Improved electron beam quality from shock-induced density downramp injection

Kelly Swanson


BELLA Center, Lawrence Berkeley National Laboratory
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Applications require stable, small energy spread, high quality electron beams

Multistage, high-energy accelerator*

- Requires small energy spread and low divergence to capture charge efficiently in successive stages

LPA-based free electron laser

- Small energy spread beams reduce gain length*
- Small divergence minimizes aberrations from downstream components


*Courtesy of S. K. Barber
Injection is facilitated by density downramp

- Local wake phase:
  \[ \varphi = k_p(z)(z - ct) \text{ where } k_p(z) \propto \sqrt{n(z)} \]

- Wake phase velocity \( \beta_p \):
  \[
  \beta_p = \frac{\omega_p}{ck_p} = \frac{-\partial_t \varphi}{c \partial_z \varphi}
  \]
  
  \[
  = \beta_g \left( 1 + \xi \frac{1}{n} \frac{dn}{dz} \right)^{-1}
  \]

- During downramp, \( \beta_p \) decreases, \( \rightarrow \) reduced trapping threshold

  \( \xi = z - ct < 0 \)

Injection happens only during downramp
  \( \rightarrow \) Small energy spreads

Investigated shock’s effect on beam quality

• Shock formed by inserting razor blade into hydrogen gas flow
  Schmid, K. et al., Phys. Rev. STAB (2010),
  Buck, A. et al., PRL (2013)

• Density profile measured using probe beam and wavefront sensor
Shock angle is dependent on blade location

- Simulations show shock angle caused by ratio of exit and ambient pressure and gas expansion/compression
- Observed shock front angle $\alpha$ changes with blade position

Mao, H.-S. et al., in progress

Swanson, K. et al., in progress
Density profiles are also dependent on blade location

- Parameters $n_1$, $n_2$, $L_{\text{acc}}$ dependent on blade position (Hai-En Tsai: $L_{\text{high}}$)
- $L_{\text{shock}}$ stayed constant at $\sim 100\mu\text{m}$
  (wavefront imaging resolution $\sim 35\mu\text{m}$)
Using density profiles, we can estimate energy and charge.

• Energy can be estimated*:

\[ W \approx eEL \propto \sqrt{n_2 L_{acc}} \]

\[ \Delta E = 10\text{MeV} \]

• Charge can also be estimated:

\[ Q \propto n\left(\lambda_{p,2} - \lambda_{p,1}\right)^2 \]

Divergence scales with energy as expected

• Motion of electrons in accelerating field $E_z$ and focusing force

$$m \frac{d \gamma \vec{v}}{dt} = eE_z \hat{z} - \frac{mw^2}{2} r\hat{r}$$

• Solving differential equation gives divergence scaling:

$$\theta \approx \frac{1}{c} \frac{dr(t)}{dt} \propto \gamma^{-3/4}$$

• Consistent with matched propagation

Swanson, K. et al., in progress
On-axis electron beam propagation occurs when shock front perpendicular to laser

- Laser refracted when passing through gas profile and shock front
- Electron beams follow laser refraction

→ Electron steering

Swanson, K. et al., in progress
Transverse ellipticity can be tuned using shock front angle

- Measure of ellipticity: $\theta_y - \theta_x$
  - Influenced by shock front angle
- Round beams when shock perpendicular to laser

- Not due to laser polarization

Swanson, K. et al., in progress
Steering and energy spread influence beam shape

- Amount of electron beam steering is energy-dependent
  - Higher energy beams are steered less
  - Elliptical beams

Swanson, K. et al., in progress
Produced tunable electron beams with reduced ellipticity and off-axis steering

- Electron beam charge, energy, divergence can be tuned with blade position
- Stable: <1mrad pointing fluctuation
- Steering and ellipticity tuned with shock front angle

Beams good for applications

\[
E = 65 \pm 4 \text{ MeV} \\
Q = 16 \pm 2 \text{ pC}
\]

\[
E = 130 \pm 2.8 \text{ MeV} \\
Q = 4.5 \pm 1 \text{ pC}
\]

Thank you for your attention!