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Hybrid accelerator to deliver therapeutic electron beams at high energies

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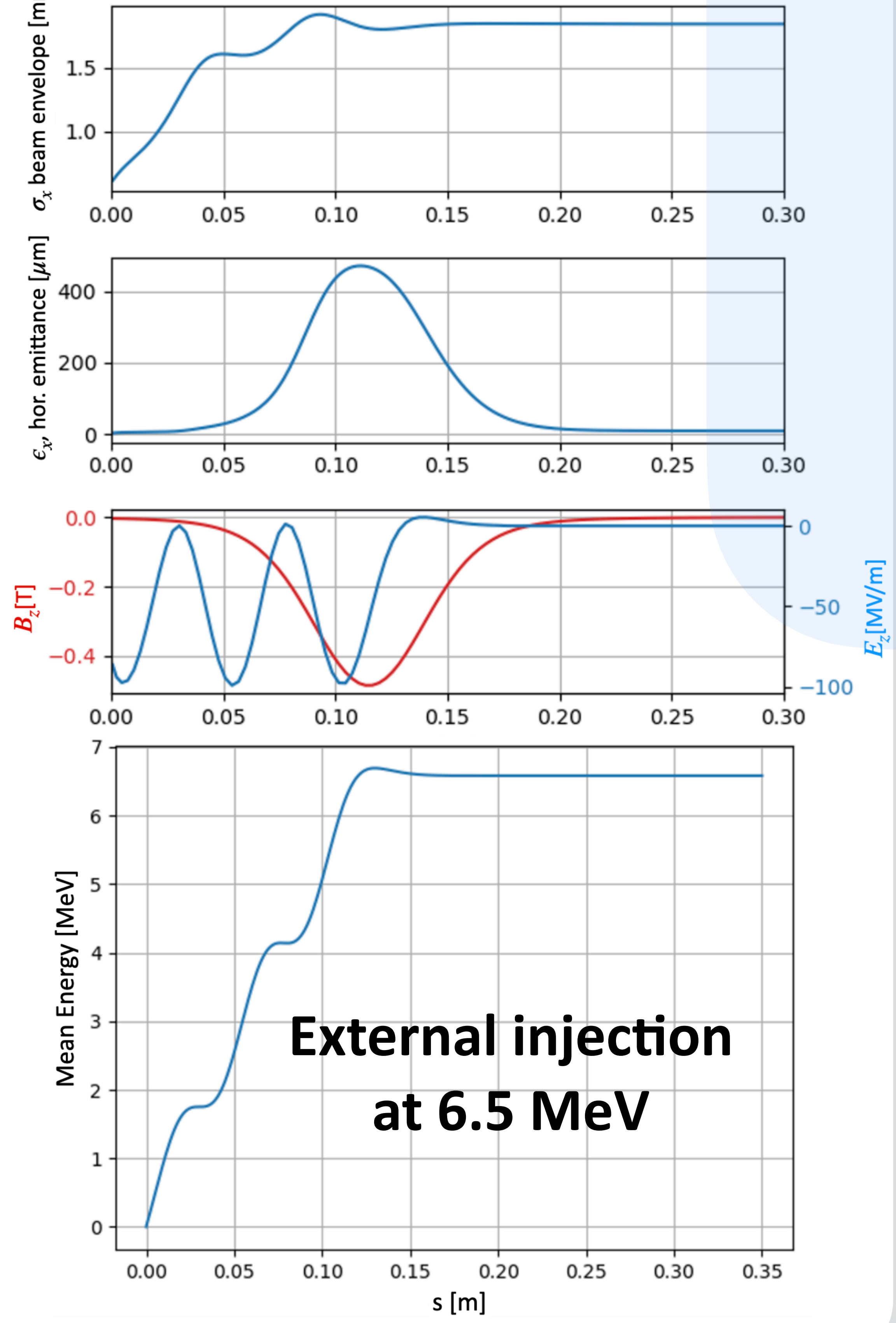
ABSTRACT Very High Energy Electrons (VHEE) are emerging as a cancer treatment commodity. Compared to protons, VHEE is less sensitive to inhomogeneities within the human body. This means they are less damaging to healthy tissue when treating dynamic organs such as the lungs, liver, and kidneys. VHEE have a range of penetration depth depending upon the energy, often ranging from 50 MeV to 250 MeV. Such beams can be generated using radiofrequency photoinjectors followed by tens of meters long copper-based booster linacs. We are envisaging a hybrid approach where high-brightness electron beams are generated using mature copper photoinjector technology and injected into a plasma module for further acceleration. The end goal is proof of a compact VHEE radiotherapy machine. In this contribution, we will review therapeutic electron beams, and discuss the layout of the hybrid VHEE machine and a technique developed to match the conventional electron source and the plasma accelerator.

Electron injector



External injection at 6.5 MeV

Matching section

The transformation of particles positions and angles is a least square fit to a system of linear equations.

$$\begin{pmatrix} x_{21}\dots x_{2N} \\ \theta_{21}\,..\,\theta_{2N} \end{pmatrix} = R_{natural} \begin{pmatrix} x_{11}\dots x_{1N} \\ \theta_{1.1}\,..\,\theta_{1N} \end{pmatrix}$$

Plasma entrance

Gun exit

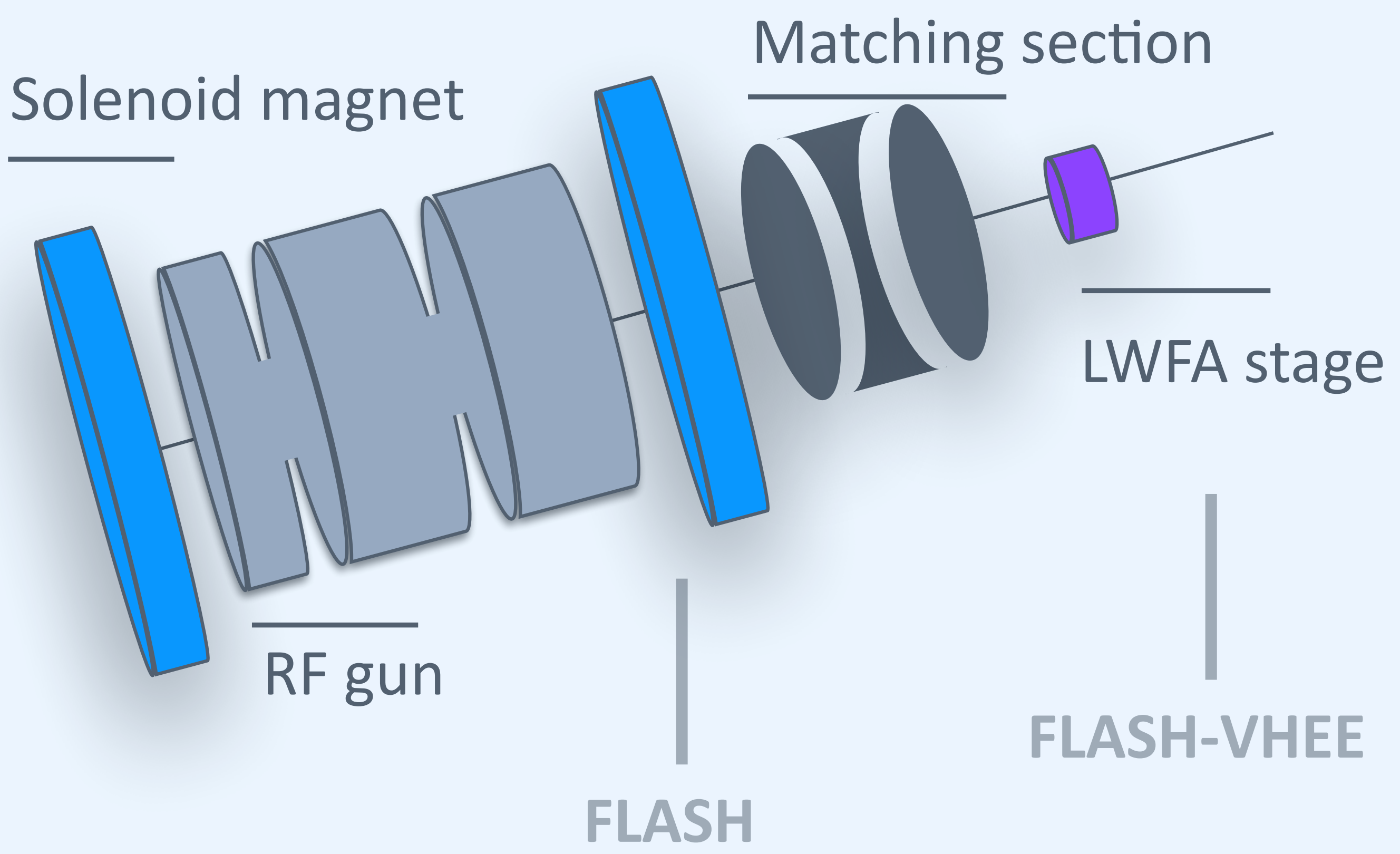
$$Y = R_{natural}X$$

$$YX^T = R_{natural}XX^T$$

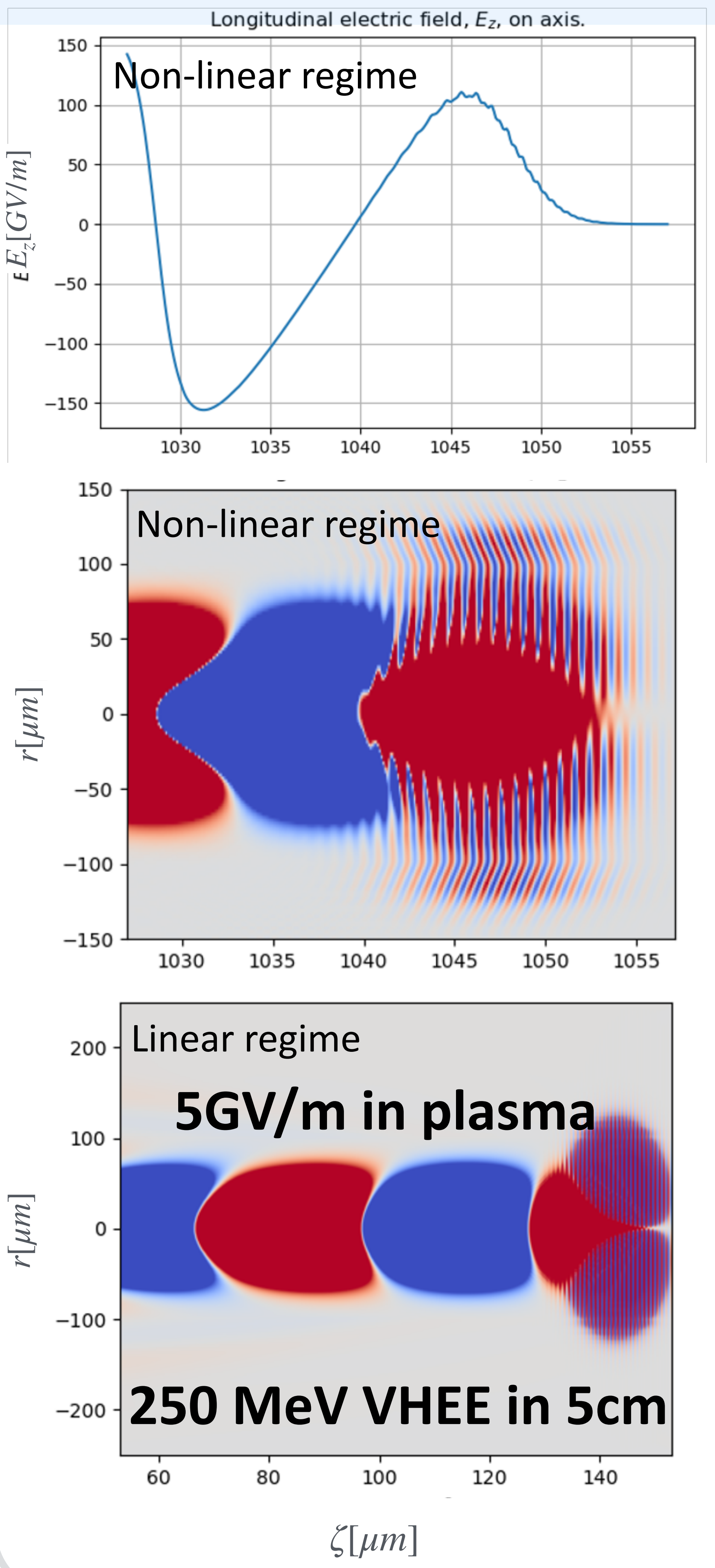
$$YX^T(XX^T) = R_{natural}XX^T(XX^T)$$

Moore-Penrose pseudo-inverse

$$YX^+ = R_{natural}$$

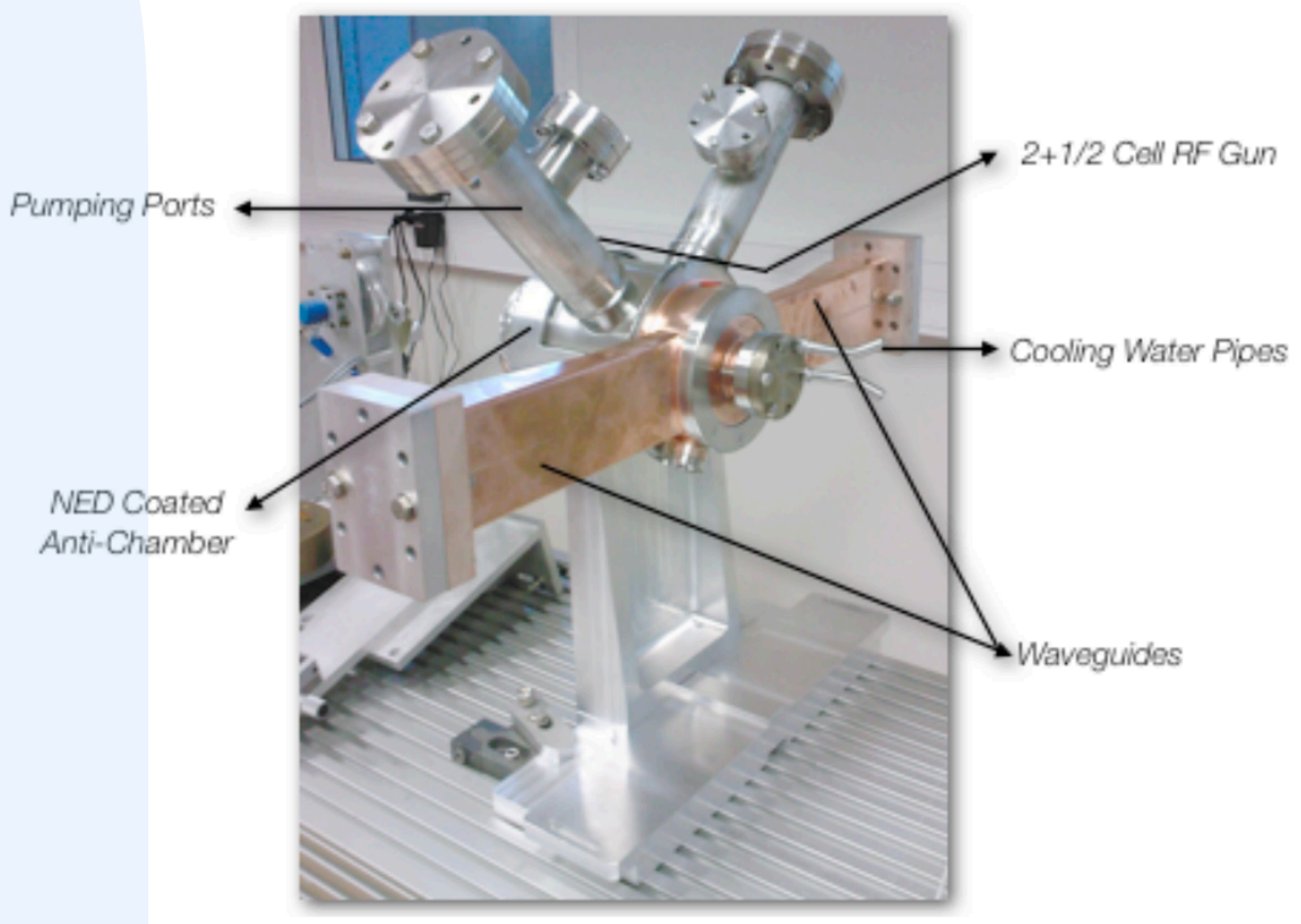


Plasma section



5GV/m in plasma

250 MeV VHEE in 5cm



A photograph of the laser-driven PHIN RF gun that consists of a $2+1/2$ cell, normal conducting, S-band standing wave cavity operating at 3GHz and 85MV/m.

Table 1: S-band gun parameters used in simulations.

Property	Values
Gradient (MV/m)	100
Length (with a bit of beam pipe) (cm)	18
Bunch charge (nC)	2
Laser radius (mm)	1.2
Laser pulse length (FWHM) (ps)	3 and 0.05

Table 2: Plasma parameters used and calculated in simulations.

Property	Values
Density (m^{-3}) (linear regime)	3×10^{23}
Density (m^{-3}) (non-linear regime)	3×10^{24}
Angular frequency (rad/s)	3.1×10^{13}
Wavelength (μm)	61
Bucket size (μm / fs)	15 / 50
Channel radius (μm)	50

Table 3: Laser parameters used in plasma simulations.

Property	Values
Wavelength (nm)	800
a_0 (linear regime)	0.8
a_0 (non-linear regime)	2
Waist at channel entrance (μm)	50
Pulse duration (fs)	16

The first FLASH treatment in Lausanne University Hospital *J. Bourhis et al., Radiotherapy and Oncology 139 (2019) 18–22*
FLASH capable VHEE studies *L. Faillace et al., Physica Medica 104 (2022) 149–159; L. Giuliano et al., IPAC22 Proceedings (THPOTK054)*
Record LWFA capability *C. Aniculaesei et al., Matter Radiat. Extremes 1 January 2024; 9 (1): 014001*
CLARA/FEBE facility in Daresbury Laboratory tailored for plasma experiments *E. W. Snedden et al., Phys. Rev. Accel. Beams 27, 041602*

Discussion

Radiofrequency injectors operate at "cigar" and "pancake" regimes. Cigar emission typically produces 10s to hundred ps electron bunches and is preferred for light sources to reduce space charge impact and deliver ultra-low emittances. Whereas pancake emission produces bunches that have much greater transverse extend compared to their longitudinal size. For injection into a plasma accelerator, one requires a bunch length at a fraction of the plasma wavelength to minimise energy spread and multi-bunching. We chose a 3GHz RF gun operating at 100MV/m delivering 6.5 MeV electrons for external injection. These conventional injectors can produce sub-100 fs bunches hence we aim to use 50 fs bunches for injection into the plasma section. This is suitable for a bunch to occupy a region of maximum acceleration on the axis field and also a focusing transverse field. We aim to optimise the set-up to deliver FLASH-capable 5-6 MeV electrons at the RF gun exit. This is a dedicated design for the tumours located on the surface such as the treatment of skin cancer. This first design will be upgraded to VHEE by the addition of a matching section and a plasma accelerator to penetrate further into the target for the treatment of tumours with deeper locations. Electrons are particularly effective for moving organs such as the lungs, liver and kidneys as they are not sensitive to inhomogeneities during propagation. Our goal is to achieve VHEE-FLASH within a meter.