JAGIELLONIAN UNIVERSITY IN KRAKOW

Jagiellonian Symposium on Fundamental and Applied Subatomic Physics

Development of a dedicated beam forming system for material and bioscience research with high intensity, small field electron beam of LILLYPUT 3 accelerator at Wroclaw Technology Park

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Abstract

The LILLYPUT 3 electron accelerator designed and manufactured at National Centre for Nuclear Research in Swierk, Poland (NCBJ) is the principal instrument of The Nondestructive Testing Laboratory at Wroclaw Technology Park.

The accelerator delivers 6 and 9 MeV electron beams. In a standard configuration the electron beam is converted into X-ray beam in a water cooled tungsten target. The primary use of the accelerator is nondestructive testing including R&D of novel techniques for industrial and medical imaging.

In addition, the high intensity electron beam can be directly extracted for a broad range of applications including material and bioscience research. For those applications a specialized beam forming system has been designed at NCBJ.

The purpose of this system is to deliver as high intensity electron beam as possible, while keeping beam flatness within 10% on a 7x7 sq. cm field in the distance of 40 cm from the beam exit window. Two alternative solutions were taken into consideration, one involving beam scanning and second based on passive beam forming with flattening foil. While it seemed that the highest beam intensity can be achieved by beam scanning, the in-depth study of the system performance revealed that, under available resources, the realistically achievable beam intensity is going to be comparable in both solutions. Taking into account simplicity and considerably lower costs of the passive beam forming system this solution was adopted. Optimization of the final system design was performed with a dedicated Geant4-based application created specifically for this purpose. The system is being currently fabricated at NCBJ.

In this paper the methodology, results as well as tools involved in the design of the specialized beam forming system will be presented.

Outline

Introduction and Motivation

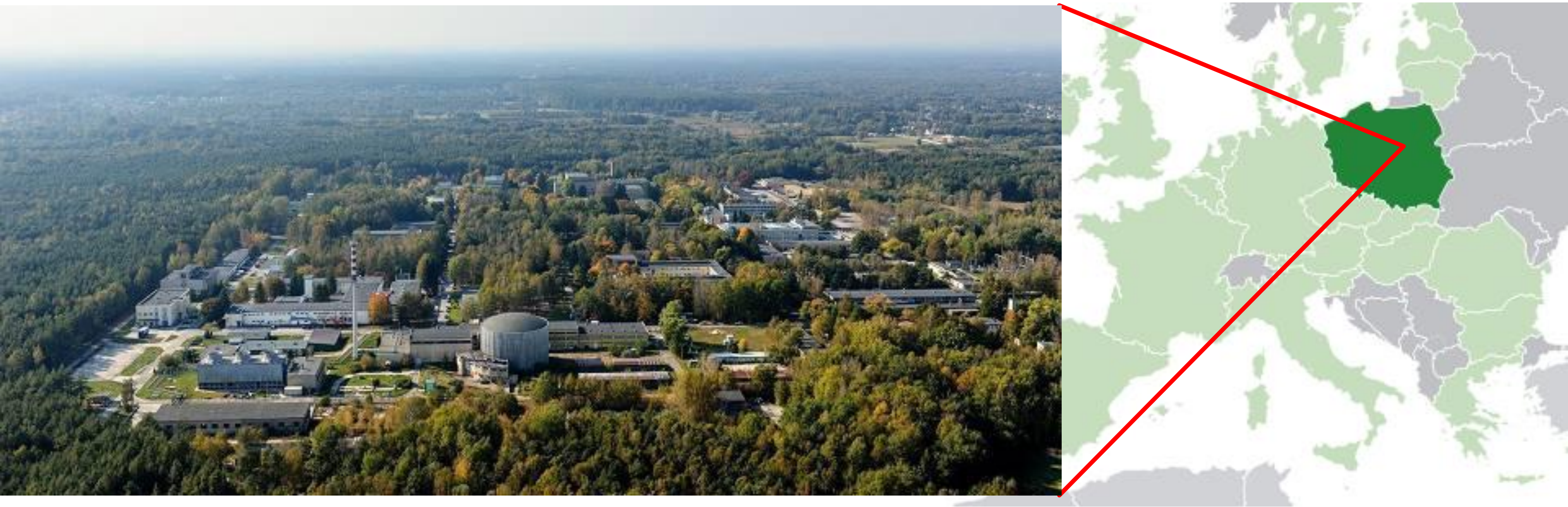
- The LILLYPUT-3 accelerator at the Nondestructive Testing Laboratory (NTL) at Wroclaw Technology Park
- High-dose irradiation under cryogenic conditions (objectives, requirements, constraints, etc.)
- Electron beam forming – active (scanning) VS passive (scattering)

Design of the system

- Beam scanning – reality check
- Physics principles of dual foil system operation
- Simple analytical model of electron fluence
- Impact of helium filled applicator – motivation for development of a MC model
- Geant4 model and tools for automatized design
- System optimization
- Calculation of expected dose rate

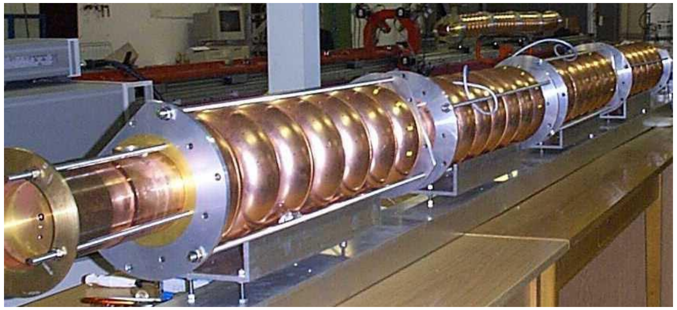
Conclusions and outlook

National Centre for Nuclear Research, Swierk, Poland

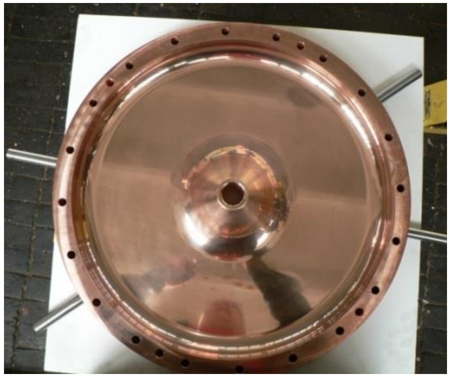


- ✓ The largest research institute in Poland (1000+ employees)
- ✓ Broad scope of fundamental and applied research
    - Nuclear physics (including reactor physics)
    - High energy physics (in collaboration with CERN and others)
    - Plasma physics
    - Material science
    - Free-electron lasers (in collaboration with XFEL)
- ✓ Tradition of development and production of radiopharmaceuticals and medical equipment, including linear accelerators

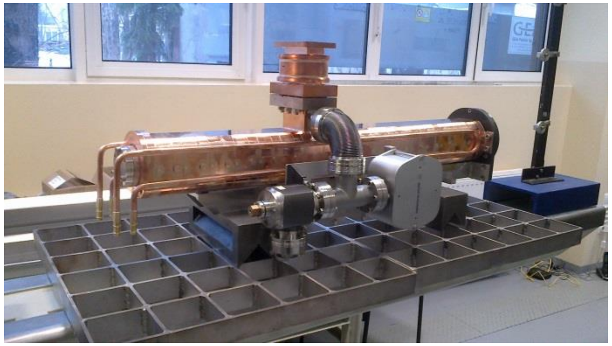
NCBJ and electron LINACs for science, industry, medicine



Prototype cavities 1.3 GHz for Tesla-FEL at DESY

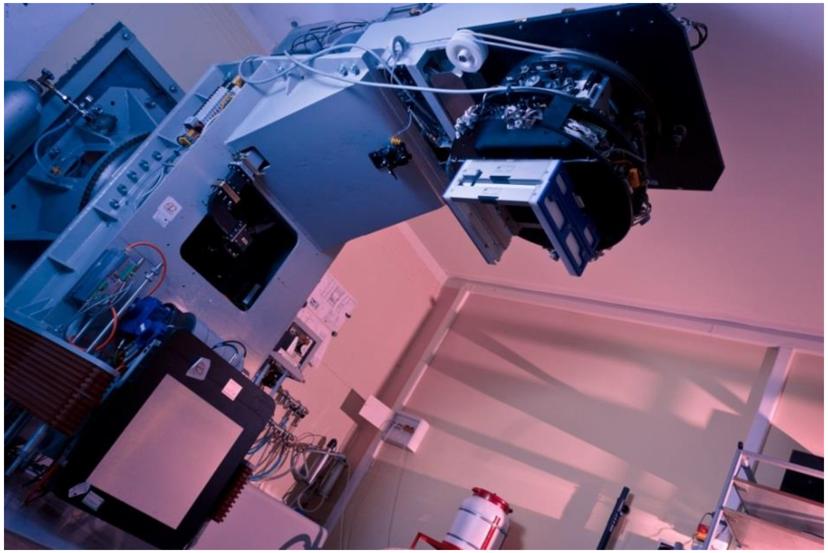


cavity for LINAC4@CERN



Prototype for mobile IOERT

Mobile linac for industrial radiography

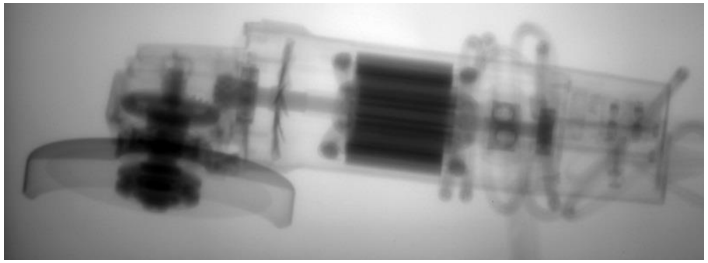


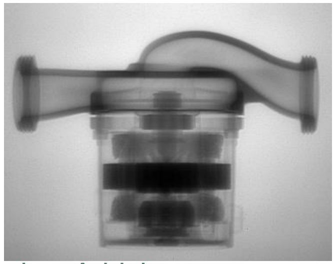
Assembly of a medical linac

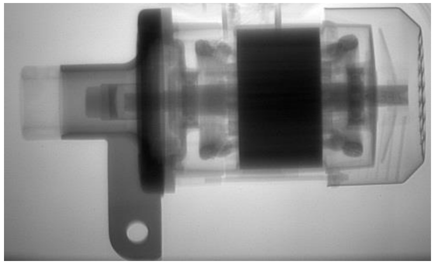
The LILLYPUT-3 accelerator at The Nondestructive Testing Laboratory at Wroclaw Technology Park

Standard radiographic configuration

- 6 and 9 MV X-ray beams
- Maximum dose rate 20 Gy/min
- Maximum field size Φ500mm @1m (adjustable with automatized jaw collimators)
- Digital imaging
- Automatized object table







High-dose electron beam irradiation at NTL

Primary motivation

- Tests of radiation hardness of insulators (tens of MGy absorbed dose, cryogenic conditions)
- R&D in sterilization of polymer based medical products (tens of kGy)
- Research in polymer structure modifications (tens of kGy)

Perspectives, R&D opportunities

- Effects of irradiation on the structure of high temperature superconductors
- Effects of irradiation on the response time of electronic circuits
- Enhancement of optical properties of gemstones
- Coating hardening and regeneration
- Purification of exhaust gases from combustion of fossil fuels
- Food preservation

High-dose electron beam irradiation under cryogenic conditions at NTL

Primary motivation

- Tests of radiation hardness of insulators (tens of MGy absorbed dose, cryogenic conditions)

Objectives

- Irradiation of samples under cryogenic conditions (LN_2)
- Maximize dose rate (~ few tens of kGy/min). Total absorbed dose in the range of few tens of MGy.

Requirements

- Well flattened beam (i.e. homogenous dose distribution over sample area)
- Relatively small field size (~Φ80mm). Square samples ~60x60 mm

Approach towards system adaptation

- 9 MeV electron beam (extracted directly in a non-standard configuration)
- Shortest possible source to sample distance (SSD ~400 mm)
- Least possible disruption of the existing system

Least possible disruption of the existing system…

RF power supply (3 GHz)

Radiation head

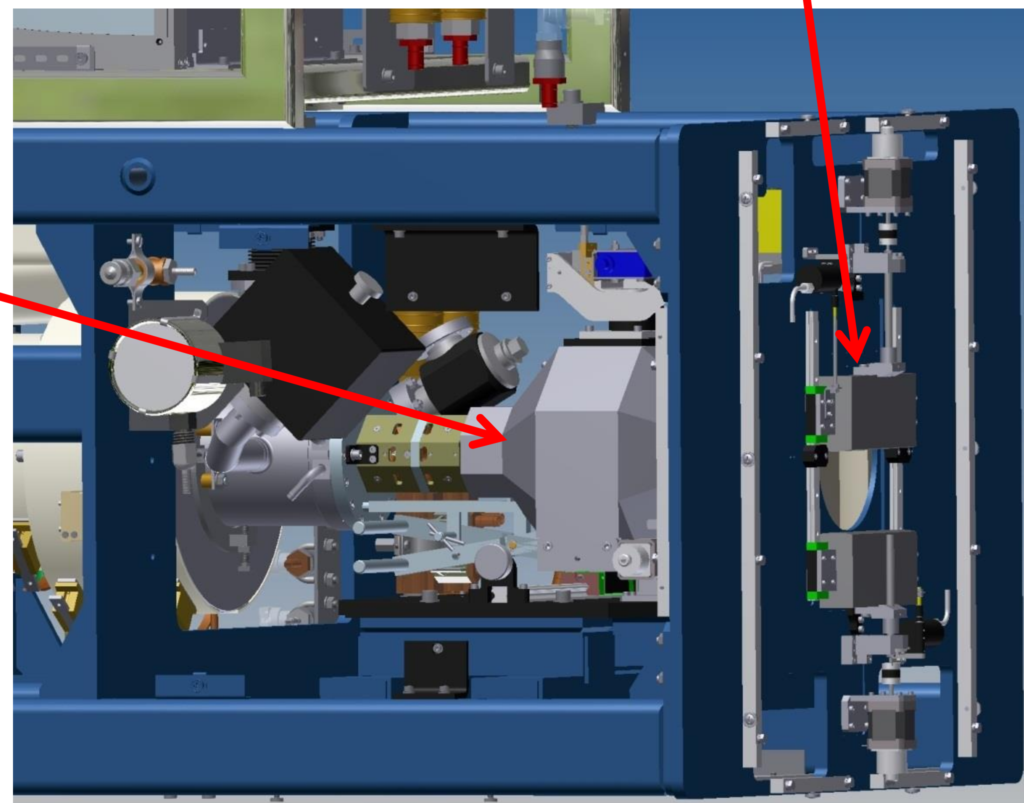
electron linac

Least possible disruption of the existing system…

Radiation head in standard configuration

Movable X-ray jaw collimators
(two pairs, X and Y axis)

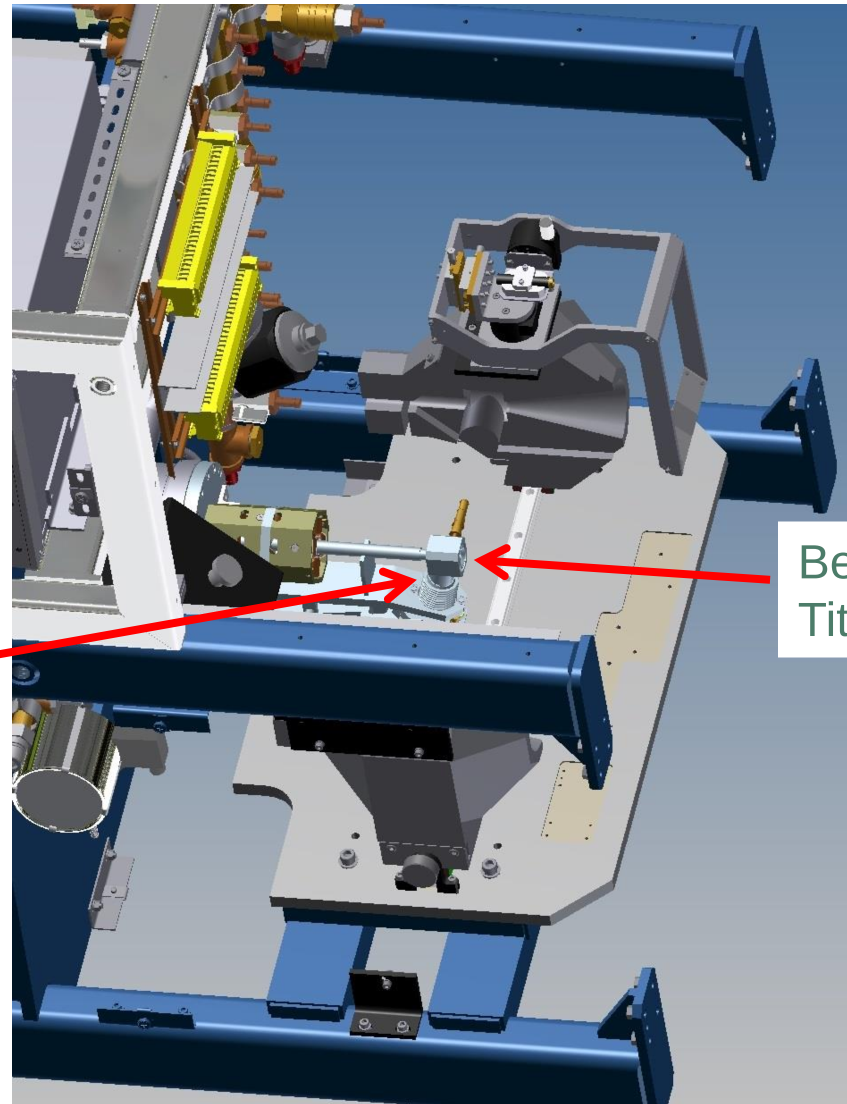
Primary X-ray collimator



Modular construction allows for reasonably simple removal of modules

Least possible disruption of the existing system…

Radiation head dismantled

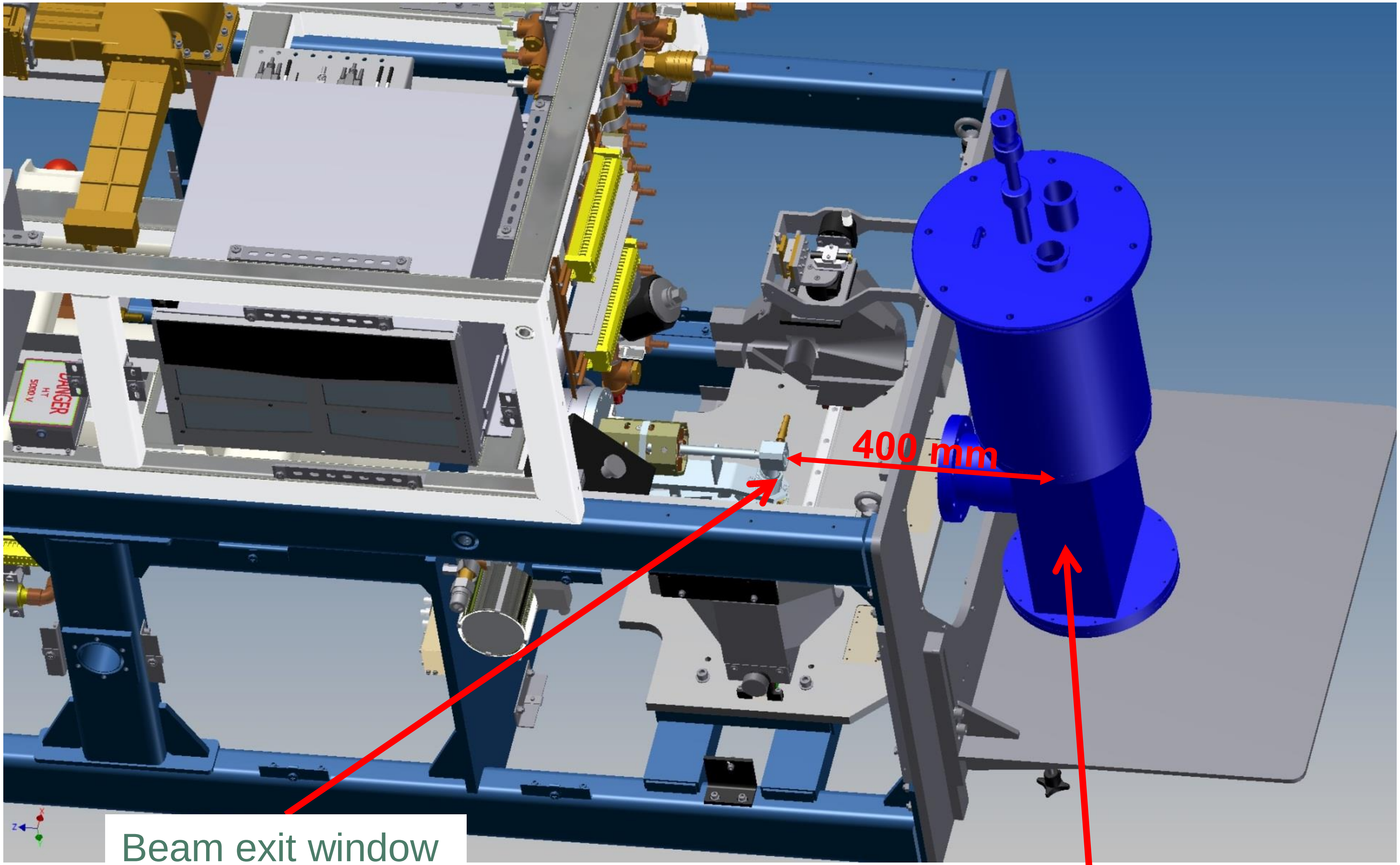


Beam exit window
Titanium, 0.05 mm

Target chamber

X-ray production targets can be moved in and out of beam path (in vacuum)

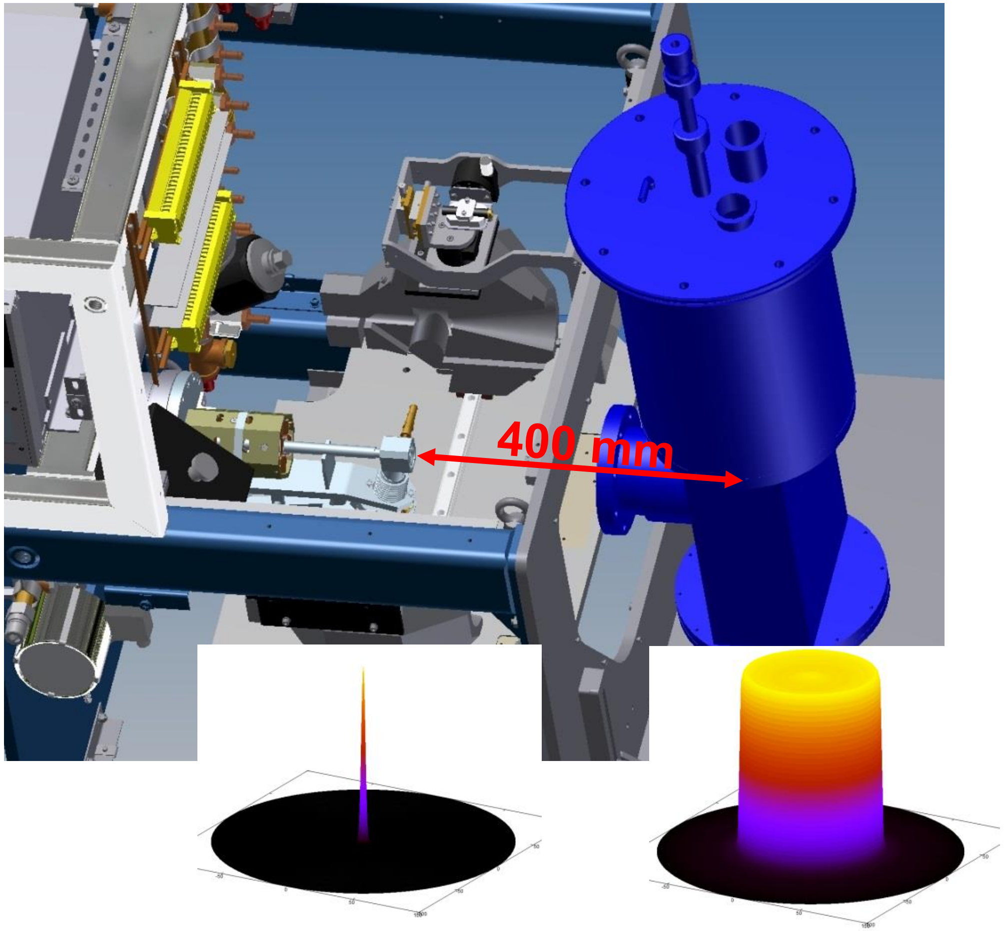
Least possible disruption of the existing system…



Beam exit window
Titanium, 0.05 mm

LN_2 cryostat
(holds irradiated samples)

Electron beam forming system – what is it good for?

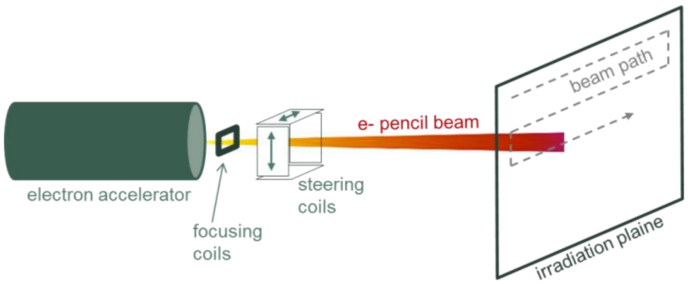


Beam fluence at the exit window
- „pencil beam”
- very narrow (FWHM ~3 mm)
- extremely nonuniform

Desired beam fluence at sample location
- uniform over large area (Φ ~ 8 cm)

Electron beam forming – active VS passive

active = beam scanning



Common applications: sterilization, industrial material processing (e.g. polymer cross linking), modern hadron therapy

- **High efficiency (→ high dose rate)**
- Relatively complex system (especially for 2D scanning)
- Nontrivial to achieve uniform dose distribution
- Difficult to control beam uniformity

Electron beam forming – active VS passive

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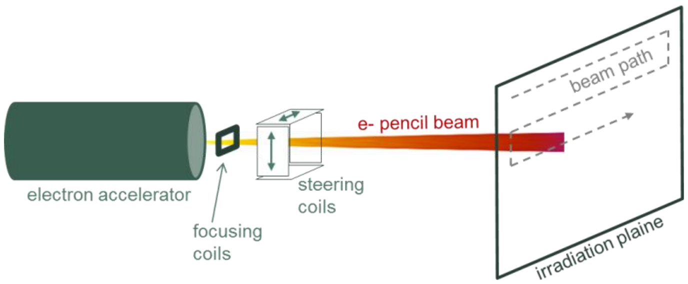
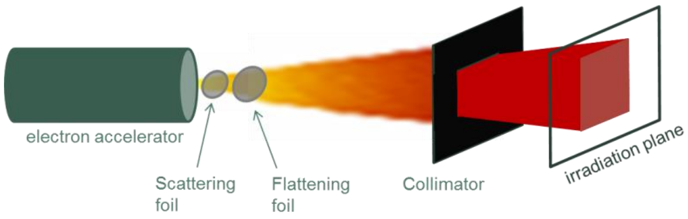


passive = beam scattering and collimation



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Common applications: electron beam therapy (also previous generation of proton therapy)

- Uniform beam distribution
- Simple, reliable
- **Significantly less efficient**

Electron beam forming – active VS passive

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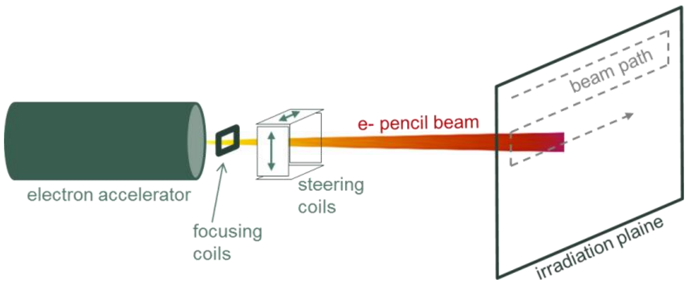

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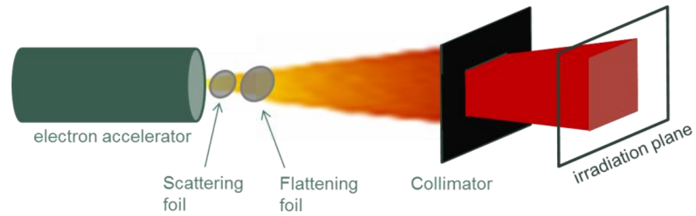

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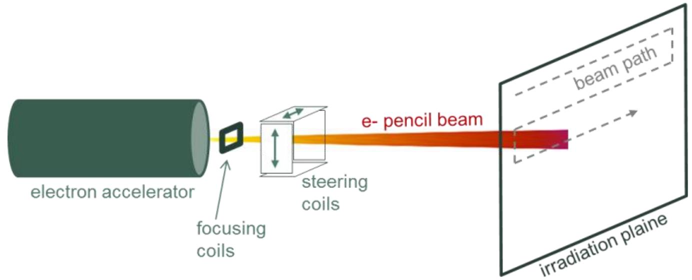
- Uniform beam distribution
- Simple, reliable
- **Significantly less efficient**

In this application, efficiency is all that matters

Electron beam scanning – reality check



e- beam
9 MeV

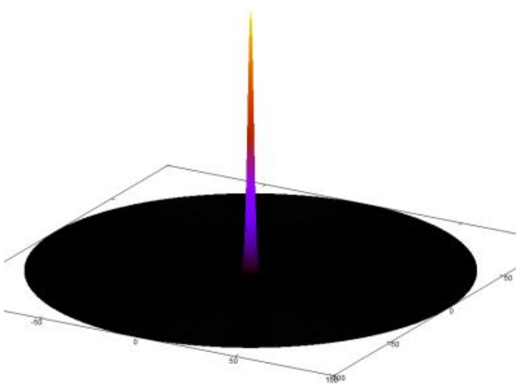
400 mm

Air
10 mm

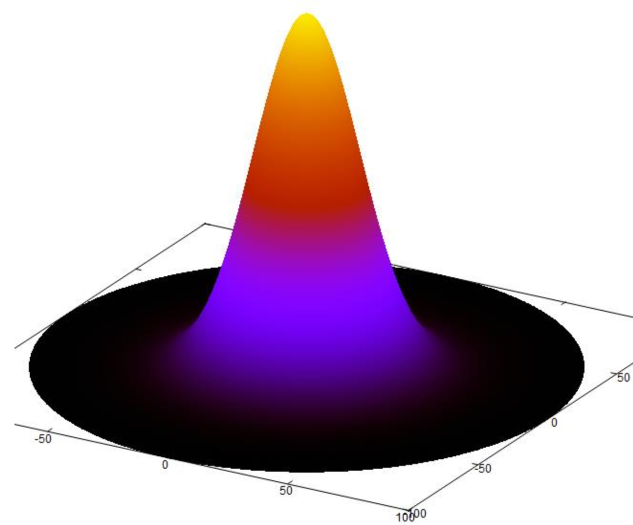
Vacuum

50 µm Ti
Exit window

50 µm Ti
Vacuum chamber entrance window



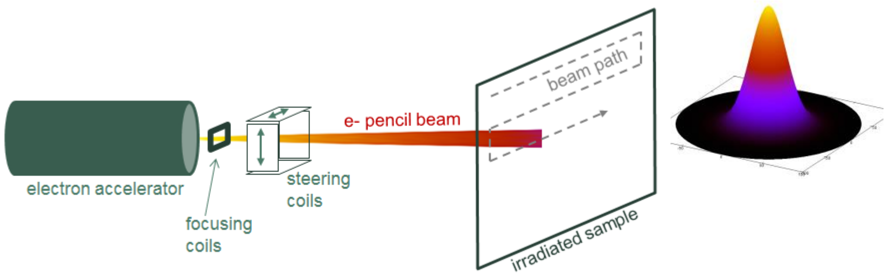
FWHM 3 mm

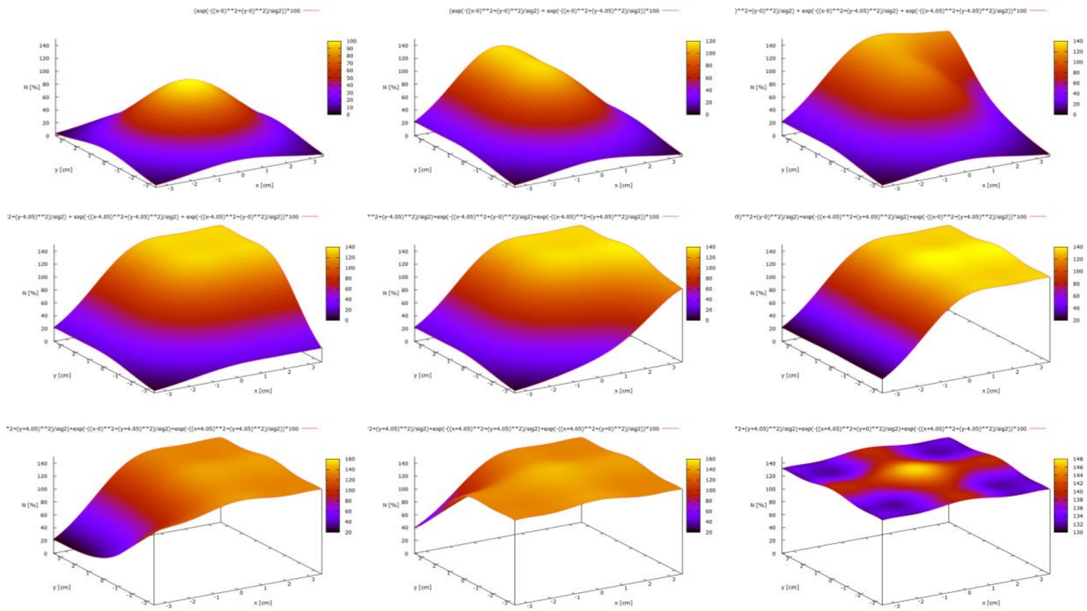


FWHM 45 mm

Electron beam scanning – reality check

Simple model of beam scanning on a 7x7 cm^2 field with a beam of FWHM = 45mm

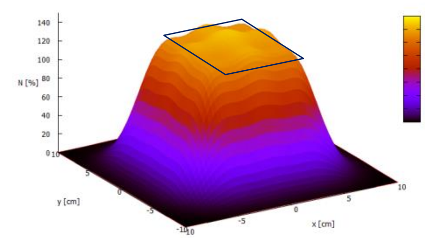




Decent uniformity* (~12%)

but

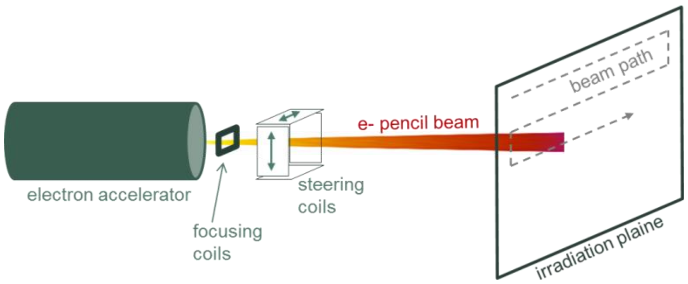
Efficiency ~ 30 % (or 70% of the beam ends up outside of the field)



*) Flatness (uniformity) of electron beam fluence calculated as $flatness = \left(\frac{\Phi_{max}}{\Phi_{min}} - 1\right) \cdot 100\%$

Electron beam forming – active VS passive

active = beam scanning



Common applications: sterilization, industrial material processing (e.g. polymer cross linking), hadron therapy

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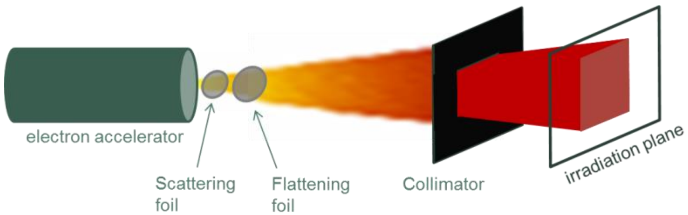

Common applications: electron beam therapy (also previous generation of proton therapy)

- Uniform beam distribution
- Simple, reliable
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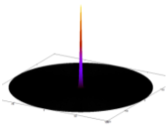
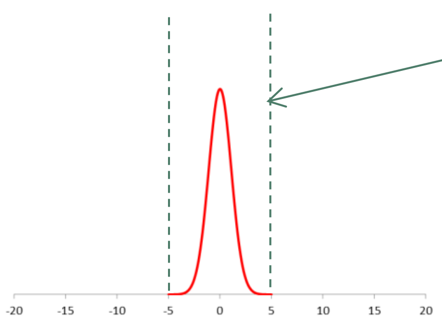
The principle of dual-foil system



Beam exiting linac

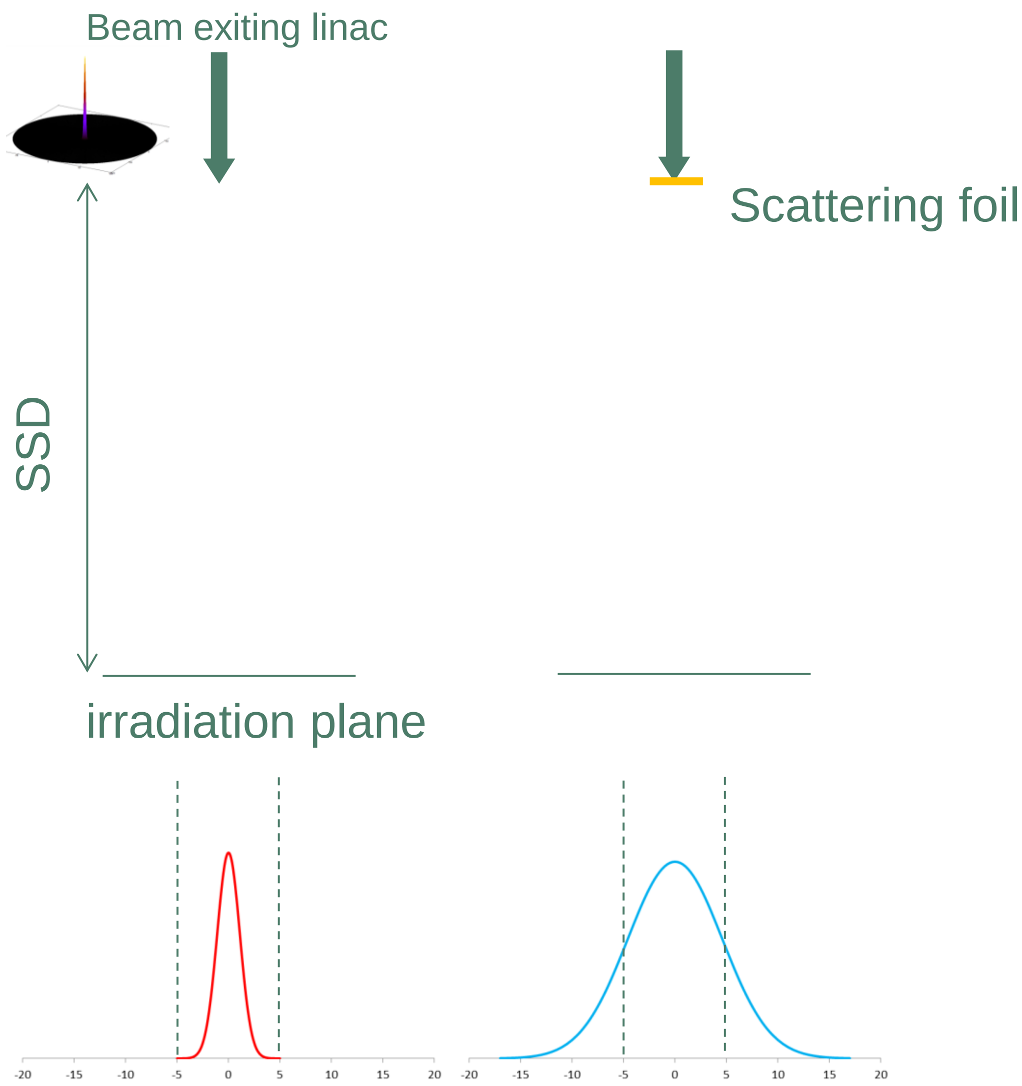
SSD

irradiation plane

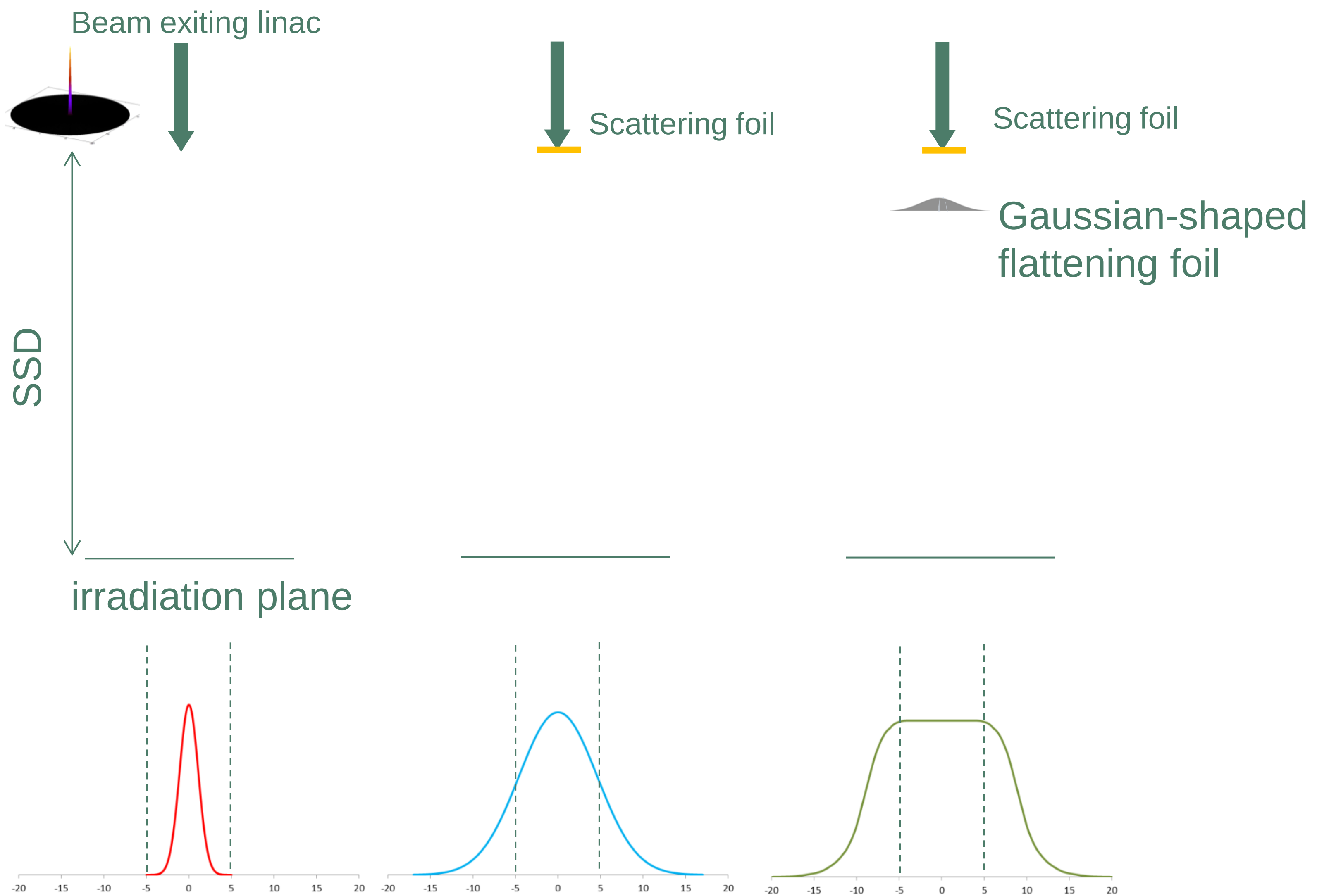


Limits of the field

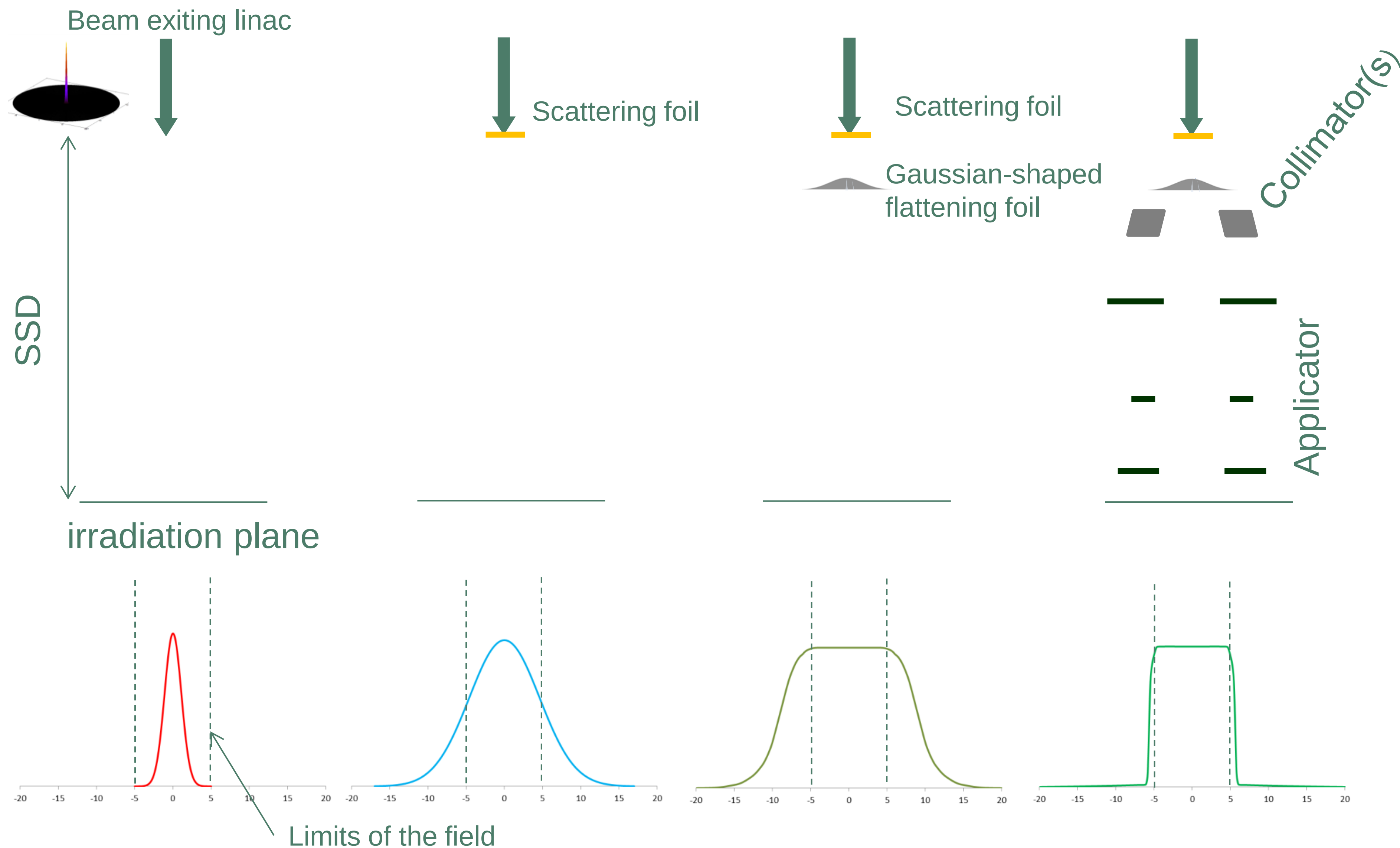
The principle of dual-foil system



The principle of dual-foil system

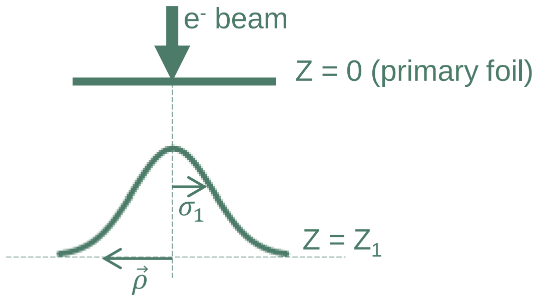


The principle of dual-foil system



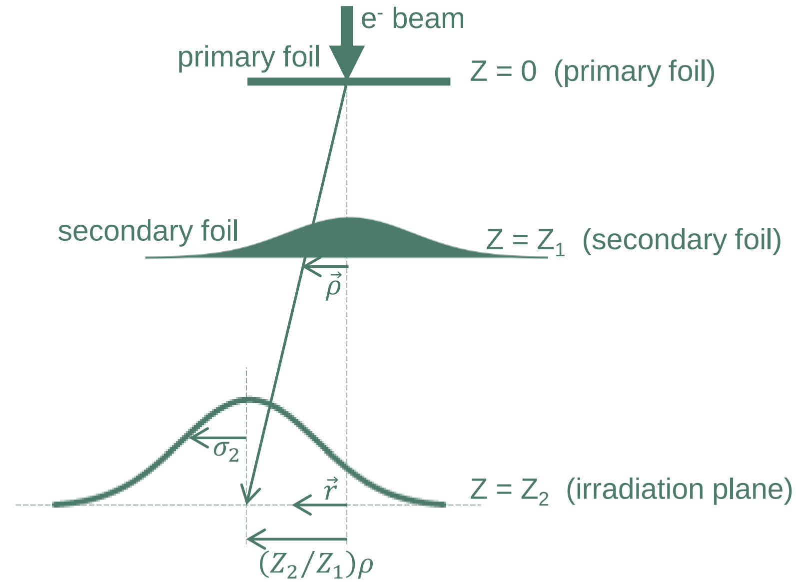
Calculation of electron fluence – simple model

Electron fluence at the position of the secondary foil due to scattering in the primary foil and in the air between foils



$$\Phi_1(Z_1,\vec{\rho}) = \frac{1}{2\pi\,\sigma_1^2}\exp\left(-\frac{\vec{\rho}^2}{2\sigma_1^2}\right)$$

Component of the fluence at the irradiation plane due to a beamlet originating from rho at the second foil



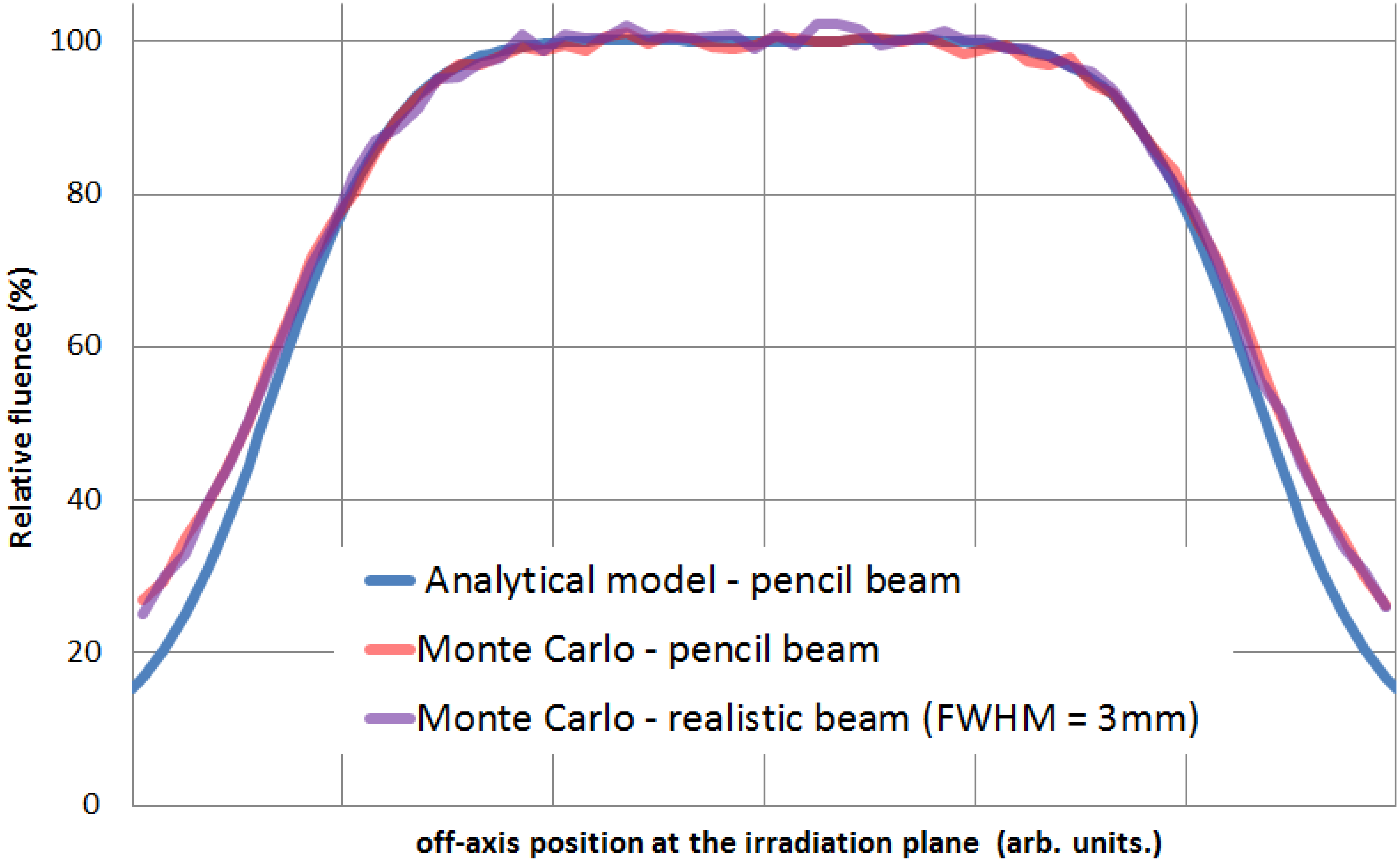
$$\Phi_2(Z_2,\vec{r};Z_1,\vec{\rho}) = \frac{1}{2\pi\,\sigma_2^2}\exp\left(-\frac{(\vec{r}-(Z_2/Z_1)\vec{\rho})^2}{2\sigma_2^2}\right)$$

Fluence at point $\vec{r}$ at the irradiation plane Z_2 is a convolution of Φ_1 and Φ_2:

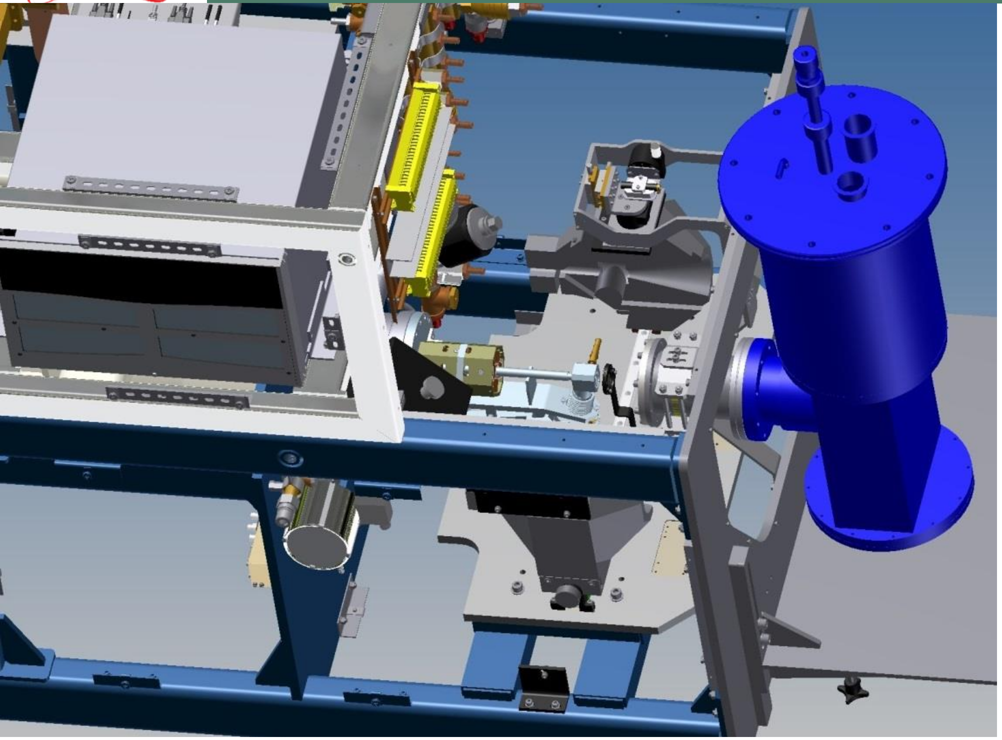
$$\Phi(Z_2,\vec{r}) = \int_0^{2\pi}\int_0^{\rho_{max}} \Phi_1(Z_1,\vec{\rho})\Phi_2(Z_2,\vec{r};Z_1,\vec{\rho})\,\rho d\rho d\varphi$$

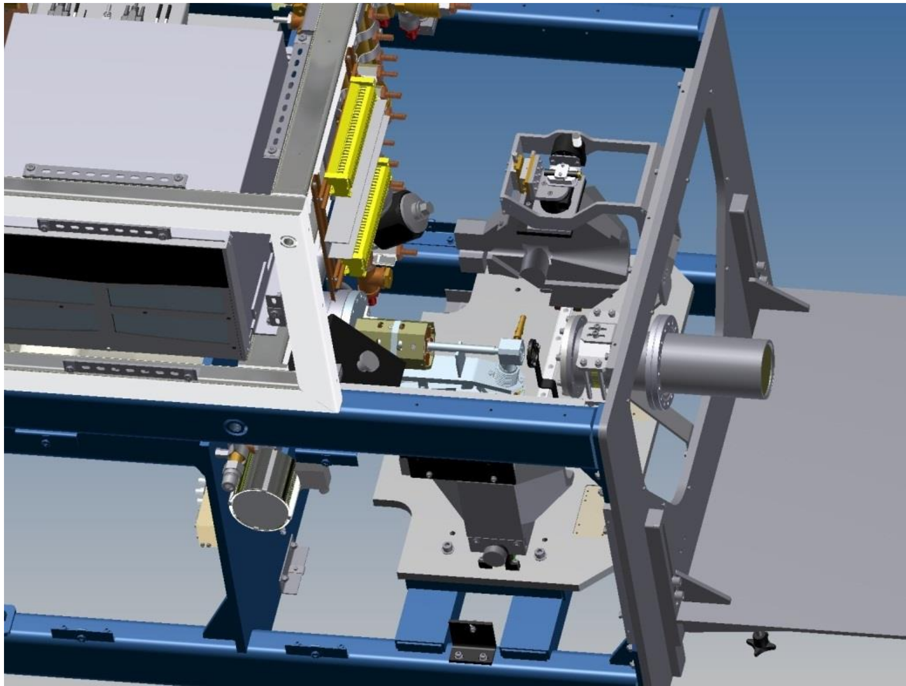
Numerical integration is straight forward

Calculation of electron fluence – simple model



Influence of the applicator on the electron distribution at the irradiation plane

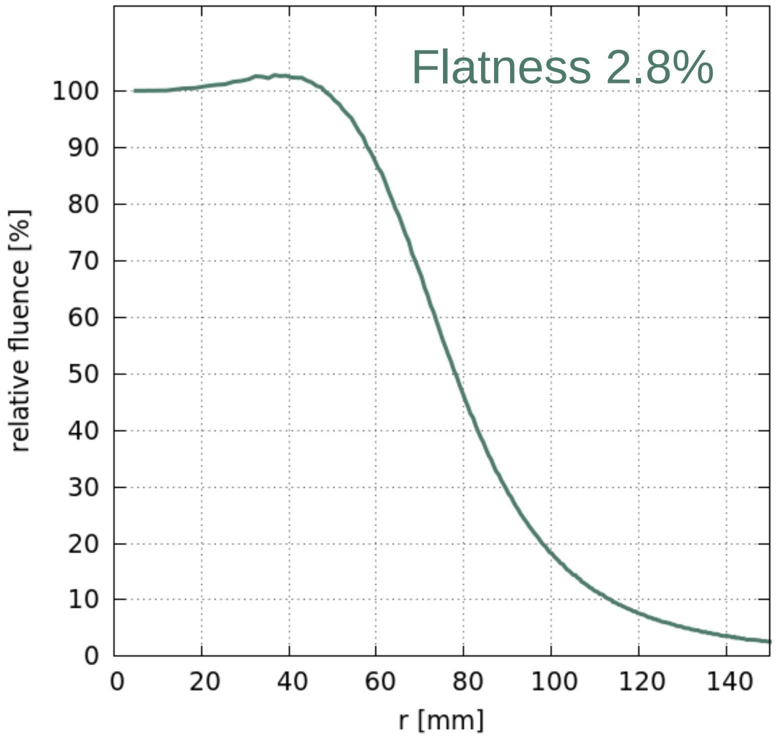




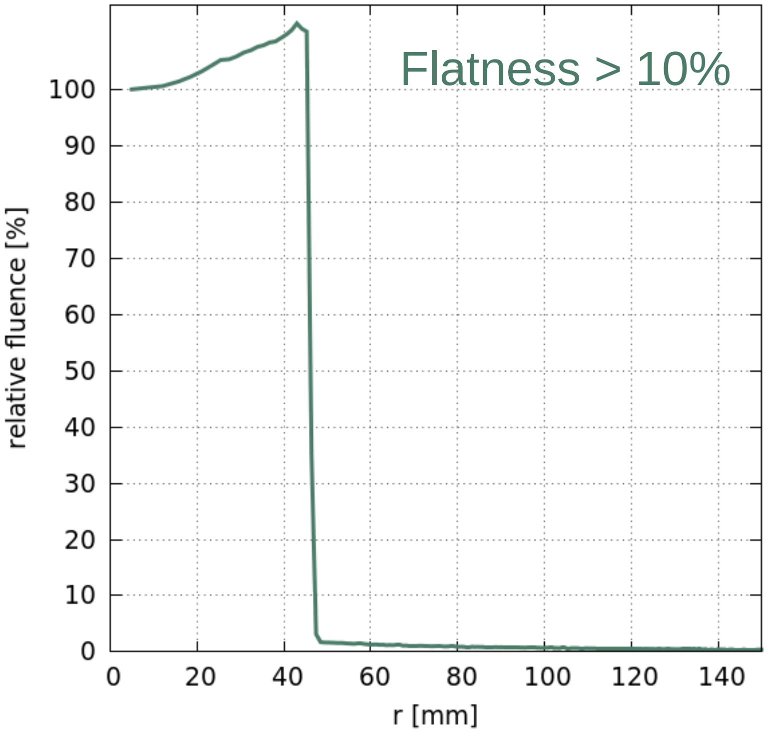
Influence of the applicator on the electron distribution at the irradiation plane

The same scattering and flattening foils (MC calculation)

Without an applicator



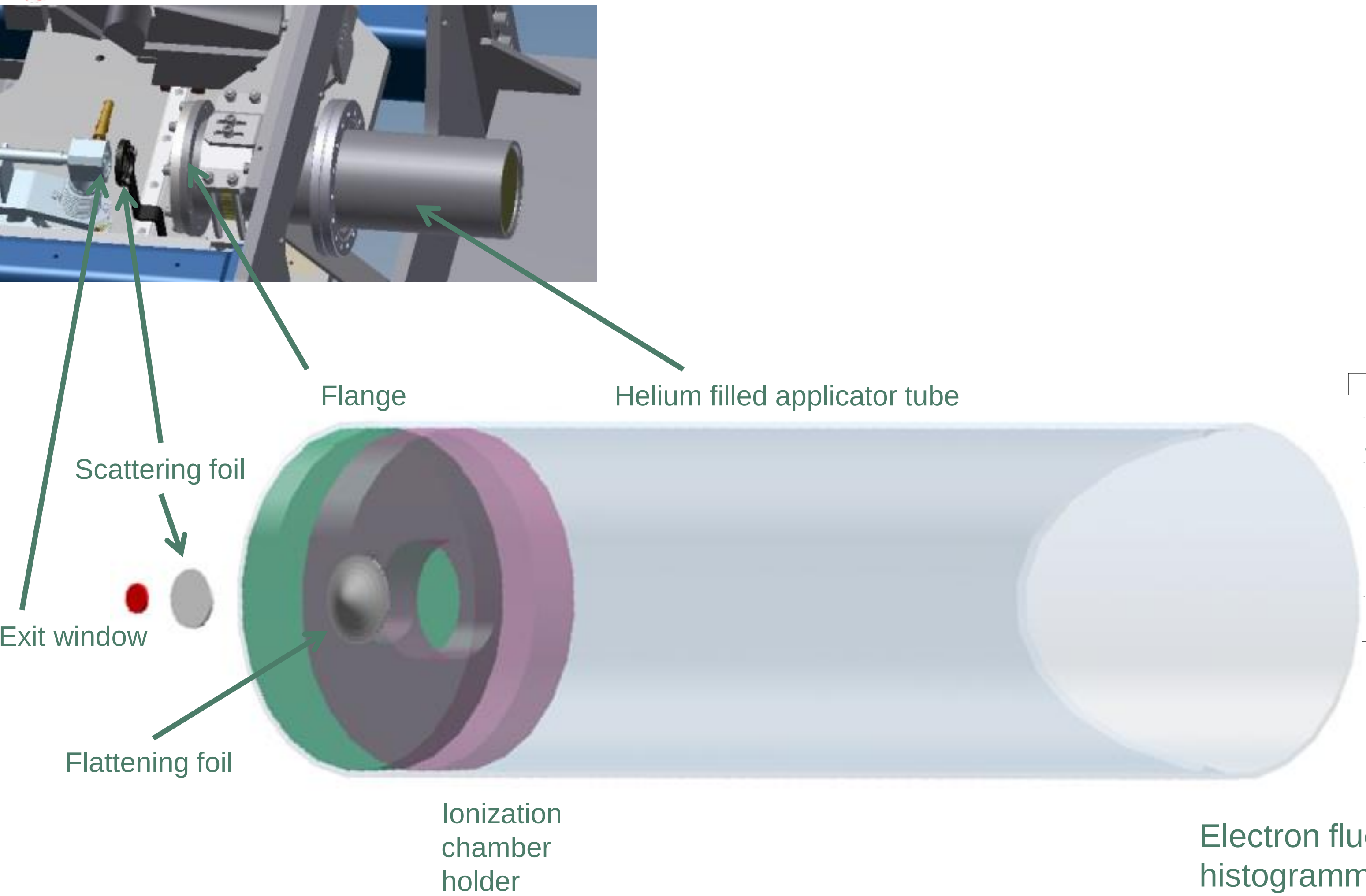
With *Φ*93 mm circular applicator

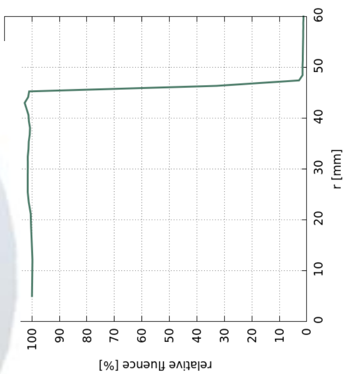


Flatness calculated within *Φ*82 mm field

Setup: exit window Ti 0.05 mm, 20 mm Air, scattering foil Ta 0.03 mm, 60 mm Air, flattening foil Al H=1mm, R=5.5 mm, SSD=400 mm

Tools for designing optimal foils – Geant4 model

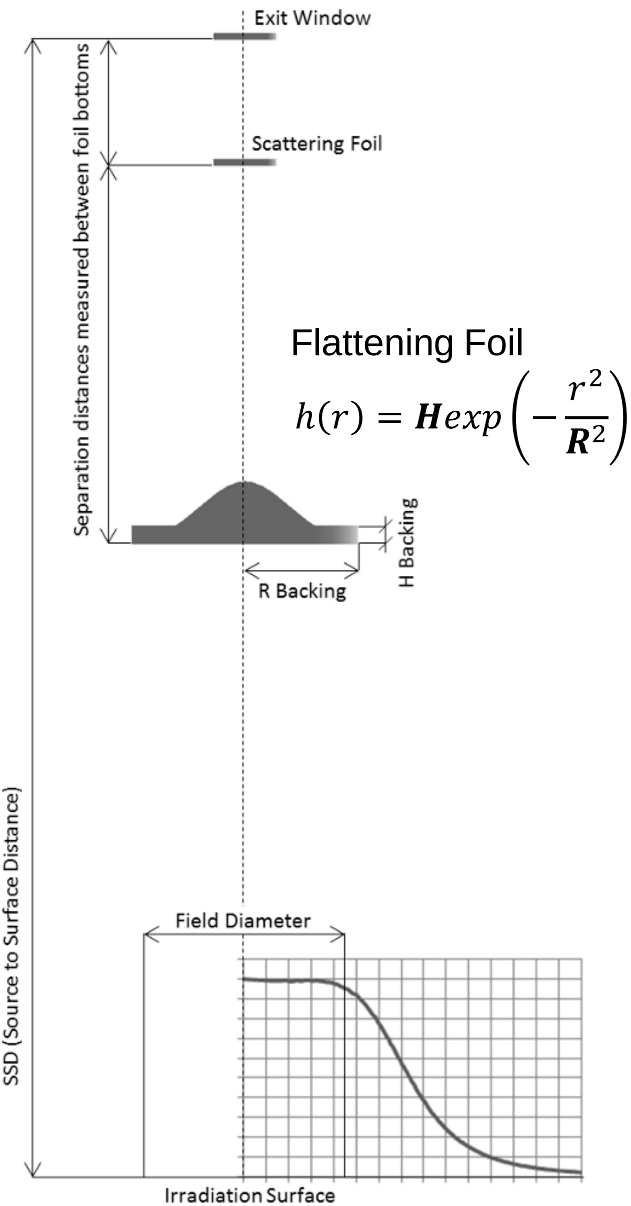




Electron fluence and energy are histogrammed at the end of the applicator.
Flatness of the fluence distribution is calculated within the field as

$$flatness = \left(\frac{\Phi_{max}}{\Phi_{min}} - 1\right) \cdot 100\%$$

Dual-foil system: degrees of freedom

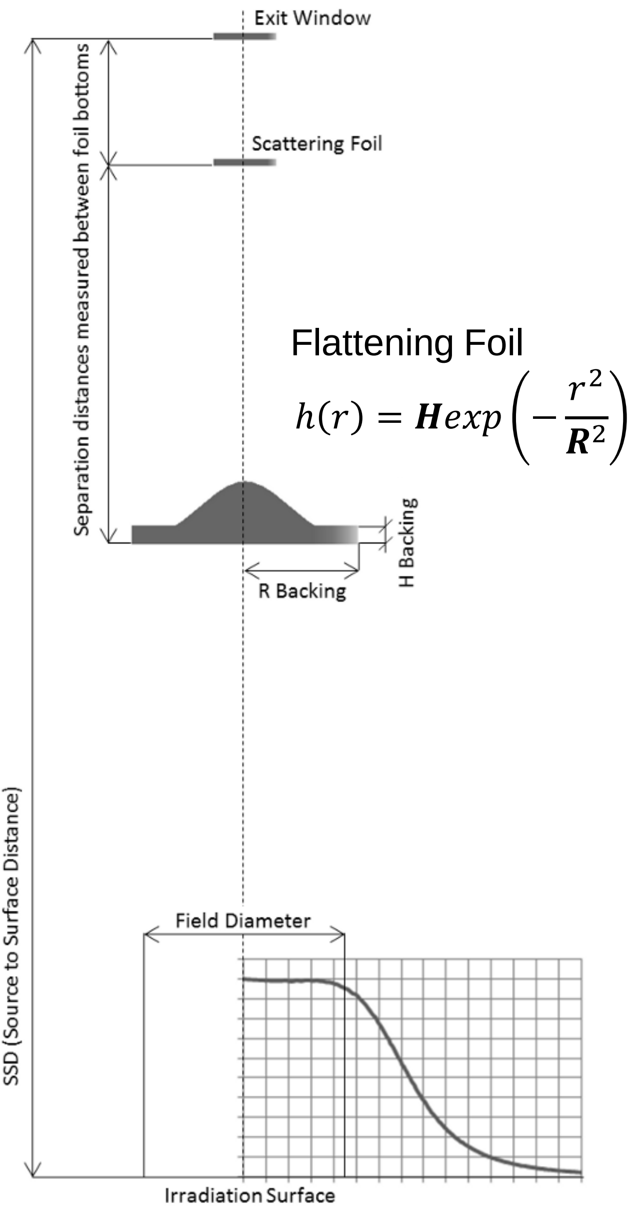


$$h(r) = \boldsymbol{H} exp\left(-\frac{r^2}{\boldsymbol{R}^2}\right)$$

Parameters of the system:

- Beam energy – fixed at 9 MeV
- Irradiation field size – fixed at Φ 82 mm
- SSD – fixed at 400 mm
- Scattering foil position – ?
- Scattering foil material – ?
- Scattering foil thickness – ?
- Flattening foil material – ?
- Flattening foil position – ?
- Flattening foil thickness and width – ?

Dual-foil system: degrees of freedom



Flattening Foil

$$h(r) = \boldsymbol{H} exp\left(-\frac{r^2}{\boldsymbol{R}^2}\right)$$

Parameters of the system:

- Beam energy – fixed at 9 MeV
- Irradiation field size – fixed at Φ 82 mm
- SSD – fixed at 400 mm
- Scattering foil position – as much upstream as possible – space for air cooling must be provided between the exit window and the scattering foil
- Scattering foil material – ?
- Scattering foil thickness – ?
- Flattening foil material – ?
- Flattening foil position – ?
- Flattening foil thickness and width – ?

Dual-foil system: Selection of materials

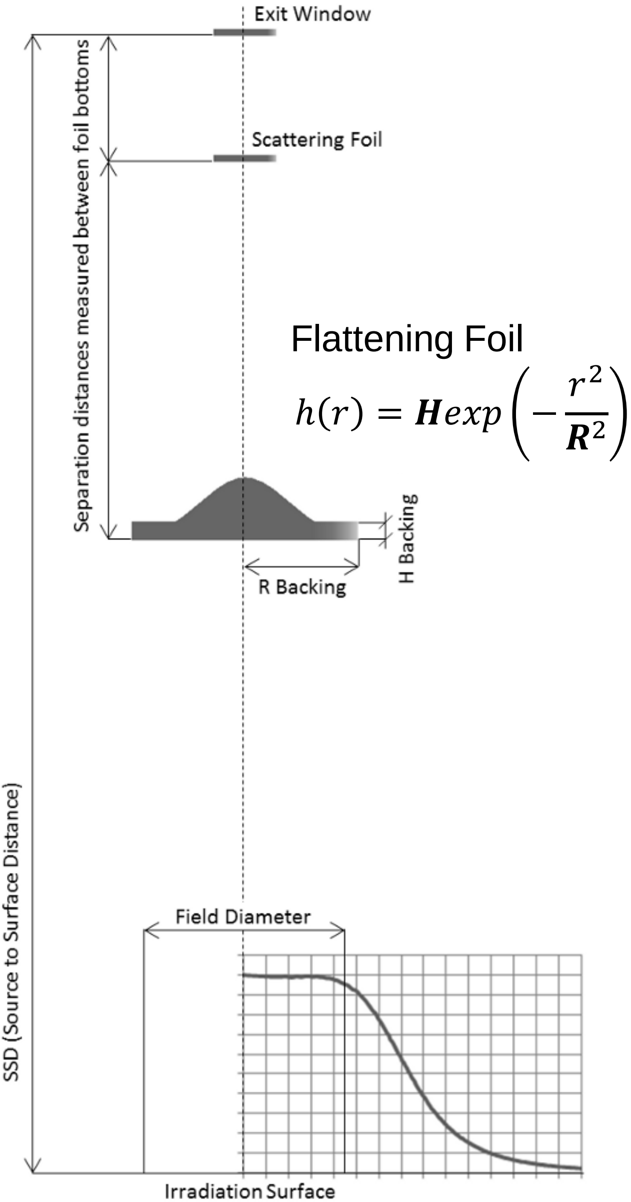
Mass Scattering Power $\frac{T}{\rho} \sim \frac{Z^2}{A}$

Collisional Stopping Power $S_{col} \sim \frac{Z}{A}$

Scattering Foil
- The higher the Z the better (Bi, Pb, Au)
- High melting point (W, Ta)
- Availability, price (Ta)

Flattening Foil
- The higher the Z the better (Bi, Pb, Au)
- Feasible to machine a profiled shape (Al)

Dual-foil system: degrees of freedom



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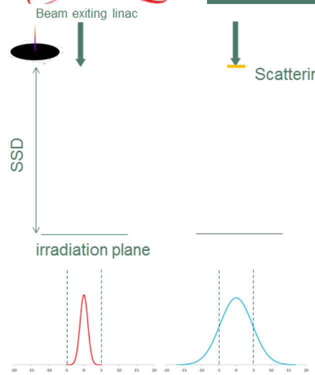
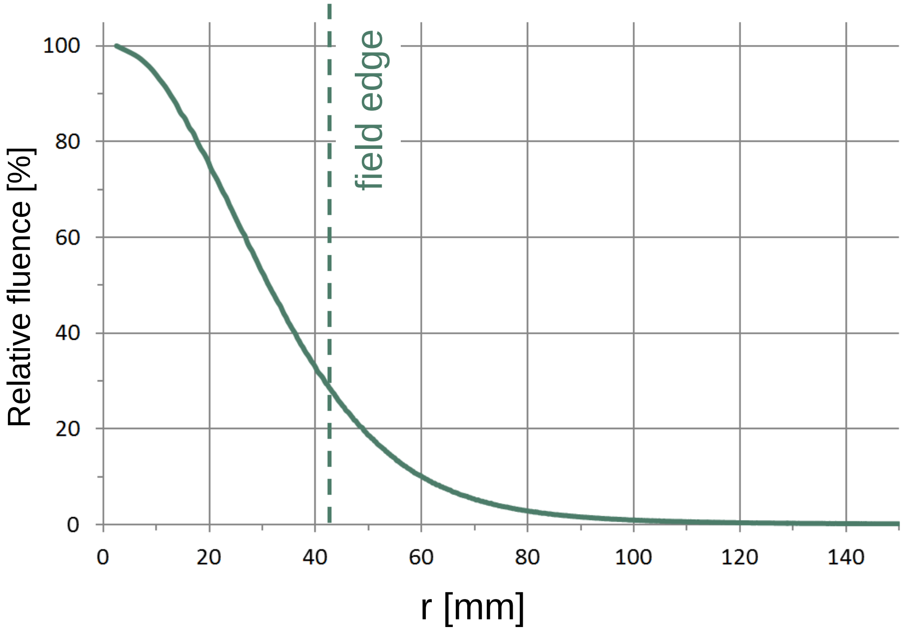
- Scattering foil position – as much upstream as possible – space for air cooling must be provided between the exit window and the scattering foil
- Scattering foil material – Ta
- Scattering foil thickness – ?
- Flattening foil material – Al
- Flattening foil position – ?
- Flattening foil thickness and width – ?

Dual-foil system: scattering foil thickness

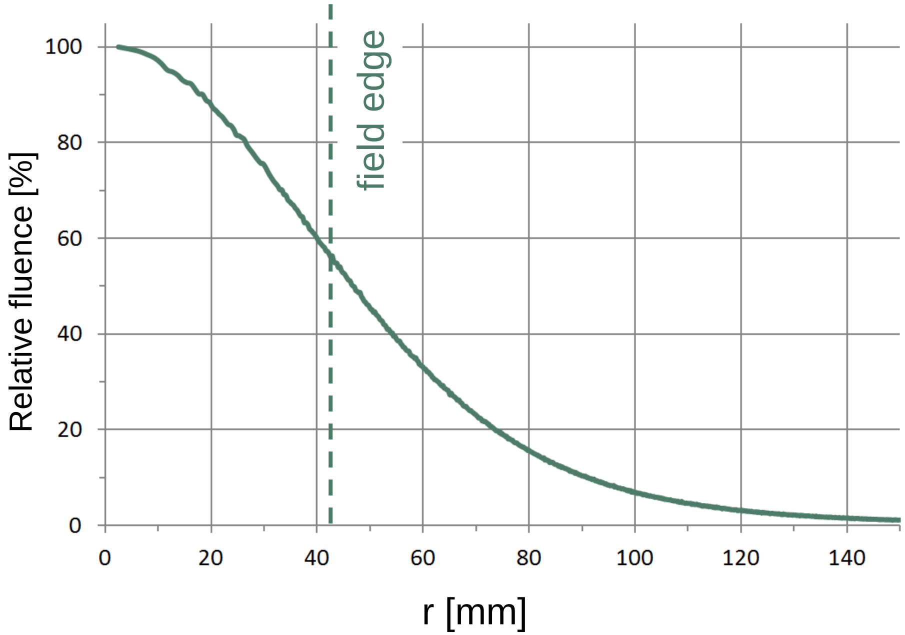


Thumb rule: total thickness of foils is minimal when the first foil thickness is such that, without the second foil, the fluence at the edge of the proposed irradiation field at SSD would be about 60% of the fluence on axis.

Ta 0.01 mm

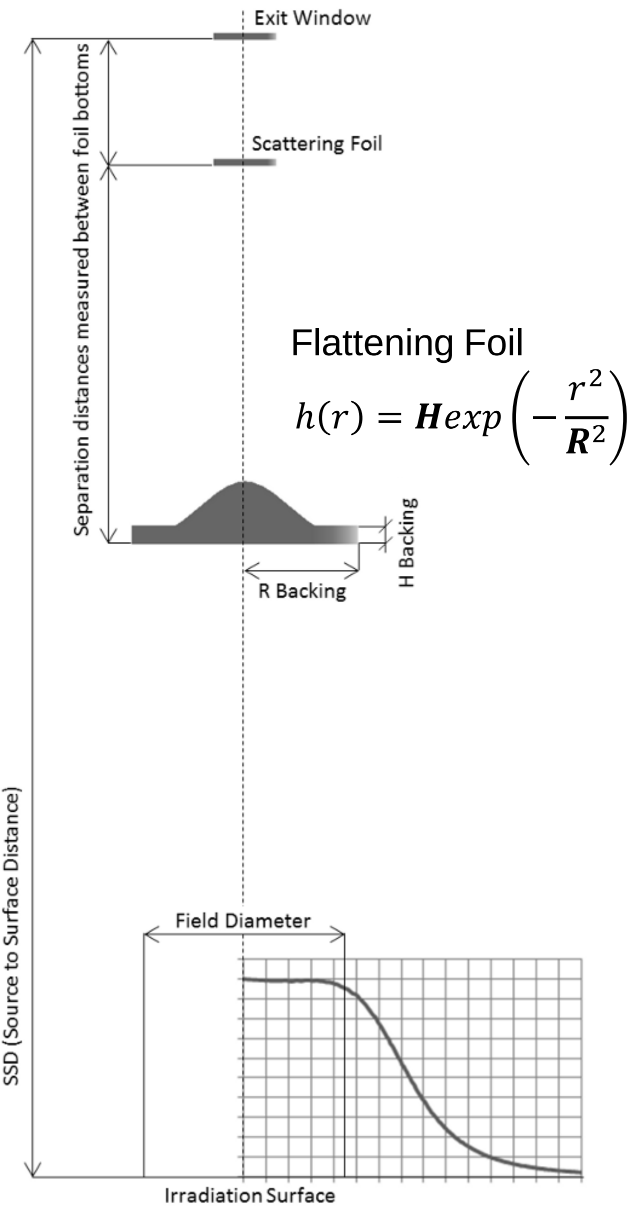


Ta 0.03 mm



- Minimal total energy degradation

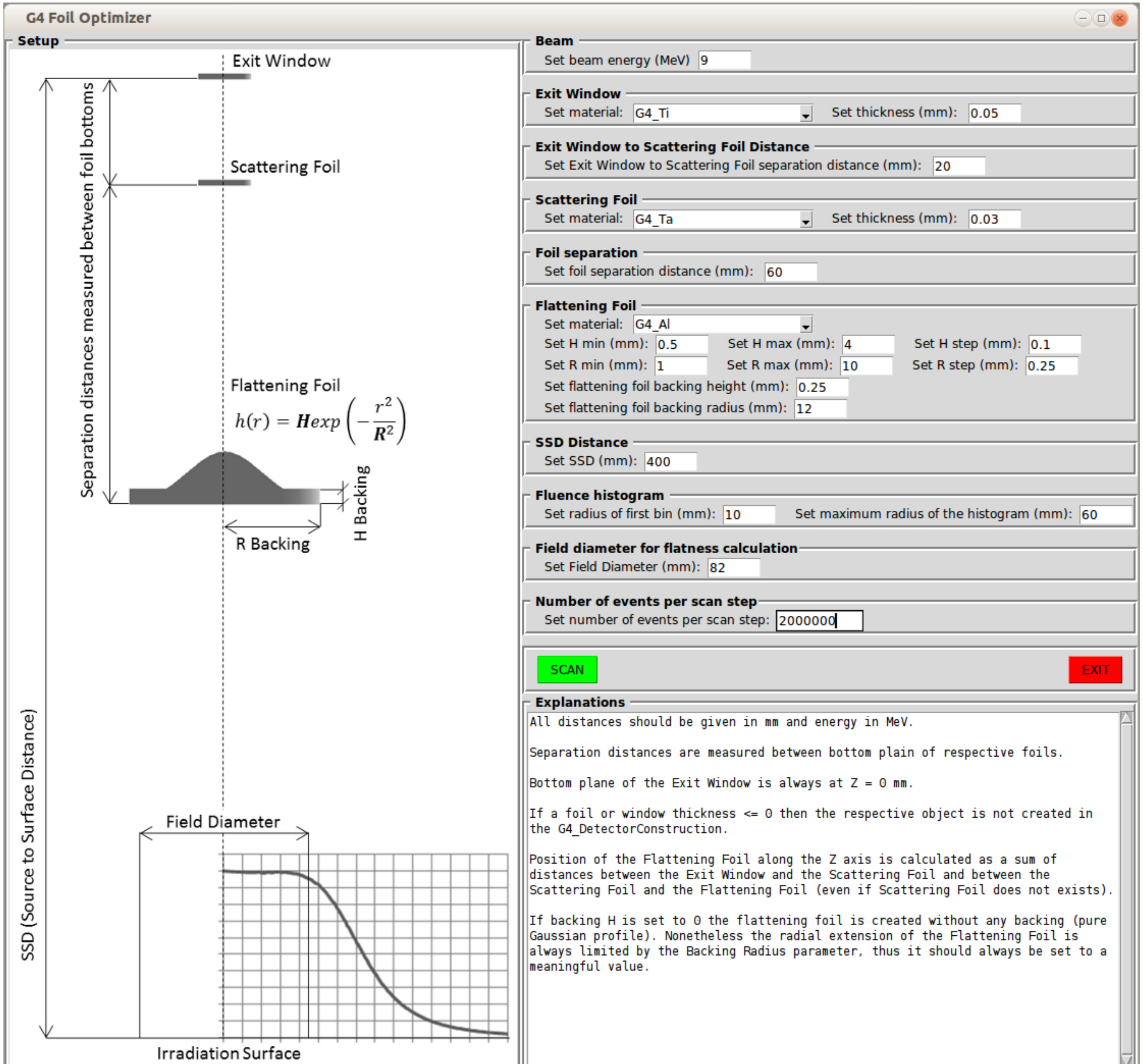
Dual-foil system: degrees of freedom

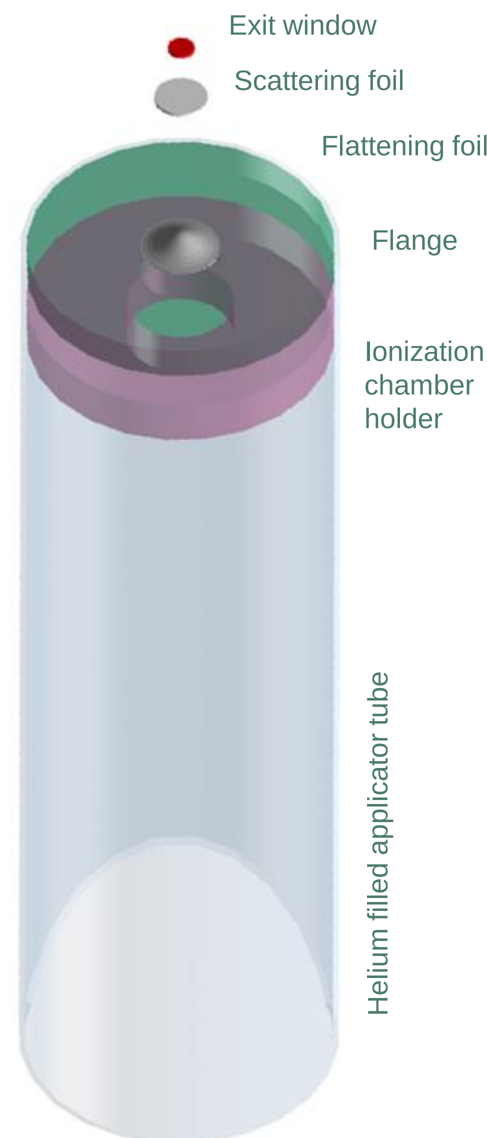


Parameters of the system:

- Beam energy – fixed at 9 MeV
- Irradiation field size – fixed at Φ 82 mm
- SSD – fixed at 400 mm
- Scattering foil position – as much upstream as possible – space for air cooling must be provided between the exit window and the scattering foil
- Scattering foil material – Ta
- Scattering foil thickness – 0.03 mm (tentatively)
- Flattening foil material – Al
- Flattening foil position – **?**
- Flattening foil thickness and width – **?**

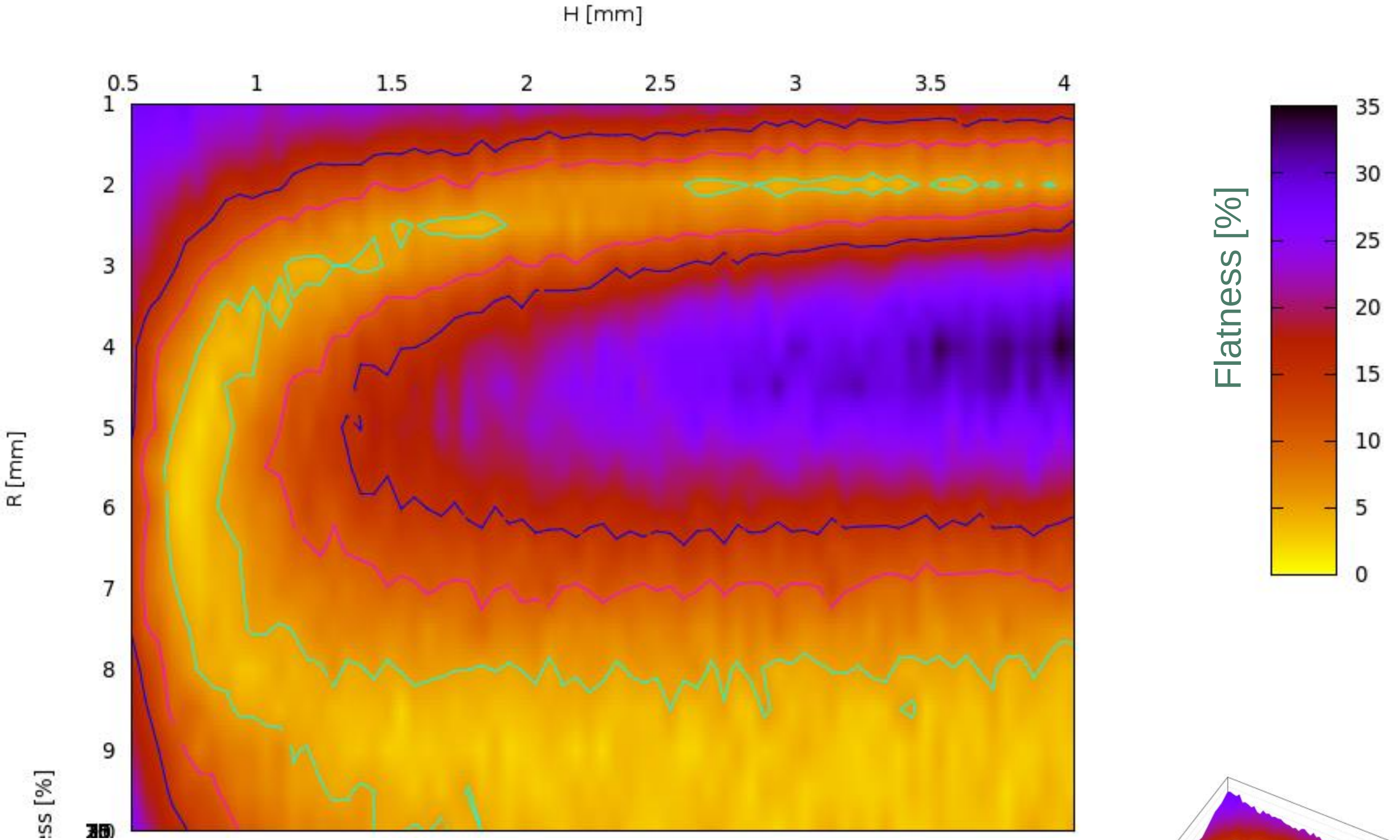
A tool for automatized design optimization

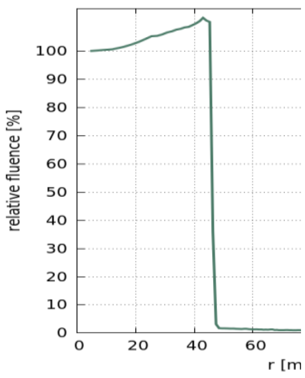




Fluence flatness in function of flattening foil parameters

Example of a flatness scan in function of aluminum flattening foil parameters H and R (at fixed scattering foil and separation distances)

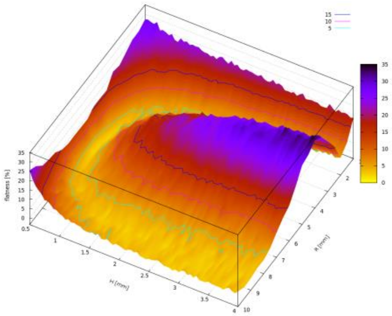


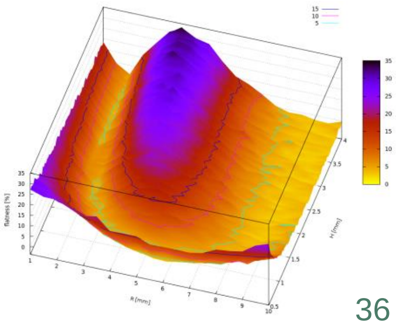


$$flatness = \left(\frac{\Phi_{max}}{\Phi_{min}} - 1\right) \cdot 100\%$$

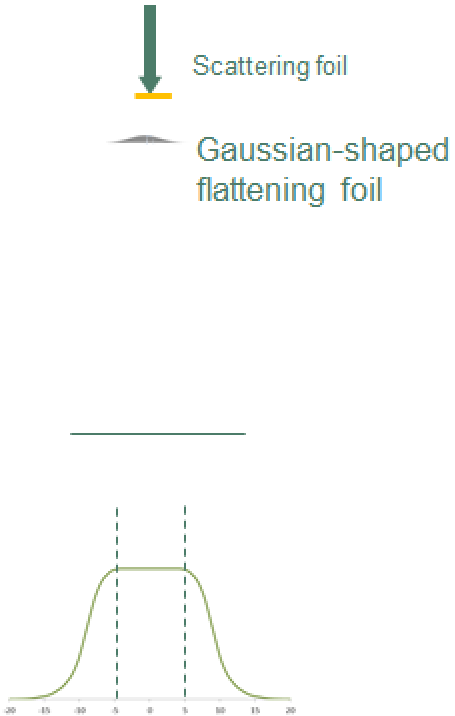
Profile of the flattening foil is:

$$h(r) = \boldsymbol{H}exp\left(-\frac{r^2}{\boldsymbol{R}^2}\right)$$

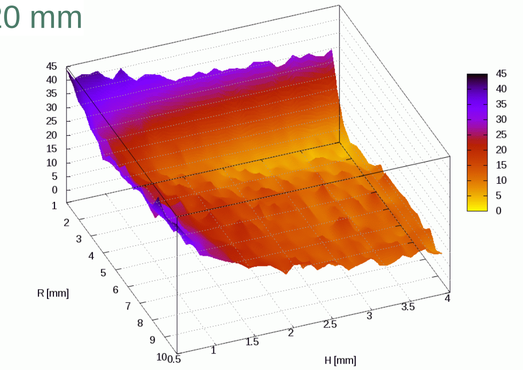




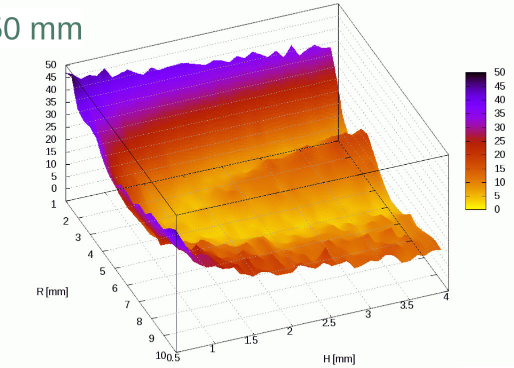
Dual-foil system: foil separation



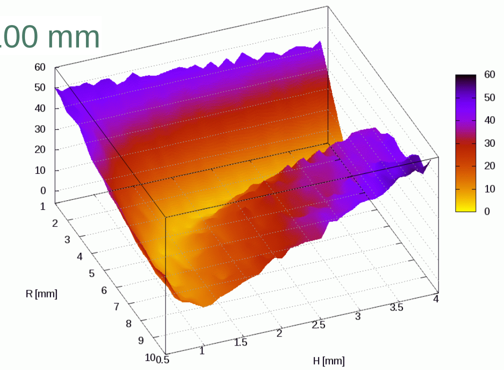
20 mm



50 mm



100 mm

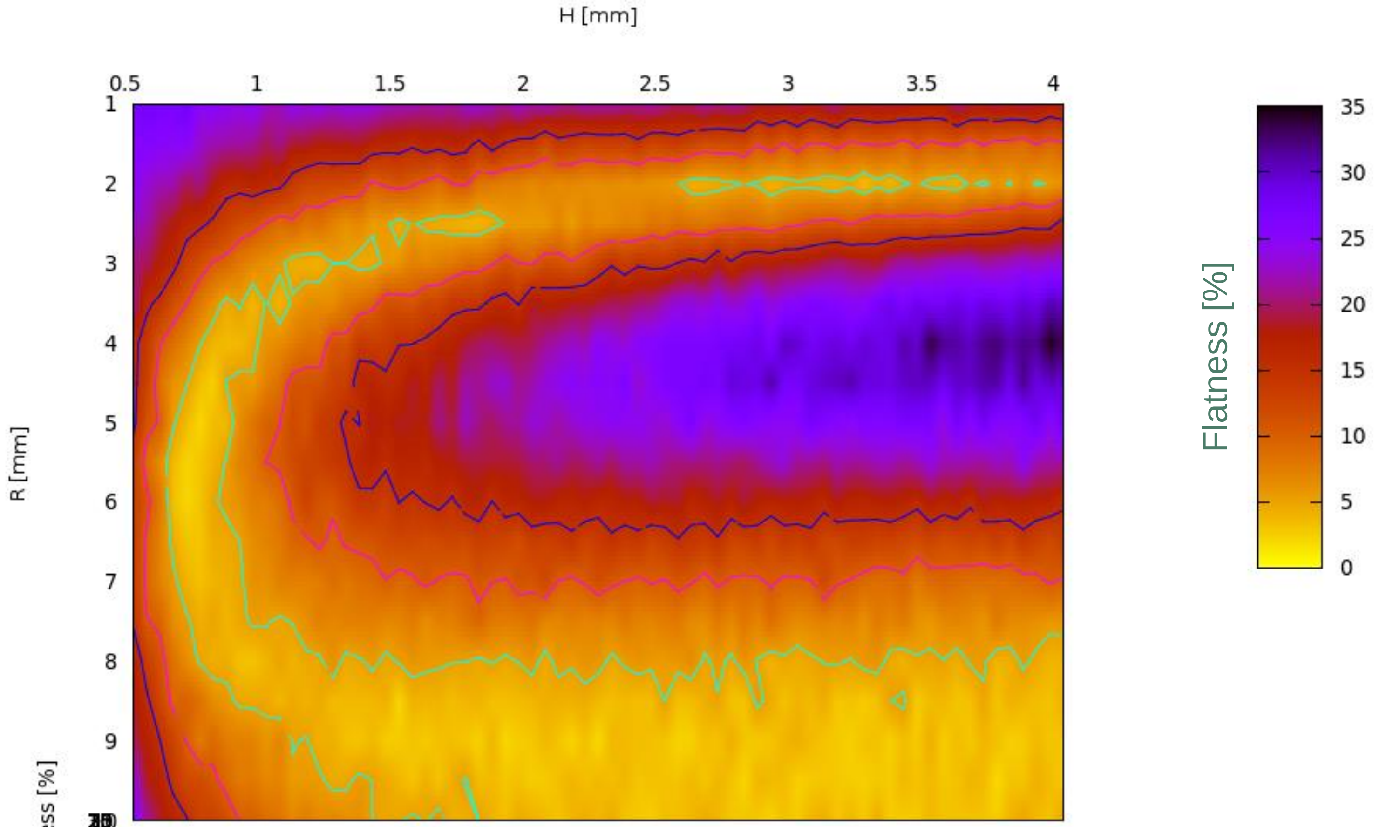


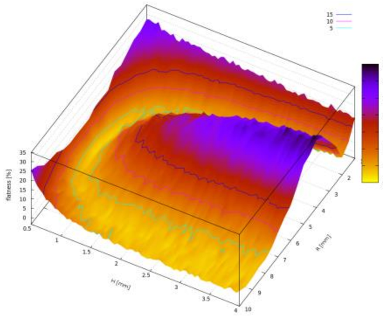
An apology of a humble Jagiellonian University graduate

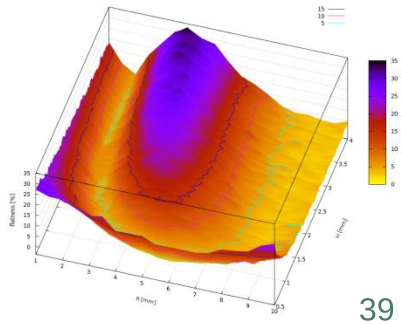
Let reason prevail over force

Assembly Hall of the Collegium Maius, Jagiellonian University, Kraków

Optimization of the Al flattening foil for the 0.03 mm Ta scattering foil



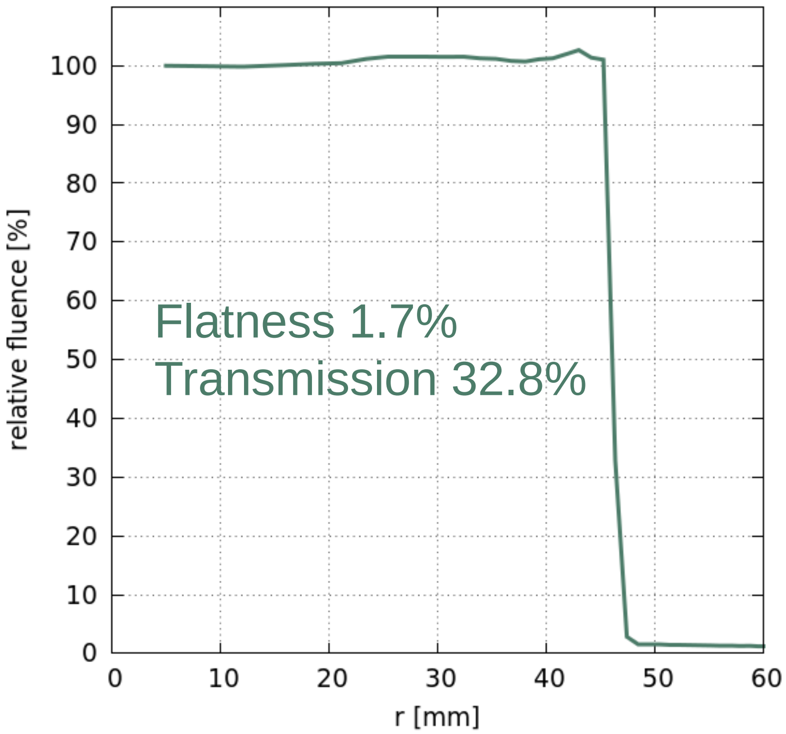


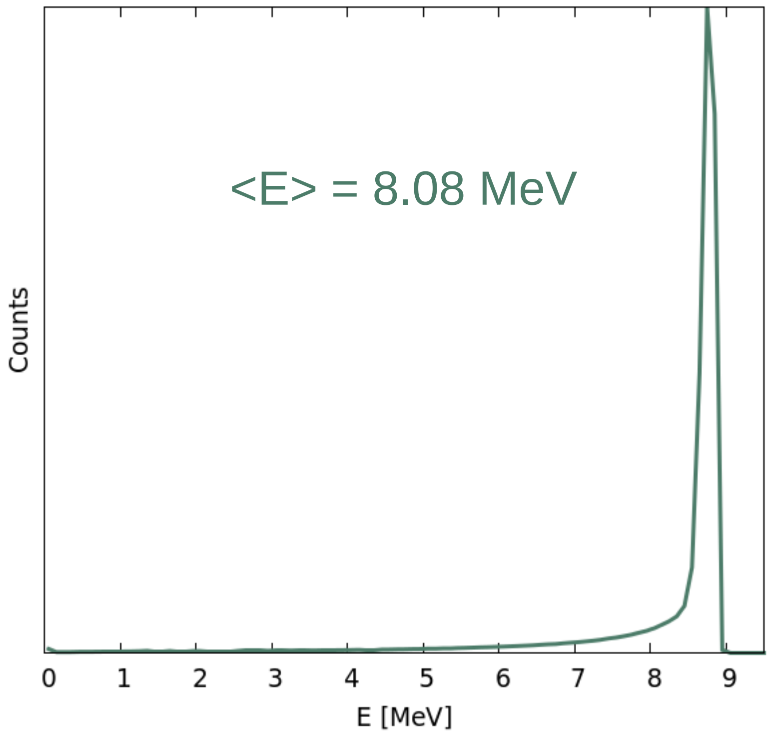


Optimal Al flattening foil for the 0.03 mm Ta scattering foil

R = 5.5 mm
H = 0.75 mm

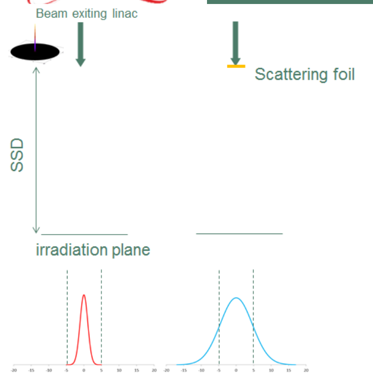
$$h(r) = \boldsymbol{H} exp\left(-\frac{r^2}{\boldsymbol{R}^2}\right)$$





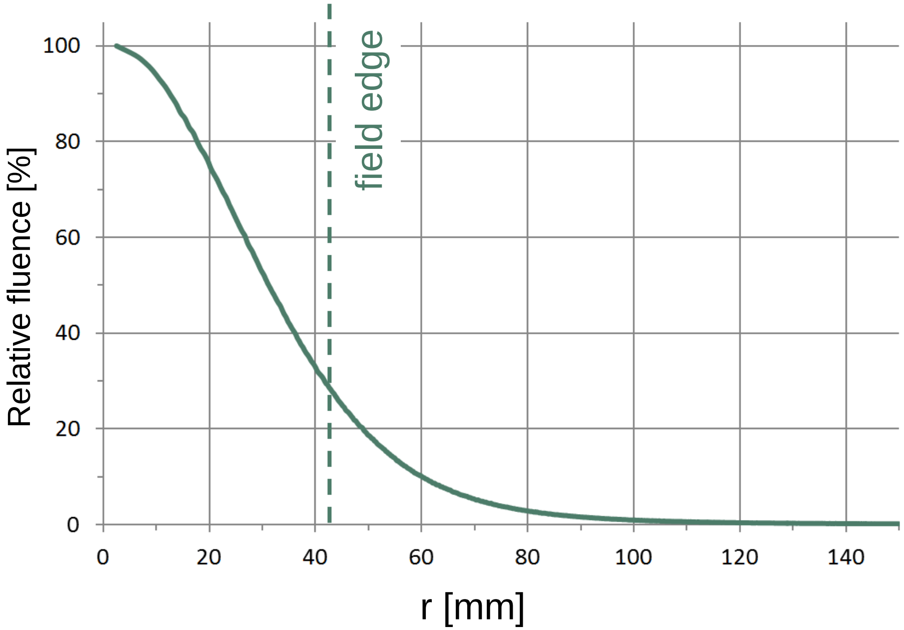
For comparison in the setup without the applicator
Transmission 24.5%
<E> = 8.48 MeV

Dual-foil system: scattering foil thickness

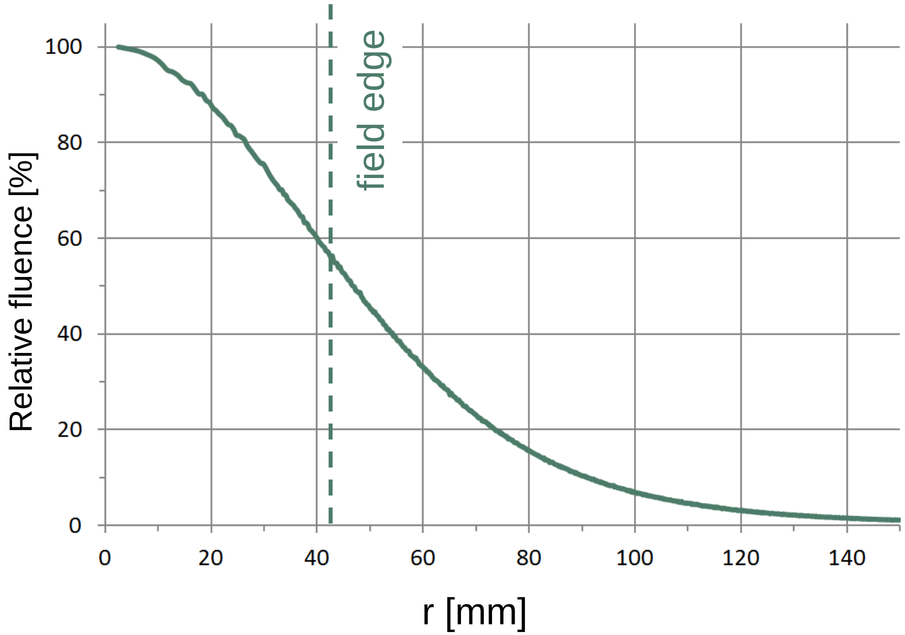


Thumb rule: total thickness of foils is minimal when the first foil thickness is such that, without the second foil, the fluence at the edge of the proposed irradiation field at SSD would be about 60% of the fluence on axis.

Ta 0.01 mm

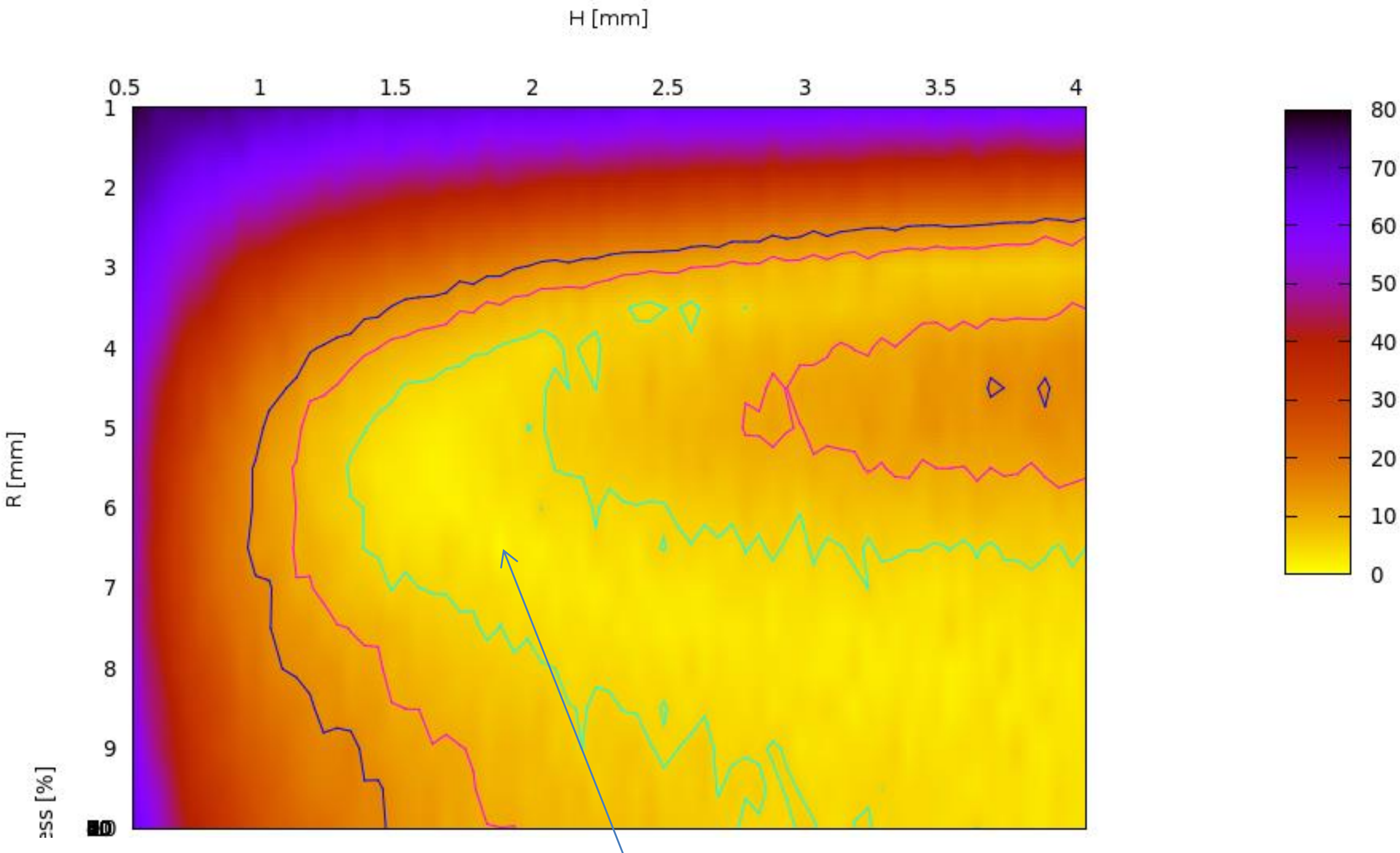


Ta 0.03 mm

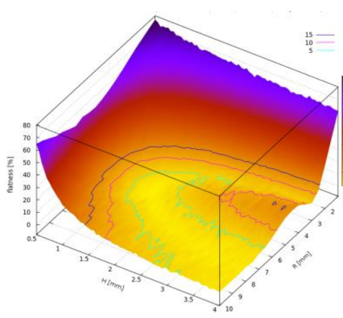


- Minimal total energy degradation

Optimization of the Al flattening foil for the 0.01 mm Ta scattering foil.



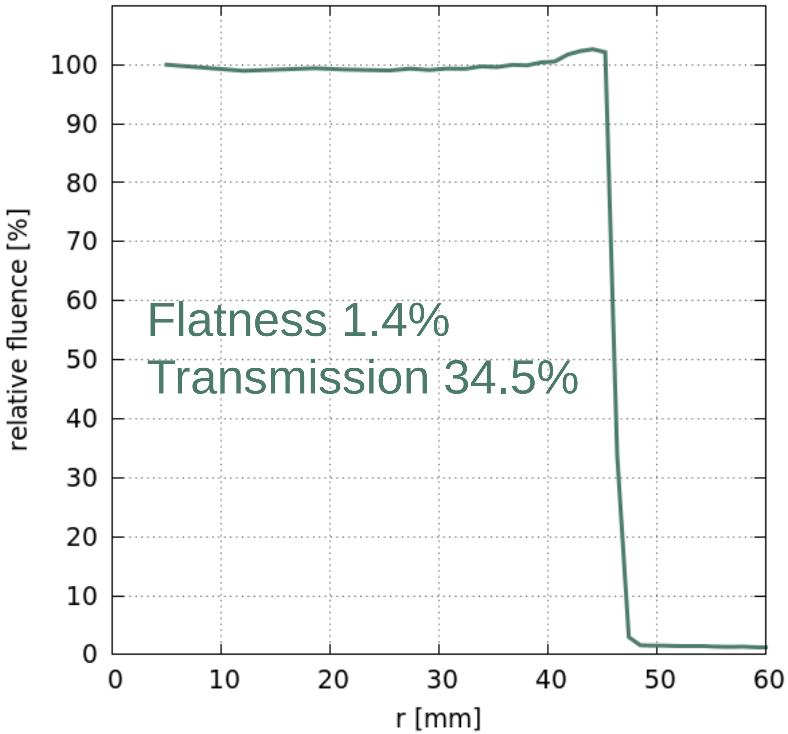
minimum

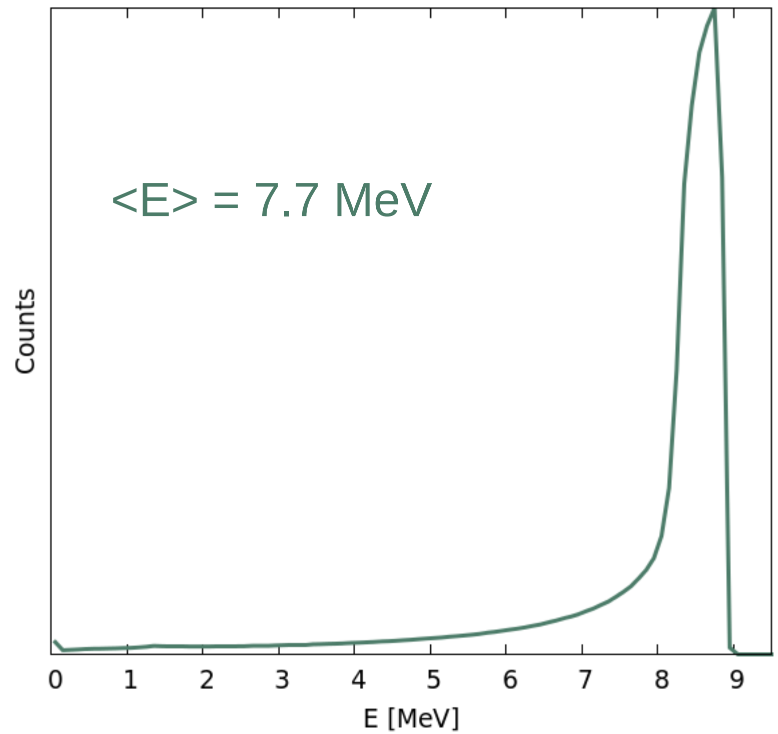


Al flattening foil for the 0.01 mm Ta scattering foil – optimal flatness

Minimal flatness
R=6.5 mm
H=1.85 mm

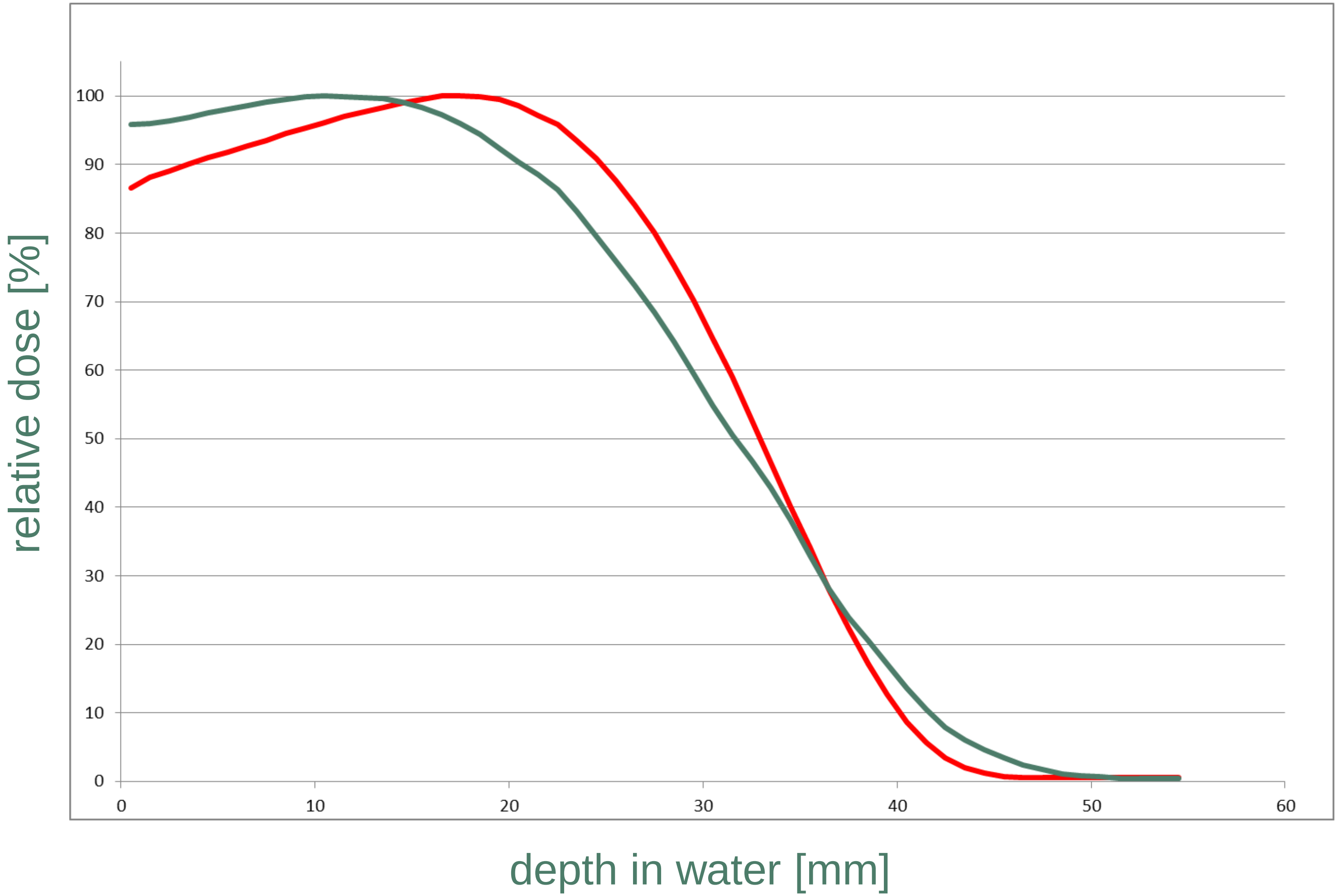
$$h(r) = \boldsymbol{H} exp\left(-\frac{r^2}{\boldsymbol{R}^2}\right)$$



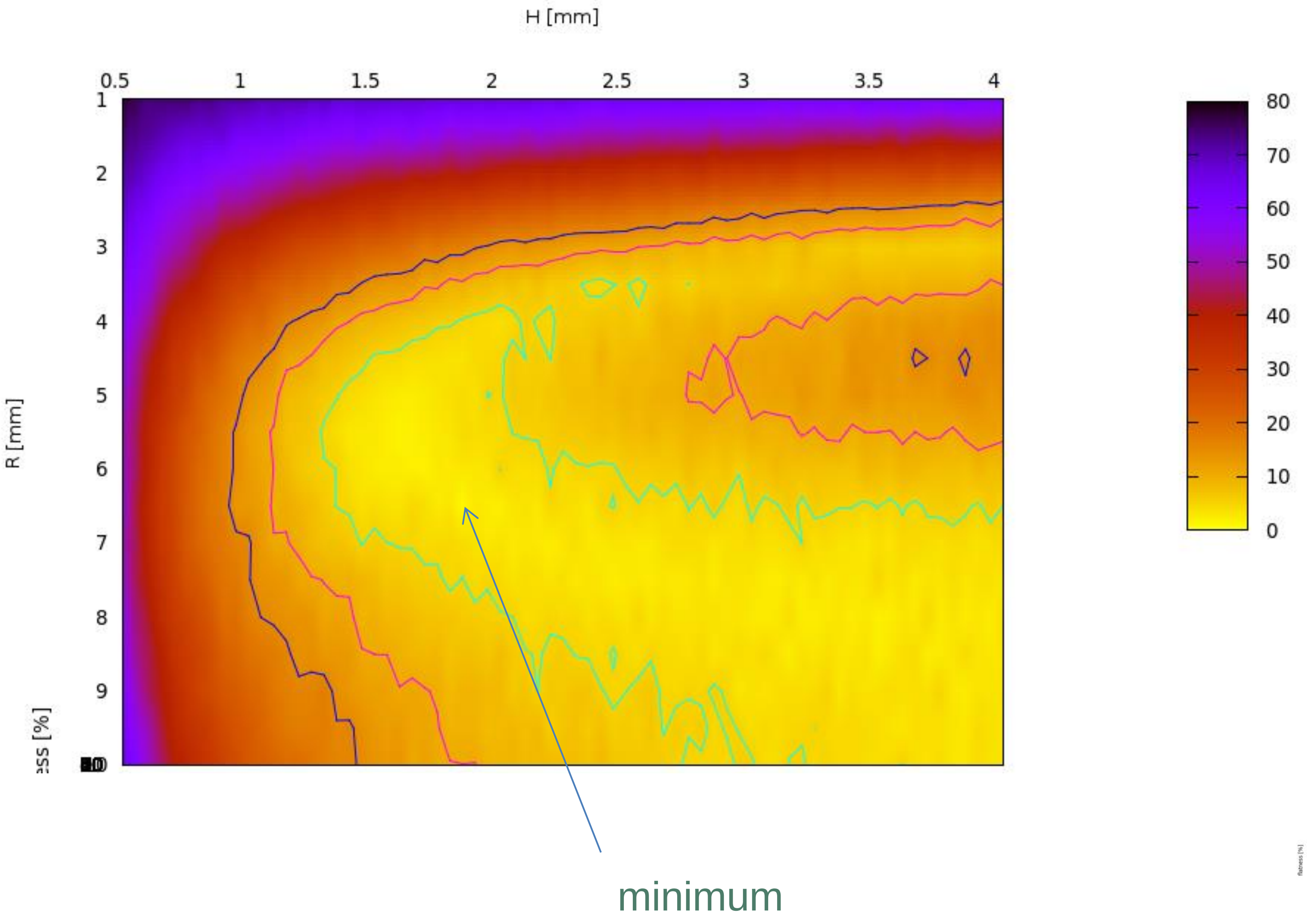


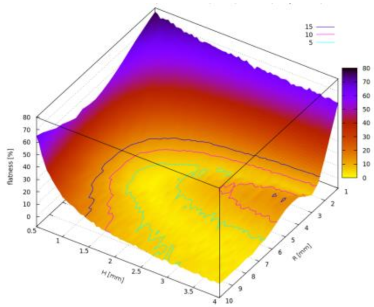
Depth Dose

„less degraded" VS „more degraded" energy spectrum



Optimization of the Al flattening foil for the 0.01 mm Ta scattering foil.

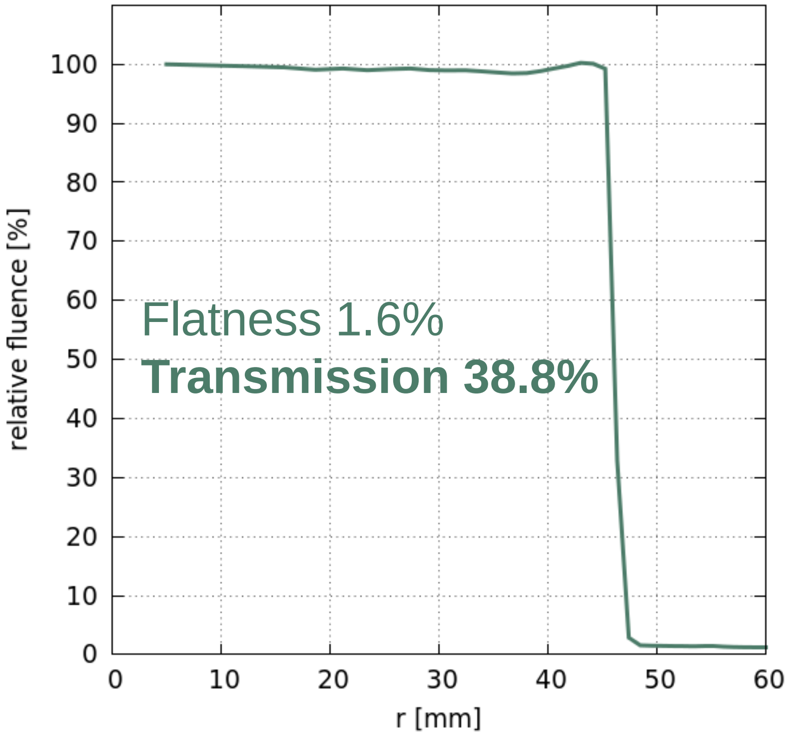


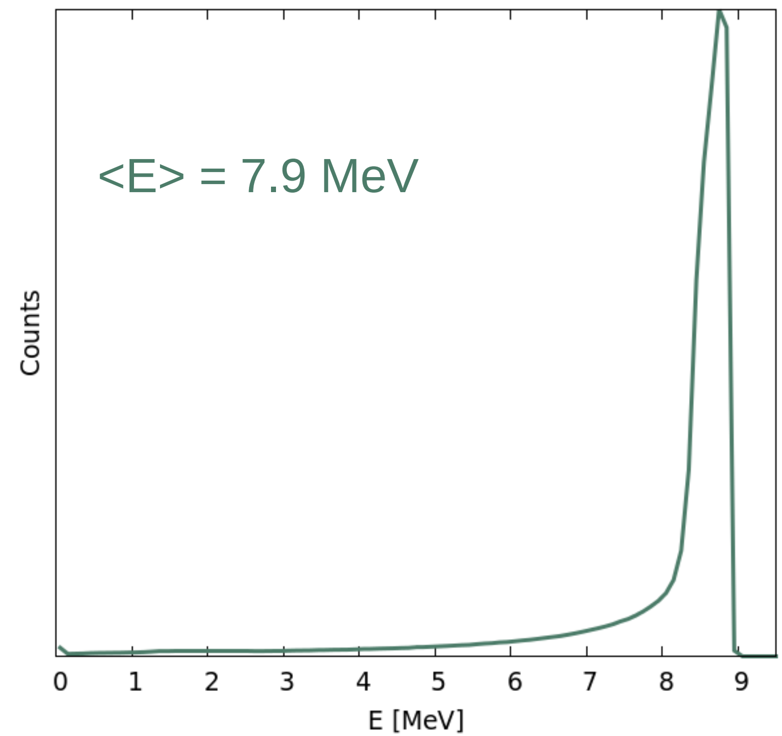


Al flattening foil for the 0.01 mm Ta scattering foil – optimal transmission

R=6 mm
H=1.5 mm

$$h(r) = \boldsymbol{H} exp\left(-\frac{r^2}{\boldsymbol{R}^2}\right)$$





Selected for production

Dose rate estimation (conservative)

Transmission to the irradiation plane 39%
Initial beam current I_{imp} = 50 mA/imp (max 100 mA)
Impulse duration t_{imp} = 4 μs
Repetition frequency = 100 Hz
Field area = Pi * $(4.1)^2$ cm^2

↓

Flux = $9.2 \cdot 10^{11}$ electrons/s*cm^2

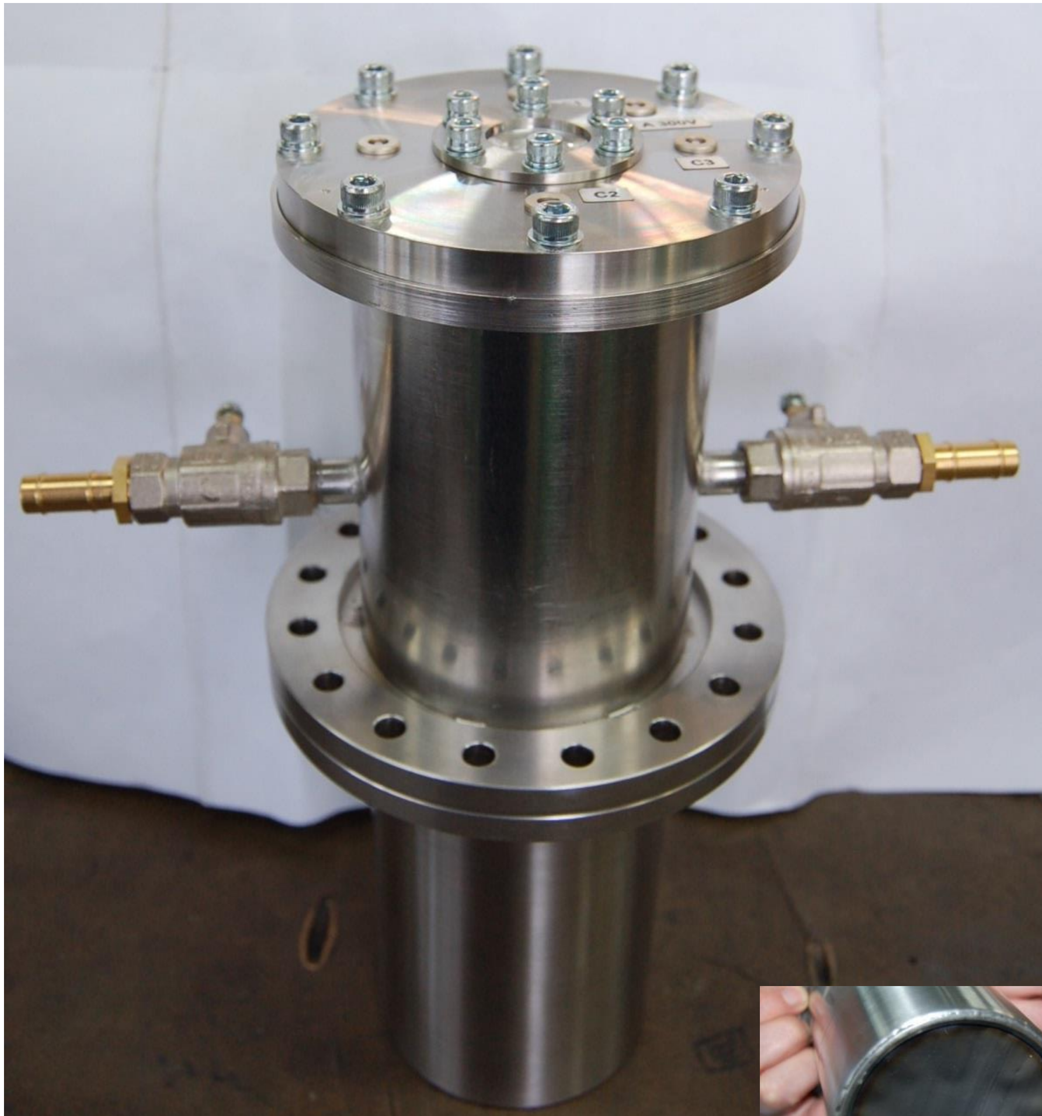
S_{col} = 1.93 MeV cm^2/g (Air, E= 7.9 MeV)

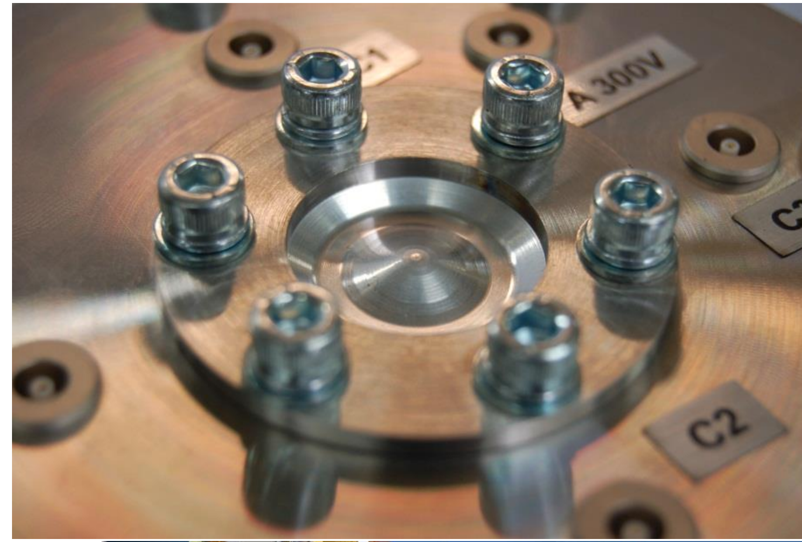
↓

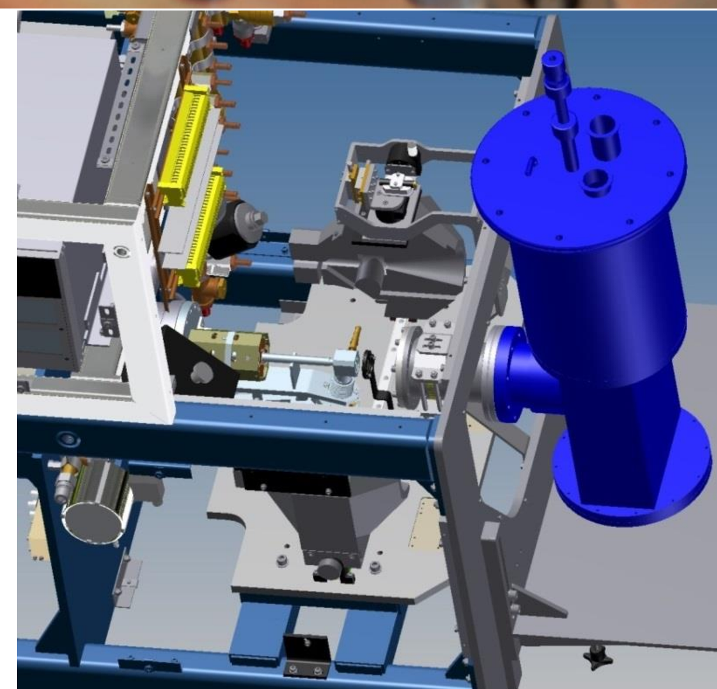
Dose deposited by 1 electron in 1 cm^3 of air:
D = E/m = $3.09 \cdot 10^{-10}$ Gy

$$\dot{D} = 284\ \mathrm{Gy/s} = 17\ \mathrm{kGy/min} = 1\ \mathrm{MGy/h}$$

Current state







Conclusions

- Passive forming could be equally efficient as scanning
- Dare to question known rules (of thumb)
- Dedicated Geant4 application with automation facility for rapid system development
- Optimum setup found via „brute force” multidimensional Monte Carlo optimization study
- Expected $\dot{\mathrm{D}} = \mathbf{284\ Gy/s = 17\ kGy/min = 1\ MGy/h}$ (at ~Φ80mm field)
- Most of the system components already fabricated at NCBJ
- Delivery, installation and tests at NTL@WPT expected in the second half of 2015

Thank you for your attention!