Energy efficiency in plasma accelerators

Large Energy Depletion of a Beam Driver in a Plasma-Wakefield Accelerator

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Why are (conventional) accelerators good?

A general purpose tool

- Today, over 30 000 accelerators Worldwide – 97% for the industry [1]

- Usage in e.g.,
  - Ion implantation for semiconductors
  - Production of isotopes
  - Material processing (e.g., welding)

Radio-frequency cavity

[2] **Table XIII.1** Total number of accelerators built worldwide (not including medical accelerators). Information courtesy of R.W. Hamm.

Application	Total
High energy accelerators of more than 1 GeV	~ 150
Ion implantation	~ 10200
Electron cutting and welding	~ 7000
Electron beam and X-ray irradiators (sterilization)	~ 2600
Ion beam analysis (including AMS)	~ 250
Radioisotope production (including PET)	~ 1000
Non destructive testing (including security)	~ 1500
Neutron generators (including sealed tubes)	~ 1500
Synchrotron radiation	~ 70
Total	24,270

[1] IAEA
[2] A. Sessler and E. Wilson, *Engines of Discovery* (2007)

Why are (conventional) accelerators good?

A workhorse for scientific research

- 25 Nobel prizes awarded with direct contribution from accelerators [1]

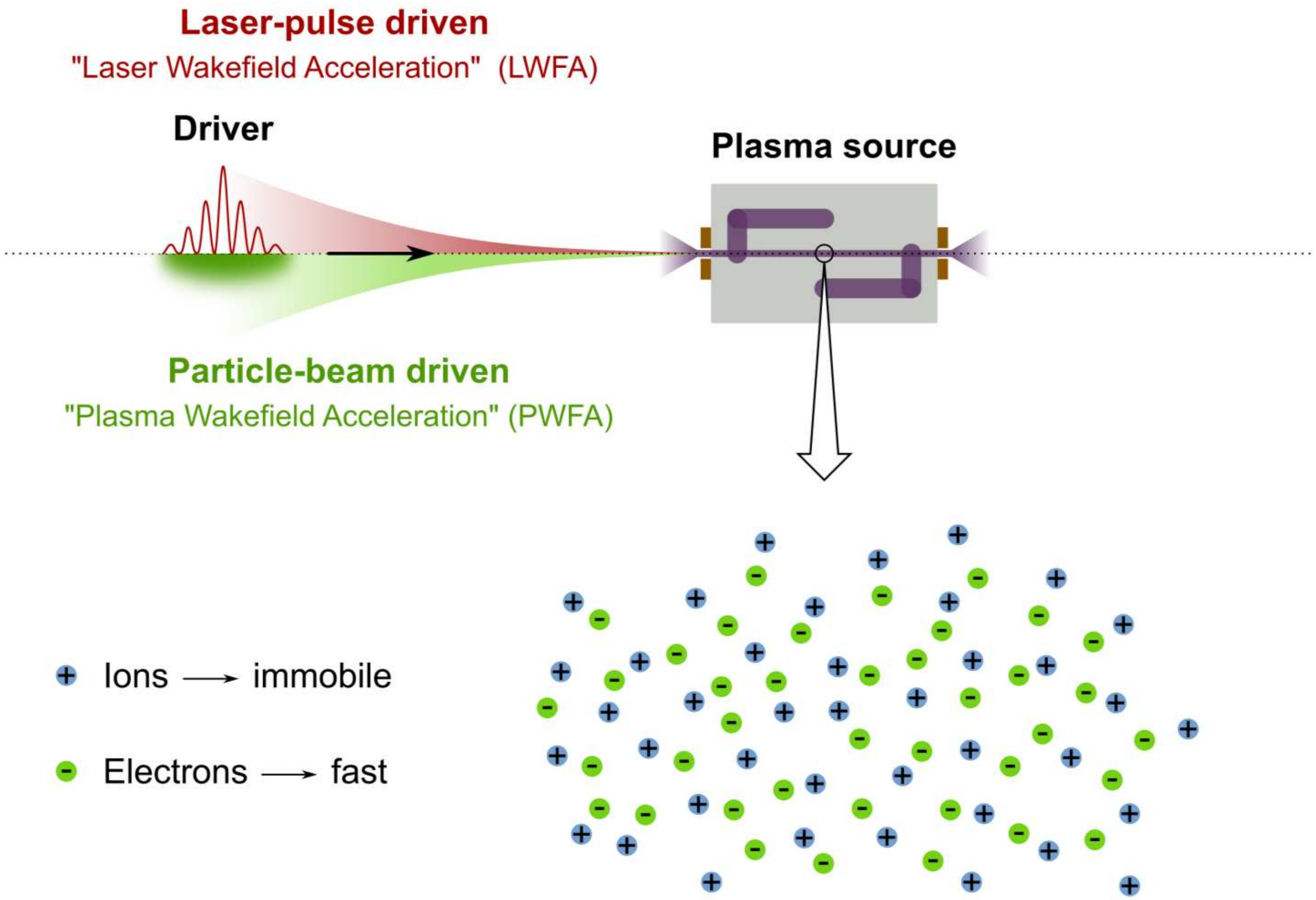
- To first order the particle energy at an accelerator-based research facility defines its discovery reach
  - High-energy physics: center-of-mass energy
  - Free-electron lasers (FELs): wavelength

- Demand for high(est) energy at low cost
  - One possible way: more compact and cheaper facilities, but *electrical breakdown* limits the accelerating gradient in conventional accelerators to O(100 MV/m)

Photo: Maximilien Brice (CERN)
[1] Nobel Prizes and Accelerators, L. Rivkin, PSI & EPFL

Accelerating cavities can also be made with plasma

Plasma does not suffer from breakdown



Schematic courtesy of P. González Caminal

Accelerating cavities can also be made with plasma

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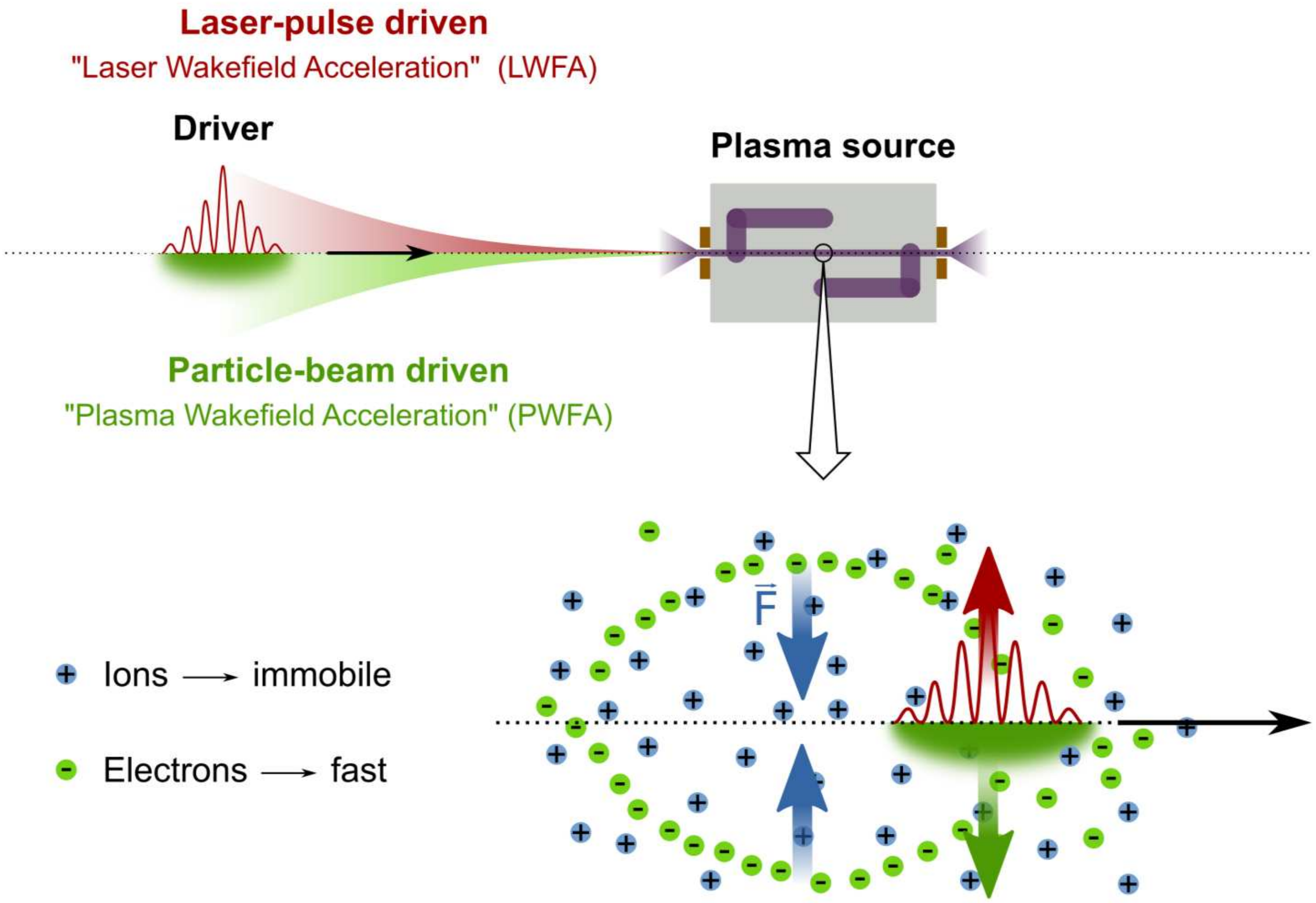

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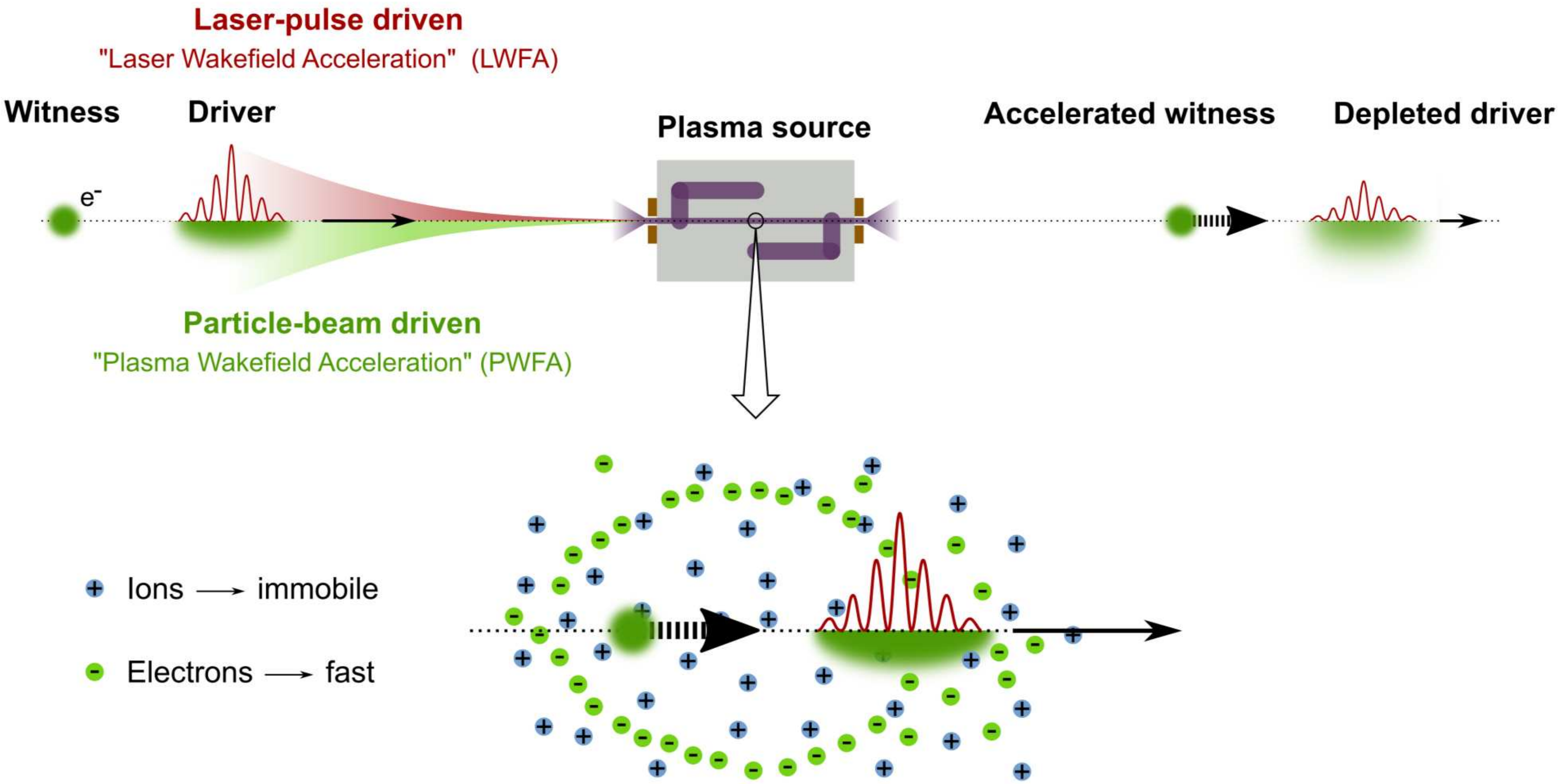

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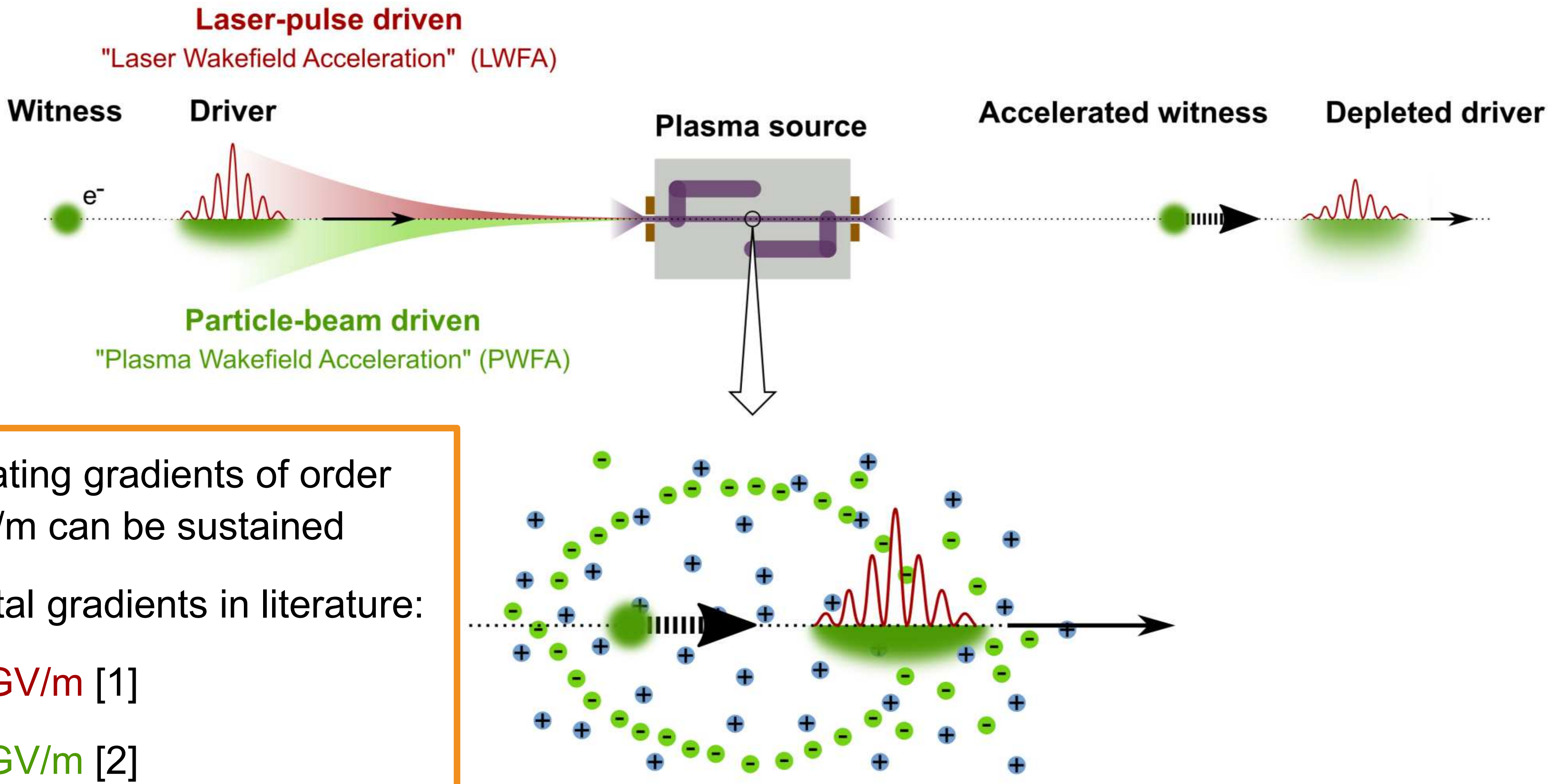

Accelerating gradients of order > GV/m can be sustained

Experimental gradients in literature:

- ~265 GV/m [1]
- ~150 GV/m [2]

Schematic courtesy of P. González Caminal

[1] S. Bohlen *et al.*, Phys. Rev. Lett. **129**, 244801 (2022)
[2] S. Corde *et al.*, Nat Commun **7**, 11898 (2016)

Accelerating only is not enough

Beam qualities need to be preserved

Figures of merit:

	Luminosity	Beam brightness
	High energy physics (colliders)	Photon science (FELs)

High repetition rate; High energy efficiency

$$\mathscr{L} = \frac{H_D}{8\pi m_e c^2} \frac{P_{\text{wall}}}{\sqrt{\beta_x \beta_y}} \frac{\eta N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

Low energy spread
(luminosity spectrum, final focusing)

Low emittance

High charge; High repetition rate

$$\frac{d}{dt} B_{\text{6D}} = \frac{Nf}{\epsilon_{nx}\epsilon_{ny}\epsilon_{nz}}$$

Low emittance

Low energy spread
Short bunches

FLASHForward: A Beam-driven plasma-wakefield accelerator

Goal: Develop a self-consistent plasma-accelerator stage

with high efficiency, high quality, and high average power, at > 1 GV/m

High-overall efficiency	**High beam quality**	**High average power**
Driver depletion	Emittance preservation ✓ [1]	Rapid recovery time (<63 ns) ✓ [5]
Plasma-to-witness efficiency	Low energy spread ✓ [2,3,4]	High repetition rate

[1] C. A. Lindstrøm *et al.*, (preprint, https://doi.org/10.21203/rs.3.rs-2300900/v1)
[2] R. D'Arcy et al., Phys. Rev. Lett. **122**, 034801 (2019)
[3] S. Schröder *et al.*, Nature Commun. **11**, 5984 (2020)
[4] C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)
[5] R. D'Arcy et al., Nature **603**, 58–62 (2022)

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High-overall efficiency

Driver depletion

Plasma-to-witness efficiency

Important for
running costs
and sustainability

High beam quality

Emittance preservation ✓ [1]

Low energy spread ✓ [2,3,4]

High average power

Rapid recovery time (<63 ns) ✓ [5]

High repetition rate

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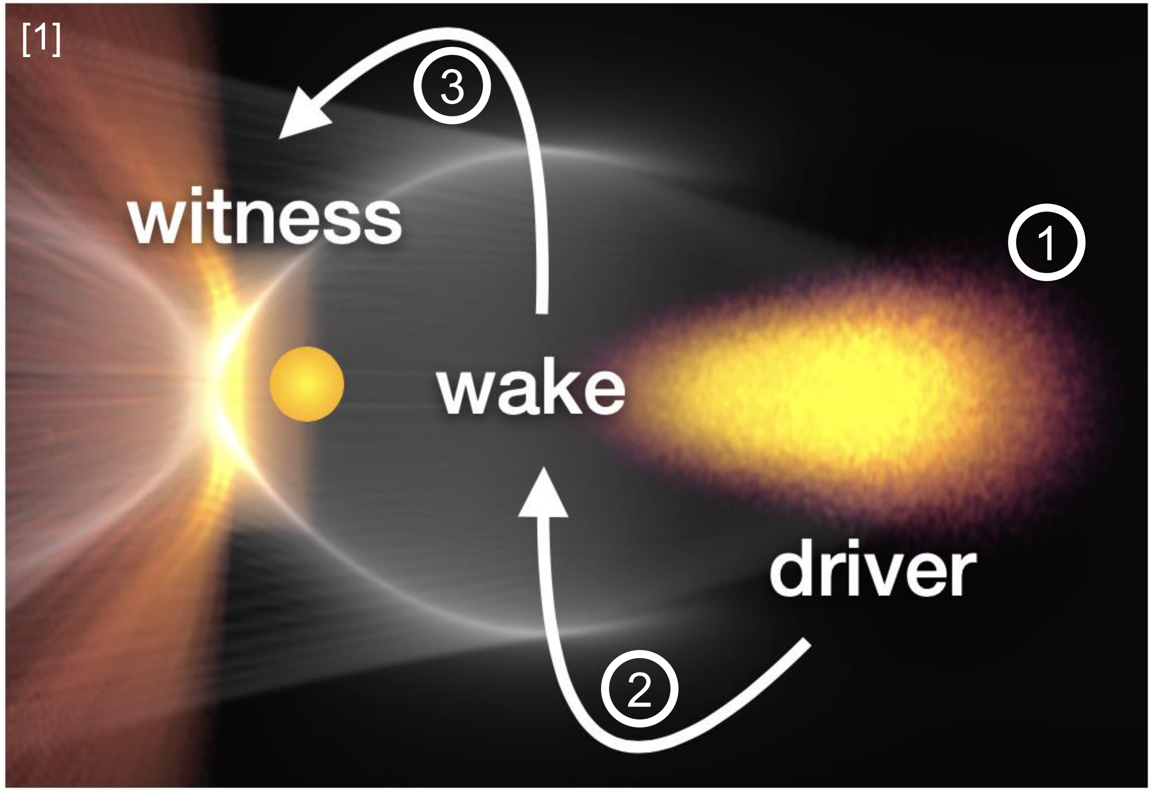
Energy transfer in a plasma-wakefield accelerator

> Wall-plug-to-witness efficiency is a product of:

1. *Wall-plug-to-driver* efficiency
2. *Driver-to-plasma* energy transfer efficiency (i.e., **driver depletion**)
3. *Plasma-to-witness* energy transfer efficiency

> The radiofrequency-based collider CLIC is envisaged to be 11% wall-plug-to-main-beam efficient [2]



[1] Image courtesy of R. D’Arcy
[2] The Compact Linear Collider (CLIC), TDR

Particle beam drivers are (for now) the most efficient to produce

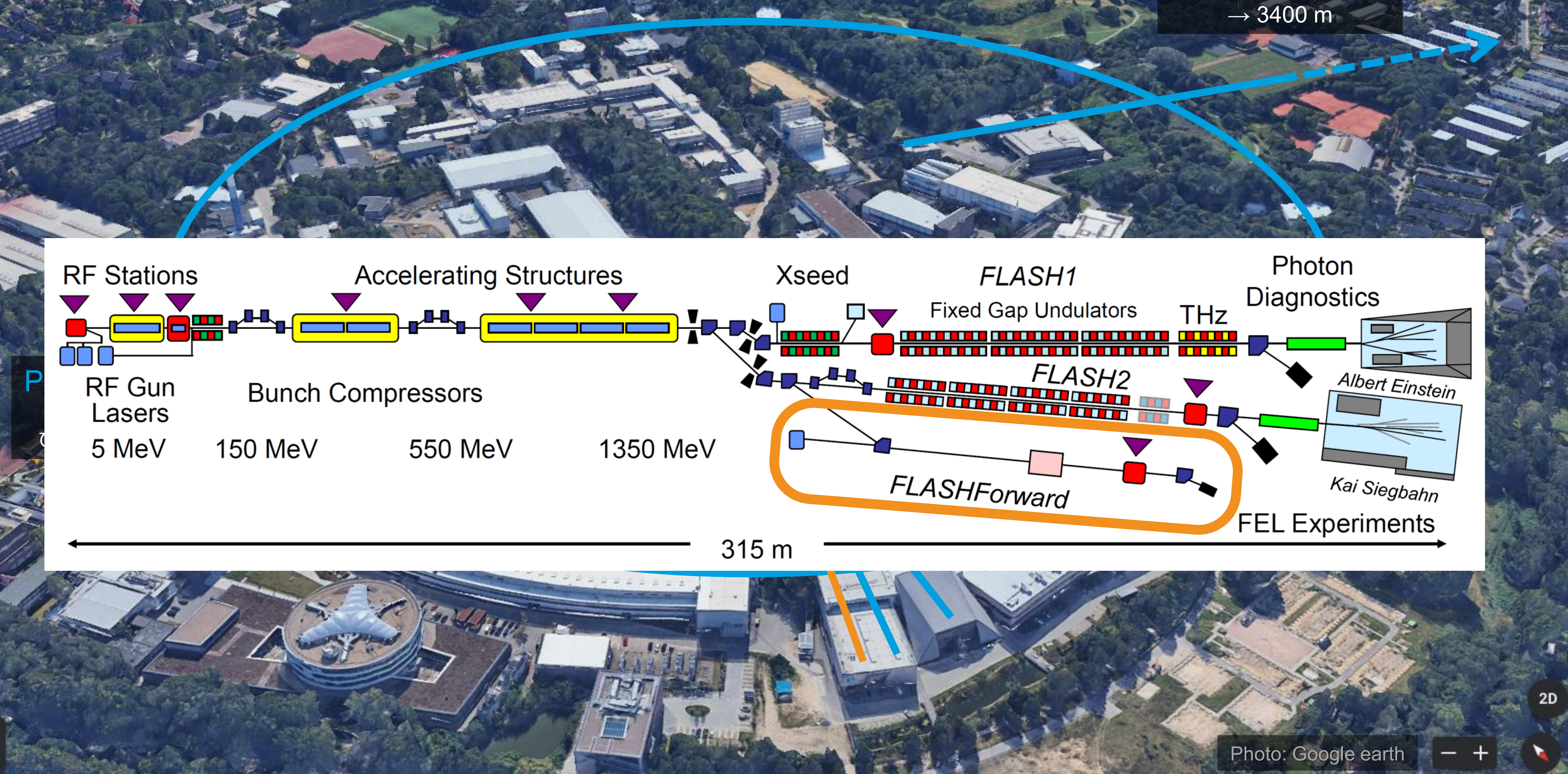
1

Wall-plug-to-driver efficiency

- Driver can be
  - Laser pulse
    - Current Ti:Sapphire lasers <1% efficient
    - There is research on using other type of lasers
    - Small but energy inefficient → ideal for small applications
  - Charged particle beam
    - O(10%) for klystrons, CLIC wall-plug-to-drive-beam envisaged to be 55%
    - Larger but energy efficient → currently the best option for high average beam power facilities (colliders & FELs)
- Research should be driver-agnostic, driver type determined by application

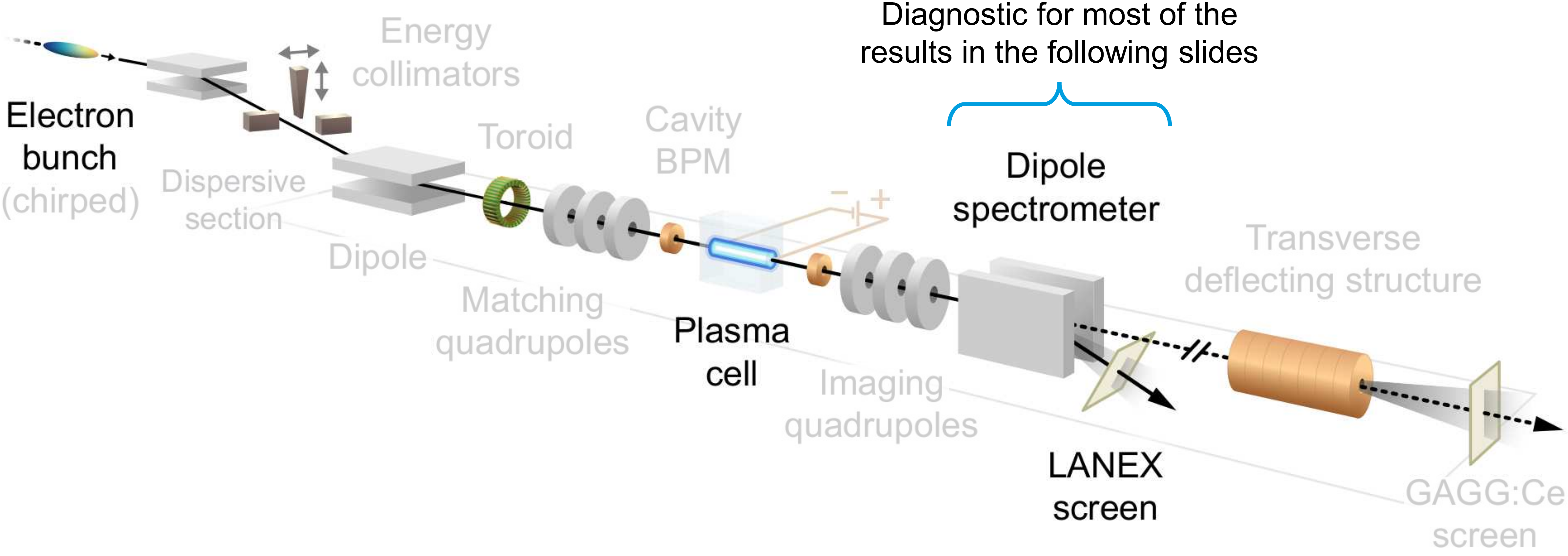

FLASHForward at DESY
European X-FEL
17.5 GeV
→ 3400 m
FLASH
1.35 GeV
→ 315 m
PETRA III
6 GeV
↻ 2300 m
FLASHForward
PWFA research
Photo: Google earth
2D

FLASHForward at DESY



A schematic of the FLASHForward beamline

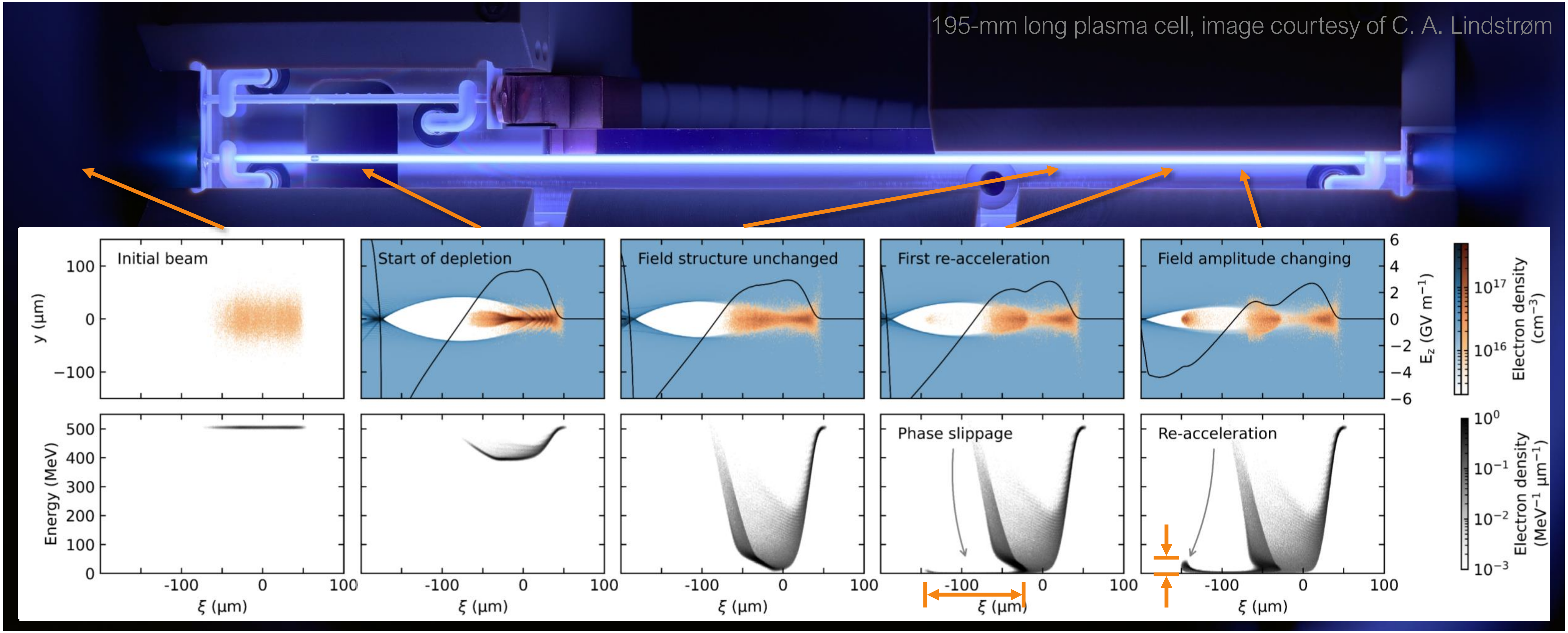
Diagnostic for most of the results in the following slides



Schematic courtesy of C. A. Lindstrøm

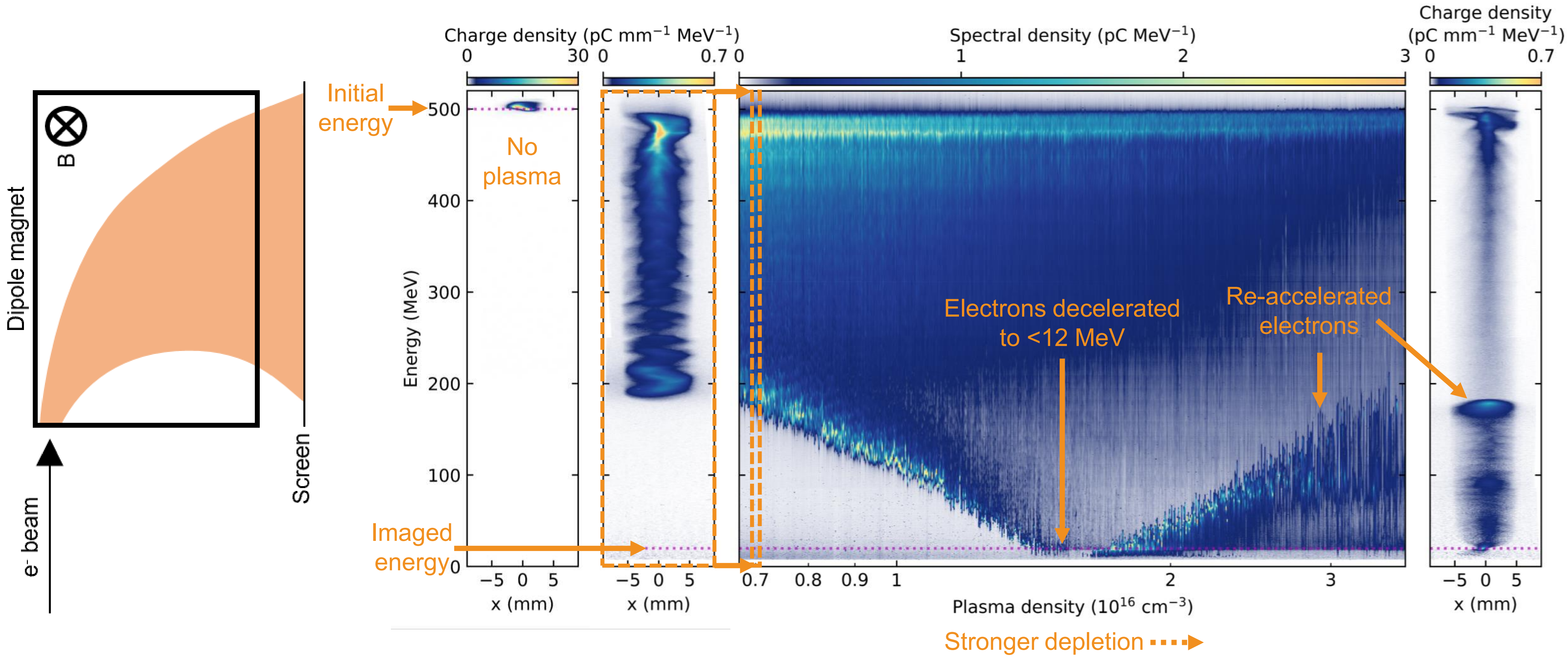
Re-acceleration of energy depleted electrons limits driver energy depletion

2



Simulation code: HiPACE++, S. Diederichs et al., CPC 278, 108421 (2022)

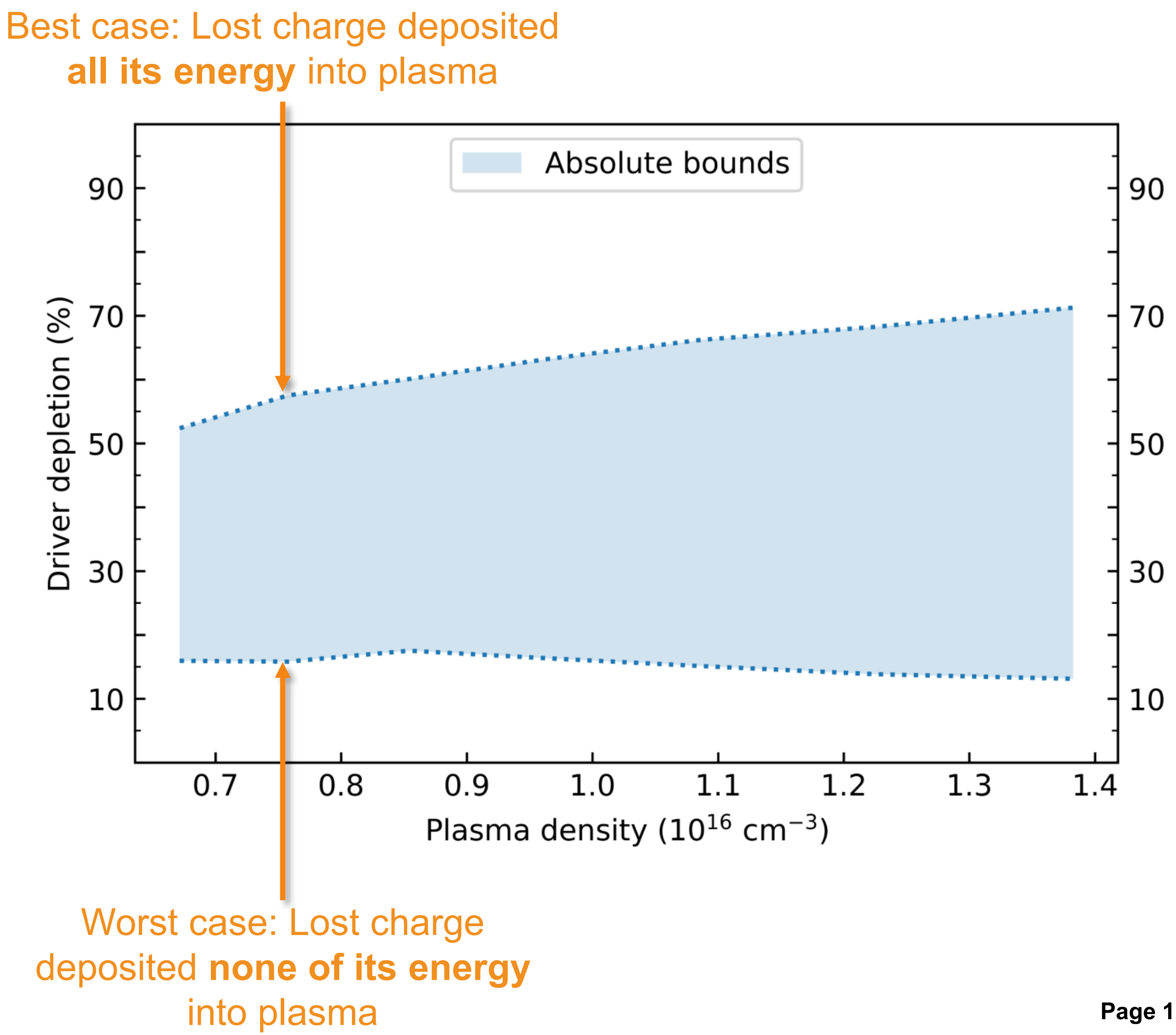
Electron re-acceleration measured for the first time



Charge loss in transport dominates uncertainty of driver depletion efficiency

2

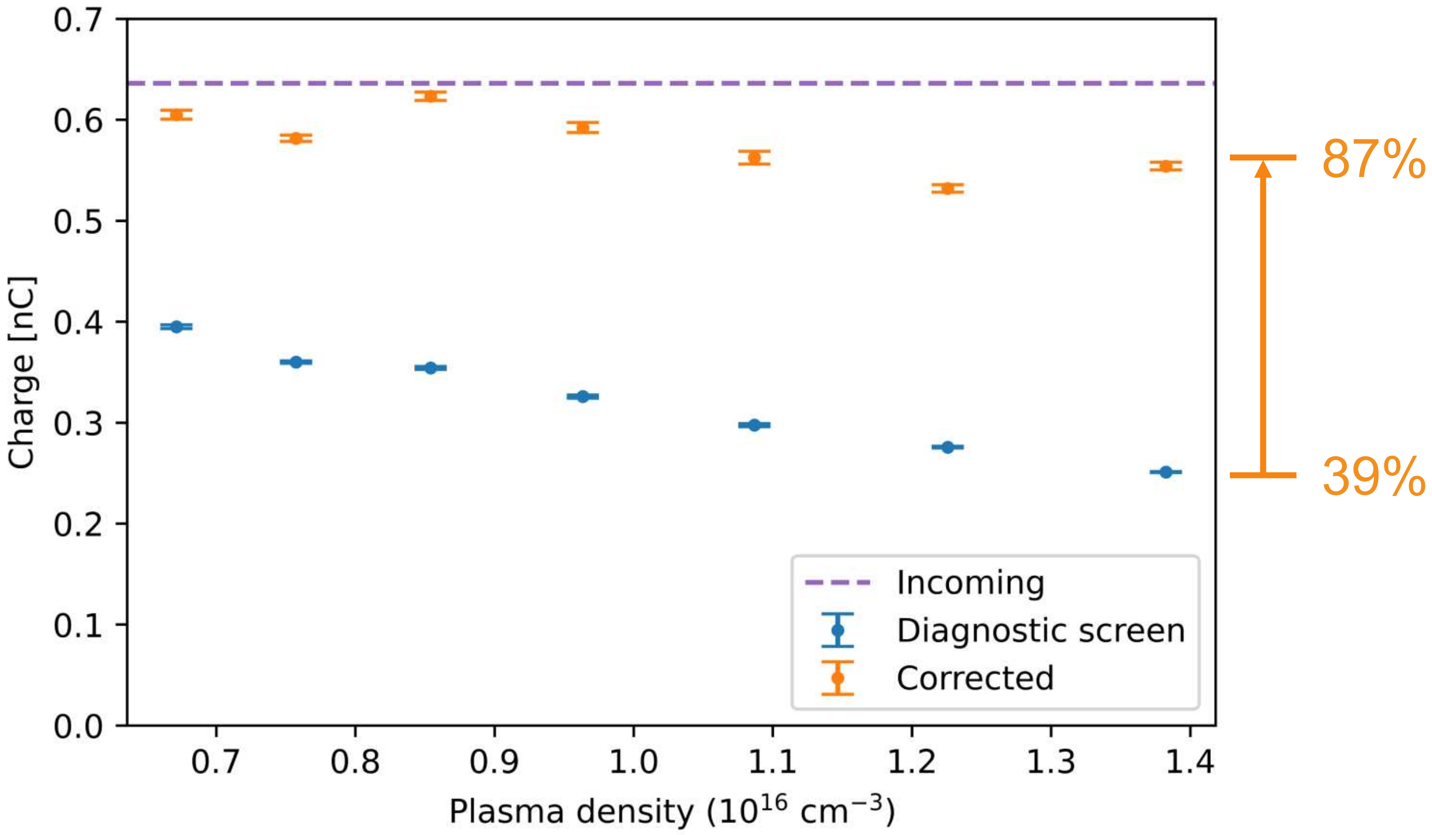
- Charge loss in transport from the plasma exit to the diagnostic produce an uncertainty (blue bands)



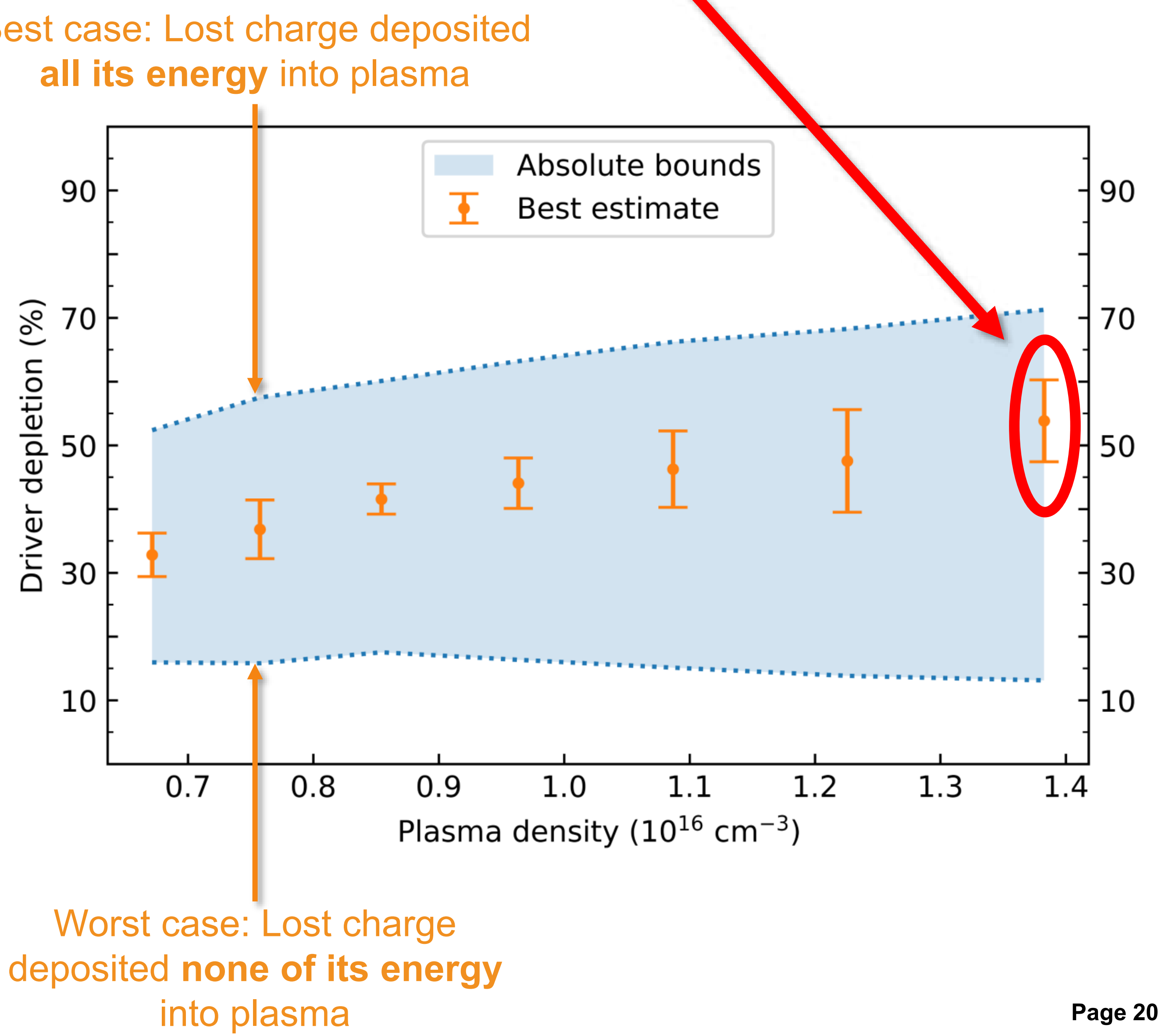
Charge loss in transport can be modelled and corrected

- Modelling the charge loss allows to correct the measured spectra and reduce uncertainty

- Model reduces the charge loss by 48 %-points



Driver depletion efficiency measured up to (54±6)%



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2 Driver depletion (54%) ✓

3 Plasma-to-witness efficiency

High beam quality

Emittance preservation ✓ [1]

Low energy spread ✓ [2,3,4]

High average power

Rapid recovery time (<63 ns) ✓ [5]

High repetition rate

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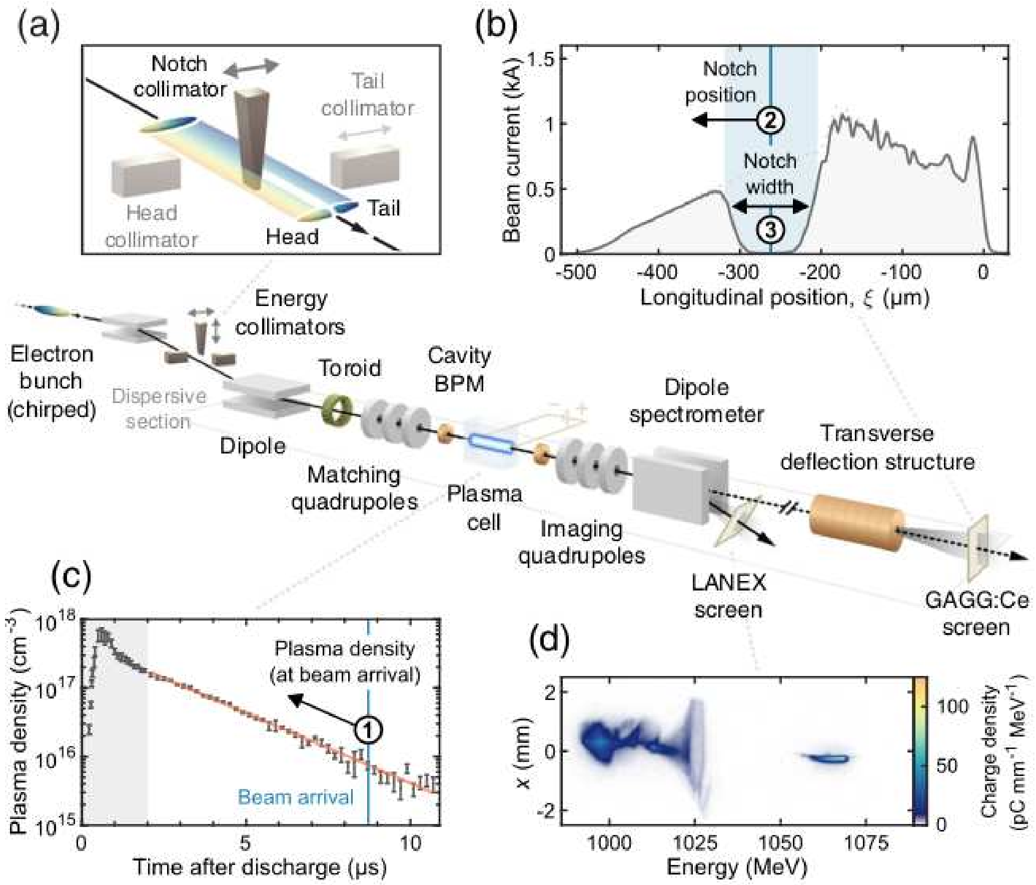
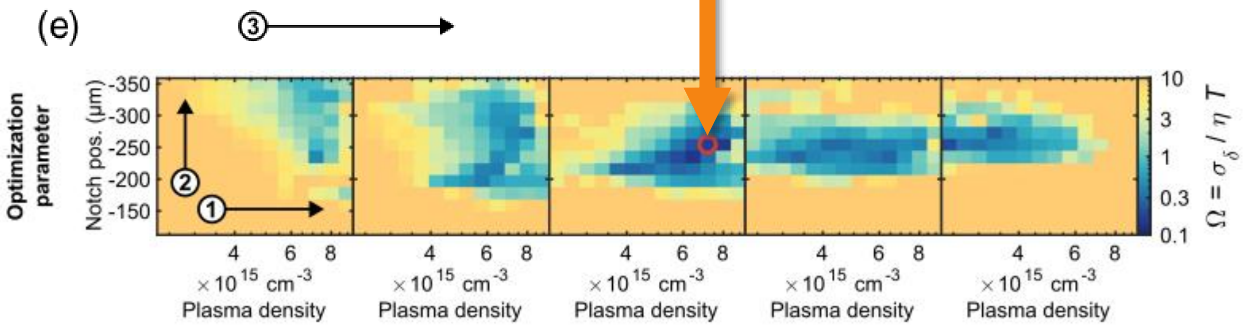
Efficient working points require precise optimization

Plasma-to-witness efficiency



Optimized for **low energy spread**, **high transformer ratio** and **high energy transfer efficiency**

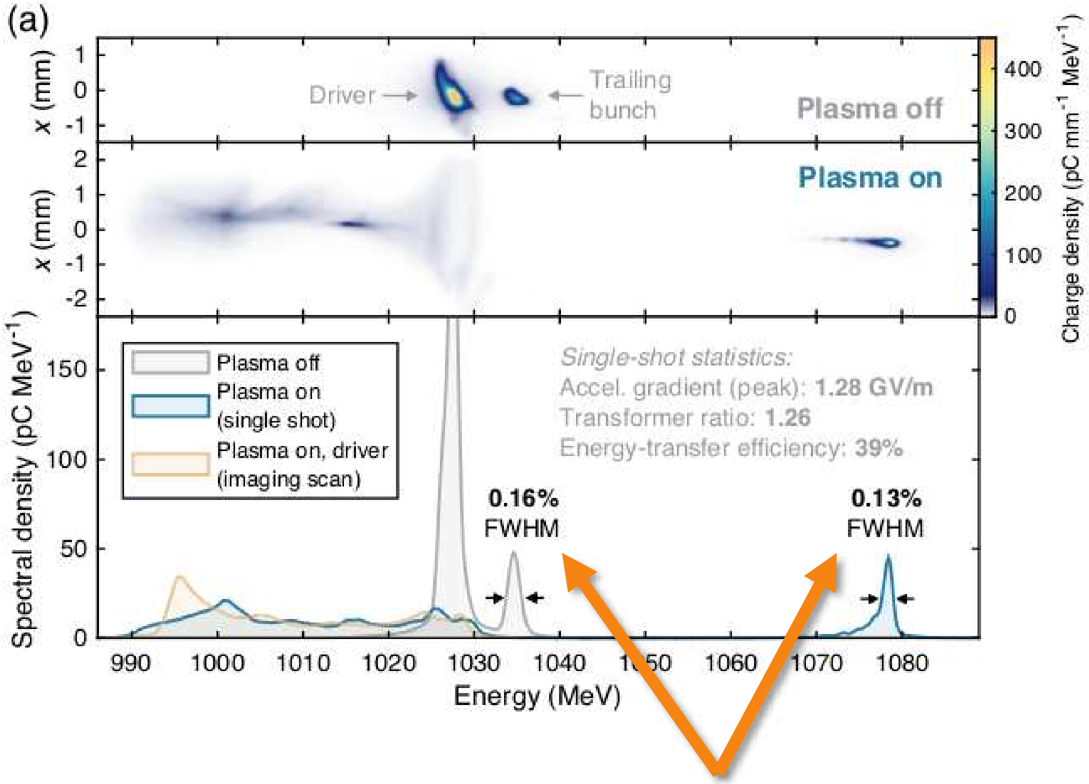


C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)

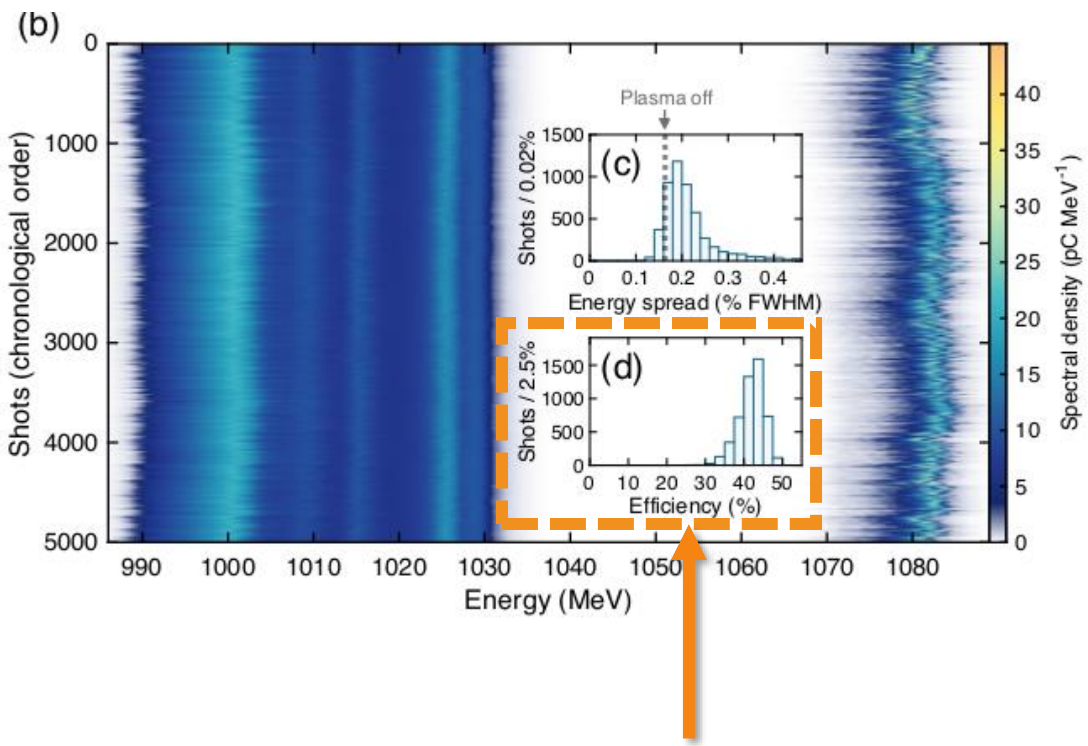
A stable and efficient working point

Plasma-to-witness efficiency

3



Energy spread preserved



Average plasma-to-witness efficiency of 42%

Theory suggests up to 90% possible [1]

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

[1] M. Tzoufras, et al., Phys. Rev. Lett. 101, 145002 (2008).

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High-overall efficiency	High beam quality	High average power
Driver depletion (54%) ✓	Emittance preservation ✓ [1]	Rapid recovery time (<63 ns) ✓ [5]
Plasma-to-witness efficiency (42%) ✓ [4]	Low energy spread ✓ [2,3,4]	High repetition rate

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PWFA could provide compact and efficient accelerators

Conclusions

- Theory suggests that high energy-transfer efficiency is possible (e.g., 90% wake-to-witness efficiency [1]), but experimental realization is difficult
- Great progress has been made at FLASHForward in recent years but there is still a long way to go
- Next step in energy efficiency:
  - Experimentally combine the independent record-efficiencies
    - 54% driver-to-wake [2] · 42% wake-to-witness [3] = 23% driver-to-witness
      - Combined with CLIC's 55% wall-plug-to-driver efficiency [4]

        → **12 % wall-plug-to-trailing-bunch efficiency** (similar to conventional accelerators)

[1] M. Tzoufras, *et al.*, Phys. Rev. Lett. **101**, 145002 (2008).
[2] F. Peña *et al.*, to be published
[3] C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)
[4] M. Aicheler *et al.*, CLIC Conceptual Design Report (2012)