The CLEAR Oslo Plasma Lens

Erik Adli

Department of Physics, University of Oslo, Norway and CERN

Work done by**: C. A. Lindstrøm, K. N. Sjøbæk** (Oslo)

W. Farabolini, D. Gamba, G. Ravida, T. Lefevre, R. Corsini (CERN)

J.H. Roeckemann, L. Schaper, M. Meisel (DESY)

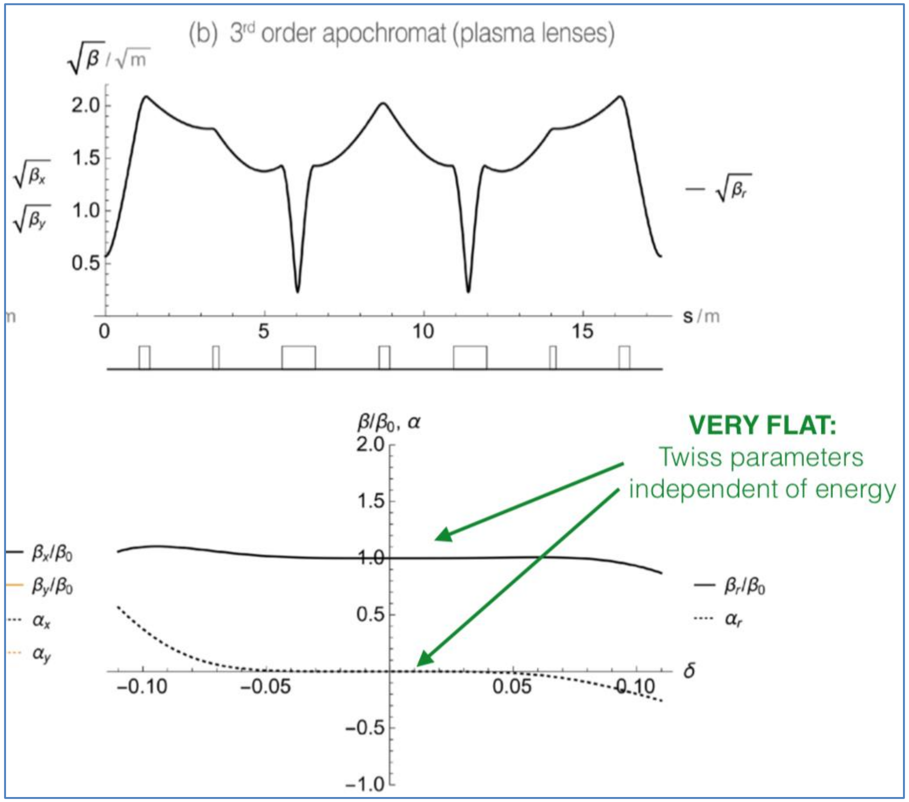
A. Dyson, S. Hooker (Oxford)

CLIC Workshop 2019, January 24, 2019

https://clear.web.cern.ch

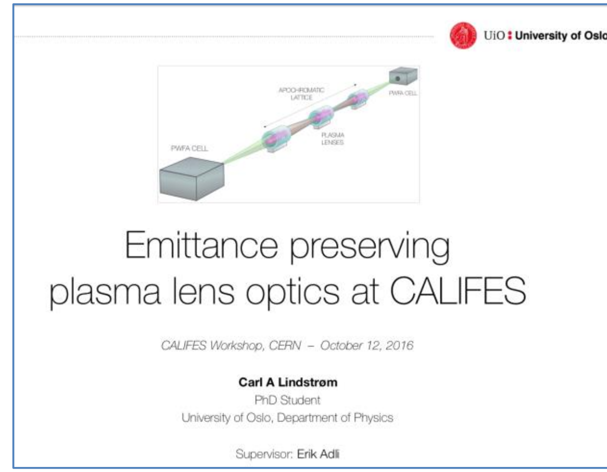
Proposal from CALIFES workshop (Oct 2016)

Oslo theoretical studies**: plasma collider interstage**, using plasma lenses
-> looked for opportunities to **implement idea**: - lattice of plasma lenses



C. A. Lindstrøm & E. Adli,
"Design of general apochromatic drift-quadrupole beam lines",
Phys. Rev. Accel. Beams (19) 071002 (2016)

Proposed to do this in CALIFES/CLEAR



Turns out CLEAR has unique parameters for one of that experiments we want to do

	LBNL BELLA	INFN Frascati	DESY Mainz	CERN CLEAR (current)	SLAC FACET-II
Energy / MeV	100	126	855	200	10000
Charge / pC	30	50	1	1-1000	1600
Beam size rms / µm	100	130	150	30 (50 pC) or 70 (1 nC) - 200	100
Bunch length / µm	2	330	> 100000	300-1200	10
Capillary radius / µm	125	500	500	500	
Capillary length / mm	33	30	7	15	
Max current / A	330	100	740	500	
Pressure / mbar	150	40	4	1-30	
Plasma density / cm-3	7×10^{18}	9×10^{16}	$\sim 10^{17}$	2×10^{16} - 7×10^{17}	1×10^{16} - 5×10^{17}
Maximum plasma wakefield / T/m	**14**	**3.5**	**1.2 x 10-4**	**0.0005 - 2260**	**~10000** 100-10^7 (blowout)

With **CLEAR approved (Dec 2016)** and informal agreement from CLIC to get beam time, Oslo went ahead to **form a collaboration** and design a prototype plasma

Timeline

Idea for
plasma lens
lattices
published

7/2016

CALIFES
workshop

10/2016

CLEAR
approval

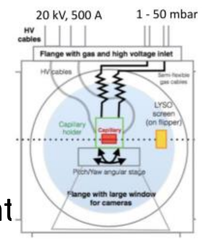
12/2016

Setting up
external coll.
J. Osterhoff (DESY)
S. Hooker (Oxford)

Learning,
planning,
designing
CLEAR PL
(in Oslo)

PhD
student
arrive
at CERN
(COAS)

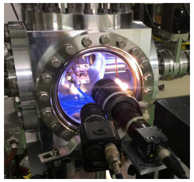
5/2017



PL
build
and
HV-tested
in the lab

8/2017

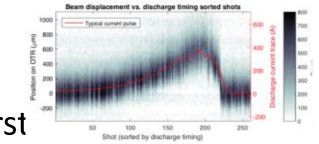
Building
and testing
PL
(at CERN)



PL
integrated
in CLEAR

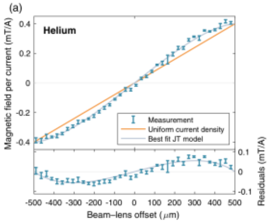
10/2017

Integrating and
debugging
PL
(at CERN)



First
experimental
results

12/2017



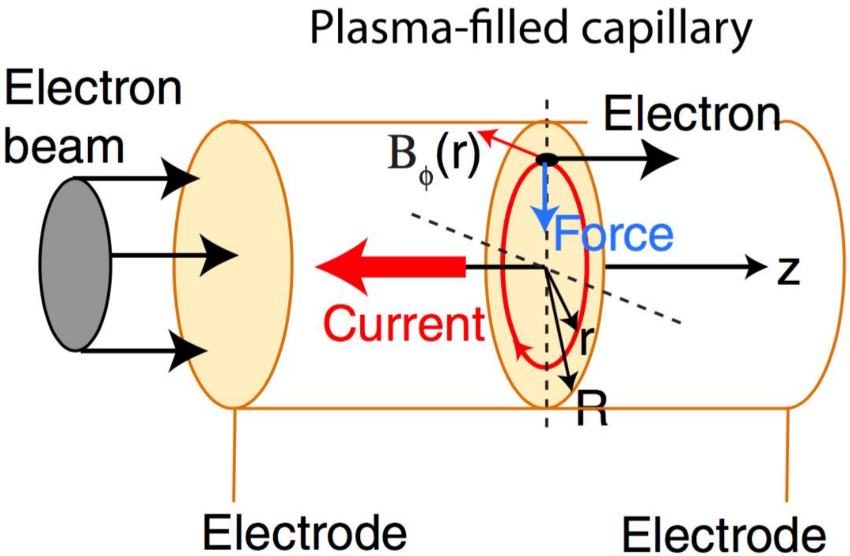
Dedicated
experimental
weeks

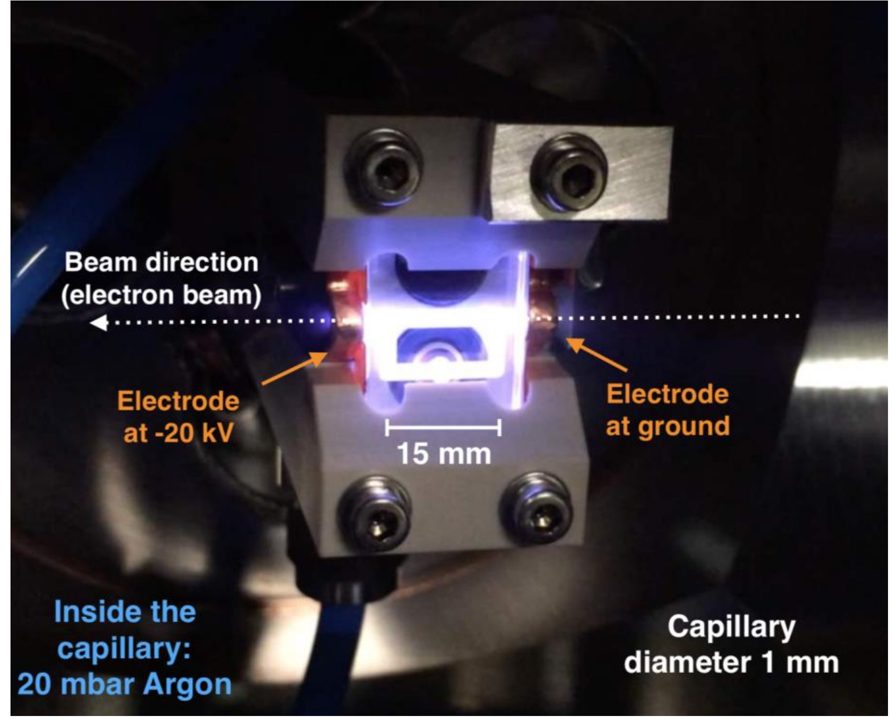
3/2018
5-6/2018

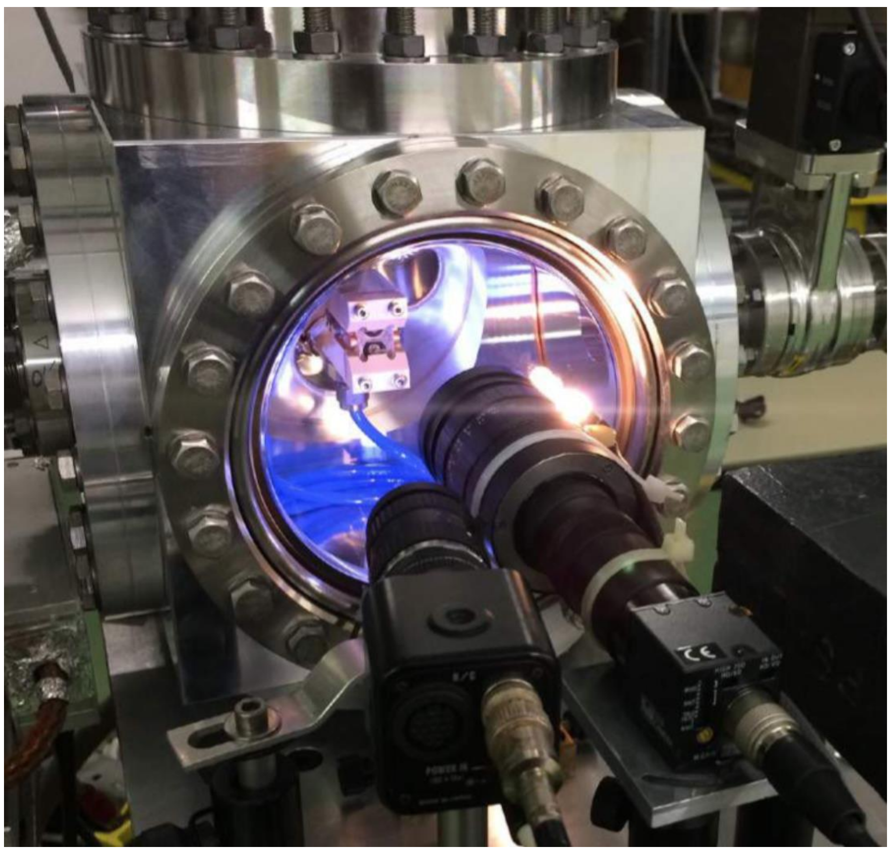
data
analysis

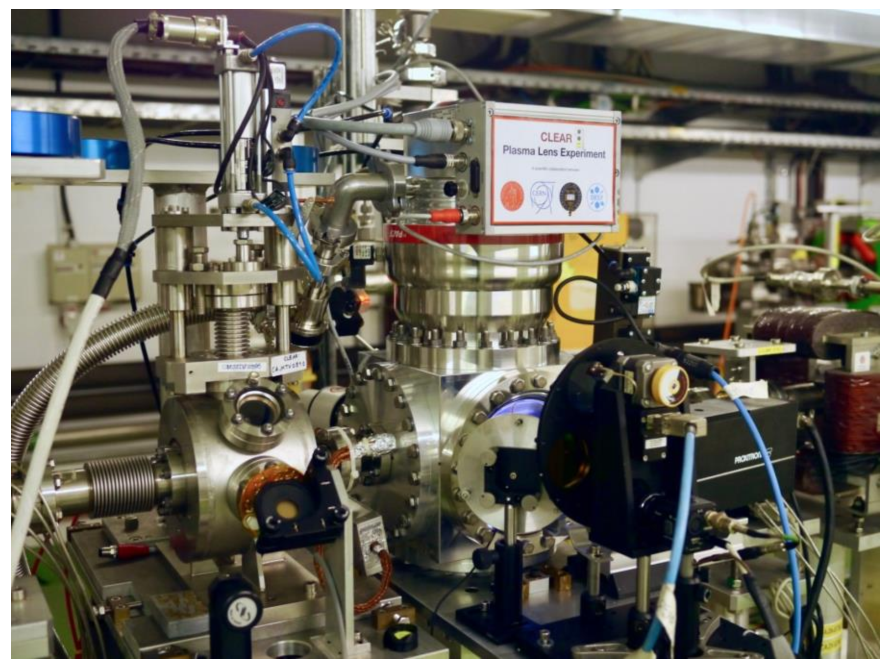
Publication
in
PRL

11/2018


Plasma-filled capillary
Electron beam
Electron
$B_\phi(r)$
Force
z
Current
r
R
Electrode
Electrode


Beam direction
(electron beam)
Electrode
at -20 kV
Electrode
at ground
15 mm
Inside the
capillary:
20 mbar Argon
Capillary
diameter 1 mm




CLEAR
Plasma Lens Experiment

Integration and HV tests:

CERN provided **lab space** for integration and test of components at CERN.
Good level of support from CERN engineers/technician was good
(Completed August 2017)

Due to Oslo being CLIC-collaborator, it was easy to integrate students as CERN-users.

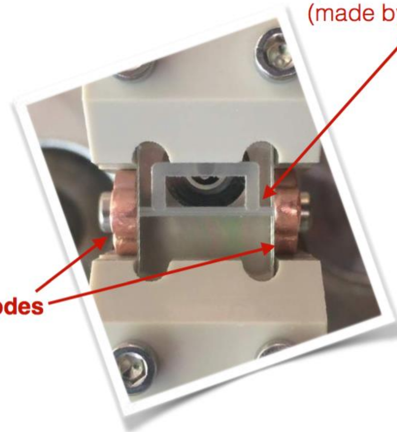
C.A. Lindstrøm
J.H. Røckemann
A. Dyson

Experimental setup

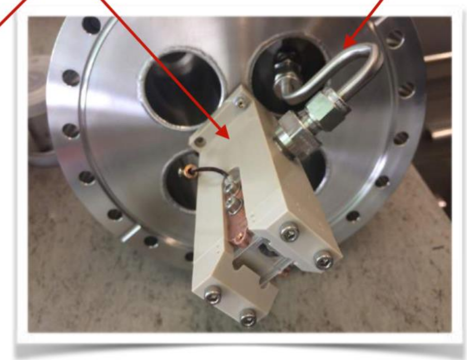
Sapphire capillary
(made by Jan-H. Röckemann, DESY)

PEEK mount
(made by Jan-H. Röckemann, DESY)

Gas line from outside

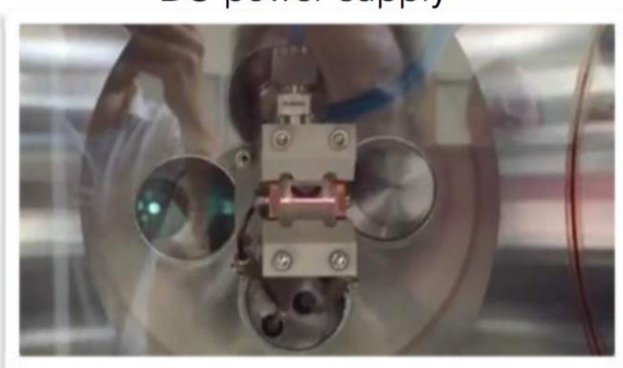


Electrodes

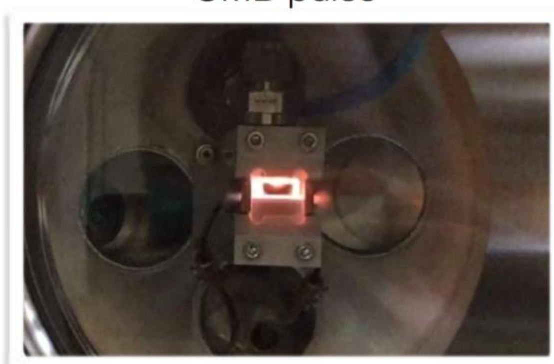


Subsystems

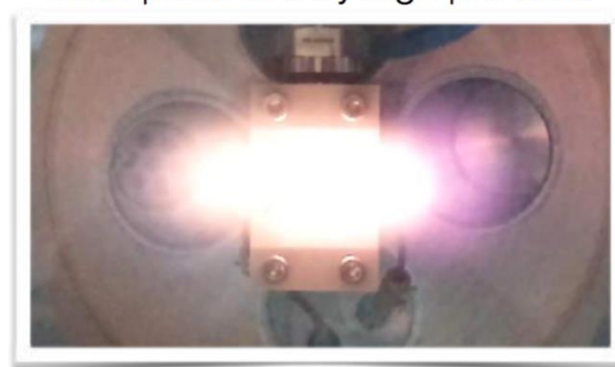
DC power supply



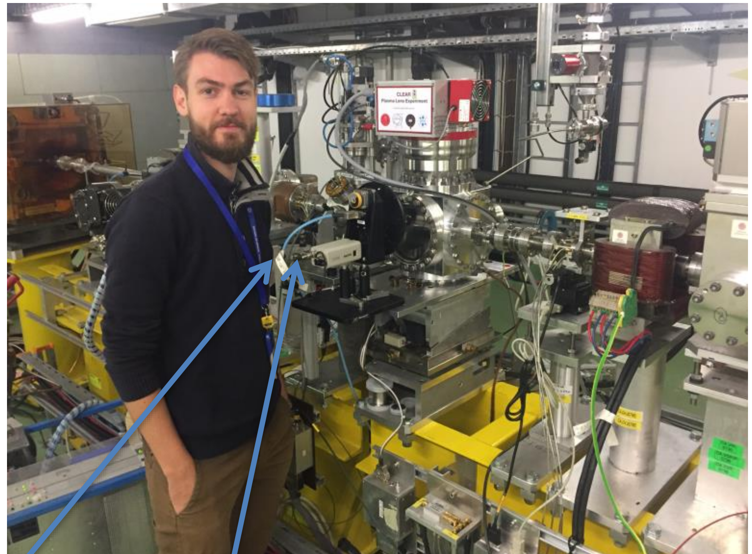
CMB pulse

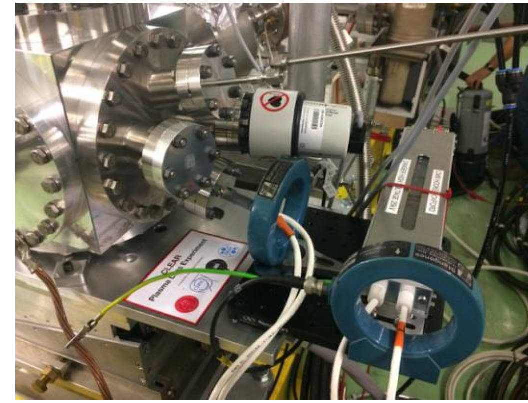


CMB pulse at very high pressure



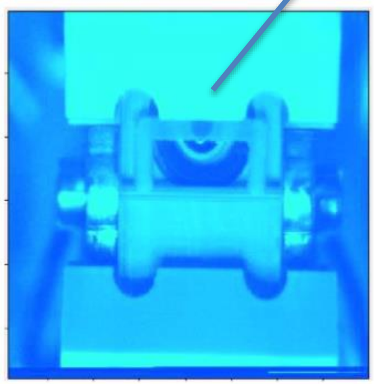
Huge amount of work (integration of gas, HV, vacuum, beam windows).
Good support from CERN, cost of HV and gas infrastructure by CERN, but c**rucial to have Oslo manpower** driving integration work.
First electron beam sent cleanly through capillary end September.



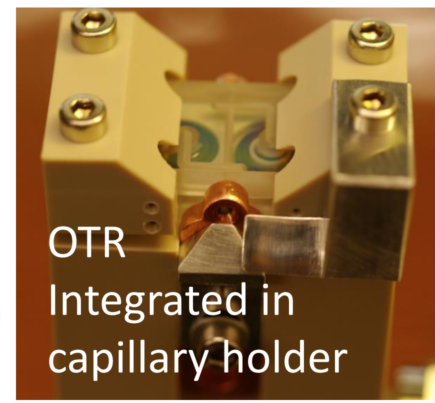


Marx bank outside vacuum, but close to capillary.

Capillary with **chamber light on**



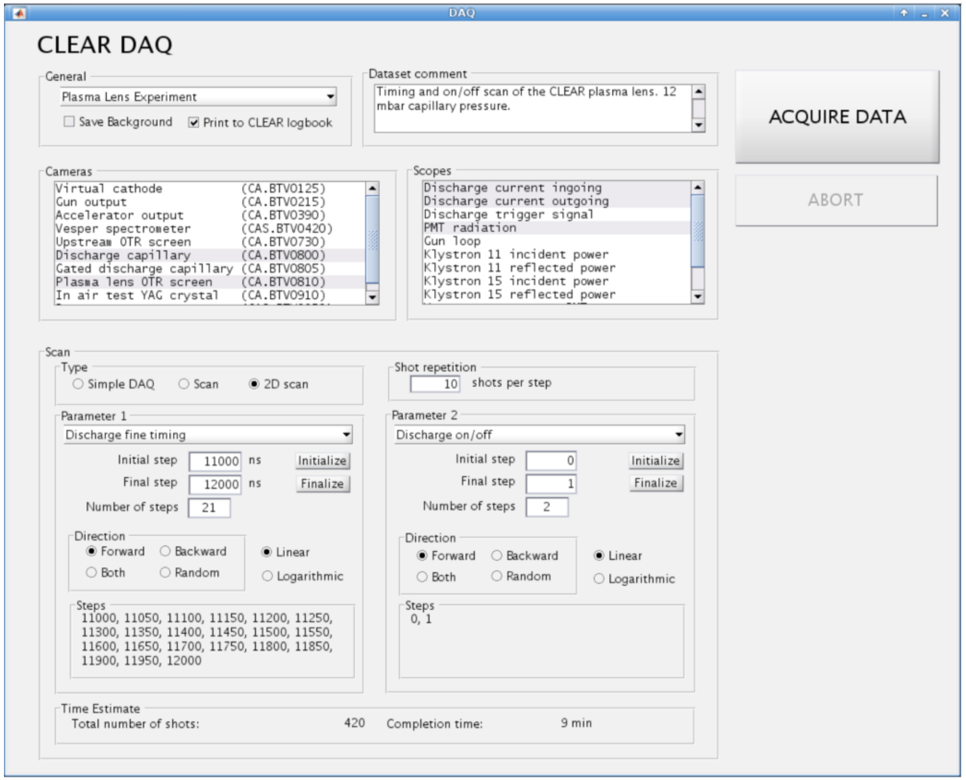
Installation and experiments conducted with help from ***Davide Gamba (CERN, left)*** *and* ***Wilfrid Farabolini (CERN, right)***



Vertical offset scan (beam scintillates in the sapphire)

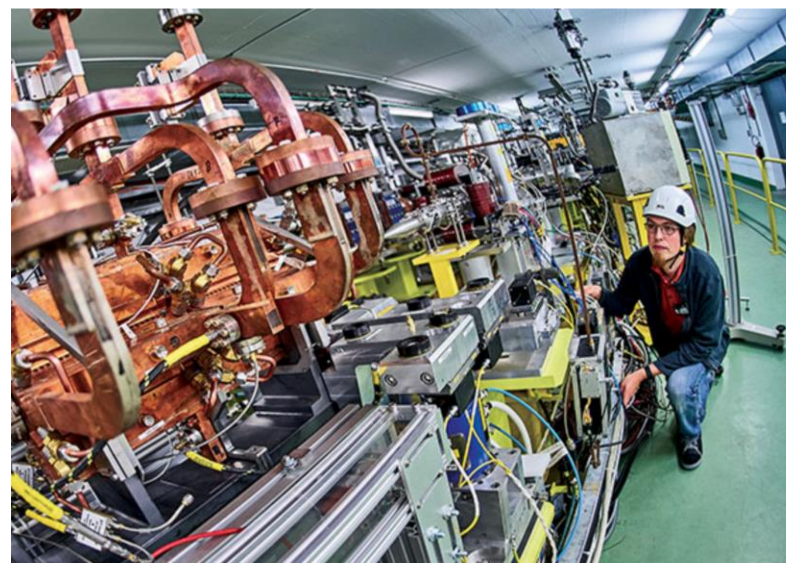
Scintillates below — **Beam passes through cleanly** (750 μm range) — Scintillates above

Plasma lens work (and WFM work) also led to Oslo contribution to general CLEAR infrastructure:



Systematic data taking-instant analysis approach, based on our experiments from FACET/SLAC), new tools available to all experiments.

General Improvement of CLEAR linac (alignment, emittance).
Improved online model.



Aberration #1: Plasma Temperature Gradients

This talk.

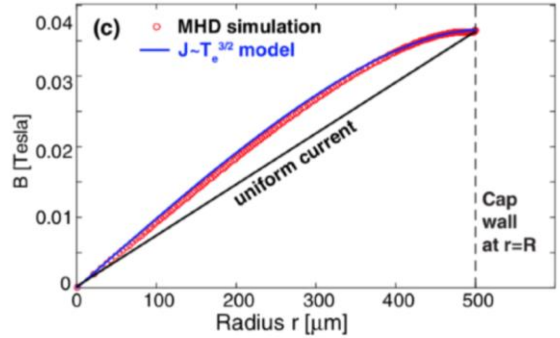
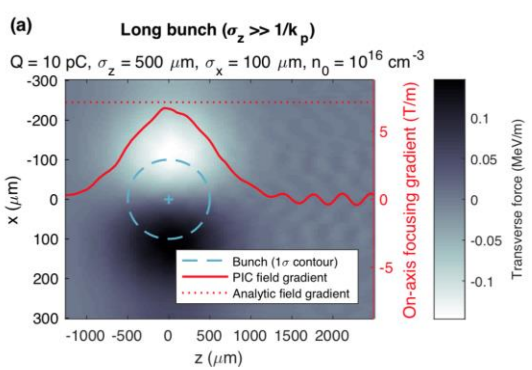


Image source: van Tilborg et al., PRAB 20, 032803 (2017)

Aberration #2: Plasma Wakefield Distortion

Carl A. Lindstrøm's talk yesterday.



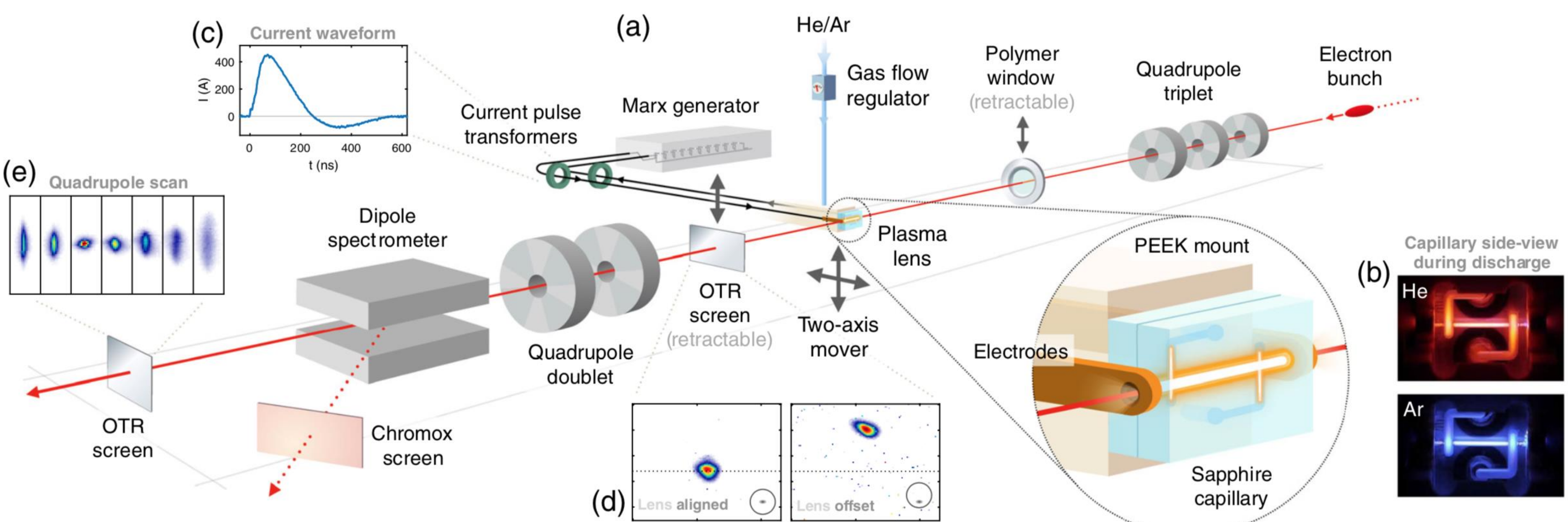
Emittance Preservation in an Aberration-Free Active Plasma Lens

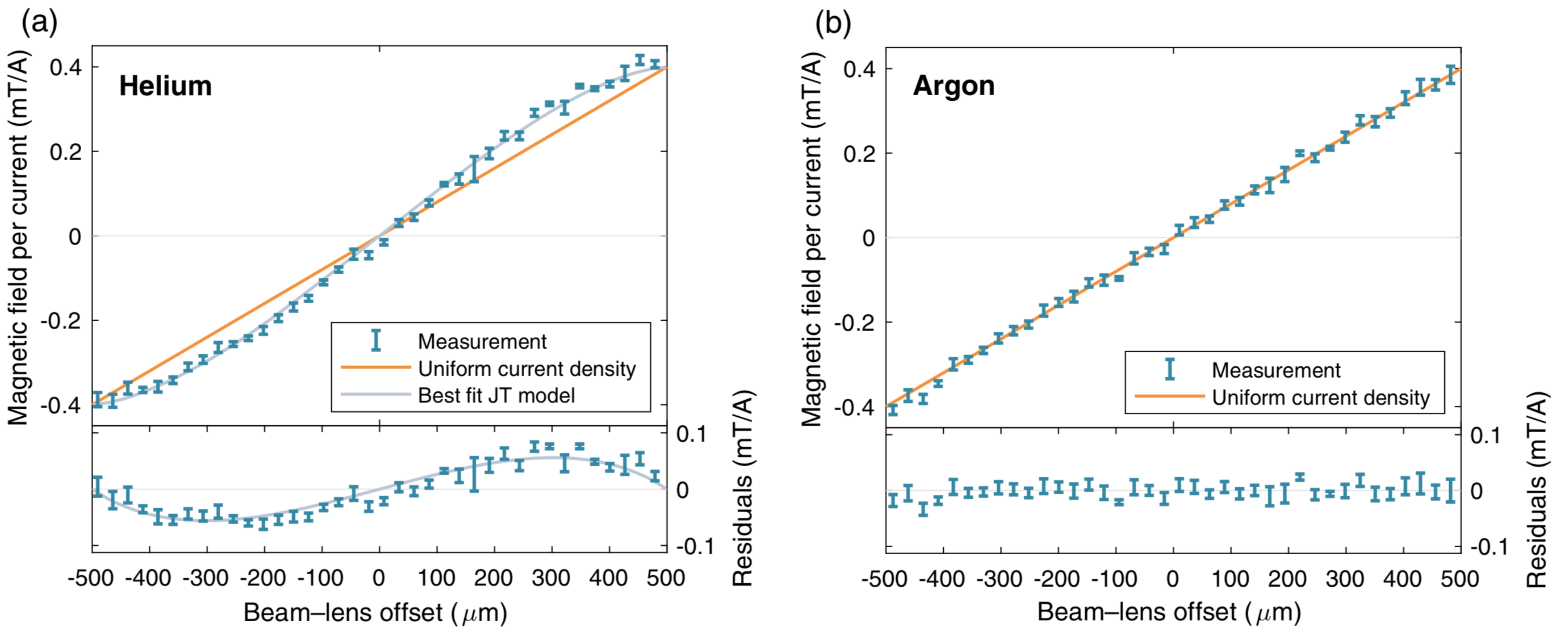
C. A. Lindstrøm,[1,*] E. Adli,[1] G. Boyle,[2] R. Corsini,[3] A. E. Dyson,[4] W. Farabolini,[3] S. M. Hooker,[4,5] M. Meisel,[2] J. Osterhoff,[2] J.-H. Röckemann,[2] L. Schaper,[2] and K. N. Sjobak[1]

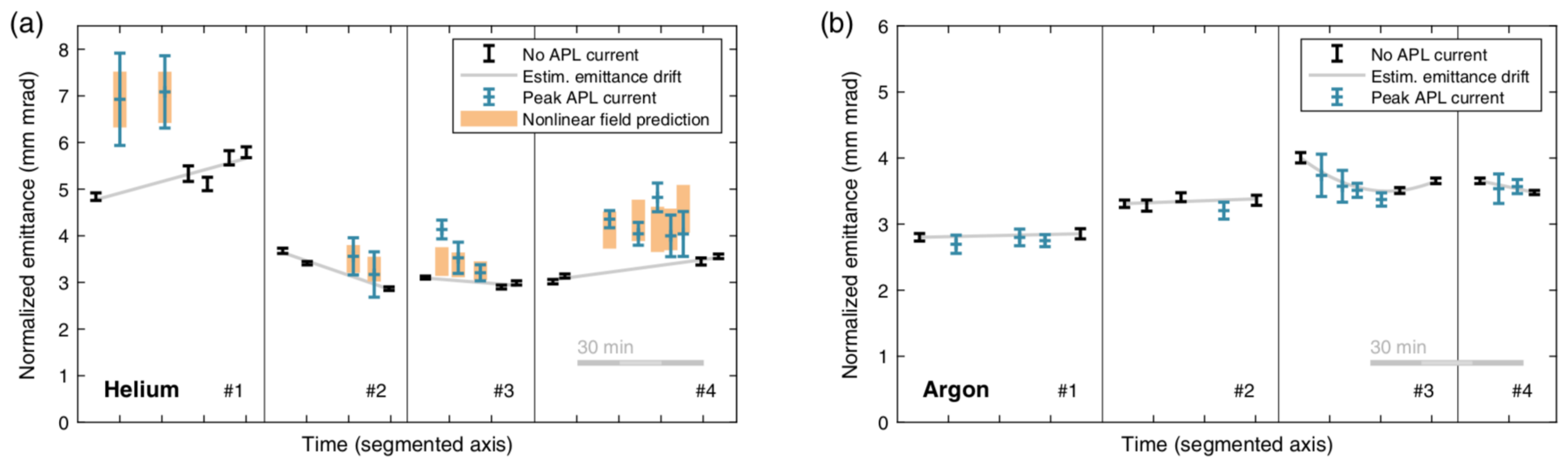
[1]*Department of Physics, University of Oslo, 0316 Oslo, Norway*
[2]*DESY, Notkestraße 85, 22607 Hamburg, Germany*
[3]*CERN, CH-1211 Geneva 23, Switzerland*
[4]*Department of Physics, Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*
[5]*John Adams Institute for Accelerator Science, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom*

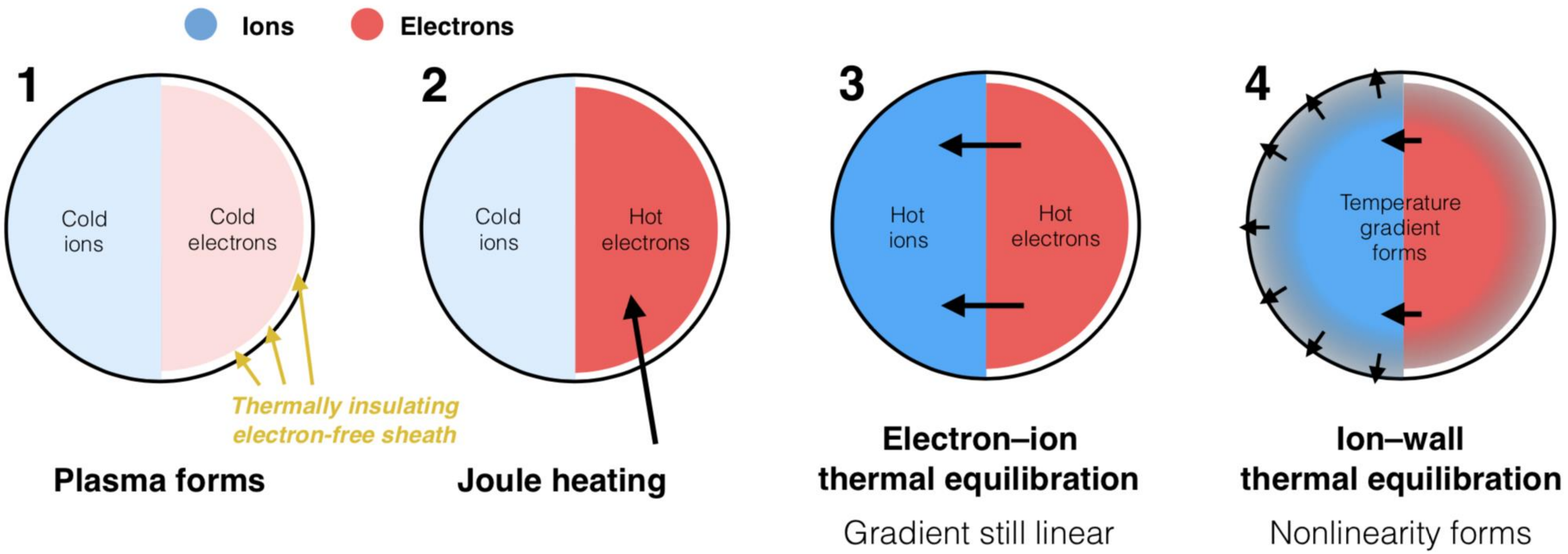
(Received 10 August 2018; published 7 November 2018)

Active plasma lensing is a compact technology for strong focusing of charged particle beams, which has gained considerable interest for use in novel accelerator schemes. While providing kT/m focusing gradients, active plasma lenses can have aberrations caused by a radially nonuniform plasma temperature profile, leading to degradation of the beam quality. We present the first direct measurement of this aberration, consistent with theory, and show that it can be fully suppressed by changing from a light gas species (helium) to a heavier gas species (argon). Based on this result, we demonstrate emittance preservation for an electron beam focused by an argon-filled active plasma lens.




(a)
Helium
Magnetic field per current (mT/A)
Residuals (mT/A)
Measurement
Uniform current density
Best fit JT model
Beam–lens offset (μm)
(b)
Argon
Magnetic field per current (mT/A)
Residuals (mT/A)
Measurement
Uniform current density
Beam–lens offset (μm)


(a)
Normalized emittance (mm mrad)
No APL current
Estim. emittance drift
Peak APL current
Nonlinear field prediction
30 min
Helium
#1
#2
#3
#4
Time (segmented axis)
(b)
Normalized emittance (mm mrad)
No APL current
Estim. emittance drift
Peak APL current
30 min
Argon
#1
#2
#3
#4
Time (segmented axis)



Hotter plasma conducts better:
more current in the center
=> **enhanced focusing in the center**

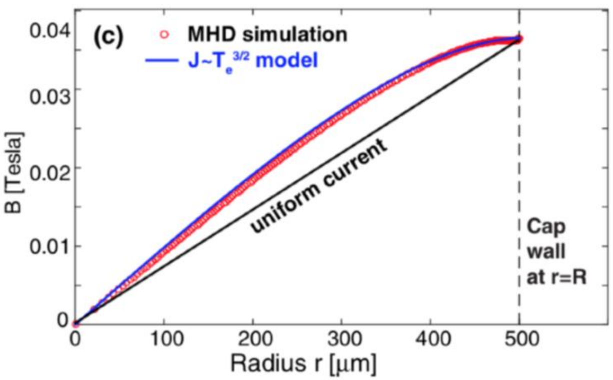
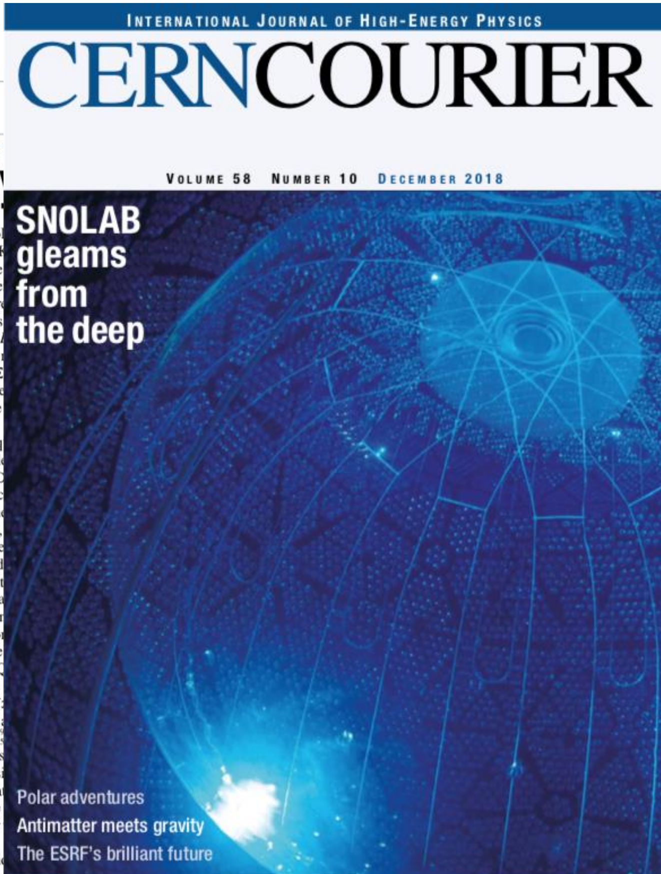


Image source: van Tilborg et al., PRAB 20, 032803 (2017)

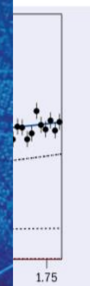
DESY-partners are working on MHD simulation to better underastand and quantify the dependence of Z on the non-linearity.
Practical goal: optimize Z for low non-linearity and also low scatter.



Hadron spe…

Doubl… pan

High-luminosity col…
positrons at the KEK…
have established the…
baryon with strange…
light on the structur…
hyperon resonances…
to *Physical Review…*
KEKB's Belle exper…
observation of the Ξ…
980 fb⁻¹ data sample…
also found evidence…
heavier Ξ(1690)⁰.
The constituent-q…
very successful in d…
"cascade" baryon. D…
experiments half a c…
corresponding to th…
flavour-SU(3) octet,…
quark plus two more…
is made of one u and…
some observed excit…
well with the Standa…
The study of such u…
probes the limitatio…
could reveal unexpe…
chromodynamics (Q…
Belle researchers…
from its decay to Ξ⁻…
measuring its mass…
1610.4 ± 6.0 (stat) $^{+5.9}_{-3.5}$…
59.9 ± 4.8 (stat) $^{+2.8}_{-3.0}$ (s…
The values are consi…
previous sightings a…
and the width of the…
be somewhat larger…
exited Ξ states.
Experimental evi…
Ξ(1620) → Ξπ deca…



…he Ξ(1530)⁰
…on
…e).

…y been
…graded
…urier
…nts at the
…states. In
…in 2014 the
…he Ξ'^{-}_{b} and
…rmed Ξ^{++}_{cc}.
…scopy studies
…e together
…ndamental
…onic matter
….
…06181.

Accelerators

Plasma lenses promise smaller accelerators

An international team has made an advance towards more compact particle accelerators, demonstrating that beams can be focused via a technique called active plasma lensing without reducing the beam quality.

Building smaller particle accelerators has been a goal of the particle accelerator community for decades, both for basic research and applications such as radiotherapy. In addition to new accelerating mechanisms, smaller accelerators require novel ways to focus particle beams.

Active plasma lensing uses a large electric current to set up strong magnetic fields in a plasma that can focus high-energy beams over distances of centimetres, rather than metres as is the case for conventional magnet-based techniques. However, the large current also heats the plasma, preferentially heating the centre of the lens. This temperature gradient leads to a nonlinear magnetic field, an aberration, which degrades the particle-beam quality.

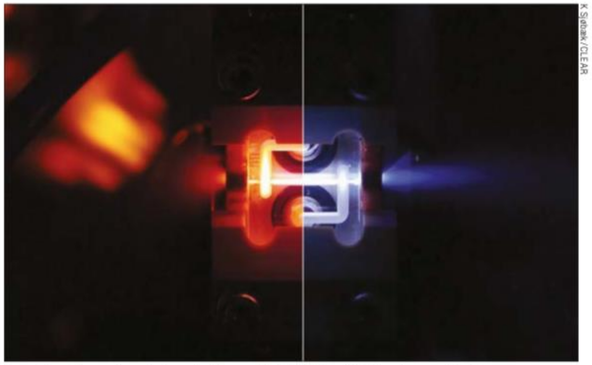
Using a high-quality 200 MeV electron beam at the CLEAR user facility at CERN (*CERN Courier* November 2017 p8), Carl A Lindstrøm of the University of Oslo, Norway, and collaborators recently made the first direct measurement of this aberration in an active plasma lens, finding it to be consistent with theory. More importantly, they discovered that this aberration can be suppressed by simply changing the gas used to make the plasma from a light gas (helium) to a heavier gas (argon). Changing the gas slows down the heat transfer so that the aberration does not have time to form, resulting in ideal, degradation-free focusing. It represents a significant step towards making active plasma lenses a standard accelerator component in the future, says the team.

CLEAR evolved from a test facility for the Compact Linear Collider (CLIC) ›

called CTF3, which ended a successful programme in 2016. CLEAR offers general accelerator R&D and component studies for existing and possible future accelerator applications, such as high-gradient "X-band" acceleration methods (*CERN Courier* April 2018 p32), as well as prototyping and validation of accelerator components for the High-Luminosity LHC upgrade.

"Working at CLEAR was very efficient and fast-paced – not always the case in large-scale accelerator facilities," says Lindstrøm. "Naturally, we hope to continue our plasma lens research at CLEAR. One exciting direction is probing the limits of how strong these lenses can be. This is clearly the lens of the future."

Further reading
C A Lindstrøm *et al.* 2018 *Phys. Rev. Lett.* **121** 194801.



K Sjøbæk/CLEAR

An active plasma lens during discharge in both helium (left) and argon (right).

Antimatter

Exploring how antimatter falls

Two new experiments at CERN, ALPHA-g and GBAR, have begun campaigns to check whether antimatter falls under gravity at the same rate as matter.

The gravitational behaviour of antimatter has never been directly probed, though indirect measurements have set limits on the deviation from standard gravity at the level of 10^{-6} (*CERN Courier* January/February 2017 p39). Detecting even a slight difference between the behaviour of antimatter and matter with respect to gravity would mean that Einstein's equivalence principle is not perfect and could have major implications for a quantum theory of gravity.

ALPHA-g, a close model of the ALPHA experiment, combines antiprotons from CERN's Antiproton Decelerator (AD) with positrons from a sodium-22 source and traps the resulting antihydrogen atoms in a vertical magnetic trap about 2 m tall. To measure their free-fall, the field is switched off so that the atoms fall under gravity and the position where the antiatoms annihilate with normal matter allows the rate to be determined precisely.

GBAR adopts a similar approach but takes antiprotons from the new and lower-energy ELENA ring attached to the AD (*CERN Courier* December 2016 p16) and combines them with positrons from a small linear accelerator to make antihydrogen ions. Once a laser has stripped all but one positron, the neutral antiatoms

CERN-PHOTO-201810-267-11

The insertion of the ALPHA-g experiment at the Antiproton Decelerator hall at CERN on 12 October.

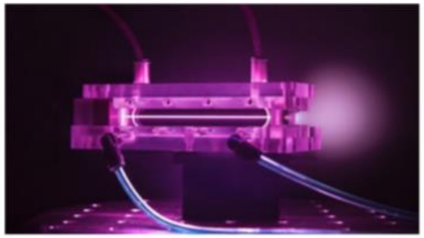
will be released from the trap and allowed to fall from a height of 20 cm.

ALPHA-g began taking beam on 30 October, while ELENA has been delivering beam to GBAR since the summer, allowing the collaboration to perfect the beam-delivery system. Both experiments are being commissioned before CERN's accelerators are shut down on 10 December for a two-year period. The ALPHA-g team hopes to be able to gather enough data during this short period to make a first measurement of antihydrogen in free fall, while the brand new GBAR experiment aims to make a first measurement when antiprotons are back in the machine in 2021. A third experiment at the AD hall, AEgIS, which has been in operation for several years, is also measuring the effect of gravity on antihydrogen using yet another approach, based on a beam of antihydrogen atoms. AEgIS is also hoping to produce its first antihydrogen atoms this year.

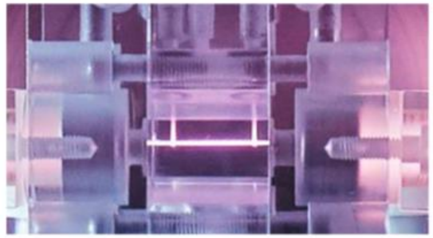
So far, most efforts at the AD have focused on looking for charge–parity–time violation by studying the spectroscopy of antihydrogen and comparing it with that of hydrogen (*CERN Courier* March 2018 p30). This latest round of experiments opens a new avenue in antimatter exploration.

We are not the only group doing plasma lenses experiments:

LBNL

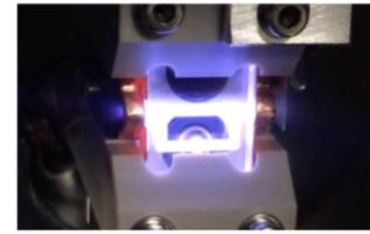


DESY



INFN

CERN



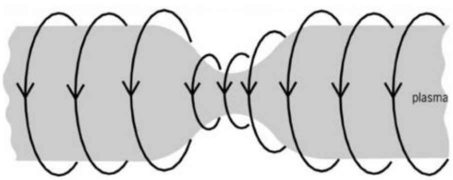
- J. van Tilborg et al., Phys. Rev. Lett. **115,** 184802 (2015)
- S. Steinke et al., Nature **530**, 190 (2016)
- R. Pompili et al., Appl. Phys. Lett. **110**, 104101 (2017)
- R. Pompili et al., AIP Advances **8**, 015326 (2018)
- A. Marocchino et al., Appl. Phys. Lett. **111**, 184101 (2017)
- J. van Tilborg et al., Phys. Rev. ST Accel. Beams **20**, 032803 (2017)
- J. H. Roeckeman et al., to be published
- R. Pompili et al., Phys. Rev. Letter 121, 174801 (2018)
- ...

However, the CLEAR plasma lens collaboration has **in a time scale of one year** managed to get to the edge of the research field, and **contributed with new results**:

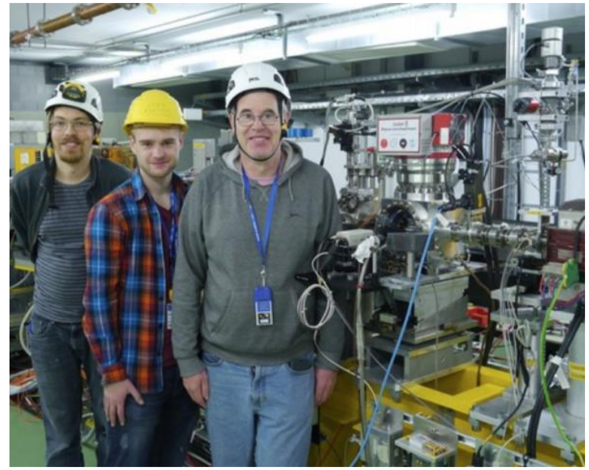
- C. A. Lindstrøm and E. Adli, Phys. Rev. Accel. Beams **19**, 071002 (2016)
- C. A. Lindstrøm et al., Nucl. Instrum. Methods Phys. Res. A, Accepted for publication (2018), https://doi.org/10.1016/j.nima.2018.01.063
- C. A. Lindstrøm and E. Adli, Submitted to Phys. Rev. Accel. Beams (2018), arXiv:1802.02750
- Linearity results: to be published:

2019 Plans

z-pinching governed by the "Bennett limit"
— only occurs at high currents



$$\frac{B_\phi^2}{2\mu_0} < n_0 k_B T$$



- Triple Marx Bank installed, potential to reach ~1000 A
- First post-PRL, post-Carl beam time in December 2018
- Very high focusing gradients measured directly**; about 2kT/m**
- Now we have data for multiple gases, He Ar, N, He,
- **No pinch observed**
- Nonlinearity turn-on observed in Neon; just on the end of the falling edge.
- Analysis ongoing!
- Completementary experiments planned for 2019

However, from our work on plasma wakefield aberration, it looks like :
No part of the active plasma lens parameter space is consistent with use for the very intesnse beams needed for linear colliders interstages (Carl's talk yesterday)

- Our original proposal of plasma lens lattices [for interstages] seems less interesting
- Perhaps more promising to look into larger lenses for proton/ion applications

Conclusions

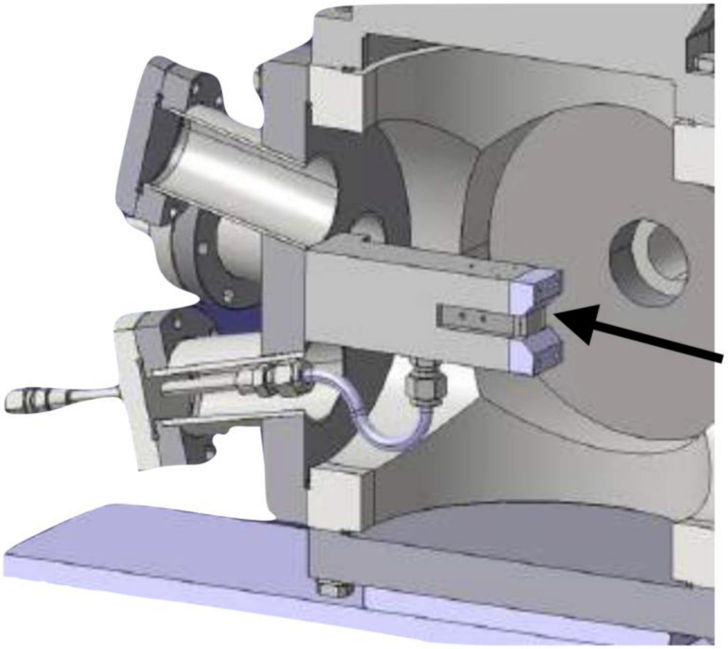
- CLEAR startup was well timed for Oslo ideas for novel plasma lens interstage demonstration with plasma lenses
- Oslo was first user to implement plasma experiments at CLEAR: gas, materials, HV in beam line
  - Could not be done without large presence by Oslo at CERN
  - Could not be done without significant contribution from CERN
- CLEAR accessibility a large plus in the integration and commissioning (easy, frequent access)
- CLEAR operational support good, but not always present
  - Useful/needed for Oslo to also know how to operate the beam
- We are happy with the amount of beam time we got
- 2018: dedicated runs led to high-impact publication(s) expected
- 2019: complement results with Oslo lens, pinching. Seek funding.

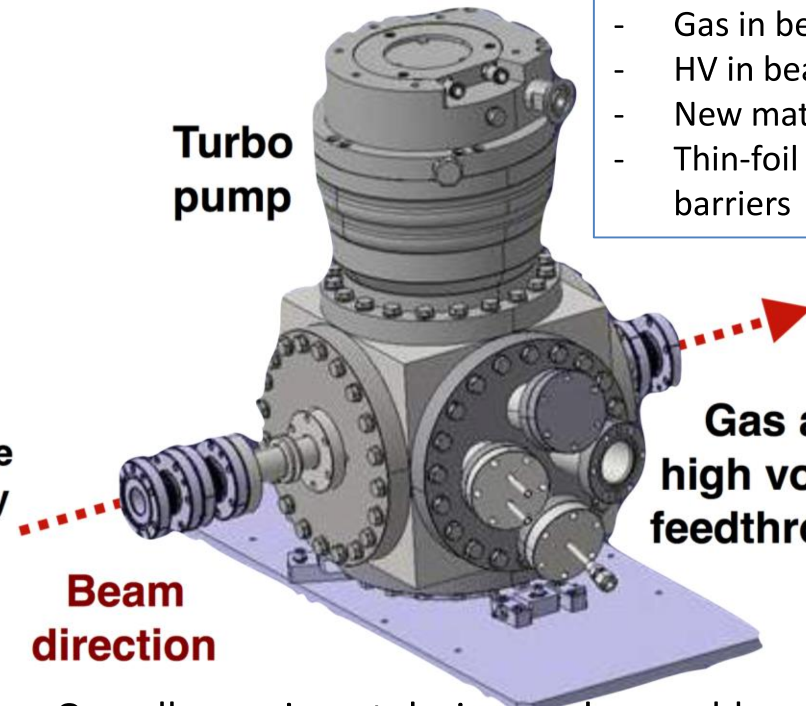
Extra

Compact plasma lens

Goal: strong, linear radial focusing from driving current a gas discharge.

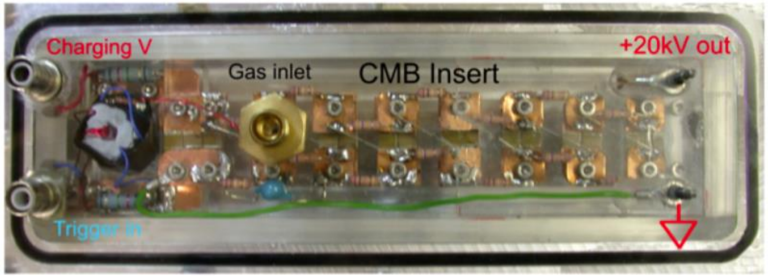
Novelty for CTF3:
- Gas in beamline
- HV in beamline
- New materials
- Thin-foil vacuum barriers





Overall experiment design, and assembly, integration and test, by Oslo.

Capillary and holder design by **DESY**, based on experience from DESY and Oxford



Oxford Compact Marx Bank:
Inexpensive and precise source of ~20 kV, ~500 A discharges

A. E. Dyson, C. Thornton, and S. M. Hooker, Rev. Sci. Instrum. ***87****, 093302 (2016)*