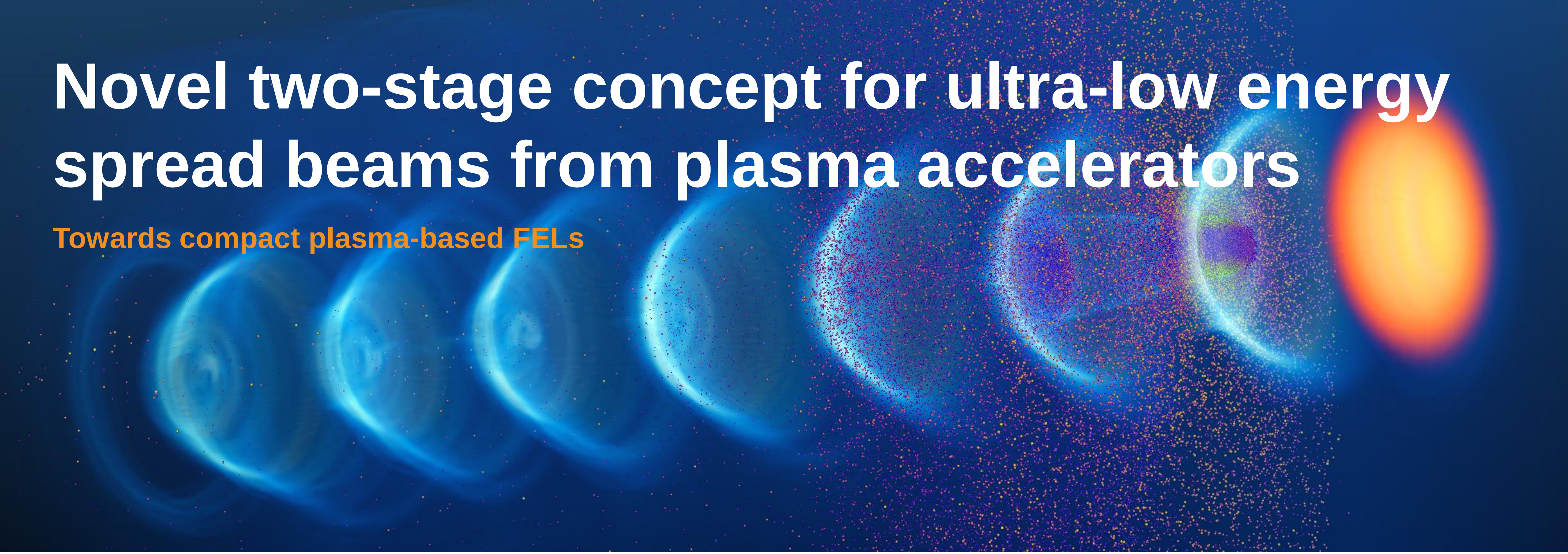
Novel two-stage concept for ultra-low energy spread beams from plasma accelerators

Towards compact plasma-based FELs



Ángel Ferran Pousa (DESY)

LEAPS WG2 Meeting, 08.09.2020

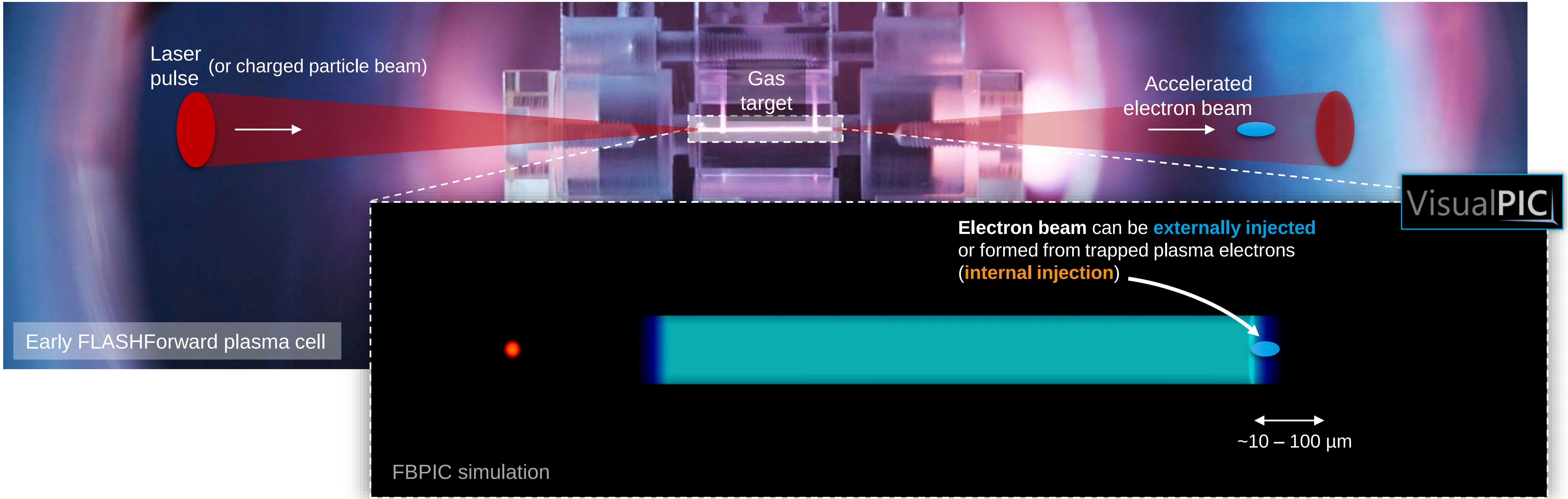
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

EuPRAXIA

DESY.

Introduction

Plasma-based acceleration



Plasma wakefields can sustain accelerating fields of up to **~10-100 GV/m** with focusing gradients above **~1 MT/m**

x1000 more than RF technology

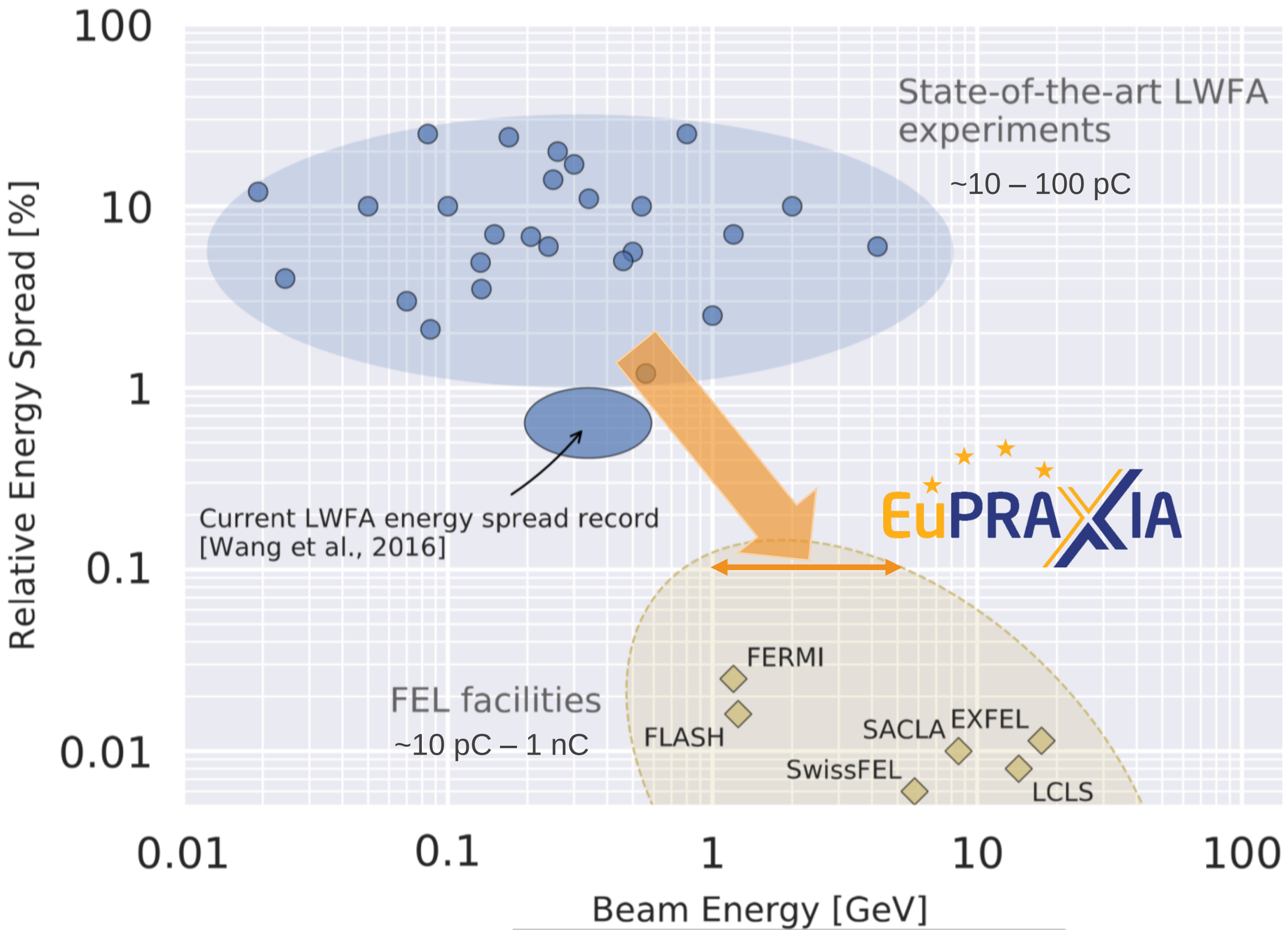
Plasma-based accelerators are a source of **fs-long** beams with **kA** current, reaching **GeV** energy in only **cm** scales [*]

[*] A. J. Gonsalves et al., PRL, 2019

Plasma accelerators as compact Free-Electron Lasers?

Electron beam requirements

- **GeV** energy in **cm**-scale: towards FELs of **reduced size and cost**?.
- FELs impose strict requirements on electron beam parameters:
  - **GeV** energy. ✓
  - **Micron**-level emittance. ✓
  - **Multi-kA peak** current. ✓
  - Relative **energy spread** <10^{-3}. ✗
  - **Femtosecond**-long bunches. ✓



See, e.g.: [A. J. Gonsalves et al., PRL, 2019; O. Lundh et al., Nat. Phys., 2011; E. Brunetti et al., PRL, 2010; J. Couperus, Nat. Comm., 2017]

The EuPRAXIA collaboration

Towards plasma accelerators ready for applications

1st EuPRAXIA Collaboration Week in Hamburg, 2017

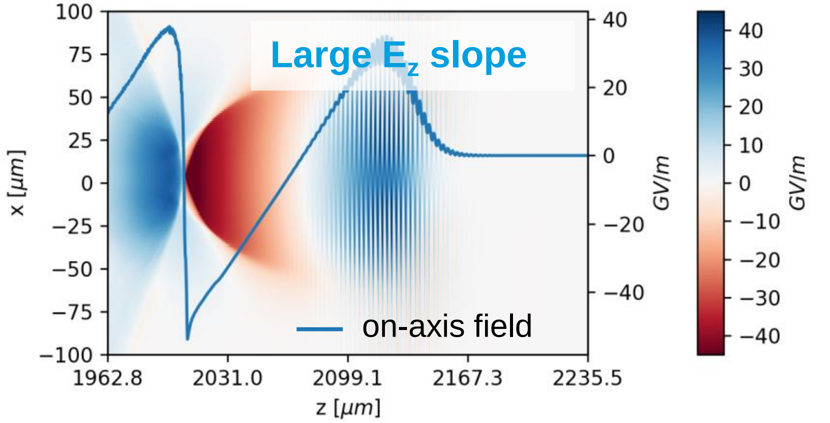
- **Horizon 2020 design study** for a **5 GeV** plasma accelerator **ready for applications** (mainly **FEL**).
- Project coordinator: **Ralph Assmann** (DESY).
- **European collaboration** of plasma-**research** groups, laser **industry** and international partners.
- Conceptual design report (**CDR**) submitted October 2019.
- Currently finalizing ESFRI roadmap application.

EuPRAXIA

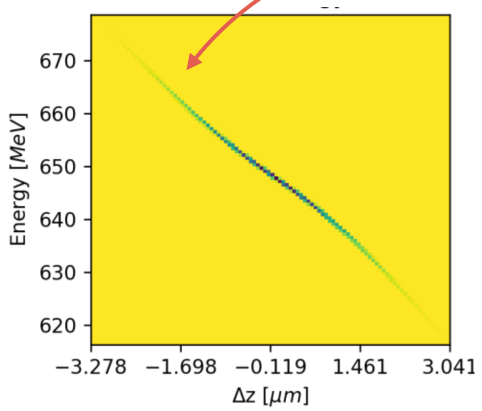
http://www.eupraxia-project.eu/

Energy spread in plasma accelerators

General overview



Linear energy chirp.



- Large **correlated energy spread.**
- Main source of energy spread (typicaly **1-10%**).

- Energy chirp can be mitigated through **beam loading** (beam can flatten E_z if peak current is large enough). [S. Van der Meer, 1985; T. Katsouleas, 1987]
- Several **other proposals** at the theoretical and experimental stage:
  - **Chirp compensation** [G. Manahan et al, 2017; R. Brinkmann et al, 2017]
  - **Beam stretching** [A. Maier et al, 2011; T. André et al, 2018].
  - **Plasma dechirper** [D'Arcy et al, 2019; V. Shpakov et al, 2019; Wu et al, 2019]
- Despite great progress, **no solution** has demonstrated required performance for FEL.

Alternative idea:

Taking advantage of energy chirp to achieve beams with **ultra-low energy spread**

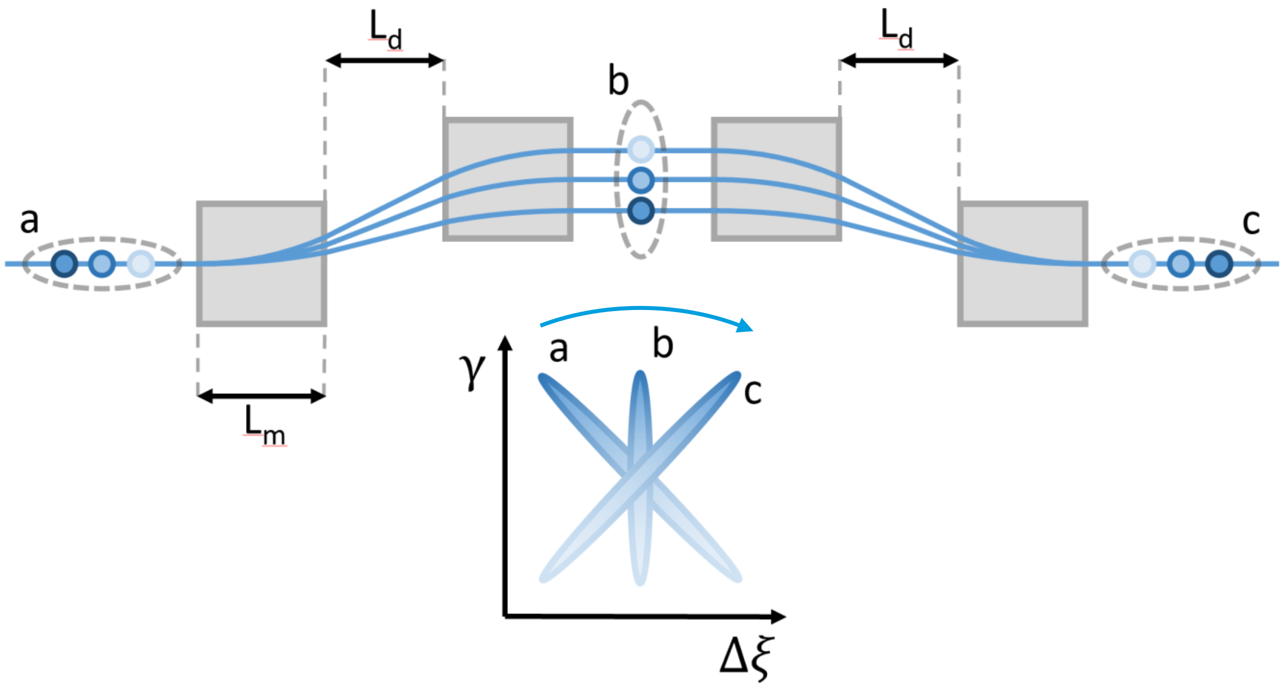
An alternative approach

Taking advantage of the energy chirp

- Energy chirp naturally occurs in plasma accelerators.
- Improves beam stability (hosing mitigation). [T. Mehrling et al., PRL, 2017; R. Lehe et al., PRL, 2017]
- Offers new possibilities for achieving low energy spread beams:

Plasma accelerating stage

Beam acquires chirp

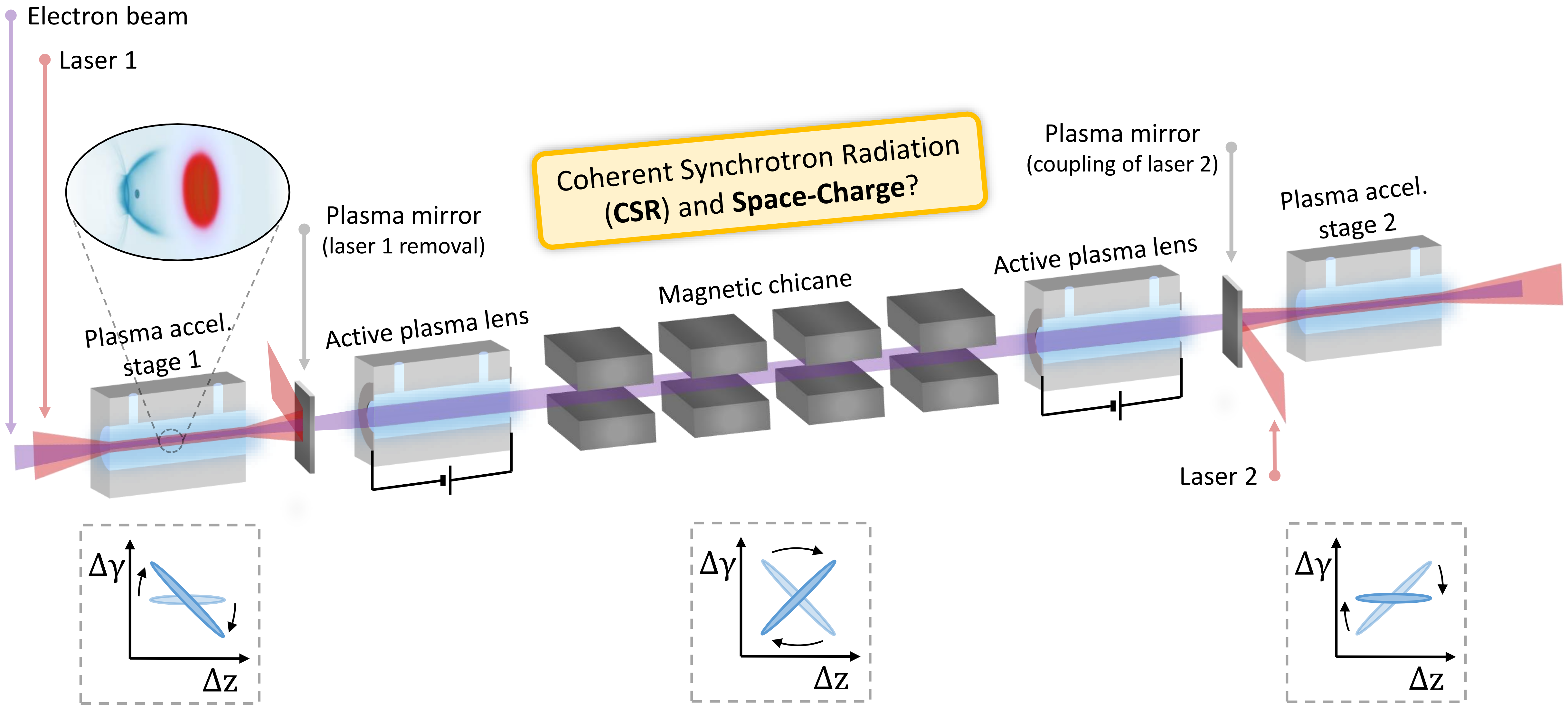


Plasma accelerating stage

Beam chirp is compensated

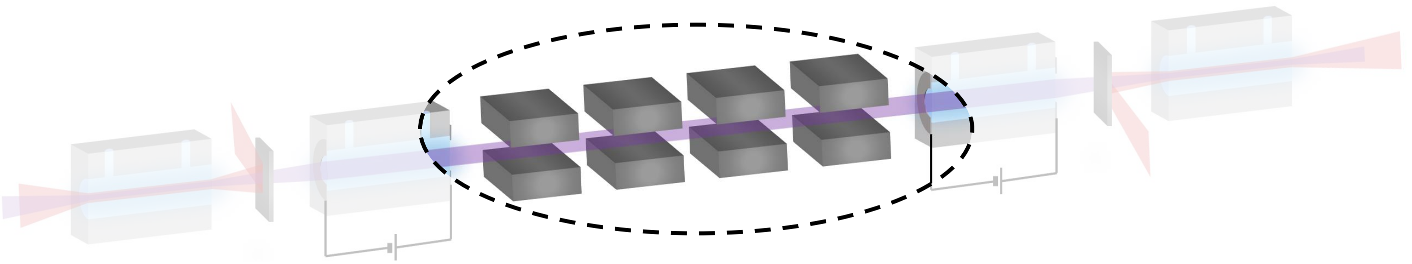
New plasma-acceleration concept

Acceleration in two stages with a magnetic chicane



Potential issues

CSR and SC in the chicane



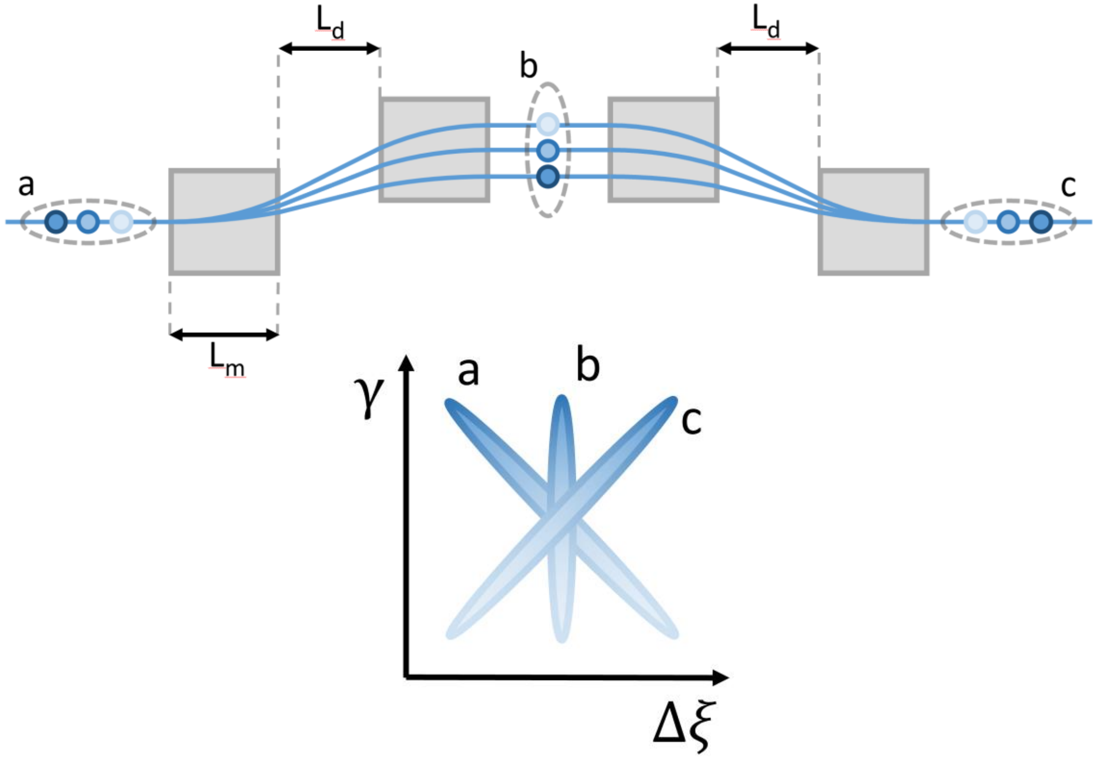
- Beam undergoes full compression ⟶ SC?
- Bending in the dipoles ⟶ CSR?

Space charge

- **GeV energy**, **$\sim$10 pC charge** and **small distance** minimize its impact.
- Detailed studies with ASTRA show negligible impact.

Coherent synchrotron radiation

- Very **small bending angle** is needed to invert the beam ($\theta < 1°$), thanks to the **large energy chirp**. **Compact chicane** possible.
- Detailed studies with CSRtrack show no negative impact on beam parameters.



Space charge and **CSR** are **not an issue** for the considered parameter range

Start-to-end simulations

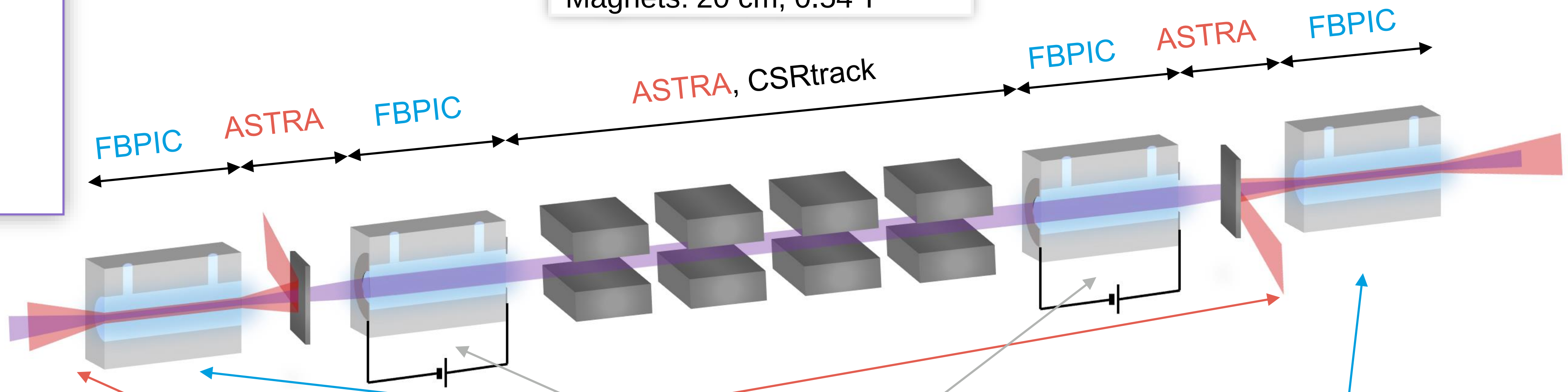
Beamline parameters for a 5 GeV accelerator

Based on simulations from J. Zhu for hypothetical 250 MeV ARES linac upgrade [*]

Not to scale.
Actual length ~1.5 m.

Electron beam
$Q = 10$ pC
$\tau_{FWHM} = 5$ fs
$I_p = 2$ kA
$E = 250$ MeV
$\varepsilon_n = 0.5$ µm rad
$\frac{\sigma_\gamma}{\gamma} = 0.5\%$

Chicane
$R_{56} = -0.067$ mm ($\theta = 0.6°$)
$L = 1.2$ m
Magnets: 20 cm, 0.54 T



Laser pulses
$E = 40$J
$a_0 = 3$
$w_0 = 50$ µm
$\tau_{FWHM} = 50$ fs

Within range of EuPRAXIA laser

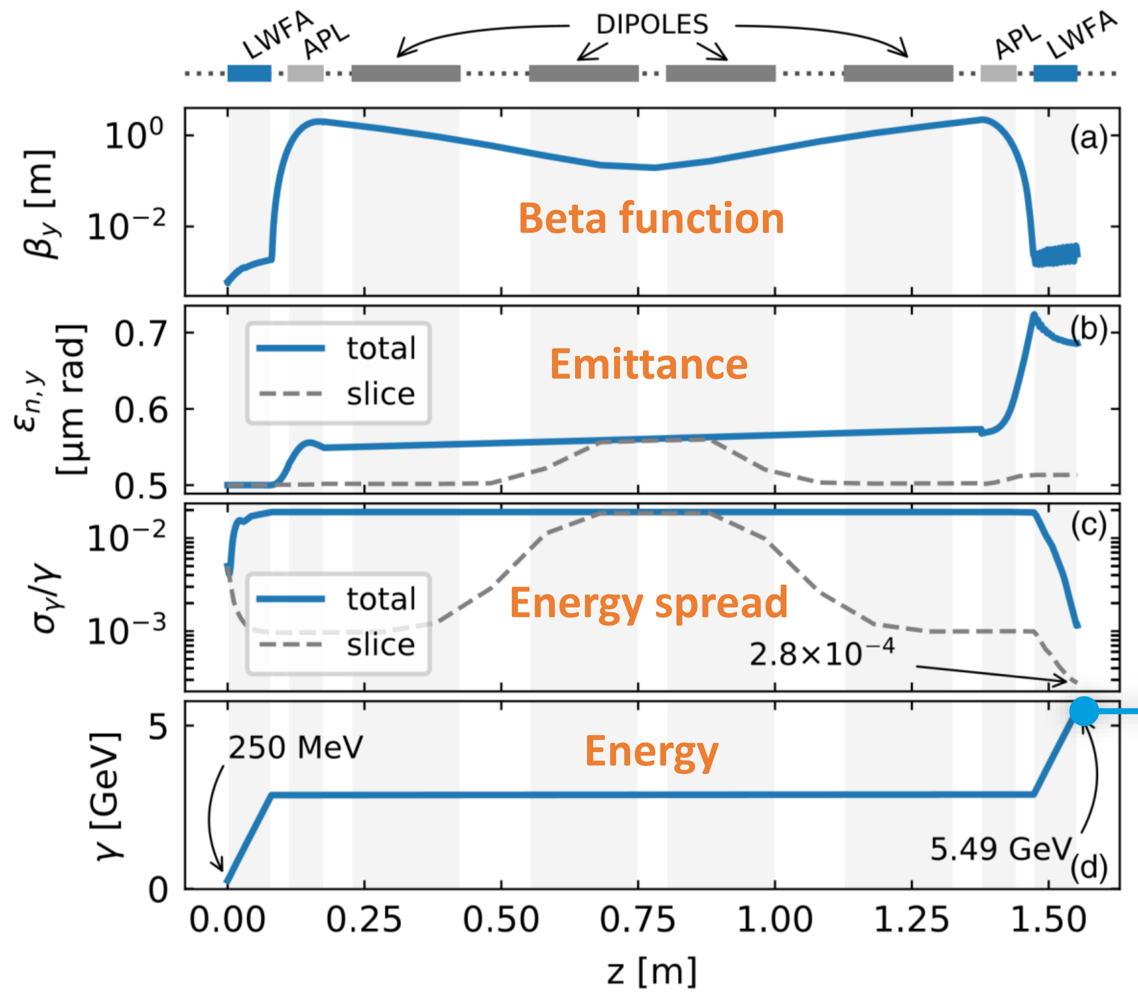
Plasma lenses
$K = 3000$ T/m
$L = 6.6$ cm
$n_p = 10^{15}$ cm^{-3}

Plasma stages
$n_p = 10^{17}$ cm^{-3}
Guiding channel
$L_p = 8$ cm

[*] - J. Zhu et al., THPAF032, IPAC 2018

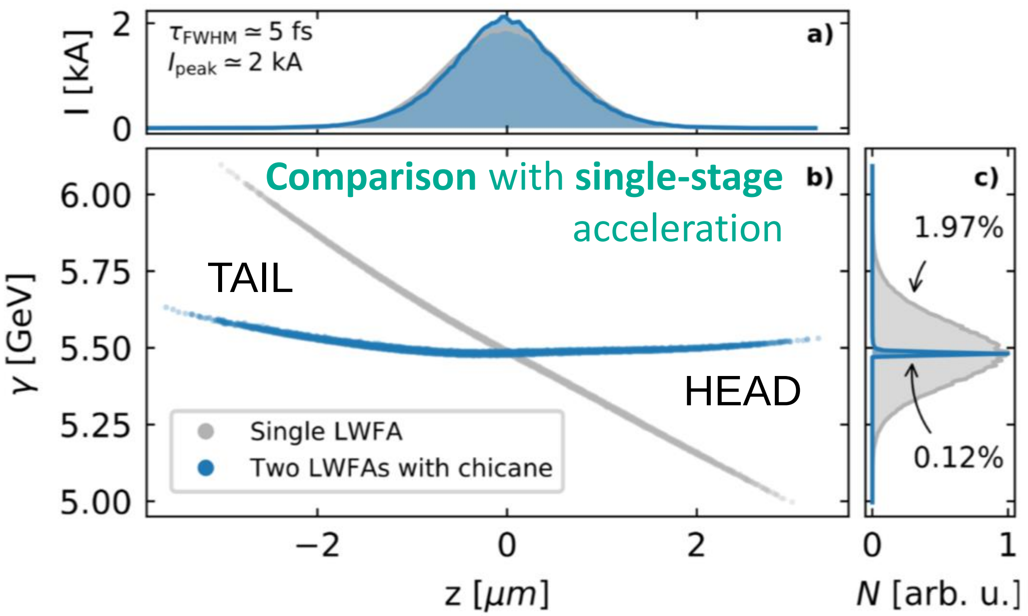
Start-to-end simulations

Results



- Beam maintains **sub-micron emittance**.
- **Energy chirp** is **successfully compensated** in second stage.
- Final **energy spread**:
  - **0.12%** (total)
  - **0.028%** (**2.8×10^{-4}**) (0.1µm slice)
- Final energy of **5.5 GeV**.

FEL-range values



x20 reduction of energy spread

Comparison to current state-of-the art experiments

Beam parameters reach FEL regime

PHYSICAL REVIEW LETTERS **123,** 054801 (2019)

Compact Multistage Plasma-Based Accelerator Design for Correlated Energy Spread Compensation

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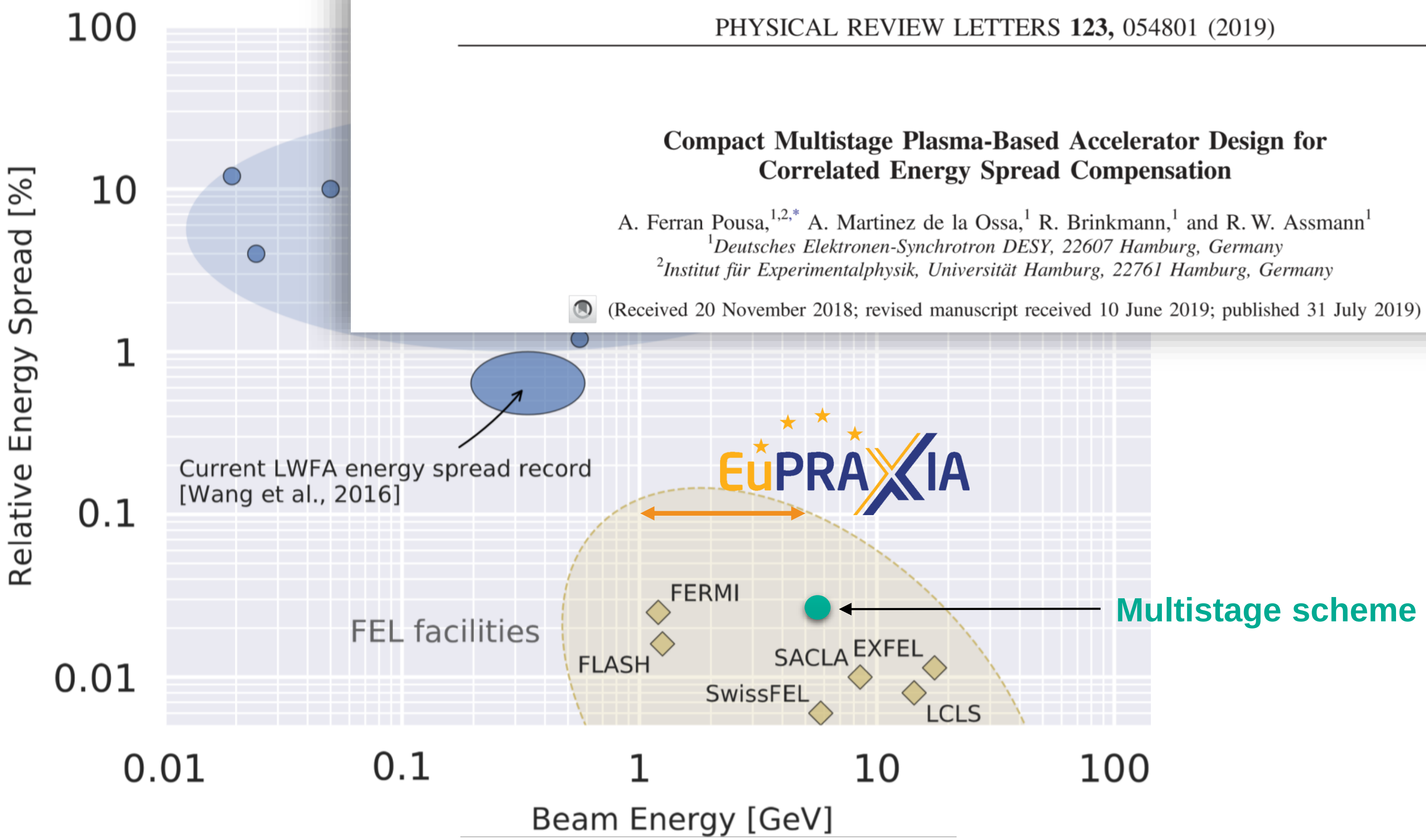
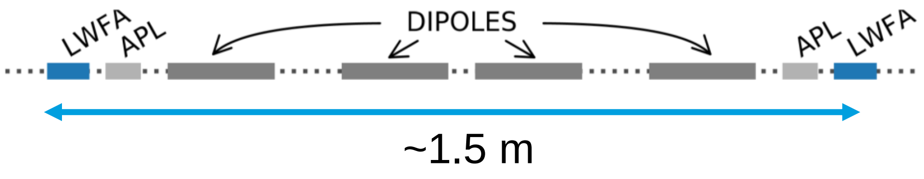


Conceptual design for EuPRAXIA

Beyond first proof-of-principle simulations

Proof-of-principle layout (to scale)



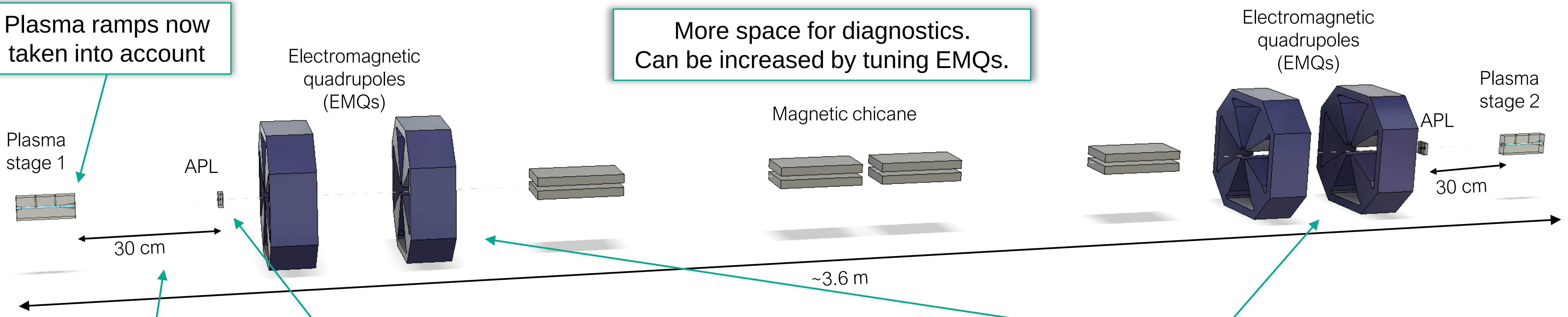
Very **compact** but:

- Short drifts.
- No space for diagnostics.
- Beam transport relies only on APLs.
- …

Conceptual design for EuPRAXIA:

Plasma ramps now taken into account

More space for diagnostics.
Can be increased by tuning EMQs.



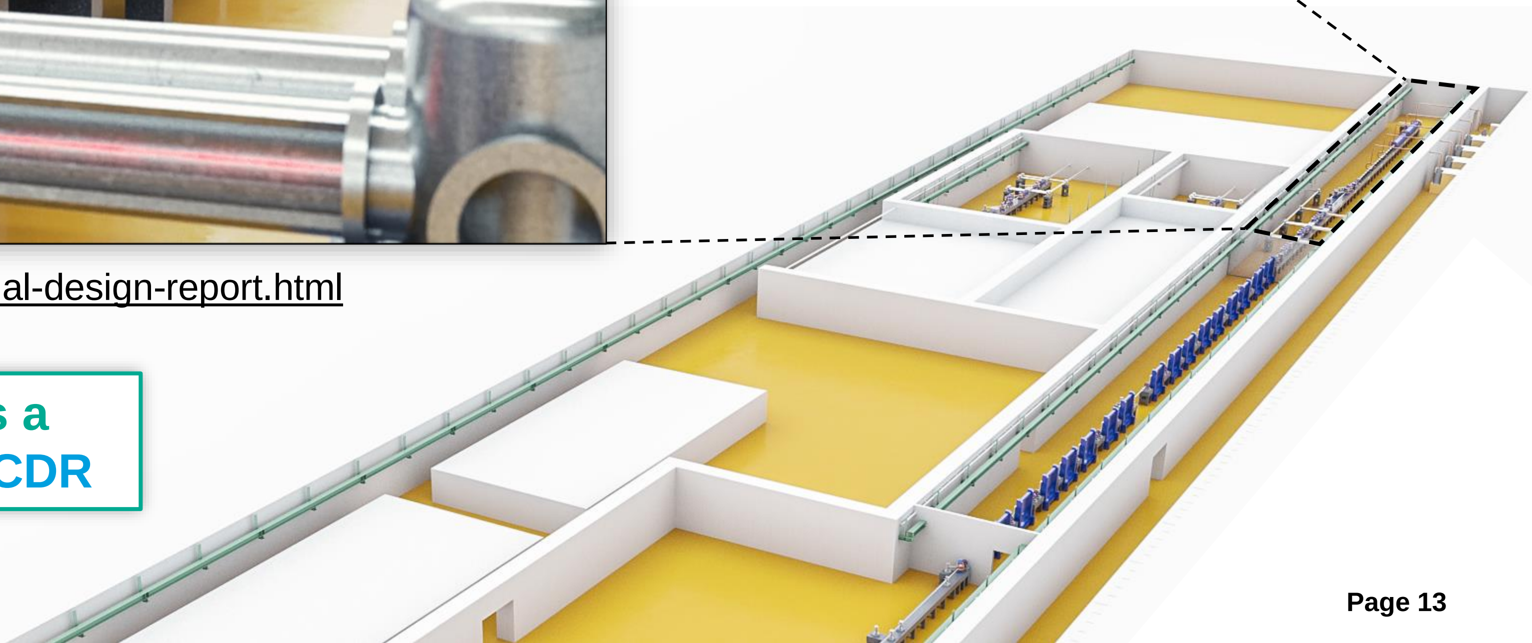
Additional space for laser removal (e.g., plasma mirror)

Much shorter APLs (6 vs 1 cm)

EMQs provide fine-tuning of beam transport and independent control of x-y planes

Conceptual design for EuPRAXIA

Multistage acceleration chosen as baseline option



CDR: http://www.eupraxia-project.eu/eupraxia-conceptual-design-report.html

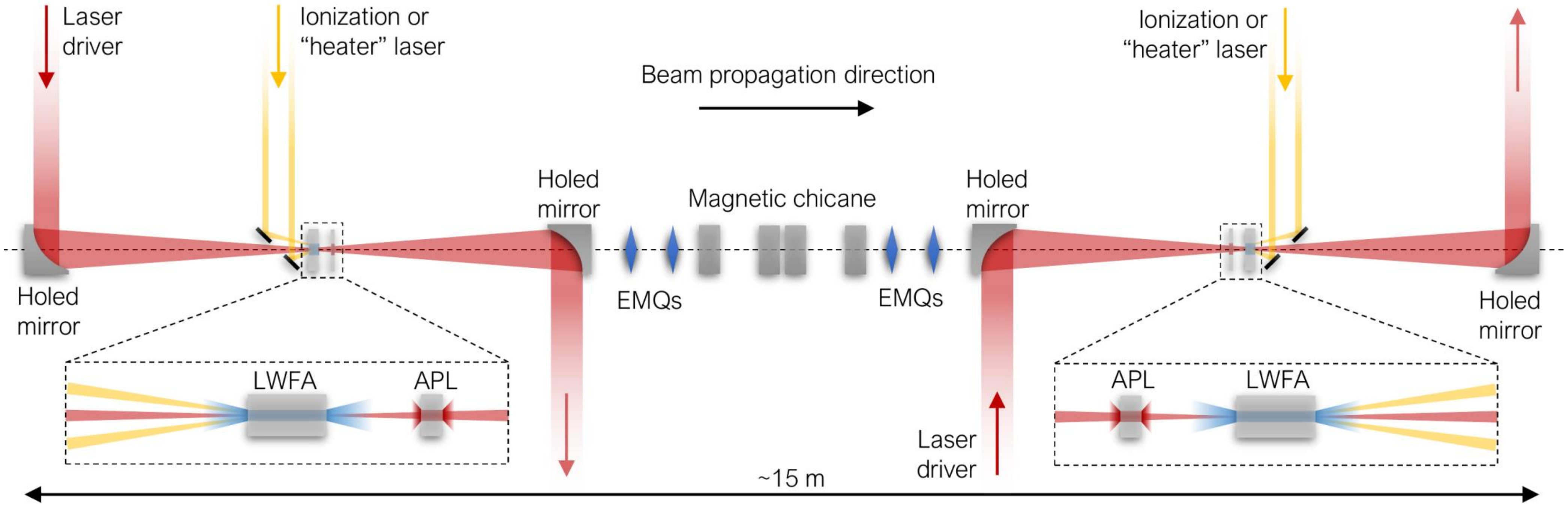
Multistage concept **chosen as a baseline option** in **EuPRAXIA CDR**

Conceptual design of a 1 GeV beamline at SINBAD

A lower energy design with current technology

- **1 GeV** beamline design with **5 J** (2x2.5 J) laser system.
- **11 pC** beam based on **ARES** parameters.
- Use **conventional** mirrors.
- More **realistic** plasma profiles based on fluid **simulations** [*].

Start-to-end simulations show good performance:
- **1 GeV** energy.
- **sub-micron** emittance.
- **sub-percent** energy spread.
- **≲0.1%** slice energy spread.



[*] From G. Bagdasarov (Keldysh Institute of Applied Mathematics)

Conclusion

- This **multistage approach** to plasma acceleration provides a new path towards ultra-low energy spread.
- Could deliver **multi-GeV** beams with **sub-permille energy spread** and **sub-micron emittance**.
- Possible path towards **compact and cost-effective FELs**.
- Potential issues such as CSR and space-charge **do not have significant impact**.
- Chosen as **baseline option** for 5 GeV plasma-based FEL in the **EuPRAXIA CDR**.
- Conceptual designs at lower energy (1 GeV) and currently-available laser technology also possible.

Thank you!