Accelerator and Beamline/Gantry Design

from a user's point of view - for optimal beam delivery

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Retired from work in 2012
("Scanning-biased")

PTCOG 52
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University of Essen

ACCELERATOR PARAMETERS RELEVANT FOR BEAM DELIVERY

Required beam energy

- Particle range up to 30-35 cm (half depth in the human body)
  - energy for protons ~ 240 MeV for protons
  - energy for ions ~ 460 MeV/nucleon for carbon
- We must transport such a beam
  - In vacuum
  - We accelerate the beam with electric fields
    - Max. voltage of order of 10 kV / cm ?
  - We direct and focus the beam with magnetic fields
    - Ferro-magnets - good field homogeneity if the field is below ~ 1.5 Tesla
    - Superconducting coils - much higher fields - field non homogeneous (beam optics)
- Beam rigidity -> limits the bending radius applied to a particle beam
  -> defines size of accelerator and facility
  - Min. bending radius R ~1.5m (p) - 3.8 m (C) -> area size 10-20 m
  - Multi-area facility ~ size 50m (p) - 100m (ions)

B*R=3.3356 * p / Z
Testa, m, GeV/c
Proton p=0.71 Z=1

Accelerator performance for scanning
Beam time structure, stability, intensity control

Increasing PERFORMANCE

- Magnetic scanning (PSI Gantry 1)
  - Beam ON-OFF at jump to next spot
    1 liter - 5 mm grid - 21^3 ~ 10'000 spots/l
  - 100 sec treatment time - 100 spots/s
  - 1% dose precision (spots mean 10 ms)
    - Trigger beam off @ 99.5% spot time
    - Resolve spots @ 100 μs time scale

- Repainted scanning (PSI Gantry 2)
  - Continuous beam scanning
  - Variable magnetic scan speed
  - Dynamic beam intensity control
  - Paint lines to reduce beam off dead time
  - 10 ms / line - 300 ms / energy - 10 s/liter

DC beam

state of the art @ PSI

Count MU
MU shorter as 100 μs

Same order as the monitor response time and time to re-act on beam

2-5% dynamic control of beam intensity @ time scale of 100 μs

Feed-back loop from monitor to ion source

Stable beam

Pulsed beam

no scanning shown ye

Count pulses @ rate c
~10 kHz pulses/s ???

or

100 pulses/s with 2% dose control precision per spot=pulse ???

Adjust dose before the pulse is accelerated

1 kHz with 2% dose control per spot/pulse ???

Increasing COSTS?

Accelerator performance for scanning
Energy variations

- Scan SOBP with a range-shifter
  - 100 ms per SOBP step?
  - Disadvantage of using a range shifter
    - Pencil beam broadening in the air gap before the patient - bad dose fall-off
- Scan energy with the beam line
- Volumetric repainted scanning
  - Moving targets and Image Guidance

- Slow energy changes per field -> minutes OK
- Medium energy changes (~1s)
- Fast energy changes (~100 ms)

Increasing PERFORMANCE

Increasing COSTS?

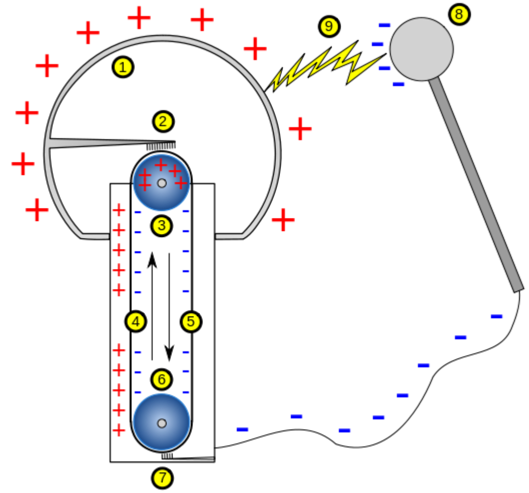
Performance of accelerators for optimal treatment delivery:

Beam duty factor	*time structure*
Beam intensity control	*stability - variability - speed*
Beam energy control	*stability - variability - speed*
Beam size	OK if below the limits of multiple Coulomb scattering
	MCS in the patient (limiting at high energy)
	MCS in the beam monitors (at low energy)

BASIC ACCELERATOR CONCEPTS

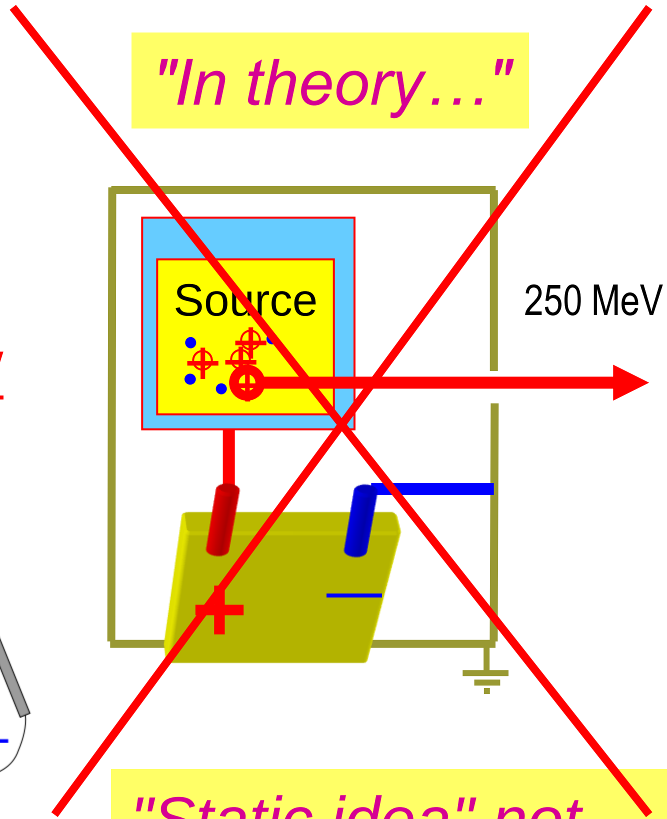
Electrostatic accelerator?

- Electrostatic - 250'000'000 Volts?
  - Conceptually simple
  - Practical limits - ΔV ~10 kV for gaps of a few cm
- Best achieved so far (nuclear physics era)
  - Tandem van de Graaf - we can get up only to 10-20 MV



- We therefore must apply a stepwise repeated acceleration (100-1000 times)
  - Oscillating electric fields -> accelerator **RADIOFREQUENCY**

"In theory…"

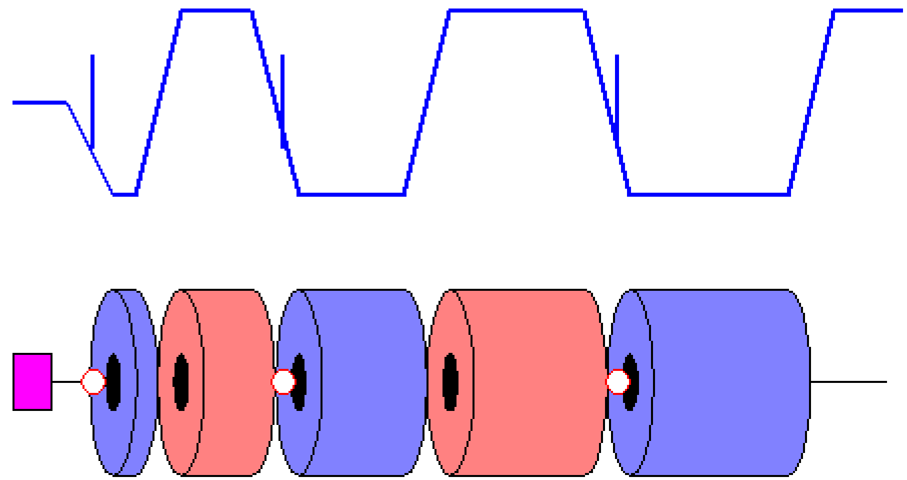


"Static idea" not feasible in practice for P-Therapy

1932 First electro-static accelerator
J.D. Cockcroft und E.T. S. Walton

Linear accelerator ?
Repeat acceleration using a sequence of RF cavities

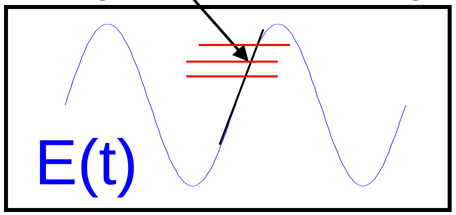
- Cavity transit time adjusted to RF
  - Constant radiofrequency
  - Synchronize particle transit time with RF via varying cell length L= v(E) .T
    - Complex mechanical construction
- Total length ~20 m
- DC beam? Possible in theory…
- Technical limitations …
  - Power
  - Heath
  - Pulsed beam with short pulses
- Presently used only as injector for PT synchrotrons



v=0 to 0.5 c   0-60 cm/ns
L= order of cm
> GHz Frequency

L = v.dt

Working point below max E field to provide longitudinal focusing



Holy grail
100 MeV / m ?

1928 First linear accelerator (50keV) by R. Wideröe
1946 proton linac L. W. Alvarez

Next idea - cyclic machine with magnetic field

Folding the linac for re-using the RF cavities

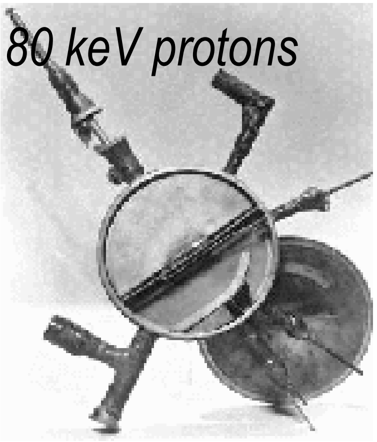
- Homogeneous magnetic field
  - Circular orbit
  - Spiral trajectory
- Constant time of revolution
  - By physical laws - in theory …
  - Valid only at very low energy

$$\frac{m \cdot v^2}{R} = e.v.B$$

$$R = \frac{m \cdot v}{e.B}$$

$$2\pi R = vT$$

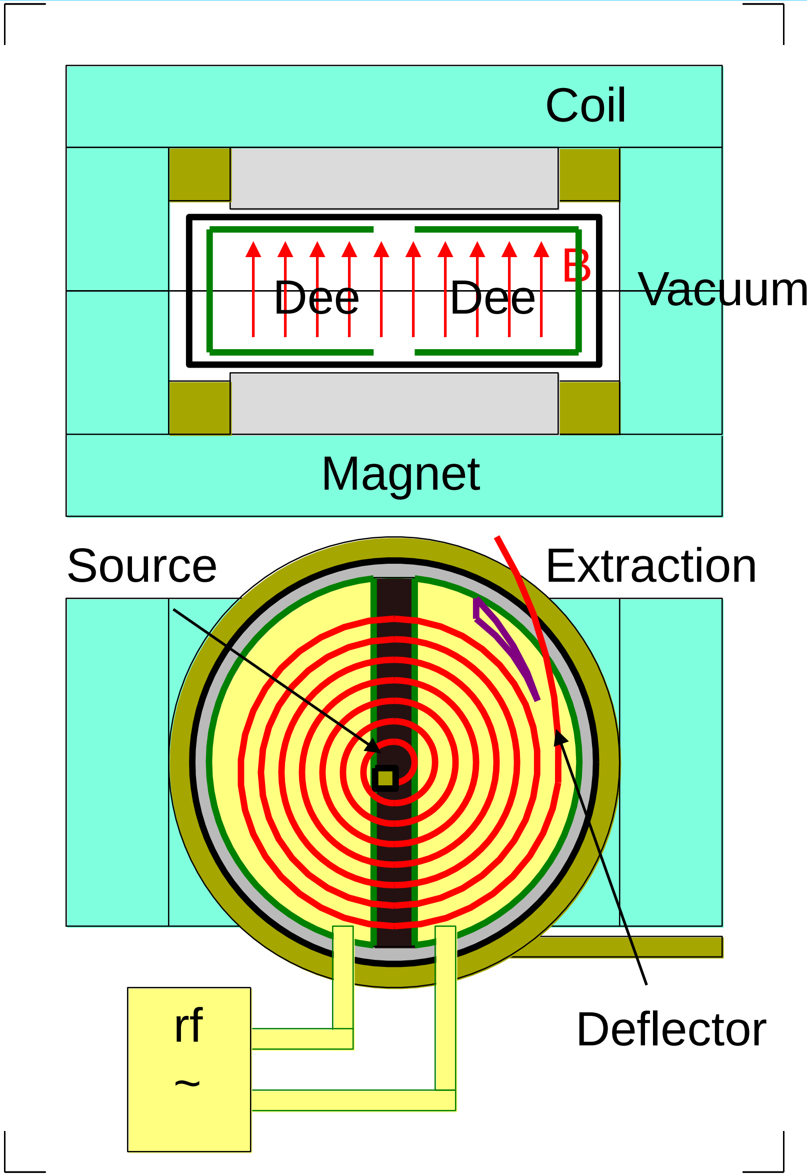
$$\upsilon_{cyclotron} = \frac{e}{2\pi} \cdot \frac{B}{m}$$



12 cm diameter
M S Livingston 1930

Relativistic effects !!

$$m = m_0 . \gamma = m(r)$$



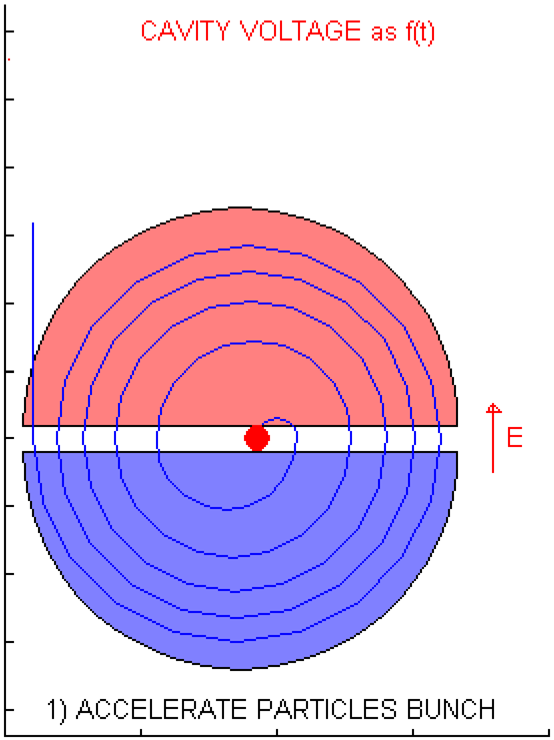
Synchronization of cyclic machines

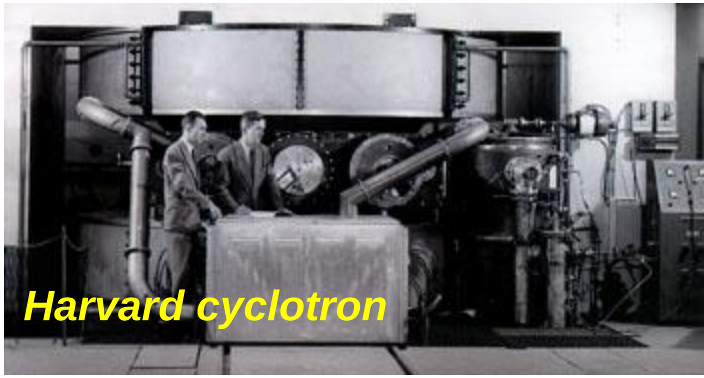
- Relativistic effects
  - 0->250 MeV protons
  - Velocity v = 0 -> 0.6c (c velocity of light)
    - Revolution time 2.π.R / v ~ 20 ns (@ R=1.5m)
    - Rotational frequency (and RF) of the order of 50 MHz
  - Mass increases from 1 to 1.3 along the spiral
    - *The synchronization of the particle bunches with the RF must be precisely adjusted - a question of accelerator design*

- Three different ways of solving the problem
  - Dynamic - RF(t) varies with particles acceleration **SYNCHRO-CYCLOTRON**
  - Static - magnetic field designed for synchronicity **ISOCHRONOUS CYCLOTRON**
  - Double dynamic - RF(t) and magnetic field B(t) **SYNCHROTRON**

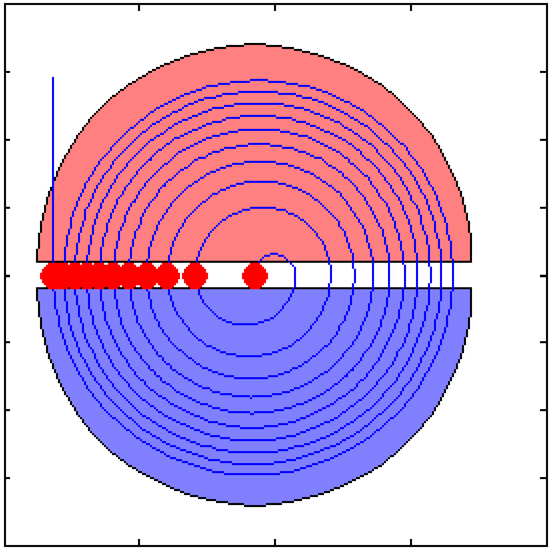
Cyclic machines - Solution 1: Synchrocyclotron
Spiral machine with modulated radiofrequency

- Adjust the radio-frequency to the particle orbit-path
    - Using big rotating condenser in the 50s (CERN SC)
    - Today RF control via digital electronics
  - Only one bunch is accelerated along spiral trajectory
    - ~ 20 ns/turn x ~10000 turns?
      - Acceleration time of the order of 200 microsecs?
  - The RF-modulation is the limiting factor for repetition rate
    - Rep rate of the order of 0.5 -1 (10?) kHz possible?
- Pulsed machine with short pulses
  - Not yet proven to be suitable for scanning
  - Fixed energy (why not variable energy? - B and RF ?)
- Accelerator type used in the early days of PT !
  - But only for scattering
- Revival : Mevion super-conducting SC; *later*





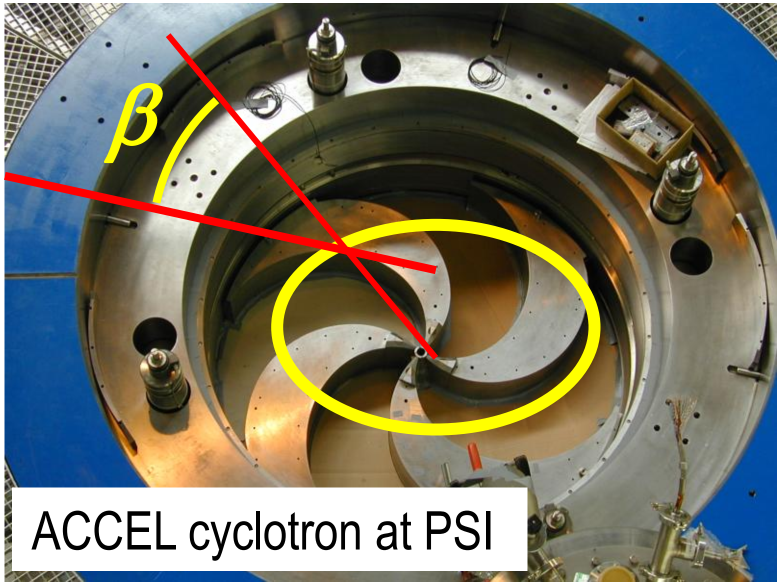
Cyclic machines - Solution 2: Isochronous cyclotron
Exact constant time of orbit revolution



First cyclotron 1930-39 E. O. Lawrence

- Magnetic field design for constant time/orbit
- Vary magnet gap as f(r)? - bad vertical focusing
- Use of separated sectors
  - With "hills" and "valleys"
  - Sectors shimmed for synchronism
  - Needs complex calculations (computers)
  - Tilted edges provide strong vertical focusing

- Synchronization applied on multiple bunches
  - More beam than with any other accelerator type
    - Used in the hospitals for isotope production nuclear medicine
- DC beam - very good for scanning
- But: accelerator with fixed energy

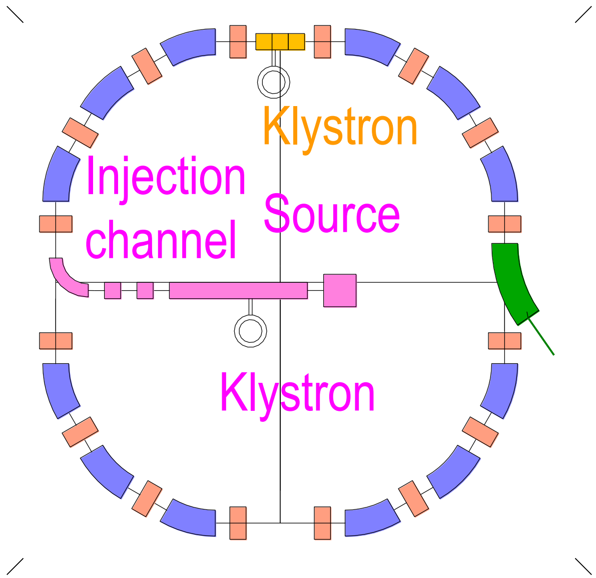


ACCEL cyclotron at PSI

Cyclic machines - Solution 3: Synchrotron

Ring machine - fixed radius - modulated magnetic field and RF

- Ring solution
  - Need separate injector - extraction
  - No energy limit (CERN - 20 km ring)



Dipole (bend)

Quads (focus)

LINAC (injection)

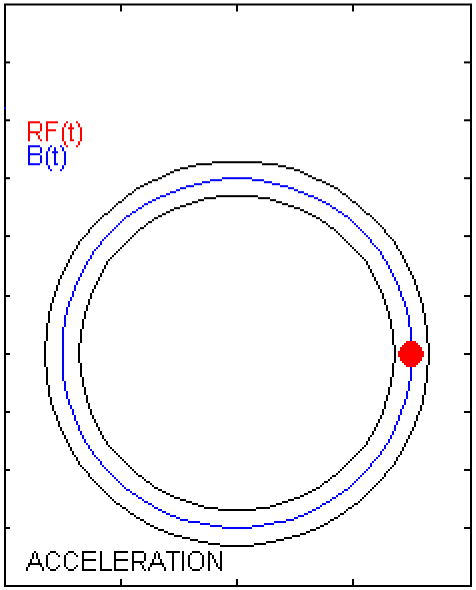
RF (acceleration

Extraction

Complex physics

Lattice

RF ramp up time = beam energy



- Variable energy but
  - Pulsed machine (secs)

- Viable solution for scanning
  - Slow extraction methods producing long lasting pulses

Invented by E.M. McMillan (USA) and V. Veksler (Russland)

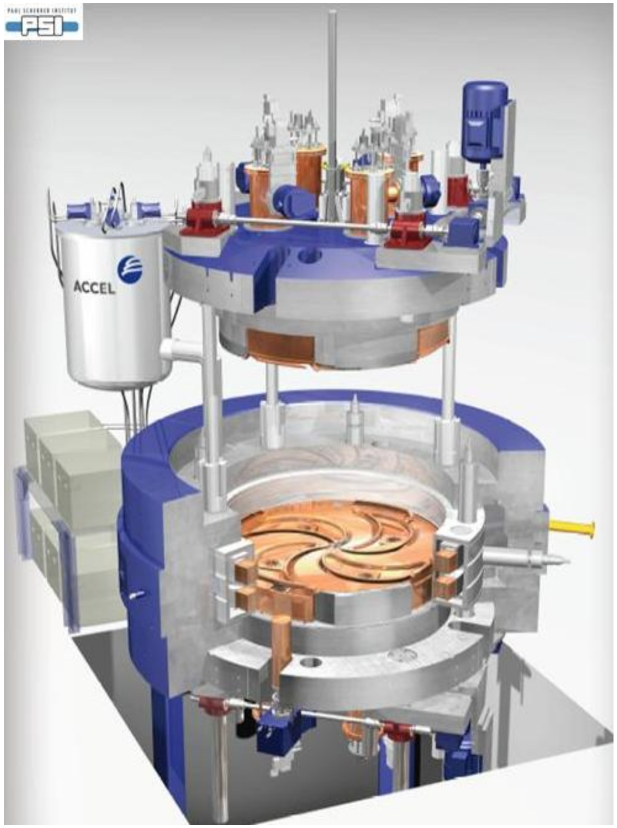
Available
ACCELERATORS WITH DC-like BEAM OUTPUT
with demonstrated capability of scanning

Commercially available cyclotrons for PT

220 tons 4.3 m diameter

- Normal-conducting magnet
  - IBA (Boston, …) - SUMITOMO (Kashiva)

300 KW - 90 tons
3.4m diameter
100 KV in 4 Dees
Closed He Loop



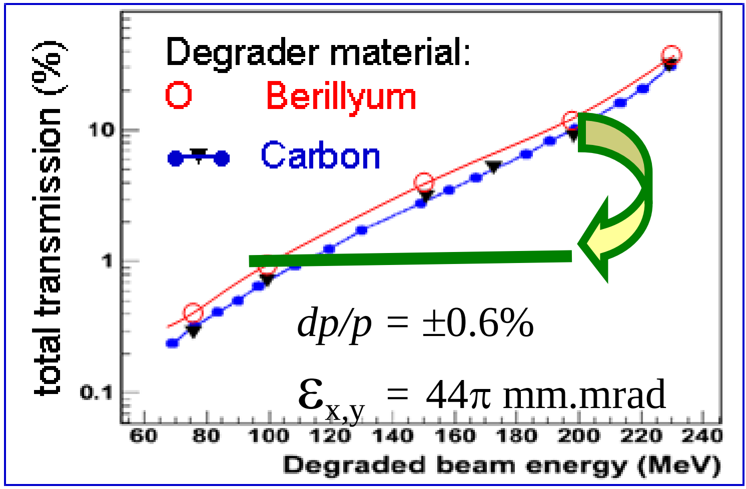
Power consumption	<- high/low ->
Weight	<- high/low ->
Magnet coil repair time	<- short/long ->

Both well established solutions

- Super-conducting solution
  - ACCEL VARIAN
    - Accelerator for PT at PSI
    - First PT facility in Munich

Disadvantage of cyclotron-based PT - the fixed energy

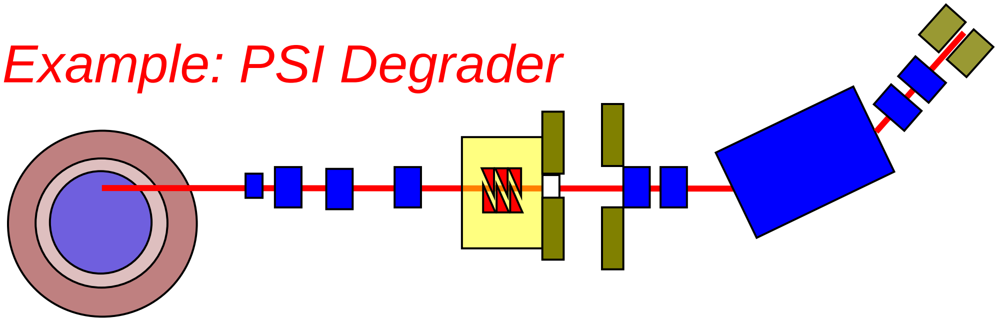
- Requires the use of a degrader
  - Variable amount of material in the beam line
  - Analyze the degraded with beam line + collimators
- Disadvantage
  - Beam intensity lost at low energy
    -> by orders of magnitude



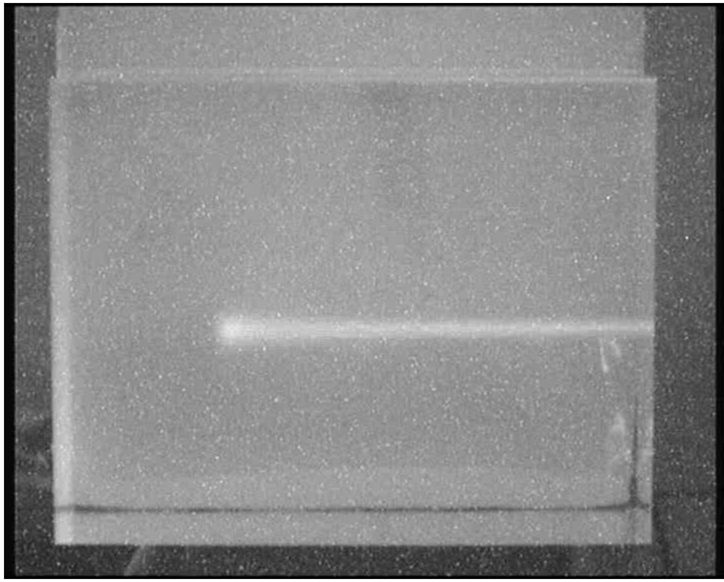
– Equalization of intensity losses (PSI new Gantry 2)

– Advantage of using a degrader
  – Fast energy changes - 80 ms for 5 mm range (PSI G2)

Example: PSI Degrader

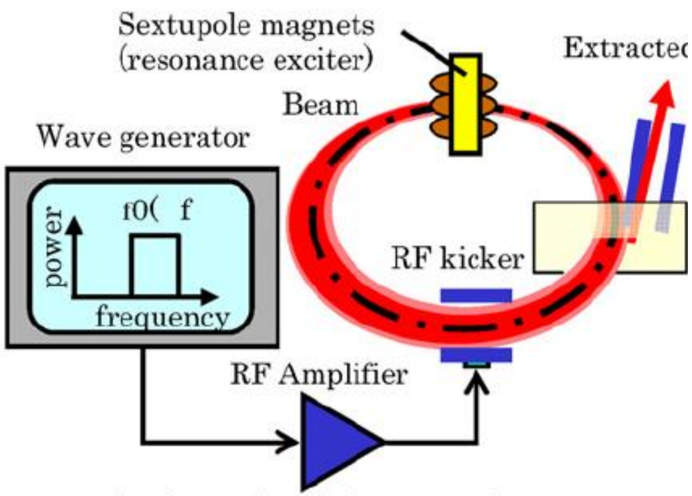


Carbon wedge degrader 238-70 MeV



Synchrotrons need slow extraction for delivering scanning

- Idea to "peel-off" slowly a small part of the circulating beam
- During an extended beam spill we have a DC beam
  - Duty factor ~ 0.5   f(spill length)



Configuration of the extraction system.

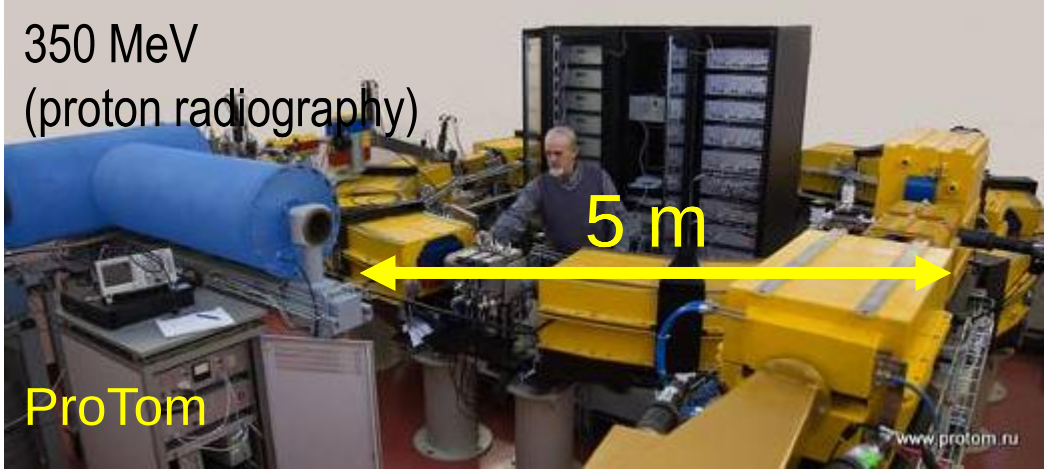
Very complex physics - an own art
…Working near a resonance
…Phase space stability regions
…Several extraction methods
most diffused
Knock Out method

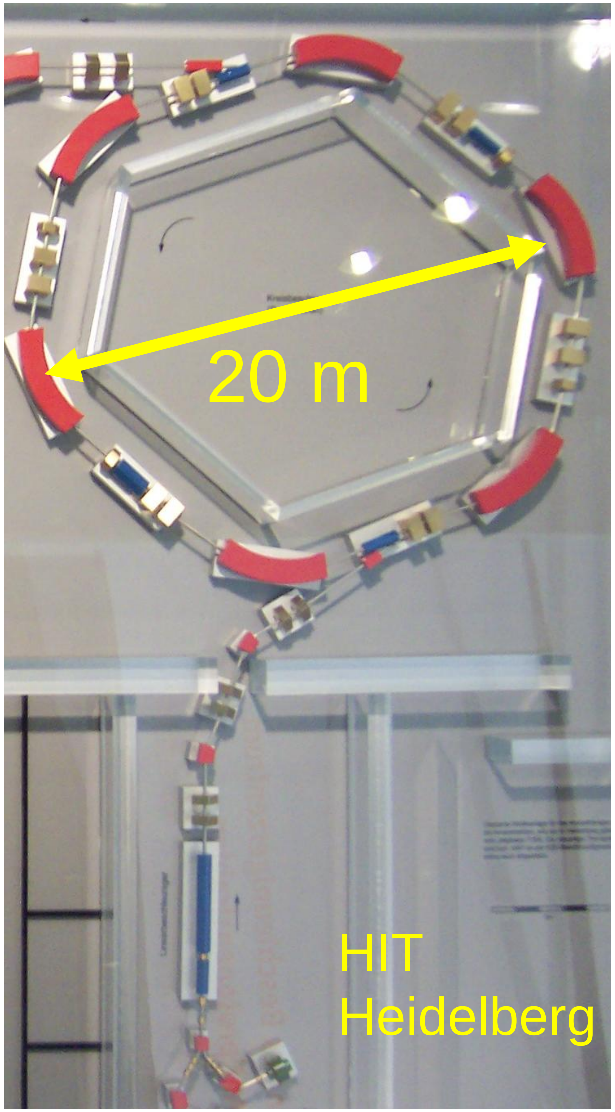
(Tsukuba - Hitachi)

The synchrotron is presently the only solution used for ion therapy

- Berkeley - pioneering work with ions - stopped
- Chiba - first facility dedicated ion therapy
- Darmstadt - first raster scanning - transfer to HIT
- Hyogo - Heidelberg - Gunma - Pavia …

- Facility size
  - Factor of two bigger than a proton facilities due to the magnetic rigidity of the beam (factor ~2.5 higher)





Comparison of cyclotron vs. synchrotron for scanning

Energy		Cyclotron + degrader		Synchrotron
Variable energy		Yes		Yes
Speed of energy changes	+	A few secs - PSI - 80 ms		A few secs - *NIRS m-energies?*
Time structure	+	DC beam		~ DC beam
Duty factor	+	100%		50% ? - ramp dead time
Beam stability		Very stable beam		Stable beam?
Beam intensity modulation	+	*Yes (IBA-PSI)*		*Yes? - NIRS I-modulated spill?*
Beam intensity		High intensity		Enough intensity
Beam size < physical limits		Yes (larger phase space)		Yes (smaller but irregular p.s.)
Size and weight		Compact		Larger - but lower weight
Degrader activation		Activation/shielding (local)	+	Cleaner machine
Dynamics		With beam line only		Accelerator + Beam line
P-Radiography		Only for head		Head and body (350 MeV)
Ions		Future SC-cyclotron?	+	Many different ions

Feasibility of synchrotron with multi-energies extraction per spill?

- Japanese research at NIRS Feasibility of
  - Several sequential energies per spill
  - Modulation of beam intensity during slow extraction
  - Use of a (limited-depth) range-shifter used within a spill-energy

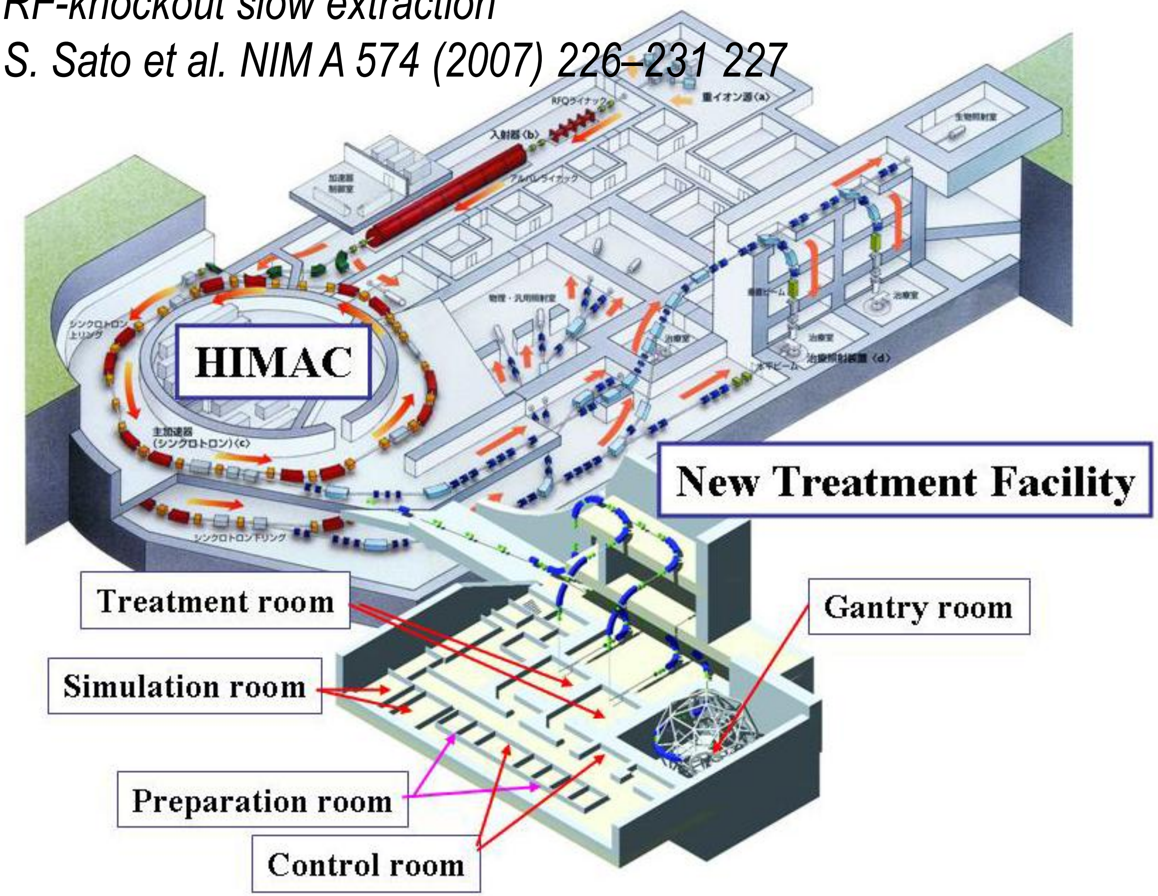
- Similar performance as with a cyclotron?

Multiple energy operation with extended flat top

Y.Iwata et al NIM A624(2010)33–38

Dynamic intensity control system with RF-knockout slow extraction

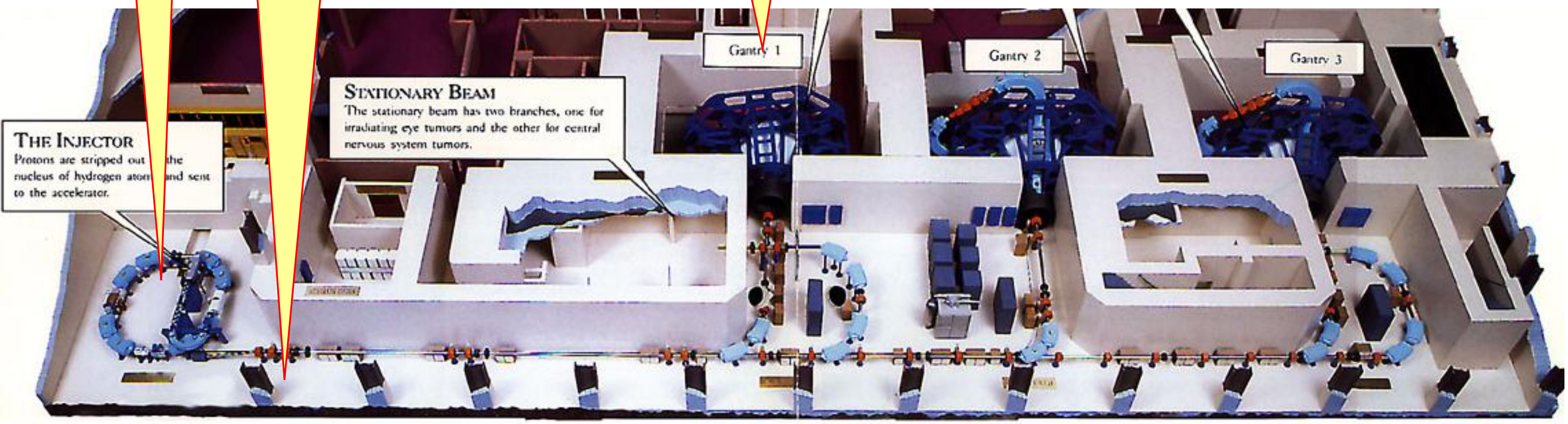
S. Sato et al. NIM A 574 (2007) 226–231 227



GANTRY CONCEPTS

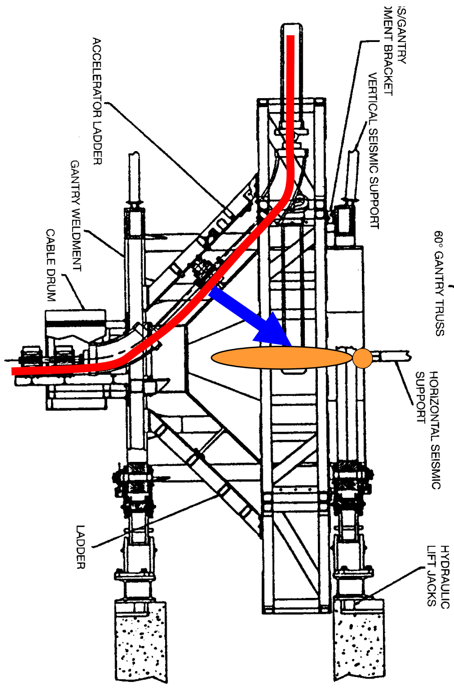
The first hospital-based proton therapy facility in the world
at Loma Linda University (California USA)

– Fermilab technology (Optivus company)
  • Synchrotron
– 3 gantries and 2 horizontal beam rooms
  • For passive scattering
  • Operational since 1991
• Shown that proton therapy can be realized on a commercial basis

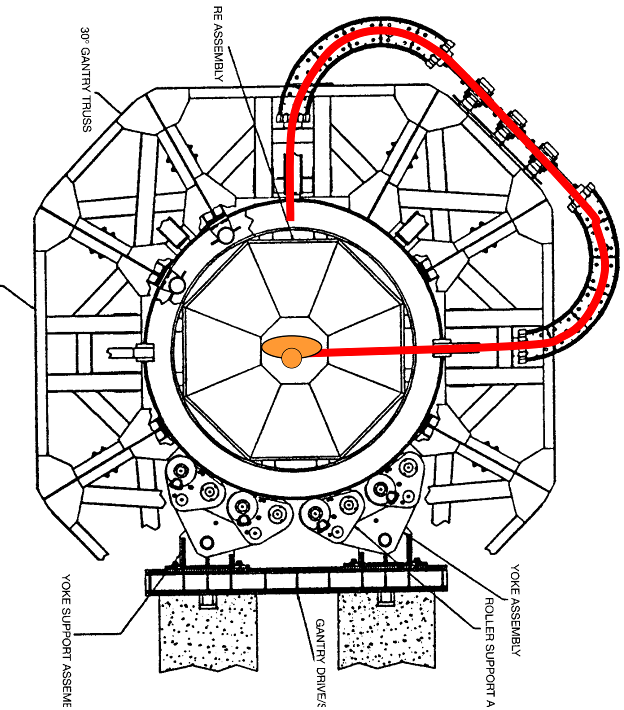


Loma Linda gantry

- cork screw gantry -



Side view



Front view

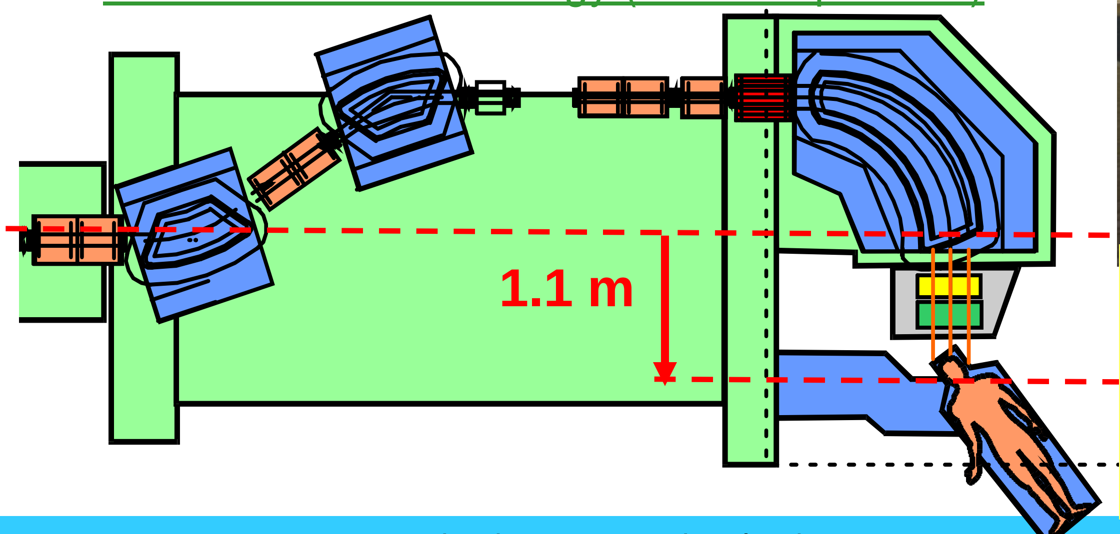
- The first proton gantry in the world
- “Cork screw” gantry
  - Invention of Handy Kohler (Harvard cyclotron)
  - Radial extent mostly on a disk
    - Saves shielding (volume)

Scattering-based (1992)
Beam spreading started downstream of the last bend

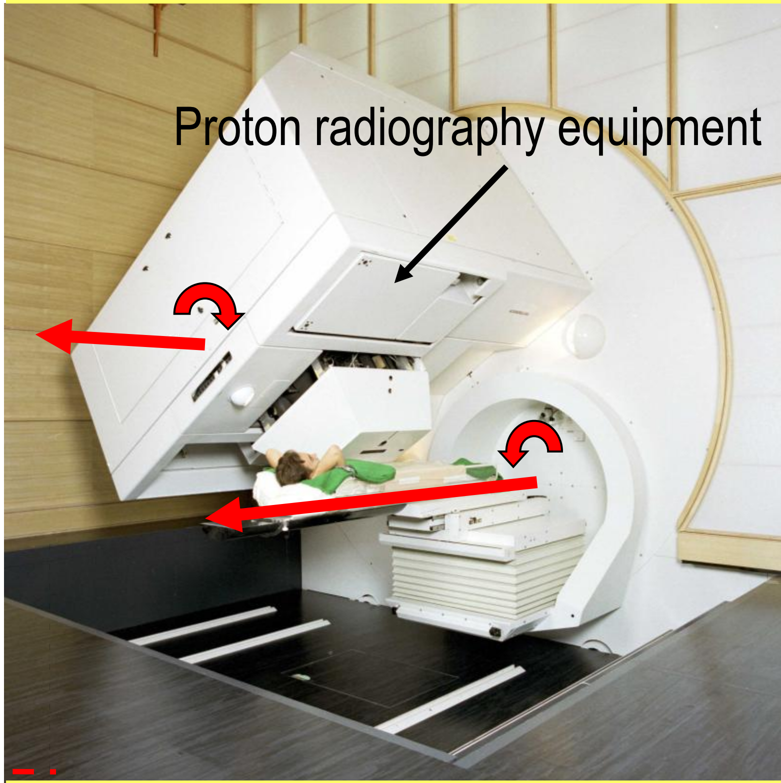
Gantry 1 of PSI in 1992 - The first scanning-gantry in the world

- *eccentric barrel gantry* -

- Gantry radius reduced to only 2m
  - Eccentric mounting of patient table on rotating gantry front wheel (counter-rotation of table)
    - *Missing: a moving floor under patient table*
  - Scanning started upstream of the last bend
    - Parallel beam scanning (infinite SSD)
    - Patient table motion as third scan axis
- SOBP with range shifter in front of the patient
  - Variable beam line energy (but fixed per field)

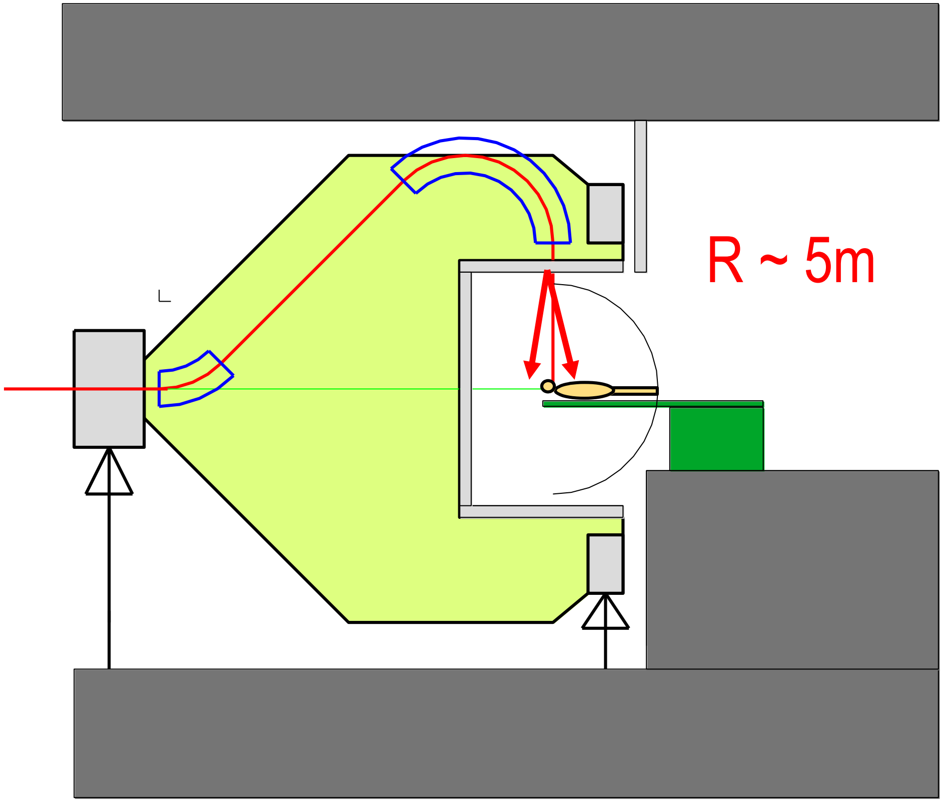


Still the radially most compact gantry system in the world.



Realized for 360° gantry rotation
A 180° rotation gantry
with a robotic table and a false floor
would have been a better solution

“Standard” layout of commercial systems – since end of 90's …
- conical gantry -



Beam spreading downstream of the last bend

IBA
Sumitomo
Hitachi
Mitsubishi
Varian

Kashiva – 1998
Tsukuba - 2001
Boston – 2001
Hyogo – 2001
….

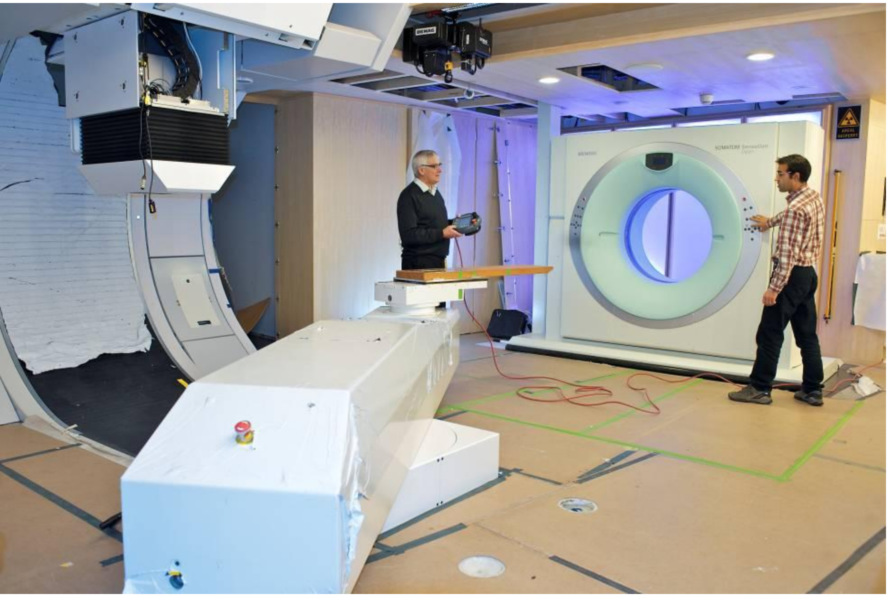
Munich

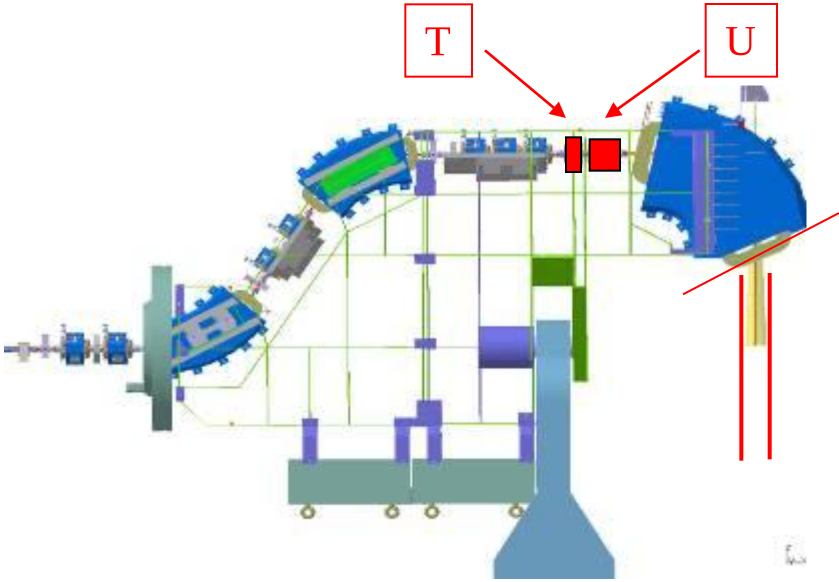
First commercial scanning-gantry of Varian in Munich

- 135°bending magnet
  - Shorter length - but larger radius
  - Cylindrical treatment cell
- Initially only for passive scattering
- Lately also for scanning

The new Gantry 2 of PSI

- *180° barrel gantry* -



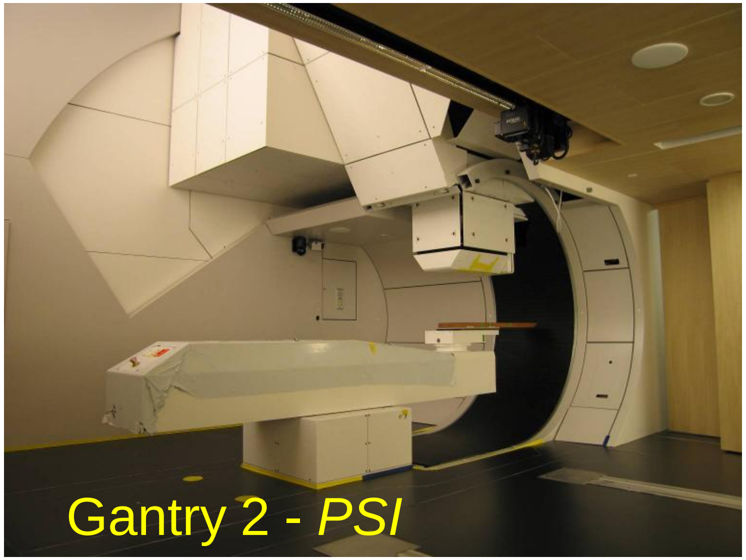


- Iso-centric layout
- Gantry rotation limited to [-30°,180°]
  - Provides very good access to isocenter
- In-room sliding-CT
  - alternative -> cone down CT?
- Gantry with upstream scanning
  - Double magnetic parallel scanning

- For developing advanced scanning
  - Volumetric repainting
    - with fast energy changes 80 ms
  - Dose painting spots / lines / contours
  - Variable magnetic scan speed and
  - Dynamic control of beam intensity

E. Pedroni *et al.* 2011 *Eur. Phys. J. Plus* 126:66

The PSI's idea of a "180° gantry" … is now taken over by industry



Compact super-conducting synchro-cyclotron mounted directly on a gantry MEVION

11 facilities ordered in the USA

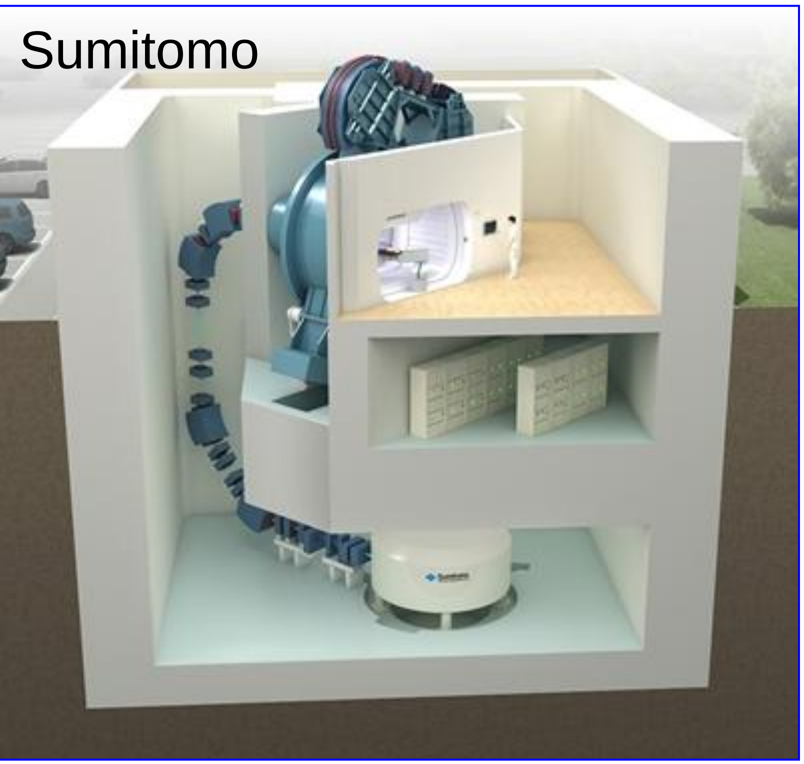
- Similarity in size with a conventional electron LINAC
  - No beam line - cheaper - simpler - for easier diffusion in hospitals
- With compromises in the beam delivery?
  - Fixed field energy at highest energy (no beam energy analysis)
    - Without limiting the quality of the dose distribution?
  - Pulsed beam - only passive scattering? (only for a start?)
    - Good enough for competing with modern photon-RT and IMRT?
- Potential to develop scanning?
  - Needs to control beam intensity pulse by pulse? (per spot?)
  - Very high repetition rate ~ kHz? (more pulses /spot?)
  - Range shifter in front of the patient? (keep air gap small !)
  - Idea to use multi-leaf collimators? (use for IMPT?)
- Eventually variable energy? a few energies (slow change)
  - Specialized units? Head gantry (160 MeV) / body gantry (250)?

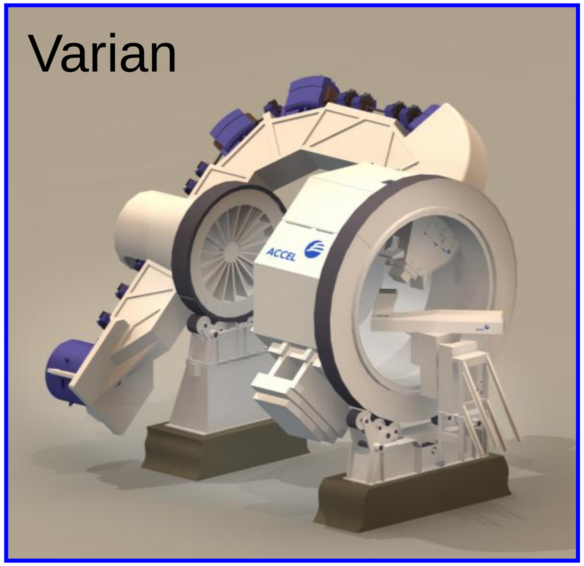
Exciting concept / worth investing in new beam delivery developments

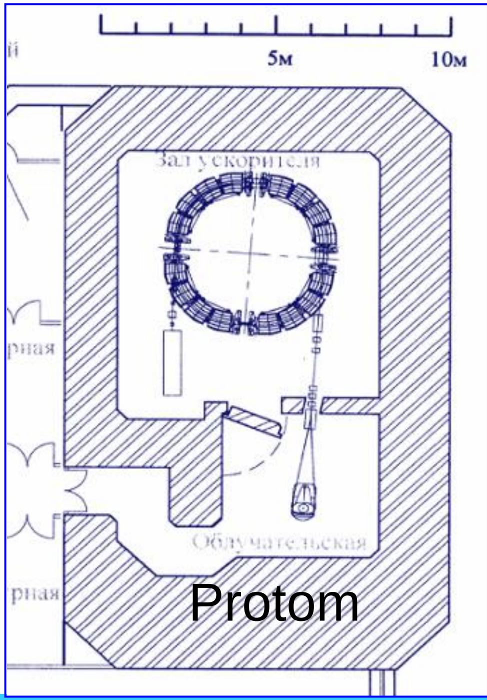
The response of the other facility providers…

- Compacts but "full-fledged" single room facilities…
  - With <u>variable energy in the beam line</u>
  - Examples: Sumitomo - Varian - Protom - IBA (Proteus Nano)

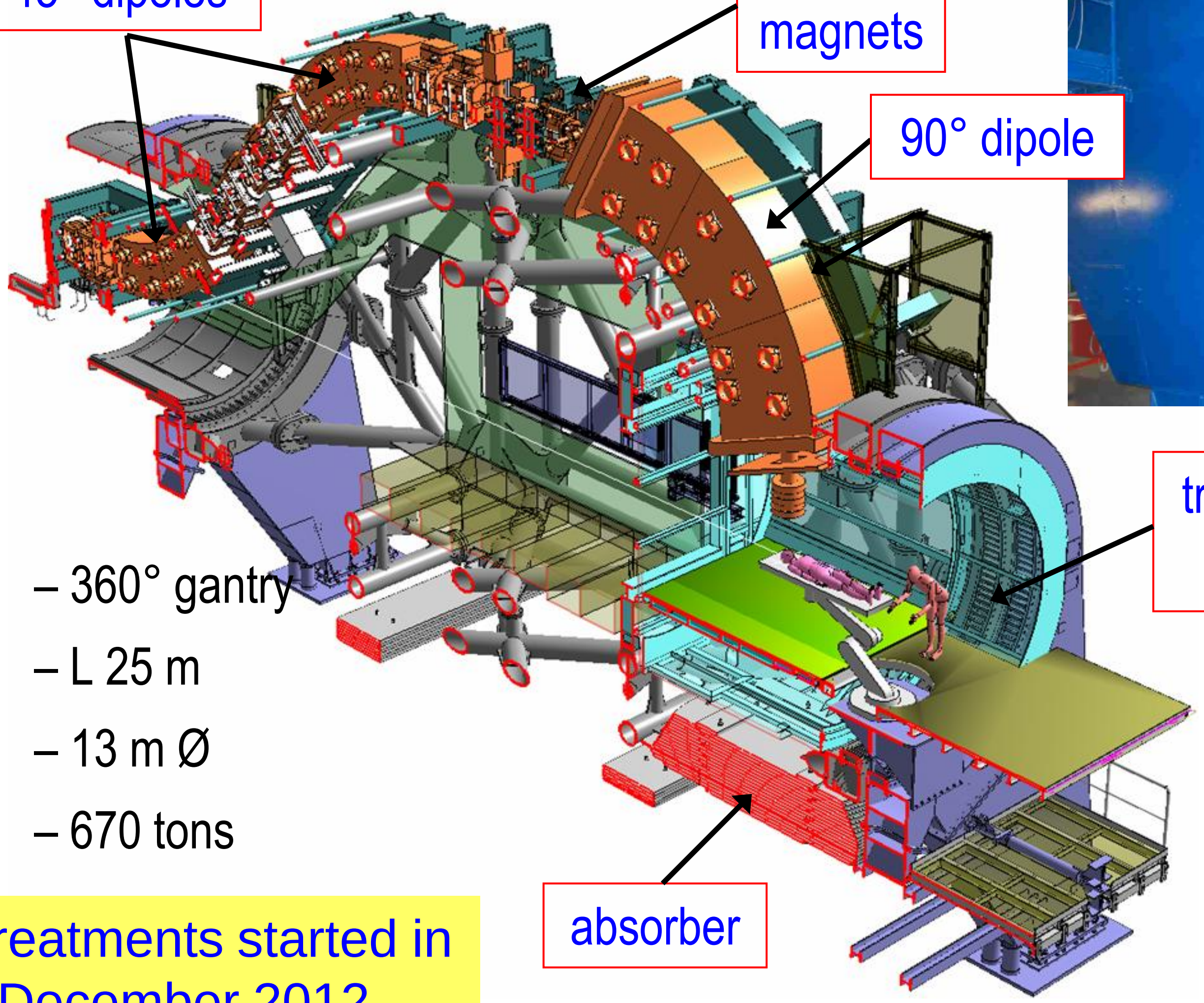
Idea to make PT accessible also to small hospitals







The first and only gantry for ion therapy – at Heidelberg (HIT)

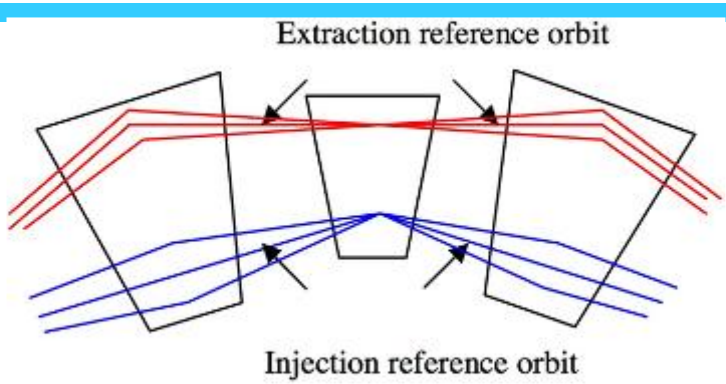


- 360° gantry
- L 25 m
- 13 m Ø
- 670 tons

Treatments started in December 2012

ONGOING AND FUTURE DEVELOPMENTS

Pulsed accelerators
with variable beam energy (per pulse) and high repetition rate

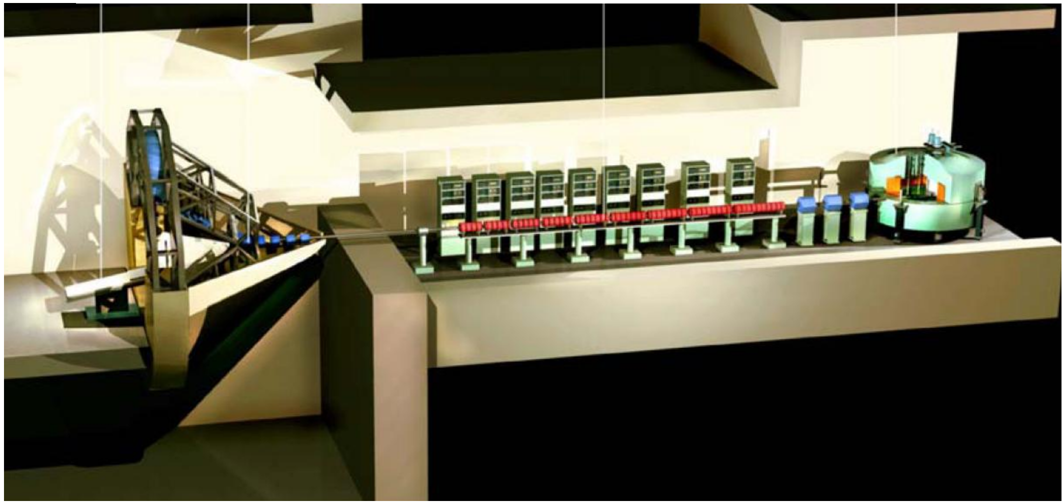


- FFAG
  - Fixed field - alternating gradient
  - Large momentum acceptance
    - Same concept also for gantry?
- Cyc-linac
  - Cyclotron for isotope production
  - Combined with a linac

Needs beam intensity control per pulse for delivering scanning

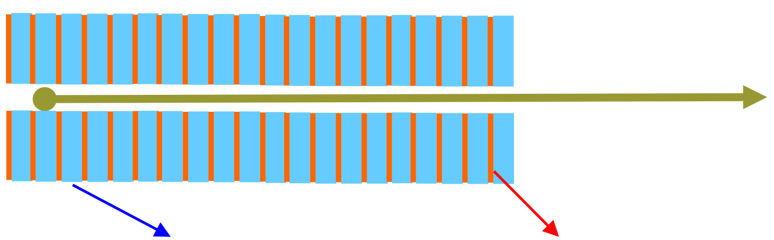
Experimental FFAG at Kyoto University
For energy amplifier

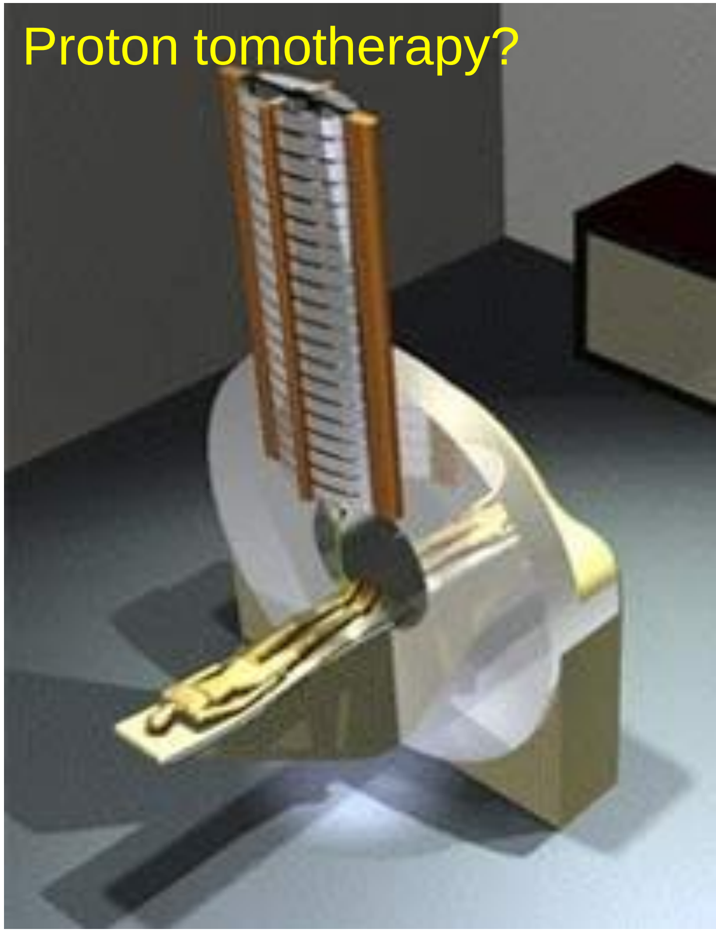
Amaldi et al, Nucl Instr Meth A 521(2004) 512



Futuristic accelerator technologies

- Basic research - Not yet mature for intended use
  - Laser acceleration *C. M. Ma, Laser Physics, 2006, V16,4,639*
  - Plasma waves *Nature 449 133-135 2007*
- Under development - within reach?
  - Dielectric Wall Accelerator (High gradient Linac)
    - Collaboration with company Tomotherapy
    - Photo-electric switches
      - Aiming at 100 MeV/m
    - Scanning?
      - Pulse rate? dose control per pulse?

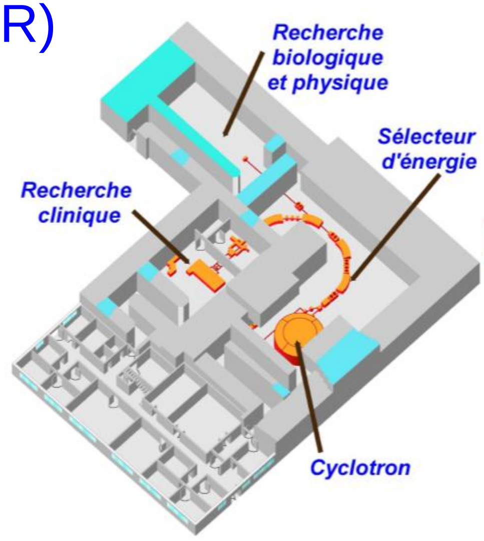


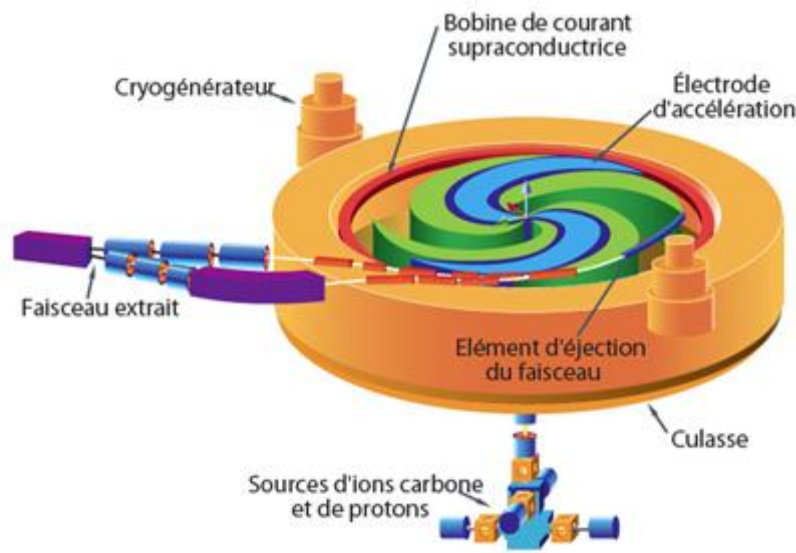


Caporaso et al, NIM B 261 2007 777

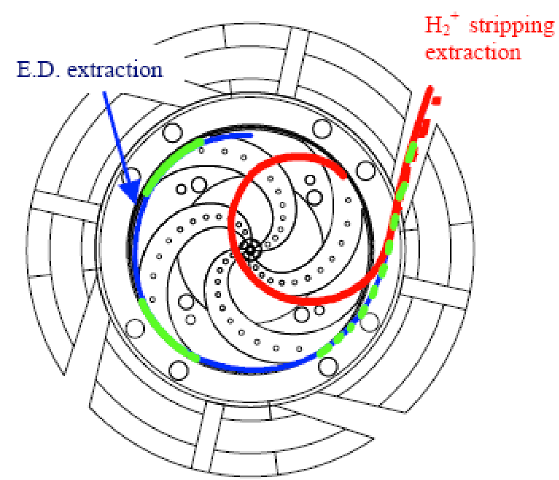
Superconducting cyclotrons for ion therapy
steady beam by design

- Project Archade Caen (FR)
- IBA prototype -> 2015
  - 260 MeV H2+
    - By stripping
  - 400 MeV/n ions
    - By deflector
  - 6.9 m diameter
  - 660 tons
- Medical facility later project Etoile in Lyon





- Catania design (INFN It)
  - Lower energy
    - 250 MeV protons
    - 300 MeV/n
    - 4.9 m Ø
    - 320 tons



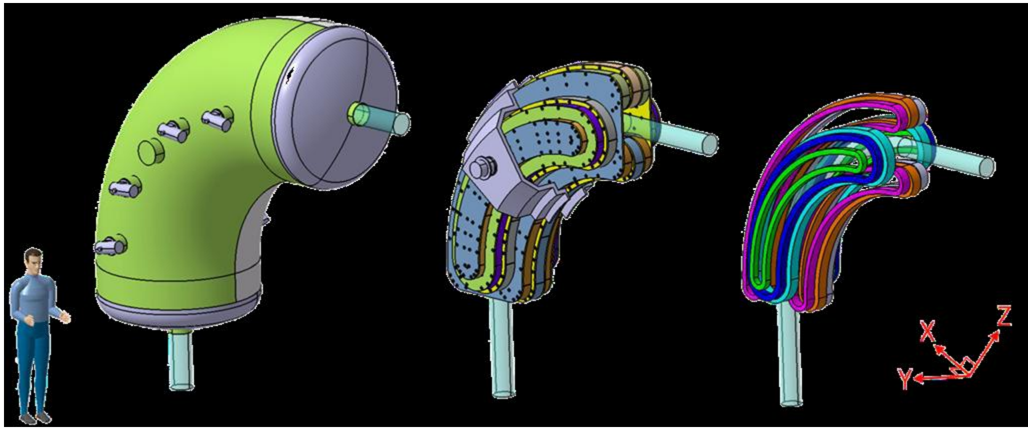
Degrader design for concurrent radioactive beams? (I. Yongen) *C^{11} ?*

Superconducting gantries?

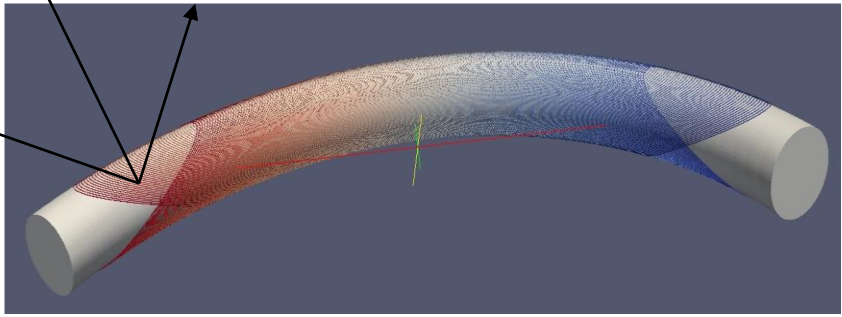
- Advantages
  - Low power consumption
  - Very high magnetic fields
    - Small magnet size
    - But large cryogenics vessels?
- Disadvantages
  - Field homogeneity difficult
    - Use of multiple coils or
    - Tilted winding along coil
  - Very slow changes of the beam energy
    - Large momentum acceptance optics
  - Fringe field (without return yoke)
    - Environment like in a MRI ?

Gain significant only for ions?

Ideas presented at the Workshop on Hadron Beam Therapy, Erice, Sicily, 2011



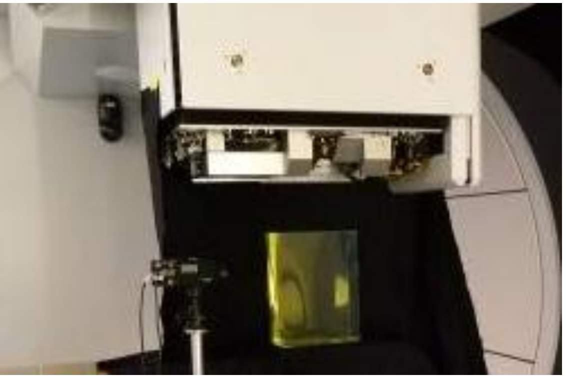
Kircher, Saclay SC Gantry

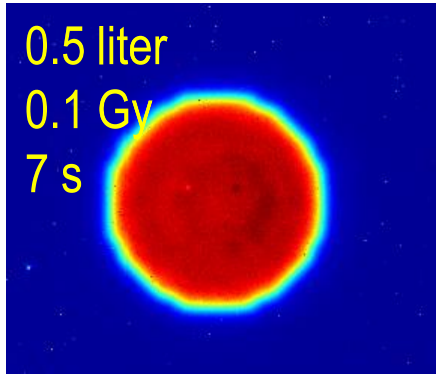


S. Caspi
Lawrence Berkeley National Laboratory

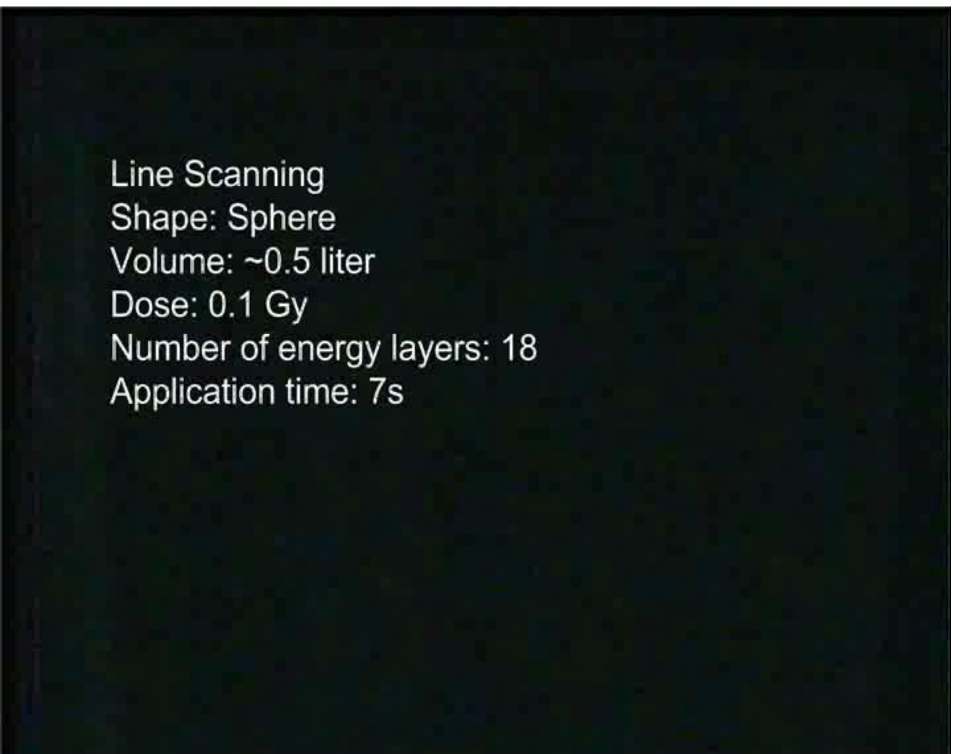
Cheap protons *OR (AND?)* *high-tech protons?*

The cheapest solution of today is may be not the best investment for tomorrow





- Example of advanced beam scanning techniques (PSI new Gantry 2)
  - Needed for competing with today's most advanced conventional therapy?



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  - D. Meer
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Books: Ion Beam Therapy, Ute Linz ed, Springer Verlag

THANK YOU