Novel Low Energy Linac Designs for Industrial Applications

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In Collaboration with:

Rapiscan systems | AS&E

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- Introduction and motivations for the project
- RF design of linac
- Electron beam capture optimization
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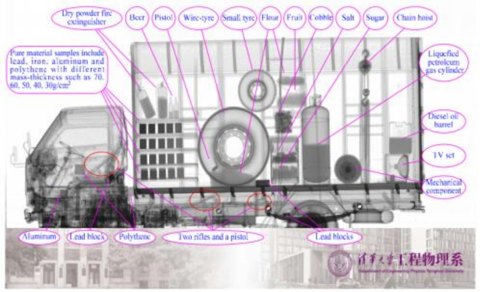
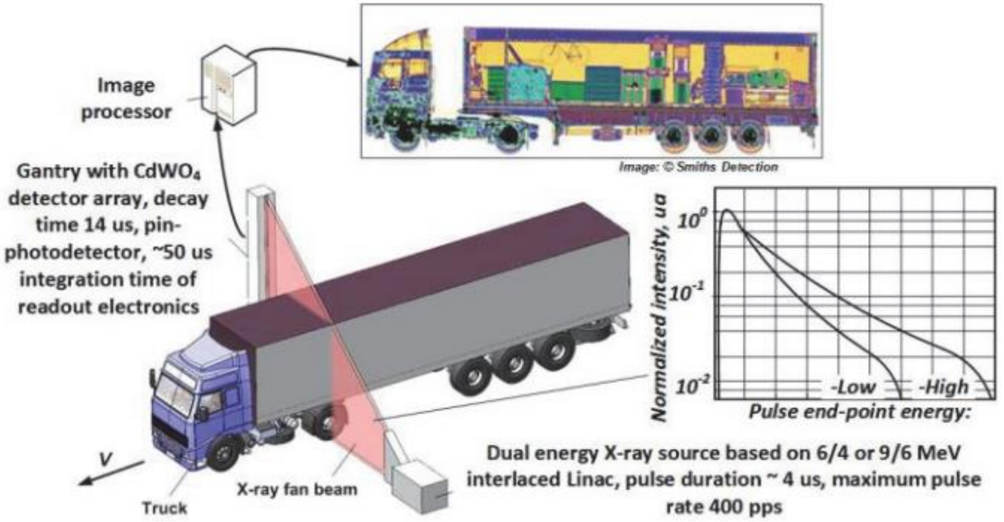
Introduction and Motivations

- X-rays are used to scan cargo at ports and airports, with the x-rays typically being generated using linacs.
- Typical energies used for scanning are 3-9 MeV, with the energy required corresponding to the material type and thickness. Dual energies are normally used for material discrimination.
- There is now an interest in scanning smaller containers with thinner walls such as aviation cargo Unit Load Devices (ULDs), or cars – meaning standard linacs are unsuitable.
- In order to obtain sufficient image contrast, lower energy solutions are required (1-2 MeV).
- This project is focused on the design of one of these systems in collaboration with Rapiscan® systems.

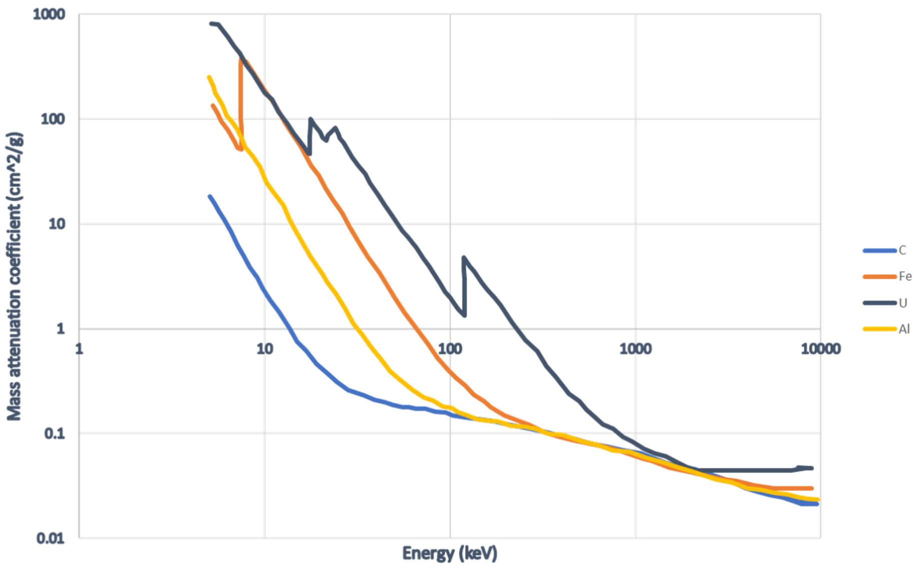

Z Portal system for scanning trucks, buses, and cargo containers



https://www.rapiscan-ase.com/products/portal/z-portal-for-trucks-cargo-screening



Arodzero, Anatoli, et al. "High speed, low dose, intelligent X-ray cargo inspection." *2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*. IEEE, 2015.



Energy	1.25 MeV	2 MeV	3 MeV	4 MeV	6 MeV	9 MeV
Steel	133 mm	205 mm	297 mm	352 mm	406 mm	430 mm
Water	880 mm	1370 mm	2050 mm	2530 mm	3160 mm	3640 mm

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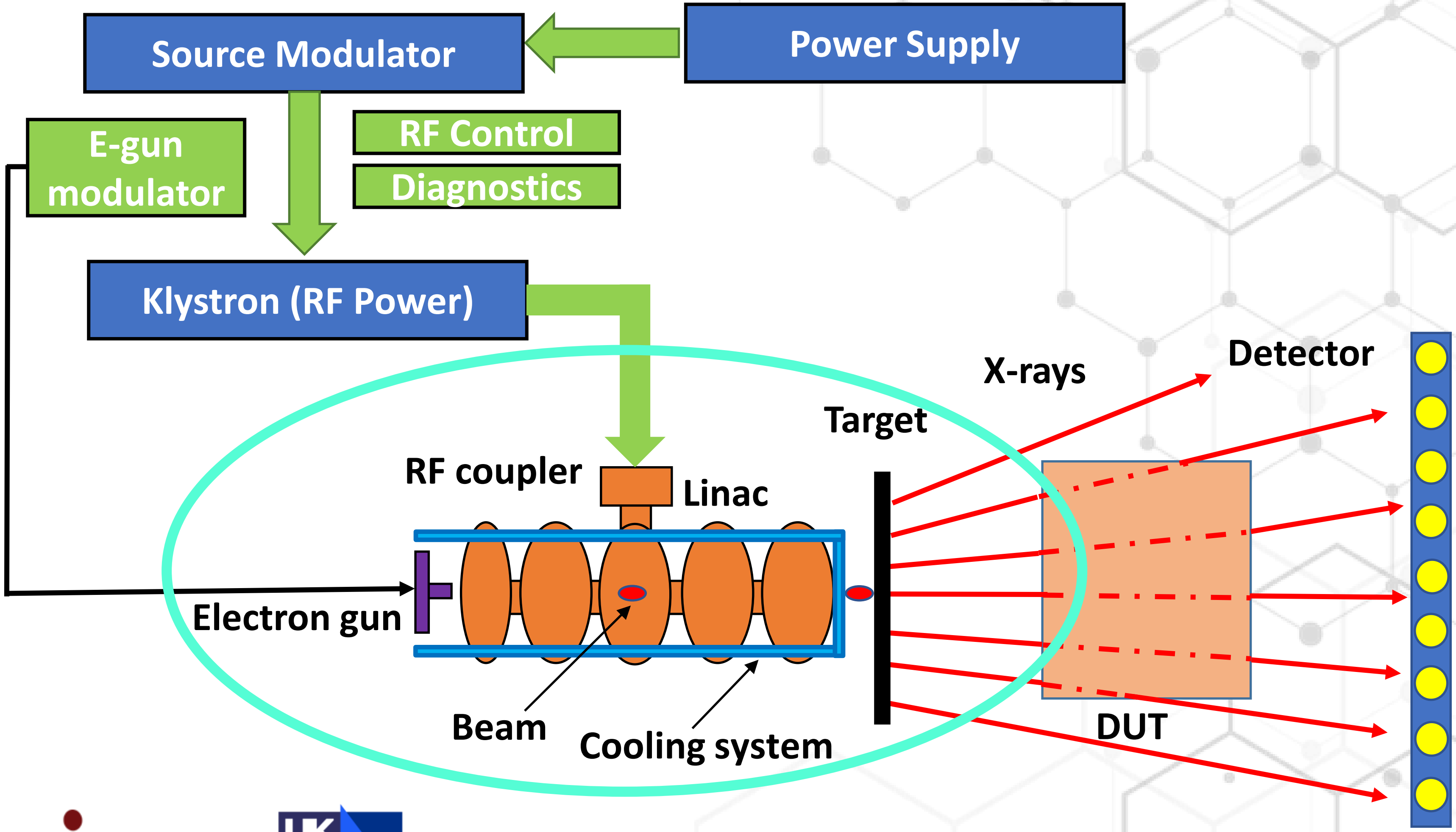
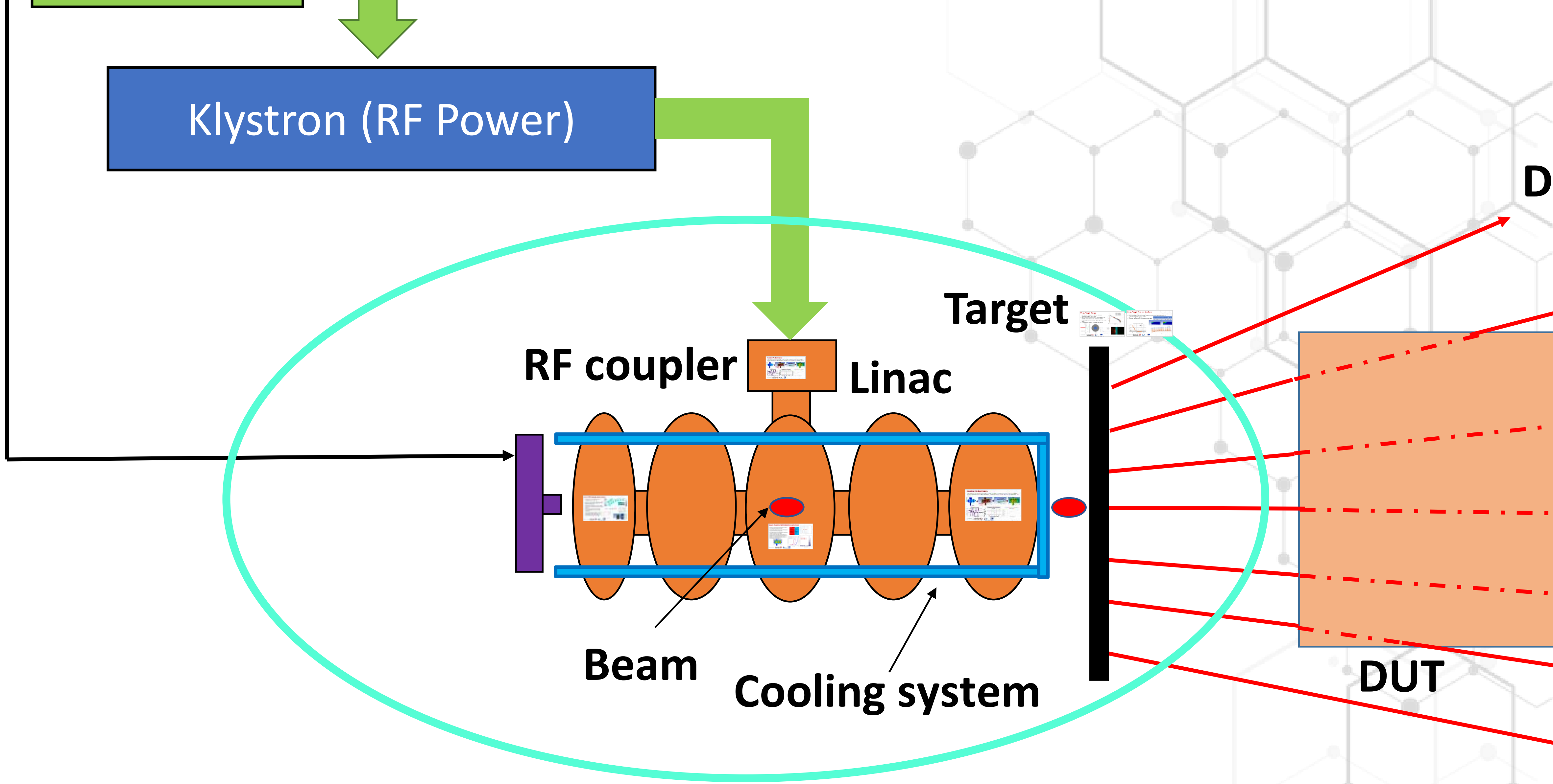
What do these systems look like?

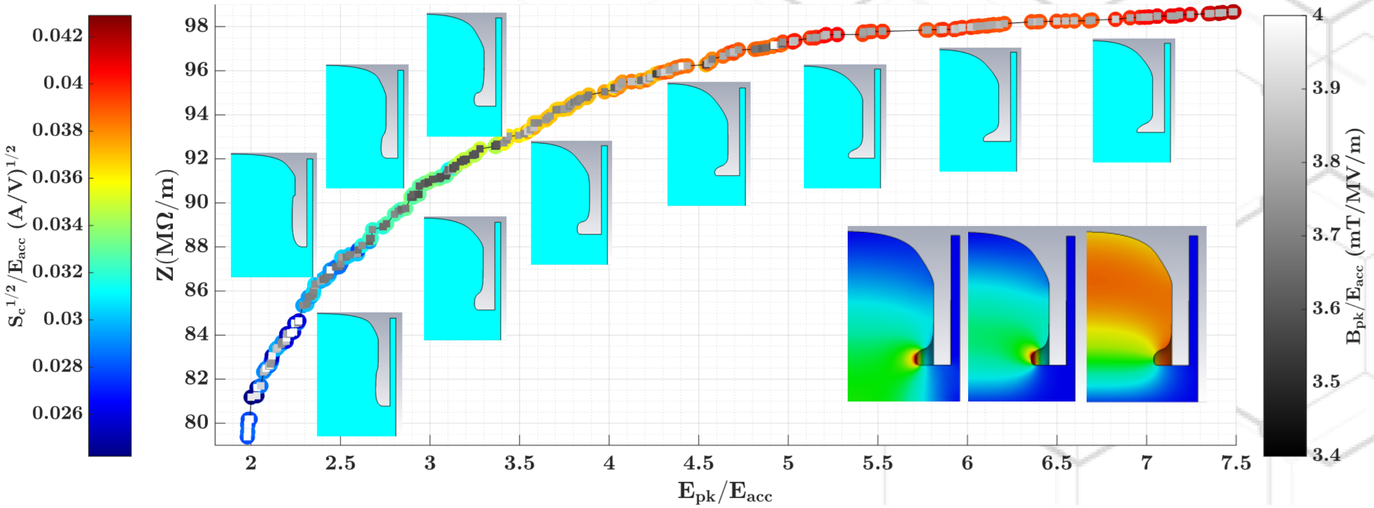
- Typical X-ray scanning system and components.




Klystron (RF Power)
RF coupler
Linac
Target
Beam
Cooling system
DUT
D

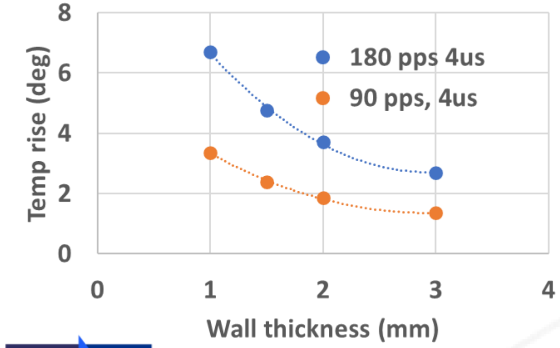
Linac RF Design (previous)

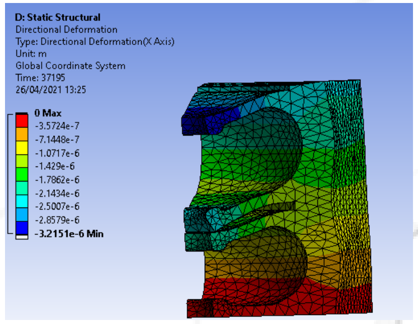
- C-band linac (5.712 GHz) for improved manufacturing costs vs. X-band.
- Needed to be robust, reliable, stable and operate well below max operating conditions 50% - 70% (peak fields, heating etc.).
- Single cell cavity optimized using multi-objective genetic algorithm and spline-based 3D modelling methods.
- Cavity design chosen based on trade offs between peak fields and cell-cell coupling requirements.
- Thermal considerations made for the single cell, ensuring that the wall thicknesses were adequate for withstanding RF heating effects, and deformation during manufacturing

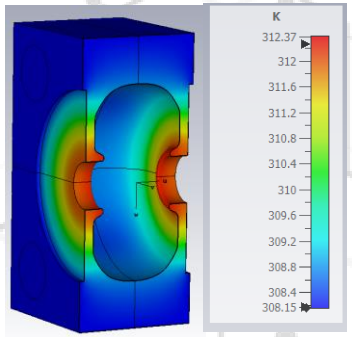


$$\text{Objectives} = \left\{ \frac{Epeak}{Eacc}, \frac{Bpeak}{Eacc}, \frac{\sqrt{MPV}}{Eacc}, Z \right\}$$

Quantity	value
E_{pk}/E_{acc}	3.99
B_{pk}/E_{acc}	3.71 (mT/MV/m)
$\sqrt{S_c}/E_{acc}$	0.0303 $\sqrt{A/V}$
Z	89.4 $M\Omega/m$
k_c	0.9%
Q_0	12400
Frequency	5.712 GHz
Aperture radius	5 mm
Wall thickness	2.5 mm
Coupling cavity length	2 mm



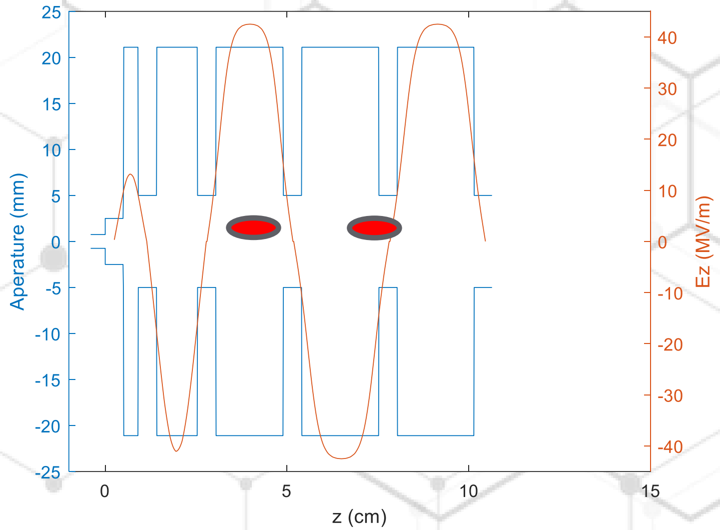


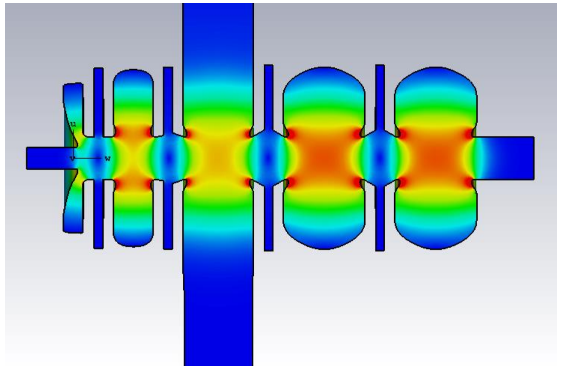


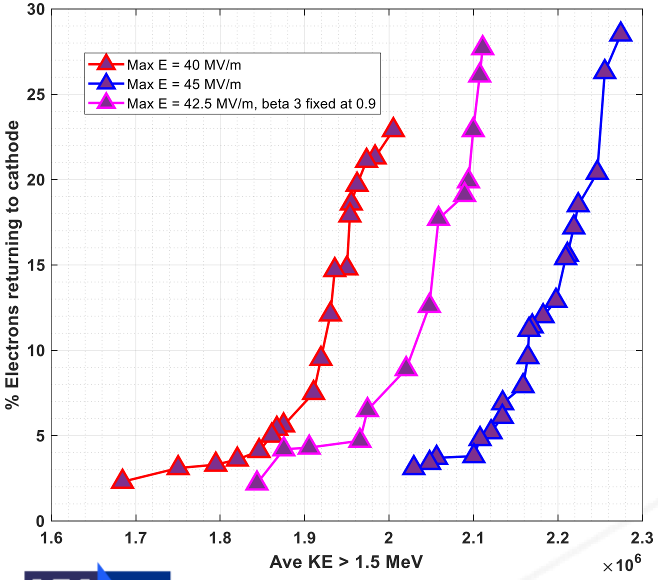
Beam Capture Optimization (previous)

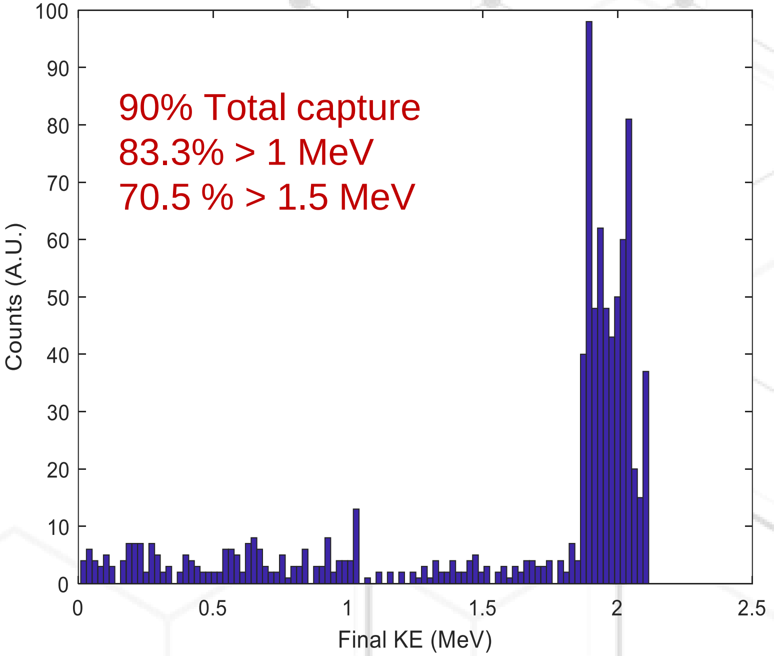
- Want to minimize back bombardment as this can determine the life of the linac.
- Cell lengths determine how much of the beam is bunch and eventually captured.
- MO optimization set up using particle tracking code to optimize the cell lengths.
- Led to a design with high capture efficiency (90%) and minimized cathode bombardment (5%). This is achieved by having a short low amplitude first bunching cell.

Inputs	Outputs
Length C1	Total capture %
Length C2	Capture E > 1.5 MeV
Length C3	Average KE > 1.5 MeV
Amplitude C1	% Return to cathode
Amplitude C2	









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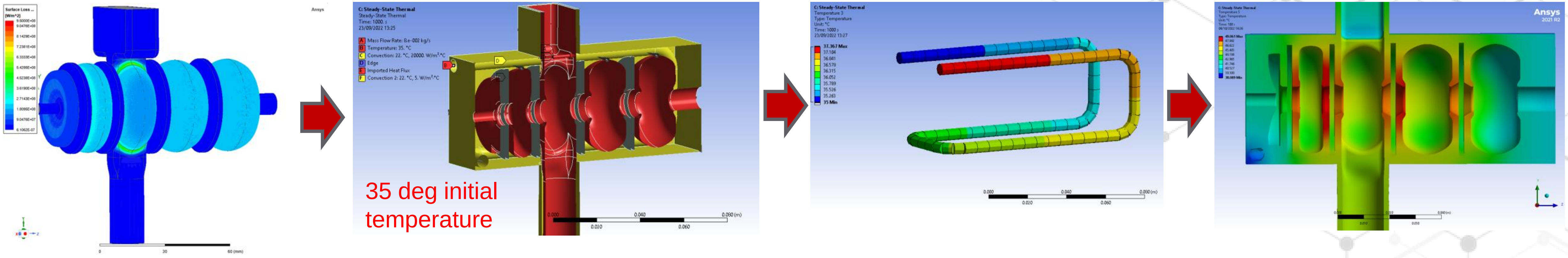
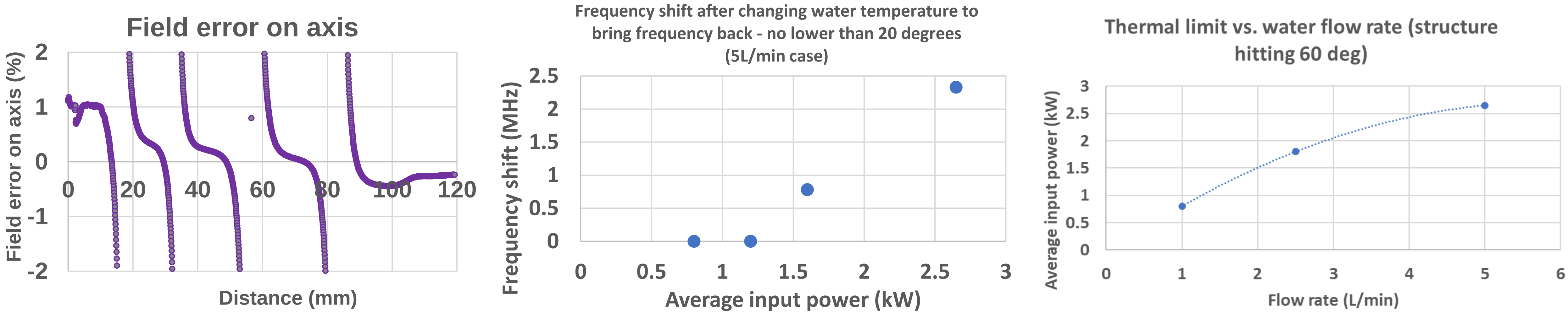
Thermal Performance

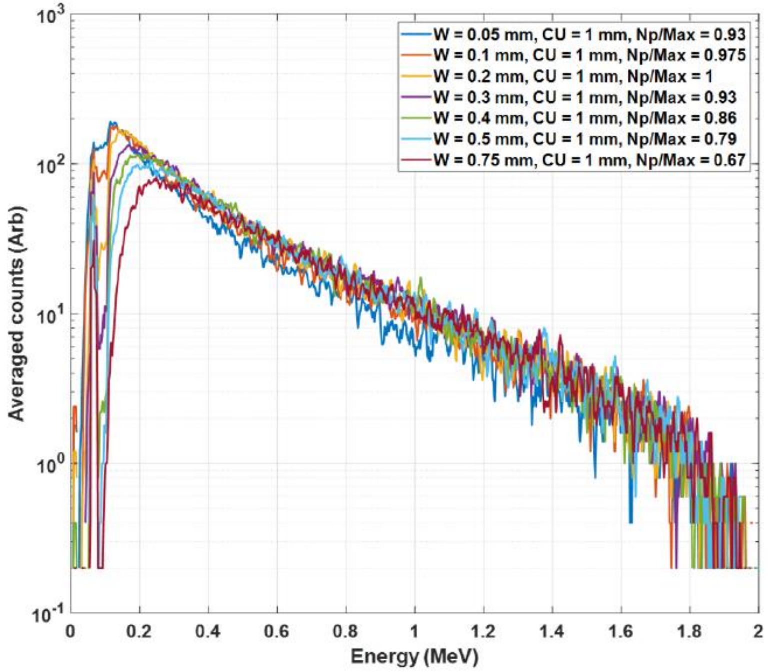
- Thermal analysis performed using Ansys HFSS and Mechanical. RF losses imported into thermal solver along with heat transfer coefficient estimates. Thermal deformation used to calculate field errors and frequency shifts. Limits of the linac explored.

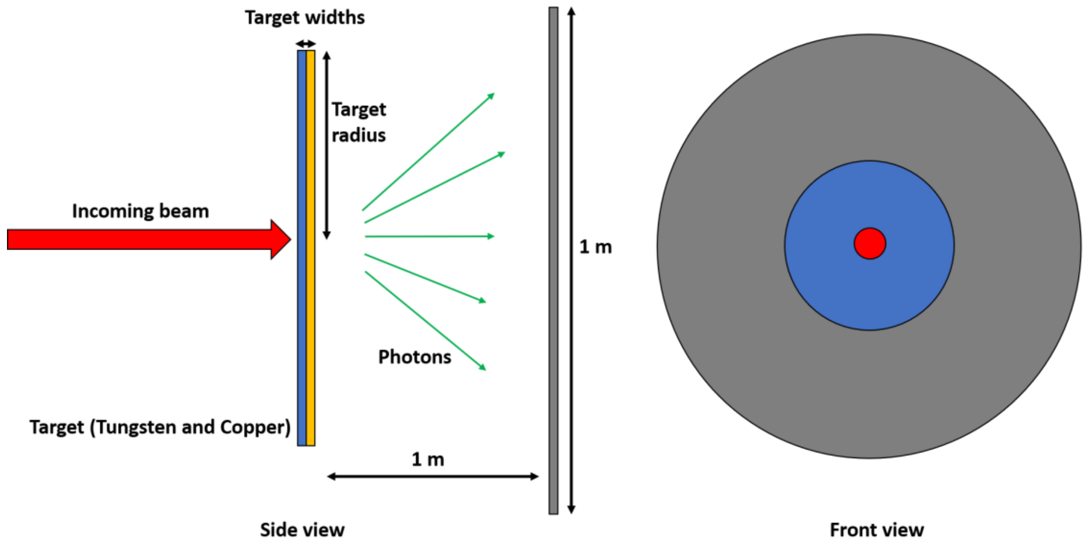


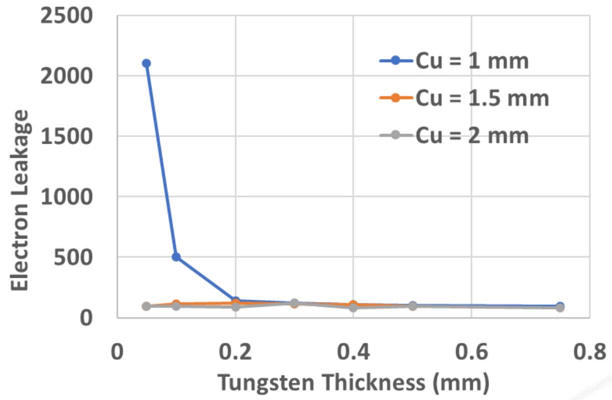


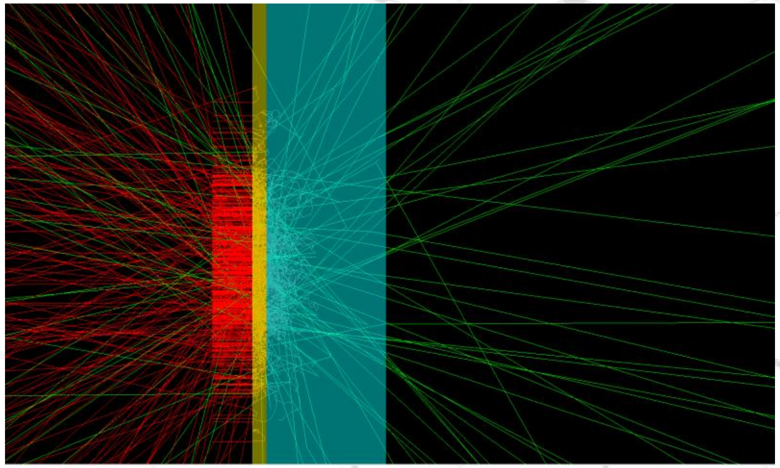
X-ray Target Design

- Final beam exported and used with Monte Carlo code (G4beamline) to design an X-ray target.
- One copper layer for heat removal and one tungsten layer that generates large numbers of X-rays due to high Z number.
- Tungsten thicknesses scanned to find optimum X-ray yield for the design.
- Copper thickness scanned to minimize electron leakage.





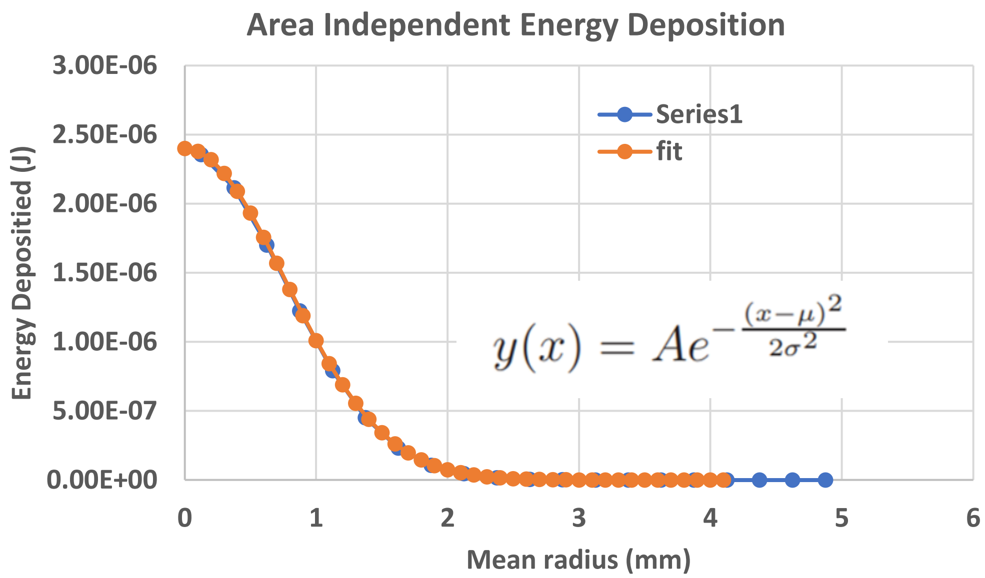


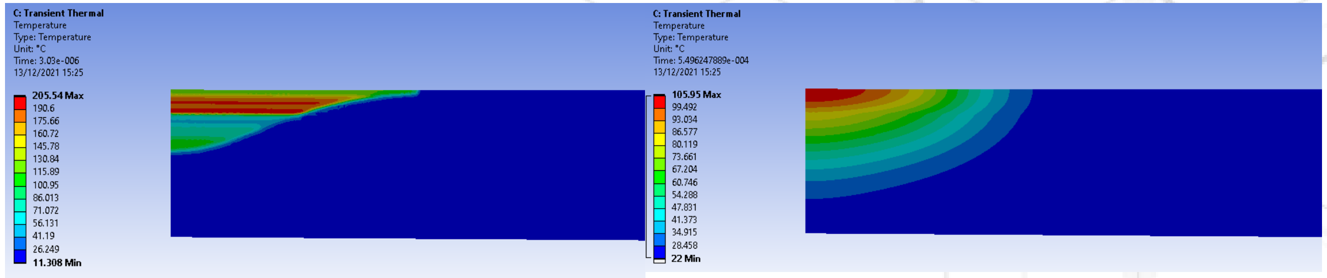


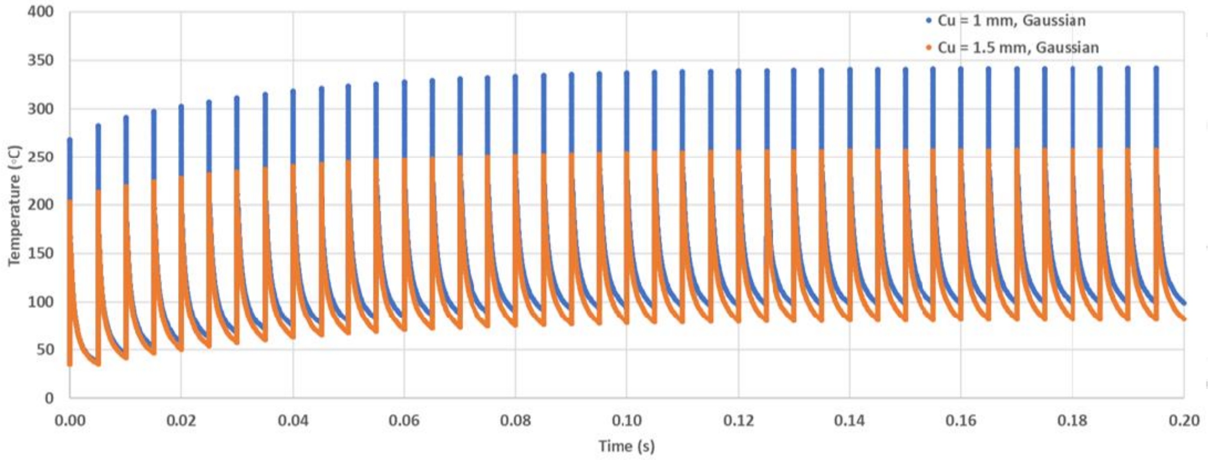
X-ray Target Thermal Analysis

- Energy deposition inside the target measured.
- Applied estimated power density*(1-radiation yield) to Gaussian volume at the centre of the target.
- Peak power density = 2e6*100e-3 = 200 kW.
- 0.9 conversion efficiency = 180 kW.
- Comparison of different copper thicknesses on target heating.

Cu thick	W thick	Pulse length	Repetition rate	Peak current	Energy	Duty cycle
1mm	0.2 mm	3 us	200	100 mA	2 MeV	0.06%







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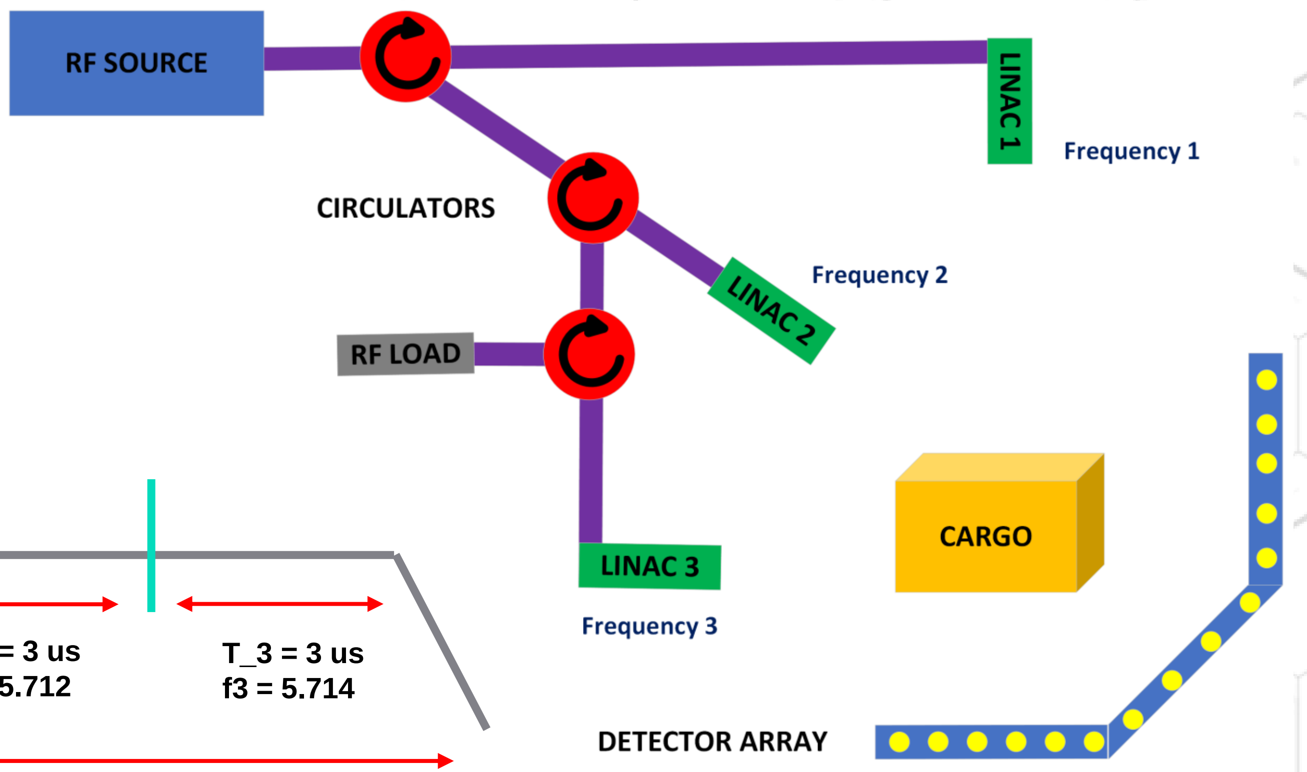
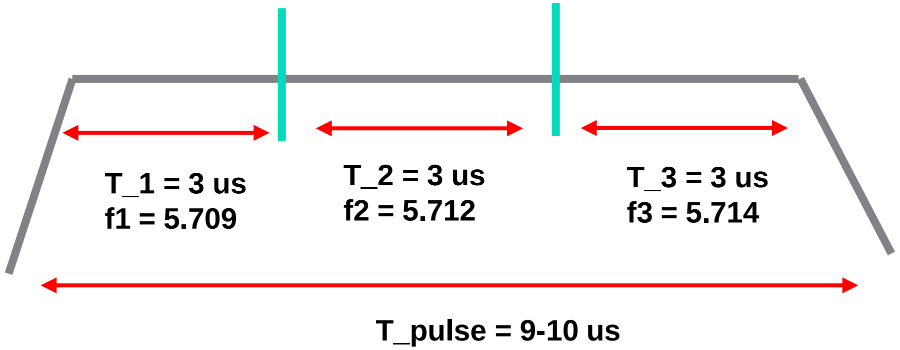
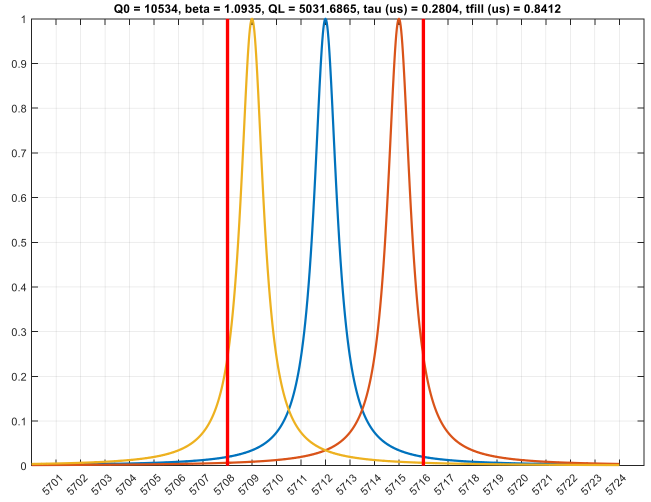
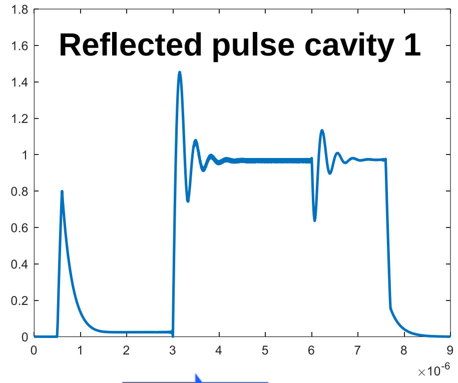
RF System Design

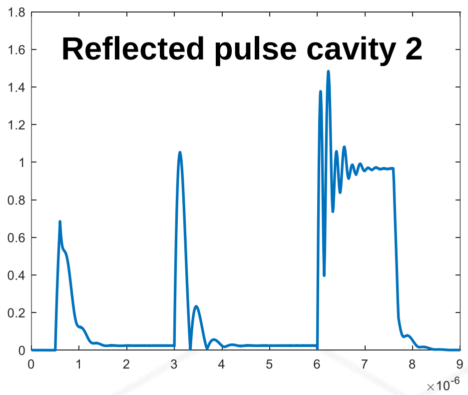
- In order to create a 3D image, a minimum of 3 linacs are required.
- A method of firing them sequentially was required, with a larger delay than waveguide alone provides.
- Idea to use 3 frequencies within a single pulse with the linacs acting as filters for the next frequencies.

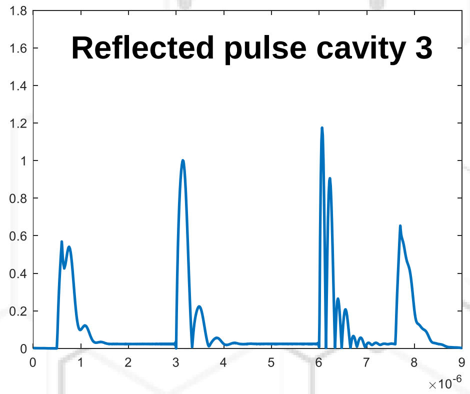












Conclusions and Future Work

- Designed a full C-band cargo scanning linac with optimized performance for low energy, and maximum lifetime.
- Full thermal analysis to ensure no operational issues.

Next steps

- Experimental validation of RF system design.
- Thermal analysis of combined linac target system.

Acknowledgments

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Publications:

IPAC 2021 conference: "Smith, S. J., R. Apsimon, and M. J. W. G Burt. "Multi-Objective Optimization of RF Structures." (2021).

Smith, S., et al. "Multiobjective optimization and Pareto front visualization techniques applied to normal conducting rf accelerating structures." Physical Review Accelerators and Beams 25.6 (2022): 062002.

IPAC 2022: Visualisation of Pareto Optimal Spaces and Optimisation Solution Selection Using Parallel Coordinate Plots (submitted)

QUESTIONS?