ALEGRO 2018 Workshop

26-29 March

Oxford, UK

Introduction to Working Group 4: LWFA

WG4 Coordinators:

Brigitte Cros (CNRS-LPGP)

Simon Hooker (Oxford)

Carl Schroeder (LBNL)

WG4 - LWFA

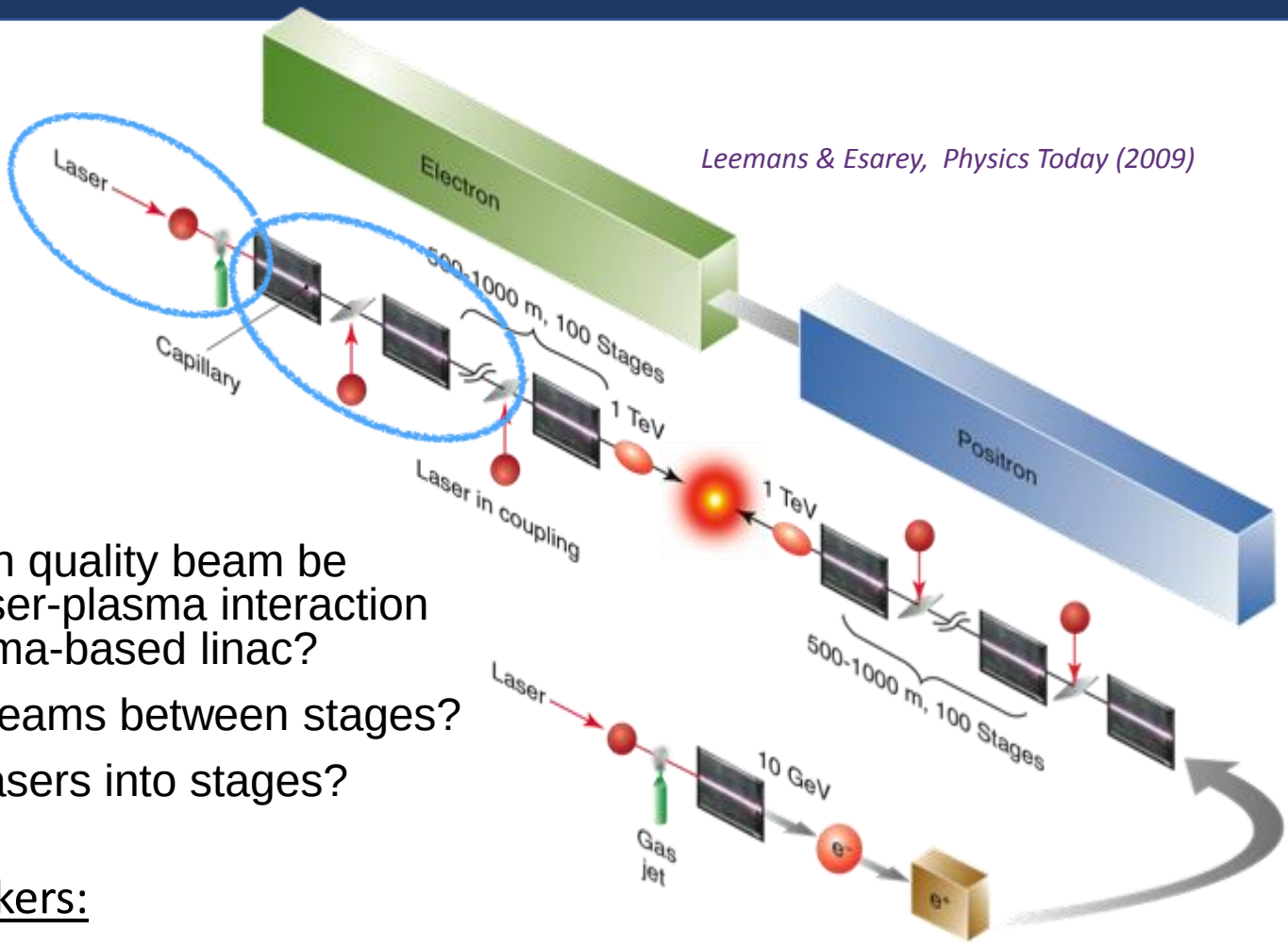
WG4 goal:
Identify R&D required to move LWFA-based collider from “strawman” design to actual conceptual design.

WG4 Sessions:
1. LWFA driver strategies
2. Electron sources and staging
3. Laser technology
4. Positron acceleration in LWFA (joint with WG8)
5. Identification of future machines and strategies
6. Next steps (joint with WG 2 + diagnostics for future machines)
7. Summary and coordination

Basic structure of WG4 organization: Sessions contain overview and strategic-direction talks, with significant time allocated for discussions.

- We welcome short contributions/presentations on detailed topics/proposals during the discussions.

Electron sources and staging



Leemans & Esarey, Physics Today (2009)

- Can a sufficiently high quality beam be generated using a laser-plasma interaction for injection into plasma-based linac?
- How best to couple beams between stages?
- How best to couple lasers into stages?

Speakers:

S. Karsch (LMU) – electron sources
J. Osterhoff (DESY) – staging

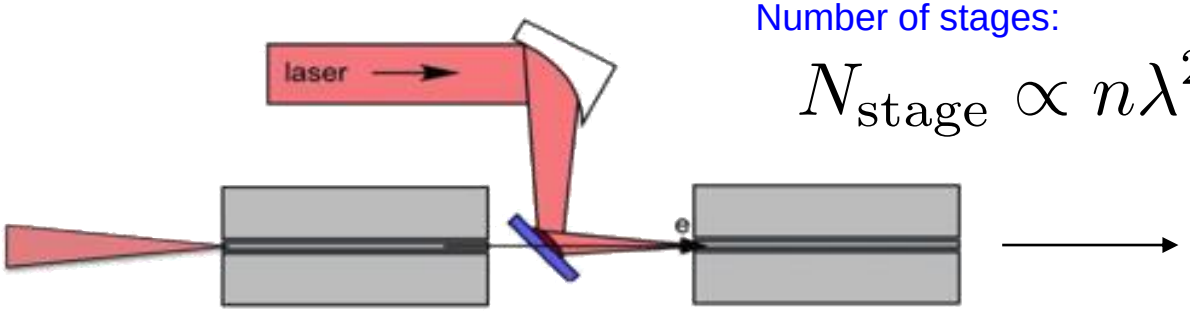
Beam quality in LWFA determined by injection method

- Can a sufficiently high quality beam be generated using a laser-plasma interaction for injection into plasma-based linac?

Many LWFA injection concepts have been proposed and experimentally studied:

- Self injection ("wavebreaking")
  - Laser-evolution-assisted bubble expansion
- Density gradient injection
  - Shock-induced (gradient < plasma wavelength)
  - Density ramp (gradient > plasma wavelength)
- Colliding pulse injection
  - 2-pulse; 3-pulse
  - transverse; longitudinal
- Ionization injection
  - Single-pulse; Multi-pulse
  - Two-color ionization injection
  - Two-color + multi-pulse ionization injection
- ….

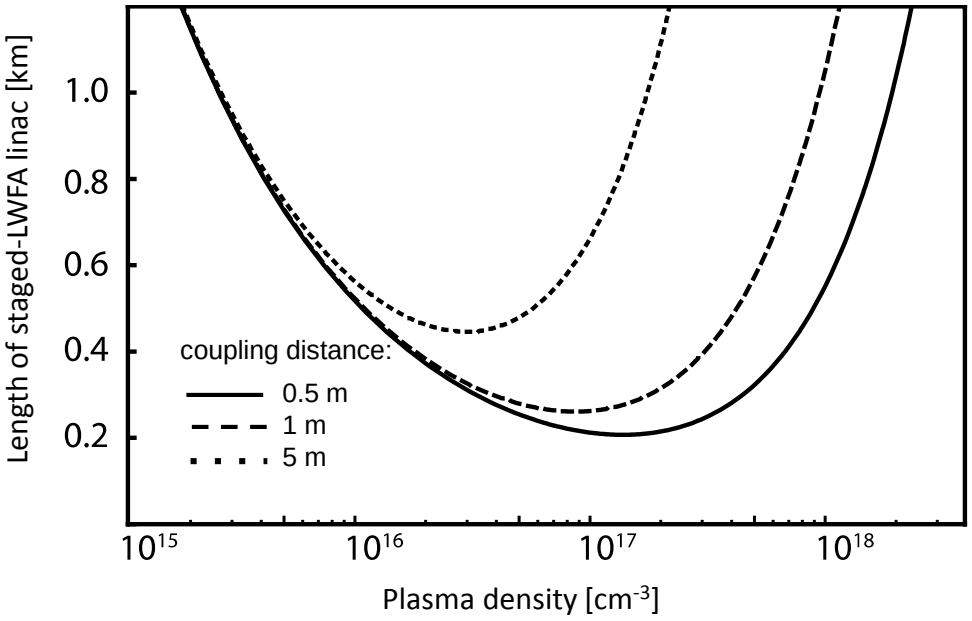
LWFA staging: geometric gradient determined by driver/beam coupling



Number of stages:

$$N_{\mathrm{stage}} \propto n\lambda^2$$

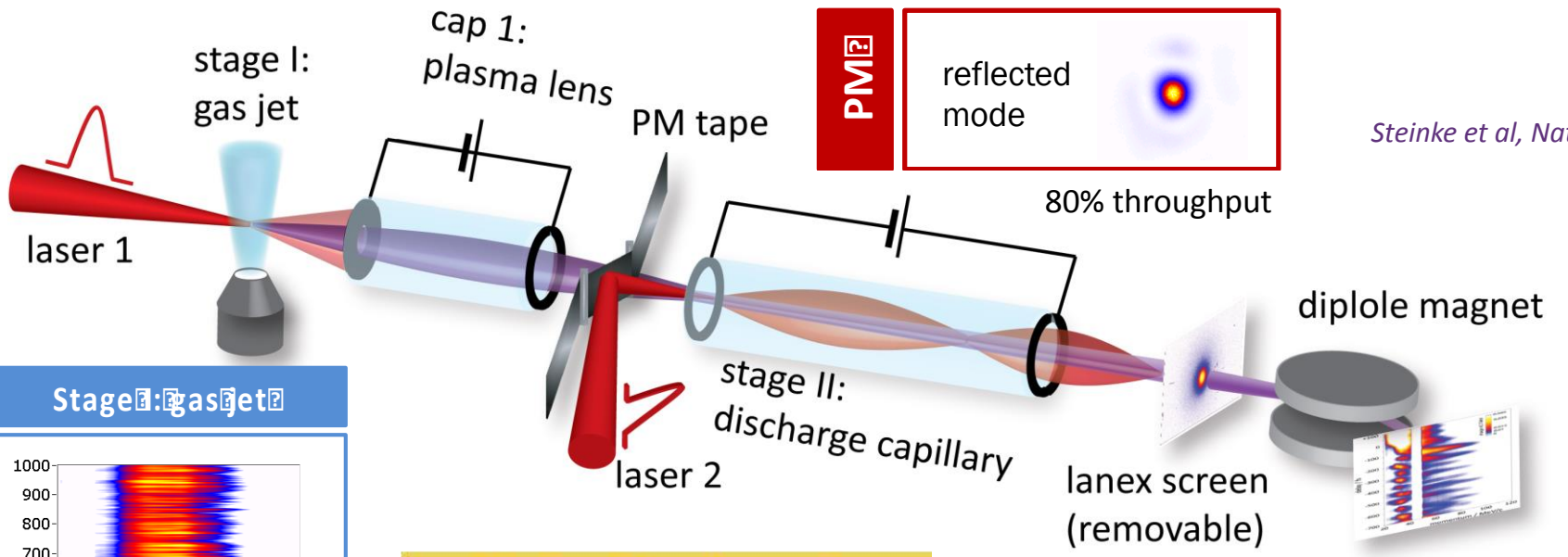
Length of 1 TeV staged-LWFA linac



Schroeder et al., PR ST-AB (2010)

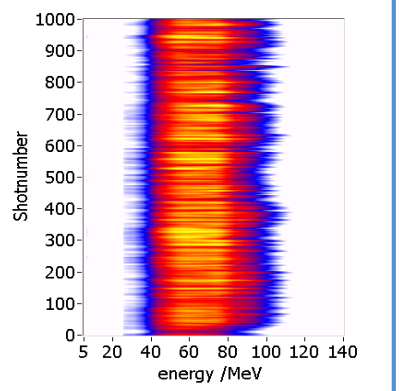
- Compact laser in-coupling distance (enables high average gradient)
  - Conventional optics: requires many Rayleigh ranges to reduce fluence on optic (avoid damage) $L_{\mathrm{coupling}} \propto n^{-5/4}\lambda^{-1}$
  - Plasma mirror: relies on critical density plasma production (high laser

Experimental work on LWFA staging

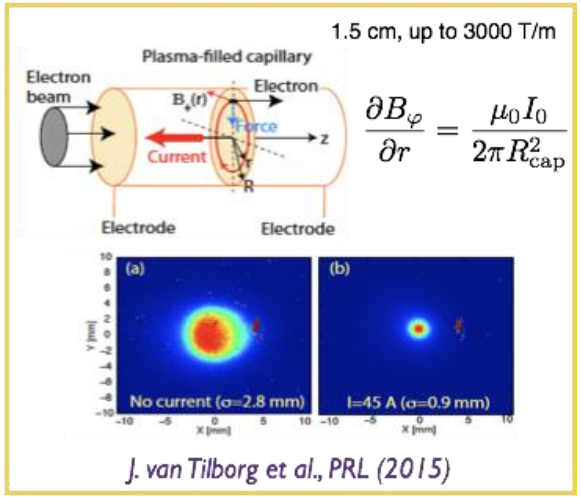


Steinke et al, Nature (2016)

Stage I: gas jet

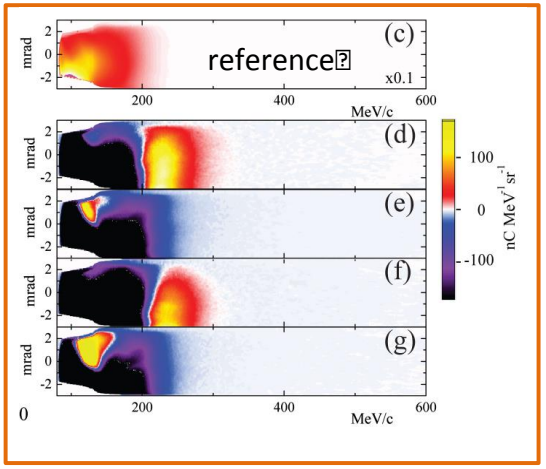


Cap 1: active plasma lens



lanex screen

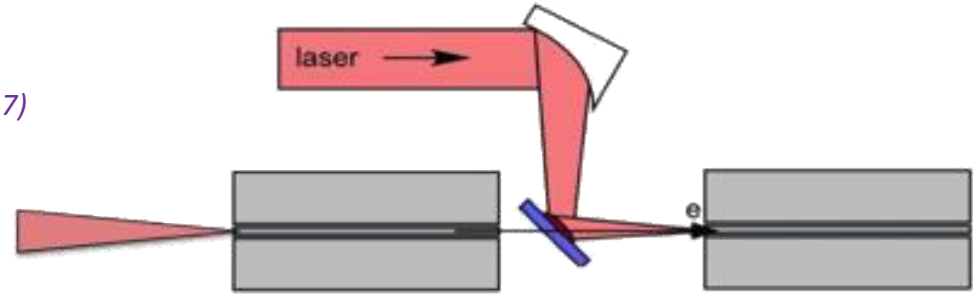
Stage II



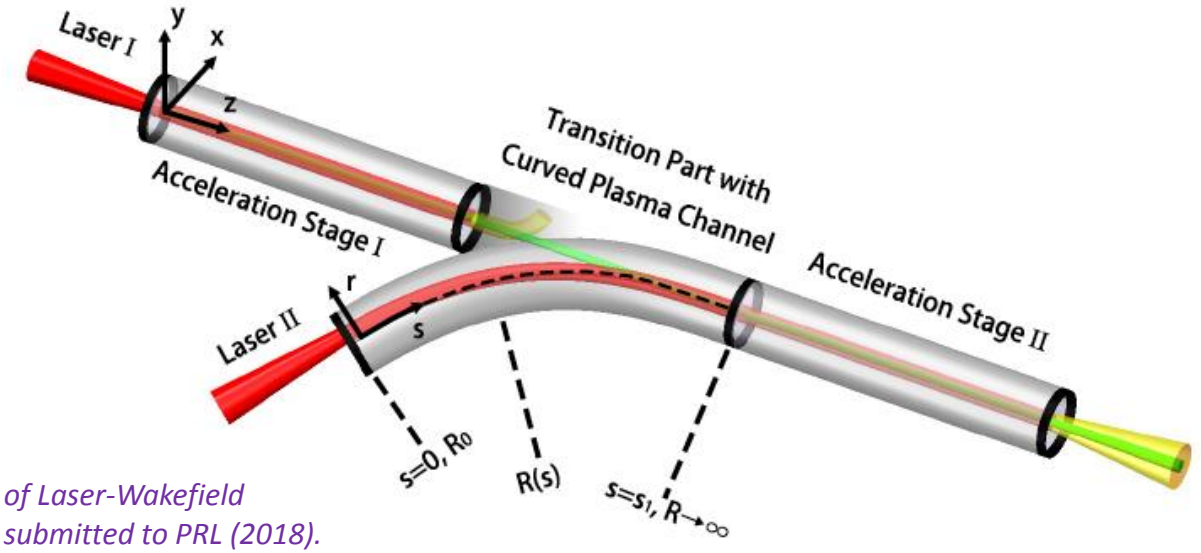
LWFA staging concepts: Lasers offer the potential of compact driver coupling between stages

- Plasma mirrors:

Steinke et al, Nature (2016); Phys. Plasmas (2017)



- Curved plasma channels:

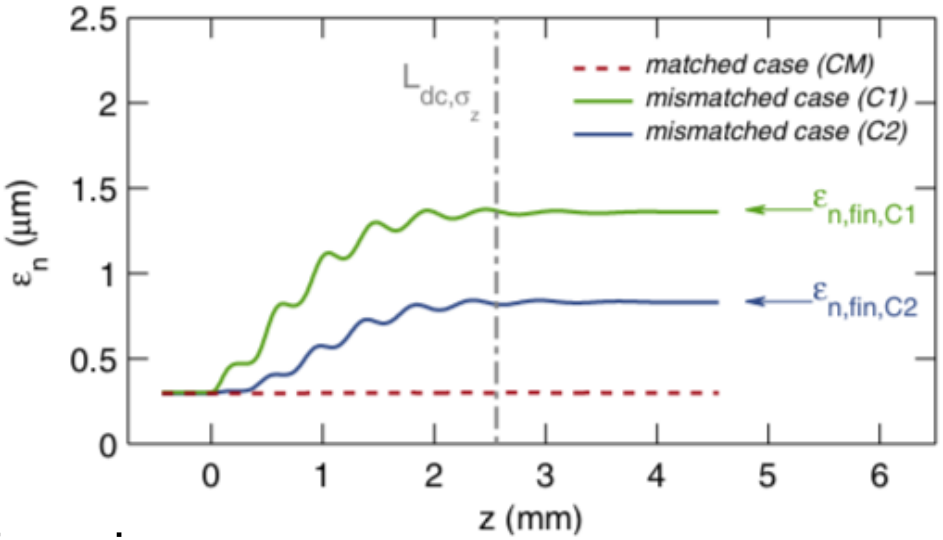


J. Luo, M. Chen, et al., "Multistage Coupling of Laser-Wakefield Accelerators with Curved Plasma Channels" submitted to PRL (2018).

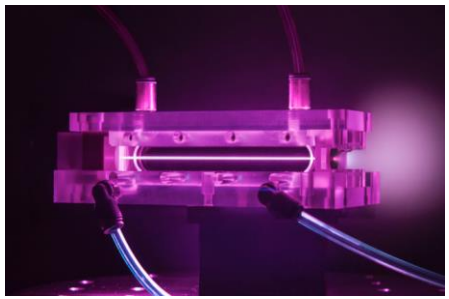
Particle Beam coupling between stages

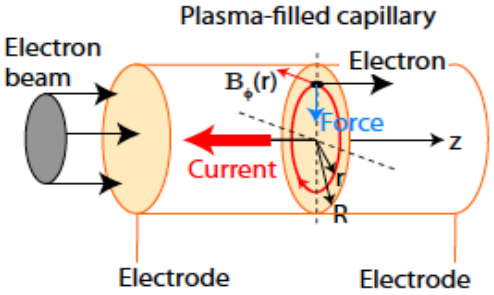
- Can electron/positron beams be compactly coupled (matched) between stages without emittance growth?

T. Mehrling, et al., "Transverse emittance growth in staged laser-wakefield acceleration" PR ST AB (2012).



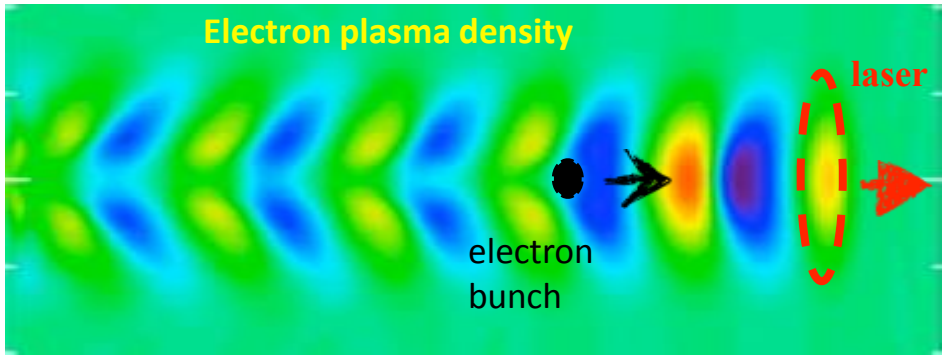
- Can high-gradient plasma-based focusing elements be used (with high-beam-quality preservation)?





J. van Tilborg et al, PRL (2015)

LWFA driver strategies



- What are the optimal laser driver parameters/configuration for a collider?
  - Laser driver choice determines required laser technology development & available laser technology constrains driver options

Speakers:

E. Esarey (LBNL) – quasi-linear regime

S. Mangles (ICL) – nonlinear bubble regime

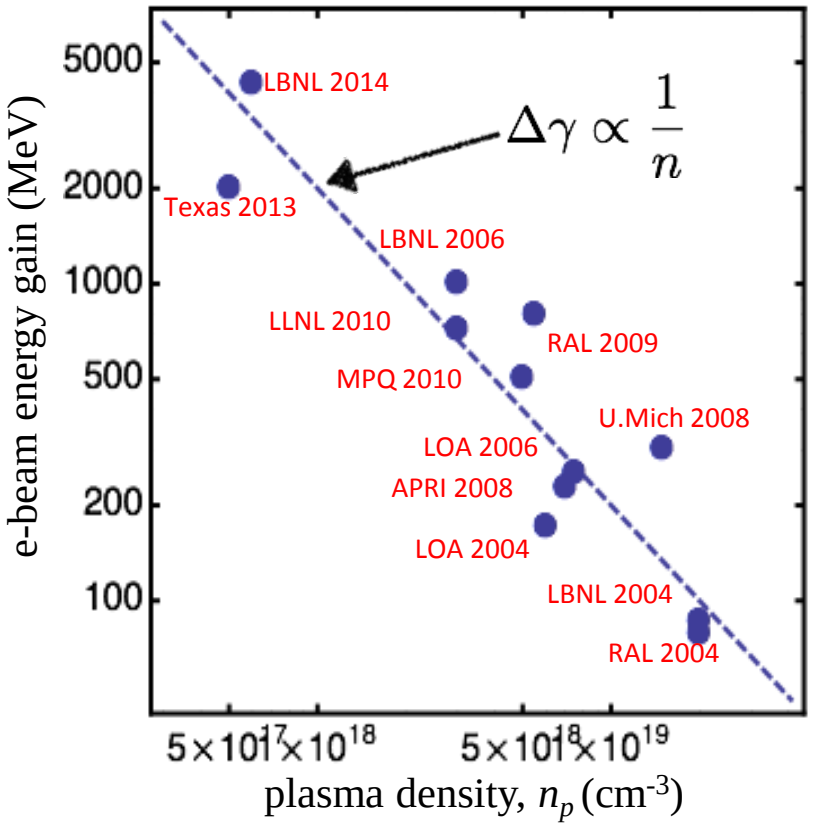
Operational plasma density determines laser parameters

- Accelerating gradient:

$$E_z \sim mc\omega_p/e \propto \sqrt{n}$$

- Energy gain:

$$\Delta\gamma \sim (mc\omega_p)\, L_{\rm acc} \propto n^{-1}\lambda^{-2}$$



Laser requirements:

- Laser energy: $U_{\rm laser} \propto \lambda_p^3 \propto n^{-3/2}$
- Laser duration: $\tau_{\rm laser} \propto \lambda_p \propto n^{-1/2}$
- Laser peak power: $P_{\rm laser} \propto n^{-1}$

➢ Multi-pulse drivers relax laser (peak power) requirements

Average power reduced at lower plasma density (Beamstrahlung limits charge/bunch)

Charge/bunch:

$$N \propto U_L/\Delta\gamma \propto n^{-1/2}$$

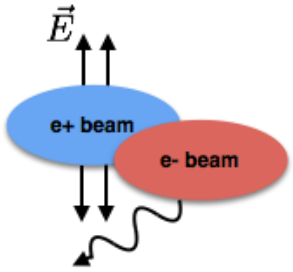
Wall-plug power: *Schroeder et al., PR ST-AB (2010)*

$$P \propto \sqrt{n}$$

Charge/bunch limited by beamstrahlung:

$$n_\gamma \propto N^{2/3}\sigma_z^{1/3} \propto n^{-1/2}$$

Schroeder et al., PR ST-AB (2012)



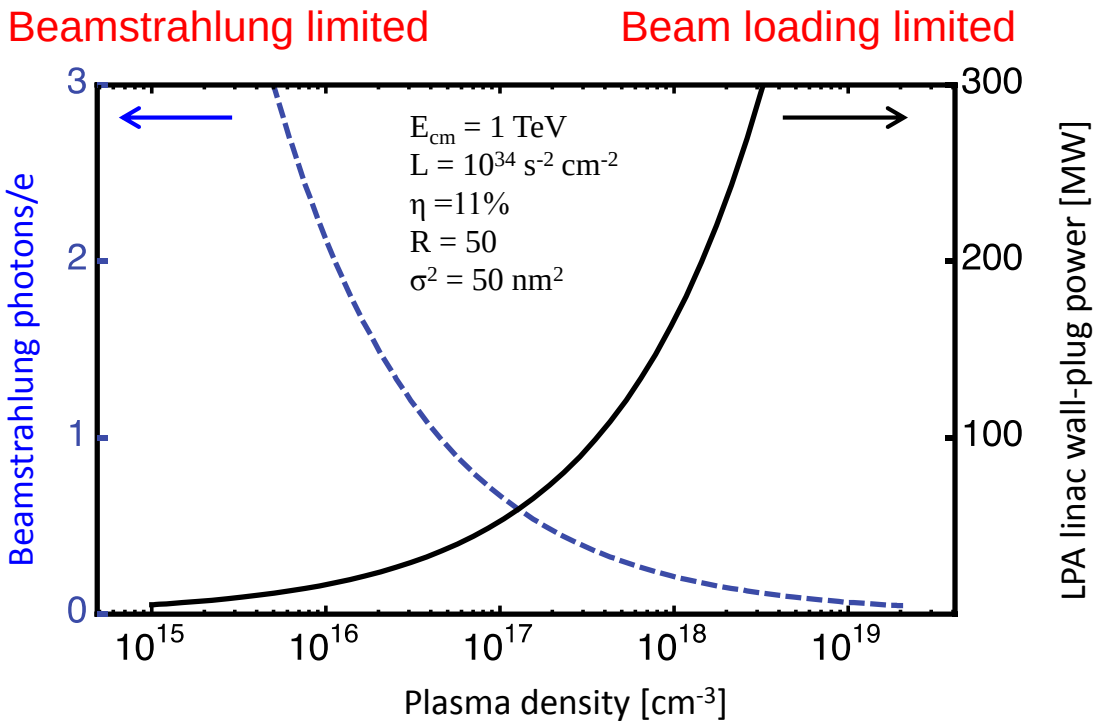
Average fractional (beamstrahlung-induced) energy loss:

$$\frac{\delta\gamma}{\gamma} \simeq 0.28\ n_\gamma$$

P. Chen (1992)

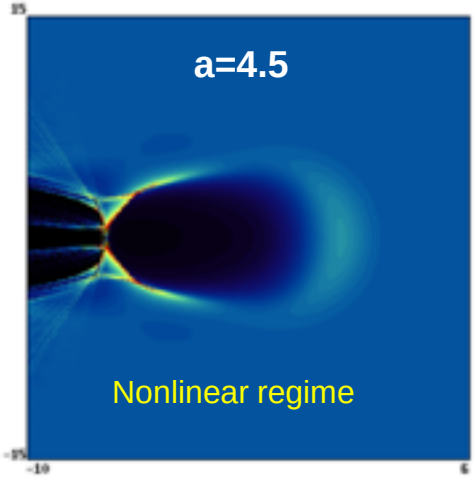
Power scalings:

$$\frac{\mathcal{L}}{U_{\rm cm}^2} \propto \frac{n_\gamma^{3/2}\eta P_{\rm wall}}{\sigma_* \gamma^{5/2}\sigma_z^{1/2}}$$

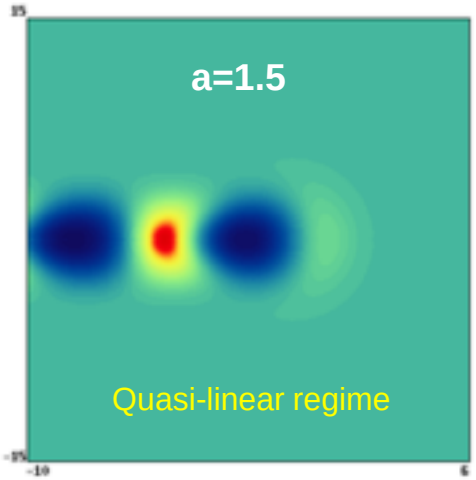


Regimes of LWFA: nonlinear bubble vs quasi-linear

LWFA may be operated in different regimes (determined by normalized laser intensity)



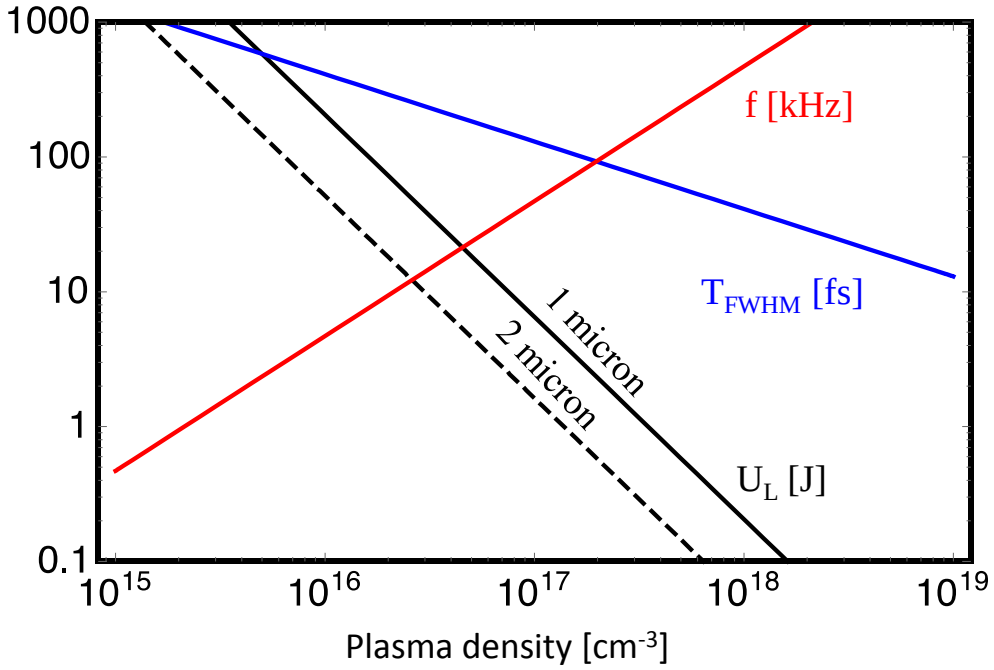
- Nonlinear bubble regime:
  - Most LWFA experiments presently operate in bubble regime
  - Self trapping, beam generation
  - Self guided (ponderomotive self-channeling)
  - High accelerating gradients
  - Excellent focusing and accelerating properties



- Quasi-linear regime:
  - Guiding provided by plasma channels
  - No self-trapping (dark current)
  - Symmetric with respect to positron acceleration
  - Control of wake structure
  - Multi-pulse drivers

Session 3 – laser technology

- Laser technology development required for LWFA-based collider.
  - tens of kHz, ~100 fs (duration or modulation), ~10 J, ~100 kW



- Laser duration (bandwidth) requirements: $\tau_L \propto n^{-1/2}$
- Laser average power requirements: $P_{\mathrm{avg}} \propto n^{-1/2}\lambda^{-2}$
- Number of LPA stages: $N_{\mathrm{stage}} \propto n\lambda^2$

- Different operational plasma densities require different laser parameters (laser technologies with varying efficiency)

Laser technology must be efficient

wall-to-beam efficiency:

Schroeder et al., NIMA (2016)

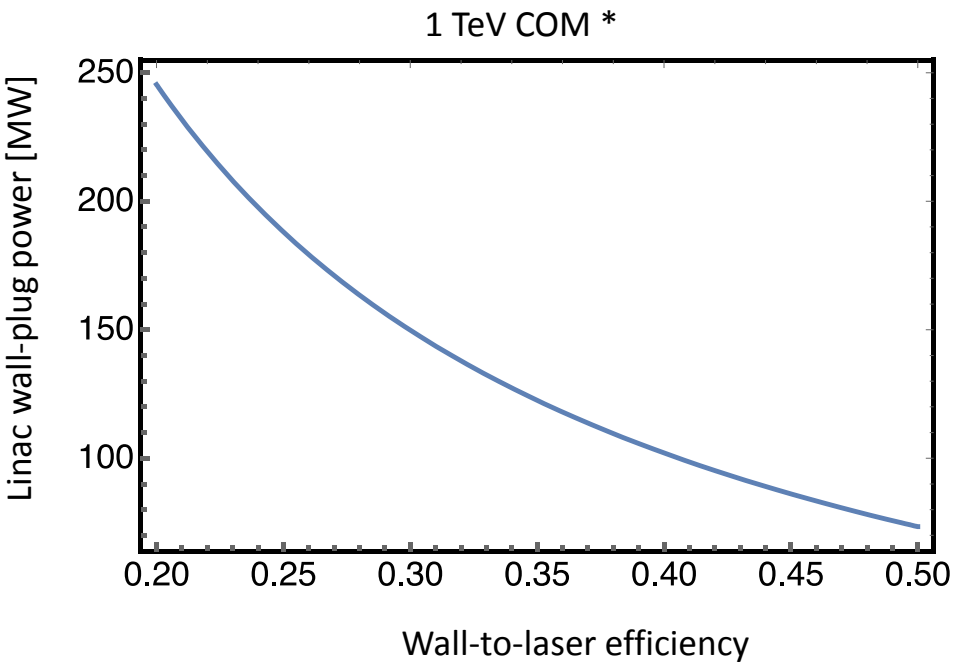
$$\eta_{\rm total} = \frac{\eta_{\rm beam}\eta_{\rm pd}}{[1/\eta_{\rm laser} - (1-\eta_{\rm pd})\eta_{\rm recovery}]}$$

Wake to beam

Laser to wake

Wall to laser

Laser energy recovery

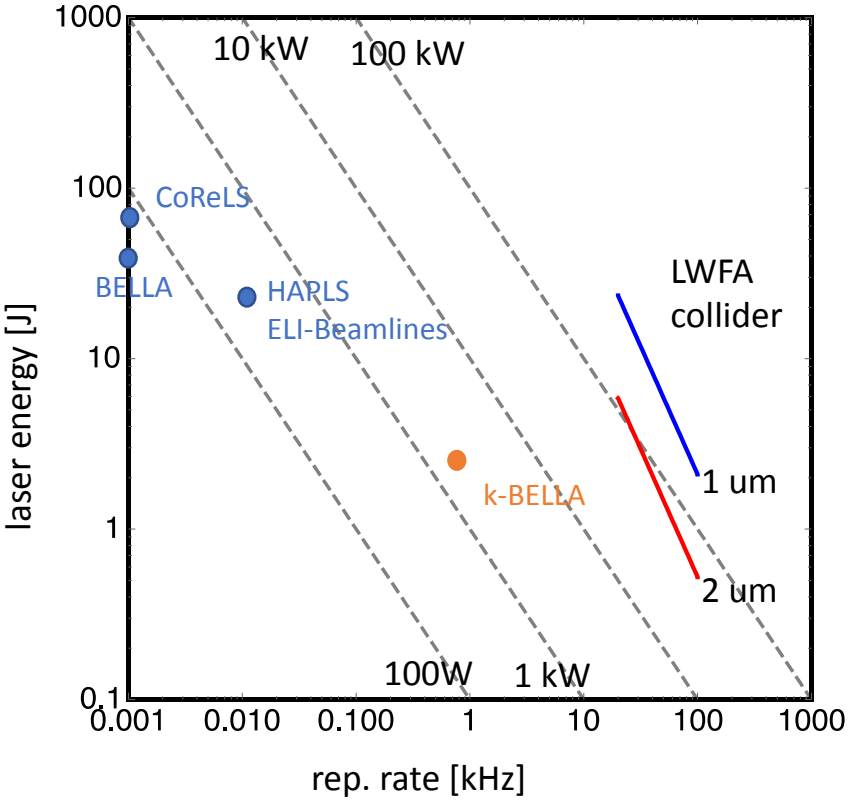


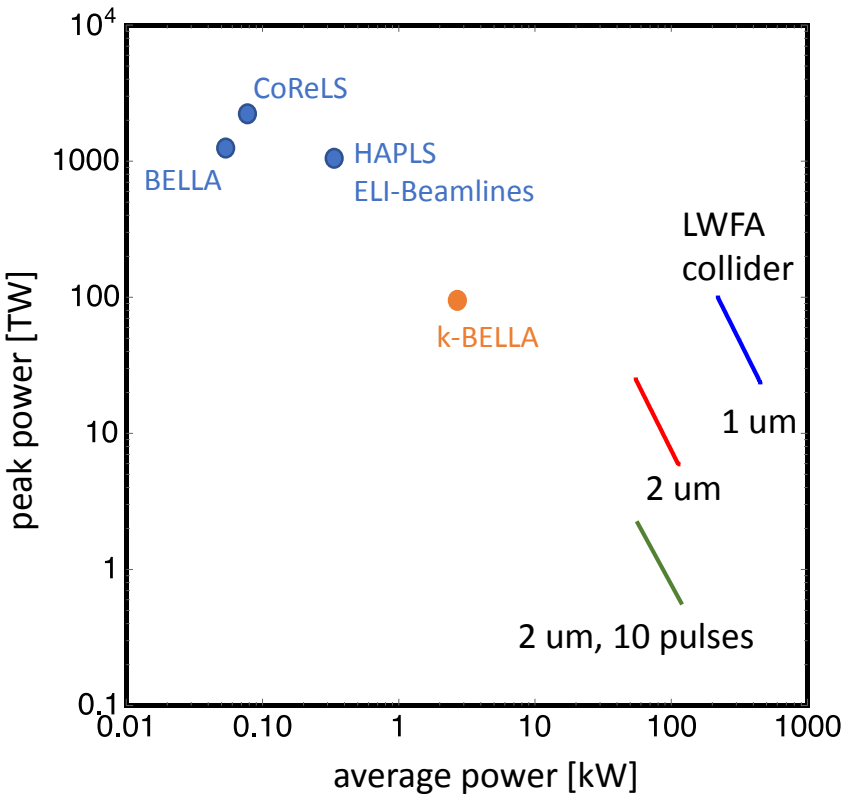
- required beam power:

$$P_{\rm beam} = \frac{4\pi\sigma_*^2}{N}\mathcal{L}\mathcal{E}_{\rm cm}$$

* For collider parameters found in Schroeder et al., "Laser-plasma-based linear collider using hollow plasma channels" NIMA (2016)

LWFA collider requires high-average and peak power short-pulse laser technology development





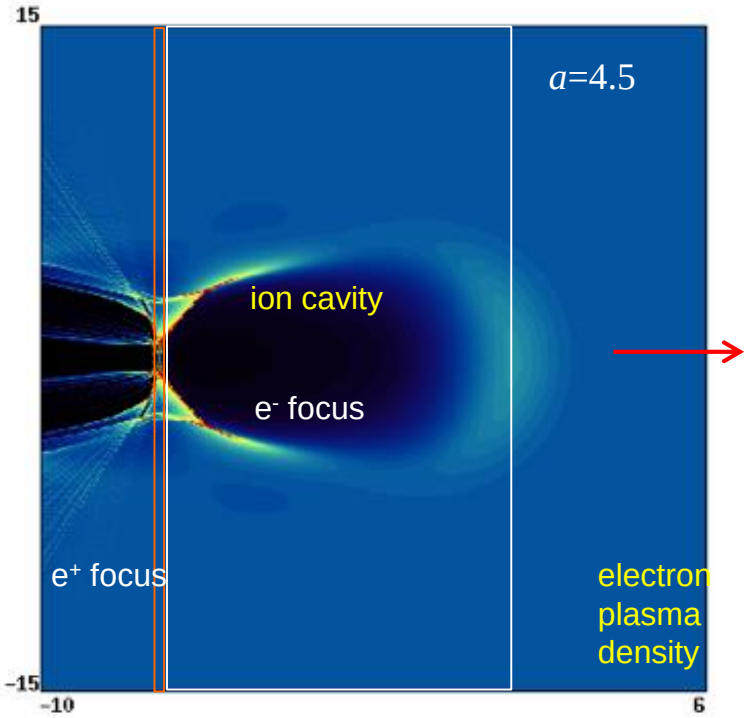
Session 3: speakers:

W. Leemans (LBNL) – kHz laser technology
L. Gizzi (Pisa) – Laser drivers for the EuPRAXIA beamlines
C. Simon-Boisson (Thales) – Laser technology for high peak and average power

Session 4 (joint with WG8) – Positron acceleration

Session 4: speakers:

S. Gessner (CERN) – Report from plasma-based positron mini-workshop
A. Pukhov (Düsseldorf) – Hollow plasma channels

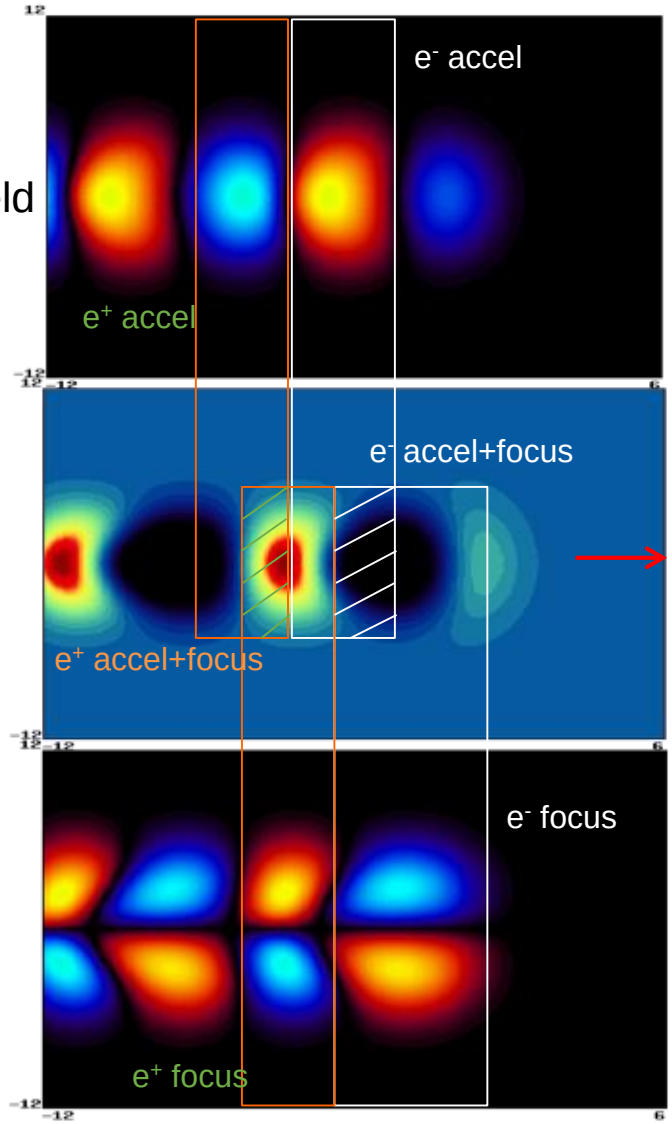


- LWFAs are capable of acceleration of positrons.

  - Nonlinear bubble regime in uniform plasma problematic for positron acceleration with high-quality preservation.

- LWFAs are capable of acceleration of low-emittance positron beams in the quasi-linear regime by controlling the focusing forces (shaping laser or plasma channel).

Quasi-linear regime: linear e+ focusing and acceleration, Independent control of acceleration and focusing



- Quiver momentum weakly-relativistic (a~1)
- Region of accelerating/focusing for both electrons and positrons
- Independent control of accelerating and focusing forces:
  - Driver transverse profile:

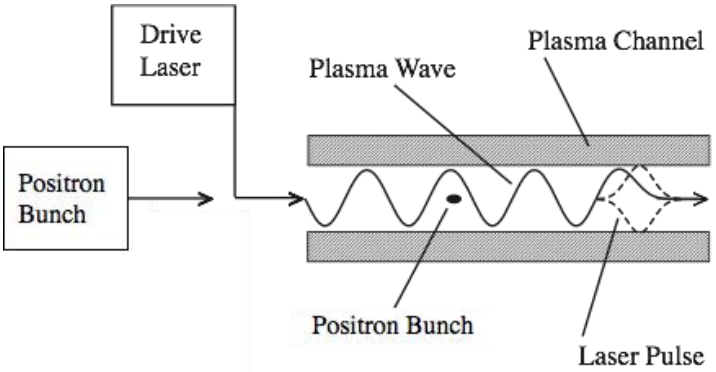
$$F_\perp \propto \nabla_\perp a^2$$

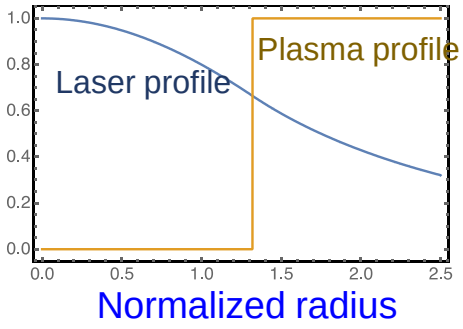
Cormier-Michel et al., PR ST-AB (2011)

  - "weak" focusing is required for low emittance beam to prevent cavitation
  - Transverse laser profile may be shaped in LWFA (HOM laser content)

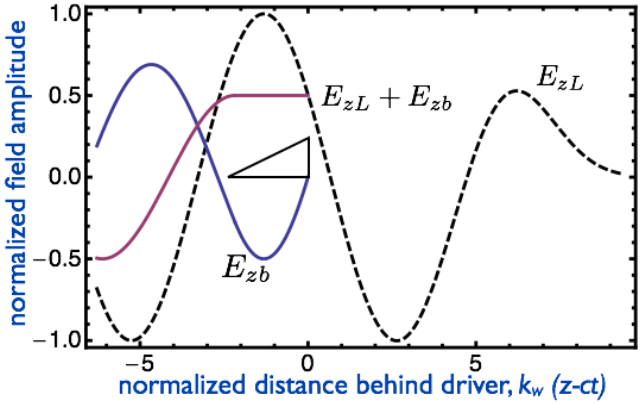
Hollow plasma channels for positron acceleration

- Positron acceleration in a hollow plasma channel in the quasi-linear regime

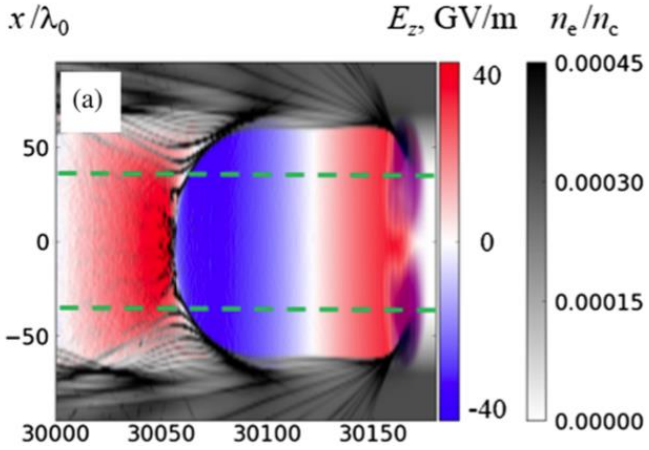




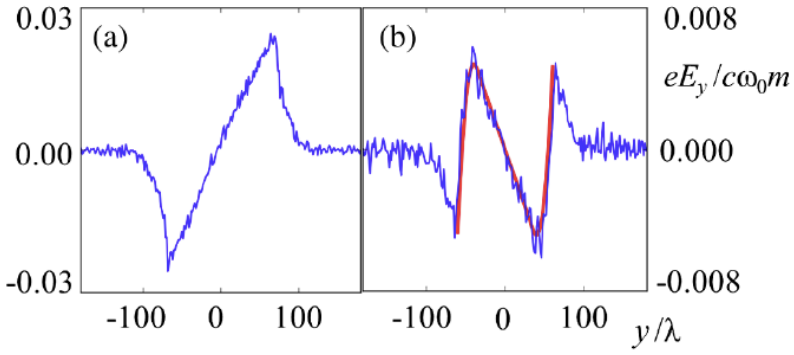
Schroeder et al., Phys. Plasmas (2013)



- Positron acceleration in a hollow plasma channel in the bubble regime

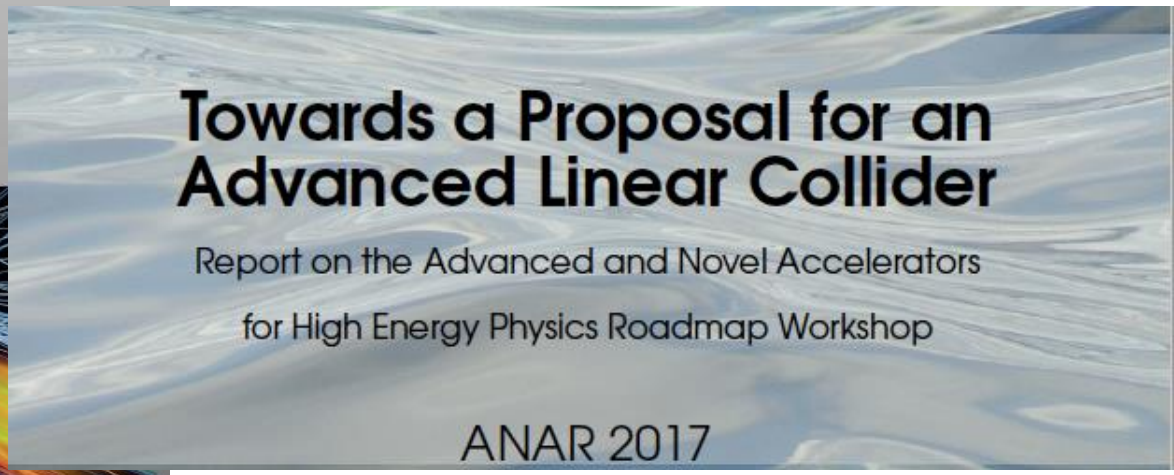


A. Pukhov et al., PRL (2014)



Session 5 – Identification of future machines and strategies

- Workshops/Reports to identify ANA R&D Roadmaps toward a collider in U.S. and Europe.

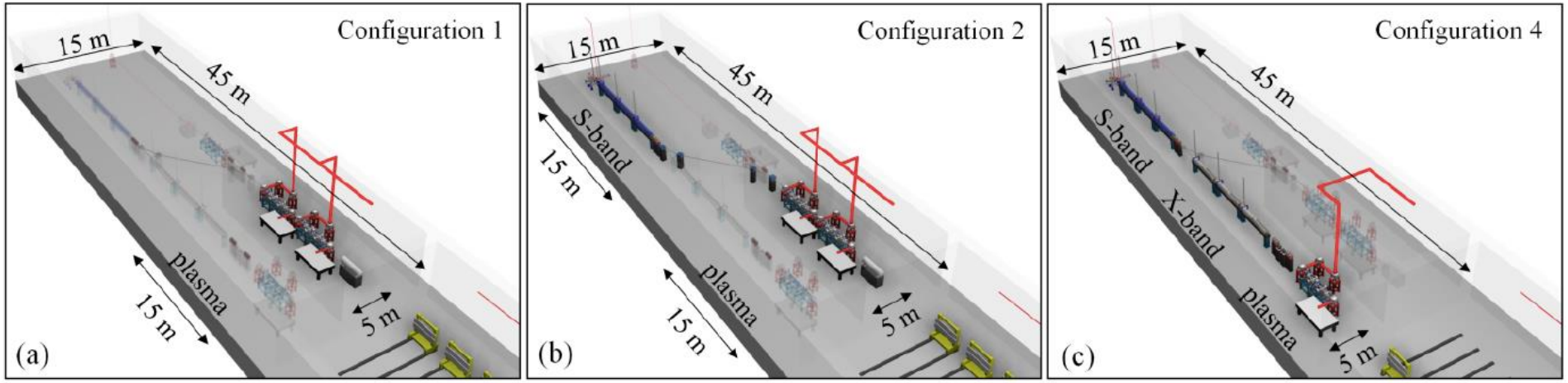


Session 5 – Identification of future machines and strategies

- What mid-term and long-term facilities are need to perform the required R&D?

- **EuPRAXIA Project**: accelerator facility for ANA R&D

P. A. Walker et al., (2017)



Session 5: speakers:

R. Walczak (Oxford) – Parameters for EuPRAXIA beamlines
W. Leemans (LBNL) – U.S. Roadmap

WG4 (LWFA) – Agenda

WG4 Sessions:

1. LWFA driver strategies [Tue 9:00]
2. Electron sources and staging [Tue 10:15]
3. Laser technology [Tue 13:00]
4. Positron acceleration in LWFA (joint with WG8) [Tue 15:30]
5. Identification of future machines and strategies [Wed 10:45]
6. Next steps (joint with WG 2 + diagnostics for future machines) [Wed 13:30]
7. Summary and coordination [Wed 16:00]

- Coordinate preparation of documents for input to European Strategy Research Group