Advanced Quality Assurance instrumentation for radiotherapy: the experience at Centre for Medical Radiation Physics

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CENTRE FOR MEDICAL RADIATION PHYSICS

UNIVERSITY OF WOLLONGONG

Japan 2015, 28 September, 2015 KEK


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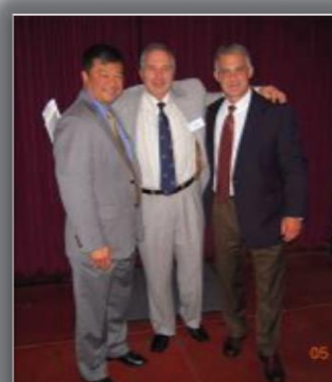
Centre for Medical Radiation Physics

Technology **SOLUTIONS**

Excellence in **EDUCATION**

Partnerships in **BUSINESS**



Research Areas

- Radiotherapy and Instrumentation
  - External Beam Radiotherapy
  - Brachytherapy
  - Proton Therapy
  - Heavy Ion Therapy
  - Microbeam Radiotherapy

- Medical Imaging
  - PET
  - CT
  - ProtonCT
  - Volumetric dosimetry reconstruction

- Radiobiology and Dosimetry
  - Personnel monitoring
  - Micro and Nano dosimetry

- High Energy Physics
  - Radiation detector optimisation and rad damage

Outline

- Semiconductor Dosimetry in Proton Therapy
  - LomaLinda Cancer Centre (US)
    - Dose Magnifying Glass (DMG)
- 1D Si High Spatial Resolution Beam Energy reconstruction
  - HIMAC (Japan)
    - Serial DMG
- Dosimetry in SRT with motion compensation
  - Royal North Shore Hospital (Sydney – AUSTRALIA)
    - MagicPlate 512
    - Serial DMG
- Conclusion

Introduction

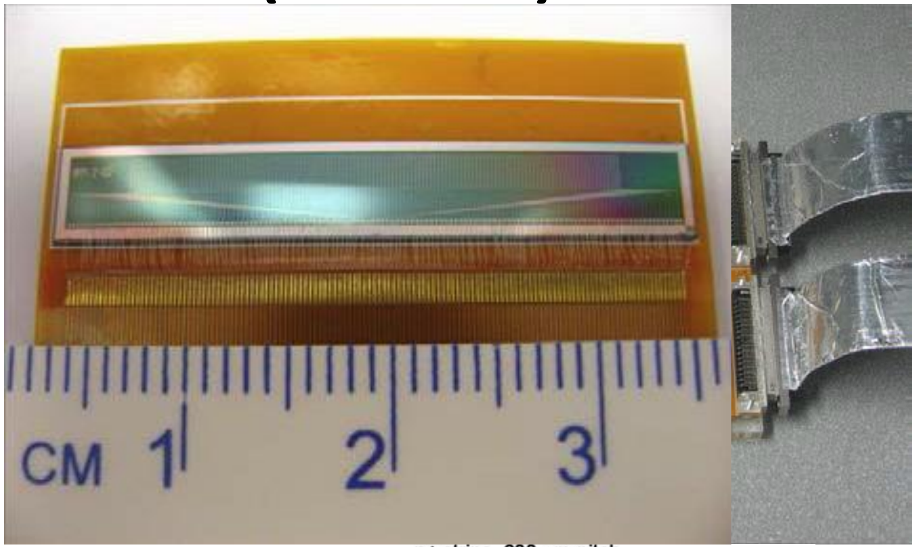
- Advanced radiotherapy techniques such as SRT (SBRT, SRS), Proton and Heavy Ion therapy produce:
  - high dose modulation and tight gradients
  - Strong hypo-fractionation with small or none margin of error
  - Conformality requires organ motion compensation → interplay effects
- Difficulties in the dosimetric verification of these new complex treatment methods using existing dosimeters has led to the need for a new generation of fast responding real time dosimeters with sub-millimetre accuracy
- Most of them are spin off from HEP radiation detectors designed for fundamental research.

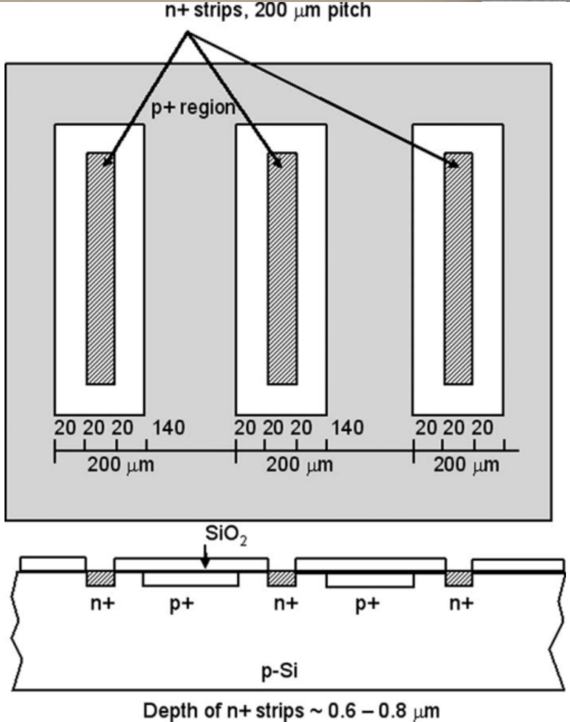
Dose Magnifying Glass (DMG)

- The DMG is a silicon strip detector
  - Designed and developed at CMRP

- **Real time and high spatial resolution**

- Each diode provides sensitive area 20 x 2000 μm^2 and 200 µm pitch, mounted on 375µm thick p-type Substrate



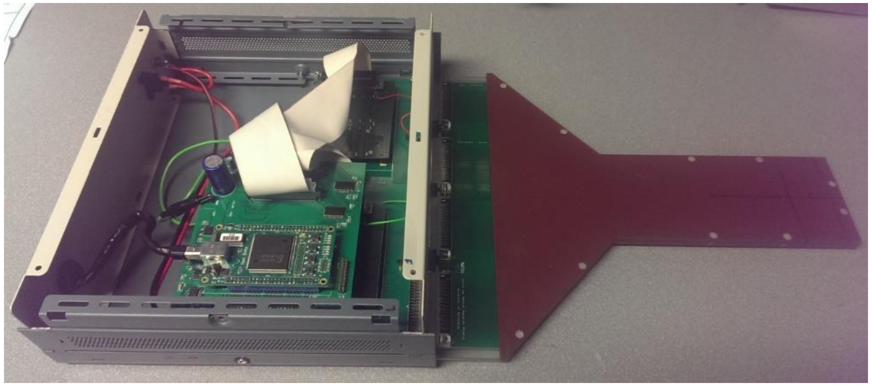


Authors:

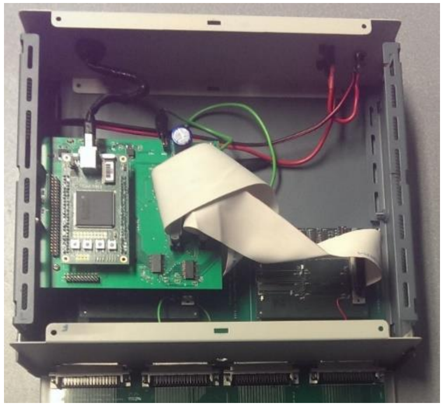
- CMRP: J. Wong, I. Fuduli, M. Newall, M. Petasecca, M. Lerch, S. Guatelli, A. Rosenfeld,
- Loma Linda university: **A. Wroe** and R. Schulte

The Data Acquisition System (DAS)

- Very large scale integration application specific integration circuit (VLSI ASIC) known as; **TERA**.



- Connected to a field programmable gate array (**FPGA**) with universal serial bus (**USB**) interface to a personal computer (**PC**).

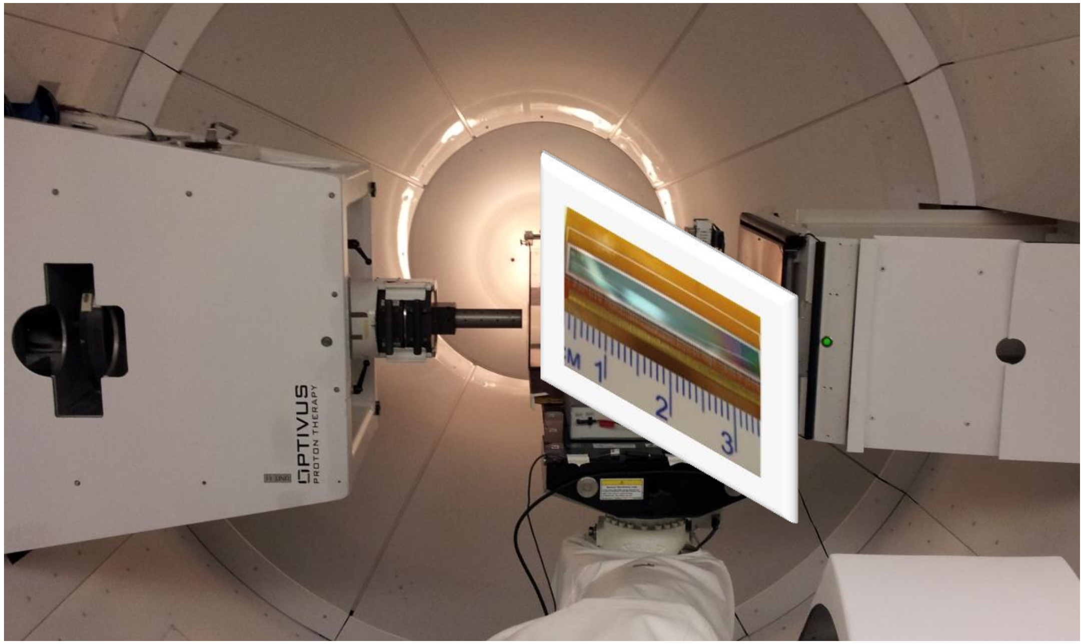


- The detector is operated in **passive mode**.

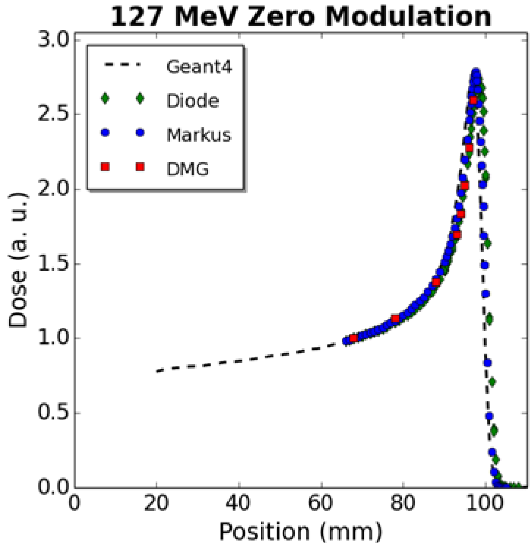
- The TERA DAS consists of a **current to frequency converter and digital counter** enabling ***continuous integration and readout of the response from 256 channels*** **during acquisition [5].**

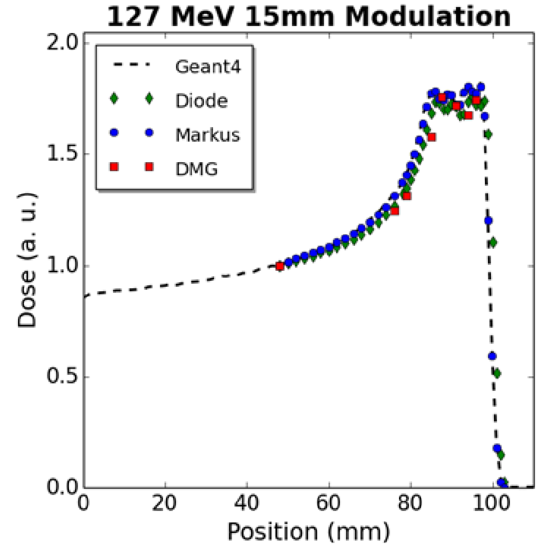
Setup at LMCC

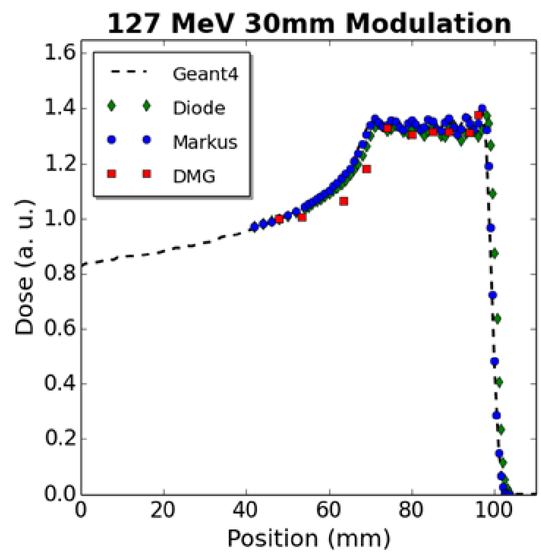
- The DMG is positioned horizontally in front of the nozzle
- Measures simultaneously profile and depth dose in a water phantom
- Waterproof
- Automatic stager for depth scanning
- 127or 157 MeV protons
- 20 mm diameter proton beam, comparison with a commercial PTW diode, PTW Markus Parallel-Plate Ionization Chamber and Monte Carlo



Results – PDD 127 MeV



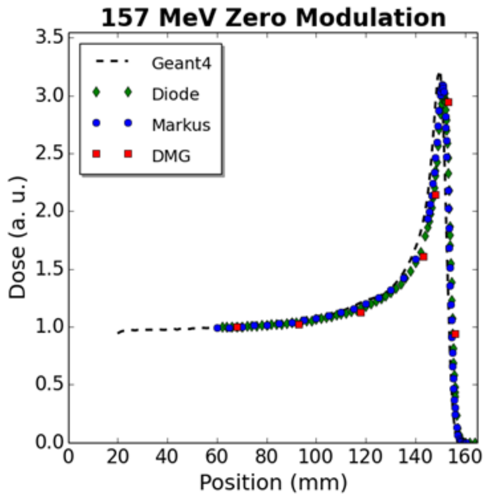


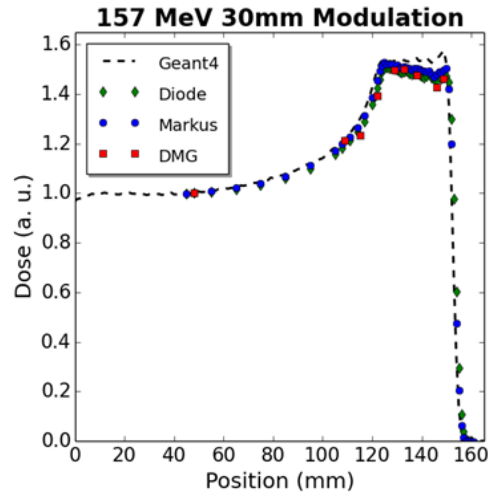


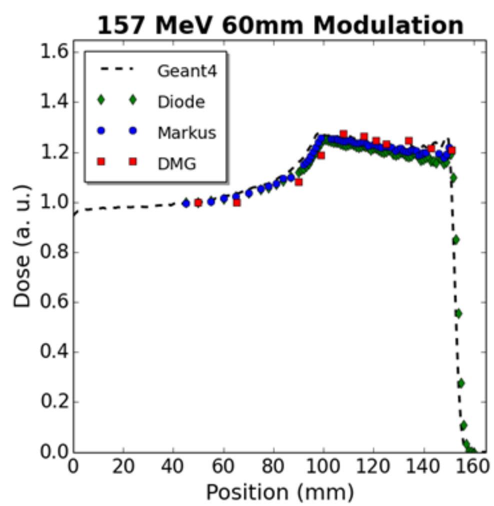
Max discrepancy 2.6%

Submitted to PMB – Aug 2015

Results – PDD 157 MeV







Max discrepancy 2.7%

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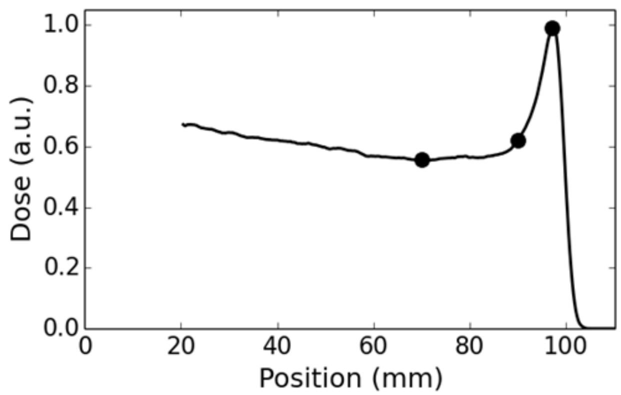
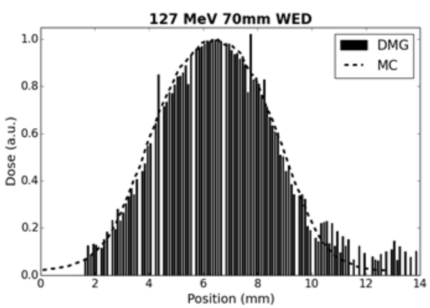
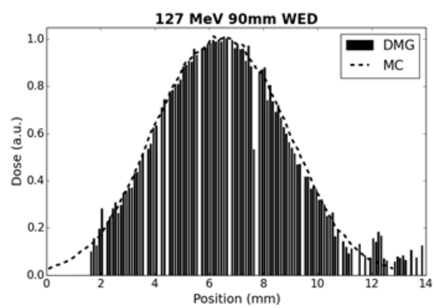
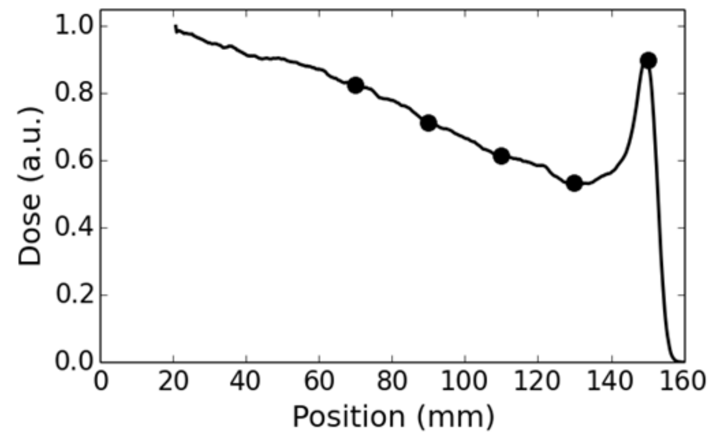
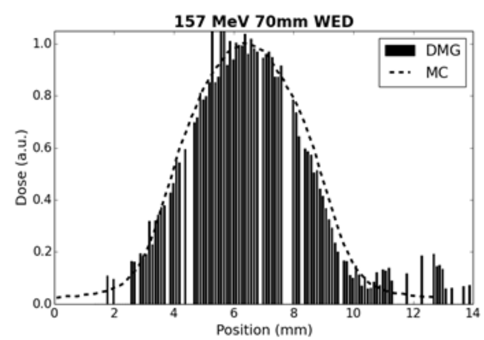
Results – Profiles 127 and 157 MeV

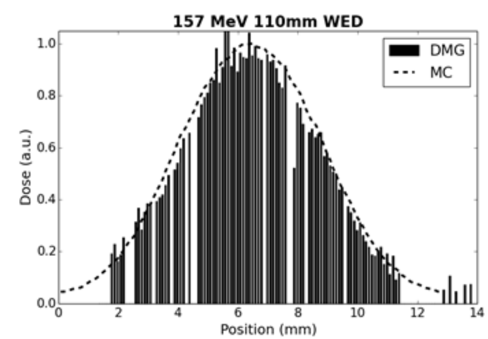












Beam Energy reconstruction in C-12 RT at HIMAC

introducing Serial DMG

- The ‘**sDMG**’ is a silicon strip detector comprised of[3]:

Form factor	**Linear, 50.8mm**
Channels	**256**
Isolation	**p-stop**
Strip area	**20 x 2000 μm²**
Pitch	**200 μm**
Substrate type	**p-type silicon**
Substrate thickness	**375 μm**
Resistivity	**10 Ωcm**
Pre-irradiation	**4 Mrad**

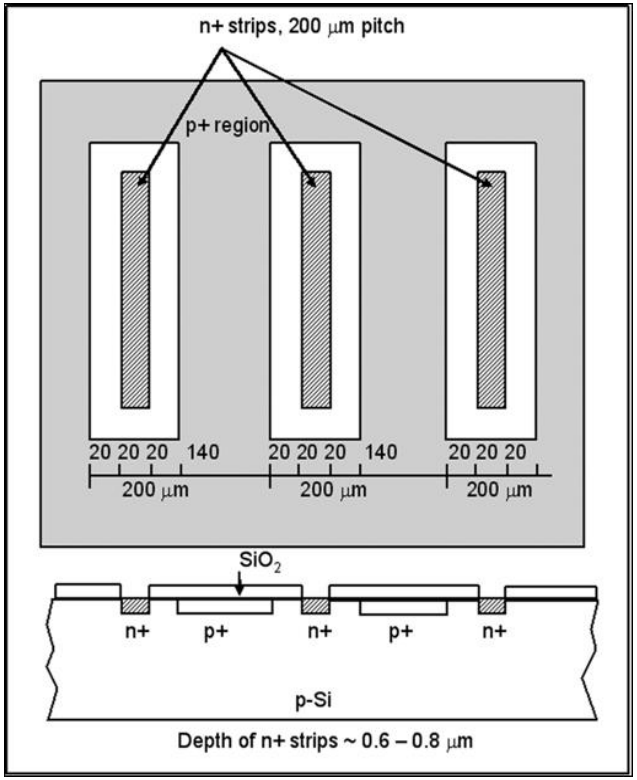


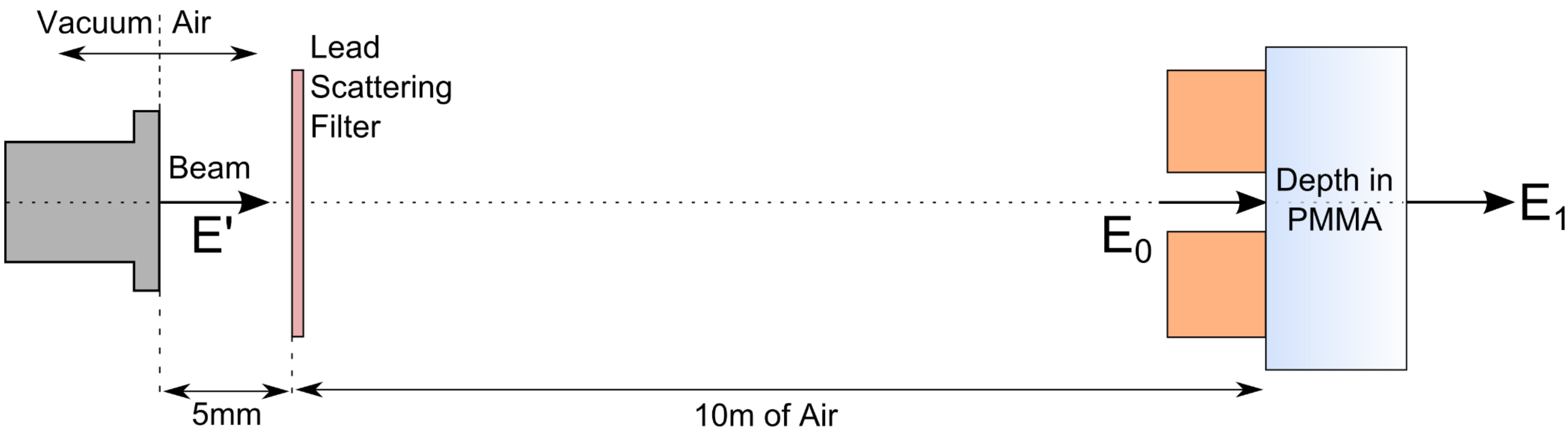
Figure – Serial Dose Magnifying Glass (sDMG) [3].

Experimental Methodology

- Experiments conducted at **HIMAC, Chiba, Japan.** The detector is irradiated by;
  - **C-12** ion beam,
  - Energy **290 MeV/u** **(E')** and
  - **10x10cm²** square field

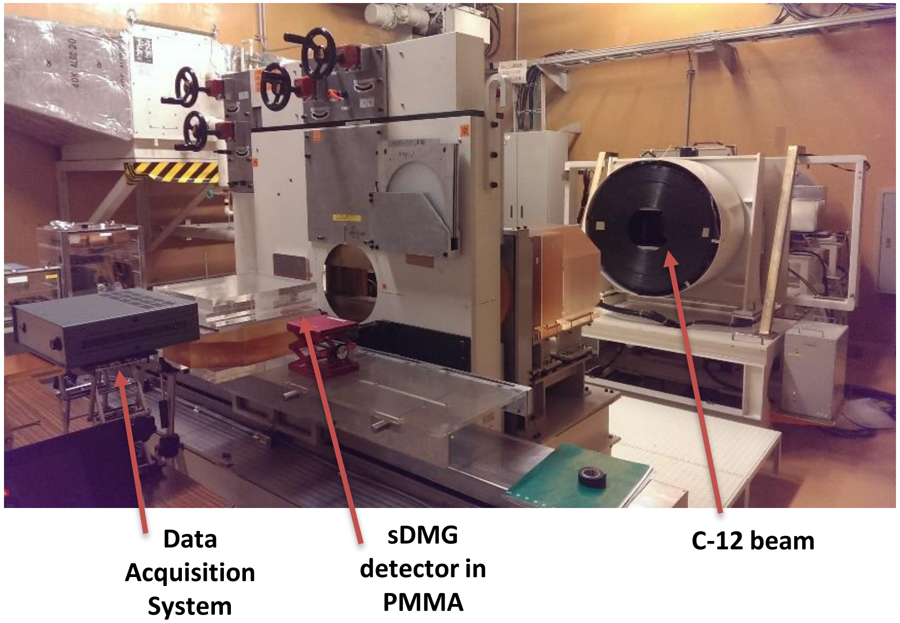
- Placed inside a PMMA phantom, the detector is setup in configurations:

1. Detection axis aligned **parallel** to beam direction
2. Detection axis aligned **perpendicular** to beam direction

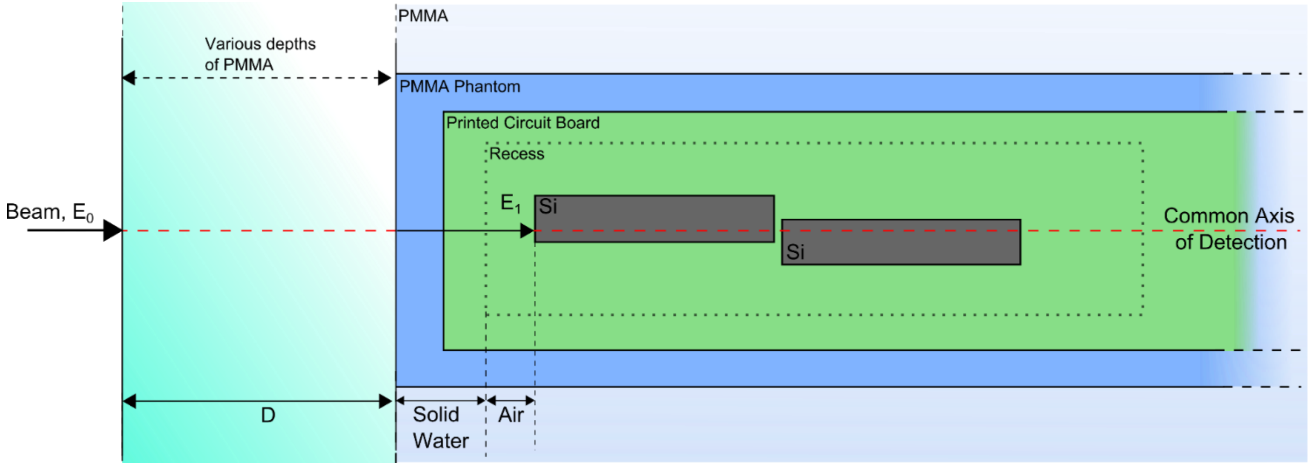


Experimental Methodology – Depth Profile

- The detection axis is aligned **parallel** to the direction of the C-12 beam.
- **C-12** ion beam, energy **290 MeV/u** and **10x10cm^2** square field.
  - **PBP** (pristine Bragg peak)
  - **SOBP** (spread-out Bragg peak, 60mm width in water)

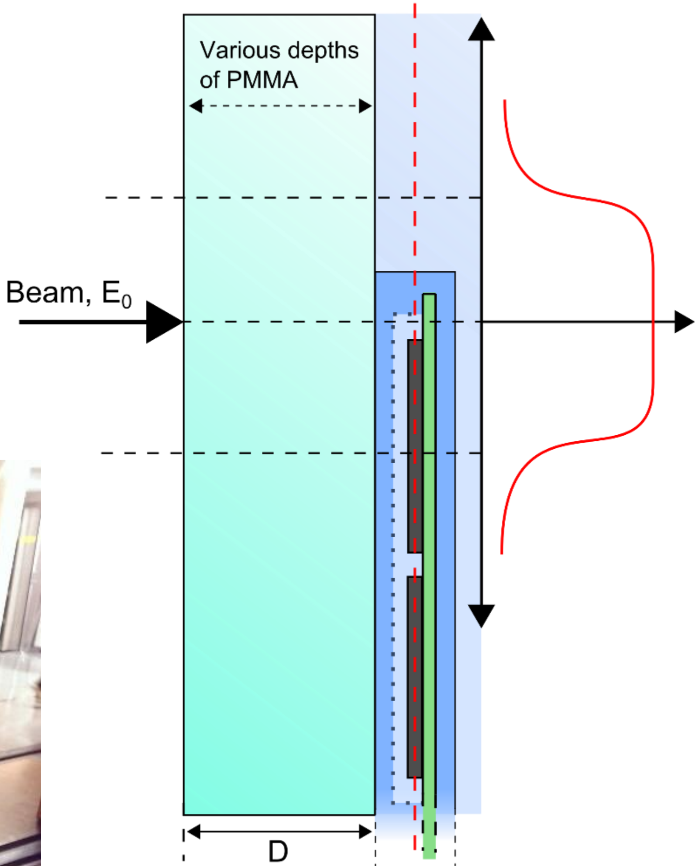


- **Depth Dose Profiles:** **PBP** measurements conducted with increasing depth in PMMA (+/- 1mm).
- **Dose-rate:** **SOBP** measurements conducted with depth in PMMA 86mm for various dose-rates.



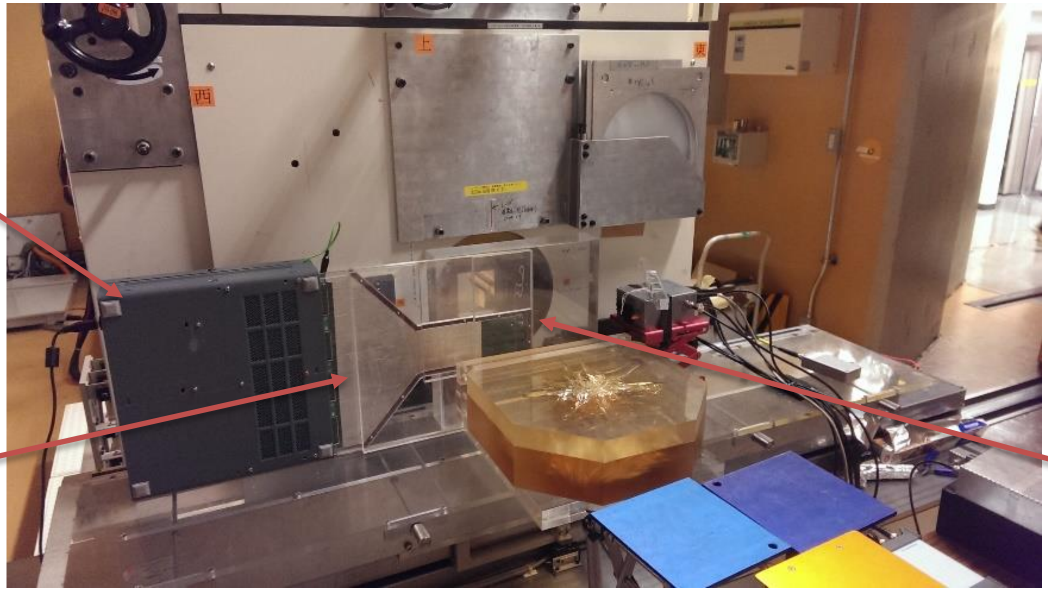
Experimental Methodology – Lateral Profile

- The detection axis is aligned **perpendicular** to the direction of the C-12 beam.
- **SOPB** (60mm width in water) **C-12** ion beam, energy **290 MeV/u** and **10x10cm^2** square field.



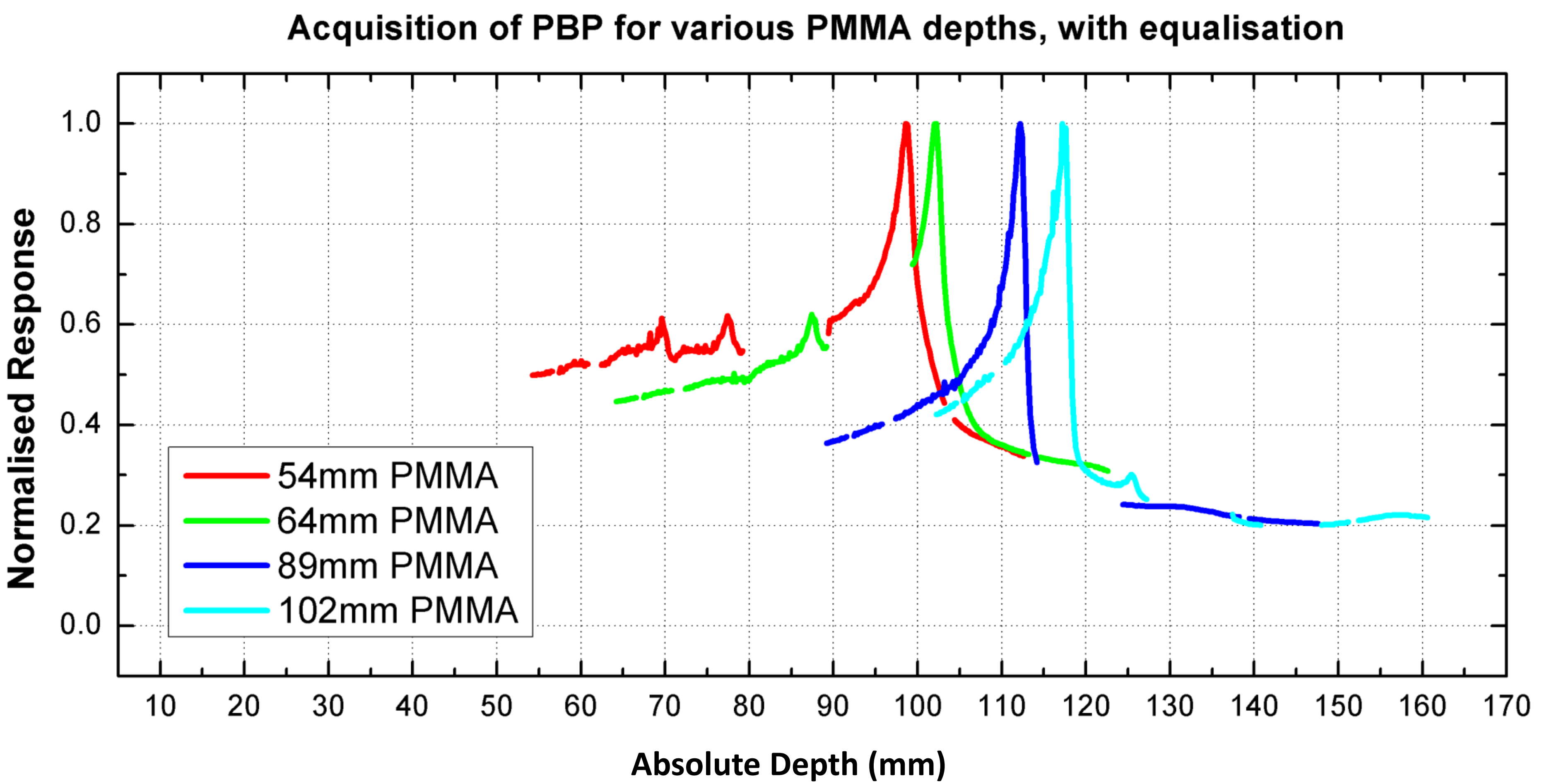
Penumbral Study:

- Measurements conducted with increasing depth in PMMA (+/- 1mm).



Results: Pristine Bragg Peak - Measurement

- Result processed with generated equalisation vector.

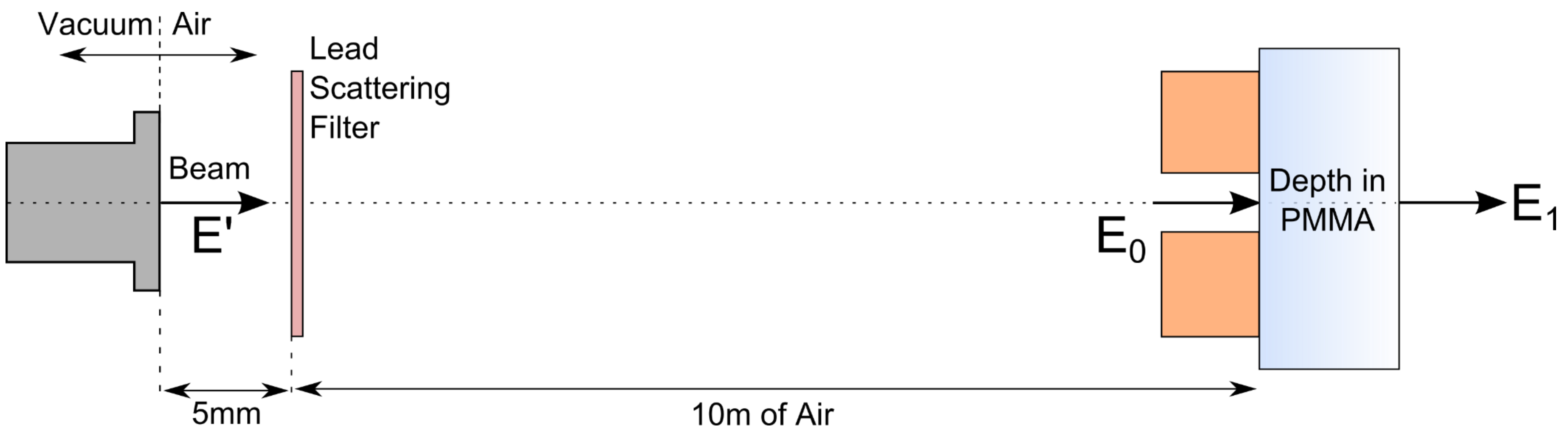


- Larger straggling effect in silicon?
- Radiation damage creates artefacts?

Results: Energy Reconstruction

- Propose method of **independent beam energy verification**.

- Calculation of **E_0** (residual energy of beam, at surface of PMMA phantom) from **PBP** measurements.



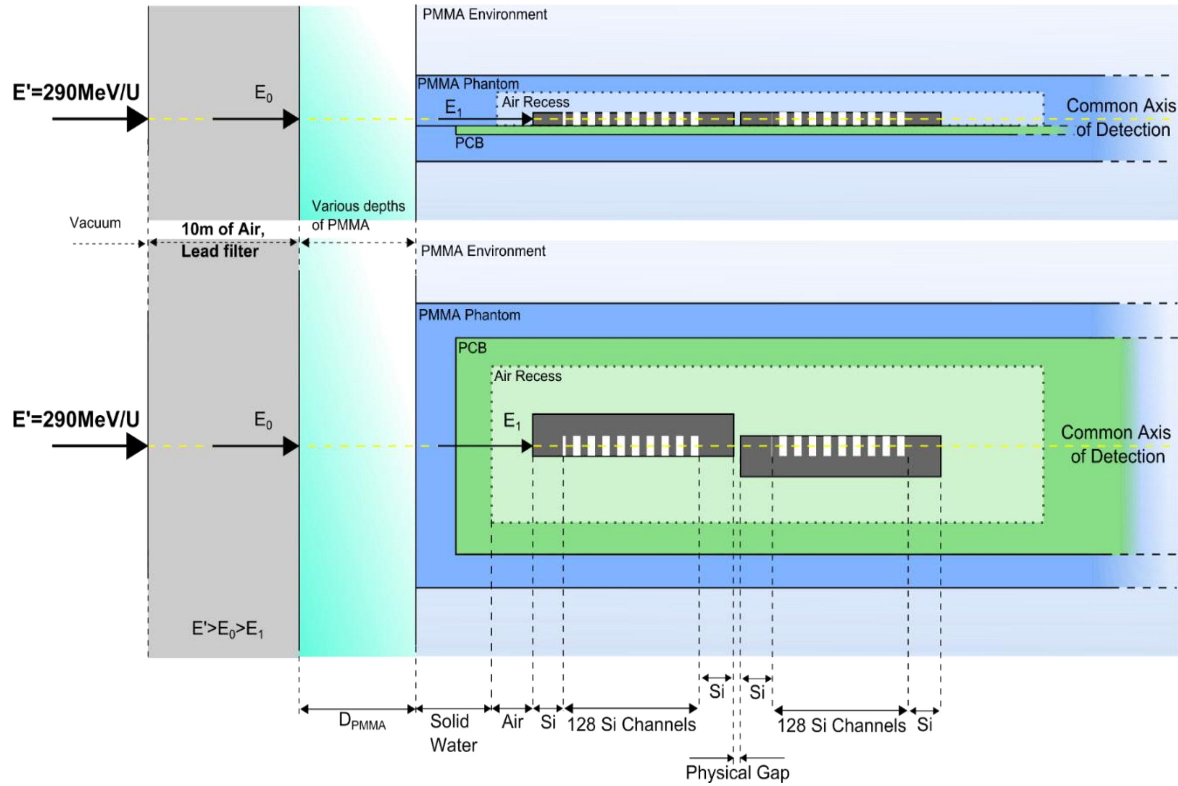
Results: Energy Reconstruction - MC

Monte-Carlo Simulation:

Geant4 9.6.p01

- Physics activated:
  - EM:– G4EmStandardPhysics_option3
  - Hadronic:-QGSP_BIC_HP
    - Binary intra-nuclear cascade model + pre-compound model + nuclear de-excitation + High precision models for neutrons with Energy <20MeV
- Geometry:
  - Cuts in the air: 10cm
  - Cuts in the phantom: 0.1mm

Detailed experimental geometry:



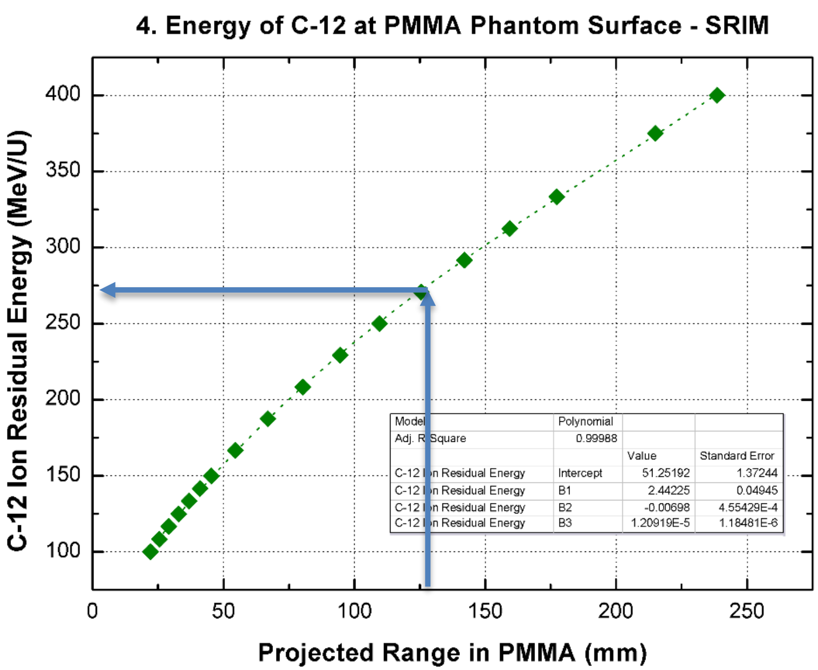
Results: Energy Reconstruction

1. Measurement of location of **PBP** in silicon detector (at known depth in PMMA).

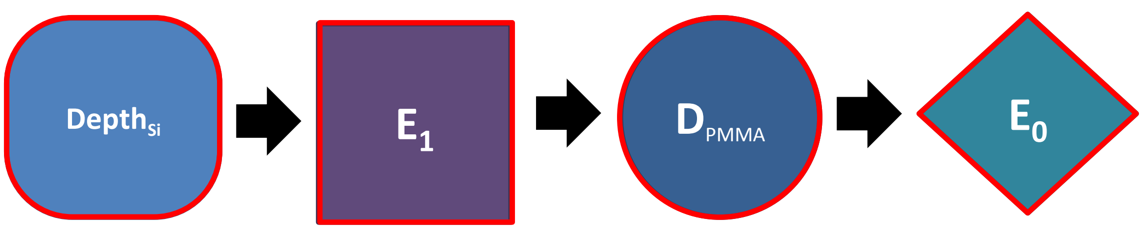
2. Energy **(E_1)** upon entrance to silicon is back-calculated from measurement of **PBP**.

3. Location of **PBP** (projected range without silicon + depth) in PMMA is determined from **E_1**.

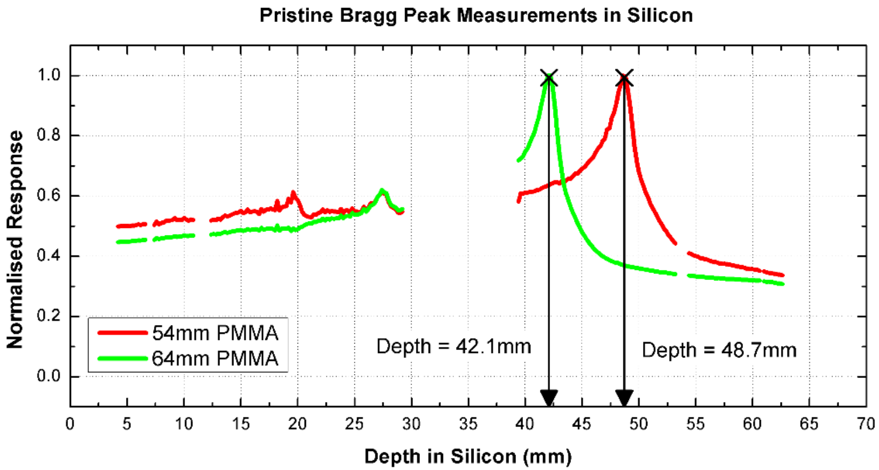
4. Residual Energy **(E_0)** at entrance to PMMA phantom calculated from location of PBP in PMMA (without silicon)

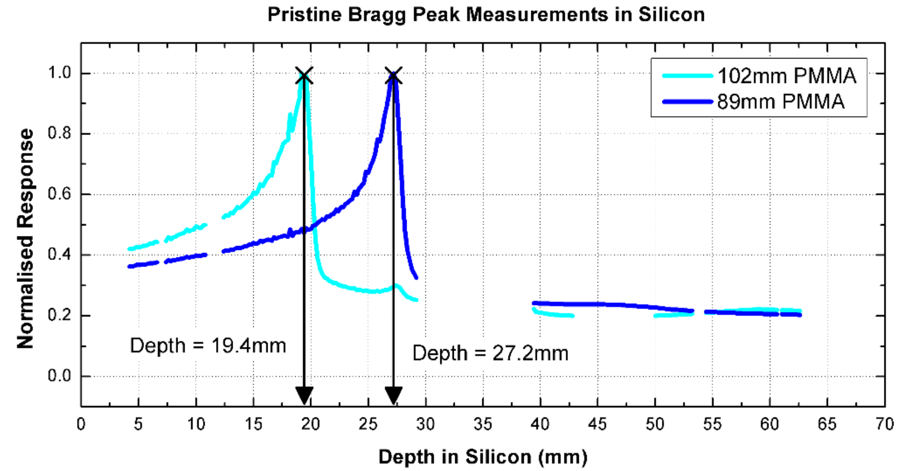


Workflow Diagram



Results: Energy Reconstruction



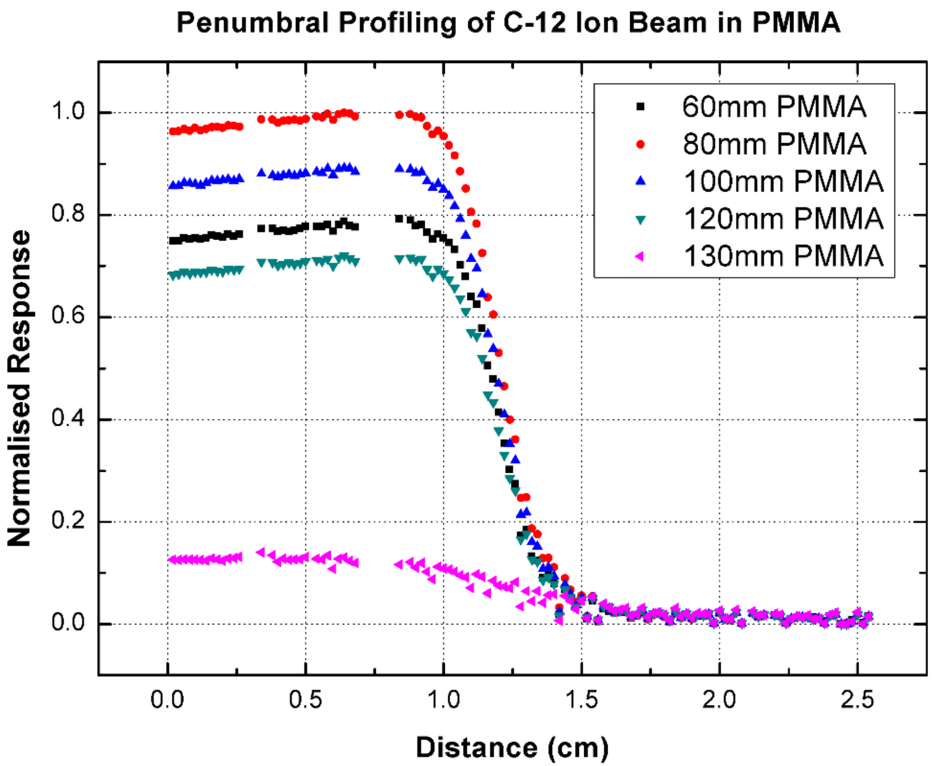


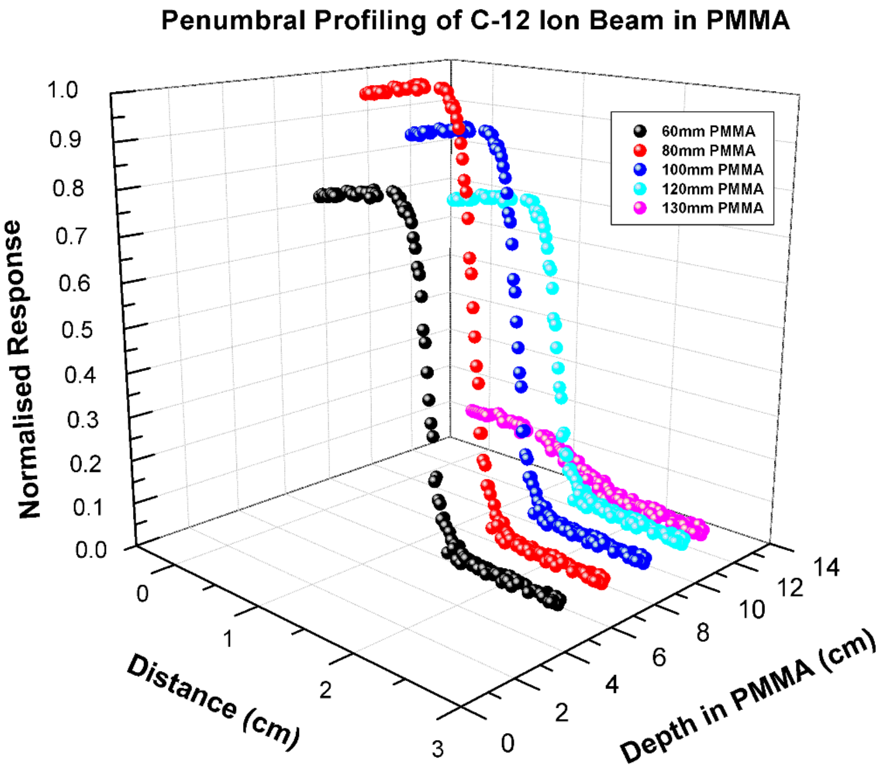
Depth in PMMA (mm), (+/- 1 mm)	Measured Peak Location in Silicon (mm), (+/- 0.4mm)	Reconstructed Energy, E_1 (MeV/u), (+/-3MeV/u)	Simulated Energy (MeV/u), (+/-0.1%)	Reconstructed Residual Energy, E_0, (MeV/u), (+/- 3MeV/u)	Percentage Difference to Monte-Carlo (%)
102	19.4	118	121	279	**1.62**
89	27.2	143	147	277	**1.25**
64	42.1	186	190	277	**0.93**
54	48.7	203	206	278	**1.30**

- E_0 determined by Monte-Carlo simulation to be **275 MeV/u +/- 0.01%,**
- E_0 determined by reconstruction to be **(278 +/- 1) MeV/u**

Results: Penumbral Study

- **SOPB** (60mm width in water) delivered for depths in PMMA; **60mm, 80mm, 100mm, 120mm and 130mm.**





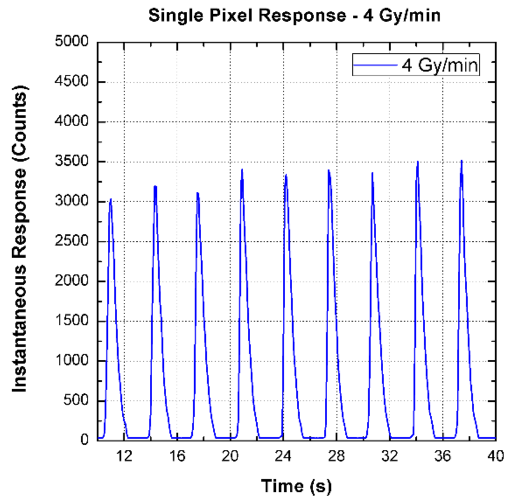
Results: Dose-Rate dependence

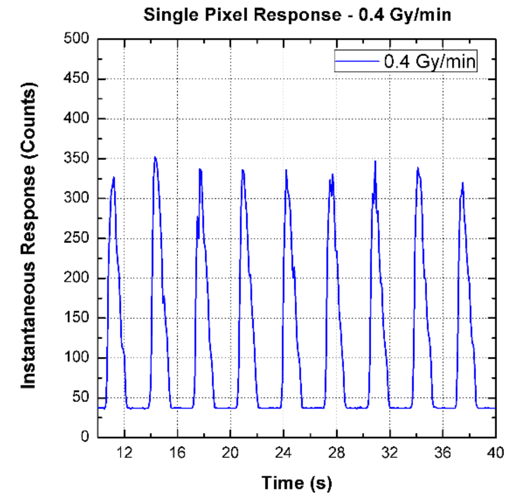
- Investigated dose-rate dependence of detector under irradiation by **SOBP** (width 60mm in water).

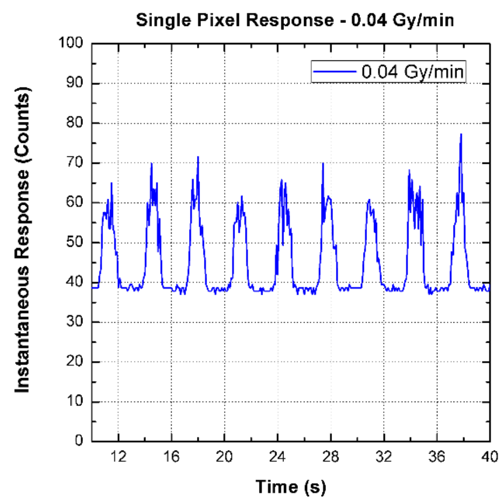
- Region of **SOBP** detector is exposed to, high-LET particles

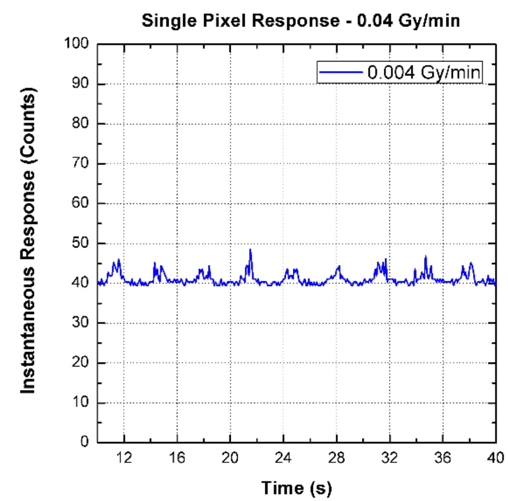
- Detector placed at 86mm in PMMA phantom, response of individual channels examined for varying dose-rates:

Dose-Rates (Gy/min)
4.000
0.400
0.040
0.004

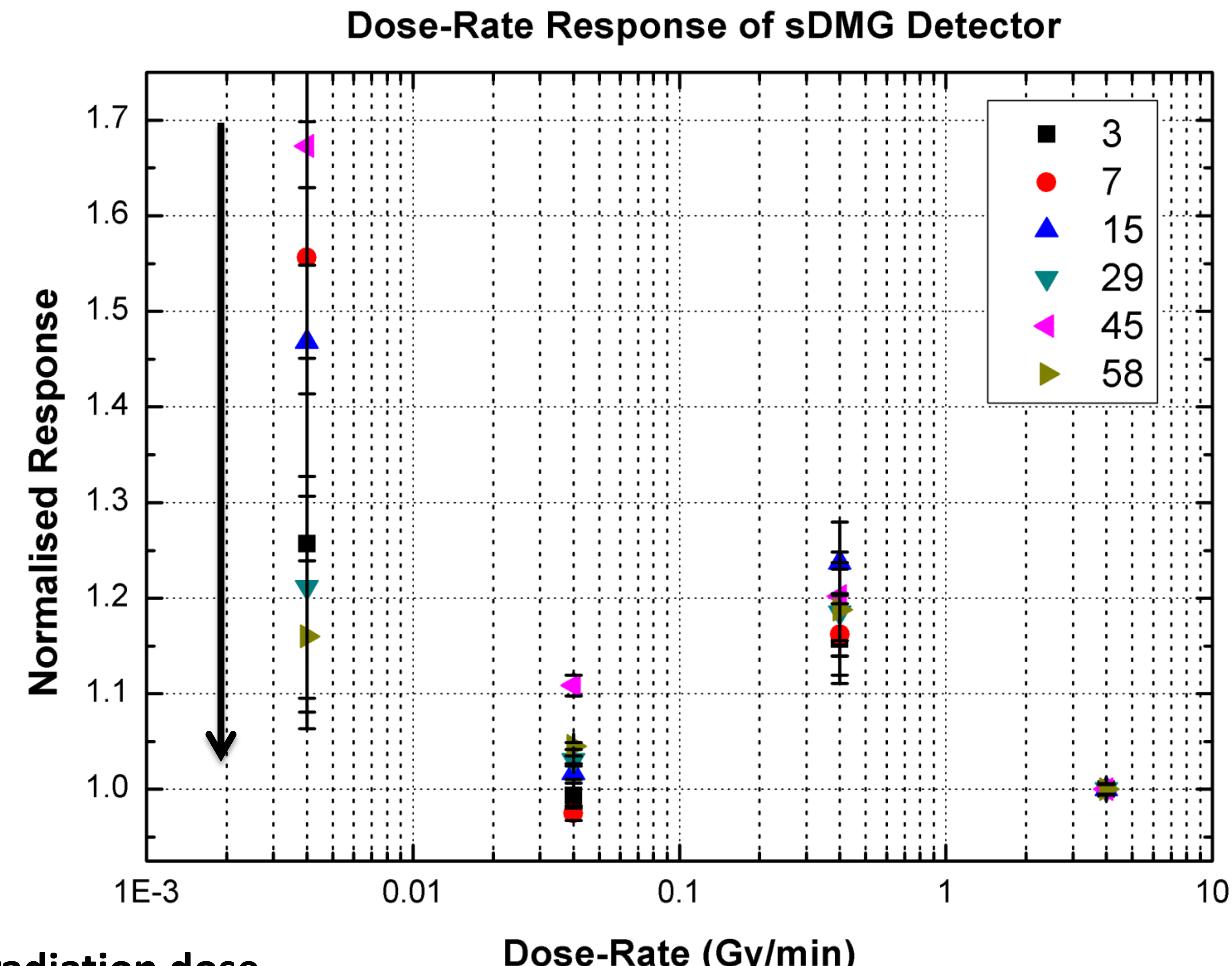








Results: Dose-Rate Dependence



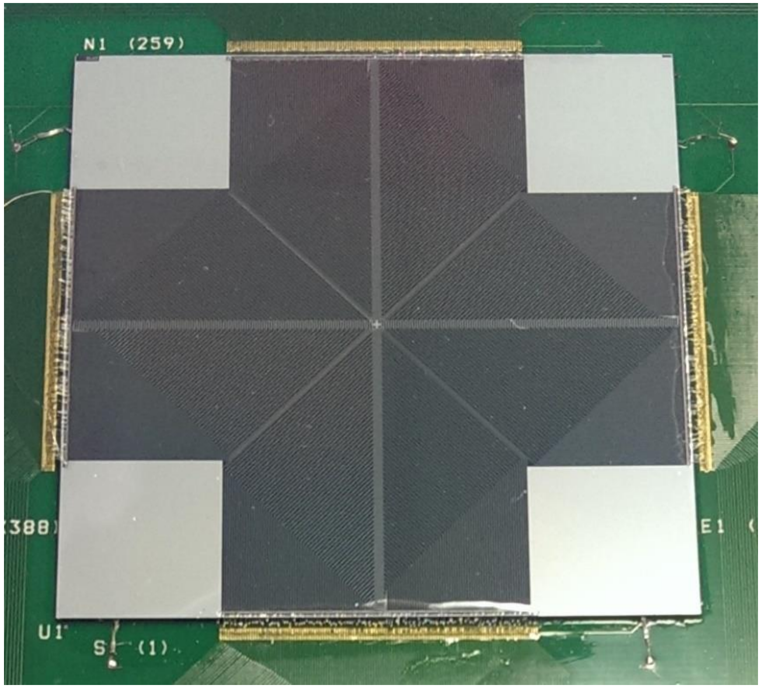
Pre-irradiation dose

Future Work

- Pristine Bragg Peak results demonstrated:

Prolonged Exposure → Radiation Damage

- *Necessitates implementation of* ***radiation harder substrate***



- Penumbral study and Pristine Bragg Peak results established feasibility of high spatial resolution silicon detector.
- **But,** necessitates ***simultaneous measurement of depth dose profile and beam profile***

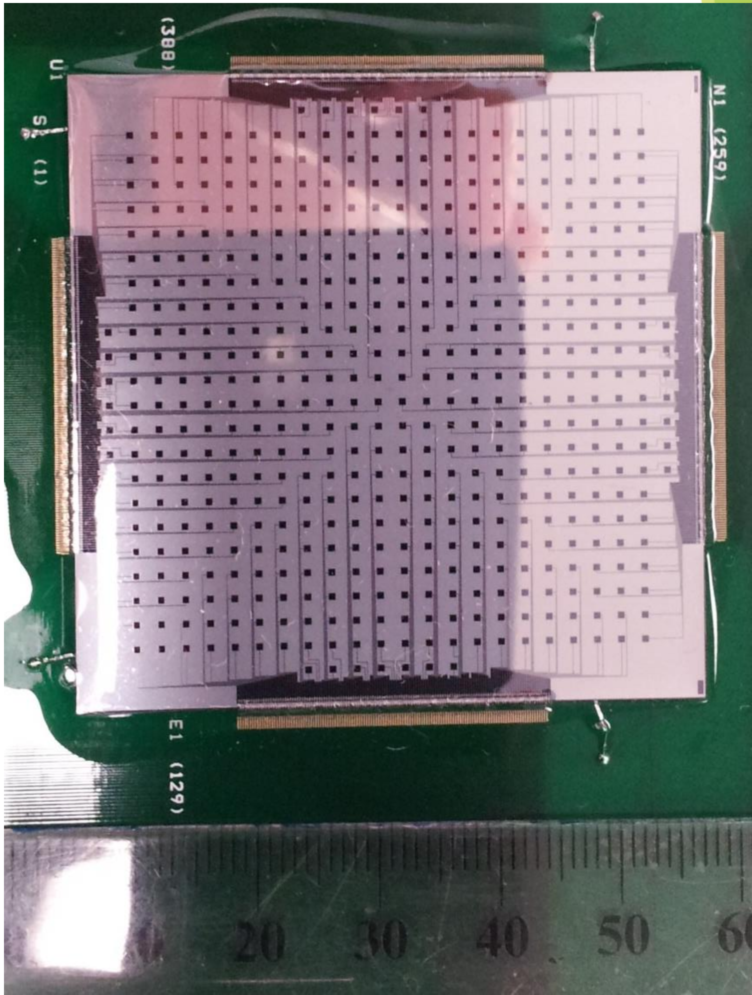
- Thus, future studies will utilise **DUO:**
  - a **two dimensional detector** for high resolution profiling, enabling simultaneous readout of X and Y profiles

Stereotactic RT and motion tracking compensation study using MP512

Designed and developed at **CMRP**, MP512 is a 2D array:

- Monolithic silicon:
  - **512** diodes in a square array
  - Sensitive volume ~ **0.5** x **0.5** x **0.1** mm^3
  - Diode separation – **2** mm
  - Size – 52 x 52 mm^2

- Readout Electronics:
  - Custom design multi-channel electrometer
  - **Pulse-by-Pulse** acquisition



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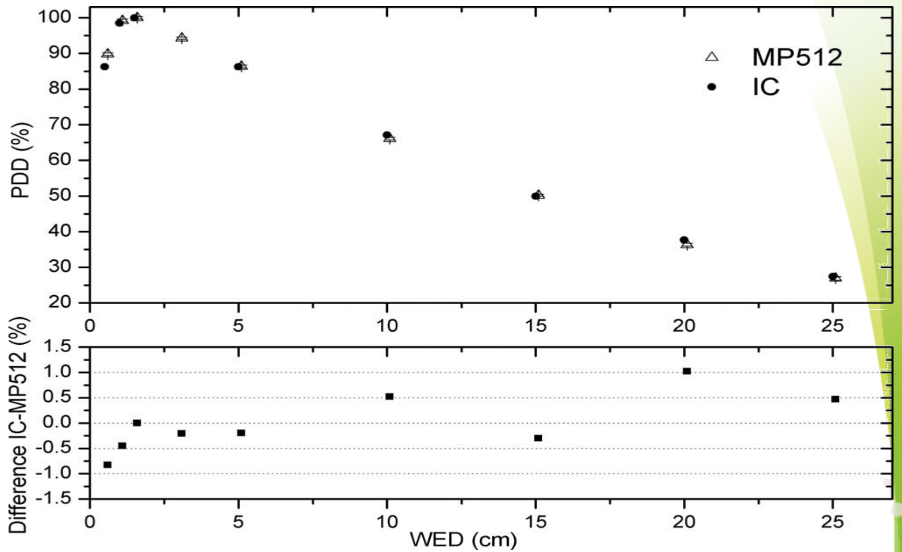
Dosimetric Characterisation of MP512: OF – PDD in 6MV photon beams

- MP512 compared to various dosimeters for varying field size.

Condition	Value
Source	Linear Accelerator
Type	6MV photon
Dose delivered	100 MU
Field Size	…
Source to surface distance	90 cm
Depth	10 cm

- For field sizes < 1x1cm² MP512 over responds <4%, for greater field sizes, results agree within +/- 1%.



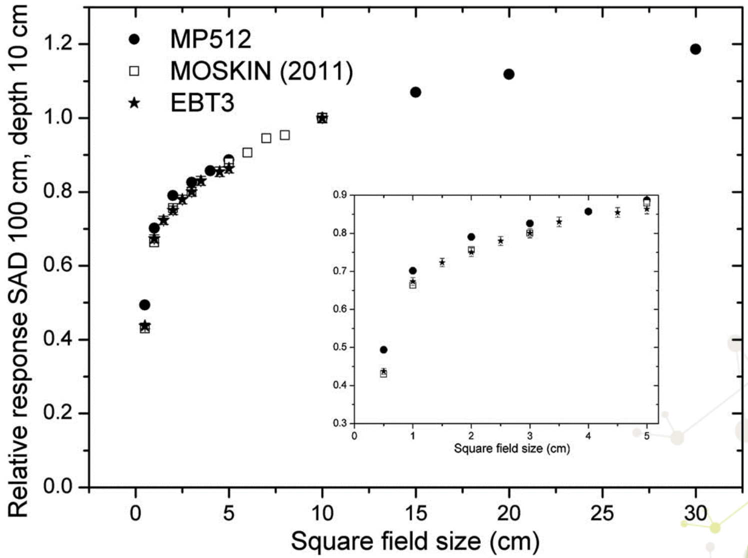


Figure – Normalised output factor measurements of 6MV beam for a variety of detectors (Aldosari et. al. 2014)

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Combining Small Field dosimetry and Motion Tracking

- Characterize the performance of a *high* ***spatial***

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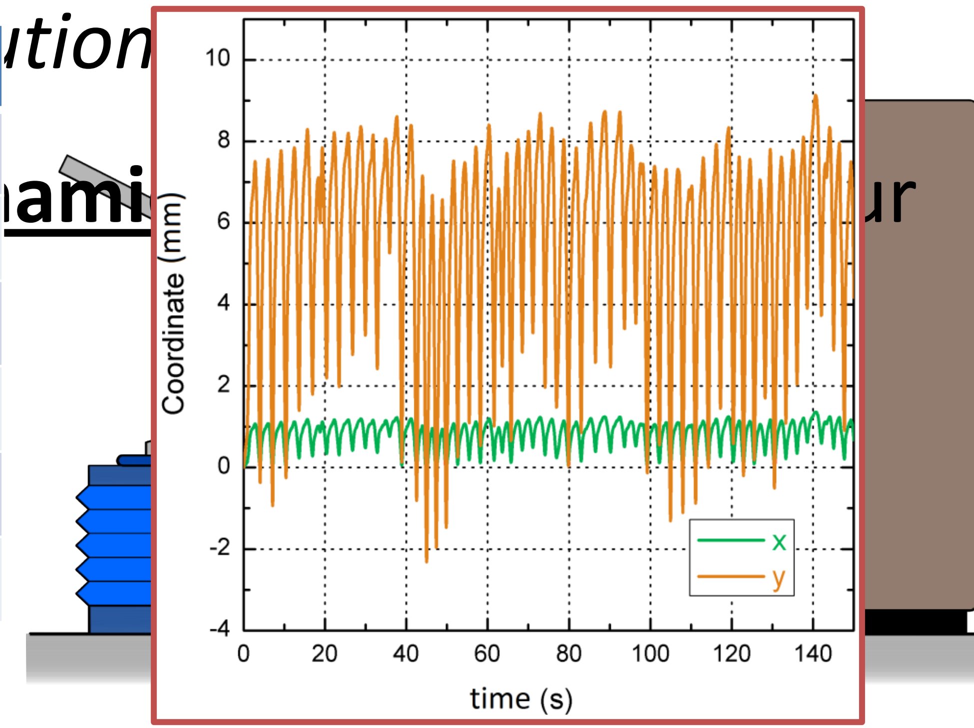
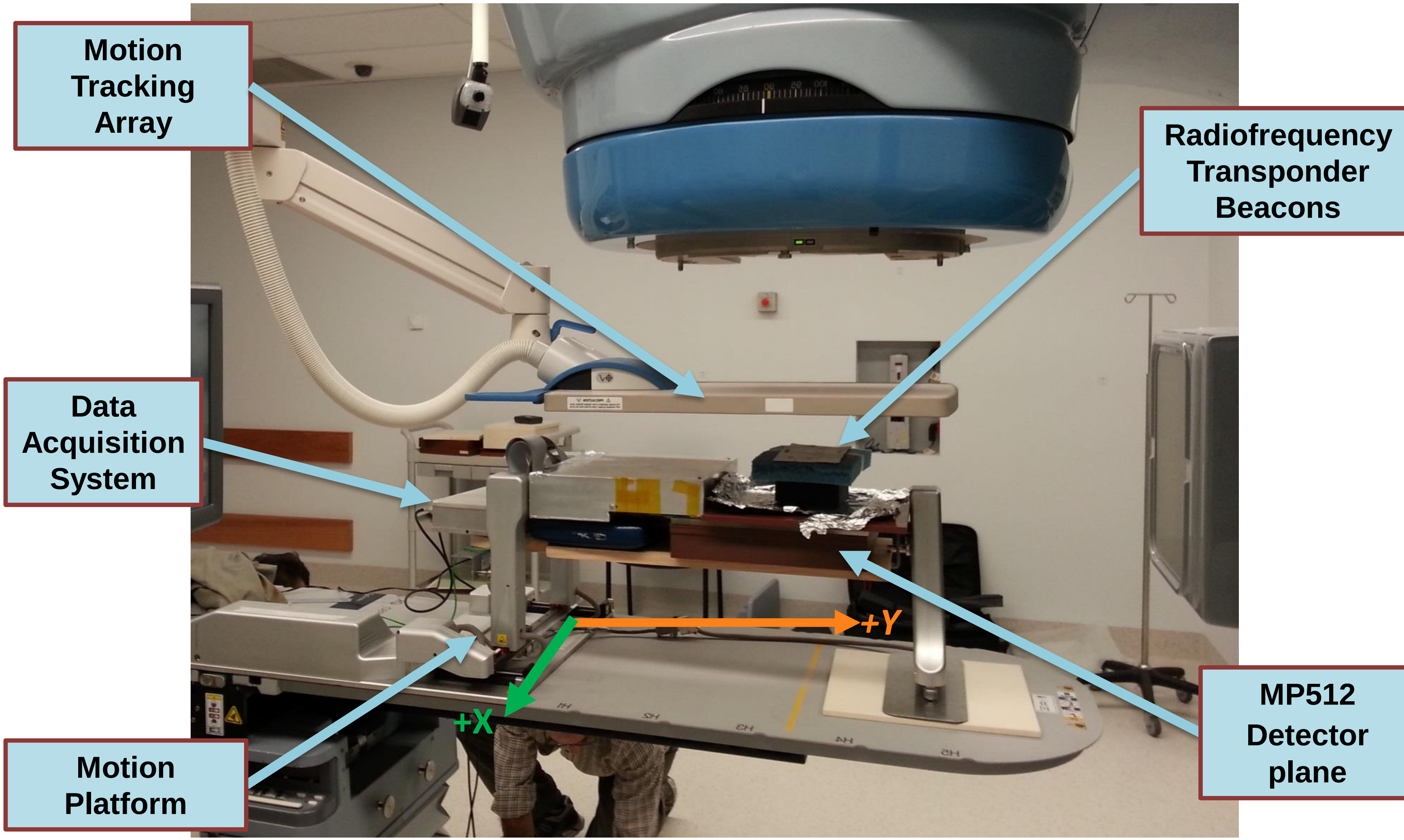
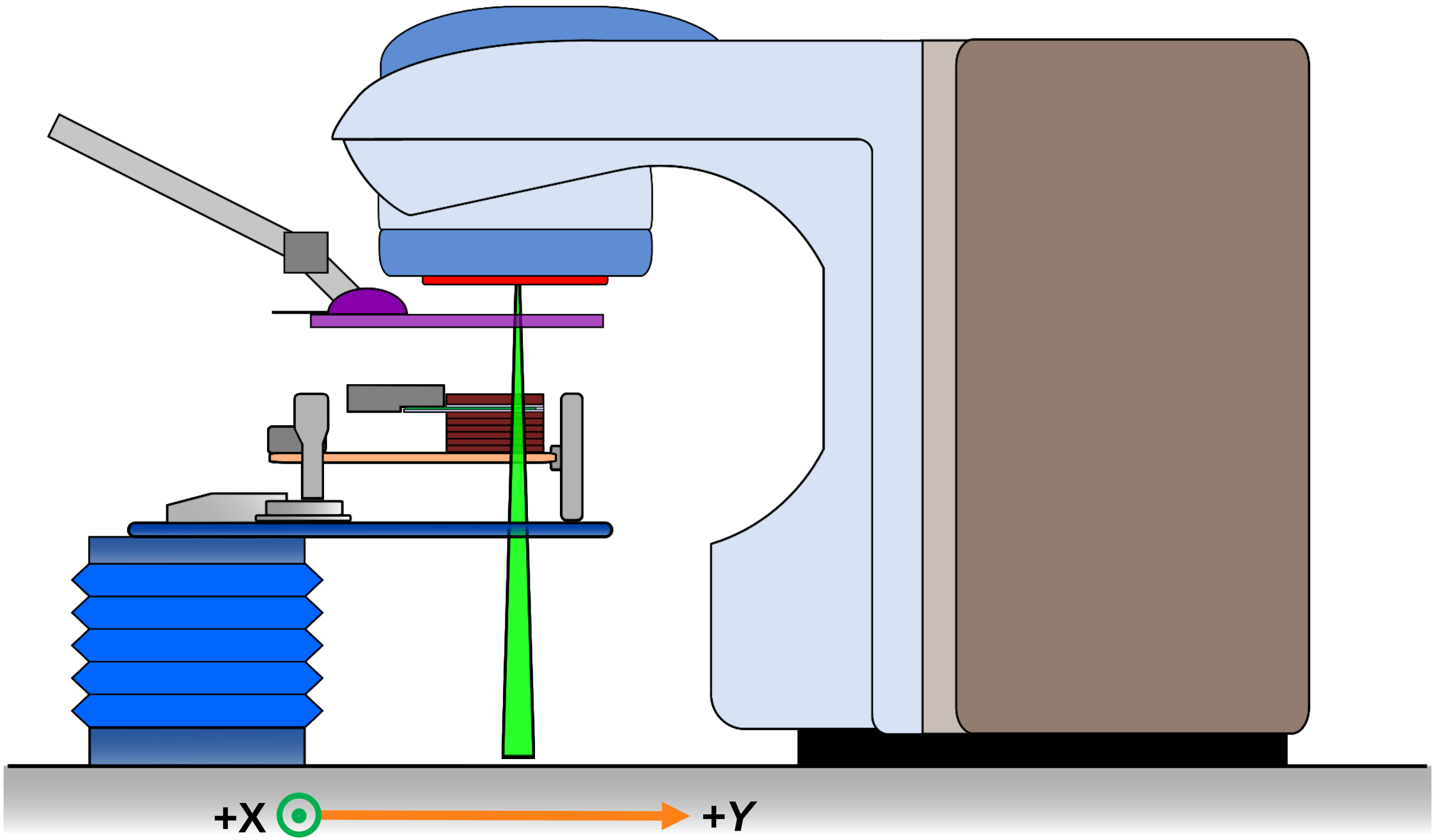
Need	Realisation
Source:	Linear Accelerator
Motion Platform:	HexaMotion
Motion:	Patient Lung trace
Detector:	MP512
Motion Tracking:	Calypso
Adaptive Strategy:	Dynamic MLC



Dynamic Characterisation of MP512



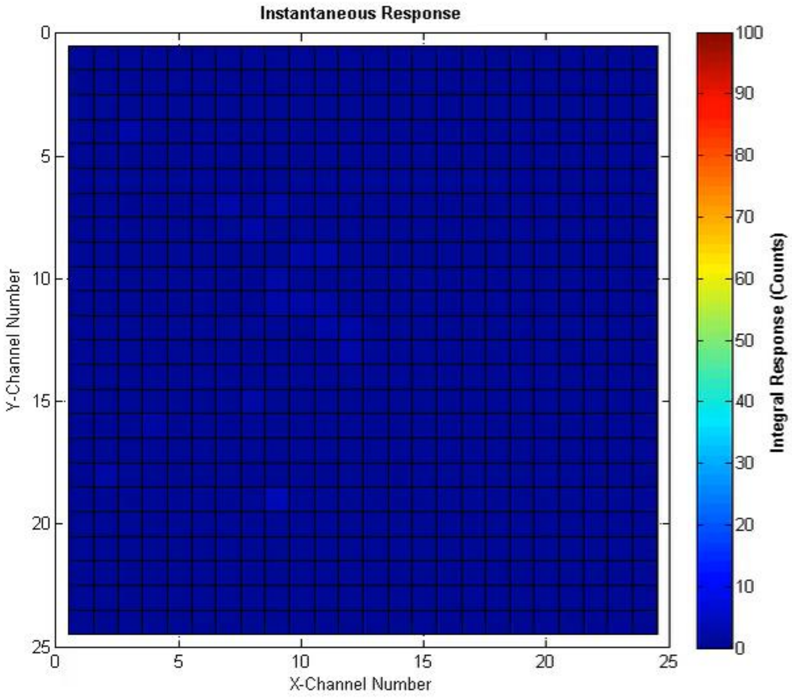
Static	Motion	Motion+Tracking

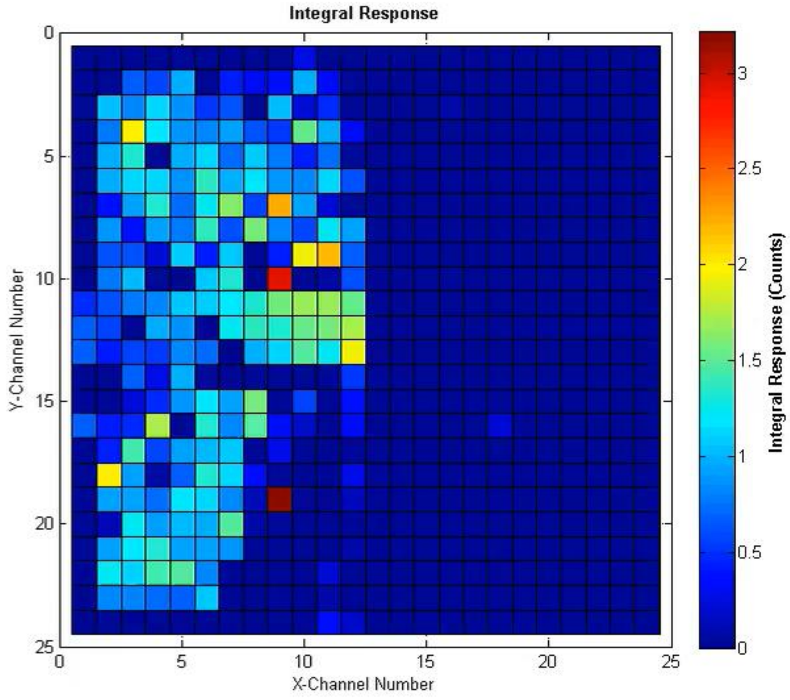


- Introduction of **motion tracking system** and **MLC tracking** throughout beam delivery to moving system → **Motion+Tracking**

Dynamic Characterisation of MP512

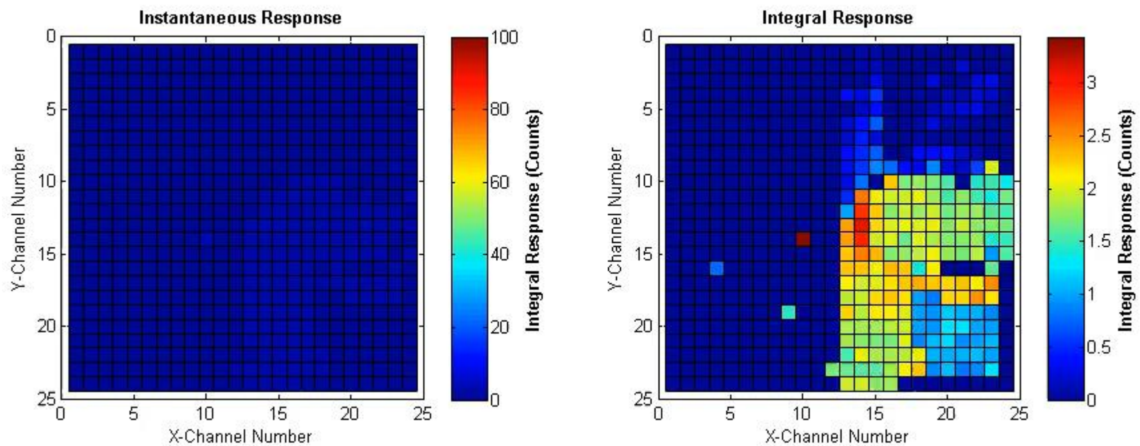
Without Motion – 1x1cm² field size

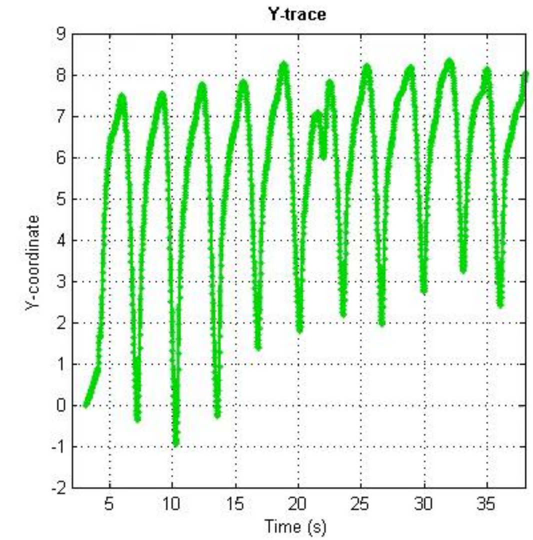




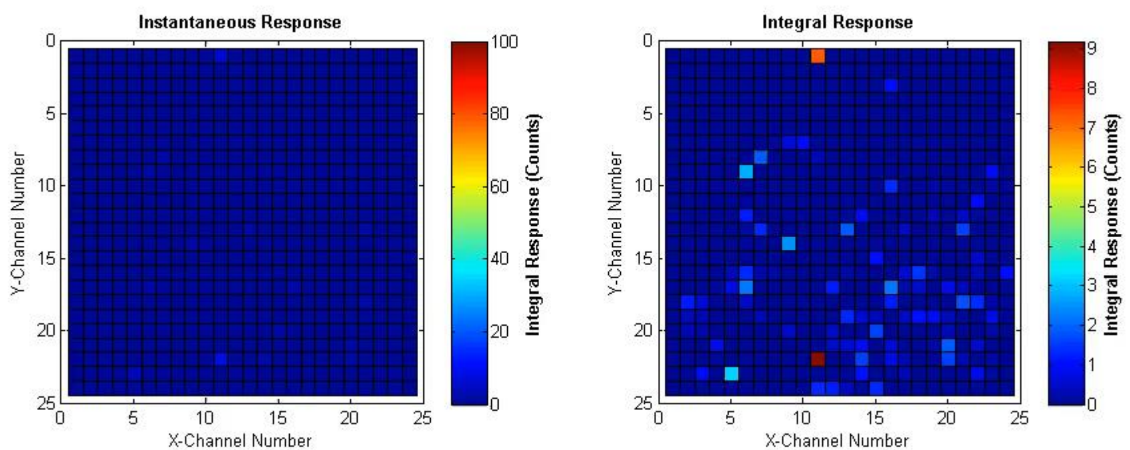
Dynamic Characterisation by MP512

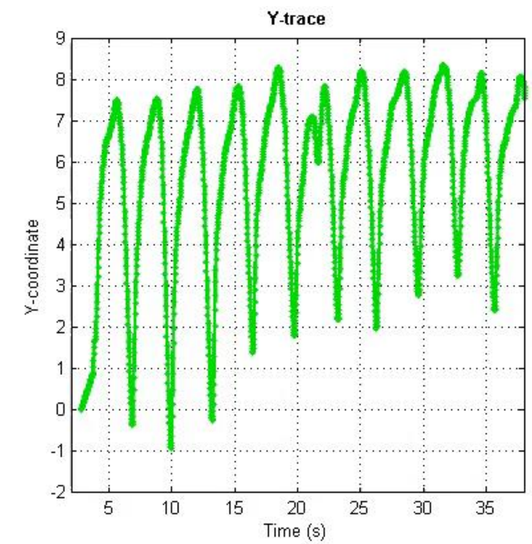
With Motion – 1x1cm² field size



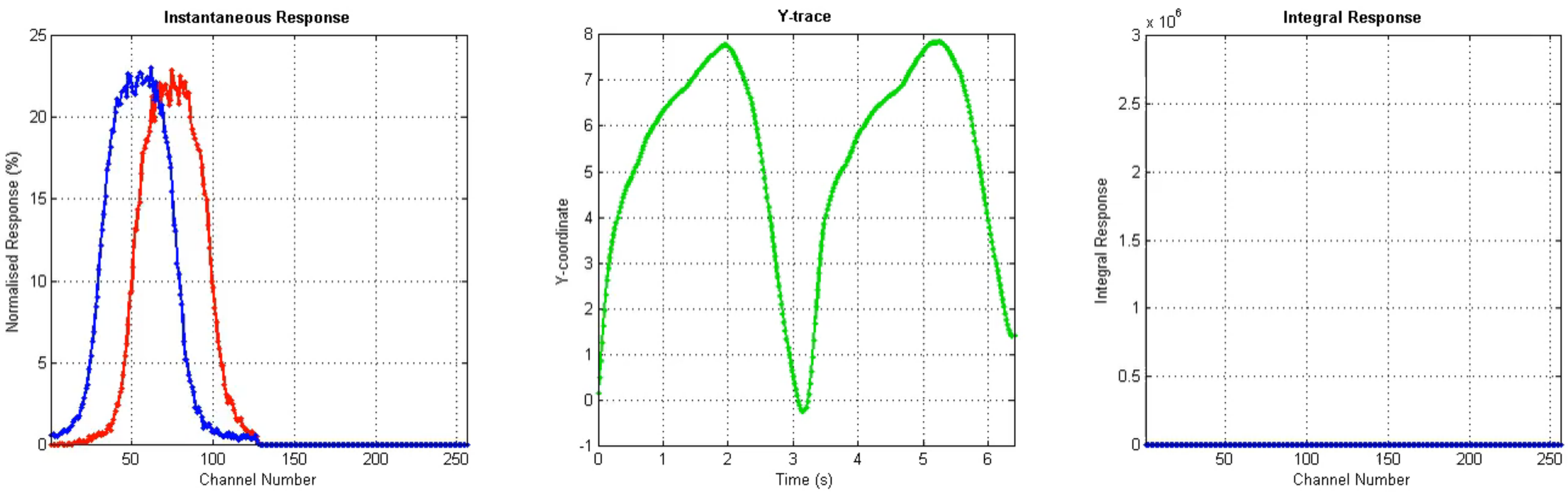


With Motion and MLC Tracking - 1x1cm² field size





sDMG – FS 1x1cm^2



Results: Beam Profiles

- Comparison of results from **MP512** to **EBT3 film** for three experimental cases for field size 1x1cm².

Y-profiles – 1x1cm²

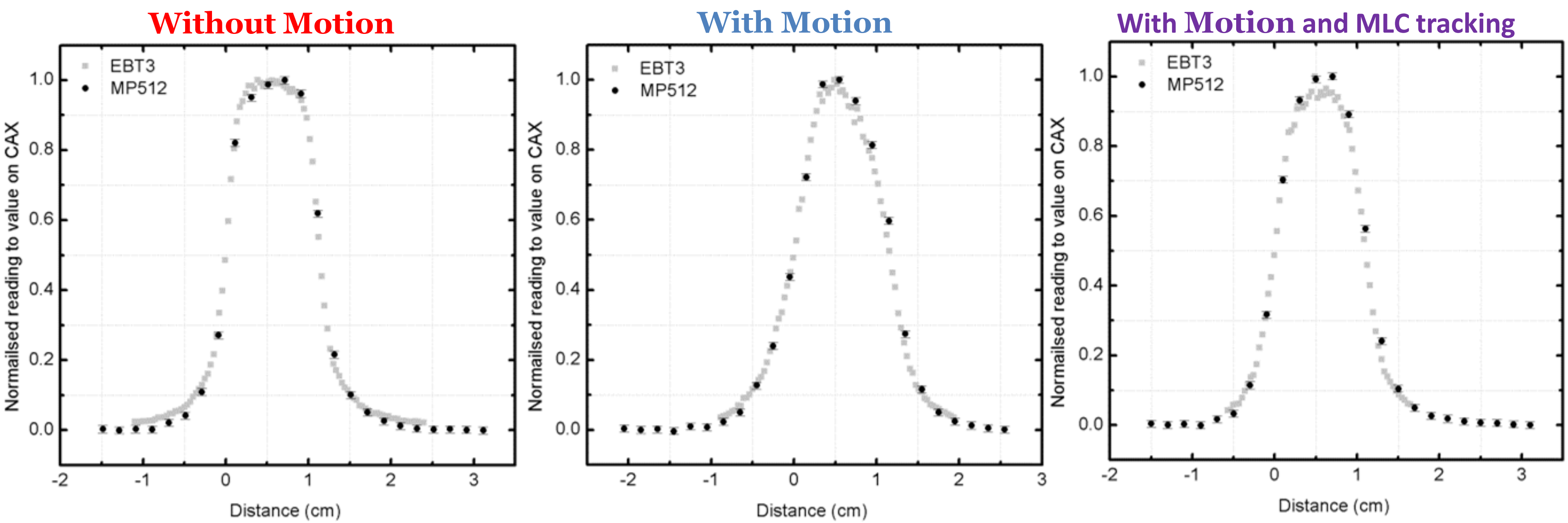


Figure – Normalised profile comparison, MP512 with EBT3 film ()

- The average uncertainty for EBT3 film is +/-1.9%, for M512 is +/-2%, induced by the RF from Calypso

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Results: Beam Profiles

- Comparison of results from **MP512** to **EBT3 film** for three experimental cases for field size 1x1cm².

X-profiles – 1x1cm²

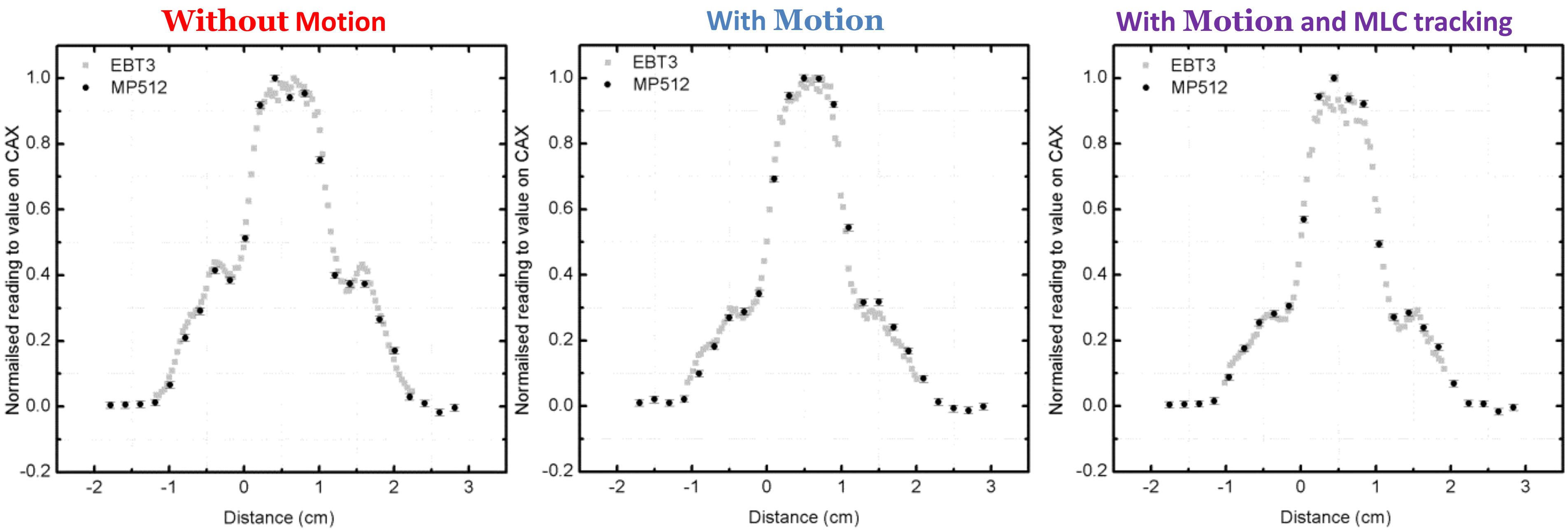
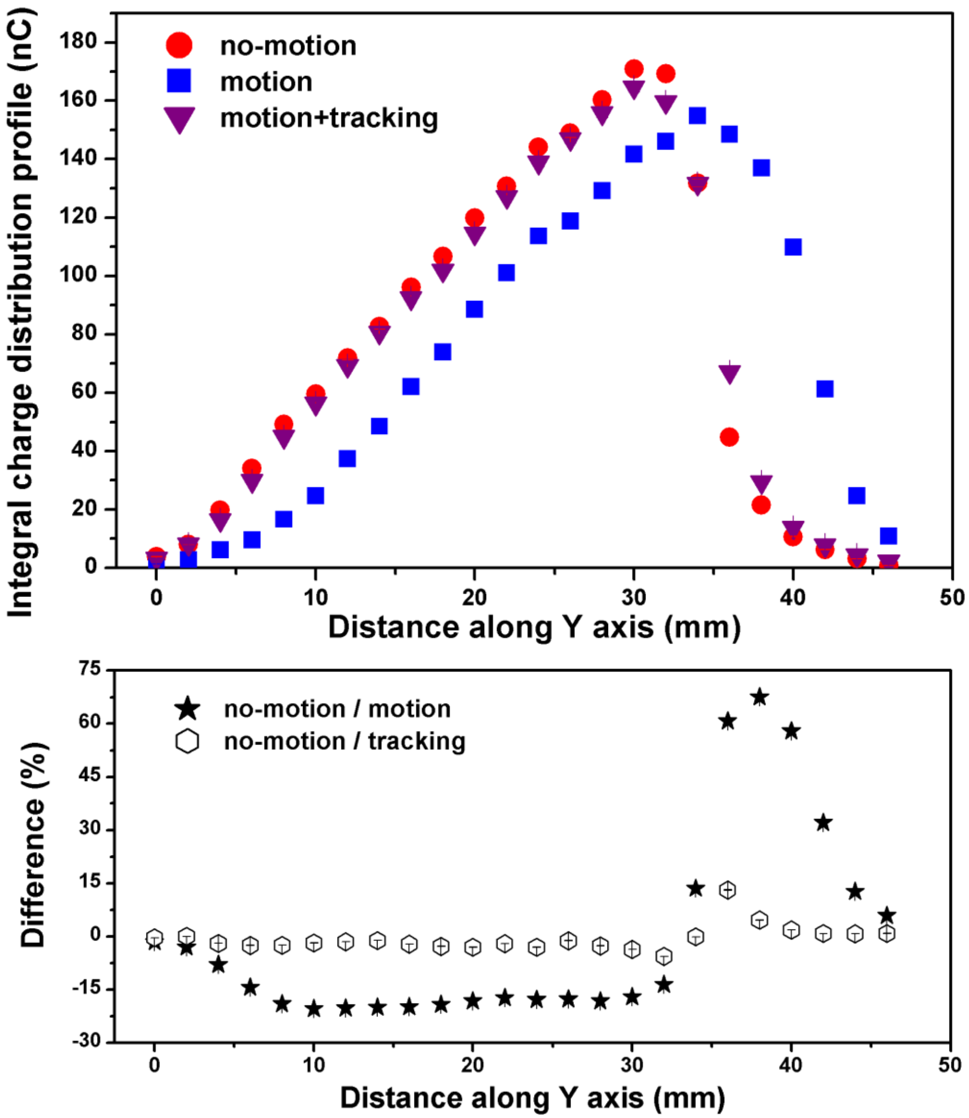


Figure – Normalised profile comparison, MP512 with EBT3 film ()

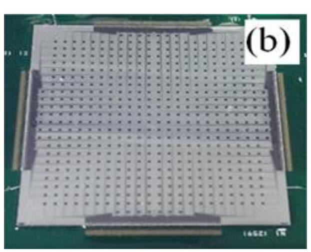
Results – MLC Dynamic Wedge

- MLC used to produce enhanced dynamic wedge to generate an intensity modulated dose profile

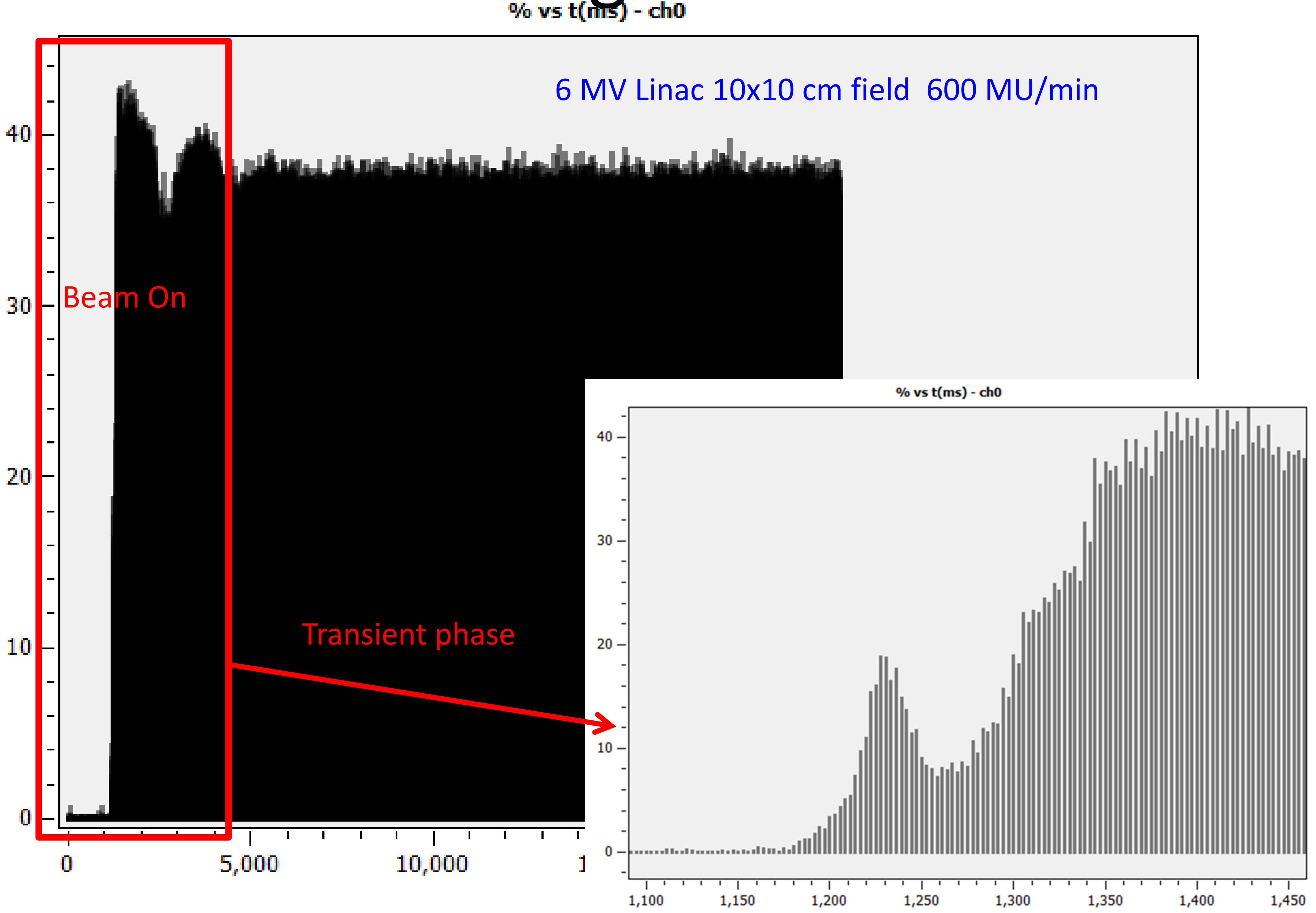
- Integral profile along y-axis is compared for cases:
  - Without Motion
  - With Motion
  - With Motion + Tracking



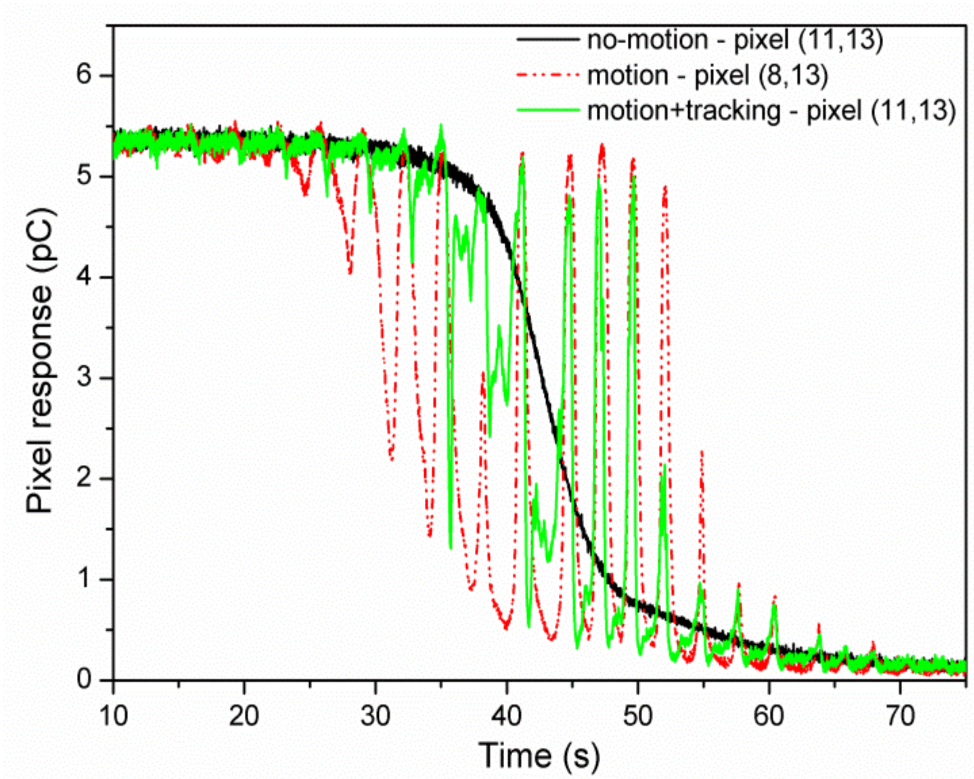
M512



Detailed timing information

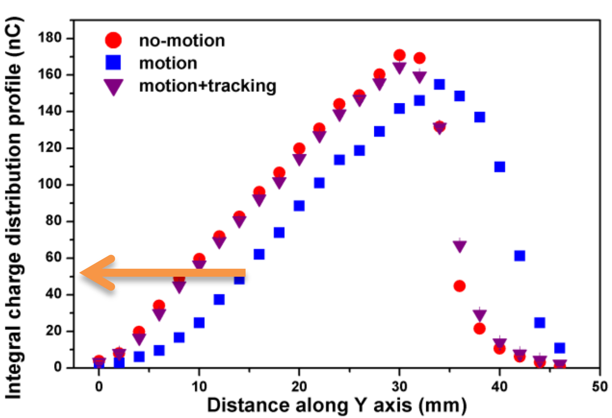


Timing analysis of motion/interplay effect



- Motion compensation algorithm/tracking software generates a lag in time (200 ms) → tracking cannot cope with fast transient components

- Integral profiles cannot display which is the phenomenon which creates the dose discrepancy



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