Multistage Plasma Accelerator for GeV, ultra-low energy spread beams

Preliminary design for a 1 GeV beamline

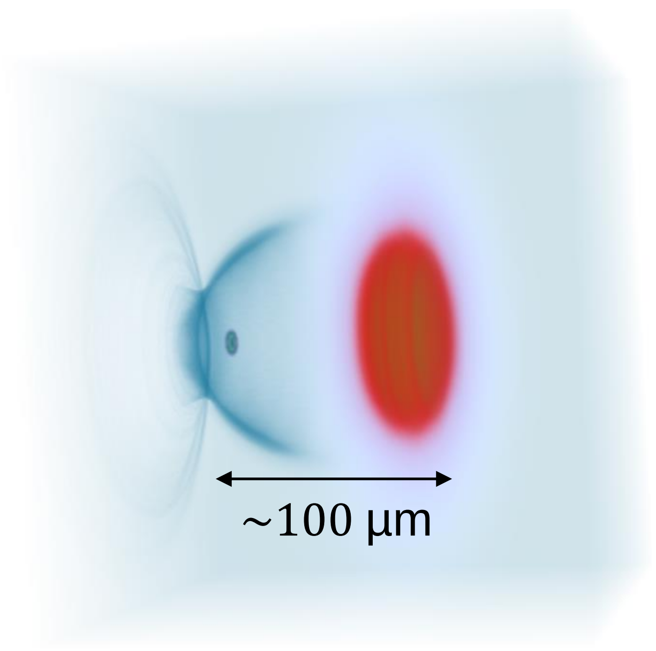
<u>Ángel Ferran Pousa</u>, A. Martinez de la Ossa, R. Brinkmann, R. Assmann.

EAAC 2019, WG6-8 joint session, 18/09/19

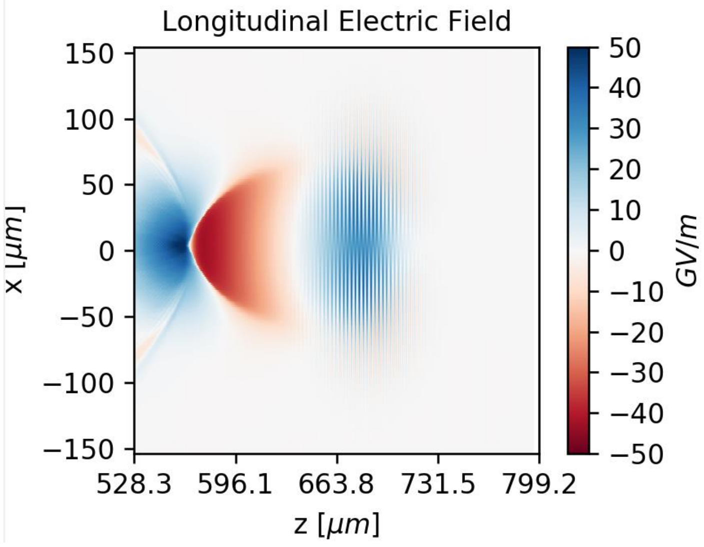
Introduction

Plasma accelerators and energy spread

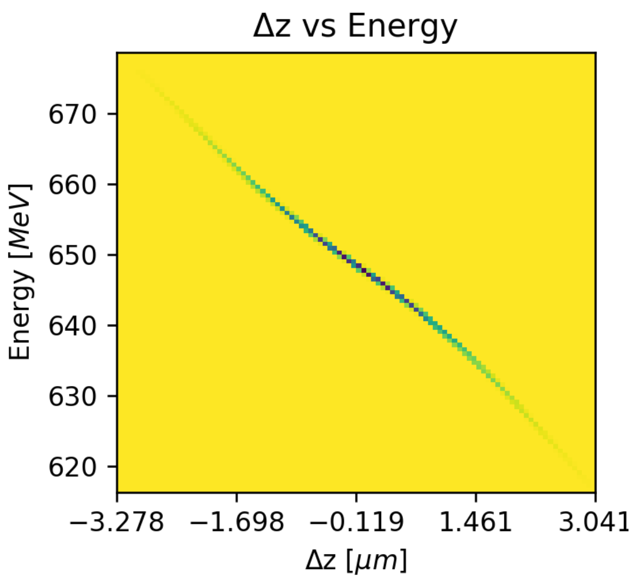
An intense **laser pulse** or **charged particle** beam is injected into a gaseous plasma.



Extreme accelerating fields **(~100 GV/m)** with short wavelength **(~100 μm)** are generated behind the driver.

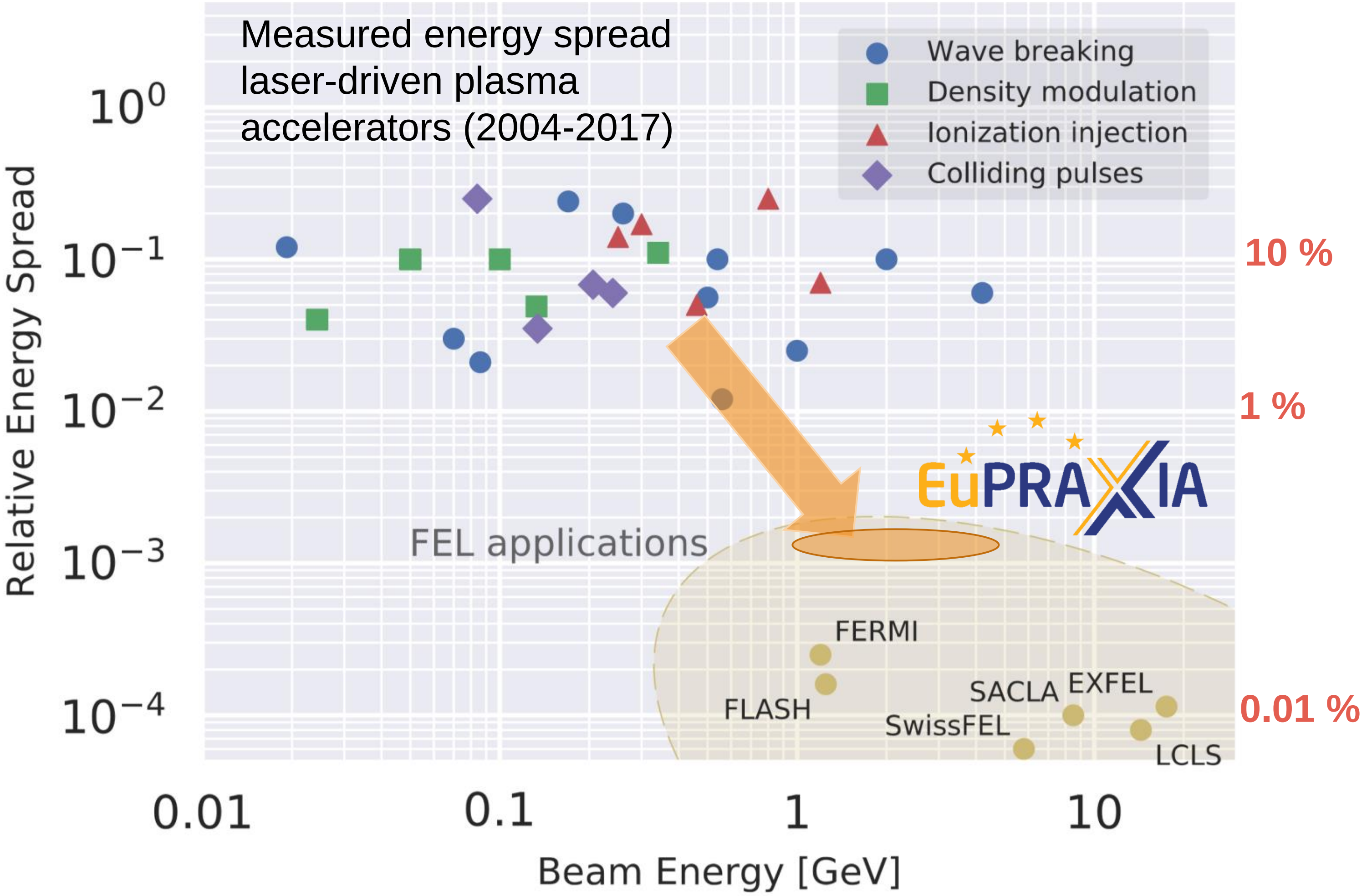


Accelerated beams develop a **large correlated energy spread** (typically 1-10%)



Introduction

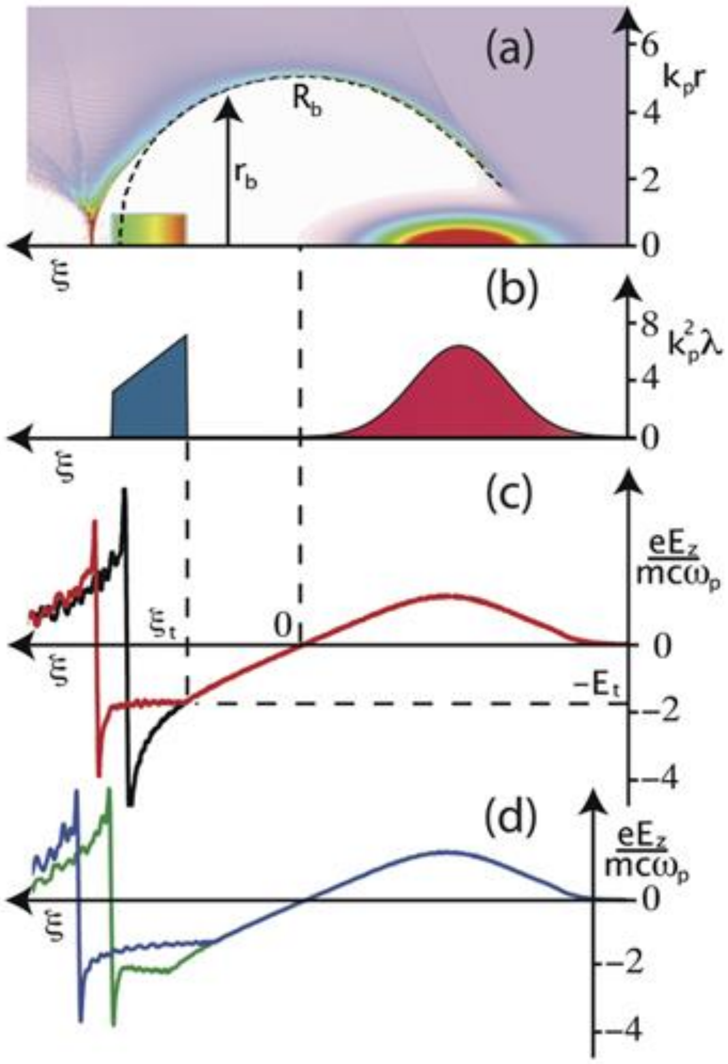
Energy chirp is one of the main reasons for high energy spread in plasma accelerators



Mitigating the energy chirp

Proposed methods

[M. Tzoufras et al., PoP, 2009]



Beam loading

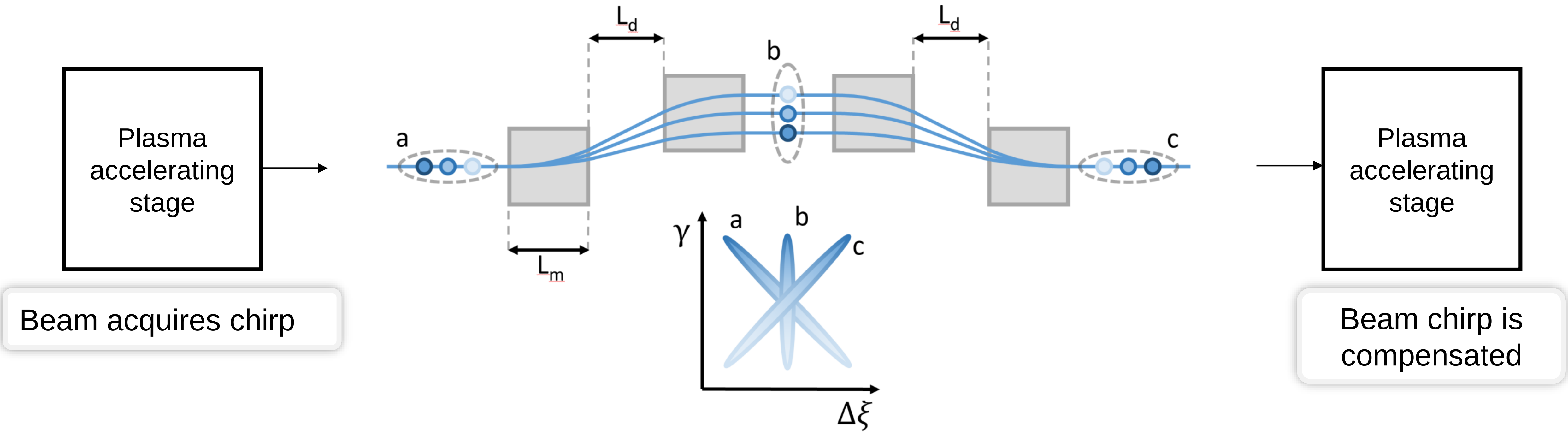
- Flatten the accelerating fields with the witness bunch itself.
- Problems:
  - Requires particular current profile. Challenging to obtain.
  - Depends on acceleration phase (high sensitivity, dephasing in laser-driven cases)
  - Not demonstrated yet with desired performance.

Other proposals

- Modulated [R. Brinkmann et al., 2017, PRL] or tailored [A. Döpp et al., 2018, PRL] plasma density profiles.
- Injection of a second bunch. [G. Manahan et al., 2017, Nat. Comm.]
- Plasma dechirper. [D'Arcy et al, 2019, PRL; V. Shpakov et al, 2019, PRL; Wu et al, 2019, PRL]
- Use shorter bunches.

How about taking advantage of the energy chirp?

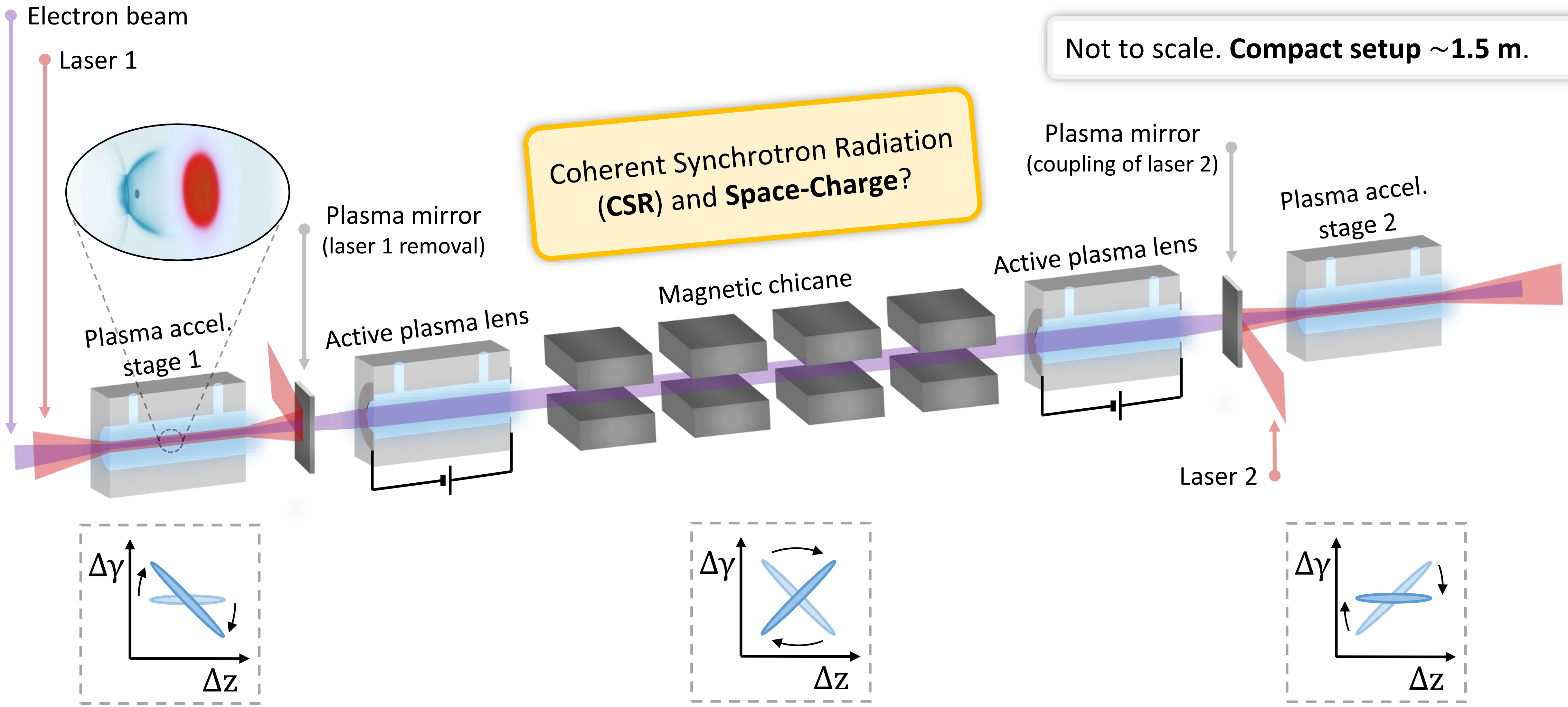
- Energy chirp naturally occurs in plasma accelerators.
- Improves beam stability (hosing mitigation) via BNS damping. [T. Mehrling et al., PRL, 2017; R. Lehe et al., PRL, 2017]
- Offers new possibilities for achieving low energy spread beams:



New scheme for energy chirp compensation

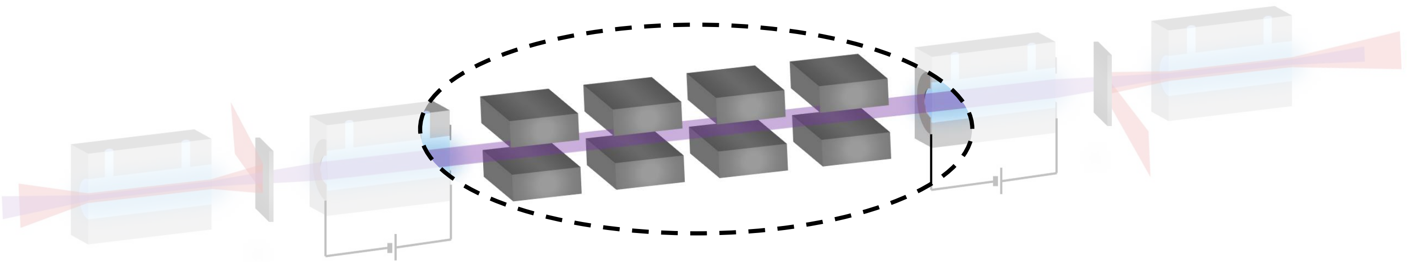
Acceleration in two stages with a magnetic chicane

Not to scale. **Compact setup ~1.5 m.**

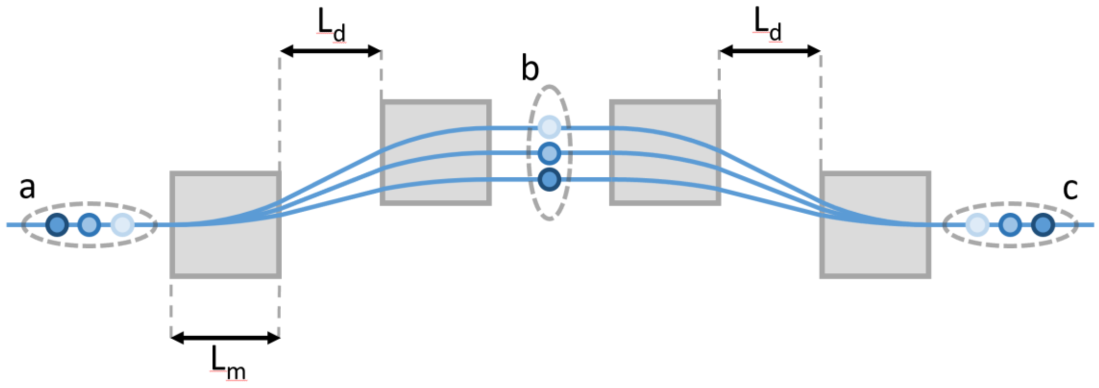


Potential issues

CSR and SC in the chicane



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

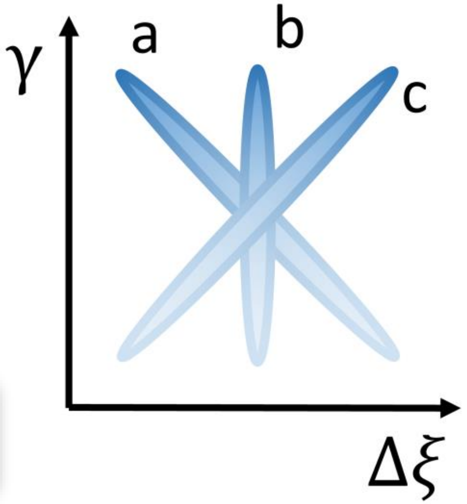


Space charge

- **GeV energy**, **~10 pC charge** and **small distance** minimize its impact.
- ASTRA simulations show negligible influence.

Coherent synchrotron radiation

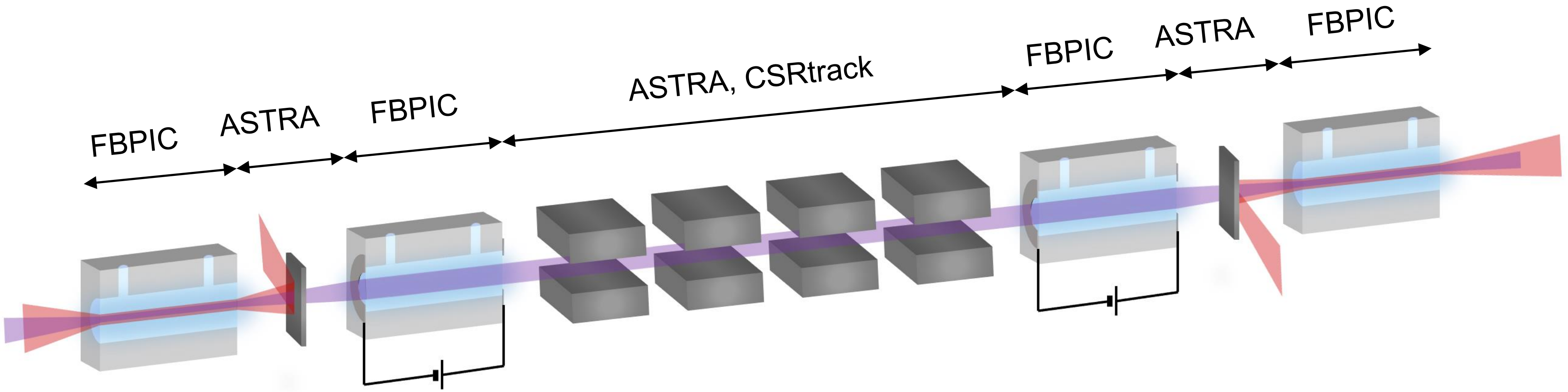
- Very **small bending angle** is needed to invert the beam ($\theta < 1°$), thanks to the **large energy chirp**.
- CSRtrack simulations also show negligible impact on the beam parameters.



Space charge and CSR are not an issue

Start-to-end simulations

Setup parameters for a 5 GeV accelerator



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

Laser pulses
E = 40J
a_0 = 3
w_0 = 50 µm
τ_{FWHM} = 50 fs

Plasma stages
$n_p = 10^{17}$ cm^{-3}
Parabolic profile
L_p = 8 cm

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

Chicane
R_{56} = 0.067 mm
L_m = 20 cm
θ = 0.6°
B = 0.54 T
L = 1.2 m

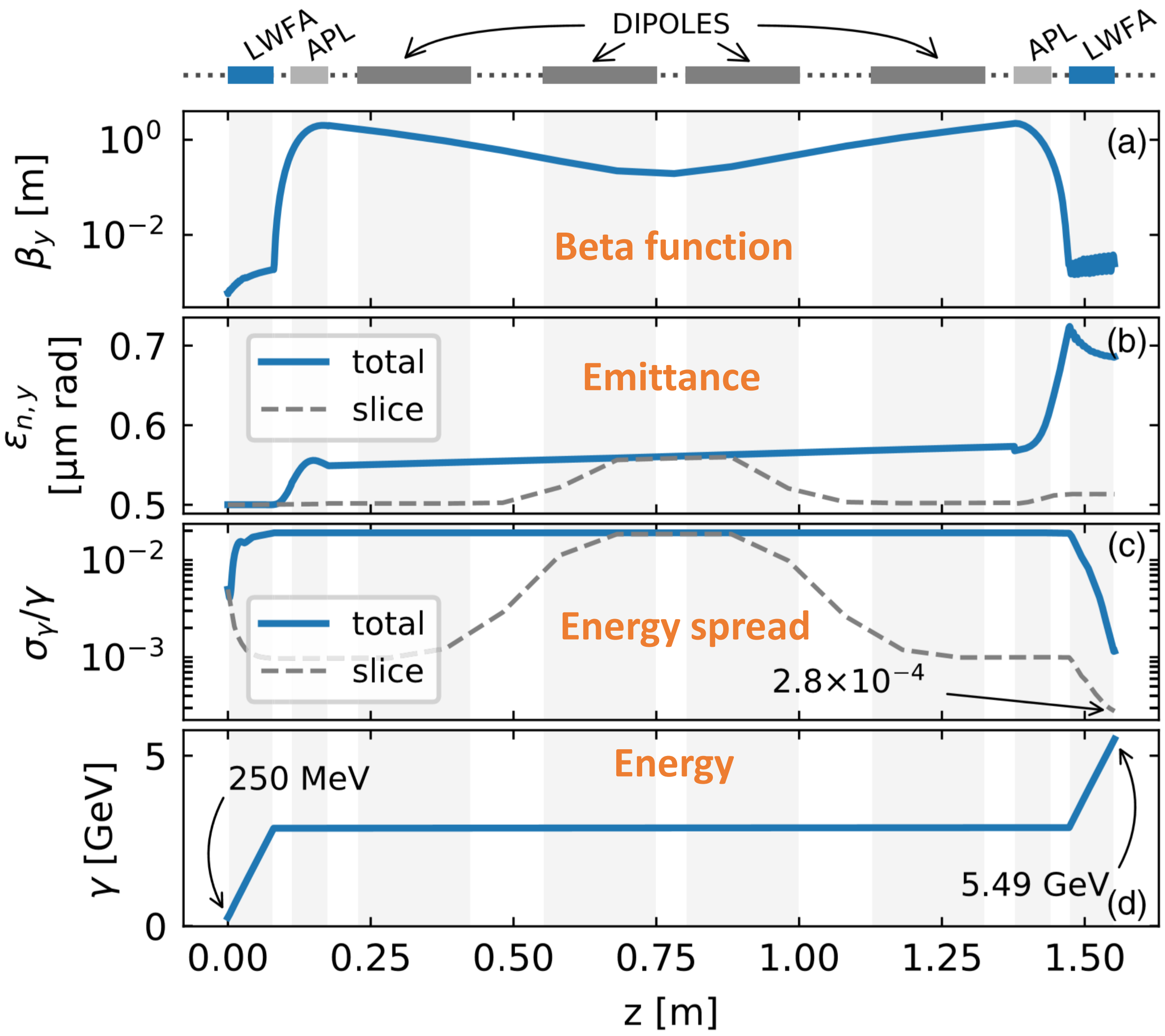
Based on simulations from J. Zhu
for possible ARES linac upgrade

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%** (0.1µm slice) or **2.8x10^-4^**
- Final energy of **5.5 GeV**.

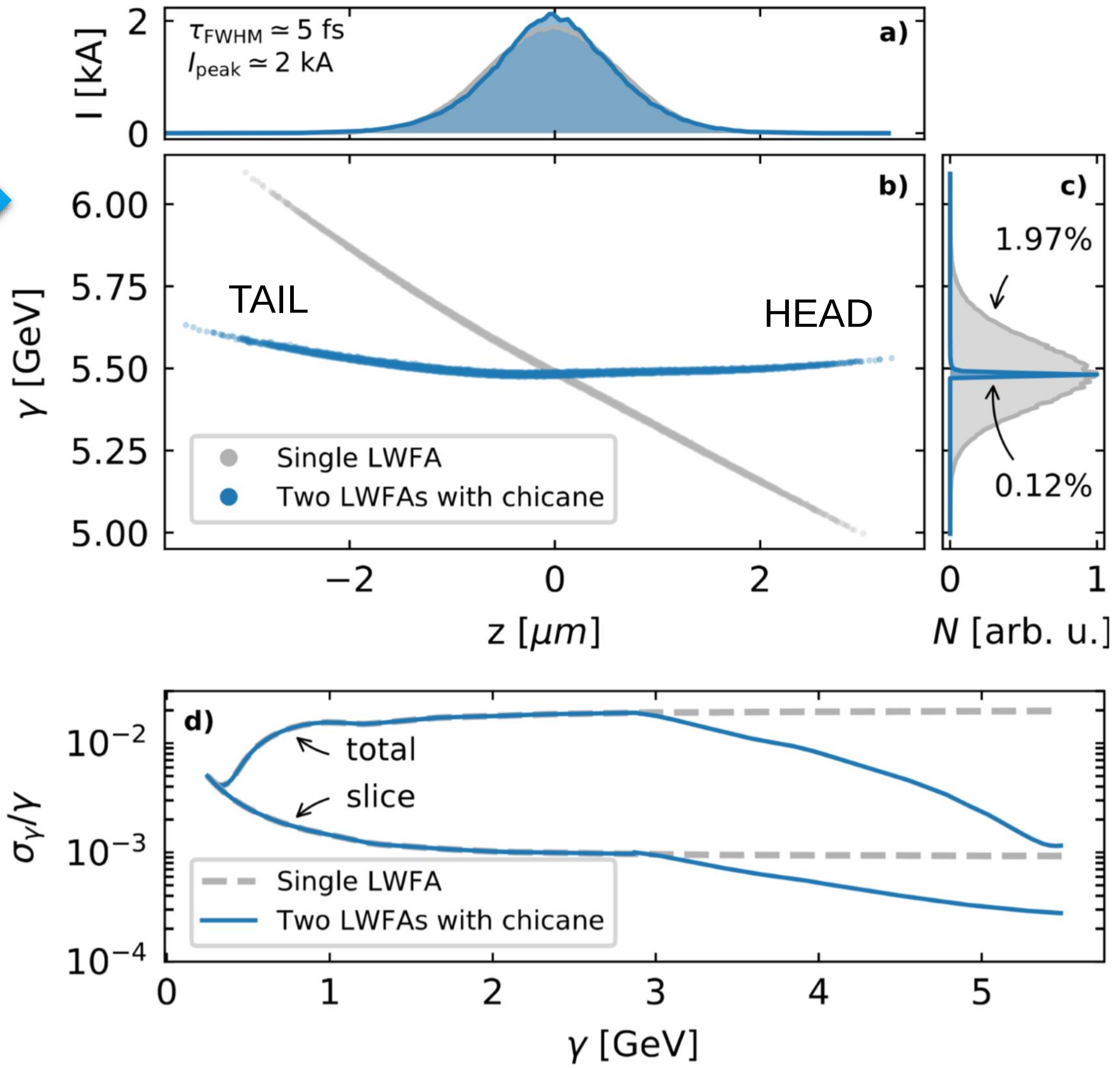
FEL-range values



Start-to-end simulations

Results compared against single-stage acceleration

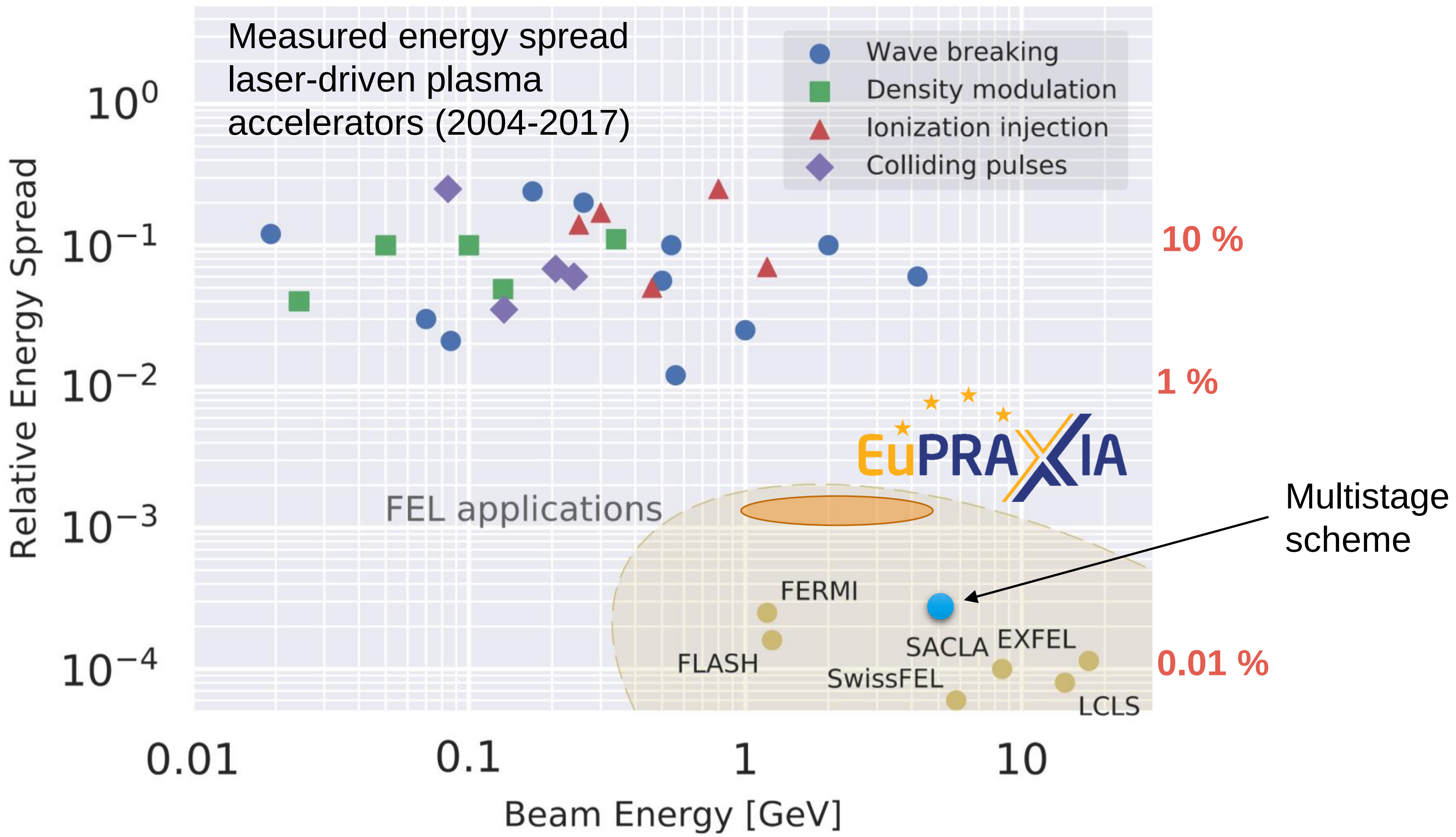
Final bunch, compared against a case with acceleration in a single stage



- Energy spread is **reduced by a factor 20**.
- Final beam is not flat in energy due to nonlinear contributions in the chicane (T_{566}).
- Current profile is maintained.
- This bunch would be well suited for FEL applications.

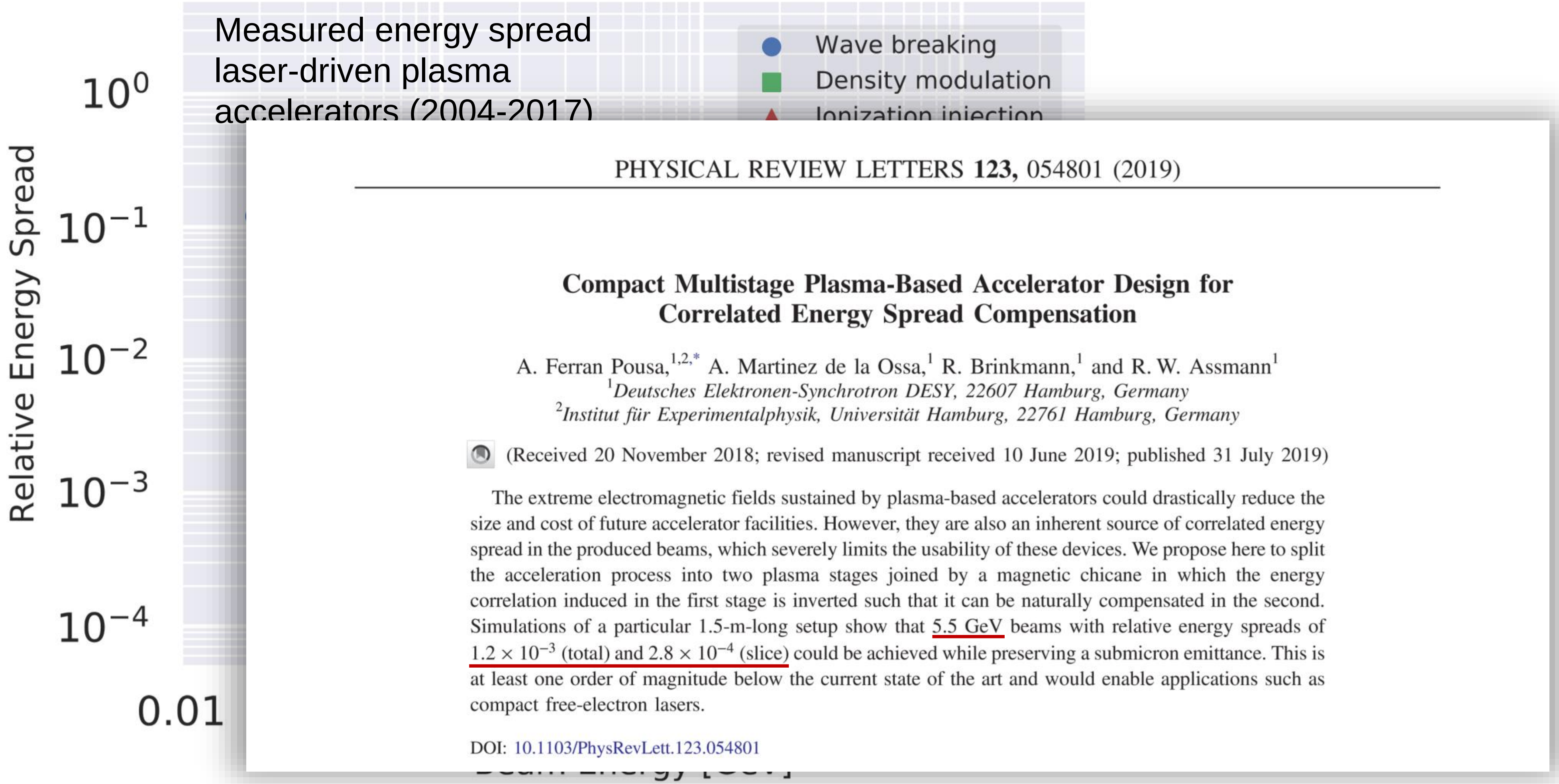
Comparison to current state-of-the art experiments

Beam parameters reach FEL regime



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

A. Ferran Pousa,[1,2,*] A. Martinez de la Ossa,[1] R. Brinkmann,[1] and R. W. Assmann[1]

[1]*Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany*

[2]*Institut für Experimentalphysik, Universität Hamburg, 22761 Hamburg, Germany*

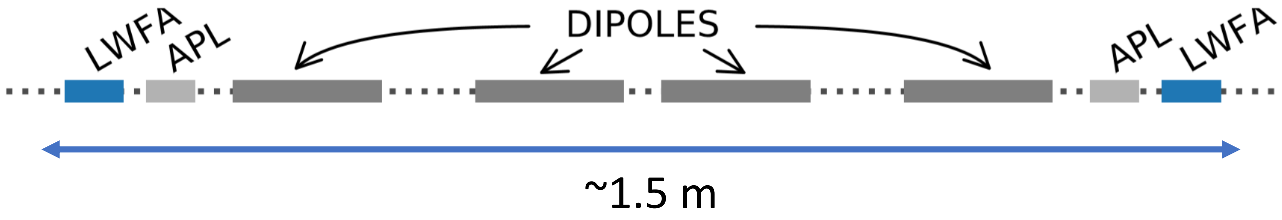
(Received 20 November 2018; revised manuscript received 10 June 2019; published 31 July 2019)

The extreme electromagnetic fields sustained by plasma-based accelerators could drastically reduce the size and cost of future accelerator facilities. However, they are also an inherent source of correlated energy spread in the produced beams, which severely limits the usability of these devices. We propose here to split the acceleration process into two plasma stages joined by a magnetic chicane in which the energy correlation induced in the first stage is inverted such that it can be naturally compensated in the second. Simulations of a particular 1.5-m-long setup show that 5.5 GeV beams with relative energy spreads of 1.2×10^{-3} (total) and 2.8×10^{-4} (slice) could be achieved while preserving a submicron emittance. This is at least one order of magnitude below the current state of the art and would enable applications such as compact free-electron lasers.

DOI: 10.1103/PhysRevLett.123.054801

Beyond the first conceptual beamline design

Proof-of-principle layout (to scale)

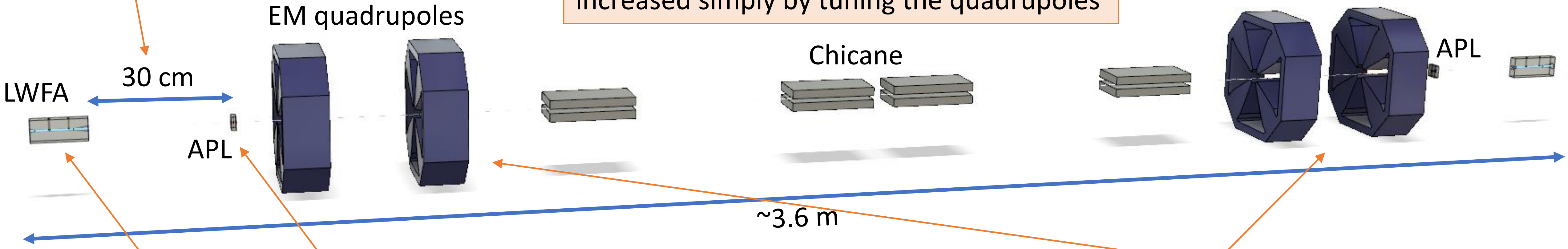


Very <u>compact</u> but:
- Short drifts.
- No space for diagnostics.
- Beam transport relies only on APLs.
- …

Layout proposal for EuPRAXIA

Additional space for laser removal

More space for diagnostics. Can be further increased simply by tuning the quadrupoles



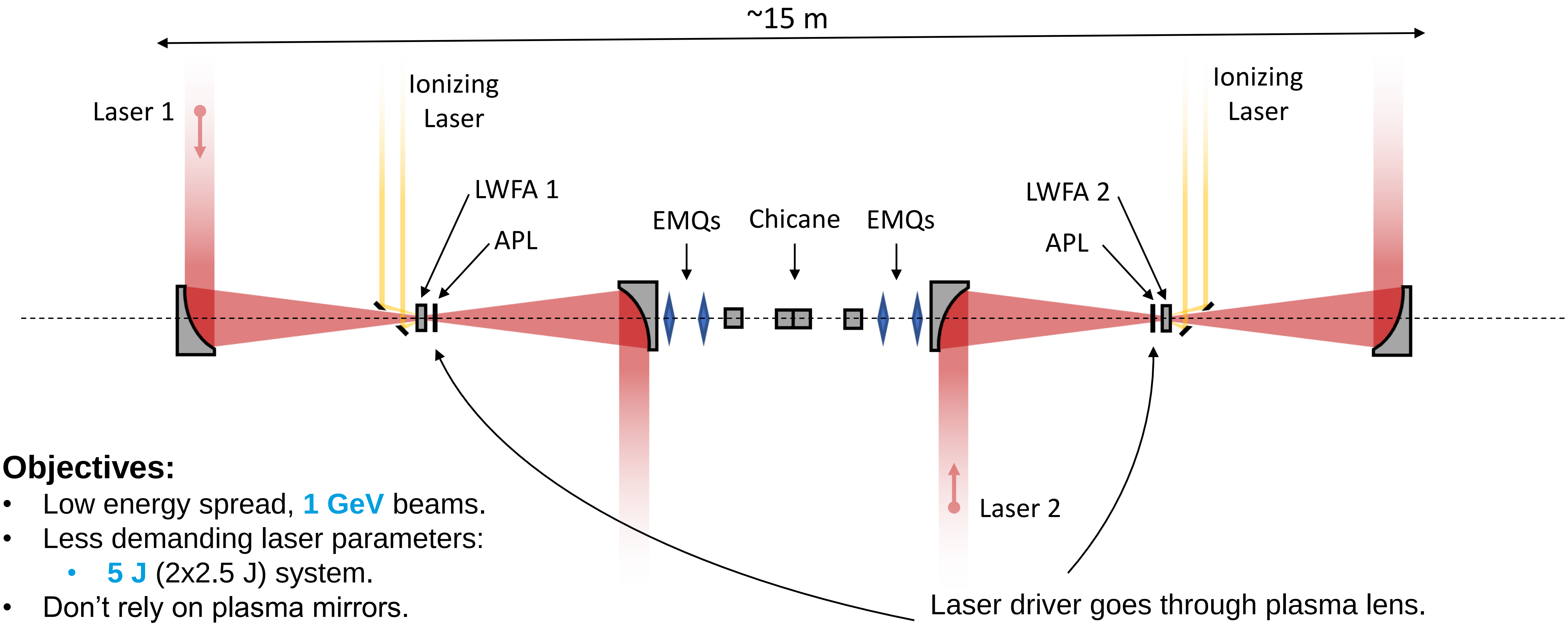
Plasma up- and downramps are now simulated

Much shorter APLs than before (6 vs 1 cm)

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

Beyond the first conceptual beamline design

A (very preliminary) proof-of-concept 1 GeV design



Objectives:

- Low energy spread, **1 GeV** beams.
- Less demanding laser parameters:
  - **5 J** (2x2.5 J) system.
- Don't rely on plasma mirrors.
- Enough space for diagnostics.
- Possible implementation at SINBAD.

Laser driver goes through plasma lens.

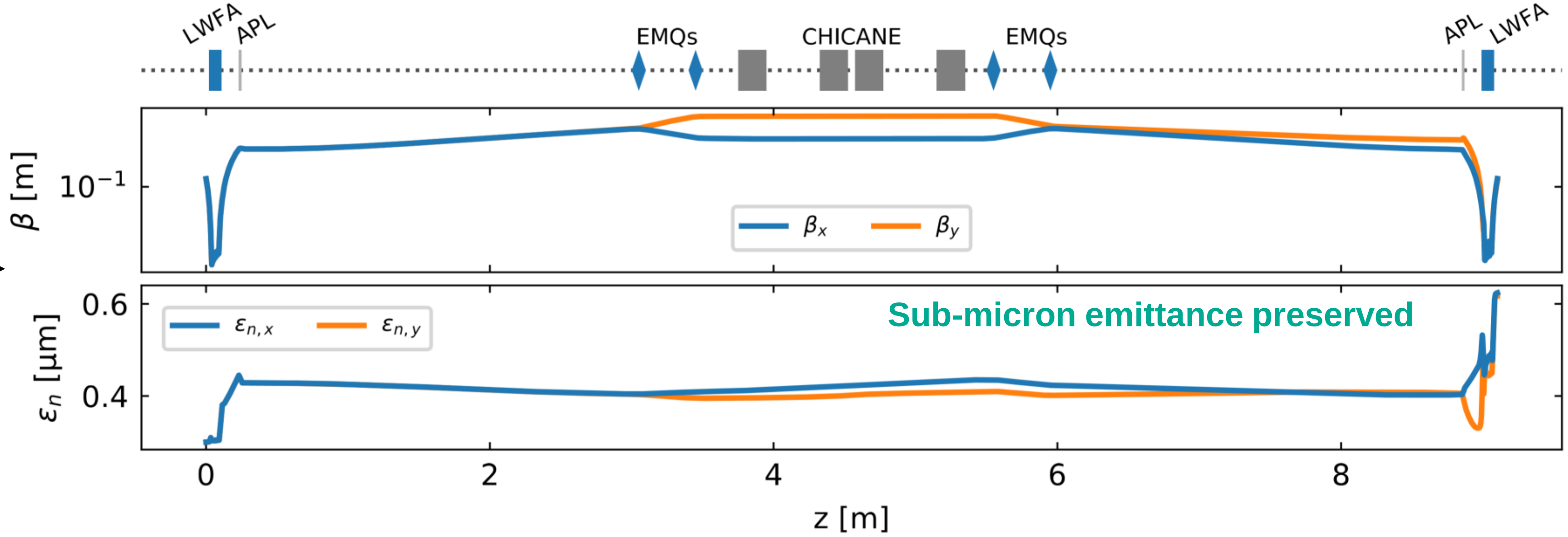
- w_0 ~ 1mm, a0~0.04, induced focusing fields <<1 T/m
- Few-mm capillary radius needed (achieved 600 T/m with 14 mm aperture [M. Steeter, 1992, Proc. 3rd EPAC])

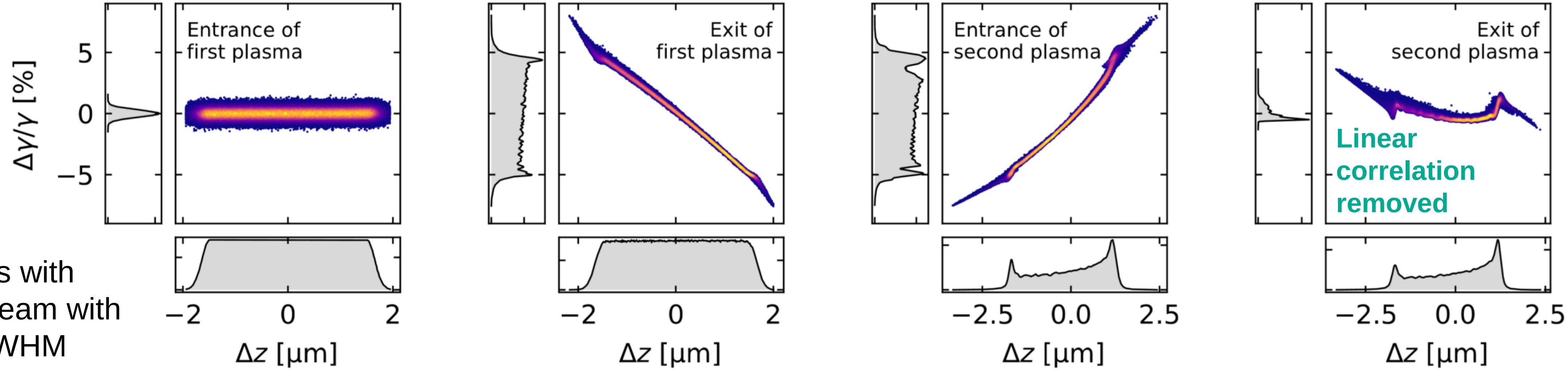
1 GeV beamline

Start-to-end simulations with idealized beam

Transport along beamline

Longitudinal phase-space evolution



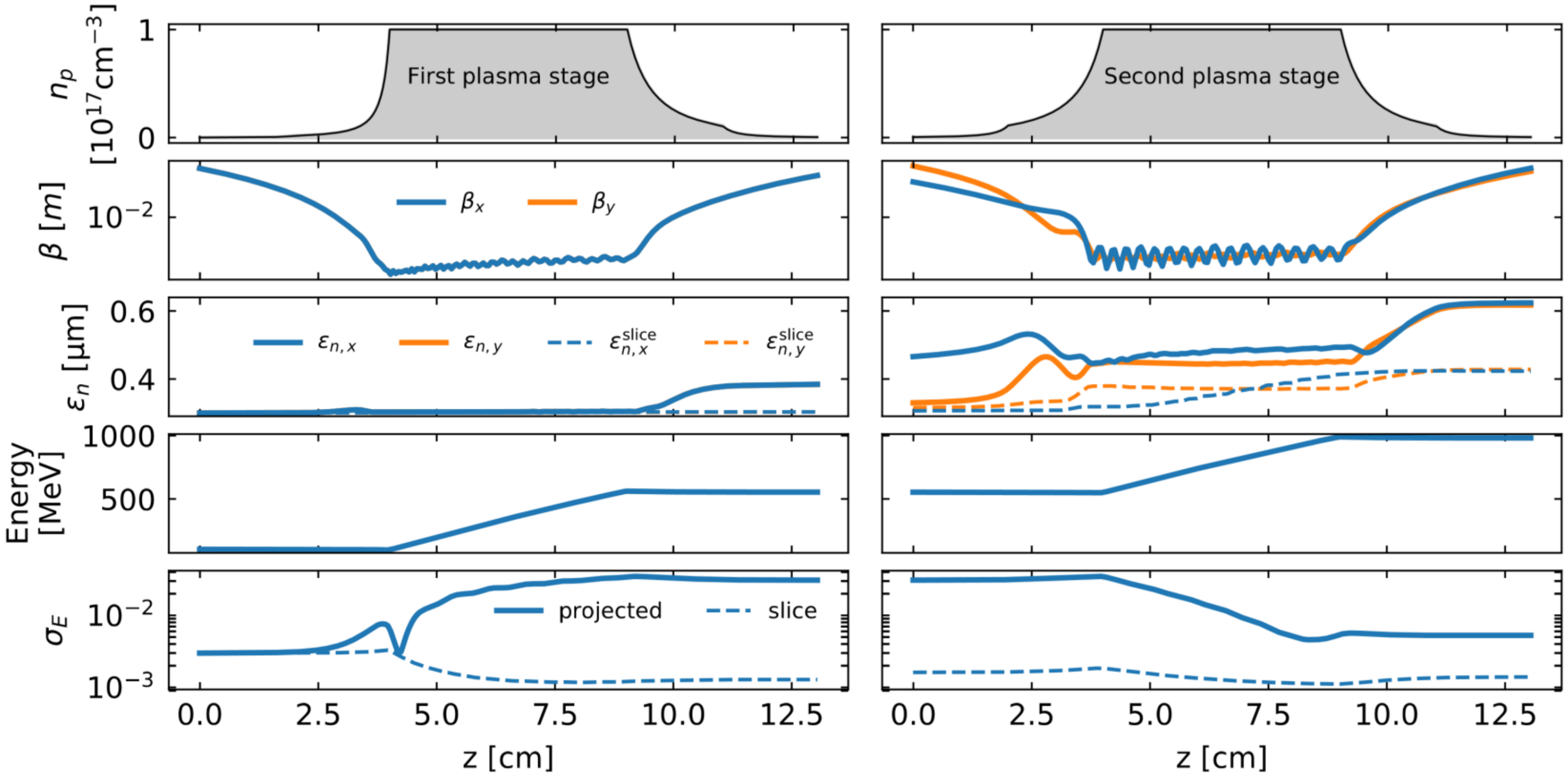


First tests with flat-top beam with ~10 fs FWHM

1 GeV beamline

Beam evolution on each plasma stage

Due to large peak at head and tail. In general ~1 kA.



Initial vs final beam parameters:

	Initial	Final
Q [pC]	11.3	11.3
σ_z [fs]	3.3	3.3
I_p [kA]	1	2.6
$\varepsilon_{n,x}$ / $\varepsilon_{n,y}$ [µm]	0.3 / 0.3	0.62 / 0.62
$\varepsilon_{n,x}$ / $\varepsilon_{n,y}$ (slice*)	0.3 / 0.3	0.43 / 0.43
Energy [GeV]	0.1	1
σ_E [%]	0.3	**0.5**
σ_E (slice*) [%]	0.3	**0.14** (avg) / **0.06** (best)

*100 nm slices

Based on parameters achievable by the ARES lineac

Achieved **1 GeV** final energy with **sub-micron emittance**, **sub-percent total energy spread** and **sub-per-mille slice energy spread**

Conclusions

- A **new scheme for chirp mitigation** in plasma accelerators has been presented.
- With this method, the beam is **dechirped while being further accelerated** and **preserving its emittance**.
- Potential issues such as **CSR** and **SC** have been shown to have **negligible impact**.
- Simulations show that **FEL-ready beams** could be produced, with **multi-GeV** energy, sub-micron emittance and **sub-per-mille energy spread**.
- Presented preliminary **1 GeV beamline** with less stringent requirements, feasible with current laser systems.
    - **Successful coupling of multiple plasma stages** with ~10 m separation.
    - **Sub-micron emittance**, **sub-percent energy spread** and up to **sub-permille slice energy spread**.

Thank you