New trends in proton and carbon ion therapy

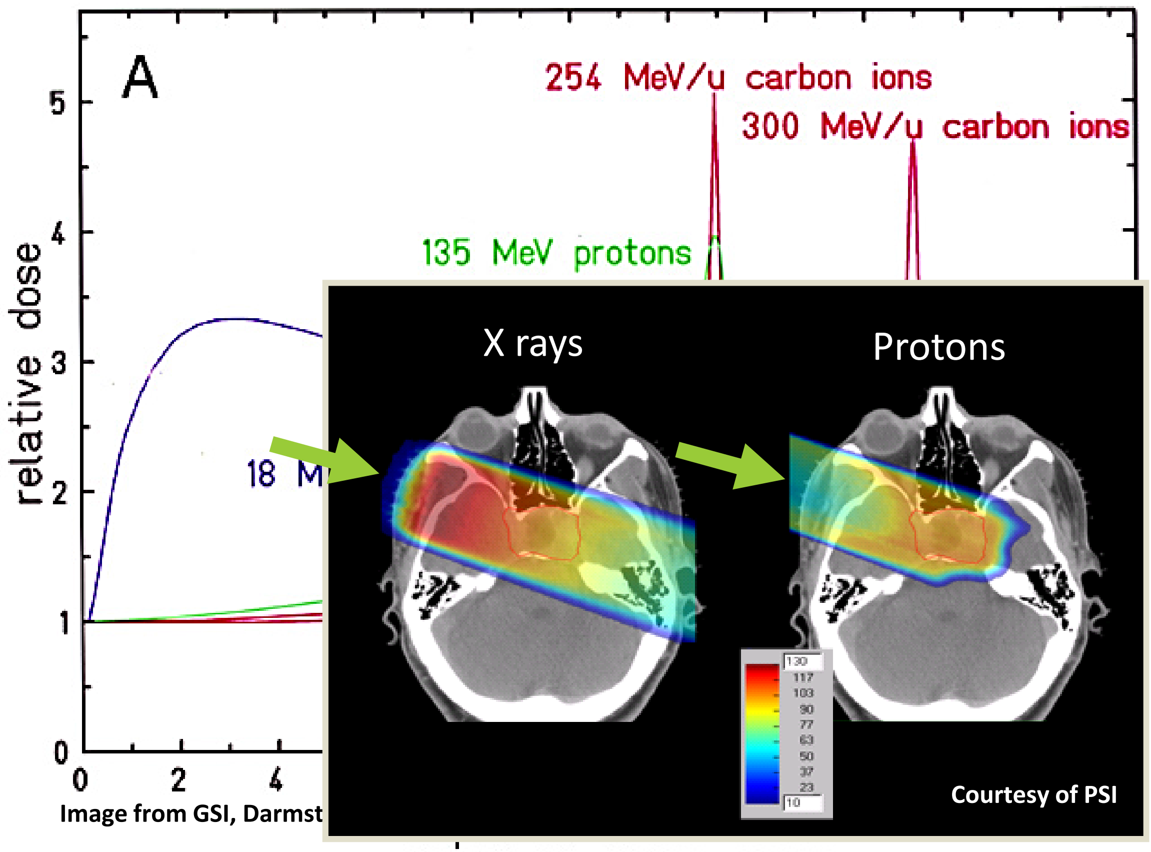
LINAC'18 CONFERENCE

16-21 SEPTEMBER – BEIJING CHINA

Presented by M. Vretenar, CERN

Hadron therapy rationale

Beam direction

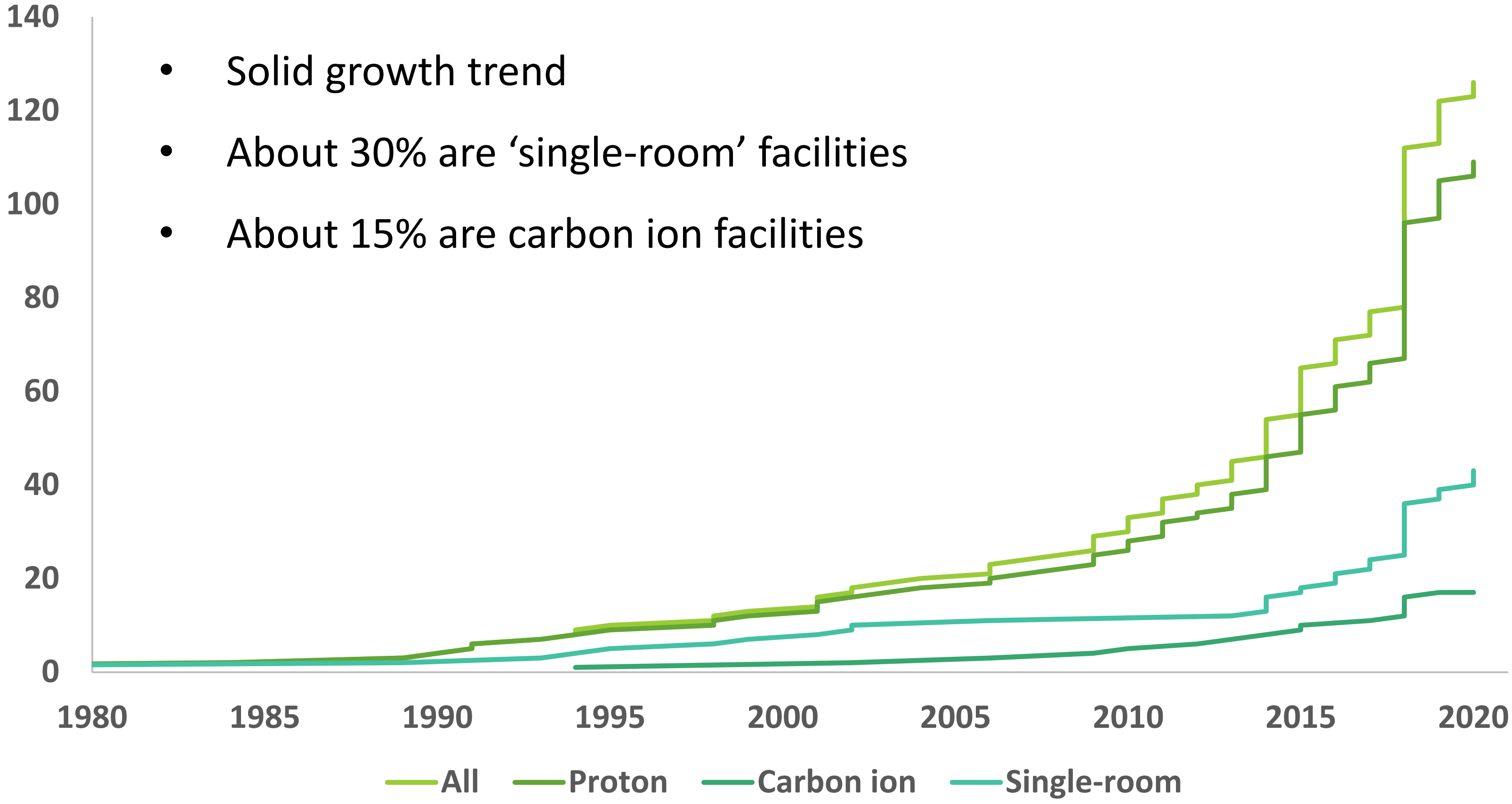


The dose (energy deposited per unit mass) is more focused for protons and light ions – Bragg peak

Carbon ions have a sharper peak, and an higher radio-biological effectiveness

Worldwide facilities

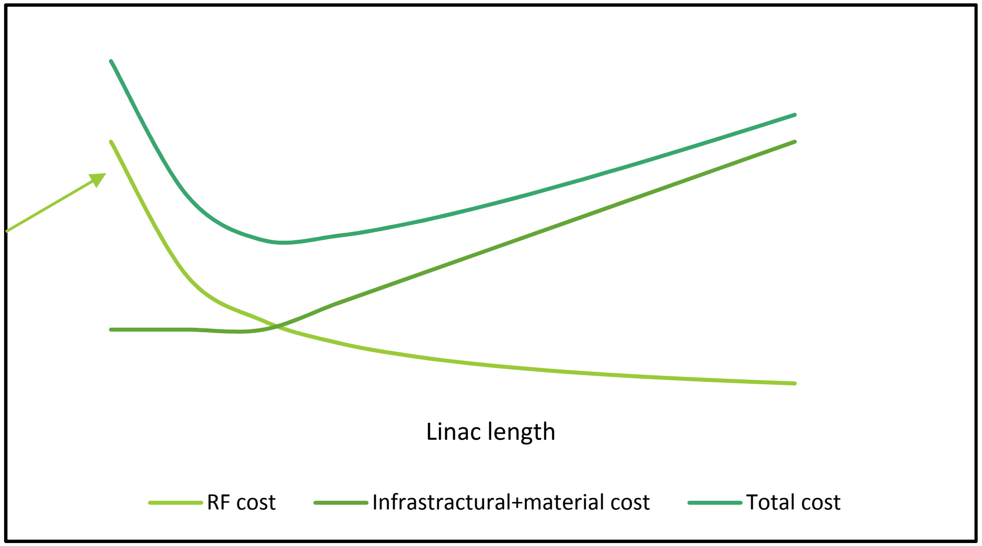
- Solid growth trend
- About 30% are 'single-room' facilities
- About 15% are carbon ion facilities



Data from www.ptcog.ch

Design choices in medical linacs

Technical limits: breakdown, RF heat dissipation



$$\Delta W \propto \sqrt{ZTT \cdot P_d \cdot L}$$

ZTT is also related to the choice of linac gradient and length: operating frequency, cavity design (BD and heat dissipation), beam dynamics choices (beam aperture)

- Historically, an RF frequency of 3 GHz was chosen
- Beam dynamics design and average accelerating gradient choice remarkably affect the efficiency (ZTT)
- Carbon therapy linacs have a factor four difference in the overall voltage gain per nucleon – fundamental difference wrt proton therapy linacs

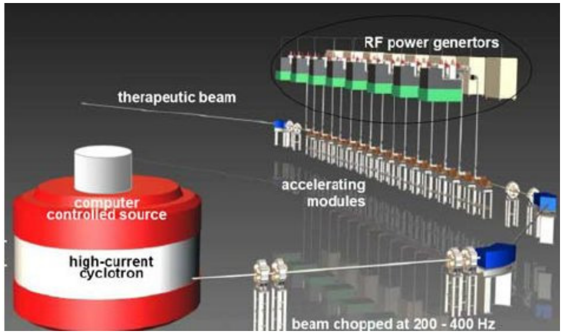
Low energy beam acceleration

Design choices for low energy beam acceleration

Commercial injector

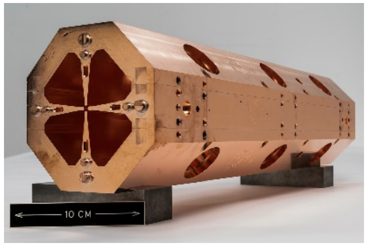
Hitachi AccSys PL-7

Cyclinac



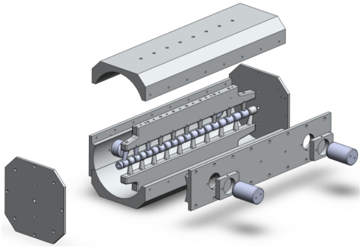
U. Amaldi, Cyclinac: Novel fast-cycling accelerators for hadrontherapy, 2007

RFQ

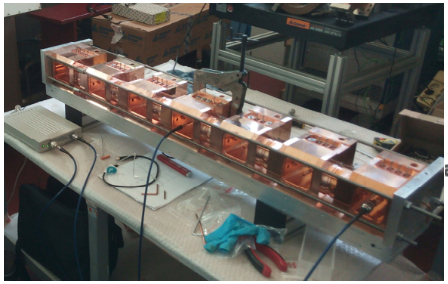


750 MHz CERN RFQ, 2014

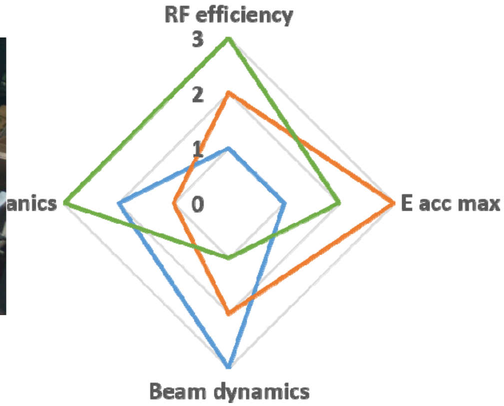
H-type DTL



SCDTL



ENEA 3 GHz SCDTL

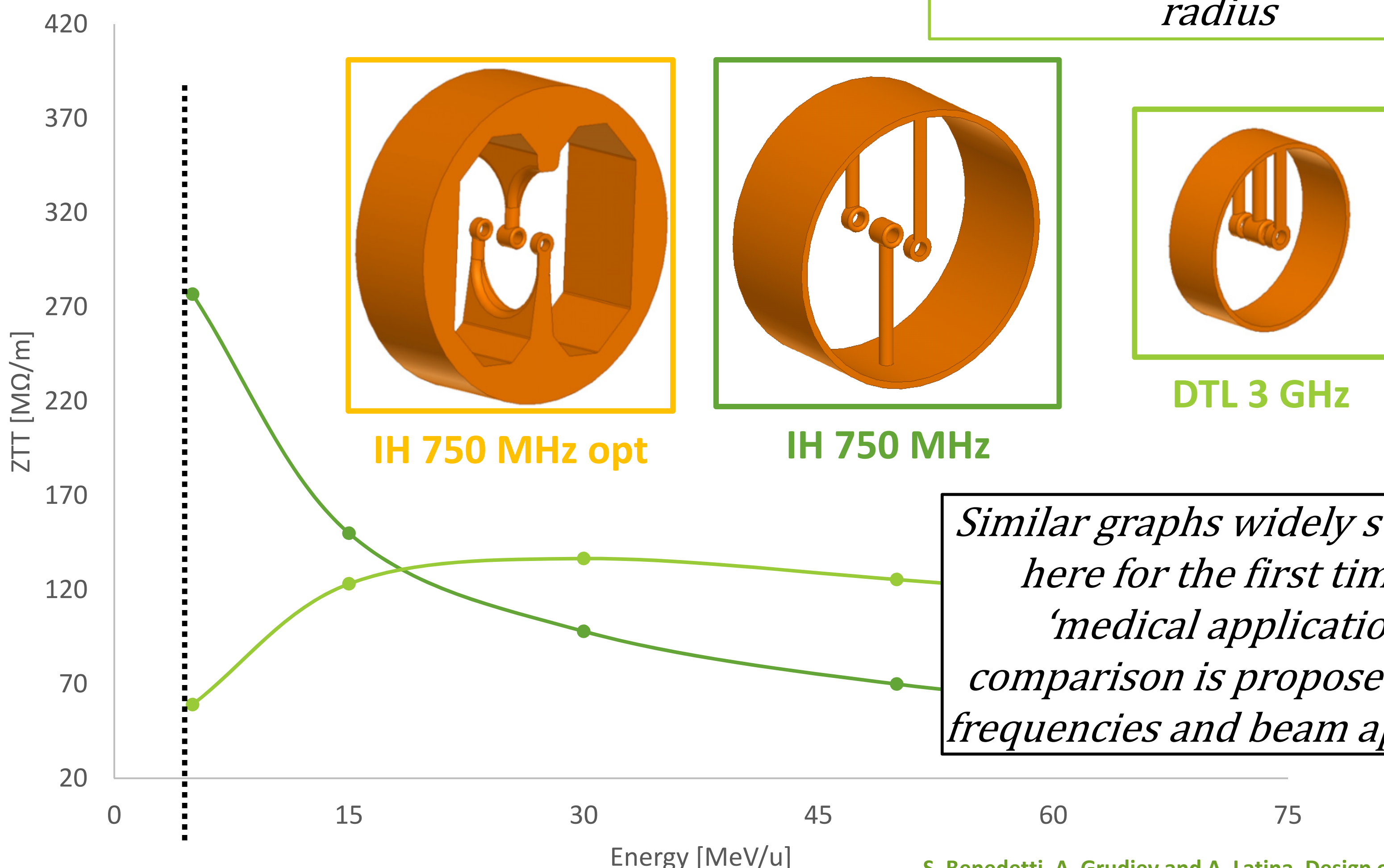


Qualitative assessment between RFQ, DTL and H-type cavities for low energy acceleration. RFQ in blue, DTL in orange, H-type cavities in green.

The 750 MHz IH

$ZTT \propto \sqrt{RF\ Frequency}$
if bore radius scales as well

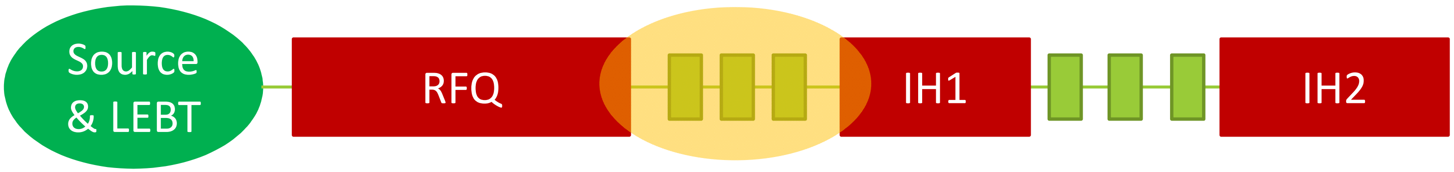
Here constant 2.5mm bore radius



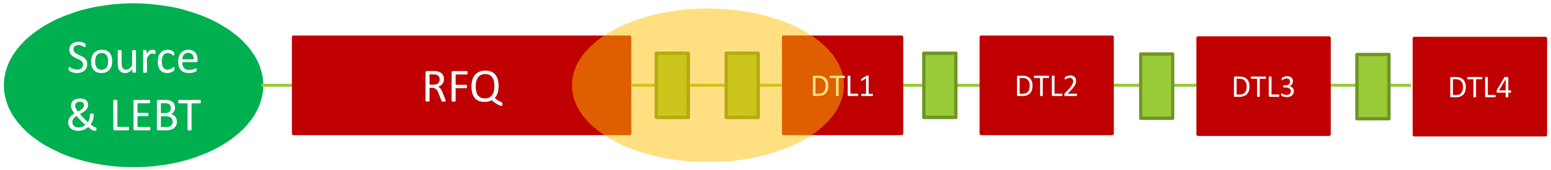
Similar graphs widely studied, here for the first time a 'medical application' comparison is proposed – RF frequencies and beam aperture

S. Benedetti, A. Grudiev and A. Latina, Design of a 750 MHz IH structure for medical applications, Linac16

Matching section: issues of a frequency jump



Challenge if **IH after RFQ**: from FODO lattice to triplet focusing



Challenge if **DTL after RFQ**: frequency jump from 750 MHz to 3 GHz

- Factor 4 in **phase acceptance** for **shorter** wavelength $\boldsymbol{\lambda}$ and in the **RF defocusing** $\boldsymbol{\Delta p_r}$

$$\Delta p_r = -\frac{\pi\ e\ E_0\ T\ L\ r\ \sin\varphi}{c\ \beta^2\ \gamma^2\ \lambda}$$

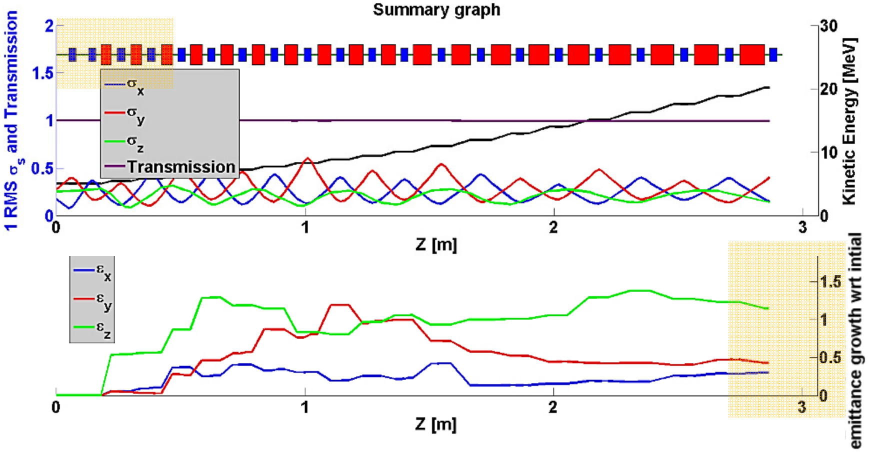
- Factor 2 in **energy acceptance** $\boldsymbol{w_{max}}$

$$w_{max} = \sqrt{\frac{2qE_0T\beta^3\gamma^3\lambda}{\pi mc^2}(\varphi_s\cos\varphi_s - \sin\varphi_s)}$$

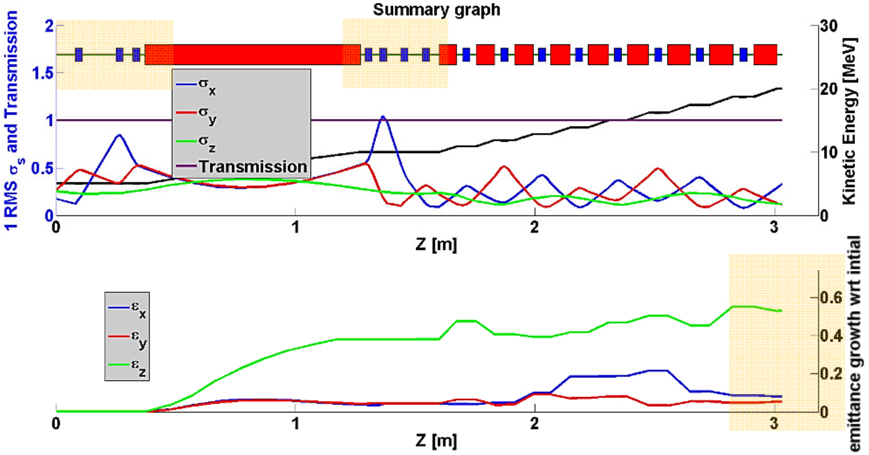
The longitudinal matching and the transverse control of the beam is more challenging with a frequency jump at low energy

750 MHz IH vs 3 GHz DTL comparison

DTL 5 to 20 MeV



IH 5 to 10 MeV – DTL 10 to 20 MeV



Linac comparison from
5 MeV to 20 MeV

Equal length and **100 % transmission** as design goals

An IH from 5 to 10 MeV followed by a DTL is advantageous for:

- Lower emittance growth
- Larger space for diagnostic
- Lower number of quadrupoles
- Machining simplicity

S. Benedetti, A. Grudiev and A. Latina, High gradient linac for proton therapy, PRAB2017

Facility size

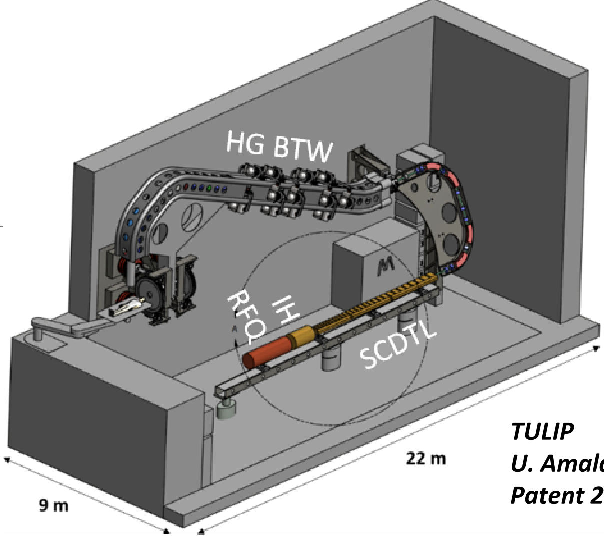
The HG BTW cavity

DESIGN GOAL AND CONSTRAINTS

$$E_a \equiv E_0 T \geq 50\, MV/m$$ → **Compact size**

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

S. Benedetti et al, RF Design of a Novel S-Band Backward Travelling Wave Linac for Proton Therapy, Linac14



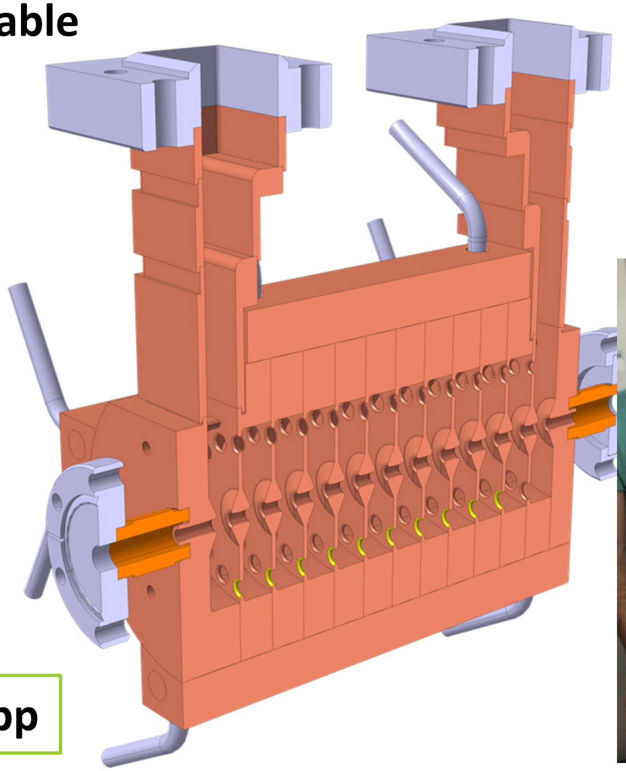
TULIP
U. Amaldi
Patent 2006

scaled values from CLIC and TERA data:

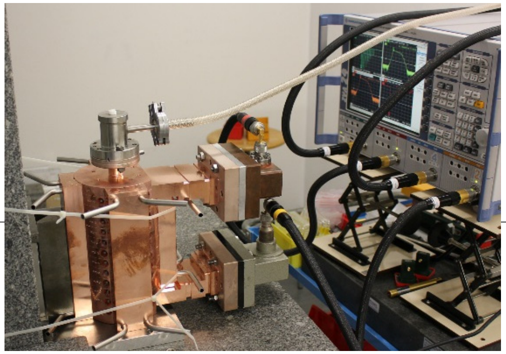
$$\frac{S_c^8 \cdot t_{pulse}^3}{BDR} = const$$

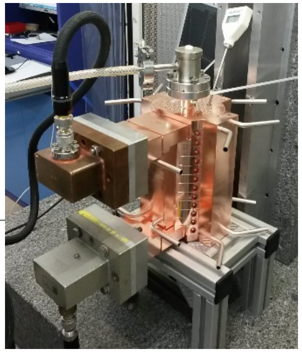
with:

- $S_c < 4\ MW/mm^2$
- $t_{TERA} = 2500$ ns
- $t_{CLIC} = 200$ ns
- $BDR_{TERA} = BDR_{CLIC} = 10^{-6}$ bpp/m → $2 \cdot 10^{-7}$ bpp



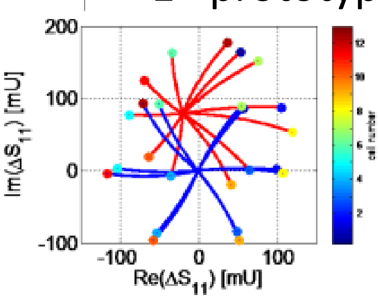
Cavity tuning

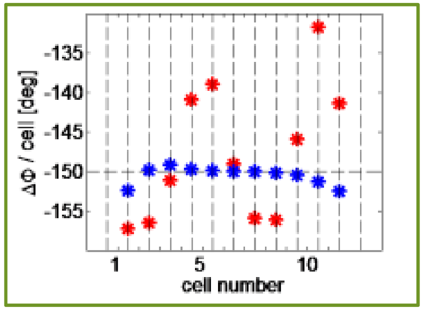


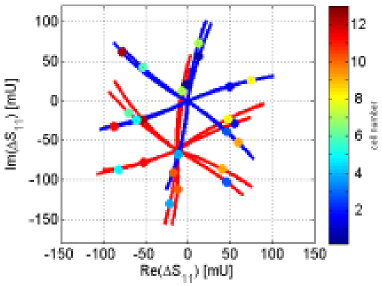


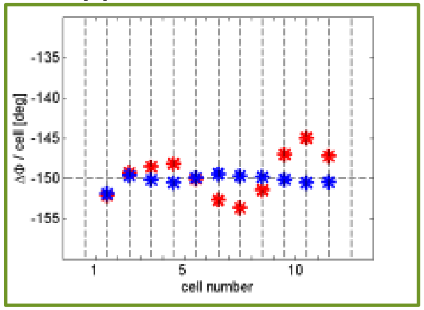
1st prototype – under HG test

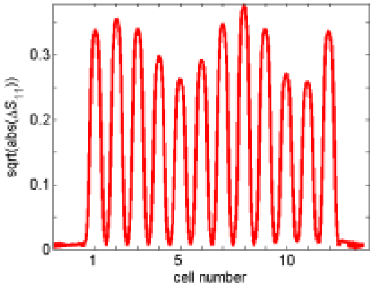
2nd prototype

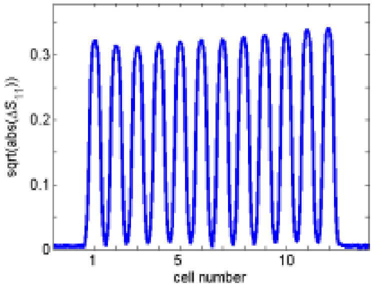


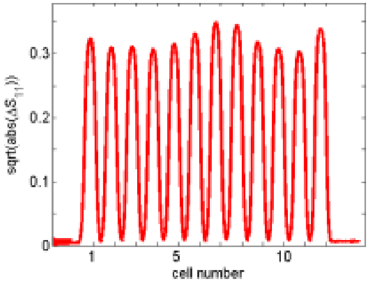


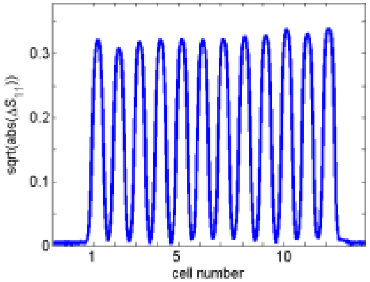












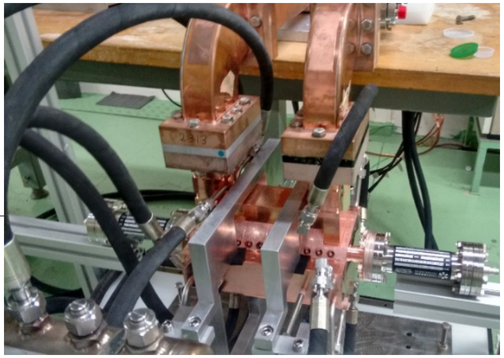
Before tuning

After tuning

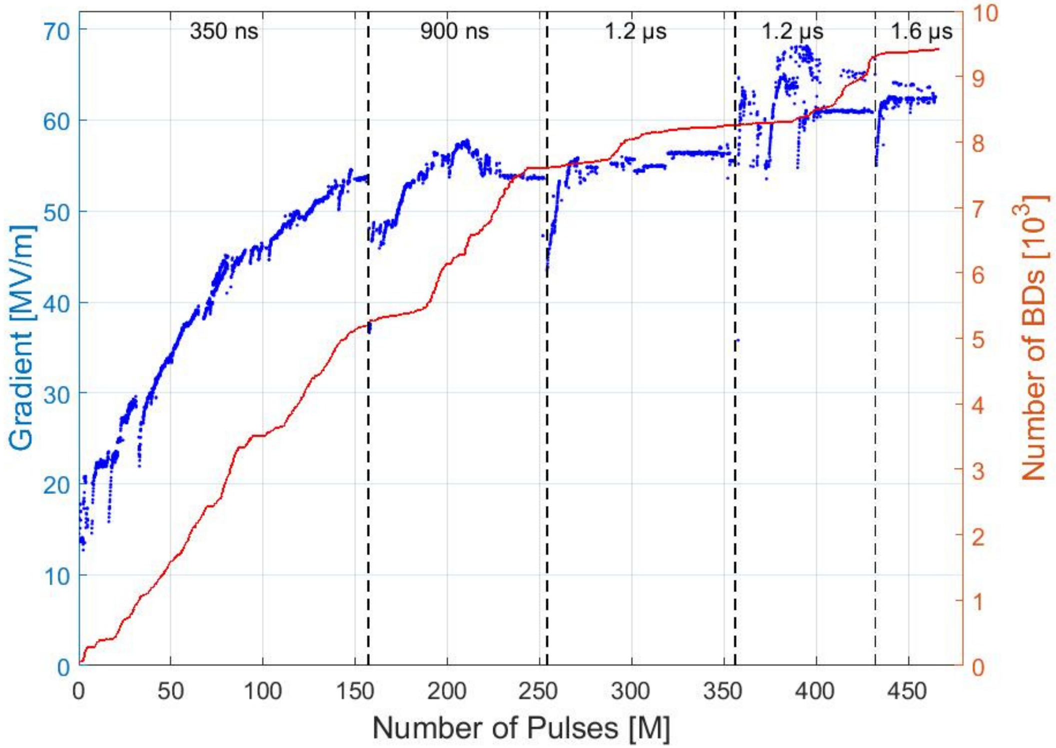
The cavity would be actually ready to accelerate particles

S. Benedetti et al, Fabrication and testing of a novel S-Band backward travelling wave accelerating structure for proton therapy linacs, Linac16

Conditioning status



The prototype installed in CLIC CTF2

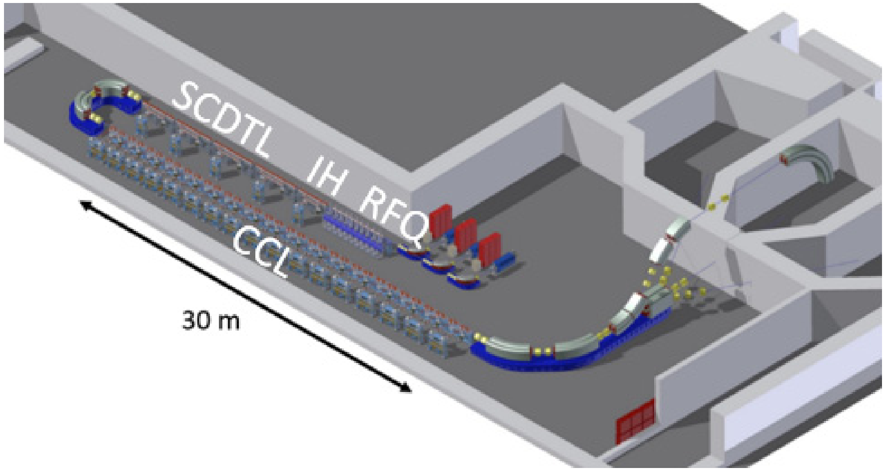


A. Vnuchenko et al, High Gradient Performance of an S-Band Backward Traveling Wave Accelerating Structure for Medical Hadron Therapy Accelerators IPAC18

The cavity is performing beyond the design goals, proving that stable operation at accelerating gradient higher than 50 MV/m can be reached in a 3 GHz medical linac

Carbon ion linacs

CABOTO (CArbon BOoster for Therapy in Oncology)



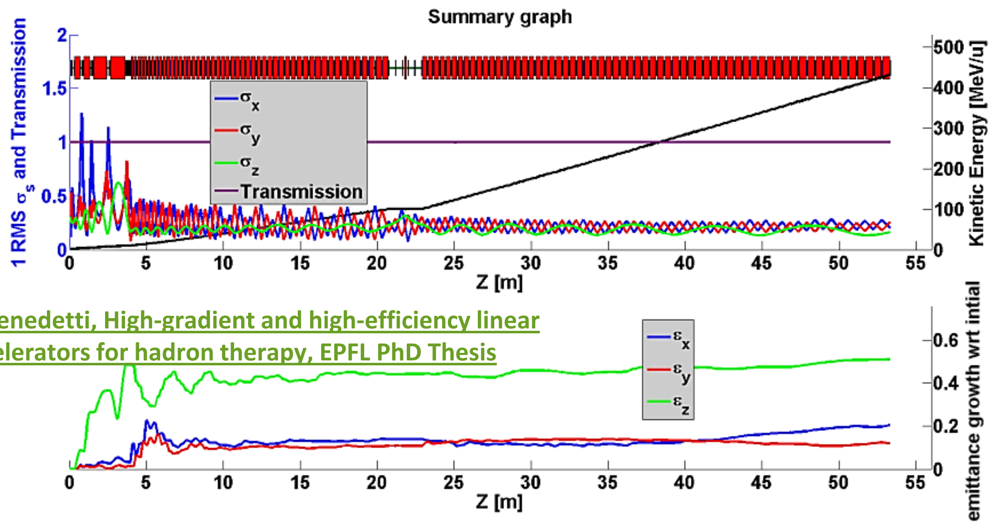
Tot. length	**53 m**
Tot. power	**260 MW**
Avg. ZTT	**108 MΩ/m**

IH **2.5 to 10 MeV/u – 4 cavities**
2.5 m long
6.5 MV/m
402 MΩ/m

DTL **10 to 100 MeV/u – 50 cavities**
11.7 m long
16.2 MV/m
117 MΩ/m

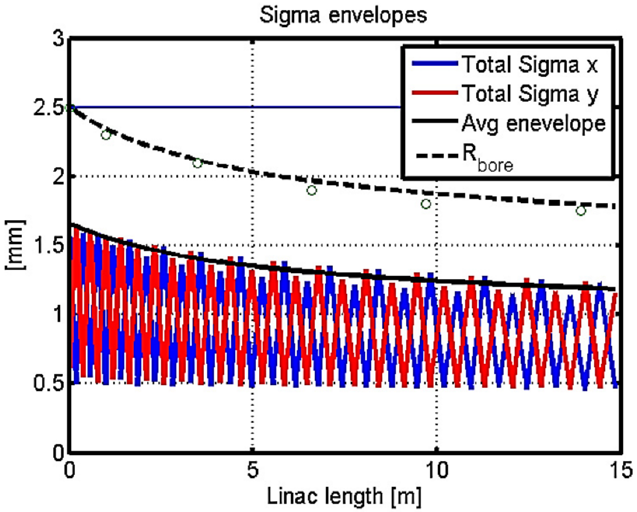
CCL **100 to 430 MeV/u – 32 cavities**
23.1 m long
29.7 MV/m
107 MΩ/m

IH **DTL** **CCL**

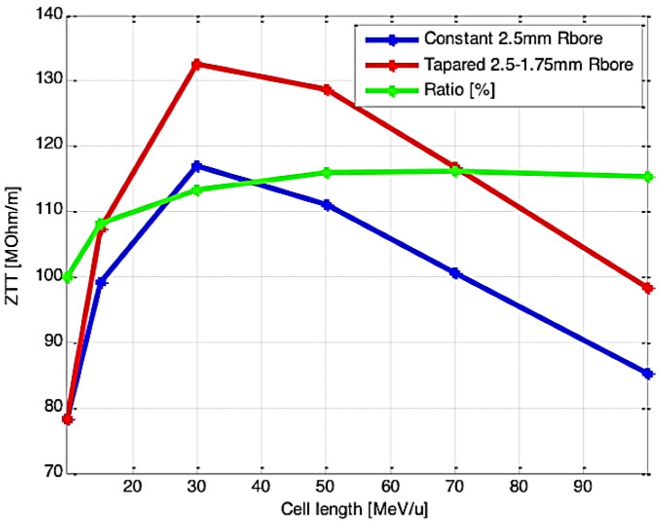


S. Benedetti, High-gradient and high-efficiency linear accelerators for hadron therapy, EPFL PhD Thesis

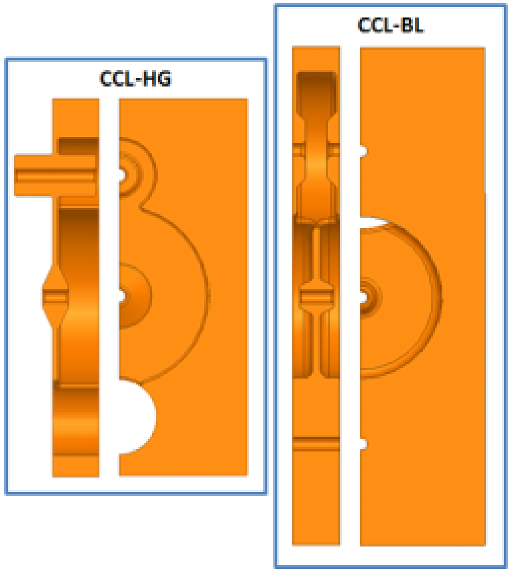
Peculariaty of the design



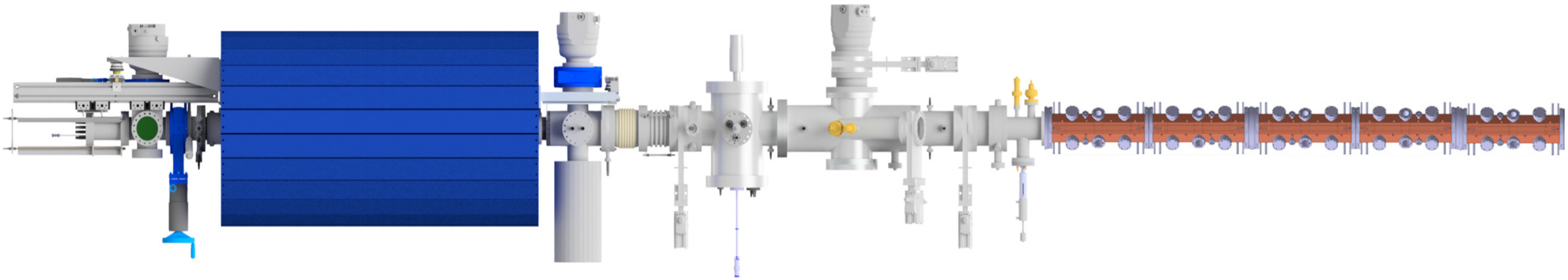
- Relatively low gradient choice (30 MV/m)
- Structures can be designed shorter
- Beam envelopes are smaller
- Cavity apertures are smaller, ZTT is increased



Lower gradient allows a sharper nose design, but the greatest improvement comes from the aperture reduction



CERN TwinEBIS and $^{12}C^{6+}$ RFQ



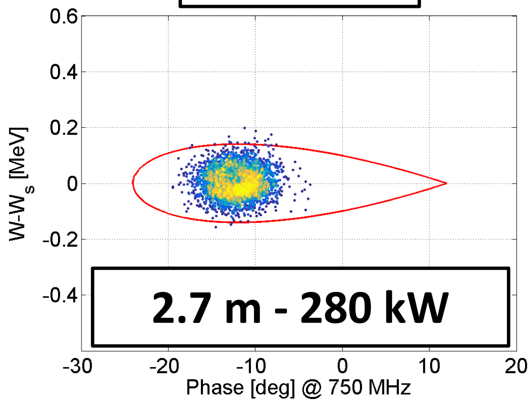
TwinEBIS: In the present set up should be able to provide $1 \cdot 10^9$ $^{12}C^{6+}$ ions in a 5 µs pulse ($2 \cdot 10^{11}$ ions/s)

LEBT: aimed to transport and match the beam to the RFQ

RFQ: Accelerate the beam up to 2.5 MeV/u (or 5 MeV/u)

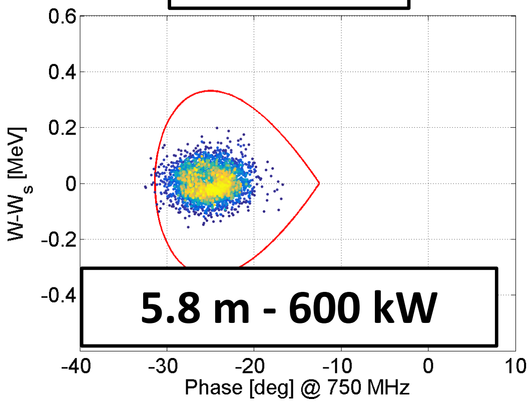
V. Bencini et al, High Gradient Performance of an S-Band Backward Traveling Wave Accelerating Structure for Medical Hadron Therapy Accelerators, this conference

2.5 MeV/u



2.7 m - 280 kW

5 MeV/u



5.8 m - 600 kW

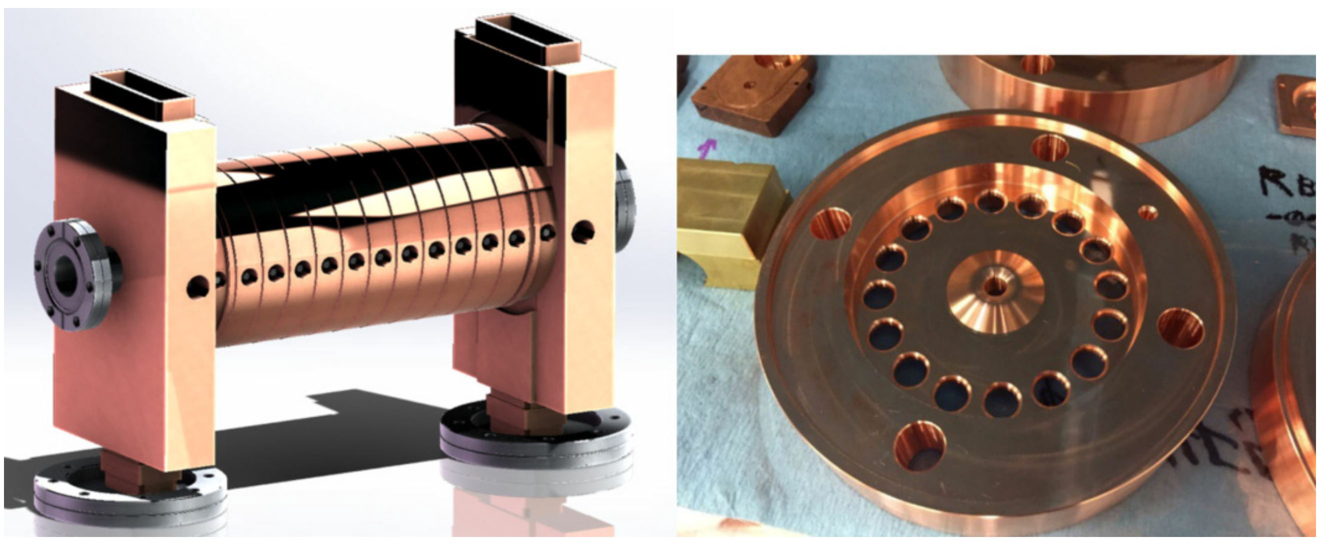
TwinEbis should deliver 10^8 $^{12}C^{6+}$ at 300-400 Hz in 1.5 µs spill. This beam would be accelerated by the RFQ with 56% transmission and output emittances in the acceptance of CABOTO. Final current of 2.2 10^{10} ions/s are 30 times higher than state-of-art carbon ion synchrotrons

ACCIL (Advanced Compact Carbon Ion Linac) RadiaBeam Technologies, Argonne Nat. Lab.

Different design choice with respect to CABOTO, privilege to compactness

Specifically, HG BTW envisaged from 45 to 450 MeV/u, 50 MV/m accelerating gradient

Commercial $^{12}C^{5+}$ ECR, 476 MHz RFQ to 3 MeV, $^{12}C^{6+}$ stripping, 476 MHz DTL till 45 MeV/u



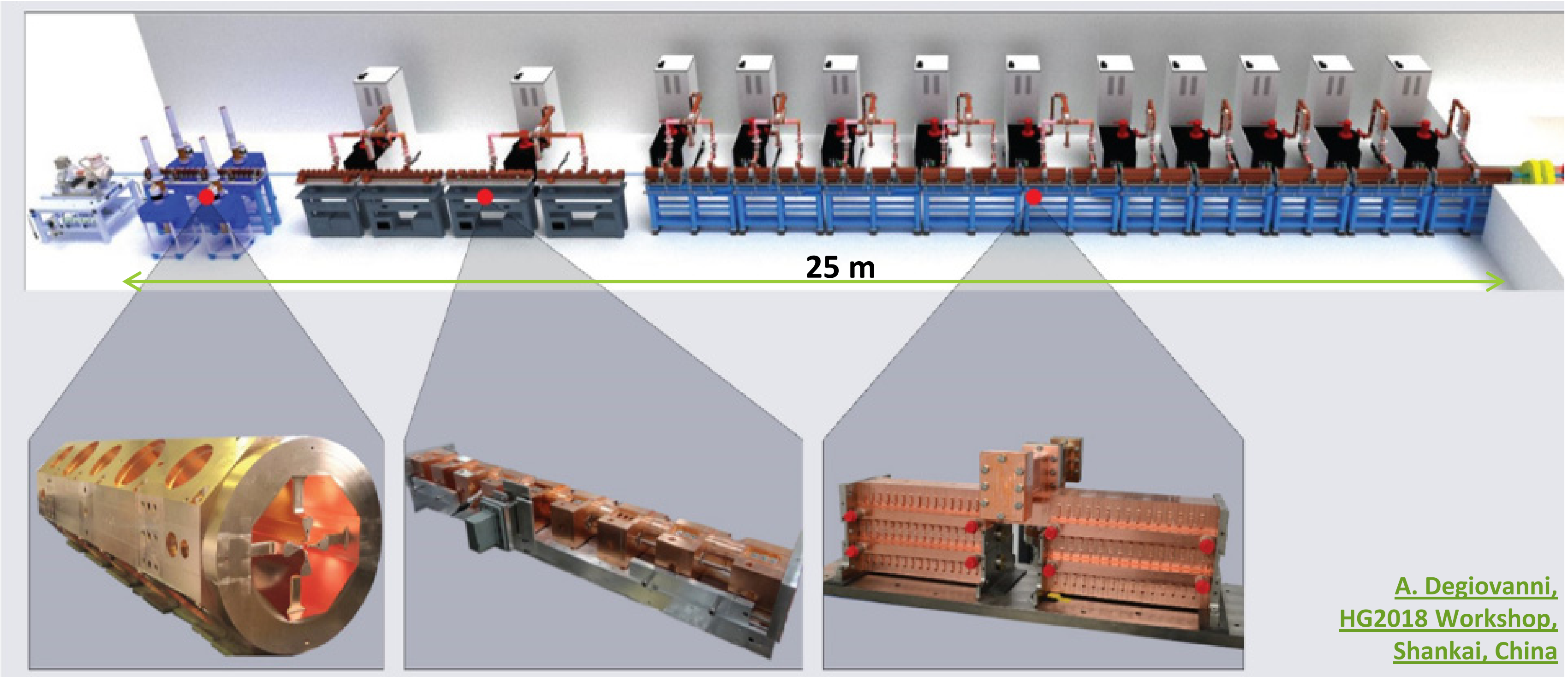
S. Kutsaev et all, High-gradient low-β accelerating structure using the first negative spatial harmonic of the fundamental mode, PRAB2017

Carbon ion linacs comparison

	CABOTO all-linac	ACCIL	CABOTO cyclinac
Source	TwinEBIS (CERN) $^{12}C^{6+}$	ECR (commercial) $^{12}C^{5+}$	Cyclotron ion source
Low energy acceleration	RFQ (750 MHz), H-type (750 MHz) up to 10 MeV/u, SCDTL up to 100 MeV/u	RFQ (476 MHz), DTL (476 MHz) up to 45 MeV/u	Cyclotron up to 150 MeV/u
High energy acceleration	CCL (3 GHz) up to 430 MeV/u, 30 MV/m accelerating gradient, 30 m long	HG BTW (3 GHz) up to 450 MeV/u, 50 MV/m, 23 m long (extimation)	CCL (3 GHz) up to 400 MeV/u, 30 MV/m accelerating gradient, 23 m long
Pro	Lower power consumption than ACCIL	More compact in length than CABOTO all-linac	Shortest in length, no low-energy acceleration 'issues'
Con	Longer than ACCIL	Higher power consumption than CABOTO all-linac	Losses and mismatch at the 150 MeV/u cyclotron-linac transition
Main reference	S. Benedetti, High-gradient and high-efficiency linear accelerators for hadron therapy, EPFL PhD Thesis	P.N. Ostroumov et all, Compact carbon ion linac, NAPAC16	S. Verdu Andres, CABOTO, a high-gradient linac for hadrontherapy, JRR 54

Facilities under construction

LIGHT (Linac for Image Guided Hadron Therapy)



750 MHz Radio Frequency Quadrupole (RFQ)

3 GHz Side Coupled Drift Tube Linac (SCDTL)

3 GHz Coupled Cavity Linac (CCL)

A. Degiovanni, HG2018 Workshop, Shankai, China

CERN spin-off company ADAM SA is building in Geneva a commercial linac for proton therapy, with **reported acceleration up to 16 MeV** (SCTDTL module 2)

ERHA (Enhanced Radiotherapy with HAdrons)

From Linkedin,
R. Prisco

Commercial development of proton therapy linac by ITEL SRL in Puglia (southern Italy) is reported to progress with significant milestones reached

Many similarities with the IMPLART research project: **commercial injector, 3 GHz SCDTL, 3 GHz CCL**

The company policy is less outreach than ADAM SA, thus the current status of the project is not known

Conclusions

Significant breakthroughs have changed the direction of hadron therapy linacs research in the past years

An **efficient acceleration at low energy** is now possible thanks to the **750 MHz RFQ** built at CERN

An **ideal continuation** have been proven to be a **750 MHz IH DTL up to 10 MeV/u**, for both carbon and proton therapy linacs

After many years of preliminary tests, a **high-gradient 3 GHz cavity has been built**, and it has proven **stable operation at 60 MV/m**, demonstrating the feasibility of compact linac-based facilities

The research is now mostly focused on **carbon therapy linacs**, which present **many advantages over state-of-art synchrotron design.**

Thank you for your attention

(and for your patience in listening to the replacement speaker!)