Workshop on Innovative Delivery
Systems in Particle Therapy
Torino, 23-24th February 2017

Advanced Linac Solutions for Hadrontherapy

A. Garonna on behalf of Prof. U. Amaldi
V. Bencini, D. Bergesio, D. Carrio Perez, C. Cuccagna, E. Felcini, P. Riboni, M. Varasteh

TERA Foundation

Disclaimer: many thanks to **S. Benedetti (CERN)**, **A. Degiovanni (ADAM),**
M. Vaziri (UC Merced) and F. Wenander (CERN) for their contribution to these slides

TErapia con Radiazioni Adroniche

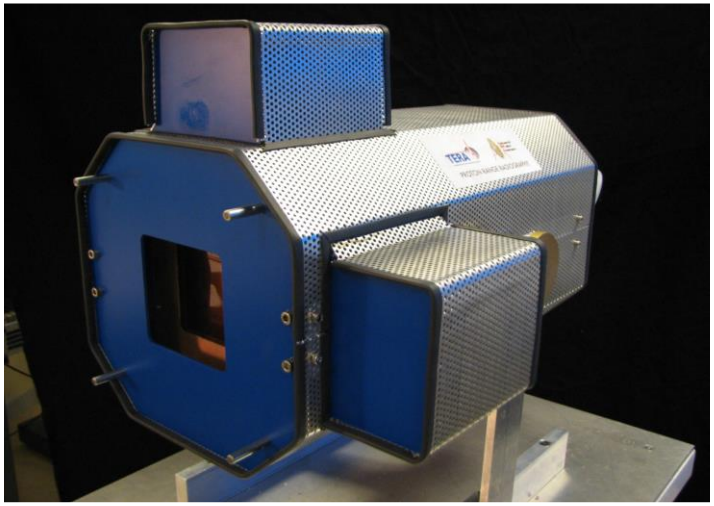
Foster the applications of physics and computing to medicine and biology

- *Proton Ion Medical Machine Study (PIMMS) with CERN*
- *Italian National Center of Oncological Hadrontherapy (CNAO)*
- *> 200 professionals trained*

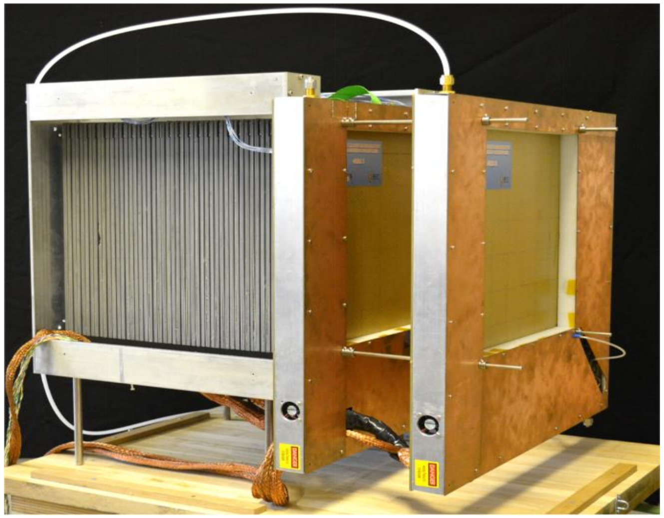
CNAO (3 rooms, 1000 patients treated)

Detectors

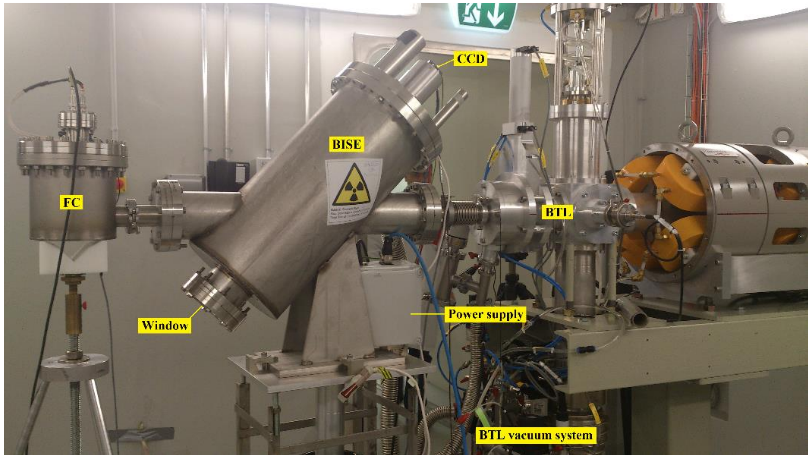
PRT10@CNAO



PRR30 (Proton Range Radiography system for Hadrontherapy)

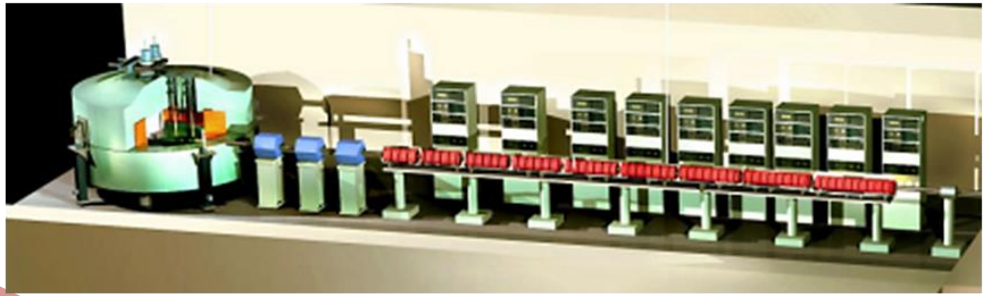


The BISE detector installed at the Bern radioisotope production center

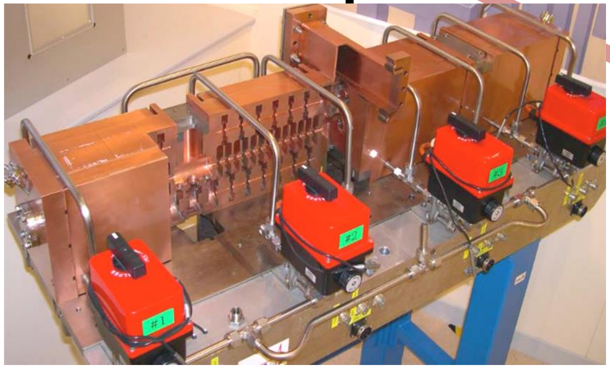


Timeline of the Cyclinac Concept

1993: first Cyclinac proposal



2002: LIBO (TERA-CERN-INFN)

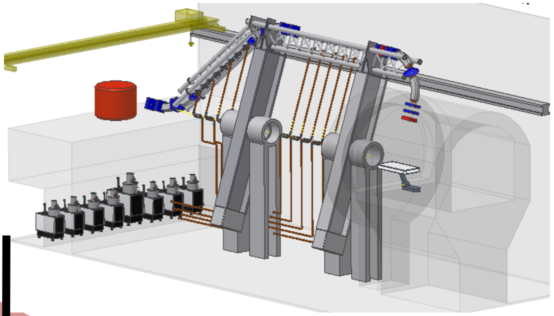


3 GHz linac (62-74 MeV)

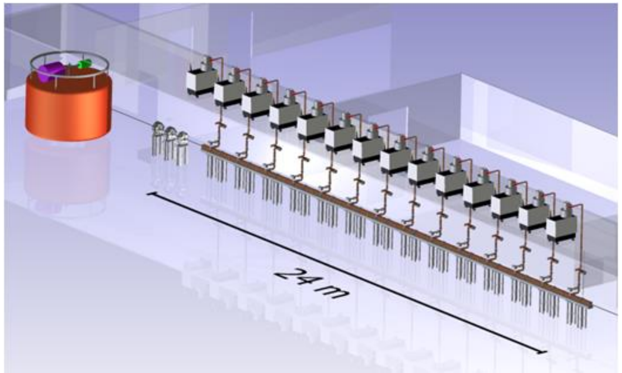
[C. De Martinis et al,NIM A 681 (2012)]

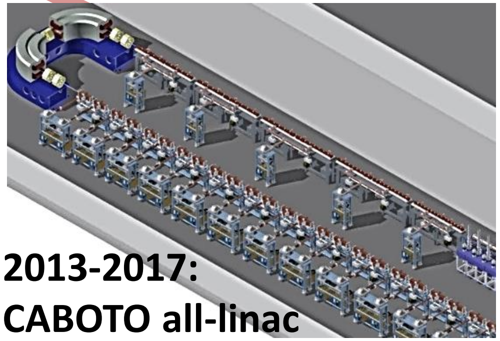
11.2010: LIGHT 1st UNIT

2011-2013: TULIP



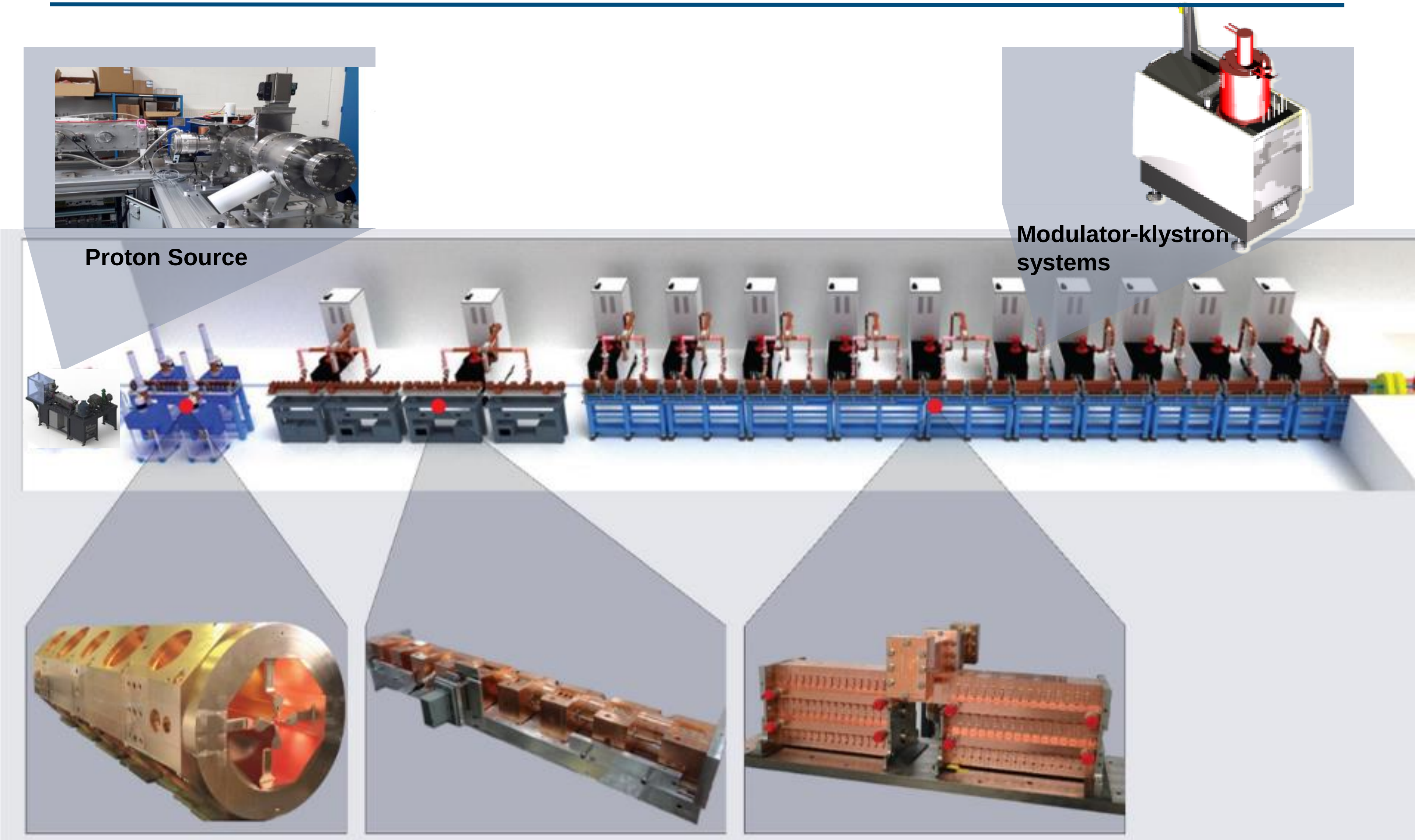
2008-2011: CABOTO-C design





2013-2017: CABOTO all-linac

ADAM's Linac for Image Guided Hadron Therapy



Radio Frequency Quadrupole (RFQ)

Side Coupled Drift Tube Linac (SCDTL)

Coupled Cavity Linac (CCL)

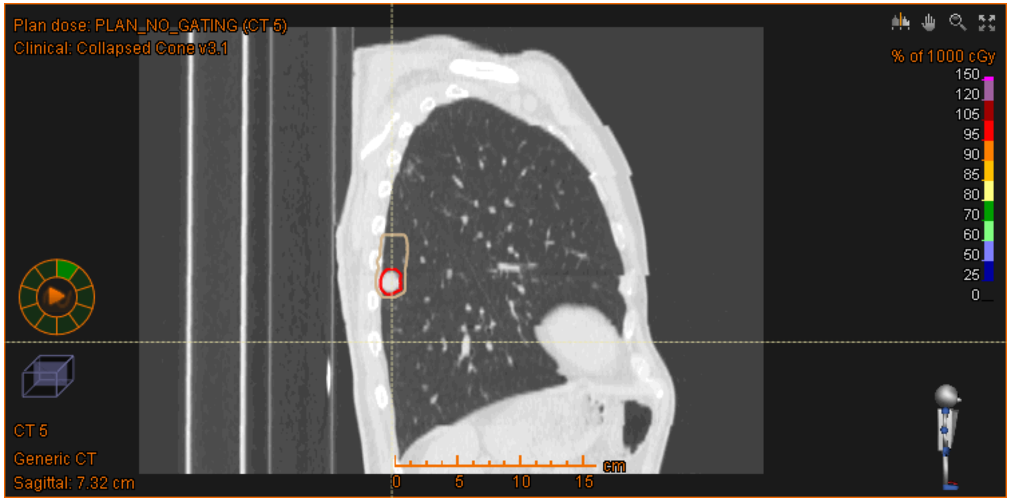
Hadrontherapy modern technical challenges

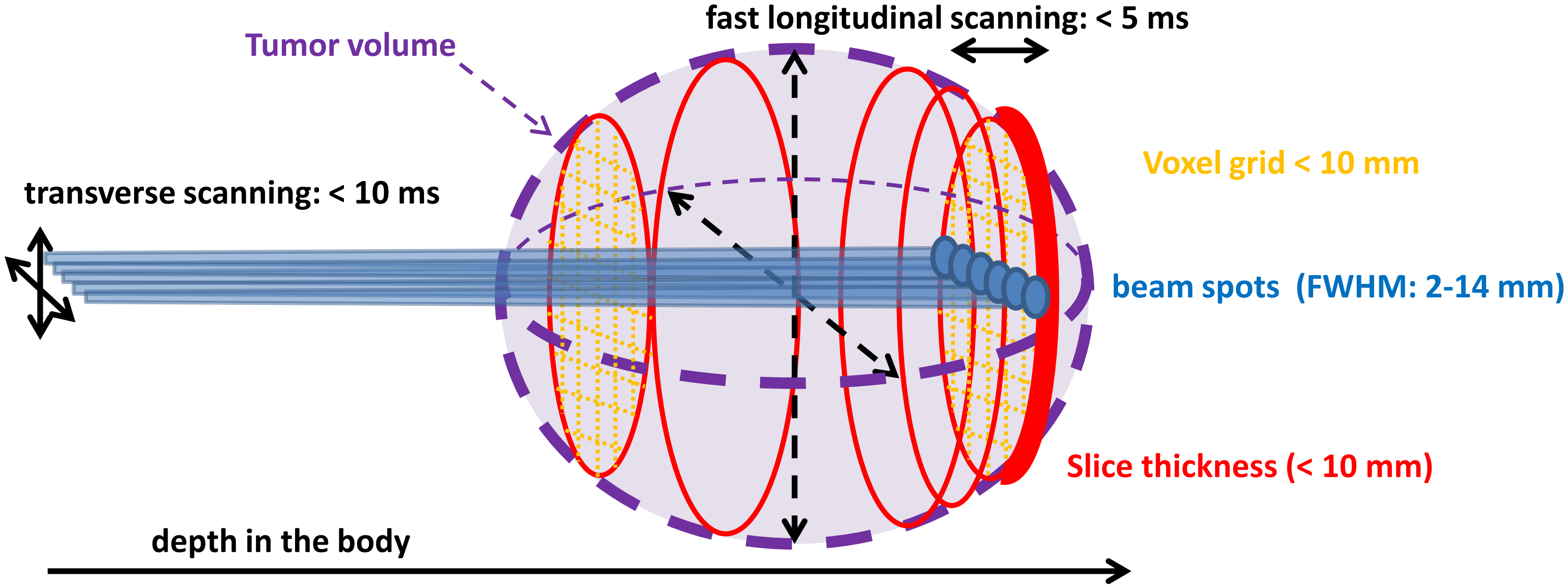
Treatment of **moving organs** requires:

a) 3D **feedbacks**

b) 3D **spot scanning**

c) **multipainting**



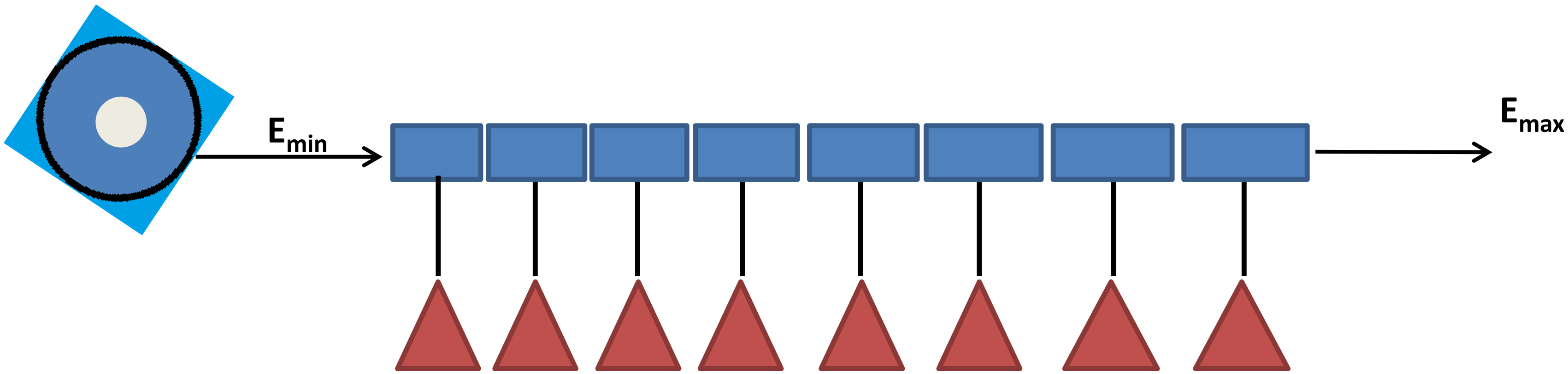


Linac systems components

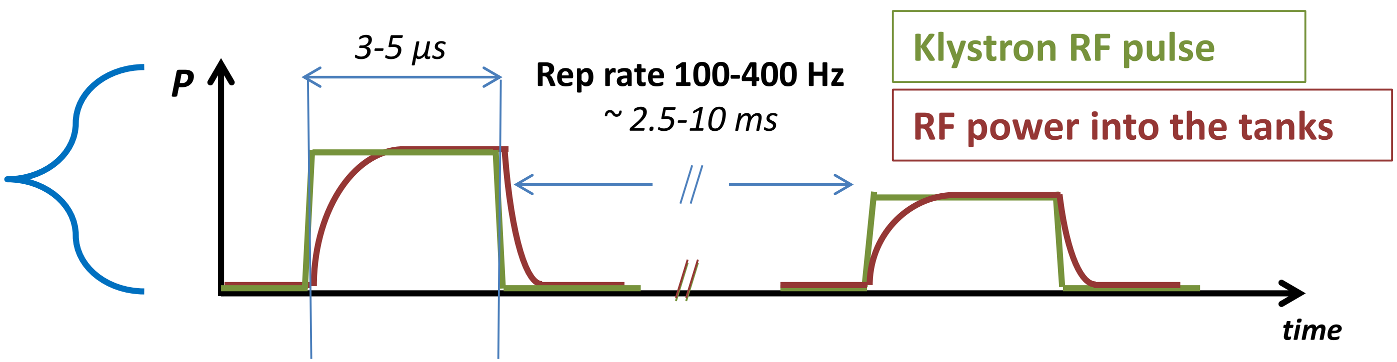
Cyclotron or RFQ+DTL

- Compact
- Power efficient

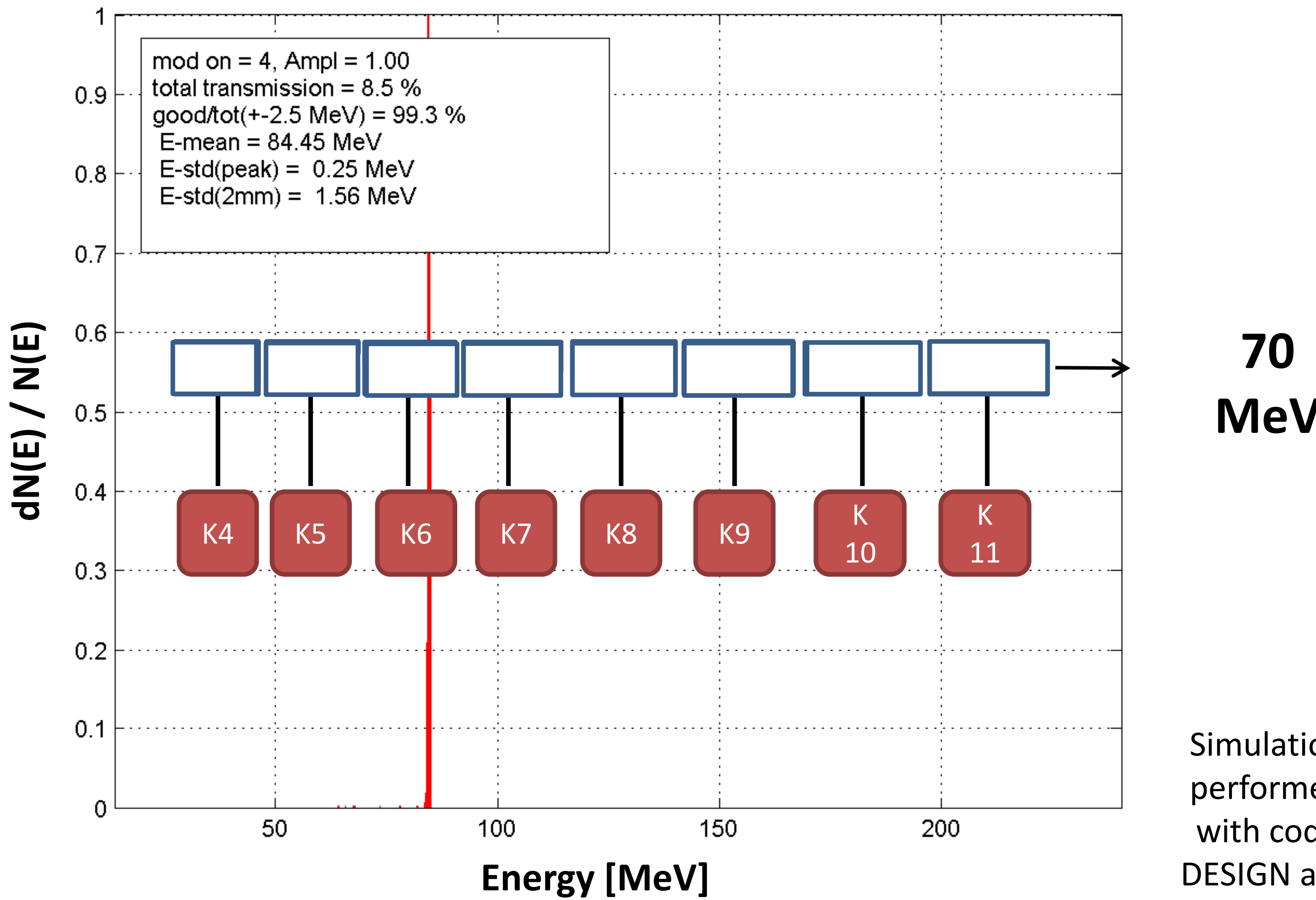
- High transmission
- Low emittance



Active energy modulation **controlled in klystron**



Linac beam



Simulation performed with code DESIGN and LINAC

CABOTO: CArbon BOoster for Therapy in Oncology

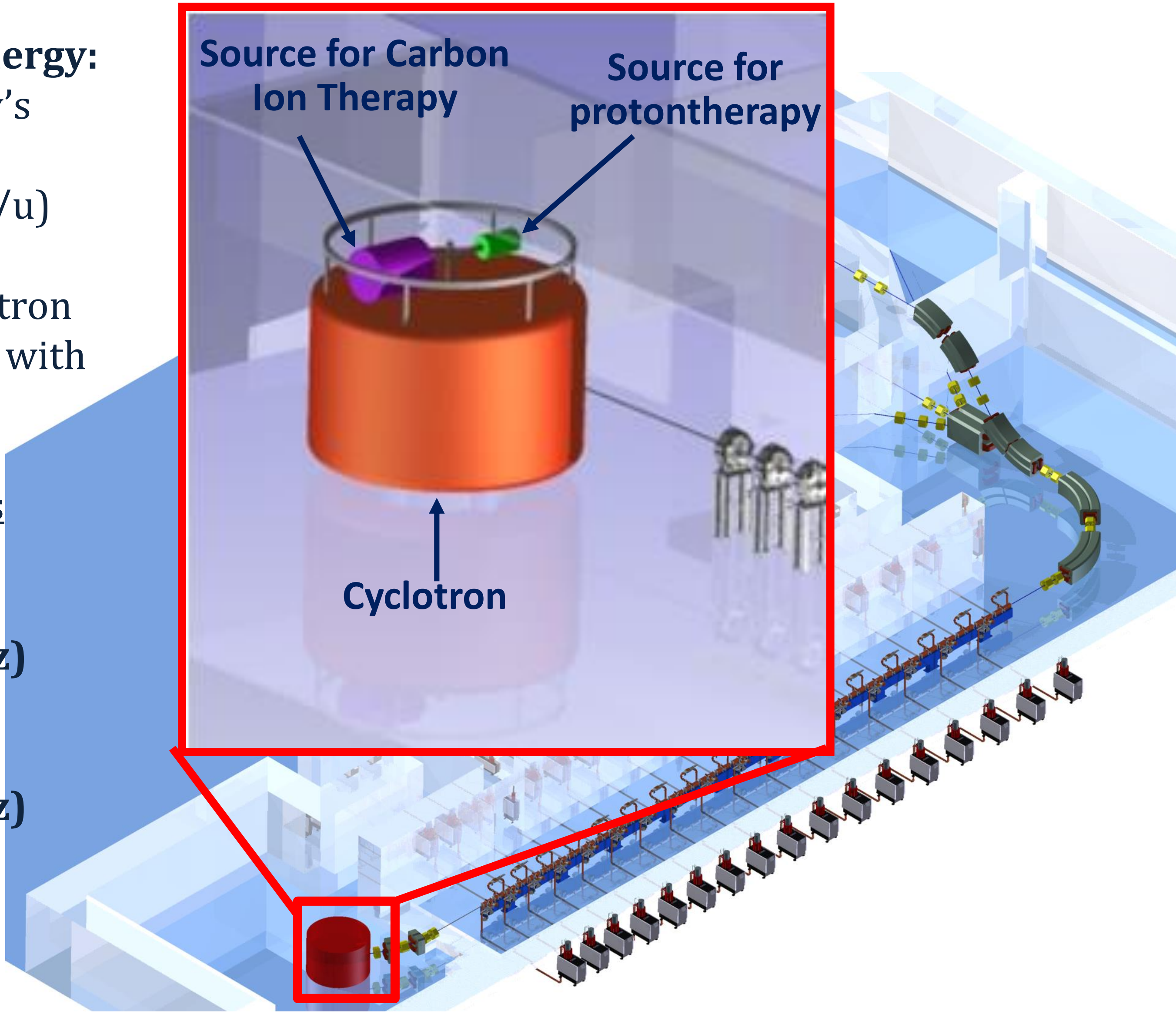
- **Cyclotron output energy:**
Choice linked to facility's clinical goals
(70 MeV/u – 230 MeV/u)

Superconducting Cyclotron design in collaboration with INFN-LNS

- External ion sources

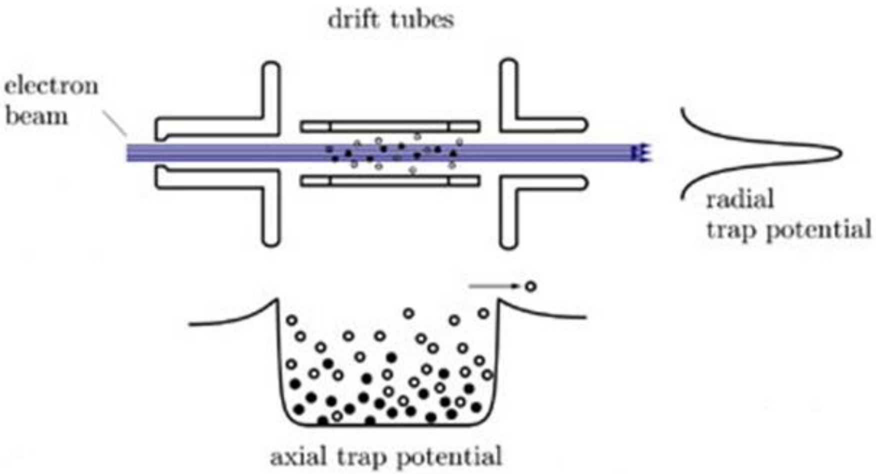
2 10^{10} H_2^+
in **1.5 µs** pulse (**100 Hz)**

1 10^8 C^{6+}
in **1.5 µs** pulse (**300 Hz)**

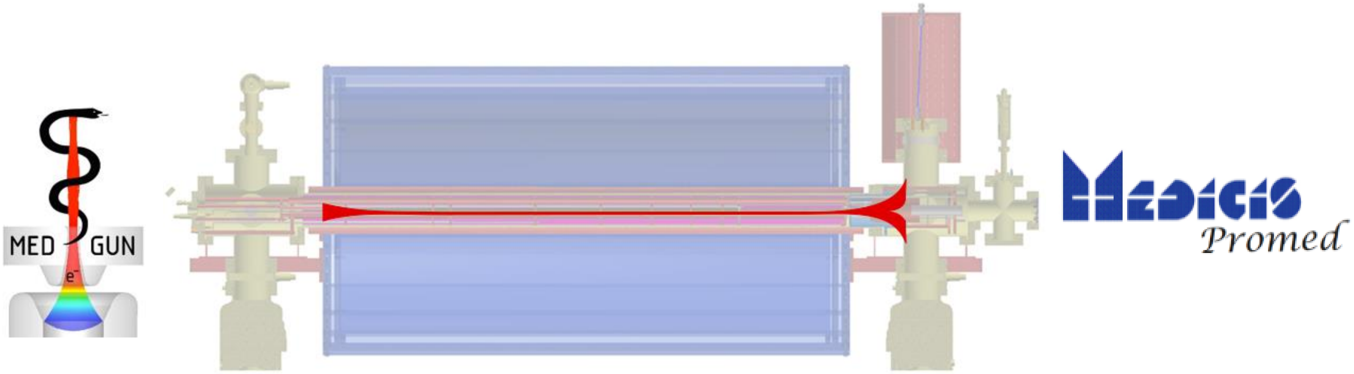


Superconducting EBIS

(courtesy of Zschornack, Dreebit Gmbh)



- Large magnetic fields and intense electron guns allow to produce **fast ionization**
- Pulsed operation at **high repetition rate** is possible
- **Very small emittances** are produced (< 0.1 µm rms normalized)
- Others: Krion-2 from JINR and EBIS-SC from Dreebit Gmbh



CERN's MEDeGUN

Example: CERN's MEDeGUN

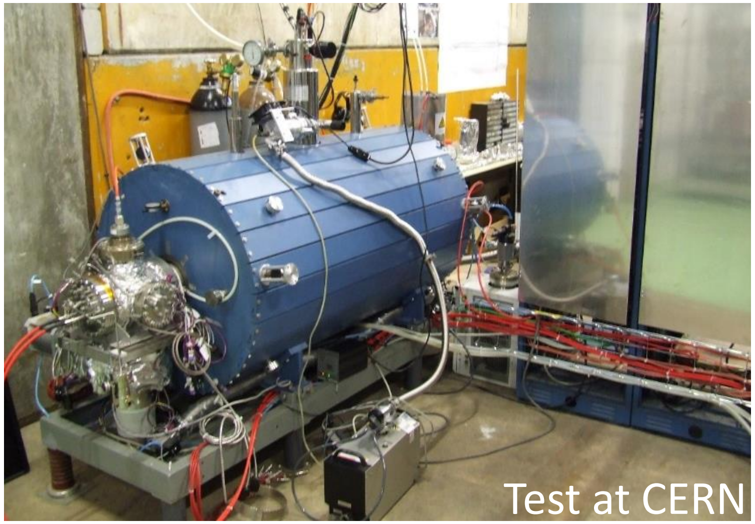
- **Dedicated EBIS** source with high-compression Brillouin electron gun

- Low **electron beam energy optimized for C^{6+}**

- **Short pulse lengths** <5 µs pulses

- **Assembly of last pieces ongoing** and first electron beam test will start soon

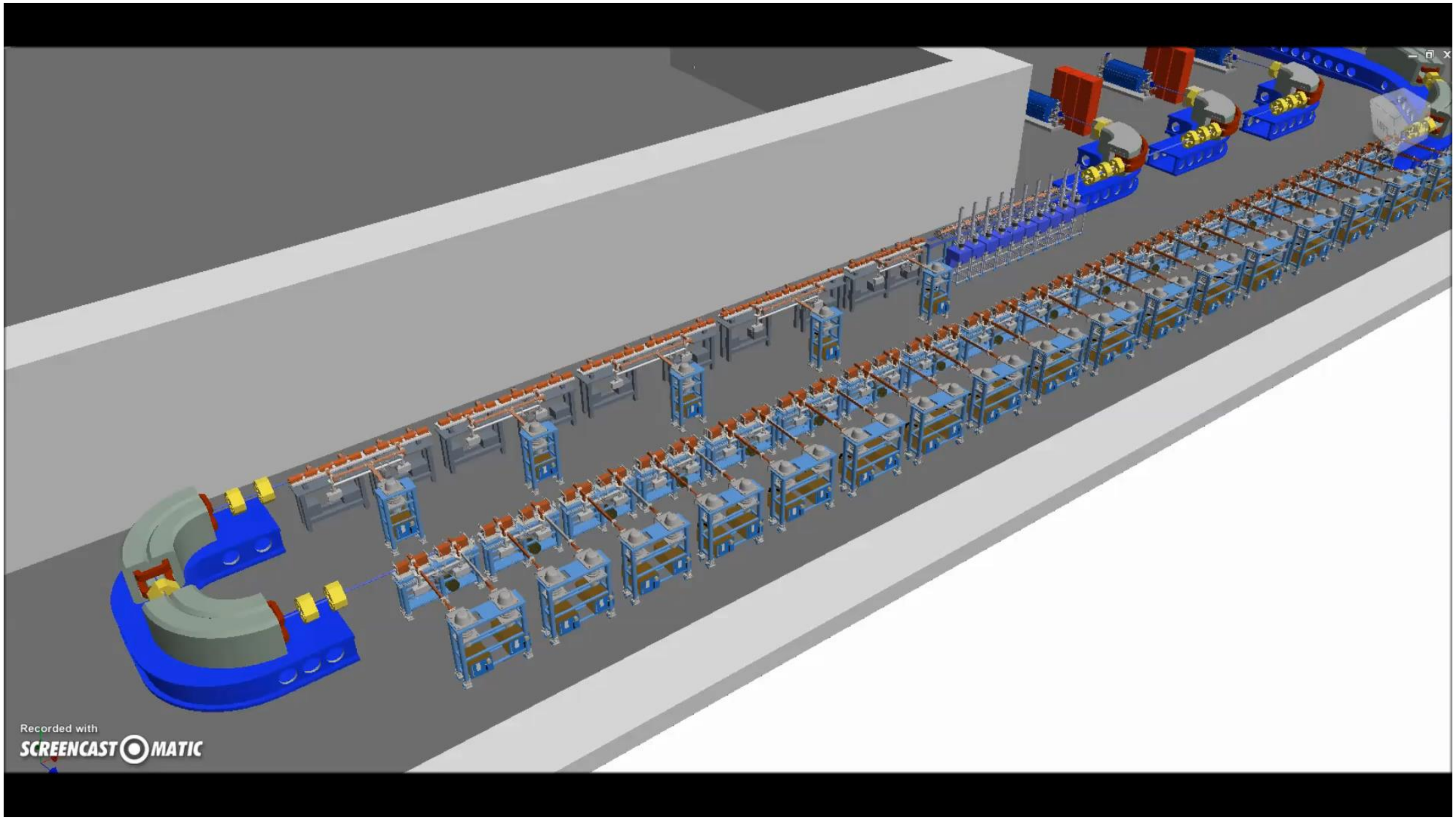
Design Parameter	MEDeGUN
Test site	TwinEBIS, CERN
Main magnet	2 T
Trap length	0.25 m
Electron current	1 A
Current density	1.5 kA/cm^2 (3.5 kA/cm^2, 5 T)
Electron energy	7.5-10 keV
Capacity C^{6+}	up to $1\cdot10^9$ ions per pulse
Repetition rate C^{6+}	180 Hz (440 Hz, 5 T)



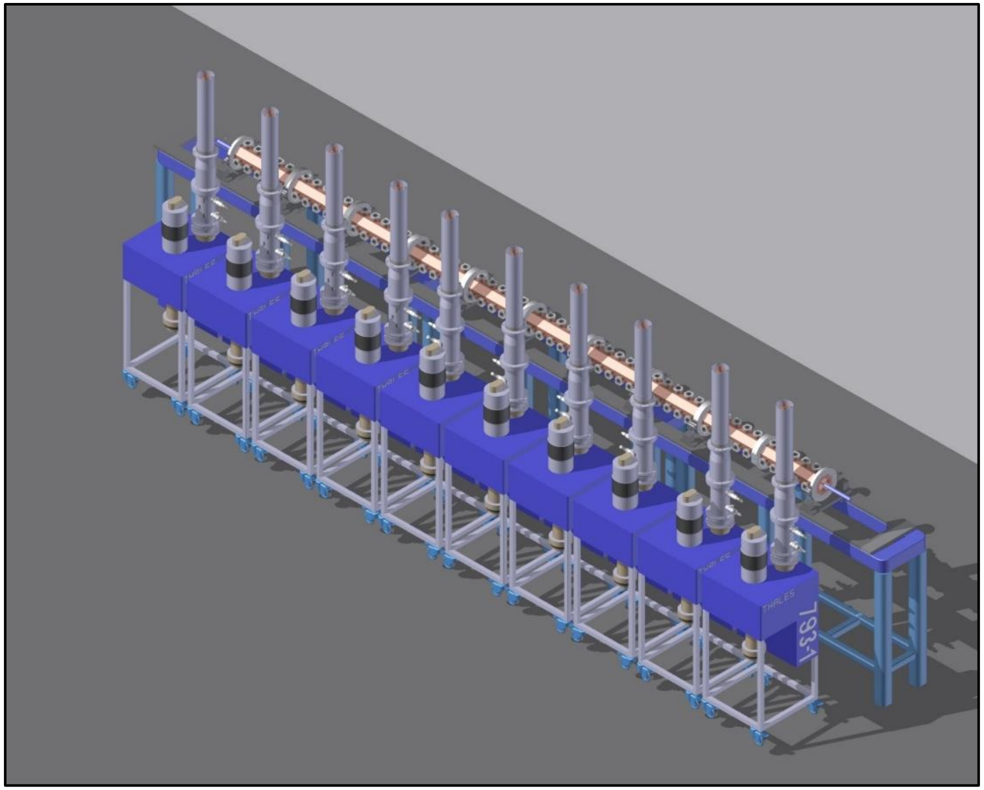
* R. Mertzig et al., *"A high-compression electron gun for C^{6+} production: concept, simulations and mechanical design"*, to be published

* 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: all-linac

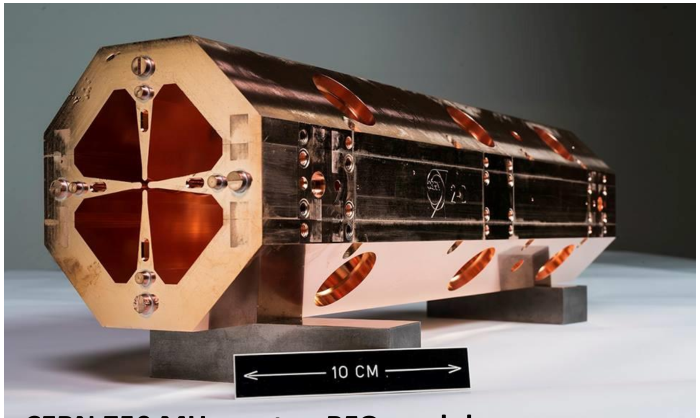


The RFQ (Lombardi et al. CERN)



- bunching and acceleration of the beam up to 5 MeV/u
- Highest frequency RFQ in the world (750 MHz)
- Proton RFQ built and presently under commissioning
- Based on the same technology, a C^{6+} RFQ is being designed

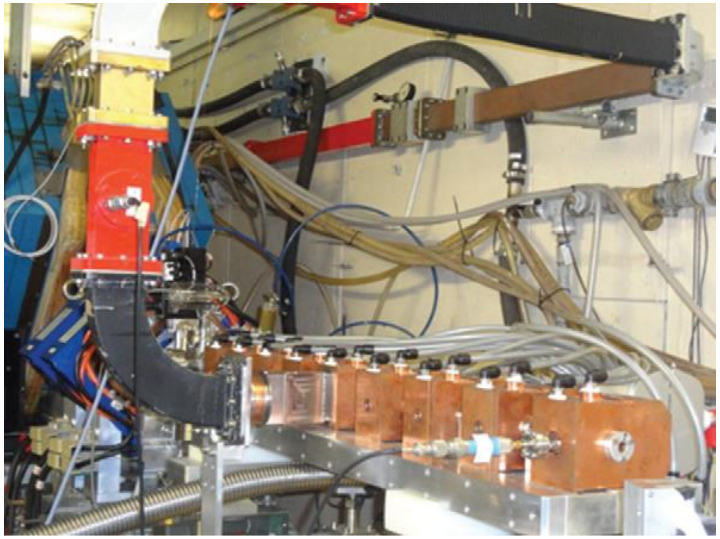
$\varepsilon_x=\varepsilon_y$ [Norm. RMS]	0.025 pi mm mrad
ε_z [Norm. RMS]	0.125 pi deg MeV



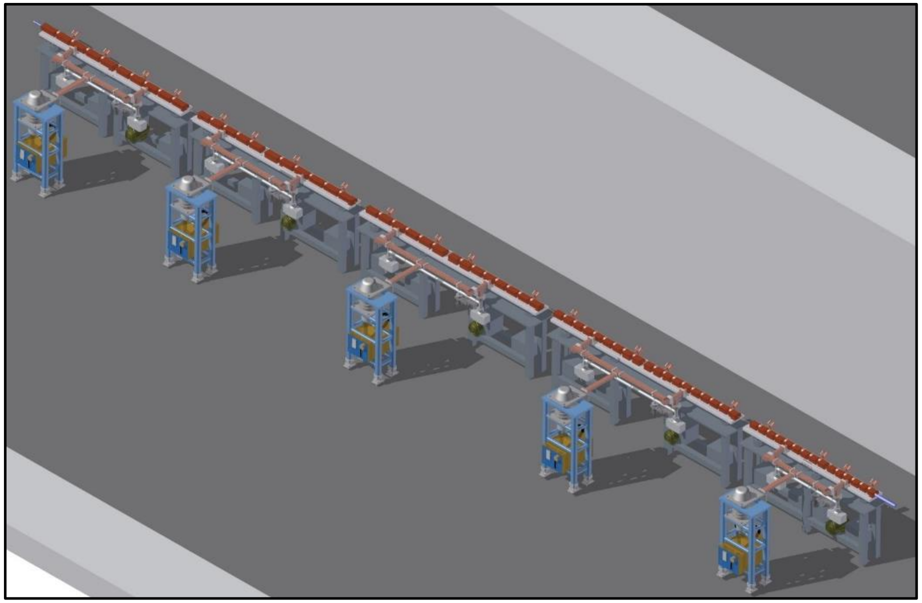
CERN 750 MHz proton RFQ module

The SCDTL (Picardi et al. ENEA)

- Low energy acceleration: C^{6+} up to 70 MeV/u
- 5 Klystrons, 18 m long
- 14 MV/m average active gradient
- 3 GHz design

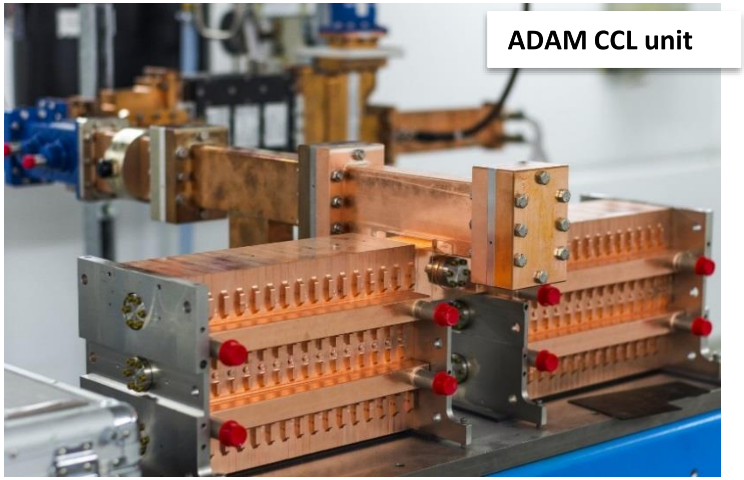


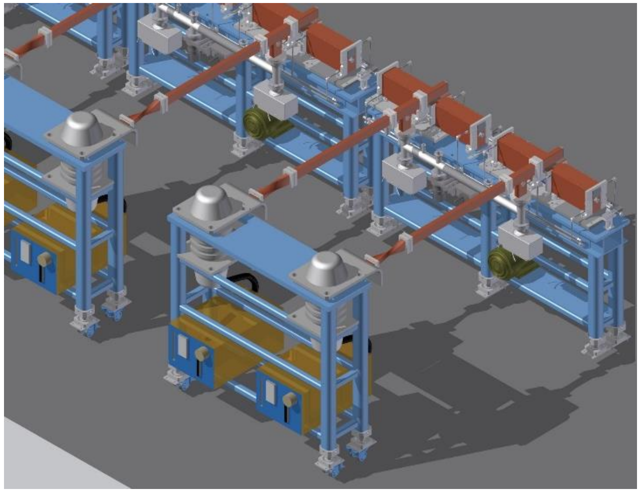
ENEA Frascati SCDTL unit test



CCL (TERA-CERN-INFN) based on LIBO (62-73 MeV)

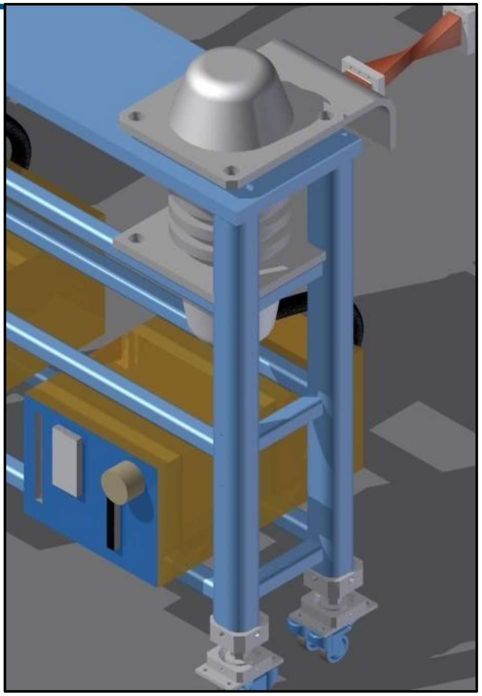
- The final accelerating section of CABOTO
- Will bring the beam up to 430 MeV/u, and be able to vary this energy in the range 100 MeV/u – 430 MeV/u
- 34 Klystrons, 34 m long
- 28 MV/m average active gradient
- No technical limits in increasing even further the final energy



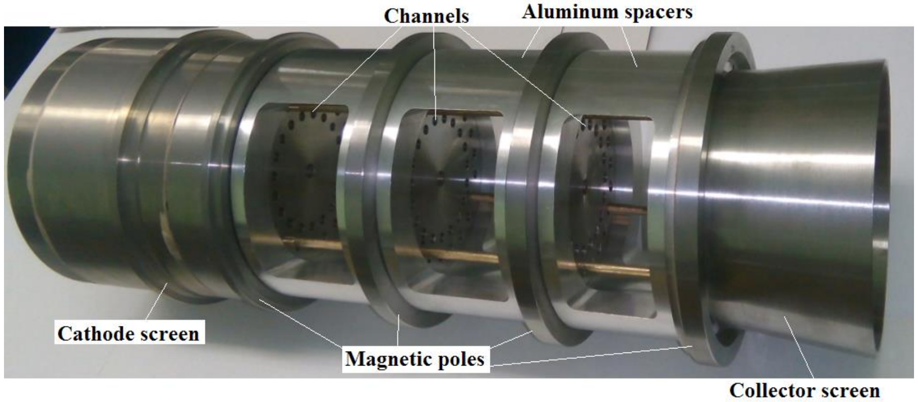


RF power source (Syratchev et al. CERN)

- New Klystron design dramatically increases efficiency wrt current available technology
- Assembly at VDBT (Russia) and tested at CERN
- 77% predicted Klystron efficiency, achieved 60 %
- 6.5 MW peak power, 90 kg, 0.9 m long



6 MW VDBT MBK



7.5 MW VDBT MBK

Overall parameters

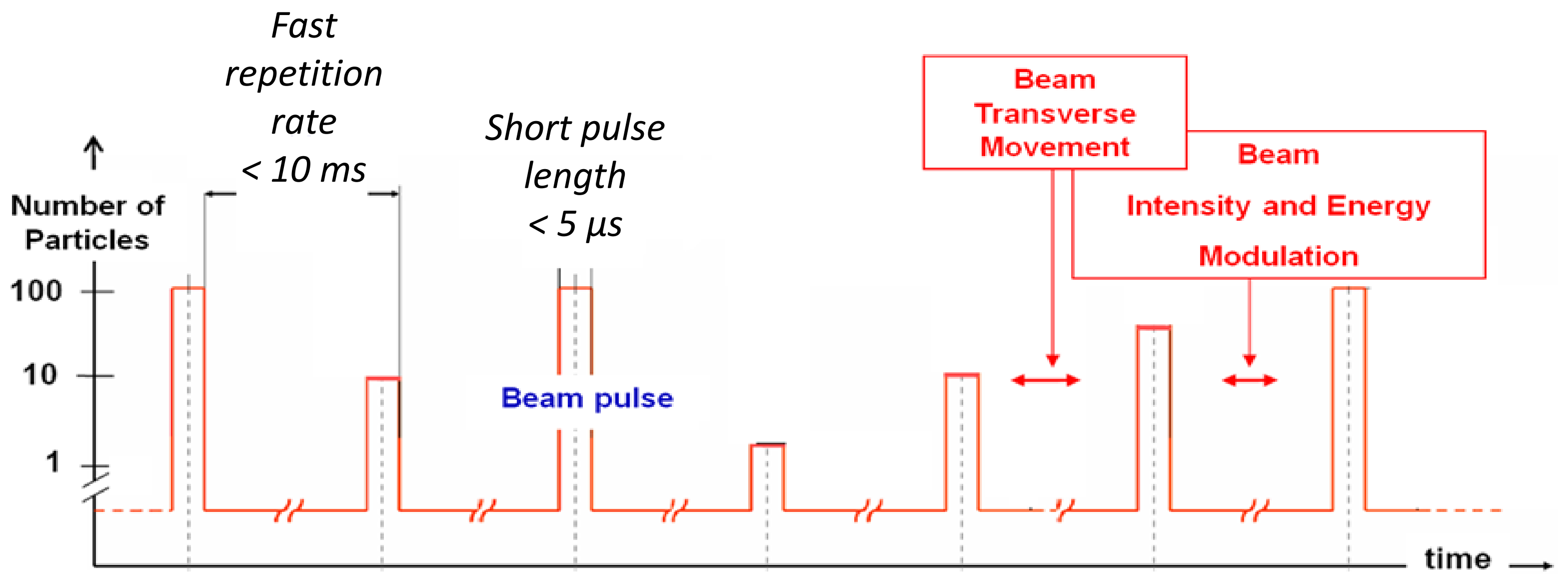
- Overall transmission of about 75%

Section	RF Peak Power	RF Avg Power*	Rel. contrib.
RFQ	1 MW	3 kW	0.4 %
SCDTL	40 MW	100 kW	13 %
CCL	260 MW	700 kW	87 %
MAX POWER	300 MW	800 kW	-

*With $Duty\ Cycle = 1.8 * 10^{-3}$ (Rep. Rate 360 Hz, 5 μs RF pulse length) and RF power sources efficiency of 65% (conservative)

- Conservative estimation of power consumption: 1.2 MW

Dedicated Beamlines

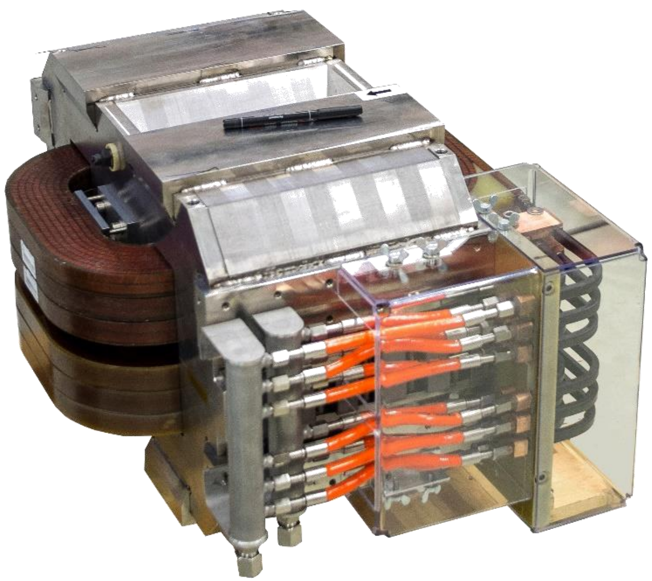


Requires dedicated High Energy Beam transfer line optics:

- **Small trans. emittance/aperture :** $\varepsilon_{norm\text{-}rms} \sim 0.3\ \mu m$
- **Large momentum acceptance :** Small dispersion and chromaticity

HEBT (Tommasini et al. CERN)

- Design based on CNAO layout with three treatment rooms
- Magnets and power supplies designed to follow beam energy variation at 200 Hz: FeCo prototype was built and tested
- Small beam emittance allows for small aperture magnets, thus reducing manufacturing and operational costs



CERN FeCo prototype

TUrning Linac for Protontherapy

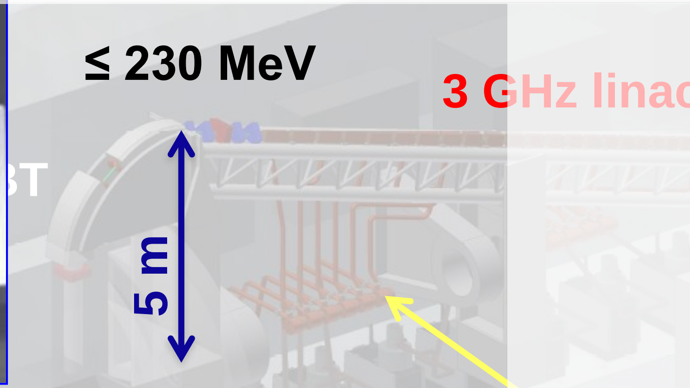
TUrning LInac for Protontherapy

TULIP

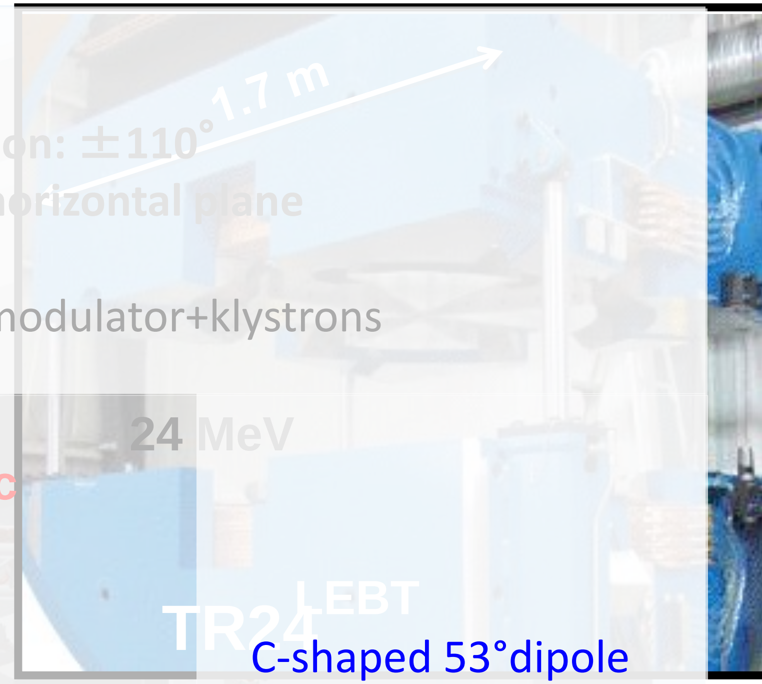
Rotation: ±110° wrt the horizontal plane

HEBT with momentum acceptance of ±2%

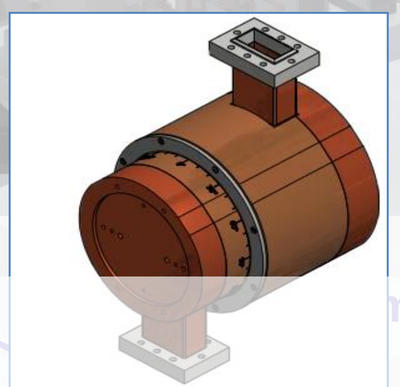
Commercially available 3 GHz modulator+klystrons



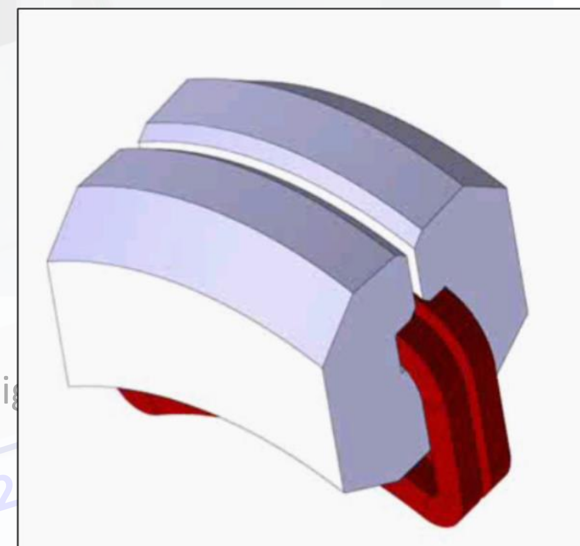
3 GHz Modulators +klystrons



C-shaped 53°dipole



RF rotary joints



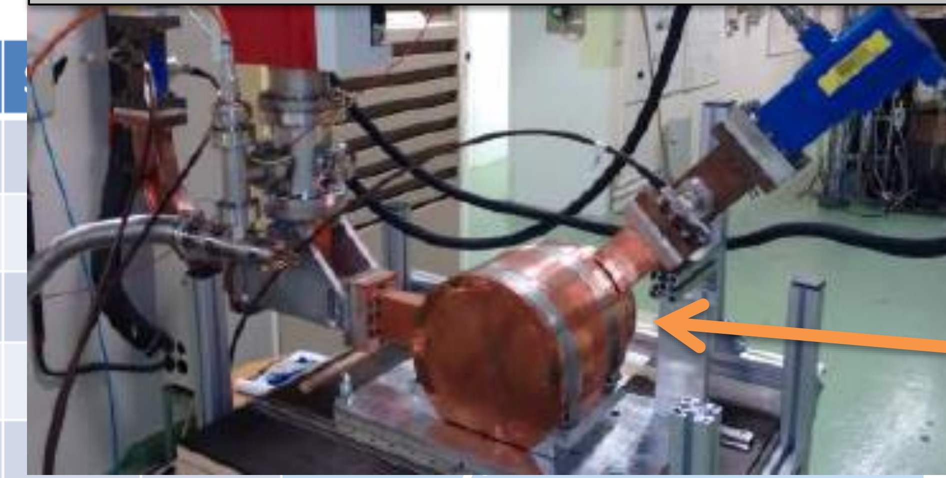
TERA-CERN desi

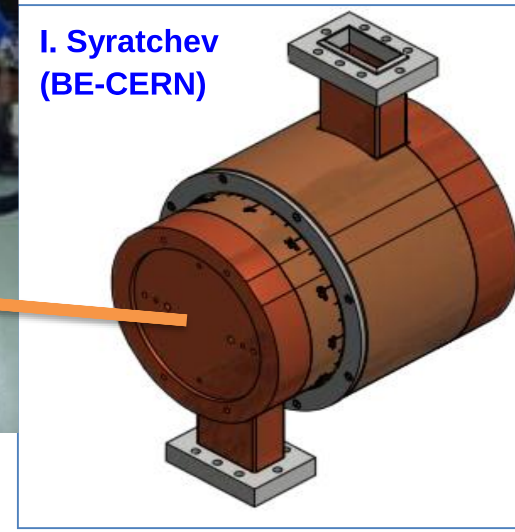
Design collaboration TERA-CERN

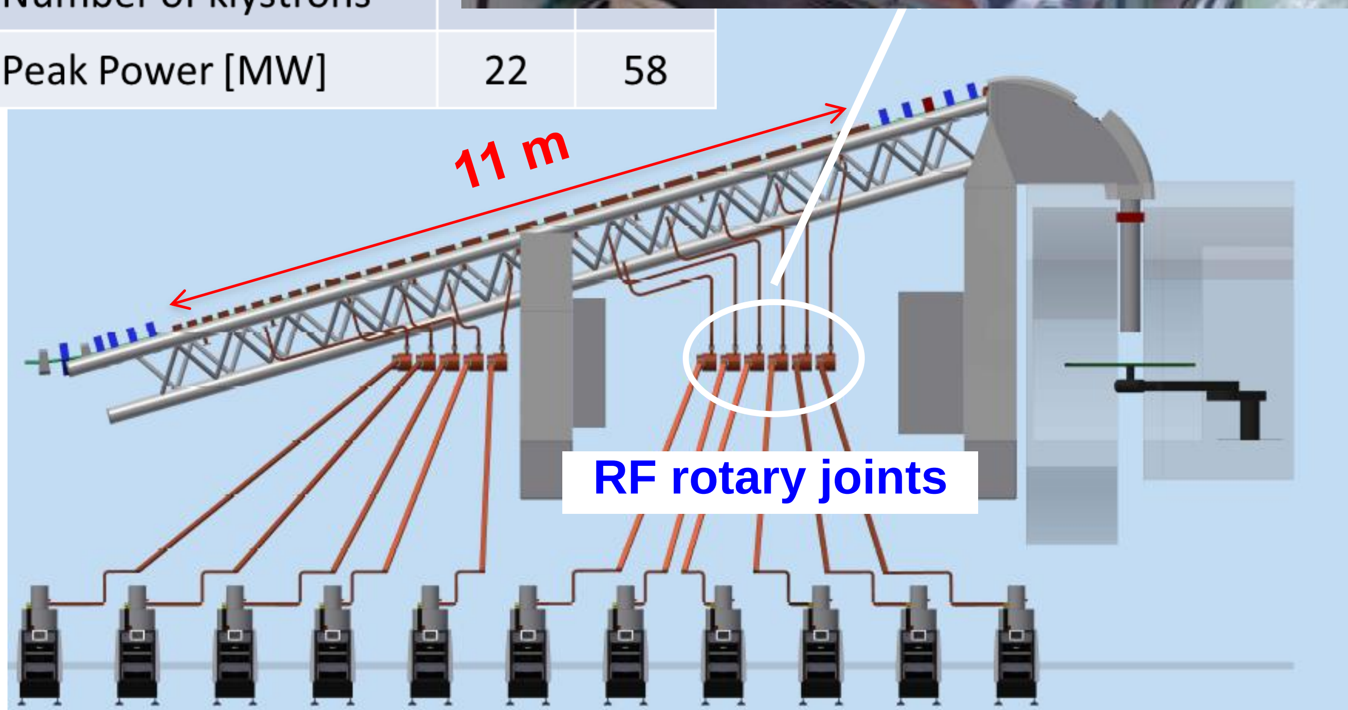
TULIP linac at 3 GHz with RF rotary joints

Quantity [unit]		
Total length [m]		
Output energy [MeV]		
Avg. axial field [MV/m]		
Max. surf. field [MV/m]		
Number of klystrons		
Peak Power [MW]	22	58

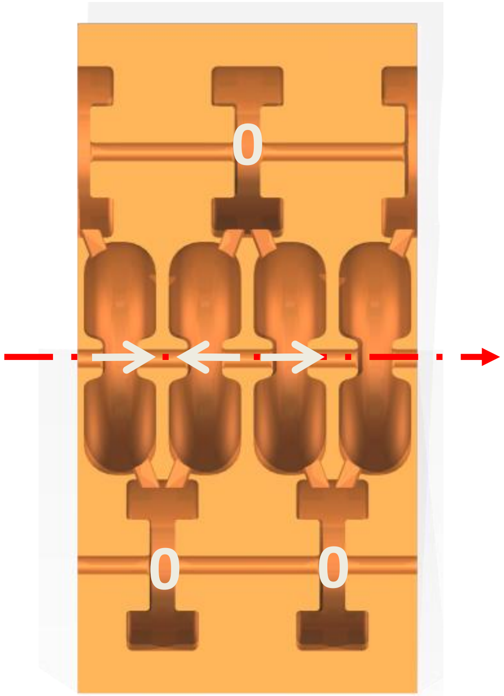
Setup of the high power test of the RJ in CTF2 at CERN.



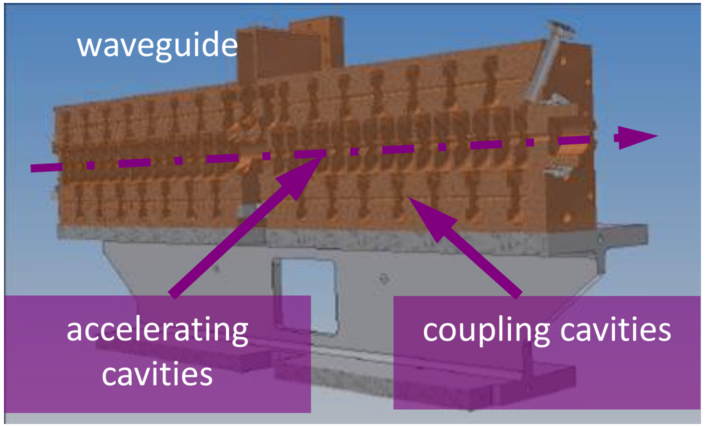


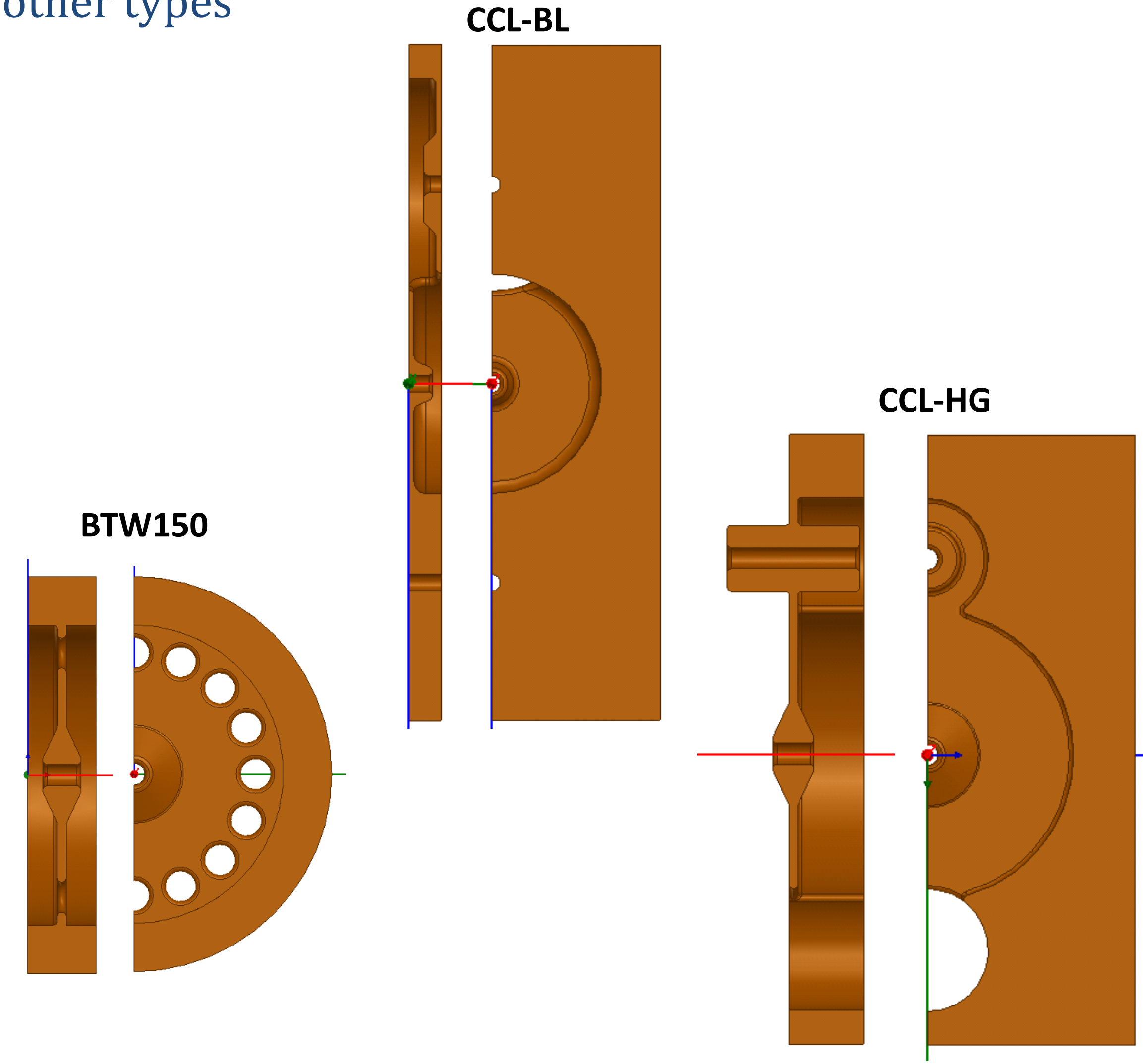


Research on high gradients and efficient structures



- Side Coupled Linac (RF cavities π/2 mode)
- Many other types



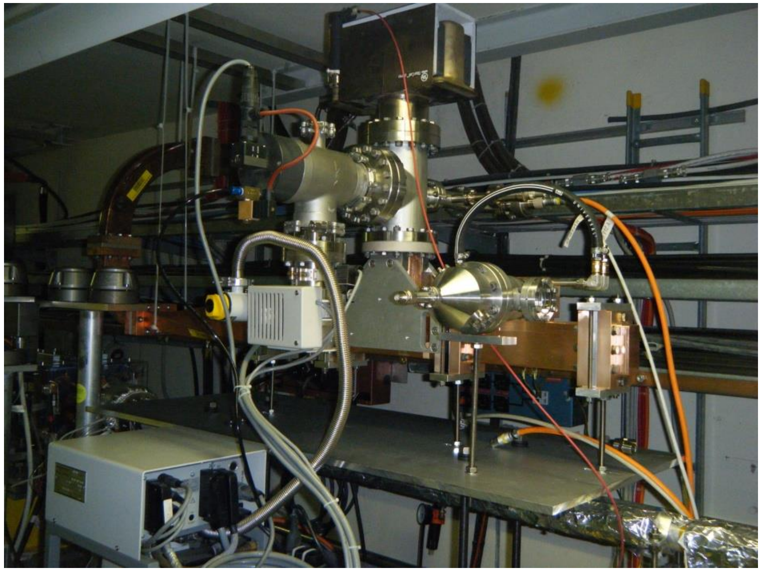


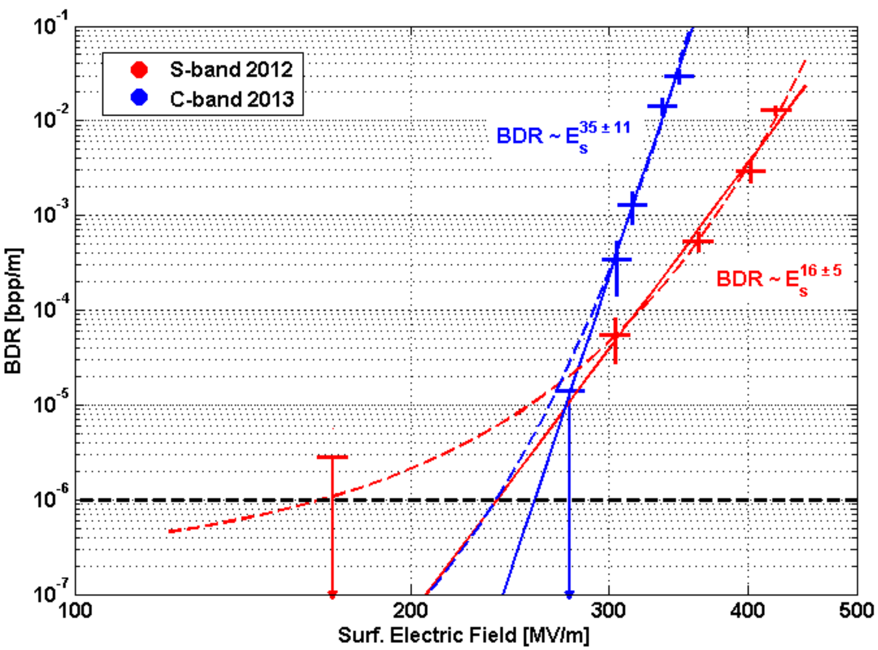
Research on CCL high gradients

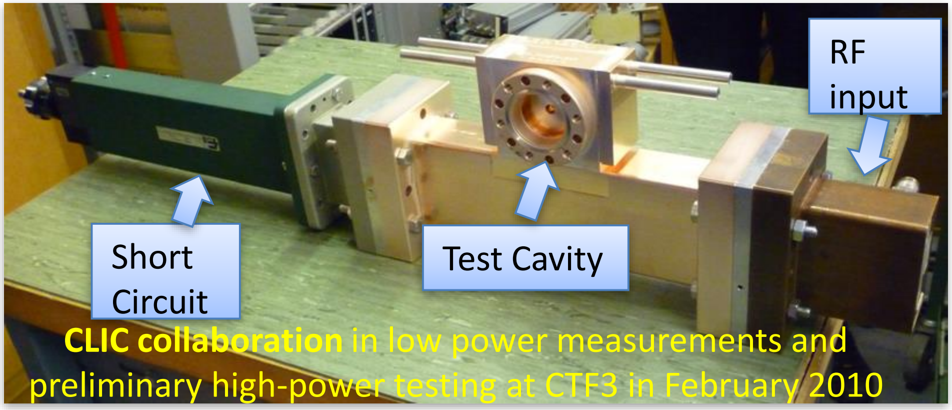
- Accelerating gradients of ~ 30 MV/m for CCL structures
- High gradient tests with CLIC at S-band and C-band

S. Verdú-Andrés et al, arXiv:1206.1930v2

A. Degiovanni et al, NIM A 657







Backward Traveling Wave prototype

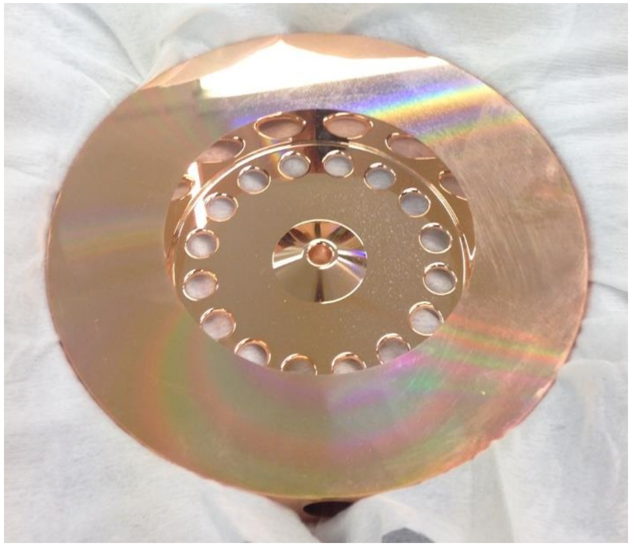
- Research program carried out in collaboration with CLIC (Syratchev et al.)

DESIGN GOAL and CONSTRAINTS

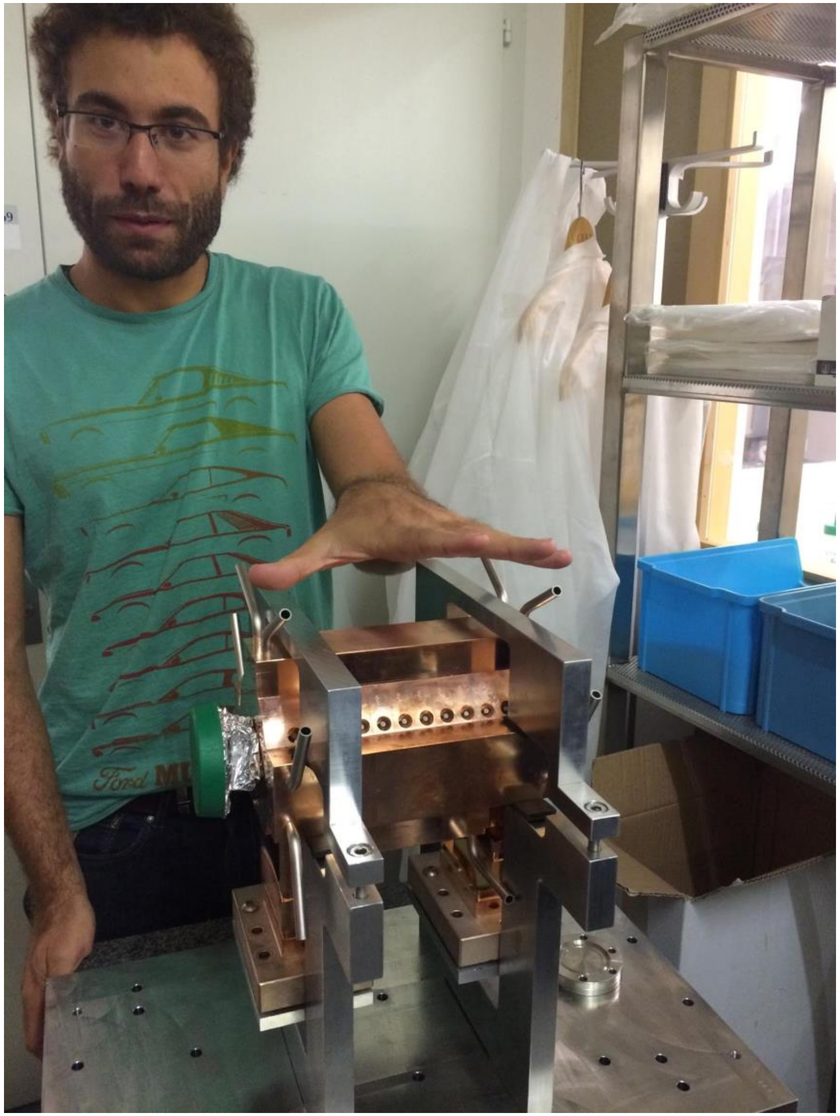
$E_a := E_0 T \geq 50$ MV/m → **Compact size**

$S_c / E_a^2 < 7\ 10^{-4}$ A/V → **Acceptable BDR**

- A structure for beta equal to 0.38 has been designed and successfully tuned
- successful candidate for the 30-80 MeV booster.

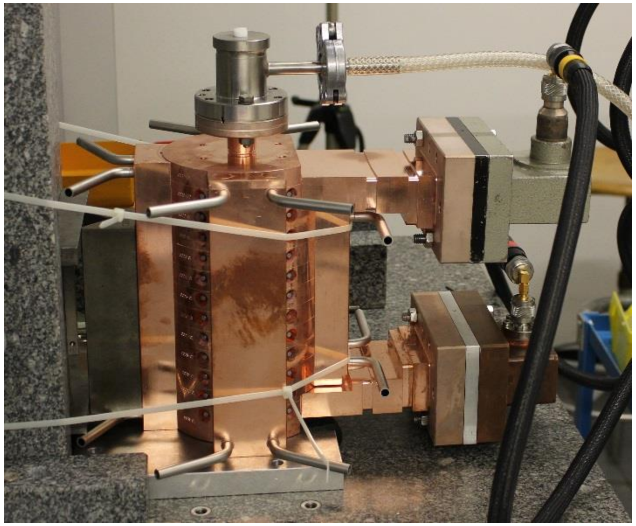


High-gradient Btw structure



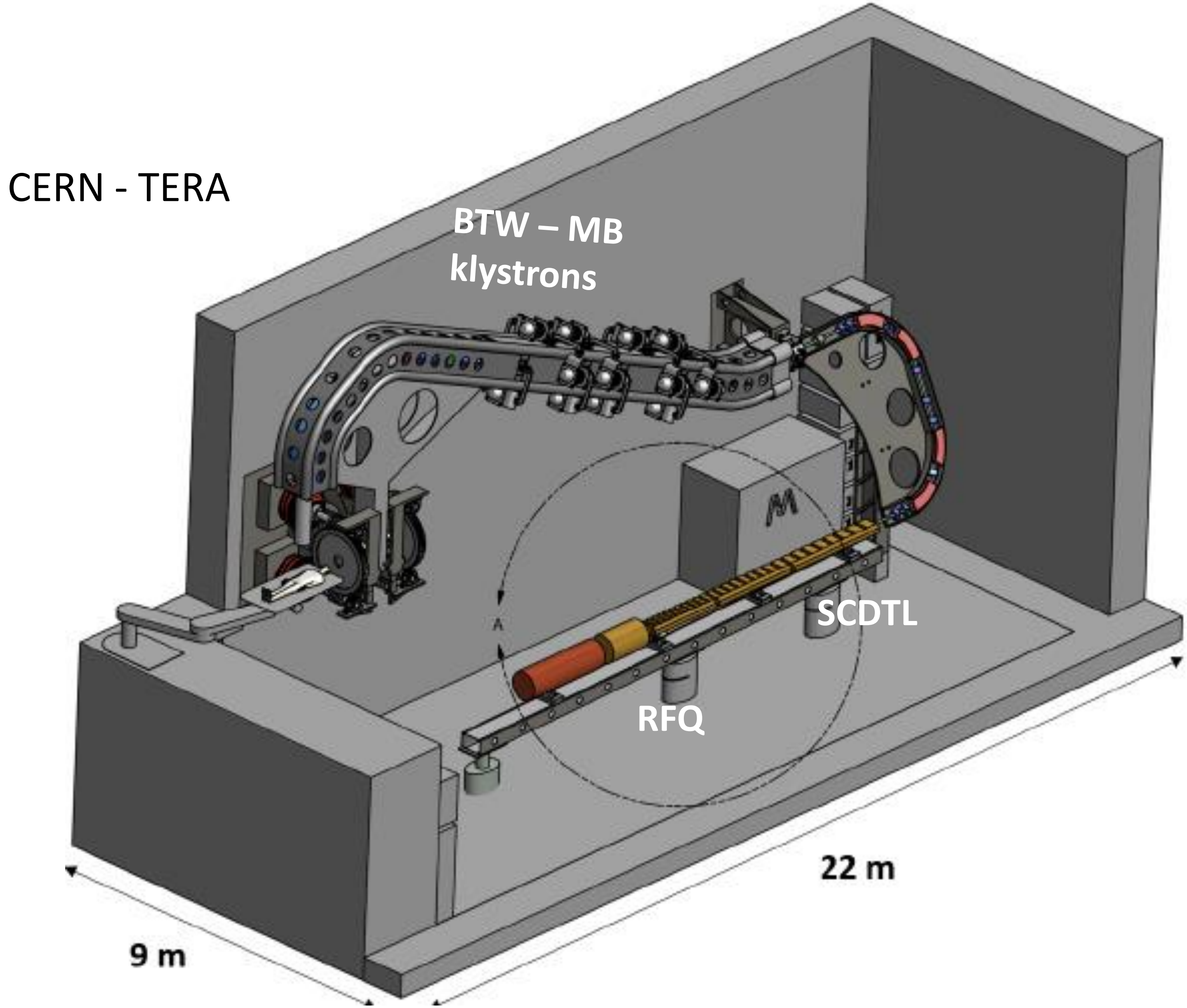
- 20 cm long

Max gradient of about 50 MV/m
10 MeV energy gain from this structure



- The high power test of the prototype is ongoing at CERN

TULIP with BwTw modules



Thank you for the attention and interest !

<u>Advanced linacs for ion beam therapy enable:</u>

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

2. fast beam energy variations for **new advanced treatment** modalities