High-gradient C-band linacs for a VHEE-FLASH radiotherapy facility

L. Faillace, D. Alesini, G. Bisogni, F. Bosco, M. Carillo, P. Cirrone, G. Cuttone, D. De Arcangelis, F. Di Martino, L. Ficcadenti, D. Francescone, G. Franciosini, A. Gallo, L. Giuliano, M. Migliorati, A. Mostacci, L. Palumbo, V. Patera, J. Pensavalle, A. Sarti, B. Spataro, G. Torrisi, A. Vannozzi

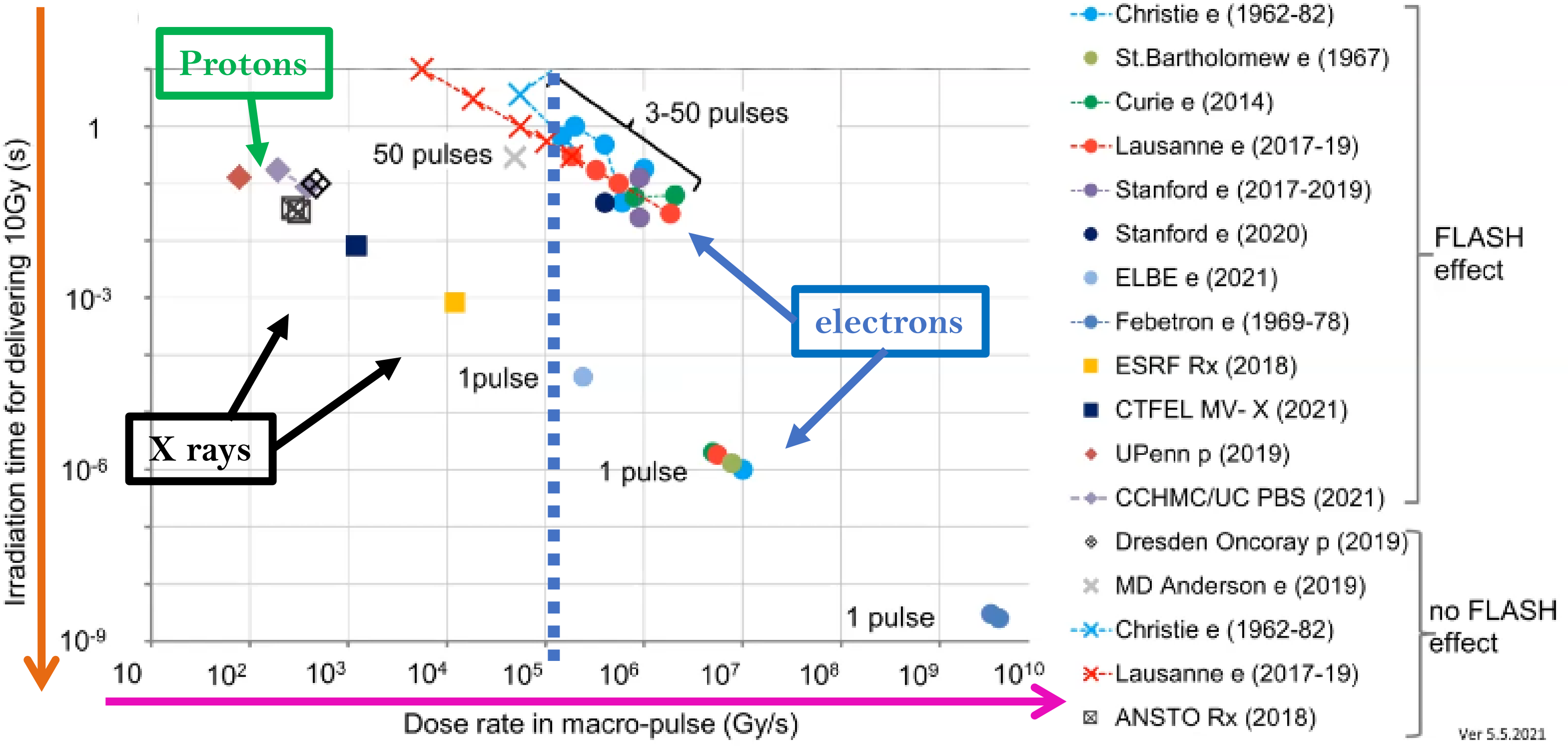
V. Favaudon, S. Henrich, A. Patriarca (Institut Curie)

14th workshop on breakdown science and high gradient technology, HG2022 May 16-19, 2022

VHEE-LINAC FLASH-RT Research Laboratory

- Sapienza University and INFN Collaboration;
- Creation of a Research Laboratory dedicated to Very High Energy Electrons (VHEE) FLASH;
- Installation of the new linac at Sapienza, near main campus, for Dosimetry, Radiobiology and Pre-clinical FLASH Experiments;
- Compact C-Band System at 5.712 GHz (decade long experience, high electron beam energies in small footprint)

Conditions to hit or miss the FLASH effect

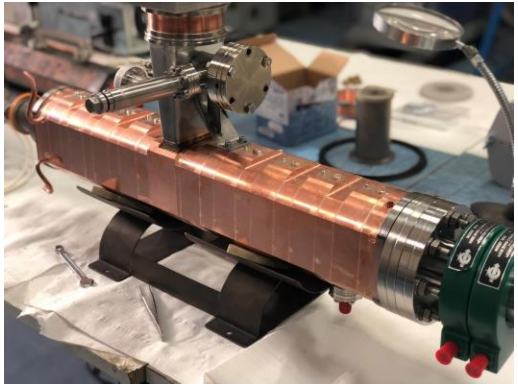


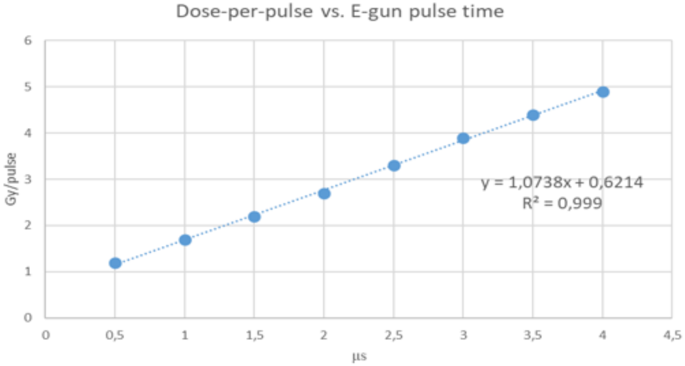
- **Highest dose rate in the pulse,**
- **Shortest irradiation time < 100 ms,**

highest is the FLASH effect.

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.





 # Publication to be submitted to Physica Medica

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]

- **The next target of this team is the development of compact VHEE demonstrator.**

Electron Beam Parameters of the new VHEE-Linac

institutCurie	Description	Measured Value
E	Beam Energy	7 MeV
f	RF frequency	2.998 GHz
PRF	Pulse repetition frequency	> 100 Hz
t_p	Pulse width	1 - 4 µs
Q_p	Pulse Charge	500 nC
I_p	Pulse Current	125 mA
D_p	Dose in a single pulse	20 Gy*
$\dot{D}_p$	In-Pulse Dose-Rate	$> 10^7$ Gy/s

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

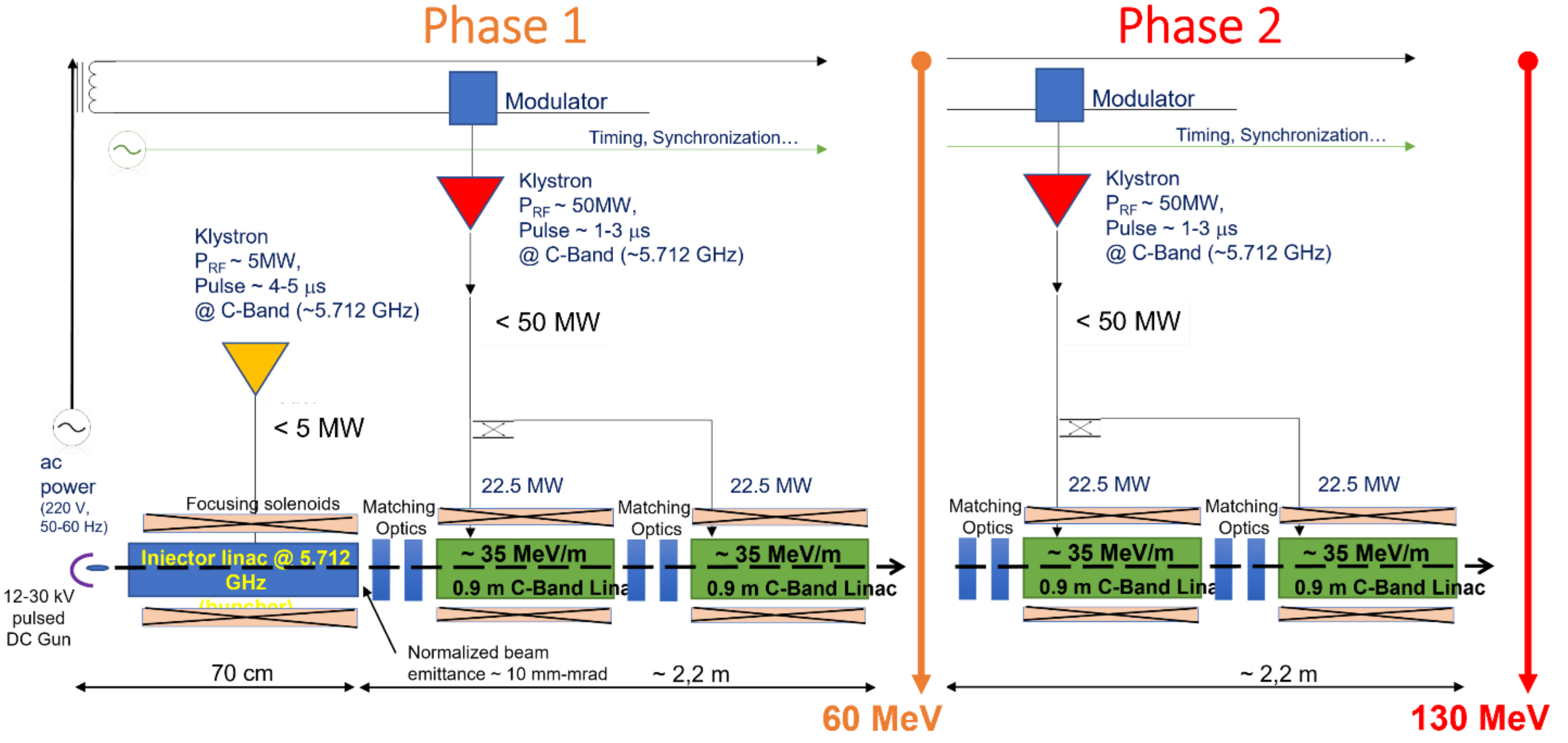
VHEE LINAC

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

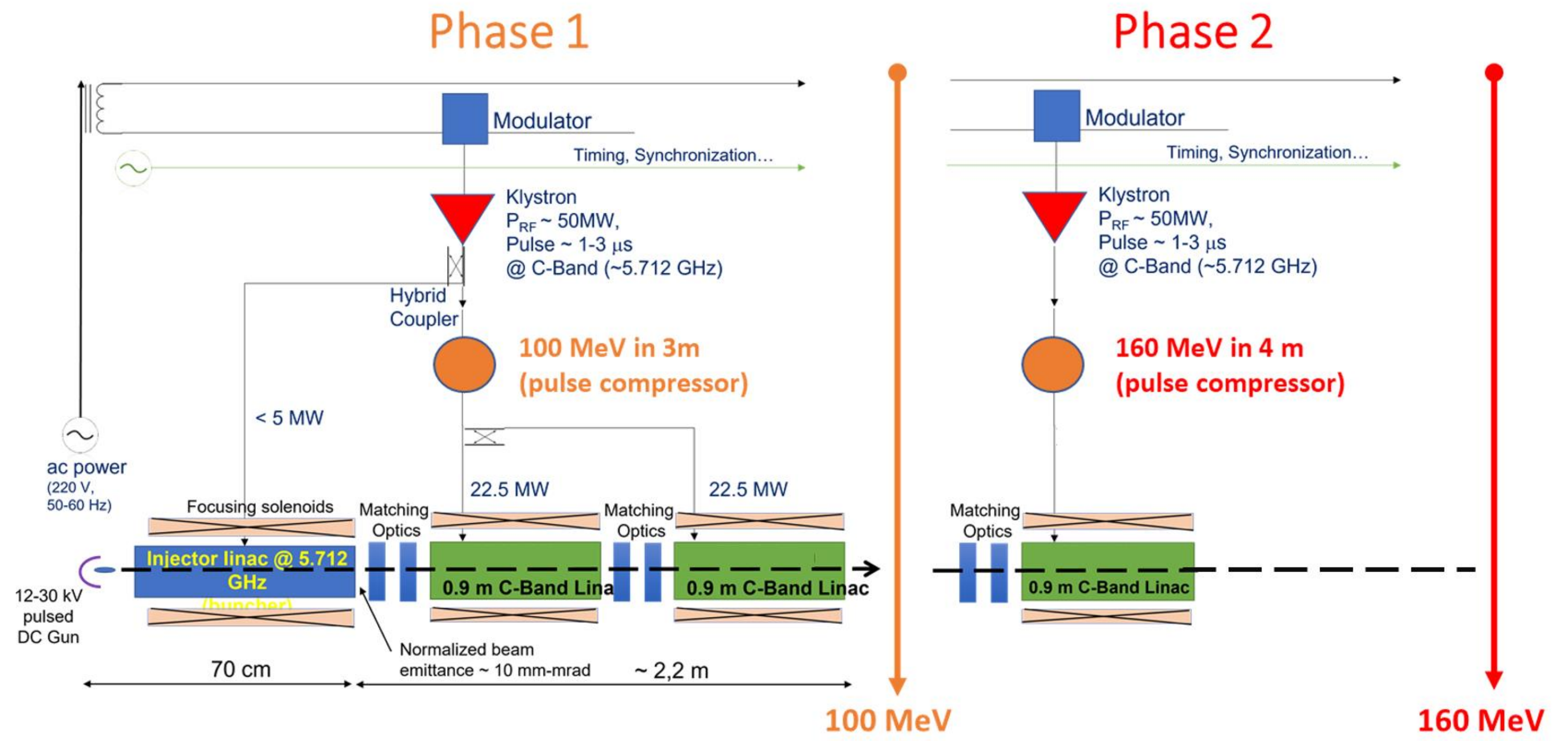
- Explore the FLASH effect both in the fixed field and pencil beam case;
- Beam intensity modulation: Pulse-to-pulse and intra-pulse;

 # Publication recently submitted to Physica Medica

VHEE Linac Layout

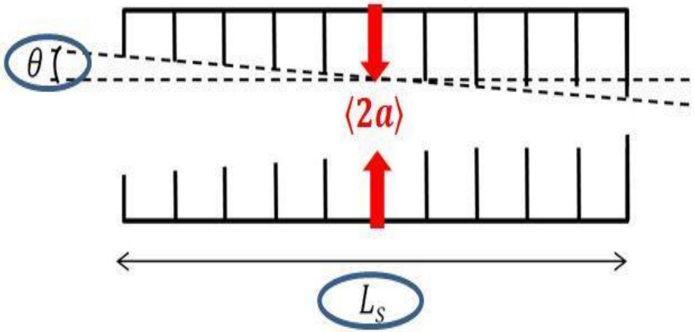


VHEE Linac Layout

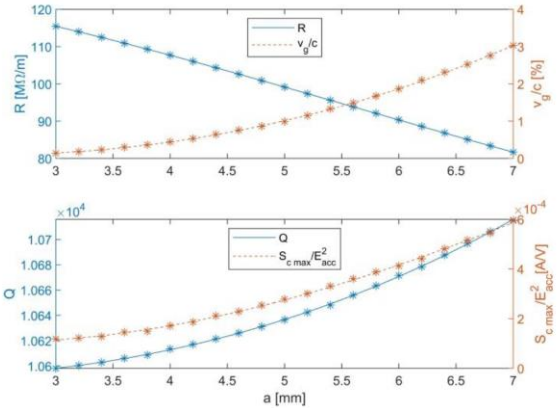


High-gradient Accelerating Structure Design Options

- Operating RF frequency: F_{rf} = 5.712 GHz in C-band;
- Operating mode: TM_{010}-like with $2\pi/3$ cell-to-cell phase advance;
- TW Constant Impedance (TW-CI) structure and a TW Constant Gradient (TW-CG) structure were simulated;
- Iris aperture radius “a” varied in the range 3÷7 mm;
- Structure Length. Two options:
  - 1.8 m (experience on ex-ELI project)
  - 0.9 m (easier handling for machining and brazing, vacuum pressure, **modularity**) → **MAX power/section ≈ 22.5 MW**

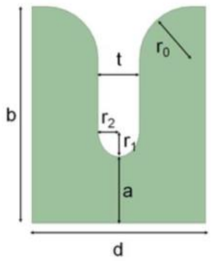


The possibility of using pulse compressors is work in-progress and NOT considered in this presentation.

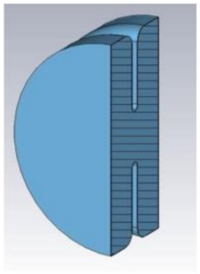


(a): Main parameter

Initial single cell RF parameters simulations



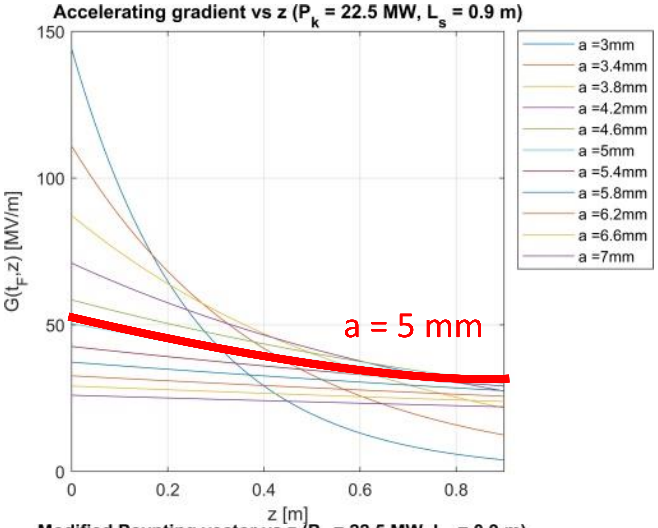
(b): Side sketch

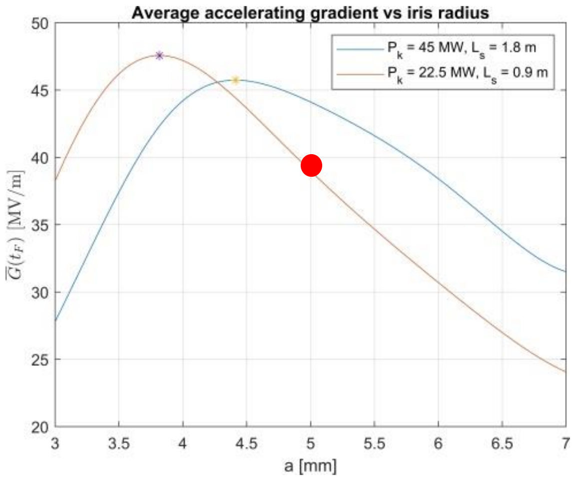


(c): Perspective view

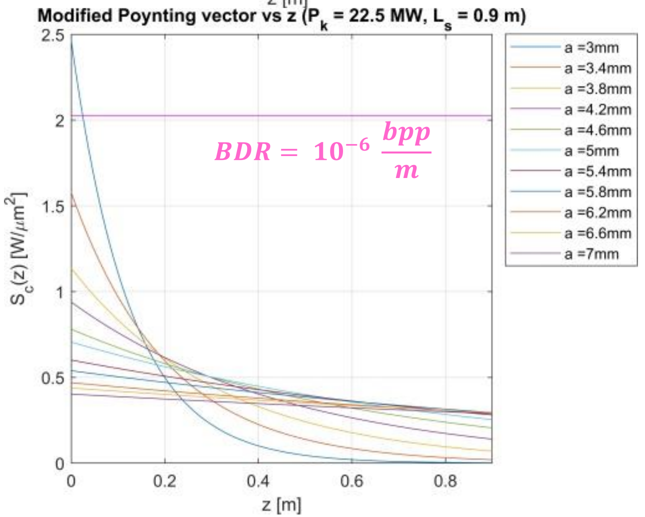
TW Constant Impedance Structure

- Structure length L_S = 90 cm;
- Average gradient for optimum $\mathrm{a} = 3.8\ \mathrm{mm}$ is equal to $\bar{G}$ = 47 MV/m, with an RF input power of P_{rf} = 22.5 MW;
- the gradient is not uniform within the structure, except in the case of irises with $\mathrm{a} \geq 6\ \mathrm{mm}$;
- Modified Poynting vector S_c below threshold of 2 MW/mm^2 (BDR = 10^{-6} bpp/m and RF pulse = 3 μs);
- Filling time t_F is about 0.75 μs, compatible with the 3 μs of the klystron pulse duration.



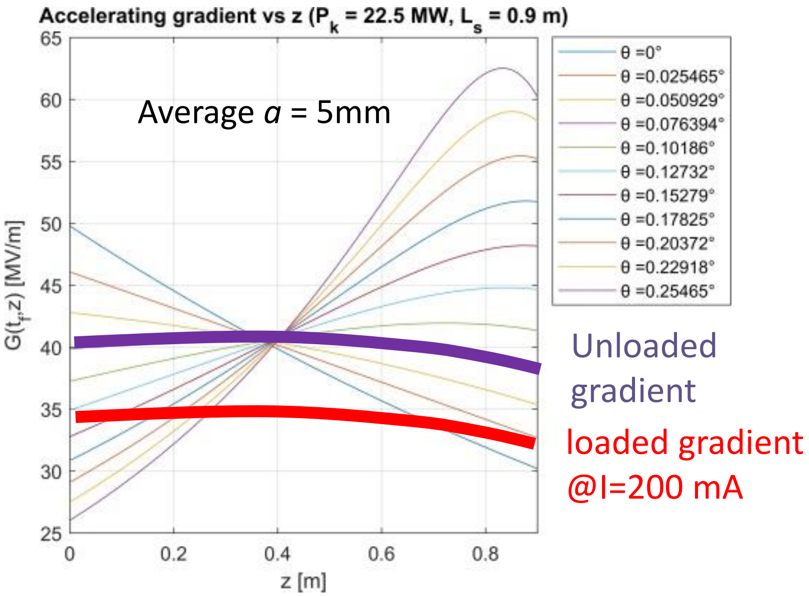


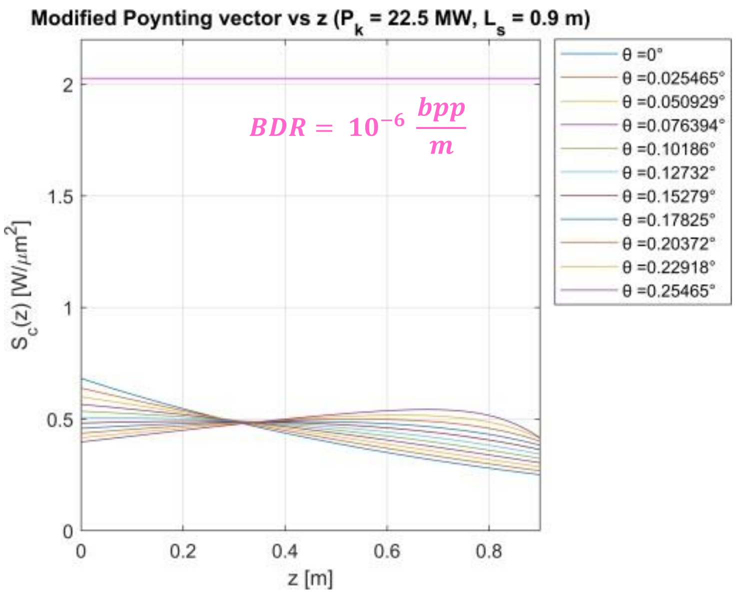
Iris radius Choice:
a = 5 mm
(short-range wakefields, BBU,...)



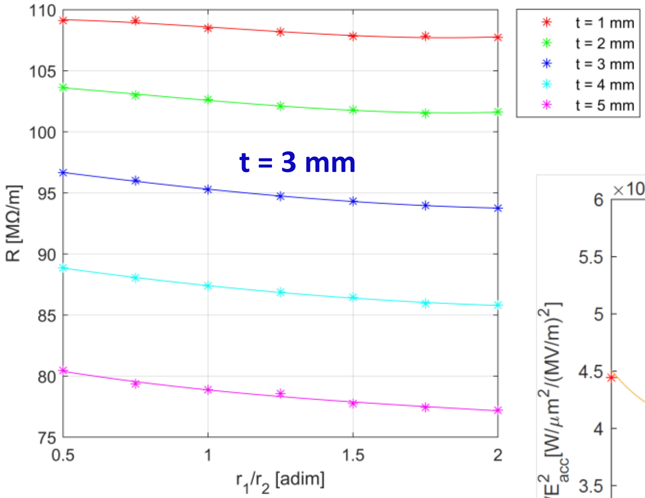
TW Constant Gradient Structure

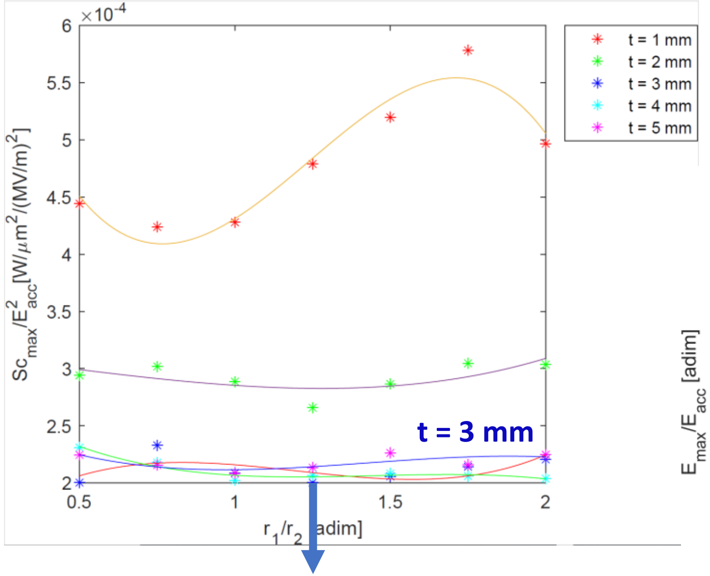
- Average iris aperture radius a = 5 mm;
- Constant G = 40 MV/m for a tapering angle $\theta = 0.076°$;
- Modified Poynting vector S_c below threshold of 2 MW/mm^2 (BDR = 10-6 bpp/m and RF pulse = 3 μs);
- the filling time t_F range is 300 – 500 ns, for a tapering angle $\theta < 0.25°$.



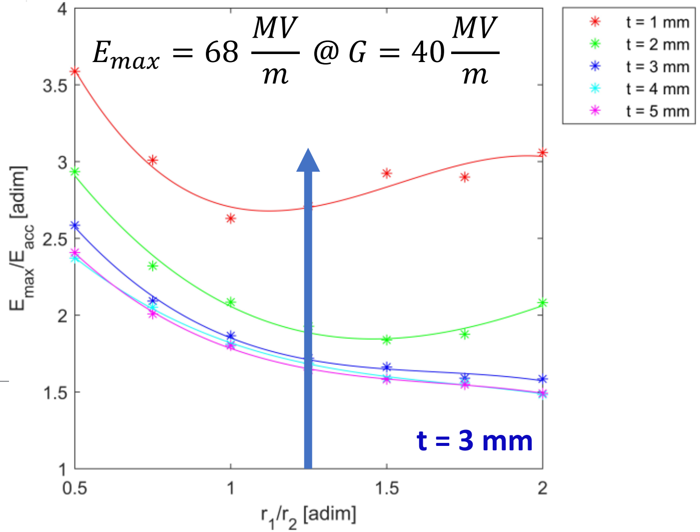


VHEE Linac – Cell Profile Optimization



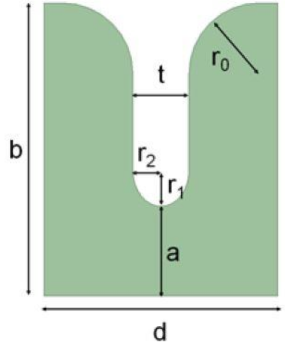


$$S_{c,\,max} = 0.32\,\frac{MW}{mm^2}\ @\ G = 40\,\frac{MV}{m}$$



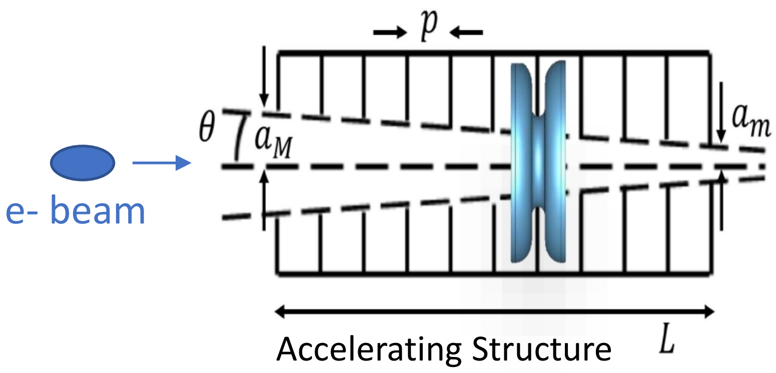
$$E_{max} = 68\,\frac{MV}{m}\ @\ G = 40\,\frac{MV}{m}$$

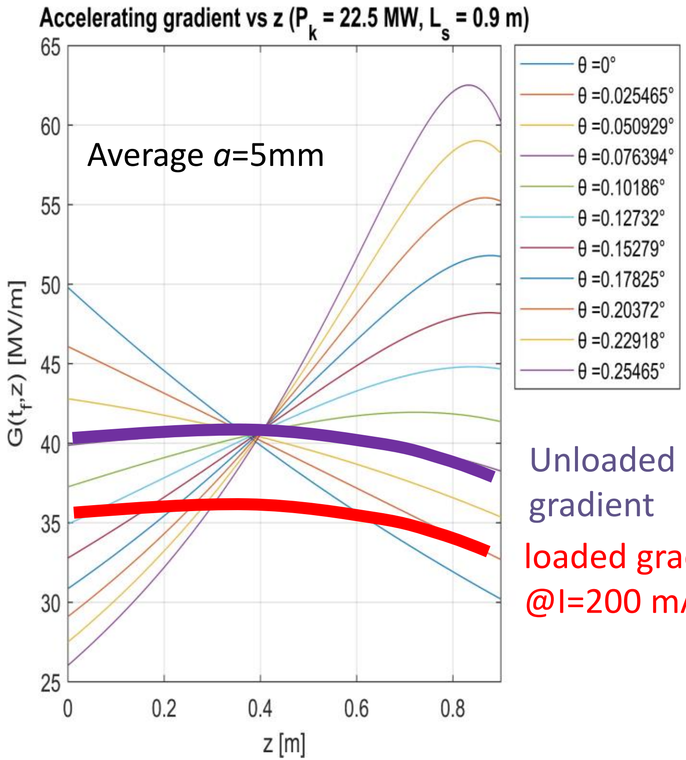
Elliptical iris profile



Choice of main Accelerator structures: Source, Injector and main linacs

- Electron source: pulsed DC thermionic electron gun (e-gun) at 15-30 kV;
- Injector Linac with matching section for low-energy capture and initial acceleration from e-gun up to ≈ 10 MeV;
- High-gradient Linac (5.712 GHz): Traveling-wave RF structure with high accelerating gradient (> **50 MV/m** with pulse compressor).

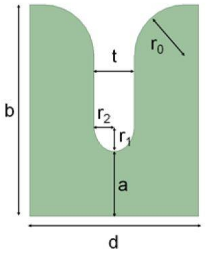




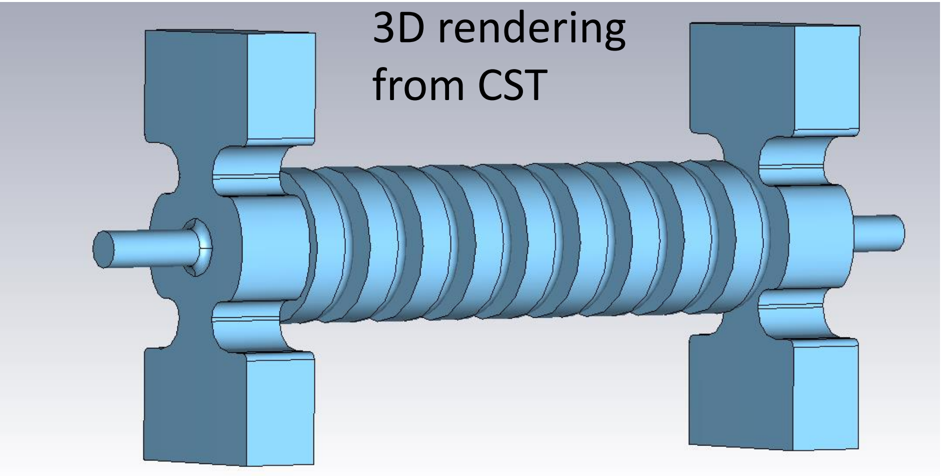
Unloaded gradient

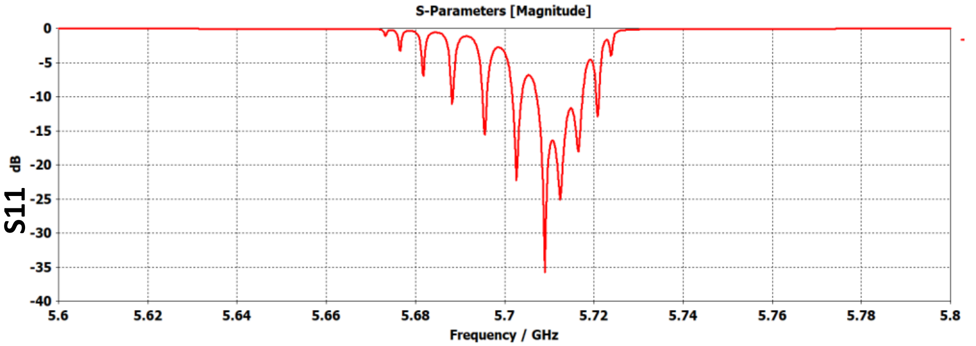
loaded gradient @I=200 mA

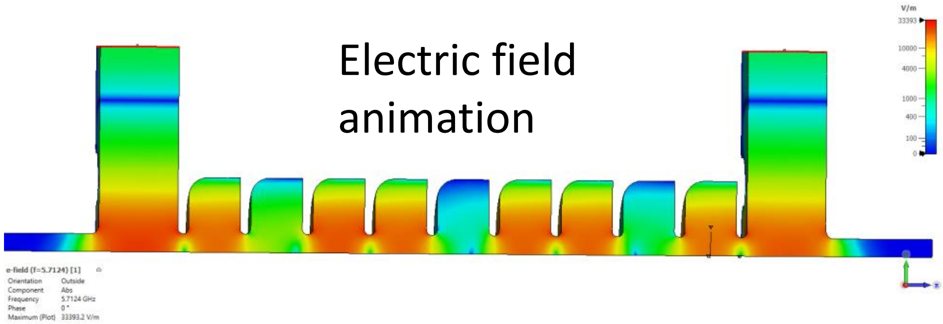
Accelerating cell profile



VHEE C-band Linac – Coupler Optimization

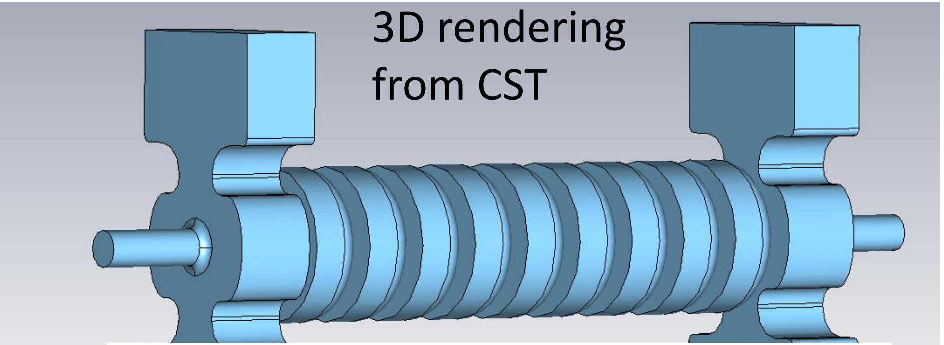




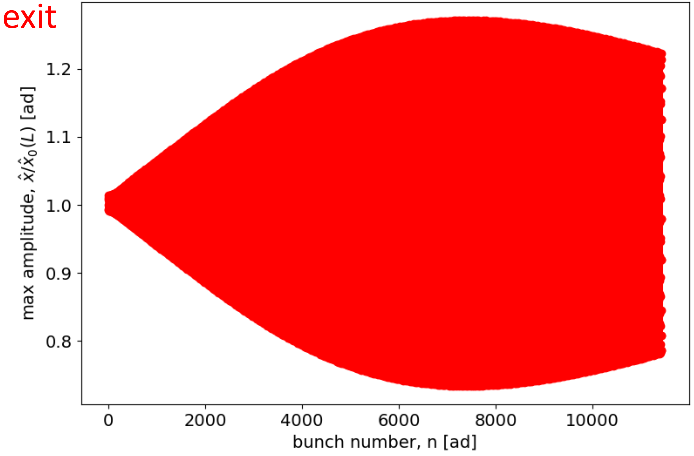


- Dual-feed input and output RF power couplers;
- Racetrack geometry for cancellation of dipole and quadrupole field components;
- Iris aperture radius a = 5 mm;
- Reflection Coefficient S11 = -35 dB at 5.712 GHz;

VHEE C-band Linac – Preliminary BBU Analysis

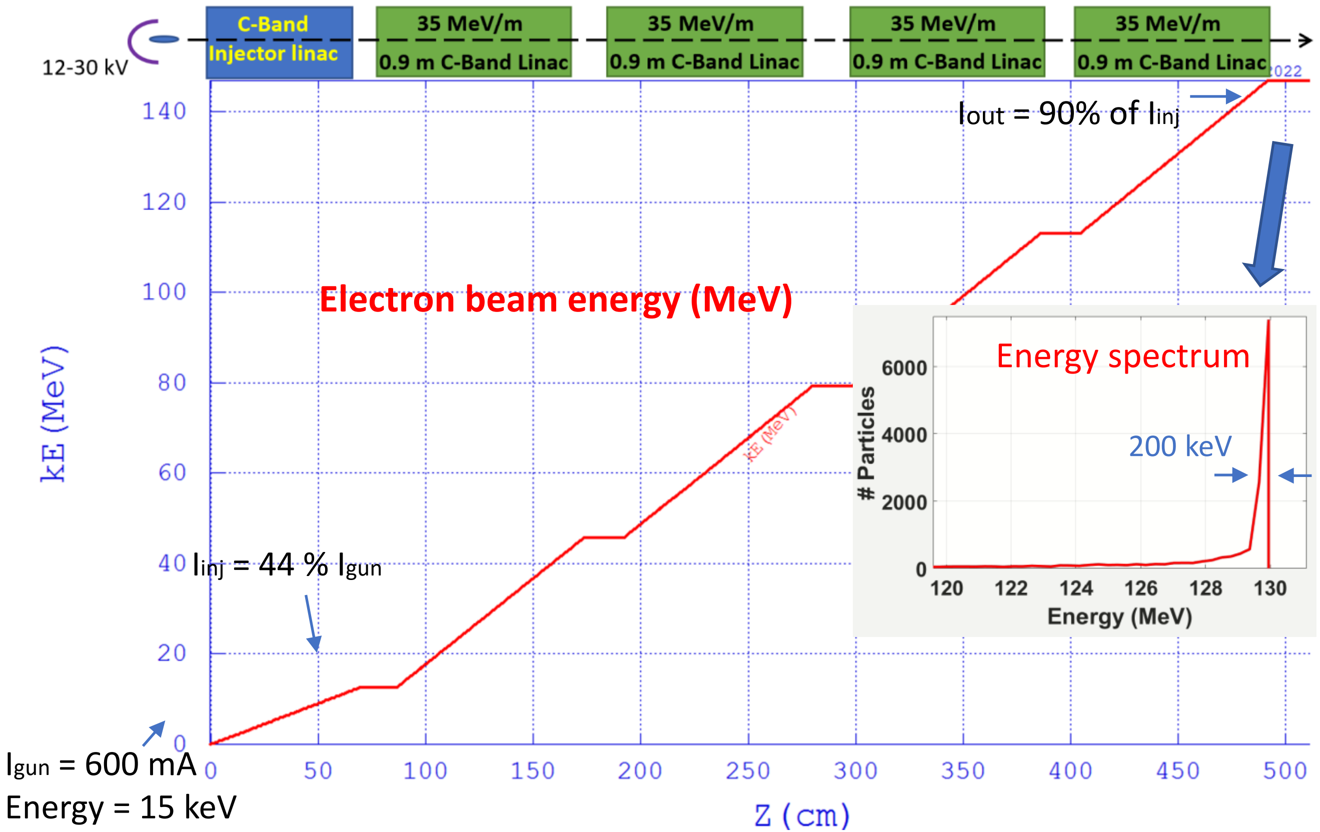


Transverse displacement of each bunch at linac exit



- Code *MILES* by F. Bosco, PhD student, and Prof. M. Migliorati (Sapienza University);
- Maximum pulse current of 200 mA;
- Bunch length = 2 µs;
- Total RF pulse charge = 400 nC;
- Number of bunches = 11424;
- Charge per bunch = 35 pC;
- The entire train of bunches is injected 50 μm off-axis;
- Worst case scenario: constant iris radius a = 3 mm and cell HOMs at same frequencies;
- **The displacement from the linac axis is contained**: bunches subjected to deflection remain close to the nominal trajectory within 20%.

Beam Dynamics for the VHEE-Linac, energy gain and beam trasport



- Output e-beam >130 MeV and 200 mA output e-beam;
- Input e-gun current = 600 mA;
- No focusing solenoids needed;
- Total beam capture ~40%;
- Lost e-current phase-space evaluated for required radiosafety protocols;
- Very low energy spread 200 keV @ 130 MeV

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 new linac is based on C-Band System which is compact: large energy range (60 – 130 MeV up to 160 MeV) in 7m x 12m footprint, 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 (200 mA per RF pulse);
- We are also considering the option with Pulse Compressors for higher gradients;
- Thermal and Mechanical simulations started for the linac prototype testing;
- Further BBU analysis is in-progress;
- Extensive dosimetry and radiosafety simulations are on-going (INFN grant «FRIDA»).

Thanks for your attention!