PARTNER Final Project Meeting

High-Gradient Linacs for Hadrontherapy

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Former **PARTNER Early Stage Researcher** in
«Novel Accelerator Concepts for Hadrontherapy»
TERA Foundation – **IFIC** (CSIC/UV)
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CNAO (Pavia, Italy) – September 14, 2012

The motivation

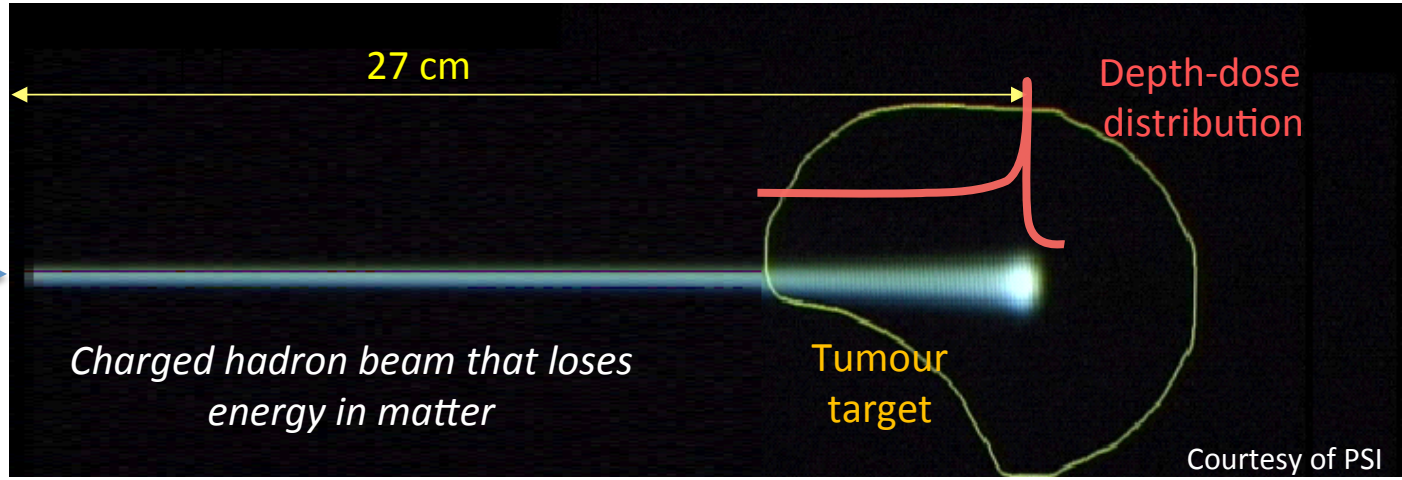
The hadrontherapy community would benefit from
i) compact, ii) reliable accelerators
with the iii) **appropriate beam performances**
for tumour treatment with ions.

Accelerators for Hadrontherapy

Characteristics of a therapeutical beam

200 MeV - 1 nA
protons

400 MeV/u – 0.1 nA
carbon ions
(radioresistant tumours)



Accelerators for Hadrontherapy

Treating moving organs requires…

❖ **Fast Active Energy Modulation**

(a couple of ms)

⇩

Fast 3D correction of

beam spot position in depth

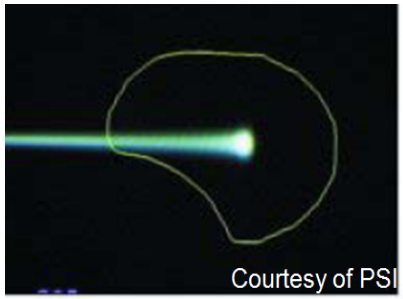
❖ **Fast Cycling machine**

(high repetition rate ~ 200-300 Hz)

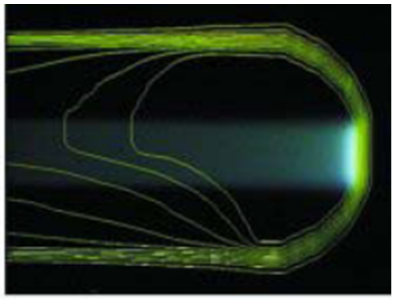
⇩

Tumour

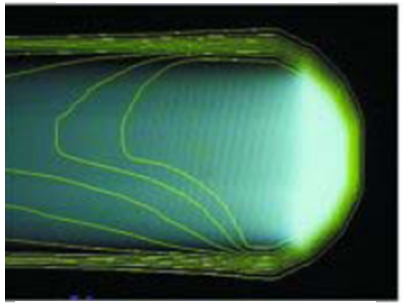
MULTIPAINTING



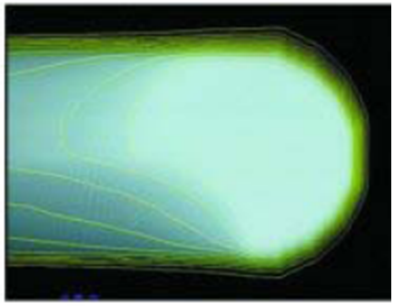
Single 'spot' pencil beam



Lateral scanning with magnets: 2 ms/step



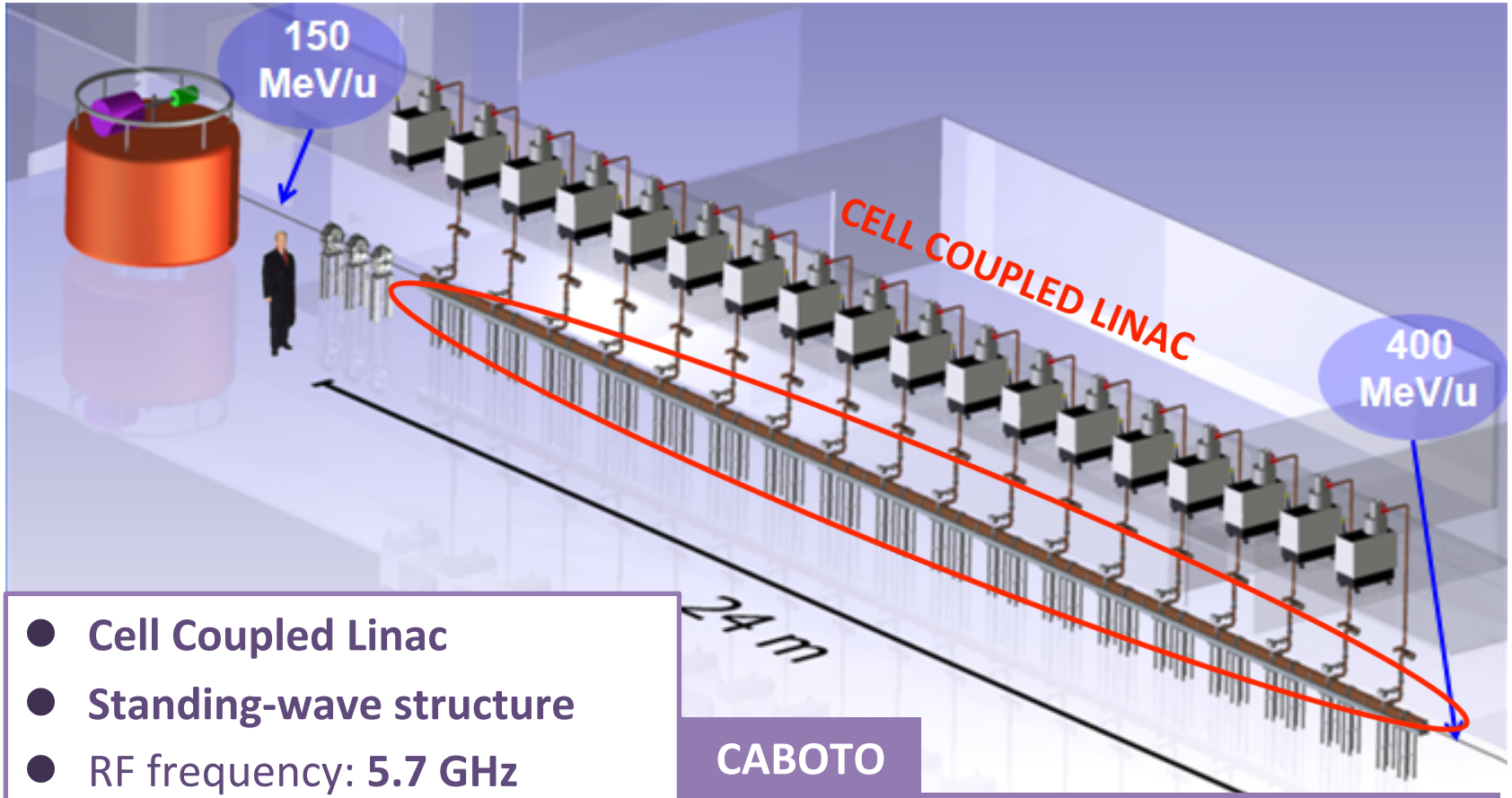
Depth scanning: ACTIVE ENERGY MODULATION



3D conformal treatment

Accelerators for Hadrontherapy

The cyclinac: cyclotron + high frequency linac



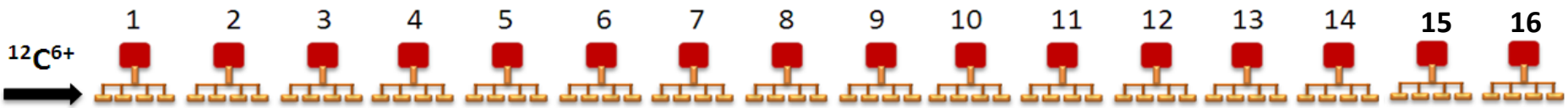
- **Cell Coupled Linac**
- **Standing-wave structure**
- RF frequency: **5.7 GHz**
- **2.5 μs**-long pulse at **300 Hz**

CABOTO

(CArbon BOoster for Therapy in Oncology)

High-Frequency Linac for Carbon Ion Therapy

Machine Performances



Structure	
# klystrons/unit	1
# tanks/unit	4
# cells/tank	18
Total length	24 m

Operation	
E_0	32-34 MV/m (E_{max}= 170 MV/m)
$P_{installed}$	192 MW
$P_{consumption}$	550 kW (2.2 μs at 300 Hz)

- *Reduced power requirement*
- *Modularity:*
  - *Implement facility in different phases*
  - *Ease maintainance*

High-Frequency Linac for Carbon Ion Therapy

Machine Performances: ***i) Compactness***

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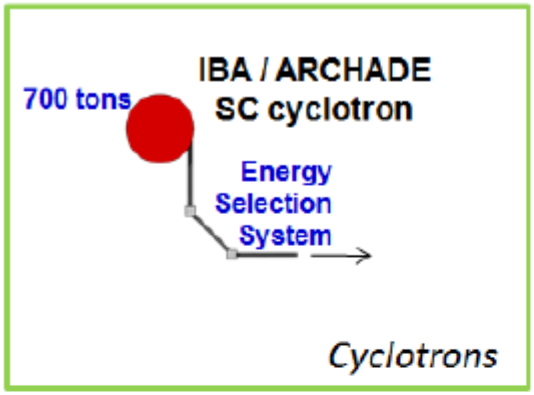
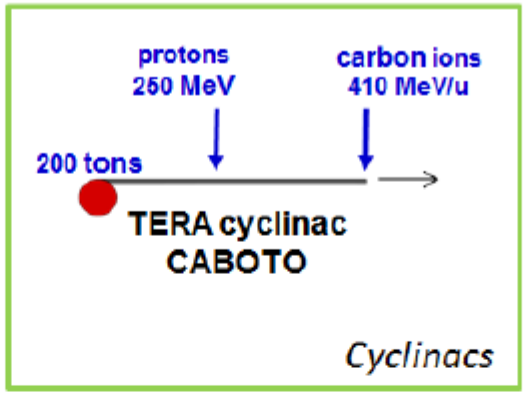
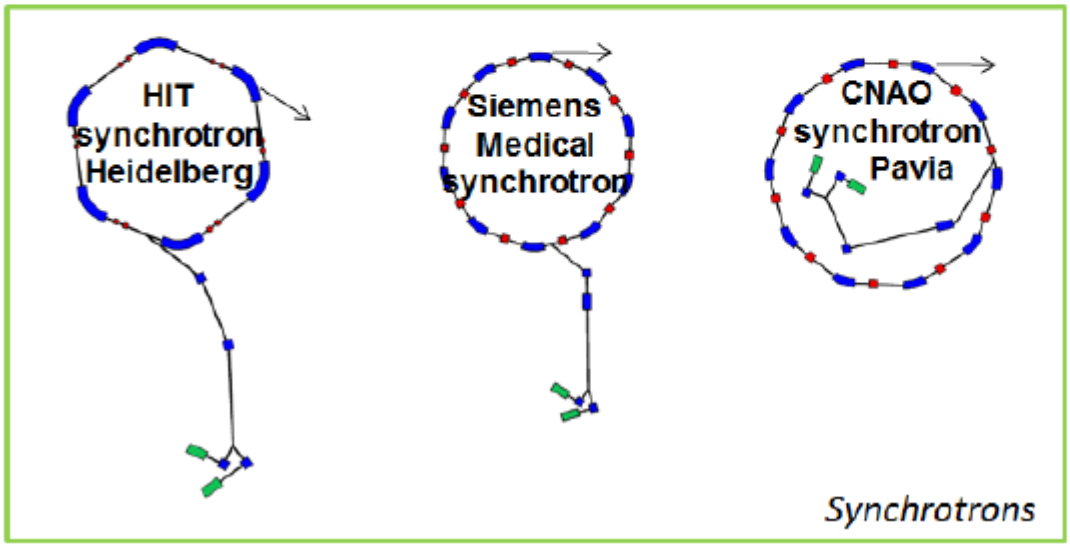
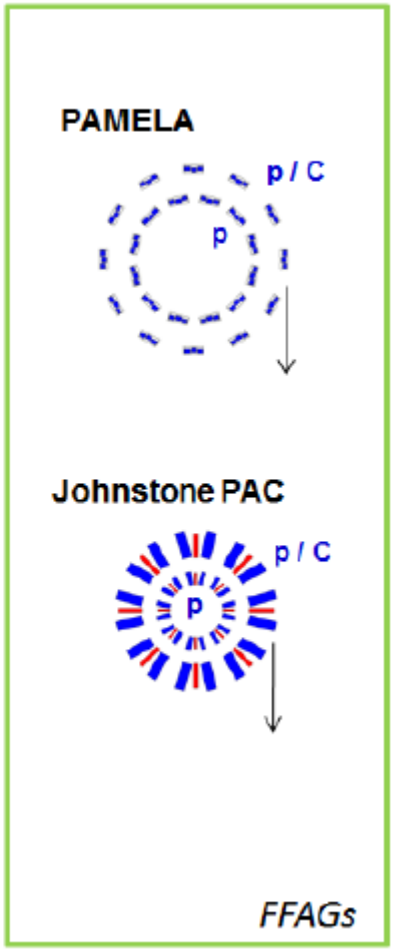


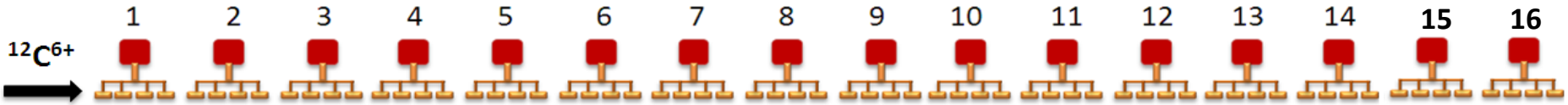






High-Frequency Linac for Carbon Ion Therapy

Linac Layout



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High-Frequency Linac for Carbon Ion Therapy

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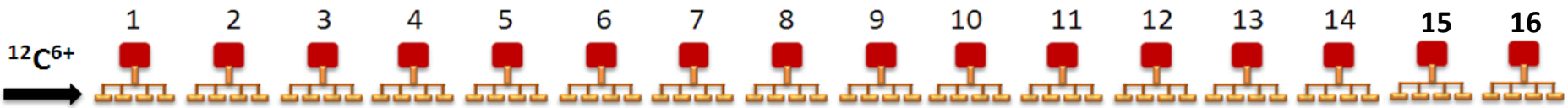

i) compactness provided by high gradients!

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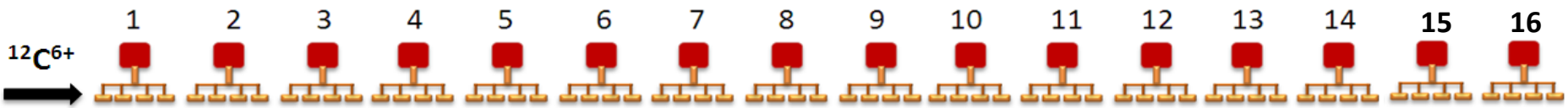

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The appearance of **electrical discharges (RF breakdowns)** associated to the **operation at high gradients** may compromise the accelerator *ii) reliability* :

TERA High Gradient Test Program

TERA High-Gradient Test Program

Objectives

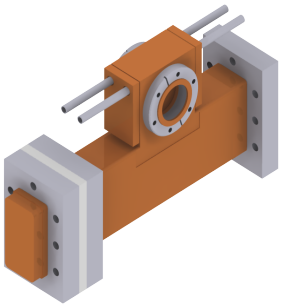
- Operation limit for high-freq cavities → BreakDownRate **BDR**

- Scaling laws (E_S, S_C, pulse length, temperature, frequency)

- Applying found limit to future designs
  - ensure reliable operation
  - optimize RF structures (efficiency, length, cost)

TERA High-Gradient Test Program

test cavities



S-band: 3 GHz

(electron linacs conventional radiotherapy)

- One 3 GHz TERA Single-Cell Cavity → **already** high-power **tested**

TERA High-Gradient Test Program

test cavities

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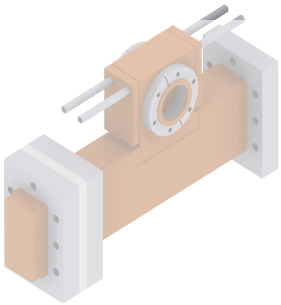
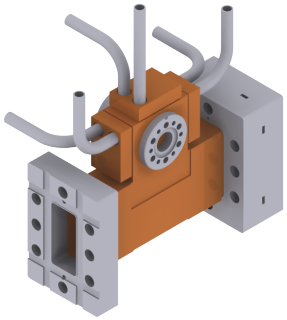


- One 3 GHz TERA Single-Cell Cavity → **already** high-power **tested**

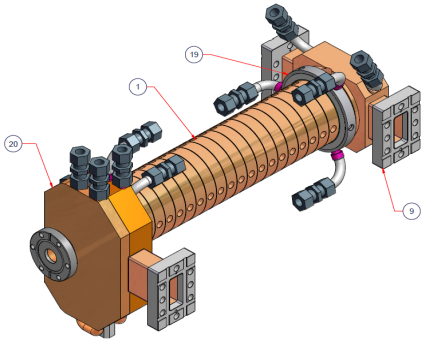
C-band: 5.7 GHz

(reduce size & cost)



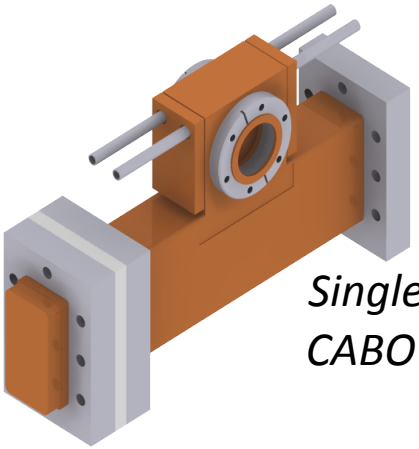
- Three 5.7 GHz TERA Single-Cell Cavities
  - 2 conventional machining → tuning ongoing
  - 1 diamond machining → brazing

- One 5.7 GHz Frascati Multi-Cell Traveling-Wave Structure
  → **already** high-power **tested**

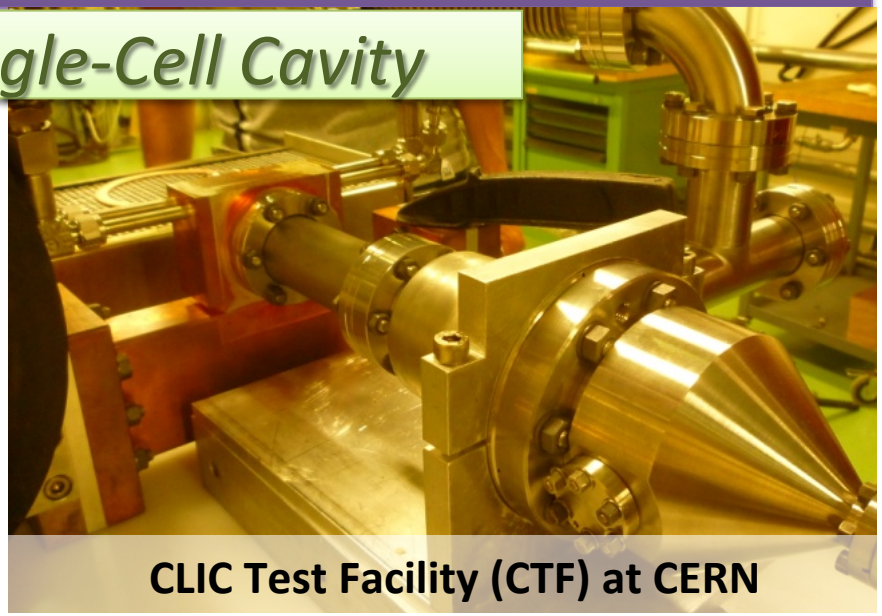


TERA High-Gradient Test Program

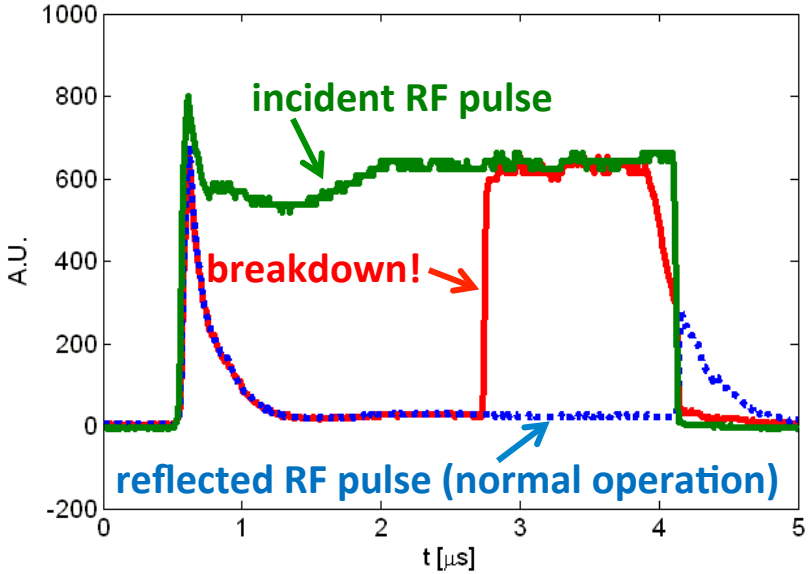
3 GHz Single-Cell Cavity



Copper
Single-cell cavity
CABOTO-like cell



CLIC Test Facility (CTF) at CERN



High-power tests completed in March 2012

Main goal:

Direct measurement of **breakdown rate**

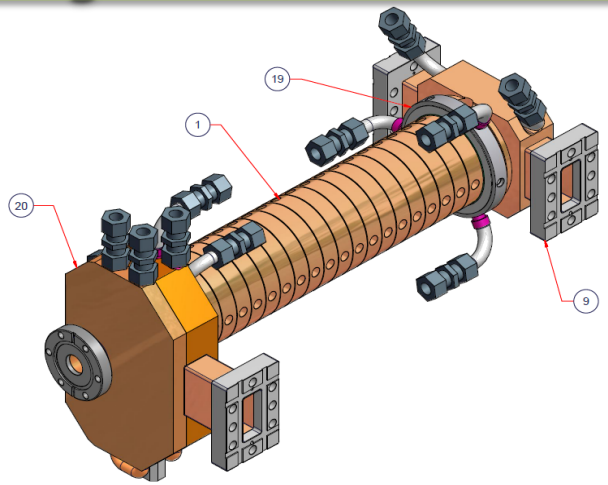
for **2.2 μs-long RF pulses**

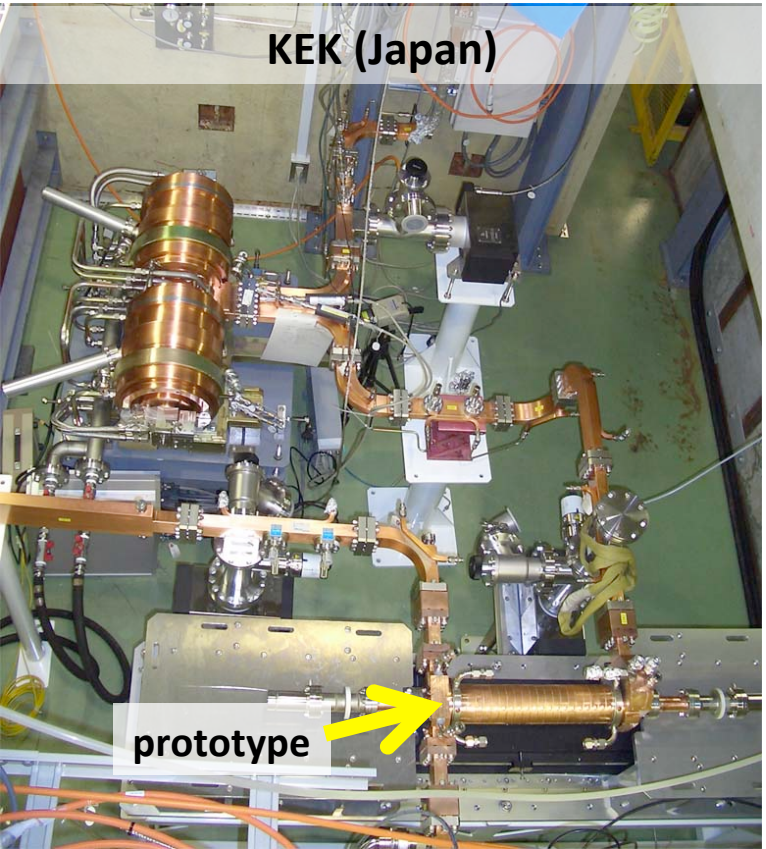
at **same operation field** of CABOTO

TERA High-Gradient Test Program

5.7 GHz Multi-Cell Traveling-Wave Structure

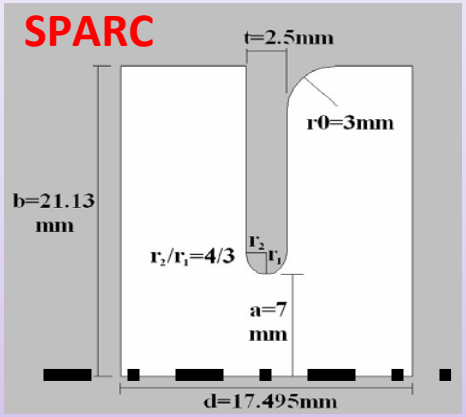
Prototype for the SPARC energy upgrade
5.7 GHz copper traveling-wave structure





High-power tests completed in December 2010

Breakdown rate measured for the SPARC prototype can be **rescaled** to CABOTO cells



High-Frequency Linac for Carbon Ion Therapy

Machine Performances: ***ii) Reliability***

ii) Reliability

modified Poynting vector

$$\sqrt{S_C^{equiv}} = \sqrt{S_C} \cdot \left(\frac{t_{pulse}}{t_{pulse}^{ref}}\right)^{\frac{1}{6}} \cdot \left(\frac{BDR^{ref}}{BDR}\right)^{\frac{1}{30}}$$

breakdown rate

pulse length

Experiment	BDR [bpp/m]	Sc,max [MW/mm^2]	t_{pulse} [μs]
3 GHz test cavity	3×10^{-6}	0.87	2.2
5.7 GHz prototype	1.5×10^{-5}	1.67	0.2

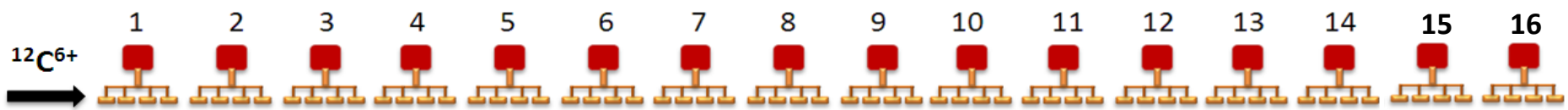
The **expected breakdown rate** for CABOTO [which presents sqrt(Sc,max)/E_0 = 0.024] operating **2.2-ms RF long pulses** at a **maximum field E_0 of 34 MV/m** is **about 10^{-6} bpp/m**.

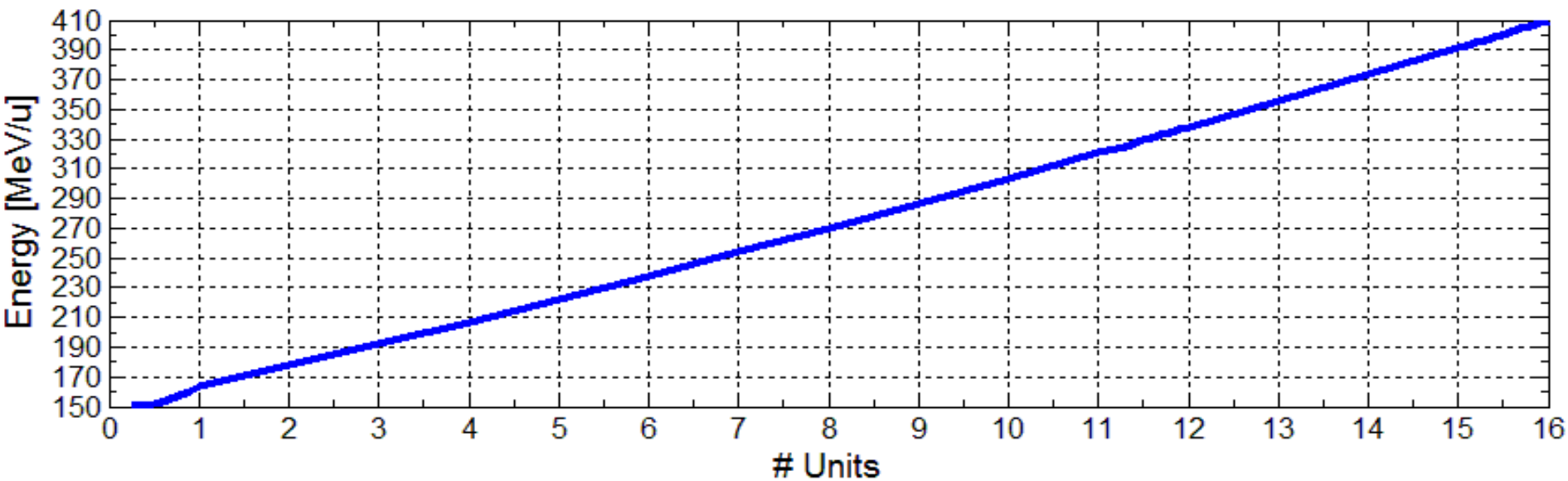
High-Frequency Linac for Carbon Ion Therapy

iii) Beam Performances

Fast active energy modulation

Power distribution allows **2 mm-range steps** within 1-2 ms. No absorbers.





High-Frequency Linac for Carbon Ion Therapy

iii) Beam Performances

iii) Beam performances

b) Output beam intensity

Assuming an output beam intensity of 100 nA at the cyclotron exit, CABOTO could provide **about 2 nA** with the appropriate energy for therapy.

c) High repetition rate

300 Hz

High-Frequency Linac for Carbon Ion Therapy

iii) Beam Performances

a) Output beam intensity

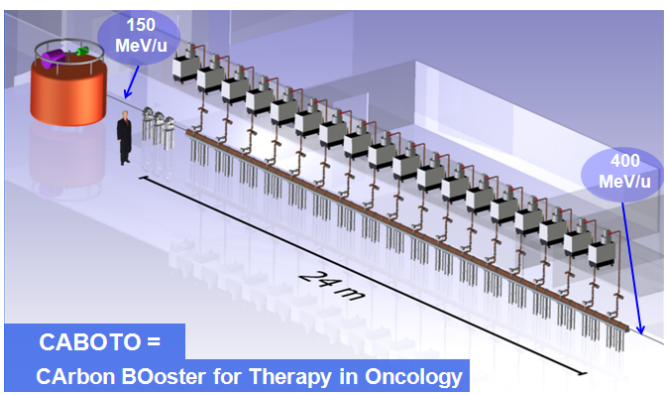
about 2 nA for 100 nA output cyclotron beam

b) Fast active energy modulation

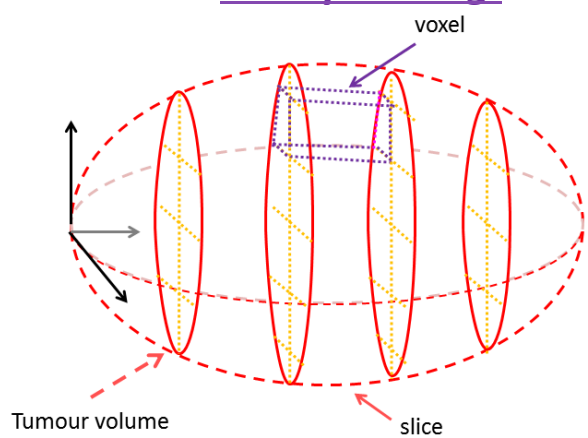
+

c) High repetition rate

CABOTO – 300 Hz



3D spot-scanning technique with multipainting



+

3D feedback system

moving organs treatment

Summary of CABOTO performances

- **Reduced power requirement:** *550 kW (for 3.2 μs-pulse at 300 Hz)*

- **Compactness:** *24 meters-long linac*

- **Reliability at operation field:** *about 10^{-6} bpp/m*

- **Beam performances:**
  - ✓ *Fast active energy modulation (within 1-2 ms):*
    - ✓ Energy range for $^{12}C^{6+}$: *150-410 MeV/u*
    - ✓ Energy step: *2 mm-range in water*

  (spot scanning technique)

  - ✓ High repetition rate: *300 Hz*

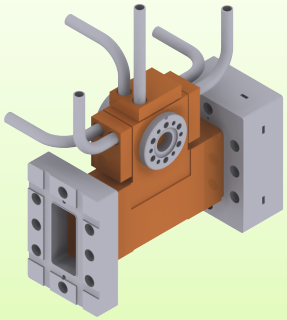
  (+ 3D feedback system → *tumour multipainting & moving organs treatment)*

- **Modularity**

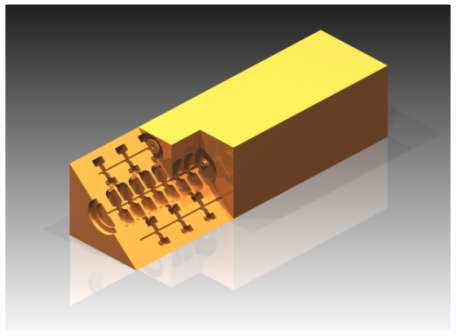
+ **Possibility to accelerate H_2**

Next steps

- High-gradient test of **5.7 GHz Single-Cell SW Cavities** (different machinings) in A.D.A.M. (Geneva, CH) at the end of 2012.



- Design, prototyping and high-power test of **Multi-Cell SW structure** at **selected frequency** (depending on experience)



- **Further studies on CABOTO** :

  effects of jitter on beam performances, energy selection system, etc.

Acknowledgements

ENLIGHT – PARTNER

CERN

INFN-LNF

KEK

Vodafone Foundation (Italy)