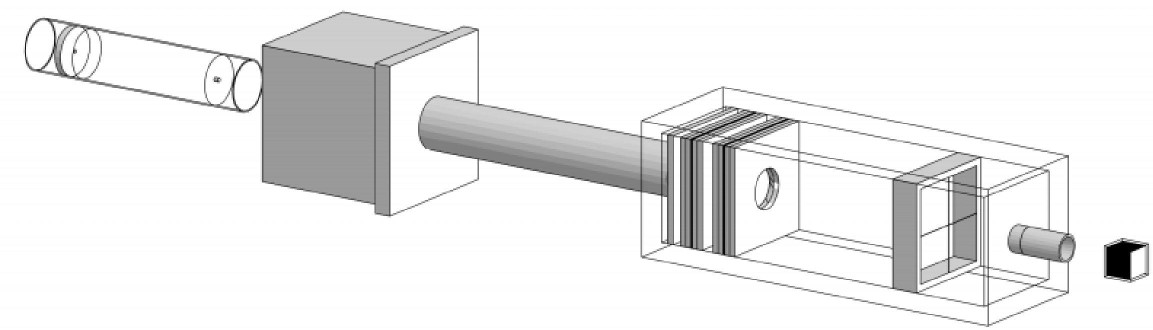


Simulation studies

- Development of accurate model for the CCC beamline
- Monte Carlo toolkit: Geant4
  - Beam dynamics
  - Delivery system

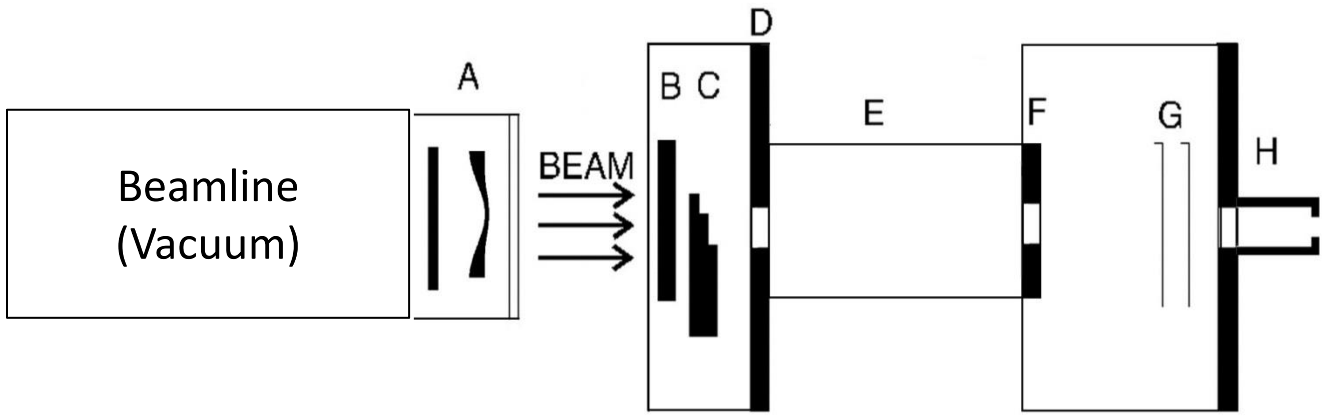


CCC delivery system

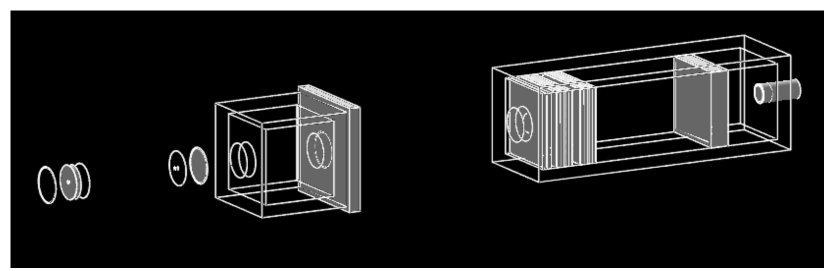


Modelled in Geant4
(geant410.02.p.01)

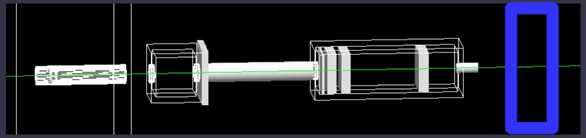
Geant4 Model



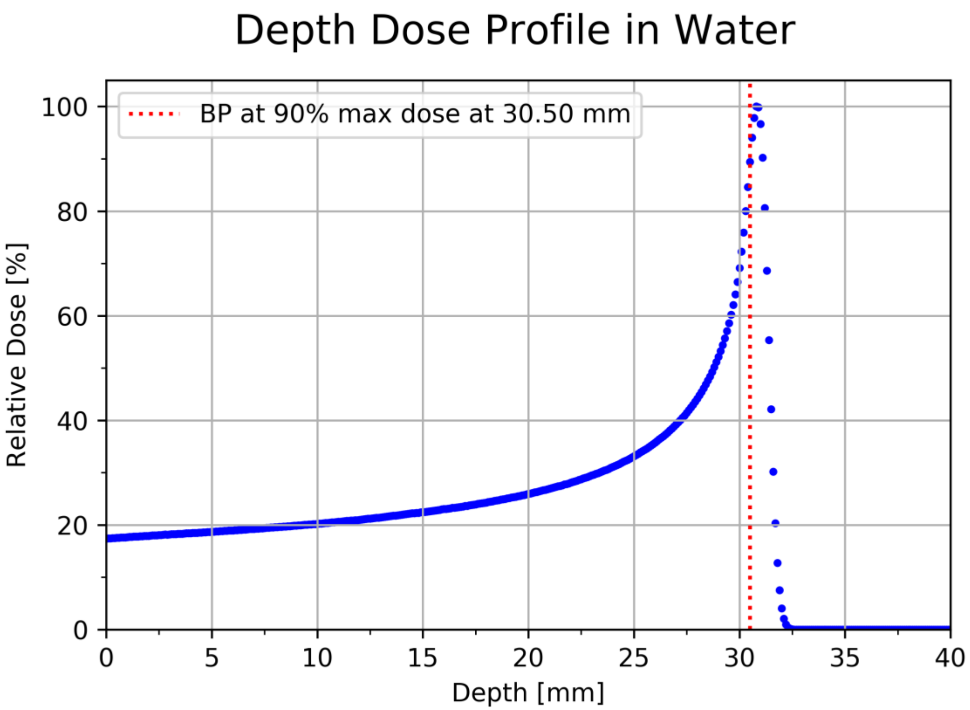
- A: Double scattering foils, beam stopper
- B: Range shifter
- C: Modulation wheel
- E: Drift pipe => <u>Integration zone</u>
- G: Ionisation dose monitors
- H: Nozzle

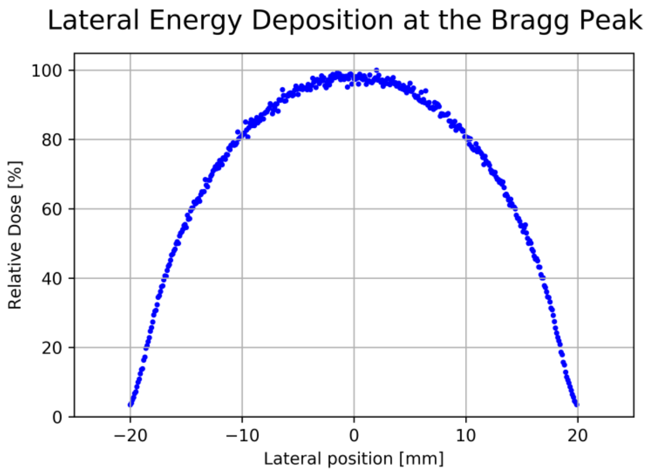


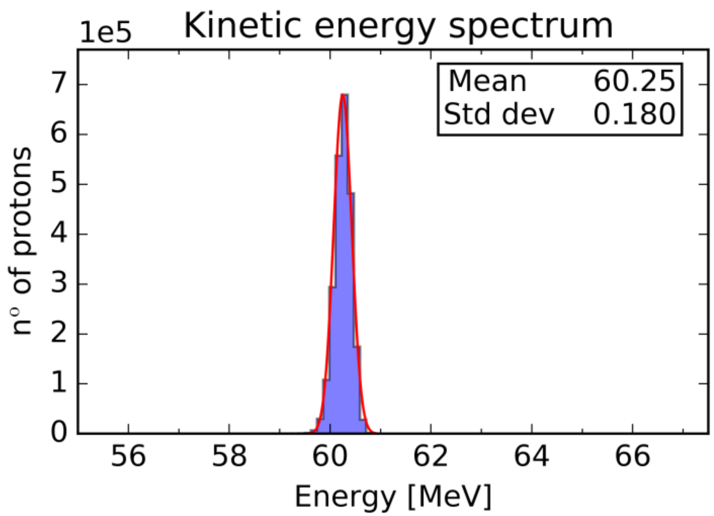
Preliminary Results



- Bragg peak & energy spectrum at isocentre

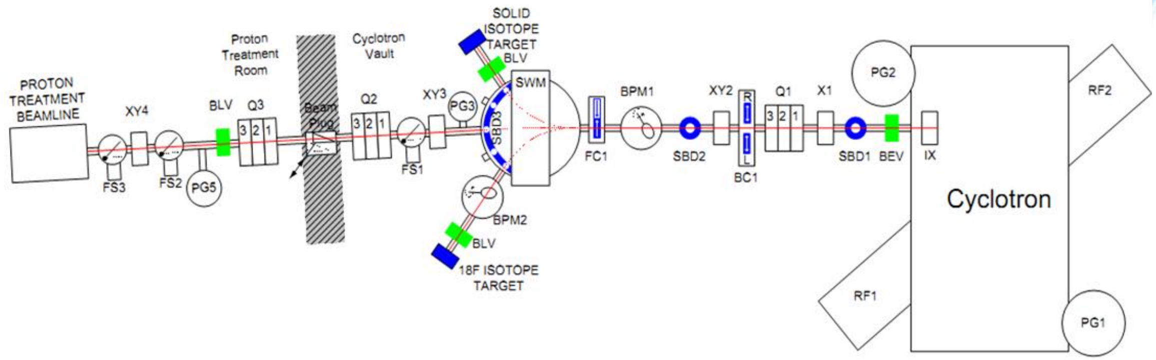






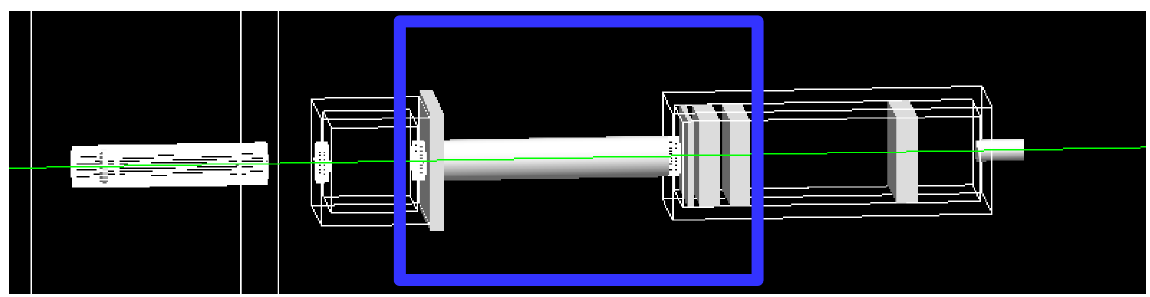
Beam behaviour

- CCC beamline
  - Beam optics
  - Particle tracking



- Analysis for system integration
- **Beam propagating through the VELO integration zone**

- Halo maps



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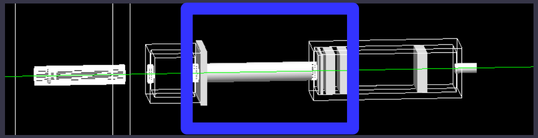
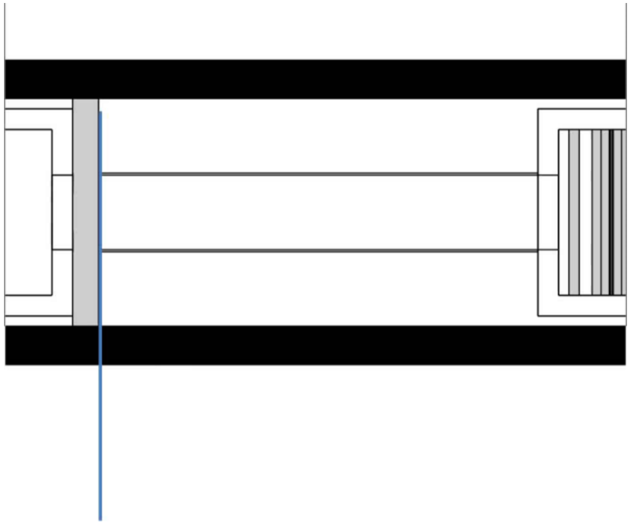
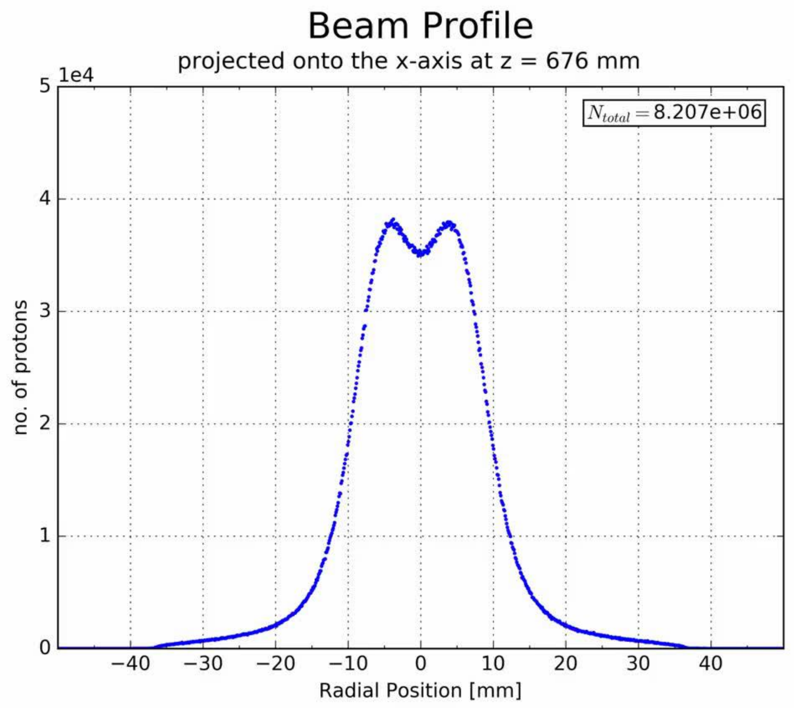


- Analysis of the beam propagating through the VELO integration zone



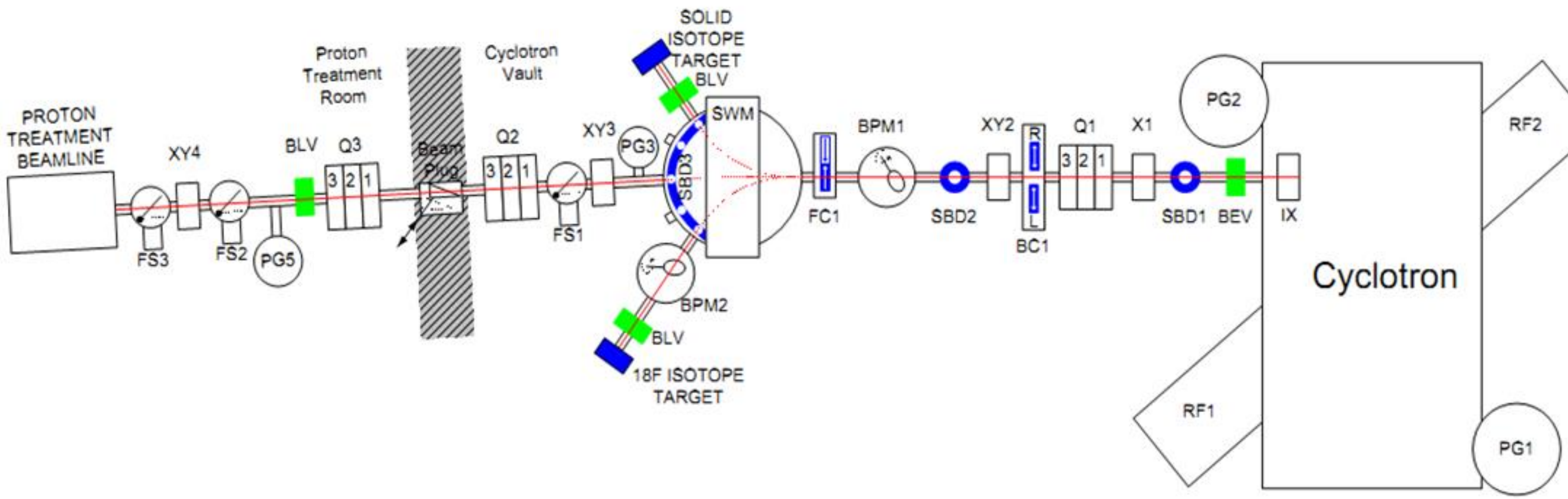


Model accuracy

- Geant4 model starts at treatment room
  - Source (= 8cm) before first scattering foil
  - Simulations run with historical information (beam size, energy, energy spread)

- How do we know our information is accurate?
  - Verify geometry
  - Experimental validation
  - Combine information upstream

CCC Beamline Study

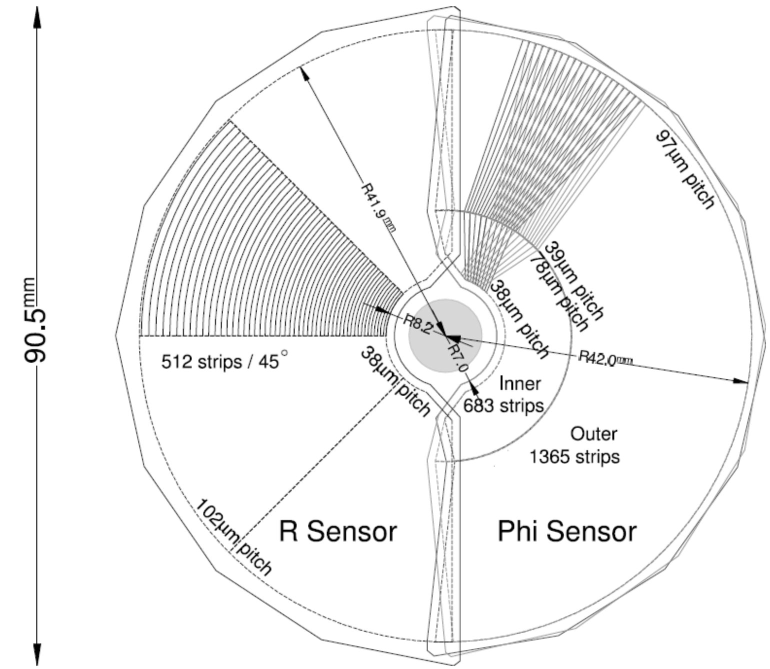


- Commissioned in ~1984
- First treatment for protons in 1989
- No diagnostics in line
- Approximately 62.5MeV protons produced

Beam parameters

- Input parameters for simulation
  - Beam energy
  - Energy spread
  - **Beam size**

- <u>Uncertainties</u>
  - Beam profile changes throughout the delivery system
  - Number of protons, density & distribution changes



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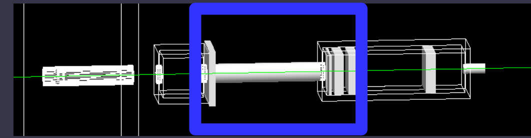
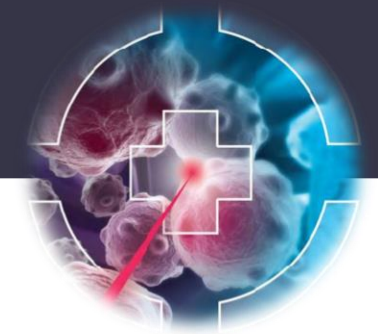
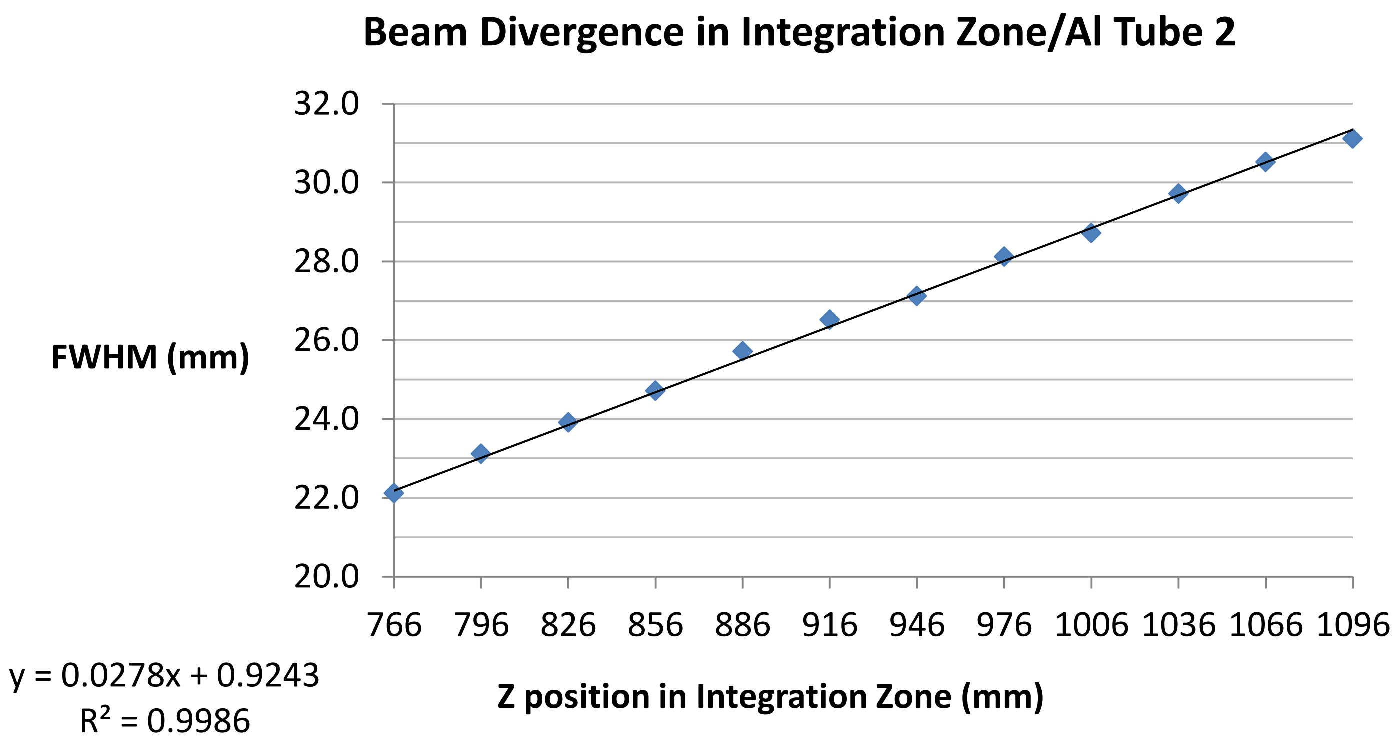
The Cockcroft Institute of Accelerator Science and Technology

Beam divergence



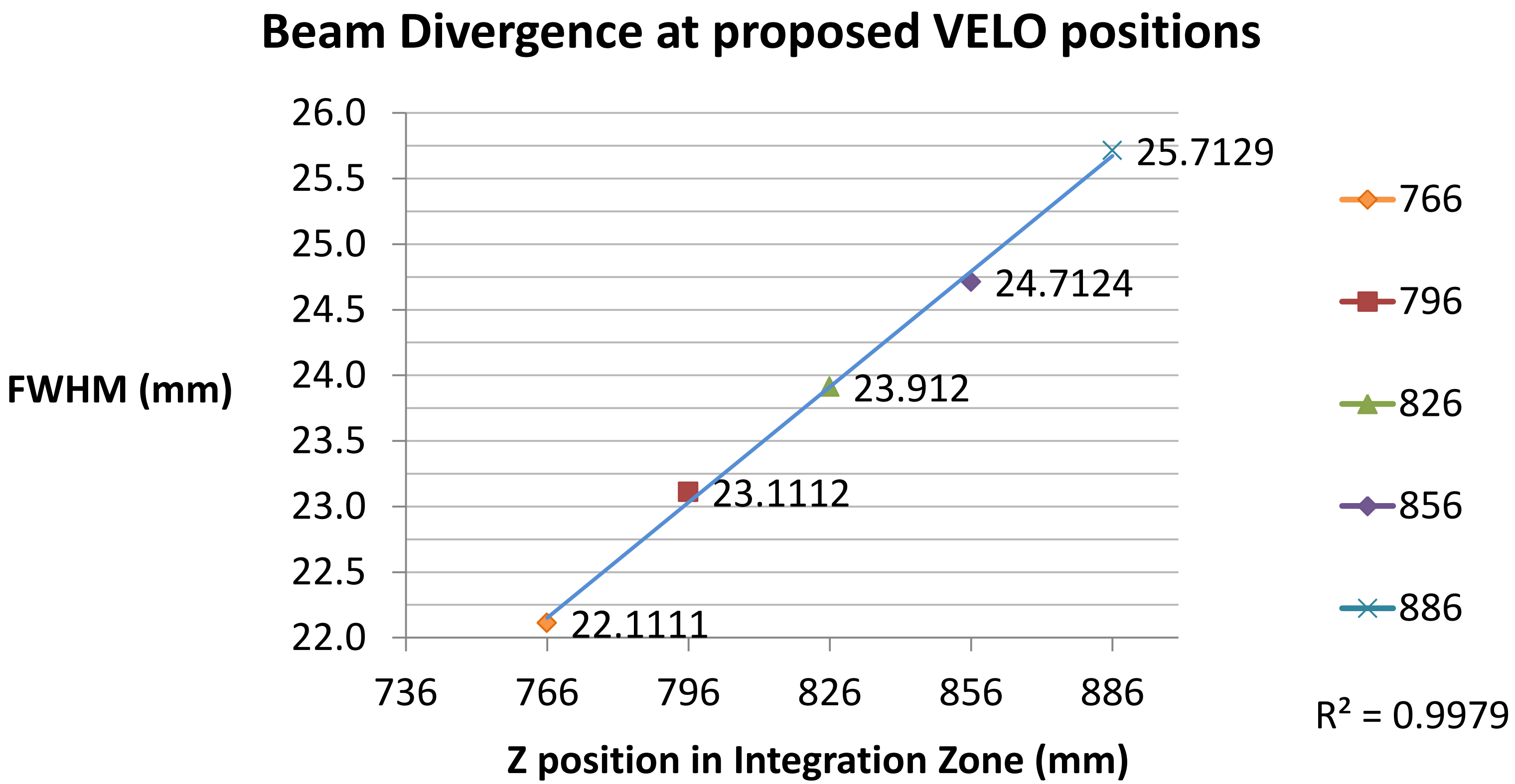


- In integration zone, beam diverges by ~12mm
- Aperture diameter ~19mm



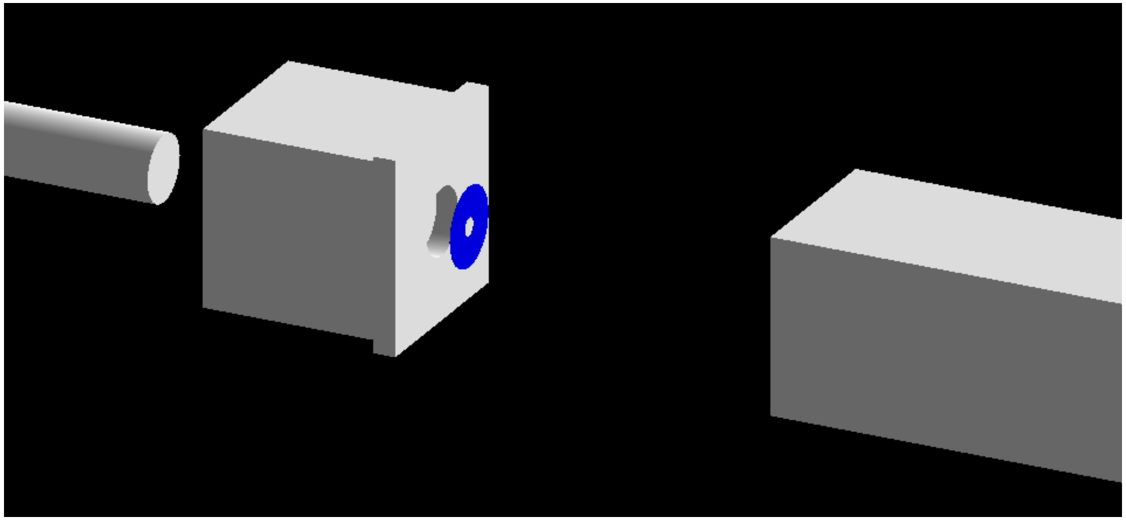
Proposed integration

- Due to increasing divergence, select positions for sensor at beginning of integration zone



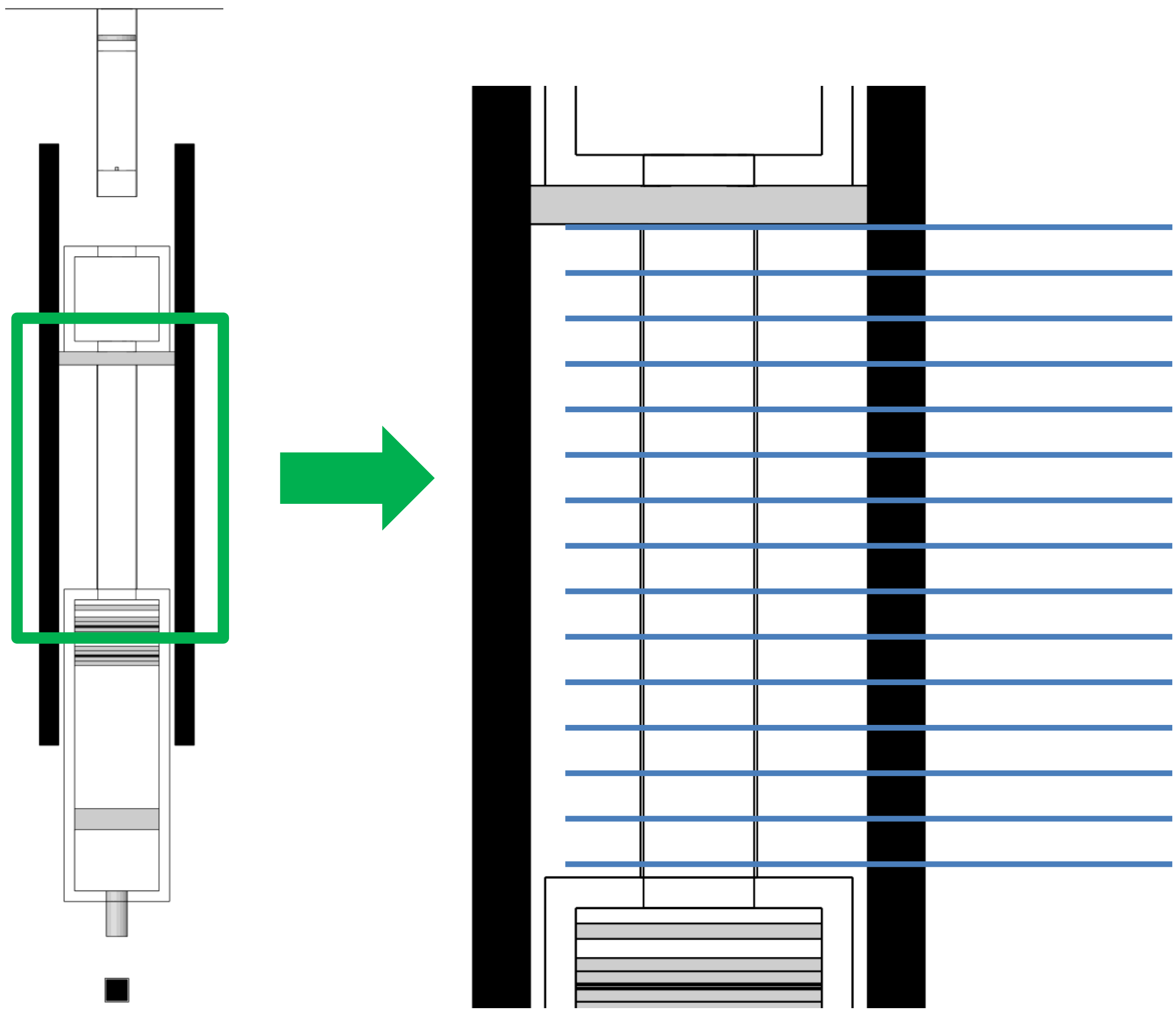
Integration of Si Disc

- Starting with geometry of arbitrary Si disc
  - Outer diameter 90.5mm
  - Inner aperture radius 9.2mm
  - Thickness 0.6mm
  - Disc placed centrally



- Small gap between halves (~2.6mm)
- Aperture radius in Sim = **10.5mm**

VELO sensor positions

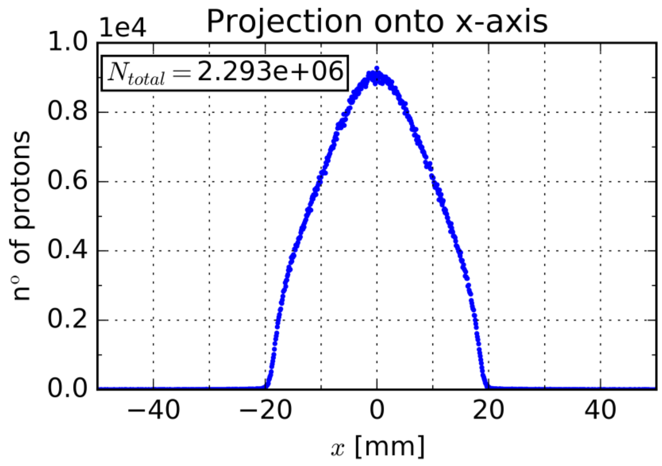


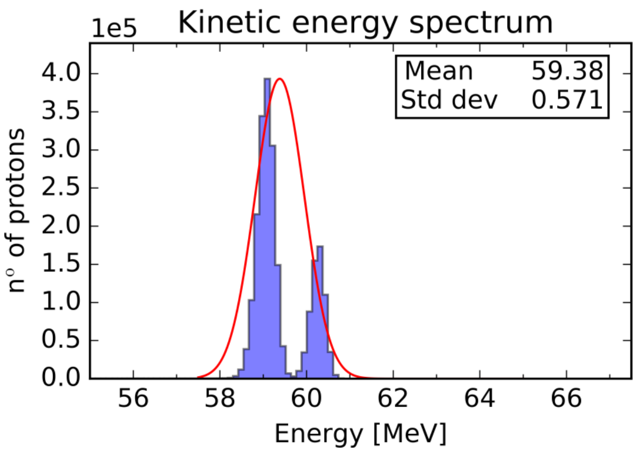
Z = [mm]	VELO Positions [cm]
676	
706	
736	0
766	3
796	6
826	9
856	12
886	15
916	
946	
976	
1006	
1036	
1066	
1096	

How does the sensor affect the beam?

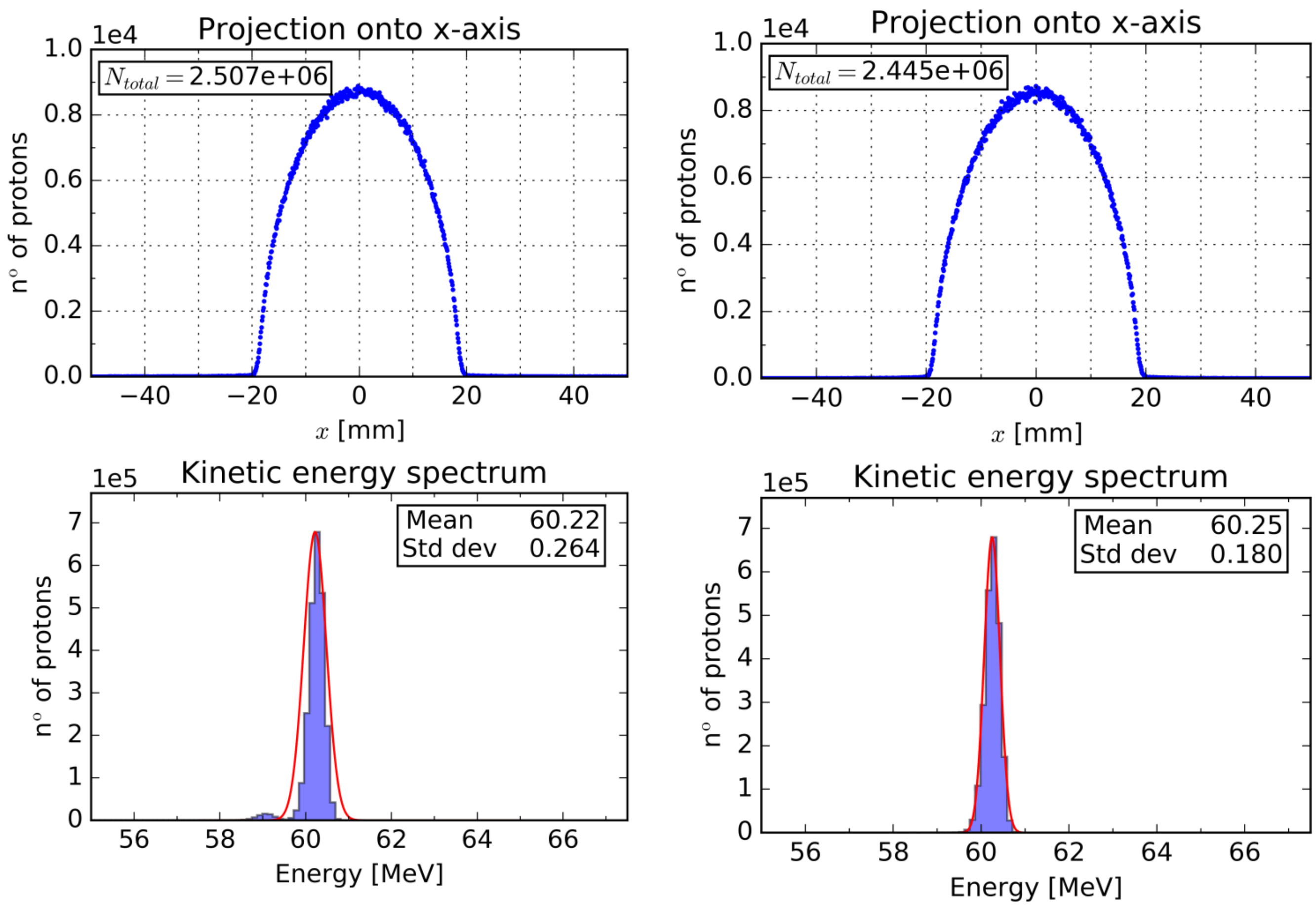
- With the sensor, could look at:
  - Beam divergence
  - Affect of sensor position on energy loss
  - To see profile widths, if aperture size for sensors is appropriate

With conservative aperture diameter 16.4mm, significant cut off to beam





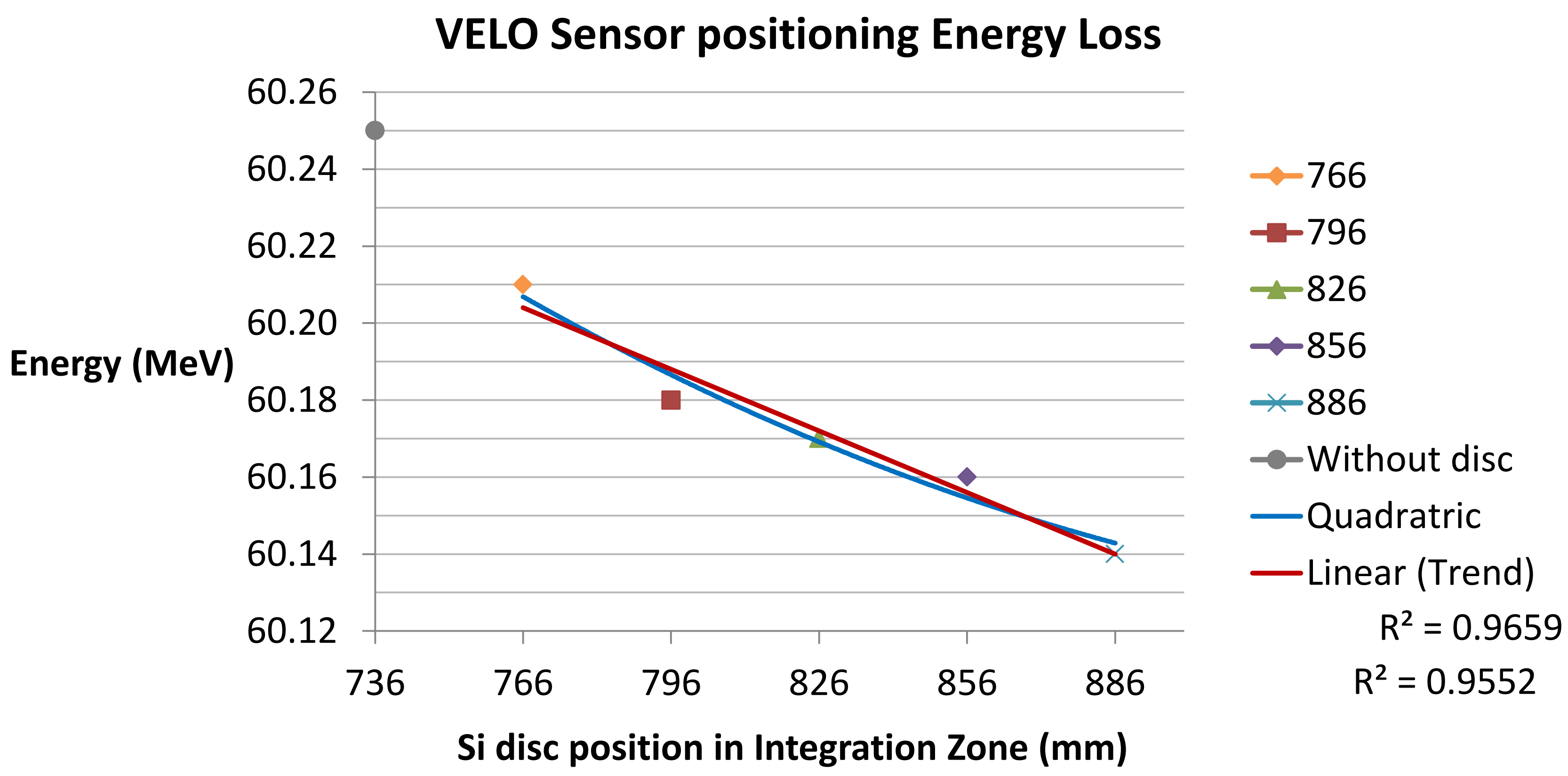
Energy spectra at isocentre



- Decrease of 0.03MeV => ~negligible

Energy at isocentre

- What if the sensor is at the other positions?

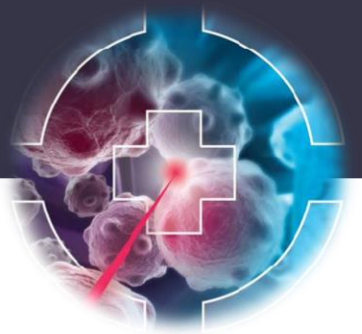


What about the input beam size?

- Ran simulations with larger & smaller beam sizes (50% to 200% σ)
  - Results in change to beam profile through out line up to ~6% ie 0-2mm difference
- Larger beam profile means more is collimated/cutoff
  - Different lateral profile at isocentre
  - Energy spectrum roughly the same
  - Profile in integration zone changes

=> Affects halo maps & VELO integration

Beam size importance



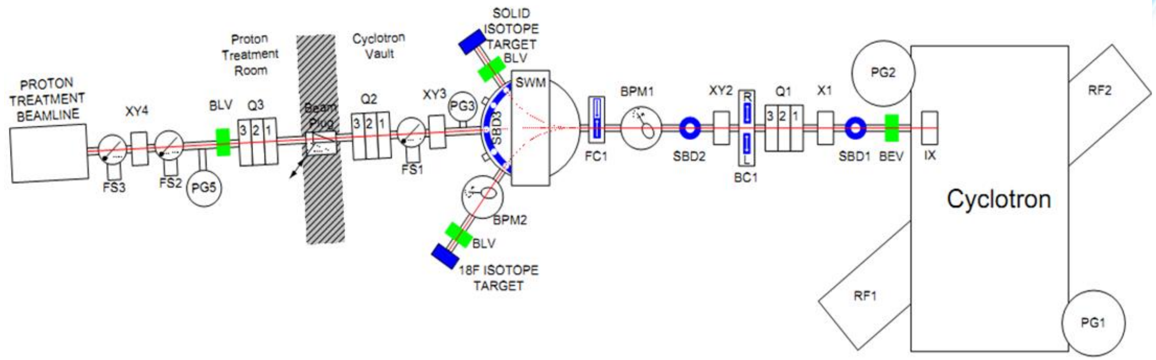
- Significant for integration!

- Balance!
  - Position of VELO sensors
  - Measurement wanted from beam
  - Energy cut off to beam

- Accurate beam size?

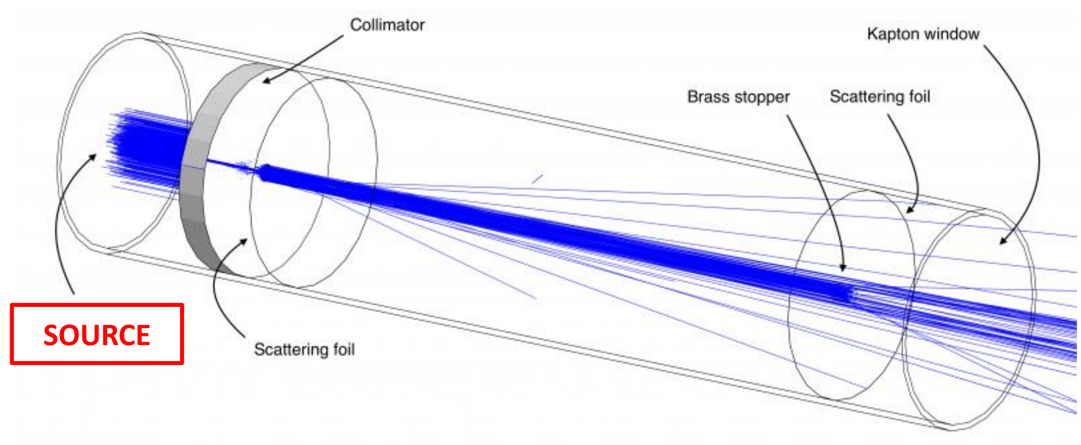
Beam behaviour

- CCC beamline
  - Beam optics
  - Particle tracking
  - **Halo maps**



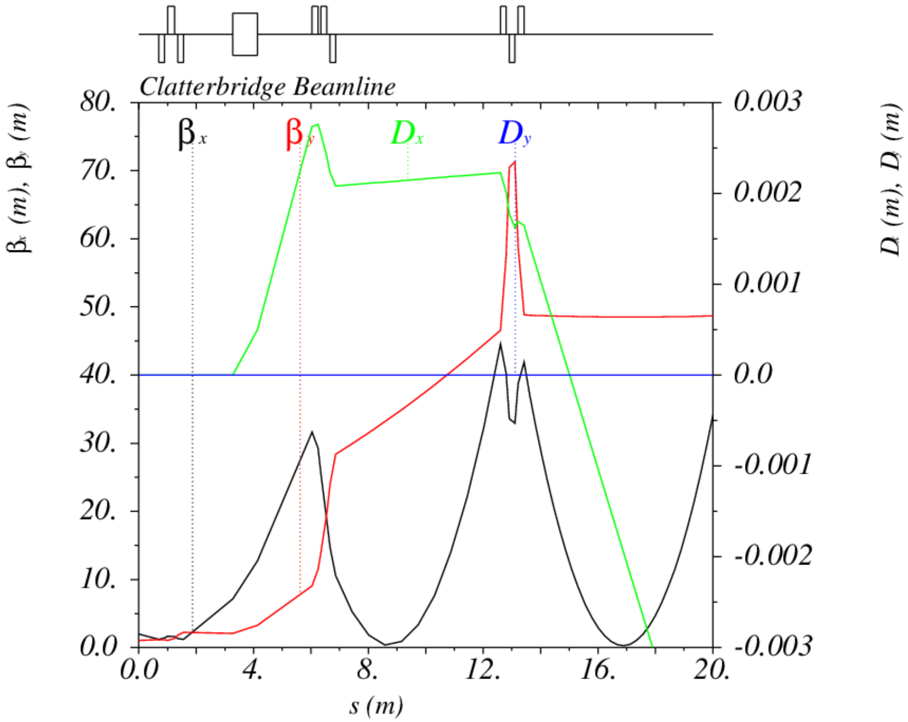
- Input parameters for the Geant4 model
  - Beam size at source

- To determine the **exact beam size**
  - Emittance studies
  - Twiss parameters



CCC beamline study

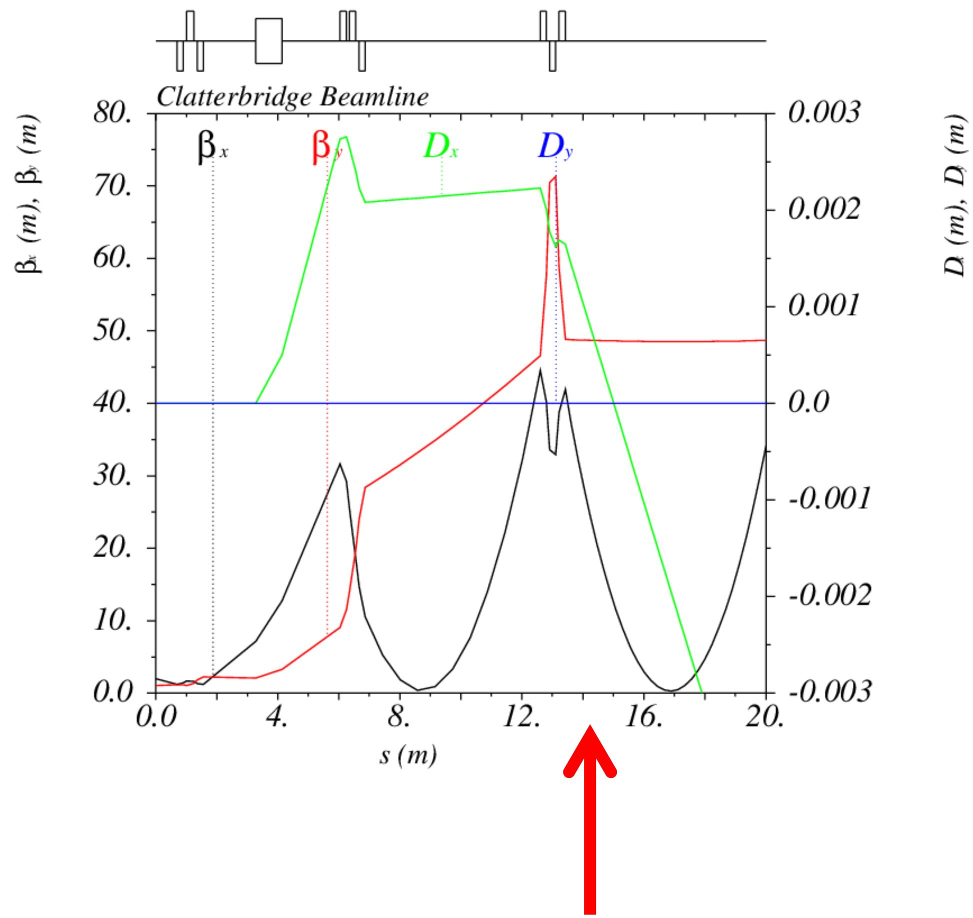
- Beam dynamics



Twiss functions

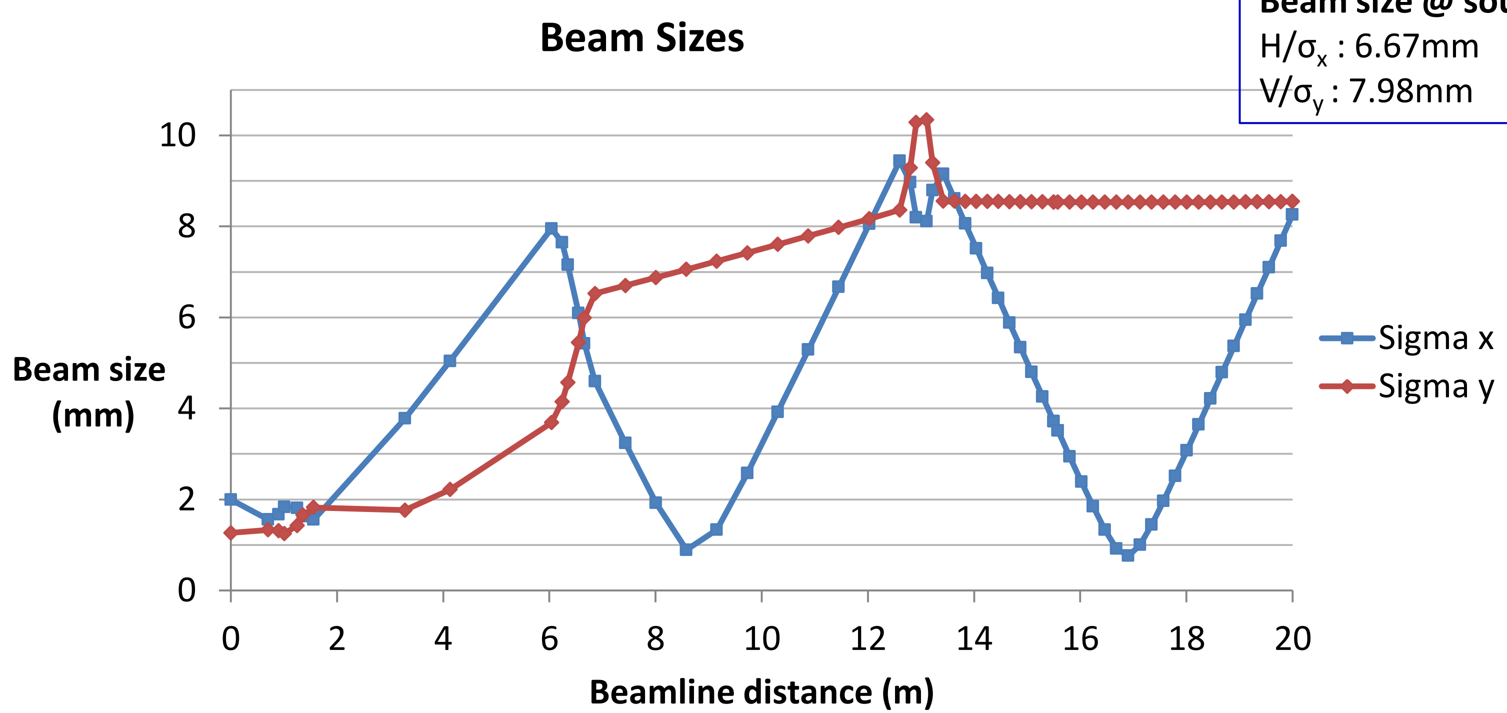
- Using optics code (MadX)
- Generate twiss parameters
- Transport to point of interest
  - Used to calculate beam size

$$\sigma_i = \sqrt{\beta_i \varepsilon_i + \eta_i^{2} \frac{\Delta E}{E^2}}$$



Beam size

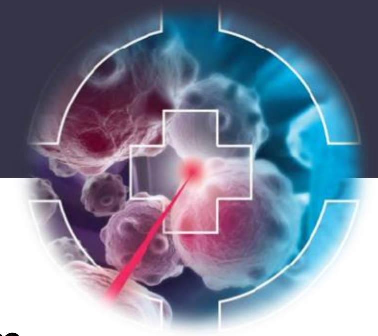
- At the source position of the simulation
  - 15.5m in beamline



Beam size @ source
H/σ_x : 6.67mm
V/σ_y : 7.98mm

  - How can this be verified?

Beam Emittance



- Beam property that characterises it's size
  - Ideally want focusing into a small space with minimum divergence
- Way to measure the quality of the beam
  - Key parameters for overall performance of an accelerator
- Particles can be characterised by density in phase space (x, px, y, py, z, pz)
  - Area in phase space at single time/location
- Liouville: Under ideal conditions, assume extent of beam (=density) in phase space is constant in time

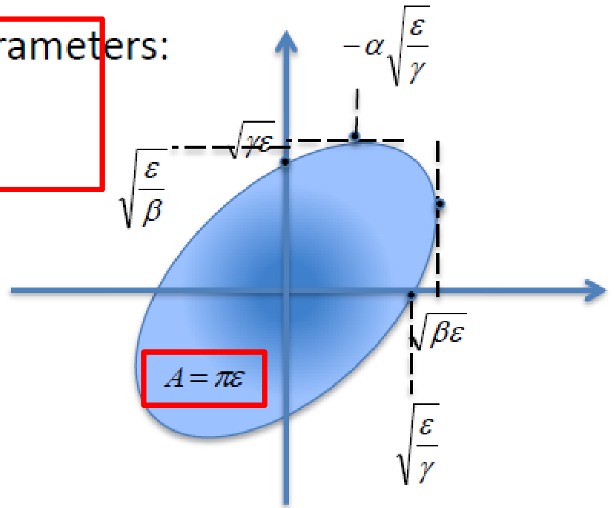
Ellipse Parameters

Beam ellipse and its orientation is defined

by the beam matrix $\begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix}$ for which the emittance is $\varepsilon = \sqrt{\sigma_{11}\sigma_{12} - \sigma_{12}^2}$

which is related to the Twiss or Courant-Snyder parameters:

$$\sigma = \varepsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$



The equation of the beam ellipse is:

$$\varepsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2 \qquad \gamma = \frac{1+\alpha^2}{\beta}$$

$\sqrt{\beta\varepsilon}$ beam half width

$\sqrt{\gamma\varepsilon}$ beam half divergence

α correlation between x and x'

α> 0 : beam is converging

α < 0 : beam is diverging

α = 0 : beam has minimum or maximum

Uli Raich , Emittance Measurements, Accelerator Beam Diagnostics, USPAS, 2009

Beam emittance from profile measurements

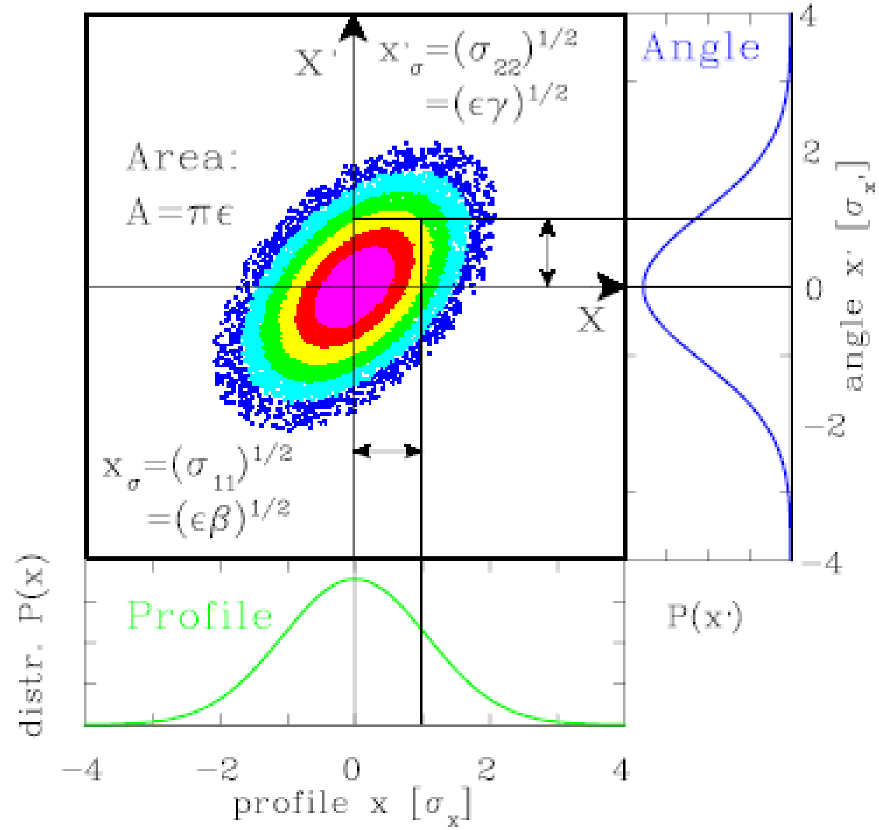


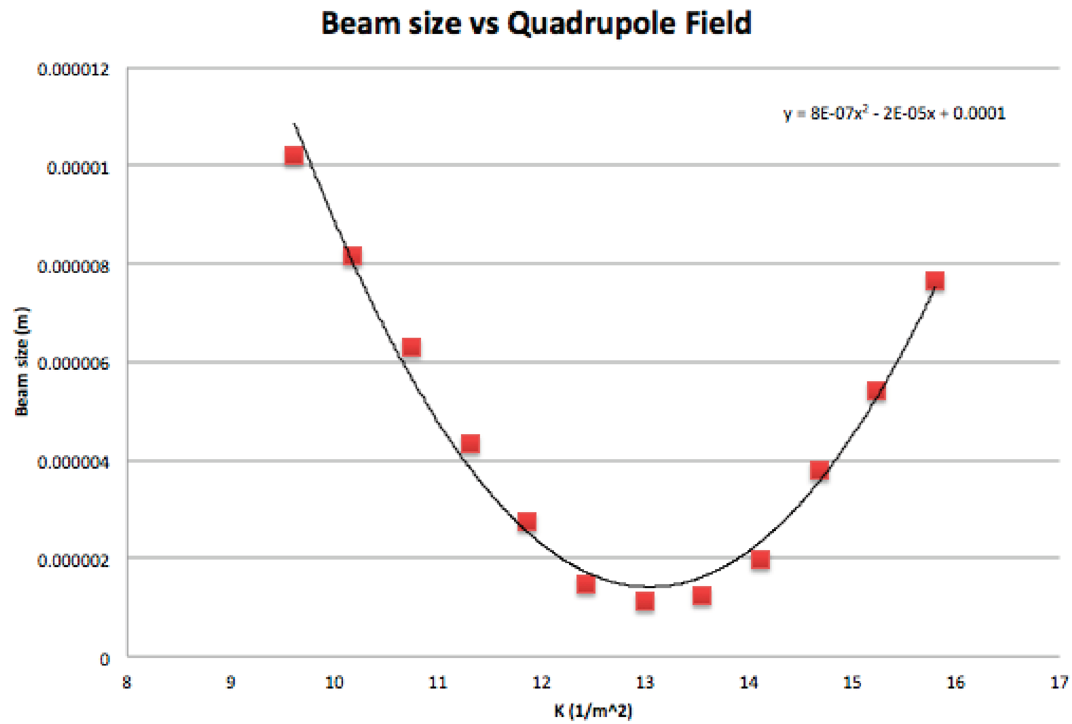
Figure 4.1: The emittance ellipse and the projection to space- and angle coordinates for a Gaussian density distribution. The values of the independent variables are given in units of the standard deviation.

Peter Forck Lecture Notes on Beam Instrumentation and Diagnostics, JUAS

Twiss parameters from emittance (QVS)

- Relationship between quadrupole strength & beam size
- Ideal quadratic
  - Equate the coefficients to transport matrix
  - Determine twiss parameters
- Compare measured twiss parameters with calculated

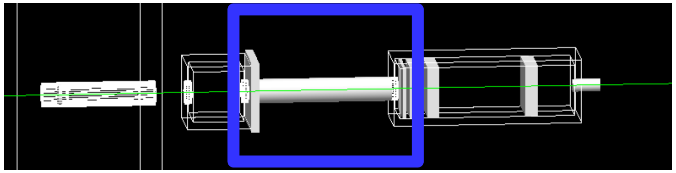
=> Accurate beam size

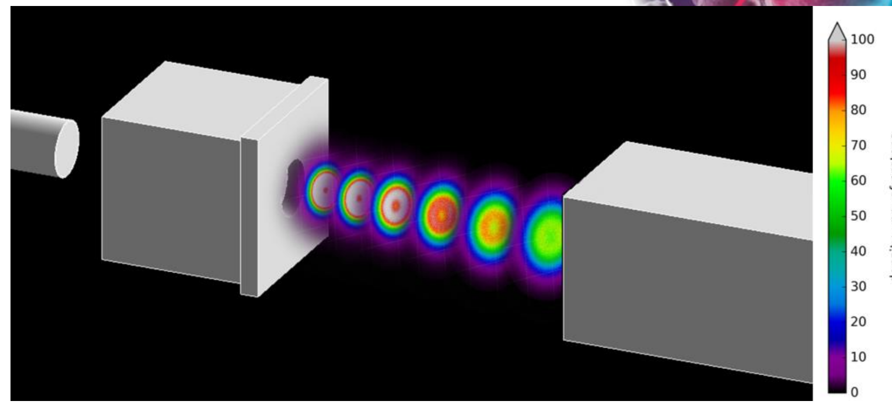


$$\Sigma_{11} = AK^2 + BK + C$$

A. T. Green et al. Proceedings of IPAC2015

Halo maps



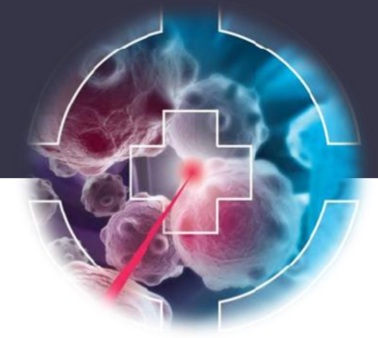


Intensity profiles

- Simulations & measurements
  - Transverse beam profile plots
  - Distribution of protons

- But how to actually correlate the halo?
  - Distinct characteristic of beam extent for correlation
  - Beam profile? Distribution? Intensity?
  - Numerical – Parameterisation?
  - Empirical – Benchmark with another detector (MediPix)?

Summary

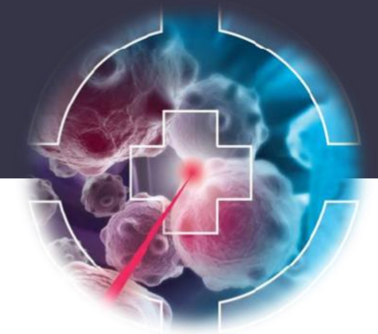


- Development of an online beam monitor, design allows approach & measurement of beam halo with minimal interference
  - Correlation of halo to core will allow online beam monitoring

- Preliminary optics & simulation studies results
  - Emittance studies: Follow up measurements
  - Geant4 model: Experimental validation & additional

- Integration into the CCC 60 MeV proton therapy beam line
  - Validate & test capabilities of performance
  - Benchmarking with MediPix
  - Halo maps for dose delivery

Thanks for listening!



Also, thank you to all collaborators & contributors to the work presented today:

Roland Schnuerer
Tomasz Cybulski
Oleg Karamyshev
Lina Hoummi
Javier Resta Lopez

Matthieu Hentz
Simon Jolly
Andrzej Kacperek
Hywel Owen
Carsten Welsch

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 675265, OMA – Optimisation of Medical Accelerators

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