30thAnniversary of the TERA Foundation

2008-2013:

The seeds of the AVO-ADAM prototype at CERN and the challenge of high-gradient linacs

Alberto Degiovanni

15thSeptember 2022

CERN Council Chamber

How did my journey with TERA start?

Spring 2004: as a high-school student passionate about physics, I attended a conference on hadrontherapy by prof. Amaldi…

Sep 2008

PROGETTO MASTER DEI TALENTI
FONDAZIONE CRT

Oct 2009

HIGH FREQUENCY LINAC FOR CARBON ION HADRONTHERAPY

UNIVERSITÀ DEGLI STUDI DI MILANO
FACOLTÀ DI SCIENZE MATEMATICHE, FISICHE E NATURALI

Mar 2014

HIGH GRADIENT PROTON LINACS FOR MEDICAL APPLICATIONS

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Thèse n. 6069
présenté le 14 Mars 2014
à la Faculté des Sciences de Base
programme doctoral en Physique
École Polytechnique Fédérale de Lausanne

Alberto Degiovanni

Outline:

- During this talk, **two main threads** related to linac studies and technology
- Apologies for all other projects happening during those years that due to time constraints may not be mentioned here (and will be covered in Fabio Sauli's talk)
- I apologize for not explicitly mention all the people that have contributed and helped during all those years! My gratitude to all of them!

TERA

ADAM
Applications of Detectors and Accelerators to Medicine

CERN

ADAM
an ADVANCED ONCOTHERAPY company

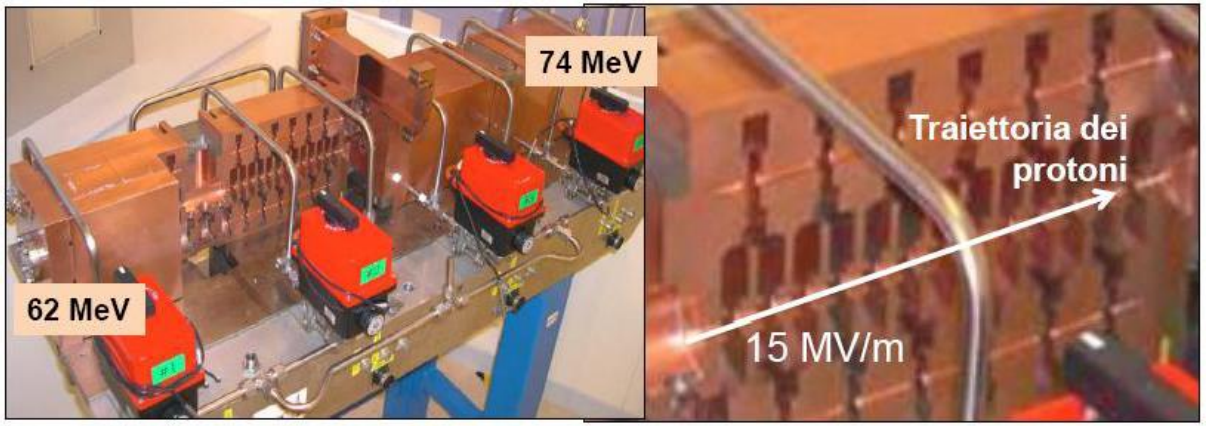
CLIC

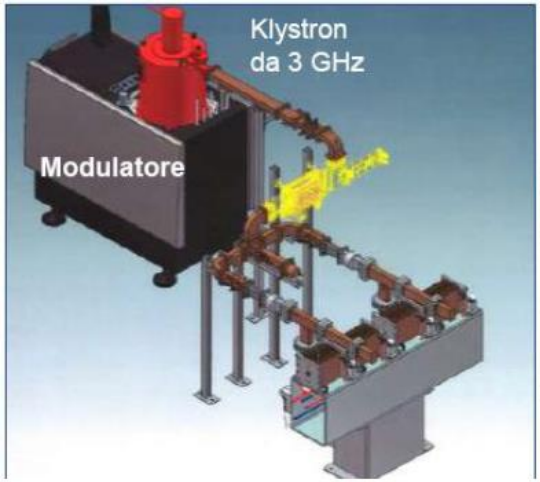
CLIC

TERA

From LIBO to LIGHT

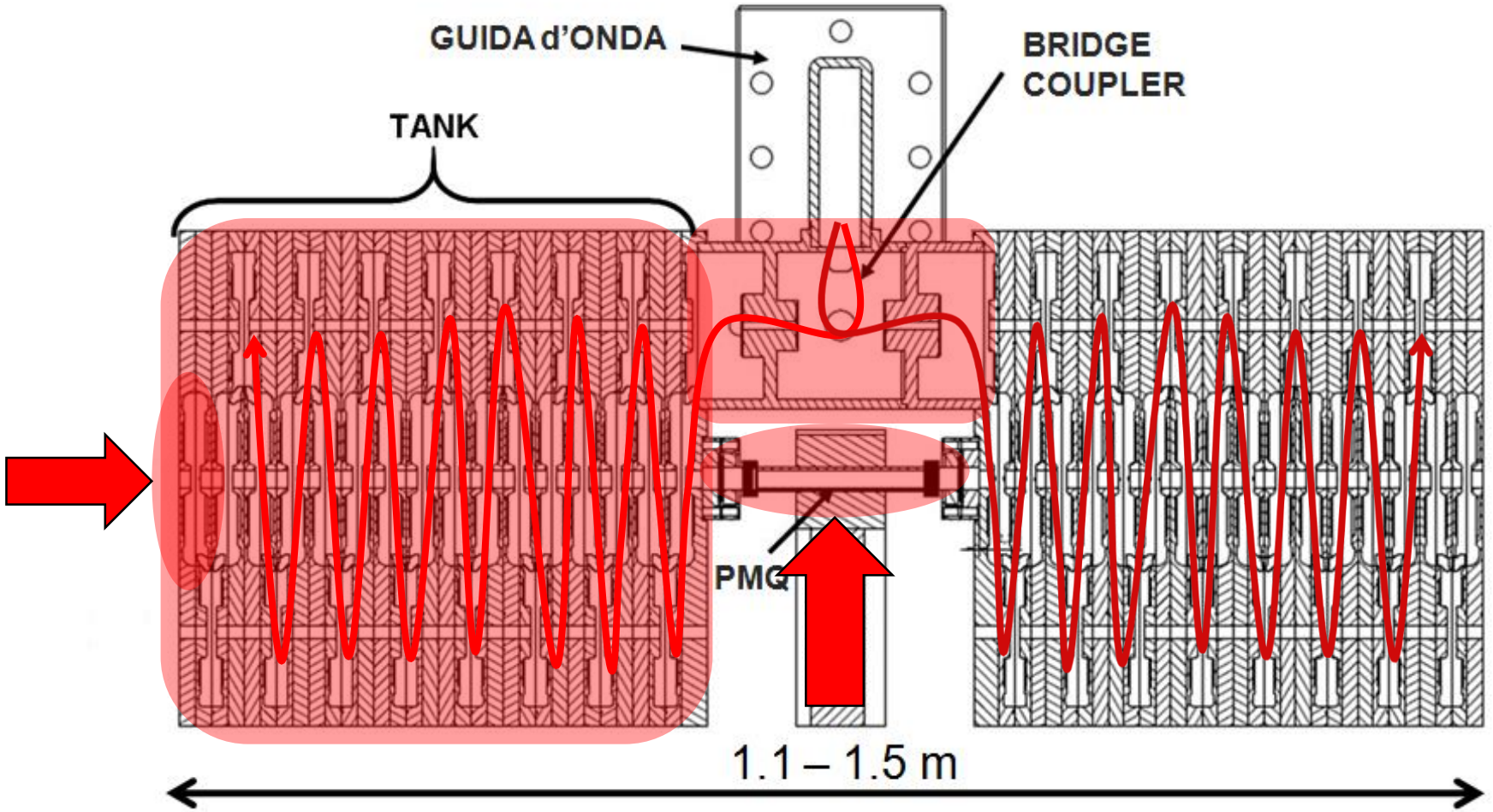
- Updates and changes in the design, moving from a prototype to an industrial unit…
- Further improvements in the overall cell design and optimization





C. Mellace, P. Puggioni

A typical RF module of LIGHT



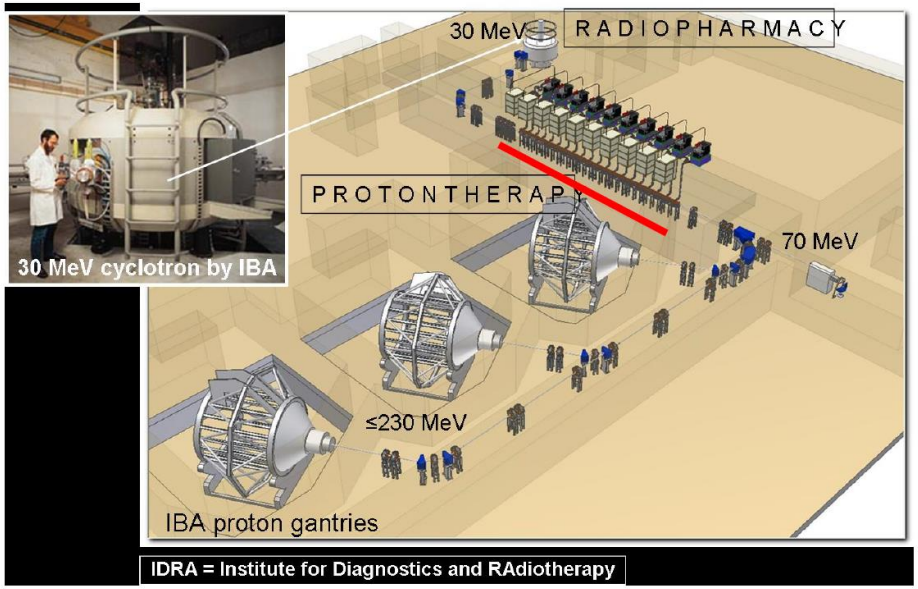
A better understanding of LIGHT…

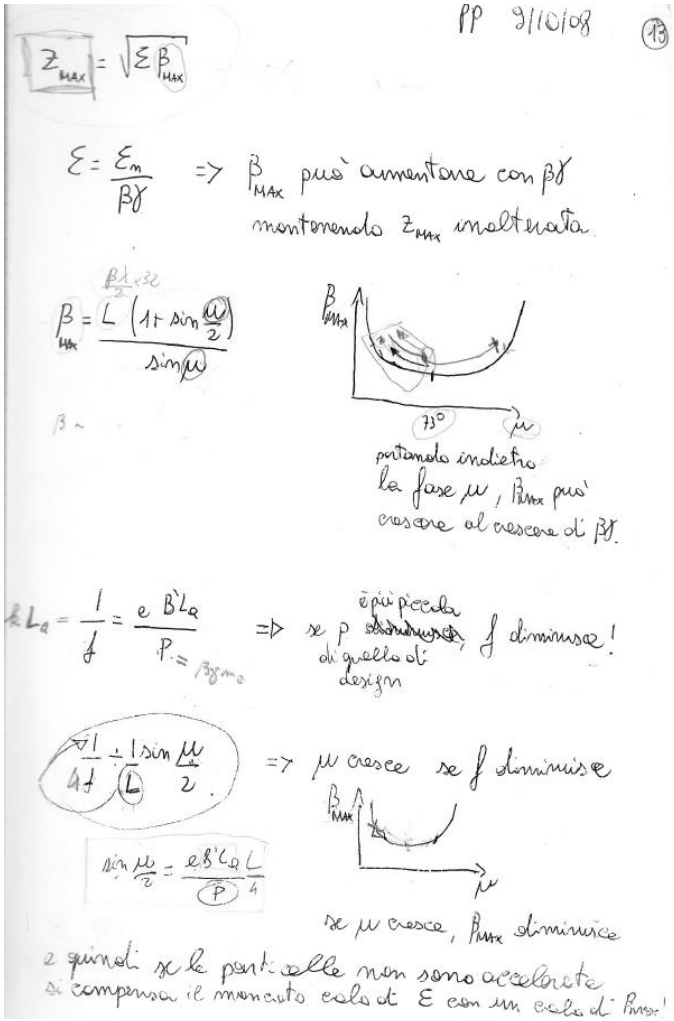
- In 2008-2009 fruitful discussions and lecture with P. Puggioni (ADAM) on the linac design and beam dynamics performance

A short course:

BEAM DYNAMICS IN LINACS FOR HADRON THERAPY

ENERGY MODULATION PROBLEM





A better understanding of LIGHT…

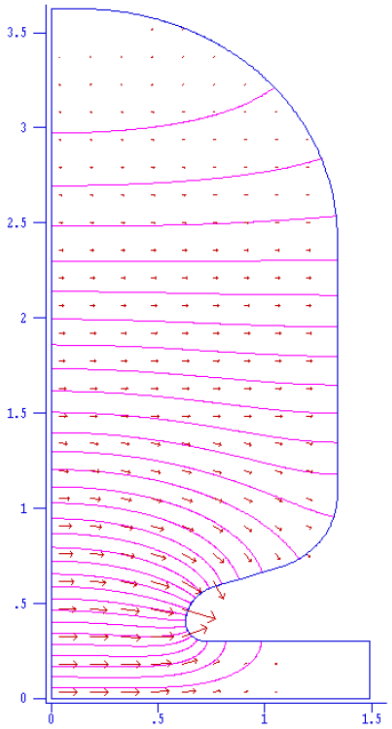
- Scaling laws
- Cavity geometry design
- Energy modulation and layout

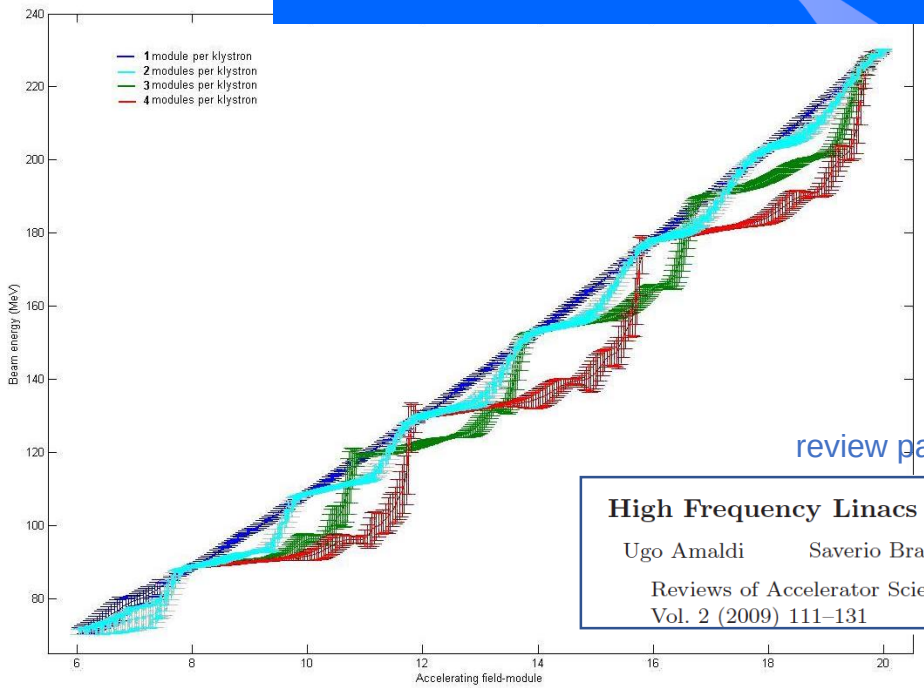
…and some important scaling laws

$$P = \frac{(E_0 T)^2}{Z T^2} l \cdot n \qquad E_0 \propto \frac{1}{\sqrt{n}}$$

$$W = q(E_0 T) \cdot l \cdot n \cdot \cos\varphi_s \qquad W \propto \sqrt{n}$$

$$L = l \cdot n \qquad L \propto n$$





review paper

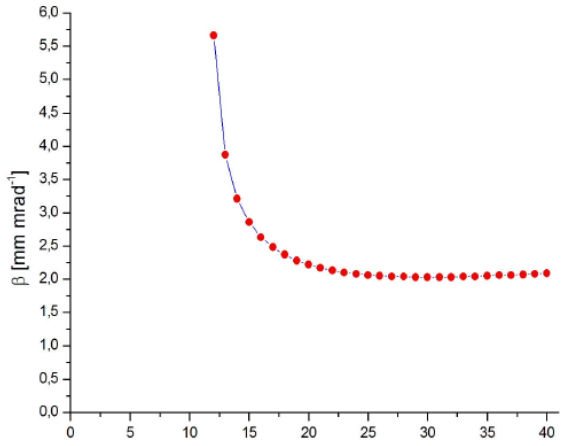
High Frequency Linacs for Hadrontherapy

Ugo Amaldi Saverio Braccini Paolo Puggioni

Reviews of Accelerator Science and Technology
Vol. 2 (2009) 111–131

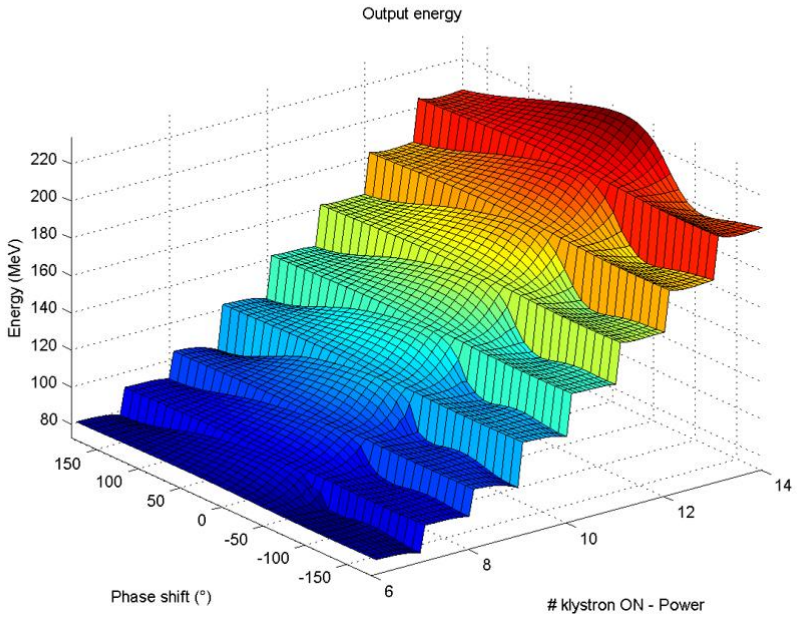
Energy modulation with multiple tanks

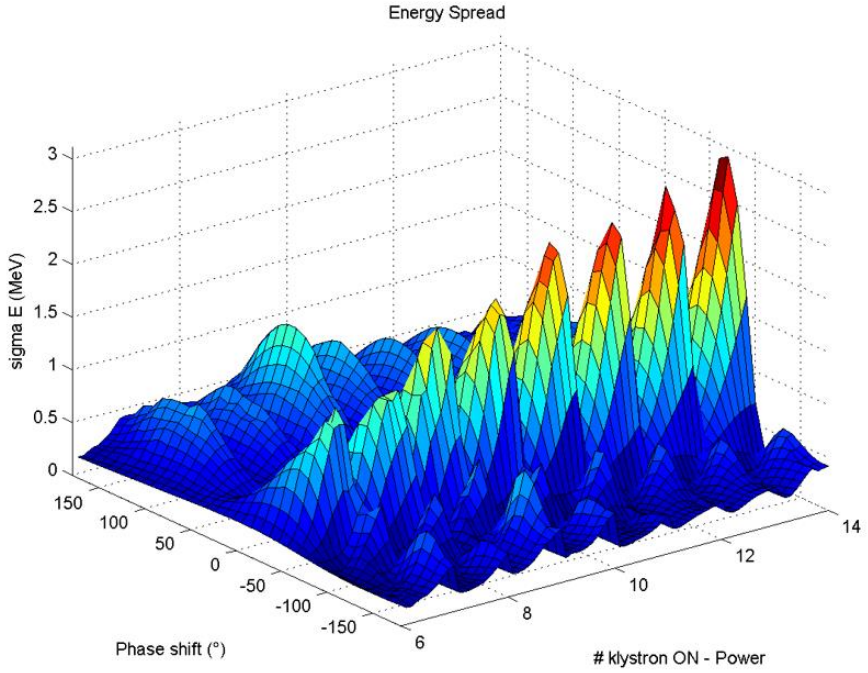
- Additional work done in the understanding of the limits for energy modulation and on the linearity of the energy gain.



Results of the simulations

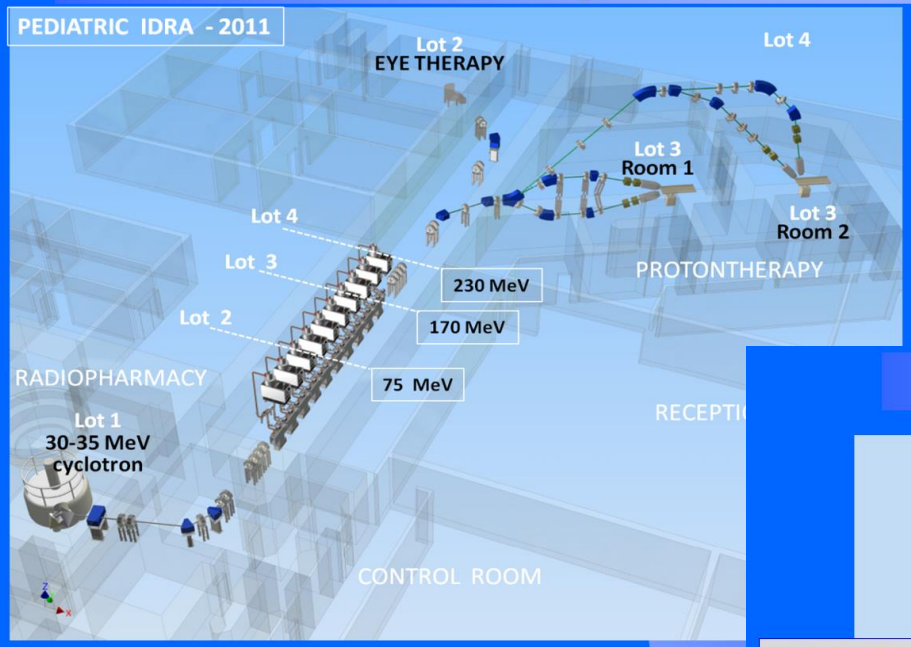
The following plots summarize the results of the simulations obtained by introducing **Field Amplitude factors** (x-axis) and **phase shifts** (y-axis) to the nominal design.



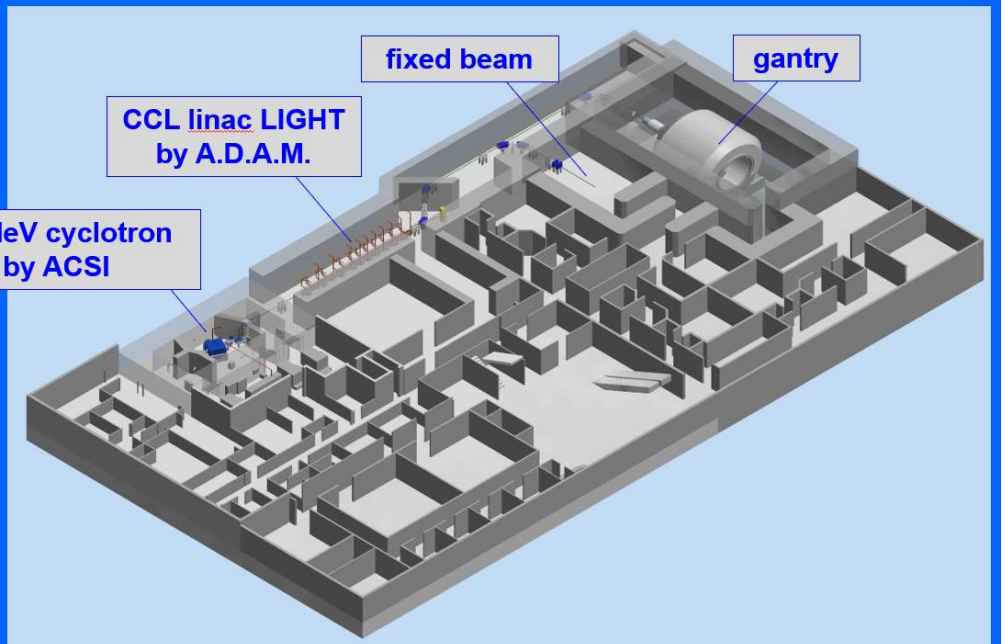


Some different design for different projects

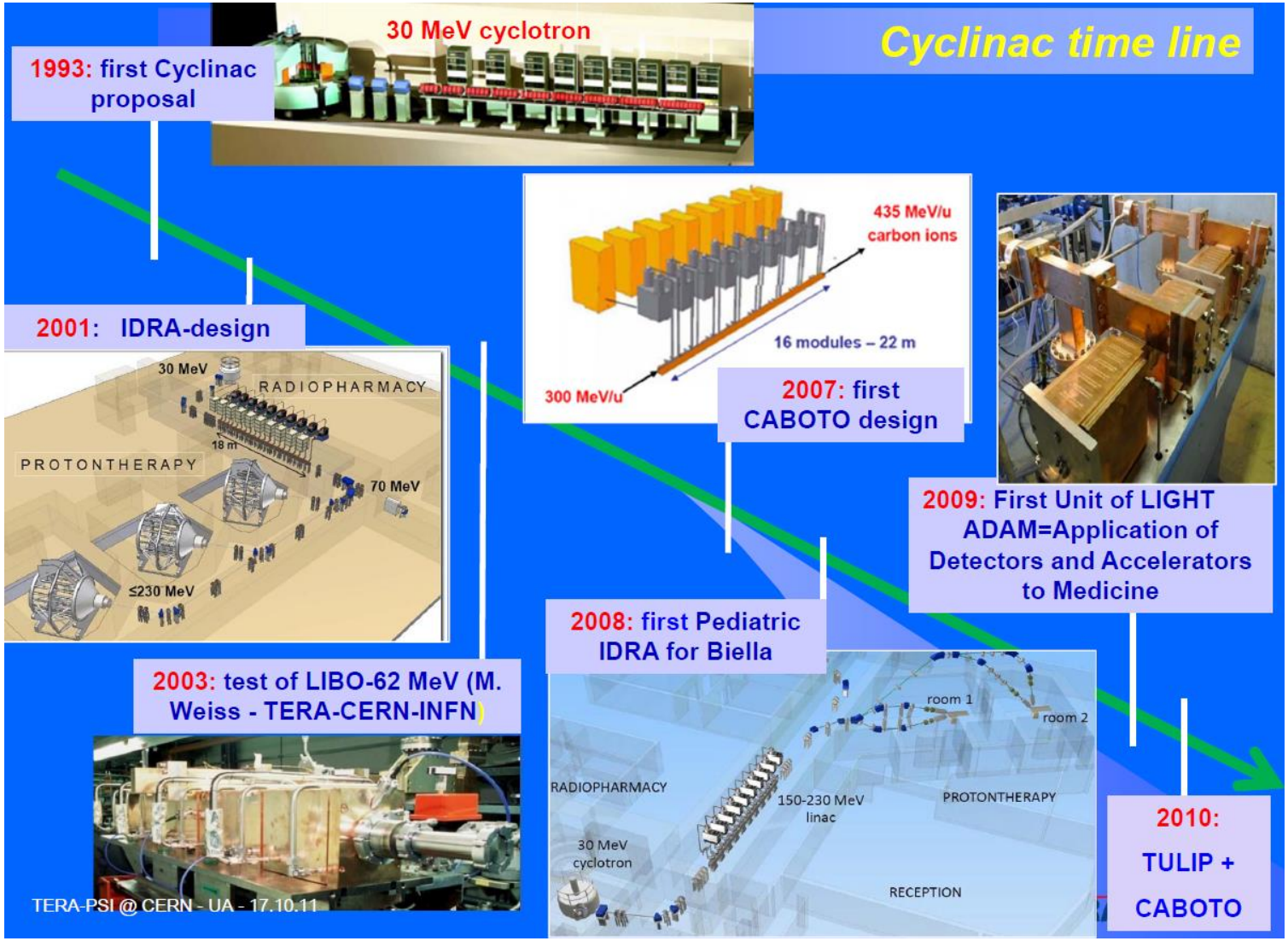
Paediatric IDRA: first design of December 2009



PERLA with a fixed beam at 230 MeV and a gantry



The Cyclinac timeline until 2010



A possible cyclotron injector…

- A possible injector cyclotron was the TR24 (ACSI) as the one installed at IPHC in Strasbourg.
- In 2013 a collaboration started, and a measurement campaign was setup to **characterize the beam transverse emittance**
- A first visit at IPHC took place in April 2013, with all the TERA cyclinac team.

A. Degiovanni et al., **Emittance Measurements at the Strasbourg TR24 Cyclotron for the Addition of a 65 MeV Linac Booster**, 329-31, CYC13 Proceedings

E. Bouquerel et al., **Transverse beam emittance studies of the CYRCé TR24 cyclotron**, NIM A, 2019

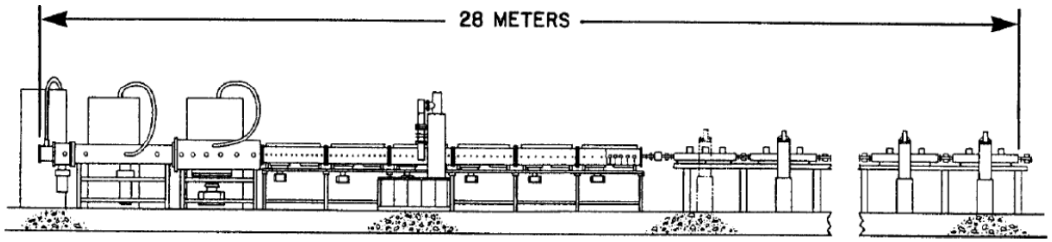
(a) The TR24 cyclotron.

(b) The external source.

From left to right: P. Magagnin, D. Bergesio, A. Lo Moro, S. Benedetti, U. Amaldi, A. Degiovanni, C. Cuccagna, V. Rizzoglio, A. Garonna

All-linacs and cyclinacs

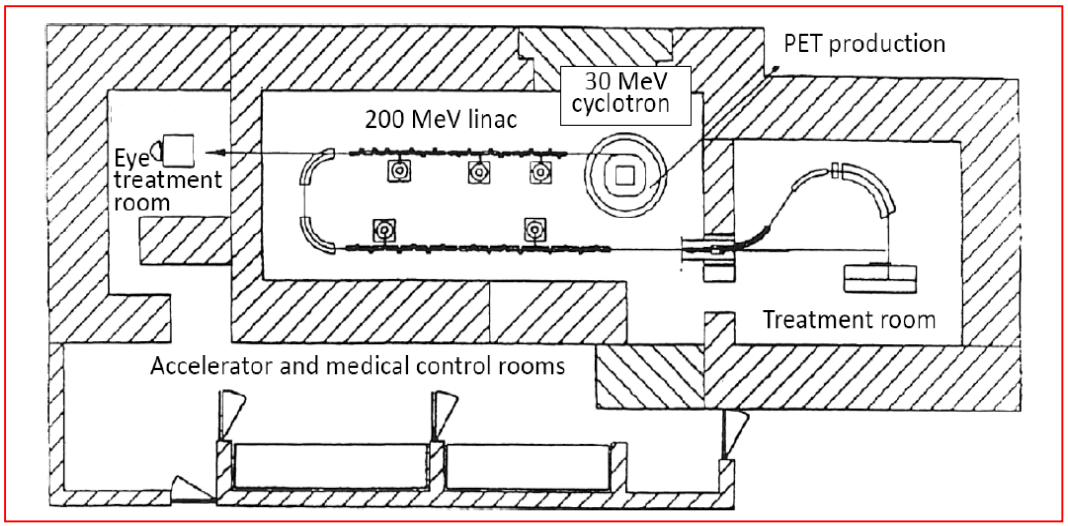
1991: first "all-linac" approach to proton therapy



Schematic layout of the model PL-250 proton therapy linac designed in 1991 by R. Hamm, K. Crandall and J. Potter

R. W. Hamm, K. R. Crandall and J. M. Potter, Preliminary design of a dedicated proton therapy linac, in *Proc. PAC90*, Vol. 4 (San Francisco, 1991), pp. 2583–2585.

1994: "cyclinac" approach to proton therapy



U. Amaldi, The Italian hadrontherapy project, in *Hadron Therapy in Oncology*, eds. U. Amaldi and B. Larsson (Elsevier, 1994), p. 45.

review paper

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TERA

LIGHT journey up to the ADAM prototype

- TERA and ENEA supported ADAM from Dec2012 to Mar2013 in developing a **proposal for a Protontherapy Linear Accelerator**.
- Two options were considered: **cyclinac and all-linac**

- In 2014 with the creation of the CERN Medical Application office and the start of the high-frequency RFQ design from CERN, **the all-linac option was chosen** by AVO-ADAM.
- The CERN Point2 site was refurbished and used for installation of the **LIGHT "demonstrator"**…

- …eventually AVO-ADAM is now commissioning a full-scale 230 MeV LIGHT machine at STFC Daresbury!

LIGHT First Unit
ADAM Proposal for a Protontherapy Linear Accelerator

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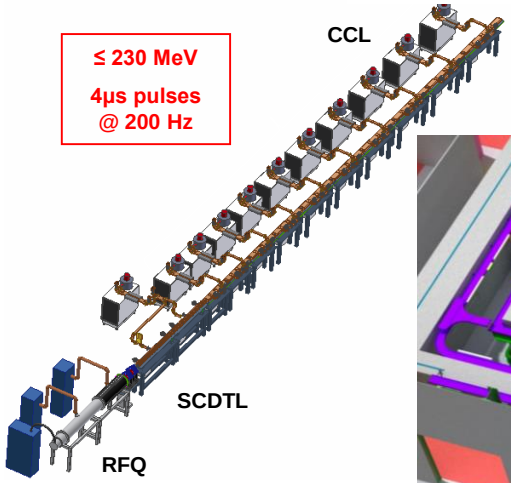
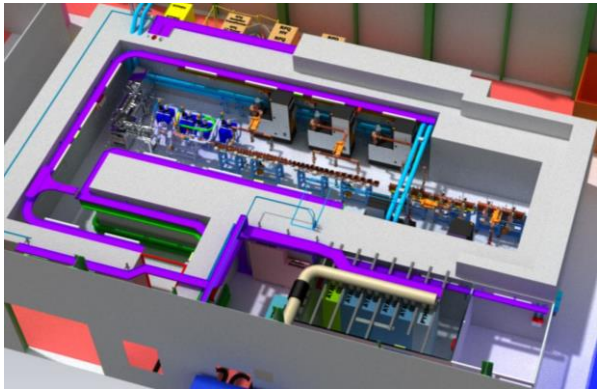
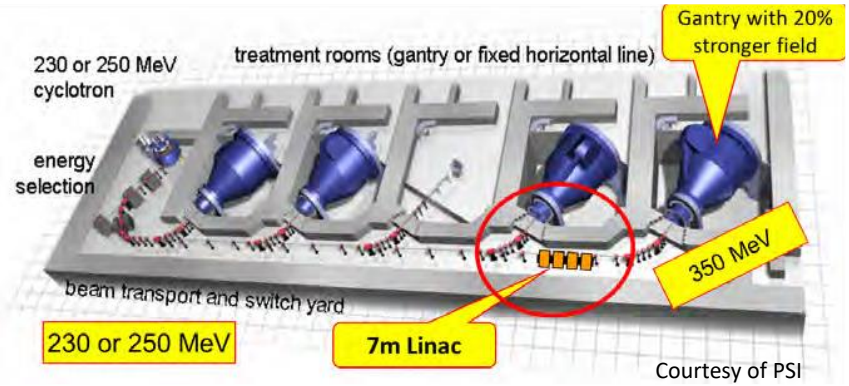
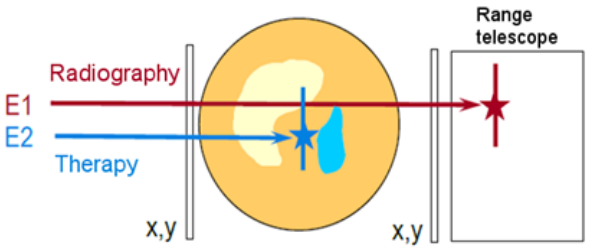


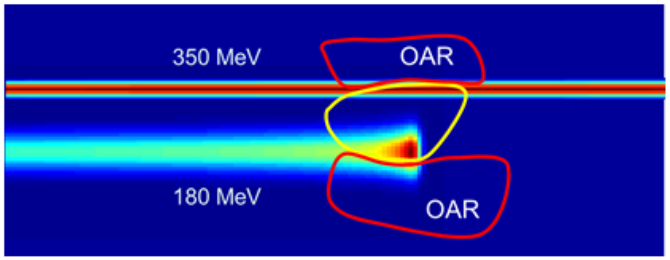


2011-2012: IMPULSE project with PSI

- IMPULSE project: **IM**aging and intensity **M**odulation **PULSE**d energy booster







J. Bilbao de Mendizabal, **3 GHz linac booster design from 250 MeV to 350 MeV for medical application at PSI**, MSc Thesis, University of Geneva, 2012

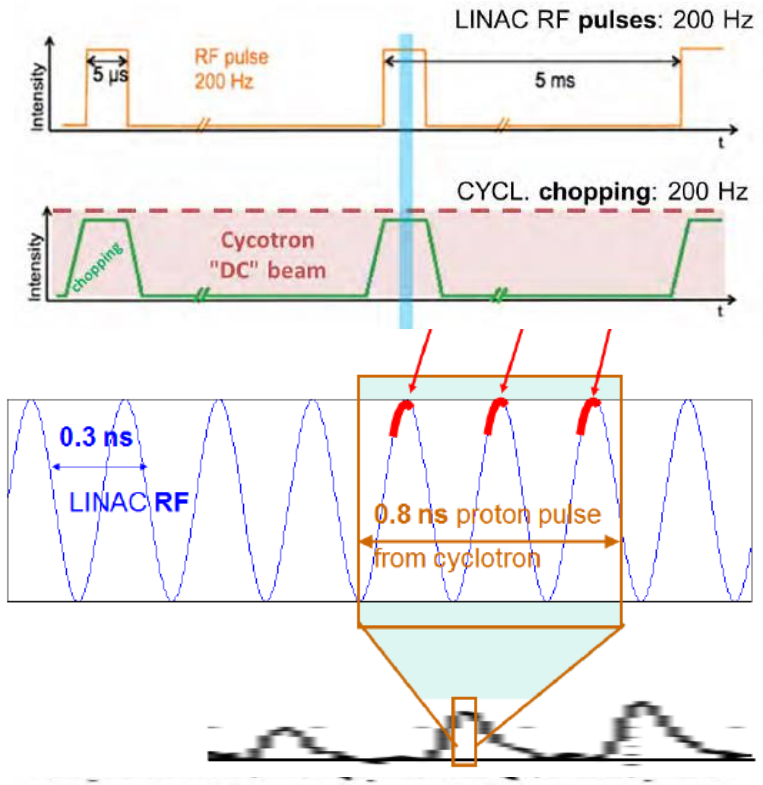
PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 064701 (2018)

Linac booster for high energy proton therapy and imaging

Alberto Degiovanni* and Ugo Amaldi

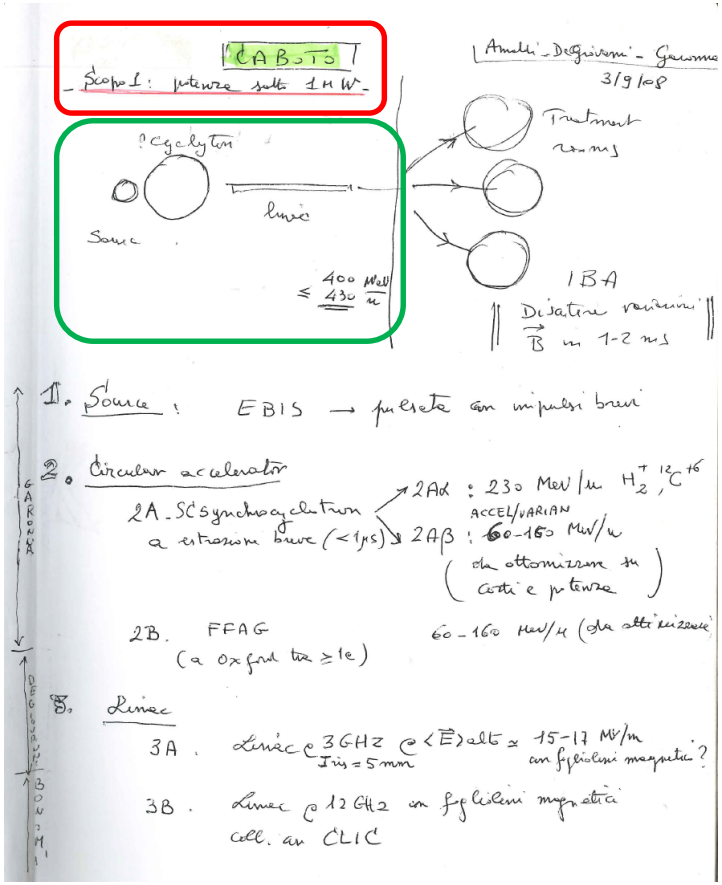
Anthony J. Lomax, Jacobus M. Schippers, and Lukas Stingelin

Javier Bilbao de Mendizabal†



CABOTO: CArbon BOoster for Therapy in Oncology (2008-2012)

- From 2009 to 2012 several designs:
  - For the source (EBIS pulsed ion source)
  - for the cyclotron (SC/isochronous)
  - for the linac (at different frequencies)



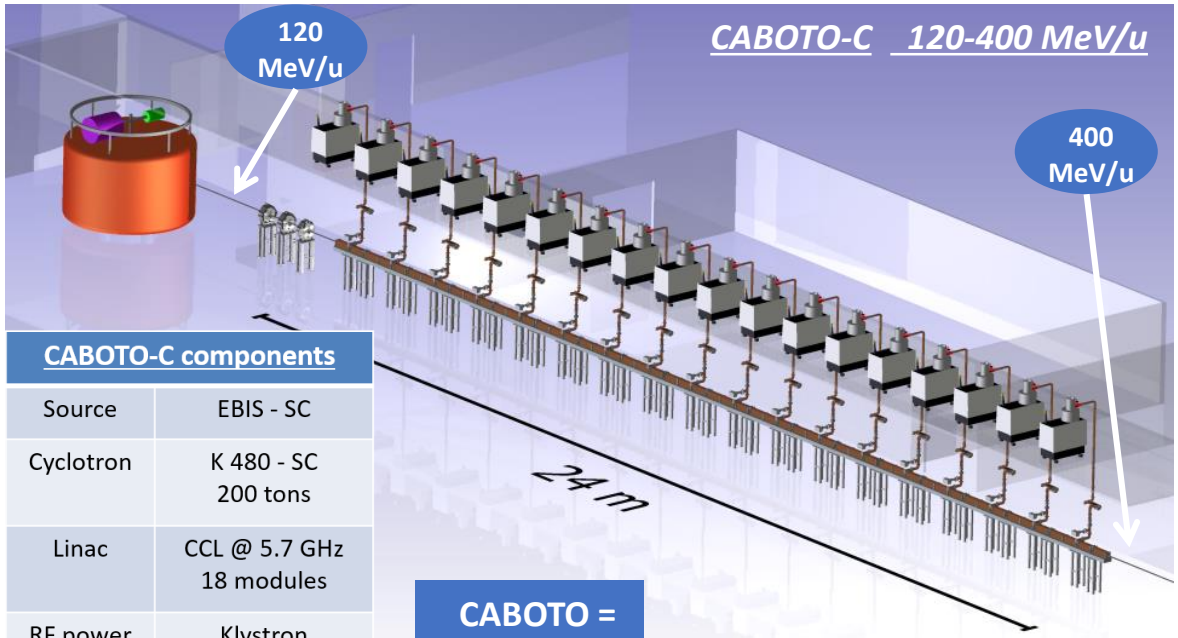
A. Degiovanni, **High Frequency Linac for Carbon Ion Hadrontherapy**, MSc Thesis, University of Milan, 2009

A. Garonna, **Cyclotron Designs for Ion Beam Therapy with Cyclinacs**, PhD Thesis, EPFL, 2011

S. Verdù Andrès, **High-Gradient Accelerating Structure Studies and their Application in Hadrontherapy**, PhD Thesis, Univ. of Valencia, 2013

A. Garonna et al., **Cyclinac medical accelerators using pulsed C6+/H2+ ion sources**, J. Instr. 5 (2010) C09004

S. Verdù Andrès et al., **Feasibility Study of a High-Gradient Linac for Hadrontherapy**, IPAC11 Proceedings, WEPS-045

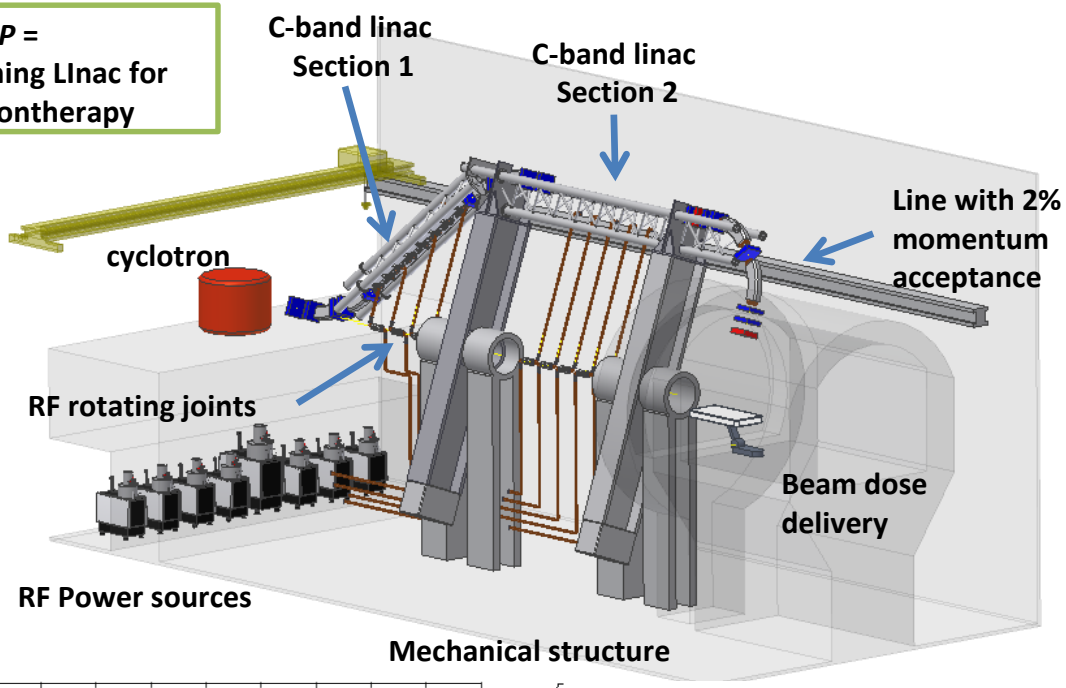


CABOTO-C components	
Source	EBIS - SC
Cyclotron	K 480 - SC 200 tons
Linac	CCL @ 5.7 GHz 18 modules
RF power system	Klystron (P_{peak} 12 MW)

CABOTO =
CArbon Booster for Therapy in Oncology

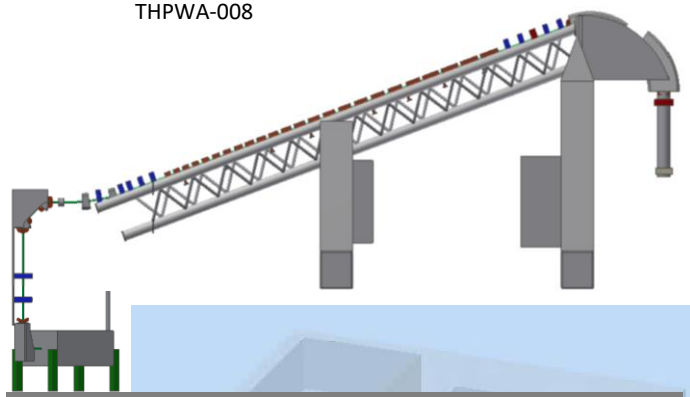
TULIP: a TUrning LInac for Protontherapy

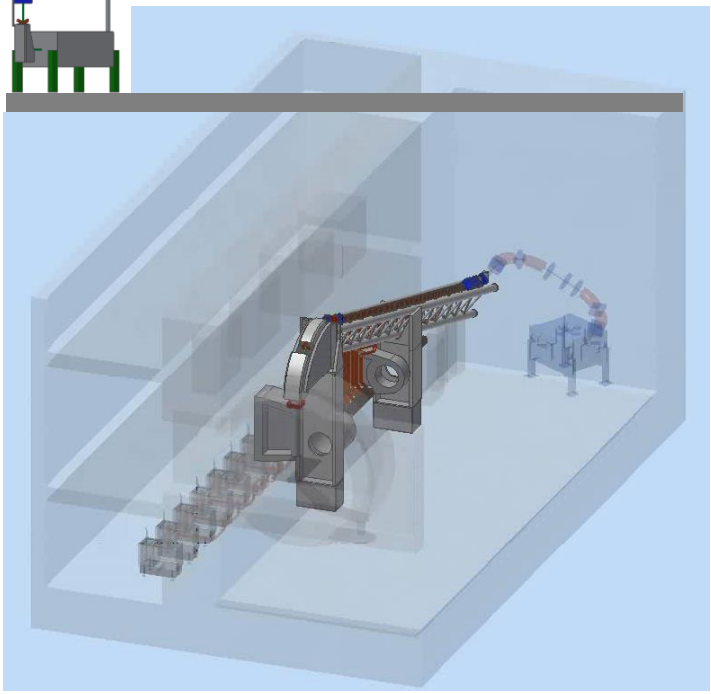
TULIP **=**
TUrning LInac for Protontherapy

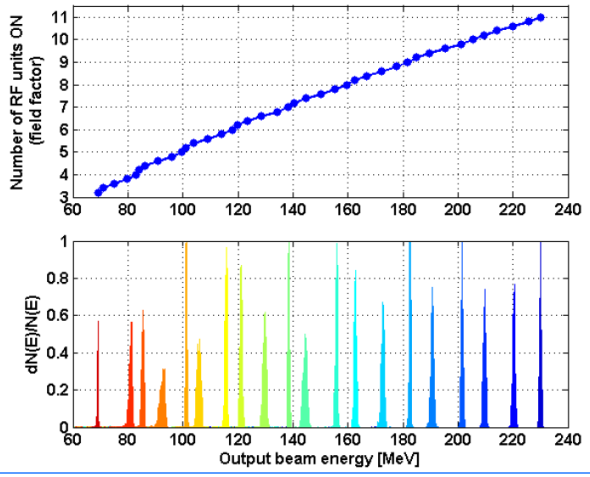


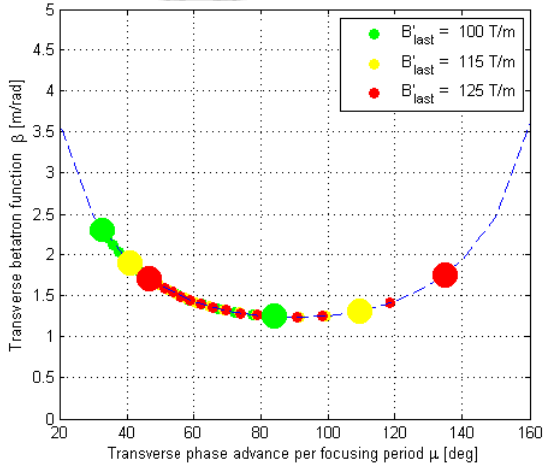
A. Degiovanni, **High gradient proton linacs for medical applications**, PhD Thesis, EPFL, 2014

A. Degiovanni et al., **Design of a Fast-cycling High-gradient Rotating Linac for Proton Therapy**, IPAC13 Proceedings, THPWA-008



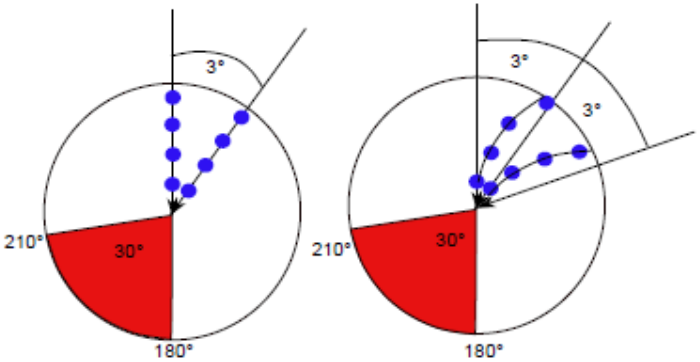






TULIP and proton tomo-therapy (or Arc therapy)

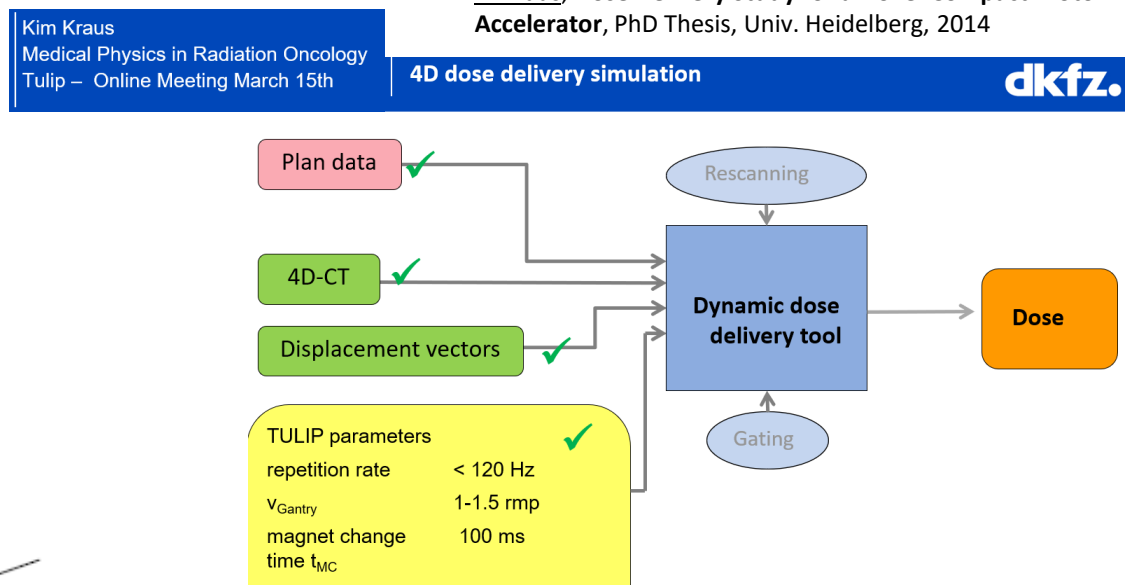
- In 2012-2013, in a collaboration with DKFZ, the option of using TULIP beams for Arc therapy was explored



(a) Static rotational delivery (b) Dynamic rotational delivery

Figure 4.1.3: Rotational dose delivery with TULIP. The static spot positions, shown in (a) are shifted during delivery for dynamic rotational delivery as indicated in (b). The 3° angular step between the static beam positions is marked.

K. Kraus, **Dose Delivery Study for a Novel Compact Proton Accelerator**, PhD Thesis, Univ. Heidelberg, 2014



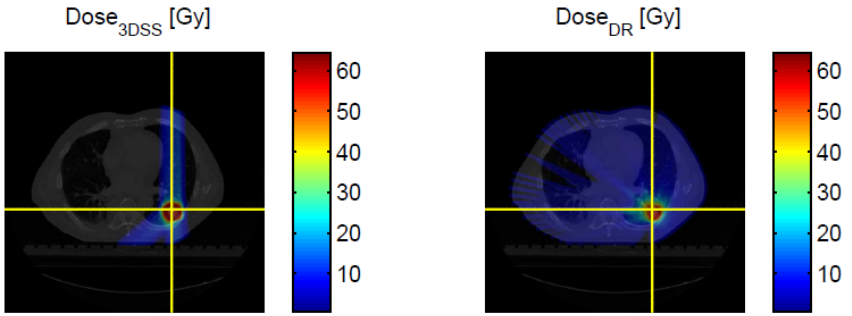


Figure 4.2.4: Comparison of dose distributions for 3D spot scanning and dynamic rotational delivery. Rotational delivery results in a detrimental dose bath to normal tissue.

High-gradient test program: the problem of the nose!

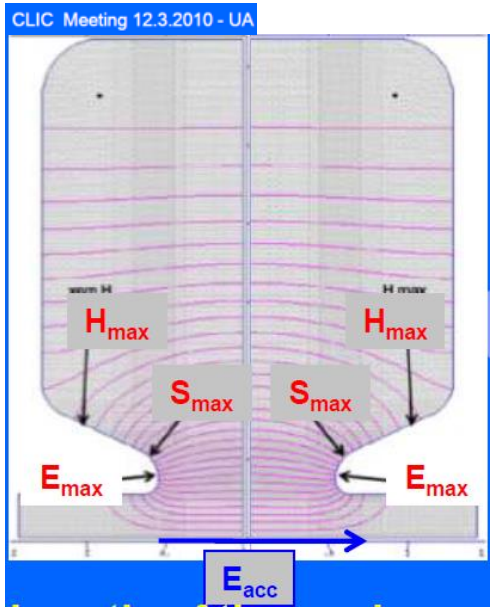
- For hadron linacs E_{max}/E_{acc} ~ 4-5, while in electron linac is ~ 2
- The CLIC goal of E_{acc} = 100 MV/m corresponds to 40 MV/m in medical hadron linacs!
- What are the limits on Eacc? How does this scale with frequency?

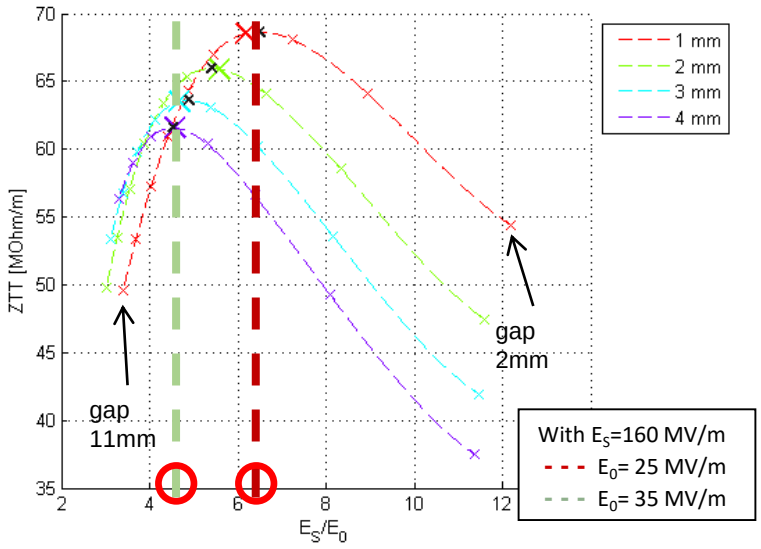
R. Bonomi, **Thermo-structural study and experimental analysis of accelerating structures for hadrontherapy linacs**, PhD Thesis, Politecnico di Torino, 2011

A. Degiovanni et al., **TERA high gradient test program of RF cavities for medical linear accelerators**, NIM A 657 (2011) 55 - 58

S. Verdú-Andrés et al., **High-power test results of a 3 GHz single-cell cavity**, arXiv:1206.1930v2, (2012)

S. Verdú-Andrés et al., **High Gradient Test of a 3 GHz single-cell Cavity**, LINAC10 Proceedings, THP-037





Back: R. Bonomi, U. Amaldi, A. Garonna, D. Campo, R. Wegner
Front: A. Degiovanni, S. Verdù Andrès, M. Garlaschè

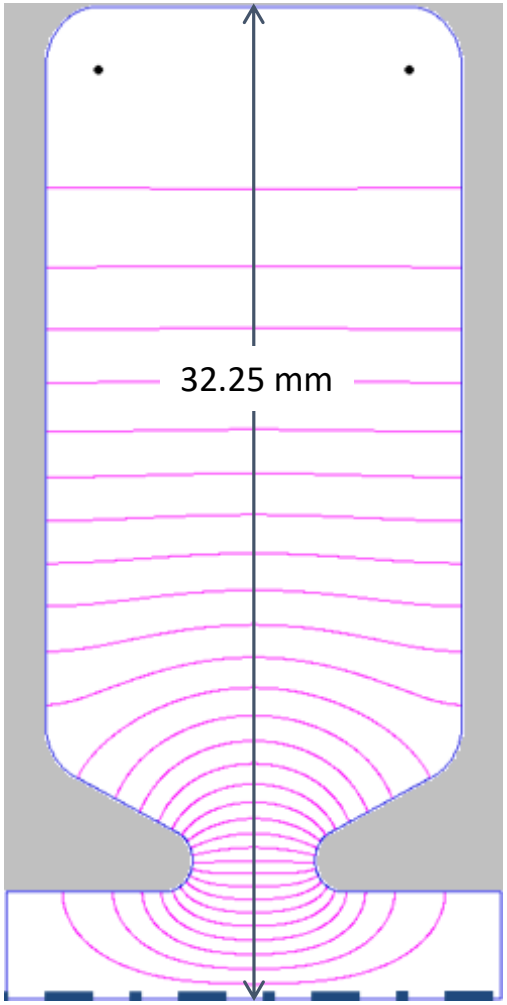
New local field quantity describing the high gradient limit of accelerating structures

A. Grudiev, S. Calatroni, and W. Wuensch
Phys. Rev. ST Accel. Beams **12**, 102001 – Published 26 October 2009; Erratum Phys. Rev. ST Accel. Beams **14**, 099902 (2011)

Modified Poynting vector

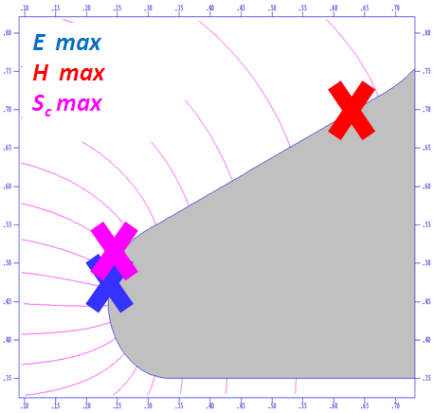
$$S_c = \mathrm{Re}(\mathbf{S}) + \frac{1}{6}\mathrm{Im}(\mathbf{S})$$

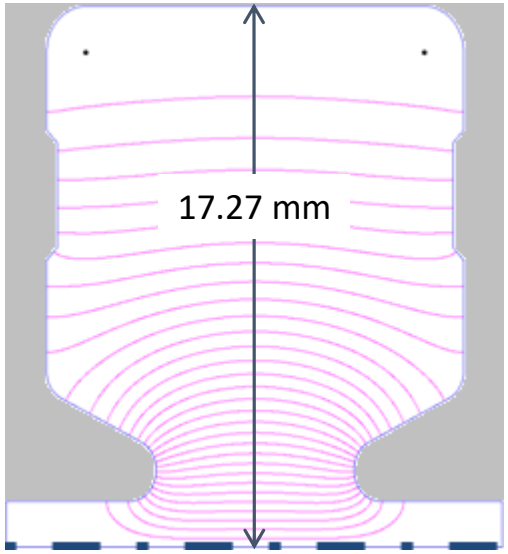
After many iterations, the cavity specs (S- and C-band)



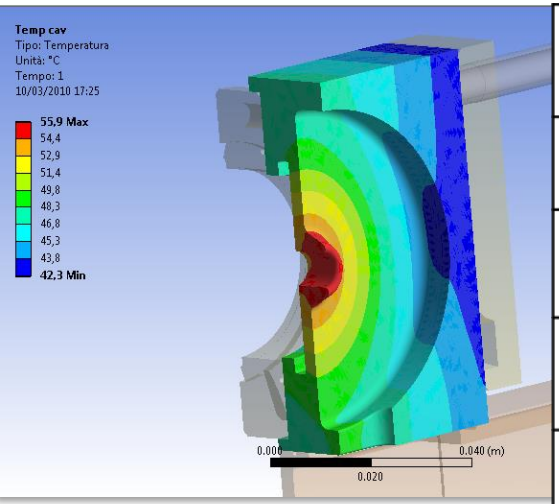
2998.5	Frequency [MHz]	5712
18.9	Cell length [mm]	18.8
84	Shut imp [MΩ/m]	150
8990	expected Q value	8990
360	Peak power [kW] *	200
6.48	E_{max}/E_0	4.63
2.66	H_{max}/E_0 [A/kV]	2.80
29 10^{-3}	$\sqrt{S_c}/E_0$ [$\sqrt{W}$/V]	25 10^{-3}
260	E_{max} [MV/m] *	185
1.38	$S_{c,max}$ [MW/mm^2] *	1.03

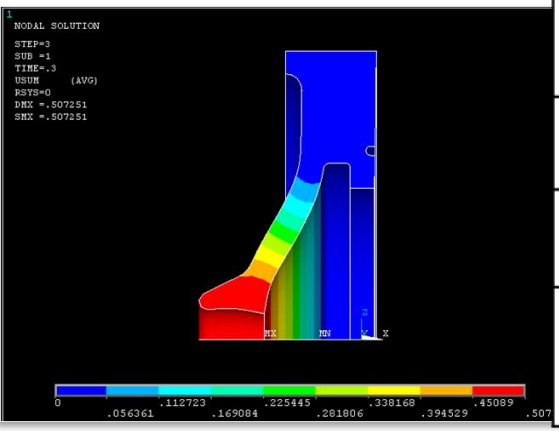
* Values for specified E_{max}
** second C-band cavity



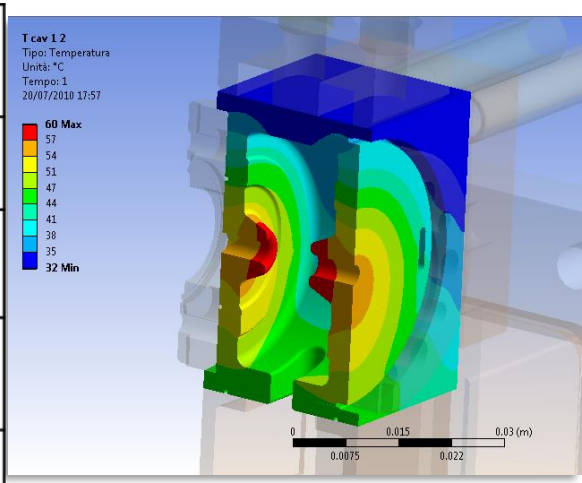


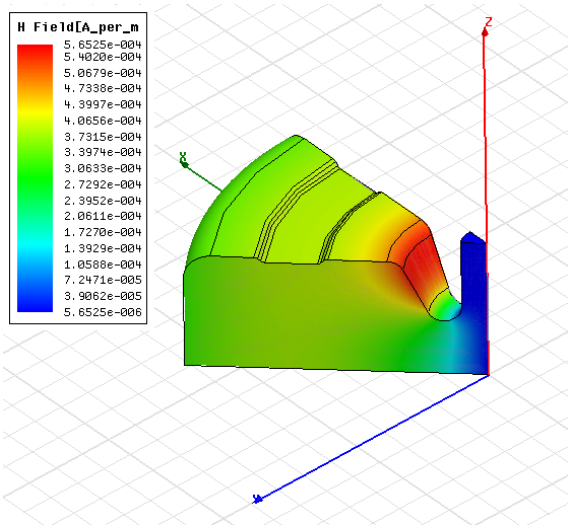
After many iterations, the cavity specs (S- and C-band)





2	# parallel cooling channels	3
5	Total water flow [l/min]	7.5
350 (260)	Avg. power [W]*	500 (400)
0.035	Thermal resistance [K/W]	0.050
6 (260)	ΔT pulsed surface heating [K]*	30 (400)
20	Tolerance bandwidth [μm]	10 (5**)
0.4	Surface roughness [μm]	0.4 (0.25**)
± 7	Tuning range [MHz]	± 12
nose cones deformation	Tuning strategy	tuning ring

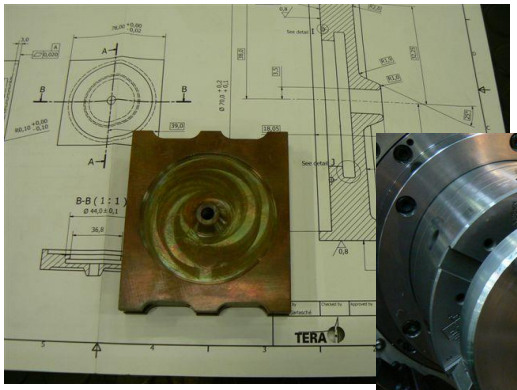


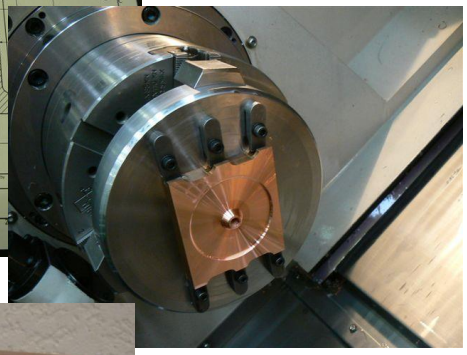


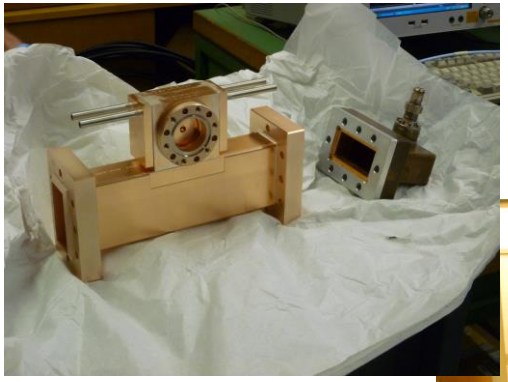
* Values for specified E_{max}
** second C-band cavity

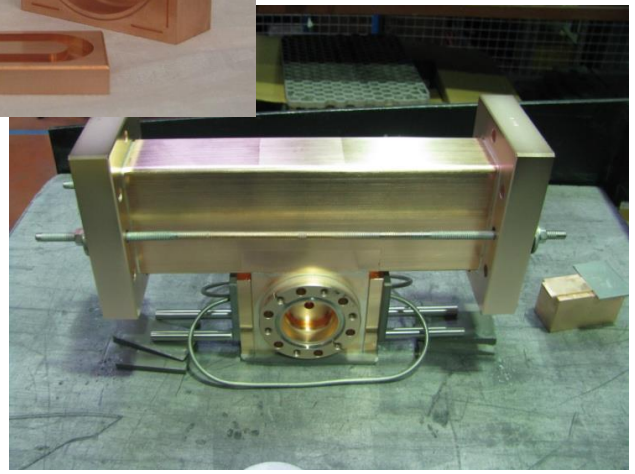
TERA

S-band high gradient tests: production and tuning (2009-2010)

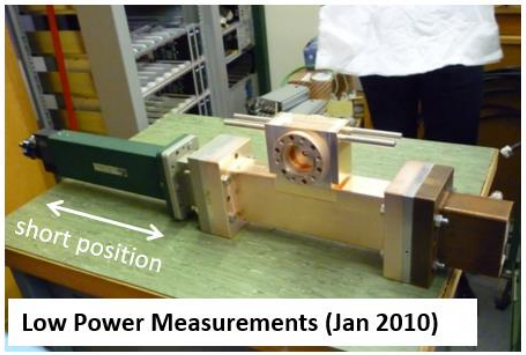




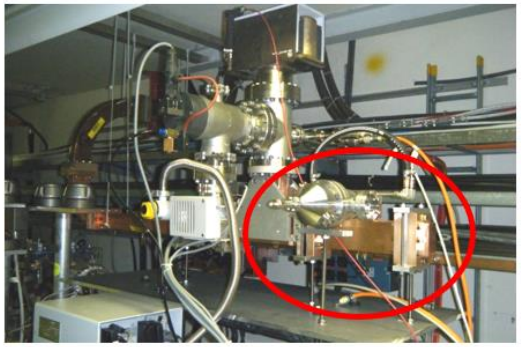




S-band high gradient tests: low power and high power (2010-2012)

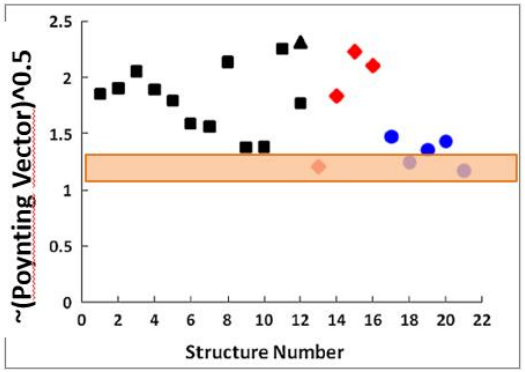


Low Power Measurements (Jan 2010)

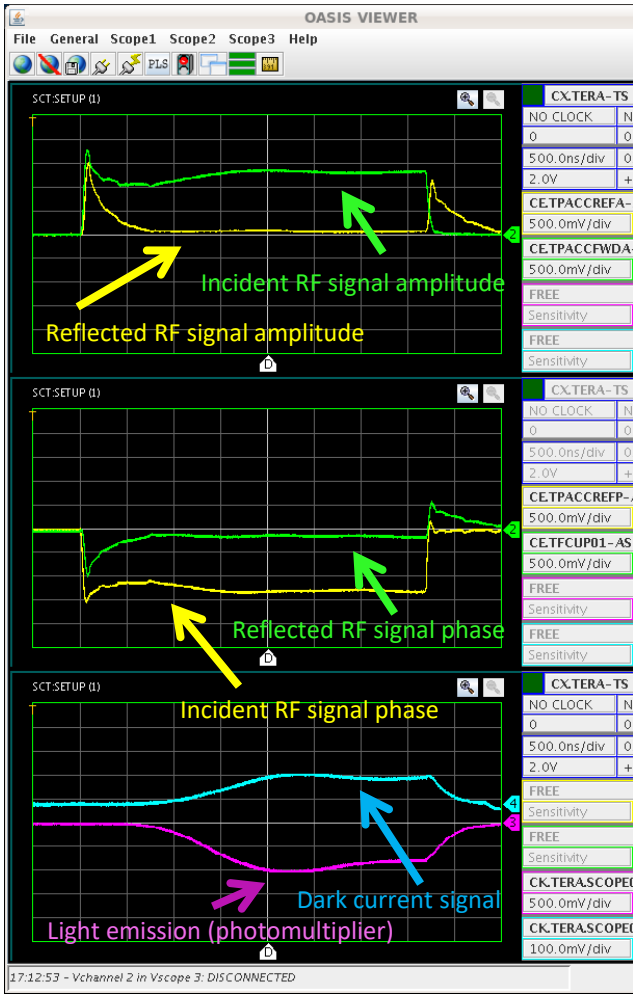


High Power Test (@CTF3 Gallery – Feb 2010)

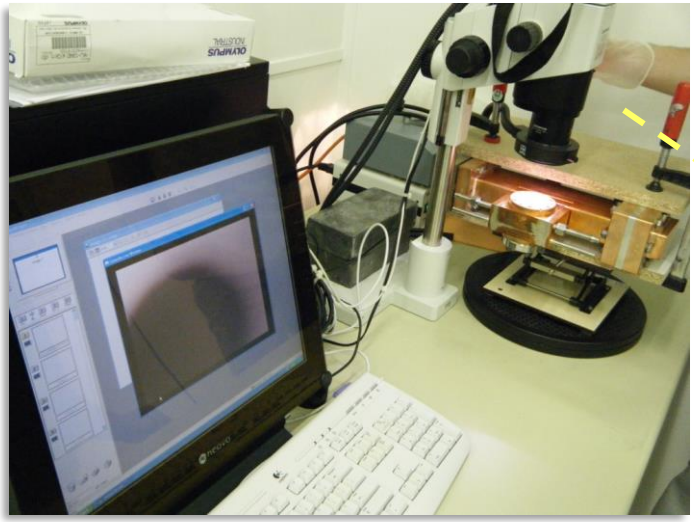
Indirect measurements of field through Faraday Cup

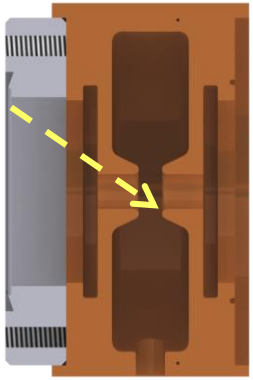


Preliminary results compared with CLIC Model

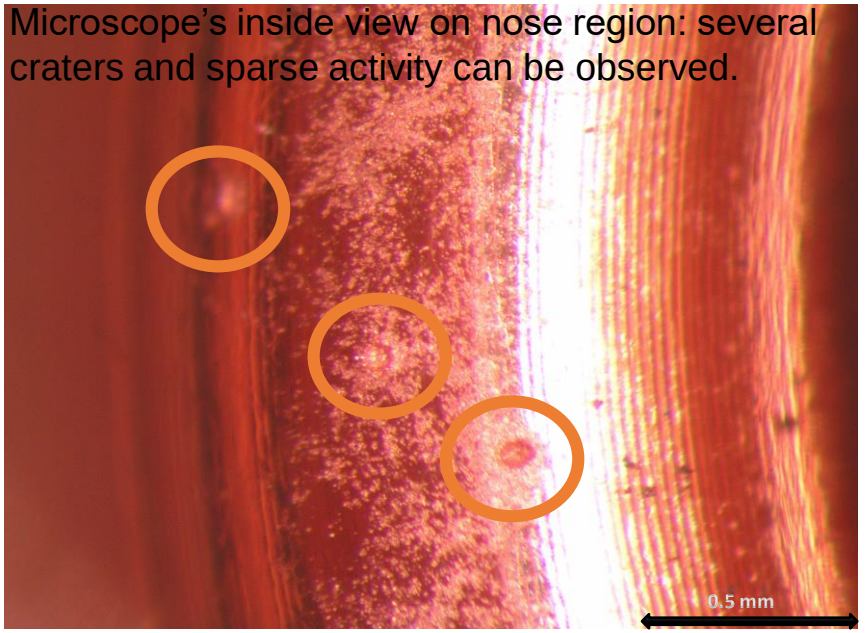


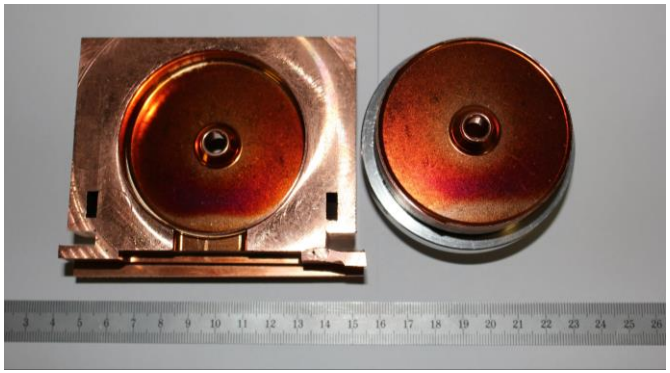
S-band high gradient tests: post mortem analysis

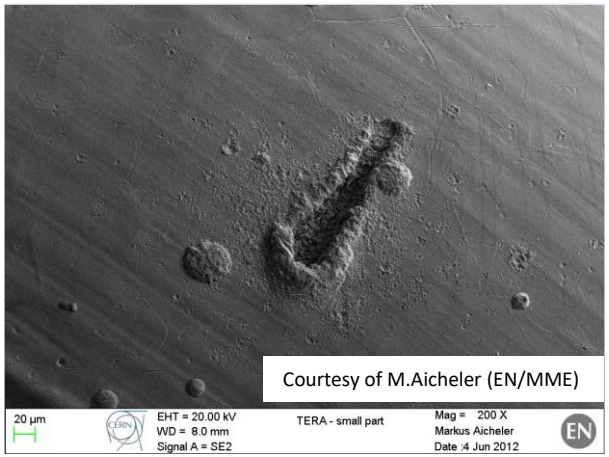


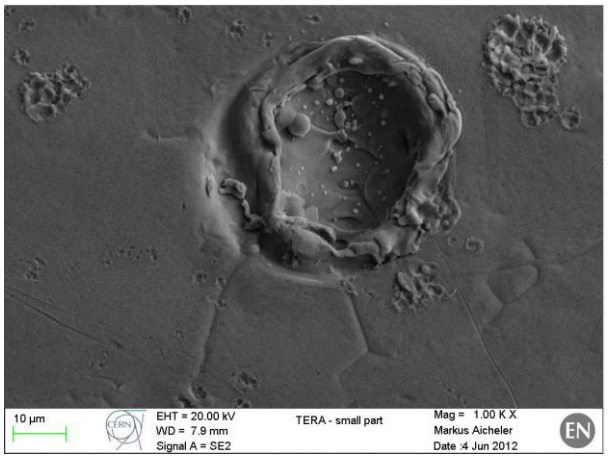


Microscope's inside view on nose region: several craters and sparse activity can be observed.

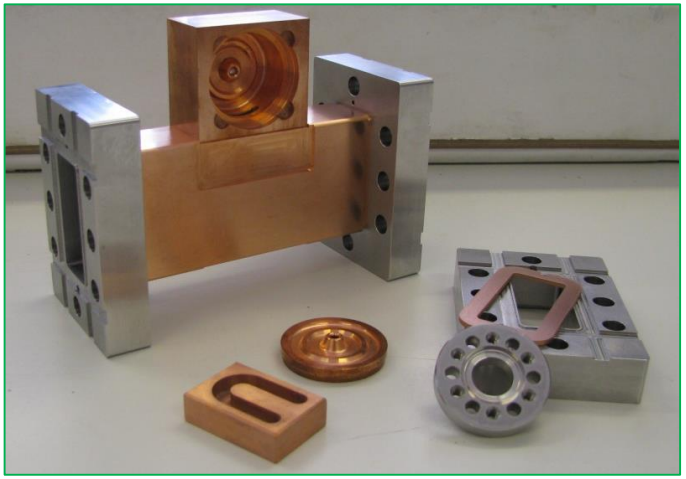


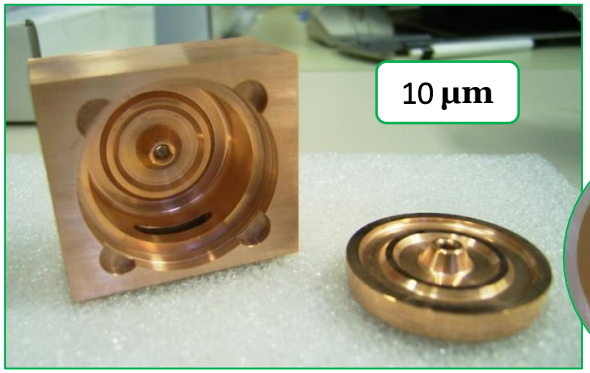


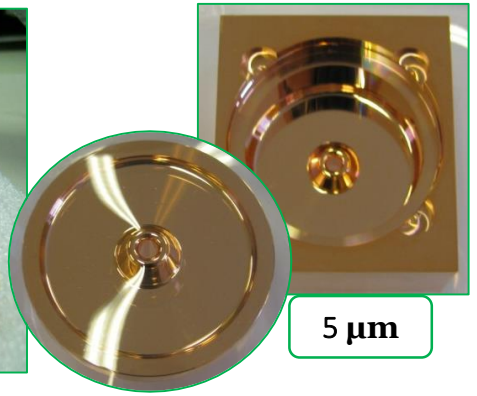


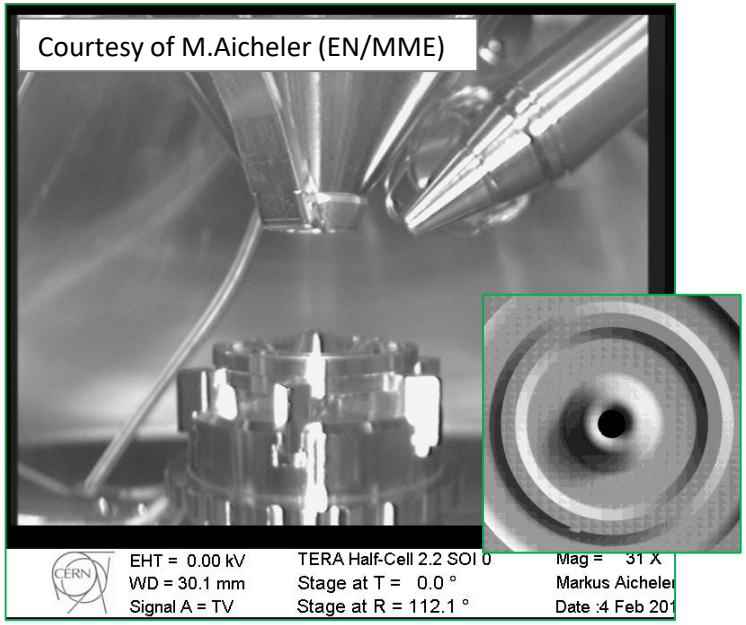


C-band high gradient tests: machining and tuning



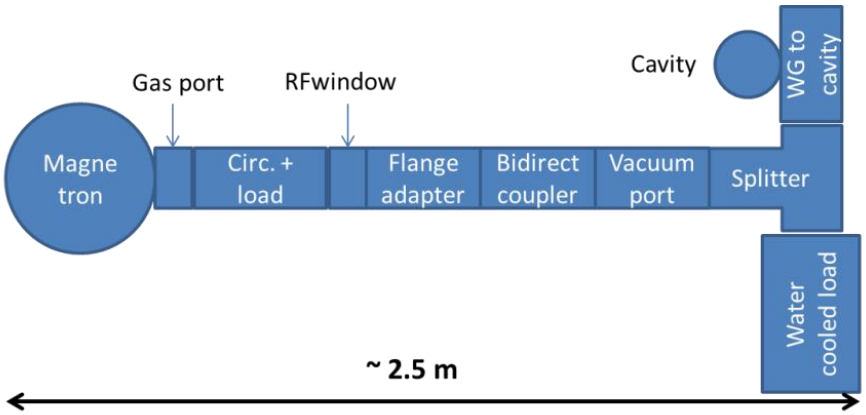


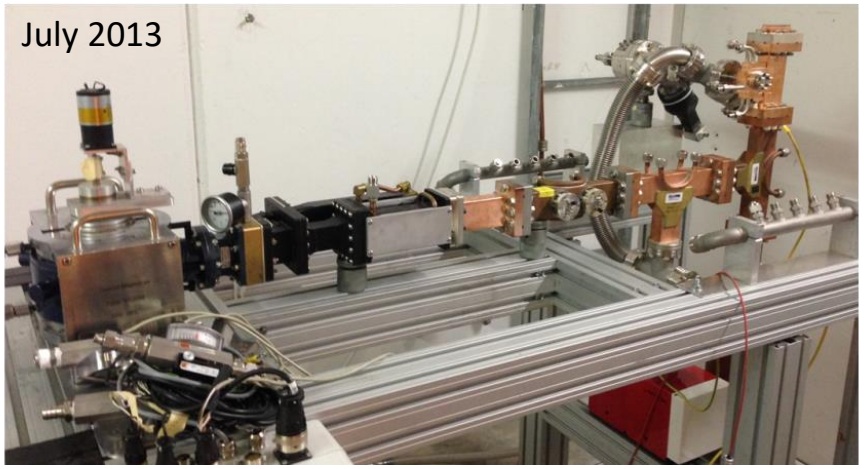




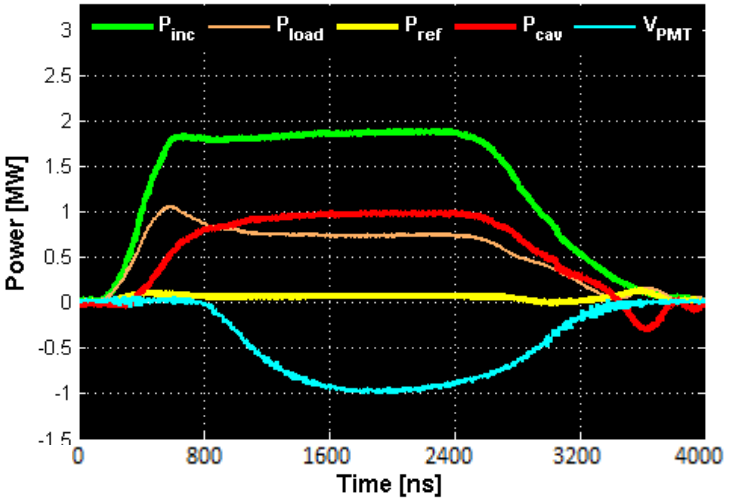
Low Power Measurements & remachining characterization (ongoing)

C-band high gradient tests: high power tests at Ponit2

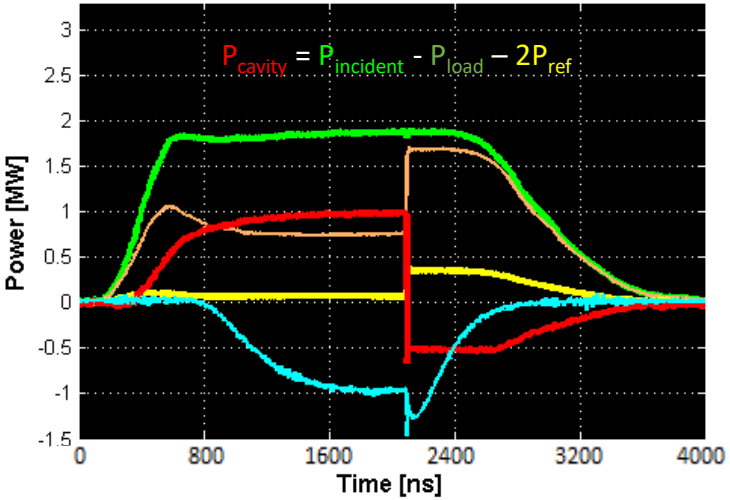




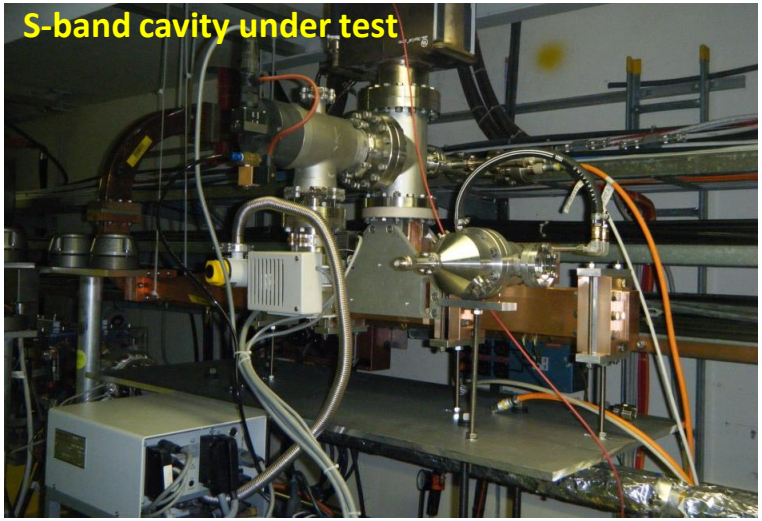
Normal pulse

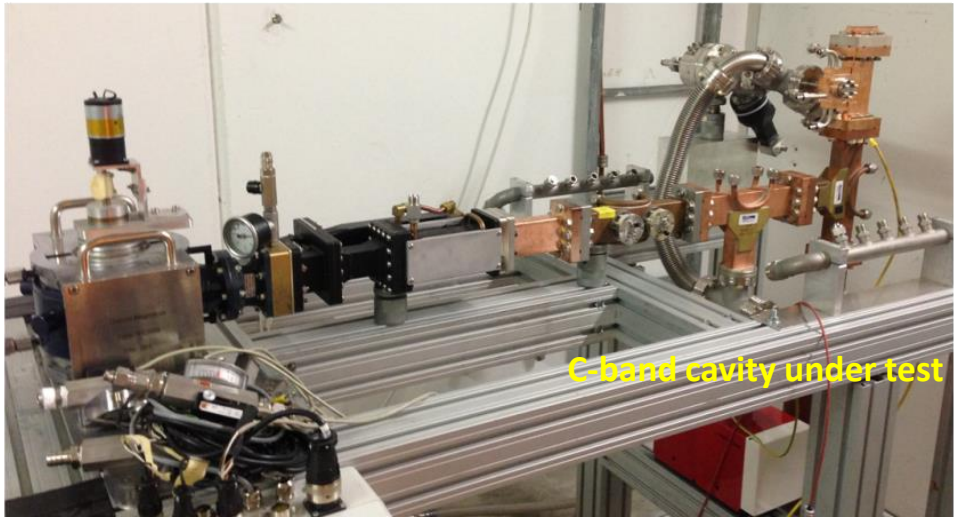


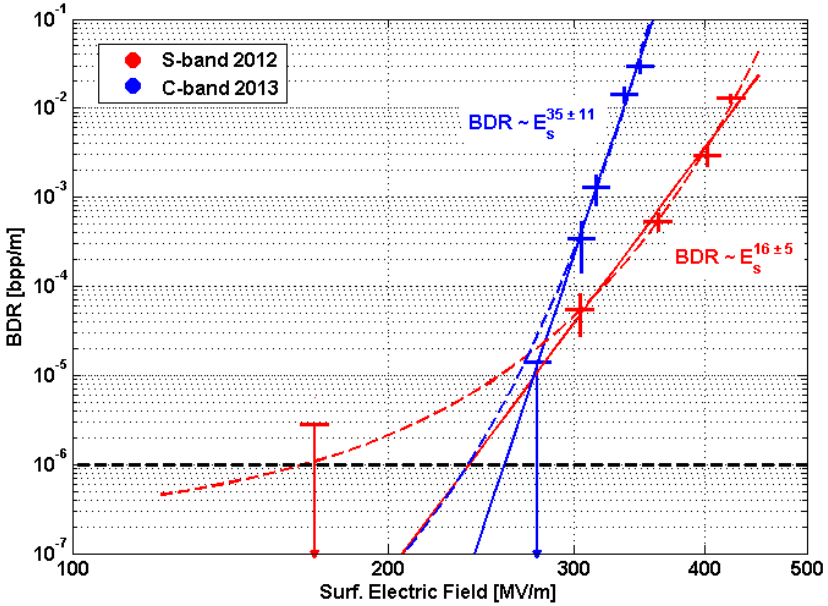
Breakdown pulse

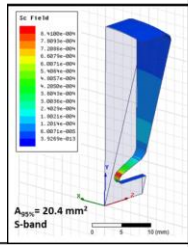
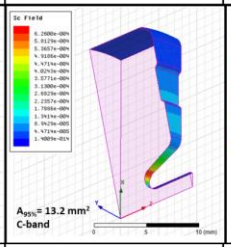
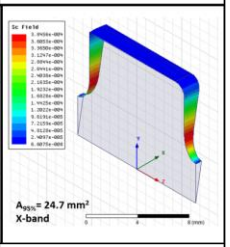


Limits on gradients and scaling laws



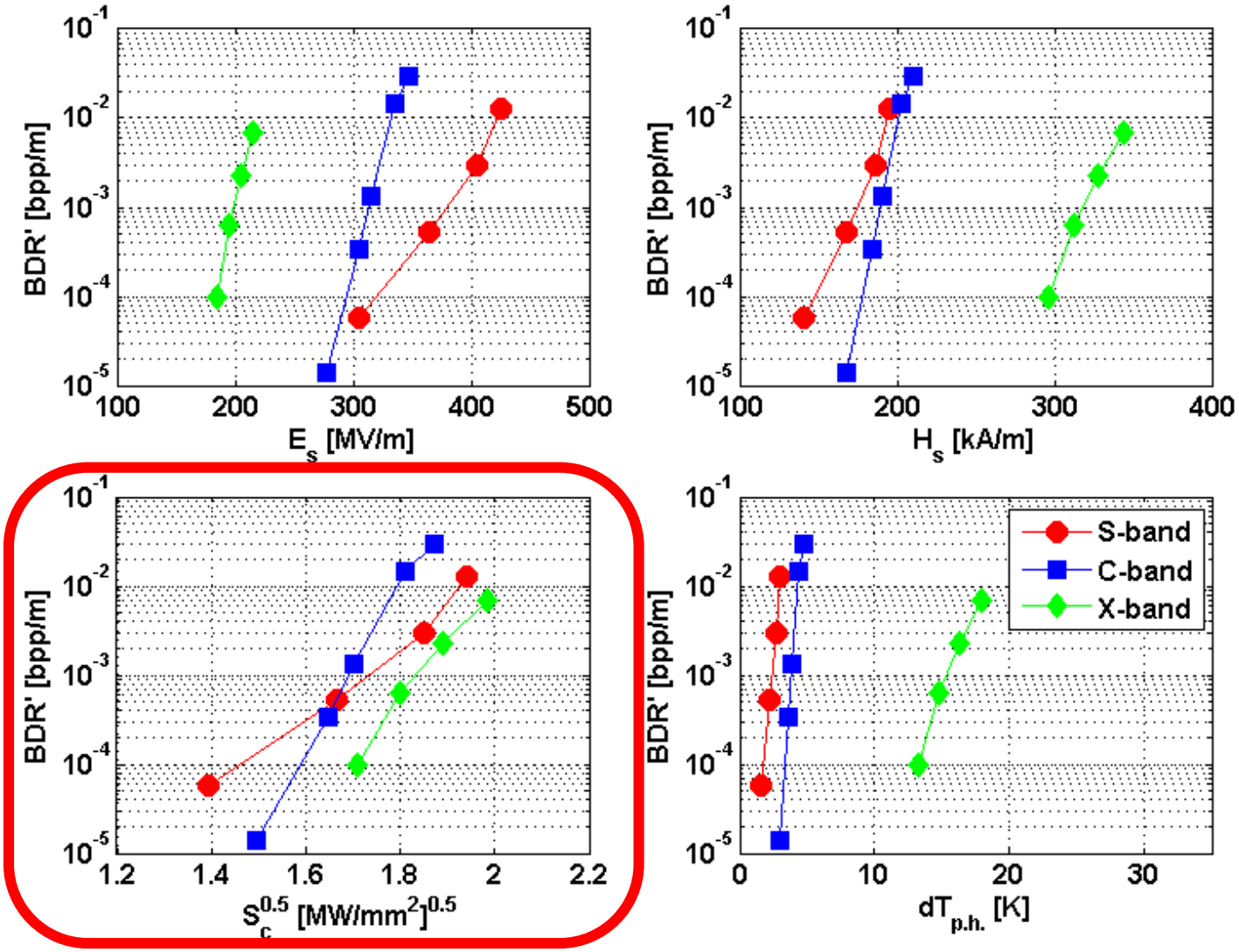




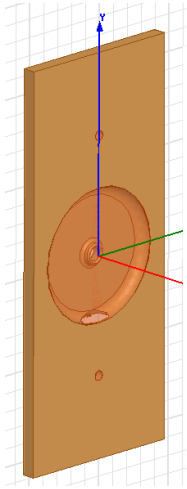
	S-band	C-band	X-band*
Cell shape			
BDR ~ t^y , y =	2.9 ± 0.5	4.9 ± 1.2	5 ± 1
BDR ~ E^x , x =	16 ± 5	35 ± 11	28 ± 8
ΔV [nm^3] (stress model fit)	1300 ± 600	80 ± 30	40 – 1100
Scaled √Sc [$(W/\mu m^2)^{0.5}$] for BDR 10^{-6} m^{-1}, 200 ns	1.6	1.9	1.2 - 2.4

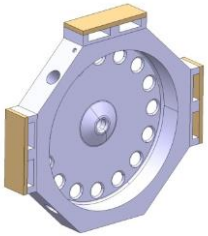
*Dolgashev et al., EPAC08, 742-44

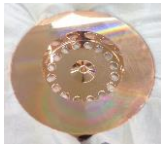
Limits on gradients and scaling laws

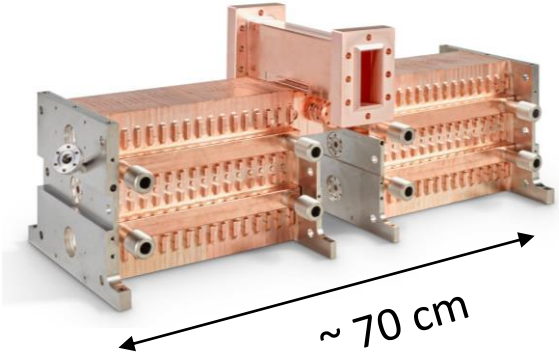


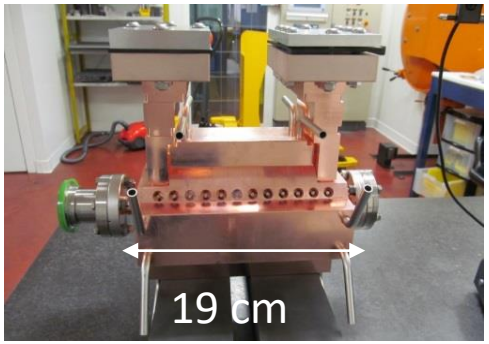
An alternative to CCLs: BTW structures development











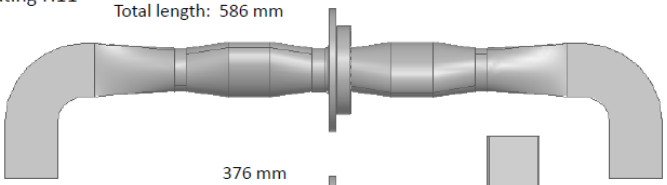
- A CLIC-TERA collaboration - funded by CERN-KT, starting in 2012
- 20 cm long
- Max gradient of more than 50 MV/m!
- 10 MeV energy gain from this structure (with peak power ~22 MW)

→ More in the next talk from Stefano Benedetti

Power transmission with RF rotating joints designed by CLIC

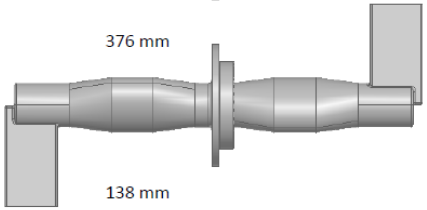
#1 with rotating H11

Total length: 586 mm



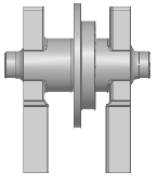
376 mm

#2 with rotating H11 and compact H10 to H11 90 degrees bend

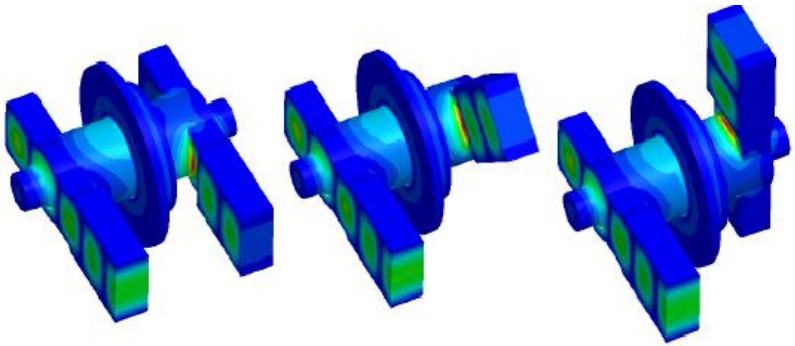


138 mm

#3 With CLIC accelerating structure type mode converter from H10 to E01



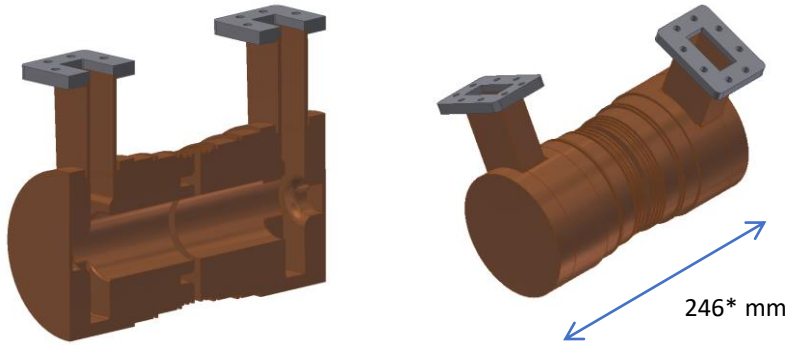
I. Syratchev, CERN, BE/RF



CLIC – Note – 1071

DESIGN AND HIGH POWER MEASUREMENTS OF A 3 GHZ ROTARY JOINT FOR MEDICAL APPLICATIONS

Alberto Degiovanni[1,2*], Stefano Benedetti[1,2], Marco Garlasché[1,2], Jorge Giner-Navarro[1], Paolo Magagnin[1,2], Gerard McMonagle[1], Igor Syratchev[1], Walter Wuensch[1]



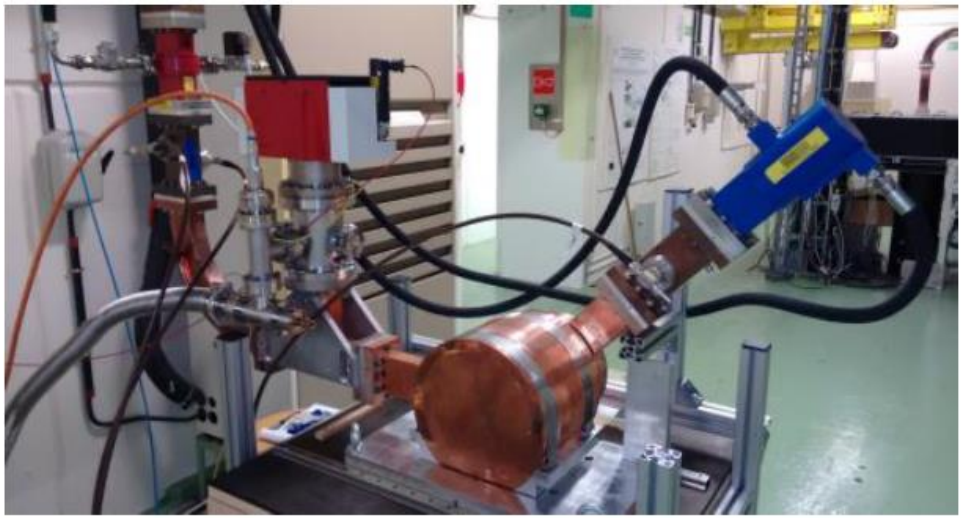
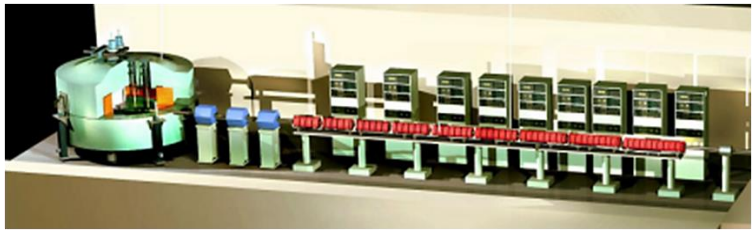


Figure 6: Setup of the high power test of the RJ in CTF2 at CERN.

TERA

…from cyclinac to all-linac designs

1993: first Cyclinac proposal

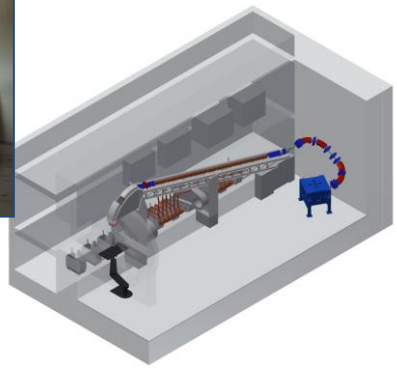


2002: LIBO (TERA-CERN-INFN)

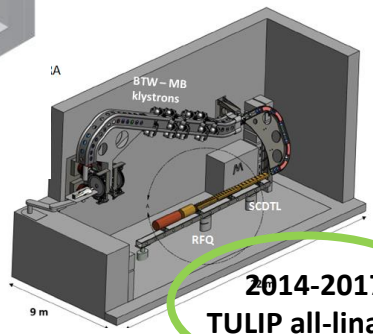
3 GHz linac (62-74 MeV)
[C. De Martinis et al,NIM A 681 (2012)]

11.2010: LIGHT 1st UNIT

2014-2017 LIGHT–all-linac

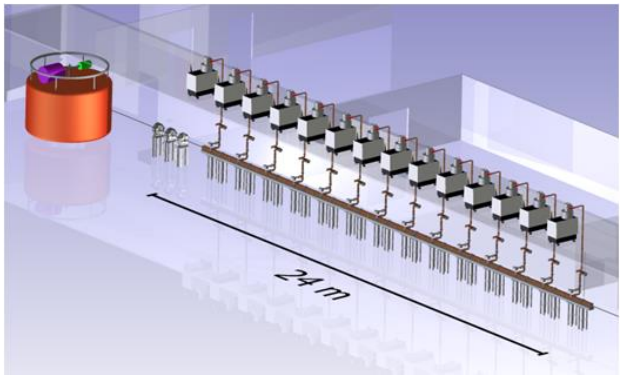


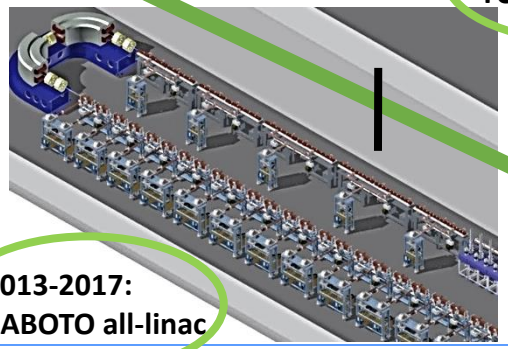
2011-2013: TULIP



2014-2017: TULIP all-linac

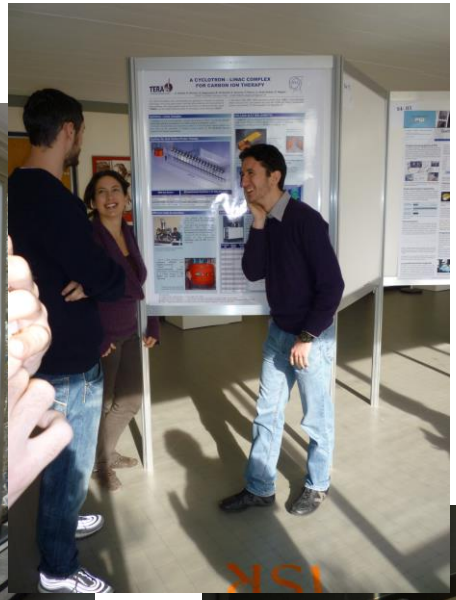
2008-2011: CABOTO-C design





2013-2017: CABOTO all-linac

"…Physics is beautiful and useful !"



“Ideas and projects move on the legs of people…”

Thank you for your attention !