Electron Source Requirements for Advanced Accelerators

Spencer Gessner

Snowmass Electron Source Workshop

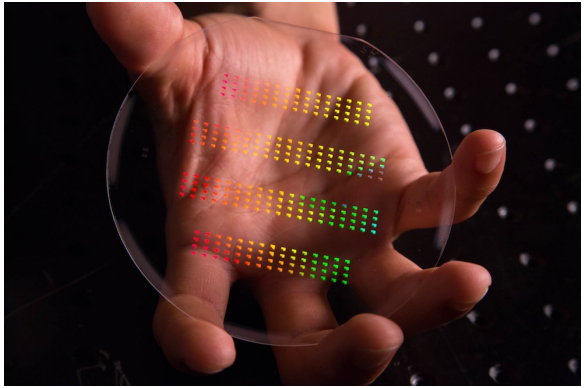
February 18, 2022

U.S. DEPARTMENT OF ENERGY | Stanford University

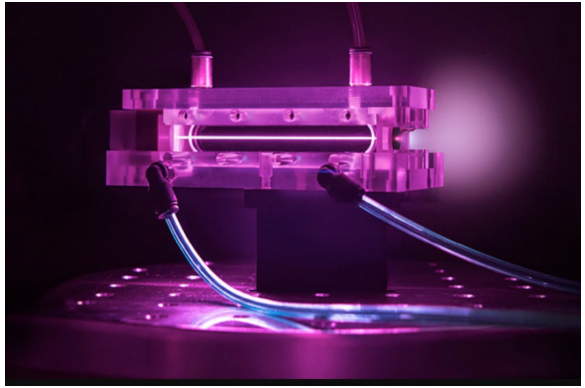
SLAC NATIONAL ACCELERATOR LABORATORY

Advanced Accelerator Technologies

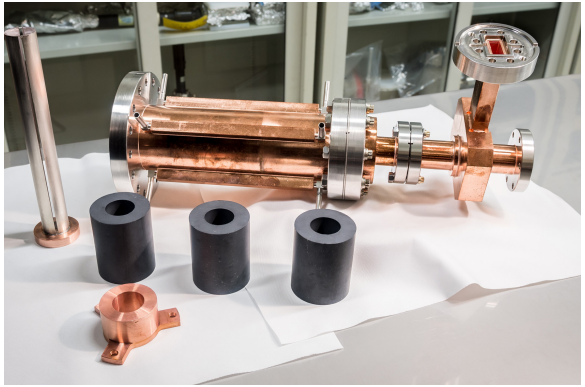
Dielectric Laser



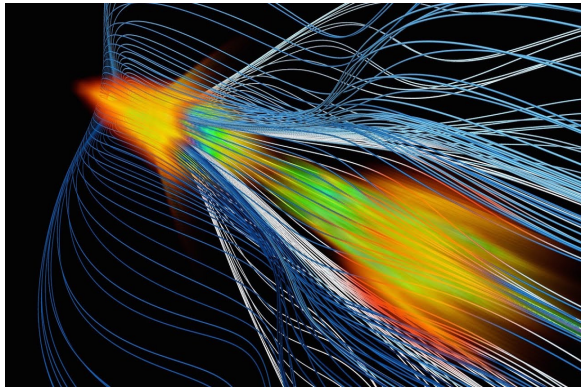
Laser Plasma



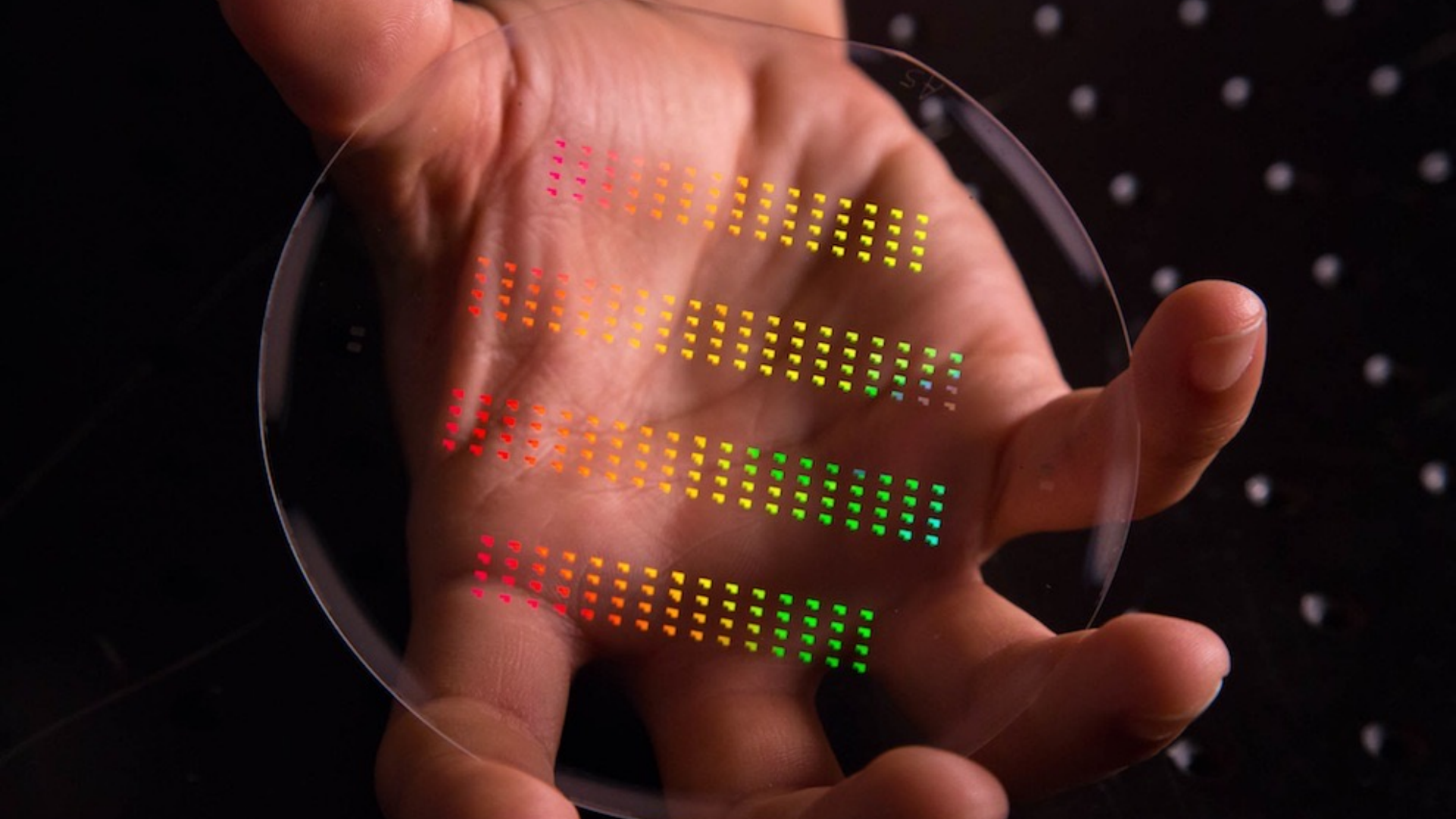
Dielectric Structure



Beam Plasma

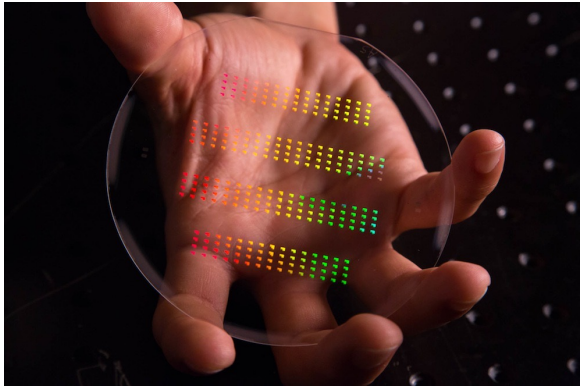


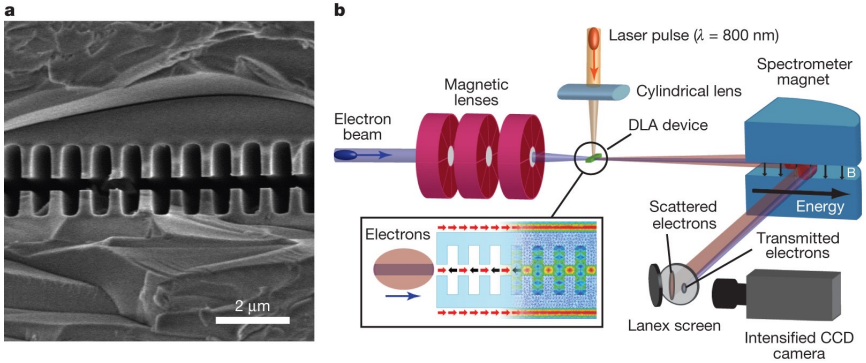
Advanced Accelerator Facilities



Sources for Dielectric Laser Accelerators

- The aperture in a dielectric laser accelerator (DLA) is the same order of magnitude as the driving laser (about 400 nm).
- These devices require low-charge, extremely low-emittance sources.



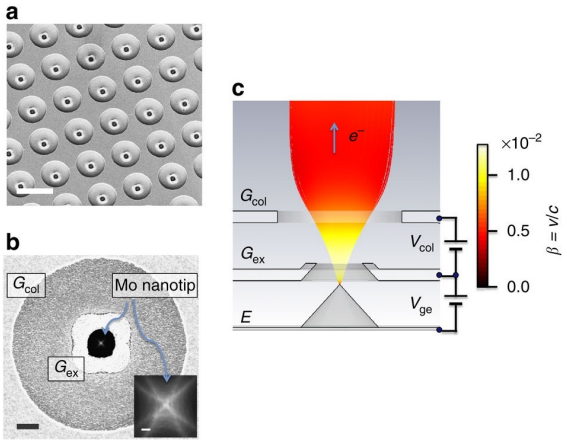


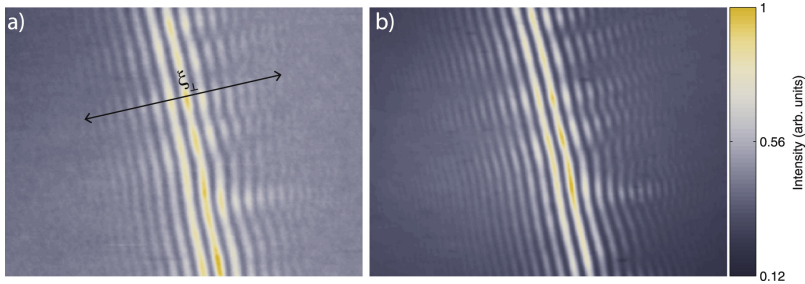
E. Peralta et. al. Nature 2013

Sources for Dielectric Laser Accelerators

- Structured cathodes have been developed to emit low-emittance, spatially coherent electron beams.
- Structured cathodes can be replaced by single nano-tips for low-intensity applications.

S. Tsujino, *et al.*. *Nat Commun* **7,** 13976 (2016).





J. McNeur *et al* 2016 *J. Phys. B: At. Mol. Opt. Phys.* **49** 034006

Sources for Dielectric Laser Accelerators

- Recent work demonstrates an Si nanotip emitter with a DLA structure acceleration stage.
  - 28 electrons/pulse!
  - f = 100 kHz
  - ε = 62 pm rad

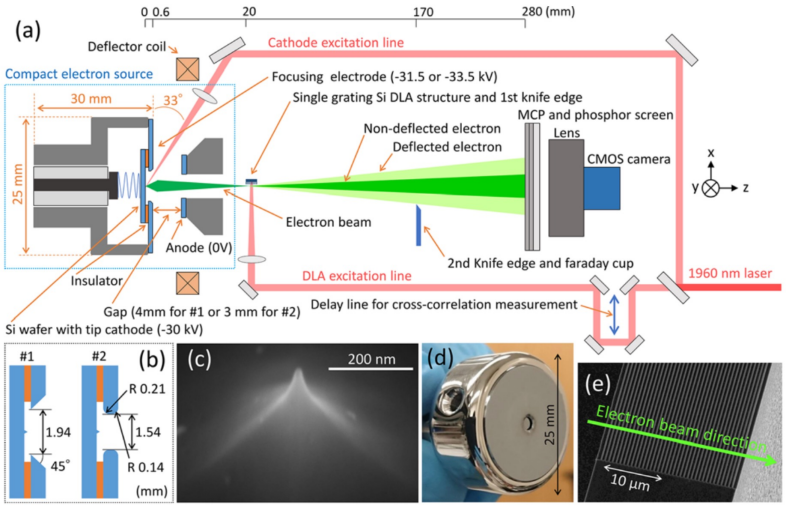
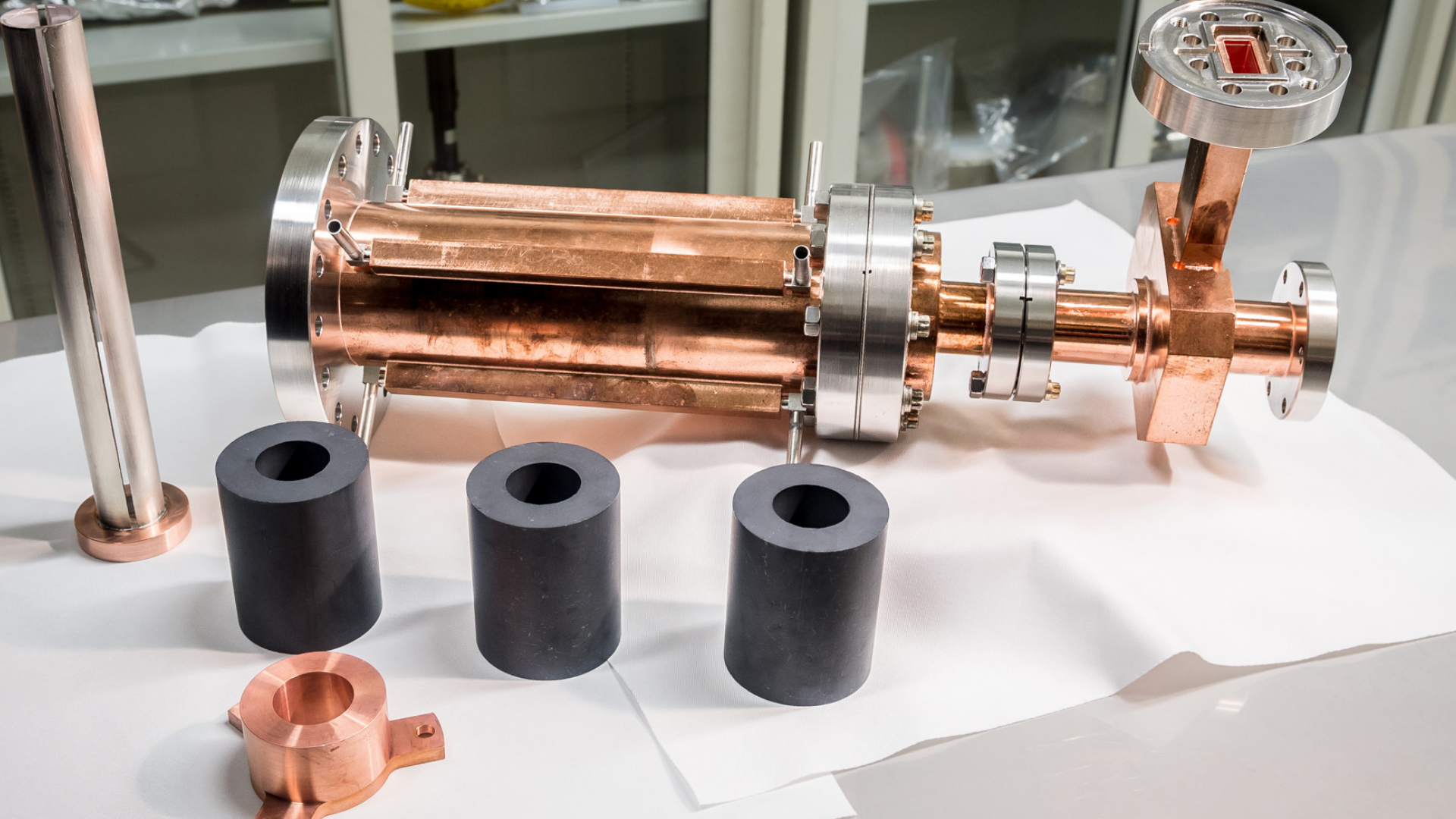


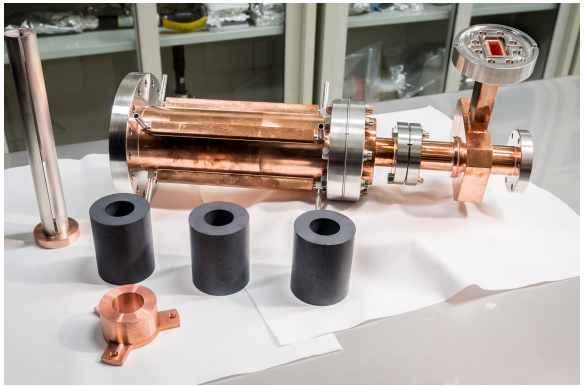
FIG. 1. Experimental setup. (a) Schematic of the compact electron source. (b) Enlarged schematic cross section around the cathode tip. (c) SEM image of the Si tip cathode for configuration #2 (see Table I) observed from an angle of 30°. (d) Assembled focusing electrode and cathode attached to the stainless-steel jacket. (e) SEM image of the silicon single grating DLA structure used for the cross correlation measurement.

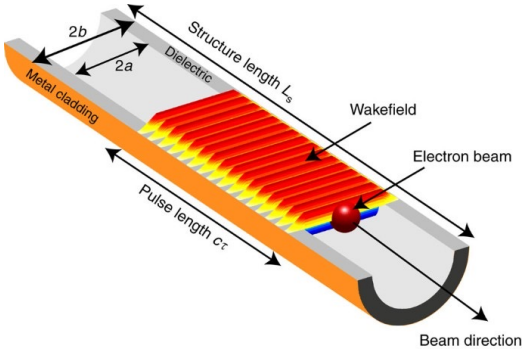
T. Hirano et. al. Appl. Phys. Lett. 116, (2020)



Sources for Structure-Based Accelerators

- Source requirements for structure-based accelerators depend on the acceleration mechanism.
  - For a two-beam accelerator (TBA), with drive and witness separated, drive charge should be very high!
  - For colinear wakefield accelerator, drive and witness charge are similar, but emittance is small.



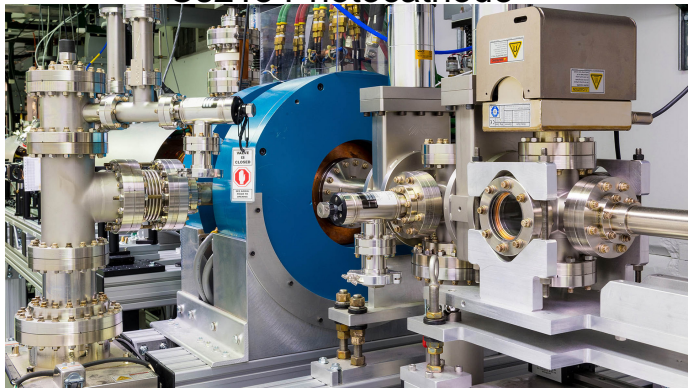


B. O'Shea, *et al.*. *Nat Commun* **7,** 12763 (2016).

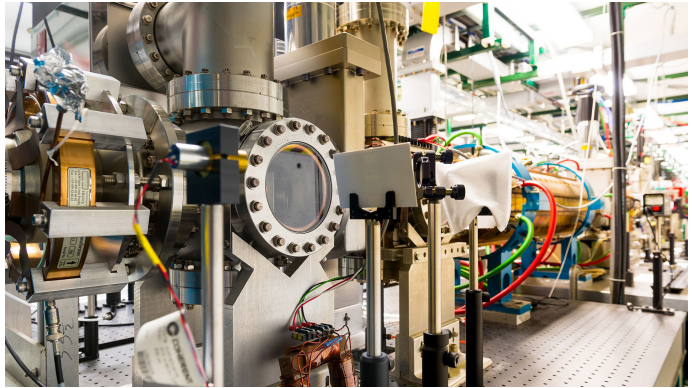
Sources for Structure-Based Accelerators

- AWA at Argonne uses two different electron beam sources
  - Cs2Te cathode produces high-charge (greater than 100 nC) drive bunch.
  - Mg photocathode produces low-charge, low-emittance witness bunch.

Cs2Te Photocathode



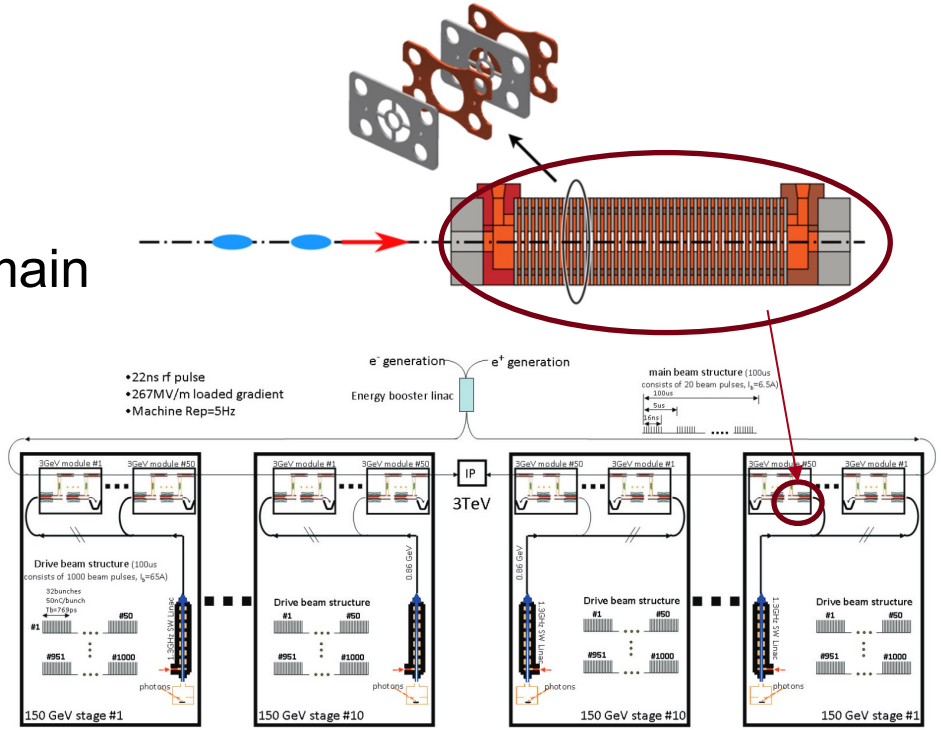
Mg Photocathode



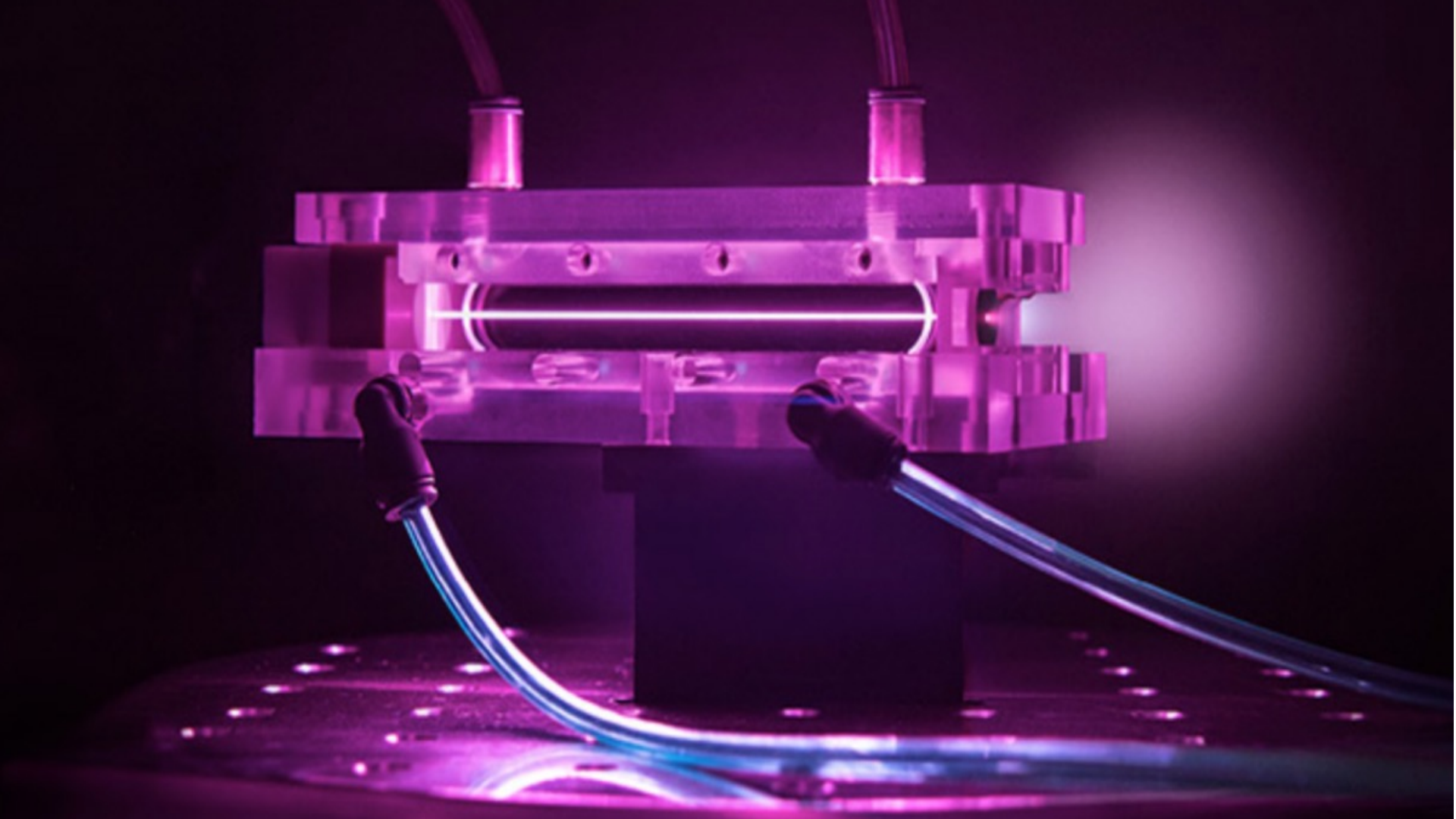
Sources for Structure-Based Accelerators

- The high charge drive beams are used to excite power extraction structures.
- RF power is coupled out of the extraction structure and into the main linac where it accelerates a low charge bunch.

X. Lu et al, PRL 122, 2019

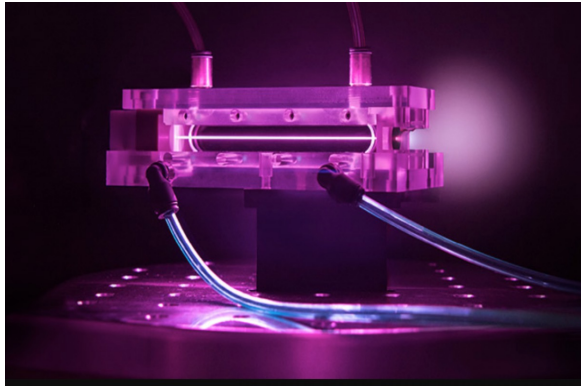


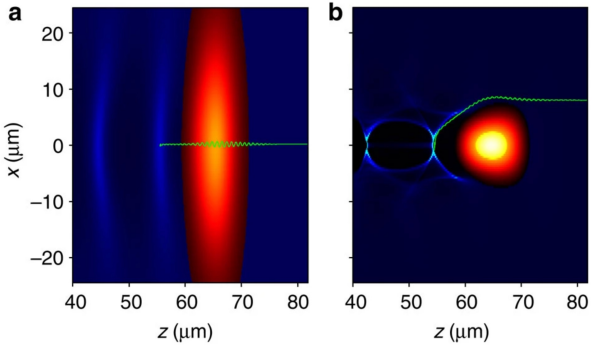
C. Jing et al, TUPEA088, IPAC 2013



Sources for Laser Wakefield Accelerators

- In general, laser wakefield accelerators do not require an external source.
- Electron self-trapping provides the beam source.

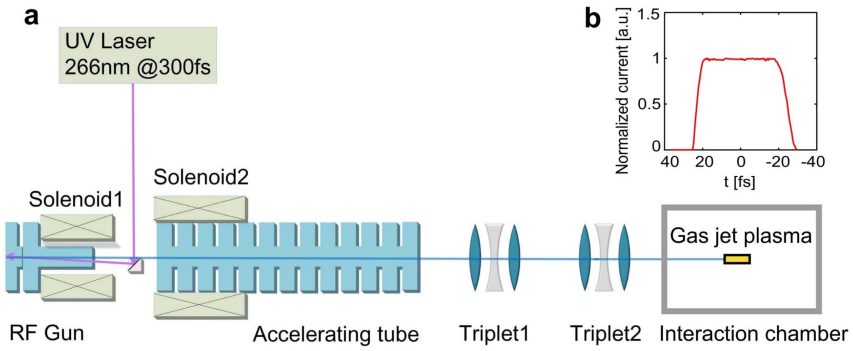


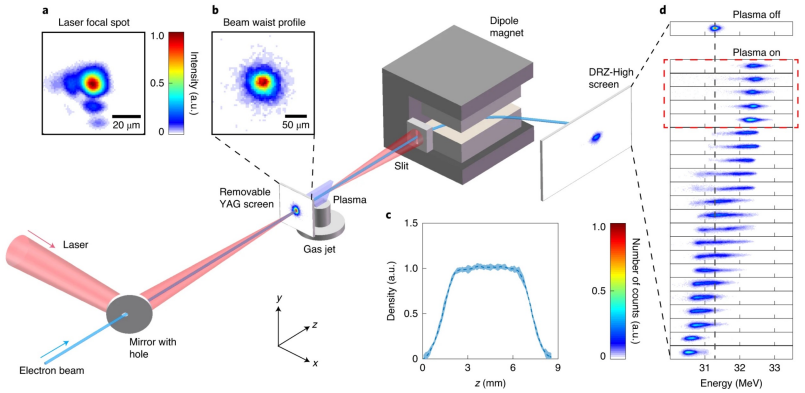


S. Corde et. al. Nat. Comm. 2013

Sources for Laser Wakefield Accelerators

- One exception is a recent experiment at Tsinghua which demonstrated 100% throughput of an electron beam from an s-band linac accelerated by laser wakefield.

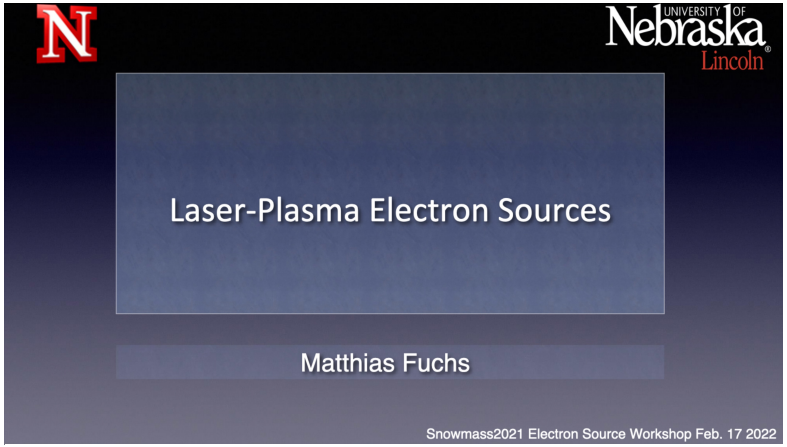




Y. Wu et. al. Nat. Phys. 2021

Sources for Laser Wakefield Accelerators

- There are *many* mechanisms for generating electron beams in a laser wakefield.
- See Matthias Fuchs' talk from yesterday or Carl Schroeder's talk today.



Summary of LWFA electron bunch parameters

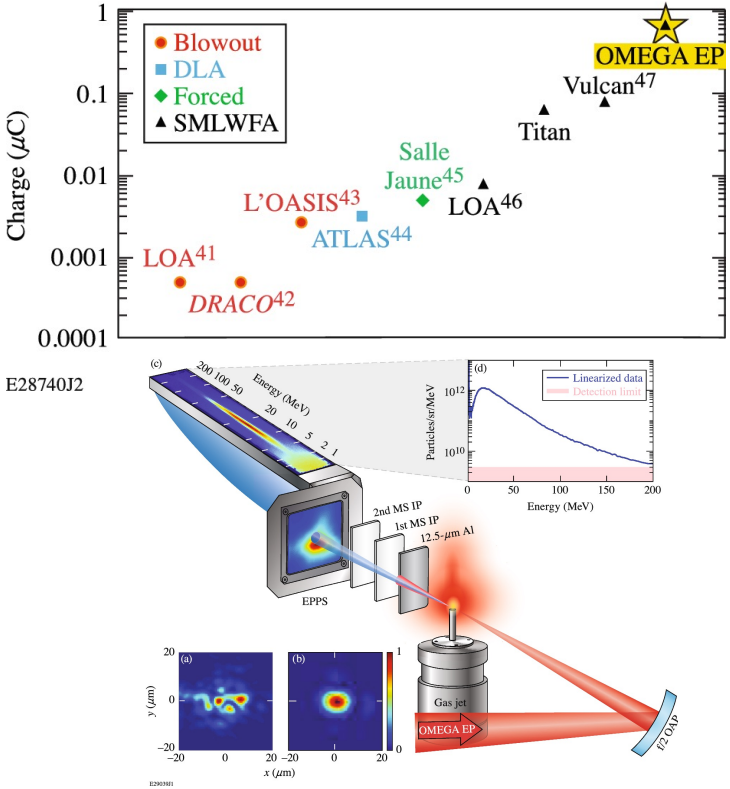
Bunch property	State of the Art	Other beam parameters	References
Bunch energy	8 GeV	5 pC, (up to 60 pC in 6 GeV peak), 0.2 mrad	Gonsalves et al., PRL (2019)
Bunch charge (quasi monoenergetic)	220 pC (dE/E = 14% FWHM*)	250 MeV, 7 mrad [ionization injection]	Couperus et al., Nat. Comm. (2017)
	338 pC (dE/E = 15% FWHM*)	216 MeV, 0.36 mrad [shock front injection]	Götzfried et al., PRX (2020)
	700 nC (dE/E = 100%)	Up to 200 MeV, laser: OMEGA-EP, 100 J, 700 fs	Shaw, et al. Sci Rep 11 (2021)
Energy spread*	0.2 – 0.4% (RMS)	800 MeV, 8.5 – 24 pC, shockwave assisted injection	Ke, et al. PRL (2021)
Bunch duration	1.4 fs (RMS)	15 pC, CTR (diagnostic limited)	Lundh et al, Nat Phys (2011)
	2.5 fs (RMS)	Faraday rotation (diagnostic limited)	Buck et al., Nat Phys (2011)
Emittance (normalized)*	0.2 π mm mrad (@245 MeV)	Single-shot measurement	Weingartner et al, PRSTAB (2012)
Repetition Rate	1 Hz	24-hour operation; 100,000 consecutive shots	Maier et al, PRX (2020)
	1 kHz	up to 15 MeV, 2.5 pC	Salehi et al, PRX (2021)
Efficiency (Laser to e beam)	3%	2J in driver laser pulse	Götzfried et al., PRX (2020)

*bunch integrated quantities **most of these properties have not been realized simultaneously** !

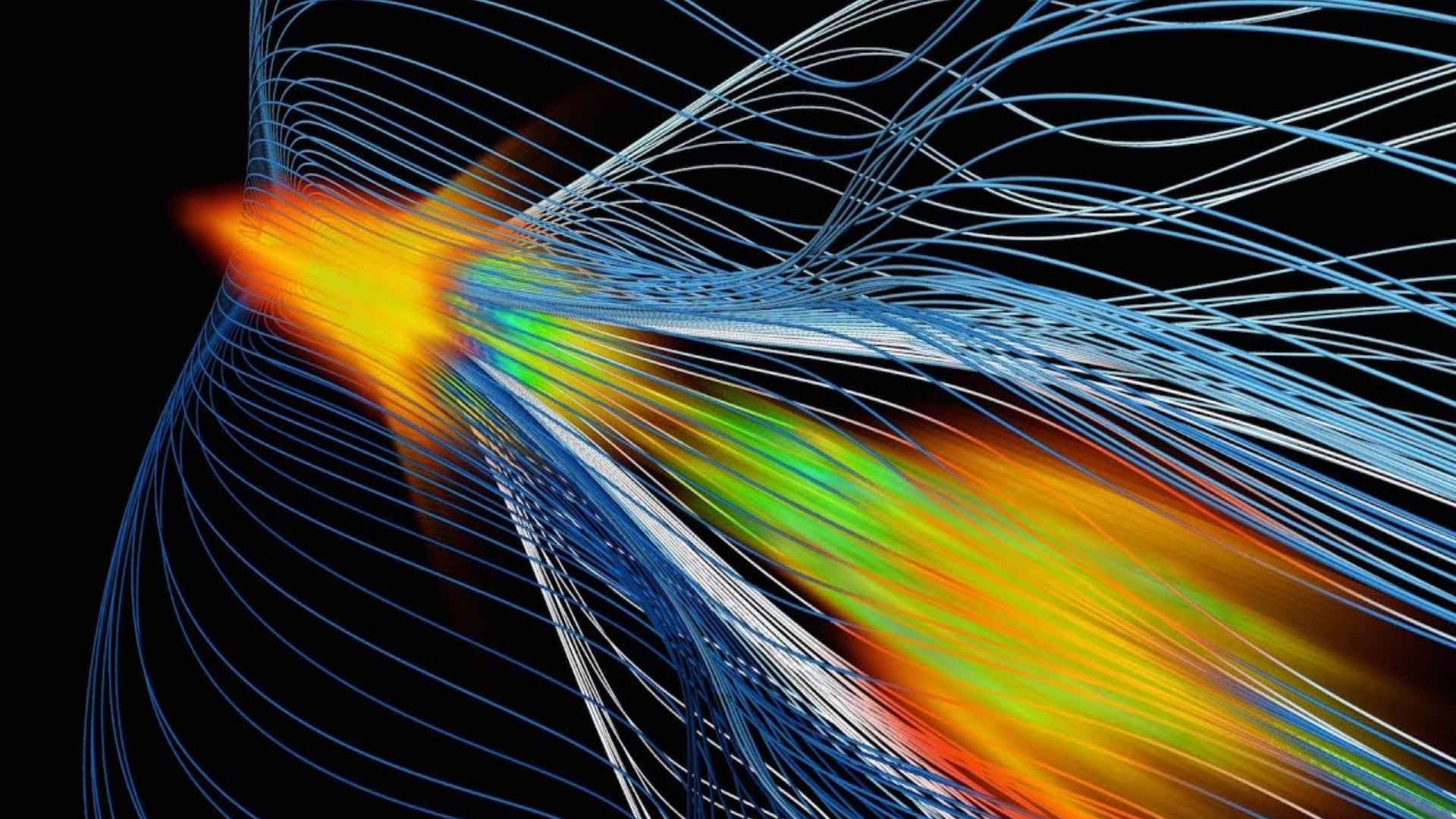
mfuchs@unl.edu

Sources for Laser Wakefield Accelerators

- Laser wakefield accelerators are not limited in the amount of charge they can produce.
- With a large laser, you can produce a lot of charge!

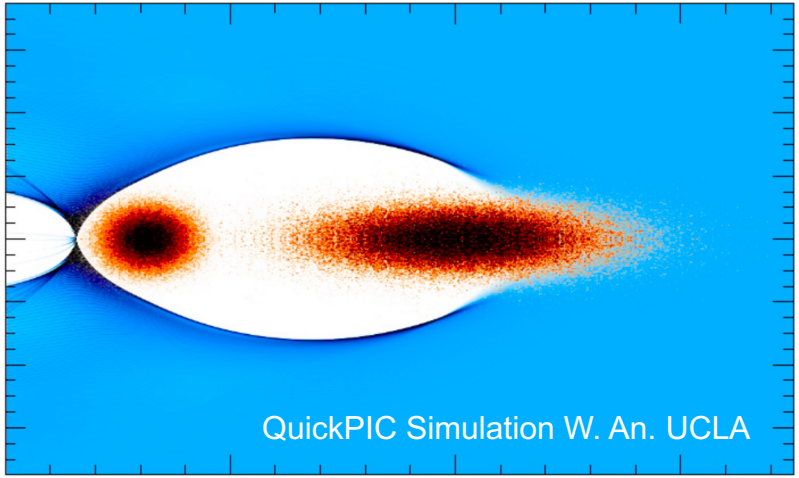


J. Shaw et. al. Nat. Sci. Rep. 2021



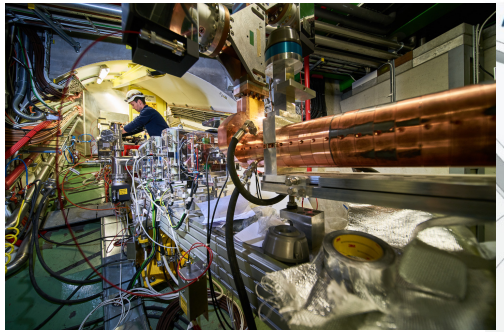
Sources for Beam-Driven Plasmas

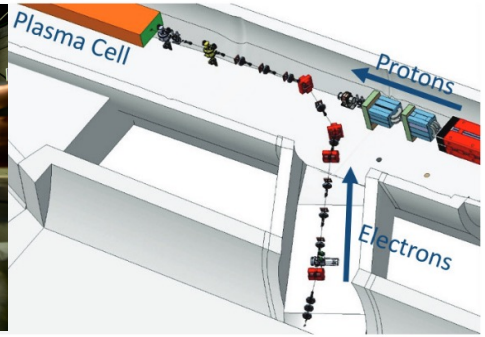
- For beam-driven plasma acceleration, both a drive and witness beam are needed. The witness beam must “load” the wake.
- This requires a high-peak current (very short) bunch.

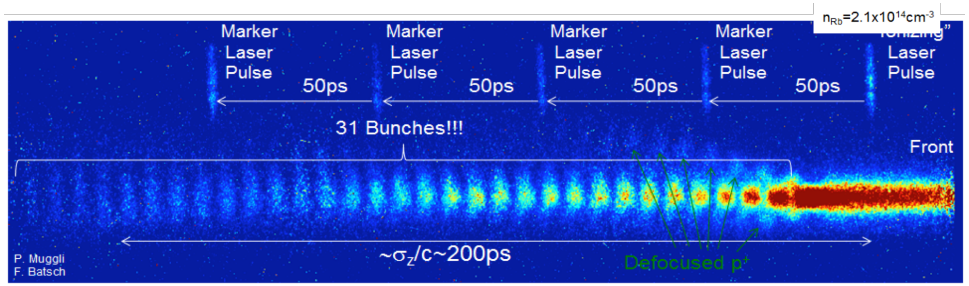


Sources for Beam-Driven Plasmas

- At the AWAKE experiment at CERN, the electron beam is externally injected into the self-modulated proton wake.
- The electron beam is 20 MeV, and this energy is too low to compress the beam and load the wake.



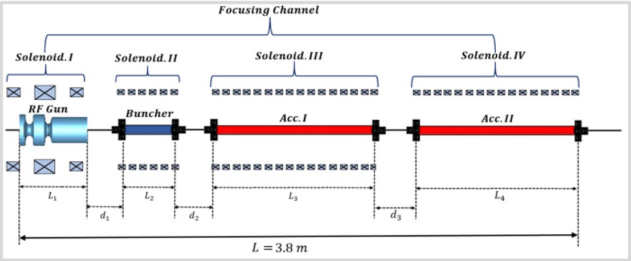


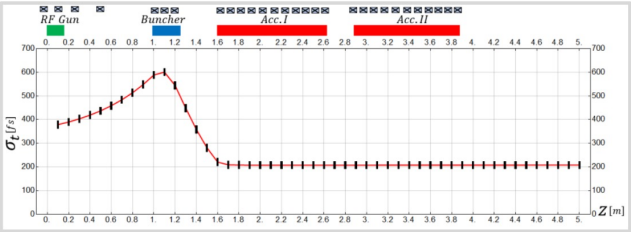


Sources for Beam-Driven Plasmas

[Run 2 c] New 150 MeV e- source

- → based on X-band
- → Well advanced design
- → Prototyping together with CLEAR

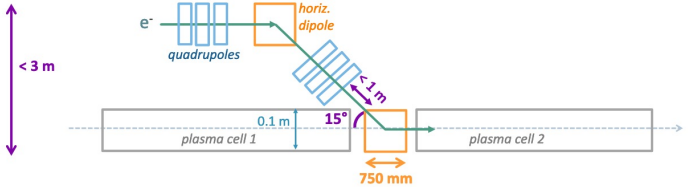


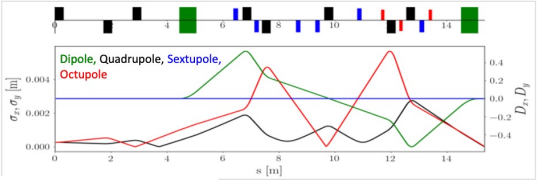


S. Doebert, M. Dayyani Kelisani, L. Garolfi

[Run 2 c] New e- line

- → Requirement of β = 5 mm at injection.
- → Require a module which is achromatic, with no bunch lengthening.
- → Limit of ~ 3m width set by tunnel width
- → Dipole bending angle > 15° so beam-pipe doesn't hit plasma cell
- → Dipole-quadrupole spacing > 1 m





R. Ramjiawan, F. Velotti

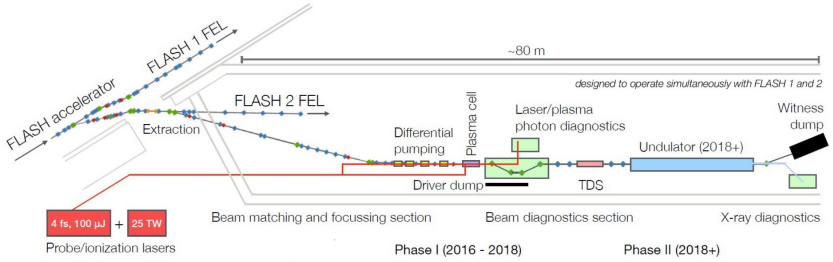
Design optimised to meet matching condition at plasma merge-point:

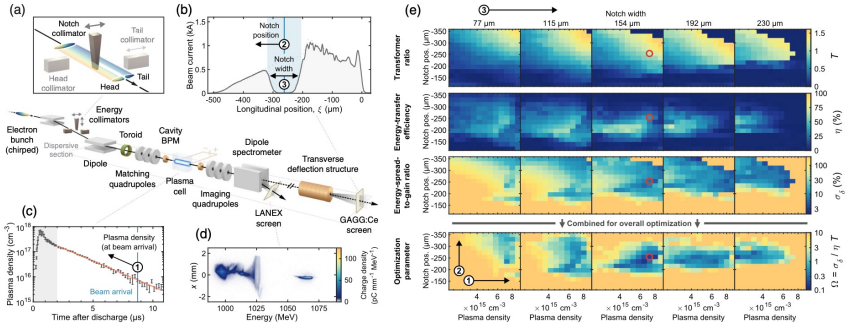
$$\sigma = \sqrt{4.87\ \mathrm{mm} \times \epsilon}$$

AWAKE is pursuing an ambitious plan to create a compact 150 MeV electron source based on x-band technology in order to inject into and load the proton wake.

Sources for Beam-Driven Plasmas

- The FlashForward facility at DESY uses beam from the FLASH FEL and the beam is generated by the 1.3 GHz gun with Cs2Te cathode.
- The high-quality beams from the gun lead to high-quality science!

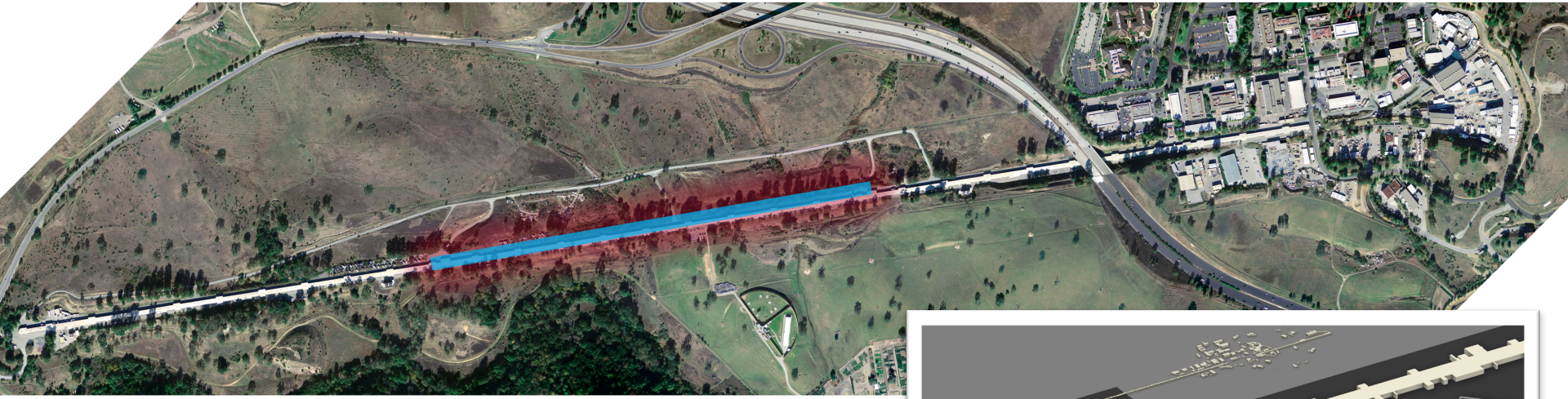


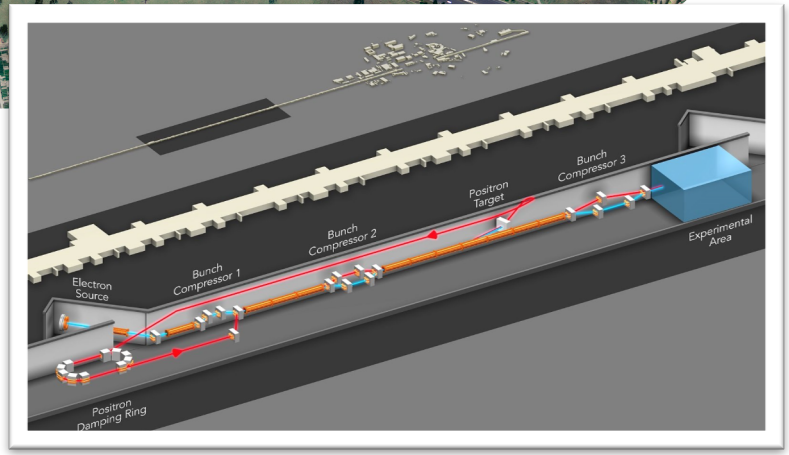


C. Lindstrom et. al. PRL. 2021

FACET-II

SLAC



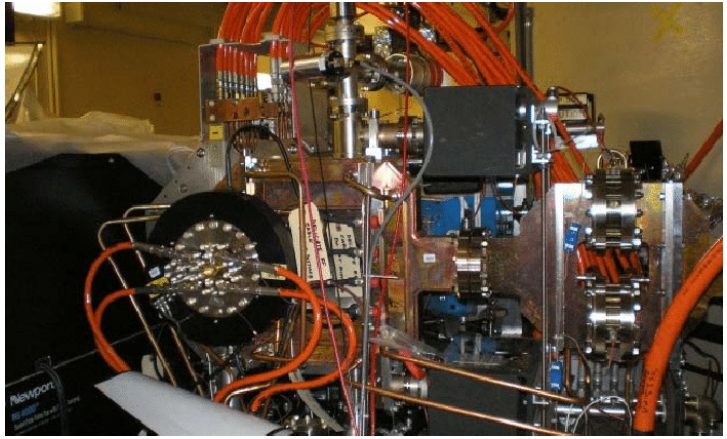


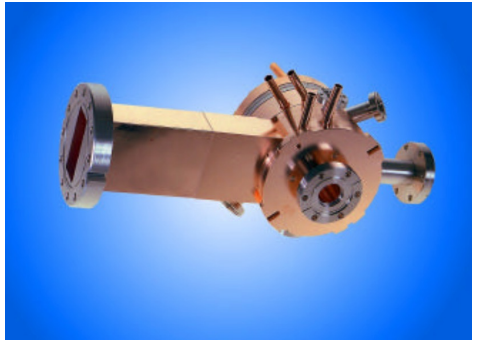
At FACET-II, we are pursuing studies that are relevant to a Plasma-based Linear Collider:

- Single-stage, high-quality acceleration.
- Low-emittance beams from plasma.
- Focusing with plasma lenses.
- Positron acceleration.

FACET Electron Gun

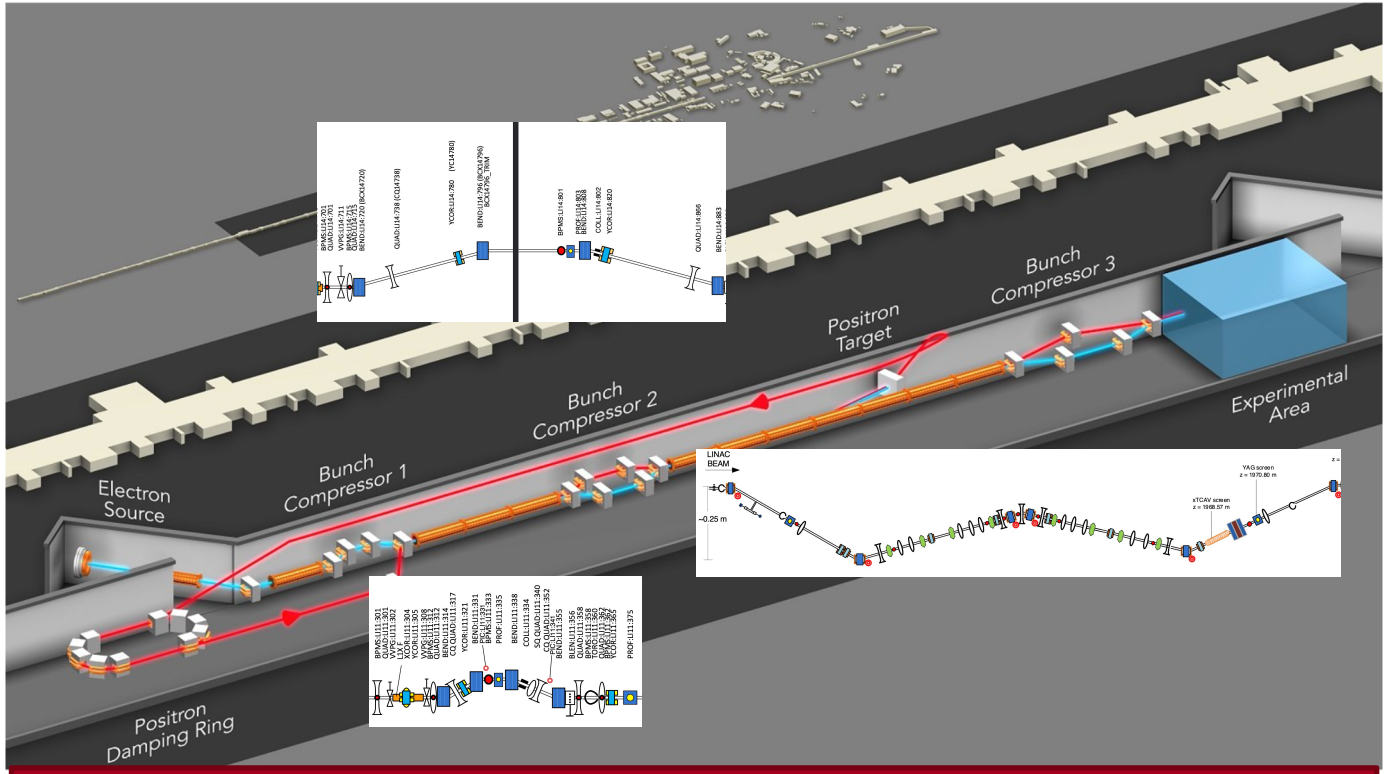
- The FACET electron gun is the same as the LCLS electron gun. It uses a copper cathode and can produce up to 3 nC. The emittance is a few microns at high charge.





SLAC/UCLA/BNL Gun

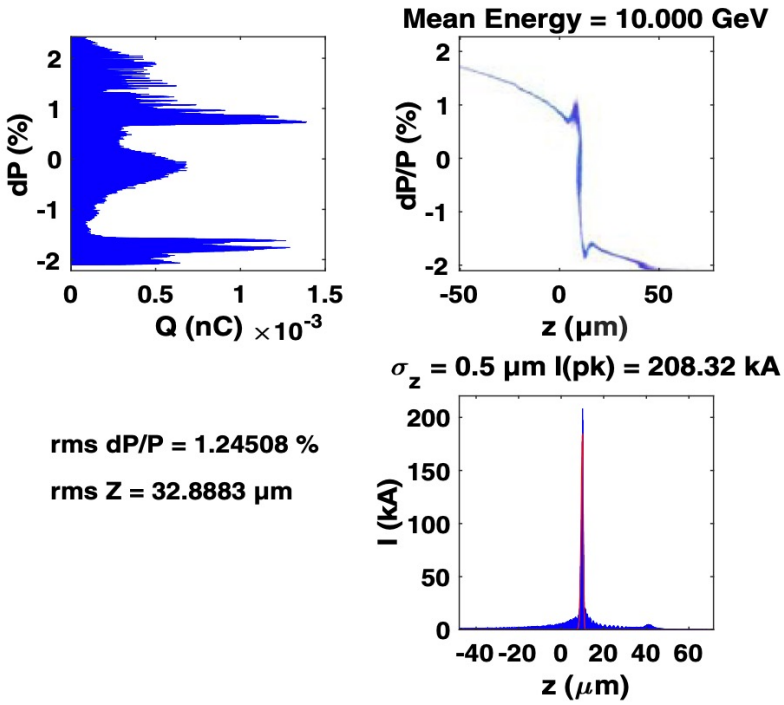
FACET Bunch Compression



FACET uses 3 bunch compressors to create the highest peak charge bunches.

FACET Bunch Compression

- At the end of the third chicane the bunch can reach peak currents in excess of 200 kA.
- We will drive extreme wakefields with this beam, but we will have a hard time diagnosing it!



V. Yakimenko, G. White et. al. PRAB. 2019

Conclusion

SLAC

- Electron sources for advanced accelerators are similar to FEL sources.
- Dielectric laser accelerators require novel nanocathodes.
- Plasma wakefield acceleration experiments require extreme compression.
- Laser wakefield accelerators can use plasma photocathodes to create ultra-low emittance beams.