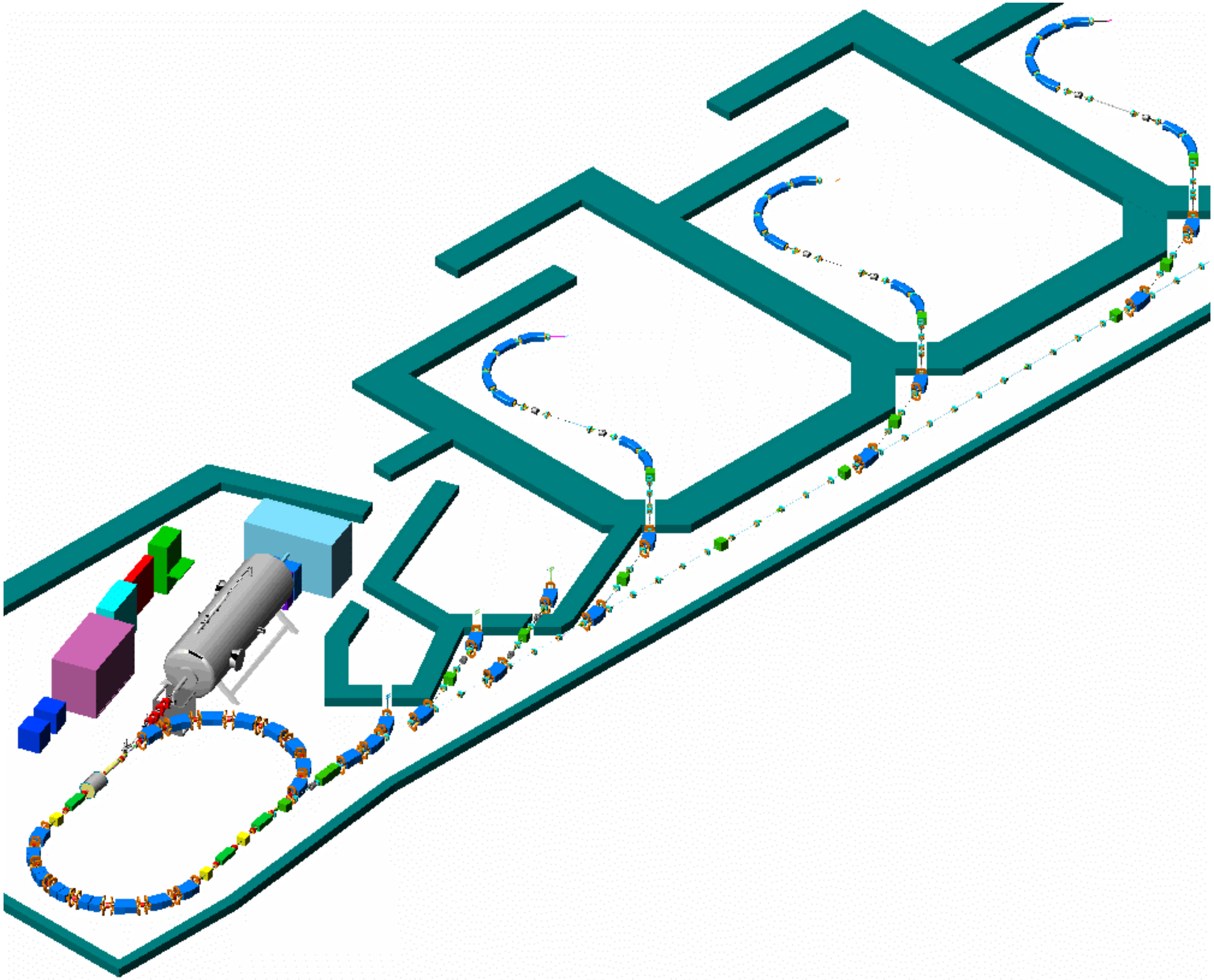
Proton Therapy & Proton Imaging

Steve Peggs, BNL



Contents

Proton Therapy

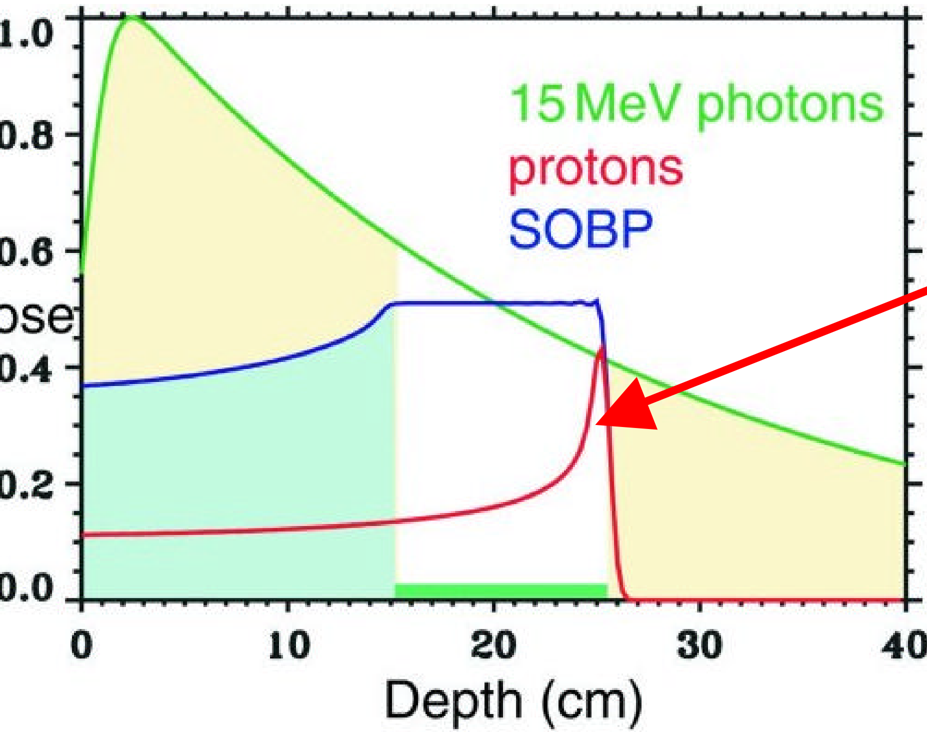
- Why protons? Why now? Where?
- Precision 3-D multi-field irradiation of cancerous tumors

Proton Imaging

- Proton driven PET
- Proton CT
- Transient devices: PRAD movies
- Periodic CT = pCT + PRAD ??

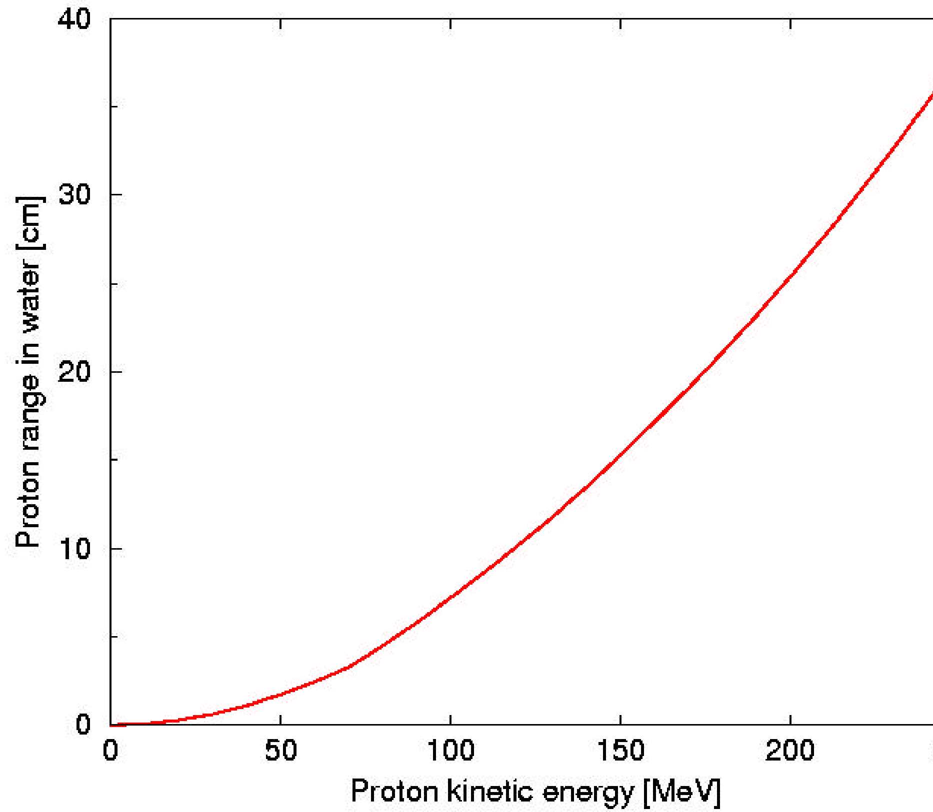
Why protons? Why now? Where?

Protons are much better than X-rays



Most dose is deposited in the sharp "Bragg Peak", with no dose beyond

Scan the energy to make a Spread Out Bragg Peak (SOBP) that spans the tumor

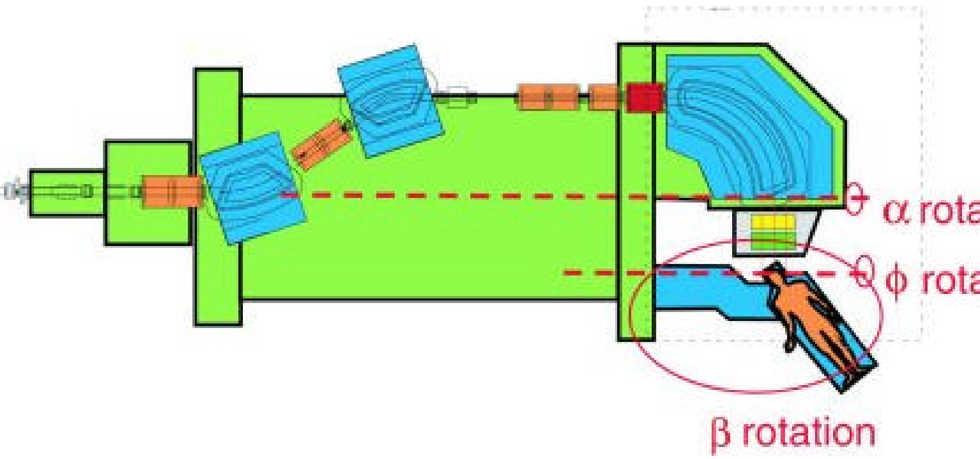


Conventional X-ray gantries are "small"

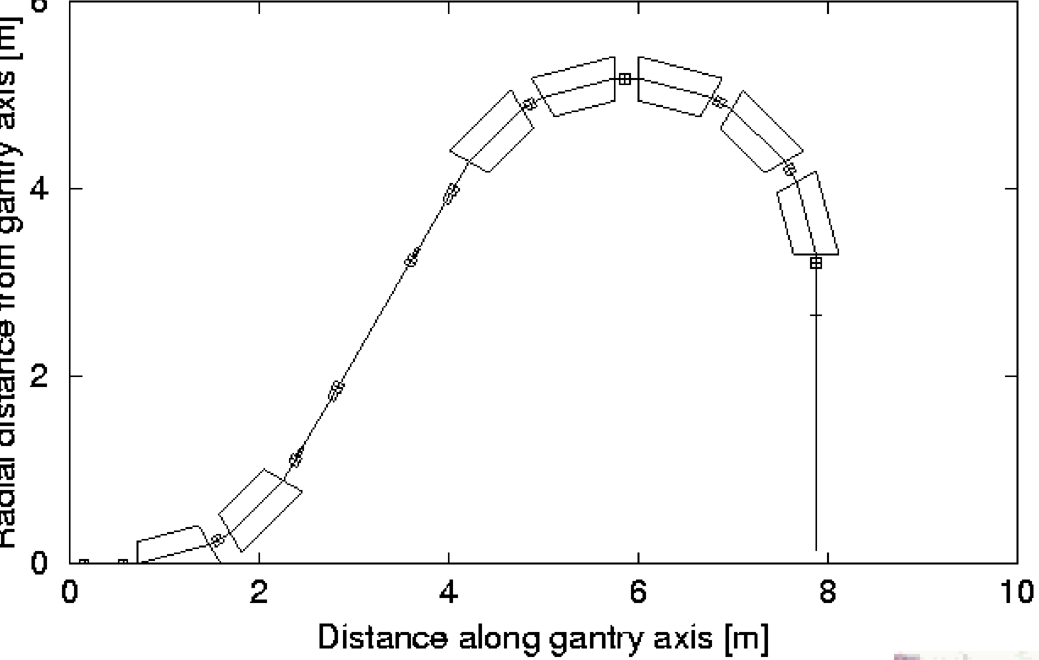
Almost all of it is visible in this photograph!

Proton gantries appear similar to the patient

But there is a lot more "behind the wall"



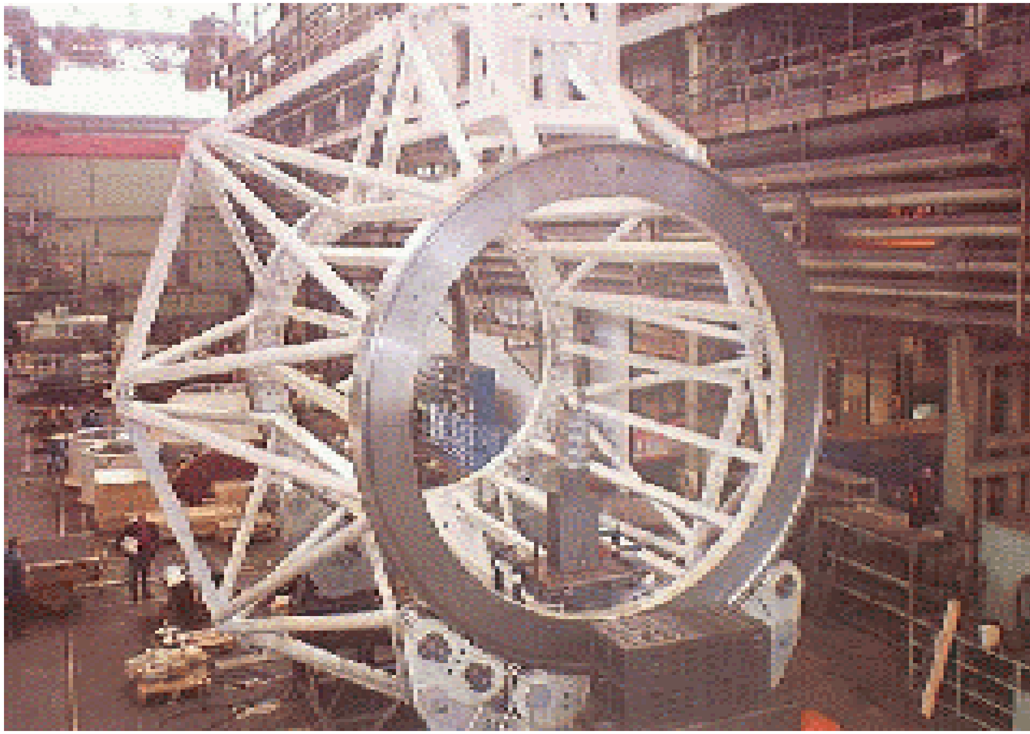
Paul Scherrer Institute (PSI), Zurich

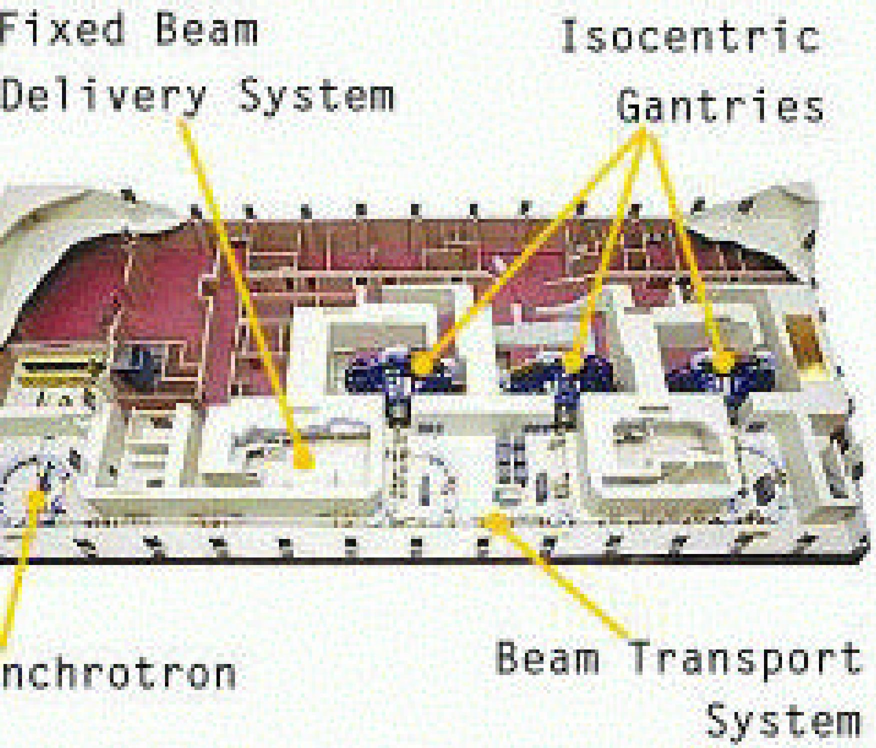


It's much harder to bend 250 MeV protons

And the strong-back to hold 1 mm tolerances is formidable

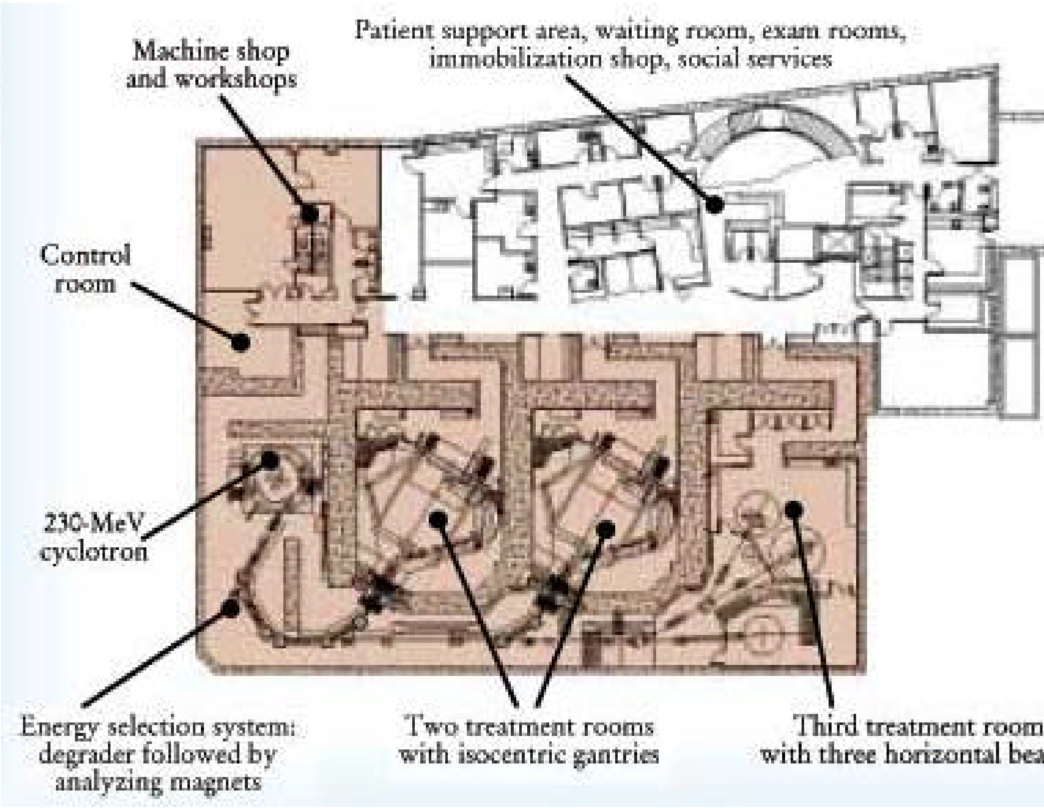
Massachusetts General Hospital (MGH)





Loma Linda (California)

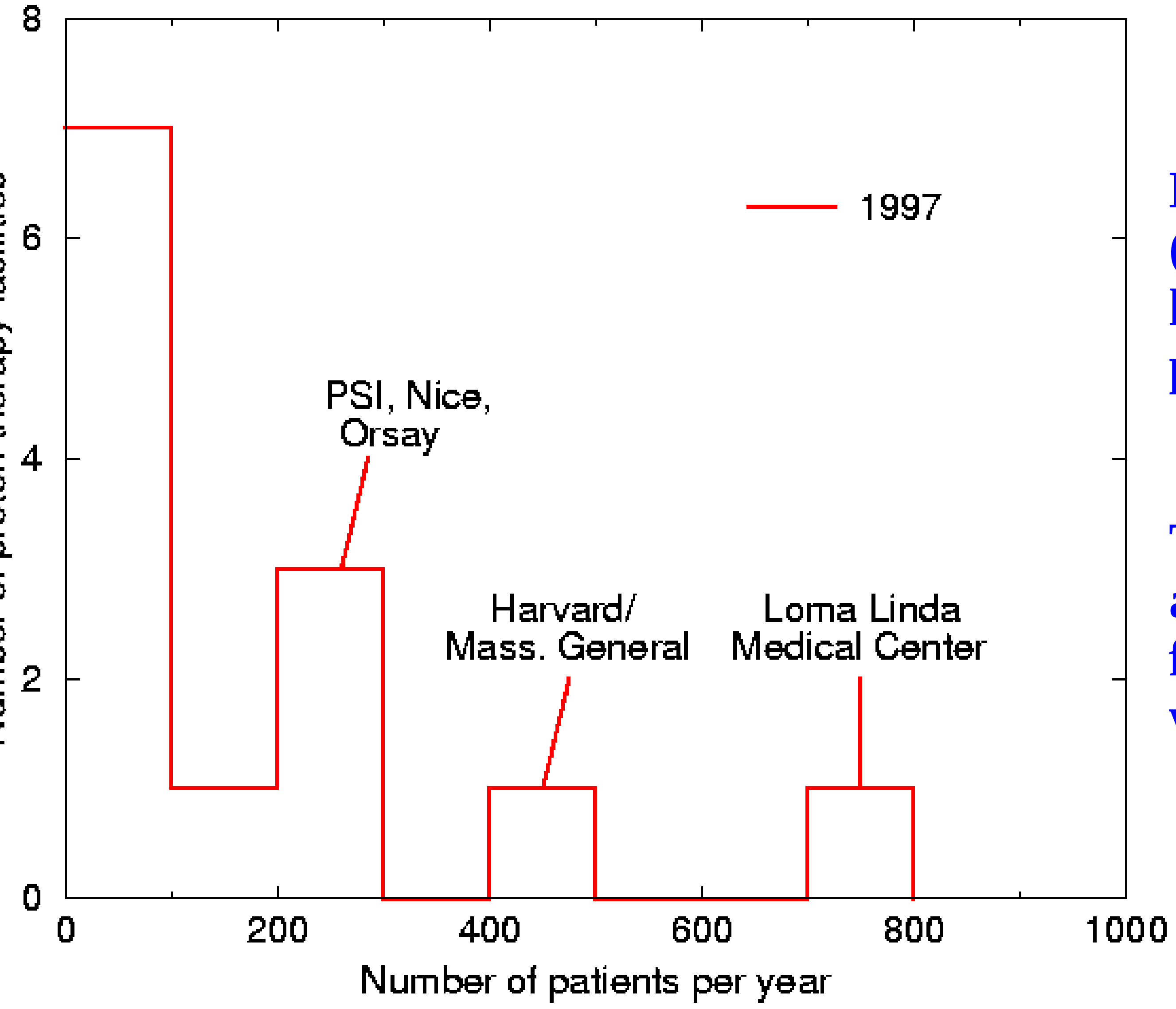
- synchrotron source
- built/commissioned at Fermilab
- world leading patient throughput



MGH (Boston)

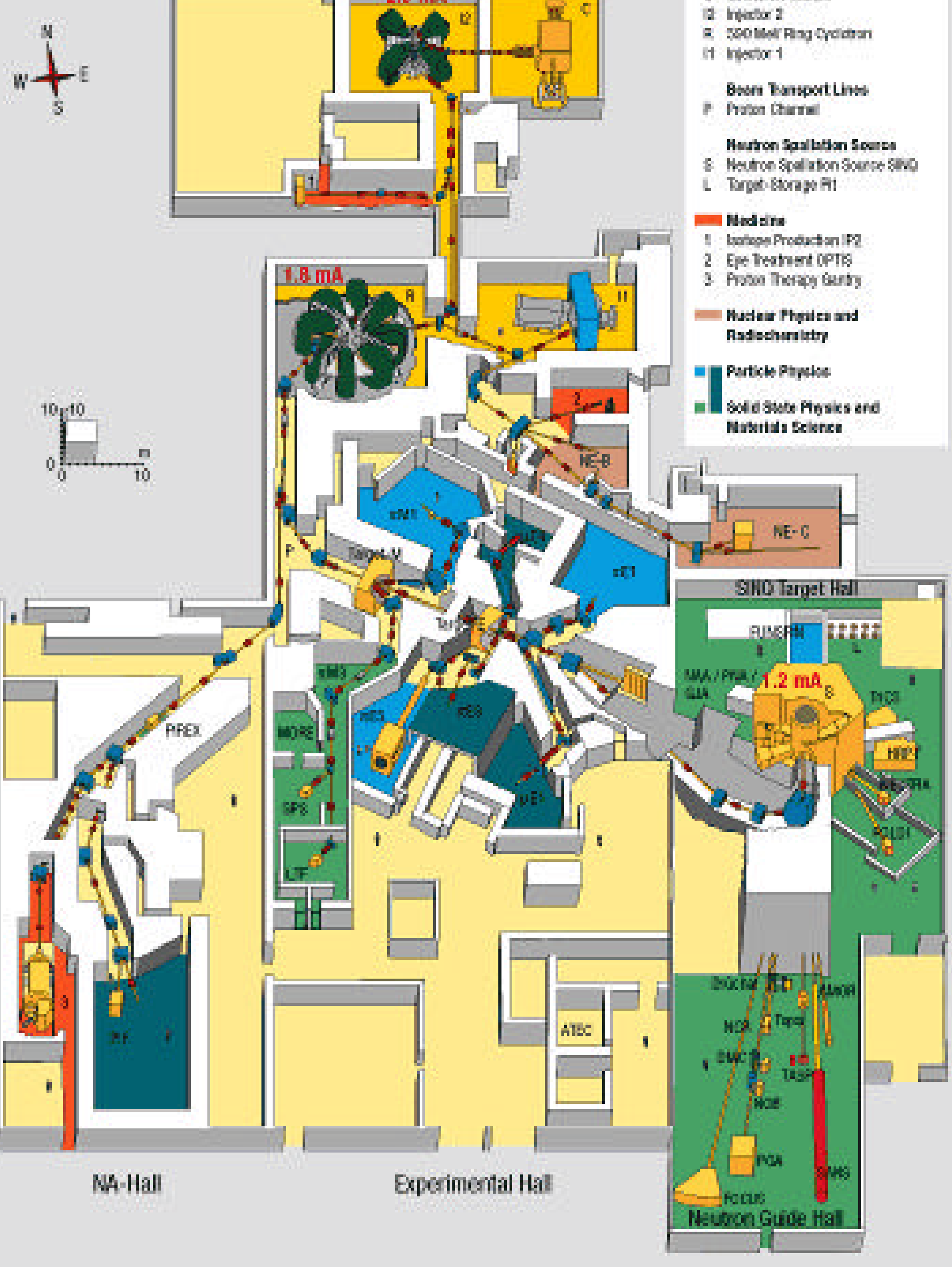
- cyclotron source (IBA)
- 1st patient Nov 2001
- coming up to speed

High and low patient throughput



Loma Linda and MGH (hospital based facilities) lead the world in high patient throughput

The state-of-the-art is also being pushed in facilities at national labs with low throughput



PSI (Zurich) (left)

- cyclotron source
- part of a national lab
- upgrade in progress
- low throughput, high tech
- new facility in progress

GSI (Darmstadt) (not shown)

- synchrotron
- national lab
- Carbon-12
- new facility at Heidelberg?

			Date	Patient Total	Total
Moscow	Russia	p	1969	3414	June-01
St. Petersburg	Russia	p	1975	1029	June-98
Chiba	Japan	p	1979	133	Apr-00
PSI (72 MeV)	Switzerland	p	1984	3360	July-00
Dubna	Russia	p	1987	88	May-01
Uppsala	Sweden	p	1989	236	June-00
Clatterbridge	England	p	1989	1033	Dec-00
Loma Linda, Cal.	USA	p	1990	6174	June-01
Nice	France	p	1991	1590	June-00
Orsay	France	p	1991	1894	Jan-01
N.A.C.	South Africa	p	1993	398	June-01
MPRI, Indiana	USA	p	1993	34	Dec-99
UCSF - CNL, Cal.	USA	p	1994	284	June-00
HIMAC, Chiba	Japan	ion	1994	917	June-01
TRIUMF	Canada	p	1995	57	June-00
PSI (200 MeV)	Switzerland	p	1996	72	Dec-00
GSI Darmstadt	Germany	ion	1997	84	June-01
Berlin	Germany	p	1998	166	Dec-00
NCC, Kashiwa	Japan	p	1998	75	May-01
HARIMAC, Hyogo	Japan	p, (ion)	2001	1	June-01
INFN-LNS, Catania	Italy	p	2001		
NPTC - MGH, Mass.	USA	p	2001		
NAC, Faure	South Africa	p	2001		
Tsukuba	Japan	p	2001		
Wakasa Bay	Japan		2002		
Bratislava	Slovakia	p, ion	2003		
IMP, Lanzhou	China	C-Ar ion	2003		
Shizuoka	Japan		2003		
Rinecker, Munich	Germany	p	2003		

The last decade has seen much construction activity

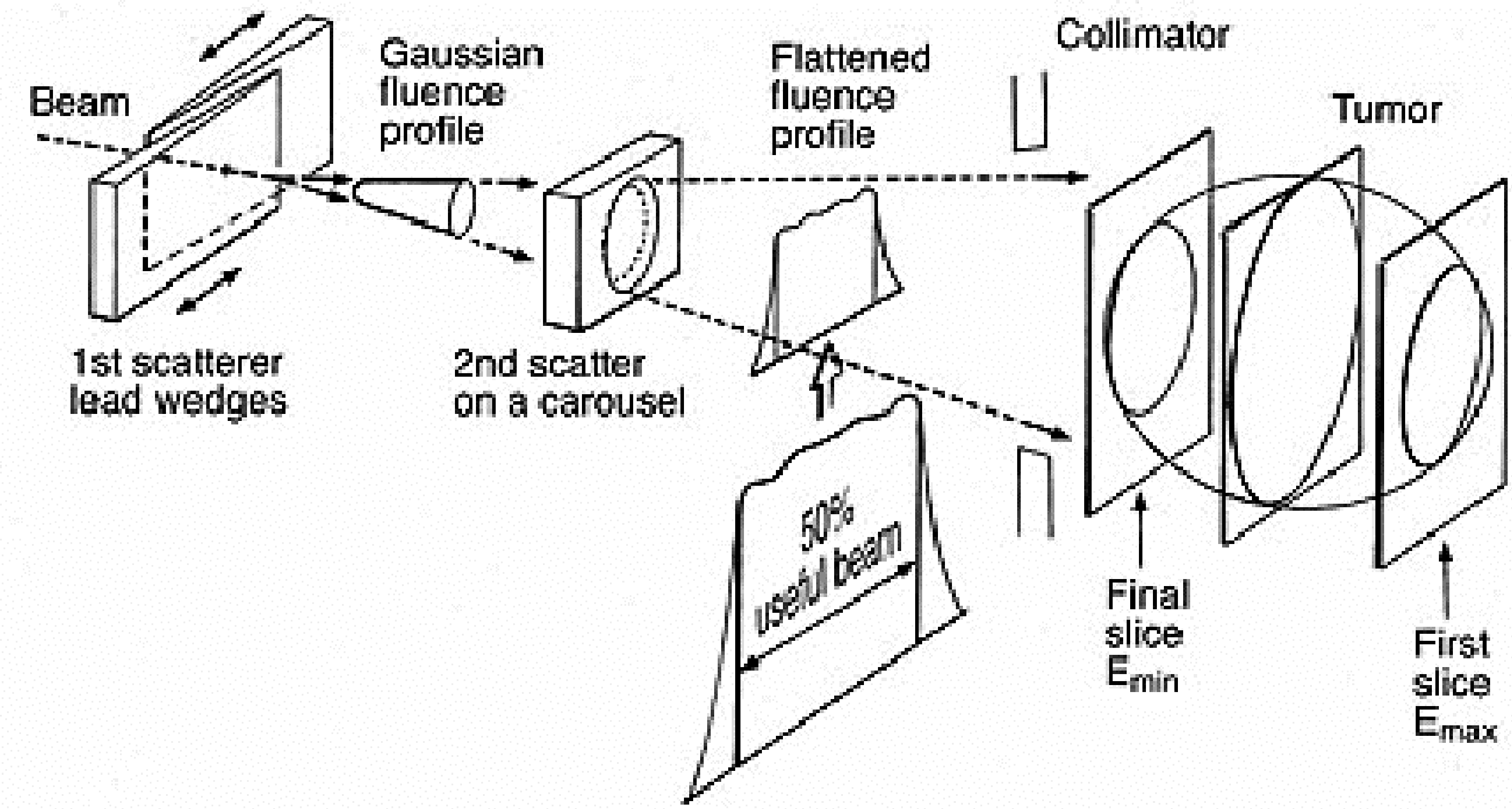
There is a national program in Japan to build proton (and Carbon-12) facilities

The continuous upgrade path

to

precision 3-D multi-field irradiation of cancerous tumors

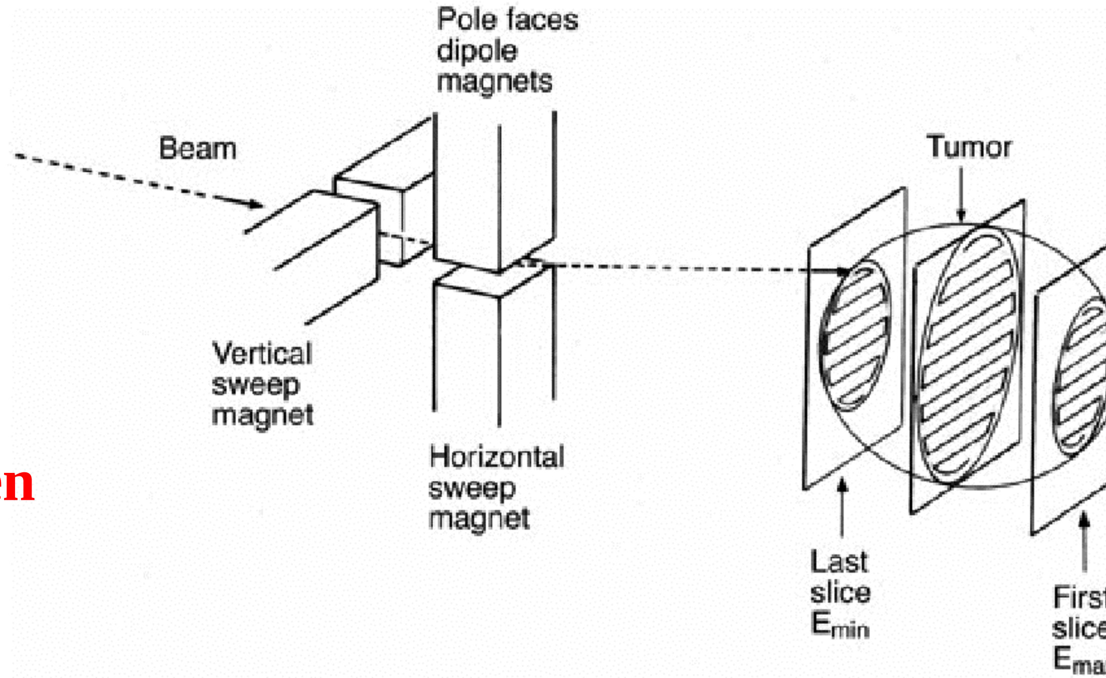
Traditional irradiation: PASSIVE SCATTERING



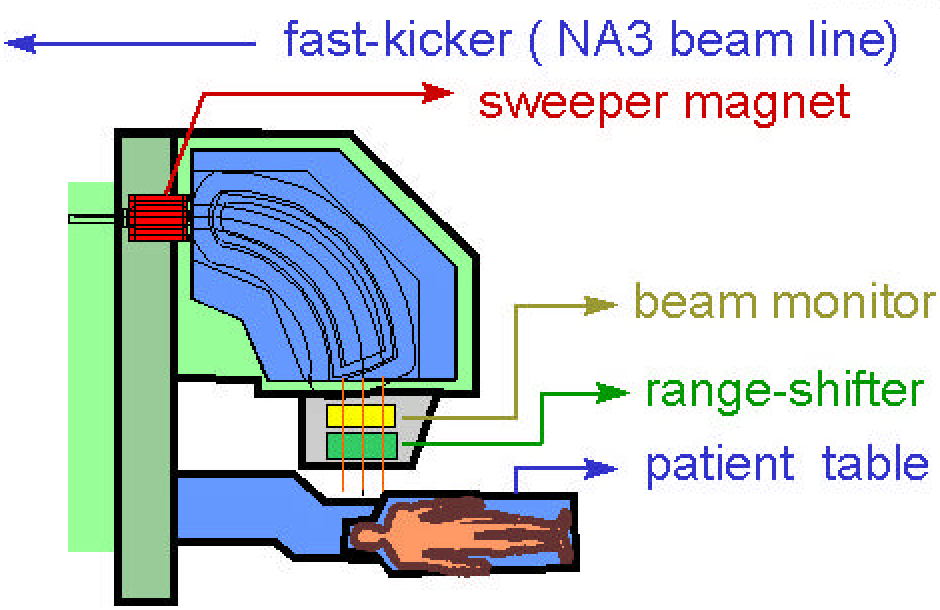
The sole (slow) variation: beam energy -> depth

Contemporary irradiation: ACTIVE SCANNING

Three variables:
- **H & V steering**
- **energy**

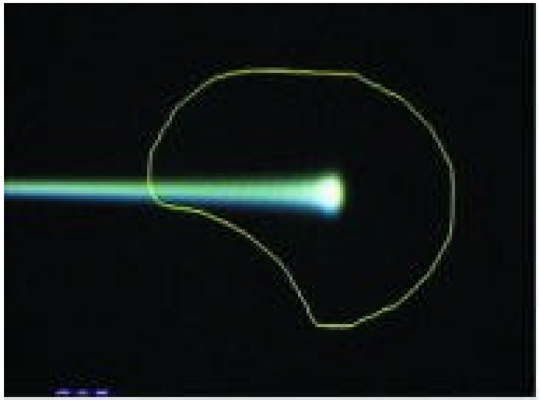


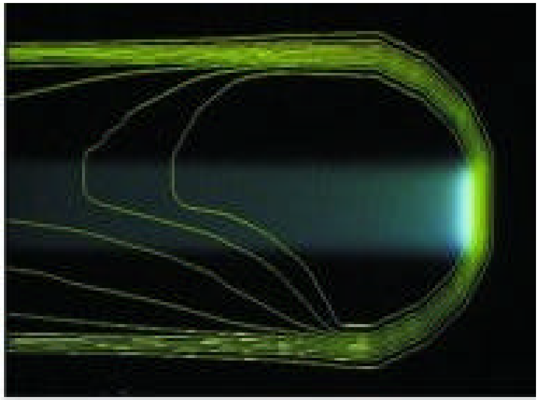
Although "simpler", active scanning has a higher controls burden



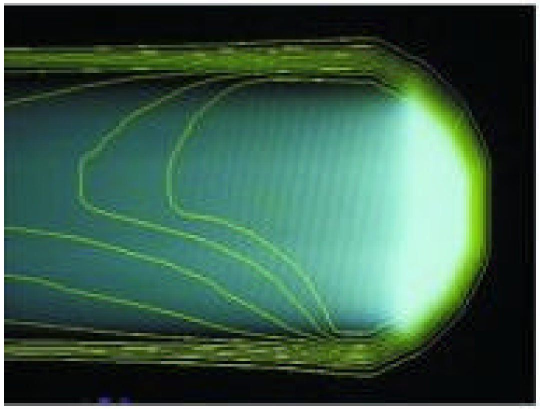
Hybrid schemes are also practical (PSI, left)
- **1.5 D steering**
- **range shifter**

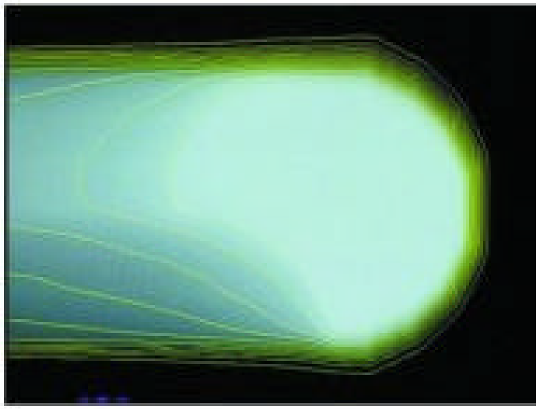
Active scanning - a much improved 3-D conformal dose





Single beam... (lateral scanning



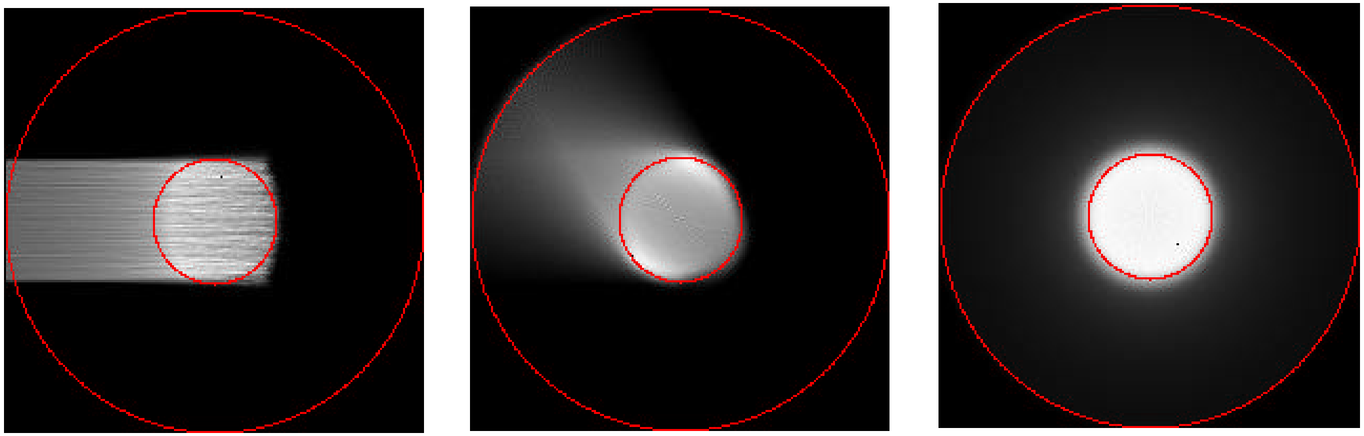


+ scanning in depth = 3d conformed dose)

(Patient treatment demos courtesy of PSI)

Multiple angles with a water phantom

One angle

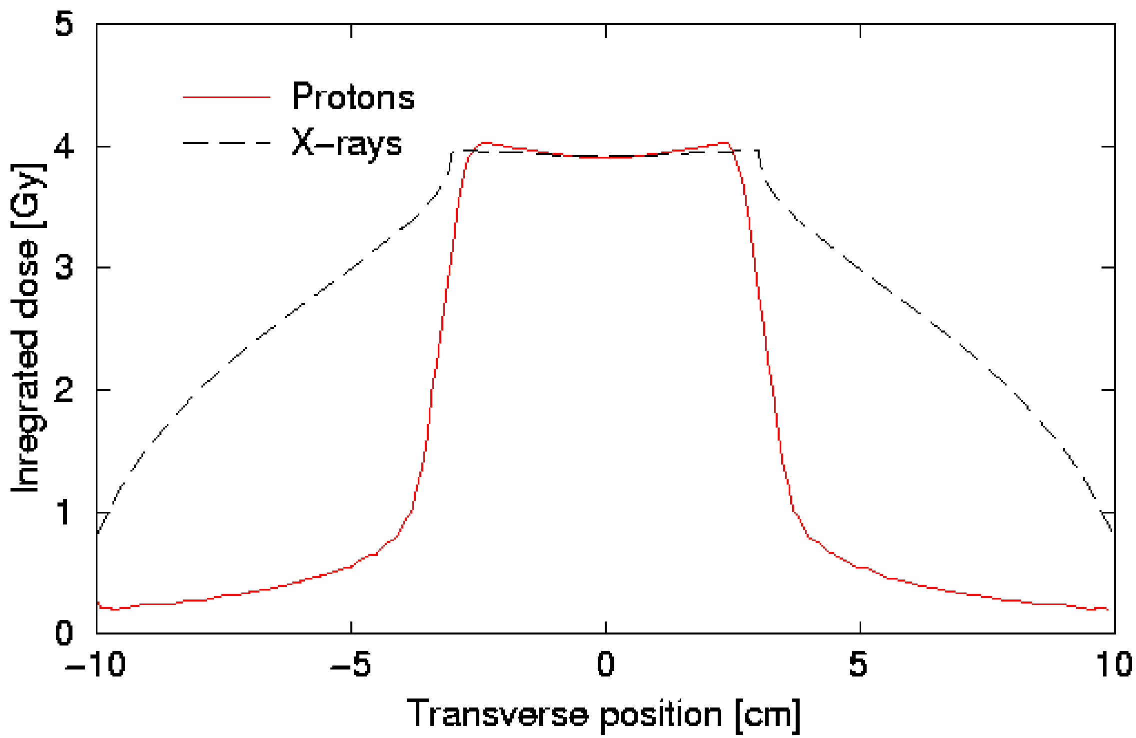


360 degrees

60 degree coverage

Ultra-low level collateral radiation with protons ...

... if ultimate multi-dimensional flexibility can be achieved !



A treatment planning example (Goitein et al, "Physics Today", Sept '02)

field, passive scattering

3 fields, passive

OOR

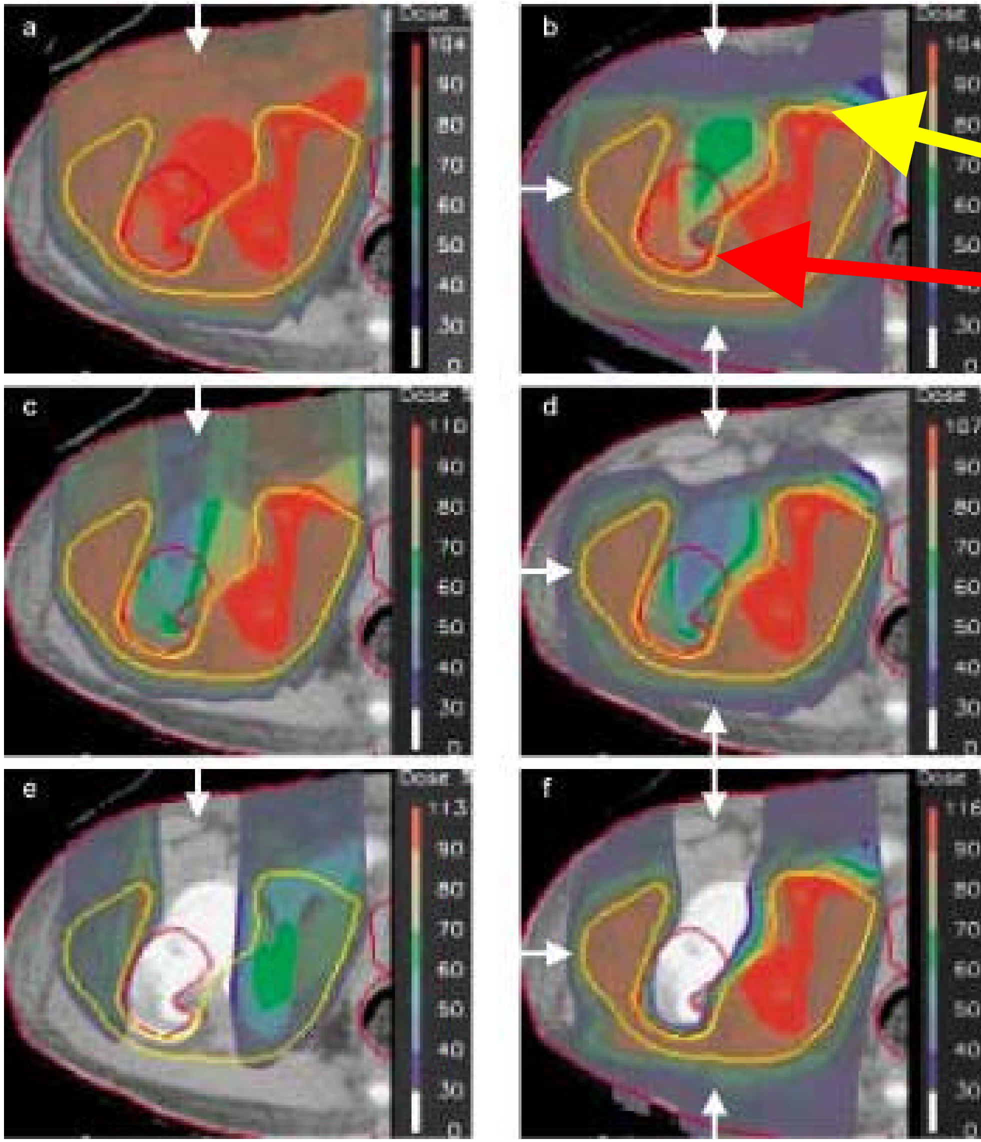
Target outlined in yellov

Critical structures in re

field,
ctive,
iform
dose

3 fields,
active,
uniform
dose

GOOD



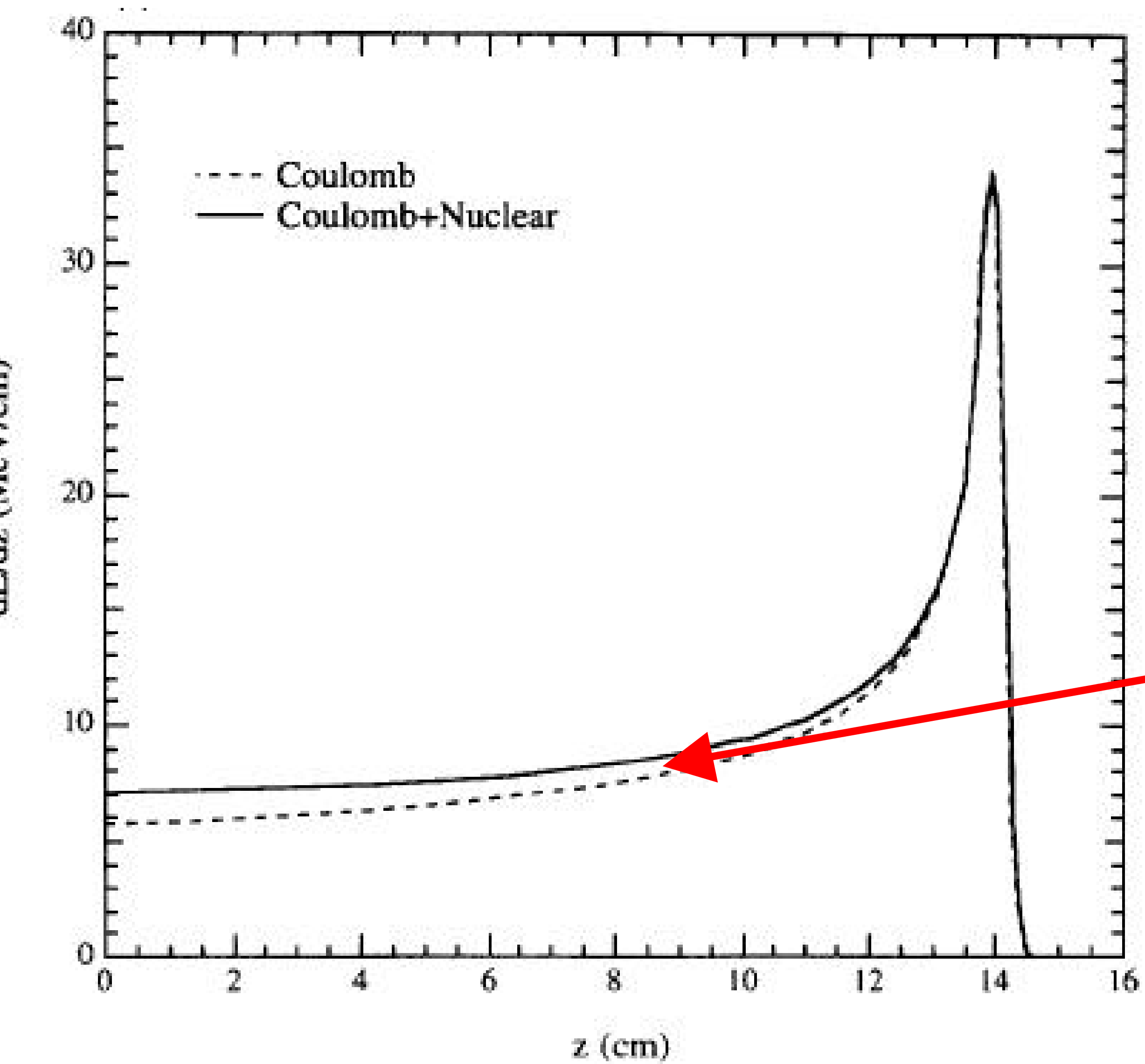
Bottom right is muc
better than top left!

1 field of 3, active,
intensity modulated

3 of 3 fields, active,
intensity modulated

Proton Driven PET

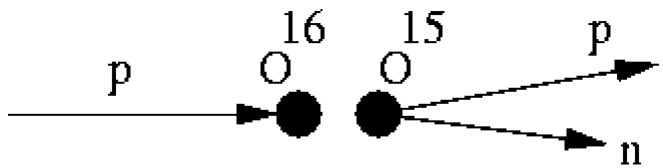
Nuclear cross sections matter, and are useful!



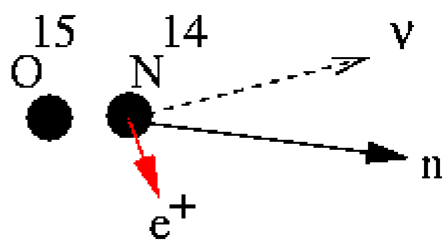
A small but significant fraction of proton dE/dx loss is due to nuclear interactions

some of which generate positron emitters

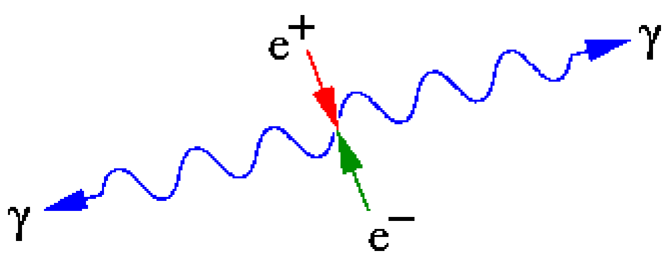
Is the (high) therapy dose going to the right place?



Occasionally a proton generates an O^{15} isotope ...



... that decays by emitting a positron ...



... which annihilates with an electron

Place a PET camera on the gantry to observe where such nuclear interactions occur

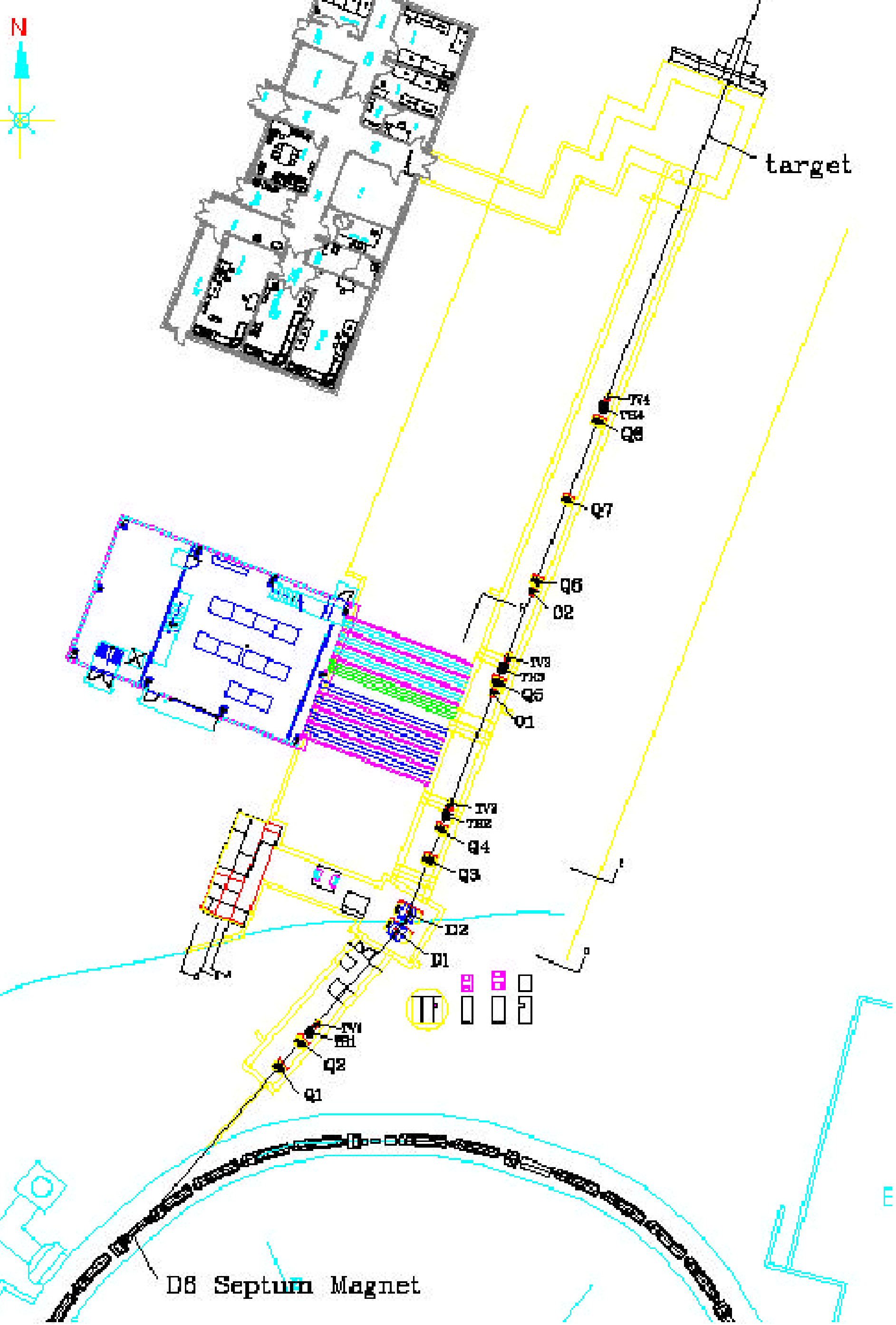
Nuclear cross sections vary rapidly with energy ...

Interesting work is also going on with C-12 driven PET, eg at GSI (Parodi et al)

Include a PET camera like this (at BNL) in a gantry room for best possible co-registration of tumor and beam

Preliminary studies are under way at PSI (also with Carbon-12) and at BNL

Proton Computed Tomograpy - pCT



The "pCT" collaboratio
is forming (?)

- BNL
- Loma Linda
- UC Santa Cruz
- Stony Brook

First meeting/workshop -
Thurs/Fri Jan 9 & 10

The BAF beamline appears to be an ideal location for pCT R&D !

Use of Proton Beam CT: Treatment Planning

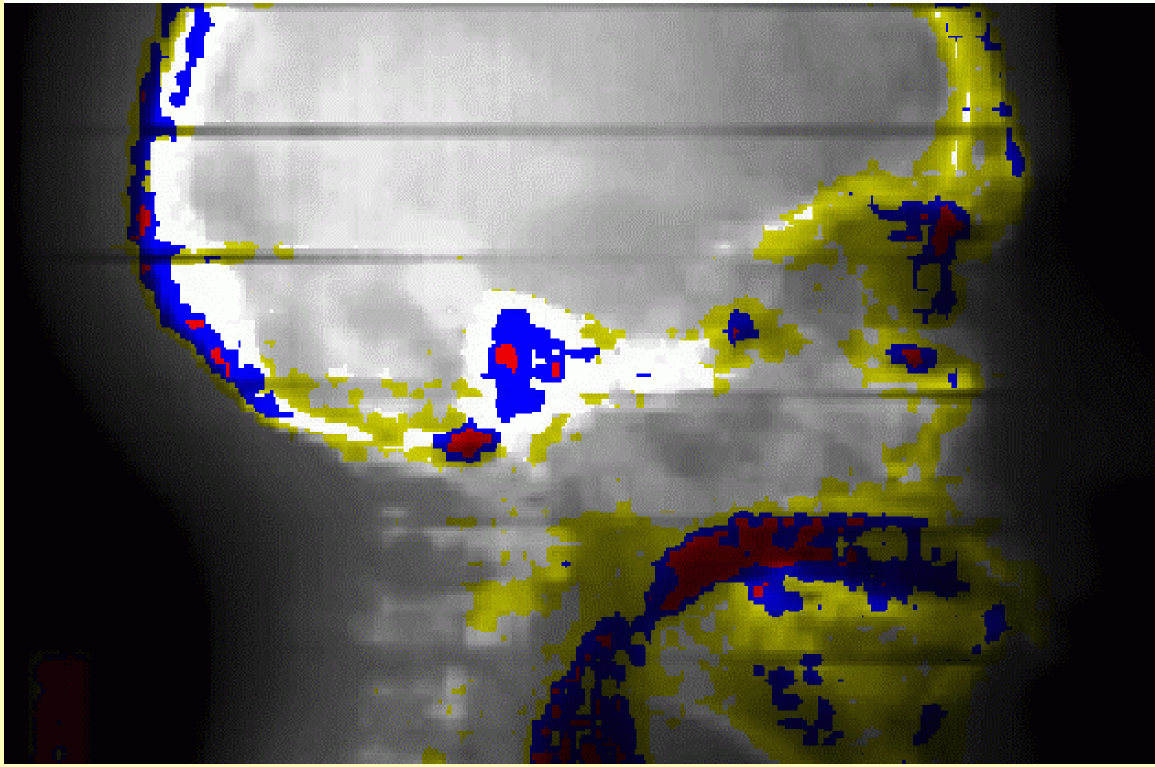
X-ray CT use in Proton Cancer Therapy can lead to large Uncertainties in Range Determination

Range Uncertainties

(measured with PTR)

- (black) > 5 mm
- (blue) > 10 mm
- (red) > 15 mm

Schneider U. & Pedroni E. (1995), "Proton radiography as a tool for quality control in proton therapy," Med Phys. 22, 353.

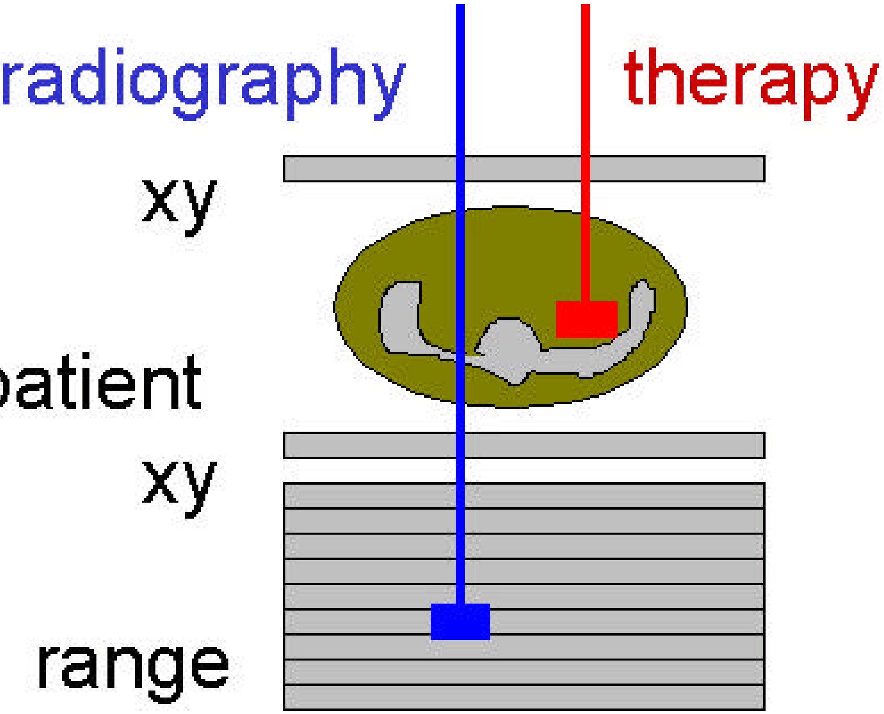


Alderson Head Phantom

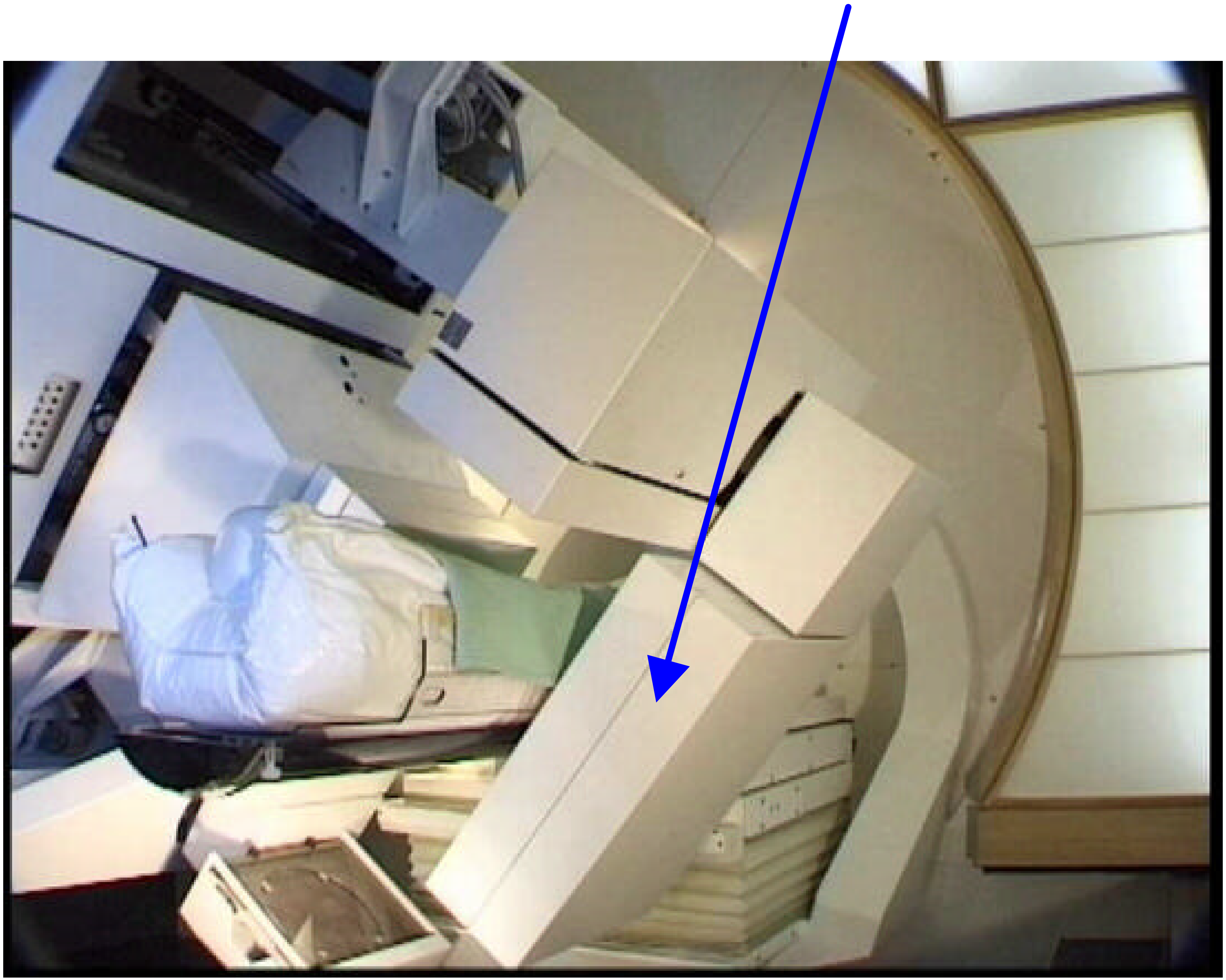
Prototype detector at PSI

The protons go through the patient
Higher energy, small dose

Radiograph of a phantom
Uwe Schneider PhD thesis (PSI)

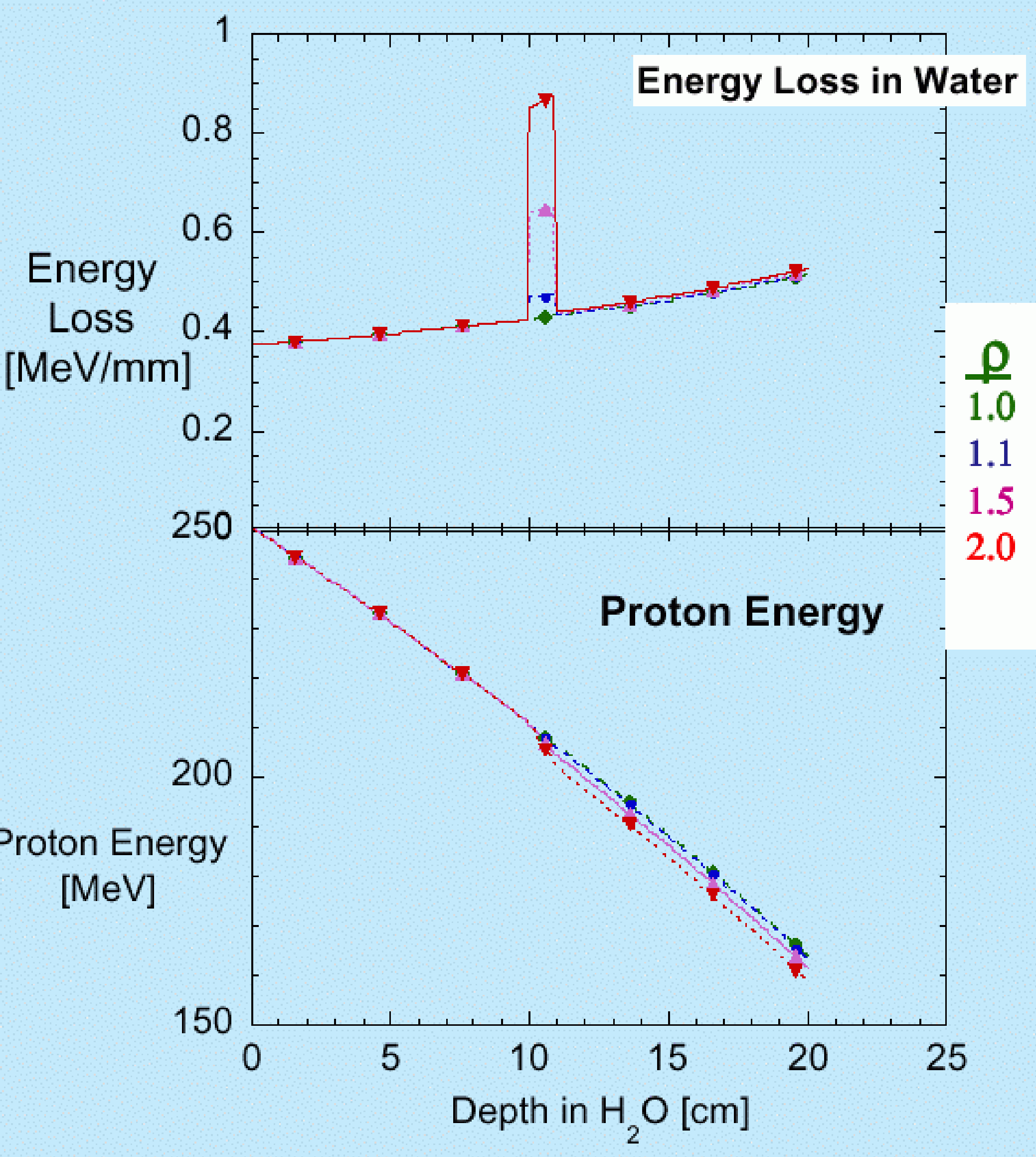


The PSI therapy gantry, with prototype detector in place, based on scintillating fiber technology (U. Schneider et al)

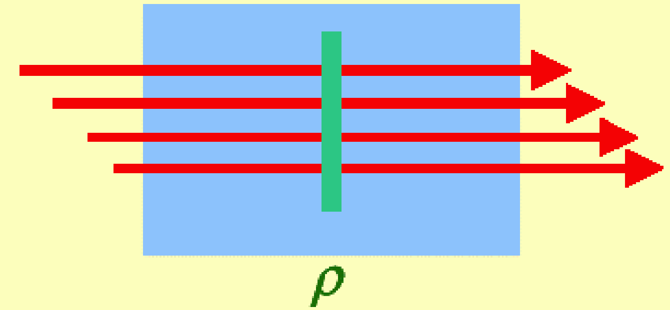


SCIPP

Low Contrast in Proton CT

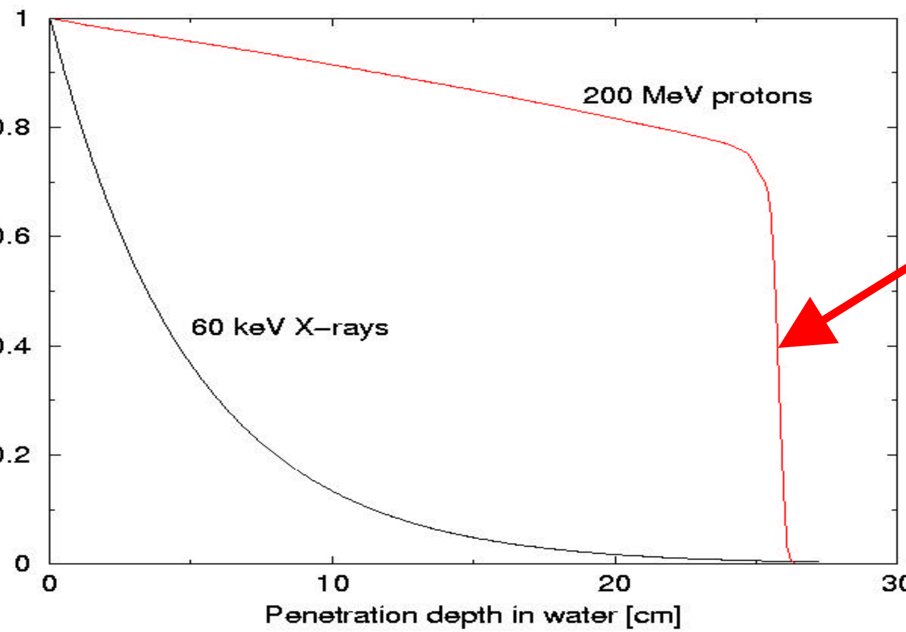


Inclusion of 1cm depth at midpoint of 20cm H_2O



ρ [g/cm²]	Energy [MeV]	Range [cm]	TOF [ps]
1.0	164.1	38.2	1309
1.1	163.6	38.1	1311
1.5	161.5	37.7	1317
2.0	158.9	37.2	1325

Modern techniques appear to promise ultra-low dose CT !



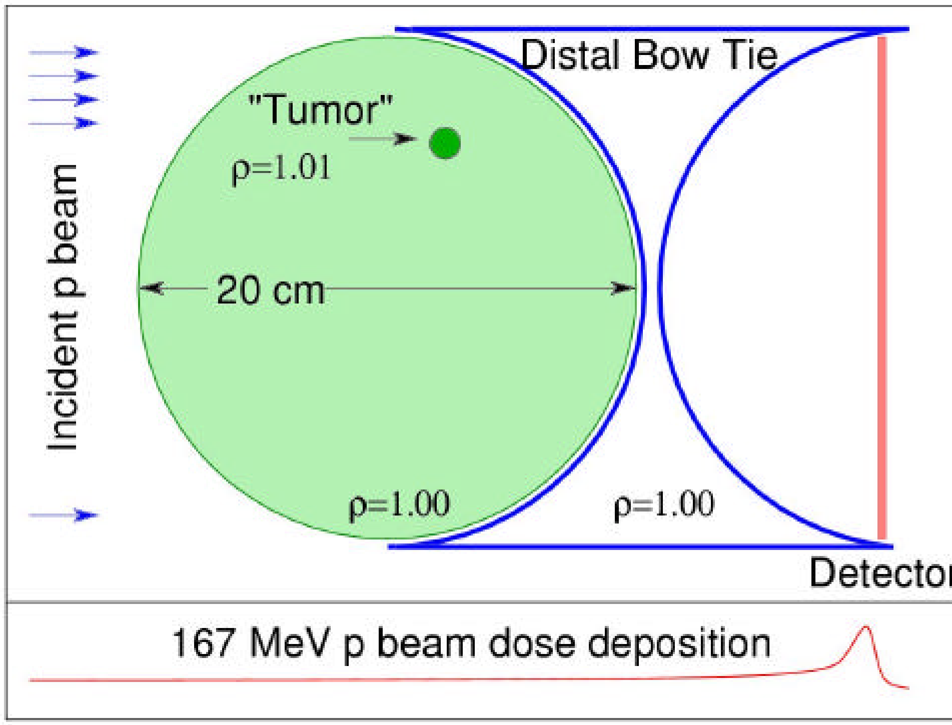
The very steep slope of transmission vs depth allows high sensitivity with few protons ...

... at especially low dose since the Bragg peak is outside the patient

Energy flexibility is desirable ...

... but is mitigated by the use of a "distal bow tie"

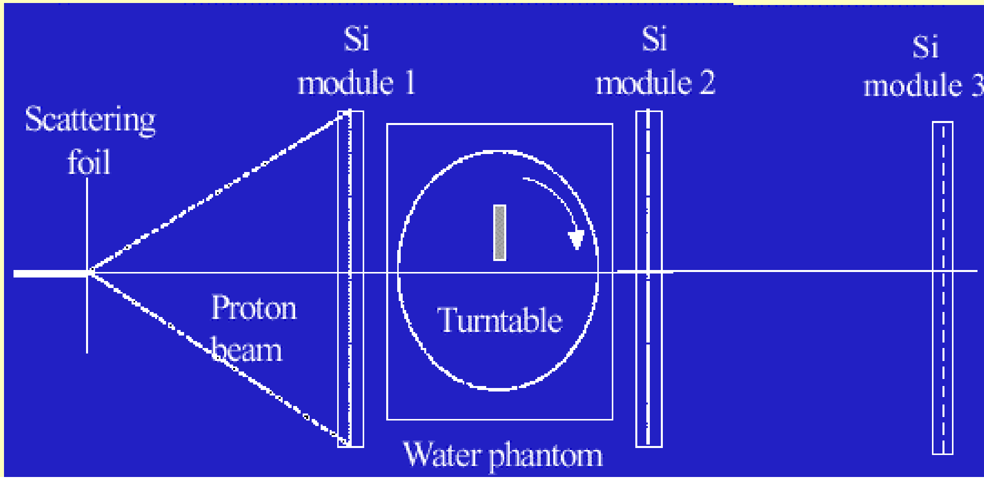
(Satogata et al)



Development of Proton Beam Computed Tomography

Collaboration
Loma Linda University Medical Center – UC Santa Cruz

- Exploratory Study in Proton Radiography
  - two x-y detector modules
  - Crude phantom in front
- Theoretical Study
  - GEANT4 MC simulation
  - influence of MCS and range straggling
  - importance of angular measurements
  - Optimization of energy
- Experimental Study in pCT
  - Three or four x-y Si planes
  - water phantom on turntable



Proton Energy Measurement with LET in Si

Simple 2D Silicon Strip Detector Telescope built for Nanodosimetry (based on GLAST Design)

2 single-sided SSD

194um Pitch

400um thick

1.3us shaping time

Binary readout

Time-over-Threshold TOT

Large dynamic range

Measure particle energy via LET

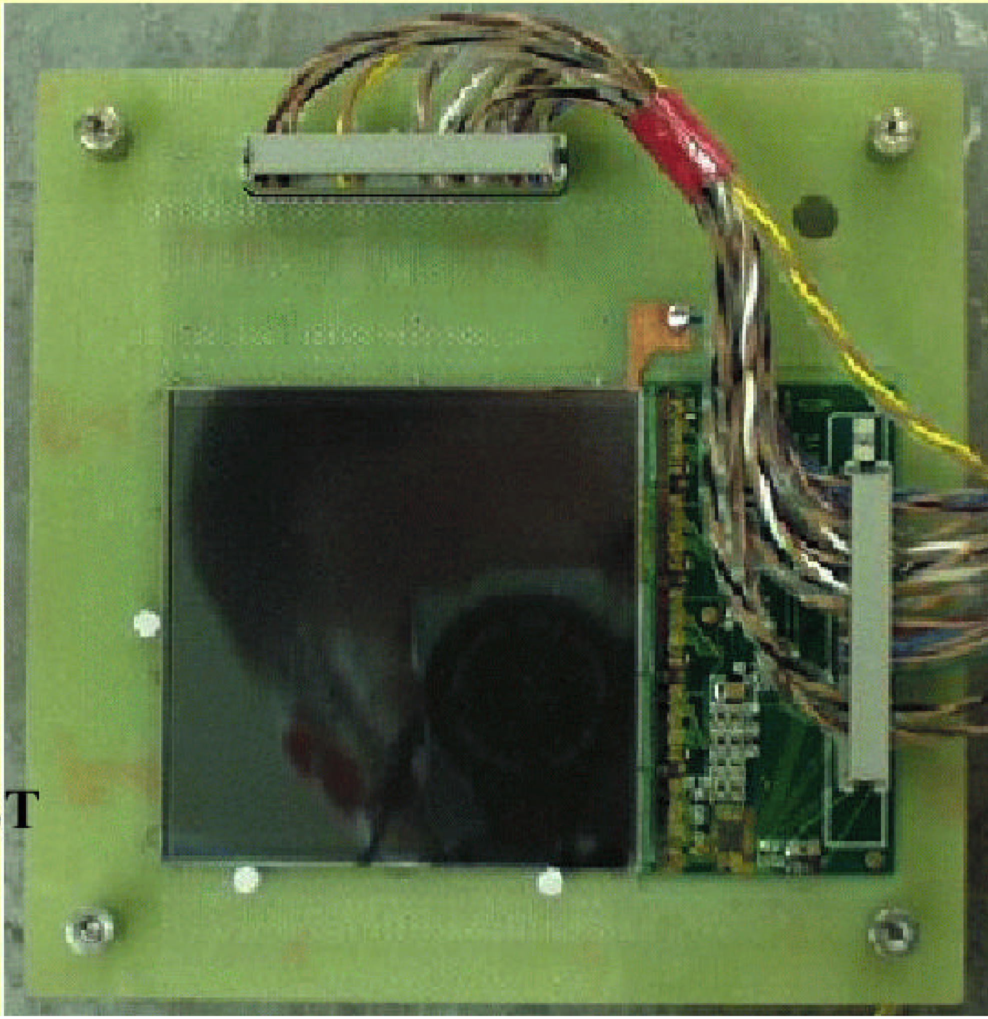
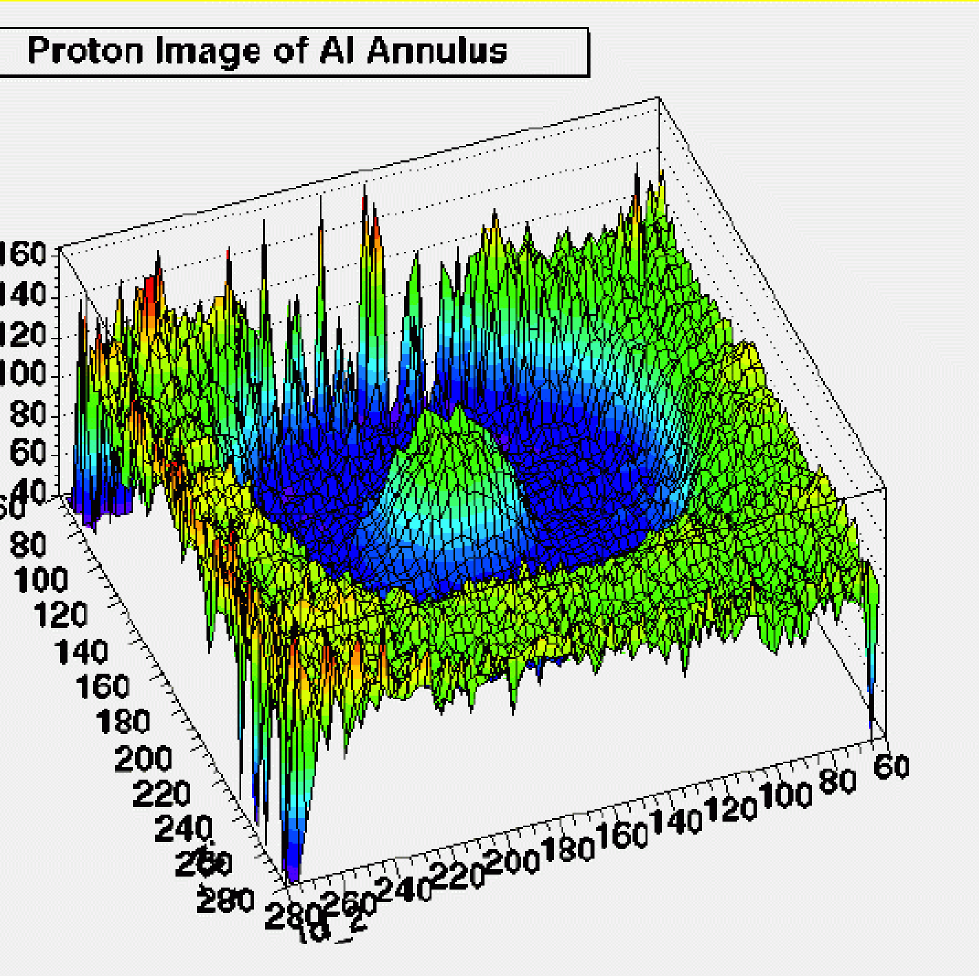


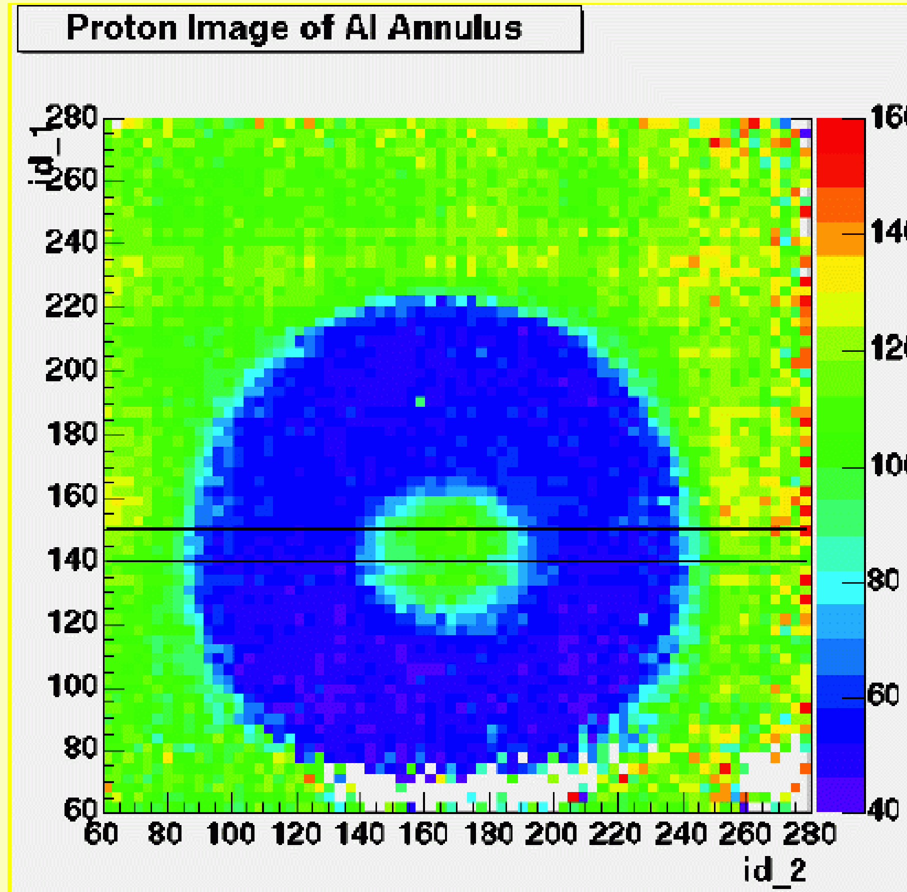
Image !



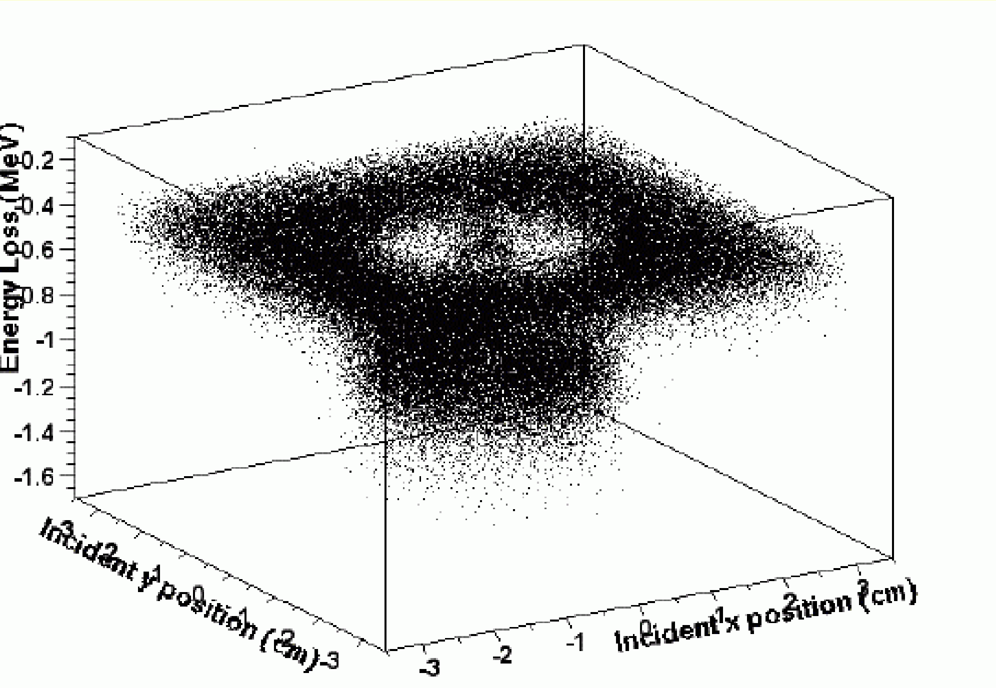
Subdivide SSD area into pixels

1. **Strip x strip 194um x 194um**
2. **4 x 4 strips (0.8mm x 0.8mm)**

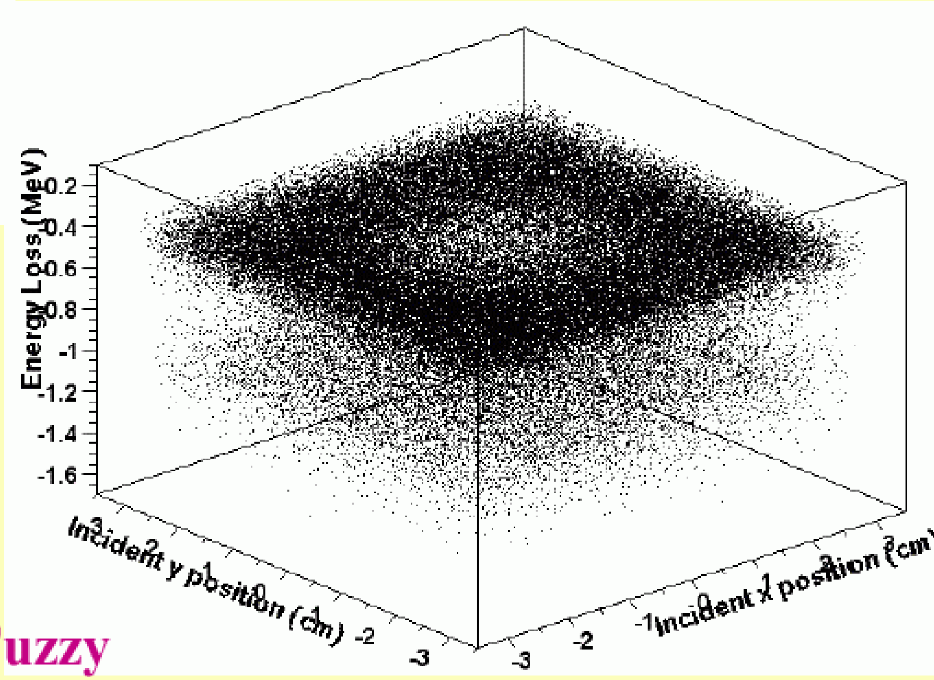
Image is average energy in pixel



MC: Loss of Resolution in Back



First Plane, 2cm behind Object

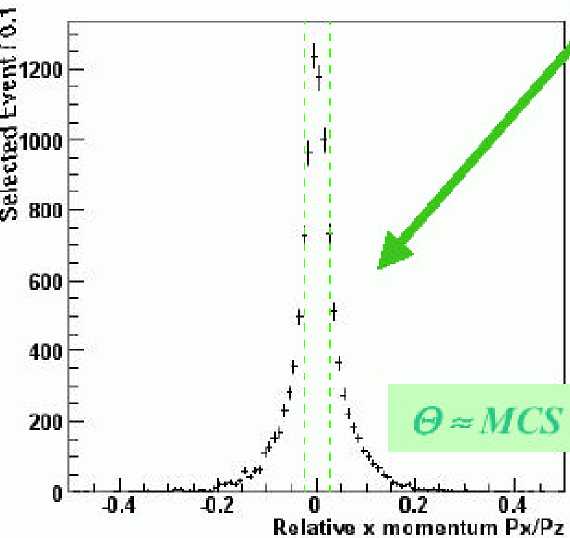


Second Plane, 30cm behind Object: Fuzzy

SCIPP

MC: Use Angular Information

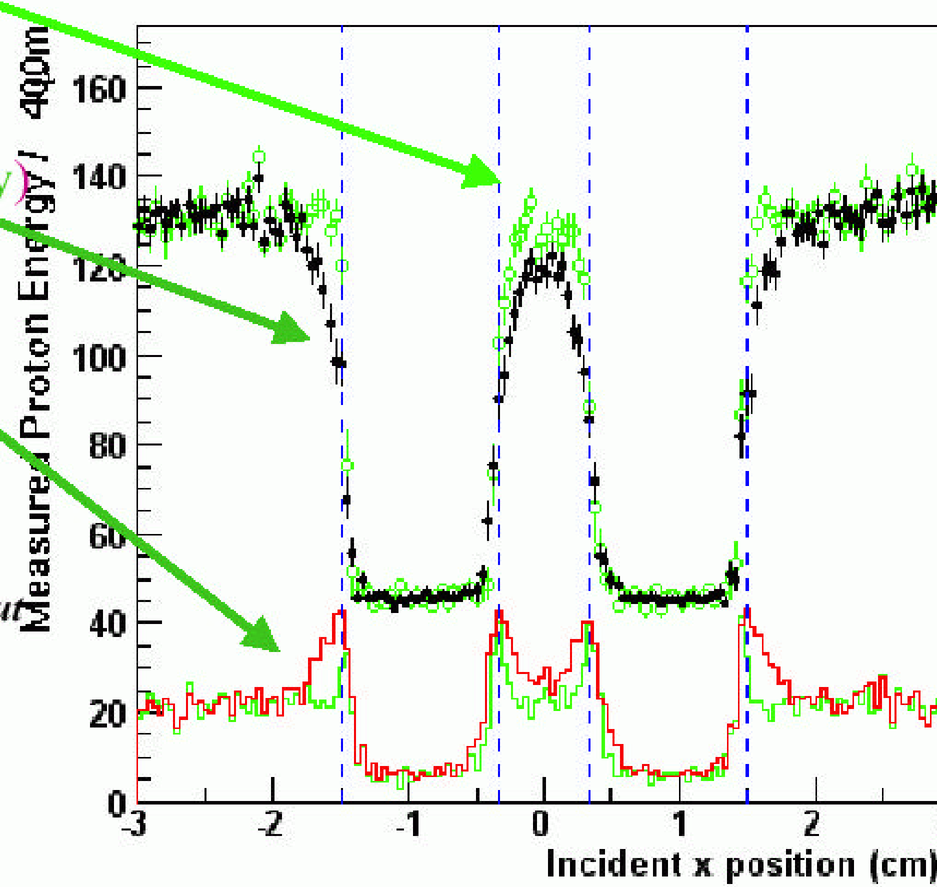
Effect of Angular Cut: Energy more uniform

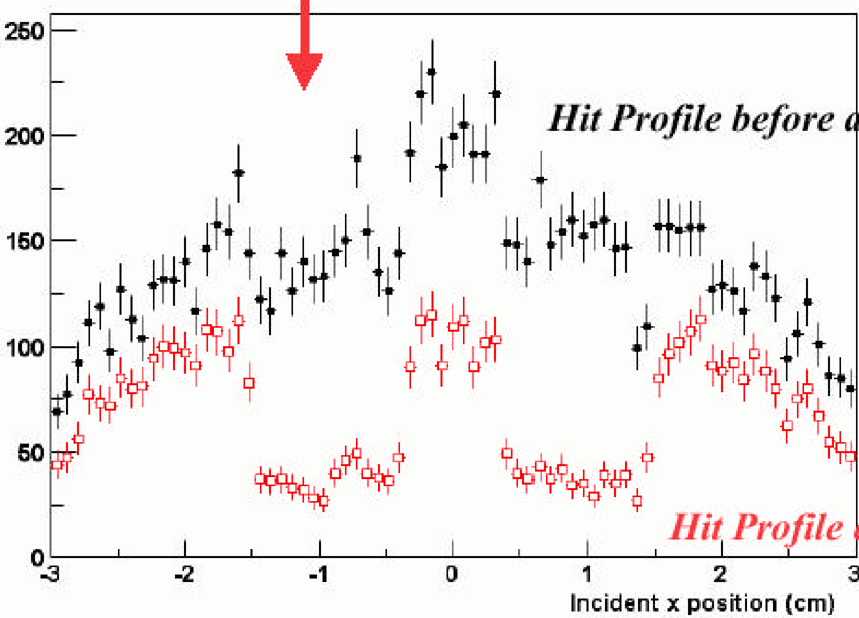


Θ ≈ MCS angle

Less Migration

Sharp edges
(RMS and Energy)



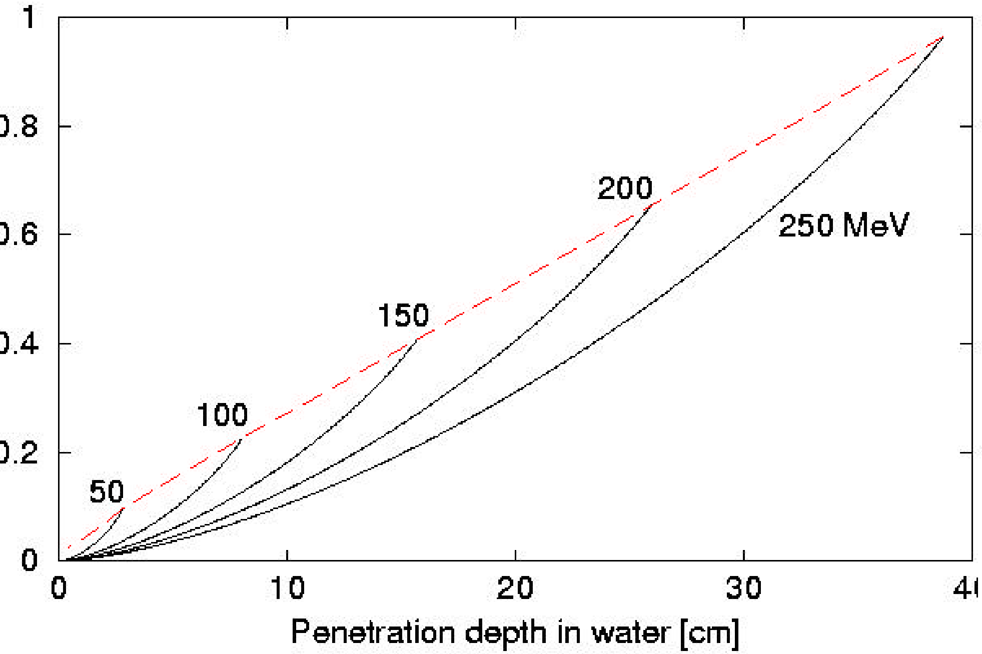


Hit Profile before angle cut

Hit Profile after angle cut

Imaging with MCS Angle?

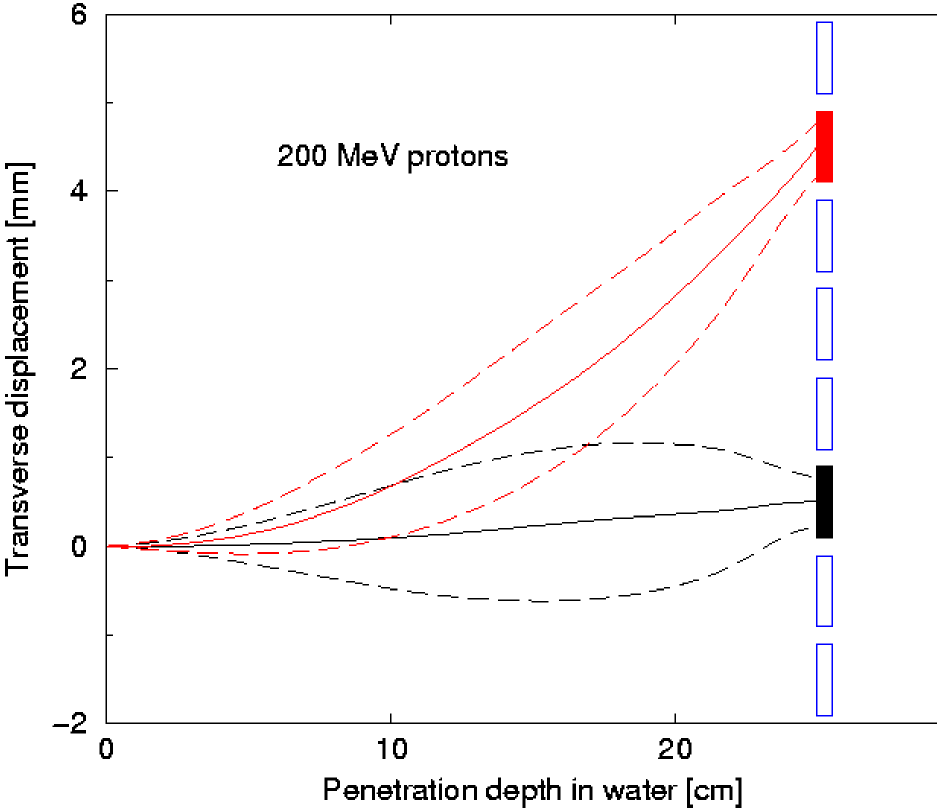
Multiple scattering:



Historically, proton radiography was rejected because multiple scattering made blurry images

Modern reconstruction algorithms can make sharp images ...

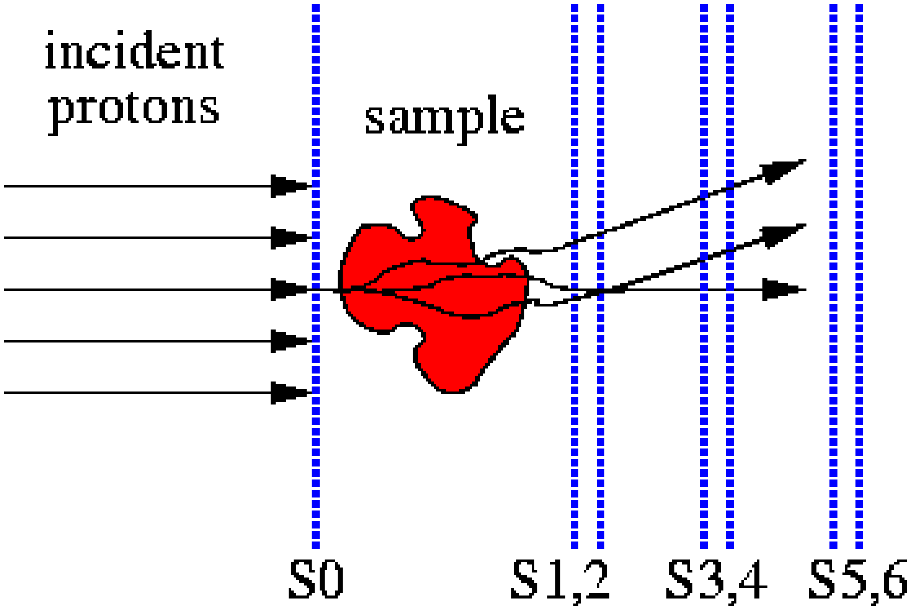
... with knowledge of incoming and outgoing displacements and angles



What should a pCT imager (on a gantry) look like -- technology choice(s) ???

- scintillating fiber?
- Silicon strips?
- GEM?
- good energy resolution?

Proton imaging spectrometer

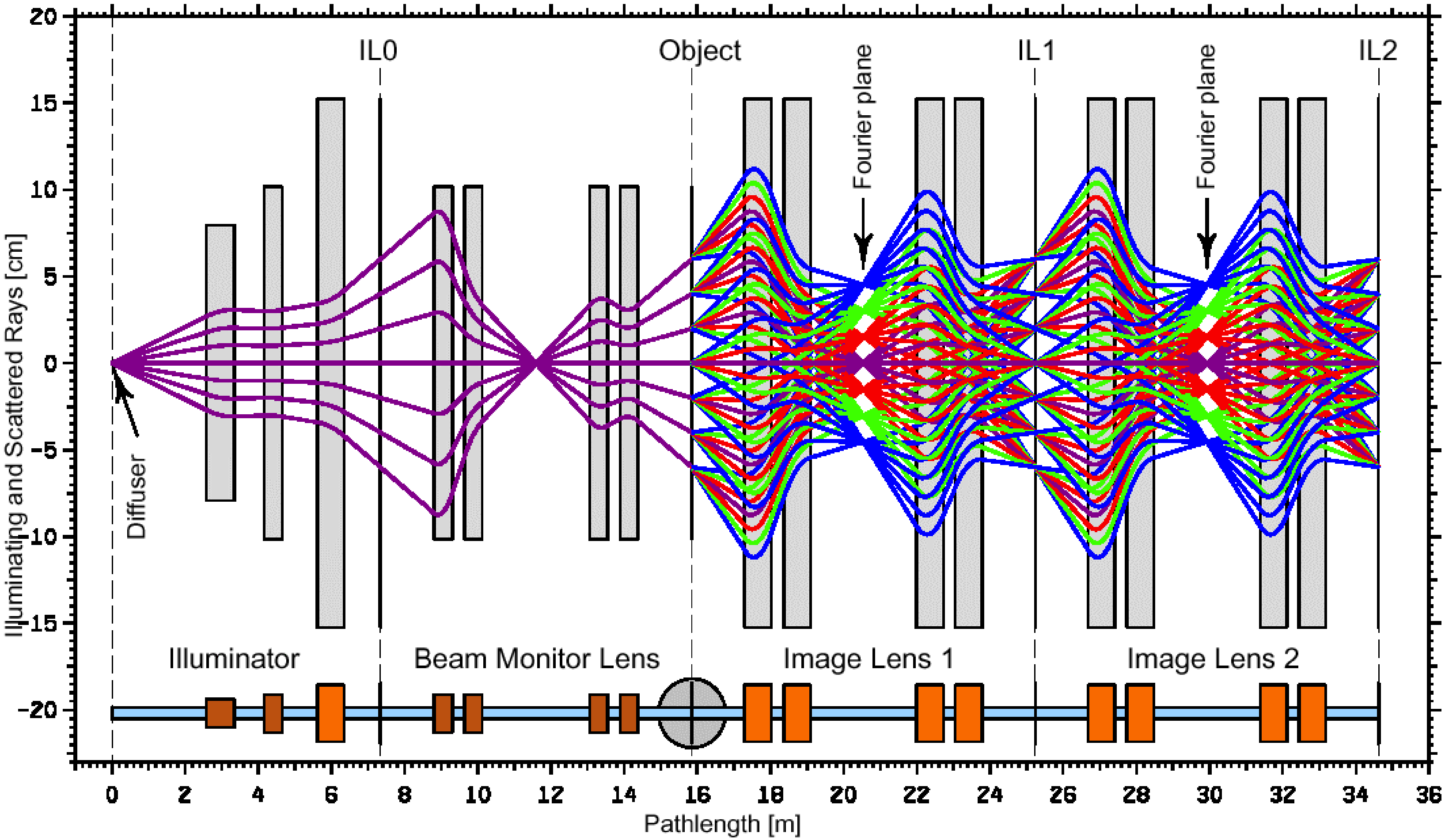


Multiple planes of silicon for position, angle, and energy measurements

Transient devices: PRAD movies

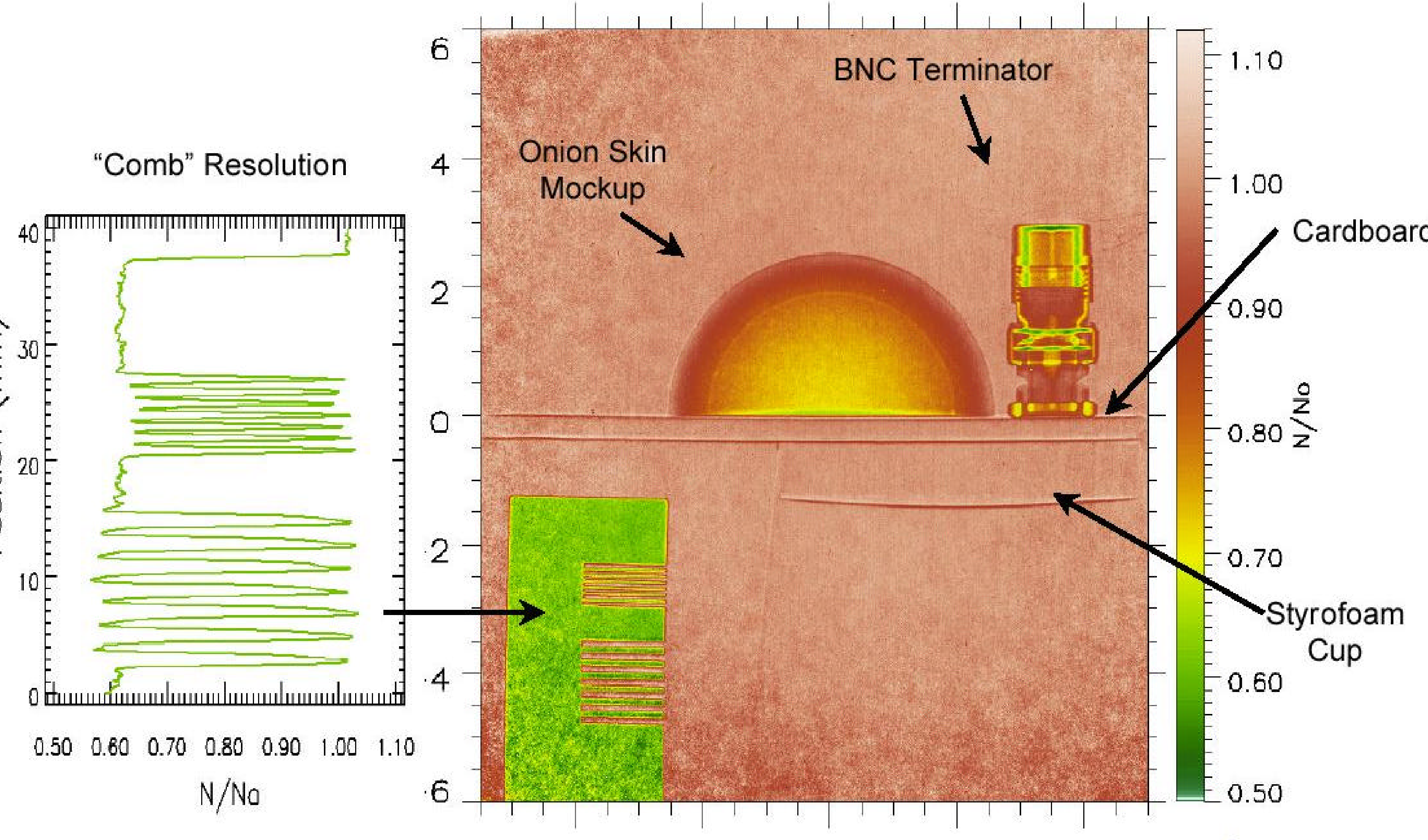
Los Alamos beam-lines at Lansce & BNL

Add magnetic lenses - but not on a gantry (4 GeV to 24 GeV!



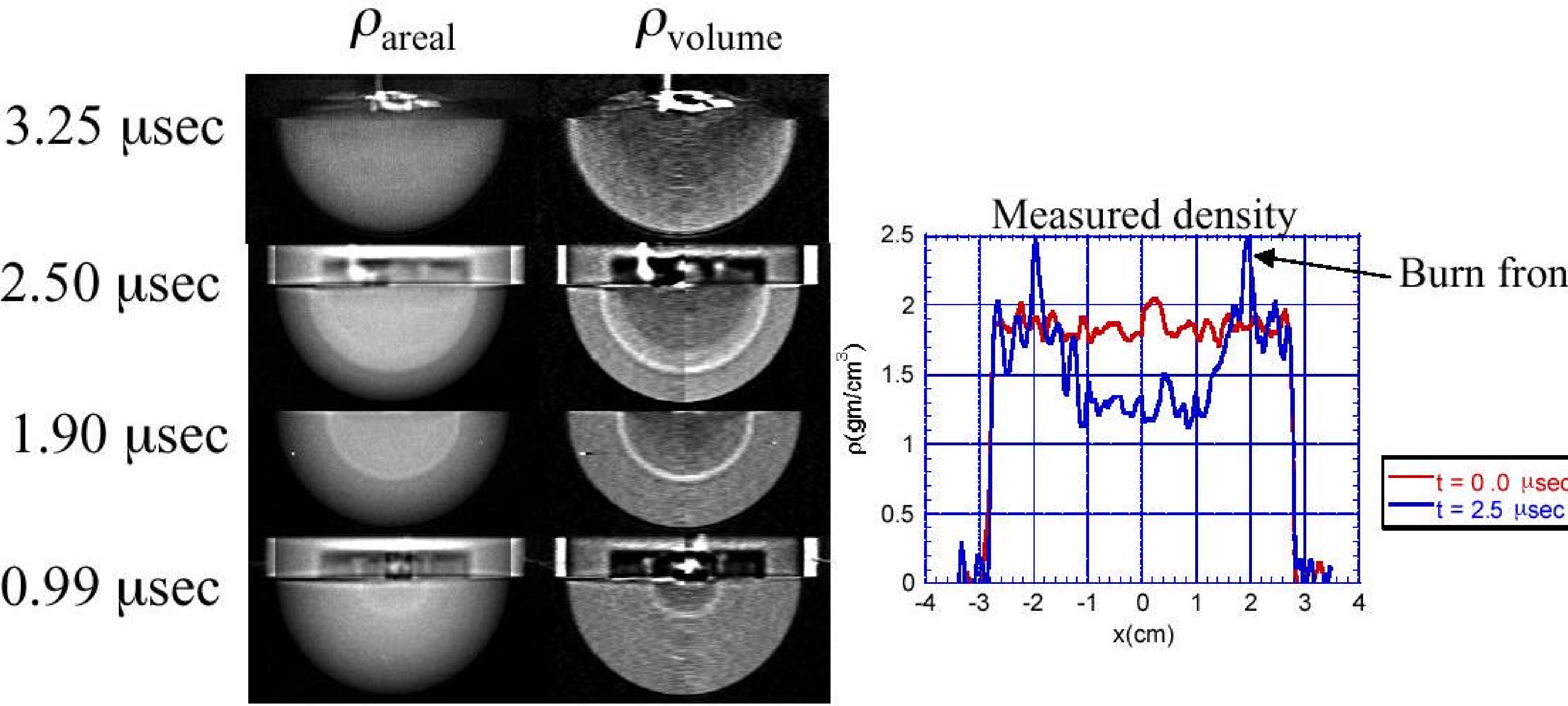
Double cuts on multiple scattering angles (at Fourier planes) enable crude material ID!

Proton radiograph with a multi-GeV beam (Los Alamos)

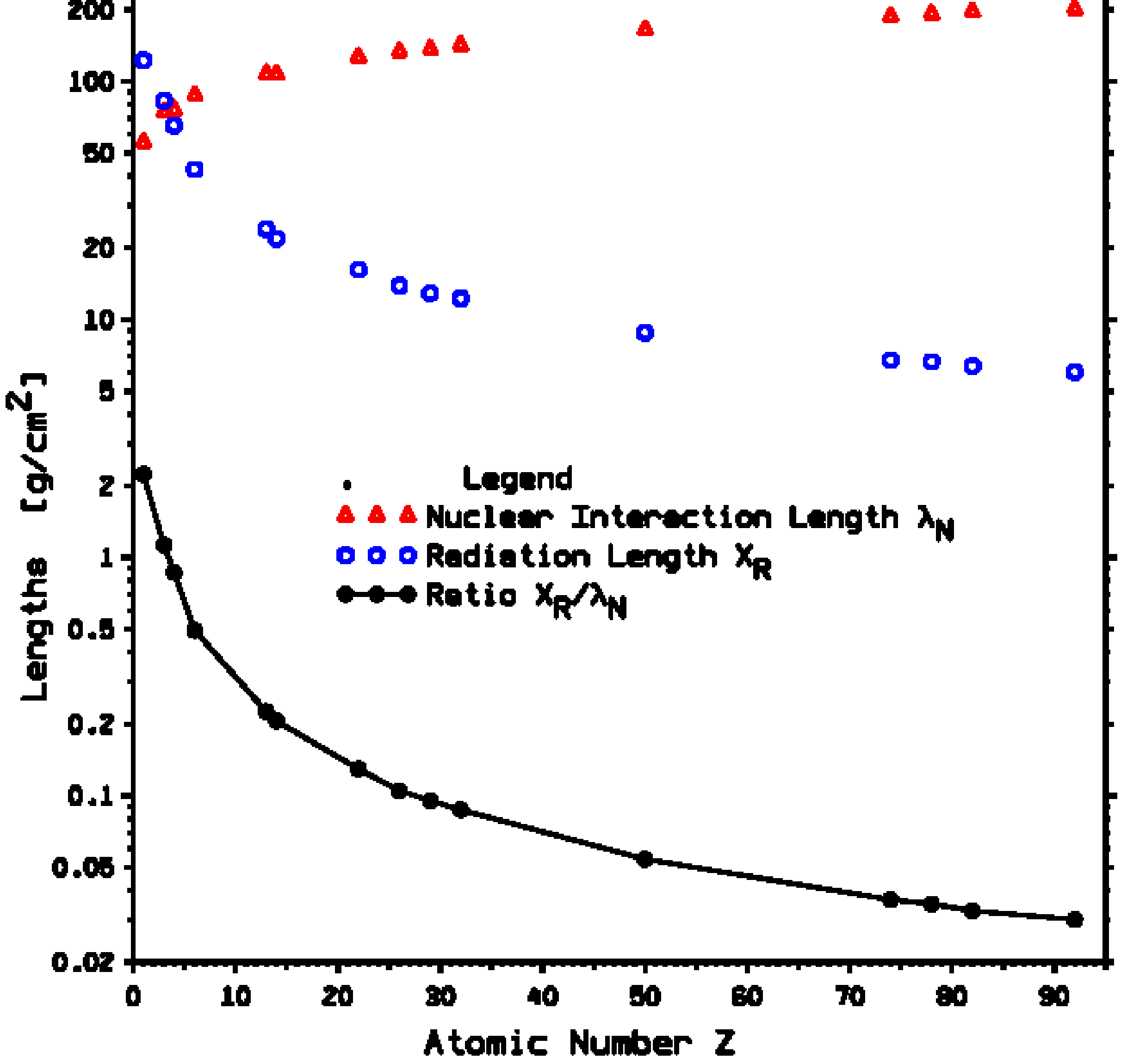


Sub-millimeter resolution

Stills from a movie of a mock "device" exploding (Los Alamos)



Can also see combustion fronts inside gasoline engines, ramjets, ...



The dependence of nuclear interaction length on Z also enables crude material ID in transmission measurements

Periodic CT = pCT + PRAD ??

The PRAD folk are exploring "civilian, periodic" systems:

- **gasoline engines**
- **jet engines**

This is a new regime that appears to benefit greatly from a hybrid approach

- **higher energies than medical**
- **with magnetic lenses & spectrometers**
- **with proton-by-proton tracking**

PRAD features, in the past:

- **fast extracted beams**
- **transient movies (few frames, microsecond time scale)**
- **transmission (intensity) measurements**
- **for material identification, play off**
    1) **nuclear interaction lengths**
    2) **multiple scattering**
    3) **Fourier plane imaging/collimation**

Periodic high energy CT movies:

- **"slow"periodic systems (10,000 rpm?)**
- **slow extracted beam (NOT U-line, not BAF?)**
- **benefits from proton-by-proton tracking:**
    1) **virtual collimators (better MCS material ID)**
    2) **energy measurements (easier than medical!)**
    3) **many more (unique!) CT movie frames**
    4) **same modeling/algorithms as medical pCT**

Watch this space -- any comments?

Summary

1) First generation proton therapy facilities are "proven" technology. Second generation therapy accelerators are arriving in force.

2) For a few dollars more, put proton imaging on a gantry
   - a) proton driven PET: high therapy dose QA
   - b) proton CT: low dose CT, treatment planning

3) What does the optimal "proton Computed Tomography" detector look like? Silicon? GEM? Scintillationg fibers?

4) How to measure proton energies accurately?

5) There appears to be an exciting field in "CT movies" for periodic mechanical systems, by hybridizing pCT and PRAD technologies!