Long Plasma Source for Heavy Ion Beam Charge Neutralization *

The Heavy Ion Fusion Science Virtual National Laboratory

Philip C. Efthimion, Erik P. Gilson, Ronald C. Davidson and Larry Grisham
Plasma Physics Laboratory, Princeton University, Princeton, NJ, 08543 USA
B. Grant Logan, Peter Seidl and William Waldron, Lawrence Berkeley National Laboratory University of California, Berkeley, CA, 94720 USA

*Research supported by the US Department of Energy.

Abstract

Plasmas are a source of unbound electrons for charge neutralizing intense heavy ion beams to focus them to a small spot size and compress their axial length. The plasma source should operate at low neutral pressures and without strong externally-applied fields. To produce long plasma columns, sources based upon ferroelectric ceramics with large dielectric coefficients have been developed. The source utilizes the ferroelectric ceramic $BaTiO_3$ to form metal plasma. The drift tube inner surface of the Neutralized Drift Compression Experiment (NDCX) is covered with ceramic material. High voltage (~ 8 kV) is applied between the drift tube and the front surface of the ceramics. A $BaTiO_3$ source comprised of five 20-cm-long sources has been tested and characterized, producing relatively uniform plasma in the 5×10^{10} cm^{-3} density range. The source was integrated into the NDCX device for charge neutralization and beam compression experiments, and yielded current compression ratios ~ 120. Present research is developing multi-meter-long and higher density sources to support beam compression experiments for high energy density physics applications.

Ferroelectric Plasma Source (FEPS)

- High voltage (3-8 kV) is applied across a ceramic with a large dielectric constant to produce a metal plasma.

- Common ceramics are $Pb(Zr,Ti)O_3$ (ε = 3000-6000) and $BaTiO_3$ (ε = 1000-3000).

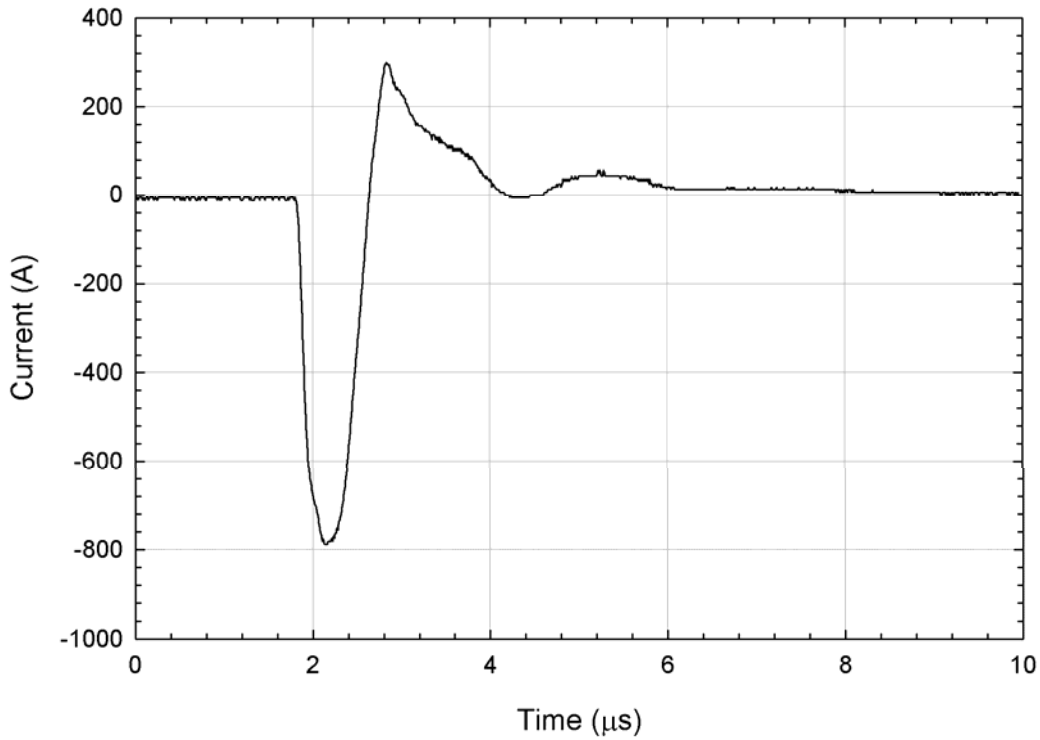
- The plasma is accelerated from the ceramic surface by the intense electric field across the ceramic.

- These sources are easy to scale to large volumes and operate at low vacuum pressures.

- For charge neutralization of intense heavy ion beams, a 2.2 m long plasma source is under development. It is cylindrical in shape to allow it to fit in the drift tube of the ion beam.

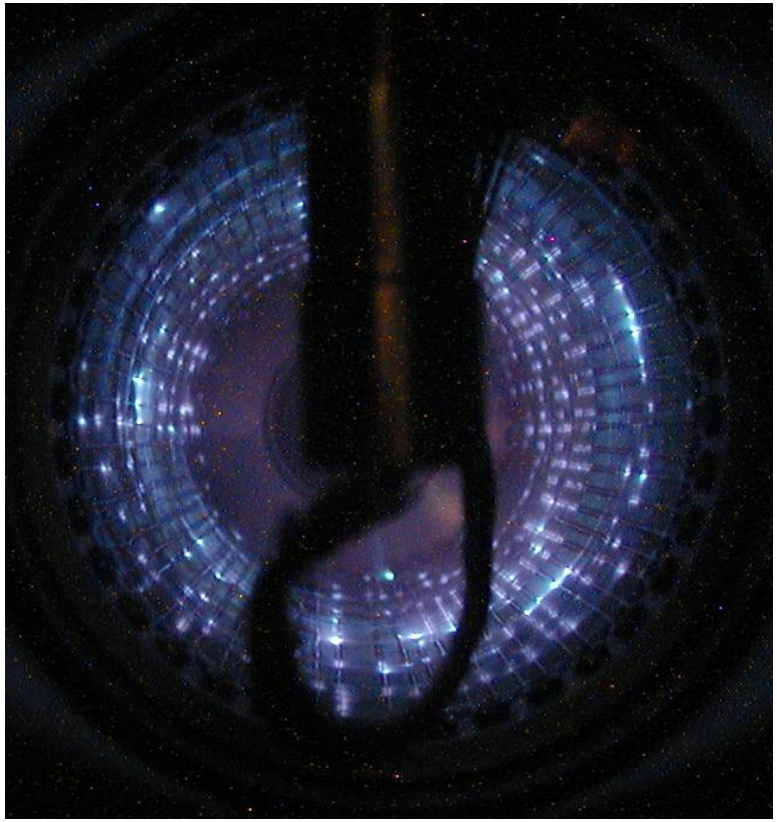
Ref. A. Dunaevsky, et al., JAP **95**, 4621 (2004).

Characterization of 15 cm long prototype



Currents pulses of 800 A and durations of several μs are generated by 6 kV voltages pulses. Measurements show that the plasma persists for tens of μs.

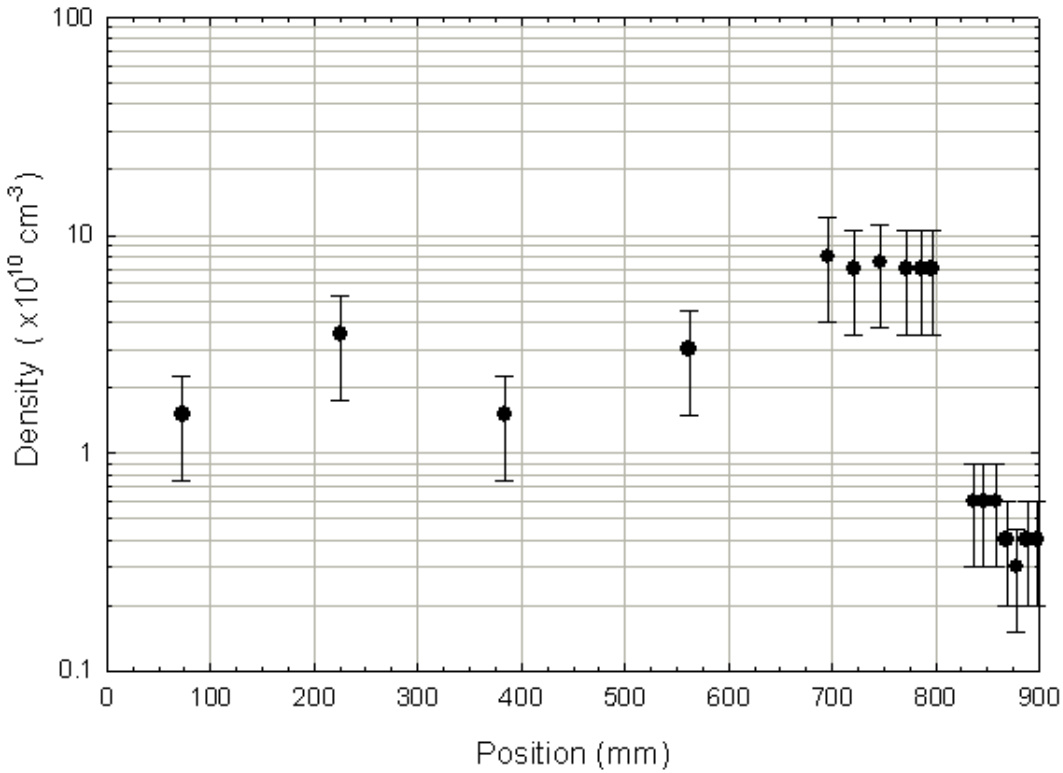
24-shot time integrated exposure.



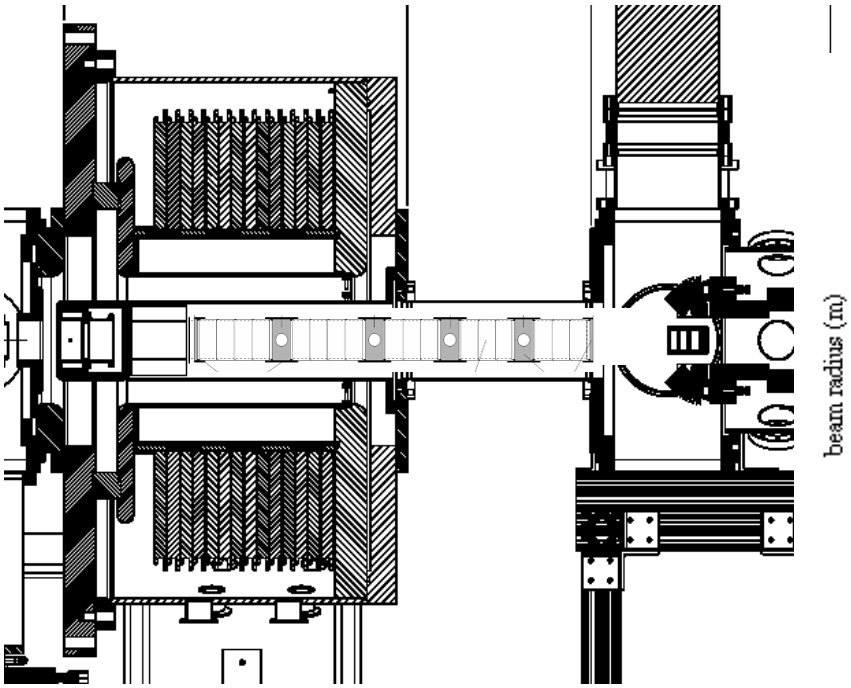
Behind the high-voltage feedthrough in the center of the frame, numerous localized discharges can be seen. Flashover and “dead spots” were corrected by filling the gaps between rings and careful alignment of neighboring rings.

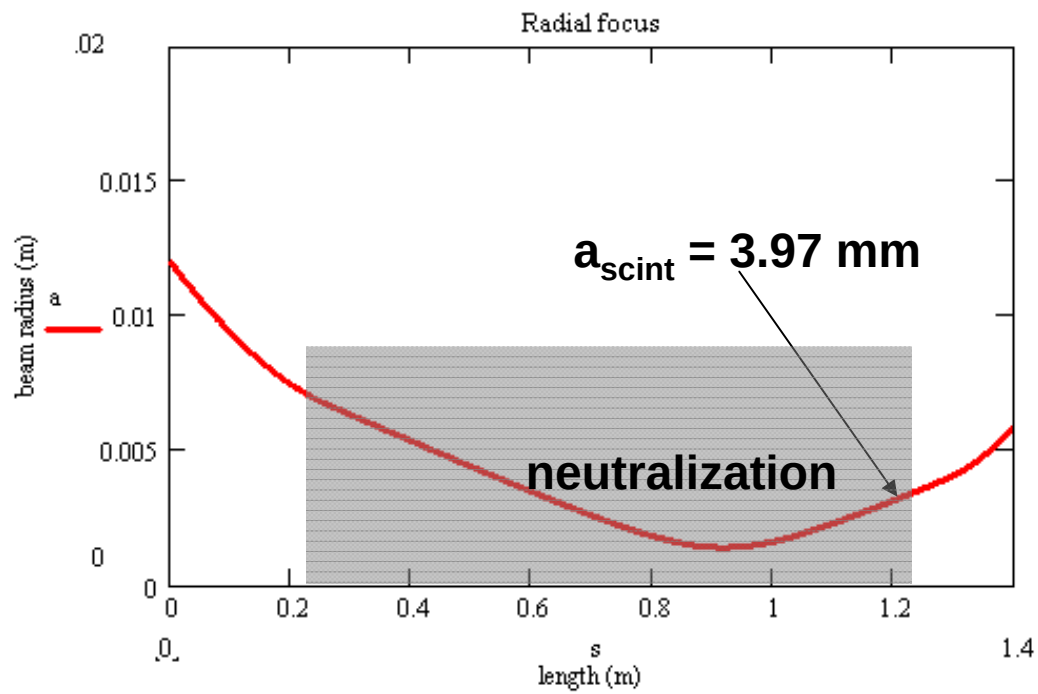
Development of New $BaTO_3$ One-Meter Ferroelectric Plasma Source (FEPS)

Steel mesh replaced wire electrodes



The $BaTiO_3$ FEPS consist of 5 individual sources with diagnostic ports between them. The 5 sources are energized in two groups with two power supplies. The sources in each group are in a parallel electrical network with resistors used to balance the performance of each source.



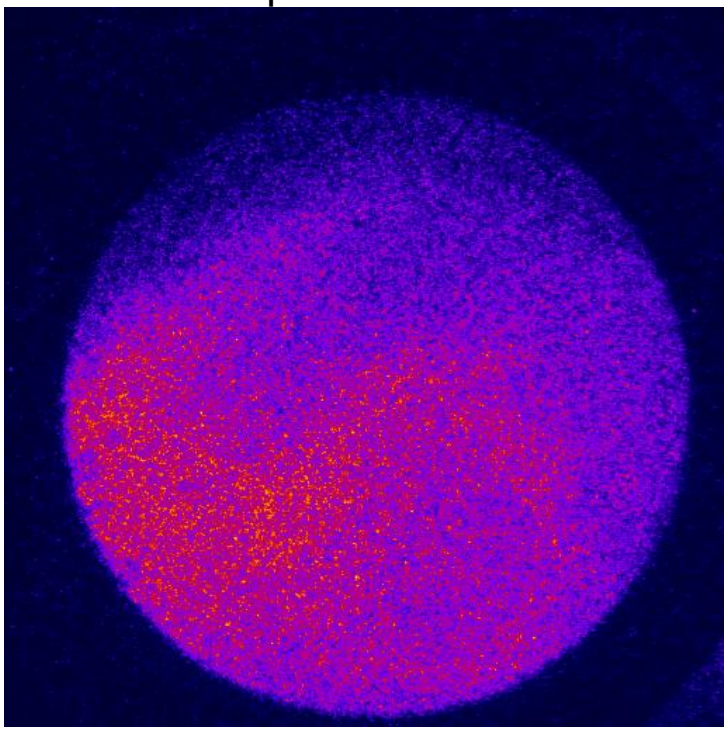


NDCX with the plasma source in its drift tube. Beam is
E = 311 keV, I_b = 25 – 30 ma , K^+.
The solenoid magnets provide transverse compression and the application of a voltage tilt at the cathode provides longitudinal compression.

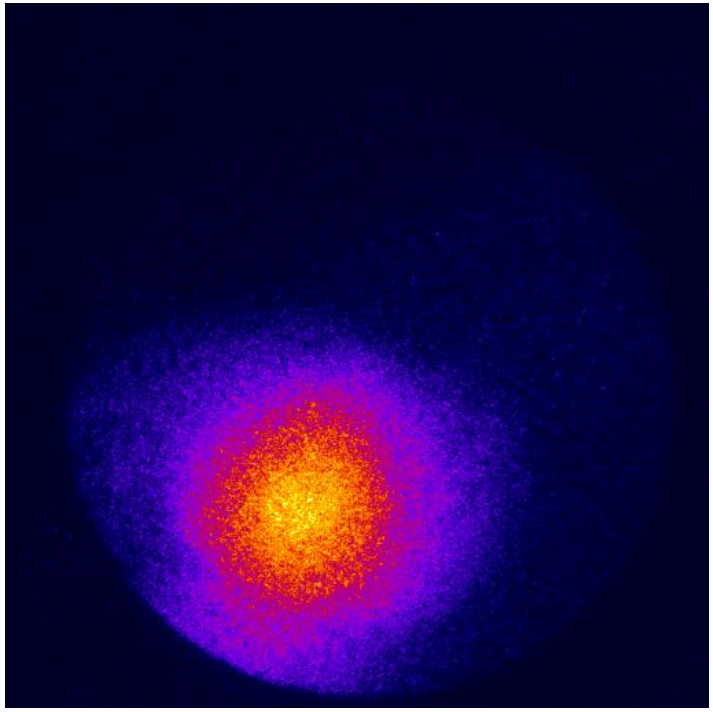
In the past, transverse compression yielded spot sizes on the order of 2 mm and not 8 mm as we have here. Here the solenoid magnets are optimized to achieve both transverse and longitudinal compression. The above calculation shows that the present magnetic settings produces the minimum spot size of ~ 2 mm before the scintillator and the measured spot size should be 8 mm.

Initial Transverse Compression Experiments with the FEPS

Optical imaging of the beam with a scintillator shows the beam compressing from 5 cm with no plasma neutralization to an image of ~ 8 mm with charge neutralization with the



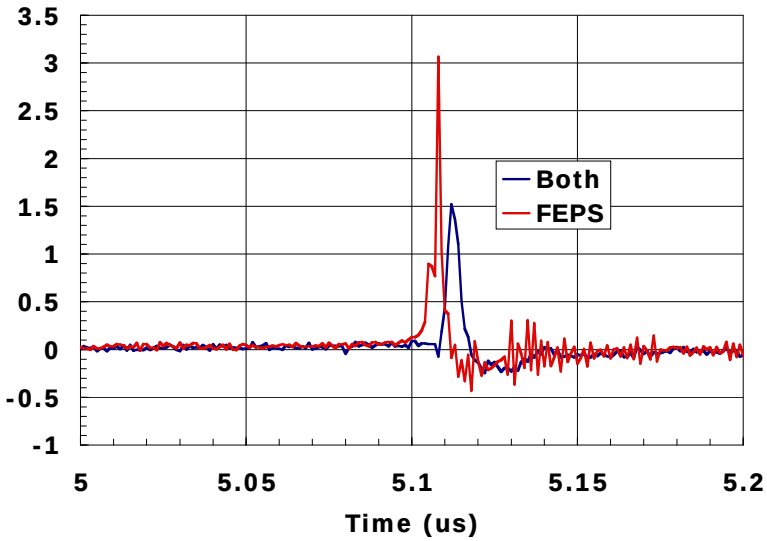
Compression with no plasma



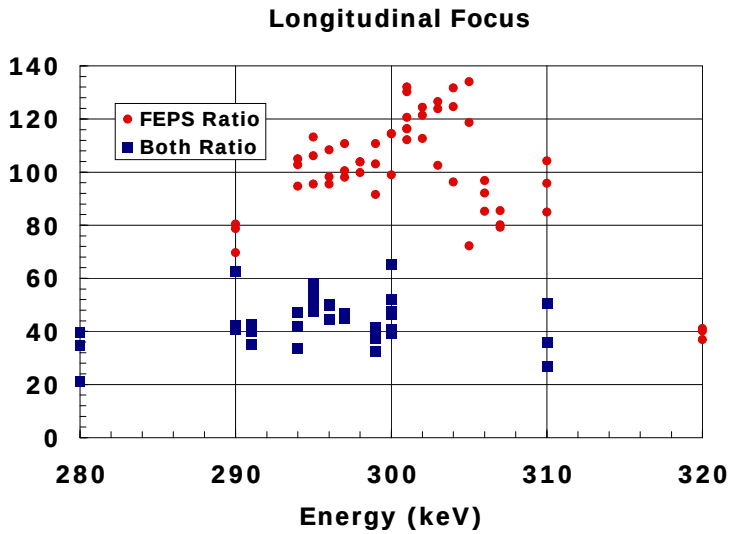
Compression with plasma

The ferroelectric plasma source was shipped to LBNL and mounted into NDCX (Neutralized Drift Compression Experiment). NDCX has the ability to apply a velocity tilt to the beam pulse so the back of the beam pulse catches up to the front of the pulse to achieve longitudinal compression. Transverse compression is achieved with focusing by solenoid magnets. Initial experiments examined transverse compression of the beam. Transverse focusing of the beam using plasma neutralization prevents the beam space charge from losing half the beam current. Current measurements were made with a Faraday Cup.

Results from the Combined Transverse and Longitudinal Compression Experiments on NDCX

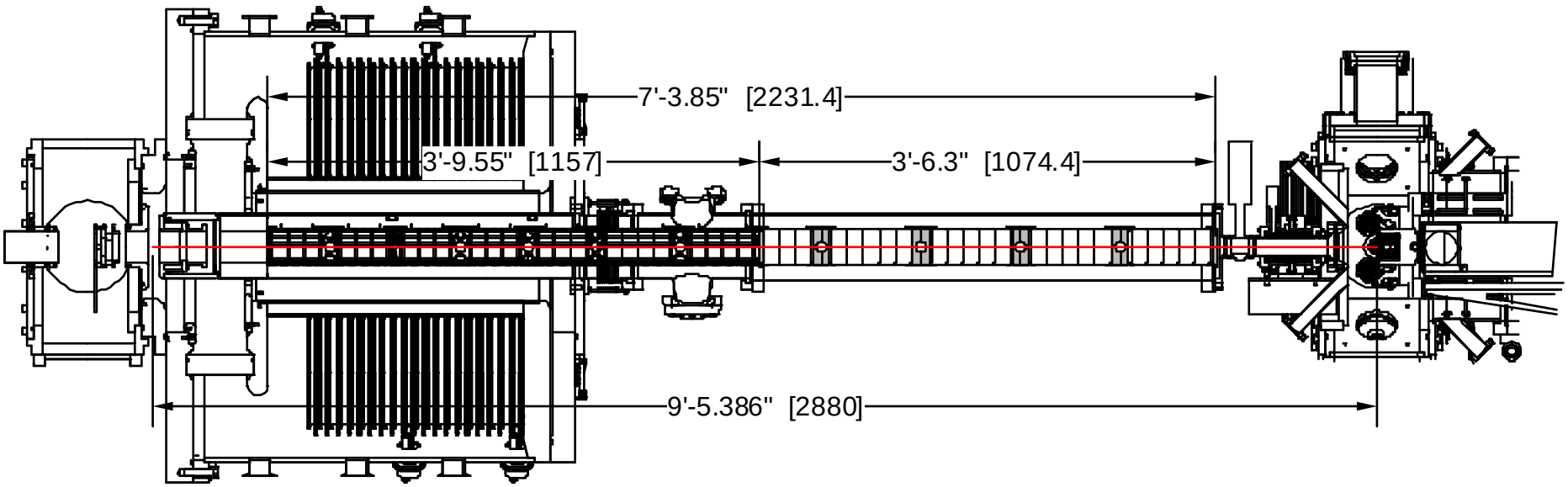


A velocity tilt is applied midway through the beam pulse to compress the beam pulse along with transverse focusing of the beam. Simultaneous transverse & longitudinal compression results in the total peak current density, measured by fast Faraday cup, increasing 120 fold for the FEPS. When the FEPS is combined with the LBNL FCAPS, there is a reduction in the longitudinal compression ratio but a reduction in the transverse spot size.



Both compression schemes are applied simultaneously but will not succeed without beam charge neutralization. Transverse beam compression was successful and the measured current was twice that achieved when compression was applied with no plasma source. Then the velocity tilt was optimized for the ferroelectric plasma Source (FEPS) and the LBNL Filtered Cathodic Arc Plasma Source (FCAPS). With both longitudinal and transverse compression applied the ferroelectric plasma source achieved a factor of 120 increase in peak current density- slightly better than previously achieved. When both the FEPS and FCAPS are used, the compression ratio is reduced, But the transverse spot size is smaller.

2.23-meter-long Plasma Source is Being Assembled



The existing 85-cm-long plasma source will be lengthened using a 30-cm-long extension, while a 107-cm-long FEPS has been built and shipped to LBNL. Aberrations created in the bunching module acceleration gap that limit the ultimate beam spot size can be reduced by reducing the rate of the head-to-tail velocity tilt. The subsequent plasma-neutralized drift length must then be made longer.

Plans

- Additional plasma sources operating at higher density than the present source will be needed for future warm dense matter experiments.
- Higher voltage and double-pulse operation will be examined to extend the density operating range of the source.
- Since the plasma density decreases rapidly away from the material surface, smaller diameter cylinders should provide higher average density near the beam axis.
- Eventually an additional source operating at four orders of magnitude higher density over a few mm will be needed for the warm dense matter experiments. Plasma sources such as laser ionized gas jets will be considered.