Towards femtosecond-scale electron bunches with high stability for accelerator R&D on the ARES linac at DESY

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Sonja Jaster-Merz, Frank Mayet, Max Kellermeier, Blae Stacey, Thomas Vinatier

DESY, Hamburg, Germany

PSI GFA seminar, 17.04.2023, Villigen, Switzerland

The authors thank all the technical groups at DESY for their work and support in the ARES implementation, maintenance and operation

Outline

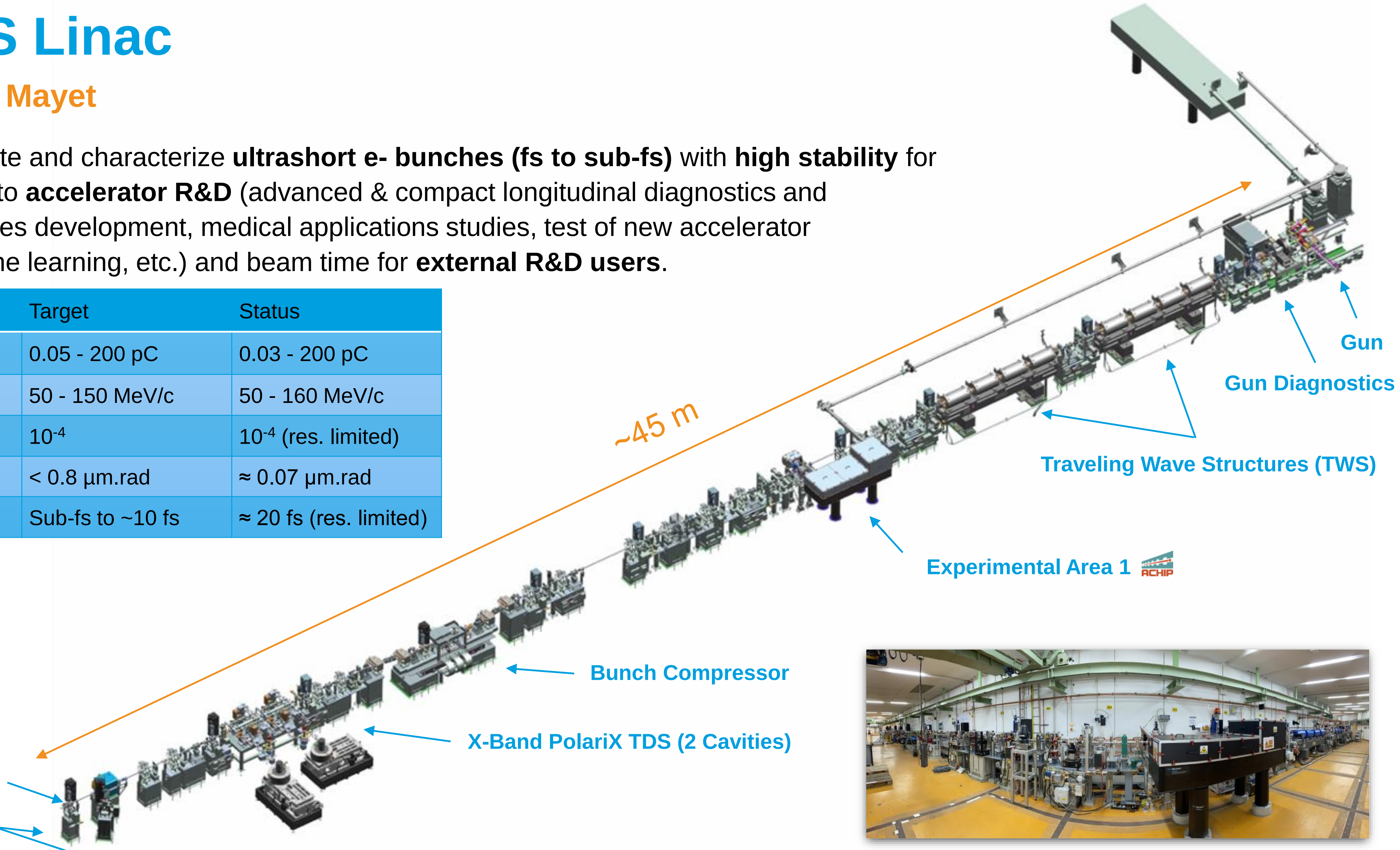
- **The ARES LINAC at DESY**
  - Layout & goals
  - Current hardware status & perspectives
- **Beam commissioning status**
  - Bunch duration measurement
  - Stability achievements
  - Current status & objectives
- **Diagnostic devices**
  - Overview
  - Measuring micrometer beam sizes
  - Dielectric gratings as beam manipulators and diagnostics

The ARES Linac

Courtesy Frank Mayet

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 R&D users**.

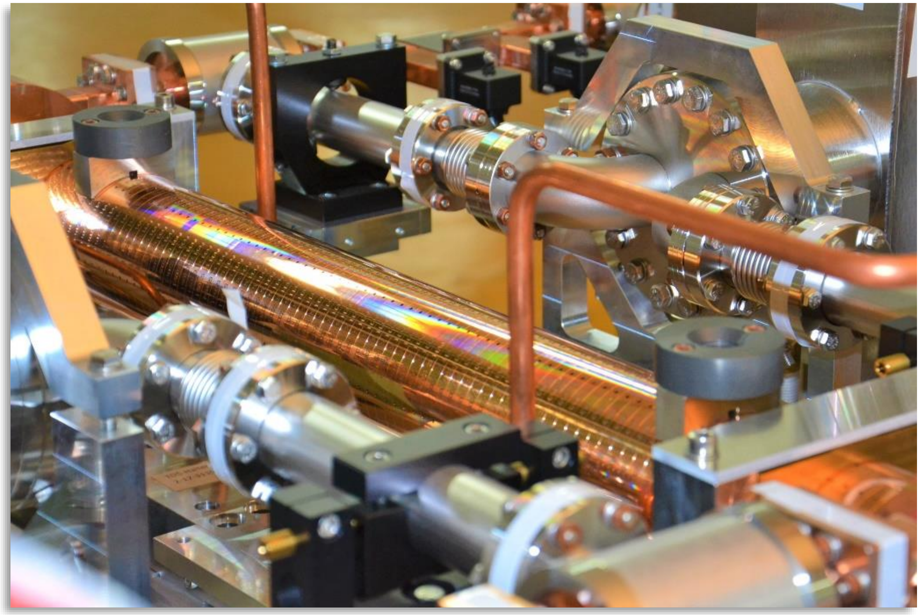
Parameter	Target	Status
Charge	0.05 - 200 pC	0.03 - 200 pC
Momentum	50 - 150 MeV/c	50 - 160 MeV/c
Momentum Spread	10^{-4}	10^{-4} (res. limited)
Transv. Norm. Emittance	< 0.8 µm.rad	≈ 0.07 µm.rad
Bunch Length	Sub-fs to ~10 fs	≈ 20 fs (res. limited)

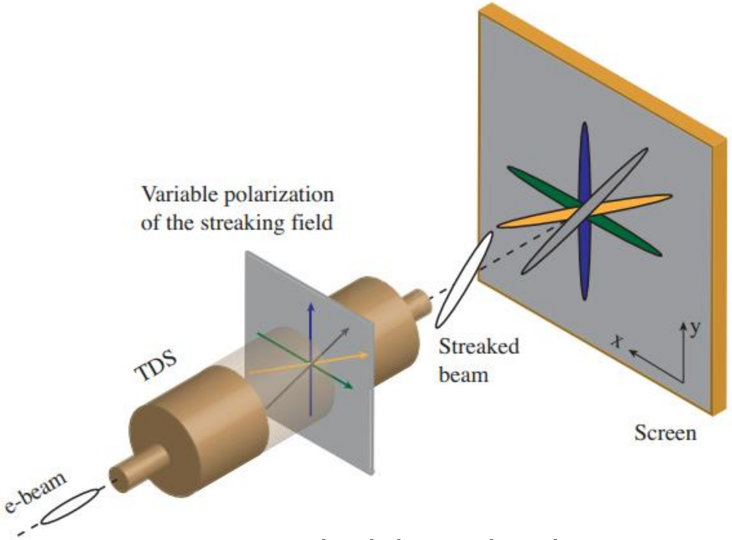


Beam commissioning status

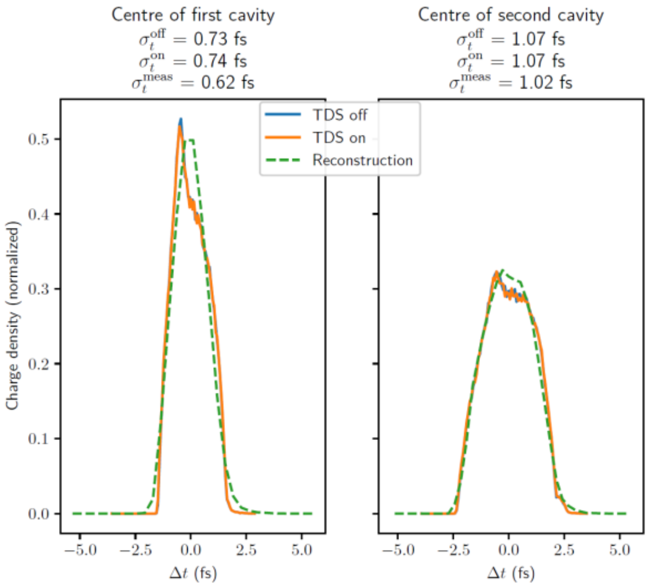
Bunch duration measurement: future steps with PolariX TDS, courtesy Thomas Vinatier

- **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). Publication in progress…





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



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

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).

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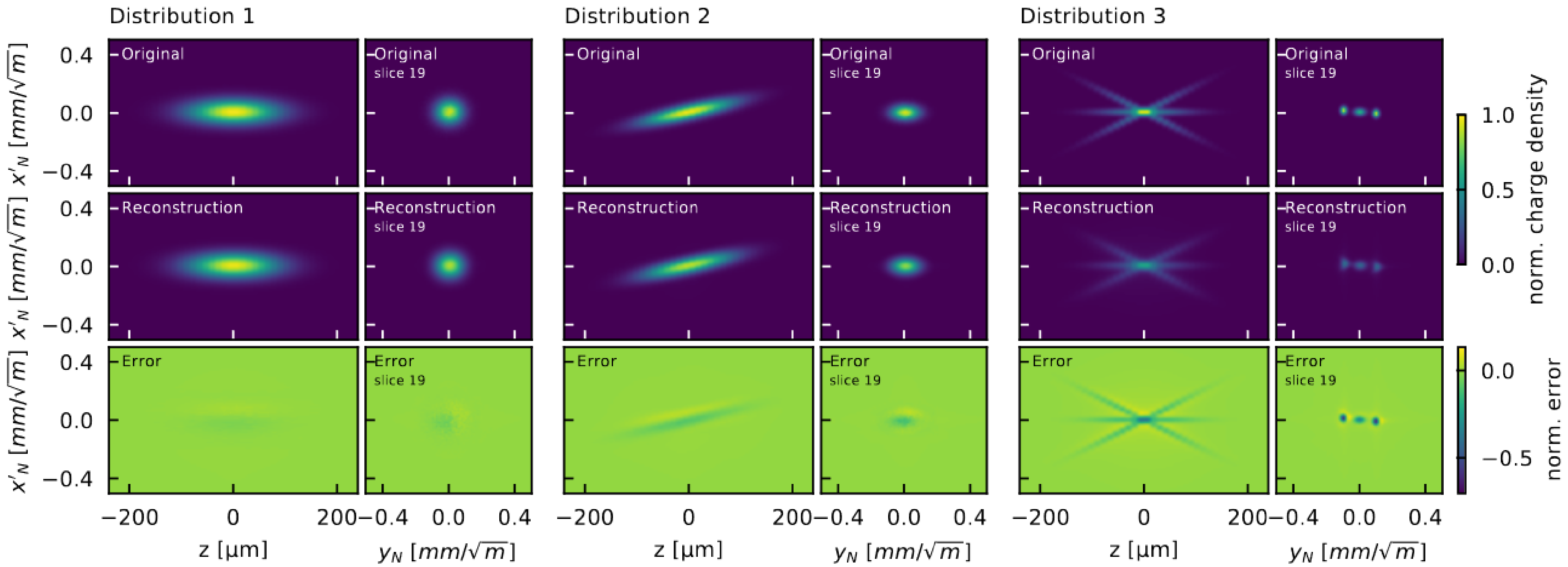
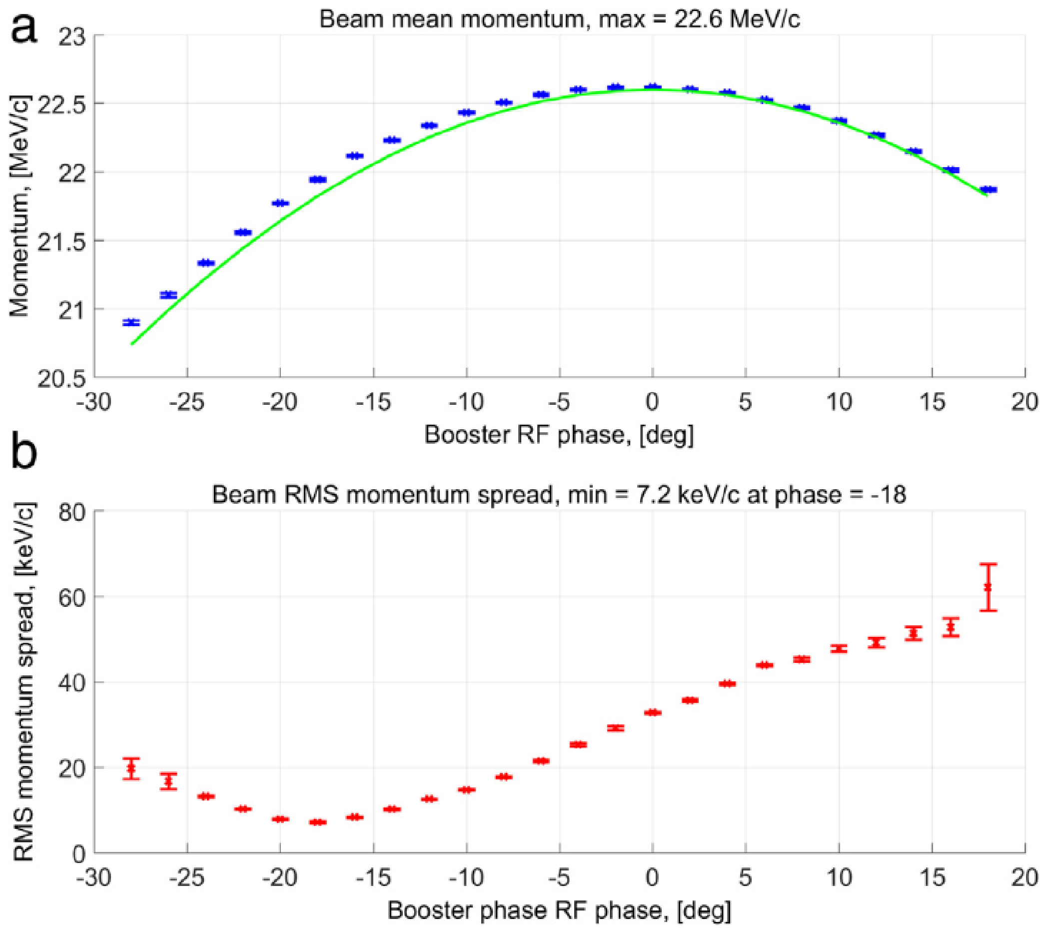


Simulation results from S. Jaster-Merz, MOPORI10, LINAC2022, Liverpool, UK

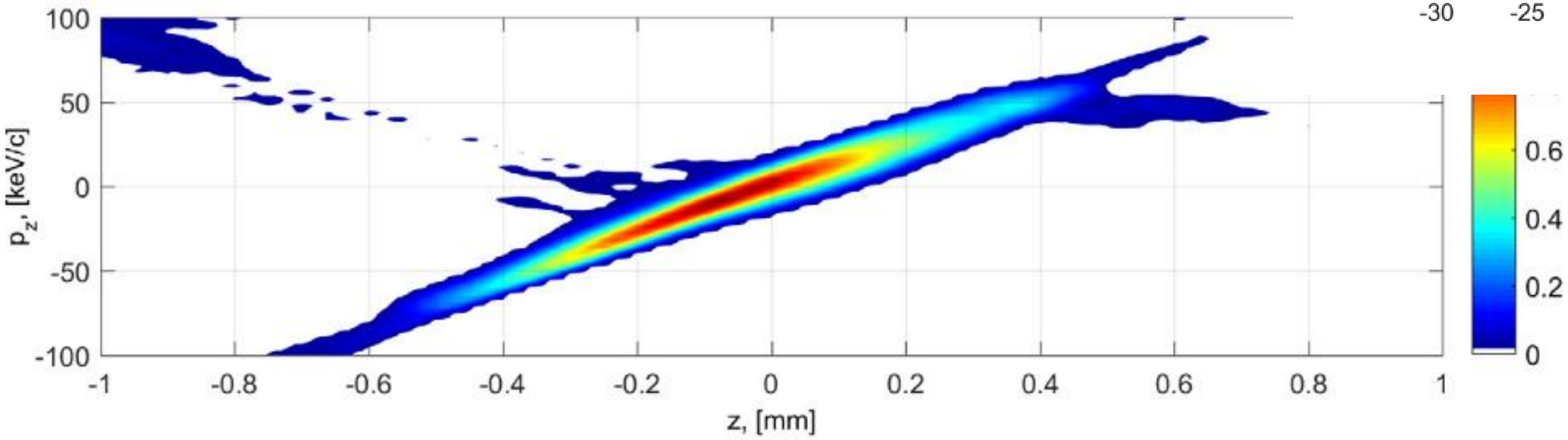
Collaboration between CERN, DESY and PSI: A. Grudiev, CLIC-note-1067 (2016); P. Craievich et al., PRAB 23 112001 (2020); B. Marchetti et al., Sci. Rep. 11 3560 (2021).

Beam commissioning status

Tomographic bunch duration measurement



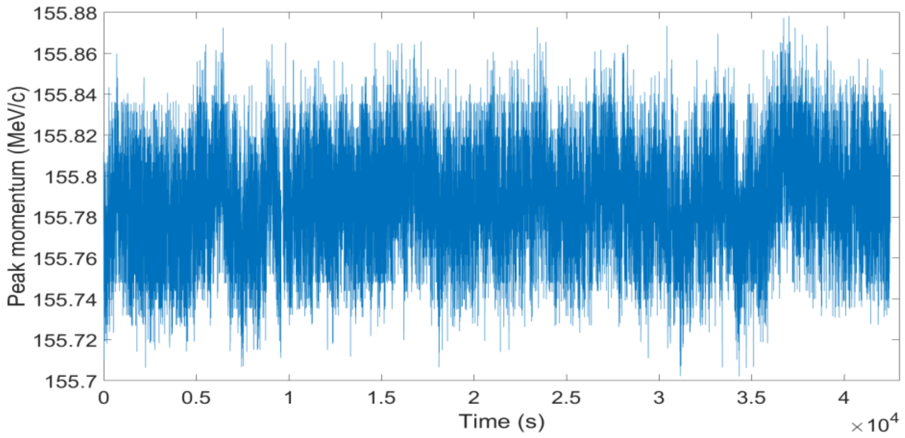
- Measurement at ARES uses TWS2 phase scan
- Achievable resolution is ~20fs
- Publication in progress…



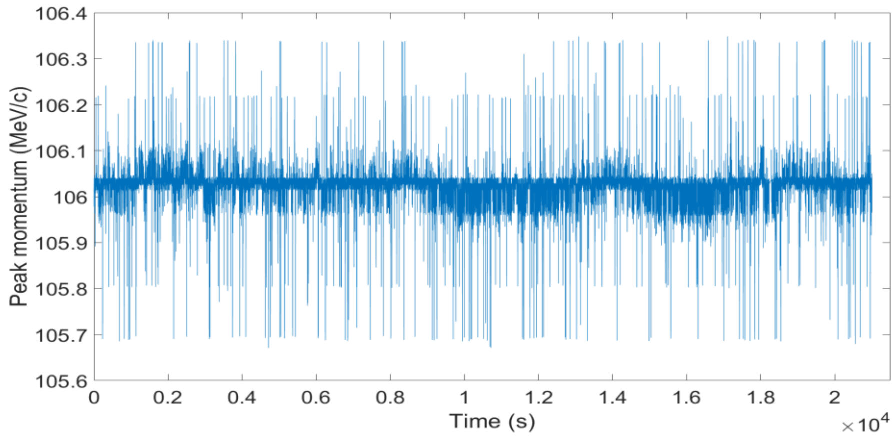
Shown are PITZ results from D. Malyutin et al., Nucl. Instr. Meth. A 871 (2017), 105-112

Beam commissioning status

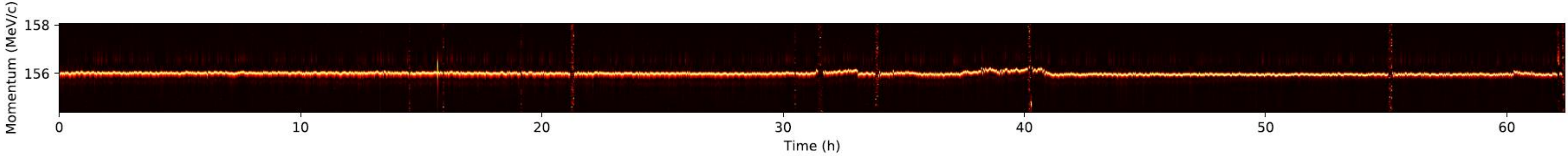
Stability achievements, courtesy Thomas Vinatier



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 Thomas 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.

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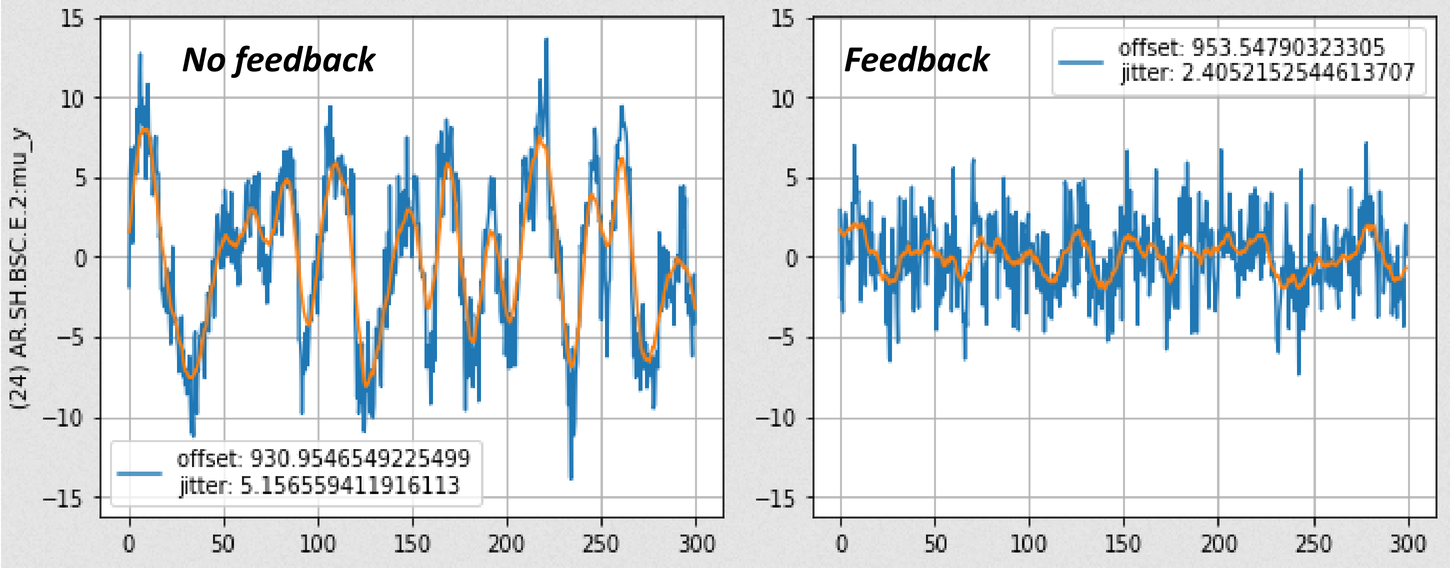
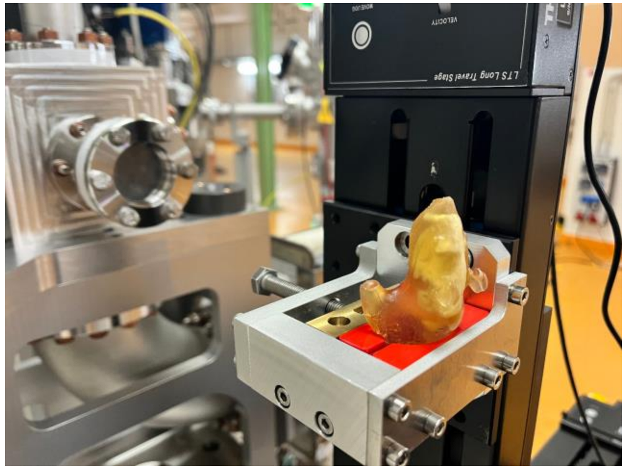
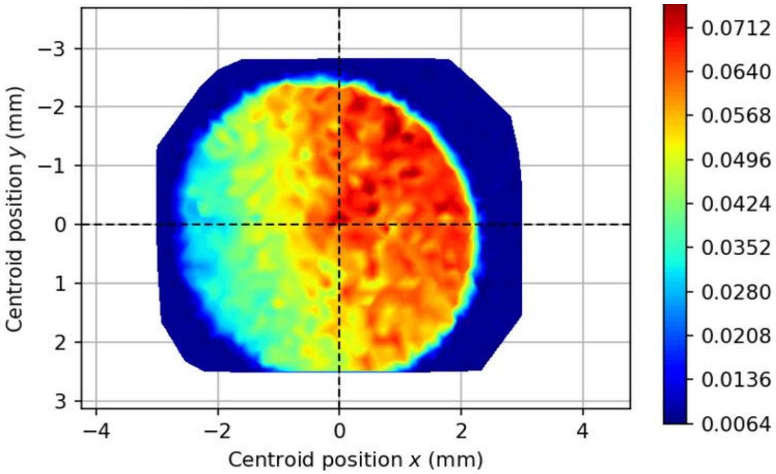


Experimental program

- Collaboration with UKE Hamburg, University Manchester, CANDLE, TU Hamburg started to study novel cancer treatment methods based on high particle momentum and short irradiation times
  - Atm. Dosimetry development, benchmarking of simulations, eCT tests
- Petra IV kicker magnet tests
- Cathode charge extraction measurements and maps
- Autonomous accelerator
  - Automated startup/shutdown
  - Beam threading and beam setup
- Dosimetry for radiation protection systems at DESY (Pandora)
- ACHIP
- Dielectric lined wave guides for streaking (part of an EIC pathfinder)
- Low charge detectors for intensity and momentum spectrum measurement (STRIDENAS)
- Accelerator component R&D (Bunch compressor, diagnostics, 3d printing, etc.)
- …



Mouse phantom for electron CT studies

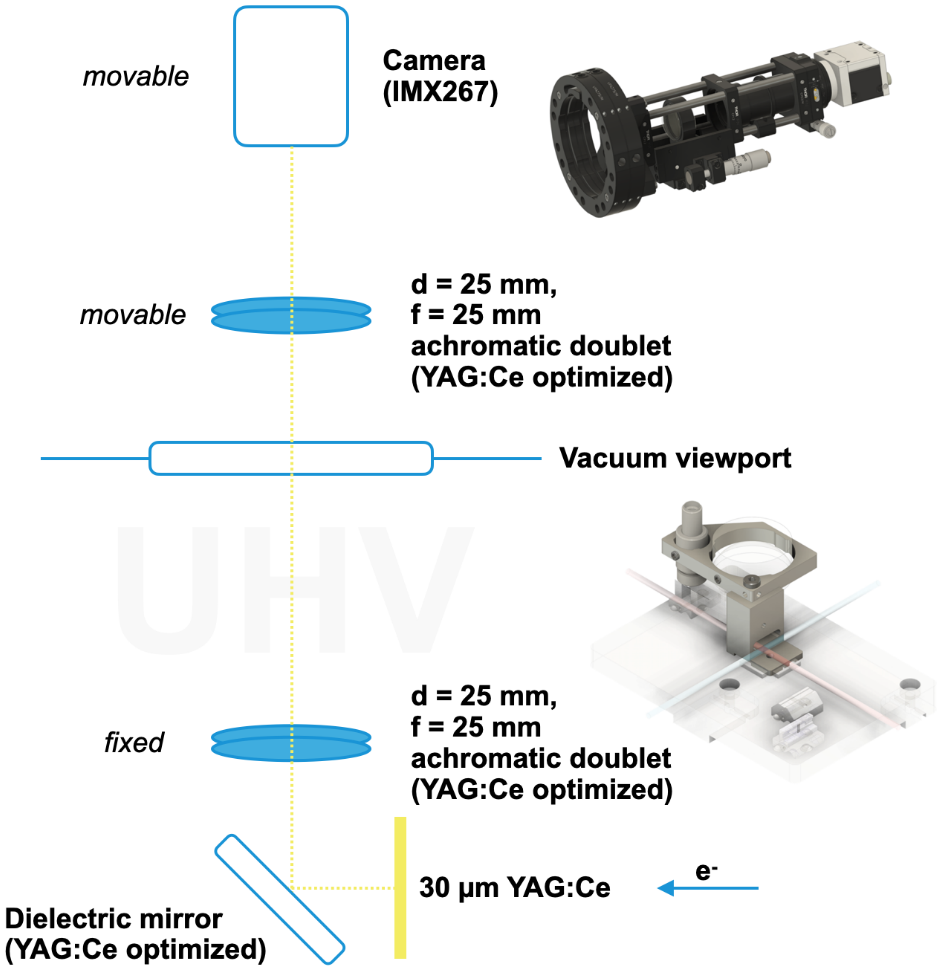


High-resolution cathode diagnostics

Numerous diagnostic devices

Artem Novokshonov, Timmy Lensch, Bastian Lorbeer, Matthias Werner, Dirk Lipka, Gero Kube and Frank Mayet

- Two Faraday cups at gun
- Intensity monitors
  - 2 Cavity based
  - 2 toroid coils
  - 2 Integrating Current Transformers at the end of the beam line
- Cavity based beam position monitors
  - six along the beamline
  - One additional XFEL type in the bunch compressor
  - One additional high precision device, not commissioned yet
  - Range of +-5mm, measured position fluctuations of ca. 10um, including beam jitter
- 11 scintillating screen stations
  - 45 deg observation angle,20um res., 200um thick GAGG
  - 2 Scheinpflug optics, bit worse resolution.
  - 1 microscope optics, < 2um res., 30um thick YAG
  - 1 in air screen station
- Wirescanners and BLMs
  - Micro-wire scanner at experimental chamber
  - At the in-air station



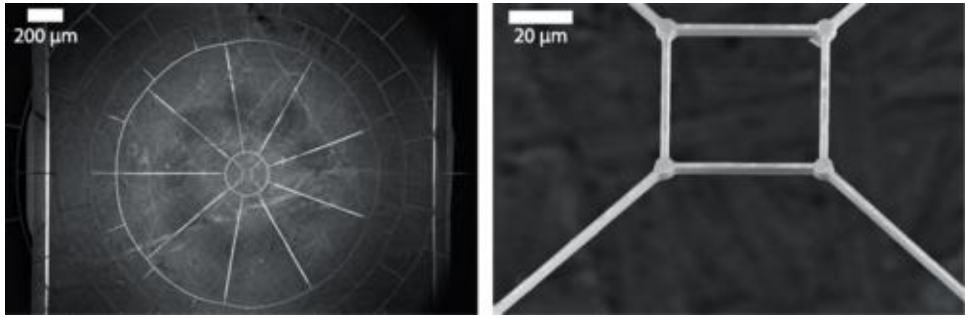
Via ZEMAX and Geant4

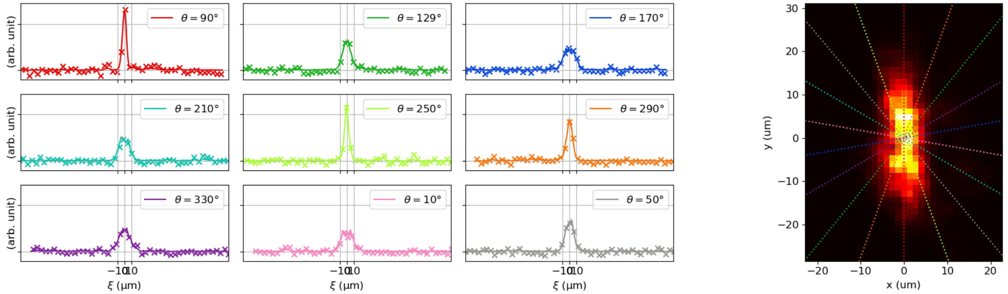
Total Magnification: 39
Efficiency: 12%
Airy Disk Size (@547 nm): 0.67 µm
Total Optical Path Length: 440 mm
YAG:Ce Emission Spread Function (> 50 MeV): < 0.2 µm

Measuring single digit beam sizes

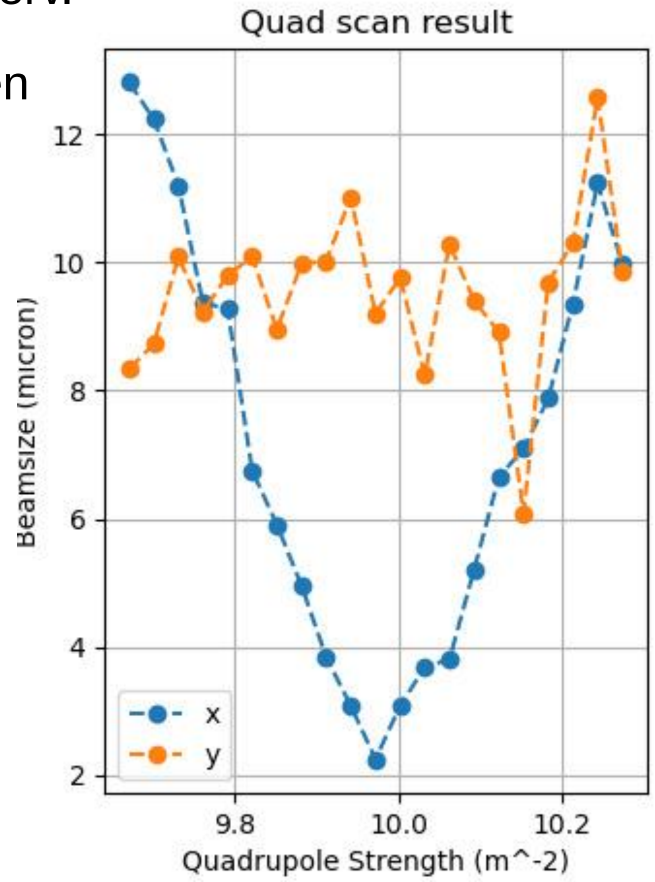
EA chamber diagnostic devices

- Screen thickness – scintillation blur, angled observ.
- Optics resolution – objective lens close to screen
- Multi-shot methods – beam position deviations

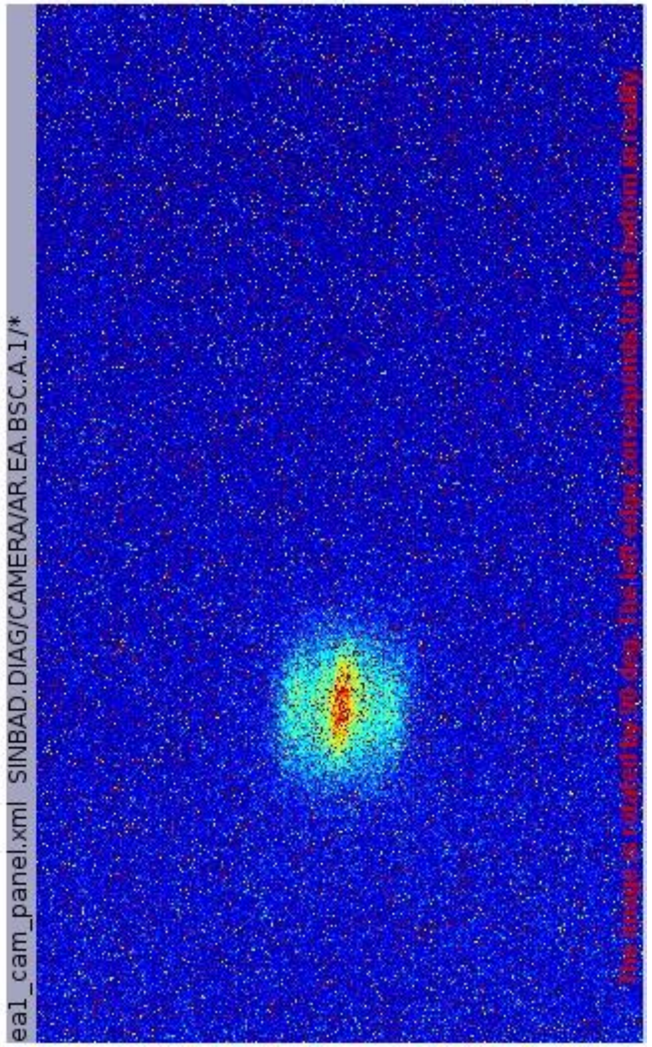




Wire scanner measurement



YAG screen image



Big thanks to Benedikt, Pavle and Rasmus!

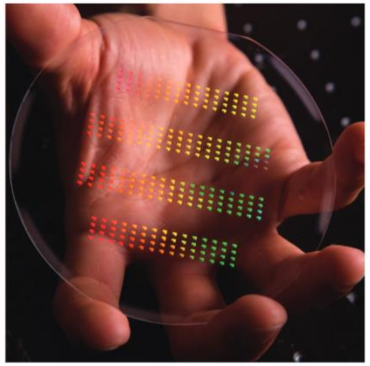
Wire scanner: B. Hermann et al., Phys. Rev. Accel. Beams 24, 022802, 2021

dielectric gratings - 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 – 03/2023

b



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

Quick Primer, courtesy Frank Mayet

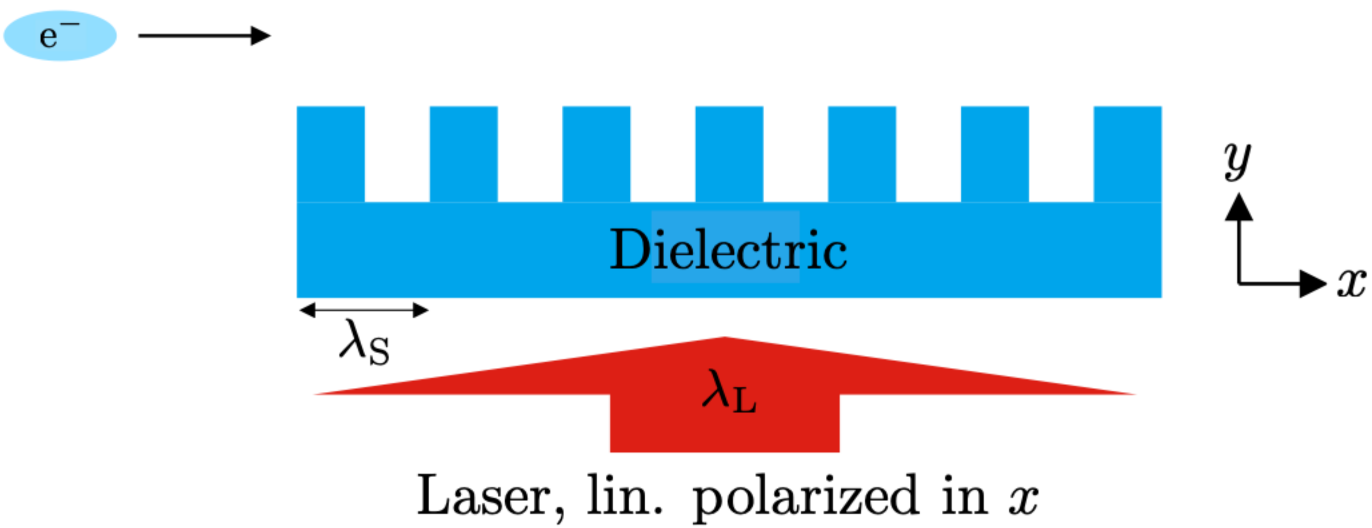
- Laser is linearly polarized in x
- Field above the grating is an infinite sum of *spatial harmonics* (0th order → transmitted part)
  - *traveling evanescent (near field) modes along the grating*
- Structure periodicity can be chosen such that the n^{th} harmonic is phase synchronous with the particle beam

$$\lambda_S = n\beta_m\lambda_L$$

DLA Period — Order — Matched normalized velocity v_m/c — Laser wavelength

Periodicity along the grating — Decay away from the grating

$$E_x \propto e^{i\cdot nk_s x}\cdot e^{-\delta_m y} \quad \Big| \quad \delta_m = k_L\sqrt{\frac{n^2}{\beta_m}-1}$$



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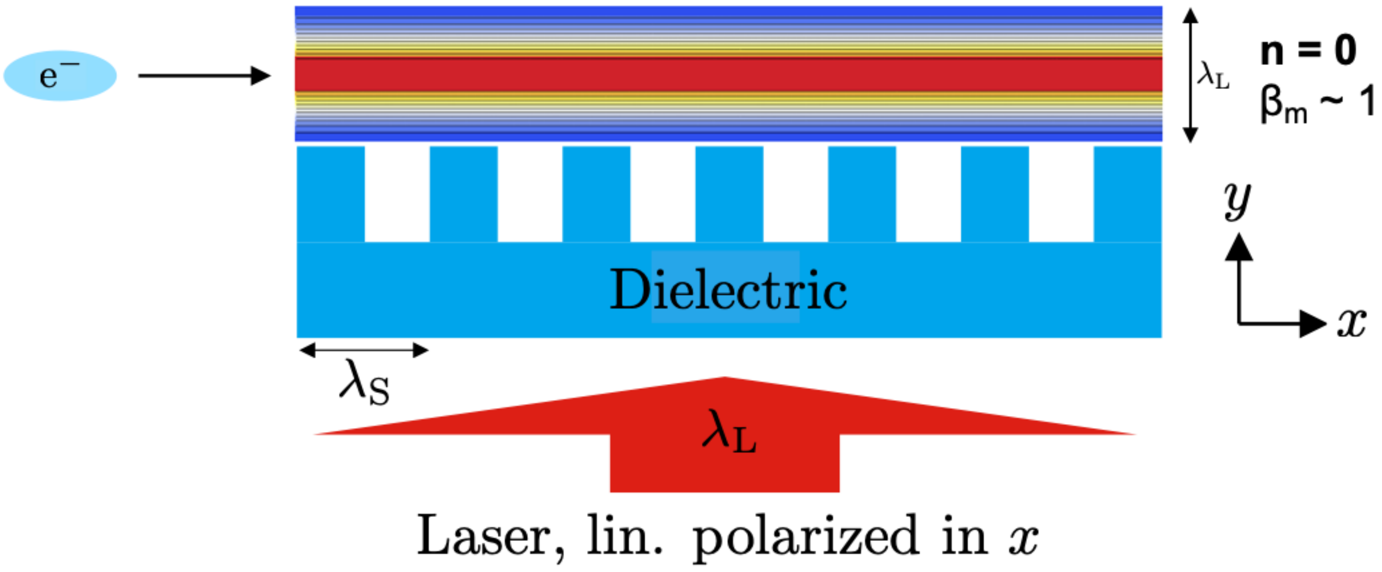

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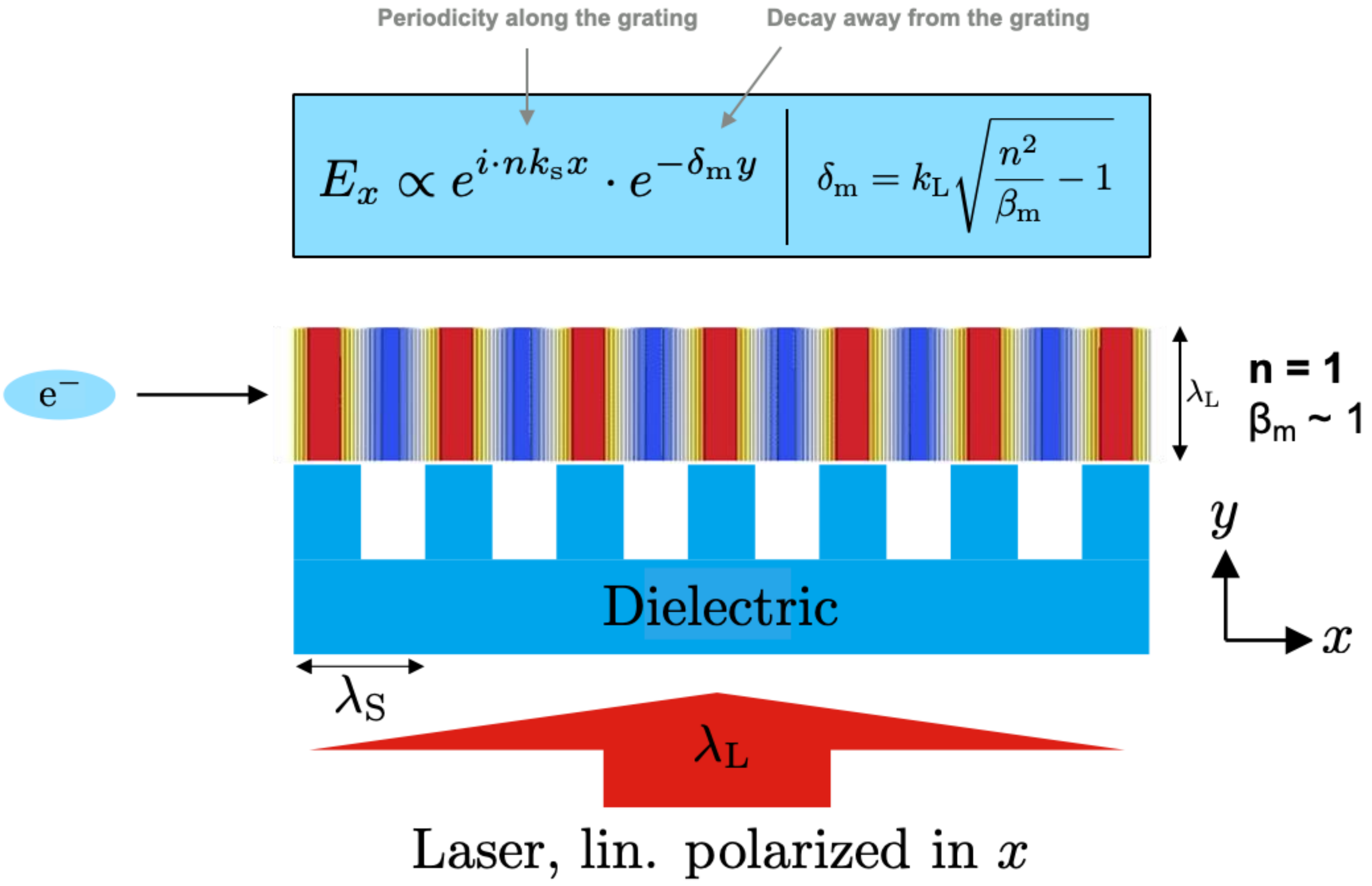

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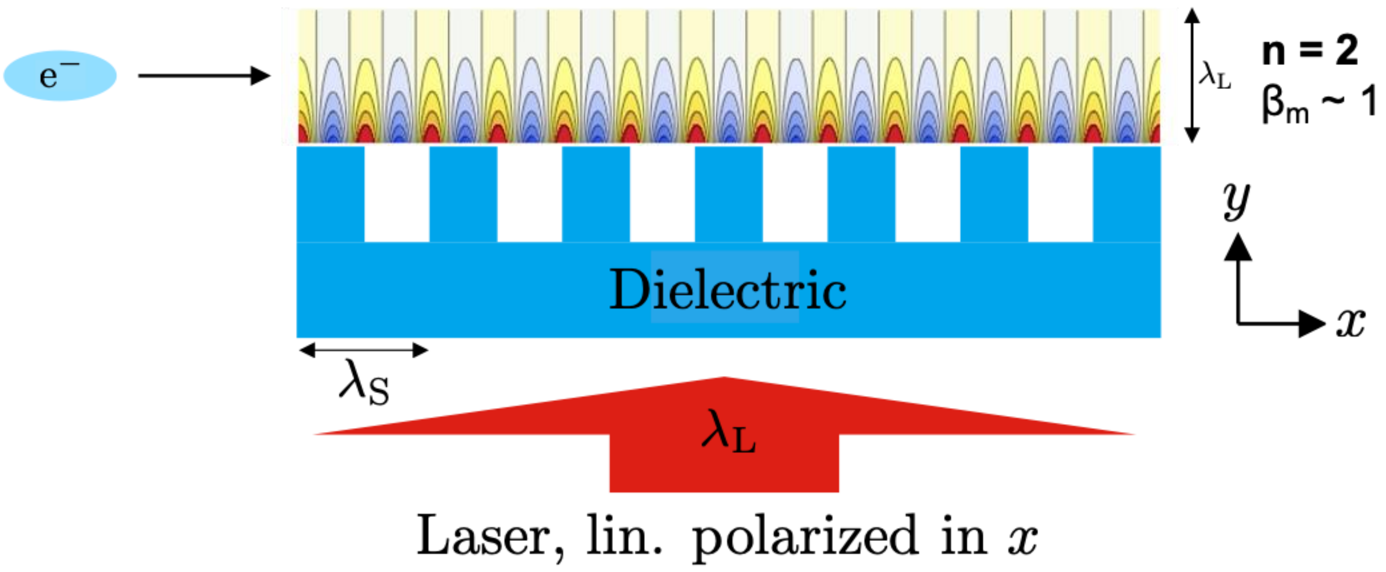
Periodicity along the grating — Decay away from the grating

$$E_x \propto e^{i \cdot n k_s x} \cdot e^{-\delta_m y} \quad \Big| \quad \delta_m = k_L \sqrt{\frac{n^2}{\beta_m} - 1}$$



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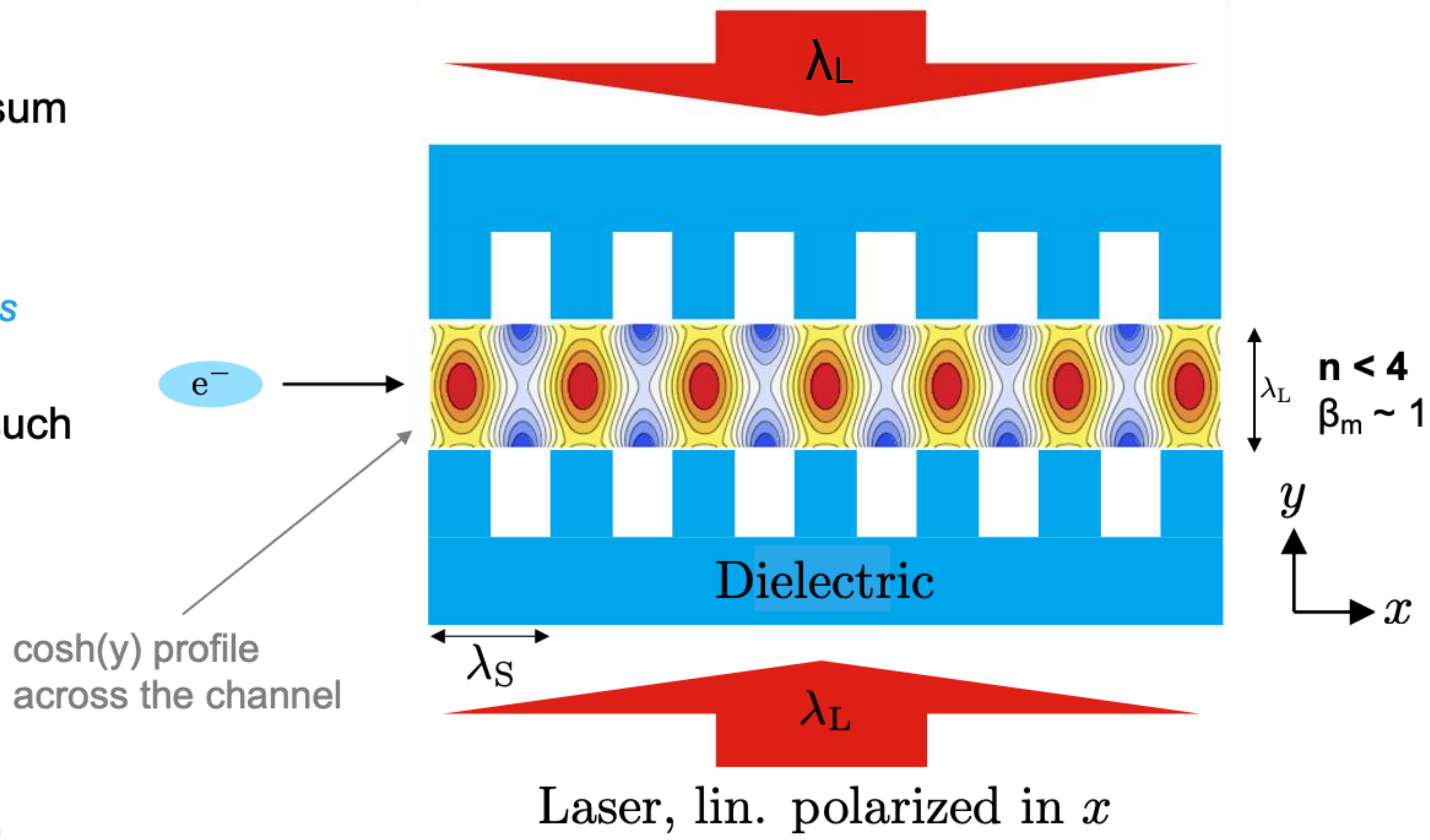
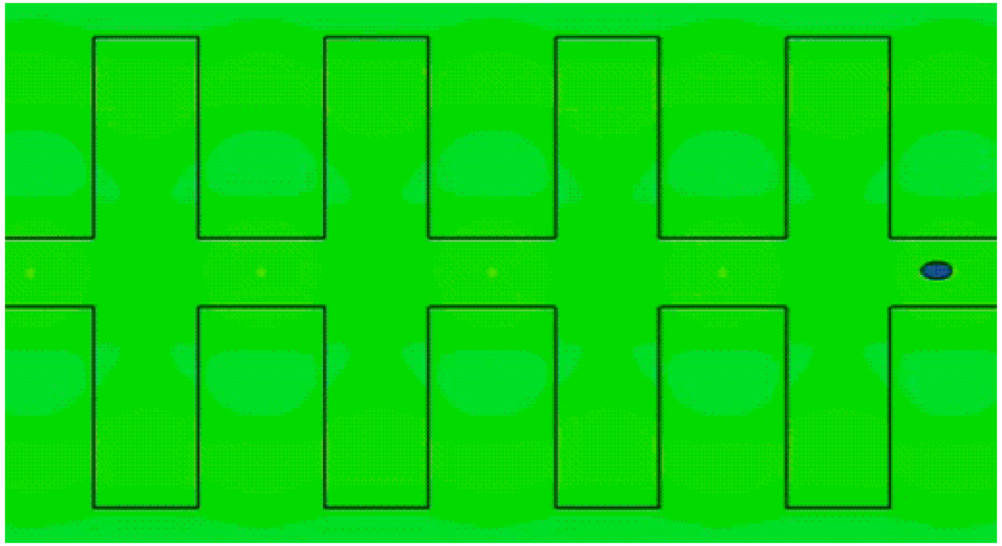


Dielectric Laser Accelerators

Quick Primer

Longitudinal Electric Field Component

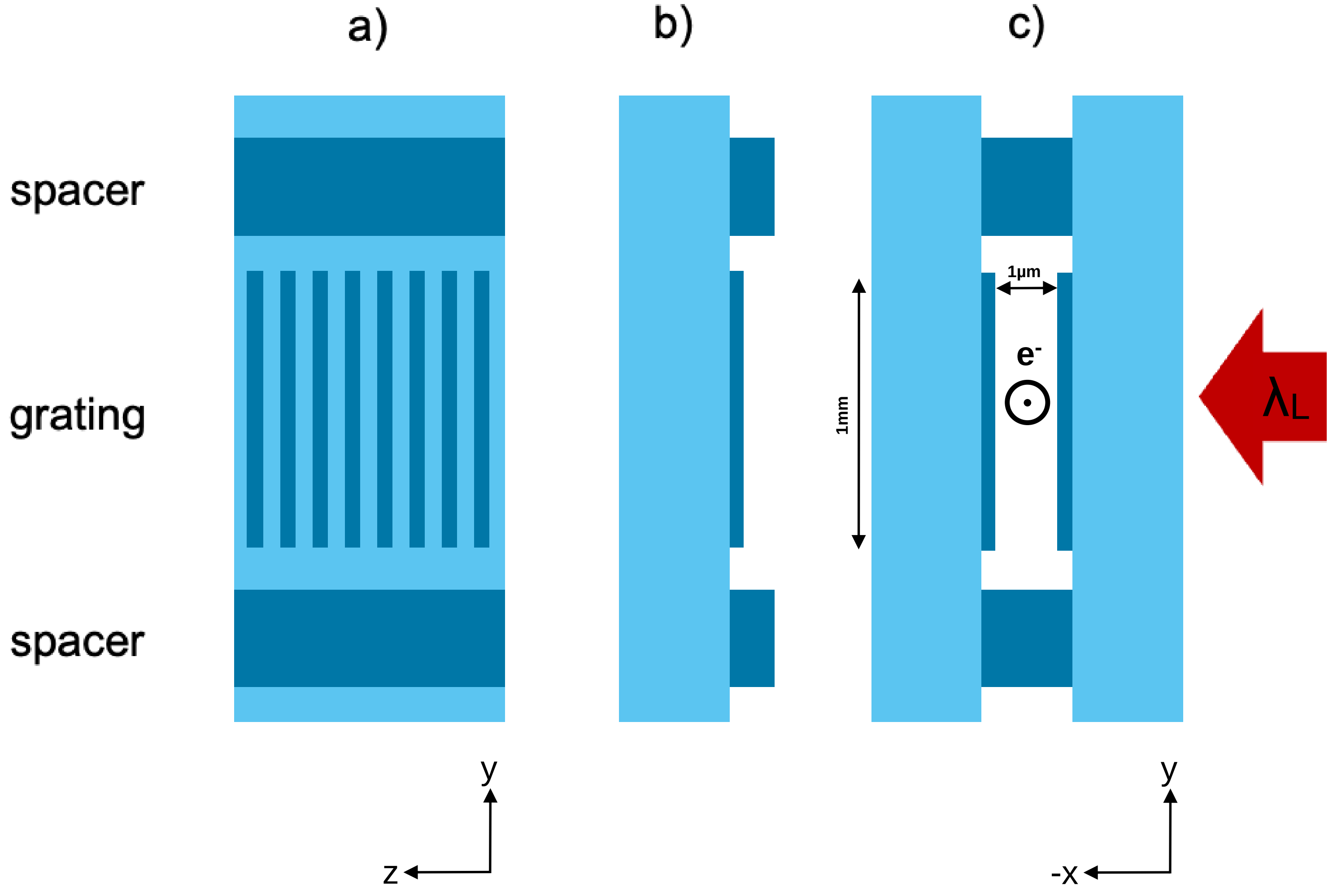


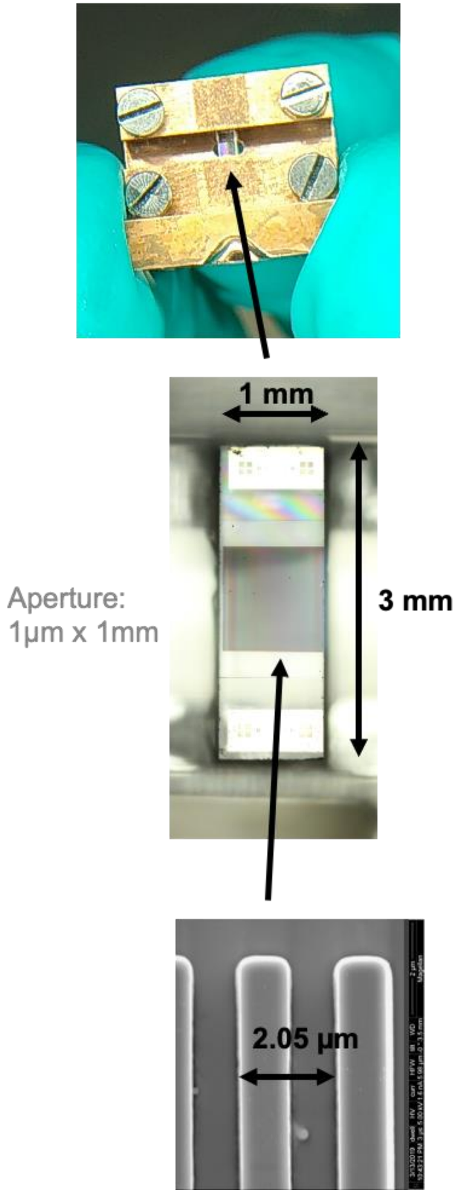
CST simulation/animation courtesy of W. Kuropka

Note: Spatial harmonics travel in both directions
→ Field looks like a standing wave

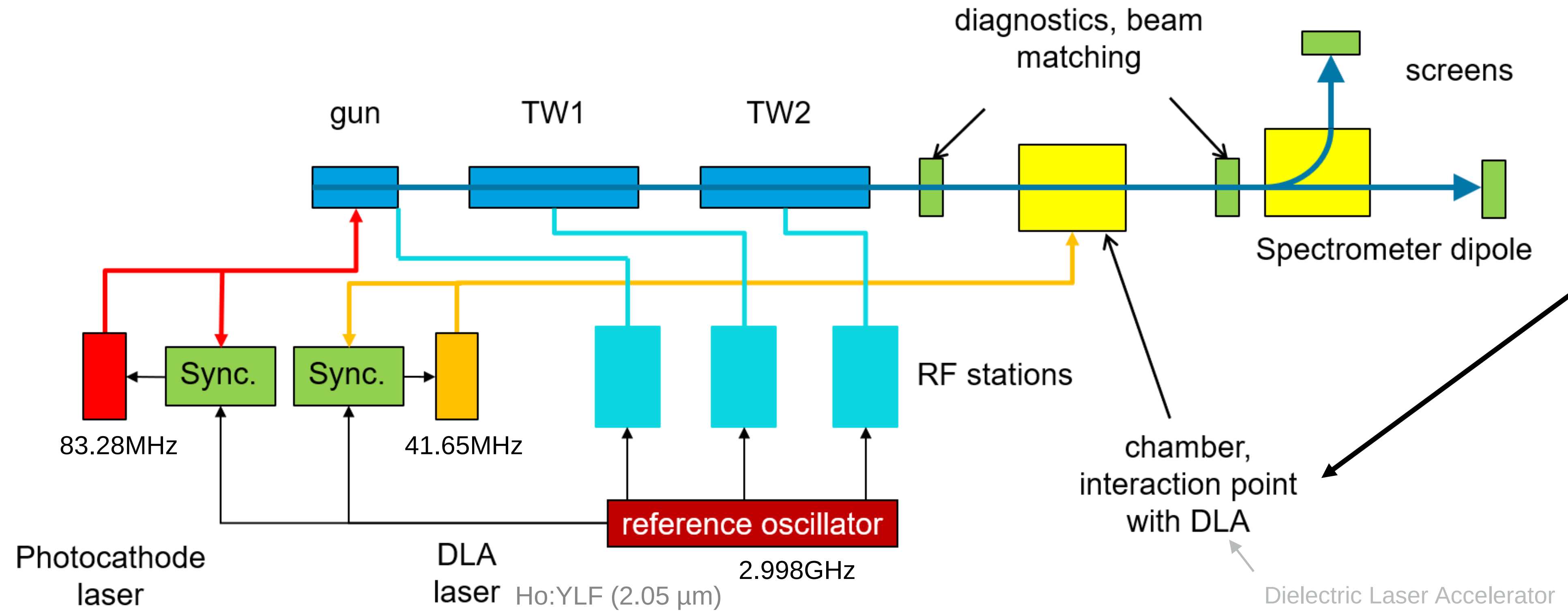
Dielectric Laser Accelerators

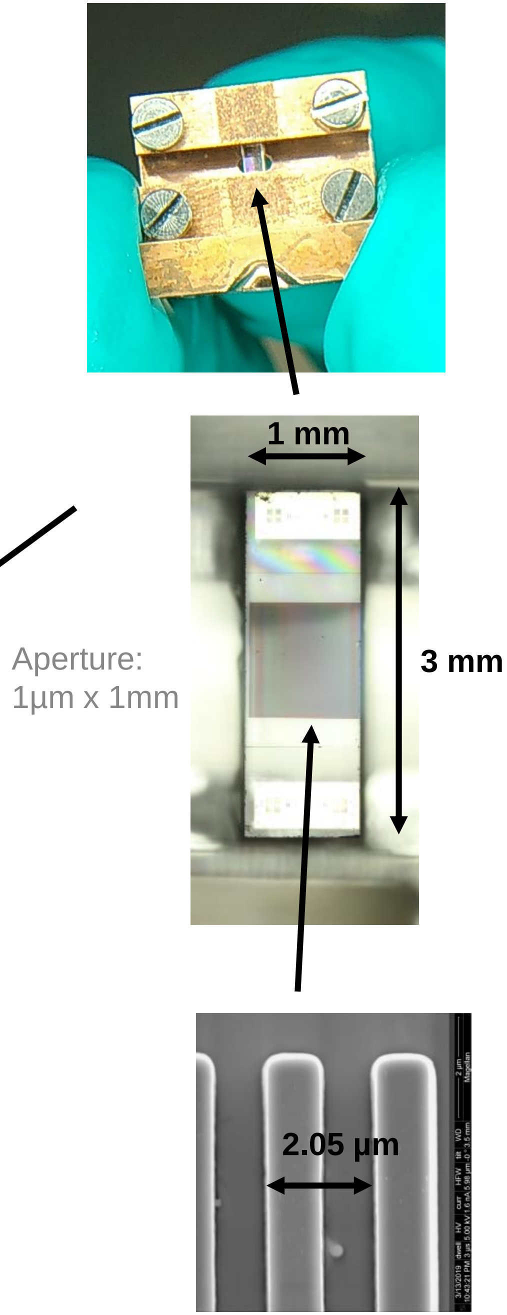
Our Structure





Momentum Modulation from a DLA at ARES





Laser timing jitters in the lab are 13fs/20fs

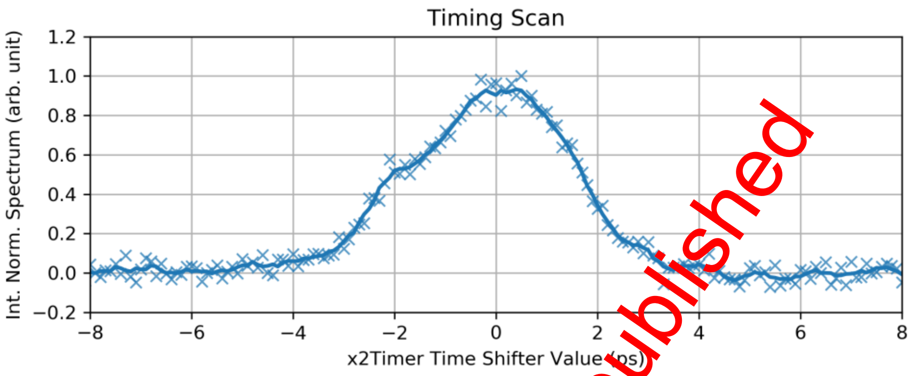
Goals:
- Higher transmission (2050nm laser)
- ~GV/m peak acceleration fields
- Hit the bucket (fs electron bunches)

First Energy Modulation from a DLA at ARES

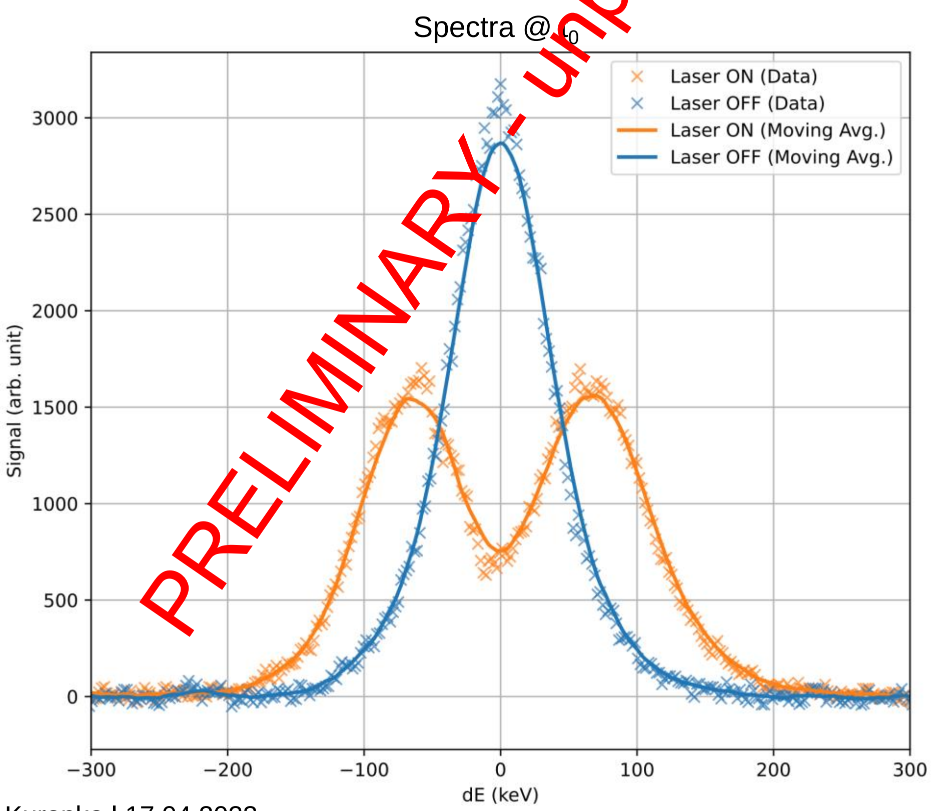
Achieved on March 24th , preliminary data analysis

- For the first time, modulation of the entire transmitted charge
- Record throughput of 60 fC (20%)

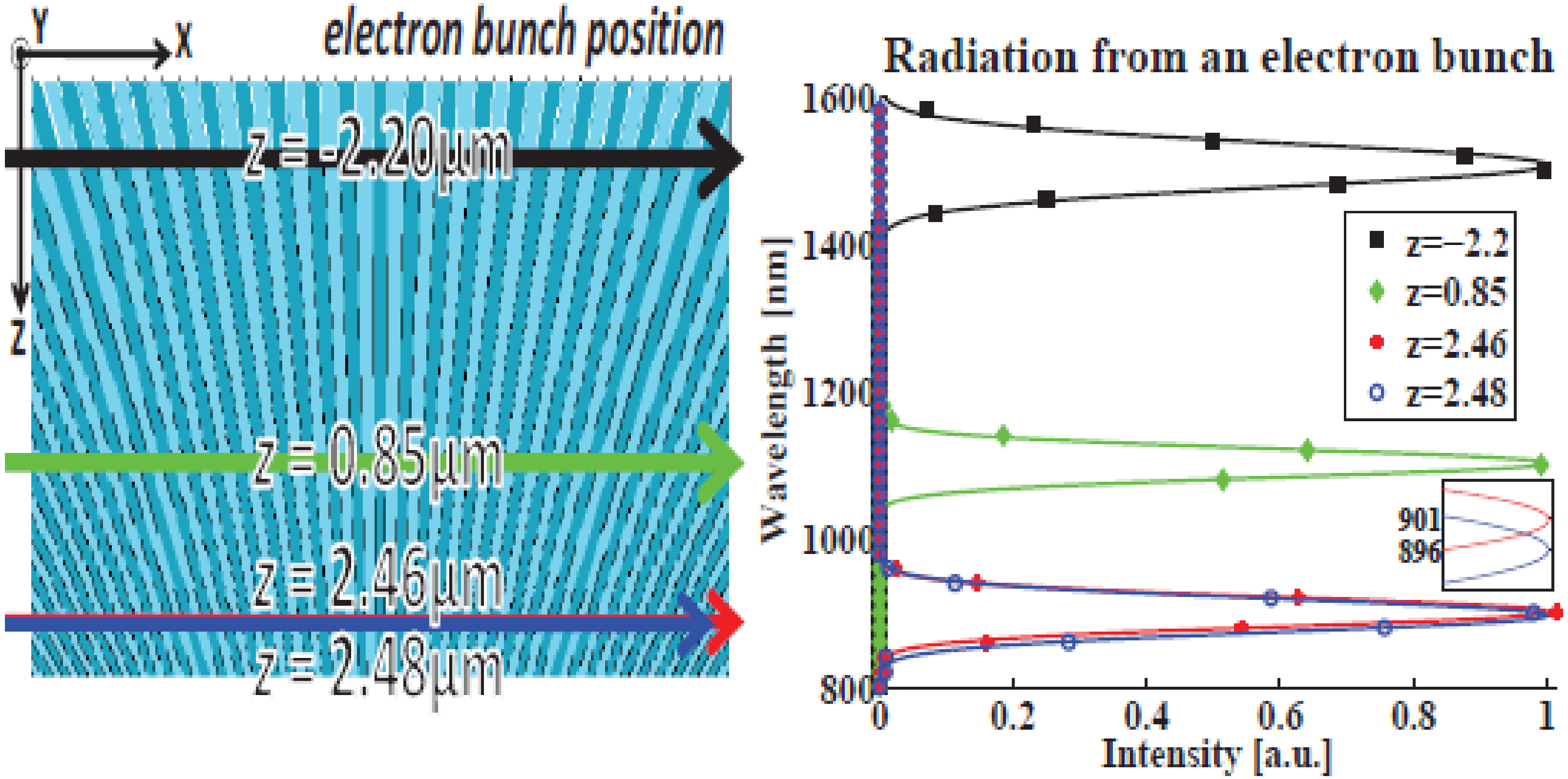
Parameter	Value
Central Momentum	154.4 MeV/c
Transmitted Charge	~60 fC
Transmission	~20%
Electron Beam Size	< 10 µm, rms
Electron Bunch Length	~100s of fs (>> λ_{DLA})
DLA Aperture	1µm x 1mm
Laser Spot Size (2σ)	1mm x 50µm
Laser Pulse Energy	~1 mJ (on target)
Laser Pulse Length	2.0 ps, FWHM
Energy Modulation Depth	~100 keV
Peak Acc. Gradient	~142 MV/m



Step size:
100 fs



Backup - DLA beam position monitor

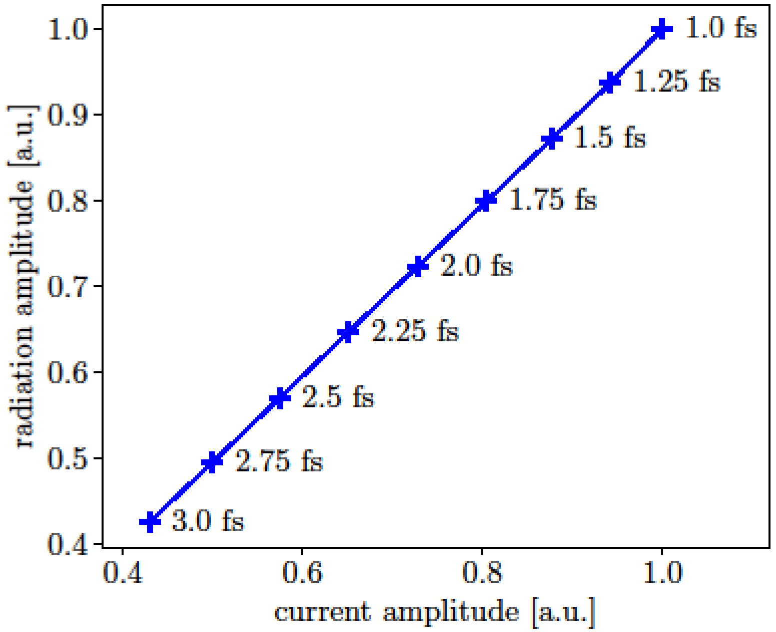


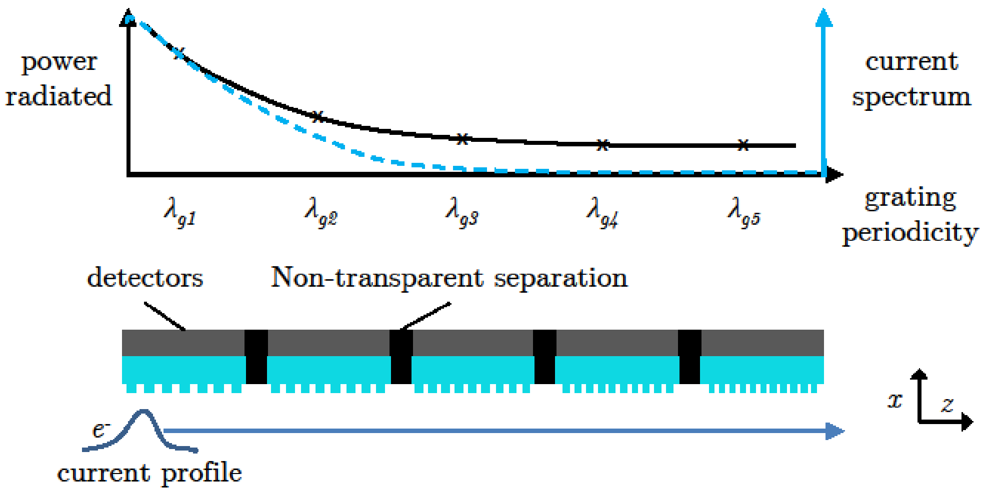
K. Soong, et. al., Proceedings of PAC2013, MOPAC32

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

Summary

- ARES is commissioned and (almost) all design parameters are achieved
- Looking forward to PolariX commissioning and first measurements
- Record charge transmission in DLA achieved, while maintaining high acceleration gradients
- Excellent ARES performance enables ACHIP DLA based experimental campaign is further pursued
- Opportunities for DLA applications as active and passive diagnostic devices
- Many experimental opportunities at ARES for collaborative efforts

Thank you for your attention!
Questions?
Acknowledgments/Funding:

- GBMF 4744
- European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 609920
- European Innovation Council Pathfinder Open 2021 / EIC Grant agreement ID: 101046504
- Deutsches Elektronen-Synchrotron DESY in the Helmholtz Association

Colleagues

Collaboration

Hartl Group

ARD Colleagues

Solgaard group

Kärtner Group

Joel England

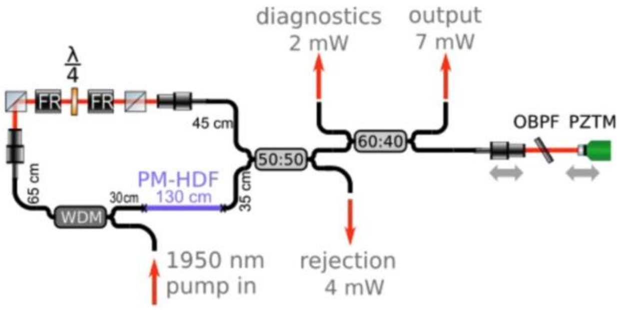
Contact: willi.kuropka@desy.de

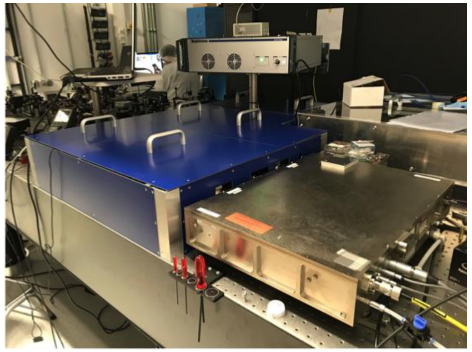
Backup slides

Ho:YLF Amplifier Laser System for DLA Experiments

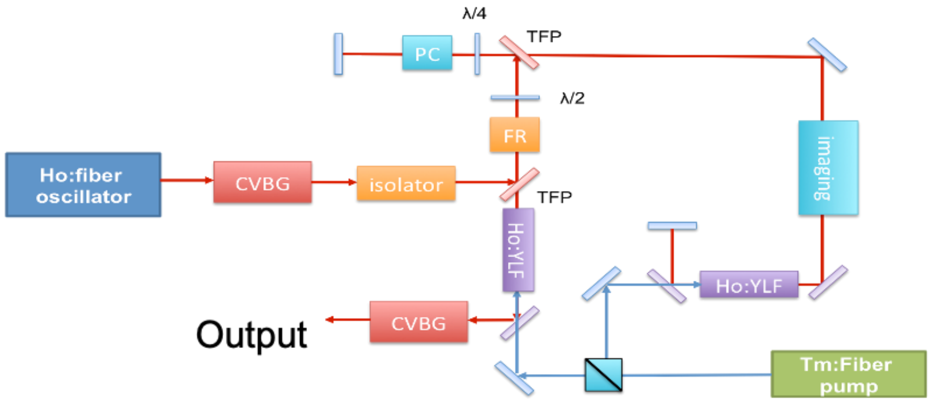
2050nm Wavelength

NALM Oscillator





Q-peak Prototype Amp. System

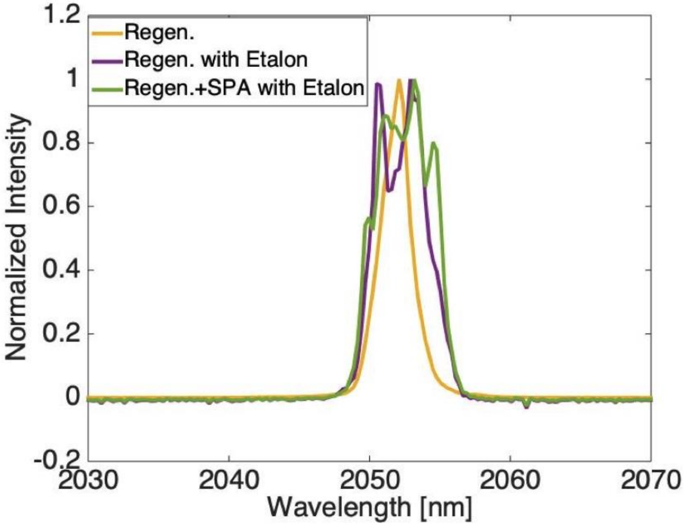


Courtesy H. Cankaya

E_p (out, max)	2.2 mJ
E_p (comp, max)	1.9 mJ
f_{rep}	1 and 5 kHz
t_p	2.2 ps, FWHM
t_{TL}	1.25 ps, FWHM

Expected effective gradient: 160-320 MV/m
(Depending on the rel. DLA grating alignment)

Intracavity gain shaping with an etalon



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

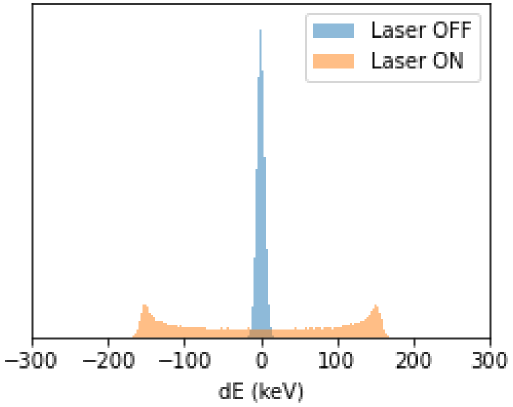
S. Pfeiffer, et al.,”LLRF CONTROL AND SYNCHRONIZATION SYSTEM OF THE ARES FACILITY”, IPAC2021, Sao Paulo, Brazil

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.

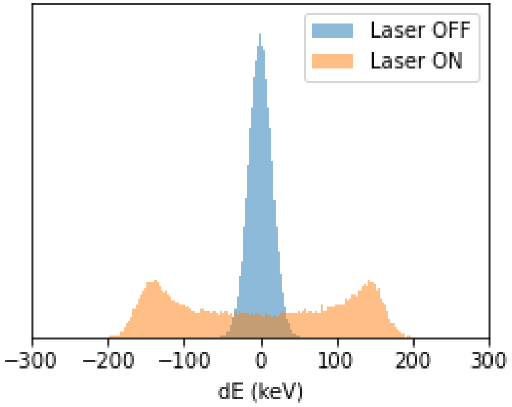
Energy Modulation

What to expect?

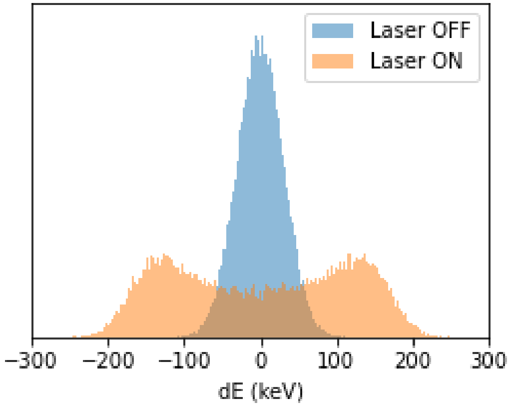
σ_E = 5 keV
ΔE = 150 keV



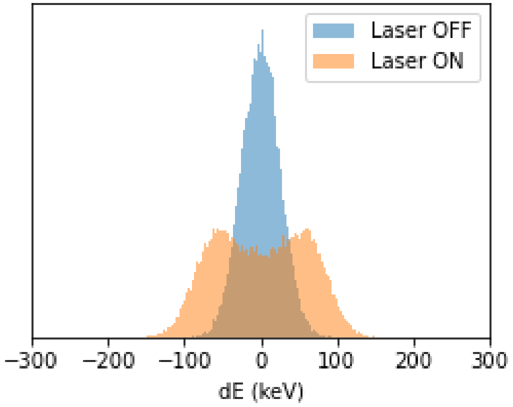
σ_E = 15 keV
ΔE = 150 keV



σ_E = 30 keV
ΔE = 150 keV



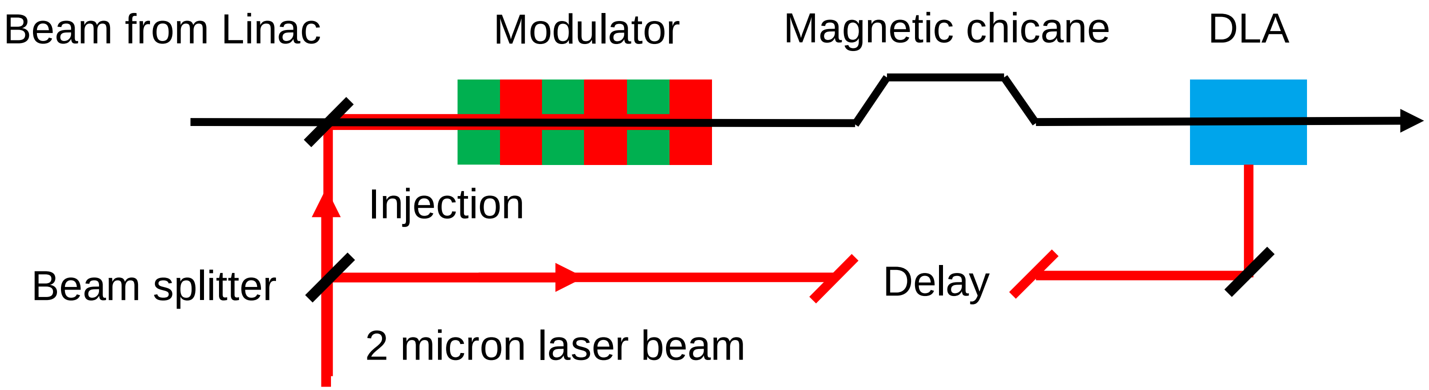
σ_E = 25 keV
ΔE = 75 keV



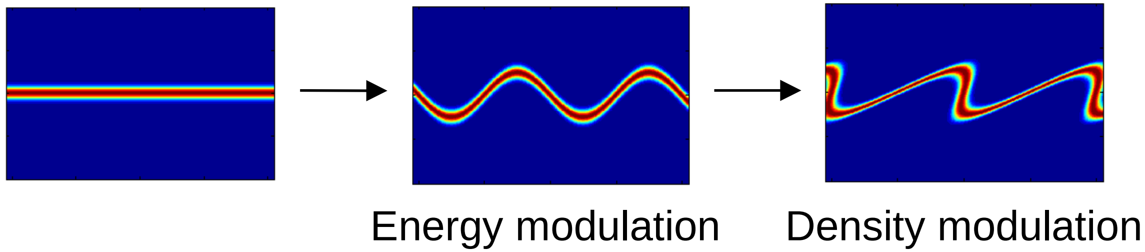
ACHIP@ARES – simulations – microbunching “stage 2”

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



Longitudinal phase space



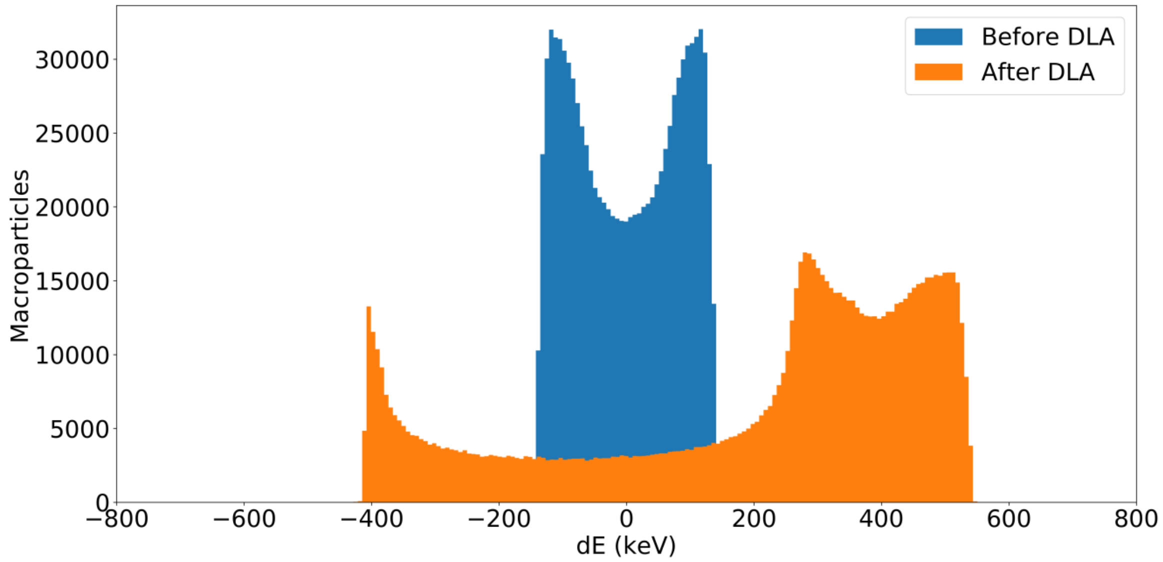
Undulator is already assembled

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)

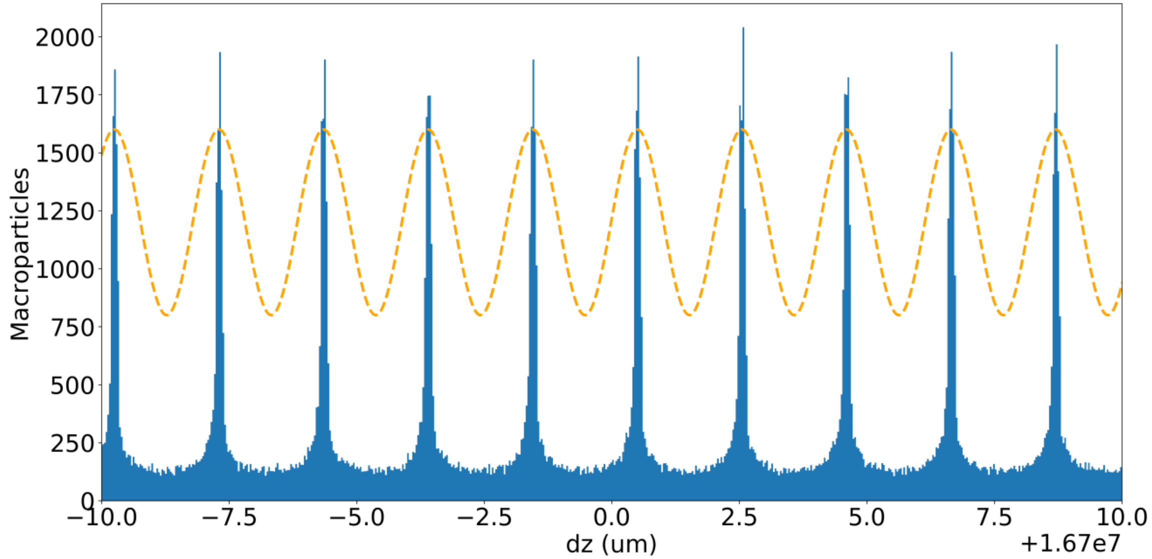
ACHIP@ARES - simulations – microbunching “stage 2”

Simulation of Microbunch trains for DLA

- Expected spectrum contains tail due to limited bunching factor



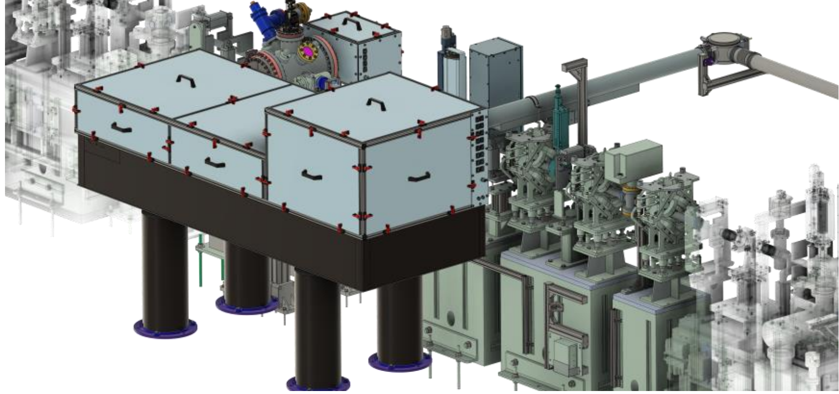
- Accelerating field can be phase shifted against micro bunches
- Here: maximum acceleration

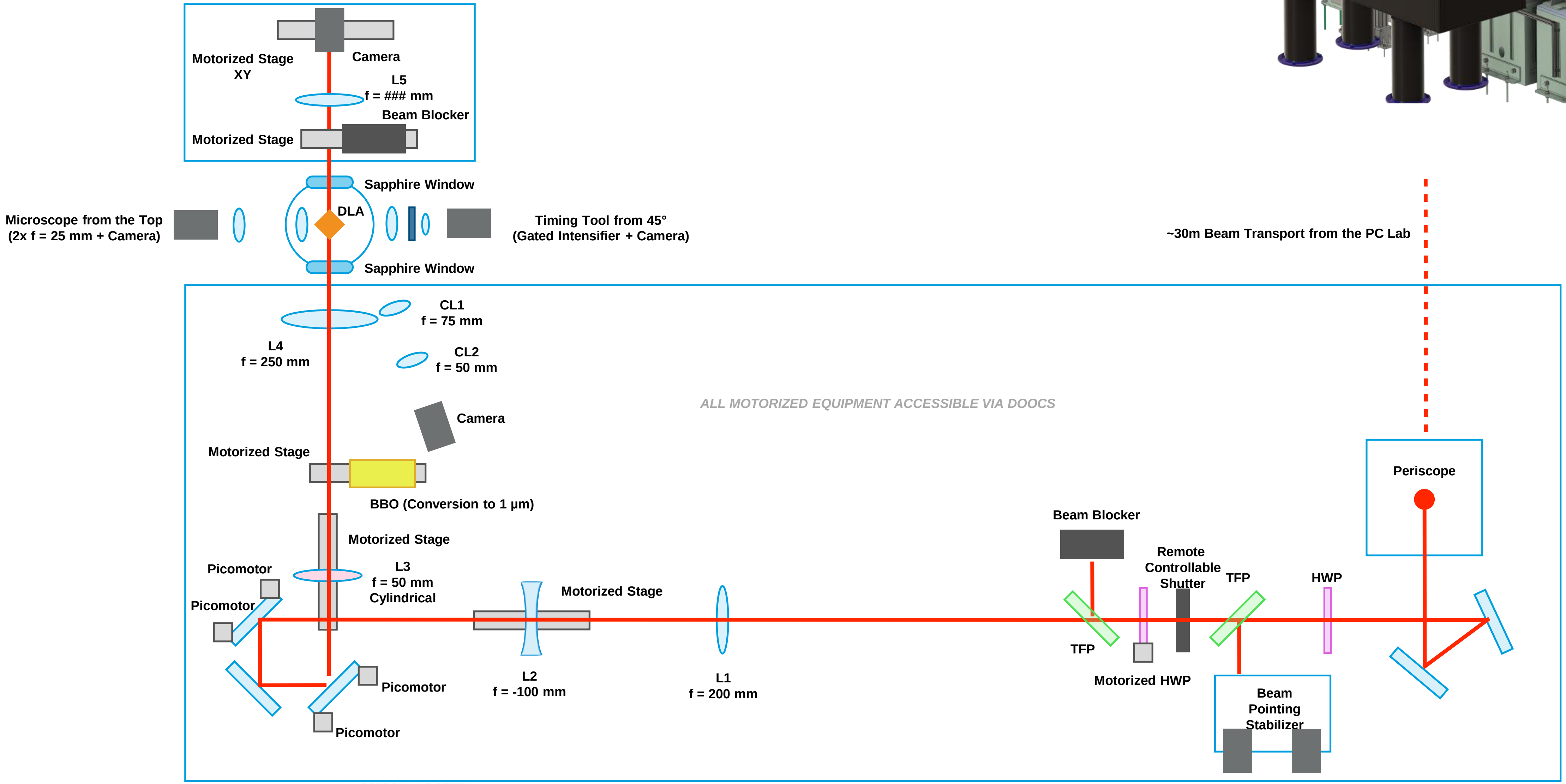


Courtesy F. Mayet

ACHIP@ARES

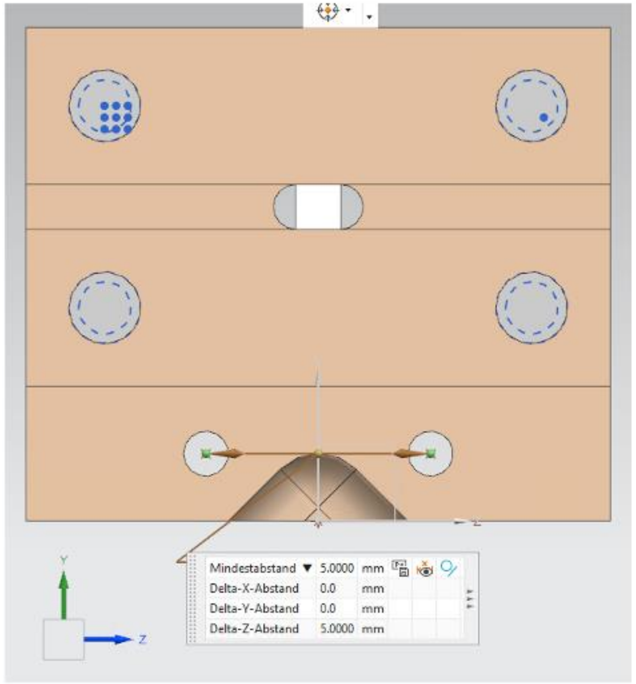
Laser Alignment

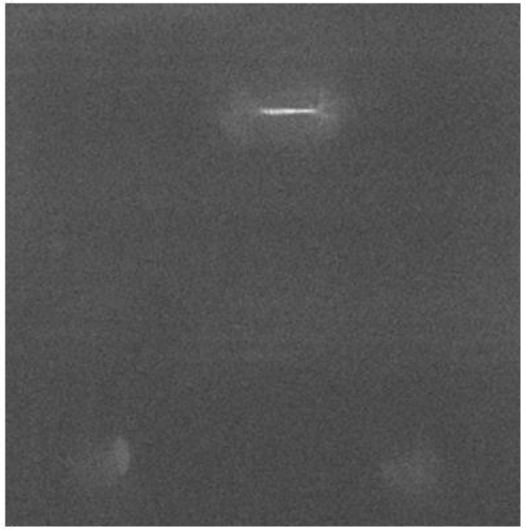




ACHIP@ARES

Laser Alignment



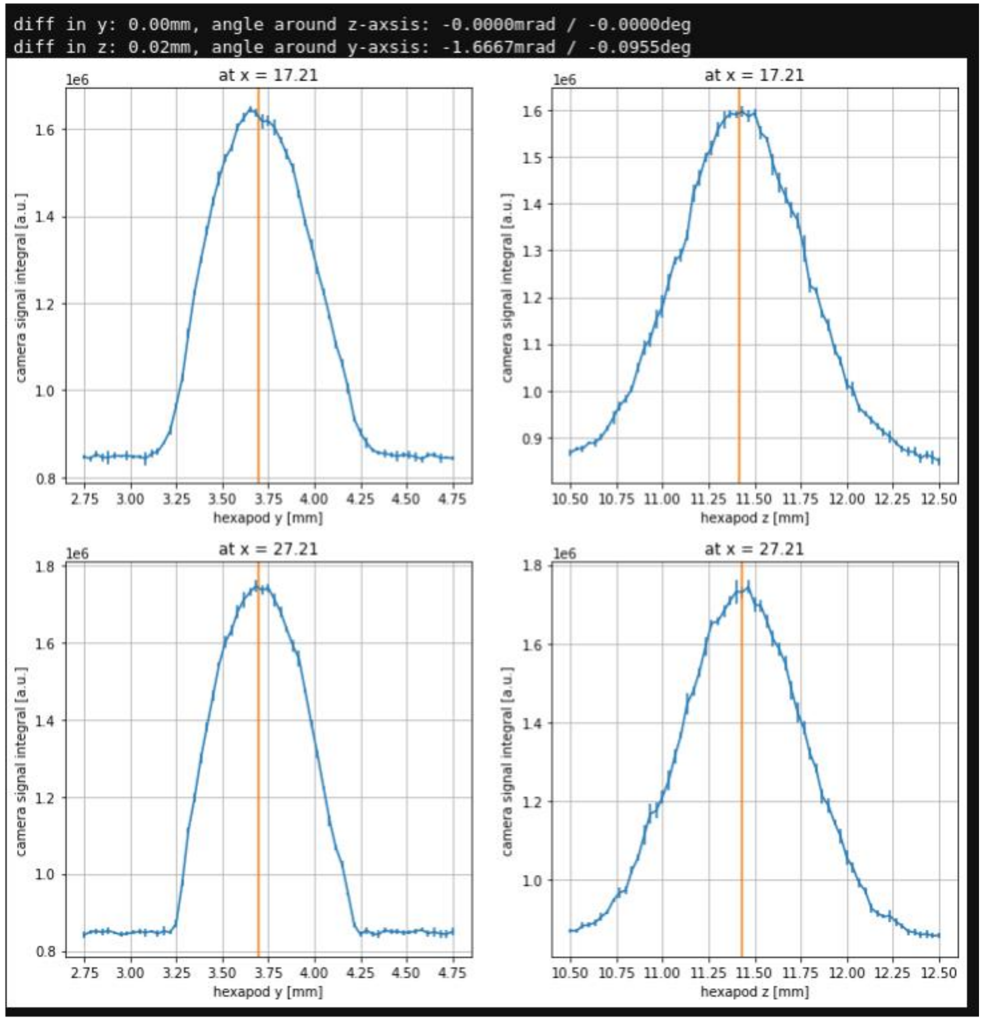


Via laser table camera

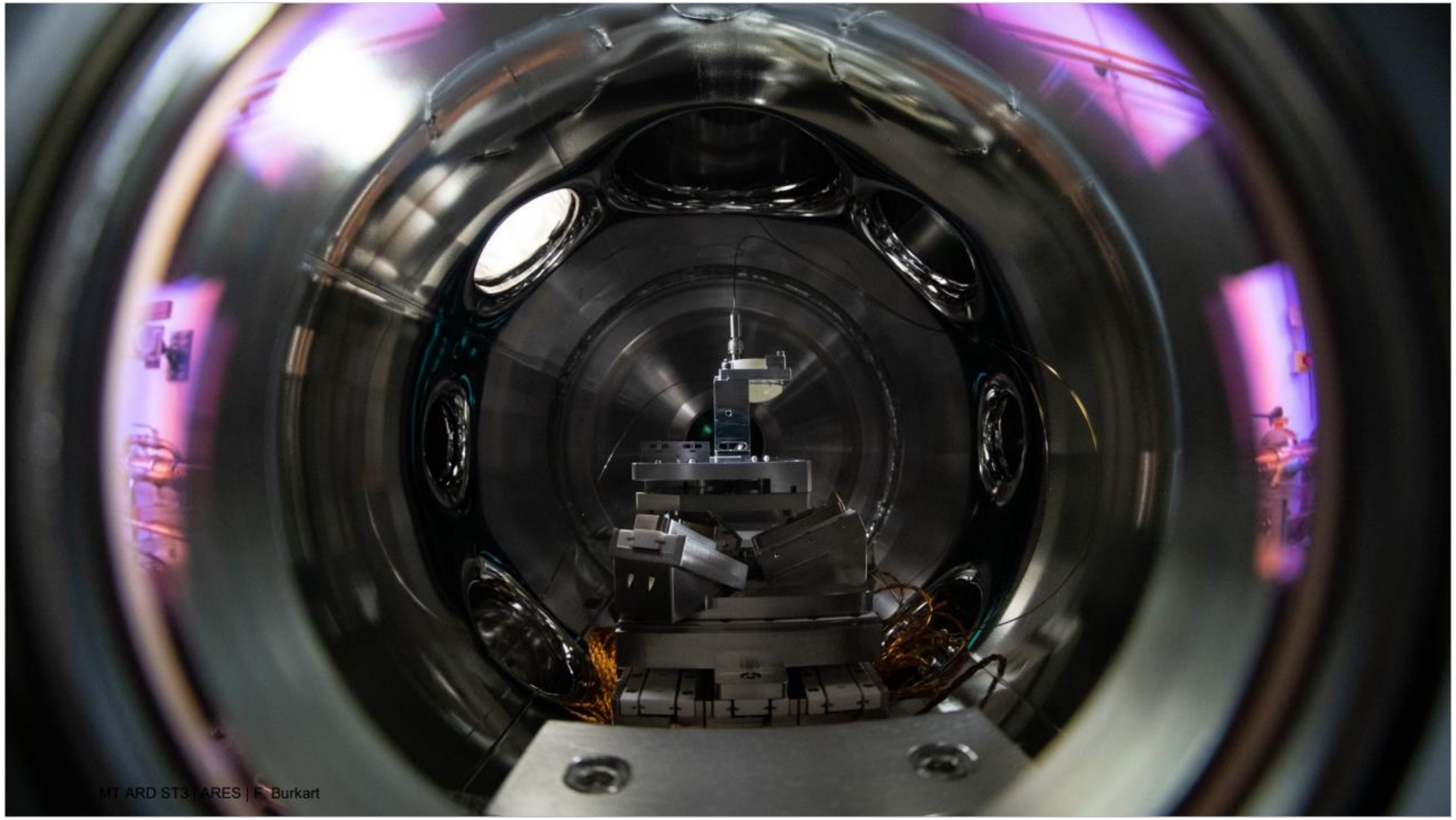
Angular alignment is especially important

Aperture scans using the hexapod

Incident angles < 1mrad



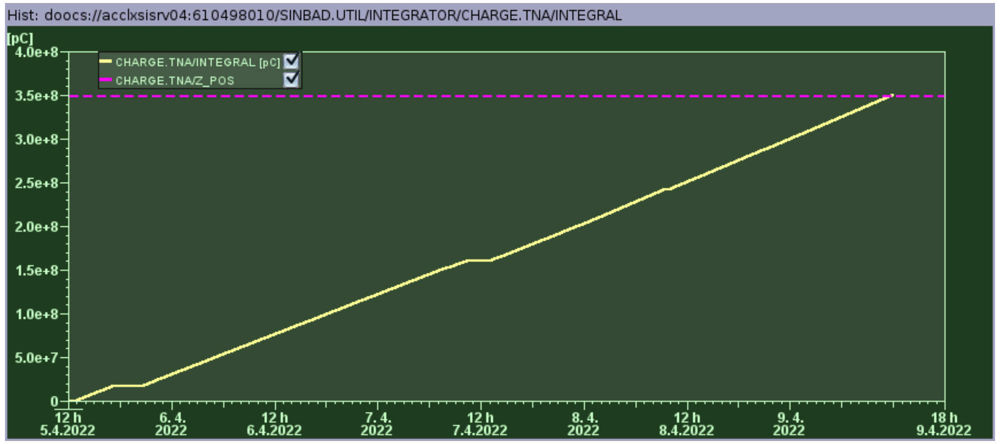
Via small breadboard camera

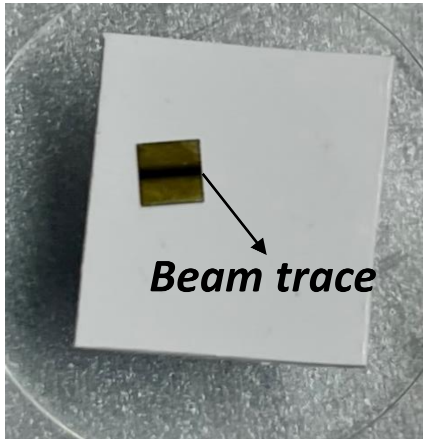

MT ARD ST3 | ARES | F. Burkart

Experimental program

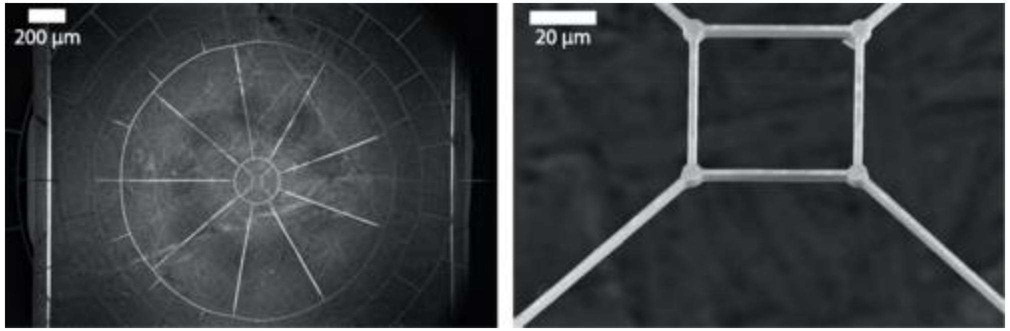
Transnational access program at ARES

- 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)

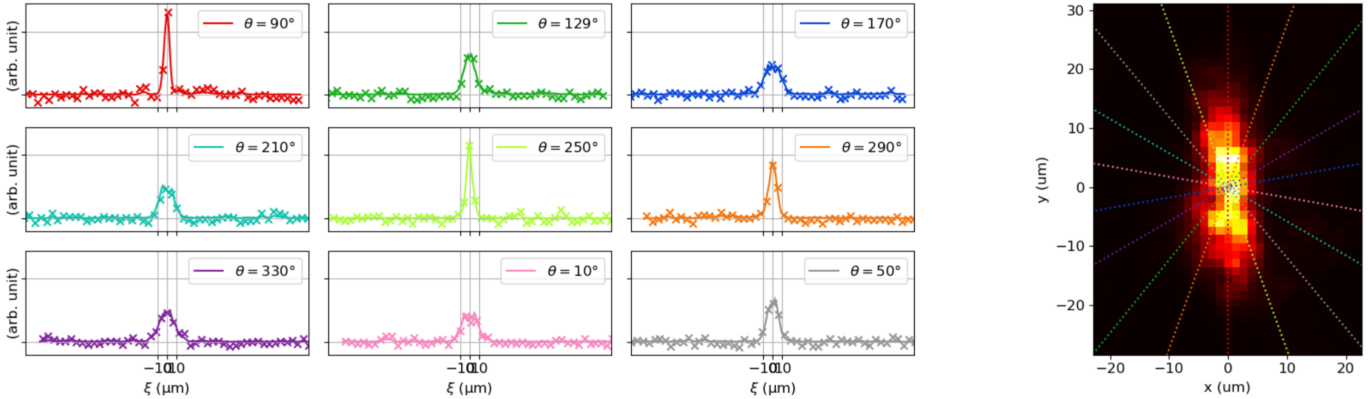




- *Around 4 days continuous beamtime to irradiate a diamond piece with a 100 pC beam ($3.5*10^8$ pC total charge). Excellent stability during the irradiation → No momentum adjustment and almost no position adjustment required.*



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.*

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

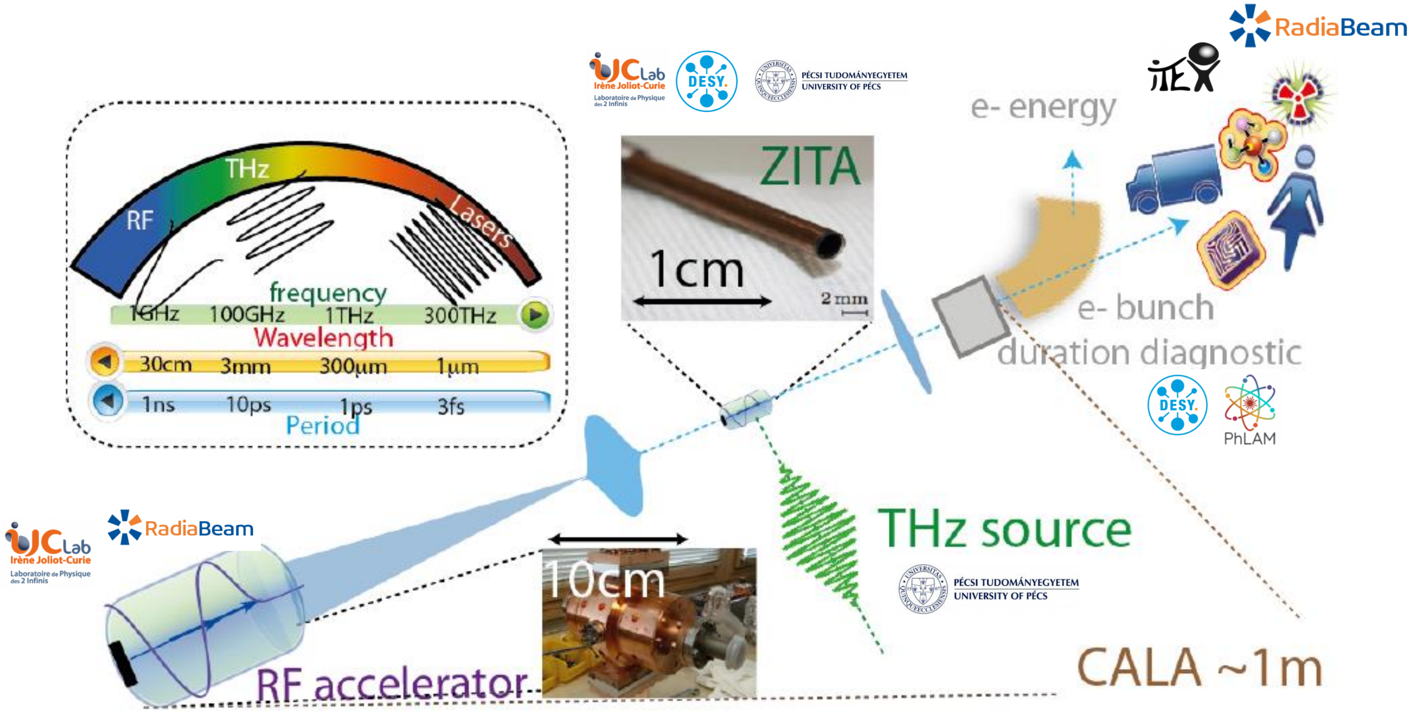
Partner laboratories

Industrial partners

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)



SINBAD

Experimental program

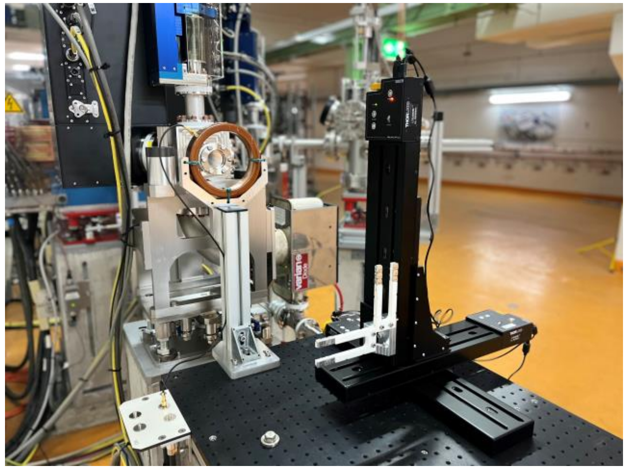
New opportunities for medical research: A chance for DESY to steep deeper into medical applications of accelerators (F. Burkart)

- 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.

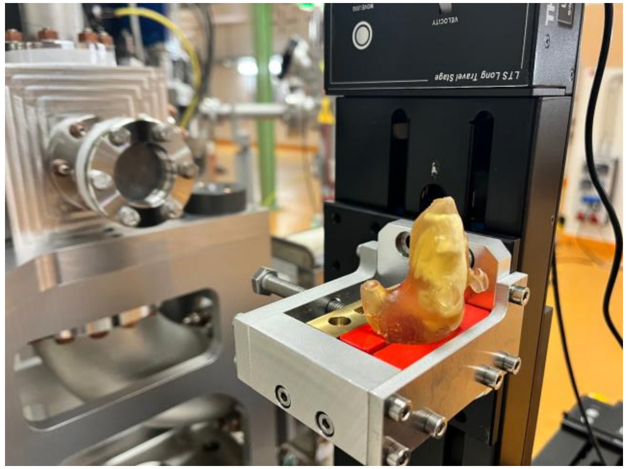
→ Started to adapt ARES to the needs of medical research.

→ 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.



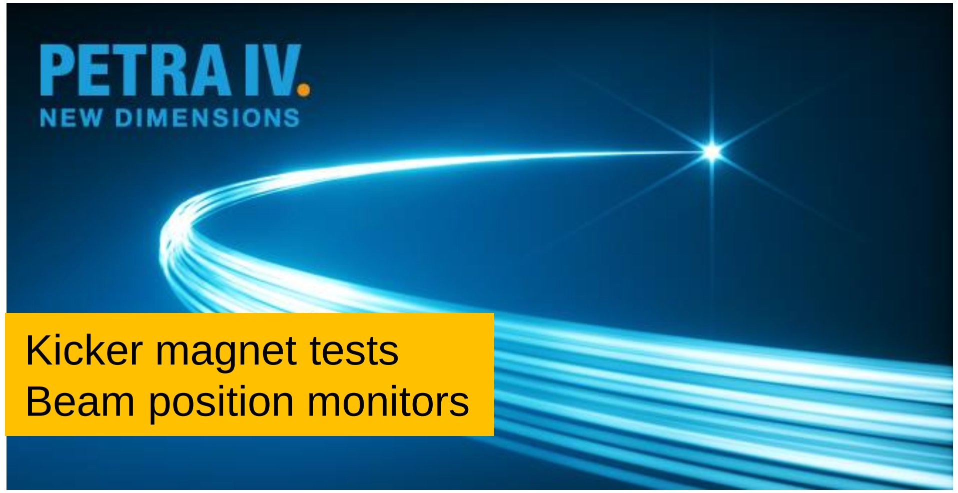
Experimental station designed for medical research



Mouse phantom for electron CT studies

Experimental program

An R&D accelerator for ST3-related topics



Test components for big user machines

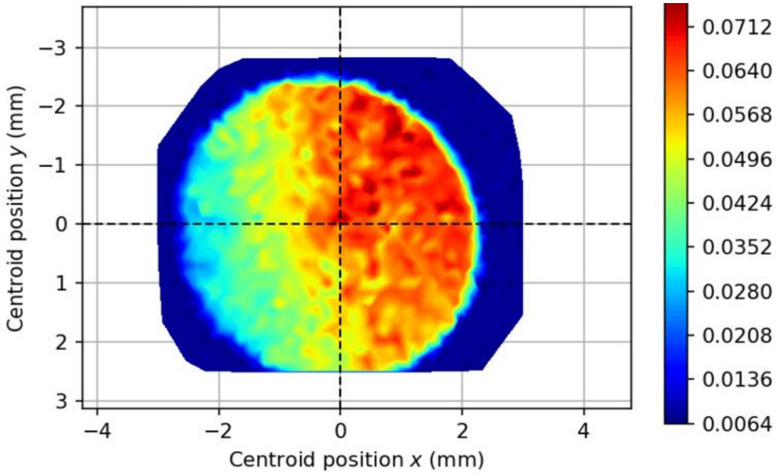
Advanced accelerator components R&D

- 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

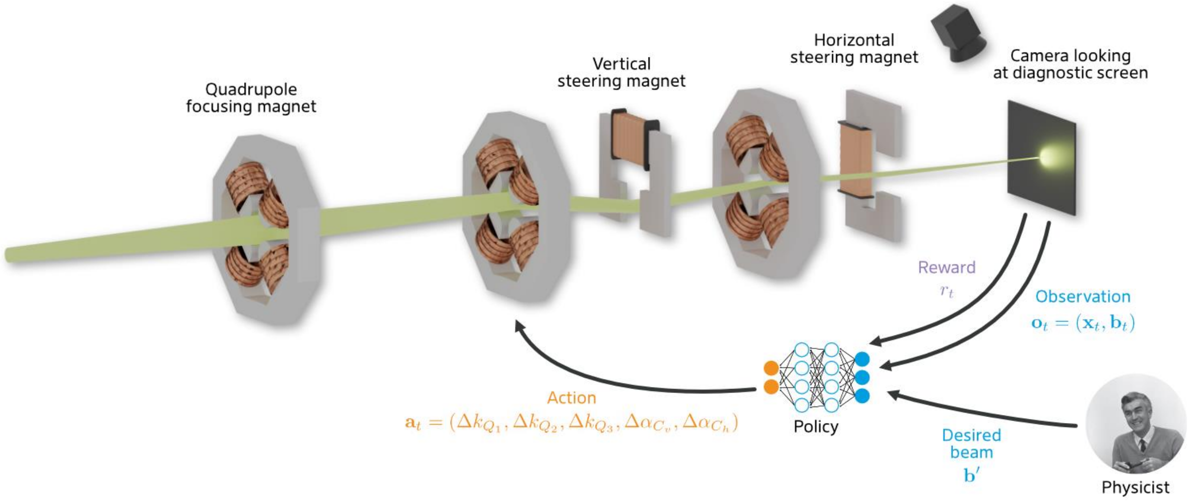
Experimental program

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

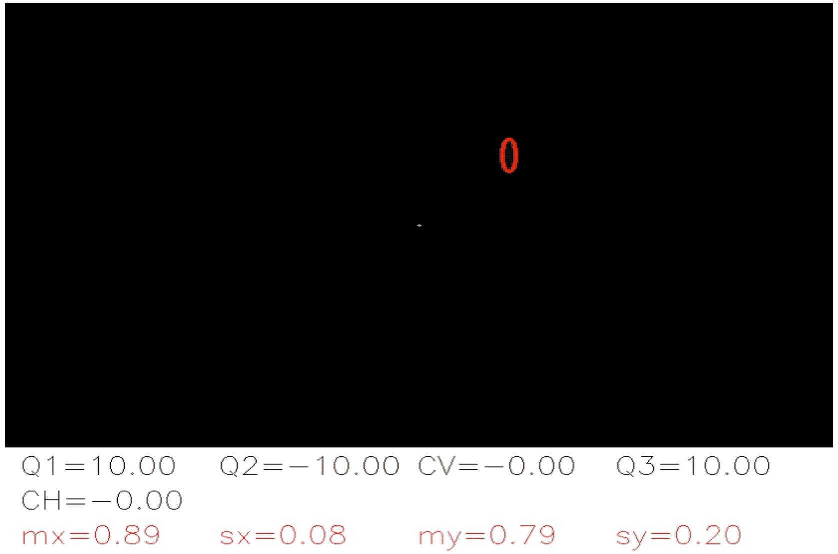
- **Reinforcement learning agents** trained and evaluated for **optimising magnets** to achieve beam parameters set by operator in the ARES Experimental Area.
- Achieved beam comparable to human operator, but 4x **faster**.
- Automated alignment of the beam to multiple quadrupoles using numerical optimisation.



Perspectives

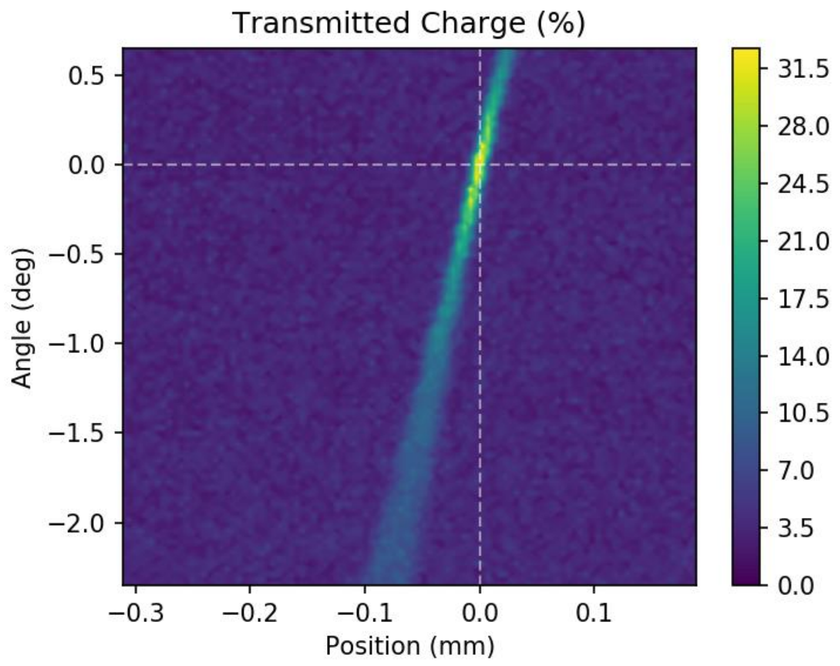
- Apply similar agents to other sections of ARES where beam parameters can be optimised on a diagnostic screen.
- Combine reinforcement learning agents to **achieve fully autonomous beam threading through ARES**.
- Faster beam-to-quad alignment by training reinforcement learning agents to do the alignment.

Publication in progress…



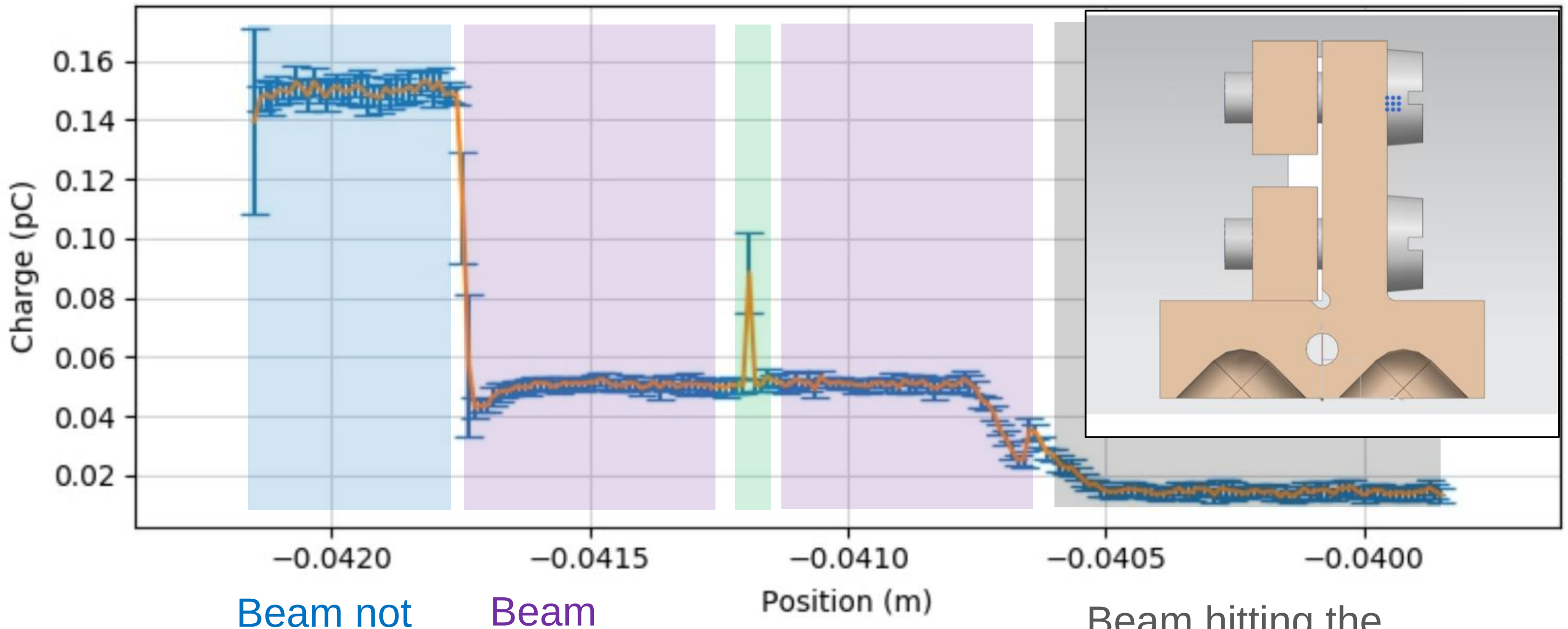
ACHIP @ ARES – experiment status

Transmission through the DLA aperture



Position and angle scan using the SmarPod 6D Positioning System

Position scan using the SmarPod → Charge on downstream intensity monitor



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!

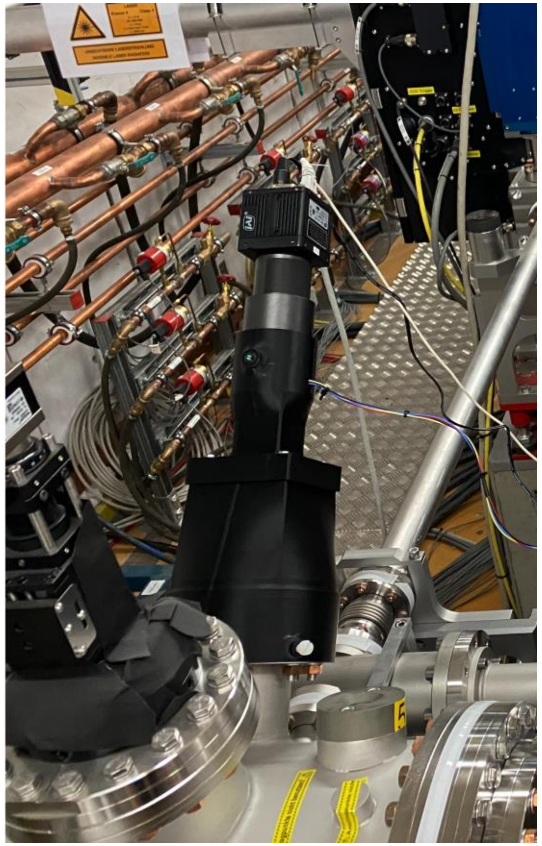
Beam hitting the metal sample holder → Blocked

ACHIP@ARES – experiment status

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)

→ Gives us timing on the 100s of ps scale; then we used 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