Plasma lenses and their (possible) application in future colliders

Positron capture at the ILC undulator-based positron source

Gregor Loisch, Manuel Formela, Klaus Flöttmann, Niclas Hamann, Gudrid Moortgat-Pick

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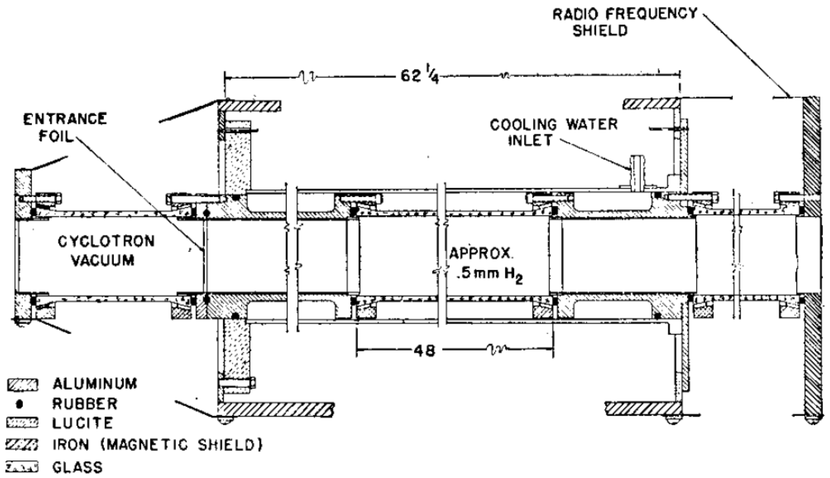
Active plasma lenses

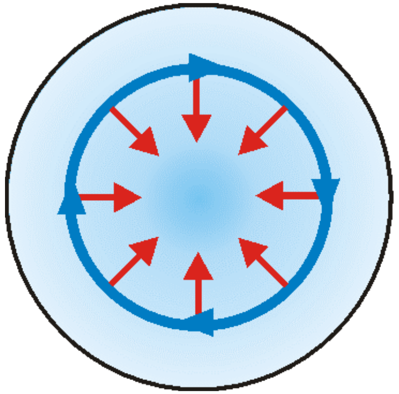
Introduction and brief historical overview

Panofsky, Wolfgang Kurt Hermann, and William R. Baker. "A focusing device for the external 350-MeV proton beam of the 184-inch cyclotron at Berkeley." *Review of Scientific Instruments* 21.5 (1950): 445-447.

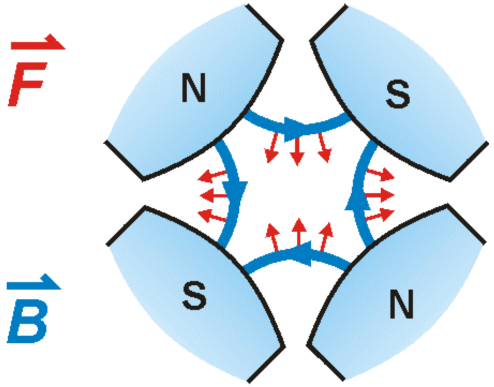


- Concept proposed by W. Panofsky and W. Baker 1950
- Focusing of charged particle beams by co-moving electrical current in plasma medium
  - → Fully symmetric focusing
  - → closest proximity of focusing current to beam
  - → focusing transverse to main direction of motion (↔ solenoid)
  - → low scattering of beam particles (compared to Li-lens or magnetic horn)
  - → high conductivity
  - → space charge mitigation by plasma electrons

APL focusing



Quadrupole focusing



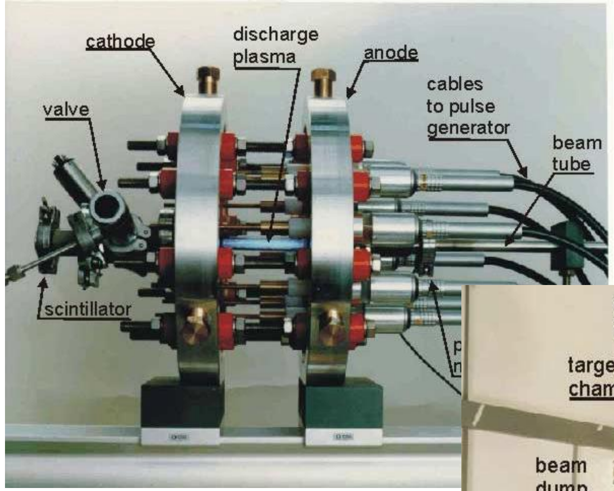
A. Tauschwitz, Plasma ion beam focusing in gas discharges, habilitation, U. Erlangen-Nürnberg, 1998
E. Chiadroni, Nuclear Instruments and Methods in Physics Research A, 2018

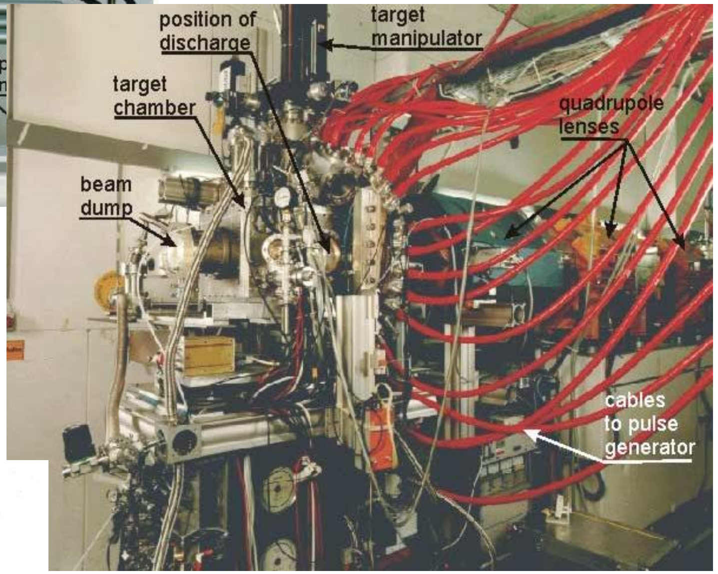
Active plasma lenses

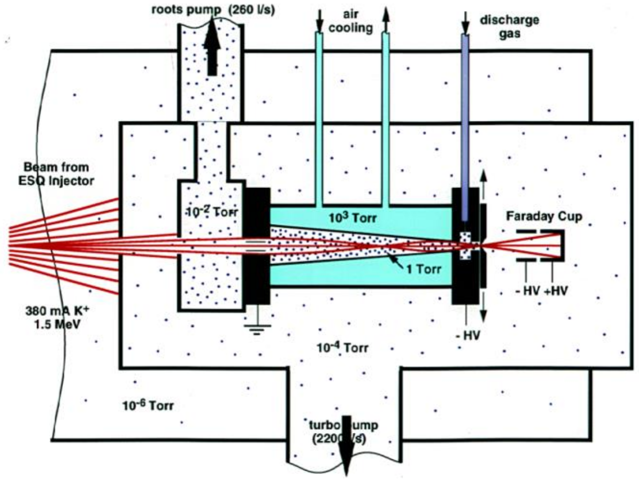
Introduction and brief historical overview

A. Tauschwitz, Plasma ion beam focusing in gas discharges, habilitation, U. Erlangen-Nürnberg, 1998

- First experiments at Berkeley, Brookhaven, NRL, Nagaoka
- Large research campaigns at Uni Erlangen-Nürnberg, GSI & CERN
  - Target applications: heavy-ion inertial conf. fusion (HIDIF), antiproton capture (ACOL facility)
  - 10 - 500 kA electrical peak current
- (Selection of) achievements:
  - Increase in beam intensity by factor ~3-30
  - Focusing of protons, heavy ions, muons, electrons
  - Tapered plasma lens focusing
    - Diameter adjusted to beam diameter along lens
- Electrode erosion considered ~fatal







Active plasma lenses

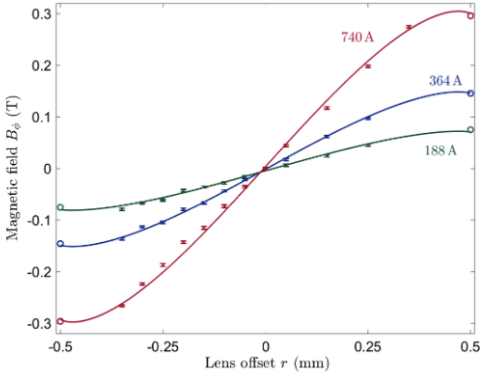
Past decade – recent years

- APLs in electron focusing gained momentum around ~2010
- Modeling of current distribution

Bobrova, N. A., et al. "Simulations of a hydrogen-filled capillary discharge waveguide." *Physical Review E* 65.1 (2001): 016407.

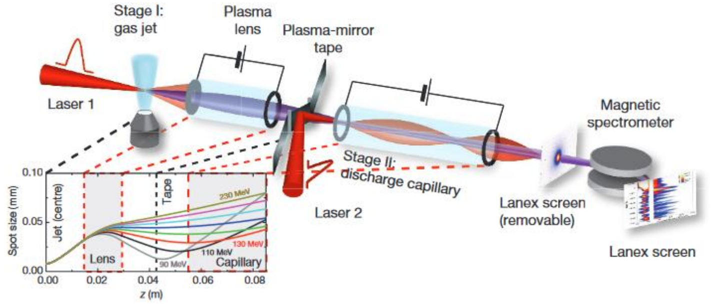
- Detailed investigation of field non-uniformity

Röckemann, J.-H., et al. "Direct measurement of focusing fields in active plasma lenses." *Physical review accelerators and beams* 21.12 (2018): 122801.



- Application of plasma lens in laser wakefield accelerator staging demonstration

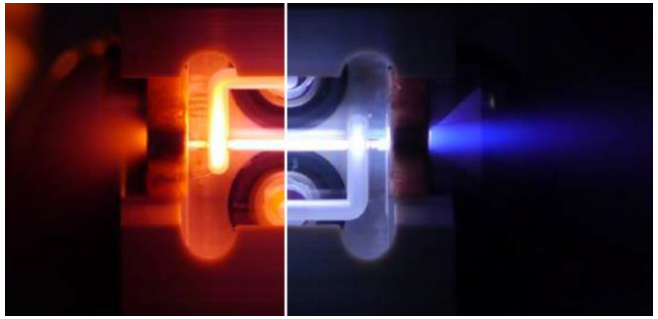
Steinke, S., et al. "Multistage coupling of independent laser-plasma accelerators." *Nature* 530.7589 (2016): 190-193.

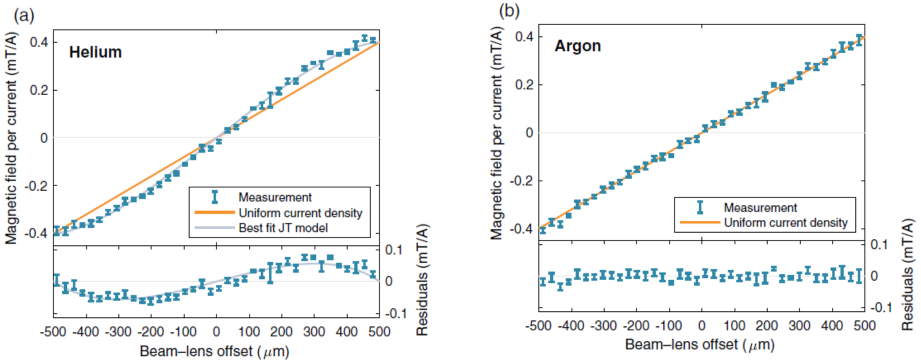


- Beam quality preservation in APL
  - Focusing before temperature equilibrium

Lindstrøm, Carl A., et al. "Emittance preservation in an aberration-free active plasma lens." *Physical review letters* 121.19 (2018): 194801.

- Gradients ≤ ~3.6 kT/m





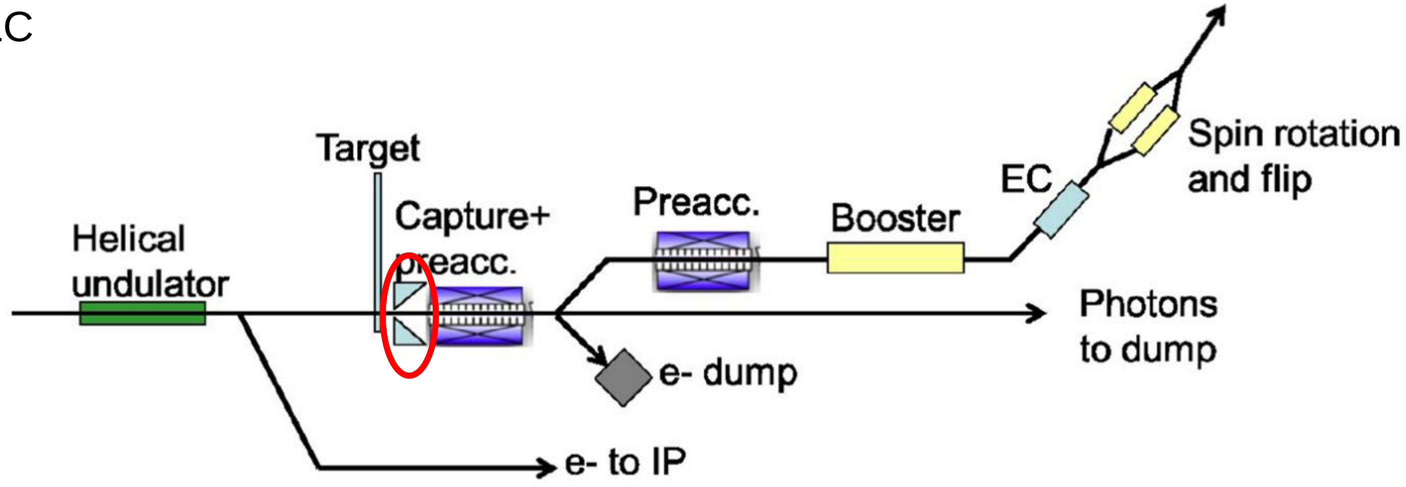
Plasma lenses at ILC positron source

Capturing highly divergent, broad-band positrons

- Positron capture w/ plasma lens first proposed by Braun et al. for LEP
  - → LEP used solenoid finally

Braun, H., et al. "Application of plasma lenses in positron sources." *Proc. of the 1992 EPAC, Berlin* (1992).

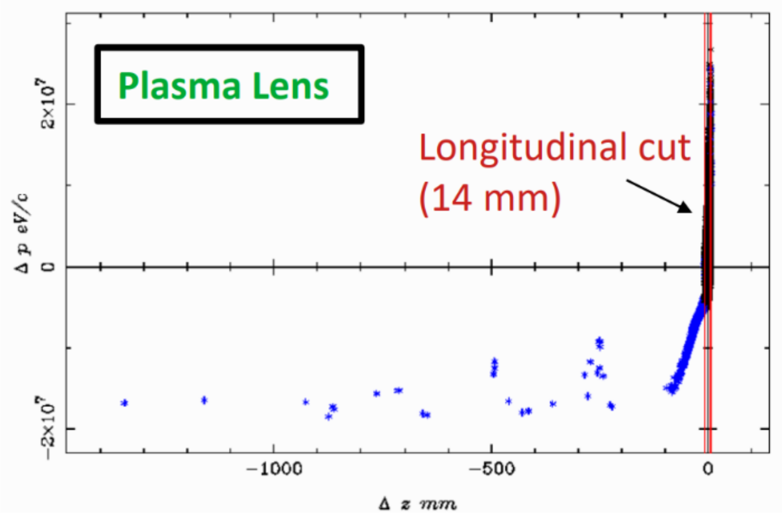
- Independently proposed by K. Flöttmann for ILC
- Positron beams after target:
  - Large energy spread
  - Highly divergent
- APL advantages:
  - Stronger focusing → higher yield
  - Selective focusing → no transport of electrons
  - Localised field → no additional force on rotating e+ target

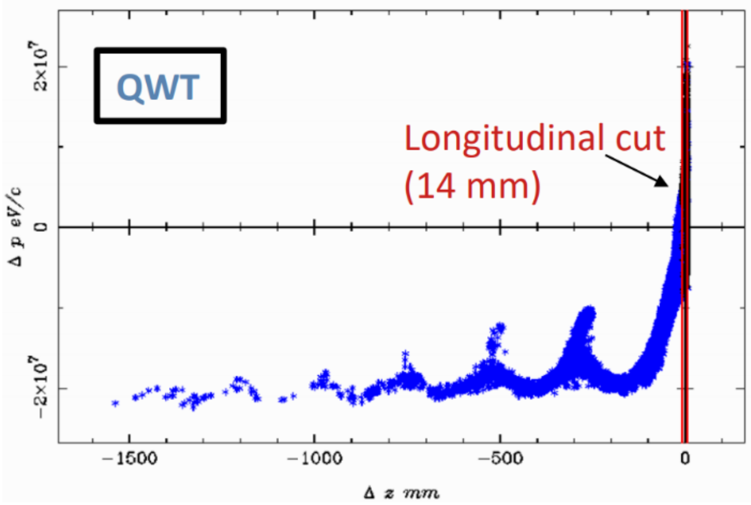


Ongoing project @DESY

Work up to now by Gudrid Moortgat-Pick, Manuel Formela and Niclas Hamann

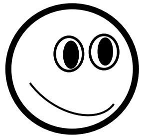
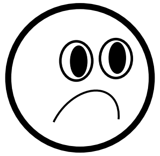
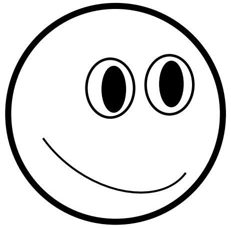
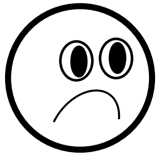
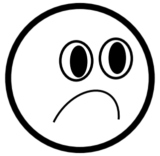
- Simulation work since 2020 → BMBF-funded since 06/2021
  - Collaboration with U FfM, GSI, TU Darmstadt
- Performed simulations with ASTRA
- Variation of plasma lens parameters
  - Length, diameter (60mm)
  - Diameter & taper (7mm → 32mm)
  - Current (3-9 kA)
  - Long. position (w.r.t. surrounding elements)
- 50% increase in positron yield w.r.t. baseline (i.e. quarter wave transformer)





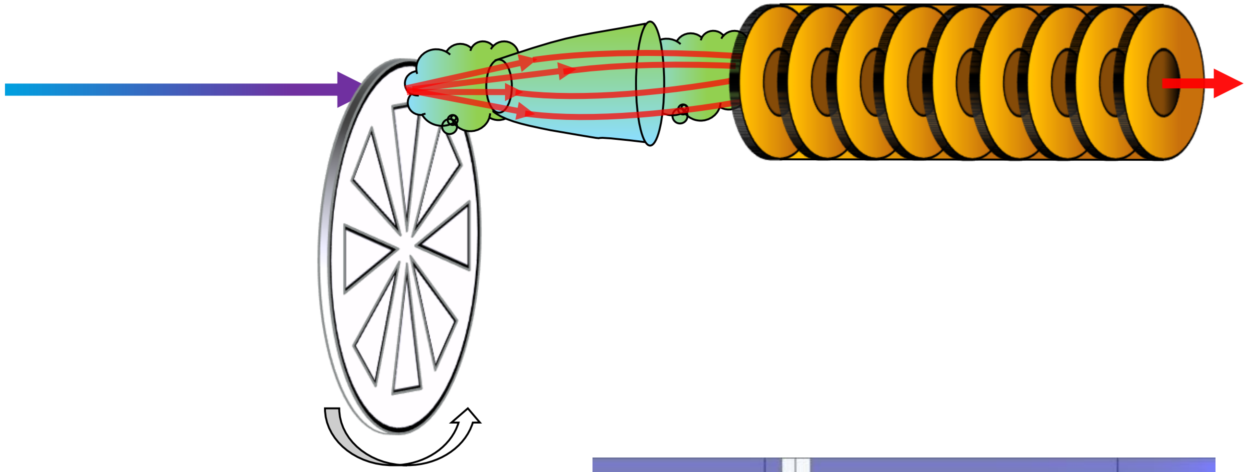
Possible future work

Main challenges of APLs and ILC e+ target application

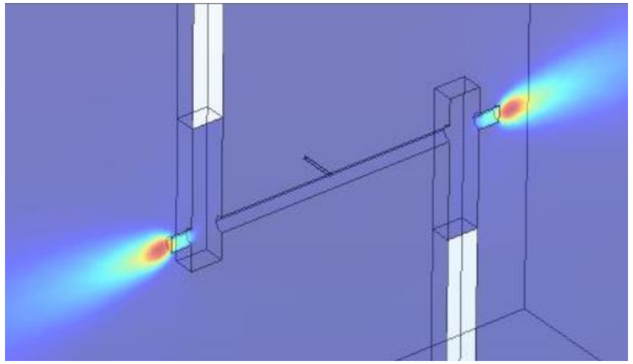
- Possible issues of APLs
  - Gas load
    
    → *Lens is rather short & low density*
    - *Scattering → emittance growth*
    - *Nearby UHV components (e.g. cavities)*
    
    → *1st accelerating cavity very close*
  - Nonlinear fields → emittance growth
    - *Pinching of plasma*
    - *Thermal equilibrium distribution of current*
    - *Wakefields by beam*
    
    → *Emittance not critical!? Impact of nonlinear fields to be studied*
  - Electrode erosion
    - *High gradient → low aperture/high current*
    - *Aperture constrained by beam size*
    
    → *Current simulations indicate ~x kA peak current; to be tested in experiments*
  - Repetition rate
    - So far single shot → ~10Hz
    
    → *ILC requires ~2 MHz in 1.6 ms long bursts @10 Hz*

Future plans

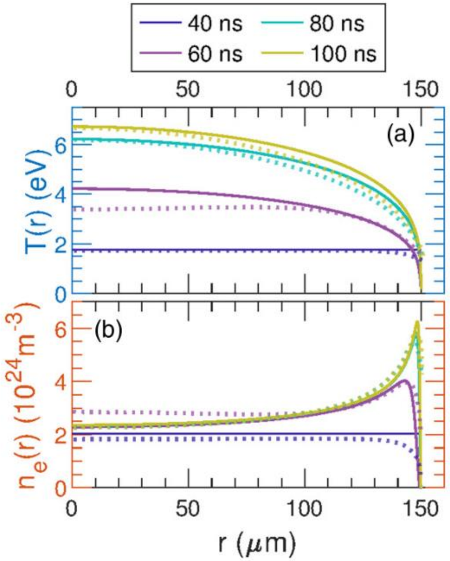
Simulations



- Understanding transport of positrons
  - Further optimise plasma lens parameters (current, geometry, max. distance to 1st cavity) → multi-dimensional optimisation!



- Simulate temperature/current distribution in ILC-like lens
  - MHD simulation of tapered & large aperture geometry
  - Simulation of repetitive discharges (>MHz)
  - → Iterate lens geometry & current optimisation



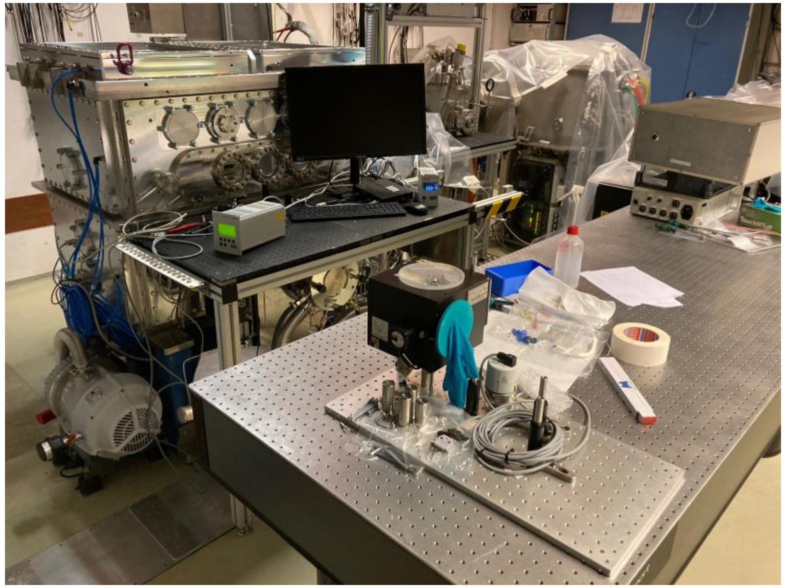
- Gas flow simulations
  - E.g. ANSYS gas flow
  - Understand constraints on nearby cavities
  - Sketch suitable differential pumping system

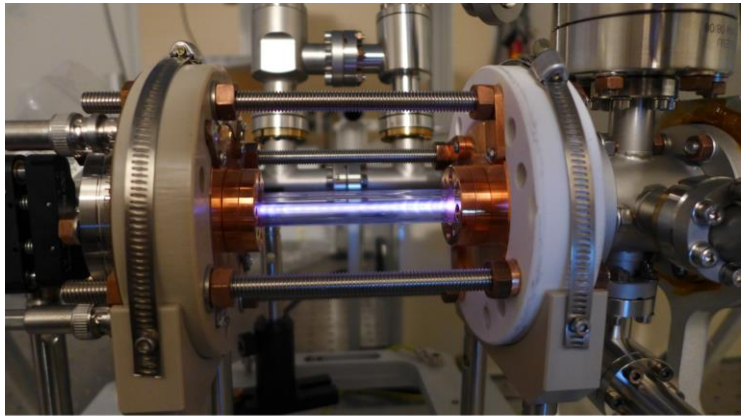
G. J. Boyle *et al.*, PRE **104**, 015211 (2021)

Initial/immediate experimental work

Preparatory measurements with available hardware

- Dedicated discharge plasma lab being commissioned
  - ADVANCE laboratory @ DESY
  - Diagnostics, infrastructure & know-how available
- Short-term goals:
  - Understand voltage/current dependency
    → engineering requirements of future setup
- Use PITZ plasma wakefield acceleration cell
  - Existing setup
  - Similar size → comparable plasma parameters



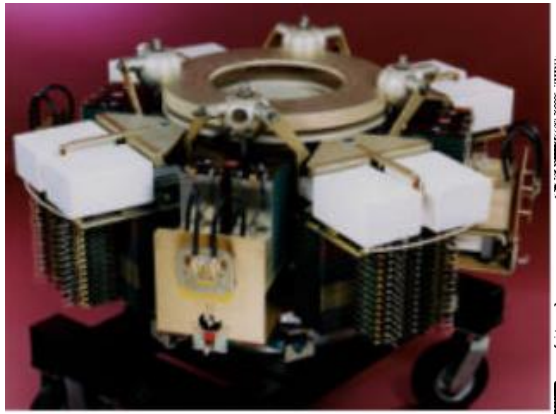


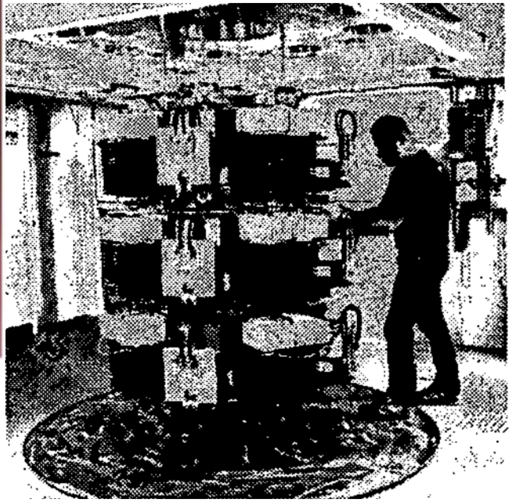
G. Loisch *et al.*, J. Appl. Phys. **125,** 063301 (2019)

Future experimental plans

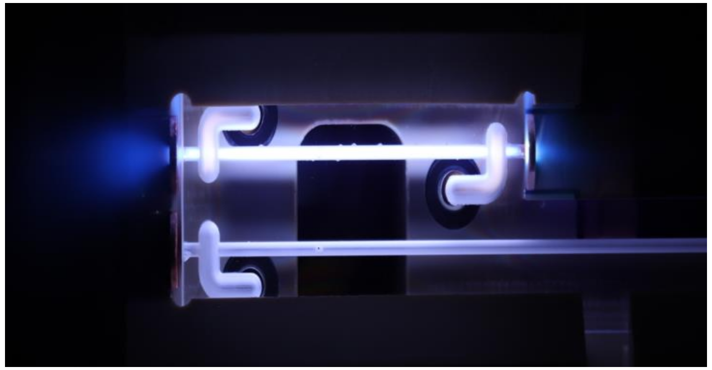
Dedicated setup to tackle ILC requirements

- New, dedicated setup
  - Scaled version of simulated cell
    - Relax requirements on pulse electronics
    - Minimise costs
    - ↔ simulate scaling of discharge behaviour!?
  - Full-scale version of simulated cell
    - Demonstrate exact lens setup
    - ~step-wise increase of pulse numbers!?
- → Diagnostics!?
  - Plasma density/temperature?
  - Beams (MAMI, ARES?)





Kirbie, H., et al. "MHz repetition rate solid-state driver for high current induction accelerators." *Proceedings of the 1999 Particle Accelerator Conference (Cat. No. 99CH36366)*. Vol. 1. IEEE, 1999.



Summary & Outlook

Plasma lenses in future colliders – identification stage

- Physics of low repetition rate, linear, small aperture plasma lenses understood
  - → First applications being planned with plasma lenses
- Significant potential gain in positron yield
- Exact requirements of ILC positron source on plasma lens yet to be investigated
  - MHD of tapered & large aperture lens
  - Current distribution at high repetition rate
  - Longevity of optimised cell
- Concentrated here on ILC, probably useful at any ep-collider with high yield requirements
  (ILC bunch time structure most demanding…)
- Increased work on plasma-based components @DESY, lab infrastructure becoming operational
  → best prerequisites for this work
- Project at the beginning, many open questions
  → exciting physics ahead!

Thank you for your attention!

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Gregor Loisch
Kicker & Septa Laboratory
Machine Injection Group MIN
gregor.loisch@desy.de
Tel. +49 8998 - 4961