Next Generation Carbon Therapy

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Contents

Radiation Therapy

- In conventional radiotherapy, high energy X-rays are used for Cancer treatment
- X-rays, electrons, protons , heavy ions - Ionizing Radiations
- Radiations damage DNAs of cancerous cells
- Photons/X-rays interact with matter by Photoelectric Effect, Pair Production and Compton effect
- Protons and ions go through Coulomb interaction with target electrons or with nuclear potential of target atoms
- High energy X-rays are generated in linear electron accelerator via Bremsstrahlung
- Protons and ions are accelerated to high energies in a circular accelerator

Radiation Therapy

- To control tumor a sufficiently high dose should be delivered to the target volume
- Dose is a ratio of imparted energy to the mass of the tissue, measured in Gray=J/kg
- LET- Linear energy transfer i.e. density of energy deposition along the track of the particles in tissue. Measured in keV/µm in water.
- RBE- Relative biological effectiveness is a quality factor in radiation protection and it gives the difference in the effects of radiations of various types

Photons	**Protons**	**Carbon ions**
RBE=1	RBE =1-2	RBE =10-20
LET=0.2-2 keV/ µm	LET=0.4-16 keV/ µm	LET=0.15-200 keV/µm

Statistics of Cancer patients in India till 2020

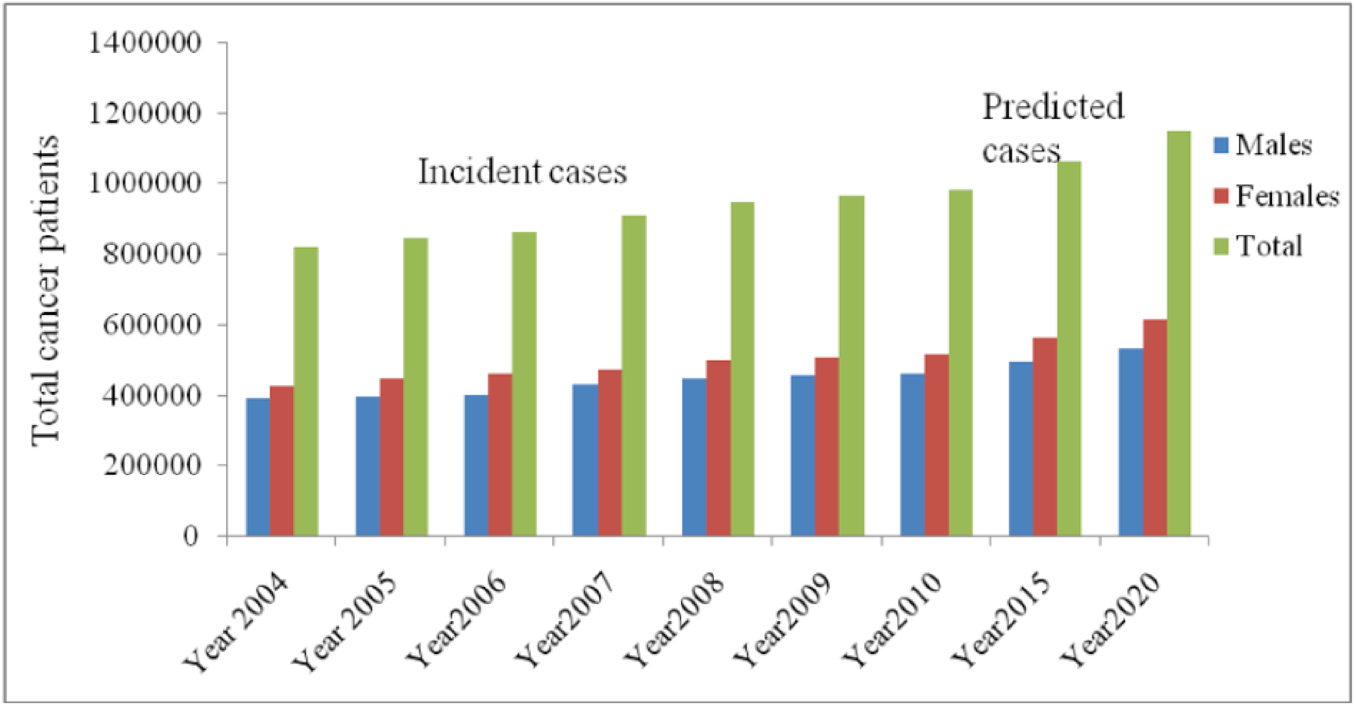


Figure 1: Year wise total cancer prevalence in India [ICMR, 2006; ICMR, 2009].

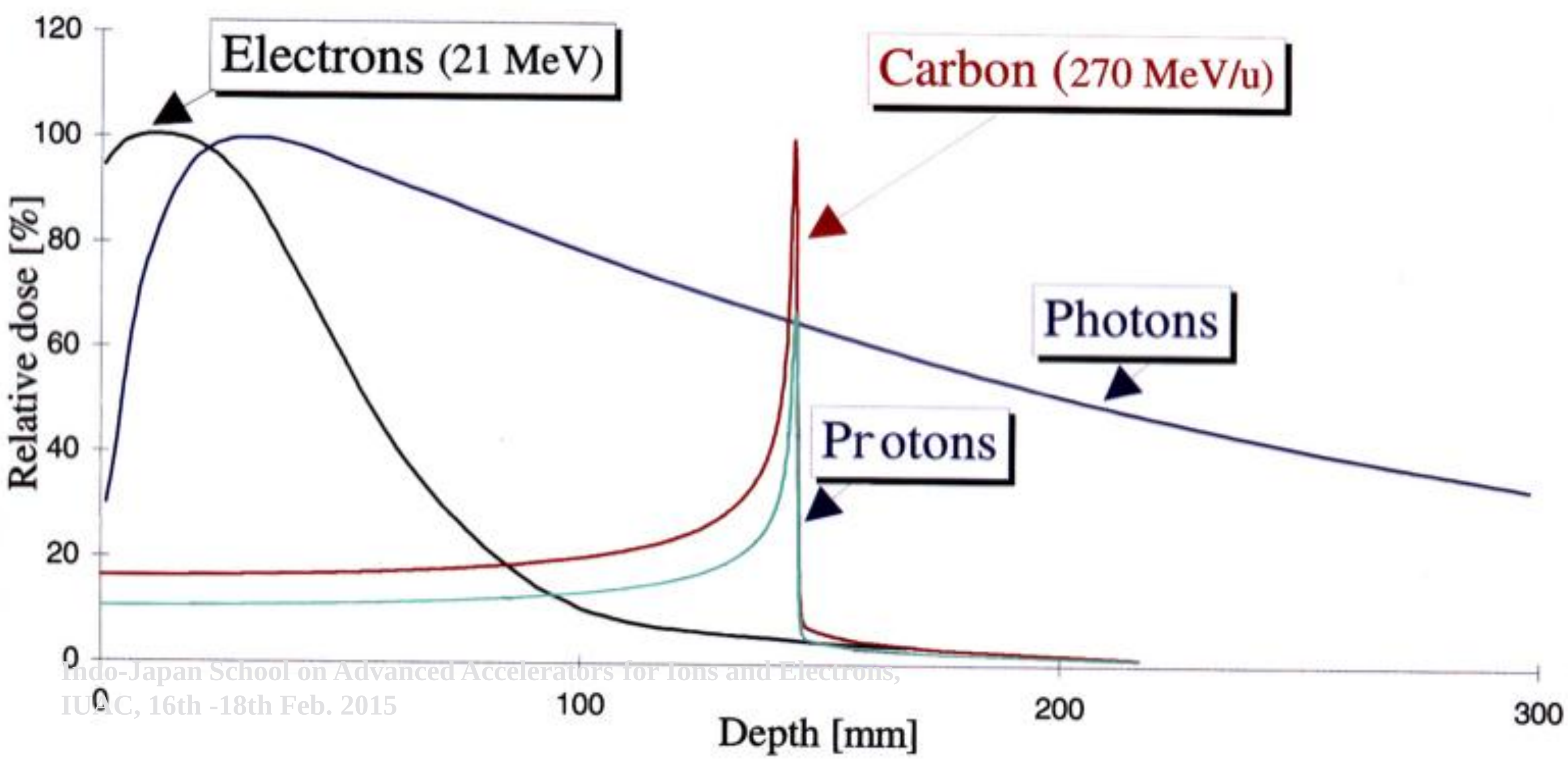
I. Ali, Cancer Therapy, Vol. 8 pg.56 2011

In India, approximately 40,000 children are diagnosed with cancer each year. Approximately, 1400 of them would potentially benefit from proton beams. Similarly, a much larger number of patients in the adult age group will also benefit from proton beam therapy.

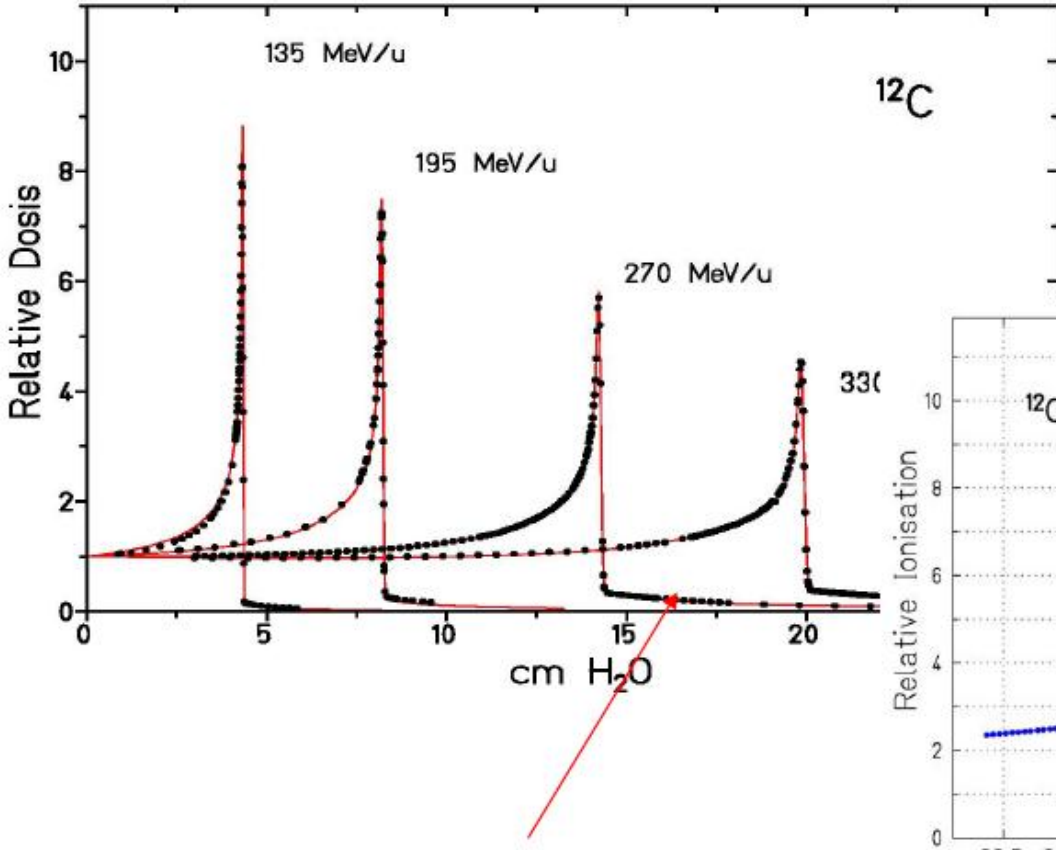
* Excerpt TMH document available online

Radiation therapy- Protons/ Heavy ions

- Hadrons are increasingly used for treatment of cancer which is located near sensitive regions - like brain, eye, spinal cord etc.
- Precise dose delivery at the desired location and largely sparing the healthy tissue
- The energy of Protons / Carbon ions required for therapy is 250 MeV or 400 MeV/n
- Range in tissue of about 30 cm

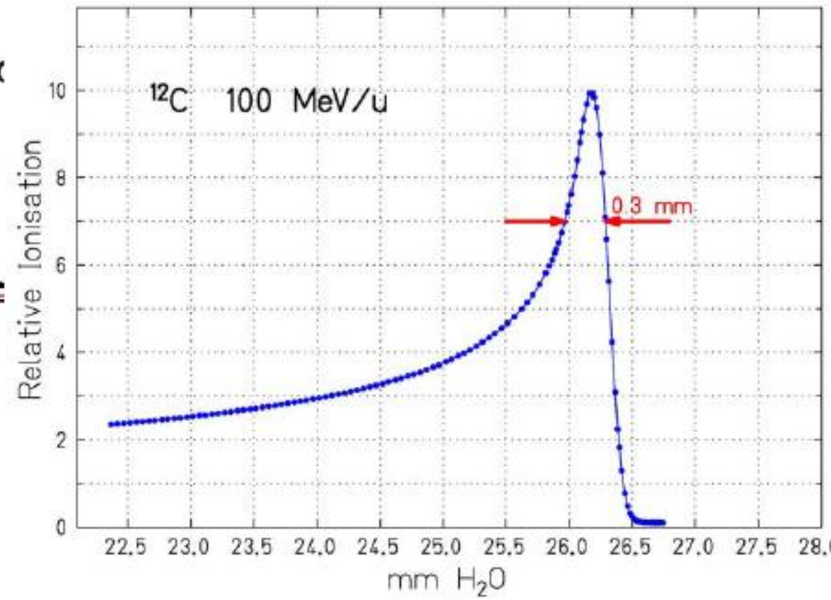


Bragg Peak of Carbon-12 in water



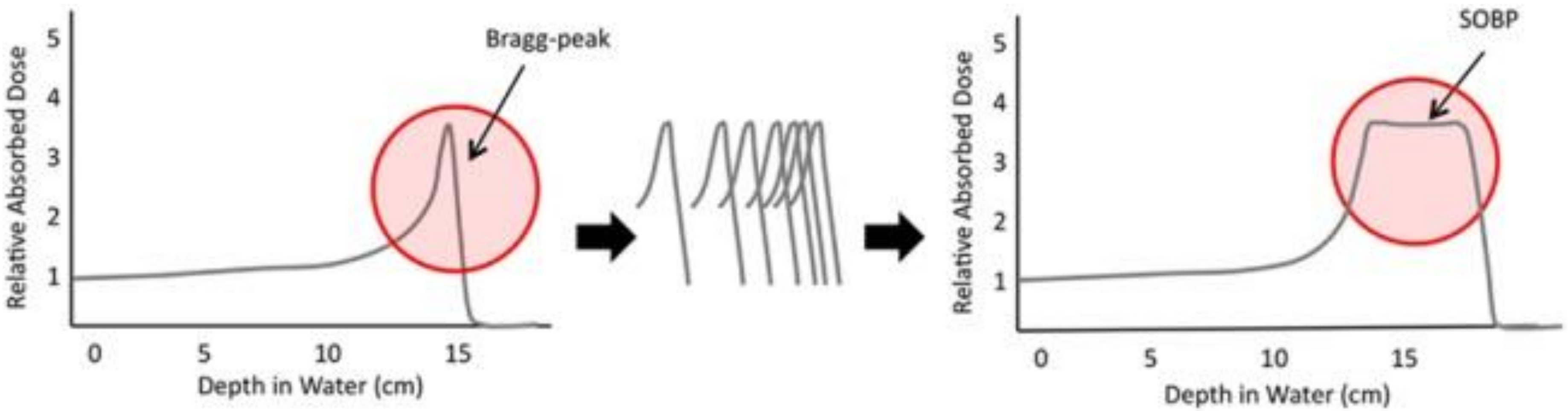
peak-width and height are affected by

- straggling
- fragmentation

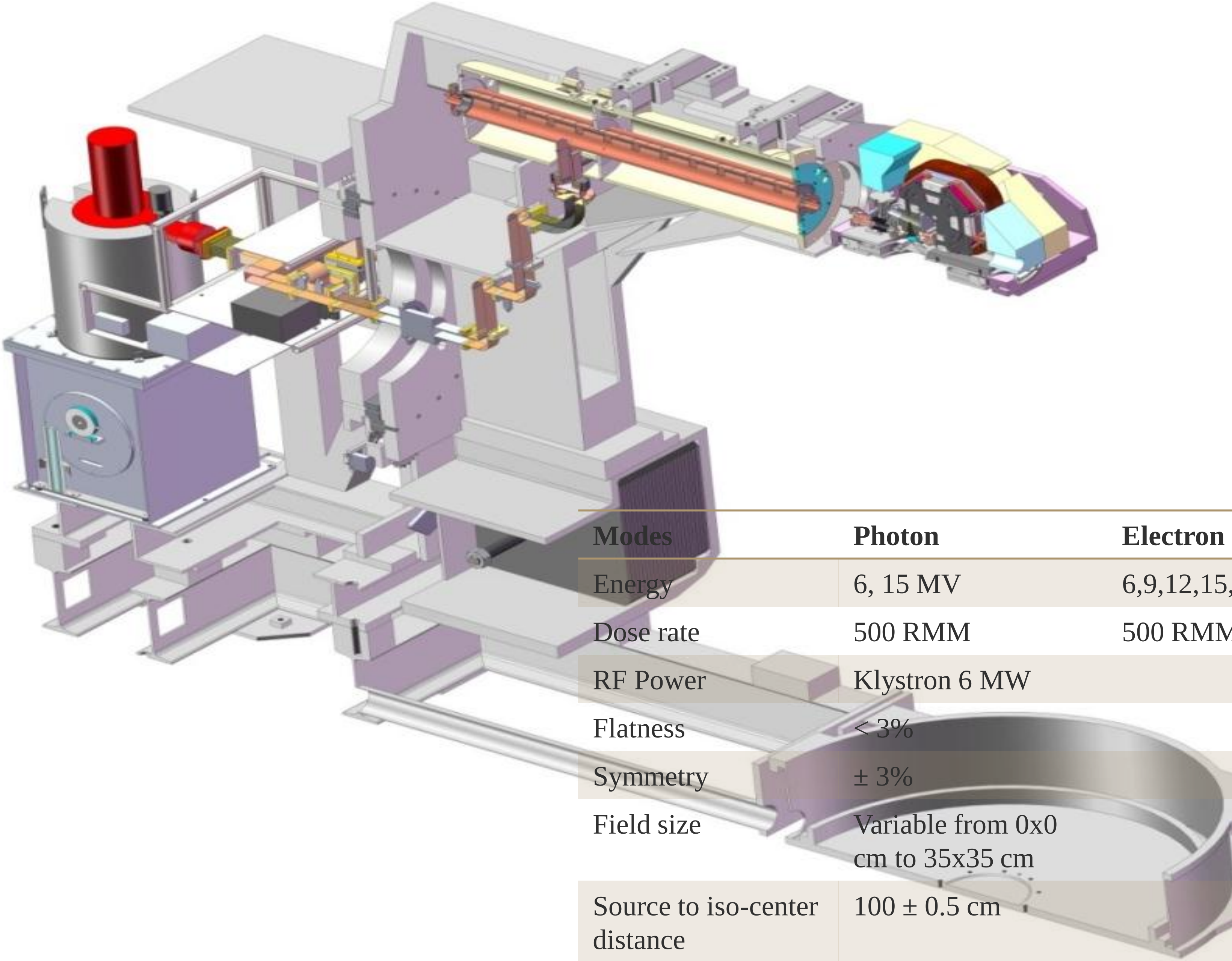


Radiation therapy- Protons/ Heavy ions

By adding Bragg peaks that are shifted in depths, a spread out Bragg Peak (SOBP) is created

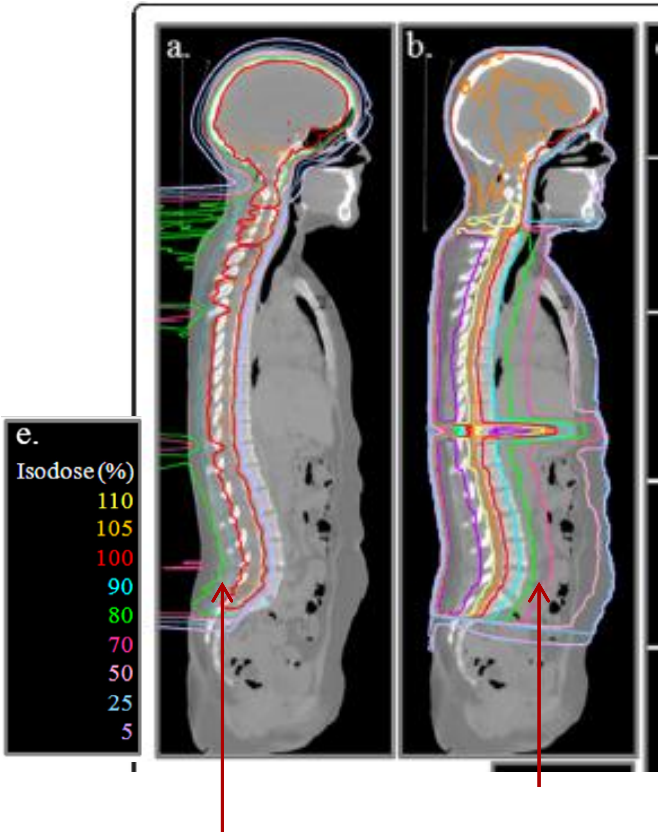


Dual mode dual photon energy Oncology system



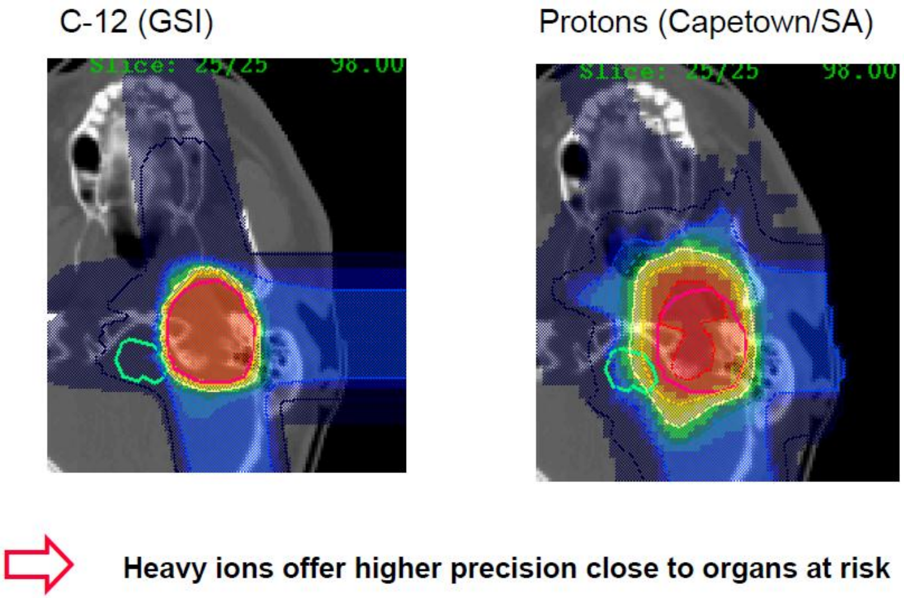
Modes	Photon	Electron
Energy	6, 15 MV	6,9,12,15,18 MeV
Dose rate	500 RMM	500 RMM
RF Power	Klystron 6 MW	
Flatness	< 3%	
Symmetry	± 3%	
Field size	Variable from 0x0 cm to 35x35 cm	
Source to iso-center distance	100 ± 0.5 cm	

Dose distribution- X rays, Proton, Carbon ion



proton

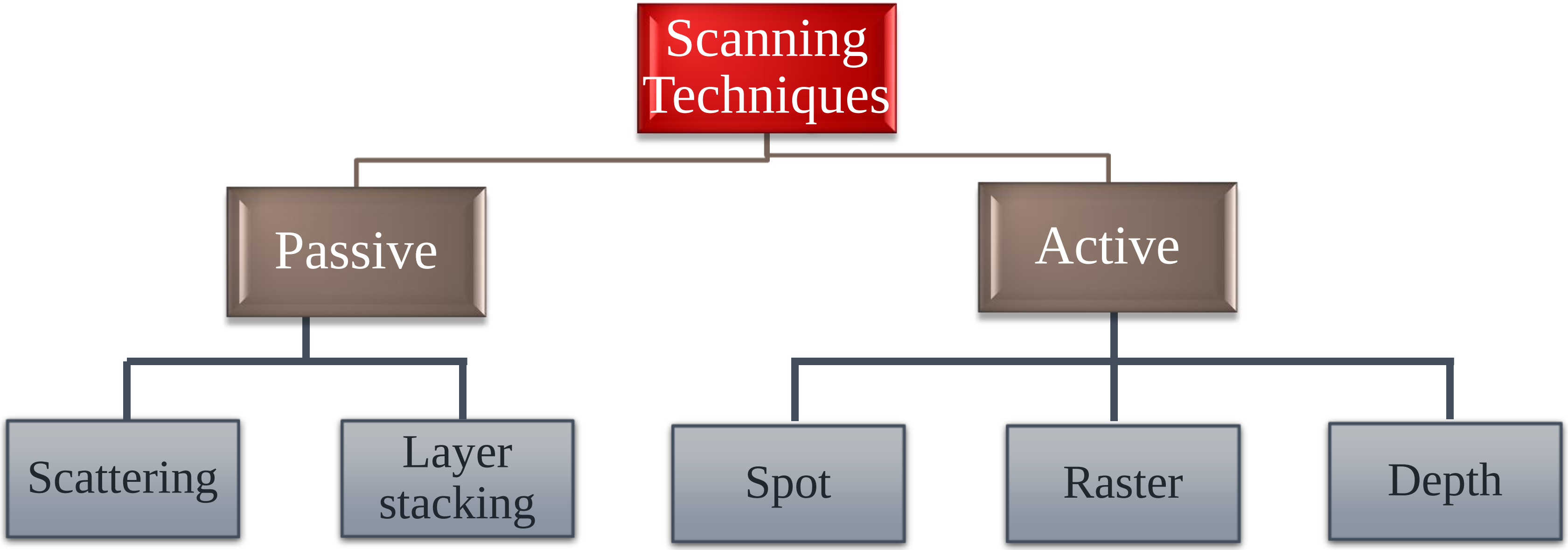
photon



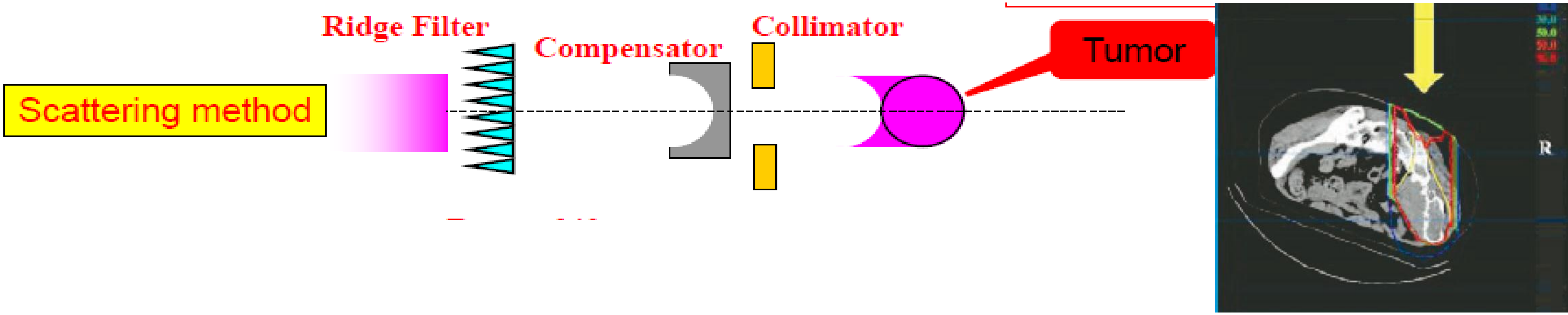
Conformity of the dose is the key point

#Howell et. Al Radiation Oncology, 2012,7:116

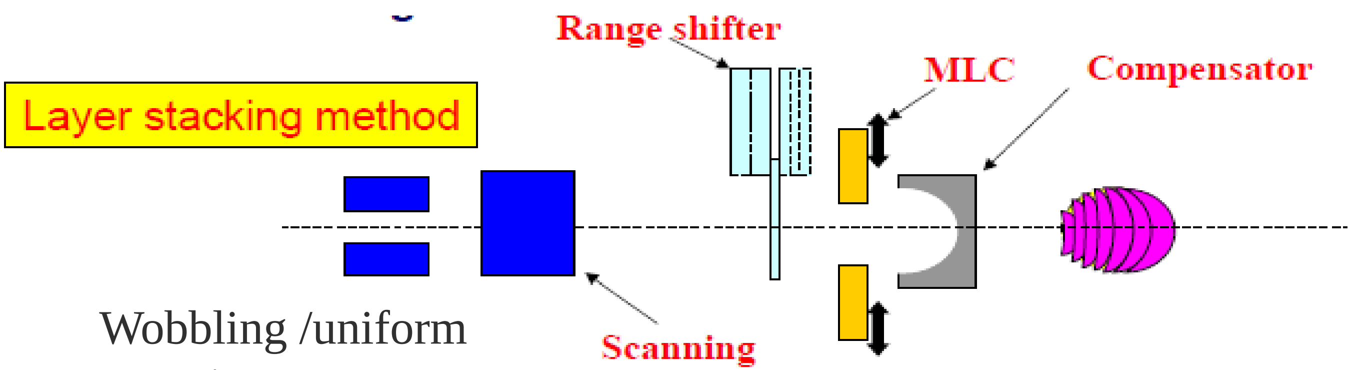
Beam Irradiation Methods

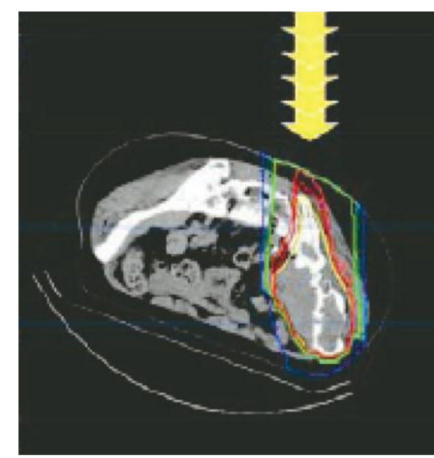


Passive Beam irradiation techniques



The width of the SOBP is adjusted to the maximum depth of the target

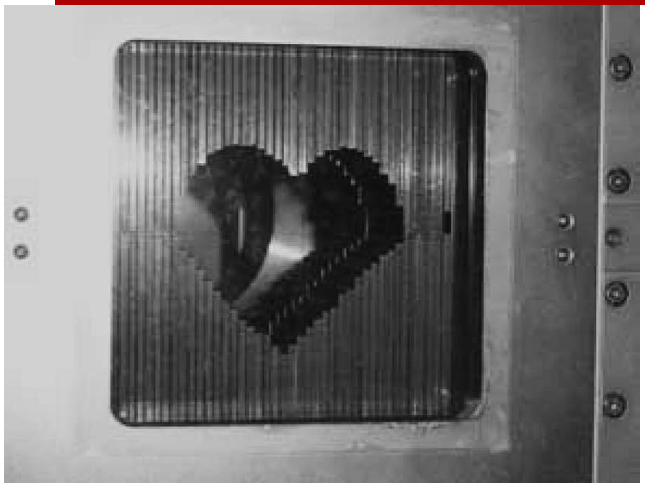




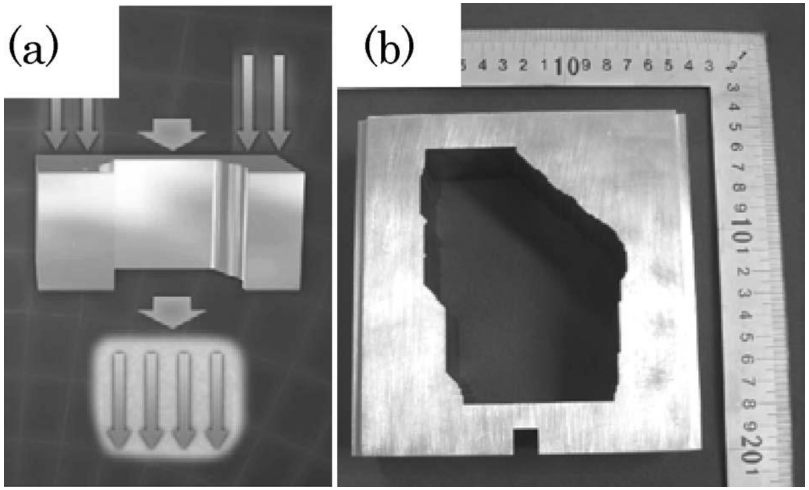
Wobbling /uniform scanning

Mini SOBP is created using ridge filter
Maximum depth of the target is adjusted using range shifter

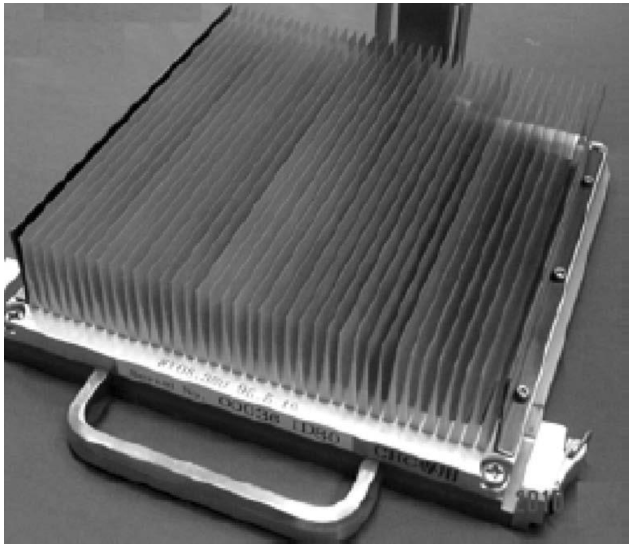
Components of Passive Beam irradiation



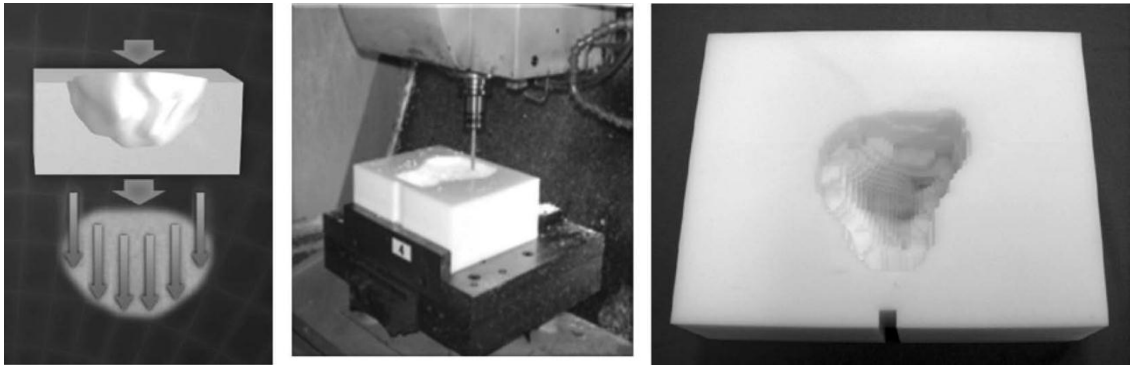
Multileaf collimator



Patient specific collimator



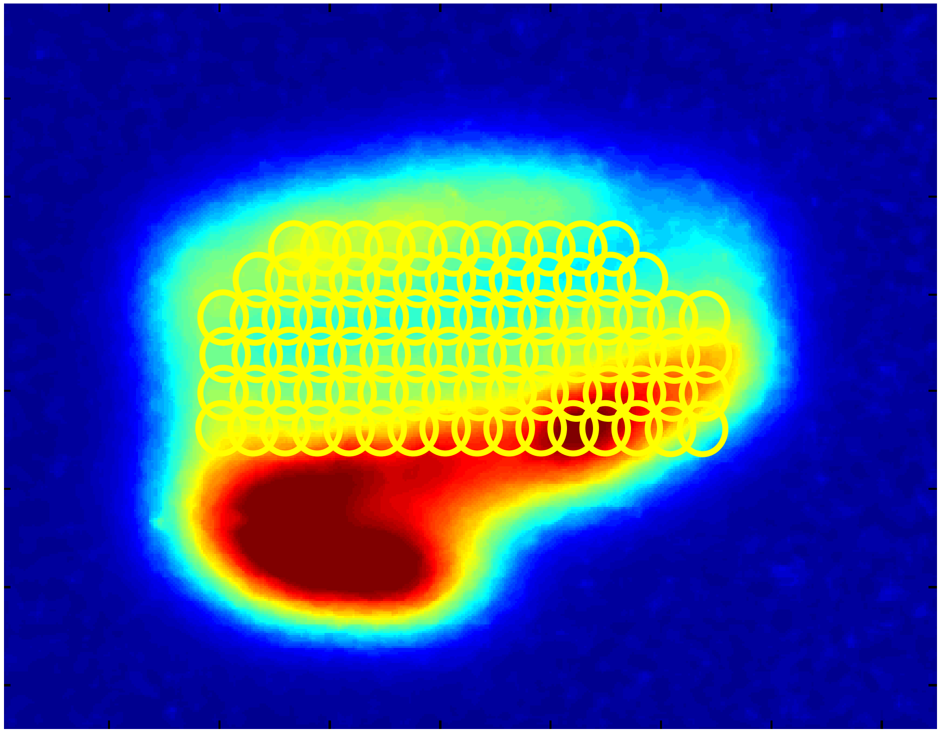
Ridge filter



Compensator

Active Beam Scanning Technique

Transverse motions via fast scanning magnet and patient table movement.
Depth variation by range shifter (lucite plates) in front of patient.



Spot scanning:

Beam is switched off after each spot

Scan magnets are adjusted

Spot irradiation is repeated

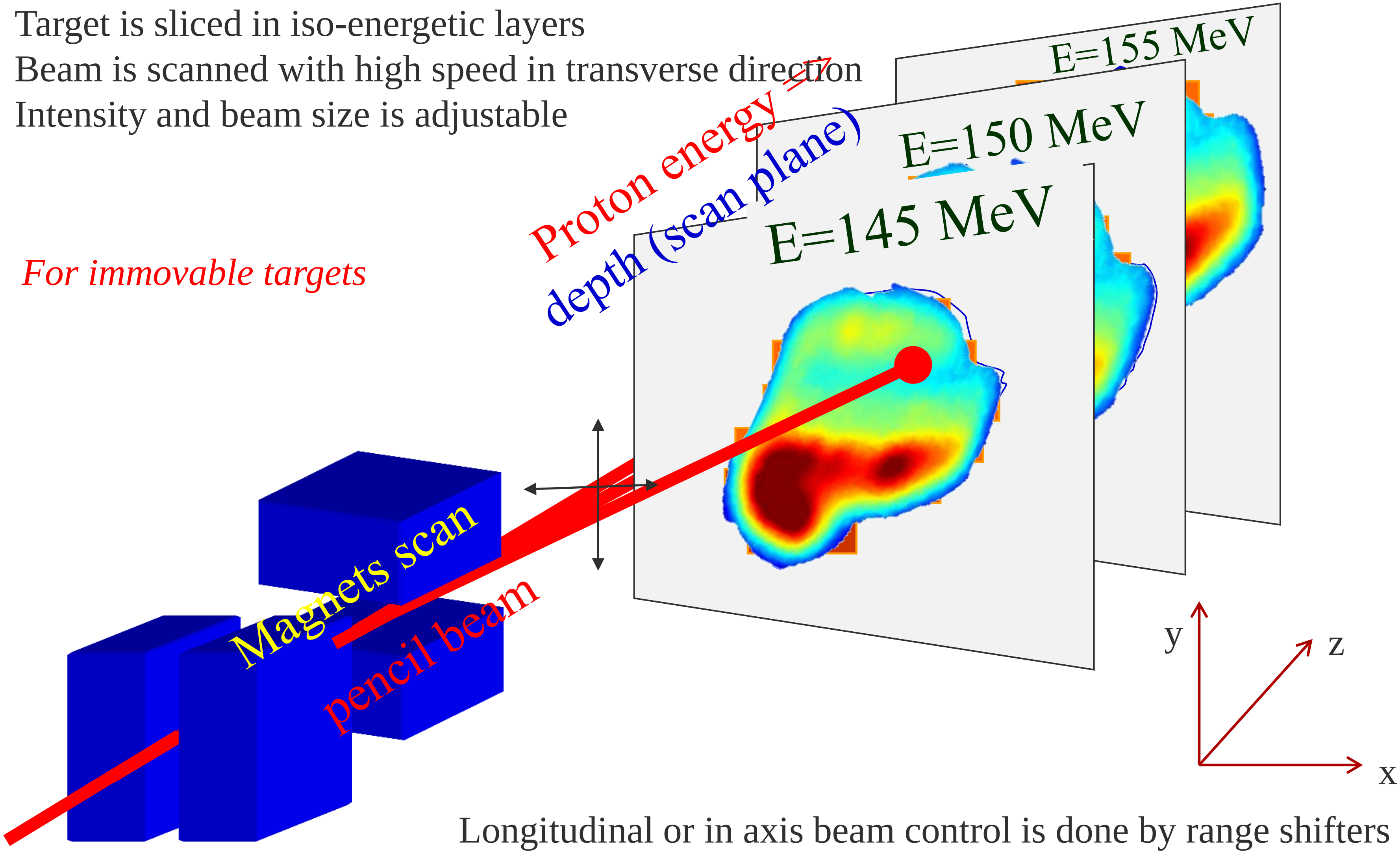
Used for proton therapy

3D position of the Bragg peak and its intensity is controlled to give a conformal dose distribution

Raster Scanning

- Target is sliced in iso-energetic layers
- Beam is scanned with high speed in transverse direction
- Intensity and beam size is adjustable

For immovable targets



Longitudinal or in axis beam control is done by range shifters
Or In synchrotrons by changing magnet parameters @GSI (HIT)

Variable energy operation of Synchrotron

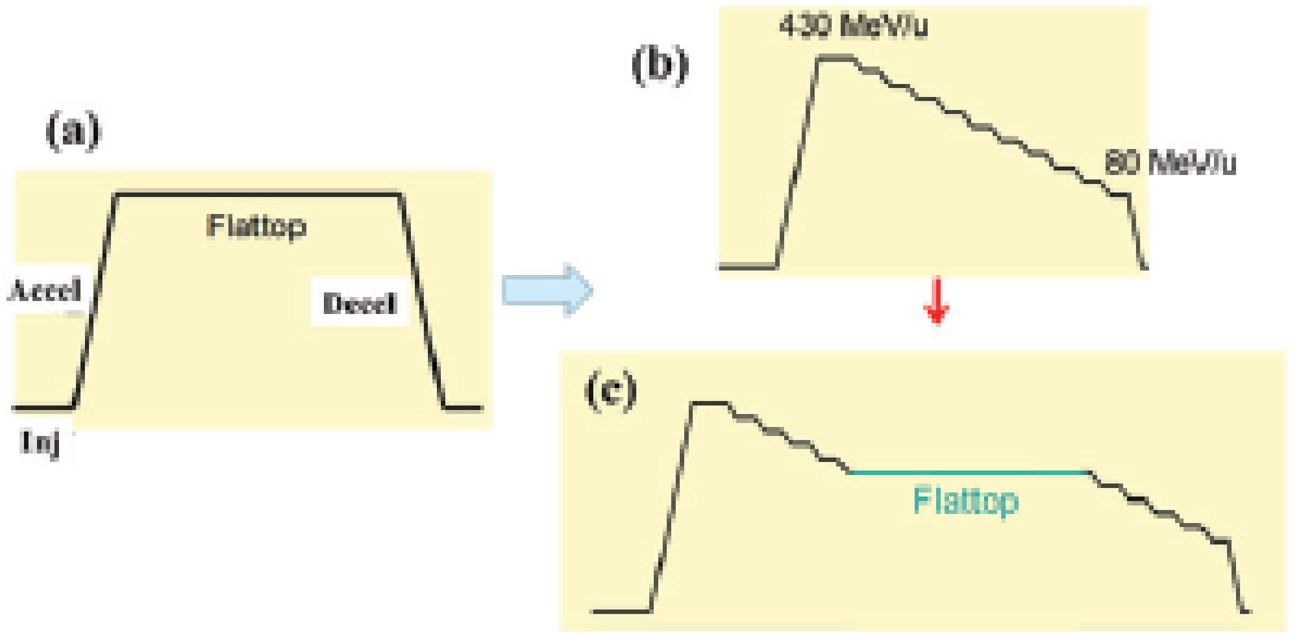
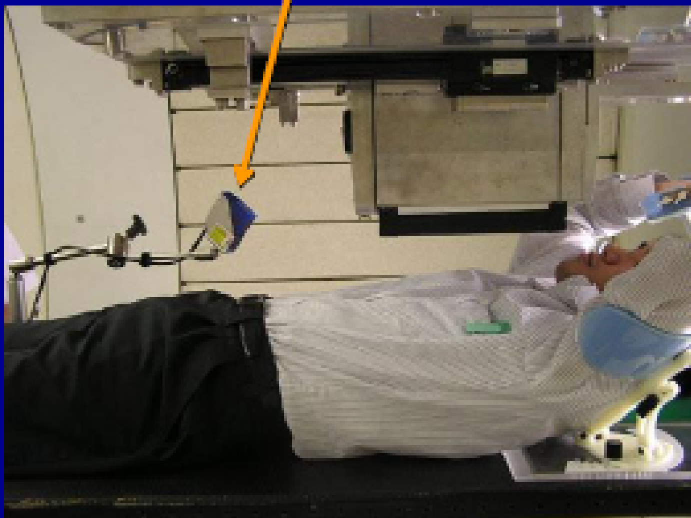


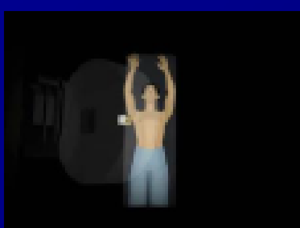
Figure 2. Schematic diagram of variable energy operation at HIMAC. (a) Conventional operation pattern, (b) Variable energy operation pattern and (c) Extended flattop with arbitrary energy by the clock on/off.

Respiratory Gating System

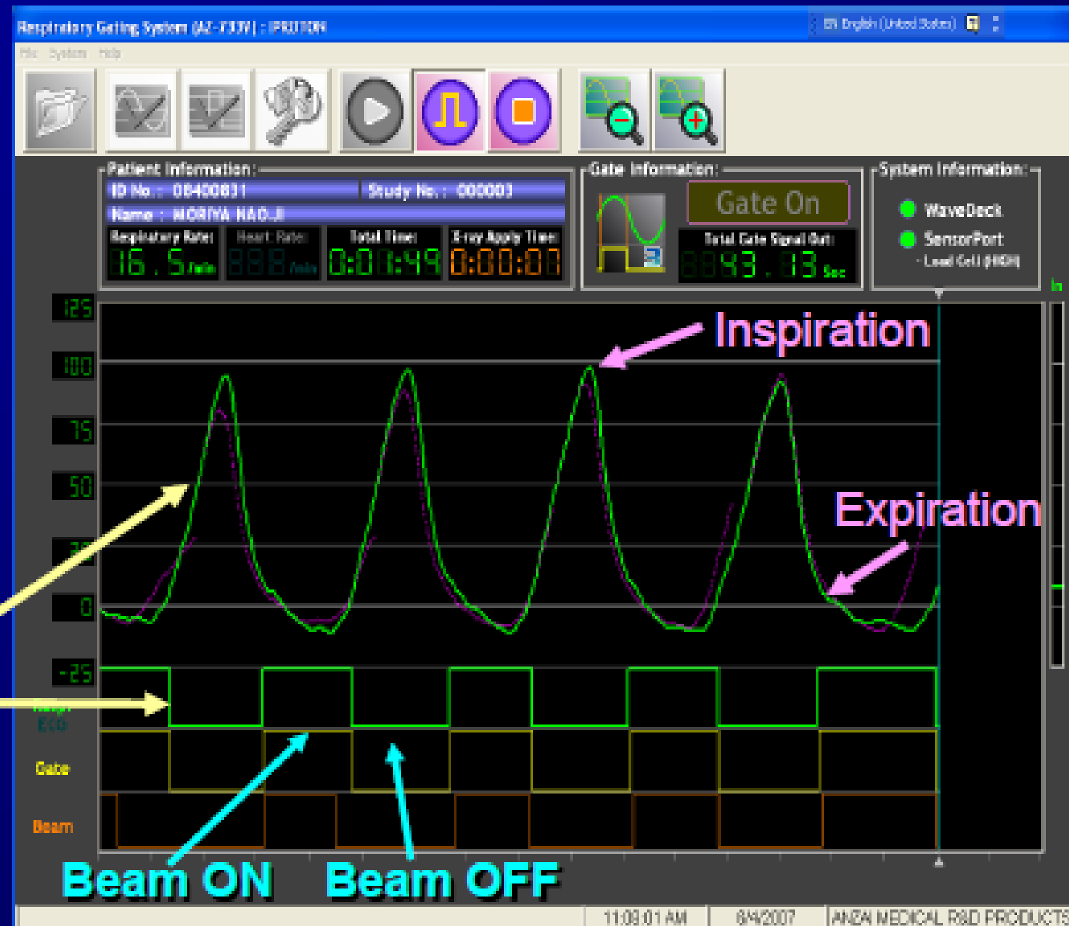
Sumitomo Heavy Industries, Ltd.

Laser sensor





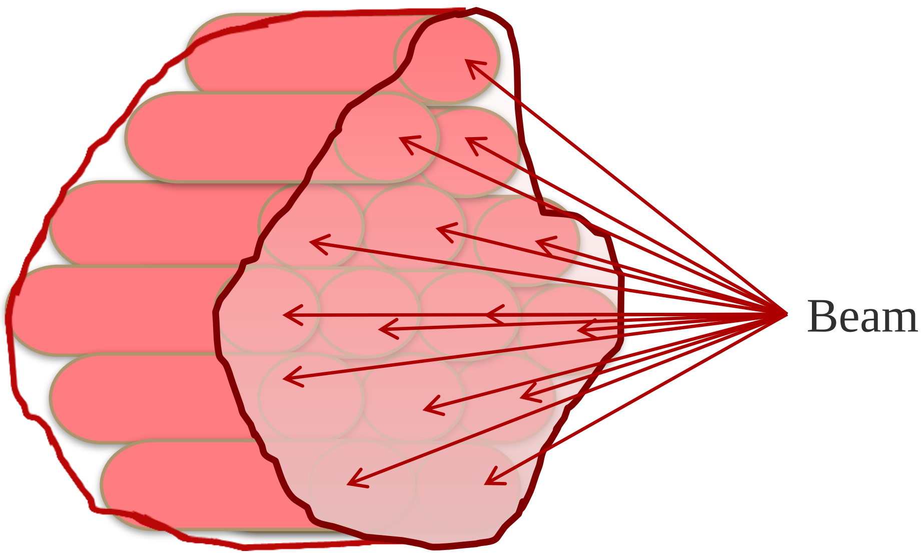
Respiratory Gating System using Laser Sensor



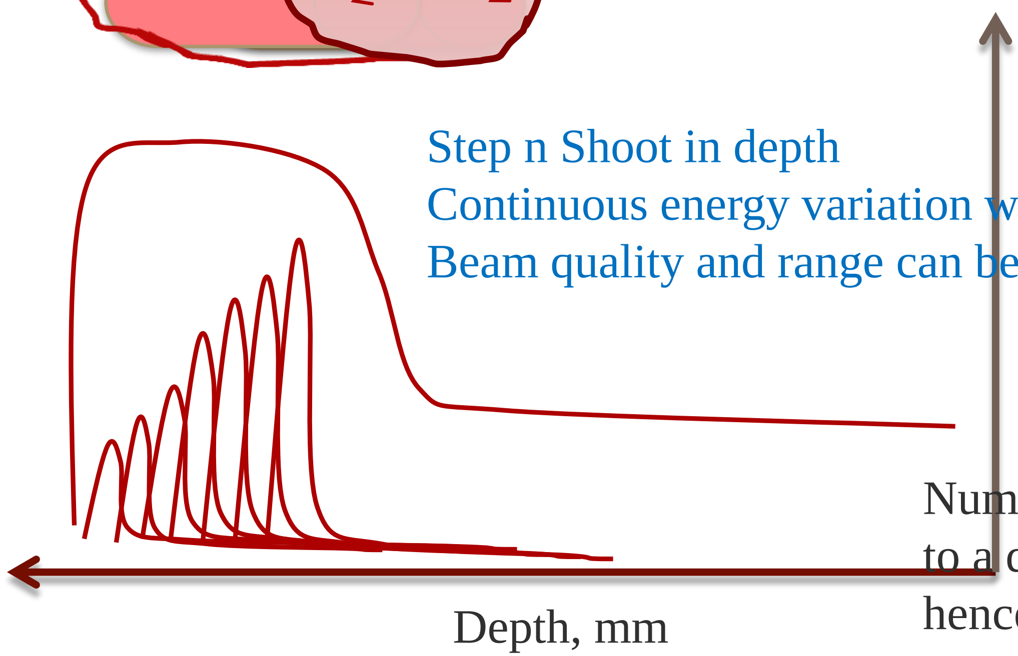
Respiratory Signal

Gating Signal

Depth Scanning using Digital Accelerator



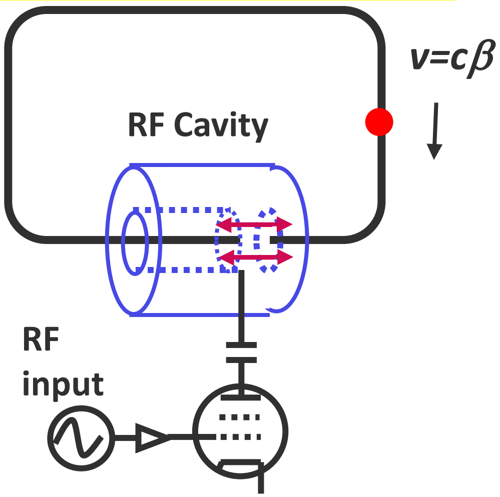
Step n Shoot in depth
Continuous energy variation without changing machine parameters
Beam quality and range can be maintained



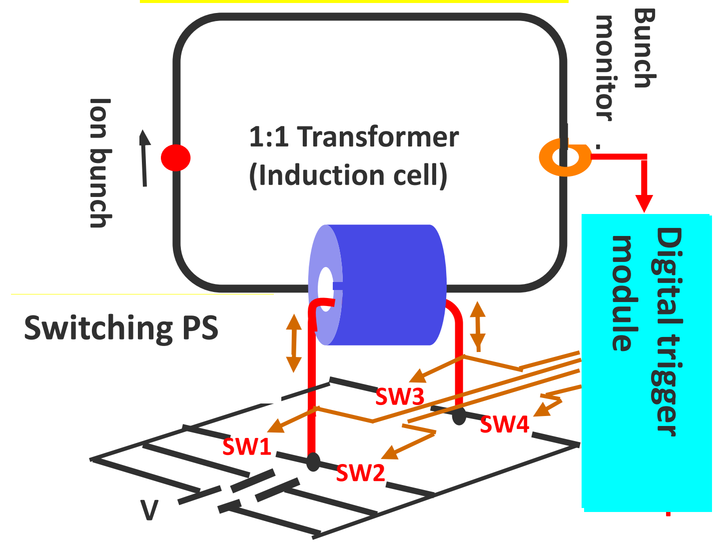
Number of objects in the beam path leads to a difference in fragmentation pattern hence range and biological effects

Digital Accelerator Concept

Conventional RF synchrotron



Induction synchrotron



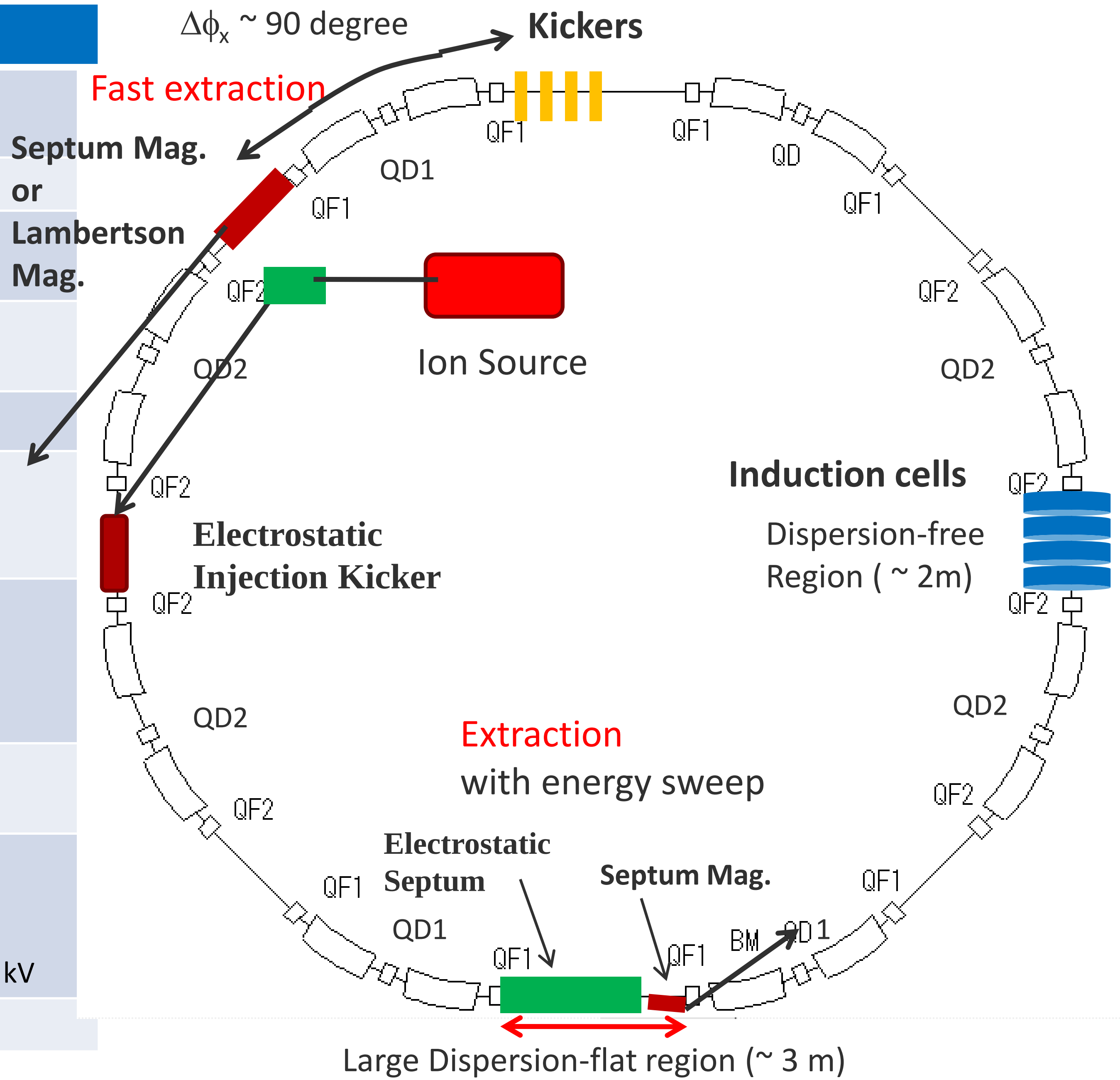
• with acceleration RF source frequency is ramped
•Limitation of source frequency bandwidth

• acceleration voltage is triggered by bunch signal
• limit on trigger frequency comes from switching elements

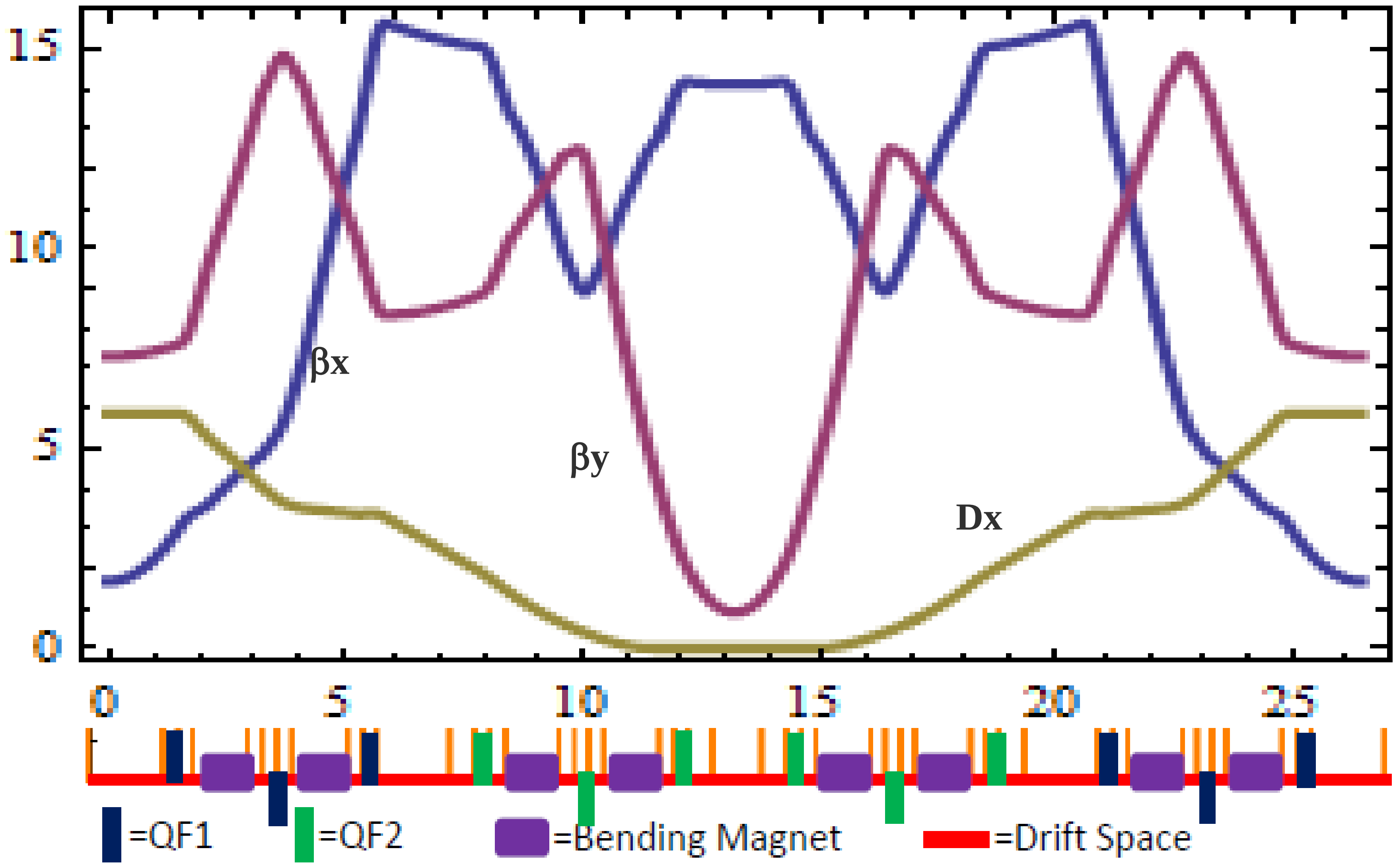
K. Takayama and J. Kishiro, “Induction Synchrotron”, *Nucl. Inst. Meth.* A **451**, 304 (2000)

Possible Layout of a Compact Digital Accelerator for Cancer Therapies

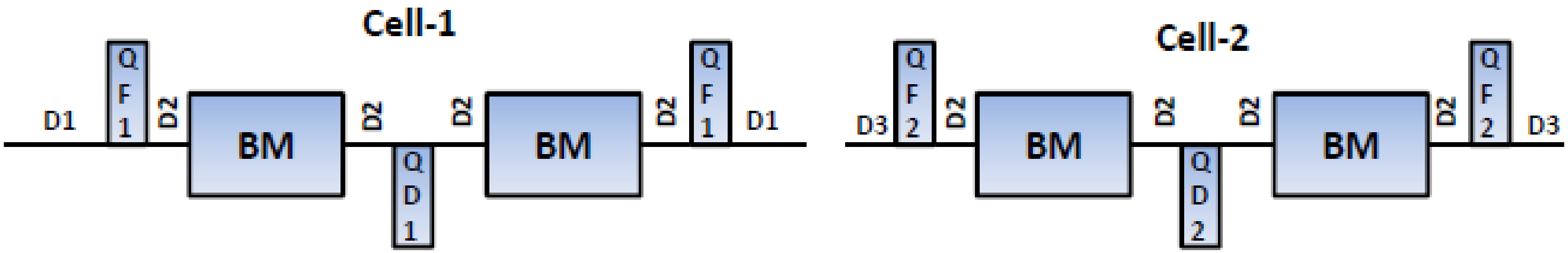
	Parameter
Energy	200 MeV/nucleon for ion with (A/Q=2)
C_0	52.8 m
Ion species	Gaseous/Metal ion
Ion Source	Laser ablation IS ECRIS
Injector	200 kV
Ring	Fast cycling (10 Hz) B_{max}=1.5 Tesla ρ=2.8662 m
	FODOF mirror symmetry with edge focus of bending magnets
	Dispersion free Large flat dispersion
Acceleration	Induction cells Compact SPS (SiC-MOSFET switch) $(V_{acc})_{max}=\rho C0dB/dt$ ~ 7 kV
Vacuum	10^{-8} Pascal



Lattice functions



Lattice parameters



Configuration =Cell-1 X Cell-2 X Drift Space 4 X Cell-2 X Cell-1

Drift Space 4=Free Dispersion Region

A/Z=2, Energy = 200 MeV/U

Total length of 25.6 m 26.4

Drift Space	S [m]
D1	1.5
D2	0.3
D3	0.1/0.5*
D4	1.8/1.0*

Bending Magnet	Bending Angle, Θ[°]	Edge Angle, Θ[°]	Curvature, ρ [m]	Magnet Length, l_B [m]
BM	22.5	11.25	2.8662	1.1256

Quadrupole Magnet	Length, l_Q[m]	K-Value [m^{-2}]
QF1	0.30	0.7840/0.75568*
QD1	0.30	-0.53774
QF2	0.30	0.40173
QD2	0.30	-0.8957

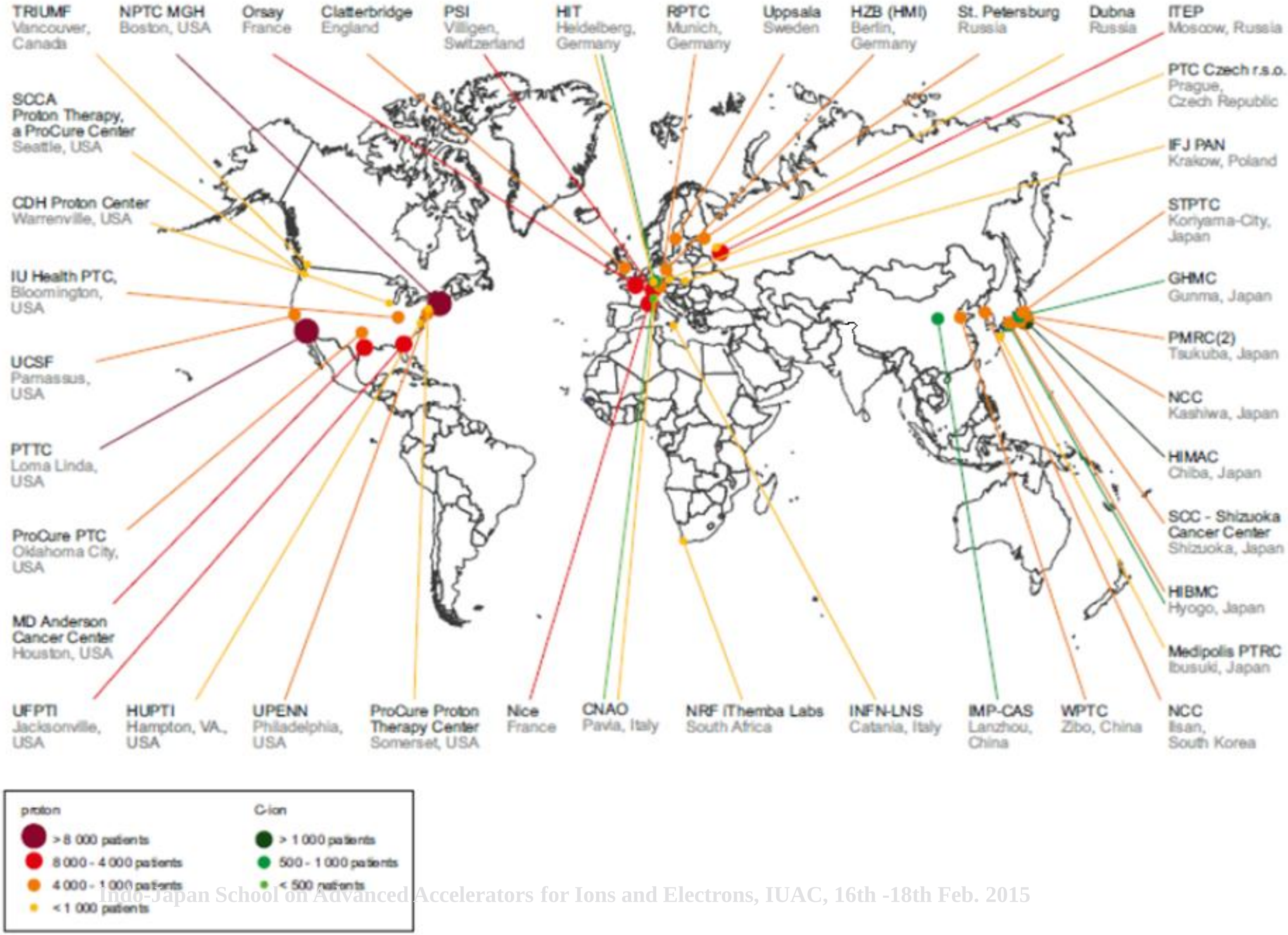
*Trial 9th

Type	Cost	Remarks	3D Spot scan.	4D Spot scan.
Conventional and Industrial Model				
Hitachi proton Synchrotron		w/experience, RF accel.	○with variable B_{max}	
Mitsubishi Carbon Synchrotron	expensive	w/ experience, RF accel.		
Sumitomo proton Cyclotron		w/ experience, RF accel.	○with range shifter	
IBA proton Cyclotron		w/ experience, RF accel.		
European Standard Model for proton and Carbon Ions (PIMMS)	expensive	CNAO MedAustron, RF accel.		

Present and Future of Accelerator Driven Cancer Therapy

Type	Cost	Remarks	3D Spot scan.	4D Spot scan.
Advanced Model				
Superconducting proton Cyclotron on Gantry (Still River)	Compact	few experiences, RF accel.		
Digital Accelerator for proton, Carbon,Carbon-11 (KEK)	effectively Compact	must be demonstrated, Induction accel.	○ with ext. energy sweep in acceleration cycle	○ with C-11
Storage ring with e-cooling (BINP)		Large flexibility small emittance, RF accel.		
Dielectric Wall proton Accelerator (LLNL)	Compact	must be demonstrated, propagating V. Pulse accel.		
iRCMS for proton and Carbon Ions (BNL)	Relatively compact	must be demonstrated, RF accel.	○ with ext. energy sweep in pulse	

Accelerators for Hadron therapy



Design study plan

Specs- Energy, Ion species, Beam intensity

Accelerator configuration-Source, Injector, Ring, Ext., Induction

Lattice design- Compact, dispersion free, finite dispersion region, FODOF

Extraction

Acceleration scenario

Ion source

Injector

LEBT/HEBT

Beam dynamics

Beam diagnostic

Main magnet

Acceleration system

Cost Estimation

Cost Estimation civil

Cost Estimation operation/ maintenance

Summary

- Hadron therapy merits were discussed
- New scanning method was proposed
- Carbon ions are used worldwide and it is future for radiotherapy
- Patients treatment will start in 2-3 years time in India in Apollo Hospital
- R&D activity at SAMEER for Next generation Carbon therapy machine is initiated and preliminary design study will be complete soon

Thank you..

Beam irradiation methods

<table>
<tr><th></th><th colspan="2">Lateral outline of target</th><th>Target thickness</th><th colspan="2">Distal target depth</th></tr>
<tr><td></td><td>Laterally spread out of pencil beam</td><td>Fine shaping of radiation filed</td><td>Spread out of Bragg peak</td><td>Adjust the maximum depth</td><td>Fine adjust to the target end</td></tr>
<tr><td rowspan="2">Scattering method</td><td>Wobbler magnets + scatterer</td><td>Patient specific collimator</td><td>Ridge filter</td><td rowspan="2">Range shifter with fixed beam energy</td><td rowspan="2">Patient specific compensator</td></tr>
<tr><td>Double scatterer</td><td>Multi-leaf collimator</td><td>Range modulator</td></tr>
<tr><td>Layer stacking method</td><td>Wobbler magnets + scatterer</td><td>Multileaf collimator (dynamic)</td><td colspan="2">Scanning mini SOBP by range shifter (or rotary range modulator) at fixed beam energy</td><td>Patient specific compensator</td></tr>
<tr><td rowspan="2">Active scanning</td><td colspan="2">Spot scanning</td><td colspan="3">Range shifter with fixed beam energy</td></tr>
<tr><td colspan="2">Raster scanning</td><td colspan="3">Variable beam energy</td></tr>
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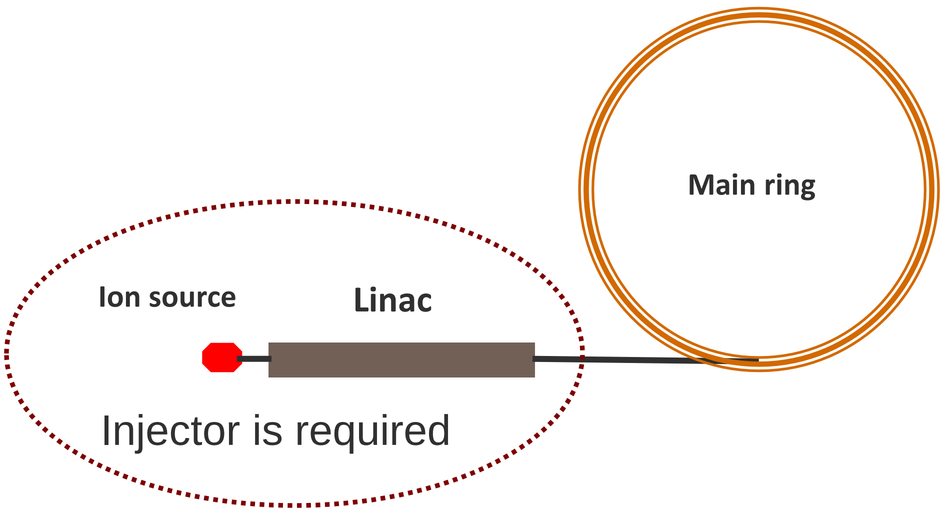
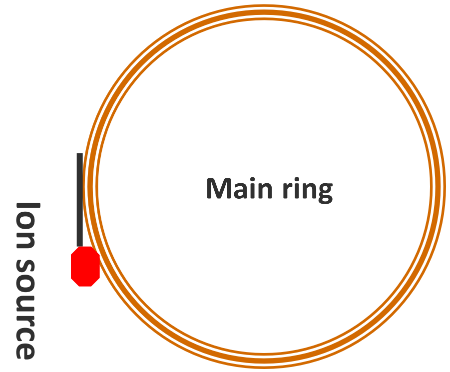
#Minohara @ HIMAC

Digital Accelerator Concept based on Induction synchrotron#

Cascade type Accelerator complex



Digital Accelerator complex

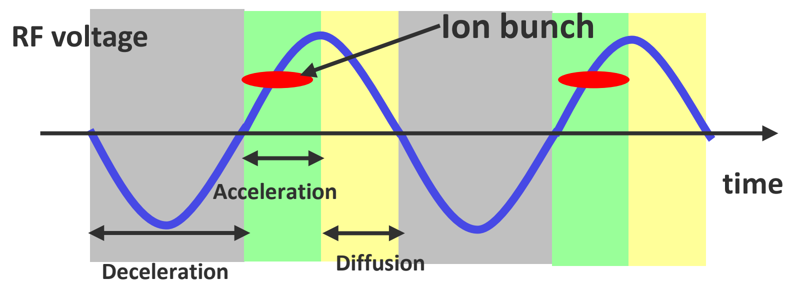


- Direct injection from ion source
- Injector free synchrotron

#K.Takayama, T.Dixit, K.Torikai, et al, "All-ion Accelerators: An Injector-free Synchrotron",*J. of Appl. Phys.* **101**, 063304 (2007)

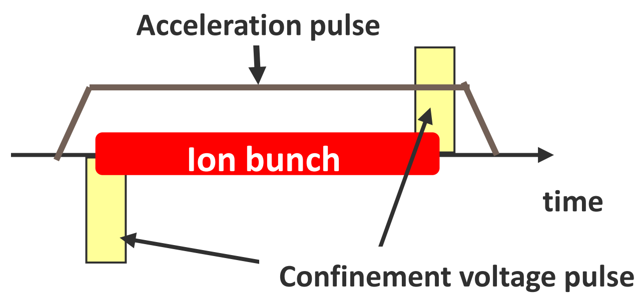
Digital Accelerator Concept based on Induction synchrotron#

RF acceleration

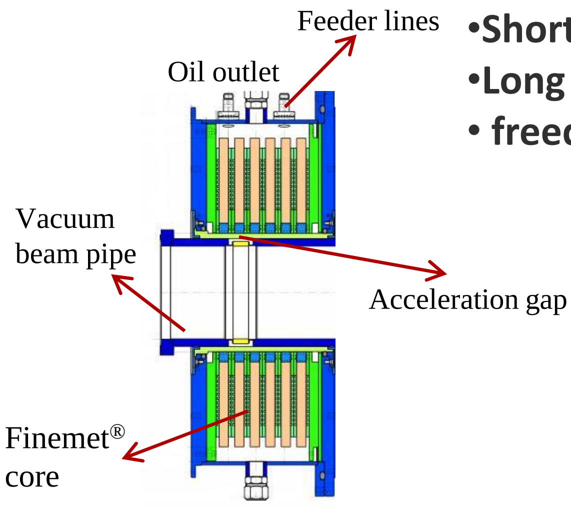


- Function of acceleration and focusing is combined
- beam current is limited

Induction acceleration



- Function of acceleration and confinement are separately handled
- Short step voltages for confinement
- Long step voltage for acceleration
- freedom of beam handling



#K.Takayama, T.Dixit, et al , "Experimental Demonstration of the Induction Synchrotron", *Phys. Rev. Lett.* **98**, 054801 (2007)

Oil inlet, 80 l/min