Laser-Plasma-Based Linear Collider

Carl B. Schroeder

and the Members of the
LOASIS Program
Lawrence Berkeley National Laboratory

Robert H. Siemann Symposium and ICFA Mini-Workshop

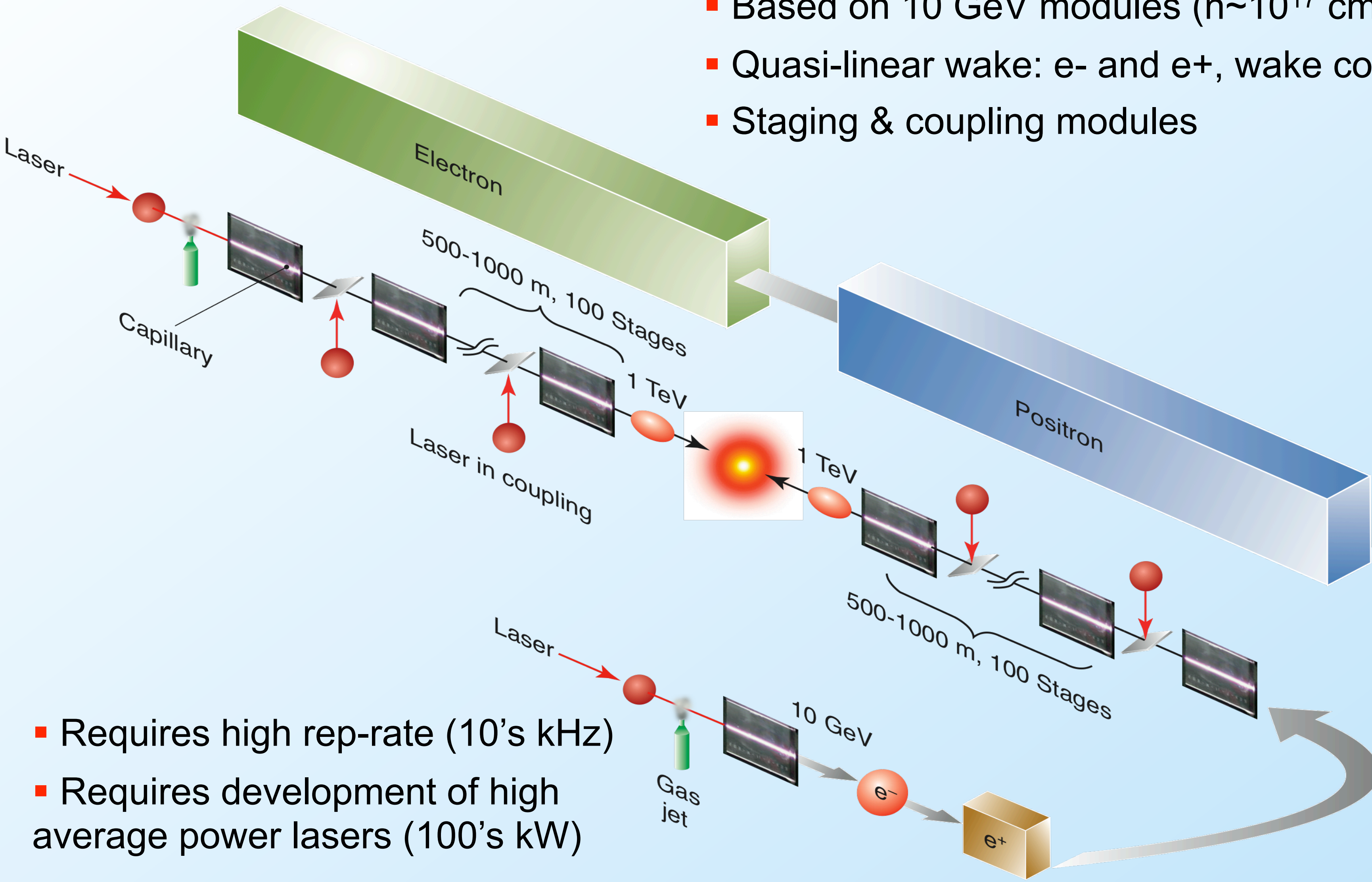
July, 7-10, 2009 – SLAC

Outline

- Review of basic laser-plasma accelerator (LPA) physics
  - Limits to single-stage energy gain: laser depletion
  - Staging laser-plasma accelerators
- Scaling laws for LPA collider design
  - Plasma density choice
  - Laser intensity choice
- Collider design issues
  - Beamstrahlung mitigation requires short bunches
  - Emittance growth via beam scattering with plasma
- Conceptual design of a laser-plasma collider at 1 TeV
  - Based on 10 GeV stages
  - Laser technology requirements
- Conclusions and R&D directions

Conceptual LPA Collider

- Based on 10 GeV modules (n~10^{17} cm^{-3})
- Quasi-linear wake: e- and e+, wake control
- Staging & coupling modules



- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

Leemans & Esarey, Physics Today, March 2009

Laser-plasma accelerators: >10 GV/m accelerating gradient

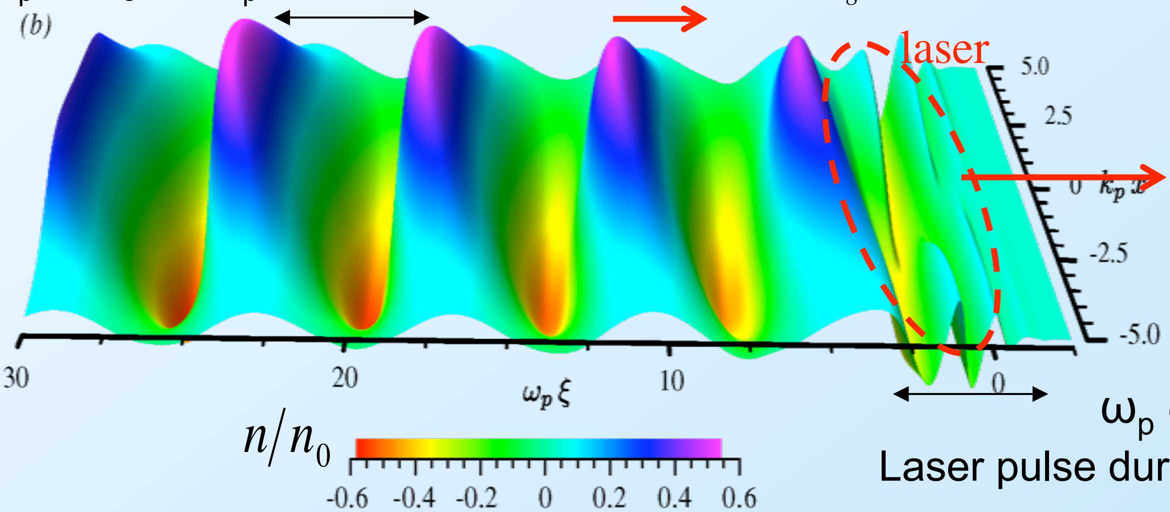
$$E \sim \left(\frac{mc\omega_p}{e}\right)\frac{a^2}{\left(1+a^2/2\right)} \approx (96\mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}\,\frac{a^2}{\left(1+a^2/2\right)}$$

plasma wave (wakefield) E ~10^2 GV/m (for n~10^{18} cm^{-3}, I~10^{18} W/cm^2)

(>10^3 larger than conventional RF accelerators)

$\lambda_p = 2\pi c/\omega_p = (\pi r_e^{-1/2})\, n_p^{-1/2} \sim 10\ \mu\mathrm{m}$

$v_{wave} \approx v_g \approx c$



$\omega_p \sigma_t \le 1$

Laser pulse duration ~ λ_p/c ~ tens fs

Limits to single-stage energy gain: Laser energy depletion necessitates multiple stages

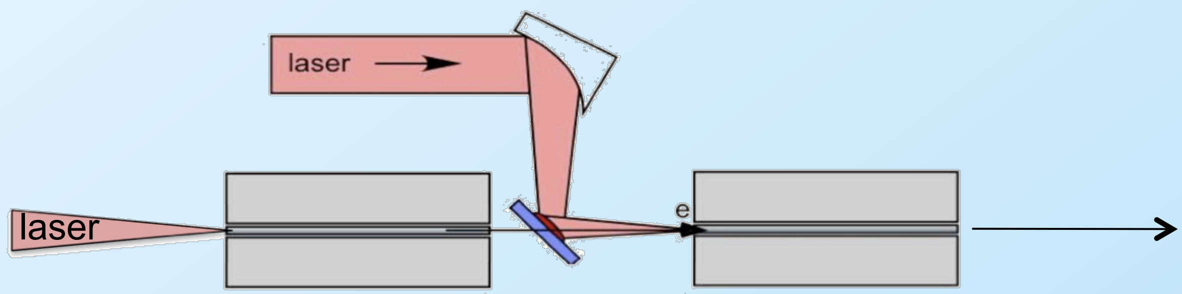
- Limits to single stage energy gain:
  - Laser Diffraction (L~Rayleigh range): mitigated by transverse plasma density tailoring (plasma channel)
  - Beam-Laser Dephasing: mitigated by longitudinal plasma density tailoring (plasma taper)
  - Laser Depletion: energy loss into plasma wave excitation

Depletion Length: $L_d \propto n^{-3/2}$

Accelerating field: $E \propto n^{1/2}$

Energy gain (linear regime): $W_{stage}[\mathrm{GeV}] \approx \dfrac{I[\mathrm{W/cm^2}]}{n[\mathrm{cm^{-3}}]}$

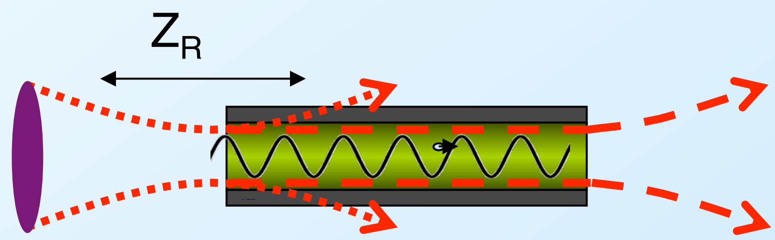
- Multiple-stages for controlled acceleration to high energy:

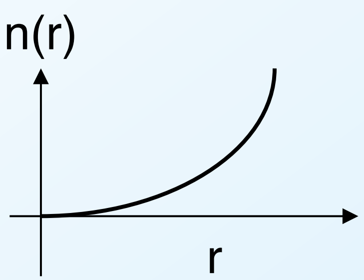


Laser diffraction controlled by plasma channel

Laser diffraction: (L ~Z_R)

Solution: tailor plasma profile to form plasma channel

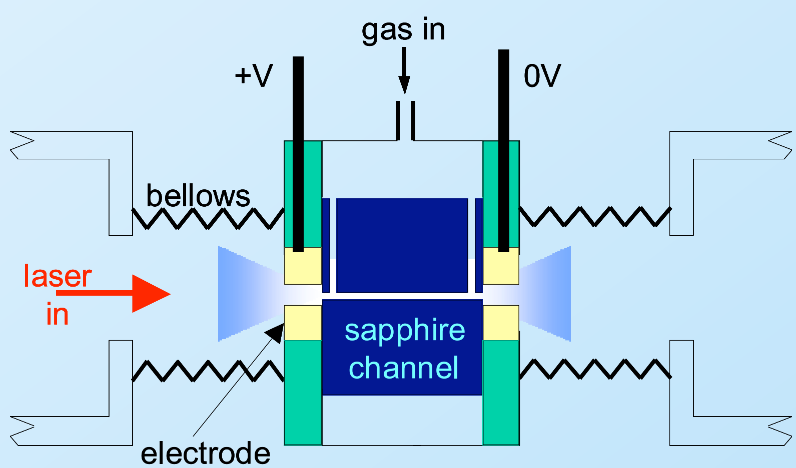




Guiding: $$\frac{d\eta}{dr} = \frac{d}{dr}\left(1 - \frac{\omega_p^2}{2\omega_L^2}\right) < 0$$

Capillary discharge plasma waveguides:

- Plasma fully ionized for t > 50 ns
- After t ~ 80 ns plasma is in quasi-equilibrium: Ohmic heating is balanced by conduction of heat to wall
- Ablation rate small: cap. lasts for >10^6 shots
- n_e ~ 10^{17} - 10^{19} cm^{-3}

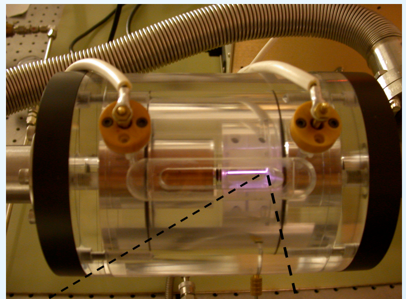


Experimental demonstration: 1 GeV high-quality beam via laser-plasma accelerator

40 TW,
38 fs,
1.5J,
10 Hz
25 micron spot
10^{18} W/cm^2

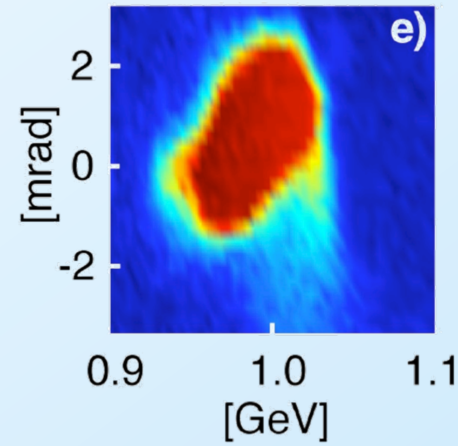
LBNL
Ti:Al_2O_3
laser

H-discharge capillary technology:
plasma channel production (1-4x10^{18} cm^{-3})



3 cm

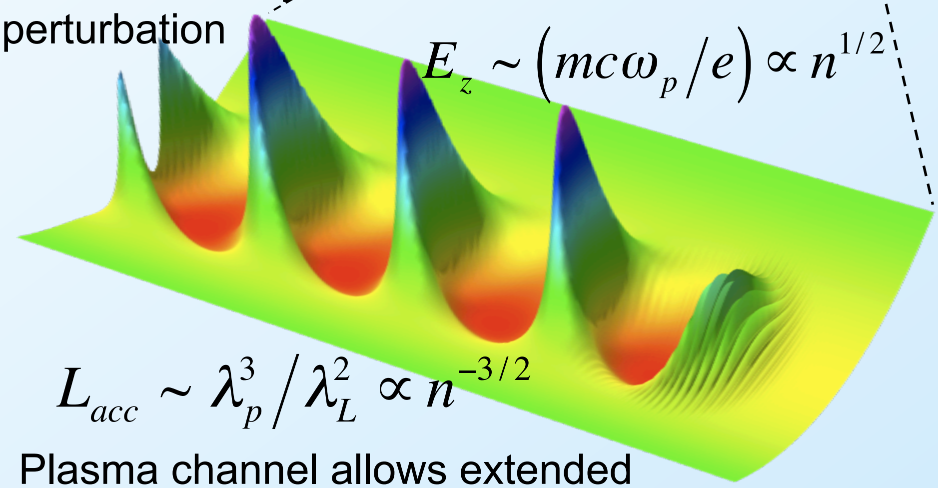
electron
beam



Beam energy =1.0 GeV
Charge= Q~30 pC
1.6 mrad rms divergence
2.5% rms energy spread

Leemans *et al.*, Nature Phys. (2006).
Nakamura *et al.*, Phys. Plasmas (2007).

Electron density
perturbation



$$E_z \sim \left(mc\omega_p / e\right) \propto n^{1/2}$$

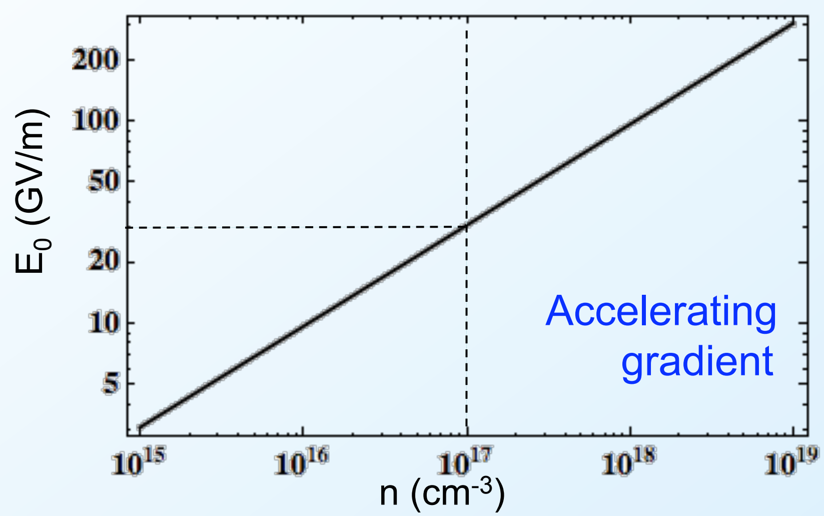
$$L_{acc} \sim \lambda_p^3 / \lambda_L^2 \propto n^{-3/2}$$

Plasma channel allows extended
laser-plasma interaction length

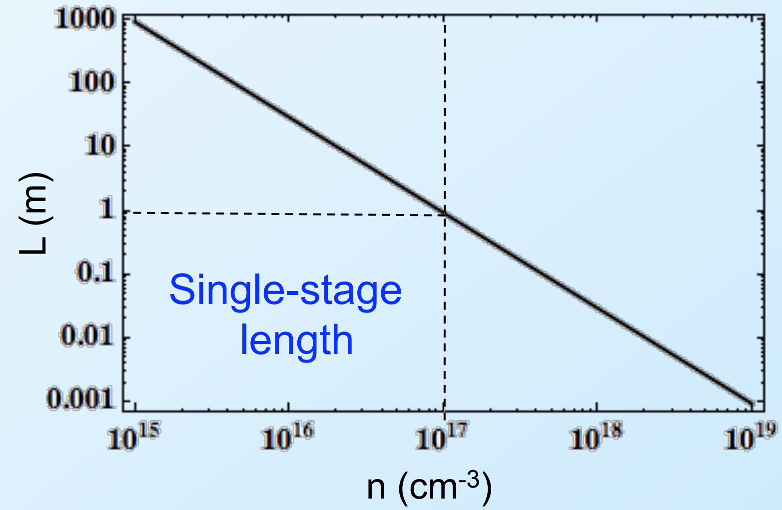
$$\Delta W[\mathrm{GeV}] \sim eE \cdot L_{acc} \sim I[\mathrm{W/cm^2}] / n[\mathrm{cm^{-3}}] \propto n^{-1}$$

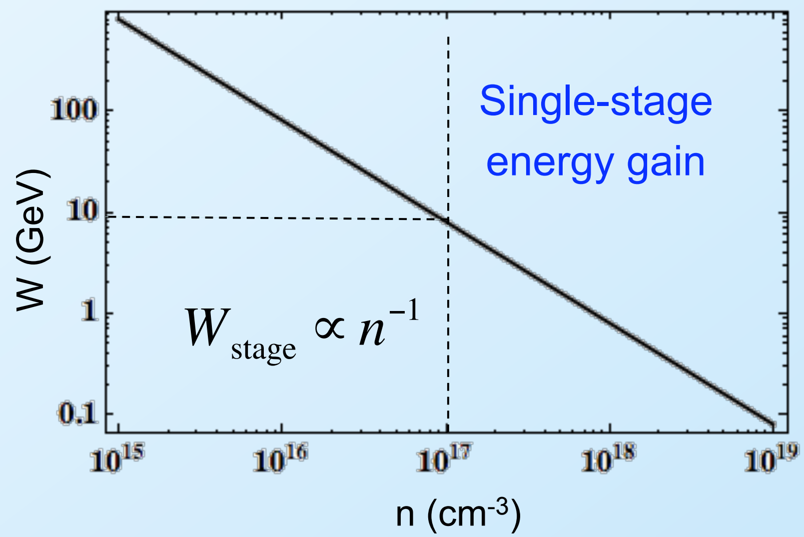
Single-stage plasma density scalings

$$E_0 \propto n^{1/2}$$



$$L_{\mathrm{dep}} \propto n^{-3/2}$$



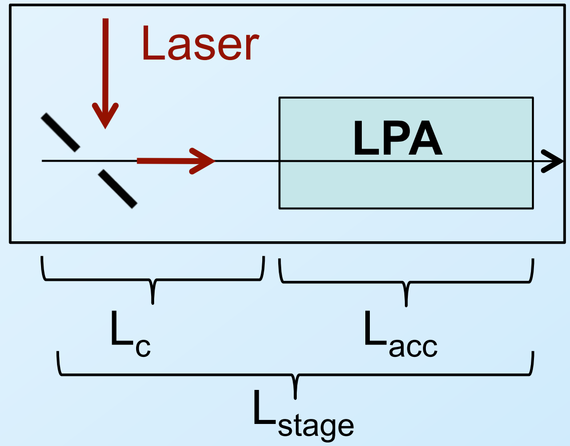


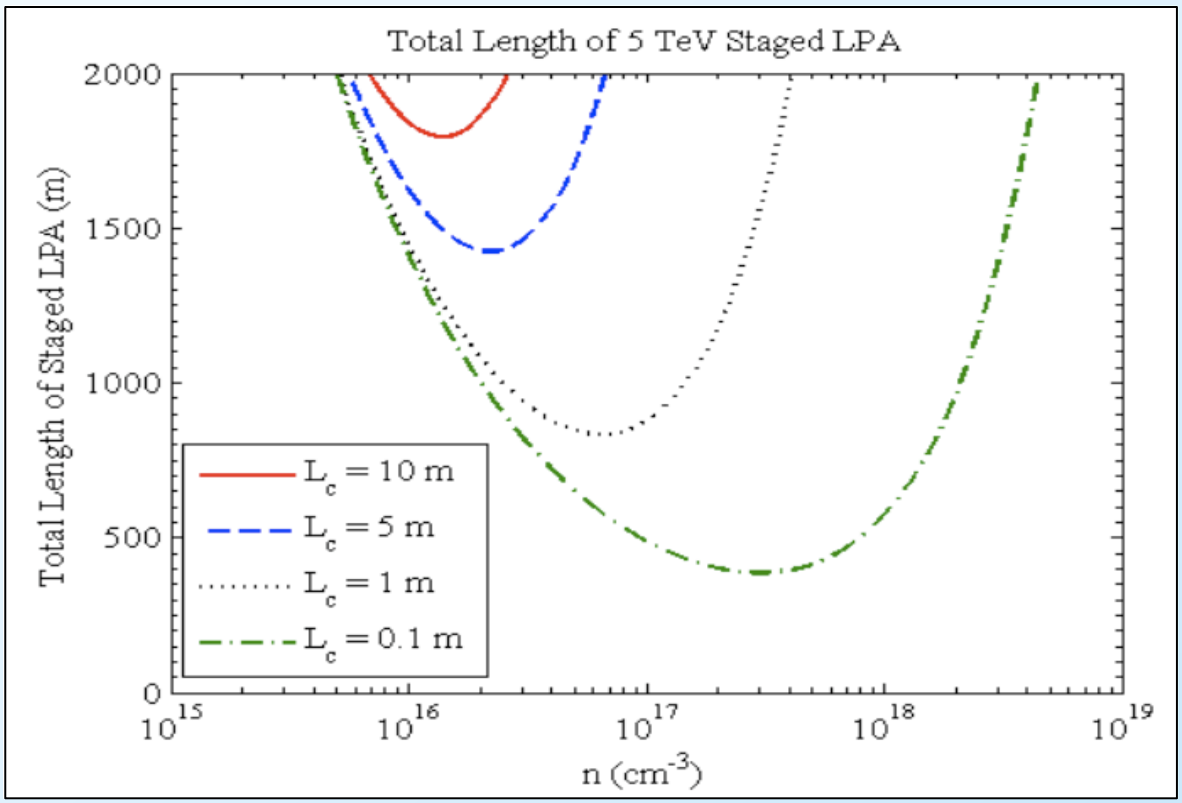
Coefficients determined from simulations of resonant laser with a=1.5

Proper choice of plasma density and staging minimizes main linac length

- Accelerator length will be determined by staging technology:

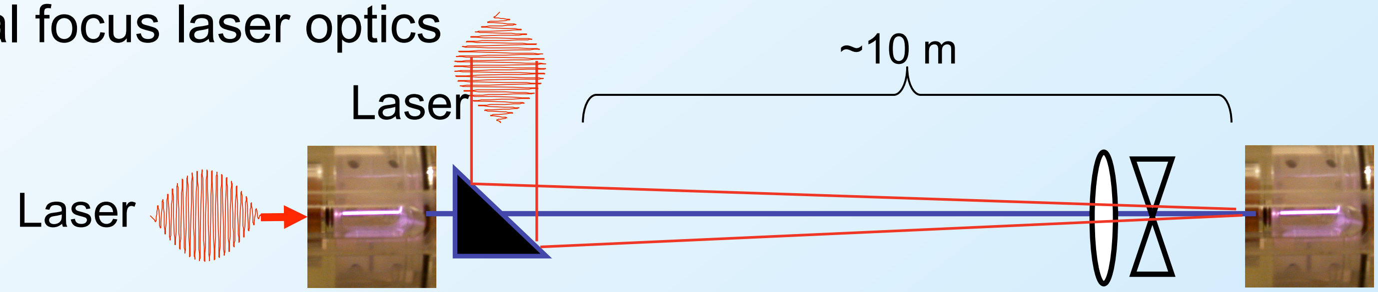
Number of stages: $N_{stage} \propto n$



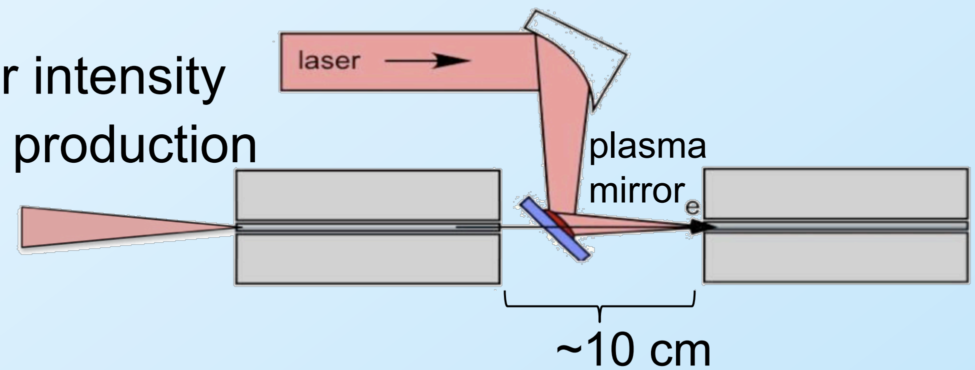


Laser in-coupling using plasma mirrors allows compact staging

- Conventional optics approach: stage length determined by damage on conventional final focus laser optics



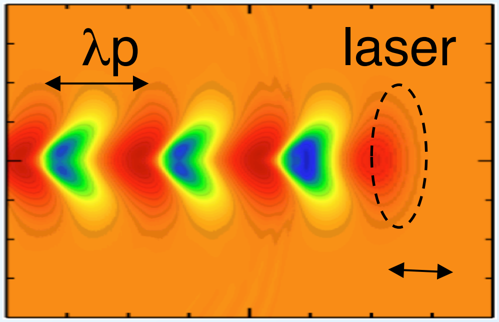
- Plasma mirror in-coupling:
  - “Renewable” mirror for high laser intensity
  - Relies on critical density plasma production
  - Thin liquid jet or foil (tape)
  - Laser contrast crucial (>10^{10})



- Advantage of laser-driven plasma waves: short in-coupling distance for plasma wave driver (high average gradient)

- Development of staging technology critical to collider application

Laser energy requirements



- Laser intensity for large accelerating field in quasi-linear regime:

$$a \approx 8.6 \times 10^{-10} \lambda[\mu m] I^{1/2} [W/cm^2] \Rightarrow a \sim 1 \Rightarrow I > 10^{18}\ W/cm^2$$

for 1 micron laser wavelength

- Laser pulse length ~ plasma wavelength $\lambda_p/2$

plasma density = $n_0 \sim 10^{17}\ cm^{-3}$ ⇒ $\lambda_p \sim 100$ micron ⇒ $T_{laser} \sim 100$ fs

- Laser energy (spot size ~ λ_p)

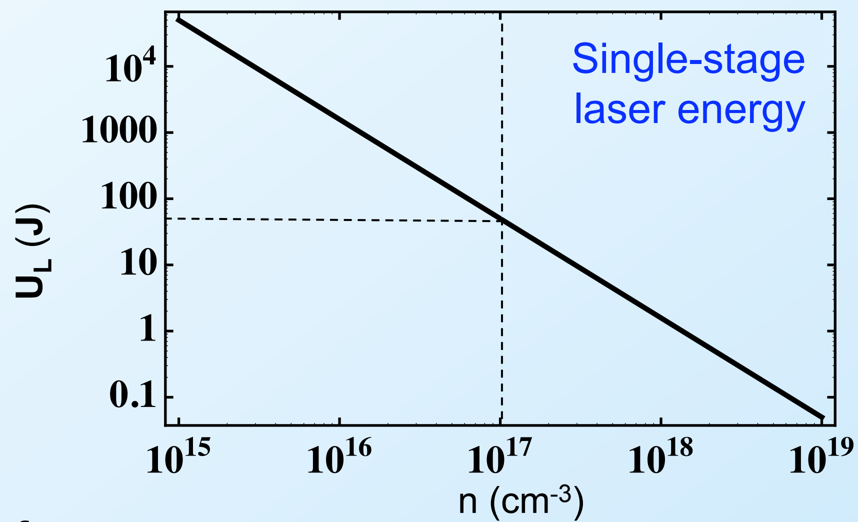
$$U_{laser}[J] = 7.2 \times 10^{-7} (k_p L)(k_p r)^2 a^2 \frac{\lambda_p^3 [\mu m]}{\lambda^2 [\mu m]} \propto n^{-3/2}$$

plasma density = $n_0 \sim 10^{17}\ cm^{-3}$ ⇒ $U_{laser} \sim$ 10's J

Collider plasma density scalings: Laser energy and Power

- Single-stage laser energy:

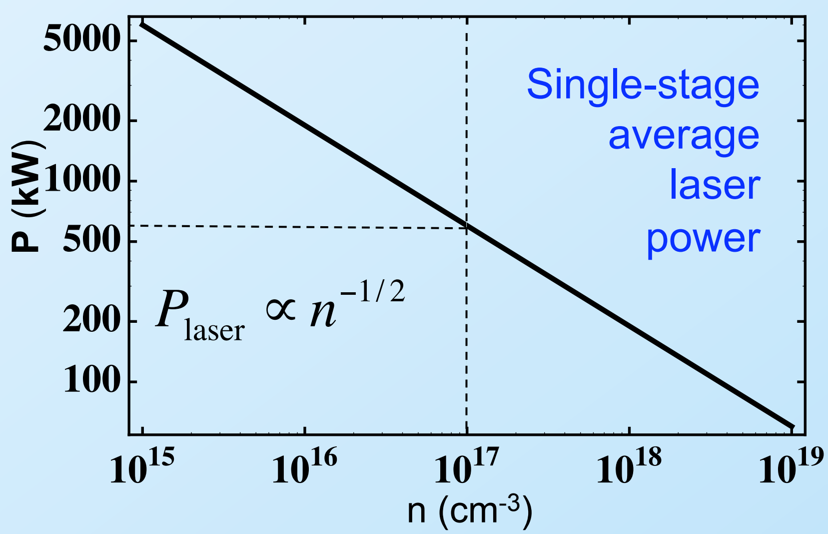
$$U_{\text{laser}} \propto n^{-3/2}$$



- For fixed luminosity (e.g., 10^{34} s^{-1} cm^{-2} for E_{cm} = 1 TeV) and IP size:

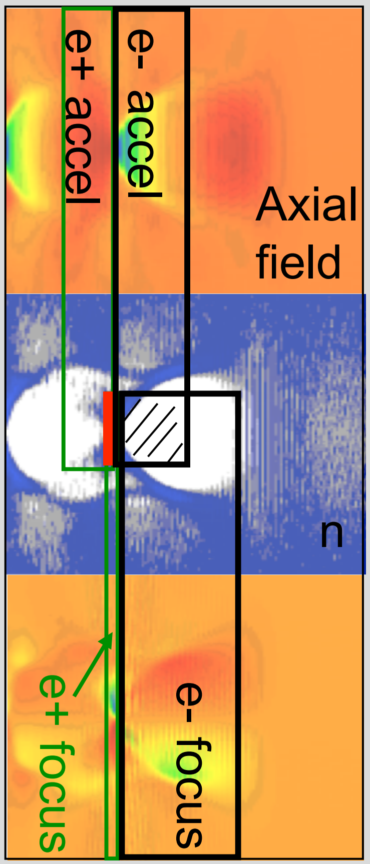
Repetition rate: $f_{rep} \propto n$

Beam power: $P_b = fNE_b \propto n^{1/2}$



Laser intensity: Quasi-linear regime allows for e^+ acceleration

a_0=4

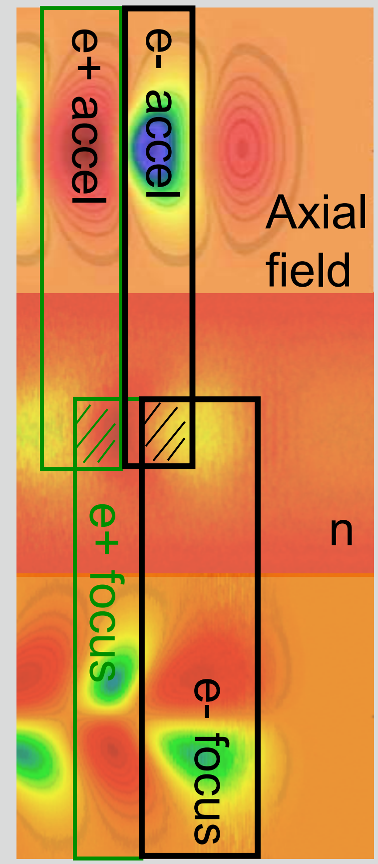


Transverse field

- Blowout/Bubble regime
  - high field (a>>1)
  - very asymmetric
    - focuses e-
    - defocuses e+
  - self-trapping (staging difficult)

- Quasi-linear regime
  - Nearly-symmetric e+/e-
  - a ~ 1
  - dark current free (no self-trapping)

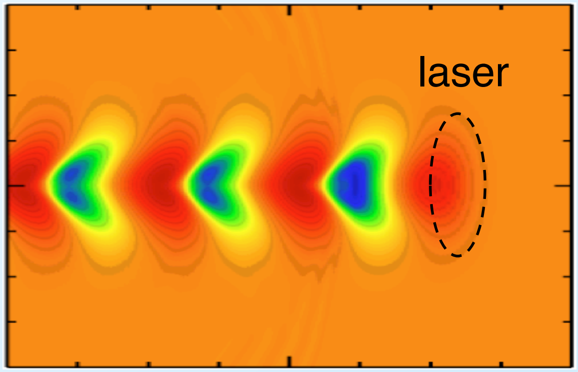
a_0=1



Transverse field

Quasi-linear laser-driven plasma wave: decouples focusing and accelerating forces

- Quasi-linear regime:
  - Nearly symmetric for e+ and e- focusing and accelerating phase regions
  - Expected to be more stable (using channel)
  - Allows for controlled injection of bunch (dark-current-free structures); high-quality beams
  - Control of focusing forces (laser pulse tailoring)



Quasi-linear regime:

$$a^2\left(1+a^2/2\right)^{-1/2} < k_p^2 r^2/2$$

Blowout/Bubble regime:
Focusing force determined by density

$$F_\perp / eE_0 = -k_p r/2$$

- Small matched beam radius:

$$\sigma_r^2 = \frac{\varepsilon_n}{\gamma k_\beta} = \sqrt{\frac{2}{\gamma}}\frac{\varepsilon_n}{k_p}$$

σ_r = 0.1 micron for ε_x= 10^{-7} m, 10 GeV, n=10^{17} cm^{-3}

- Stringent alignment tolerances

Quasi-linear regime:
Focusing force determined by density and transverse laser intensity gradient

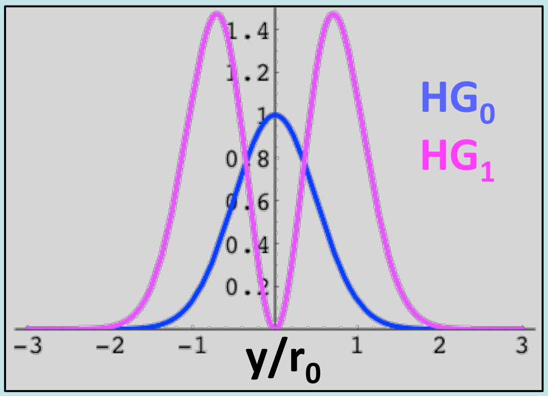
$$F_\perp / eE_0 \propto \nabla_\perp a^2$$

- Flexibility via laser tailoring:
  - allows additional control of focusing forces (and matched spot)

$$\sigma_r^2 = \frac{\varepsilon_n}{\gamma k_\beta}$$

Higher order laser modes to tailor transverse wakefield (focusing forces)

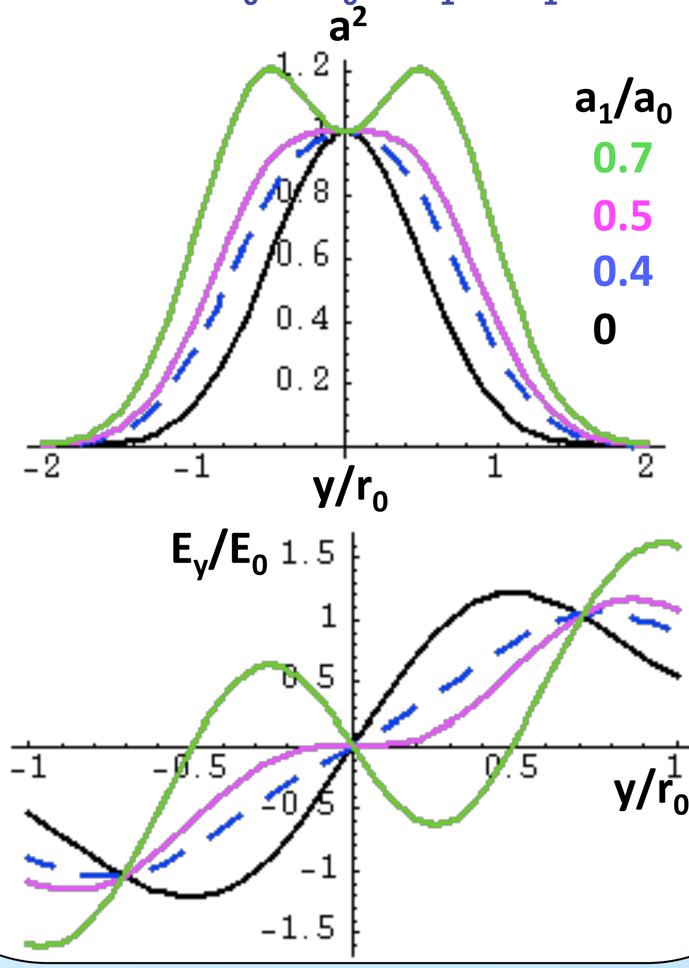
- $E_\perp/E_0 \sim \nabla_\perp a^2/2$
- Add Hermite-Gaussian modes:



— gaussian e^{-y^2/r_0^2}

— first order hermite-gaussian mode $e^{-y^2/r_0^2}\, 2\sqrt{2}\, y/r_0$

$a^2 = a_0^2\, HG_0^2 + a_1^2\, HG_1^2$



- **All modes guided in parabolic plasma channel**

Cormier-Michel et al.

Future linear colliders with >1 TeV will operate in quantum beamstrahlung regime

Beamstrahlung parameter

$$\Upsilon = \left(\frac{5\sqrt{2\pi} r_e^2 m^{1/2} c}{3\alpha} \right) \left(\frac{R^{1/2}}{1+R} \right) \left(\frac{\gamma^3 L}{P_b} \right)^{1/2} \frac{N^{1/2}}{\sigma_z}$$

- Quantum beamstrahlung regime: $\Upsilon >> 1$

$$L \propto E_{cm}^2 \longrightarrow \Upsilon \propto E_{cm}^{5/2}$$

  - High energy colliders > 1TeV will have Y >1
  - Beamstrahlung effects for fixed E_{cm}, L, P_b

Beamstrahlung photons

$$N_\gamma \approx \frac{12\alpha^2}{5 r_e \gamma} \sigma_z \frac{\Upsilon}{\left(1+\Upsilon^{2/3}\right)^{1/2}} \propto \left(N\sigma_z\right)^{1/3}$$

Beamstrahlung energy spread

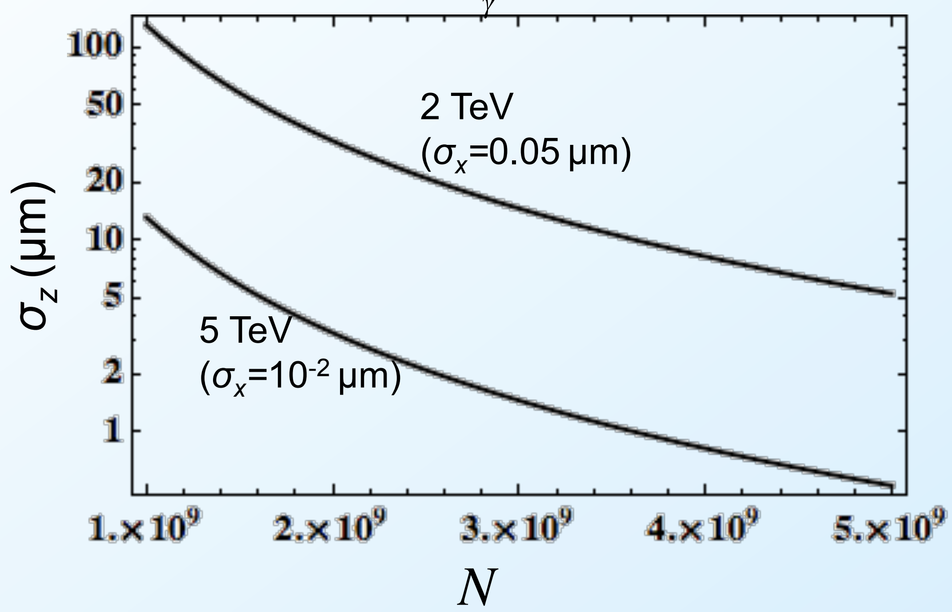
$$\delta_\gamma \propto N_\gamma \propto \left(N\sigma_z\right)^{1/3}$$

minimize beamstrahlung by reducing *charge/bunch* and/or *bunch length*

Quantum beamstrahlung regime requires ultra-short bunches

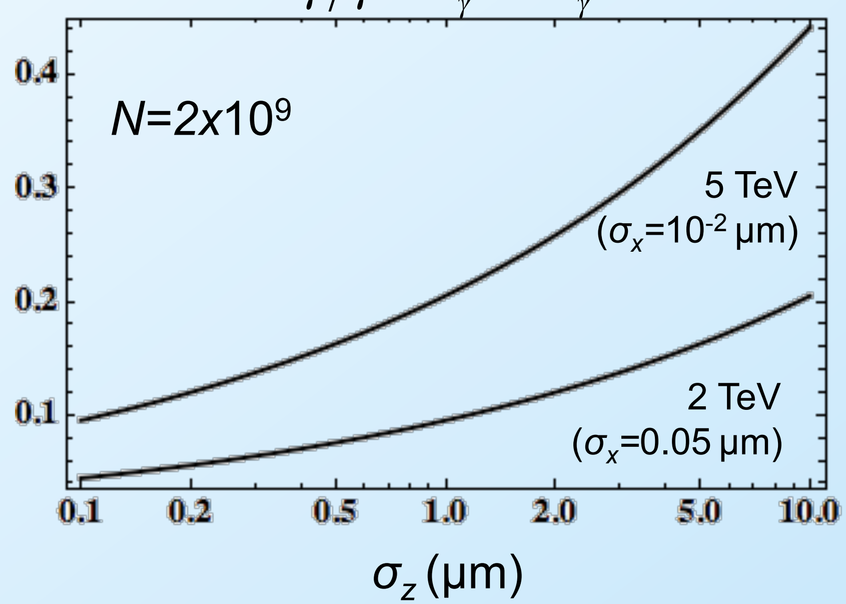
Background beamstrahlung photons:

$N_\gamma = 1$



Beamstrahlung induced energy spread:

$\delta\gamma/\gamma = \delta_\gamma \propto N_\gamma$



For fixed beamstrahlung (N_γ or δ_γ):

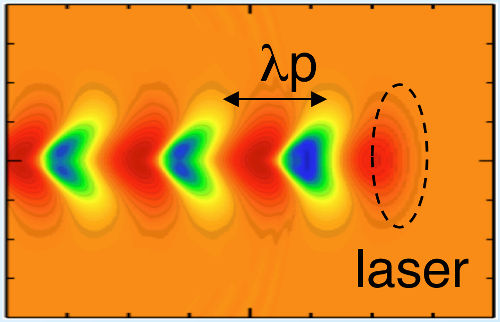
$$\frac{L}{P_b} \propto \frac{1}{\sigma_z^{1/2}}$$

- plasma-based accelerators are intrinsically sources of fs beams

Plasma accelerators are sources of ultra-short bunches

• (high-density) plasma-based accelerators are intrinsically sources of femtosecond beams:

$$\sigma_z << \lambda_p[\mu\text{m}] \approx \frac{33}{\sqrt{n[10^{18}\text{cm}^{-3}]}}$$



• Methods for controlled injection in plasma wave:

  • Plasma density gradient injection (Bulanov et al., PRE 1998; Geddes et al., PRL 2008)

  • Laser-triggered injection: colliding pulse injection (Esarey et al., PRL 1997; Faure et al., Nature 2006)

• In principle, triggered injection in a plasma wave could achieve beam quality (low emittance) beyond state-of-the-art photocathodes (space-charge shielding provided by ions, rapid acceleration)

Collider power and efficiency requirements: High average power laser

- Beam power: $P_b = fNE_{cm}$

$$\left.\begin{array}{r} N \sim 4\text{x}10^9 \\ f \sim 15\text{ kHz} \\ E_{cm} \sim 1\text{ TeV} \end{array}\right\} \quad P_b \sim 5\text{ MW}$$

- AC wall-plug power: ~ 200 MW ➔ 5% efficiency

- Laser to plasma wave efficiency: ~50%
- Plasma wave to beam efficiency: ~30%

} ➔~15% laser to beam efficiency
➔~33% wall-plug to laser efficiency

- Collider based on 10-GeV stages:
  - (total beam energy ~300 J)/(50 stages) = ~6 J/stage
  - ~40 J/laser at 15 kHz = ~600 kW average power laser

beyond state-of-the-art laser technology
➔ Laser technology development required

- Energy remaining in plasma-based accelerator (damped plasma wave)
  - ~10J/stage remains in plasma ➔ >100 kW/m

1 TeV LPA Collider Parameters

Plasma density scalings:

Stage density scalings:

$E_0 \propto n^{1/2}$

$L_{stage} \propto n^{-3/2}$

$W_{stage} \propto n^{-1}$

$U_L \propto n^{-3/2}$

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

Collider density scalings (for fixed luminosity):

$f \propto n$

$N_{stage} \propto n$

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

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

Plasma number density, n_0	10^{17} cm^{-3}
Energy, center of mass, E_{cm}	1 TeV
Beam energy, γmc^2	0.5 TeV
Number per bunch, N	4×10^9
Collision rate, f	15 kHz
Beam Power, $P_b = fN\gamma mc^2$	4.8 MW
Luminosity, $\mathscr{L}$	2×10^{34} s^{-1} cm^{-2}
Bunch length, σ_z	1 μm
Horizontal rms beam size at IP, σ_x	0.1 μm
Vertical rms beam size at IP, σ_y	1 nm
Horizontal normalized emittance, ε_{nx}	1 mm-mrad
Vertical normalized emittance, ε_{ny}	0.01 mm-mrad
Beamstrahlung parameter, Υ	35
Plasma wavelength, λ_p	105 μm
Energy gain per stage, W_{stage}	10 GeV
Single stage laser-plasma interaction length	0.9 m
Drive laser coupling distance between stages	0.5 m
Laser energy per stage	40 J
Laser wavelength	1 μm
Initial normalized laser intensity, a_0	1.5
Average laser power per stage	600 kW
Number of stages	50
Main linac length	70 m
Efficiency (wall-plug to beam)	5%
Total wall-plug power	190 MW

Schroeder et al., AAC08

Summary

- Design considerations for a laser-plasma collider module
  - Laser Depletion: necessitates staging
  - Operation in quasi-linear regime
    - Allows positron acceleration
    - Control transverse fields
- Conceptual design of laser-plasma collider at 1 TeV
  - 10 GeV modules: Laser pulse 40 J, 130 fs, 15 kHz
    - Requires development of 100's kW average power lasers
  - Requires research on LPA physics and staging technology
    - Demonstrate low emittance, high charge, short e-bunches
- R&D with BELLA (BErkeley Lab Laser Accelerator):
  - 10 GeV LPA stage
  - Positron acceleration in quasi-linear regime
  - Beam-plasma interactions