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Cyclotrons and their Applications
Zurich, 12th September 2016

Coupling of Cyclotrons to Linacs for Medical Applications

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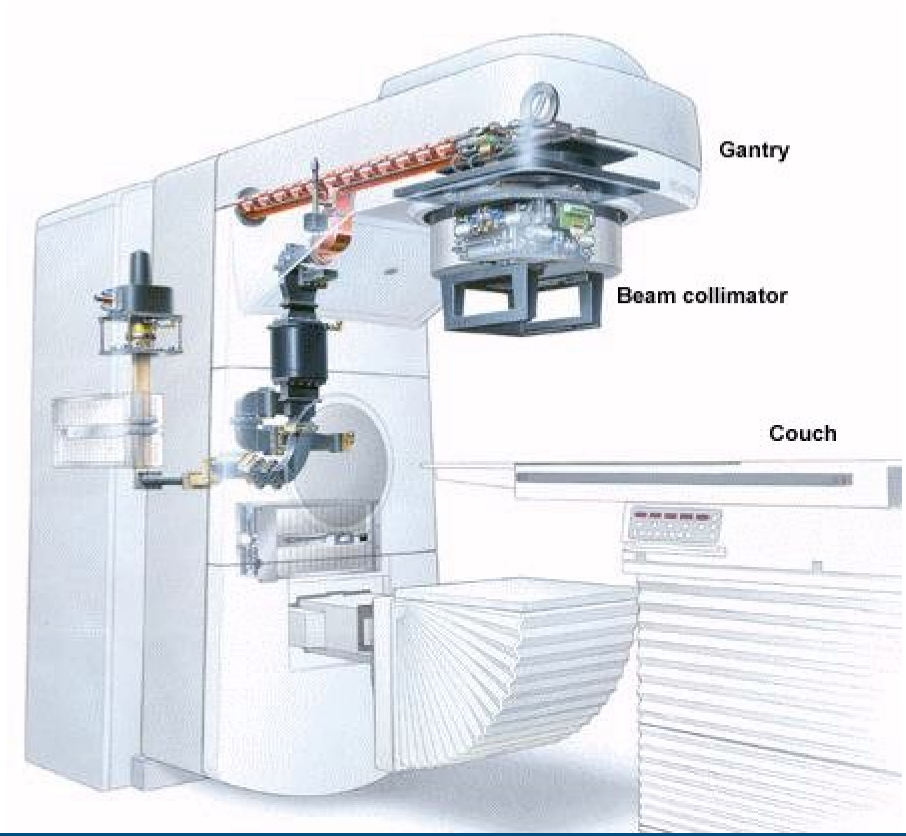
TERA Foundation, Novara, Italy

<u>Disclaimer</u>: precise references of all figures, tables and projects are in the proceedings

Accelerators are fundamental in modern Medecine

- 50% of accelerators used for **biomedical** applications

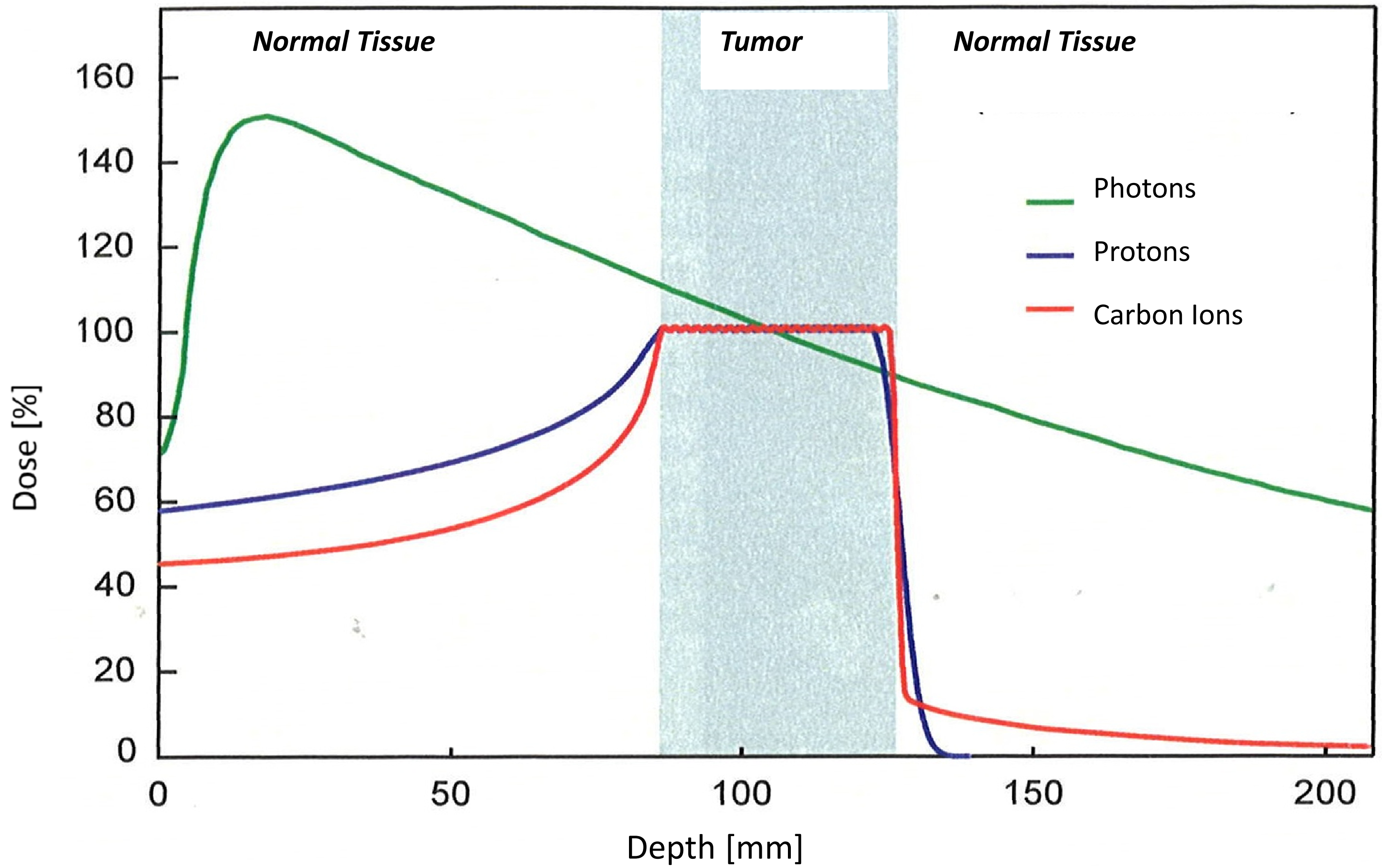
- 80 % of those are used in **radiotherapy** of solid tumours



- **Conventional radiotherapy** uses 1.5 m long linear accelerators (**linacs**)

- Beams of radiation (photons/ **X-rays**) are used to **destroy tumor** cells, while **sparing** the surrounding **healthy tissues**

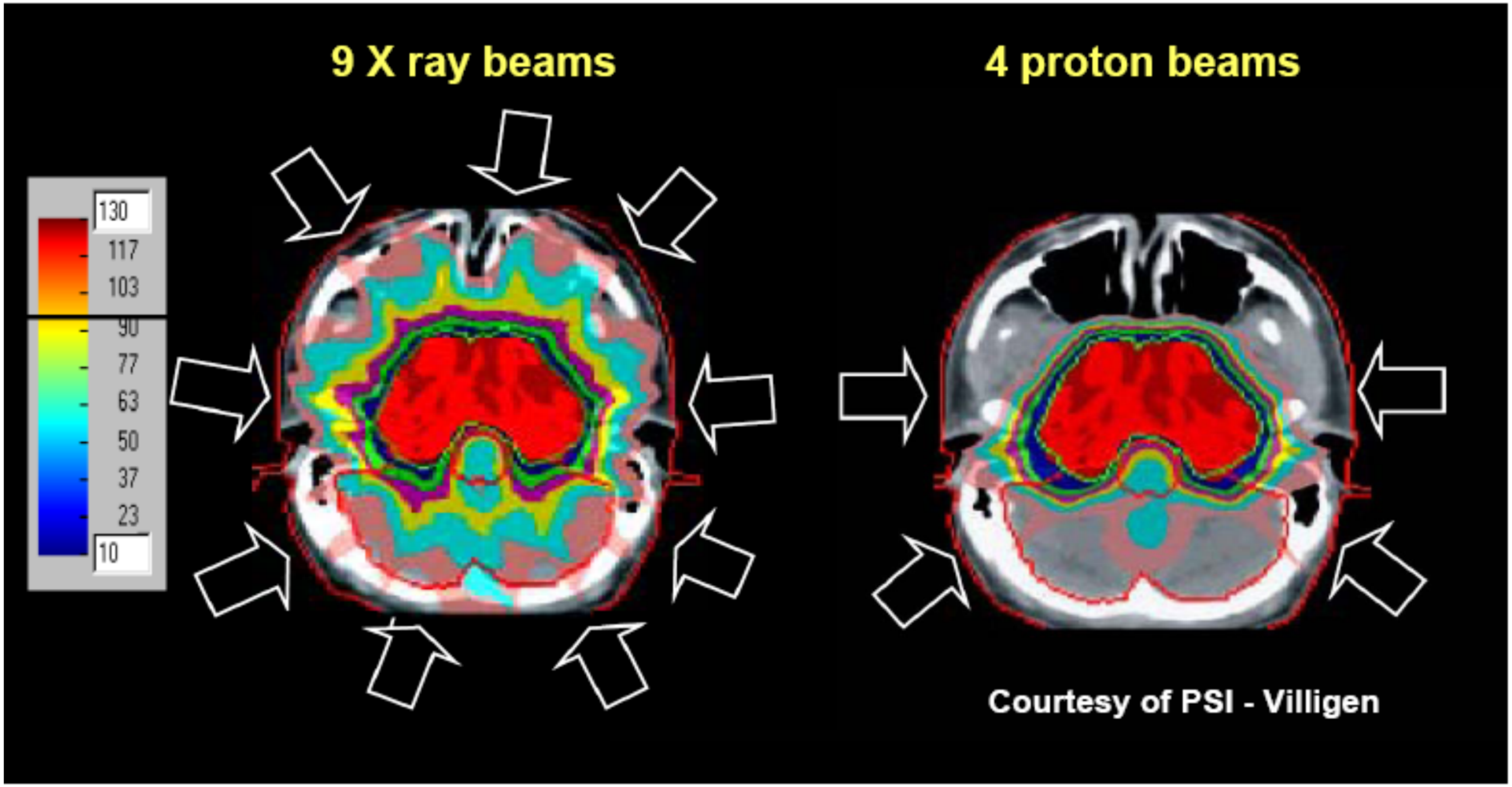
Hadrontherapy limits entrance/exit doses to healthy tissues



- **Protons** and **carbon ions** present **physical advantages** over photons and are effective in treatment of **deep-seated tumors**

- Carbon ions are used in the rare cases of **radioresistant tumors**

Advantages of hadrontherapy come at a cost

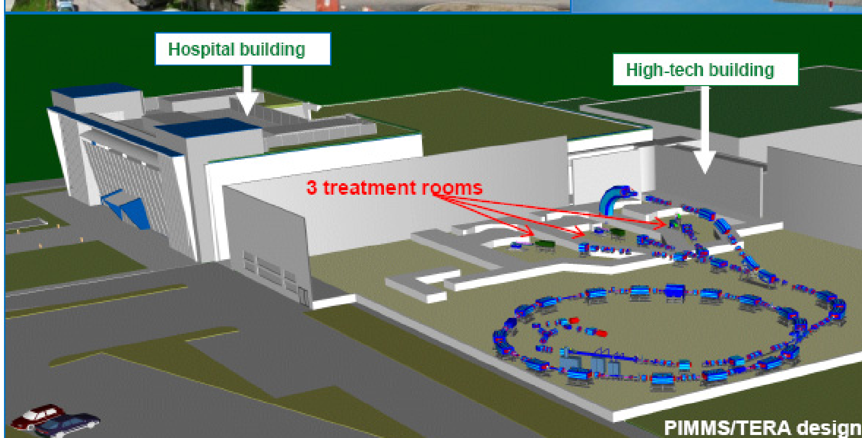


• 120k proton and 20k carbon ion patients in 50 centers worldwide (ptcog, 2014)

• Beams of energies up to **250 MeV for protons** and **430 MeV/u for carbon ions** are needed

TERA Foundation has 20 years' history in hadrontherapy

- TERA = TErapia con Radiazioni Adroniche
- Application of physics and computing to medicine and biology
  - Proton Ion Medical Machine Study (PIMMS)
  - Italian National Center of Oncological Hadrontherapy (CNAO)



Centro Nazionale di Adroterapia Oncologica

is built by CNAO Foundation

in collaboration with INFN

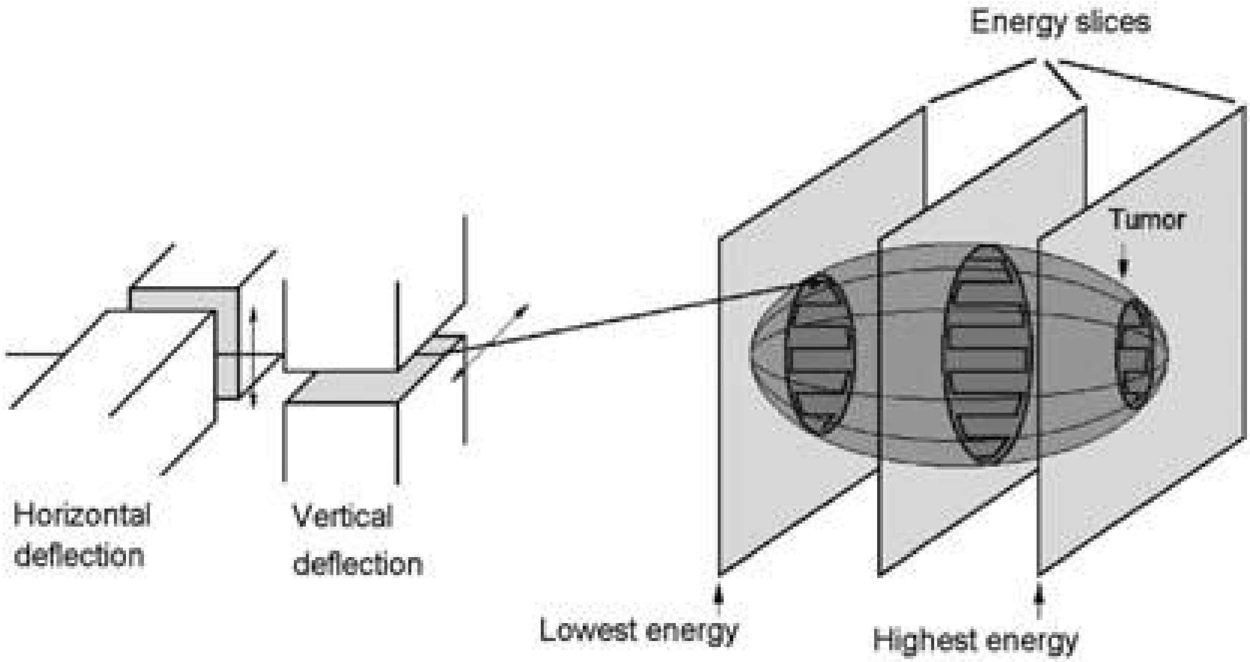
Hadrontherapy modern technical challenges

Treatment of **moving organs** requires :

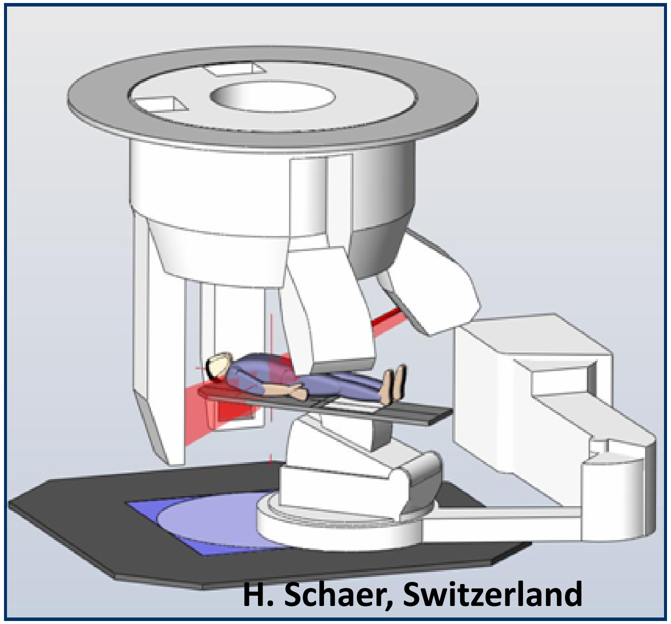
a) 3D **feedbacks**

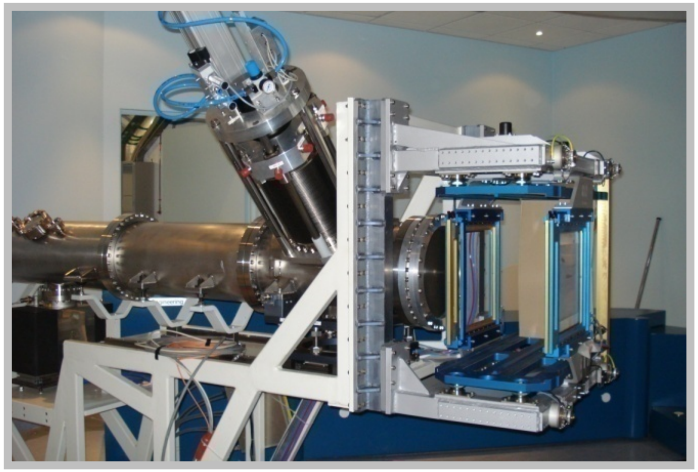
b) 3D **spot scanning**

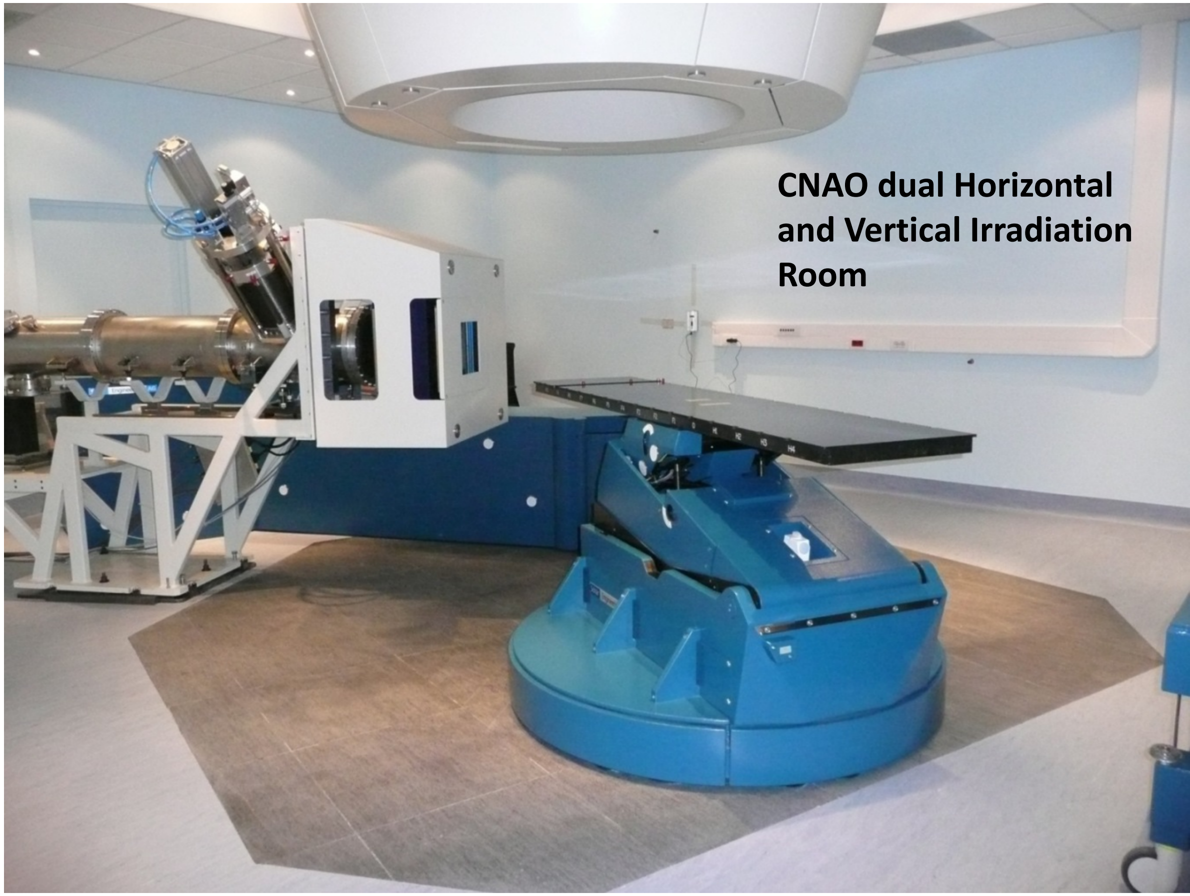
c) **multipainting**



CNAO example: beam delivery and in-room equipment

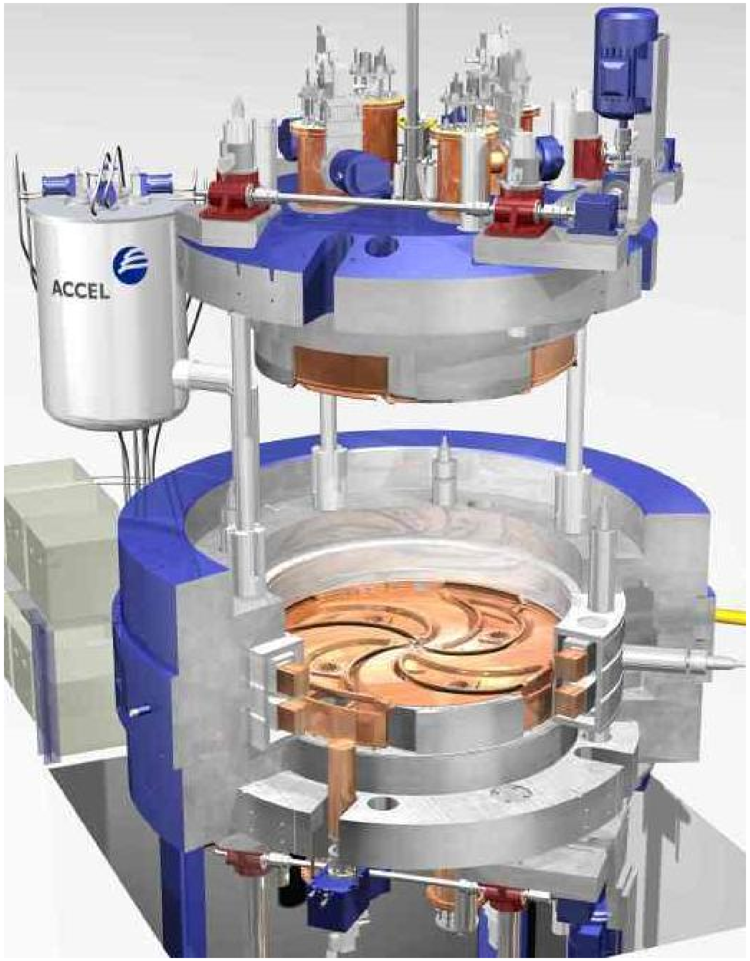






CNAO dual Horizontal and Vertical Irradiation Room

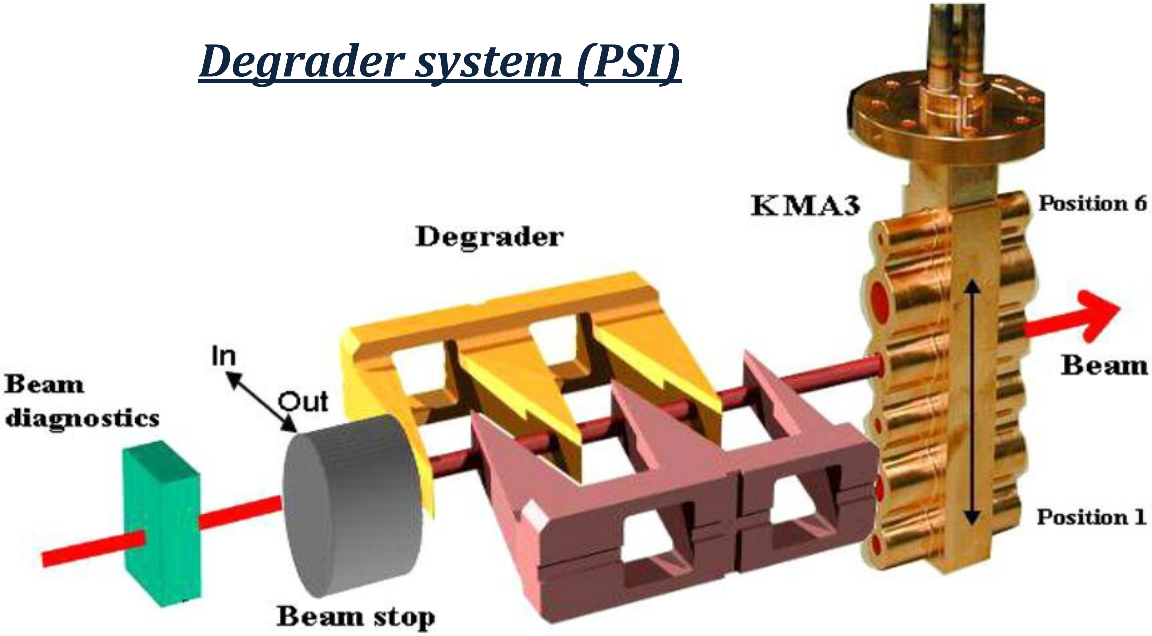
Cyclotrons require passive energy modulation



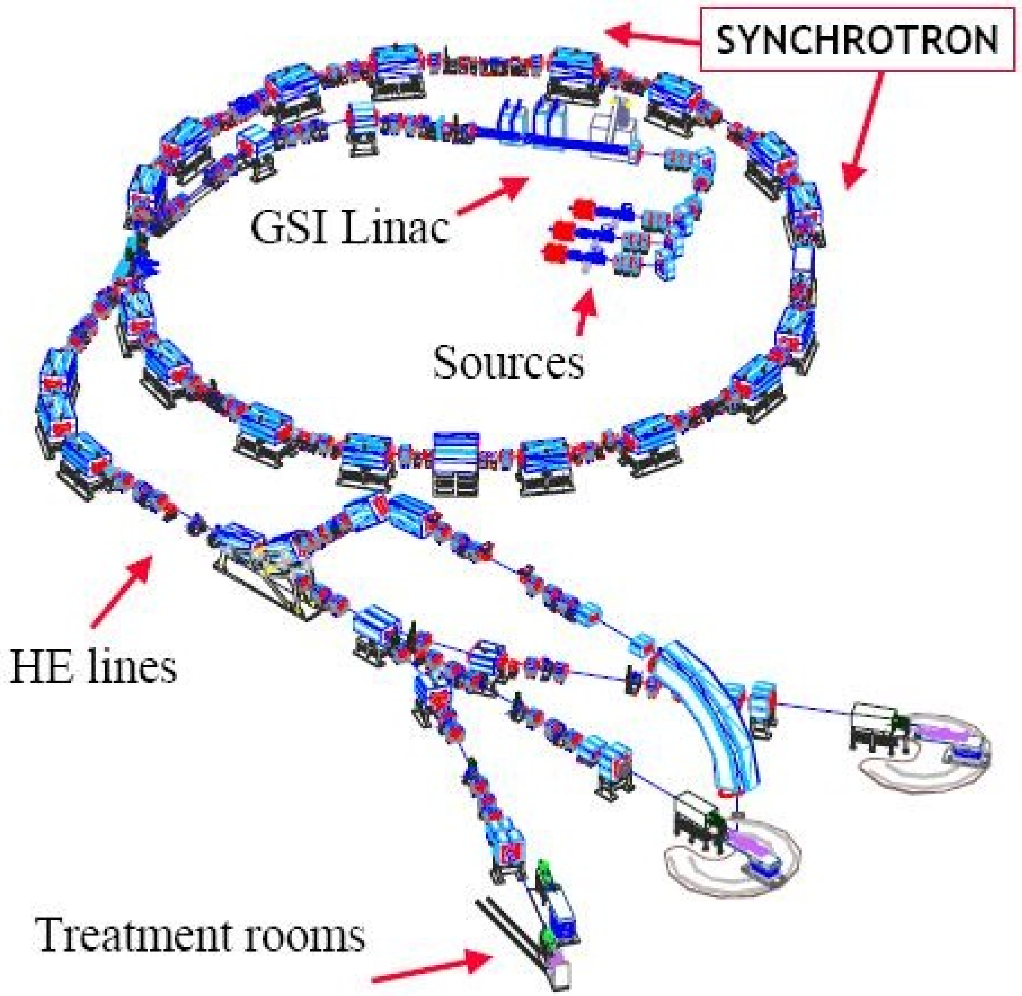
COMET (PSI)

- 90 tons (3.2 m diameter, 1.6 m height)

Degrader system (PSI)



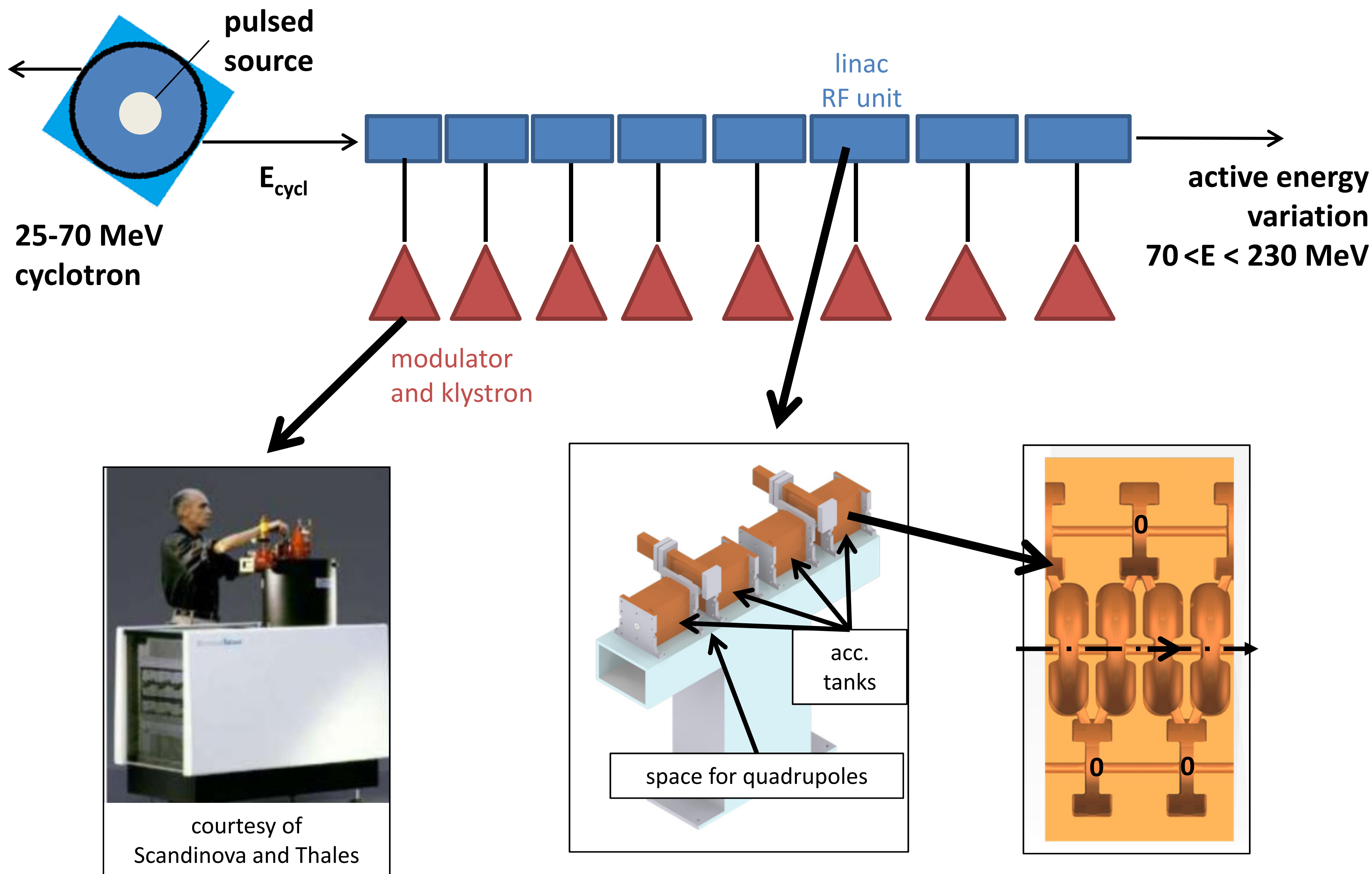
Synchrotrons have slow active energy variation



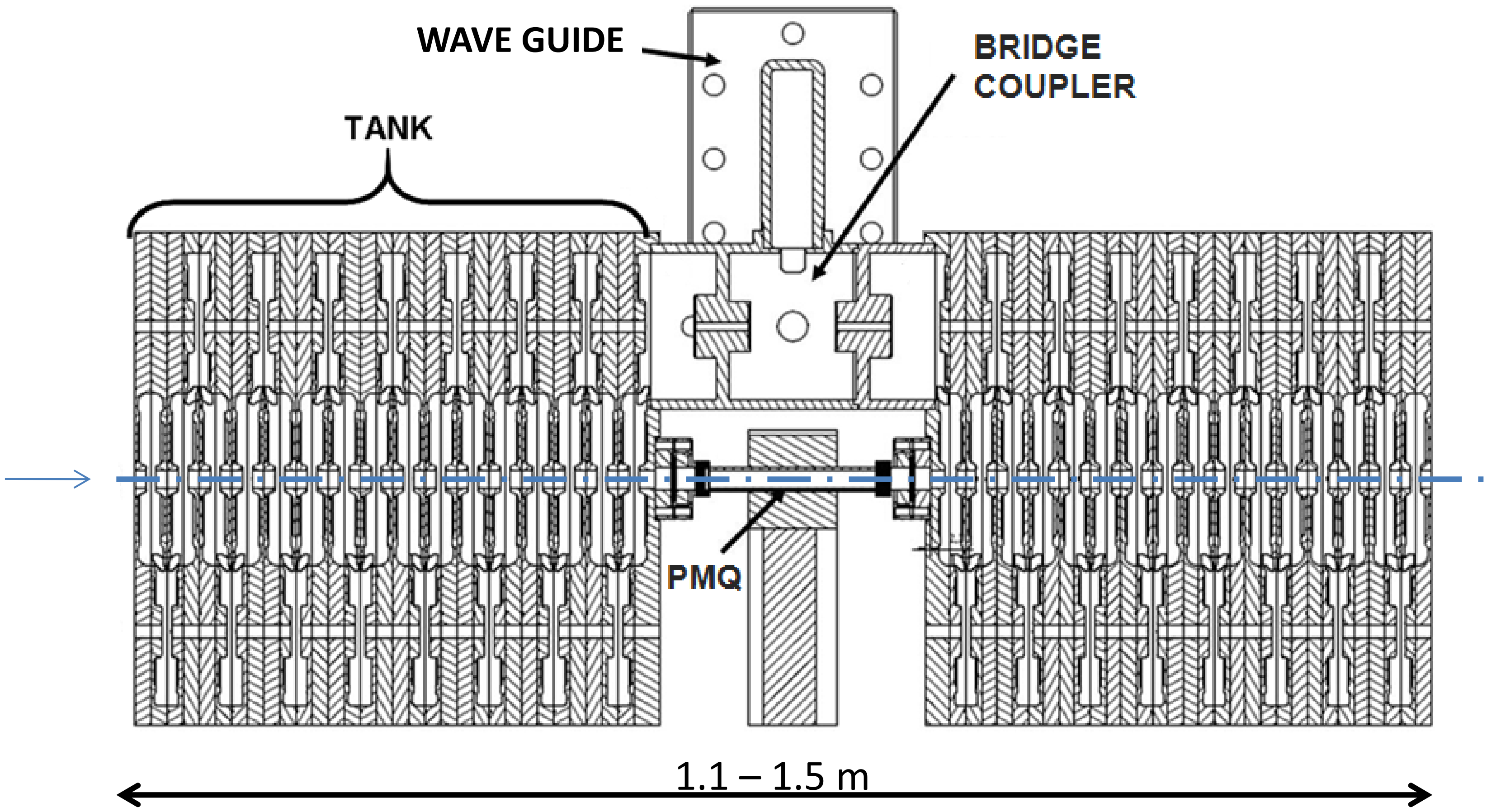
CNAO in Pavia

- 25 m diameter
- **0.5 Hz** repetition rate
- Carbon ion source: **ECRIS (C^{4+})**

The cyclinac concept



The linac has a modular structure



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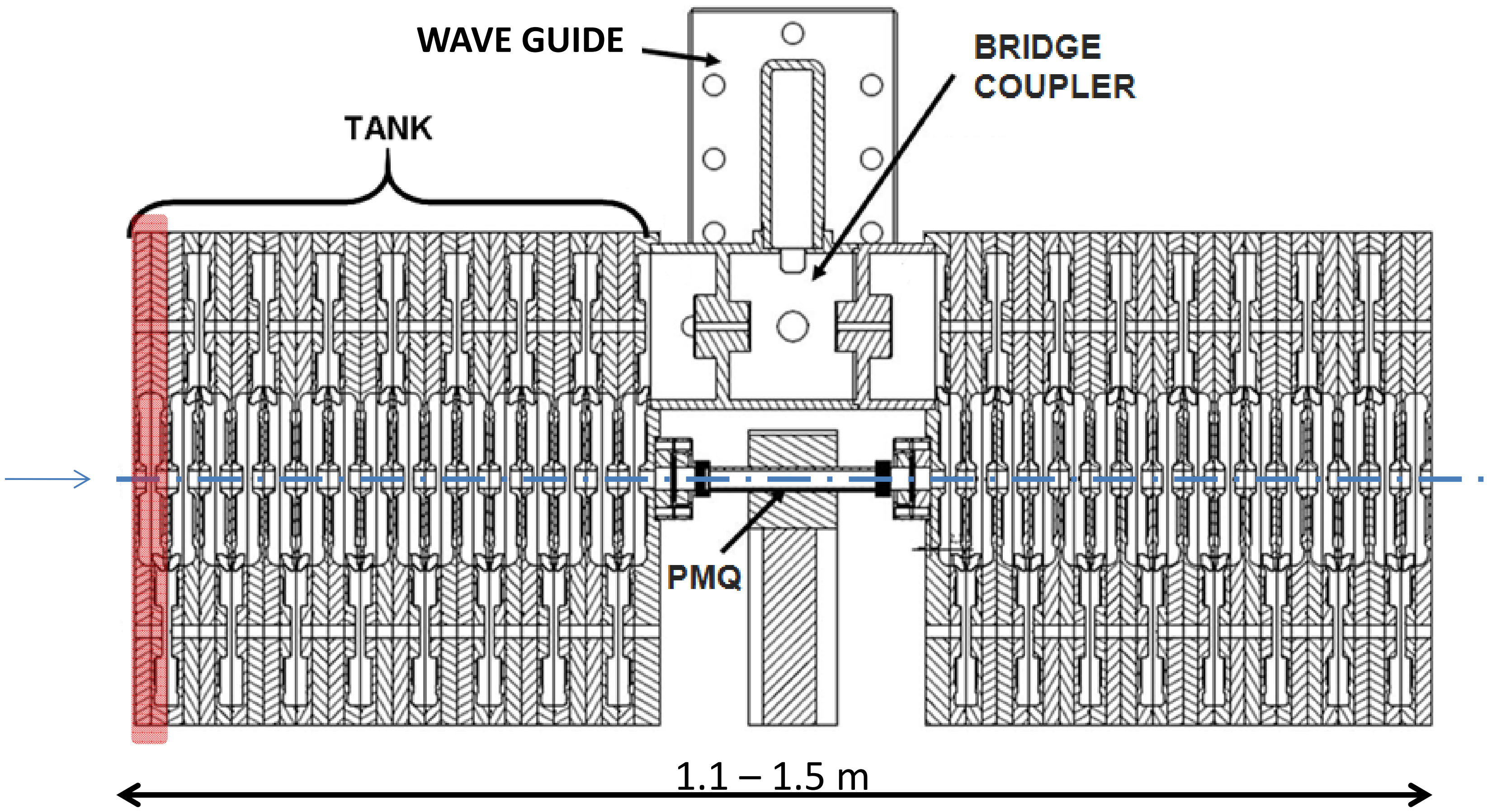

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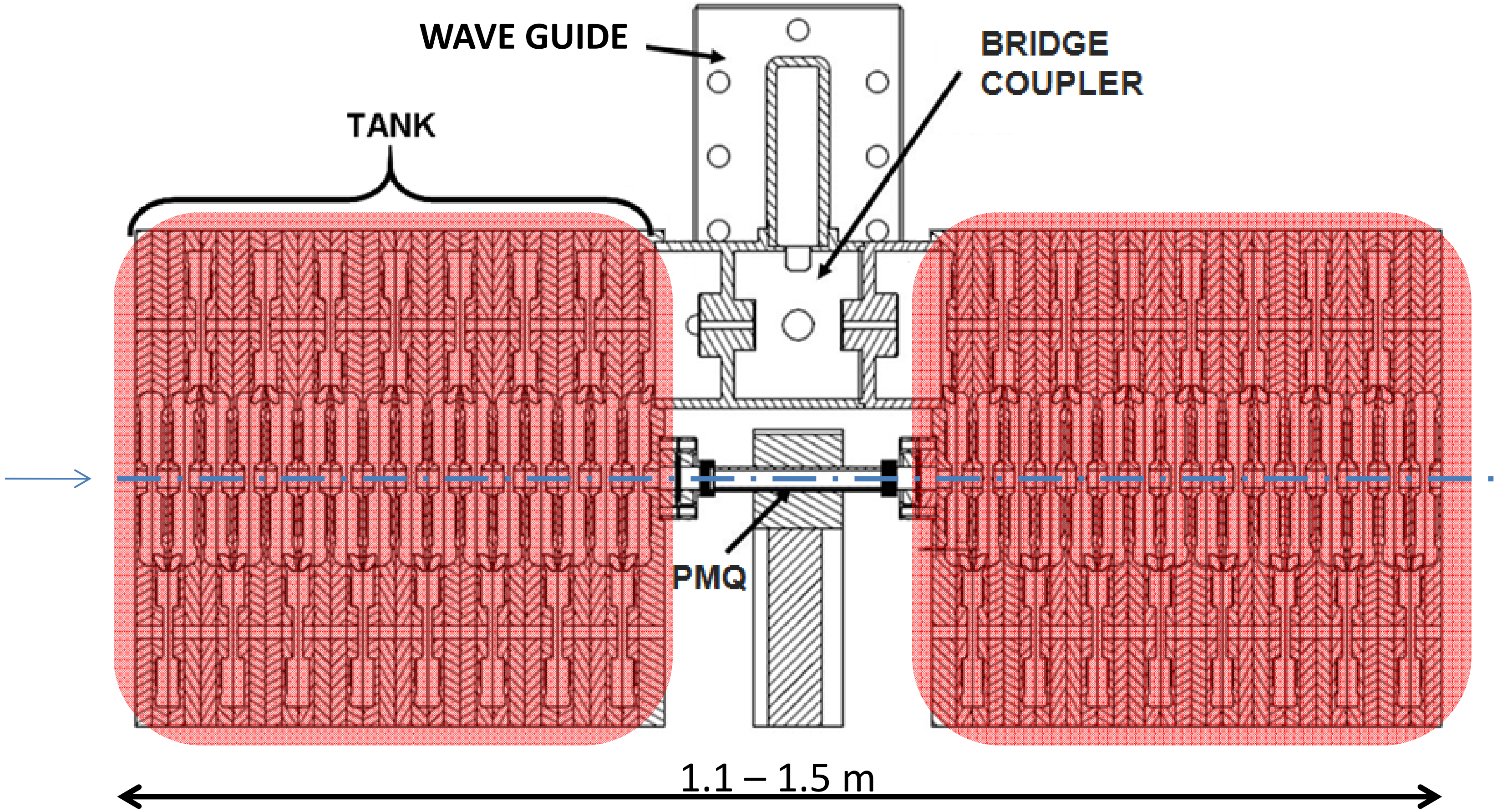

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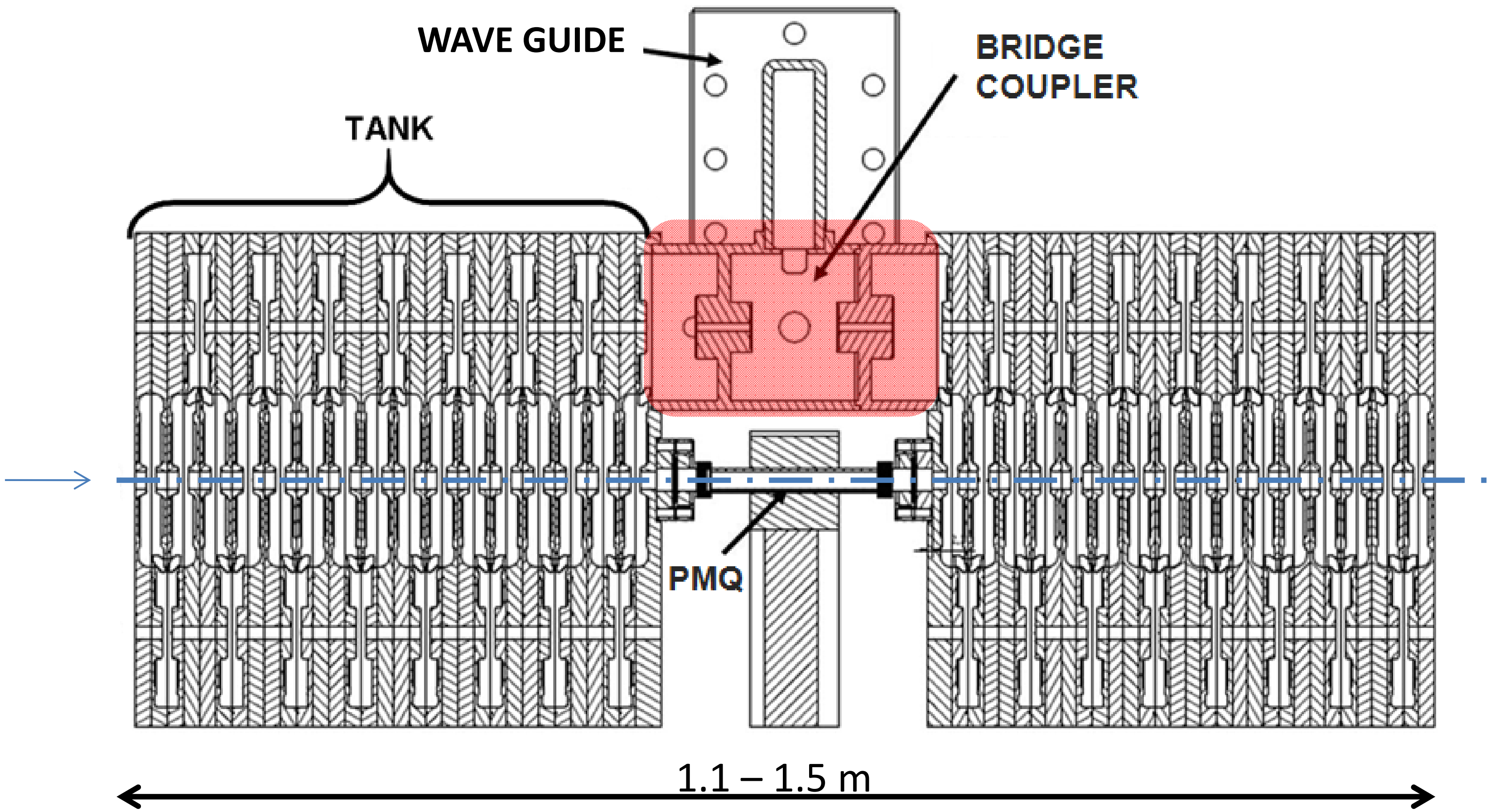
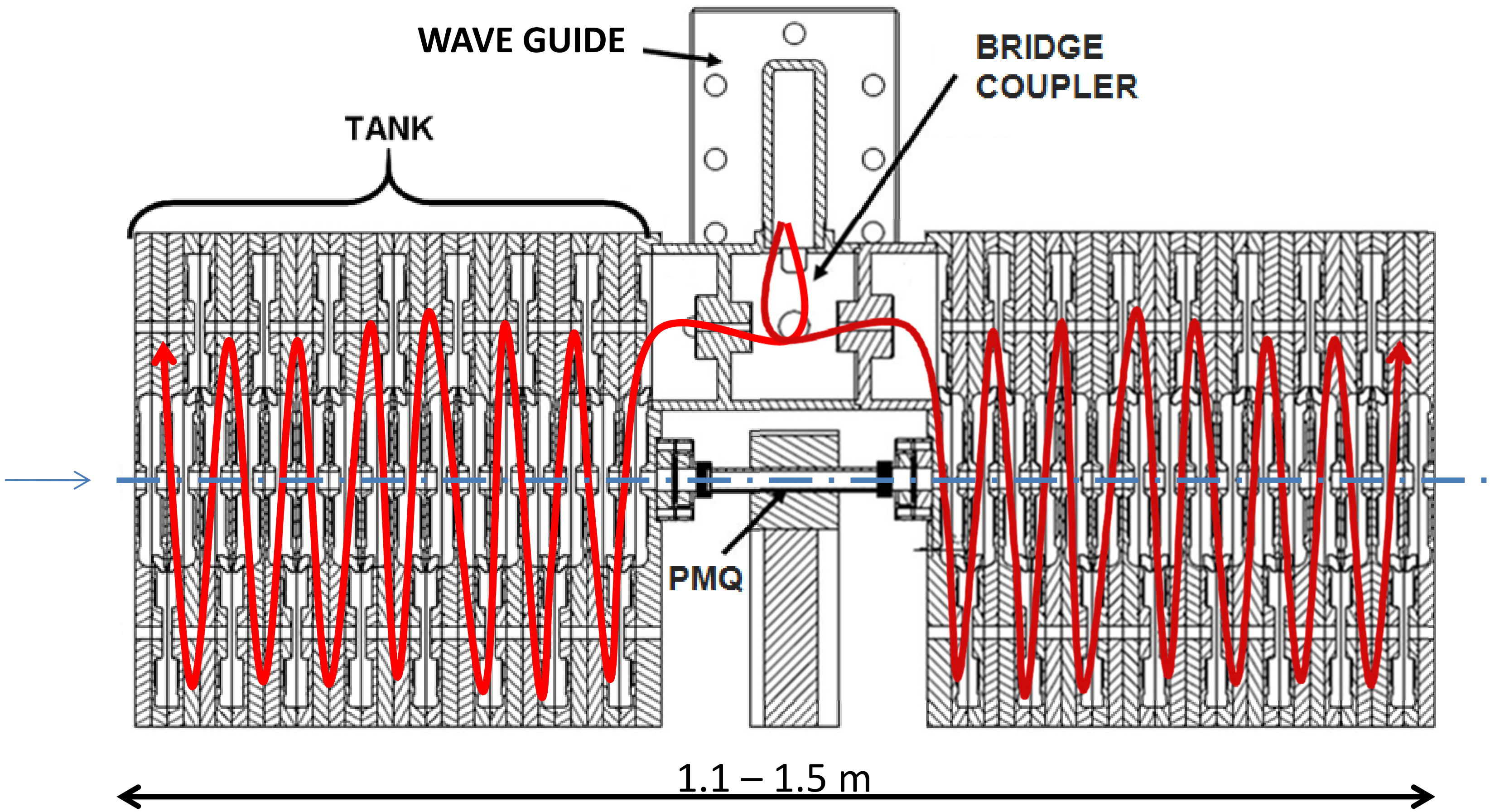
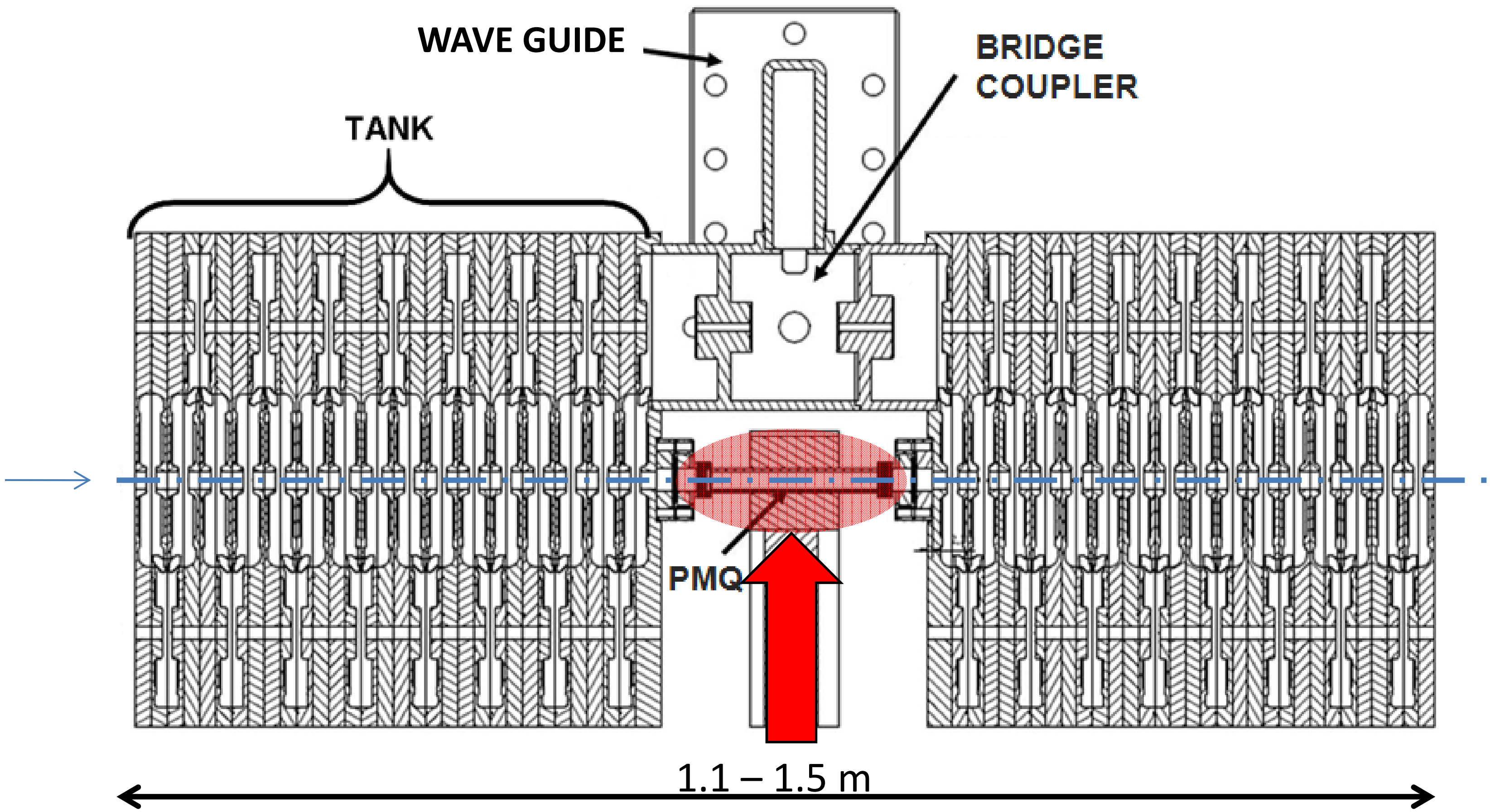


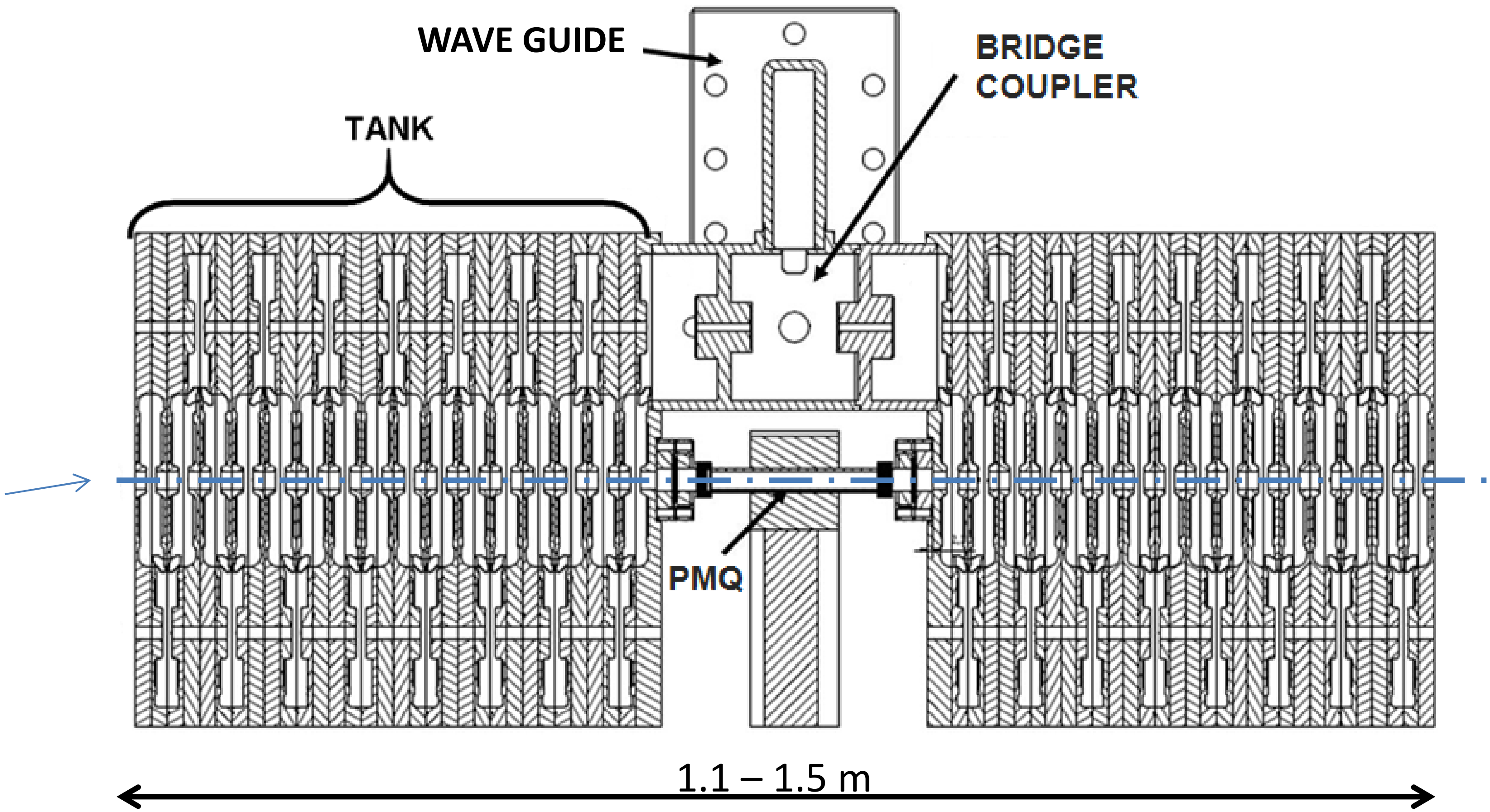
The linac has a modular structure



The linac has a modular structure

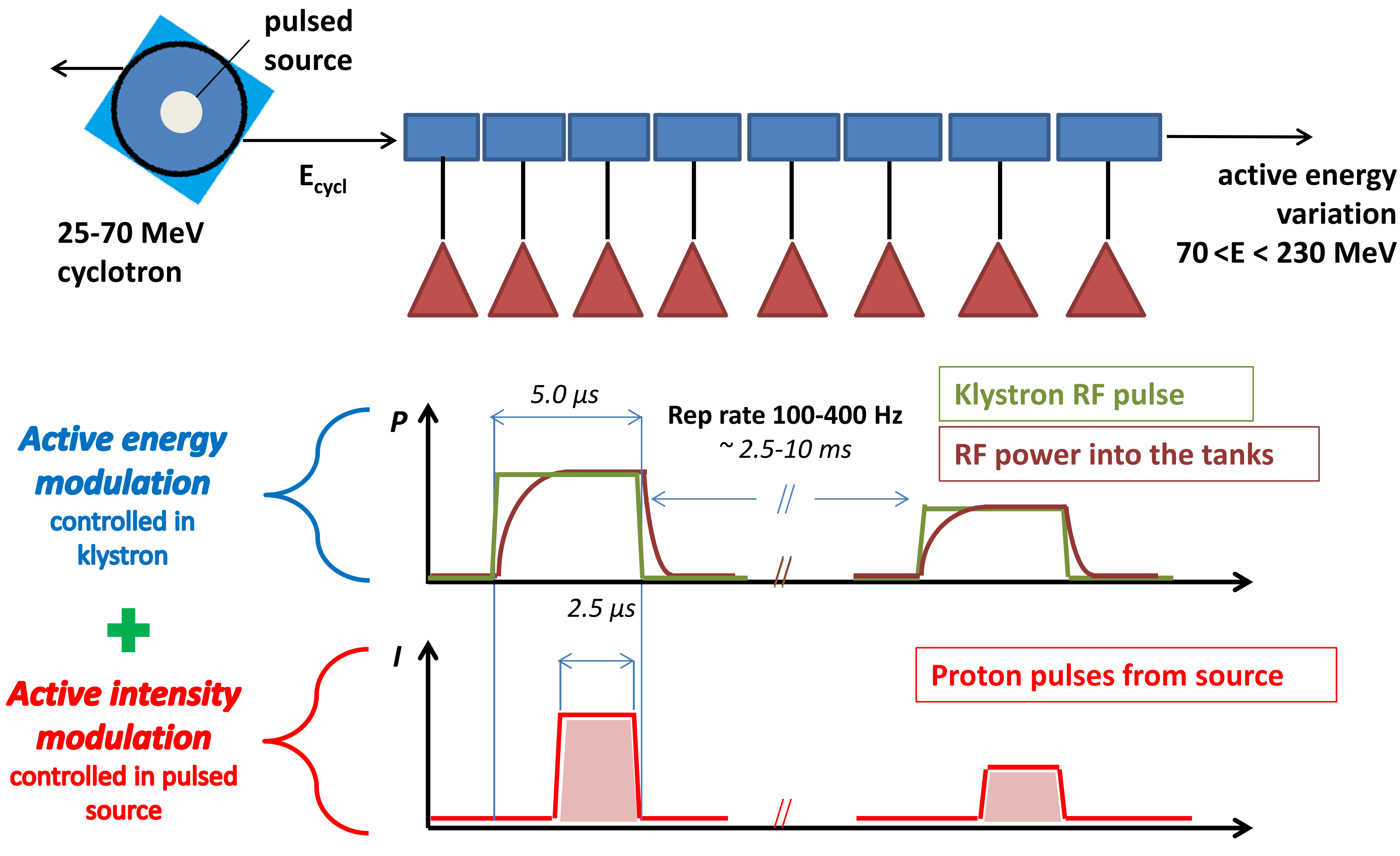


The linac has a modular structure

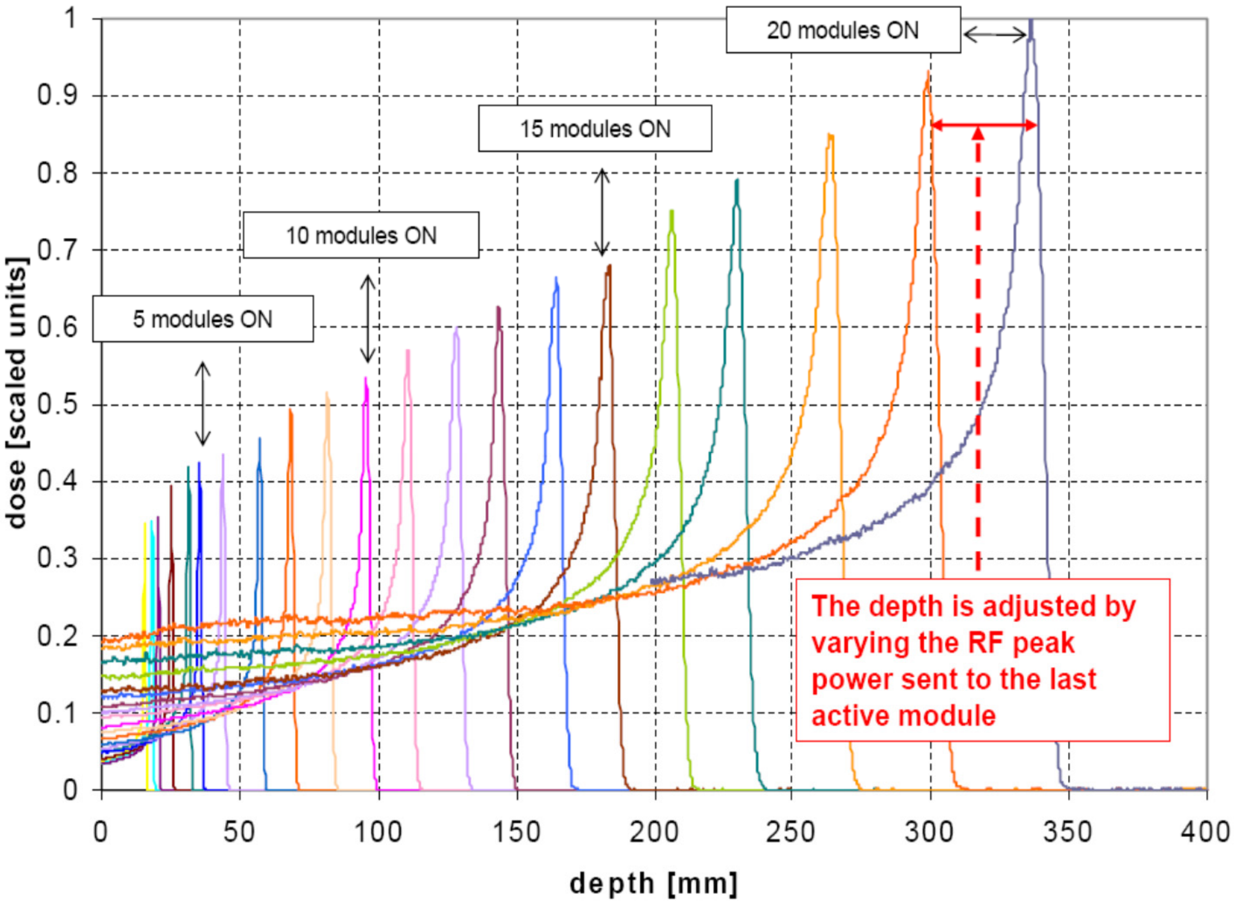


Typical axial field of 15 MV/m → linac from 30 to 230 MeV ~ 20 m

Cyclinac beam characteristics



Linac offers possibility of active/fast energy modulation

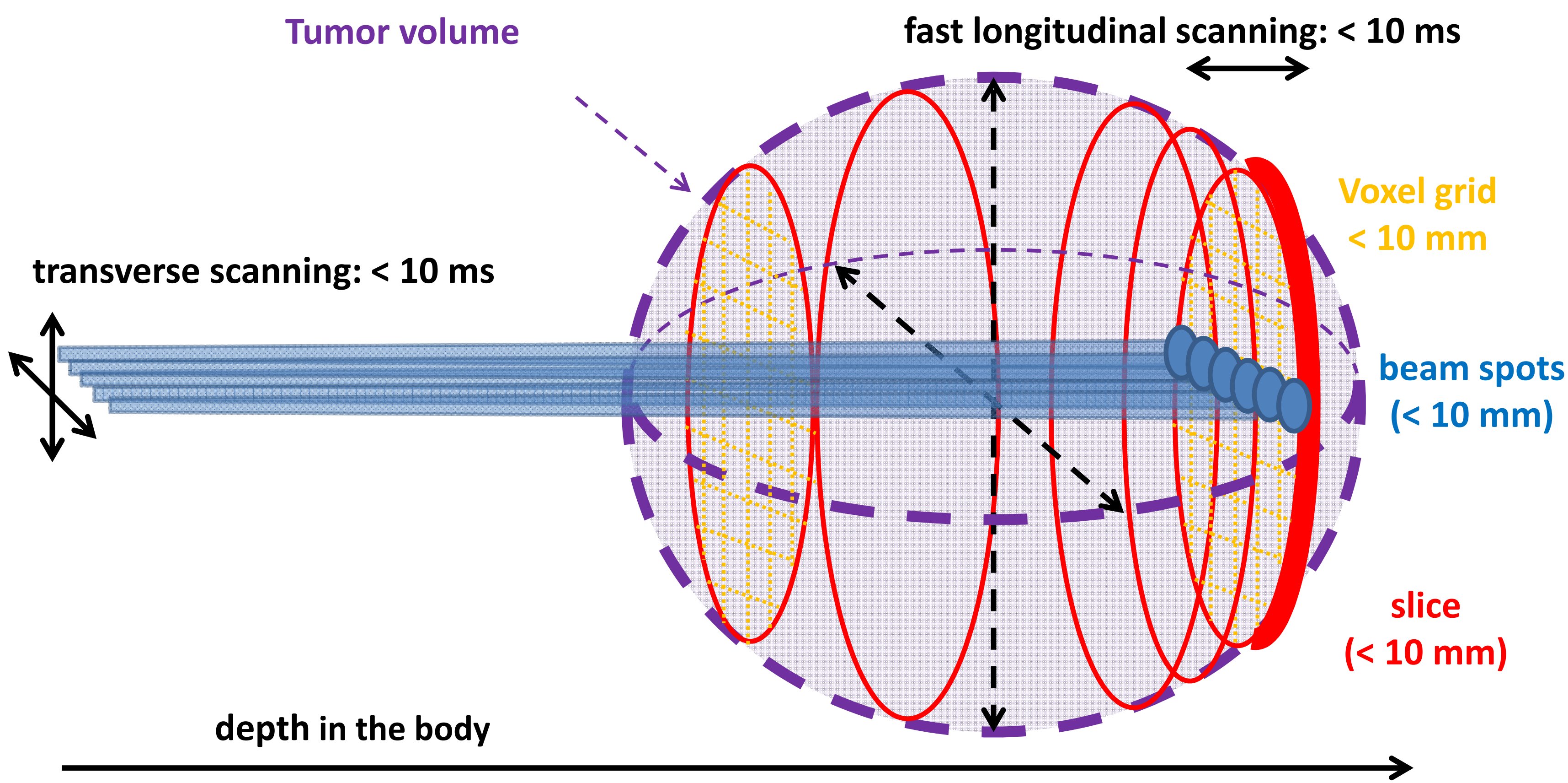


The advantages are:

1) **Reduction of HEBT size and activation** (no degrader system)

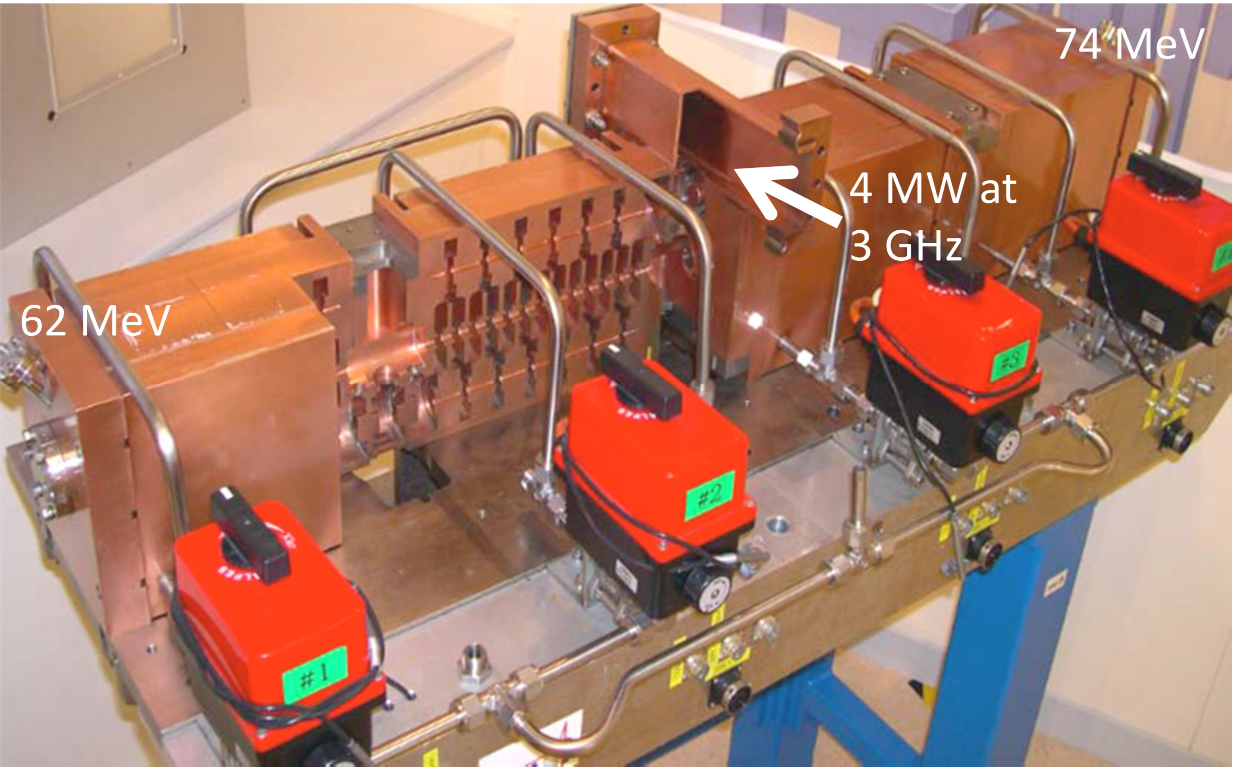
2) Versatile beam characteristics for **advanced beam delivery**

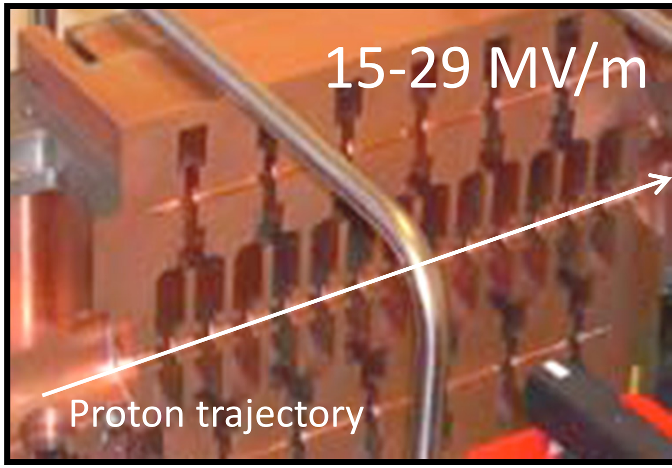
3D spot scanning with linacs



Prototype of Linac Booster (LIBO)

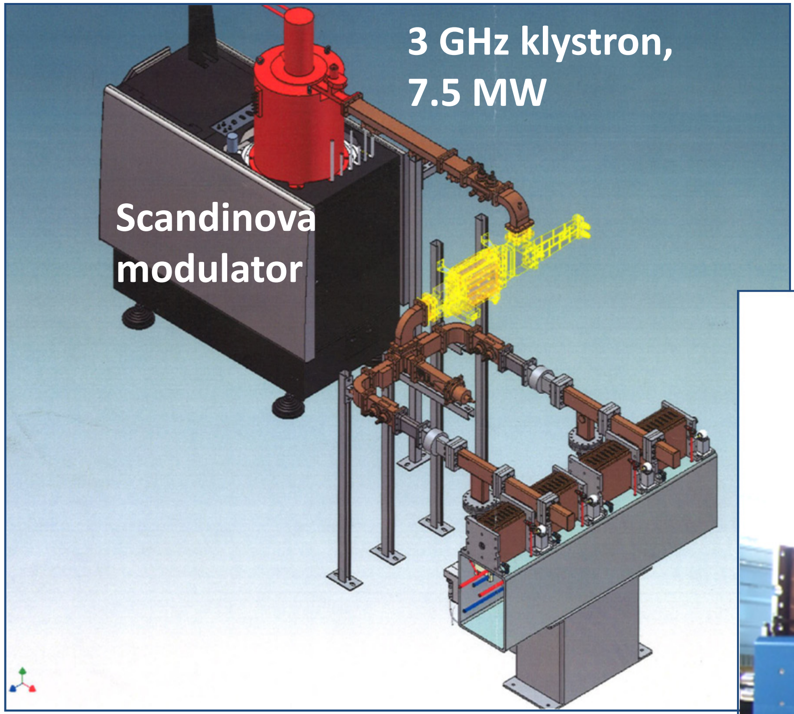
- Module of 4 tanks tested with protons at the cyclotron of Laboratori Nazionali del Sud - INFN , Catania



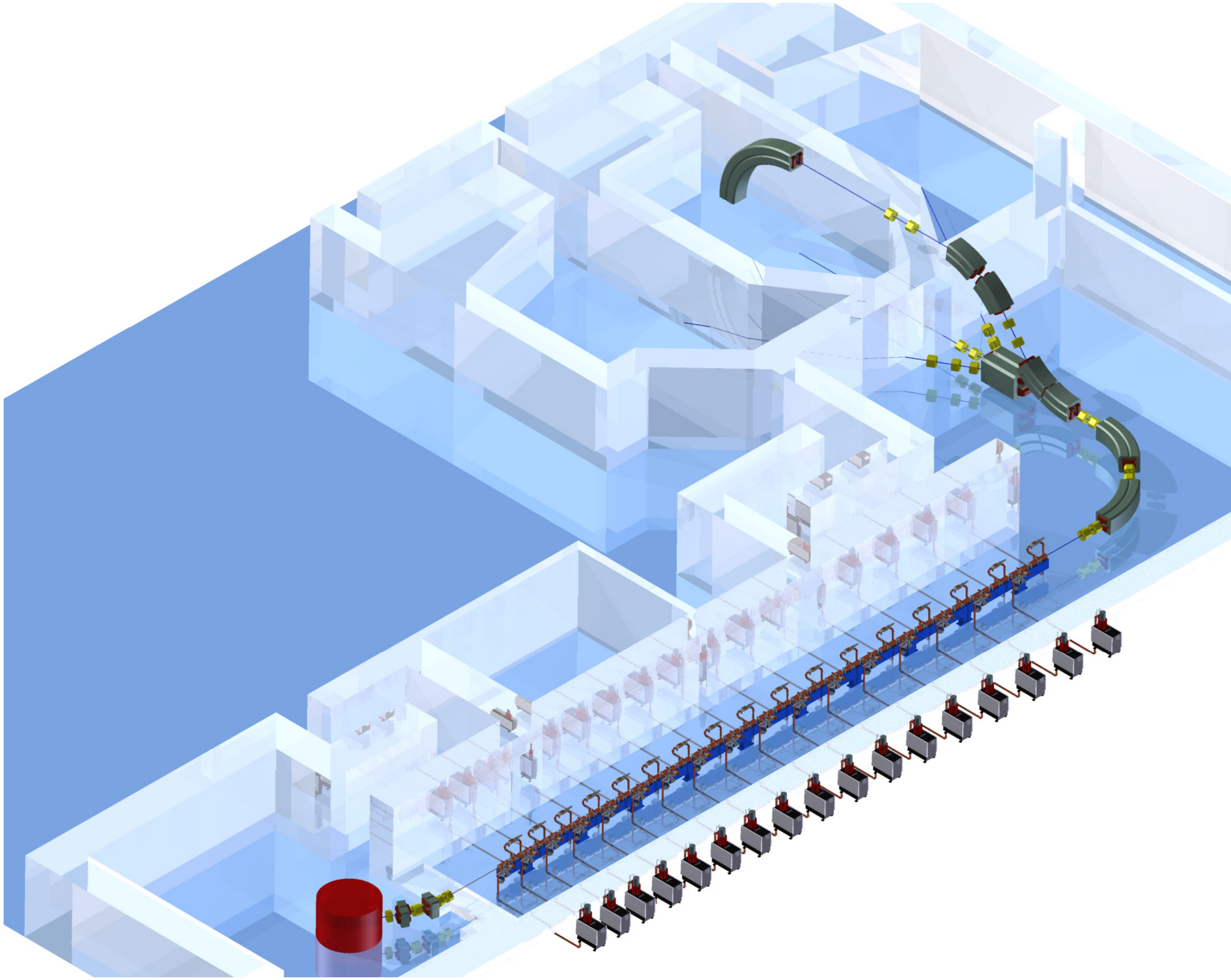


Collaboration of TERA with INFN (Mi- Na) and CERN 1999-2002

‘First Unit’ power-tested at CERN



CABOTO: CArbon BOoster for Therapy in Oncology

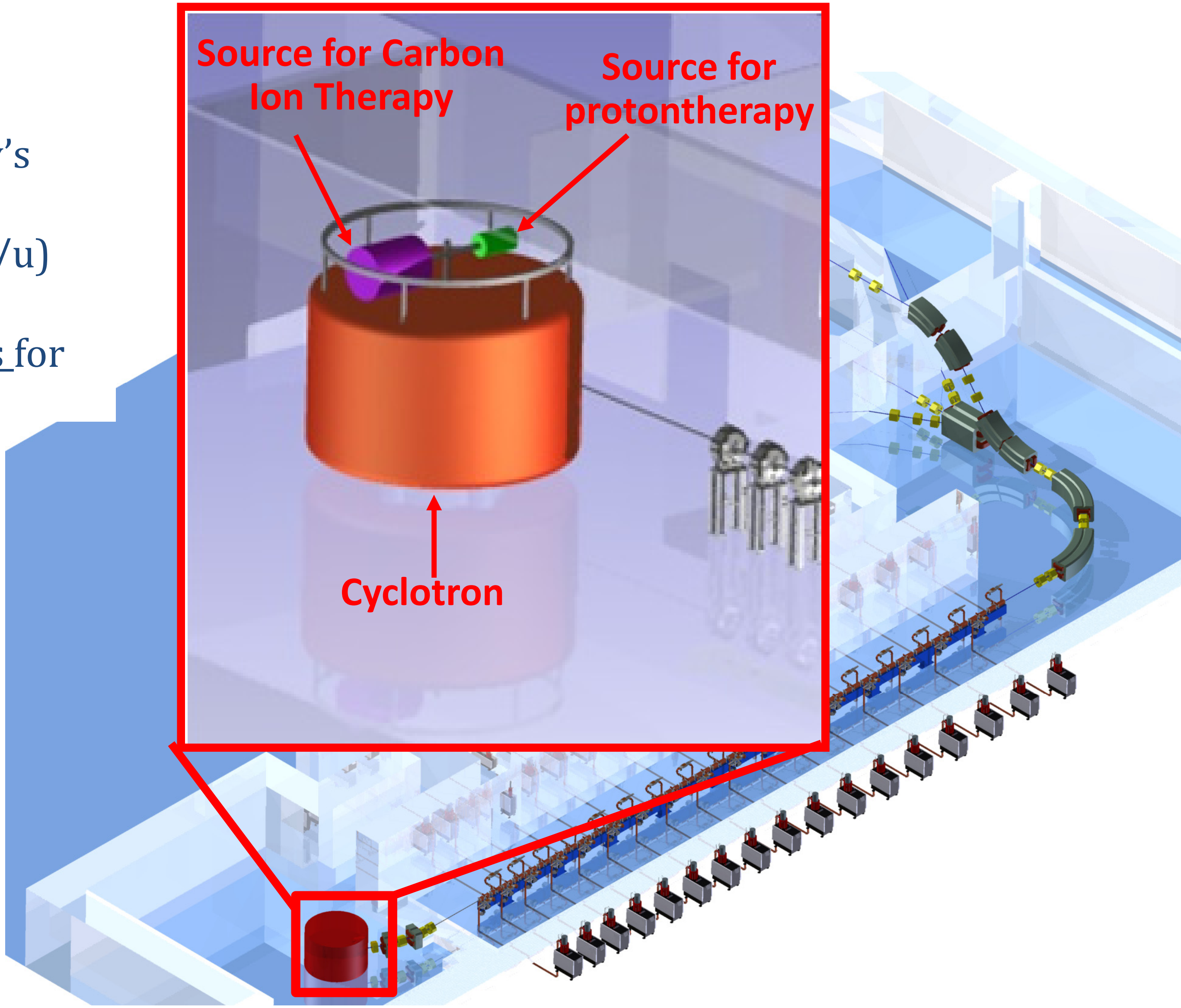


CABOTO: CArbon BOoster for Therapy in Oncology

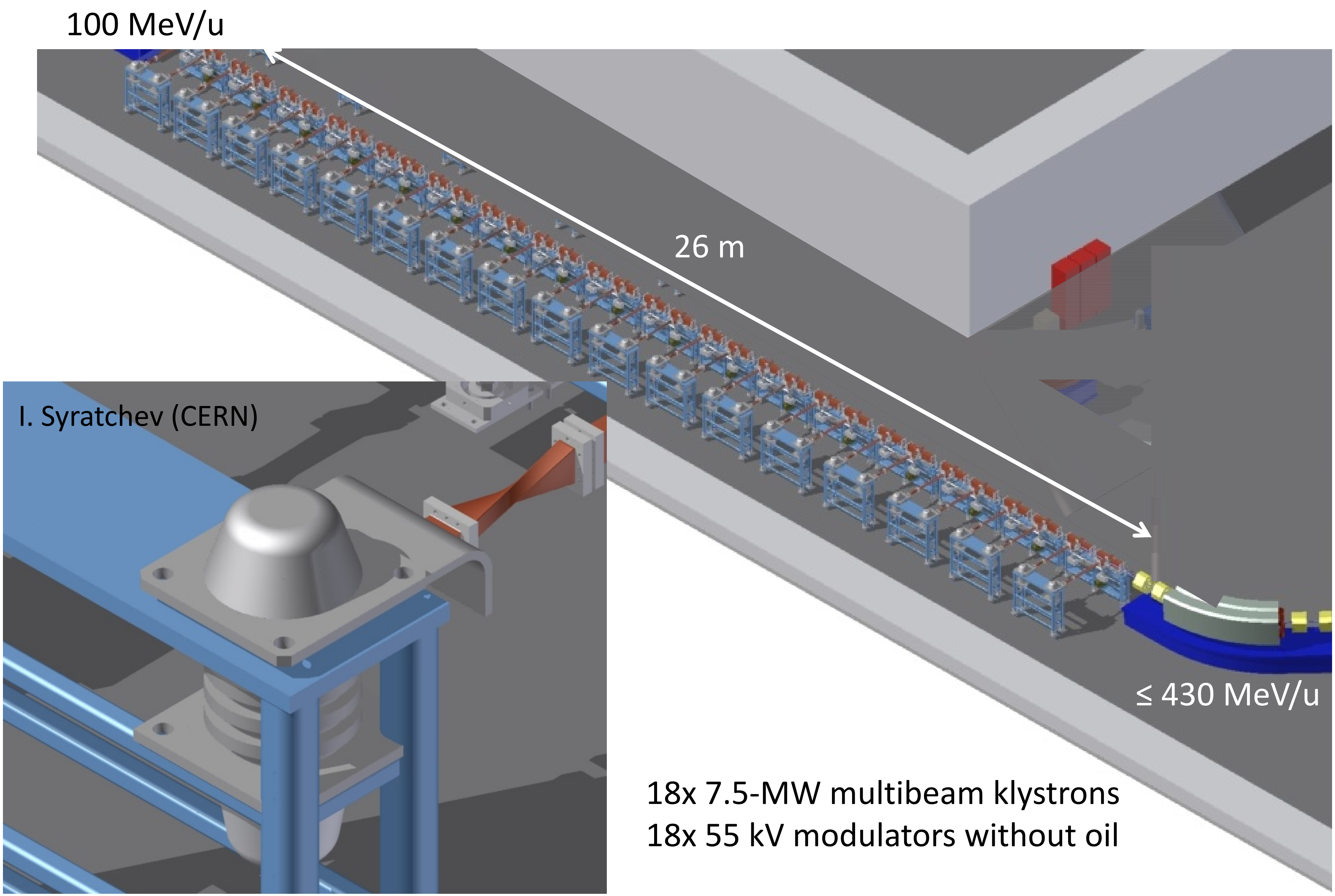
- **Cyclotron output energy:**

Choice linked to facility's clinical goals
(70 MeV/u – 230 MeV/u)

- <u>External ion sources</u> for **H_2^+ and C^{6+}**

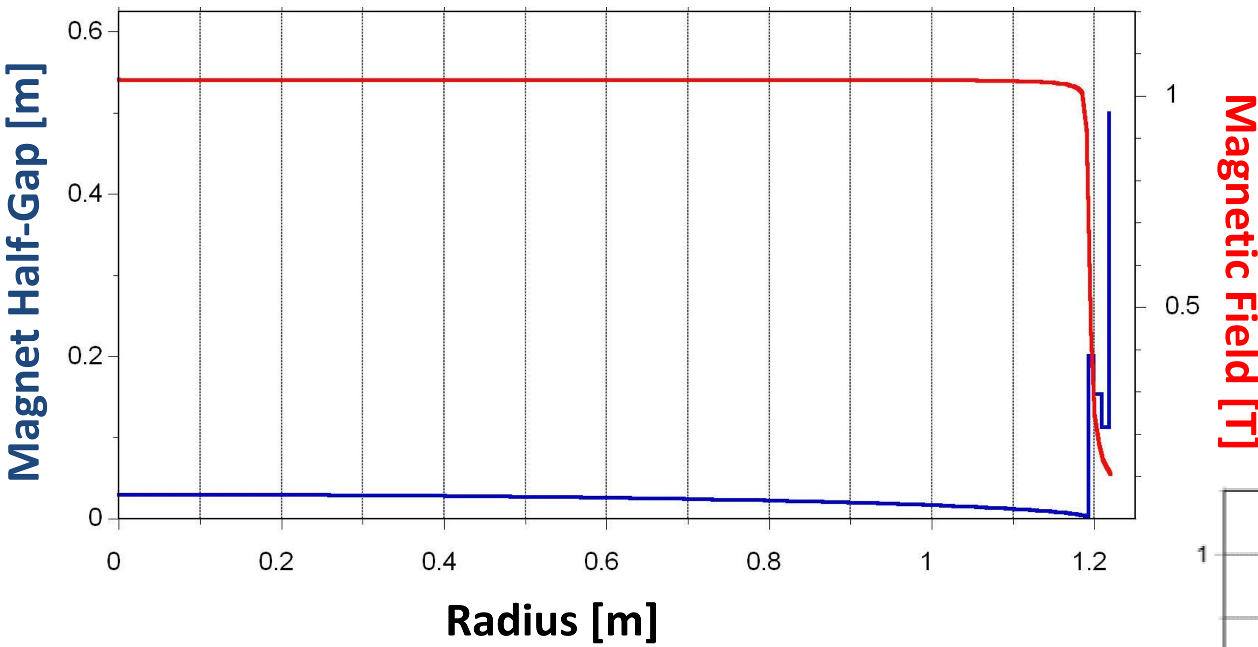


CABOTO example



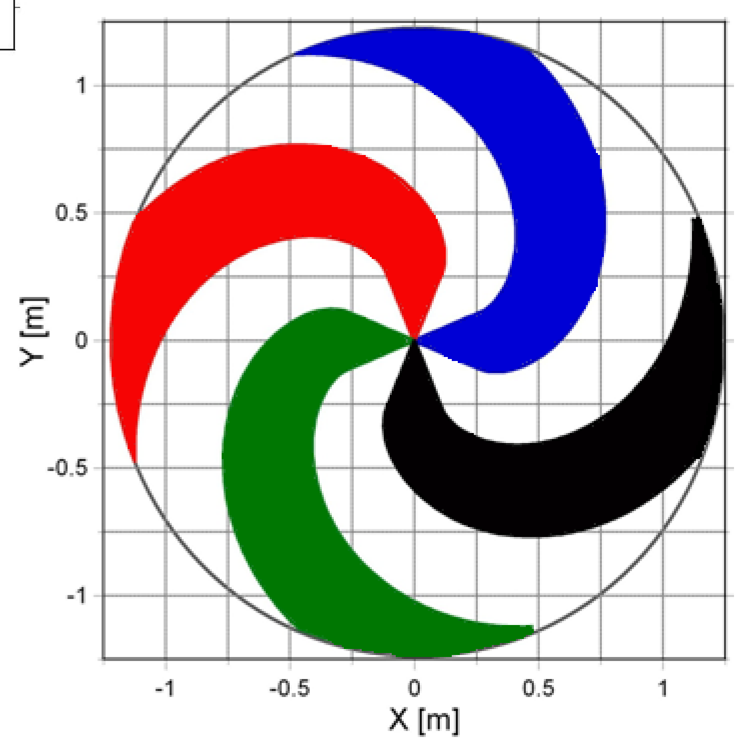
18x 7.5-MW multibeam klystrons
18x 55 kV modulators without oil

Isochronous Cyclotron design for 230 MeV/u



- **highest field** for elliptical pole

- 4 sectors
- Hill gap: 3 cm to 3 mm
- Valley gap: 50 cm to 11 cm
- Hill azimuthal width: 45°



- **Limited spiraling** (from radius of 0.4 m): max 85° hill axis rotation (COMET)

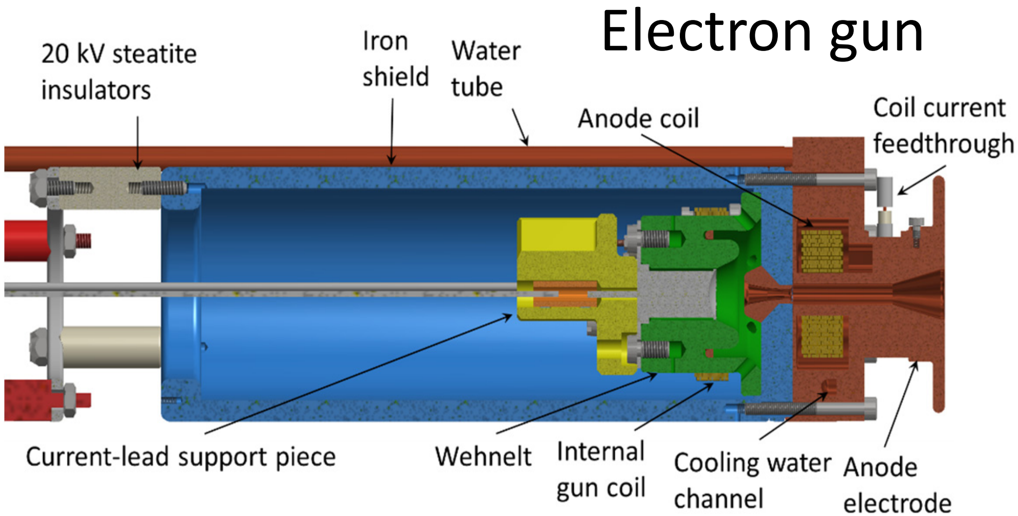
- Vertical Betatron Tunes between 0.2 and 0.5 (only 4th order resonance crossings)

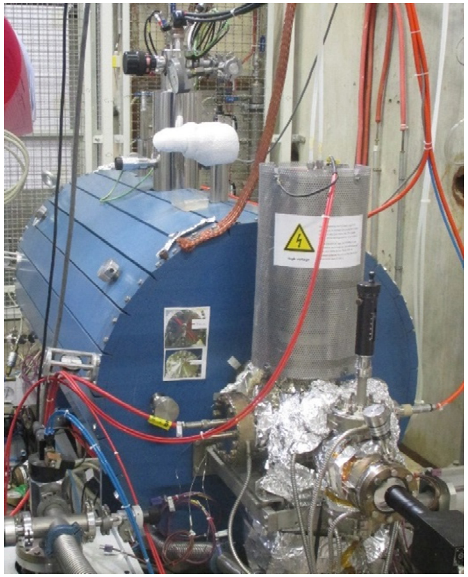
Isochronous Cyclotrons conceptual designs

Magnetic Rigidity [T m]	2.45	3.25	3.92	4.63
Output Kinetic Energy [MeV/u]	**70**	**120**	**170**	**230**
Number of Sectors	4 , Elliptical			
Central Hill Half-gap [cm]	3.0			
Central Magnetic Field [T]	3.2			
Pole Radius [m]	**0.761**	**0.955**	**1.092**	**1.218**
Elliptical Hill Profile Radius [m]	0.735	0.923	1.067	1.193
Central Valley Half-gap [cm]	45	50	52	50
Max. Spiral Angle [°]	49	57	63	68
Max. Sector Azimuthal Rotation [°]	**34**	**54**	**69**	**85**
Max. Coil Current Density [A/mm^2]	40			
Coil Centroid Radius [m]	0.946	1.135	1.268	1.393
Coil Centroid Height [m]	0.235	0.235	0.205	0.185
Max. Magnetic Field Modulus in Yoke inner edge [T]	2.0			
Yoke Diameter [m]	3.18	3.8	4.3	4.75
Yoke Height [m]	2.2	2.5	2.7	2.9
Iron Weight [tons]	**100**	**170**	**240**	**310**

CERN's MEDeGUN – EBIS based C^{6+} injector

- EBIS source with high-compression electron gun
- Repetition rate >180 Hz, <5 µs pulses
- Up to 1e9 C^{6+} per 5 µs long spill





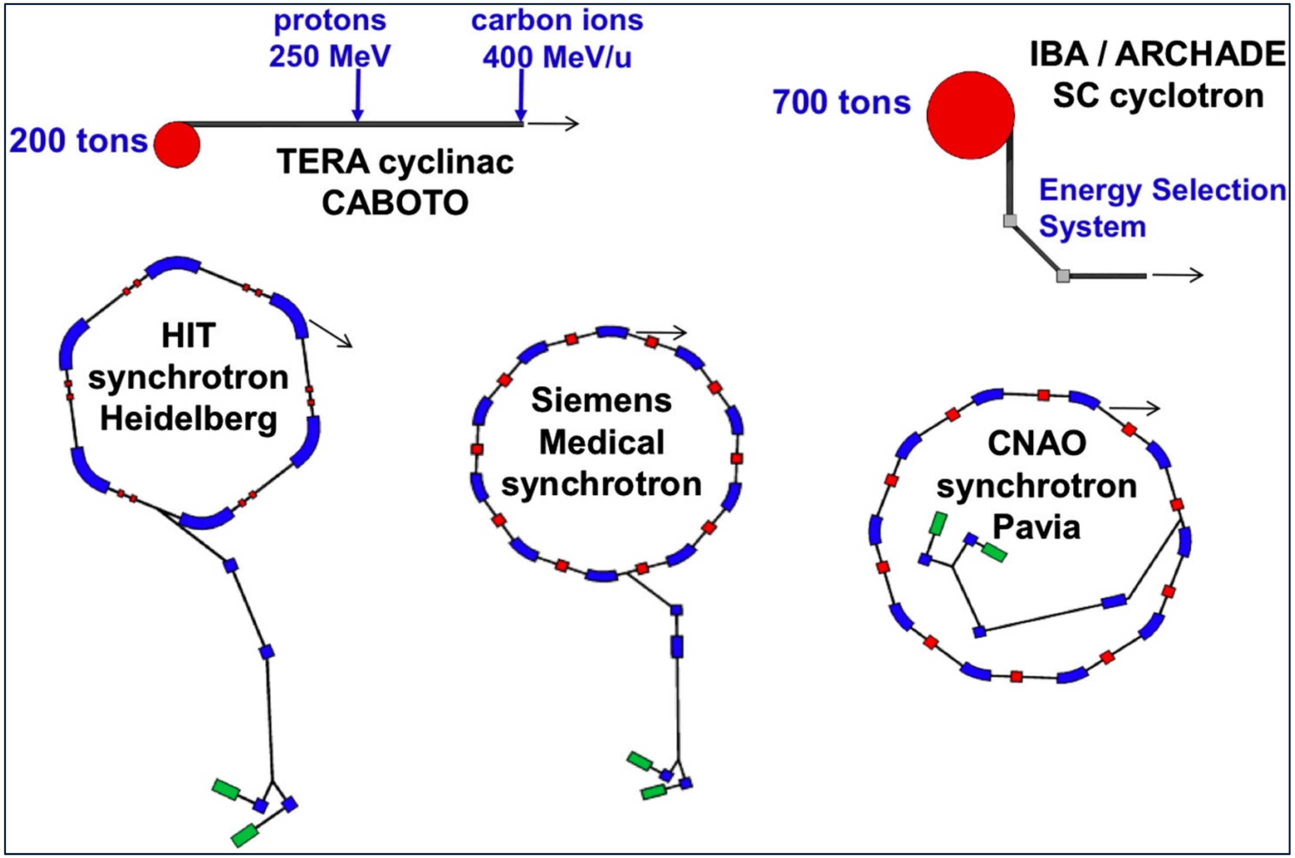
- Assembly of last pieces ongoing
- First electron beam test scheduled before Christmas

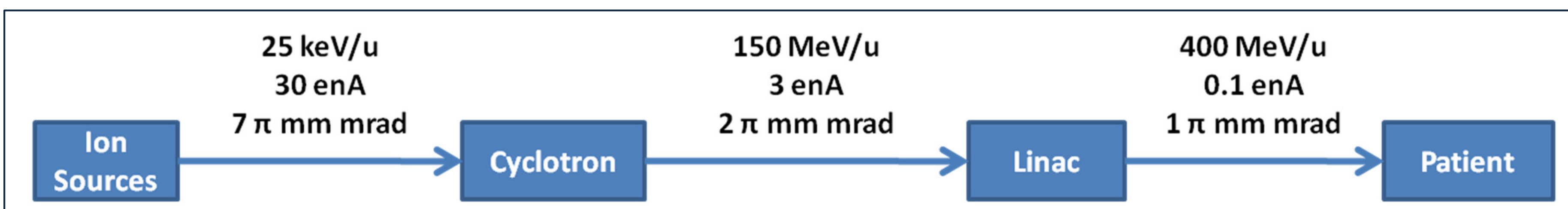
(courtesy of F. Wenander – CERN)

* R. Mertzig et al., *"A high-compression electron gun for C^{6+} production: concept, simulations and mechanical design"*, to be published

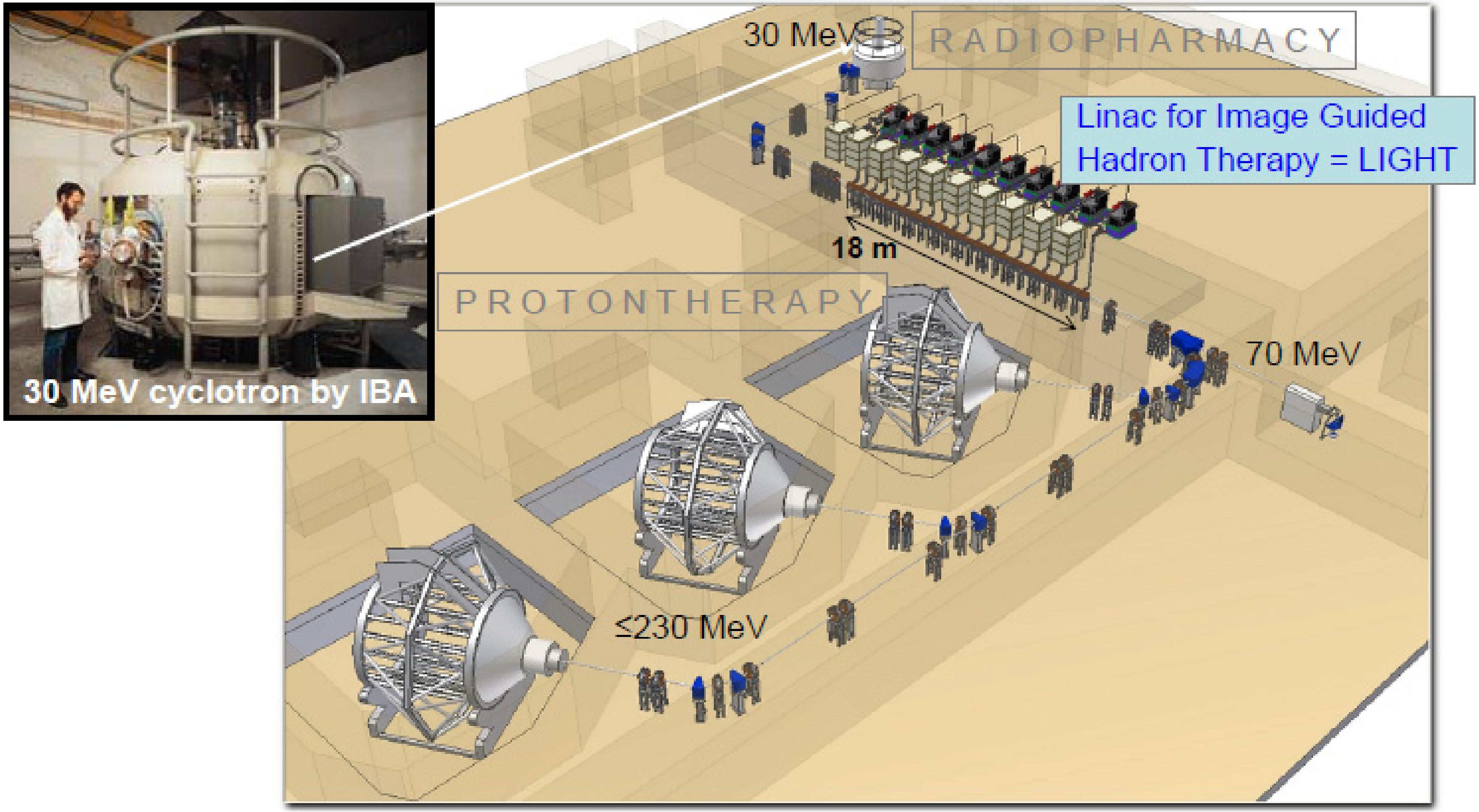
* A. Shornikov and F. Wenander, *"Advanced Electron Beam Ion Sources (EBIS) for 2-nd generation carbon radiotherapy facilities"*, http://dx.doi.org/10.1088/1748-0221/11/04/T04001

CABOTO is competitive solution for hadrontherapy

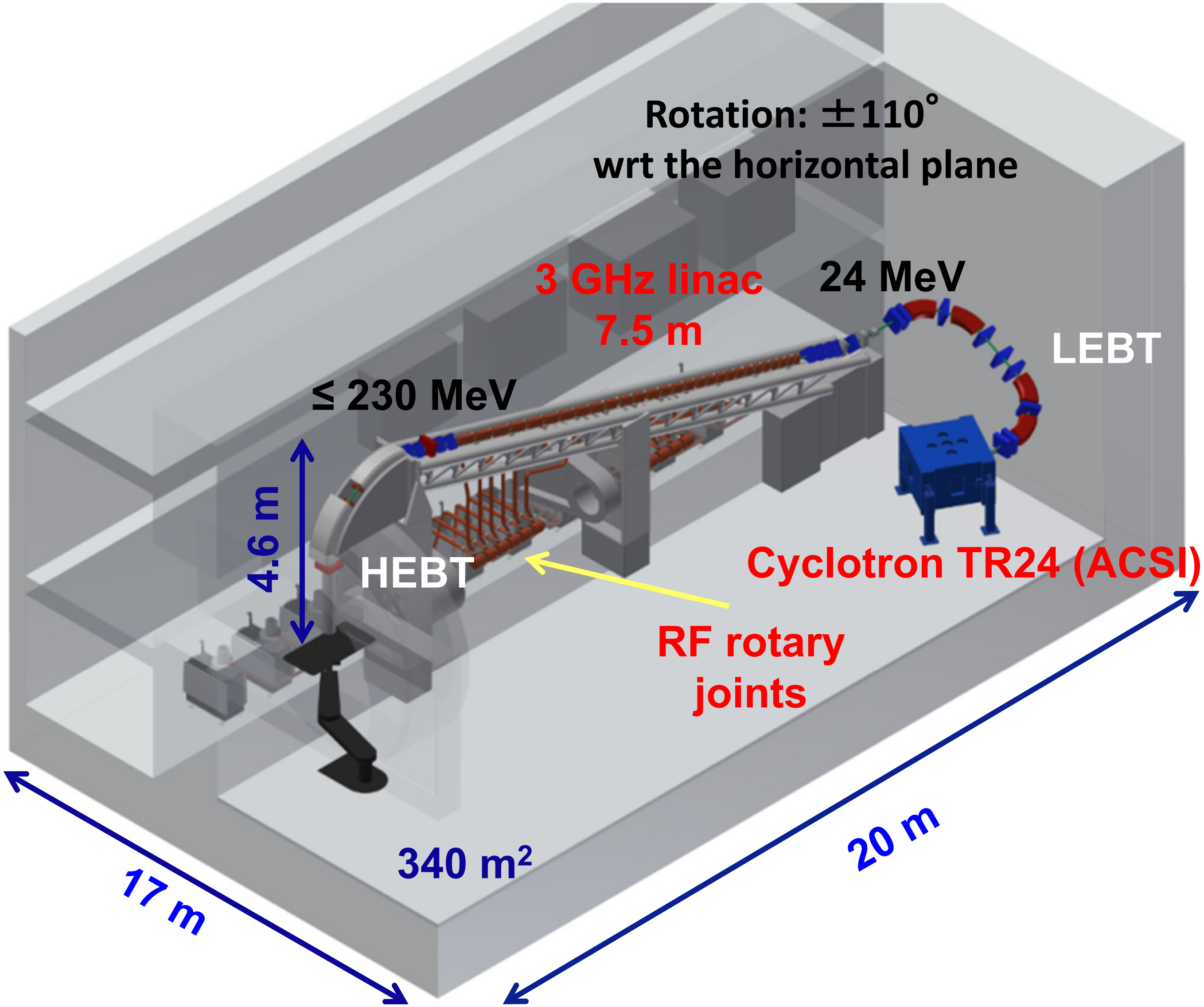




IDRA: Institute for advanced Diagnostics and RAdiotherapy

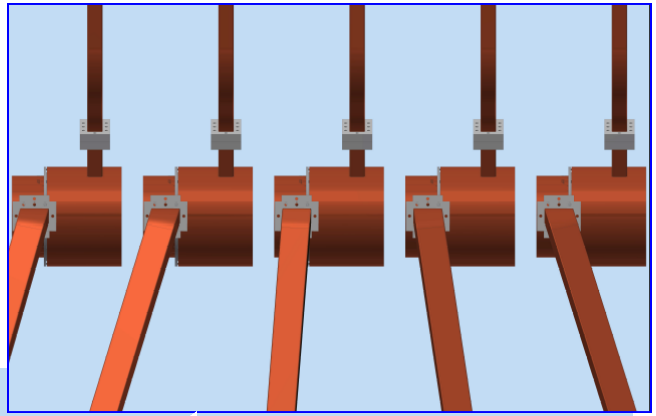


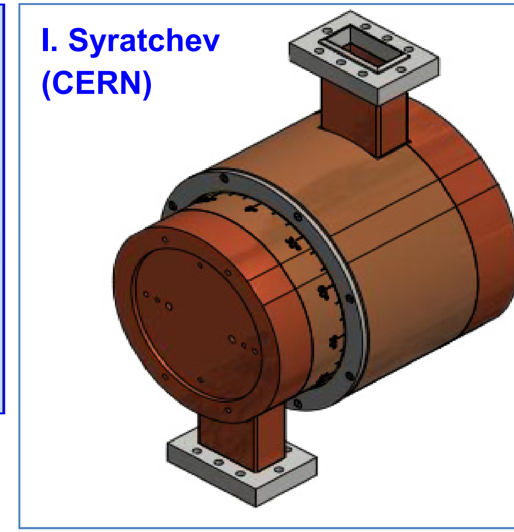
TULIP: Turning Linac for Protontherapy

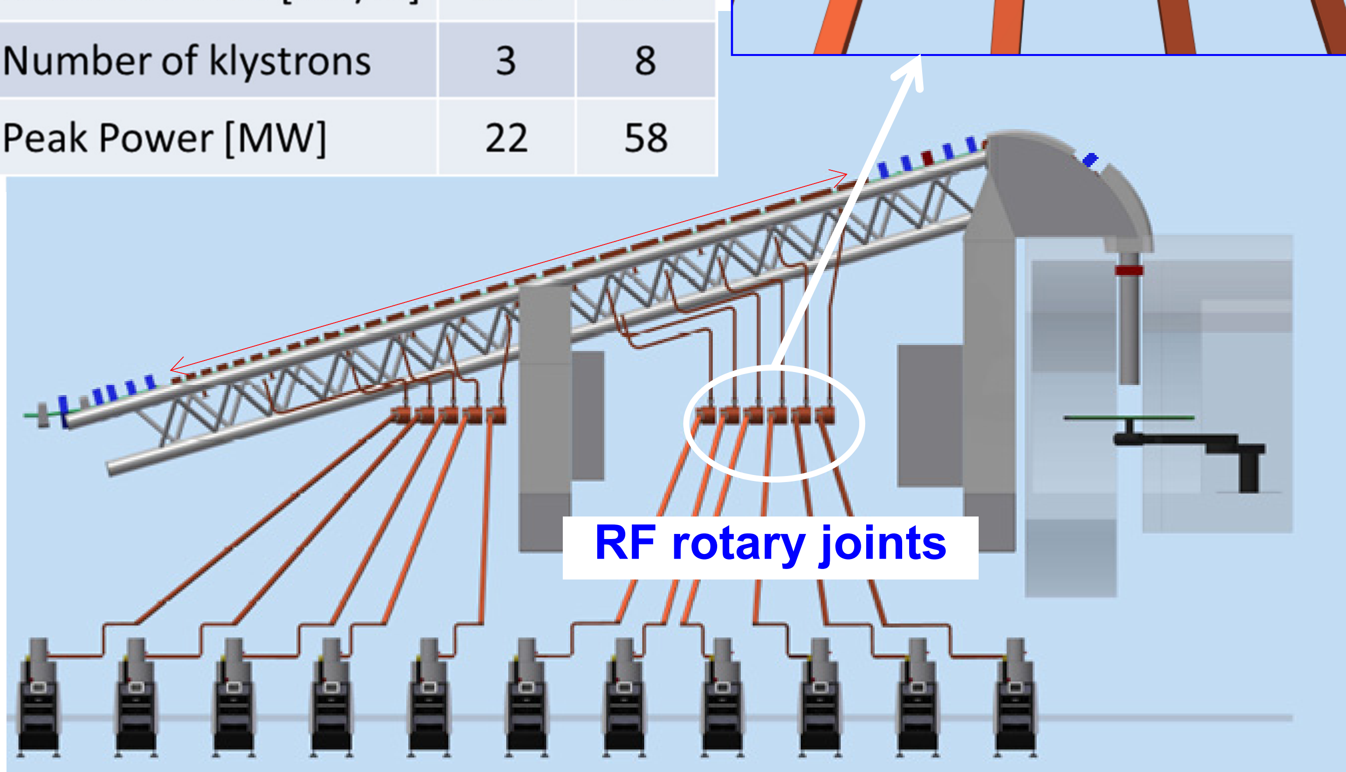


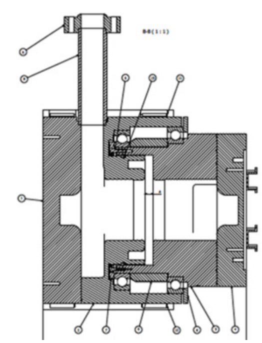
TULIP linac at 3 GHz with RF rotary joints

Quantity [unit]	Sec.1	Sec. 2
Total length [m]	3.4	7.9
Output energy [MeV]	70	230
Avg. axial field [MV/m]	22.8	29.4
Max. surf. field [MV/m]	150	170
Number of klystrons	3	8
Peak Power [MW]	22	58

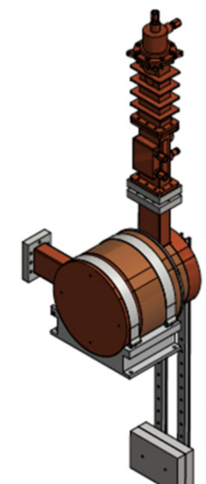




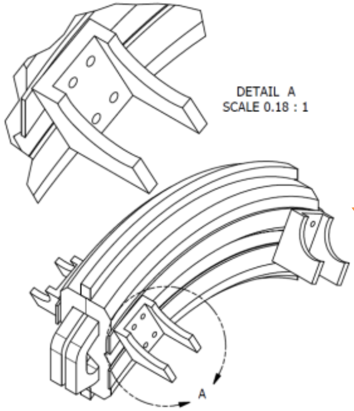


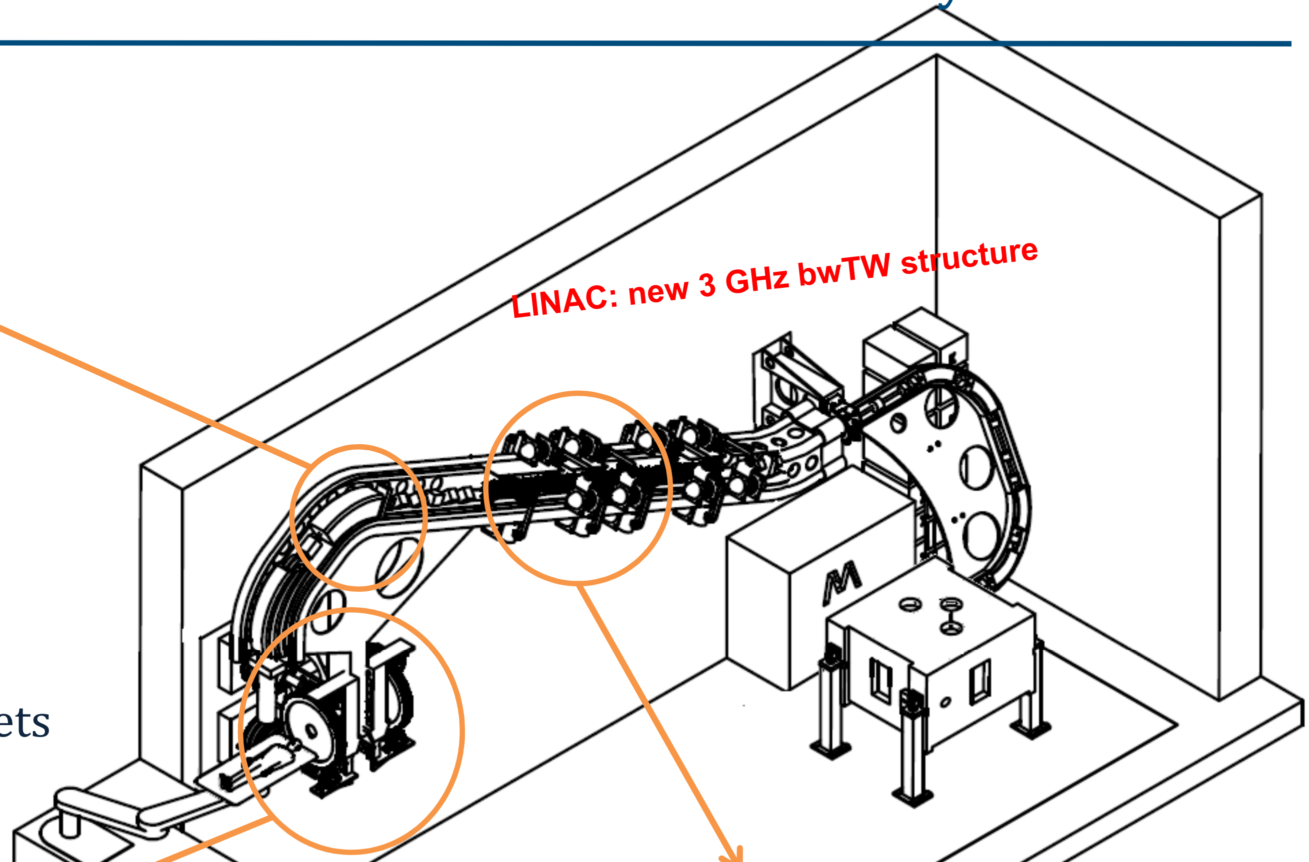


Design collaboration TERA-CERN

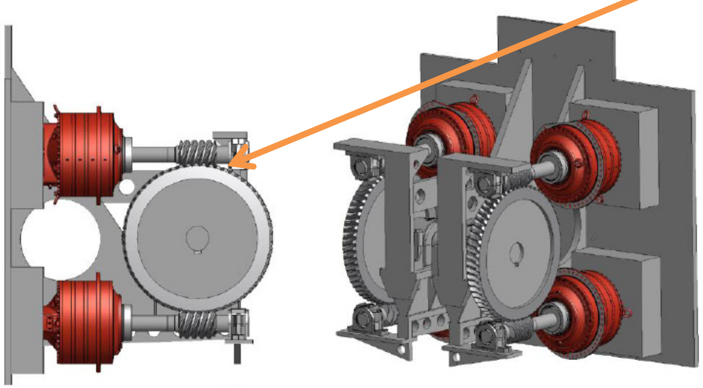


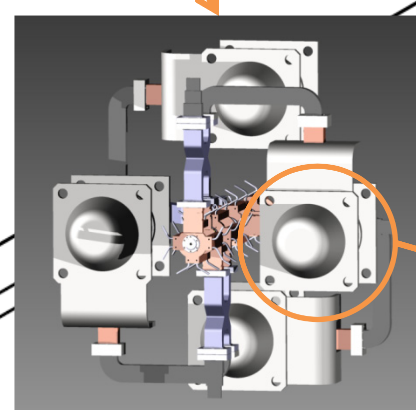
TULIP linac at 3 GHz with bwTW linac and new klystron





- Linac: 18 tanks, 18 klystrons and RF wave splitter.
- Total weight of magnets and Linac < 20 tons





PSI's IMPULSE project

- <u>New imaging: proton radiography</u>

Measure residual proton range after passing trough whole body

More precise input for treatment planning

- <u>New treatment modality: High Energy Proton Treatment</u>

Reduce the lateral penumbra to similar levels of carbon beams

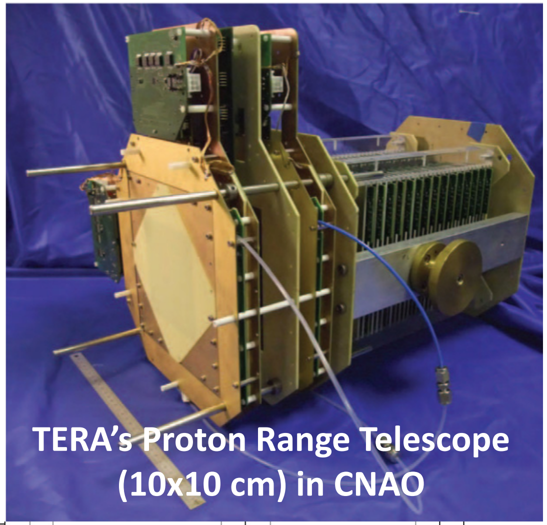
Treating small volumes close to critical organs

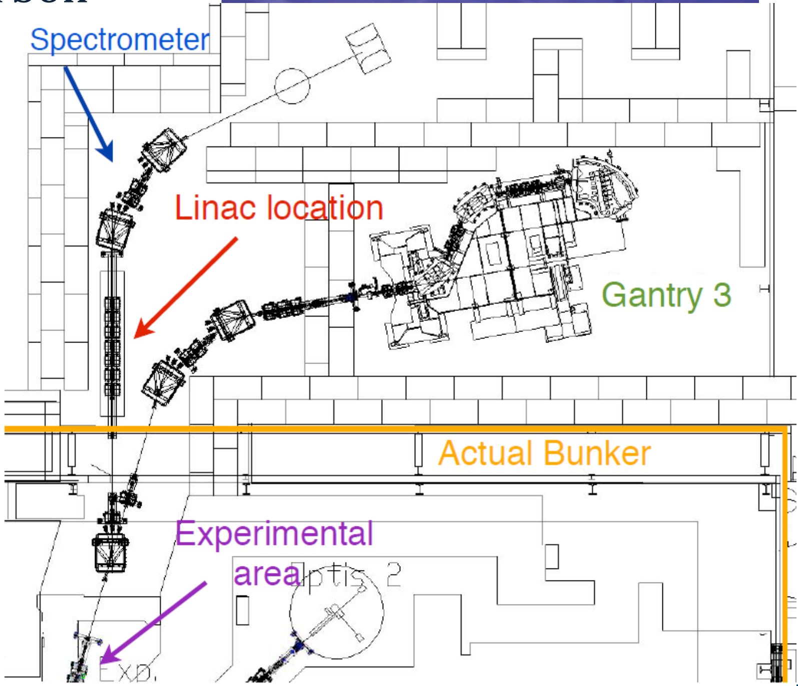
- <u>Linac booster for 250-350 MeV protons</u>

7 m long, compatible with available space at PSI or other centers

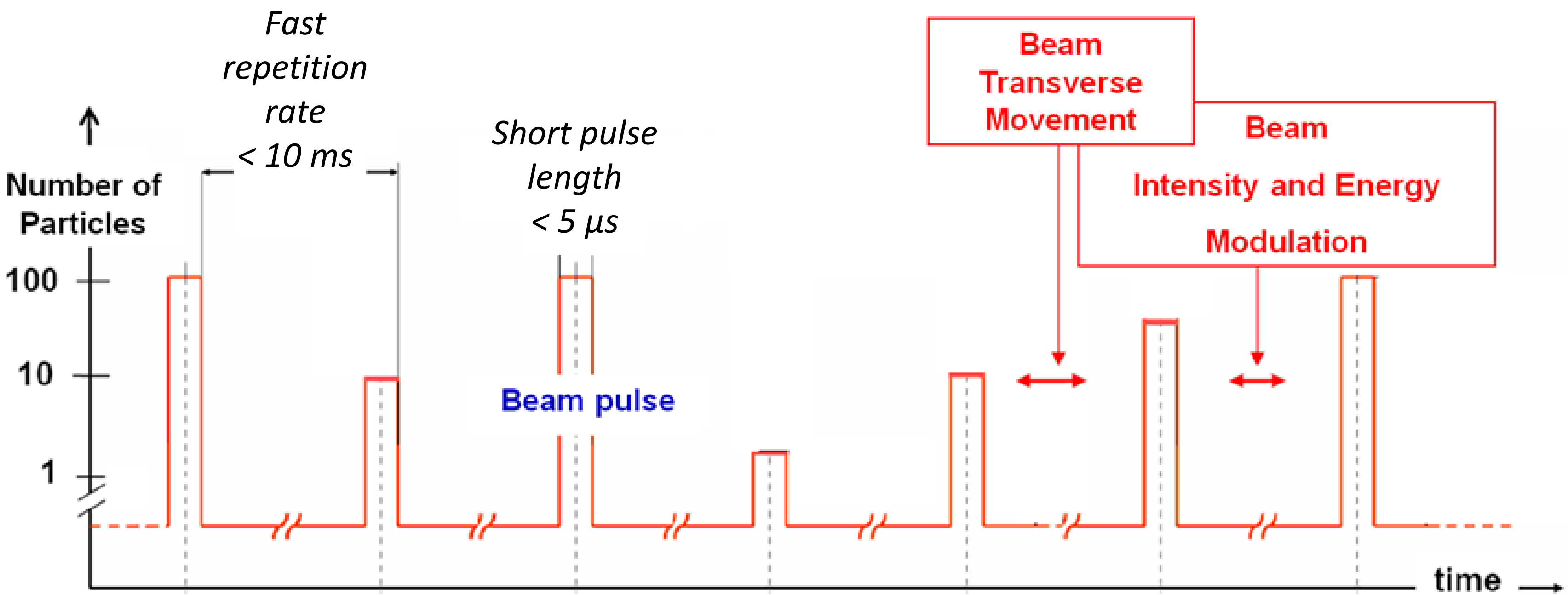
MSc thesis, J. Bilbao de Mendizabal, UNIGE, 2012

PhD thesis, A. Degiovanni, EPFL, 2014





Linacs are interesting future candidates



- Requires dedicated High Energy Beam transfer line optics:

Small aperture

Small dispersion and chromaticity

Fast field regulation

Thank you for the attention and interest !

• <u>Coupling cyclotron to linacs enables:</u>

1. reduction of the accelerator **footprint** (size and power consumption)

2. **modular/staged approaches** in terms of investment and clinical goals

3. **new advanced treatment and imaging** modalities