ALIC Plans at CLEAR

R. Corsini - CERN

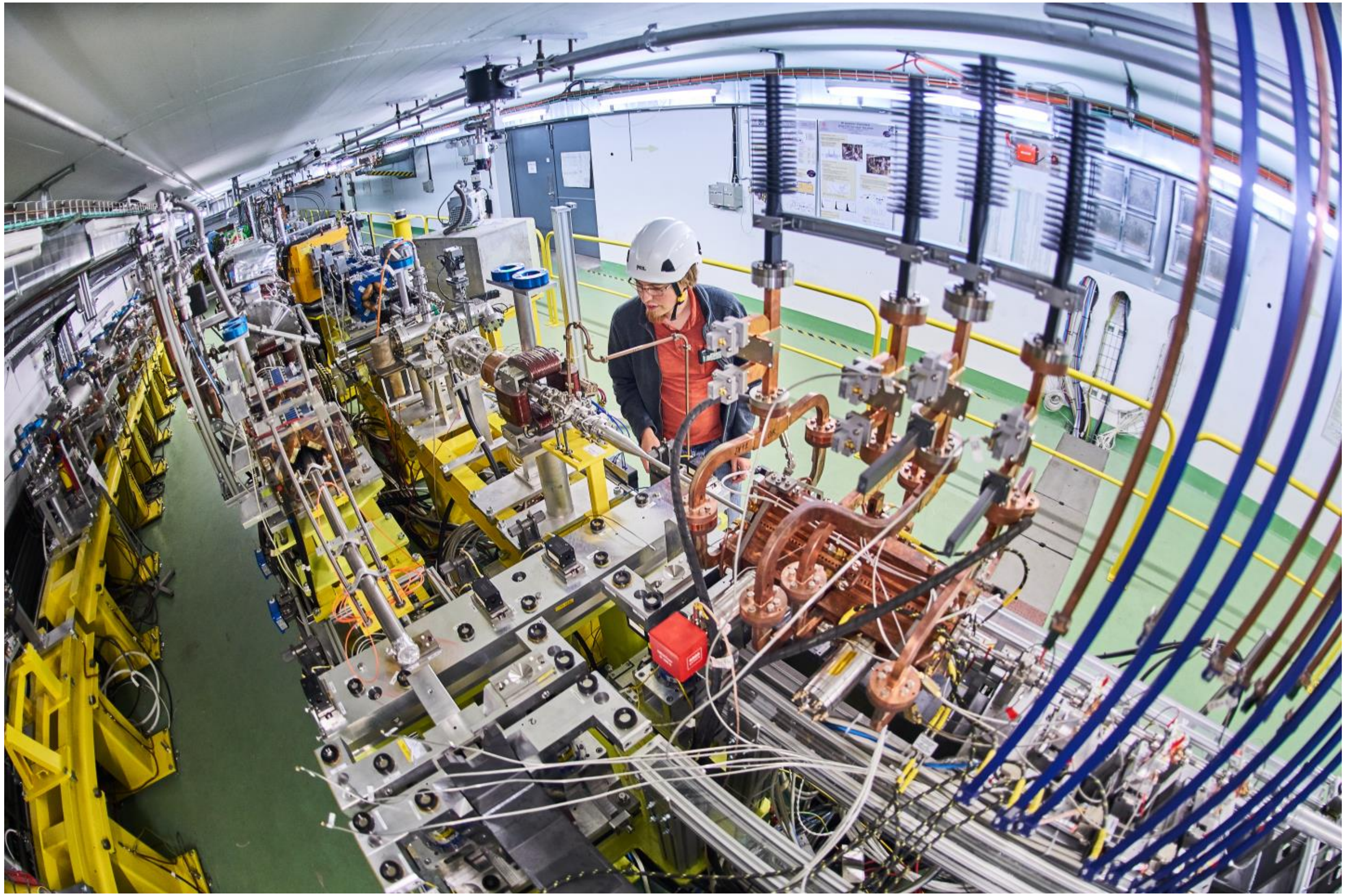
OUTLINE

Introduction on CLEAR

Past results:
- Plasma Lens
- THz radiation

Future plans

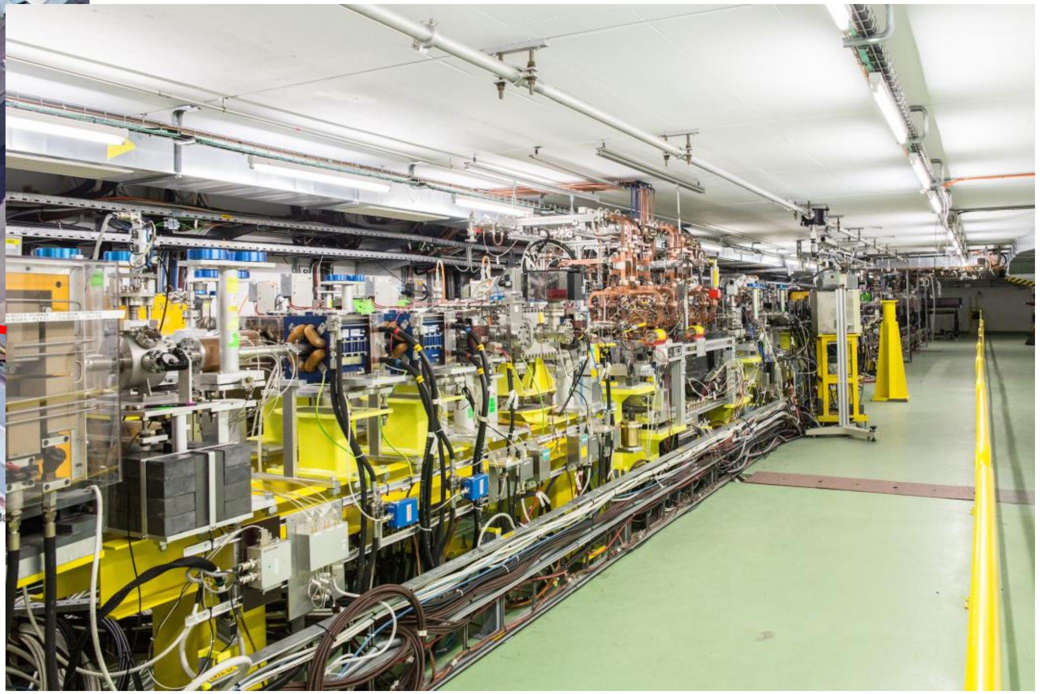
Conclusions



CERN Linear Electron Accelerator for Research

CLIC Test Facility (CTF3) - completed its experimental program in 2016

Proposal to reuse the CLEX area and the CALIFES e- linac for accelerator R&D



CLEAR is a user facility at CERN, running in parallel with the main CERN accelerator complex, with the primary goal of enhancing and complementing the existing accelerator R&D and testing capabilities at CERN.

Approved December 2016

CLEAR Scope and Motivations

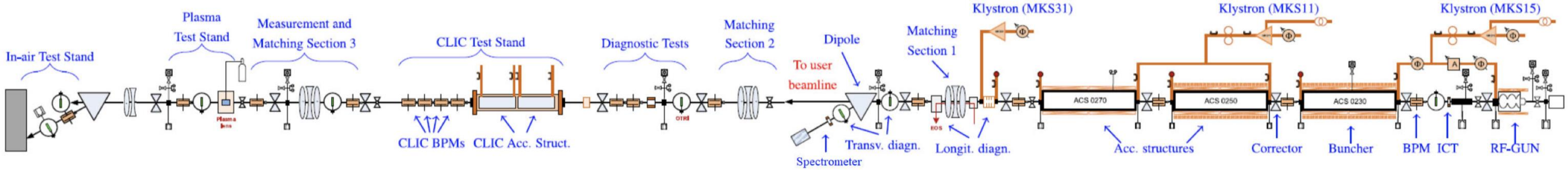
CLEAR - Scientific and strategic goals:

- Providing a test facility at CERN with high availability, easy access and high quality e- beams.
  - Performing R&D on accelerator components, including innovative beam instrumentation prototyping, high gradient RF technology realistic beam tests and beam-based impedance measurements.
  - Providing an irradiation facility with high-energy electrons, e.g. for testing electronic components in collaboration with ESA or for medical purposes(VHEE), possibly also for particle physic detectors.
  - Performing R&D on novel accelerating techniques – electron driven plasma and THz acceleration. In particular developing technology and solutions needed for future particle physics applications, e.g. beam emittance preservation for reaching high luminosities.
- Maintaining CERN and European expertise for electron linacs linked to future collider studies (e.g. CLIC and ILC, but also AWAKE), and providing a focus for strengthening collaboration in this area.
- Using CLEAR as a training infrastructure for the next generation of accelerator scientists and engineers.

CLEAR Beamline & parameters

Experimental beam line

200 MeV injector



Beam parameters	Range	Comments
Energy	60 – 220 MeV	More flexible with 2 klystrons. > 220 MeV with pulse compression.
Energy Spread	< 1 MeV (FWHM)	
Bunch Charge	10 pC – 3 nC	Photocathode changed - laser improvement
Bunch Length	0.2 ps – 10 ps	Optimized velocity bunching - limited by measurements resolution
Normalized emittances	3 μm to 30 μm	Bunch charge dependent
Repetition rate	0.8 to 5 Hz	25 Hz with klystrons and laser upgrade
Number of micro-bunches in train	1 to >150	Single bunch capability assessed
Micro-bunch spacing	1.5 GHz (Laser)	3.0 GHz: Dark current

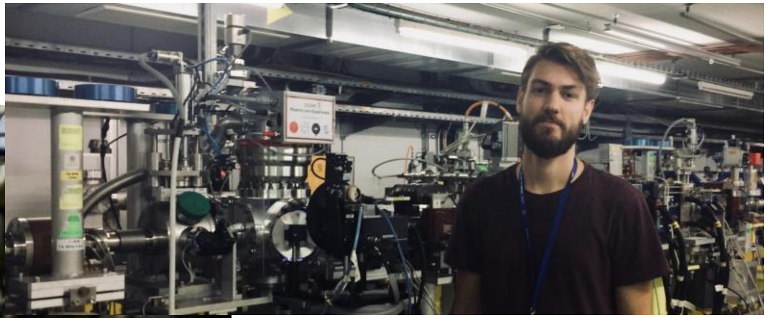
CLEAR operation 2017-2018

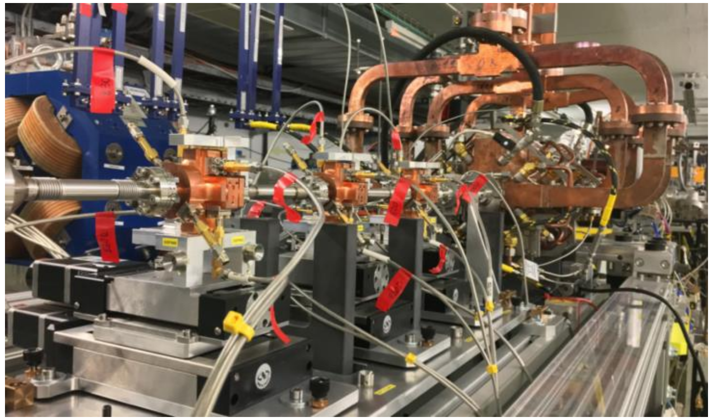
Start with beam August 2017

- 55 weeks of operation in 2017-2018

Main activities:

- CLIC & high-gradient X-band
- Instrumentation R&D
- VESPER irradiation test stand:
  - Electronic components for accelerators detectors and space applications (with ESA)
  - Medical applications (VHEE, FLASH)
- Novel acceleration techniques: plasma focusing and acceleration, THz radiation



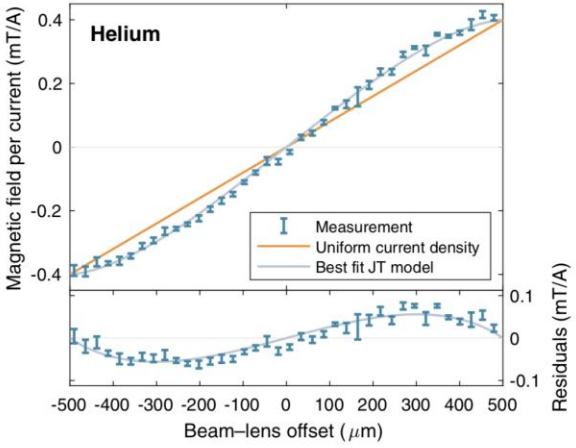


Plasma lens experiment

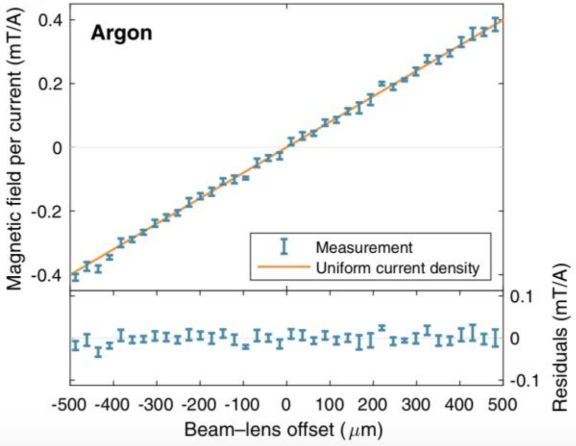
Collaboration between Oslo and Oxford Universities, CERN and DESY

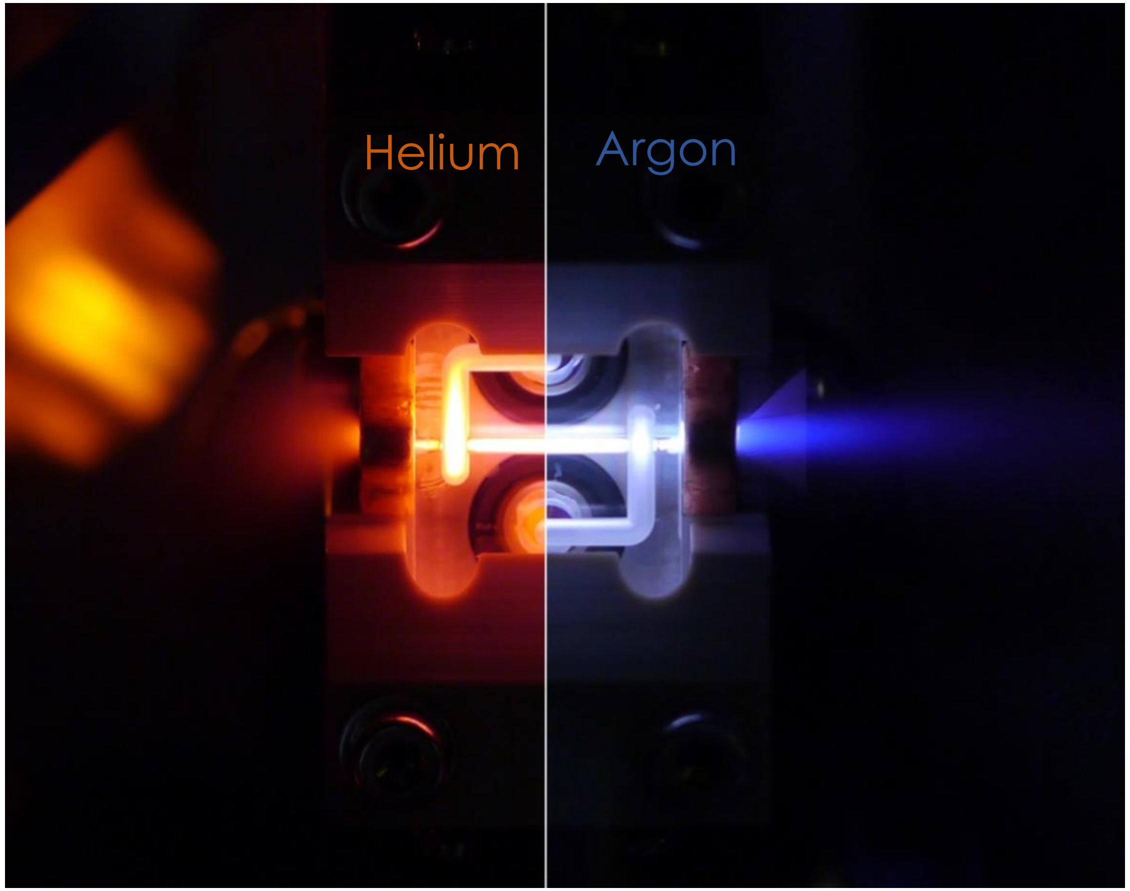
Demonstrated linearity in active plasma lens and explained linear/nonlinear behavior linked to Gas species in plasma.

(a)



(b)

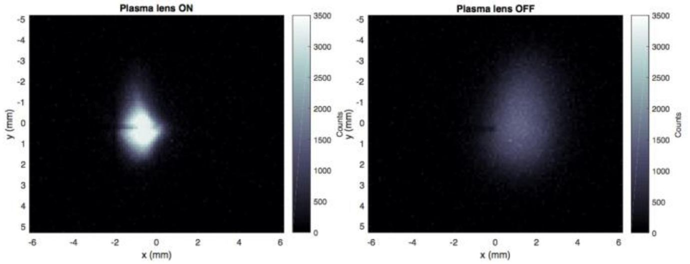


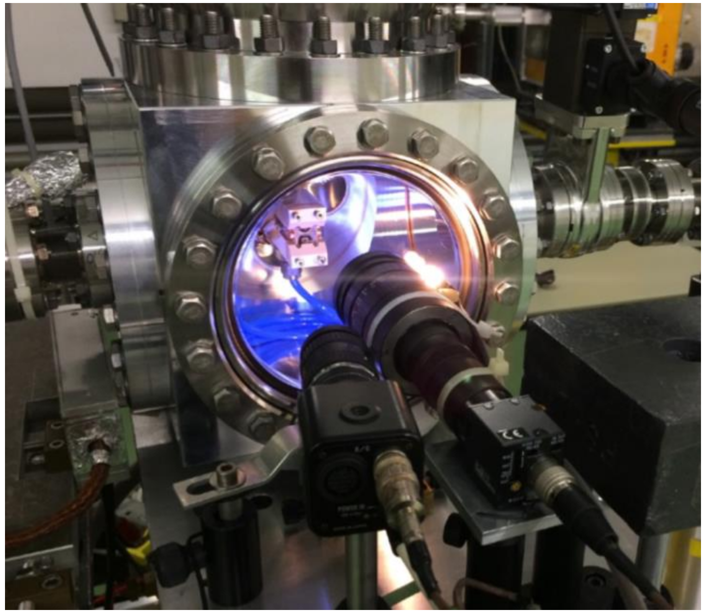


Emittance Preservation in an Aberration-Free Active Plasma Lens

C. A. Lindstrøm, E. Adli, G. Boyle, R. Corsini, A. E. Dyson, W. Farabolini, S. M. Hooker, M. Meisel, J. Osterhoff, J.-H. Röckemann, L. Schaper, and K. N. Sjobak
Phys. Rev. Lett. **121**, 194801 – Published 7 November 2018

Plasma lens on/off

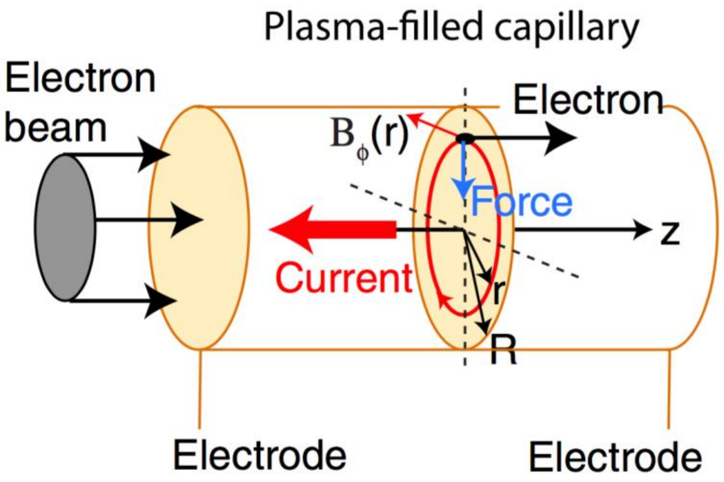


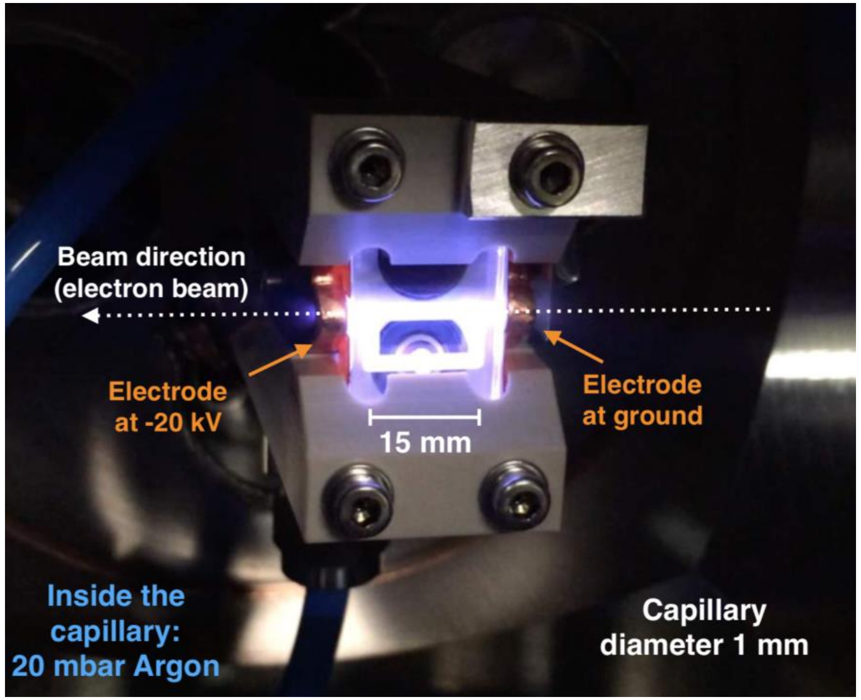


https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.121.194801

Active Plasma Lenses

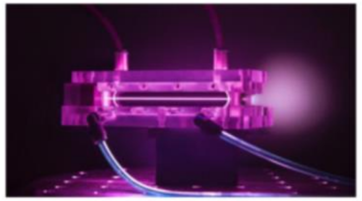
Thin capillary, ~1 mm diameter, 1–10 cm length > Gas pressure 1–100 mbar
High voltage electrodes at either end, 10–30 kV
Large currents, 100–1000 A
Uniform current density ⇒ linear B-field and focusing



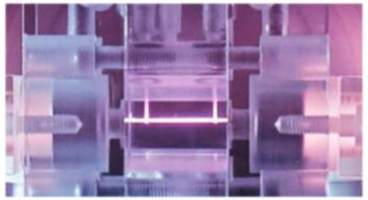


Panofsky, Wolfgang Kurt Hermann, and W. R. Baker. "A Focusing Device for the External 350-Mev Proton Beam of the 184-Inch Cyclotron at Berkeley." Review of Scientific Instruments 21.5 (1950): 445-447.

LBNL



DESY



INFN

- 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)
- …

Active Plasma Lens - Issues

For emittance preservation, the APL must be aberration-free.

Three main aberrations occur in an active plasma lens:

- Plasma temperature gradients
- Plasma wake-field distortion (passive plasma lensing)
- z-pinching

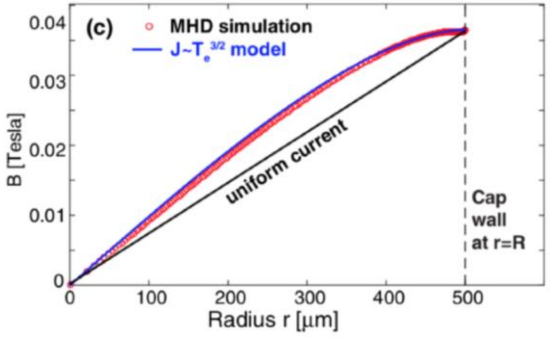
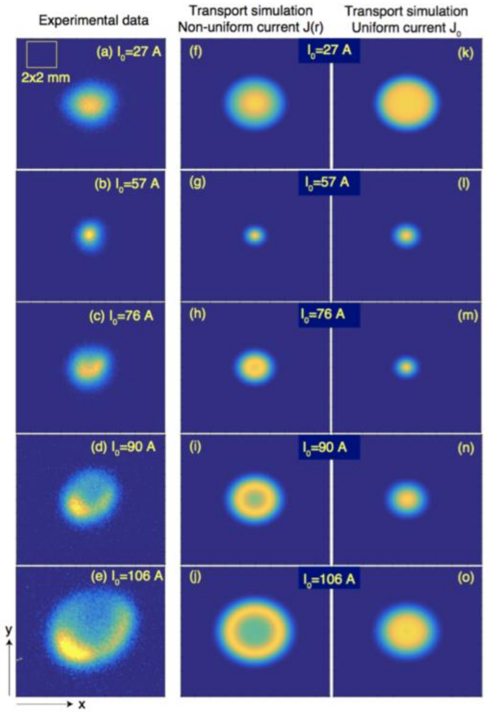


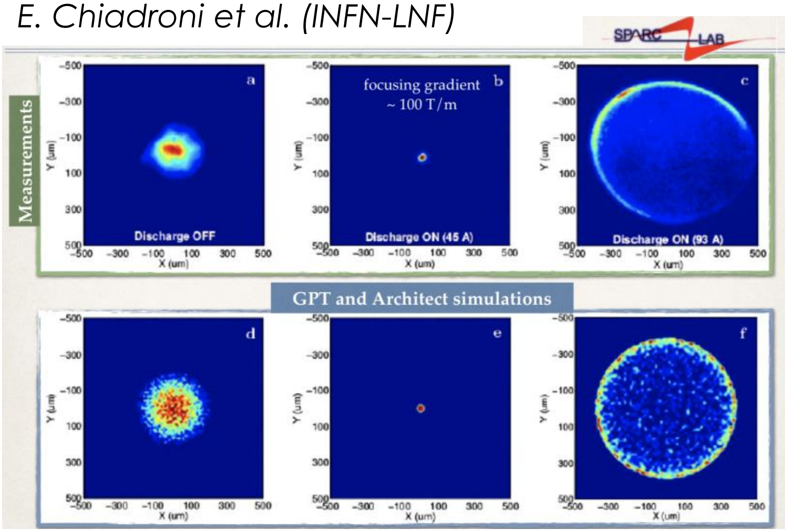
Image source: van Tilborg et al., PRAB 20, 032803 (2017)

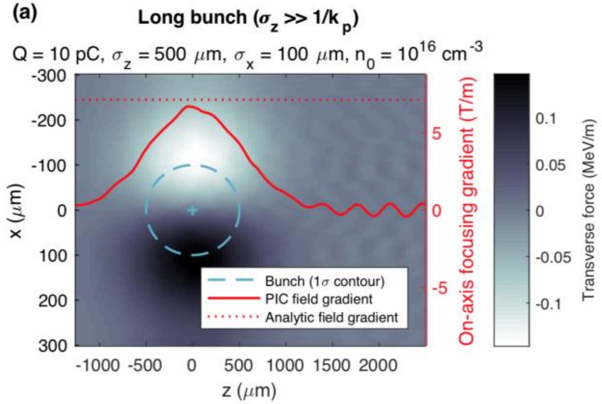
J. Van Tilborg et al. (LBNL)



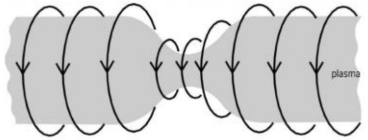
Aberrations observed at BELLE – LBNL and SPARC LAB (INFN-LNF)

E. Chiadroni et al. (INFN-LNF)





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

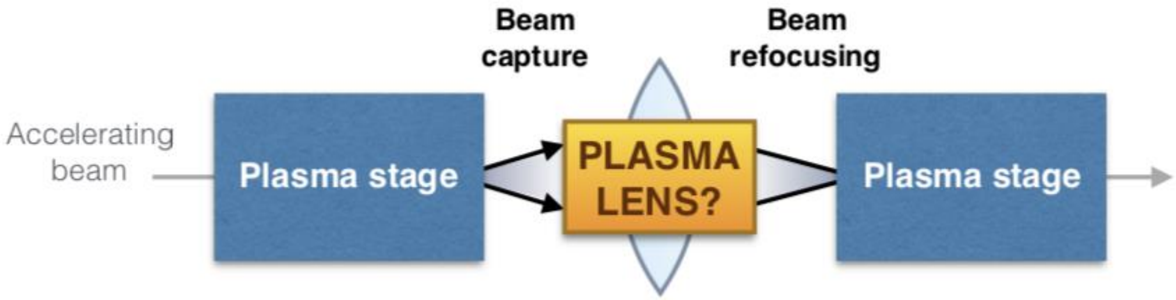


$$\frac{B_\phi^2}{2\mu_0} < n_0 k_B T$$

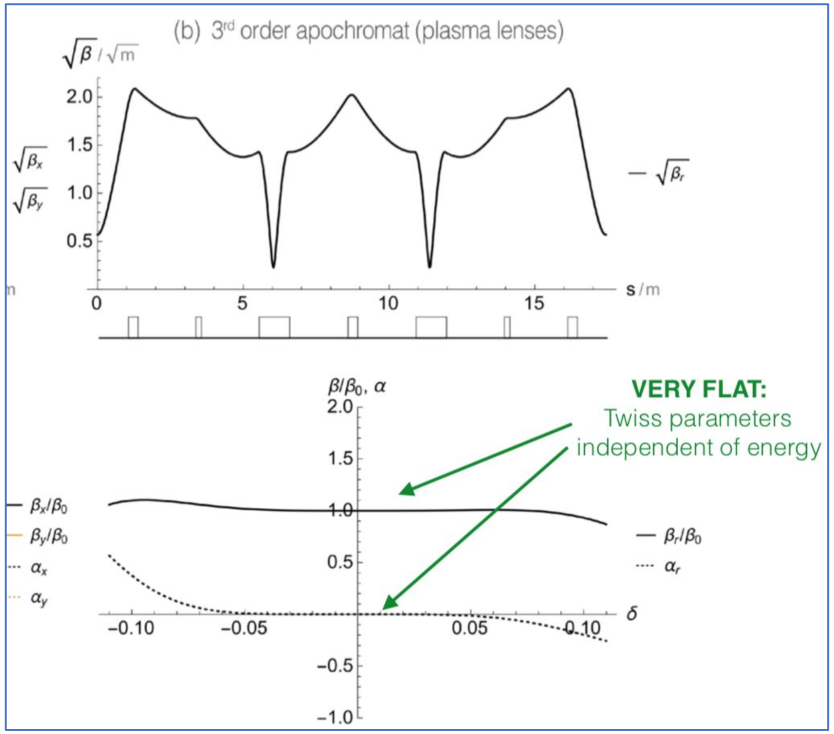
The Plasma Lens Experiment – how it started

Proposal from CALIFES workshop (Oct 2016)

Oslo theoretical studies: plasma collider interstage using plasma lenses

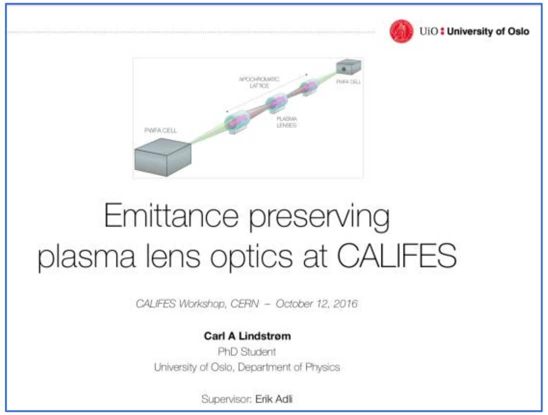


C. A. Lindstrøm & E. Adli,
"Design of general apochromatic drift-quadrupole beam lines",
Phys. Rev. Accel. Beams (19) 071002 (2016)



VERY FLAT:
Twiss parameters
independent of energy

→ looked for opportunities to implement idea:
lattice of active plasma lenses


UiO : University of Oslo

Emittance preserving
plasma lens optics at CALIFES

CALIFES Workshop, CERN – October 12, 2016

Carl A Lindstrøm
PhD Student
University of Oslo, Department of Physics

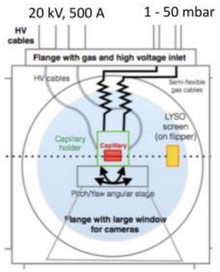
Supervisor: Erik Adli

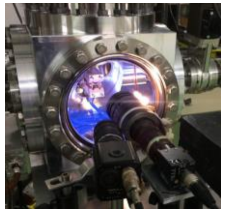
With CLEAR approved (Dec 2016) and informal agreement from CLIC to get beam time, Oslo went ahead to form a collaboration and design a prototype plasma

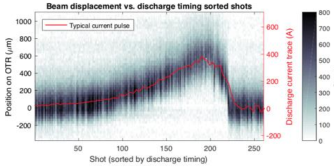
Timeline

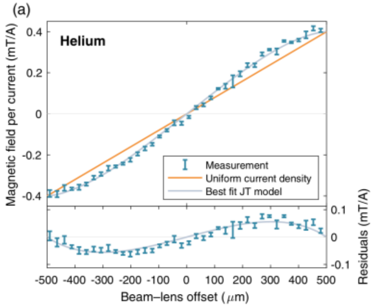
Emittance preserving
plasma lens optics at CALIFES

CALIFES Workshop, CERN – October 12, 2016









Idea for
plasma lens
lattices
published

7/2016

CALIFES
workshop

10/2016

CLEAR
approval

12/2016

PhD
student
arrive
at CERN

5/2017

PL
Build and
HV-tested
in the lab

8/2017

PL
integrated
in CLEAR

10/2017

First
experimental
results

12/2017

Dedicated
experimental
weeks

3/2018
5-6/2018

data
analysis

Publication
in
PRL

11/2018

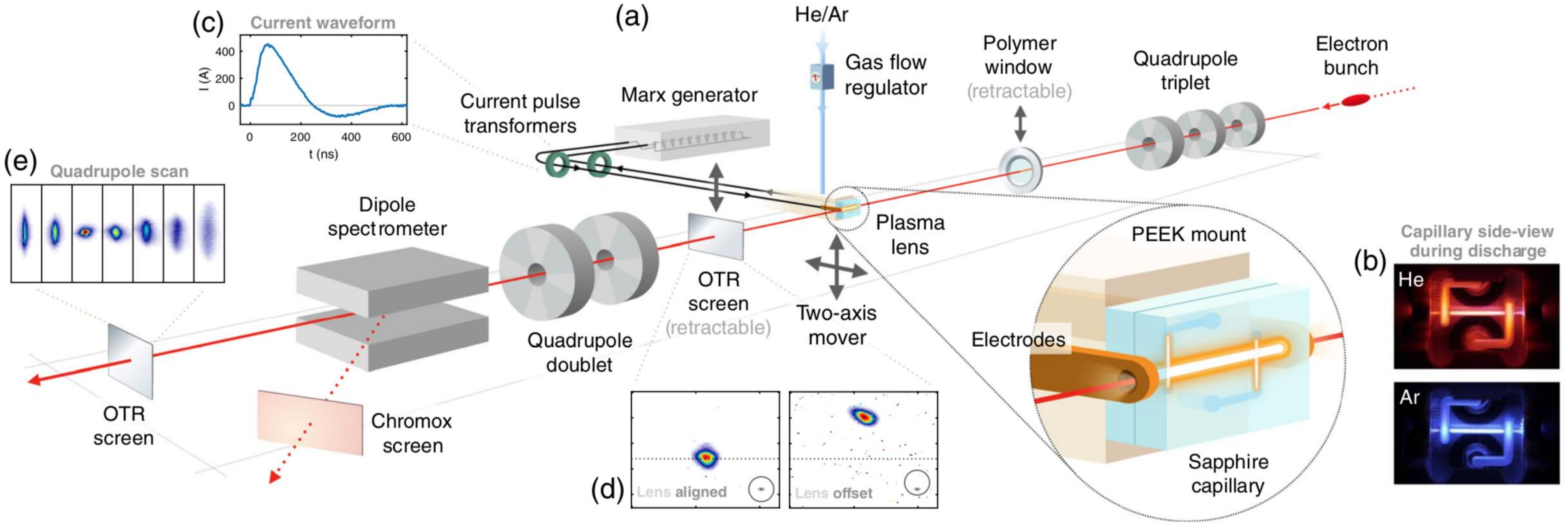
Setting up
external coll.
J. Osterhoff (DESY)
S. Hooker (Oxford)

Learning,
planning,
designing
CLEAR PL
(in Oslo)

Building
and testing
PL
(at CERN)

Integrating and
debugging
PL
(at CERN)

Final Results – gradient linearity



PHYSICAL REVIEW LETTERS 121, 194801 (2018)

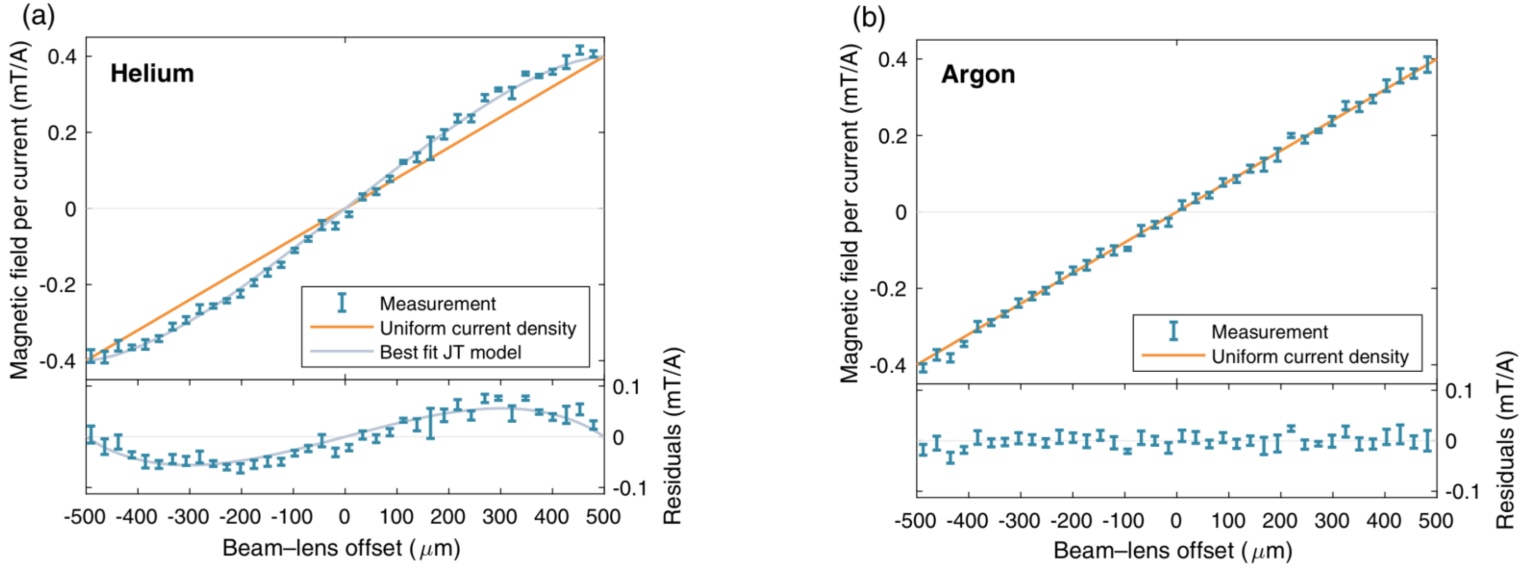
Emittance Preservation in an Aberration-Free Active Plasma Lens

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*

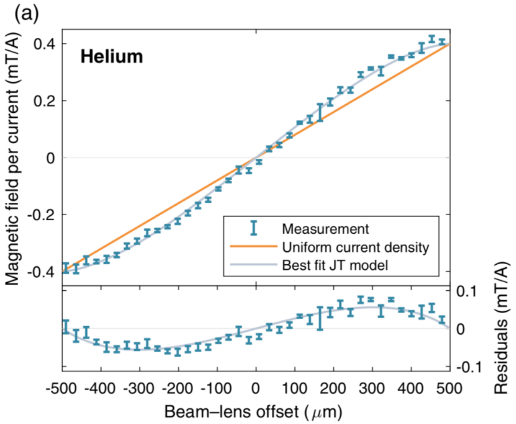
(Received 10 August 2018; published 7 November 2018)

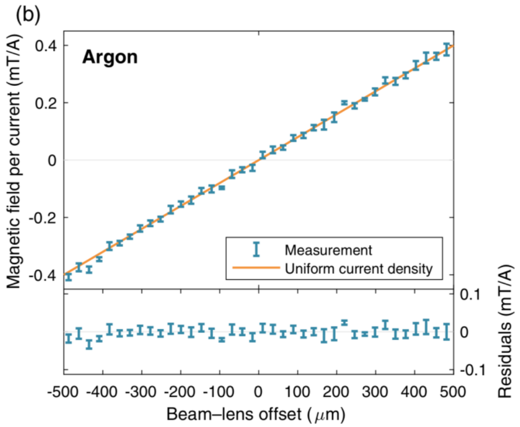
Active plasma lensing is a compact technology for strong focusing of charged particle beams, which has gained considerable interest for use in novel accelerator schemes. While providing kT/m focusing gradients, active plasma lenses can have aberrations caused by a radially nonuniform plasma temperature 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.

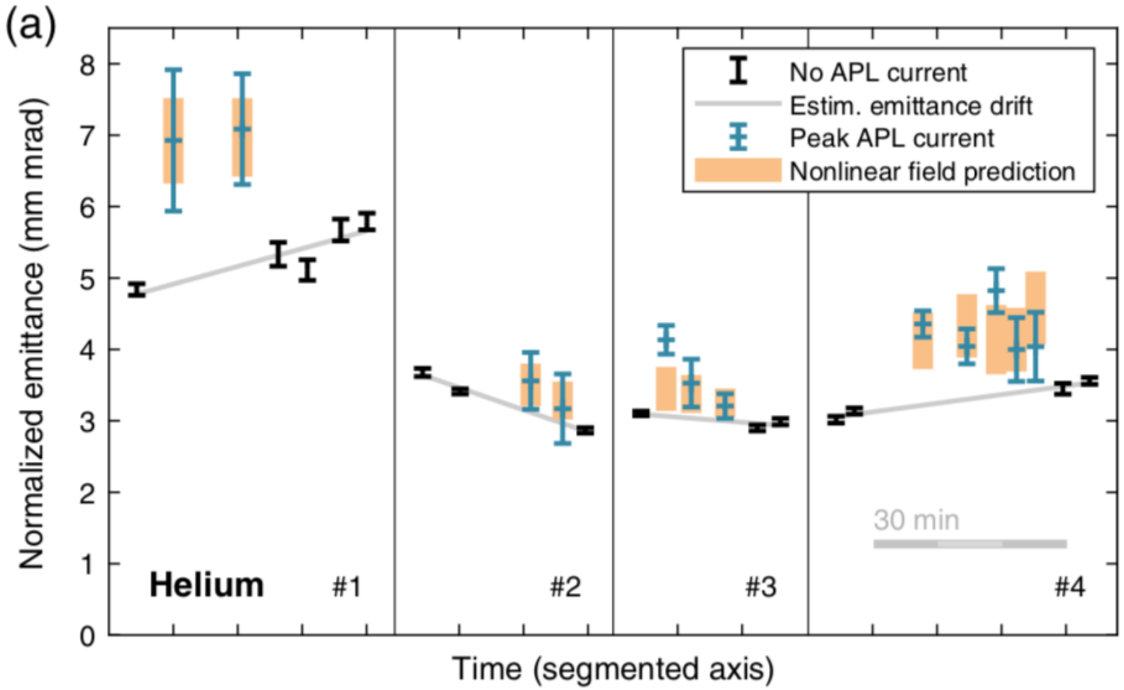
DOI: 10.1103/PhysRevLett.121.194801

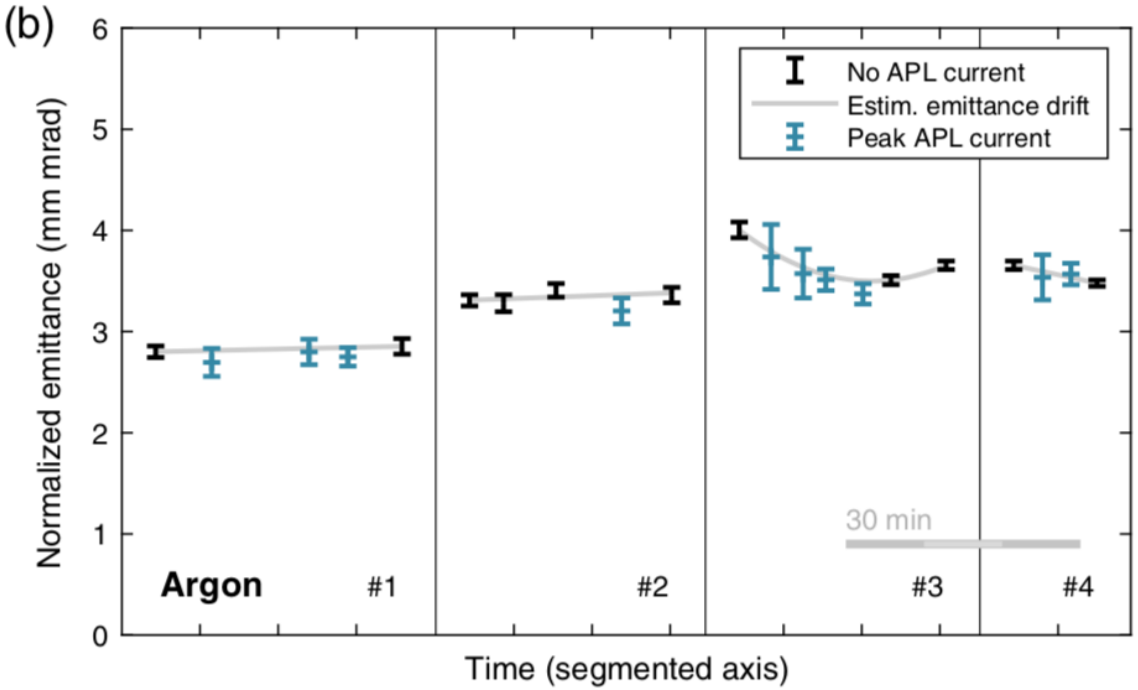


Final results – emittance preservation





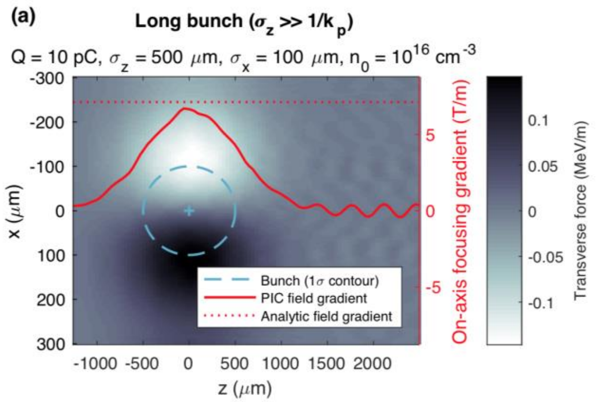




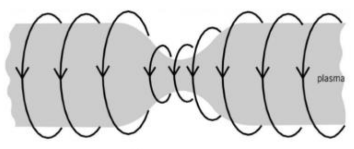
Outlook 2019

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 – understanding of thermal aberrations

Future program will in the short term concentrate on demonstration of higher gradient and exploration of other limitations



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 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,
- Thermal nonlinearity turn-on observed in Neon, just on the end of the falling edge.
- Evidence of plasma wake-fields distortion – quantitative analysis to be done
- No pinch observed
- Completementary experiments planned for 2019 (5x MarxBank!)

THz studies

- First tests with beam produced radiation in the sub-THz region, demonstrated use as bunch length diagnostics
- Bunch length diagnostics for CLEAR
  - Close to be operational - Teflon conical Cherenkov diffraction radiator, 4 frequency detection bands.
- Characterization of high power THz radiation from different sources
  - Tested so far: diamond, TR screens, Teflon, gratings, metamaterials

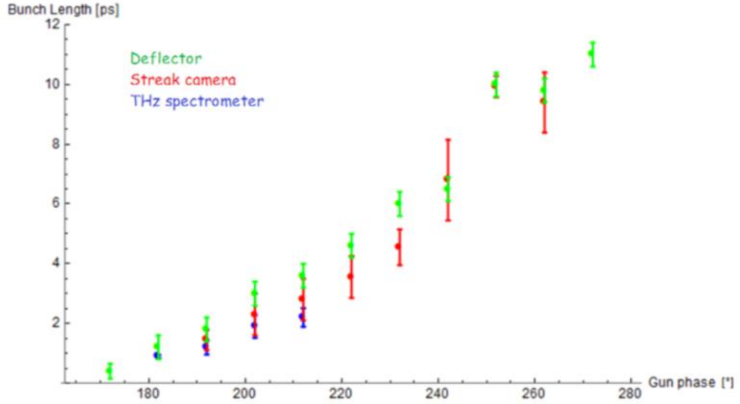


Figure 2: Bunch length measurement with different techniques/detectors. The bunch length compression in this case was made only by varying the gun phase, March 2018.

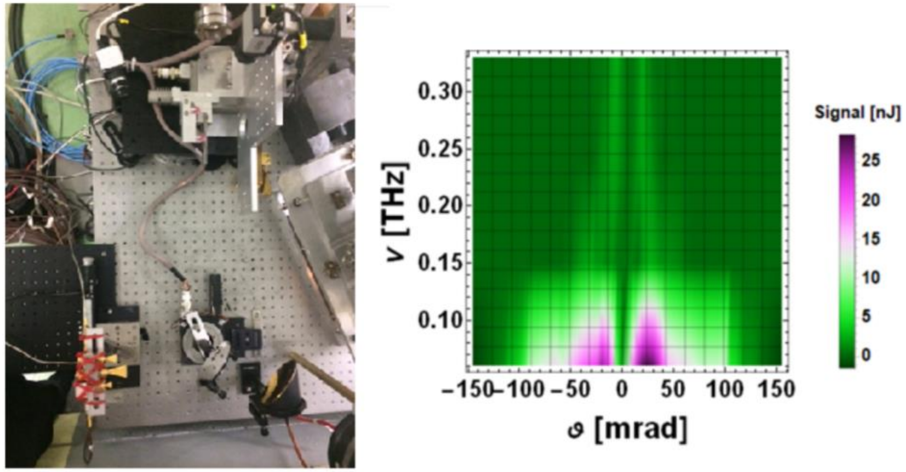
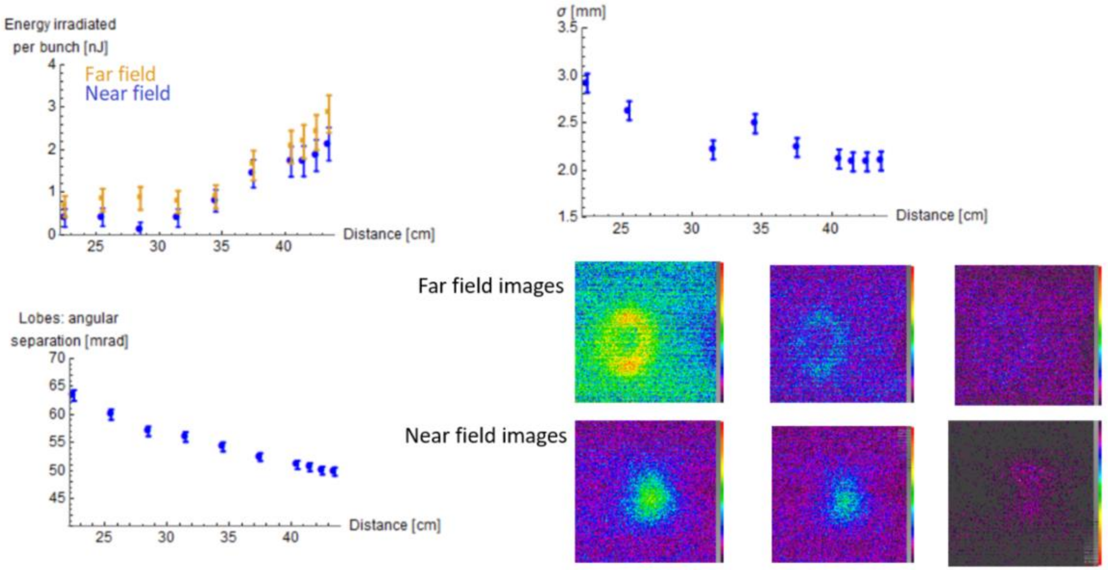


Figure 3: **Left**: Experimental setup for the spectral-angular characterization of CTR light. **Right**: Experimental results on spectral-angular characterization of the CTR light emitted by a 215 MeV, 40 pC, 1.5 ps long electron bunch, April 2018.



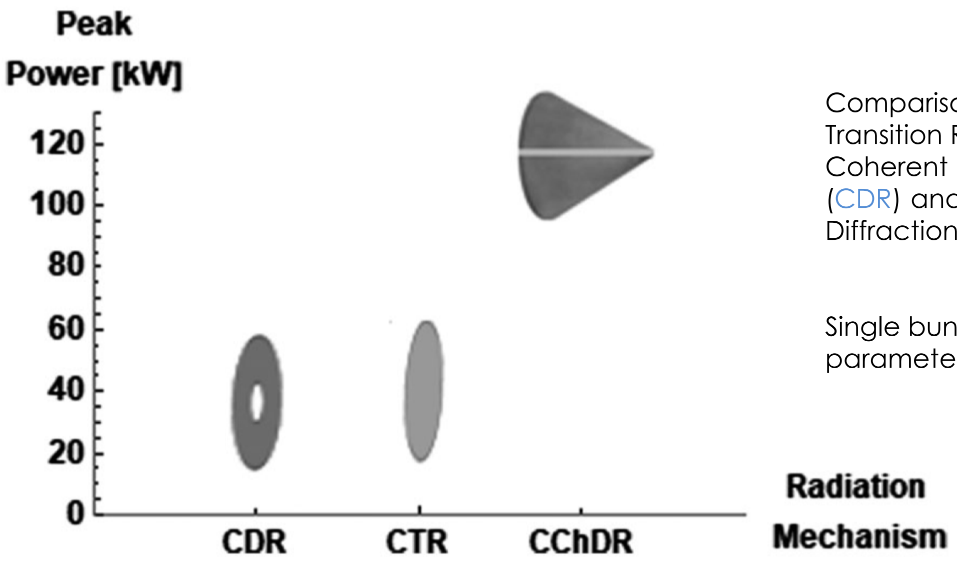
A. Curcio, M. Bergamaschi, T. Lefevre et al.

CLEAR THz source studies

Beam-based sub-THz source at the CERN linac electron accelerator for research facility

A. Curcio, M. Bergamaschi, R. Corsini, D. Gamba, W. Farabolini, T. Lefevre, S. Mazzoni, V. Dolci, M. Petrarca, and S. Lupi

Phys. Rev. Accel. Beams **22**, 020402 – Published 4 February 2019



Comparison among Coherent Transition Radiation (CTR), Coherent Diffraction Radiation (CDR) and Coherent Cherenkov-Diffraction Radiation (CChDR)

Single bunch electron beam parameters 215 MeV, 1.5 ps, 40 pC.

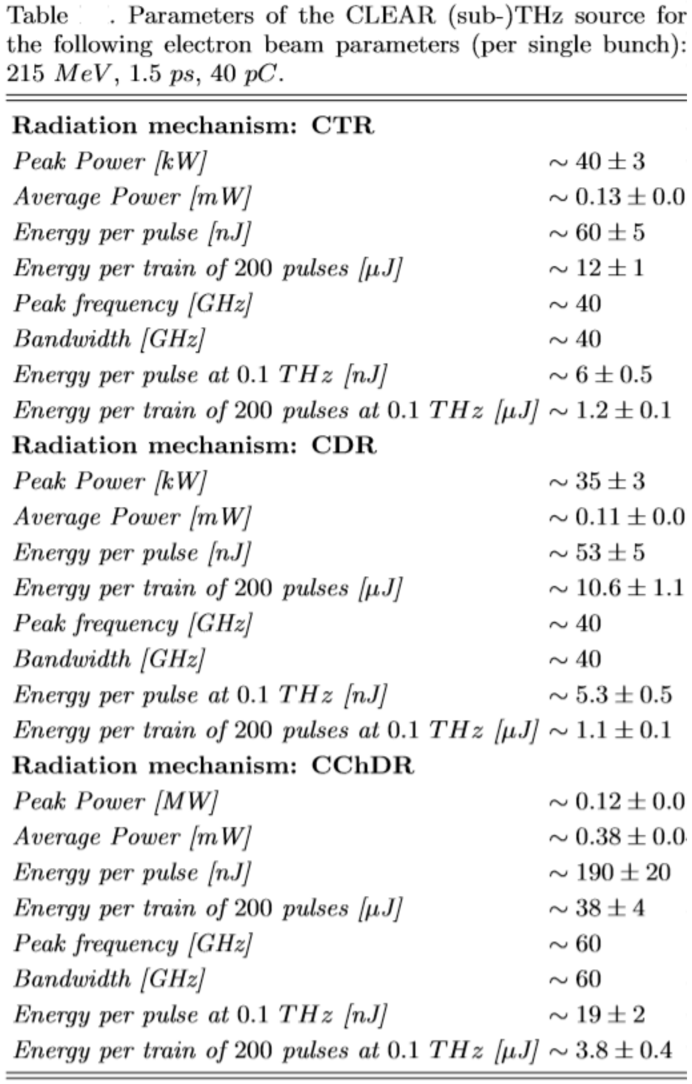


Table . Parameters of the CLEAR (sub-)THz source for the following electron beam parameters (per single bunch): 215 MeV, 1.5 ps, 40 pC.

Radiation mechanism: CTR	
Peak Power [kW]	$\sim 40 \pm 3$
Average Power [mW]	$\sim 0.13 \pm 0.0$
Energy per pulse [nJ]	$\sim 60 \pm 5$
Energy per train of 200 pulses [μJ]	$\sim 12 \pm 1$
Peak frequency [GHz]	~ 40
Bandwidth [GHz]	~ 40
Energy per pulse at 0.1 THz [nJ]	$\sim 6 \pm 0.5$
Energy per train of 200 pulses at 0.1 THz [μJ]	$\sim 1.2 \pm 0.1$
Radiation mechanism: CDR	
Peak Power [kW]	$\sim 35 \pm 3$
Average Power [mW]	$\sim 0.11 \pm 0.0$
Energy per pulse [nJ]	$\sim 53 \pm 5$
Energy per train of 200 pulses [μJ]	$\sim 10.6 \pm 1.1$
Peak frequency [GHz]	~ 40
Bandwidth [GHz]	~ 40
Energy per pulse at 0.1 THz [nJ]	$\sim 5.3 \pm 0.5$
Energy per train of 200 pulses at 0.1 THz [μJ]	$\sim 1.1 \pm 0.1$
Radiation mechanism: CChDR	
Peak Power [MW]	$\sim 0.12 \pm 0.0$
Average Power [mW]	$\sim 0.38 \pm 0.0$
Energy per pulse [nJ]	$\sim 190 \pm 20$
Energy per train of 200 pulses [μJ]	$\sim 38 \pm 4$
Peak frequency [GHz]	~ 60
Bandwidth [GHz]	~ 60
Energy per pulse at 0.1 THz [nJ]	$\sim 19 \pm 2$
Energy per train of 200 pulses at 0.1 THz [μJ]	$\sim 3.8 \pm 0.4$

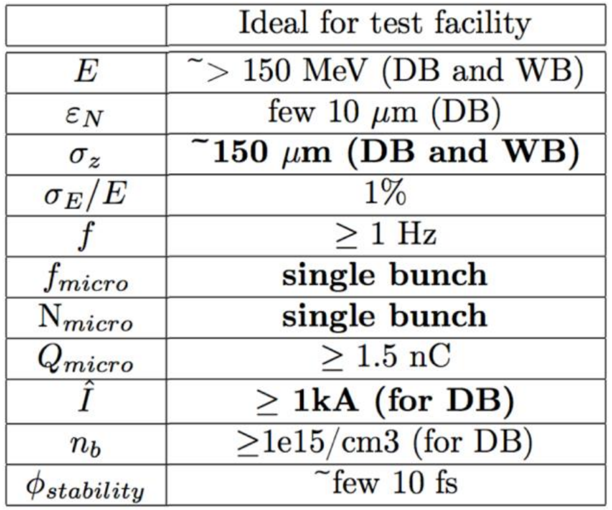
Optimized CChDR targets tested in December 2018 with higher charge, shorter bunches produced >1 MW peak power

Will continue to explore other sources and increase power, in view of possible applications including advanced accelerator techniques (e.g., dielectric structure tests)

Potential for PWFA research in CLEAR

Summary of requirements for PWFA@CLEAR

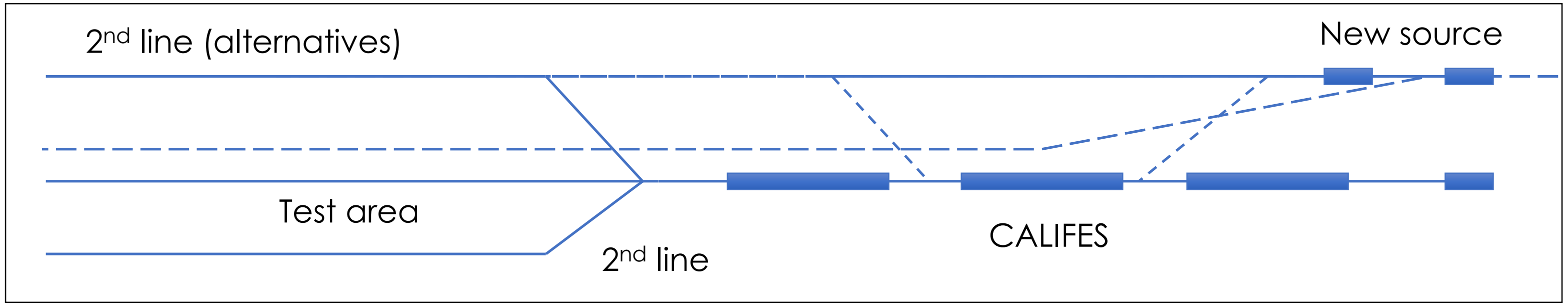
E. Adli - From CLIC workshop 2015.

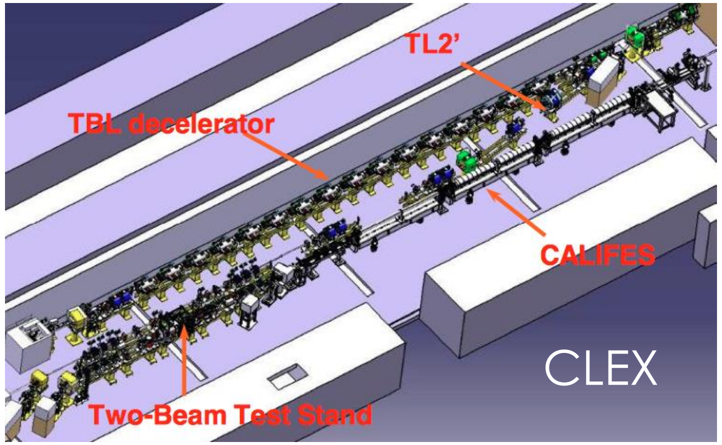


	Ideal for test facility
E	~> 150 MeV (DB and WB)
ε_N	few 10 μm (DB)
σ_z	**~150 μm (DB and WB)**
σ_E/E	1%
f	$\geq$ 1 Hz
f_{micro}	**single bunch**
N_{micro}	**single bunch**
Q_{micro}	$\geq$ 1.5 nC
$\hat{I}$	**$\geq$ 1kA (for DB)**
n_b	$\geq$1e15/cm3 (for DB)
$\phi_{stability}$	~few 10 fs

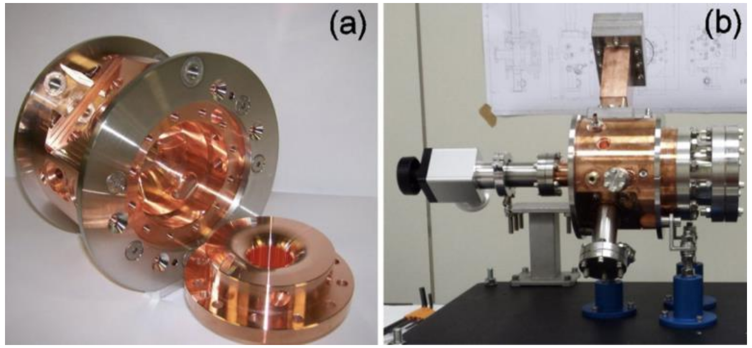
- Required upgrades to CLEAR :
  - less than 150 μm bunch length ✓ 60 μm measured
  - as large single bunch charge as possible (ideal is about 1 nC or more) ✓ 3 nC so far
  - while still having few μm emittances
  - possibility to extract single bunch ✓
- Two independent co-linear electron beams
  - adjustable relative timing with accuracy of ~10 fs
  - DB line with 100 MeV, 10 μm emittances, 150 μm bunch length
- Other required upgrades
  - Installation of appropriate plasma cell and plasma diagnostics
  - Beam diagnostics

Options for a second beam line + source



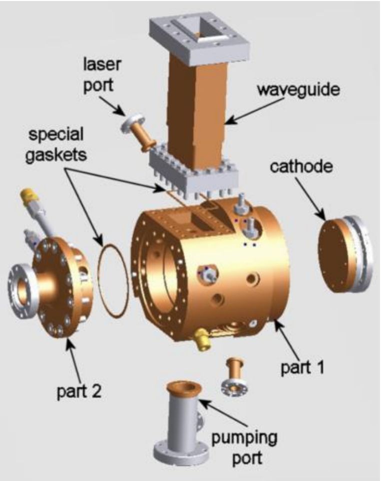


D. Alesini, M. Ferrario et al.

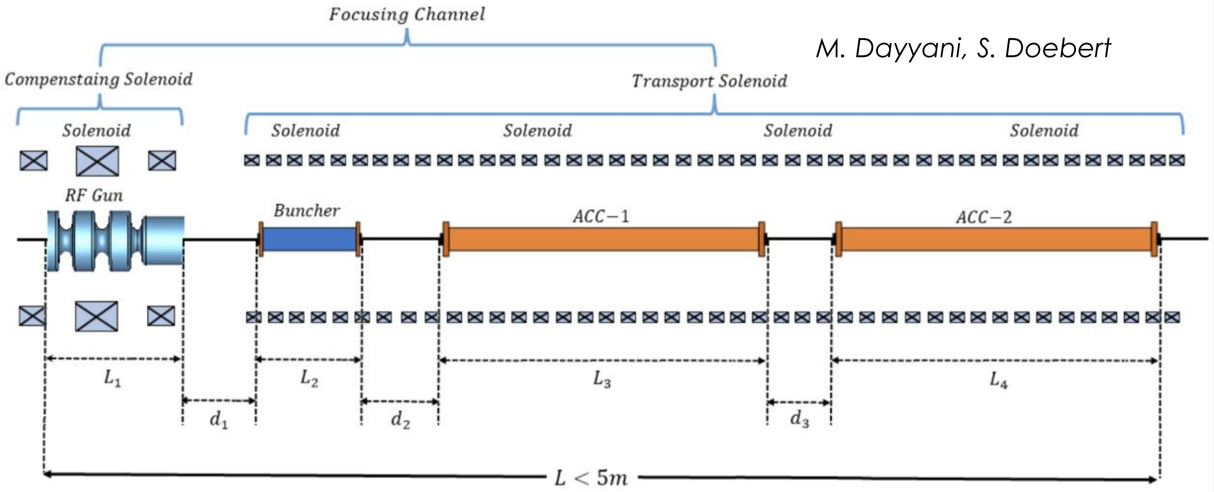


New Source common development
CLEAR/AWAKE

- RF gun provided by INFN-Frascati
- S-band gun + X-band high gradient acceleration validated by simulations
- Most hardware existing



M. Dayyani, S. Doebert



Parameter	Nominal Value	Size
Total Length	$< 5\ m$	$4\ m$
Beam Energy	$220 > 60\ MeV$	$100\ MeV$
Energy Spread	$< 1\ \%$	$0.45\ \%$
Bunch Charge	$100\ pC$	$100\ pC$
RMS Bunch Length	$< 100\ fs$	$81\ fs$
Emittance	$< 10\ \mu m$	$0.6\ \mu$

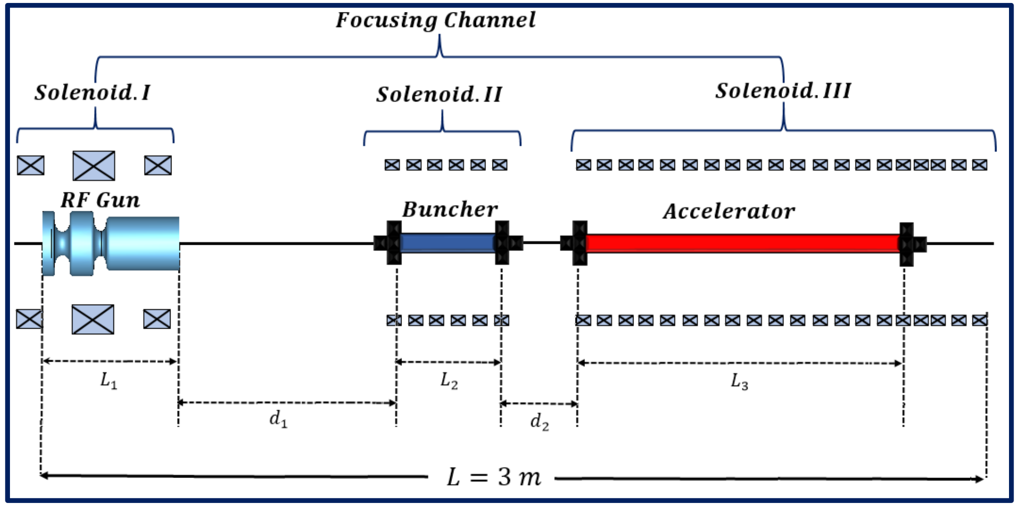
Synergies for e- source

A similar injector could serve for:
AWAKE Run2, e-SPS, Compact- and SMART-Light sources, Advanced accelerator research (ALEGRO goals)

- Extremely compact injector : 85 MeV in 3 m
- Possibly very small emittance < 1 um
- Very short bunches ~ 100 fs
- Generic study for a compact injector

S. Doebert

- Could study external injection into a plasma accelerator
- Emittance preservation during plasma acceleration
- Wakefield measurement via probe bunch deflection
- Radiation generation with short bunches and high charge density



Potential experimental activities on PWFA in CLEAR

CLEAR might address several PWFA R&D issues
after new injector upgrade from 2021

- External injection
- Bunch quality, efficiency, stability and reproducibility
- Operation at high (moderate) repetition rate
- High-quality electron bunches

Need further upgrades

- Independently shaped drive and main beams
- Multi-stage challenges with high-energy beams