Design of a high power 8 MeV electron beam injector for the LERF

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Outline

- Motivation
- 8 MeV beamline layout
- Positron generation at 8 MeV
- Low energy beamline for commissioning

Motivation

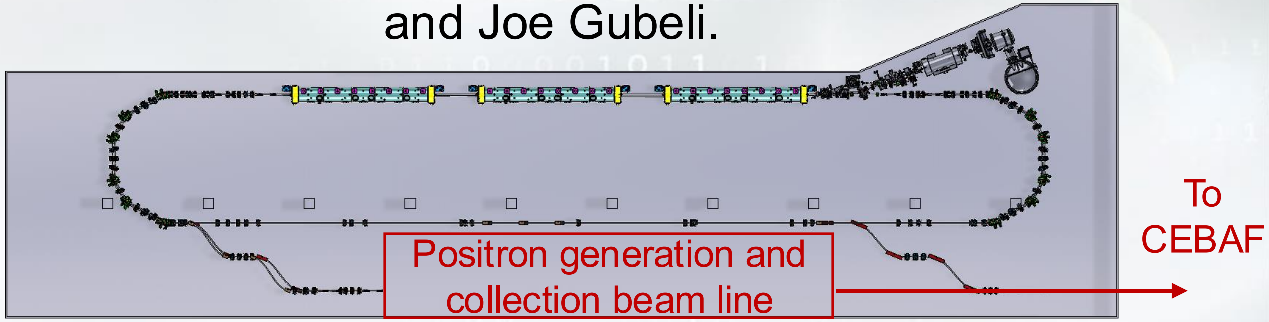
Design the injector beam line that is compatible with the proposed Ce$^+$BAF upgrade

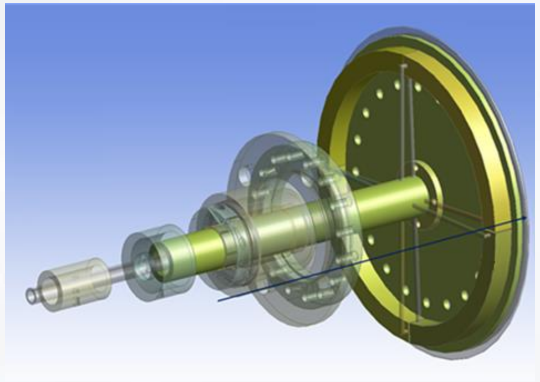
Test of two positron converter target candidates

- Details in the next two presentations!

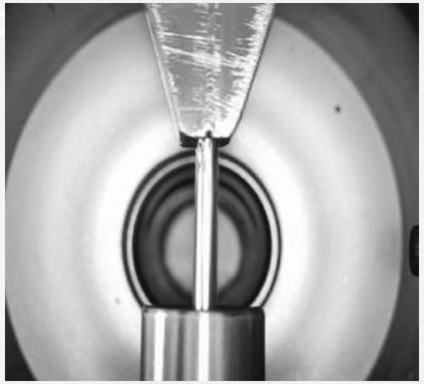
Possible source of sub 10 MeV positron beams

Latest multi-pass LERF linac design. Design and layout by Alex Bogacz and Joe Gubeli.





S. Covrig, "The solid positron converter target at Jefferson Lab"



K. Smolenski, "A high-power positron converter based on a recirculated liquid metal in-vacuum target"

8 MeV injector layout

Goal: to deliver an electron beam to a possible target location

- Maximum energy: 8 MeV
  - Limited by cryomodule power
- Maximum current: 10 mA

Divided in two sections:

Injector

- Accelerate beam to 8 MeV while minimizing emittance growth

Transport line to the target

- Provide flexibility for beam size at the target location while maintaining good vacuum for protection of cryomodules

Compatible with the 'Universal Injector' at LERF serving 22 GeV CEBAF and the positron program

- See Alex Bogacz presentation from earlier today

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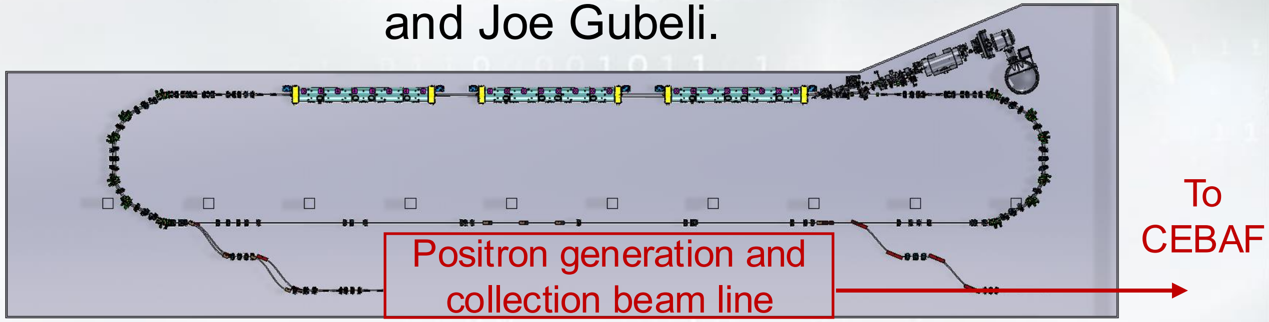
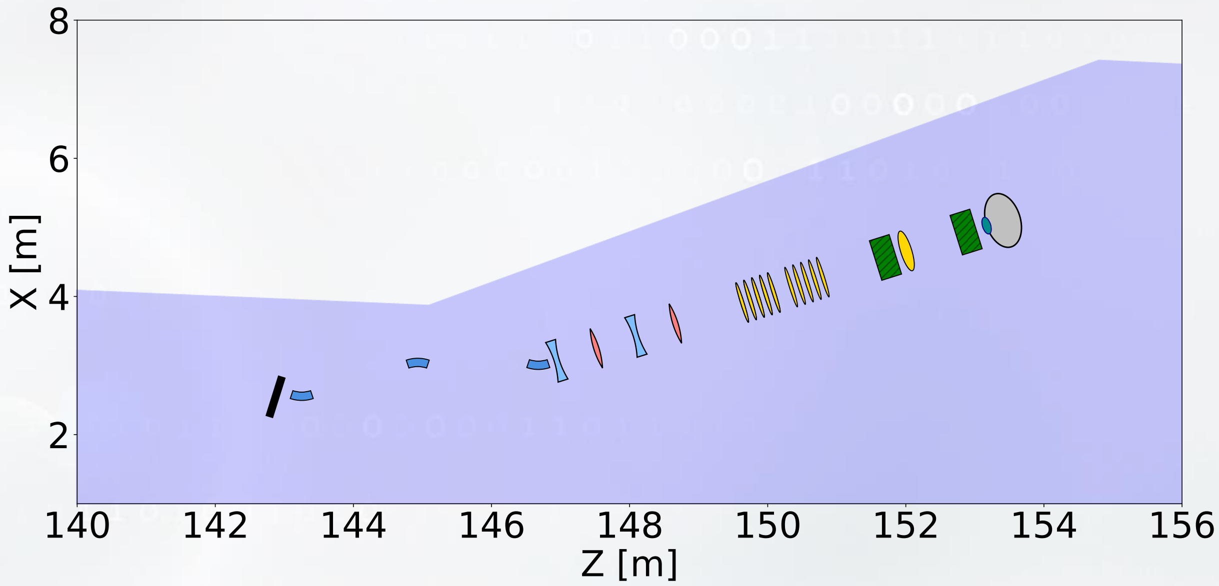




8 MeV injector layout – Gun to QCMs

Beam tracking performed with General Particle Tracer (GPT)

- Easy implementation of realistic electric/magnetic field maps
- Space charge calculations

Optimization of electromagnetic elements setpoints using full multiple objective optimization via pymoo libraries

- Ability to find the pareto fronts for different beam parameters

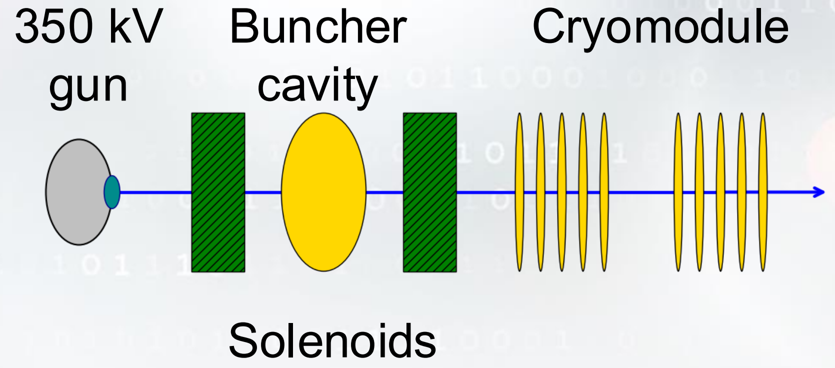
Optimization knobs:

- Sol1 magnetic field, Sol2 magnetic field
- Buncher cavity gradient
- Phase and gradient of the two 5-cell accelerating cavities

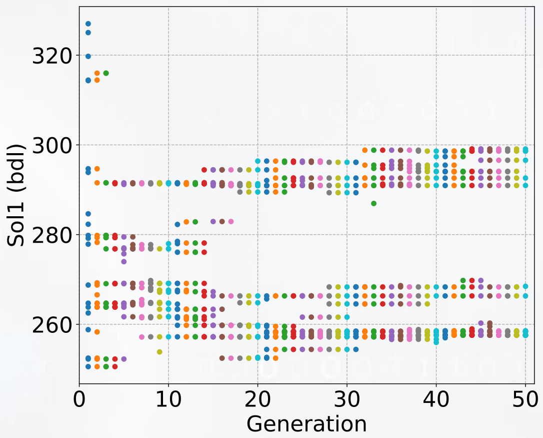
Optimized beam parameters:

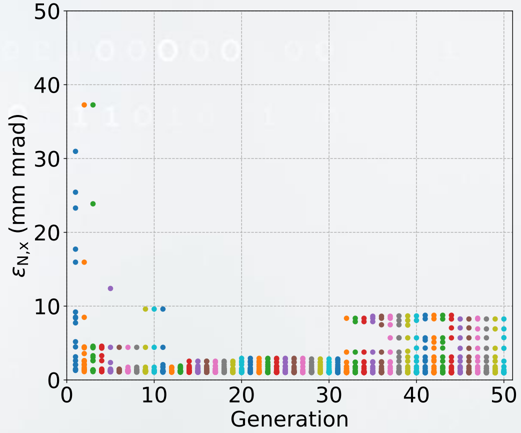
- Normalized transverse emittance, average energy, energy spread and bunch length
- All parameters were calculated a few cm downstream of the second 5-cell cavity (exactly 4 m downstream of the gun)

Constraints: zero beam loss



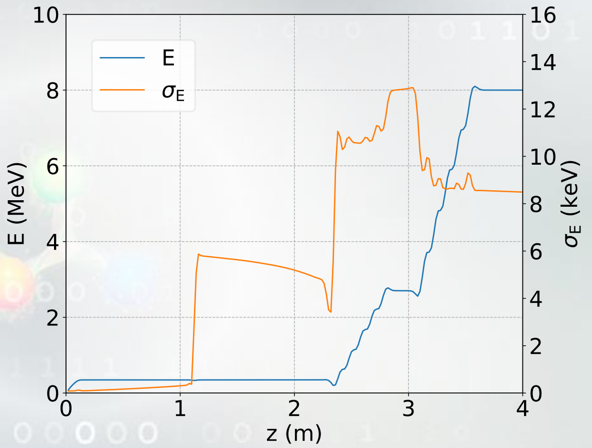
Example of optimization knobs and optimization terms for 50 generations with population of 20.

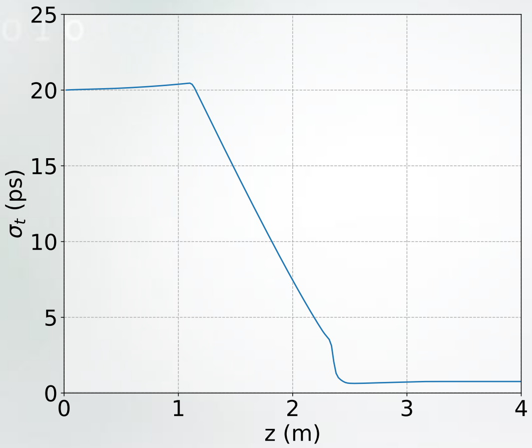


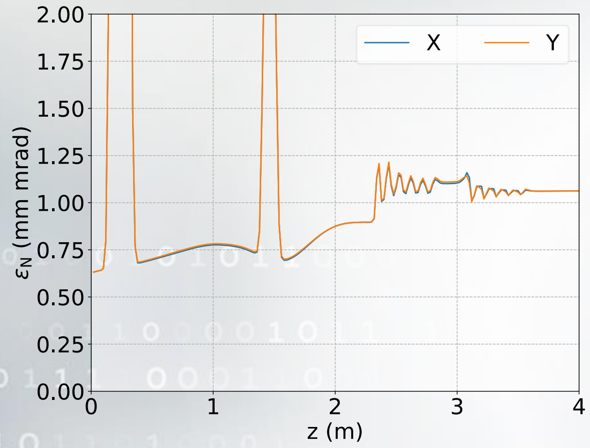


8 MeV injector layout – Gun to QCMs (cont.)

Beam evolution using one of the settings in the last generation.







Final beam parameters downstream of the second QCM for the same setpoints.. These parameters were used as input for simulation of the next section

Beam parameter	Value
β_x, β_y (m)	37, 37
α_x, α_y (−)	7.44, 7.45
$\varepsilon_{N,x}, \varepsilon_{N,y}$ (mm mrad)	1.06, 1.06
$\langle E \rangle$ (MeV)	8
σ_E (keV)	8.5
σ_t (ps)	0.76

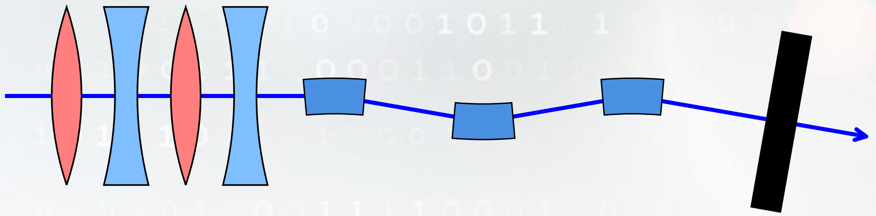
8 MeV injector layout – Transport line to the target

Beam tracking performed with Elegant

Beam line composed of

- 4 quadrupole matching section
- 3-bend chicane for protection of cryomodules

Quadrupole setpoints were optimized to find desired beam spots at the target location with the pymoo libraries



Optimization parameters are the four quadrupole focusing strengths (K values)

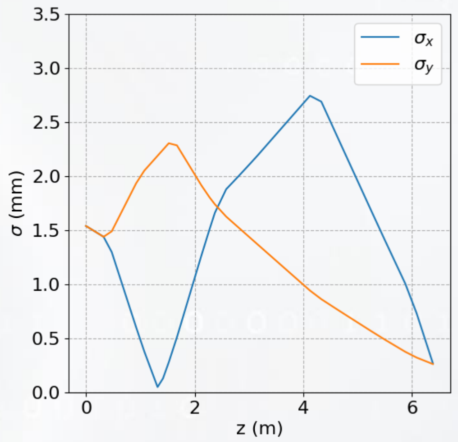
Optimization term is an array of possible beam spots at the target

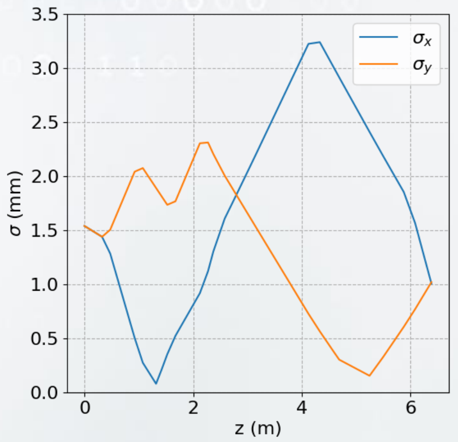
- More sophisticated matches can also be performed, if necessary, e.g., if a certain beam α is preferred

The only constraint is beam loss

- Assumed a transverse aperture diameter of 3.5 cm throughout

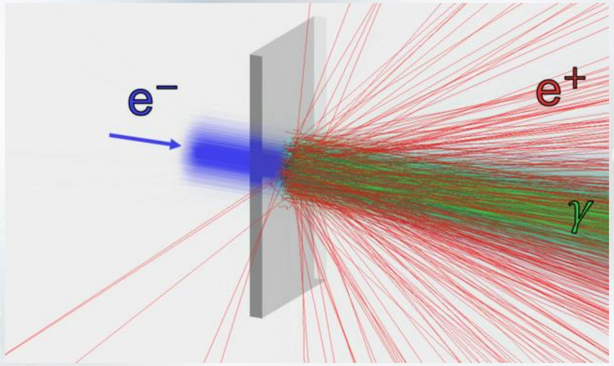
Two examples of beam size evolution in the transport line to achieve 250-and-1000-micron beam size at the target location





- ➢ No beam loss
- ➢ Range of available beam sizes at the target: 250 um - 1000 um →

Positron generation – Liquid GaInSn

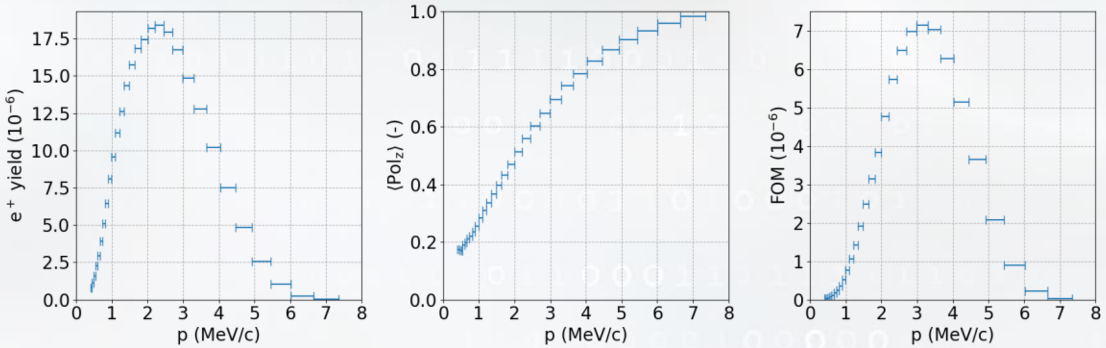


Simulations performed with Geant4

Outgoing positron data recorded at the downstream face of the target

Positron beam parameters of interest:

- Positron yield (ϵ)
- *Relative* longitudinal polarization (P_z)
- Figure-of-merit (ϵP_z^2)



Target properties

- Material: GaInSn eutectic
- Jet thickness: 3 mm (based on prototype)

Drive beam properties

- Kinetic energy: 8 MeV
- Transverse beam size (rms): 0.5 mm
- Current: 10 mA

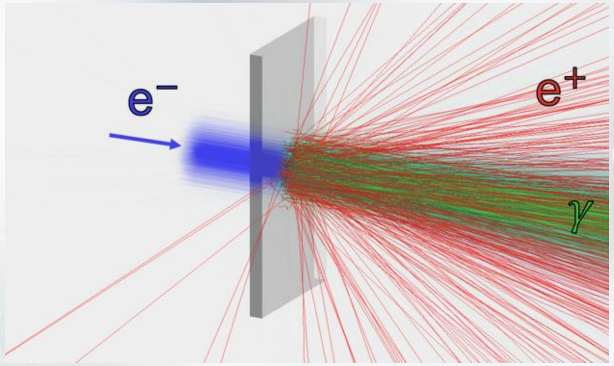
Parameter	Max Yield	Max FOM
p (MeV/c)	2.3	3.2
$\mathrm{Pol}_z(-)$	**50%**	**70%**
$\epsilon\ (10^{-6})$	18.4	14.9
$I_{e^+}(nA)$	**184**	**149**

Only cut on the momentum assuming an acceptance of $\pm 5\%$

No transverse cuts applied here, outgoing positrons have extremely high transverse emittance, i.e. overall useful current might be lower

Jet thickness can be optimized to actual collection system

Positron generation – Rotating tungsten



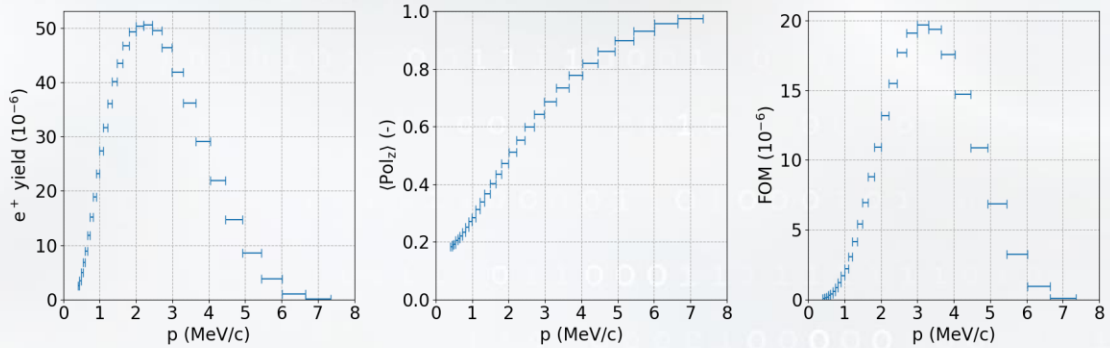
Simulated only one thin slab of the tungsten disk (wide and tall enough fit the full primary beam and secondary particles)

Target properties

- Material: Tungsten
- Target thickness: 2 mm (based on prototype)

Same drive beam properties

- Kinetic energy: 8 MeV
- Transverse beam size (rms): 0.5 mm
- Current: 10 m



Only cut on the momentum

- Assuming acceptance of $\pm 5\%$

Again, extremely high transverse emittance of outgoing positrons, no transverse cuts applied here

Target thickness can be optimized to actual collection system

Parameter	Max Yield	Max FOM
p (MeV/c)	2.3	3.2
$\mathrm{Pol}_z(-)$	**50%**	**70%**
$\epsilon\ (10^{-6})$	50.36	42
$I_{e^+}(nA)$	**503**	**420**

350 keV layout I

Preliminary beam line to test a photogun beam with a windowless target before adding a cryomodule

Test of the target heating with a low energy beam

Constraints:

Energy limited by the gun voltage ~350 kV

- No quarter cryomodules planned for these tests

10 mA maximum beam current

Buncher cavity not powered

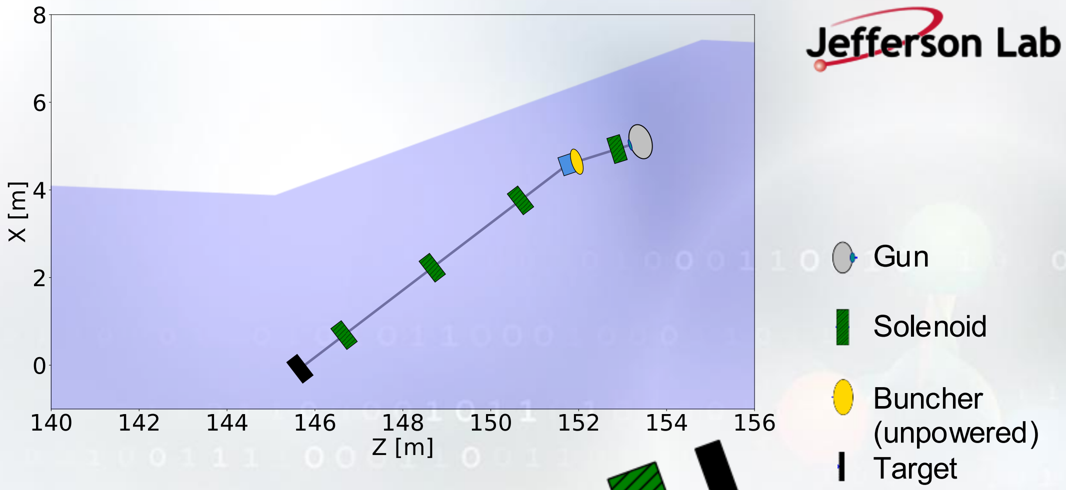
- Could be used in acceleration mode, but energy gain is very limited

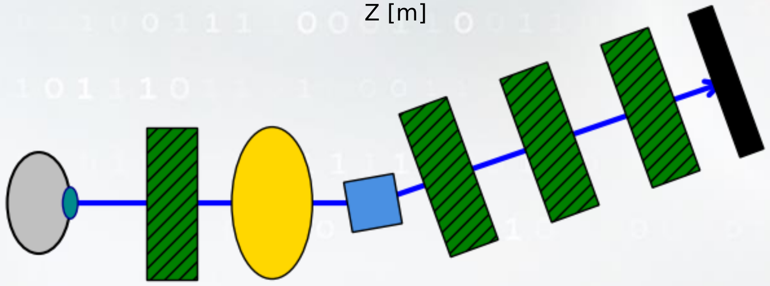
1 bending dipole for gun protection reasons

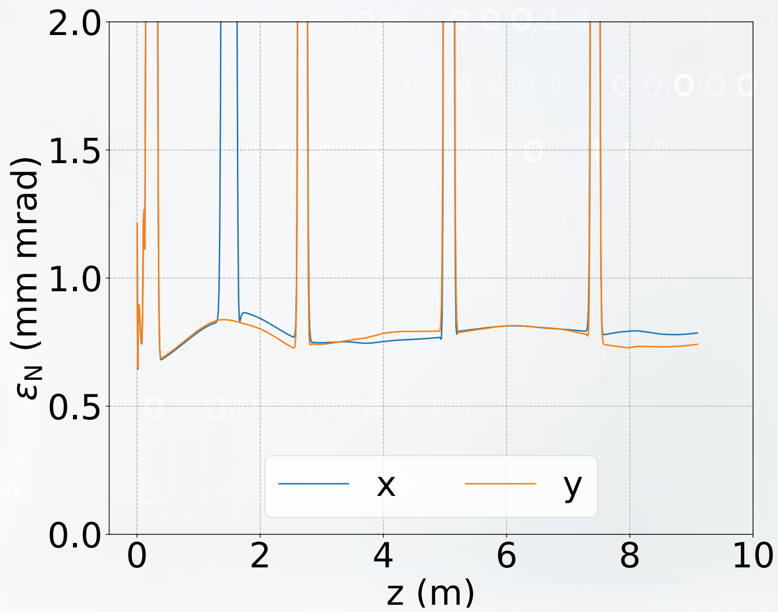
- Location is dependent on the available real-estate

Plenty of space for beam diagnostics along the way

➢ Solenoids suitable for controlling the transverse emittance growth, and focusing at the target location





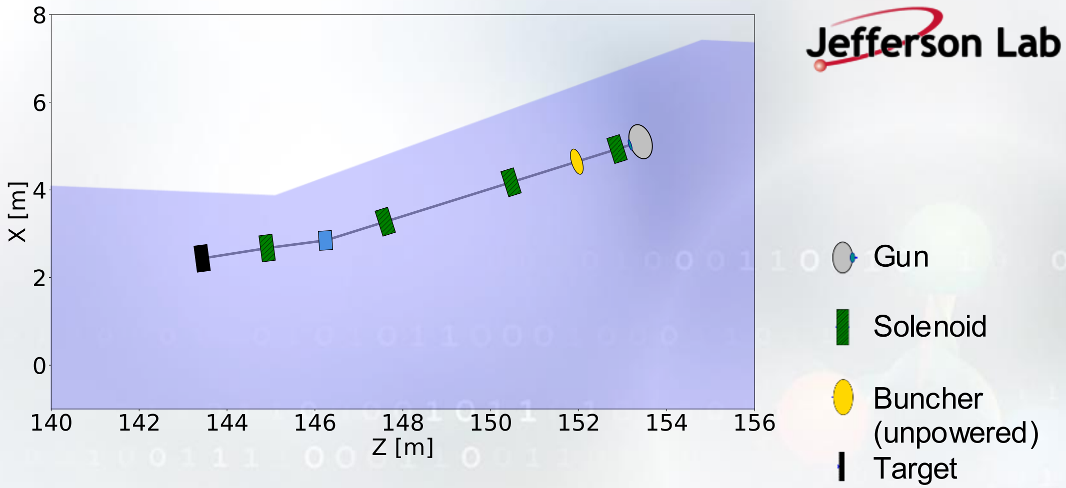


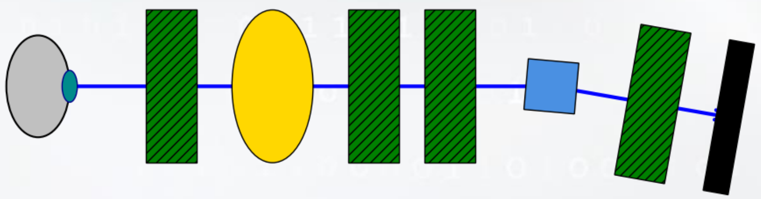
350 keV layout II

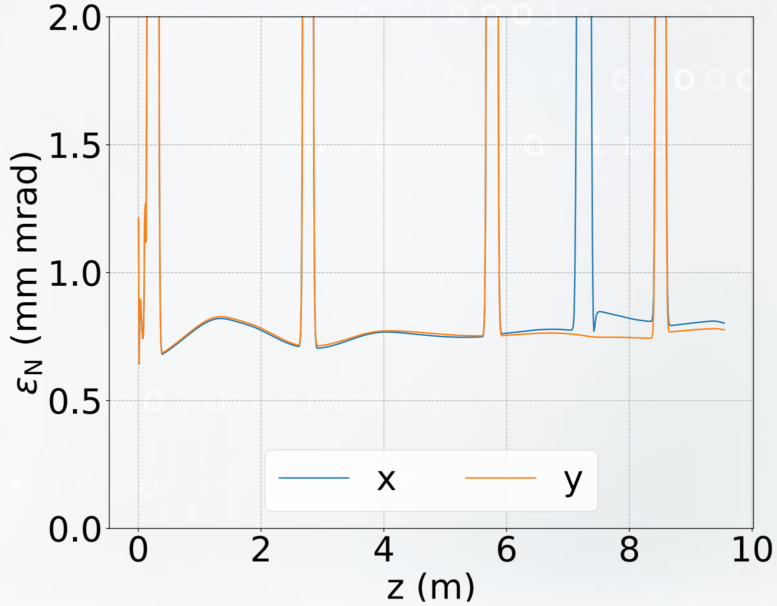
Alternative layout for spacing reasons

Same beam line components, this is an alternative where the bend is located further downstream with opposite bending angle

Any other bend location is possible too, provided there are ideally spaced solenoids in the beam line





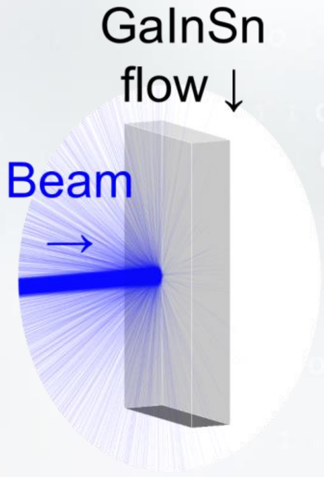


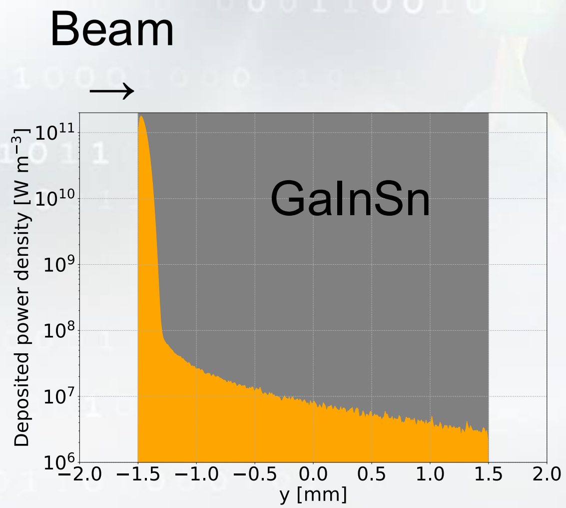
Preliminary low energy simulations

350 keV electron beam incident to 3 mm thick GaInSn jet

10 mA beam current -> 3.5 kW total beam power

- Most of the power is deposited near the surface of the liquid metal jet
- 78% of the beam power is deposited in the target
- 12.5% of the beam power is reflected back
- The rest of the beam power (9%) ends in the transverse (radial) direction
- Small amount of gamma radiation is created (~0.4% of beam power is transformed to gamma radiation)





Volume	Deposited e- power (W)	Deposited power (%)
Target	2730	78
Backwards	437	12.5
Forward	4	0.1
Transverse	315	9

Summary & further work

- Designed an 8 MeV beam line for a 10 mA current electron beam
- Implemented a framework to implement multiple objective optimizations in both GPT and Elegant with pymoo
- Expected **unpolarized** positron current 180 nA and 500 nA for 3 mm of GaInSn and 2 mm of Tungsten, respectively
- For **polarized** positrons, expected current is 150 nA and 450 nA for GaInSn and Tungsten, respectively
  - Target thickness needs to be optimized
  - Depending on the collection scheme, positron current will be further reduced as no transverse cuts were included here
- A 350 keV beam line for a 10 mA current beam is also feasible for commissioning of liquid GaInSn target

Further work

- Simulate full beam line in GPT for accurate spin tracking
- Study distribution of other secondary particle, as well as the expected energy deposition with an 8 MeV drive electron beam for both target designs
- Study effect of different bunch charges

Acknowledgments

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QUESTIONS?