First Optimization of Plasma Wakefield Acceleration in Virtual FLASHForward▸▸

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HELMHOLTZ

AfLS and AfPS 2024

Lascala
Erasmus Mundus Master

DESY.

Search for New Physics

Acceleration of particles to higher energies

Limitations of linear colliders: RF Cavities

- Limited accelerating fields less than 100MV/m
- Future colliders: tens of Kilometers

LHC

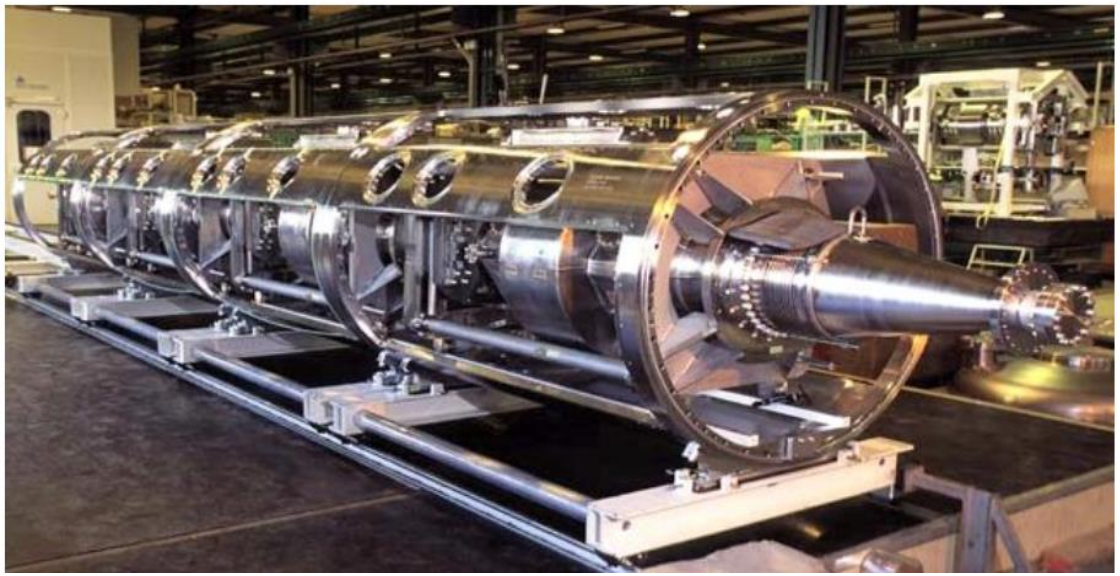


Image credit: E. Gschwendtner, CERN, 2019

195mm Plasma Cell at FLASHForward

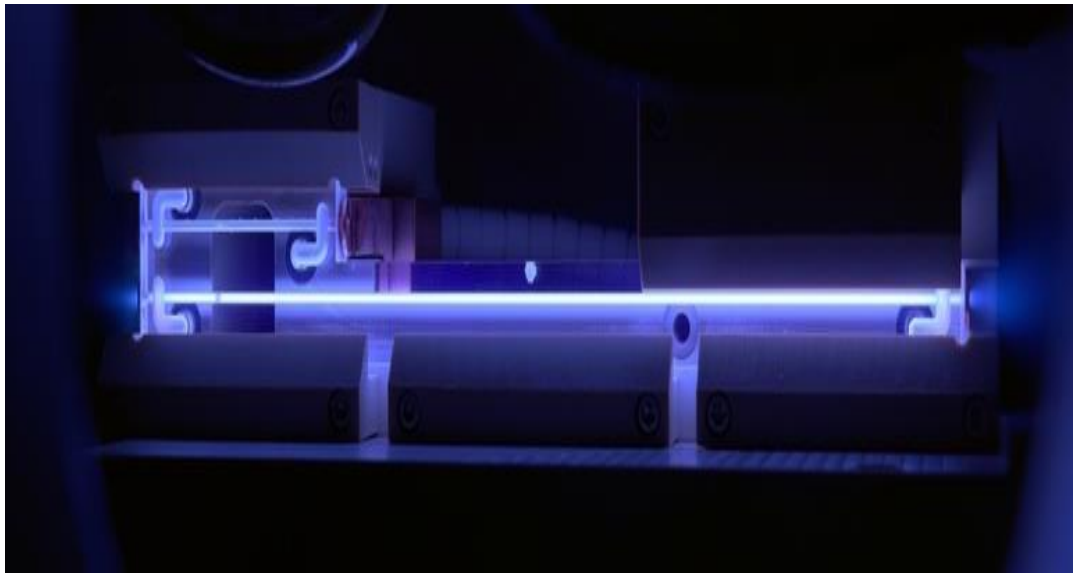


Image credit: C. Lindstrøm

Can we reach higher accelerating gradients and save costs at the same time?

Plasma and Plasma-Wakefield

Plasma: ions and electrons

- Ionized gas consisting of positive ions and free electrons in proportions

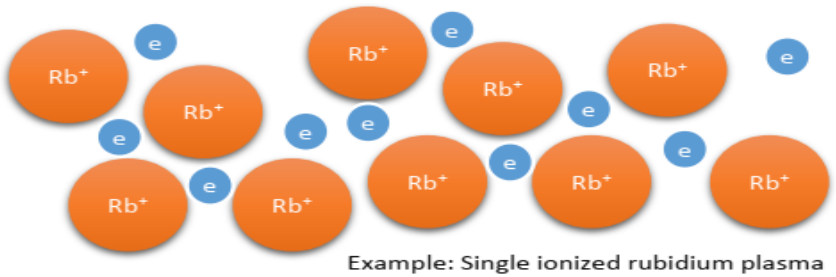


Image credit: E. Gschwendtner, CERN, 2019

Plasma-Wakefield

- Fields created from the collective motion of plasma charged particles

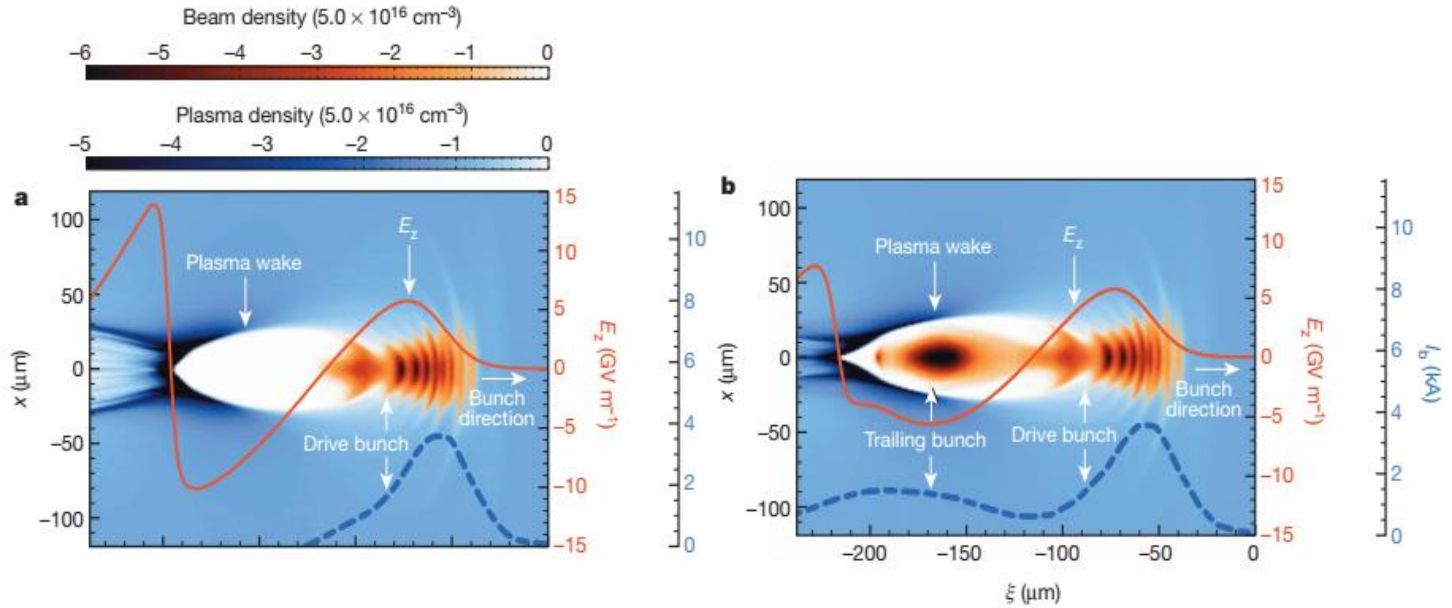


Image credit: M. Litos et al., Nature 515, 92 (2014)

Core Plasma Parameter

- Plasma density

$$E_z[\mathrm{V/m}] \approx 96\sqrt{n_0[\mathrm{cm}^{-3}]}$$

Plasma-Wakefield Acceleration

Image credit: E. Gschwendtner, CERN, 2019

Relation:

- Water ➡ Plasma
- Driving beam ➡ boat
- Trailing (accelerating) beam ➡ surfer

Plasma-Wakefield Acceleration:

- ~1000 stronger accelerating gradient than RF cavities
- High energy physics and photon science application

FLASHForward

Scientific goals at FLASHForward

Goal:

- **Develop a self-consistent plasma-accelerator stage**
  - with high-efficiency, high-quality, and high-average-power

- **High efficiency**
  - Beam loading
- **High beam quality**
  - Beam quality preservation
- **High average power**
  - High repetition rate

➡ **At high luminosity**

FLASHForward

SCIENTIFIC GOALS AT FLASHFORWARD

***Goal*:**

- **Develop a self-consistent plasma-accelerator stage**
  - with high-efficiency, high-quality, and high-average-power

This Project

- **High efficiency**
  - Beam loading
- **High beam quality**
  - Beam quality preservation
- **High average power**
  - High repetition rate

At high luminosity

FLASHForward FACILITY AT DESY

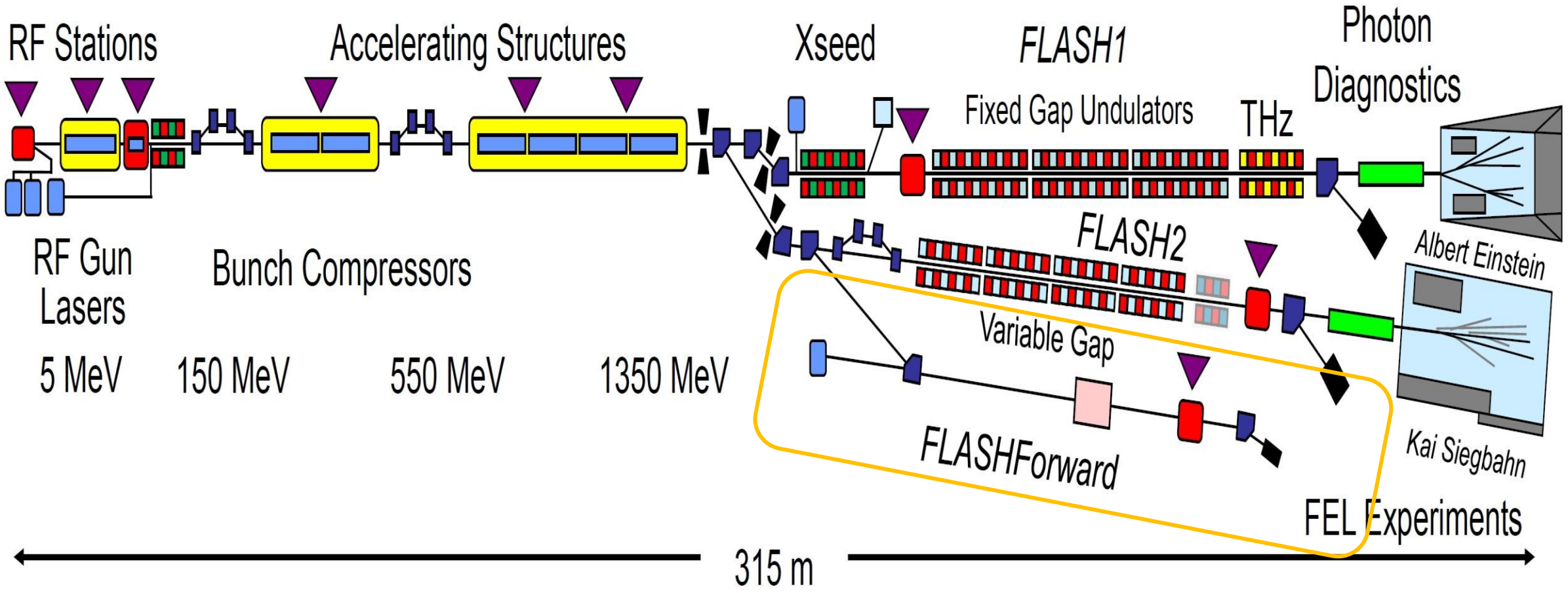
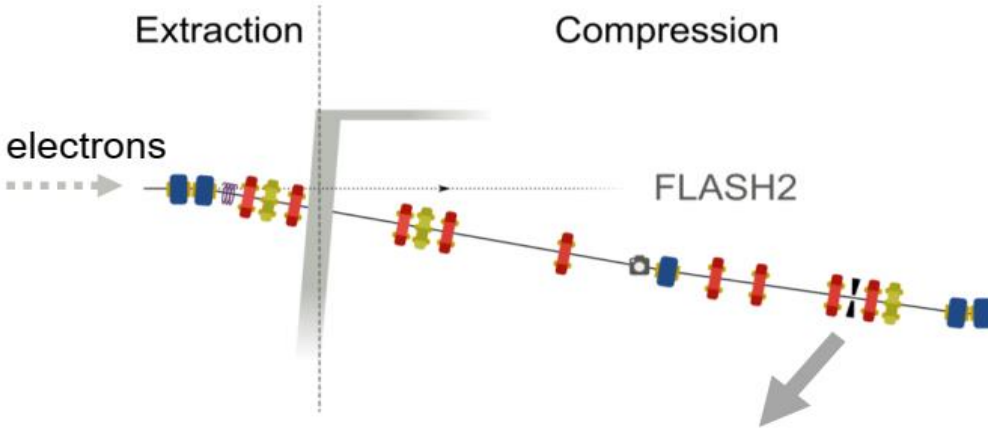
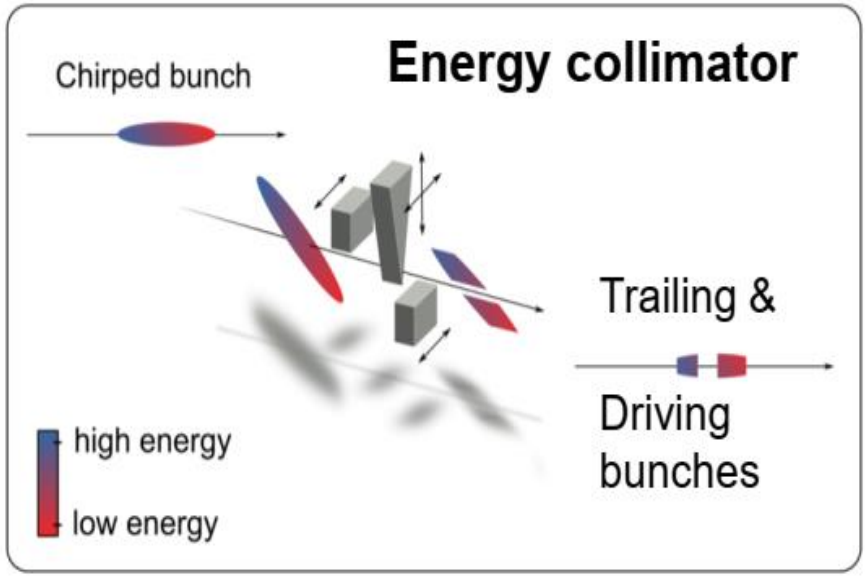


Image credit: Siegfried Schreibe

FLASHForward FACILITY AT DESY

PWFA Beamline



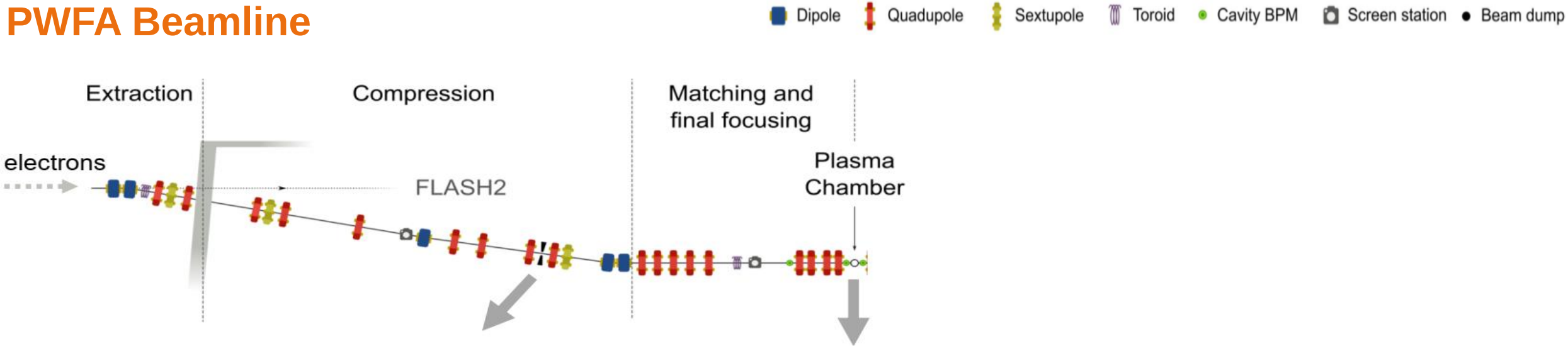


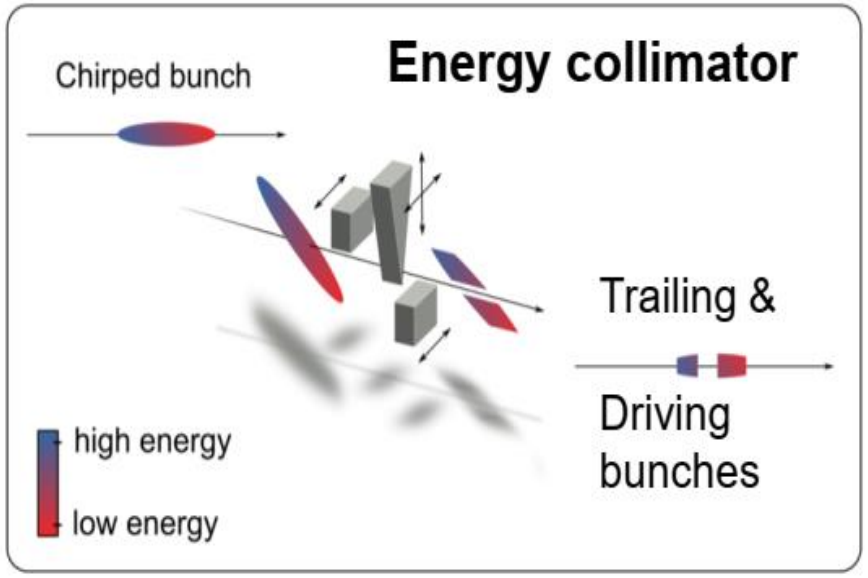
Dipole Quadupole Sextupole Toroid Cavity BPM Screen station Beam dump

S Schröder et al., J. Phys. Conf. Ser. 1596 012002 (2020)

FLASHForward FACILITY AT DESY

PWFA Beamline





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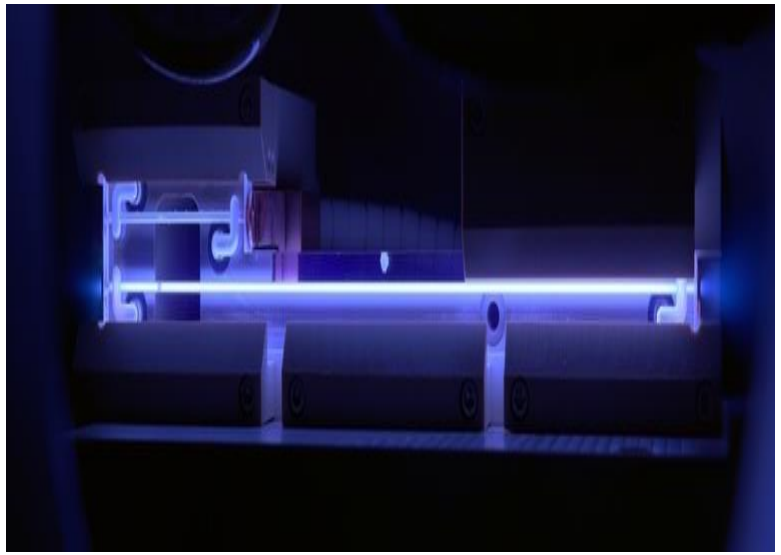
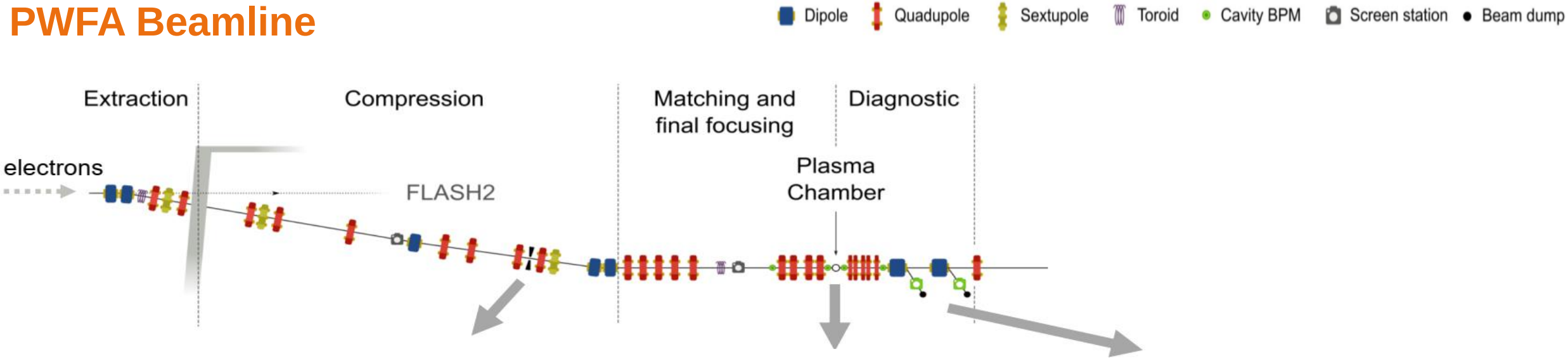
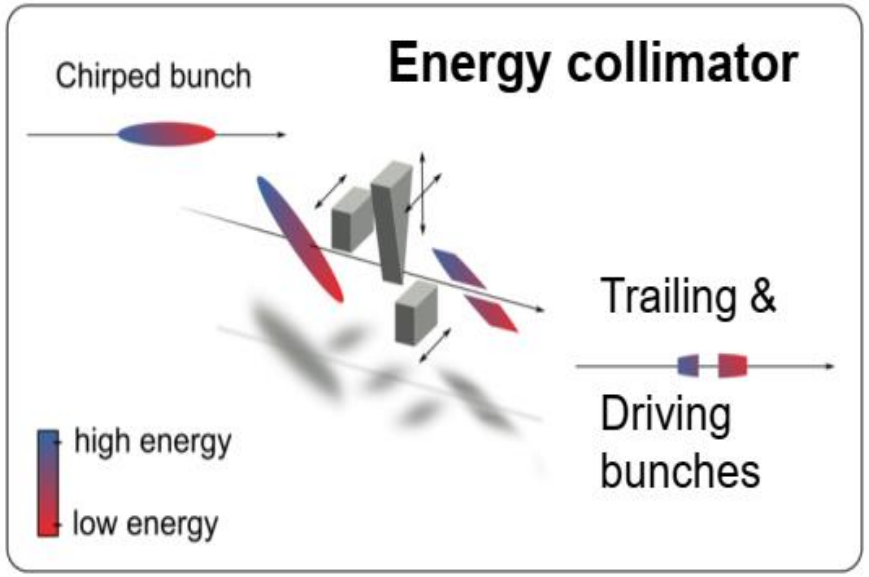


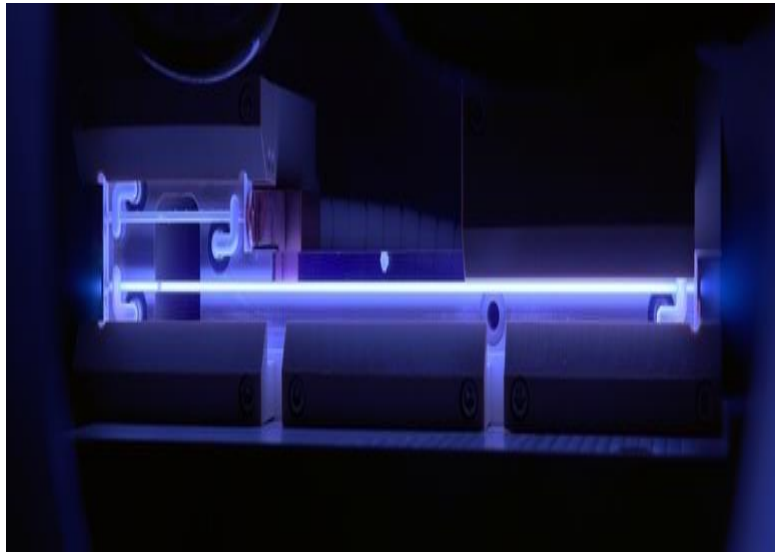
Image credit: C. Lindstrøm

FLASHForward FACILITY AT DESY

PWFA Beamline







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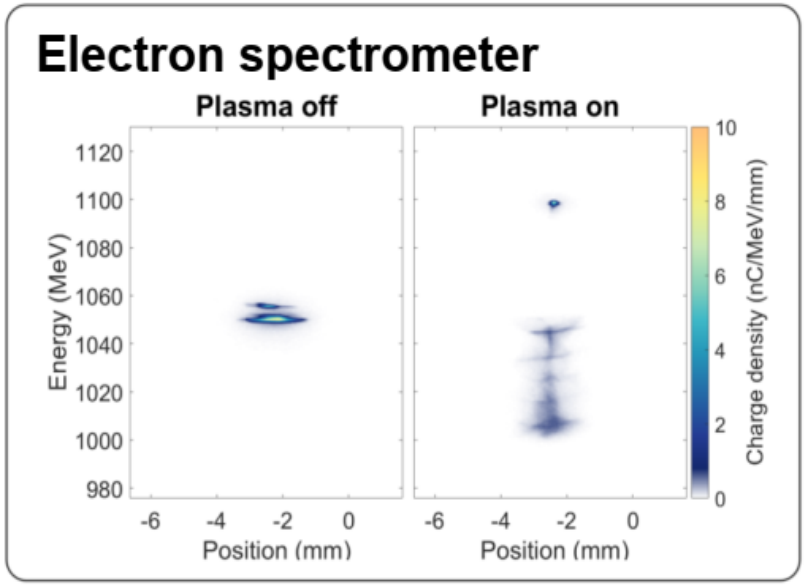


Image credit: J. Beinortaitė

S Schröder et al., J. Phys. Conf. Ser. 1596 012002 (2020)

Virtual FLASHForward

MAIN PURPOSE OF Virtual FLASHForward ▸▸

***Goal*:**

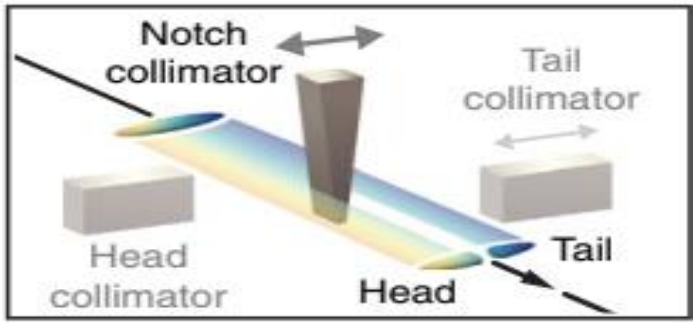
- **Virtually replicate FLASHForward experiments**
  - ➢ **Ocelot: tracking in the beam-line, Wake-T: plasma simulation**

- **Deeper experimental insights**
- **Artificial Intelligence and Machine learning**

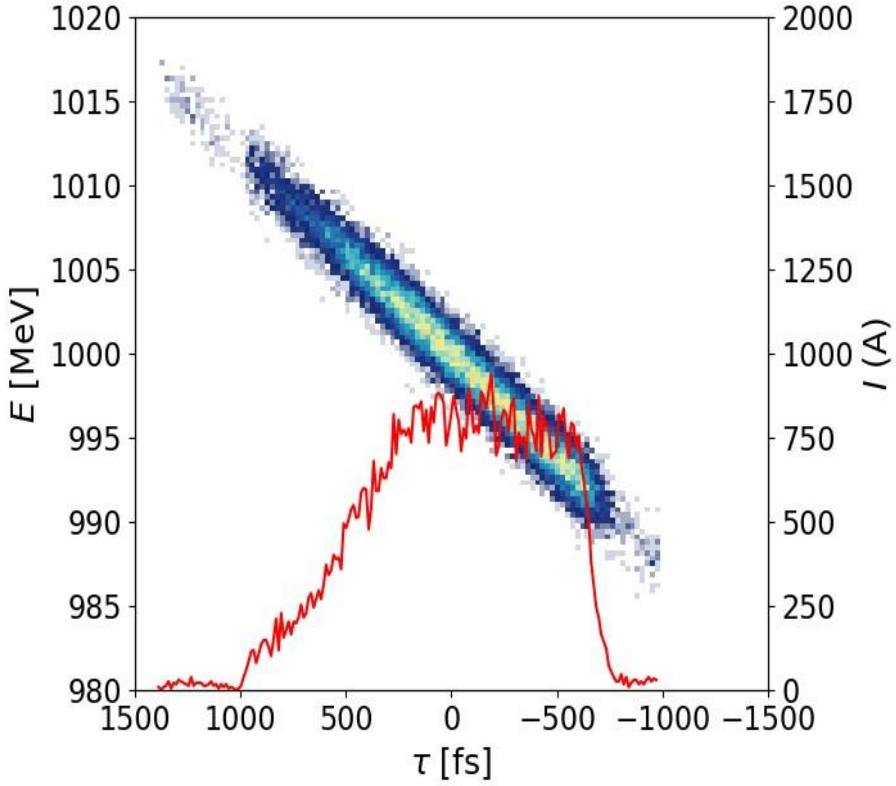
Tuning Parameters...

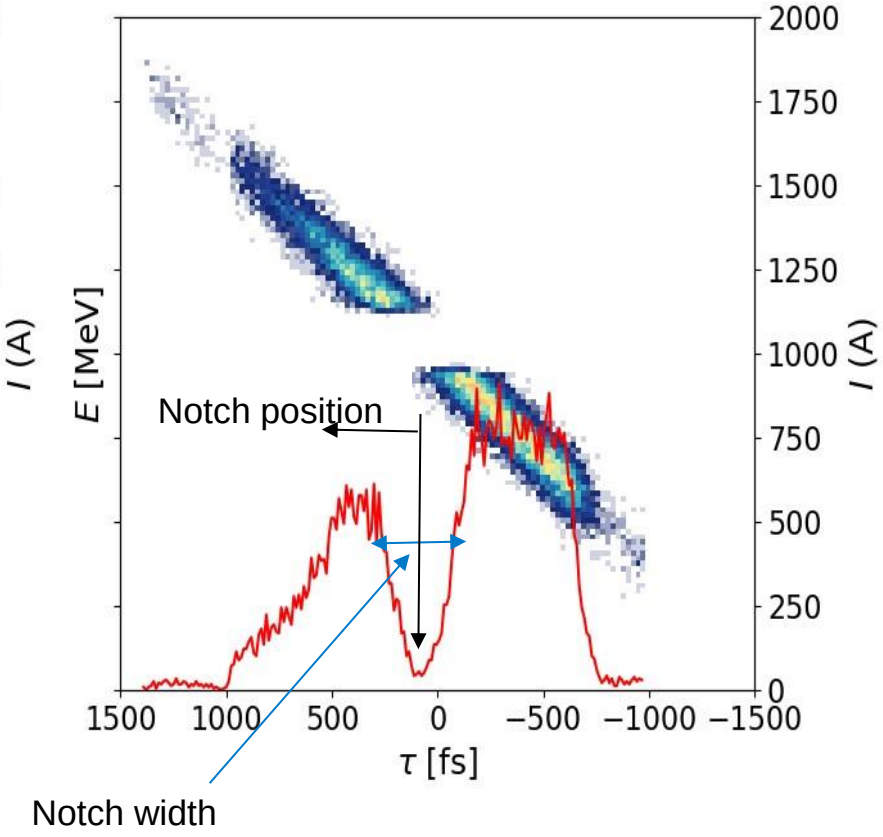
Notch Collimator

- Adjustable width and position
- Creates two bunches from an electron bunch:
  - Driving bunch
  - Trailing bunch



C. Lindstrøm et al., Phys. Rev. Lett. 126, 014801 (2021)





...Tuning Parameters

Plasma Density

- An idealized density profile

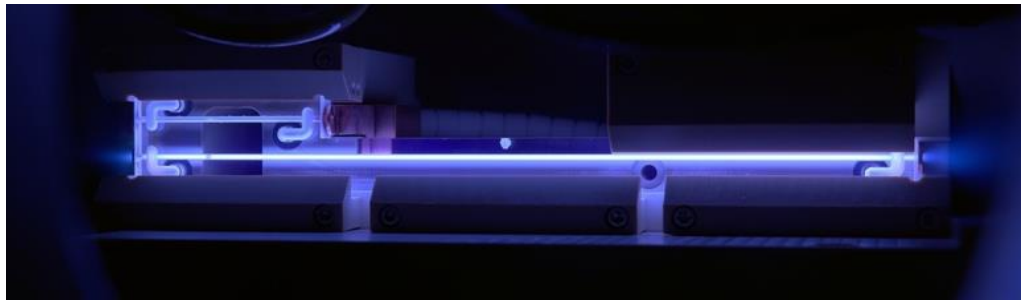
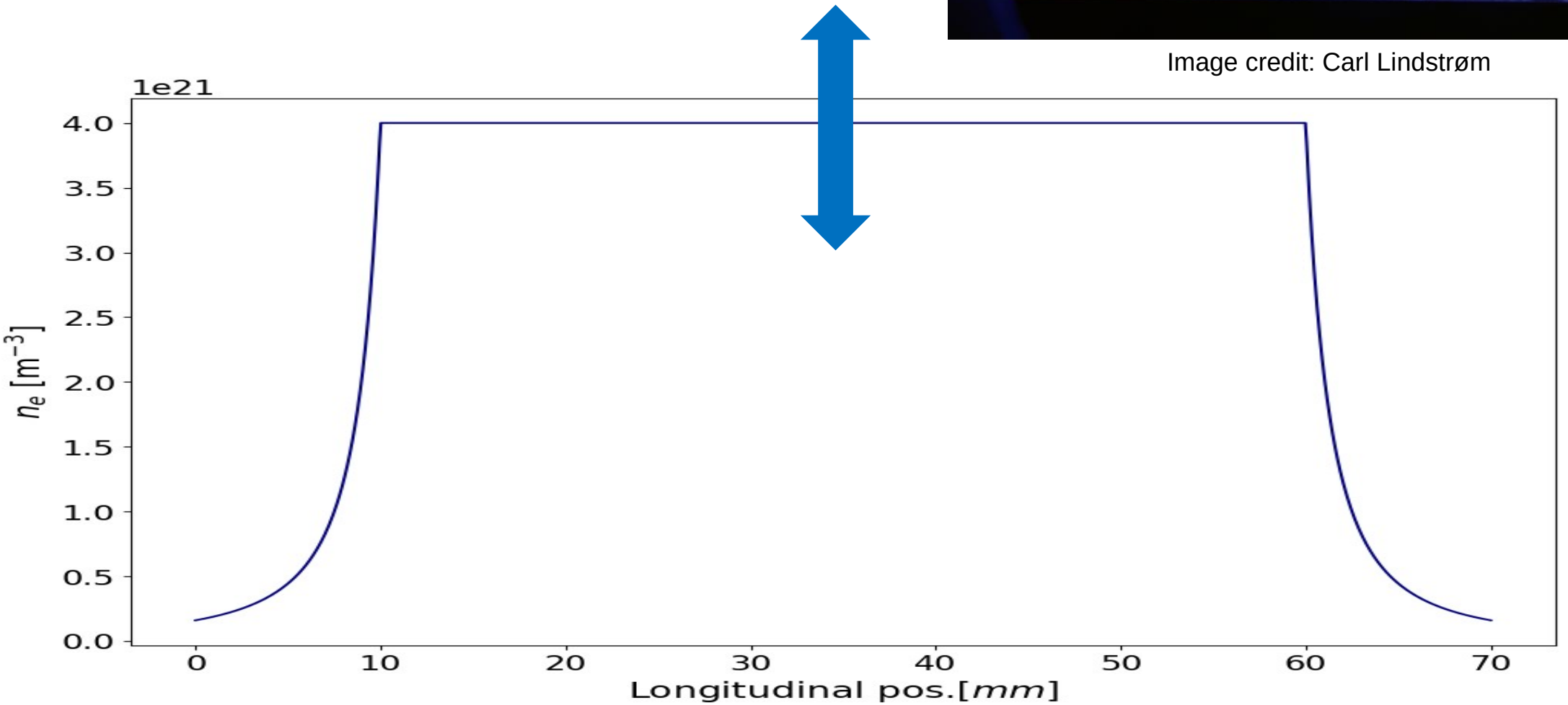


Image credit: Carl Lindstrøm



Analysis

Optimization Parameter, P

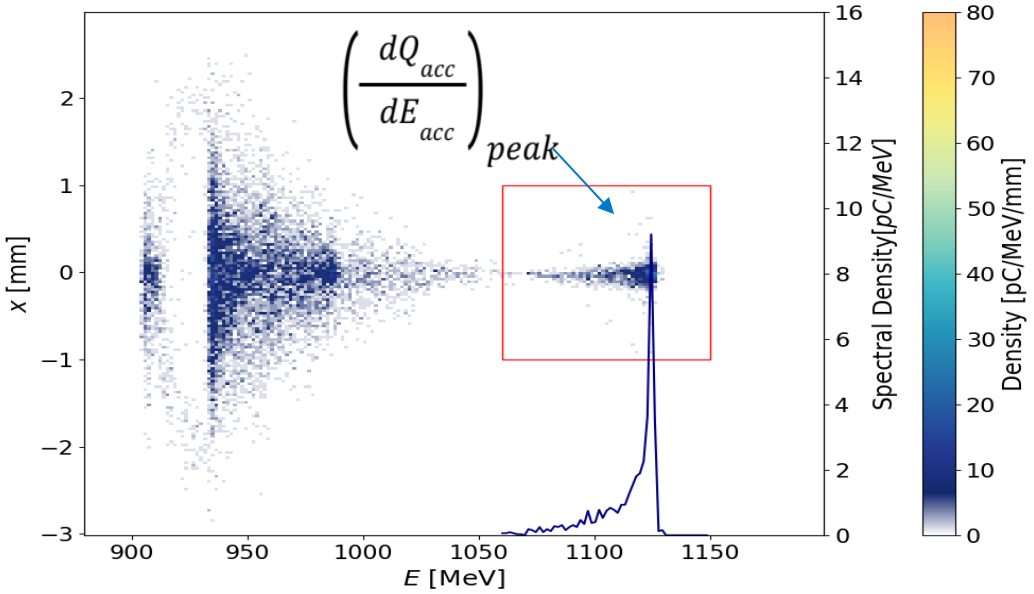
Energy-gain

$$P = \frac{\Delta E_{acc}^{2} * Q_{acc}}{\sigma_{E}}$$

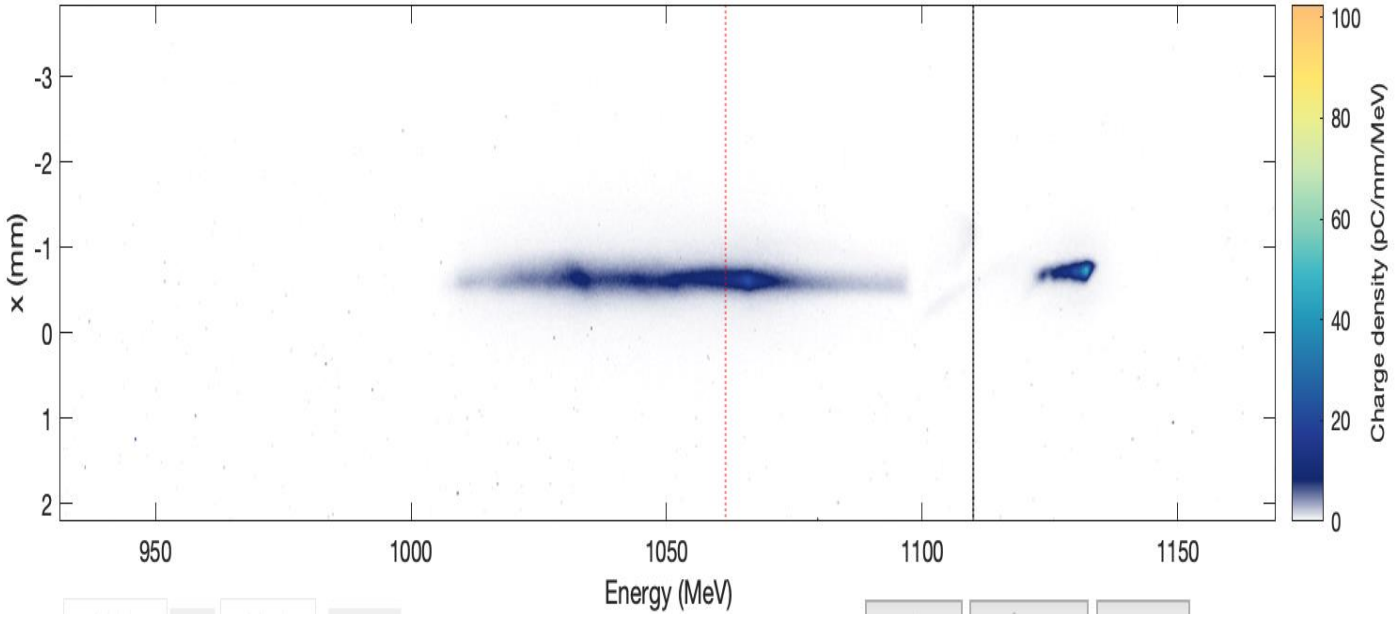
Witness charge

Energy-spread

Virtual ESPEC



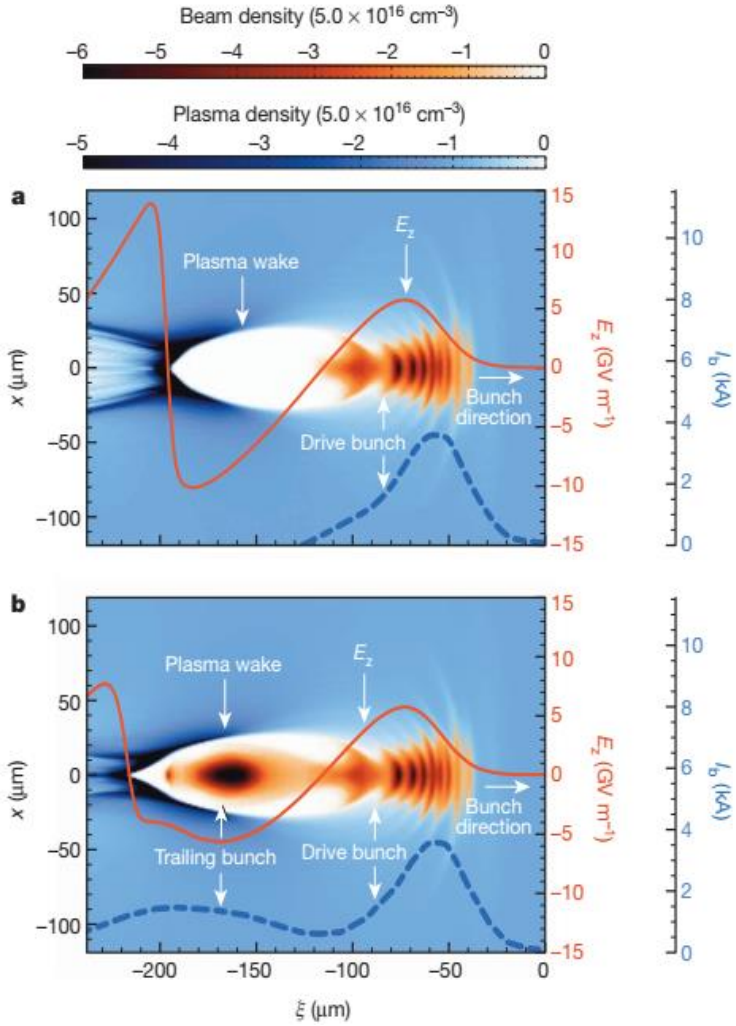
Experimental ESPEC



Beam Loading

Optimal Beam Loading — Uniform and Efficient Acceleration

- **Problem 1:** Compared to RF cavities (Q ~ 10^4–10^{10}), the electric fields in a plasma decay very rapidly (Q ~ 1–10)
  - ➢ *Need for energy to be rapidly extracted*
- **Solution:** Beam loading
  - ➢ *Efficient energy extraction*
- **Problem 2:** Beam experiences large range of accelerating gradients
  - ➢ *Large energy spread is induced*
- **Solution:** Optimal beam loading
  - ➢ Precise tailoring of the witness bunch current profile
    - ➢ flatten the wakefield



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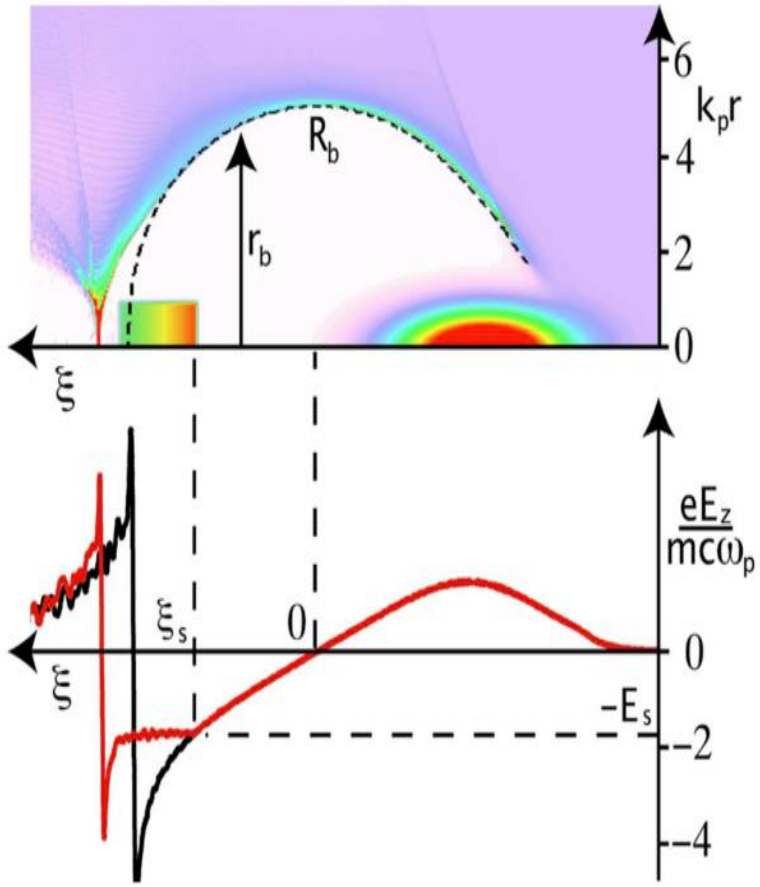
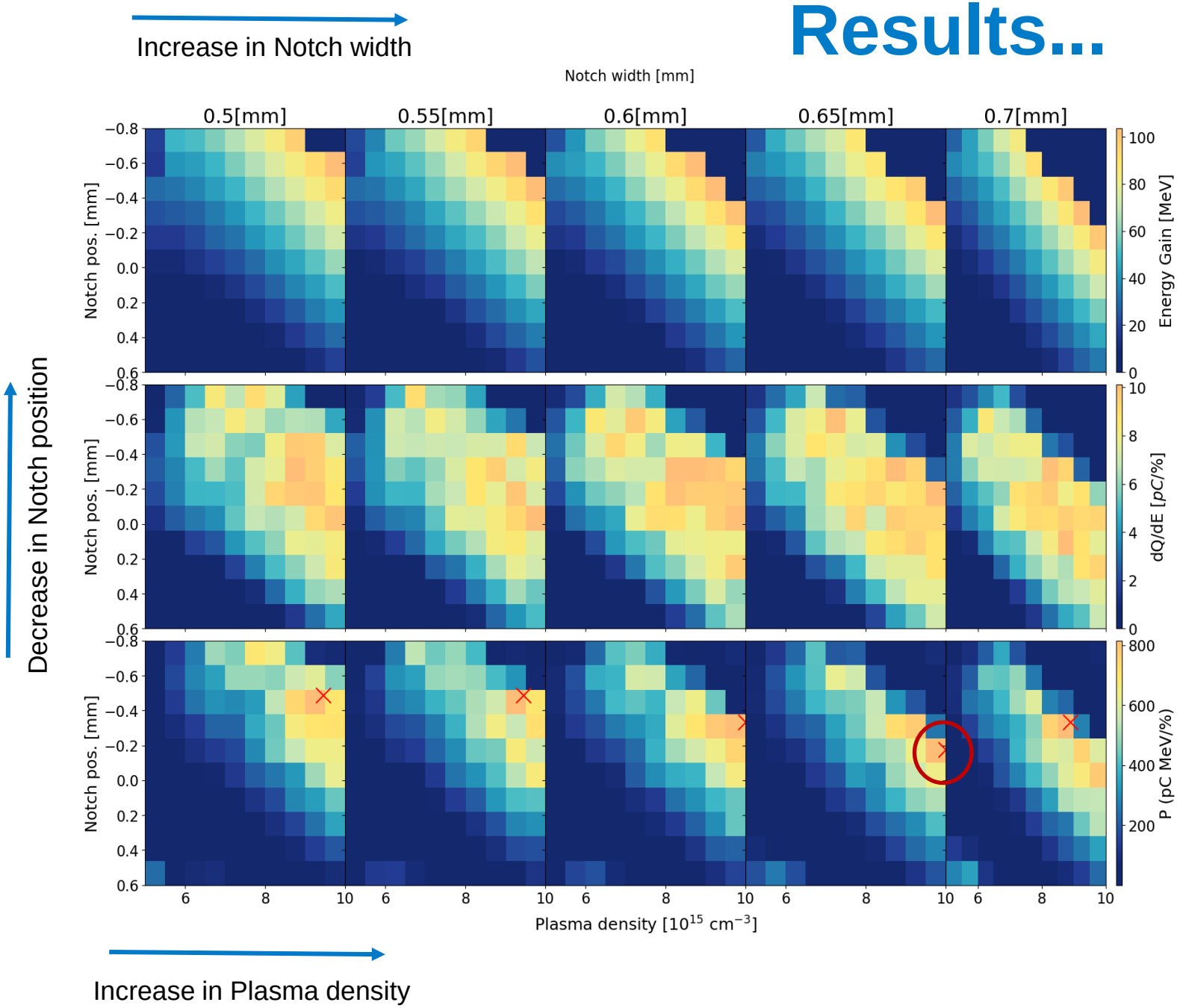
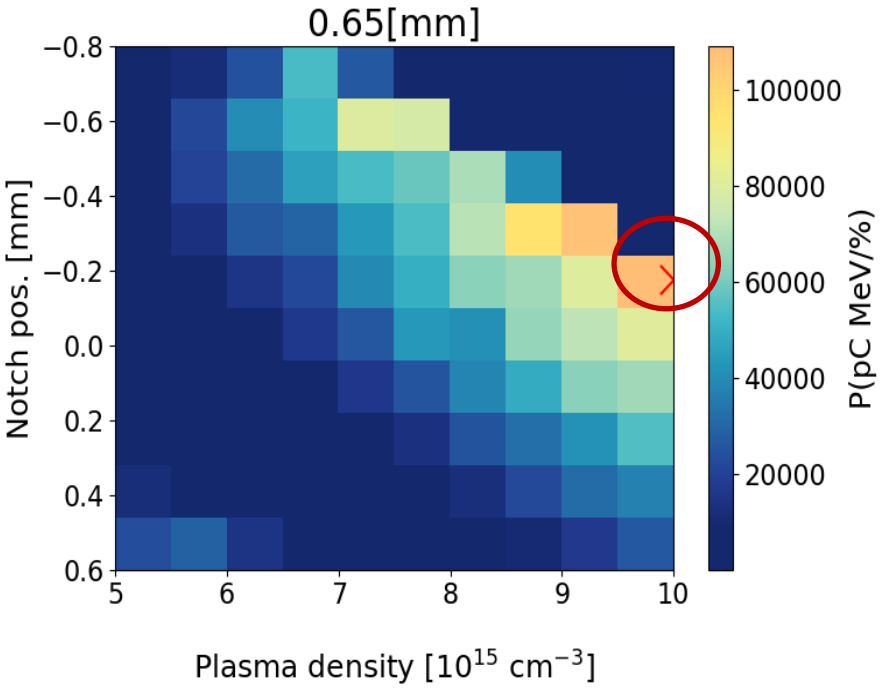


Image credit: M. Tzoufras et al., Phys. Rev. Lett. 101, 145002 (2008)

Results...

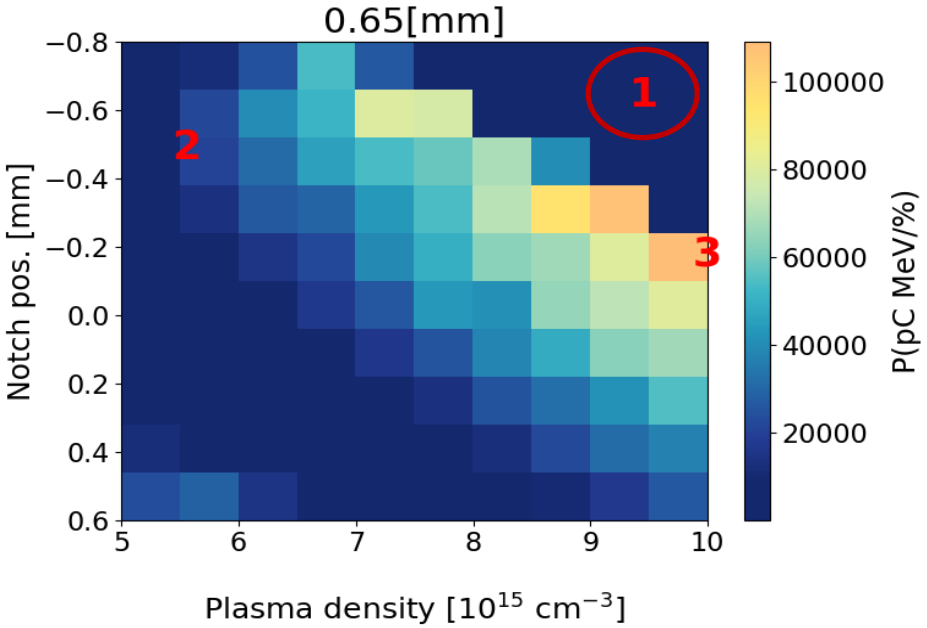


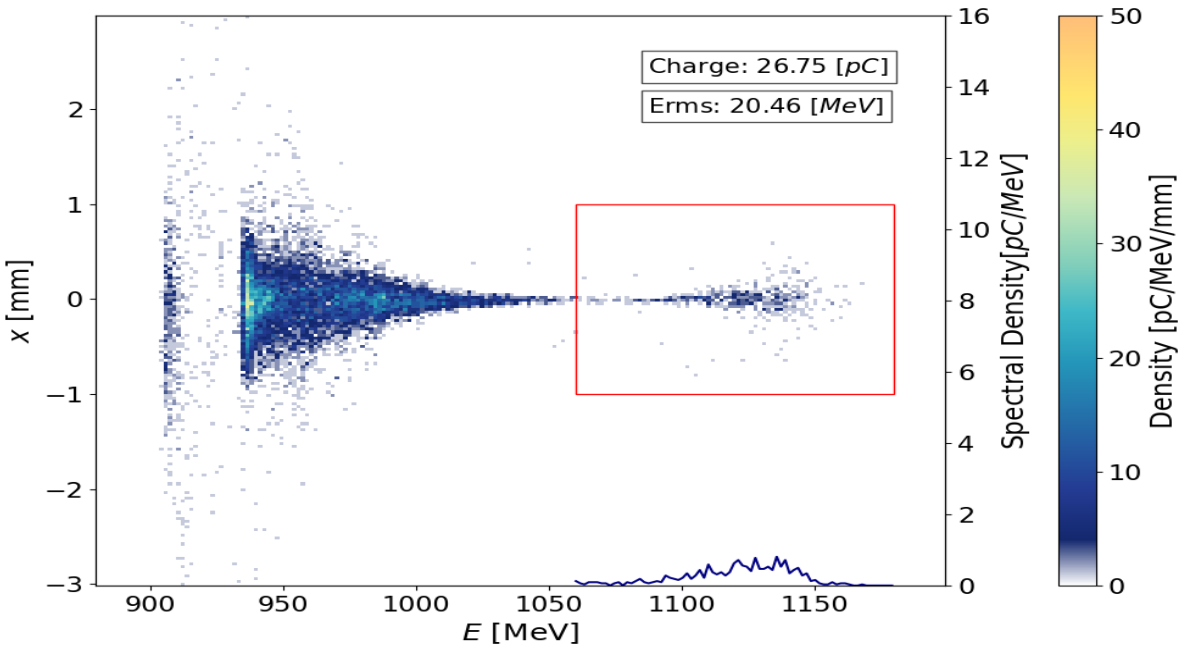
- **Witness bunch parameters:**
  - Energy gain: ~100MeV
  - Charge: 59.75pC
  - Energy-spread: 13.44MeV

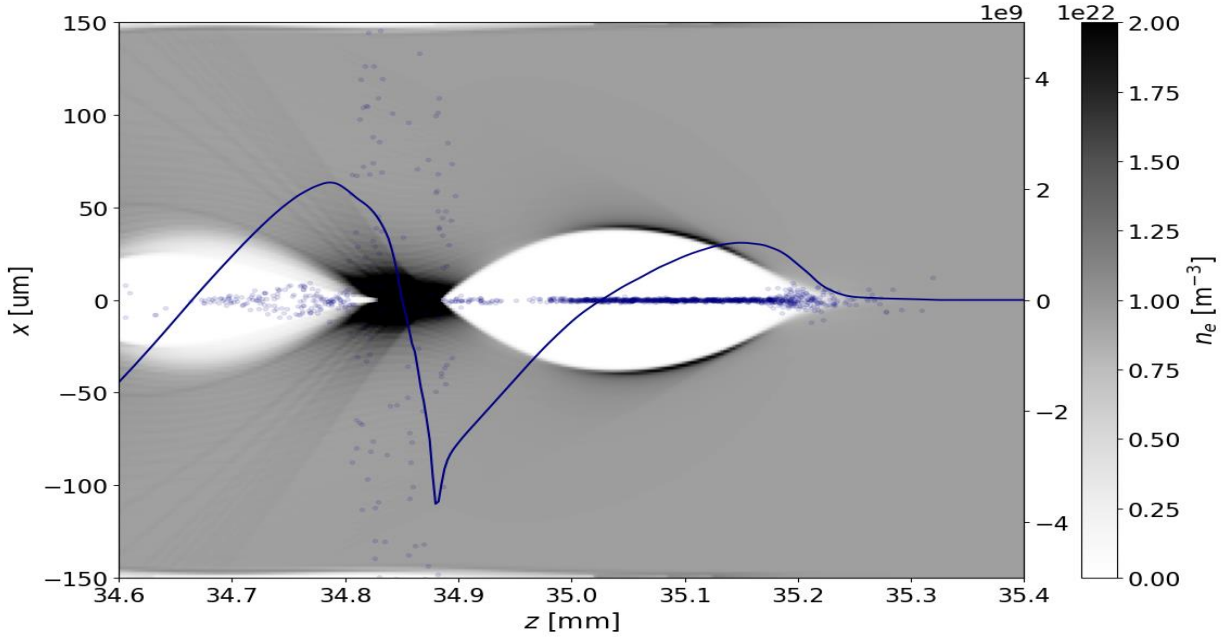


...Results

- Large energy-spread
- Less acceleration of charge
- No flattening of field
- Not an optimal beam loading working point

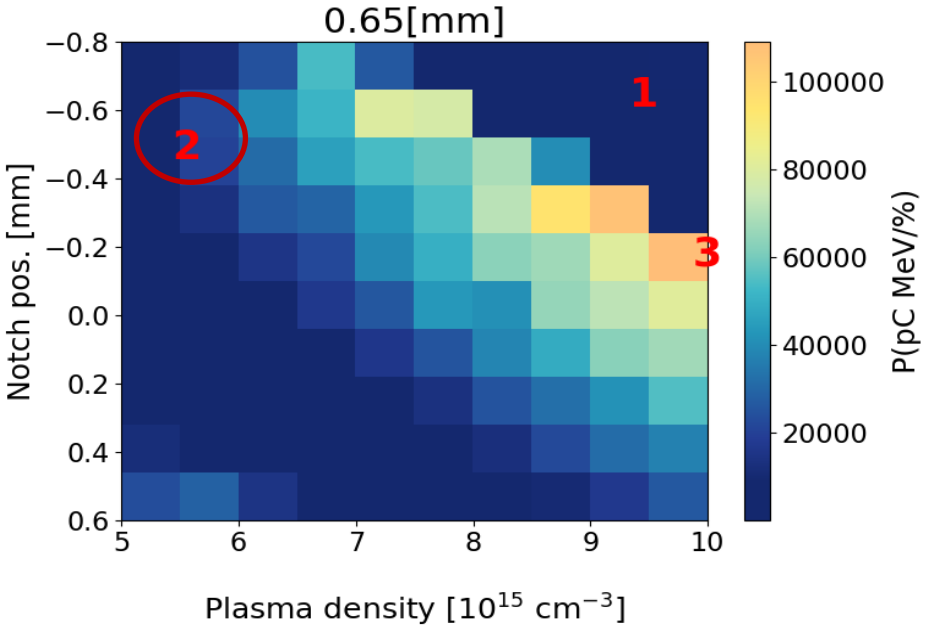


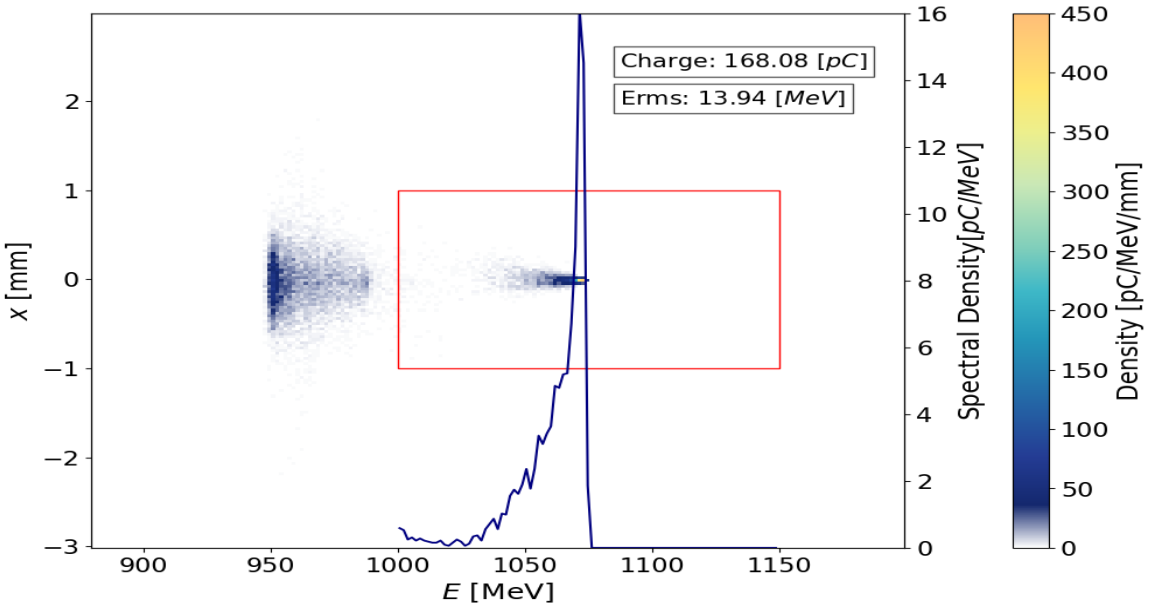


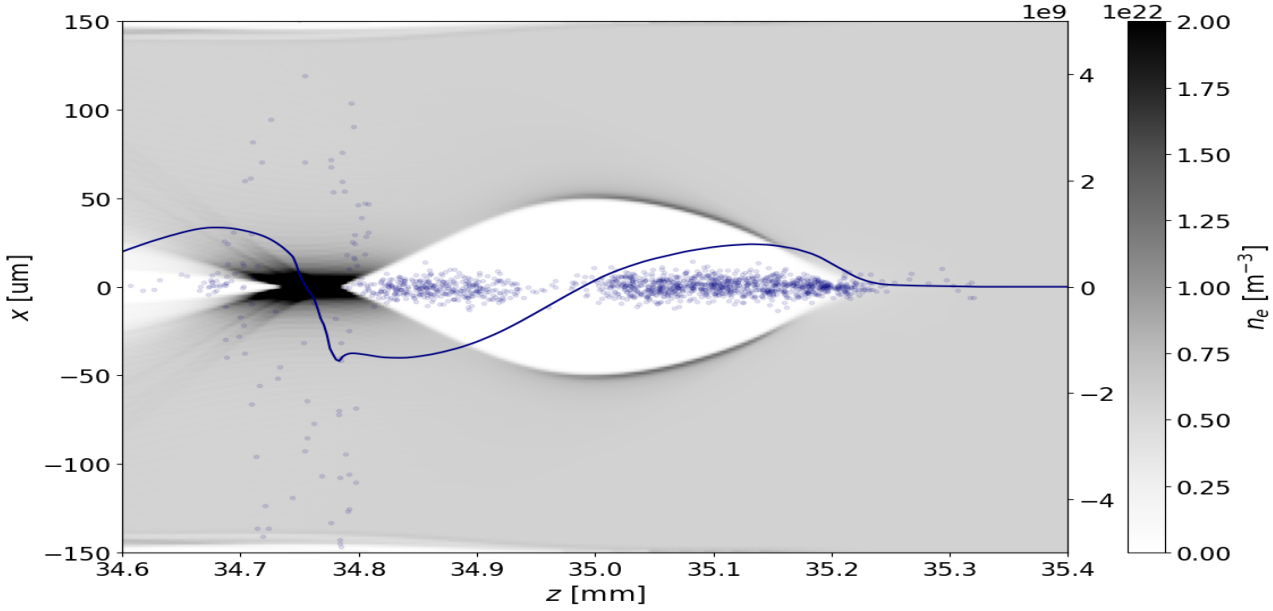


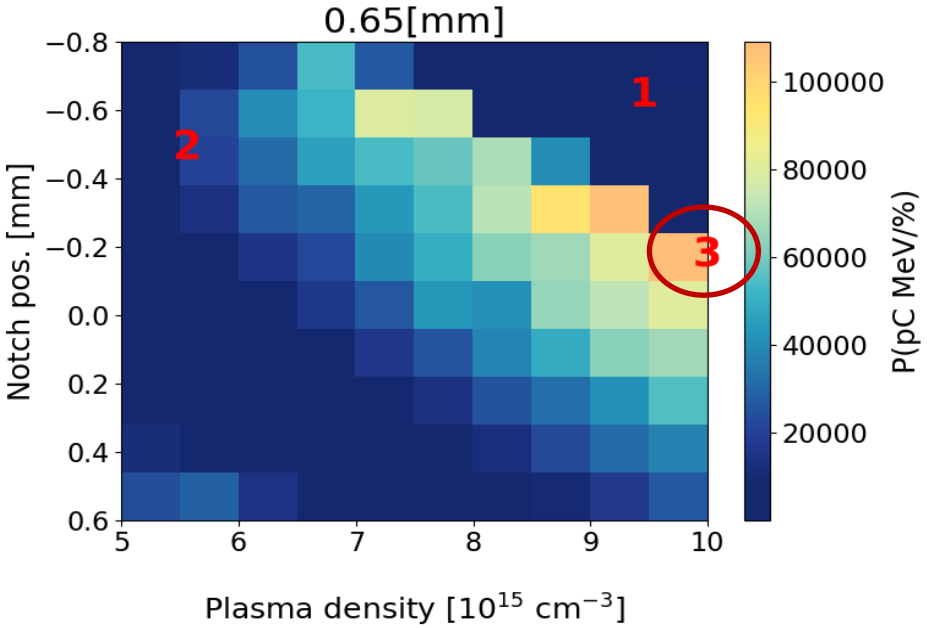
...Results

- Low energy spread
- Low density
- Less acceleration of charge
- Not an optimal beam loading working point



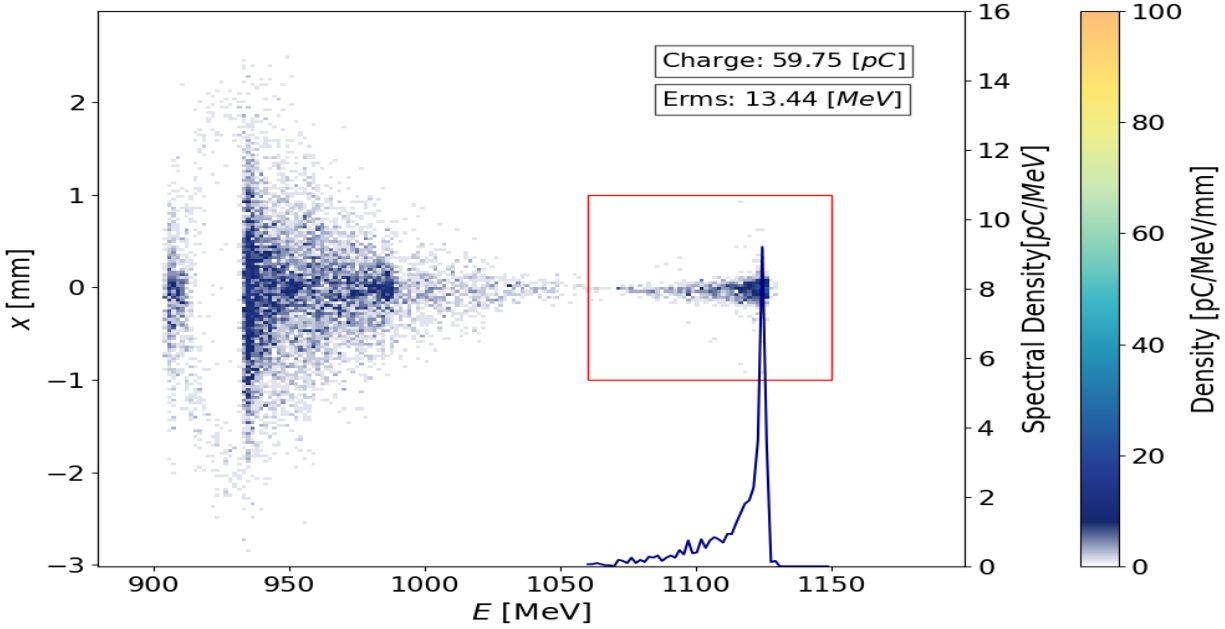


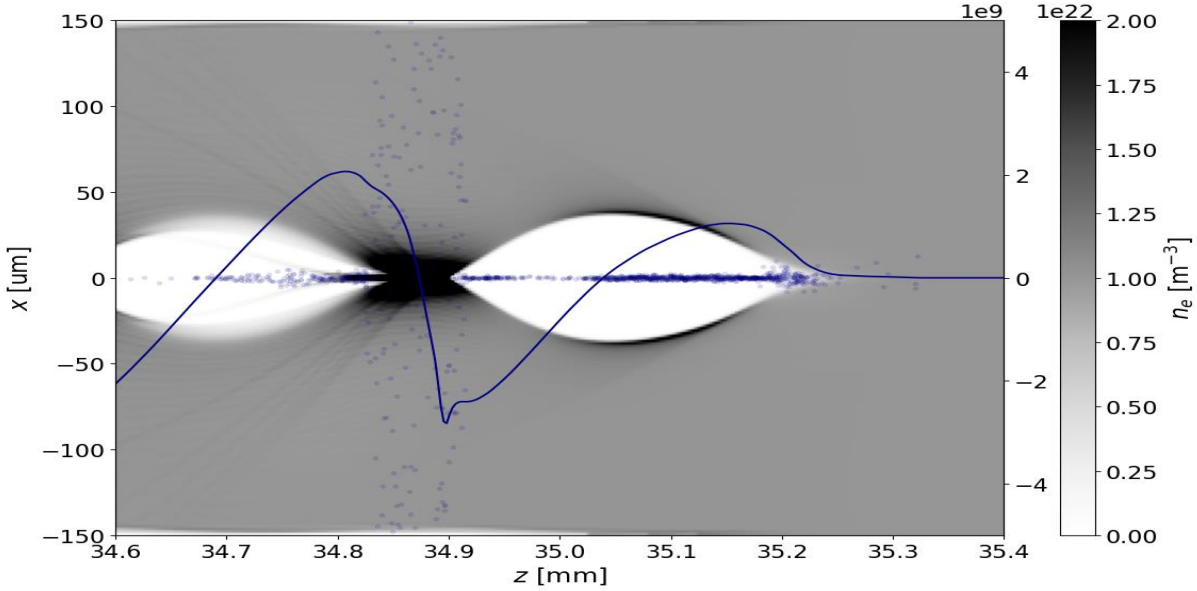




...Results

- Could be stable at high density fluctuations
- **Least** energy-spread
- strong acceleration of charge
- Flattening of field
- **Good optimal beam loading** working point





Outlook...

Conclusion: Virtually found an optimal beam loading point

- First time Virtual FLASHForward is used to optimize plasma wakefield acceleration
- 3D parameter scan of the plasma density versus notch position as a function of notch width
- Energy gain: ~100MeV, Charge: 59.75pC, Energy-spread: 13.44MeV

Recommendation: Future work

- Larger parameter scan range: higher resolution
- More plasma density profiles: higher densities
- Optimization using machine learning
- Replicate actual FLASHForward experiments

...Outlook


Danke


Danke


Danke