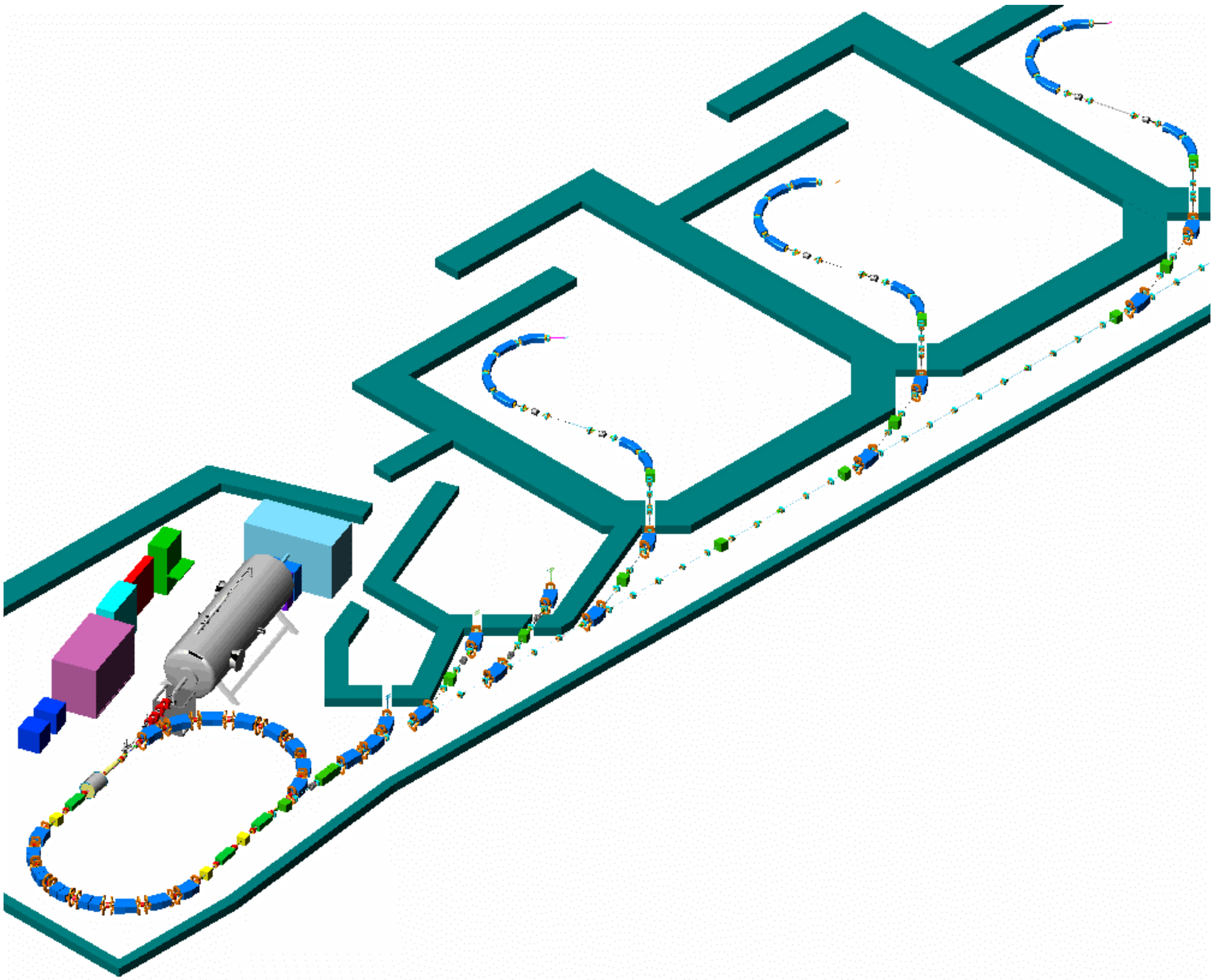
Proton Accelerators for Therapy & Imaging

Steve Peggs, BNL



Contents

Why protons? Why now?

Where are the facilities? When?

Precision 3-D multi-field irradiation of cancerous tumors

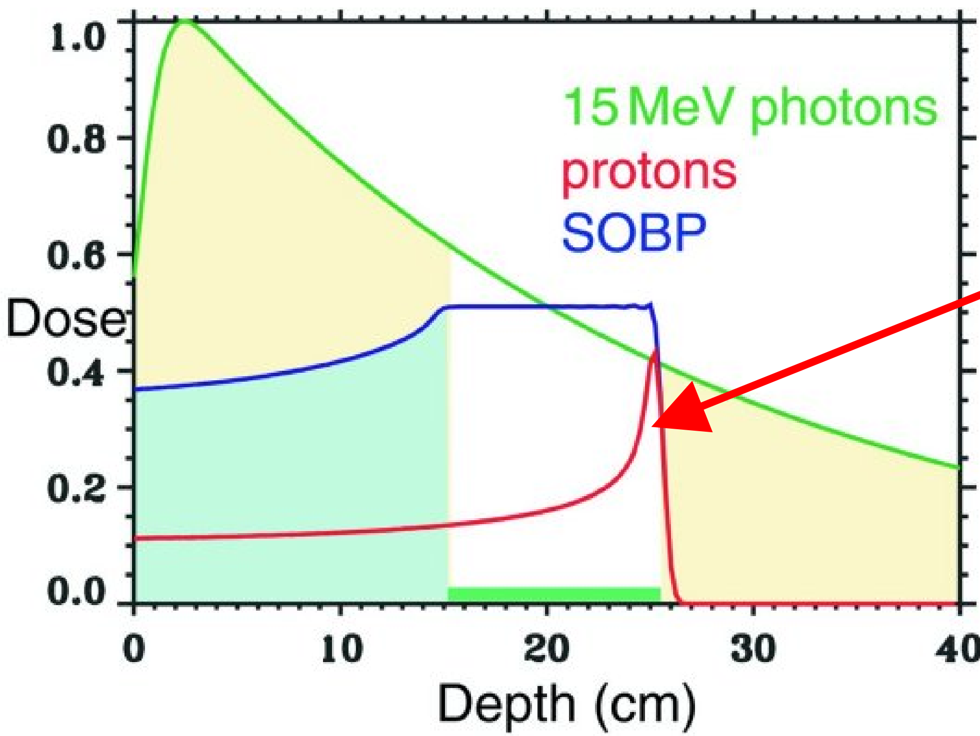
Technology choices

Proton Imaging

- **proton driven PET**
- **radiography**
- **movies**

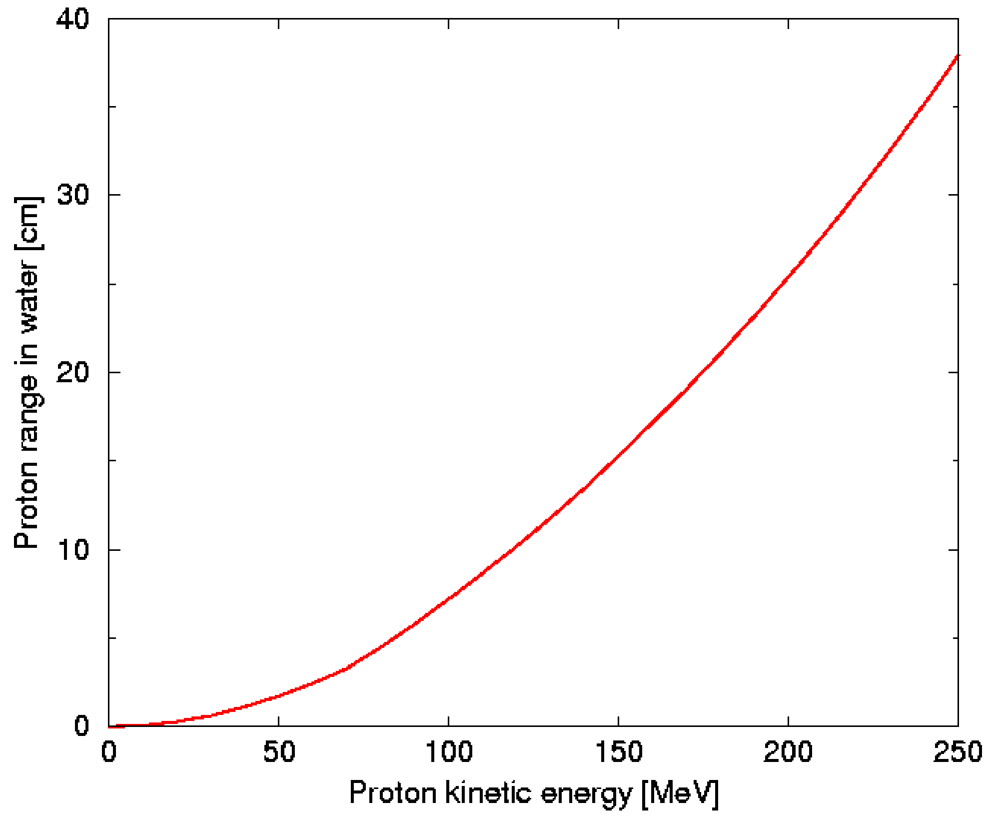
Why protons? Why now?

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

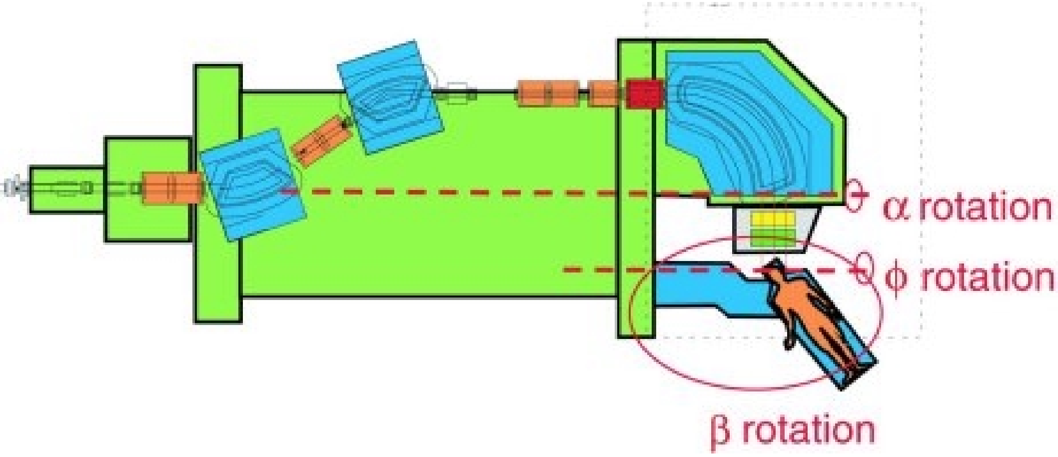


Conventional X-ray gantries are "small"

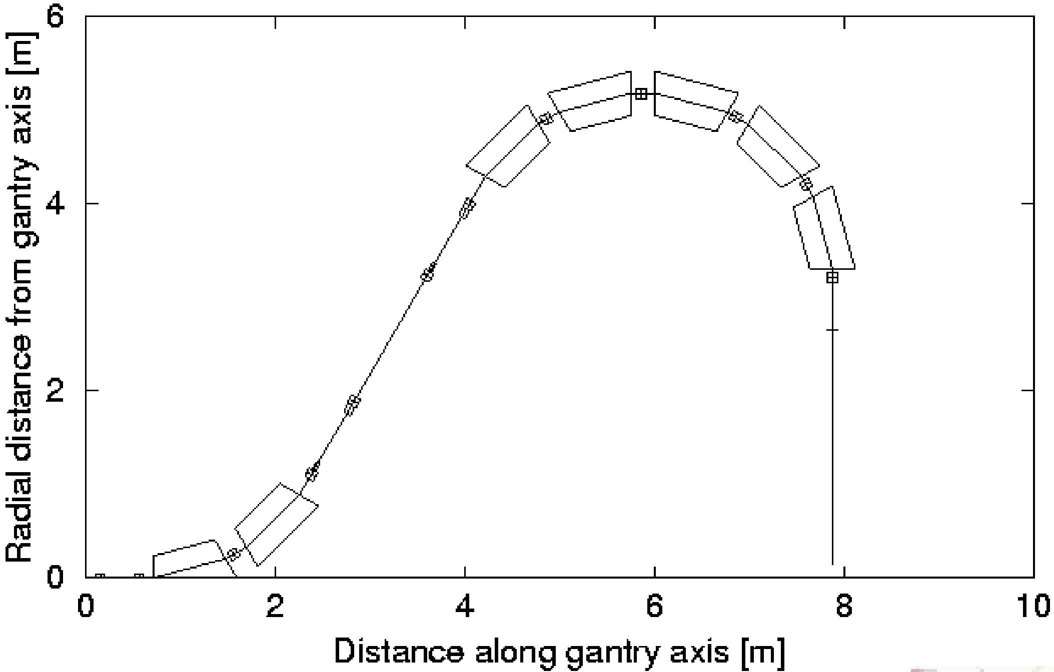
Almost all of it is visible in this photograph!

Proton gantries appear similar to the patient

But there is a lot more "behind the wall"



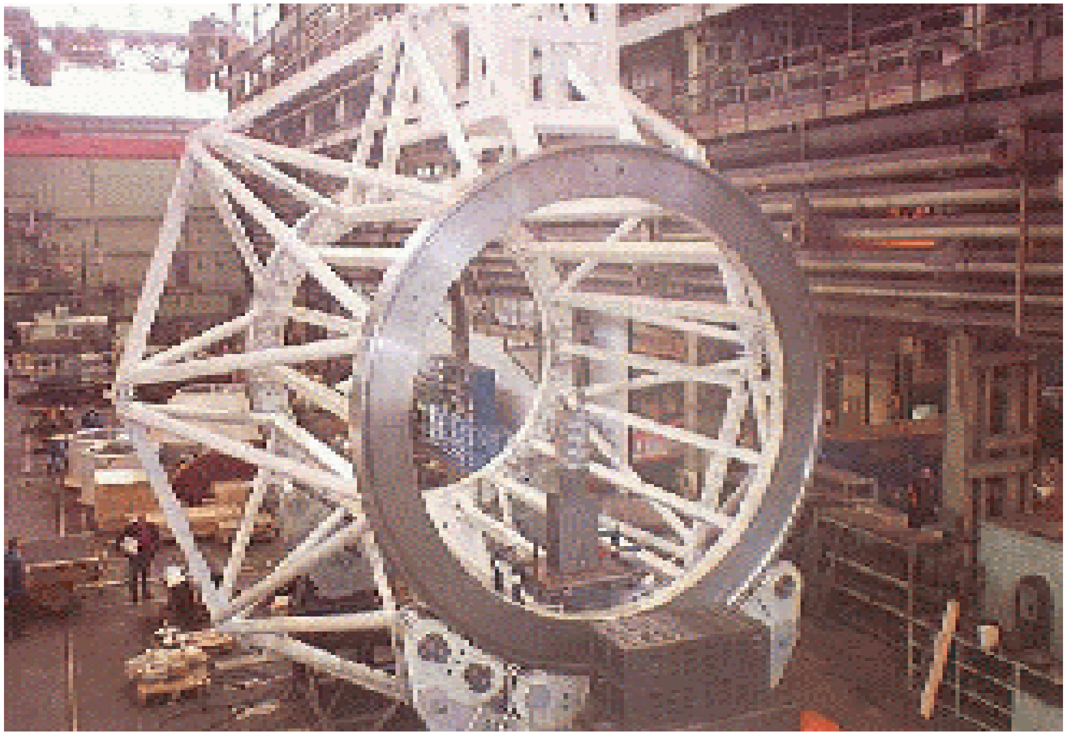
Paul Scherrer Institute (PSI), Zurich



It's much harder to bend 250 MeV protons

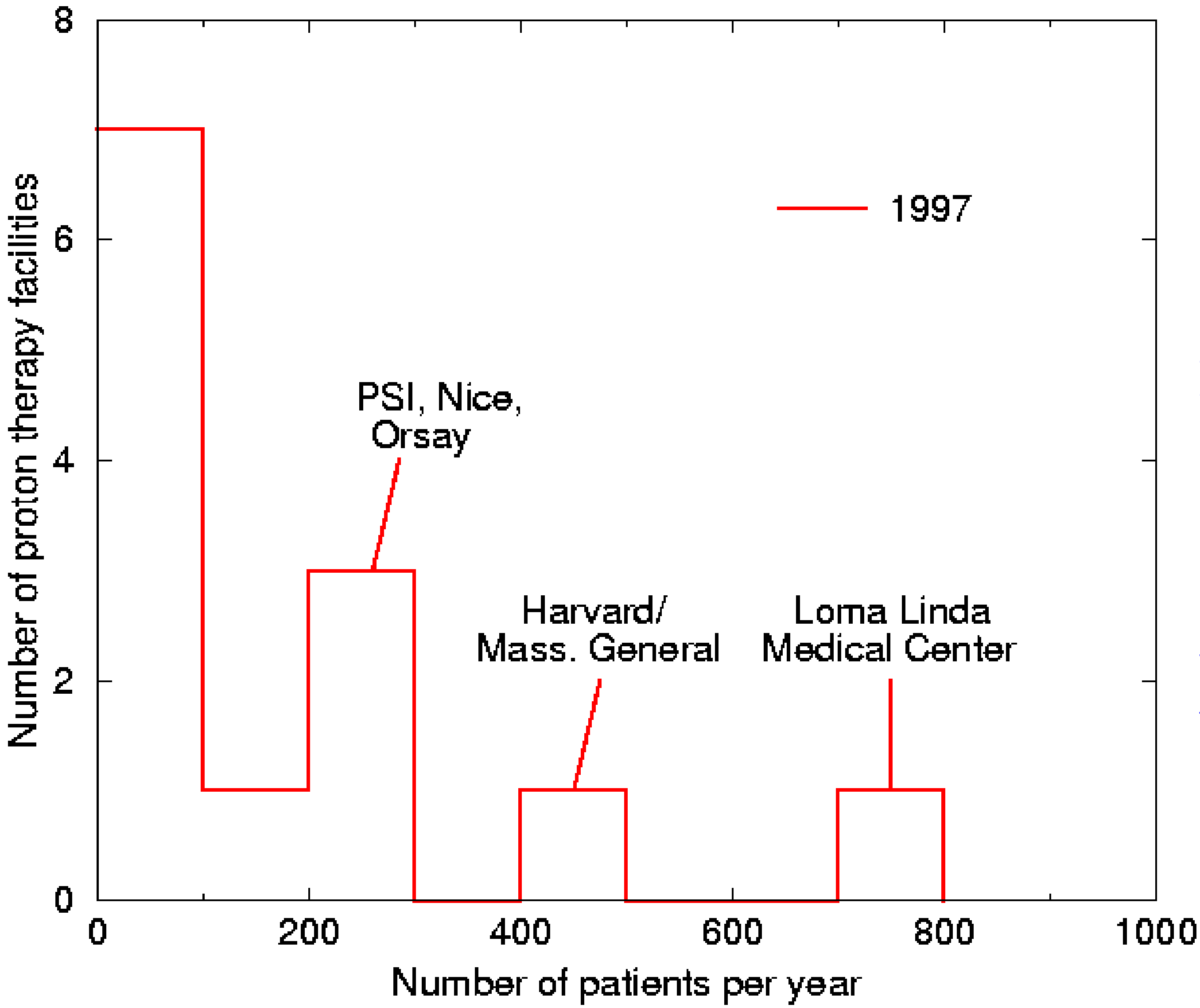
And the strong-back to hold 1 mm tolerances is formidable

Massachusetts General Hospital (MGH)



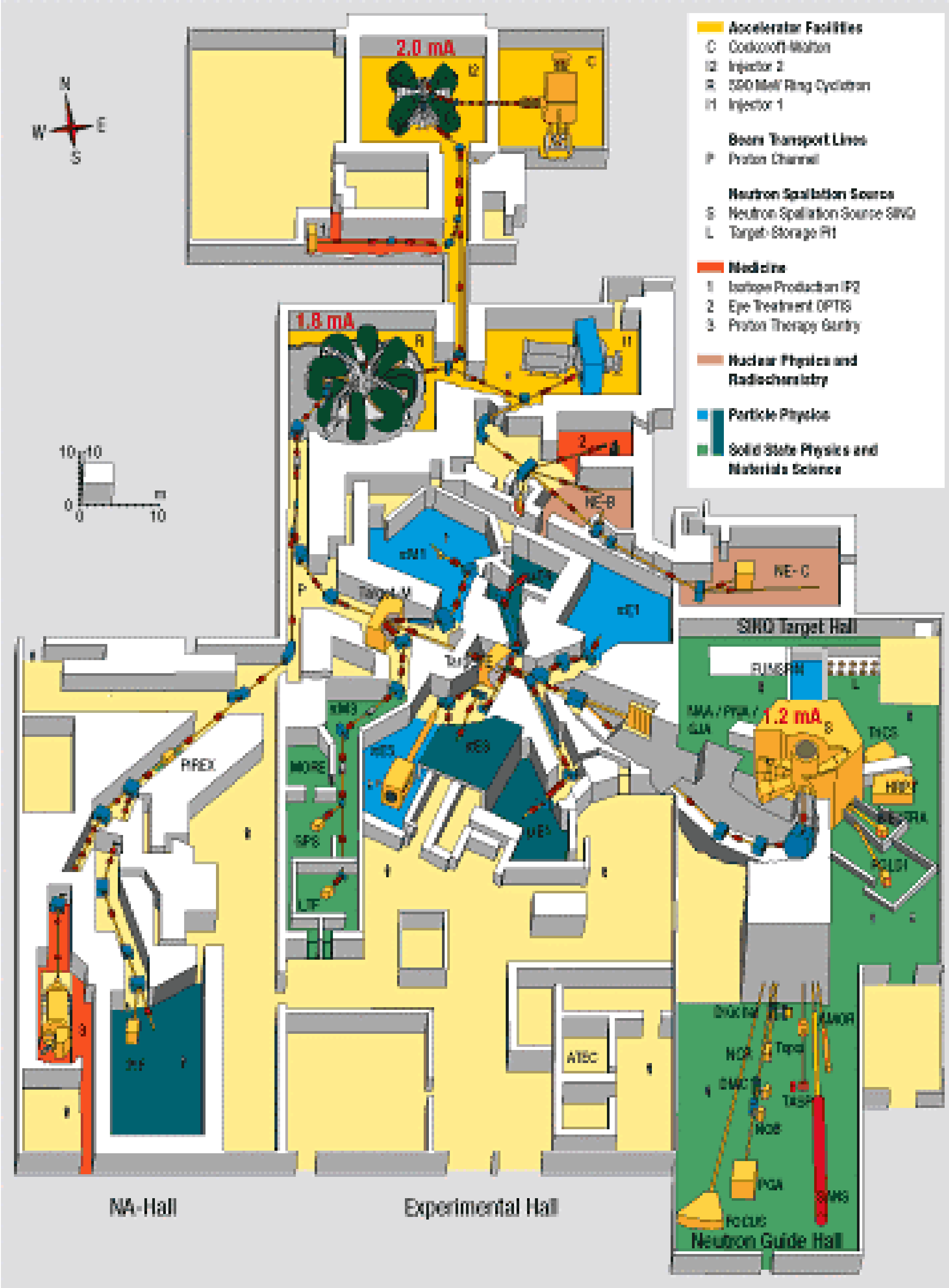
Where are the facilities? When?

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

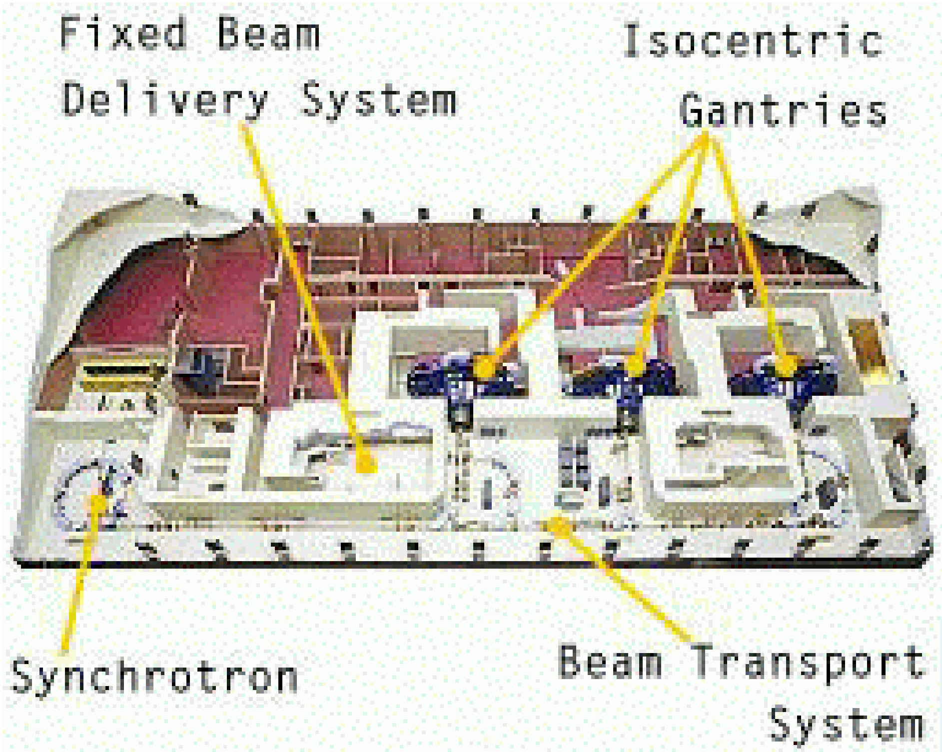


PSI (Zurich) (left)

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

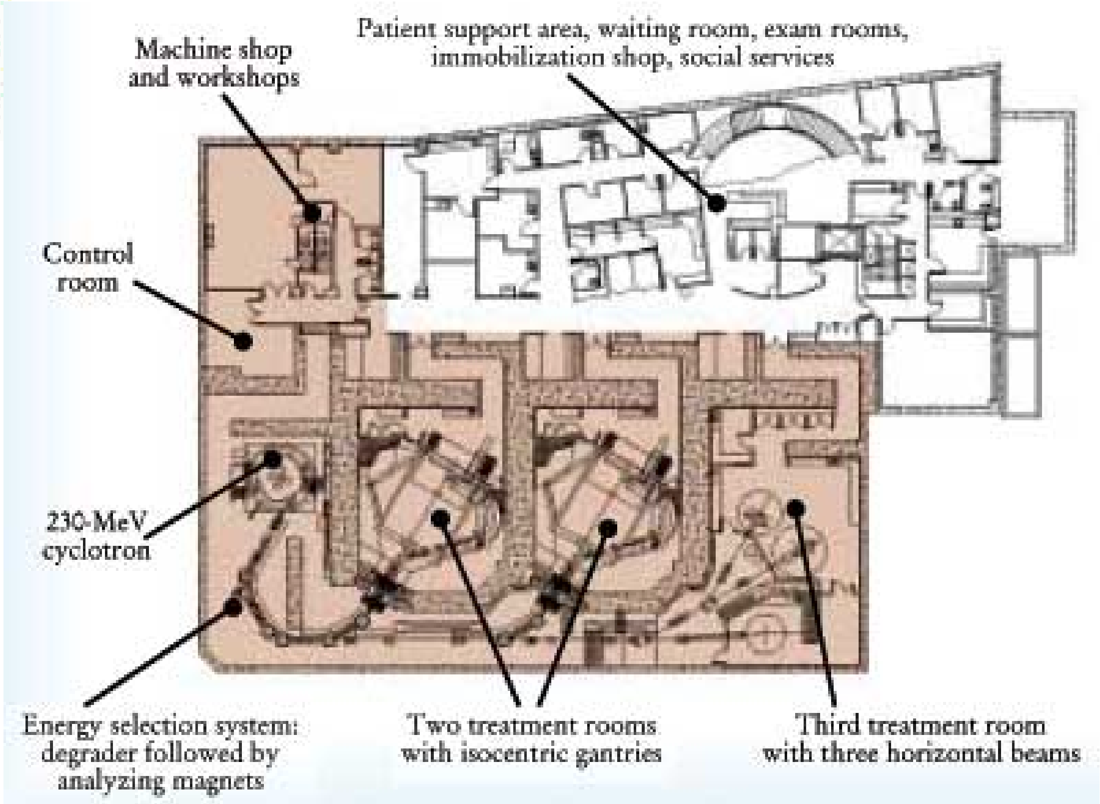
GSI (Darmstadt) (not shown)

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



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



Who	Country	Particle	Start Date	Recent Patient Total	Date of 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

Many sites are (considering) entering the field

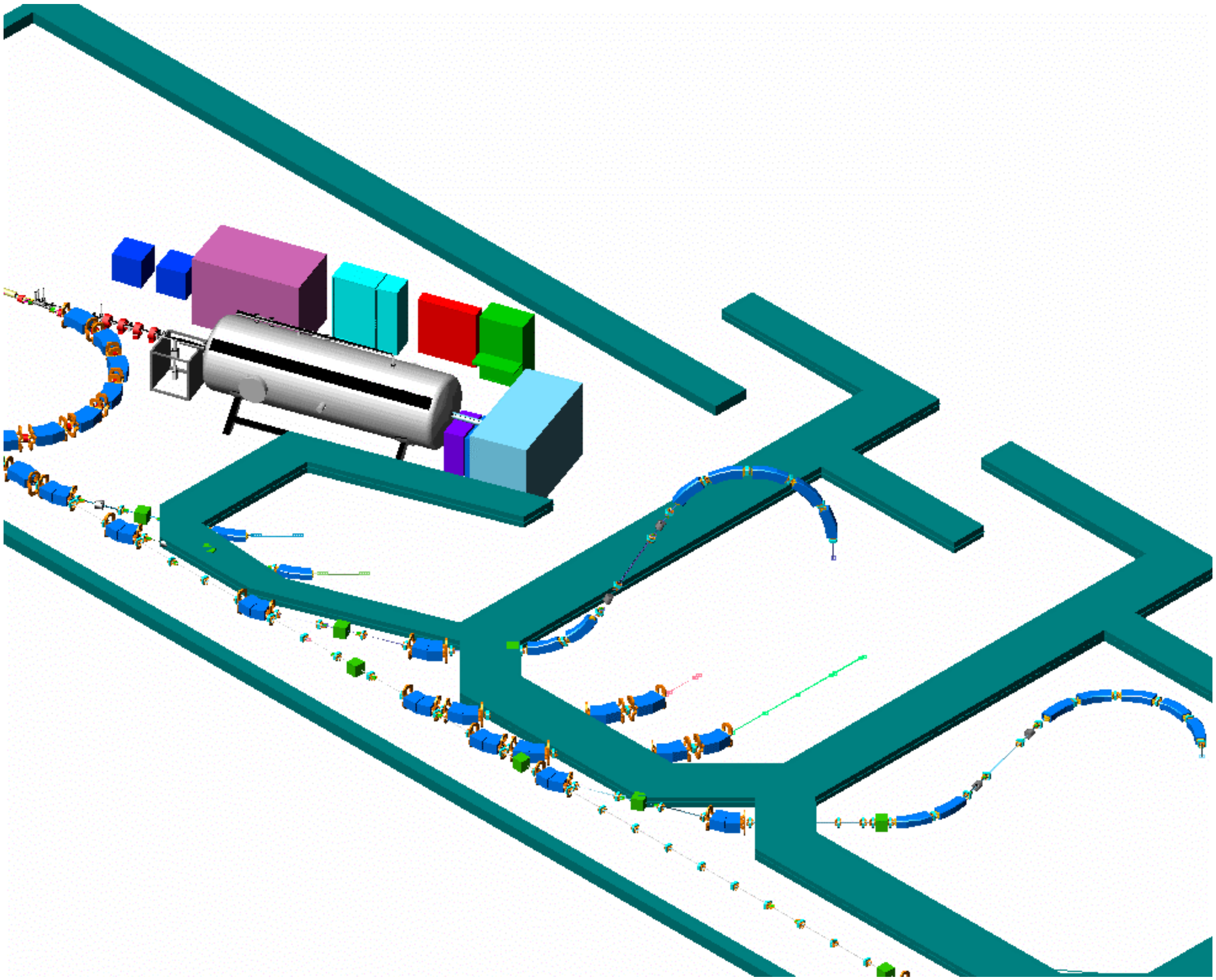
Including:

- **Karolinska (Stockholm)**
- **MD Anderson (Houston)**
- **"TERA" sites (Europe)**
- **U. Penn (left)**
- **U. of Florida (Gainesville)**

How is BNL involved?

Rapid Cycling Medical Synchrotron (RCMS)

BNL/ACCEL/AES/U. Penn(Physics)



RCMS is a second generation synchrotron

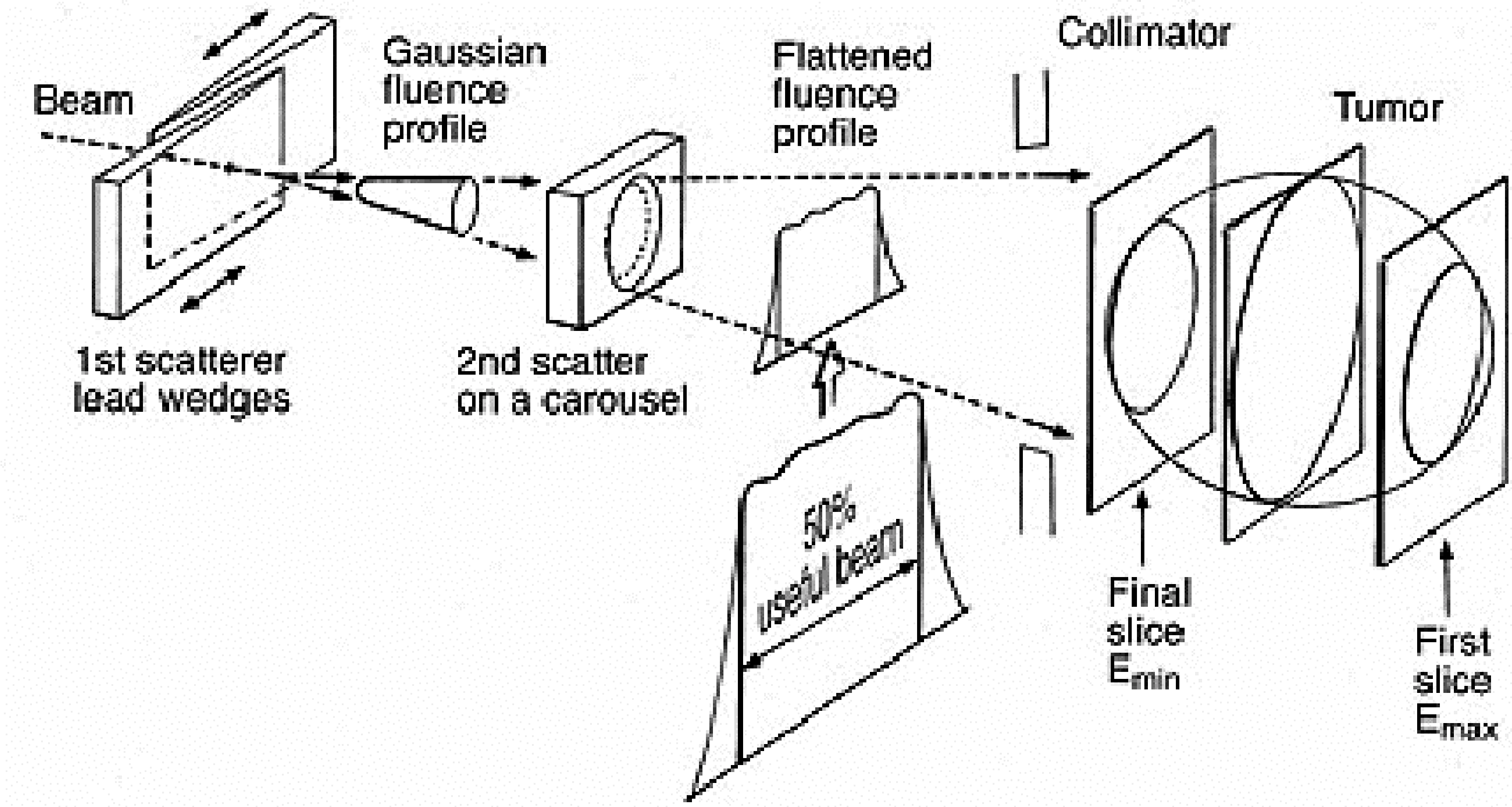
- **rapid cycling (30 Hz)**
- **strong focusing**
- **fast extraction**
- **ultimate flexibility**

The continuous upgrade path

to

precision 3-D multi-field irradiation of cancerous tumors

Traditional irradiation: PASSIVE SCATTERING

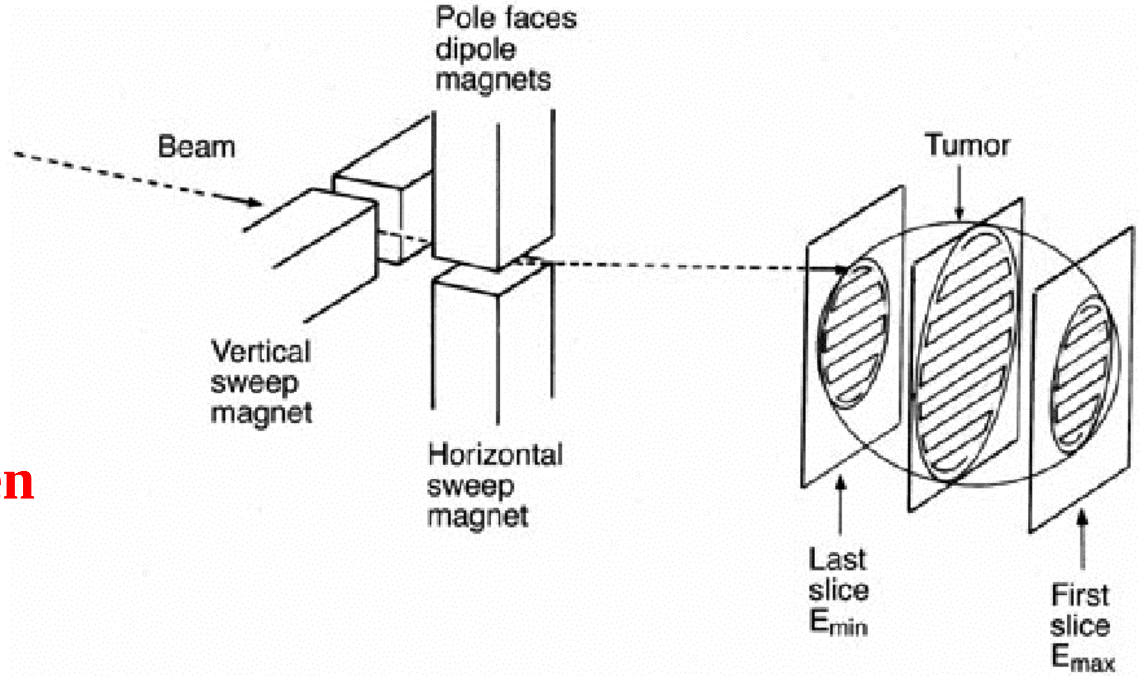


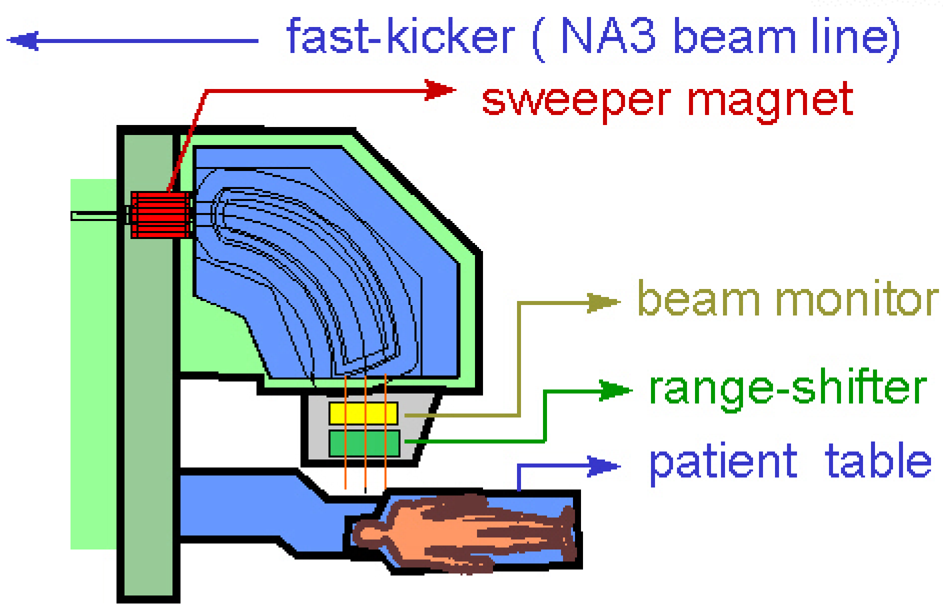
The sole (slow) variation: beam energy → depth

Contemporary irradiation: ACTIVE SCANNING

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

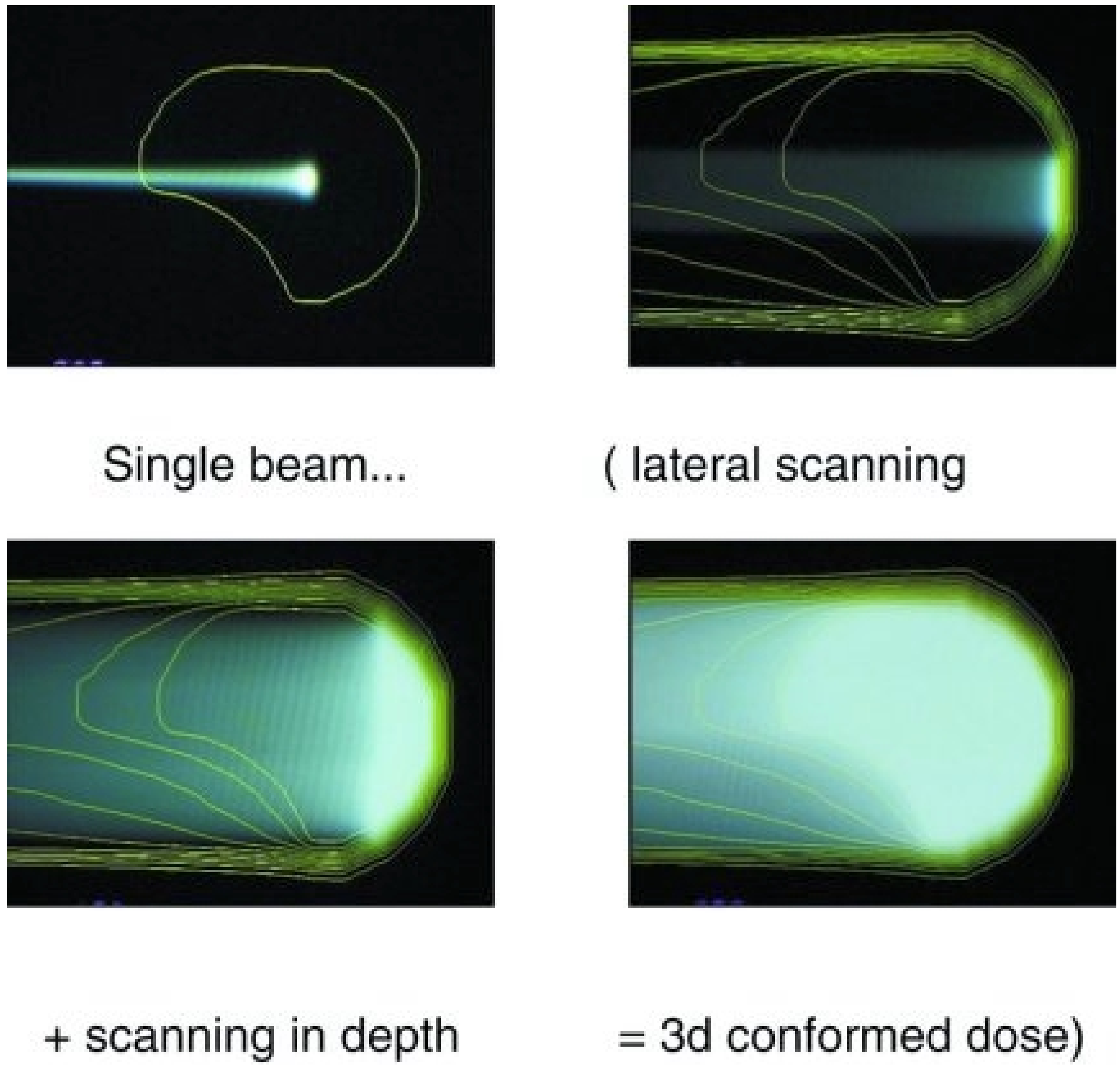
Although "simpler", active scanning has a higher controls burden





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

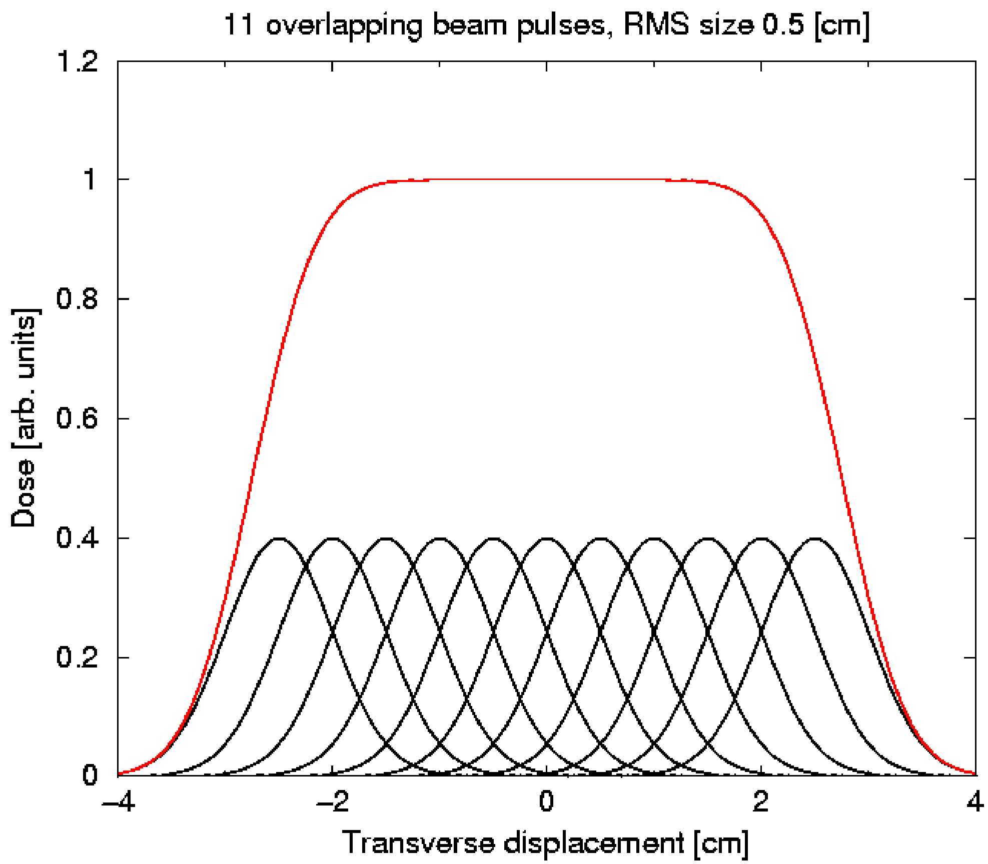
Active scanning - a much improved 3-D conformal dose

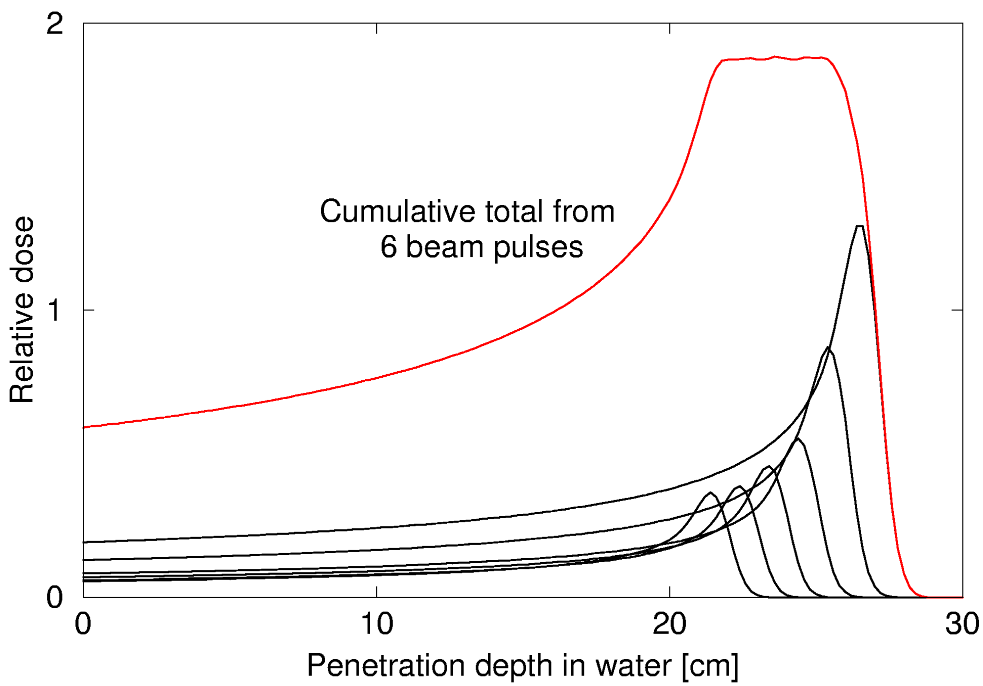


(Patient treatment demos courtesy of PSI)

The basic principles of overlapping doses are simple (and surprisingly effective) ...

... although fully realistic Patient Treatment Planning is a complex software challenge ...



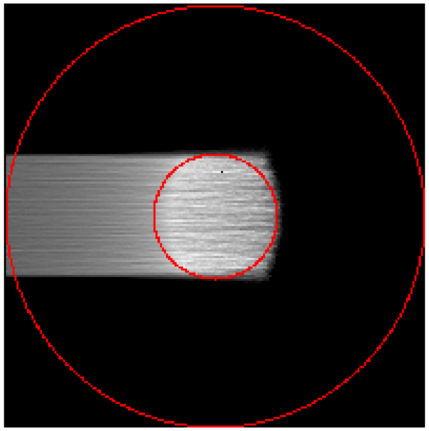


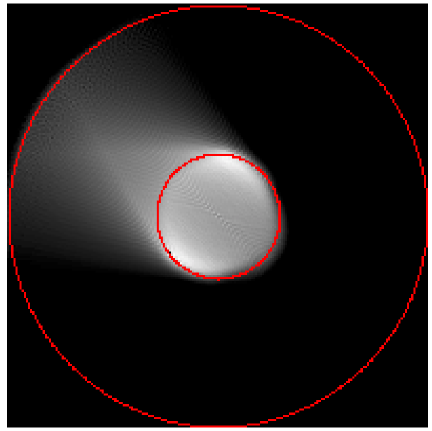
Fourth dimension: intensity (left)

Fifth dimension: field angle (over)

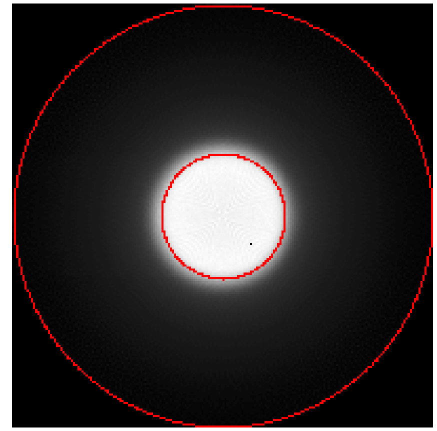
Multiple angles with a water "phantom"

One angle





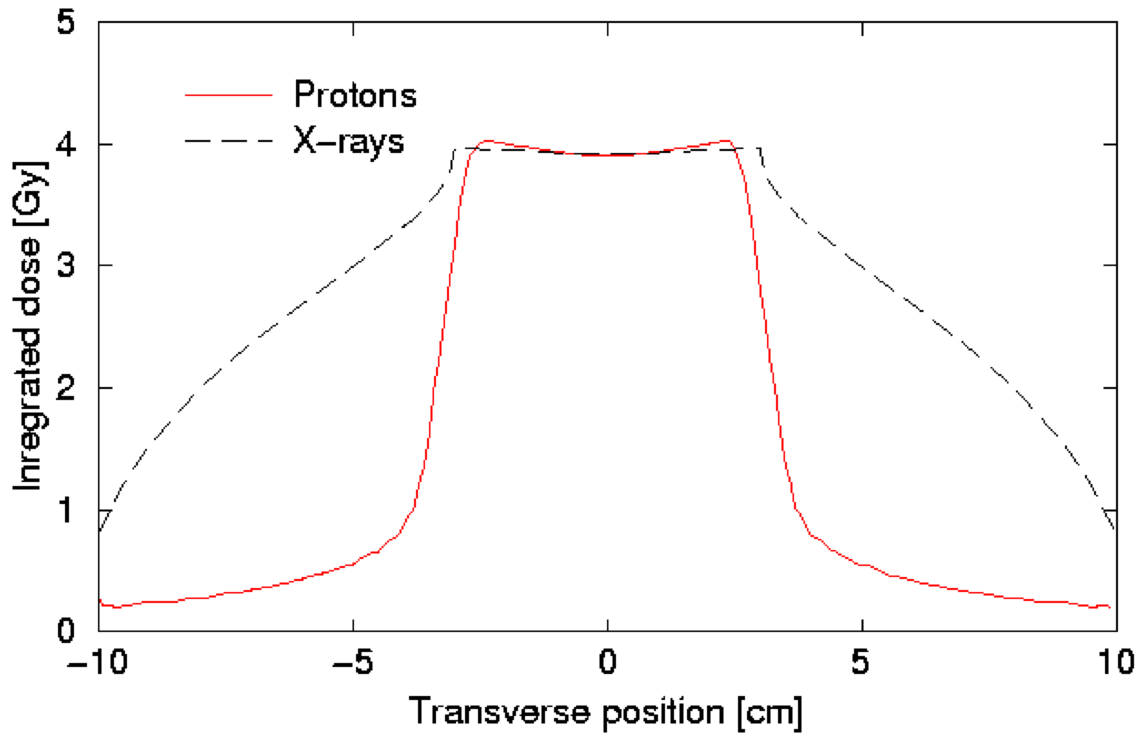
60 degree coverage



360 degrees

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)

1 field, passive scattering | **3 fields, passive**

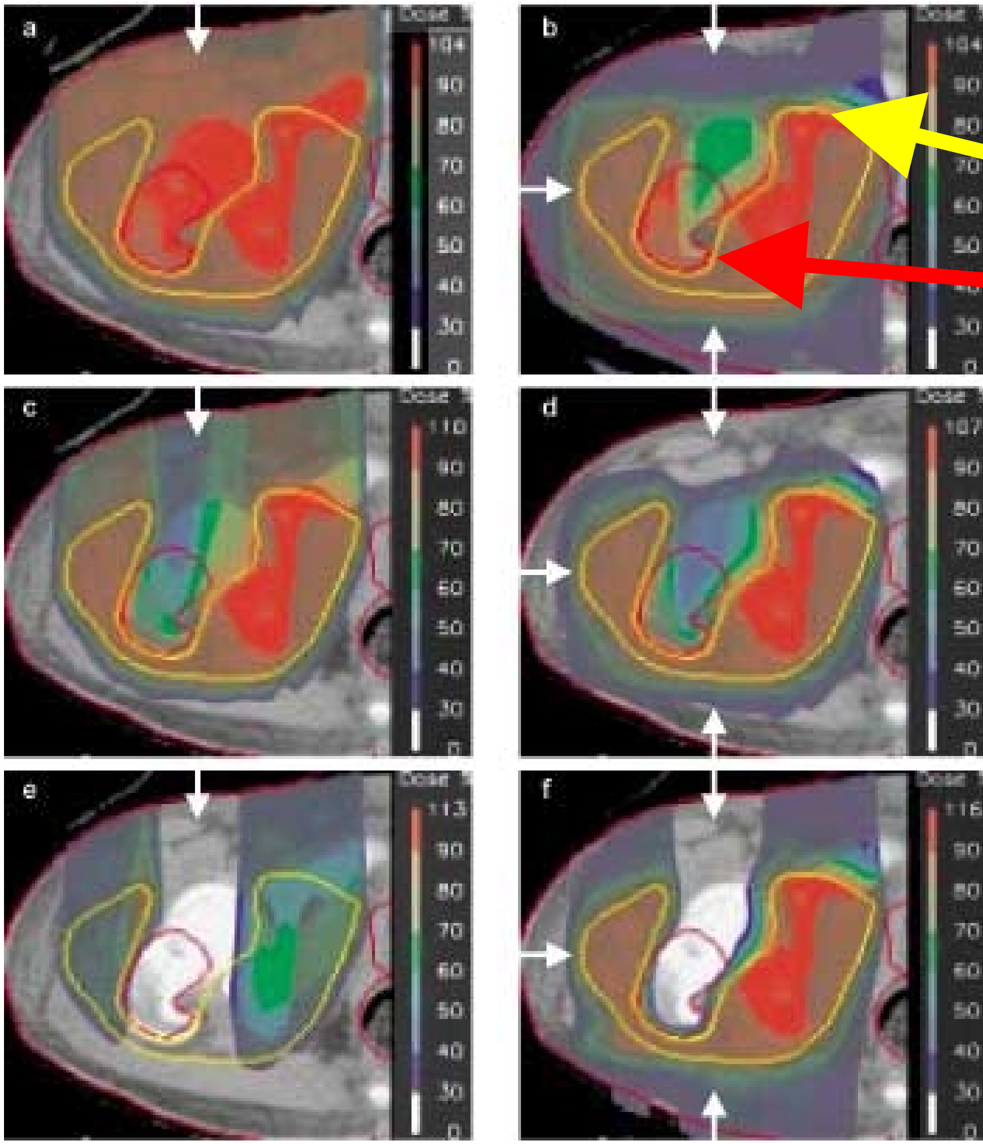
POOR

Target outlined in yellow

Critical structures in red

1 field, active, uniform dose

3 fields, active, uniform dose



GOOD

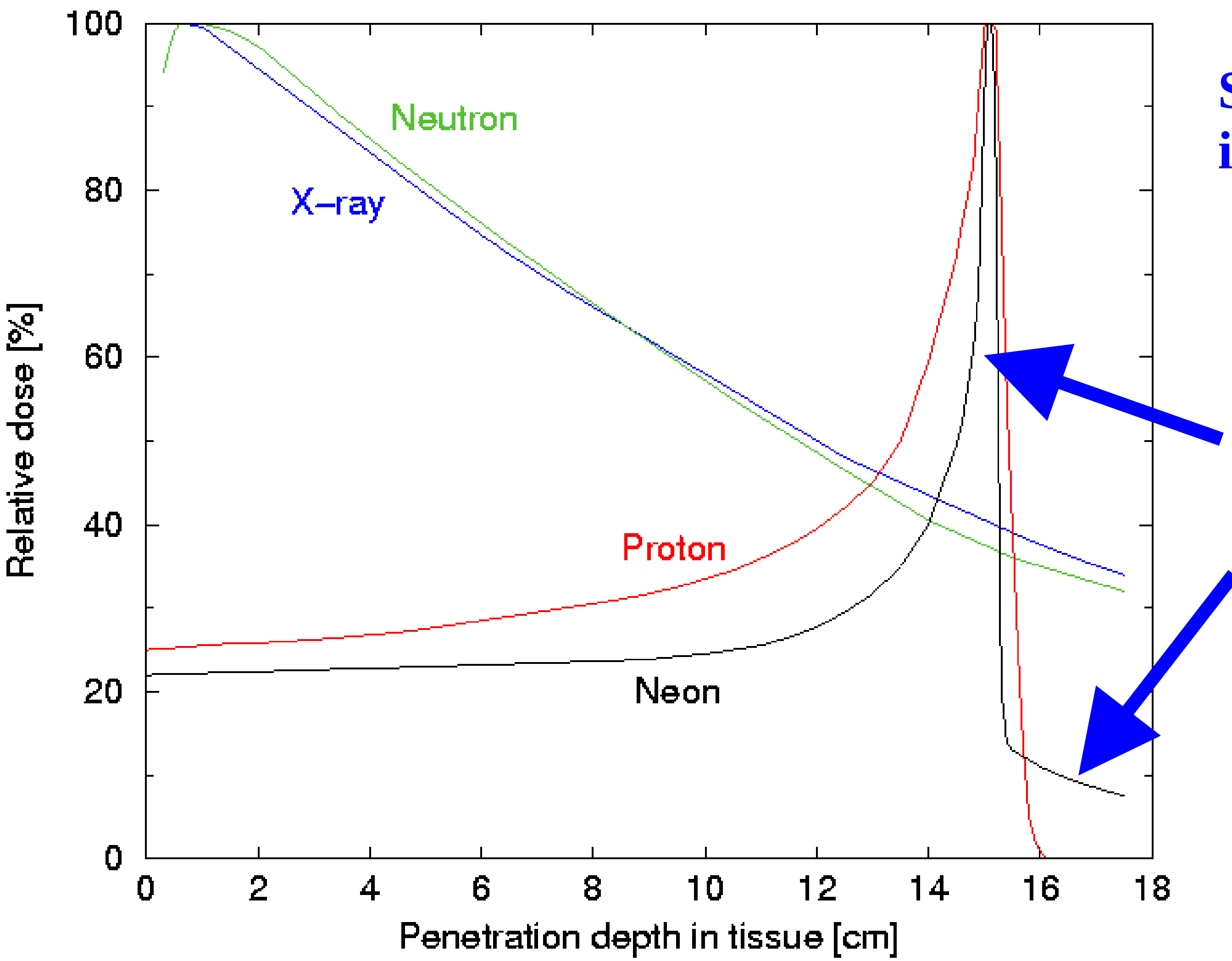
Bottom right is much better than top left!

1 field of 3, active, intensity modulated

3 of 3 fields, active, intensity modulated

Technology choices

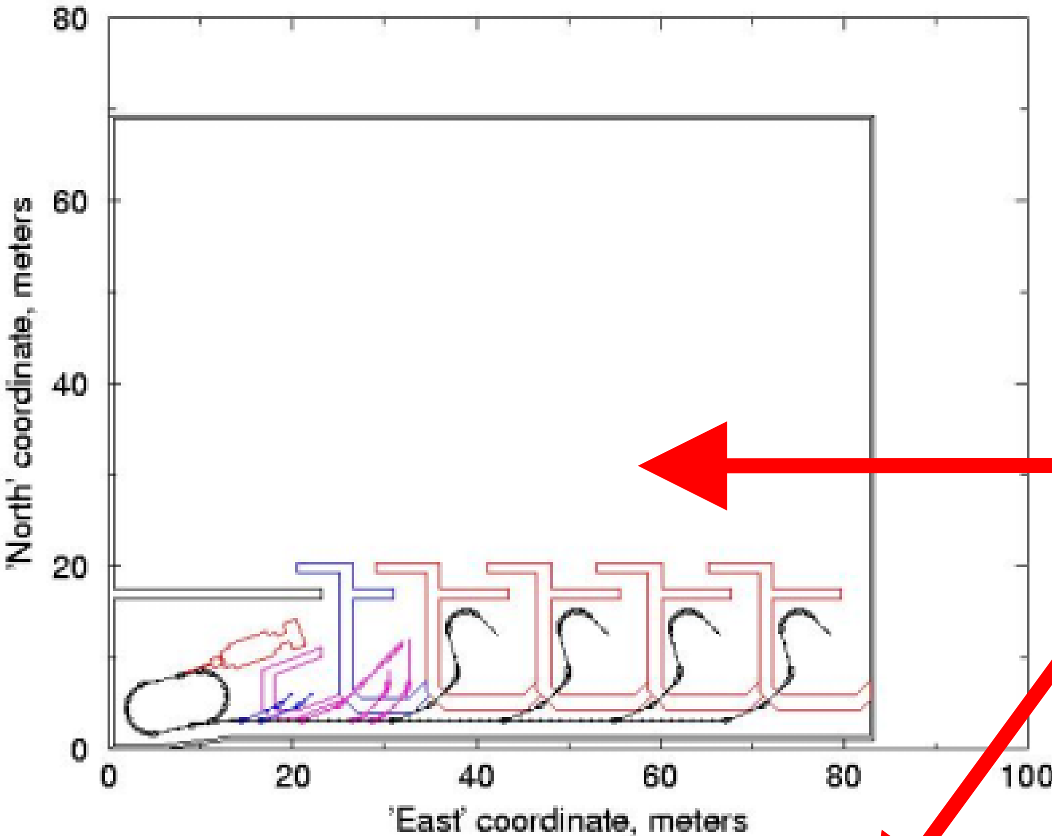
Which particle?



Some facilities favor light ions, eg Carbon or Neon

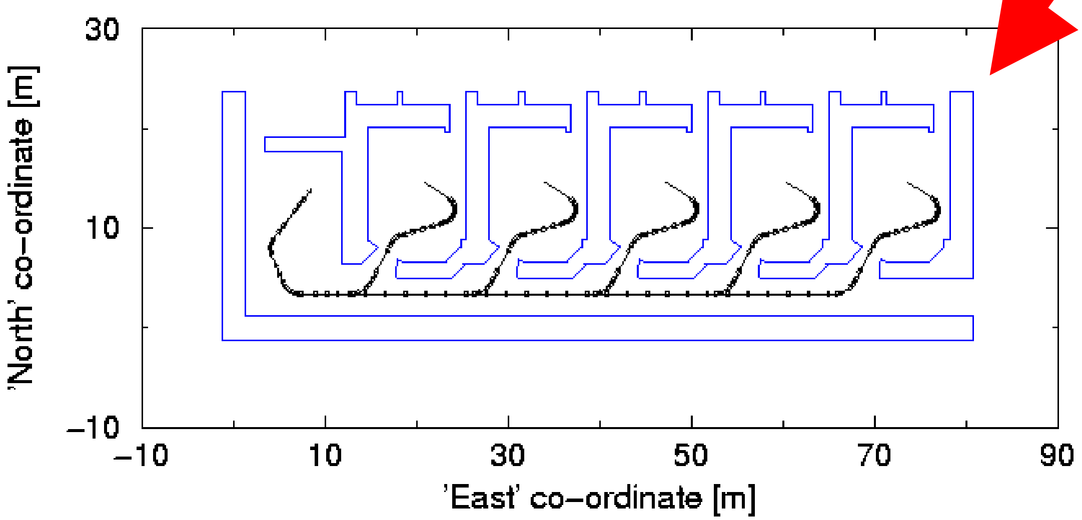
- **better clinical results ?**
- **sharper Bragg peak**
- **"knock-on" nuclear fragments**
- **require MUCH more magnetic field for same penetration depth**

Cyclotron or Synchrotron source?



A facility with a synchrotron source looks much like one with a cyclotron source (to a bird)

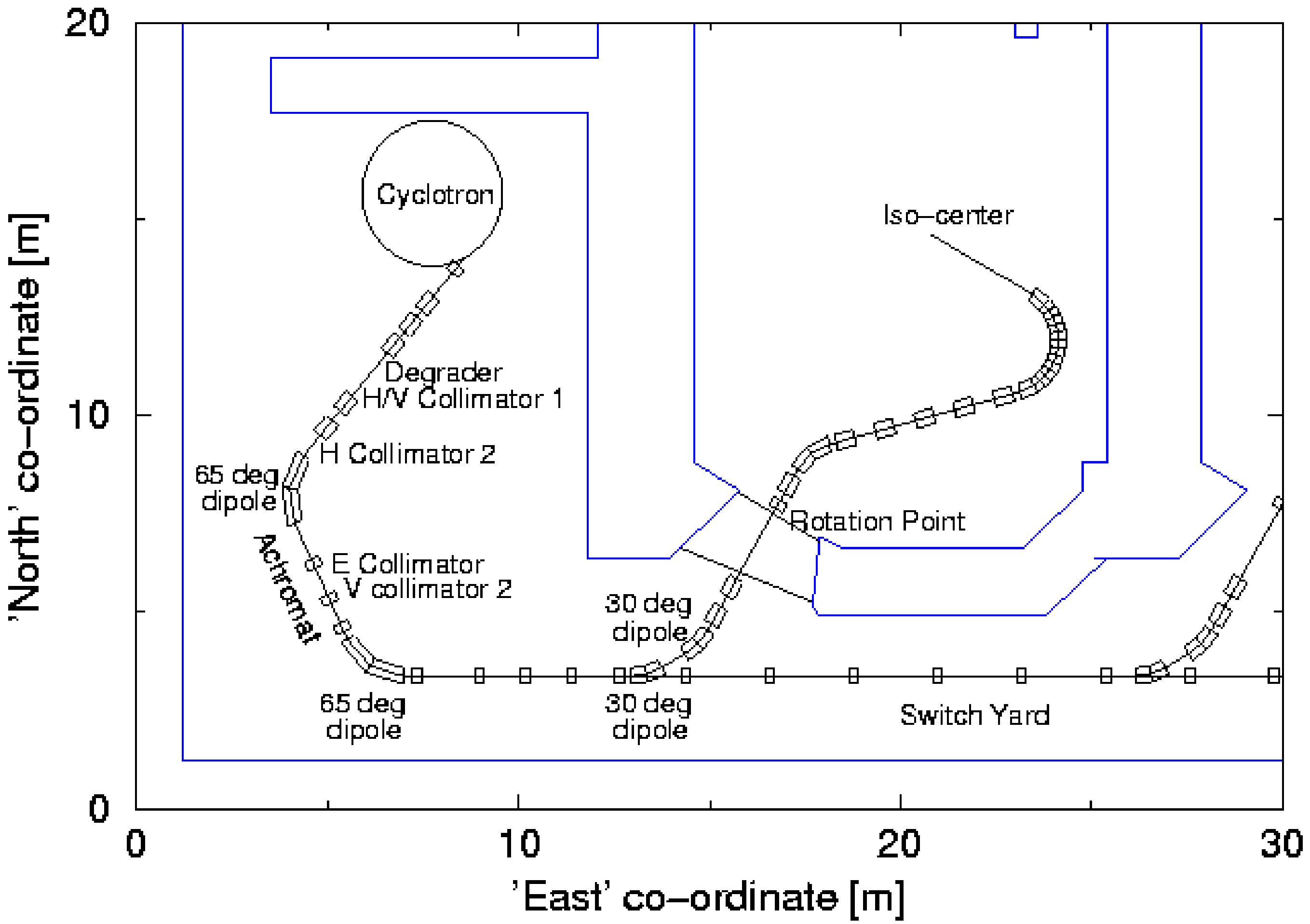
- **similar cost ~ $10 million**
- **modest fraction of total**



But the technical comparison goes beyond just "simplicity vs flexibility" ...

Modern cyclotron features

(ACCEL superconducting cyclotron for RPTC, Munich)



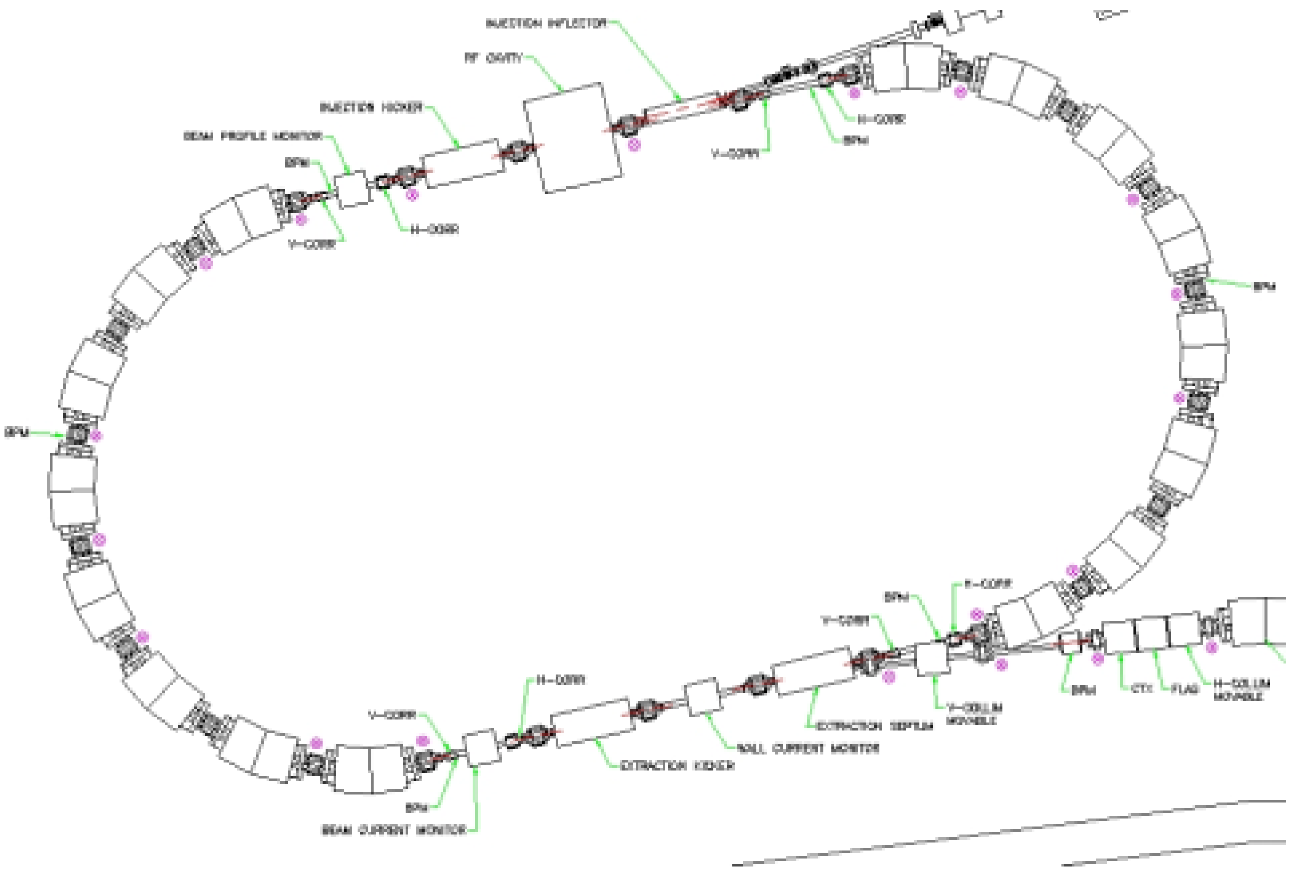
Fixed energy output, at constant current

- **Energy degrader reduces the energy**
- **Collimators scrape the beam**
- **Large "intrinsic" beam size (emittance) in all 3 dimensions**

Modern synchrotron features

(Rapid Cycling Medical Synchrotron, RCMS)

(see Cardona et al, N5-5)



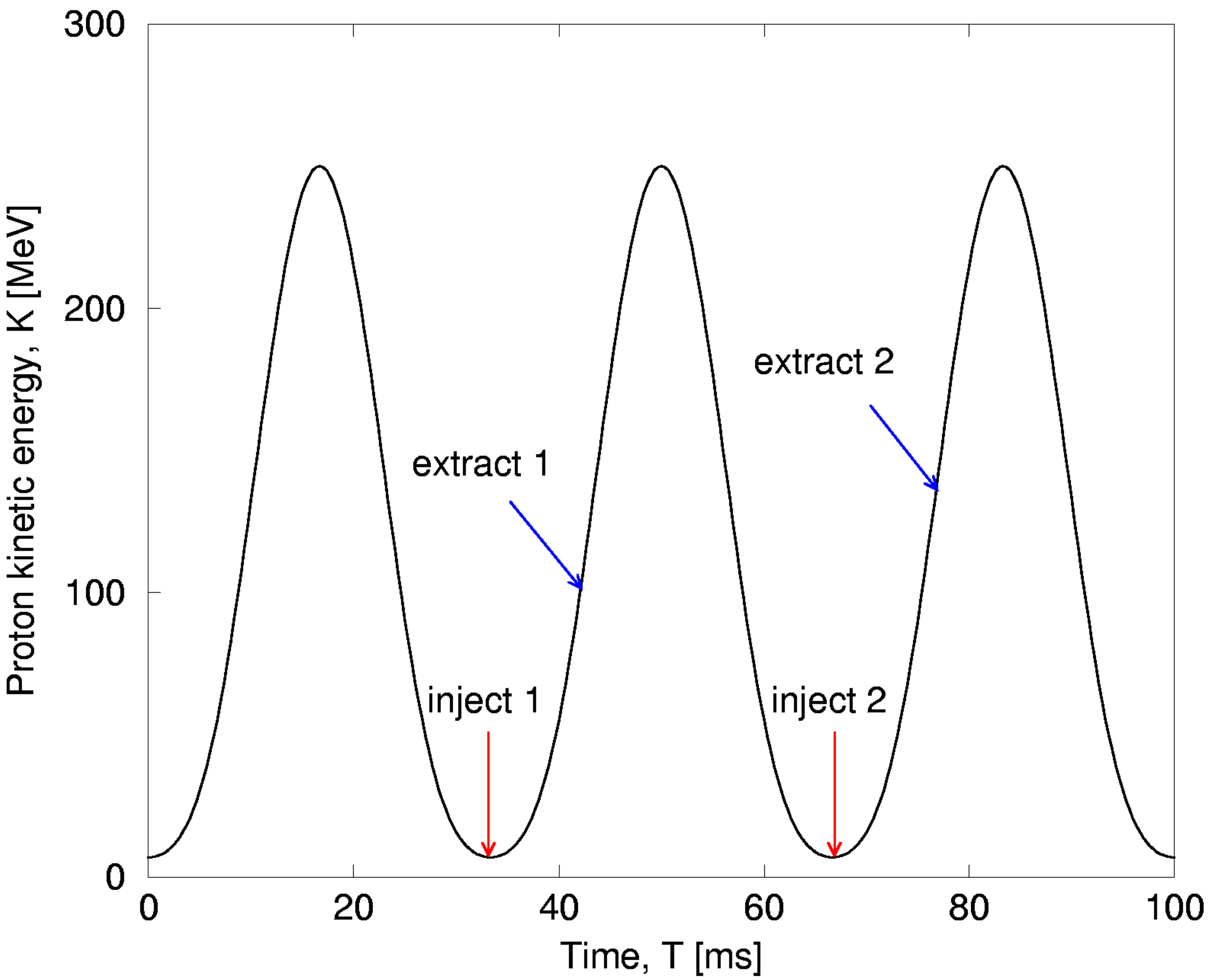
Accelerate
variable amount of beam
to a variable energy output

- **No energy degrader**
- **Small intrinsic beam size**

Accelerate
EITHER
- **a little beam often, extract in 1 turn**

OR
- **a lot of beam rarely, extract slowly in many turns**

Rapid cycling - energy flexibility



RCMS "rings"
like a transformer

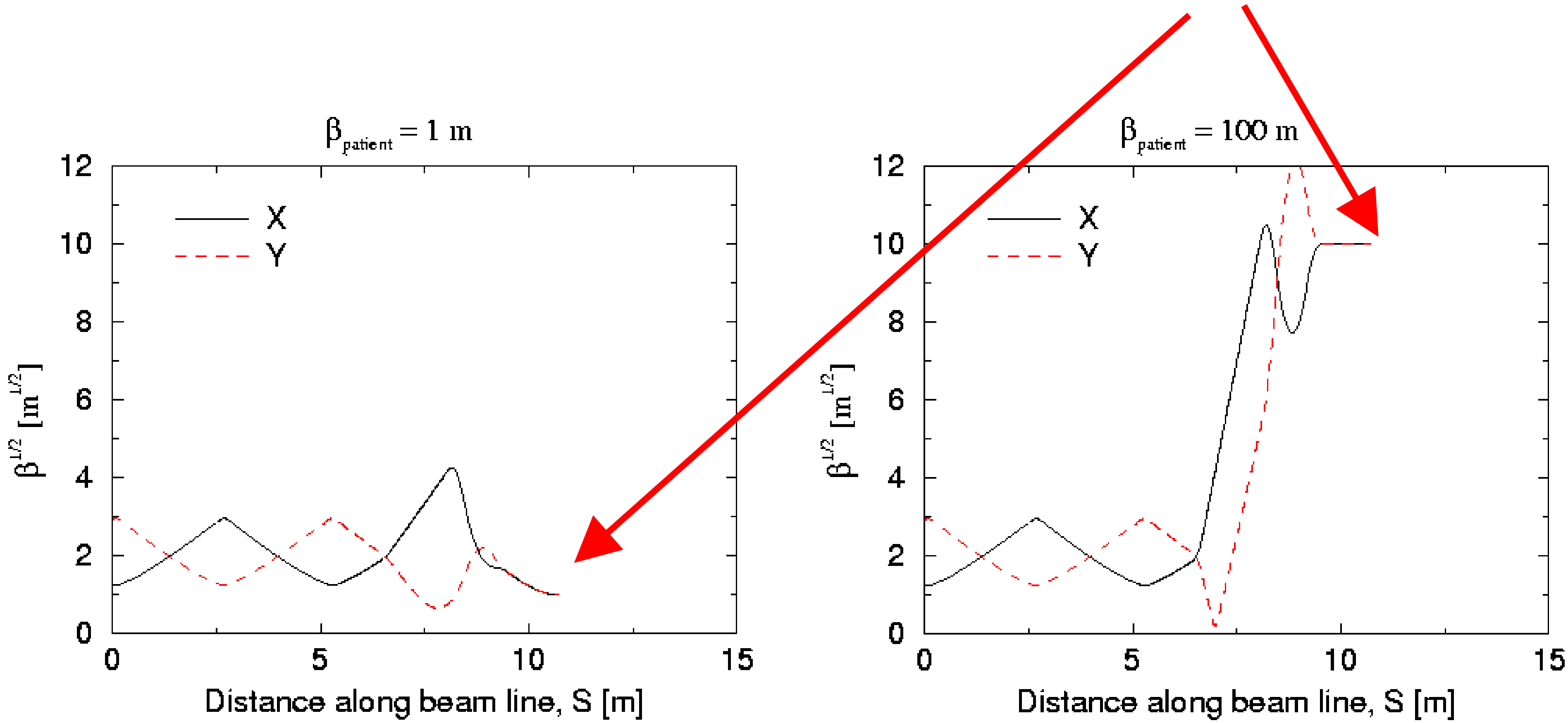
- **permitting ultimate energy flexibility**
- **discrete low intensity beam delivery**
- **intrinsic safety!**

Flexible beam size at patient

Small emittances (with synchrotrons)

- **small transverse beam size**
- **small beam pipes**
- **small cross section magnets**

- **light gantries**
- **flexible spot size at the patient (eg, factor of 10)**

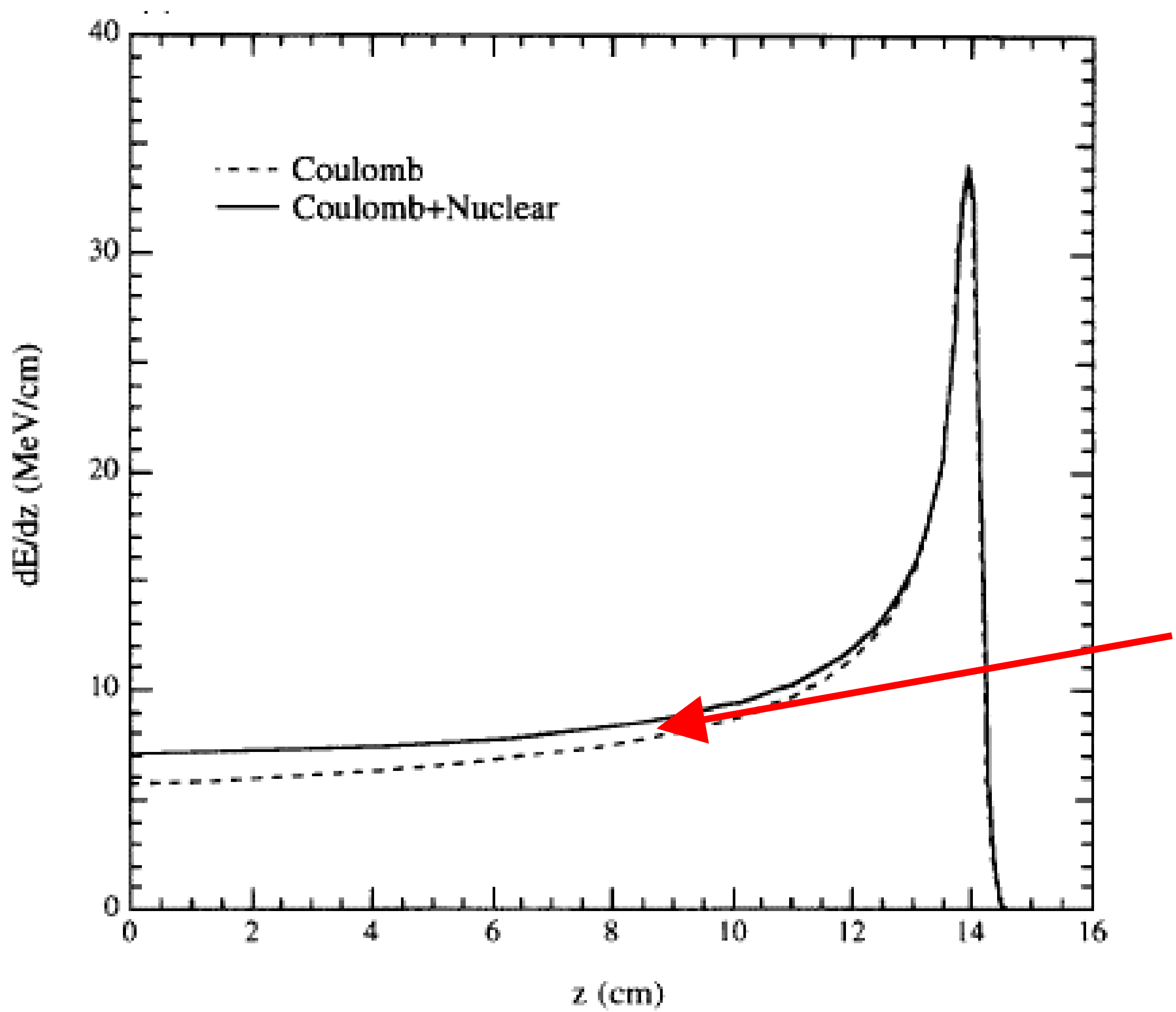


	Synchrotron	Cyclotron
Energy flexibility	Very high (fast extraction)	Fixed (needs degraders)
Typical diameter	7 m	4 m
Power consumption	Low	High (except supercon.)
Typical beam size	1 mm	10 mm
Typical energy spread	$< 0.1\%$	$\sim 0.5\%$
Beam intensity	High	Very high
Beam delivery efficiency	$> 95\%$	$1\% - 95\%$
Complexity	Flexible	Simple
Weight	Light	Massive
Approximate cost	10 M$	10 M$
Other costs	Lower	Higher

Proton Imaging:

- proton driven PET
- proton radiography (< 500 MeV)
- proton movies (multi GeV)

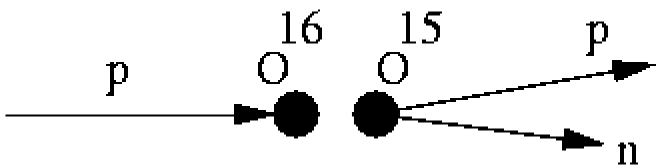
Proton driven PET



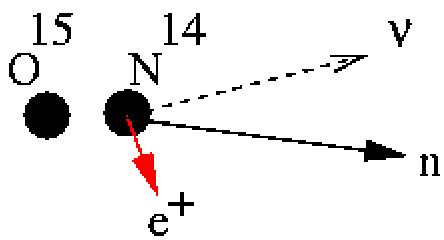
A small but significant fraction of proton dE/dx loss is due to nuclear interactions

some of which generate positron emitters

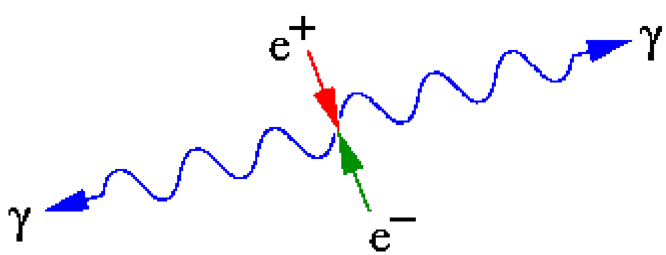
Is the (high) therapy dose going to the right place?



Occasionally a proton generates an ^{15}O 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

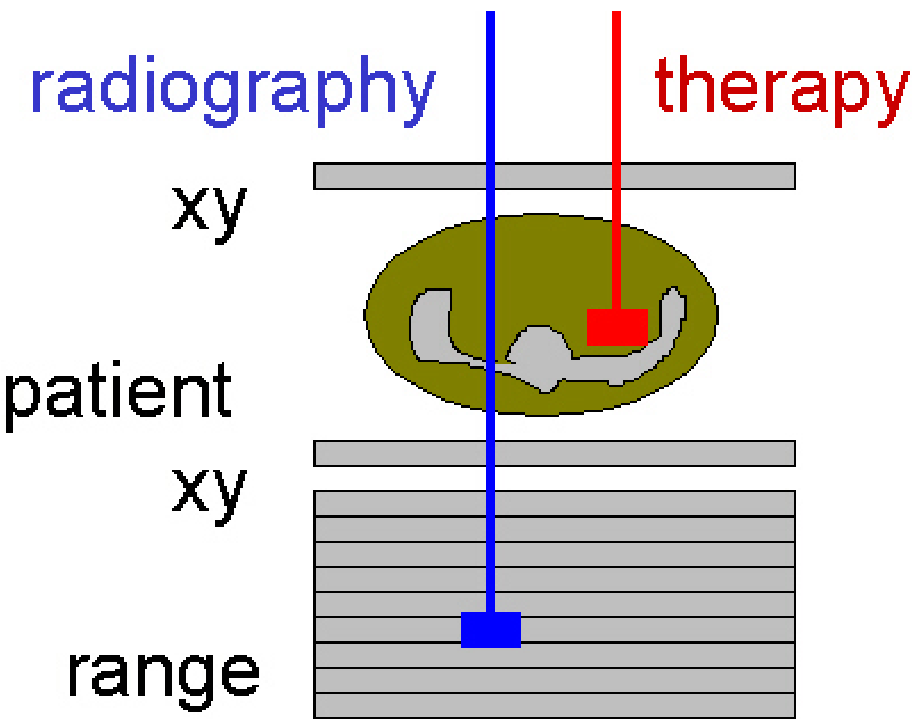
Nuclear cross sections vary rapidly with energy ...

Interesting work is also going on with C-12 driven PET, eg at GSI

(see Parodi et al, M7-53)

Proton Radiography

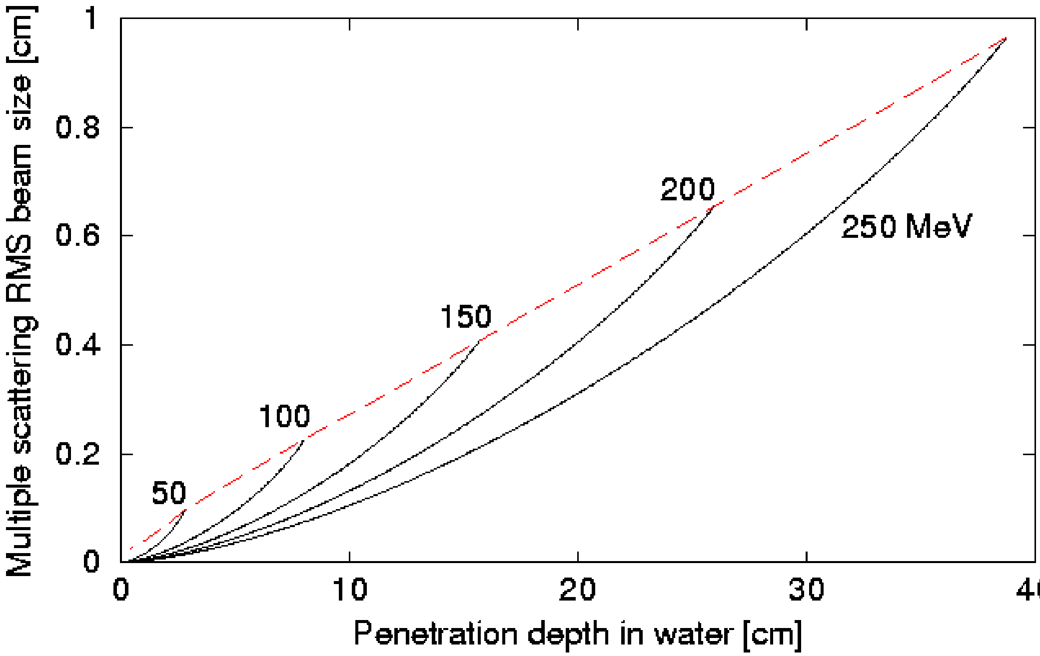
The protons go through the patient
Higher energy, small dose



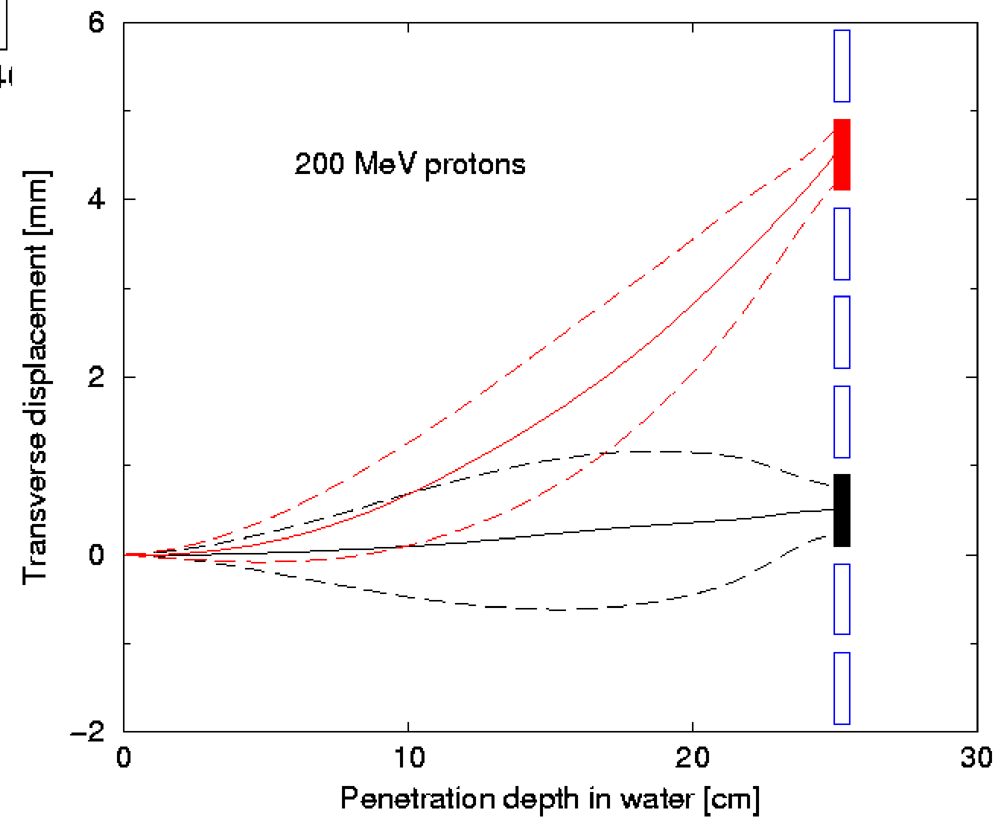
Radiograph of a phantom
Uwe Schneider PhD thesis (PSI)

The PSI therapy gantry, with prototype detector in place

Multiple scattering!



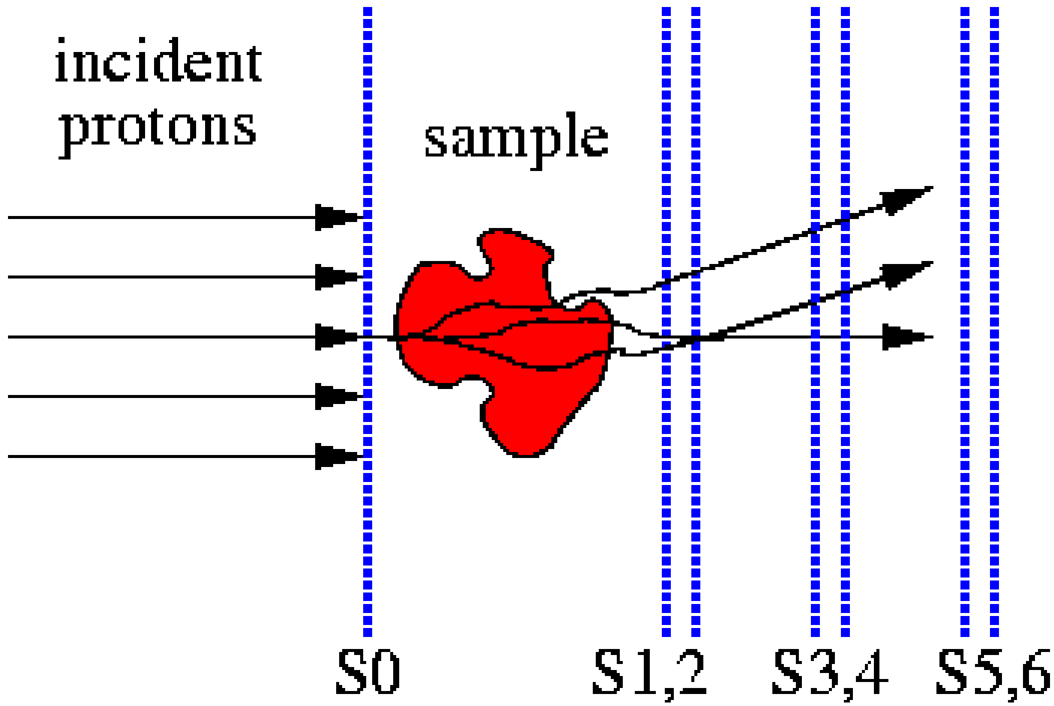
Historically, proton radiography was rejected because multiple scattering made blurry images



Modern reconstruction algorithms can make sharp images ...

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

Proton imaging spectrometer



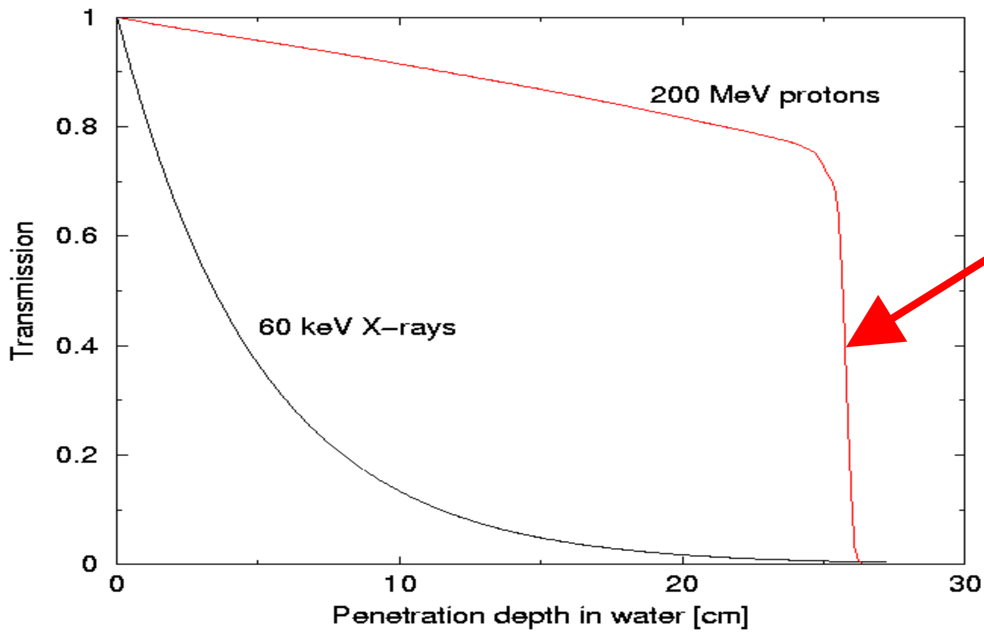
Multiple planes of silicon for position, angle, and energy measurements

How might such a detector be implemented?

see

- **Sadrozinski, M2-1**
- **Sadrozinski et al, M6-2**
- **Yoshida et al, N22-3**

Modern techniques appear to promise ultra-low dose CT !



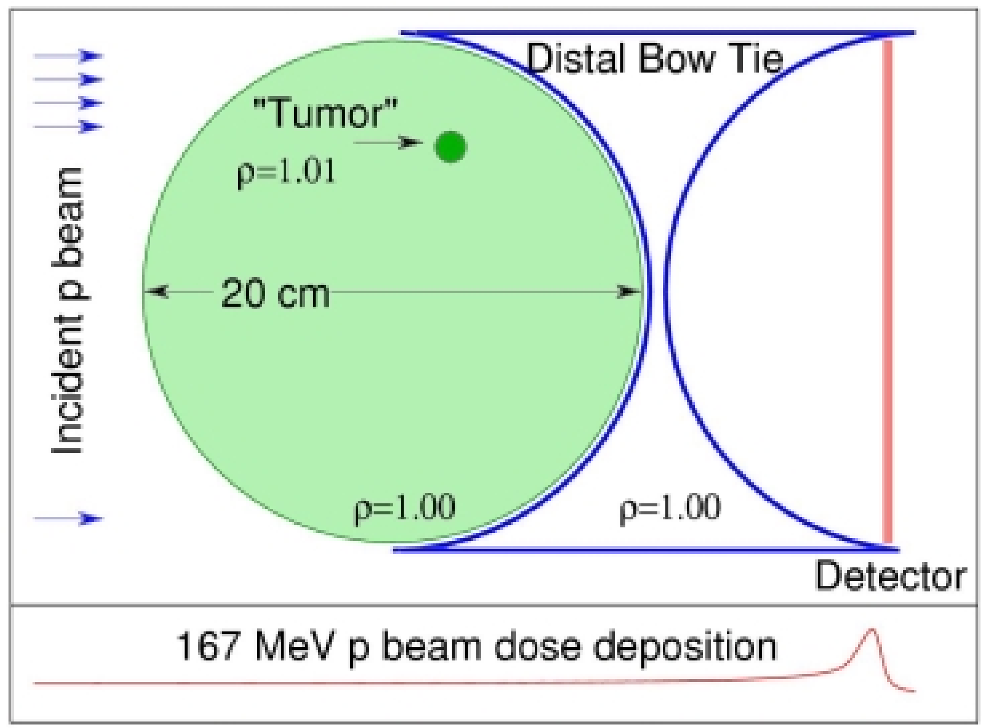
The very steep slope of transmission vs depth allows high sensitivity with few protons ...

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

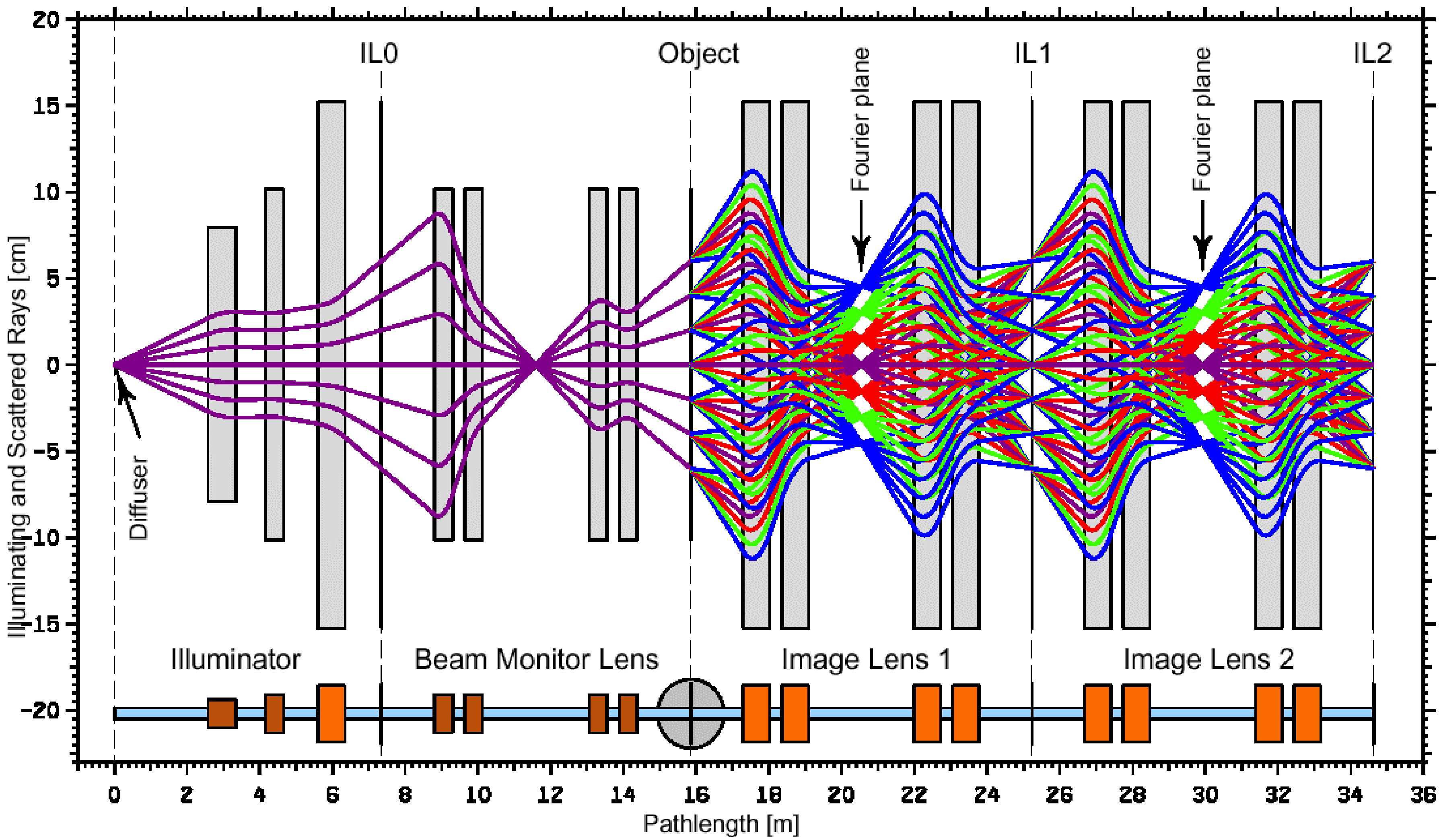
Energy flexibility is desirable ...

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

(see Satogata et al, M10-204)

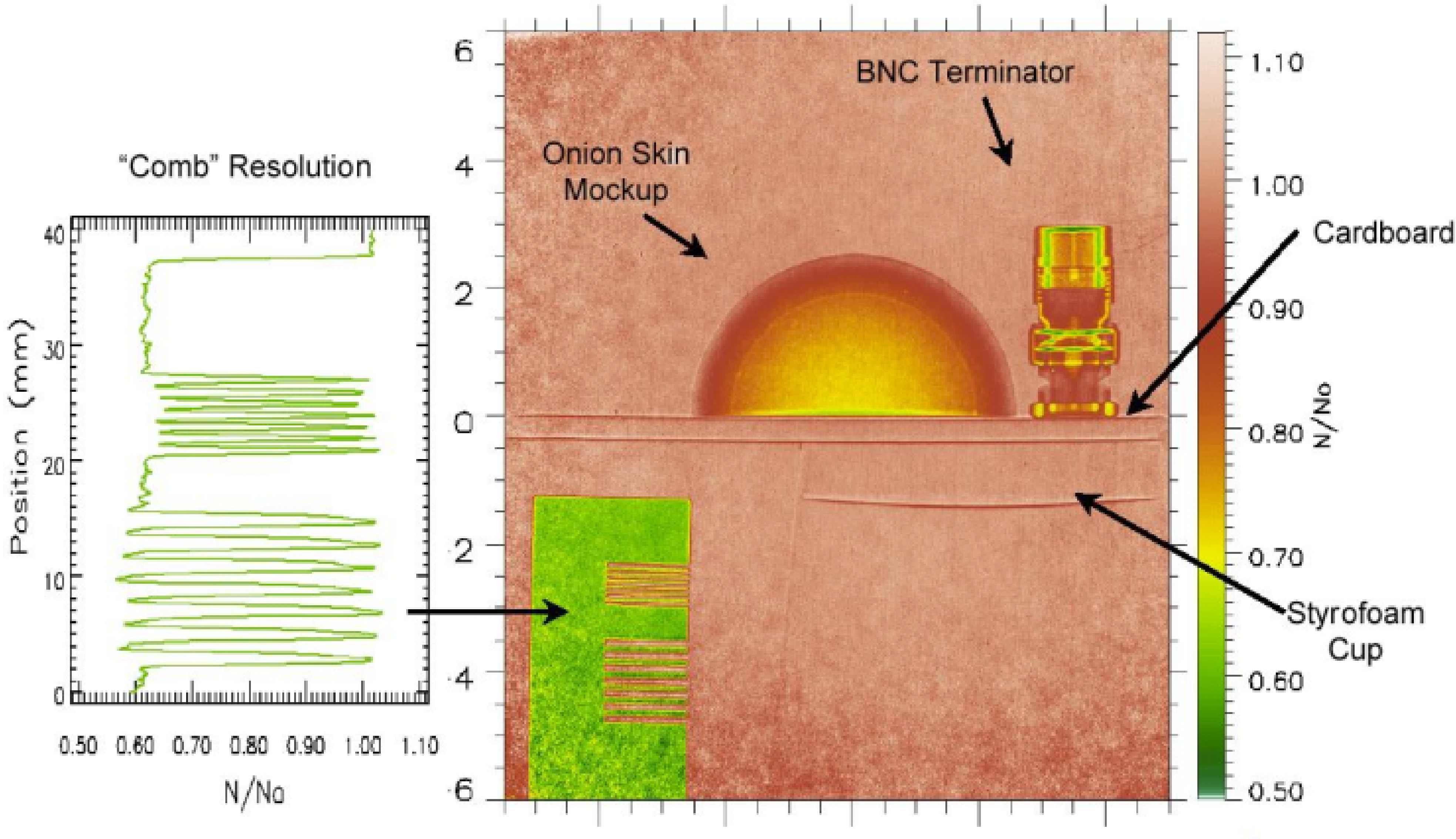


Proton Movies (multi-GeV)



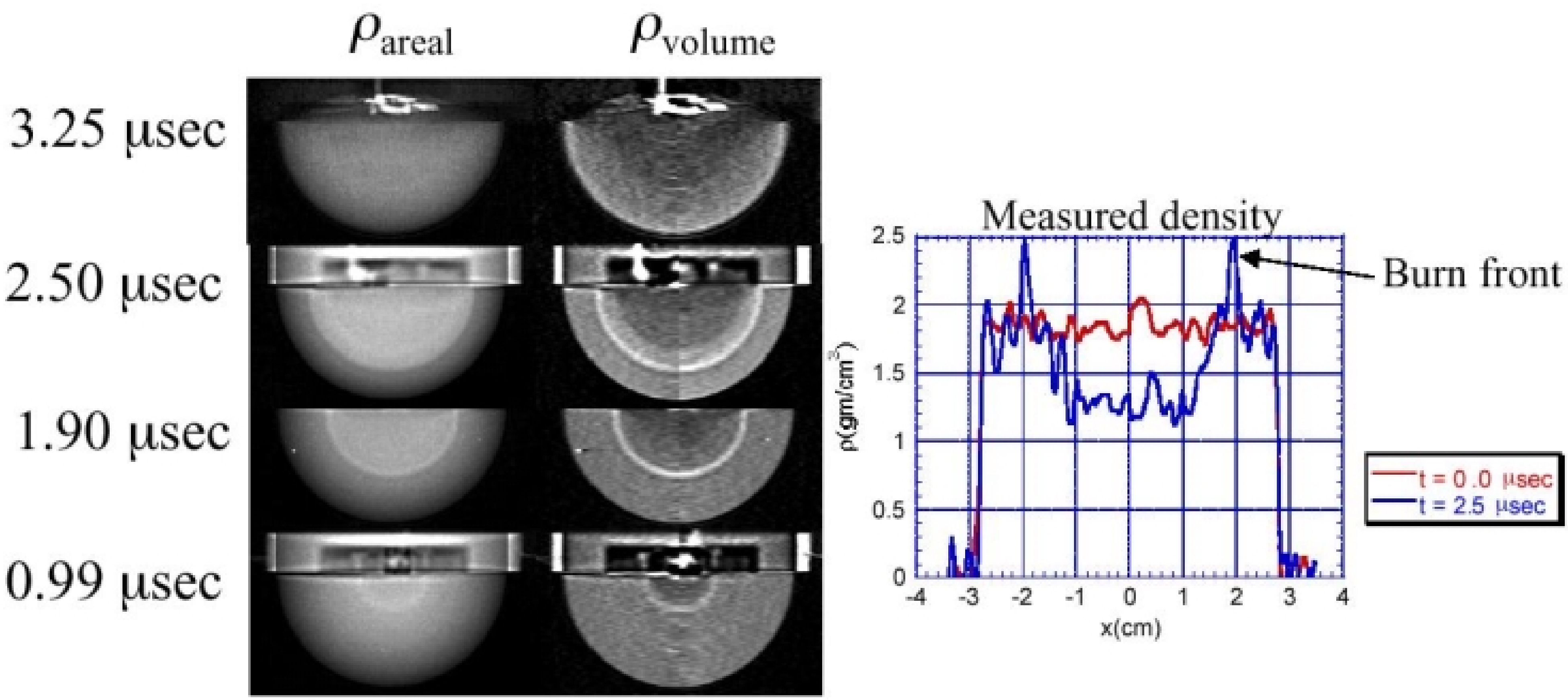
Lensing system (4 to 24 GeV) in place at BNL - not on a gantry!

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



Sub-millimeter resolution

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



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

Summary

1) First generation proton therapy facilities are now "proven" technology

2) They are one (or more) orders of magnitude more complex, and expensive, than conventional (electron/photon) facilities

3) Second generation proton therapy accelerators are arriving in force

4) For a few dollars more, put proton imaging on a gantry?

a) proton driven PET	high therapy dose QA
b) radiography	low dose CT

5) What does the optimal radiography detector look like?