E304 Plans for FY24: Gas-jet in Static fill (GiS) configuration

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on behalf of the E300 Collaboration

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E304 experiment

Internal generation of low-emittance, high-brightness bunches using density downramp

Example parameters: driver: $\Lambda=4$, $\sigma_r=\sigma_z=\epsilon_n=5.3\ \mu m$ $\Lambda = 2I_b/I_A$ $I_A \approx 17\ \text{kA}$

<table>
<thead>
<tr>
<th>$n_{ph}$ [cm$^{-3}$]</th>
<th>$n_{p0}$ [cm$^{-3}$]</th>
<th>ramp [mm]</th>
<th>$I$ [kA]</th>
<th>$\epsilon_n$ [nm]</th>
<th>$B$ [A/m$^2$/rad$^2$]</th>
<th>$E$ [MeV]</th>
<th>$\sigma_E/E$</th>
<th>$Q$ [pC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.5\times10^{18}$</td>
<td>$10^{18}$</td>
<td>1.3</td>
<td>14</td>
<td>80</td>
<td>$4E+18$</td>
<td>620</td>
<td>0.15%</td>
<td>140</td>
</tr>
</tbody>
</table>
Experimental layout

- Focusing quads
- Picnic basket
- Li oven & bypass line
- Spectrometer quads
- Dipole
- Butterfly chamber
- Dump table
- vacuum waist (beta ~ 5 cm)

Same target assembly as E305 but different nozzles.

E304 plasma source:
- 2-cm gas jets
- Sharp downramp (~10 c/ωₚ) by shock front
- Gentle downramp (~100 c/ωₚ) by structured nozzle
- Laser ionization & beam ionization

TopView, DTOTR1&2, LFOV, CHER

CAD drawings made by Robert Ariniello, CU

Ionization laser
Hardware readiness

Hardwares sent to SLAC
- A new plate with additional tapped holes
- A 0.5” stage for moving the blade
- SST blade
- 2-cm nozzles
Quasi3D simulation using a simulated 2-cm nozzle density profile

density profile from fluid simulation (200psi, @4mm)

Driver parameter:
\[ Q = 2.0 \text{ nC} \]
\[ \sigma_r = 15 \mu m, \sigma_z = 10 \mu m \]
\[ \Lambda = 2.8, n_b \approx 3.5 n_p \]

Final energy spectrum
- \( E: \sim 0.8 \text{ GeV (peak)} \)
- \( \sim 1.4 \text{ GeV (Max)} \)
- total charge \( \sim 500 \text{ pC} \)
- \( \epsilon_n: \sim 0.4 \mu m \)
- \( \sigma_E/E: <0.4\% \)
Time structured electron beam (without laser heater)

Start-to-end beamline simulation and PWFA experiments (2022 run) suggest time-structured bunches

- µm scale >50 kA current spike(s) + a longer but lower-current (<10 kA) structure
- such bunches can self-ionize meter-scale H₂ plasmas and excite nonlinear wakes

The nominal bunch reproduces experimental results
An alternative configuration: Gas-jet in Static fill (GiS)

- 10 GeV drive beam
- 5-mm gas-jet (or 2-cm gas jet)
- ~4 m H₂ between the Be windows
- Adjustable peak (e.g., >2e17 cm⁻³)

Drive beam self-focuses (modeled using QPAD)

- ~3 m, up to 5 Torr static-fill for acceleration of injected bunch (6.5e16 cm⁻³) (modeled using QPAD)

Existing e-beam
NO laser needed
Step I: QPAD simulation of self-focusing of the driver

Beam ionization of H$_2$ and self-focusing

- 1.5 Torr static fill ($n_e\sim5\times10^{16}$ cm$^{-3}$)
- atomic hydrogen with 15.4 eV IP, ADK model
- “nominal” driver
Self-focused beam from the QPAD simulation

Initial driver

Self-focused driver density map @ 1m

spot size evolution

beam parameters evaluated here

$\sigma_r : 30 \rightarrow 3 \mu m$

$n_b$ increases by 100 times

put gas jet here to inject electrons
Low-density gas jet had been characterized using IPG

We need a low-density (~$10^{17}$ cm$^{-3}$) gas jet to make a density bump in the static fill gas

- Difficult to characterize using interferometer (or wavefront sensor)
- We have developed a new method to measure density down to $10^{15}$ cm$^{-3}$
- It's based on ionization induced plasma grating (IPG)

C. Zhang et al. PPCF 63, 095011 (2021)
Density profile from fluid simulations

- 1.5 Torr static fill ($n_e \sim 5 \times 10^{16} \text{ cm}^{-3}$)
- 5-mm dia. round nozzle
- Backing pressure 10 psi
- Mach number $\sim 5$
- Density downramp
  - Peak density @2 mm: $1.7 \times 10^{17} \text{ cm}^{-3}$
  - Ramp length: 1 mm
  - Density ratio $n_{\text{peak}}/n_{e0} \sim 3.5$
- Density ratio is tunable by changing backing pressure
Step II: Downramp injection modeled using Osiris quasi-3D

Injection process

Bunch parameters at z=10 mm:
- slice and normalized emittance: ~0.5 µm
- peak current: ~1 kA, total charge 83 pC

Longitudinal phase space

Current profile
Step III: Acceleration of the injected bunch modeled using QPAD

- Import the downramp injected bunch into the 2nd QPAD simulation
- Reload the self-focused driver

\[
\begin{align*}
\rho &= 200.00 \left[ \frac{1}{\omega_p} \right] \\
\end{align*}
\]

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Diagram showing the beam direction and the injected bunch with the already self-focused driver.
Final parameters of the electron bunch

Longitudinal phase space and current profile of the injected bunch

- Linear chirp: 2-5 GeV over 25 µm (1.7%/µm)

Slice beam parameters:
- $\epsilon_n$: ~0.7 µm, $\sigma_E/E$: ~0.2%, I: ~1 kA
Distinguish the injected bunch from the decelerated driver electrons

The injected bunch has a much smaller emittance (0.7 µm vs 20 µm of the driver)

Synthetic spectrometer images on the DTOTR screen

- Driver
- Injected bunch

Energy gain:
- 10 GeV
- 3 GeV

Injected bunch

Driver
Summary: E304 Gas-jet in Static fill (GiS) configuration

- **Setup:** Ready to go
- **Outcome:** multi-GeV high-brightness e- bunch
  - $\epsilon_n: 0.7 \mu m$, $\sigma_E/E: 0.2\%$, I: $\sim 1$ kA

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**Diagram:**

- **Setup: 10 GeV drive beam**
  - 5-mm gas-jet (or 2-cm gas jet)

- **Existing e- beam**
  - NO laser needed

- **Outcome: multi-GeV high-brightness e- bunch**
  - $\epsilon_n: 0.7 \mu m$, $\sigma_E/E: 0.2\%$, I: $\sim 1$ kA

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**Graphs:**

- **Energy spectrum**
- **Distributions**
- **LPS**
- **Inj. bunch**
- **Driver**
Collaborations

C. Joshi, K. Marsh, W. B. Mori, Y. Wu, Z. Nie

X. Xu, M. Hogan, FACET-II staff

Sebastien Corde’s group

Mike Litos’ group
Thank you for your attention

Questions?