5th NUCLEAR PHOTONICS CONFERENCE
October 6 - 10 2025, Darmstadt, Germany

CONICAL COIL FOCUSING OF LASER-PLASMA ACCELERATED PROTON BEAMS FOR BIOMEDICAL APPLICATIONS

Laura-Anamaria Nălbaru[1], Michaela Arnold[2], Cătălin Ticoş[1,3]

[1]SDSA, National University of Science and Technology Politehnica Bucharest, Splaiul Independentei no. 313, RO-060042, Bucharest, Romania

[2]Institut fur Kernphysik, Technische Universitat Darmstadt, Schlossgartenstr. 9,64289 Darmstadt, Germany

[3]Extreme Light Infrastructure - Nuclear Physics (ELI-NP), "Horia Hulubei" National Institute for Physics and Nuclear Engineering (IFIN-HH), 30 Reactorului Street, RO-077125 Bucharest-Măgurele, Romania

Content

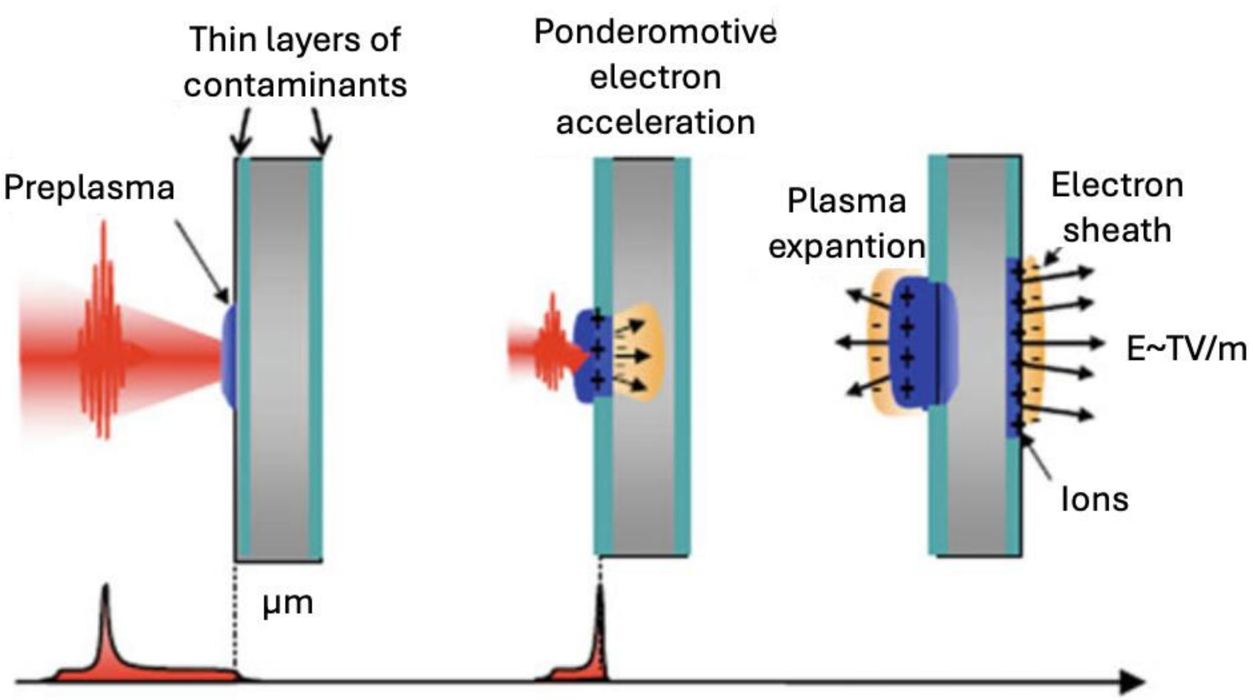
Laser-driven proton acceleration: TNSA

Application development: FLASH effect in proton beam therapy

COMSOL Simulations – Results and Discussions

Conclusions

TNSA: Target Normal Sheath Acceleration



Paul McKenna, et. al., Phil. Trans. R. Soc. A (2006) 364, 711–723

Typical TNSA energies obtained are less than 100 MeV
Hybrid (TNSA +RPA) acceleration schemes >100 MeV

Laser-driven proton beams with energies up to 120-150 MeV have already been achieved.
(Tim Ziegler, et. al., Nat. PhyS. (2024))

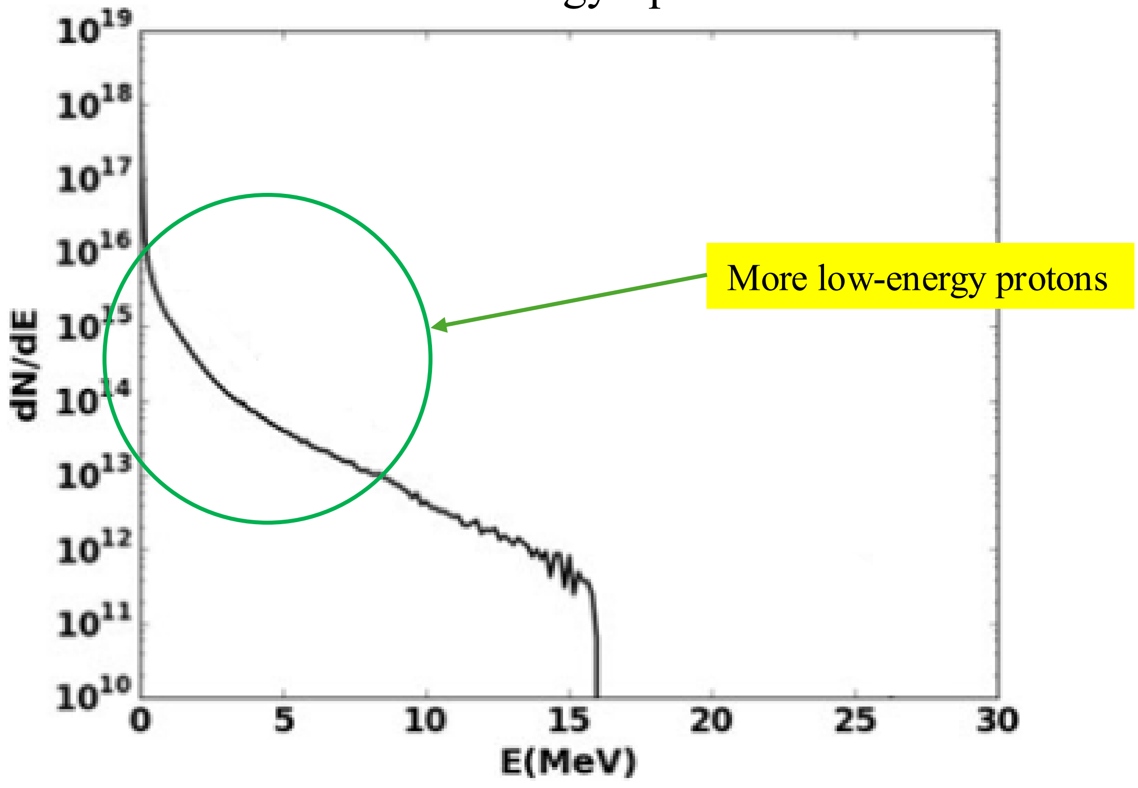
Proton beams with energies up to 200 MeV are expected from using lasers with intensities of $10^{23} W/cm^2$

In Radiation Pressure Acceleration (RPA), the whole ultra-thin target is ionized and accelerated forward by the sheath field

Laser-plasma accelerated proton beams in TNSA

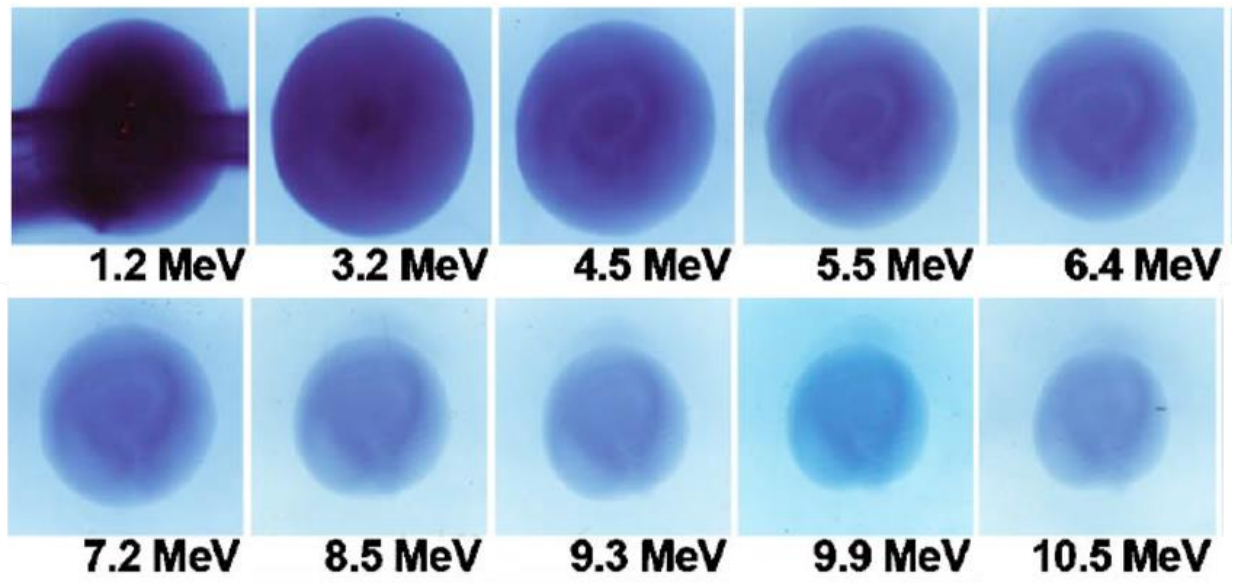
Exponentially decaying energy distribution of particles

Proton Energy Spectrum



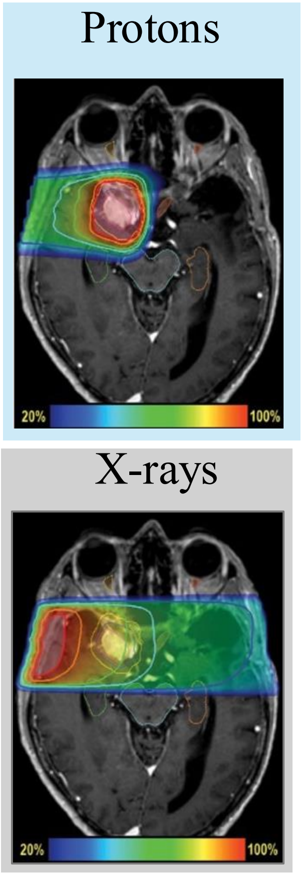
S. Kumar, D.N. Gupta, *Lasers and Particle Beams, 1-6* (2020)

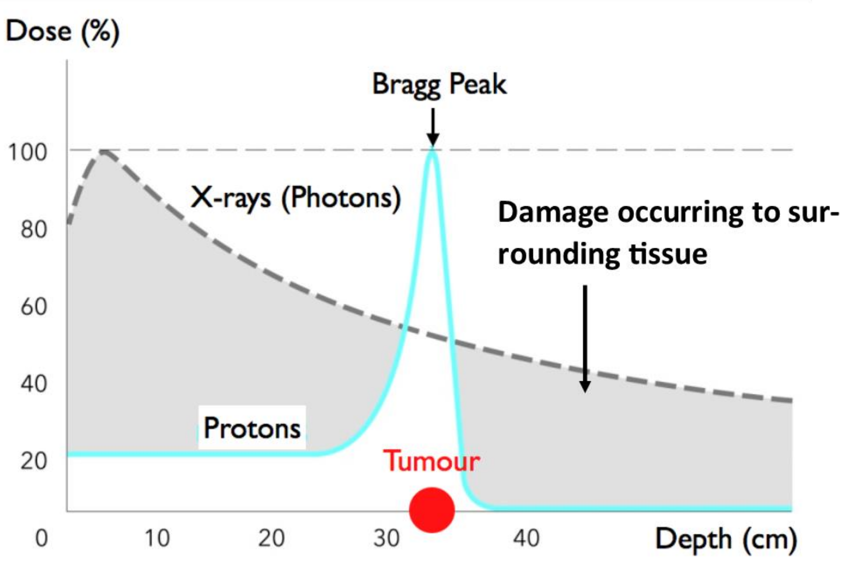
RCF stacks

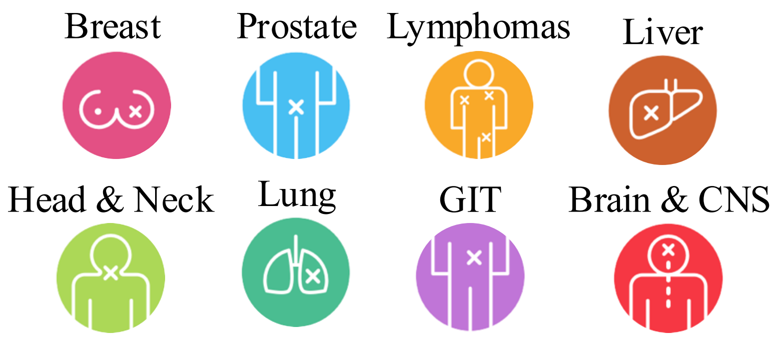


F. Nürnberg, et. al., *Rev. Sci. Instrum.* 80, 033301 (2009)

Proton beam therapy - FLASH Effect







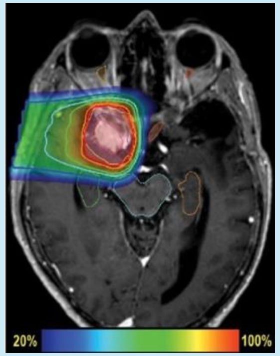
Advantages of proton beam therapy

- Precise targeting of the tumor;
- Higher radiation dose to the tumor;
- Lower risk of radiation damage to healthy tissue;
- Fewer and milder side effects;
- Lower chances of secondary cancer;

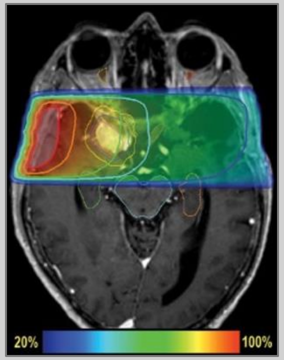
Approximately 140 operating proton therapy centers worldwide

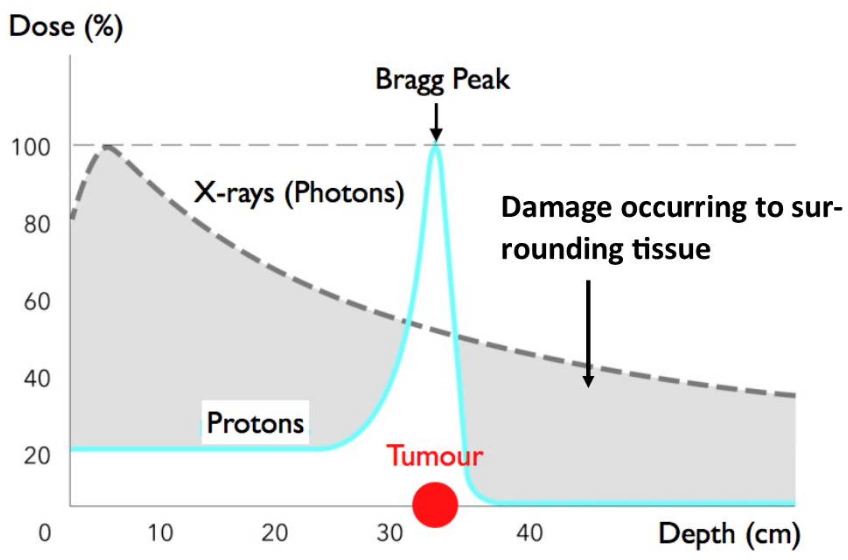
Proton beam therapy - FLASH Effect

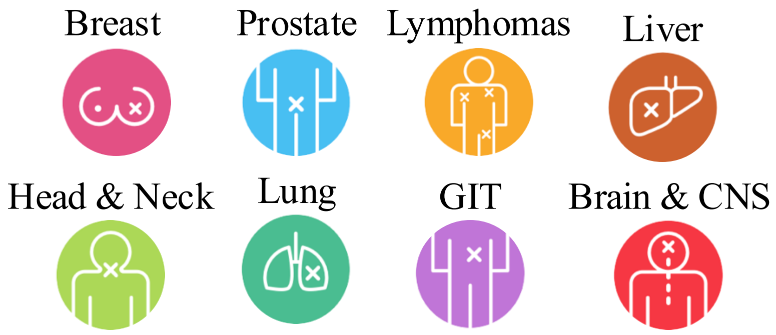
Protons



X-rays







Advantages of proton beam therapy

- Precise targeting of the tumor;
- Higher radiation dose to the tumor;
- Lower risk of radiation damage to healthy tissue;
- Fewer and milder side effects;
- Lower chances of secondary cancer;

FLASH Effect

- Effect triggered by delivering an **ultra-high dose rate** of radiation (> 40 Gy/s)
- Unaltered tumoral response & reduced normal tissue toxicity (“spar effect”)
- Rapid dose application allows for the freezing of organ motion.

Approximately 140 operating proton therapy centers worldwide

Laser-plasma accelerated proton beams in TNSA Characteristics

Broadband energy spectra

Large Divergence (~20 degrees)

Ultrashort pulse duration of proton bunch (~ps)

High flux ($10^{11} - 10^{13}$ protons per shot)

Laser-plasma accelerated proton beams in TNSA Characteristics

Broadband energy spectra

Large Divergence (~20 degrees)

Ultrashort pulse duration of proton bunch (~ps)

High flux ($10^{11} - 10^{13}$ protons per shot)

Ultra-high dose rate

Laser-plasma accelerated proton beams in TNSA Characteristics

Broadband energy spectra

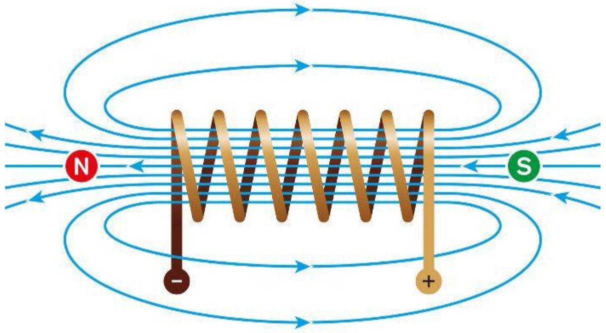
Large Divergence (~20 degrees)

Ultrashort pulse duration of proton bunch (~ps)

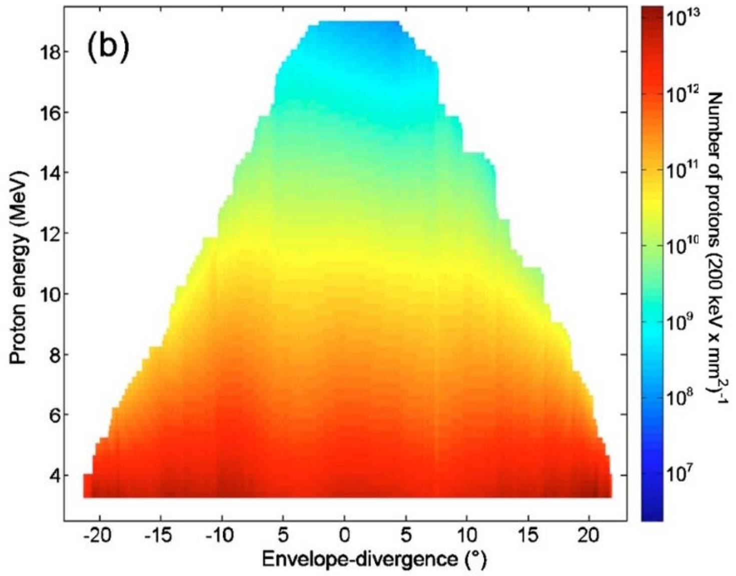
High flux ($10^{11} - 10^{13}$ protons per shot)

Ultra-high dose rate

Solenoid-based Focusing of Laser-Driven Proton Beams



Energy and divergence of LPA proton beams



F. Nürnberg, et. al., *Rev. Sci. Instrum.* 80, 033301 (2009)

$$\frac{1}{f} = \frac{B^2 l_{coil}}{4\left(\frac{p}{q}\right)^2}$$

f=focal length,
B=axial magnetic field
l_{coil}=length
p,q =momentum and charge of particle

- Stronger focusing (f shorter) when p is small

Advantages / Drawbacks of solenoid focusing solution

Simple geometry

Variable magnetic field controlled by the coil current

Very effective for smaller energy protons

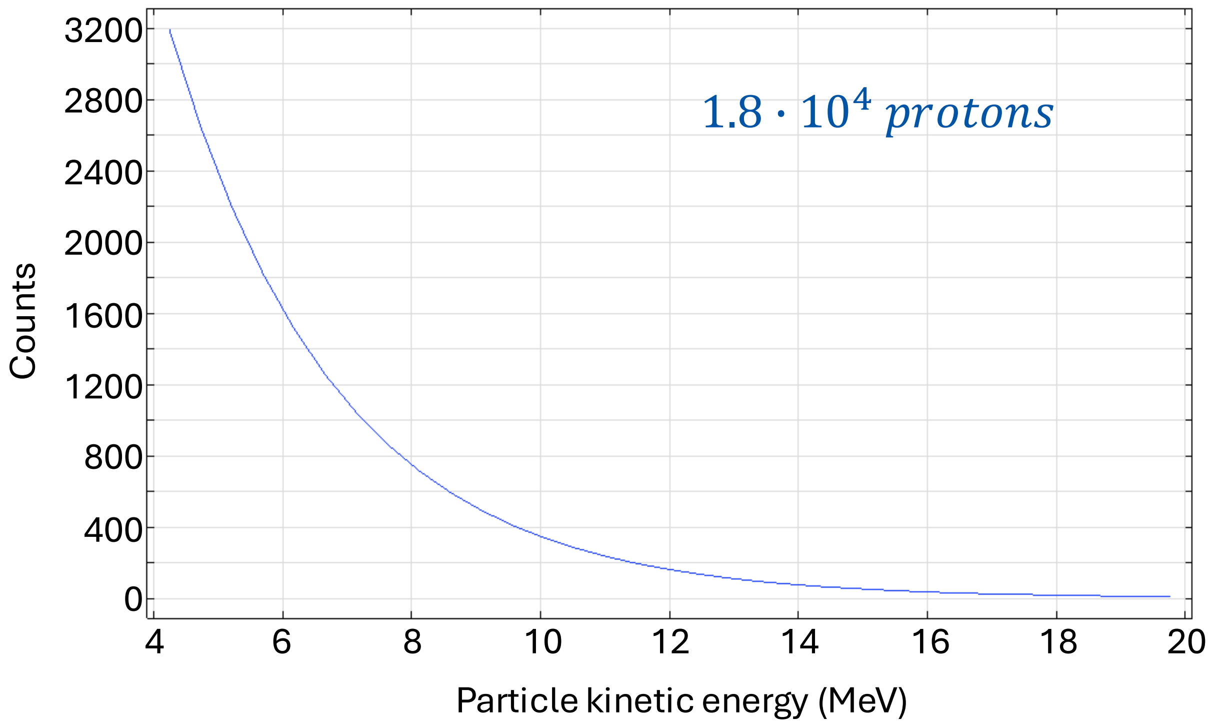
Needs high currents for high magnetic fields

We propose a new approach based on A CONICAL COIL to capture the divergent proton beam

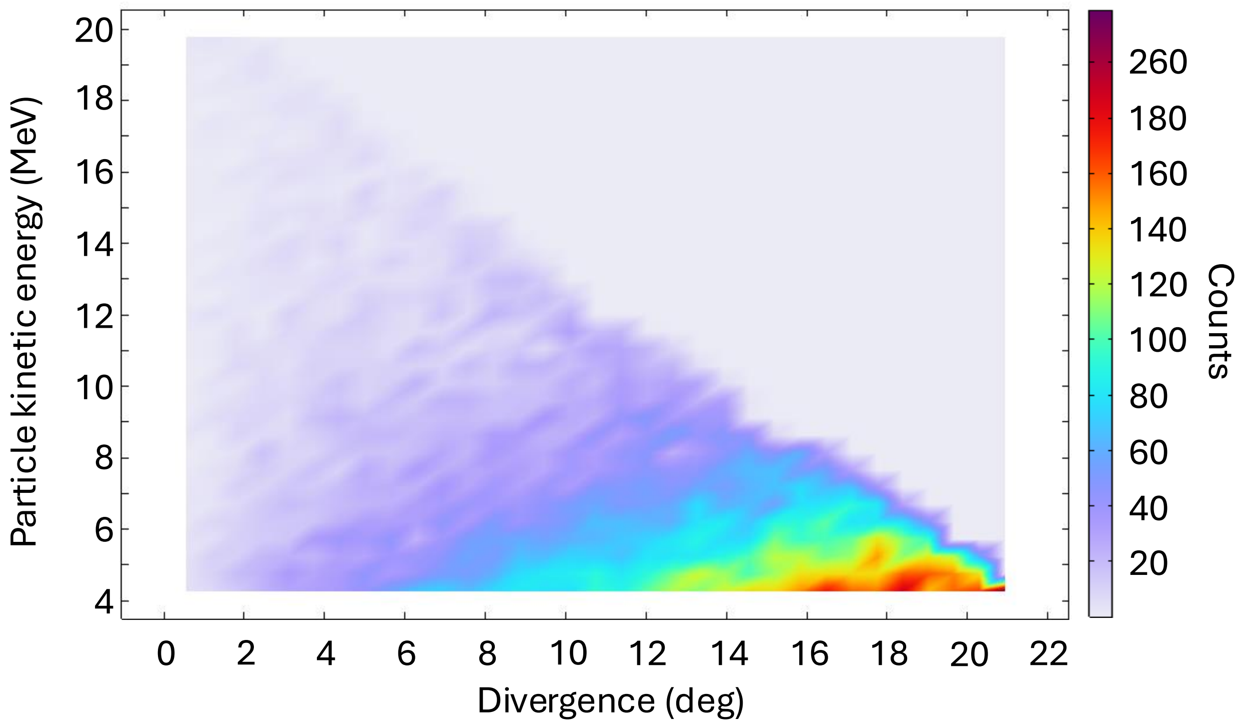
COMSOL simulation
Proton source size and distribution

Proton source size: radius of **2 micrometers**.

Proton Energy Spectrum

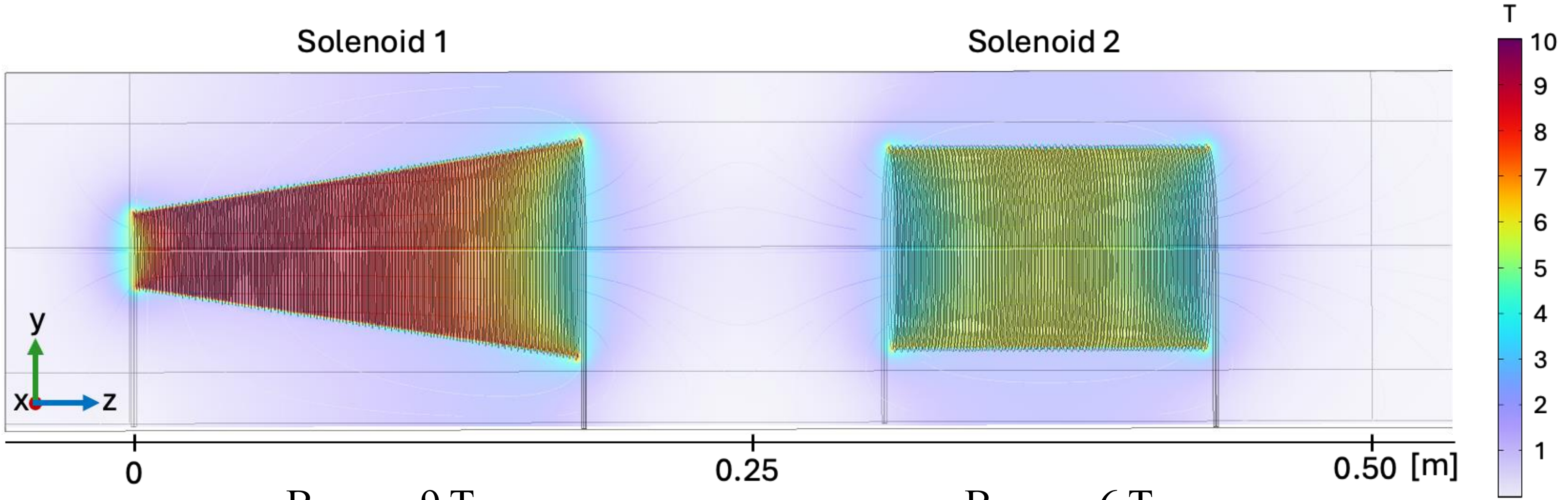


Angular Distribution



F. Nürnberg, et. al., *Rev. Sci. Instrum.* 80, 033301 (2009)

COMSOL simulation
Geometric description of two-solenoid system

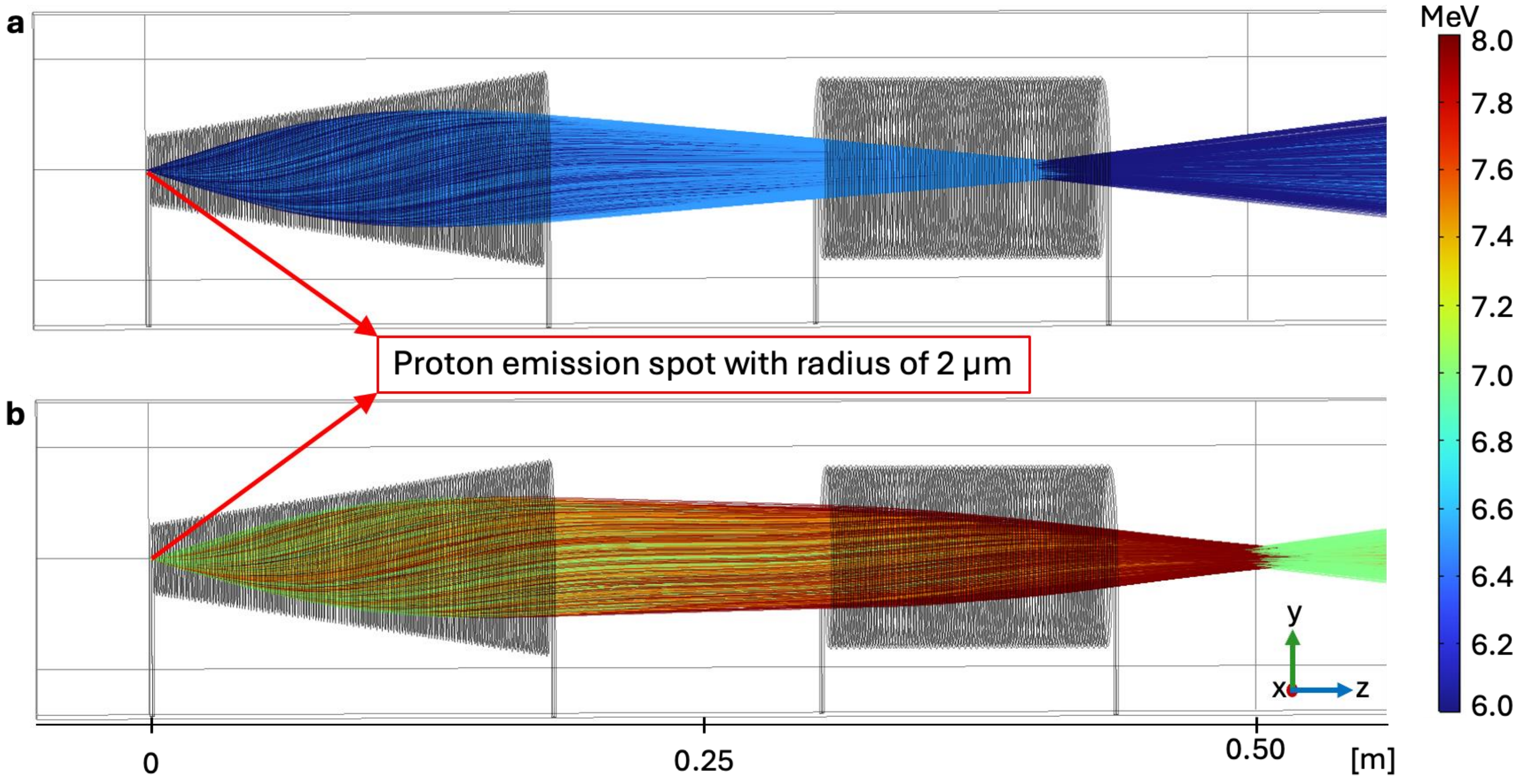


$B_{max1} = 9$ T

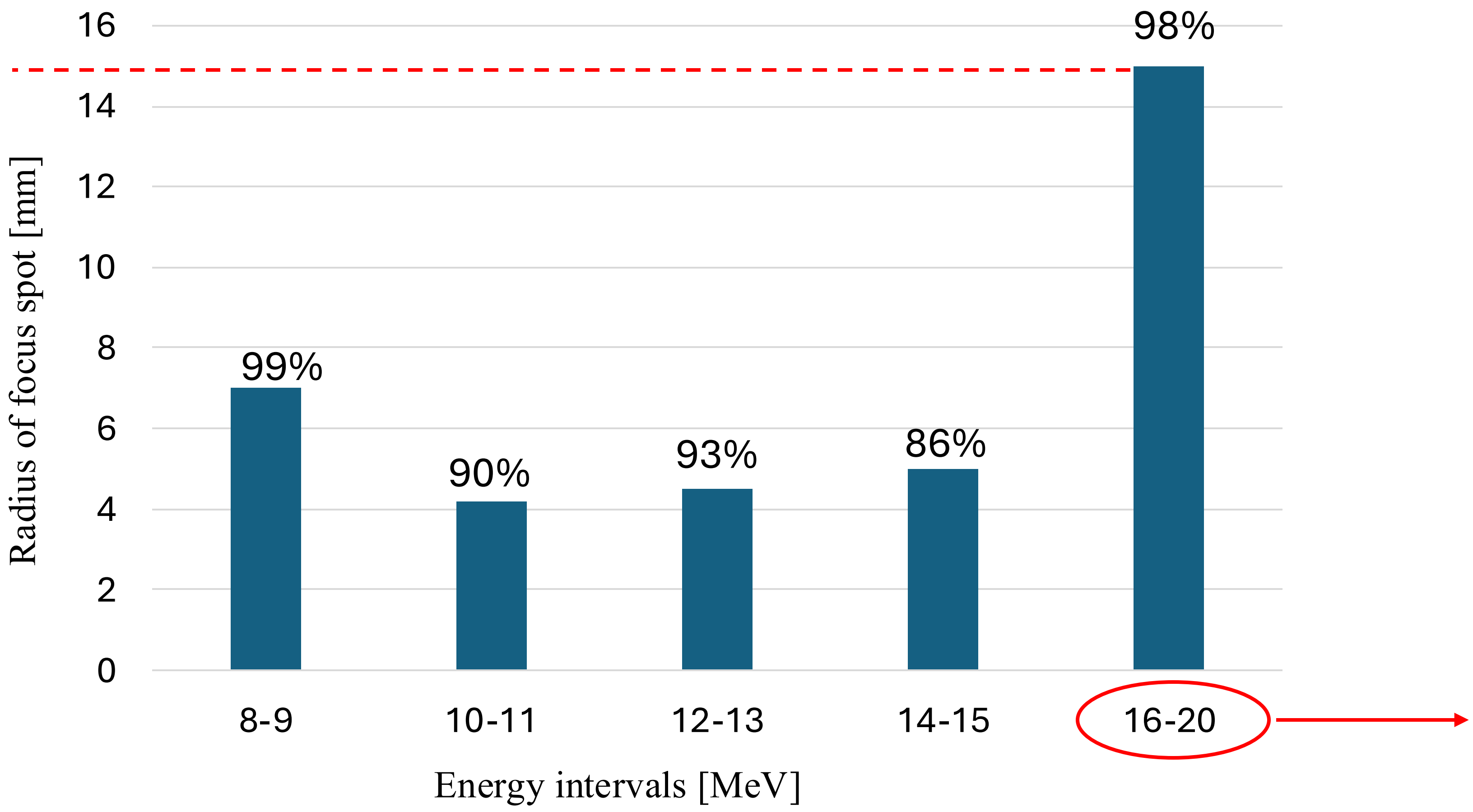
$B_{max2} = 6$ T

Parameters	Nb. of turns	Major Radius [mm]	Minor radius [mm]	Axial pitch [mm]	Radial pitch [mm]	Position z [m]	Coil current [kA]
Conical Coil	70.5	1.5	1	2.5	0.4	0.001	20
Cylindrical Coil	50.5	4	1	2.5	0	0.3	16

Solenoid-based Focusing of Laser-Driven Proton Beams



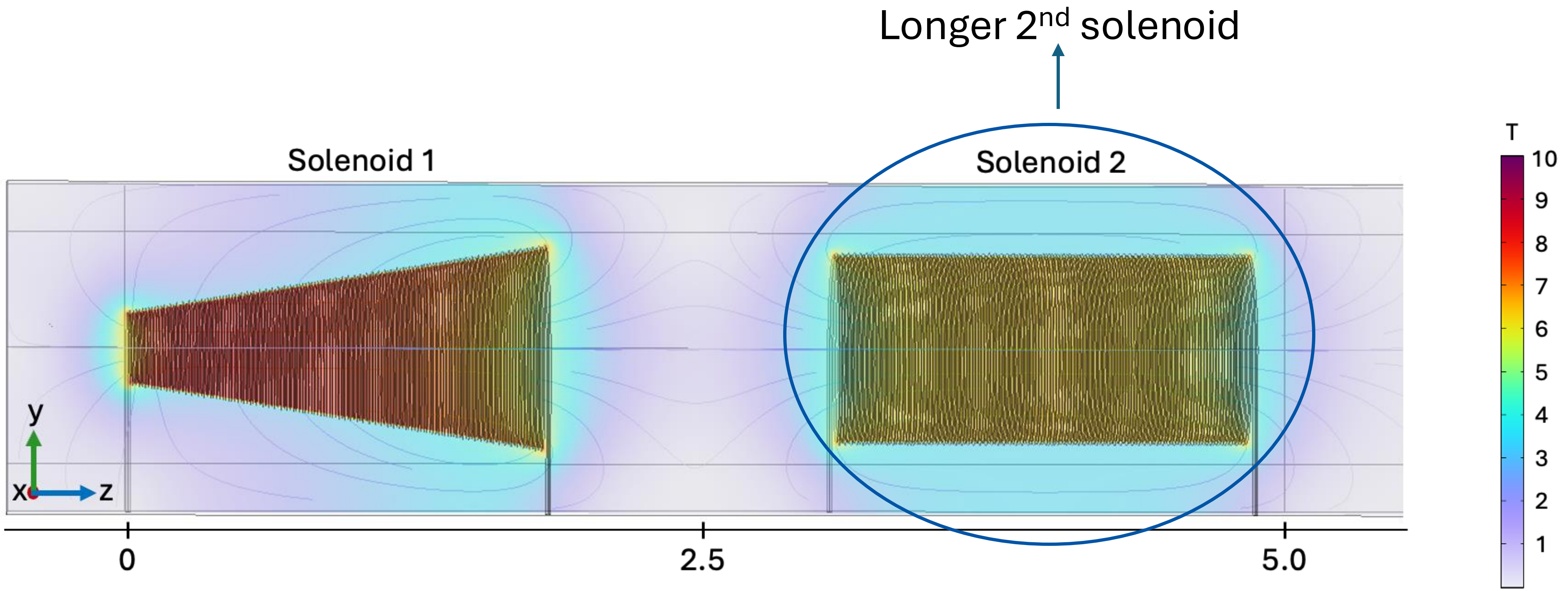
Data analysis on specific energy intervals



Focal length~1.9 m

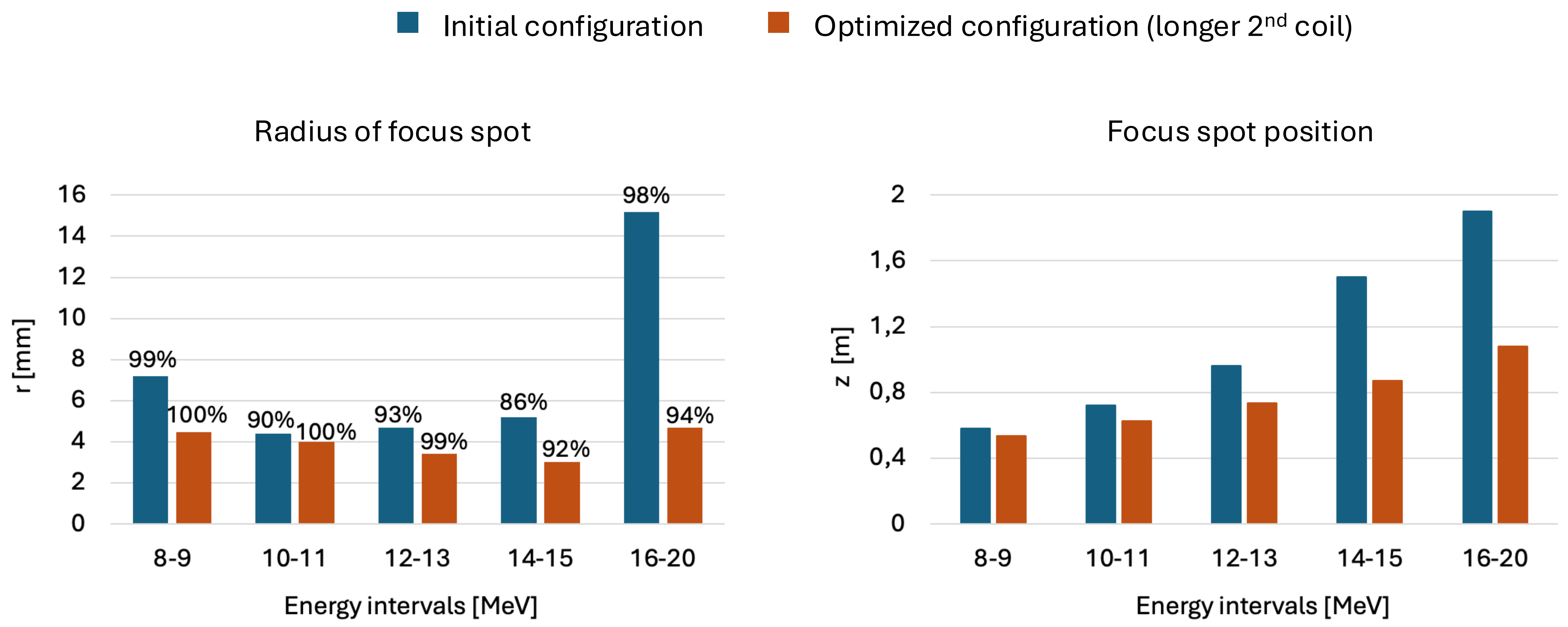
Efficiencies calculated considering ONLY the specific energy range

COMSOL simulation
Geometric description of optimized two-solenoid system



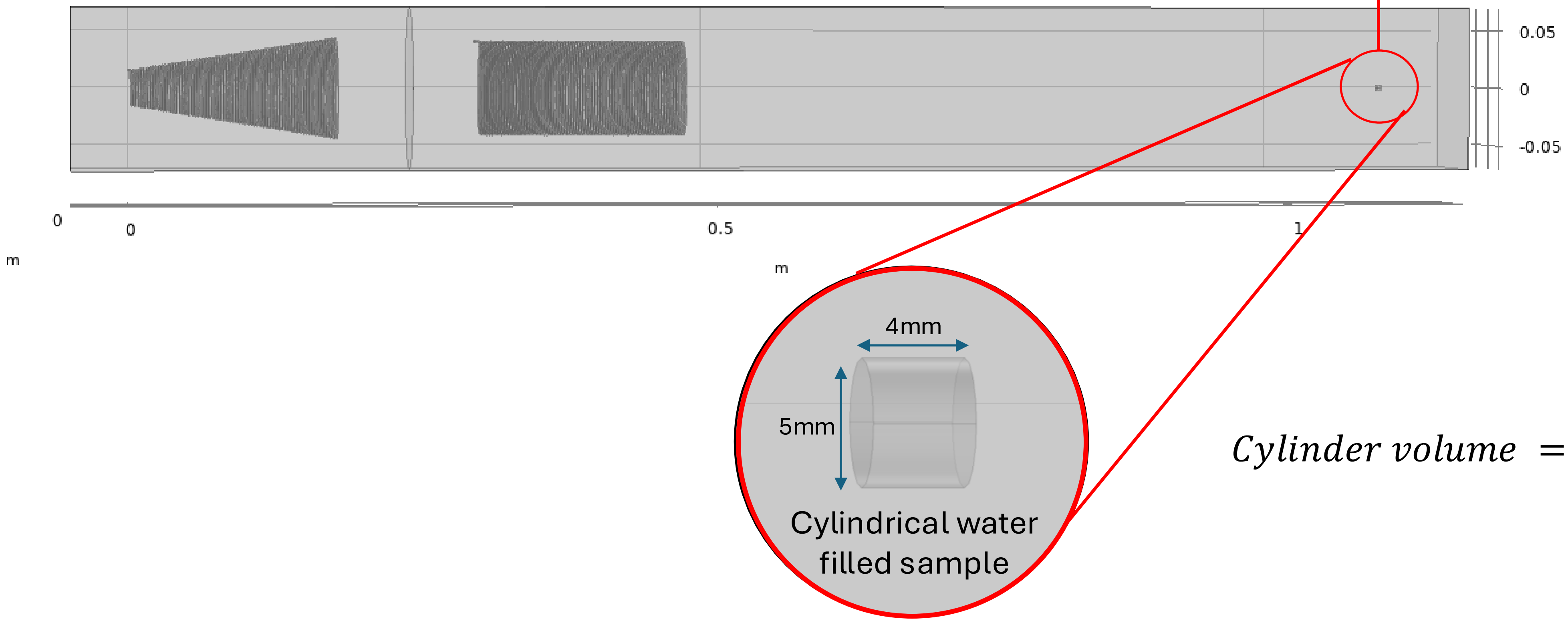
Parameters	Nb. of turns	Major Radius [mm]	Minor radius [mm]	Axial pitch [mm]	Radial pitch [mm]	Position z [m]	Coil current [kA]
Conical Coil	70.5	1.5	1	2.5	0.4	0.001	20
Cylindrical Coil	~~50.5.~~ 70.5	4	1	2.5	0	0.3	16

Comparison between the focusing effects induced by the two-solenoid focusing systems



Dose distribution study in a specific target volume

z = 1.08 m
(focus point for 16-20 MeV protons)

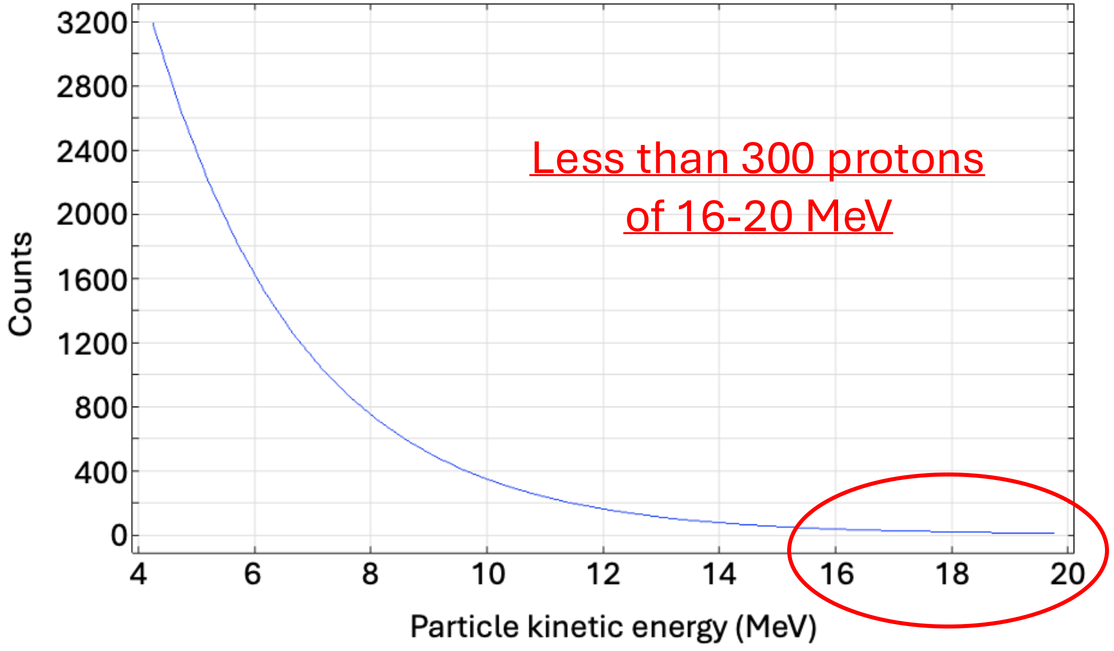


$$Cylinder\ volume = 78.54 \cdot 10^{-9} m^3$$

PTV inspired from: F. Kroll, et. Al., *Tumour irradiation in mice with a laser-accelerated proton beam*, Nat. Phys. 18 (2022)

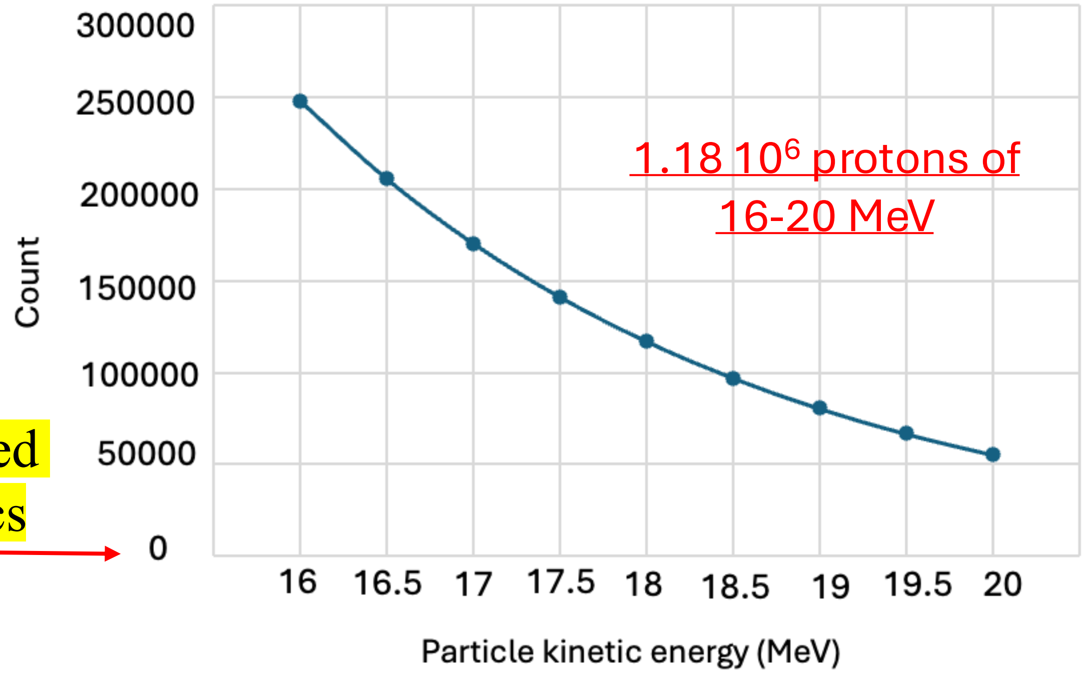
Taylor the energy spectra within a specific energy domain

Initial Proton Energy Spectrum



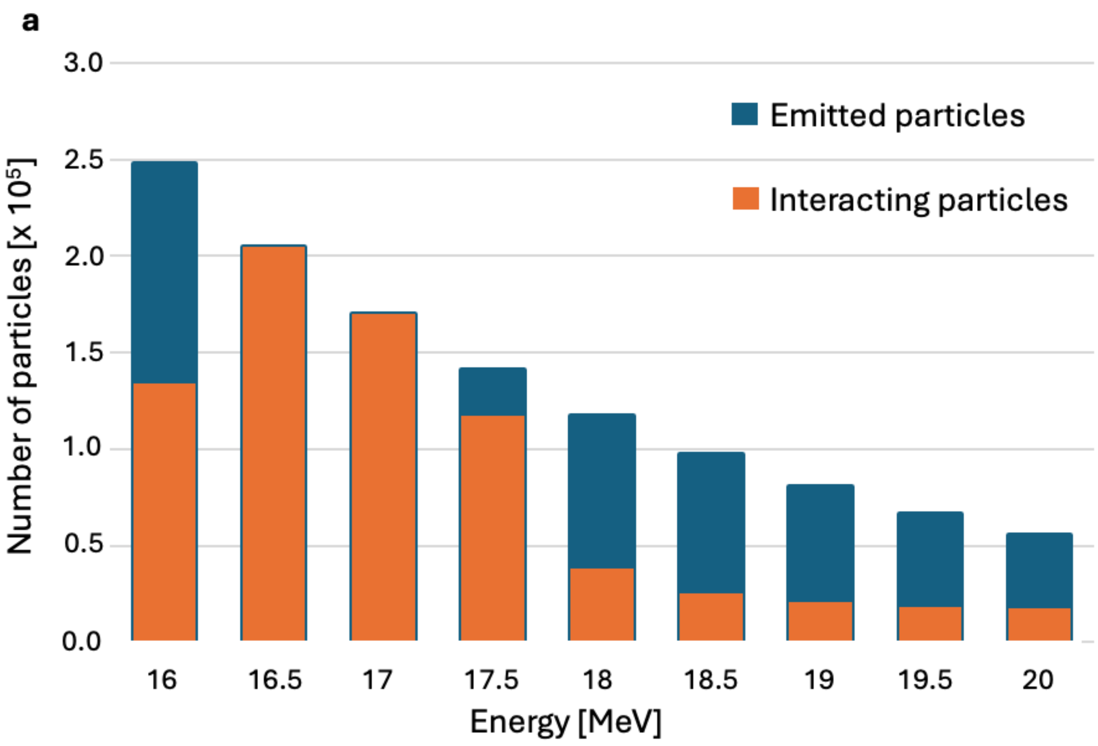
Increased statistics

Proton Energy Spectrum for Dose Monitoring Study

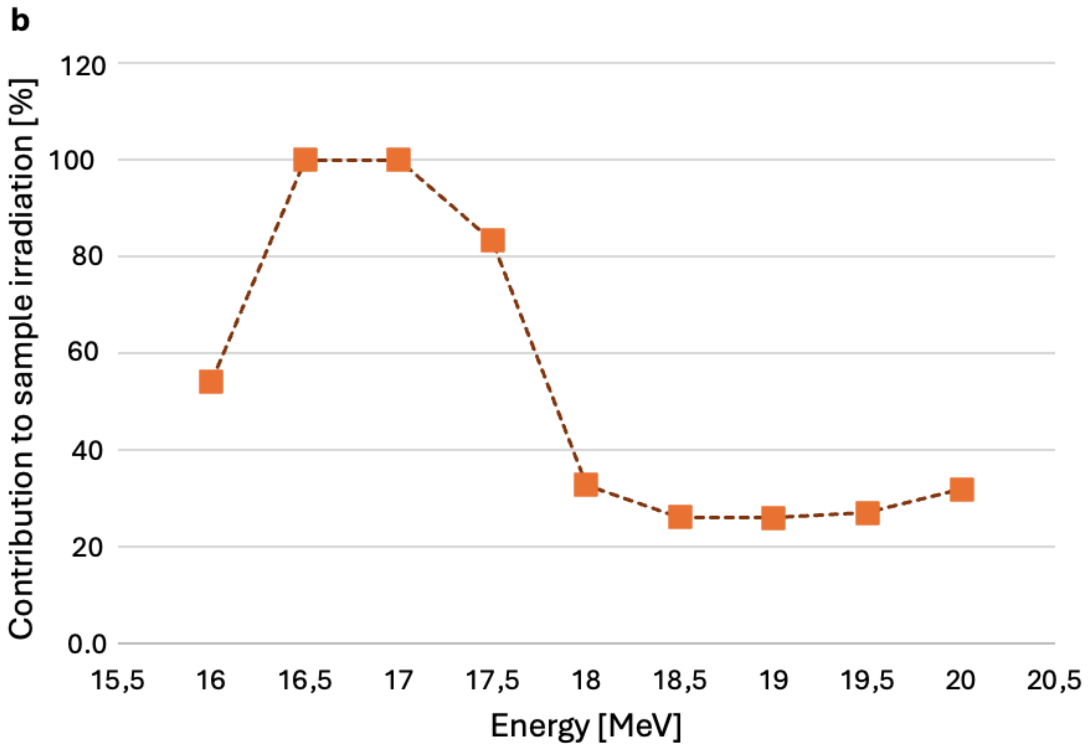


Statistics of particles interacting with the target volume

Emitted particles VS Interacting particles

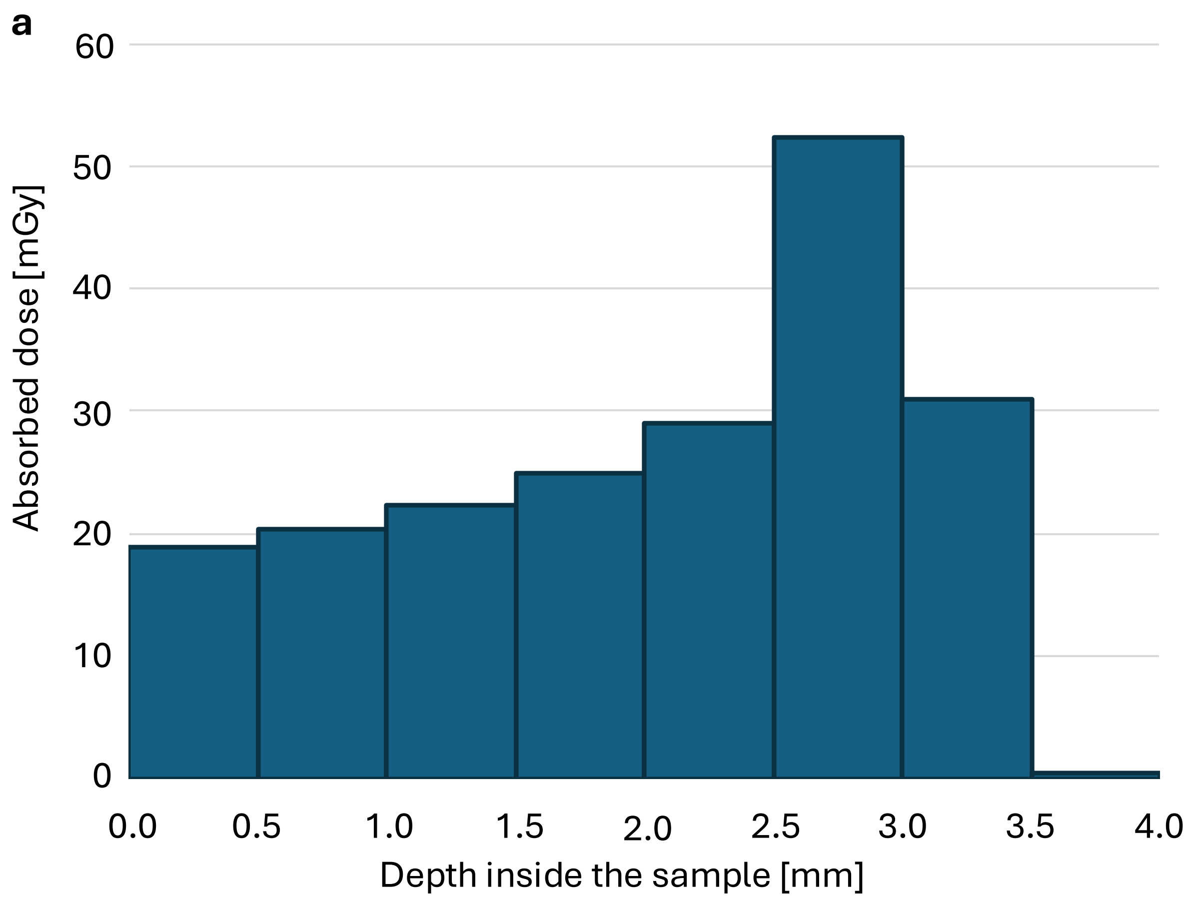


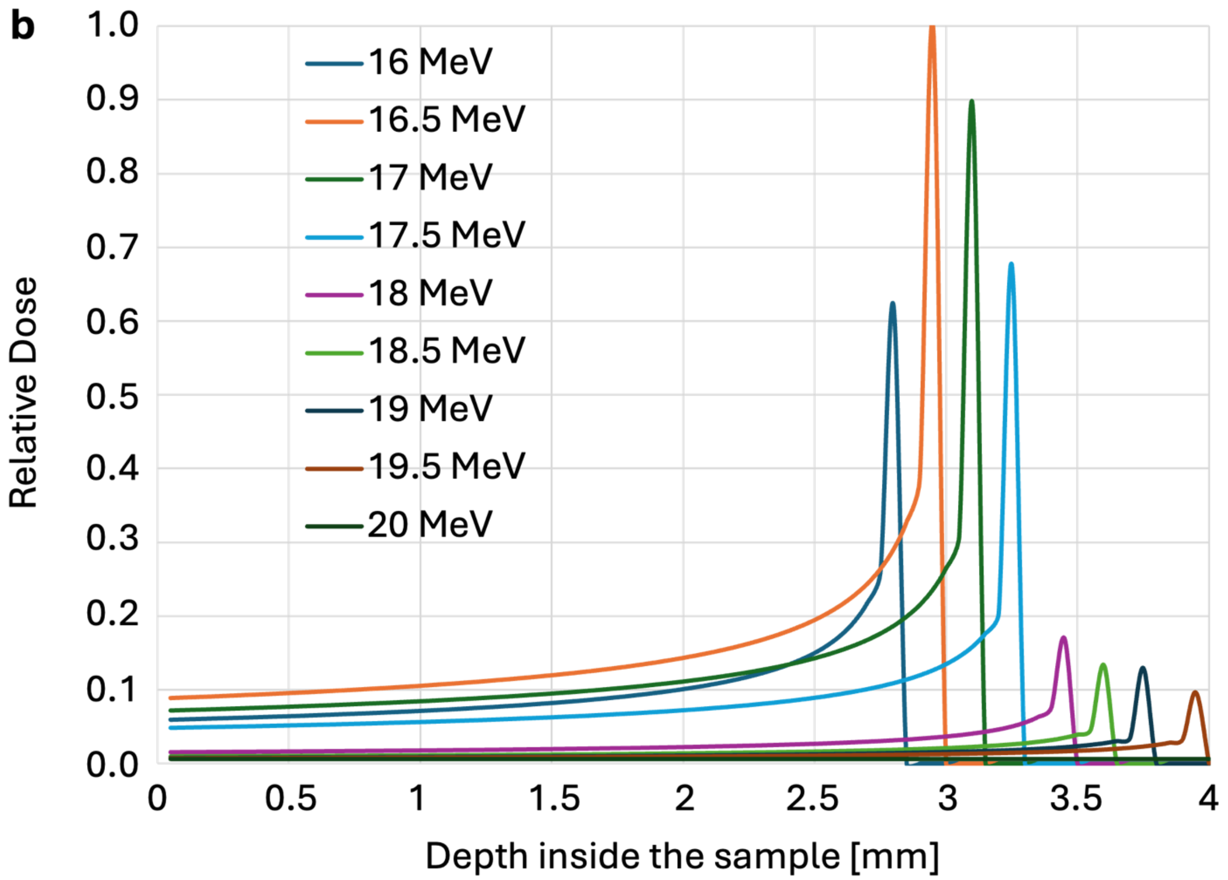
Percentage of protons contributing to sample irradiation



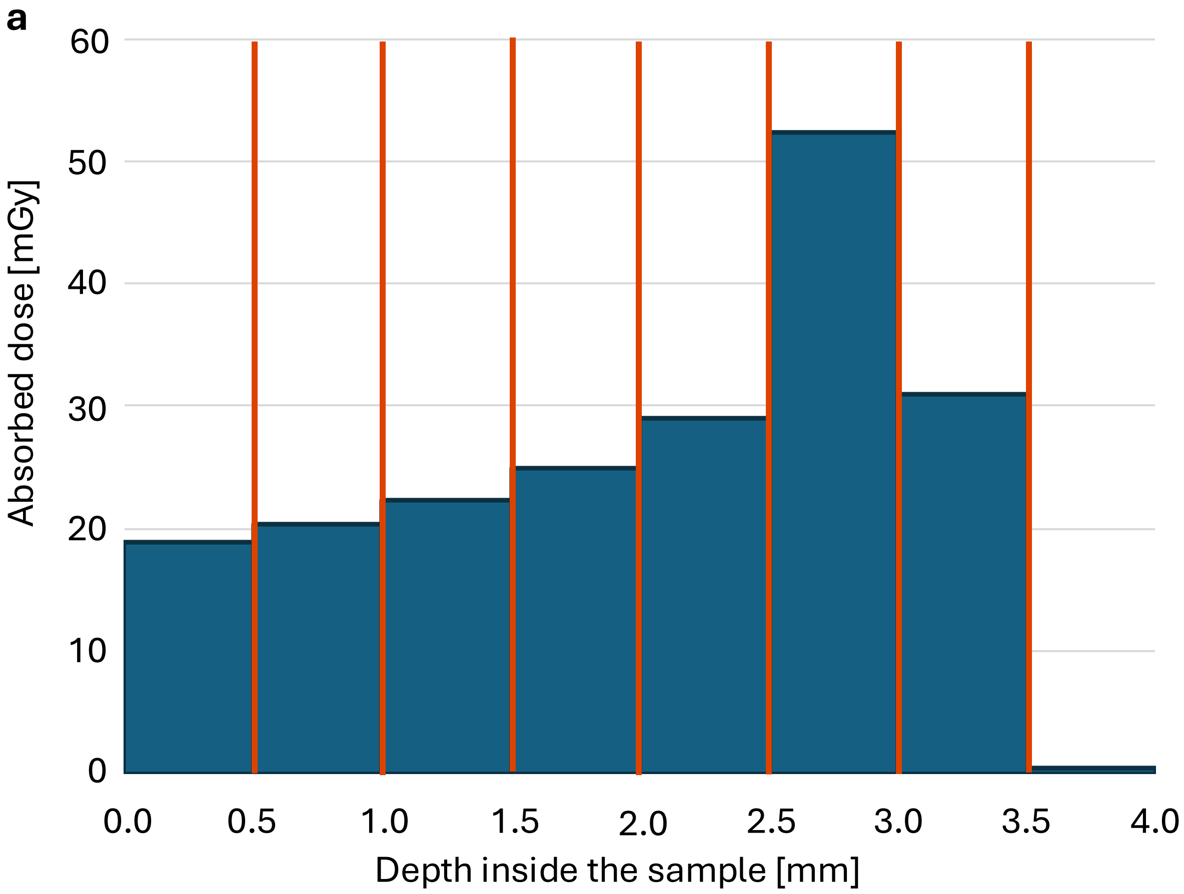
63% of the generated spectrum contributed to the irradiation of the sample.

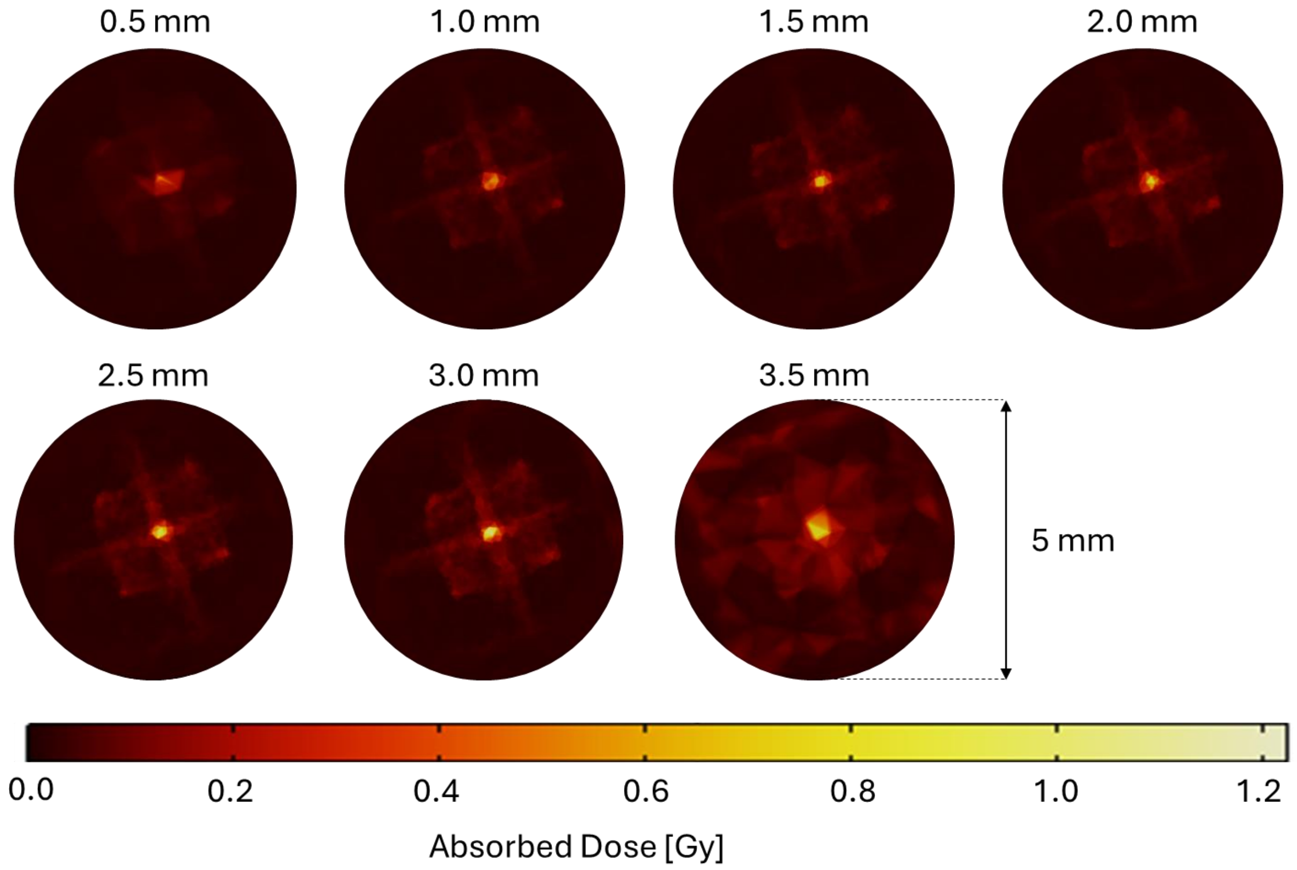
Dose distribution study in a specific target volume





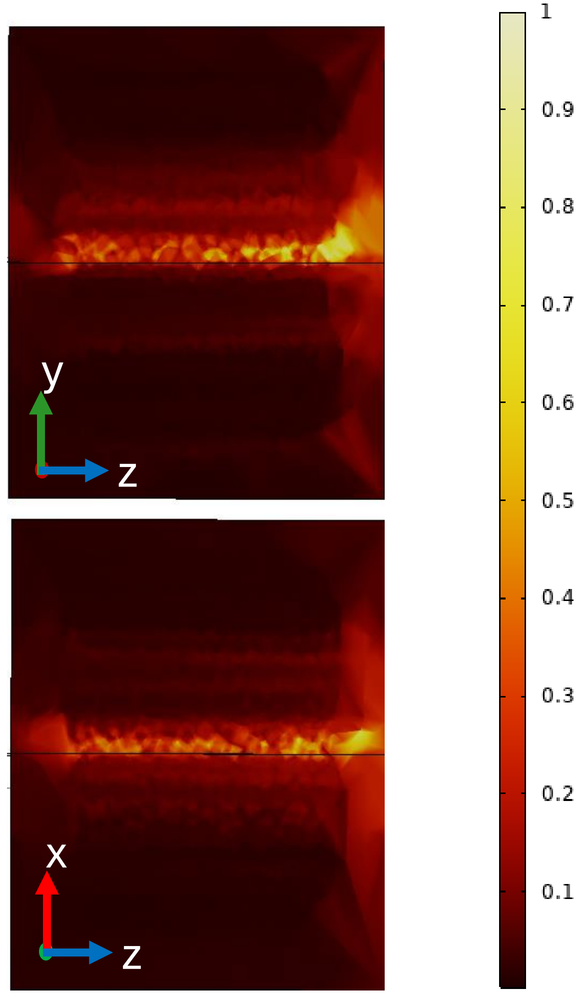
Dose distribution in cross sectional profiles





Dose distribution in longitudinal profile and dose rate

Absorbed Dose [Gy]



$$Simulated\ Absorbed\ Dose = 2 \cdot 10^{-9} Gy \cdot m^3$$

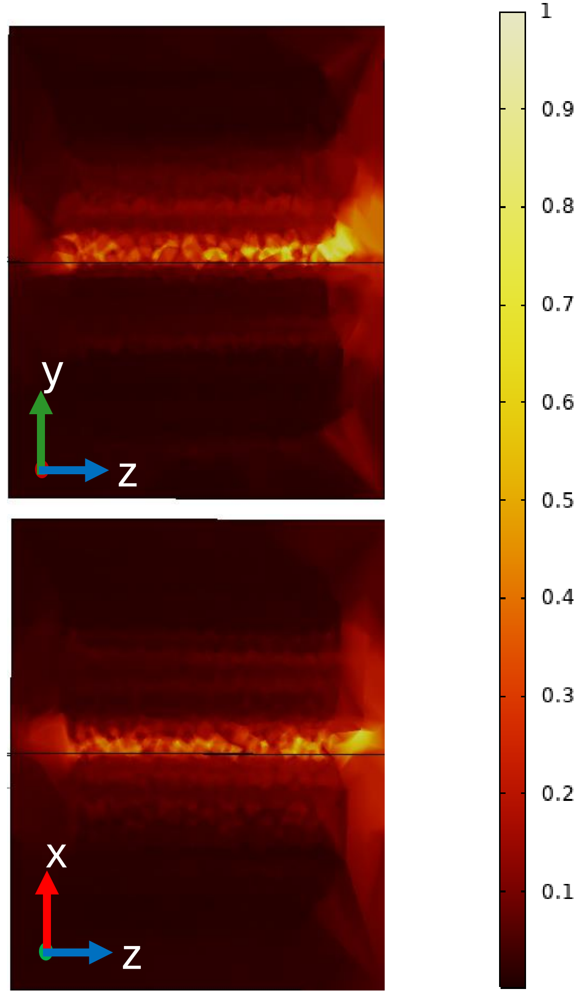
$$Absorbed\ Dose\ in\ The\ Sample = \frac{Simulated\ Absorbed\ Dose}{Cylinder\ volume} \sim 2.54 \cdot 10^{-2}\ Gy$$

$$Dose\ Rate = \frac{Absorbed\ Dose}{Pulse\ Duration} \sim 1.2 \cdot 10^{7}\ Gy/s$$

Absorbed Dose (AD) $\propto$ nr. of protons
In experiments AD/shot ~ 1 Gy, 10^9 protons

Dose distribution in longitudinal profile and dose rate

Absorbed Dose [Gy]



$$Simulated\ Absorbed\ Dose = 2 \cdot 10^{-9} Gy \cdot m^3$$

$$Absorbed\ Dose\ in\ The\ Sample = \frac{Simulated\ Absorbed\ Dose}{Cylinder\ volume} \sim 2.54 \cdot 10^{-2}\ Gy$$

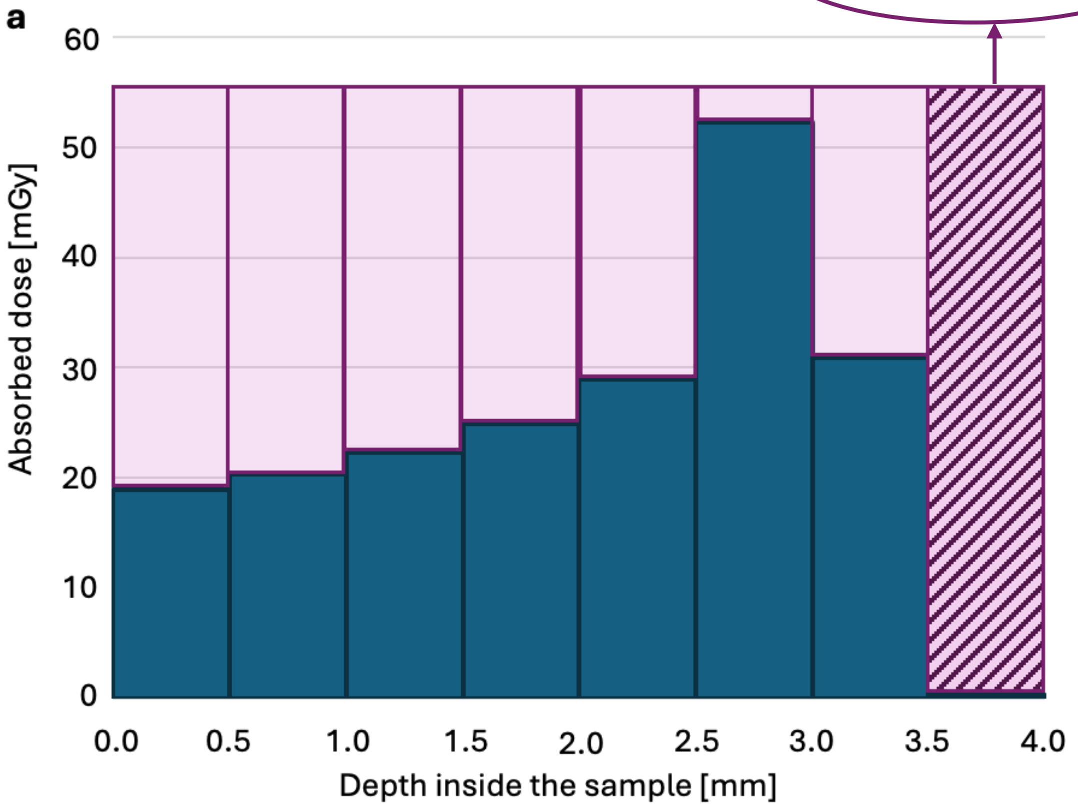
$$Dose\ Rate = \frac{Absorbed\ Dose}{Pulse\ Duration} \sim 1.2 \cdot 10^{7}\ Gy/s \longrightarrow FLASH\ Therapy\ Regime$$

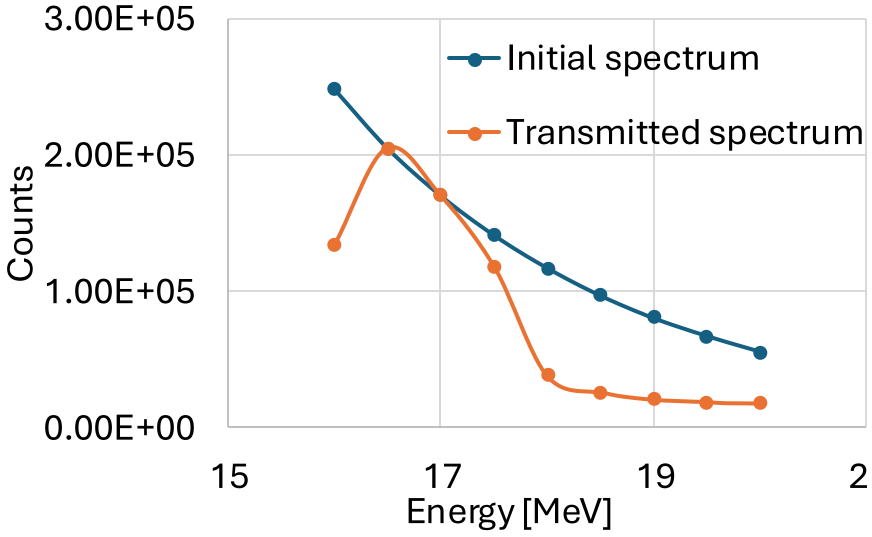
Absorbed Dose (AD) ∝ nr. of protons
In experiments AD/shot ~ 1 Gy, 10^9 protons

Tune the coils currents in order to achieve uniform longitudinal dose

Initial current values: I_1 = 20 kA, I_2 = 16 kA

Emax = 20 MeV

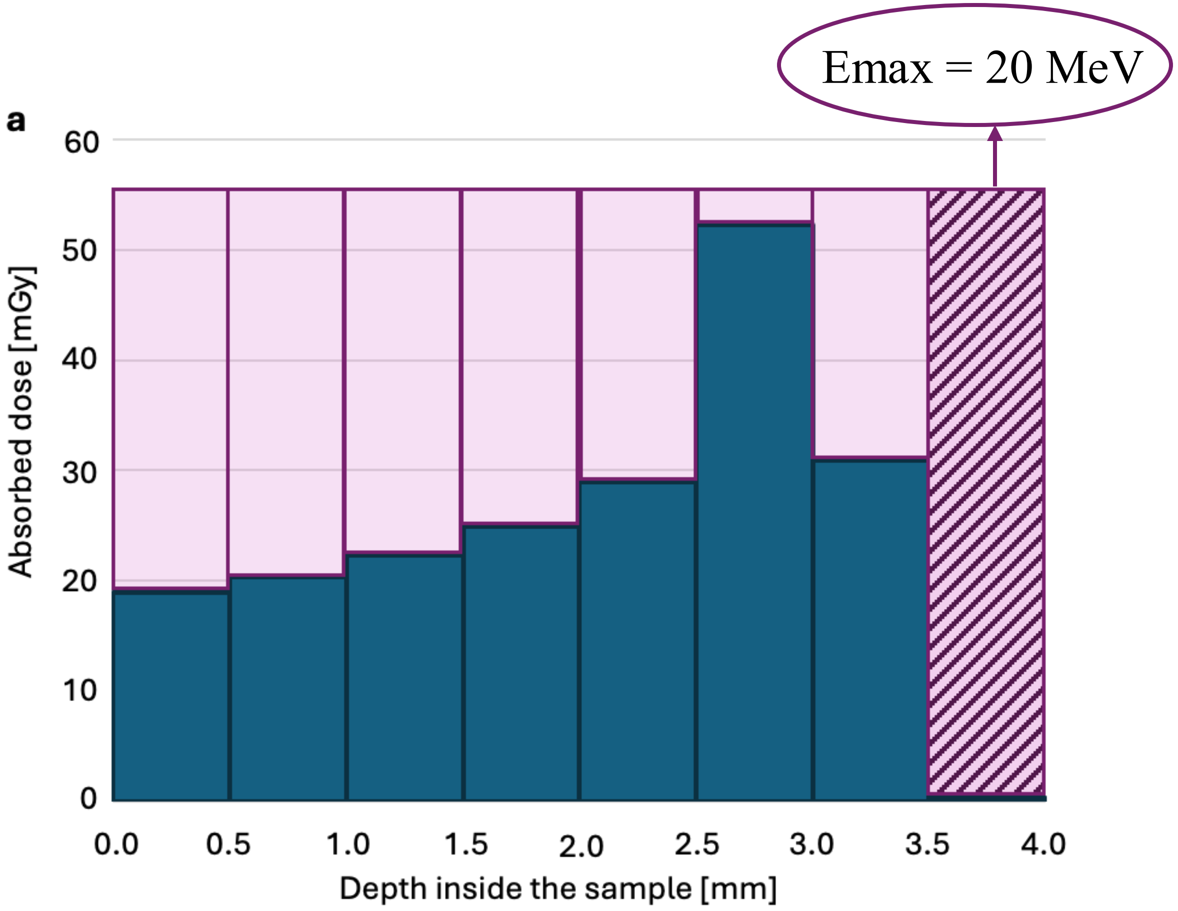


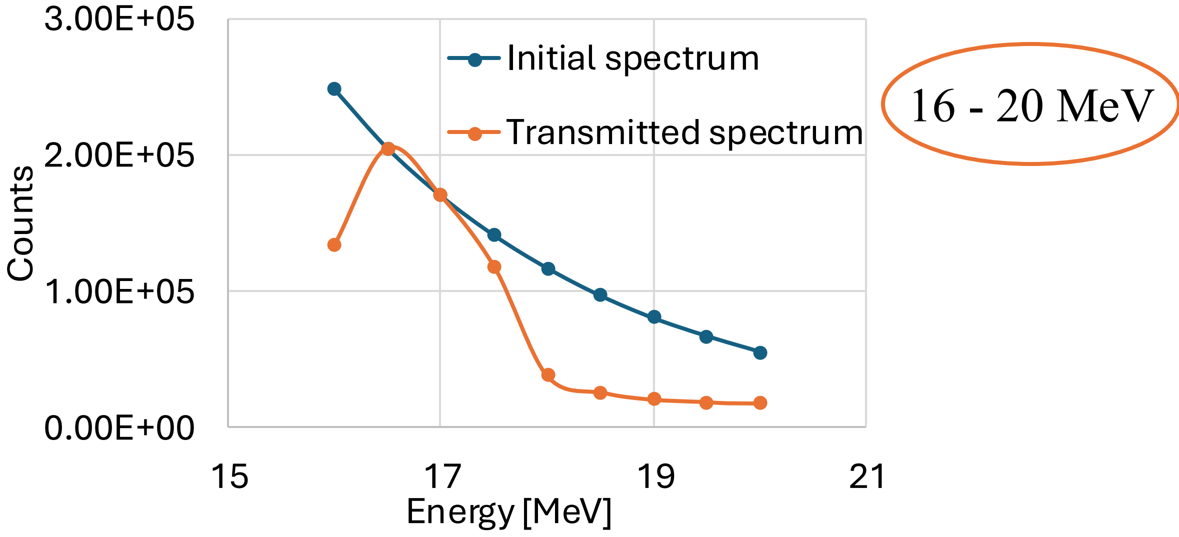


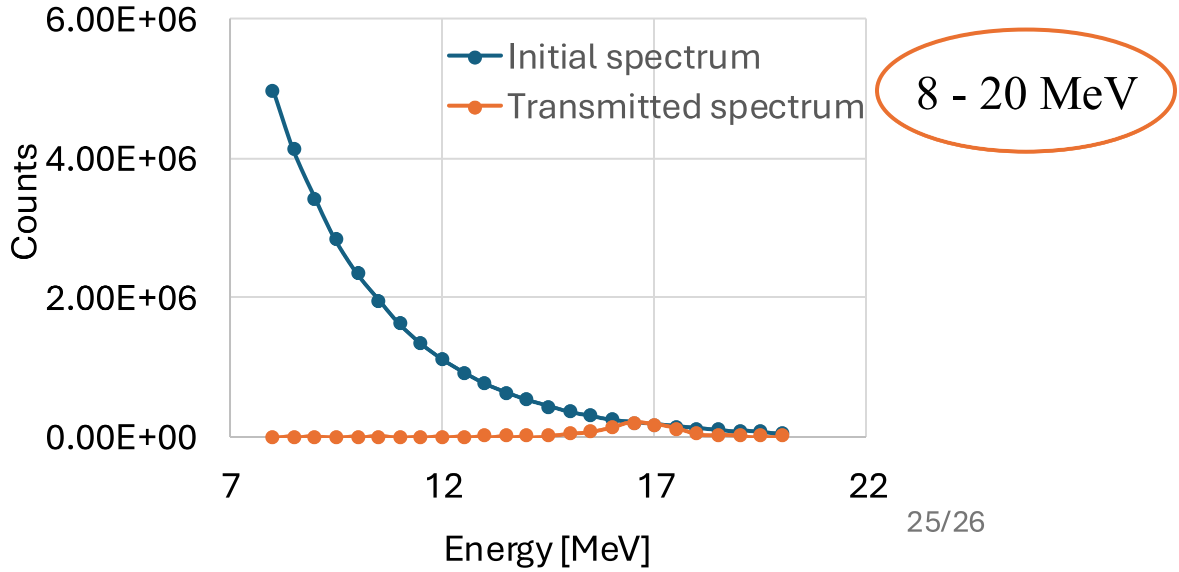
16 - 20 MeV

Tune the coils currents in order to achieve uniform longitudinal dose

Initial current values: I_1 = 20 kA, I_2 = 16 kA

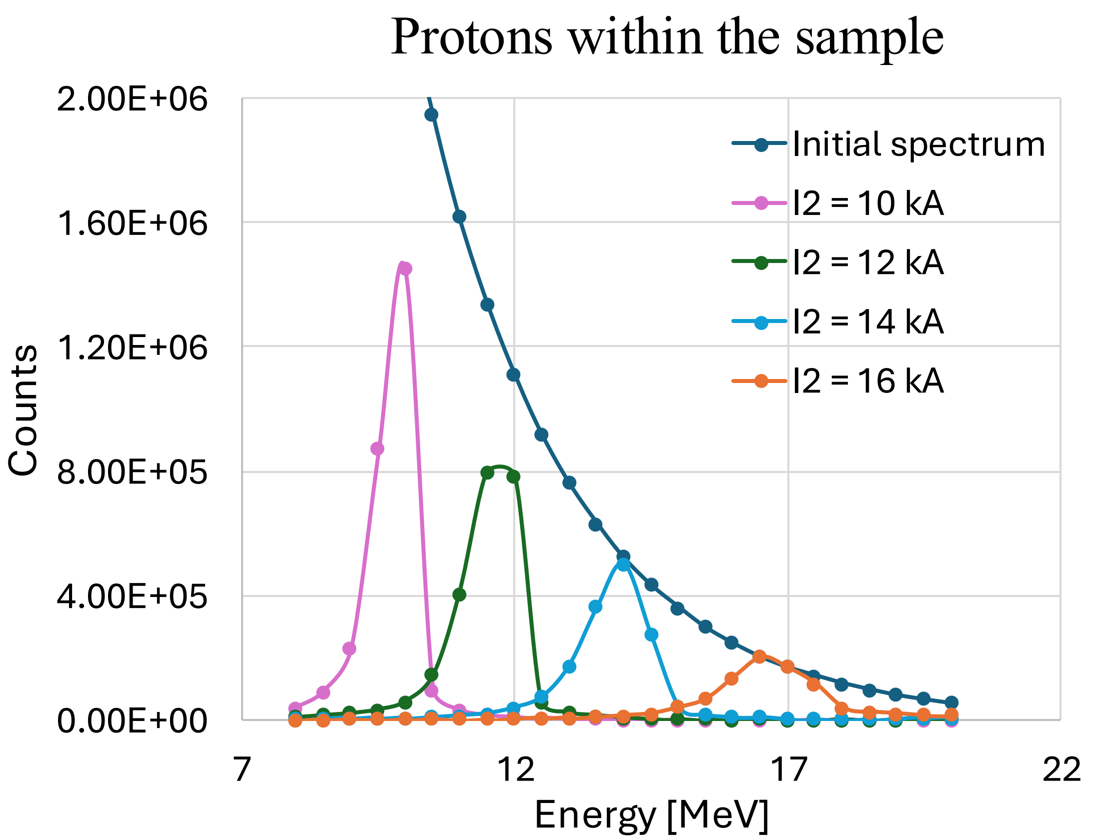




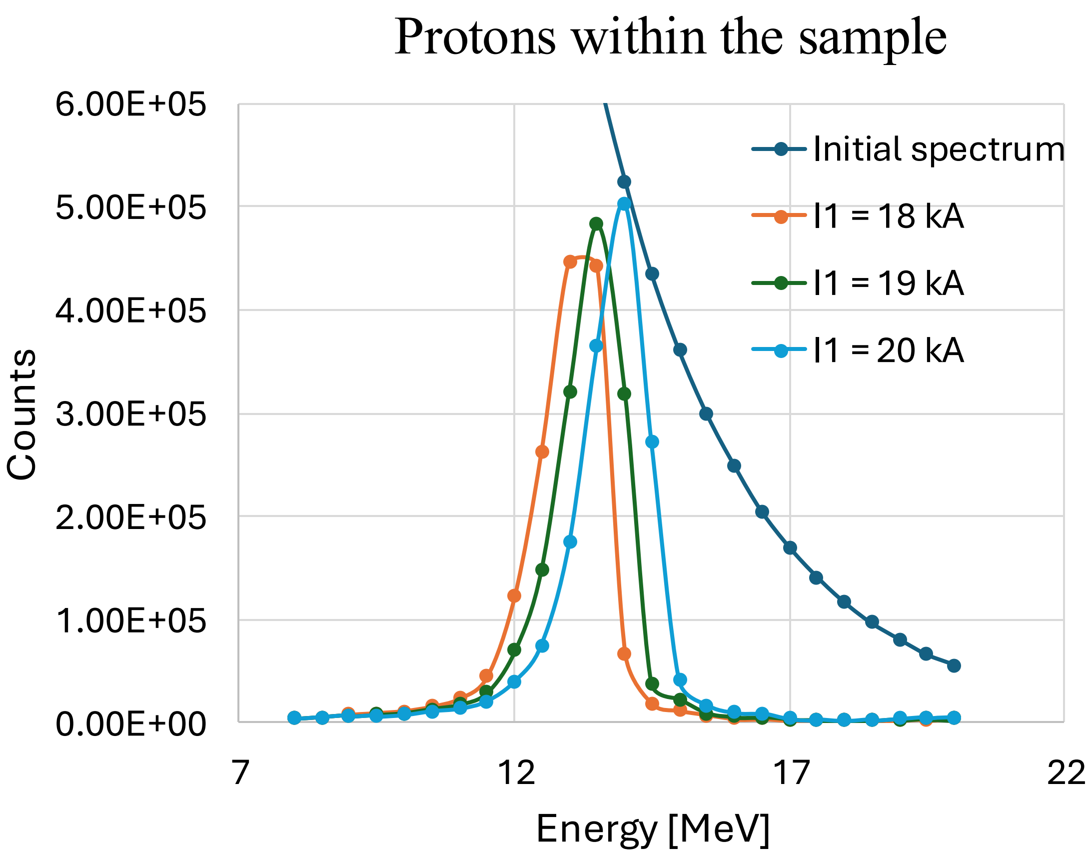


Tune the coils currents in order to achieve uniform longitudinal dose

$I_1 = 20$ kA
$I_2 = \{10, 12, 14, 16\}$ kA



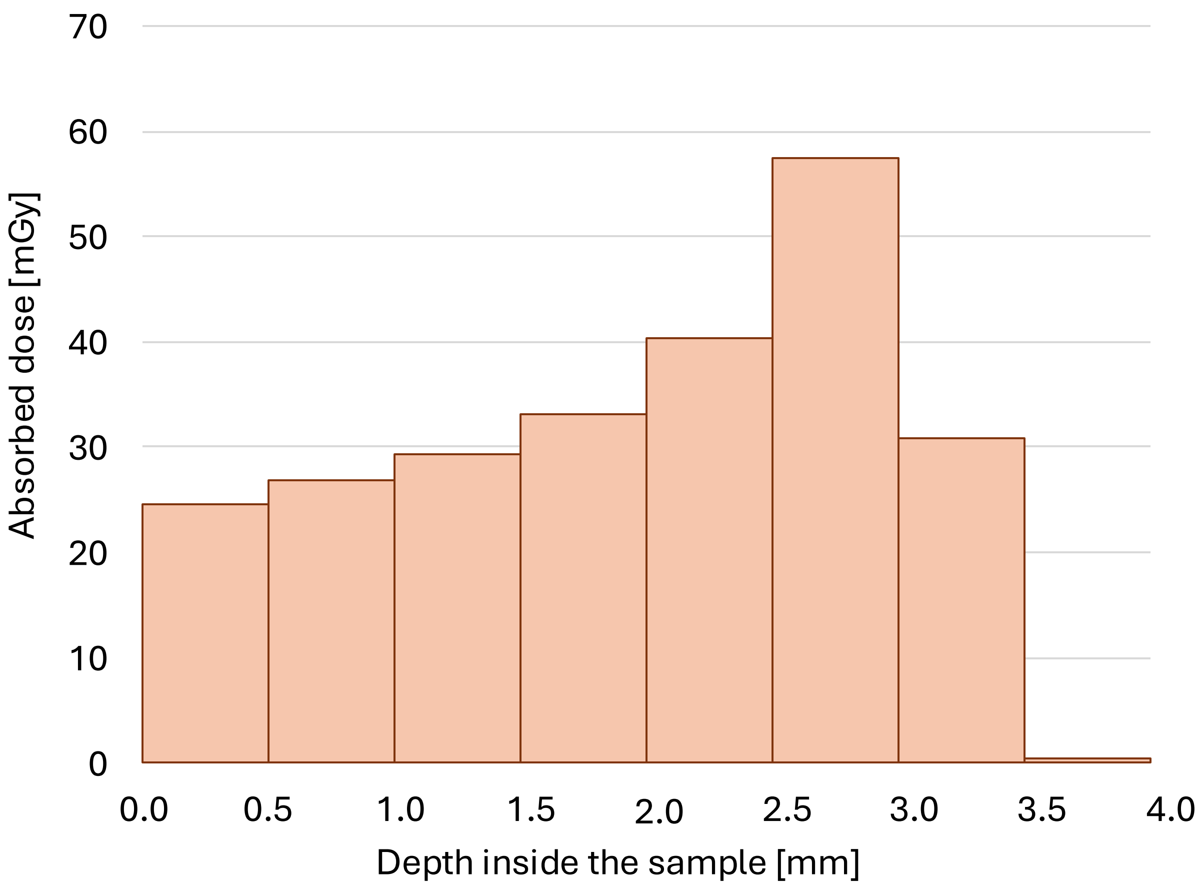
$I_1 = \{18, 19, 20\}$ kA
$I_2 = 14$ kA



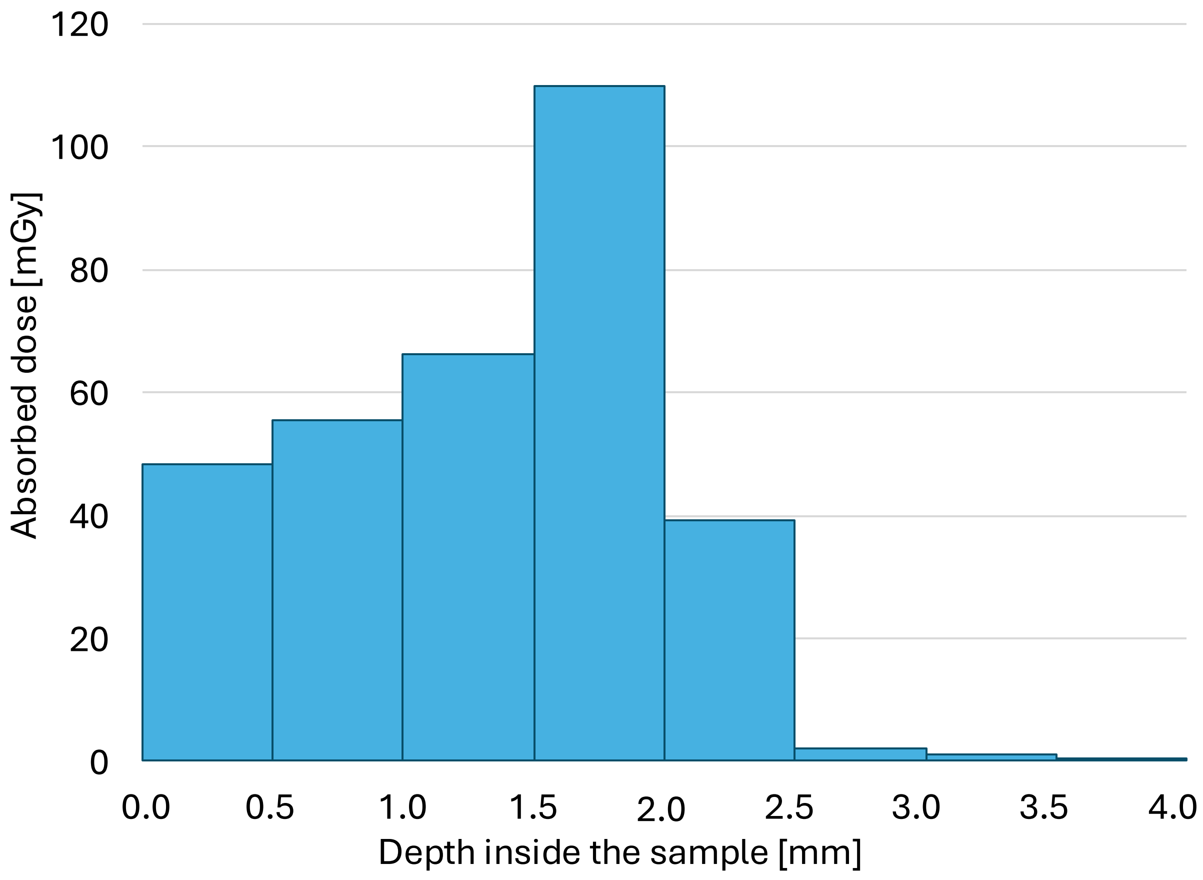
Tune the coils currents in order to achieve uniform longitudinal dose

Extended spectrum for sample irradiation: 8 - 20 MeV protons

$I_1 = 20$ kA, $I_2 = 16$ kA



$I_1 = 18$ kA and $I_2 = 14$ kA

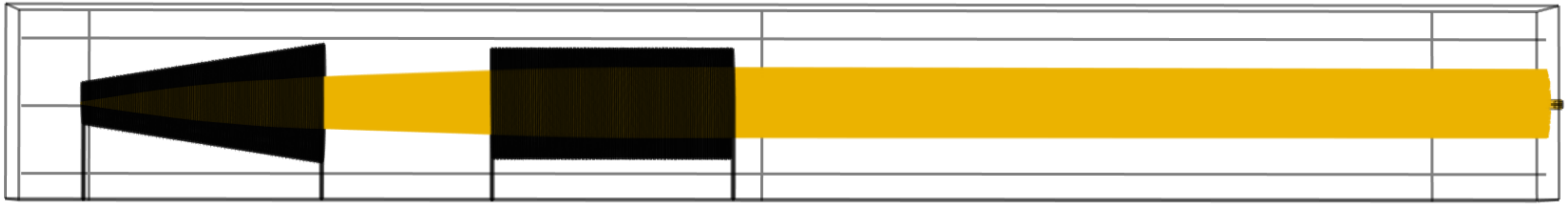


Expand for a higher energy range, e.g. to 100 or 200 MeV

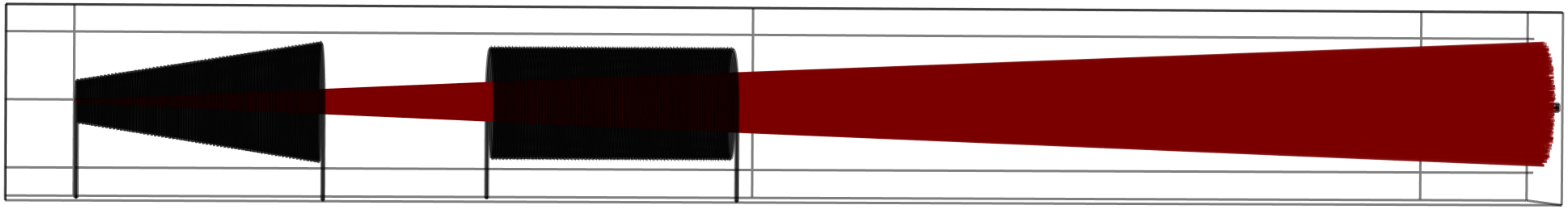
RPA expected to produce a beam with different spatial focusing properties

- Likely reduction in beam divergence
- Requires new simulations to evaluate changes
- Potential benefits: Lower coil currents
Improved proton capture in the focal spot

13 Mev protons collimated with system's parameters: I_1 = 22 kA and I_2 = 9 kA



100 Mev protons collimated with system's parameters: I_1 = 22 kA and I_2 = 9 kA



Conclusions

Results obtained

94% capturing efficiency for $> 16\ MeV$ protons

Focus spot size: 9 mm diameter

Focus spot position: $z \sim 1\ m$ from the source

25 mGy absorbed dose with $1.2 \cdot 10^7\ Gy/s$ dose rate

Future work

Achieving uniform longitudinal dose

Expanding for higher energy range

Laser-driven proton therapy may offer a compact and cost-effective alternative to conventional accelerators, enabling ultra-fast dose delivery, thereby giving access to FLASH regime.

Thank you for your attention!

Acknowledgements

This work was supported by Project ELI-RO/DFG/2023_001 ARNPhot funded by Institute of Atomic Physics Romania