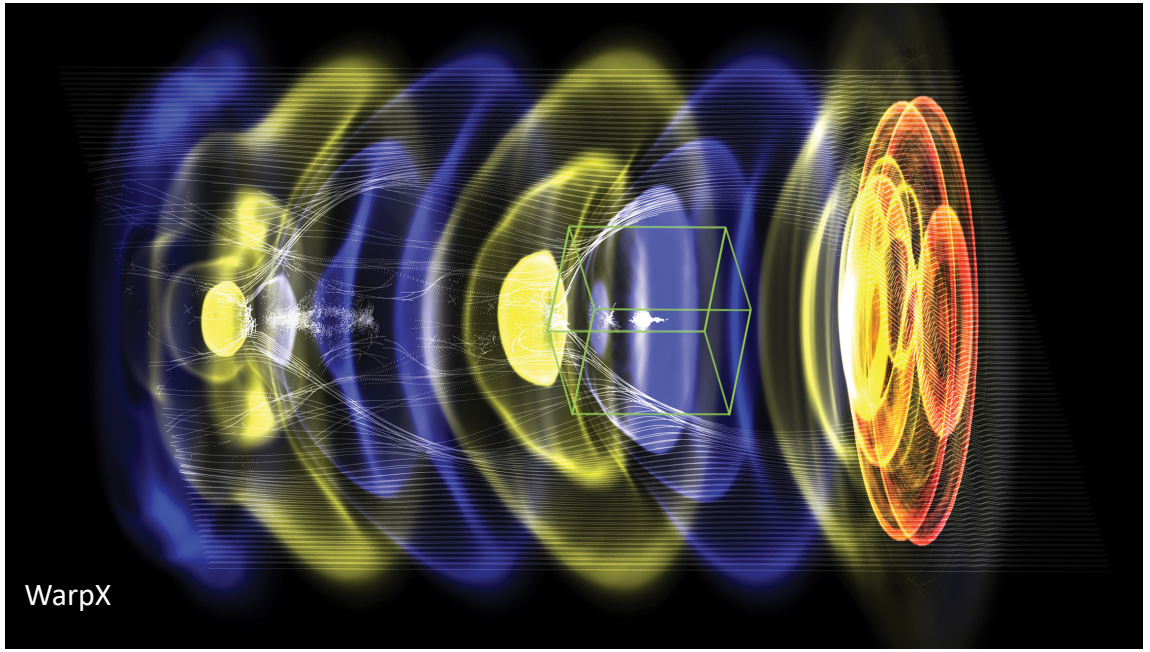
Laser-driven plasma-wakefield accelerators

Carl Schroeder
BELLA Center
Lawrence Berkeley National Laboratory



Townhall Meeting High Gradient Acceleration Plasma/Laser,
30 March 2021

Work supported by the U.S. DOE, Office of Science, Office of High Energy Physics, under Contract No. DE-AC02-05CH11231

Outline

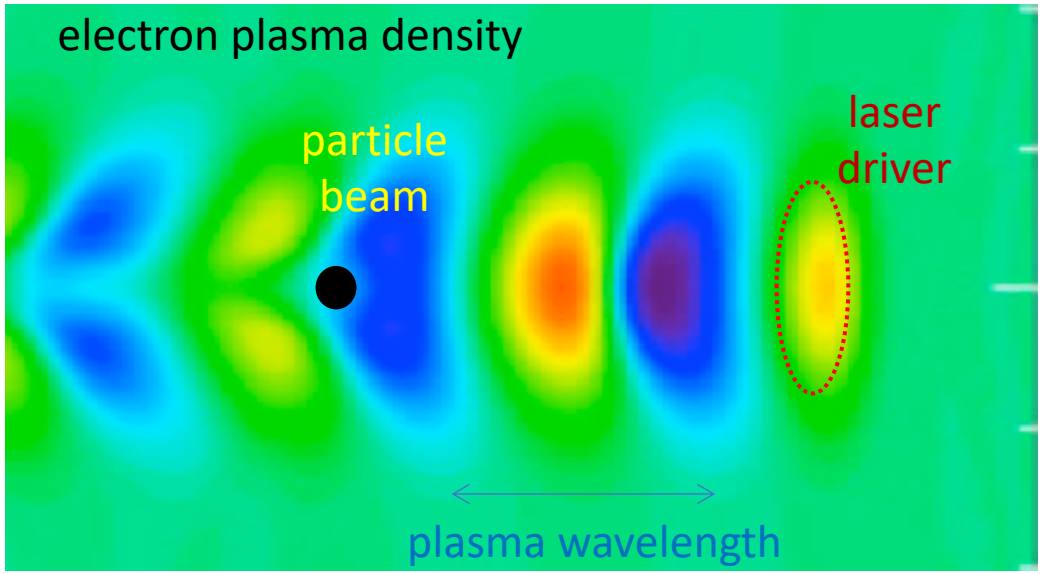
- Introduction to laser-driven plasma-wakefield accelerators (LWFAs)
  - Basic configuration of LWFA-based collider
  - Optimization of operating parameters
- Experimental progress
  - Multi-GeV LWFA
  - LWFA Staging
- Energy reach of an LWFA-based collider
  - Power requirements
- Laser-technology requirements and R&D
- Key accelerator R&D challenges
- R&D goals for next 5-10 years

Laser-driven plasma-wakefield accelerators (LWFAs): compact acceleration (>GV/m) of fs beams

- Wakefield (plasma wave) driven by the ponderomotive force of a resonant laser pulse in plasma
- Requires high intensity, short duration laser drivers
- Plasma density $n_0 \sim 10^{17}$ cm^{-3} yields $E \sim 10$ GV/m
- Focusing and acceleration provided by plasma wave
- Compact coupling (< 1 m) of laser drivers using plasma mirrors

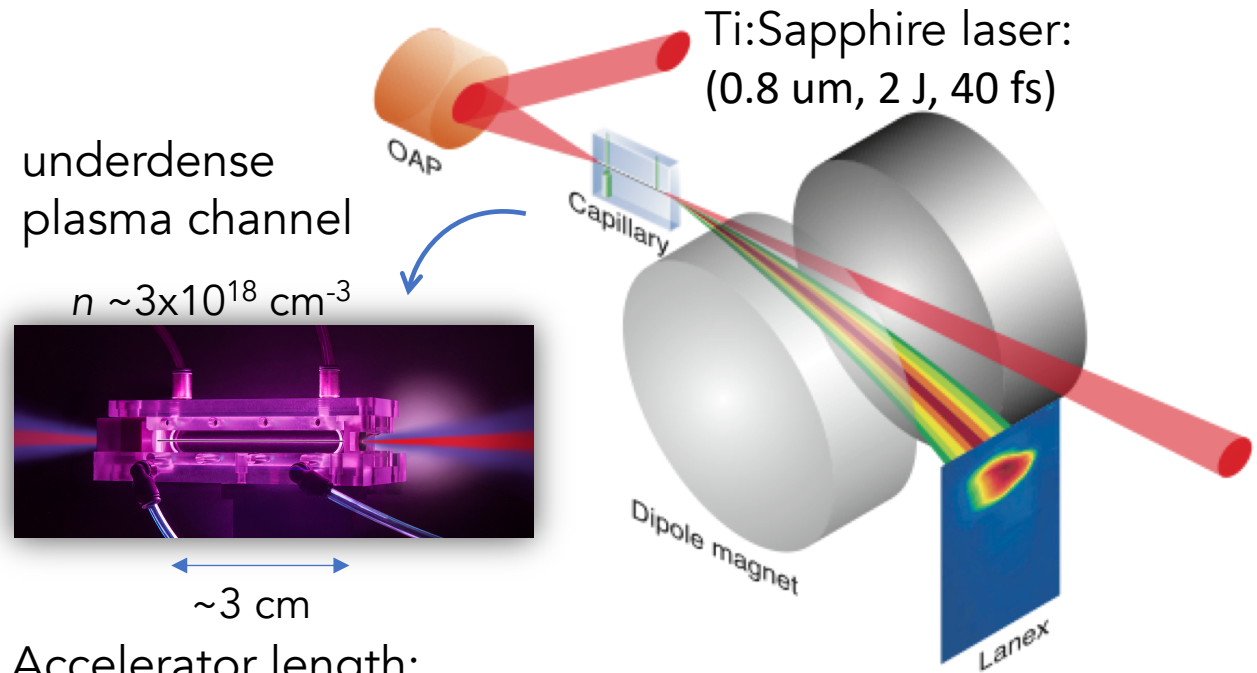
Esarey et al Rev. Mod. Phys. (2009)

Laser-driven plasma accelerator
(in quasi-linear regime)



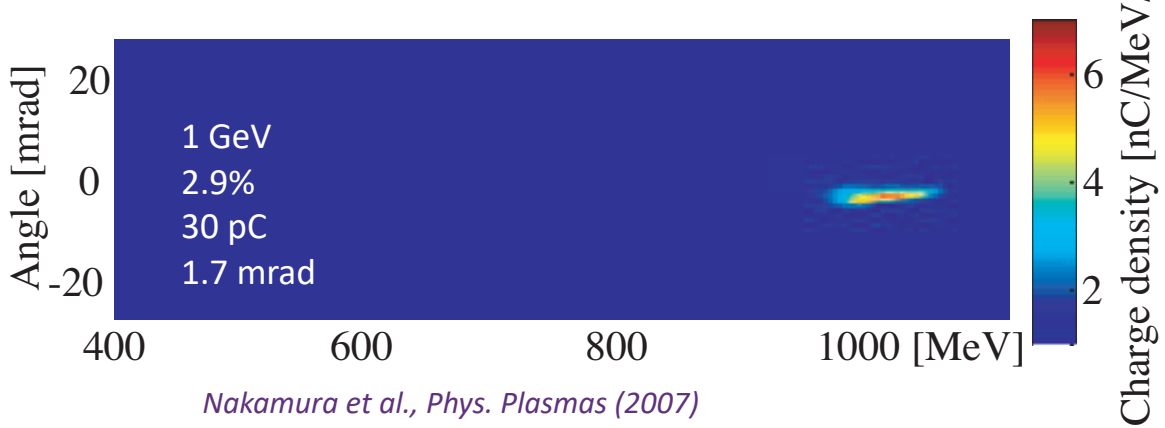
- Main advantages of laser-plasma accelerator technology (for collider applications):
  1. compact accelerator footprint (both accelerating plasma cell, drive laser beam, drive coupling)
  2. ultra-short bunches (few micron bunches reduce beamstrahlung, yield collider power savings)

GV/cm gradients experimentally demonstrated



Accelerator length:

$$L_{\rm acc} \sim \lambda_p^3/\lambda^2 \propto n^{-3/2}\lambda^{-2}$$



Nakamura et al., Phys. Plasmas (2007)

Laser energy: $U_{\rm laser} \propto \lambda_p^3 \propto n^{-3/2}$

Pulse duration: $\tau_{\rm laser} \propto \lambda_p \propto n^{-1/2}$

Accelerating gradient:

$$E \sim E_0 = (m_e c\omega_p/e) \propto \sqrt{n}$$

Charge/bunch:

$$N_b \propto n^{-1/2}$$

Energy gain:

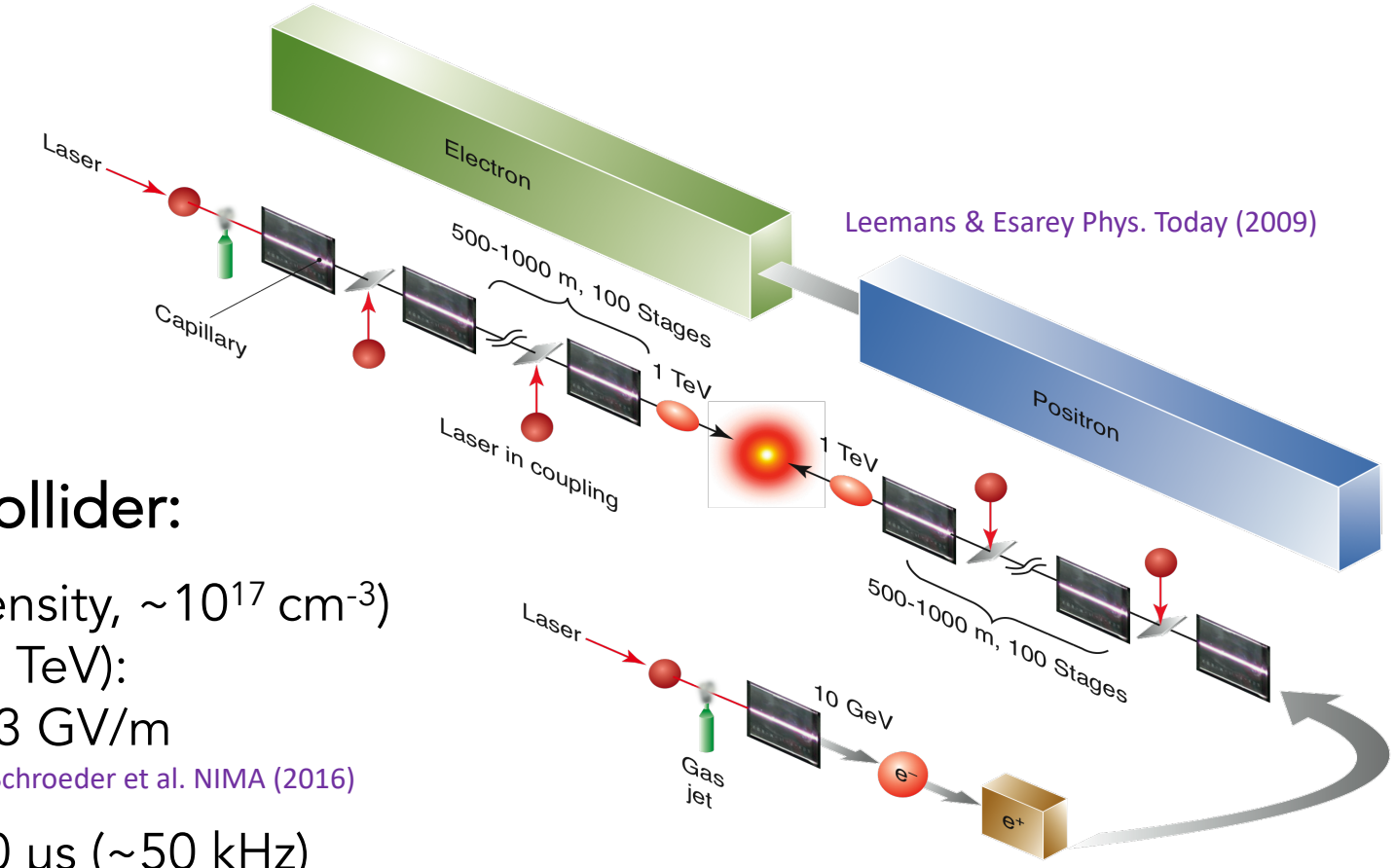
$$W \sim (mc\omega_p/e)L_{\rm acc} \propto n^{-1}\lambda^{-2}$$

- Laser depletion, reasonable gradient (>1GV/m), and high charge/bunch, necessitates staging of LWFAs to reach high energy.

Basic configuration of a laser-plasma linear collider

Linac: staged laser wakefield accelerators (LWFAs):

- Preliminary/Strawperson designs have been produced to guide R&D
- R&D focus has been on developing laser-plasma accelerator technology
- No complete conceptual design is ready (Laser technology is developing)



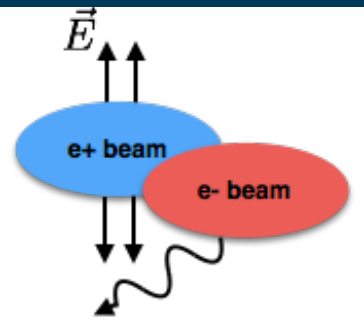
Leemans & Esarey Phys. Today (2009)

Key characteristics of a LWFA-based collider:

- Design (optimizing operational plasma density, ~10^{17} cm^{-3}) yields 5 GeV/stage (100 stages/linac for 1 TeV):
  - Geometric/average gradient = 2.3 GV/m
- Time structure at IP:
  - single bunches, separated by ~20 μs (~50 kHz)
- Short (8.5 μm rms), shaped (trapezoidal current dist.):
  - beamstrahlung reduction: $\delta_\gamma \propto \sigma_z^{1/3}$
  - $\boldsymbol{\sigma_z < \beta^*}$
- Flat or round beams may be accelerated

C. Schroeder et al. NIMA (2016)

Luminosity challenges—IP considerations



- e-e+ beam parameters constrained by IP interaction
- In general, maximize beam charge up to limits set by beamstrahlung

- Future linear colliders (> 1TeV) will operate in high (quantum) beamstrahlung regime
  - Mean beam field strength in beam rest frame large compared to Schwinger field
  - If *local constant field approximation* holds (bunch durations > radiation formation length), then average fractional energy loss is

P. Chen, K. Yokoya (1995)

$$n_\gamma \simeq 3.5\delta_b \propto \frac{N^{2/3}\sigma_z^{1/3}}{(\sigma_x+\sigma_y)^{2/3}\gamma^{1/3}}$$

In plasma accel., bunch charge and length (optimized for efficiency) not independent and depends on density choice:

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

- Plasma accelerators operate with short bunches (~10 um)
- Short beams save power:

$$\frac{\mathcal{L}}{\mathcal{E}_{\rm cm}^2} \propto \frac{n_\gamma^{3/2} P_{\rm beam}}{\sigma_z^{1/2}\gamma^{5/2}}$$

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

Plasma accelerators produce short beams and short beams save power

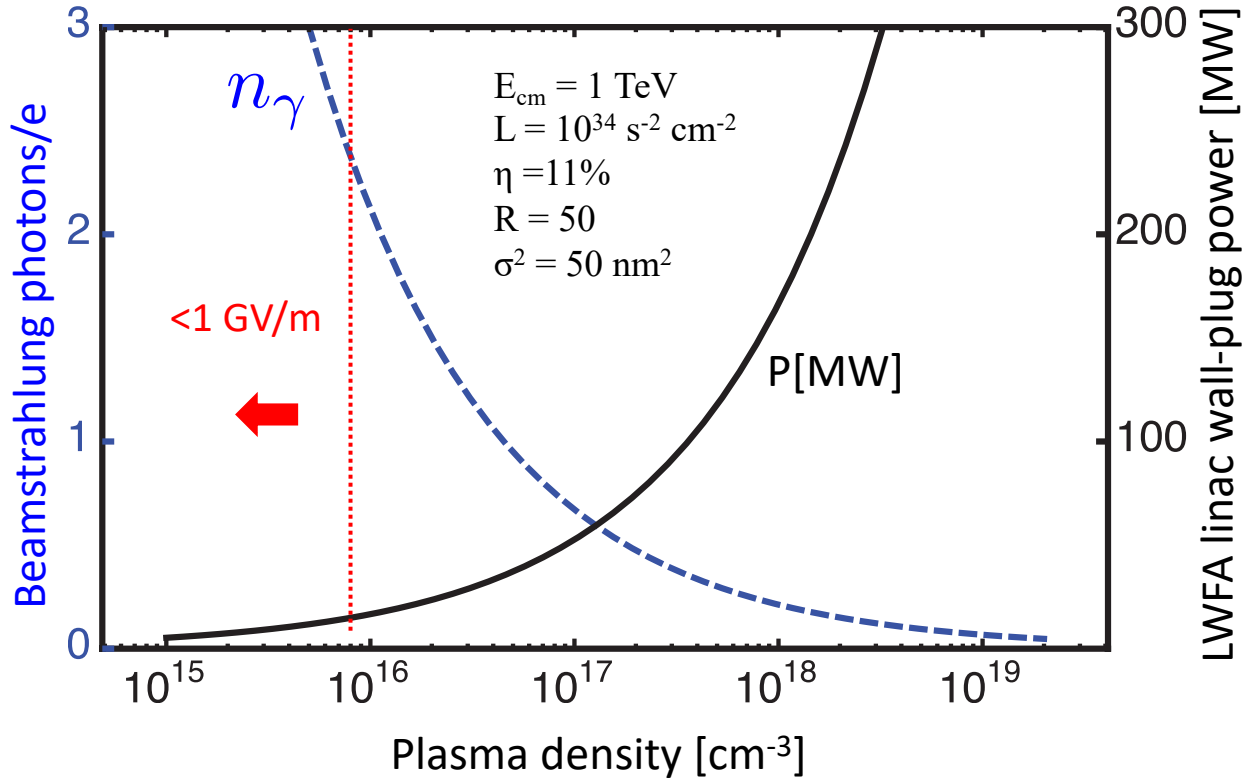
Operational plasma density

- Power requirements reduced at low plasma density
- Beamstrahlung limits charge/bunch

Average fractional (beamstrahlung-induced) energy loss:

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

P. Chen (1992)



➢ Optimized plasma density: ~10^{17} cm^{-3}

Collider parameter scalings with density and laser wavelength

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

$$N_{\text{stages}} \propto n\lambda^2$$

$$L_{\text{linac}} \propto n^{-1/2}$$

$$f_{\text{rep}} \propto n$$

$$P_b \propto n^{1/2}$$

$$P_{\text{avg laser}} \propto n^{-1/2}\lambda^{-2}$$

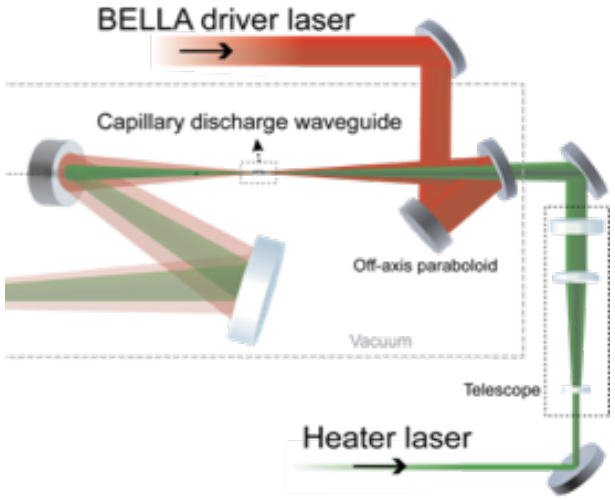
$$P_{\text{wall}} \propto n^{1/2}$$

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

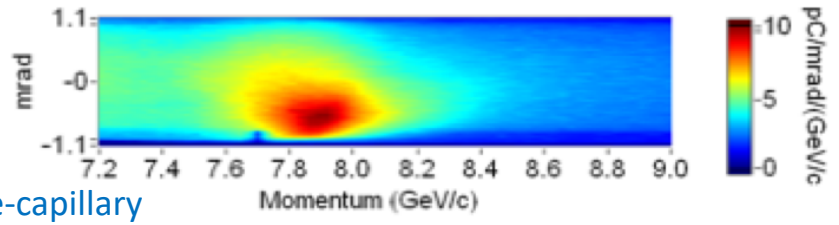
Power independent of laser wavelength

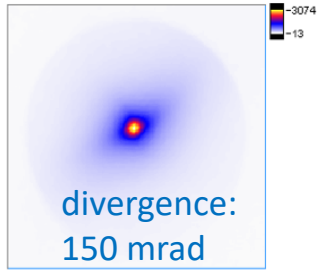
LWFA state-of-the-art: multi-GeV acceleration

- **Single LWFA stage achieved multi-GeV acceleration:** 8 GeV in 20 cm (40 GV/m)

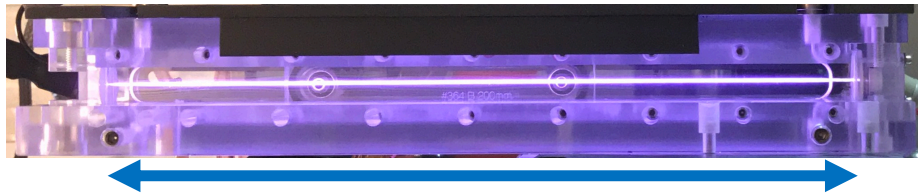


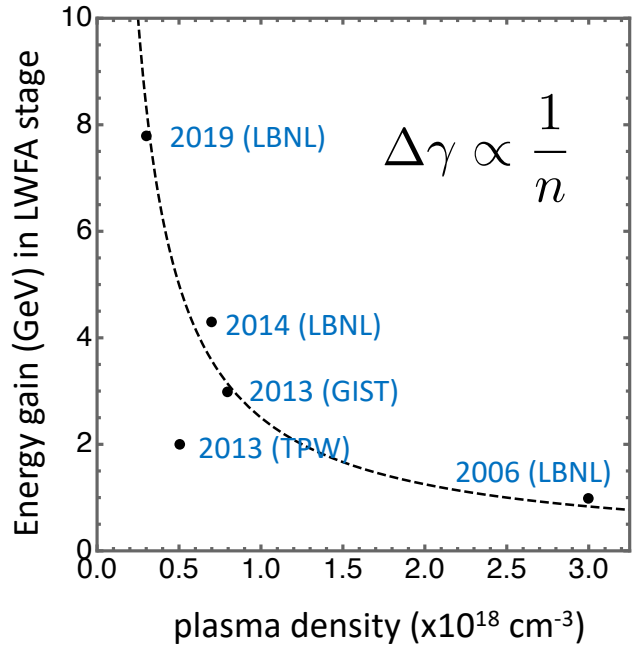
Gonsalves et al. PRL (2019)





Laser-heater-assisted discharge-capillary plasma waveguide



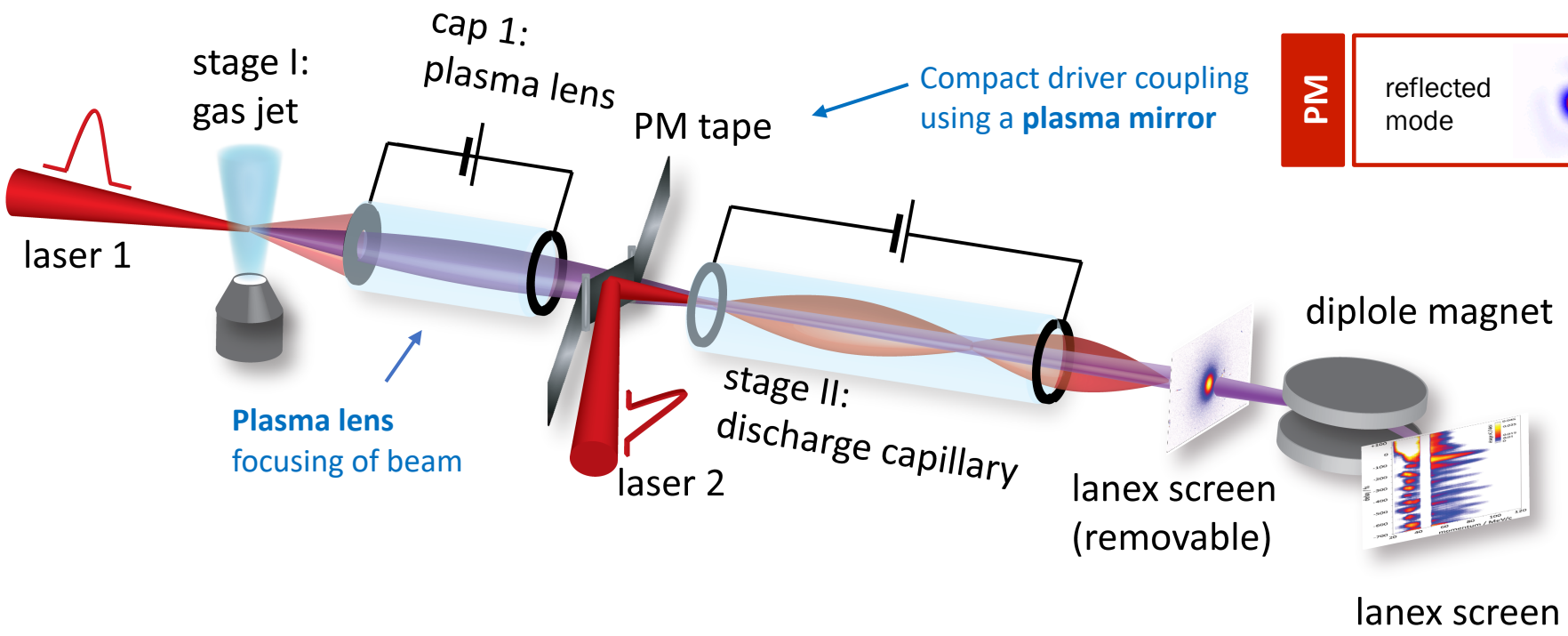


- *Key technology*: plasma channel creation for guiding at low density (3×10^{17} cm^{-3}) – discharge capillary + laser heater
- *New technologies emerging*: hydrodynamic optical-field-ionized plasma channels R. J Shallo .et al. PRE (2018); PRAB (2019) B. Miao et al., PRL (2020)

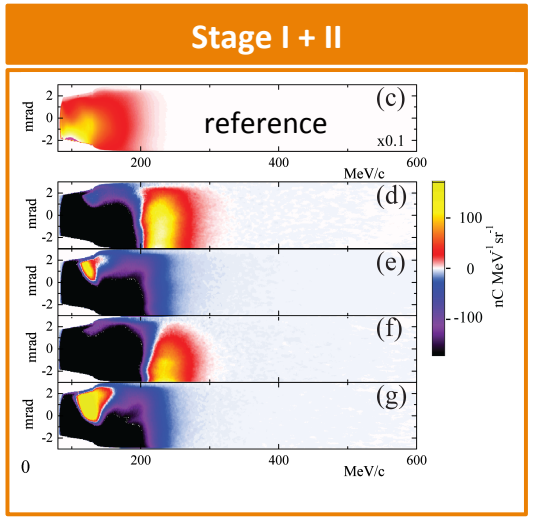
- 1 Hz rep. rate
- Reproducibility limited by laser fluctuations (at ~100 Hz)

Experimental R&D: Staging of LWFAs

- Proof-of-principle staging of LWFAs



Steinke et al. Nature (2016)



- Proof-of-principle experiment demonstrate 100 MeV energy gain
  - Poor capture efficiency, beam-quality preservation

- Multi-GeV staging experiments are planned / commissioning underway at Berkeley Lab (BELLA PW 2nd beamline)
  - *Goal*: near-100% capture efficiency, quality preservation

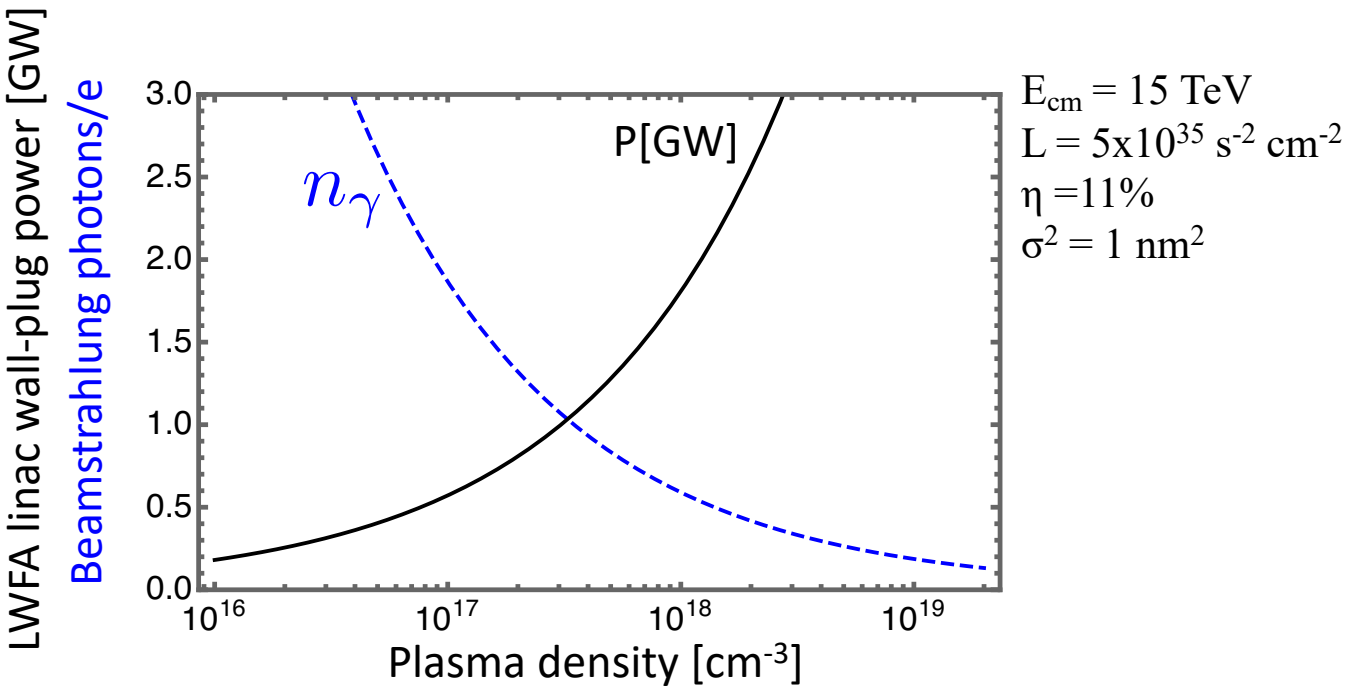
Energy reach of laser-plasma colliders

(Greenfield) LWFA-based collider:

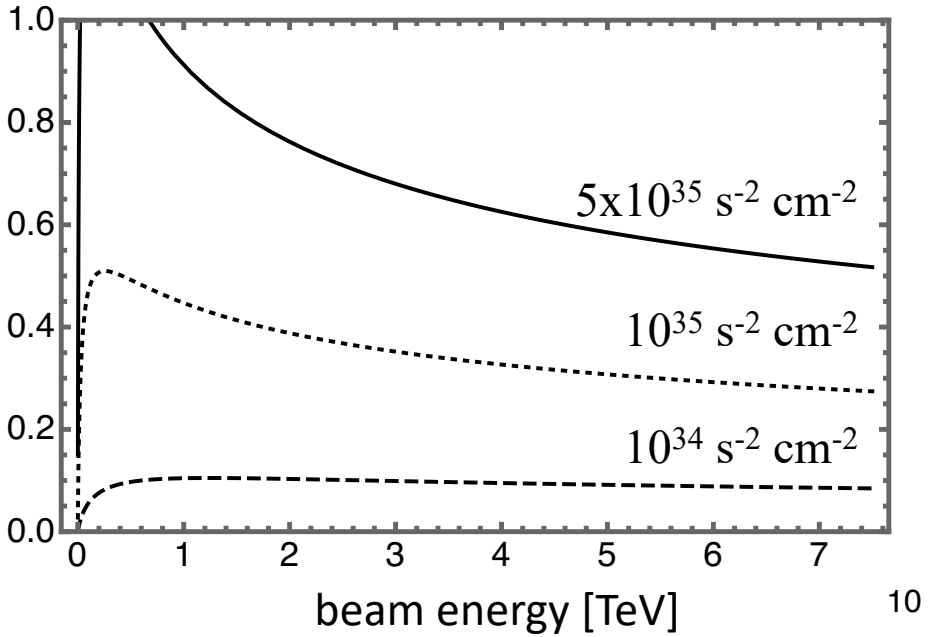
- Plasma acceleration gradients yield compact linacs: km-scale for multi-TeV
  - LWFA collider: 0.65 km linacs for √s = 3 TeV
  - LWFA collider: 3.3 km linacs for √s = 15 TeV

- Power limitations (assuming luminosity requirements increase quadratically with energy):

$$P_{\mathrm{beam}} \propto \gamma^{5/2} \sigma_z^{1/2} \sigma_x$$

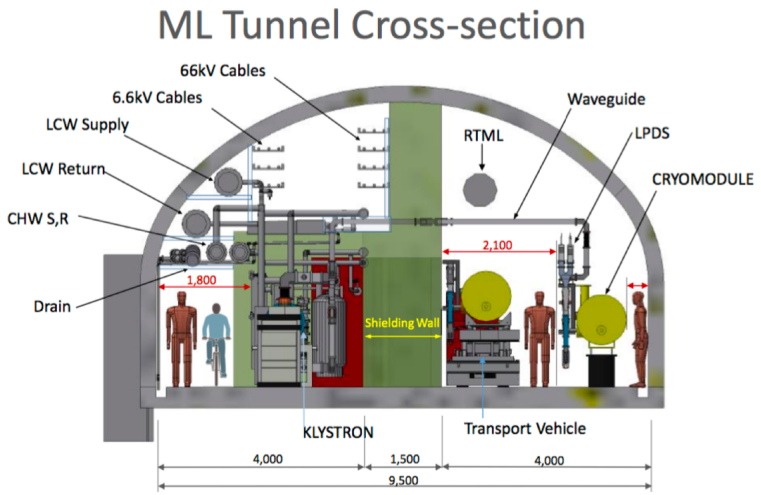


Average fractional energy loss: $\delta_b \propto \dfrac{N^{2/3}\sigma_z^{1/3}}{(\sigma_x+\sigma_y)^{2/3}\gamma^{1/3}}$

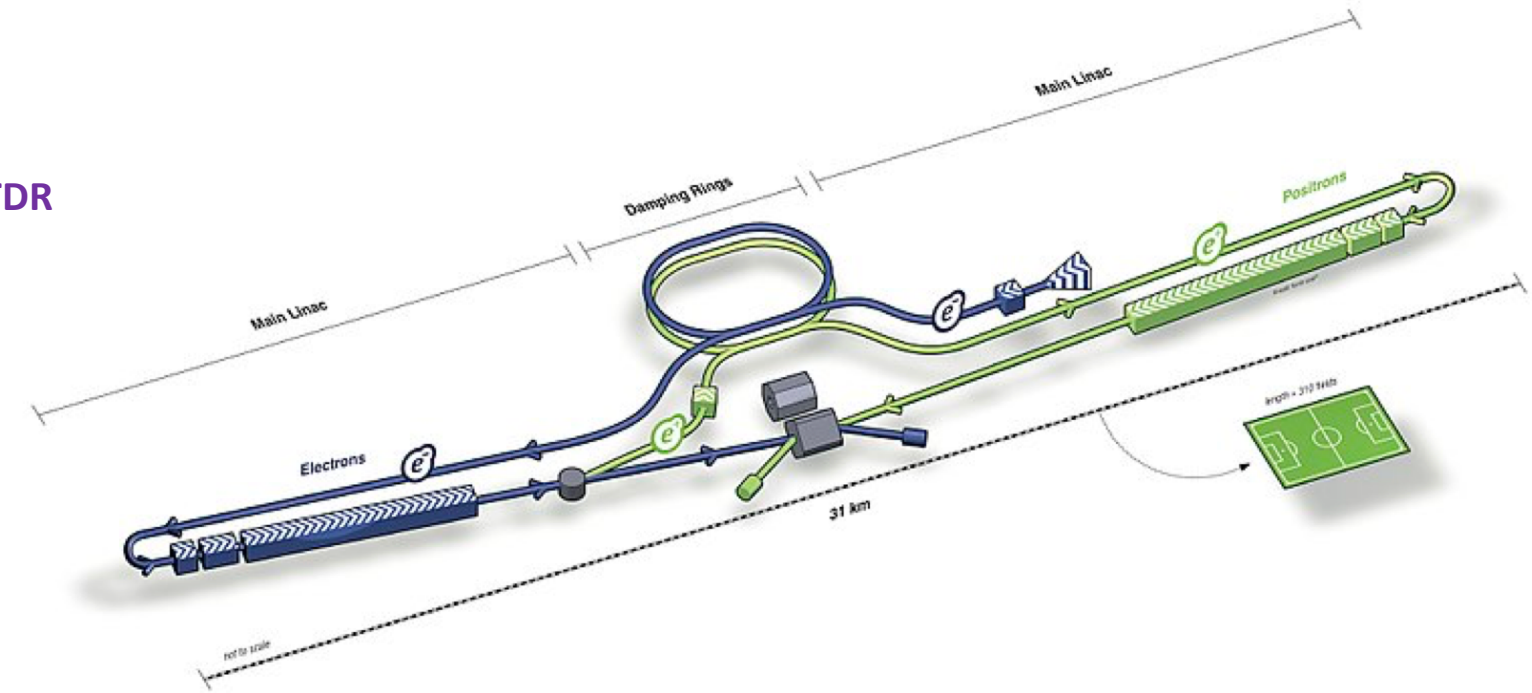


Plasma-based collider using ILC infrastructure

- ILC upgrade:
  - Replace SCRF with LWFA stages
  - Laser drivers (~m^2) and plasma cells fits in ILC main linac tunnel
  - 300 MW site power could support $\sqrt{s}$ = 3 TeV LWFA design
  - 12 MW beam power for $\sqrt{s}$ = 3 TeV LWFA design (ILC beam dumps rated for 17 MW)



ILC TDR



High energies (1-15 TeV) accessible in conventional accelerator facility footprint

Laser technology requirements for a collider

Laser drivers:

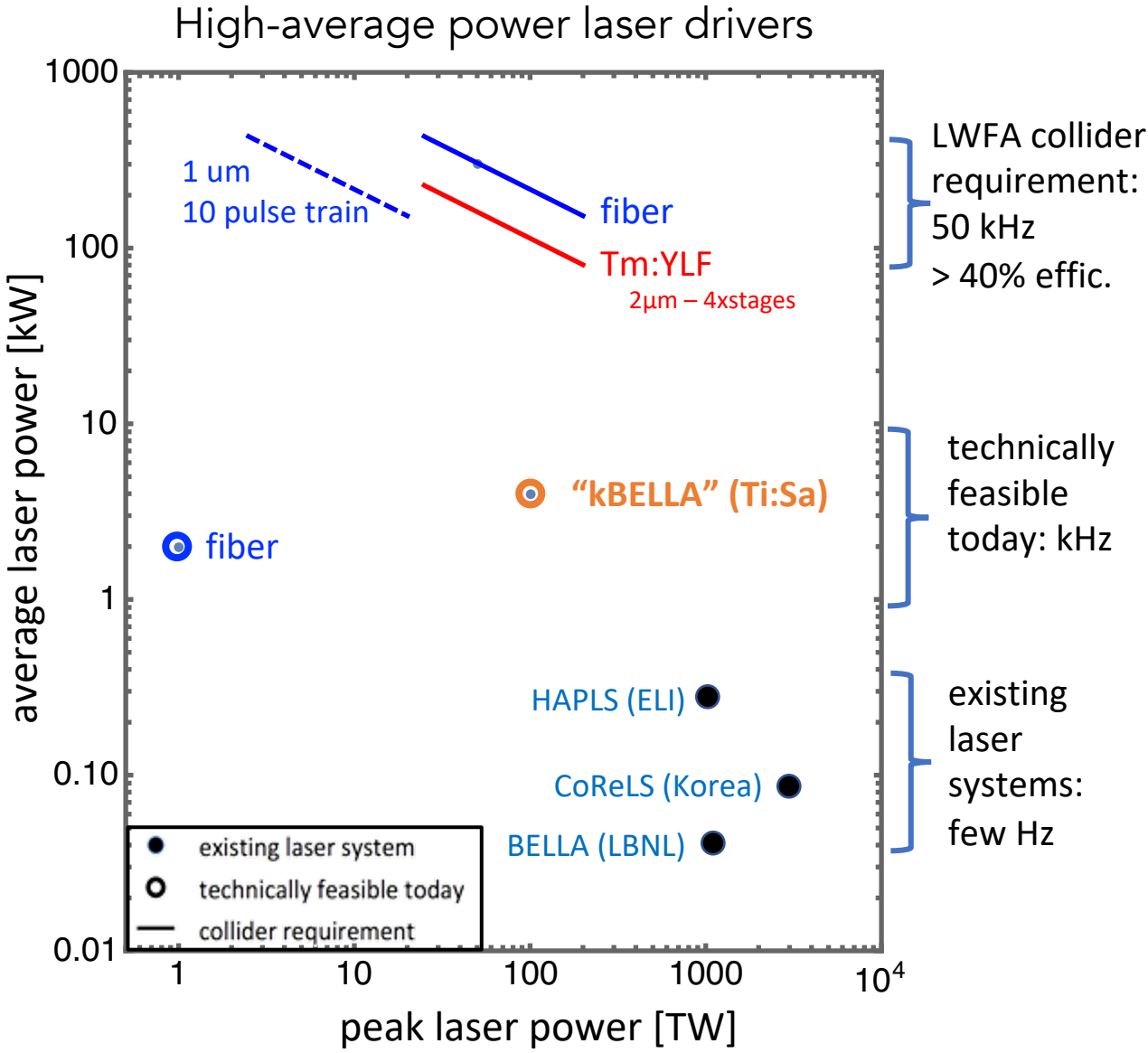
- Requires R&D to reach collider parameters:

10 J, 100 fs class, 50 kHz, high wall-to-laser efficiency

- Two promising laser architectures:
  - Coherent combination of fiber lasers (1 um).
    R&D at Jena, Michigan, LBNL, LLNL, et al.
    ~60% wall-to-laser efficiency
  - Tm:YLF (1.9 micron) – (4x as many LWFA stages).
    R&D at LLNL
- Peak laser power requirements may be relaxed by excitation using laser pulse trains

J. Cowley et al. PRL (2017)

➢ Facilities needed to demonstrate active-feedback stabilization, develop high-rep-rate LWFA technology (plasma targetry, diagnostics, etc.)



Key accelerator R&D challenges

- Laser technology development
  - Coherent combining of fiber lasers
  - Development of Tm:YLF
  - kW average power systems feasible today (kHz rep rate enables laser stability)

- Robust e+ acceleration configuration
  - Proposed configurations (hollow plasma channels, plasma columns) require experimental demonstrations

- Beam matching/coupling between stages
  - Strong focusing forces in plasma: $\beta \sim 0.01 - 0.1$ m

- Alignment
  - Small structures (~10-100 um) place severe (~nm) alignment tolerances

- Stability in main linac
  - Transverse stability (BBU) is issue in strong wakefield regime
  - Proposed mitigation methods (ion motion, LWFA focusing chirp) require R&D

common challenges for plasma accelerator concepts

Emittance growth by Coulomb scattering in plasma

- Coulomb scattering of beam on background ions leads to emittance growth

$$\frac{d\epsilon_n}{dz} \simeq \frac{\gamma}{2k_\beta}\frac{d\langle\theta_x^2\rangle}{dz}$$

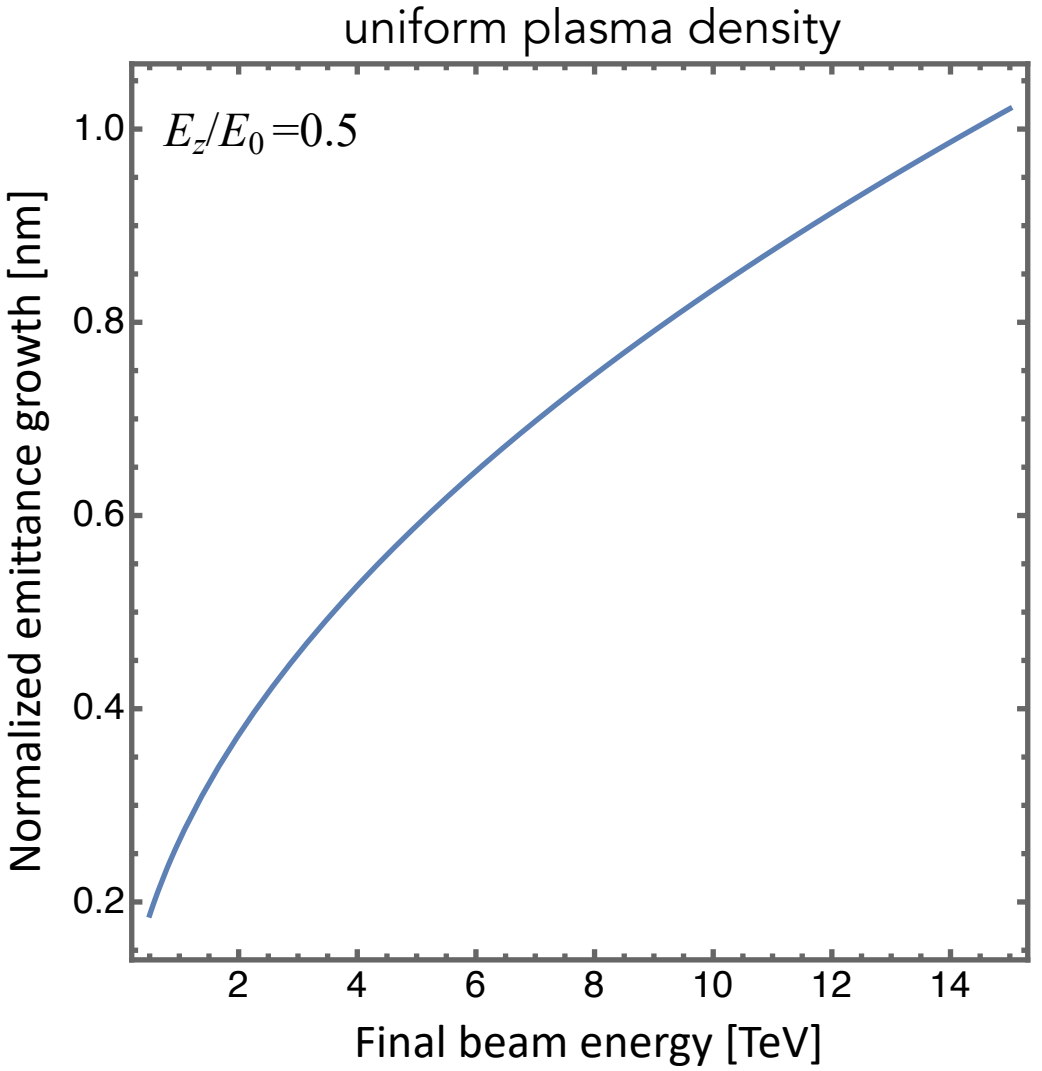
Strong focusing suppress emittance growth

- Emittance growth weakly dependent on plasma density

$$\Delta\epsilon_n = \frac{\sqrt{2}r_e Z}{(E_z/E_0)}\ln\left(\frac{r_{\max}}{r_{\min}}\right)\gamma^{1/2} \sim r_e\gamma^{1/2}$$

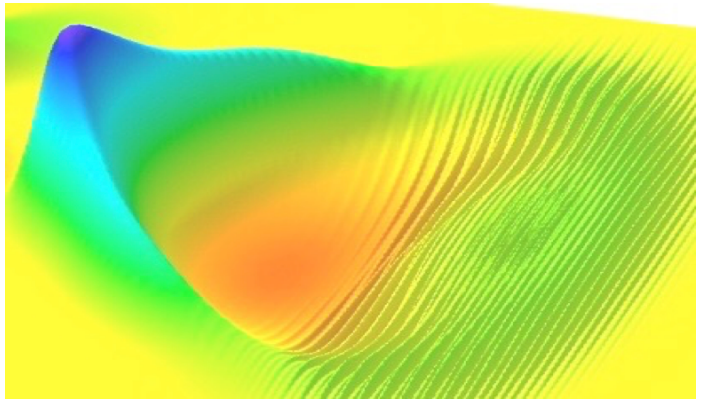
Sub-nm normalized emittance growth from scattering with plasma for 10-TeV-class collider

- Sub-nm emittances could be achieved at higher energies using near-hollow plasma channels to reduce scattering



Schroeder et al., Phys. Plasmas (2013)

Synchrotron radiation in plasma linacs



Wiggler/betatron period:

$$\lambda_\beta \simeq (2\gamma)^{1/2}\lambda_p$$

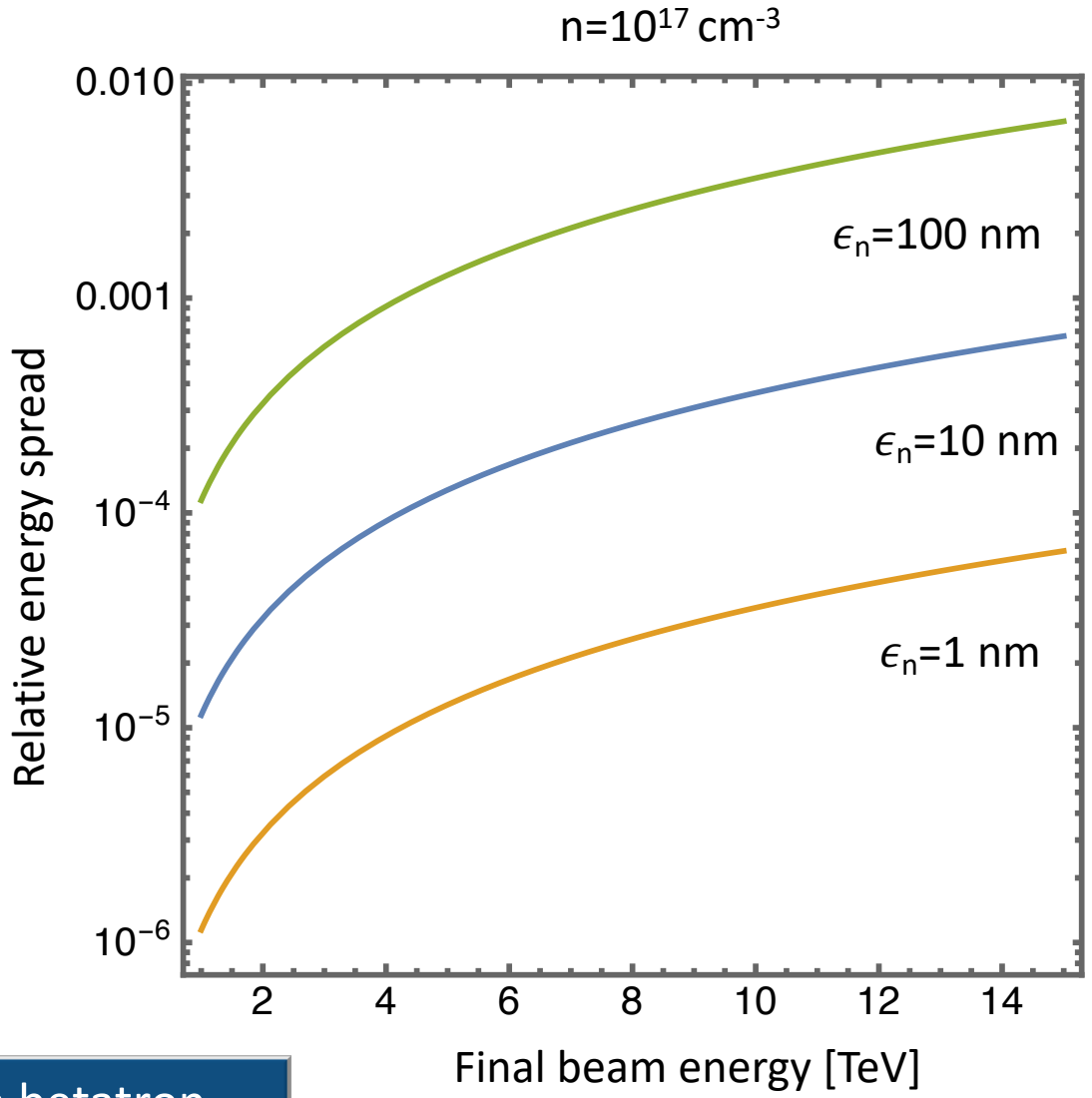
Wiggler strength parameter:

$$a_\beta = \gamma k_\beta r_\beta$$

- Energy spread growth linearly proportional to emittance (betatron amplitude)
- Assuming focusing from ion cavity:

$$\frac{\sigma_\gamma}{\gamma} \simeq \frac{\sqrt{2}k_p^2 r_e}{15(E_z/E_0)}\gamma^{3/2}\epsilon_n \propto n\gamma^{3/2}\epsilon_n$$

Schroeder et al., PRSTAB (2010)



Energy spread induced by synchrotron radiation from plasma betatron motion (assuming low-emittance matched beam) is not a strong limit

Transverse stability – hosing leads to emittance growth
Ion motion mitigates instability growth

- Strong beam loading (for efficiency) associated with transverse wakefield induced instability (hosing/BBU)

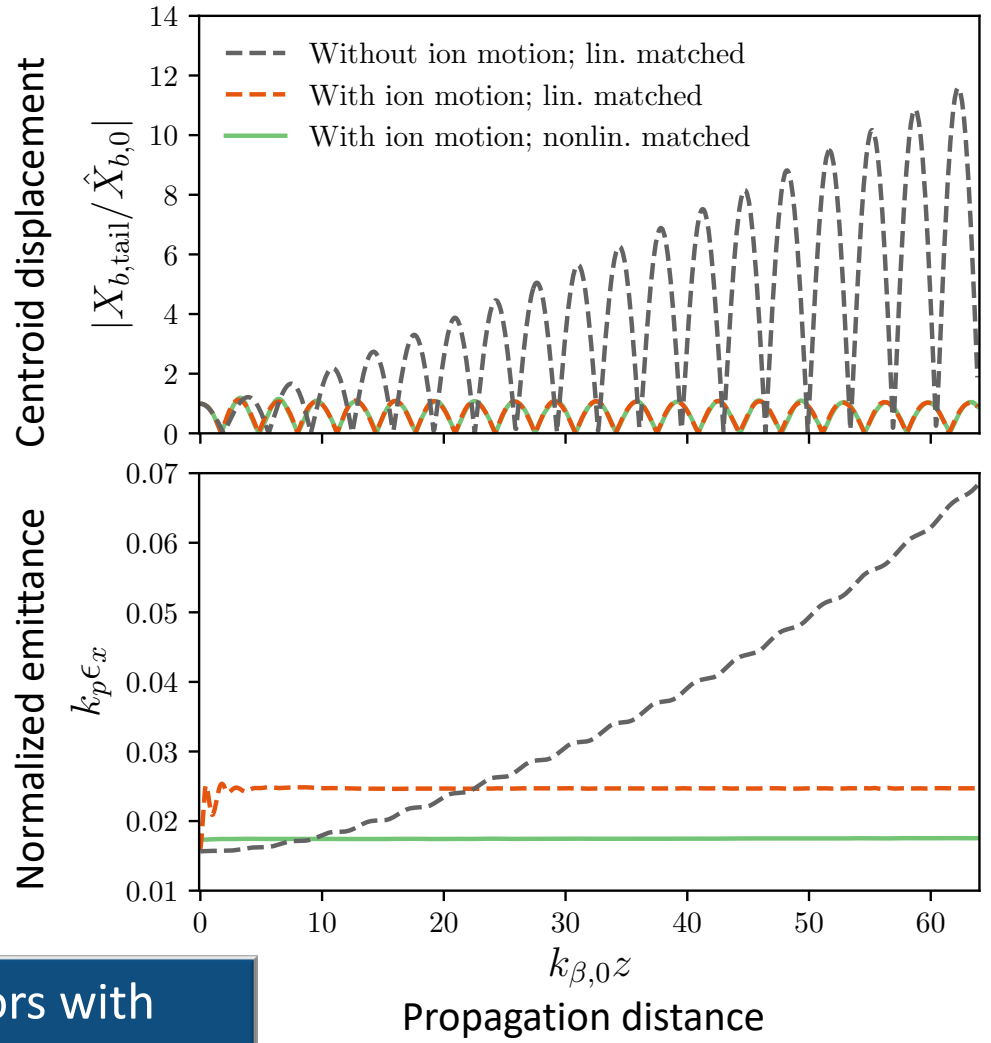
- Stability to hosing/BBU achieved via BNS damping:
  - Requires large (~10%) energy chirp, owing to strong beam loading
  - large chirps have transport challenges

$$k_\beta(\xi) = k_p/\sqrt{2\gamma(\xi)}$$

- Stability also achieved with head-to-tail density variation
  - Naturally created by ion motion

Mehrling et al., PRL (2018)

$$k_\beta(\xi) = k_p(\xi)/\sqrt{2\gamma}$$



Stable beams may be efficiently accelerated in plasma accelerators with emittance preservation and without energy spread growth with bunch shaping

R&D on auxiliary systems for integrated design

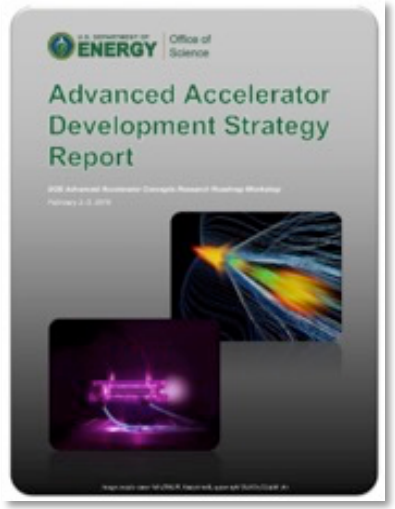
- R&D needed on auxiliary systems compatible with LWFA linacs
  - LWFA beam time structure: 1 ultra-short bunch (~20 fs) every 20 us.

- **Injector** (e-/e+ sources, damping, bunch compression)
  - *option*: traditional injector with additional bunch compression (and cooling)
  - *option*: LWFA e- sources using laser-injection for ultra-low emittance beams (beam polarization?)
- **Beam delivery system and final focus**
  - *option*: traditional BDS (compatible with short bunches) up to few TeV
  - *option*: novel system with plasma-based lenses (sub-mm final focus **β**-function)

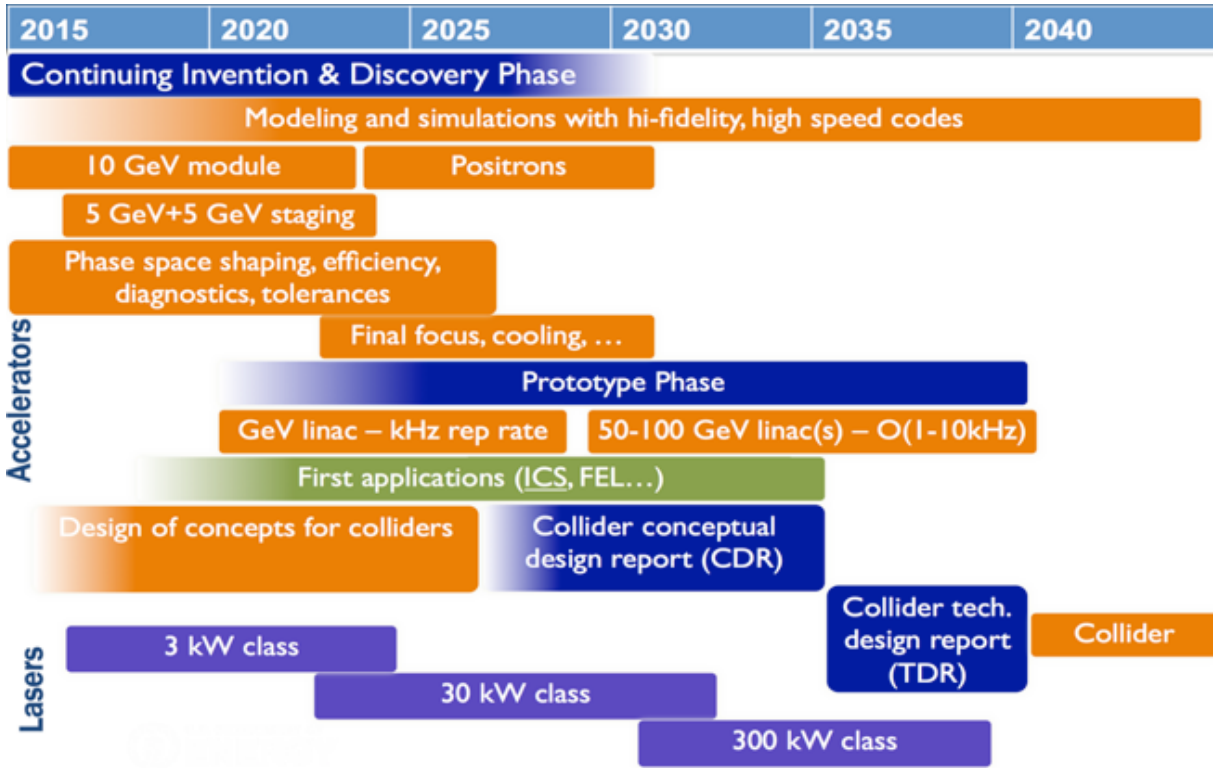
LWFA R&D timeline towards a collider

- US AAC community outlined R&D goals in 2016 roadmap
- Progress on all R&D goals
- Update to roadmap underway

(part of US Snowmass process)



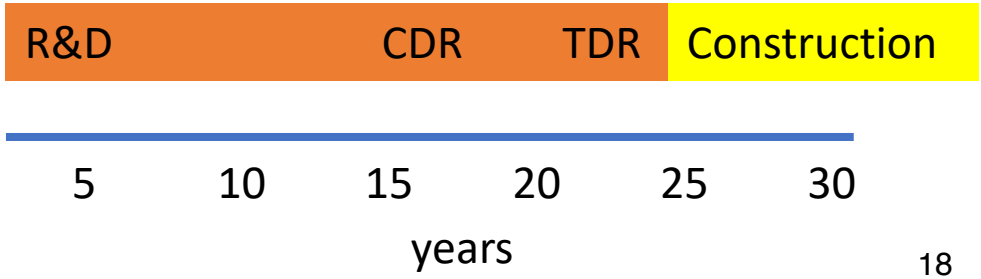
DOE HEP AAC Roadmap (2016)



Critical Technologies:

- High average power laser development
- Plasma cell development
- Multi-GeV/cell acceleration
- Staging of LWFAs
- Positron acceleration methods
- Stability
- Alignment

- Technically-limited timeline:



Conclusions / comments

- Primary advantages of LWFAs:
  - High gradient (>GV/m geometric gradient) – compactness (laser driver, plasma cell & coupling with plasma mirrors)
  - Short bunches – beamstrahlung reduction, power savings

- Multi-TeV linear e+e- colliders (based on any technology) will operate in high-beamstrahlung regime (tens of % fractional energy loss at IP)
  - Limits bunch charge, determines power requirements: $P_{\mathrm{beam}} \propto \gamma^{5/2}\sigma_z^{1/2}\sigma_x$

- Efficiency critical:
  - Laser technology R&D for efficient, high-average, high-peak power lasers
  - laser energy recovery (spent laser to photovoltaic)
  - trailing laser pulse could be used to remove plasma wake energy

- $\gamma\,\gamma$-collider is possible to avoid beam-beam interaction issues & remove need for positrons
  - Scattering laser wavelength to avoid e+e- pair creation: $\lambda_L[\mu\mathrm{m}] \approx 4E_b[\mathrm{TeV}]$

- R&D required on auxiliary collider systems compatible with LWFAs (e.g., bunch time structure)

Scientific goals in next 5/10 years

- Demonstrate multi-GeV staging of LWFAs
  - high capture efficiency and beam quality preservation
- Demonstrate kHz LWFA
  - LWFA stabilization with active feedback
  - Develop plasma targetry and diagnostics at kHz (and higher)
- Proof-of-principle demonstrations of novel laser technology (coherent combining of fiber lasers or Tm:YLF), showing scaling toward collider applications
- Demonstrate of robust plasma-based e+ acceleration configuration
- Develop integrated collider design (injector, cooling, linac, BDS, final focus, etc.)
- Develop near- and mid-term applications: (near-term applications are important demonstrations of LWFA technology that will advance collider R&D)
  - Laser-triggered generation of ultra-high brightness (tens of nm emittance) e-beams
  - Radiation sources: LWFA-driven FEL

Thank you