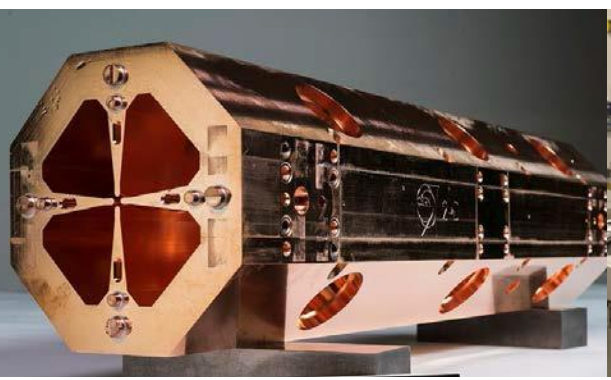
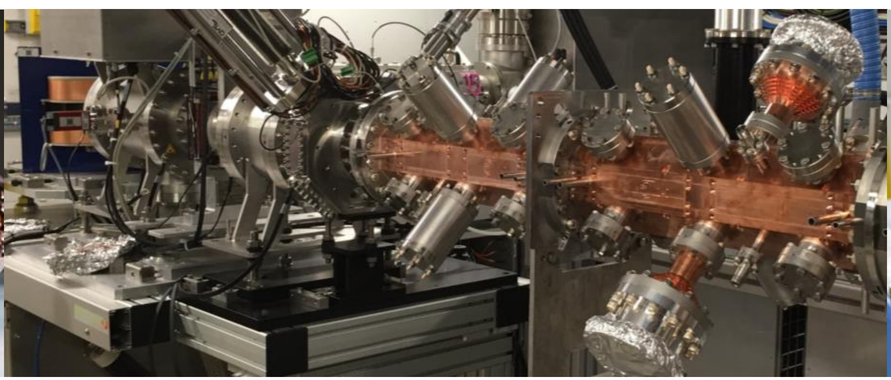
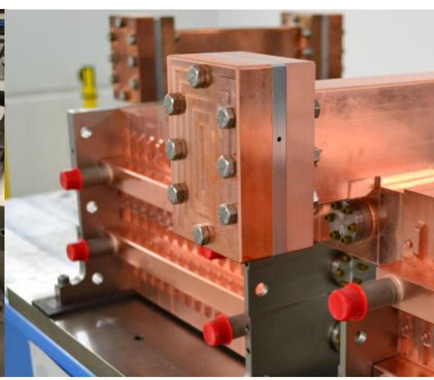
30.08.2017

an ADVANCED **ONCOTHERAPY** company

Hadron linac developments in TERA and ADAM

Dr. Alberto Degiovanni

Workshop on Ions for Cancer Therapy, Space Research and Material Science

28-30 August 2017, Chania (GR)

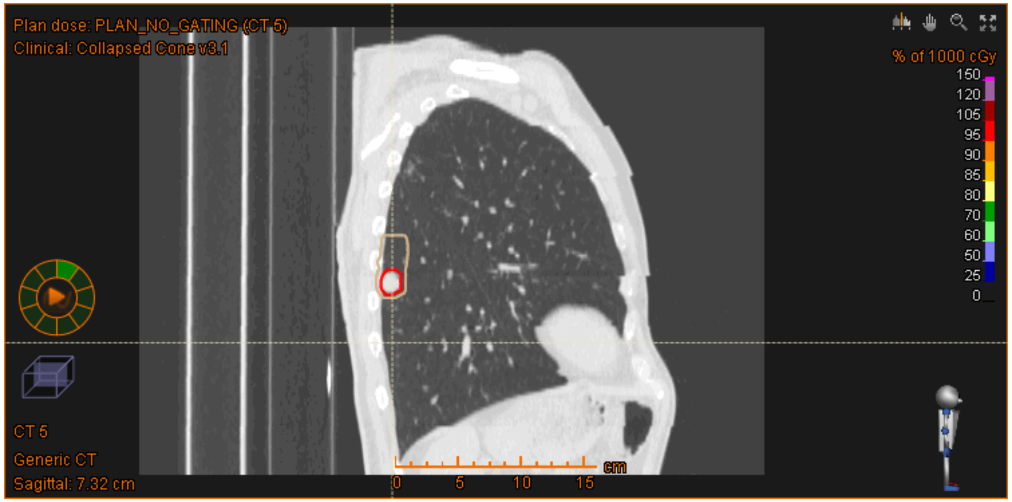
CERN spin-off

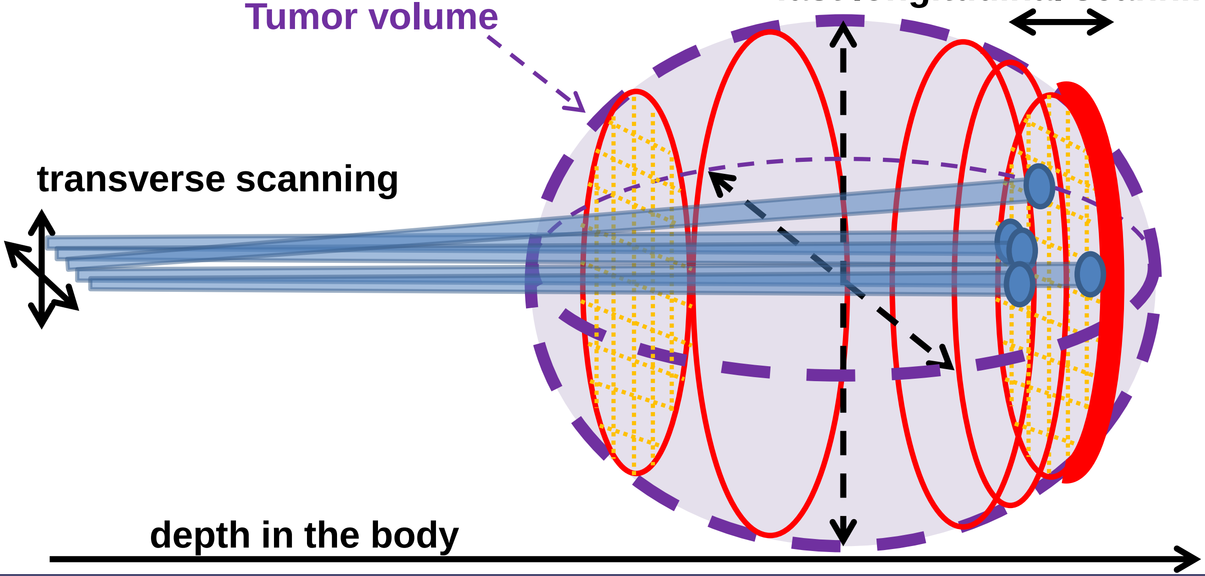
Outline

- **LIGHT – A Linac for Image Guided Hadron Therapy**
- **Status and developments of LIGHT for protons**
- **From LIGHT to CABOTO**
- **Recent developments on CABOTO**
- **CABOTO and Cyclinacs**
- **Conclusion**

Treatment of moving organs requires:

a) 3D feedbacks
b) 3D spot scanning
c) multipainting



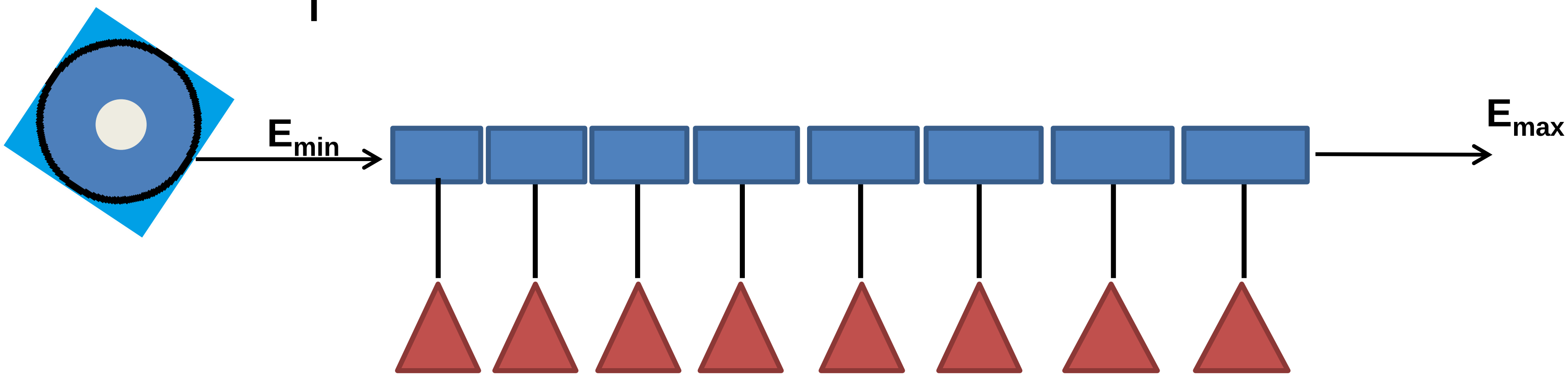


Why a linac for proton therapy

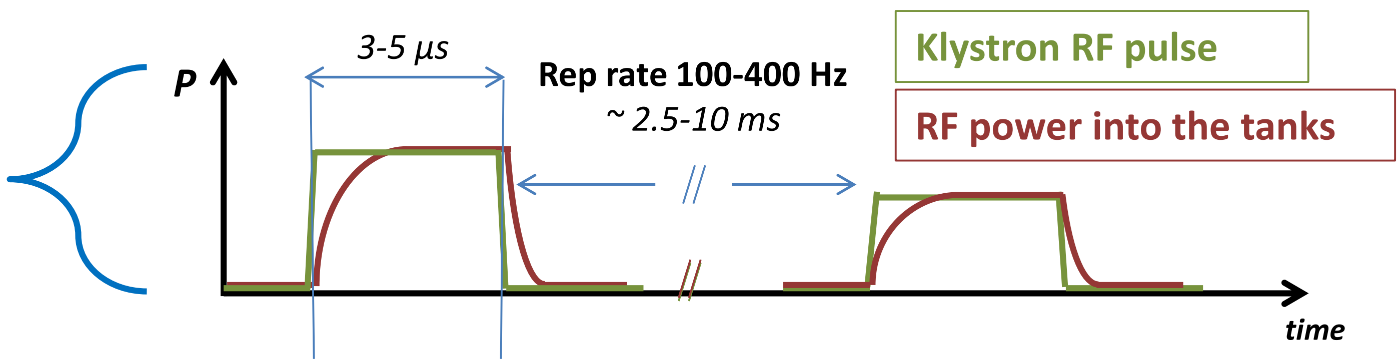
Cyclotron or RFQ+DTL

- Compact
- Power efficient

- High transmission
- Low emittance

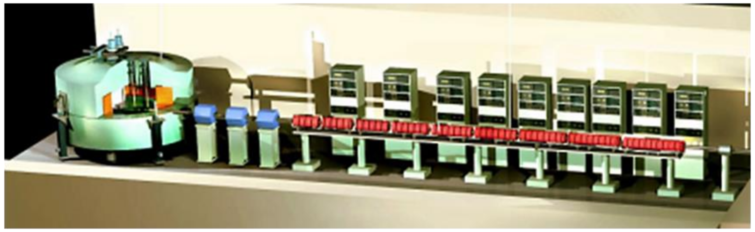


Active energy modulation
controlled in klystron

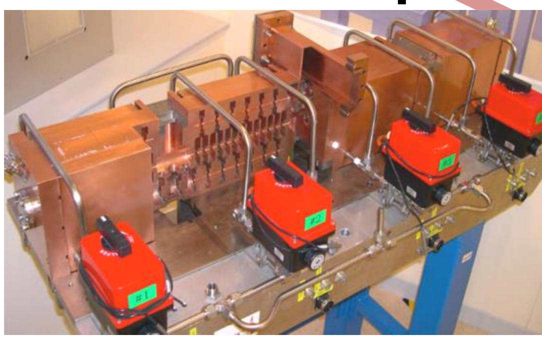


Timeline of the Cyclinac Concept

1993: first Cyclinac proposal

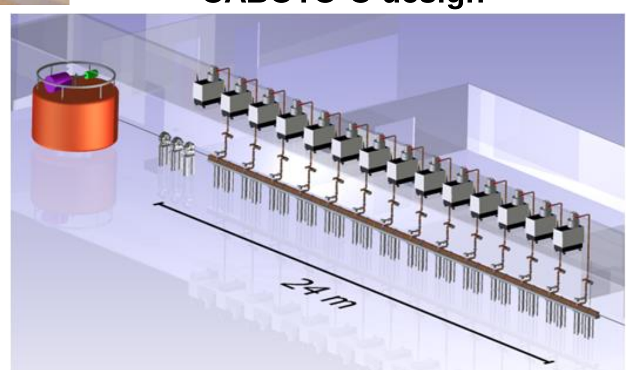


2002: LIBO (TERA-CERN-INFN)



3 GHz linac (62-74 MeV)
[C. De Martinis et al,NIM A 681 (2012)]

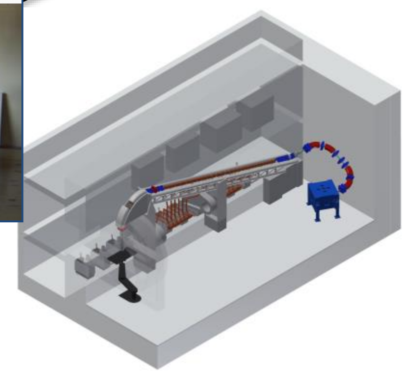
2008-2011: CABOTO-C design



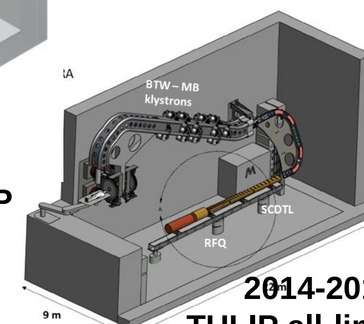
11.2010: LIGHT 1st UNIT

2014-2017 LIGHT– all-linac

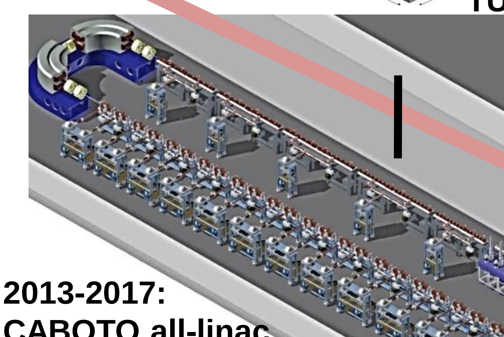
2011-2013: TULIP



2014-2017: TULIP all-linac



2013-2017: CABOTO all-linac



ADAM ADVANCED ONCOTHERAPY

LIGHT (Linac for Image Guided Hadron Therapy) Overview

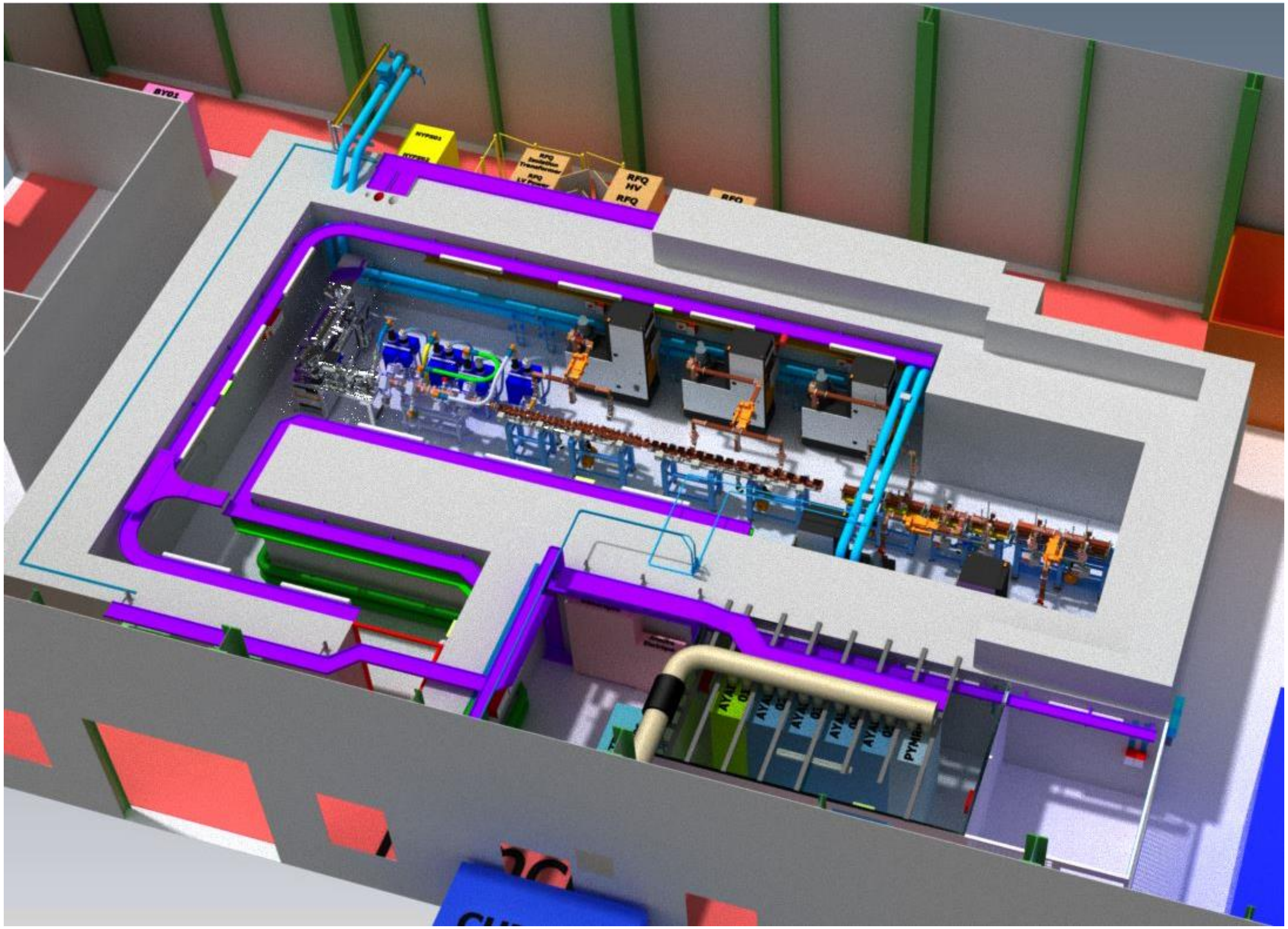
Radio Frequency Quadrupole (RFQ)

Side Coupled Drift Tube Linac (SCDTL)

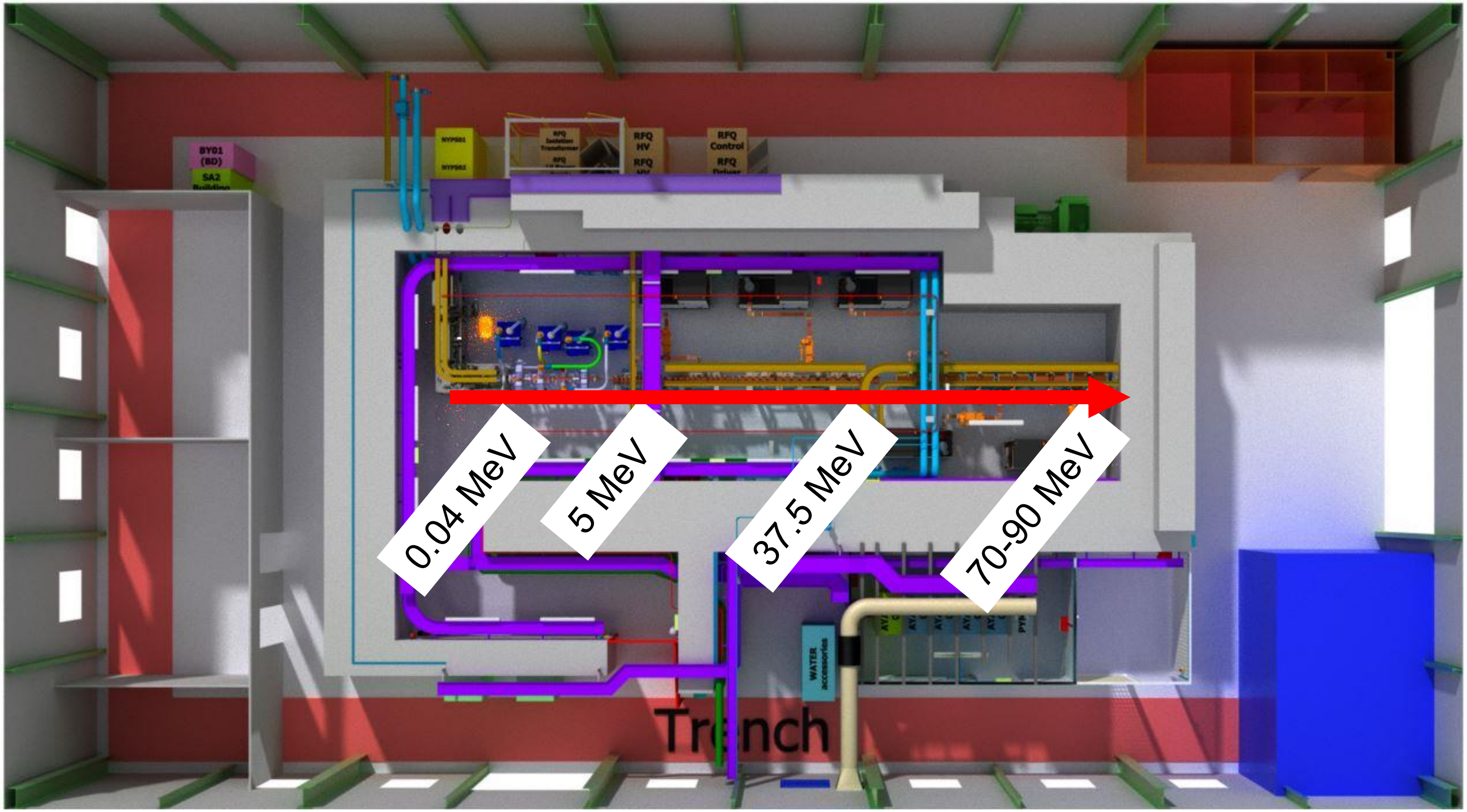
Coupled Cavity Linac (CCL)

LIGHT At CERN

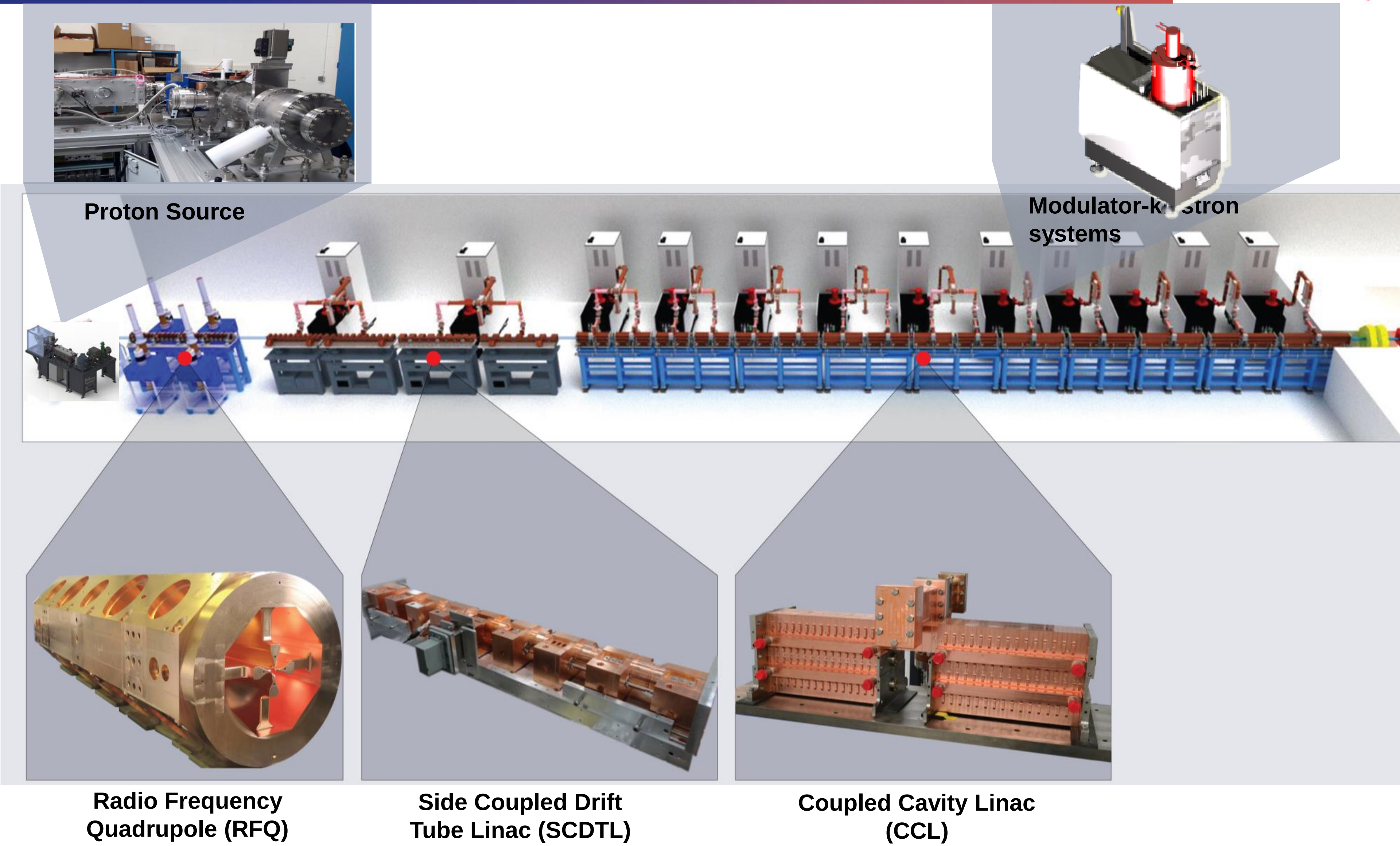
- **Up to 90 MeV**



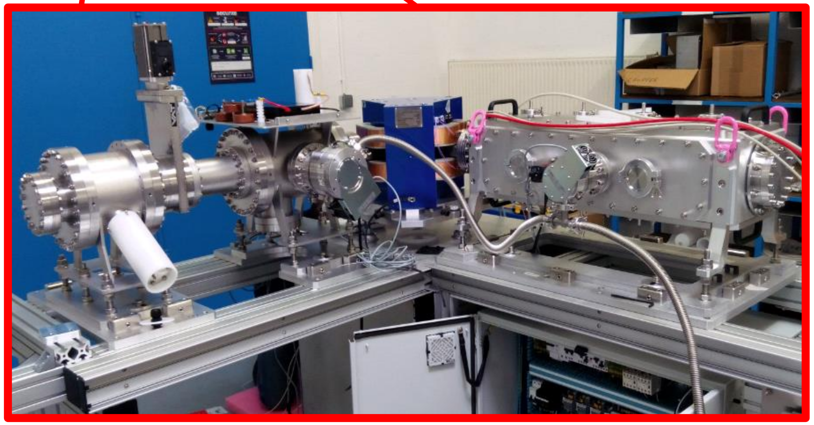
LIGHT prototype at CERN p2



LIGHT (Linac for Image Guided Hadron Therapy) Overview



LIGHT – Source

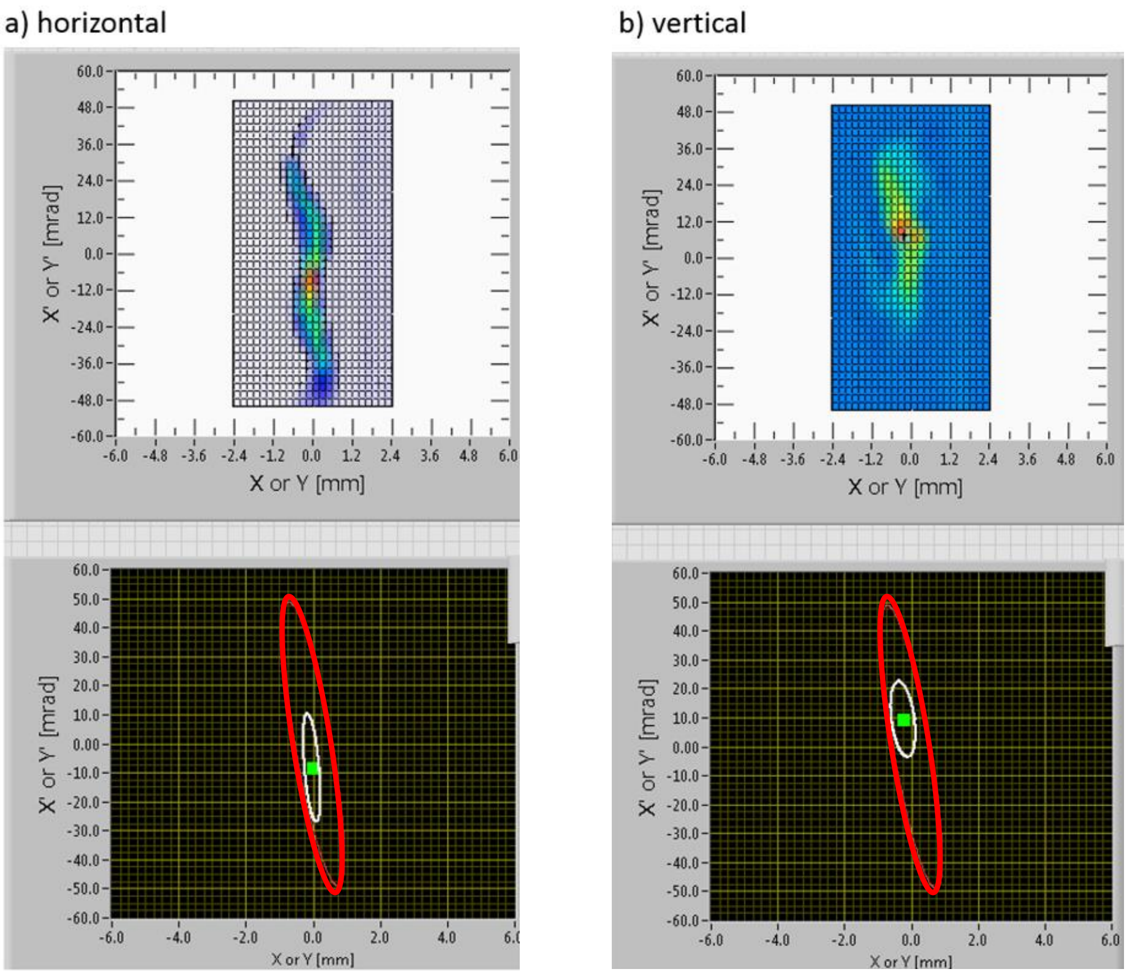


Quantity	Value	Unit
Output Energy	40 ± 0.4	keV
Output pulsed Current	Range: [1-300] ± 2%	µA
Pulse to pulse current reproducibility	± 2-3	%
Repetition rate	Range: [5-200]	Hz
Beam pulse width	Range: [0.5-5]	µs

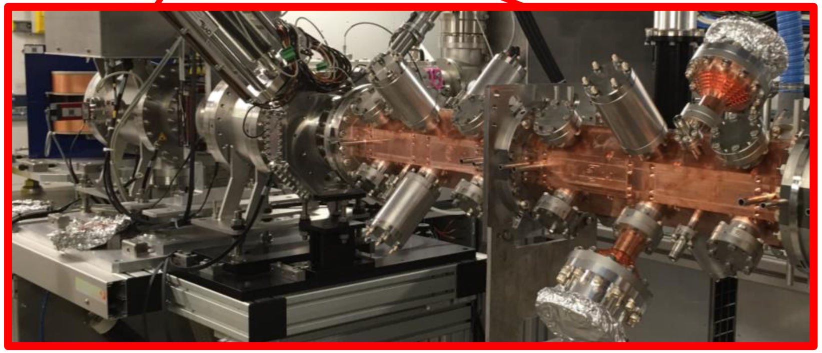
Proton source test results

- Example of **emittance measurements** in transverse planes

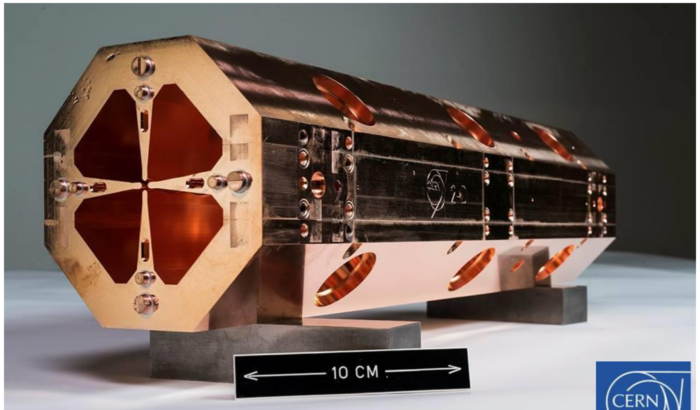
- Statistical rms emittances (white) and RFQ acceptance ellipse (red).



LIGHT - Radio Frequency Quadrupole (RFQ)



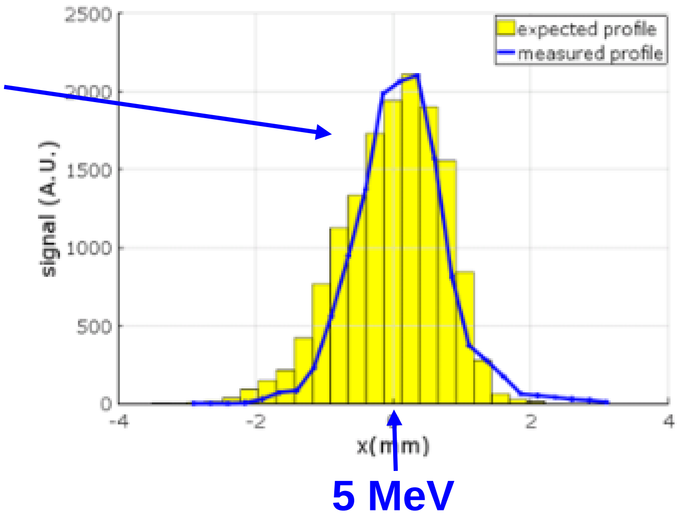
Section	RFQ
RF frequency [GHz]	0.749
Energy [MeV]	0.04-5
Length [m]	2



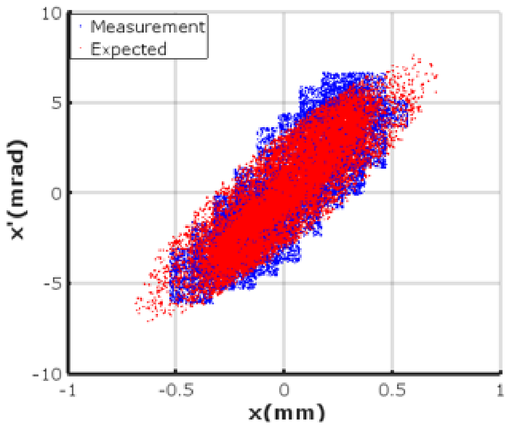
CERN 750 MHz proton RFQ module

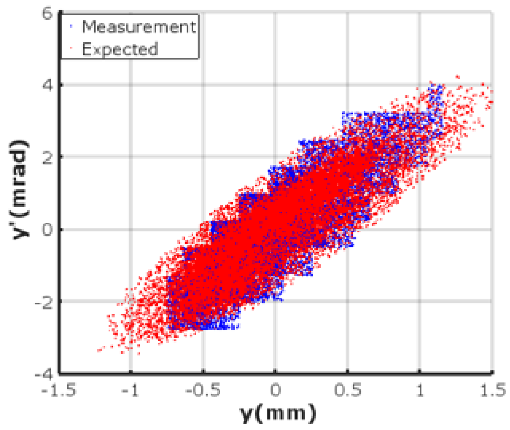
Results from the RFQ commissioning

- **Profile and energy measurements**
  - Comparison of measured and expected beam profiles at the spectrometer profile monitor
  - Calculated average beam energy from the spectrometer measurement is 5.07 MeV (expected energy 5.0 MeV)
  - Energy spread: measured rms energy spread is 7.0 keV (expected value is 7.5 keV)



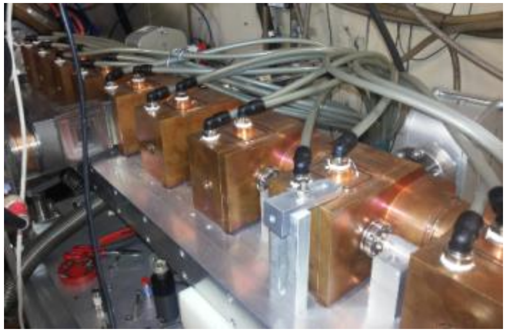
- **Emittance measurements**
  - The rms emittance is 0.33 p.mm.mrad in both planes



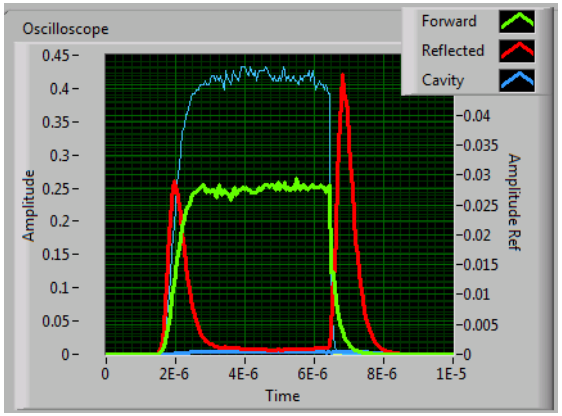


LIGHT – Side Coupled Drift Tube Linac (SCDTL)

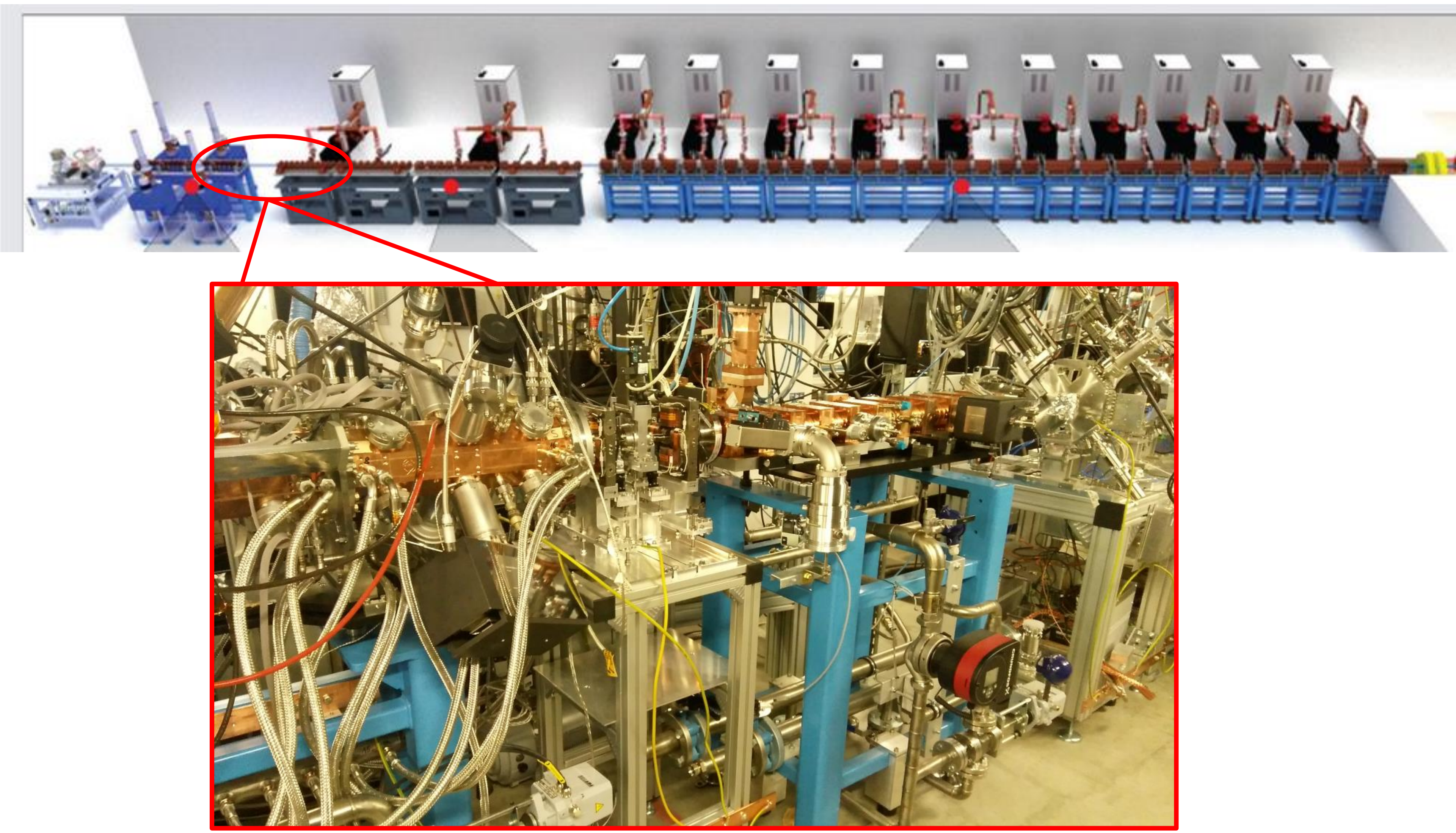
- **Designed in collaboration with ENEA (Frascati, I)**
- **Manufactured at TSC/VDL**



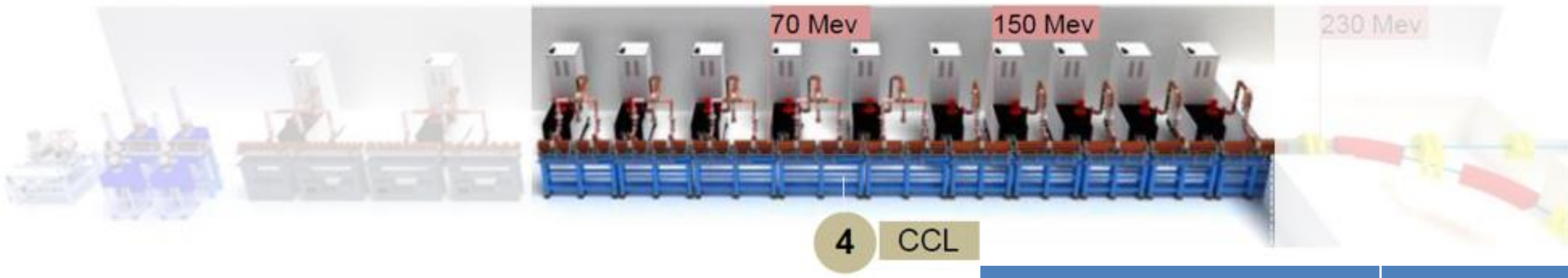
Section	SCDTL
RF frequency [GHz]	2.998
Energy [MeV]	5-37.5
Length [m]	6.2



LIGHT – SCDTLs

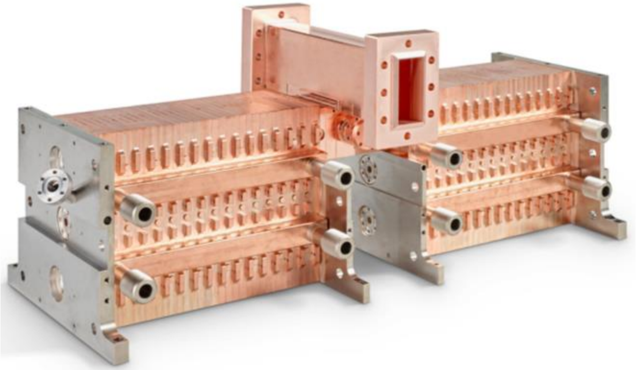


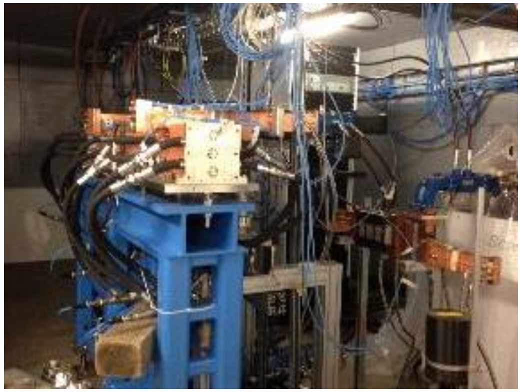
LIGHT - Coupled Cavity Linac (CCL)



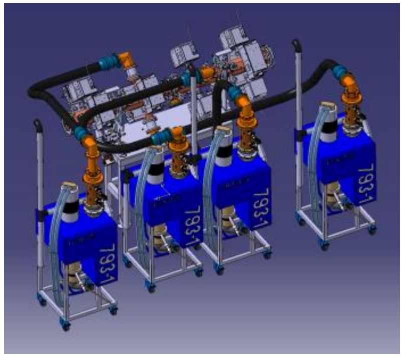
- Mechanical design by ADAM, based on previous TERA design
- High precision machining of single components
- 4 modules already tested at high power

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





LIGHT – RF power plants



IOT (Thales)	
Cathode voltage	38 KV
Grid voltage	200 V
Average beam current	4 A
RF drive power	800 W
RF output power	100 KW

Modulator (Scandinova)	
Pulse Voltage	155 KV
Pulse Current	110 A
Pulse Rep. Rate	5 to 200 Hz
Pulse Length	5 µsec

Klystron (Toshiba)	
Frequency	2998.5 MHz
Peak RF Drive Power	120 W
Peak RF Output Power	7.5 MW
RF Pulse Width	5 µsec

ADAM ADVANCED ONCOTHERAPY

A modular approach – the LIGHT RF Unit

Accelerating System

Cooling System

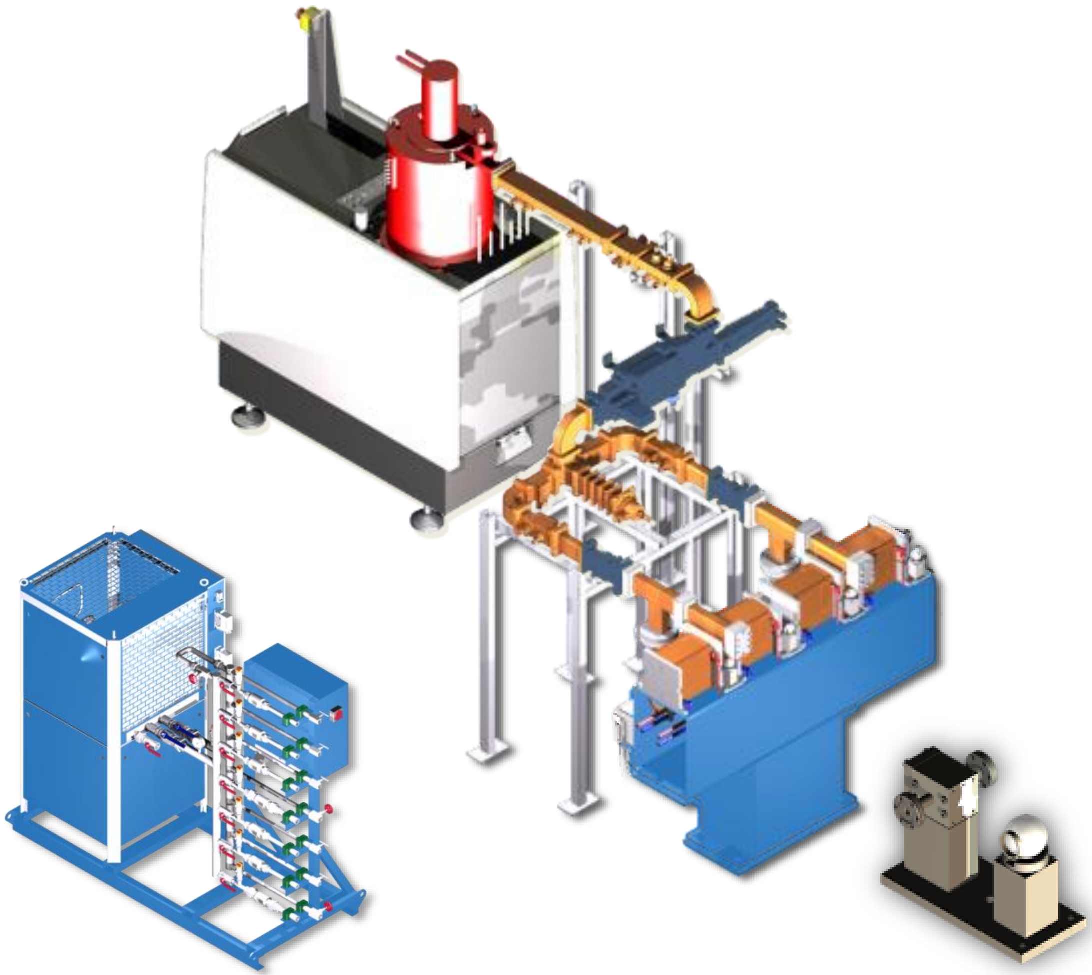
Focusing System

RF Network System

RF Power System

Support System

Vacuum System



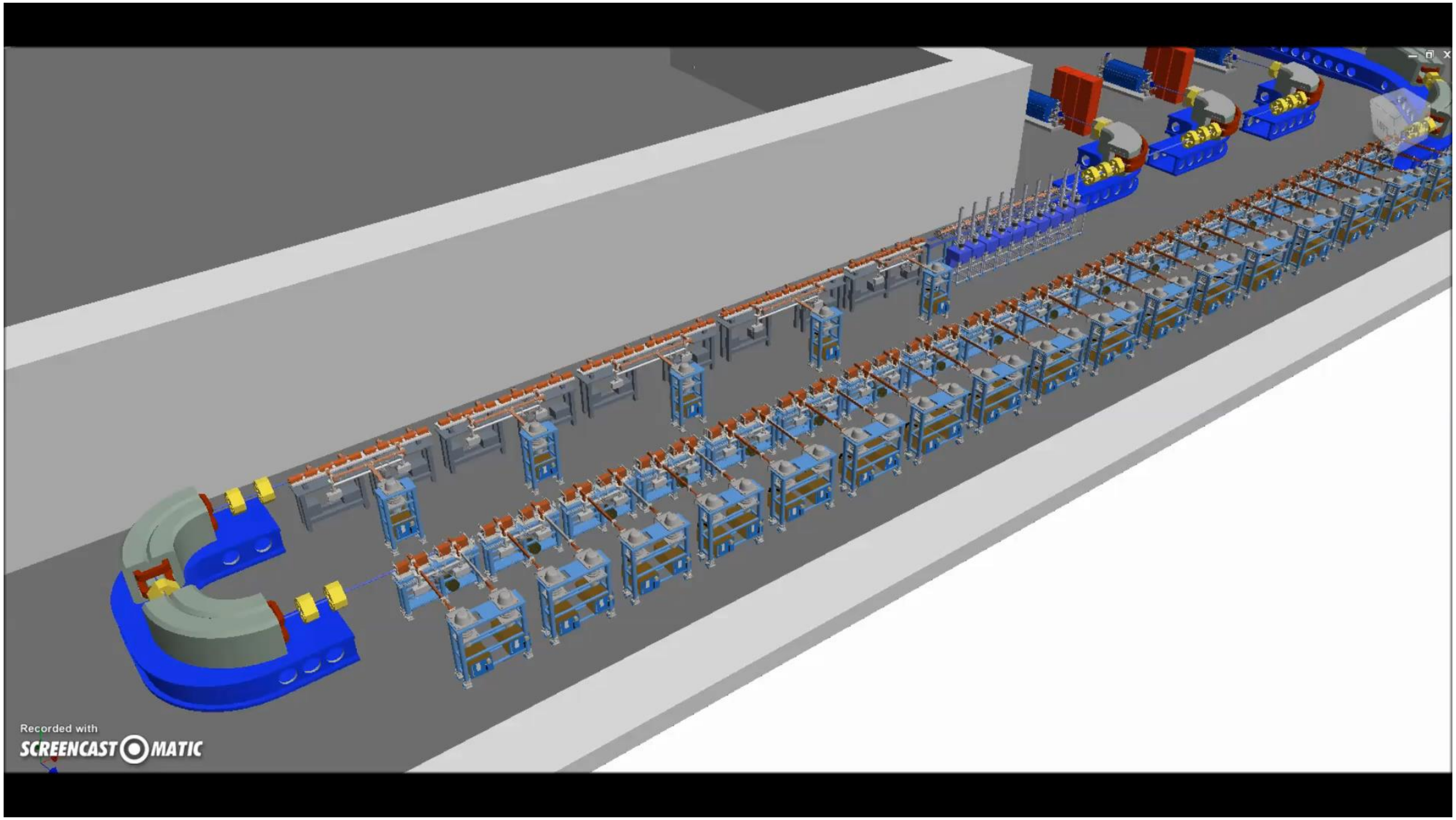
From protons to carbon ions...

- **Carbon spots are smaller (4mm vs 7mm FWHM) → more spots needed to cover the same volume!**
- **Carbon ions require higher energy per nucleon to achieve the same range (430 MeV/u vs 230 MeV)!**
- **In a fully stripped carbon ion only the 6 protons are charged and are accelerated by the electric field (Q/A = 1/2 vs 1)!**

Higher Repetition Rate needed!
→ Source and efficient RF sources!

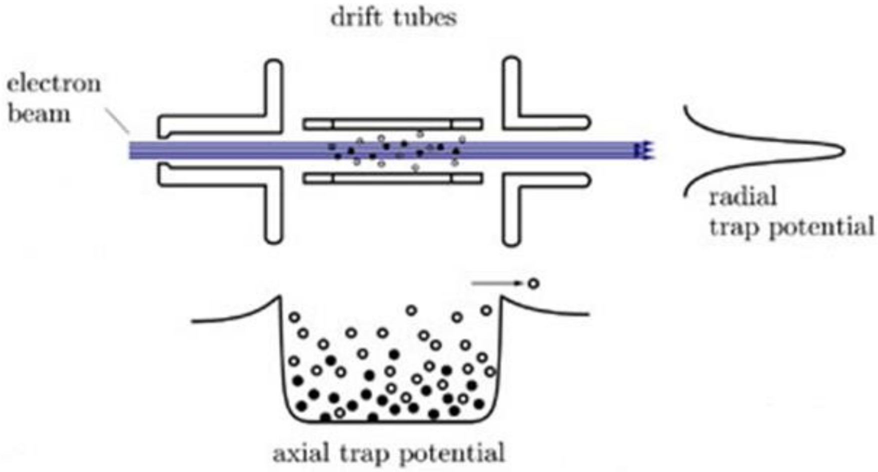
Total Voltage gain = 2 x 430 = 860 MV!
→ Accelerating efficiency and gradient !

CABOTO all-linac solution of the TERA Foundation

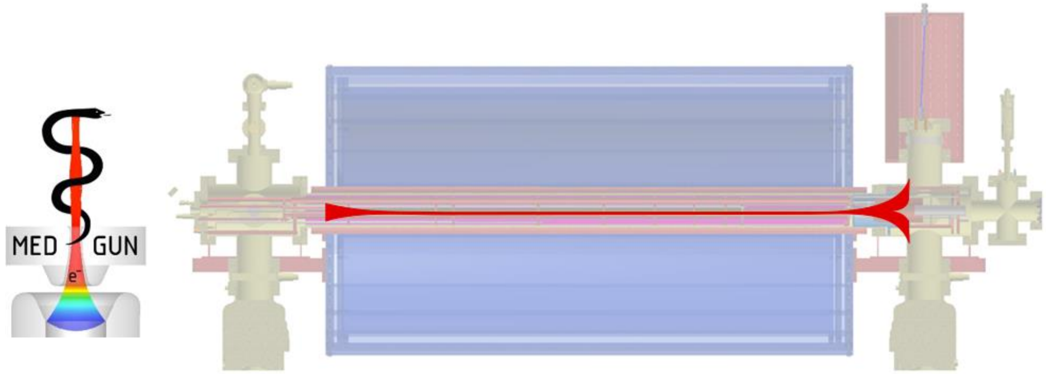


The ion source – Superconducting EBIS

(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

The ion source – EBIS MEDeGUN

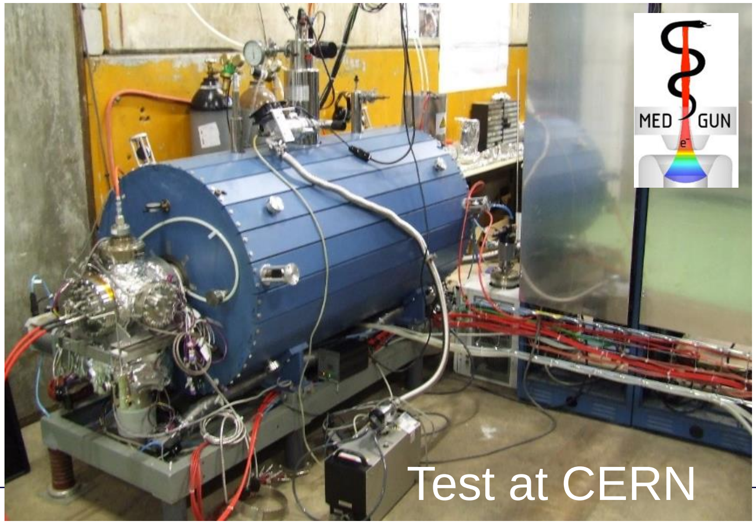
- **Dedicated EBIS source for CABOTO with high-compression Brillouin electron gun**

- **Low electron beam energy optimized for C^{6+}**
- **Short pulse lengths <5 μs pulses**

- **First electron beam has been propagated. (stable 1 A electron beam under 2T magnetic field - design goal)**
- **Future stages include introduction of carbon and extraction of carbon ions**

Design Parameter	MEDeGUN
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 $1 \cdot 10^9$ ions per pulse
Repetition rate C^{6+}	180 Hz (440 Hz, 5 T)

Courtesy of F. Wenander (CERN)

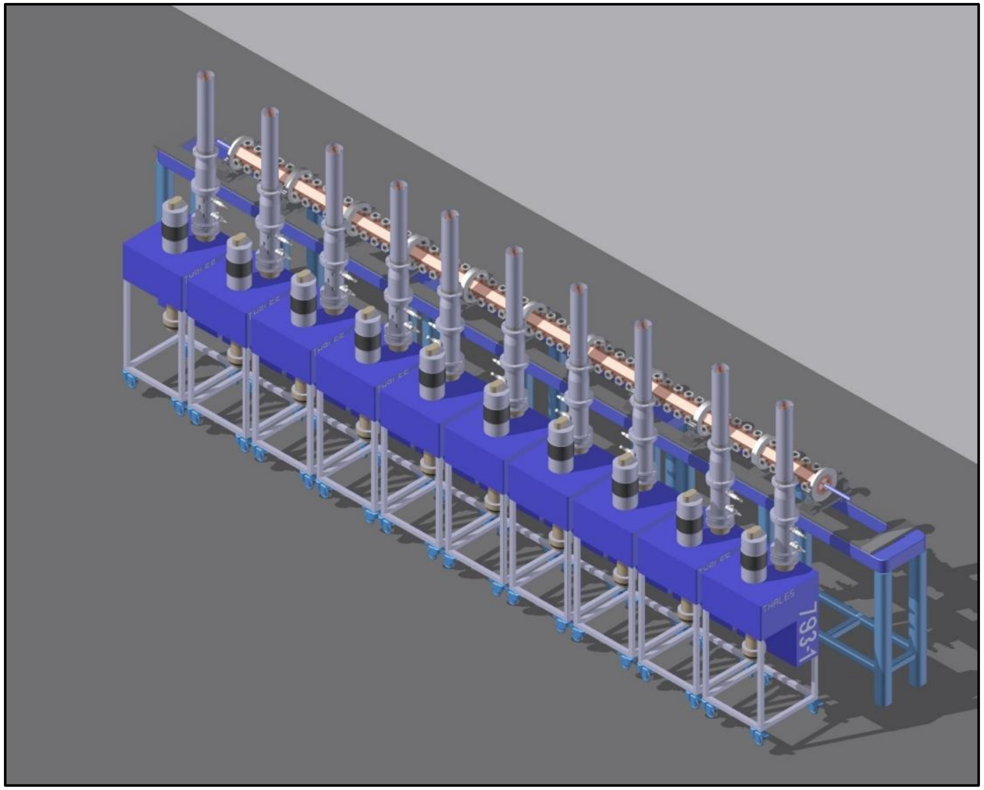


* R. Mertzig et al., *"A high-compression electron gun for C^{6+} production: concept, simulations and mechanical design"*, NIM A 859 (2017)

* 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

New HF-RFQ for Carbon ions

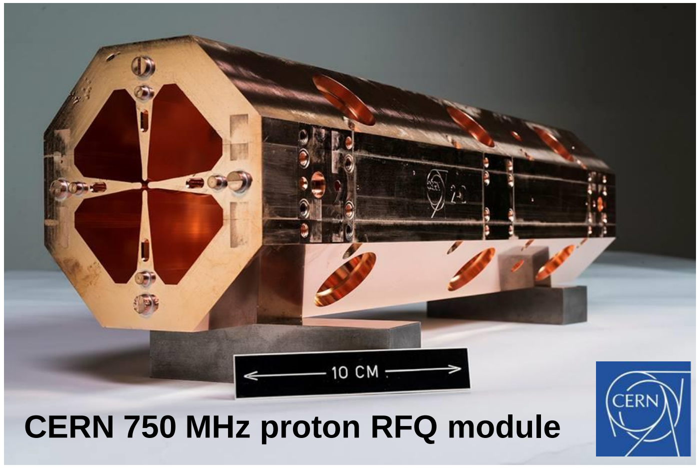
TERA



- **Proton RFQ built and presently under commissioning**
- **Based on the same technology, a C6+ RFQ is being designed**

- **bunching and acceleration of the beam up to 5 MeV/u**
- **Highest frequency RFQ in the world (750 MHz)**

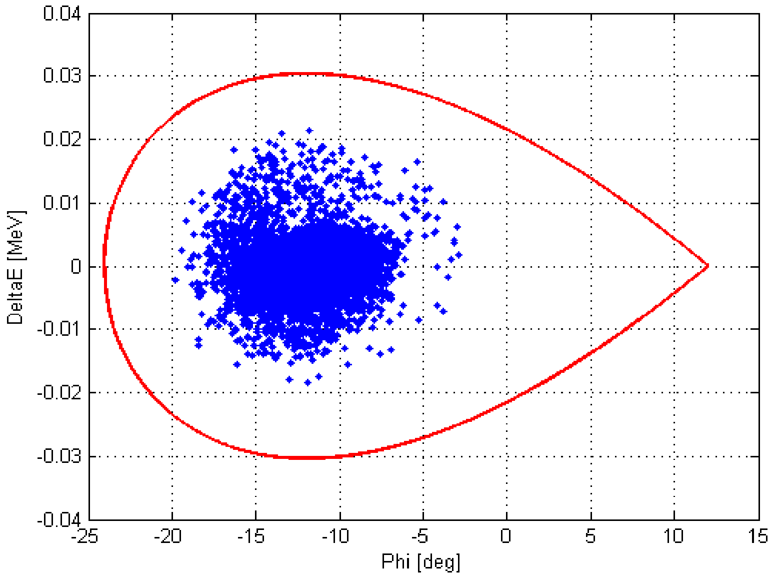
$\varepsilon_x=\varepsilon_y$ [Norm. RMS]	0.025 pi mm mrad
ε_z [Norm. RMS]	0.125 pi deg MeV



CERN 750 MHz proton RFQ module

New HF-RFQ designs for ions

Based on experience of the 750 MHz RFQ for protons, a new design optimized for carbon ions (Q/A=1/2)

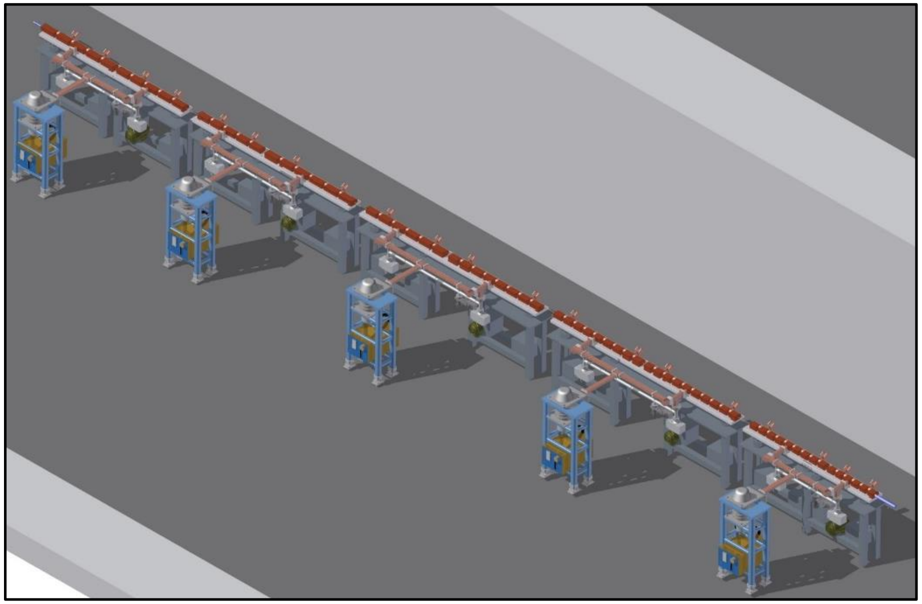


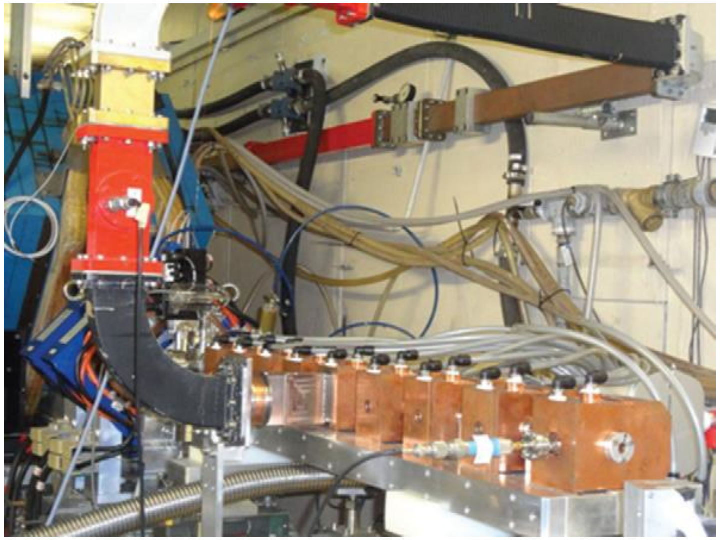
Parameter	Value
Length [m]	2.58
Transmission [%]	51.2
Average aperture r [cm]	0.13
Energy range [MeV/u]	0.04-5
Output transverse emittance 99.5% [π·mm·mrad]	0.12
Output longitudinal emittance 99.5% [π·deg·MeV]	0.16

Shaping the synchronous phase and the modulation of the RFQ the output beam was adjusted to fit into the IH-structure acceptance

CABOTO – SCDTL structures

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



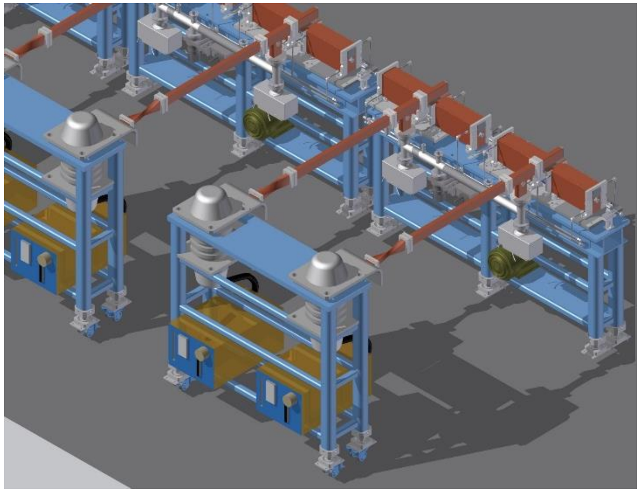


ENEA Frascati SCDTL unit test

CABOTO – CCL structures

- 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

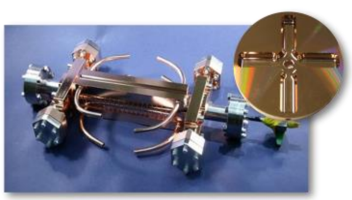


Accelerating structures developements

- **High efficiency design to reduce the power consumption**

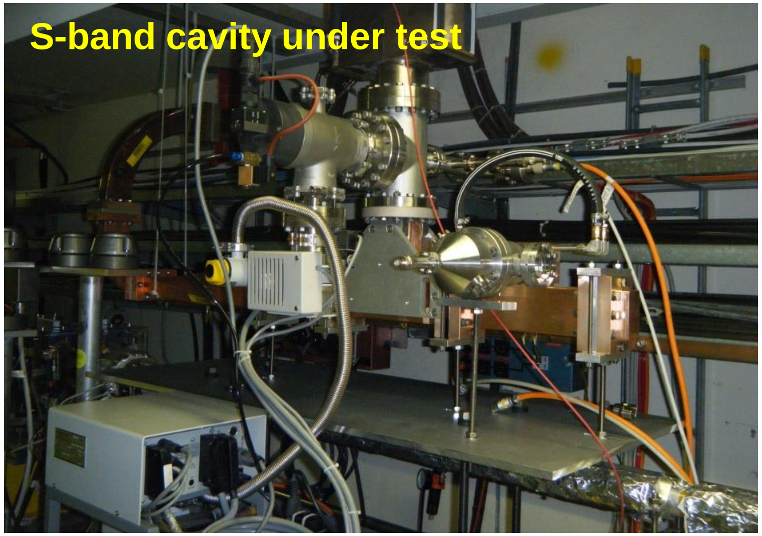
- **“Reliable” high gradient structures to reduce the length of the linac**

→ Very important and fruitful collaboration with CLIC

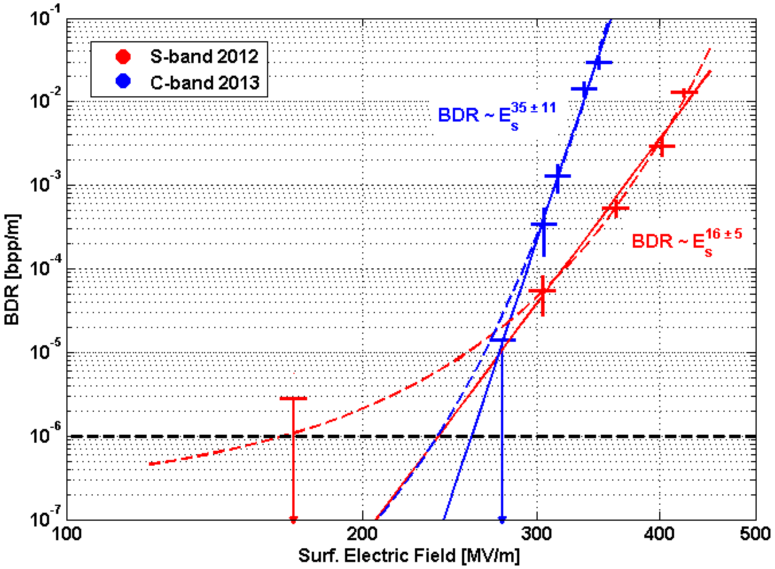


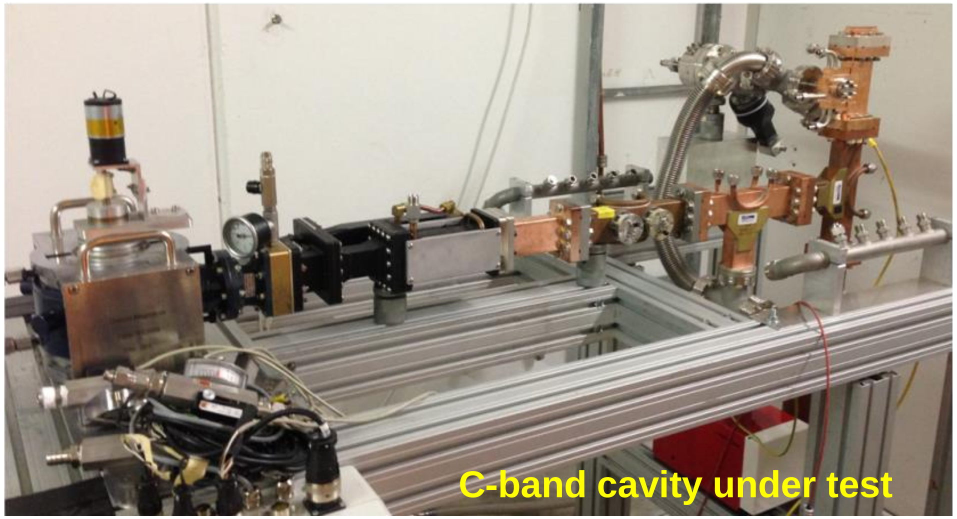
A TERA project: understanding the limits on gradients

- High gradients are needed to reduce the linac size
- Accelerating gradients for CABOTO ~ 30 MV/m (in LIGHT ~ 16 MV/m)
- Collaboration with CLIC for understanding the limits on gradients…(see talk by W. Wuensch)

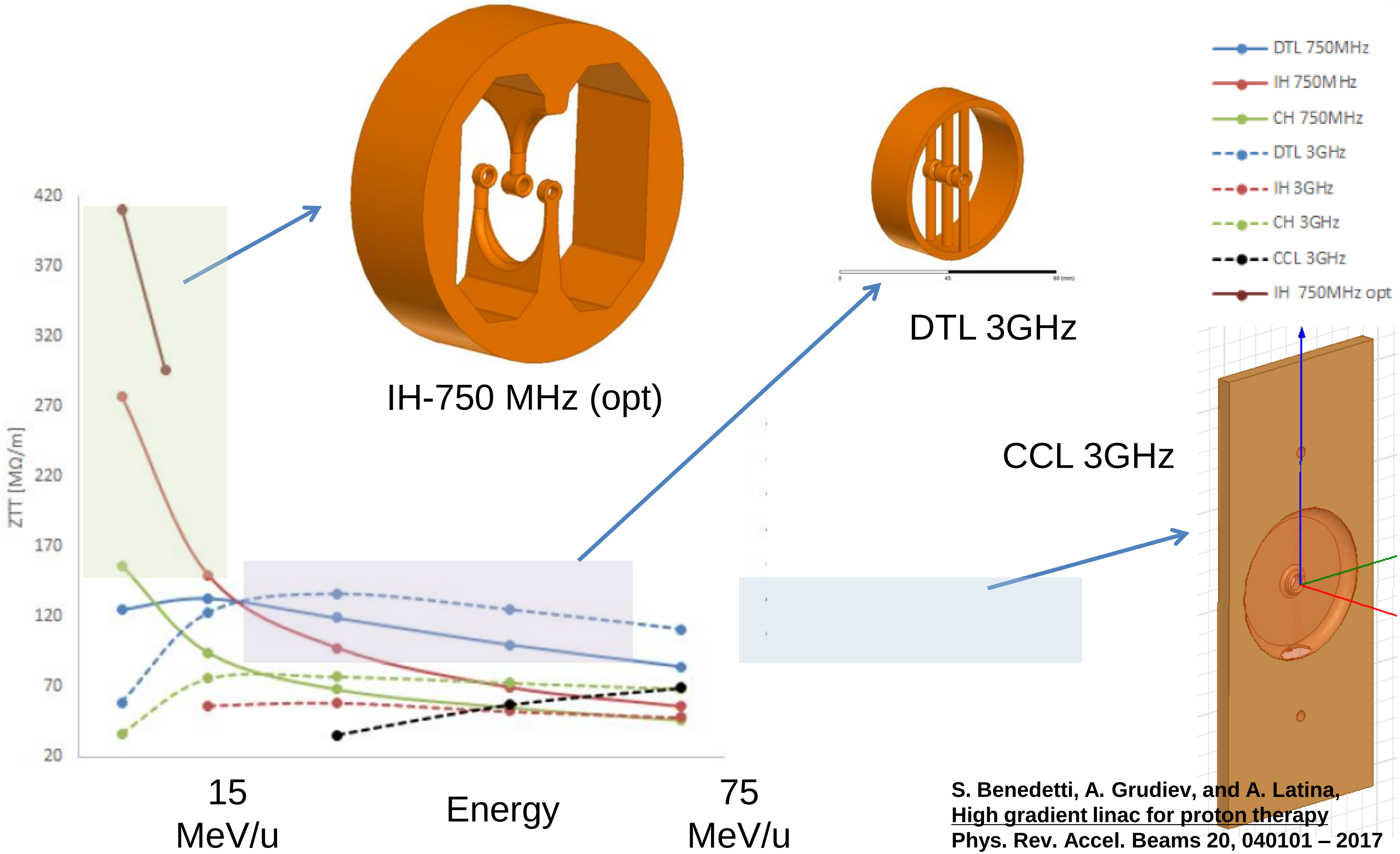


S. Verdú-Andrés et al, arXiv:1206.1930v2
A. Degiovanni et al, NIM A 657



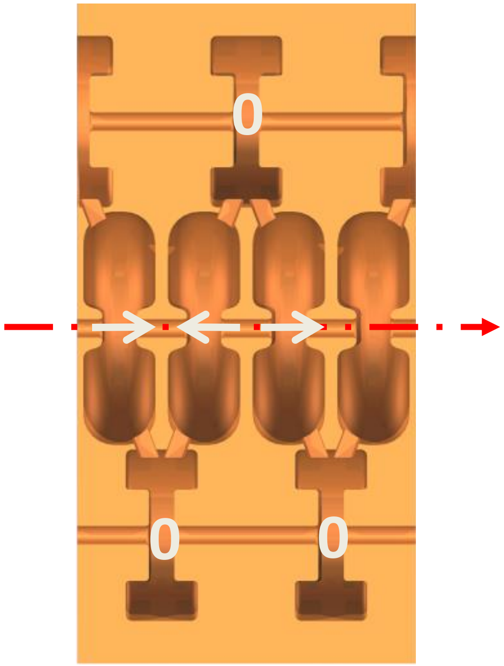


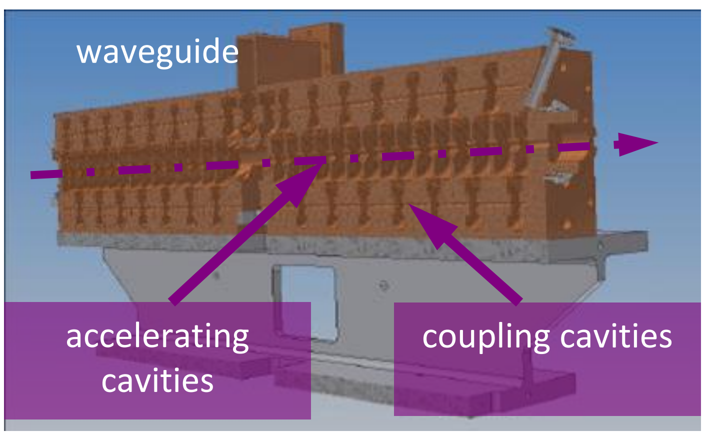
CABOTO - low beta structures for higher efficiency



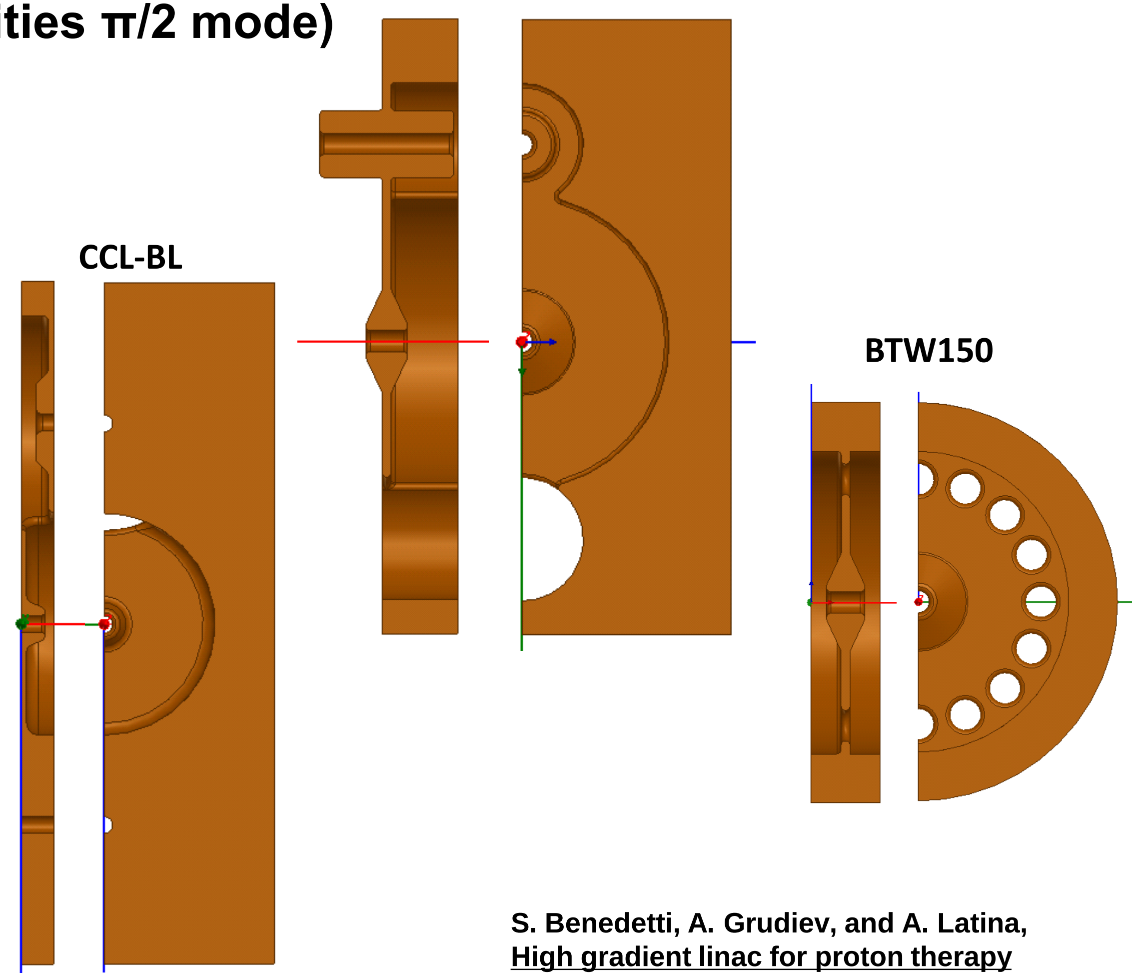
S. Benedetti, A. Grudiev, and A. Latina,
<u>High gradient linac for proton therapy</u>
Phys. Rev. Accel. Beams 20, 040101 – 2017

CABOTO - CCL structures optimization by TERA





- **Side Coupled Linac (RF cavities π/2 mode)**



S. Benedetti, A. Grudiev, and A. Latina,
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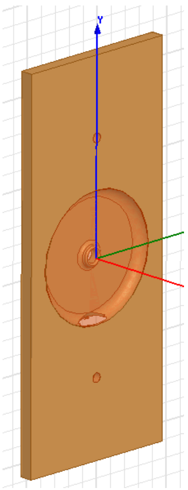
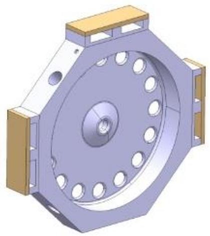
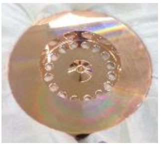
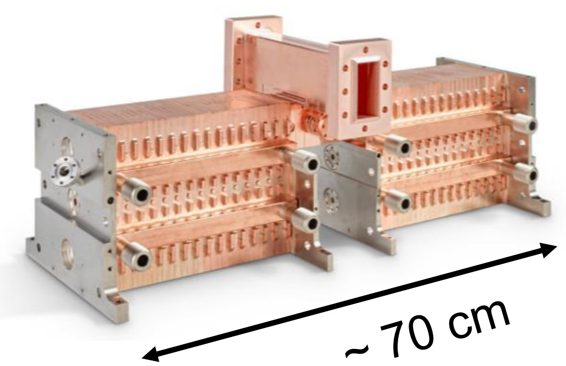
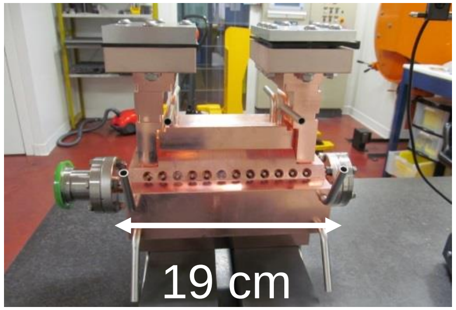
An alternative to CCLs → BTW structures development











- **A CERN-TERA collaboration - funded by CERN-KT**

- **20 cm long**
- **Max gradient of about 50 MV/m!**
- **10 MeV energy gain from this structure (with peak power ~22 MW)**

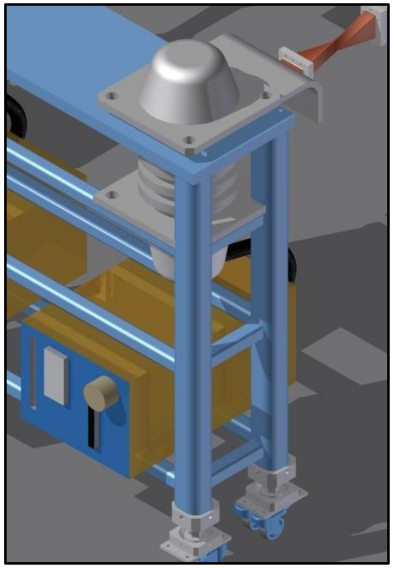
- **The high power test of the prototype is ongoing at CERN**

→ see talk by W. Wuensch

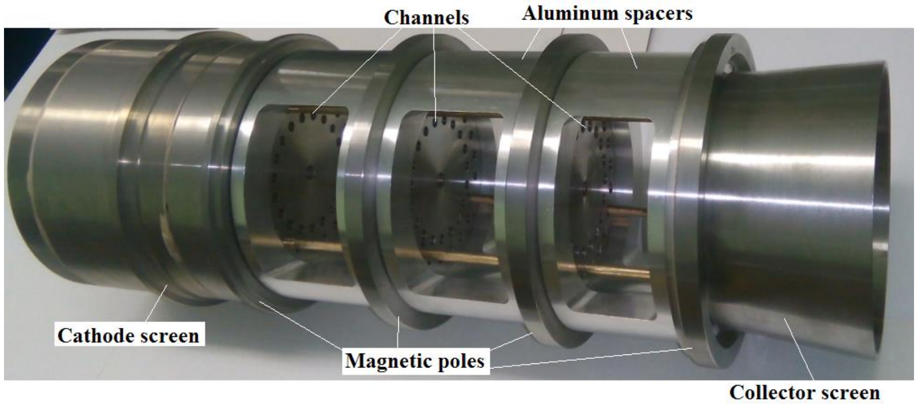
Efficient RF power source (Syratchev et al. CERN)

- 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

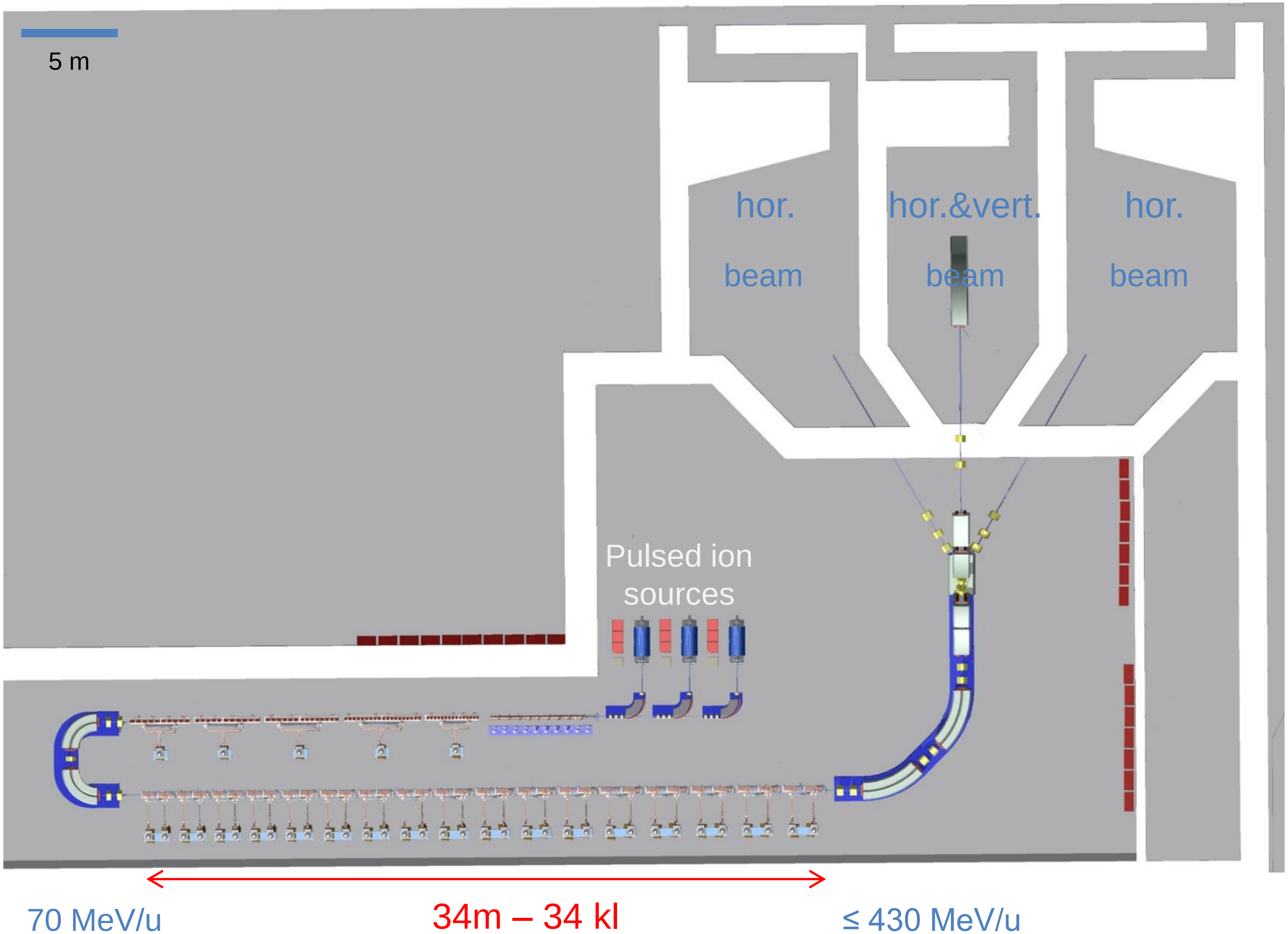


6 MW VDBT MBK



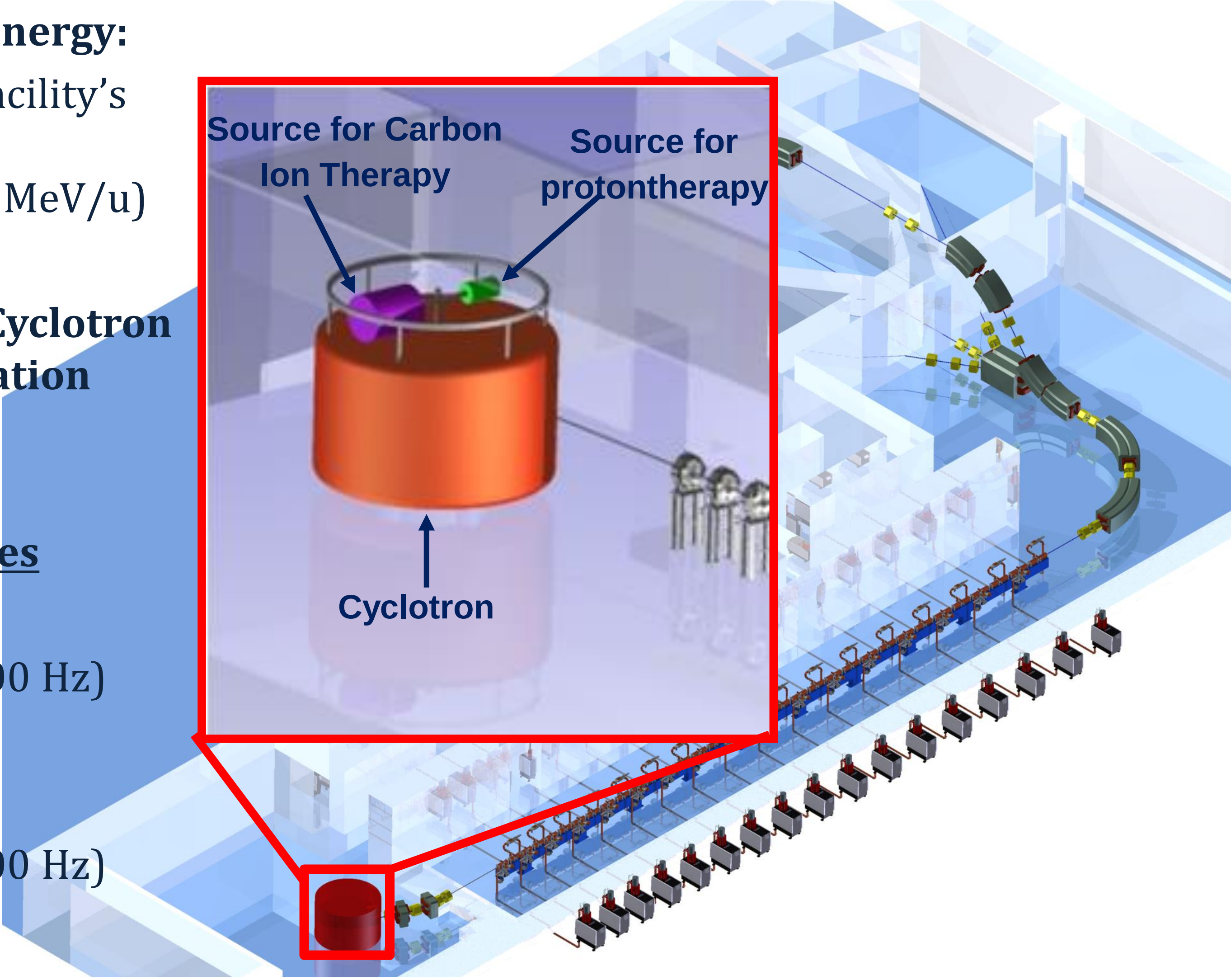
7.5 MW VDBT MBK

CABOTO - Top view



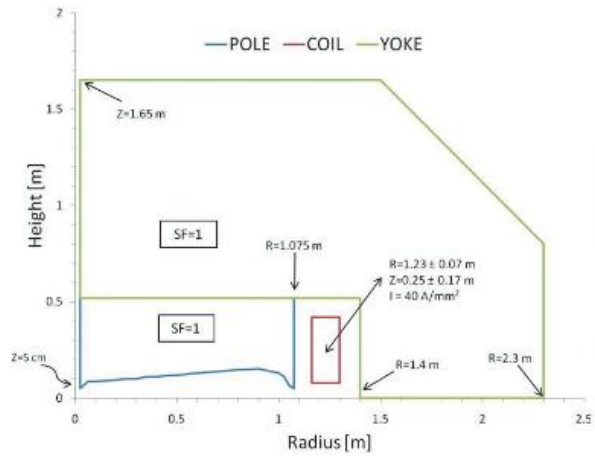
CABOTO cyclinac solution

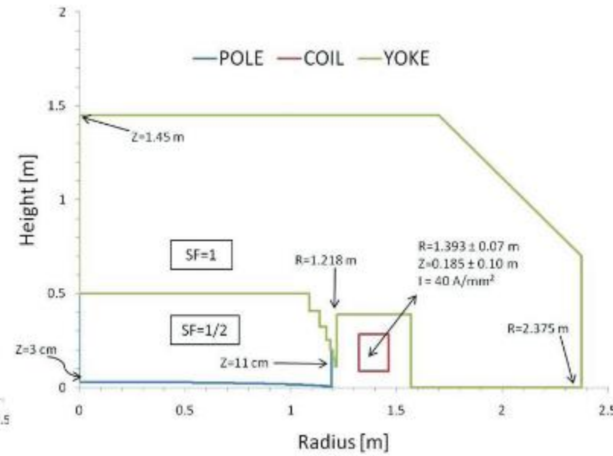
- **Cyclotron output energy:**
  - Choice linked to facility's clinical goals (70 MeV/u – 230 MeV/u)
- **Superconducting Cyclotron design in collaboration with INFN-LNS**
- **<u>External ion sources</u>**
  - 2 10^{10} H_2^+
  - in 1.5 μs pulse (100 Hz)
  - 1 10^{8} C^{6+}
  - in 1.5 μs pulse (300 Hz)



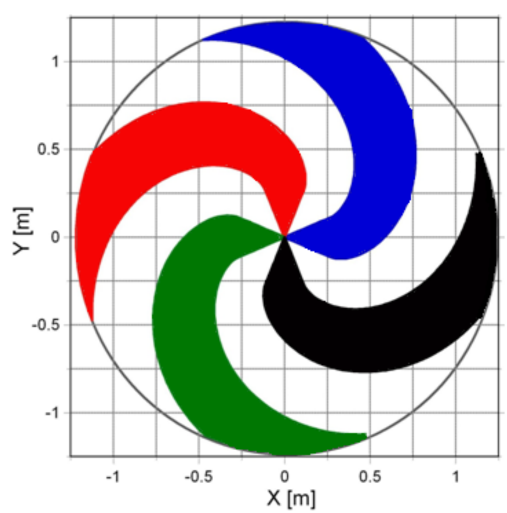
The CABOTO cyclotron injectors studied by TERA

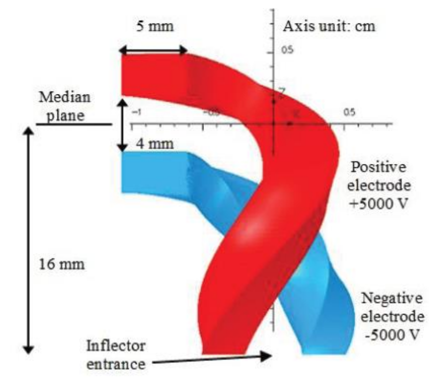
- **Comparison between two possible solutions at 230 MeV/u**
  - Isochronous Cyclotron
  - Synchro-cyclotron





- **Conceptual design of IC for intermediate energies at 70-120-170 and 230 MeV/u**





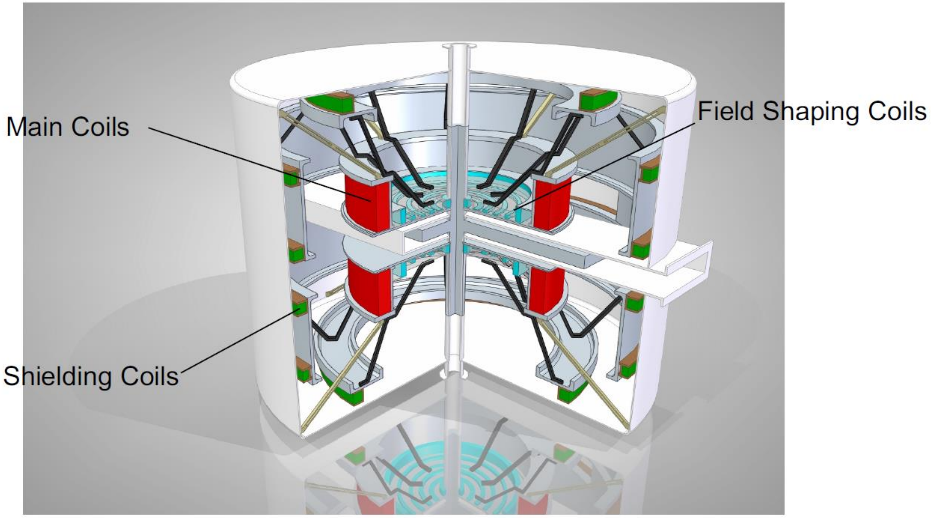
A. Garonna et al., CYCLOTRON 13 Conference
A. Garonna, PhD Thesis EPFL 5156 (2011)

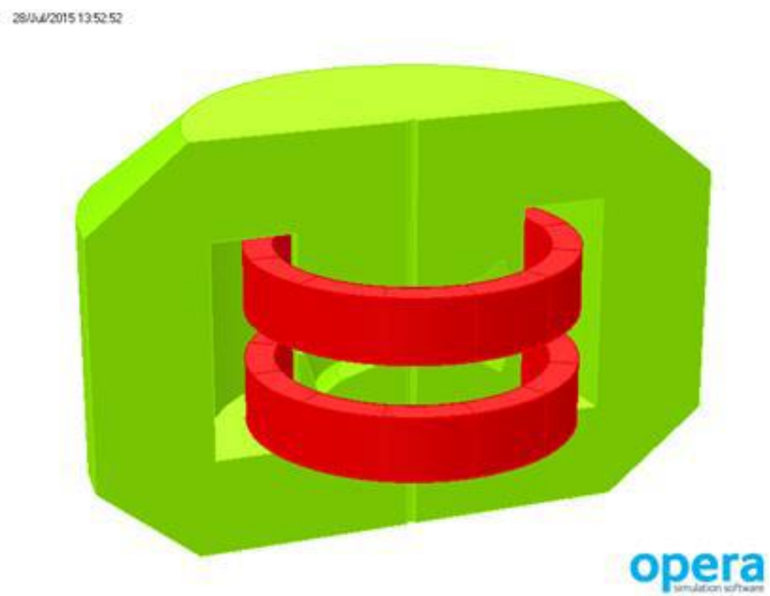
Isochronous Cyclotrons conceptual designs

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**

- **Iron-less Synchrocyclotron (Minervini et al., MIT)**
  - Design for 245 MeV protons
  - Rextraction= 0.3 m, Ryoke=1.6 m, 7 tons
  - 8.8 T central field, 8.1 T at extraction radius

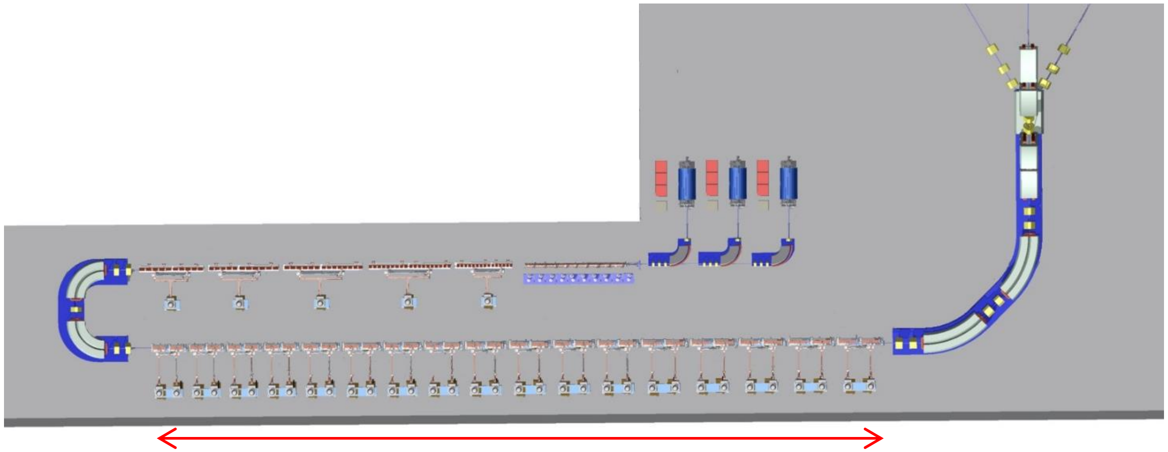
Model		With Iron		Ironless	
Parts	Density	Volume	Weight	Volume	Weight
	kg/m^3	m^3	kg	m3	kg
Iron Yoke	7,860	2.105	**16,545**	0	**0**
Bobbin	7,860	0.299	2,350	0.342	2,686
Windings	8,000	0.181	1,448	0.278	2,225
MLI			24		24
Cold Structure			**3,822**		**4,935**
Cryostat	7,860	0.137	1,078	0.184	1,446
Supports			89		65
Thermal Shield	7,860	0.027	216	0.037	289
Cryocoolers			74		74
Magnet			**5,278**		**6,808**
Total (Magnet + Iron)			**21,823**		**6,808**





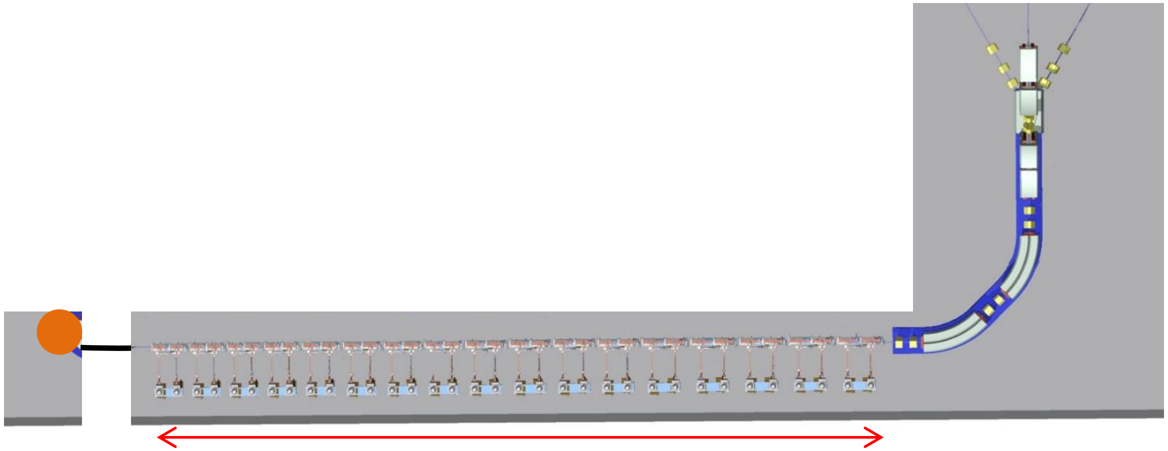
CABOTO cyclinac / all-linac

- **All-Linac (RFQ+DTL “injector”)**
  - High transmission
  - Low emittance



70 MeV/u — 34m – 34 kl — ≤ 430 MeV/u

- **Cyclinac (Cyclotron injection)**
  - Compact
  - Power efficient



70 MeV/u — 34m – 34 kl — ≤ 430 MeV/u

Conclusion

- **Linacs are very well suited for treatment of moving organs with 3D spot scanning technique with multi-painting**
- **High frequency proton linac is now moving towards industrialization. A prototype of a proton linac is being built by ADAM and is now under test**
- **Based on the proton experience, light ions is natural extension!**
- **Design of Carbon ion linac (CABOTO), patented and designed by TERA Foundation, has included several new developments in:**
  - Ion source (F. Wenander et al.)
  - High Frequency RFQ (A. Lombardi et al.)
  - High gradient cavity design and testing (W. Wuensch, A. Grudiev, G. McMonagle)
  - High efficiency klystrons (I. Syratchev)
- **Collaboration with several groups and CERN-KT has been fundamental!**

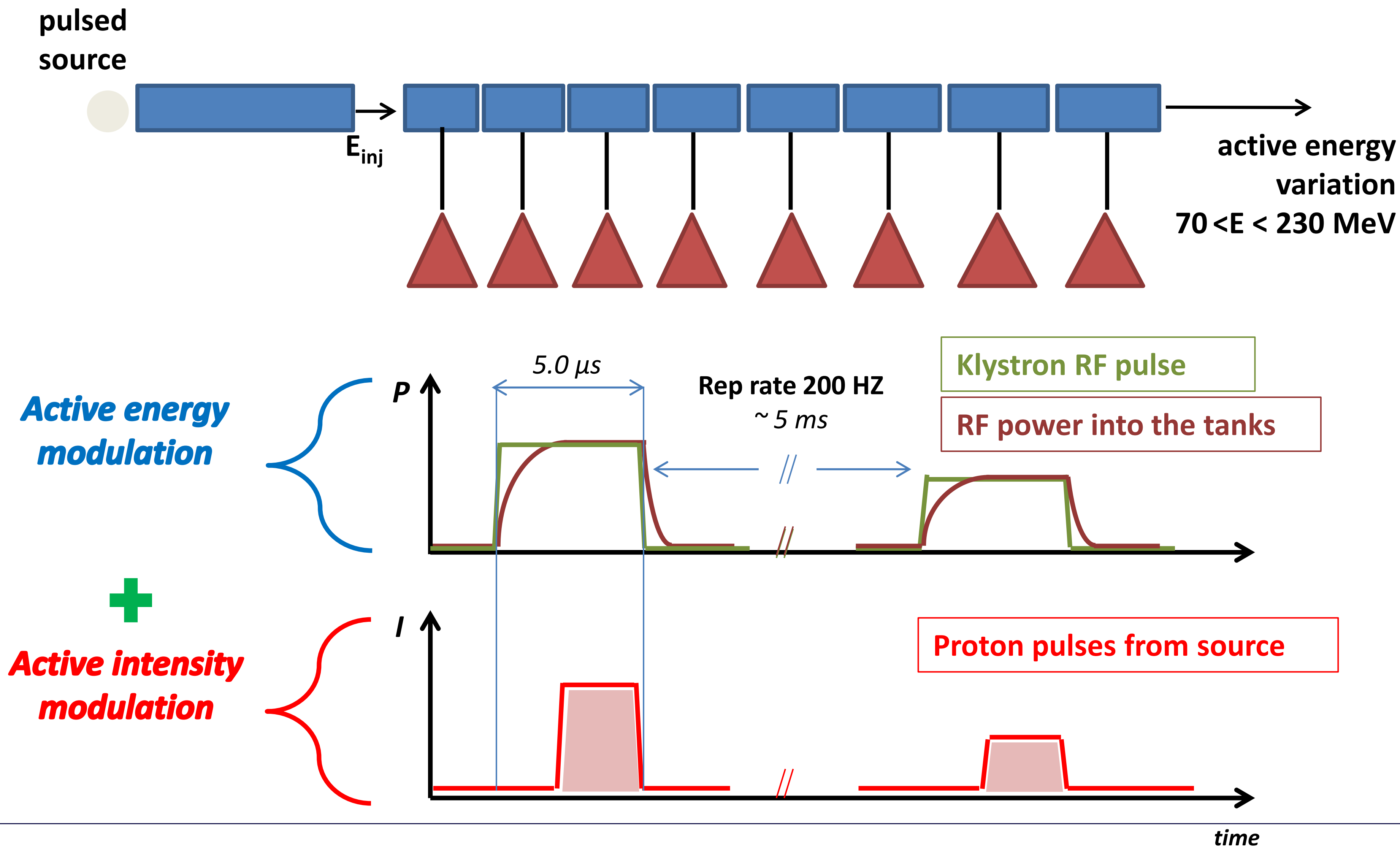
... A big THANK to all of them!

Ευχαριστώ για την προσοχή σας

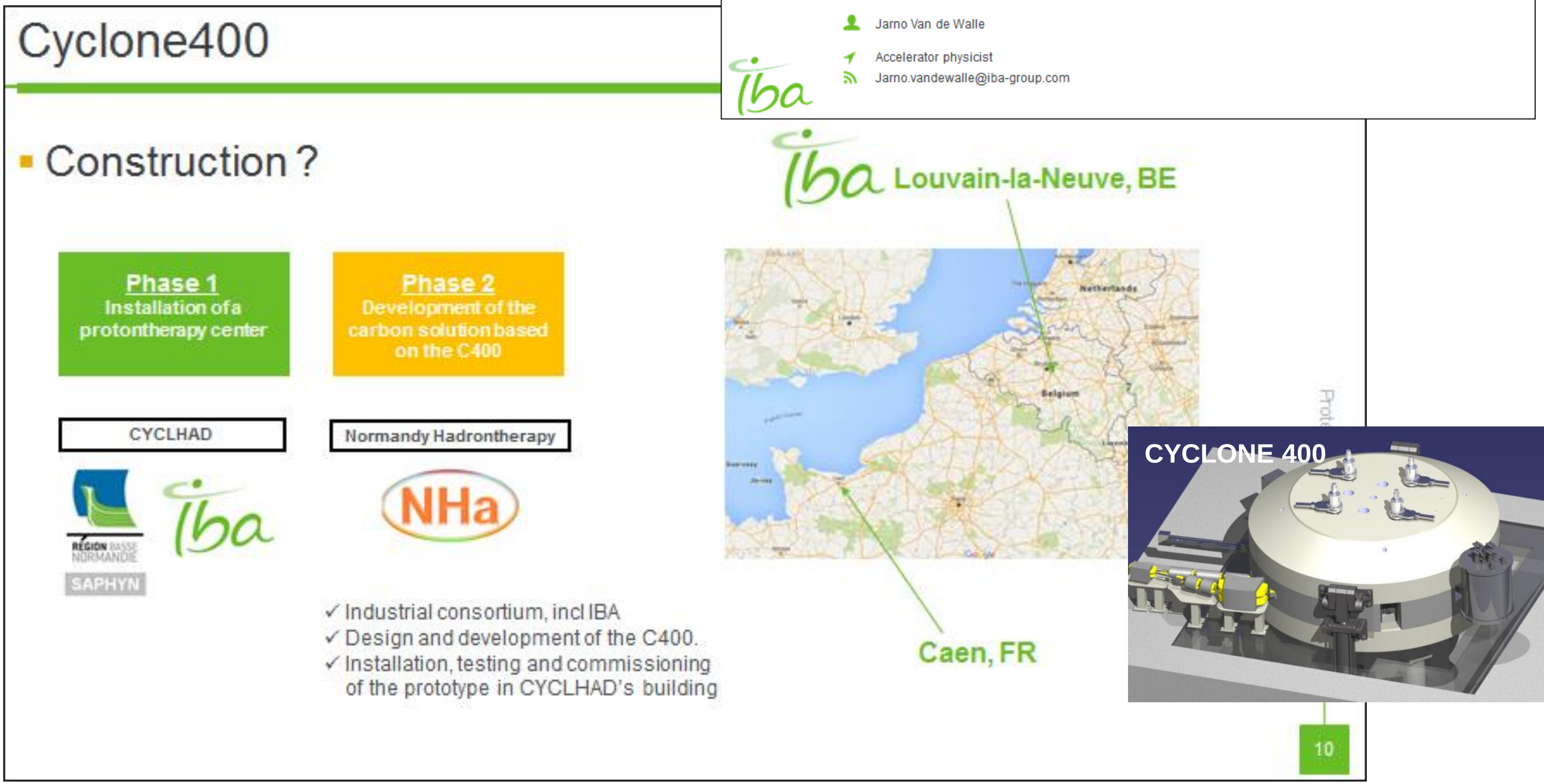
THANK YOU FOR YOUR ATTENTION

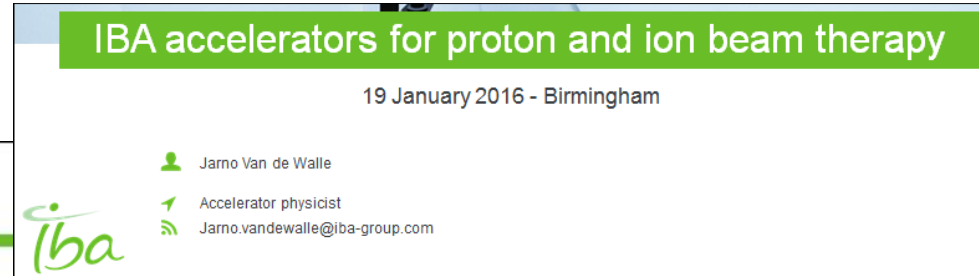
BACKUP

Energy and Intensity modulations



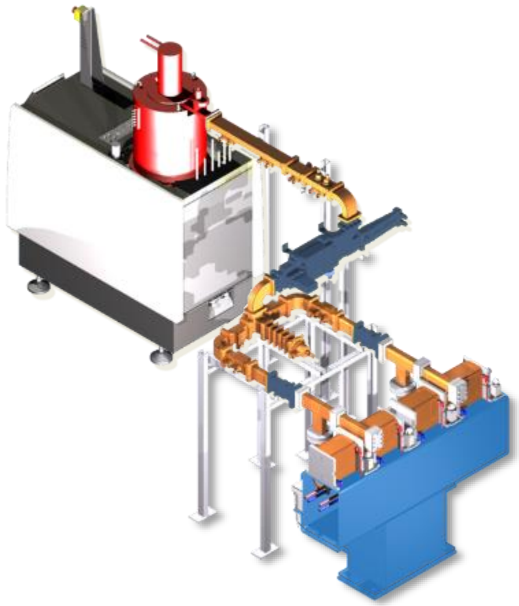
- **IBA cyclone C400**





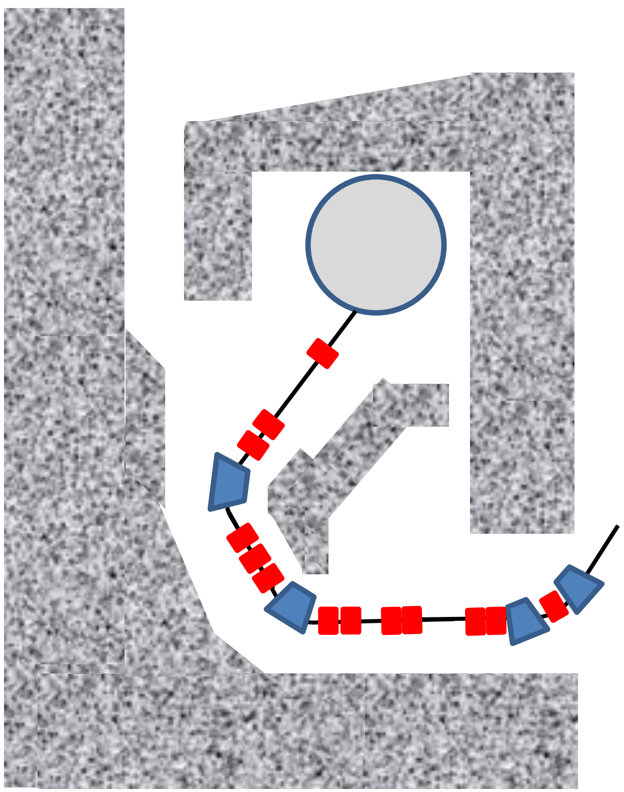
Conservative/safety aspect in LIGHT 1

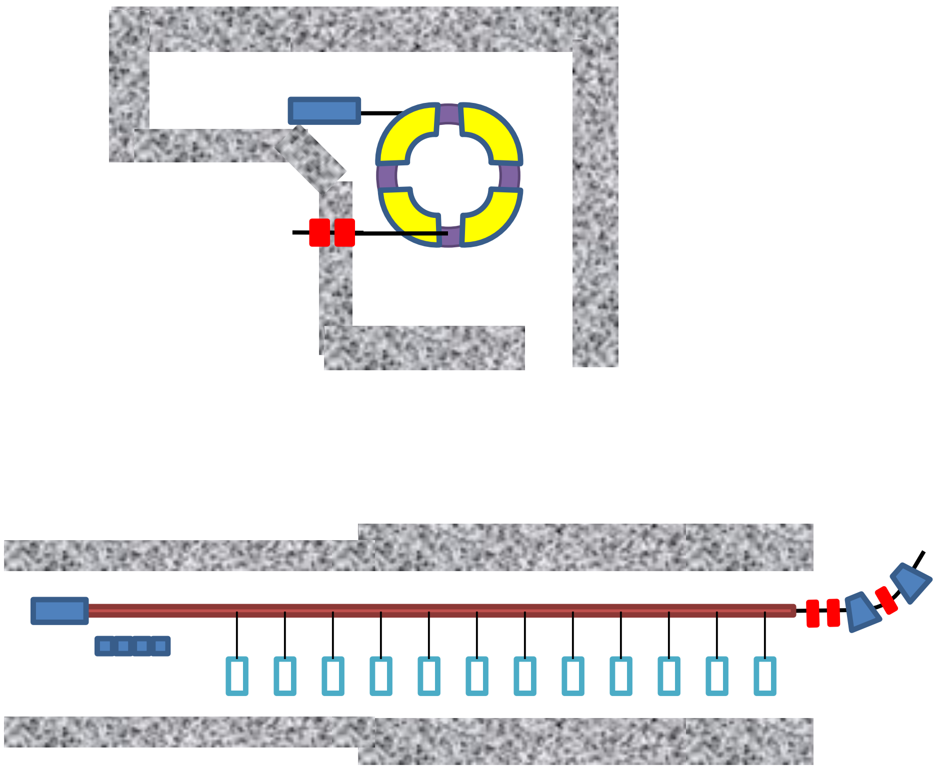
- **Power from klystron: 7.5 MW**
- **P_loss wg network: ~ 15%**
- **Power available per unit: ~ 6.4 MW**
- **Max power used: ~5 MW**
- **Power safety/operational margin: ~ 28%**
- **RF network includes Isolator for protection of the klystron from reflected power.**
- **Part of RF network under SF6 !**



LIGHT: 70-230 MeV	
Peak power [Mw]	48
Total length [m]	12.3
Active length [m]	9.5
Fill factor	0.77
Number of kl.	8

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



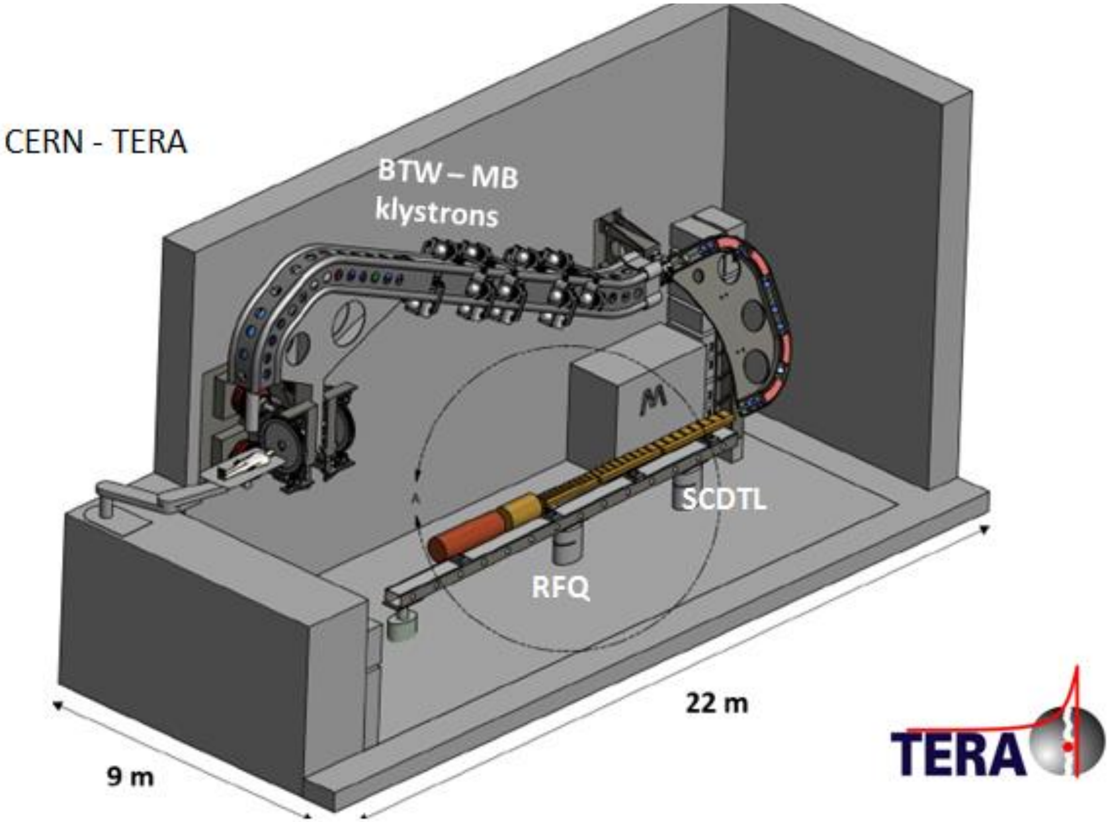


TULIP all-linac with new btw structures

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 040101 (2017)

High gradient linac for proton therapy

S. Benedetti,* A. Grudiev, and A. Latina
CERN, CH-1211 Geneva-23, Switzerland
(Received 23 January 2017; published 13 April 2017)



Btw: 70-230 MeV	
Peak power [Mw]	108
Total length [m]	7.7
Active length [m]	4.4
Fill factor	0.57
Number of kl.	18