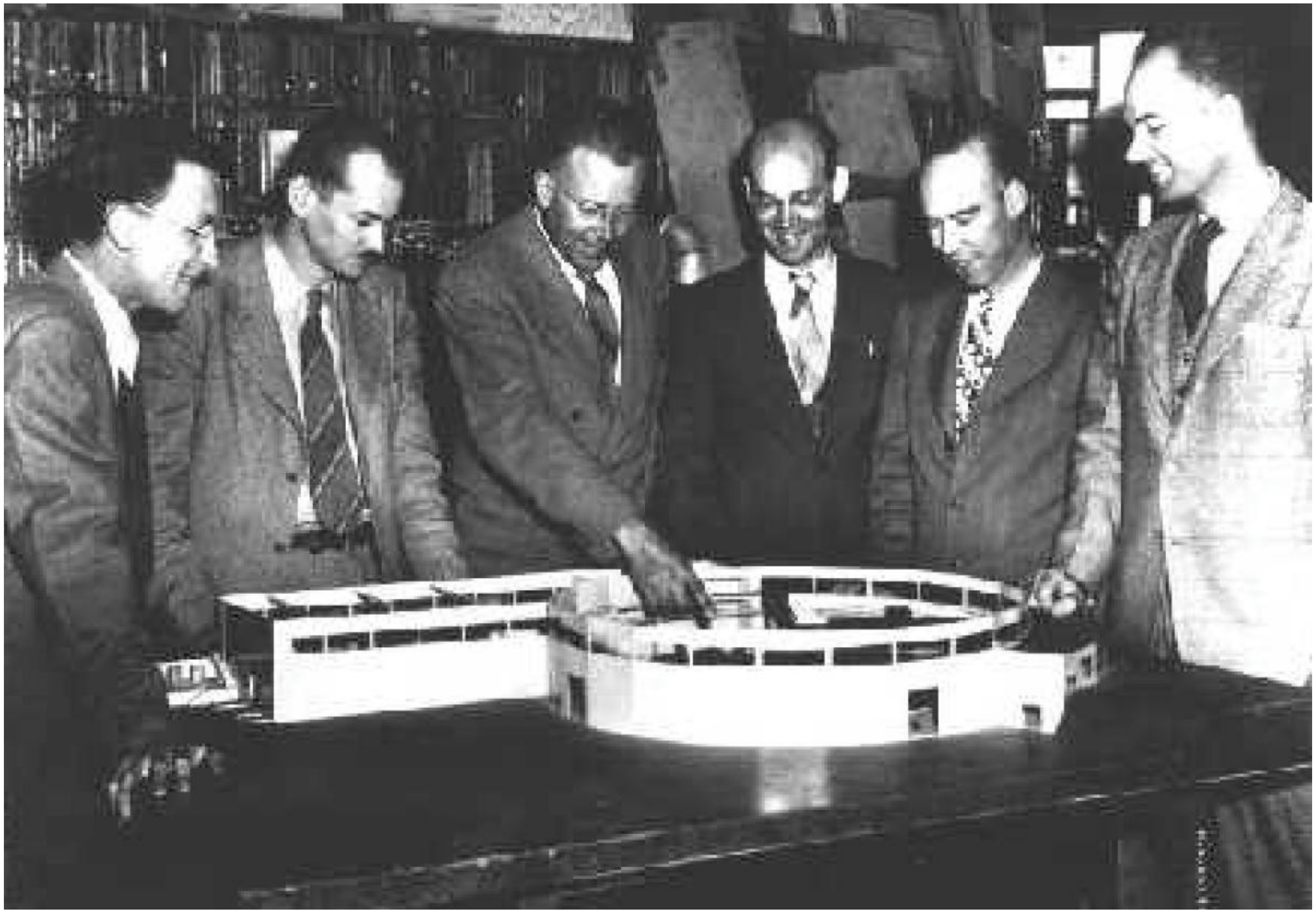
Hadron Therapy Technologies

S. Peggs, BNL & ESS-S



Bevalac
1950-1993

Many figures courtesy of Jay Flanz

Consumer demand

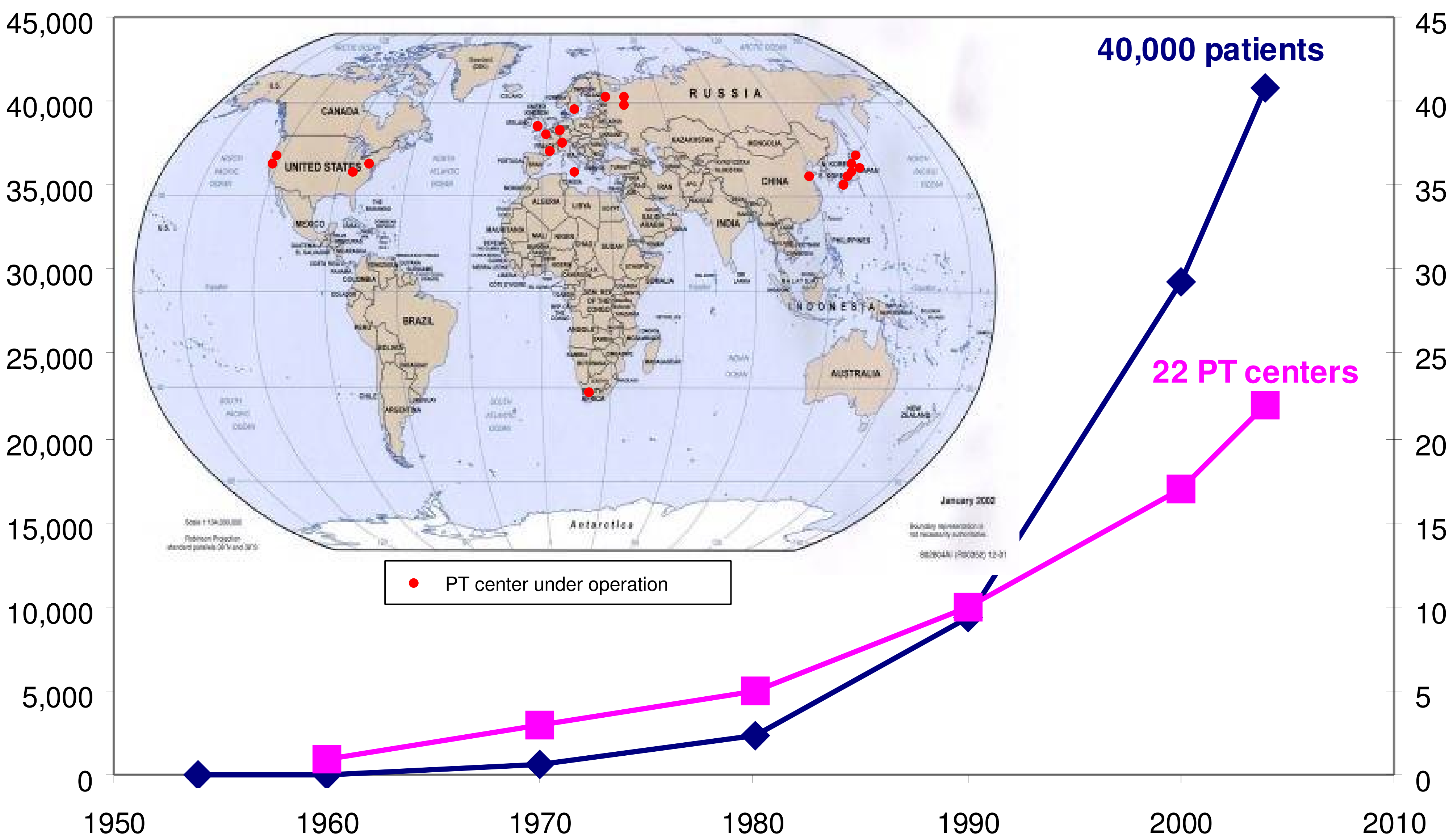
1 in 3 Europeans will confront some form of cancer in their lifetime.

Cancer is the 2nd most frequent cause of death.

Hadron therapy [protons, carbon, neutrons] is 2nd only to surgery in its success rates.

45% of cancer cases can be treated, mainly by surgery and/or radiation therapy.

Rapid growth



Courtesy J. Sisterson, MGH

Clinical requirements

A hadron therapy facility in a hospital must be:

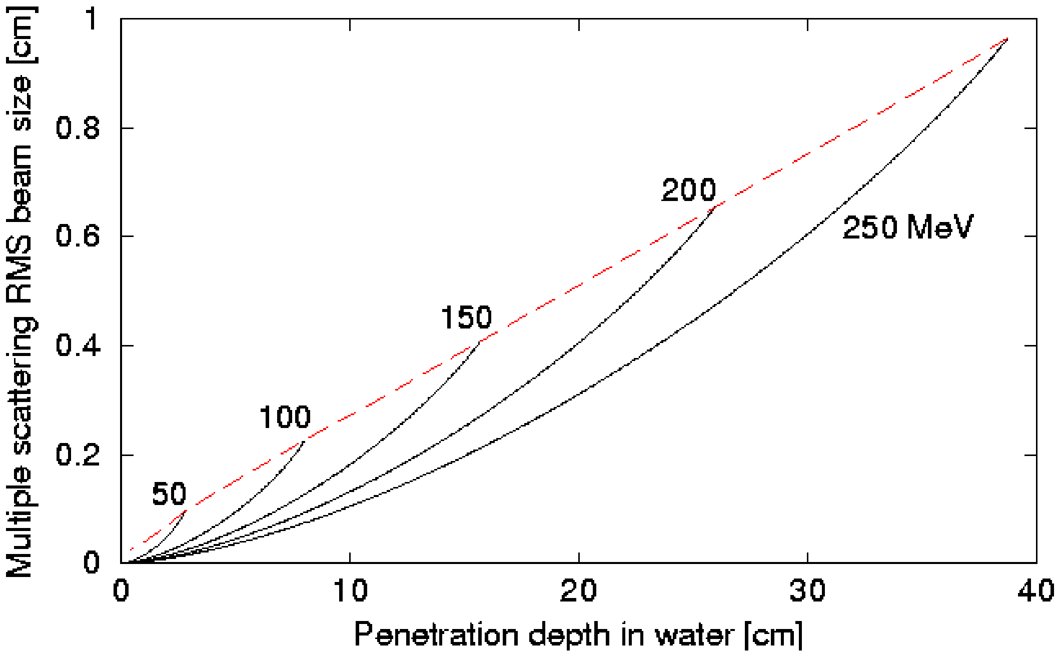
Easy to operate
– environment is very different from a national lab

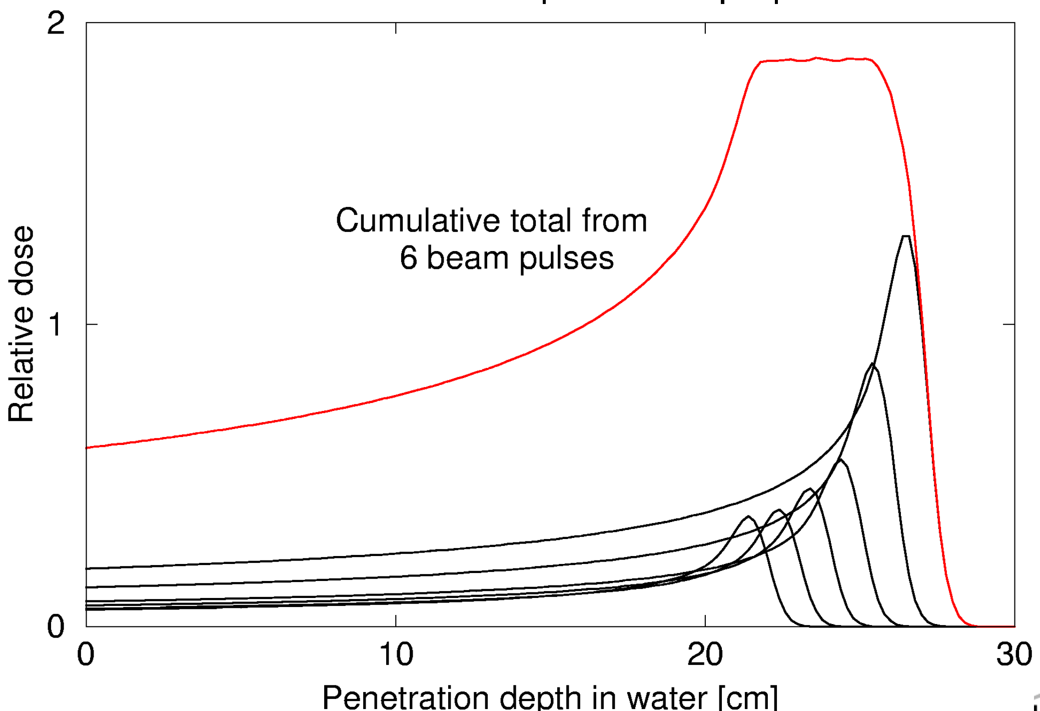
Overall availibility of 95%
– accelerator availibility greater than 99%

Compact
– less than 10 m across, or
– fit in a single treatment room

Beam parameters must deliver the treatment plan!
– depends on details of treatment sites & modalities
– but some generalization can be made

Painting a tumor





A perfect monochromatic proton beam, with zero initial emittance:

TOP spreads out transversely

BOTTOM acquires an energy spread that blurs the Bragg peak

Steer the beam and modulate its energy to "paint" the tumor!

Beam parameters

Penetration depth

– 250 MeV protons penetrate 38 cm in water
– carbon equivalent is 410 MeV/u, with
  2.6 times the rigidity

Dose rate

– deliver daily dose of 2 Grays (J/kg) in 1 or 2 minutes
– 1 liter tumor needs (only) ~ 0.02 W
  (0.08 nA @200 MeV)
– need x10 or x100 with degraders & passive scattering

Conformity

– integrated dose must agree with plan within 1% or 2%
– dose should decrease sharply across the tumor surface

History

1930's Experimental neutron therapy

1946 R.R. Wilson proposes proton & ion therapy

1950's Proton & helium therapy, LBL (184” cyclotron)

1975 Begin carbon therapy in Bevalac synchrotron
including wobbling & scanning

1984 Proton therapy begins at PSI

1990 Neutrons on gantry mounted SC cyclo, Harper-Grace

1990 Protons with 1st hospital based synchrotron, LLUMC

1993 Precision raster scanning with carbon, GSI

1994 Carbon therapy begins at HIMAC, Chiba

1996 Spot scanning, PSI

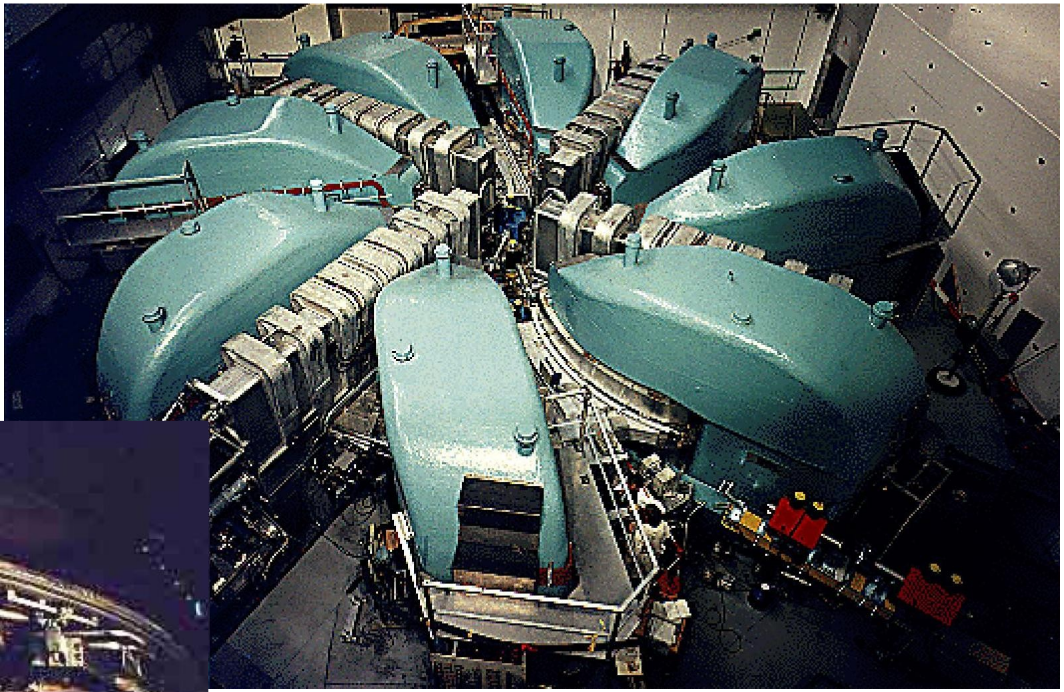
1997 Protons with 1st hospital based cyclotron, MGH

Cyclotrons

Cyclotrons, big ...

Proof-of-principle & R&D therapy was performed in national labs

National lab operation is increasingly deprecated, especially in U.S.



PSI

TRIUMF
Pion therapy, briefly

… "small" …

IBA C230

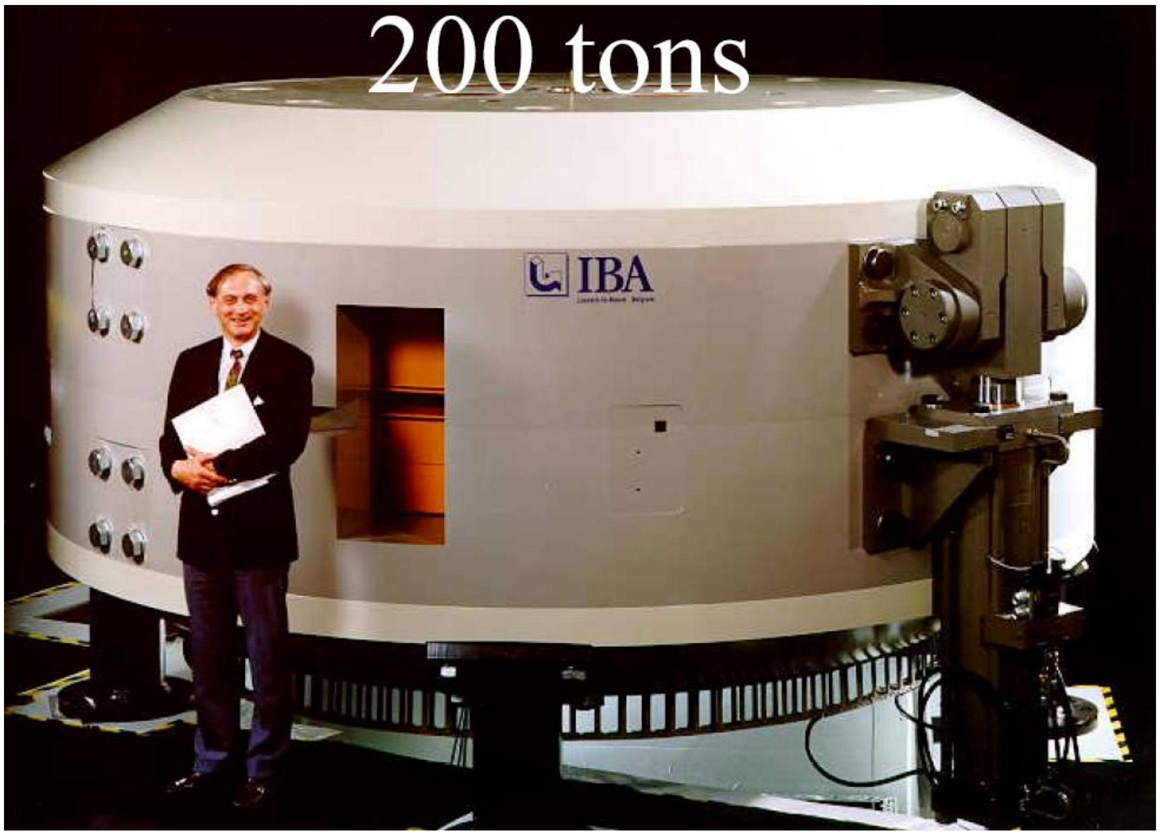
230 MeV protons, 300 nA

Saturated field ~ 3 T

200 tons 4 m diameter

1997

First C230 begins operation at MGH as 1st hospital based commercial cyclotron



Isochronous cyclotrons

Few adjustable parameters

CW beams, constant energy

- energy degraders
- larger emittance,
- larger energy spread

Easy to operate !

... smaller ...

1980's Design studies confirm $1/B^3$ scaling of SC cyclotrons, but leave synchrocyclotrons (swept RF frequency) out of reach.

ACCEL Superconducting COMET (below): 80 tons, 3 m dia.
250 MeV protons with markedly better extraction efficiency

... smallest: cyclotron on a gantry

1990 MSU / Harper-Grace

Superconducting NbTi

~5.6 T 70 MeV neutrons

2008 MIT / Still River Systems

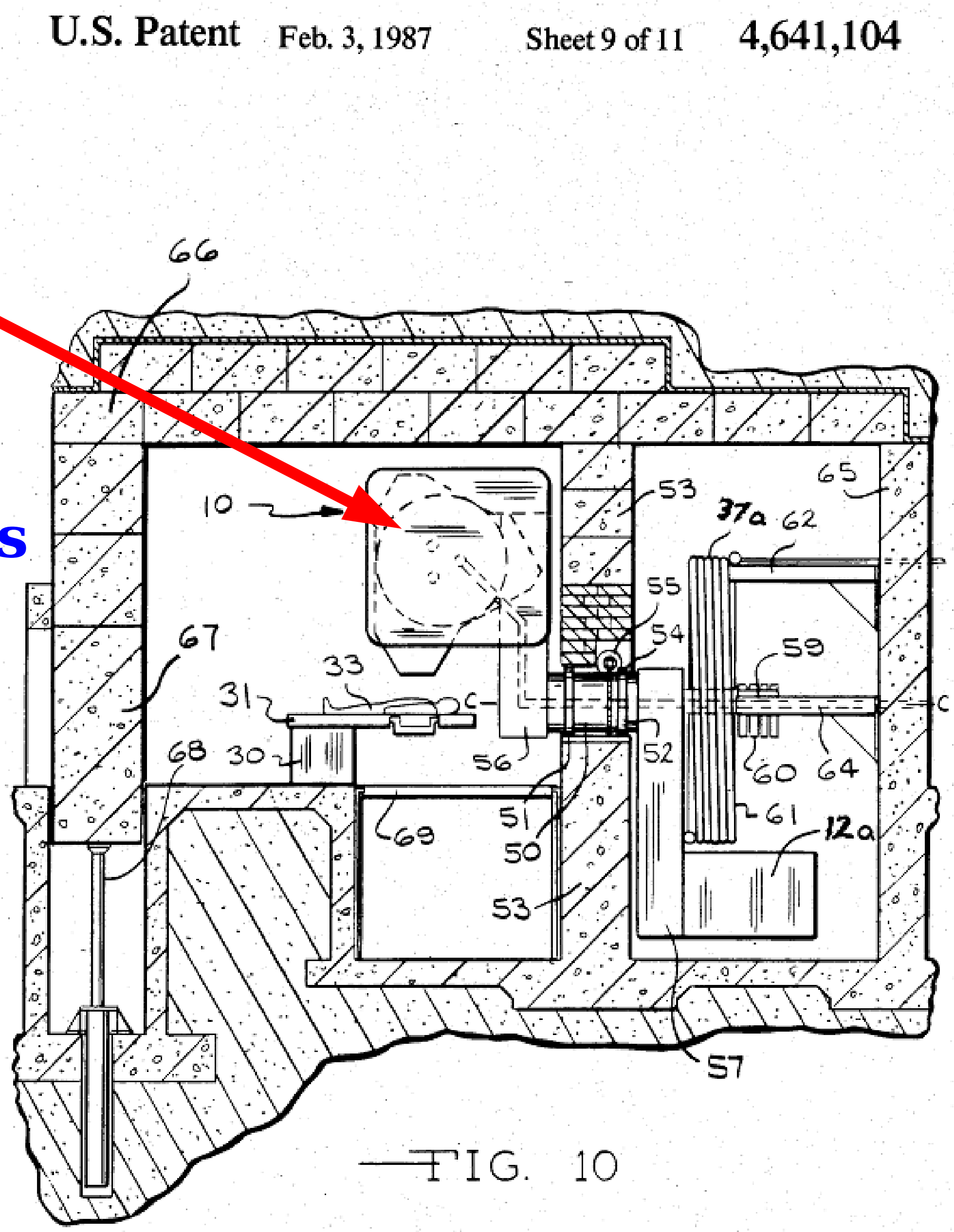
React-and-Wind Nb_3Sn

~9 T 250 MeV protons

Synchrocyclotron < 35 tons

pulsed bunch structure

Cryogen free (cryo-coolers)

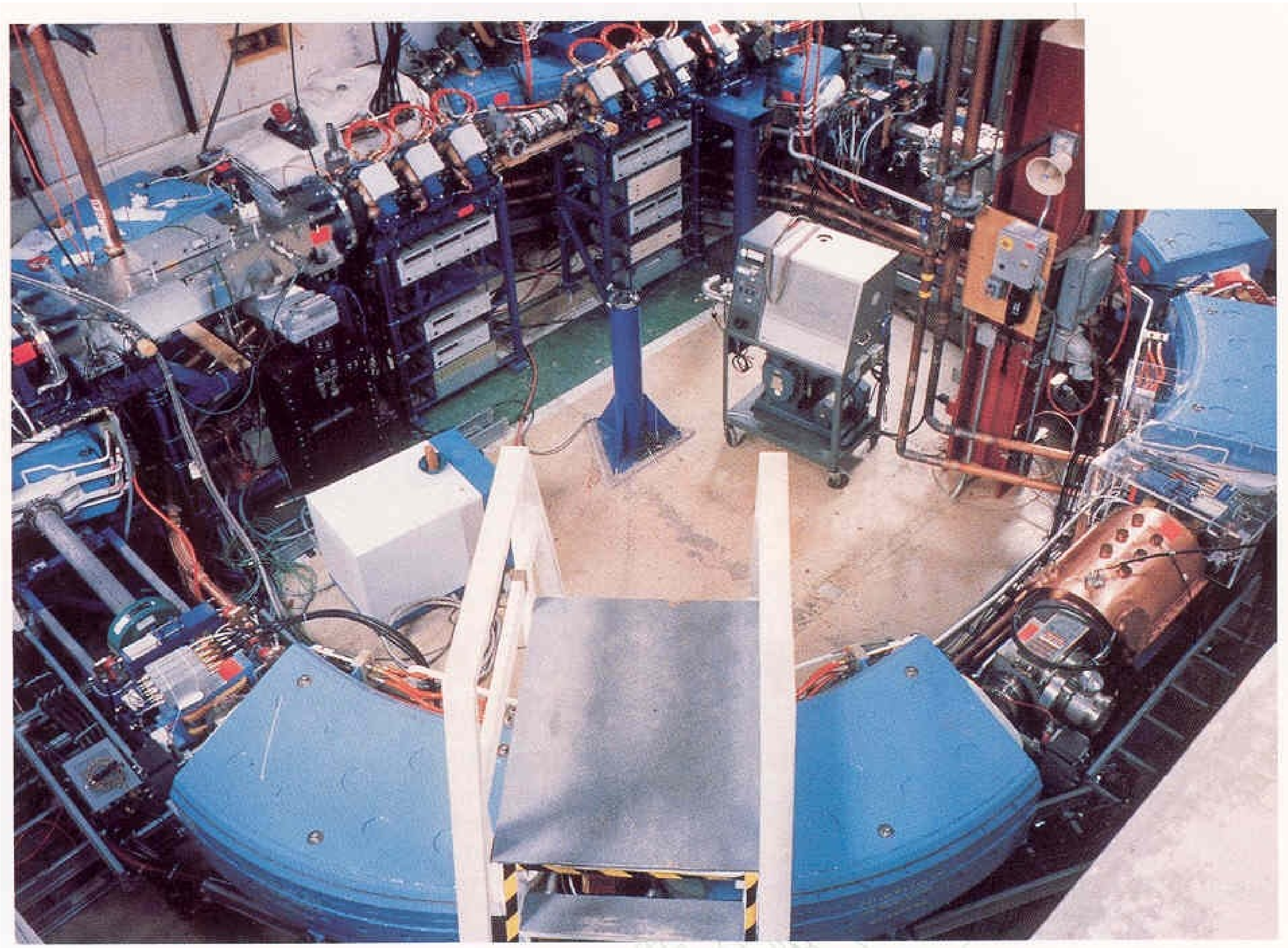


Slow cycling synchrotrons

Synchrotrons

1990 **Loma Linda:** 1st hospital based proton therapy center

Standard against which other synchrotrons are measured



Designed and commissioned at **FNAL**

Weak focusing

Slow extraction

Space charge dominated

Small number of operating energies

Slow extraction

Resonant extraction, acceleration driven, RF knockout, betatron core, or stochastic noise

– feedback runs against “easy operation” & “availibility”

– often deforms beam distribution (enlarged beam size)

– energy degraders sometimes necessary

But it works!

LEFT: Hitachi synchrotron at MDACC

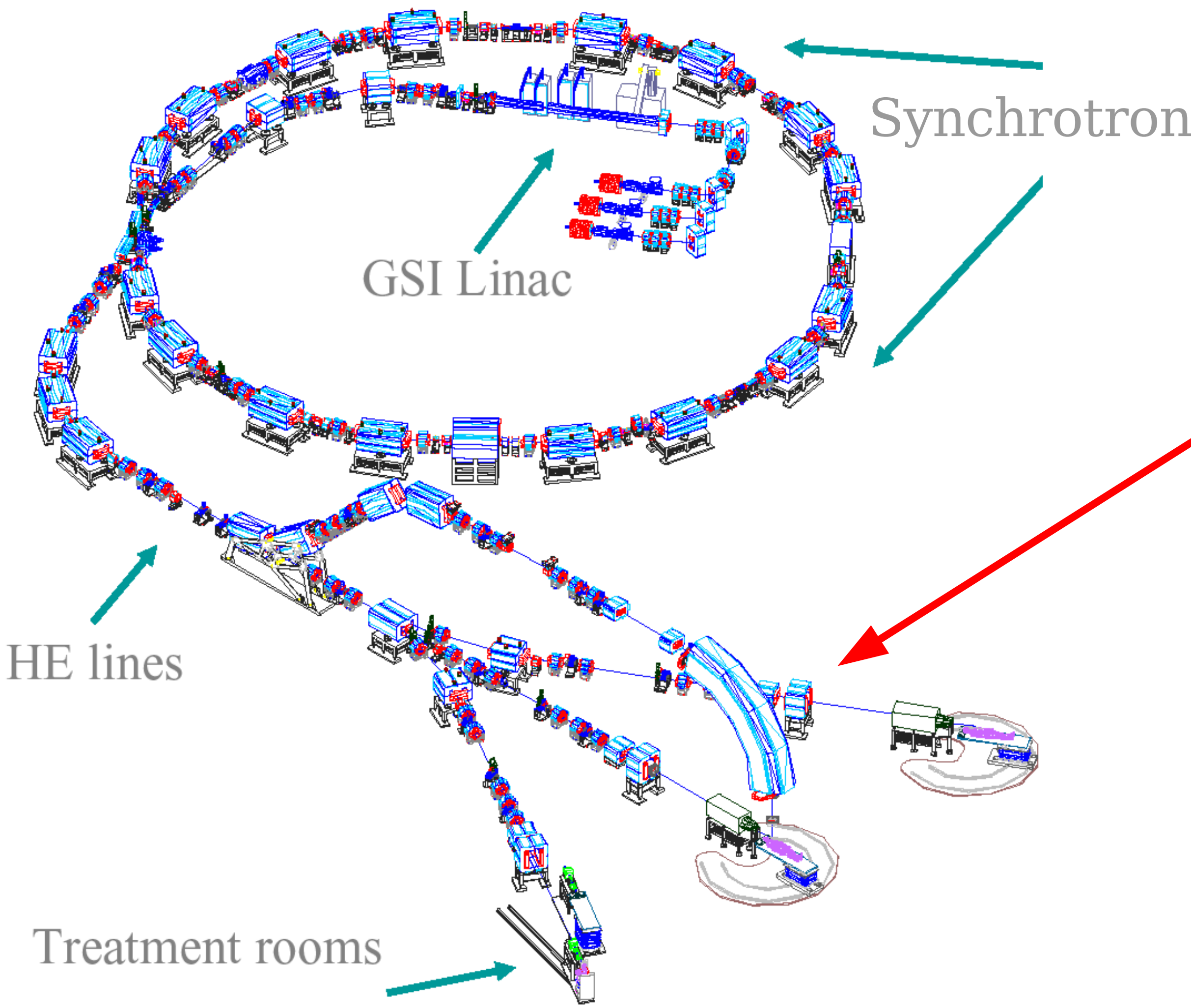
Strong focusing

Synchronize beam delivery with respiration!

Carbon

"Synchrotrons are better suited to high rigidity beams"

(but SC cyclotron designers are pushing towards carbon)



LEFT: Pavia design uses PIMMS (CERN) design synchrotron

Avoids a gantry in the initial layout

Siemens/GSI carbon synchrotron at HIT includes a gantry (commissioning)

Med-Austron / CERN

New & revisited concepts

Perception ...

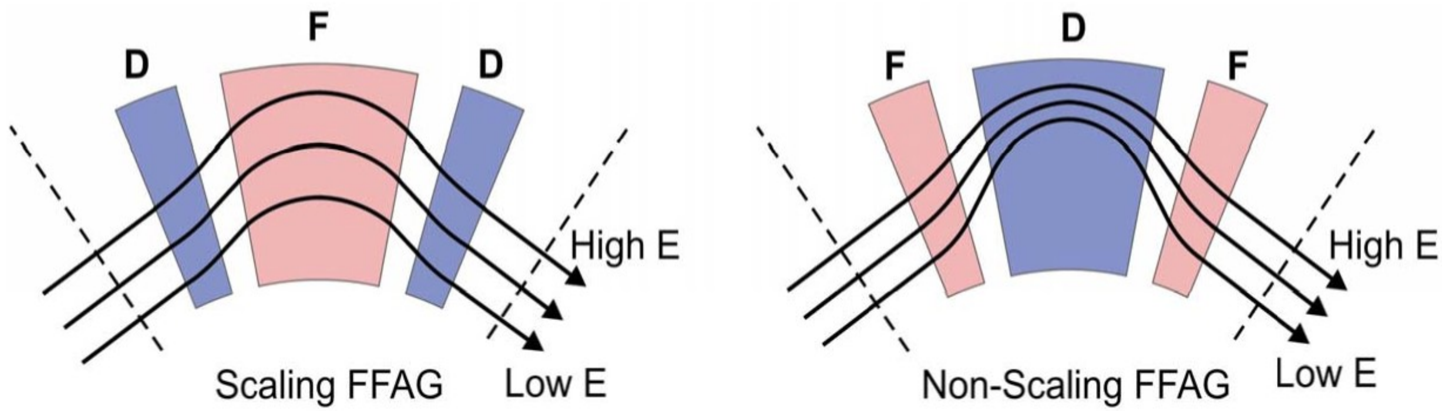
FFAG reprise

Ring of magnets like a synchrotron, fixed field like a cyclotron.

Fast acceleration (think muons)

Compact footprint

Magnet aperture must accept large momentum range



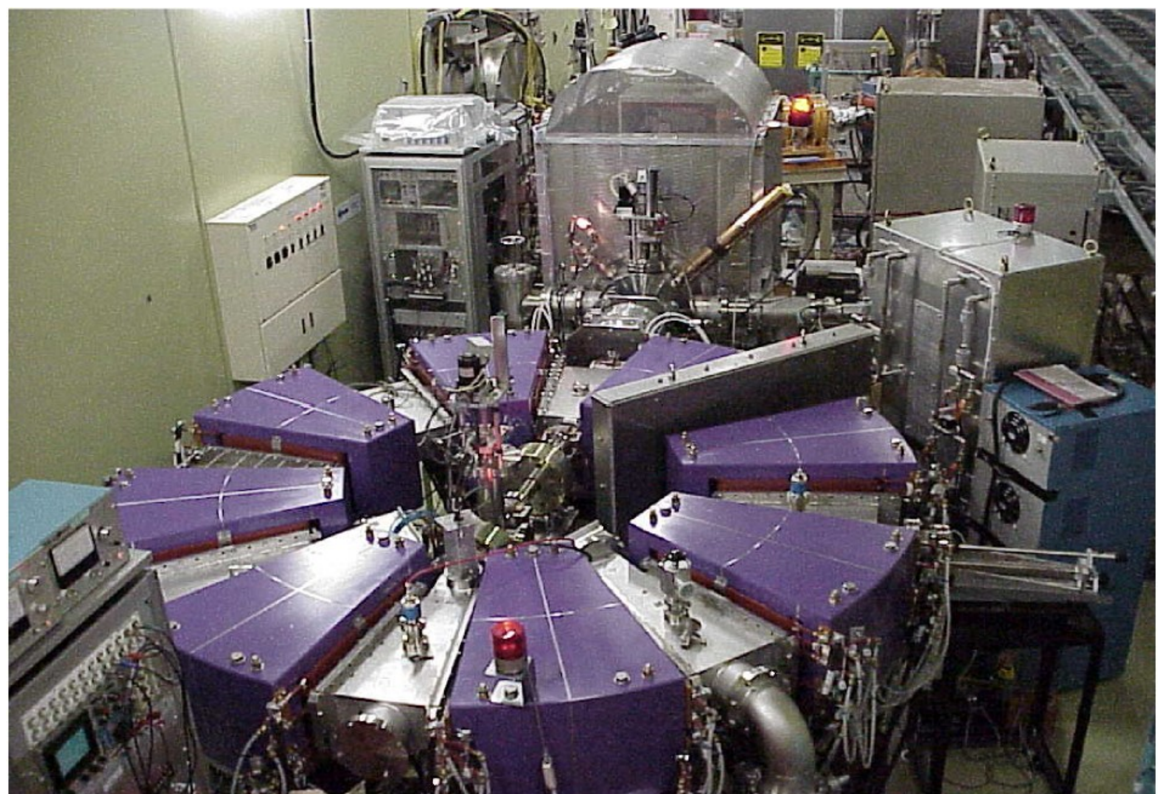
Variable energy extraction?

Possible very high rep rate

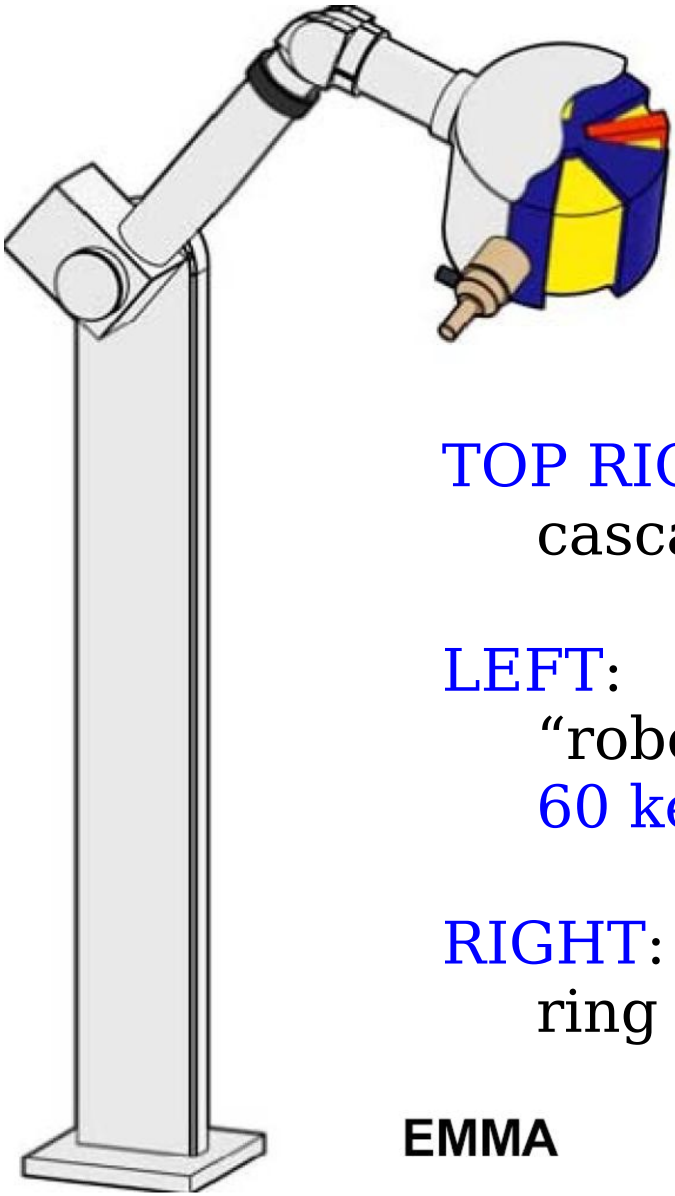
Much world wide interest.

Demo machines in early operation, construction & design

KEK



FFAG - continued

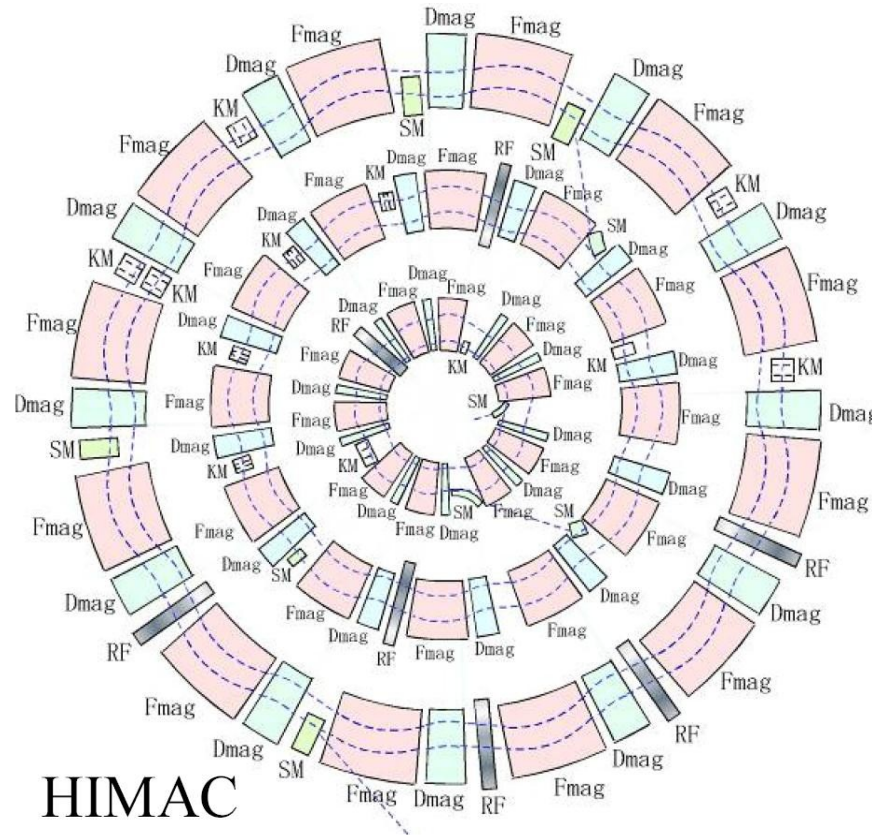


EMMA

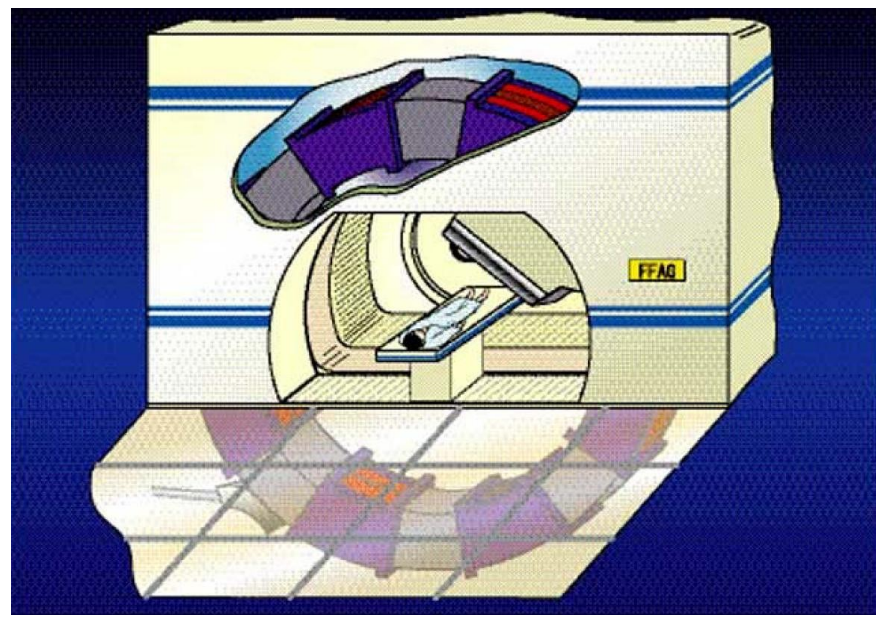
TOP RIGHT:
cascaded rings

LEFT:
“robot” gantry
60 keV – 1 MeV

RIGHT:
ring gantry



HIMAC



Linacs

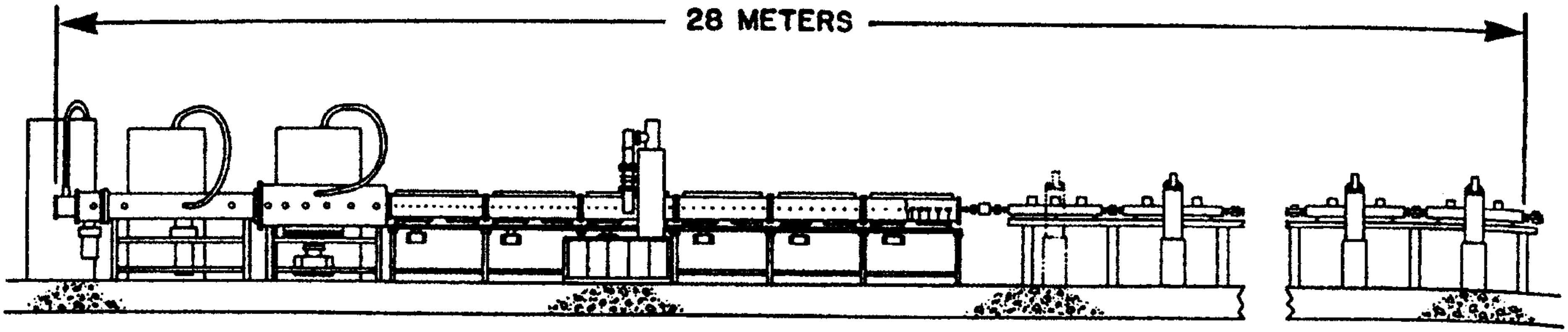


Figure 1. Schematic Layout of Model PL-250 Proton Therapy Linac.

Table I
Preliminary Specifications for
a Dedicated Proton Therapy Linac

Accelerated particle	H^+	
Maximum beam energy	250	MeV
Minimum beam energy	70	MeV
No. energy increments	11	
Peak beam current	100-300	μA
Beam pulse width	1-3	μsec
Repetition rate	100-300	Hz
Average intensity	10-270	nA
Beam emittance (norm.)	<0.1	πmm-mrad
Beam energy spread	±0.4	%
Max. rf duty factor	0.125	%
Peak rf power	62	MW
Maximum input power	350	kW
Stand-by power	25	kW
Accelerator length	28	m

Linacs

< 10 MeV/m

complex RF

"TOP" @ ENEA

SCDTL

200 MeV protons

1^{st} in hospital?

HERE: 1999

R. Hamm PL-250

Fast neutrons proposal

"High Gradient Induction Accelerator"

G. Caporaso et al, LLNL

250 MeV protons in 2.5 m?

Pulse-to-pulse energy & intensity variation

"Hoping to build a full-scale prototype soon"

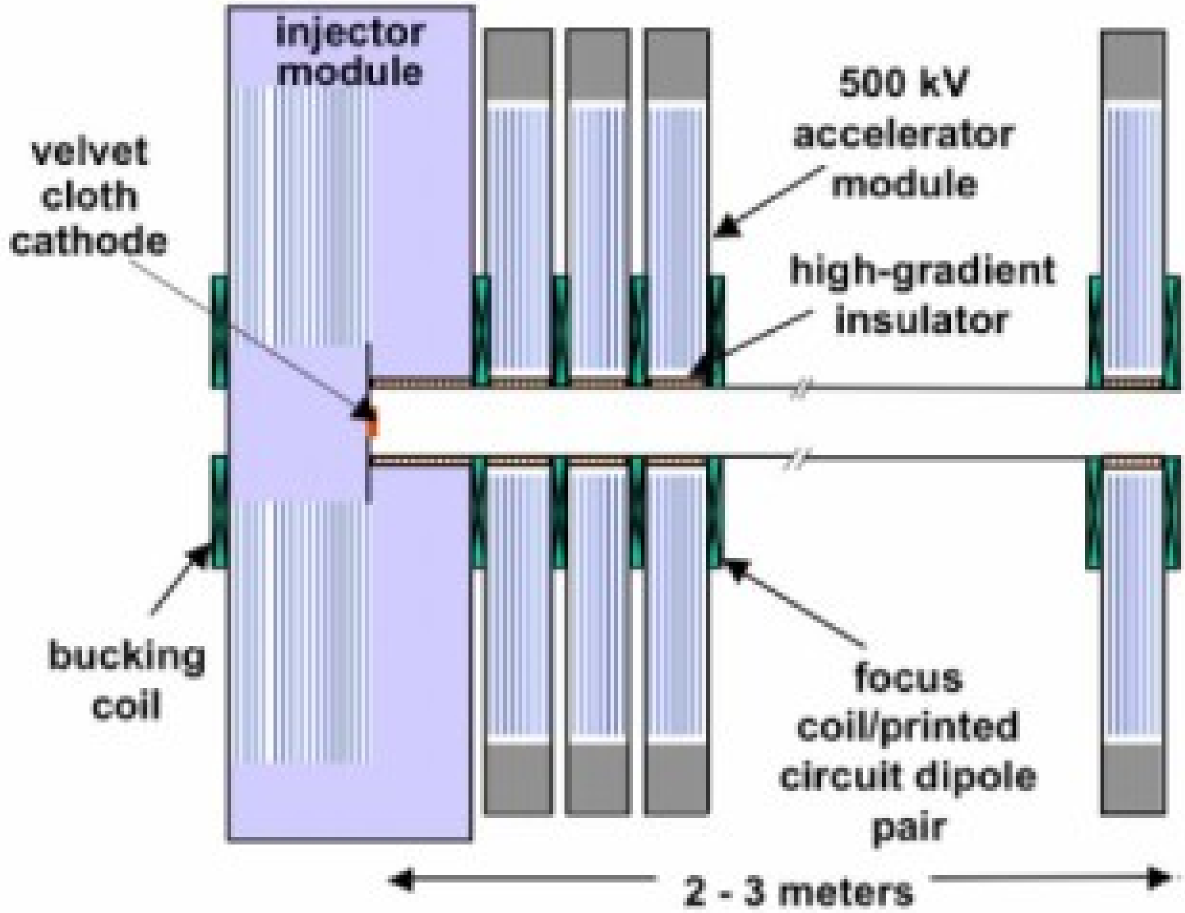
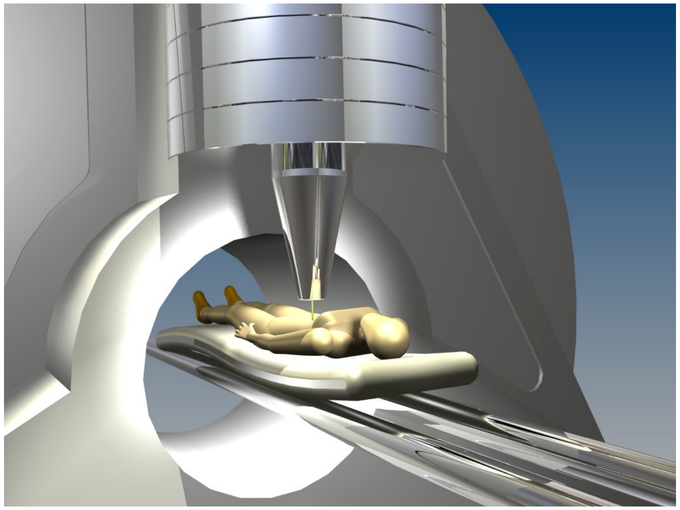
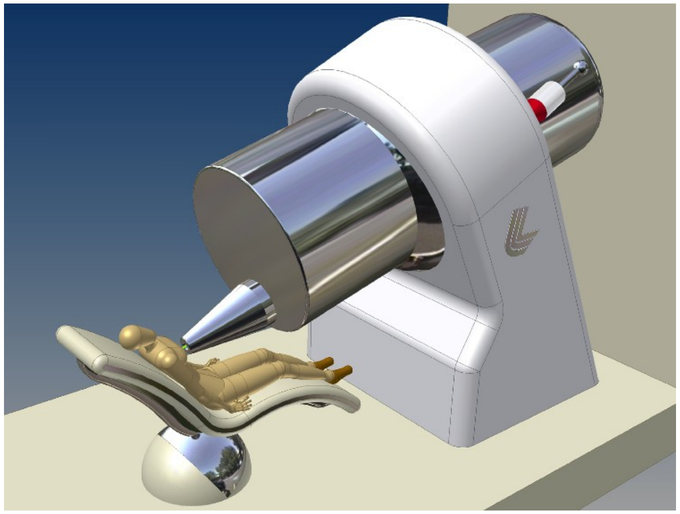


Figure 1: Dielectric wall induction accelerator configuration.





Gantries

Proton gantries

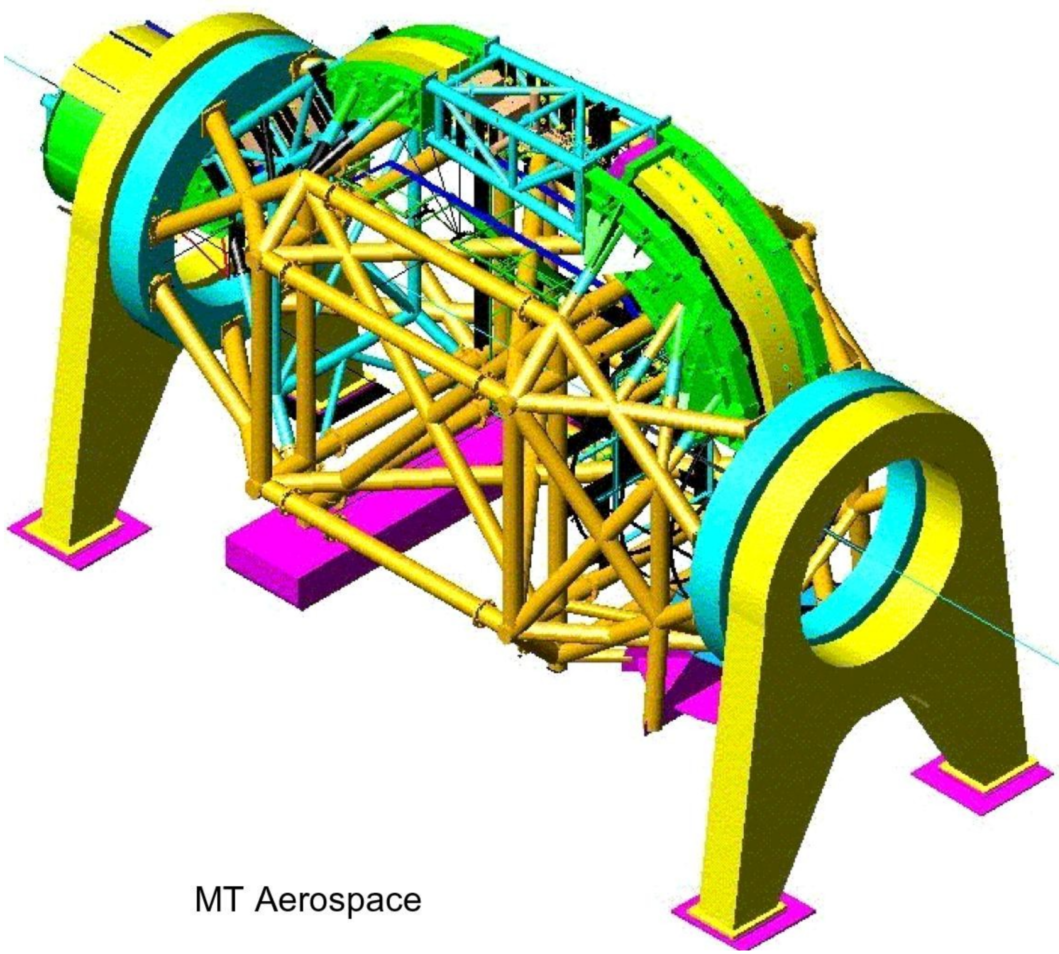
PSI	IBA
	

Normal conducting proton gantries:

weight	> 100 tons
diameter	~ 10 m
max deformation	~ 0.5 mm

Carbon gantries

It is hard to bend same-depth carbon ions
(2.6 times the rigidity of protons)



MT Aerospace

Heidelberg carbon gantry
13 m diameter
25 m length
630 tons !!

New gantry technologies – for Carbon?

Emerging technologies mainly aimed at carbon gantries

- direct wind iron-free NbTi superconducting magnets
- High Temperature Superconductor magnets one day?
- cryo-coolers
- FFAG optics

Small beams (eg the BNL RCMS)

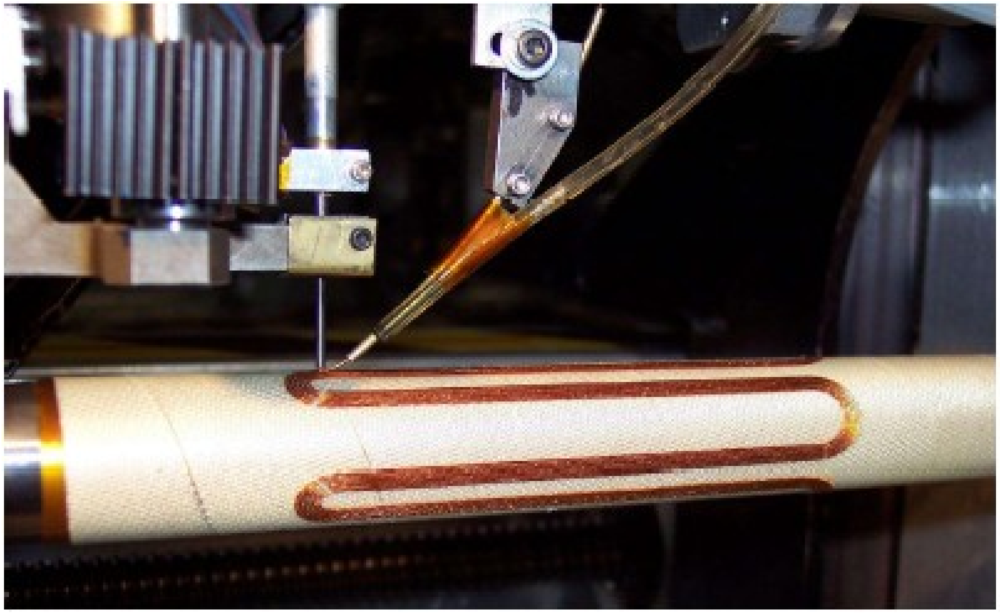
enable small light magnets & simple light gantries

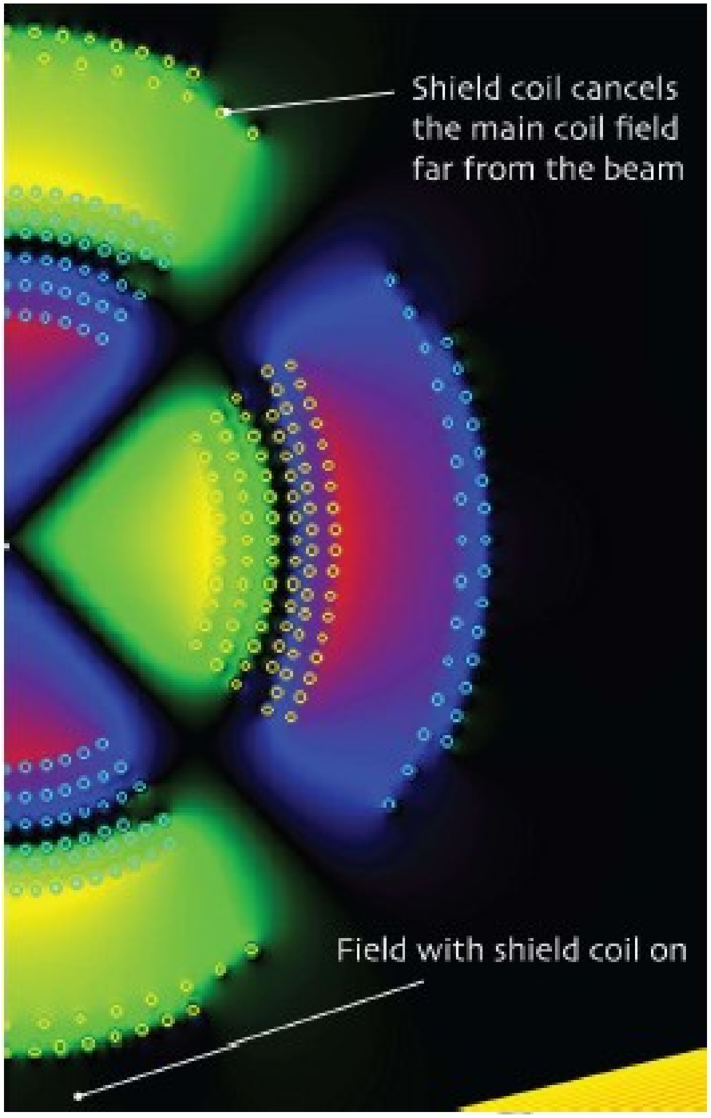
Superconducting gantry magnets

SC magnets + small beam size = practical light gantries

New SC magnets are light & strong

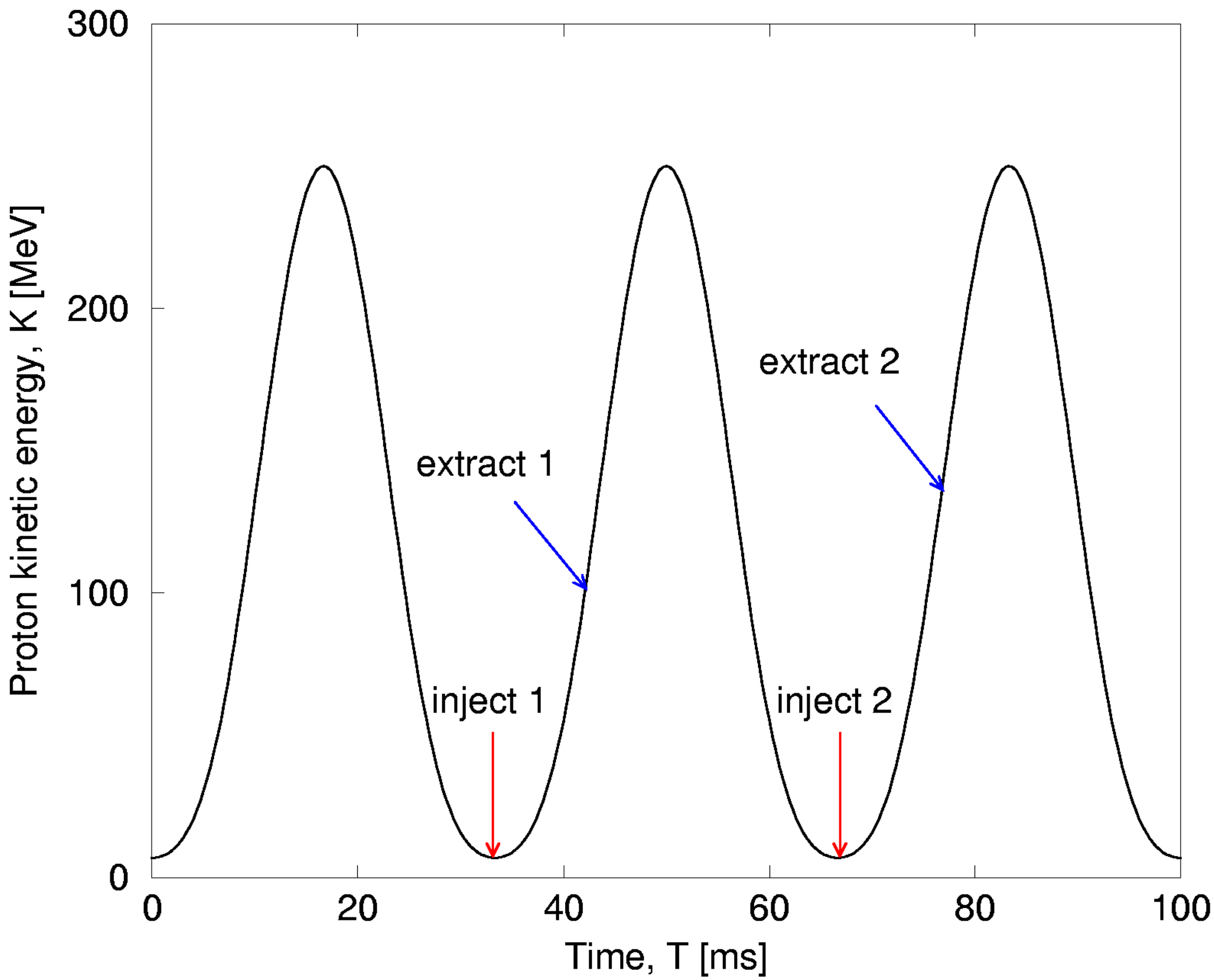
- Iron-free (coil dominated fields)
- Solid state coolers (no He)
- Field containment
- “Direct wind” construction





BNLs
Rapid Cycling Medical Synchrotron
RCMS

Multiple RCS proposals, from 25 Hz to 60 Hz



Inject in one turn, extract on any single turn (any energy)

Beam scanning rates

What rates do current "point-and-shoot" slow extraction facilities deliver?

PSI 50 Hz (Med. Phys. 31 (11) Nov 2004)

- 20 to 4,500 ml per treatment volume
- 1 to 4 fields per plan
- 200 to 45,000 Bragg peaks per field
- 3,000 Bragg peaks per minute
- few seconds to 20 minutes per field

MDACC ~ 70 Hz (PTCOG 42, Al Smith, 2005)

- 10x10x10 cm tumor treated in 71 seconds
- 22 layers, 5,000 voxels

RCS advantages & challenges

Advantages

- “No” space charge
- High efficiency (eg antiprotons?)
- Small emittances enable small light (air-cooled?) magnets
- Light gantries
- Extreme flexibility – the sharpest possible scalpel

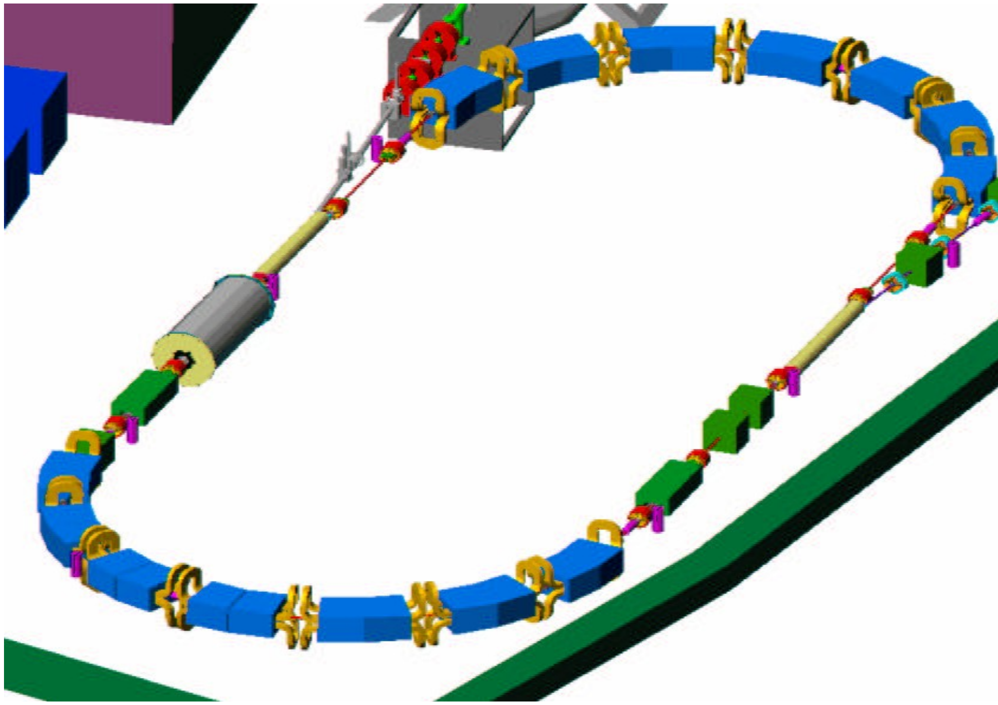
Challenges

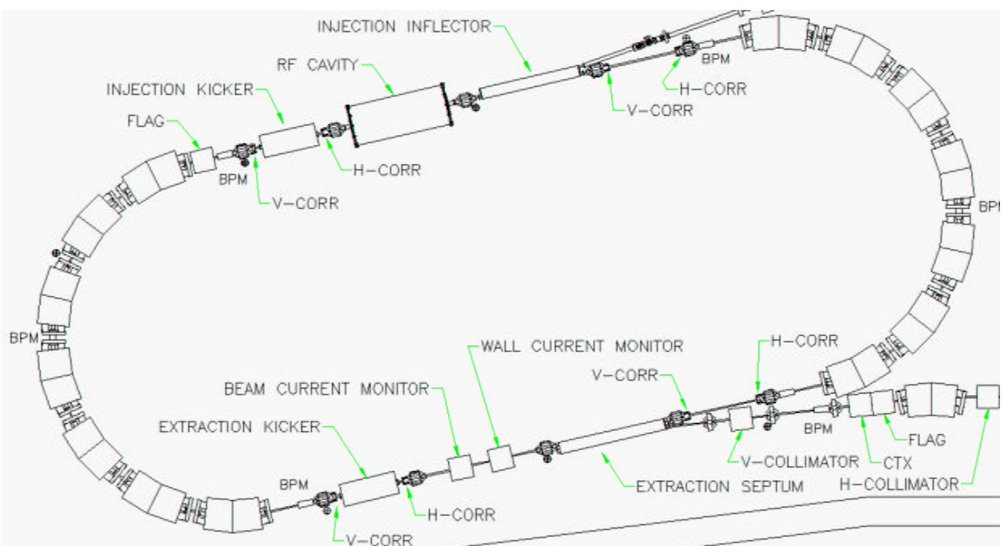
- Rapid RF frequency swing (eg 1.2 MHz to 6.0 Mhz in ms)
- Eddy currents
  - ISIS 50 Hz, Cornell 60 Hz, transformers 50/60 Hz
- Nozzle beam diagnostics with short (100 ns) bunches

RCS vs Cyclotron

	Rapid Cycling Synch.	Cyclotron
Energy flexibility	Flexible (fast extraction)	Fixed (needs degraders)
Typical diameter	5-7 m	4 m
Power consumption	Low (resonant)	High (except SC)
Typical beam size	1 mm	10 mm
Typical energy spread	< 2e-3	> 5e-3
Beam intensity	High	Very high
Complexity	Flexible	Simple
Weight	Light (7-10 tons)	Heavy (100-200 tons)
Approximate cost	$10M	$10M
Other costs	Lower	Higher

The BNL RCMS





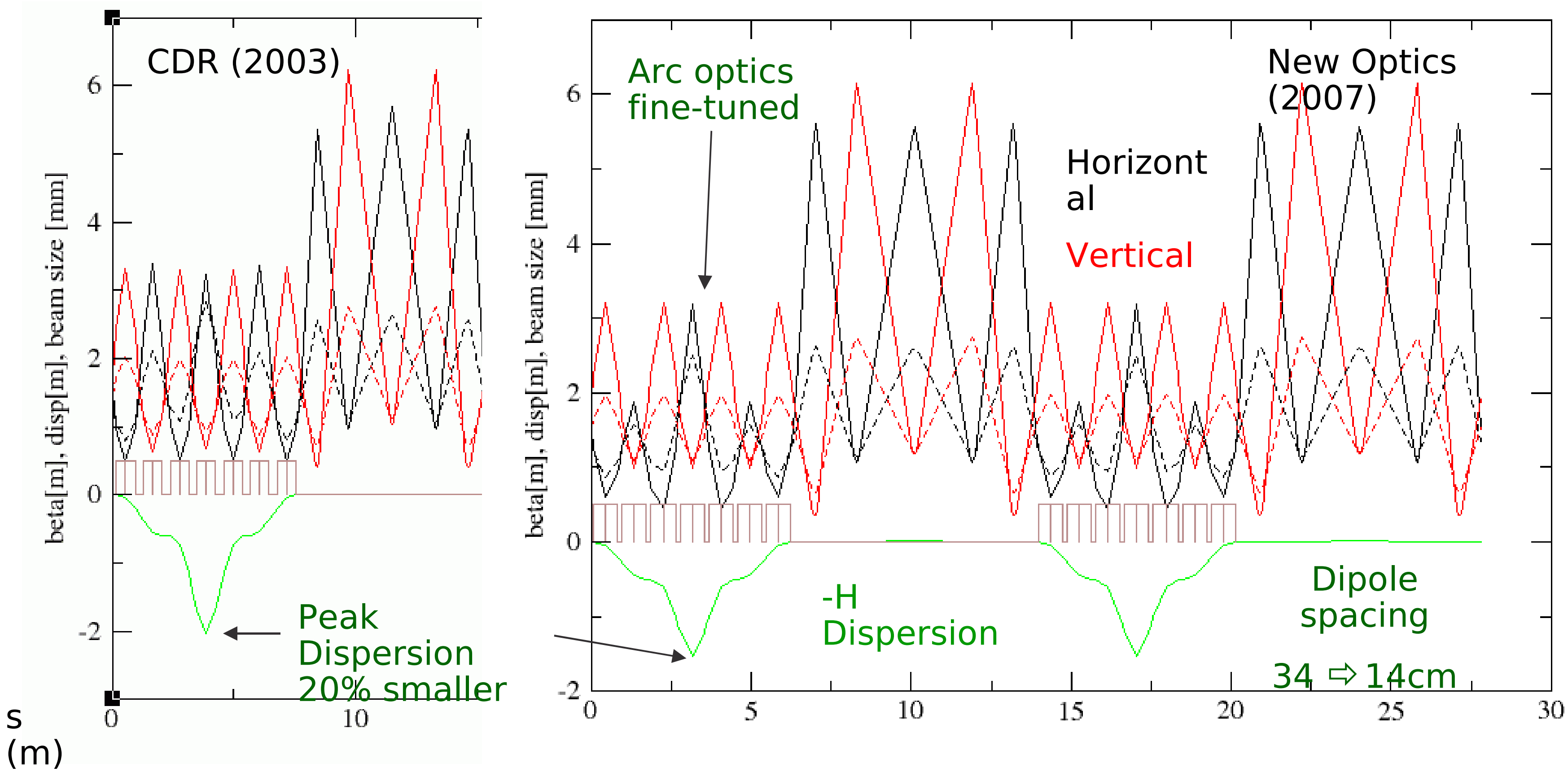
Racetrack design

- 2 super-periods
- Strong focusing minimizes the beam size
- FODO/combined function mags with edge focusing
- 2x7.6m straight sections, zero dispersion, tune quads
- Working tunes: 3.38, 3.36

Compact footprint

- Circumference: 27.8 m
- Area: 37 sq m

RCMS Optics



Zero dispersion in straights: injection/extraction/RF

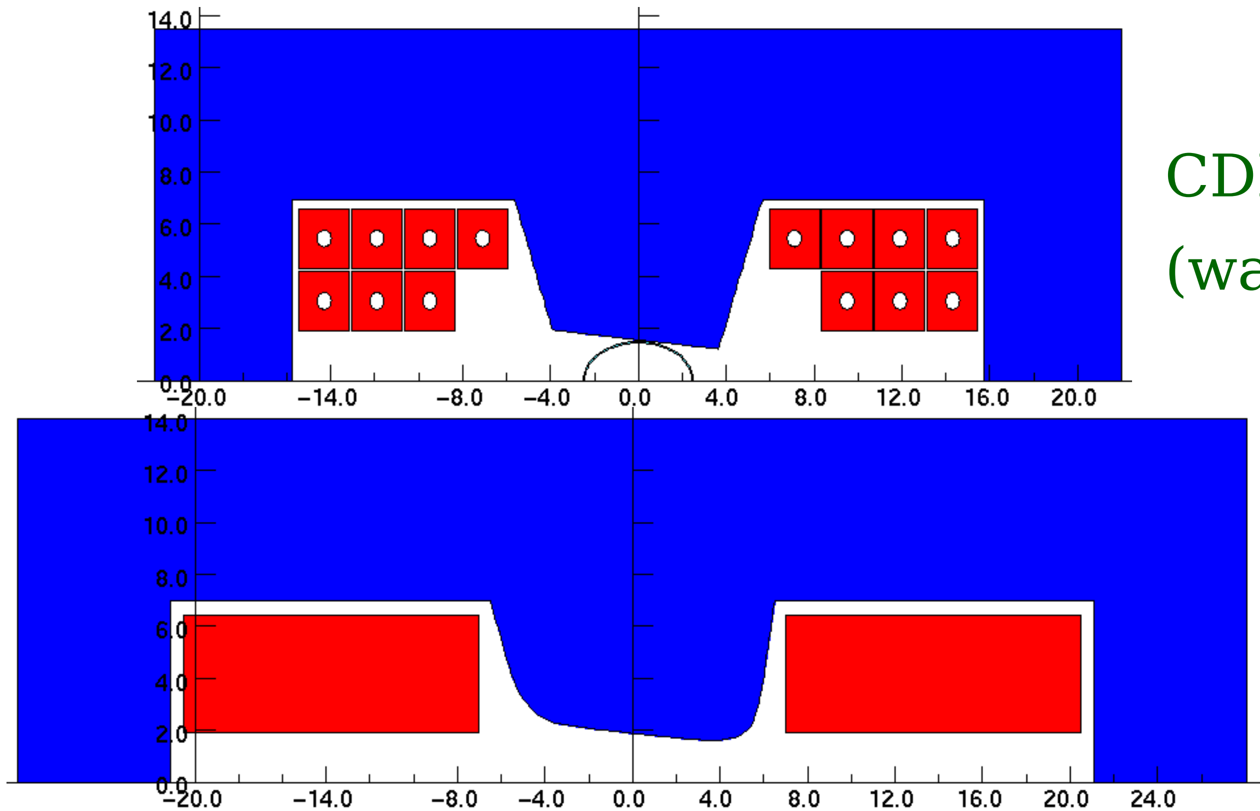
Room for two RF cavities, long injection/extraction

Strong focusing: small beam, large γ_T, large natural negative chromaticities, improved beam stability

BROOKHAVEN NATIONAL LABORATORY

RCMS arc magnets

Courtesy W. Meng



CDR design
(water cooled)

Present design
(air cooled)

Latest design (2007) has improved field quality
- Careful shaping of pole tips; broader pole face; air cooled
- 2.5% change through cycle for quad gradient, optimized for injection

RCMS RF cavities

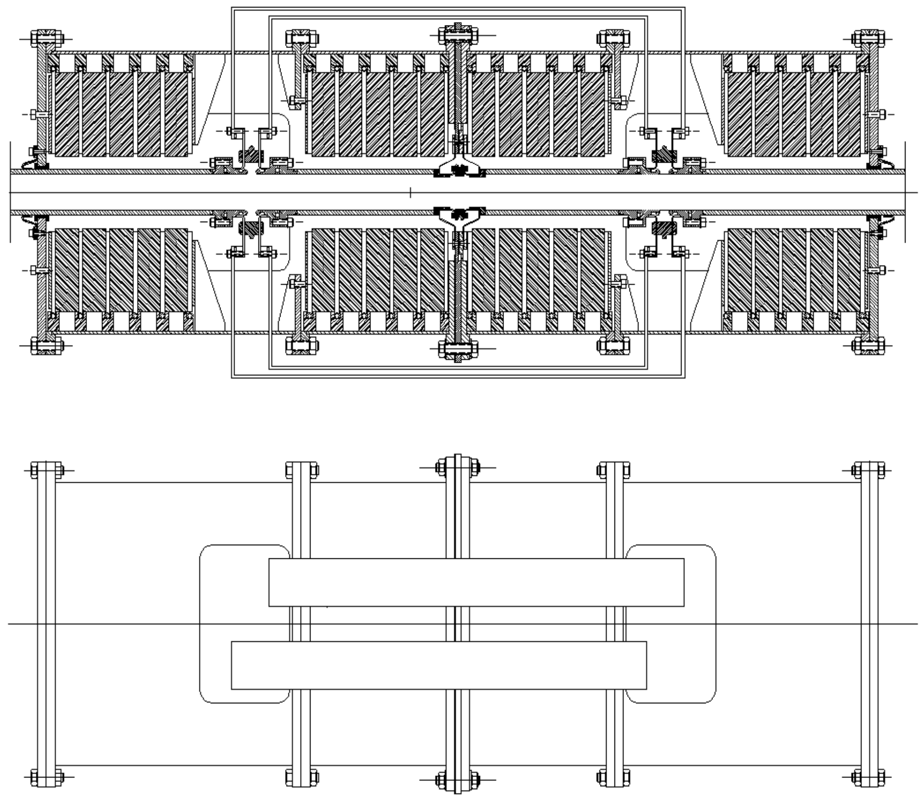
½ RF cavity design is ready for early prototyping

Ferrites procured and tested for large frequency swing

- 1.3-6.6 MHz
- 60 Hz is aggressive, feasible

60 Hz requires two cavities

- Expected voltage limit is about 6-7 kV/cavity



Proton Imaging

Conventional CT measures the wrong thing

Vertex2002 pCT: Hartmut F.-W. Sadrozinski , SCIPP

Use of Proton Beam CT: Treatment Planning

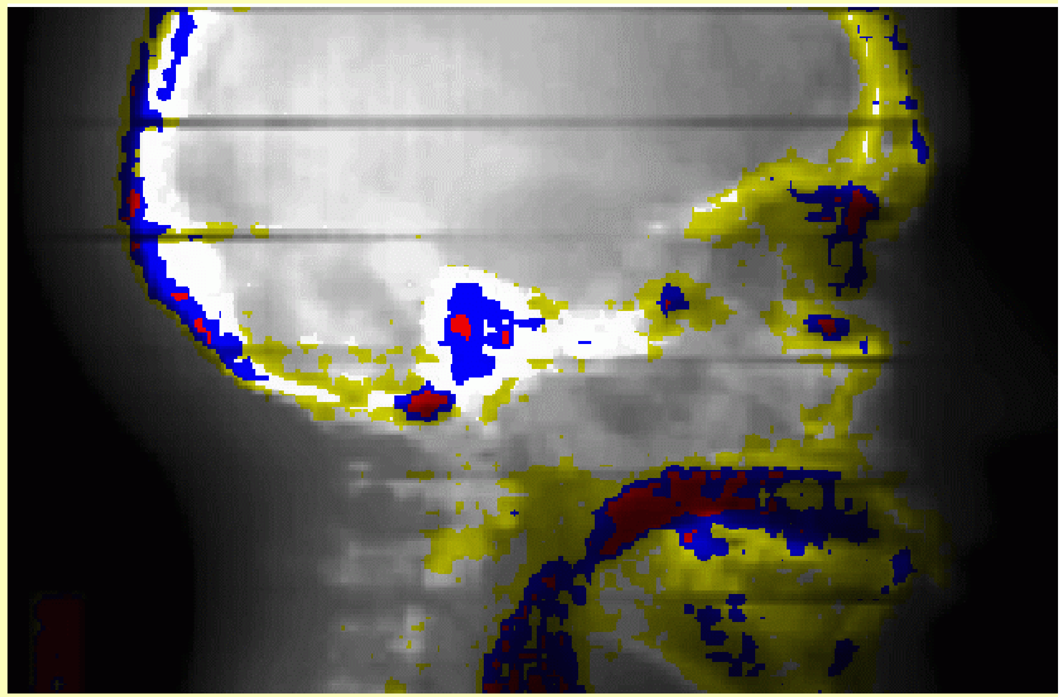
X-ray CT use in Proton Cancer Therapy can lead to large Uncertainties in Range Determination

Range Uncertainties

(measured with PTR)

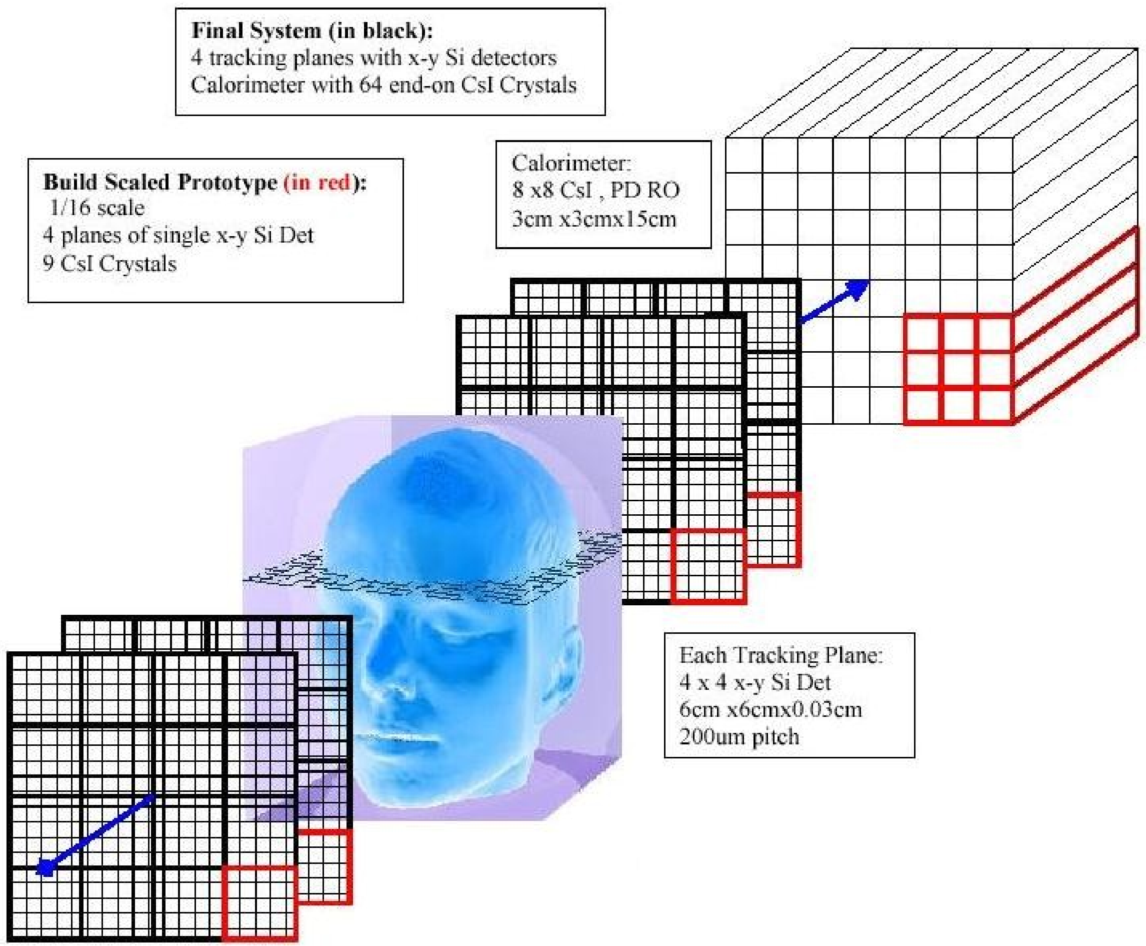
- Black: > 5 mm
- Blue: > 10 mm
- Red: > 15 mm

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



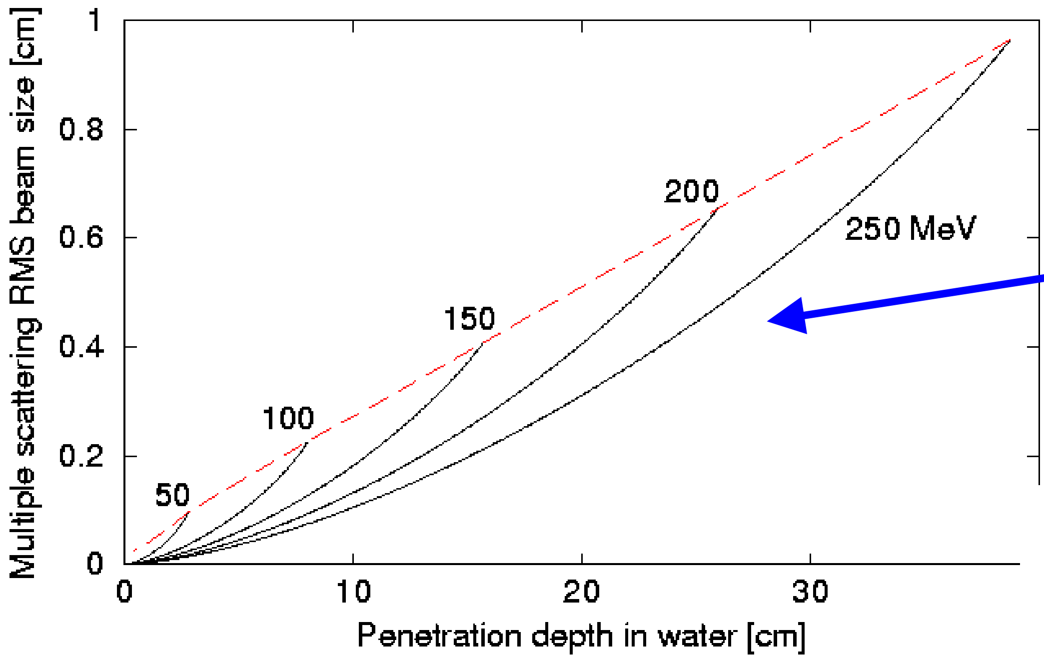
Alderson Head Phantom

Advanced proton cameras are under development



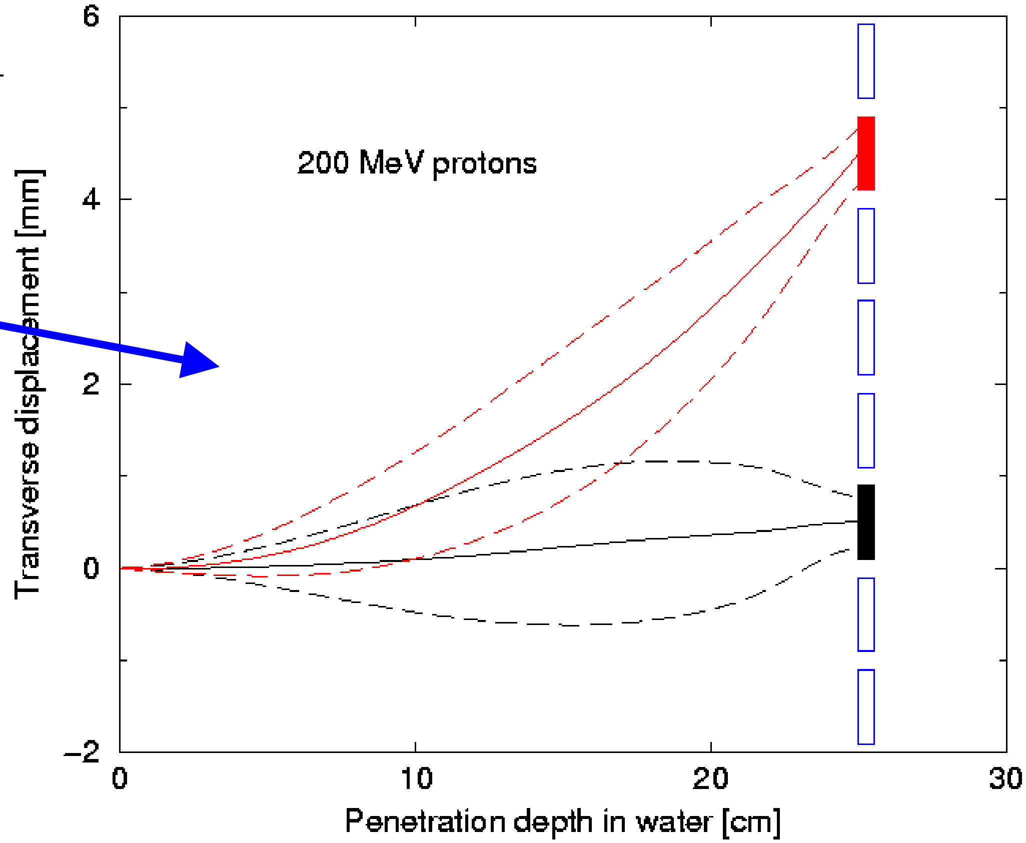
(Potentially) a very nice example of tech transfer from HEP/NP

Silicon strip/pixel detectors defeat blurring!



Simple proton radiography is rejected because multiple scattering makes blurry images

Modern silicon strip detectors can acquire individual proton trajectories at high bandwidth.



Track reconstruction enables sharp images of the right thing!

Conclusion – the Environment

Accelerator Science & Technology

Why is the U.S. accelerator industry so strikingly underdeveloped in comparison with EU and Japan?

Medical accelerators provide the clearest example: (ACCEL), Danfysik, Hitachi, IBA, Mitsubishi, Siemens, …

The U.S. Department of Energy HEP/NP program is the "steward" of Accelerator Science at a time when:

1) HEP/NP budgets are in decline

2) Accelerator Science & Technology blossom

3) The economy suffers

How to teach & do research in Accelerator Science, across University & national lab boundaries?

Accelerator Science & Technology - 2

1) Accelerator Physics is a science in its own right, not just a provider of technology for particular users

2) “Centers for Accelerator Science & Engineering” need reinventing, across laboratory & university boundaries

But accelerator technology needs direct stimulation:

3) “What challenges should be put to accelerator companies to make them profit sources, and not tax sinks, in the global economy?”

What is the “third way” that synthesizes these apparently antithetical statements?