DOSE IMAGING DETECTORS FOR CHARGED PARTICLE THERAPY BASED ON GAS ELECTRON MULTIPLIERS

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Outline:

- Proton Therapy status
- Need for detectors – clinical specs
- GEMs in dose profile measurements – basic principles, detector design
- Electronic readout – test results
- Optical readout – test results
- Summary

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PROTON THERAPY COMMUNITY IS GROWING FAST

Institution	Country	Particle	Energy	Beam lines	# of rooms	Starting date
PSI, Villigen	Switzerland	p	250 MeV Cyclotron	New gantry + horiz fixed beam	1+2	2009
UPenn, PA	USA	p	230 MeV Cyclotron	4 gantries, 1 horiz. beam	5	2010
CNAO, Pavia	Italy	p, C-ion	430 MeV/u synchrotron	1 gantry? 3 horiz. 1 vertical	3-4	2010?
HIT, Heidelberg	Germany	p, C-ion	430 MeV/u synchrotron	1 gantry (C-ions), 2 fixed beams	3	2010
WPE, Essen	Germany	p	230 MeV cyclotron	3 gantries, 1 horiz beam.	4	2010
CPO, Orsay	France	p	230 MeV cyclotron	1 gantry, 4 horiz beams	3	2010
PTC, Marburg	Germany	p, C-ion	430MeV/u synchrotron	3 horiz. fixed beams ,1 45 deg fixed beam	4	2010
Chang Gung Hospital	Taiwan	p	230 MeV cyclotron	4 gantries, 1 experimental room	4	2011
Gunma University, Maebashi	Japan	C-ion	400MeV/u synchrotron	90 deg fixed beam, 0 deg fixed beam, 0+90 deg fixed beam	3	2010
PCPTC, Chicago	USA	p	230 MeV cyclotron	2 horiz., 2 dual fixed beams	4	2011
NIU, Chicago	USA	p	250 MeV cyclotron	2 gantries 2 fixed beams	4	2011?
HUPBTC, Hampton, VA	USA	p	230 MeV cyclotron	4 gantries 1 horiz.	5	2010

MOST PLAN TO HAVE PENCIL BEAM SCANNING CAPABILITY!

Pencil Beam Scanning (IMPT) technology refers to a method in which a small area beam is swept laterally across the tumor with dynamically varying lateral position, intensity and energy for each spot (voxel) to achieve a dose distribution that conforms exactly the tumor area. Dose distributions in IMPT are characterized by high lateral and depth dose gradients. A typical radiotherapy treatment requires several hundred Hz voxel by voxel dose delivery frequency.

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Radiation detector clinical specifications

Dose delivery method	Application	Position resolution, mm	Timing resolution, ms	Material in beam, mm water equiv.	Other param.
Passive beam spreading	On-line dose monitoring	n/a, centering ±1%	100	<1	a), b), c), e)
	Quality assurance, dose profile measurements	1-2	500	n/a	a), b), d), f)
Uniform scanning beam	On-line dose monitoring	2-3	<1	<1	a), b), c), e)
	Quality assurance, dose profile measurements	1-2	5	n/a	a), b), d), f)
IMPT/ pencil beam scanning	On-line dose monitoring	<1	<0.1	<0.3	a), b), c), e)
	Quality assurance, dose profile measurements	<1	0.1 - 5	n/a	a), b), d), f)

a) Dose rate linearity - ≤1%
b) Response non-uniformity across the detector - ≤1%
c) Sensitive area ~20×20 cm^2
d) Sensitive area ~30×30 cm^2
e) Tissue equivalence in 70 – 250 MeV range - ±0.1%
f) Tissue equivalence in 20 – 250 MeV range - ±1%

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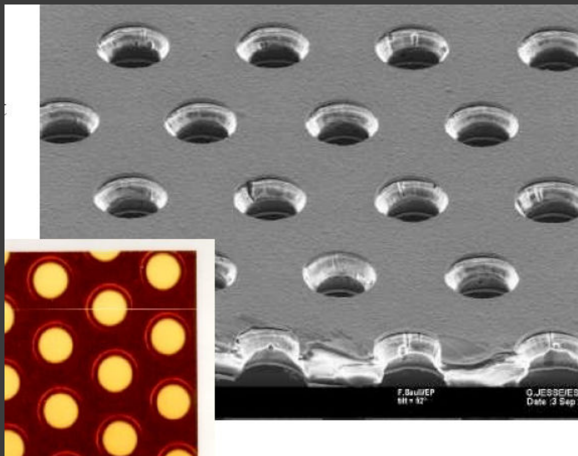
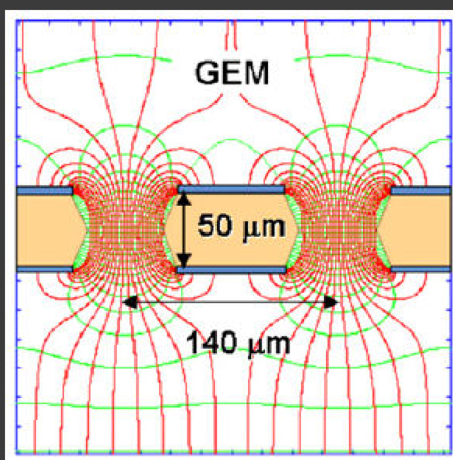


GEMs (Sauli 1997) offer:

- fast performance
- robustness and design flexibility
- excellent spatial resolution
- cascade option to improve signal to noise ratio
- electronic and optical readout schemes
- various pickup electrode layouts in electronic readout mode
- …



From: F. Sauli, Physics Reports, 2004. **403**: p. 471-504

10×10 cm^2 GEM foils from

Tech-Etch Corp, Plymouth, MA.

Up to 30×30 cm^2 foils are commercially available, bigger foils could be produced upon request

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Optical Readout of GEMs

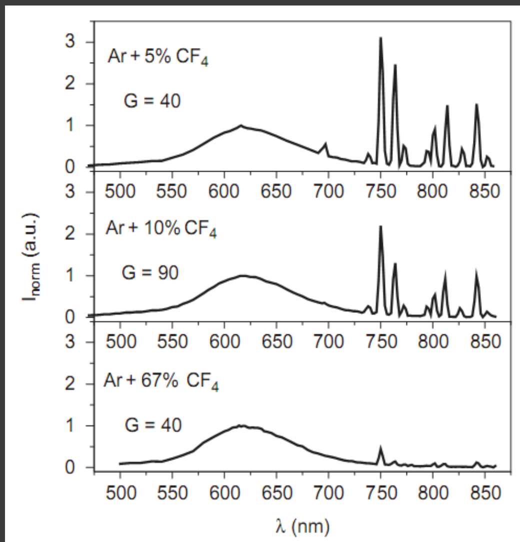
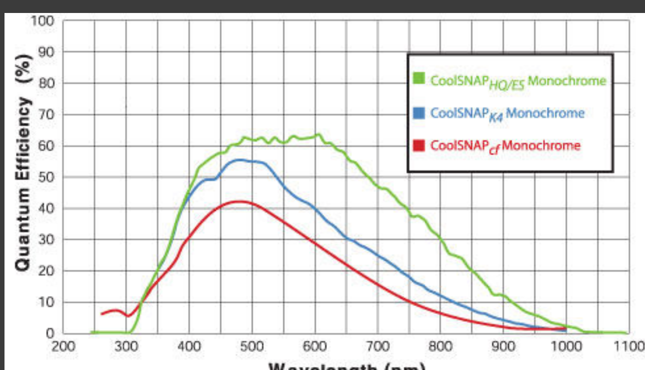


Fig. 8. Visible and NIR emission spectra of Ar–CF_4 mixtures,

From F.A.F. Fraga et al., NIM A513 (2003) 379



- Although the GEM has been mainly used as a gaseous preamplifier device with electronic readout, it is known that when suitable gaseous mixtures are used, the avalanches emit a large number of photons in the UV, visible, and/or near infrared (NIR) bands. This scintillation, read out by CCD camera, has been used for the development of imaging detectors (PSI-Delft-Coimbra):
- M.M.F.R. Fraga *et al*, *The GEM scintillation in He-CF4, Ar-CF4, Ar-TEA and Xe-TEA mixtures.*

  NIM **A504** (2003) 88.
- F.A.F. Fraga *et al*, *Luminescence and imaging with gas electron multipliers.*

  NIM **A513** (2003) 379.
- S. Fetal *et al*, *Dose imaging in radiotherapy with an Ar-CF4 filled scintillating GEM.*

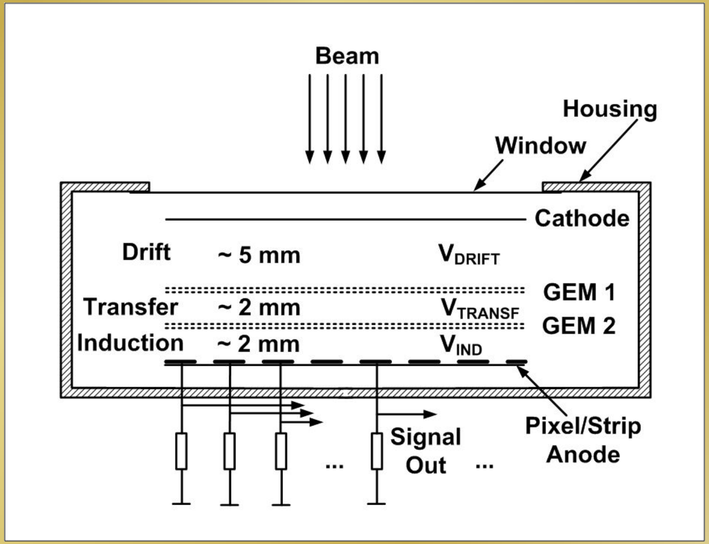
  NIM **A513** (2003) 42.
- E. Seravalli *et al*, 2D dosimetry in a proton beam with a scintillating GEM detector .

  Phys. Med. Biol. **54** (2009) 3755

dGEM (GEM-based Dose Imaging Detector)

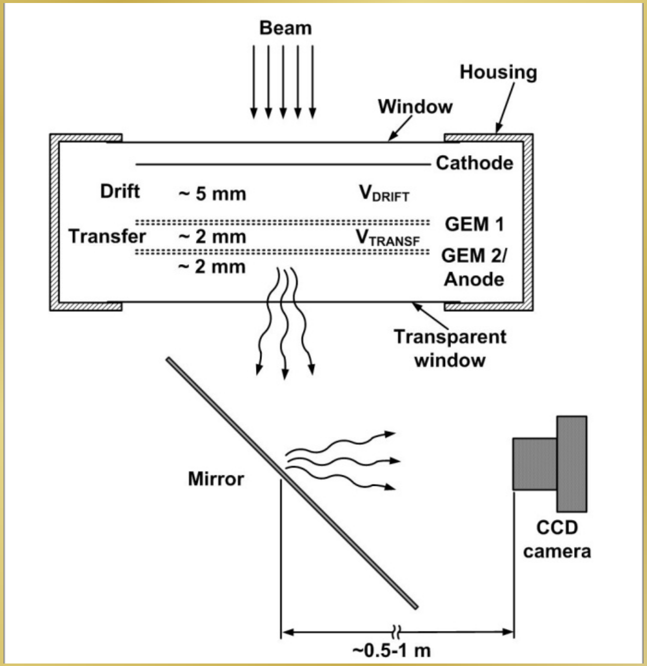
Electronic Readout

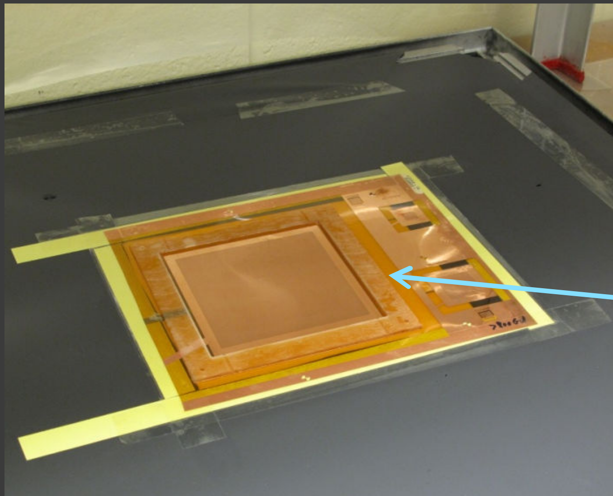
- **Online beam monitoring (with multi-pad anode), proton tomography (cross-strip anode)**
- **Fast**
- **Moderate spatial resolution limited by electronics cost**



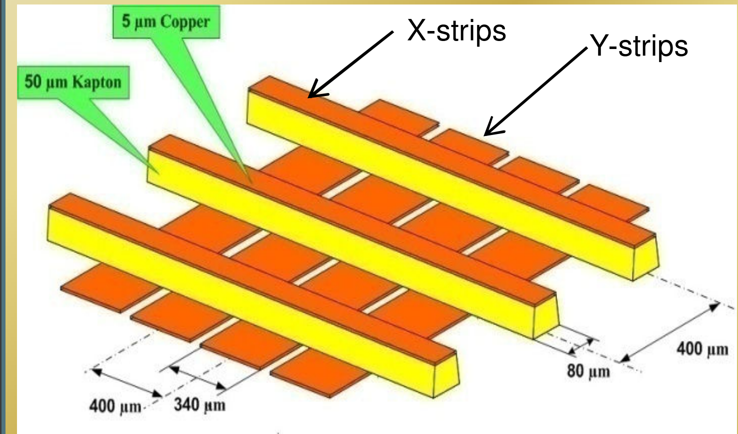
Optical Readout

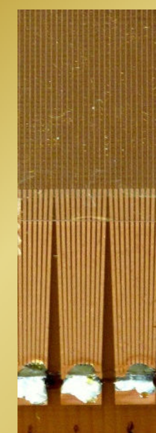
- **Quality assurance, dose profile measurements**
- **High spatial resolution**
- **Relatively slow**



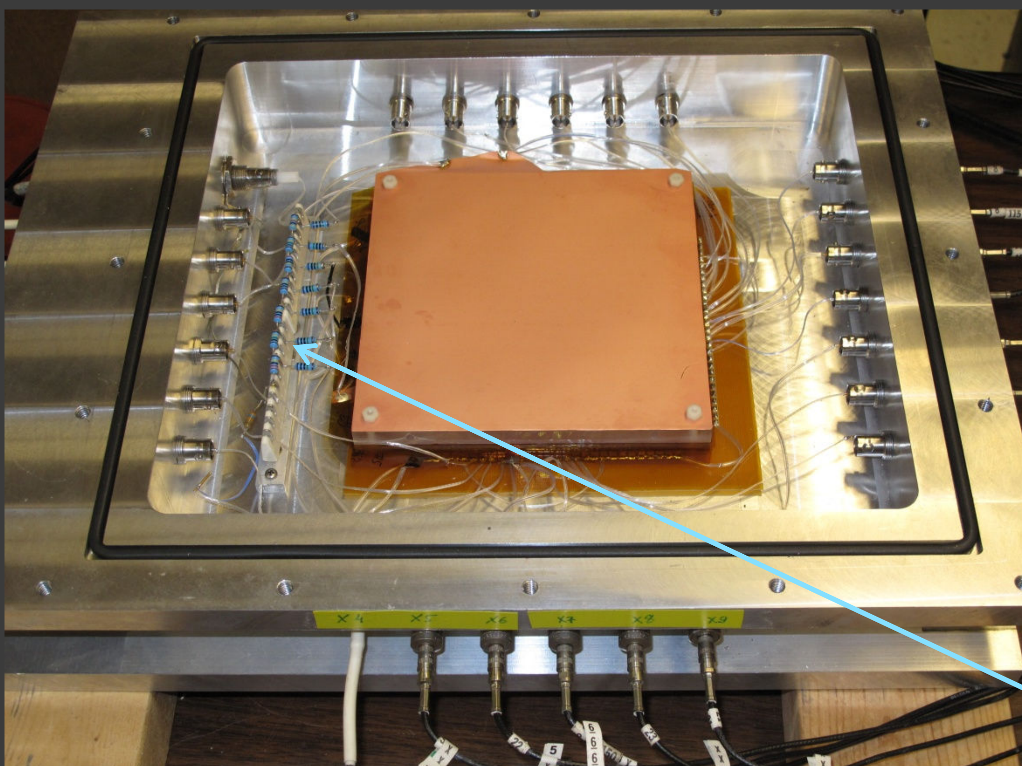


GEM foil being glued to the frame in a laminar flow enclosure





Strip anode follows COMPASS design: 400 µm pitch, strips connected in groups of ten to form 4 mm readout pixel



Shown with resistive voltage divider – later replaced with individual power supplies for each stage

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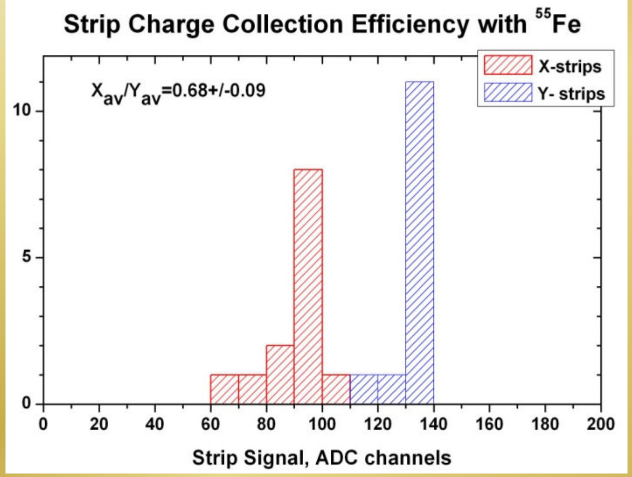
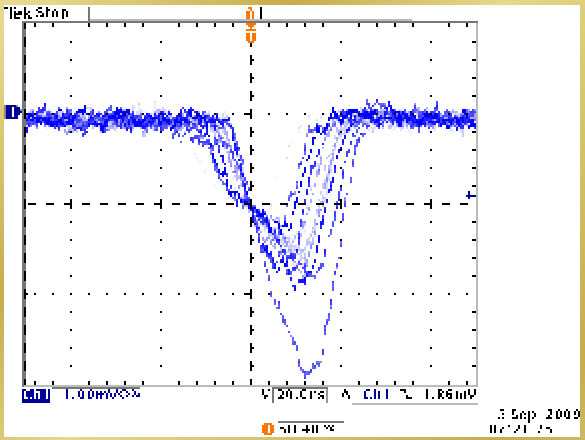
Ar/CO_2 70/30% vol.

Electronic Readout

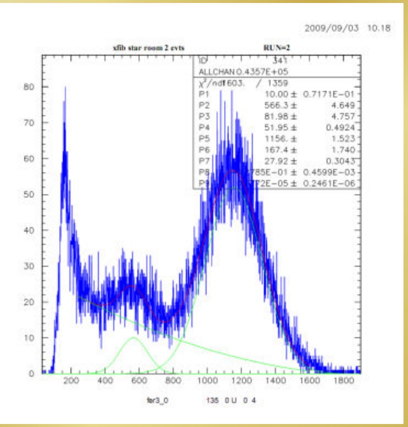


Strip anode charge collection efficiency measured with ^{55}Fe.

Gain ratio with with proton beam X/Y=0.78+/-0.01



Electron drift time in the 5 mm drift gap is estimated ~70 ns



^{55}Fe pulse height distribution from a single strip

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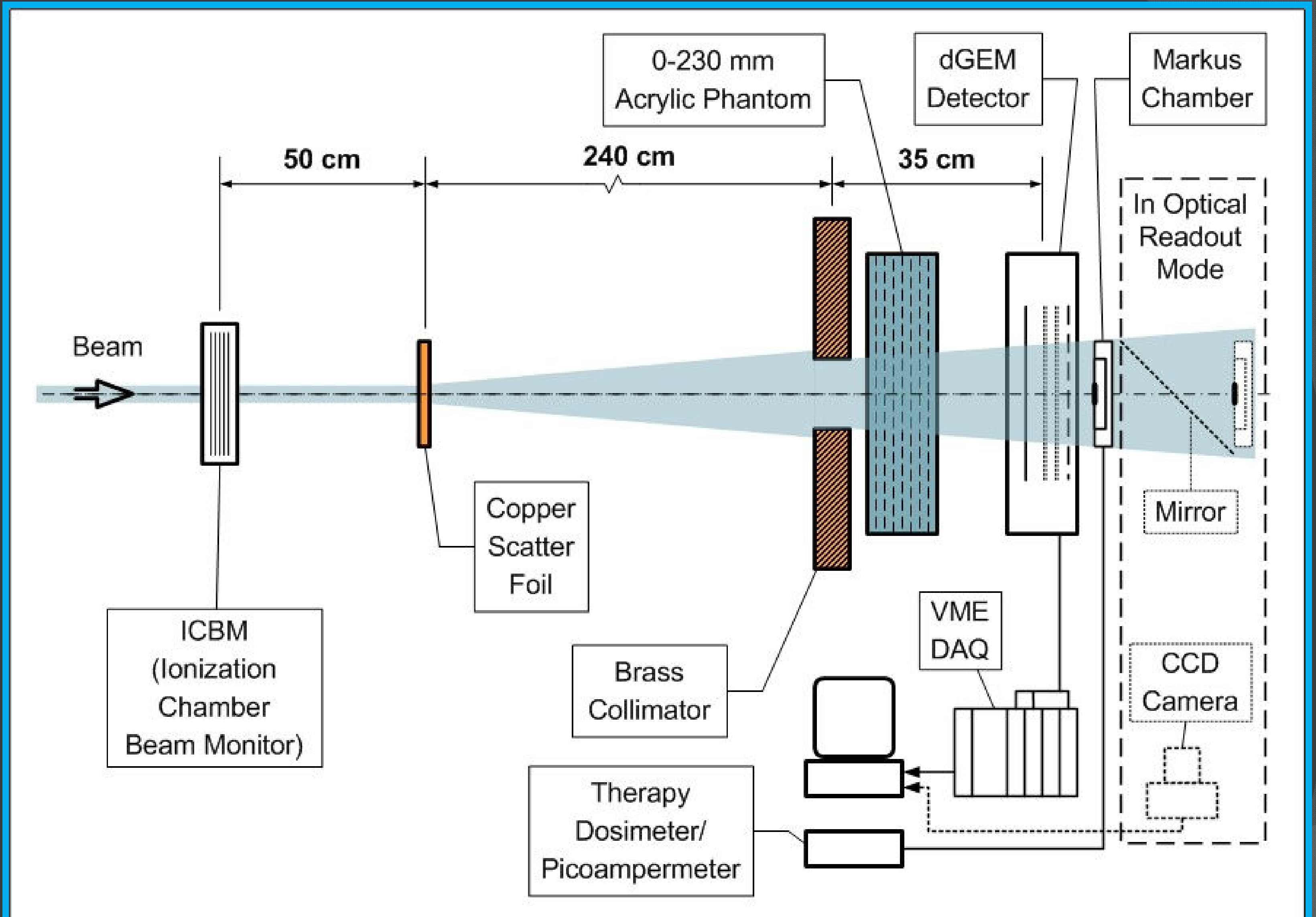

Markus ionization chamber (PTW, Model TN23343) with a 5.3 mm diameter active area and NIST-traceable absolute calibration in absorbed dose to water was used to estimate the dose rate.

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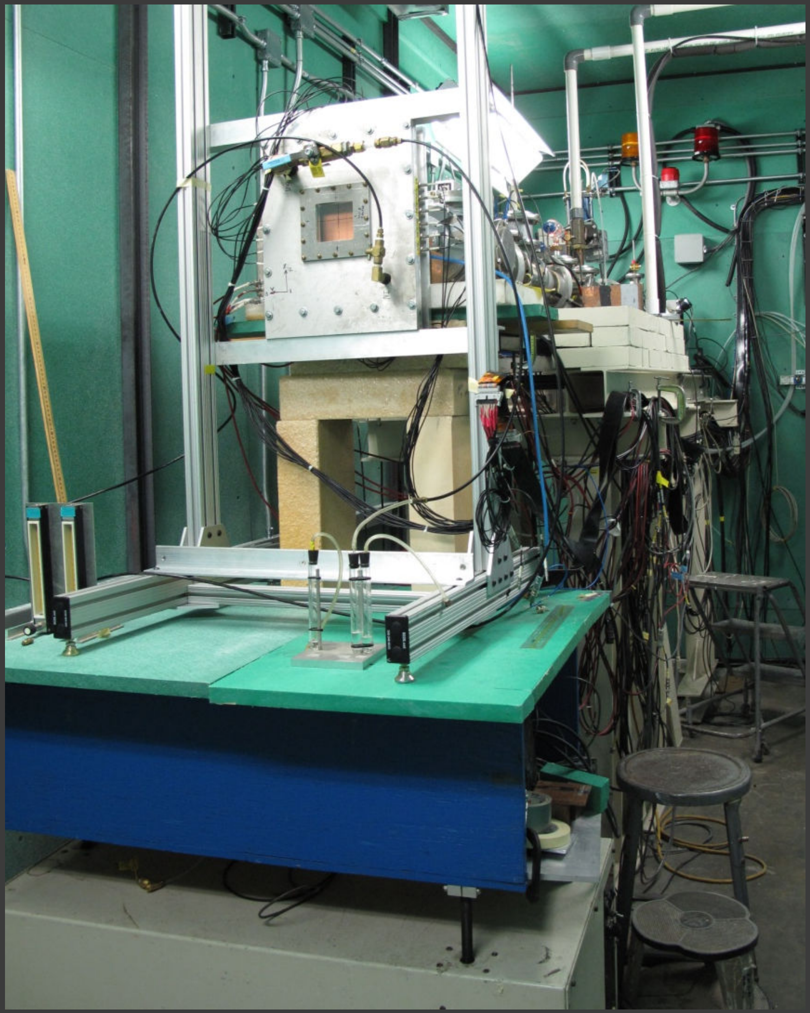
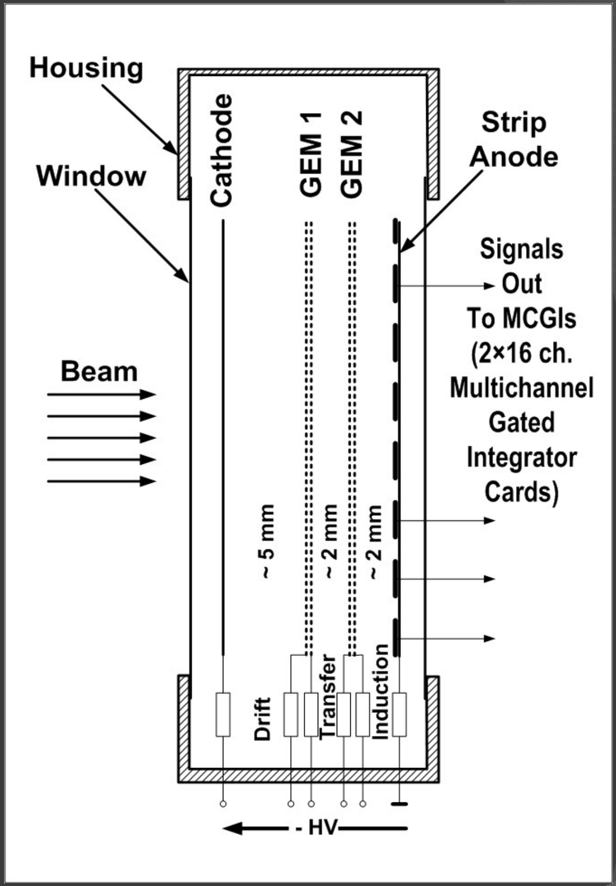
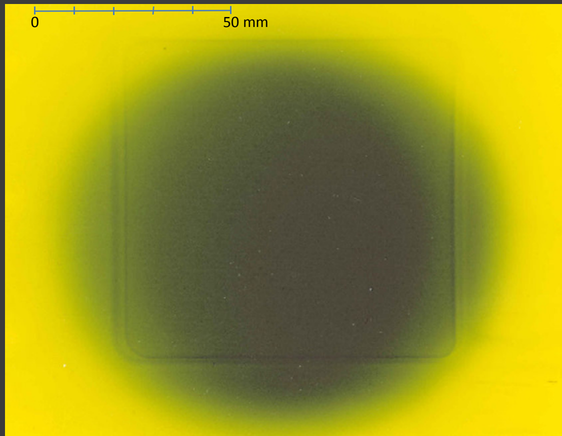
Electronic readout



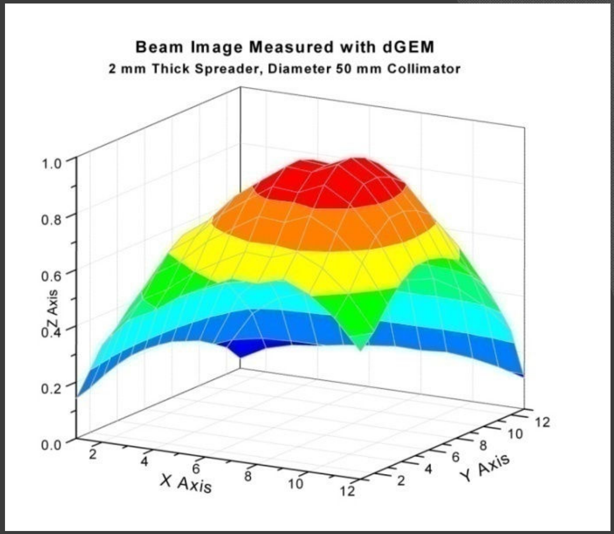


Gas mixture: Ar/CO_2 70/30%;
V_{GEM1}=350 V, V_{GEM2}=340 V, drift field 1.5 kV/cm, transfer and induction fields 1.7 kV/cm

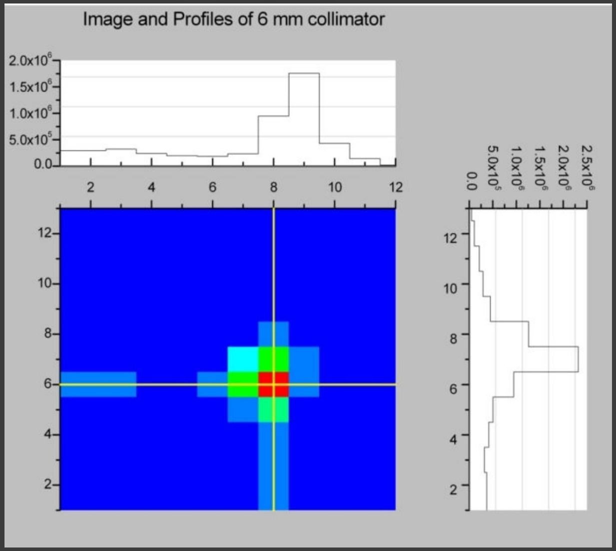
Background was measured between the beam runs and automatically subtracted

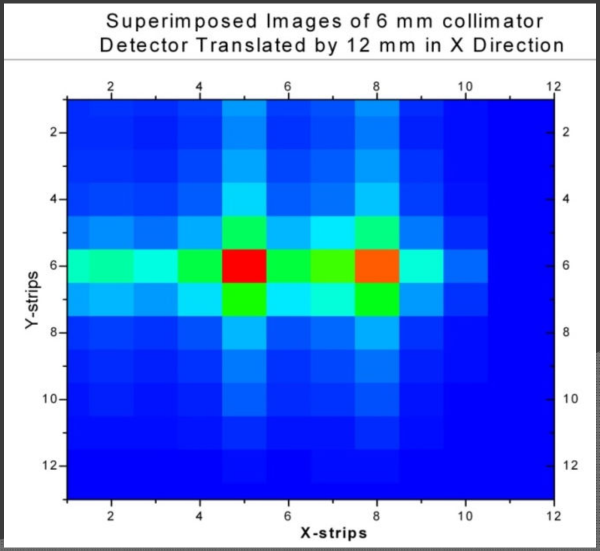


Beam profile, Gafchromic film



Beam profile, dGEM, Ø50 mm collimator





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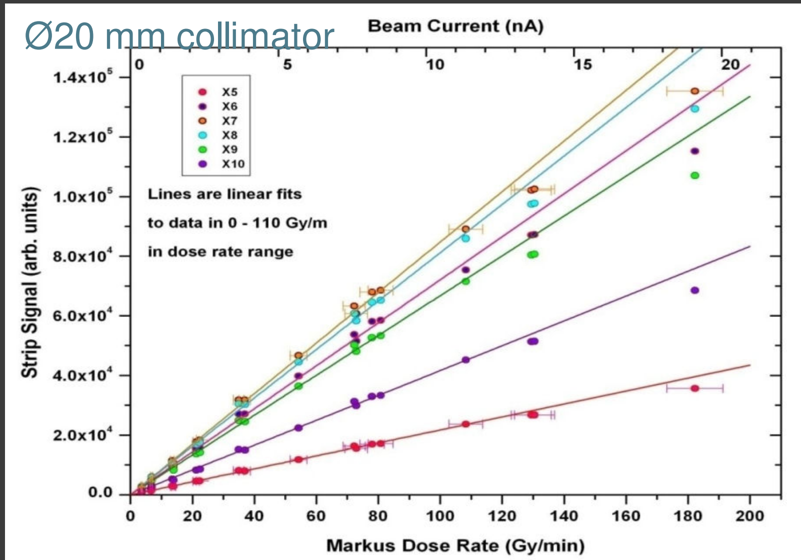
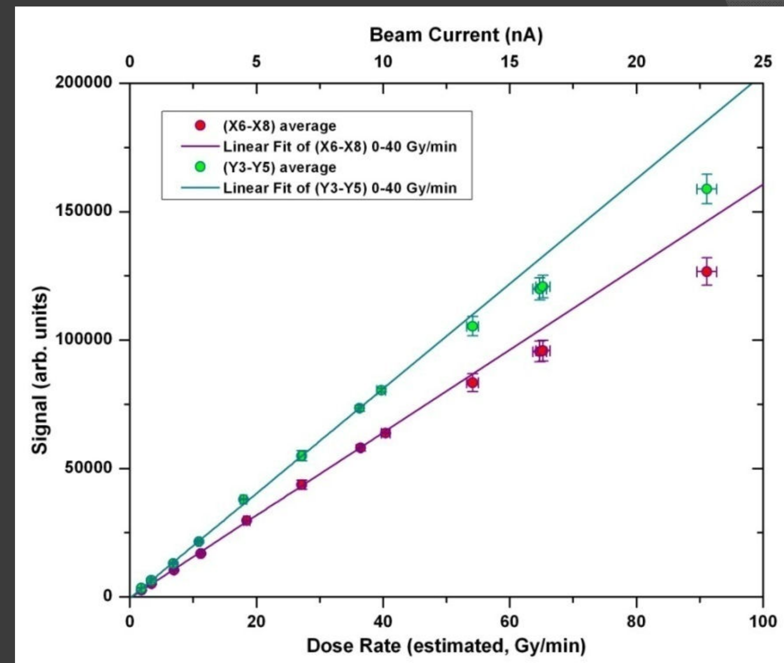


Individual X-strip signals as a function of estimated dose rate (bottom axis) and beam current (top axis).



dGEM signal as a function of estimated dose rate (bottom axis) and beam current (top axis). The signal is averaged over X-strips 6-8 and Y-strips 3-5, corresponding to the beam central area.

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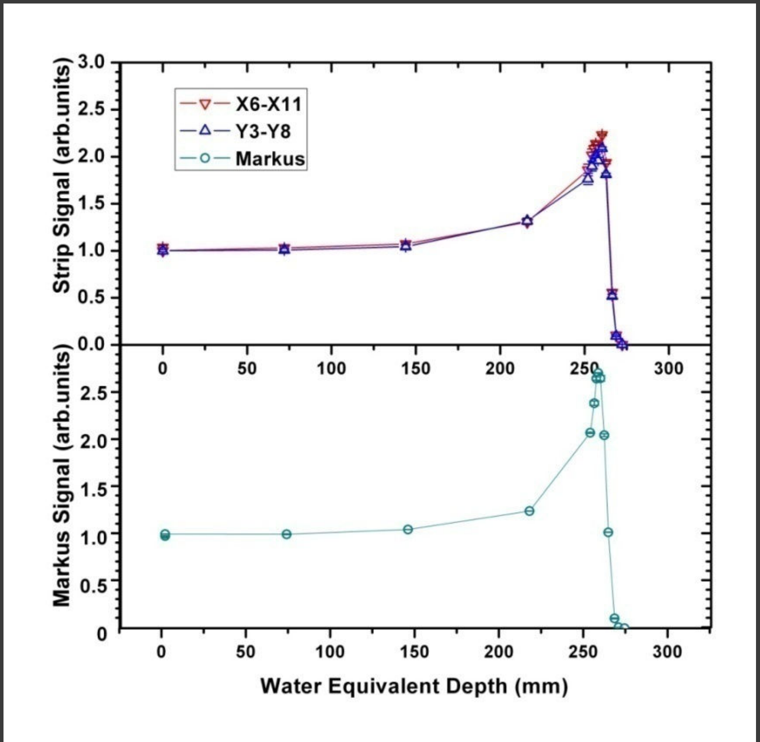
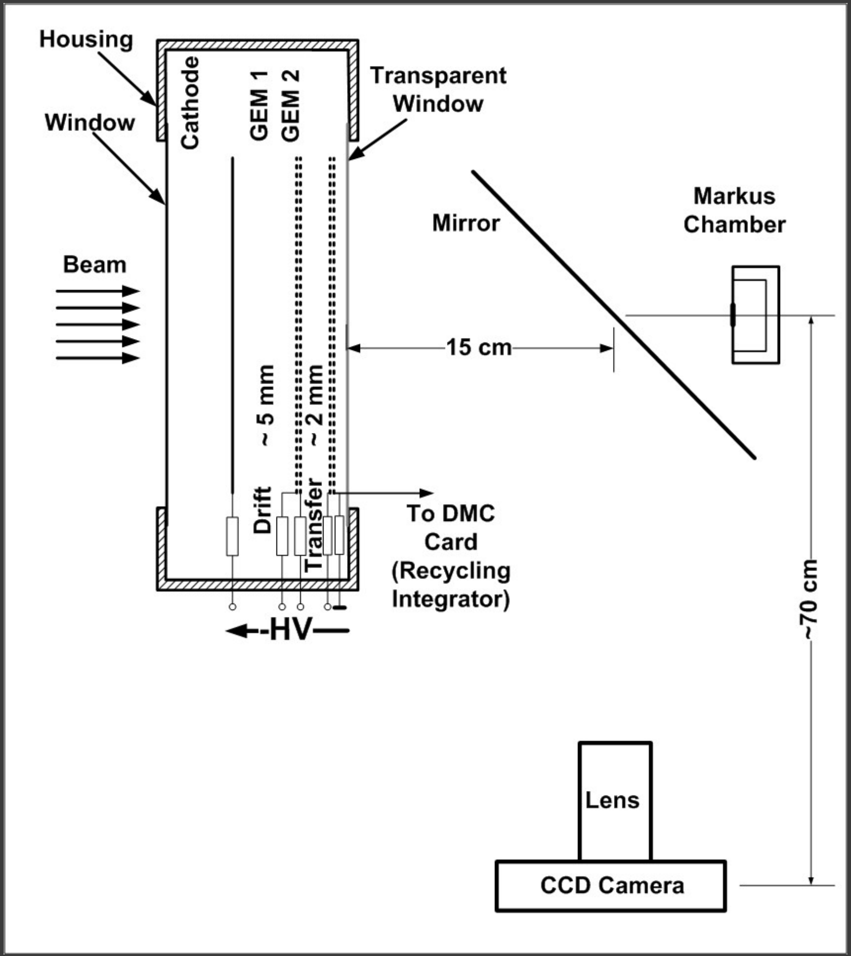
dGEM Energy Response – Bragg Peak



Dose-depth response. The signal is averaged over X-strips 6-8 and Y-strips 3-5, corresponding to the beam central area.

Optical readout

Gas mixture: Ar/CF_4 95/5%



SBIG ST-6 CCD Camera

Santa Barbara Instrument Group

Thermoelectric Peltier Cooling to -30°C

QE 62% at 650 nm

375 × 242 pixels 23×27 μm^2, translates to 0.36×0.42 mm^2 at the GEM_2 location

Vacuum gauge

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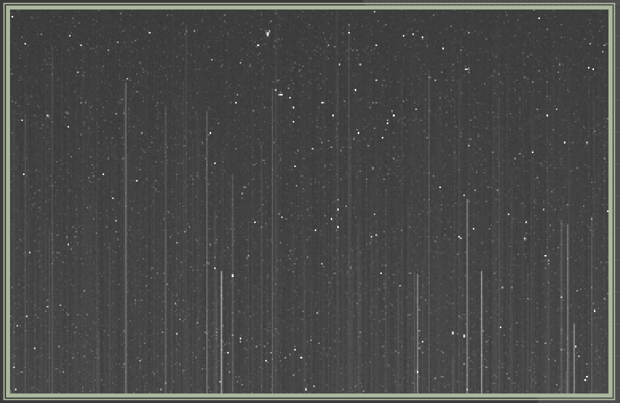
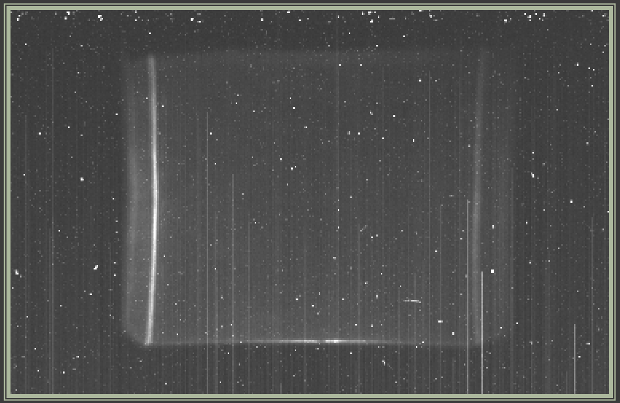
Background Sources:

- Camera offset (bias level) - subtract
- Dark current (noise) - subtract
- Ambient light - subtract
- Interactions of scattered beam and secondary particles with camera's sensor – estimate <0.2%
- Scintillations in the detector gas and exit window caused by beam particles – estimate <0.7%

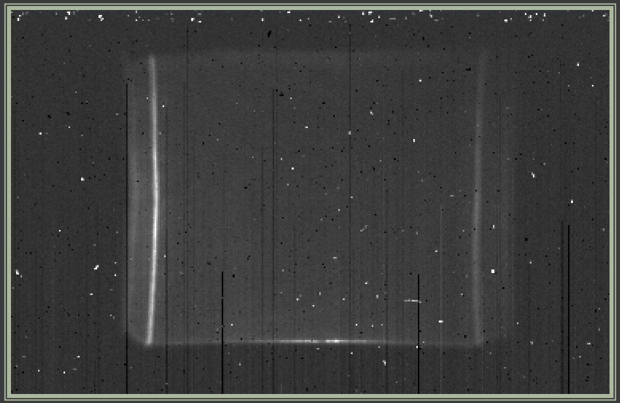


Dark frame, 3 s exposure

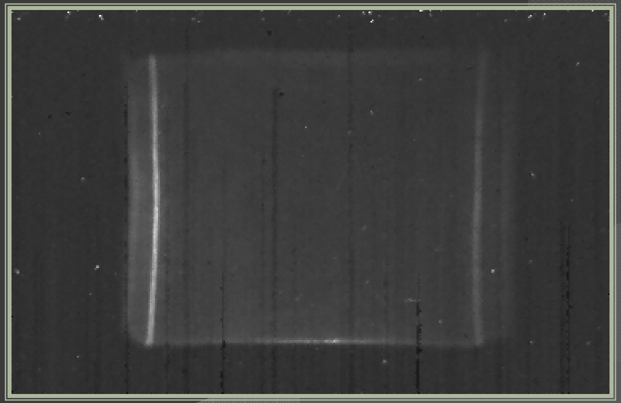
Estimates based on E. Seravalli *et al,*
Phys. Med. Biol. **54** (2009) 3755



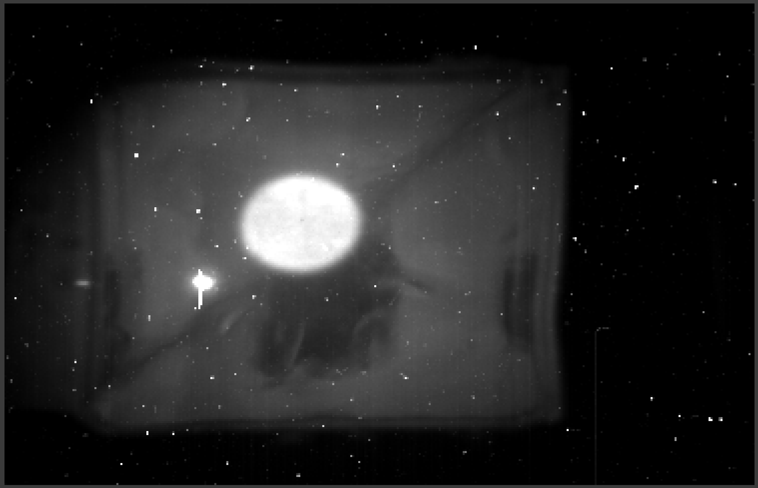
Ambient light
(w/o beam), 3 s exposure



(Ambient) – (Dark frame)

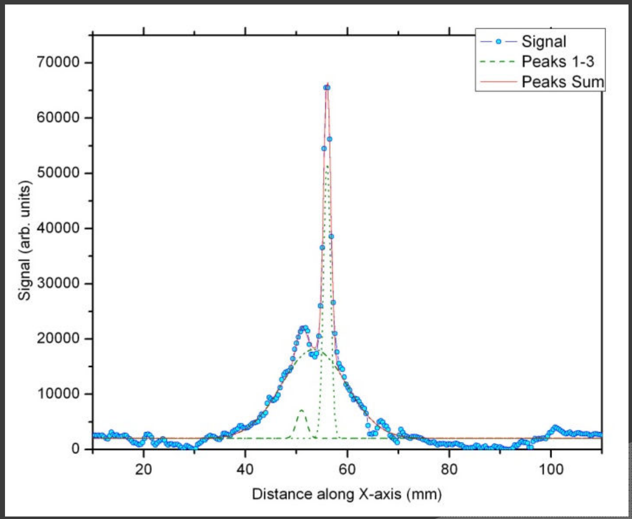


(Ambient) – (Dark frame), filtered (kill hot and cold pixels)



Spark, right before HV dropped

Image of 20x1.6 mm collimator
5 nA beam current, 3 s exposure



Signal profile
along the single-pixel line above.
The main peak has σ=0.7 mm.

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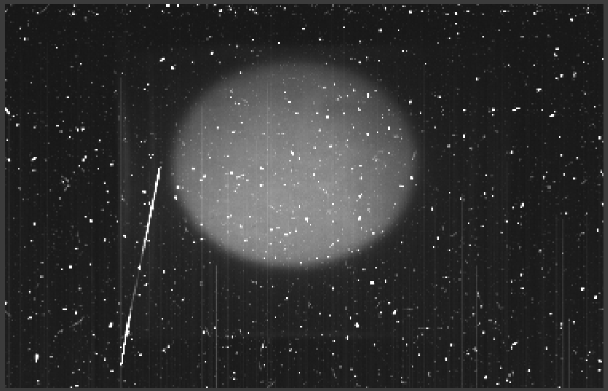
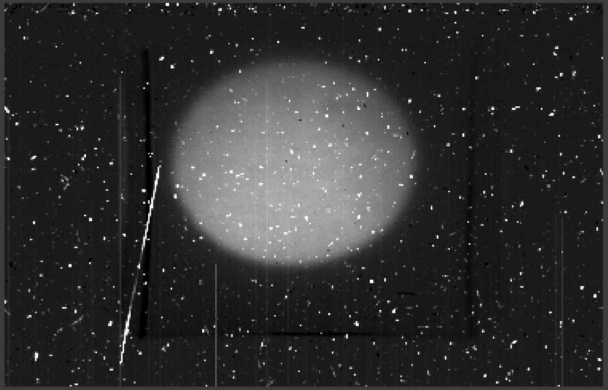
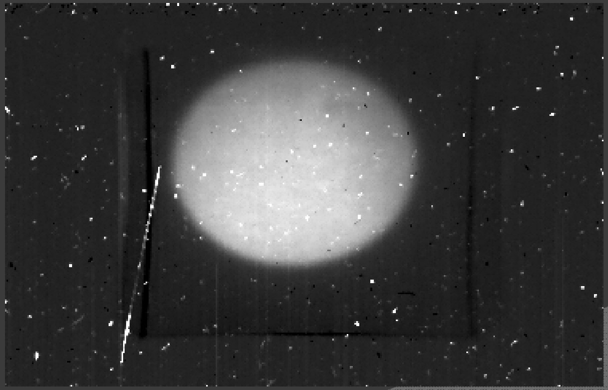


5 nA beam current, 3 s exposure

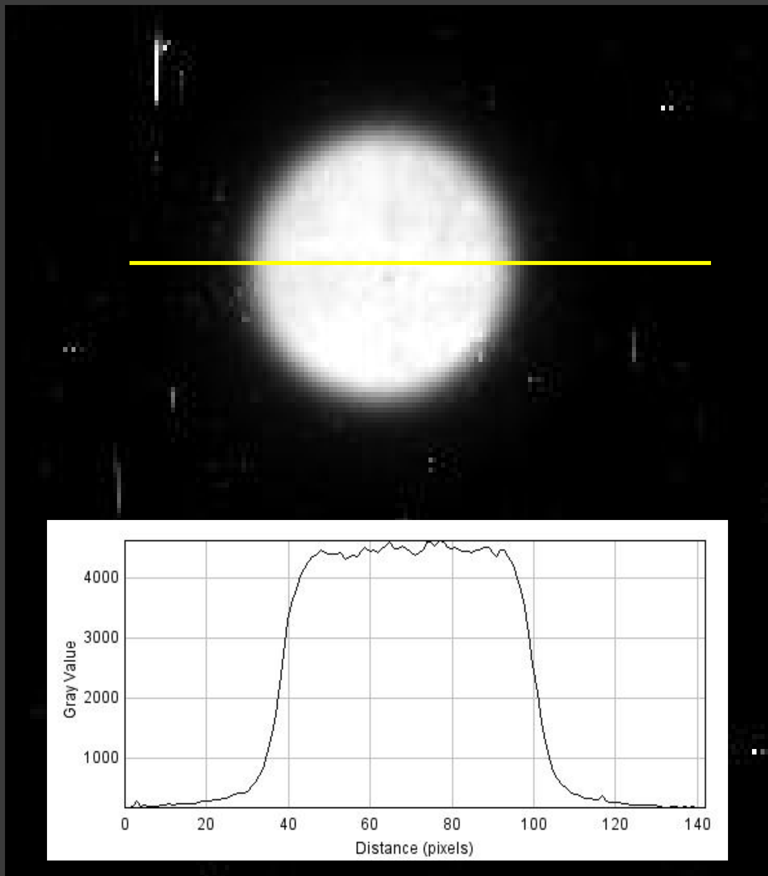
Same, re-pixilated

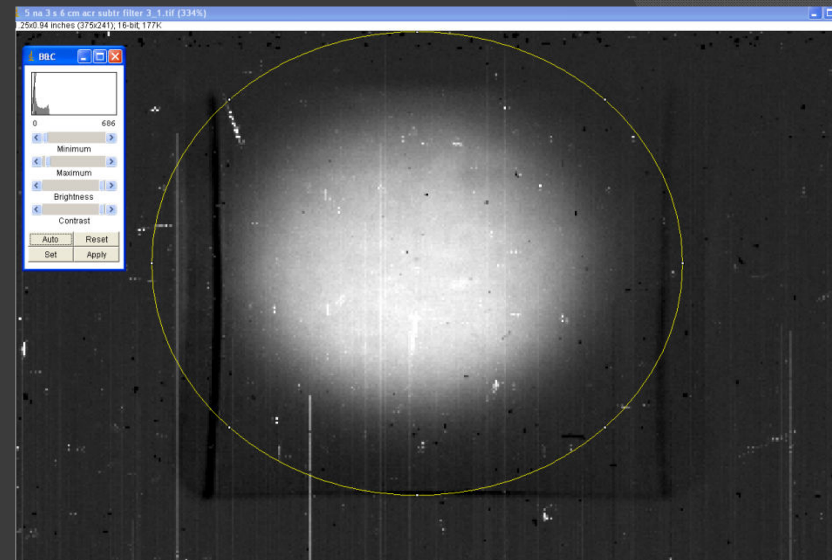


Same, ambient frame subtracted



Same, ambient frame subtracted, filtered





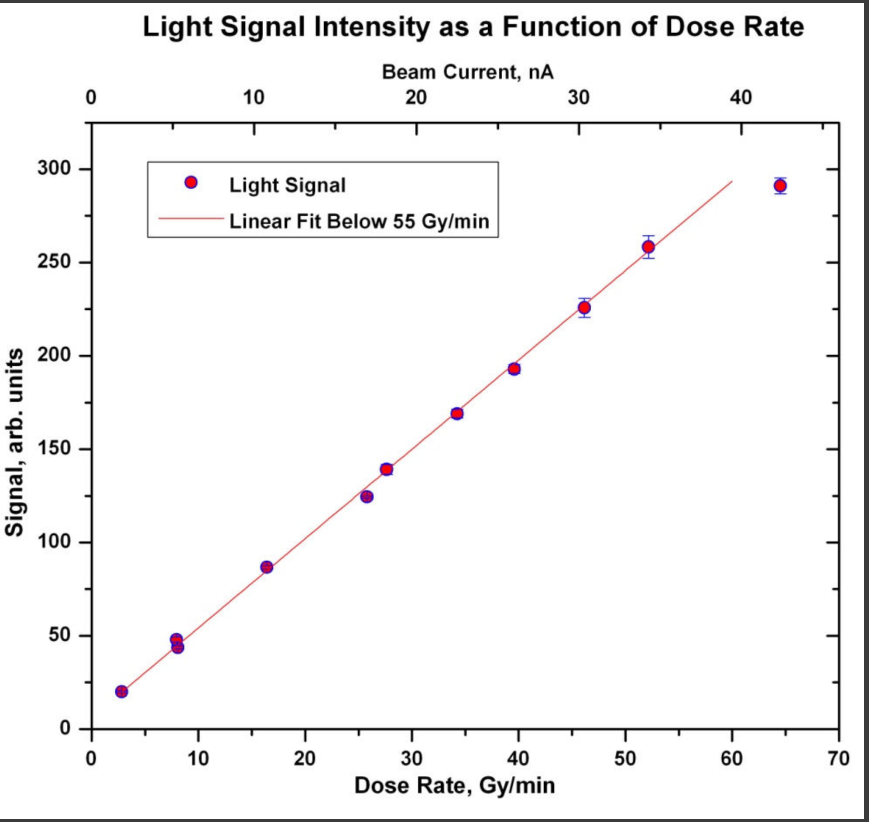
Beam image

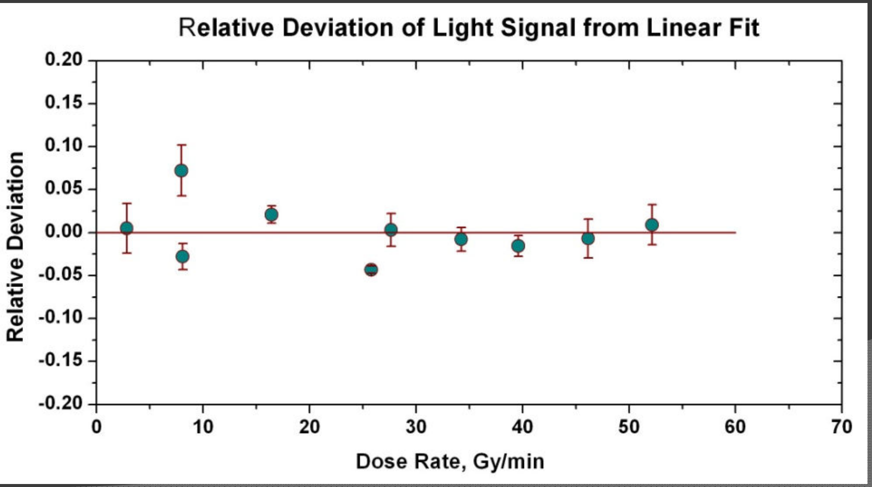
(50 mm collimator, 6 cm of acrylic)

Yellow line – integration area

ImageJ beam profile

(20 nA, ¾” collimator, 3 s exposure)


Light Signal Intensity as a Function of Dose Rate
Beam Current, nA
0
10
20
30
40
300
250
200
150
100
50
0
Signal, arb. units
Light Signal
Linear Fit Below 55 Gy/min
0
10
20
30
40
50
60
70
Dose Rate, Gy/min


Relative Deviation of Light Signal from Linear Fit
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
Relative Deviation
0
10
20
30
40
50
60
70
Dose Rate, Gy/min

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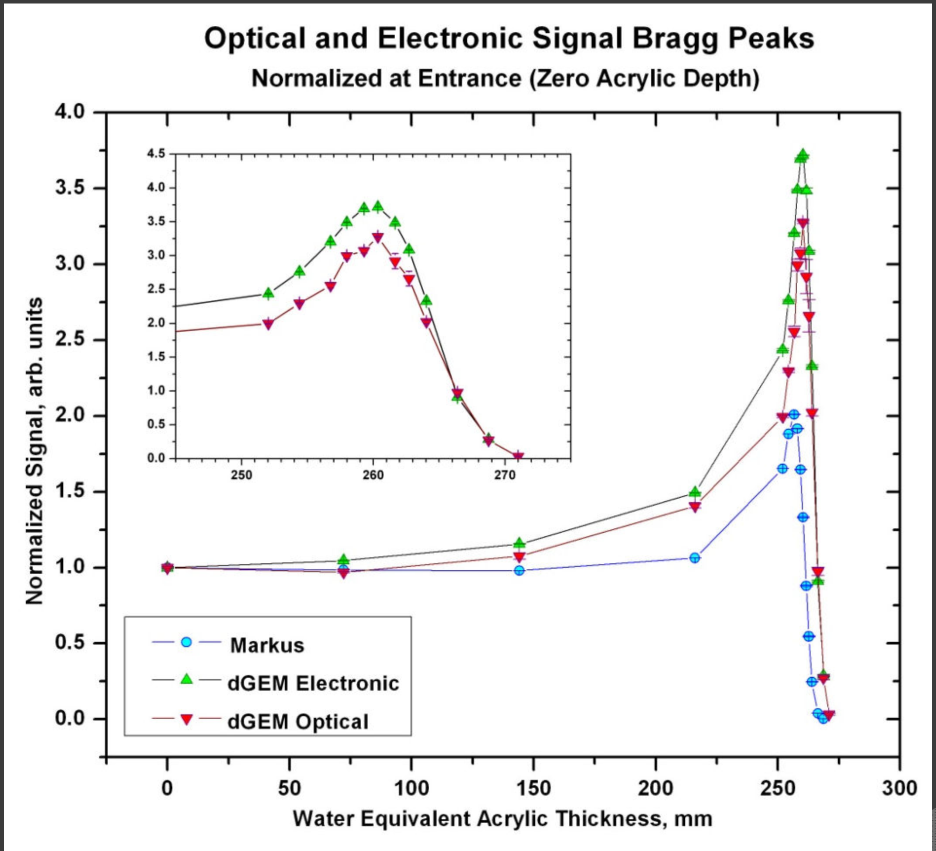
dGEM Energy Response – Bragg Peak



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Conclusions:

- We have developed a prototype detector system for two-dimensional dose imaging in hadron therapy based on double-GEM amplification structure, using either electronic or optical readout.
- In both modes, detectors exhibit linear dose rate response up to about 50 Gy/min and adequately reproduce the Bragg peak in depth-dose measurements.
- In electronic readout mode, the position resolution of 4 mm (single pixel) was observed. We expect that with multi-pad readout electrode with smaller pitch, position resolution of such detector can be significantly improved.
- In optical readout mode, the line spread function of the detector was found to have $\sigma<0.7$ mm. Position resolution in this mode also can be improved by using higher pixel count CCD camera.

- The GEM-based detectors are promising candidates for creation of two kinds of dosimetry systems:
  - one, with electronic readout, would be a fast (timing resolution in microsecond range), moderate spatial resolution (~1-2 mm, limited by the cost of electronics) dose imaging detector for scanning beam monitoring.
  - Such detector, with cross-strip readout, would also be a good candidate for low-rate applications, such as proton tomography.
  - Another detector system, with optical readout, would be a slower, moderately priced detector with sub-millimeter spatial resolution suitable for dose distribution verification and quality assurance measurements in hadron therapy. Timing resolution would be limited by light output and readout speeds (~ 30 ms with modern CCD cameras)