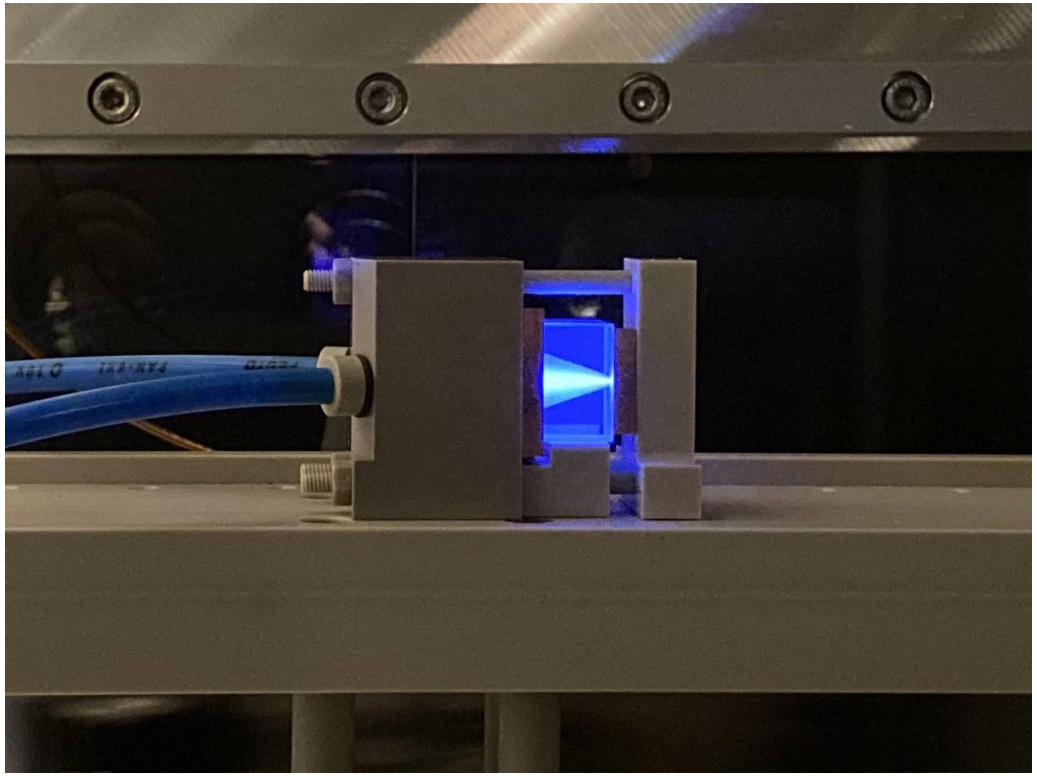
Update on plasma stability measurements of the prototype plasma lens for positron matching



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1: Universität Hamburg, 2: DESY Hamburg, 3: Berkeley Lab

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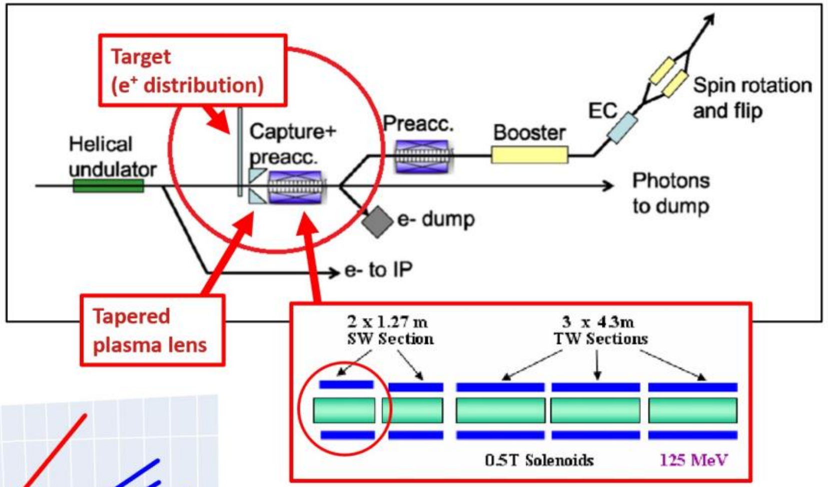
Motivation

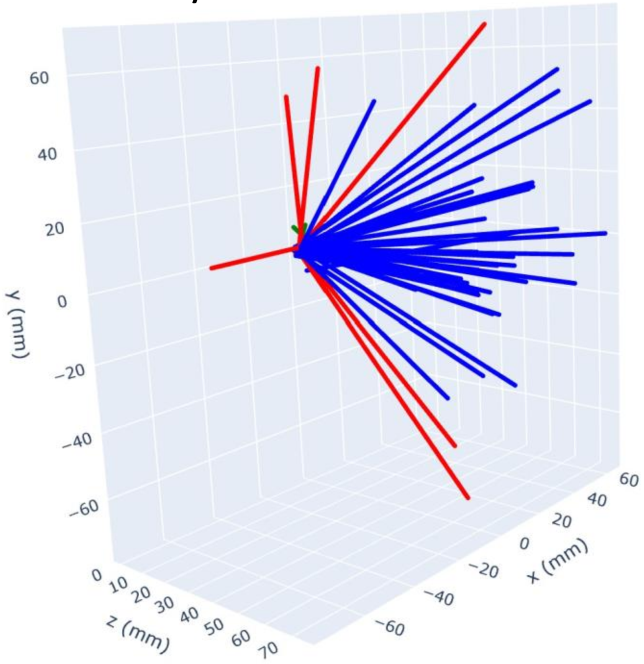
- Plasma lens development for undulator-based ILC positron source concept
  → fast rotating Ti wheel with incident high energy photons producing e+/e- pairs
- Alternative beam optics, as previous methods do not meet the requirements
  → Low positron yield or heat load on the target due to eddy currents



1) J.W. Wang, Positron Injector Accelerator and RF System for the ILC, 2007
2) F. Dietrich, Status of the undulator-based ILC positron source, 2019

Beam structure:

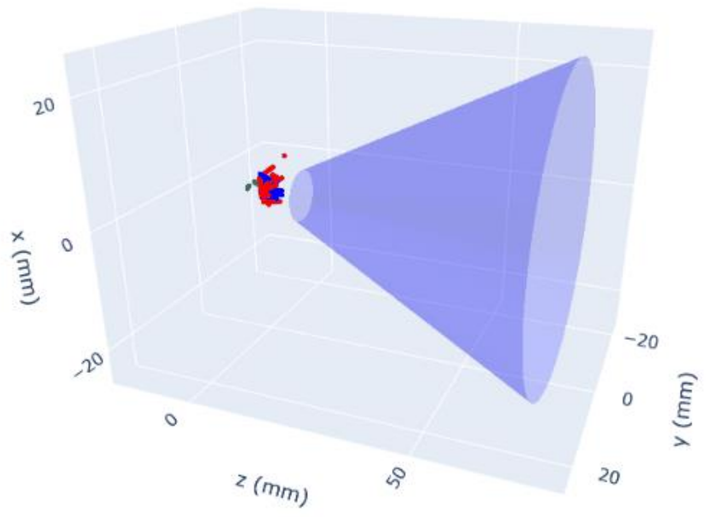
- Pulse repetition rate: 5 Hz
  → per pulse ~1300 bunches
- Bunch spacing: 554 ns
  → Repetition rate of plasma lens in MHz
- Average e+ energy: 6.1 MeV
- Energy spread: 4.8 MeV
- Divergence: 63.28 – 75.24 mrad



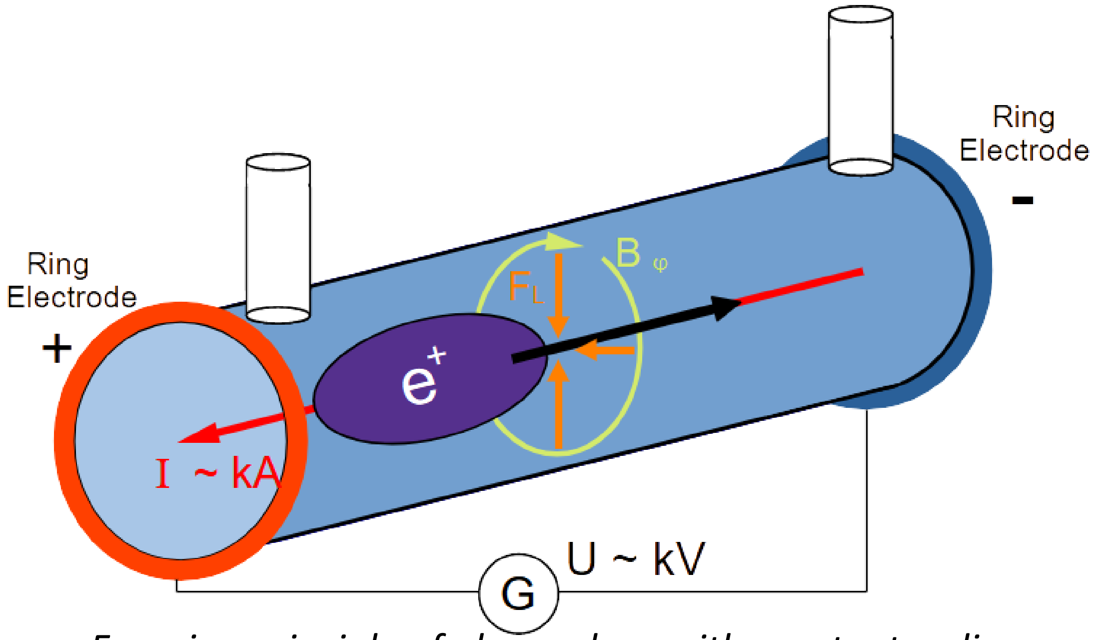
G. Moortgat-Pick, A. Ushakov: The ILC Positron Source
https://indico.cern.ch/event/356420/contributions/1764521/attachments/1132036/1618360/source-eps.pdf

Plasma lens - principle

- Azimuthal magnetic field component
  → No helical pathway of positrons
- So far mostly constant radius focusing channels are used
- Our case: Cone shape to adjust diameter to the envelope of the diverging beam



Particle tracks inside tapered plasma lens



Focusing principle of plasma lens with constant radius
I: Current, U: Voltage, G: HV Generator

- Direct focusing of positrons onto the beam axis
  → Broader energy acceptance than other positron matching devices

Development of own tracking code

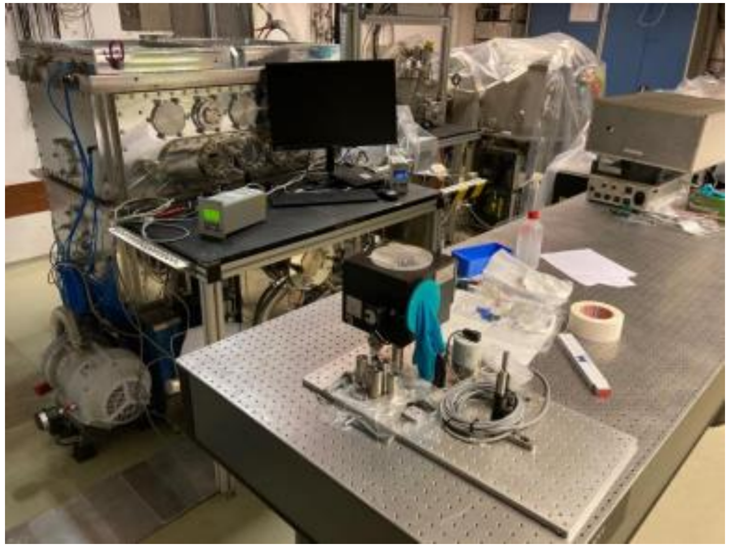
- Ongoing development of own tracking simulation specifically for plasma lenses
- Goal: 1) Automated optimisation of plasma lens parameters for arbitrary particle distributions with respect to different target parameters
  2) Simple implementation of different models of magnetic field/current distributions

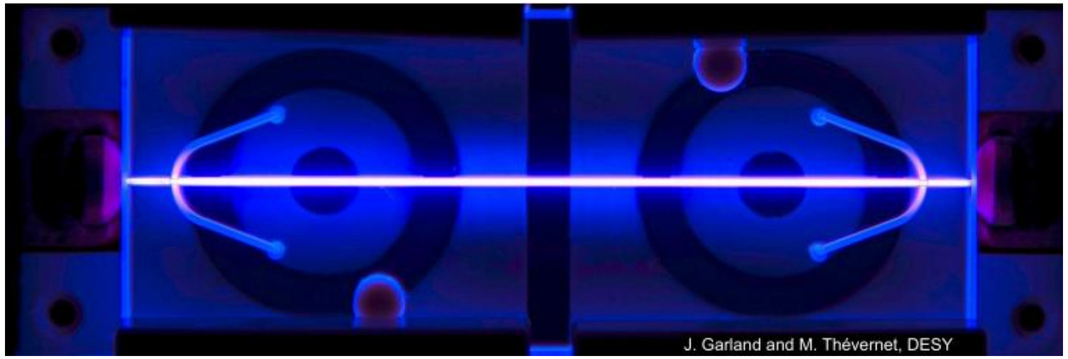
- Optimization based on Bayesian Optimization
- Already included: simple plasma lens model, constant solenoid and standing wave tube

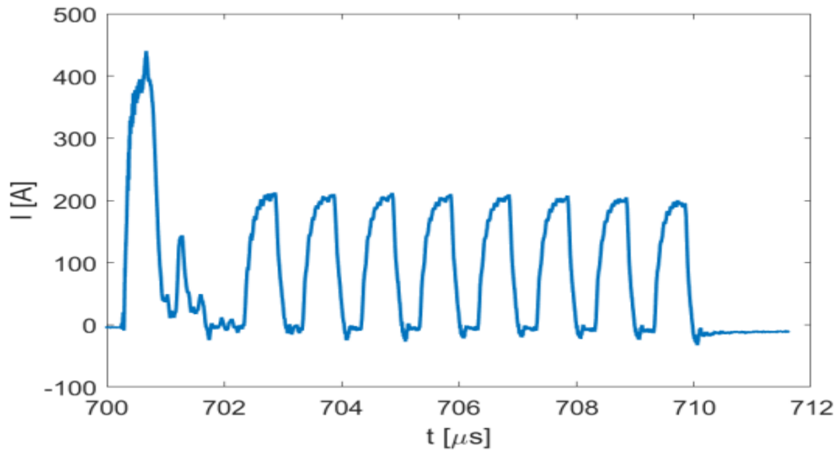
- Current status:
  → Bayesian Optimization already working for active particle count (with or without long. cut) of nonparallel simulations

ADVANCE laboratory at DESY Hamburg

- Already existing discharge plasma lab
  - → Diagnostics and infrastructure available
  - → Constantly in development
- Highly flexible vacuum chamber for plasma cells up to 1 m in length
- Multiple HV pulse modulators
- Optical emission spectroscopy and two-color laser interferometry
- On-site plasma source design and production







G. Loisch, Pulsed power electronics to drive plasma sources for future particle accelerators, Poster EAPPC

Down-scaling the prototype

- Future setup at ADVANCE Laboratory at DESY Hamburg
- Already existing vacuum chamber und MHz pulse modulator

  → Existing maximum current ~350 A

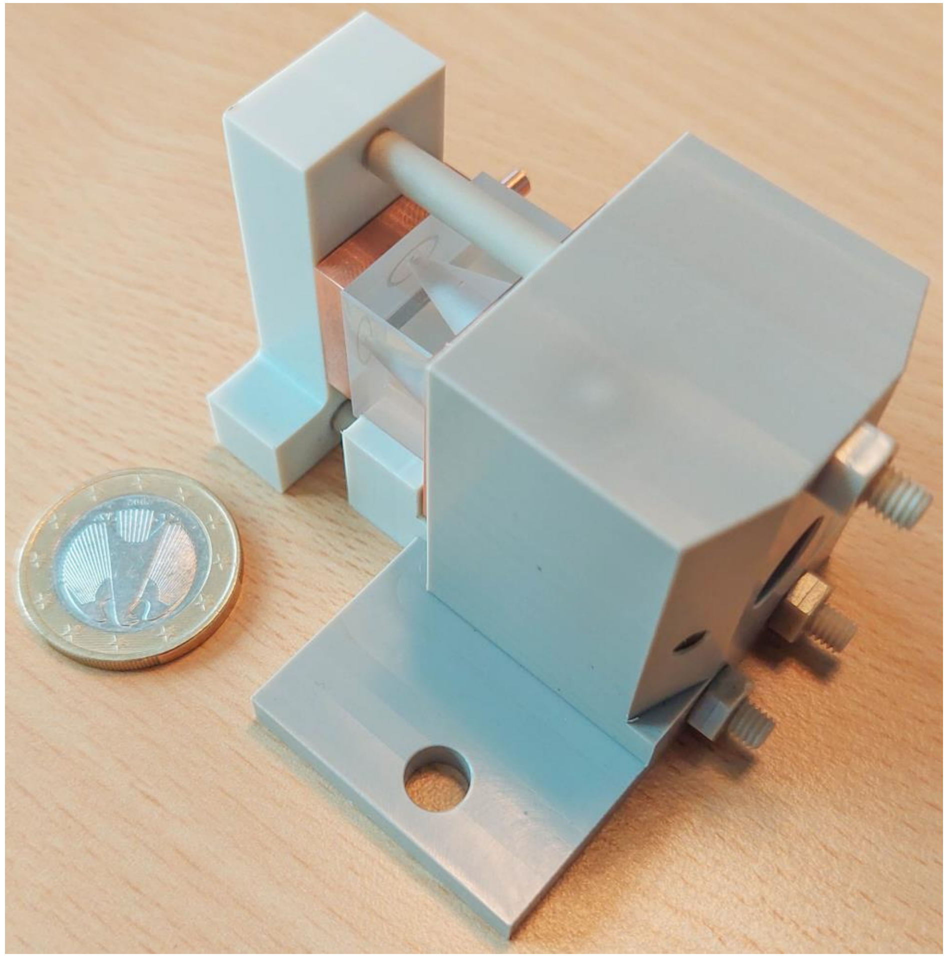
  → Max. leakage rate of 1.7 Pa · m^3/s results in max. mass flow rate of 2.72 ·10^{-5} kg/s (Argon)

- Same current density in prototype → Scaling dimensions of plasma lens
- Factor for scaling $b = \frac{\sqrt{9000A}}{\sqrt{350A}} \approx 5.07$

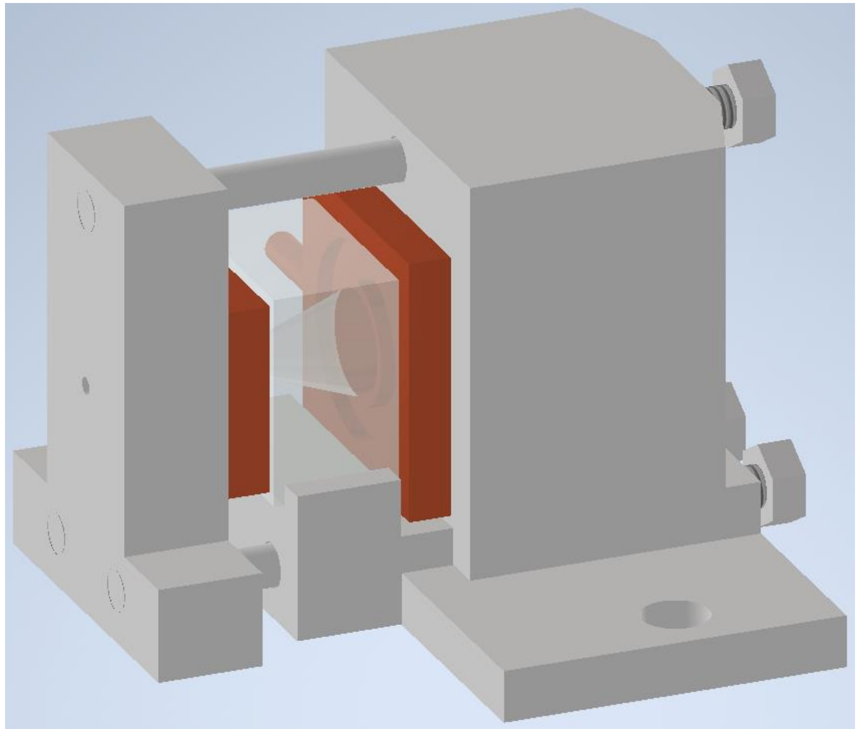
Peak current strength	I_0	350 A
Opening radius	R_0	0.848 mm
Ending radius	R_1	5.029 mm
Tapering parameter	g	0.416 mm^{-1}
Length	L	11.832 mm

Parameters of down-scaled plasma lens

Finished Prototype



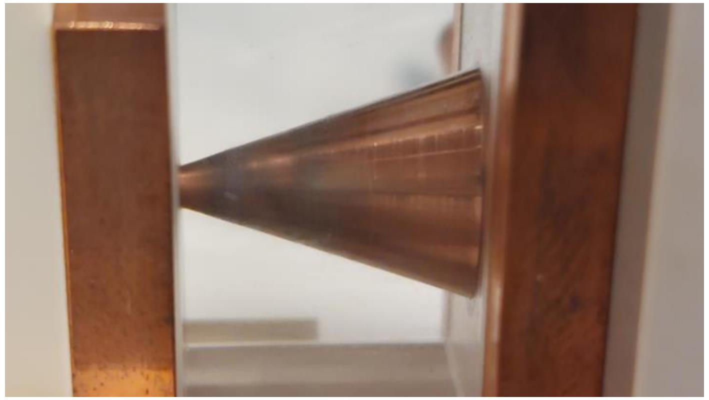
Assembled down-scaled plasma lens prototype



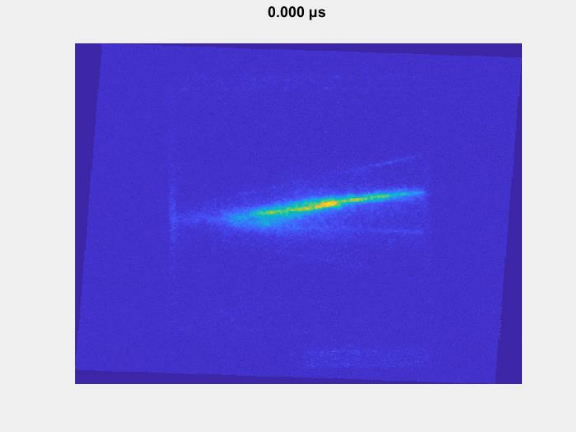
CAD drawing of assembled plasma lens set-up

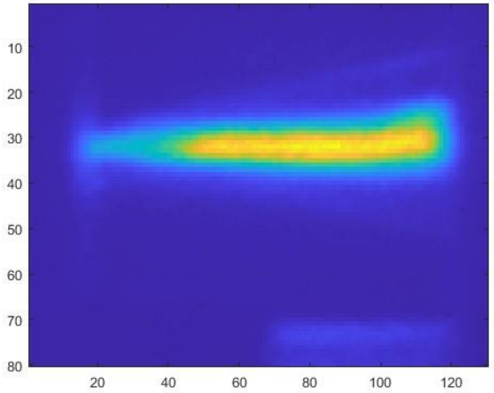
Observed problems

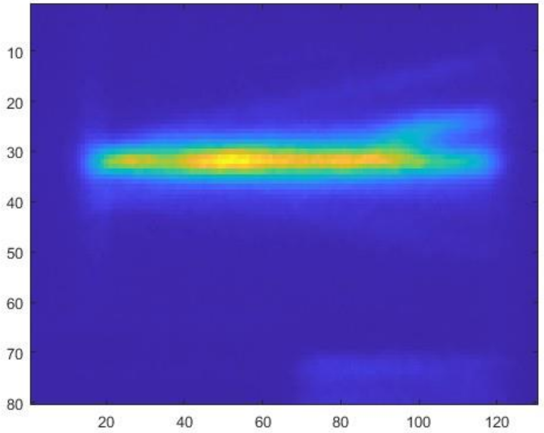
- Copper coating of the plasma lens
  - → Blocking light of plasma for the camera to detect
  - → Probably changing plasma/current distribution
- Discharge has unstabil behaviour under certain circumstances
  - → Splitting into two discharge channels
  - → Flickering of discharge channel towards positive y-axis
- Plasma production mainly around beam axis



Picture of coated plasma lens after 8 days of testing

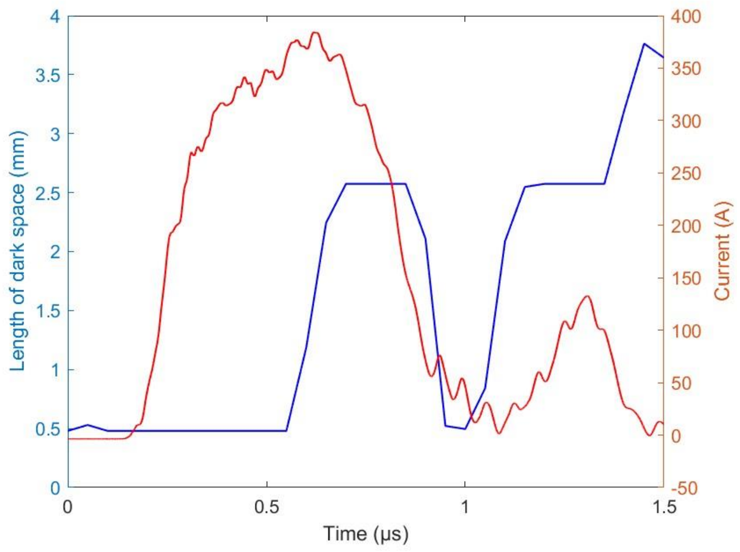






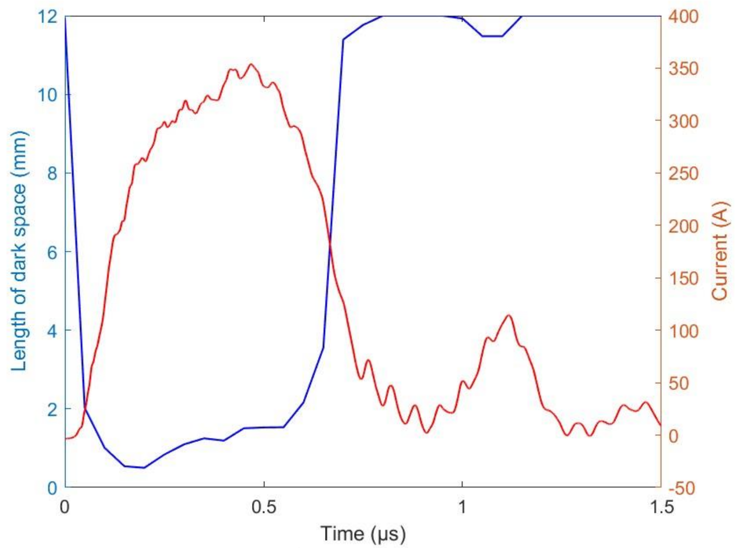
Coated surface comparison

- Measurements on 28.02 and 06.03. Approx.: 22.270 shots in between
- Parameters: Flow rate: 1.5 mbar*l/s, Cable pulser: 20 kV, 0 µs – 1.5 µs, Exposure 50 ns, 31 steps with 100 shots each
- Only difference: reversed electrodes
- Threshold for plasma light detection: 120
- First preliminary results, still time needed!



Data taken on 28.02.24

Copper coating shields light from being detected!



Data taken on 06.03.24

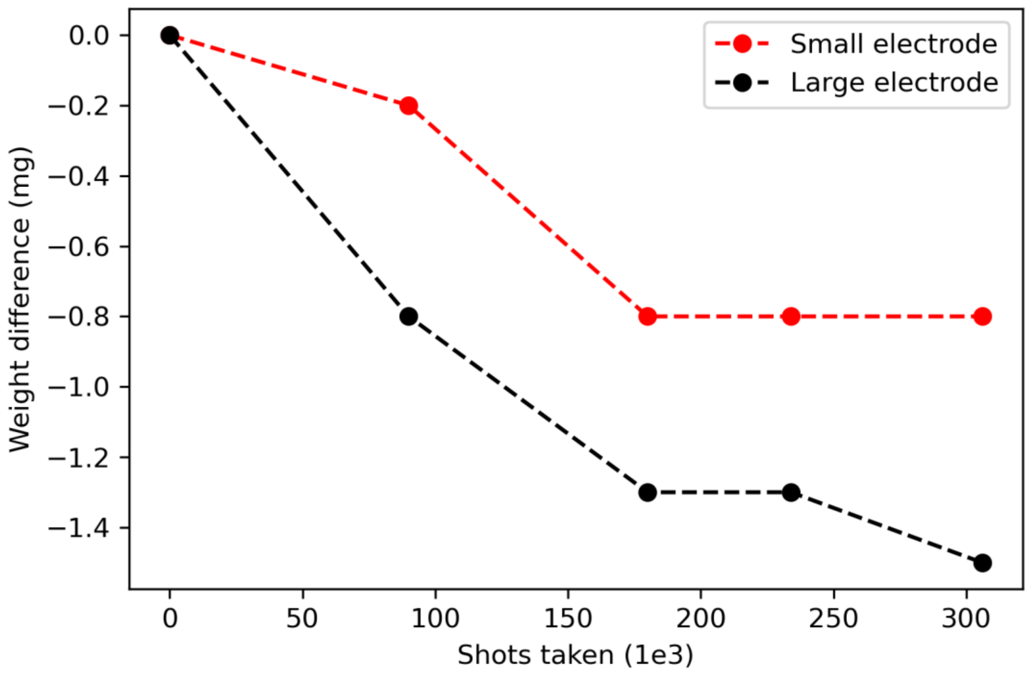
Total loss of copper material

- Longevity test of copper electrodes
- Operation time in total 1035 min (~300k shots)
- Parameters: Flow rate: 0.3 mbar*l/s, Cable pulser: 20 kV
- Weight measured after: 0, 90k, 180k, 234k, 306k shots

- Most signifikant change inside the first 180k shots
  → Possible conditioning of plasma cell/electrodes

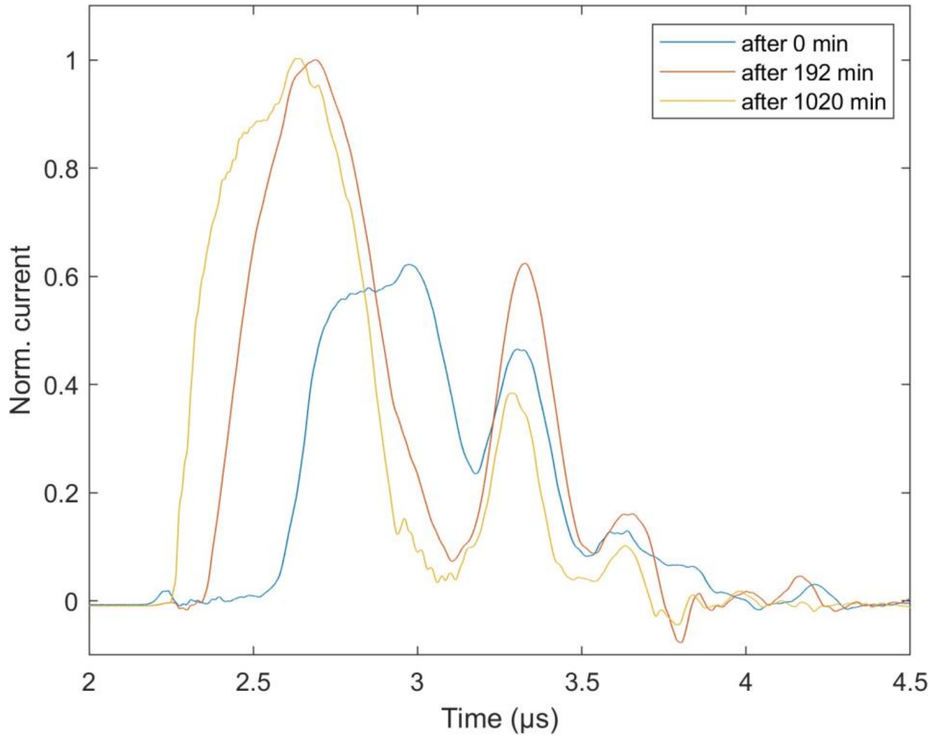
- Electrode erosion is probably pressure dependent
  → More measurements at different pressures

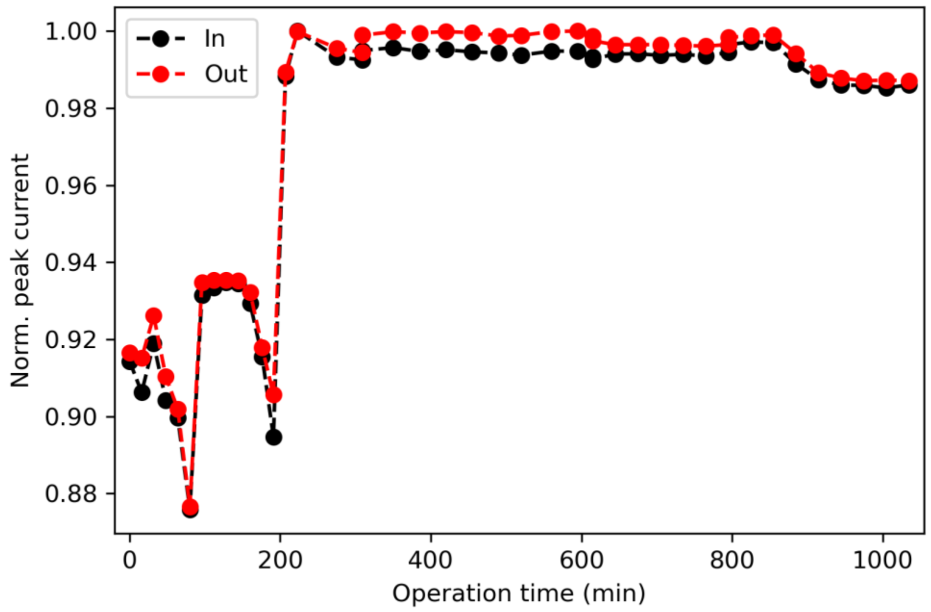
- Other dependencies have to be investigated (peak current, integrated current)



Change of electrical current

- Recording of ingoing and outgoing current every 15 min to 30 min
- Sudden increase of overall peak current after 200 min (~60k shots)



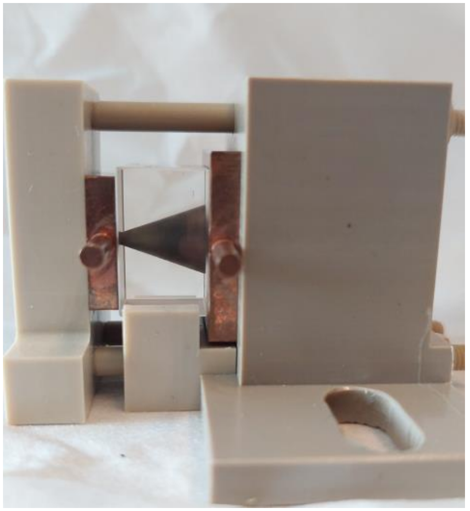


- Decrease of second peak after ~260 min

  → Reflection of current because of imperfect impedance matching

  → Possible change of resistivity inside plasma lens

Conclusion and outlook



- Plasma lens has high potential (positron yield up to factor 2 better than Quarter Wave Transformer)
- Operation down-scaled prototype for testing due to high requirements
- Ongoing BMBF grant for prototyping of plasma lenses for the ILC e+ source
- Tapered plasma lenses are largely unexplored
- High temporal resolution imaging at ADVANCE LAB at DESY ✓

→ Comparison of coated surface between 22.000 shots ✓

→ First measurements of copper electrode erosion ✓

→ Additional measurements to investigate dependencies (Pressure, Overall current, Tungsten-copper electrodes)

- Development of own particle tracking code ✓

Thank you for your attention!

References

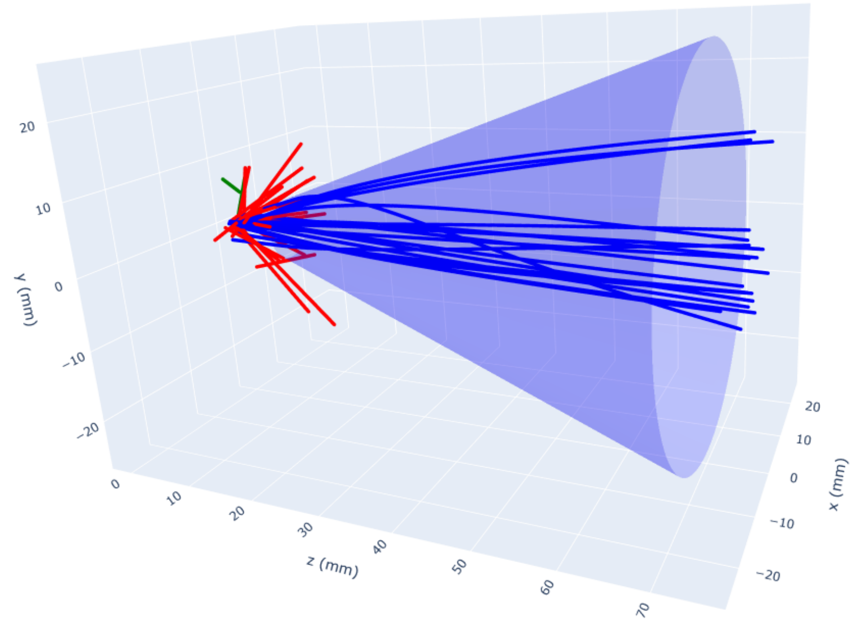
- M. Barish, B. Buesser, K. Adolphsen, C. Barone: Technical Design Report | Volume 3.I: Accelerator RD, 2013
- K. Flöttmann: ASTRA: A space charge tracking algorithm, 2017, https://www.desy.de/ ~mpyflo/
- J. W. Wang: Positron Injector Accelerator and RF System for the ILC, APAC 2007
- F. Dietrich: Status of the undulator-based ILC positron source, 2019
- M. Fukuda: private communication, 2019
- M. Fukuda, Development of Start-to-End Simulation for ILC positron sources, https://indico.cern.ch/event/727621/contributions/3114267/ POSIPOL 2018
- G. Loisch: Jitter mitigation in low density discharge plasma cells for Wakefield accelerators, 2019
- G. Loisch: Demonstrating High Transformer Ratio Beam-Driven Plasma Wakefield Acceleration, PHD thesis, 2019
- G. Moortgat-Pick, A. Ushakov: The ILC Positron Source https://indico.cern.ch/event/356420/contributions/1764521/attachments/1132036/1618360/source-eps.pdf
- M. Formela: Particle-Tracking-Based Optimizations of Plasma Lens Parameters for Optical Matching at the ILC Positron Source, Master thesis 2022
- N. Hamann: Design of a plasma lens test setup for optical matching at the ILC positron source, Master Thesis, 2022
- N. Hamann: Plasma Lens Prototype Progress: Plasma Diagnostics And Particle Tracking For ILC e+ Source, LCWS23, 2023

Beam parameters

- Beam current for 43k positrons: 0.08 mA
- Beam charge for 43k positrons: $6.9*10^{-6}$ nC
- Beam current for 1 pulse: 5.8 mA
- Beam charge for 1 pulse: 4204 nC

Particle tracking simulations with ASTRA

- Common positron distribution for ILC e+ source
- Simulations based on ASTRA code (K. Flöttmann)
- Simplifications: no space charge, homogeneous current density, no edge fields



- Energy acceptances

  → Longitudinal cut: ± 7 mm
  taken from M. Fukuda (ILC Positron Group)

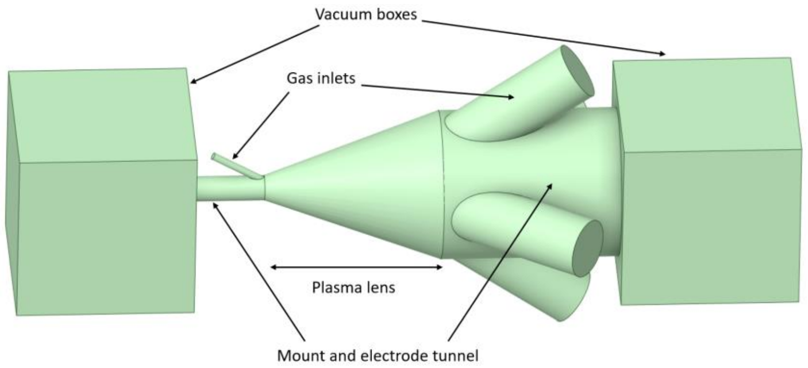
Positron Energy	5 GeV
Dynamic Aperture	<0.07 mrad
Energy Acceptance	0.75 %
Longitudinal Acceptances	3.4 x 37.5 cm-MeV
Longitudinal Emittance	0.75 x 33 % x mm

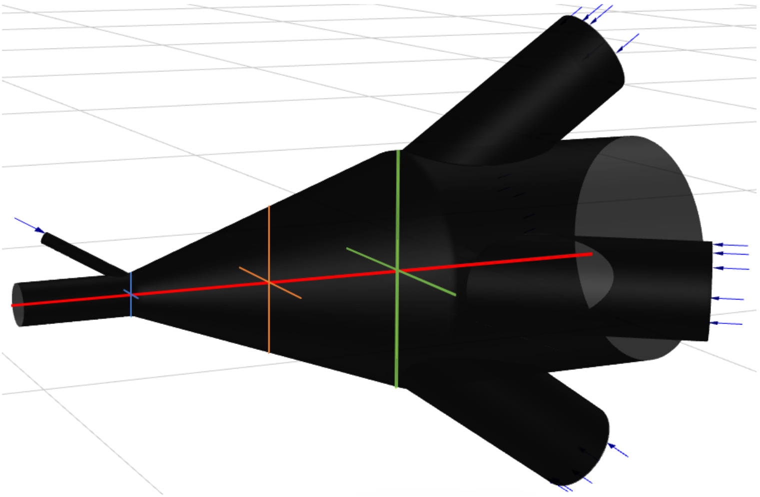
M. Barish B. Buesser K. Adolphsen, C. Barone: Technical Design Report | Volume 3.i: Accelerator RD, 2013

Gas flow simulations with ANSYS Fluent

- Influence of gas inlet geometry on gas distribution within plasma lens
- Goal: Pressure distribution as uniform as possible

- Simulations consists of plasma lens, gas inlets, extensions for electrodes and insulators and vacuum boxes for gas flow outside of plasma lens
- Target pressure: 50 Pa, mass flow rate: 2.4 $\cdot 10^{-5}$ kg/s (Argon)



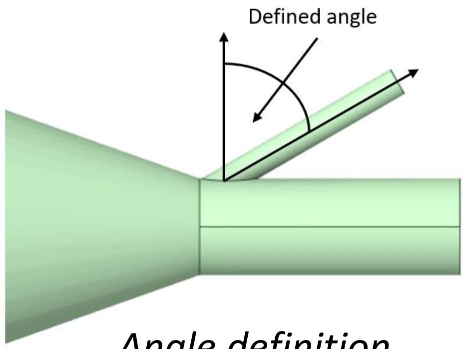


- Pressure profile along drawn lines
- X- and Y-axis show similar results
  → Only X-axis is shown

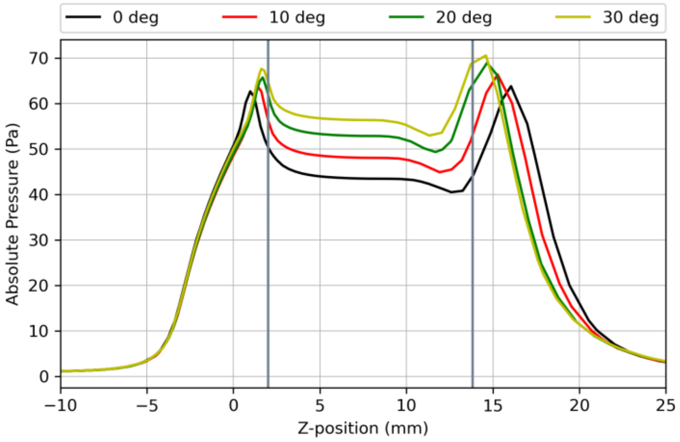
Angle of gas inlets

- Angle from 0 degrees to 30 degrees in 10 degree steps
- Four inlets with 2 mm diameter at the exit
- Two inlets with 0.48 mm diameter at the entry

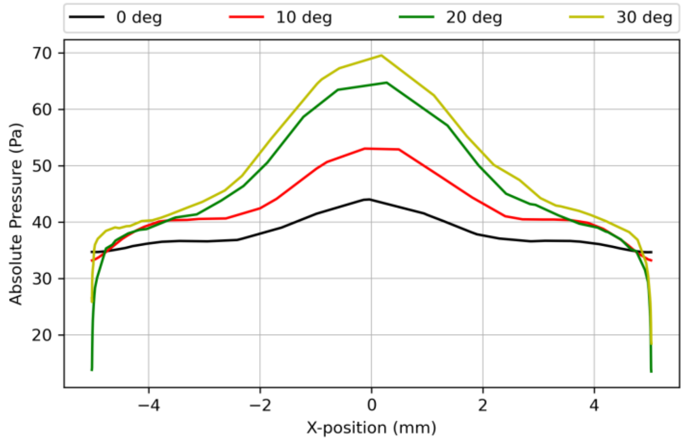
- Higher pressure in the plasma lens due to larger angles
  → Gas is shot directly into the plasma lens
- Gas accumulation in the extensions in front of and behind the plasma lens



Angle definition



Pressure profile along the Z-axis
Grey lines indicate the plasma lens

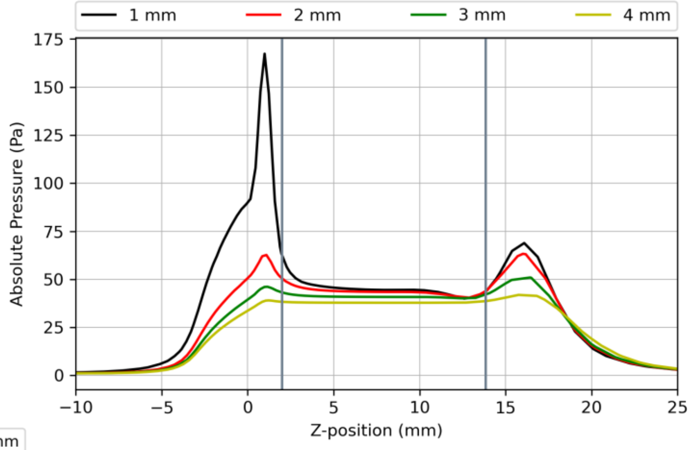


Pressure profile along the X-axis at the output

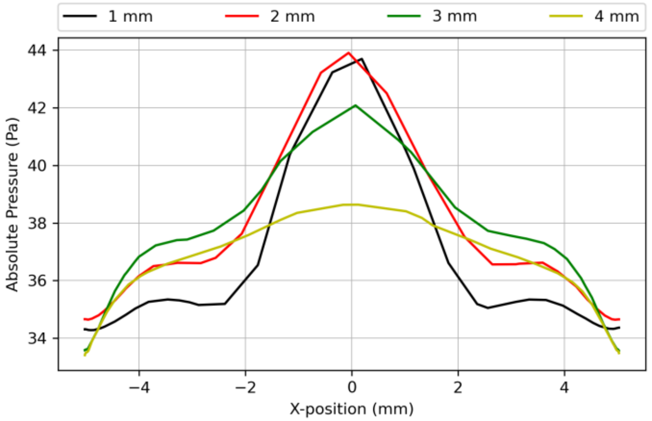
Gas inlet diameter

- Diameter of inlets at the exit from 1 mm to 4 mm in 1 mm steps
- No angles for all inlets (0 degrees)
- Four inlets at the exit and two 0.48 mm at the entry

- Larger diameters lead to lower pressure in the plasma lens
- Larger diameters distribute the gas accumulations more evenly
- Gas pressure at the entry can be modulated by inlets at the exit



Pressure profile along the Z-axis



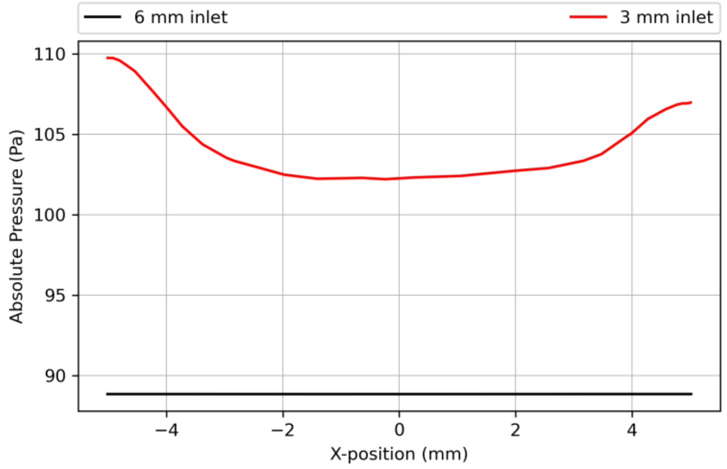
Pressure profile along the X-axis at the exit

Design simplification for prototype setup

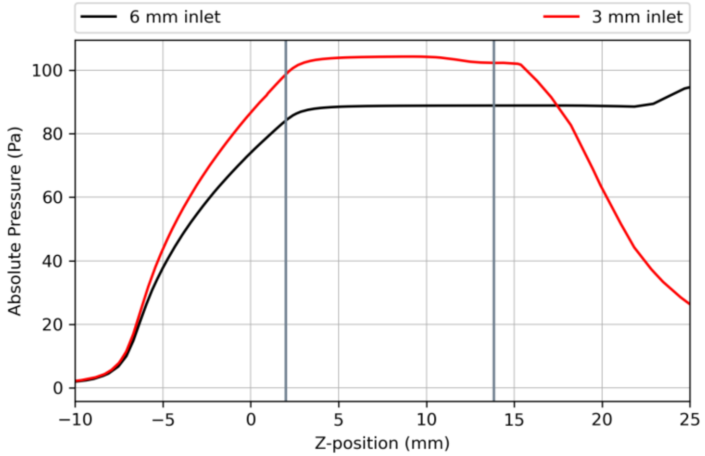
- Goal: Adapt structure to laboratory and manufacturing conditions
- No inlets at the entrance (too small)
- Fewer inlets
- Target pressure adjusted to 100 Pa for lab environment
- Mass flow rate $2 \cdot 10^{-5}$ kg/s for Argon

- No inlets at the entry
- 2 inlets at the exit
- Angle: 70 degrees
- Two versions: 6 mm and 3 mm diameter, same mass flow rate

- 3 mm achieve higher overall pressure
- 6 mm more even distribution along the Z-axis



Pressure profile along the X-axis at the exit

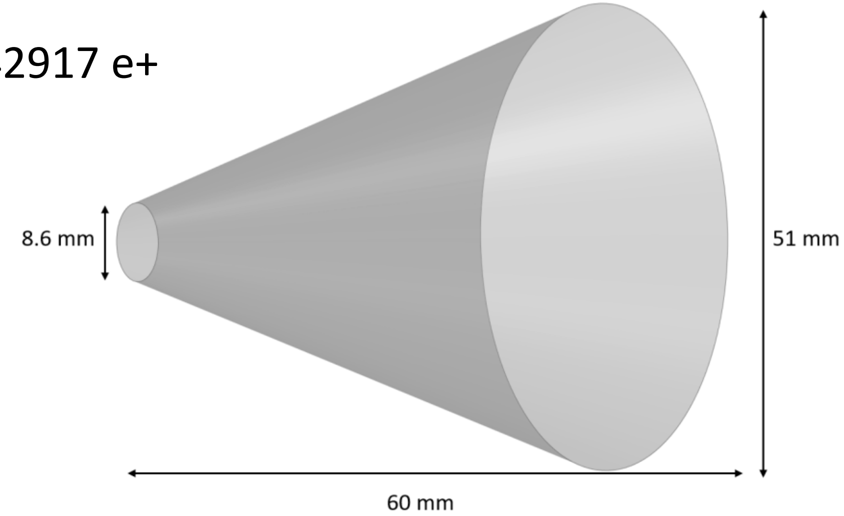


Pressure profile along the Z-axis

Particle tracking simulation results

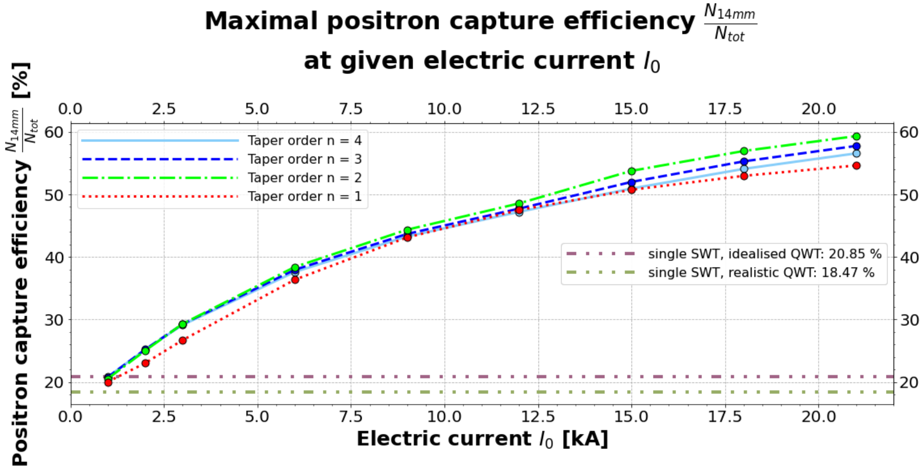
- Result: After long. cut (14 mm) 44.35 % capture efficiency of 42917 e+
- Highest currents produce highest capture efficiency

  → current limited to ~9kA to reduce electrode erosion

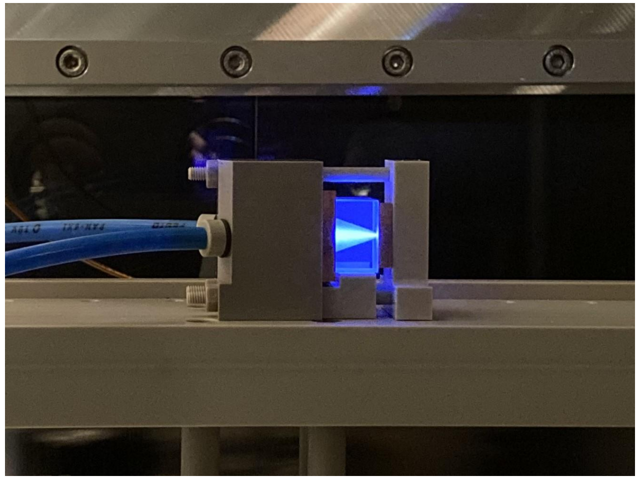


Sketch of the optimal design

Parameter name	Symbol	Optimal Value
Plasma Lens Length	z_{max}	$60\,\mathrm{mm}$
Opening Radius	R_0	$4.3\,\mathrm{mm}$
Tapering Order	n	2
Tapering Strength	g	$0.082\,\mathrm{mm}^{-1}$
PL-SWT distance	d	$10\,\mathrm{mm}$
SWT Phase	φ_0	$225\,\mathrm{deg}$
Current strength	I_0	$9\,\mathrm{kA}$



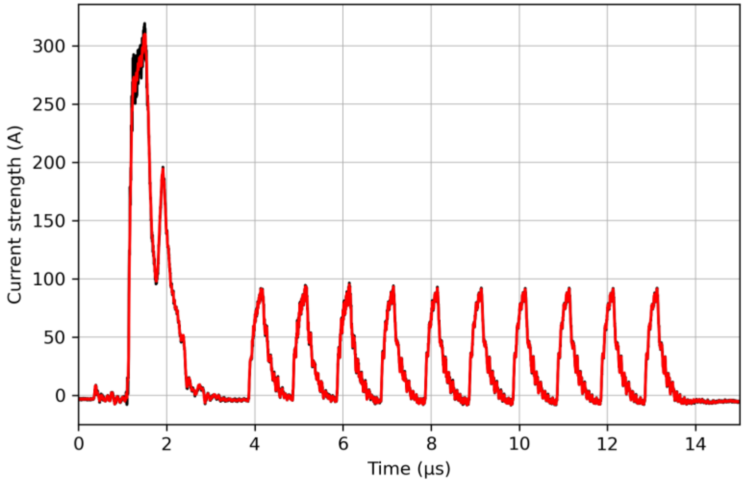
Update on the latest tests



- Used gas: Argon
- Flow rates: 0.2 mbar*l/s – 1.5 mbar*l/s
- Cable pulser: 20 kV
- Glow discharge: < 5 kV
- ICCD exposure time: 50 ns

- Measurements taken:
  → Plasma development from 0 µs – 1.5 µs taken at different flow rates
  → Comparison of plasma development with glow discharge
  → Long time plasma evolution up to 4 µs
  → Plasma stability with reversed electrodes
  → Breakdown voltage for different flow rates

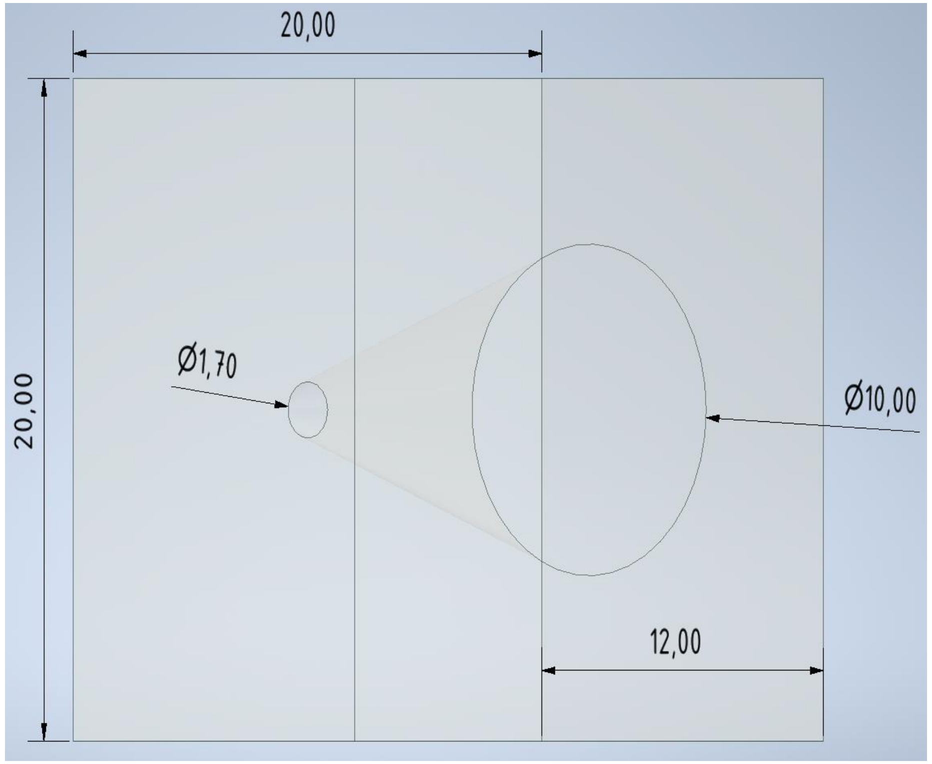
<u>Detailed analysis still ongoing!</u>



Technical design concept – gas cell

- Mounts for fixating positions of plasma lens and electrodes made out of PEEK
- Electrodes made out of copper
- Plasma lens made of 20 mm x 20 mm x 12 mm sapphire block
- Principle: lens is pressed in between PEEK mounts with threaded rods and sealed with O-rings

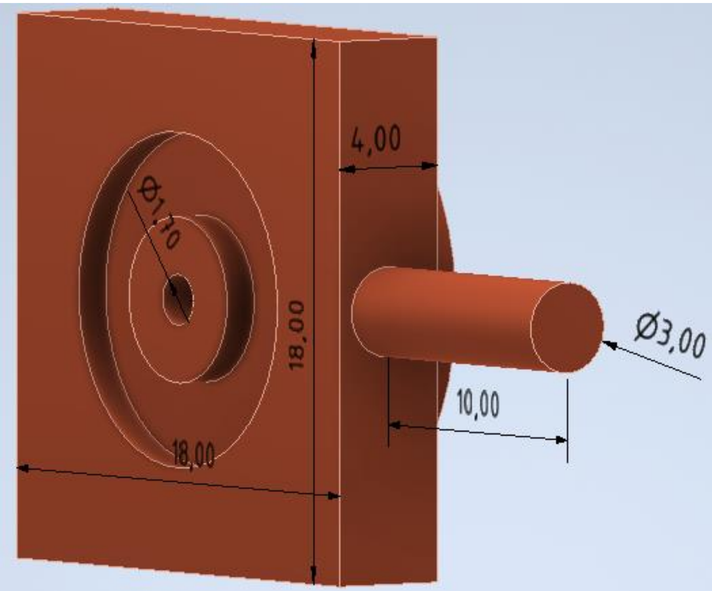
- All specifications of technical designs noted in mm



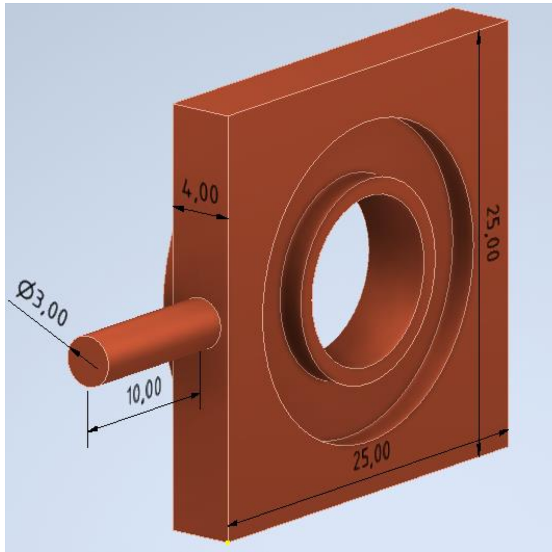
Plasma lens

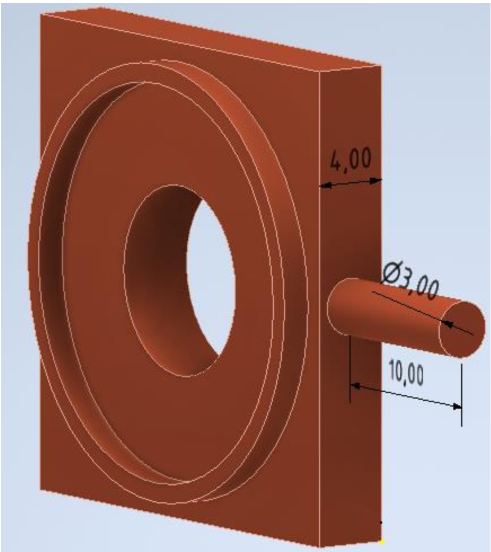
Technical design concept - electrodes

- Electrodes with central hole
  → Diameter 1.7 mm and 10 mm
- Groove for O-ring with 1.5 mm and 2 mm cord thickness
- Ring extensions placed into red groove of PEEK mounts
- Pins for connecting the electrodes



Electrode at the entry

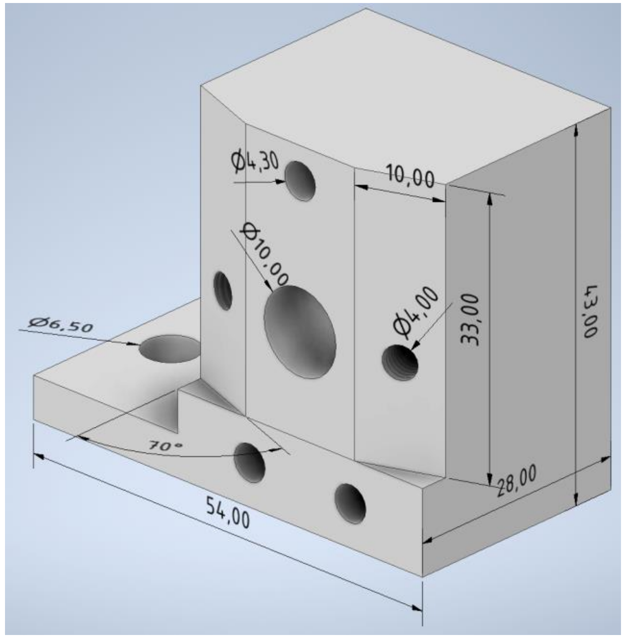


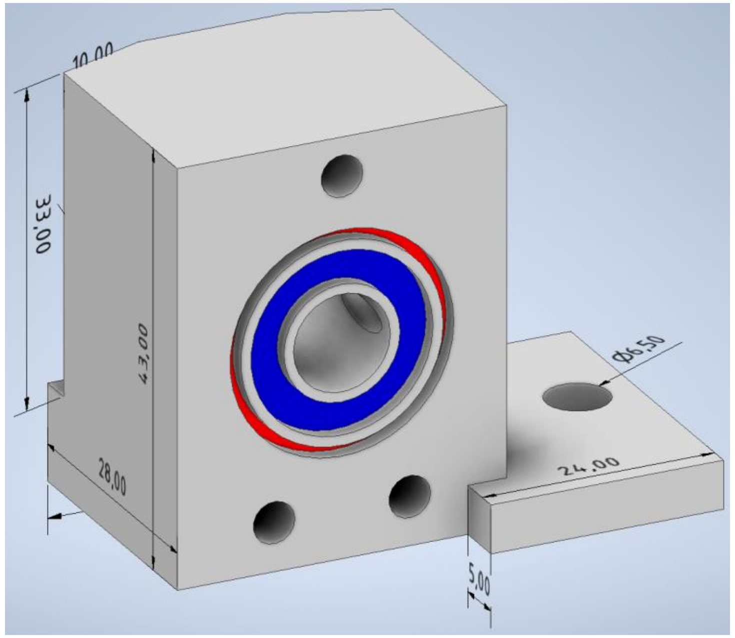


Electrode at the exit

Technical design concept – gas supply

- Mount at entry, exit and bottom of plasma lens
- 3 mm gas inlets on bevelled edges with 70 degrees
- Blue groove for O-ring with thickness of 2 mm
- Red groove for positioning the electrode



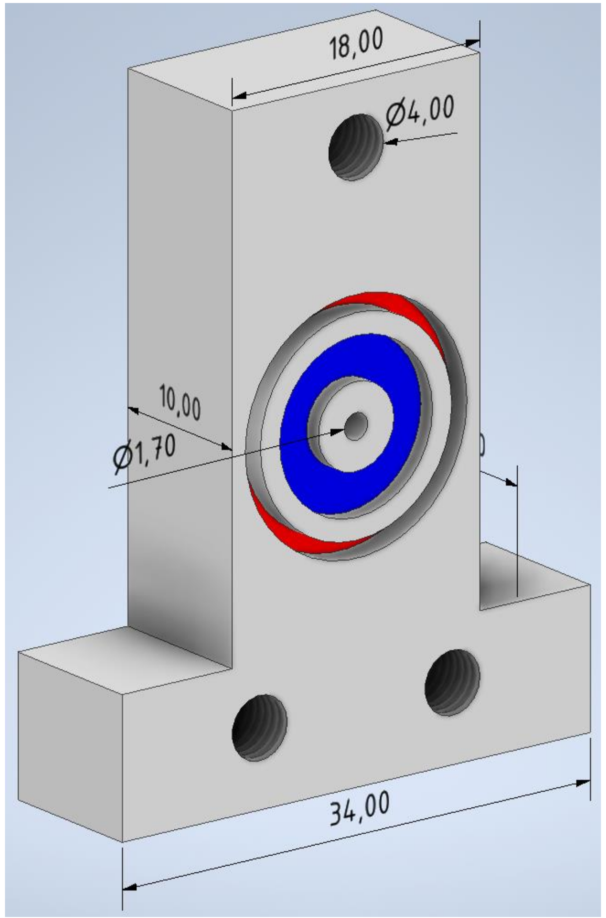


Mount at the exit with gas inlets

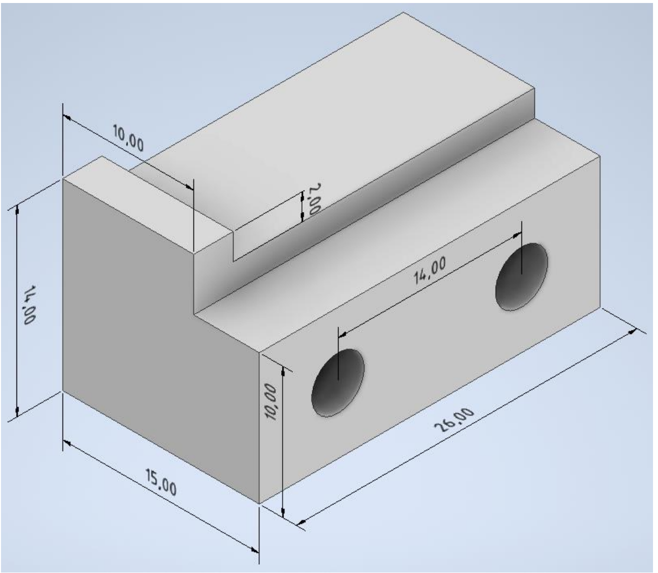
Technical design concept - support

- Mount with the same concept as at the exit
  → Exception: no gas inlets

- Edge on bottom mount to fix position of plasma lens
- Bottom mount should not touch electrode
  → Would over-define position
- Blue groove for O-ring with thickness of 1.5 mm
- Red groove for inlet of electrode



Mount at the entry



Mount below the plasma lens