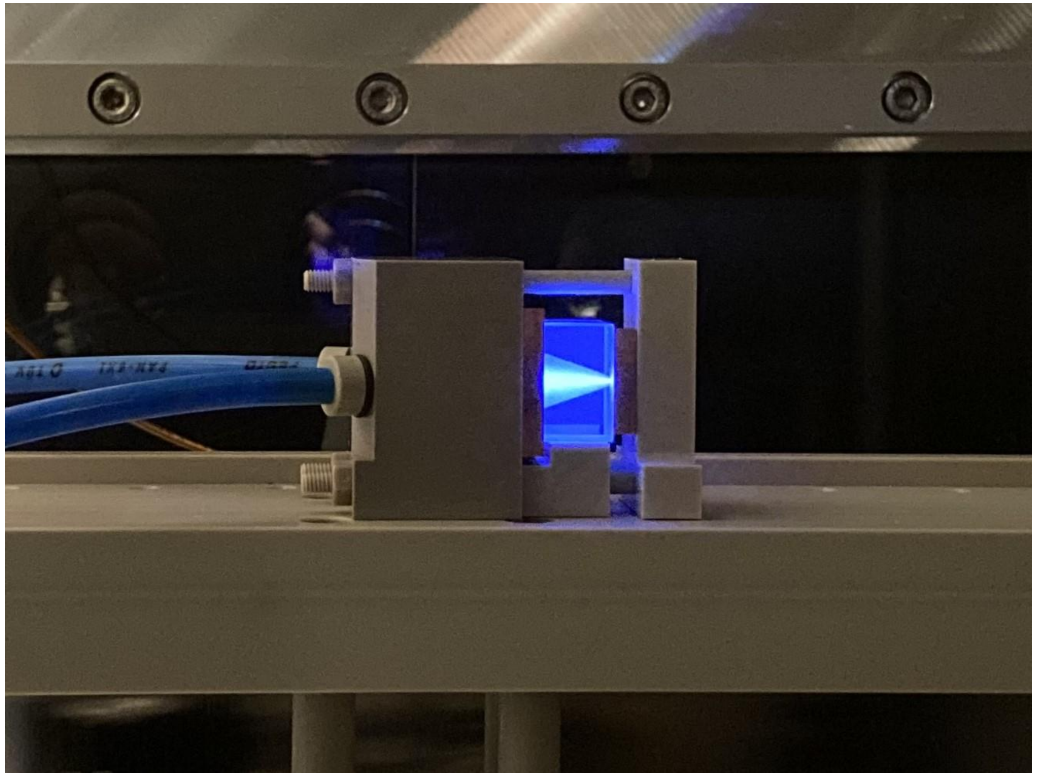
Longevity Measurements Of A Prototype Plasma Lens For Positron Matching



N. Hamann[1], M. Formela[1], G. Loisch[1], K. Ludwig[1], S. Wesch[1], J. Wood[1], G. Moortgat-Pick[1,2]

1: DESY Hamburg, 2: Universität Hamburg

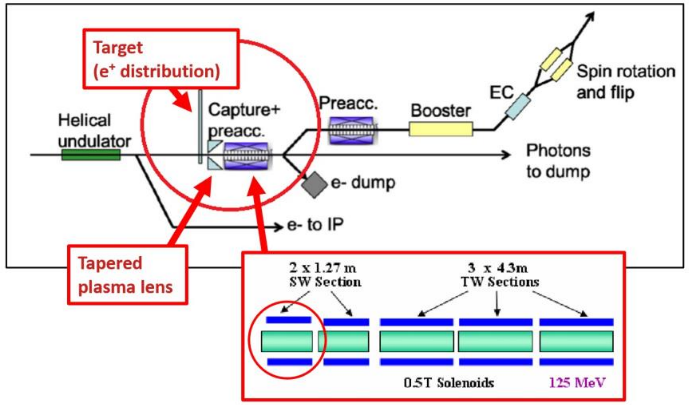
niclas.hamann@desy.de

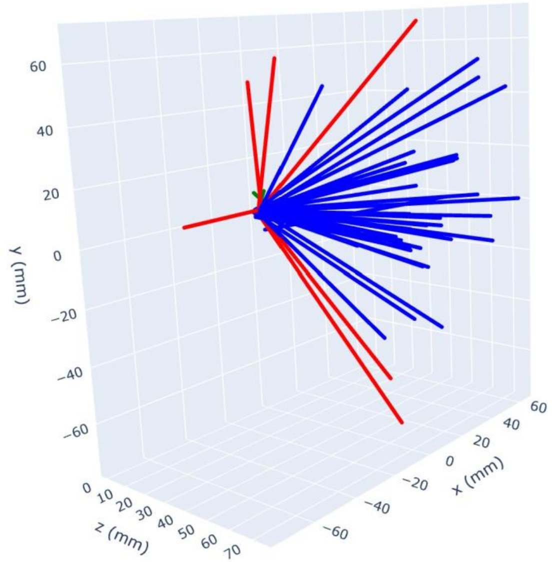
Motivation

- Positron sources are essential for future e+e− colliders
  - → Typically yield low-energy, highly divergent positron beams
  - → Unsuitable for immediate acceleration without beam focusing

- Optical Matching Device Challenge
  - → Quarter wave transformer: insufficient e+ capture, target heating issues
  - → Flux concentrator: unstable yield over bunch train length

- New Alternative: Active Plasma Lens





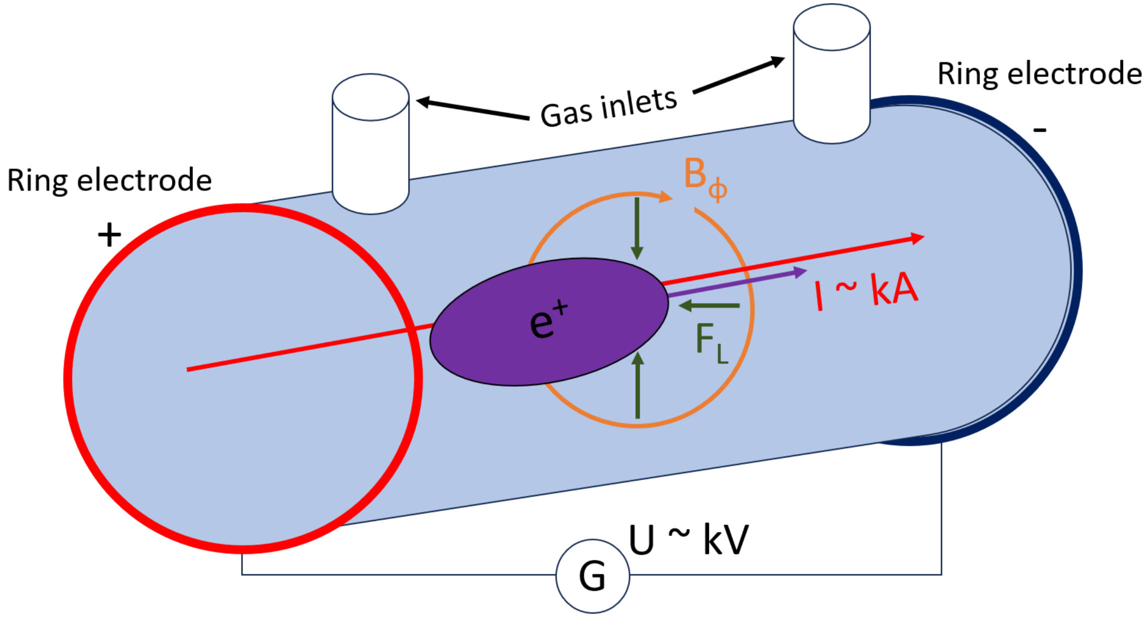
1) J.W. Wang, Positron Injector Accelerator and RF System for the ILC, 2007
2) F. Dietrich, Status of the undulator-based ILC positron source, 2019

Plasma lens - principle

- Capillary filled with gas
- Current applied to electrodes ionizes the gas
- Density of current induces magnetic field

- Azimuthal magnetic field component
  → Direct focusing of positrons onto the beam axis

- Broader energy acceptance than other positron matching devices



Focusing principle of plasma lens with constant diameter
I: Current, U: Voltage, G: HV generator

Plasma lens prototype design

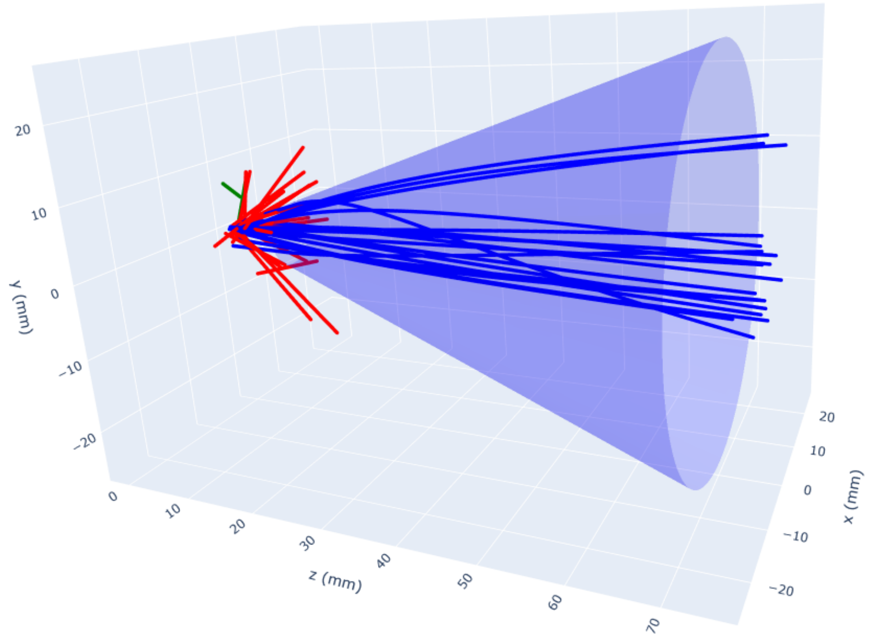
- Optimized ASTRA particle tracking simulations
- Divergent positrons need to be shaped to parallel beam

- Cone shape to optimize the magnetic field as the diameter follows the beam diameter

- Test stand at DESY Hamburg (ADVANCE Lab)
- Downscaling of prototype to fit available peak current
  → Downscaled by a factor of 5.07

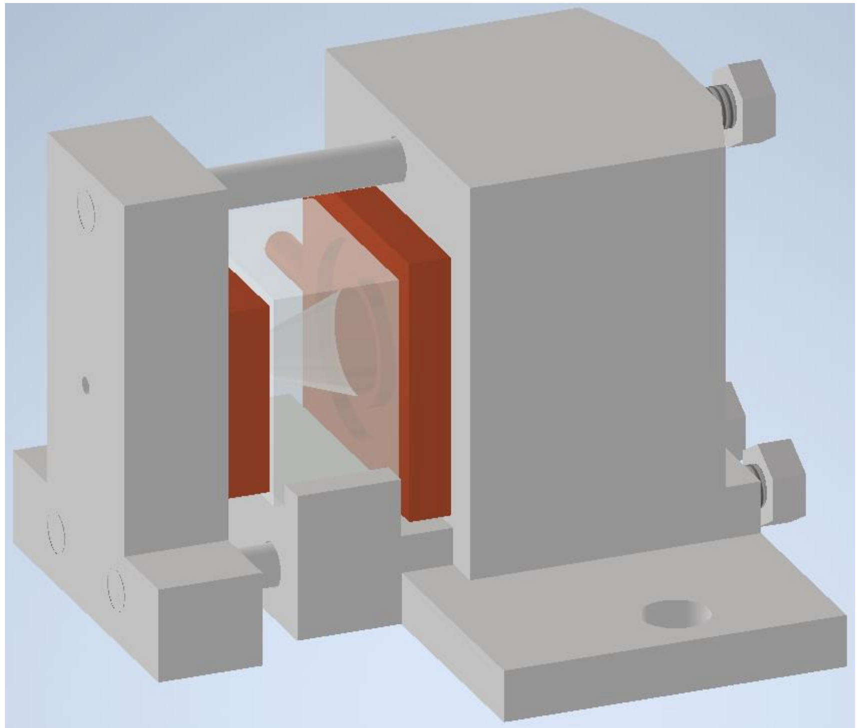
Peak current strength	I_0	350 A
Opening radius	R_0	0.848 mm
Ending radius	R_1	5.029 mm
Tapering parameter	g	0.416 mm^{-1}
Length	L	11.832 mm

Parameters of downscaled plasma lens.

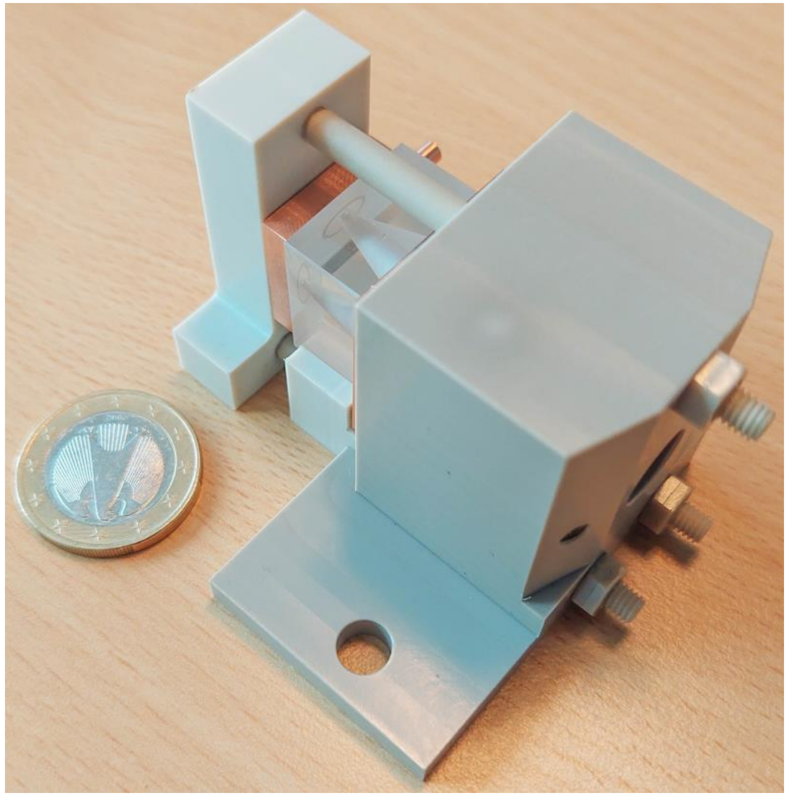


Positrons tracks inside plasma lens. Blue positrons are captured, red are lost and green are traveling backwards.

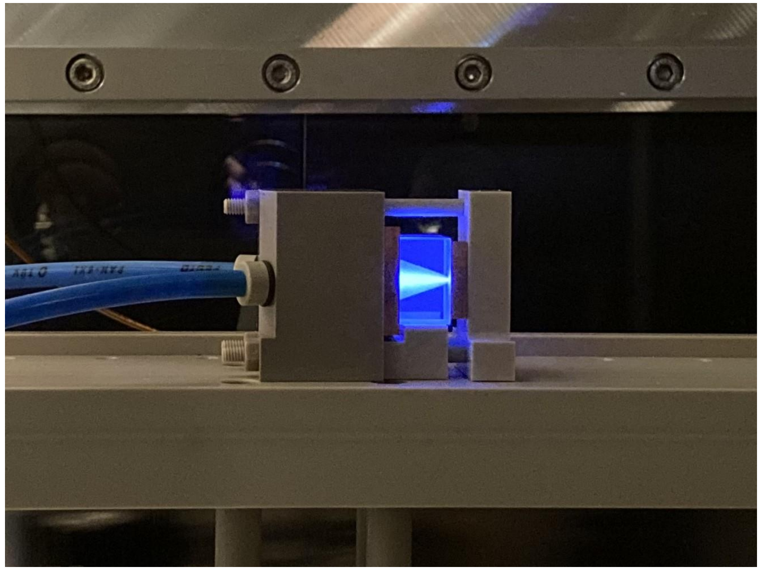
Finished Prototype



CAD drawing of assembled plasma lens set-up.



Assembled plasma lens prototype.

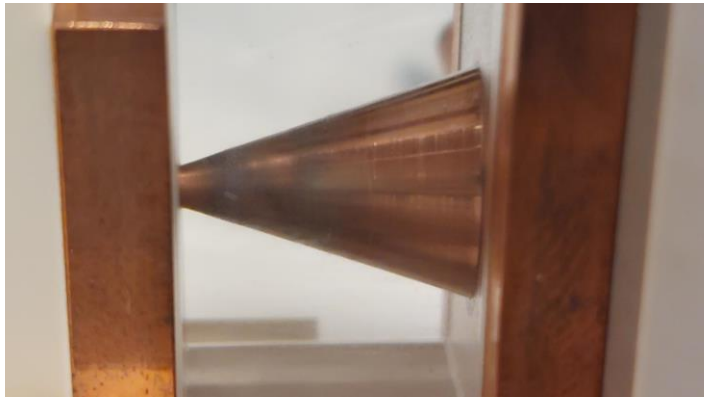


Prototype during operation.

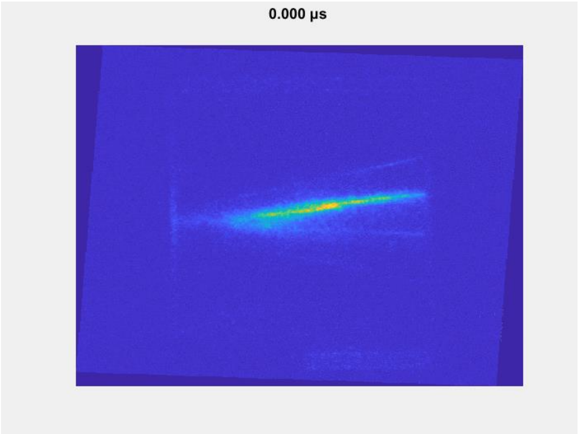
Observed issues

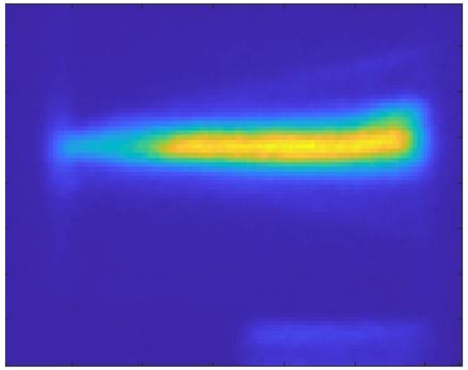
- Discharge has unstable behaviour under certain circumstances
  → Splitting into two discharge channels
  → Bending of discharge channel

- Copper coating of the plasma lens
  → Blocking light of plasma for the camera to detect
  → Probably changing plasma/current distribution

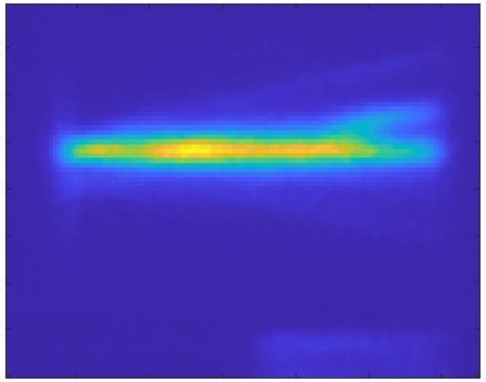


Picture of coated plasma lens after around 90 mins of operation.





Bending of discharge channels.



Splitting of discharge channels.

Electrode longevity studies

- 4 different measurement runs
  - Pure copper
    → Low pressure at flowrate of 10 mln/min
    → Middle pressure flowrate of 80 mln/min
    → High pressure flowrate of 160 mln/min

  - Tungsten/Copper (W-Cu-alloy) electrodes (30/70)
    → High pressure at flowrate of 160 mln/min

- Each run: 20 total hours operation, weight in every 5 hours
  → Used scale has accuracy of 0.1 mg (Sartorius New Entris II)

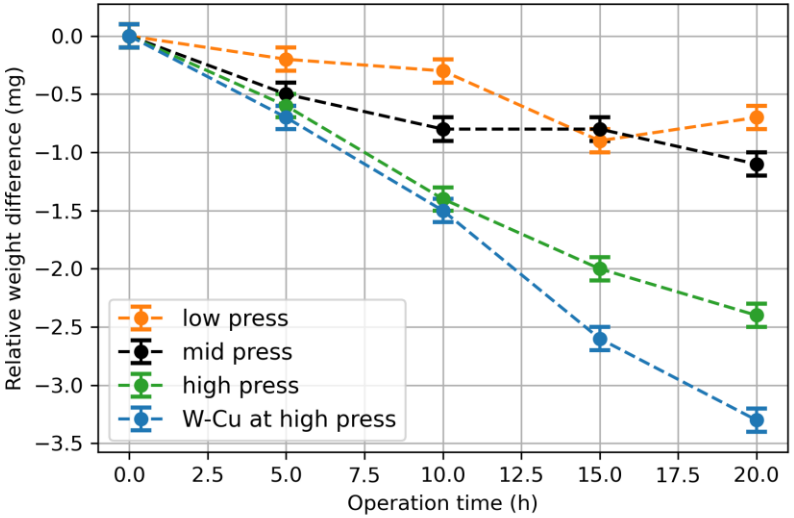
- Every 30 min: current traces and scan with ICCD camera (PCO dicam pro)
  → 0 µs - 1.2 µs (50 ns steps) with exposure time of 50 ns

Electrode erosion

- Big electrode (cathode) shows more significant weight loss

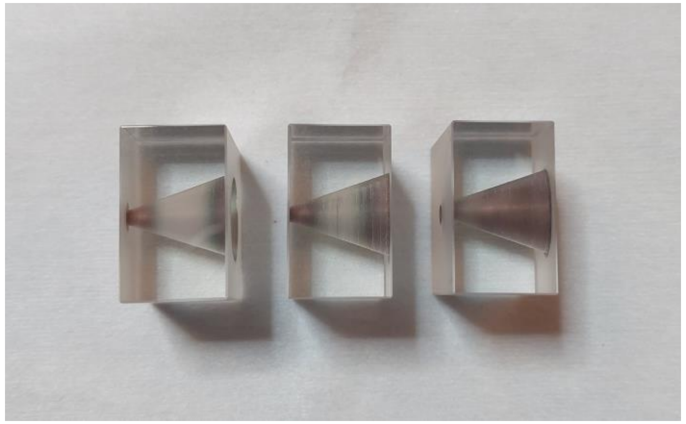
- Highest pressure leads to highest erosion rate
- Lowest pressure leads to highest copper coating inside lens
  → Gas inlets shoot the copper through entire cell

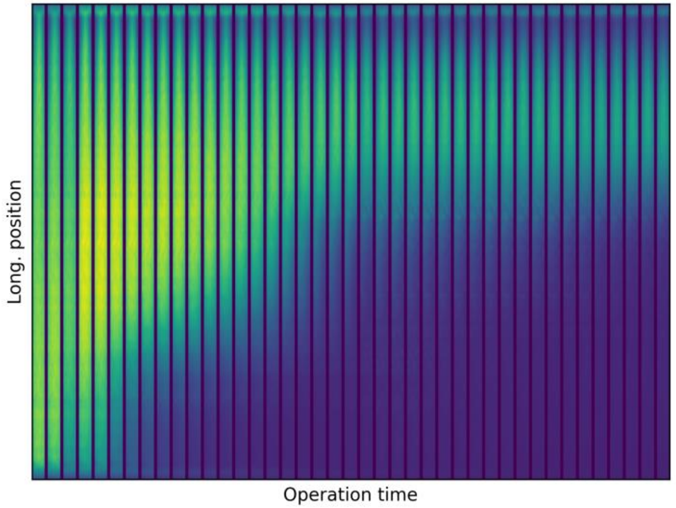
- W-Cu-alloy exhibits similar erosion
  → Additional run with pure tungsten planned



Relative cathode weight loss during 20 hour 5 Hz operation for all four runs.

Lenses after 20h erosion measurements. Highest to lowest pressure from left to right.





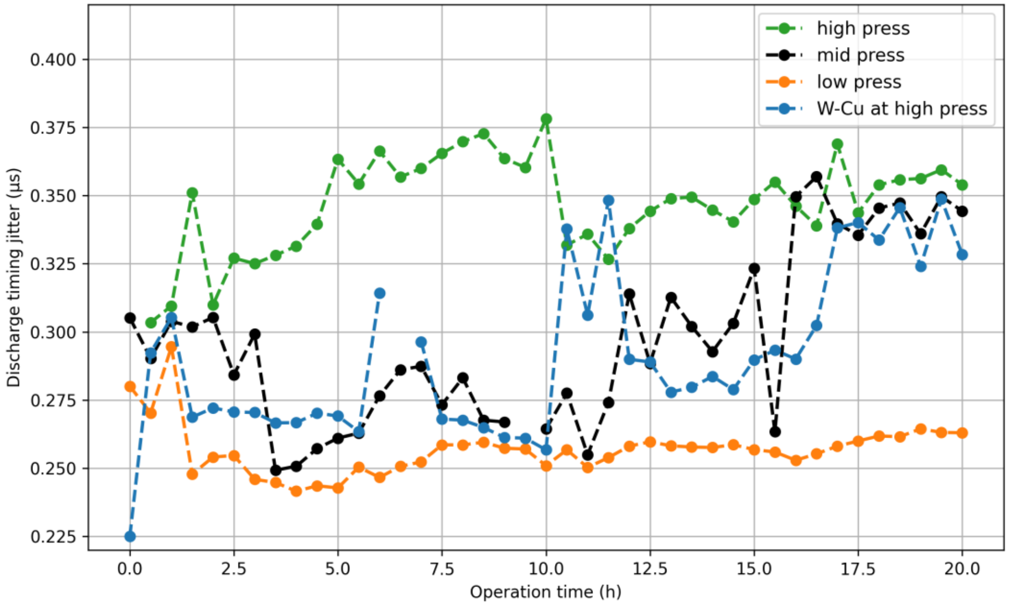
Light emission along beam axis during low pressure measurement.

Discharge timing jitter

- Defined as σ of 50% of peak current on the rising edge

- Best timing jitter performance for lowest pressure (0.24 µs – 0.3 µs)
- Worst timing jitter performance for highest pressure (0.3 µs – 0.38 µs)
- Timing jitter increases with ongoing operation time

- Jitter for W-Cu alloy (blue) is lower compared to high pressure Cu electrode
- Most significant increase in timing jitter



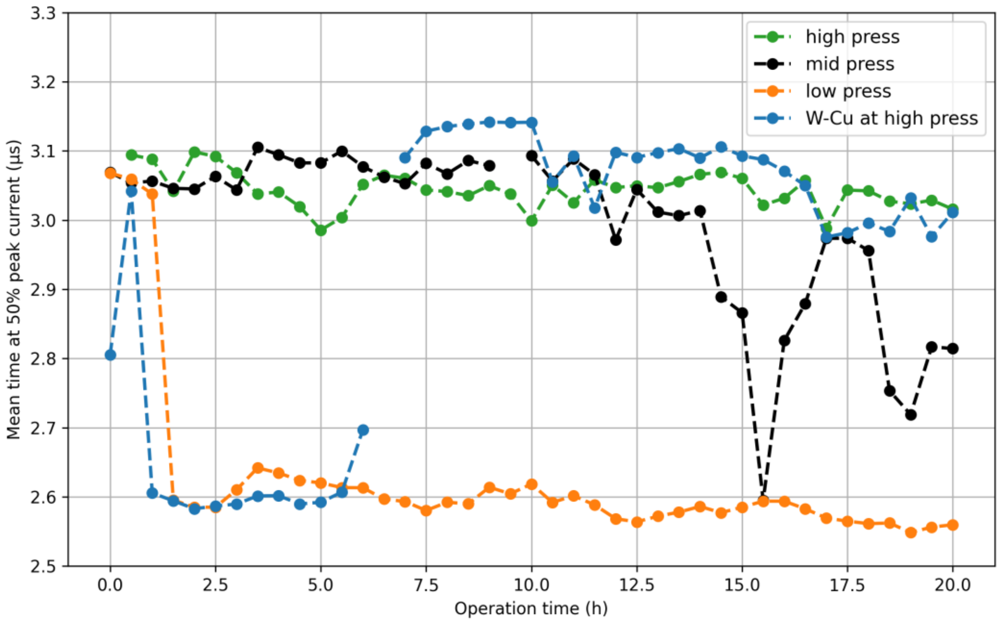
Discharge timing jitter during 20 hour operation for all four runs.

Discharge mean time at 50% peak current

- Defined as µ of 50% of peak current on the rising edge

- High pressure run is the most stable
- First three measurements of low pressure run are standing out
- Mean timing decreases with ongoing operation time

- W-Cu alloy (blue) has worst perfomance
- Jump in discharge mean timing after 6 hours of operation
- Most significant increase mean timing during operation



Mean time at 50% peak current during 20 hour operation for all four runs.

Hypotheses for electrode erosion

- Localized Cathode Hot Spots
  → Unstable discharge produces tiny, transient regions ("spots") with extreme local Joule heating
  → These spots locally exceed melting temperatures, leading to rapid, concentrated erosion

- Energetic Ion Bombardment
  → Cathode is bombarded by high-energy ions formed in the cathode region
  → Erosion depends on the balance between ion mean free path and ion flux
    → Low Pressure: Longer mean free paths yield higher ion energies (more erosion)
    → Increased Pressure: Higher flux but lower ion energies can reduce erosion

- Just hypotheses, can be incorrect

Conclusion and outlook

- Plasma lens has high potential due to direct on-axis focusing

- Tapered plasma lenses are largely unexplored
- First downscaled prototype tests showed two major issues
  - → Unstable discharge
  - → Heavy material coating due to electrode erosion
- Electrode longevity tests at ADVANCE LAB at DESY ✓
  - → Electrode erosion is pressure dependent
  - → W-Cu alloy does not lead to less erosion

- Pure tungsten as electrode material
- Modification of lens with 1 mm gas outlet instead of 10 mm
  - → Higher gas accumulation inside lens

- Simple set-up of 100 mm long plasma cell with constant diameter
  - → Is cone shape or huge diameter more influential?

Thank you for your attention!

References

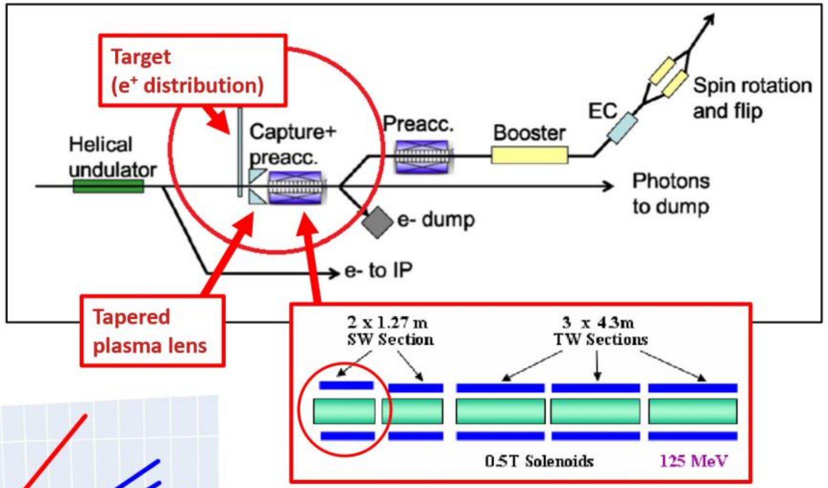
- M. Barish, B. Buesser, K. Adolphsen, C. Barone: Technical Design Report | Volume 3.I: Accelerator RD, 2013
- K. Flöttmann: ASTRA: A space charge tracking algorithm, 2017, https://www.desy.de/ ~mpyflo/
- J. W. Wang: Positron Injector Accelerator and RF System for the ILC, APAC 2007
- F. Dietrich: Status 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
- N. Hamann: Status of plasma diagnostics on the prototype plasma lens for optical matching at the ILC e+ source, IPAC23, 2023
- N. Hamann: Investigation of plasma stability of the prototype plasma lens for positron matching, IPAC24, 2024

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

Motivation

- Undulator-based source: e+/e- pairs from high energy photon beam hitting Ti wheel
- Focusing needed to capture low energy, highly divergent e+
- Conventional focusing optics do not meet requirements
  - → Quarter wave transformer: low e+ yield, thermal load on target
  - → Flux concentrator: unstable yield over bunch train length



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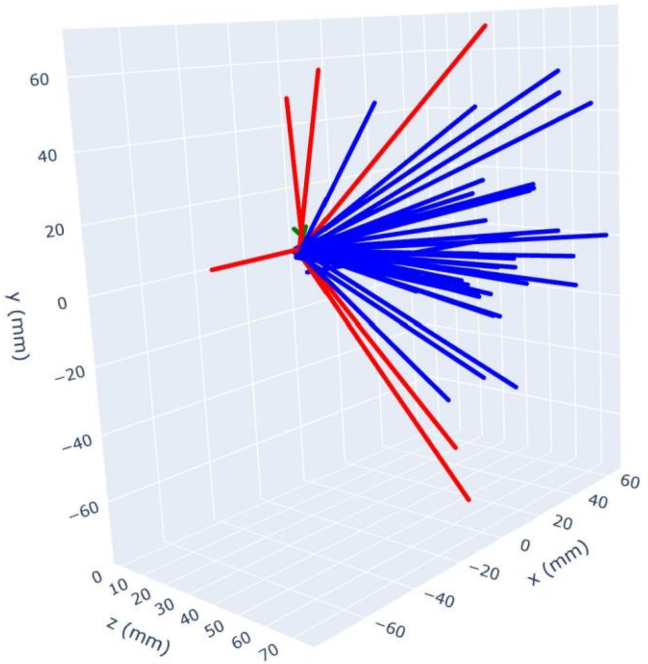
- New alternative: Active plasma lens



Beam structure:

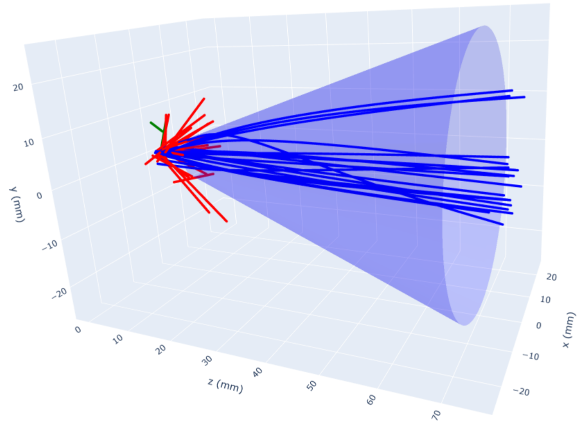
- Pulse repetition rate: 5 Hz
  - → per pulse ~1300 bunches
- Bunch spacing: 554 ns
  - → Repetition rate of plasma lens in MHz
- Average e+ energy: 6.1 MeV
- Energy spread: 4.8 MeV
- Divergence: 63.28 – 75.24 mrad

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

Particle tracking simulations with ASTRA

- Initial positron distribution for ILC e+ source (M. Fukuda)
- Simulations based on ASTRA code (K. Flöttmann)
- Simplifications: no space charge, homogeneous current density, no edge fields
- Goal: Parameter set of plasma lens optimized for positron yield
- 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

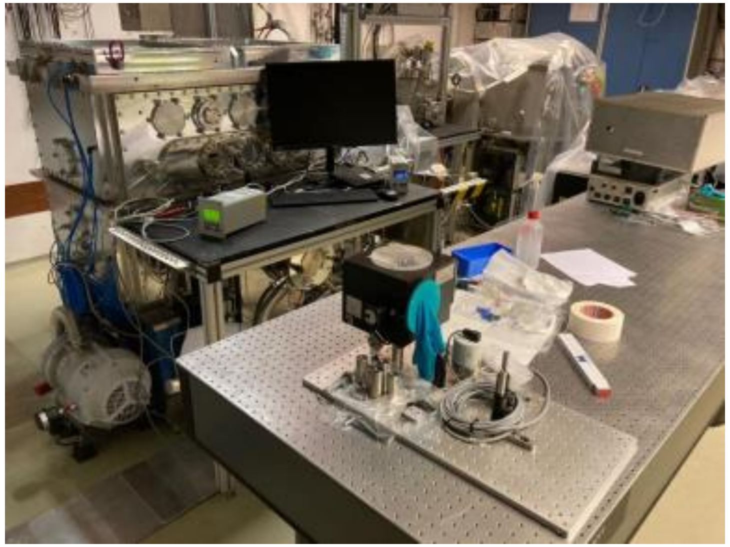
Parameter name	Symbol	Optimal Value
Plasma Lens Length	z_{max}	60 mm
Opening Radius	R_0	4.3 mm
Tapering Order	n	2
Tapering Strength	g	$0.082\,\mathrm{mm}^{-1}$
PL-SWT distance	d	10 mm
SWT Phase	φ_0	225 deg
Current strength	I_0	9 kA

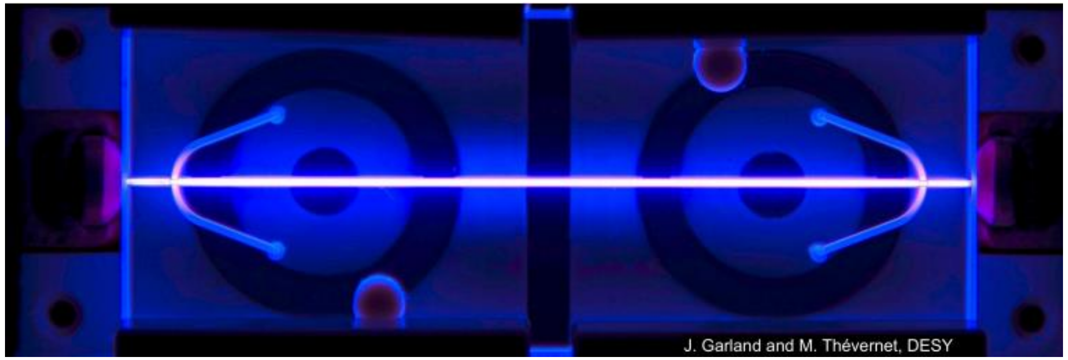
Parameters of simulated plasma lens.

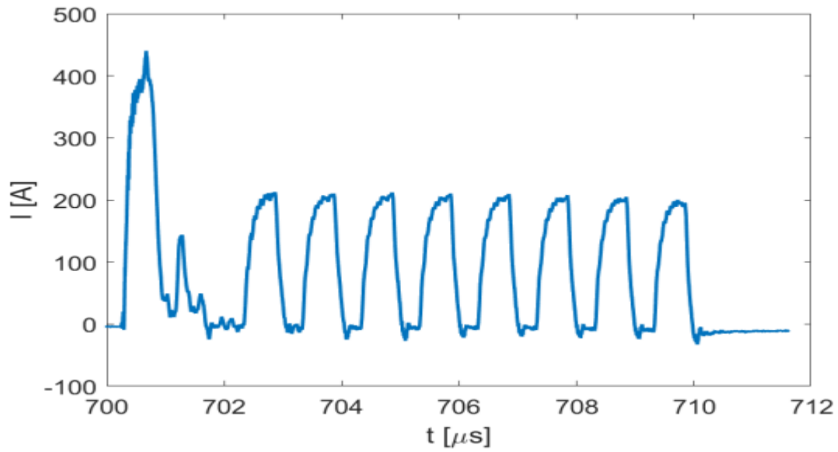
M. Barish B. Buesser K. Adolphsen, C. Barone: Technical Design Report | Volume 3.i: Accelerator RD, 2013

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

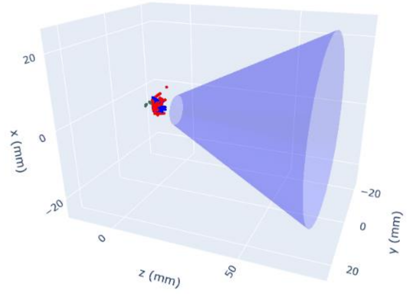
Down-scaling the prototype

- Set-up at ADVANCE Laboratory at DESY Hamburg
- Already existing vacuum chamber und MHz pulse modulator

  → Maximum available peak current ~350 A

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

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



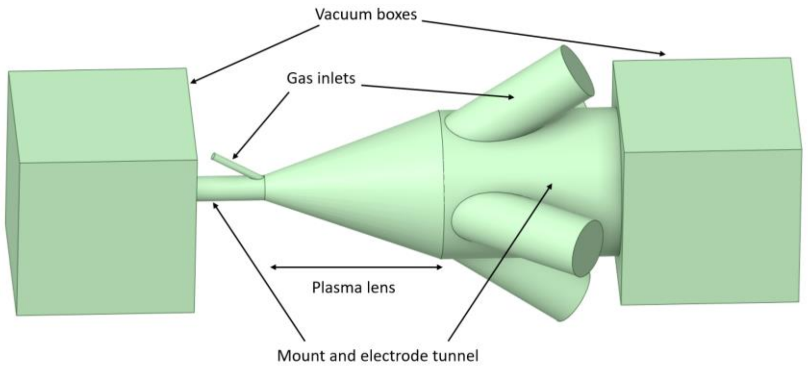
Peak current strength	I_0	350 A
Opening radius	R_0	0.848 mm
Ending radius	R_1	5.029 mm
Tapering parameter	g	0.416 mm^{-1}
Length	L	11.832 mm

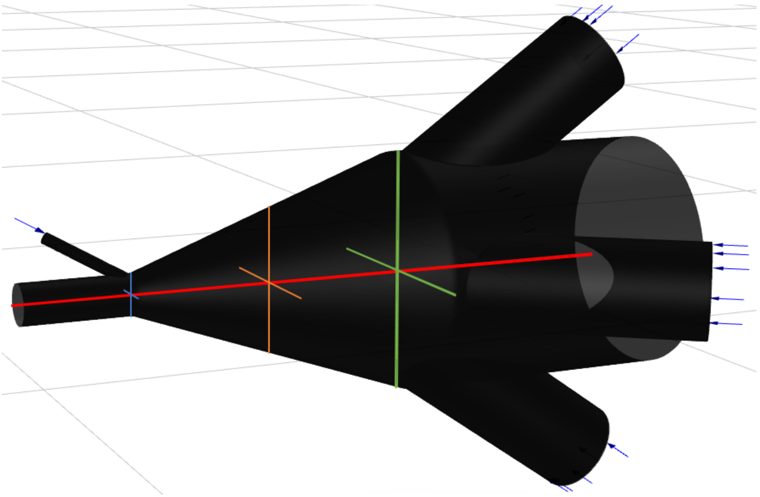
Parameters of down-scaled plasma lens.

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)



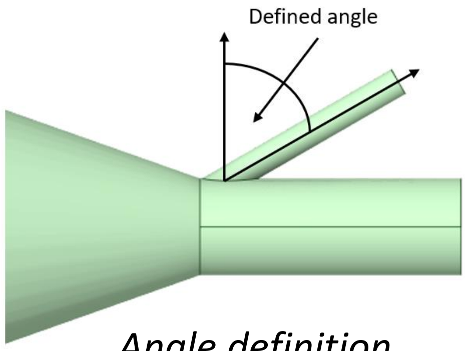


- Pressure profile along drawn lines
- X- and Y-axis show similar results
  → Only X-axis is shown

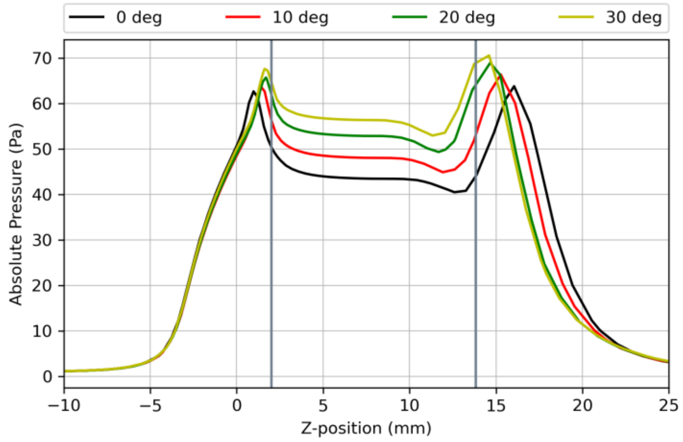
Angle of gas inlets

- 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

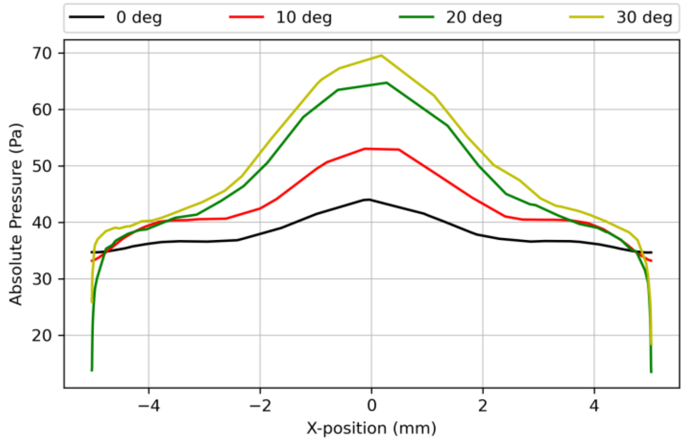
- Higher pressure in the plasma lens due to larger angles
  → Gas is shot directly into the plasma lens
- Gas accumulation in the extensions in front of and behind the plasma lens



Angle definition



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

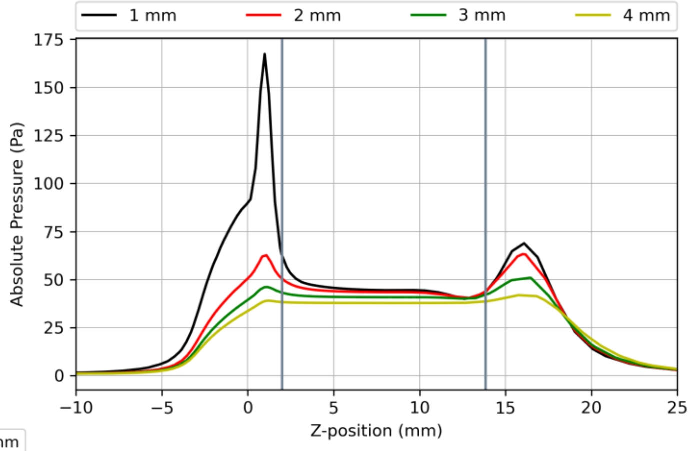


Pressure profile along the X-axis at the output

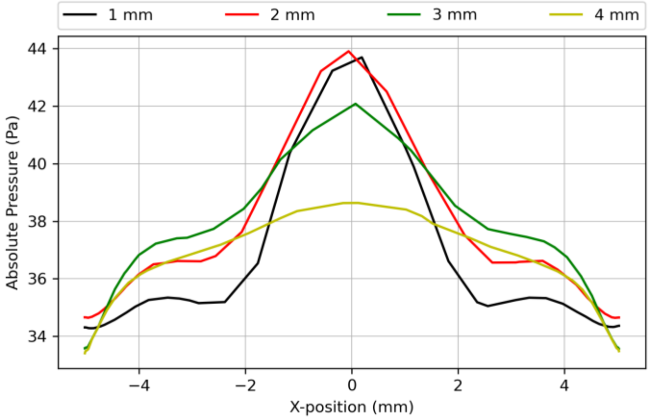
Gas inlet diameter

- 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



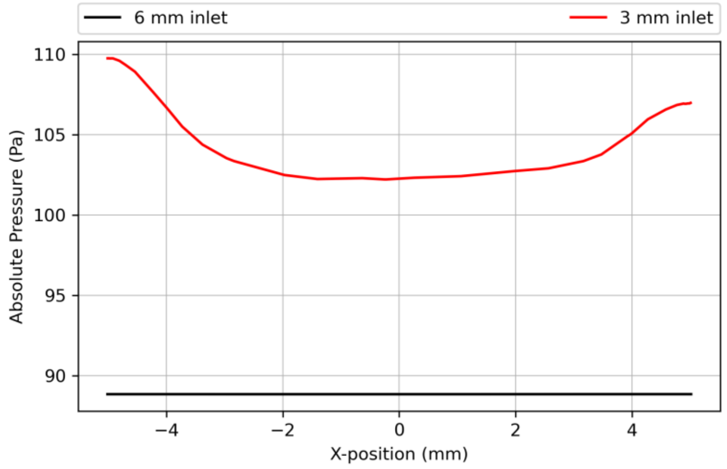
Pressure profile along the X-axis at the exit

Design simplification for prototype setup

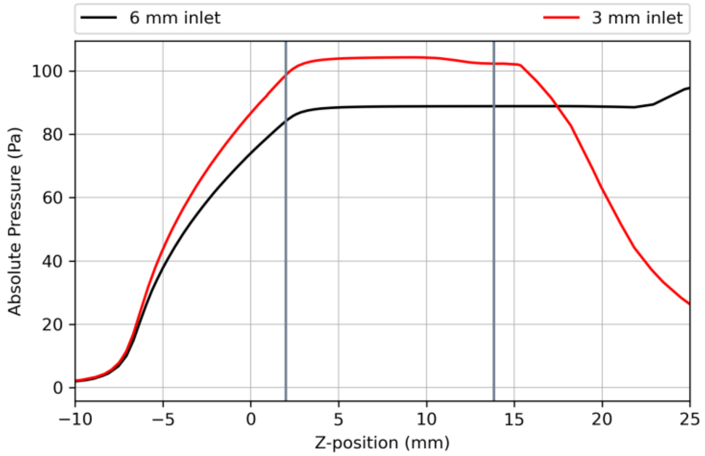
- Goal: Adapt structure to laboratory and manufacturing conditions
- No inlets at the entrance (too small)
- Fewer inlets
- Target pressure adjusted to 100 Pa for lab environment
- Mass flow rate $2 \cdot 10^{-5}$ kg/s for Argon

- 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

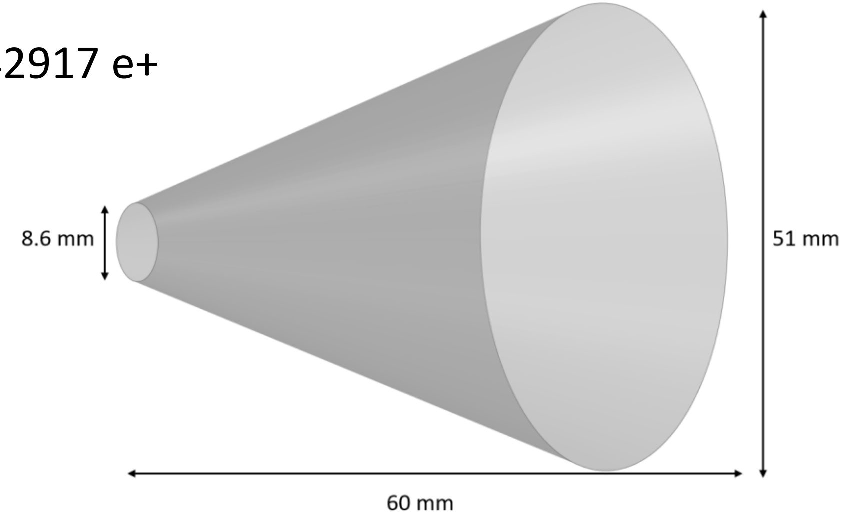


Pressure profile along the Z-axis

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 mm
Opening Radius	R_0	4.3 mm
Tapering Order	n	2
Tapering Strength	g	$0.082\,\mathrm{mm}^{-1}$
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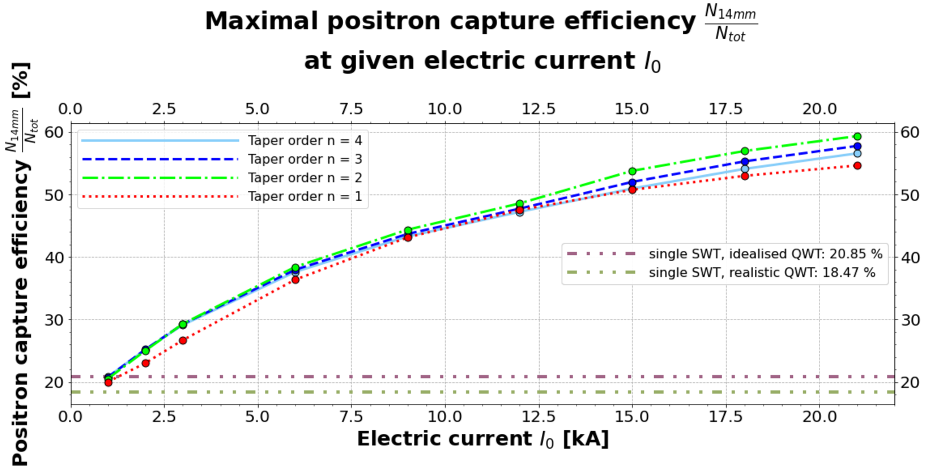
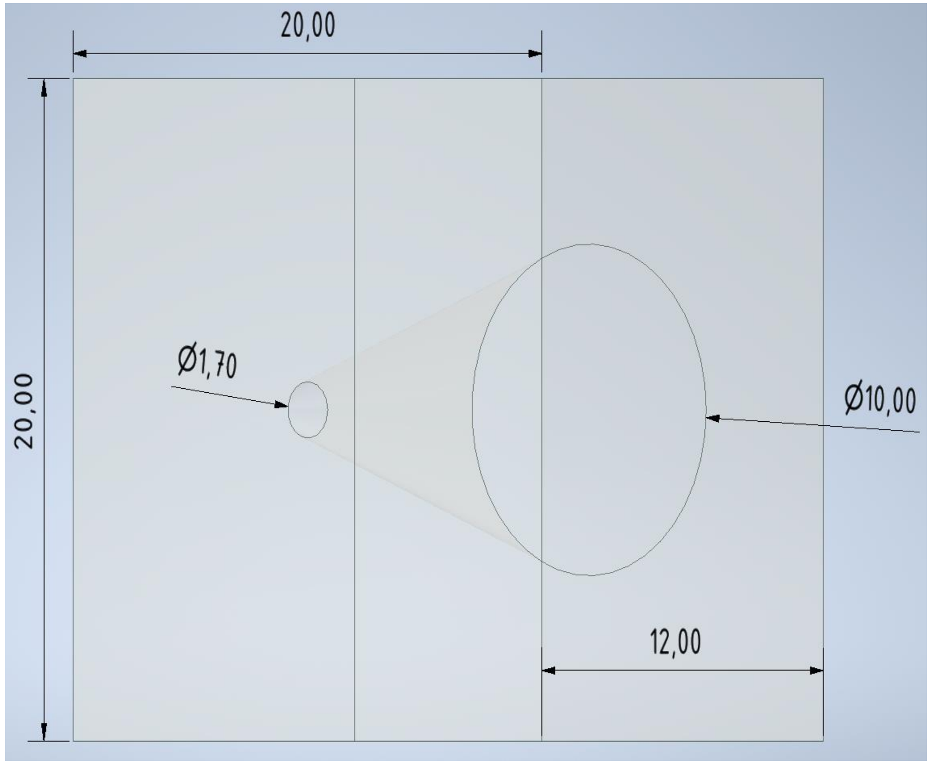


Technical design concept – gas cell

- 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

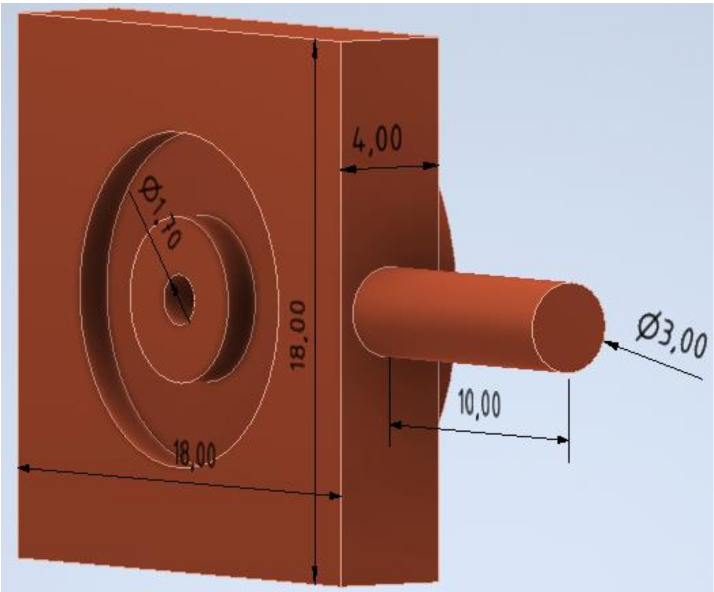
- All specifications of technical designs noted in mm



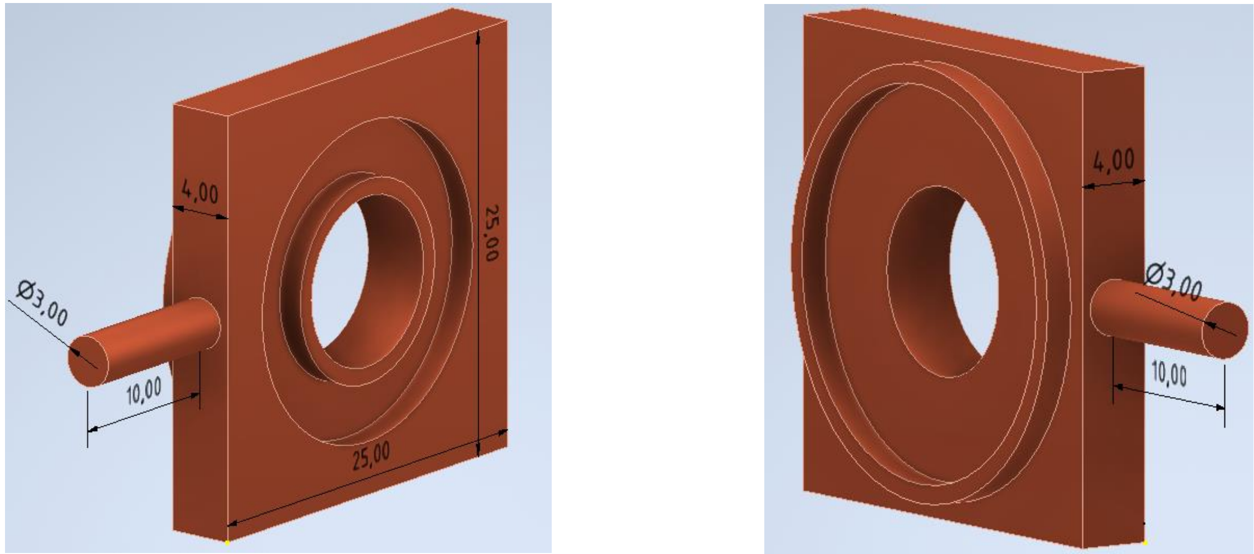
Plasma lens

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



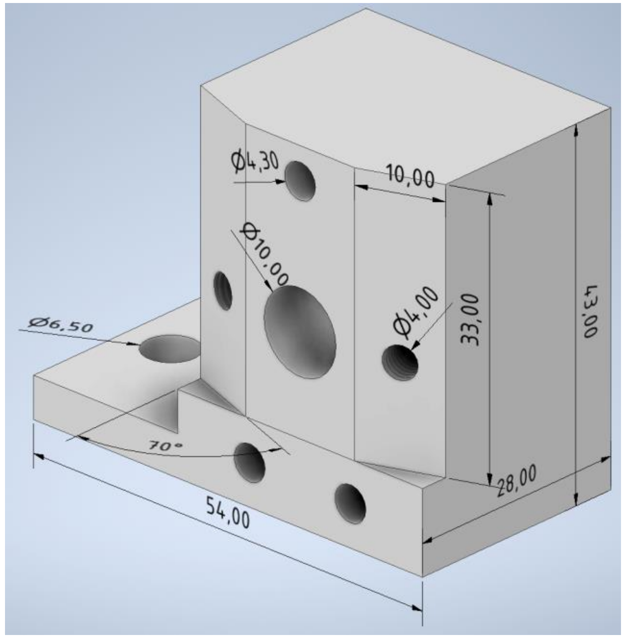
Electrode at the entry

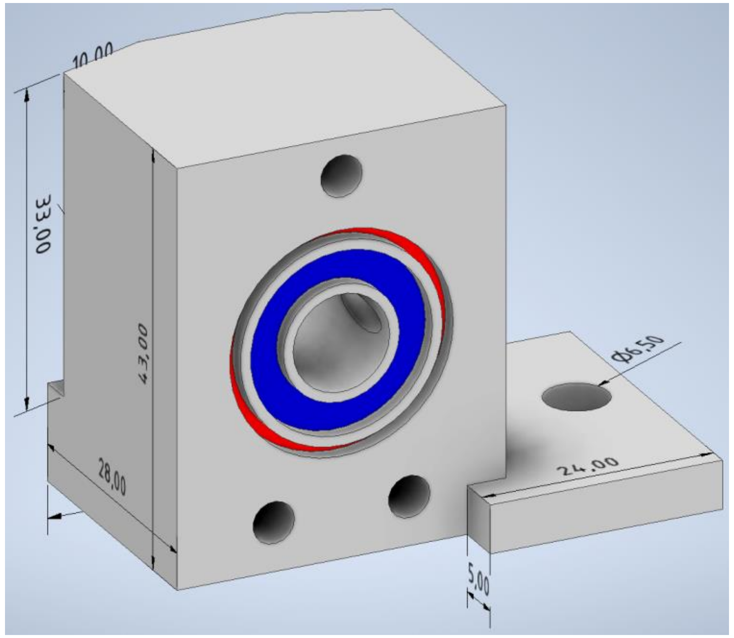


Electrode at the exit

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



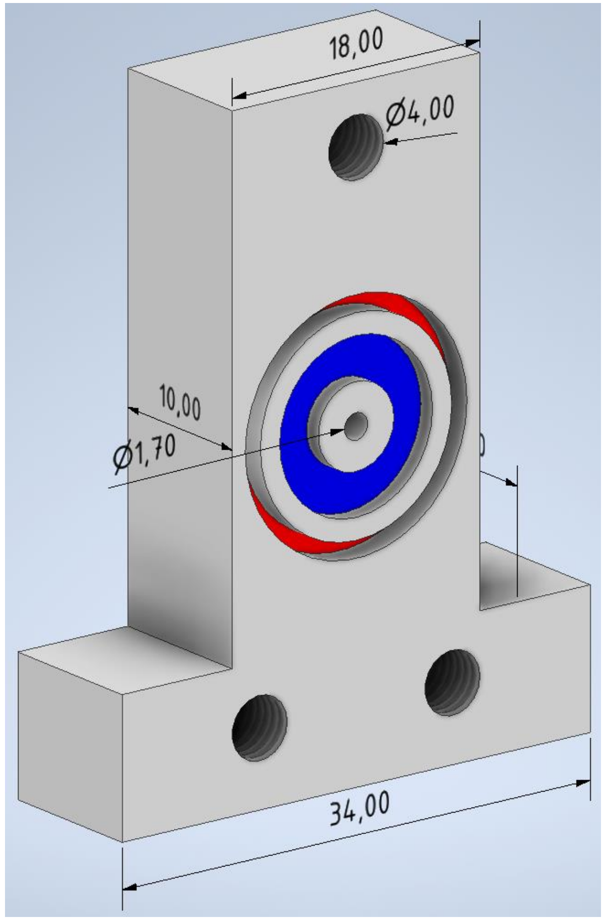


Mount at the exit with gas inlets

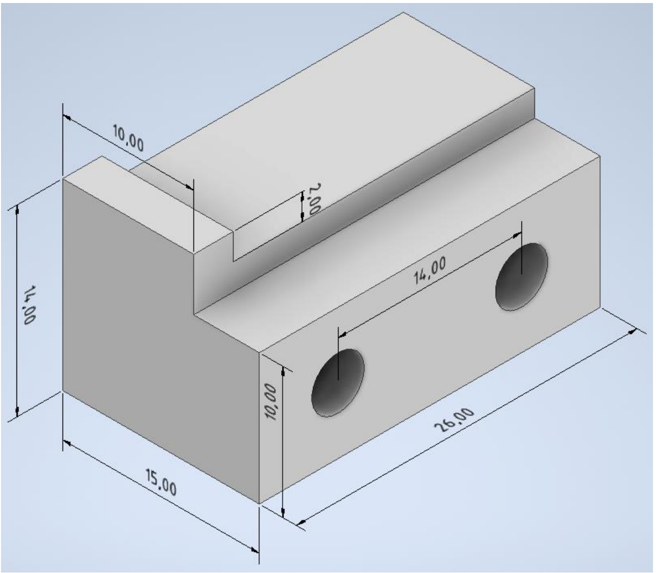
Technical design concept - support

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

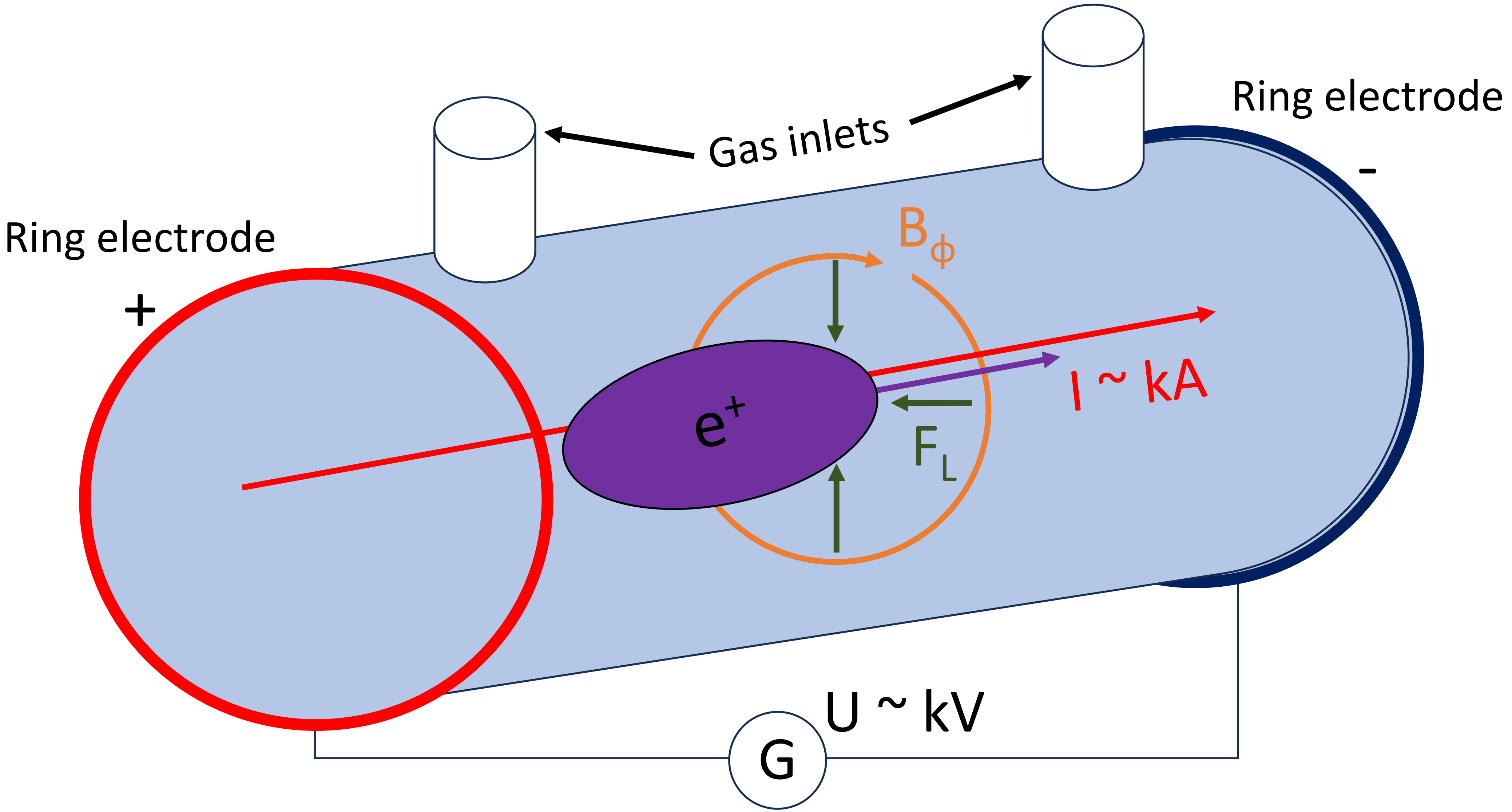
- Edge on bottom mount to fix position of plasma lens
- Bottom mount should not touch electrode
  → Would over-define position
- Blue groove for O-ring with thickness of 1.5 mm
- Red groove for inlet of electrode



Mount at the entry



Mount below the plasma lens



Gas inlets
Ring electrode
-
Ring electrode
+
Bϕ
e+
I ~ kA
FL
U ~ kV
G