Development of a linear electron accelerator for FLASH radiotherapy: design and experimental results

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XIV ciclo - PhD school in accelerator physics

Passaggio al III anno

Contents

- The Flash therapy
- 7 Mev **S-band** linac for Flash therapy: study, design and realization
- New geometry and future perspectives: **C –band** structures
- Beam dynamics preliminary studies
- Future studies: dosimetry measurements at Marie Curie Institute (Orsay) and the development of 12 MeV linac C-band accelerator

Flash Therapy

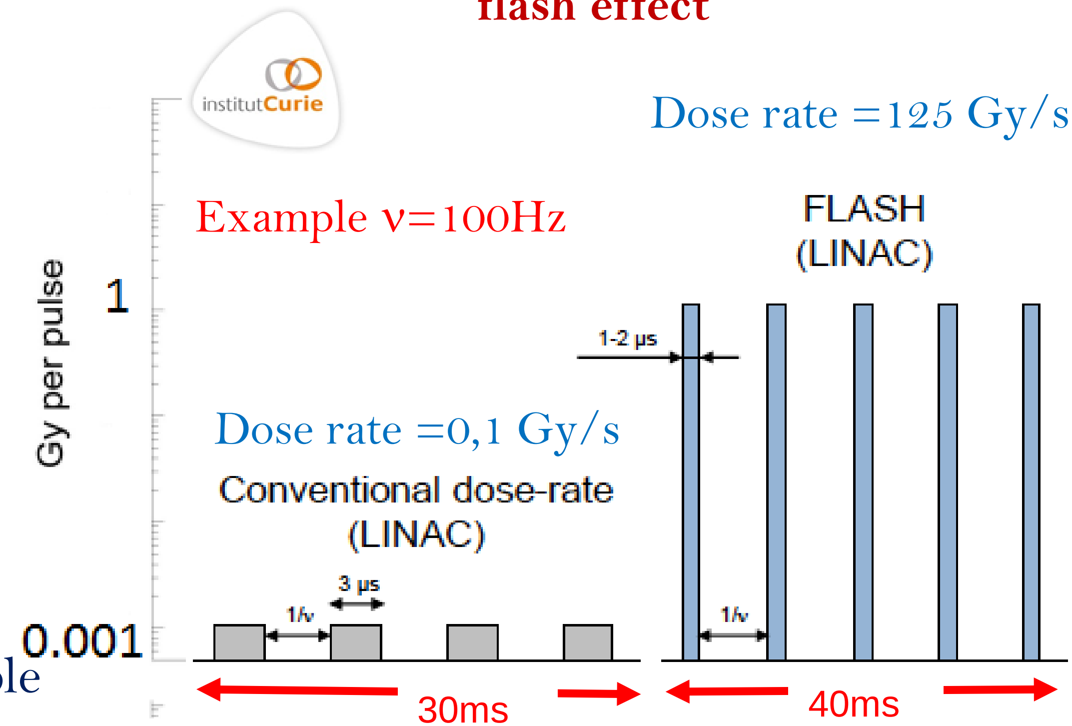
FLASH THERAPY is a new way to deliver the dose:

- μs pulses of radiation,
- beam-on time < 100-500ms
- high dose per pulse

FLASH EFFECT is the improvement of the healthy tissue tolerance to the delivered dose.

The FLASH therapy makes possible to deliver higher dose rate (>40-100Gy/s).

Temporal structure of energy deposition in the flash effect



For a given dose FLASH irradiation time is over 1000 times shorter than conventional treatments.

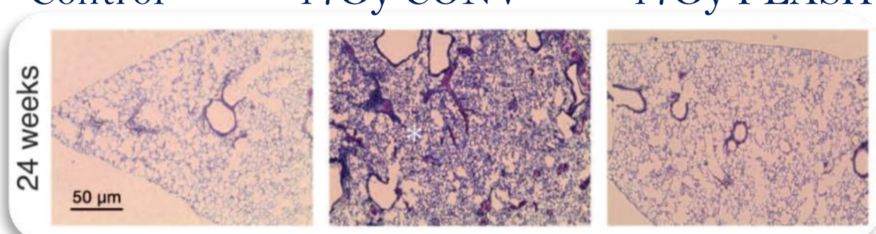
Courtesy of Vincent Favaudon- Curie Institute

Flash therapy in mice: first experiment

	γ-rays	electrons
Facility	^{137}Cs irradiator	LINAC
Nominal energy (MeV)	0,66	4,5
Pulse vs continuous	Continuous	Pulsed
Pulse repetition frequency (Hz)	-	150 Hz
Dose (Gy)	17	17
Mean Dose rate (Gy/s)	0,03	60
Temporal width of pulse	few µs	1 µs

FLASH irradiation protects lungs from radiation-induced fibrosis and is as efficient as **CONV** irradiation in the repression of tumor growth

Control 17Gy CONV 17Gy FLASH



Healthy **Fibrosis** **Healthy**

Favaudon et al., "Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumour tissue in mice", Science Translational Medicine 6, 2014

Flash therapy in mice: first experiment

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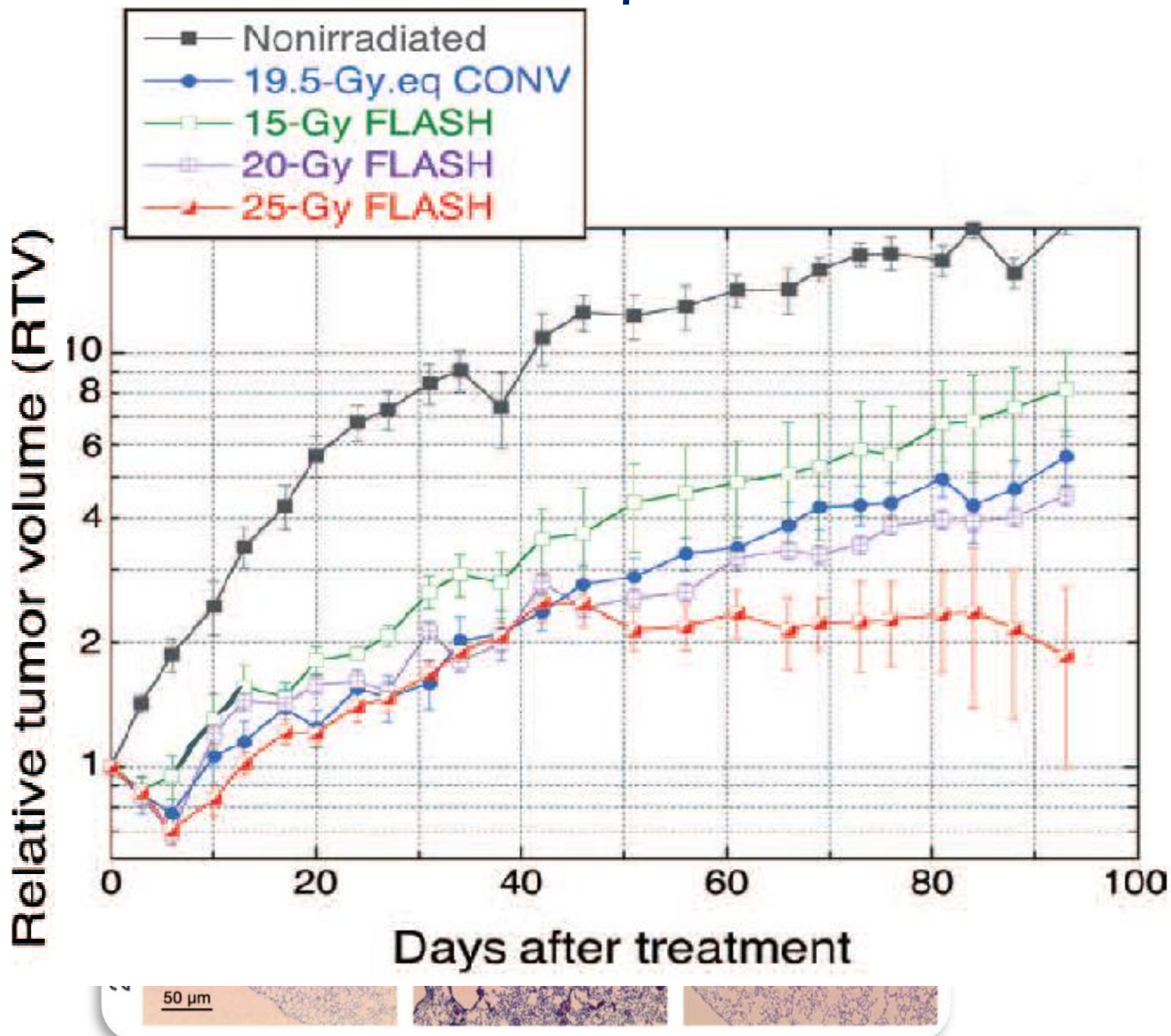

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Treatment of a first patient with Flash therapy

Type of cancer: cutaneous lymphoma on skin surface.

	FLASH
Facility	LINAC eRT6
Nominal energy (MeV)	5,6
Pulse repetition frequency (Hz)	100
Time of exposure	90 ms
Dose (Gy)	15
Mean Dose rate (Gy/s)	166
Temporal width of pulse	1 μs (10pulses)

Day 0

5 months

It was shown no decrease of the thickness of the epidermis and no disruption at the basal membrane with limited increase of the vascularization.

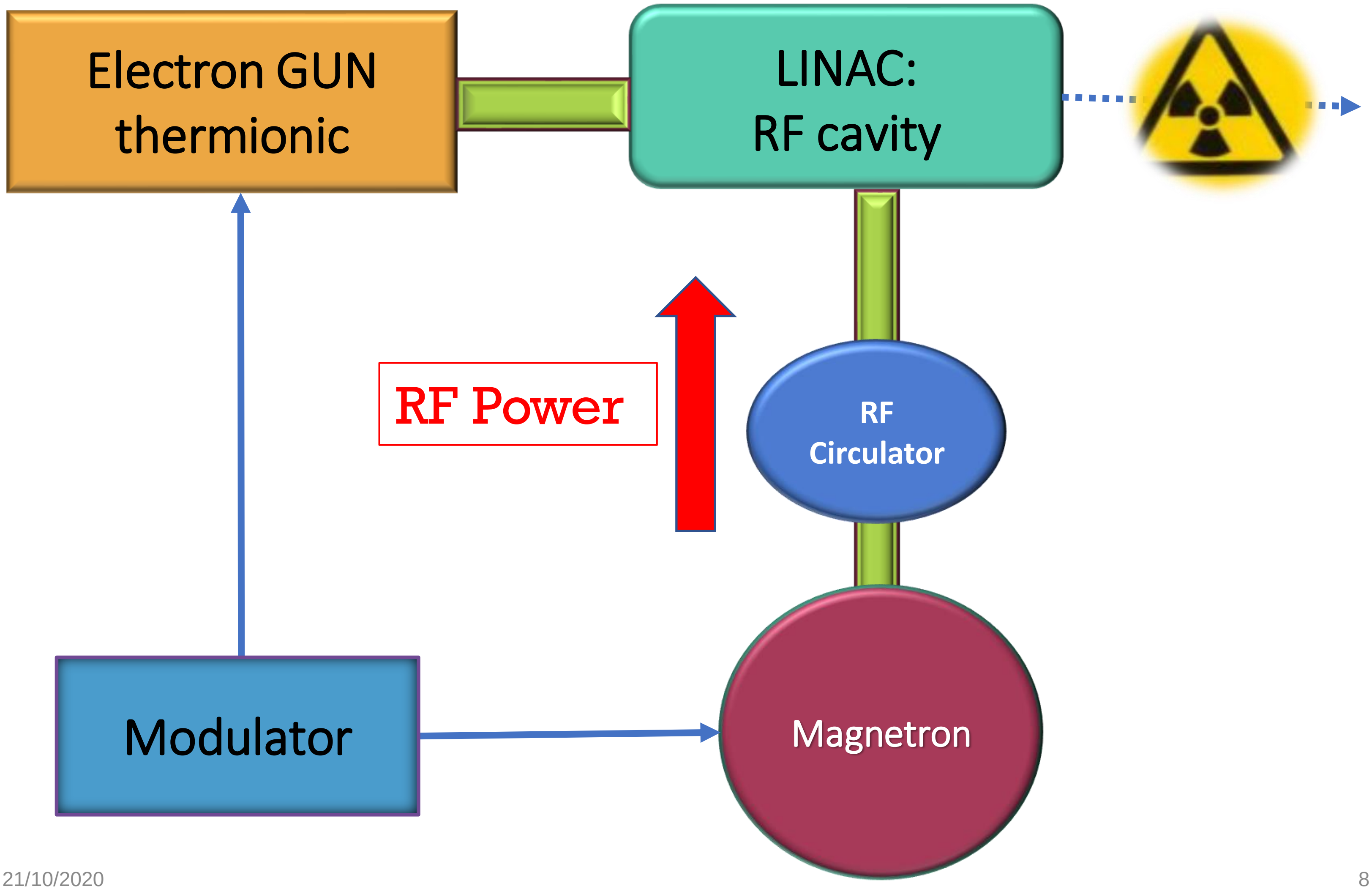
Jean Bourhis et al., «Treatment of a first patient with FLASH-radiotherapy», Radiotherapy and Oncology. 2019

Dedicated accelerator: why we want it

Understanding the FLASH RT limits (min/max dose/time) → Clarifying bio mechanisms underlying FLASH effect → Defining conditions for clinical practice → First accelerator for clinical use

- Marie Curie Institute commisioned a new Linac dedicated for Flash therapy and radiobiology experiments.
- We have developed the design of the accelerator built by the company S.I.T. Sordina IORT Technologies S.p.A.

Scheme of a medical Linac



7 MeV electron linac for FLASH

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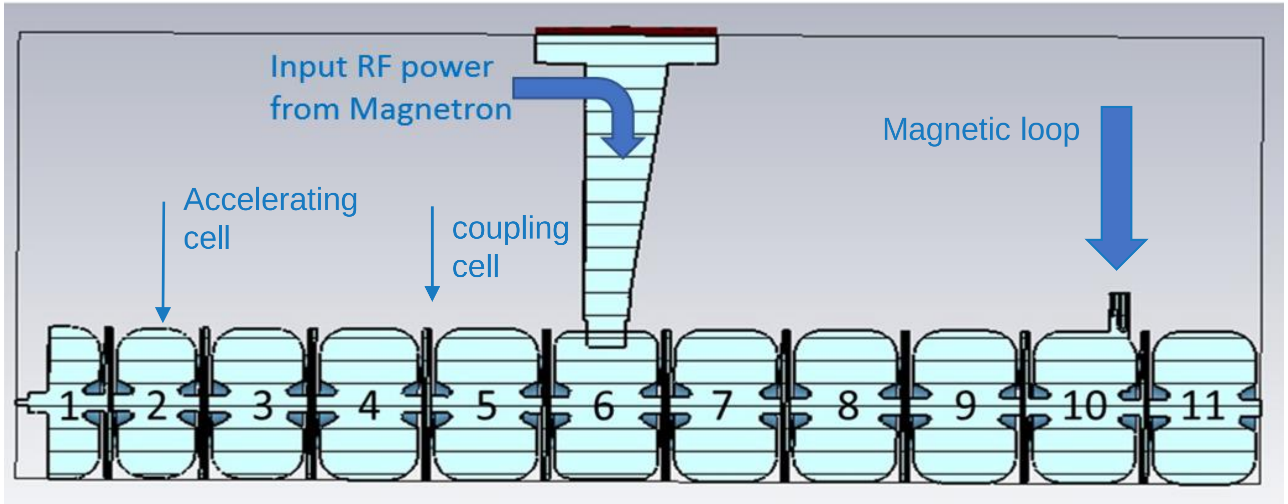
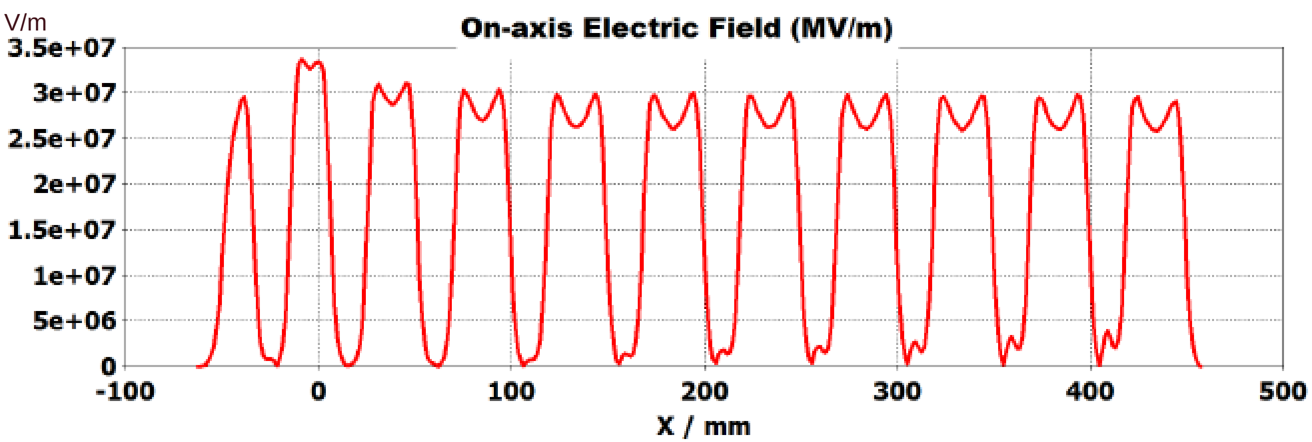
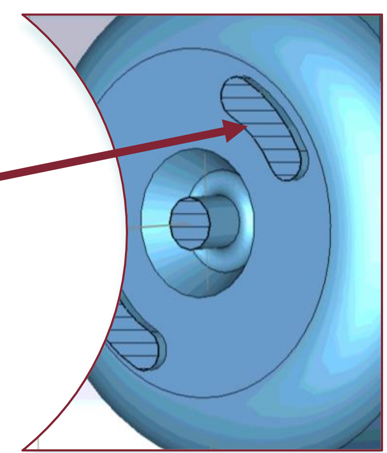


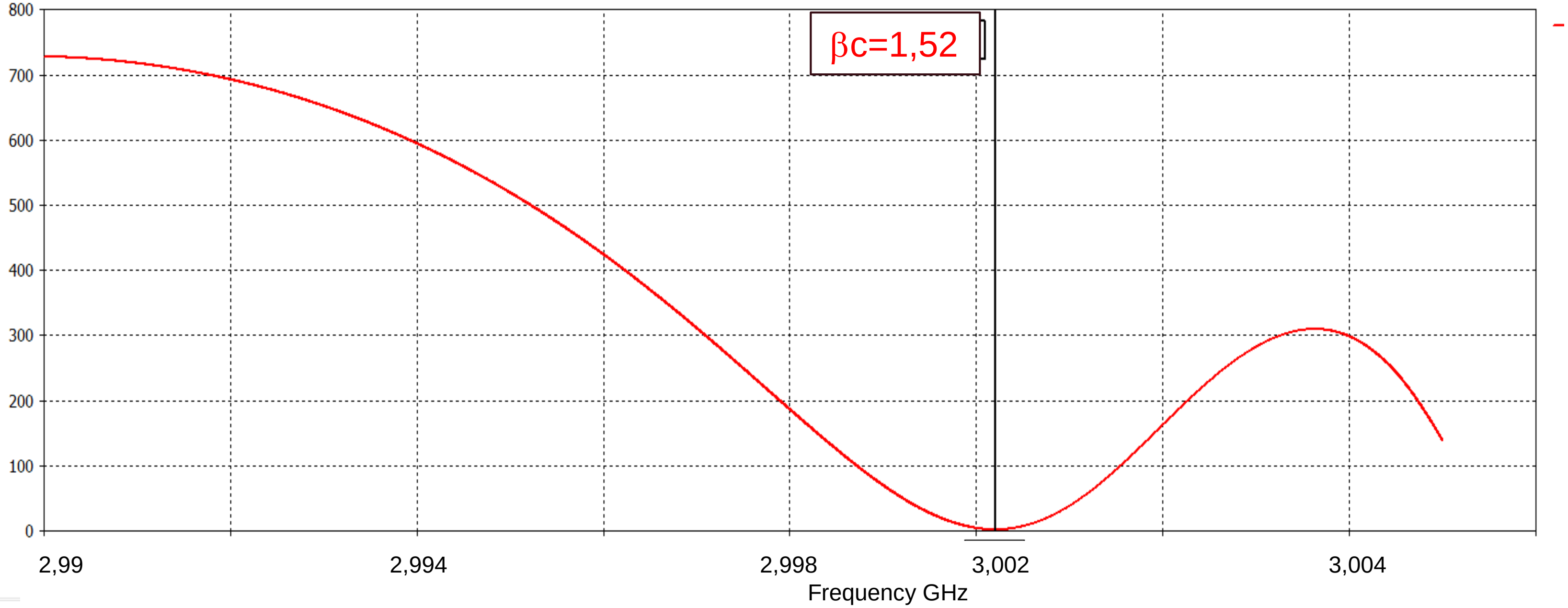


- S-band linac ($f=2{,}998$ GHz)
- Standing wave structure (SW)
- $\pi/2$ mode
- Bi-periodic geometry: accelerating and on-axis coupling cells

- Magnetic coupling with hole off axis
- Magnetic loop for e.m. field measurment



Optimization of waveguide-to-linac: RF power matching



- The RF wave guide is inserted in the middle cell (coupler cell).
- The waveguide-to-linac coupling coefficient βc must be optimized to minimize the reflected RF power when the electron beam is accelerated.
- The formula we used is : $\beta_c = 1 + \frac{P_b}{P_d} = 1 + \frac{I_p R_{sh} l}{V_{acc}}$
- The best value for the coupling coefficient is **βc= 1,52**

Target performance for an accelerator for pre-clinical studies

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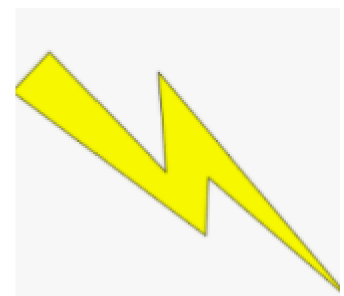
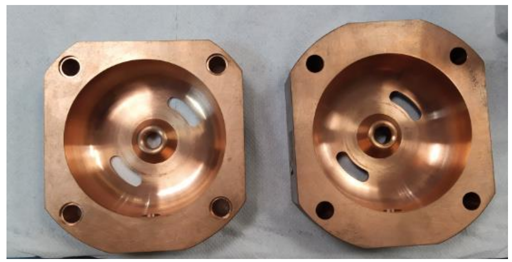
- Variable energy: 5-7 MeV (for other pre-clinical investigations)
- Samples surface variable: 10x10 cm – 4x4cm (**high homogeneity** for in-vitro screening)
- Target dose per pulse: 5 Gy
- Pulse width: few μs
- Mean Dose rate: 1000 Gy/s
- Dose-rate in pulse: **10^6** $< D'p <$ **10^7** Gy/s
- Pulse repetition frequency: n= 300Hz

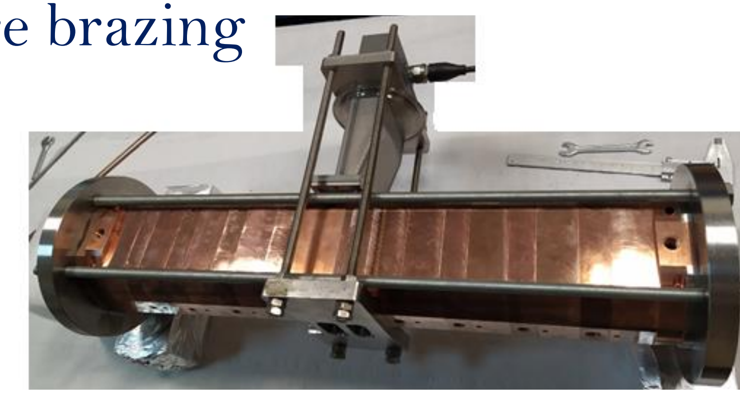


FLASH conditions

Realization of ElettronFlash4000

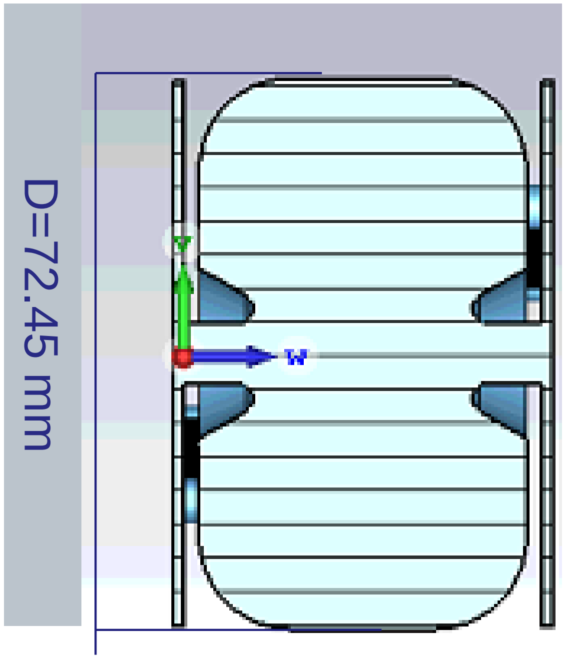
Accelerating cells and clamped linac before brazing

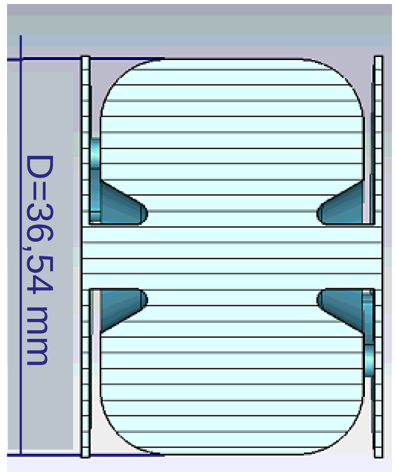




Linac installed at Curie Institute

Compact electron linac for FLASH





- **Reduce the size**

Starting from the S-band (2.998 GHz) accelerator's structure we scale down the geometric dimensions to get C-band design (5,712 GHz).

$$f \propto \frac{1}{D}$$

- **Increase Energy gradient**

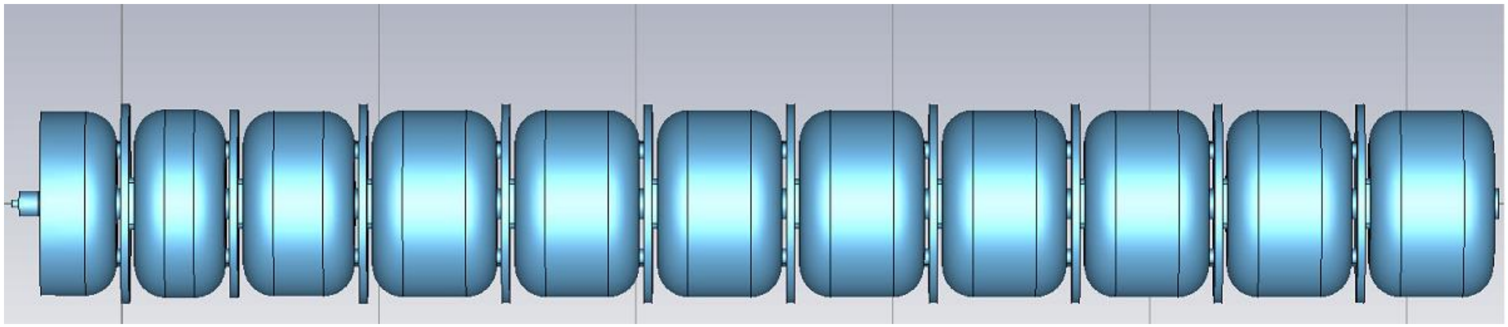
Increase the energy gain per meter (energy gradient)

Example

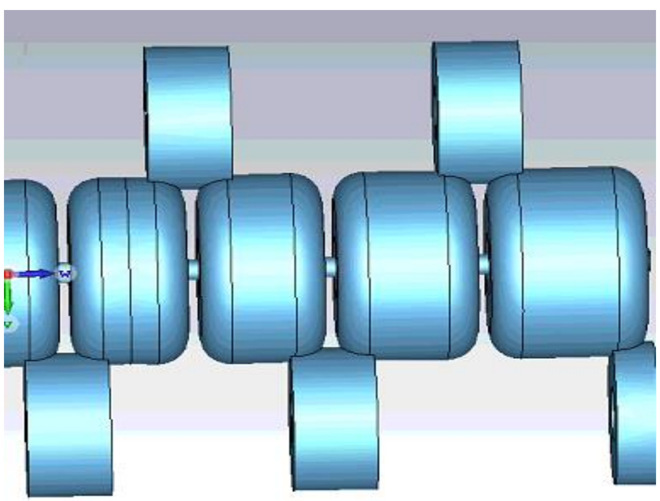
- 3GHz → 6GHz
- $D_{\text{s-band}}$ = 7cm → $D_{\text{C-band}}$ =3,5 cm
- $\text{Gradient}_{\text{s-band}}$ 15 MV/m → $\text{Gradient}_{\text{C-band}}$ 30MV/m

Geometry choice

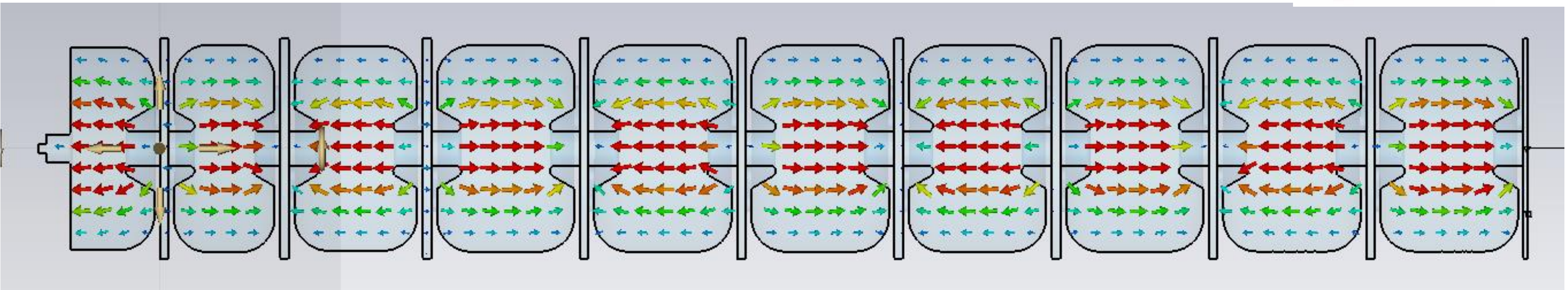
- On axis Coupled cells

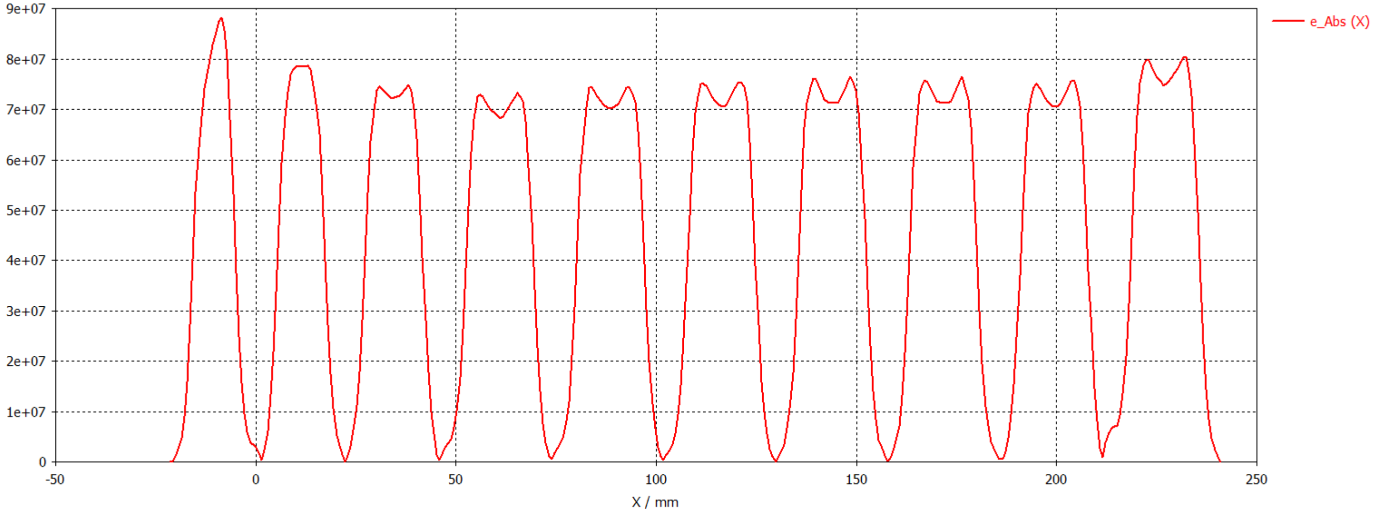


- Side Coupled Cells



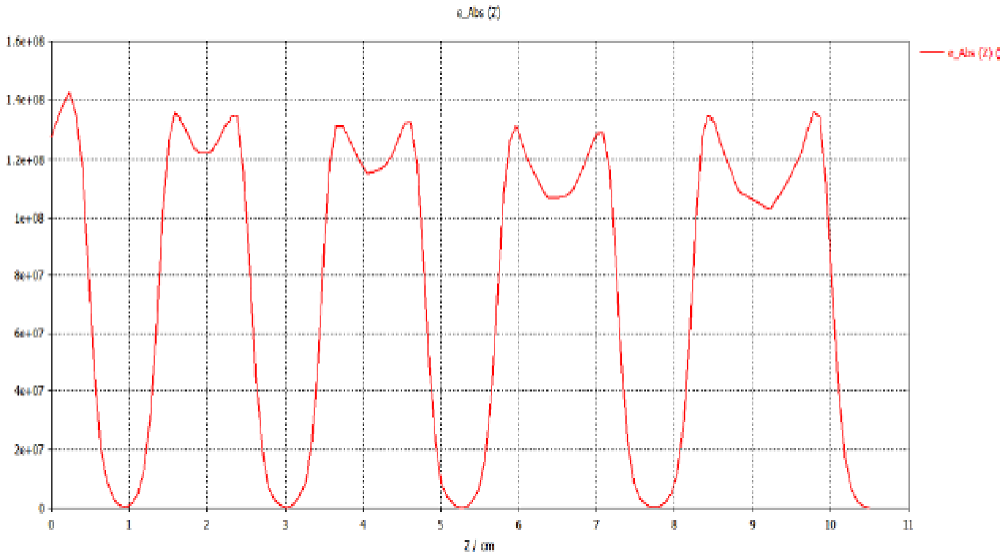
On axis Coupled cells

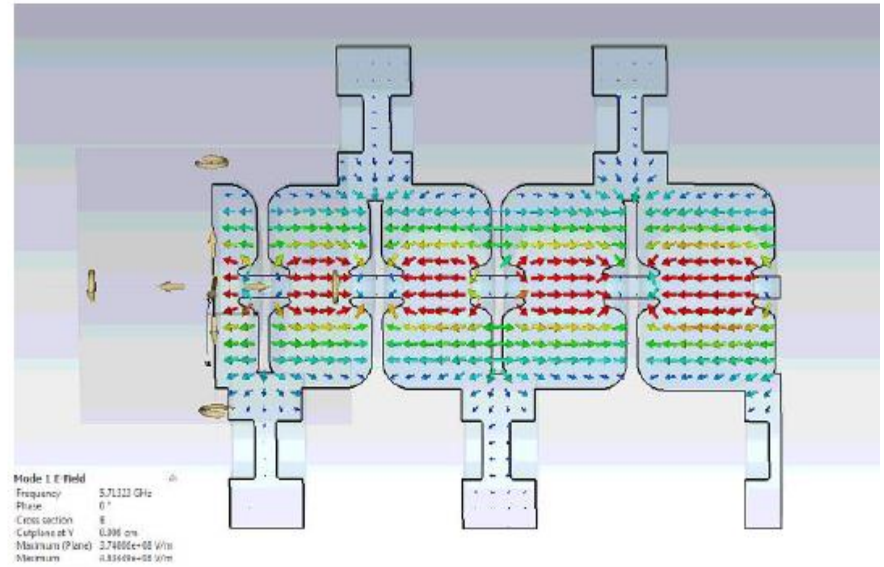




- Accelerating and coupling cavities on beam axis
- 5.712 GHz (C-band)
- Linac operation mode: π / 2 mode
- Magnetic coupling with coupling hole off axis

Side coupled cells





- L= $\beta\lambda/2$
- 5.712 GHz (C-band)
- Accelerating cavities on beam axis
- Off-axis coupling cells
- Linac operation mode: π / 2 mode
- Longitudinal compactness
- Lighter
- More stability against perturbations from tuning errors

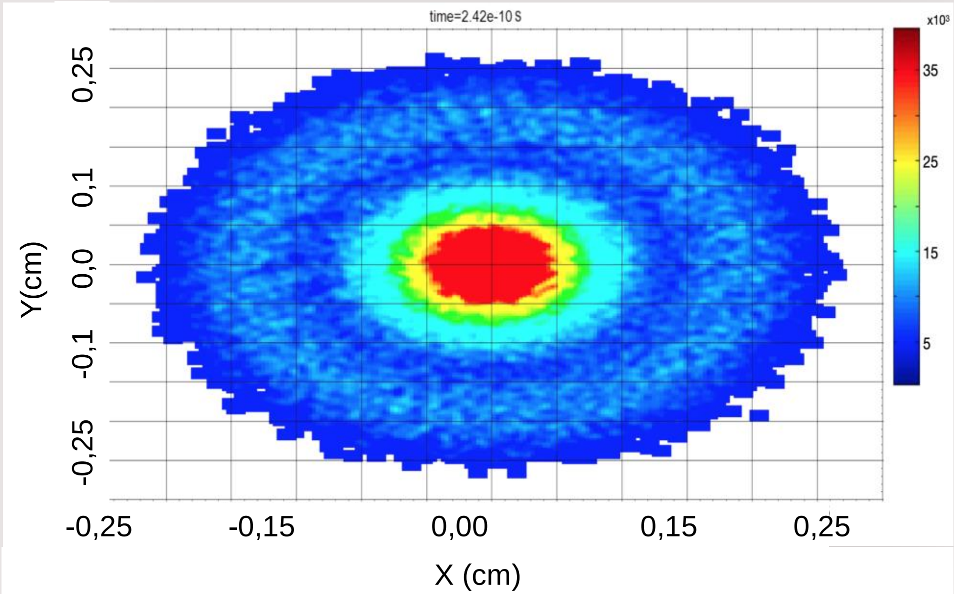
Beam dynamics preliminary studies

- The simulation of beam dynamics was carried out with the code ***GPT*** (general Particle Tracer)
- The input electron beam distribution was imported from the ***Poisson Superfish***
- The BD performance is optimized to achieve:

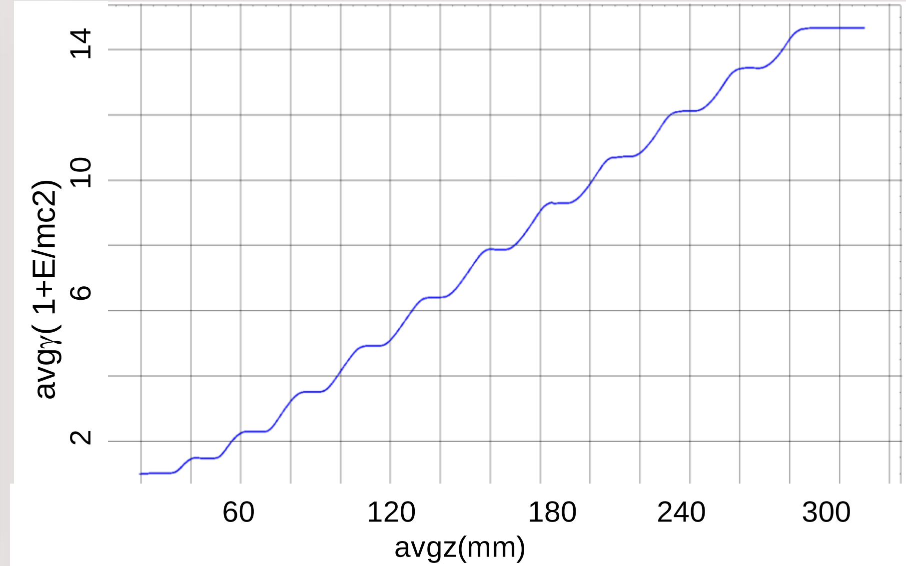
Parameter	**Value**
Frequency	5,712 GHz
Output beam energy	7MeV
Output beam current	100mA
Beam diameter	4 mm
Beam capture	>30%

Beam dynamics preliminary plots

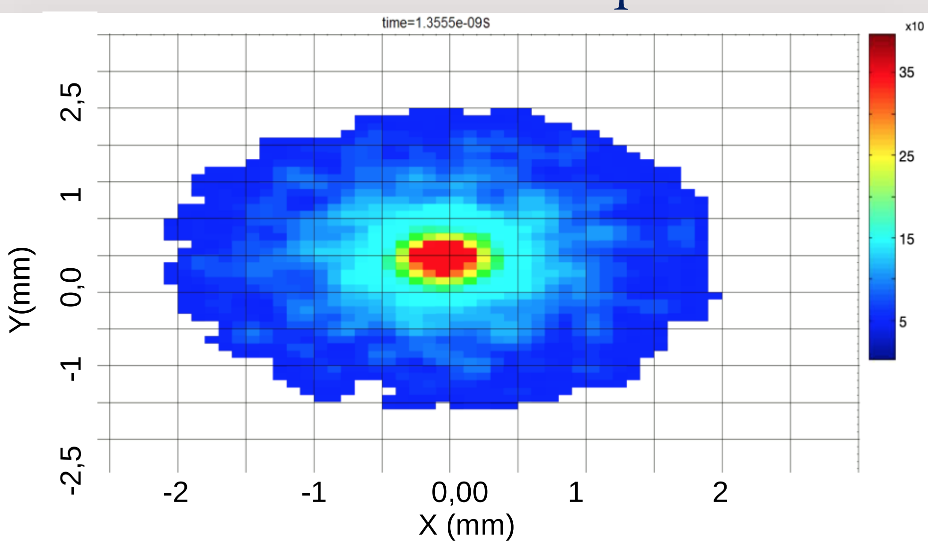
Initial beam transverse spot size in cm



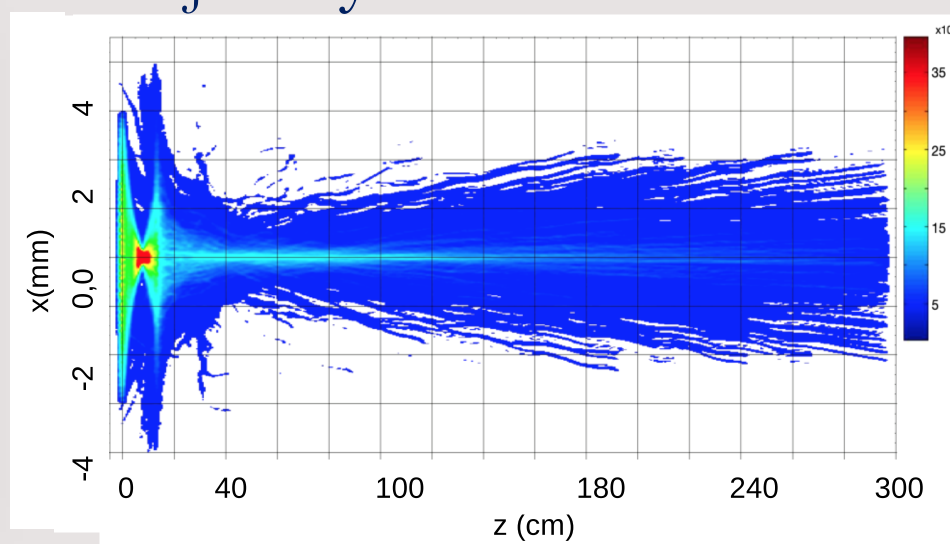
Energy gain



Final beam transverse spot size in cm



Trajectory



Future studies

Study and developed of C-band 12 MeV linac for S.I.T.

- RF design
- Beam dynamics simulation
- Test on linac prototipe
- Test on final linac

Dosimetry measurements at Curie Institute

- Two toroidal inductors can provide a non-destructive measure of the beam current, and hence, dose output.
- Dosimetry study goal: validate the reliability, stability, and accuracy of the toroidal inductors

Poster and presentations

- **Oral presentation at international and national meeting**:

-International Conference on Medical Accelerators and Particle Therapy, 4-6 September 2019 CNA **Seville (Spain)**

- 105° Congresso Nazionale della Società Italiana di Fisica

Gran Sasso Science Institute, 23-27 Settembre 2019 **L'Aquila (Italy)**

(**Premio migliore comunicazione sezione Acceleratori e Beni culturali**)

- **Paper in press**

L.Giuliano «Flash therapy: an innovation in radiation therapy» Il Nuovo Cimento 43 C (2020) 125

- **Paper in progress**

L.Faillace et al. "Compact S-band Linear Accelerator System for FLASH Radiotherapy"

Conclusions

- **Flash therapy** is an innovation in radiation therapy: it releases high Gy level dose in microsecond pulses.
- The healthy tissues can support **high dose rate without harmful effects** of ionizing radiation.

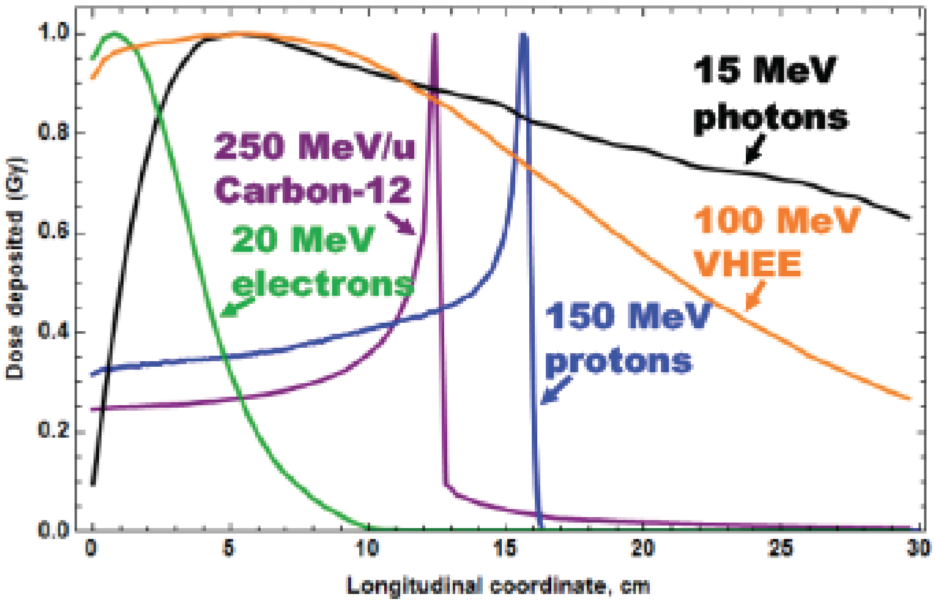
- We studied and developed a **novel accelerator** in **S-band** (SIT-Sapienza University cooperation) **for Flash** pre-clinical studies.
- We did the upgrade to **C-band** technology (5.712 GHz) to **reduce the size, the weight and increase the energy gradient.**
- We carried out preliminary study of beam dynamics for C–band linac.

- Design and development of C band 12 MeV linac have to be completed and optimized
- I will go to Curie Institute in January 2021 to perform dosimetry measurements

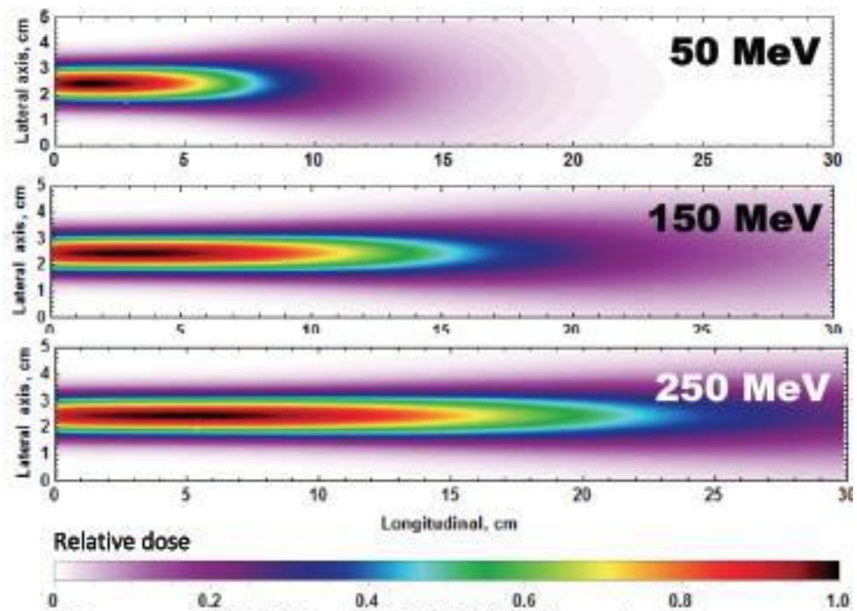

Thank you for your attention

Future perspectives: cure of tumor depth

Future challenges: cure of tumor depth → Very high electron energy VHEE



Dose profiles for various particle beams in water (beam widths $r = 0.5$ cm)



Dose maps of 50, 150 and 250 MeV VHEE beams in water

Courtesy of Dr. A. Faus Golfe, ARIES 2nd annual meeting –April 2019