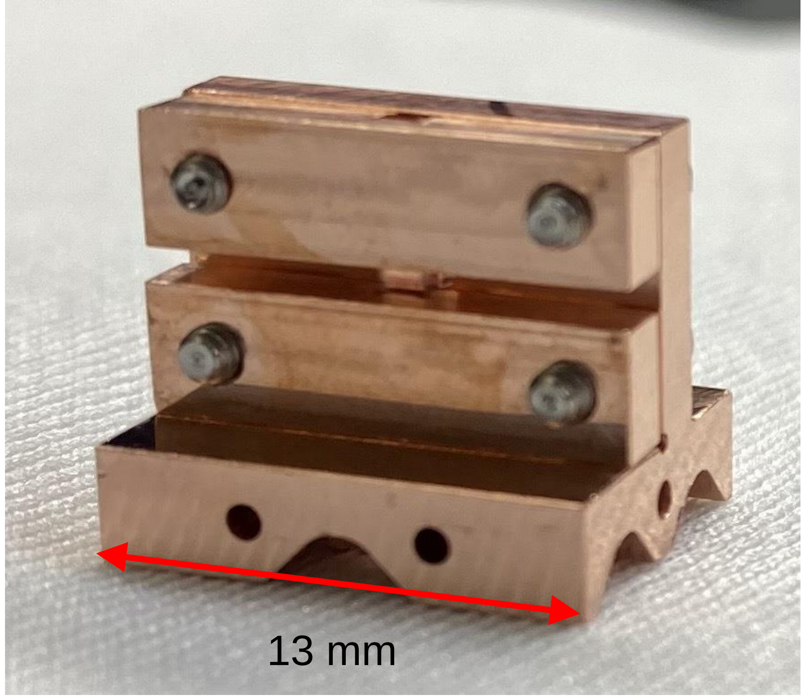
ACHIP experiments at the ARES linac



Advanced Accelerator Concepts Workshop, November 9th 2022, NY, USA

WG3: Laser and High-Gradient Structure-Based Acceleration

Willi Kuropka, Ralph Assmann, Florian Burkart, Anne-Laure Calendron, Huseyin Cankaya, Hannes Dinter, Ingmar Hartl, Sonja Jaster-Merz, Franz Kärtner*, Thorsten Lamb, Christoph Mahnke, Frank Mayet, Christian Mohr, Jost Müller, Sebastian Schulz, Blae Stacey, Thomas Vinatier, Uwe Grosse-Wortmann

Deutsches Elektronen-Synchrotron DESY, Germany

***Center for free-electron laser science, Germany**

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CFEL SCIENCE

ACHIP

GORDON AND BETTY MOORE FOUNDATION

SINBAD

DESY.

Outline

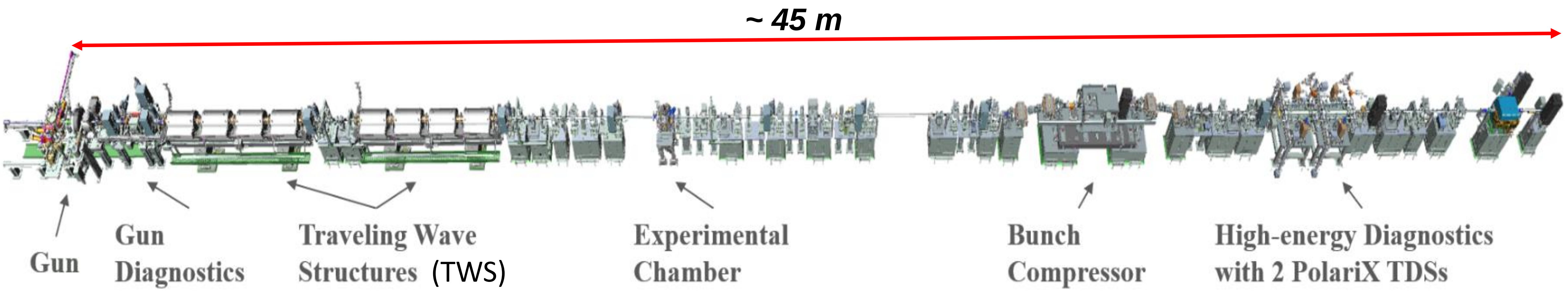
- **ARES - ultra-short low emittance electron beams**
  - Facility overview
  - Beam commissioning status
- **ACHIP@ARES**
  - Collaboration
  - Experiment
  - Simulations
  - Status

The ARES linac at DESY

Layout & goals, courtesy T. Vinatier

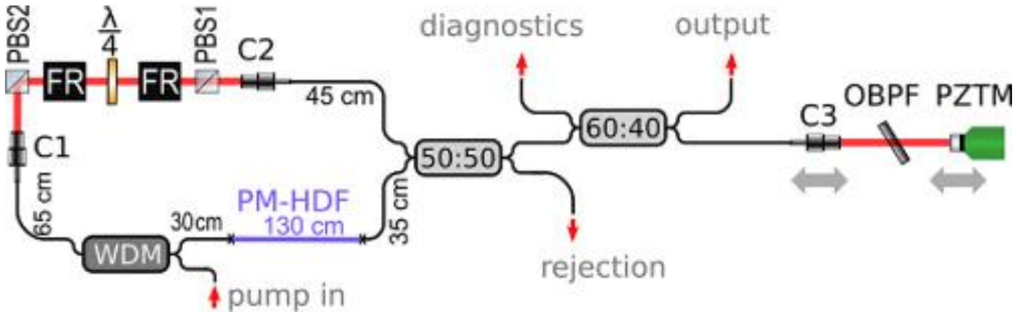
- **ARES goal**: Generate and characterize **ultrashort e^- bunches (fs to sub-fs)** with **high stability** for applications related to **accelerator R&D** (advanced & compact longitudinal diagnostics and accelerating structures development, medical applications studies, test of new accelerator components, machine learning, etc.) and beam time for external users.

Properties	Target value	Status
Charge	0.05 – 200 pC	0.03 – 200 pC
Momentum	50 – 150 MeV/c	50 – 160 MeV/c
Momentum spread	10^{-4}	10^{-4} (resolution limited)
Transverse emittance*	< 0.8 π.mm.mrad	≈ 0.15 π.mm.mrad
Duration	Sub-fs to ≈ 10 fs	≈ 20 fs (resolution limited)



Ho:YLF amplifier laser system for DLA experiments

2050nm

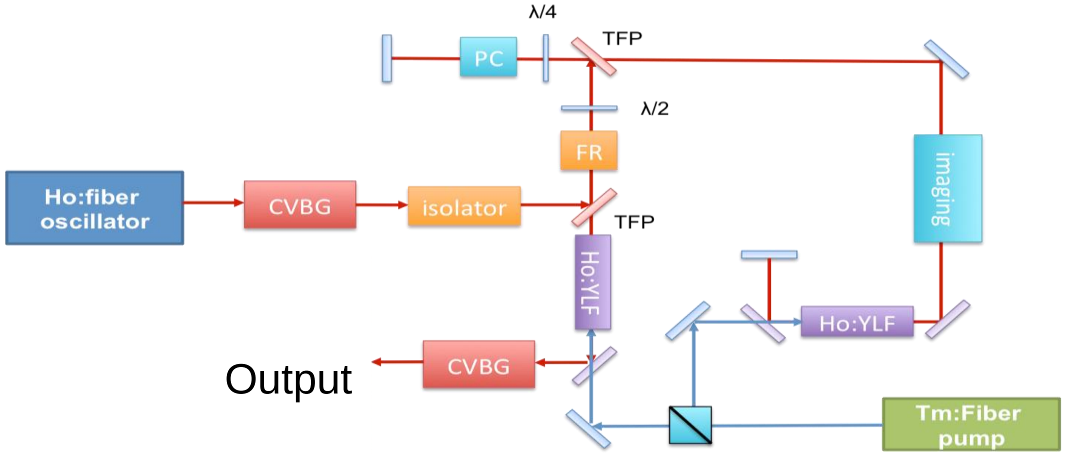


Amplifier Output Parameters	
E_p [out,max]	2.2 mJ
E_p [comp,max]	1.9 mJ
f_{rep}	1 and 5 kHz
τ_p	~ 3 ps
τ_{TL}	1.25 ps

Expected eff. Gradient ~450 MV/m
Maximum accelerating field ~0.5 GV/m

~10s fs jitter in cathode and DLA laser

Q-peak Prototype Amp. System



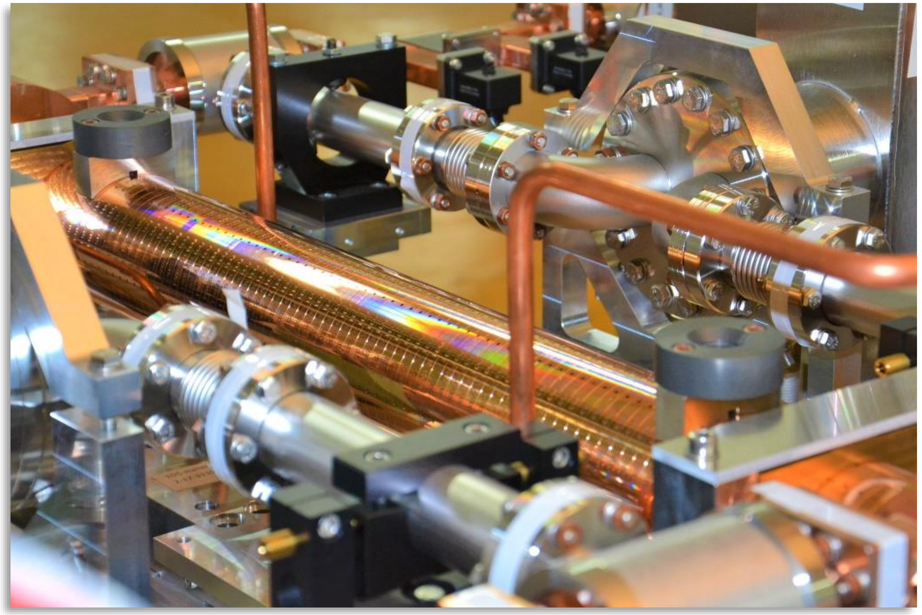
Courtesy H. Cankaya

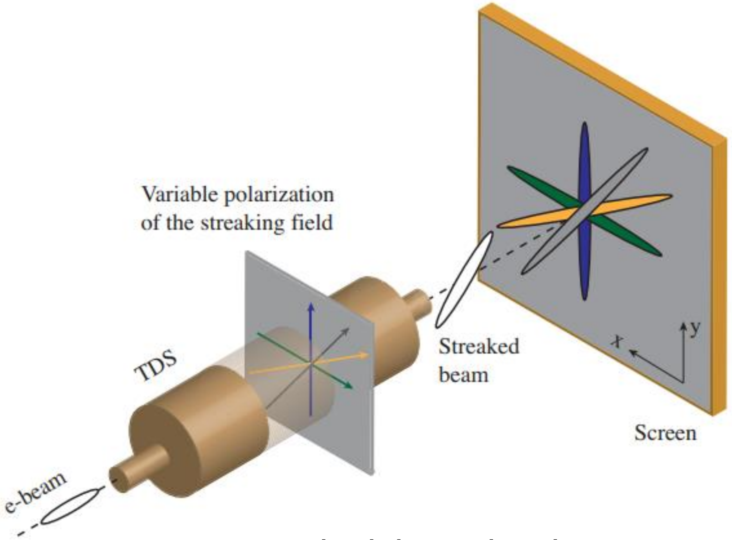
Murari K., et. al., "Kagome-fiber-based pulse compression of midinfrared picosecond pulses from a Ho:YLF amplifier." DOI:10.1364/OPTICA.3.000816 (2016)
Murari K., et. al., "Intracavity gain shaping in millijoule-level, high gain Ho:YLF regenerative amplifiers." DOI:10.1364/OL.41.001114 (2016)
C. Mahnke, et al., "Long-term stable, synchronizable, low-noise picosecond Ho:fiber NALM oscillator for Ho:YLF amplifier seeding," Opt. Lett. **47**, 822-825 (2022)
M. Titberidze, et al.,"FIRST RESULTS ON FEMTOSECOND LEVEL PHOTOCATHODE LASER SYNCHRONIZATION AT THE SINBAD FACILITY", IBIC2019, Malmö, Sweden
S. Pfeiffer, et al.,"LLRF CONTROL AND SYNCHRONIZATION SYSTEM OF THE ARES FACILITY", IPAC2021, Sao Paulo, Brazil
A.-L. Calendron *et al.*, "Optical synchronization of a 2 µm Ho:fiber oscillator and phase-noise analysis," *2022 Conference on Lasers and Electro-Optics (CLEO)*, 2022, pp. 1-2.

Beam commissioning status

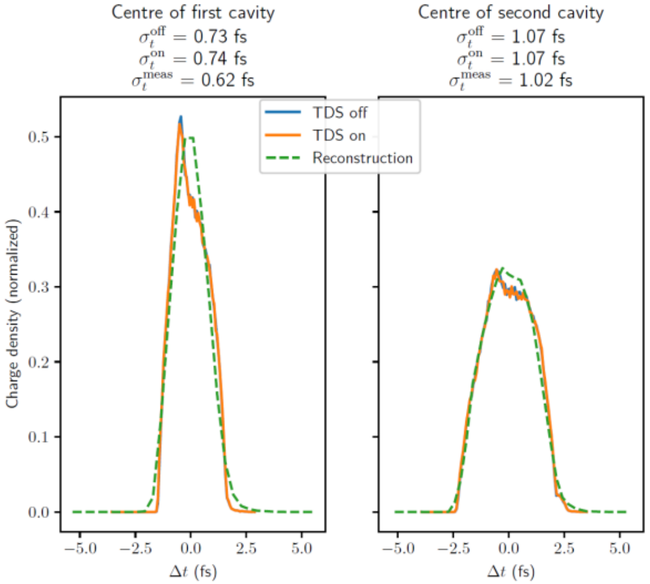
Bunch duration measurement: future steps with PolariX TDS, courtesy T. Vinatier

- **PolariX-TDS**: Transverse deflecting structure operating in X-band (≈ 12 GHz), with down to **sub-fs resolution** and the novel feature to allow for **arbitrary streaking direction** → allow for complete tomographic reconstruction up to 5D (x,x',y,y',t).





From P. Craievich et al., Phys. Rev. ST Accel. Beams 23, 112001, 2020

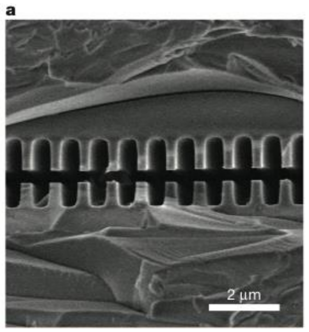


From D. Marx et al., Scientific reports 9, 19912, 2019

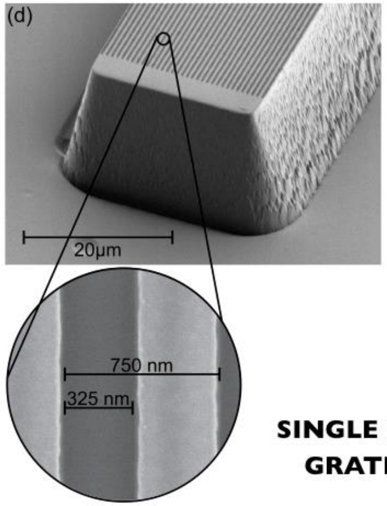
- **Status at ARES**: 2 structures and waveguide network installed in the beamline, modulators at DESY, **waiting for the klystrons** to start conditioning/commissioning (first klystron expected first quarter 2023).

Collaboration between CERN, DESY and PSI: A. Grudiev, CLIC-note-1067 (2016); P. Craievich et al., PRAB 23 112001 (2020); B. Marchetti et al., Sci. Rep. 11 3560 (2021).

ACHIP@ARES



DUAL LAYER GRATING[1]



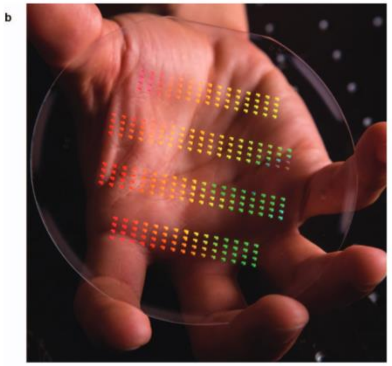
SINGLE LAYER GRATING[2]

[1] Peralta E. A., et. al., “Demonstration of electron acceleration in a laser-drive dielectric micro structure”, Nature 503, 91-94, (2013)
[2] Breuer J., et. al., “”Dielectric laser acceleration of nonrelativistic electrons at a single fused silica grating structure: Experimental part.”, PRSTAB 17, 021301 (2014)

ACHIP

Accelerator on a CHip International Program

- Collaboration comprised of multiple national laboratories and universities
- funded by the Gordon and Betty Moore Foundation
- Time frame: 10/2015 – 02/2023



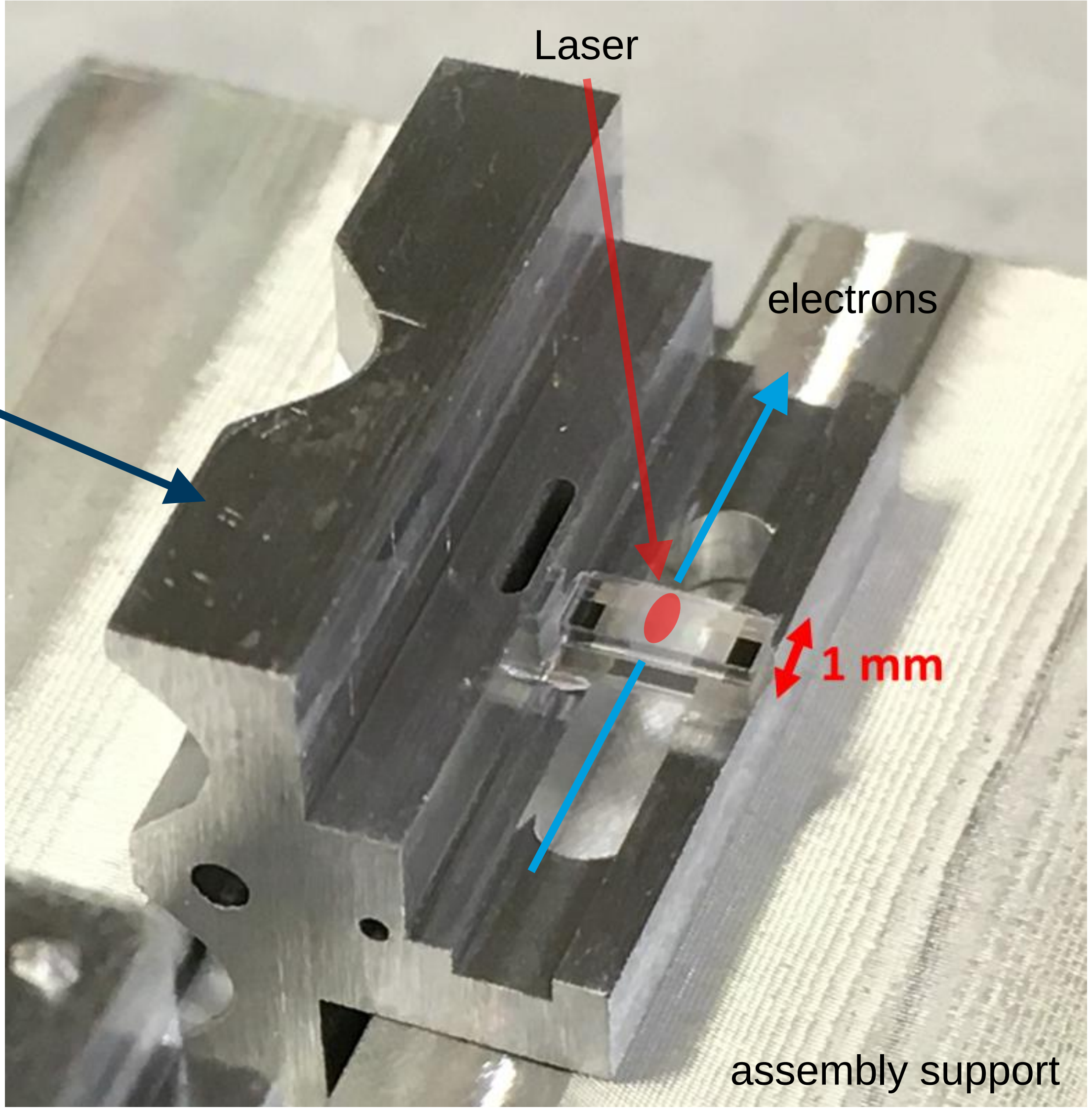
achip.stanford.edu

High gradient electron beam acceleration and phase space manipulation in micrometer scale dielectrics – but: ***small apertures, short acceleration buckets***

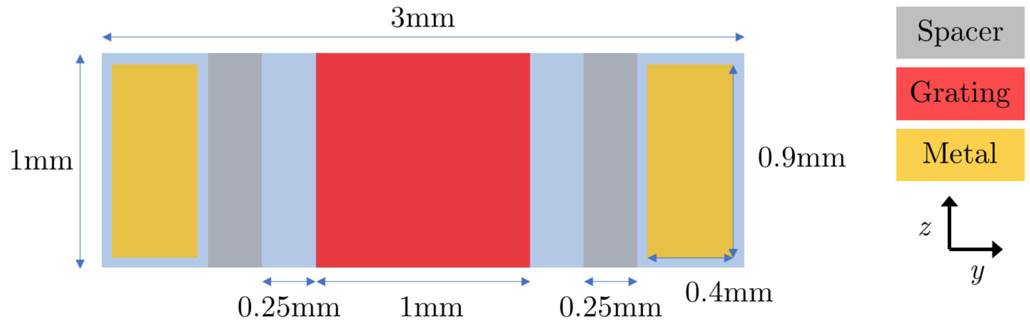
Dielectric laser accelerators

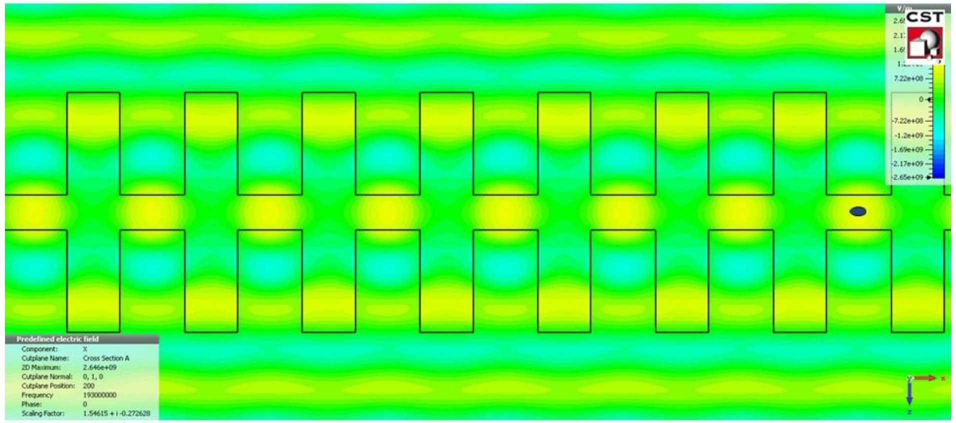
Grating-type DLA: electromagnetic fields

sample holder



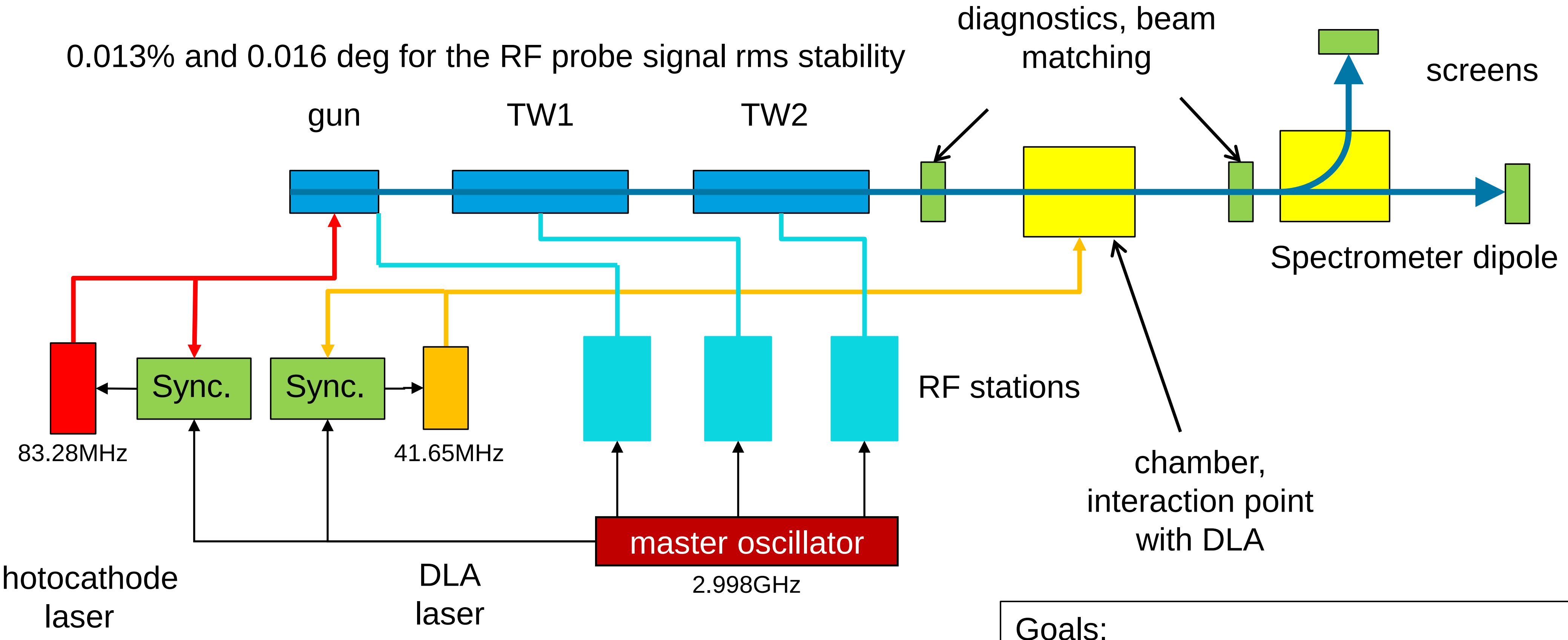
Micro structured fused silica





ACHIP@ARES - schematic

ARES – S-band photo-injector and linac for electron bunches



~10s fs jitter in cathode and DLA laser

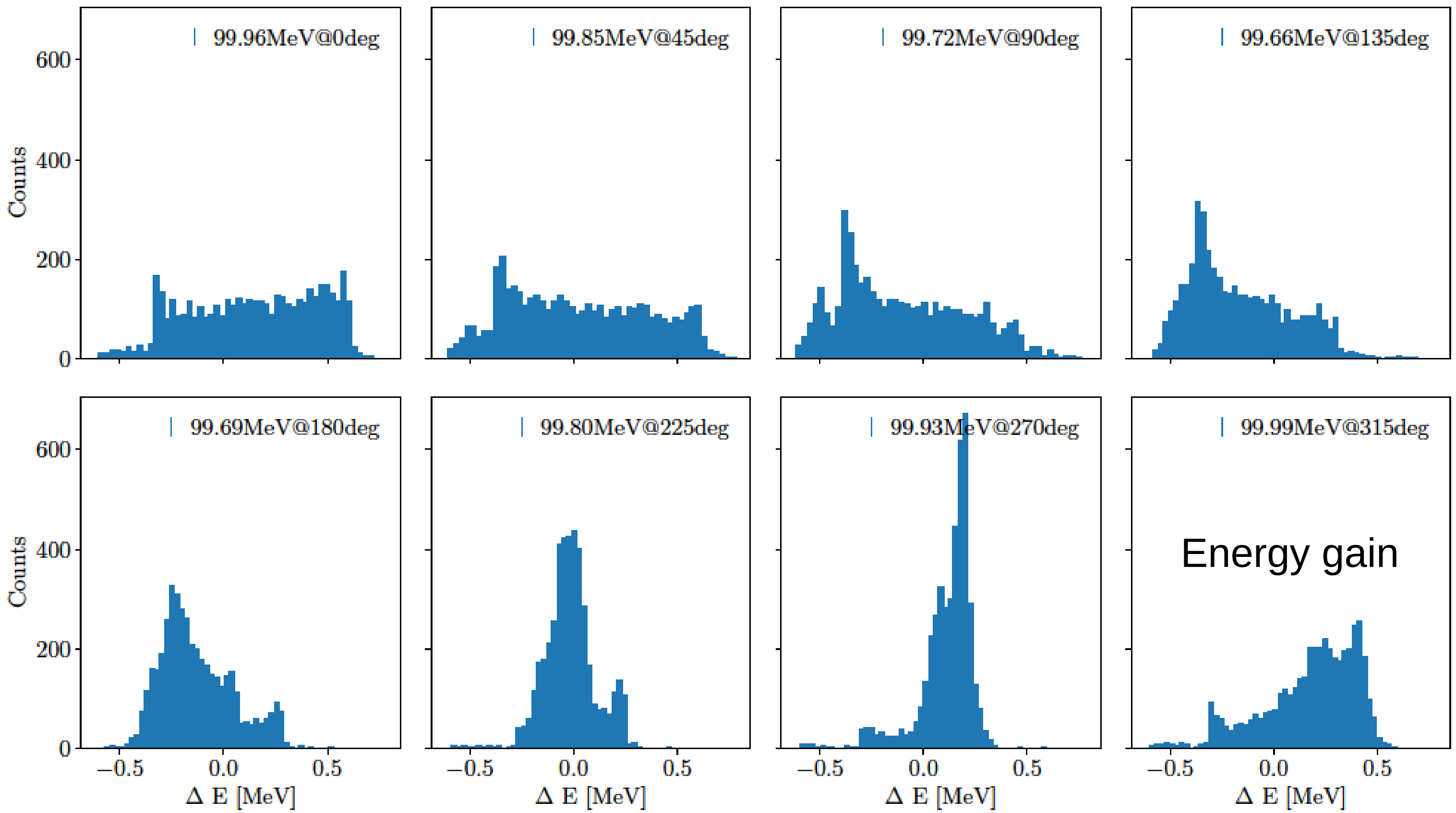
Goals:

- Higher transmission (2050nm laser)
- ~GV/m peak acceleration fields
- Hit the bucket (fs electron bunches)

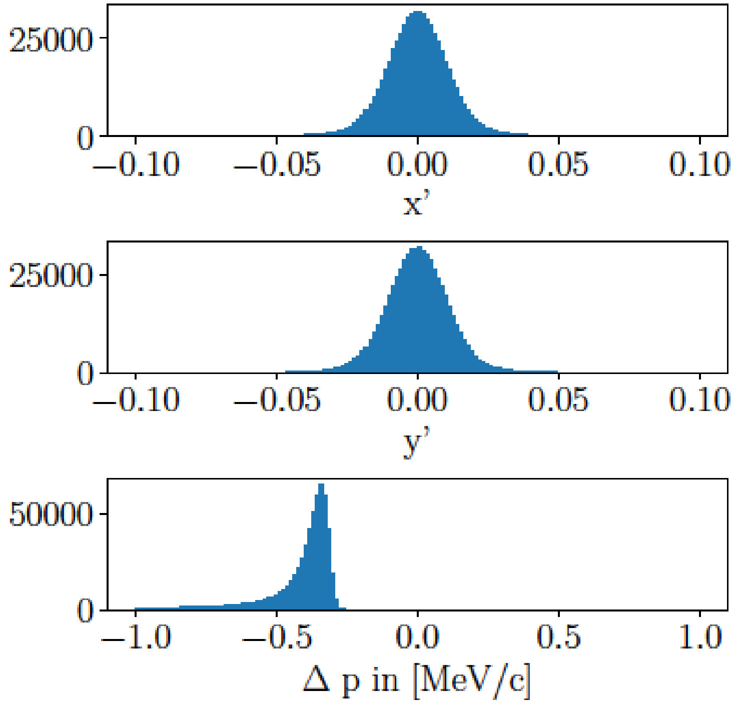
ACHIP@ARES – simulations – short bunch “stage 1”

DLA interaction at IP

Beam through the aperture



Scattering in dielectric from G4Beamline simulation



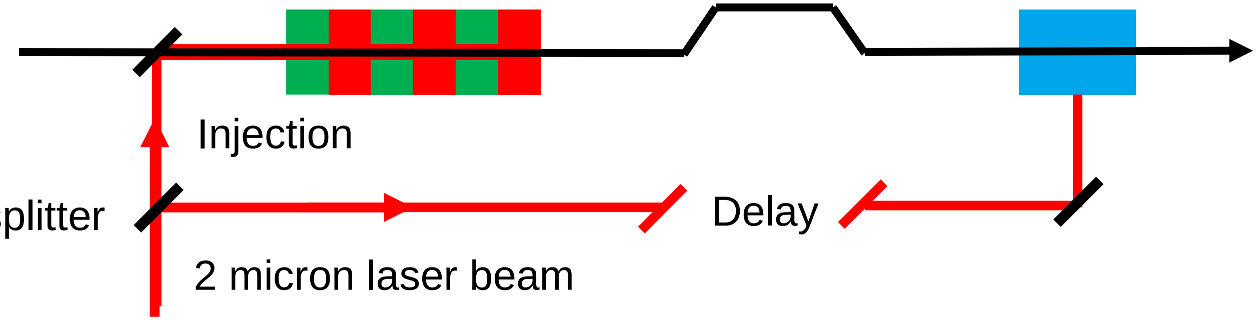
Bremsstrahlung, ionization losses

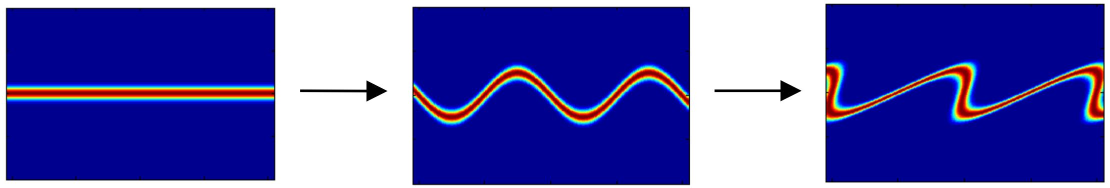
- Bunch length of 1.6fs FWHM, but arrival time jitter is larger than laser period
- 300 keV maximum energy change with 1.5 ps, 1.9 mJ laser pulse
- If mean bunch length is shorter than wavelength, bunch length can be estimated from several spectra

ACHIP@ARES – simulations – microbunching "stage 2"

Simulation of Microbunch trains for DLA

- Scheme alike HGHG in FELs → maximum bunching factor < 0.6
- Phase control like RF → phase scan
- Reduces timing jitter to laser phase stability between laser arms





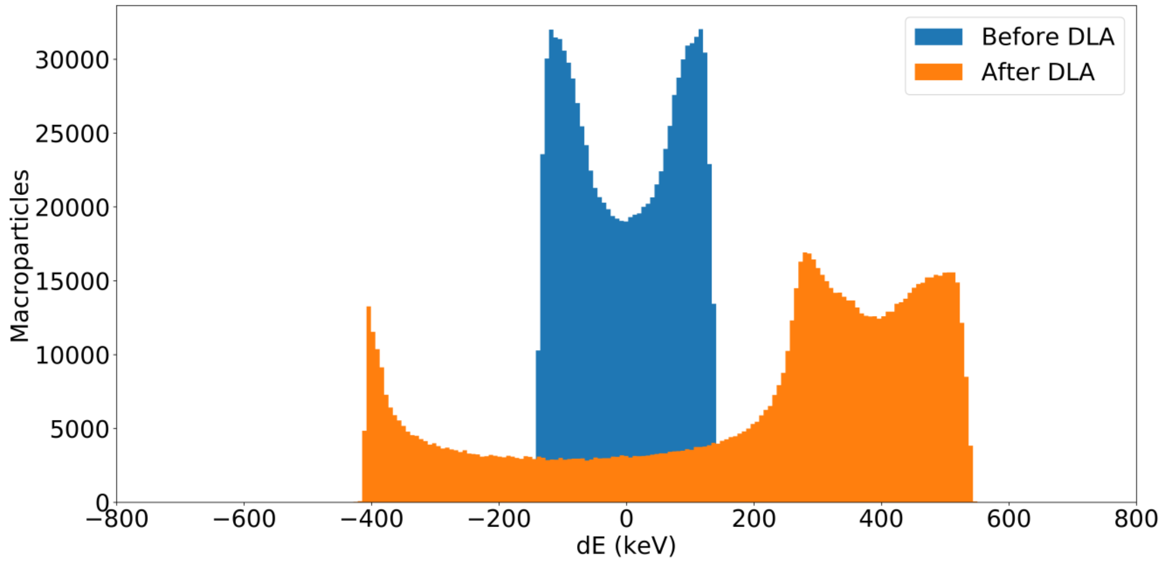
Undulator is already assembled

Sears C. M. S. , "Phase stable net acceleration of electrons from a two-stage optical accelerator." DOI:10.1103/PhysRevSTAB.11.101301 (2008)
Mayet F., et. al., "Simulations and plans for possible DLA experiments at SINBAD." DOI:10.1016/j.nima.2018.01.088 (2018)

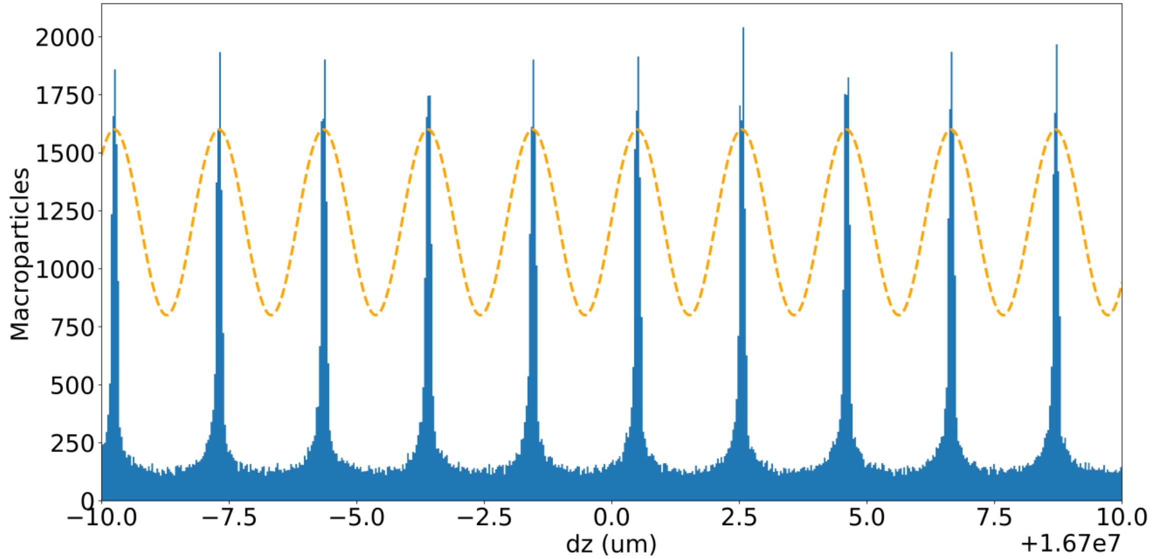
ACHIP@ARES - simulations – microbunching “stage 2”

Simulation of Microbunch trains for DLA

- Expected spectrum contains tail due to limited bunching factor



- Accelerating field can be phase shifted against micro bunches
- Here: maximum acceleration



Courtesy F. Mayet

ACHIP@ARES – experiment status

“the base line experiment”

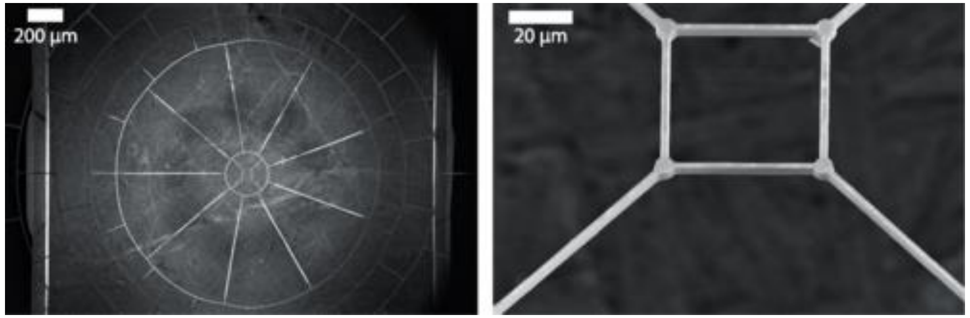
- **Goal**: High transmission / stable energy modulation (100s of keV), repeat/improve on previous relativistic experiments
- **Initial Parameters:**
  - “Long” e-bunch - 250fs rms, triple on-crest working point (154 MeV)
  - “Long” 2 μm laser pulse - 1.25ps rms, no pulse front tilt
  - Low charge - ~300fC initial

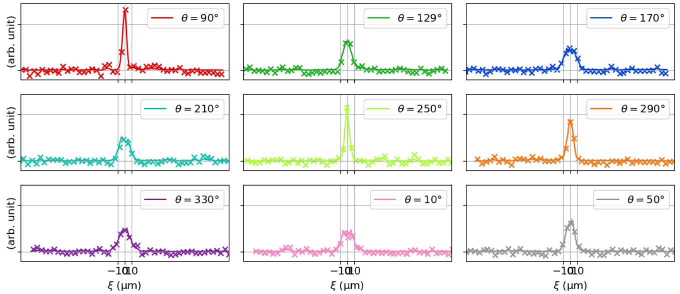
Previous relativistic experiments:
S. Crisp, et al., Phys. Rev. Accel. Beams 24, 121305, 2021, doi:10.1103/PhysRevAccelBeams.24.121305
D. Cesar, et al., Opt. Express 26, 29216-29224, 2018 doi:10.1364/OE.26.029216
D. Cesar, et al., *Commun Phys* **1**, 46 2018, doi:10.1038/s42005-018-0047-y
E.A. Peralta , et. al., Nature 503, 91-94, (2013)

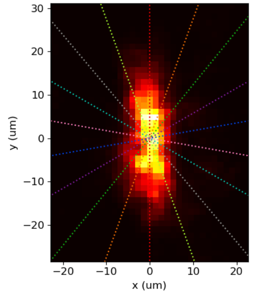
ACHIP @ ARES – experiment status

Electron beam at interaction point

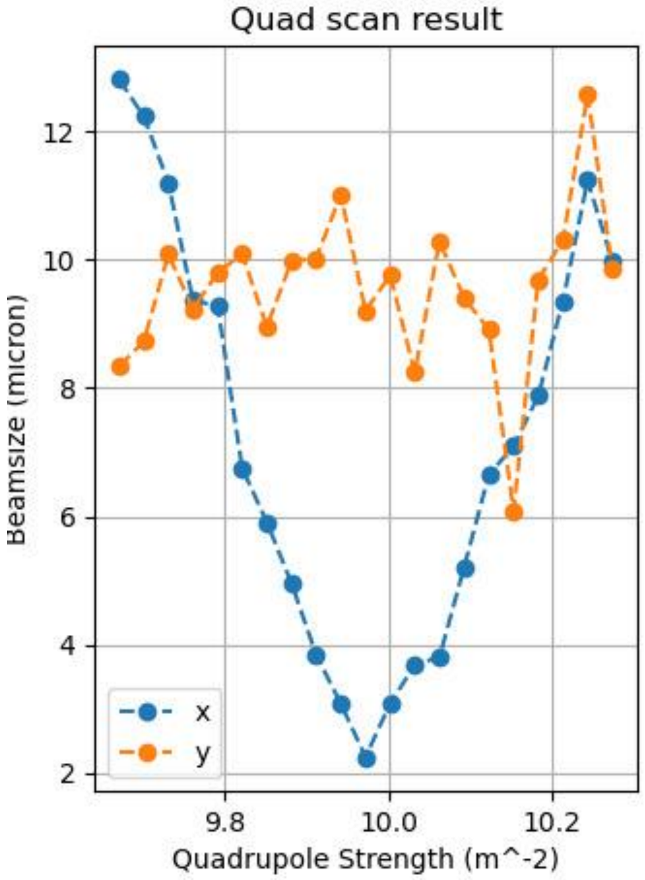
- Small beam size achieved
- Asymmetric focus achieved
- on-crest working point



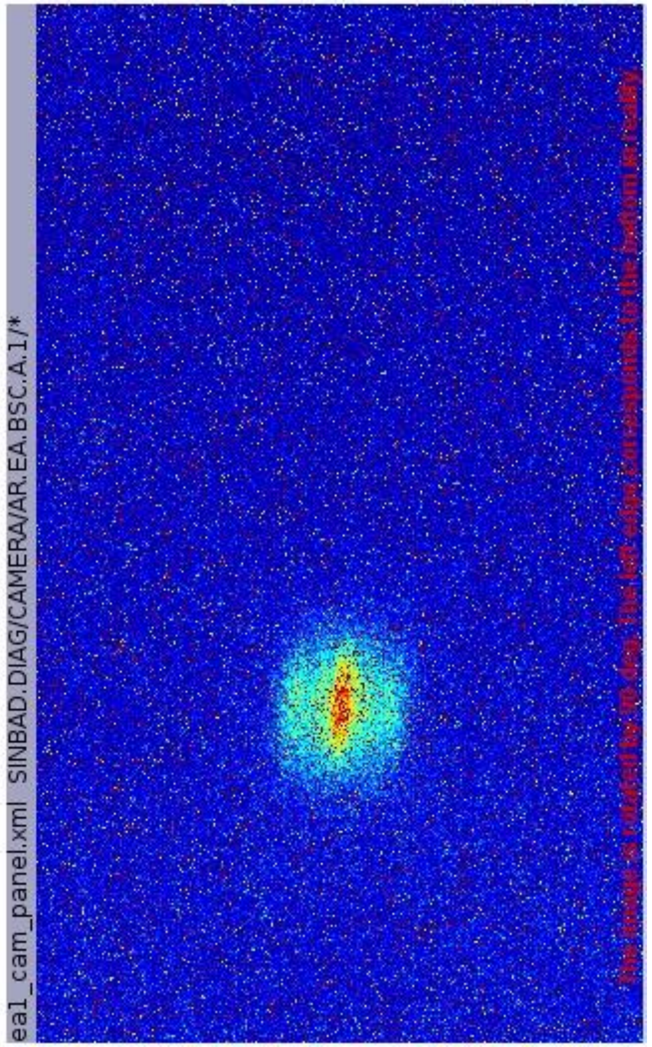




Wire scanner measurement



YAG screen image



PAUL SCHERRER INSTITUT PSI

Big thanks to Benedikt, Pavle and Rasmus!

Wire scanner: B. Hermann et al., Phys. Rev. Accel. Beams 24, 022802, 2021

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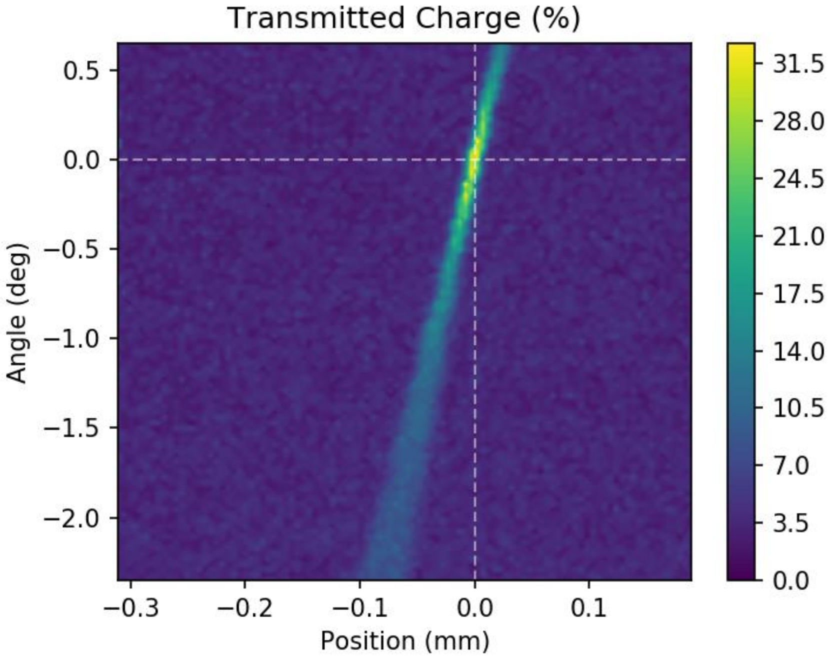
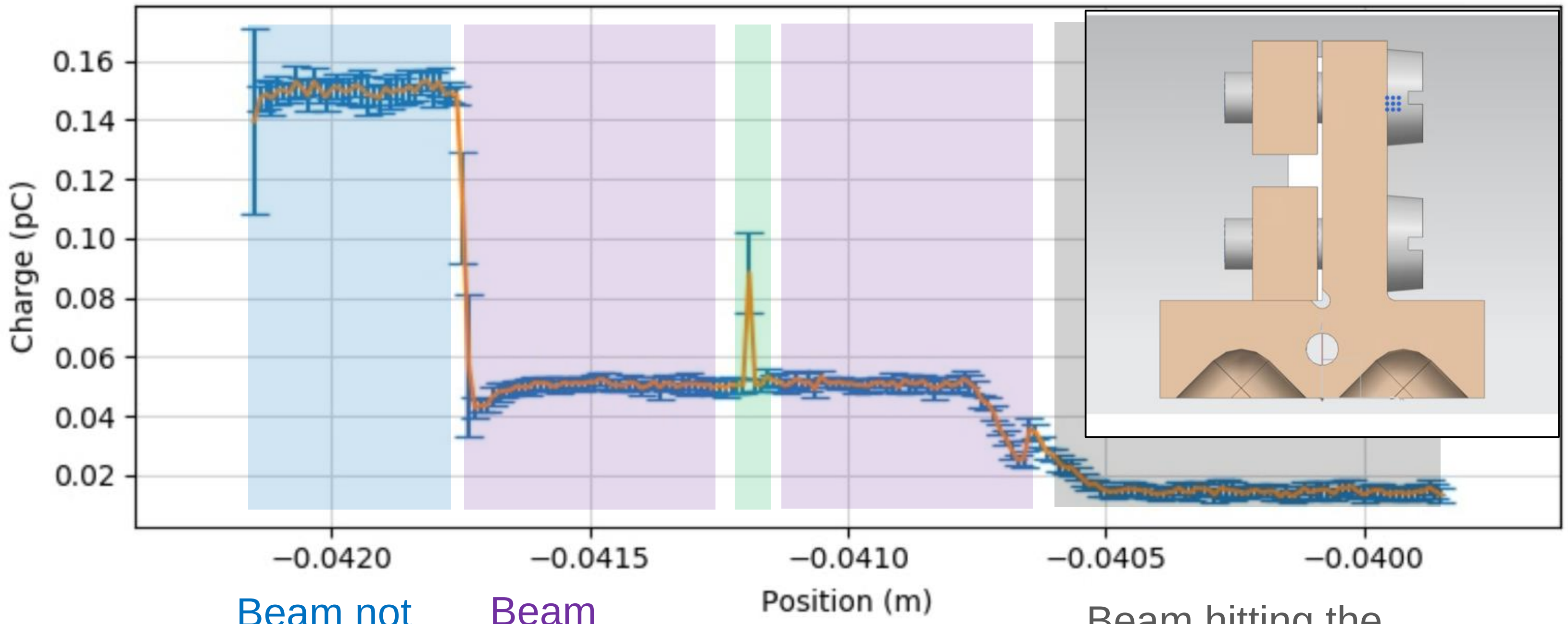
ACHIP @ ARES – experiment status

Transmission through the DLA aperture



Position and angle scan using the SmarPod 6D Positioning System

Position scan using the SmarPod → Charge on downstream DaMon



Beam not hitting the sample or holder

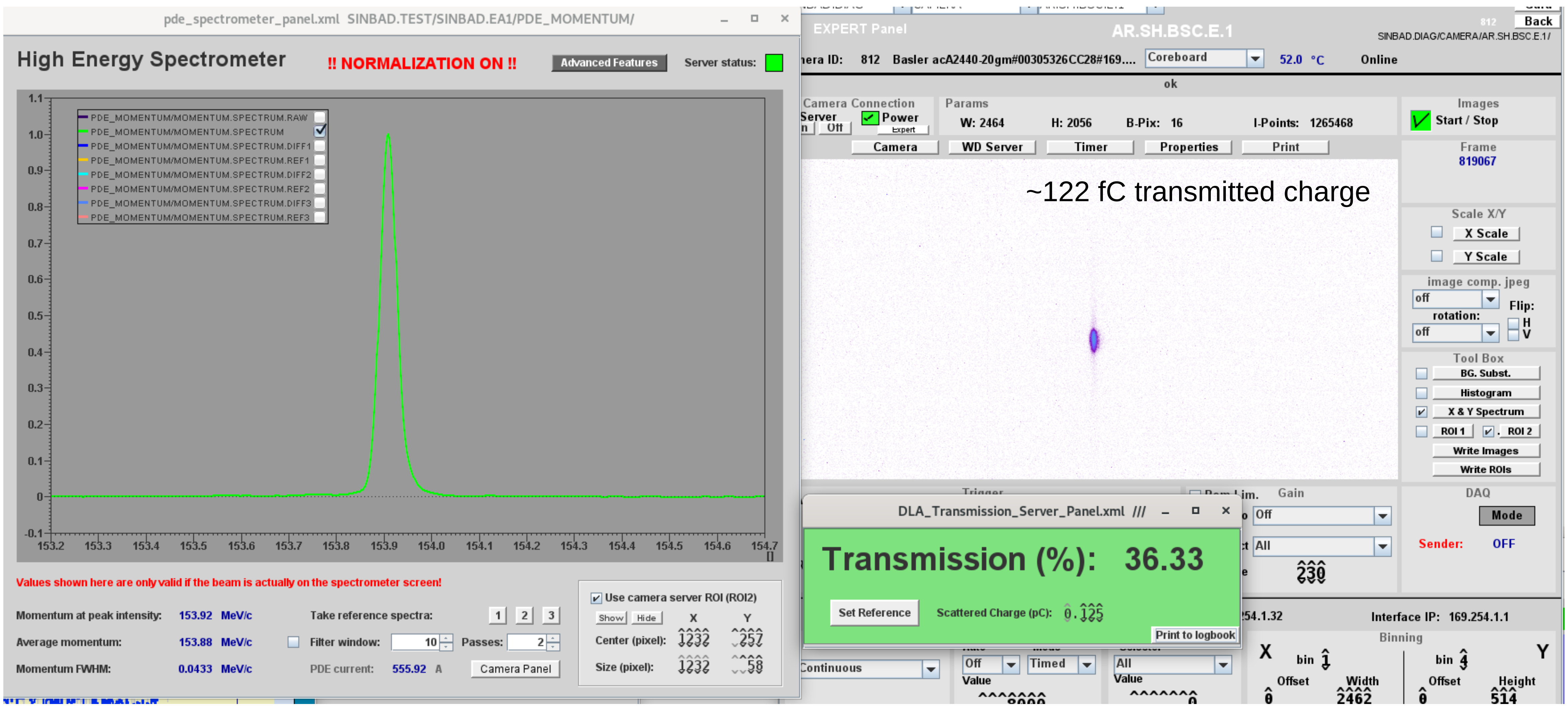
Beam hitting the DLA SiO_2 substrate → Some scattered electrons detected

Transmission through the 1 mm long 1 µm wide aperture!

Beam hitting the metal sample holder → Blocked

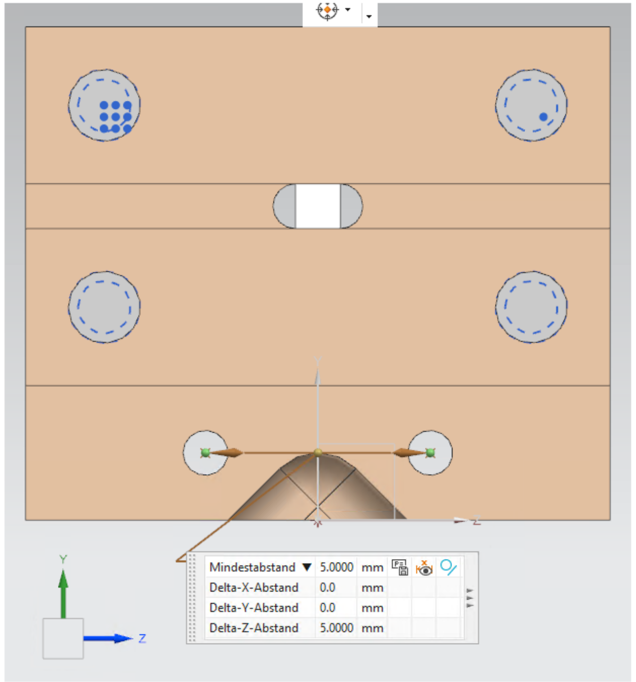
ACHIP@ARES – experiment status

Transmission transported downstream to spectrometer



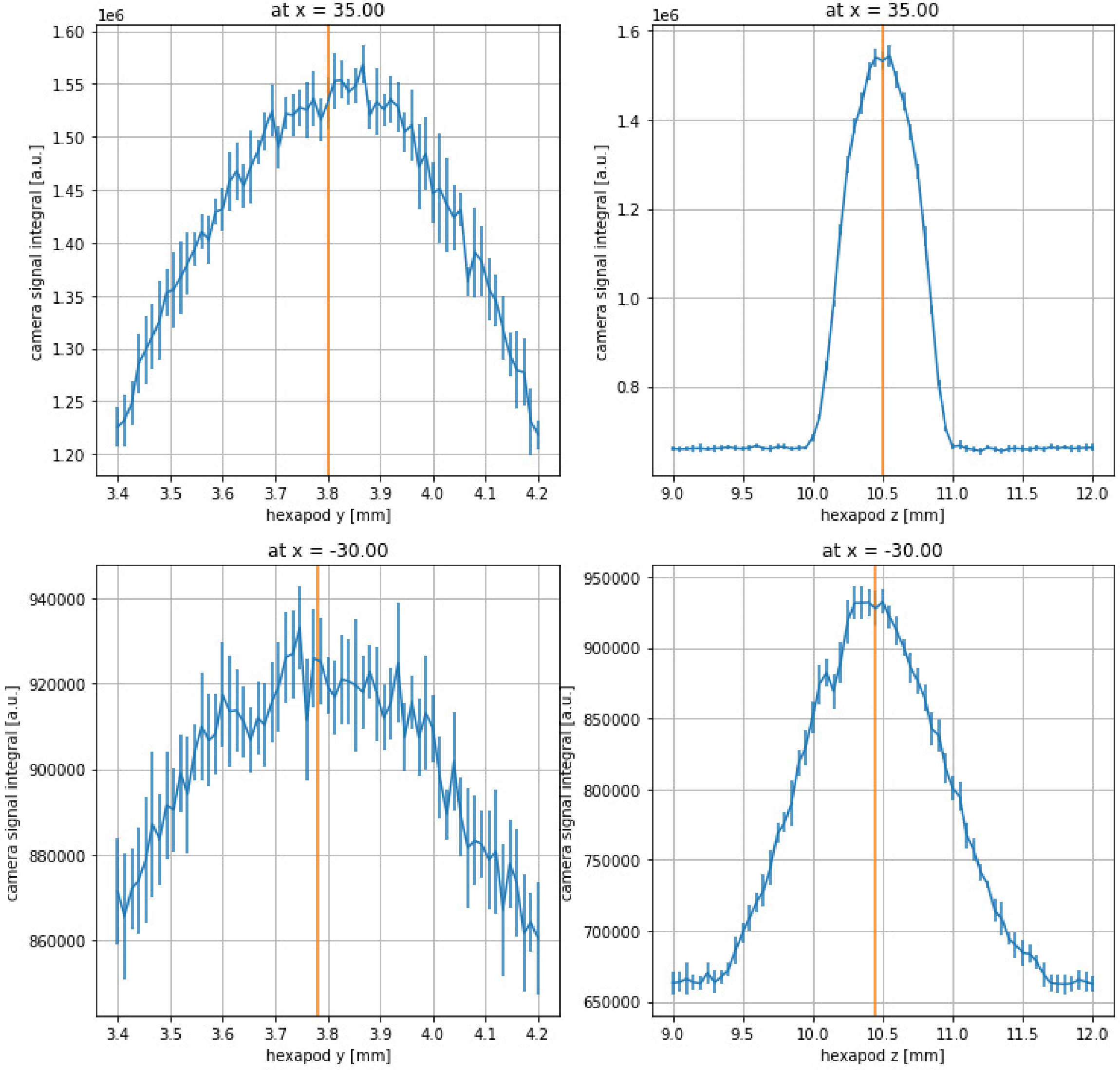
ACHIP@ARES – experiment status

Laser aligned to DLA



Angular alignment is especially important

Incident angles < 1mrad

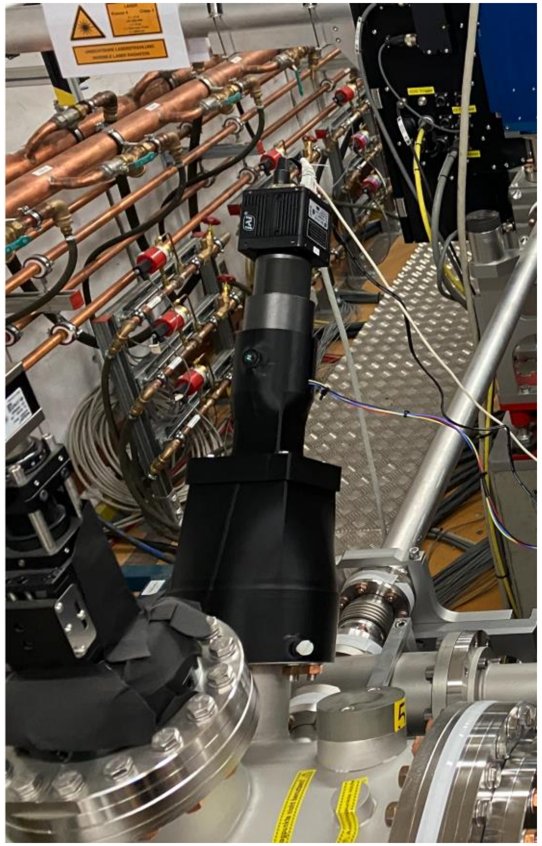


ACHIP@ARES – experiment status

Temporal overlap – rough timing, Courtesy Hossein Delsim-Hashemi

- **Timing setup** on the 45° observation port of the experimental chamber
  - Electron signature: Cherenkov radiation – Laser: Direct detection of scattered light

After that: Fine scan in a shorter window with fs precision possible via the laser sync



Low-noise precision delay generator (SRS DG645)

→ Will give us timing on the 10s of ps scale; then we will use the laser sync.

EA Laser table 10Hz trigger

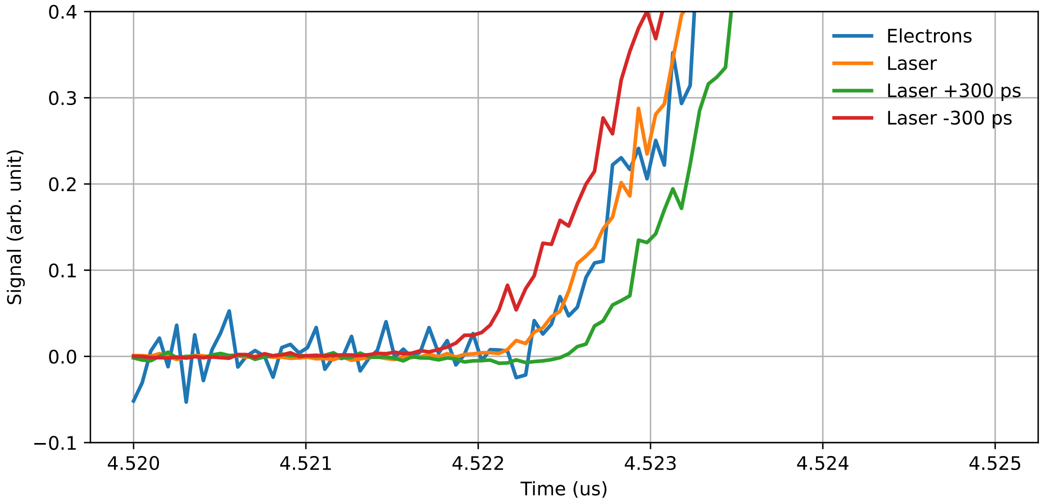
T_1 to camera with dt_1

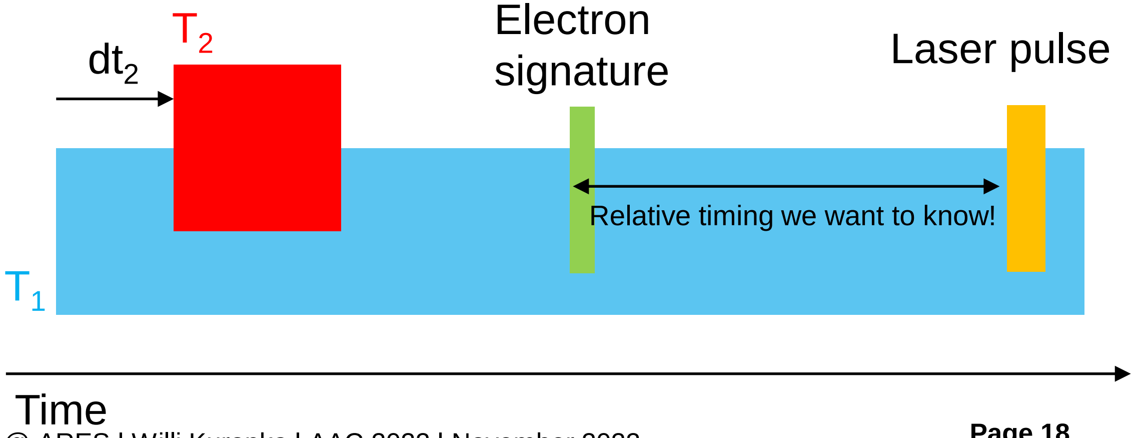
T_2 to intensifier with dt_1+dt_2

Trigger pass through to table

3D-printed holder

- 3-lens optics
- MCP-based gated intensifier
- Triggered camera





Summary

- ARES commissioning has been successful and continues towards sub-fs bunches
  - Almost all design electron beam parameters demonstrated
  - Two successful ARIES transnational access runs, machine learning experiments, electron imaging, dosimetry towards medical applications, high precision electron beam diagnostic devices
  - PolariX transverse deflecting structure commissioning starting Q1 2023
- DLA experiment
  - Spatial and temporal overlap of laser and electron beam has been established
  - Will continue as soon as pump laser for the 2um amplifier system is repaired
  - After base line experiment the short electron bunch experiment (“stage 1”) will start
  - Installation of laser modulator in Q1 2023
  - Later on microbunching experiment (“stage 2”) will start

Thank you for your attention!

Questions?

Acknowledgments:

Colleagues

Collaboration

Hartl Group

ARD Colleagues

Solgaard group

Kärtner Group

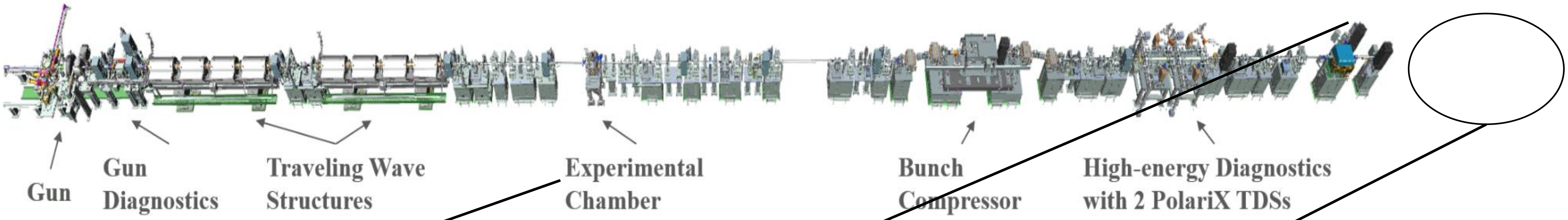
Joel England

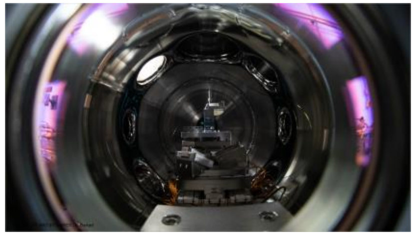
Contact: willi.kuropka@desy.de

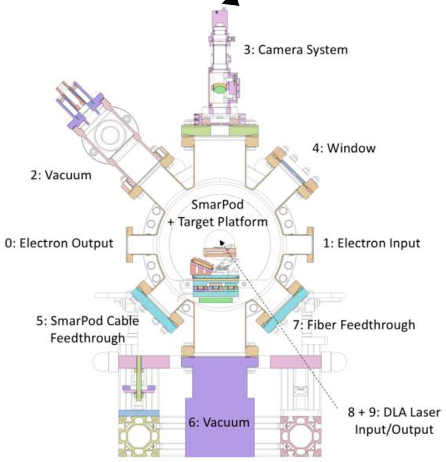
The ARES linac at DESY

Current hardware status & perspectives, courtesy T. Vinatier

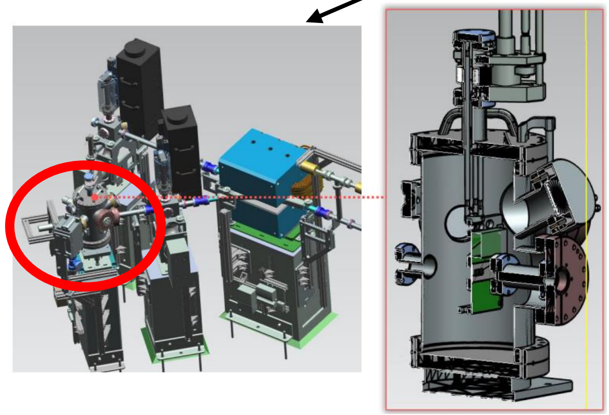
- **Beamline installation almost completed** (hardware point of view). Several locations for experimental program.
- Still ongoing: First klystron for PolariX TDS expected beginning 2023; BPM calibration; Upgrade of in-air experimental area.



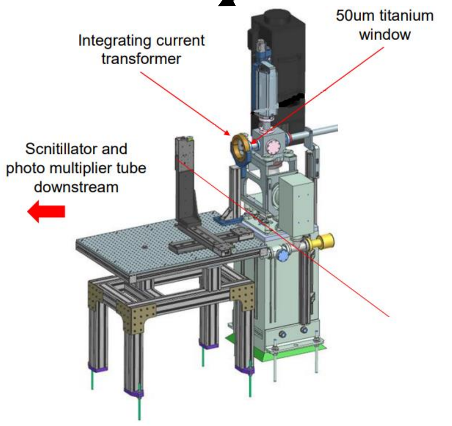


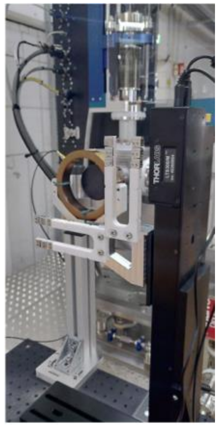


Smaract hexapod, beam diagnostics, UHV requirements.



In the dispersive section Equiped with mover. No UHV requirements.



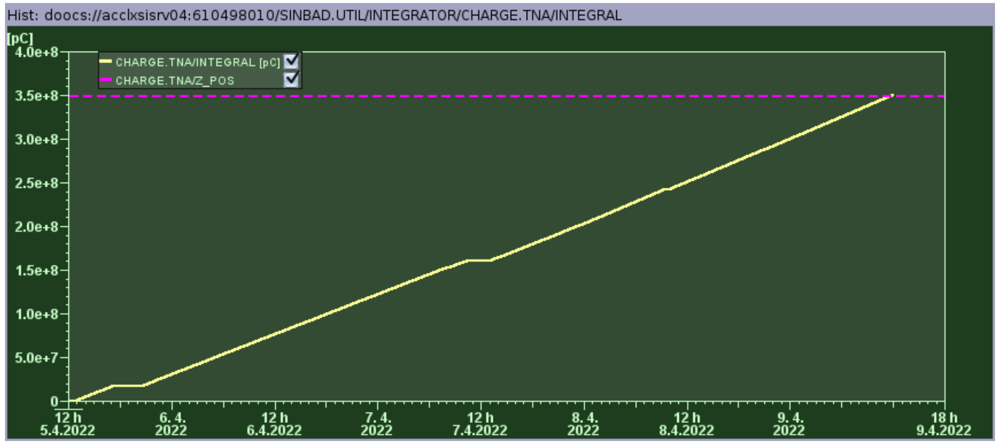


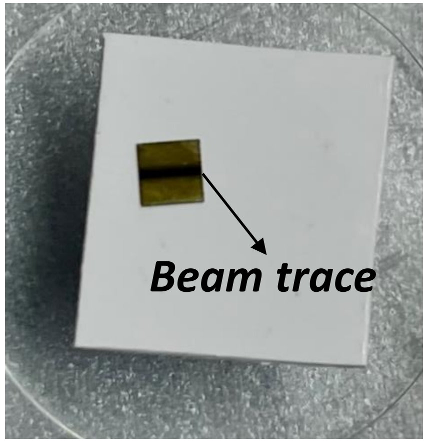
Equiped with exit window, wire scanners (both planes), screen and ICT. Upgrade with quadrupole triplet and steerers planned.

Experimental program

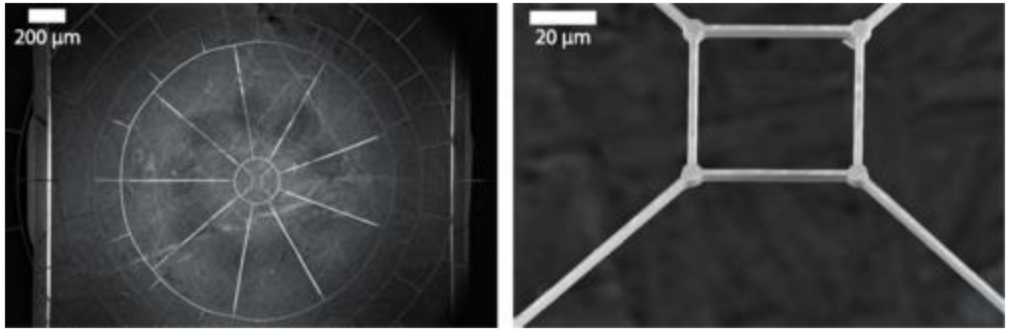
Transnational access program at ARES

- During first quarter of 2022, **ARES delivered beamtime to 2 external users** as part of the ARIES TNA program: Irradiation of diamond sensor for damage study (EPFL) & Micro wire-scanner measurements (PSI)

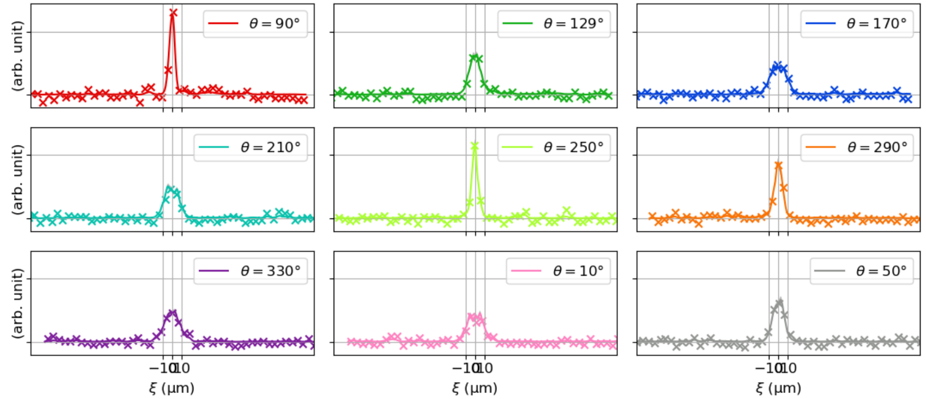


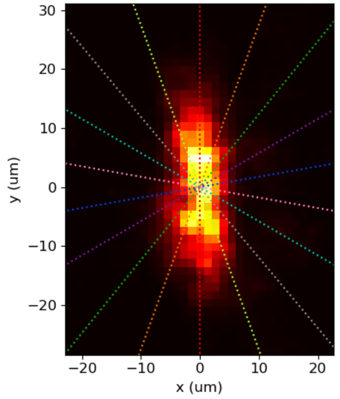


- *Around 4 days continuous beamtime to irradiate a diamond piece with a 100 pC beam (3.5*10^8 pC total charge). Excellent stability during the irradiation → No momentum adjustment and almost no position adjustment required.*



See B. Hermann et al., Phys. Rev. Accel. Beams 24, 022802, 2021





- ***Micro-wire from PSI installed in experimental chamber and tested in TNA run. Still in place and allows for transverse size and emittance measurements of µm-scale bunches.***

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Experimental program

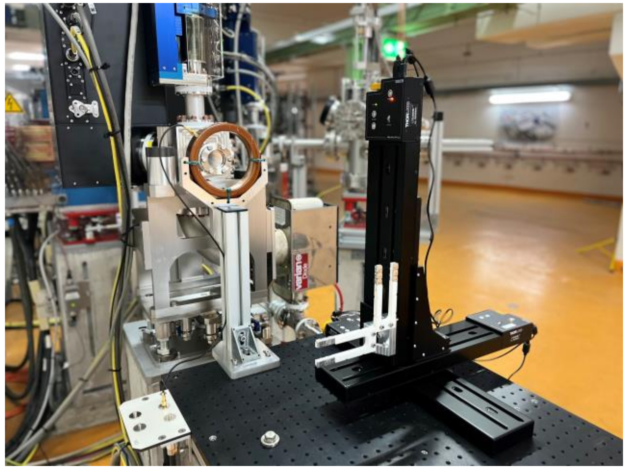
New opportunities for medical research: A chance for DESY to steep deeper into medical applications of accelerators (F. Burkart)

- Up to 160 MeV high precision electron beams for **research & development**.
  - **Cutting-edge stability** of the electron pulse energy
  - **Excellent beam control**
- Easy access and a lot of space.
- Ready for first VHEE and medical experiments.

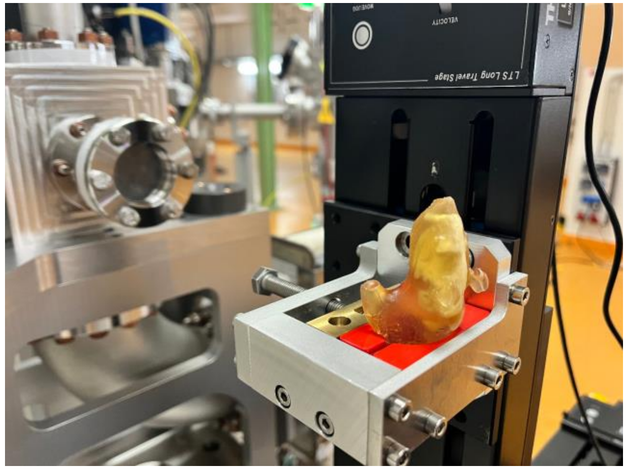
→ Started to adapt ARES to the needs of medical research.

→ Setting up collaborations and infrastructure.

- **Collaboration with UKE Hamburg** started to study **novel cancer treatment** methods (Prof. Dr. Kai Rothkamm, Dr. Nina Struve & al.)
  - Diagnostics (dose measurements) development.
  - First benchmarking of simulations.
  - Studies on medulloblastom treatments.



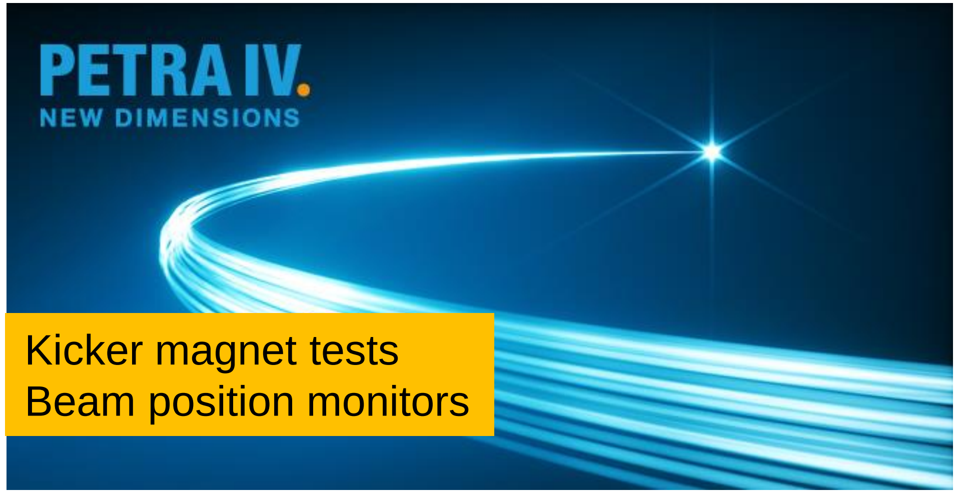
Experimental station designed for medical research



Mouse phantom for electron CT studies

Experimental program

An R&D accelerator for ST3-related topics



Test components for big user machines

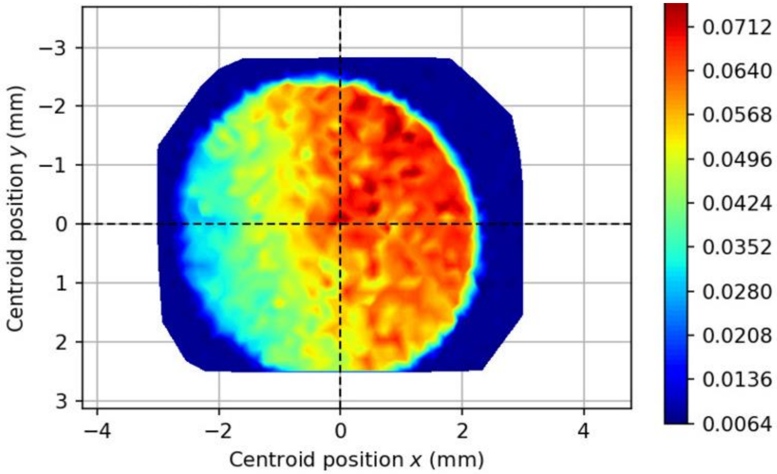
Advanced accelerator components R&D

- Intensity monitors development
- Vacuum windows
- High stability infrastructures (LLRF, …)
- 3D printing of components
- Prototyping
- Photocathode Laser development
- …

Autonomous accelerators workshop with collaboration partners from KIT

State of the art beam controls & diagnostics

- Machine learning towards autonomous accelerators
- fs synchronization
- PolariX Transverse deflecting structures
- High-resolution screens
- …



High-resolution cathode diagnostics

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Experimental program

Autonomous accelerator studies: Reinforcement learning for particle accelerator optimization (O. Stein & J. Kaiser)

Weekly beamtimes at ARES allow testing and evaluating of the latest developments directly on a real accelerator.

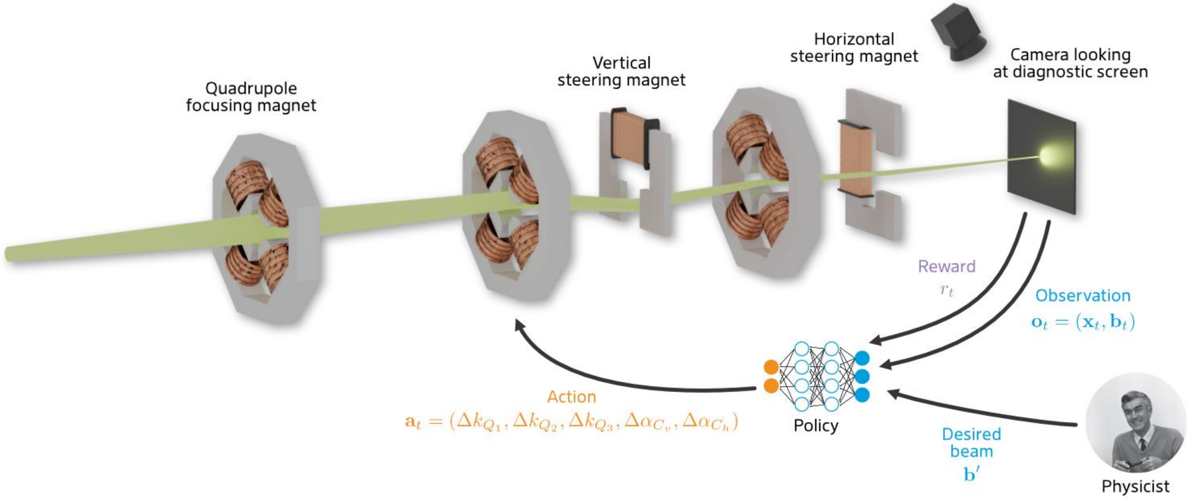
Current Status

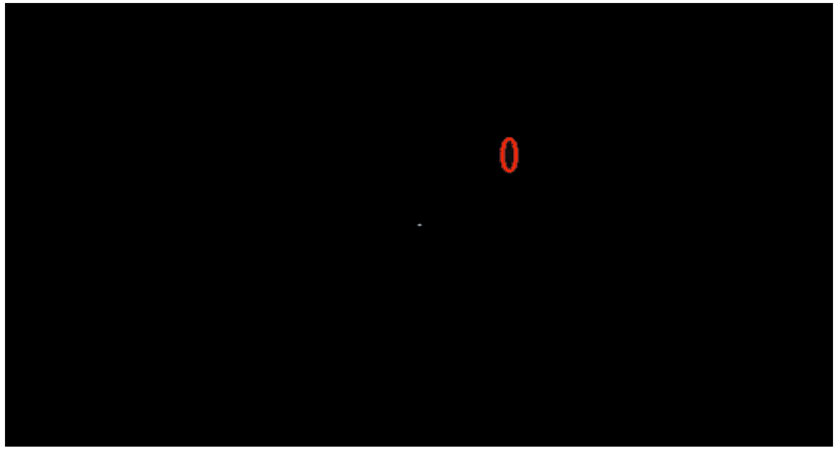
- **Reinforcement learning agents** trained and evaluated for **optimising magnets** to achieve beam parameters set by operator in the ARES Experimental Area.
- Achieved beam comparable to human operator, but 4x **faster**.
- Automated alignment of the beam to multiple quadrupoles using numerical optimisation.

Perspectives

- Apply similar agents to other sections of ARES where beam parameters can be optimised on a diagnostic screen.
- Combine reinforcement learning agents to **achieve fully autonomous beam threading through ARES**.
- Faster beam-to-quad alignment by training reinforcement learning agents to do the alignment.

Checkout poster on **Reinforcement Learning for Particle Accelerators**!





Q1=10.00 Q2=−10.00 CV=−0.00 Q3=10.00
CH=−0.00
mx=0.89 sx=0.08 my=0.79 sy=0.20

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Experimental program

Advanced accelerator R&D: The TWAC project

- **TWAC**: 4 years project (04-2022 → 04-2026) aiming to develop a prototype towards a compact hybrid accelerator (conventional RF + THz-driven structures) delivering low-energy (~ 10 MeV) and high peak current bunches (~ kA).

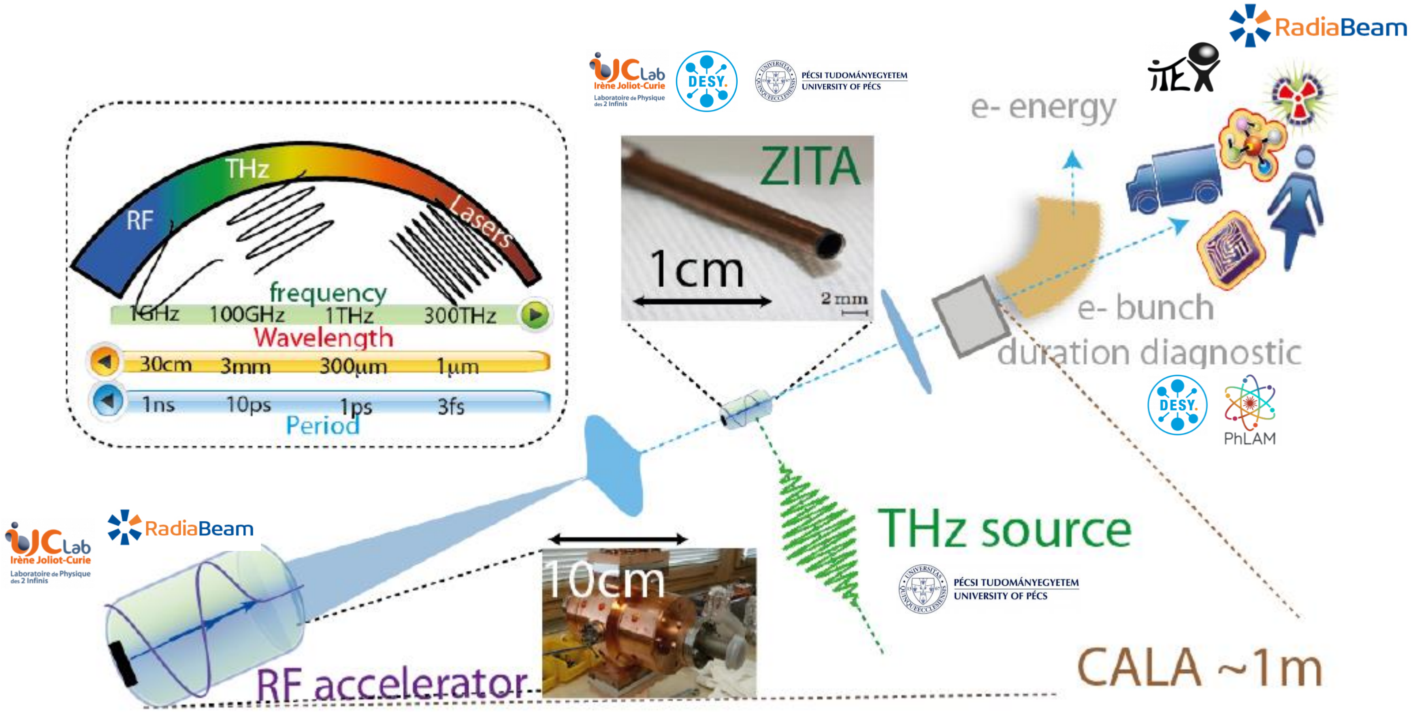
Coordinator — CNRS, IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis, PhLAM

Partner laboratories — DESY, PÉCSI TUDOMÁNYEGYETEM UNIVERSITY OF PÉCS

Industrial partners — RadiaBeam, ITEX

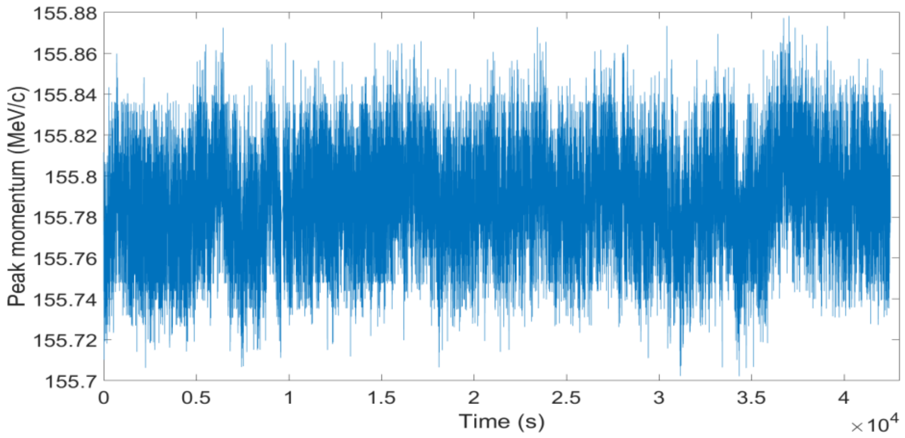
EIC Pathfinder funding — Funded by the European Union

- **At ARES:**
  - Development of compact bunch duration diag. with fs resolution & minimal complexity of the technical environment
  - Benchmark with conventional diagnostics: Tomography and X-band deflecting structure
  - Funding for 1 Post-doc for 4 years+ equipment (65 kE) and travel (22 kE)

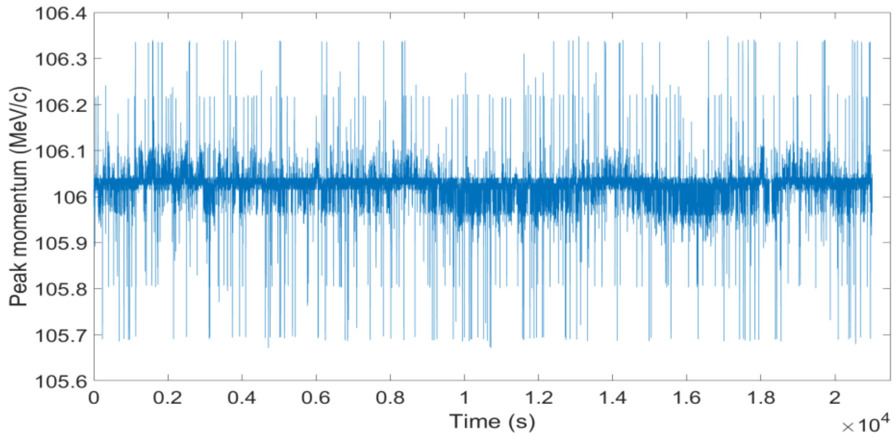


Beam commissioning status

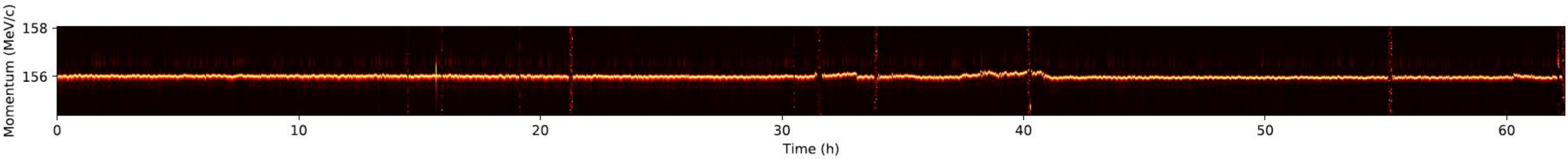
Stability achievements, courtesy T. Vinatier



Mid-term momentum stability at ARES for on-crest working point: 22.7 keV/c std at 155.79 MeV/c → 1.46*10^{-4} over 12 hours (1 shot per 0.5 s recorded)



Mid-term momentum stability at ARES for velocity bunching working point: 45.3 keV/c std at 106.02 MeV/c → 4.27*10^{-4} over 6 hours (1 shot per s)



Long-term momentum stability at ARES: 43.7 keV/c std at 156.22 MeV/c → 2.80*10^{-4} over 62 hours (1 shot per min recorded)

- The **numbers are upper limits**, since not yet decorrelated from position jitter. Moreover, no feedback is active on the accelerating structures (only output vector correction) and no drift compensation monitor is active on TWS2 → Room for further improvement.

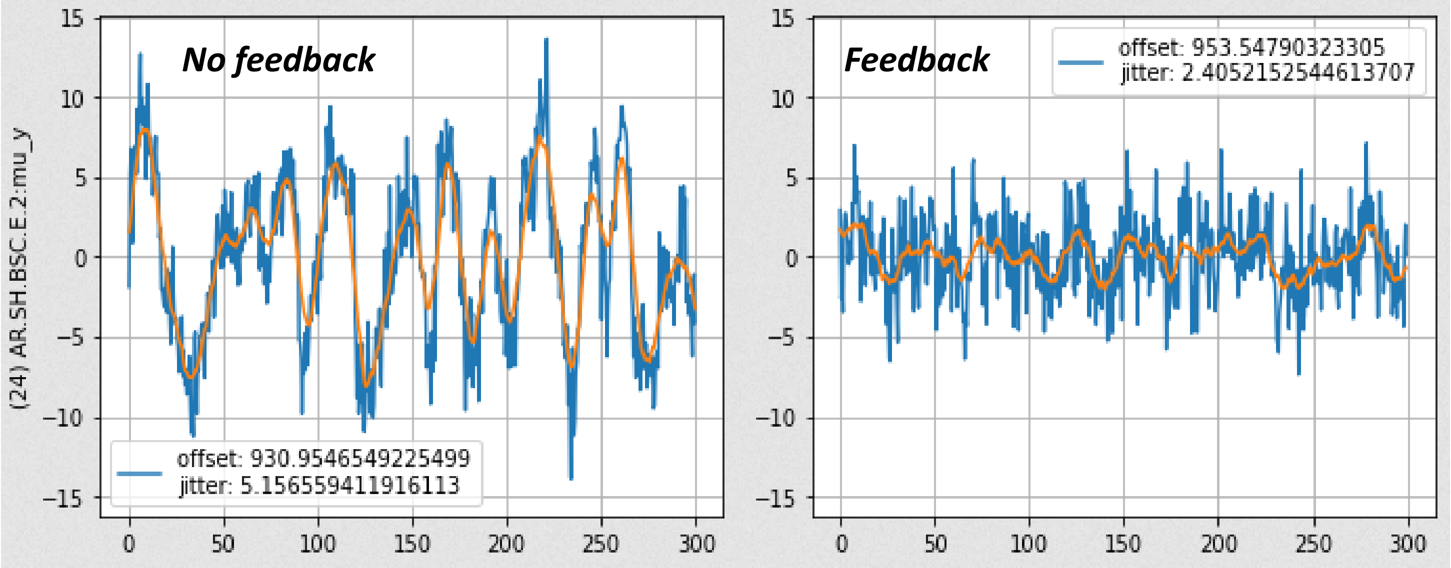
Beam commissioning status

Current status & objectives, courtesy T. Vinatier

- Commissioning phase still ongoing. **Most of the ARES target bunch properties have however already been demonstrated**.
- Only the single-digit to sub fs duration has not yet been measured (resolution limit). The upcoming PolariX TDS should remedy to this.
- Work ongoing on discrete beam position feedback. It will greatly help to investigate the real momentum stability.
- Magnetic bunch compressor currently under commissioning.
- 8 beam position monitors along the beamline under commissioning
- STRIDENAS detector under commissioning for very low charge diagnostics.

Mayet, F., et al., Phys. Rev. Accel. Beams, Vol. 25, Iss. 9, 2022, DOI:10.1103/PhysRevAccelBeams.25.094601

Properties	Target value	Status
Charge	0.05 – 200 pC	0.03 – 200 pC
Momentum	50 – 150 MeV/c	50 – 160 MeV/c
Momentum spread	10^{-4}	10^{-4} (resolution limited)
Transverse emittance*	< 0.8 π.mm.mrad	≈ 0.15 π.mm.mrad
Duration	Sub-fs to ≈ 10 fs	≈ 20 fs (resolution limited)

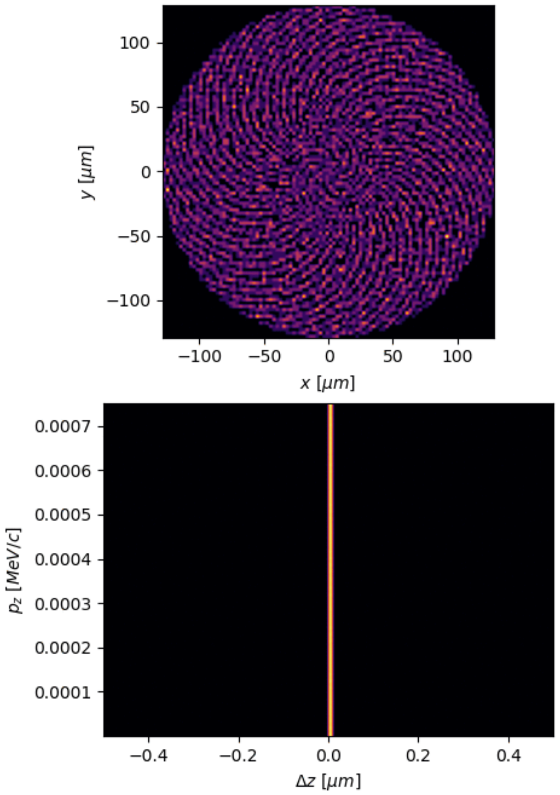


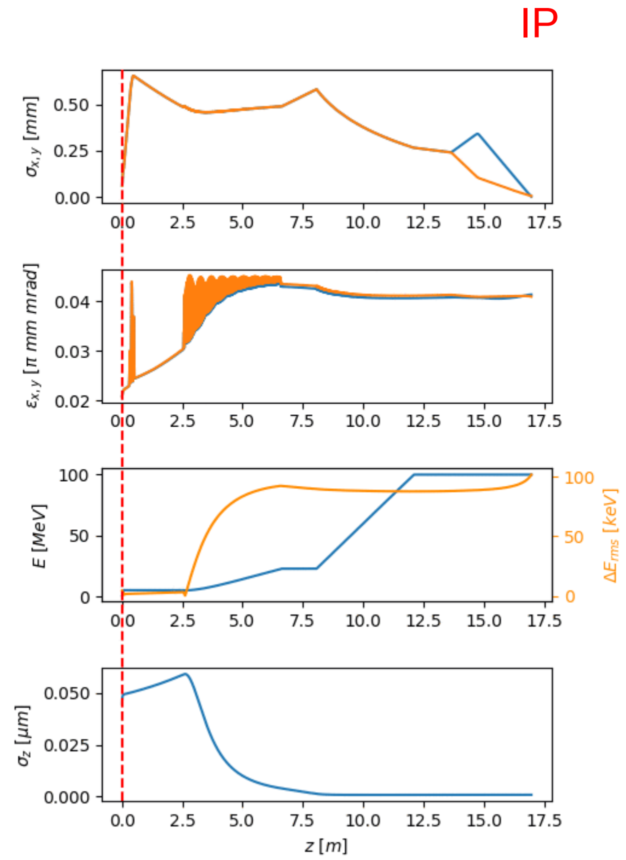
ACHIP@ARES – simulations – short bunch

Electron beam matching to the DLA

- Velocity bunching in TW1
- Acceleration on TW2
- Quadrupoles for asymmetric focus

Charge	0.5 pC
Mean Energy	99.82 MeV
Energy spread rms	102 keV
Trans. Emittance x	45 π µm mrad
Trans. Emittance y	38 π µm mrad
Beam size x rms	2.04 µm
Beam size y rms	9.73 µm
Bunch length FWHM	1.6 fs

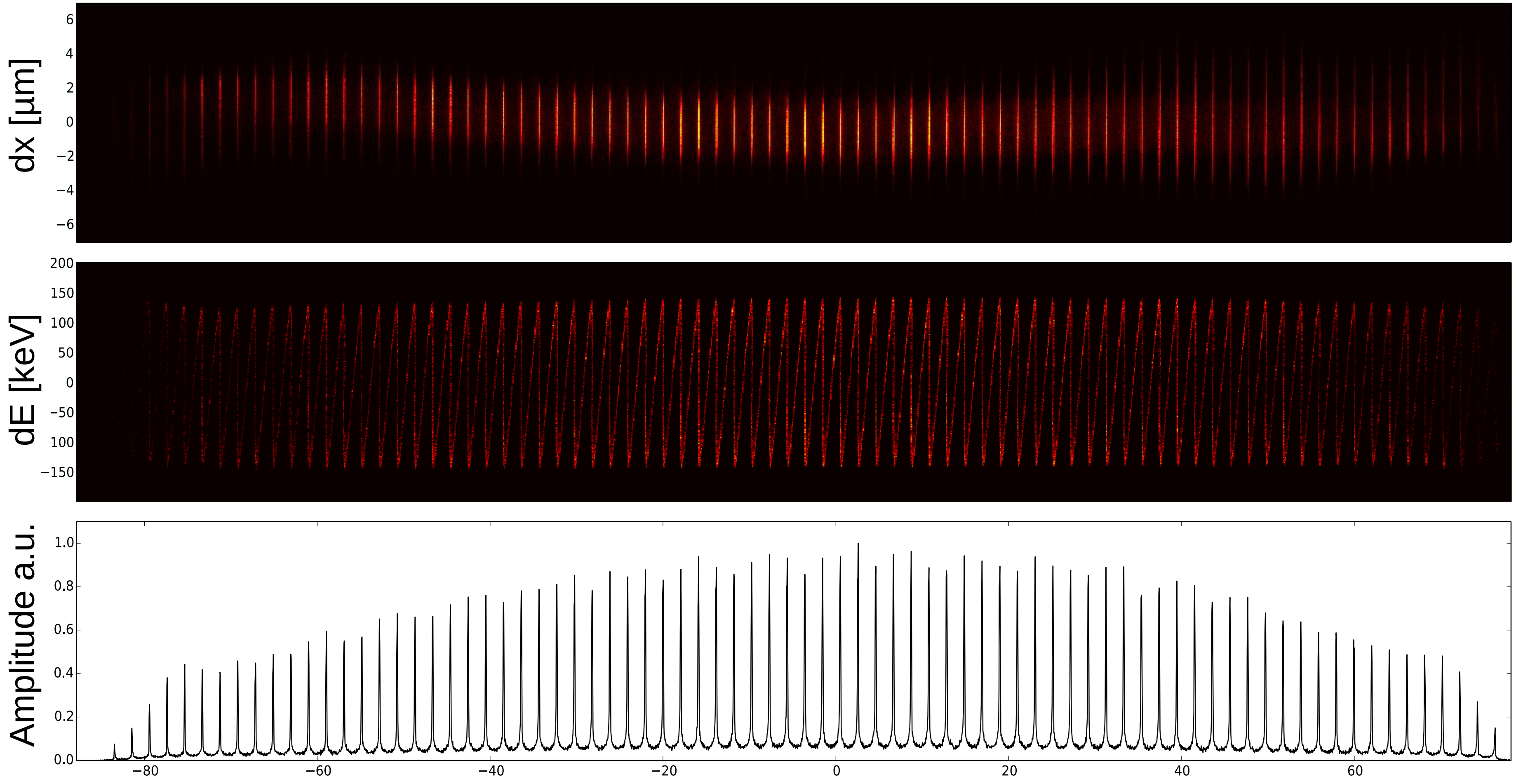




ACHIP@ARES - simulations – microbunching “stage 2”

Simulation of Microbunch trains for DLA

Real space top view, long. Phase space and current



Microbunches ~500 as FWHM
with bunching factor ~0.53

Courtesy F. Mayet

What DLAs are good for

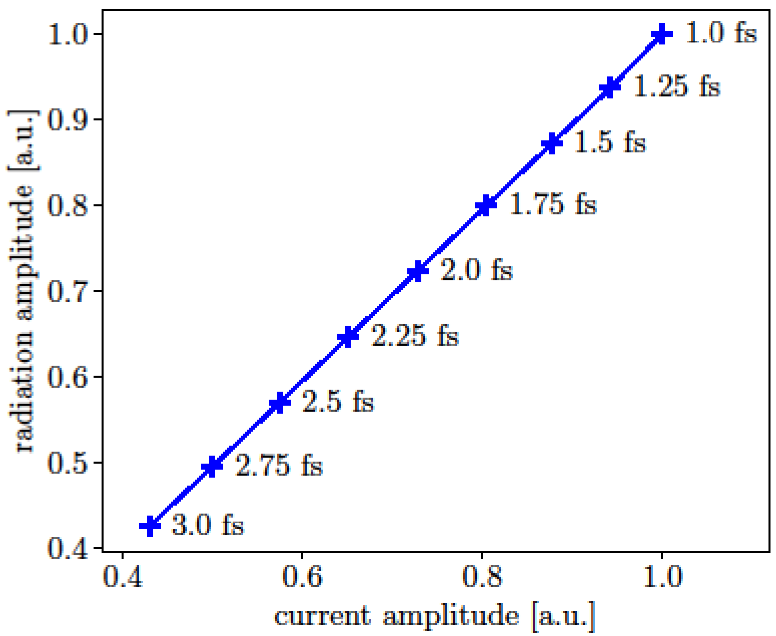
See PDF

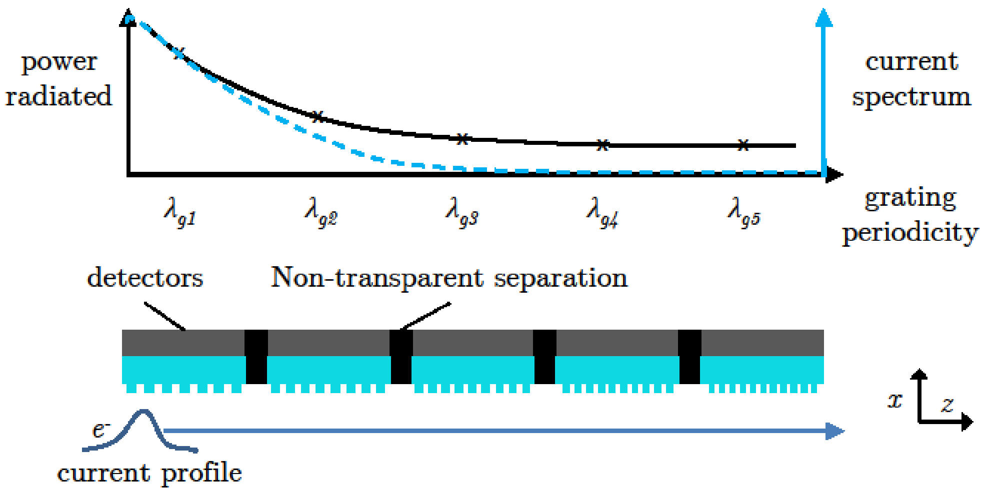
https://opg.optica.org/viewmedia.cfm?r=1&uri=CLEO_SI-2020-SW4G.4&seq=0

Short-bunch experiment at ARES

Dielectric gratings as particle beam diagnostic

PIC simulation data

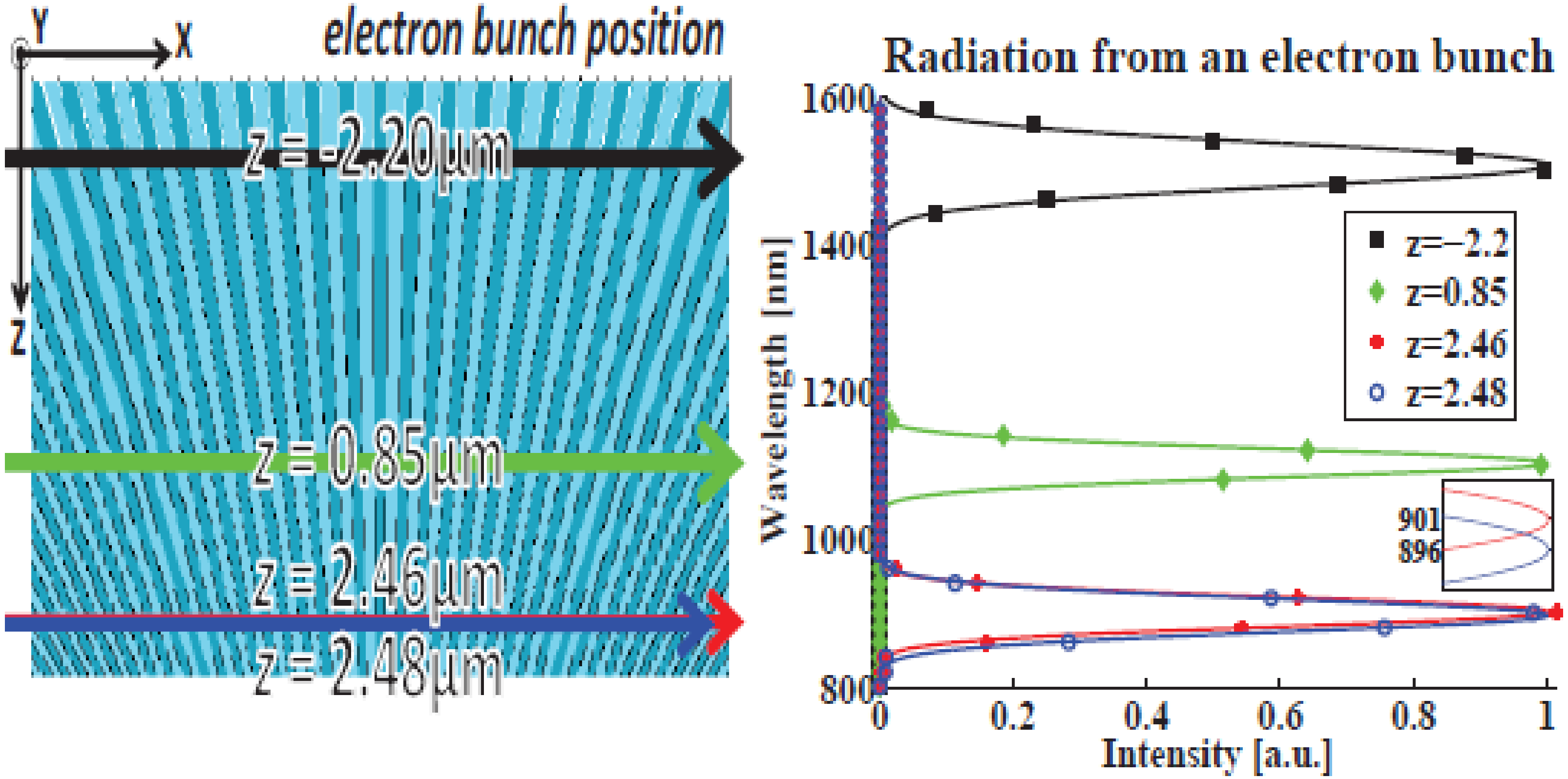




- Smith-purcell radiation generation experiment using the same setup
- 2 µm grating passed by bunch of varying bunch length

- Several gratings with different periods in longitudinal direction
- Compact, potentially inexpensive, passive device for fs-resolutions
- Potentially single shot for high current beams like FELs

Backup - DLA beam position monitor



K. Soong, et. al., Proceedings of PAC2013, MOPAC32