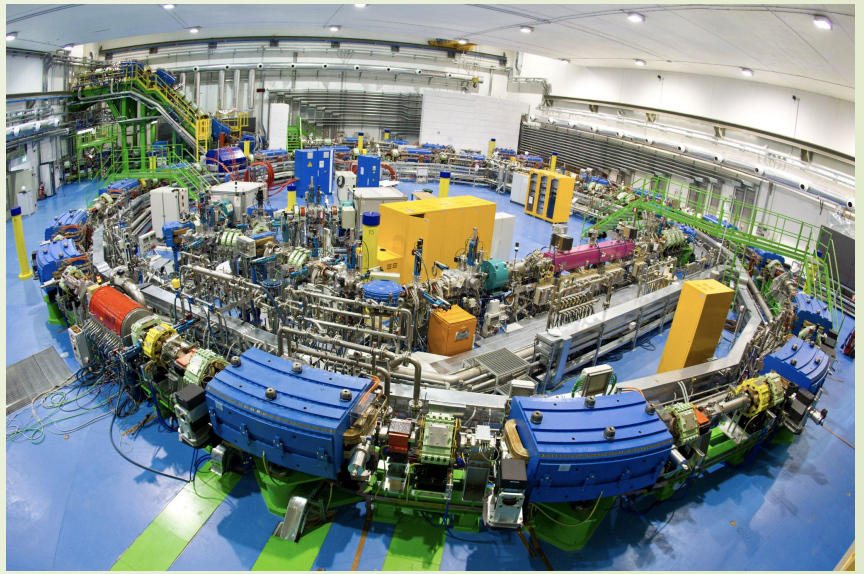
Medical Physics Applications

A. Sarti

The “therapy” applications

Accelerators are a fundamental ingredient for External Beam Radio Therapy (EBRT) applications.. Fighting cancer requires a diversified strategy to maximise the therapy efficacy: surgery, chemotherapy and EBRT are possible instruments to target tumours. Within EBRT particle accelerators are used to produce photons (IMRT - VMAT); e- (IORT/VHEE); p and ions (PT and CIRT) with the needed a) energy b) intensity c) direction to treat the target volume identified by the radiotherapists.

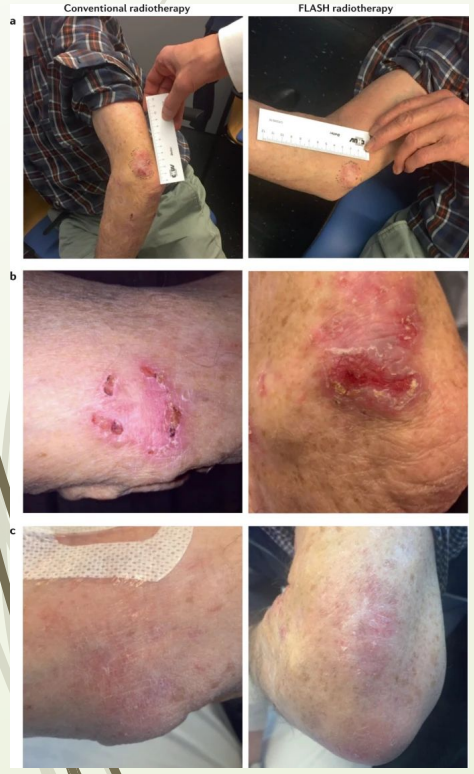
LIAC HWL: 10^{10} elettroni/impulso
Energia elettroni in uscita: **6** MeV
Frequenza: 10 Hz
Dose rate: 10-30 Gy/min
Larghezza fascio in uscita: ~1cm (raggio)
Testa mobile: utile per una corretta valutazione della posizione

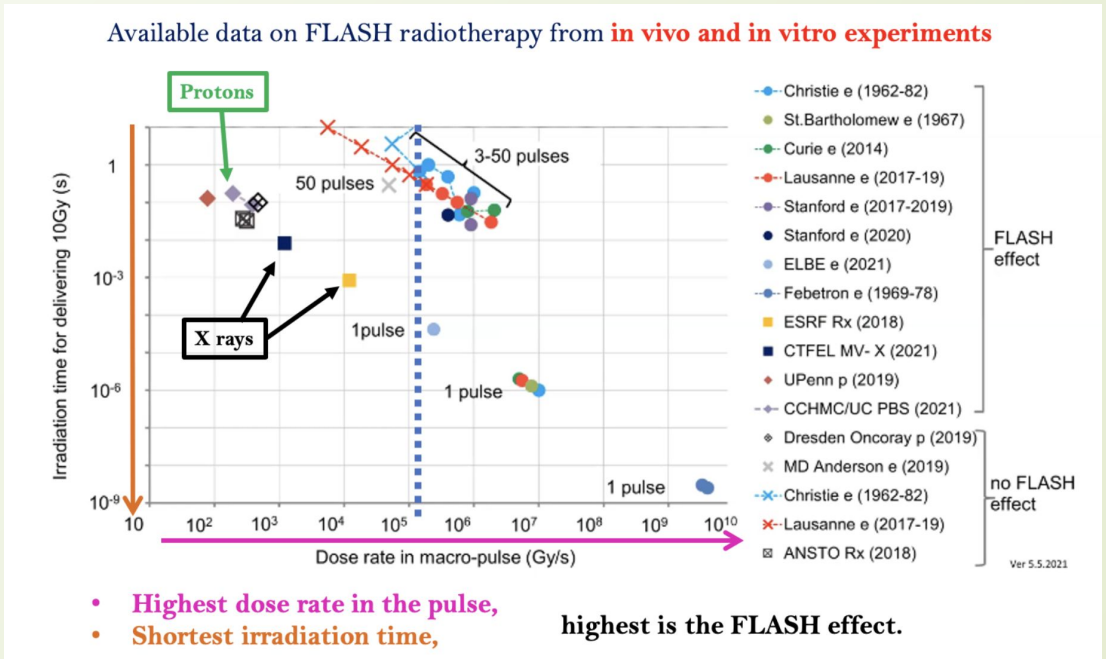


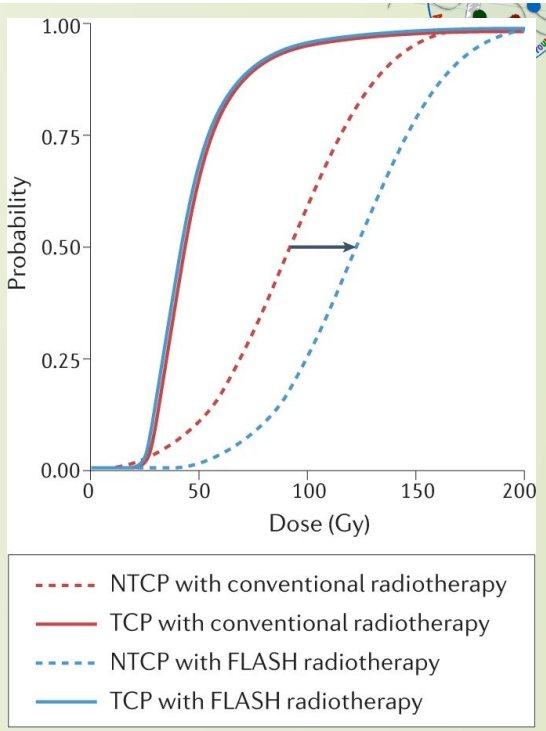
The "FLASH" revolution

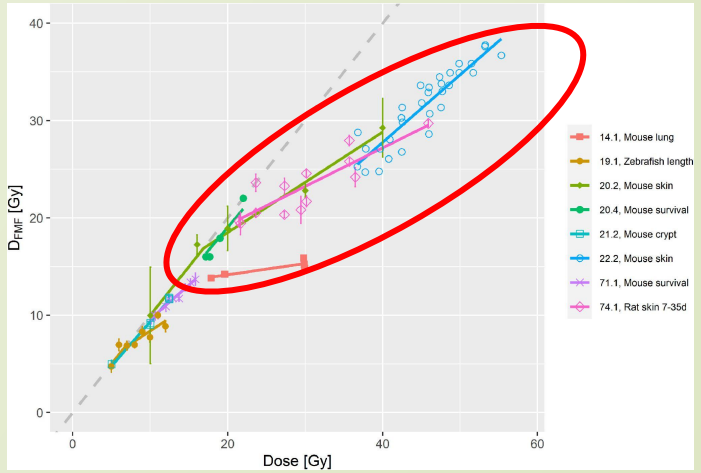
Clinical translation of FLASH therapy
https://www.nature.com/articles/s41571-022-00697-z

Ultra high dose rate irradiations (going from 0.01 Gy/s of conventional to >40 Gy/s for FLASH) have demonstrated an increased organs at risk sparing capability that can be exploited to widen the RT therapeutic window.









https://doi.org/10.1016/j.radonc.2021.12.045

The planning/monitoring challenge

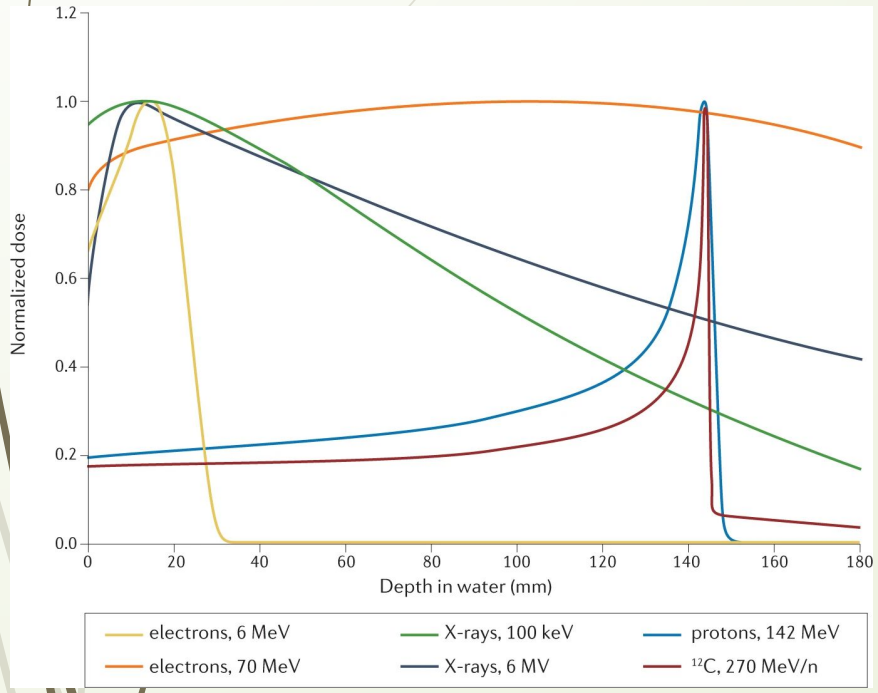
Two main tasks are related to the world of therapy applications:

- Developing new accelerating technologies: higher fields, higher dose per pulse, higher dose rate (FLASH!) [**see talk from M. Migliorati**], **improve the beam delivery allowing a better customisation of how the beam enters the patient** [few slides from L. Rossi @ end of this presentation]

- Developing the tools to plan the treatment / control the beam: understand how the beam characteristics affect the treatment plans, develop the techniques needed to monitor the beam and provide 'online' control and diagnostics

In this presentation we focus on the latter topic

The FLASH challenge: high energy e^-



Light particles, suffer from MS.. BUT: show a BP distribution (better sparing of OARs for deep tumors), are intrinsically more robust against morph changes wrt p and ^{12}C ions.

Problem: **we need ~100 MeV to reach deep tumors! not easy to implement in a clinical facility**…

Profiting from FLASH (better sparing of OARs, can lower the energy of e-) and compact C band accelerators… **e- might re-enter the deep tumors EBRT game**!

INFN & Sapienza are jointly started a project to deliver 70-150 MeV e-, using a C-band RF technology linac, with FLASH intensities in Sapienza!

Details in the talk from Mauro… Hereafter: what can we expect from a FLASH beam coming from this machine?

FLASH: the ‘planning’ task

- FLASH with VHEE:
  - Potential of FLASH VHEE for the treatment of deep seated tumors: already explored ‘golden districts’ (lung, pancreas) .. Now it’s time to understand how to match the FLASH requirements in clinical conditions!
  - The treatment planning problem: **moving in an uncharted territory in which there’s a huge phase space that has to be explored**!

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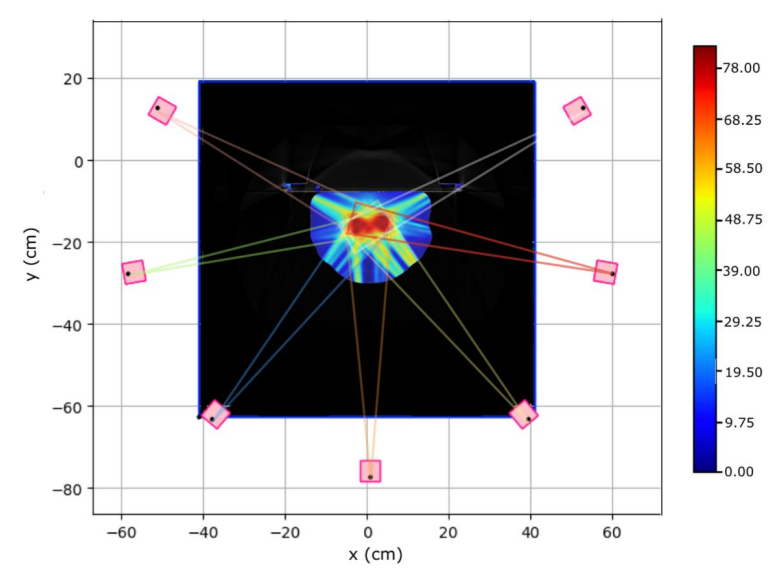
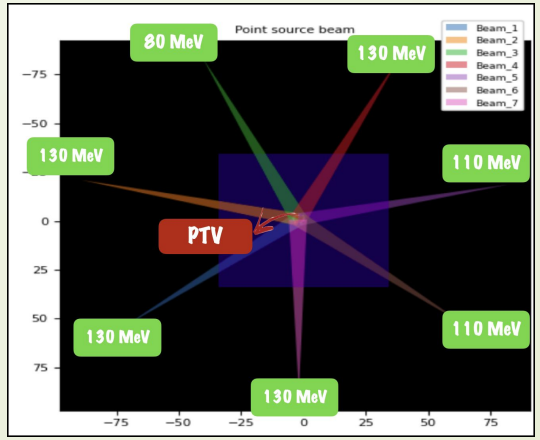


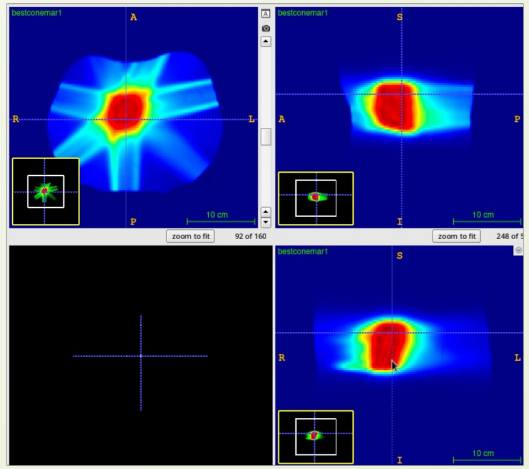


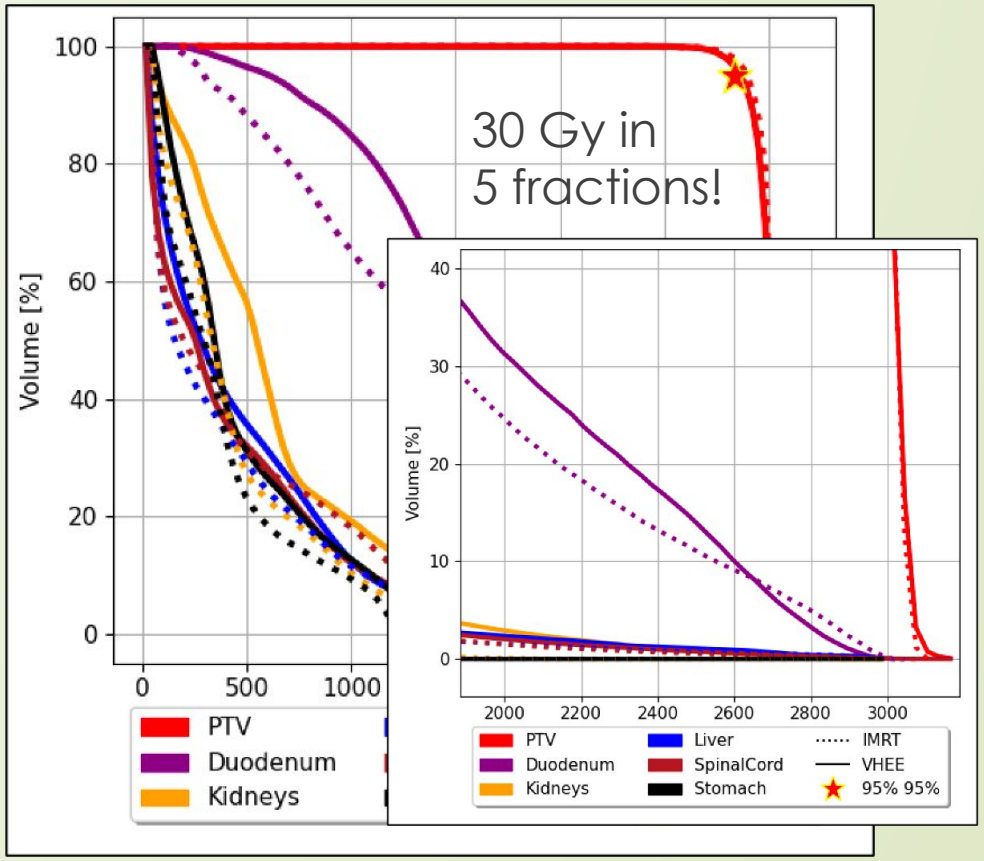
1. Starting from actual treatments (either protons or VMAT/IMRT)
2. Obtain the ‘entry points’ to place the origin of the electron fields [IMRT like approach], identify how many pencil beams (PB) are needed to ‘cover’ the PTV ‘projected area’
3. Choose the energy of each electron field placing the electron BP on the centre of the PTV

VHEE + FLASH planning

Current status: one can mimic the IMRT plans and obtain something that is already promising… [pancreatic & lung cancer already foresee severe hypofractionation → good for FLASH!]

VHEE look promising.. But: this is not yet the full story. **We still need to explore the full potential of e- in clinical conditions**!





The future of FLASH VHEE planning

Deeply interconnected with the beam acceleration and delivery tech.

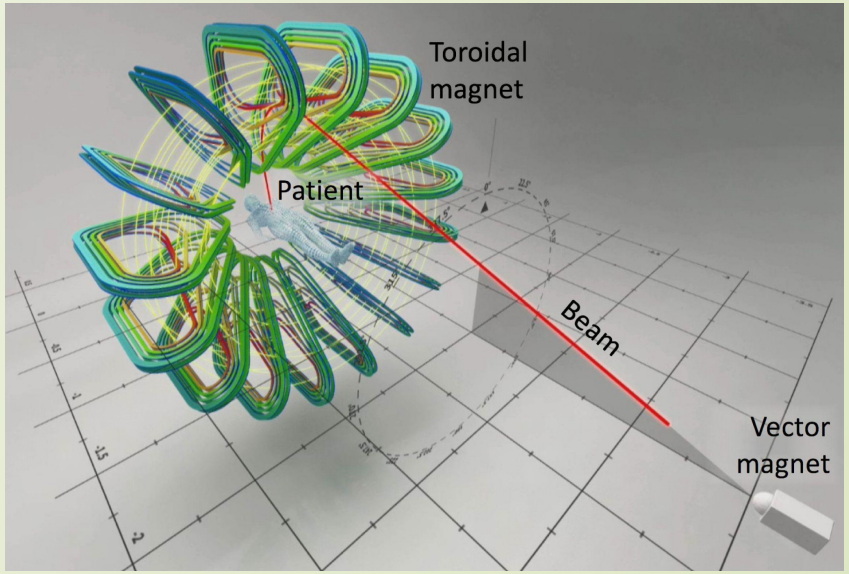
Improve the treatment plans quality check (Isodose, hypo-fract.)

Explore the beam parameter phase space in order to 'pre-optimise' the dose distribution, and look at the PB fluences only after..

- Look for Machine Learning implementations of such high number of parameters problem
- Look for analytical/numerical solver for this minimisation problem also starting from the tomotherapy experience

Implement different beam delivery methods (e.g. single beam, with multileaf shaper)

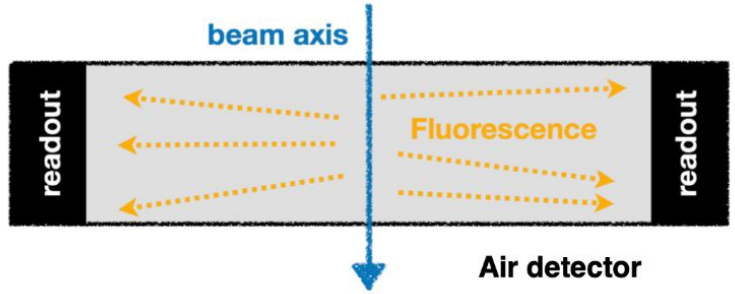
Implement a FMF(D, **DR**), take into account the FMF dependence on the organ, and on the irradiation strategy (and hence dose rate!)..

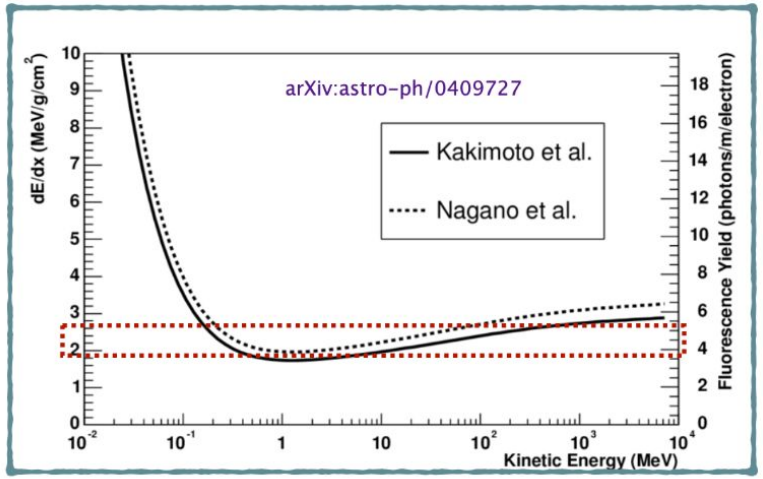


The monitoring challenge: an example..

- At present, there is no standard device for beam monitoring in UHDR conditions. Detectors commonly used in clinics (standard ionization chambers) undergo substantial energy dependencies due to **volume recombination**.
- It is clear that we need *new monitoring devices* to precisely measure **the rate of impinging particles per pulse** (real-time, position by position). Promising results from **luminescence-based** detectors (thin scintillators, Cherenkov detectors…).
- According to data in literature, **air fluorescence** can do the job for us.

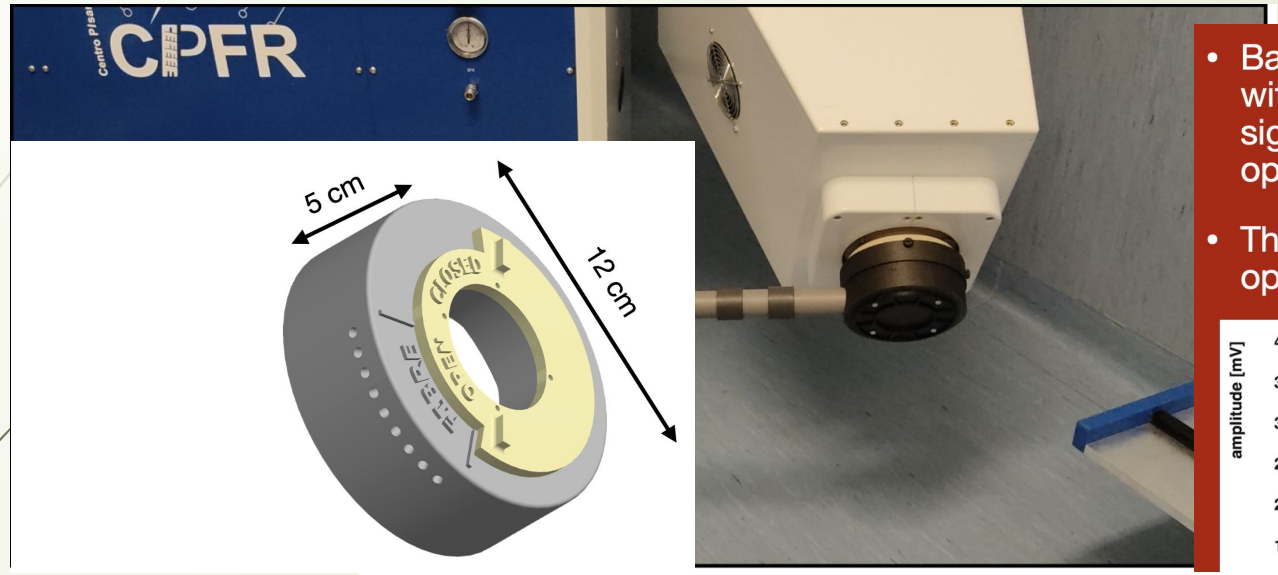
Photon emission	Isotropic (3D)
Excited state lifetime	10 ns
Wavelength spectrum	290-430 nm
Fluorescence yield	$\propto dE/dx$ (~ 4 ph./m)
Signal-to-#e⁻ relation	**LINEAR**
Transparency wrt ref. cond.	100%
Radiation hardness	Optimal



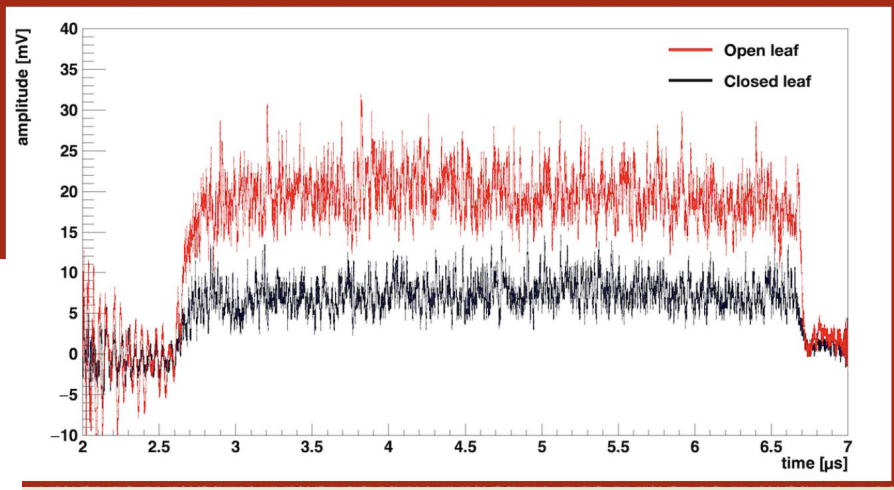


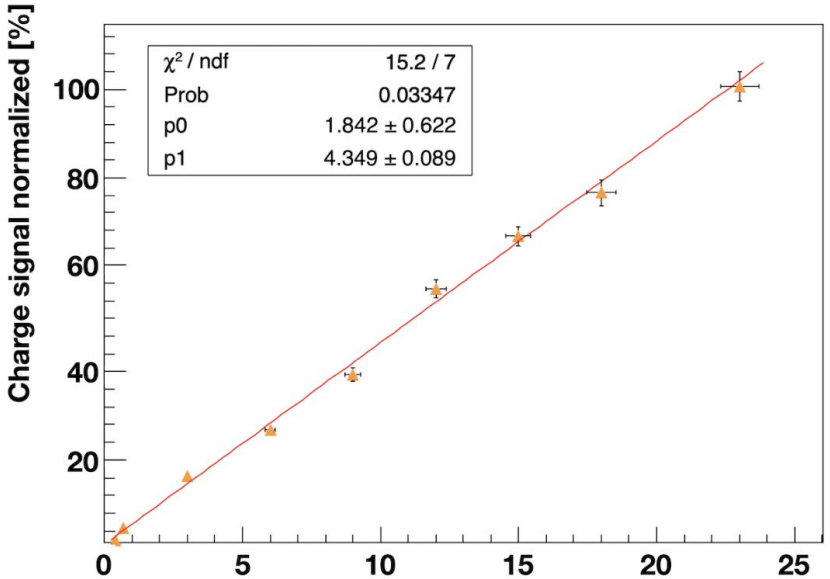
courtesy of A. Trigilio

The monitoring challenge: an example..



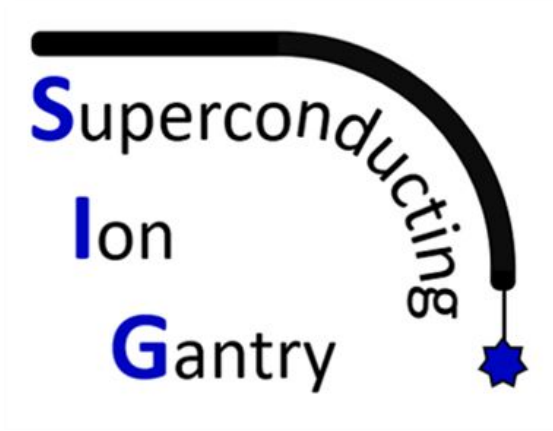
- Background can be successfully subtracted, although with this setup it is a sizable portion (~35%) of the total signal. Moreover, the gain of the PMT is still non-optimal for the fluctuations of the signal amplitude.
- The readout system and the geometry need to be optimized to increase the signal-to-noise ratio.





courtesy of A. Trigilio

Spare slides



Superconducting Line for a heavy ion gantry (**SIG** project with INFN-CERN-CNAO)

Thesis supervisor : Prof. Lucio Rossi (lucio.rossi@unimi.it)

Professor of Accelerator Physics at University of Milano

National Coordinator of th Committee for Science & Technology of Accelerators

(formerly head of the LHC Superconducting Magnets 2000-2011 at CERN

and High Luminosity LHC Project Leader 2010-2020 at CERN)

Place of thesis work: Milano at the LASA Laboratory of University and INFN

What's next for particle therapy?

- **Multiple ions delivered with light-weighted Gantry**
- **Rotatable gantry allow non-coplar irradiation, enhancing effectiveness**
- Treatment rooms equipped with patient imaging
- Dose Delivery and Range Verification Systems able to adapt online the dose delivered

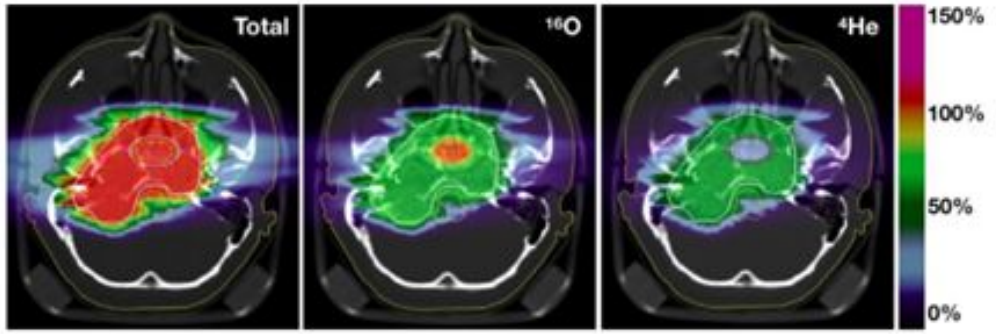
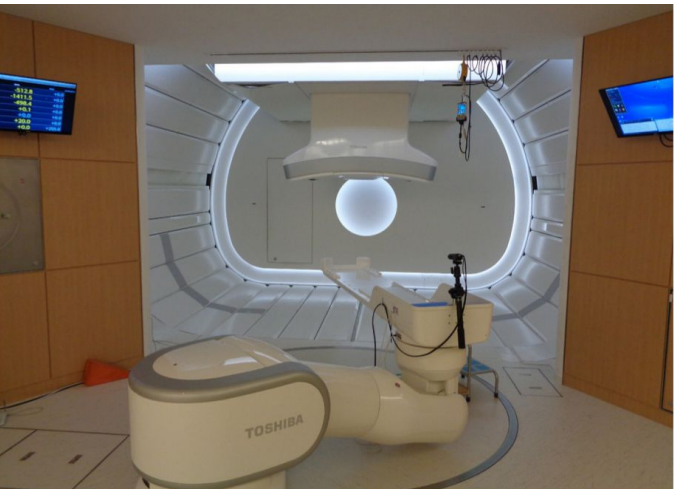
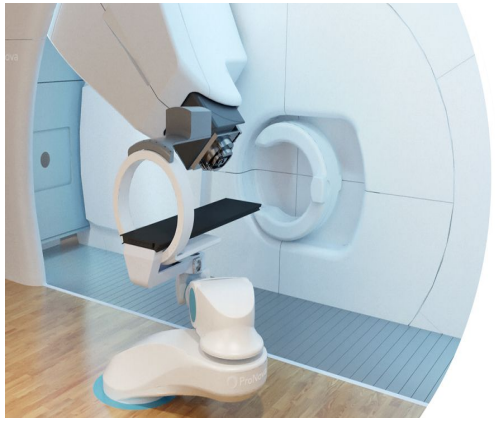


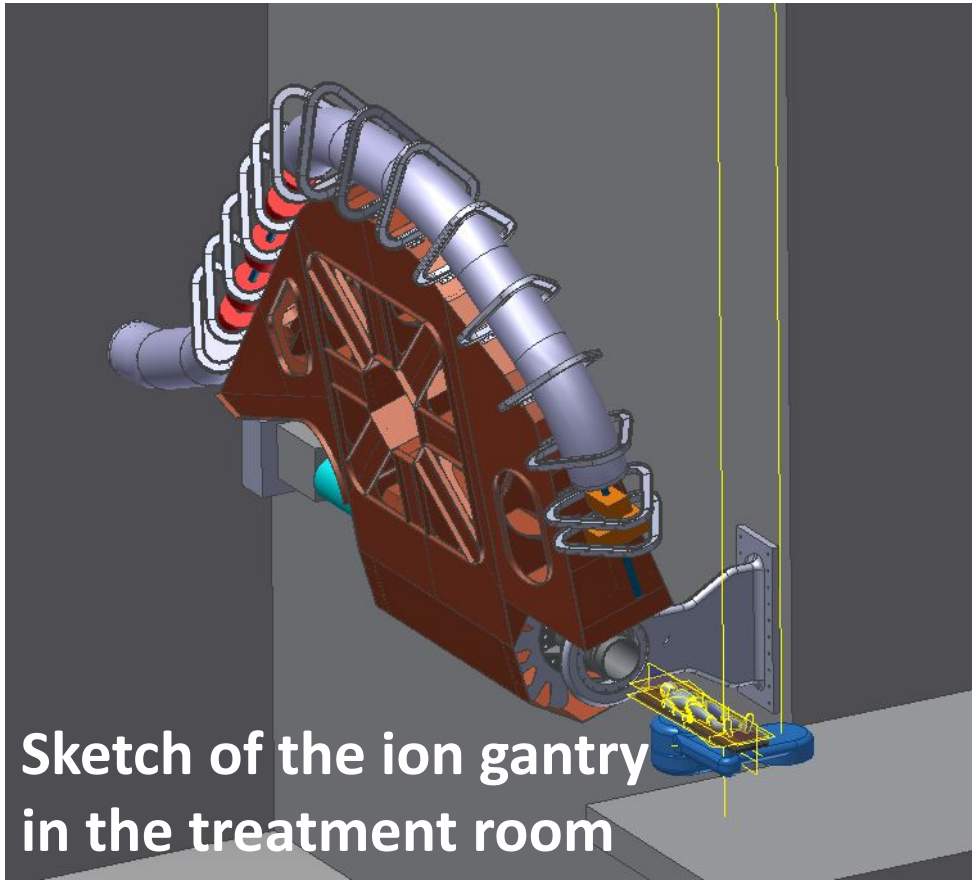
Figure1: Total profile of biologically effective (RBE and OER weighted) dose and single particles' contributions, arising from the Multiple-ion full biological optimization (MIBO) with 2 pairs of ^{16}O and ^{4}He fields.

Ion gantry @ Himac (Jp)



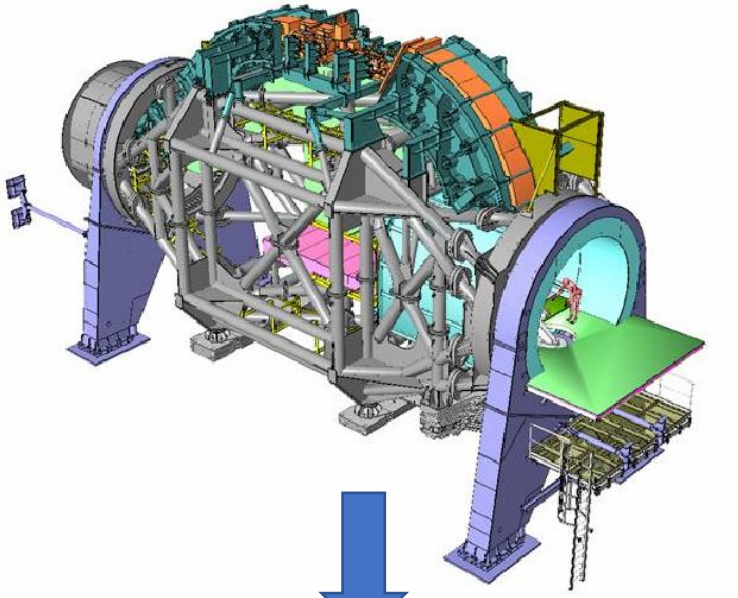
Gantry and imaging system of a proton therapy center

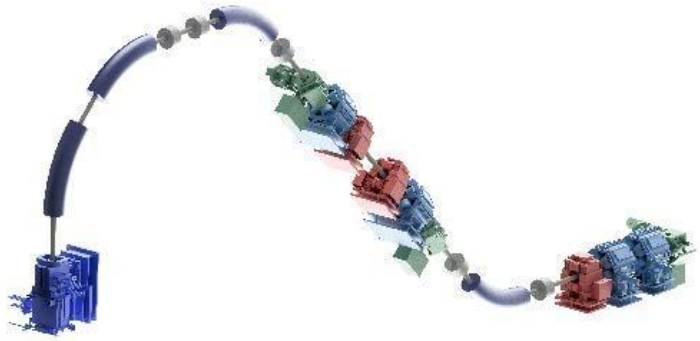




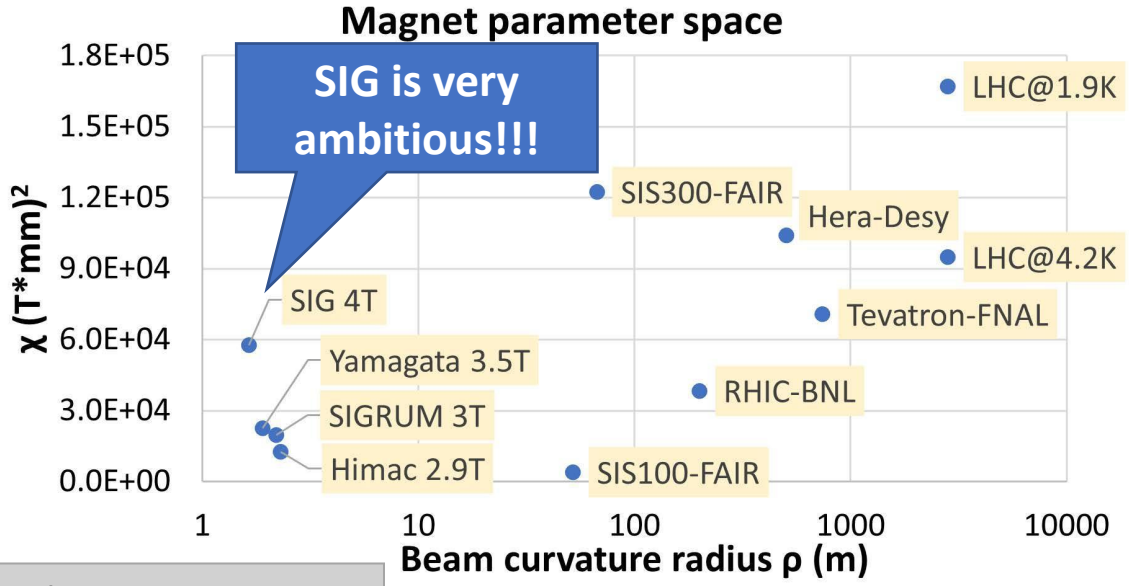
Sketch of the ion gantry in the treatment room

Heidelberg Gantry ~600 tons



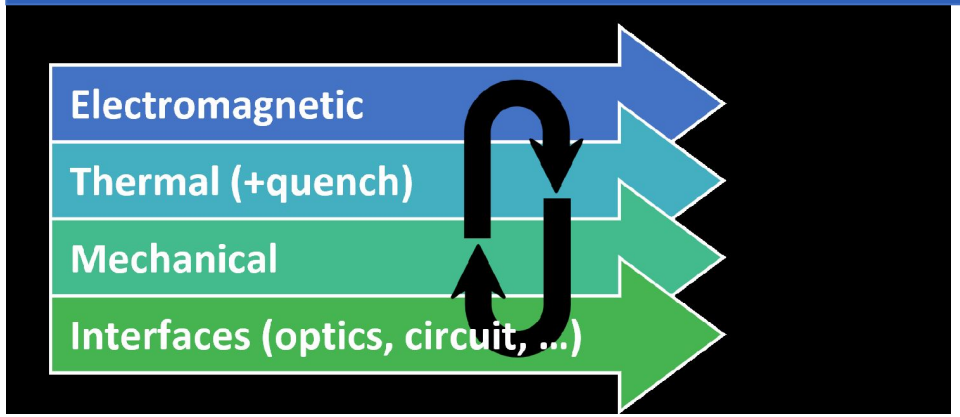


Compact SIG Gantry ~50-80 tons easy-to rotate and accessible.



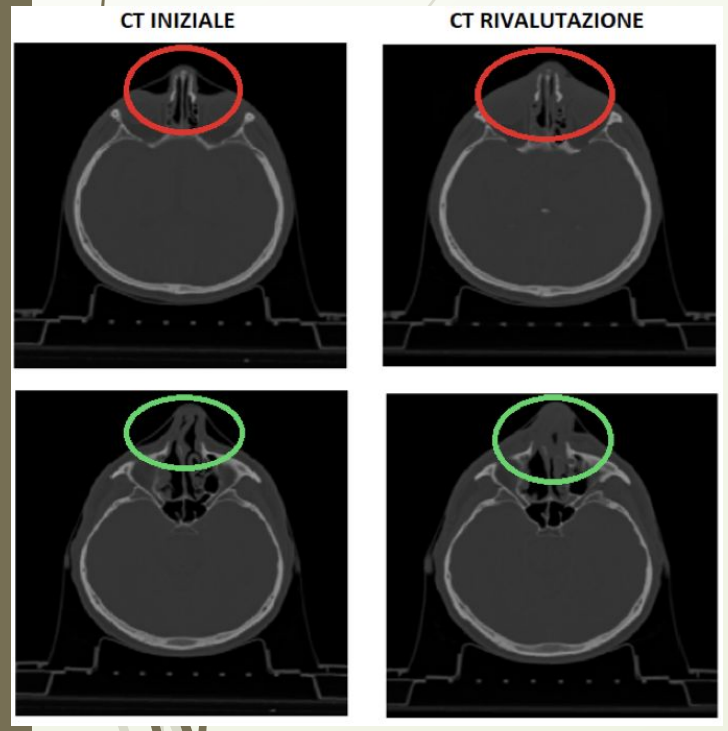
THESIS work:
MultiPhysics design
Construction of prototype
Test & Qualification of a new CURVED SUPERCOND. DIPOLE magnet as demonstrator for next generation gantry.
Project already financed by INFN-CNAO-CERN.

Technologies to be explored both with simulation (FE) and with experimental work

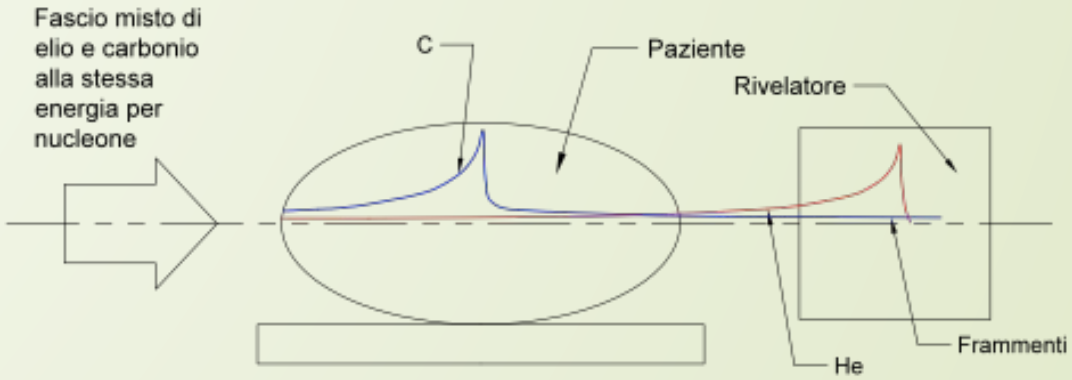


Candidate Profile: Applied Physicists or Engineer.

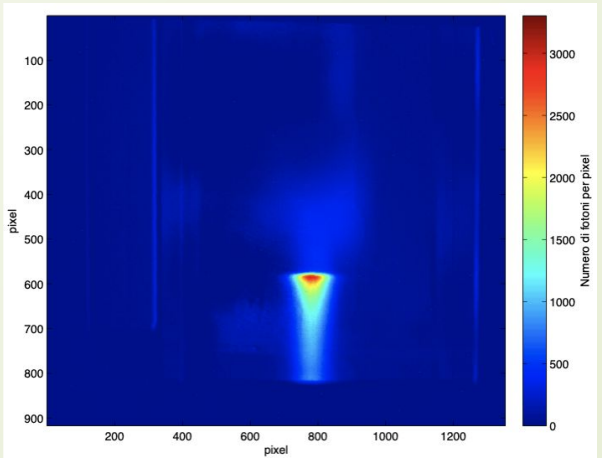
Monitoring the ^{12}C CNAO treatments

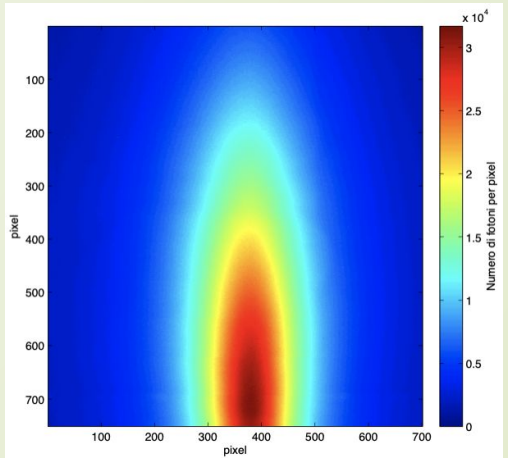


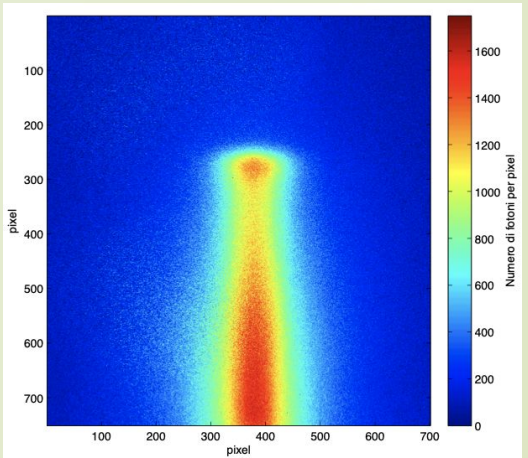
Morphological changes (wrt what was planned) can arise during a treatment. Using a mixed beam of ^{12}C and He one can detect the morphological changes using the He longer range



plastic scintillator 20x20x20 cm^3



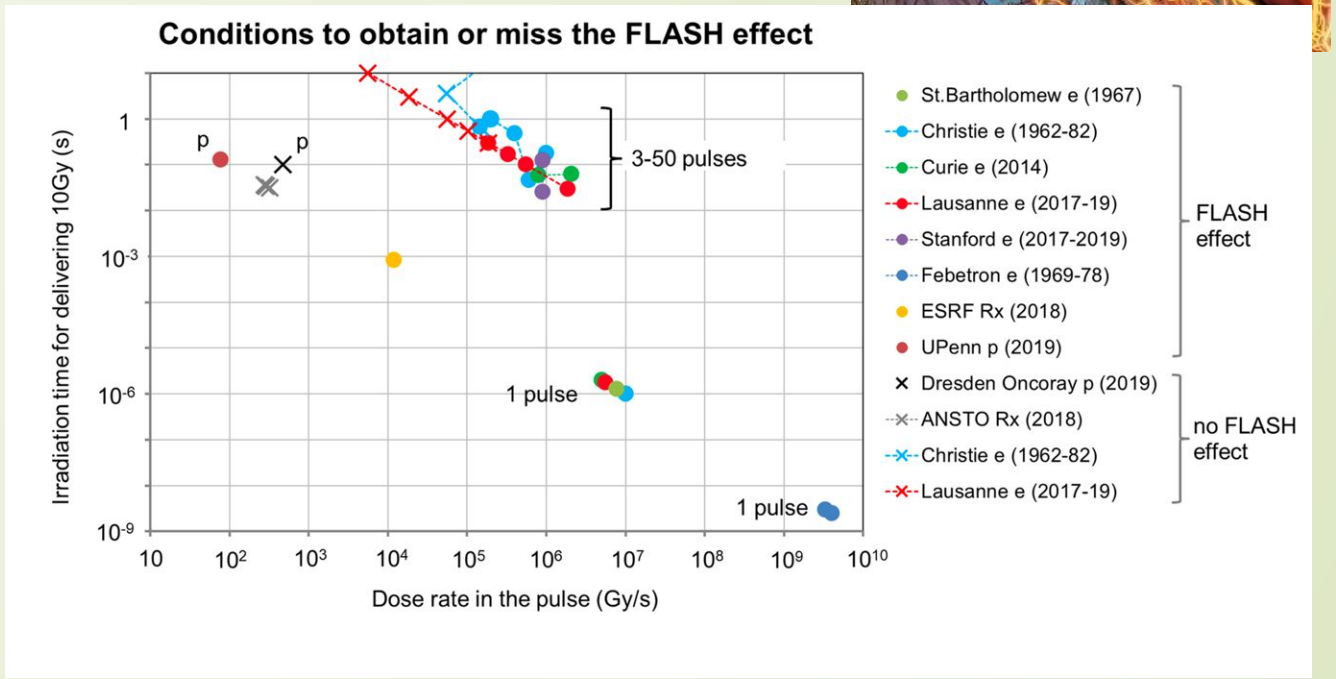




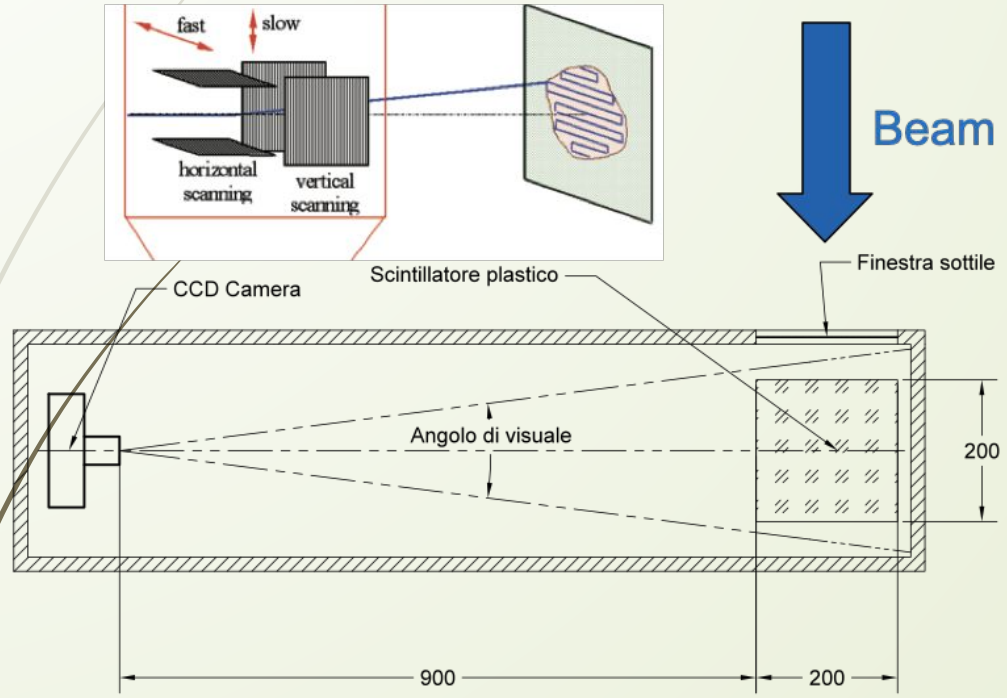
Beside CIRT → going 'FLASH'

The standard, in EBRT so far, was to deliver the dose with rates ~ 0.1 Gy/s or less. A typical treatment of a tumor foresees several sessions (fractions) with low dose (~ 2 - 6 Gy) delivered in ~minutes or less.

A change of paradigm: to achieve a better sparing of the OARs (Organs At Risk, normal tissue), the **a large** dose (> 6 Gy?) has to be delivered **at ultra high dose rates** (>10^3 Gy/s)



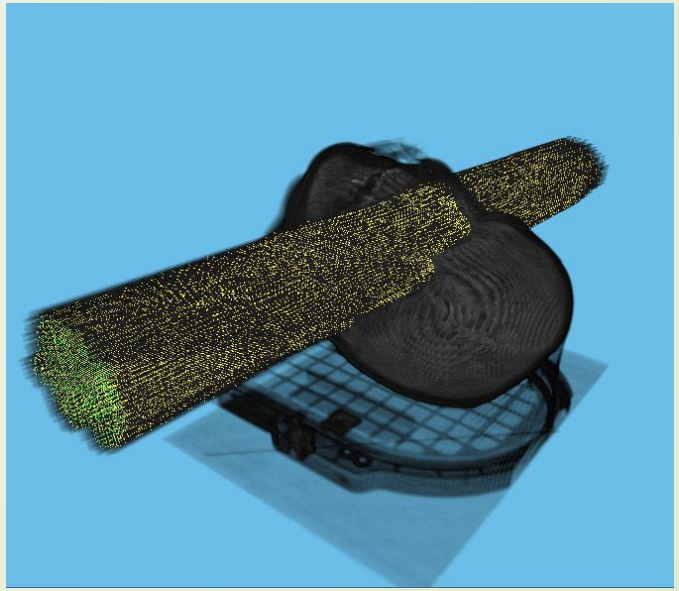
HeCheck @ CNAO

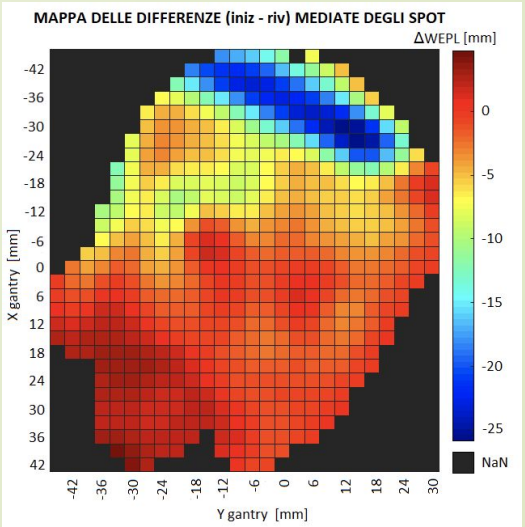


SBIG camera with Nikkor photographic lens

Detector DAQ finalisation, sync with beam delivery, evaluation of the method sensitivity

He beams expected in 2022!





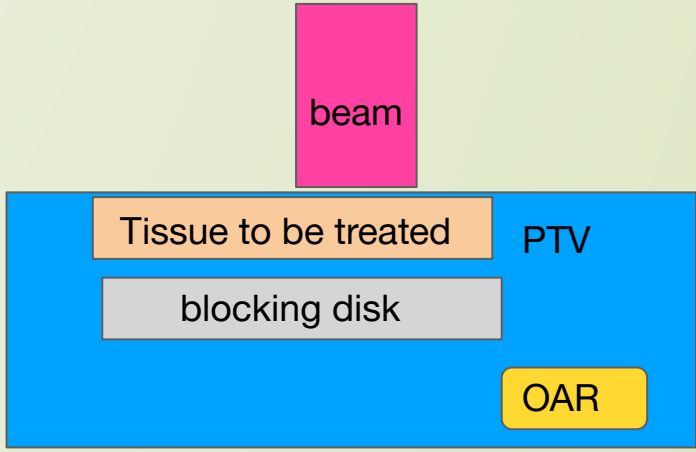
FLASH low energy → IORT TPS

In principle the idea behind TPS x IORT (FLASH or not, does not make any difference at this stage) is simple:

- Someone provides the imaging &the PTV + the OARs
- Someone else provides the prescription (e.g.: 25 Gy @ PTV and less than XX Gy @ OAR1 and YY Gy @ OAR2)
- And then...

... things are challenging.

- We need to be fast (1 min), We need to explore several different options (positions, angles, energies)
- We need to compare them on solid grounds (avoid false minima due to too low statistics)
- We need to provide the best options that matches the requirements of “Dose to the PTV” and “Sparing of the OARs”.



Simplified scheme for IORT breast cancer optimisation

TPS IORT - what's next

The dose evaluation is ~ done… We still need to develop a tool that

- ★ Scans the different positions/energies/angles [for that one we still need some time to play with geometry in FRED]
- ★ Computes/compares the DVHs once the constraints/prescriptions are known
- ★ Gives you the 'best' plan

Once the full chain will be technically available, we will be ready to answer the question: "are we fast enough to provide a solid answer to the optimisation problem?"...

In the meanwhile we have to start with SIT & FLASH gurus the study of reasonable use cases (breast cancer / prostate)