DIOCLES
EXTREME LIGHT LABORATORY

Stable, monoenergetic 50-400 MeV electron beams with a matched laser wakefield accelerator

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Laser wakefield accelerator

➢ Rationale

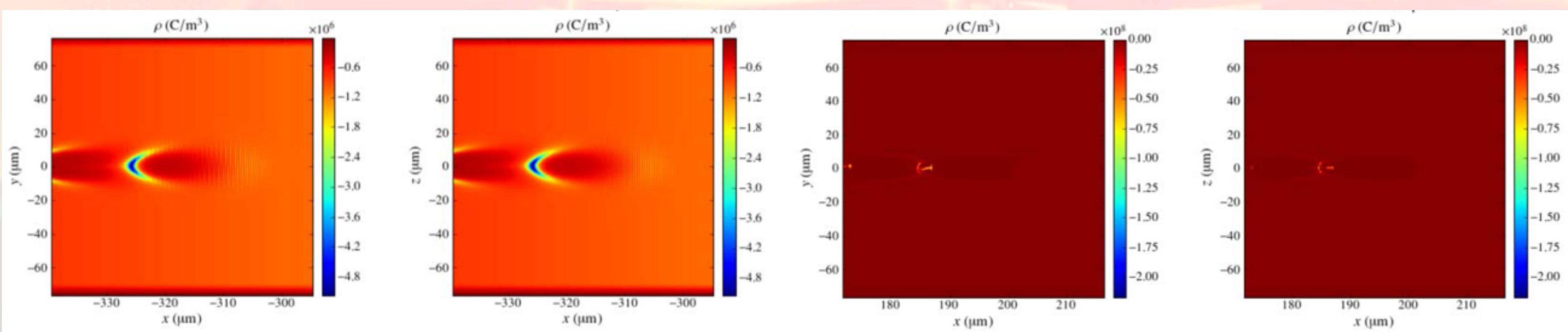
- ❑ Ultrahigh field gradient makes possible extremely compact acceleration devices: GeV/cm
- ❑ Small footprint (~100 sq. ft.) and potentially portable
- ❑ High-brightness electron beams – transverse emittance superior to conventional accelerators
- ❑ **Develop sources for long-standoff nuclear detection**

➢Challenges

- ❑ Stable and robust laser accelerator: Electron beam needs to be reproducible shot-to-shot in terms of energy and pointing
- ❑ Minimum energy spread and highest possible charge
- ❑ High-repetition rate operation

Mechanism of plasma wakefield acceleration

- High-power laser pulse propagating through an underdense medium, produces strong longitudinal forces.
- The ponderomotive force of the laser expels electrons along the propagation axis. The ions however, are relatively immobile.
- The resultant field distribution corresponds to an electron plasma wave moving at a speed governed by the density of the medium which, in the underdense regime, is close to the speed of light.
- Energetic electrons are produced when the free electrons in the plasma are trapped and accelerated by the wave.

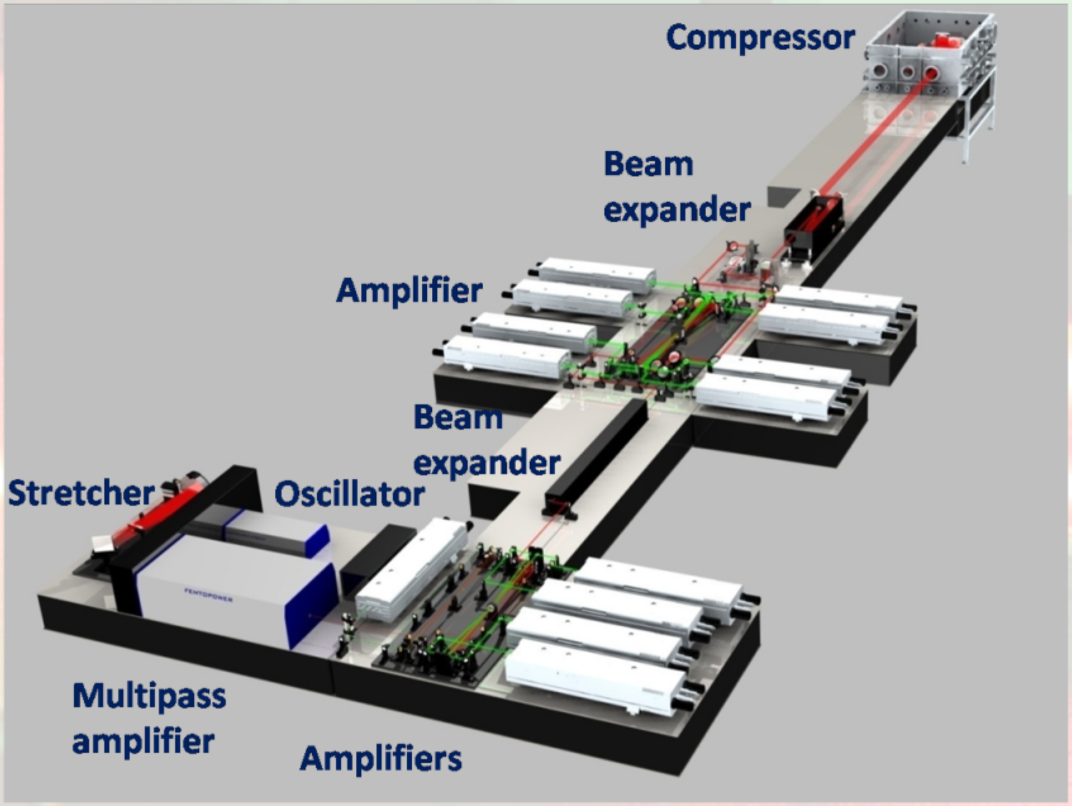


Courtesy: Tech-X Corporation

Key issues in laser wakefield acceleration

- Optimum conditions for electron acceleration
- Dark current and beam stability
- Matched regime
- Scalability of acceleration process
  - PW lasers and multi-GeV beams
- Benchmarking of simulations – optimize accelerator performance with reliable codes
- Demonstrate unique applications

Optical driver for high-energy electron accelerator



Peak power: 140 TW.

Repetition rate: 10 Hz (0.1 Hz)

Central wavelength: 805 nm

Pulse duration: < 30 fs

Pulse energy: 3.5 J (compressed)

Energy Stability:

•Short-term (1 min): 1.5% rms

•Medium (1 hr): 0.5% rms, 2.5%

•Long (8 hours): 0.8% rms, 4.9%

Pointing stability (1 min): 3.5 μrad

Contrast: 3×10^{-8} at 1 ns

Strehl ratio: 0.95

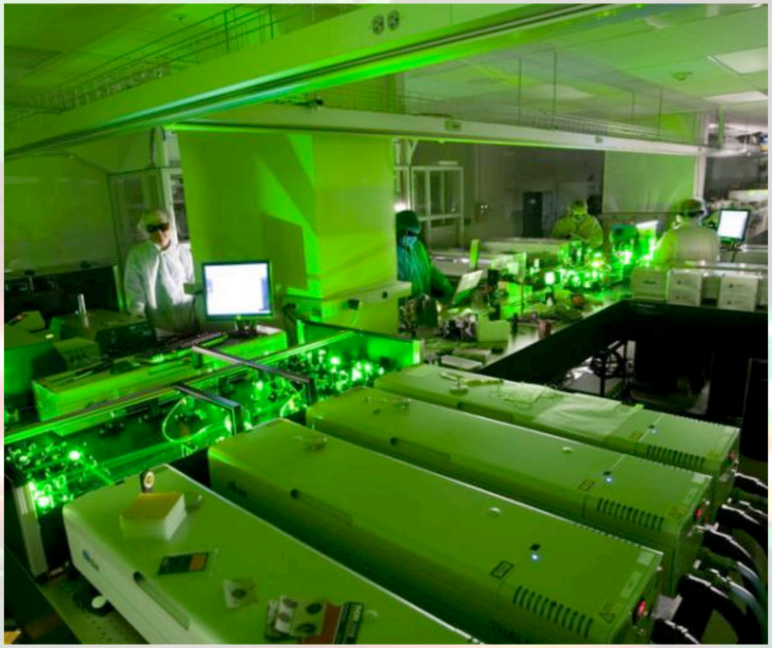
Focusabilty: diffraction-limited

Maximum intensity: 10^{22} W/cm^2 (f/2)

The Diocles laser system, based on chirped pulse amplification produces high-power, ultrashort laser pulses at 10 Hz.

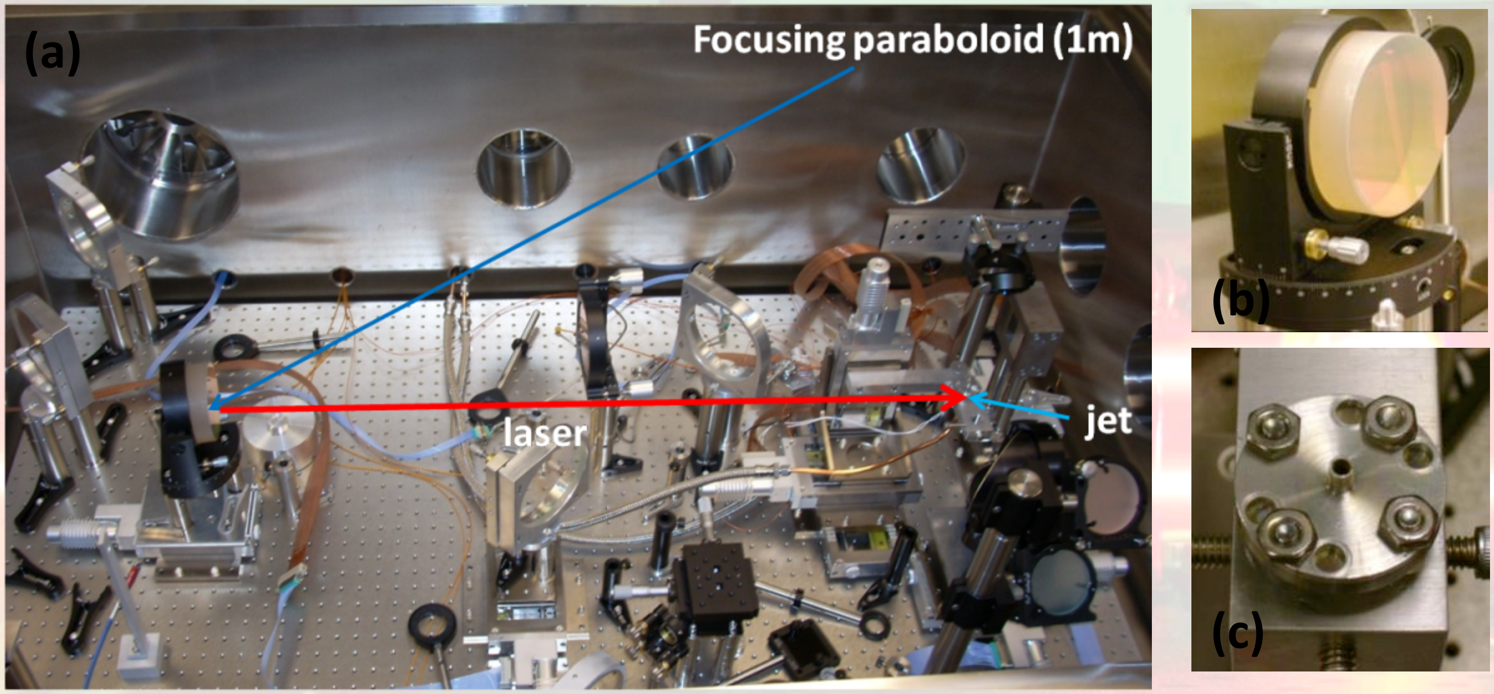
Stable and controllable laser system enables "clean" experiments

- How controllable are laser-driven accelerators, when driven by a reproducible laser driver?
- The role of plasma nonlinearities in the stability of the acceleration process
- Is it possible to use multiple lasers or real-time feedback control of laser/plasma parameters to stabilize and tailor the output radiation?



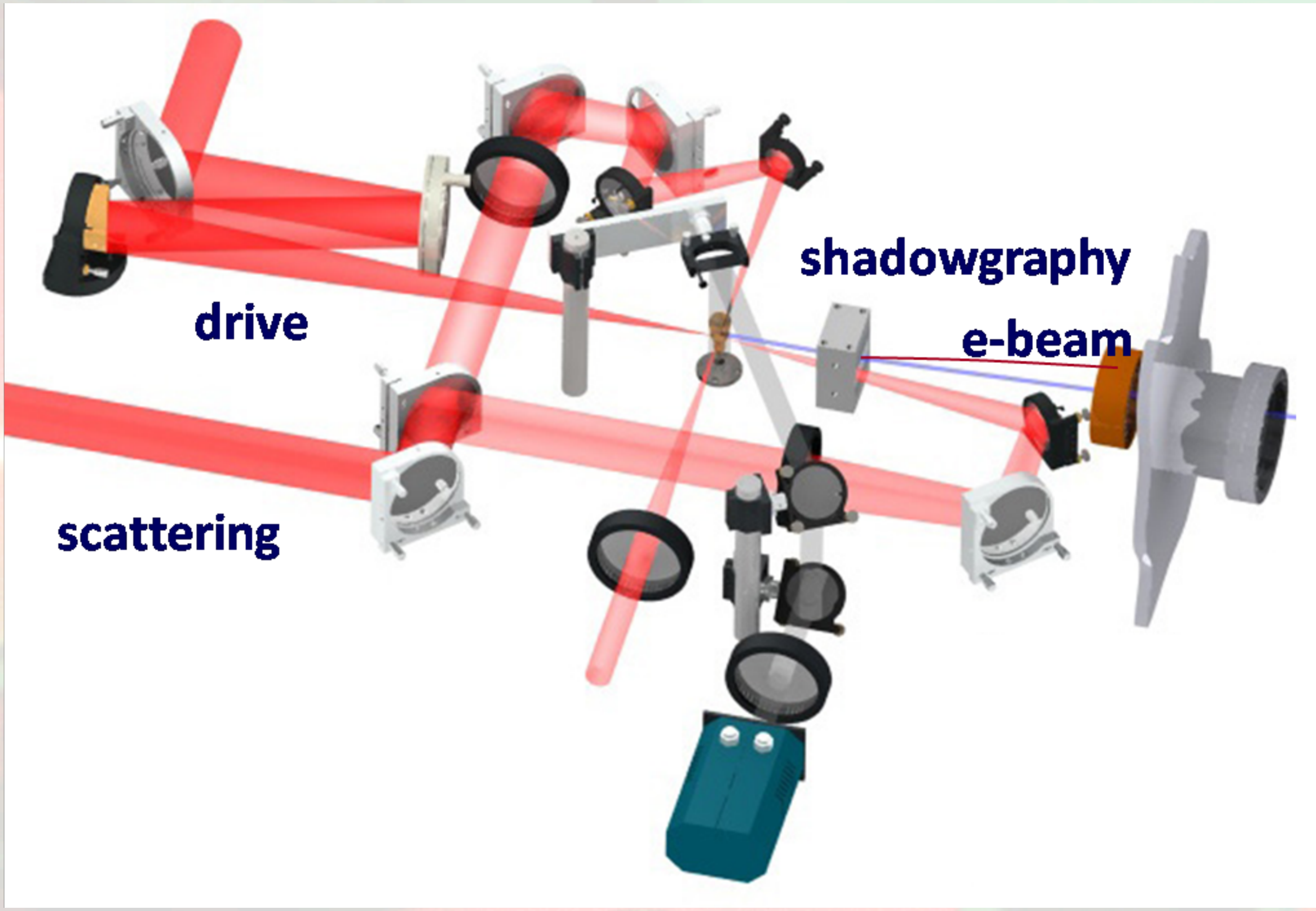
Laser system is housed in a temperature and humidity controlled class-10000 clean room.

Single-stage laser wakefield accelerator

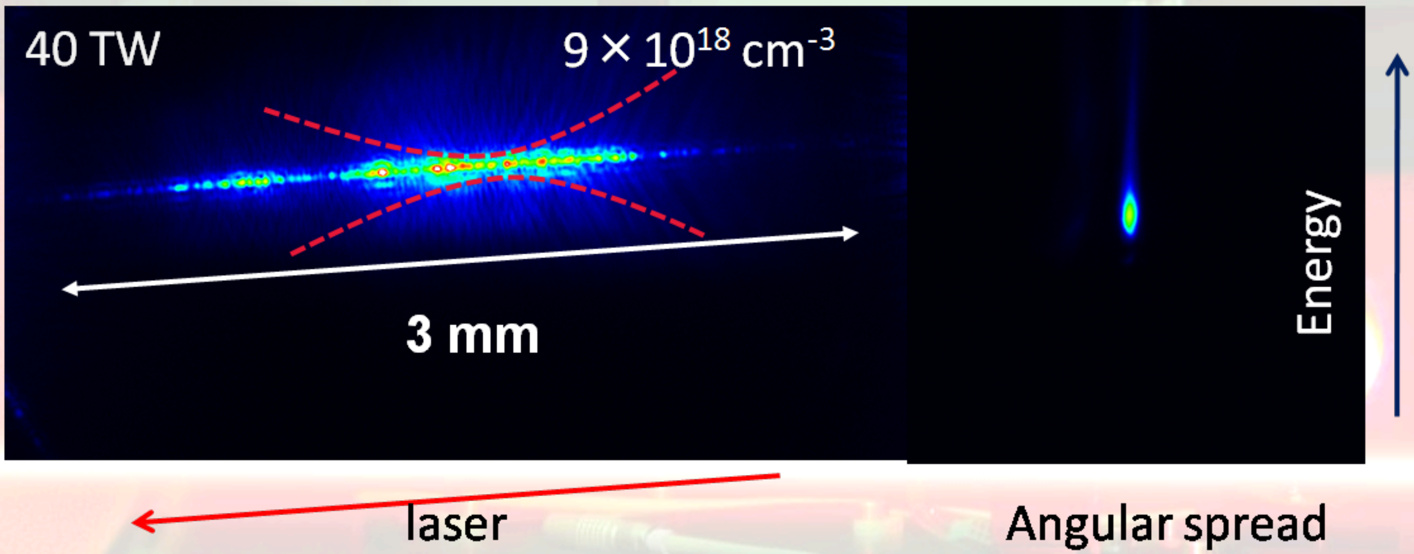


(a) Layout of laser-wakefield accelerator. 30-100 TW laser pulses are focused by a 1 m paraboloid (b) onto a supersonic helium jet (c) to produce energetic electron beams.

Device to produce high-energy, optically driven electron beams



Self channeling of laser pulse to optimize plasma



Laser pulse is self-guided through the jet by the process of relativistic self-focusing ($P>>P_c$)

Focal spot diameter (FWHM) is 16 μm (w_0=13μm), the Rayleigh range is 650 μm and **stable propagation over 3-15 Rayleigh ranges** is possible.

Monoenergetic electron beams are produced in the resonant regime

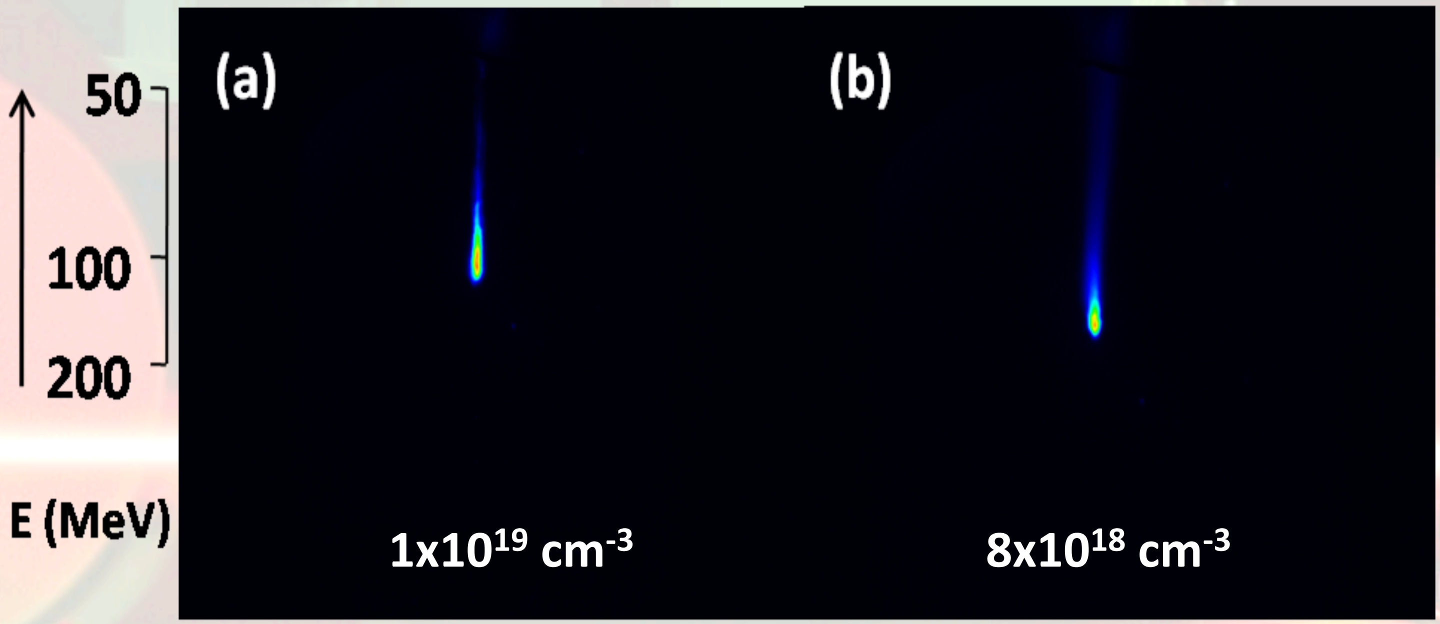
- Longer laser pulses (>100 fs) produced polychromatic electron beams with a quasi-maxwellian energy spread
- Quasi-monoenergetic beams can be produced in the resonant regime

$$c\tau_L \sim \frac{\lambda_p}{2}, \quad \lambda_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}$$

- Laser pulse duration is fixed: plasma density determines resonant condition
- Matched condition for stable propagation of the laser

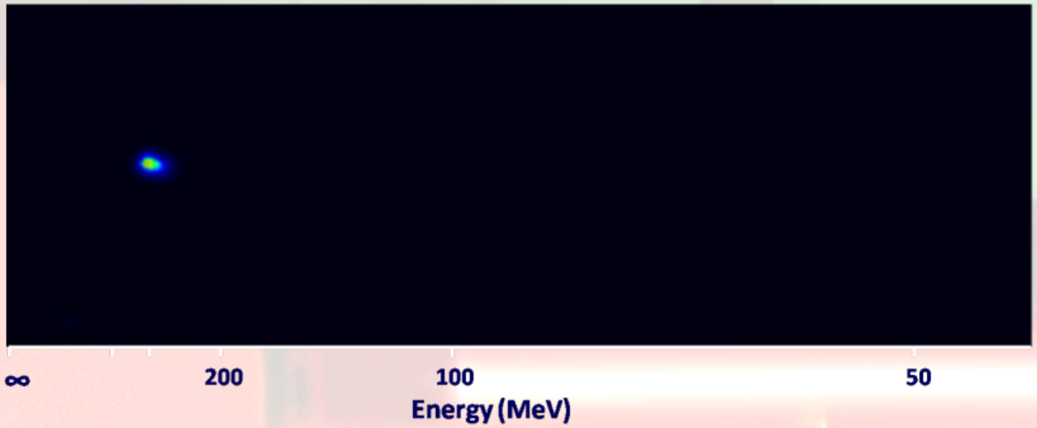
$$c\tau_L < R$$

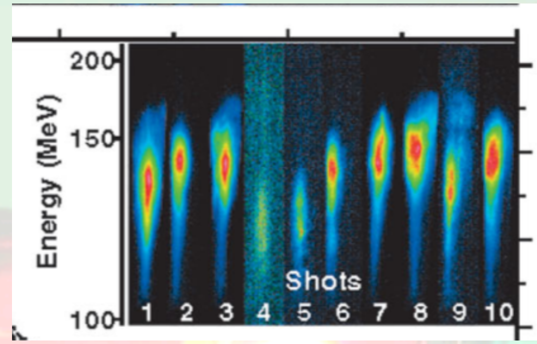
Monoenergetic beams are produced close to resonant density



Close to resonance density, monoenergetic beams are observed with a pronounced low-energy tail

300-400 MeV electron beams obtained via laser wakefield acceleration



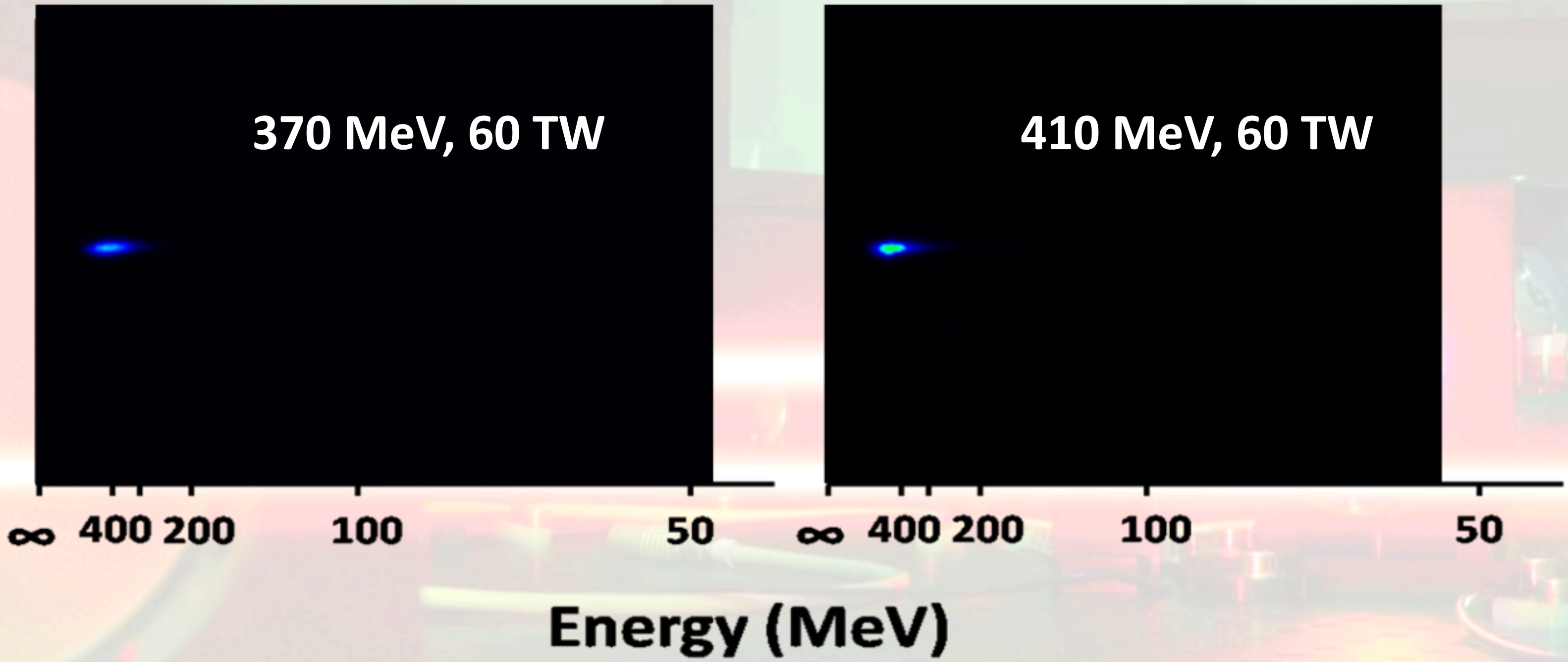


Osterhoff, PRL (2008)

Monoenergetic, low-divergence beam with 45 TW of laser power at a plasma density of **$7x10^{18}$ cm^{-3}**. The energy is peaked around 320 MeV with a spread of 10%. The angular divergence of the beam (vertical axis) is 6 mrad.

Dark current is lower by 3-orders of magnitude compared to main beam

Higher laser power and lower density produces higher energy electron beams



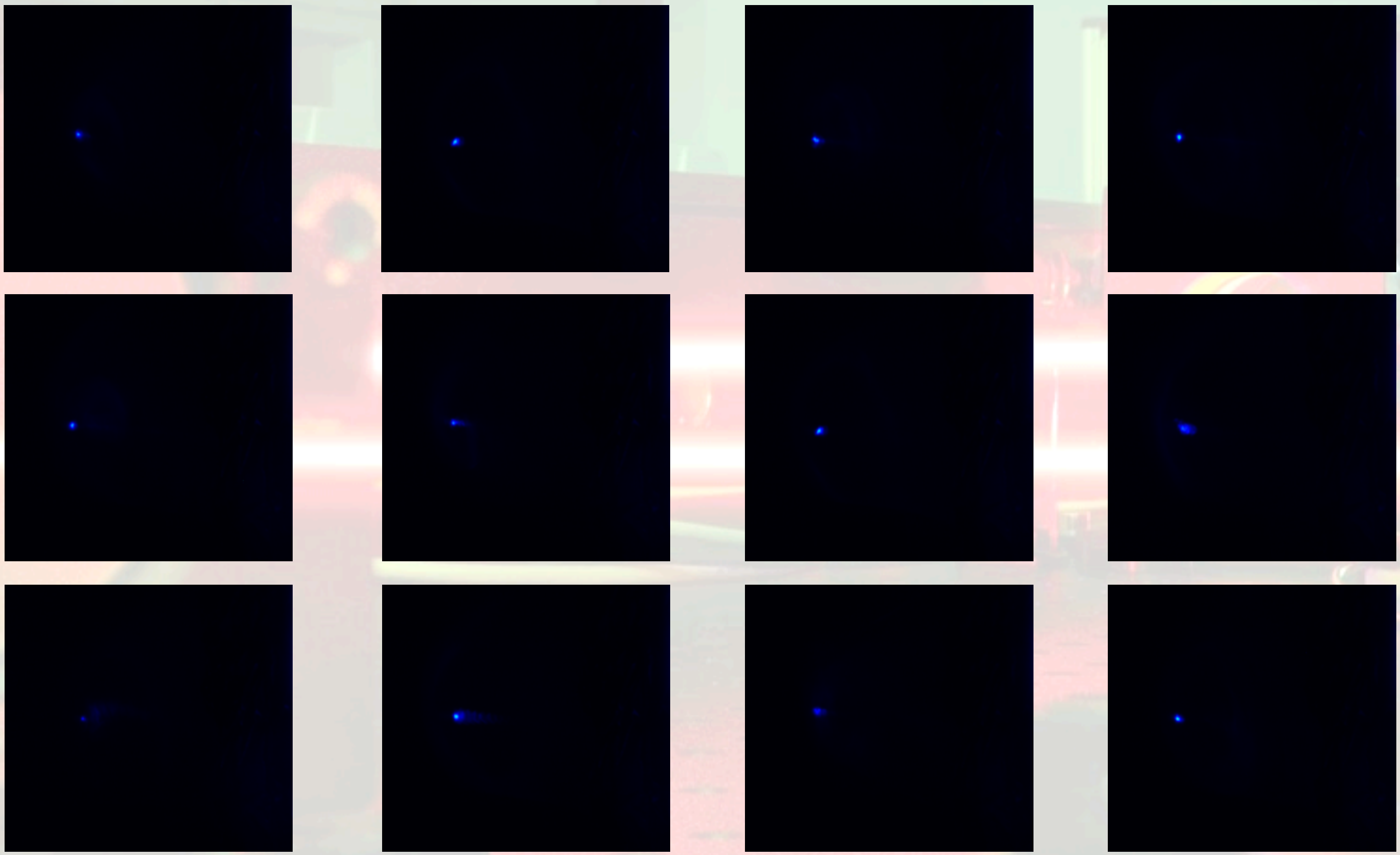
Electron beam energy: 50-400 MeV with 1-4 mm cylindrical nozzles
Energy spread: ~10%
Beam charge: 100-600 pC
Angular divergence: 2-5 mrad

Stability measurements of accelerator at 60 TW

Parameter	Angular position (mrad)	Divergence (mrad)	Energy (MeV)	Energy spread (MeV)
Mean	0	5.3	344	38.4
Standard deviation	1.1	1.7	35	4.8

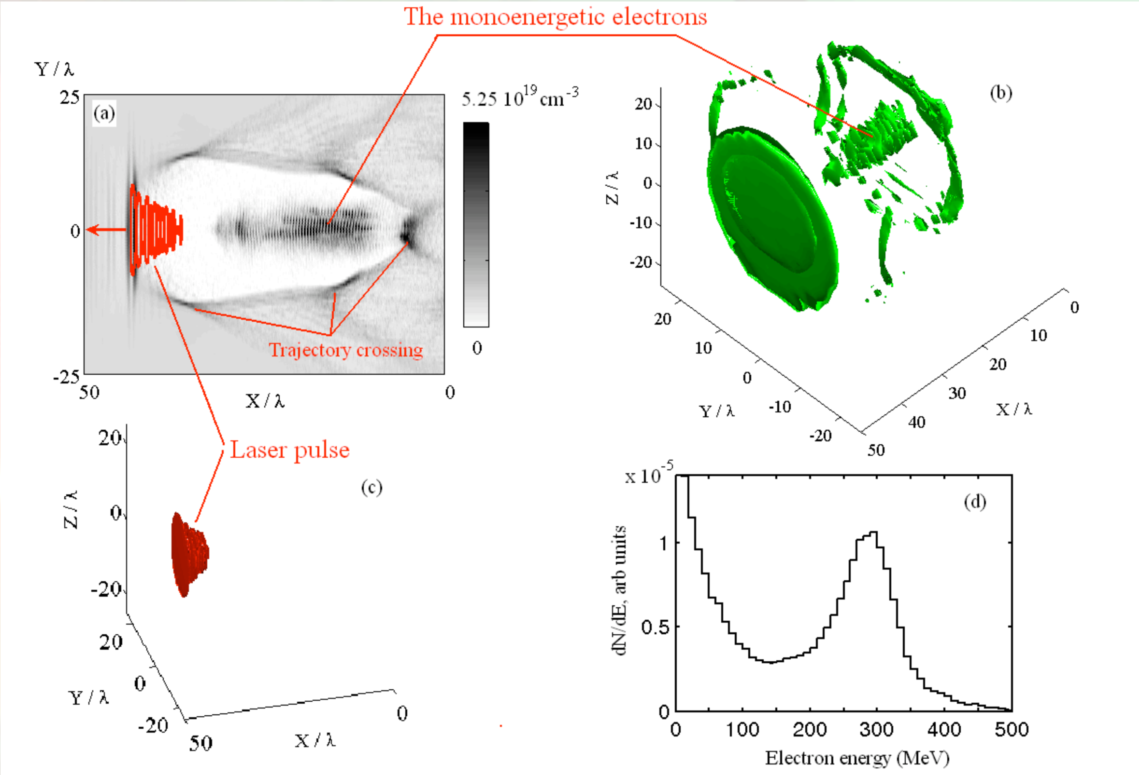
0 ±1.8 mrad **5.8 ± 2 mrad** **External injection – 117 MeV**
Faure et al. Nature (2007)

Electron beam produced by optical injection is extremely stable



250 ±10 MeV optically injected electron beam

PIC simulations qualitatively reproduce experimental observations



DIOCLES laser facility:
45 TW peak power
30 fs duration 13.5 μm focal spot size

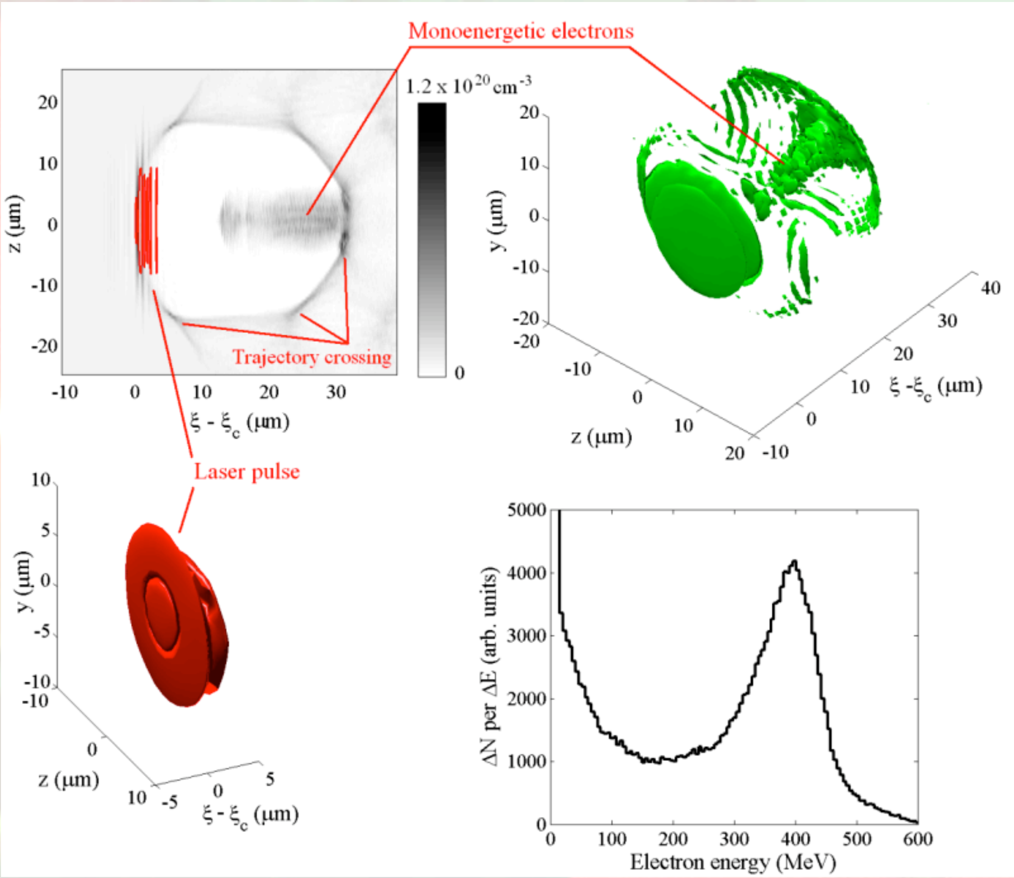
Simulation code: VLPL
Fully 3D, moving window, relativistic, parallelized (MPI)

Simulation facility:
Lonestar cluster (TACC-UT Austin) - 512 processors, runtime up to 48 hours

Radiation pressure of the laser pulse blows the electrons out of the region behind the laser pulse; thus a co-moving "bubble" of electron density is created

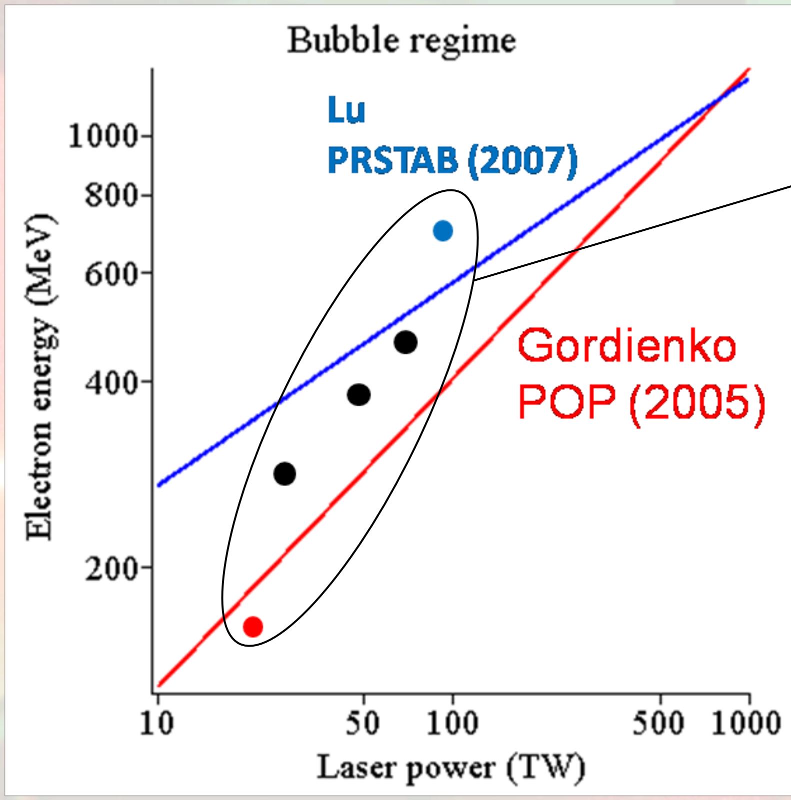
Electrons trapped in the "bubble" are accelerated over ~ 2 mm of He^{2+} plasma (electron density 7×10^{18} cm^{-3}) to 300±30 MeV

3D PIC simulations of the non-guided (gas-jet) LWFA experiments 70 TW



Electrons trapped in the "bubble" are accelerated over ~ 3 mm of He^{2+} plasma (electron density 6.5×10^{18} cm^{-3}) to 400±30 MeV

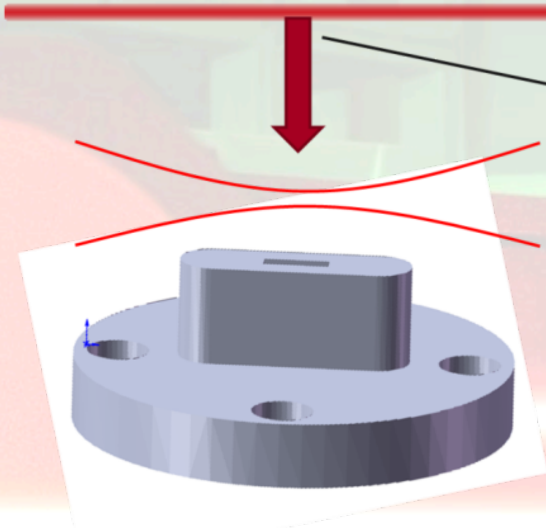
Scalability of accelerator

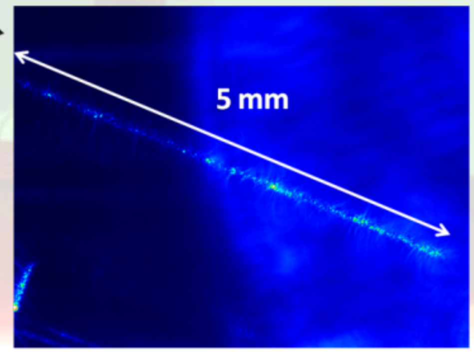


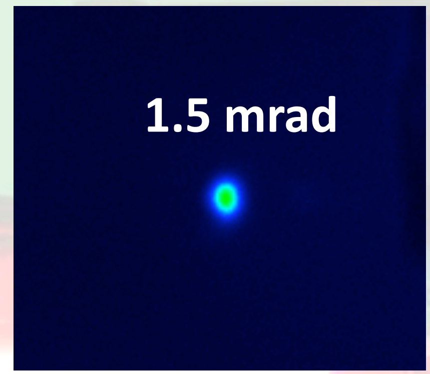
Experimental data (UNL)

Experimentally obtained energies are in approximate agreement with predicted scaling

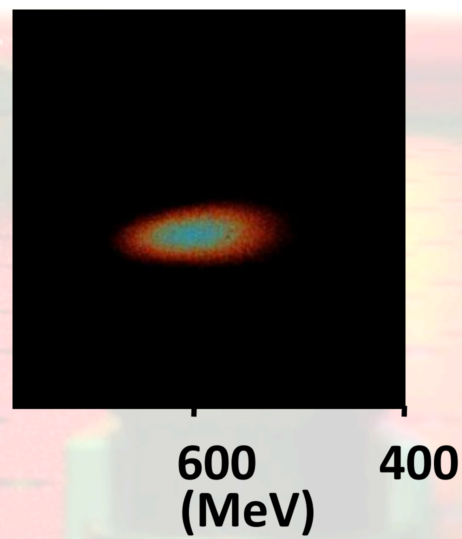
Slit nozzles for extended propagation lengths







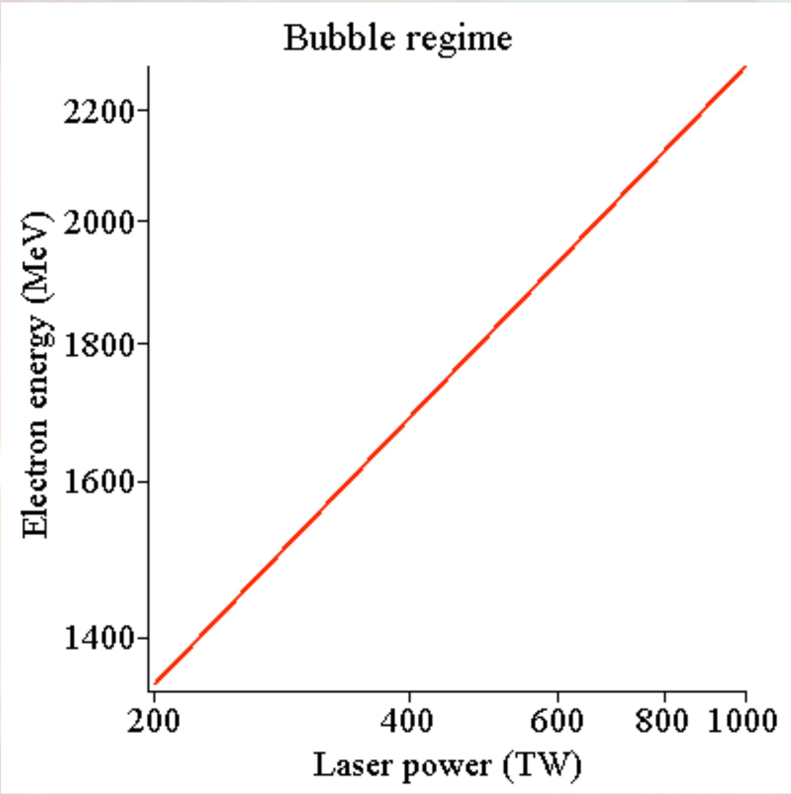
80 TW (616 MeV)



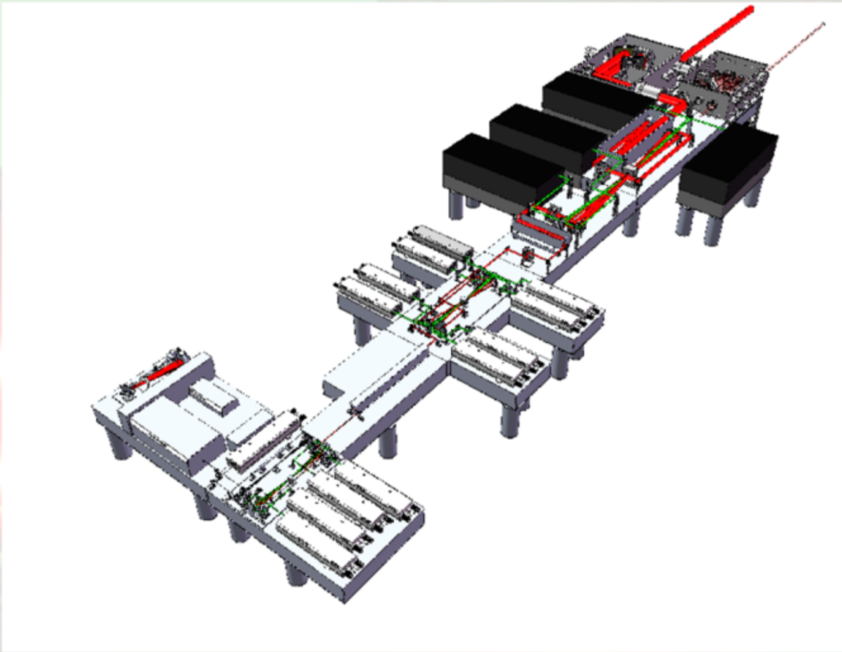
Long propagation lengths, higher laser power and lower plasma density produces near-GeV electron beams .

Relativistic self-focusing is sufficient to ensure propagation over a cm length plasma and self-trapping generates monoenergetic electron beams.

GeV beams with PW laser pulses



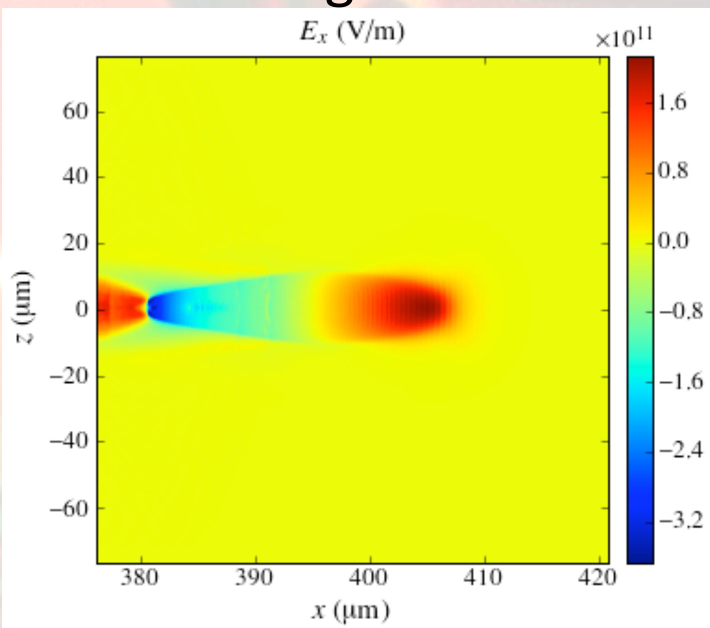
Multi-GeV beams can be obtained with PW powers using low-density plasma.

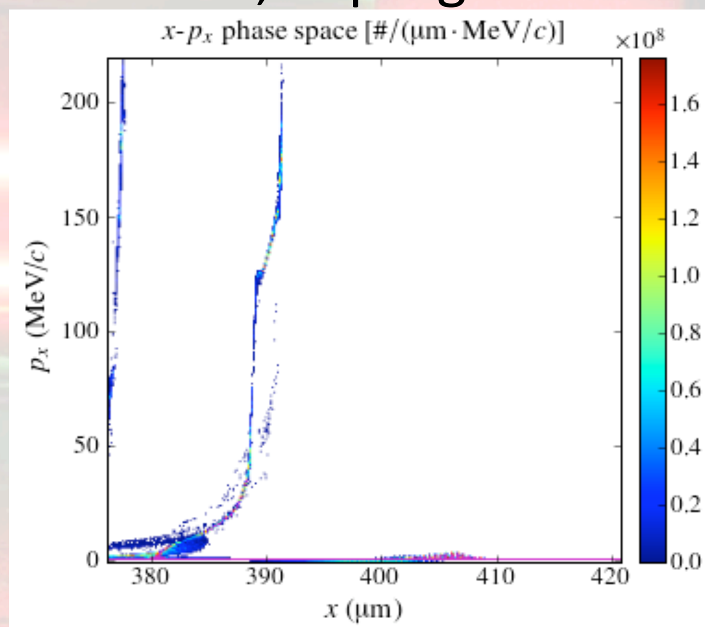


Laser system is being upgraded to 1 PW level this year.

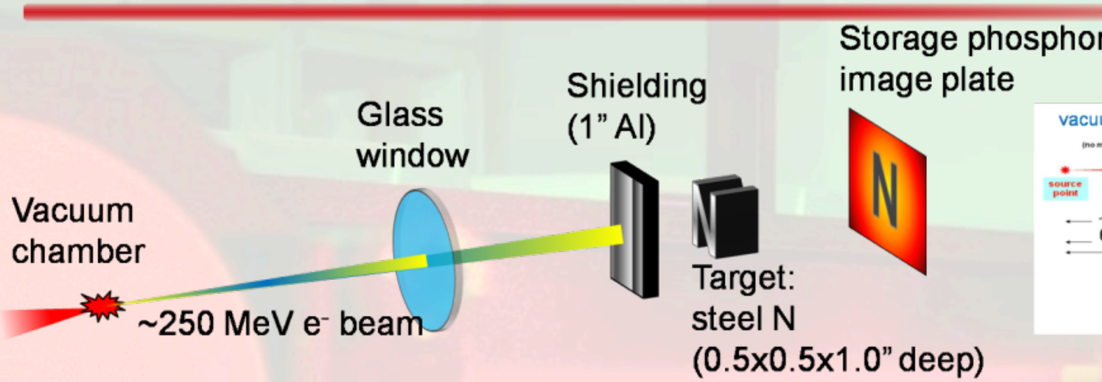
3D VORPAL simulations of UNL gas jet LWFA experiments underway

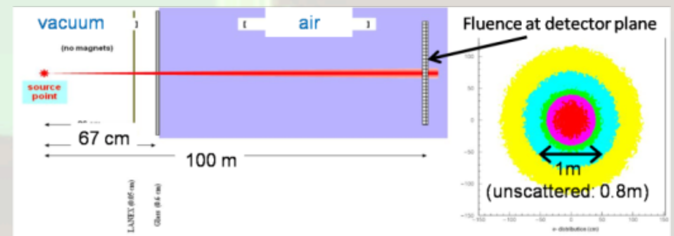
- Long term goal: Simulation results will guide experimental parameters
- Near term goal: Validation of simulation, in progress





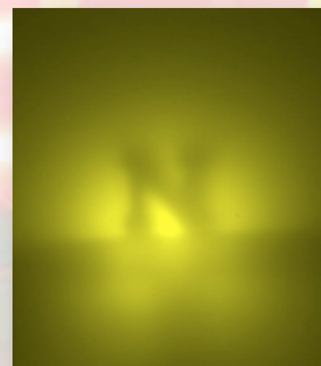
Standoff electron beam radiography





Clear "N" image (~1 m)

- Single shot
- 1" aluminum shielding
- mm-scale resolution



Steel "N"

- >4m source standoff
- no shielding

Summary and conclusions

1. >500 MeV, monoenergetic electron beams generated using ~100 TW, 30 fs laser pulses.
2. Self guiding of laser pulse and self-trapping is sufficient for low-divergence, high-brightness electron beams.
3. Stable operation is demonstrated by operating in the matched regime.
4. Accelerator is scalable to multi-GeV energies using PW lasers.
5. Preliminary studies indicate that the electron beam can be used for long-standoff interrogation.

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