Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare

SAPIENZA UNIVERSITÀ DI ROMA

SAFEST: proposal of a compact C-band linear accelerator with Very High Energy Electrons for FLASH Radiotherapy

L. Faillace, D. Alesini, G. Bisogni, F. Bosco, F. Cardelli, M. Carillo, E. Chiadroni, G. Cuttone, D. De Arcangelis, A. Di Gregorio, R. Di Raddo, L. Ficcadenti, G. Franciosini, G. Franzini, A. Gallo, L. Giuliano, V. Lollo, M. Magi, M. Migliorati, A. Mostacci, P. Cirrone, L. Palumbo, V. Patera, L. Piersanti, S. Pioli, R. Remetti, A. Sarti, B. Spataro, G.Torrisi, A. Vannozzi

Outline

- Sapienza University and INFN Collaboration (VHEE Linac for FLASH Radiotherapy);

- Compact C-Band System at 5.712 GHz (decade long experience, high electron beam energies in small footprint)
  - RF and beam dynamics
  - Manufacturing
  - Low-power measurements of linac prototypes

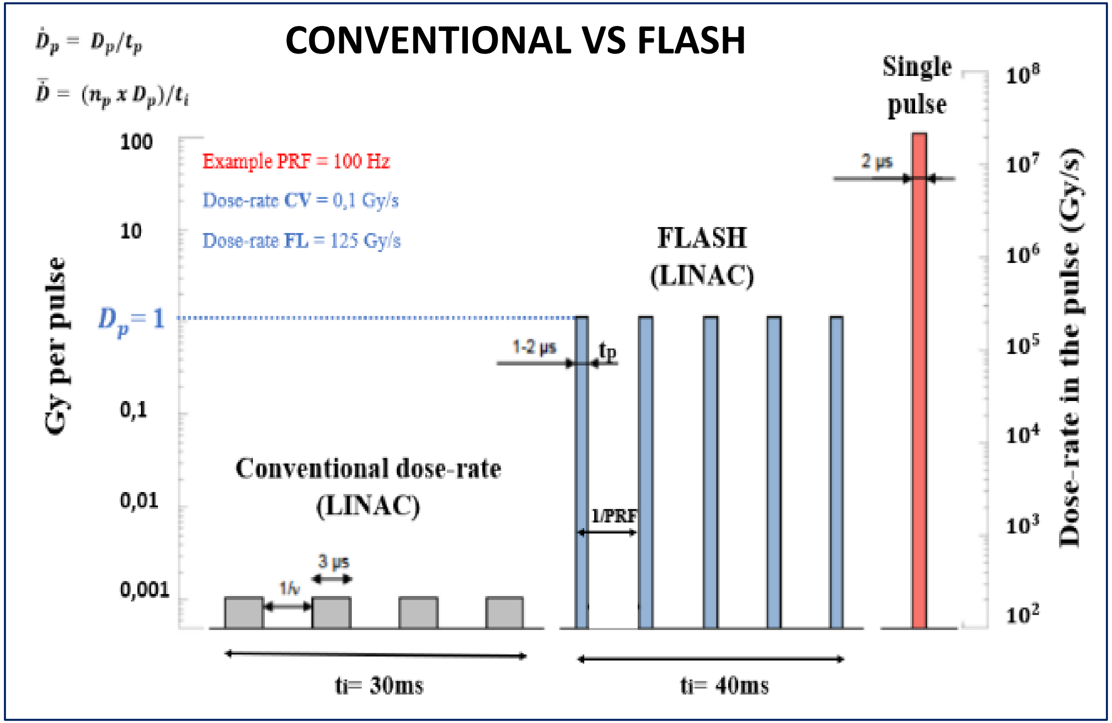
- **SAFEST**: Research Laboratory dedicated to VHEE FLASH (100 MeV nominal energy) to be installed at Sapienza University;

First step → Installation of a low-energy accelerator Lab (up to 24 MeV electron beams) at Sapienza University, near the main campus, for **Dosimetry, Radiobiology and Pre-clinics FLASH Experiments**.

FLASH Therapy: a revolutionary technique in the perspective of cancer cure.

- **Sparing of healthy tissues** from the damage of the ionizing radiation maintaining the tumor control as efficient as in conventional therapy;

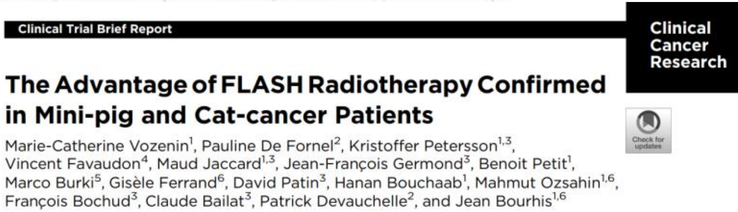
- For the implementation of the revolutionary FLASH therapy concept into actual clinic use, electron linear accelerators are required to deliver **very high dose-rate in the pulse (> 10^6 Gy/s) in very short total irradiation time (≤ 100 ms).**



Courtesy of V. Favaudon

Is the evidence robust?

DOSE
MODIFYING
FACTOR


Clinical Trial Brief Report

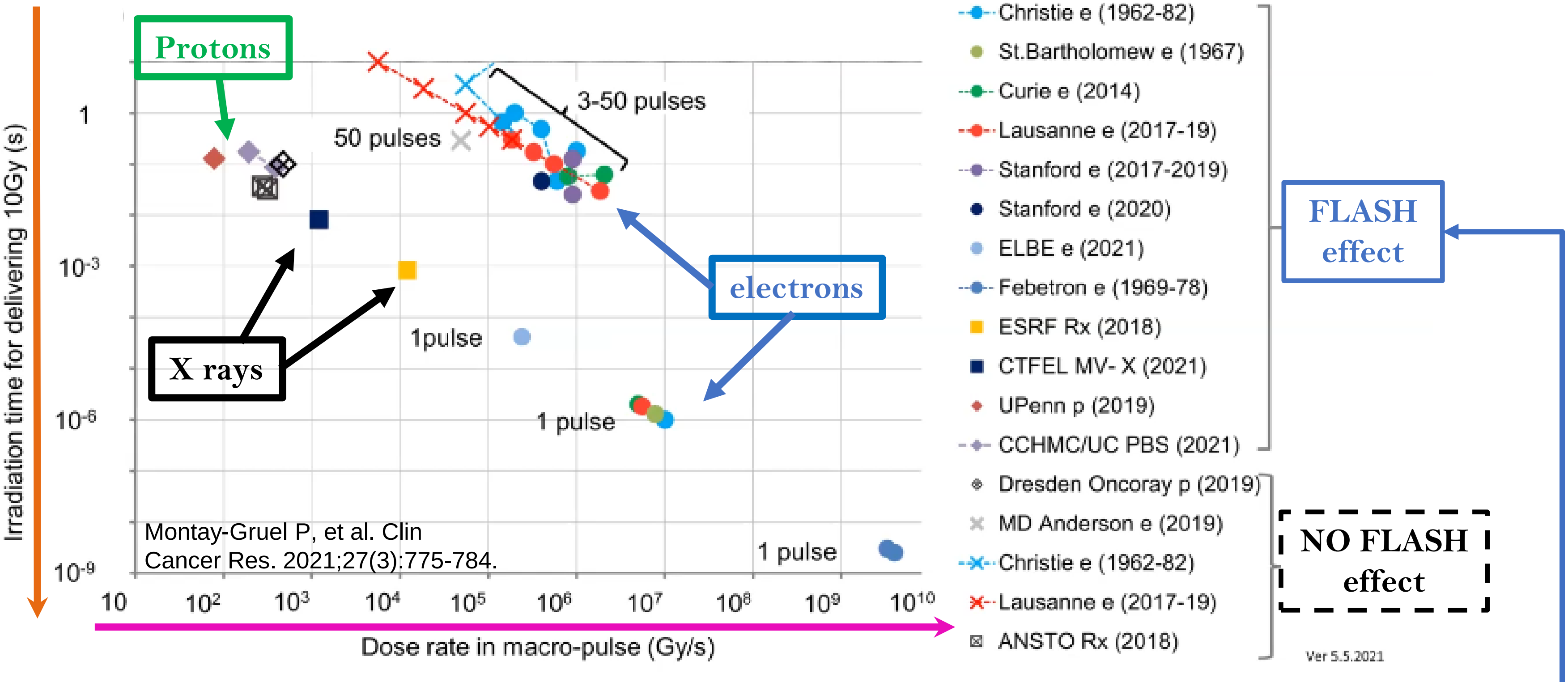
Clinical Cancer Research

The Advantage of FLASH Radiotherapy Confirmed in Mini-pig and Cat-cancer Patients

Marie-Catherine Vozenin[1], Pauline De Fornel[2], Kristoffer Petersson[1,3], Vincent Favaudon[4], Maud Jaccard[1,3], Jean-François Germond[3], Benoit Petit[1], Marco Burki[5], Gisèle Ferrand[6], David Patin[3], Hanan Bouchaab[1], Mahmut Ozsahin[1,6], François Bochud[3], Claude Bailat[3], Patrick Devauchelle[2], and Jean Bourhis[1,6]

The evidence seems robust, even if the exact features are yet to be explored.
The first patient has been already treated!!!

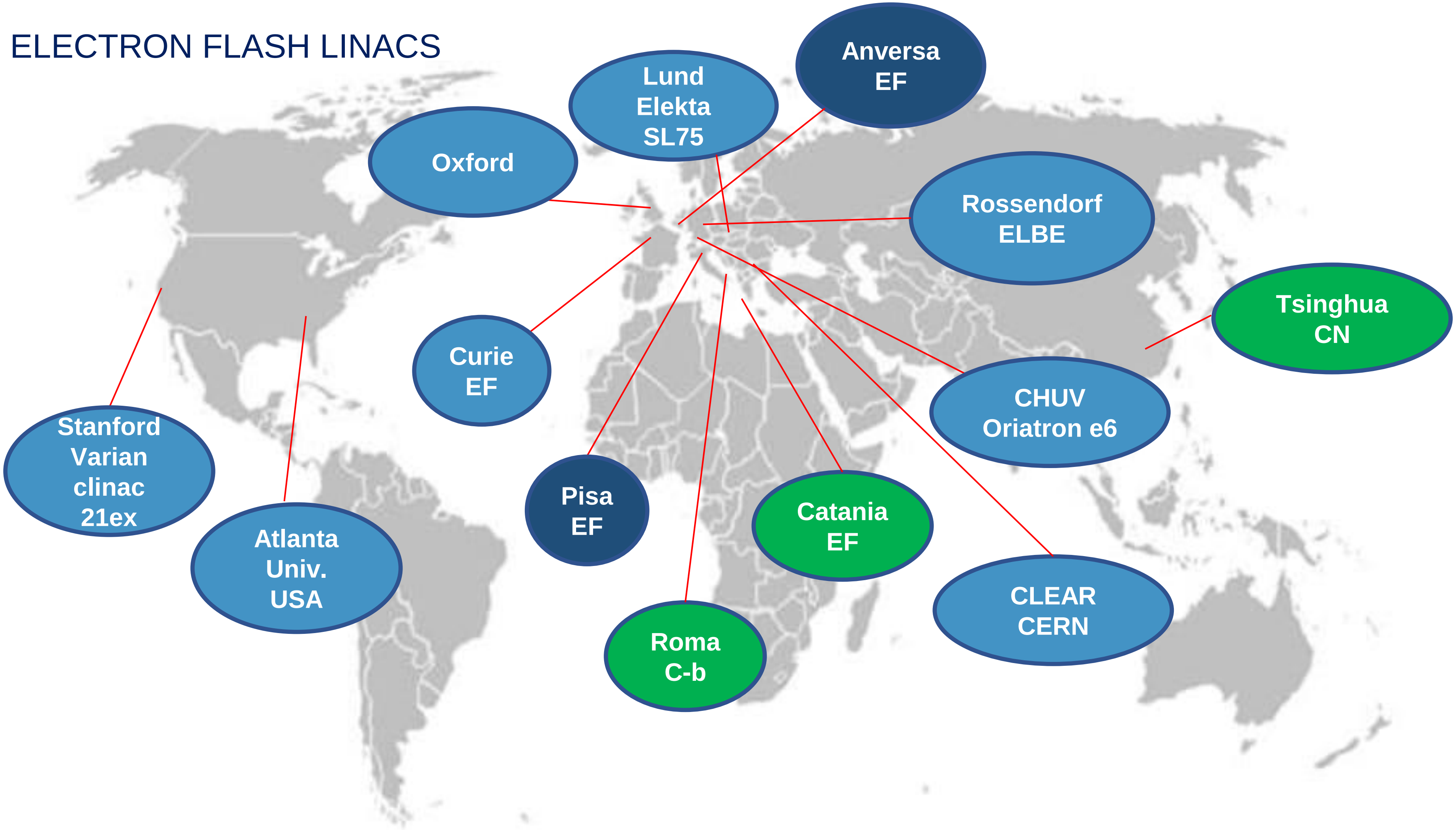
Conditions to hit or miss the FLASH effect



- Higher dose rate in the pulse,
- Shorter irradiation time < 100 ms,

highest is the FLASH effect.

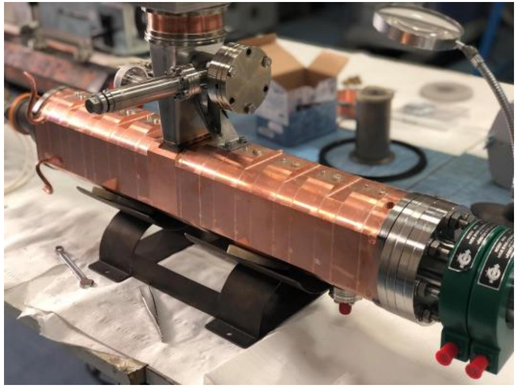
ELECTRON FLASH LINACS



From LOW ENERGY

Experience with Linac installed at Curie Institute

- S-Band Linac-based machine (7 MeV) for FLASH with SIT company, the ElectronFLASH, commissioned and installed at the Curie Institute.



EF features	Value
Output energy	5 or 7 MeV
Pulse repetition frequency	1 - 250 Hz
Pulse width	0.5 - 4 μs
Maximum peak beam current	120 mA
Maximum Istantaneous Dose rate	7.5x10^6 Gy/s
Maximum Average Dose rate	7500 Gy/s
Max Dose per pulse	30 Gy in a circular surface of ∅ 10 mm

PATENT: Sapienza-SIT

applied sciences MDPI

Article

Characterization of Ultra-High-Dose Rate Electron Beams with ElectronFlash Linac

Lucia Giuliano [1,2], Gaia Franciosini [1,2], Luigi Palumbo [1,2,*], Lilia Aggar [3], Marie Dutreix [3], Luigi Faillace [4], Vincent Favaudon [3], Giuseppe Felici [5], Federica Galante [5], Andrea Mostacci [1,2], Mauro Migliorati [1,2], Matteo Pacitti [5], Annalisa Patriarca [6] and Sophie Heinrich [3]

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24**, 050102 (2021)

Compact *S*-band linear accelerator system for ultrafast, ultrahigh dose-rate radiotherapy

L. Faillace,[1,6,*] S. Barone,[2] G. Battistoni,[3] M. Di Francesco,[2] G. Felici,[2] L. Ficcadenti,[4] G. Franciosini,[4,5] F. Galante,[2] L. Giuliano,[1,4] L. Grasso,[2] A. Mostacci,[1,4] S. Muraro,[3] M. Pacitti,[2] L. Palumbo,[1,4] V. Patera,[1,4] and M. Migliorati[1,4]

SAFEST

SApienza Flash Electron Source for radio-Therapy

Proposal of a

VHEE-FLASH-RT Research Facility

2022

D. Alesini[2], D. Alvaro[1], M.G. Bisogni[5], F. Bosco[1], F. Cardelli[2], V. Cardinale[1], M. Carillo[1,3], G. Cenci[1], E. Chiadroni[1,2], I. Chiarotto[1], P. Cirrone[4], M. Coppola[1], G. Cuttone[4], D. De Arcangelis[1], F. De Felice[1], A. De Gregorio[1,3], G. De Vincentis1, F. Di Martino[7], R. Di Raddo[2], R. Faccini[1,3], L. Faillace[2], M. Feroci[1], L. Ficcadenti[3], A. Filippini[1], D. Francescone[1,3], G. Franciosini[1,3], G. Franzini[2], A. Gallo[2], E. Gaudio[1], L. Giuliano[1,3], V. Lollo[2], M. Magi[1,3], C. Mancini Terracciano[1,3]. M. Marafini[3,8], F. Marampon[1], M. Migliorati[1,3], G. Minniti[1], A. Mostacci[1,3], A. Muscato[1], A. Napolitano[1], R. Negri[1], M. Osti[1], M. Pacilio[6], G. Pellacani[1], F. Palma[1], L. Palumbo[1,3], R. Pani[1], M. Pasquali[1], L. Passalacqua[1], V. Patera[1,3], F. Perondi[1], M. Petrarca[1,3], R. Petrucci[1], F. Pitolli[1], R. Remetti[1], A. Sarti[1,3], A. Schiavi[1,3], A Sciubba[1,3], B. Spataro[2], V. Tombolini[1], M. Toppi[1,3], G. Torrisi[4], G. Traini[3], A. Trigilio[1,3], A. Vannozzi[2].

(1) Università La Sapienza
(2) INFN, Laboratori Nazionali di Frascati
(3) INFN, Sezione di Roma
(4) INFN, Laboratori Nazionali del SUD
(5) Università di Pisa & INFN Pisa
(6) Fisica Sanitaria, Azienda Ospedaliera Policlinico Umberto I, Roma
(7) Fisica Sanitaria, Azienda Universitaria Ospedaliera Pisana, Pisa
(8) Centro Ricerche Enrico Fermi , Roma

JOINT
STUDY GROUP
SAPIENZA – INFN
2021

Towards HIGH ENERGY

Coordinator Prof. L. Palumbo

SIMULATIONS WITH MONTECARLO CODE SHOW THAT

1. VHEE BETTER THAT PHOTONS EVEN WITHOUT FLASH
2. VHEE COMPARABLE WITH PROTONS IN CASE OF FLASH

(Prof. V. PATERA)

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

ELSEVIER

Original Paper

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B. Spataro[a], G. Torrisi[e], A. Vannozzi[a], L. Giuliano[b,c]

2022

PE6 : FLASH-LAB

Referente Sapienza PNRR
Prof. Vincenzo Patera

Project Coordinator
Prof. Luigi Palumbo

SIT s.p.a.

Treatment Plans VHEE
A. Sarti

- Dose engine: G. Traini & G. Franciosini
- Optimization: A. Schiavi & A. Di Gregorio
- Online Beam Monitor : M. Marafini

LINAC VHEE-FLASH
M. Migliorati

- Linac Parameters : M. Migliorati & L. Giuliano
- RF Design : L. Giuliano
- RF prototype: A. Mostacci
- Diagnostics : A. Mostacci
- Beam Dynamics : L. Giuliano
- Beam measur. : E. Chiadroni
- Linac Controls : A. Mostacci
- Magnets: A. Vannozzi (INFN)
- Mech. machining: M. Magi

Shared:

- Radioprotection: A. Di Gregorio & G. Franciosini, F. Perondi
- Beam Delivery : A. Vannozzi (INFN) & A. Trigilio
- e-beam/dose character L. Giuliano
- WEB, Repository & Network M. Coppola

LNS Collaboration

- G. Cuttone
- G. Torrisi (Pulse compresor)
- P. Cirrone

Roma1 Collaboration

- L. Ficcadenti
- Facilities (off. Meccanica)
- ……….

LNF Collaboration

- RF Design : L Faillace, Alesini
- RF prototype: Faillace, Alesini
- Diagnostics : G. Franzini
- Beam Dynamics : L. Faillace
- RF Linac Controls : S. Gallo
- Magnets: A. Vannozzi
- Beam delivery : A. Vannozzi
- C power test: Cardelli/Pioli
- Controls: Piersanti
- Brasatura: Lollo, Di Raddo

Istituto Nazionale di Fisica Nucleare

TOWARD VHEE LINACS
FOR DEEP TUMORS : FUNDINGS

SAPIENZA
UNIVERSITÀ DI ROMA

A compact C-band Linac for FLASH therapy: accelerator and dosimetry study (2020)

- **Commissione Scientifica Ateneo**
- **Sapienza medie attrezzature**
- **SBAI Contracts**
- **260 kE**

INFN PROJECT
2021
FRIDA

FLASH Radiotherapy with hIgh Dose-rate particle beAms

R&D RF Structure 120 kE
Pulse compressor 70 kE

PNRR NATIONAL PROJECT
2022

HEAL ITALIA
Health Extended ALliance for Innovative Therapies, Advanced Lab-research, and Integrated Approaches of Precision Medicine

Basic VHEE Prototype
SAPIENZA 1.500 kE
SIT 230 KE

Electron Beam Parameters of the new VHEE-Linac

institut Curie	Description	Measured Value
E	Beam Energy	7 MeV
f	RF frequency	2.998 GHz
PRF	Pulse repetition frequency	> 100 Hz
	Pulse width	1 - 4 μs
	Pulse Charge	500 nC
	Pulse Current	125 mA
	Dose in a single pulse	20 Gy*
	In-Pulse Dose-Rate	$> 10^7$ Gy/s

*Ø 3 cm applicator, homogeneous (95%) field size at 55 cm of the exit window

VHEE LINAC

	Description	Proposed Value for New Linac #
E	Beam Energy	60 - 130 MeV
f	RF frequency	5.712 GHz
PRF	Pulse repetition frequency	> 100 Hz
	Pulse width	1 - 3 μs
	Pulse Charge	200 - 600 nC
	Pulse Current	200 mA
	In-Pulse Dose-Rate	$>> 10^7$ Gy/s

- Explore the FLASH effect both in the fixed field and pencil beam case;
- Beam intensity modulation: Pulse-to-pulse and intra-pulse;

Electron Beam Parameters of the new VHEE-Linac

institut Curie	Description	Measured Value
E	Beam Energy	7 MeV
f	RF frequency	2.998 GHz
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	Pulse Charge	
	Pulse Current	
	Dose in a single pulse	
	In-Pulse Dose-Rate	

*Ø 3 cm applicator, homogeneous (
at 55 cm of the exit window

VHEE LINAC

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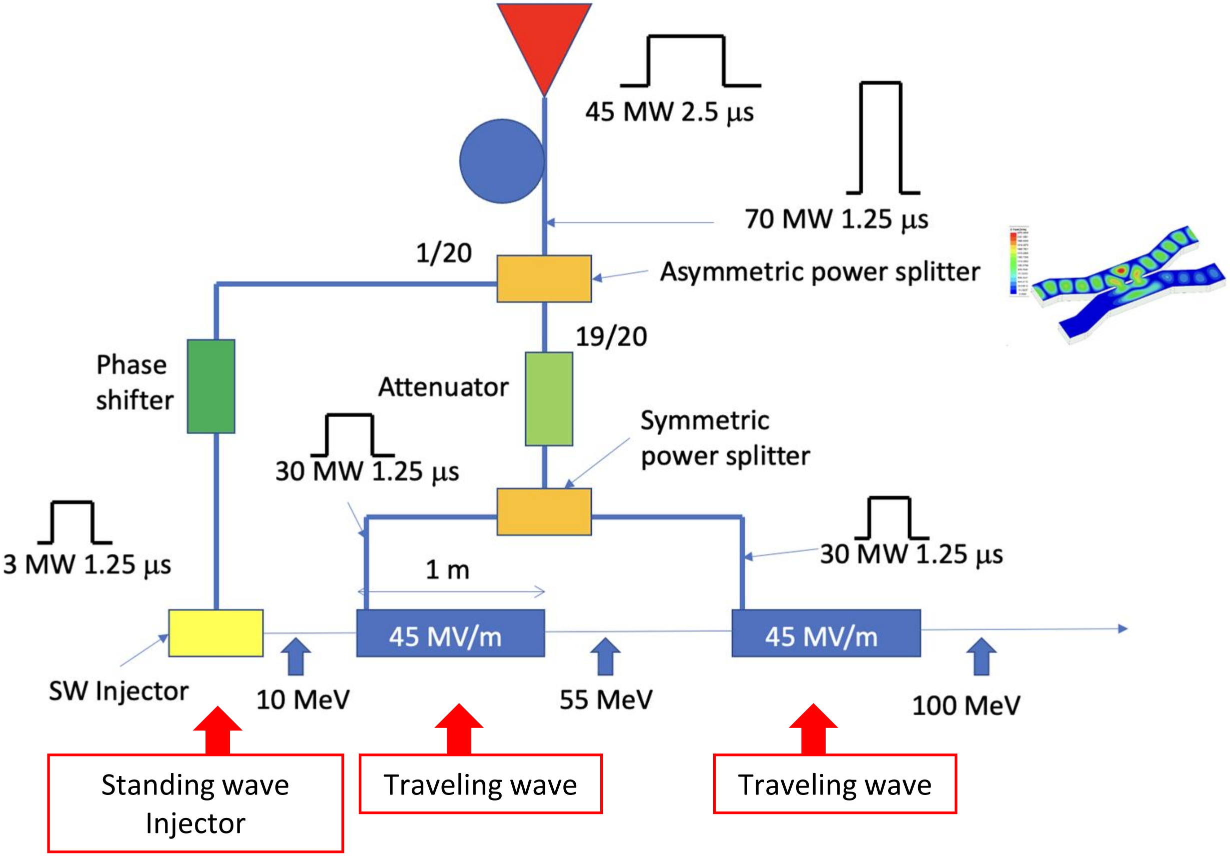
B. Spataro [a], G. Torrisi [e], A. Vannozzi [a], L. Giuliano [b,c]

SCHEME FOR 100 MeV Linac

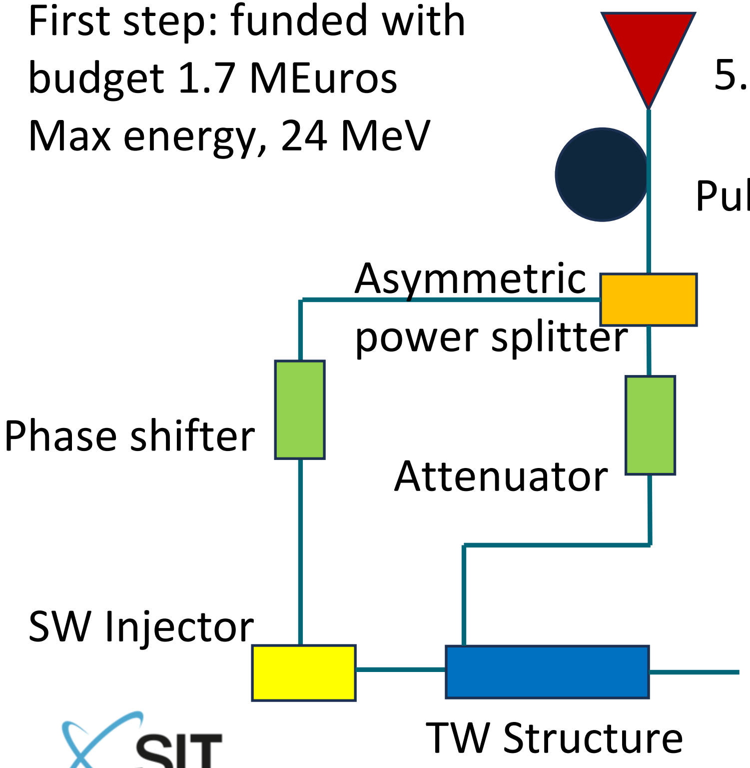
Health Extended ALliance for
Innovative Therapies, Advanced Lab-research, and Integrated Approaches
of Precision Medicine

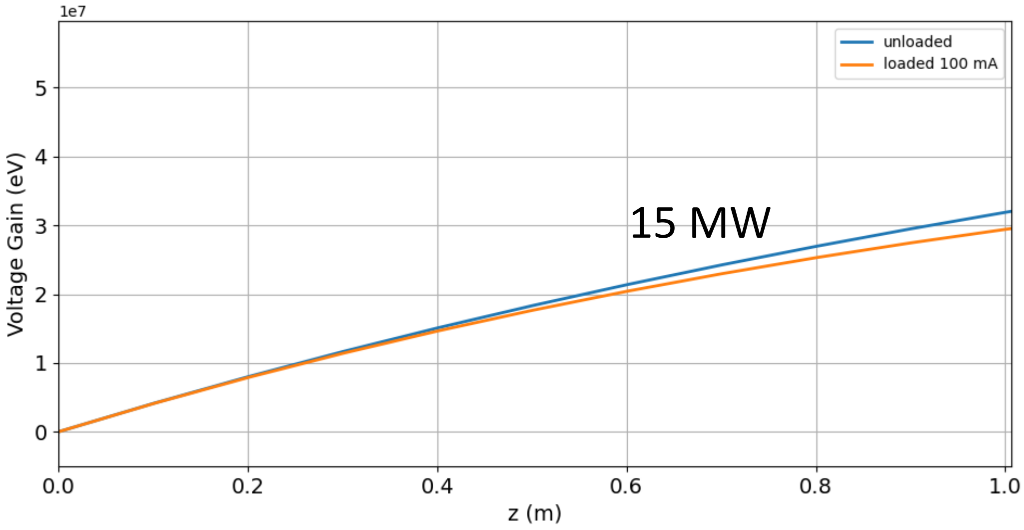


Frequency	5.712 GHz
Beam Energy	65 - 100 MeV
RF Repetition rate	100 Hz
Current	100 mA
C-band average accelerating gradient	45 MV/m
RF pulse duration	1.5 – 2.5 μs
In pulse dose rate	> 10^6 Gy/s
Average dose rate	> 100 Gy/s
Dose per pulse	>> 1 Gy

LAB at Sapienza University for Low-energy FLASH

- First step: funded with budget 1.7 MEuros
- Max energy, 24 MeV





Courtesy of Prof. L. Palumbo

RF DESIGN OF A COMPACT C-BAND RF PULSE COMPRESSOR FOR A VHEE LINAC FOR FLASH RADIOTHERAPY

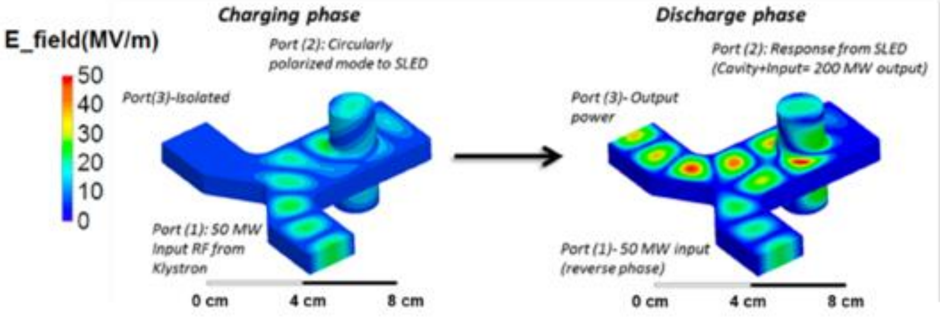
G. Torrisi*, G. S. Mauro and G. Sorbello[2], INFN-LNS, Catania, Italy
L. Faillace and B. Spataro, INFN Laboratori Nazionali di Frascati, Italy
L. Giuliano[5], A. Mostacci[5] and L. Palumbo[5], SBAI Department, Sapienza University of Rome, Italy
[2]also at University of Catania, Catania, Italy
[5]also at INFN-Sezione di Roma, Italy

Spherical Pulse compression

FLASH Radiotherapy with hIgh Dose-rate particle beAms

RF dual-mode polarizer coupler

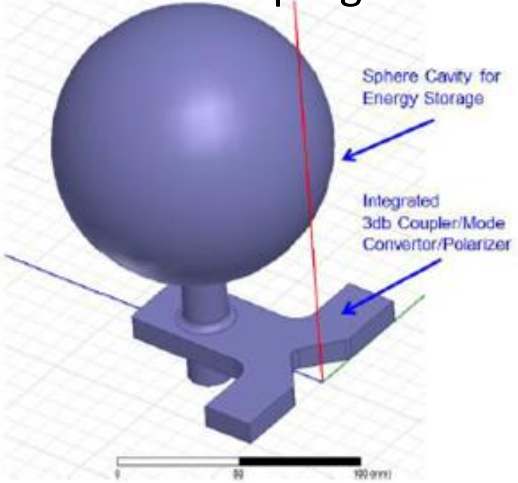
- ❑ Each rectangular waveguide mode excite a TE_{11} mode
  - Excitation in quadrature produces quasi circularly polarized wave
- ❑ TE_{11} modes excite degenerate TE_{114} modes of spherical resonator
  - TE_{20} and TE_{10} emitted/reflected from the cavity cancel at input port



Wang et al., "New SLED 3 system for Multi-mega Watt RF compressdr, 2014 arXiv

single High-Q spherical resonator SLED

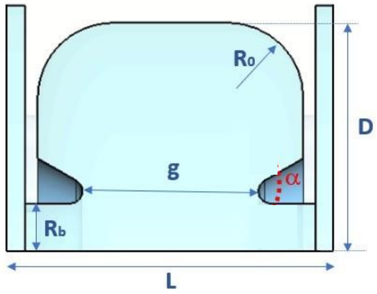
→ Fabrication is in-progress



works on two TE_{11n} mode

Courtesy of G. Torrisi

DESIGN AND PROTOTYPING OF SW injector



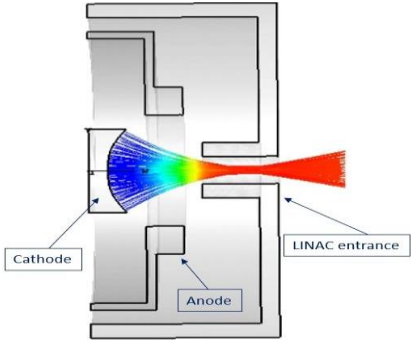
Single cell parameters [mm]

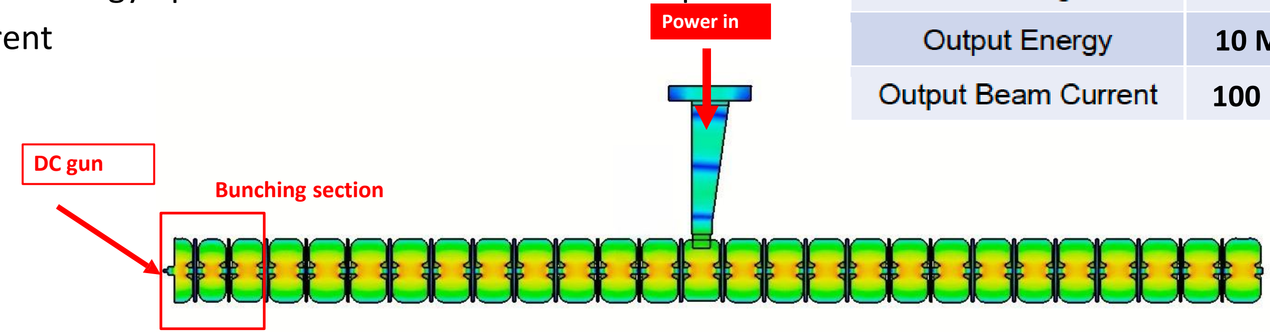
D	g	L	Rb	Ro	α
38.25	15.6	24.4	3	6	30°

- Cavity type: **standing wave**, bi-periodic, **on-axis coupling cells**
- Electromagnetic field: π/2 accelerating mode
- **Nose - cone** geometry: **high electric field** at the noses zone
- **Bunching section for low-energy beam capture (> 45%)**
- Beam energy up to ≈ **10 MeV** and **100 mA** beam peak current

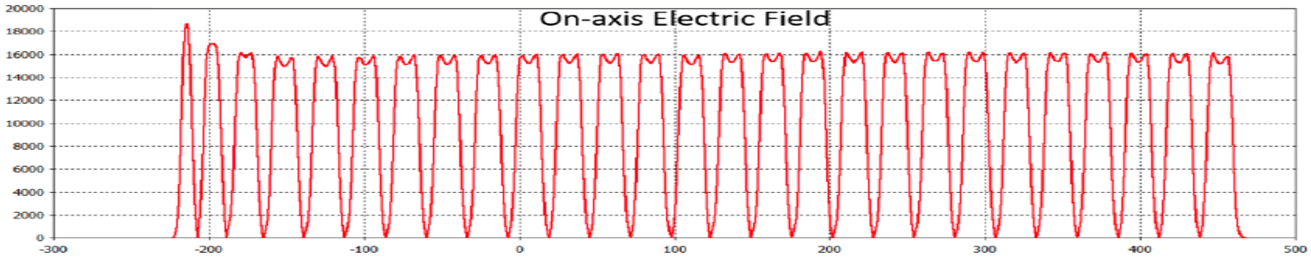
Parameter	Value
Frequency	5.714 GHz
Magnetron Power	2.5 MW
Number of accelerating cells	27
Linac length	70 cm
Output Energy	**10 MeV**
Output Beam Current	**100 mA**

Electron source:
DC thermionic gun
at 15 kV.



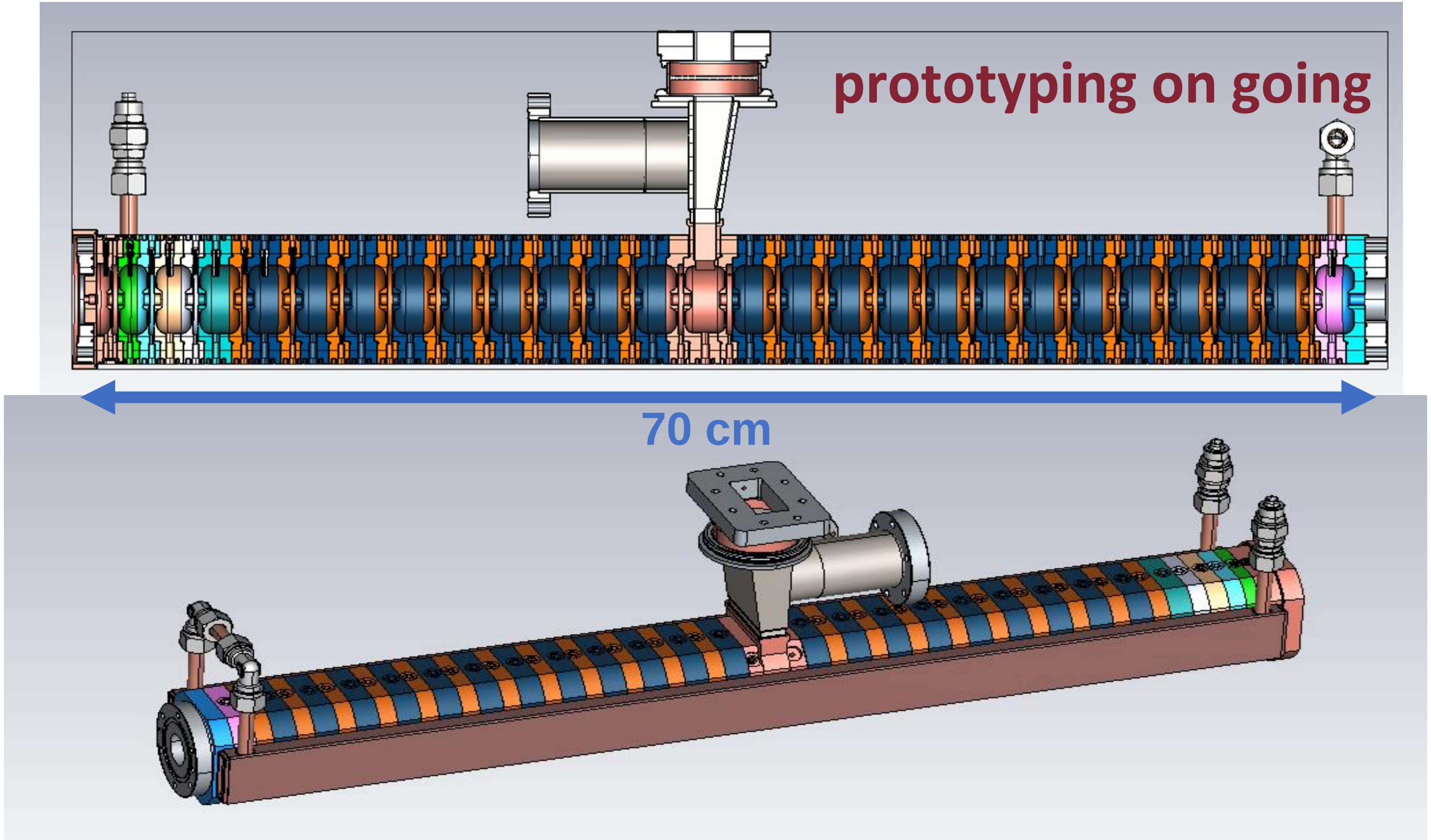


2023



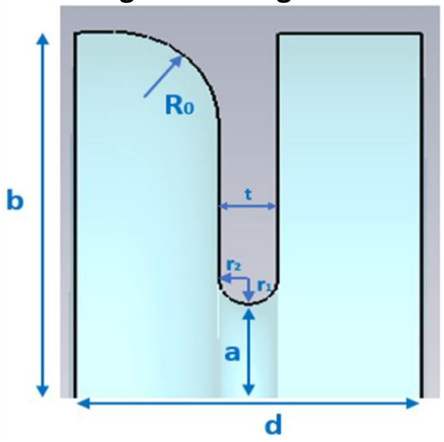
Courtesy of L. Giuliano

Mechanical drawing of the SW linac (SIT)



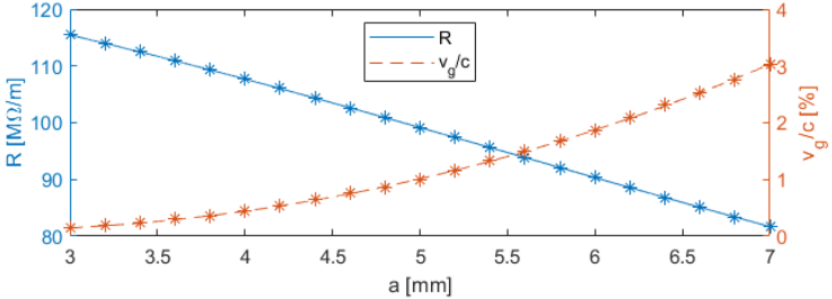
DESIGN AND PROTOTYPE TW HIGH GRADIENT ($2\pi/3$)

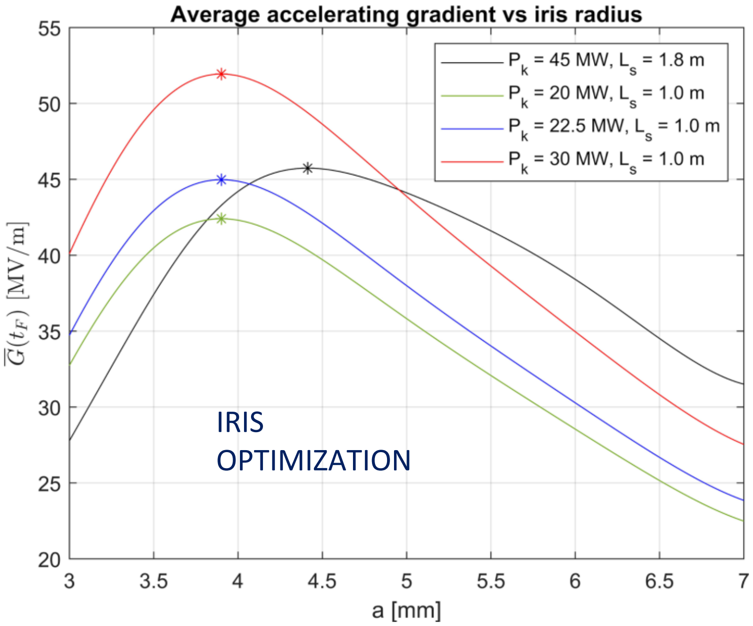
Single Cell design

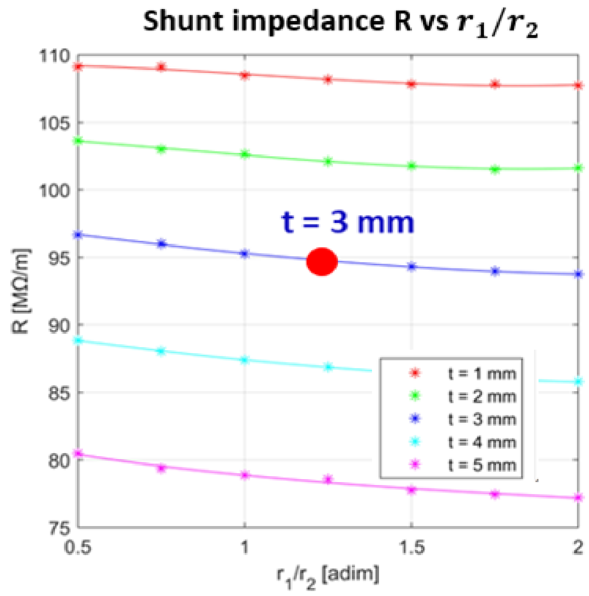


Single cell RF parameters in mm

a	b	d	R_0	t	r_1/r_2
5	21.03	17.5	6	3	1.25





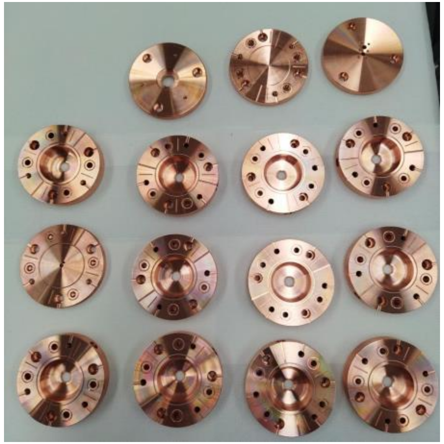


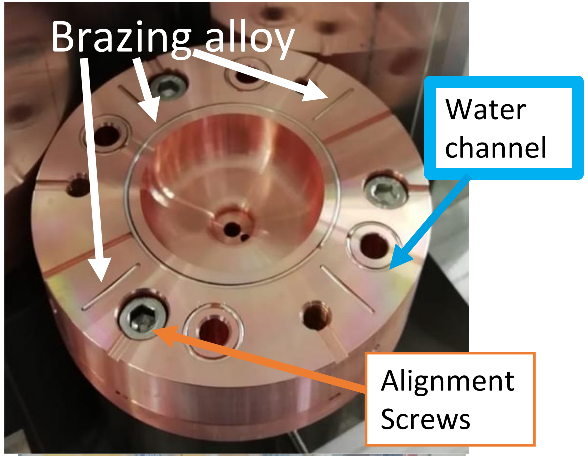
Shunt impedance **R = 95 MΩ/m** for r1/r2 = 1.25 and t=3 mm.

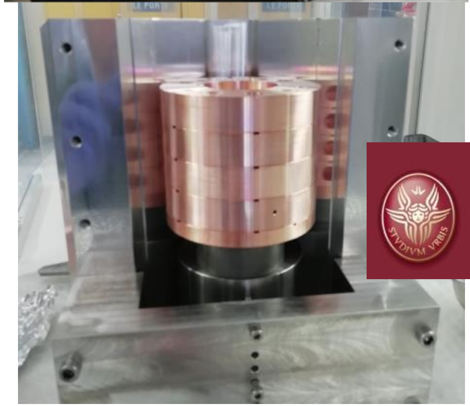
Courtesy of D. De Arcangelis

Prototyping phase 1

Two pre-prototypes of 5-cells without couplers to test the brazing procedure, vacuum sealing and the in-house mechanical design.







INFN
LNF
Istituto Nazionale di Fisica Nucleare

In house building of the accelerating cavities

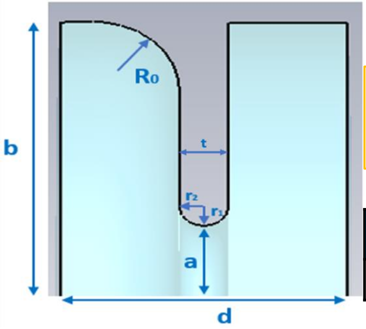
FLASH Radiotherapy with hIgh Dose-rate particle beAms

SAPIENZA UNIVERSITÀ DI ROMA

Main contributors: D. Alesini, **R. Di Raddo,** L. Faillace, L. Giuliano, **M. Magi,** M. Migliorati

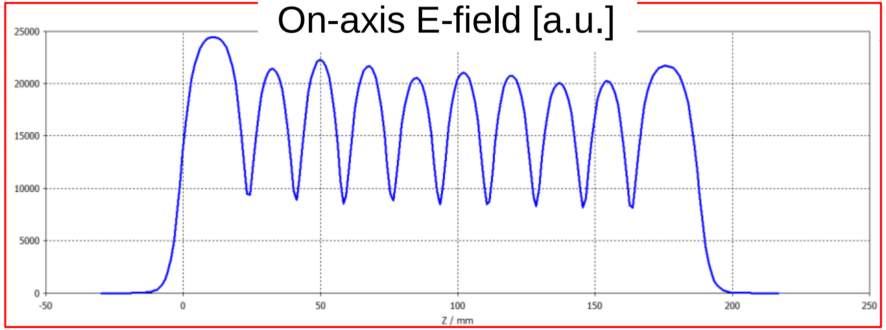
Prototyping phase 2

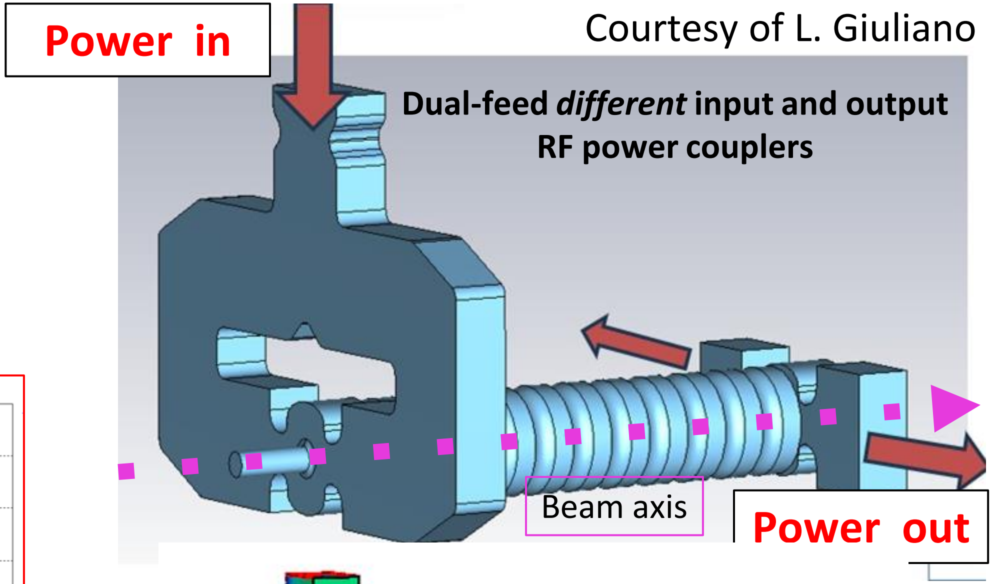
Single Cell design

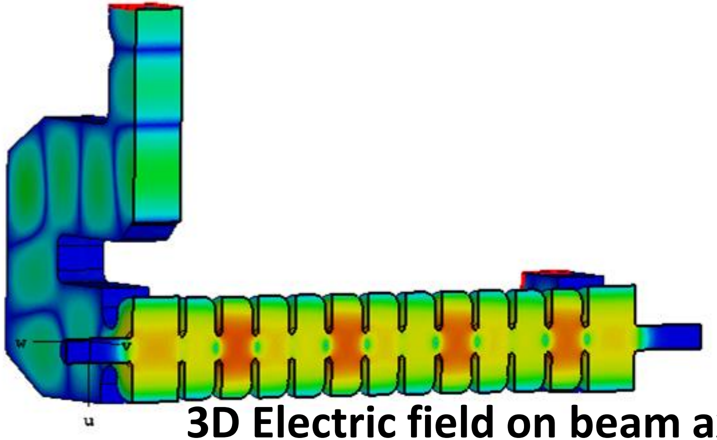


Asymmetric cell to facilitate in-house mechanical processing.

a	b	d	R0	t	r_1/r_2
5	21.03	17.5	6	3	1.25





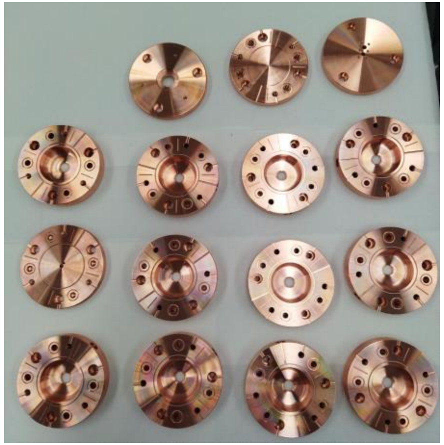


3D Electric field on beam axis

- Operating RF frequency: fRF = **5.712 GHz in C-band;**
- Operating mode: TM010-like with 2π/3 cell-to-cell phase advance;
- **TW Constant Impedance**: Iris aperture radius a = 5 mm;

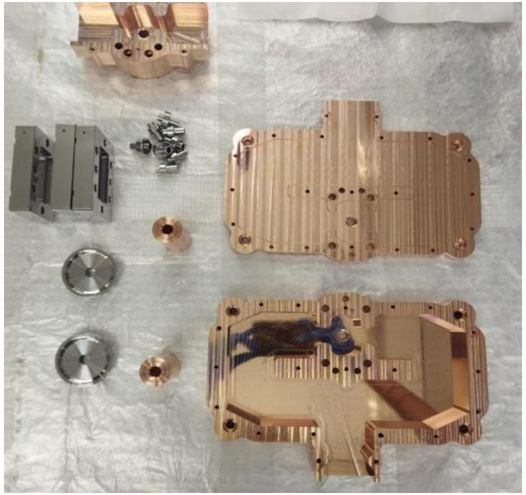
Prototyping phase 2

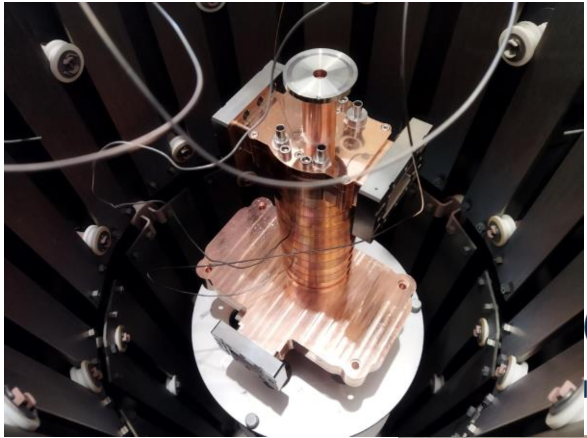
A prototype of 12 cells with couplers has been **brazed** @INFN LNF –FRASCATI oven to perform low-power RF tests.



In house building of the accelerating cavities

FLASH Radiotherapy with hIgh Dose-rate particle beAms

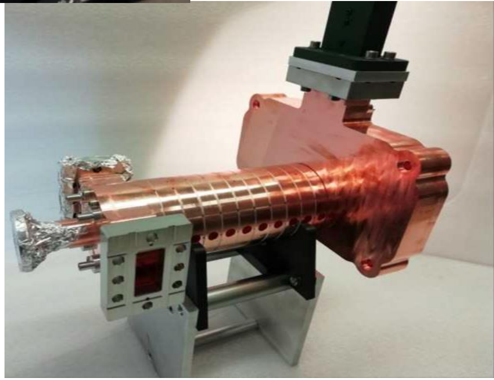




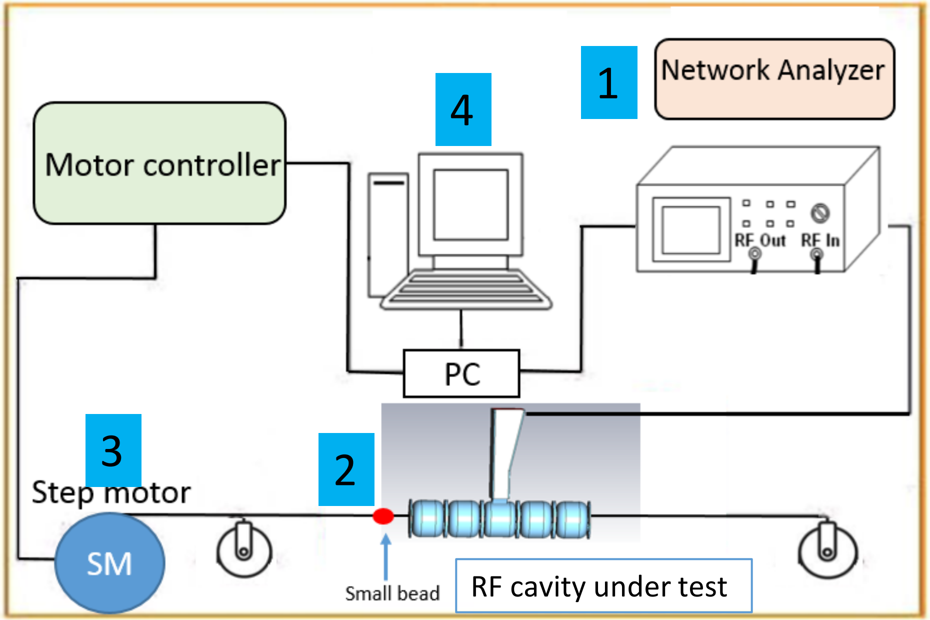
Structure in the INFN LNF – brazed in FRASCATI oven

INFN LNF
Istituto Nazionale di Fisica Nucleare

Main contributors: D. Alesini, **R. Di Raddo**, L. Faillace, L. Giuliano, **M. Magi**, M. Migliorati

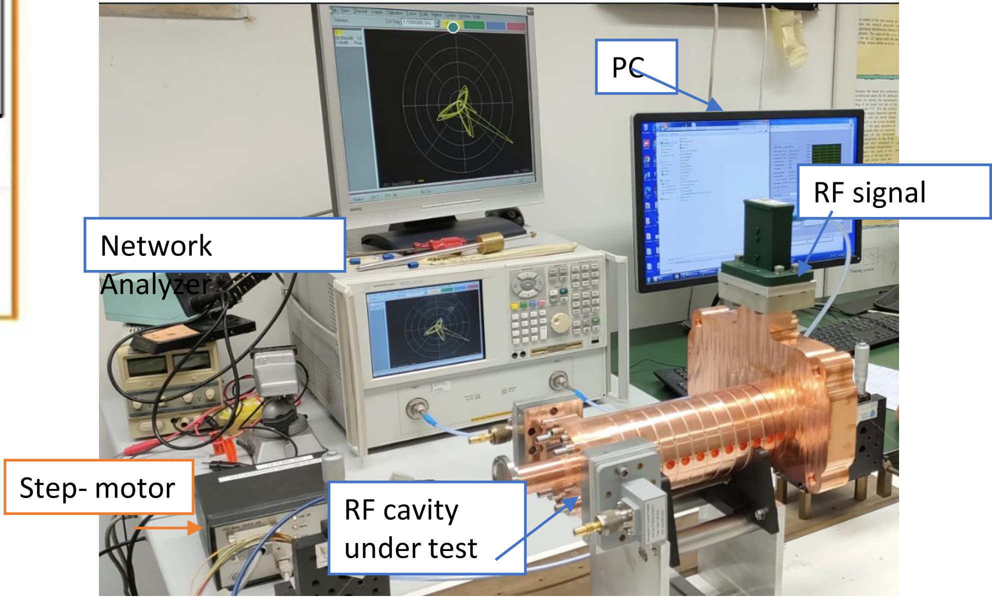


Measurement of electric field with "bead-pull" @ Sapienza



1. A Radio Frequency (RF) signal is applied by the Network Analyzer (VNA)

2. A perturbing object (glue bead) is attached to a horizontal fish wire.



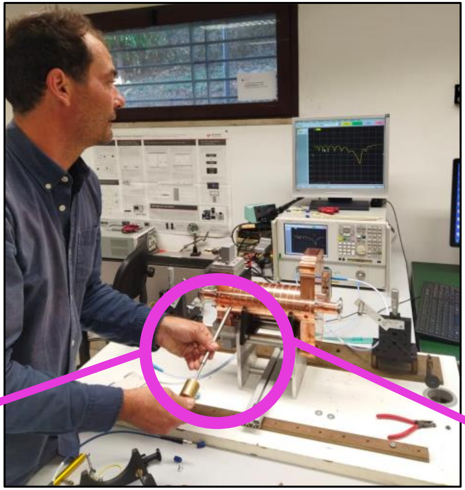
3. Using a step-by-step motor, the wire goes through the structure and measures the electric field perturbations caused by the bead.

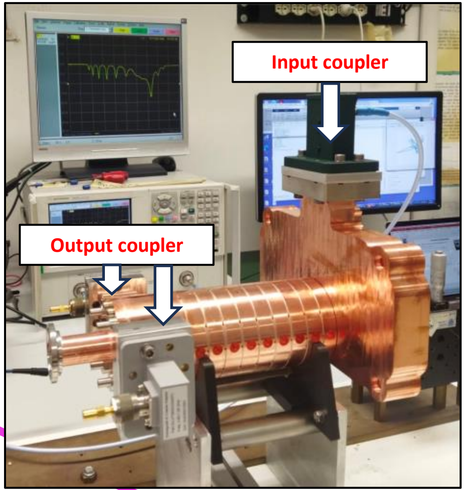
4. All the data are stored in a PC

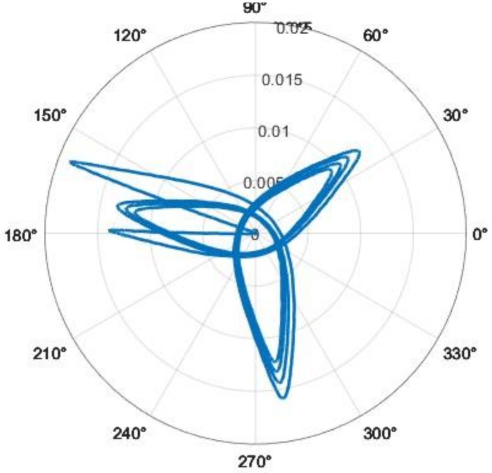
BeadPull measurements after tuning

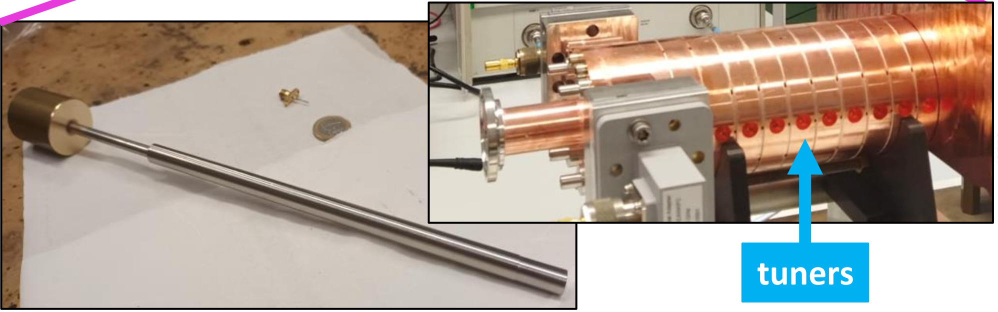
- After tuning the structure presents a average phase advance is 120,38° , the petals are superimposed in the RF phase diagram
- The electric field presented still a stationary pattern: final coupler needed to be tuned

Tuning by deformation

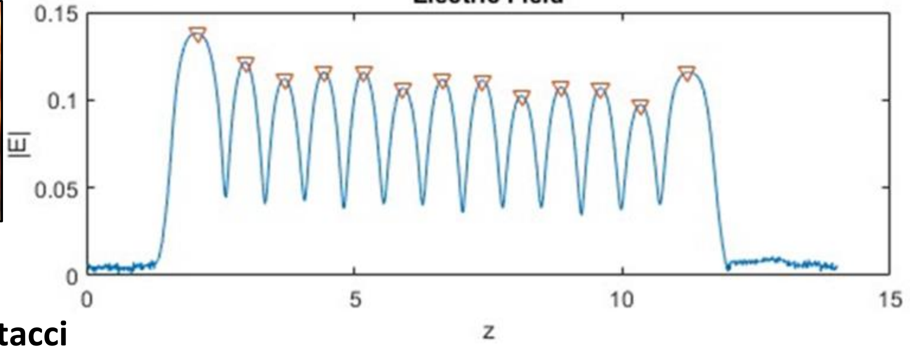








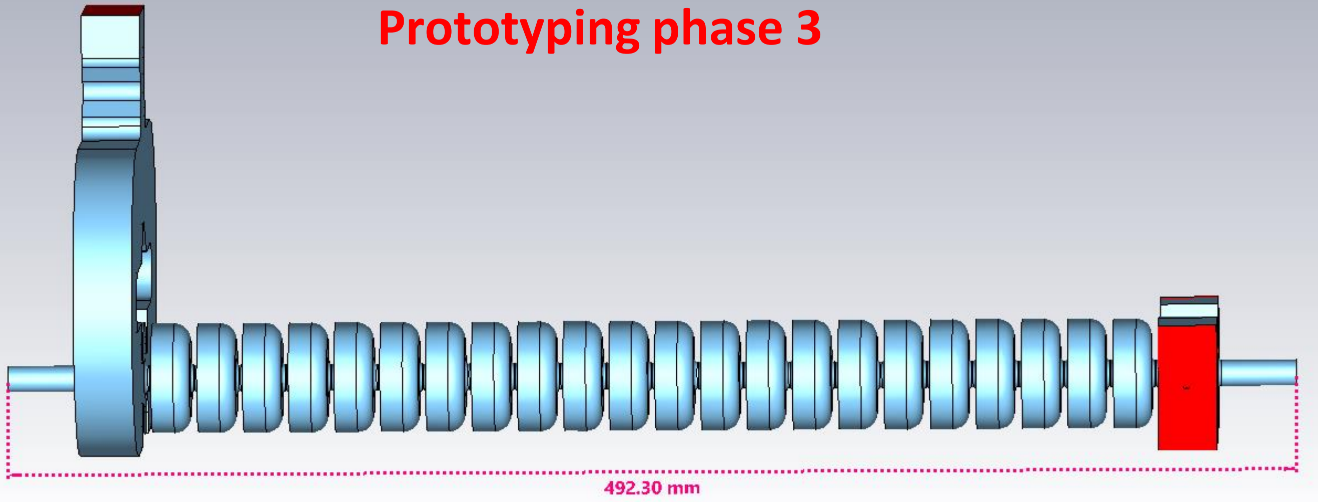
Electric Field



L. Giuliano, F. Cardelli, D. Alesini, L.Faillace, **L.Ficcadenti A. Mostacci**

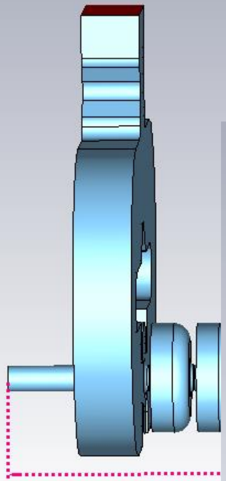
Prototyping phase 3

Courtesy of L. Giuliano

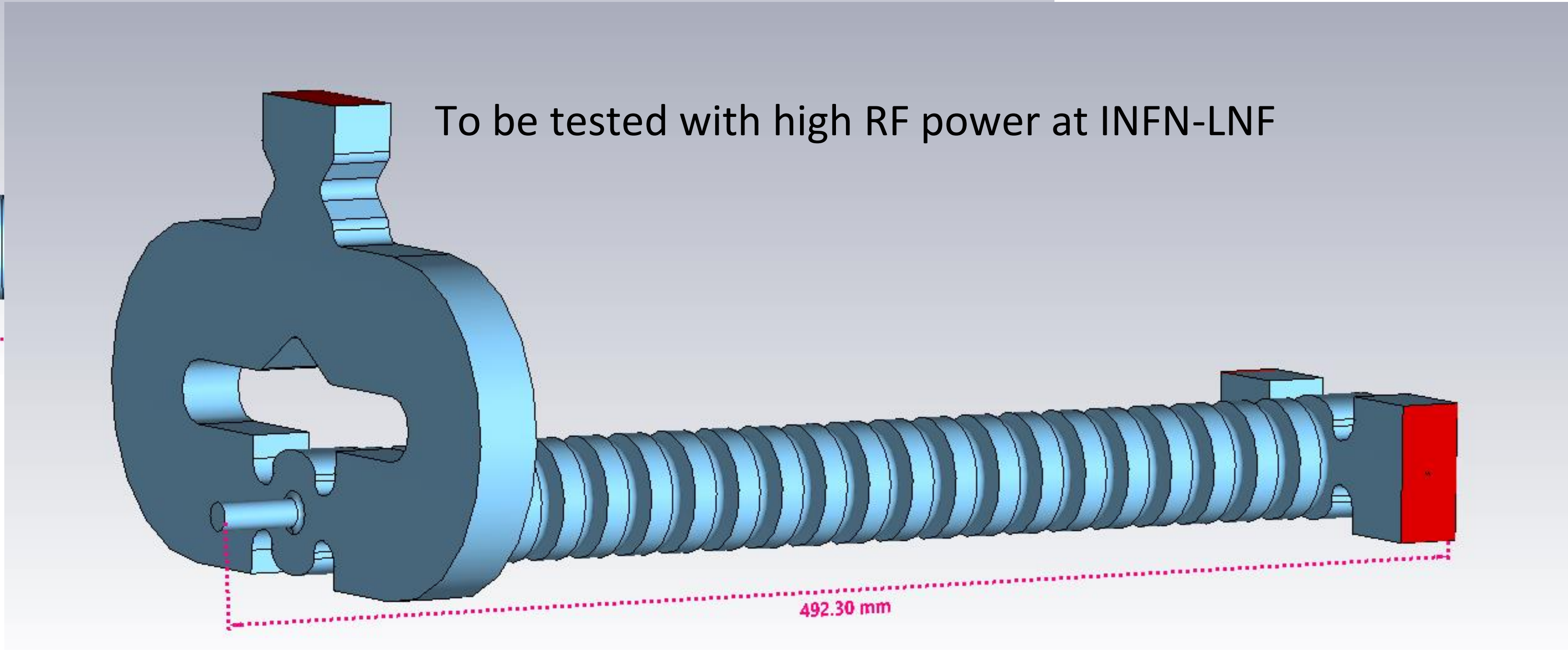


Prototyping phase 3

Courtesy of L. Giuliano

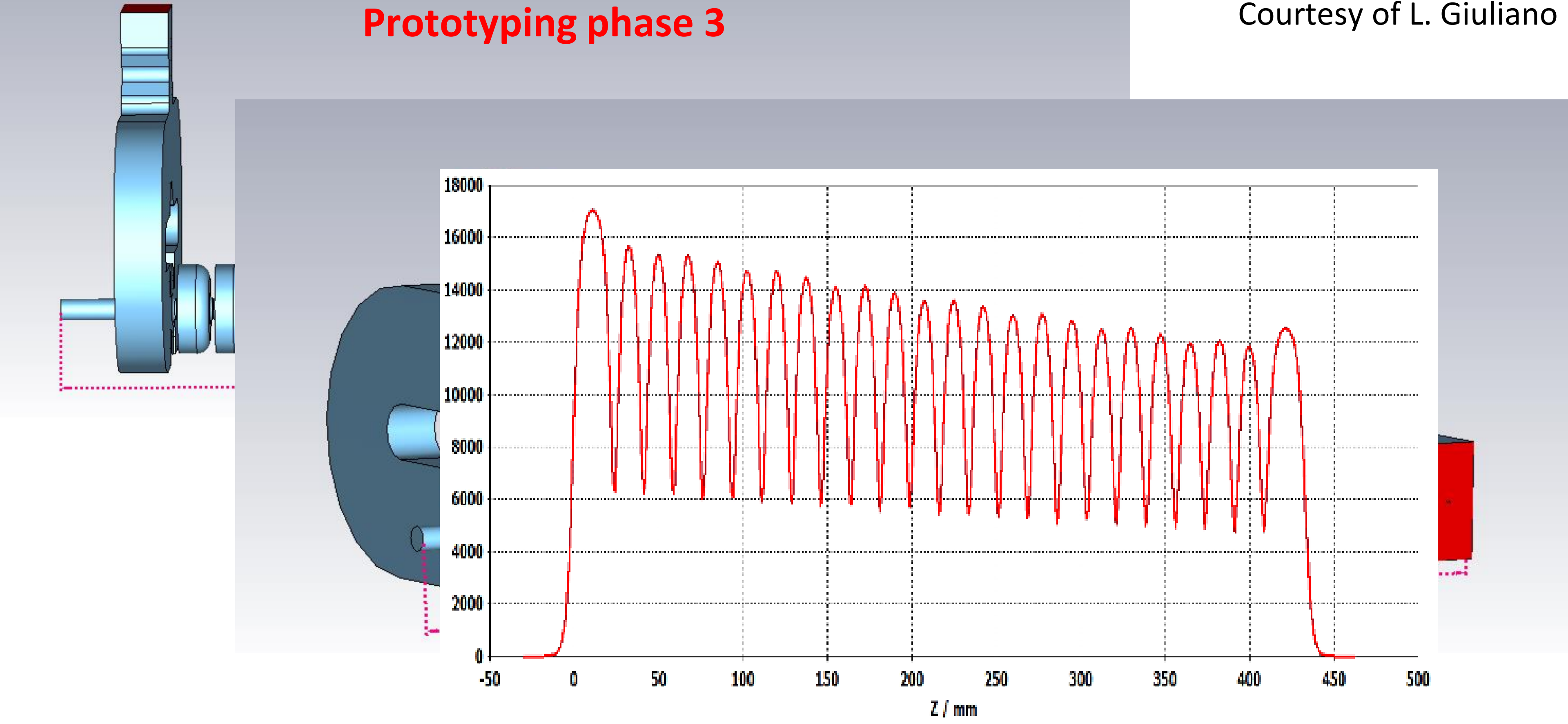


To be tested with high RF power at INFN-LNF



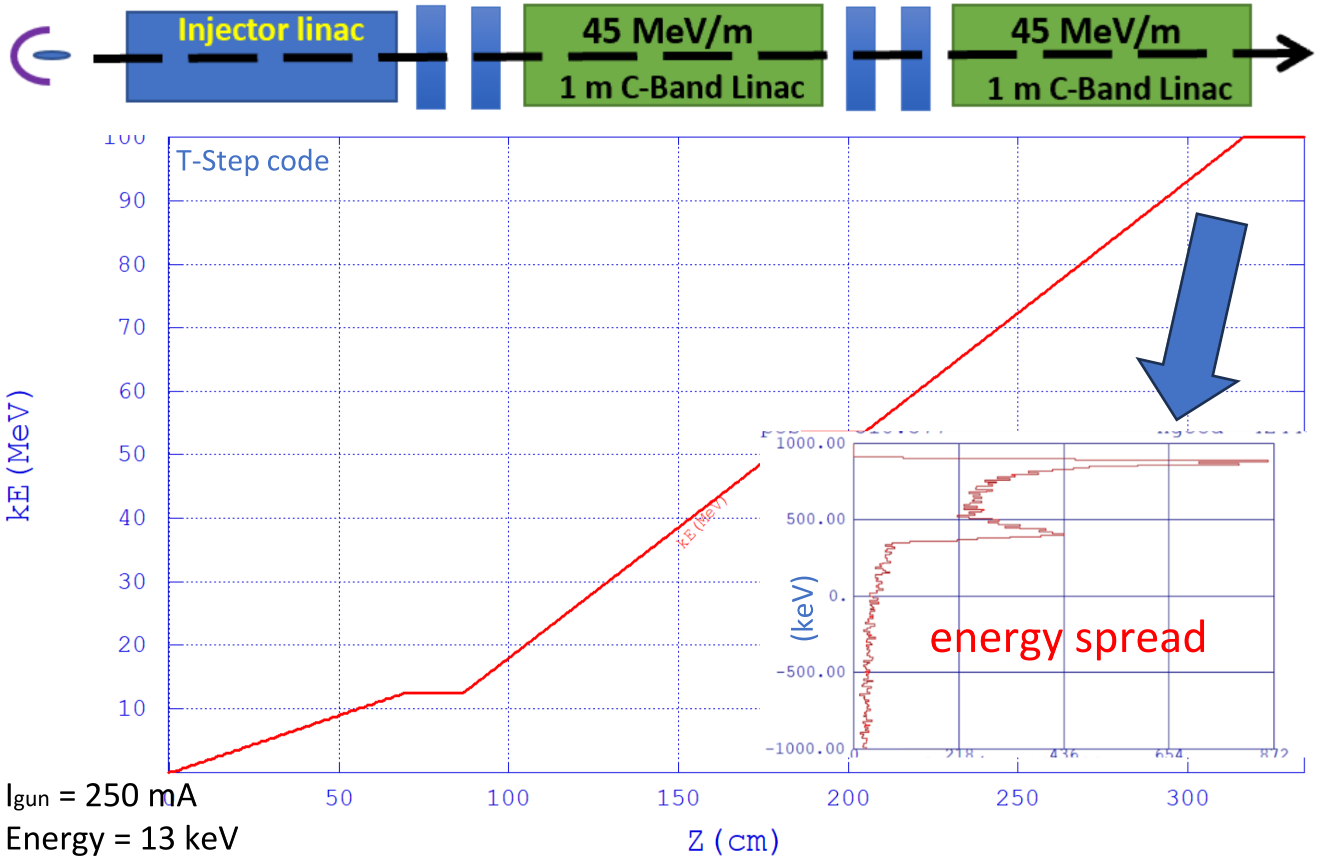
Prototyping phase 3

Courtesy of L. Giuliano



3D Electric field on beam axis

Beam Dynamics for the SAFEST project (100MeV nominal case)
Energy gain and beam transport

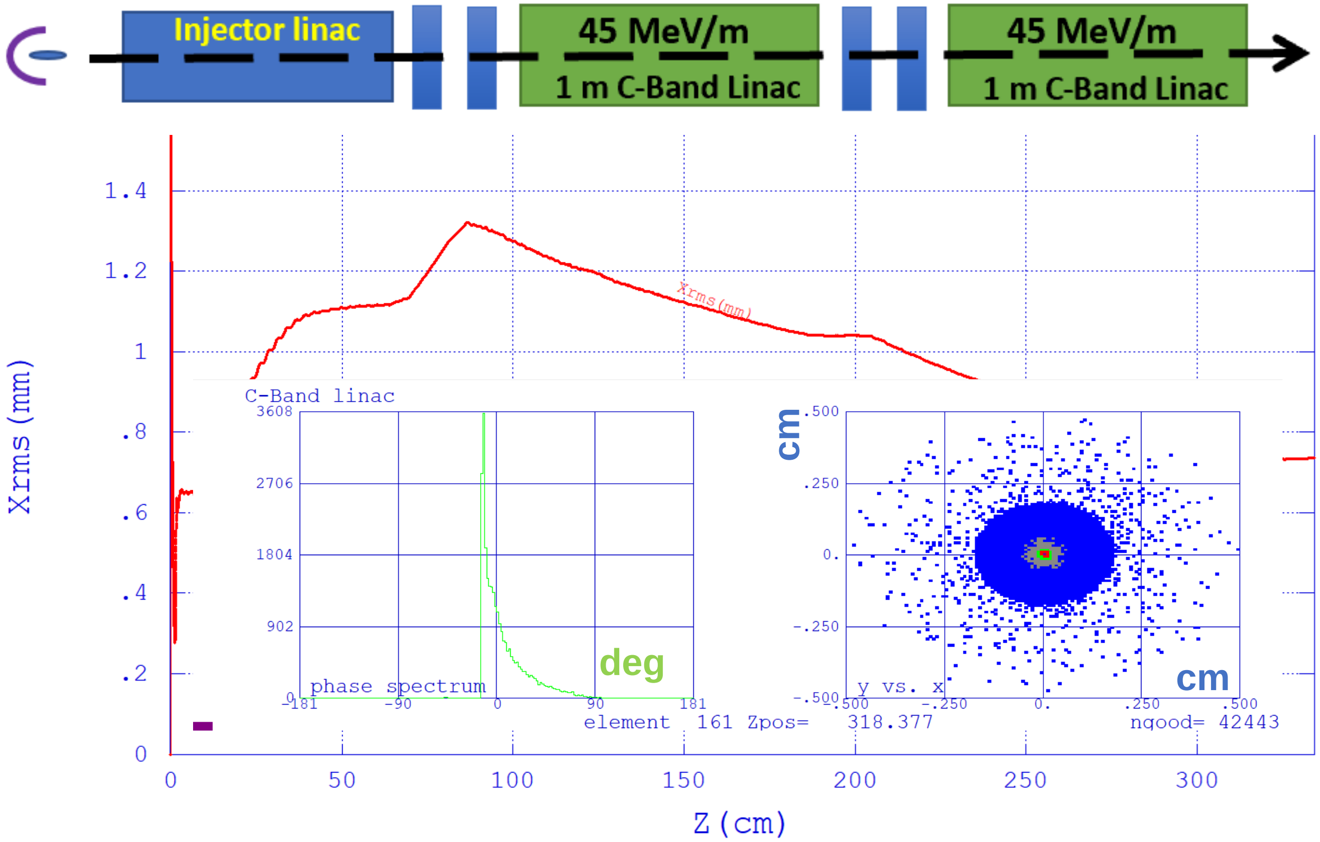


I_{gun} = 250 mA
Energy = 13 keV

- Output e-beam 100 MeV and 100 mA output e-beam;
- Input e-gun current = 250 mA;
- No focusing solenoids needed;
- Total beam capture ~40%;
- Lost e-current evaluated with FLUKA for required radiosafety protocols;

Very low energy spread
500 keV @ 100 MeV

Beam Dynamics for the SAFEST project (100MeV nominal case)
Beam envelope



- The high-gradient linacs induce beam RF focusing in order to confine the beam without the use of solenoids.
- The linac exit is located at about 320 cm.
- The beam transverse RMS size is about $\sigma_{x,y}$ = 0.7 mm at linac exit.

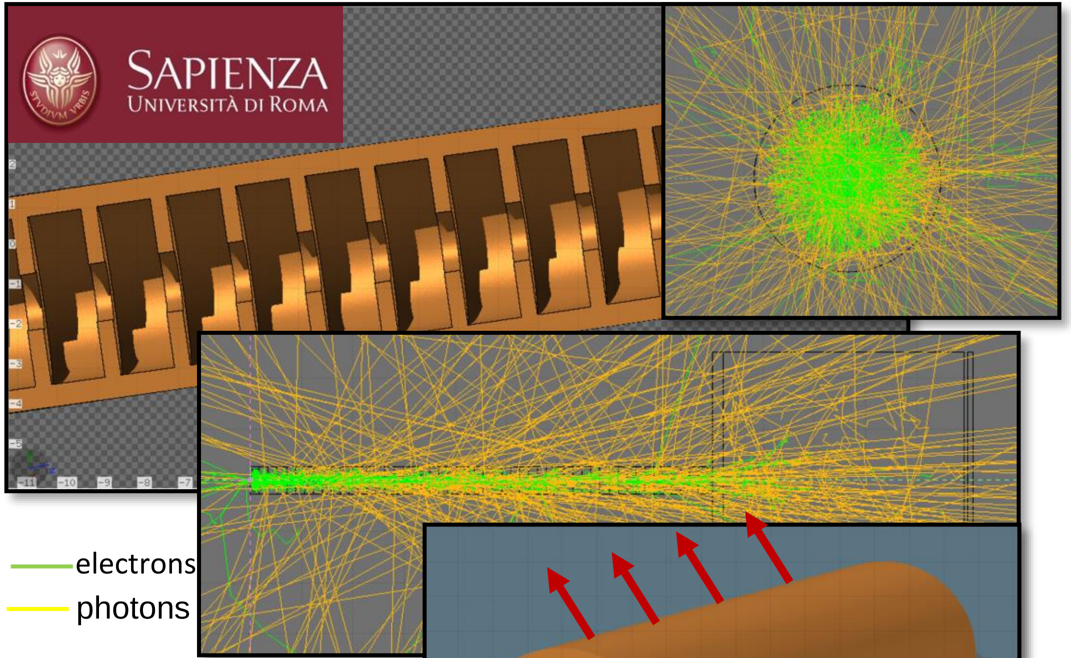
RADIOPROTECTION STUDIES

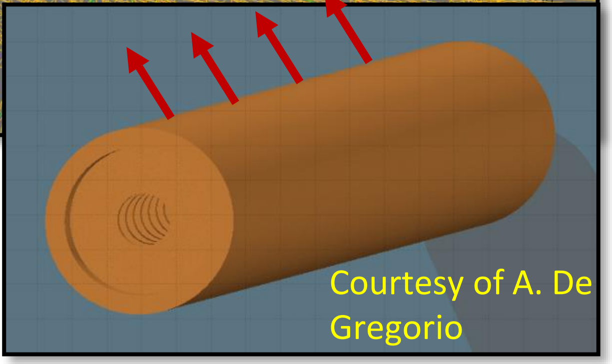
- A proper evaluation of the radiation background induced by such machine has a crucial importance in order to put the realization effort on a solid ground;

1. The first step was to reproduce the geometry of the accelerator in FLUKA, both for the injector and the first accelerating section.

2. From the beam dynamics simulations, we extracted all the electrons exiting the beam pipe, which interact with the external material of the accelerator (copper), thus inducing a scattered flux.

3. We simulated and propagated the outgoing particles (and their respective interactions) using FLUKA, and from these, we calculated dose and fluence.





Dose in air
$2.886\, 10^{-6} \frac{GeV}{g} /primary$

200 mA and 3 µs pulse →

$3.75 \ * 10^{12}$ primary electrons

Dose in air
$\mathbf{172\ mGy}$

No confinement issues → recipe for bunker design

Conclusions and Future Work

- We are working on a VHEE linac for next generation FLASH with electrons in the framework of the Sapienza-INFN collaboration: the ***SAFEST*** project;
- The new linac is based on C-Band System which is compact: large energy range (60 – 130 MeV, **100 MeV** Nominal) in small footprint to be installed at Sapienza, including experimental hutches for dosimetry, radiobiology and preclinics;
- Initial RF parameters analysis and design as well as Beam Dynamics Simulations of the VHEE C-Band show promising results for trasport of high-current electron beams (**100 mA** per RF pulse);
- Further BBU and Beam-loading analyses are in-progress;
- The C-band linac prototype was fabricated, brazing in-progess, soon to be high-power tested at INFN-LNF.
- Bunker for low-energy accelerator Lab (24 MeV) for testing of basic VHEE prototypes is being built (6m x 3m) at Sapienza University.

Thanks for your attention!


New horizon in
therapy & treatment
FRPT
FLASH
RADIOTHERAPY
& PARTICLE
THERAPY
2024
ROME, ITALY
4-6 DECEMBER 2024
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Radioterapia e Oncologia clinica
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