Hadron Therapy Accelerator Technologies

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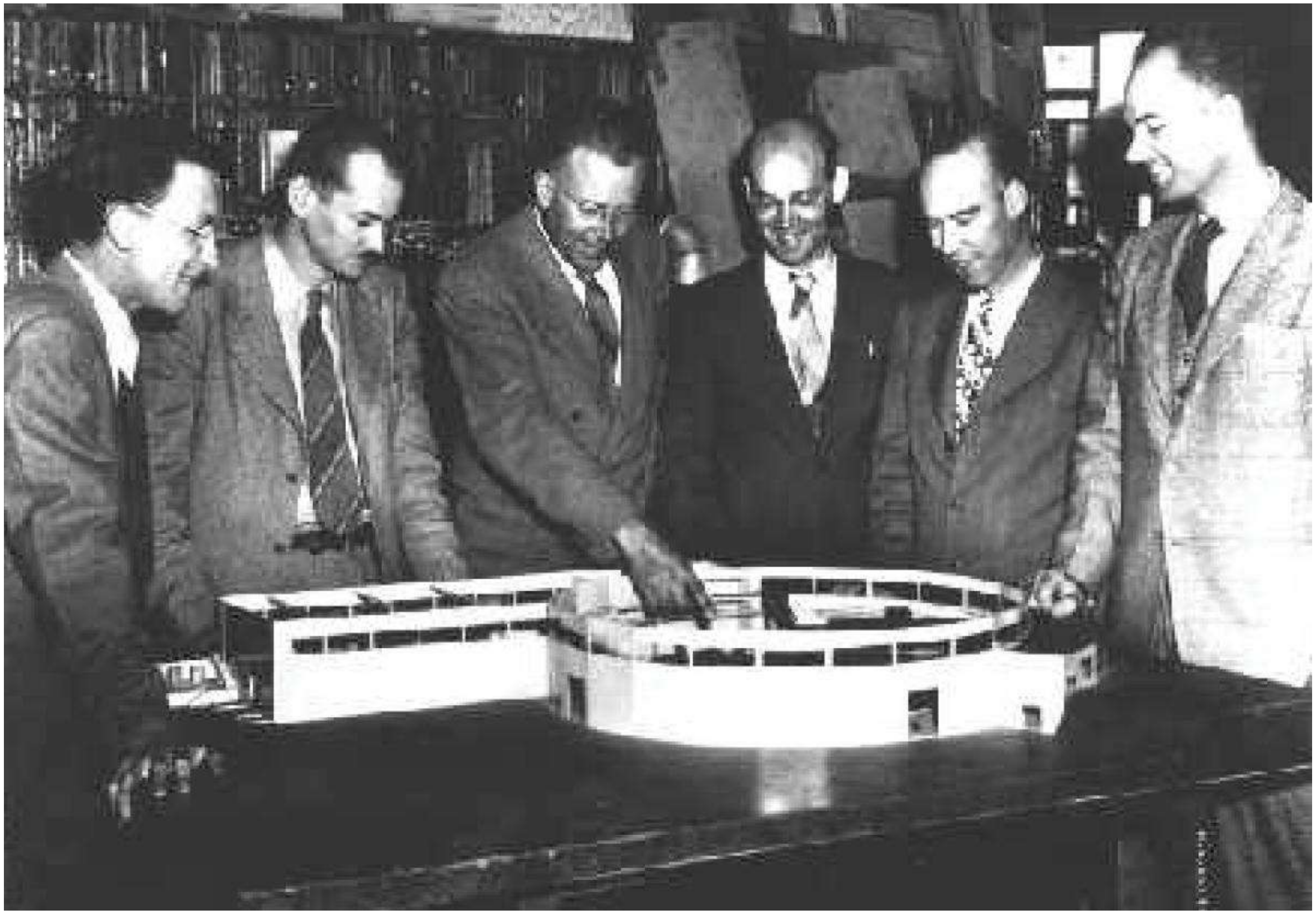


Bevalac
1950-1993

Many figures courtesy of Jay Flanz

Consumer demand

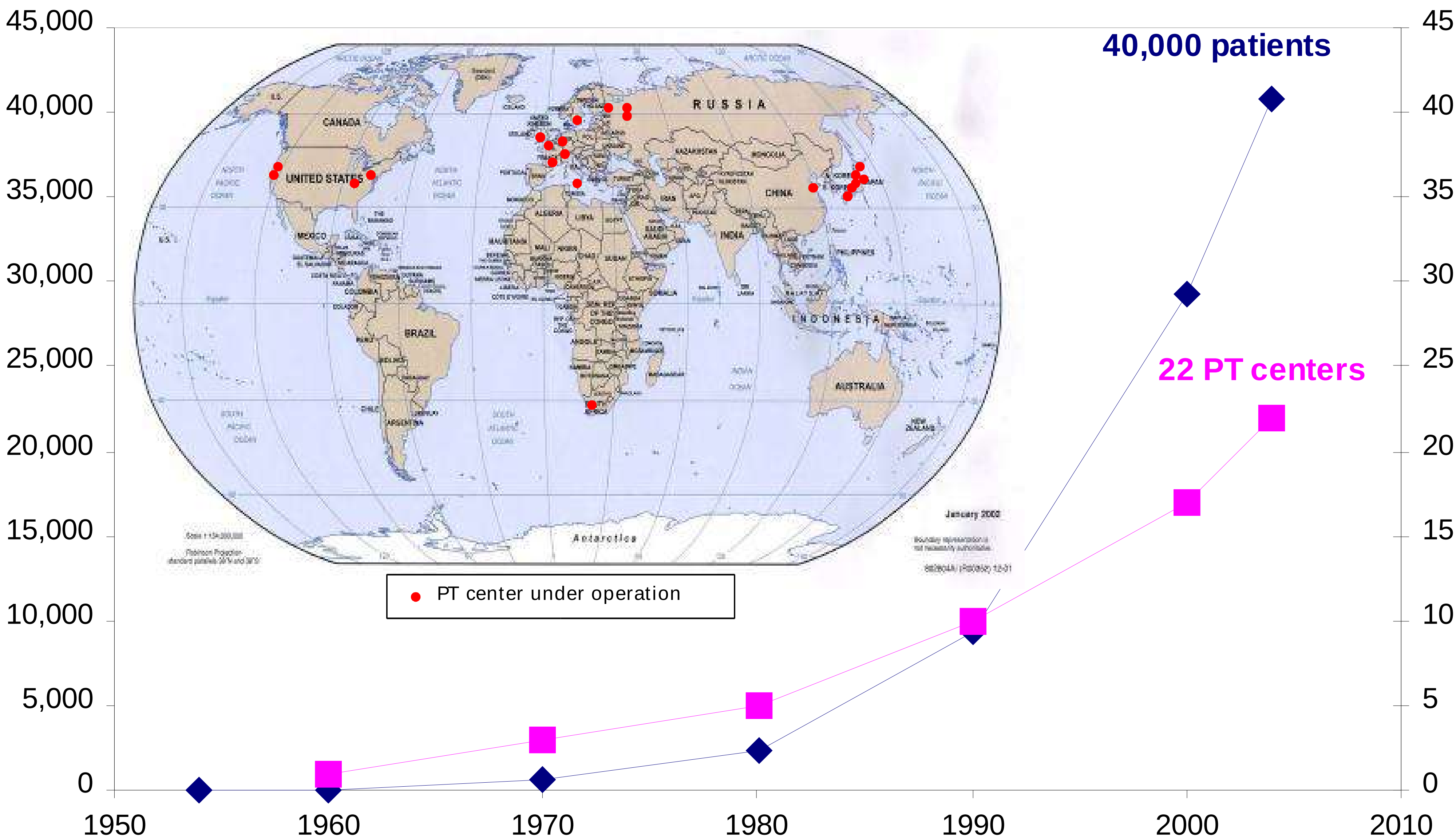
1 in 3 Europeans will confront some form of cancer in their lifetime.

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

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 1^{st} 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 1^{st} hospital based cyclotron, 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

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

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

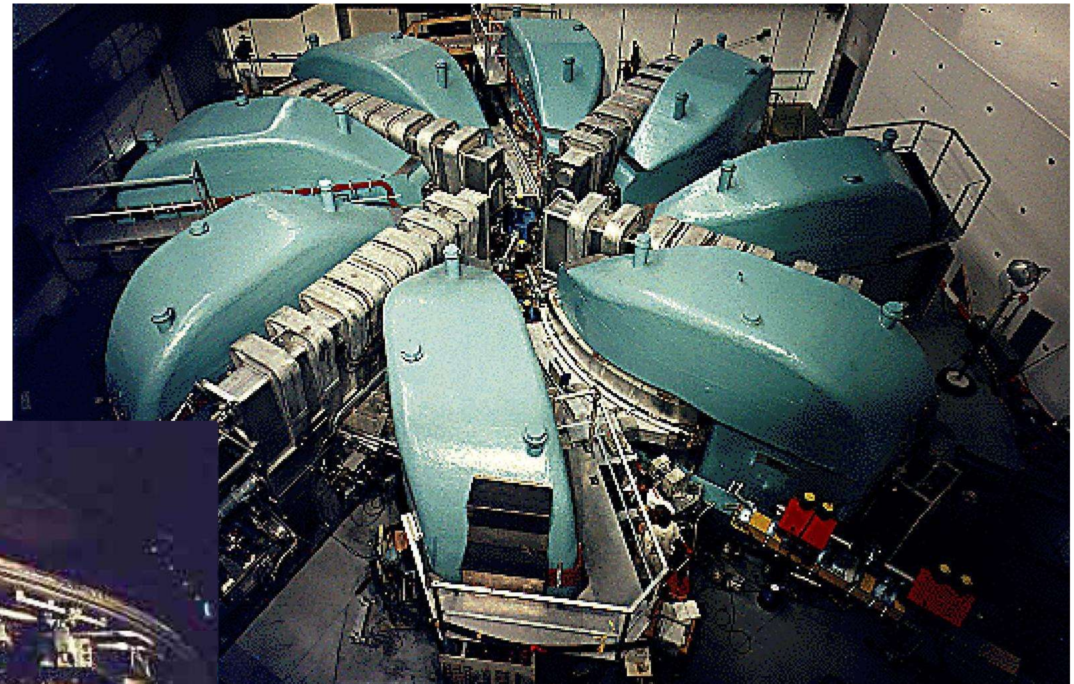
MDACC ~ 70 Hz (PTCOG 42, Al Smith, 2005)

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

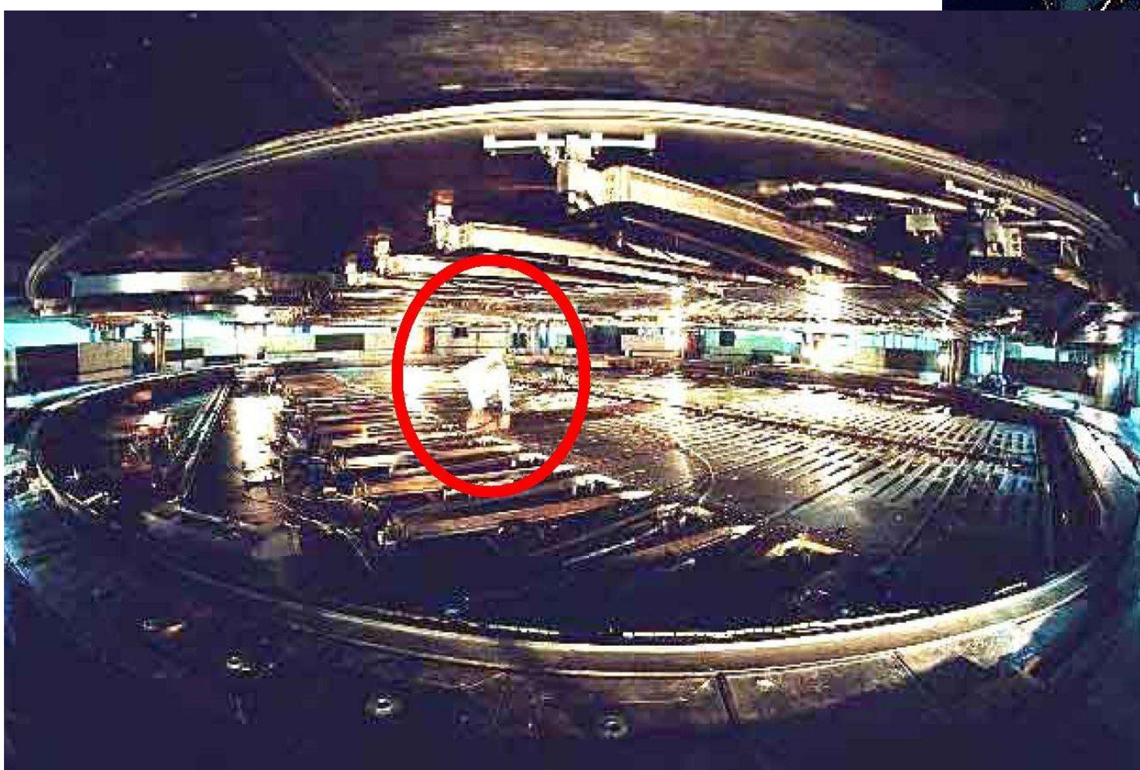
Cyclotrons, big …

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

National lab operation is increasingly deprecated, especially in US



PSI



TRIUMF
Pion therapy, briefly

… "small" …

IBA C230

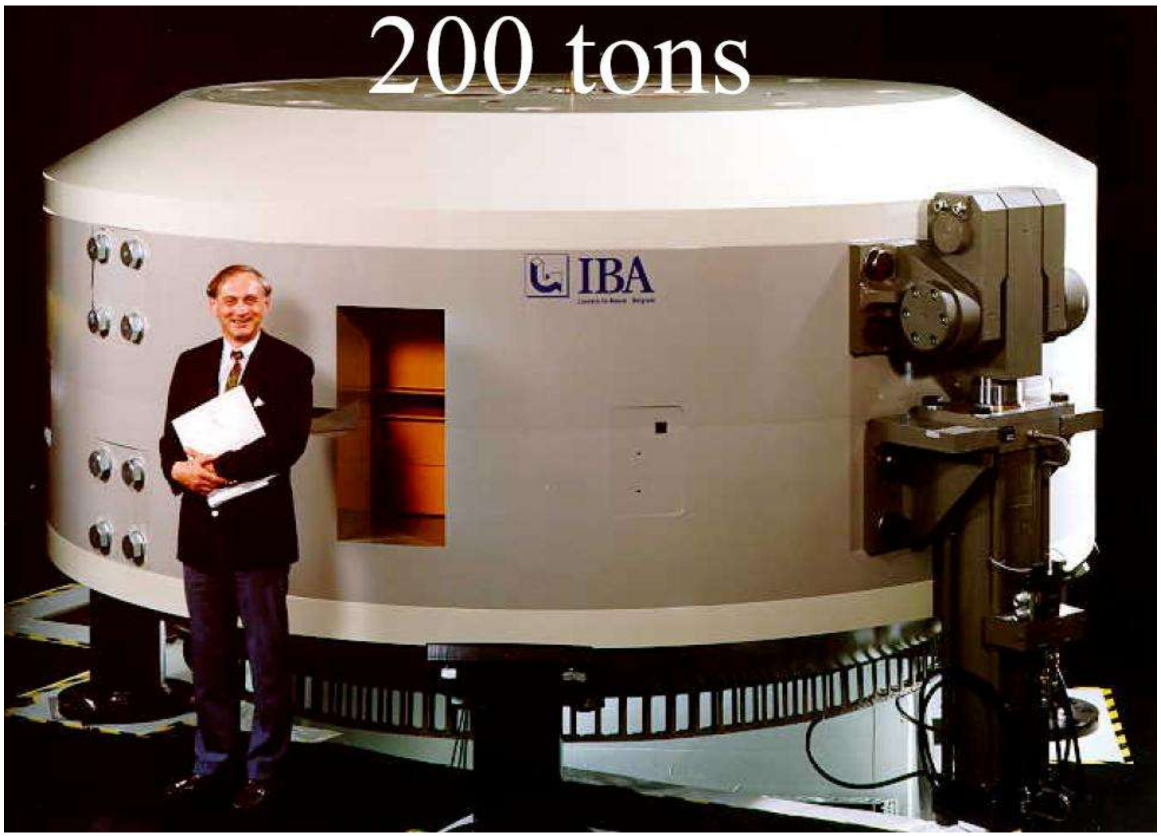
230 MeV protons, 300 nA

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)

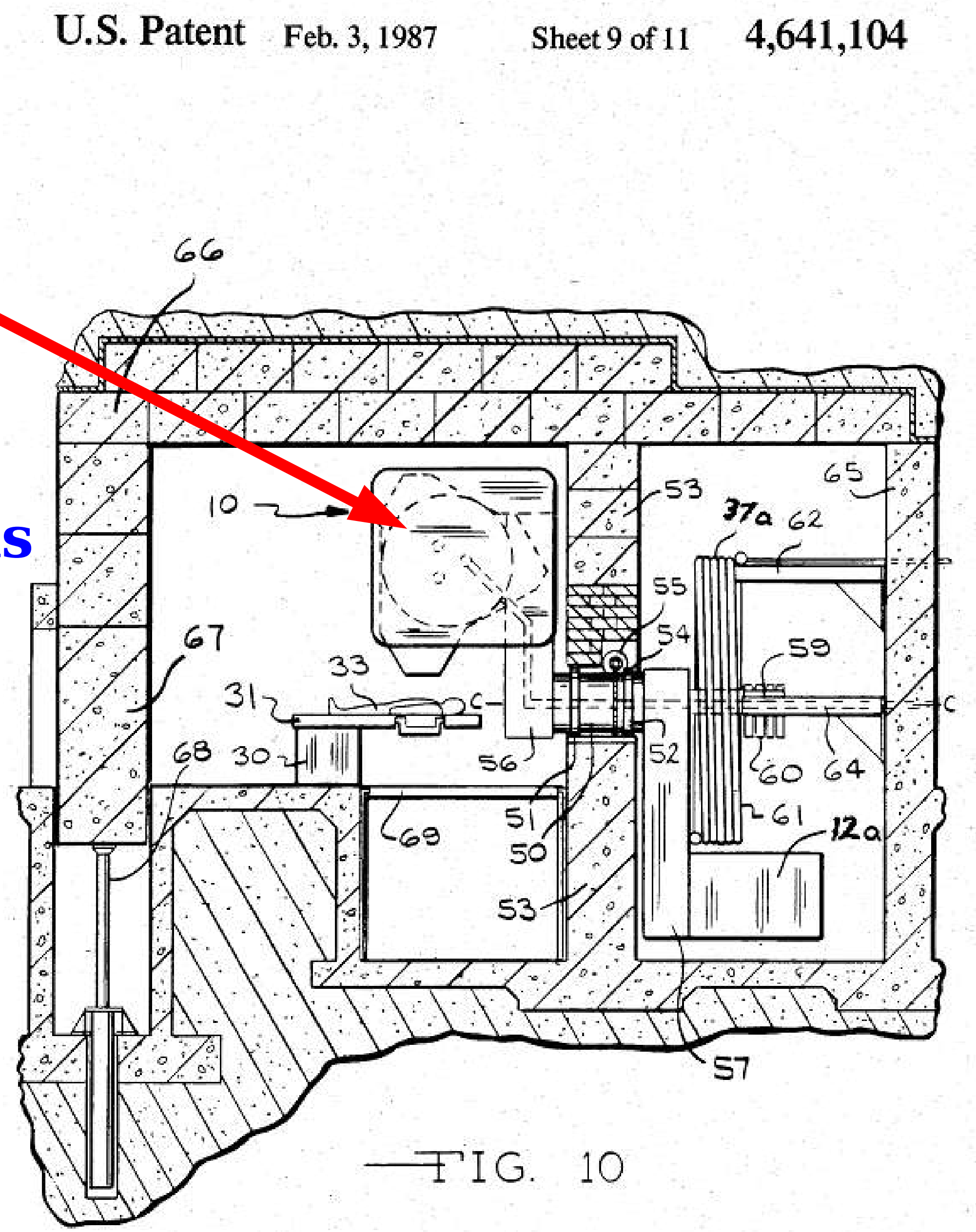
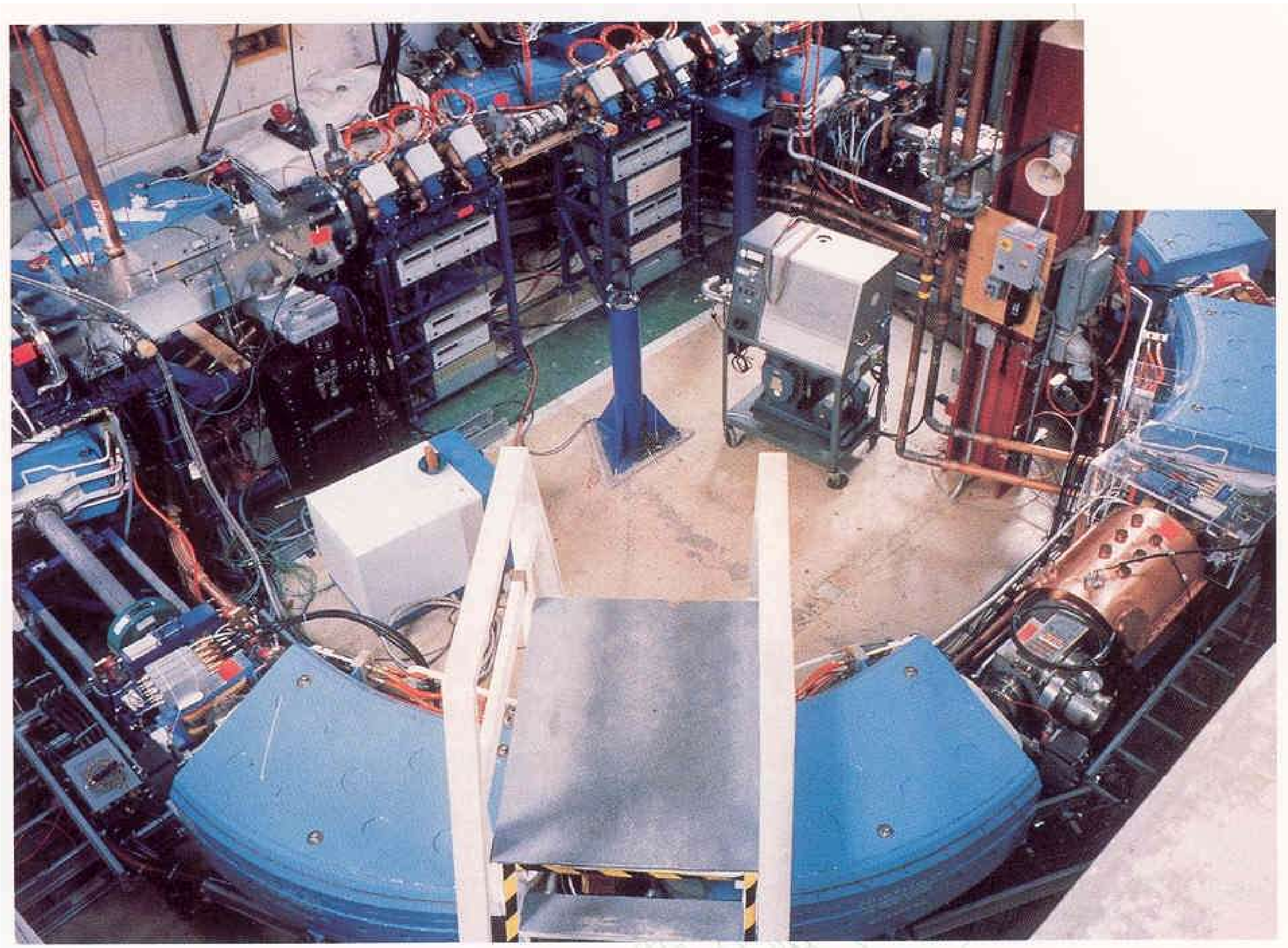


FIG. 10

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 (enlarges emittance)
- energy degraders sometimes necessary

But it works!

LEFT: Hitachi synchrotron at MDACC

Strong focusing

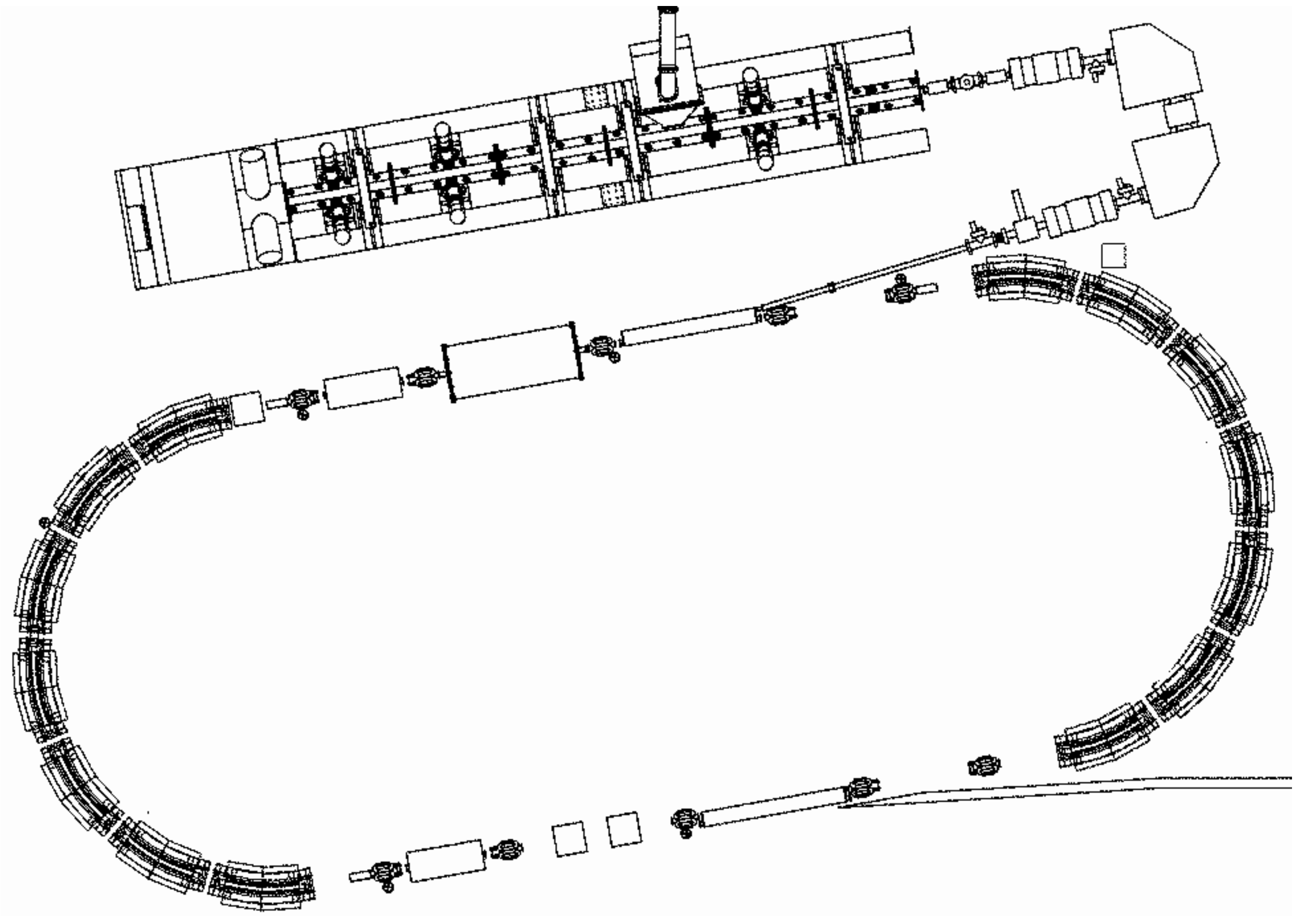
Synchronize beam delivery with respiration!

Rapid cycling, fast extraction

Multiple proposals (none operating): 25 Hz to 60 Hz

Three challenges:

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



RCMS Rapid Cycling Medical Synchrotron
(BNL, AES, NanoLife)

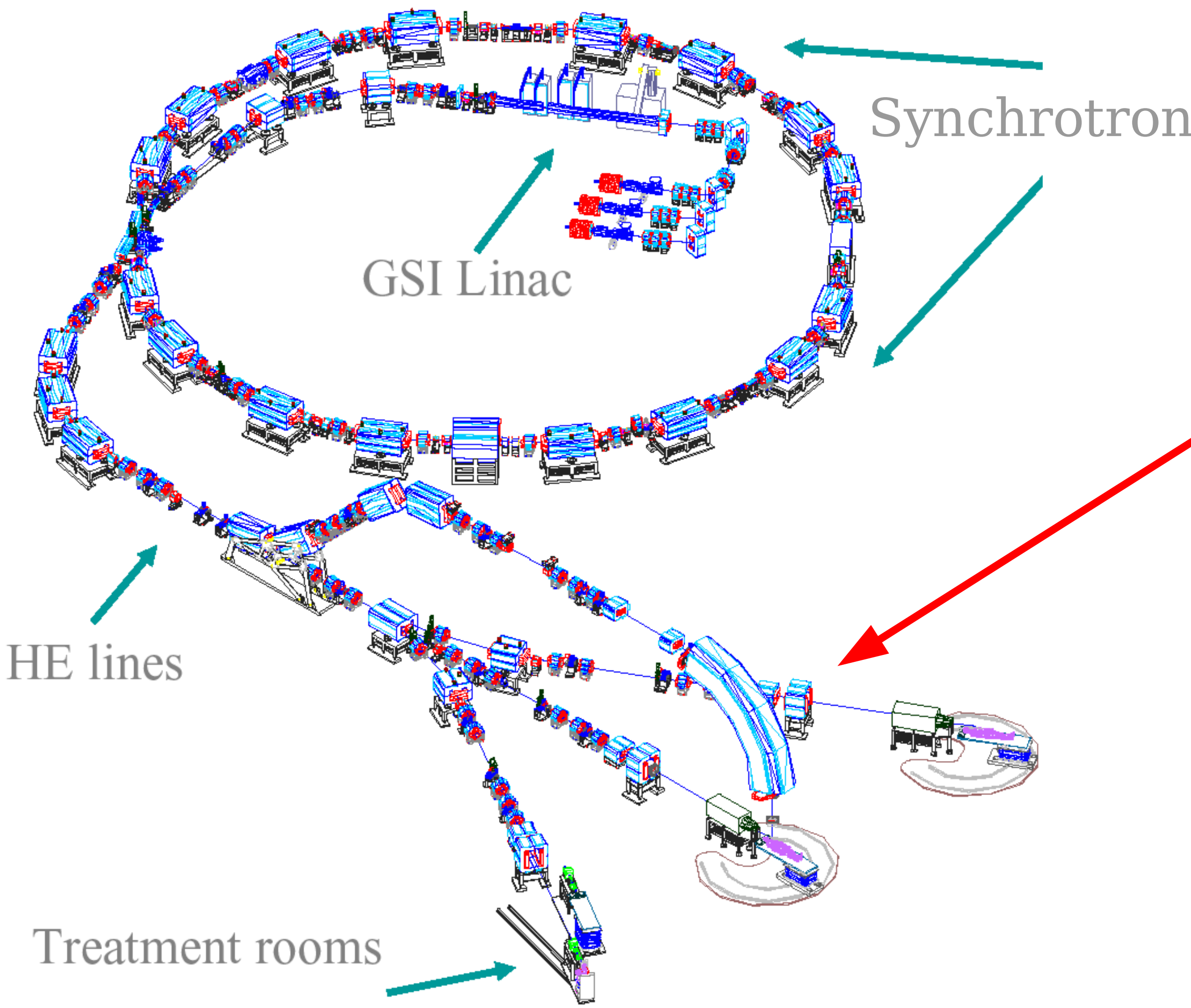
"No" space charge

High efficiency (eg antiprotons?)

Small emittances enable
- small light magnets
  air-cooled
- light gantries

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)

New & revisited concepts

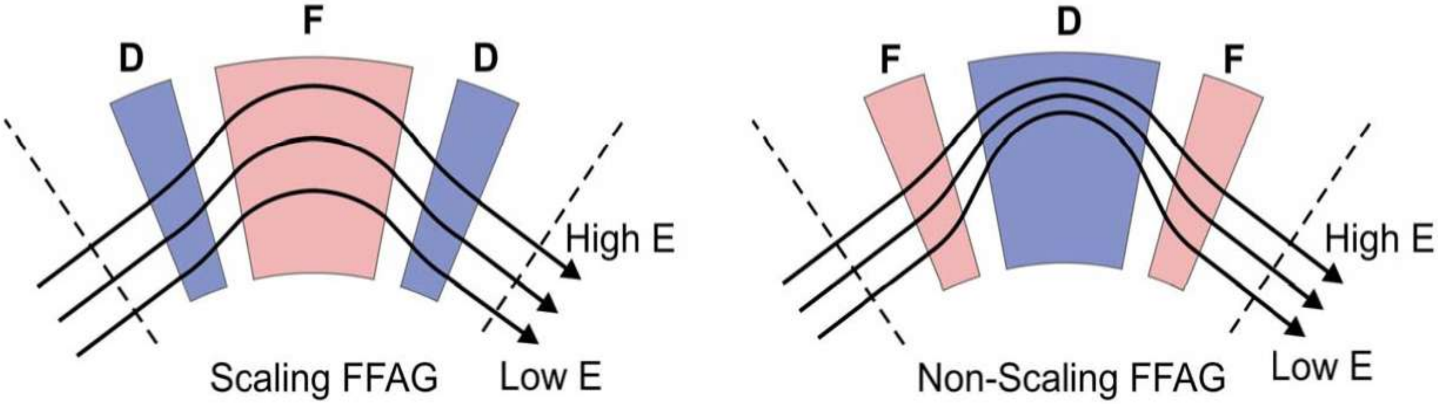
FFAG reprise

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

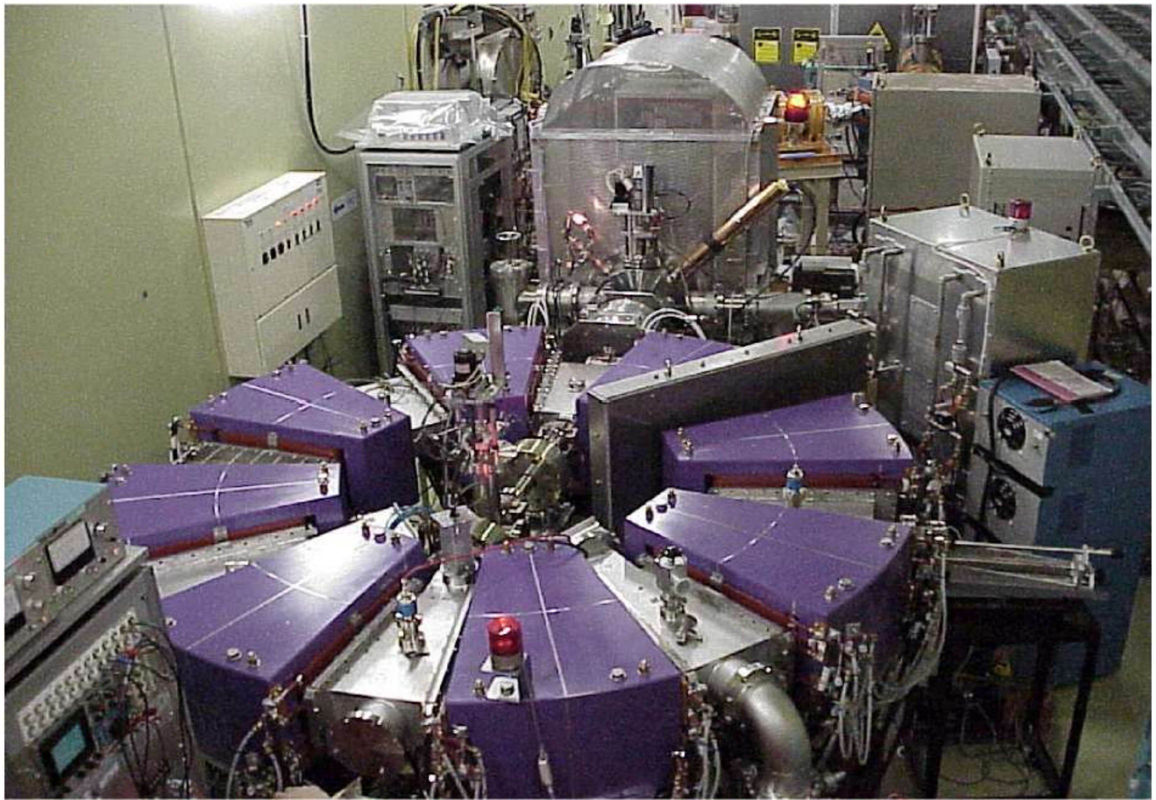
Fast acceleration (think muons)

Compact footprint

Magnet aperture must accept large momentum range



KEK



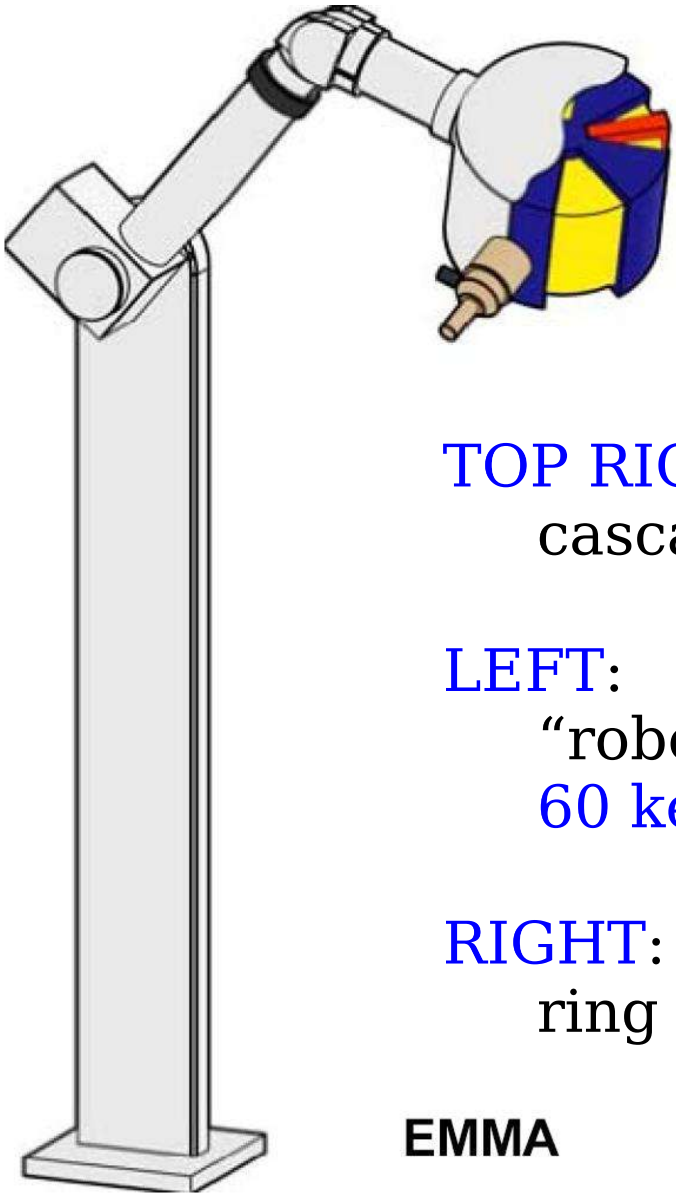
Variable energy extraction?

Possible very high rep rate

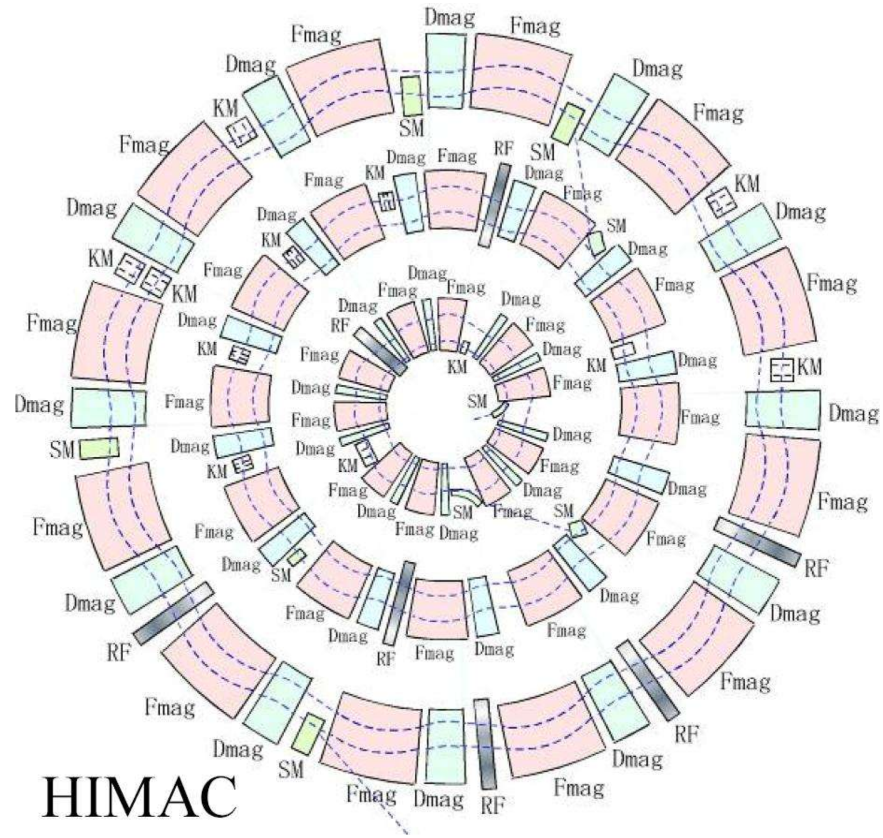
Much world wide interest.

Demo machines in early operation, construction & design

FFAG - continued



EMMA

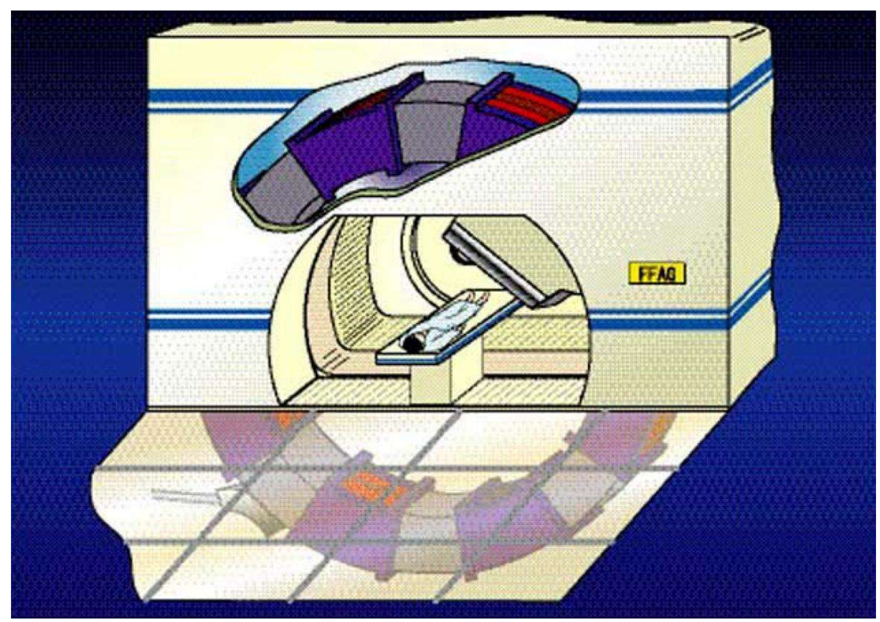


HIMAC

TOP RIGHT:
cascaded rings

LEFT:
“robot” gantry
60 keV – 1 MeV

RIGHT:
ring gantry



Linacs

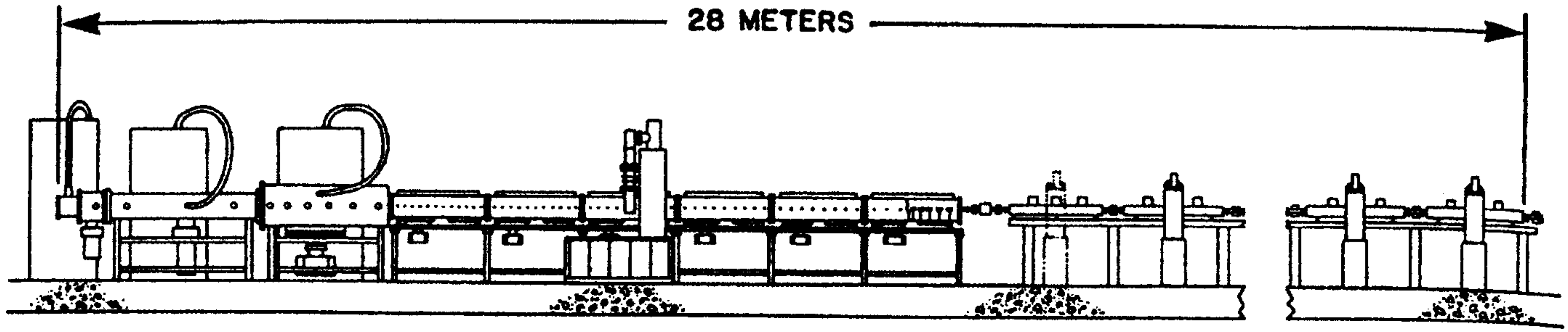


Figure 1. Schematic Layout of Model PL-250 Proton Therapy Linac.

Linacs

< 10 MeV/m

complex RF

"TOP" @ ENEA

SCDTL

200 MeV protons

1st in hospital?

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

HERE: 1999

R. Hamm PL-250

Fast neutrons proposal

TUYC02 "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"

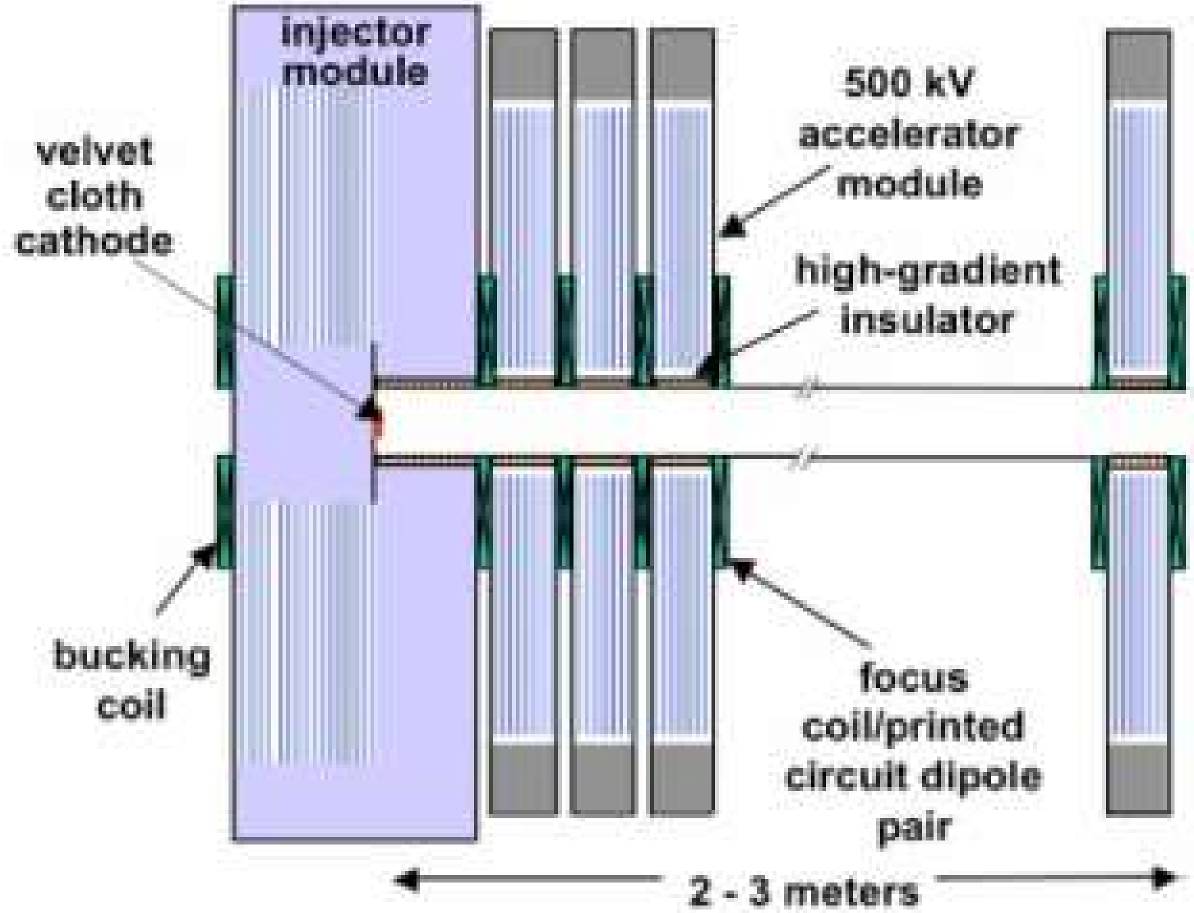
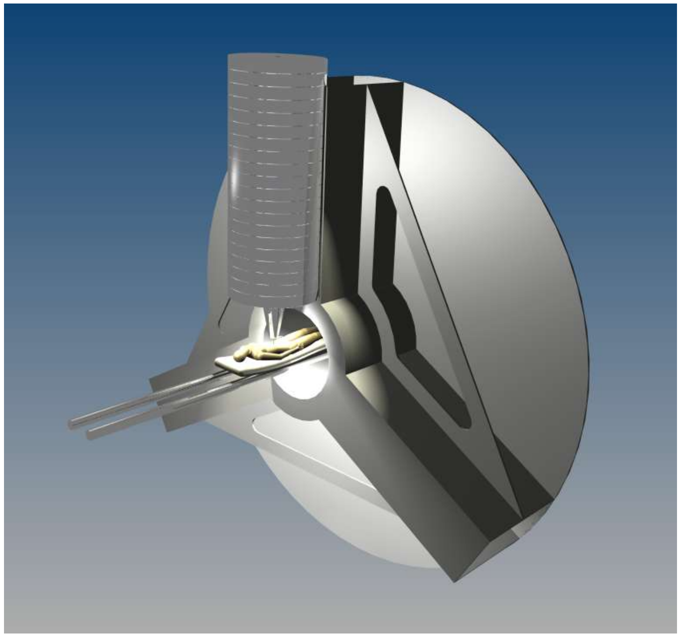
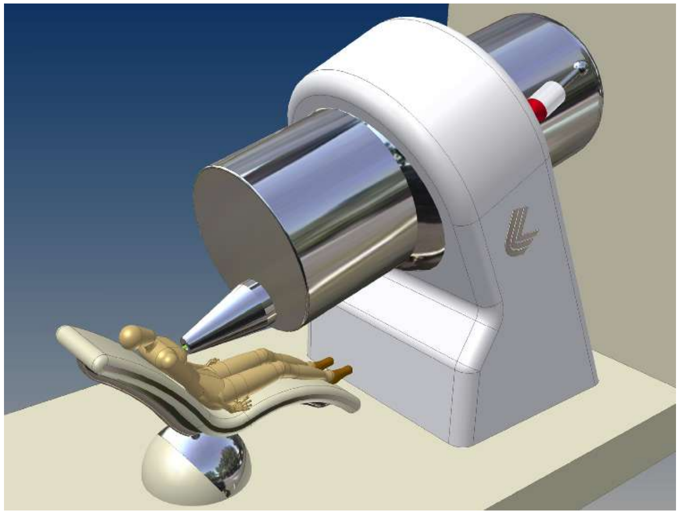


Figure 1: Dielectric wall induction accelerator configuration.





Proton gantries

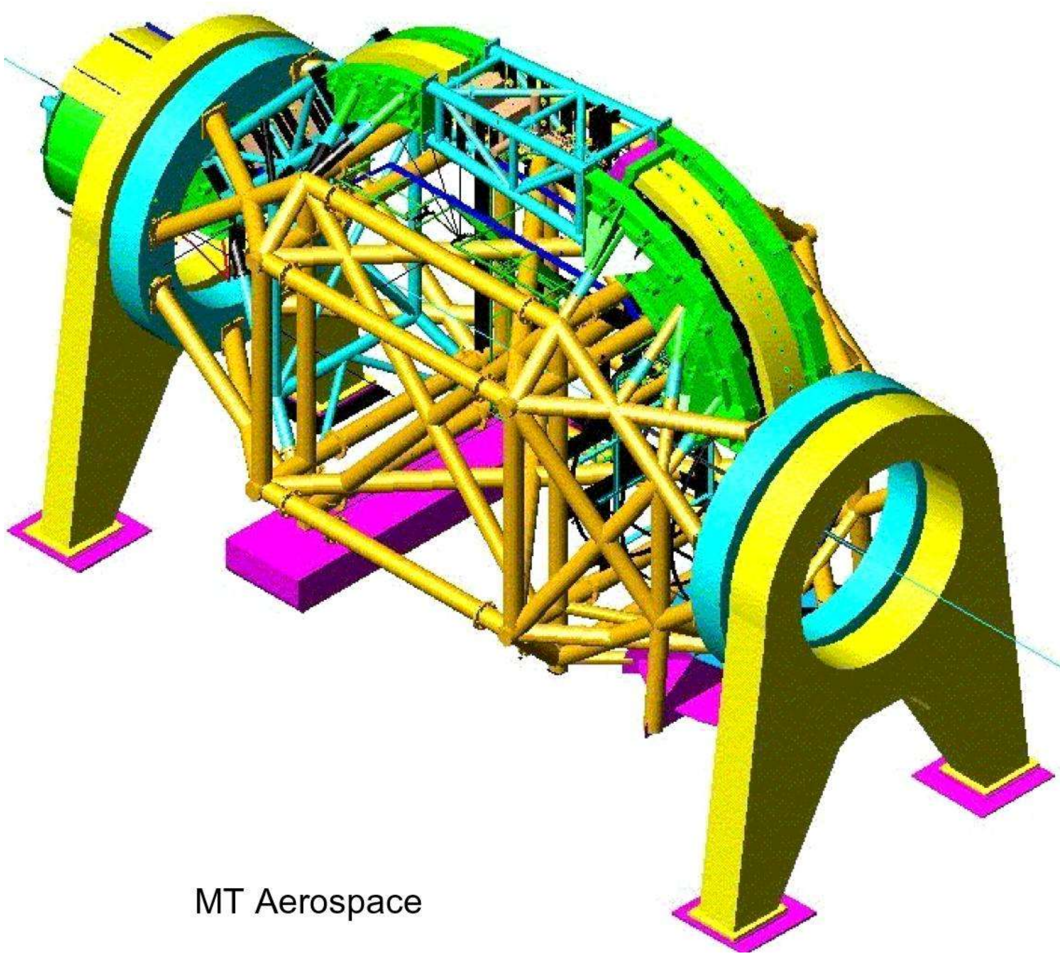
PSI **IBA**

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 !!

Future gantries

Emerging technologies mainly aimed at carbon gantries

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

  (THPMS092 "Superconducting Non-Scaling FFAG Gantry")

Small beams

enable small light magnets & simple light gantries

16 more PAC07 papers ....

RED = oral, BLUE = FFAG, GREEN = DWA, MAGENTA = cyclotron

MOOAC01	Radiological centre at **INR RAS**	S. Akulinichev (INR)
MOZBC02	Hadrontherapy projects in Europe	J-M. Lagniel (GANIL)
TUPAN008	Spiral FFAG for Protontherapy	J. Pasternak (LPSC)
TUPAS059	Compact Proton Accelerator for Therapy	Y-J Chen (LLNL)
THPMN076	**PAMELA** - Model for FFAG based Therapy	J. Pozimski (IC)
THPMN103	Nonscaling FFAG Design for Therapy	C. Johnstone (FNAL)
TUPAS061	Simulations for Compact Proton Accelerator	L. Wang (LLNL)
TUPAS058	Simulations of Dielectric Wall Accelerator	S. Nelson (LLNL)
TUYC02	High Gradient Induction Accelerator	G. Caporaso (LLNL)
THPMN020	300 AMeV SC Cyclotron for Hadrontherapy	M. Maggiore (INFN)
TUPAN081	Axial Injection .. of C400 Cyclotron	N. Kazarinov (JINR)
THPMN004	Compact Proton and Light Ion Synchrotron	S. Moller (Danfysik)
THPMN013	The **ACCEL** Single Room PT Facility	J. Timmer (ACCEL)
THPMN014	Commissioning the Linac for **HICAT**	M. Maier (GSI)
THPMN078	The **CONFORM** NonScaling FFAG	R. Barlow (UMAN)
THPMS092	Superconducting Non-Scaling FFAG Gantry	D. Trbojevic (BNL)