Phase Space Manipulation with Chicanes

Advanced External Injection Schemes for Novel Accelerators at ARES

Frank Mayet
Beschleuniger Betriebsseminar 2020
12.02.2020

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Phase Space Manipulation with Chicanes

Motivation – External Injection into Novel Accelerators at SINBAD/ARES

- **The ARES linac is ideally suited for external injection into novel accelerators**
  - Design parameters: Sub-fs bunches with 10 fs rms arrival time jitter (cf. e.g. PhD thesis, J. Zhu, 2017)

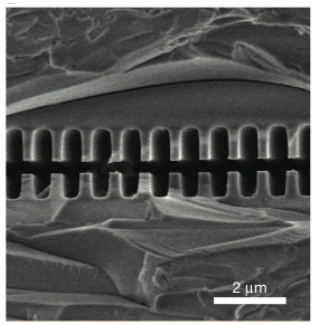
- **Two external injection experiments planned**
  - Laser-driven grating-type dielectric laser acceleration structures (2 µm period)
    - *Setup being implemented at ARES as we speak (thanks to all involved technical groups!)*
  - Laser-driven plasma acceleration (~100 µm period)

- **Challenges (Longitudinal Phase Space)**
  - Short enough bunches from ARES with $\sigma_\phi < \pi/4$ (1 - 10s of fs)
  - Synchronisation of drive laser and electron bunch arrival time (*also 1 - 10s of fs !!*)

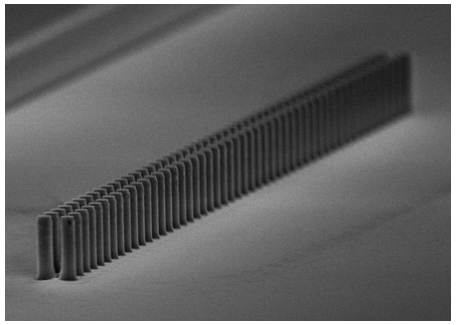
Phase Space Manipulation with Chicanes

Phase Synchronous Acceleration of Microbunch Trains in DLA Structures

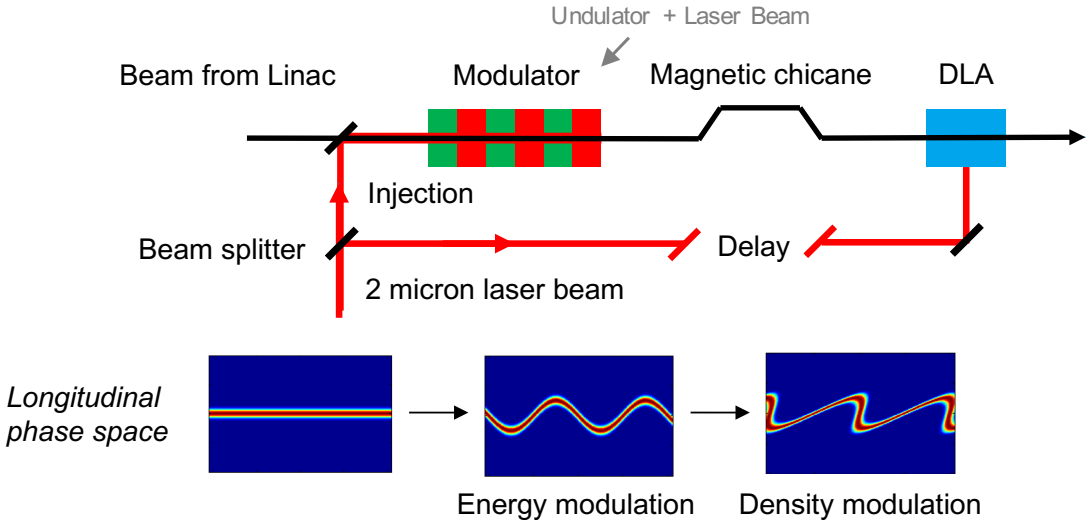
- **Period of the structure and accelerating field:** 2 µm
  - In order not to induce too much energy spread („net energy gain“)
    ➞ Single digit fs rms bunch length and laser/electron timing jitter
- **Concept**: Drive both the energy modulation of a long bunch and the DLA interaction with the same laser



Dual Grating



Dual Pillar Structure



Sketch: C. Lechner

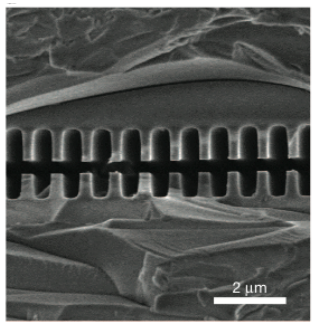
F. Mayet et al., *A Concept For Phase-Synchronous Acceleration Of Microbunch Trains In DLA Structures At SINBAD,* Proc. IPAC'17, Copenhagen, Denmark, WEPVA006, (2017)

F. Mayet et al., *Simulations and plans for possible DLA experiments at SINBAD,* Nuclear Inst. and Methods in Physics Research, A (2018)

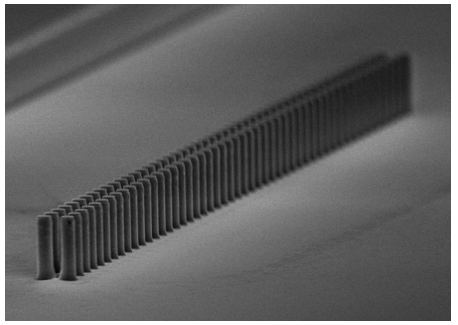
Phase Space Manipulation with Chicanes

Phase Synchronous Acceleration of Microbunch Trains in DLA Structures

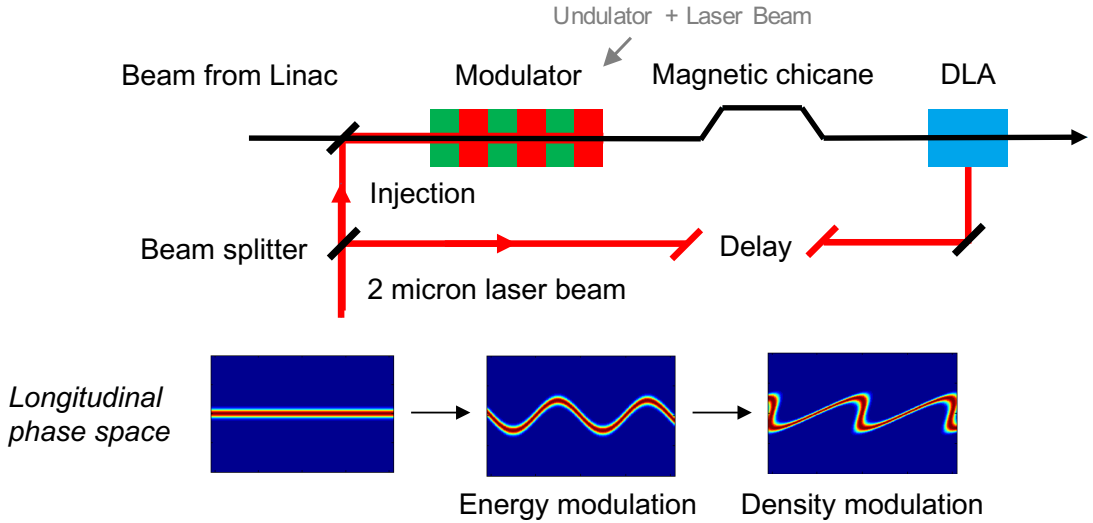
- **Period of the structure and accelerating field:** 2 µm
  - In order not to induce too much energy spread („net energy gain“)
    ➞ Single digit fs rms bunch length and laser/electron timing jitter
- **Concept**: Drive both the energy modulation of a long bunch and the DLA interaction with the same laser



Dual Grating



Dual Pillar Structure



Sketch: C. Lechner

- **Remaining jitter sources**
  - Mean energy stability from the linac (R_{56}!!, needs to be < 1e-3, which is expected at ARES)
  - Phase stability between the two laser arms (decisive contribution!)

F. Mayet et al., *A Concept For Phase-Synchronous Acceleration Of Microbunch Trains In DLA Structures At SINBAD,* Proc. IPAC'17, Copenhagen, Denmark, WEPVA006, (2017)

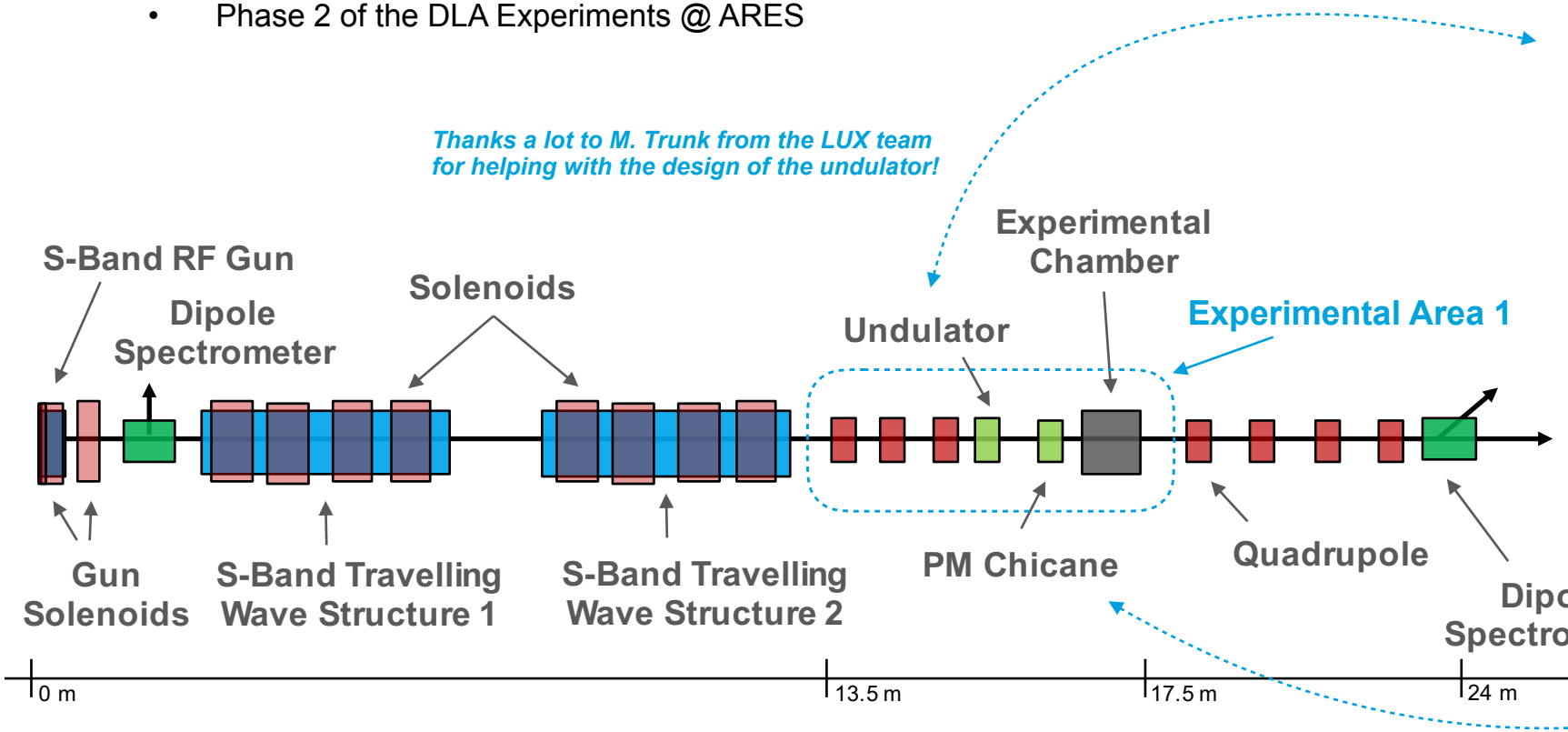
F. Mayet et al., *Simulations and plans for possible DLA experiments at SINBAD,* Nuclear Inst. and Methods in Physics Research, A (2018)

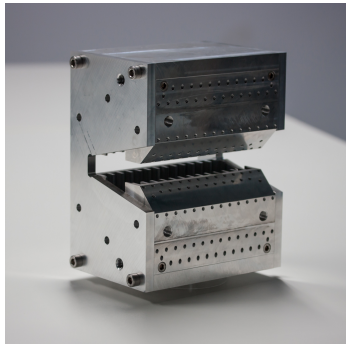
Phase Space Manipulation with Chicanes

Phase Synchronous Acceleration of Microbunch Trains in DLA Structures

- **Experiment planned to be conducted in second half of 2020**
  - Phase 2 of the DLA Experiments @ ARES

Thanks a lot to M. Trunk from the LUX team for helping with the design of the undulator!





Purpose-built fixed gap undulator

XFEL-type phase shifter delivers enough R_{56}

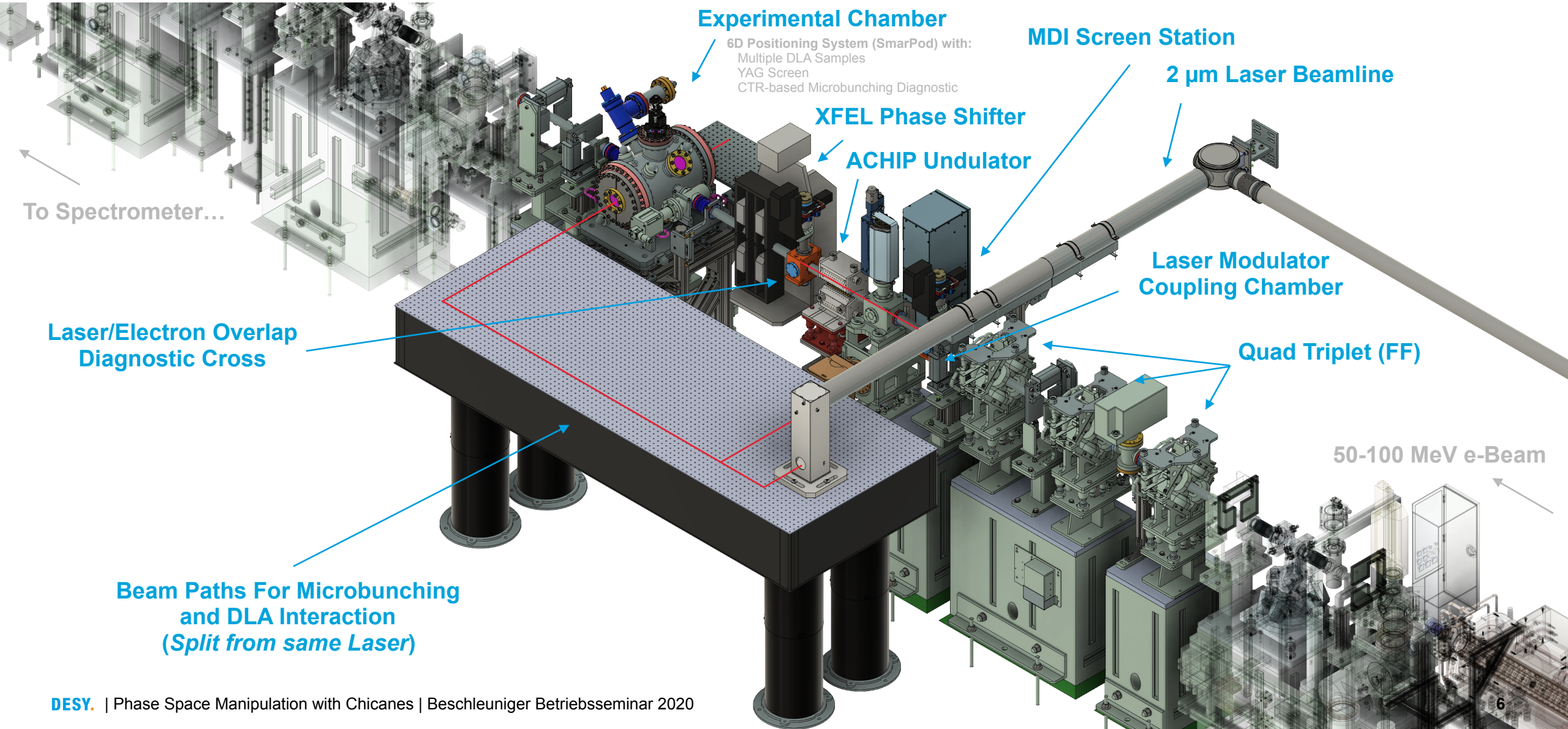
5 MeV

150 MeV (on-crest)

100 MeV (compressed)

Phase Space Manipulation with Chicanes

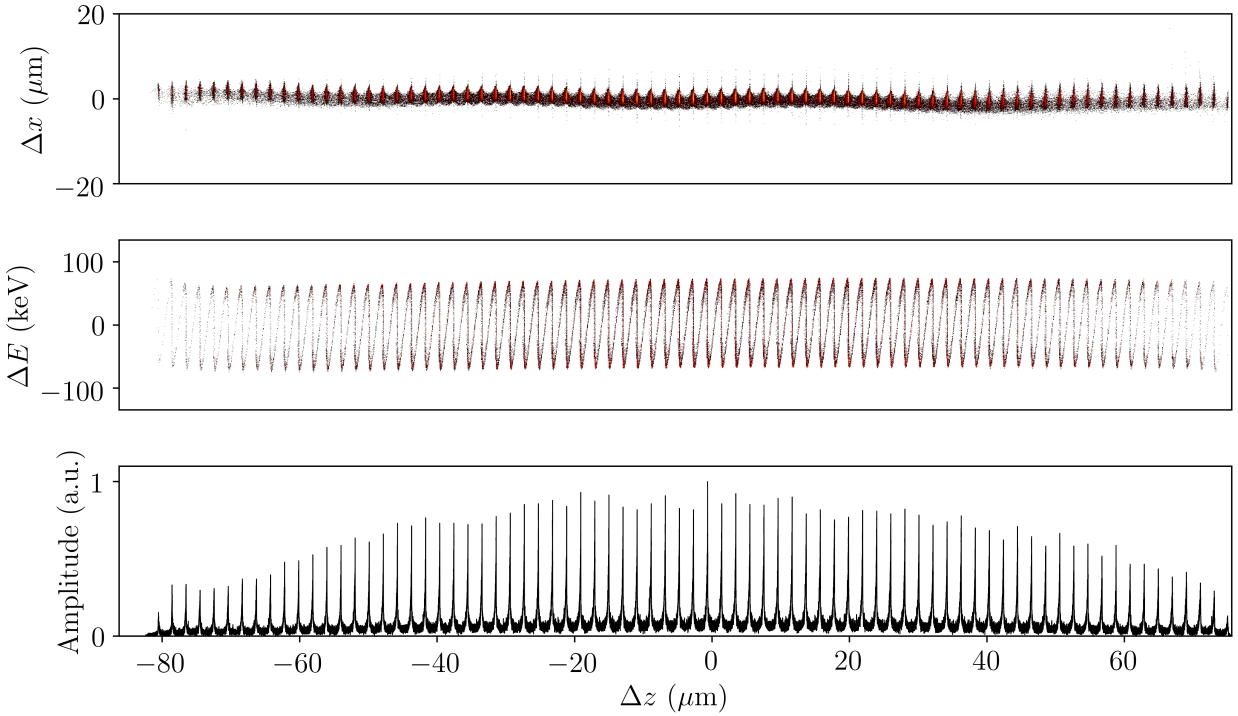
Phase Synchronous Acceleration of Microbunch Trains in DLA Structures



Phase Space Manipulation with Chicanes

Phase Synchronous Acceleration of Microbunch Trains in DLA Structures

Start to End Simulation with ASTRA – ~50 MeV Beam @ DLA

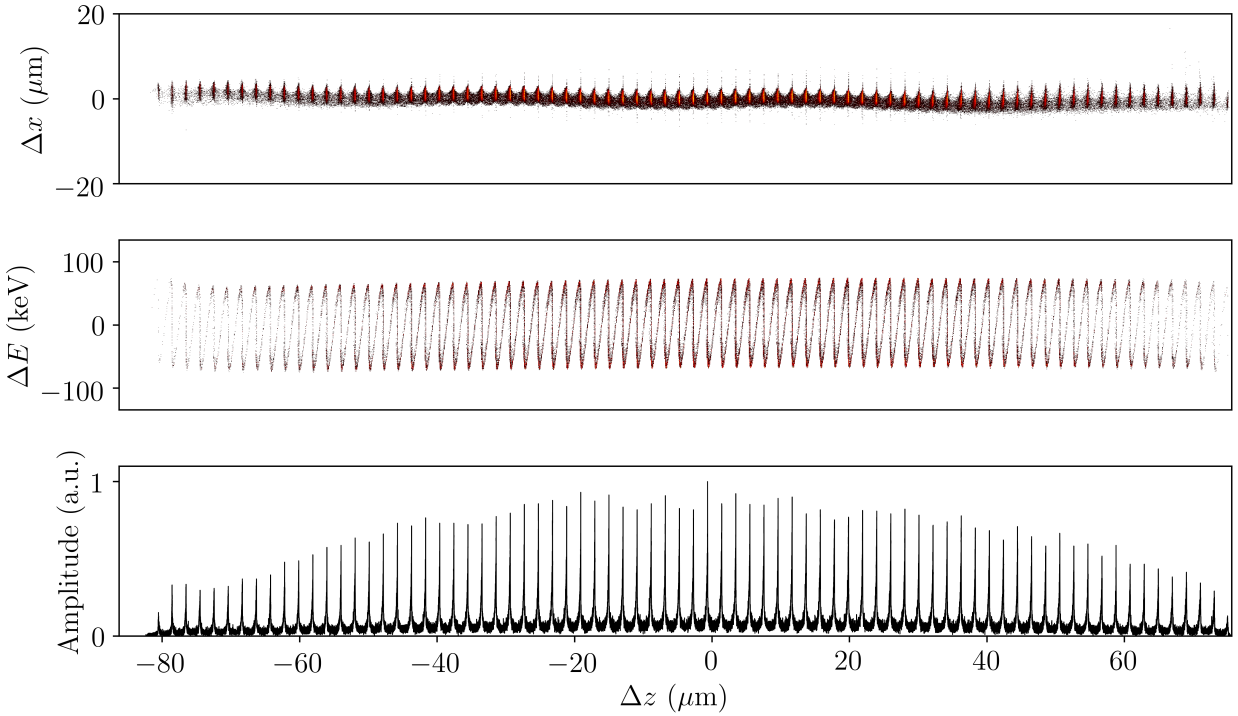


- 70 Microbunches á ~10 fC
- Microbunch length: **352 ± 43 as FWHM**
- Spacing: **2.0500 ± 0.0078 µm**

Phase Space Manipulation with Chicanes

Phase Synchronous Acceleration of Microbunch Trains in DLA Structures

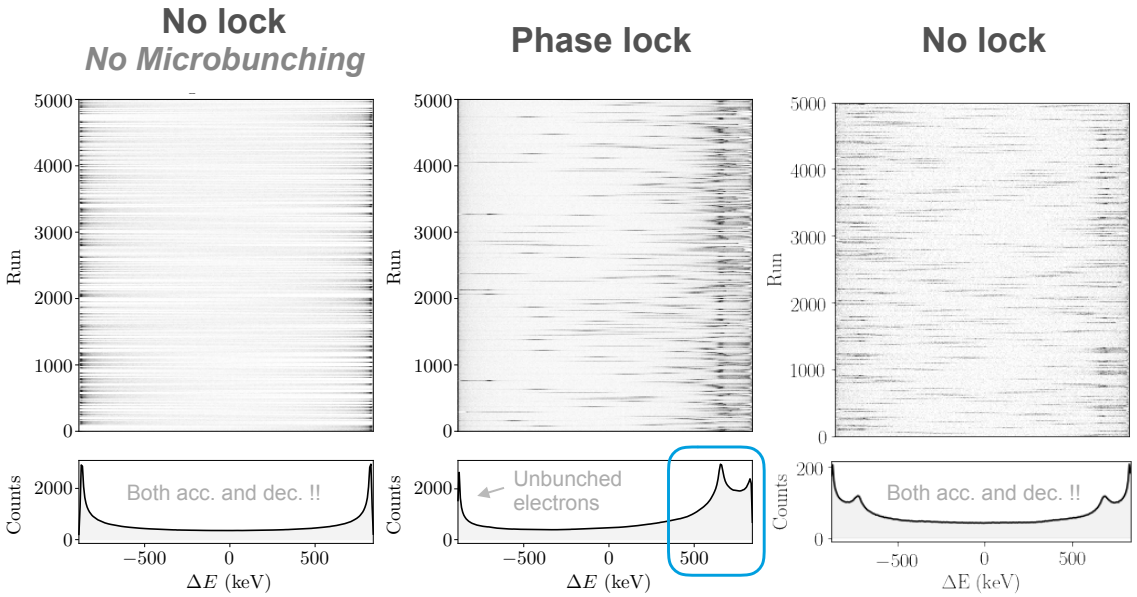
Start to End Simulation with ASTRA – ~50 MeV Beam @ DLA



- 70 Microbunches á ~10 fC
- Microbunch length: **352 ± 43 as FWHM**
- Spacing: **2.0500 ± 0.0078 µm**

Timing Stability Simulation (5000 Runs)

Taking all jitter sources into account



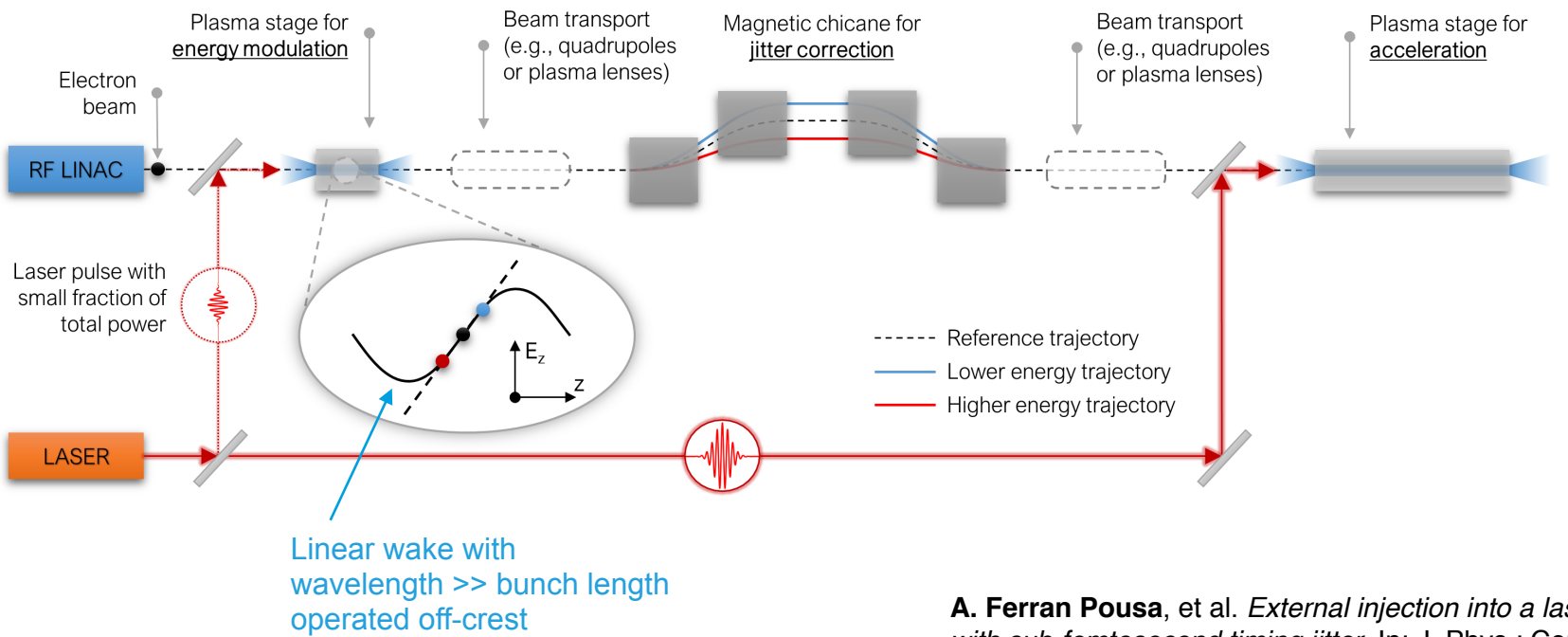
Double horn of the pre-modulated beam clearly shifted in the mean spectrum!

- **Significant shot-to-shot stability improvement expected, leading to sub-10 fs synchronisation**
- **Short micro bunches enable *net energy gain***

Phase Space Manipulation with Chicanes

External Injection with sub-fs Timing Jitter into a Plasma-based Accelerator

- **Period of the accelerating field:** ~100 µm, **field amplitude:** ~10 GV/m, **timing stability requirement** ~0.1 fs
- **Concept:** Add an additional plasma stage before the main LWFA in which the beam energy is linearly correlated to its relative arrival time w.r.t. the drive laser pulse. Then, the path length differences in a classical chicane are used to compensate the timing differences
- ➞ Longer acc. period and plasma-based version of the DLA scheme shown before ➞ same remaining stability requirements!!

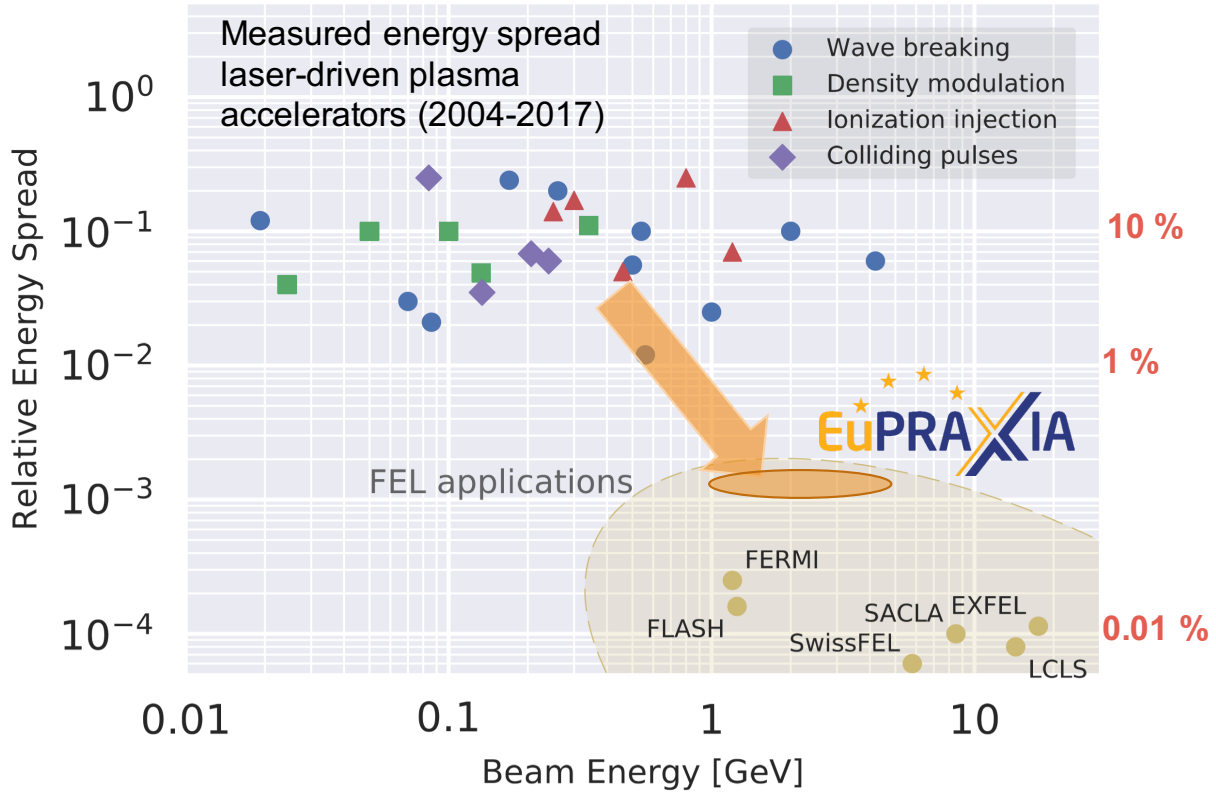


A. Ferran Pousa, et al. *External injection into a laser-driven plasma accelerator with sub-femtosecond timing jitter*. In: J. Phys.: Conf. Ser. 874.1 (2017)

Phase Space Manipulation with Chicanes

A Multi-Stage Plasma-Acceleration Concept for Ultra-Low Energy Spread Beams

- **One of the main challenges of plasma accelerators:** Energy spread
- **Without sophisticated mitigation schemes:** Typically on the order of 1 - 10%, but FELs, for example, need < 0.1%

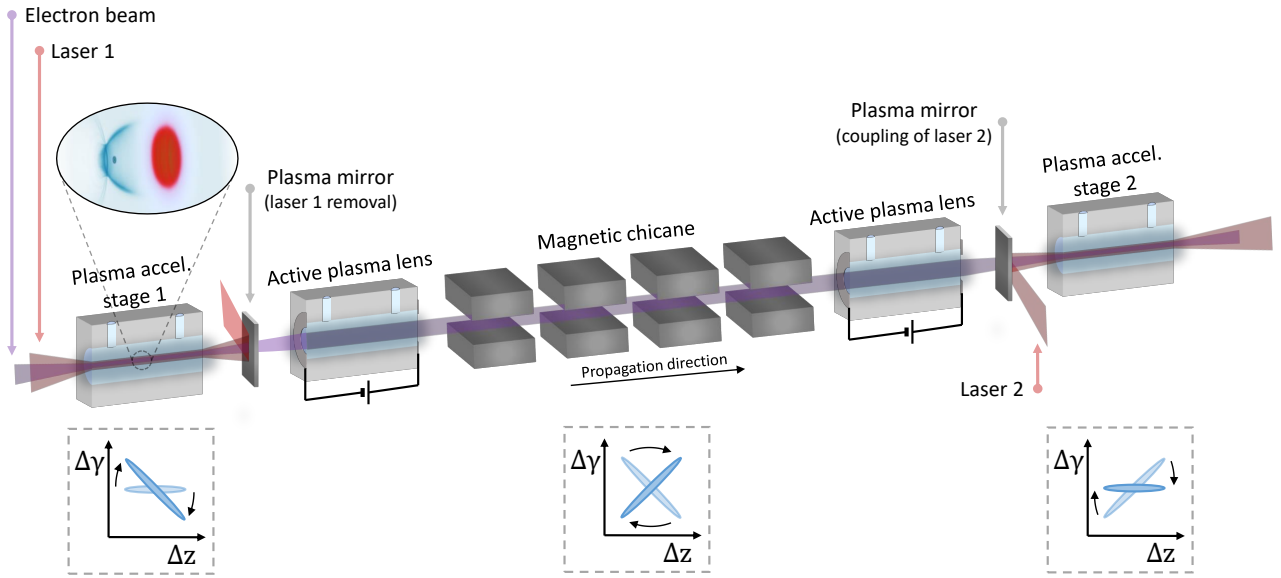


Plot: A. Ferran Pousa

Phase Space Manipulation with Chicanes

A Multi-Stage Plasma-Acceleration Concept for Ultra-Low Energy Spread Beams

- **One of the main challenges of plasma accelerators:** Energy spread
- **Without sophisticated mitigation schemes:** Typically on the order of 1 - 10%, but FELs, for example, need < 0.1%



1st plasma stage imprints a strong negative chirp onto the externally injected bunch

A classical 4 dipole chicane inverts the longitudinal phase space based on its R_{56}

2nd plasma stage accelerates the beam and compensates the initial chirp caused by the 1st stage

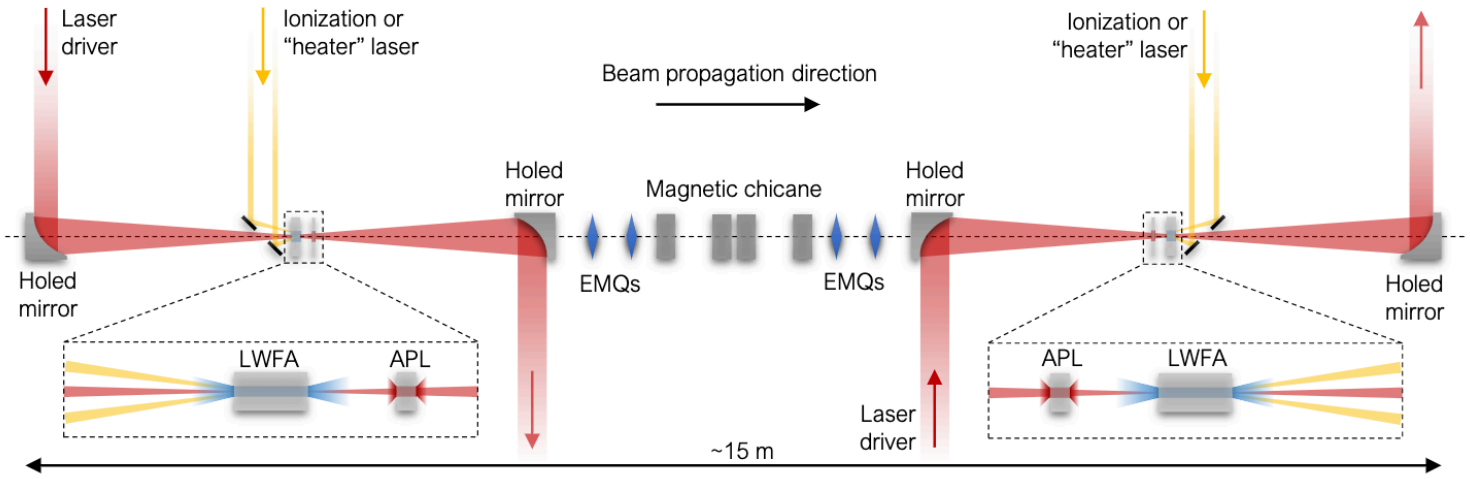
Sketch: A. Ferran Pousa

A. Ferran Pousa, et al. *Compact Multistage Plasma-Based Accelerator Design for Correlated Energy Spread Compensation.* In: Phys. Rev. Lett. 123 (2019)

Phase Space Manipulation with Chicanes

A Multi-Stage Plasma-Acceleration Concept for Ultra-Low Energy Spread Beams

- **Potential implementation of a 1 GeV accelerator for ATHENA_e**

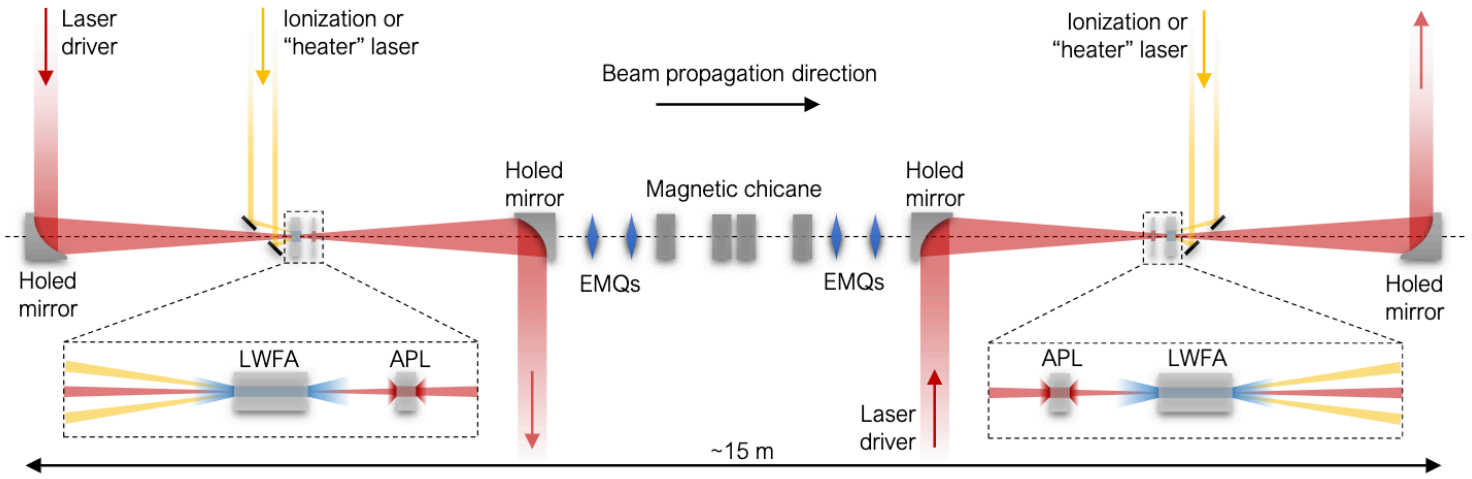


Sketch: A. Ferran Pousa

Phase Space Manipulation with Chicanes

A Multi-Stage Plasma-Acceleration Concept for Ultra-Low Energy Spread Beams

- **Potential implementation of a 1 GeV accelerator for ATHENA_e**



Sketch: A. Ferran Pousa

Start to end simulation using FBPIC + ASTRA

Simulation incl. space charge
CSR effects excluded based on pre-study

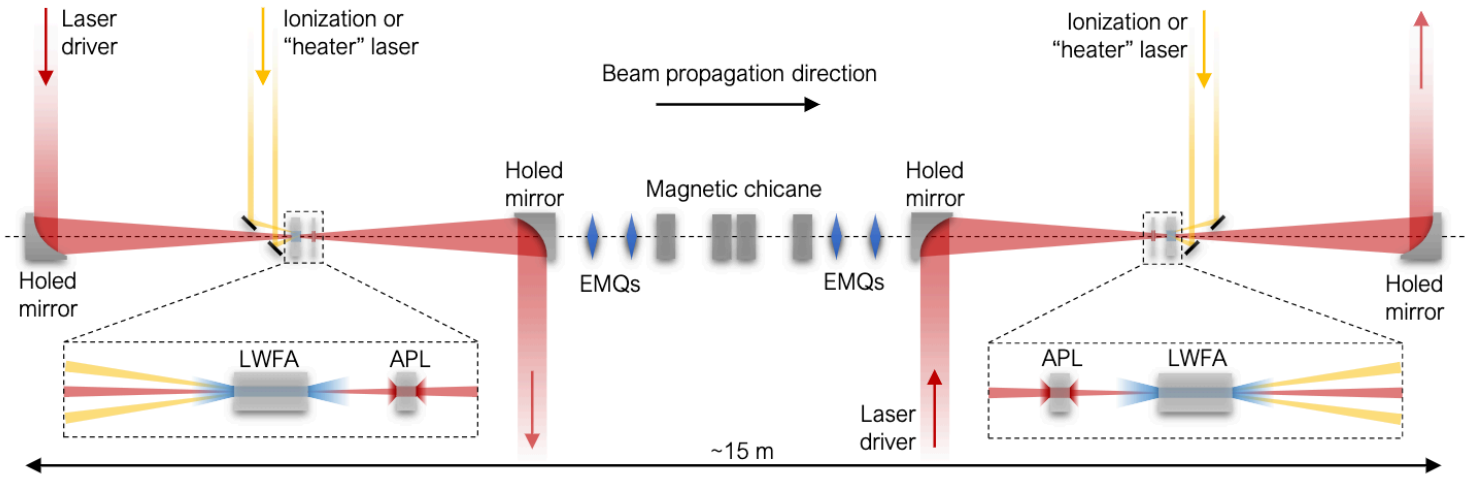
Parameter	Units	Initial value	Final value
Q	pC	11.3	11.3
$\langle\gamma\rangle$	MeV	102	981
σ_δ	10^{-3}	3.01	5.27
I_{peak}	kA	1	2.41
τ_{FWHM}	fs	10.7	1.1
σ_t	fs	3.26	3.32
β_x | β_y	cm	18.0 | 18.0	18.3 | 15.1
α_x | α_y	-	5.00 | 5.00	-4.89 | -3.79
$\epsilon_{\mathrm{n,x}}$ | $\epsilon_{\mathrm{n,y}}$	µm	0.30 | 0.30	0.63 | 0.61
$\epsilon_{\mathrm{n,x,sl}}$ | $\epsilon_{\mathrm{n,y,sl}}$	µm	0.30 | 0.30	0.43 | 0.42
$\sigma_{\delta,\mathrm{sl}}$	10^{-3}	3.00	1.39

Parameters approach FEL quality!

Phase Space Manipulation with Chicanes

A Multi-Stage Plasma-Acceleration Concept for Ultra-Low Energy Spread Beams

- **Potential implementation of a 1 GeV accelerator for ATHENA_e**



Start to end simulation using FBPIC + ASTRA

Simulation incl. space charge
CSR effects excluded based on pre-study

Parameter	Units	Initial value	Final value
Q	pC	11.3	11.3
$\langle\gamma\rangle$	MeV	102	981
σ_δ	10^{-3}	3.01	5.27
I_{peak}	kA	1	2.41
τ_{FWHM}	fs	10.7	1.1
σ_t	fs	3.26	3.32
β_x | β_y	cm	18.0 | 18.0	18.3 | 15.1
α_x | α_y	-	5.00 | 5.00	-4.89 | -3.79
$\epsilon_{\mathrm{n,x}}$ | $\epsilon_{\mathrm{n,y}}$	µm	0.30 | 0.30	0.63 | 0.61
$\epsilon_{\mathrm{n,x,sl}}$ | $\epsilon_{\mathrm{n,y,sl}}$	µm	0.30 | 0.30	0.43 | 0.42
$\sigma_{\delta,\mathrm{sl}}$	10^{-3}	3.00	1.39

But: Wake-T stability simulations show that due to the non-linearities in the chicane a laser-to-electron timing jitter <1 fs is required.

Next steps: A combination of this scheme and the jitter compensation scheme, or the implementation of sextupoles.

Phase Space Manipulation with Chicanes

Summary

- **Phase space manipulation with chicanes can improve the performance of external injection experiments**
  - Ultra-short bunches
  - Drive-laser to electron timing stability

- **The DLA experiments at ARES are being setup**
  - …will be the first benchmark for ARES (*ultra-short bunches, timing, etc.*)

- **Simulation studies: *Towards a low energy spread plasma accelerator***
  - *…done by Angel Ferran Pousa as part of his Phd thesis*

Thank you!