First ML-Based Start-to-End Simulation of a Plasma Acceleration Facility integrated into Geant4: PALLAS - laser-plasma accelerator test facility

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https://geant4.web.cern.ch/

Motivation

Plasma acceleration is a groundbreaking technology with applications in accelerator and light source facilities, medical and nuclear physics etc.
GEANT4[1] is a widely used Monte Carlo toolkit for modeling particle interactions with matter in high-energy, nuclear, accelerator, medical physics and space science. Many **Geant4 applications are adaptable for plasma acceleration**, which is **currently missing in this toolkit**.

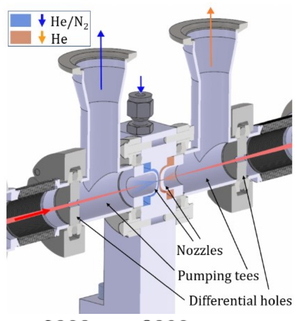
Key idea

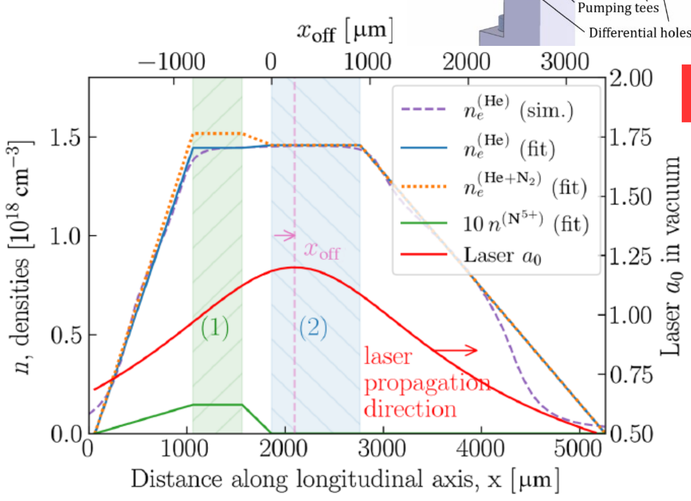
PIC simulations → **ML surrogate model** → Integration of the **ML model** into **Geant4** as a **particle source** → **Start-to-end simulations** of a **plasma facility** and its **applications** with **Geant4**

Implementation[2] of the PALLAS[3] laser-plasma accelerator test facility setup into Geant4

PALLAS gas cells[4]

Gas density profile generated[4] using **OpenFOAM**[5] code

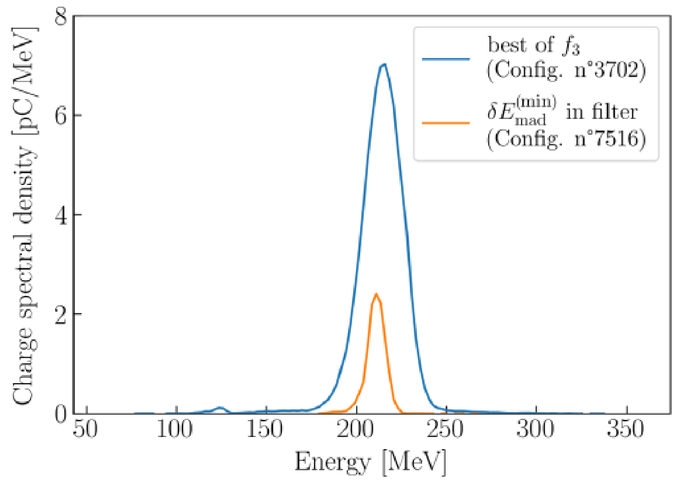




model input
- p (mbar) → pressure
- $a_{0,\mathrm{vac,max}}$ → normalized peak vector potential
- x_{off} (μm) → laser focal position offset
- c_{N_2} (%) → dopant concentration

model output
- Q (pC) → beam charge
- E_{med} (MeV) → beam energy
- δE_{mad} (%) → beam energy spread
- $\epsilon_{y,n}$ (μm) → beam emittance

PIC simulations with SMILEI[6]



ML surrogate model[2,4,7]

Layer (type)	Output Shape	Param #
Input Layer (InputLayer)	(None, 4)	0
Hidden Layer 1 (Dense)	(None, 100)	500
PReLU activation 1 (PReLU)	(None, 100)	100
Hidden Layer 2 (Dense)	(None, 100)	10,100
PReLU activation 2 (PReLU)	(None, 100)	100
Hidden Layer 3 (Dense)	(None, 100)	10,100
PReLU activation 3 (PReLU)	(None, 100)	100
Output Layer (Dense)	(None, 4)	404

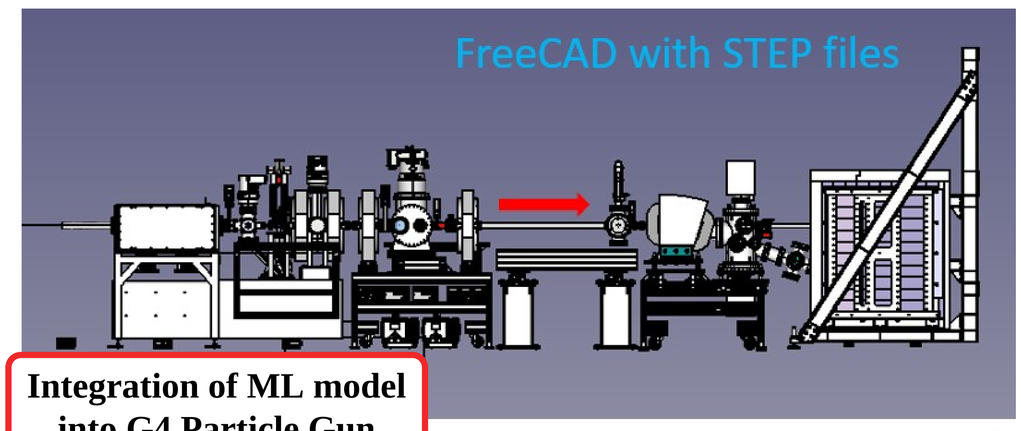
Total params: 21,404 (83.61 KB)
Trainable params: 21,404 (83.61 KB)
Non-trainable params: 0 (0.00 B)

PALLAS goal – building a 10Hz laser-plasma accelerator test facility aiming to achieve **reliability** and **control** comparable to conventional RF accelerator standards. The PALLAS project is involved in the EUPRAXIA[8].

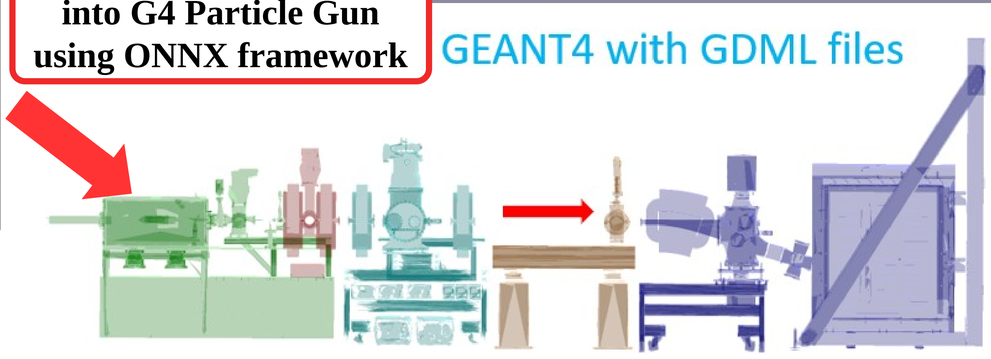
PALLAS

Geant4 example

Convertion from STEP files into GDML using **FreeCAD**[9]

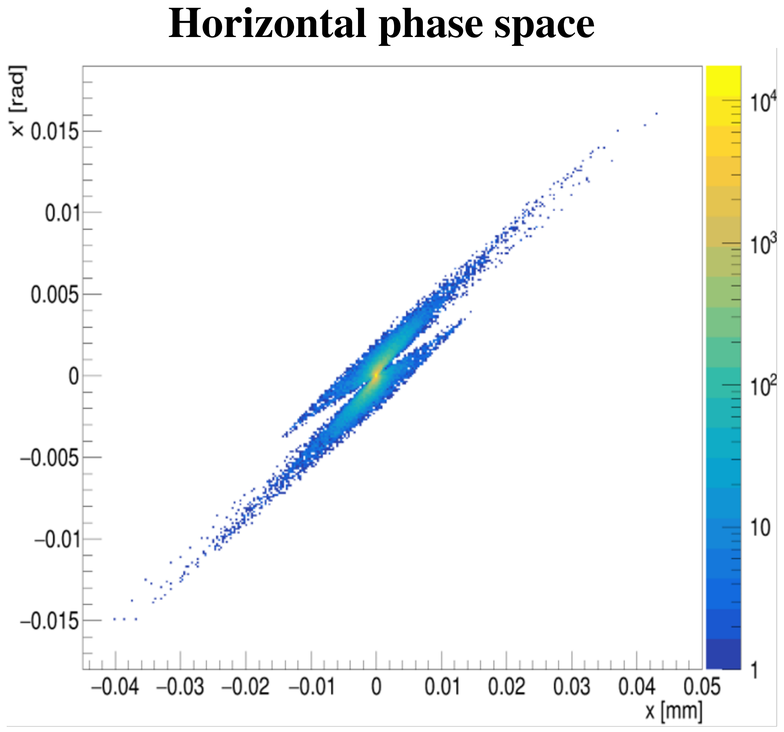


Integration of ML model into G4 Particle Gun using ONNX framework

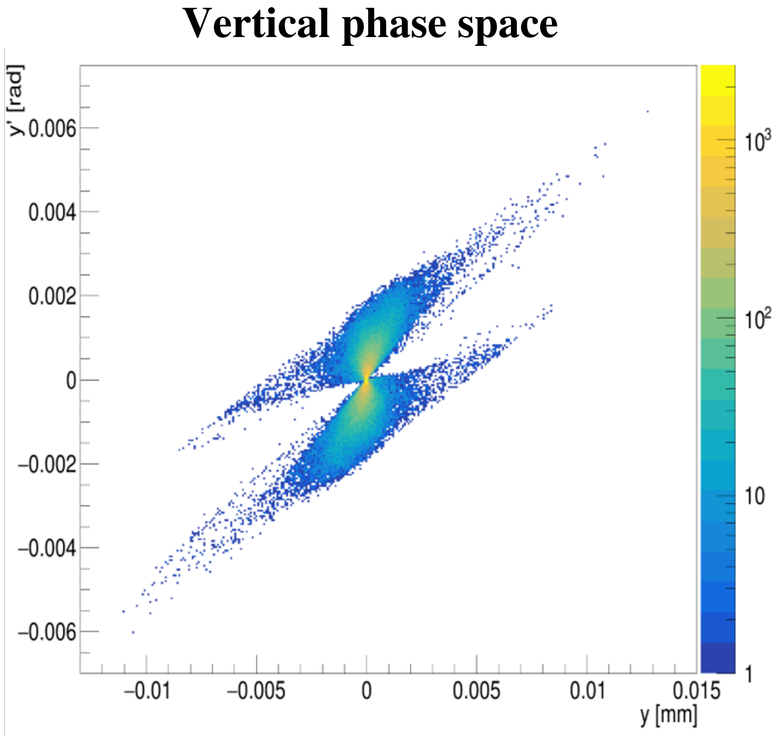


Simulation results: electron beam at the detector system

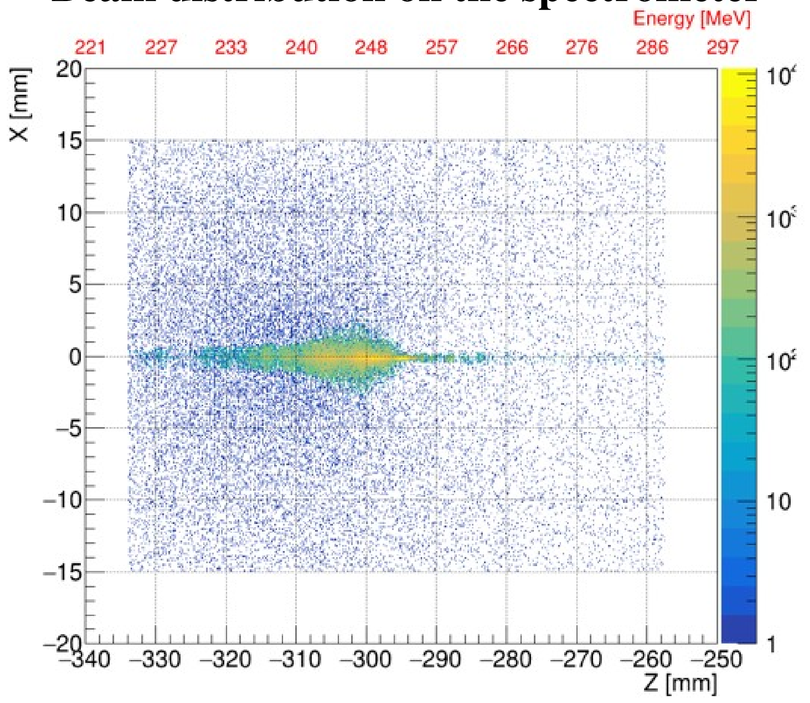
Horizontal phase space



Vertical phase space



Beam distribution on the spectrometer



Conclusions

We present the successful integration of a ML surrogate model, trained on PIC simulations of LPA, into the Geant4 toolkit. Centered on the PALLAS facility, this enables unified start-to-end simulations of laser-plasma acceleration facilities and their potential applications in synchrotron light sources, free electron lasers, nuclear physics, and advanced radiotherapy.
Acknowledgments: A. Sytov acknowledges Geant4INFN.

References:

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9. https://www.freecad.org/