# Principles of Plasma Accelerators
## and their Impact on Science and Society

**Jens Osterhoff**
Head of Plasma Accelerator R&D
DESY. Accelerator Division

Quantum Universe Lectures
January 21th, 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

# Outlook

## What you signed up for…

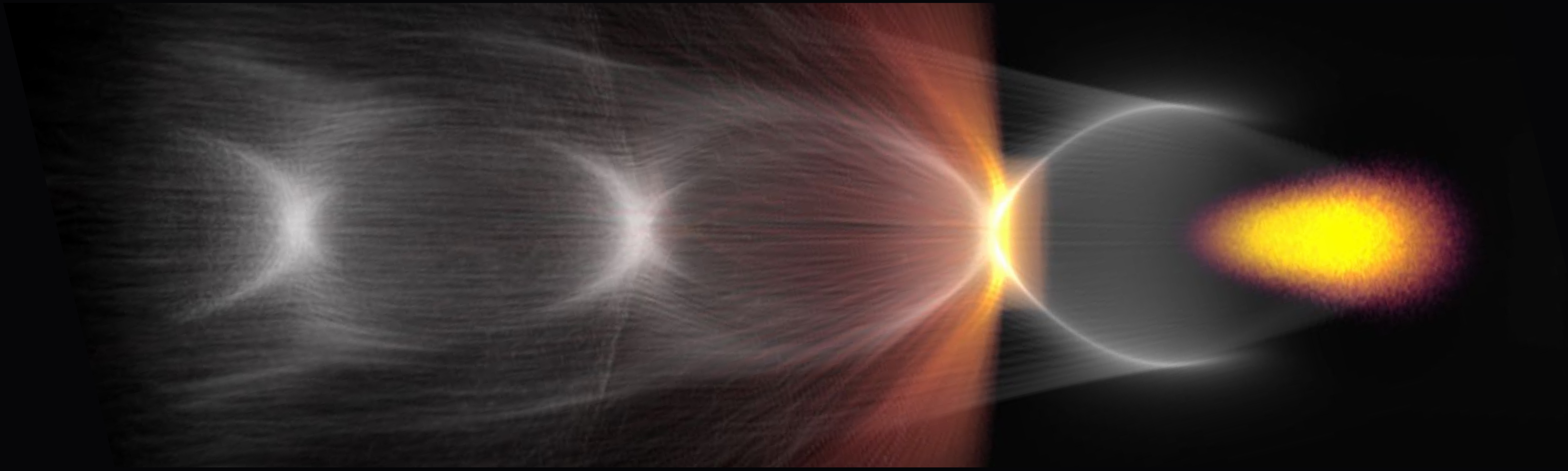
> **Introduction** Lecture I → January 7
  - Why are traditional particle accelerators large?
  - The popular introduction to plasma accelerators
  - Important differences between conventional and plasma accelerators
  - Plasma accelerators 101 — the key mechanisms and properties

> **State-of-the-art and current notable projects and goals** Lecture II → January 14
  - State-of-the-art projects and current challenges
    - The ultimate (single) plasma stage

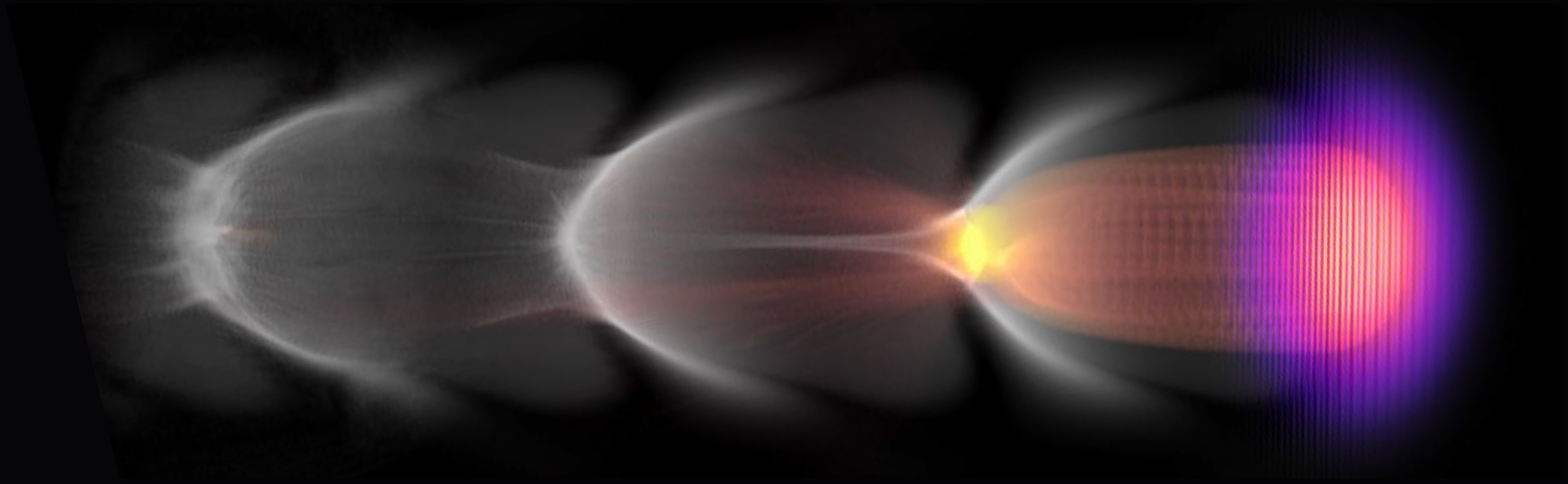
> **Future applications and challenges** Lecture III → January 21
  - The long and winding road to a particle collider in a nutshell
    - Single-stage energy gain
    - The staging challenge
    - Plasma-based collider concept

# Energy gain in a single stage

# Particle beams and lasers can efficiently excite plasma wakefields



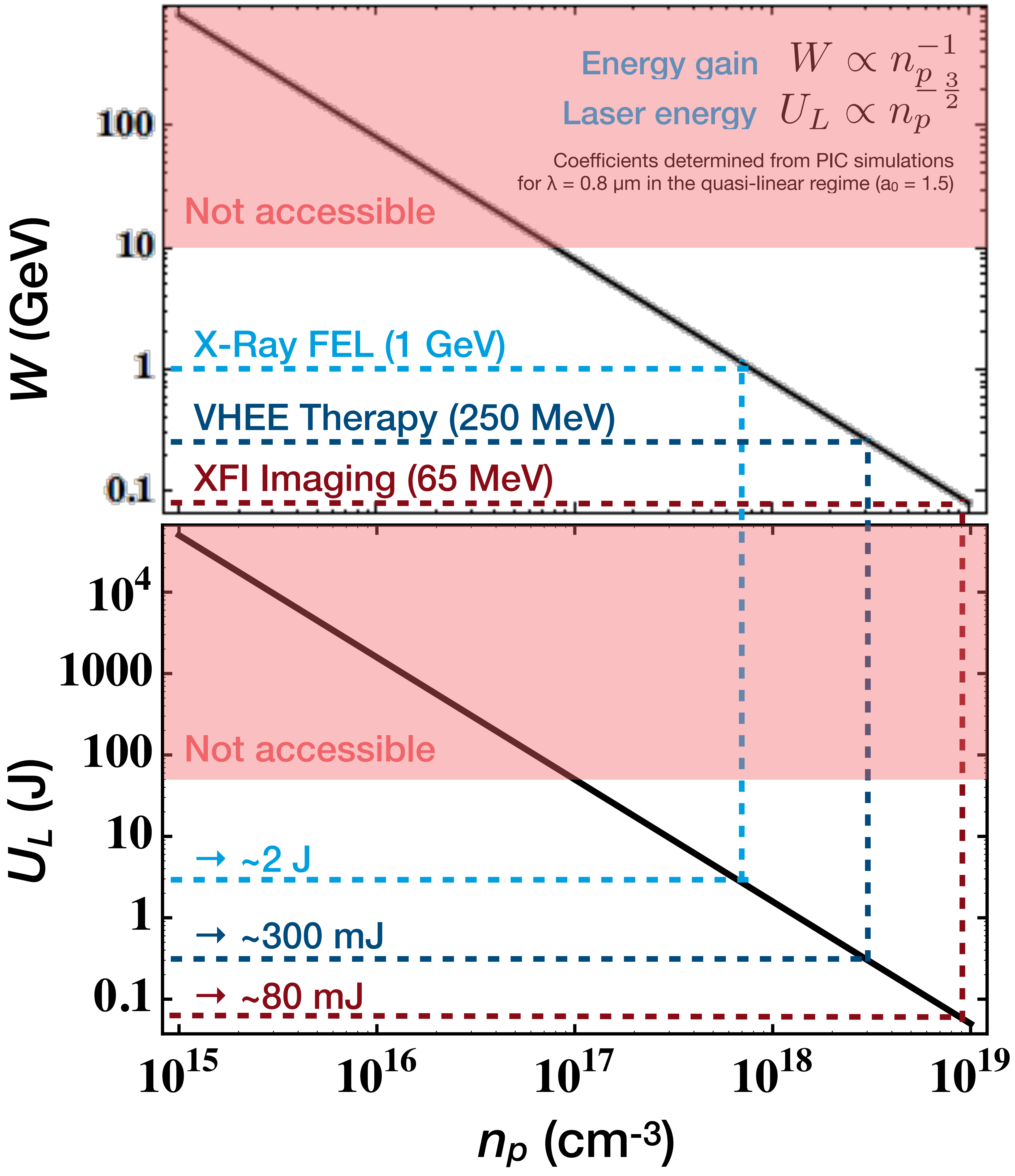
**PWFA**

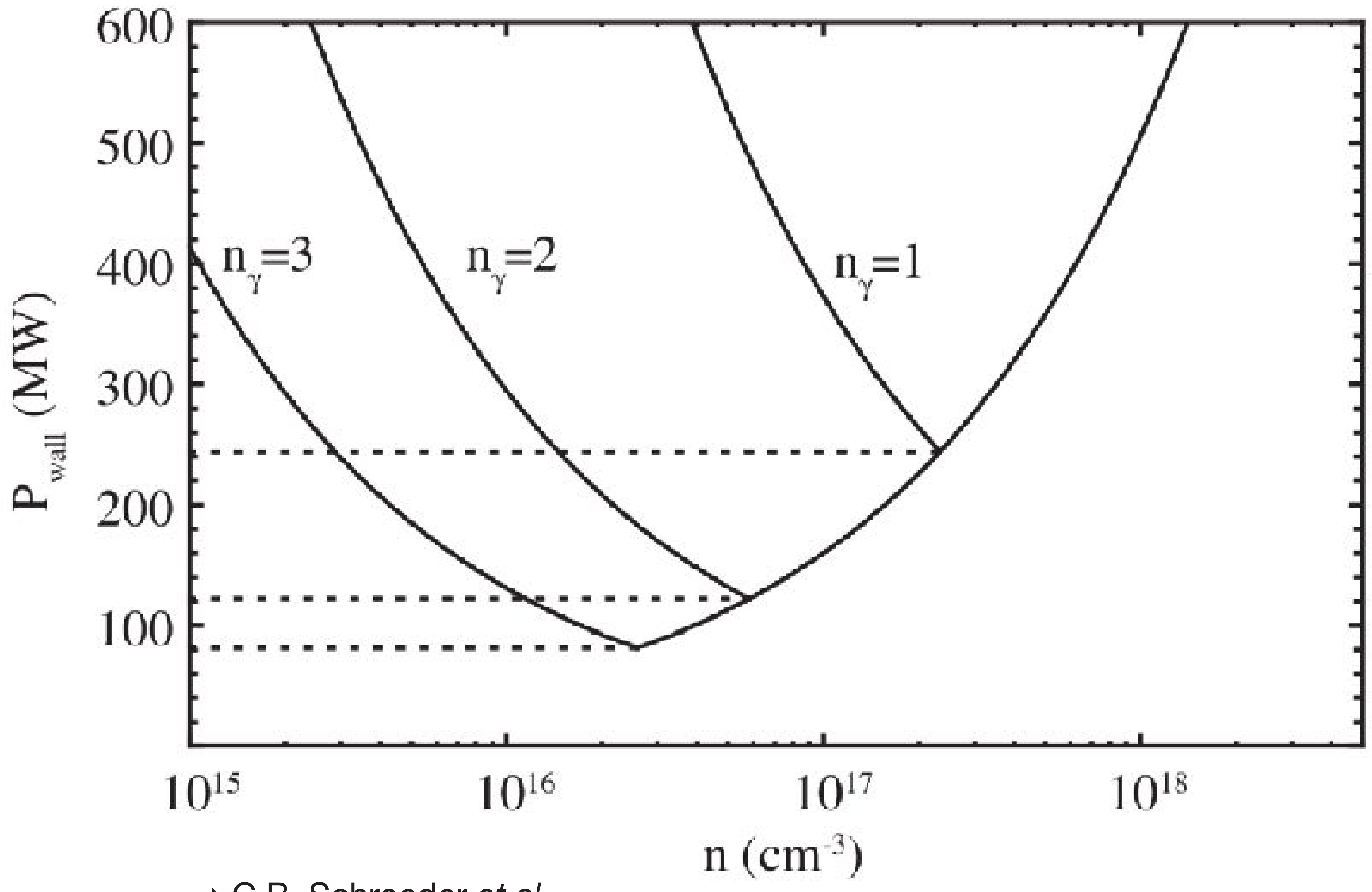


**LWFA / LPA**

# Energy gain per stage in an LPA is limited by laser pulse energy

## Plasma density is directly linked to laser pulse duration and particle bunch length → Beamstrahlung




→ C.B. Schroeder *et al.*, Phys. Rev. STAB **15**, 051301 (2012)

10 GeV energy gain per plasma stage seems a good compromise

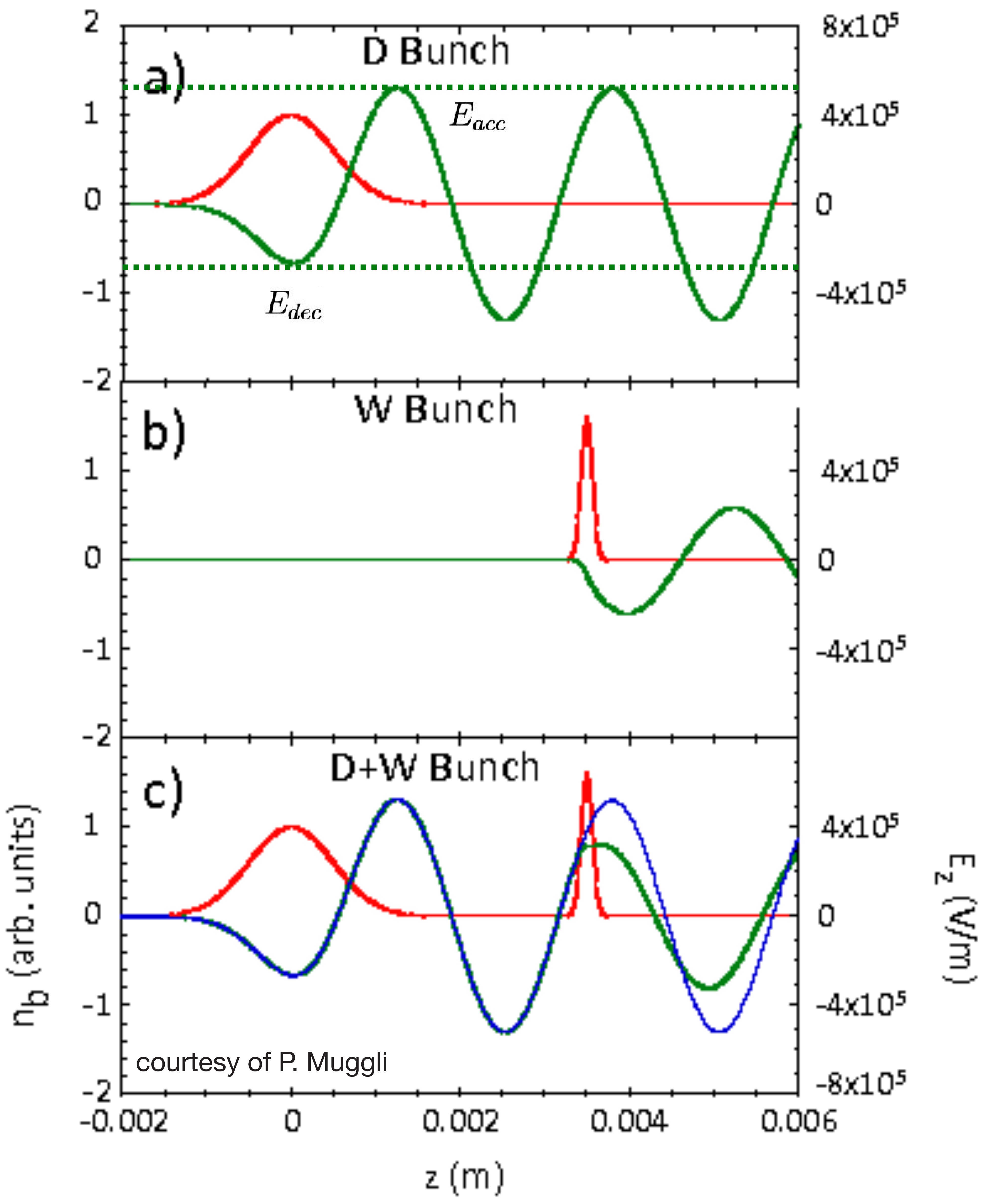
# Energy gain limits in PWFA: the transformer ratio *R*

## Optimum plasma module gain is yet to be determinedd

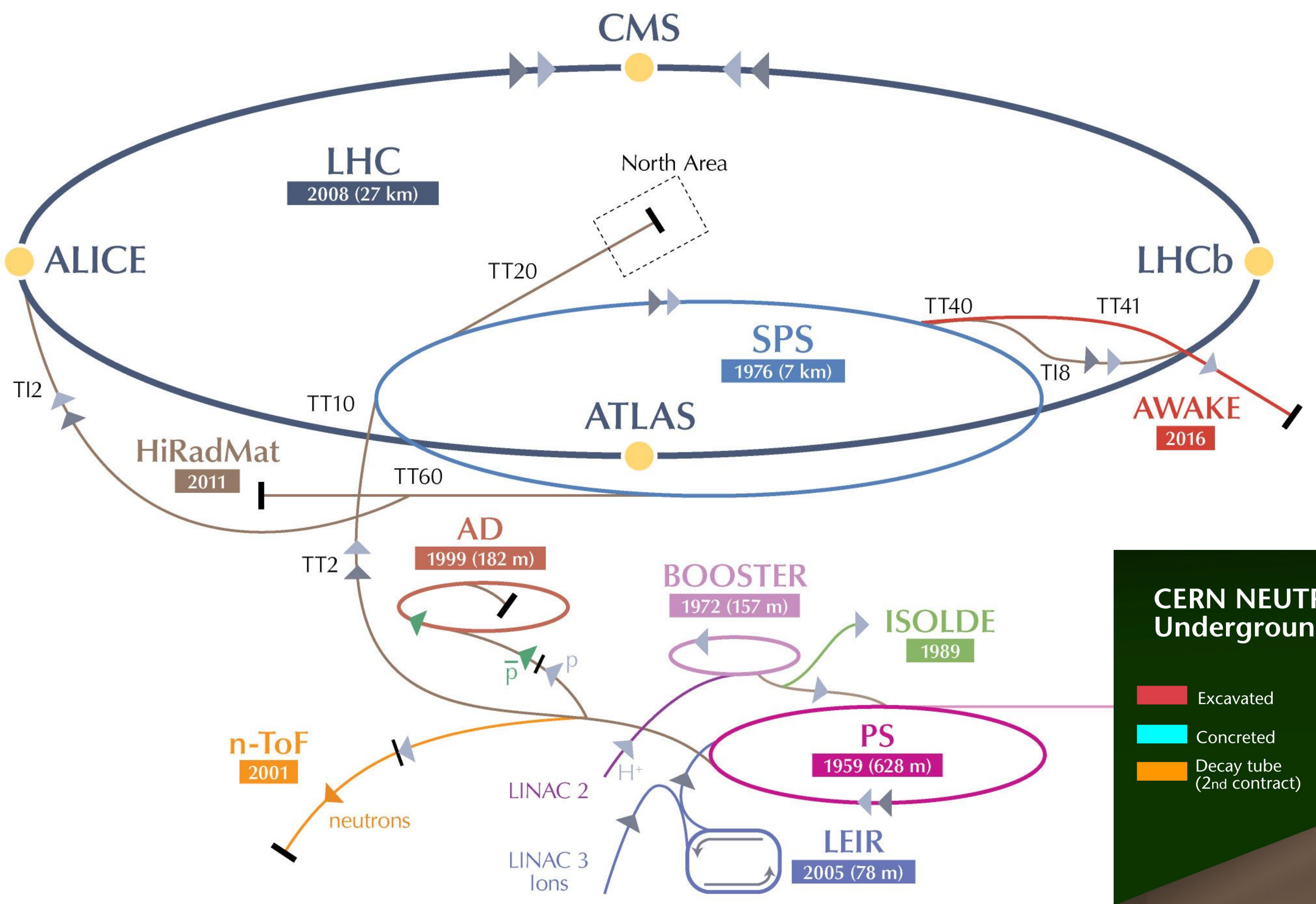
$$\Delta\mathcal{E}_{witness} \approx \frac{E_{acc}}{E_{dec}} \cdot \mathcal{E}_{driver,0} = R \cdot \mathcal{E}_{driver,0}$$

- R = 2 in the linear, unloaded regime
- R can slightly exceed 2 in the nonlinear regime
- Beamloading reduces R and is needed for high efficiency
- R ~ 1 is a realistic value for a nonlinear, high efficiency wake
- Energy gain per stage depends on drive beam energy
- Same beamstrahlung considerations as for LPA apply

**→ Optimum energy gain per plasma stage will be the result of a detailed collider design, likely at around 10 GeV**



# AWAKE experiment at CERN

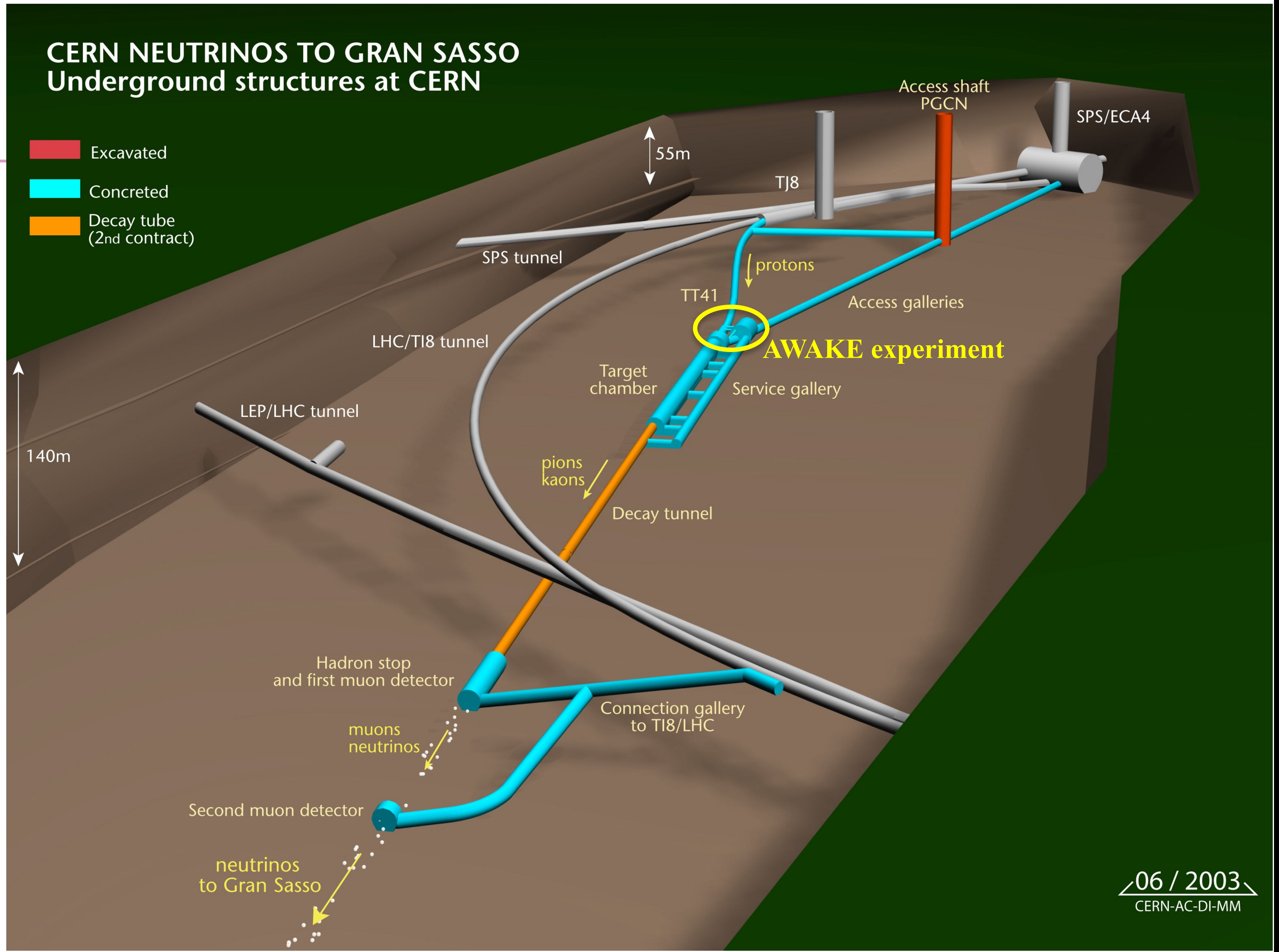



Demonstrate for the first time proton-driven plasma wakefield acceleration.

Advanced proton-driven plasma wakefield experiment.

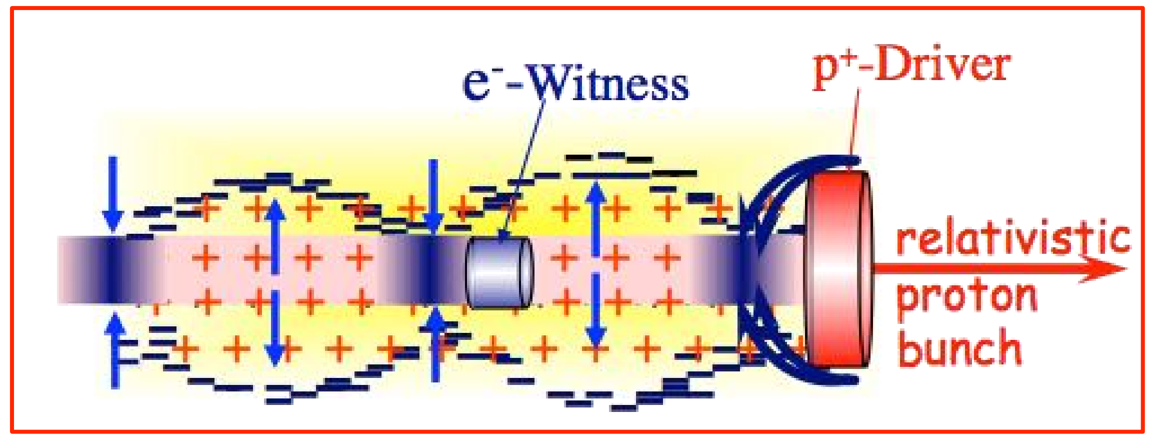
Using *400 GeV* SPS beam in former CNGS target area.

AWAKE Coll., R. Assmann et al., Plasma Phys. Control. Fusion **56** (2014) 084013



Rubidium vapor oven

# AWAKE*?




- p⁺-driven, plasma wakefield experiment @ CERN
- Relativistic p⁺ bunches carry kJ of energy => acceleration over 100's m
- Relativistic p⁺ are long (~10cm) => need self-modulation for mm μ-bunches to drive GV/m accelerating fields

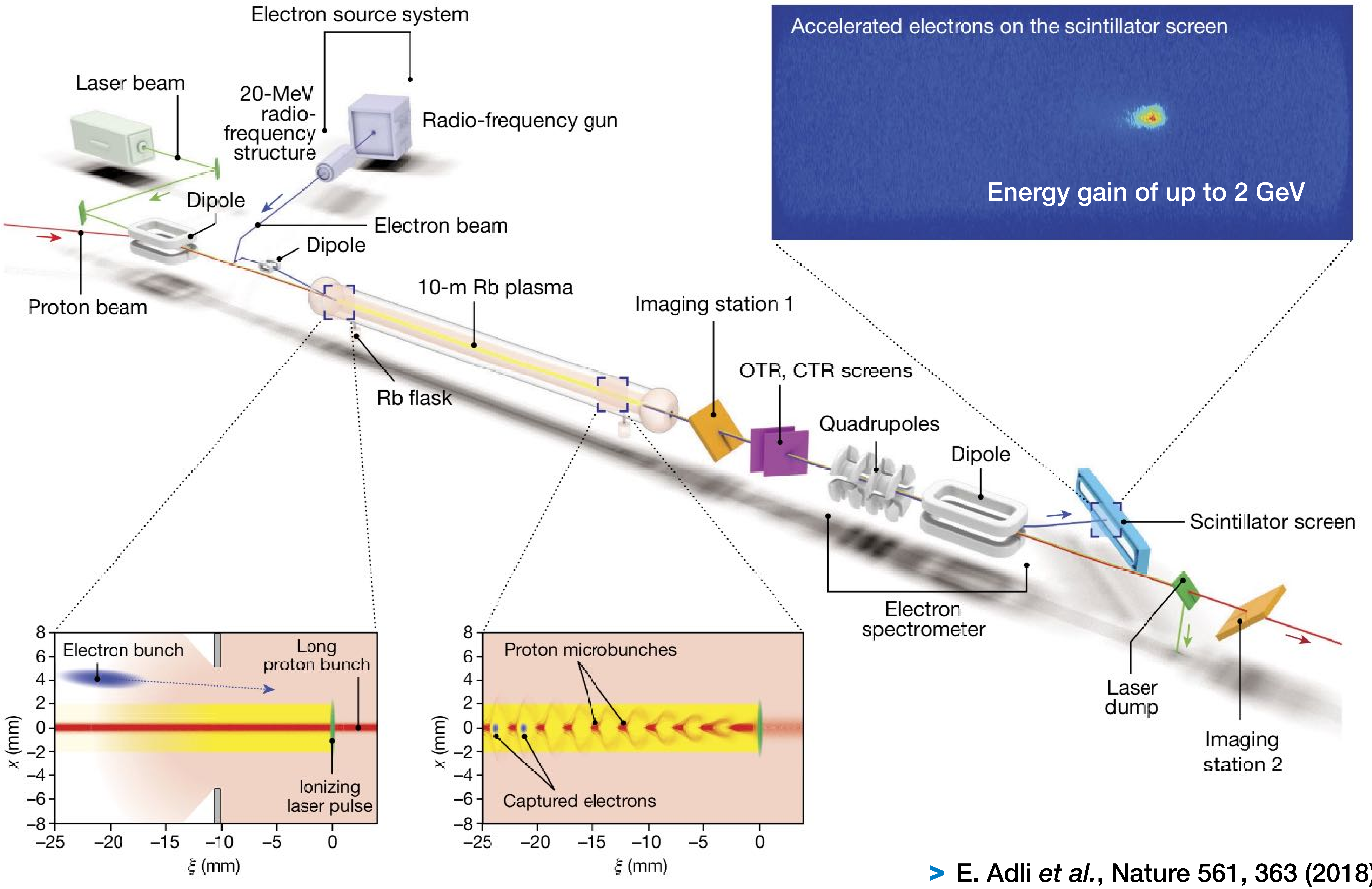
$$E_z \cong 100\sqrt{n_e\left(cm^{-3}\right)}\left(V/m\right)$$

$$E_z \cong \frac{3\times10^9}{\lambda_{pe}(mm)} = \frac{3\times10^9}{\sigma_z(mm)}(V/m)$$

- 1$^{st}$ step: demonstrate self-modulation of the 400GeV, SPS p+ bunch in a 10m, 1-10x10$^{14}$cm$^{-3}$ density plasma
- 2$^{nd}$ step: externally inject ~15MeV e⁻ and accelerate them to ~1GeV
- Explore and develop acceleration to 10s-100sGeV in long (10-100m) plasmas
- Explore applications to HEP: solid target experiments and e⁻/p⁺ collisions

*AWAKE = Advanced WAKefield Experiment

# AWAKE demonstrates first proton-driven PWFA




> E. Adli *et al.*, Nature 561, 363 (2018)

# Plasmas for mid-term particle physics applications

## AWAKE scheme enables high-energy experiments

**Requirements on emittance are moderate for fixed target and e/p collider experiments**

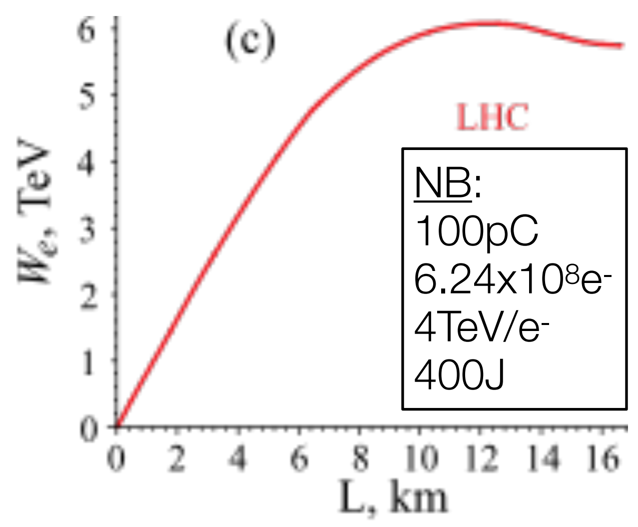
**Scalable AWAKE technology could be application-ready in 10 year-time frame**

Opportunity to use high-energy proton bunches:

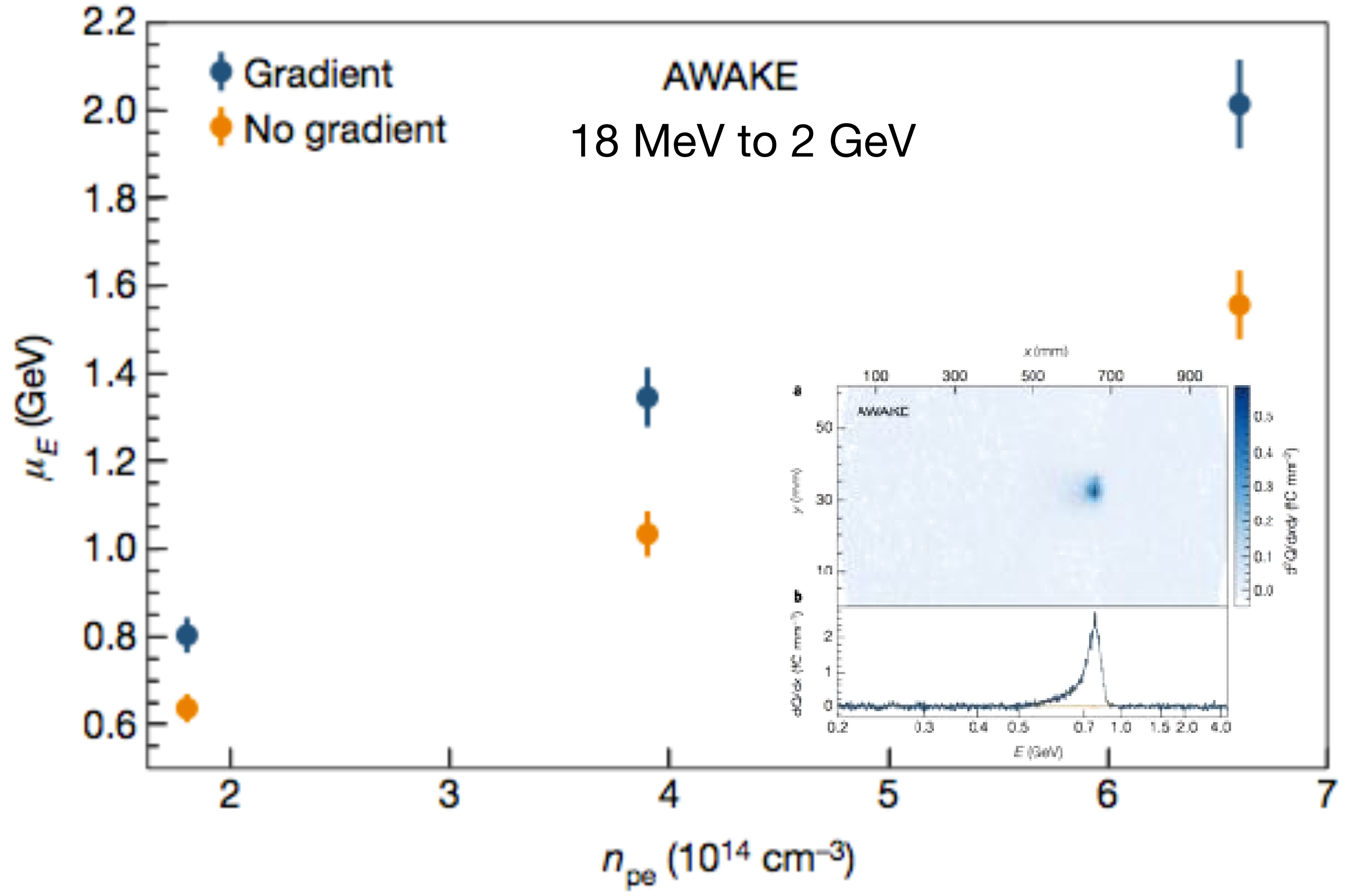
- **SPS** 400 GeV, 19 kJ SPS
- **LHC** 7TeV, 120 kJ LHC

to drive GeV/m accelerating gradients
in a single, long plasma for acceleration of electrons

~TeV in km ⇔ ~GeV/m



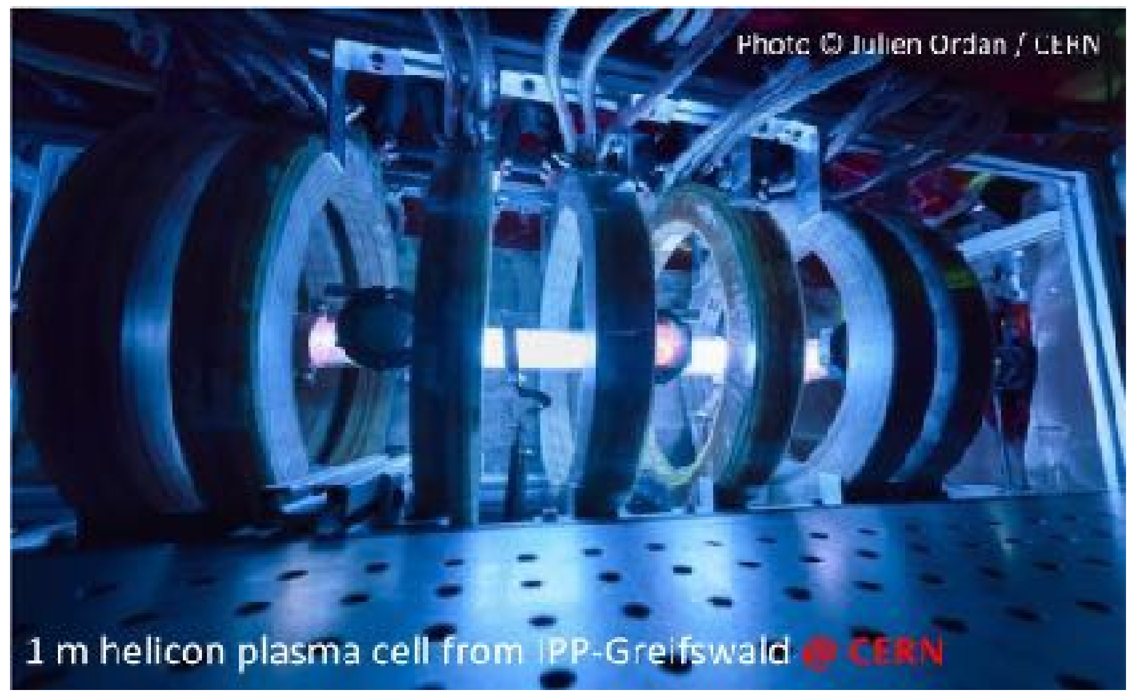

Caldwell, PoP **18**, 13101 (2011)




AWAKE, Nature **561**, 363 (2018)

Develop technology to enable

- high-quality electron beams
- scalable plasma lengths




**Applications**

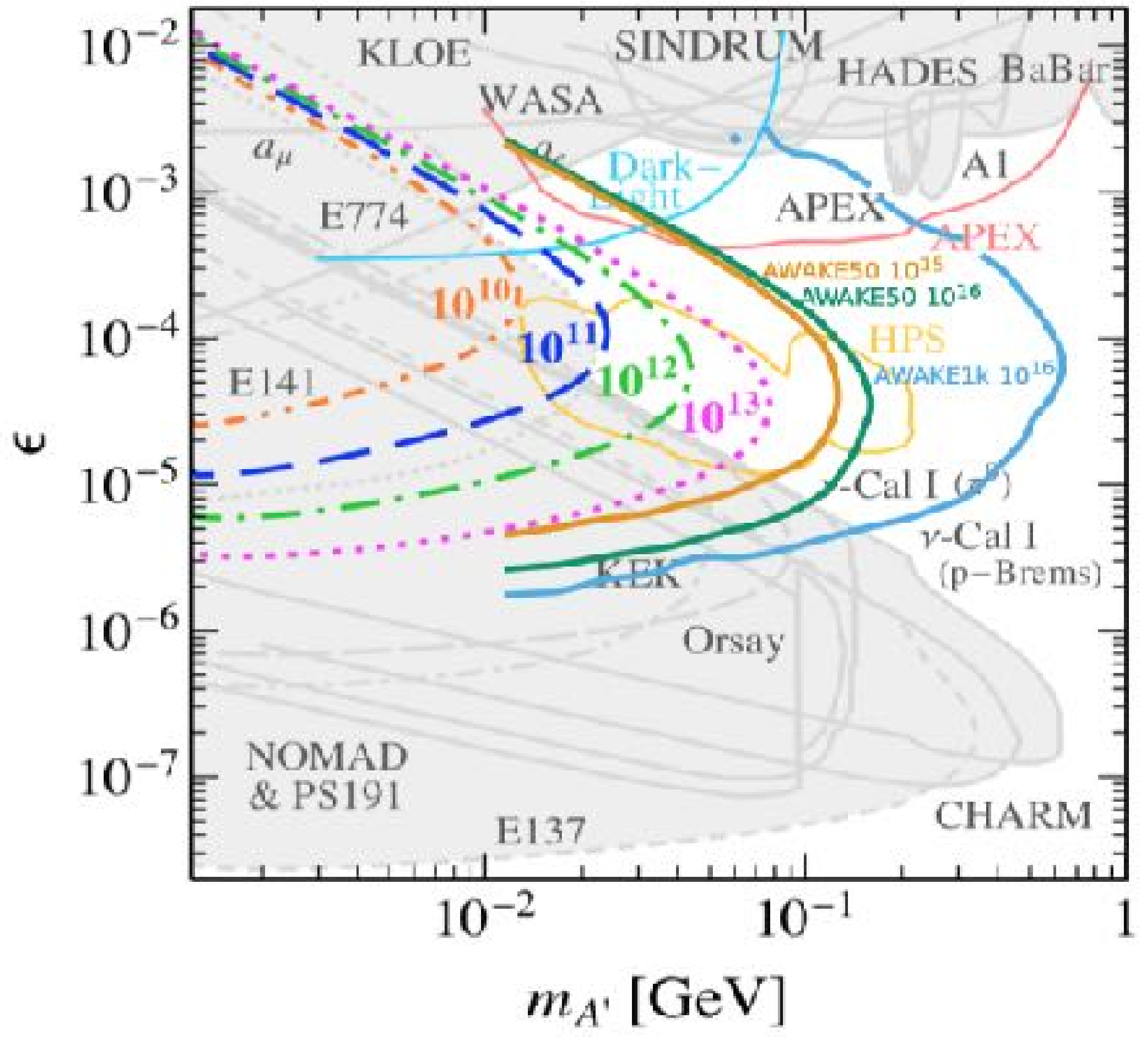
Mid-term (~10 years)

- Fixed target experiments, 30 GeV e-
- Search for dark photons

Long-term

- Very High Energy Electron-Proton (VHEEP) collider

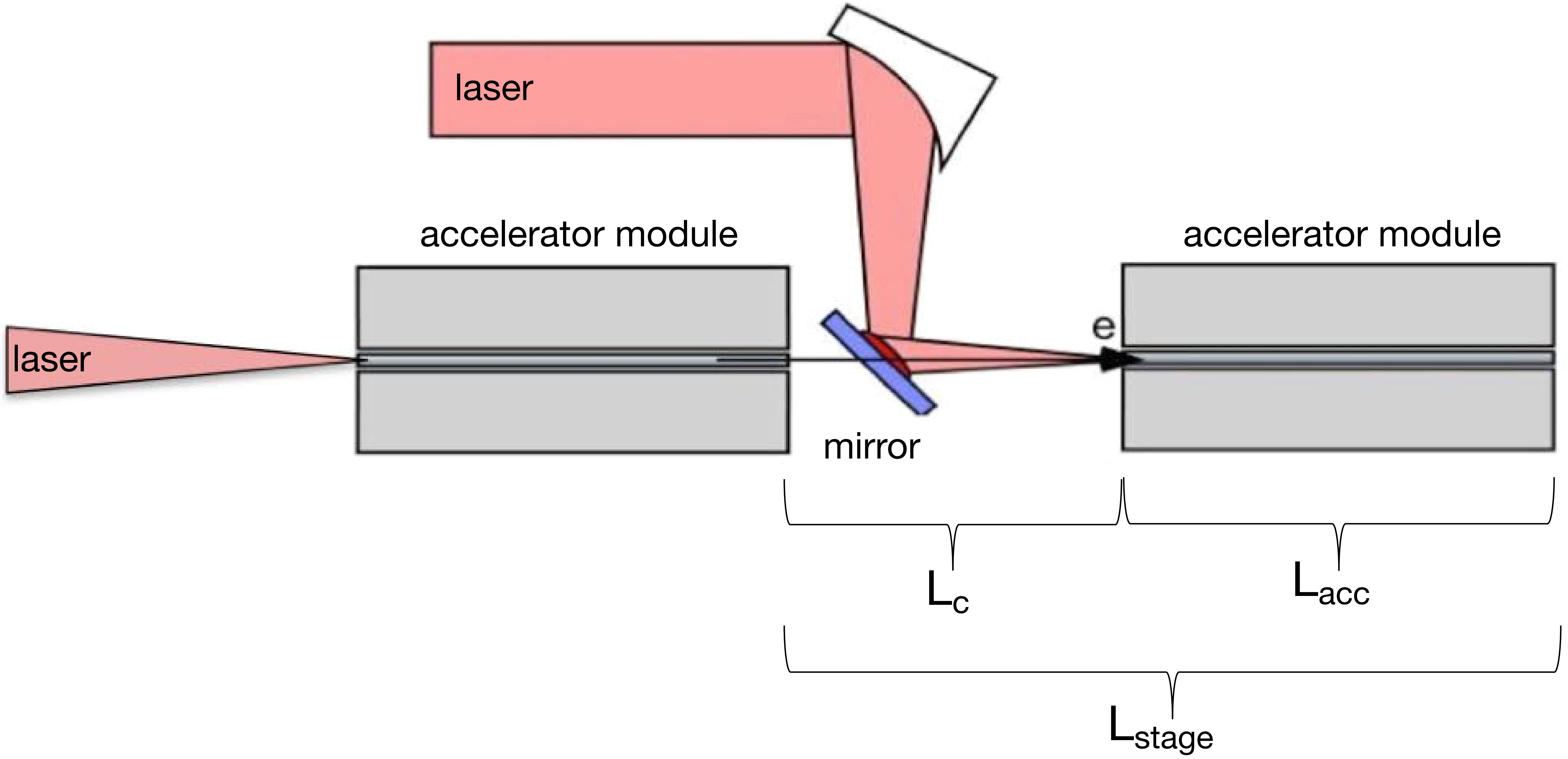
Caldwell *et al.*, Eur Phys J C **76**, 463 (2016)
Wing *et al.*, Phil Trans A Math Phys Eng Sci., **377**, 2151 (2019)



# Multi-stage acceleration

# Definition of staging

## Staging requires a fresh wakefield driver per stage




- **Two things need to occur between stages**
  - Out-coupling of the depleted driver, and in-coupling of a fresh driver
  - Capture and refocusing of the accelerated/witness bunch

# Simplest staging concept demonstrated at Berkeley Lab

## Deployed setup contains all crucial ingredients, needs further development for applications

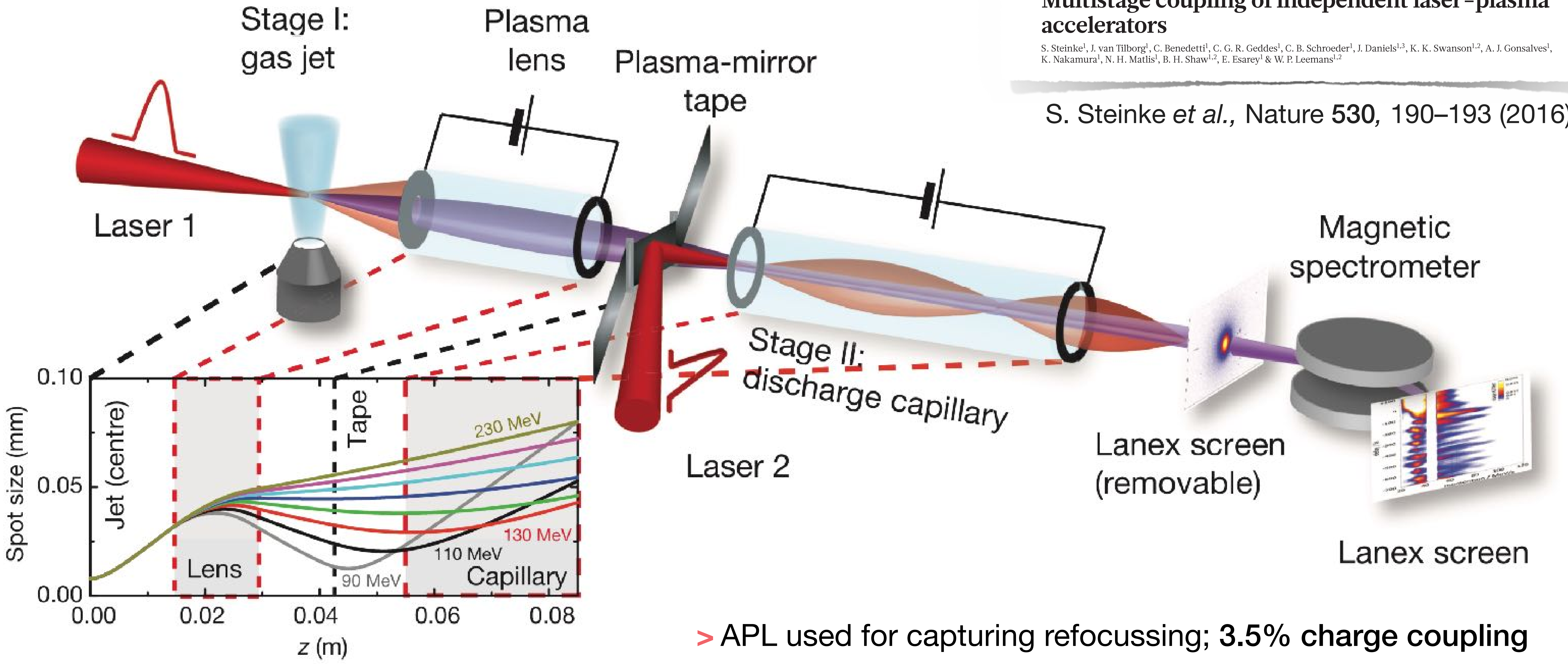

LETTER

doi:10.1038/nature16525

**Multistage coupling of independent laser–plasma accelerators**

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]

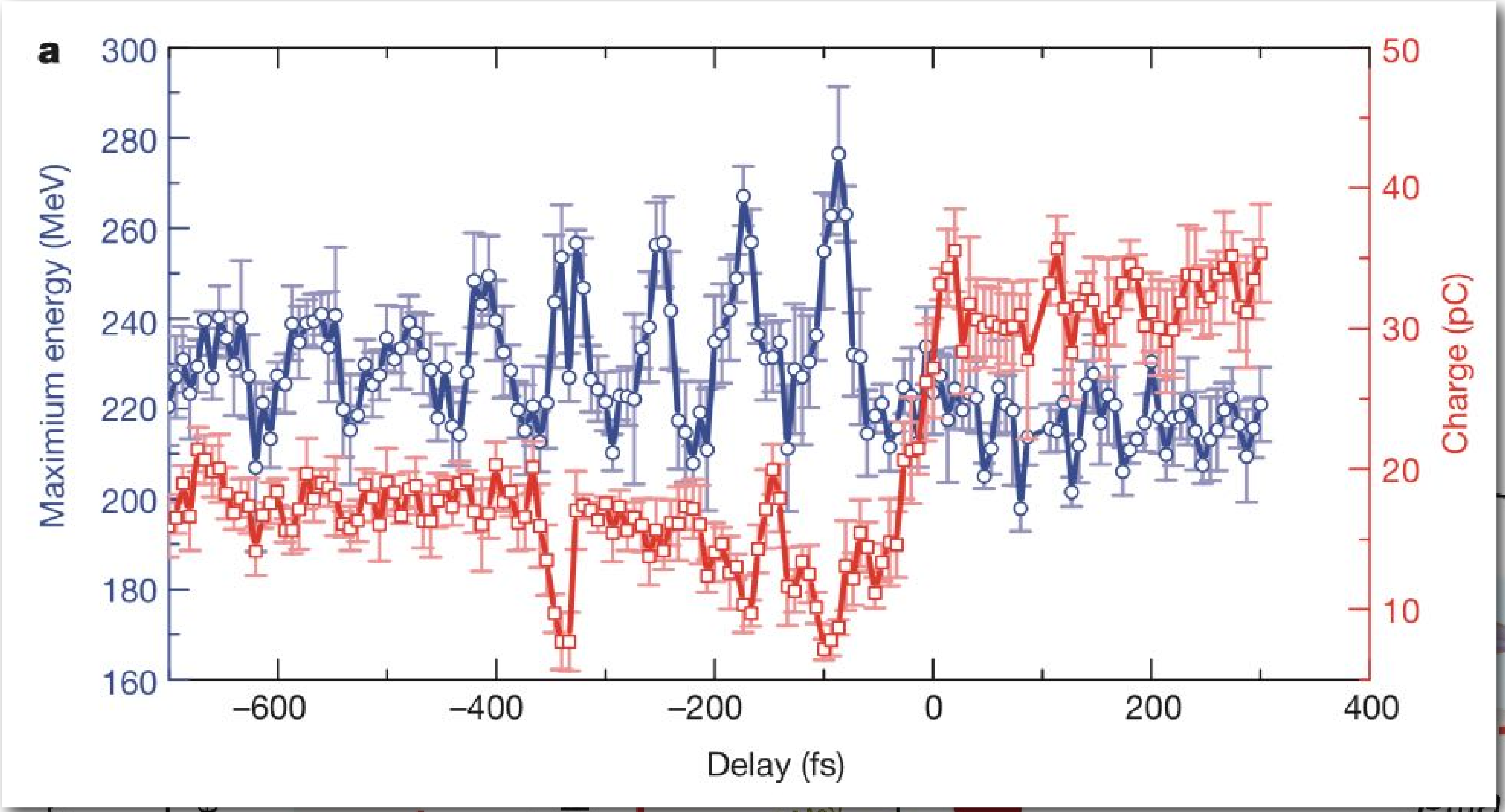
S. Steinke *et al.*, Nature **530**, 190–193 (2016)




> APL used for capturing refocussing; **3.5% charge coupling**

# Simplest staging concept demonstrated at Berkeley Lab

## Deployed setup contains all crucial ingredients, needs further development for applications





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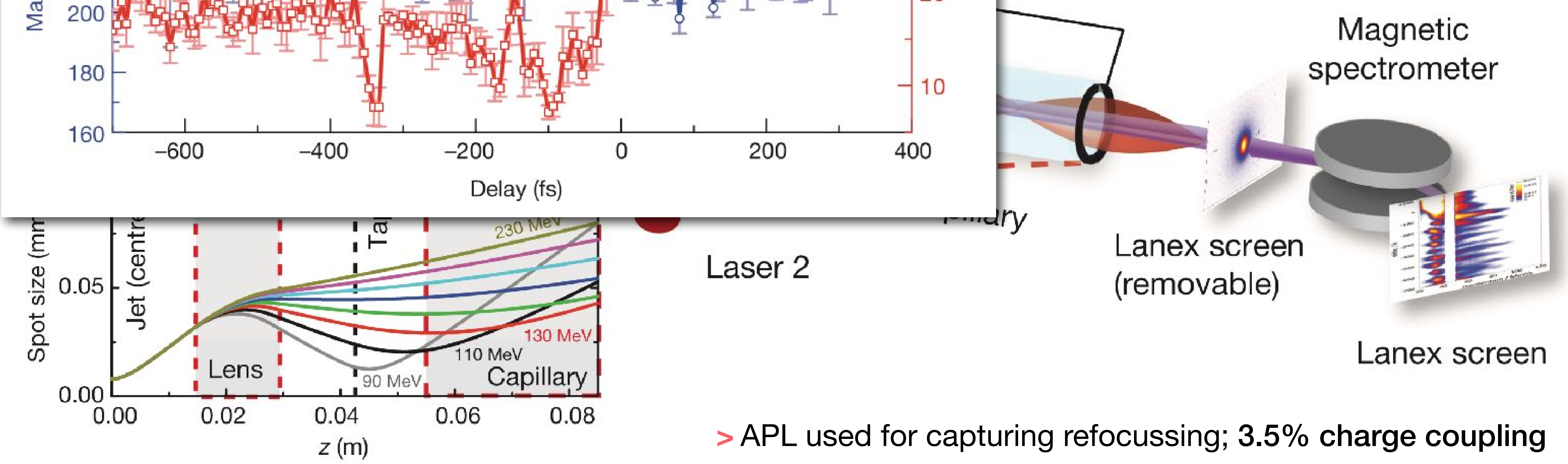
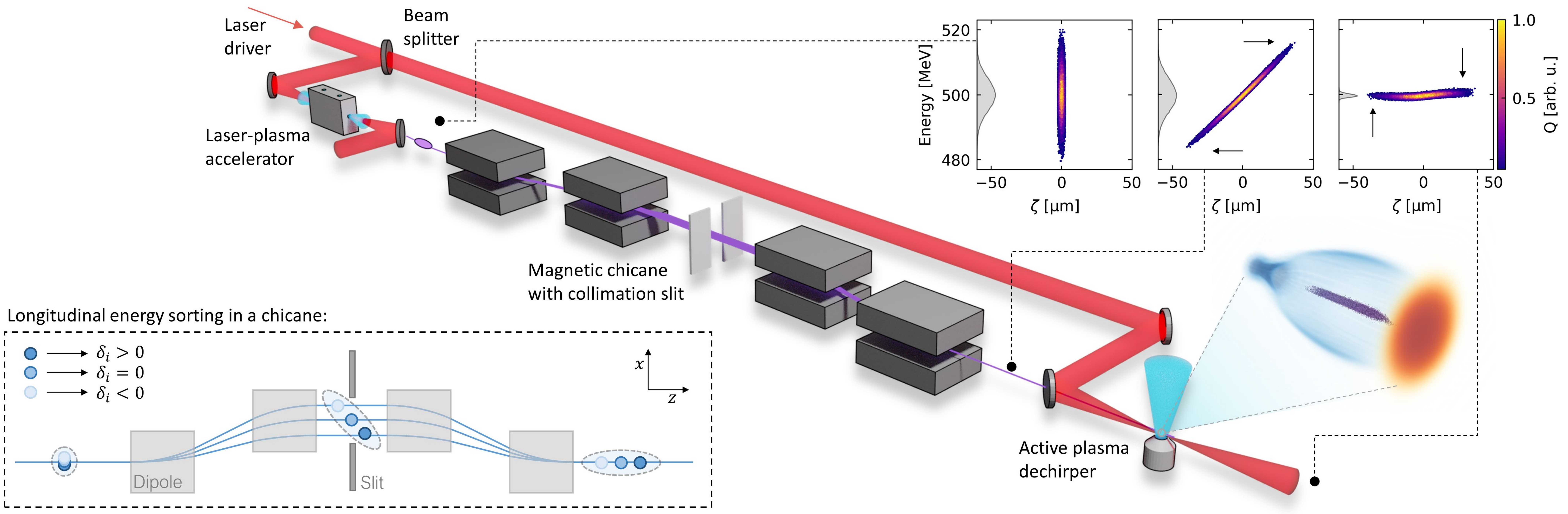



> APL used for capturing refocussing; **3.5% charge coupling**

# An active plasma dechirper for reducing energy bandwidth and jitter

## Permille-level energy spread conceptually achievable



# An active plasma dechirper for reducing energy bandwidth and jitter

## Permille-level energy spread conceptually achievable

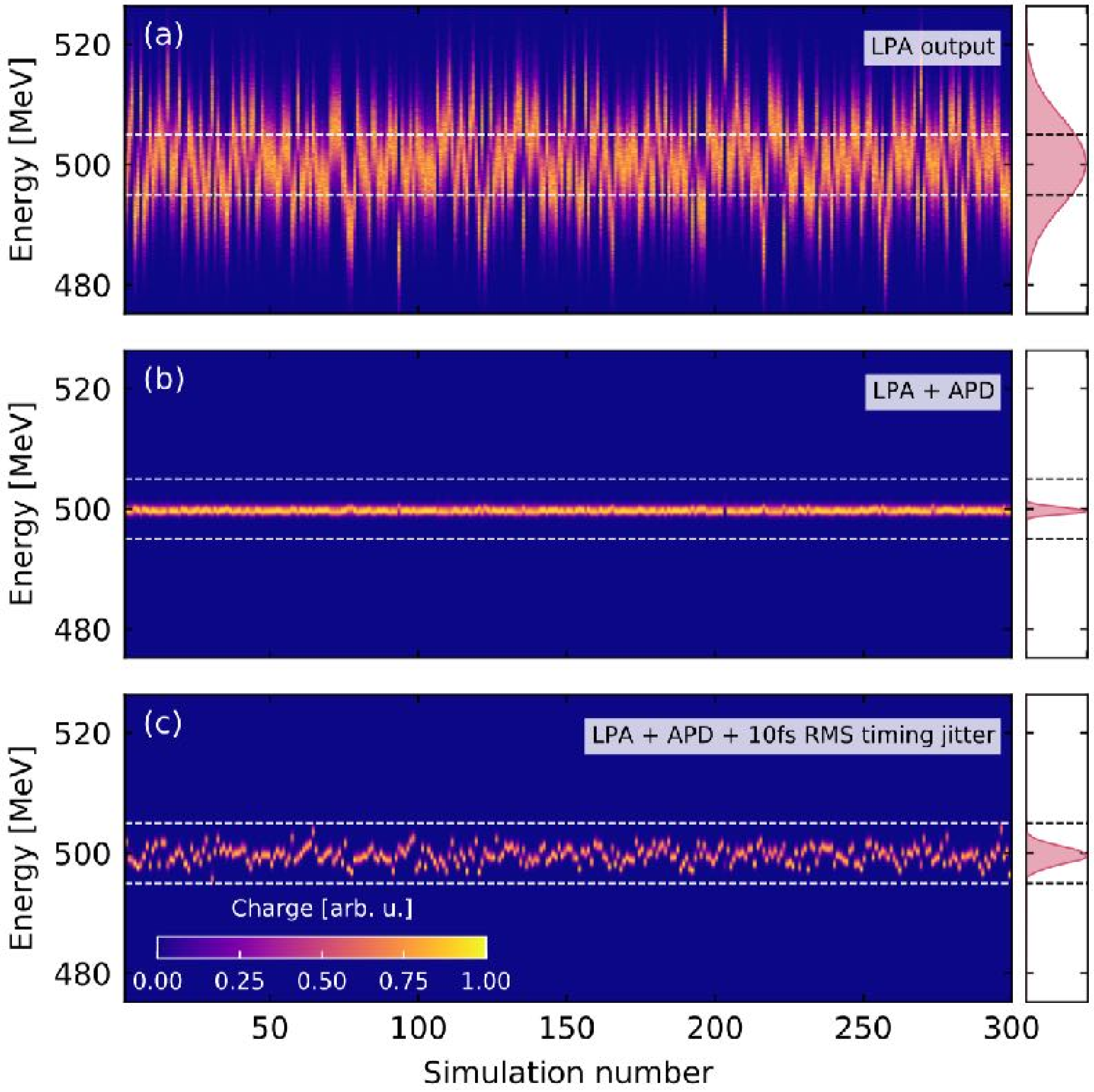
**Beam** $\varepsilon_{x,y} = 1\ \mu\text{m}$, $\mathcal{E} = 500\ \text{MeV}$
$\Delta\,\mathcal{E} = 1\ \%$ $\delta\mathcal{E} = 1\ \%$ div = 0.5 mrad

**With stabilizer (chicane + dechirper)**
**Plasma** $n_e = 4 \times 10^{16}\ \text{cm}^{-3}$, 5.5 mm
**Laser** $\tau = 25\ \text{fs}$, $a_0 = 2$ 2J $w_0 = 24\ \mu\text{m}$

**With stabilizer (chicane + dechirper) and 10 fs timing jitter**

**Energy Compression and Stabilization of Laser-Plasma Accelerators**

A. Ferran Pousa,[1,*] I. Agapov,[1] S. A. Antipov,[1] R. W. Assmann,[1,2] R. Brinkmann,[1] W. P. Leemans,[1,3] A. Martinez de la Ossa,[1] J. Osterhoff,[1] and M. Thévenet[1]
[1]*Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
[2]*Laboratori Nazionali di Frascati, Via Enrico Fermi 40, 00044 Frascati, Italy*
[3]*Department of Physics Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*
(Dated: June 9, 2021)
arXiv



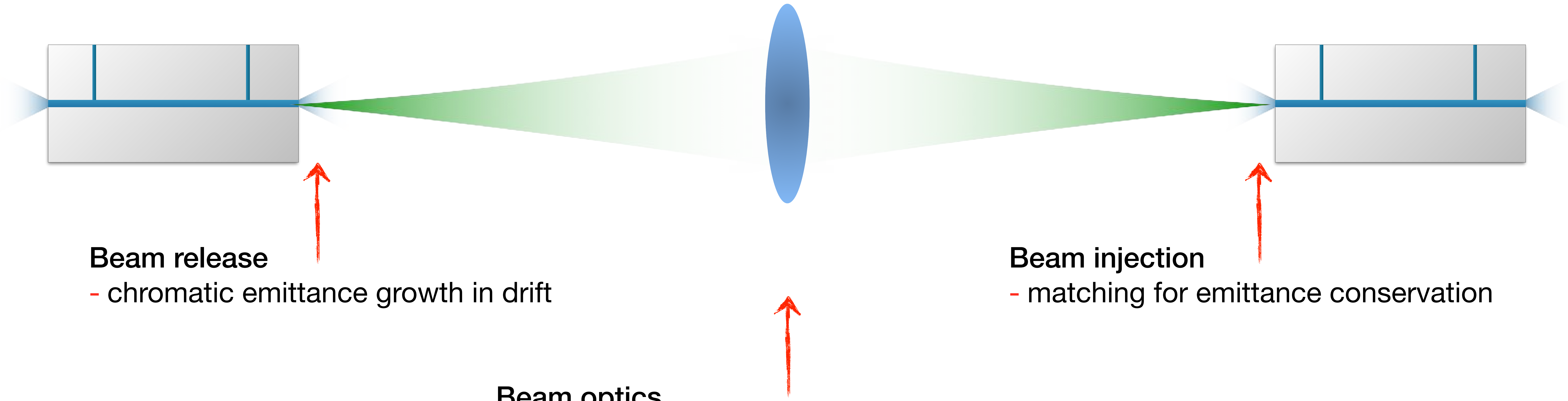
# Staging demands for collider application

## Going beyond what has been demonstrated

- Preservation of bunch charge → efficiency → luminosity (→ operation cost)
- Preservation of normalized transverse emittance on ~10 nm level → spot size at IP → luminosity
- Operation at high repetition rate and average power → luminosity
- Limited inter-stage distance to keep effective gradient > 1 GV/m, implying < 1 km/TeV → construction cost

# Compact, emittance-conserving interstage beam transport

## I. Particle beam transport



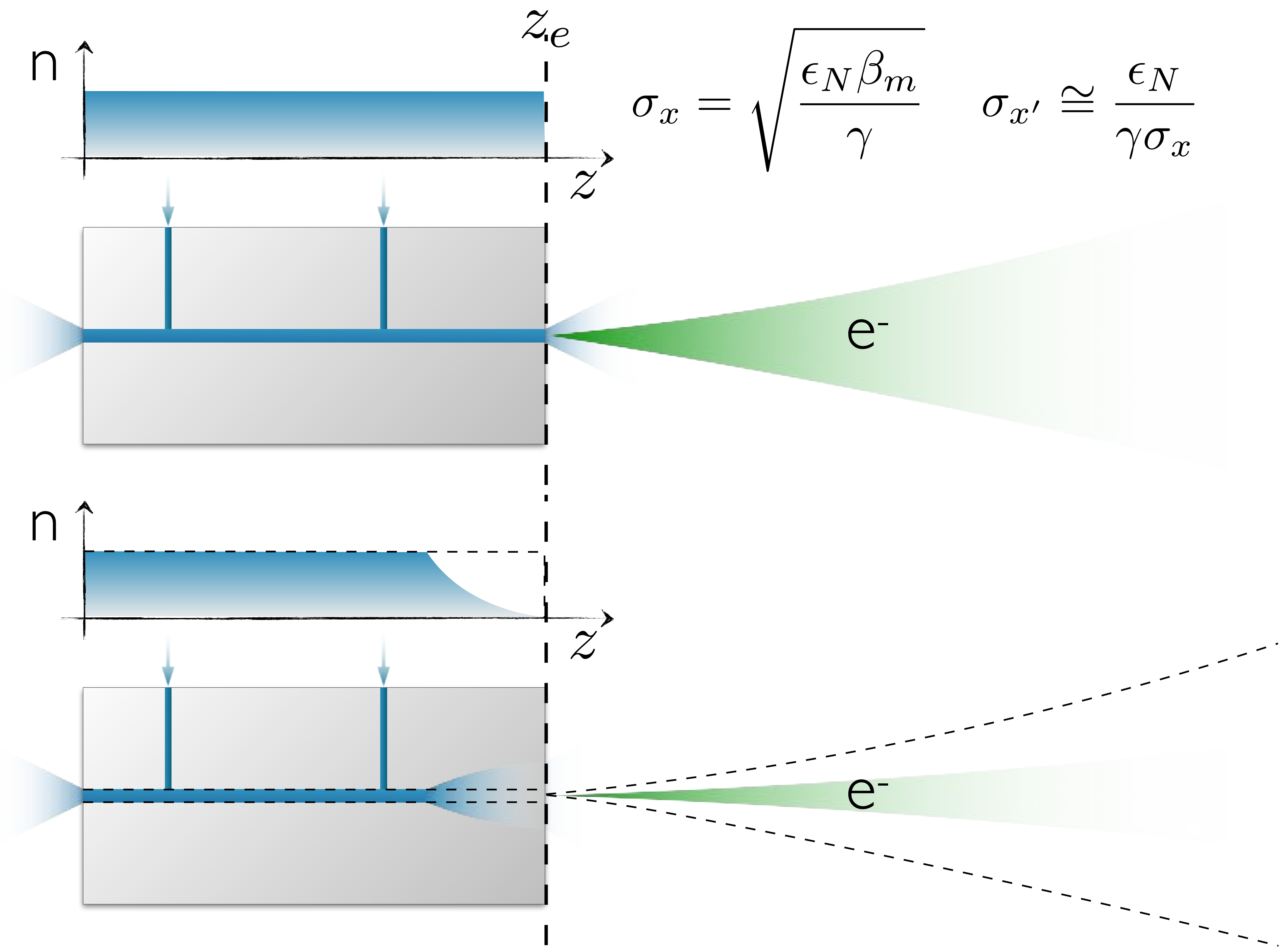
**Beam release**
- chromatic emittance growth in drift

**Beam injection**
- matching for emittance conservation

**Beam optics**
- nonlinear fields → emittance growth
- field gradient × length → coupling distance

# Beam release from plasma

## I. Particle beam transport




$$\sigma_x = \sqrt{\frac{\epsilon_N \beta_m}{\gamma}} \qquad \sigma_{x'} \cong \frac{\epsilon_N}{\gamma \sigma_x}$$

**Case:** $n_e = 10^{17}\ \mathrm{cm}^{-3}$, $\varepsilon_N = 10$ nm, $\sigma_p/p = 0.5\%$

- **10 GeV stage**
  - → $\beta_m \approx 3$ mm, $\sigma_x \approx 40$ nm, $\sigma_{x'} \approx 10$ µrad
  - → **10 nm / m emittance growth in drift**
- **1 TeV stage**
  - → $\beta_m \approx 30$ mm, $\sigma_x \approx 10$ nm, $\sigma_{x'} \approx 0.3$ µrad
  - → **1 nm / m emittance growth in drift**

$$\epsilon_N^{*\,2}(z) \cong \epsilon_N^2 + \gamma^2 \frac{\sigma_p^2}{p^2} \sigma_{x'}^4 z^2$$

> beams at plasma exit
- finite energy spread
- finite emittance and matched β → finite divergence

> leads to growth of transverse emittance in free drift

→ K. Floettmann, Phys. Rev. STAB **6**, 034202 (2003)

R. Robson *et al.*, Annals of Physics **356,** 306 (2015)
T. Mehrling *et al.*, NIM A **829**, 367 (2016)

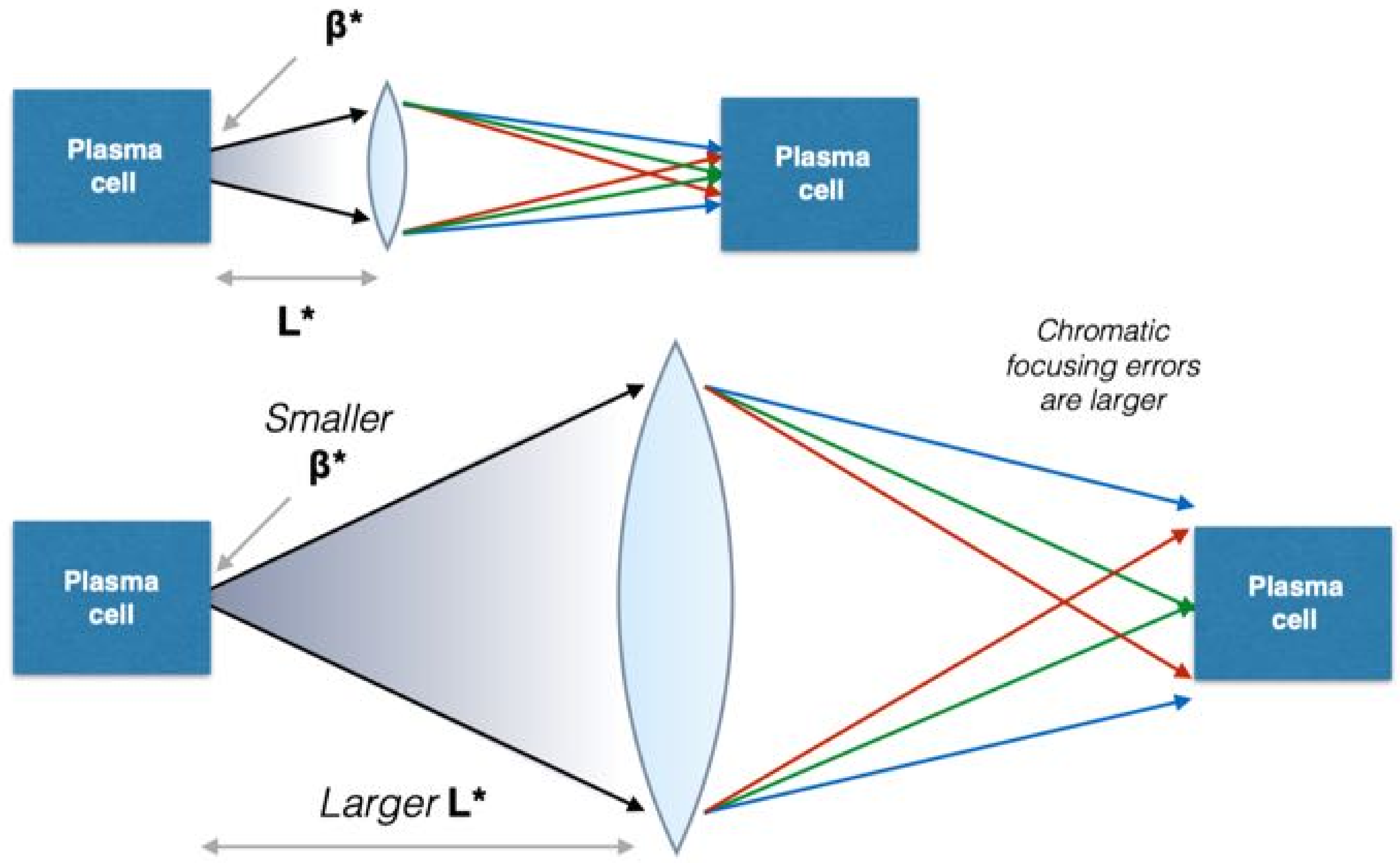
# Beam matching into plasma

## I. Particle beam transport

> Chromaticity = Different energies are focused differently.

> While the emittance of each energy slice IS preserved, the **projected (energy-averaged) emittance IS NOT preserved**.

> For plasma wakefield accelerators, all energy slices must be matched to avoid further emittance growth in the plasma ion column.




Matching conditions

$$\alpha_m = 0 \qquad \beta_m \simeq \frac{c}{\omega_\beta} \qquad \omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$$

> **Do we need matching even at high energies?**

→ T. Mehrling *et al.*, Phys. Rev. STAB **15**, 111303 (2012)

$$\epsilon_{n,\mathrm{fin}} = \frac{\epsilon_{n,\mathrm{init}}}{2}\left(\frac{1+\alpha^2}{\beta^*} + \beta^*\right) \quad \text{with} \quad \beta^* = \beta/\beta_m$$

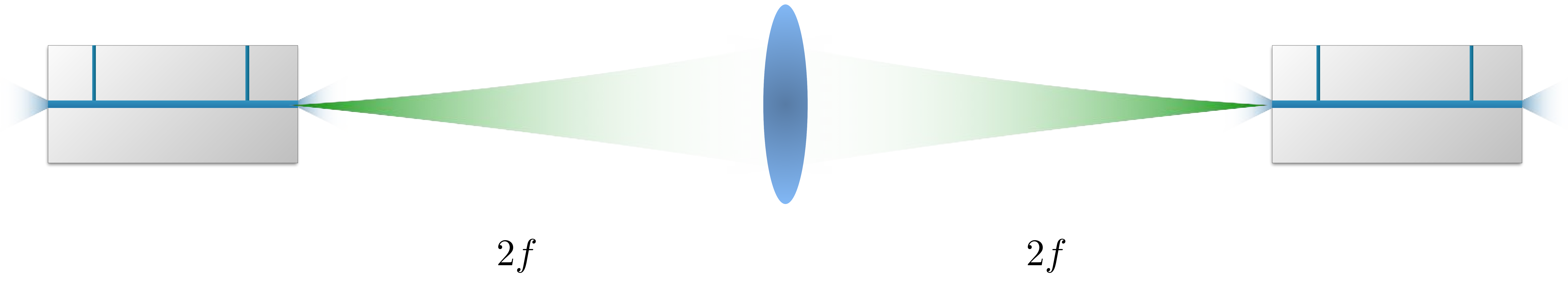
and $\alpha(z) = -\frac{z}{\beta_m} \qquad \beta(z) = \beta_m + \frac{z^2}{\beta_m}$

$$\rightarrow \epsilon_N^* = \epsilon_N\left(1 + \frac{z^2}{2\beta_m^2}\right)$$

> **for z = $\beta_m$ emittance grows by 50% w/o matching ($\beta_m \approx$ 33 mm for 1 TeV)**

# Scaling of coupling distances

## I. Particle beam transport




**Coupling distance $L_c$**

- 1:1 point-to-point imaging of beam with $\alpha=0$ and $\beta=\beta_m$ at exit cell $n$ and entrance cell $n+1$, thin lens approximation…

$$L_c = 4f \quad \text{with} \quad f = (kL_{lens})^{-1} \qquad k[m^{-2}] = \frac{0.3 \cdot g[T/m]}{p[GeV/c]}$$

- aim at $L_c = L_{acc}$ with $L_{acc} \approx$ 1m
- **$L_{lens}$ = 0.13m for 10 GeV beam with $g$ = 1kT/m**

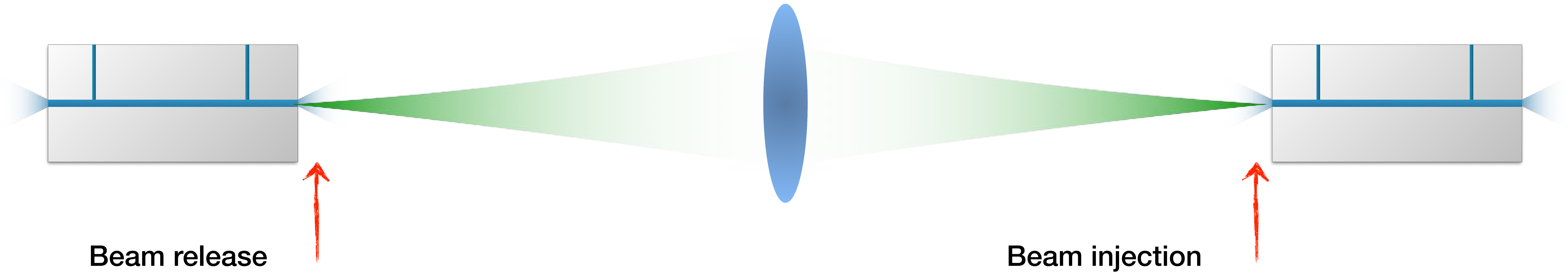
$$L_{lens} f = \frac{p}{0.3 \cdot g}$$

→ **solution for 1 TeV with fixed $g$: $L_{lens}$ = 1.3m mit $L_c$ = 10m**

***But:*** beam size in lens!
6 µm for 10 GeV
2 µm for 1 TeV

# Summary of interstage beam transport

## I. Particle beam transport



**Beam release**
- want small energy spread
- want plasma density tailoring for adiabatic release

**Beam injection**
- need beam matching even at TeV energies

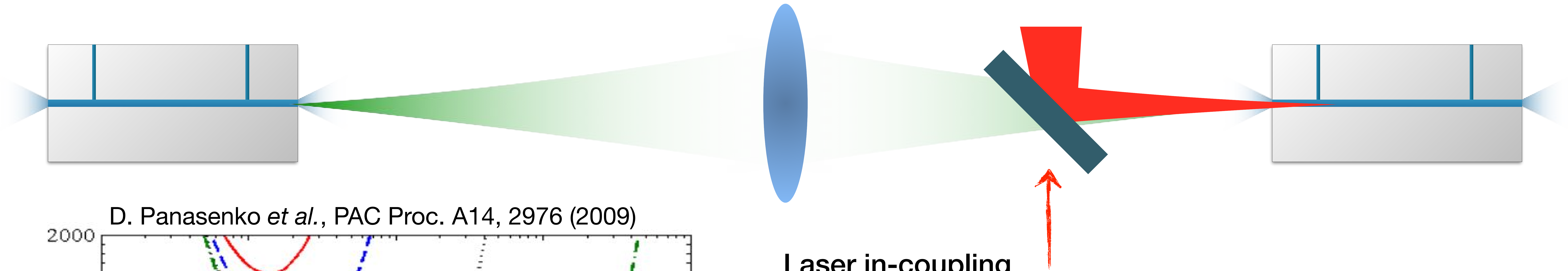
**Beam optics**
- want 1 kT/m × 1 m scale focussing optics to conserve emittance and keep coupling distances in range 1 to 10 $L_{acc}$
- plasma-based lenses may not work owing to generated wakefields

# Compact laser in-coupling

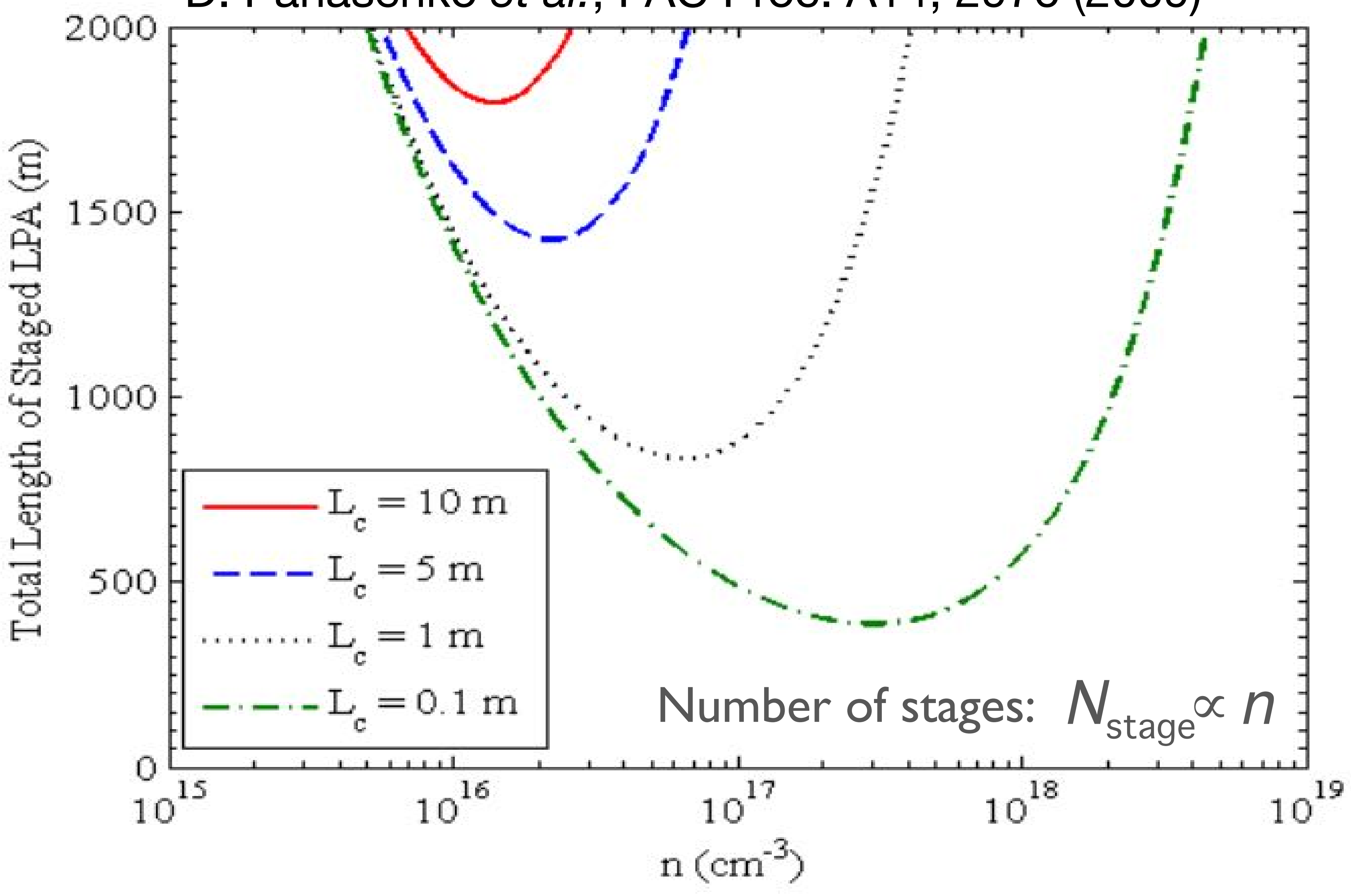
## II. Laser beam transport

**Challenge: jitter/pointing tolerances**

- **jitter in timing**
  → jitter in energy + energy bandwidth (beamloading)
- **pointing fluctuations** must be less than matched
  $\sigma_x \approx$ 10 nm (compare to laser spot size of $\sim\lambda_p$)
  → emittance degradation
  cf. R. Assmann and K. Yokoya, NIM A 410, 544 (1998)



D. Panasenko *et al.*, PAC Proc. A14, 2976 (2009)




**Laser in-coupling**

- mirror technology for short coupling distances

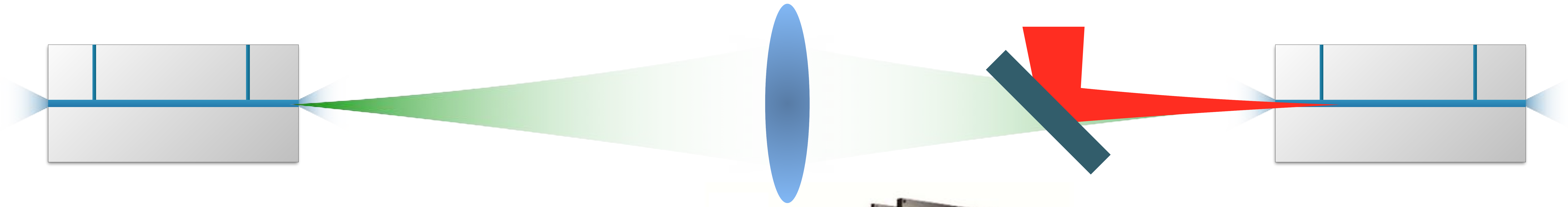
> conventional mirrors require ~10 m distance from focal point to prevent damage (for PW-class lasers and required f-number)

> degradation of effective accelerating field strength by > 1 order of magnitude acceptable?

> $L_c$ may dictate multi-stage accelerator length for $L_{acc} \approx$ 1 m

# Compact laser in-coupling

## II. Laser beam transport

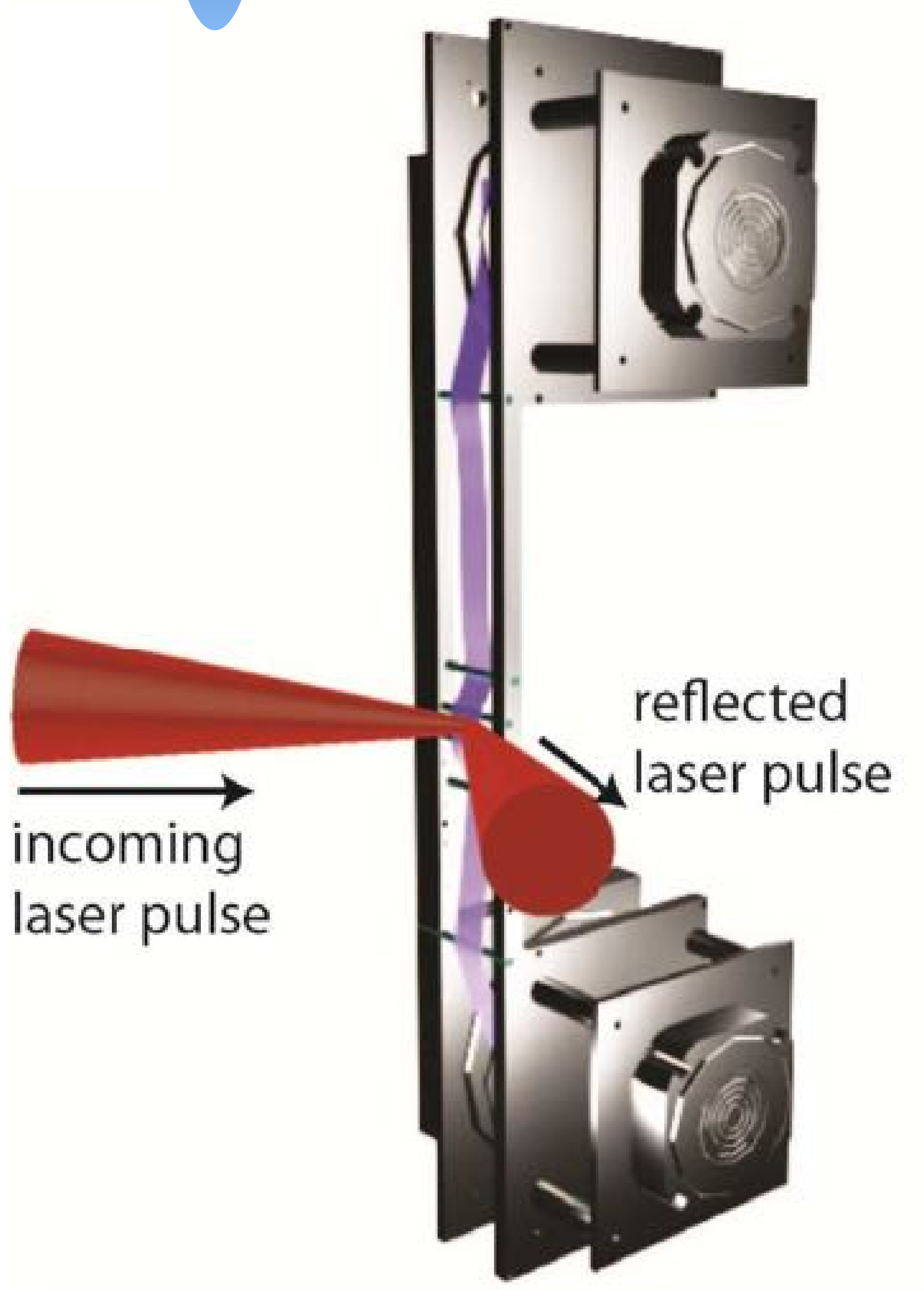


**Option: plasma mirror**

- based on liquid jet
  → D. Panasenko *et al.*, PAC Proc. A14, 2976 (2009)
- based on tape drive
  → T. Sokollik *et al.*, AIP Conf. Proc. 1299, 233 (2010)

**Challenge**

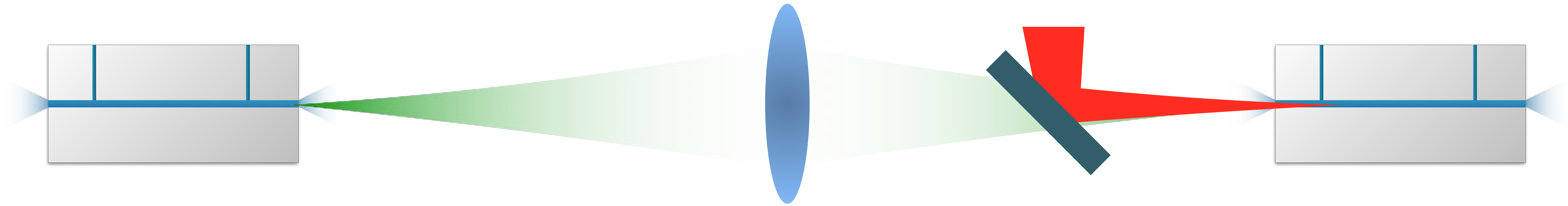
- emittance growth due to beam scattering in mirror & collective plasma effects?
- impact on efficiency? reflectivity ~80%




High laser intensity (~$10^{16}$ W/cm$^2$) generates an optically flat, critical-density plasma surface
→ minimizes $L_c$ to cm-scale

# Emittance growth to multiple small-angle scattering

## II. Laser beam transport



Minimum mirror thickness → order of plasma skin depth (efficiency, do not want to waste laser energy)

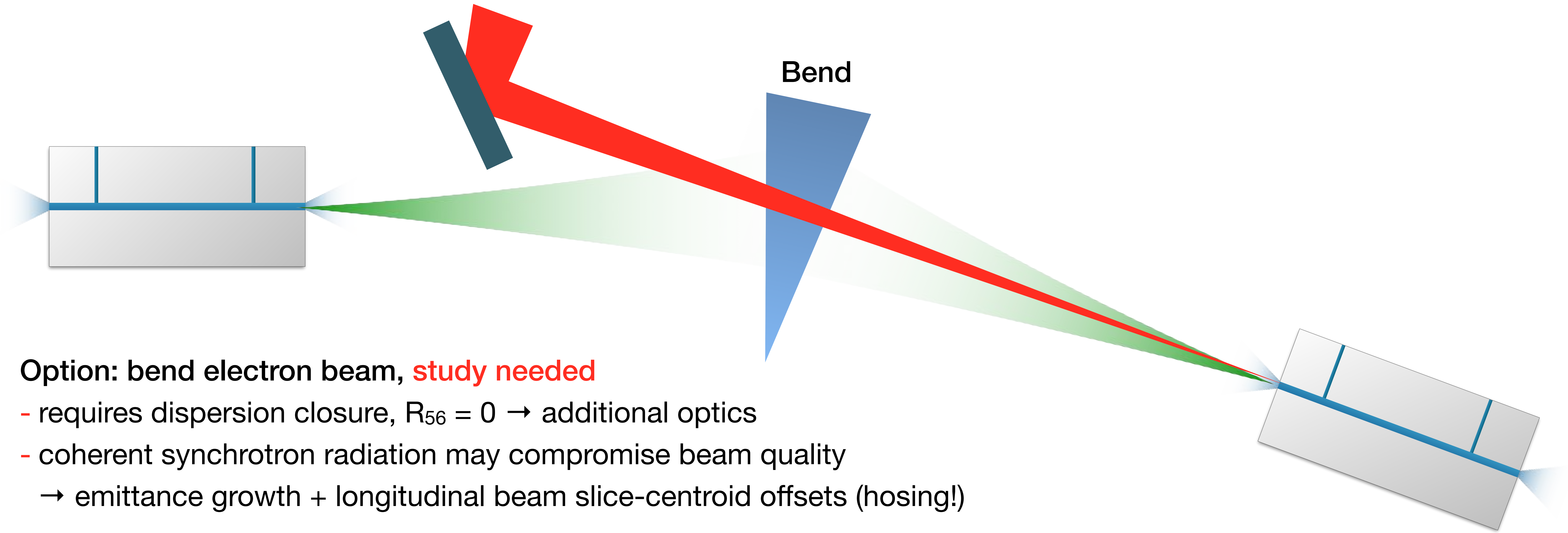
- skin depth ~50 nm for $10^{22}$ cm$^{-3}$ plasma
- scattering angle $$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$
- $x/X_0$ is mirror thickness in radiation lengths
- z is charge number of incident particle
- *example:* thin water-jet with $X_0$ = 36 cm

**→ $\theta_0$ (10 GeV) = 1.3 µrad (compare to $\sigma_{x'}$ = 10 µrad, ~13%/stage)**

**→ $\theta_0$ (1 TeV) = 0.013 µrad (compare to $\sigma_{x'}$ = 0.3 µrad, ~4%/stage)**

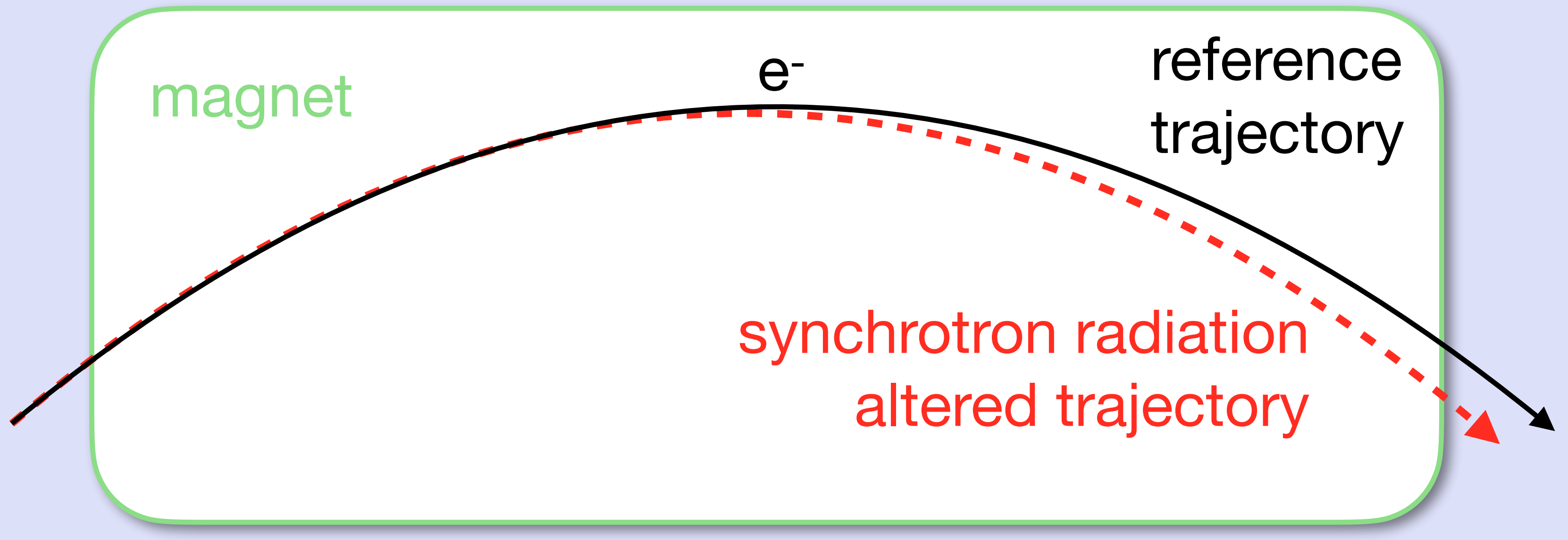
# Alternatives to straight solutions?

## II. Laser beam transport




**Option: bend electron beam, study needed**

- requires dispersion closure, $R_{56} = 0$ → additional optics
- coherent synchrotron radiation may compromise beam quality
  → emittance growth + longitudinal beam slice-centroid offsets (hosing!)




**Formation of slice-centroid offsets in high-current bunches**

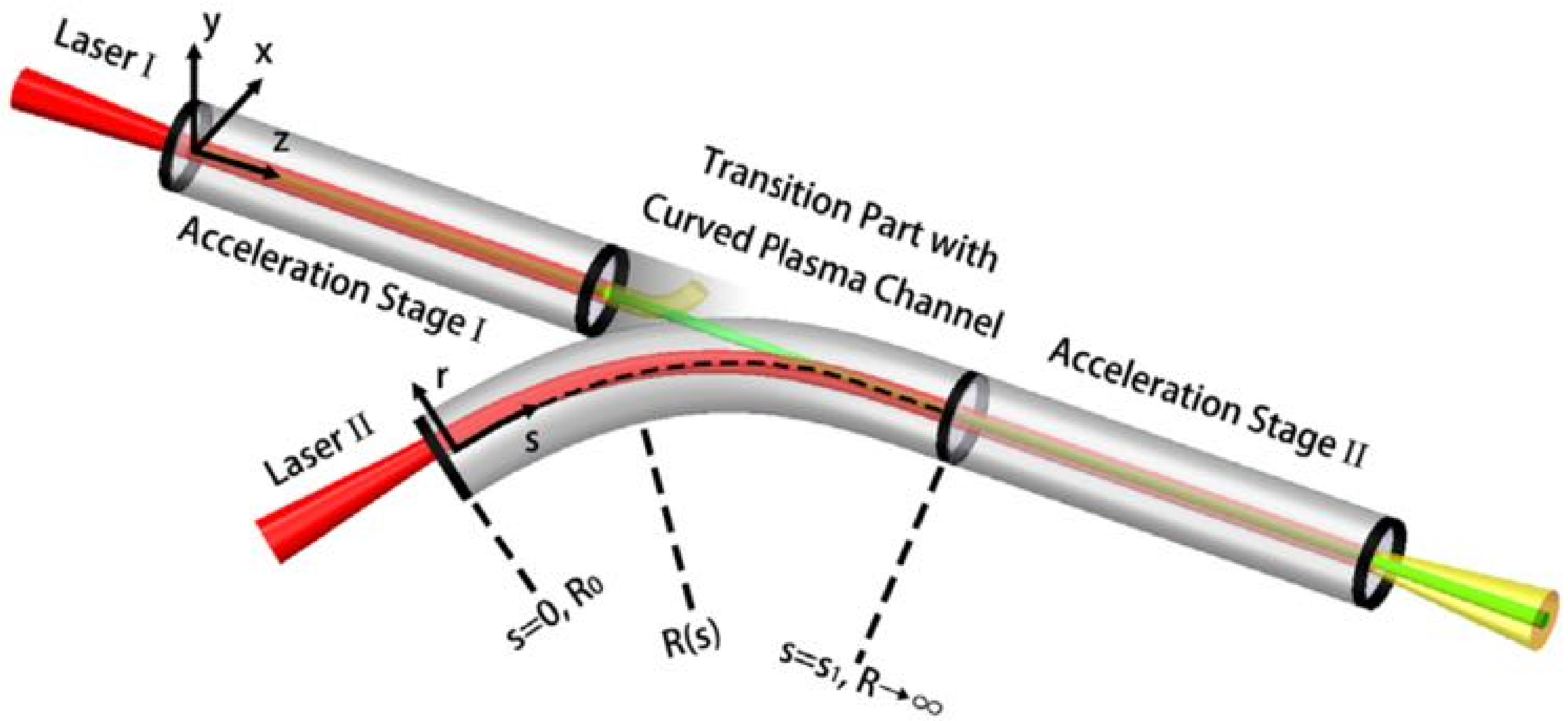
> emission of synchrotron radiation in dispersive element
→ causes energy loss → dispersion not closed
→ kick/offset w.r.t. reference orbit

> energy loss/kick dependent on slice current
→ non-uniform along beam

> emitted radiation acts back on beam

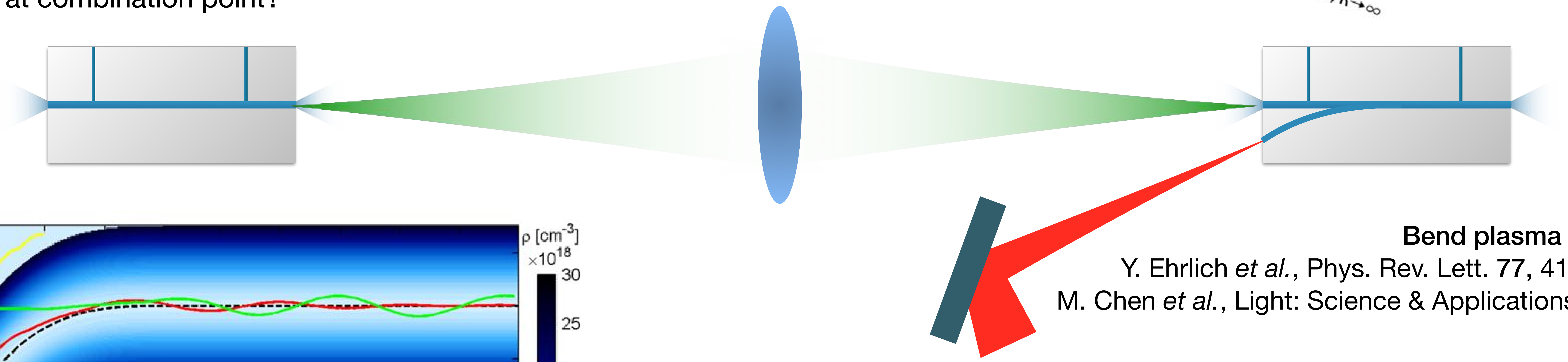
# Alternatives to straight solutions?

## II. Laser beam transport




**Option: bend plasma channel to combine laser and beam**

- allowed radius of curvature?
- effects at combination point?



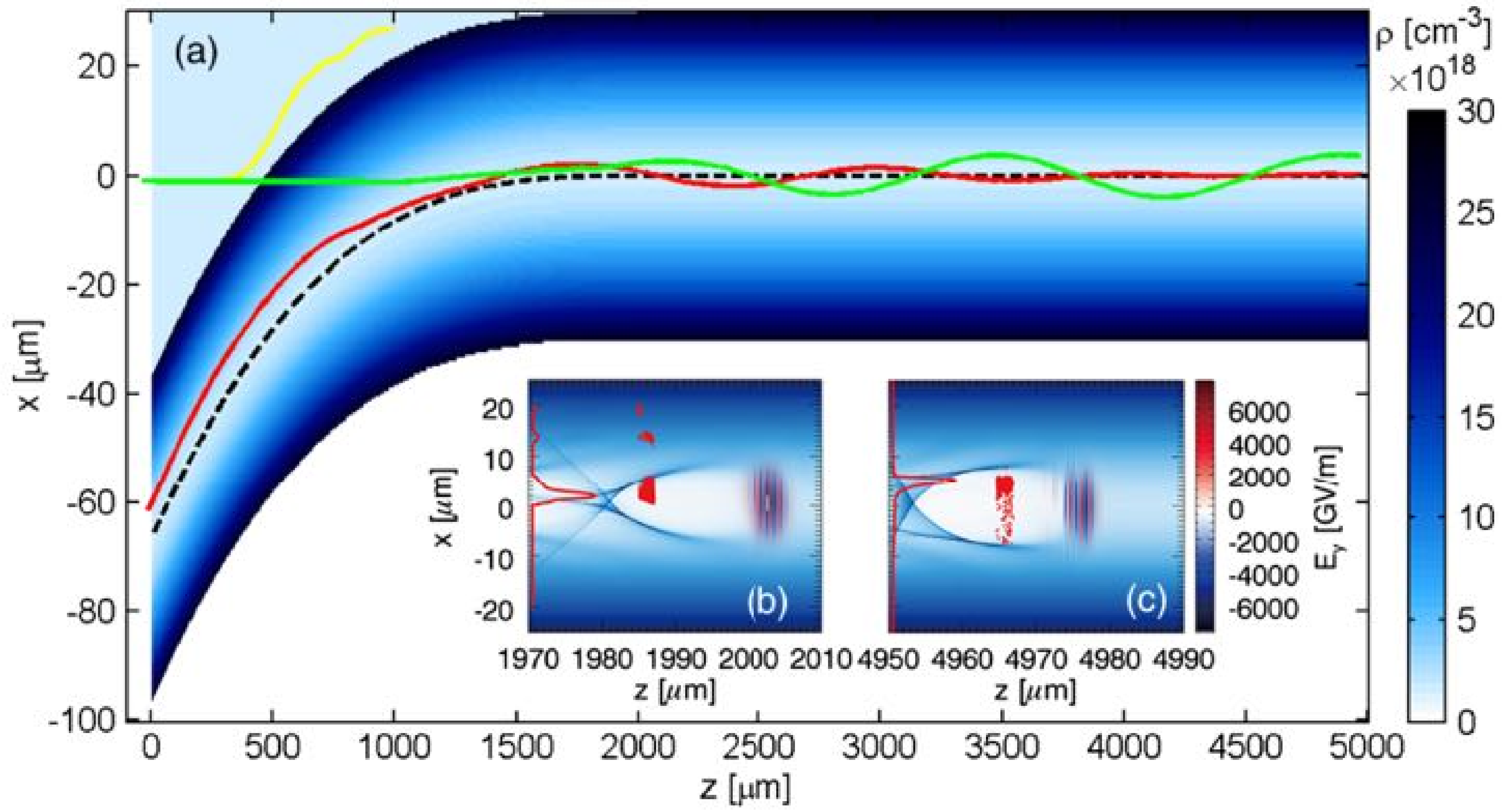



Image source: J. Luo et al., Phys. Rev. Lett. 120, 154801 (2018)

**Bend plasma channels**

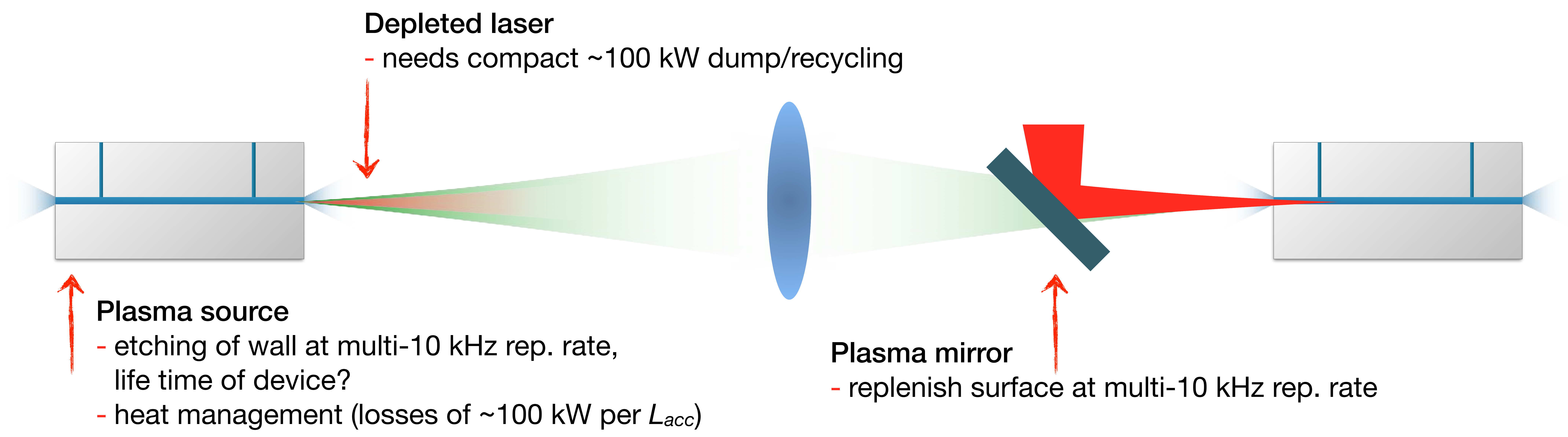
Y. Ehrlich *et al.*, Phys. Rev. Lett. **77,** 4186 (1996)

M. Chen *et al.*, Light: Science & Applications **5** (2016)

Misalignment and dispersion is induced
→ emittance increase

# Scalability to multi-10 kHz rep. rate and high avg. power

## III. High-average power operation

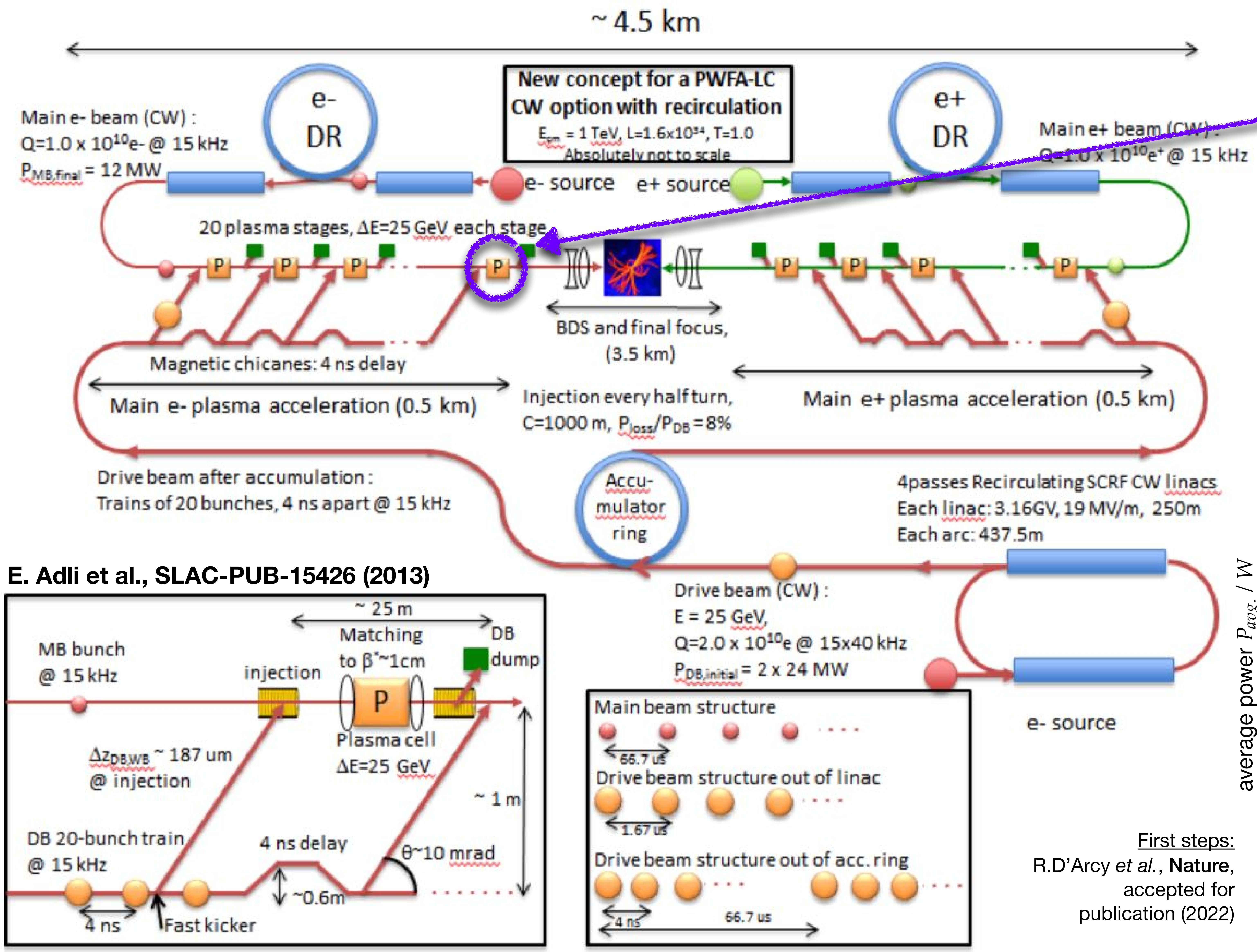



**What is the maximum repetition rate that plasma wakes can support?**

# Plasma-based collider concept

# Concept of a plasma-based collider facility

## Particle physics driven plasma-accelerator programs investigate key issues

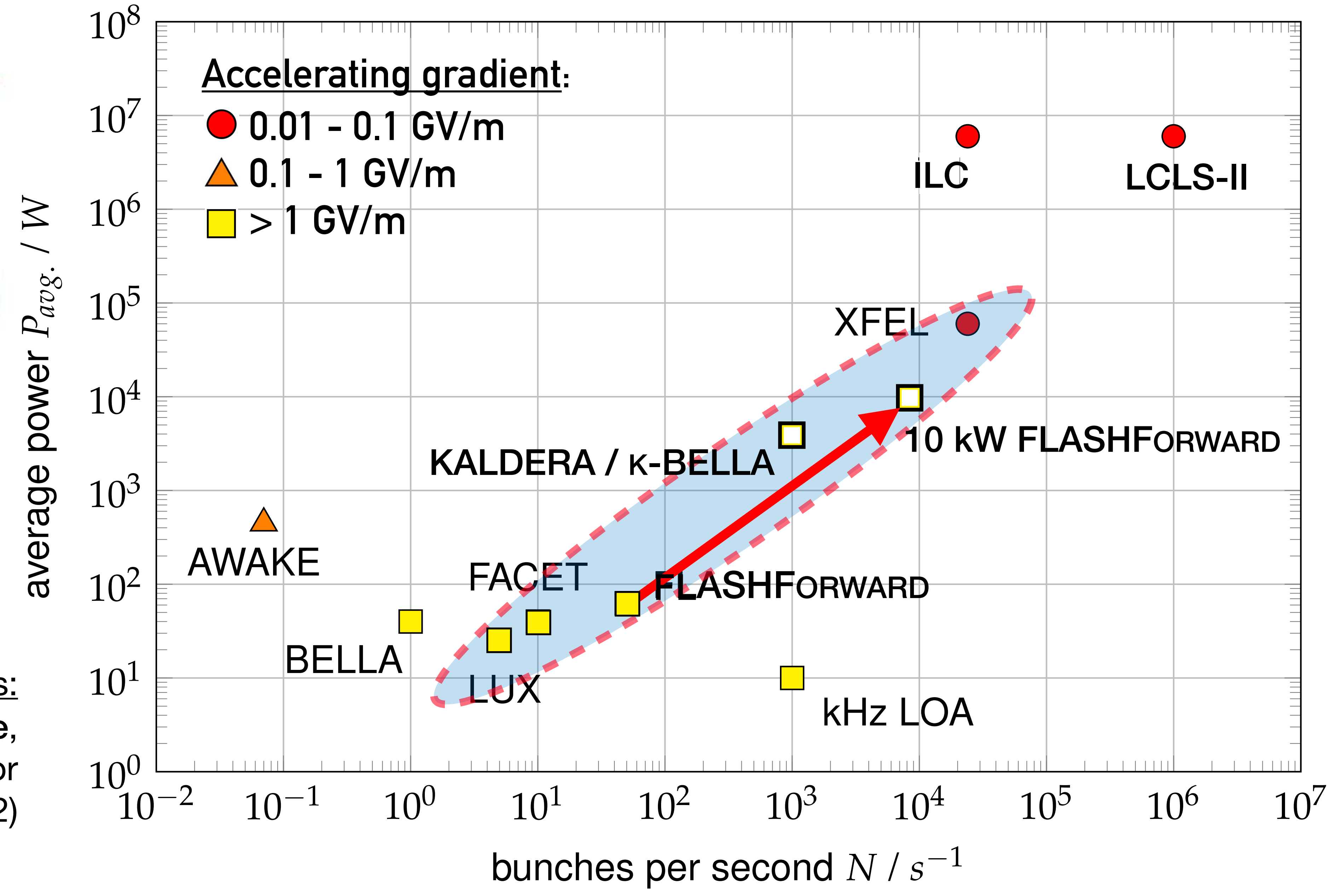



**E. Adli et al., SLAC-PUB-15426 (2013)**

### Specific challenges for plasma-based collider

- **Single acceleration module**
  support consistent high beam quality,
  efficient energy transfer to witness
  → PWFA: AWAKE, FF▸▸, FACET-II, SPARC_LAB
  → LWFA: most programs
- **High-rep. rate, high-average power operation**
  plasma heat management, plasma response,
  drive-beam removal, energy recovery
  → PWFA: FF▸▸ (10 kW, kHz-MHz)
  → LWFA: KALDERA, k-BELLA (1 kW, kHz)

First steps:
R.D'Arcy *et al.*, **Nature**,
accepted for
publication (2022)



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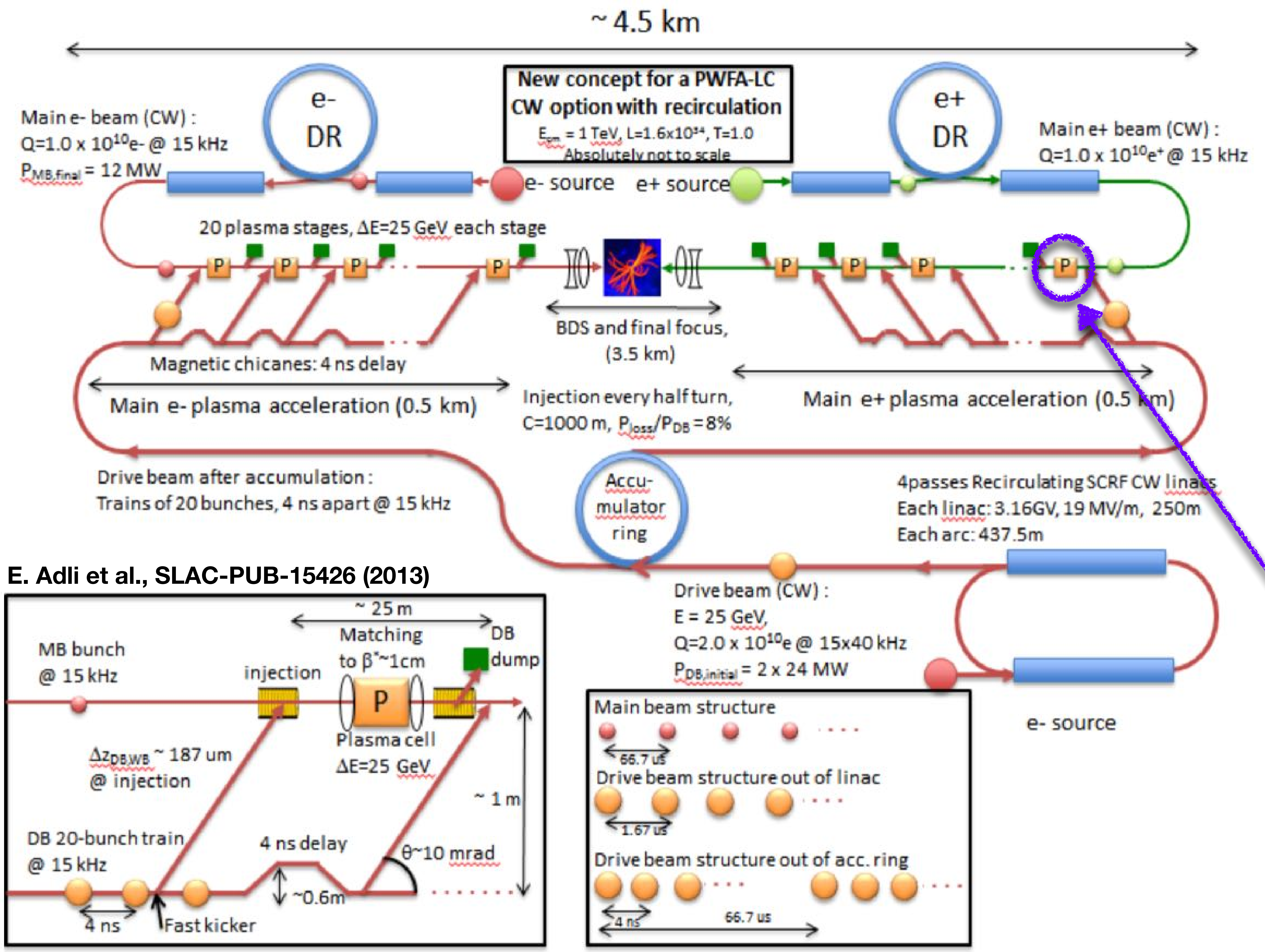


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# Concept of a plasma-based collider facility

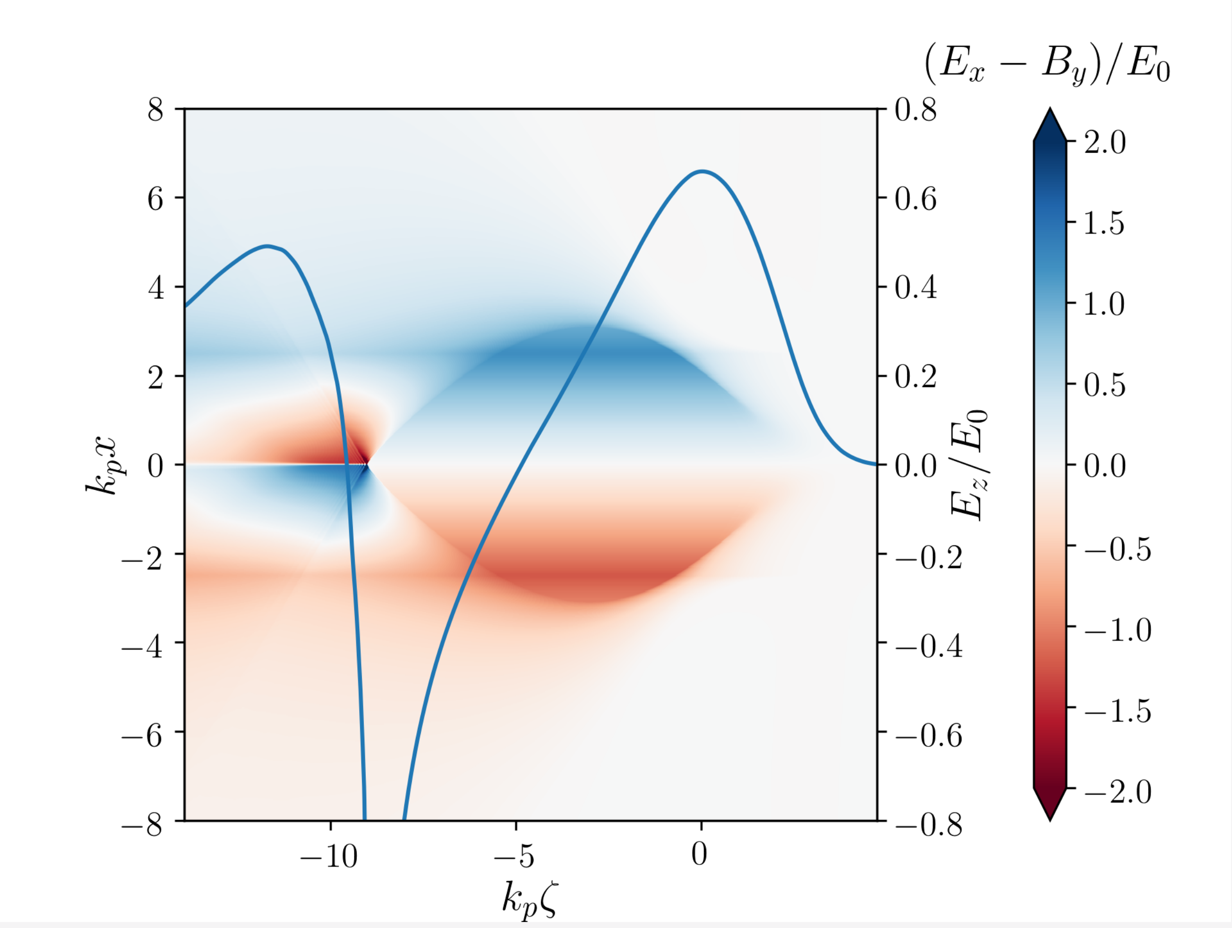
## Particle physics driven plasma-accelerator programs investigate key issues

**FACET-II**
Facility for Advanced Accelerator Experimental Tests

> only facility worldwide to test e+ acceleration

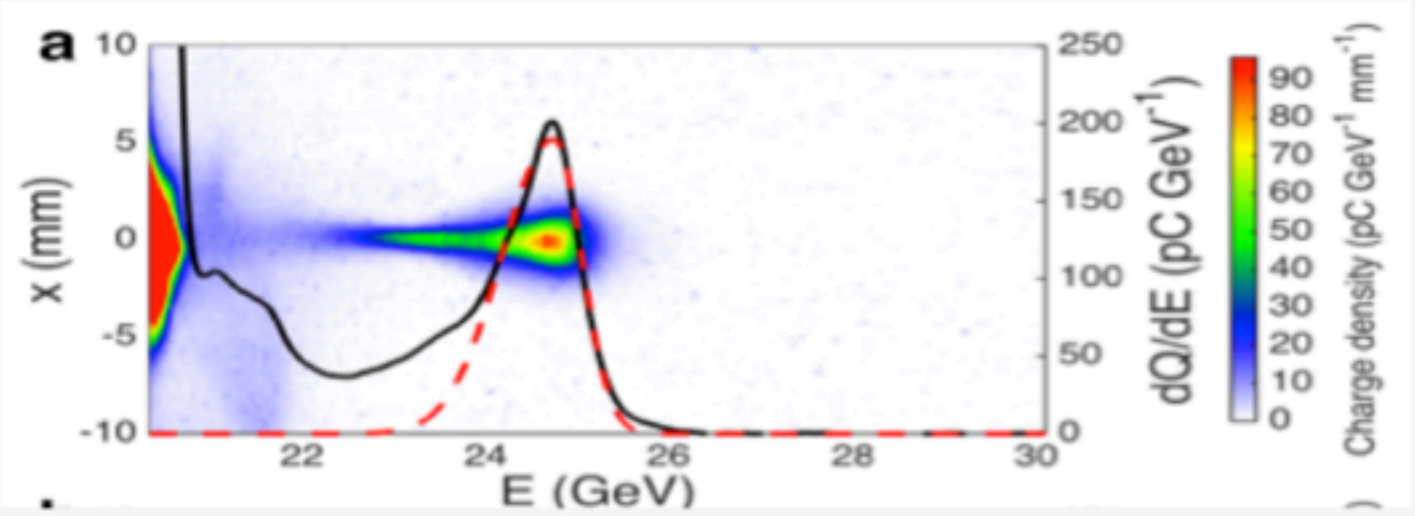
**Finite plasma channel**

*S. Diederichs et al.,*
*Phys Rev Accel Beams* ***22****, 081301 (2019)*
*Phys Rev Accel Beams* ***23****, 121301 (2020)*

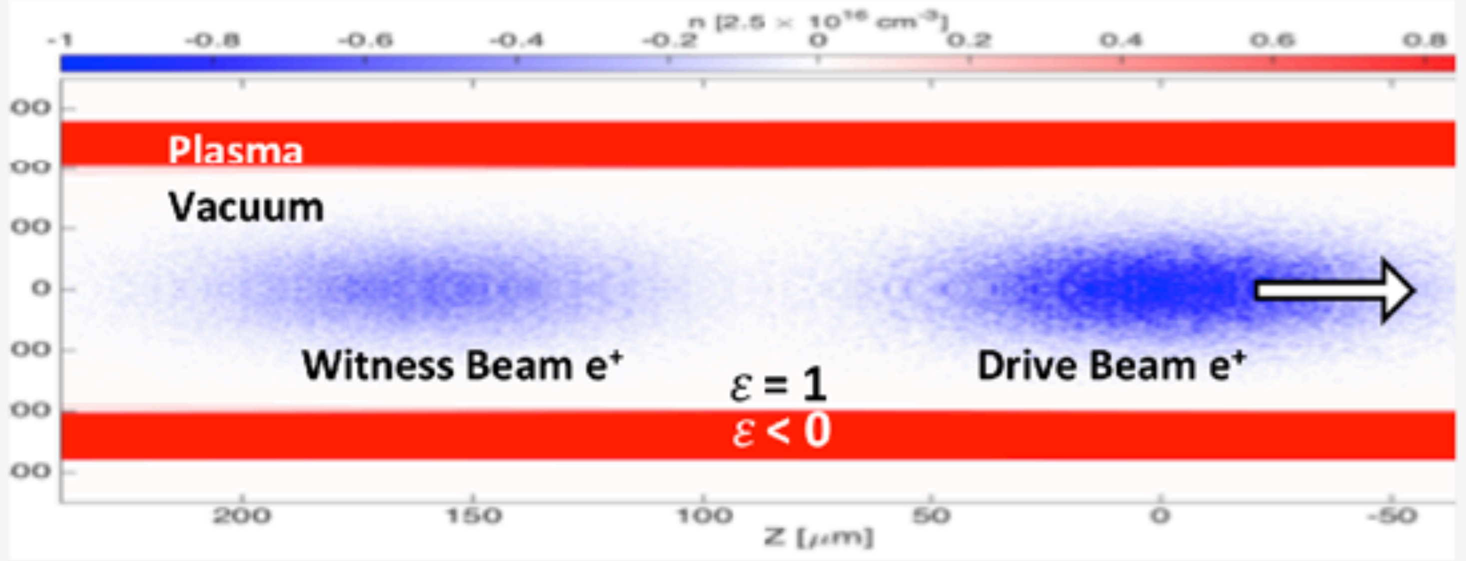


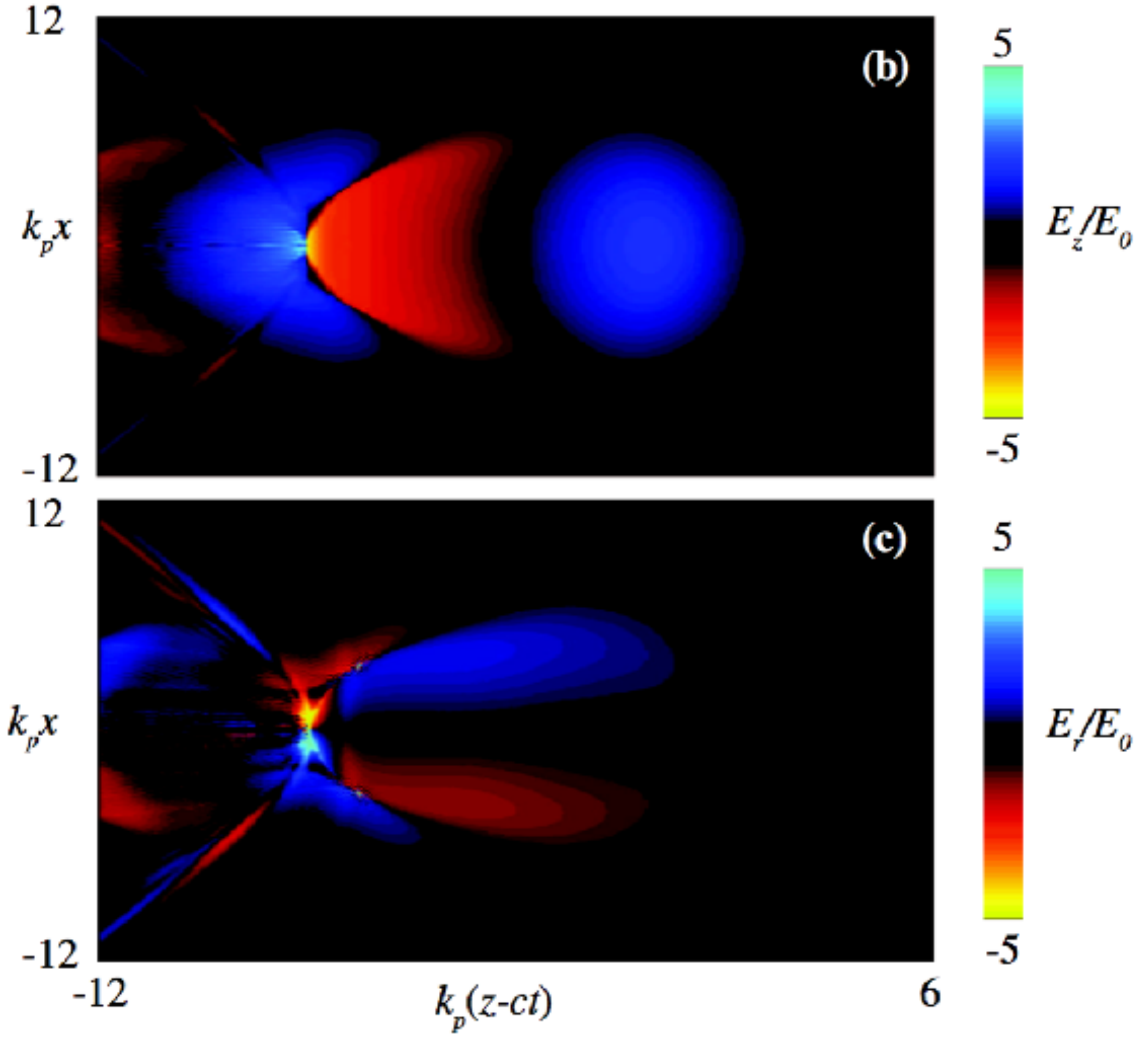

**Energy gain of 5 GeV.** Energy spread can be as low as **1.8%** (r.m.s.)

*S. Corde et al., Nature* ***524****, 442 (2015)*




**Hollow plasma channel:** positron propagation, wake excitation, acceleration in 30 cm channel.
*S. Gessner et. al. Nat. Comm. 7, 11785 (2016)*




> Positron acceleration
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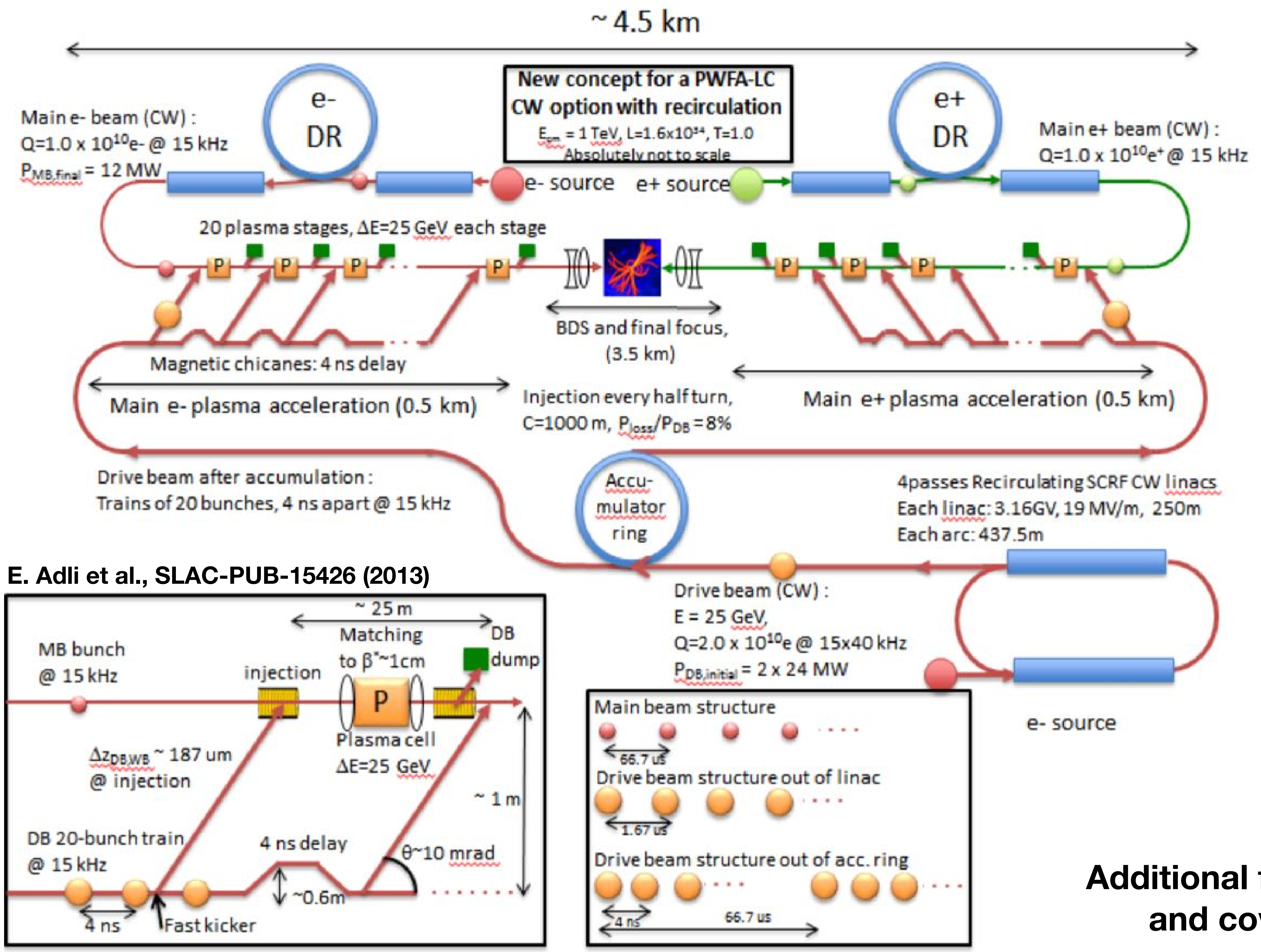
## Particle physics driven plasma-accelerator programs investigate key issues

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- **Positron acceleration**
  → PWFA: FACET-II (test of concepts)
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- **Acceleration of polarized beams**
  → PWFA & LWFA: -

**Additional facilities to target collider parameters and cover missing activities are required**

# Collider is the ultimate challenge, requires specific solutions

## Ballpark requirements and state-of-the-art

| | FEL | Collider | Current |
|---|---|---|---|
| **Charge per bunch (nC)** | 0.01 - 0.1 | 0.1 - 1 | 0.01 - 0.1 |
| **Energy gain (GeV)** | 0.1 - 10 | 1000 | 0.1 - 10 |
| **Energy spread (%)** | 0.1 | 0.1 | 0.1 |
| **Wall-plug efficiency (%)** | < 0.1 - 10 | 10 | < 0.1 |
| **Emittance (μm)** | 0.1 - 1 | 0.01 | 0.1 - 10 |
| **Rep. rate (Hz)** | $10^1$ - $10^6$ | $10^4$ - $10^5$ | 10 |
| **Avg. beam power (W)** | $10^1$ - $10^6$ | $10^6$ | 10 |
| **Continuous run** | 24/1 - 24/7 | 24/365 | 24/1 |
| **Parameter stability** | 0.1% | 0.1% | 1% |

- *highest energy:* **staging of plasma modules**
- *lowest emittance:* precision beam and plasma control
- *efficiency:* high wall-plug efficiency (energy recovery?)
- *rep. rate and avg. power:* kW/cm thermal plasma management
- ***positron acceleration*** *with exquisite quality*
- ***beam polarization*** *maintenance*
- *computing capabilities for full start-to-end optimization*

**Needs a coordinated worldwide effort**
**→ for a self-consistent collider design**
**→ to demonstrate viability of technical concepts**

**Well on track to realize plasma-based FEL**
**→ *proof-of-principle:* W. Wang *et al.*, Nature 595, 516 (2021)**

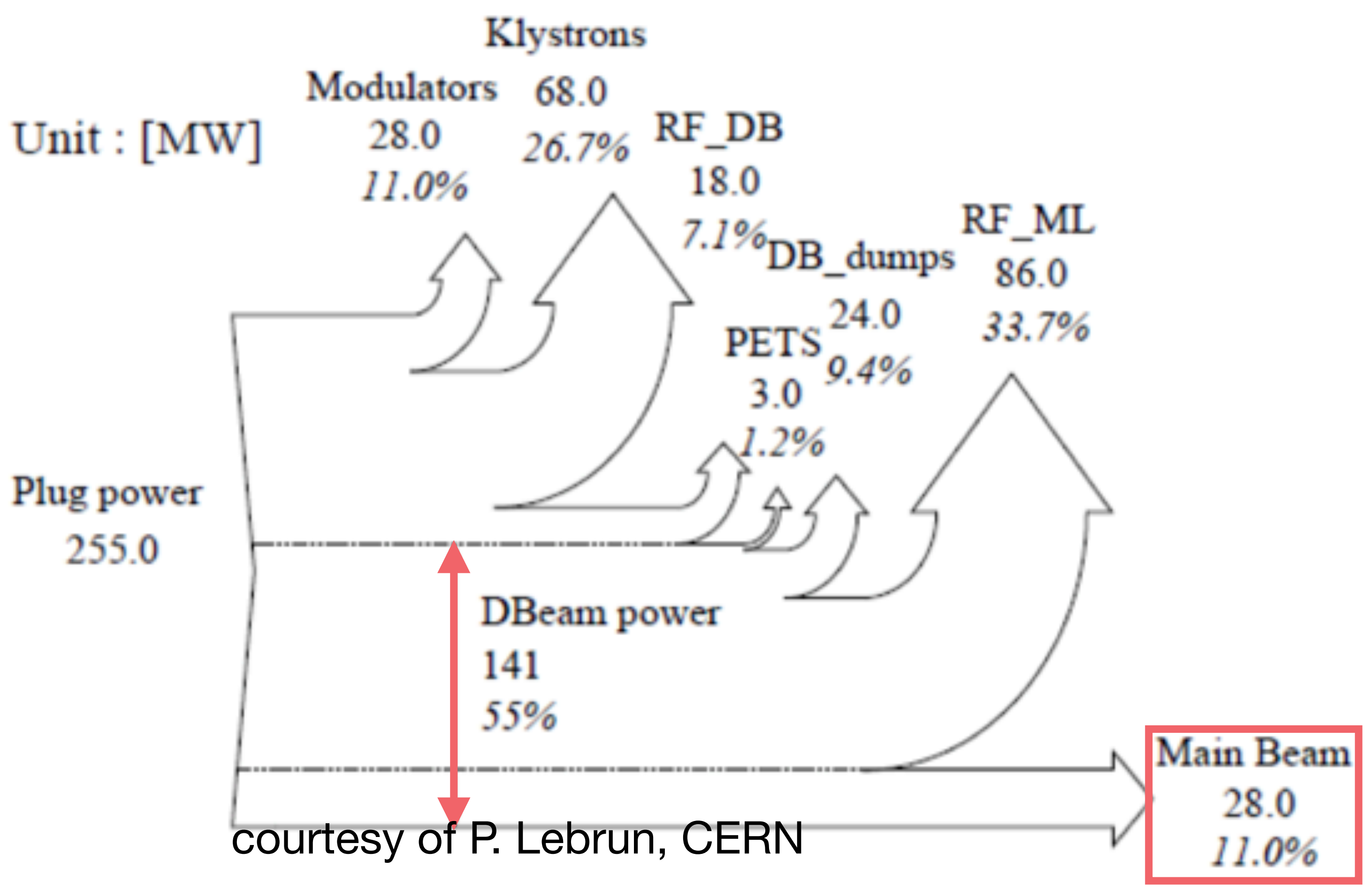
**Needs solutions specifically developed for particle colliders**

# What do we gain?

## If the technical R&D is successful, how would plasma colliders stack up with established concepts?

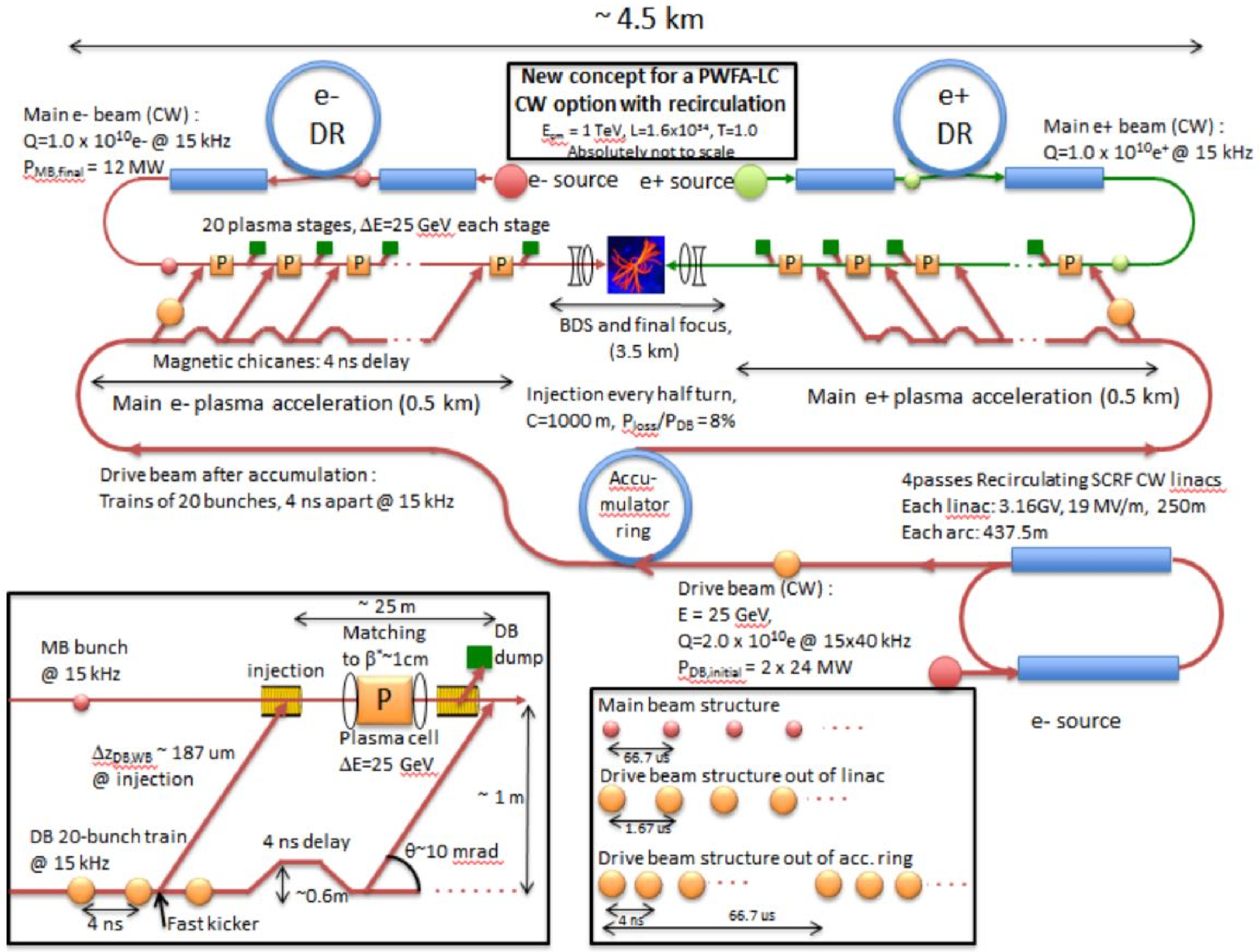
- More compact linear colliders: straw man designs show TeV collisions on ~4.5 km length
  - final focussing 3.5 km thereof!
  - **potentially greatly reduced construction cost**

- Potential efficiency gains: ×2.5 luminosity for same average power vs. CLIC
  - **similar operation cost at slightly higher lumi, but requires further analysis**




DB to Main Beam efficiencies of 50% seem possible (without energy recovery)

Power flow for the main RF system of CLIC at 3 TeV



# Principles of Plasma Accelerators

## Summary — Lecture III — The long and winding road to a particle collider in a nutshell

- Plasma accelerators target ~10 GeV energy gain per plasma stage for particle physics
- AWAKE-scheme enables single stage ~TeV energy gain, but at low luminosity
  - interesting for intermediate applications, e.g. dark photon search
- High-luminosity applications require staging of acceleration modules (which is in its infancy)
- Single-stage development greatly profits from R&D for photon science applications
- Particle-physics exclusive solutions
  for positron acceleration and polarization maintenance are required
- A lot of research ahead of us…