Image : UniversitatsKlinikum Heidelberg 2010

Particle Therapy Beam Diagnostics: Risks and Rewards for Industry

J Gordon, Pyramid Technical Consultants, Inc.

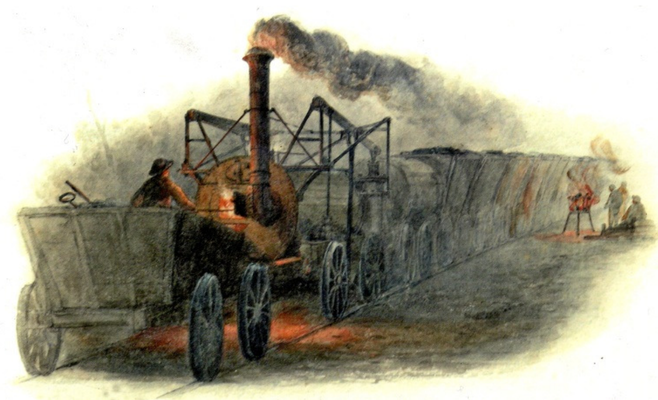
Overview

- Disclaimer
- Who are Pyramid?
- Particle Therapy Technology
- A view of the commercial market for Particle Therapy
- Beam Diagnostic Devices for Particle Therapy
- Ionization chamber developments
- Readout electronics: architecture and circuit topologies
- Acknowledgements

Disclaimer

Coming to GSI to talk about ion beam diagnostics is like:

-Taking coals to Newcastle



Attempting to say anything new about particle therapy or beam diagnostics to this audience is like:

- Teaching Grandmother to suck eggs

Some information sources

Bernie Gottschalk (Harvard Cyclotron Laboratory)
http://www.physics.harvard.edu/~gottschalk/
History, and all you will ever need to know about beam scattering.

Andrew Slesser
http://www.pitt.edu/~super1/lecture/lec32751/32751.pdf
History, and opinions on the relative merits of hadrons and of accelerator types

Andreas Peters (HIT)
http://heraeus-technology.desy.de/e8/e44866/PetersMedApplofAccelerators.pdf
Excellent recent (2009) overview of particle therapy technology, beam scanning.

Thomas De Laney and Hanne Kooy (eds)
Proton and Charged Particle Radiotherapy (2008) ISBN 978-0-7817-6552-7

Particle Therapy Cooperative Group
http://ptcog.web.psi.ch/
Many papers and statistics on particle therapy centres

Pyramid

Engineering company based in MA, USA. Formed 1986. Conveniently close to, MIT, Harvard and importantly, Mass General Hospital.

Supplier of sensor readout electronics, control systems and software to industrial, medical and research markets.

Background in beam scanning and dosimetry for semiconductor ion implantation led to opportunities in the particle therapy market.

Since 2004, supplier of scan control, dosimetry, software and beamline diagnostic devices to many of the major particle therapy equipment companies.

Radiation Therapy

Radiation therapy is one of the three primary methods for treating established tumours (the others are surgery and chemotherapy).
Doses are ten's of Gy, to kill tumours via DNA disruption. A 3 Gy whole body dose can be lethal, so precise targeting is vital (you must hit all of the tumour and as little as possible of surrounding healthy tissue). Particles offer a physically obvious advantage over photons due to the difference in the dose/depth curve.

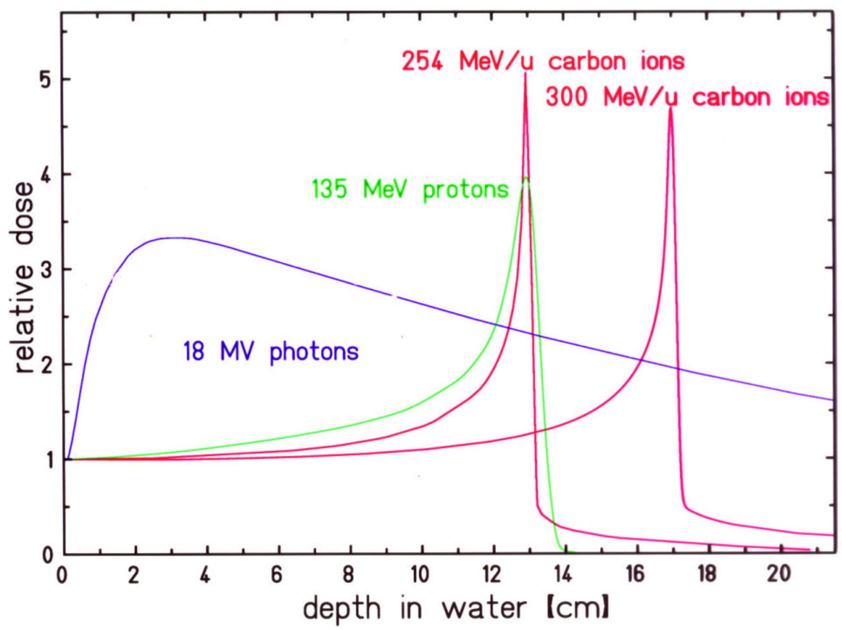


Image: A Peters

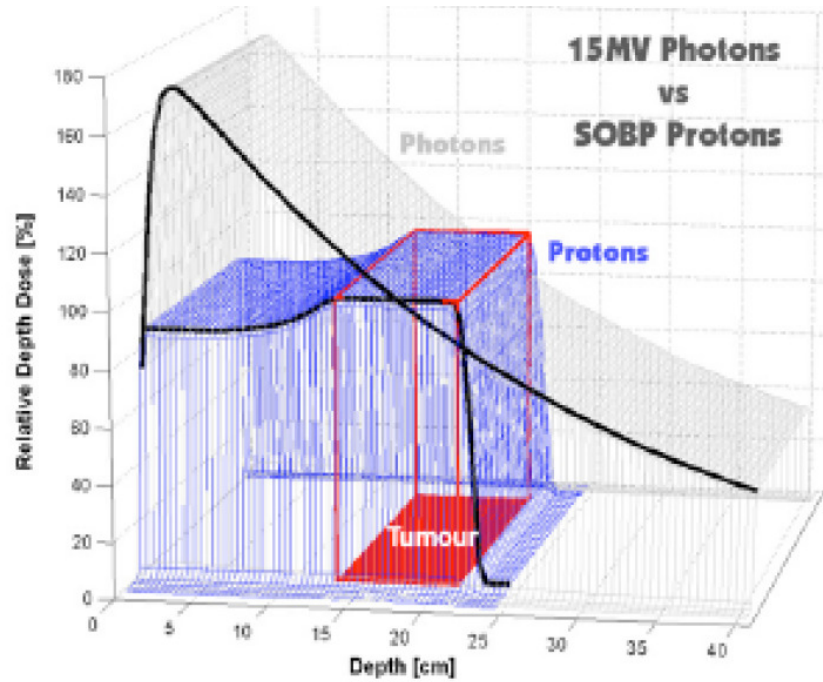


Image: Del Laney & Kooy

Photons vs Particles

So is everybody using particles?

Worldwide: one million patients per year (2004).
Used in 2/3 of cancer treatment plans.
50% of treatments are breast, prostate and lung.

Worldwide: about 90000 patients since initial trials in the 1950's.
Generally accepted for head, eye and spinal column tumours.
Often used for prostate.

Photons vs Particles

So why isn't everybody using particles? Look behind the covers ....

It's an accelerator lab! With physicists!

Rather like a big CT system. All fits in a single shielded room.

Particle Therapy Costs

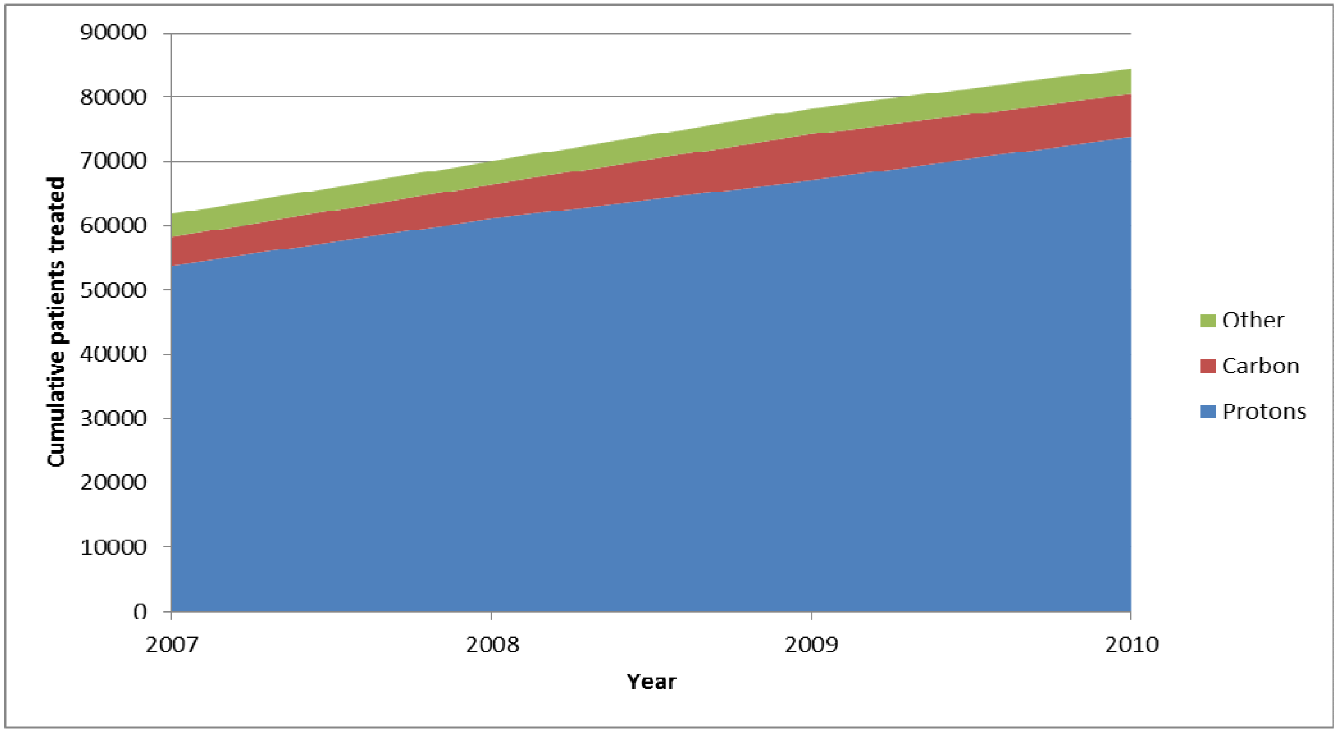
"How costly is particle therapy? Cost analysis of external beam radiotherapy with carbon-ions, protons and photons."
A Peeters et al, MAASTRO Clinic, Netherlands, Radiother. Oncol. 95.1(2010) 45-53.

Type of centre	Capital cost	Total annual costs	Cost per fraction (delivery)
Conventional	€ 23.4 million	€ 9.6 million	€ 233 (€ 190-407)
Proton	€ 94.9 million	€ 24.9 million	€ 743 (€ 578-1300)
Proton and carbon	€ 138.6 million	€ 36.7 million	€ 1128 (€ 877-1974)

It is not clear what patient throughput was assumed in the delivery cost.
Reimbursement rates in the US (2010) are $942 per fraction for "simple" plans and $1,233 for "complex" plans.

Particle Therapy Status

Data summarised from PTCOG website (Martin Jermann, PSI). Cumulative treatments in recent years.

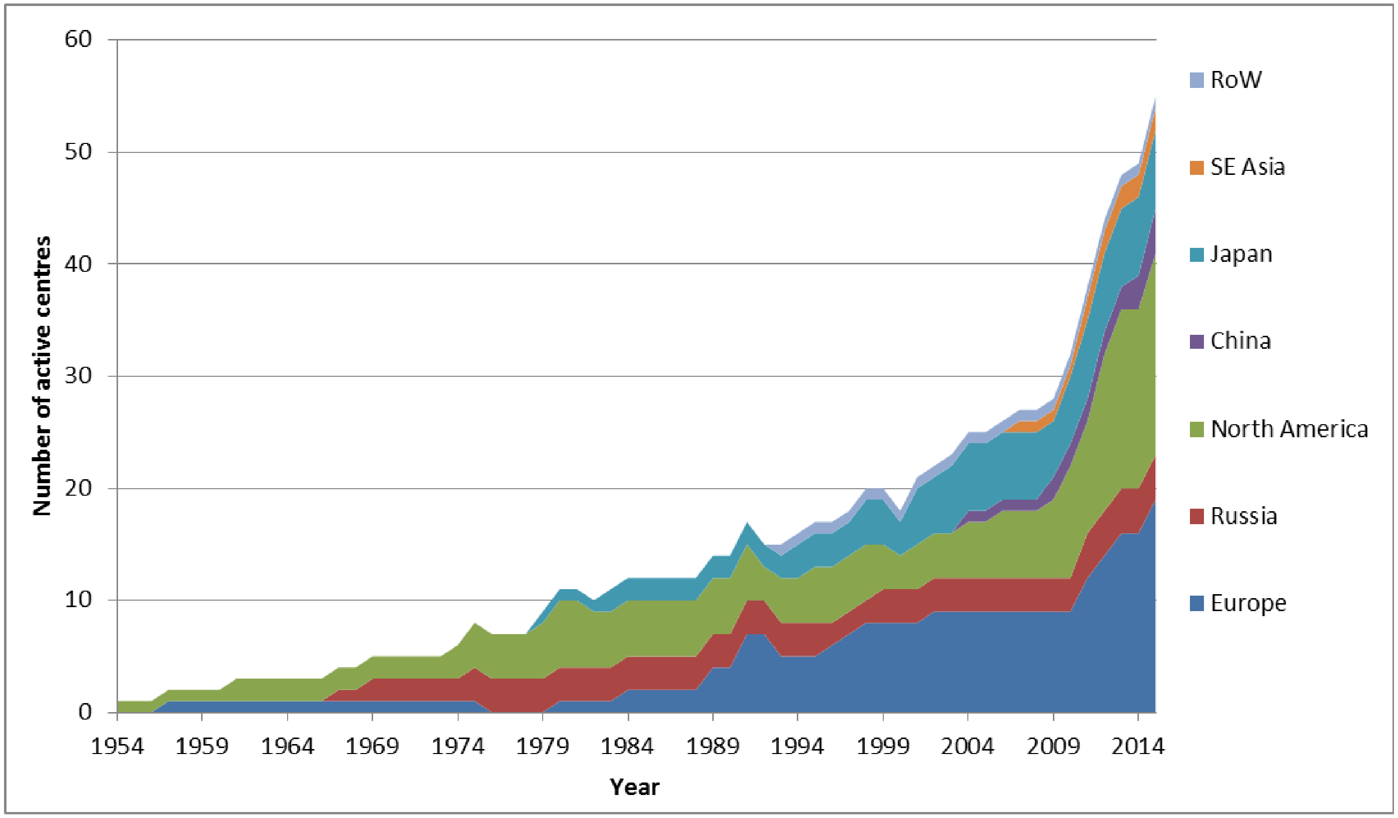


This averages to 200-300 patients per year but data includes many research facilities.
A busy centre like MGH handles 600 to 800 patients per year.

There is no evidence of recent increase in activity from this data, but ……….

Particle Therapy - Active Centres

We are in the middle of a modest boom, fueled by the emergence of commercial suppliers.

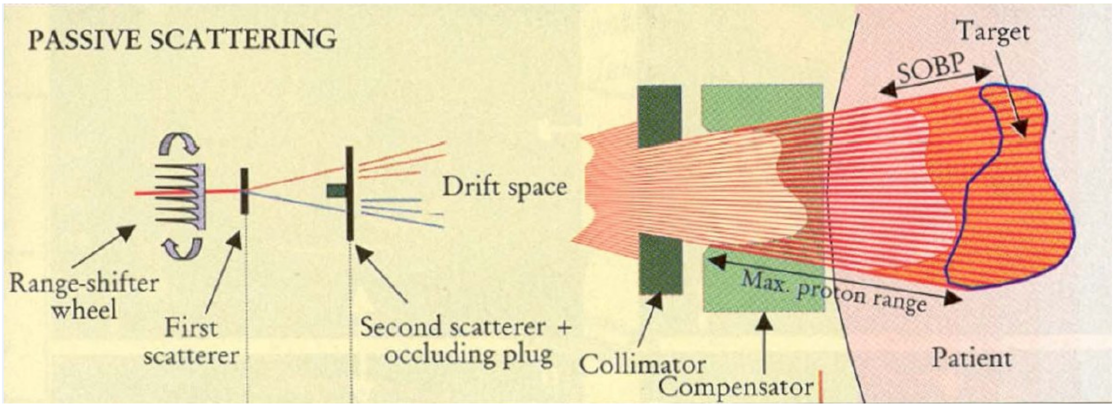


Data summarised from PTCOG website (Martin Jermann, PSI). Active particle therapy centres worldwide.

Particle Therapy Commercial Suppliers

Supplier	Particles	Accelerator	Nozzle	Notes
IBA	p^+ 230	Iso-cyclo, SC synchro-cyclo	Scattering & scanning	Largest customer base (20). Multiroom and compact systems. MGH.
Varian	p^+ 250	SC iso-cyclo	Scanning	Accel system.
Hitachi	p^+ 250	Synchrotron	Scattering & scanning	MD Anderson.
Siemens	p^+ 250, C^{6+} 430/u	Synchrotron	Scanning	Reducing commercial activity?
Optivus	p^+ 250	Synchrotron	Scattering	Loma Linda.
ProTom	p^+ 250/330	Synchrotron	Scanning	Lower capital cost objective.
Mevion	p^+ 250	SC synchro-cyclo	Scattering	Still River Systems. Single room, lower capital cost objective.

Technical Trends – Nozzles



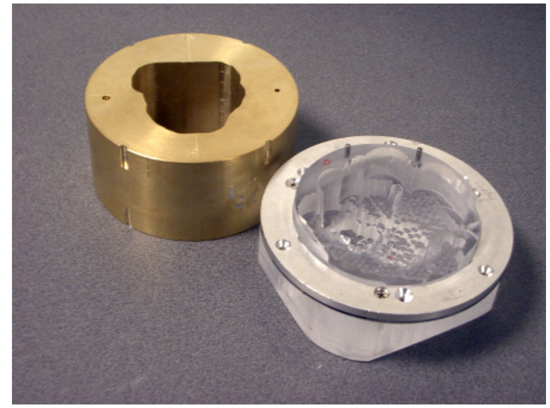


Image : B Gottschalk

Scattering

A system of lateral scatterers, energy degraders, apertures and range compensators produces a quasi-simultaneous irradiation of the whole tumor volume (like conventional radiotherapy).

Pro: Used for the vast majority of treatments to date.
Good compatibility with beam gating.
Relatively simple (human-friendly) dosimetry.

Con: Need for patient-specific collimators and range compensators.
Increased radiation background from beam interactions with scattering and degrading materials.

Technical Trends – Nozzles

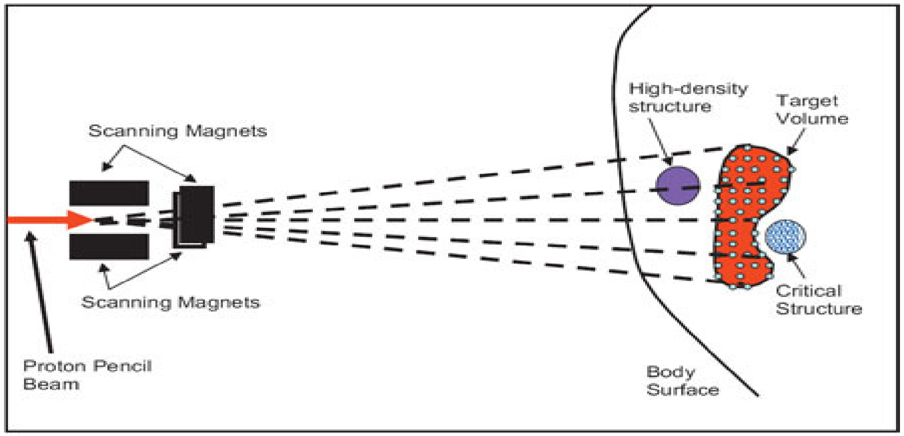


Image : MD Anderson

Pencil beam scanning has the market momentum at the present time.

Scanning (Pencil Beam, or Spot Scanning)

Energy and intensity control from the accelerator are combined with fast magnets in the nozzle (or just upstream) to permit the tumour to be "painted" directly.

Pro: Minimal wasted beam, and thus lower background radiation.
Able to paint arbitrary shapes (such as Albert Einstein) in the lateral axes.
Relatively simple (human-friendly) dosimetry.
No patient-specific hardware.

Con: Higher initial cost – scan magnets and power amplifiers.
More demanding dosimetry, too fast for human intervention.

Technical Trends – Accelerators

- **Isochronous cyclotrons** (resistive or superconducting).
  Pro: Continuous beam, plenty of beam current, fairly compact, proven.
  Con: Need energy degrader/selector, activation, carbon inconvenient.

Image IBA

- **Synchrocyclotrons** (superconducting)
  Pro: Very compact, even single room.
  Con: Pulsed beam (kHz)

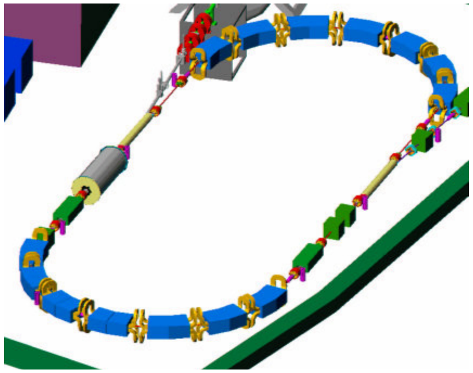
Image: Mevion

- **Synchrotrons**
  Pro: Variable energy, carbon more convenient, less activation and background.
  Con: Fill/ramp/spill cycle (deadtime). More floorspace (but compact designs emerging)

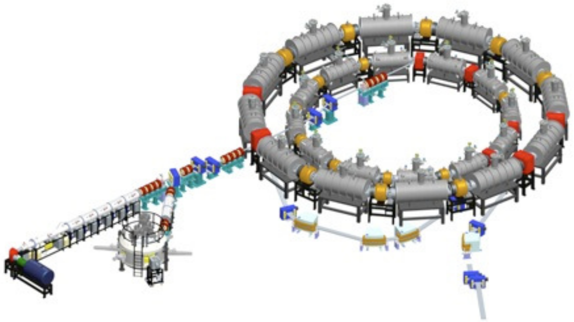
Image ProTom Intl

Technical Trends – Accelerators

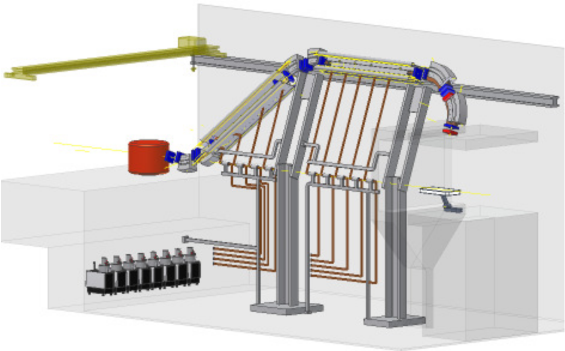
- **Rapid-cycling synchrotron**
  Proposed for fast energy changes (BNL).
  Dosimetry becomes more difficult.



- **Non-scaling FFAG**
  Proposed as combining the best features of cyclotrons and synchrotrons (BASROC). But needs to demonstrate real (medical or economic) advantage over them.

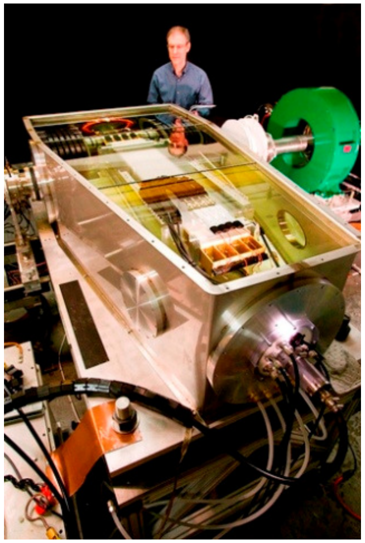


- **Compact proton linac**
  Proposed for reduced mechanical costs and fast energy changes (TERA/CERN).
  An engineering challenge! Dosimetry becomes more difficult. Real (medical or cost) advantage over cyclotrons and synchrotrons?



Technical Trends – Accelerators

- **Laser acceleration**
  Possible highly compact accelerator for the future? Still have to solve rep rate, energy spread, transport and beam delivery.



- **Dielectric wall DC accelerator**
  Possible highly compact accelerator for the future (LLNL)?
  An engineering challenge!

The future of particle therapy?

It works. Cost is the issue, especially in the current world economy.

Is Proton Therapy On Pres. Obama's Health-Care Hatchet List?

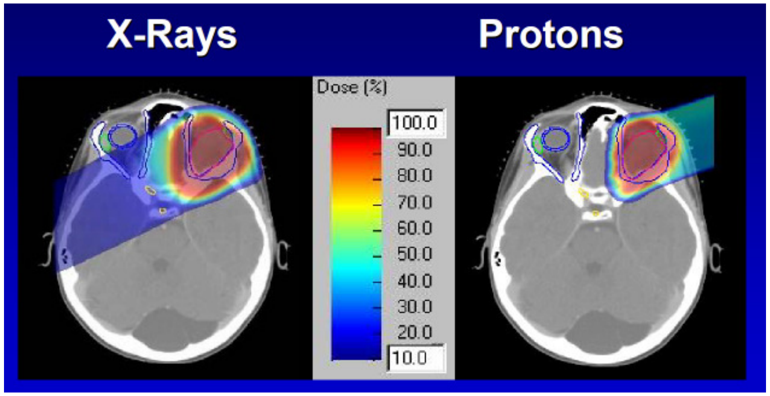
08 July 2009 Filed under Beam Radiation, PCa Treatments, Prostate Cancer, Proton, Side Effects Posted by jacquie strax » No Comments

Proton beam therapy for prostate cancer, a treatment that attracts more than an average numbers of engineers, scientists and pilots, is coming under intense scrutiny from reporters who expect it to be questioned by the Obama adminstration's health-care reform team.

Some positive indications:

- There is some concern about long-term outcomes in conventional radiotherapy, due to damage to healthy tissue.
- It is possible that the number of fractions per treatment can be reduced considerably if particles are fully exploited. This is evidenced by Japanese practice using carbon.
- Several research groups and manufacturers are looking for ways to drive down the capital cost.
- Compared to the regular procession of new cures for cancer, particle therapy is very unsubtle (locate the tumour – hit it, and only it, with a lethal radiation dose)

A non-financial, non-technical viewpoint



Particle therapy can be the overwhelming treatment of choice in some cases.

Beam Diagnostics

The ion accelerator hidden behind the PT centre wall requires the typical collection of beam diagnostics:

Faraday cups (injection),
Profile grids (injection),
DC and AC beam transformers (injection and rings),
Phase probes (injection),
Capacitive beam position monitors (rings),
Scintillation screens (transfer lines),
*Ion chambers (transfer lines and **dosimetry**),*
*Multi-electrode ion chambers and proportional chambers (transfer lines and **dosimetry**),*
Multilayer Faraday collectors (energy verification), *etc etc*

We'll look specifically at some of the dosimetry diagnostics. These are the most important because they measure, regulate and interlock the dose delivered to the patient.

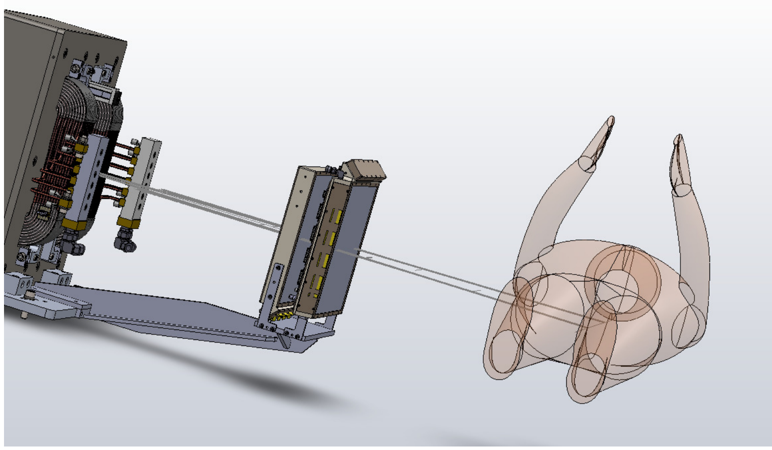
A key challenge for the future of commercial particle therapy is to hide all this interesting physics behind a protective wall of automation and software.

Beam Ready

Pencil Beam Scanning Dosimetry

Measure the beam current, position and shape for each position in the irradiation, in real time, for each delivered spot or line. Any deviation from the pre-determined map must automatically abort the treatment.

Ion chambers are favoured for their robustness and stability.
The safety analysis for a given system will dictate the number of chambers that are required for safety redundancy. Typically there must be not less than two fully independent chambers measuring beam current, and some redundant means of determining beam spot position.
The more chambers are added, the more the beam is scattered laterally. Each chamber must thus produce the lowest practicable scattering.



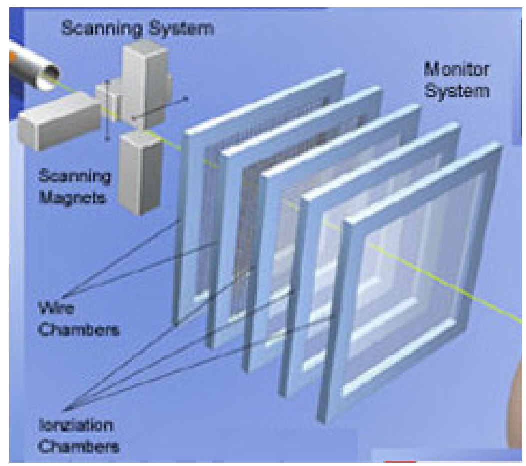


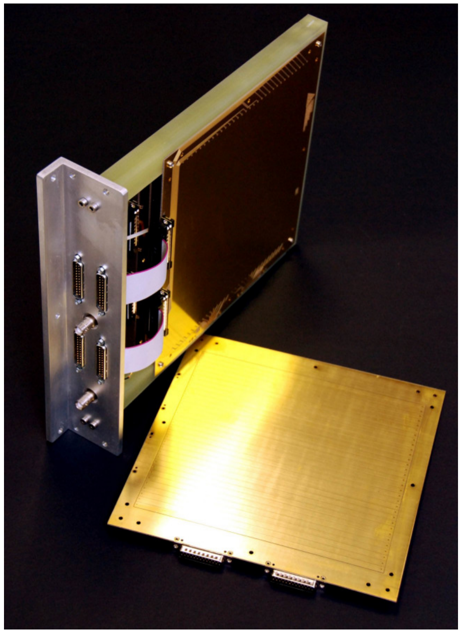
Image : Siemens Healthcare

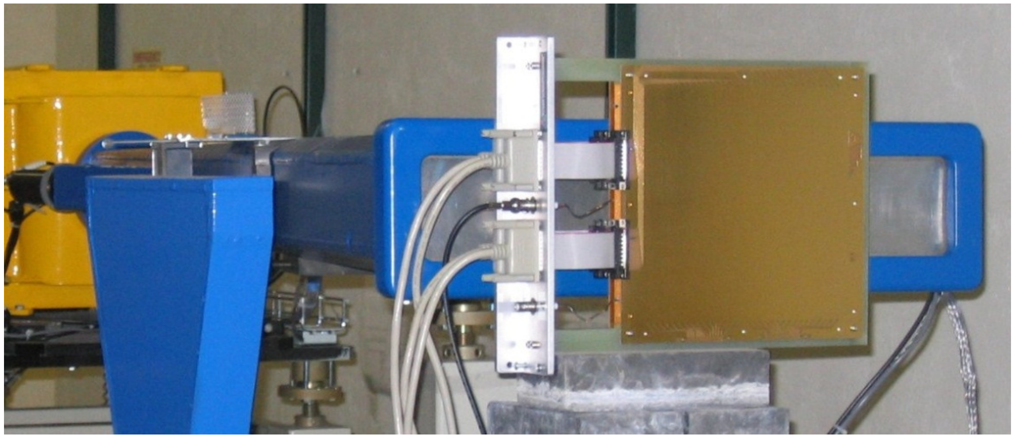
Ion chamber development at Pyramid

Our objective is to develop precise and reliable ion chambers and readout for beam tracking that can be manufactured with excellent repeatability, using standard processes and components.

Generation 1

Proof of concept using standard PCB fabrication and thin (0.152 mm FR4 and 17 µm gold-flashed copper) electrodes. Two 32-strip cathodes and one double-sided anode. 20 x 20 cm active area. Atmospheric fill gas.

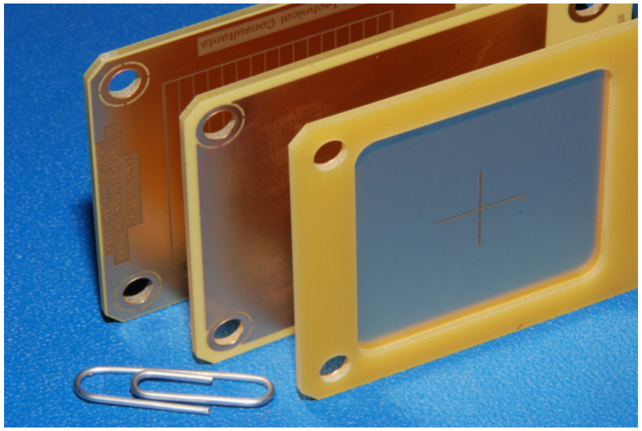




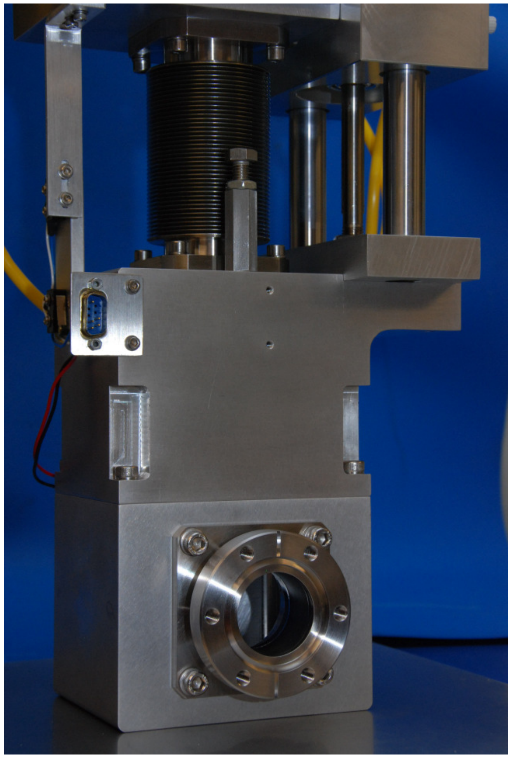
Stable and reliable, but as expected, too much scattering for dosimetry.

Ion chamber development at Pyramid

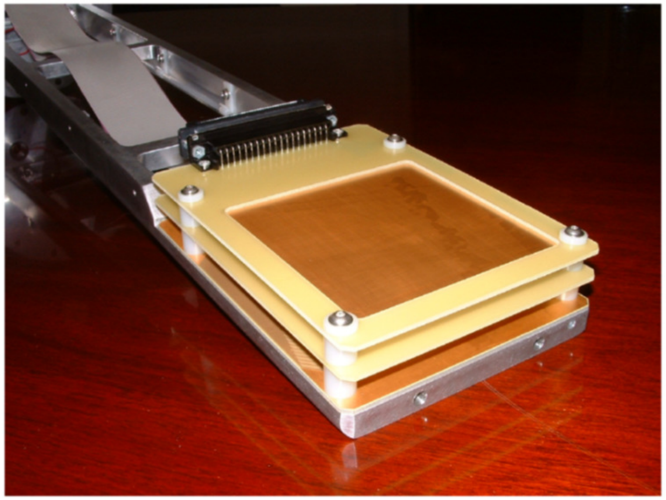
The generation 1 design proved excellent for transfer line beam position monitoring, however, where the diagnostic does not have to remain in the beam.



3.8 x 3.8 cm,
16 by 16 strips.



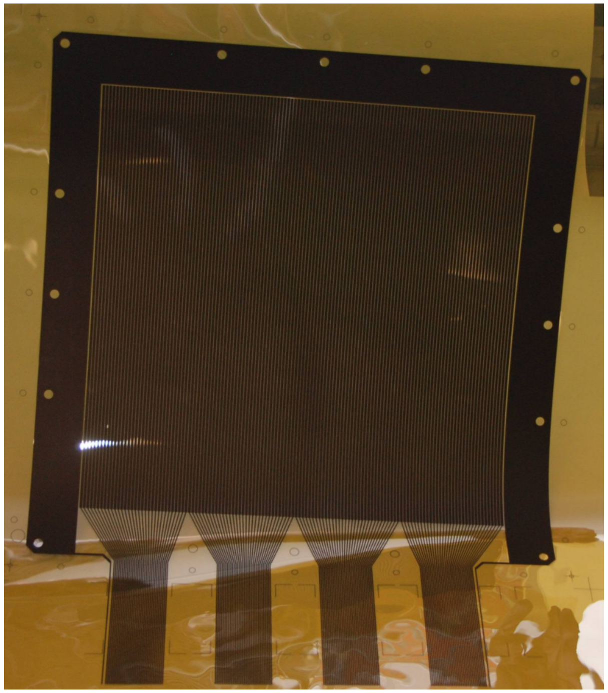
7.6 x 7.6 cm,
32 by 32 strips.



Ion chamber development at Pyramid

Generation 3

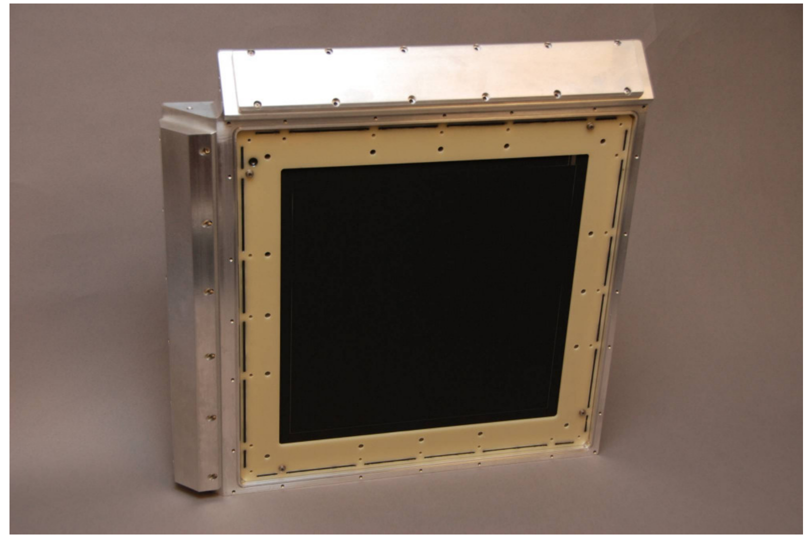
Full-function production chamber for pencil beam scanning dosimetry. Design objective: for typical nozzle geometry and 50 MeV proton beams, add no more than 1mm spread to a 1 cm nominal beam spot at isocentre, with two chambers in the beam. Carbon ink electrodes (9 µm) printed onto Kapton (25 µm); bulk resistance kapton anodes. Total water equivalent thickness < 250 µm. Two 128 strip cathodes, one integral plane cathode, 25 x 25 cm active area.



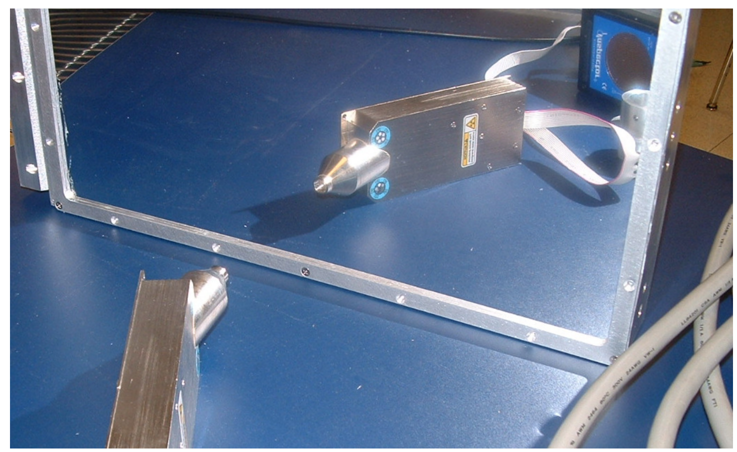
Cathode planes prior to assembly.

Ion chamber development at Pyramid

Generation 3



Calibrate for gain uniformity and stability using a miniature emission-stabilised X-ray gun (mounted on a precision table).



Ion chamber development at Pyramid

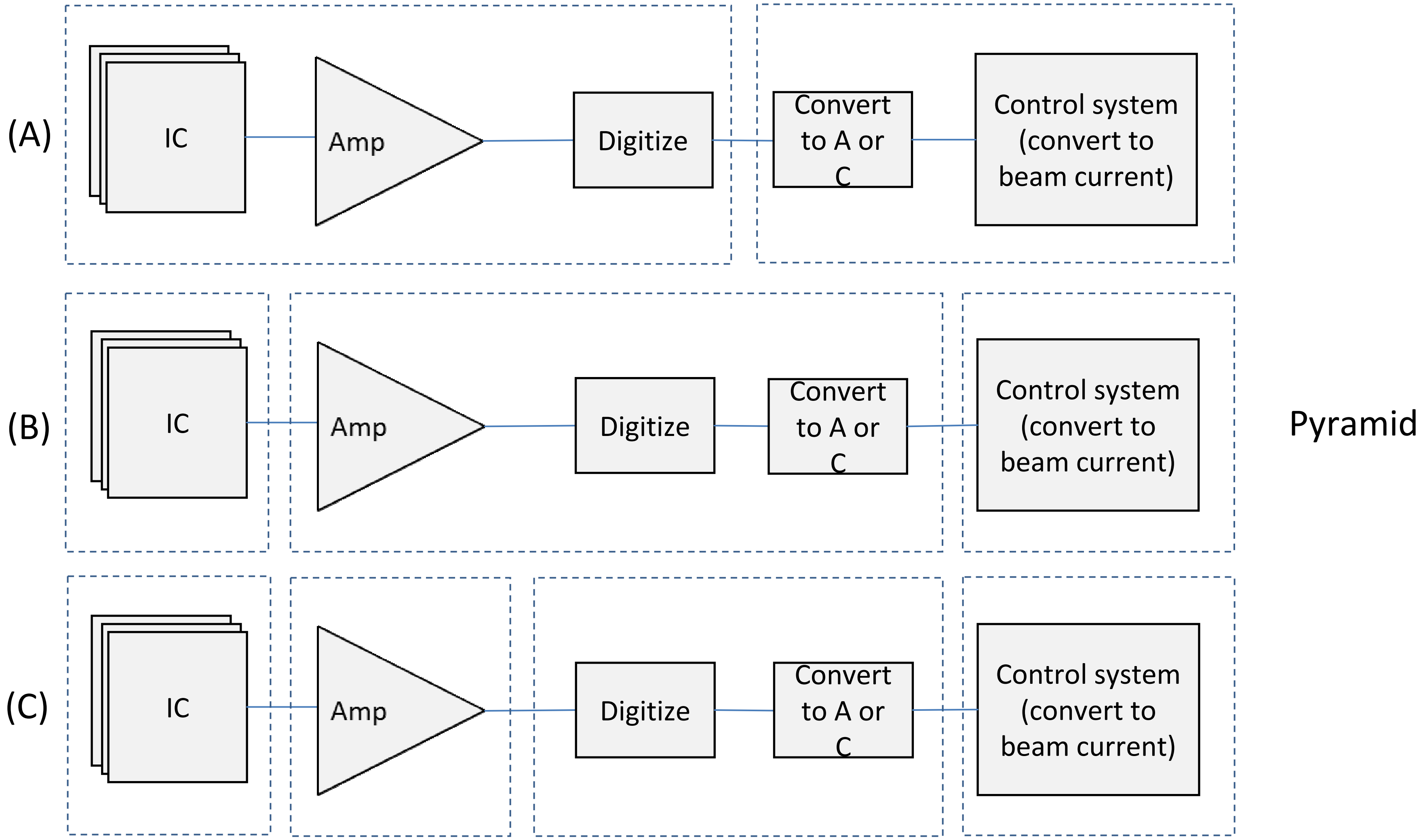
Generation 4

In development.
Design objective : Total water equivalent thickness ≈ 100 µm.
Two 128 strip cathodes, one integral plane cathode, 25 x 25 cm active area.

Optimisation of gas fill, gap and operating voltage for best compromise of
-Sensitivity
-Uniformity
-Recombination (upper current density limit)
-Stability in operation
-Immunity to environmental changes

Ion chamber readout – system architectures

Tradeoffs: electrical noise immunity – risk of radiation damage - serviceability.



Ion chamber readout – some circuit topologies

I-V converter (OP2177, AD8512) – F3200E, I128 integral input

Dynamic range with 200 µsec effective integration down to about 500 pA (3 sigma, 1M feedback), loaded.
Excellent accuracy (built-in precision calibrator).
Fast digitization with digital averaging allows configurable effective increase in integration time.
Continuous measurement – OK for beam current dosimetry

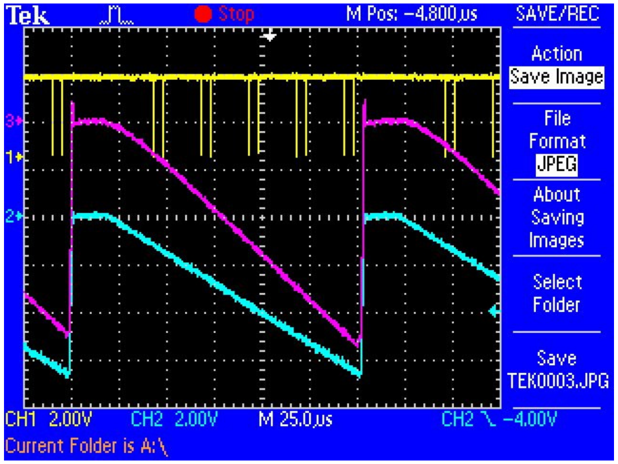
Gated integrator (IVC102) – I3200

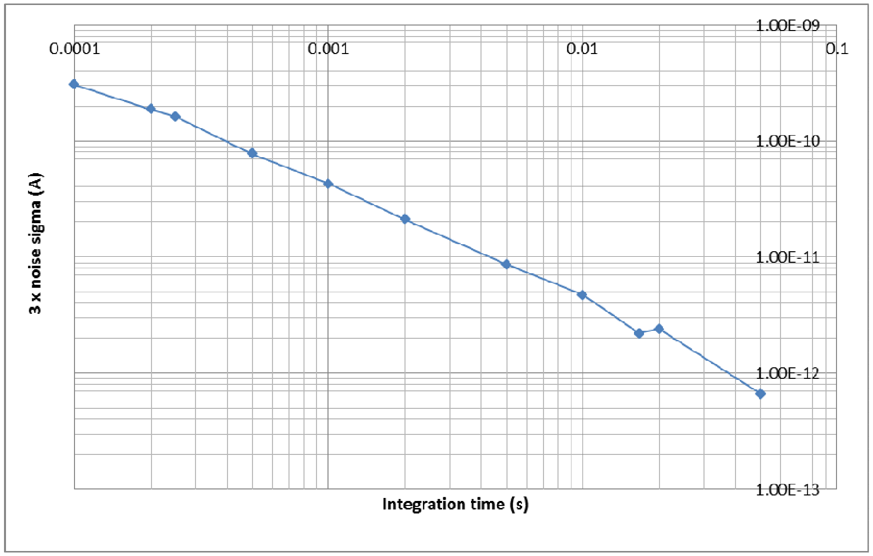
Dynamic range with 200 µsec integration in use down to about 160 pA (30 fC). loaded.
Good accuracy (built-in precision calibrator).
Deadtime during resets – unsuitable for beam current dosimetry, good for dosimetry position readout.

Charge to digital converter (ADAS1128) - I128 strip inputs

Dynamic range similar to I3200.
Good accuracy (using built-in precision calibrator).
Continuous measurement (resets do not interrupt integration).
Very high channel count.

Ion chamber readout – I3200





Widely used for transfer line BPM readout and dosimetry position tracking IC readout.

Thirty-two parallel integrator channels.

Sixteen parallel ADCs (all channels converted in 4 usec).

Integrated calibration current source.

Ion chamber readout – I128

Designed for dosimetry IC readout (current and position).

128 parallel integrator/digitizer channels.

On-board buffer memory and data processing.

Single I-V converter channel for integral plane readout.

Integrated calibration current source.

Integrated HV supply with loopback verification.

Integrated safety interlock features.

The Future Challenge

Particle therapy dosimetry detector and readout system for scanned beams.

-Uniform contiguous active area (25 x 25 cm or greater)
-Negligible lateral scattering (< 100 µm water equivalent thickness)
-Excellent stability and robustness (10 years of beam exposure)
-Rapid response time (signal collected and processed in < 10 µsec)
-Dynamic range sufficient for fast pulsed beam systems (up to 1 µA beam)
-Position resolution (peak centroid and shape parameter recovery better than 0.1 mm both axes). Maybe 2D sensing
-Predictable and highly consistent response f(beam current), f(beam current density), f(beam energy), f(beam ion species)
-Simple to cross calibrate with reference dosimetry standards
-Insensitive to environmental conditions (temperature, pressure, humidty)
-Good radiation hardness in electronics
-Simple to install, mechanically robust, tolerant to gantry rotation, no servicing requirement

and ……… ……………… Reasonable cost !

Acknowledgements

- My colleagues at Pyramid.
- Jay Flanz (MGH) for encouragement, guidance and many opportunities.
- Andreas Peters (HIT) for his interest and this invitation to talk.
- Peter Strehl (NPT) for many interesting conversations.
- Our customers in the particle therapy community.