28th April 2017

Challenges in Medical Physics

Stephen Myers
ADAM SA
Former CERN Director of Accelerators and Technology

Some Personal History

- 1972—1979 Intersecting Storage Rings (ISR): First Proton-Proton Collider ever built
- 1980—1989 Design of Large Electron Positron Collider (LEP)
- 1983 Myers & Schnell: “Proton Collider in the LEP Tunnel”: LEP Note 440. First documented proposal for LHC.
- 1989-2000 Commissioning and Operation of LEP
- 1996—2008 Design of major accelerator components of the LHC
- 2009—2014 CERN Director of Accelerators and Technology
    - LHC “accident” in September 2008 repaired November 2009
    - Higgs discovery 2012
    - August 2012: “High Energy LHC (Document prepared for the European HEP strategy update)” now FCC

Some Personal History (2)

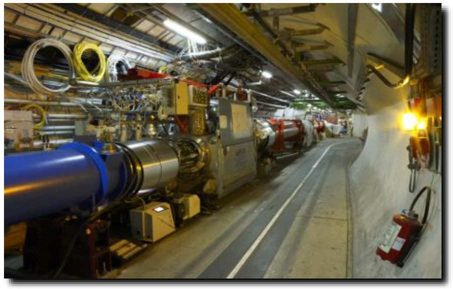
- 2014-2015 Head of CERN Medical Applications

- 2016 – present: Executive Chair of ADAM SA
  - Development a proton Linear accelerator for cancer therapy

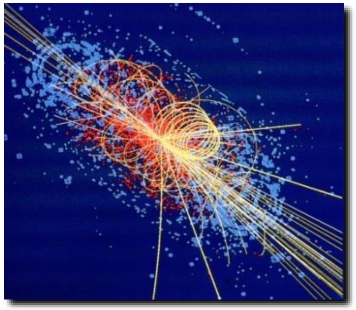
Development and Application of Technologies developed for particle physics to Medicine

What are “CERN” Technologies

CERN Technologies and Innovation



Accelerating particle beams



Detecting particles

Large-scale computing (Grid)

The Challenges of Medical Physics

Initiative 1996-2000: Accelerator Design "PIMMS"

"In 1996, CERN initiated the Proton Ion Medical Machine Study (PIMMS), which aimed at designing a synchrotron optimized for the treatment of moving organs with carbon ions (and protons). The project was adapted by TERA and used as a basis for the CNAO centre, which has been completed in Pavia by the CNAO Foundation and INFN. The MedAustron facility utilises the same synchrotron design, and is currently being built in Wiener Neustadt (Austria)."

What has happened since 2000 on the technology side?

- LHC accelerator technology development
    - Operation of 8T magnets
    - Testing of 11T magnets for Luminosity upgrade
    - Development of 18-20T magnets for energy upgrade

MRI

- LHC Detectors developments
    - Crystal scintillators improvements
    - Medipix proliferation and enhancements
    - Developments of new vertex detectors for LHC luminosity upgrade
    - Development of TOF resolution for Luminosity Upgrade

Medical Imaging and Diagnostics

- CLIC
    - Accelerating structure frequency reduced from 30GHz to 12GHz
    - Development of room temperature structures for 100MV/m gradient
    - Proposals for structures of 3 and 5.7 GHz with 30 and 50 MV/m for medical applications

Compact Accelerators Protons and Light Ions

- LHC Grid
    - Demonstration of the efficiency and reliability
    - Rapid adoption to new domains; Medicine

Large scale data storage, transfer and analysis

- Developments of medical simulations with FLUKA/GEANT

Treatment planning, medical research

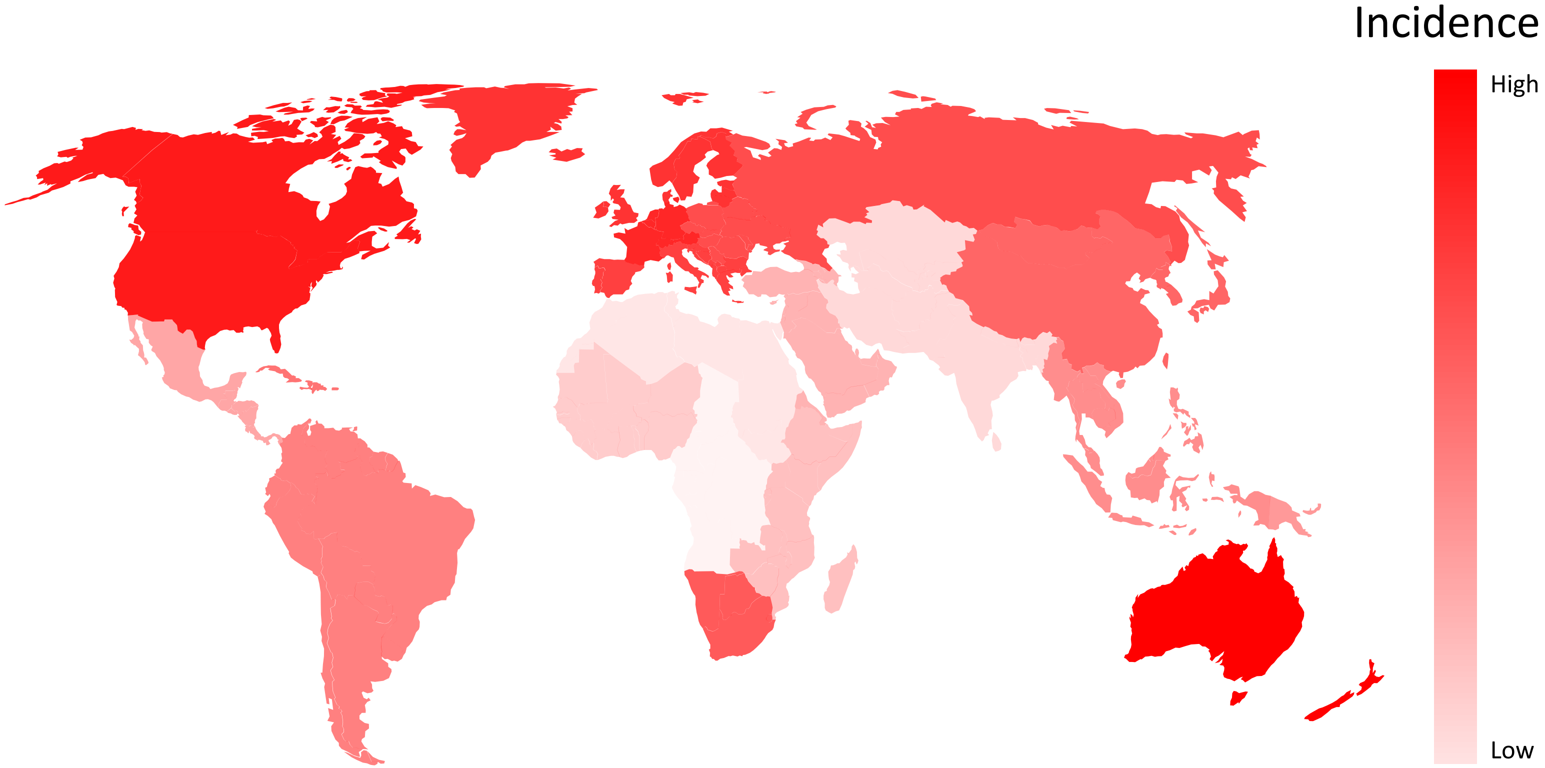
Why is this work so important?

Cancer, a Worldwide Fatality with an Astronomical Cost

2nd leading cause of death worldwide

21m new cancer cases by 2030

$286bn, the global economic cost of new cancer cases in 2009



Cure from cancer achieved for only 45% of patients

8m people likely to die as a result of cancer p.a.

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1. *Alone or in combination with other modalities*
2. *By 1934 Coutard had developed a protracted, fractionated process that remains the basis for current radiation therapy*
3. *GLOBOCAN 2008, Cancer incidence and Mortality Worldwide. IARC, 2010 (http://globocan.iarc.fr) http://info.cancerresearchuk.org/cancerstats/*

CMA: The 7 CERN Initiativ

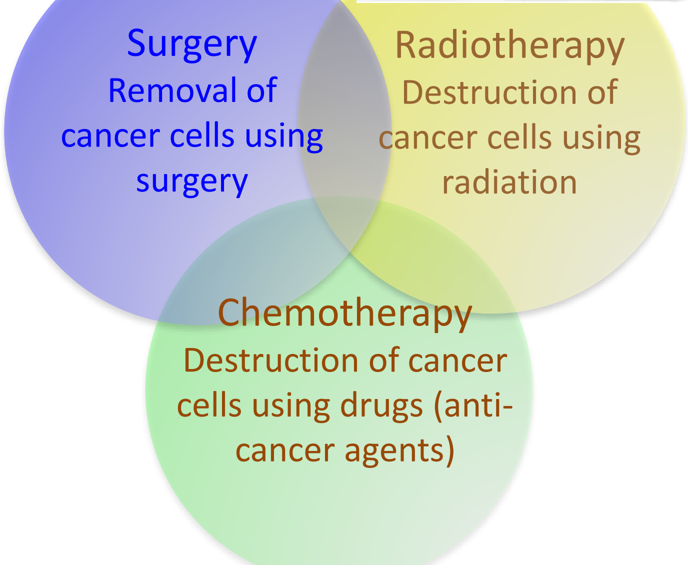
- New Updated Medical Accelerator Design
  - coordinate an international collaboration to desi , cost-effective accelerator facility, using the most ad gies
- Radio-Isotopes (imaging and poss it)
- Detectors for beam control an aging
  Diagnostics and Dosimetry trol of radiation
- Biomedical Facility
  - creation of a facility at C s particle beams of different types and energies to external ogy and detector development
  - Iterative experim of simulation results
- Large Scale C d data (simulations, treatment planning etc)
- Comp ons for Medical Applications
- "C ations; Ablative Therapies…

Each Initiative is part of a "package" but is also important as a stand-alone project

The “Package”: Treatment of Cancer

- Tumor:
  - Abnormal growth of cells
  - Benign: remain at origin, compact
  - Malignant: uncontrolled, can spread → cancer

- Treatment with
  - Surgery
  - Radiation
  - Chemotherapy

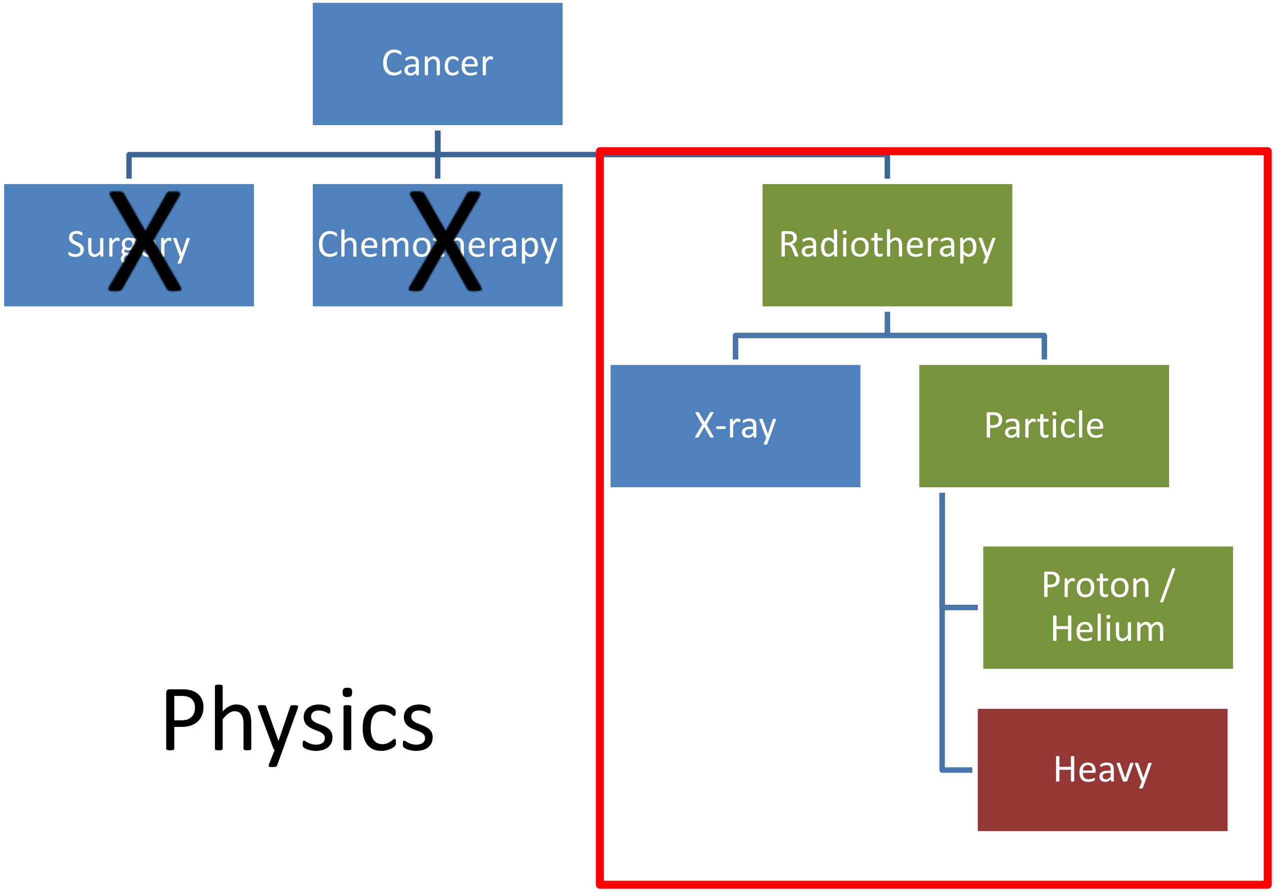


Surgery
Removal of cancer cells using surgery

Radiotherapy
Destruction of cancer cells using radiation

Chemotherapy
Destruction of cancer cells using drugs (anti-cancer agents)

The Challenge of Medical Physics
-Cancer treatment-



Cancer

~~Surgery~~

~~Chemotherapy~~

Radiotherapy

X-ray

Particle

Proton / Helium

Heavy

Physics

Radiotherapy

Radiotherapy methods

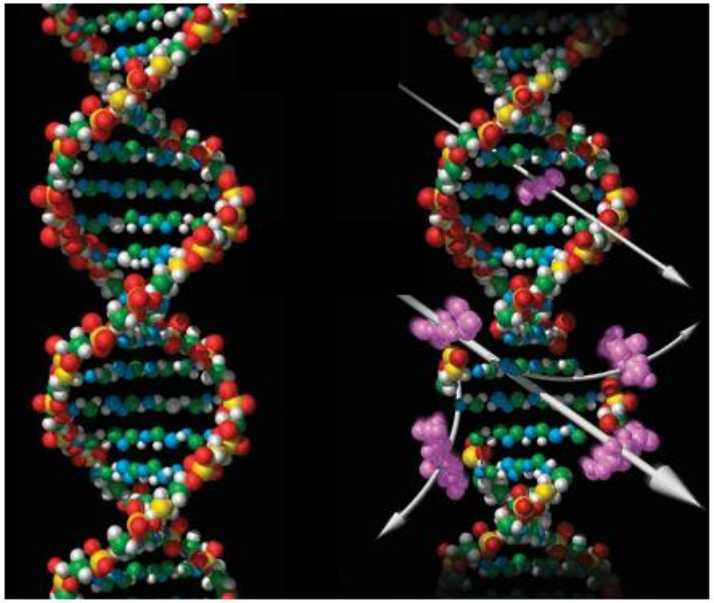
X-rays/gamma rays/electron beams

Most current treatments

Particle beams:
E.g. protons

New treatments

- Radiation can break the DNA of the cells they collide with
- Healthy cells get damaged too…
- **Advantage of protons (see next)**
  - Stop and loose dose in **well-localized** position
  - It is charged (can be steered with magnetic field)

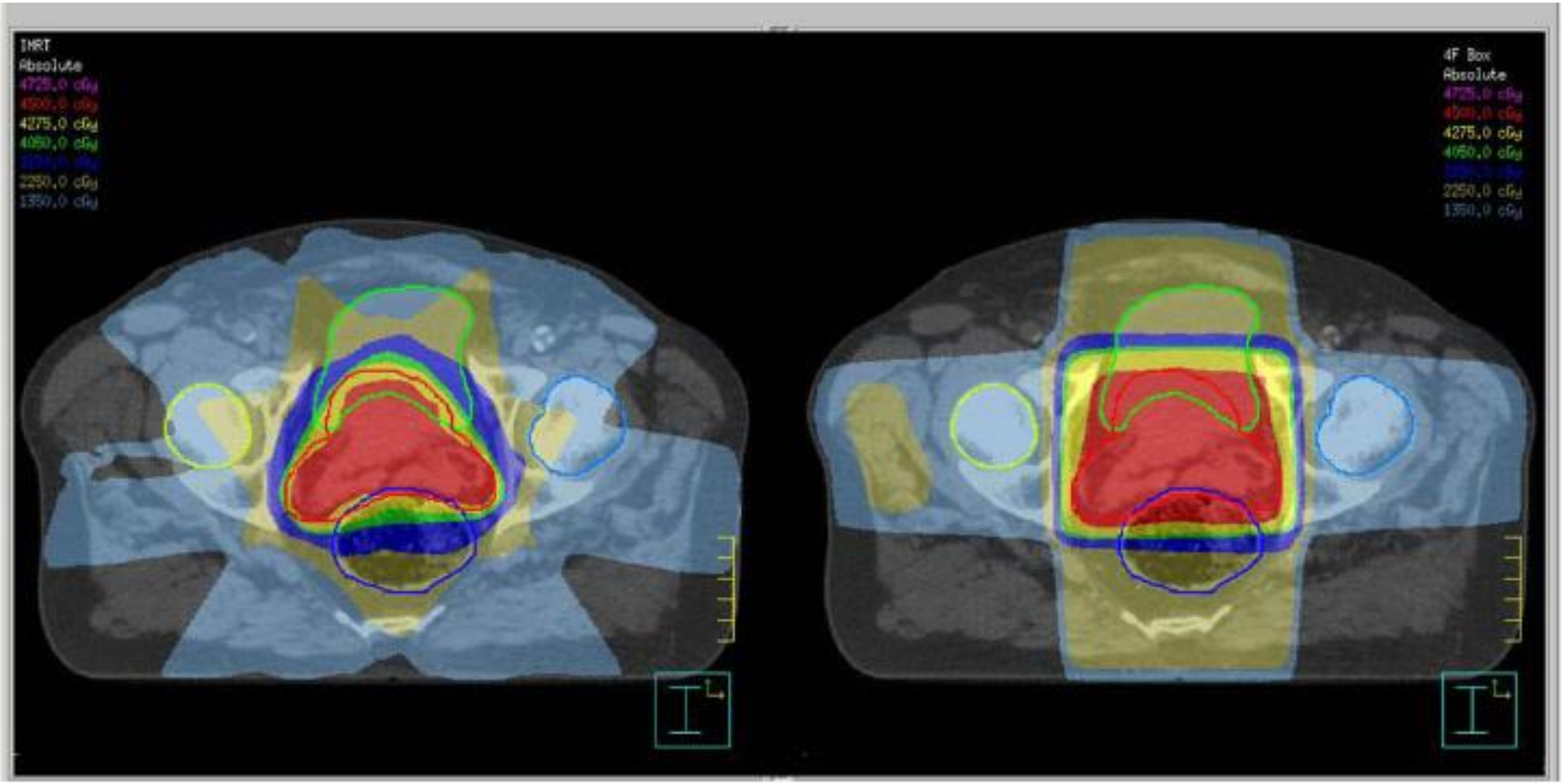


The Challenge of Radio Therapy

- “To irradiate
  - The tumour
  - The whole tumour
  - And nothing BUT the tumour”

Radiotherapy: X-rays

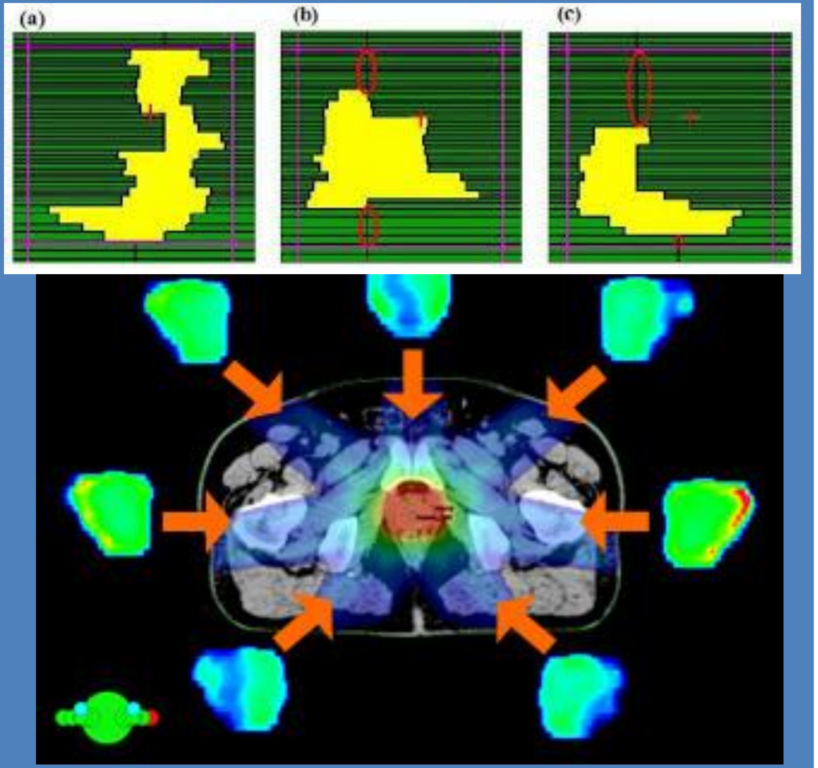
(Ratio of Target to Normal Tissue Doses)



Current state of RT: Intensity Modulated Radiotherapy (IMRT) – Multiple converging field with planar (2D) intensity variations

1990s: 4 constant intensity fields

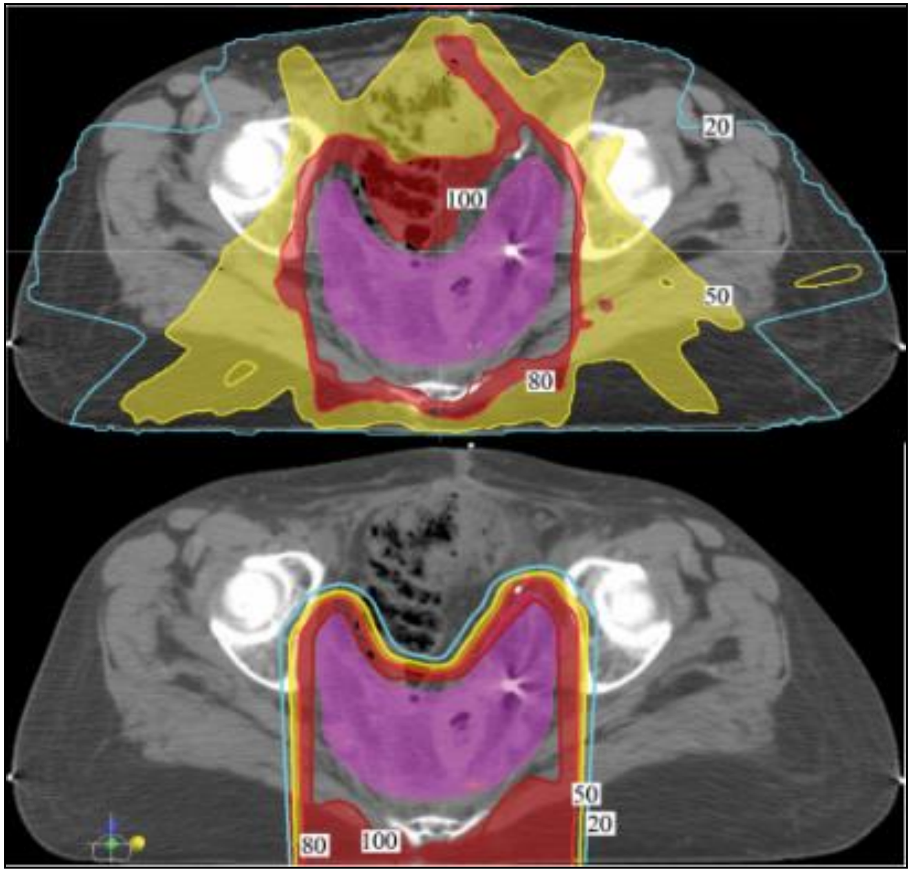
Modern X-ray Therapy



Varian TrueBeam accelerator system with gantry, patient positioner and X-ray panels to acquire CBCT and planar X-rays.

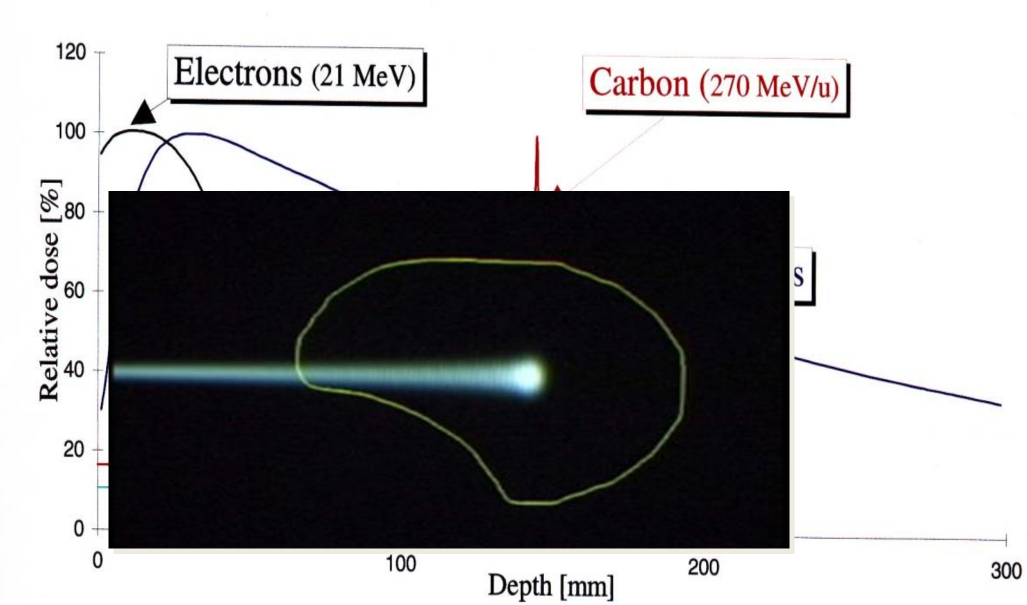
Intensity modulation is achieved by changing the multi-leaf collimator (MLC) patterns (right), gantry rotation and dose rate. Thus, intensity modulation is achieved through mechanical (slow) means.

Ion therapy best advances future of RT



- **State-of-Art X-ray (IMRT) has reached its physical limit**
- **Any advances in radiotherapy are best achieved with light ions**
  - **proton is currently available**
  - **Helium and beyond tomorrow**
  - **Carbon is “popular” but exclusive**
- **Ion therapy must achieve significant “market / clinical” penetration (~20%) to be relevant**

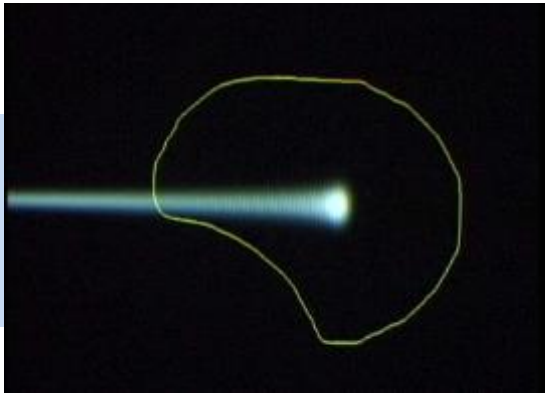
Why Protons (hadrons) are potentially a much better weapon for radiation therapy



The BRAGG Peak

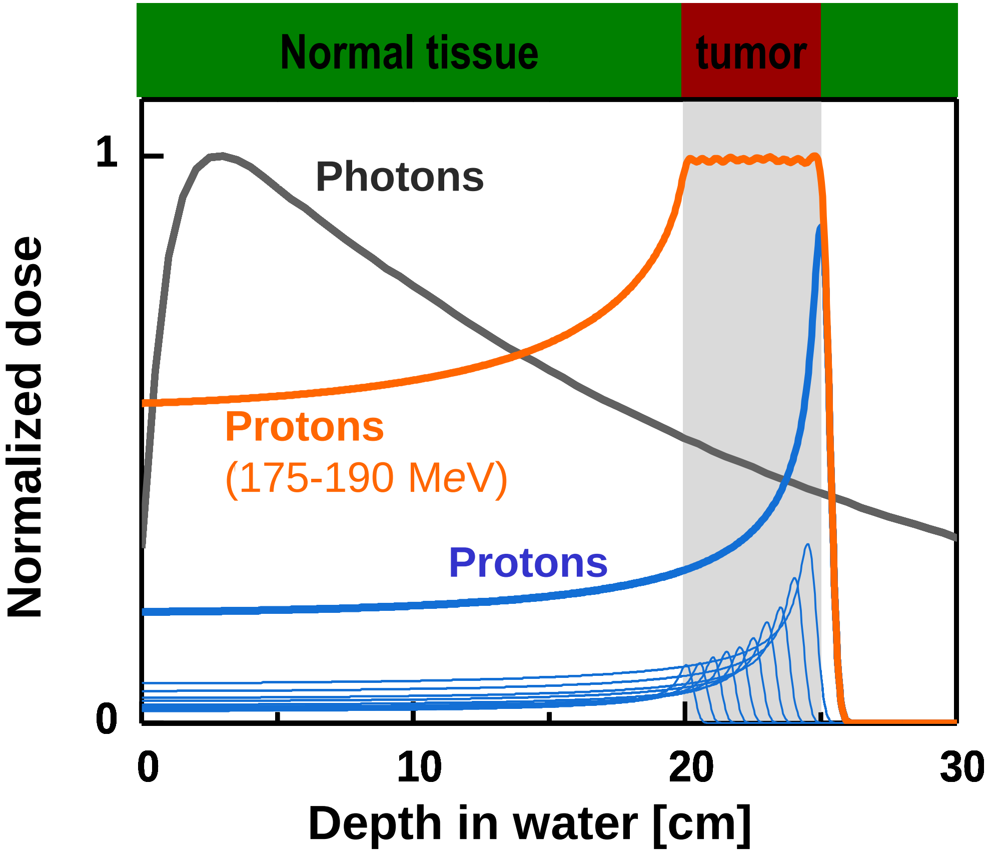
- Tumours close to critical organs
- **Tumours in children**
- Radio-resistant tumours

The physics properties of light ions (Bragg) may make them much more efficient in treating tumours

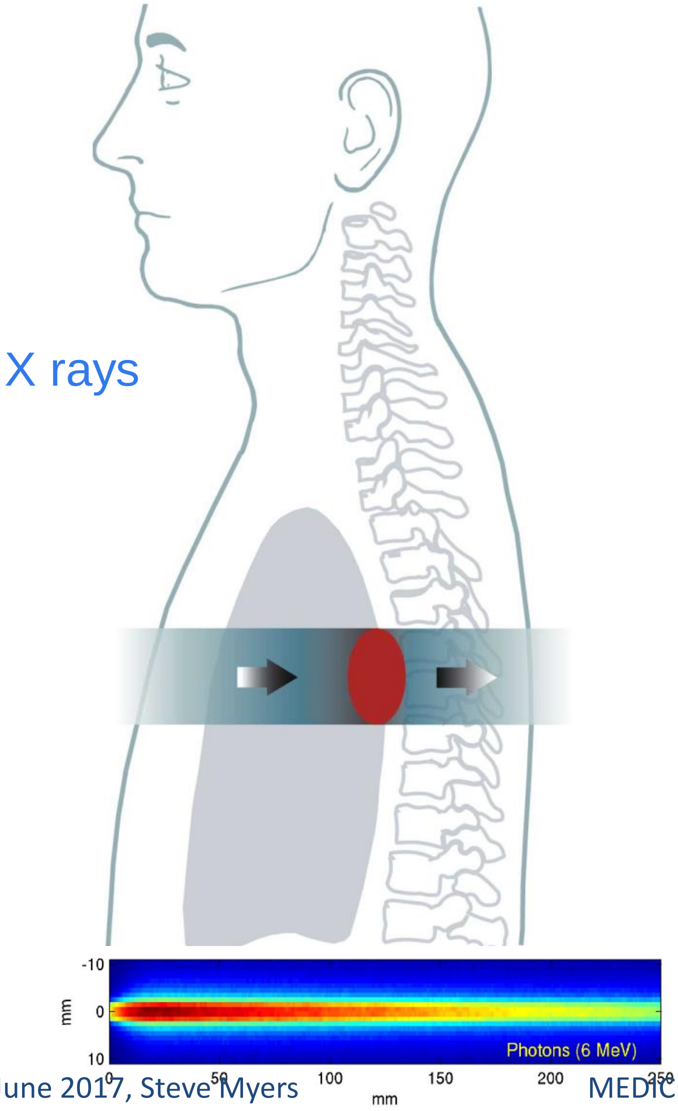


Energy deposition

Physical basis



X-Rays and Protons



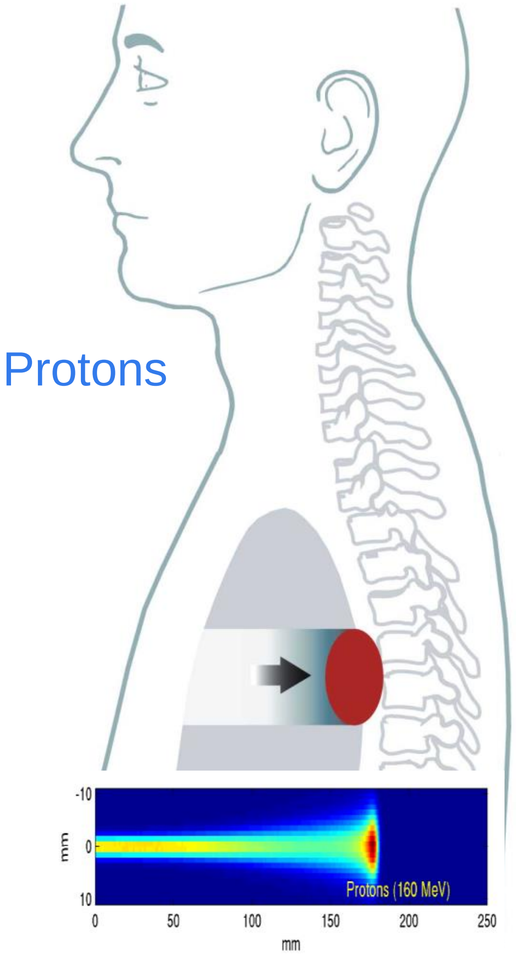
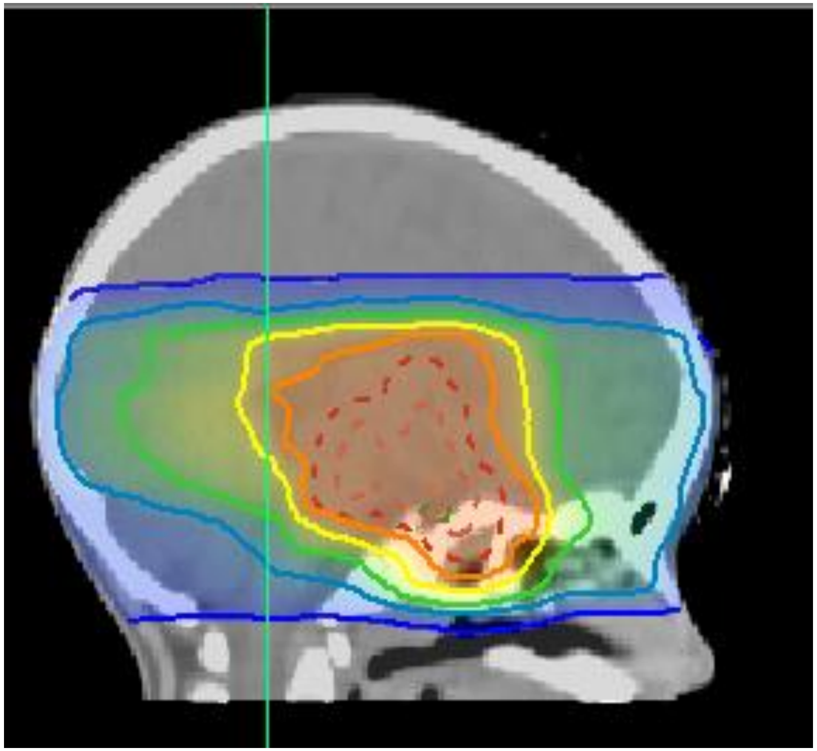


Image courtesy
MedAustron

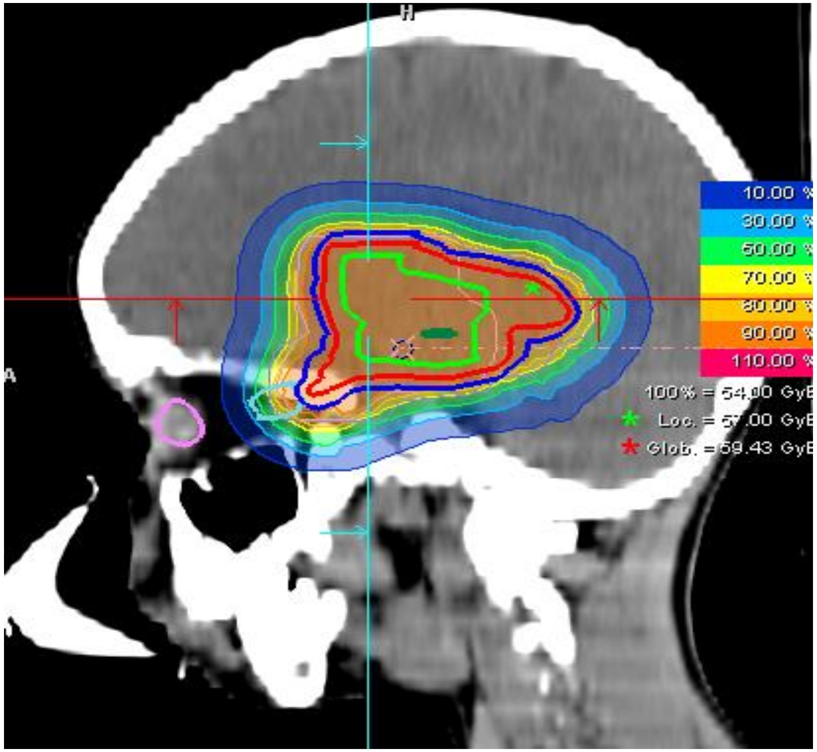
Potential of particle therapy

Photon-IMRT



Universitätsklinikum Dresden

Protons



HIT, Heidelberg

Light Ions (protons etc)

- Advantage of light ions
  - They stop! (good for precision of energy deposition)
  - They are charged: can be guided and focused magnetically
- Disdvantages of light ions
  - They stop! (But WHERE? Difficult for diagnostics)
  - They are charged: Effected by strong magnetic fields (e.g. MRI)

The Challenges of Particle Therapy

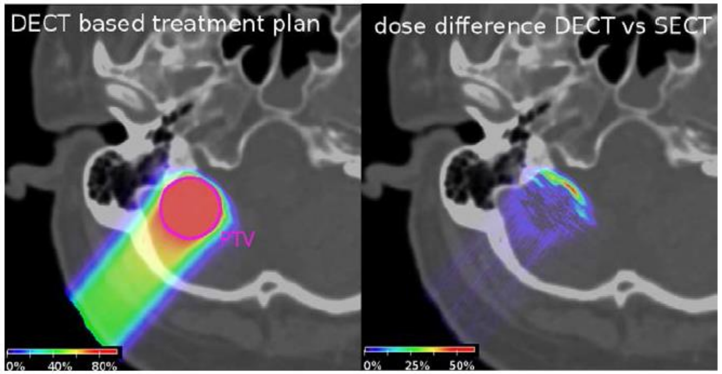
- Cost
- Protons have the advantage of stopping in patient (compared to MV x-ray therapy), but where exactly?
- Treatment with scanned beams is sensitive to organ motion.
- The radiobiology of particle therapy is not completely understood.
- Patients are always treated to the maximum tolerable radiation dose, therefore additional conformity is desirable either minimizing side effects or increasing cure rate.

Acknowledge: Jonathan Farr

Proton Range Determination

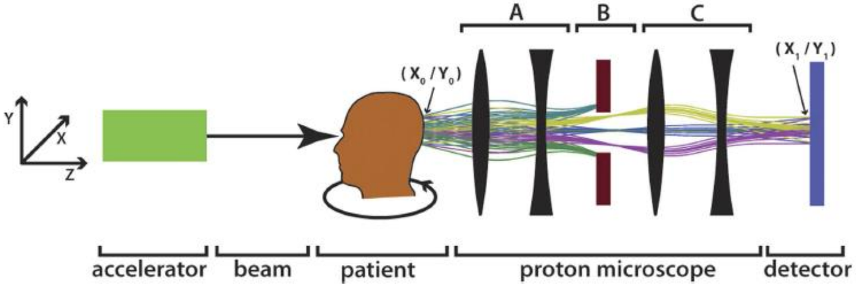
- Current practice 3% of range + 1 mm required planning uncertainty; This is because patient planning is performed with kilo-voltage x-ray data from CT scans and mapped to approximate proton stopping powers in tissues.
- Possibilities to determine in-vivo range more accurately:
  - **As Part of the Radiotherapy Planning Process**

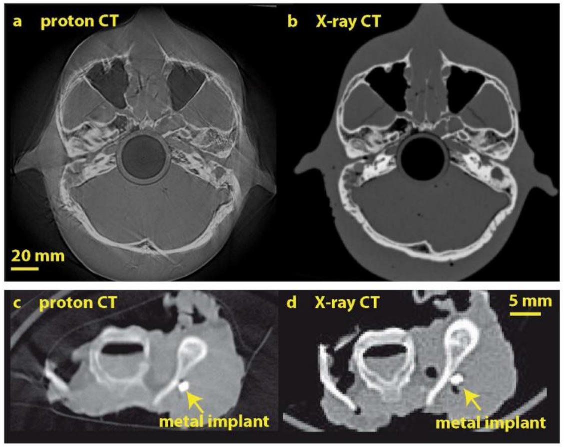
Dual energy CT: using effective Z and electron density, proton stopping power mapping is improved.



Van Elmpt, Landry et al. Radiother Oncol **119** 20016 137

Proton Tomography: Determine (measure) proton stopping powers on a voxel basis directly with the proton beam in imaging mode



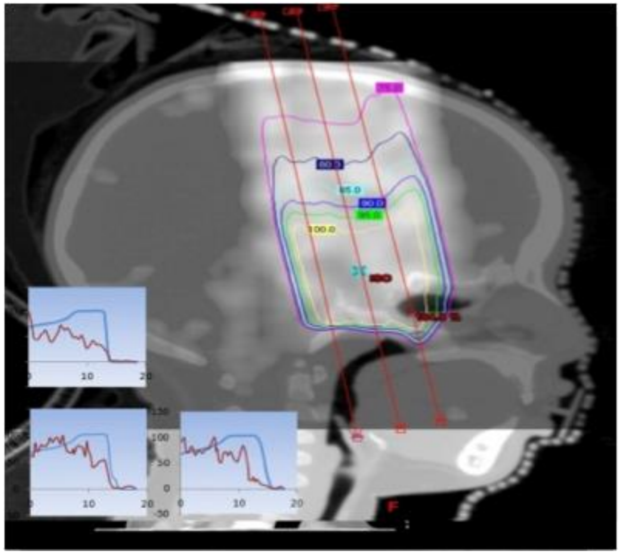


M. Prall, M. Durante, et. al, "High-energy proton imaging for biomedical applications," Sci Rep-Uk **6**, 27651 (2016).

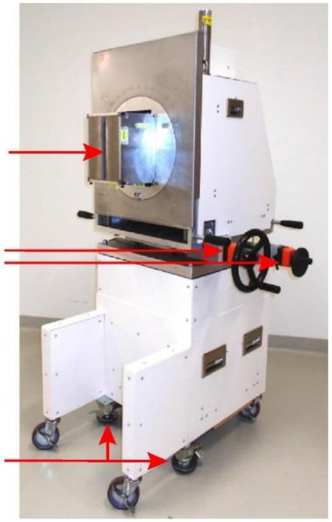
Proton Range Determination

– As Part of the Radiotherapy Verification Process

Proton-PET: using positron β+ generation from treating protons, acquire post-treatment Positron Emission Tomography (PET) scans and correlate to proton dose. PET distribution ≠ dose distribution, biological washout also problematic.



In Vivo Proton Beam Centroid and Range Uncertainties Determined Empirically From Positron Emission Tomography Due to Single Uniform Field Patient Treatment Activation
Farr, J.B. et al.
International Journal of Radiation Oncology • Biology • Physics , Volume 87 , Issue 2 , S185

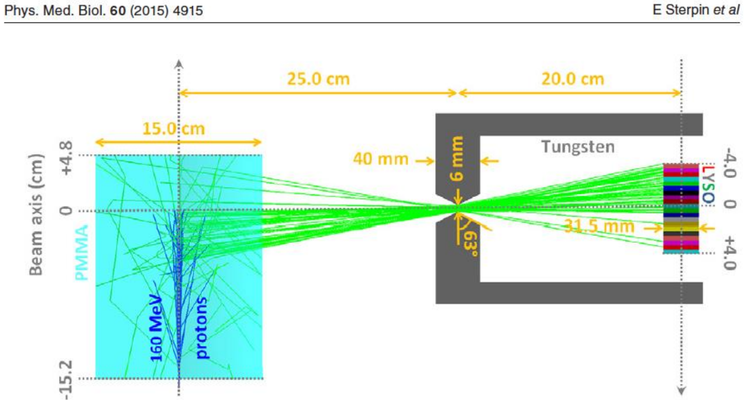


Slit collimator
(360° rotatable)

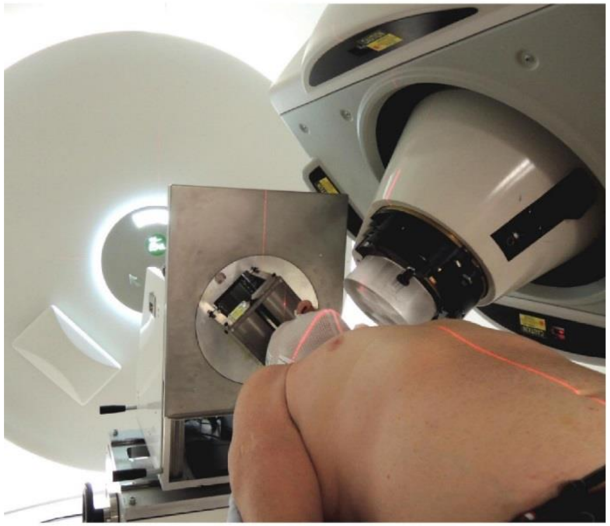
Linear stages for left-right and up-down movements (not shown for forward-backward and rotational movement)

Fixation feet

Prompt Gamma: Using gamma camera and collimation, correlate (p,gamma) events to proton range in patient



Phys. Med. Biol. 60 (2015) 4915 E Sterpin *et al*



First clinical application of a prompt gamma based in vivo proton range verification system
Richter, Christian et al.
Radiotherapy and Oncology , Volume 118 , Issue 2 , 232 - 237

Others: Ultrasound, MRI, point dosimeters

Prompt Gamma

Nuclear Instruments and Methods in Physics Research A 857 (2017) 82-97

“Prototype system for proton beam range measurement based on gamma electron vertex imaging”

Han Rim Lee at al.

H.R. Lee et al.

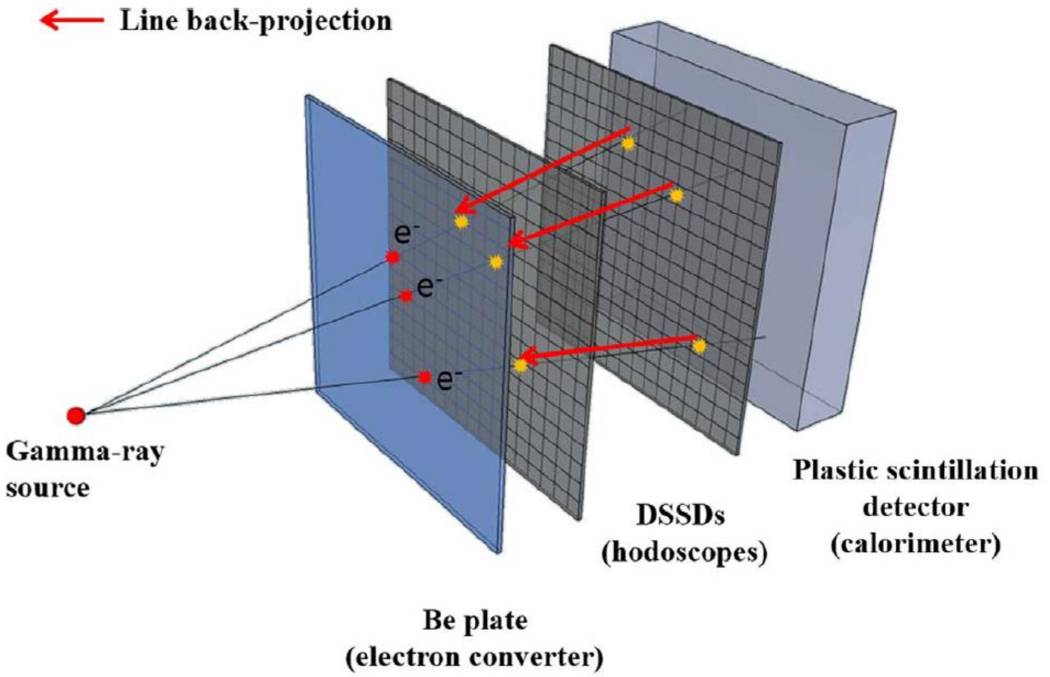
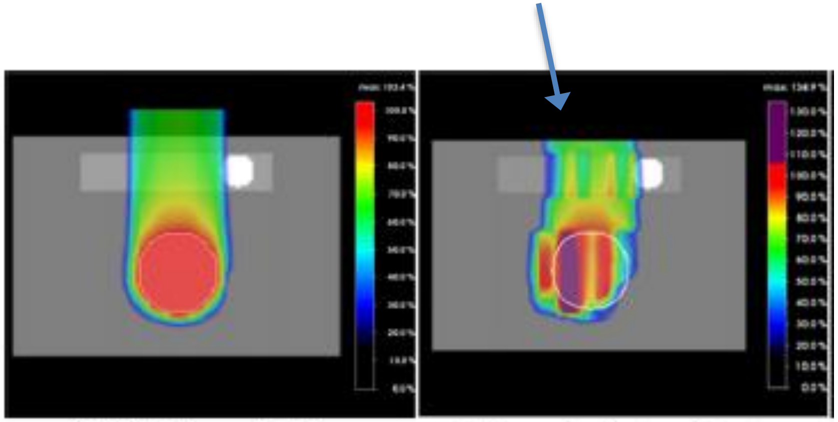


Fig. 1. Principle of gamma electron vertex imaging (GEVI). The high-energy prompt gammas are converted to electrons by Compton scattering, and then the converted electrons are tracked to image the emission locations (= vertices) of prompt gammas. To locate the vertices of prompt gammas, trajectories of electrons are back-tracked by the line back-projection method.

Proton Plan and Delivery Sensitivity to Geometry

- Because protons stop, unlike photons, they are more sensitive to geometric changes either:
- During treatment (inter-fractional); Target motion during treatment gives susceptibility to interplay effect between scanning beam and target.

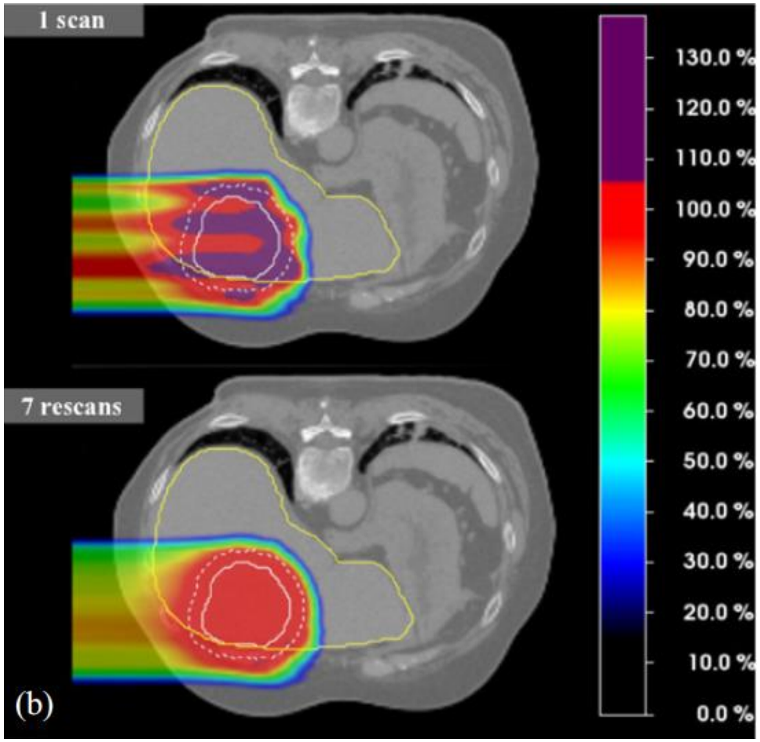


(i) static dose calculation

(ii) dose calculation taking into account dynamic dose delivery (1 x scanning) and motion of the geometry

“Adequate margin definition for scanned particle therapy in the incidence of intrafractional motion”
Antje-Christin Knopf, et al
Physics in Medicine and Biology, Volume 58, Number 17 (2013)

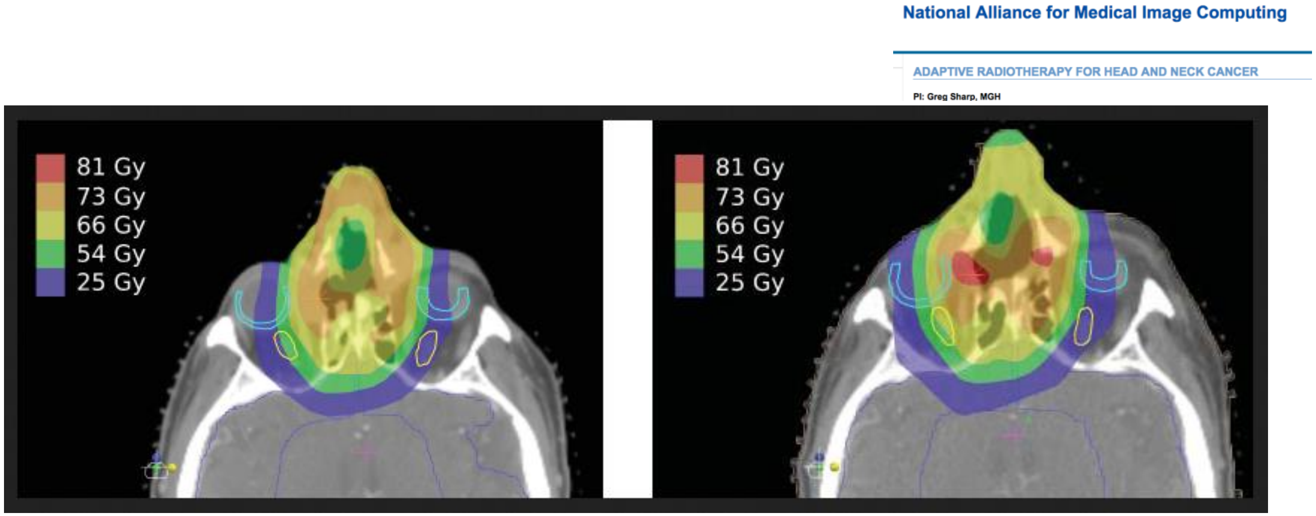
Volumetric rescanning could solve the problem, but need fast delivery and spot by spot energy changes (not available today).



“Comparative study of layered and volumetric rescanning for different scanning speeds of proton beam in liver patients”
K Bernatowicz, A J Lomax et al
Physics in Medicine and Biology, Volume 58, Number 22 (2013)

Proton Plan and Delivery Sensitivity to Geometry

- Between sessions (intra-fractional); Target changes during a typical 25-30 day course of treatments are common in head and neck cancers, and others as well. Plan adaptation, usually a completely new treatment plan is required taking significant clinic resources, doctors, planners, physicists. Consider instead a rapid re-planning system.

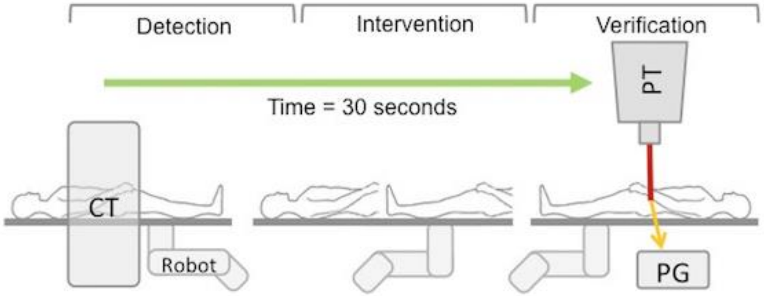


National Alliance for Medical Image Computing

ADAPTIVE RADIOTHERAPY FOR HEAD AND NECK CANCER

PI: Greg Sharp, MGH

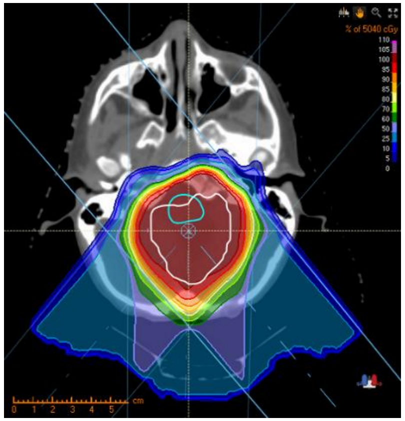
AdaptNow concept from Delft: Combines on the fly patient re-planning with range verification. Typically plans require quality assurance prior to treatment, and additional challenge to re-planning. The range verification seeks to obviate the need for this.

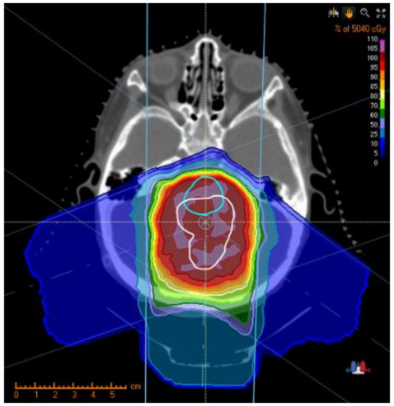


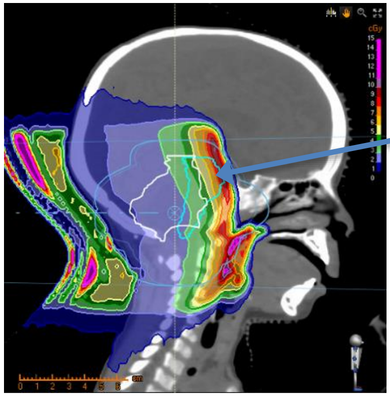
Proton Biological Effects

- Radiobiological effectiveness (RBE) = proton effect/photon effect at same physical dose
- Depends on E, tissue type, oxygenation
- A universal factor of RBE = 1.1 is applied
- We know this is incorrect, especially for central nervous system (CNS) tissues

Equivalent physical dose treatment plans

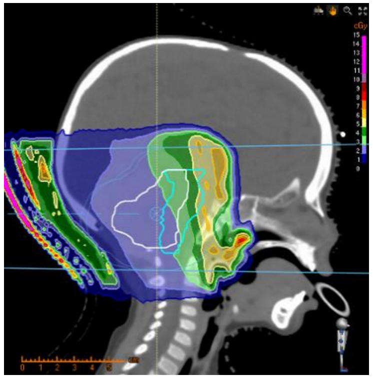






Excess RBE to brainstem; patient with related patient effect

Can give different biological modeling



Patient without related effect

CMA: The 6 CERN Initiatives

- New Updated Medical Accelerator Design
  - coordinate an international collaboration to design a new compact, cost-effective accelerator facility, using the most advanced technologies

Cost, manufacturability, treatment efficiency, modularity, reduced footprint

- Radio-Isotopes (imaging and possibly treatment)

Generation of new types of radio-isotopes for improved diagnostics and new treatment scenarios

- Detectors for beam control and medical imaging
  Diagnostics and Dosimetry (pot) for control of radiation

Improved diagnostics, measurement of beam on target in real time

- Biomedical Facility
  - creation of a facility at CERN that provides particle beams of different types and energies to external users for radiobiology and detector development
  - Iterative experimental verification of simulation results

Measurements of radiobiology of different ions, testing of new diagnostics, verification of radiobiological simulations

- Large Scale Computing and data (simulations, treatment planning telemedicine etc)

Large scale data handling, remote acquisition to medical data, correlation of medical results

- Computer Simulations for Medical Applications

Improved predictions of radiobiological processes

Important Parameters for PT Accelerators

- Beam Size (emittance): Cost and Treatment Efficiency
  - Small size for Pencil Beam Scanning
  - Small size allows small aperture magnets for the beam transfer line
    - Cheaper magnets
    - Lighter magnets
    - More simple gantry
- Energy Modulation (Depth modulation): Treatment Efficiency
  - Adaptive Radiotherapy
    - Allows fast feedback on organ movements
      - E.g. MRI guided treatment in real time
      - «random» feedback difficult using ESS
    - Not bound to «energy» layers; could paint along depth
- Fast Speed of Change of Beam energy: Treatment Efficiency
  - Allows many beam spots in an organ movement cycle time
  - Allows volumetric rescanning

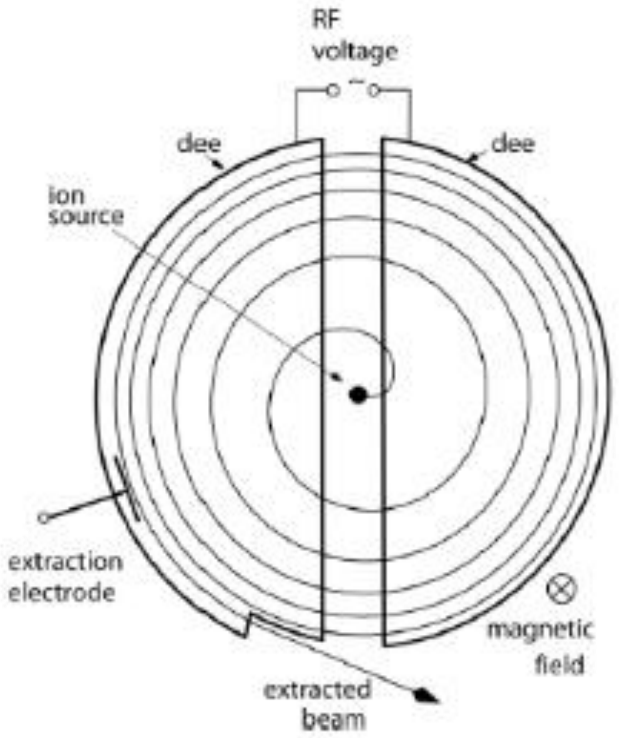
- Modularity: Cost
  - Allows installation in ''difficult'' locations (e.g Harley Street)
  - Ease and cost of installation
  - Allows installation without expensive load handling devices

Important Parameters for PT Accelerators

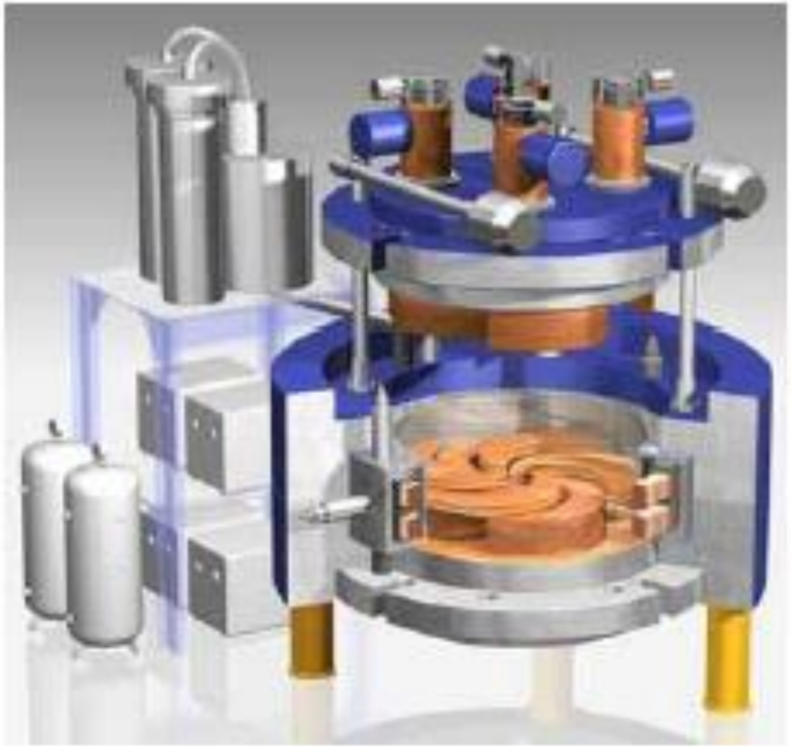
- Spot size regulation: Treatment Efficiency
  - Allows high intensity large spots at centre of tumour and smaller low intensity spots at the penumbra: less collateral radiation
- Spot Dose Regulation (speed): Treatment Efficiency
  - Allows more precise dose distribution
- Radiation Activation due to Proton losses: Cost
  - Reduced shielding
  - Reduced Decommissioning costs
- Footprint Size: Cost
  - Construction cost
- Operational Costs: Cost
  - Electrical power consumption
  - Number of highly trained personnel needed to operate

Cyclotrons (Isochronous)

- **Constant B-field**
- **Revolution period (almost) independent of beam energy →**
  - Fixed RF frequency
  - Beam can be continously sent from the source (CW, not pulsed)
- **Fixed extraction energy !**
  - Need Energy Selection System



Photographic Examples (Isochronous Cyclotrons)

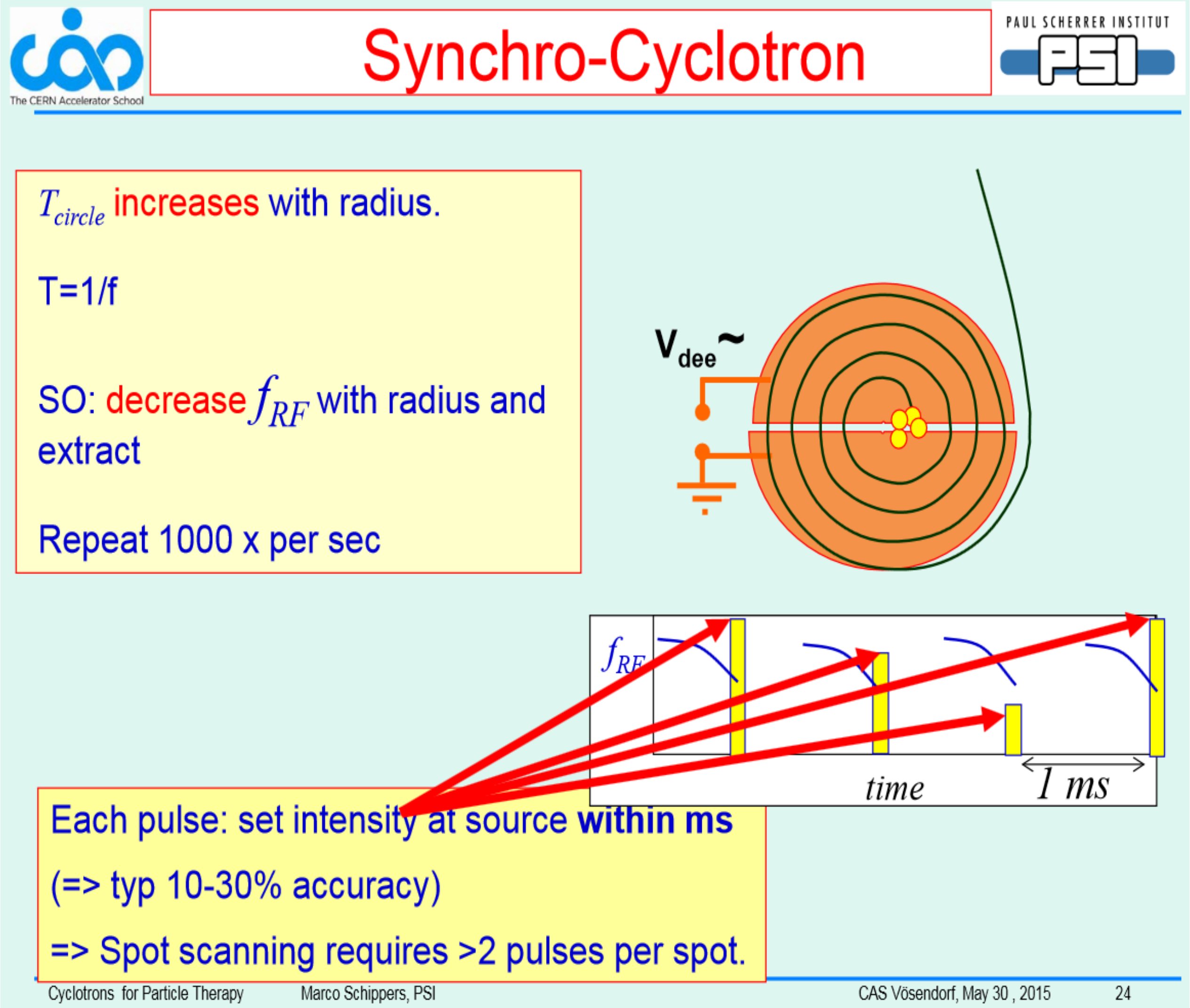


Varian
SC isochronous cyclotron

IBA Normal conducting cyclotron

Synchro–Cyclotrons

- **Synchro**-: RF frequency and spatial value of B are synchronous
- **Cyclotron**: Only one magnet (spiralling trajectory)
- Beam is pulsed (need to wait extraction before restarting the RF frequency cycle)
- Intensity can be adapted from pulse to pulse -> IMPT



Synchro-Cyclotron

T_{circle} increases with radius.

T=1/f

SO: decrease f_{RF} with radius and extract

Repeat 1000 x per sec

Each pulse: set intensity at source **within ms**

(=> typ 10-30% accuracy)

=> Spot scanning requires >2 pulses per spot.

Cyclotrons for Particle Therapy Marco Schippers, PSI CAS Vösendorf, May 30 , 2015 24

Photographic Examples of Synchro – Cyclotrons

Mevlon TriNiobium Core

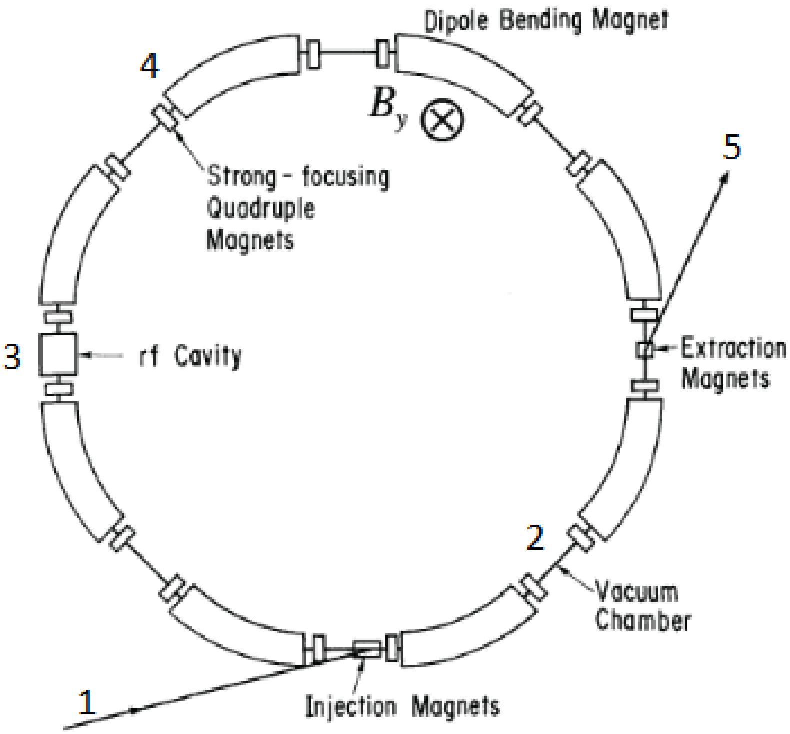
SC synchrocyclotron

IBA S2C2

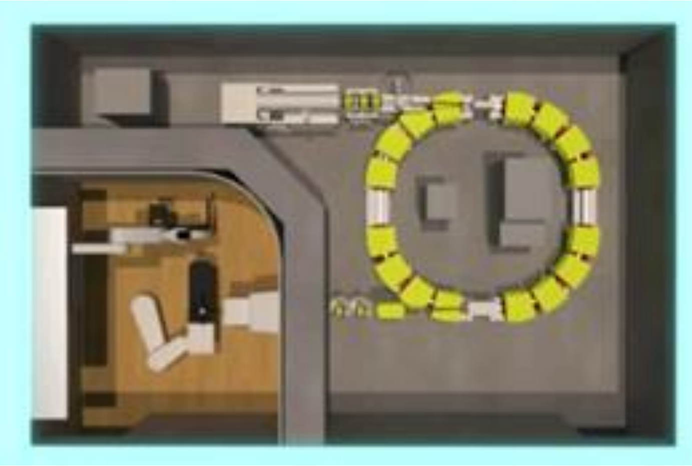
SC synchrocyclotron

Synchrotrons

- Both RF freqeuncy and magnetic field vary in time during the acceleration (in **synchronism**)
- Need pre-injector, **injection** and **extraction systems**
  - **Critical and generate asymmetric beams in transverse phase space**
- Cycling machine, with CW beam during spills (slow extraction)
- Variable energy: Output energy can be changed on a pulse to pulse basis
- Recent: Extraction at «flat-top» with variations in energy

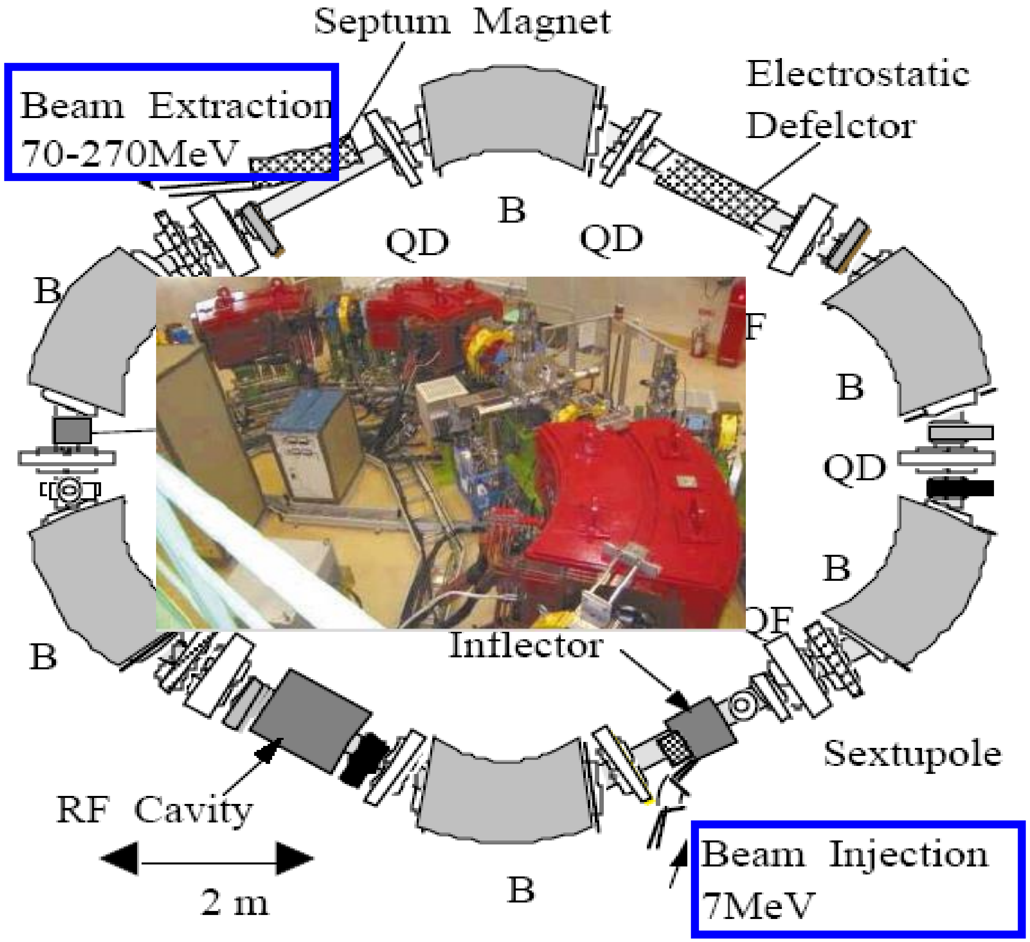


Photographic Examples of some Synchrotrons



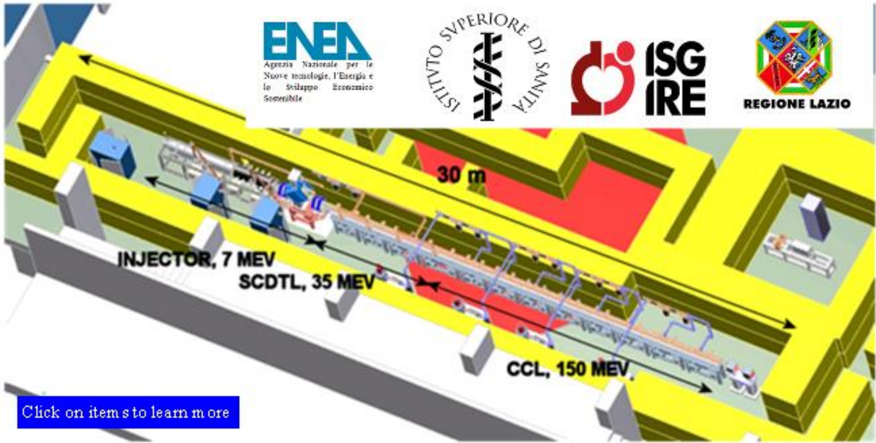
ProTom compact synchrotron

Mitsubishi



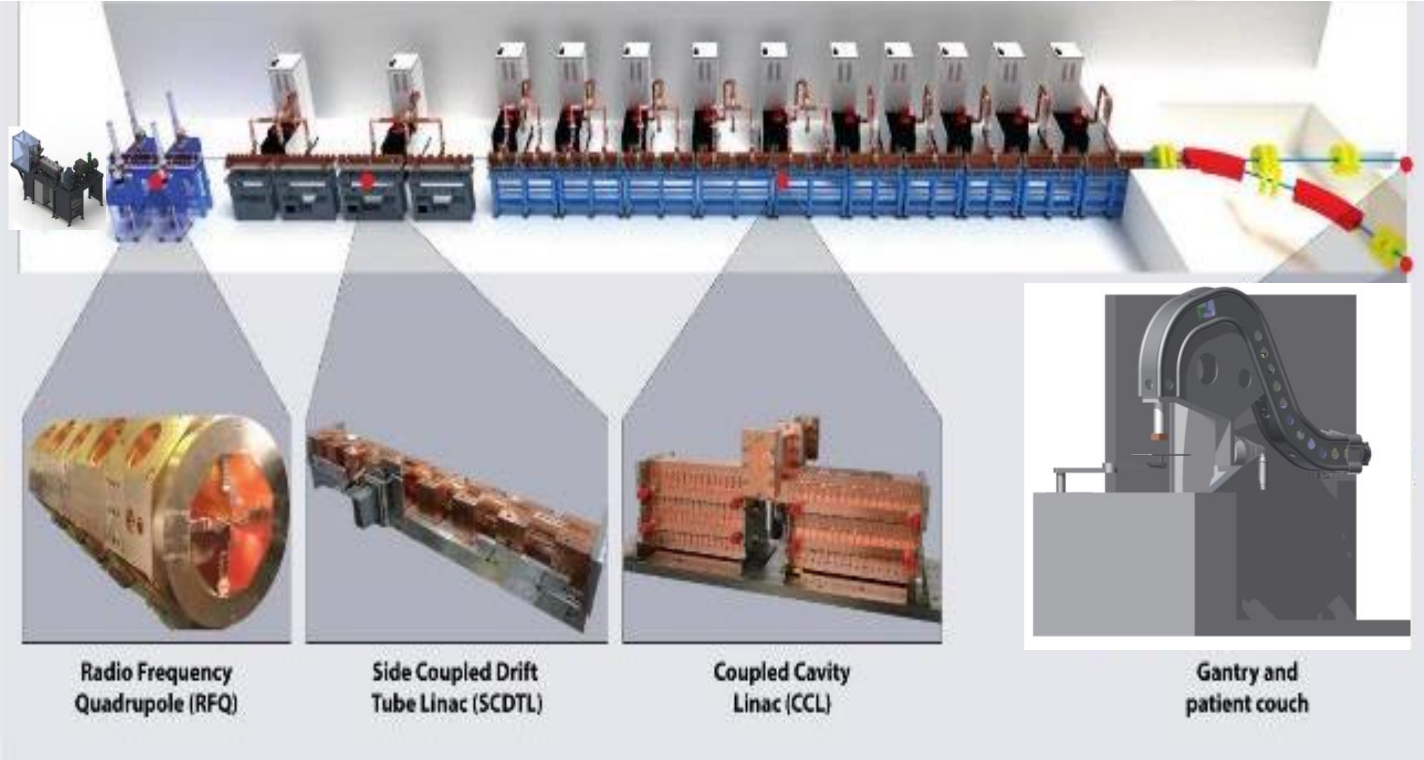
Hitachi synchrotron

Examples of Linacs



TOP-IMPLART

RFQ at 750MHz;
Accelerating Structures at 3000MHz

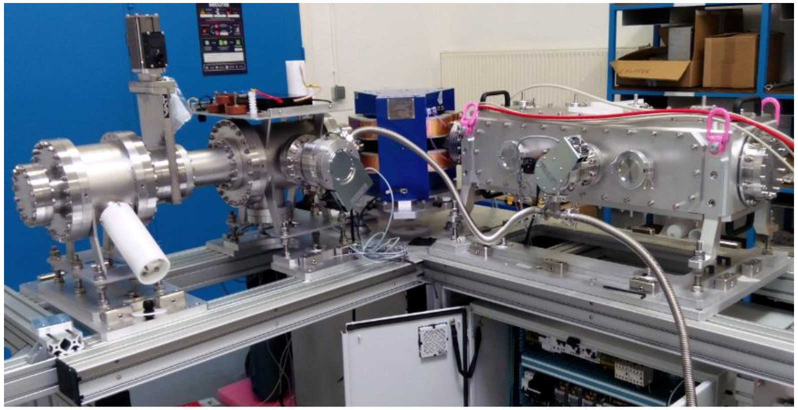


AVO
LIGHT

LIGHT Main Parameters

Parameter	Value	Unit
Length	~25	m
Max. Energy	230	MeV
Output Peak Current (at the end)	0.3 - 90	µA
Pulse Length	0.5-5	µs
RF Frequency	2997.92	MHz
Max. Repetition Rate	200	Hz
Peak RF Power	~60	MW

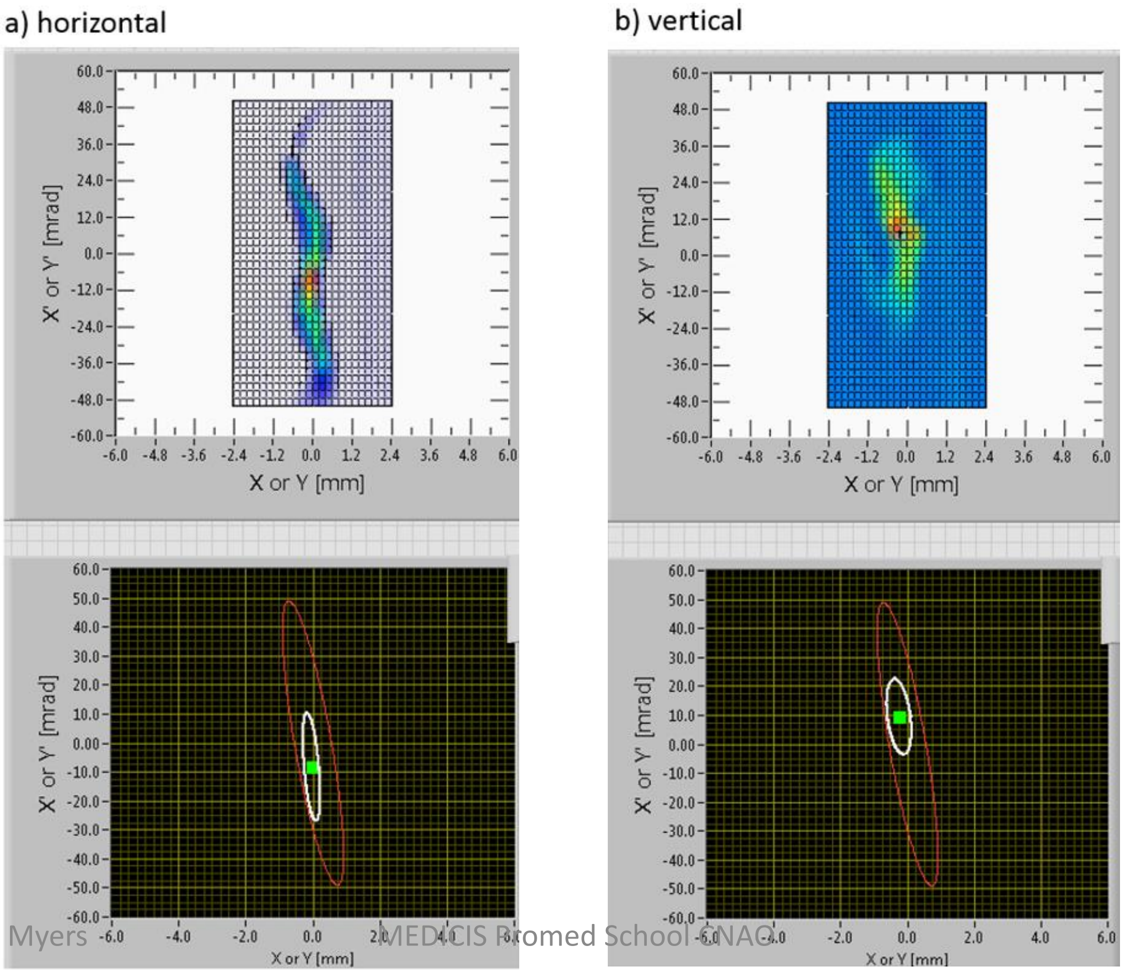
Proton Source



Quantity	Value	Unit
Output Energy	40 ± 0.4	keV
Output pulsed Current	Range: [1-300] ± 2%	µA
Current ripple during flattop	± 1	%
Pulse to pulse current reproducibility	± 2-3	%
Repetition rate	Range: [5-200]	Hz
Beam pulse width	Range: [0.5-5]	µs

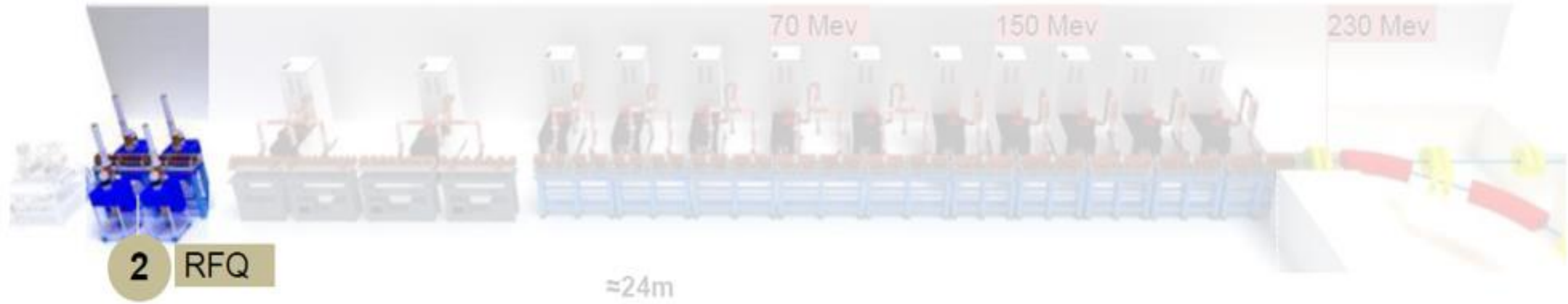
Proton source test results

Example of emittance measurements and corresponding rms emittances (white) with the representation of the extrapolated RFQ acceptance ellipse (red).


a) horizontal

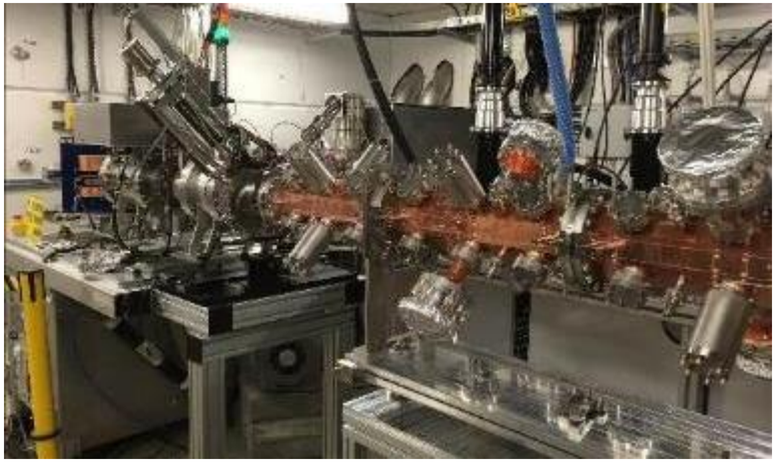
b) vertical

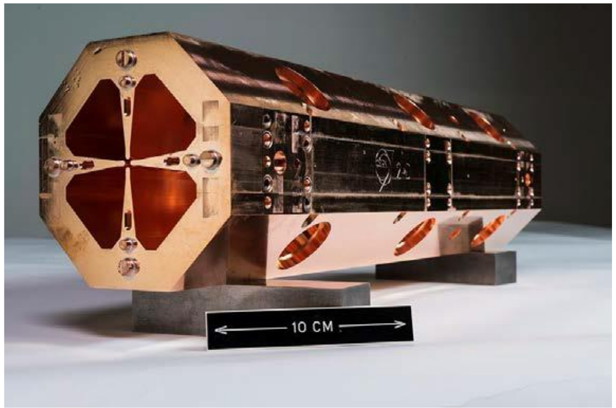
The Radio Frequency Quadrupole (RFQ)



- High frequency RFQ designed by CERN
  - 4 vanes type
  - 750 MHz
  - 4 modules - 2 m
  - 5 MeV energy gain

Section	RFQ
RF frequency [GHz]	0.749
Energy [MeV]	0.04-5
Length [m]	2



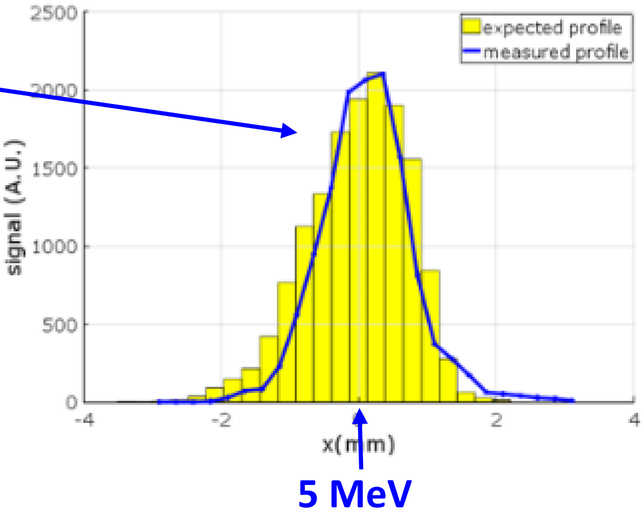


RFQ test results

- Results from the RFQ commissioning with beam

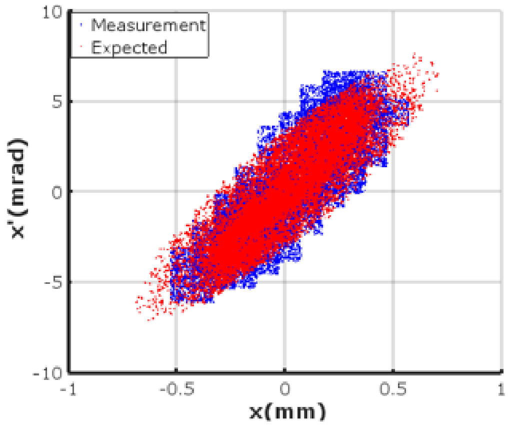
Profile and energy measurements

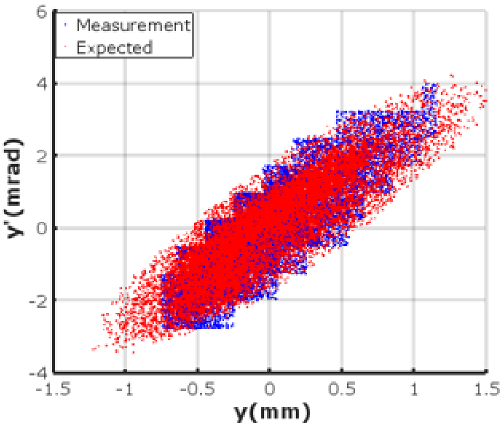
- Comparison of measured and expected beam profiles at the spectrometer profile monitor
- calculated average beam energy from the spectrome measurement is 5.07 MeV (expected energy 5.0 M
- Energy spread: measured rms energy spread is 7.0 ke (expected value is 7.5 keV)



Emittance

- The expected rms emittance is 0.33 π.mm.mrad in both planes

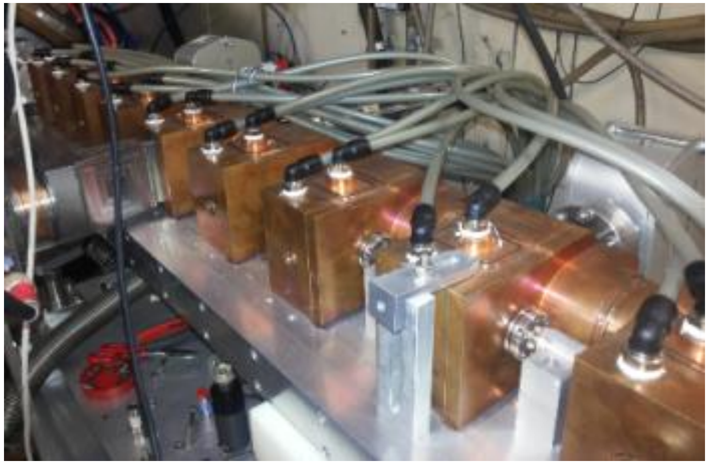




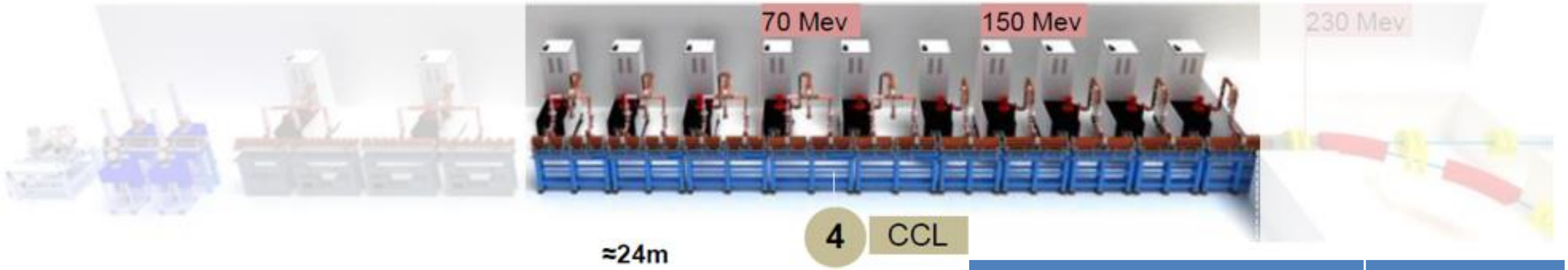
The Side Coupled Drift Tube Linac (SCDTL)

- Designed in collaboration with ENEA (Frascati, I)
- Manufactured at TSC/VDL

Section	SCDTL
RF frequency [GHz]	2.998
Energy [MeV]	5-37.5
Length [m]	6.2

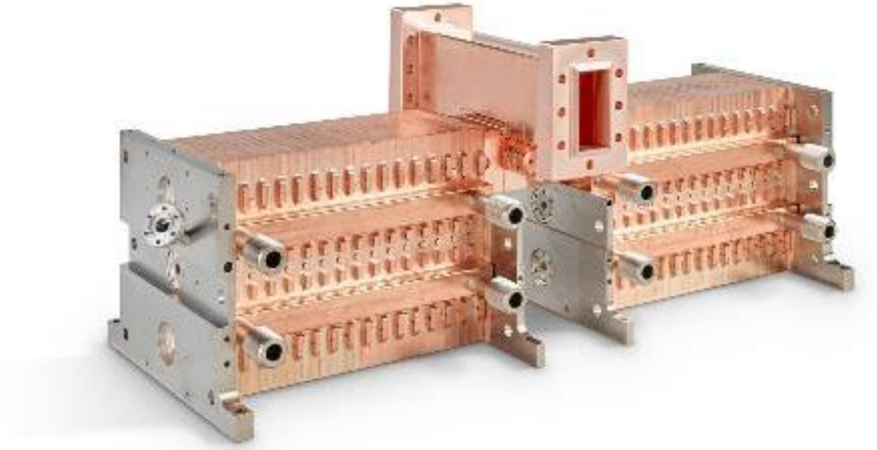


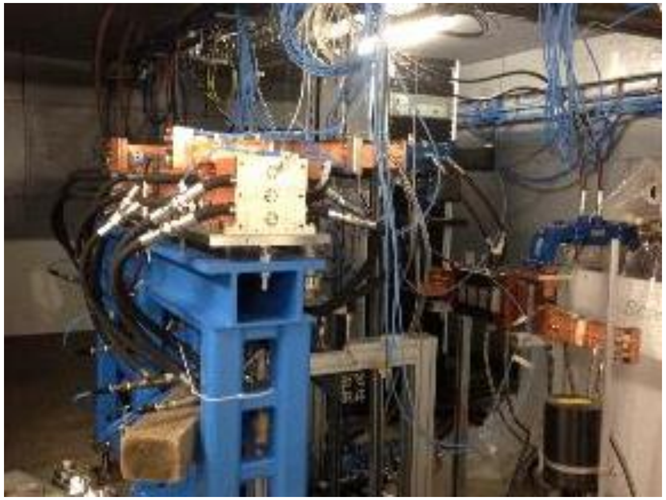
The Coupled Cavity Linac (CCL)



Section	CCL
RF frequency [GHz]	2.998
Energy [MeV]	37.5-230
Length [m]	15.5

- Designed by ADAM
- Manufactured by VDL
- 4 modules already in the bunker (conditioned)
- All remaining modules in production

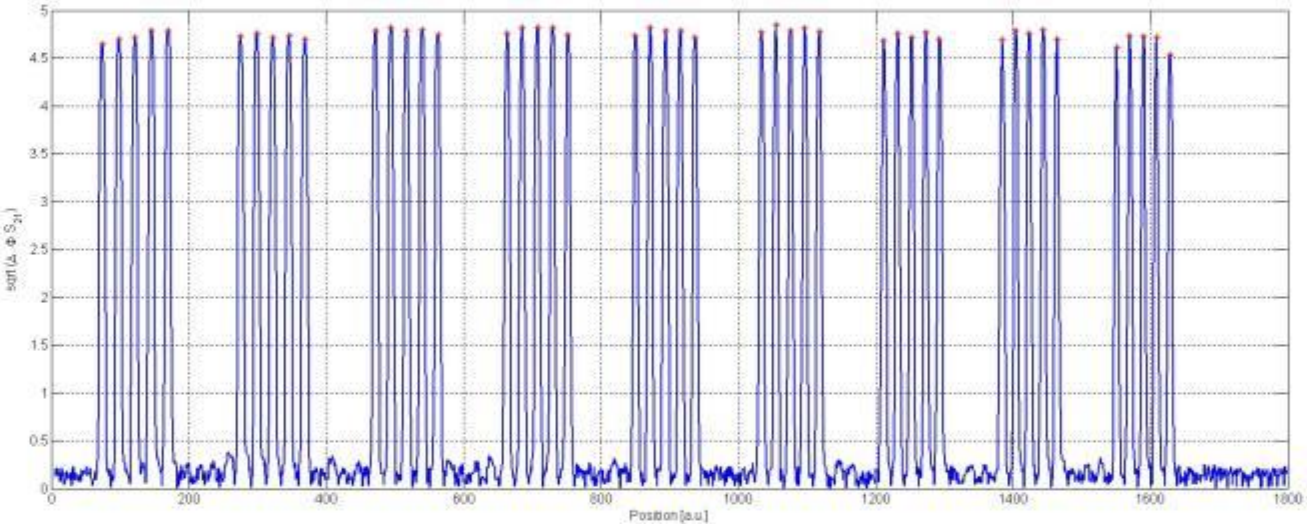




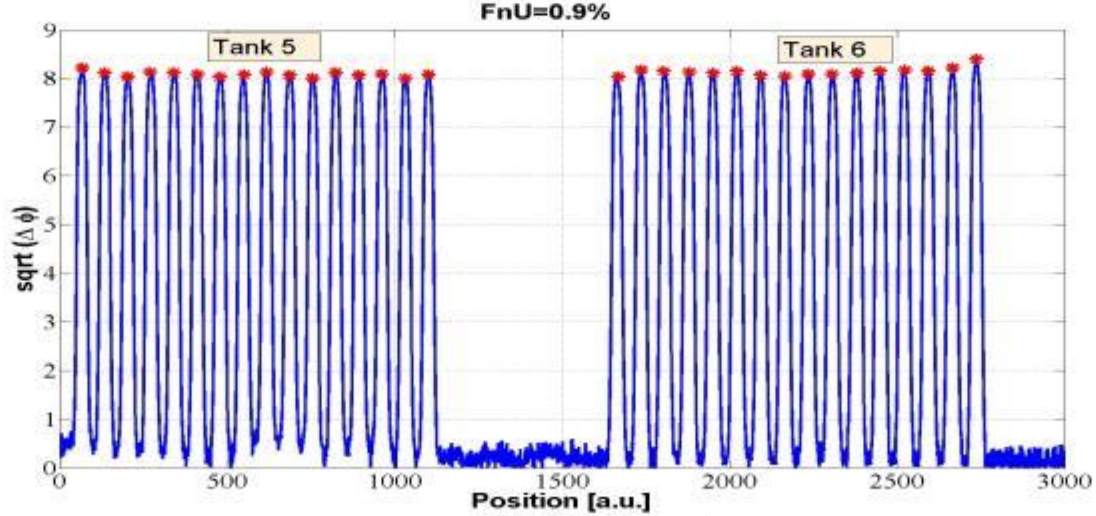
Acknowledge: Alberto Degiovanni

SCDTL and CCL E-field measurements

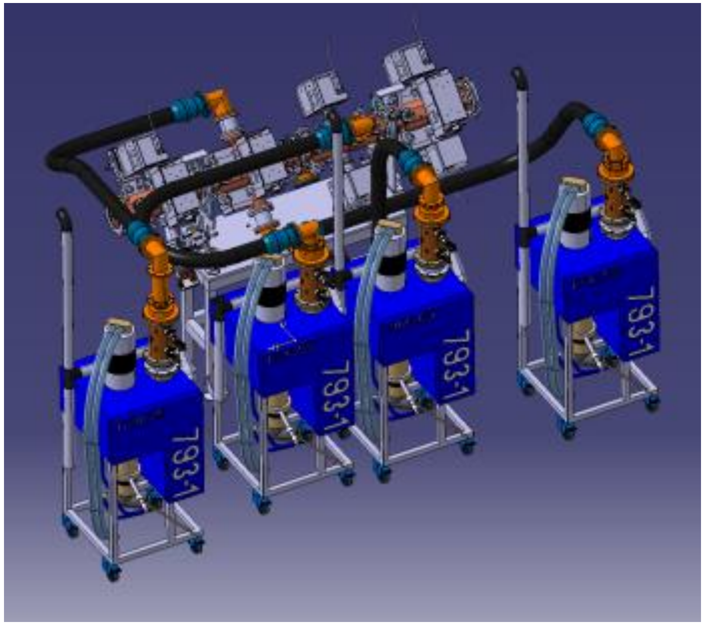
- SCDTL



- CCL



RFQ Power System



Parameter	Value
Cathode voltage	38 KV
Grid voltage	200 V
Average beam current	4 A
RF drive power	800 W
RF output power	100 KW
Load mismatch	1.5:1

SCDTL and CCL RF Power System

- Commercial modulator and klystron systems

SCANDINOVA Modulator

Parameter	Value
Pulse Voltage	155 KV
Pulse Current	110 A
Pulse Rep. Rate	5 to 200 Hz
Pulse Length (top)	0.5 to 5 µsec
Pulse Flatness (top)	<1%

Toshiba Klystron

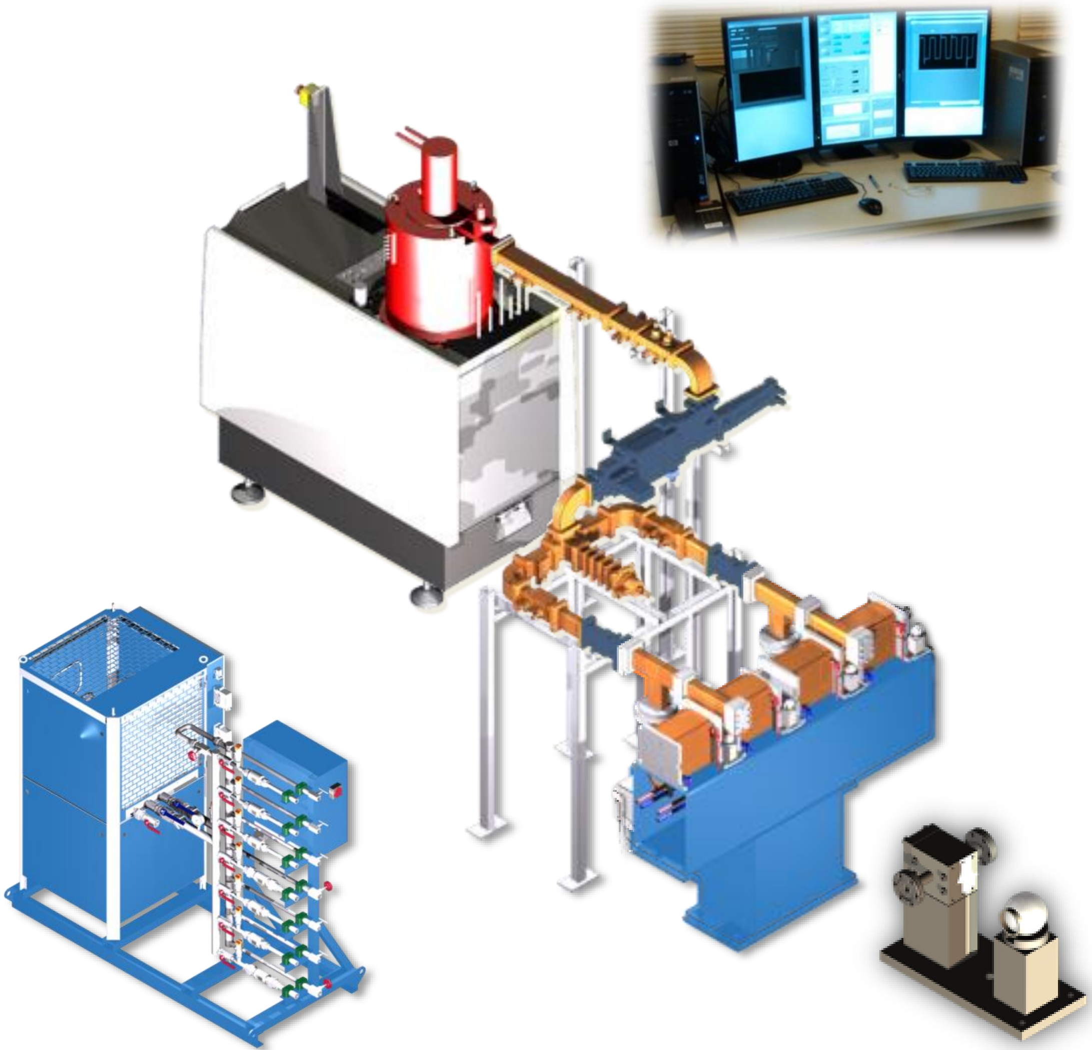
Parameter	Value
Frequency	2998.5 MHz
Peak RF Drive Power	120 W
Peak RF Output Power	7.5 MW
Gain	48 dB
RF Pulse Width	5 µsec

Acknowledge: Alberto Degiovanni

A modular approach towards industrialization

Unit Systems

1) Accelerating System
2) Control System
3) Cooling System
4) Focusing System
5) RF Network System
6) RF Power System
7) Support System
8) Vacuum System

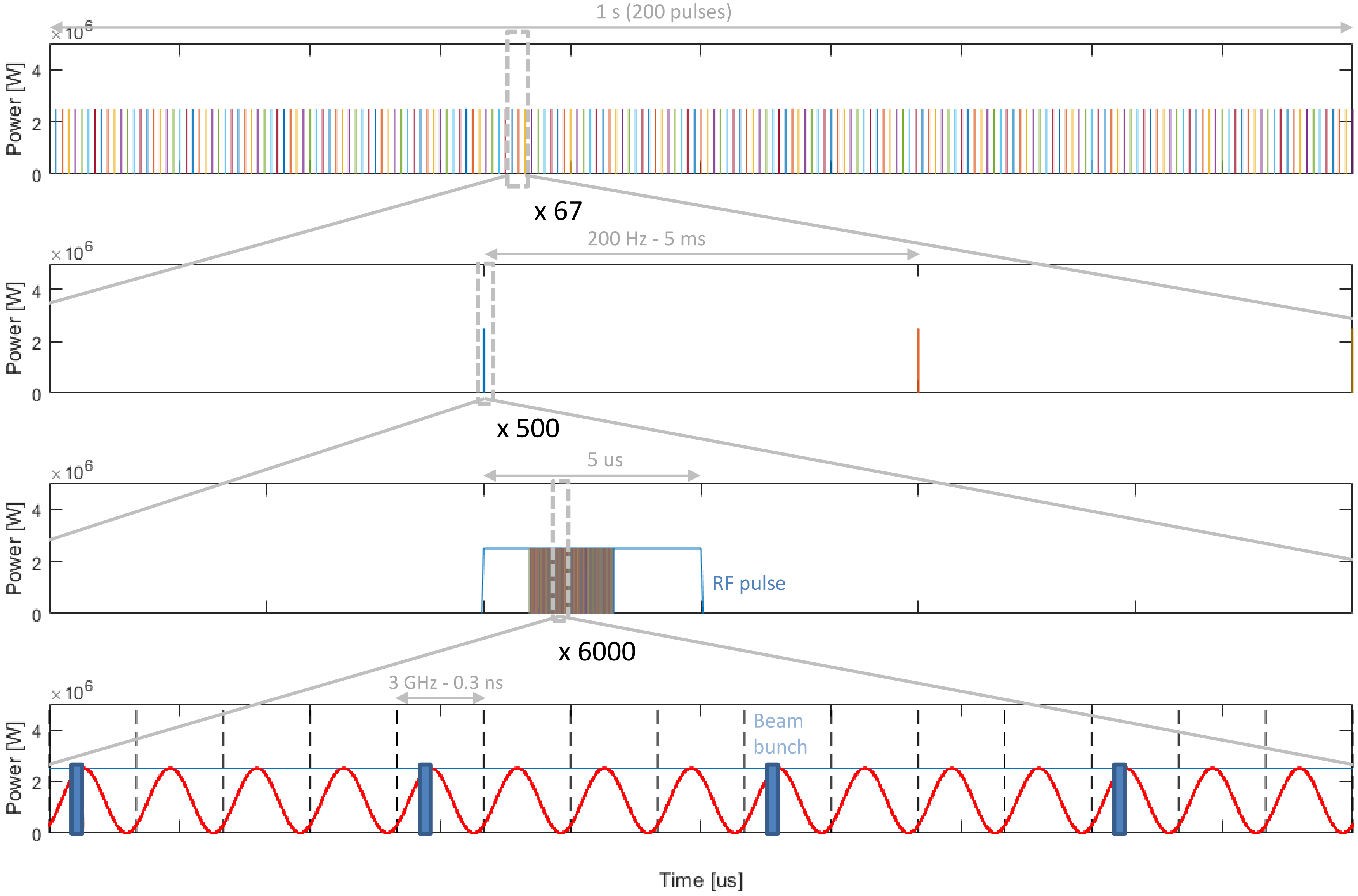


LIGHT features for proton therapy

- Active energy modulation → no absorber and degrader
- Pulsed beam at 200 Hz → intensity and energy modulation in 5 ms
- Small beam emittance → small magnets aperture
- Almost no losses! → reduced shielding

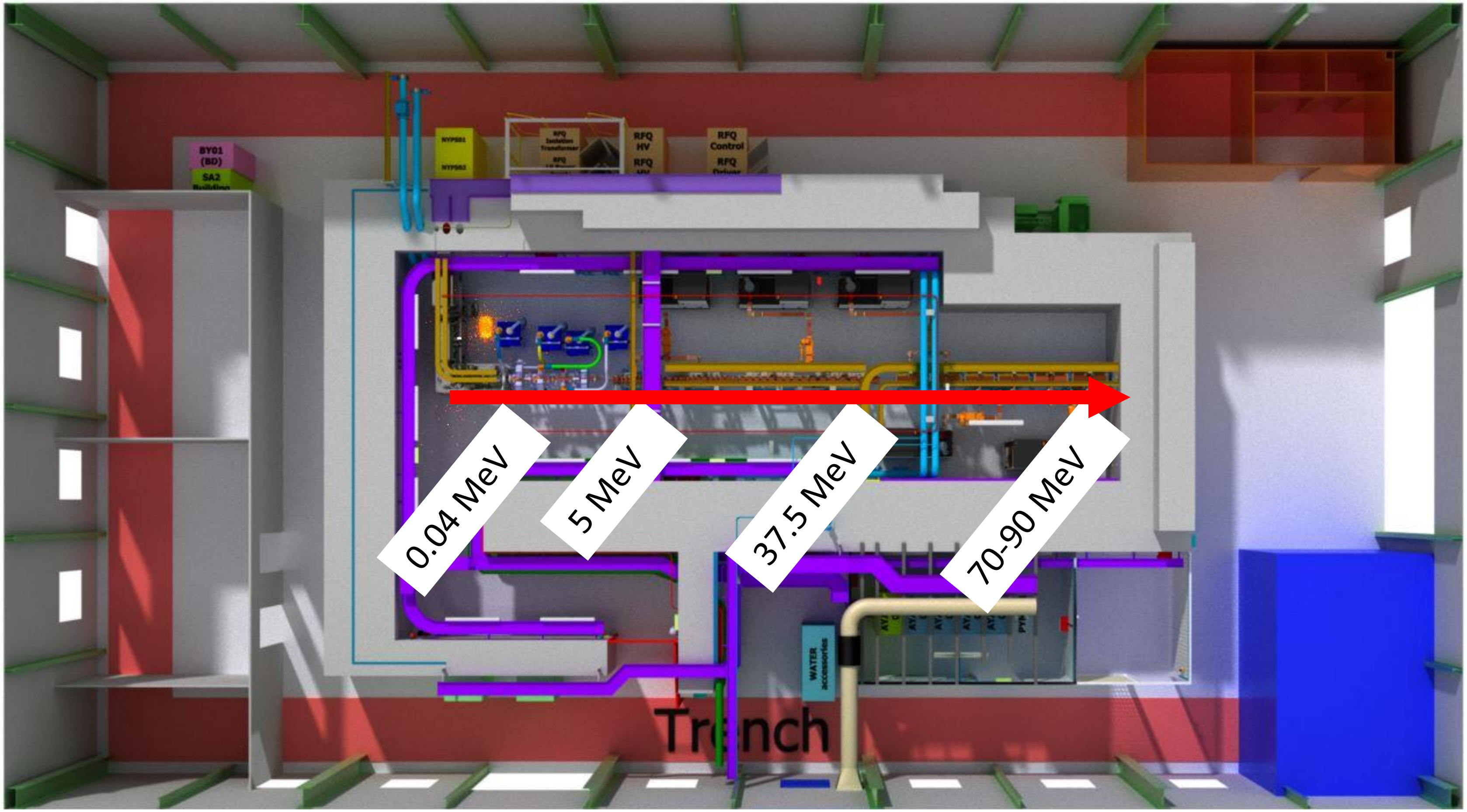
→ **beam suited for 3D spot scanning**

LIGHT - Pulsed beam structure



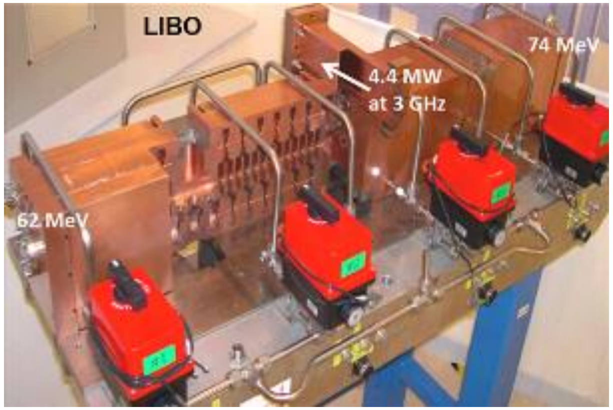
Commissioning of LIGHT @ CERN

source	RFQ	SCDTL1	SCDTL 2-3		SCDTL4	CCL1-2	CCL3-6
40 keV	5 MeV	7.5 MeV	16 MeV	26.5 MeV	37.5 MeV	52 MeV	70-90 MeV

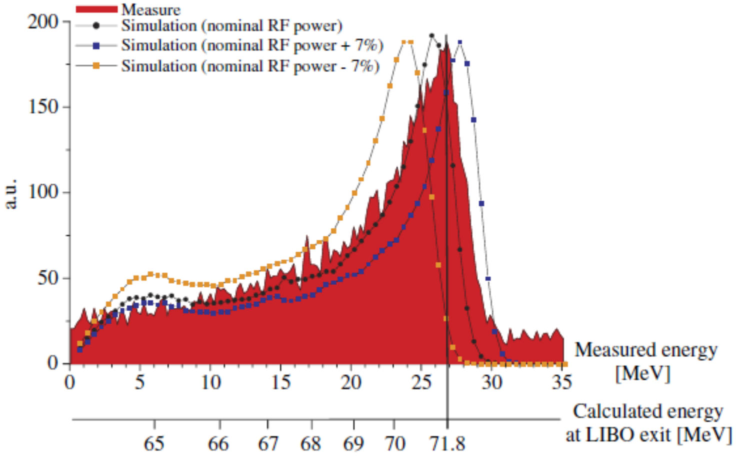


LIGHT background: the LIBO prototype

- LIBO (Linac Booster) prototype by TERA-CERN-INFN
  - Built in 1999-2000
  - First proof of principle
  - Tested with beam in LNS (Catania)



Amaldi et al., NIM A(521), 512-529, 2004

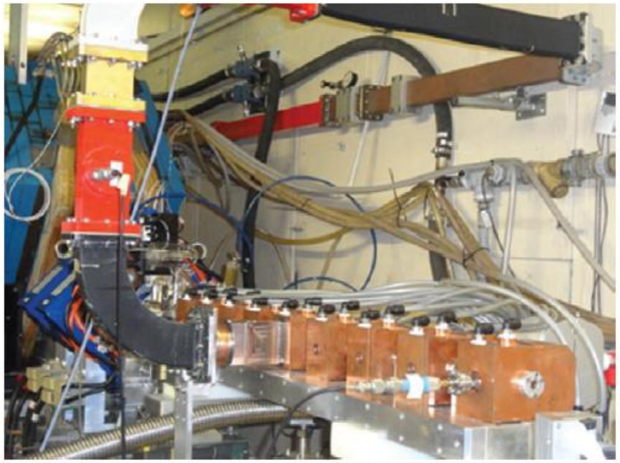


De Martinis et al., NIM A(681), 10-15, 2012

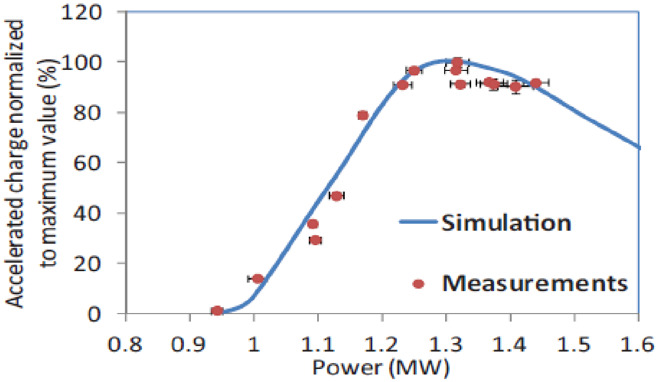
LIGHT background: the first unit by ADAM

- First Unit of ADAM (2009)
  - first industrial 3 GHz linac unit for PT
  - Optimized for industrial production

LIGHT background: acceleration in SCDTL at ENEA



- First Unit of SCDTL built and tested at ENEA
  - SCDTL designed by L. Picardi (ENEA)
  - Tested with beam at ENEA Frascati (Italy)



C. Ronsivalle et al., EPL, **111** (2015) 14002

Beam Delivery

Delivery of protons to patient

Delivery techniques on the market today

- **Passive scattering**: scattering through a material to spread the beam over tumor (until a few years ago: the only method used)
  - High dose delivered outside target
  - Individual scattering device for each patient
  - Neutron background
  - “Old technology” (…but still in use in many centers!)

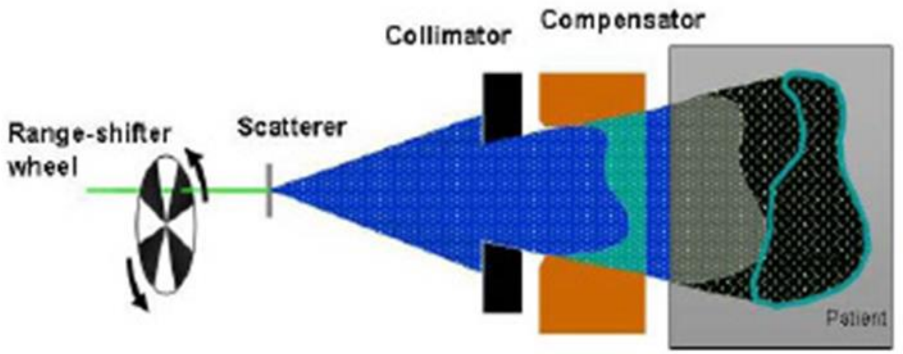


Figure-2a. Diagrammatic representation of a typical passive scattering proton beam delivery system.

Spot Scanning

Second delivery technique:

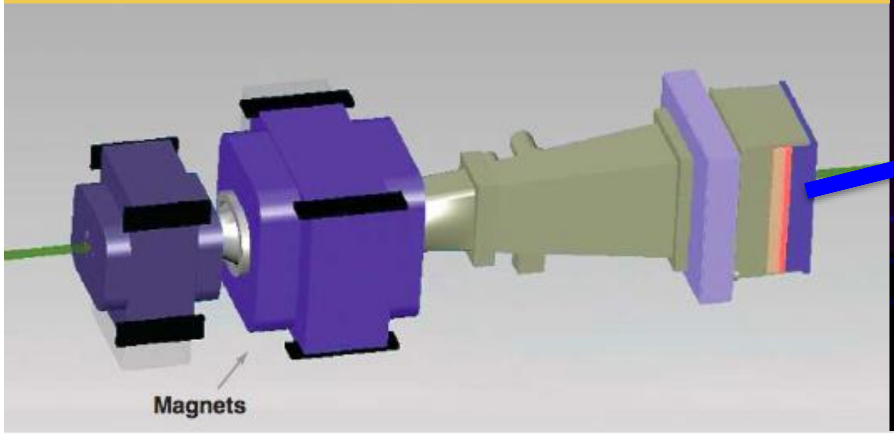
Spot scanning: beam is steered with magnets towards the target position

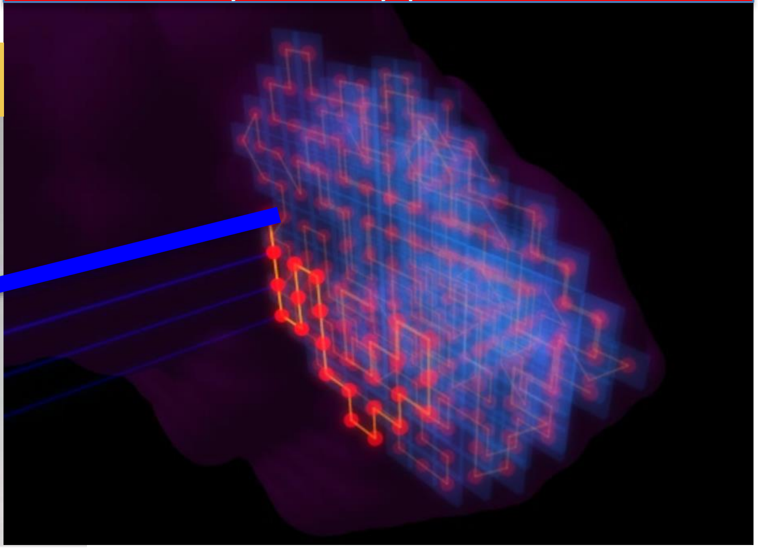
- \+ More conformal dose
- \+ No individual hardware
- \+ Less neutrons
- \+ **Modern state-of the art technique**

Strong points of LIGHT system:

- XY position accuracy < 0.5 mm
- We can change energy, position and intensity of every pulse

Spot scanning is chosen for LIGHT





Pencil Beam

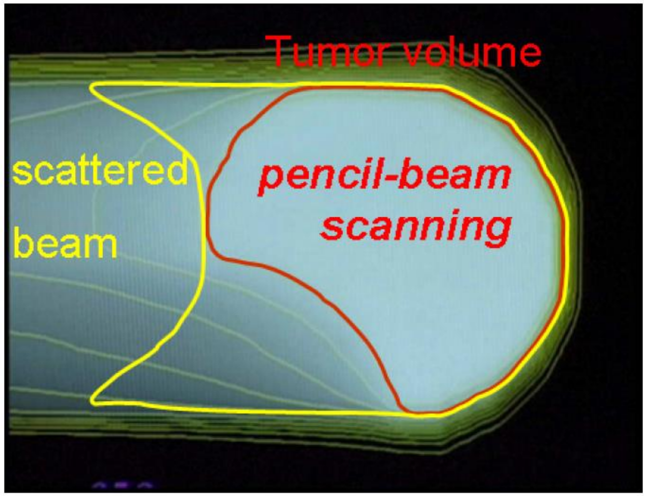


Fig. 17. Comparison of the dose distributions for a scattered beam (the light curve represents the 95% isodose line) and one obtained with pencil beam scanning (gray value; the dark curve is the 95% isodose line and coincides with the target volume).

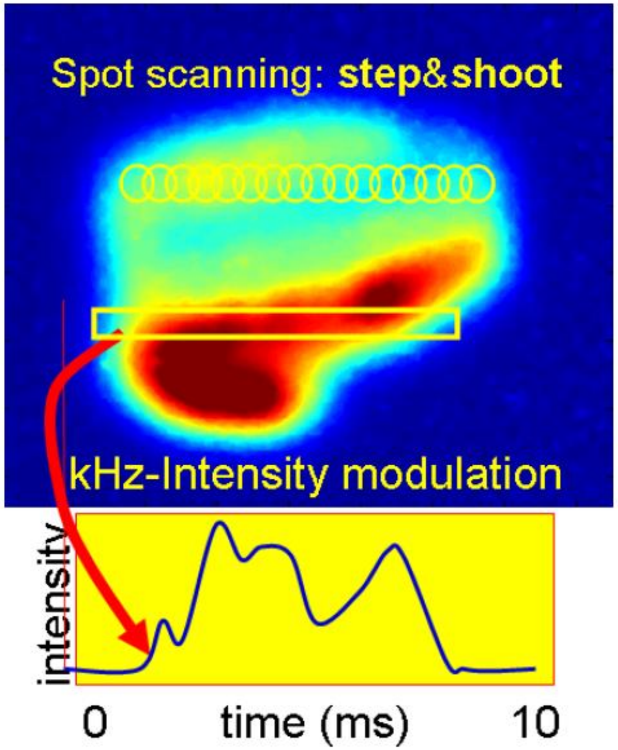


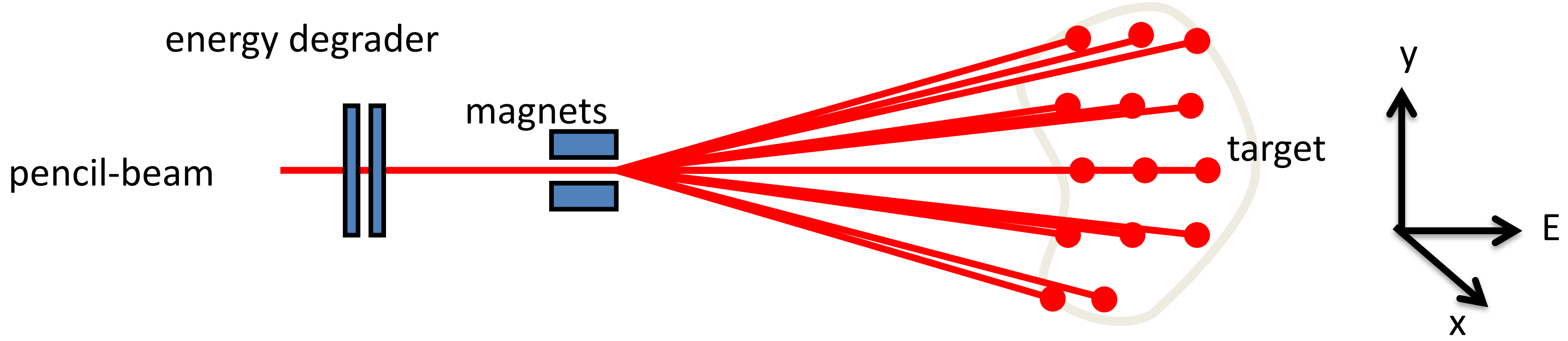
Fig. 18. Dose application with pencil beam scanning by means of spot scanning (top row of circles) and line scanning, where the beam intensity (curve at bottom) varies in time during the continuous sweep made by the scanning magnet.

J.M.Schippers: "Beam Delivery Systems for Particle Radiation Therapy: Current Status and Recent Developments": Review of Avvelerator Science and Technology Vol.2 (2009) 179-200

Treatment Plan with Spots (PBS)

Definition of pulse characteristics for the accelerator

What is a spot (=pencil beam)?



Pencil beam= small proton beam

Spot (pulse) parameters:

- x-value
- y-value
- Energy E
- Charge Q (determines the dose)
- Width sigma
- Spacing between them (lateral and longitudinal)

A treatment planning system calculates the best list of spots

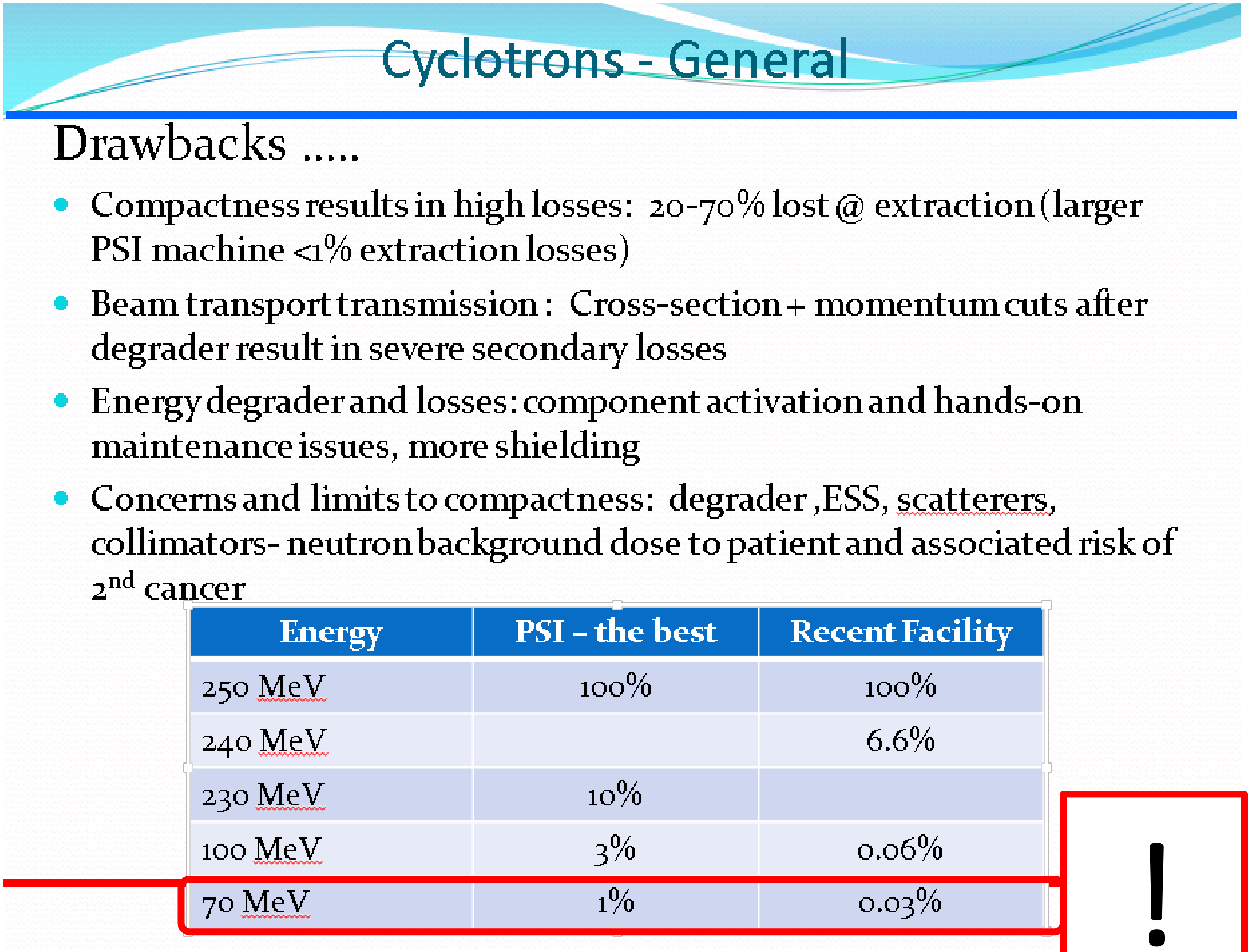
Particle Losses and Radiation

Fixed and Variable Energy Accelerators

In fixed energy accelerators, the energy is reduced by placing an energy absorber (ESS) in the path of the beam. This ESS

- Reduces the energy
- Reduces the number of protons dramatically (mitigated by increasing the number of protons accelerated)
- Causes local increased radiation (mitigated by locally enhanced shielding)
- Increases the beam size (mitigated by collimation)

Current (Protons) Needed with Cyclotrons



Cyclotrons - General

Drawbacks .....

- Compactness results in high losses: 20-70% lost @ extraction (larger PSI machine <1% extraction losses)
- Beam transport transmission: Cross-section + momentum cuts after degrader result in severe secondary losses
- Energy degrader and losses: component activation and hands-on maintenance issues, more shielding
- Concerns and limits to compactness: degrader, ESS, scatterers, collimators- neutron background dose to patient and associated risk of 2nd cancer

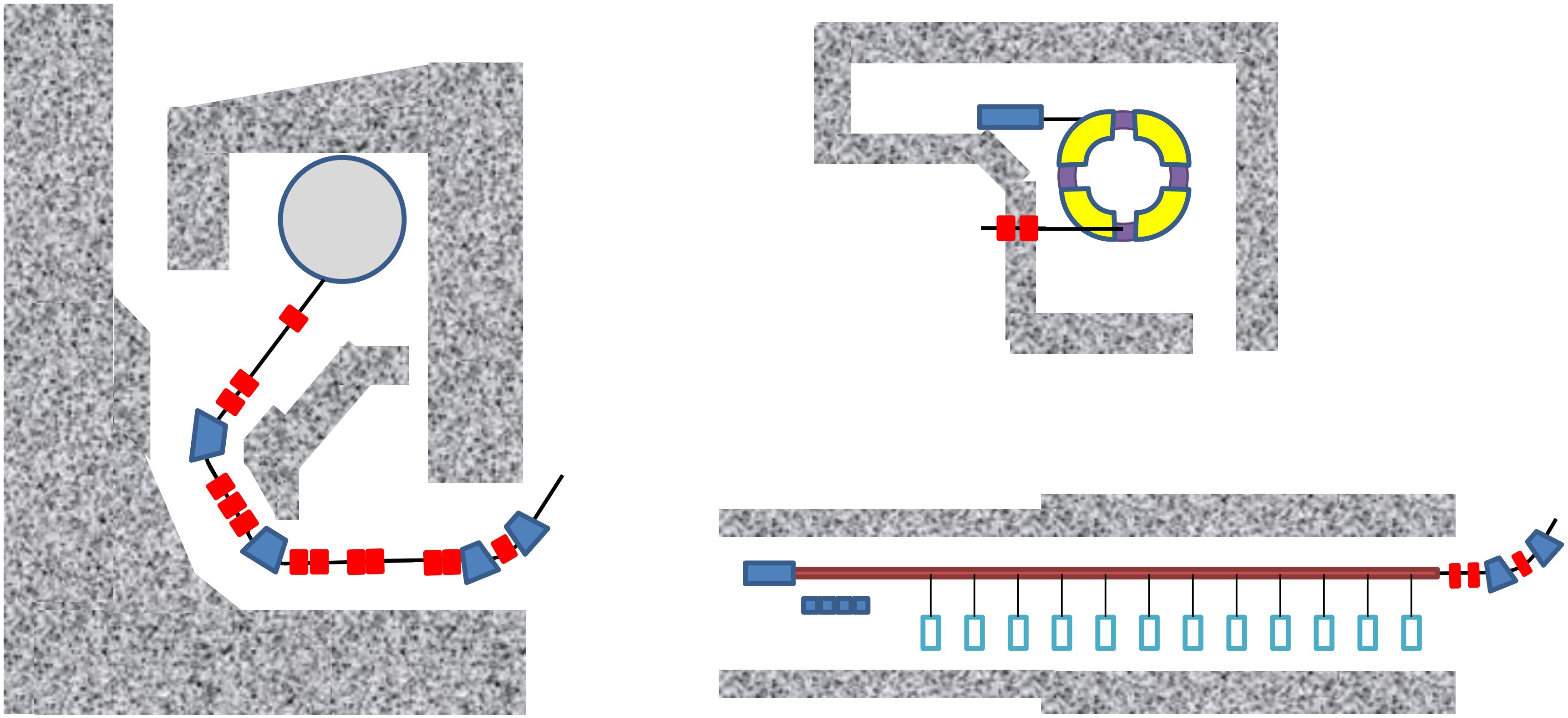
Energy	PSI – the best	Recent Facility
250 MeV	100%	100%
240 MeV		6.6%
230 MeV	10%	
100 MeV	3%	0.06%
70 MeV	1%	0.03%

!

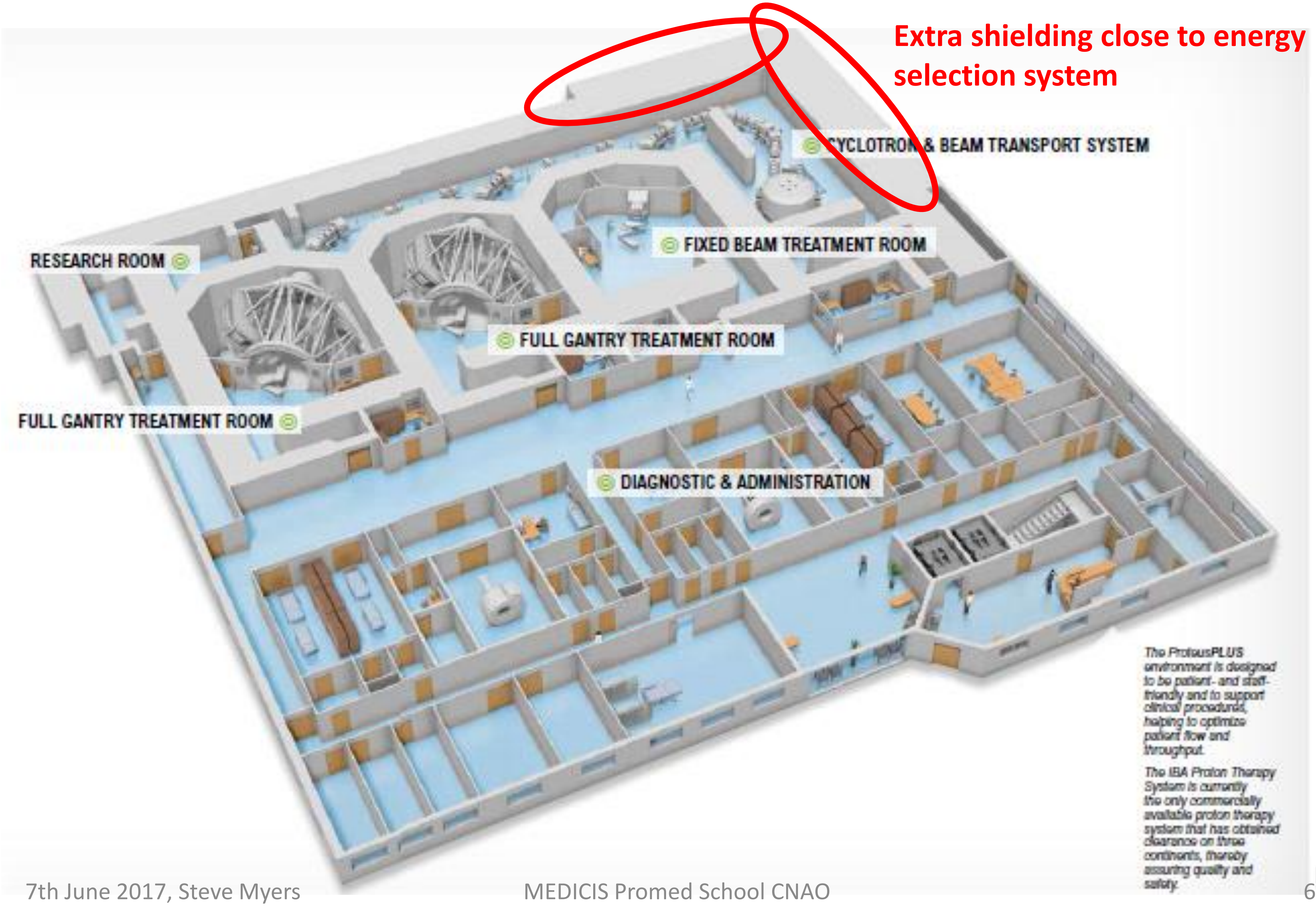
[Johnstone] Medical Accelerator Work in the U.S. – C. Johnstone 13.01.2012 - Proton Accelerators for Science and Innovation Workshop – Fermilab

What About Shielding ?

Example of shielding impact on the foot-print (only accelerator is considered, since treatment room will be all the same independent of accelerator)



Example IBA proteusPLUS with Cyclotron



Extra shielding close to energy selection system

The ProteusPLUS environment is designed to be patient- and staff-friendly and to support clinical procedures, helping to optimize patient flow and throughput.

The IBA Proton Therapy System is currently the only commercially available proton therapy system that has obtained clearance on three continents, thereby assuring quality and safety.

Beam Transport

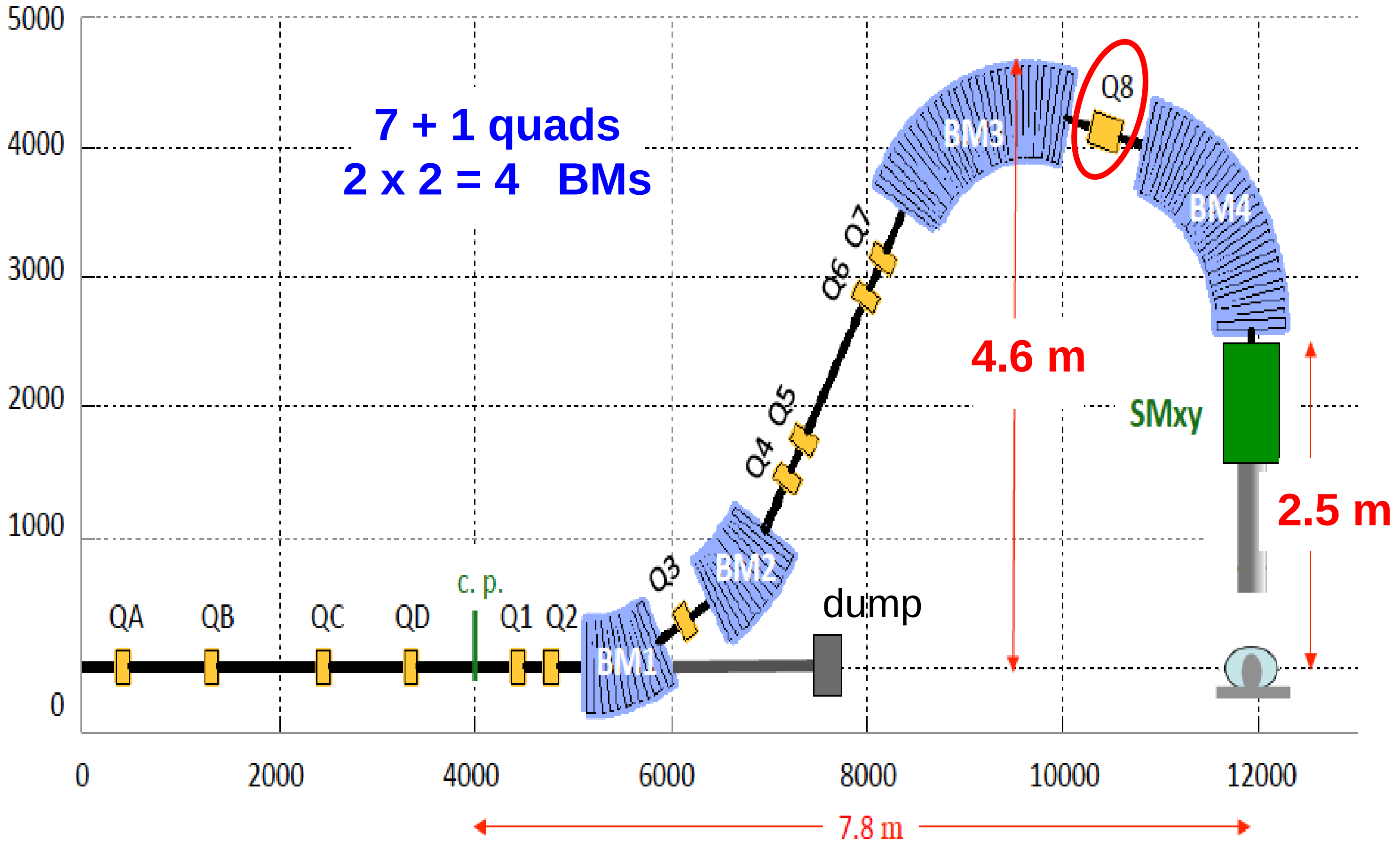
Beam Transport from Accelerator to Treatment Room

- Charged particles can be steered and focused by electro-magnets
- In “conventional” beam transfer lines there is a one-to-one relationship between the beam energy and the magnetic field (spectrometer)
- Hence fast changes in beam energy require fast changes in magnetic fields (magnetic hysterisis and power converters)

Gantry

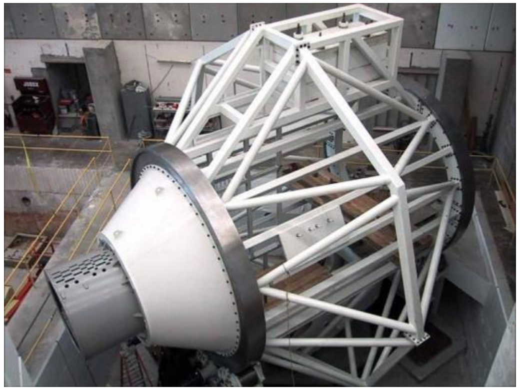
- Support structure for a beam transfer line which allows rotation of the beam around the patient. Allows improved distribution of dose.
  - Mechanical movement (electrical, vacuum, magnets etc)
  - Optics stability for all rotational angles
  - Matching beam properties to beam delivery system (x-y scanning magnet etc)

Example Gantry (TERA design)



7 + 1 quads
2 x 2 = 4 BMs

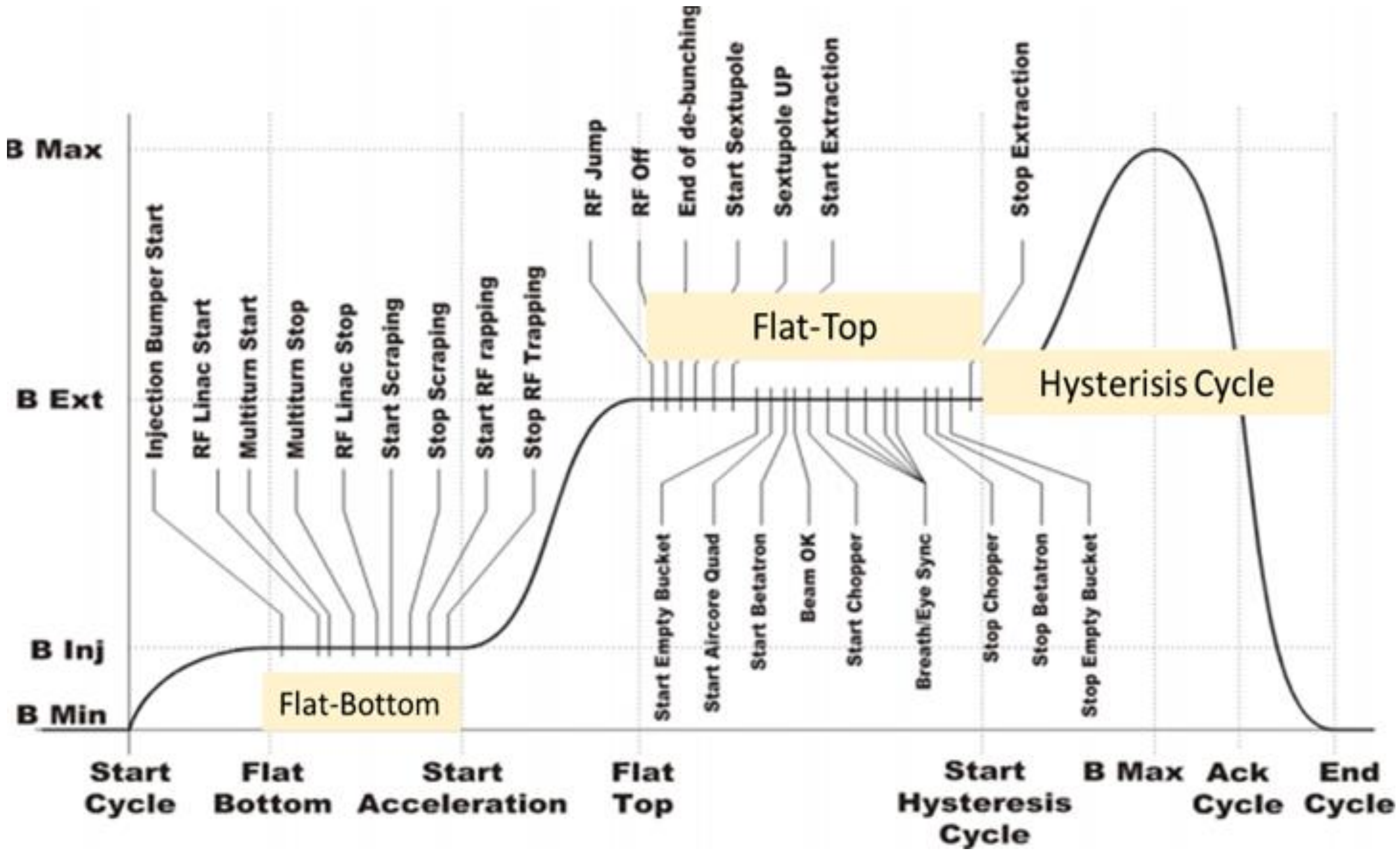
The ½ gantry



- Popularized (PSI …) to
  - minimize bulk (cost),
  - decrease vault size
  - increase floor space
- Requires rotating the patient by 180 in about 35% of sessions
- Smaller emittance decreases mass very significantly
  - "Old" synchrotron gantries (>100 ton) & required counter weight in a 360 configuration

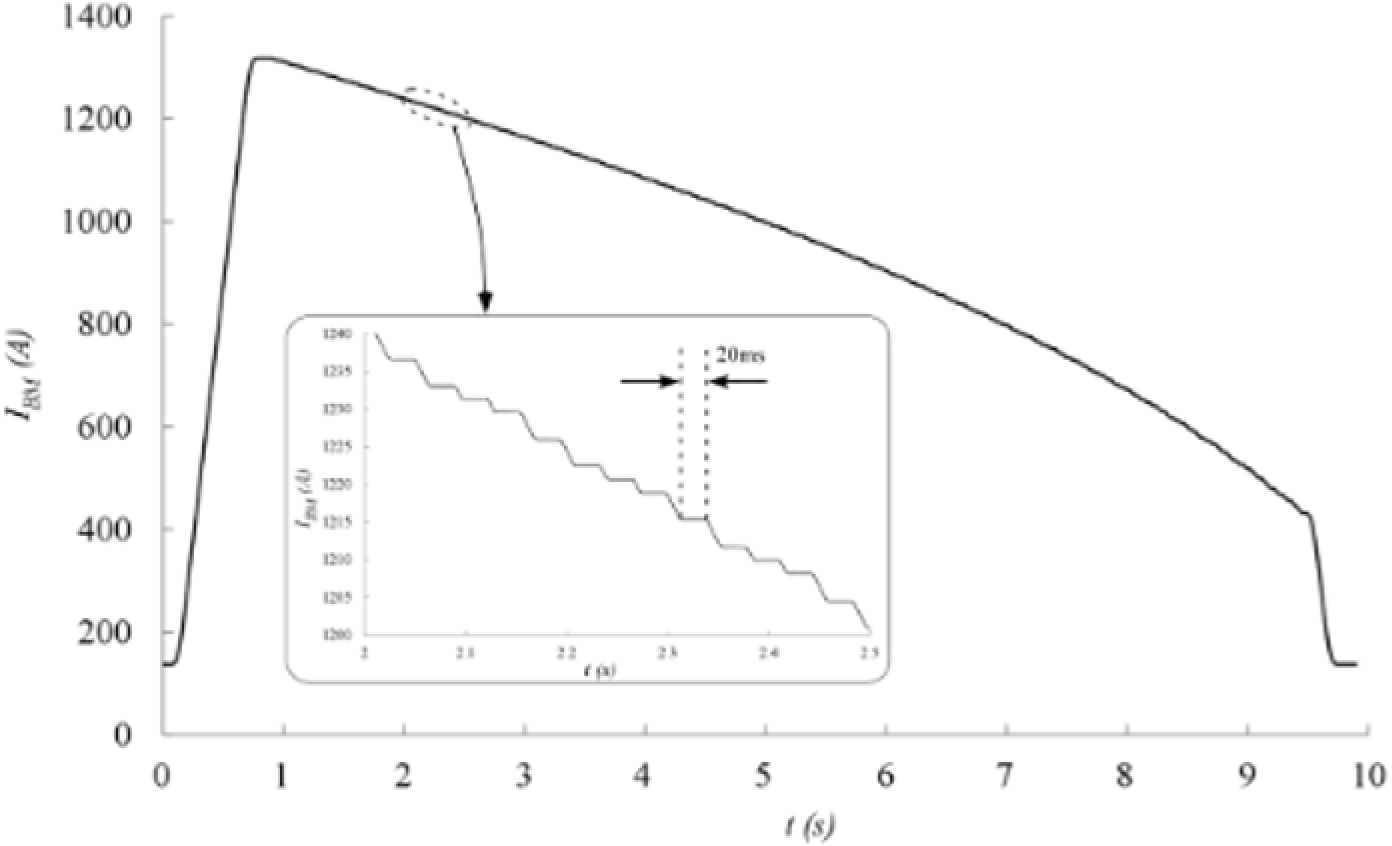
Beam Energy Variation

Variable Energy in a Synchrotron at Flat Top

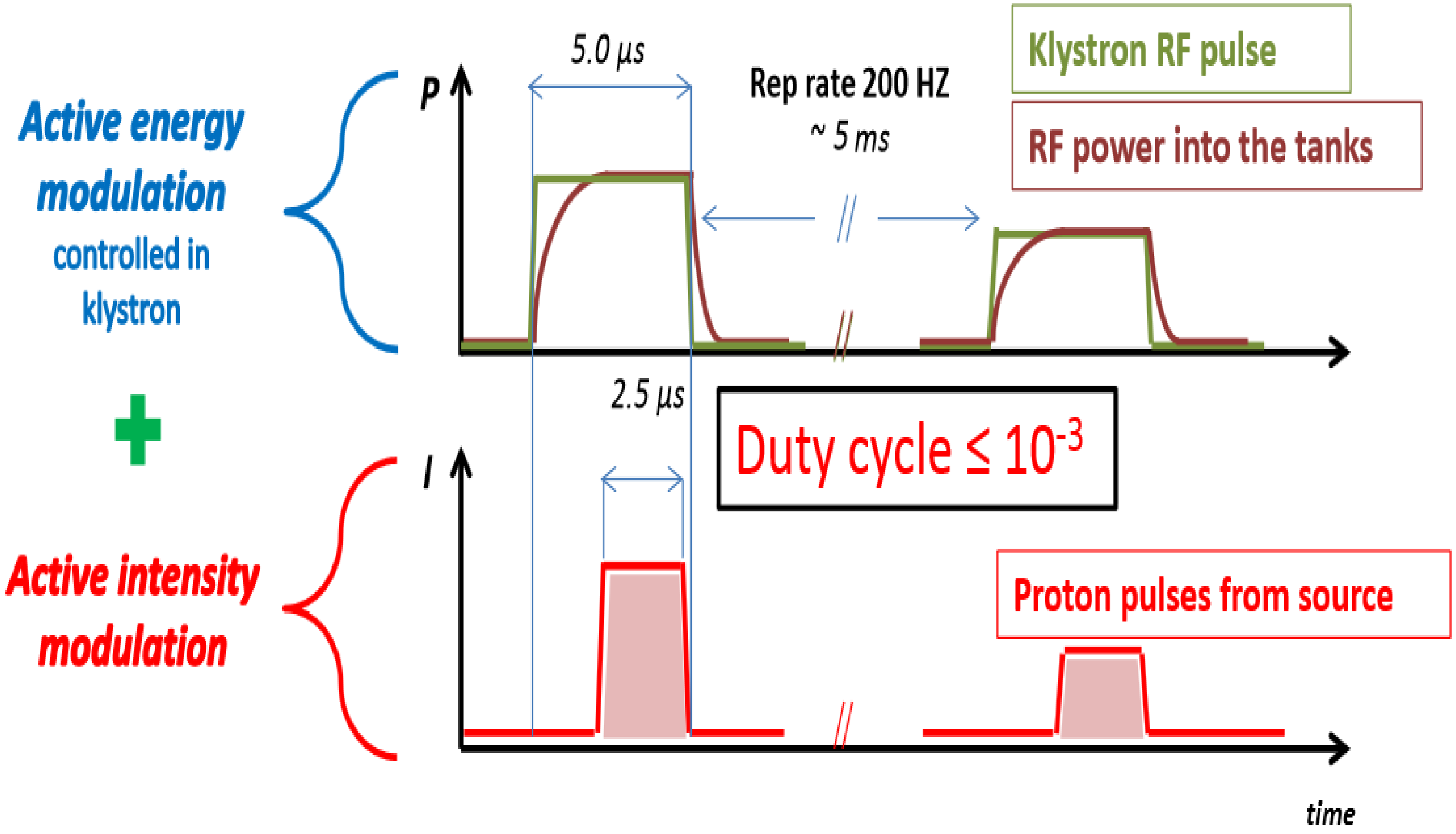


Synchrotrons; Energy Variation with multi flat-top extractions

- *(NIRS synchrotron). [NIRSGantry2014]*



Linac Active Energy and Intensity Modulation



Active energy modulation controlled in klystron

+

Active intensity modulation

Klystron RF pulse

RF power into the tanks

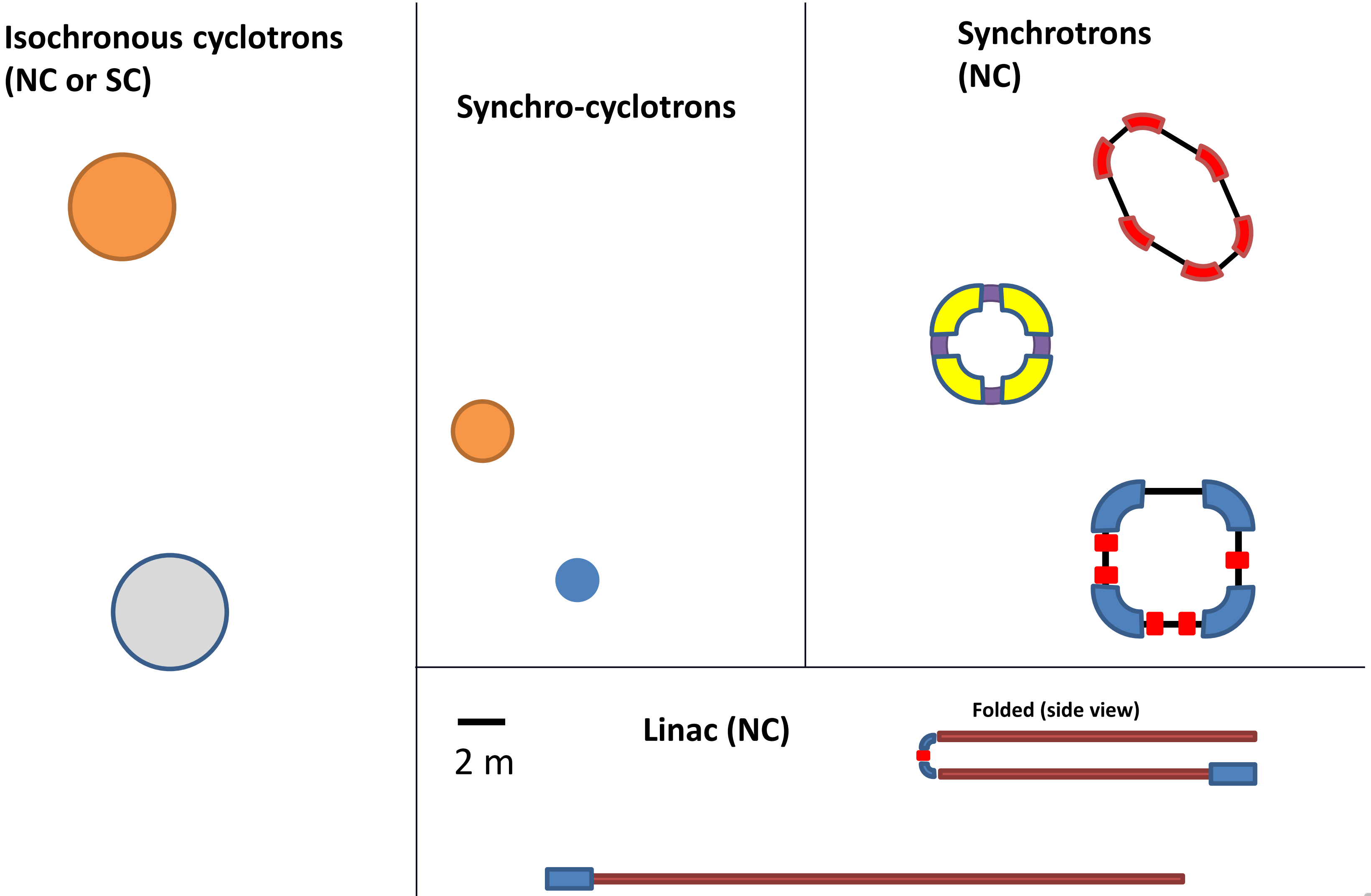
Duty cycle ≤ 10^{-3}

Proton pulses from source

http://indico.hep.manchester.ac.uk/getFile.py/access?contribId=22&resId=0&materialId=slides&confId=4226\

Footprint, modularity and Flexibility

Relative Footprints Accelerator Only



Isochronous cyclotrons (NC or SC)

Synchro-cyclotrons

Synchrotrons (NC)

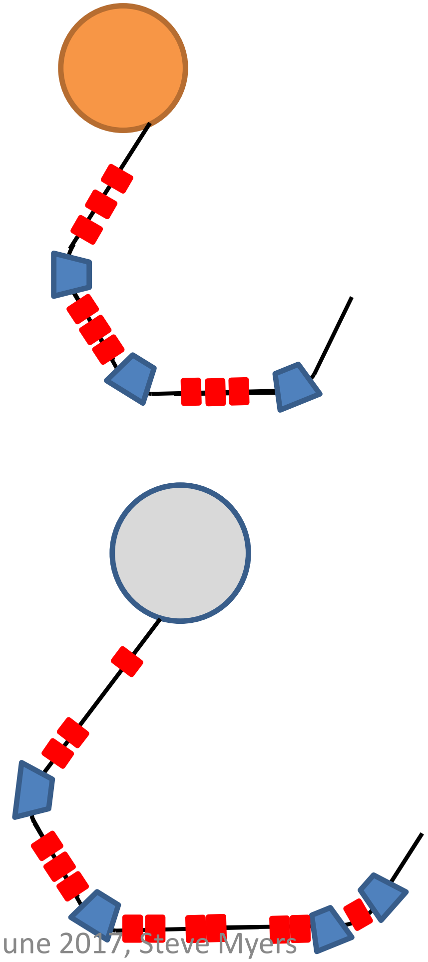
2 m

Linac (NC)

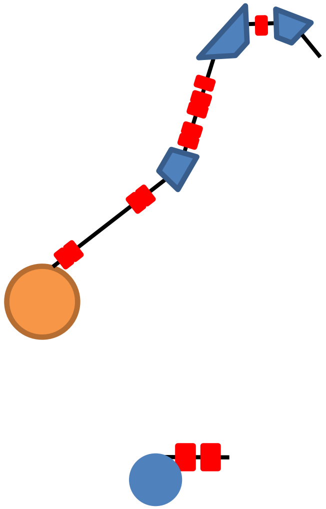
Folded (side view)

Real Size (with ESS, Inj., Extraction, Klystrons)

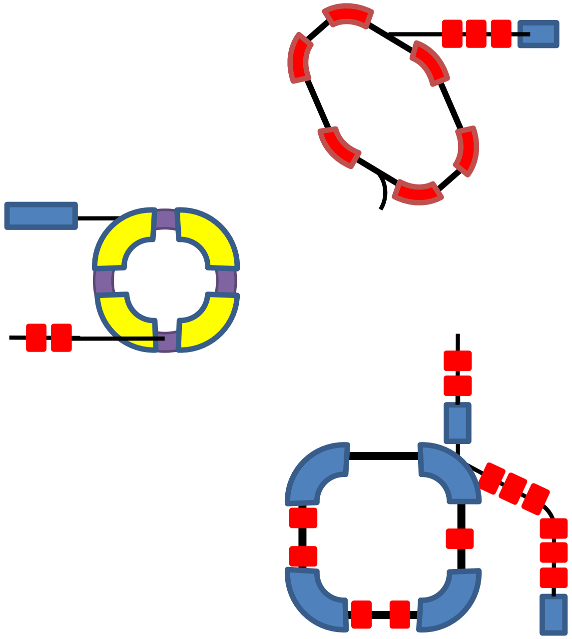
Isochronous cyclotrons (NC or SC)



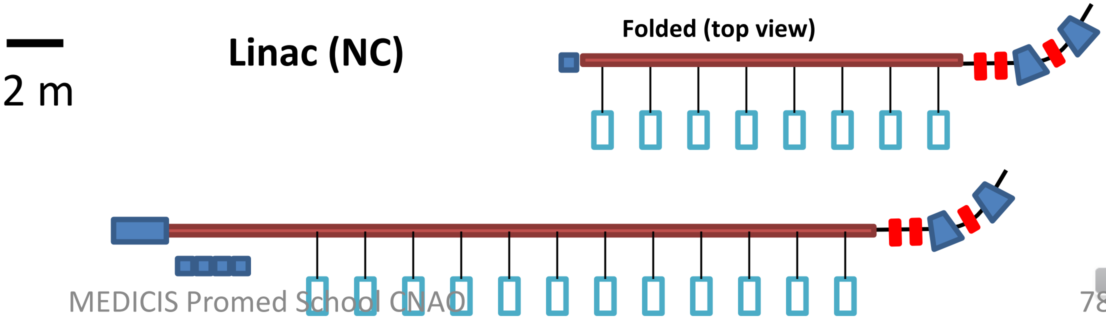
Synchro-cyclotrons



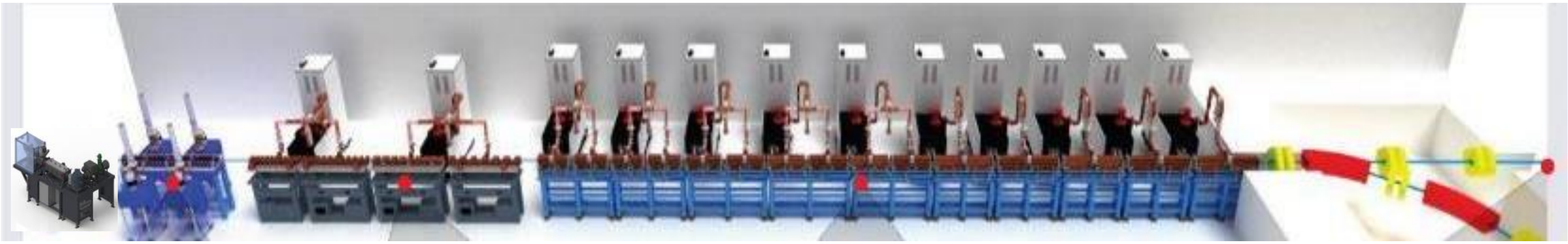
Synchrotrons (NC)

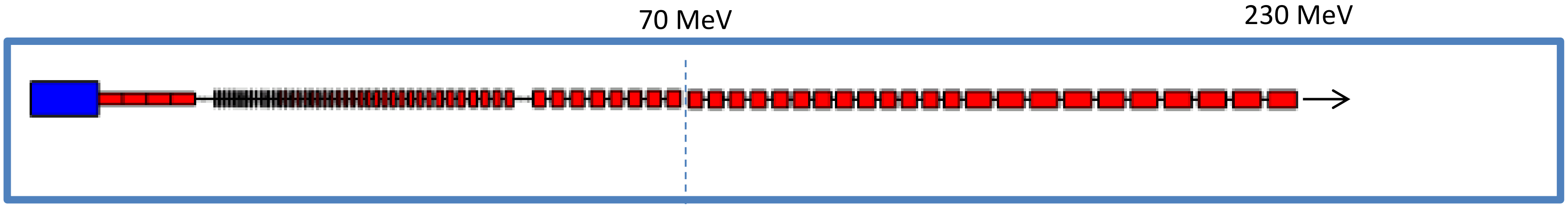


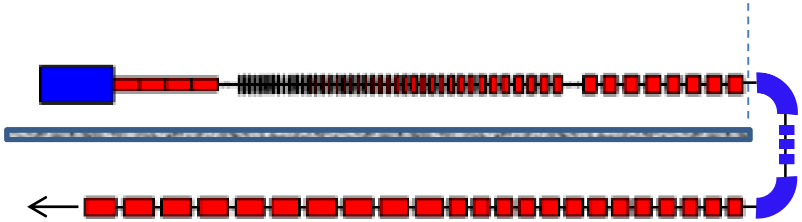
Linac (NC)



Examples of Linac ‘Flexibility’







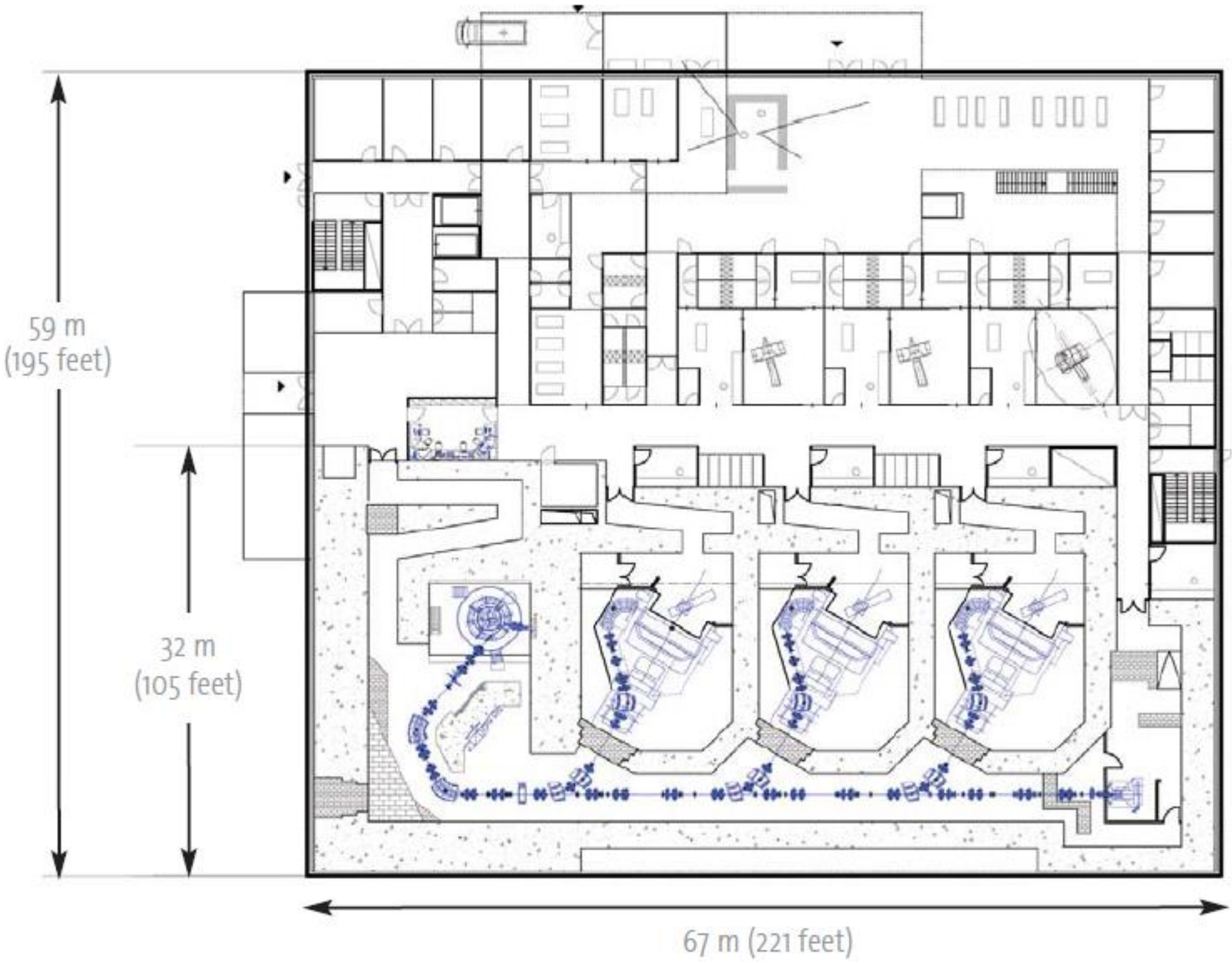
Fixed energy bend (70 MeV)

Variable energy beam (70-230 MeV)

Reduced foot-print

Number of Treatment Rooms

Multi-room Facility... 3-4-5 Rooms?



Shrink Size of Cyclotrons → Super-conducting

Shrink size accelerator – superconducting cyclo

Varian
SC isochronous cyclotron

MevIon TriNiobium Core
SC synchrocyclotron

IBA S2C2
SC synchrocyclotron

http://www.aapm.org/meetings/2013AM/documents/Sumitomo.pdf

Example of Compact Synchrotron

Linear Accelerator and Compact Synchroton

Radiance 330 Proton Therapy System – ProTom International

<u>Linear Accelerator RFQ Injector</u>: Energy ~1.6 MeV. <u>Compact Synchrotron</u>: Low-cost, novel high-energy synchrotron. Energies from <70 MeV to 250 MeV for therapy applications, and up to 330 MeV for proton imaging techniques. Proton Beam Intensity: 2 Gy/liter/minute dose rate. ~ 1 E(10) protons/cycle. Extracted beam emittance between 1.0 x10^{-6} and 2.5 x10^{-6} m-rad. Energy and Momentum Spread: $\Delta E/E \leq 0.2\%$; $\Delta p/p \sim 0.0012$ (rms). Diameter = 16 ft.

Diameter	4.8 m
Energies for therapy	70 - 250 MeV
… for proton imaging	up to 330 MeV
Dose rate	2 Gy/liter/minute
Protons per pulse	~ $1\text{x}10^{10}$
Extracted beam emittance	1.0 x10^{-6} to 2.5 x10^{-6} m-rad

29 | VARIAN PARTICLE THERAPY

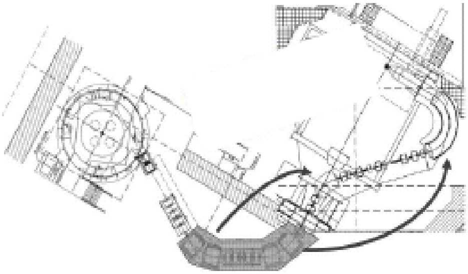
VARIAN medical systems

[Schillo IPAC2014] http://accelconf.web.cern.ch/accelconf/IPAC2014/talks/weib01_talk.pdf

Multi-room vs Single-room Facilities?

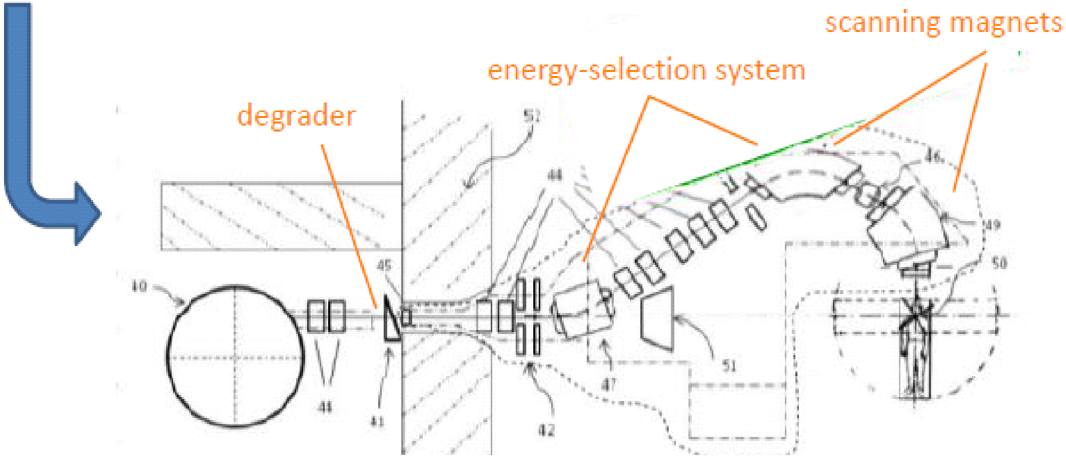
- Single room facilities allow:
  - Reduced investment cost
  - Spread of proton therapy in smaller centres
- Cost/room is slightly higher
- In some cases adding second «single room» afterward to increase patient throughput

Example from multi-room to single-room



IBA Proteus One:

- incorporate energy-selection system into gantry
- move scanning magnets from nozzle to gantry
- conventional to superconducting cyclotron
- limited-angle gantry



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Summary and Conclusions

↓Type/Properties→	Trajectory	RF frequency	Magnetic field	Time structure
Cyclotron	Spiraling	Fixed in time	1 dipole – fixed in time	CW (with RF micro-bunch structure)
Synchrotron	Circular	Varying during acceleration	Several dipoles – increasing in time	CW during spills (limited in time by storage capacity)
Synchro-cyclotron	Spiraling	Decreasing during acceleration	1 dipole – fixed in time	Pulsed
Linac	Linear	Fixed in time	Not needed! (but several high power RF klystrons!)	Pulsed at low duty cycle (10^{-3})

Fundamental Parameters due to TYPE of Accelerator

Accelerator type → Parameters ↓	**Cyclotron**	**Synchro-cyclotron**	**Synchrotron**	**Linac**
Beam Emittances (size) [pi-mm-mrad]	3.0-9.0 (before ESS)	Collimators 3.0-6.0 Radial / 3.0-4.0 Vertical	1.0-2.5	**0.25**
Energy modulation (variation)	Only with degrader-absorbers	Only with degrader-absorbers	Possible, but slow (now multi flat-top extraction)	**By LLRF control**
Modularity	1 module (two half dees), internal source, BUT ESS	1-2 large units	Several magnets + 1 RF cavity + injection linac	12 RF units + ~ 80 PMQs
Proton losses, activation	High in ESS (1/E dependent)	High in degrader	Small losses in extraction	**Low**
Beam time structure	CW	pulsed 1%D.C.	CW during spills	pulsed 0.1%D.C.

Clinical Efficiency Related Parameters

Accelerator type → Parameters ↓	Cyclotron	Synchro-cyclotron	Synchrotron	Linac
Change of energy (speed ms)	80 to 2100	50 to 2000	2000 to 3000	**5**
"spot" size regulation (σ in air at 230 MeV)	3-10 mm	3 - 8 mm to scatter	Horizontal plane needs 3.0-6.0 mm	< 3, 6 mm
"Spot Dose" regulation (speed)	By timing spent in each voxel	Pulse by pulse, 6e8-1e12 pps	By timing the end of extraction	Pulse by pulse, 2e8-1e11 pps

Financial Parameters

Accelerator type → Parameters ↓	Cyclotron	Synchro-cyclotron	Synchrotron	Linac
Construction costs (comments)	Shielding and vault opening from roof	Shielding and vault opening from roof	Big surface hall	Corridor-like(small amount of shielding close to linac)
Accelerator electrical power	320 – 1800 kW	**100 kW** (for superconducting)	100 kW (to 3MW)	~450 kW
Dismantling or re-location costs	ESS degrader activation	Activated degrader	Activated extraction septum	**Almost no losses + low duty cycle**
Requirements of gantry	80 -- 280 tons 7.2 -- 11.5 m diameter	100 -- 120 tons 7.6 -- 9 m diameter	~125 tons, 8 m diameter	20 – 35 tons (tiny beam size →Small magnets apertures)
System foot print	4 rooms facility: 59x67 m^2 1672 -- 4000 m^2	single room facilities **110** -- 380 m^2	See diagram above	80 -140 m2

Summary

- The major challenges for particle (proton) therapy
  - Overall system must be affordable.
    - Ideally come down to the price per patient for the top of the range conventional radiotherapy (IMRT)
    - Not only capital cost, but also operational costs and decommissioning costs
  - Spot placement must be precise in 3 dimensions
    - Eventually image guided for movement of tumours
    - Adaptive treatment for volumetric rescanning (increases precision)
    - Fast controlled depth variation: energy modulation of beam
    - Gantry size and cost must be reduced
  - Impervious to Error
    - Integrated system design

Thank you for your attention