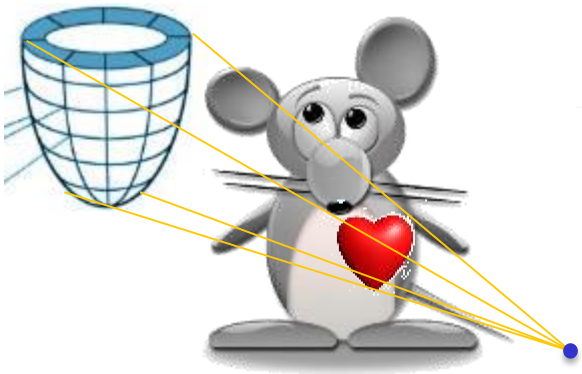
International Conference on Monte Carlo Techniques for Medical Applications (MCMA2017)

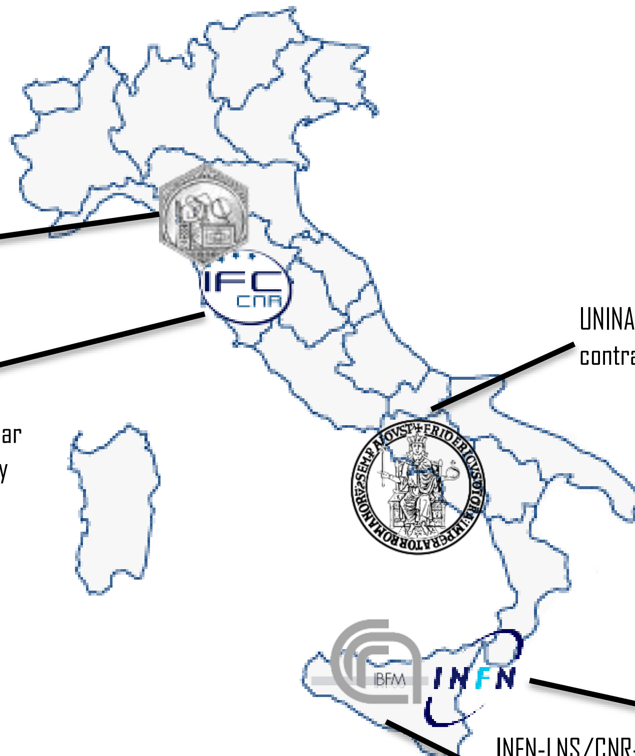
15th - 18th October 2017 Napoli, Italy

Characterization of an X-ray source based on laser-target interaction using the Geant4 Monte Carlo toolkit.



Pietro Pisciotta, Giorgio Russo, Luciano Pandola, Leonida A. Gizzi, Luca Labate, Debora Lamia, Daniele Panetta and Paolo Russo

Collaboration



CNR-INO: Ultra-intense lasers, laser-driven particle accelerators, nonlinear optics

CNR-IFC: Preclinical multimodal molecular imaging, animal facility, CBCT technology development

UNINA: CBCT technology development, phase contrast X-ray imaging

INFN-LNS/CNR-IBFM: Monte Carlo simulation

PRIN 2015: **Clinically Compatible Tool For Advanced Translational Research with Ultrashort and Ultraintense X-ray Pulses**

Background and motivations

Espe *et al. Journal of Cardiovascular Magnetic Resonance* 2013, **15**:82
http://jcmr-online.com/content/15/1/82

Journal of Cardiovascular Magnetic Resonance

RESEARCH **Open Access**

Novel insight into the detailed myocardial motion and deformation of the rodent heart using high-resolution phase contrast cardiovascular magnetic resonance

Emil KS Espe[1,2*], Jan Magnus Aronsen[1,2,3], Kristine Skårdal[1,2], Jürgen E Schneider[4], Lili Zhang[1,2] and Ivar Sjaastad[1,2]

conventional forward-backward motion tracking, intra- and interstudy limits-of-agreements were reduced using this extension (Table 3). However, to accurately capture complex three-directional motion and thus true 3D strain, volumetric data is required [42], and should be addressed by future studies. Volumetric PC-CMR might be achieved by embedding velocity encoding gradients into conventional or accelerated 3D imaging protocols, and has been demonstrated to allow comprehensive evaluation of both blood flow and myocardial motion in humans [43-45], but not, to our knowledge, in small animals.

Vevo® 2100 System

The first high-frequency, high-resolution digital imaging platform with linear array technology and Color Doppler Mode

- Superior resolution and image uniformity through entire field of view
- 30 micron resolution
- Frame rates in 2D up to 740 fps (for a 4x4 mm field of view)
- Wider field of view

Vevo2100

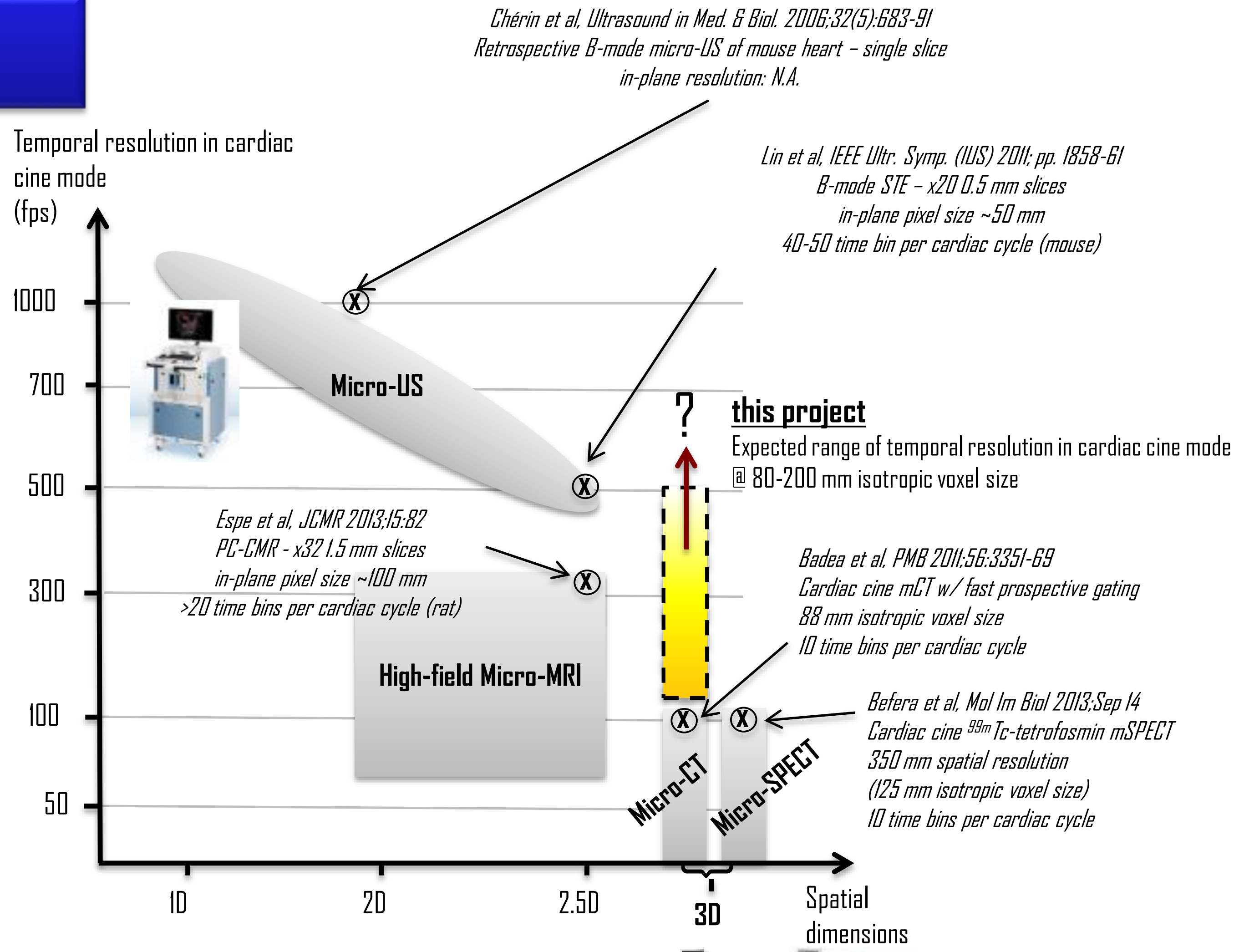
- Superb B-Mode (2D) imaging for anatomical visualization and quantification, with enhanced temporal resolution with frame rates up to 740 fps (in 2D for a 4x4 mm FOV) , and enhanced image uniformity with multiple focal zones (included in base package)
- M-Mode for visualization and quantification of wall motion in cardiovascular research, single line acquisition allows for the very high-temporal (1000 fps) resolution necessary for analysis of LV function
- Anatomical M-Mode for adjustable anatomical orientation in reconstructed M-Mode imaging; software automatically optimizes field of view for maximum frame rate

Expected results - imaging

Typical small rodent heart rates
Mice: 300-600 bpm, RR 100-200 ms
Rats: 170-400 bpm, RR 150-350 ms

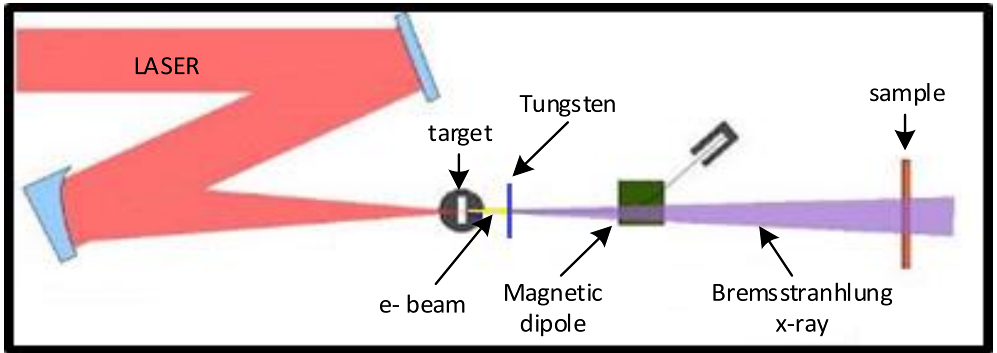
- Mice and rats are the most validated animal models for CVD such as heart failure and myocardial infarction*
- Real volumetric (isotropic) data is required to capture the complex 3D motion and strain of the rodent heart**

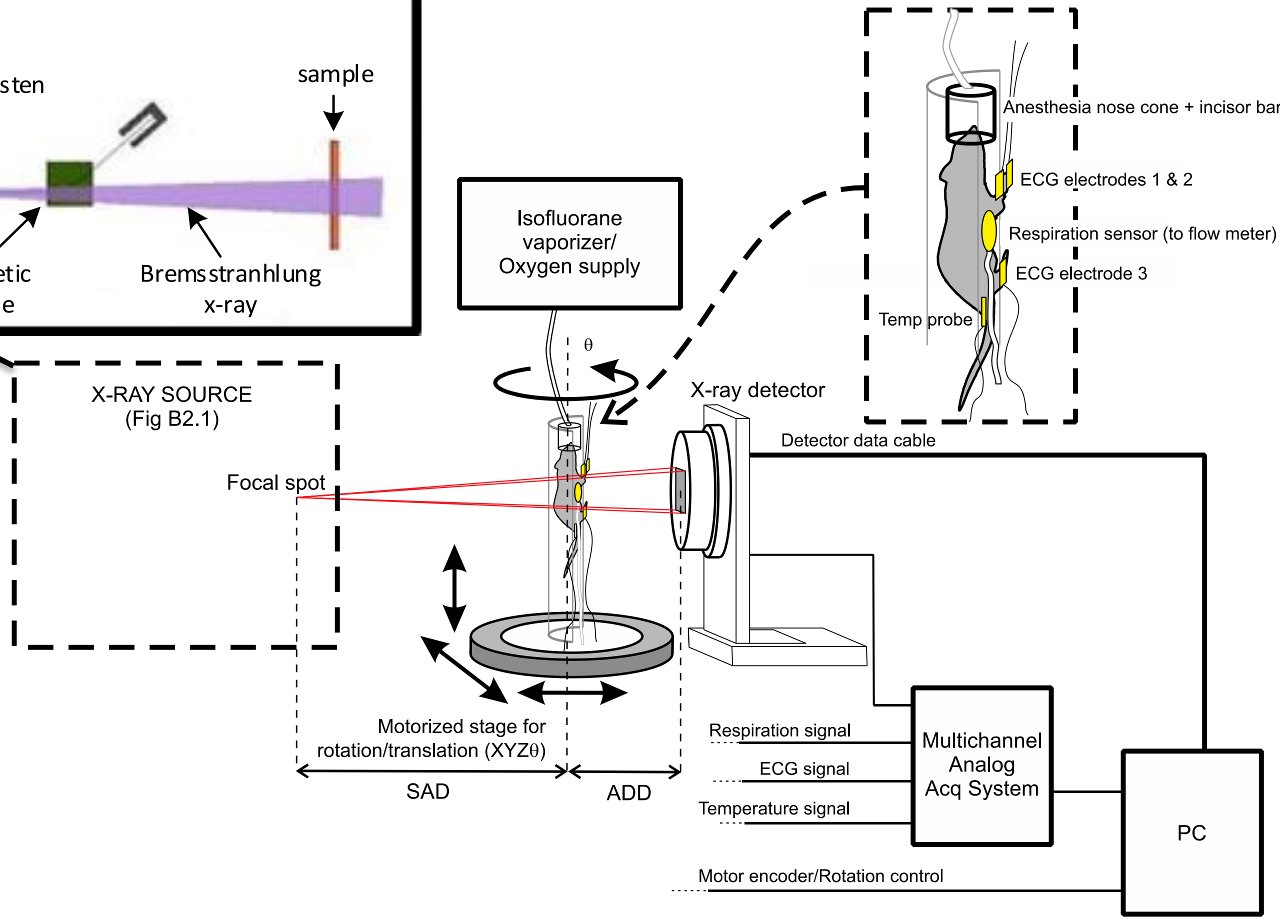
- **Cardiac 4D micro-CT with retrospective gating:**
  - **Pro's: high spatial resolution, isotropic.**
  - **Con's: trade-off between temporal resolution, image quality and dose.**



(*) Russel et al, Cardiovasc Pathol 2006; 15:318
(**) Espe et al, J Cardiovas Mag Res 2013, 15:82

Preclinical imaging experimental setup





The X-ray source is designed on top of the laser-driven electron accelerator already running at the Intense Laser Irradiation Laboratory of the INO-CNR in Pisa. It is based upon a:

- 10 TW laser system delivering
- <40 fs duration pulses with
- >400 mJ energy at
- a 10 Hz repetition rate.

This accelerator has been already proved to be able to deliver electron bunches with

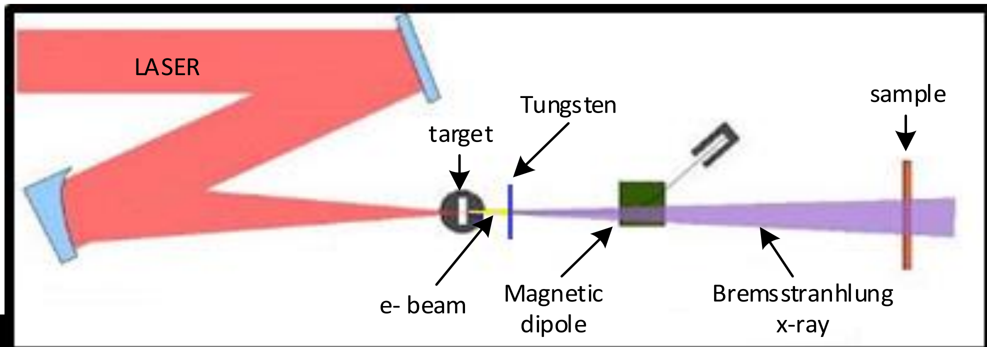
- up to around 80 MeV with
- energy spread down to around 25% and
- bunch charge ranging from few tens of pC up to few nC.

MC study: geometry

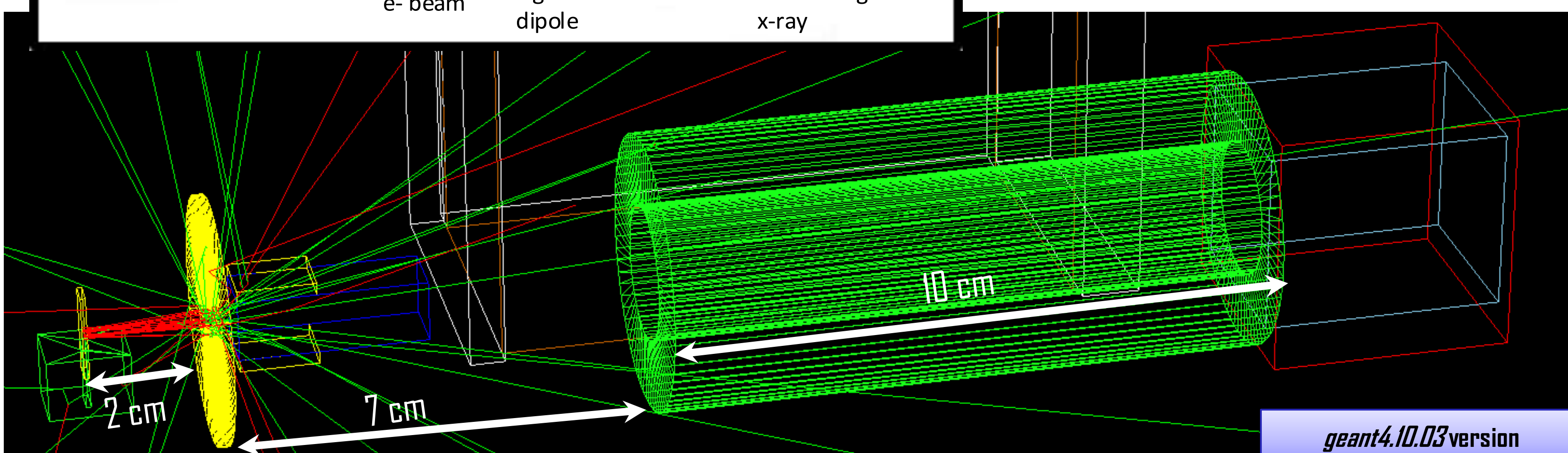
Aims:

- To design,
- To study and
- To optimize

the main characteristics of an X-ray bremsstrahlung source based on a laser-driven electron beam accelerated via Laser Wake-Field Acceleration

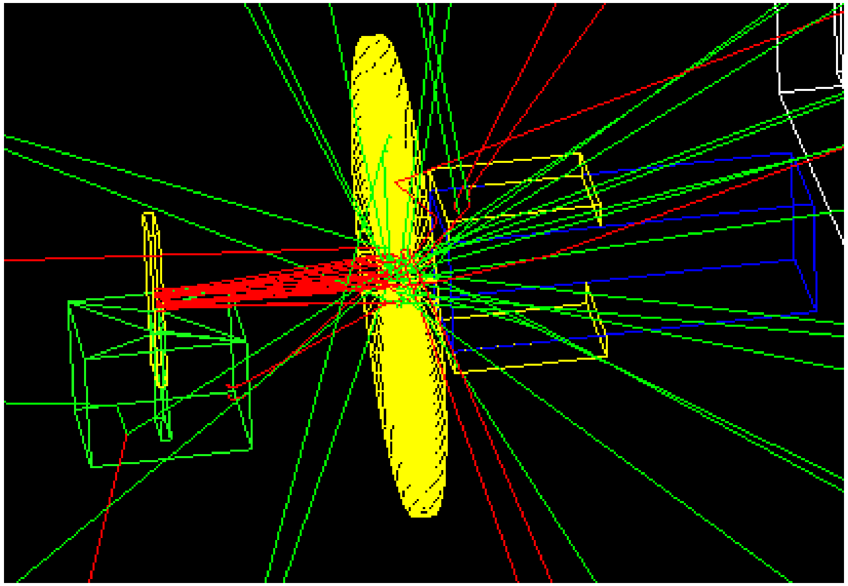


Development of a new Geant4 application



Source features

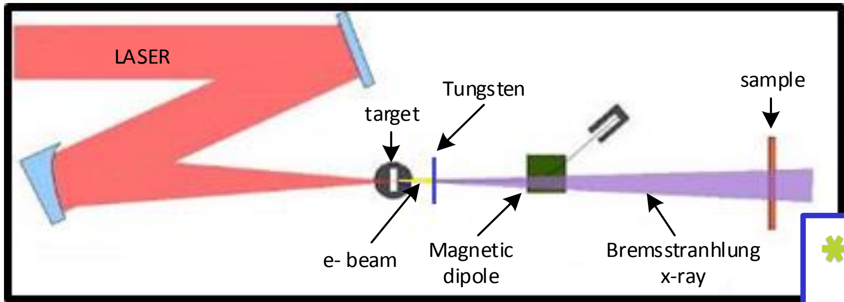
Spectrum of the source



- shape: decreasing exponential
- particle: e-
- Energy MAX = 30 MeV
- Source dimension = 0.5 mm
- Divergence = 6°

Electron interactions are simulated, starting form an exponentially decreasing e- energy spectrum; a thin tungsten foil has been used in order to generate X-rays via bremsstrahlung.

What we studied…

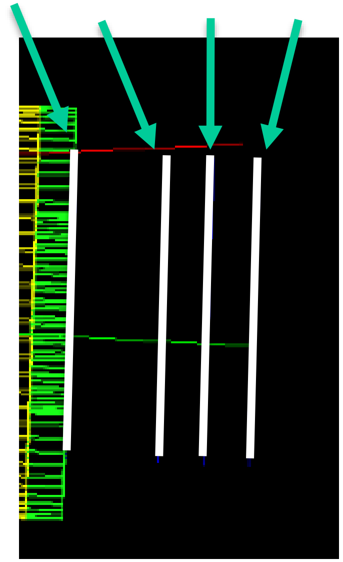


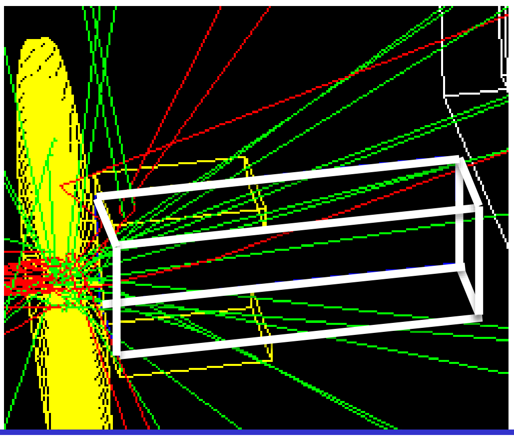
- Magnetic deflector dipole to reduce electron contamination

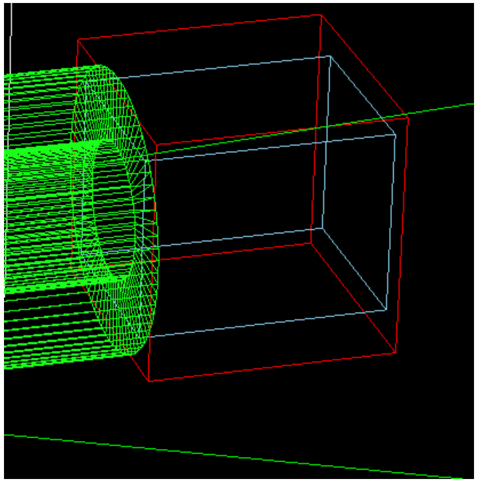
- Water phantom for dosimetric study

- Layer for spectra study

0 – 10 – 15 – 20 mm







The Monte Carlo application allows studying many features of the resulting X-ray beam such as:

- conversion efficiency using different foil thicknesses and materials
- particle spectra in the output beam
- X-ray source size
- the out-of-beam scattered radiation for external shielding design.

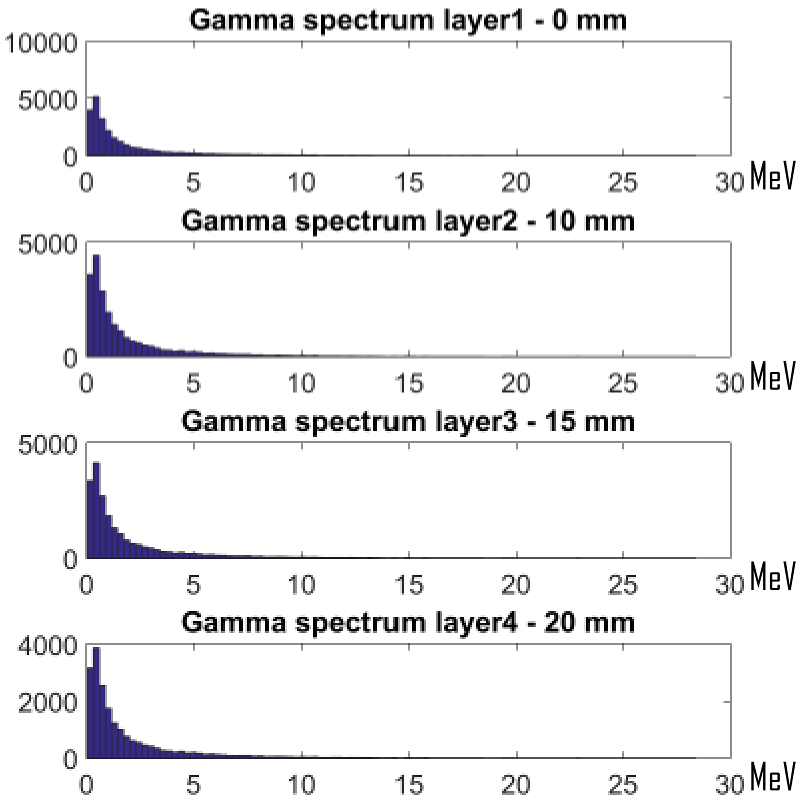
Spectra - study results

Results

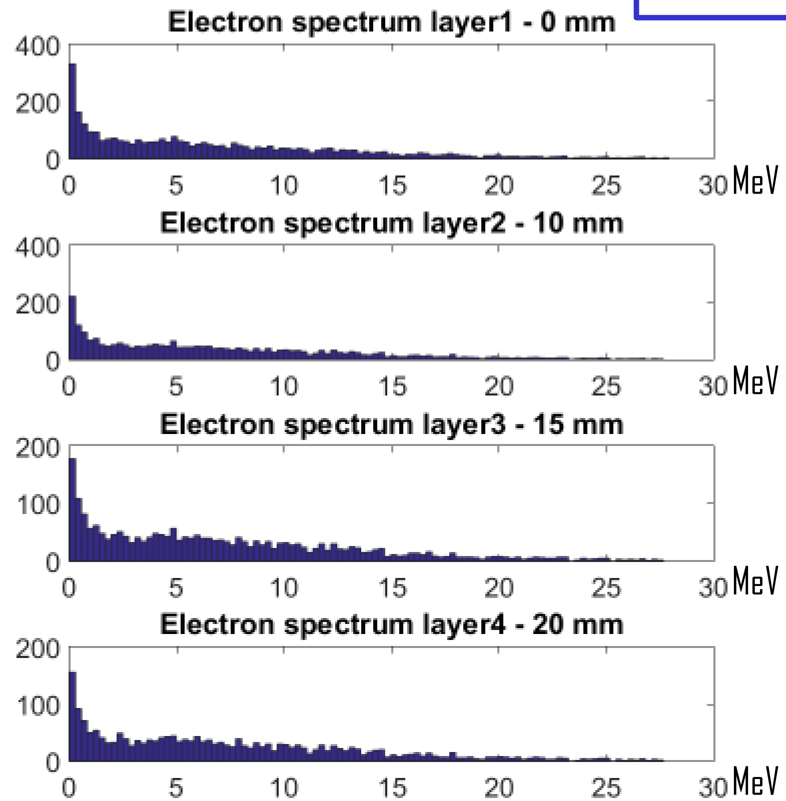
- $W_{thickness}$ = 0.75 mm

	particle	#	%Electronic contamination
Layer 1	photons	49108	11,70
	electrons	6505	
Layer 2	photons	42943	11,06
	electrons	5339	
Layer 3	photons	40559	10,55
	electrons	4786	
Layer 4	photons	38390	9,97
	electrons	4252	

Gamma spectra



Electron spectra



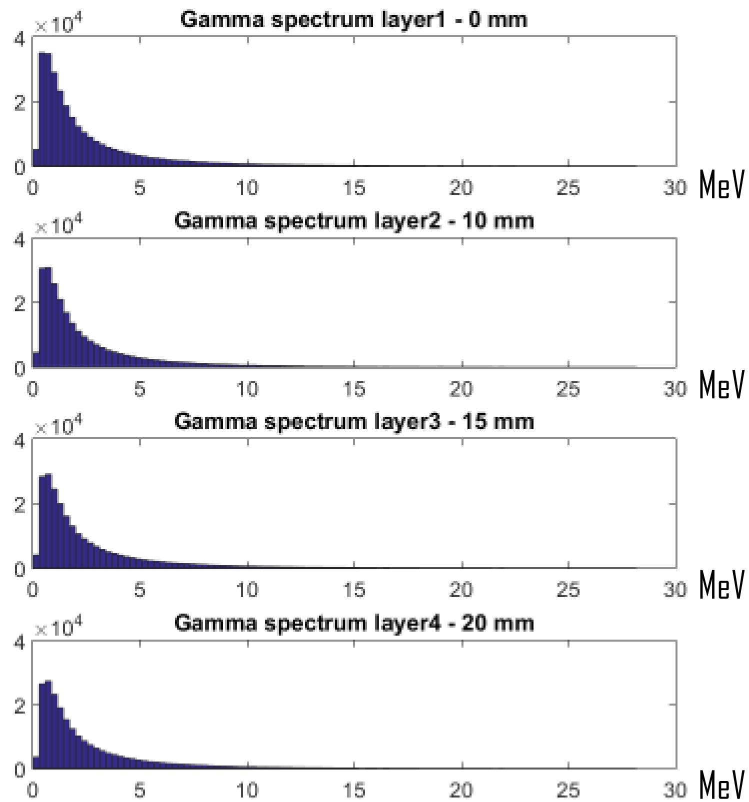
Spectra - study results

Results

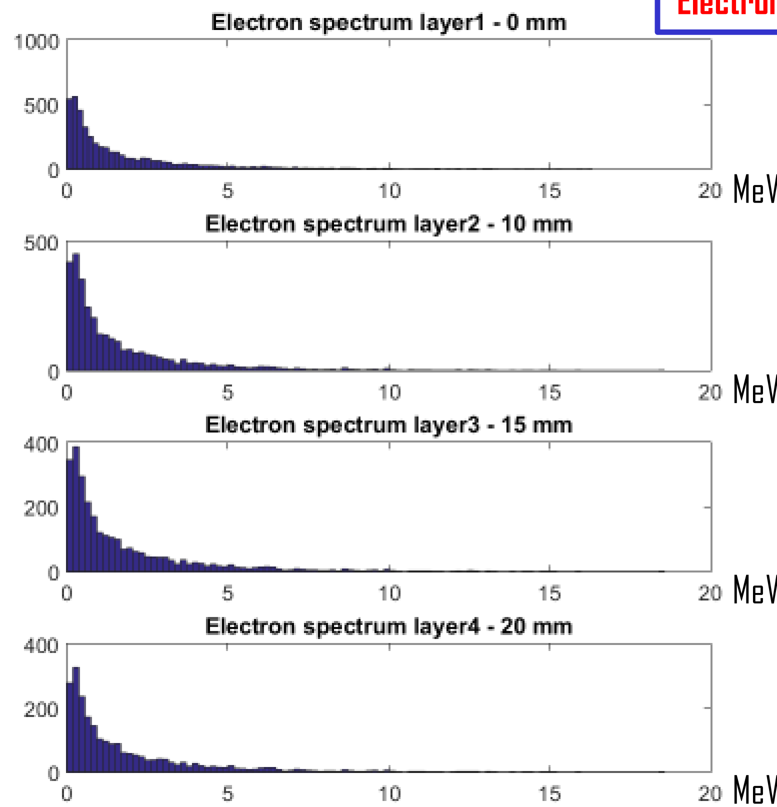
- $W_{thickness}$ = 4.00 mm

	particle	#	%Electronic contamination
Layer 1	photons	174008	1,59
	electrons	2815	
Layer 2	photons	156256	1,33
	electrons	2105	
Layer 3	photons	147924	1,20
	electrons	1802	
Layer 4	photons	140308	1,07
	electrons	1517	

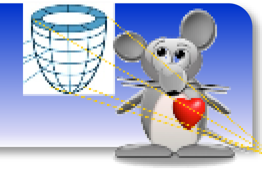
Gamma spectra



Electron spectra



Spectra - study results

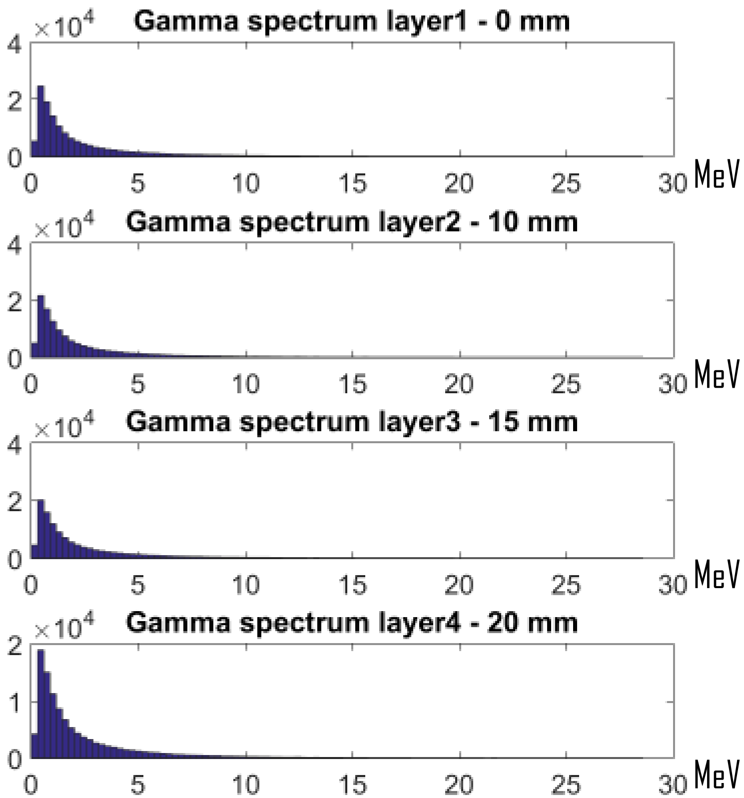


Results

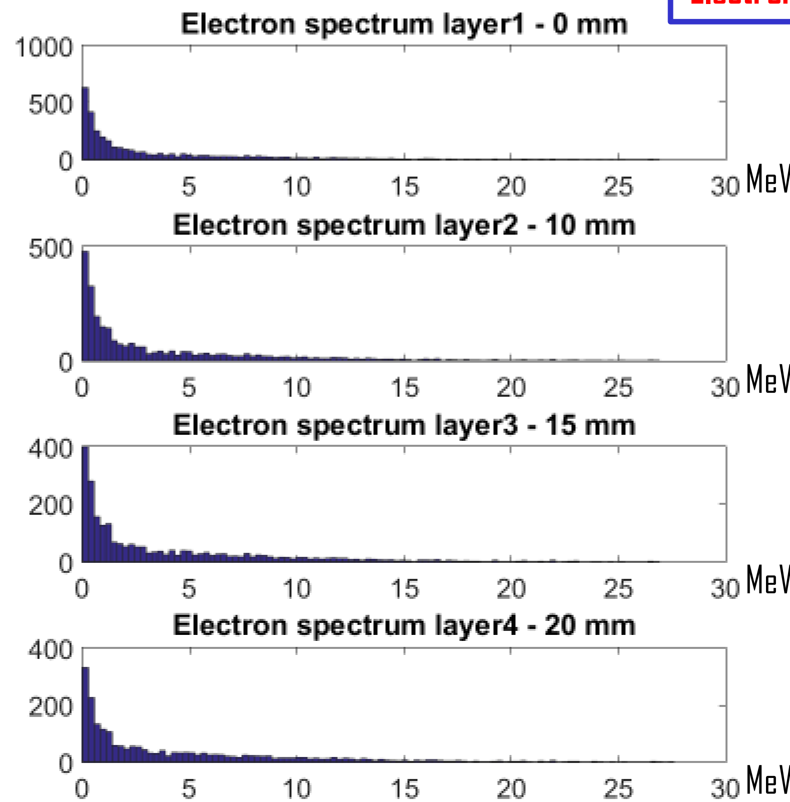
- $W_{thickness}$ = 6.00 mm

	particle	#	%Electronic contamination
Layer 1	photons	130001	1,65
	electrons	2184	
Layer 2	photons	116684	1,38
	electrons	1627	
Layer 3	photons	110394	1,23
	electrons	1378	
Layer 4	photons	104570	1,13
	electrons	1192	

Gamma spectra



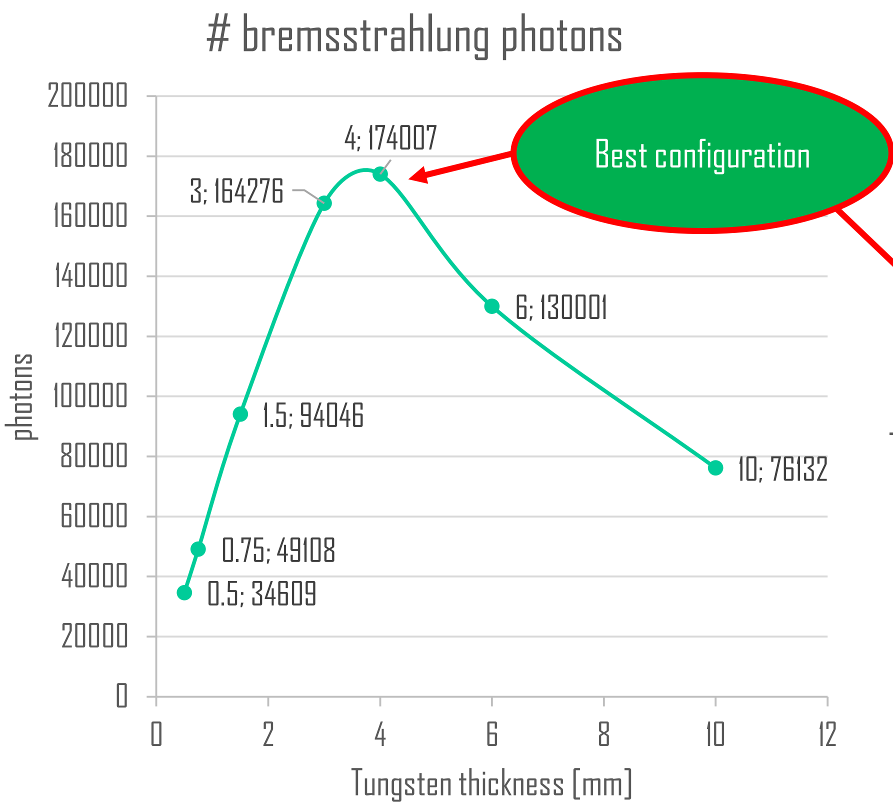
Electron spectra

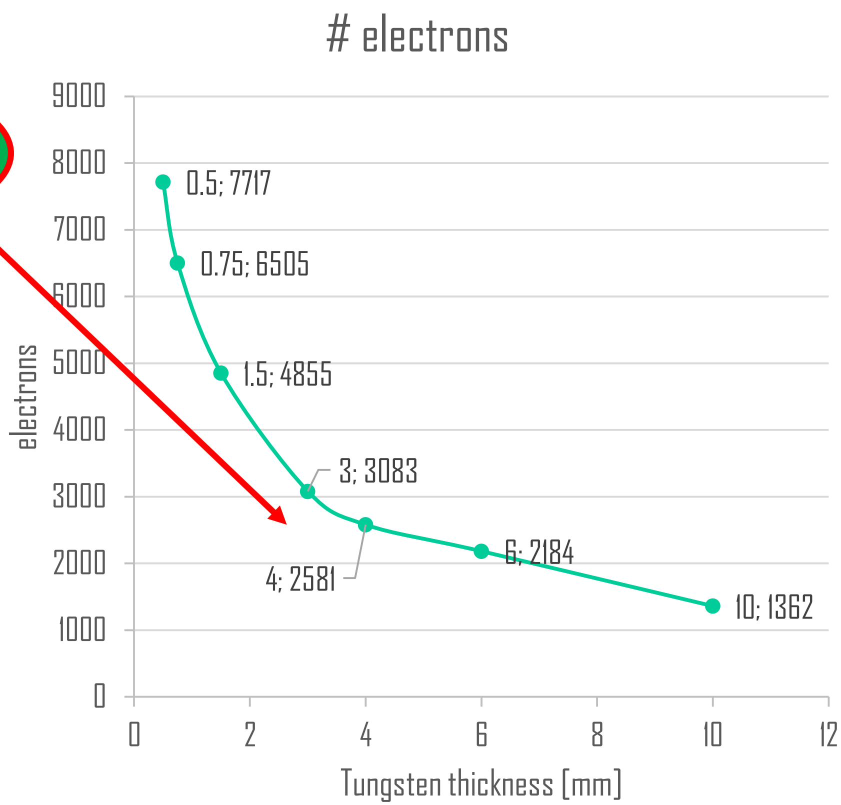


Photons & e- $W_{thickness}$

- conversion efficiency using different foil thicknesses

- particle contamination of the output beam



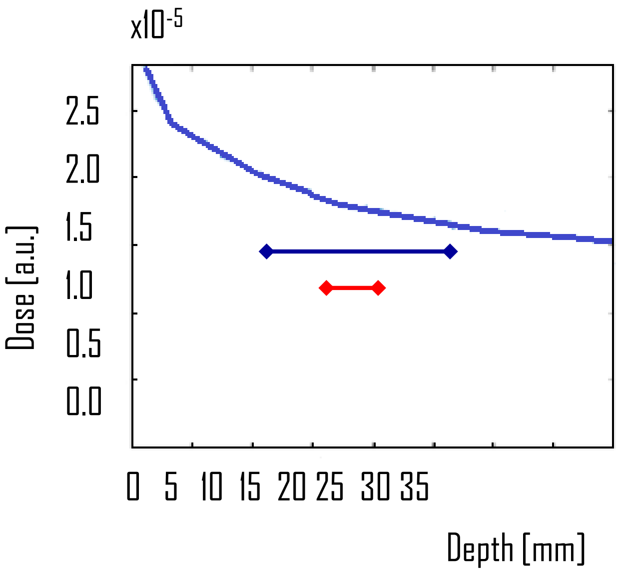


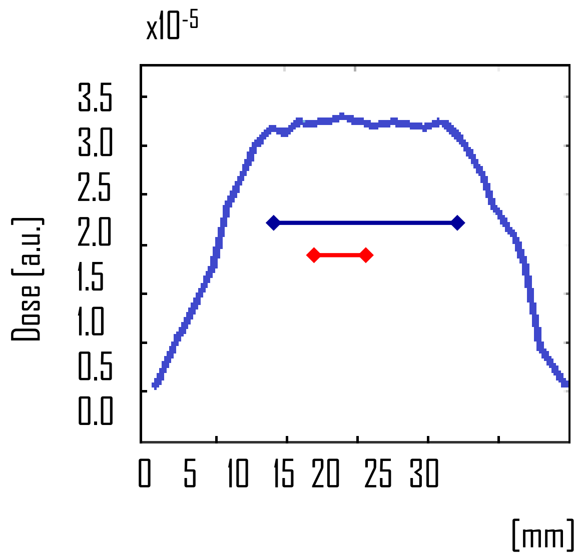
Dose distributions study results

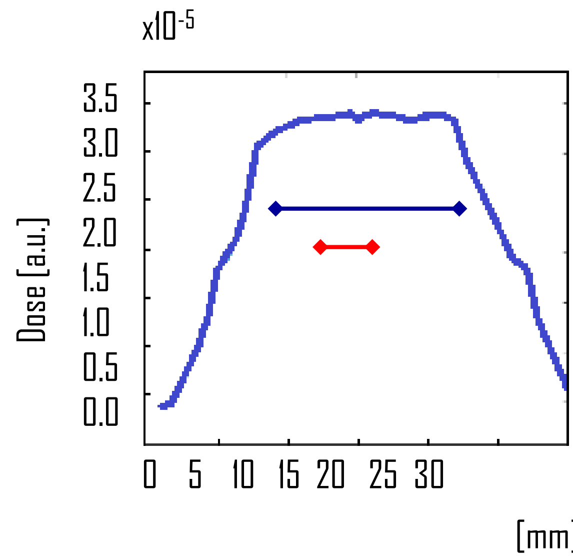
Results

- Preliminary dose distribution

The x-y profile dimensions permit to cover the entire thorax dimension and, in particular, the mouse heart dimension.







$$Dose^{e^-}_{mean} \approx 10^{-12} Gy/e^-$$

$$Dose^{shot}_{mean} \approx 10^{-4} Gy/shot$$

Mouse heart dimension

Thorax dimension

Conclusions and future impact

MC allows us to simulate:

Electron interactions with tungsten foil to generate X-rays via bremsstrahlung.
In particular, starting form an exponentially decreasing e- energy spectrum.

$W_{thickness}$	4 mm
yield	≈ 1%
e- reaching target	< 1.6%
$Dose^{e^-}_{mean}$	$\approx 10^{-12} Gy/e^-$
$Dose^{shot}_{mean}$	$\approx 10^{-4} Gy/shot$

Best configuration

This preliminary work will be important to study and develop a new source to perform preclinical imaging
.
The next step will be to perform the system and dosimetric validation using Gafchromic film.
This study lays the foundation for future laser Thompson source for imaging.

That's all !!! Thank you for attention!

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Conclusions and future impact

4 – Possible application potentialities and scientific and/or technological and/or social and/or economic impact of the project

MC -> studiare metodo di produzione

[…] cardiovascular diseases such as myocardial infarction and postischemic heart failure represent the main cause of mortality and morbidity in the western world, **and the availability of cutting edge technology for preclinical studies of these diseases is of paramount importance.** […] the ability to perform imaging studies with the expected performances in a table-top system, installed in a multidiscliplinary context fully ready for preclinical research, such as the CNR campus in Pisa, **might open new possibilities of high impact translational research in the context of heart diseases.**

[…] The investigation of the high-energy regime of the Thomson X-ray source is even more interesting in a long-term perspective, due to **the lack of radiation facilities for reliable preclinical studies of tumor radiotherapy. To the best of our knowledge, this type of technology is completely absent in Italy.** Setting up a complete micro-RT system for small animals is beyond the reasonable goals of this project; nonetheless, the physical characterization of the new laser-based X-ray source in an experimental setup already optimized for high-resolution imaging is particularly interesting for future applications in image guided radiation therapy experiments.

[…] **one important result of our project is the finalization of a non-conventional table-top X-ray source** based on Thomson scattering with tunable quasi-monochromatic energy, **fully covering the diagnostic energy range and allowing low-dose phase contrast imaging. The modularity of the scanner design will allow**, upon completion of this project, to allocate beam-time for **the assessment of such new source for future application in medical imaging,**

[…] We believe that the employment of the new X-ray source, reproducing beam qualities not far from those obtained at synchrotron facilities in a table-top system […] is potentially of very high impact. In this sense, **the significance of the expected project's results** on source performance characterization for radiographic and tomographic imaging in animals **might extend well beyond the project scope itself.**

Cardiac imaging in mice - State of art

- Mice and rats are the most validated animal models for CVD such as heart failure and myocardial infarction*
- Real volumetric (isotropic) data is required to capture the complex 3D motion and strain of the rodent heart**

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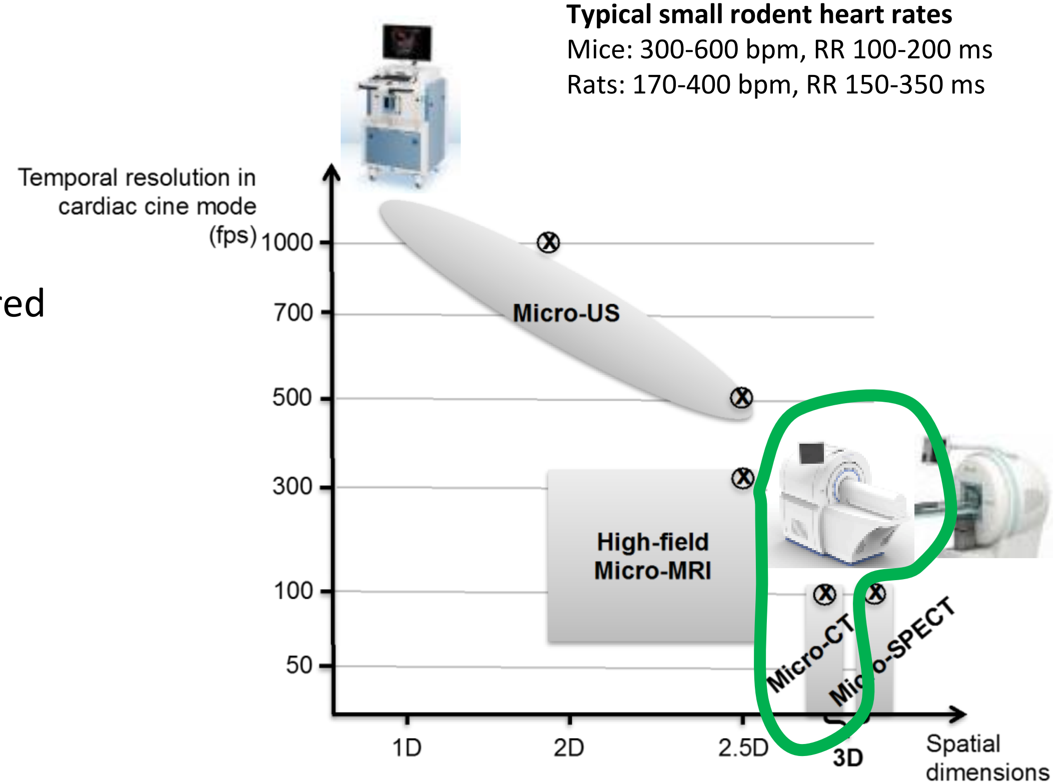

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Geant4 toolkit → *Geometry and Tracking*

...is a toolkit for simulation of particles passing through and interacting with matter

Object Oriented Toolkit (C++) born for the simulation of large scale HEP experiments at CERN (Geneva)

Agostinelli S. et al., GEANT4-a simulation toolkit, Nucl. Inst. And Methods in Phys. Res. A 506, 250-303 (2003)

- ***Hadronic (validation)***
- ***Low Energy EM physics (validation)***
- ***Advanced Example (application development)***

Reference:

1. G. A. P. Cirrone et al., **"Implementation of a new Monte Carlo - GEANT4 simulation tool for the development of a proton therapy beam line and verification of the related dose distributions"**, *IEEE Transactions on Nuclear Science*, Vol. 52, **2005**
2. Romano F, Cirrone GAP, Cuttone G, Rosa FD, Mazzaglia SE, Petrovic I, Fira AR, Varisano A. "**A monte carlo study for the calculation of the average linear energy transfer (LET) distributions for a clinical proton beam line and a radiobiological carbon ion beam line.**" *Phys Med Biol* . **2014**; 59(12):2863-82.