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.
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
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

Prototype for mobile IOERT

Mobile linac for industrial radiography

Assembly of a medical linac
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 M Gy absorbed dose, cryogenic conditions)
• R&D in sterilization of polymer based medical products (tens of k Gy)
• Research in polymer structure modifications (tens of k Gy)

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 ($\text{LN}_2$)
• 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 (~$\Phi80\text{mm}$). 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

Target chamber

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

Beam exit window
Titanium, 0.05 mm
Least possible disruption of the existing system…

Beam exit window
Titanium, 0.05 mm

LN2 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

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

**passive = beam scattering and collimation**
- Uniform beam distribution
- Simple, reliable
- Significantly less efficient

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

Common applications: electron beam therapy (also previous generation of proton therapy)
Electron beam forming – active VS passive

active = beam scanning

- electron accelerator
- focusing coils
- steering coils
- e-pencil beam
- irradiation plane

passive = beam scattering and collimation

- electron accelerator
- scattering foil
- flattening foil
- collimator
- irradiation plane

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

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

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

Uniform beam distribution
- Simple, reliable
- \textbf{Significantly less efficient}

In this application, efficiency is all that matters
Electron beam scanning – reality check

- **e- beam**
  - 9 MeV
  - 400 mm

- **Exit window**
  - 50 μm Ti

- **Vacuum chamber entrance window**
  - 50 μm Ti

- **Air**
  - 10 mm

- **FWHM**
  - 3 mm
  - 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 $flatness = \left( \frac{\Phi_{\text{max}}}{\Phi_{\text{min}}} - 1 \right) \cdot 100\%$
Electron beam forming – active VS passive

active = beam scanning

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

- High efficiency (→ high dose rate)
- Relatively complex system (especially for 2D scanning)
- Nontrivial to achieve uniform dose distribution
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passive = beam scattering and collimation

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

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

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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

Beam exiting linac

Scattering foil

SSD

irradiation plane
The principle of dual-foil system

Beam exiting linac

Scattering foil

Gaussian-shaped flattening foil

irradiation plane

SSD

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The principle of dual-foil system

Beam exiting linac

Scattering foil

Gaussian-shaped flattening foil

SSD plane

irradiation plane

Limits of the field

Przemysław Adrich
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

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

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

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

Fluence at point \( \vec{r} \) at the irradiation plane \( Z_2 \) is a convolution of \( \Phi_1 \) and \( \Phi_2 \):

\[ \Phi(Z_2, \vec{r}) = \int_0^{\rho_{\text{max}}} \int_0^{2\pi} \Phi_1(Z_1, \rho) \Phi_2(Z_2, \vec{r}; Z_1, \rho) \rho d\rho d\phi \]

Numerical integration is straightforward

Calculation of electron fluence – simple model

- Analytical model - pencil beam
- Monte Carlo - pencil beam
- Monte Carlo - realistic beam (FWHM = 3mm)

Relative fluence (%)

off-axis position at the irradiation plane (arb. units.)
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

Flatness 2.8%

With \(\Phi93\) mm circular applicator

Flatness > 10%

Flatness calculated within \(\Phi82\) 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=1 mm, R=5.5 mm, SSD=400 mm
Electron fluence and energy are histogrammed at the end of the applicator. Flatness of the fluence distribution is calculated within the field as

$$flatness = \left( \frac{\Phi_{\text{max}}}{\Phi_{\text{min}}} - 1 \right) \cdot 100\%$$
Parameters of the system:
- Beam energy – fixed at 9 MeV
- Irradiation field size – fixed at \( \Phi \) 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 – ?

\[ h(r) = H \exp \left( -\frac{r^2}{R^2} \right) \]
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 – ?
- Scattering foil thickness – ?
- Flattening foil material – ?
- Flattening foil position – ?
- Flattening foil thickness and width – ?

Flattening Foil

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

Parameters of the system:
- Beam energy – fixed at 9 MeV
- Irradiation field size – fixed at $\Phi$ 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 – ?
- Flattening foil material – Al
- Flattening foil position – ?
- Flattening foil thickness and width – ?

Flattening Foil

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

- 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

**Exit window**

**Scattering foil**

**Flattening foil**

**Helium filled applicator tube**

**Flange**

**Ionization chamber holder**

**Field Diameter**

**SSD (Source to Surface Distance)**

**Irradiation Surface**

**Separation distances measured between foil bottoms**

**Flattening Foil**

\[ h(r) = A e^{-r^2 / R^2} \]

**Beam**

- **Exit Window**
  - Set beam energy (MeV): 9

- **Exit Window**
  - Set material: G4_Ti
  - Set thickness (mm): 0.05

- **Exit Window to Scattering Foil Distance**
  - Set Exit Window to Scattering Foil separation distance (mm): 20

- **Scattering Foil**
  - Set material: G4_Ti
  - Set thickness (mm): 0.03

- **Foil separation**
  - Set foil separation distance (mm): 60

- **Flattening Foil**
  - Set material: G4_AI
  - Set H min (mm): 0.5
  - Set H max (mm): 4
  - Set H step (mm): 0.1
  - Set R min (mm): 1
  - Set R max (mm): 10
  - Set R step (mm): 0.25
  - Set flattening foil backing height (mm): 0.25
  - Set flattening foil backing radius (mm): 12

- **SSD Distance**
  - Set SSD (mm): 400

- **Fluence histogram**
  - Set radius of first bin (mm): 10
  - Set maximum radius of the histogram (mm): 60

- **Field diameter for flatness calculation**
  - Set Field Diameter (mm): 82

- **Number of events per scan step**
  - Set number of events per scan step: 2000000

**Explanations**

All distances should be given in mm and energy in MeV.

Separation distances are measured between bottom plane of respective foils.

Bottom plane of the Exit Window is always at Z = 0 mm.

If a foil or window thickness <= 0 then the respective object is not created in the G4_DetectorConstruction.

Position of the Flattening Foil along the Z axis is calculated as a sum of distances between the Exit Window and the Scattering Foil and between the Scattering Foil and the Flattening Foil (even if Scattering Foil does not exists).

If backing H is set to 0 the flattening foil is created without any backing (pure Gaussian profile). Nonetheless the radial extension of the Flattening Foil is always limited by the Backing Radius parameter, thus it should always be set to a meaningful value.
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)

Profile of the flattening foil is:

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

$$flatness = \left( \frac{\Phi_{\text{max}}}{\Phi_{\text{min}}} - 1 \right) \cdot 100\%$$
Dual-foil system: foil separation

Scattering foil
Gaussian-shaped flattening foil

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

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

\[ \text{Flatness } 1.7\% \]
\[ \text{Transmission } 32.8\% \]

\[ \langle E \rangle = 8.08 \text{ MeV} \]

For comparison in the setup without the applicator
\[ \text{Transmission } 24.5\% \]
\[ \langle E \rangle = 8.48 \text{ MeV} \]
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.

- Minimal total energy degradation

Ta 0.01 mm

Ta 0.03 mm
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

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

Flatness 1.4%
Transmission 34.5%

\(<E> = 7.7 \text{ MeV}\)
"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

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

Selected for production
Dose rate estimation (conservative)

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

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

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

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

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

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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 $\dot{D} = 284 \text{ Gy/s} = 17 \text{ kGy/min} = 1 \text{ MGy/h}$ (at $\sim \Phi 80\text{mm field}$)
- 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!