Recent Results from Plasma Wakefield Experiments at FACET

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Overview

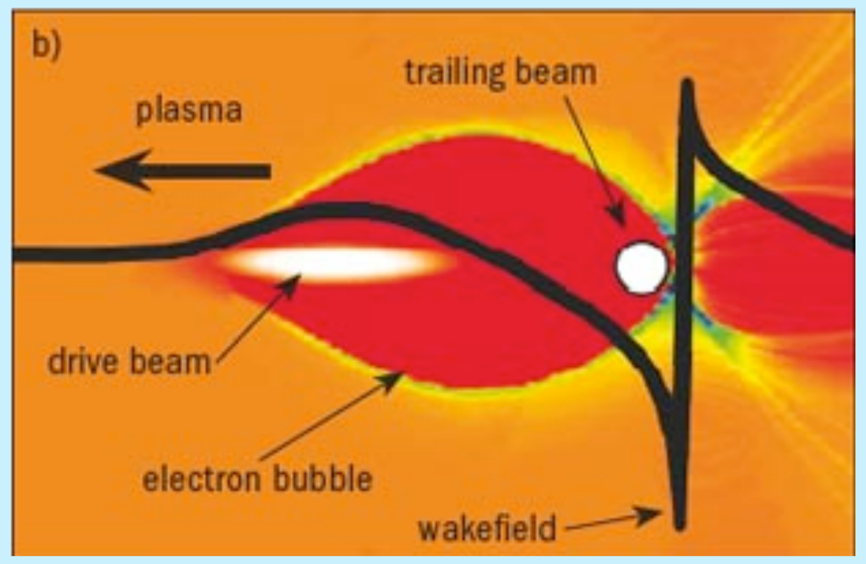
The FACET accelerator delivered a high quality electron beam during the 2013 run. The beam is notable for its high peak current:

- $N = 2 \times 10^{10}$ e⁻/bunch
- $E = 20.35$ GeV
- $\sigma_x, \sigma_y < 15$ μm
- $\sigma_z < 20$ μm $\Rightarrow I_{peak} > 20$ kA

The E200 Plasma Wakefield Acceleration (PWFA) experiment used this beam to produce gradients in the plasma in excess of 100 GeV/m. In addition, FACET commissioned a new 10 TW ionization laser that allowed E200 to demonstrate the first drive-witness plasma accelerator with energy gain greater than 1 GeV.

Plasma Wakefield Acceleration

PWFA works by transferring energy from the drive electron bunch into a plasma. The electrons at the head of the bunch expel plasma electrons from the beam path and leave behind a bubble of heavy positive ions. The positive ions provide a focusing force that pulls the plasma electrons back toward the axis. This collective plasma oscillation is called the wake.

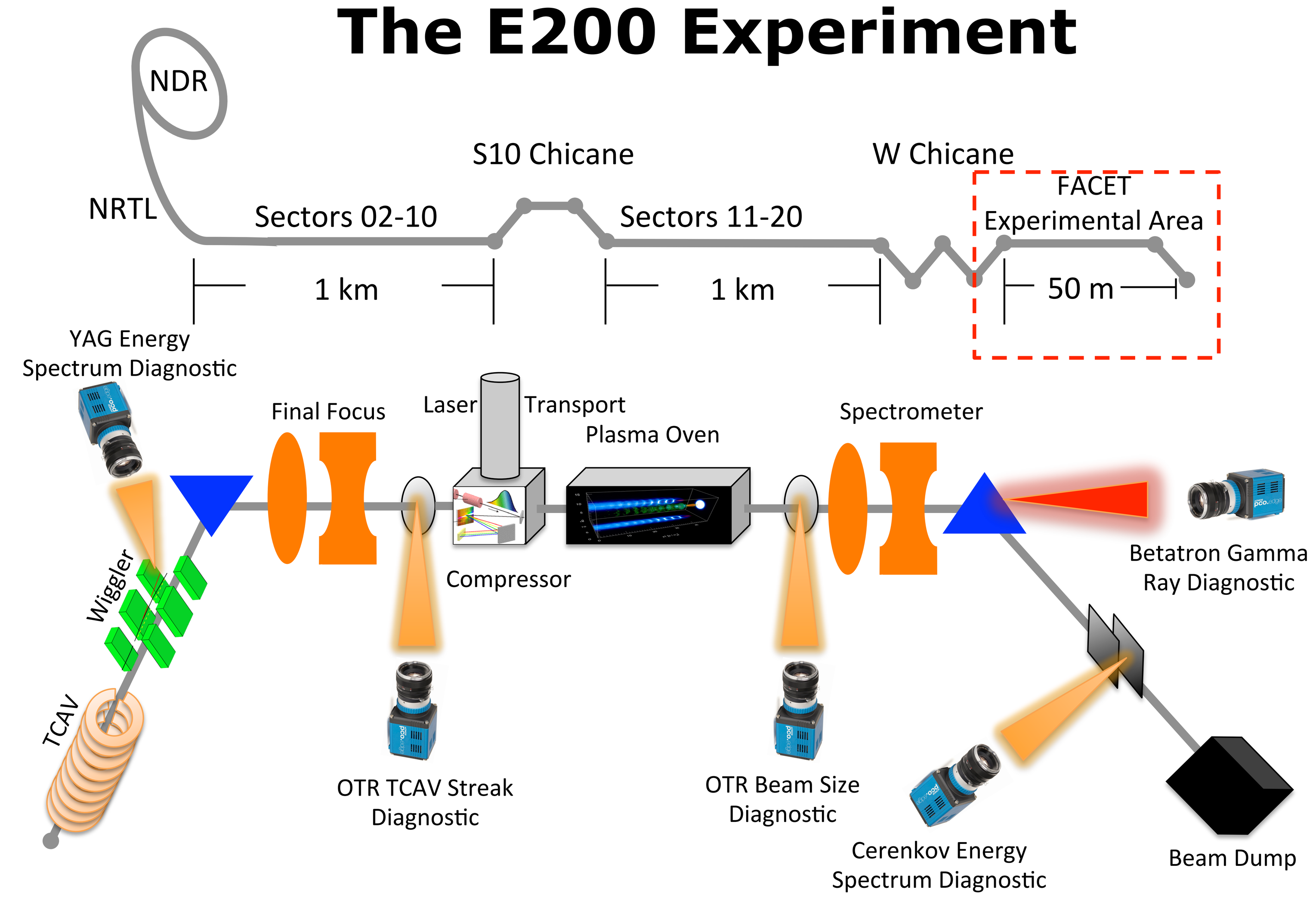


The wake is decelerating over the length of the drive bunch. The wake is accelerating at the back of the bubble where the plasma electrons cross the axis. A witness bunch placed in this region of the wake experiences a large accelerating field. The field strength goes as the square root of the plasma density:

$$E_{max} = T \times 9.6\sqrt{\frac{n_p}{1 \times 10^{16} cm^{-3}}} [\mathrm{GV/m}]$$

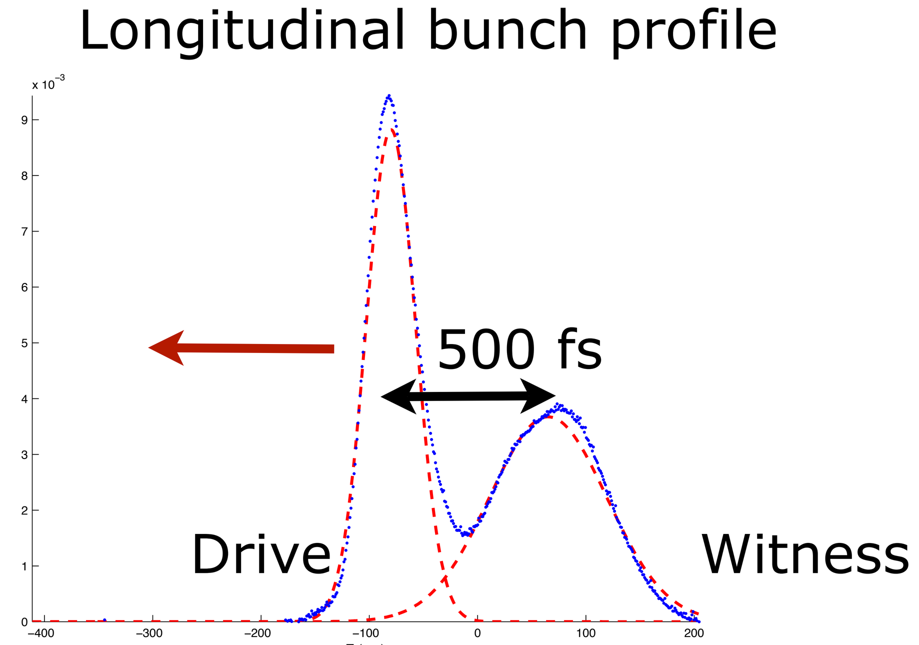
The transformer ratio T is the ratio of the accelerating field to the decelerating field. Note that it may be greater than 1.

The E200 Experiment



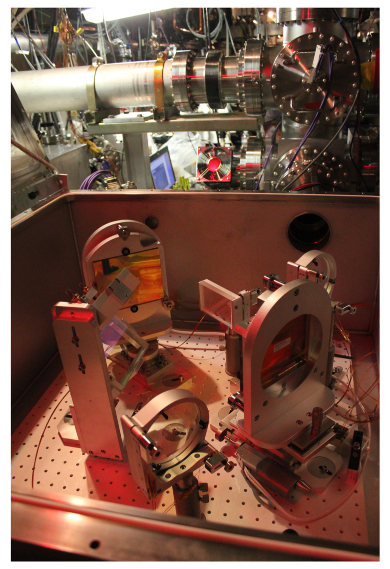
Two-Bunch Results

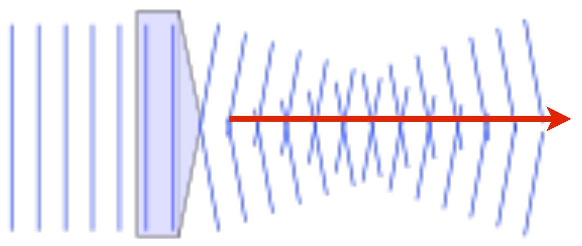
Longitudinal bunch profile



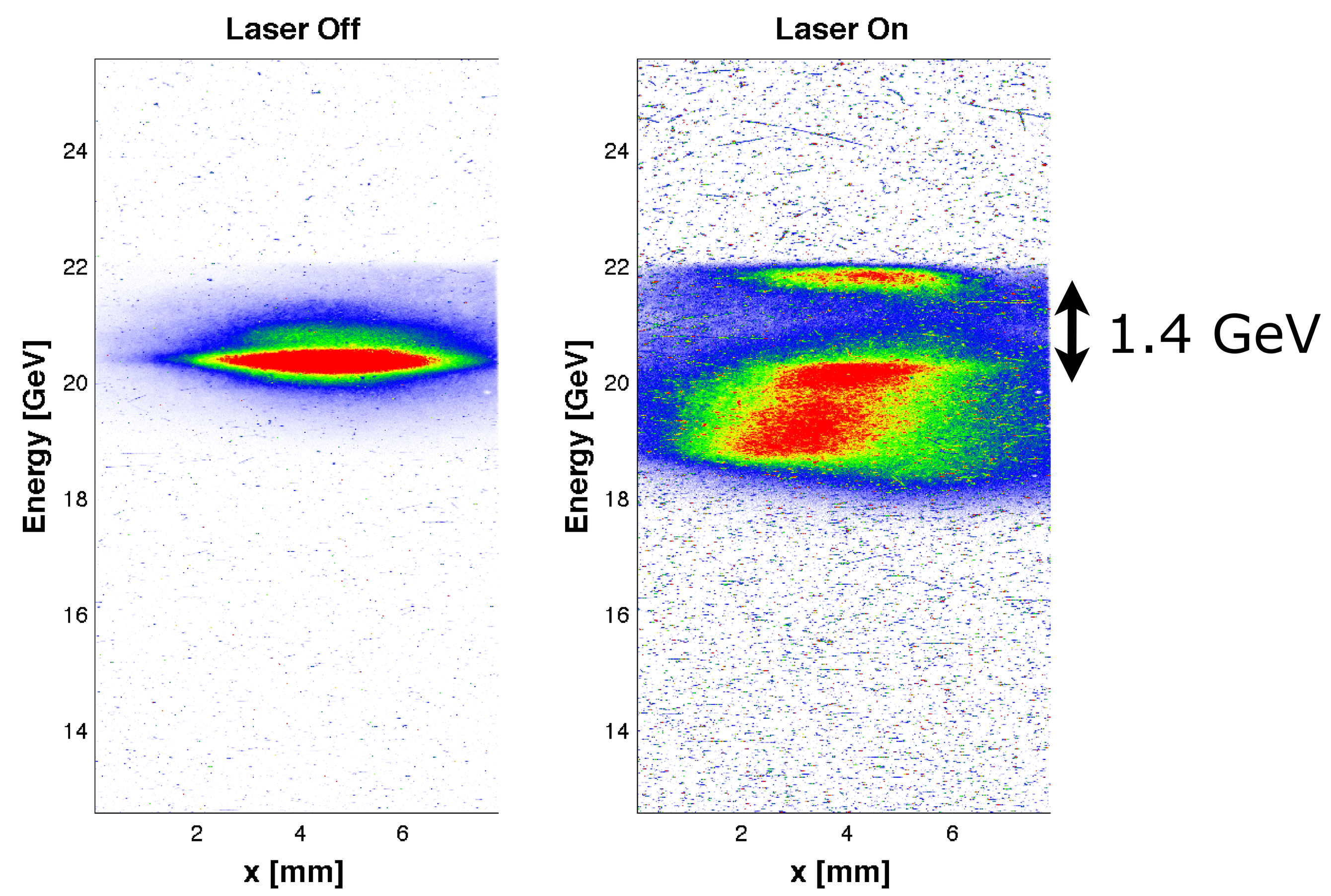
A notch collimator is used to make two electron bunches from a single electron bunch.

Laser Grating Compressor and Axicon





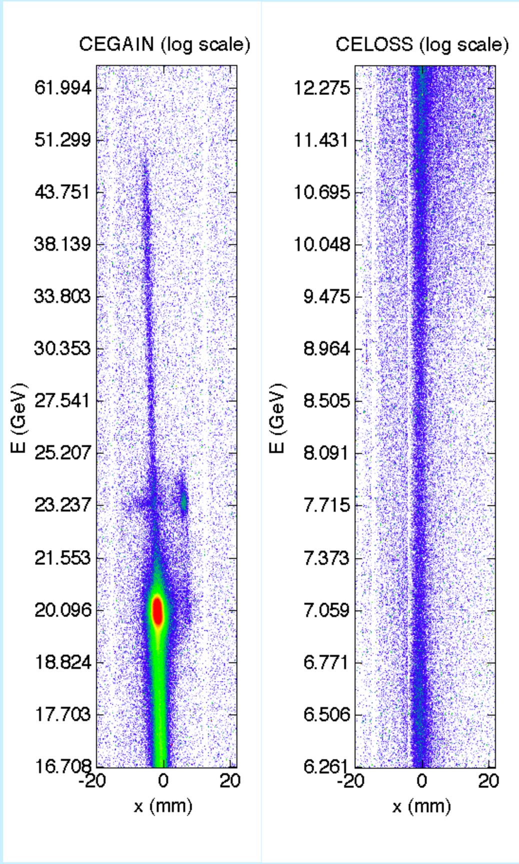
A high power laser pre-ionizes the plasma before the beam arrives. A special optical element called an axicon creates a 30 cm long line focus in the lithium vapor to create the plasma.



With the pre-ionized plasma, the witness bunch experiences a 1.4 GeV energy gain in the plasma wake. The gradient is roughly 5 GV/m. Without pre-ionization, there is little to no interaction. The energy spread of the witness bunch after acceleration is roughly 200 MeV, or 1% of the total 22 GeV witness beam energy.

Field Ionization and Self-Focusing

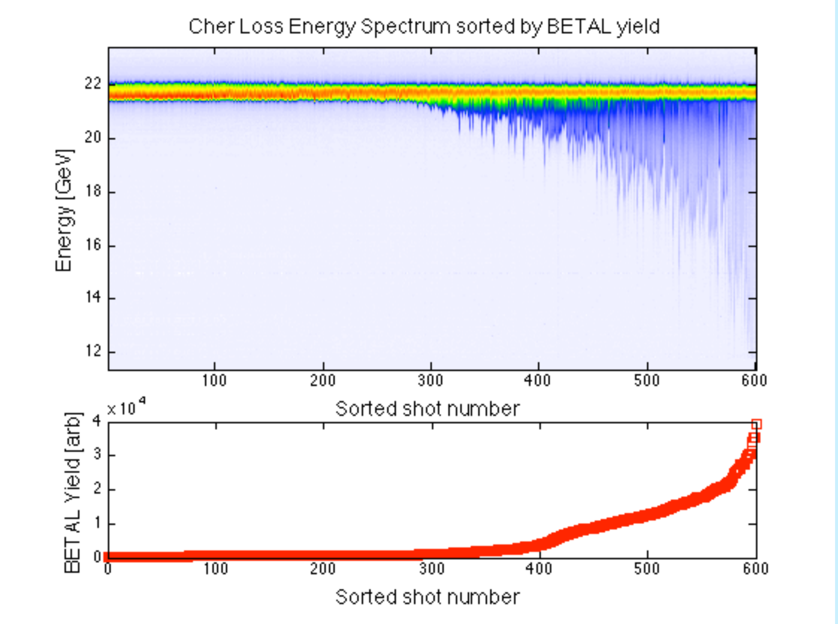
We observed energy-doubling in field-ionized argon gas. In this experiment, the field of the beam is strong enough to ionize the Ar without the need of a laser. The maximum particle energy is about 47 GeV, more than twice the initial energy. The estimated plasma length is 27 cm and the maximum energy gain is 27 GeV. The accelerating gradient is roughly 100 GV/m.



We also observed plasma interaction in field-ionized helium. The beam parameters at FACET are excellent, but in general not good enough to fully ionize helium. However, partial ionization of He induces self-focusing which squeezes the beam until it fully ionizes He.

$$\beta^* = k_\beta^{-1} \qquad k_\beta = \frac{k_p}{\sqrt{2\gamma}}$$

Self-focusing occurs when the focusing forces in the plasma are comparable to or exceed the natural beam divergence. This works out to be the simple formula shown above for the beam at a waist. It turns out that these forces can be achieved when only 0.1 % of the plasma is ionized.



The self-focusing force is very strong, measured in MT/m. It causes the beam to undergo strong betatron oscillations and the beam radiates gamma rays. We used the gamma ray yield to measure the strength of the plasma interaction. It correlates with the wake strength as shown above.