

A story about Applied Nuclear Physics

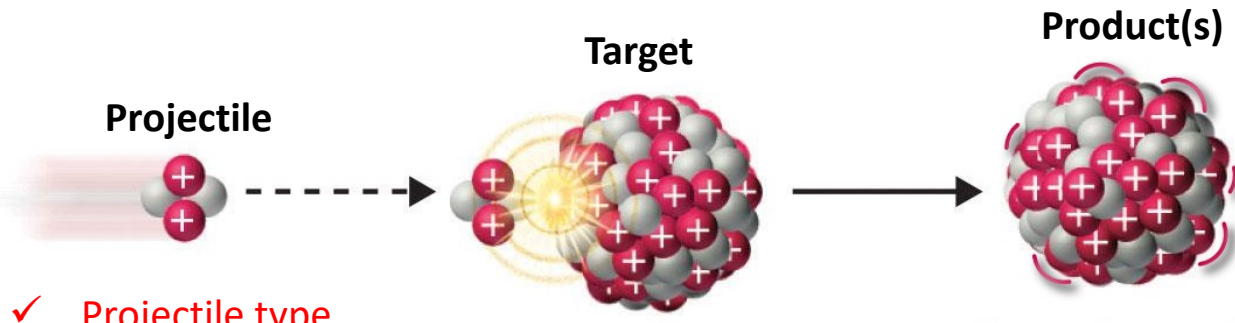
Mateusz Sitarz

Open Meeting of SFJ
Student Accelerator Workshop in HIL

27.10.2023

- Medical radioisotopes (PhD, Warsaw+France)
- Radiobiology and dosimetry (postdoc, Denmark)
- Radiation protection and treatment planning (postdoc, France)

Production of medical radioisotopes



- ✓ Projectile type
- ✓ Energy range
- ✓ Beam current

* Physics
* Applications

- ✓ Reaction cross-section (data vs calculations)
- ✓ Target composition
- ✓ Target form
- ✓ Target thickness
- ✓ Target heating

- ✓ Production efficiency
- ✓ Medical properties
- ✓ Activity for patient
- ✓ Radioactive impurities (chelating)

	⁴⁴ Sc	⁶⁸ Ga
OS	+3	+3
E_{β^+} (av)	630 keV	830 keV
I_{β^+}	94%	89%
$T_{1/2}$	3.9 h	68 min



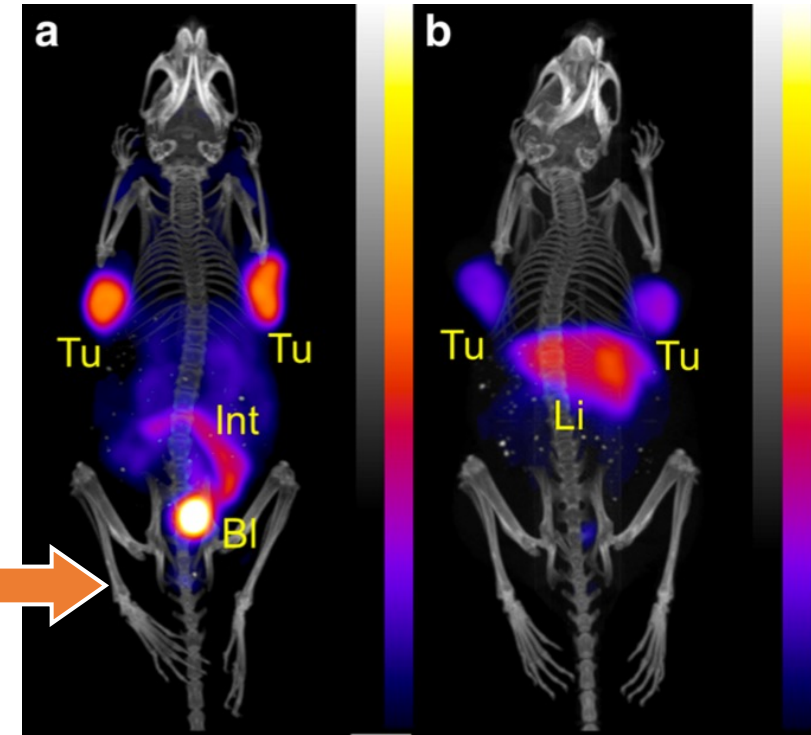
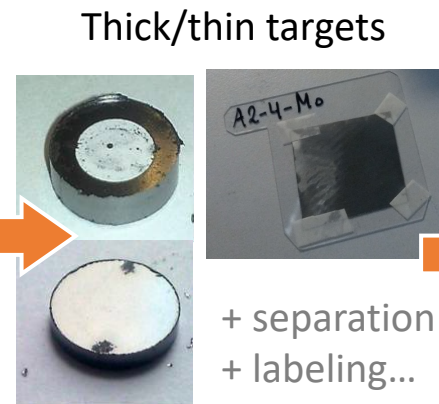
U-200P
SLCJ, Warsaw



C70
ARRONAX, Nantes



PETtrace
SLCJ, Warsaw



⁴⁴Sc-DOTA-RGD

⁶⁸Ga-DOTA-RGD

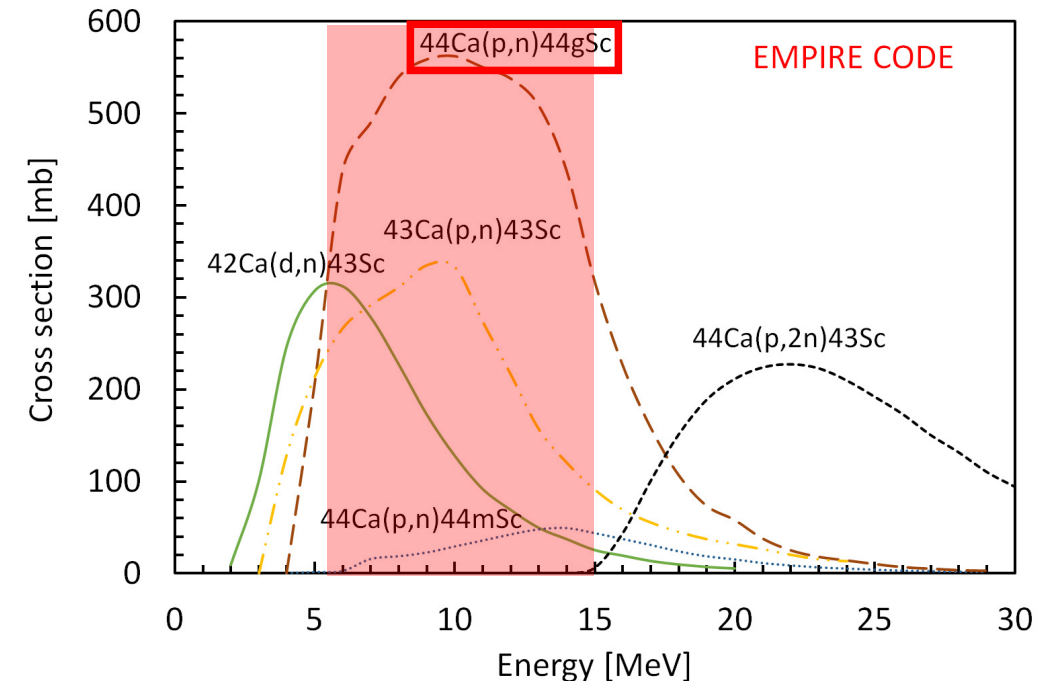
Budget

- ➔ Reaction routes
- ➔ Available targets
- ➔ Competitive reactions

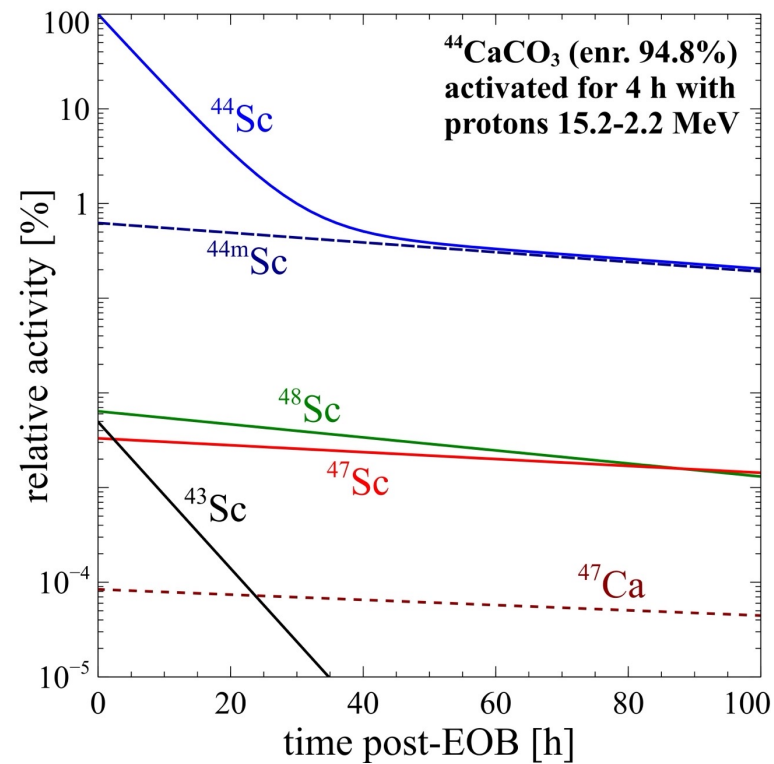
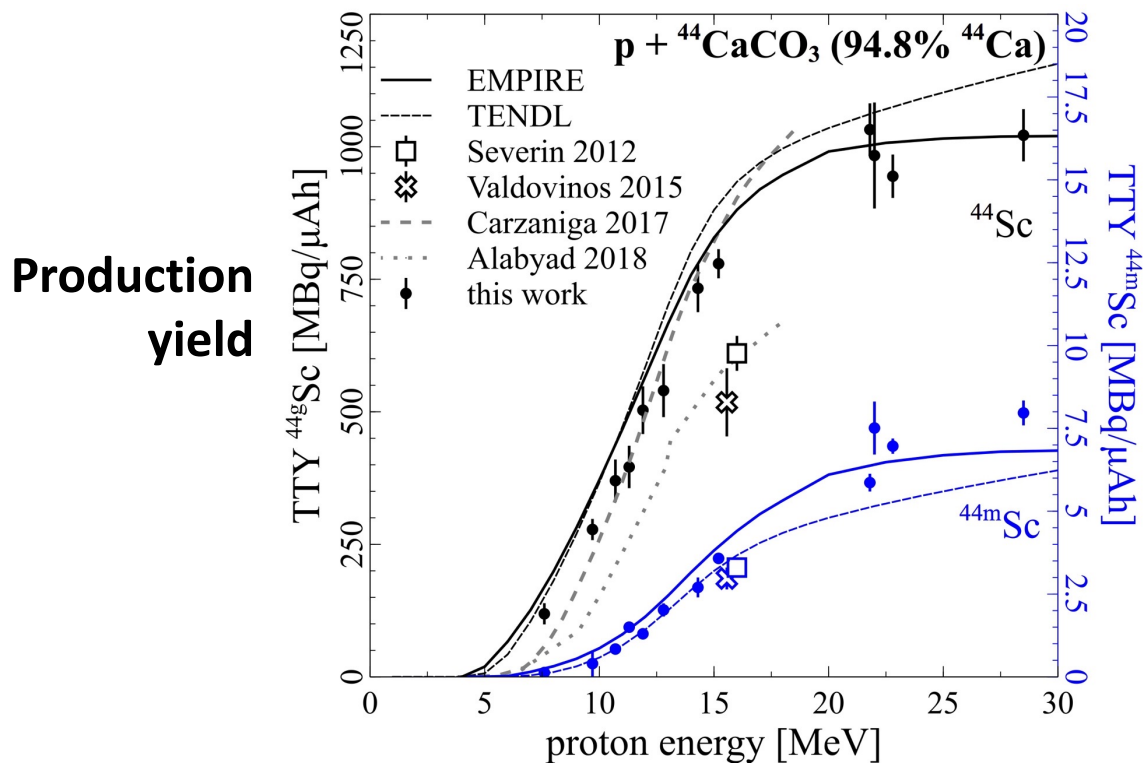
42Ti 199 MS ε: 100.00%	43Ti 509 MS ε: 100.00%	44Ti 60.0 Y ε: 100.00%	45Ti 184.8 M ε: 100.00%	46Ti STABLE 8.25%	47Ti STABLE 7.44%	48Ti STABLE 73.72%
41Sc 596.3 MS ε: 100.00%	42Sc 681.3 MS ε: 100.00%	43Sc 3.891 H ε: 100.00%	44Sc 3.97 Y ε: 100.00%	45Sc STABLE 100%	46Sc 83.79 D β-: 100.00%	47Sc 3.3492 D β-: 100.00%
40Ca >3.0E+21 Y 96.94% 2ε	41Ca 1.02E+5 Y ε: 100.00%	42Ca STABLE 0.647%	43Ca STABLE 0.135%	44Ca STABLE 2.09%	45Ca 162.61 D β-: 100.00%	46Ca >0.28E+16 Y 0.004% 2β-



	$^{\text{nat}}\text{CaCO}_3$	commercially available (CaCO_3)	
^{40}Ca	96.9%	99.99%	1.4 \$/mg
^{42}Ca	0.65%	68% 95.9%	43 \$/mg 81 \$/mg
^{44}Ca	2.1%	94.8% 99.2%	20 \$/mg 23 \$/mg
^{48}Ca	0.19%	69.2% 97.1%	89 \$/mg 230 \$/mg



Production efficiency



Beam, energy		p 15-2 MeV		d 15-8 MeV	α 29-12 MeV
Target		natCaCO ₃	${}^{44}\text{CaCO}_3$ (94.8%)	${}^{44}\text{CaCO}_3$ (96.9%)	${}^{42}\text{CaCO}_3$ (95.9%)
Irradiation: 4 h, 25 μA	${}^{44}\text{Sc}$ A _{EOB} [GBq]	1.4	63	16	3.3
	Main impurity	${}^{43}\text{Sc}$ 3.0%	${}^{44\text{m}}\text{Sc}$ 0.7%	${}^{44\text{m}}\text{Sc}$ 2.0%	${}^{44\text{m}}\text{Sc}$ 14%

Automatisation

Radionuclide Yield Calculator v1.3

example 1 clear example 2 clear

E [MeV]	σ [mb]	E [MeV]	σ [mb]
5	0	4.5E0	18
6	15	5.5E0	215
10	600	12	440
12	555		
20	60		

test clear TENDL-2015 clear

E [MeV]	σ [mb]	E [MeV]	σ [mb]
3.0	0	28.0	32.7399
4.0	2E-1	30.0	28.9305
8	4.5E2	35.0	21.6378
10	625	40.0	16.6622
		45.0	13.2648

plot σ plot + fit σ

Fit type: yield without σ fit

Irradiation Planner

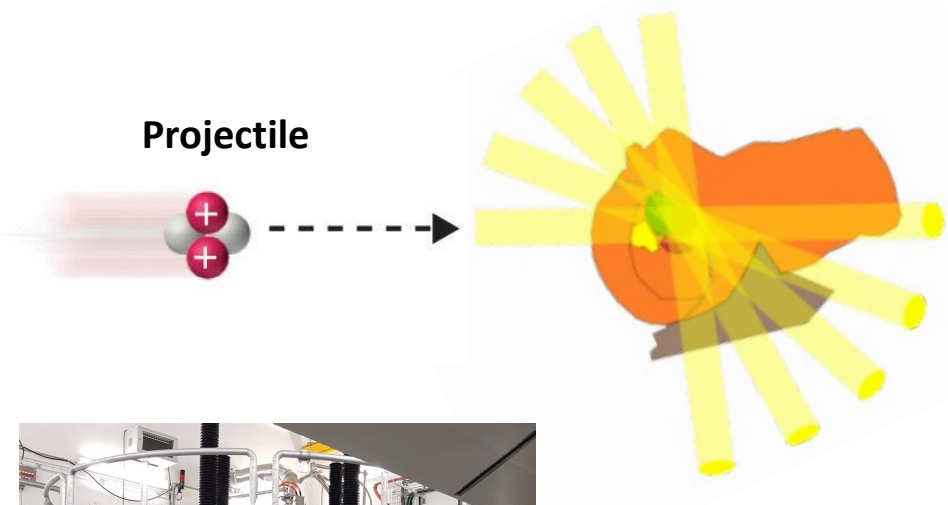
Irradiation **E @ target**
 I [μ A]: min [MeV]:
 t [h]: max [MeV]:

EOB = 1440.0 MBq
 thickness = 259.0 mg/cm²
 = 0.954 mm

Competitive reactions can produce:
43K 43Ca 44Ca 43Sc 45Sc

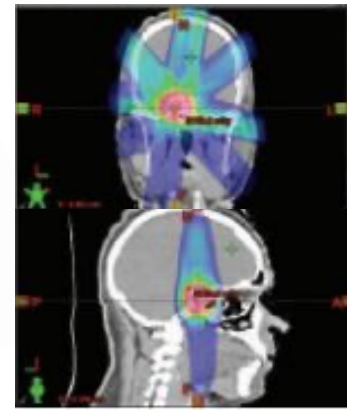
collimator activation
(radioprotection)

Radiotherapy

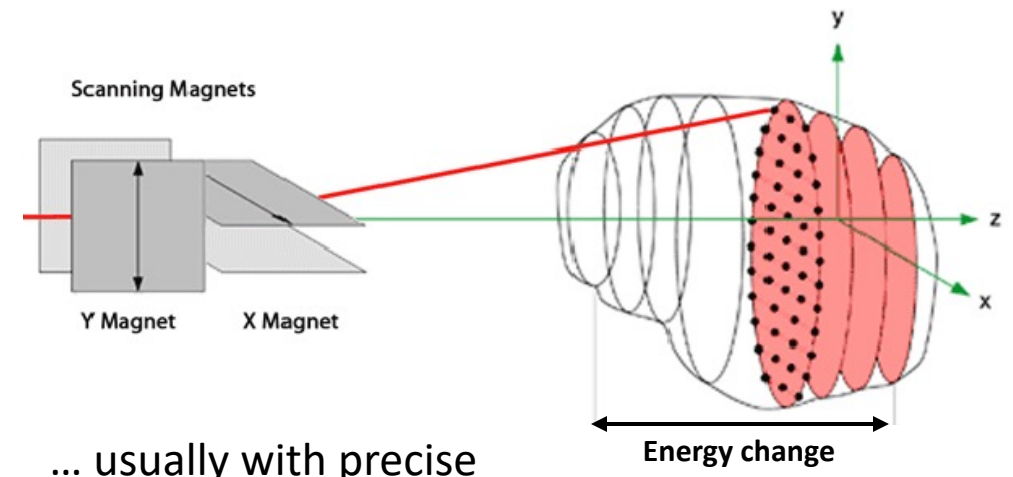


ProBeam: p
Danish Centre for Particle Therapy

Current@target: ~1 nA (~0.1 Gy/s)
Energy: 70-244 MeV



Deposit prescribed **radiation dose** (energy) in tumor



... usually with precise Pencil Beam Scanning technique

FLASH effect



Increase to > 40 Gy/s
Short treatment times (< 0.5s)
High fraction doses (> ~8Gy)

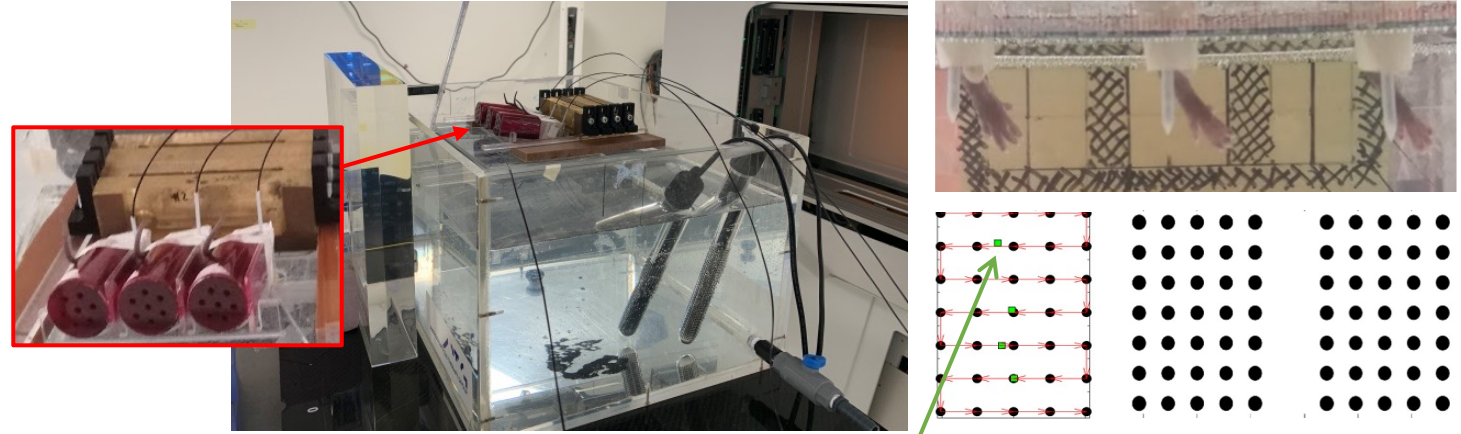
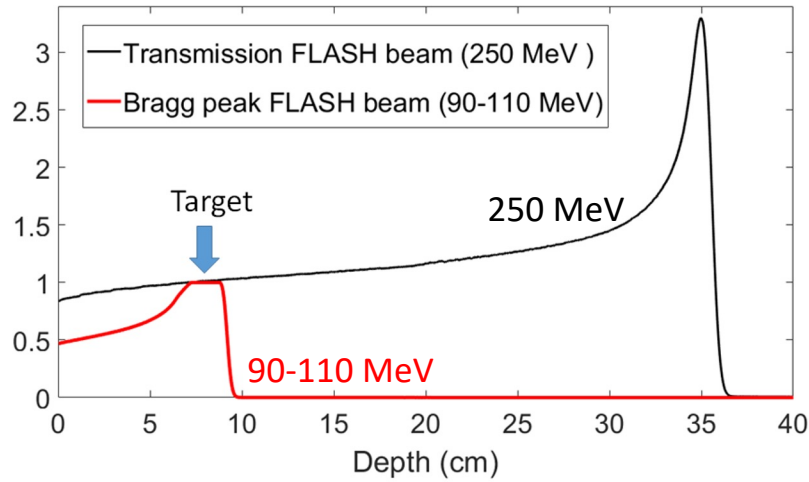


spares healthy tissues
same tumor response

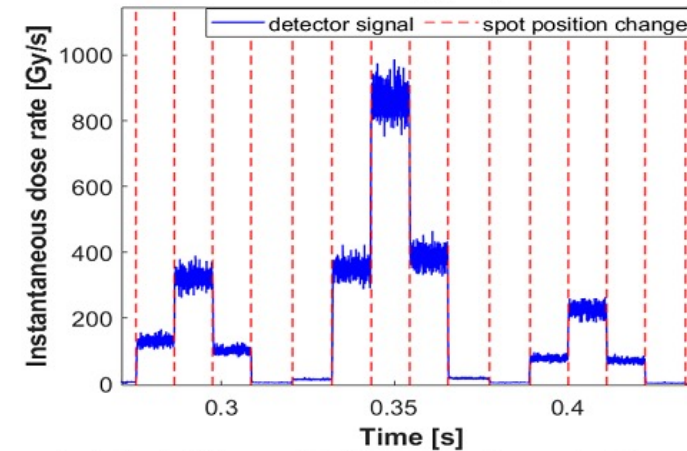
FLASH at the Danish Centre for Particle Therapy

How to trick clinical machine (1 nA \approx 0.1 Gy/s) to deliver FLASH dose rates (40 Gy/s)?

- Highest energy (250 MeV) for highest transmission
- Highest available cyclotron current (550 nA)
- Only one energy (energy switch = 1 s)
- Small treatment fields (2x3 cm²)



Monitoring with scintillator crystals



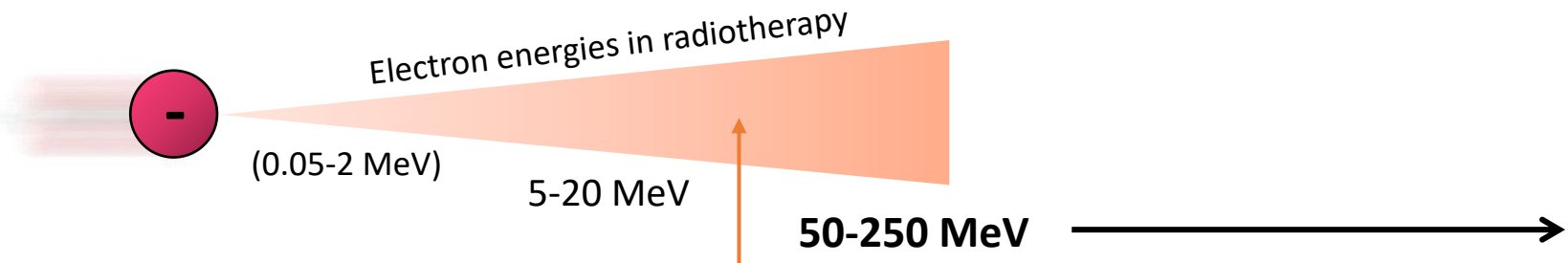
...and other projects

Ridge filters

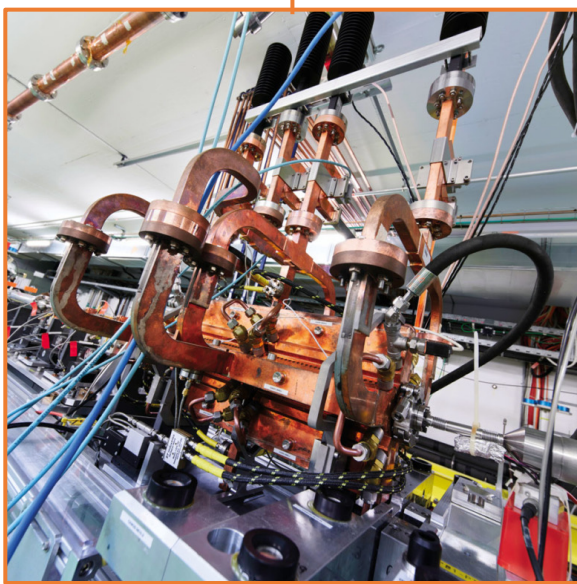
3D gel dosimetry

GRID collimators

Very High Energy Electrons (VHEE)



- Deeper penetration
- Sharper transverse penumbra
- Compact technology
- Easily focused
- FLASH dose rates



high-gradient linac

laser accelerated plasma

VHEE modeling

Beam shape:

$$\Phi(z, \rho) = \underbrace{\frac{1 - W_B}{\pi r_A^2(z)} e^{-\rho^2/r_A^2(z)}}_{\text{primaries}} + \underbrace{\frac{W_B}{\pi r_B^2(z)} e^{-\rho^2/r_B^2(z)}}_{\text{secondaries}}$$

Radial spread (2-nd Fermi-Eyges moment):

$$r^2(z) = r_0^2 + 2\theta r_0 z + \theta_0 z^2 + \int_0^z (z - u)^2 T(u) du$$

Scattering power:

$$T = \frac{\chi_c^2 B}{l} \quad \chi_c^2 = \frac{4 \pi r_e^2 N_A Z^2}{A \gamma^2 \beta^4} \rho l \quad B - \ln B = \ln \frac{6680 \rho l (Z + 1) Z^{1/3}}{\beta^2 A (1 + 3.34 \alpha^2)}$$

Applied nuclear/radiation physics in research:

- Production of radioisotopes
- Dosimetry, radiobiology
- Irradiation campaigns
- Beam modeling
- (Programming)