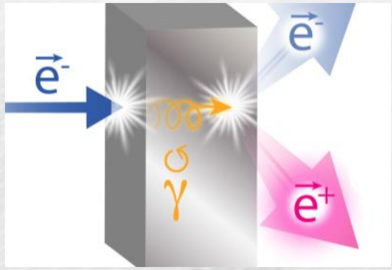

Liquid metal-based polarized positron generation benchmark using the GEANT4 toolkit

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2024 Workshop on Polarized Sources, Targets, and Polarimetry (PSTP24)

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Outline

- Overview of different polarized positron source schemes
- Liquid metal target project
- Polarized positron generation simulations with Geant4
- Results
- Summary and further work

- Circularly polarized gamma-rays incident to a target

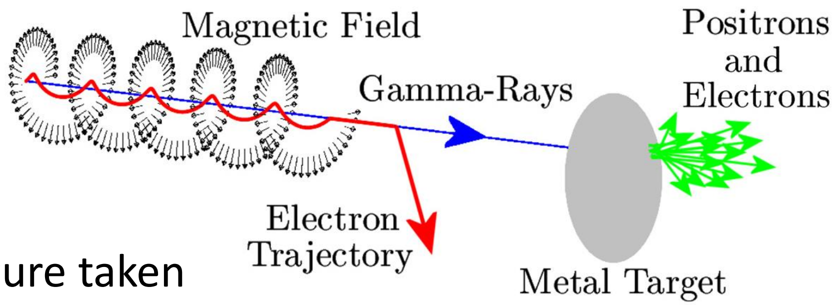
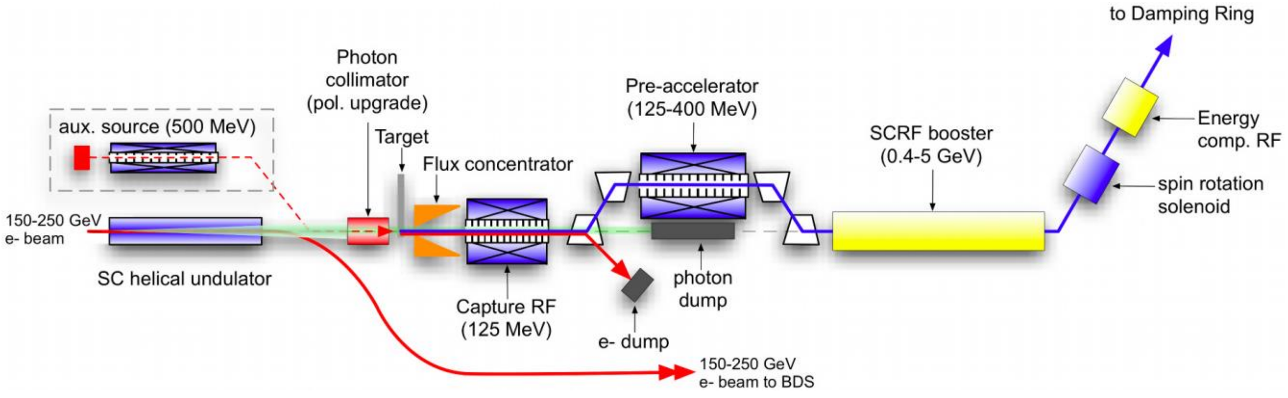


Figure taken from Scott D. PhD. Thesis.



ILC positron capture section layout. From The International Linear Collider Technical Design Report-Volume 3. II: Accelerator Baseline Design. arXiv:1306.6328

- Circularly polarized gamma rays and longitudinally polarized positron generation in the same target
- Polarization transfer from primary electron beam is possible in the MeV range as in the PEPPo experiment (Abbott, D., *et al.* https://doi.org/10.1103/PhysRevLett.116.214801)

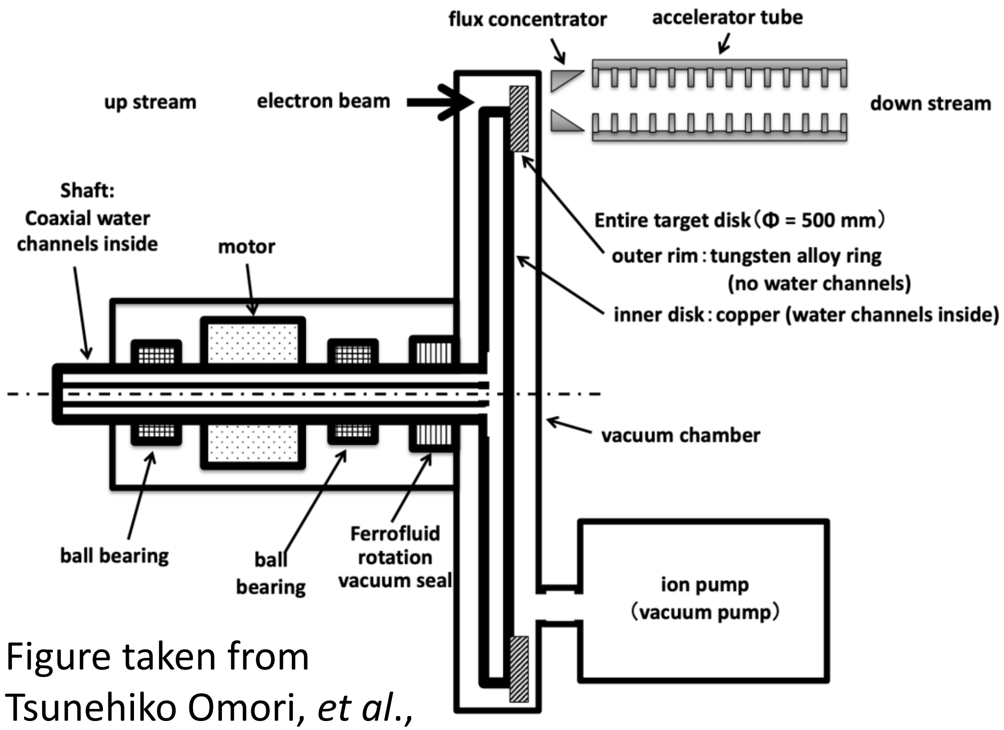


Figure taken from Tsunehiko Omori, *et al.*, arXiv:2407.00587

Liquid metal target project

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- The main problems of target design are heat dissipation, radiation damage, thermal stress and fatigue. The high radiation can bring problems of heating, activation and radiation damage to surrounding components.

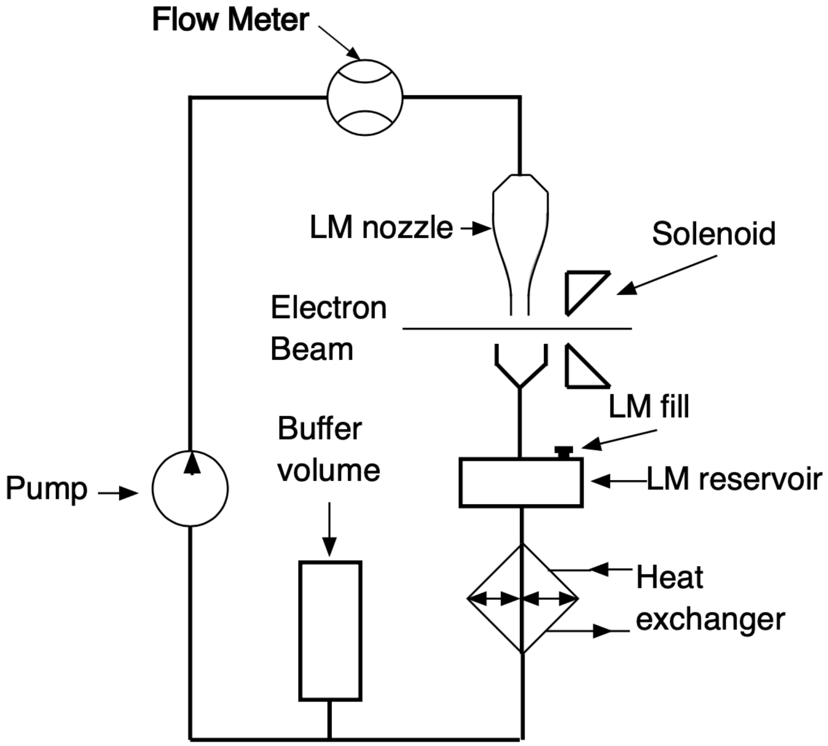
  A possible solution to the problem of high power (10-100's of kW) positron targets is a converter based on a recirculating free surface liquid metal jet in vacuum. Liquid metals of interest: GaInSn and PbBi

  Advantages:

  - Relative mechanical simplicity of the device
  - Liquid metal serves both as target material and coolant
  - Material does not suffer damage and is continuously replenished
  - There is no stress in the liquid GaInSn
  - PbBi have very low vapor pressures at operating temperatures so it can be incorporated directly in the beamline

  Disadvantage:

  - PbBi has to be heated to 150 C so whole apparatus has to be heated



Slide courtesy of Val Kostroun

Prototype test stand

GaInSn selected as working fluid Properties:

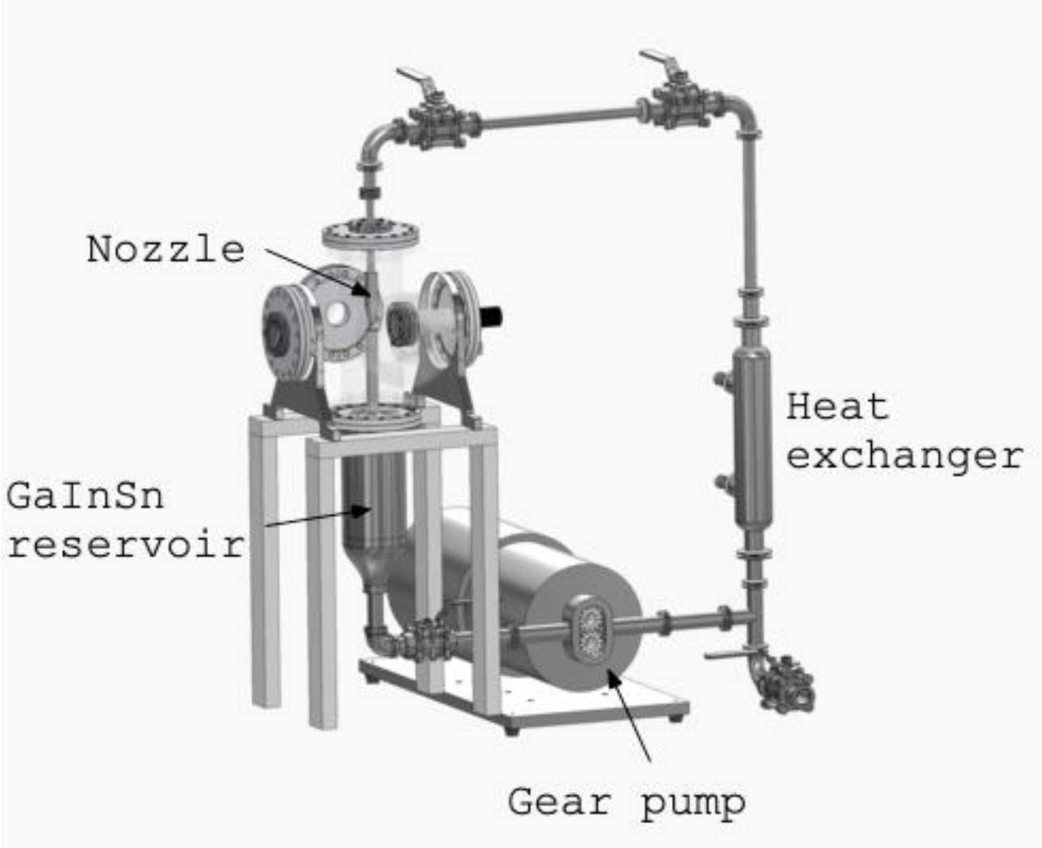
- Non-toxic, fluid at 25 C, vapor pressure 10^{-8} Torr @ 500 C thermal conductivity, viscosity similar to PbBi.

Idea is to use this as a development project to debug and learn from, without having to heat the entire system to 150 C as needed by PbBi.

Once prototype tested and evaluated, the 6 way cross will be replaced by an appropriate chamber suitable for electron beam tests at LERF at JLab.

Ultimate goal is a PbBi converter.

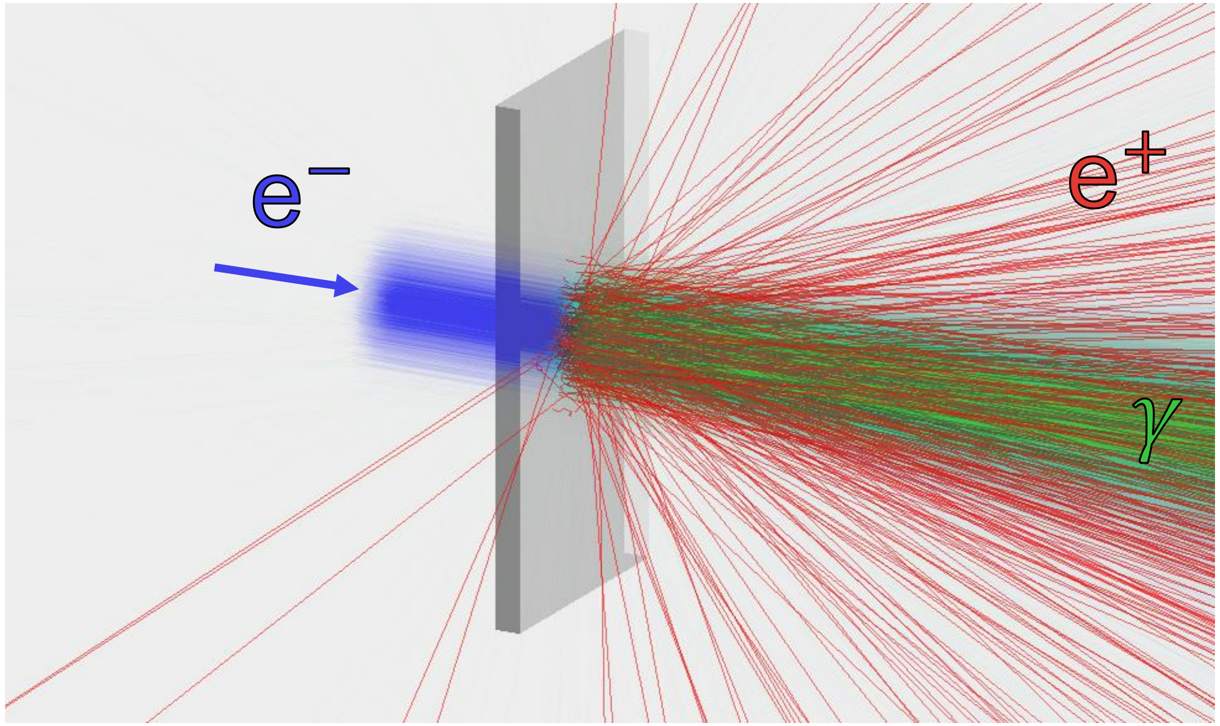
More information in reference [5].



Slide courtesy of Val Kostroun

Polarized positron generation simulations with Geant4

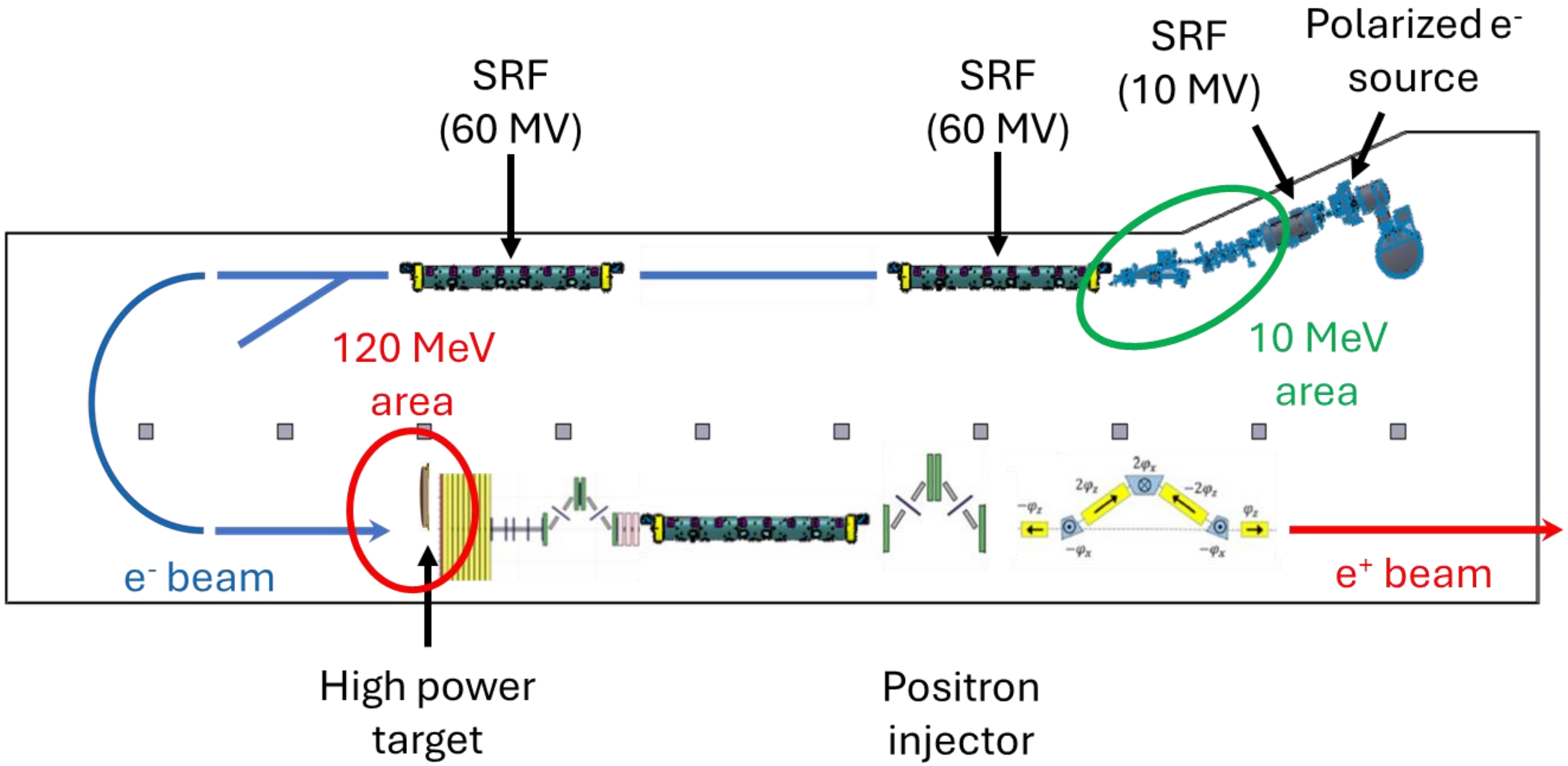
- Geant4 toolkit*
  - Monte Carlo simulations
  - Particle tracking, beam-matter interaction, polarization tracking
- Processes
  - Gamma rays created from Bremsstrahlung with material nuclei
  - e-/e+ pair creation from gammas
- Polarization tracking in both processes
- Positron data recorded at the downstream face of the target
- Relevant quantities:
  - Positron yield: $\boldsymbol{\varepsilon} = \mathbf{\#\ e^{+}/\#\ primary\ e^{-}}$
  - Mean longitudinal polarization: $\langle \boldsymbol{P_z} \rangle$
  - Figure-of-merit: $\mathbf{FOM} = \boldsymbol{\varepsilon}\langle \boldsymbol{P_z} \rangle^{2}$
  - Energy spectrum



Visualization of an event of a Geant4 simulation. Primary electron beam incident to a few millimeters of a thick high Z target. e- in blue, photons in green and e+ in red.

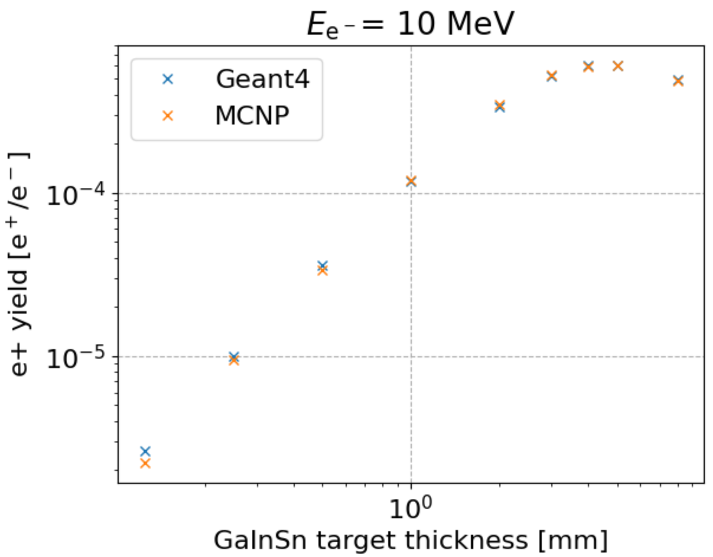
*Geant4 reference: S. Agostinelli, *et al.*, https://doi.org/10.1016/S0168-9002(03)01368-8

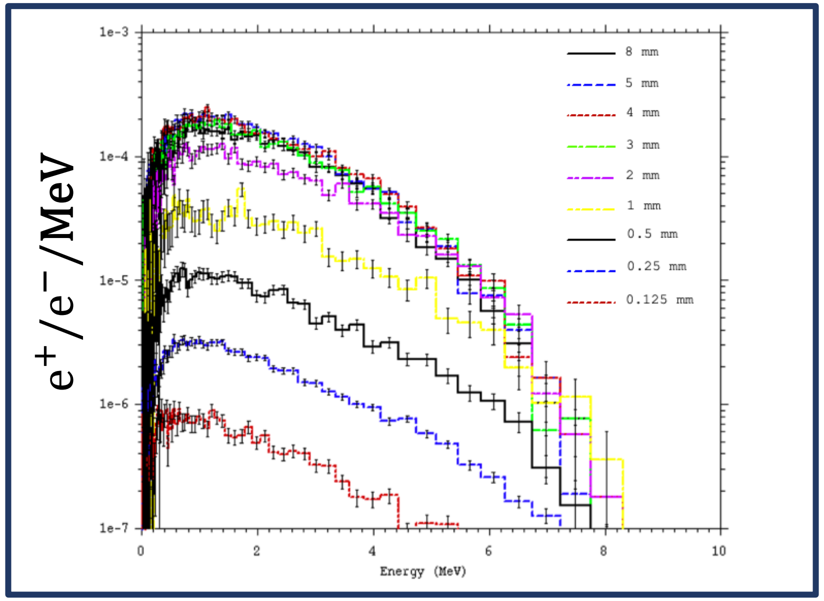
- Simulations will inform the future target beam tests
- Planned **GaInSn** liquid metal target test with 10 MeV polarized electron beam (green)
- *Possible* **PbBi** liquid metal target test with 120 MeV polarized electron beam (red)

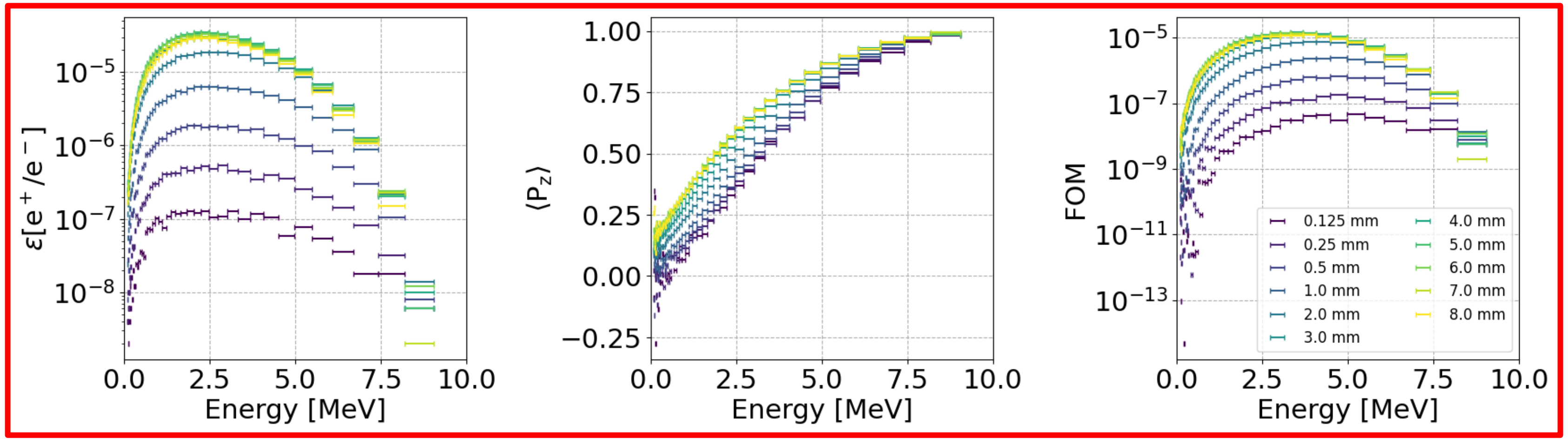


Geant4 and MCNP benchmark - GaInSn liquid target

- Simulations in both Geant4 and MCNP6* (no polarization tracking)
  - MCNP simulations done by Val Kostroun
- *Objective*: find optimum jet thickness for positron yield and polarization and compare results between codes
- Primary e- beam parameters:
  - Energy: 10 MeV
  - Beam transverse size (RMS-gaussian): 1 mm
- Target thicknesses (mm):
  - 0.125, 0.25, 0.5, 1, 2, 3, 4, 5, 8
- Energy bin size is $\Delta E/E = \pm 5\%$
- No angular cuts





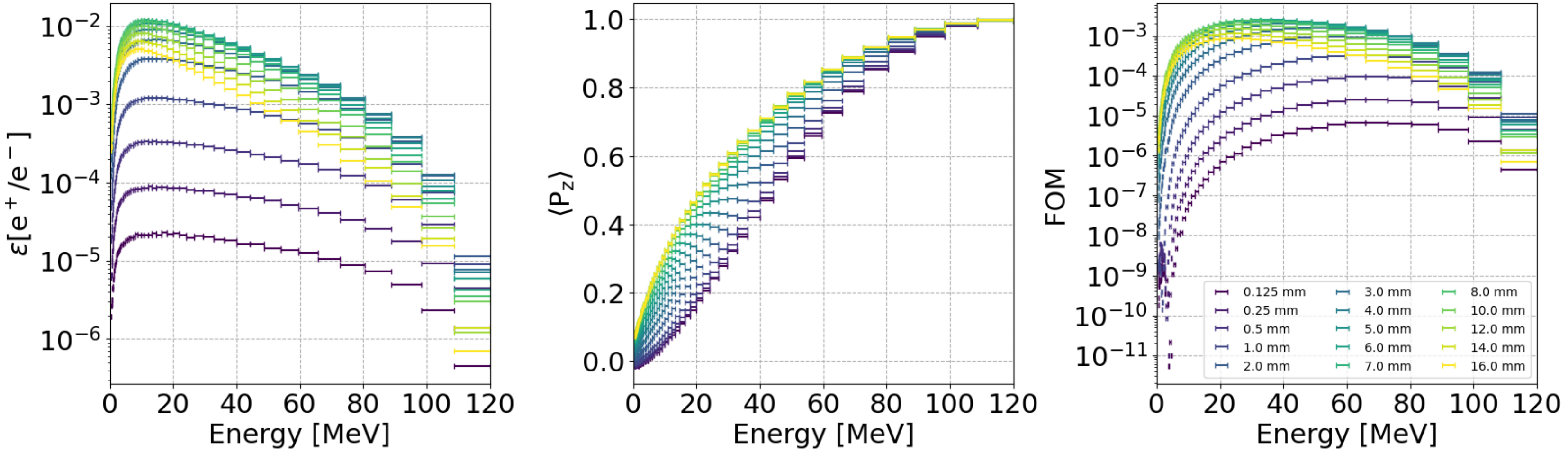


*MCNP6 reference: T. Goorley, *et al*., https://doi.org/10.13182/NT11-135

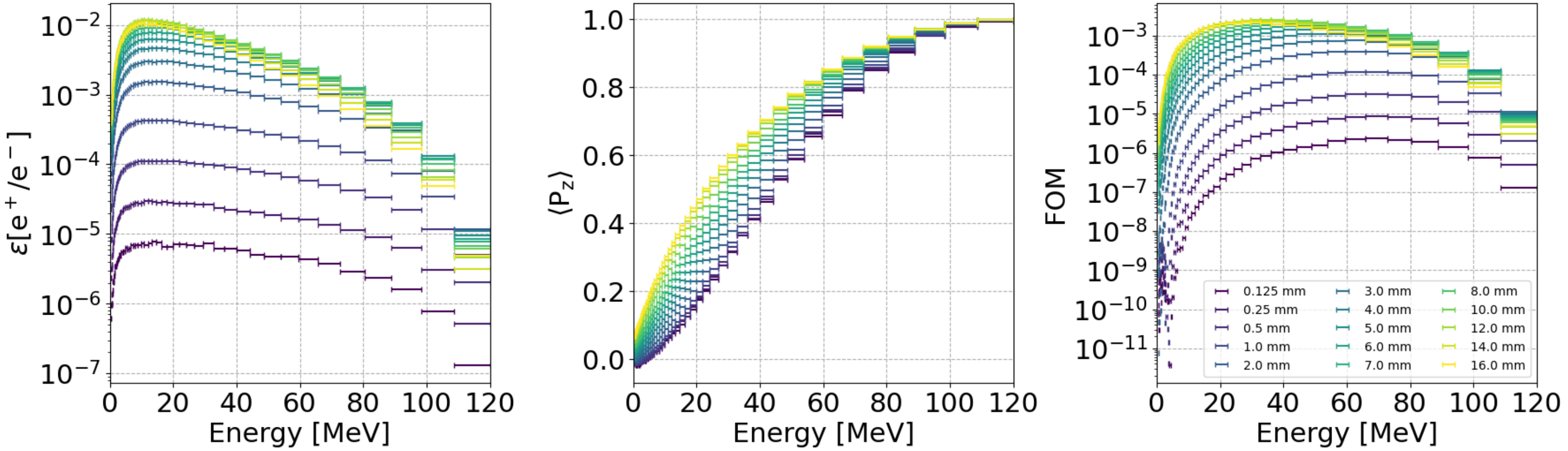
Liquid Lead-Bismuth and solid Tungsten comparison

- Simulations done in Geant4
- Study of the difference between positron yield and polarization at different thicknesses
  - Comparable material properties
  - Tungsten: $Z = 74, X_0 = 3.504$ mm $\rho = 19.30$ gr/cm^3
  - Lead-Bismuth: $Z_{eff} = 83.4$ $X_{0,eff} = 6.176$ mm, $\rho = 10.242$ gr/cm^3
- Primary e- beam parameters:
  - Energy: 120 MeV
  - Beam transverse size (RMS-gaussian): 1 mm
- Target thicknesses (mm):
  - 0.125, 0.25, 0.5, 1, 2, 3, 4,…,16
- Energy bin size is $\Delta E/E = \pm 5\%$
- No angular cuts

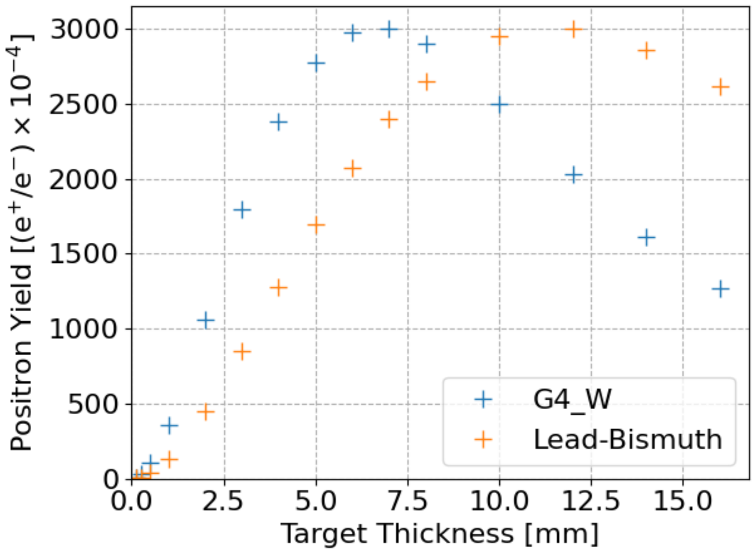
Solid Tungsten

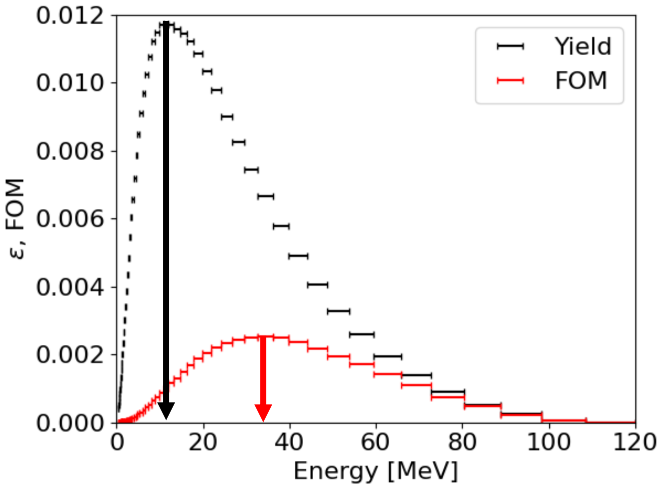


Liquid Lead-Bismuth

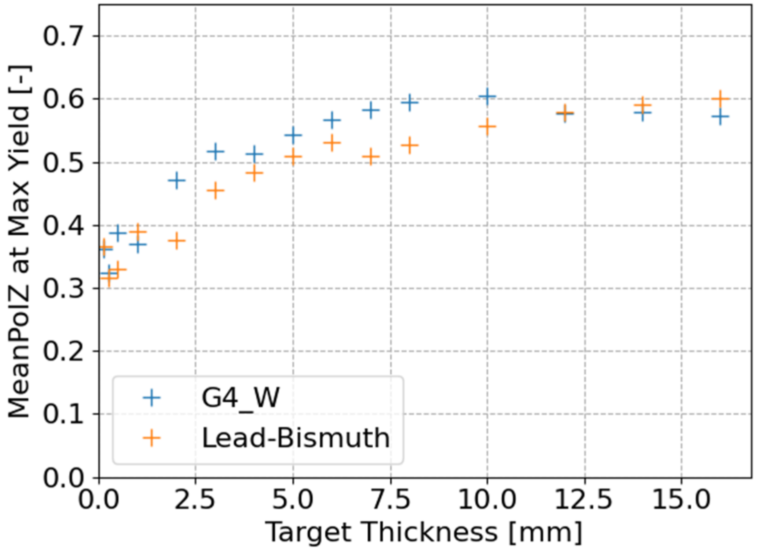


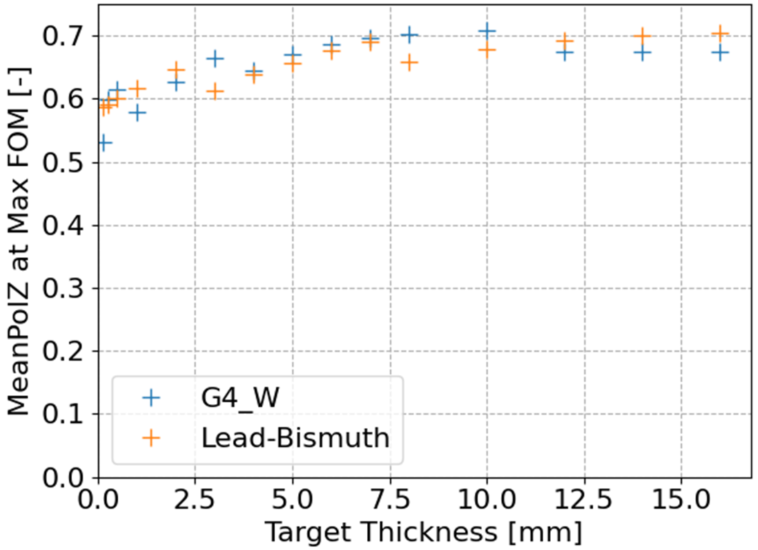
- Maximum yield for Tungsten at 7 mm thickness
- Maximum yield for PbBi at 12 mm
  - Same thickness in Radiation Length units
- Two operational modes:
  - Optimized yield and optimized polarization (FOM)
- Max mean polarization in Max yield mode ~60%
- Max mean polarization in Max FOM mode ~70%





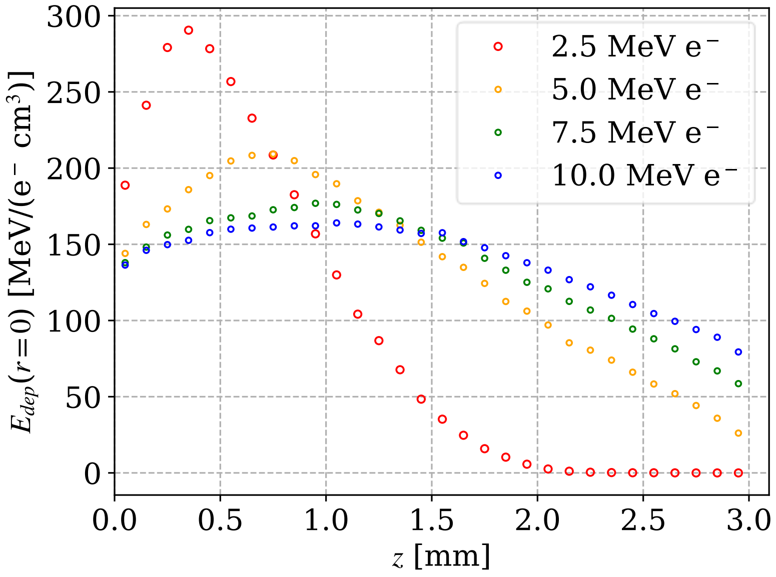
Example selection of two operational modes.

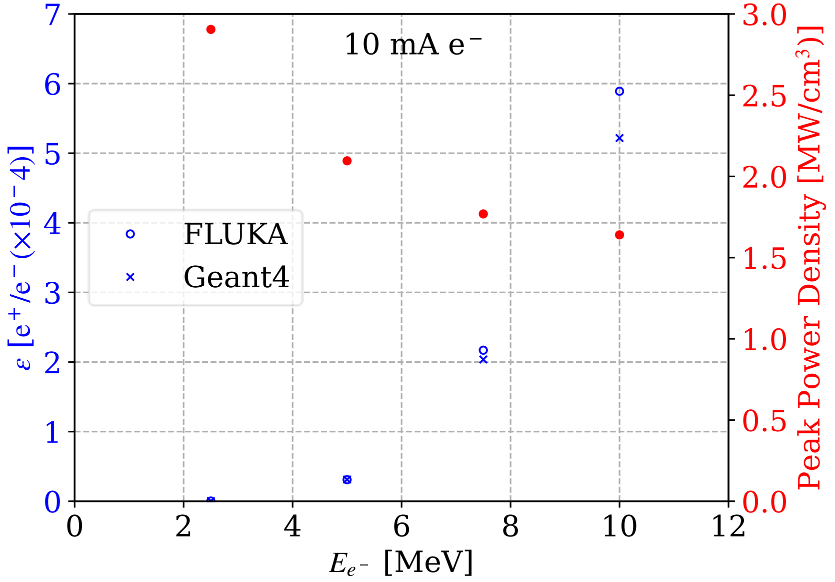




GaInSn liquid target power deposition study

- Simulations in both FLUKA* and Geant4
  - Study the power deposition by variation of primary electron beam energy
  - Another benchmark for positron generation
  - FLUKA simulations were done by Andriy Ushakov
- Target thickness:
  - 3 mm
- Simulated e- beam energies (MeV):
  - 2.5, 5, 7.5, 10





*FLUKA reference: G. Battistoni, et al., https://doi.org/10.1016/j.anucene.2014.11.007

- Good agreement in positron generation simulations with Geant4 and MNCP6 for a 10 MeV e- beam incident to a GaInSn liquid metal target.
  - Maximum positron yield with 4-5 mm target thickness.
  - Maximum yield at ~2 MeV.
  - Maximum FOM at ~4 MeV with ~75% polarization.
- Benchmark Geant4 positron generation simulations with FLUKA.
- Peak Power Density decrease with drive beam energy.
- Similar behavior between liquid PbBi and solid Tungsten for equivalent thickness (in radiation length units).
  - 60% polarization for optimized yield and 70% for optimized FOM.

Further work

- Energy deposition study in Geant4.
- Angular cuts effect in optimized performance for both yield and FOM.
- Setup of the GaInSn test beamline at the LERF in JLab.
- Feasibility of PbBi test at 120 MeV primary beam energy.