From table-top laser plasma accelerator to future free electron laser

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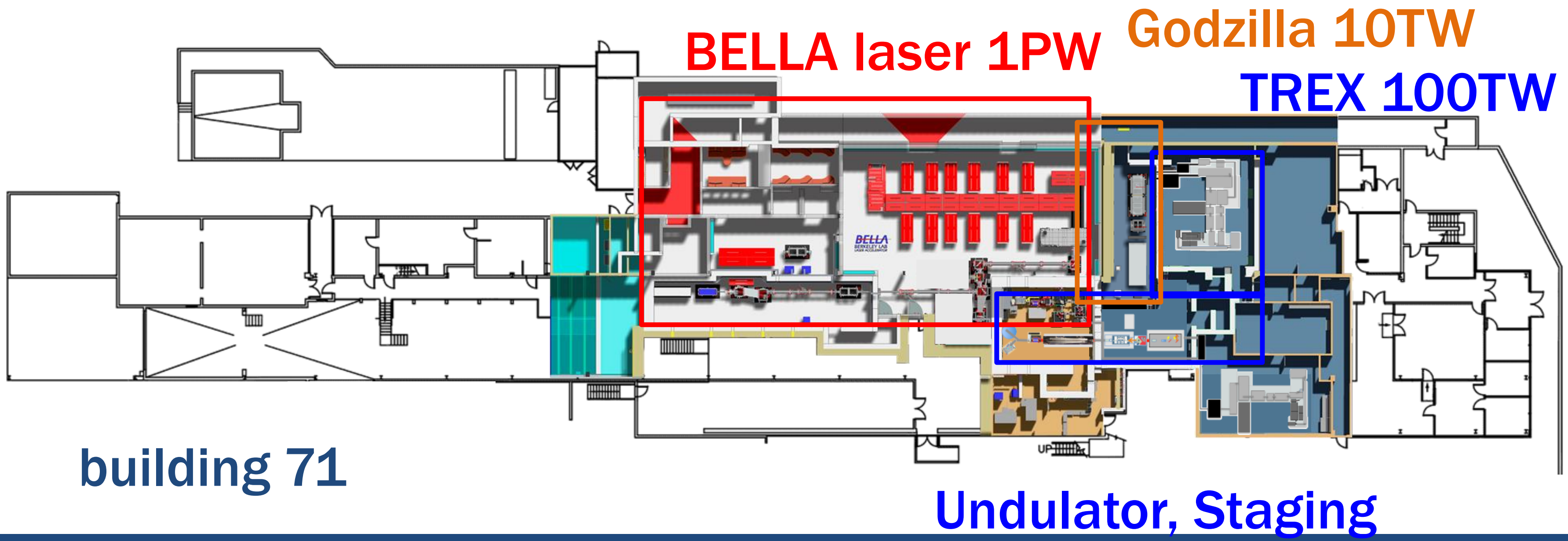
Outline

- LPAs
- Plasma targets
- BELLA 4.2 GeV
- FEL application
  - Active plasma e-beam lens
  - Staged LPA acceleration
  - Realization of new FEL line

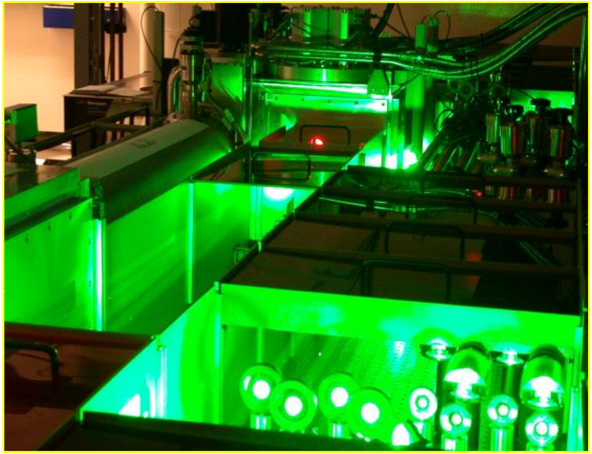
BELLA Center (*bella.lbl.gov*)
ATAP Accelerator Technology & Applied Physics

S. Barber, *F. Isono*, A. J. Gonsalves, K. Nakamura, J. Daniels, H.-S. Mao, C. Benedetti, D. E. Mittelberger, E. Esarey, *C. B. Schroeder*, Cs. Tóth, C. G. R. Geddes, H.-E. Tsai, K. Swanson, S. Steinke, R. Lehe, H. Vincenti, B. Djordjevic, P. Lee, *J. van Tilborg*, S. S. Bulanov, J. L. Vay, C. Pieronek, and ***W. P. Leemans***

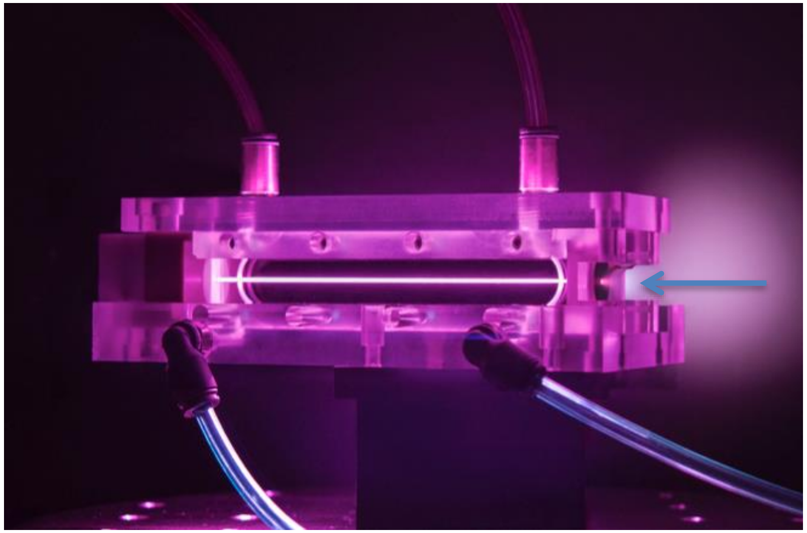


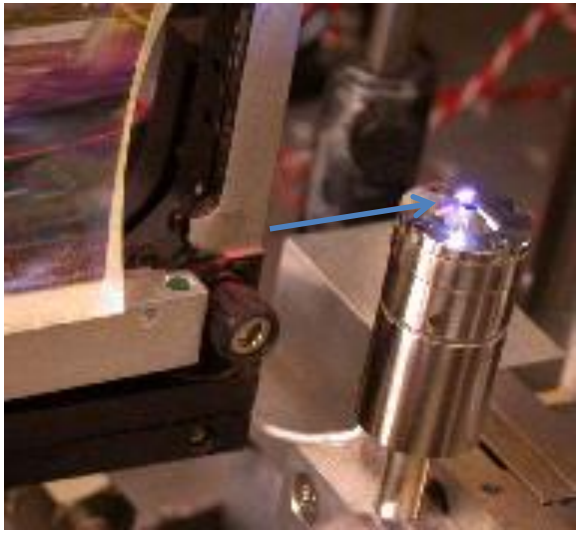
Laser Plasma Accelerator: laser pulses on a gas target

TREX laser system
10 Hz
3.7 J (2 J on target)
35 fs, 60 TW
Parabola F=2m (F# 40)
w_0=19 µm
I=1×10^{19} W/cm^2



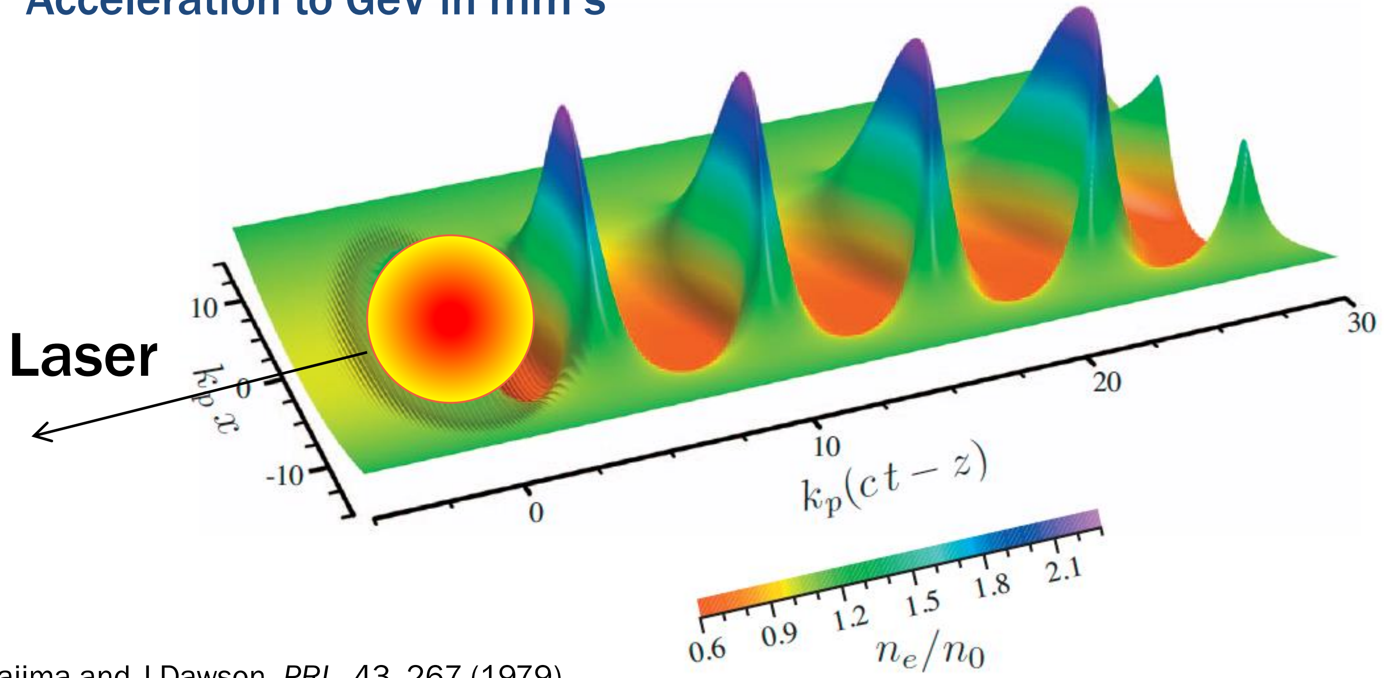
Gas Targets
Gas jet, gas cell,
discharged guiding channel
1mm to 10cm in length
density ~10^{16}-10^{18} cm^{-3}





Laser plasma accelerators (LPAs) are compact and produce femtosecond relativistic e-beams

- Laser foot ionizes gas
- Ponderomotive force keeps pushing electrons away → charge separation
- Ions pull back electrons (time scale $t_p=\lambda_p/c \sim 10\text{-}100$ fs)
- Ultra-high axial electric fields co-propagate with laser at c
- Electrons externally injected, or trapped from background plasma
- Acceleration to GeV in mm's

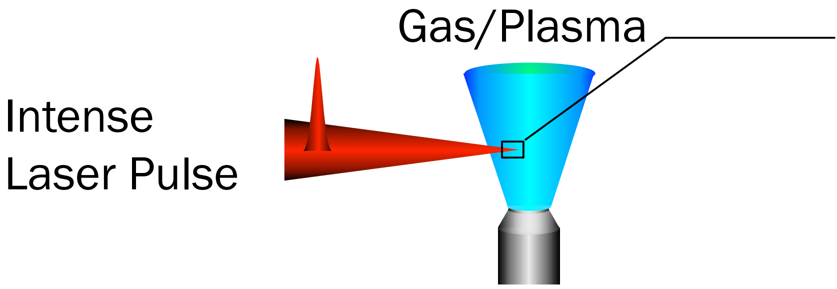


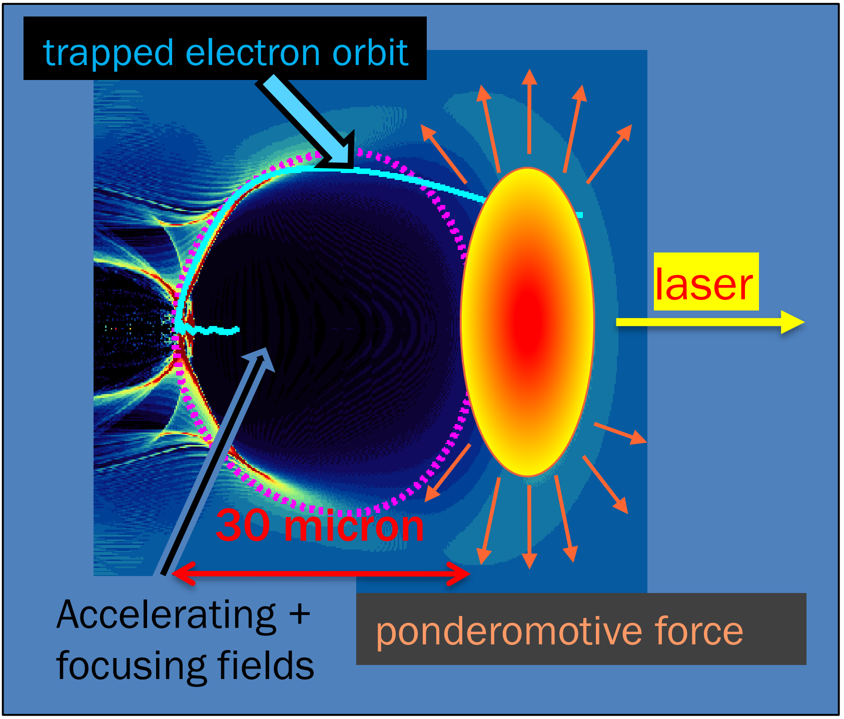
T. Tajima and J.Dawson, *PRL*, 43, 267 (1979)
Esarey et al., RMP 81, 1229 (2009)

B.A. Shadwick et al., IEEE PS. 2002

Laser plasma accelerators (LPAs): Wealth of physics and complexities

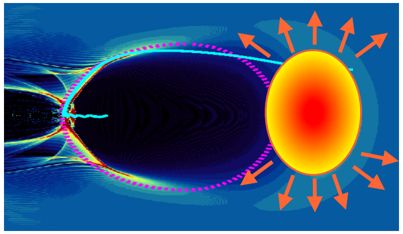
- Setting up the plasma
  - Foot laser pulse
  - Pre-ionization with 2nd laser (guiding channel)
  - Pre-ionization with electric discharge pulse
- Laser drives strong co-propagating plasma wave (with an accelerating region)
  - Transverse laser evolution (diffraction $z_R=\pi w^2/\lambda$, self-focusing, guiding channel)
  - Longitudinal laser evolution (pulse steepening, self-modulation)
- Electron injection
  - External injection
  - Transverse wavebreaking
  - Ionization-induced at peak of laser pulse
  - Down-ramp induced
  - Colliding pulse
- Acceleration of injected electrons (10-100 GeV/m)



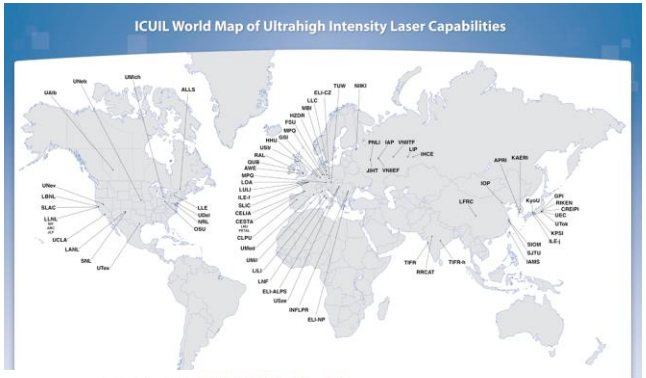


Why the global interest?

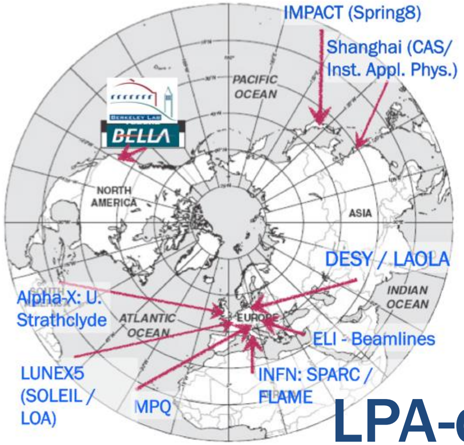
Conventional structure:
~ 30 MV/m



LPA:
~ 30,000 MV/m



High-power lasers



LPA-driven FELs

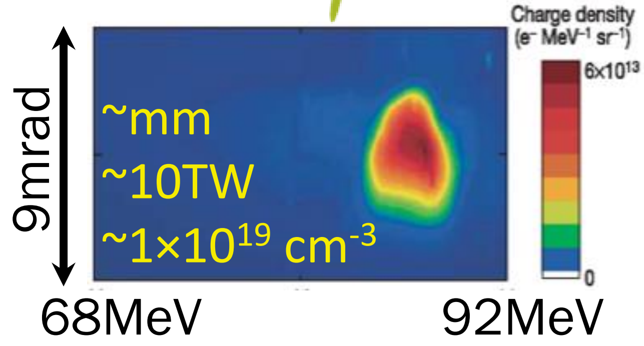
PROS

- Compact (plasma ~cm, laser ~single room, cave ~ single room) vs. 100-1000m. Think $$$$$
- High charge (10-100 pC), short (few fs) e-beams
- Emittance is excellent
- Laser-synchronized
- Modular system (easy to re-configure)

CHALLENGES

- Shot-to-shot fluctuations
- Rep rates 1-10 Hz (kHz studies ongoing)
- Multi-% energy spread. Matters for some applications (solutions!)
- >1 mrad divergence. Matters for some applications (solutions!)

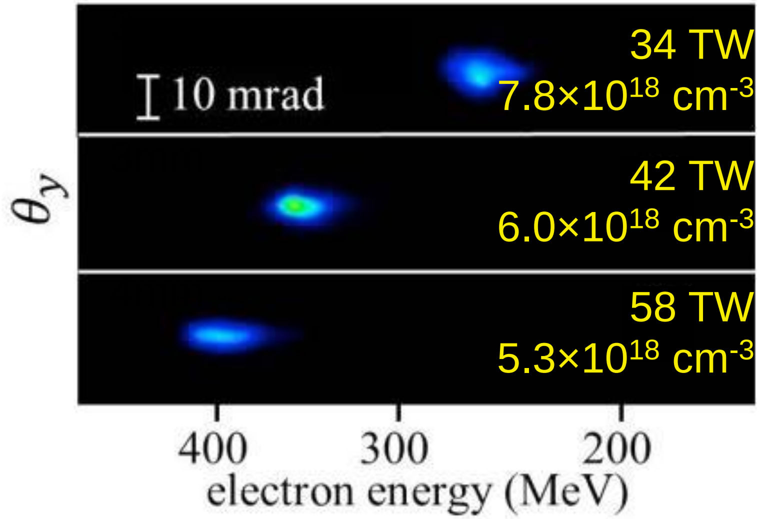
Recent milestone results from global LPA community



~mm

~10TW

~1×10^{19} cm^{-3}



34 TW
7.8×10^{18} cm^{-3}

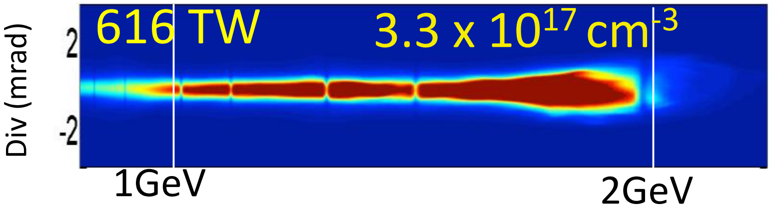
42 TW
6.0×10^{18} cm^{-3}

58 TW
5.3×10^{18} cm^{-3}

~cm

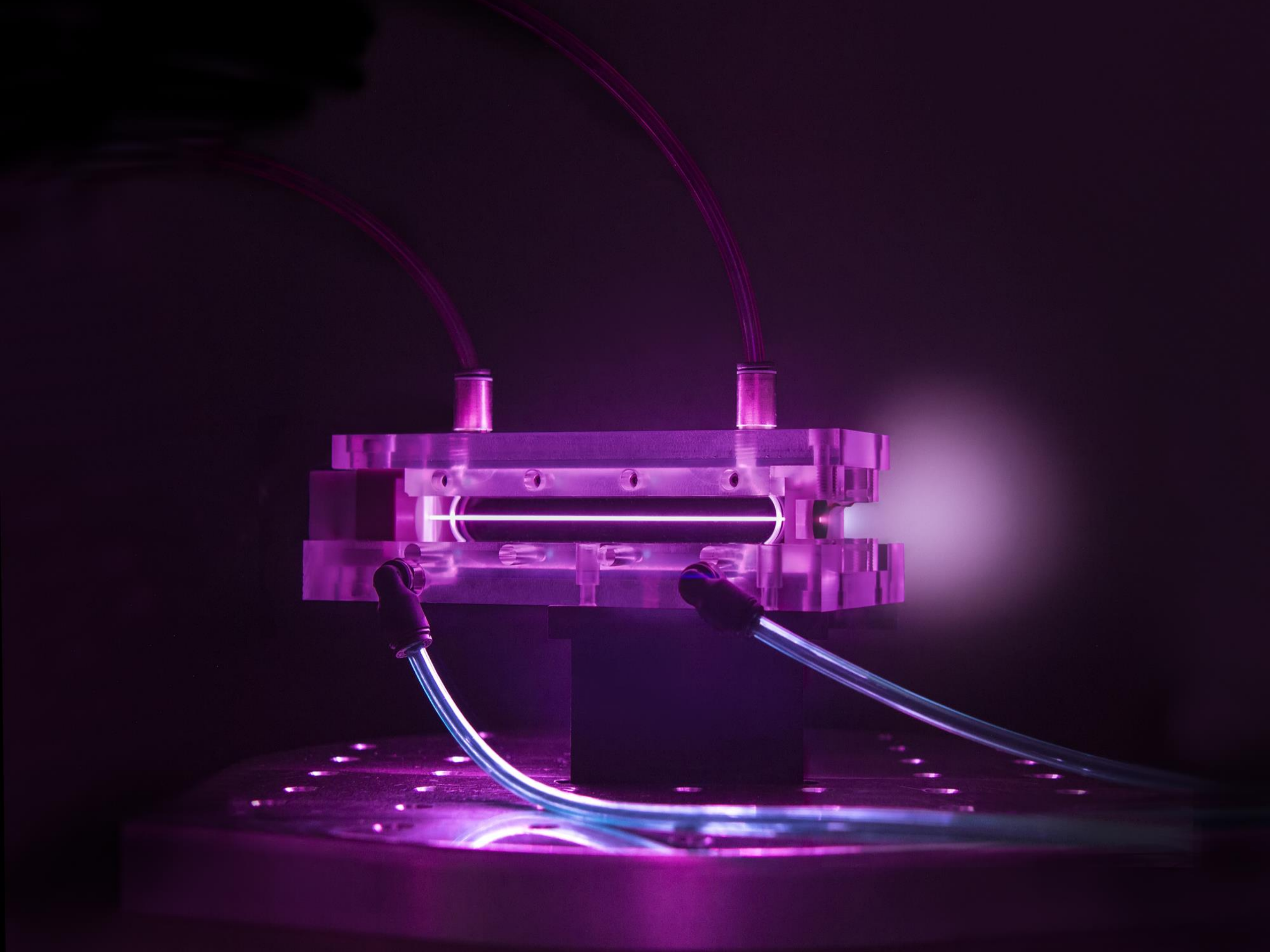
~40TW

~5×10^{18} cm^{-3}

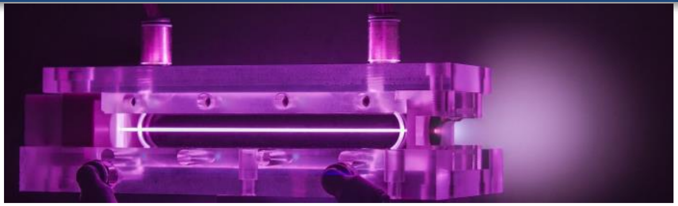


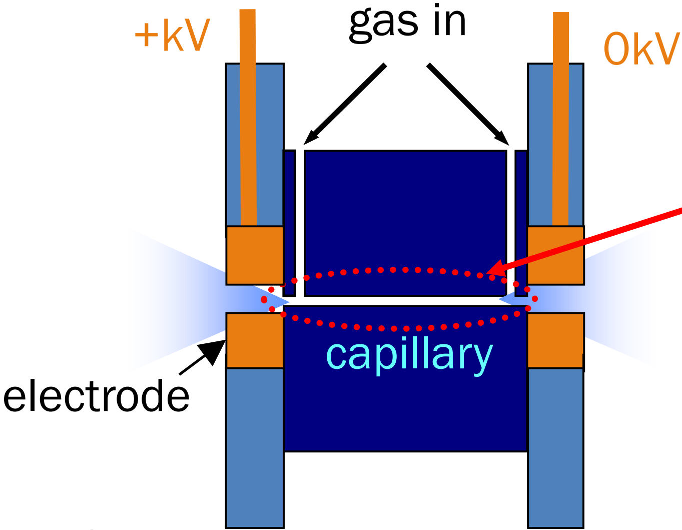
616 TW 3.3 x 10^{17} cm^{-3}

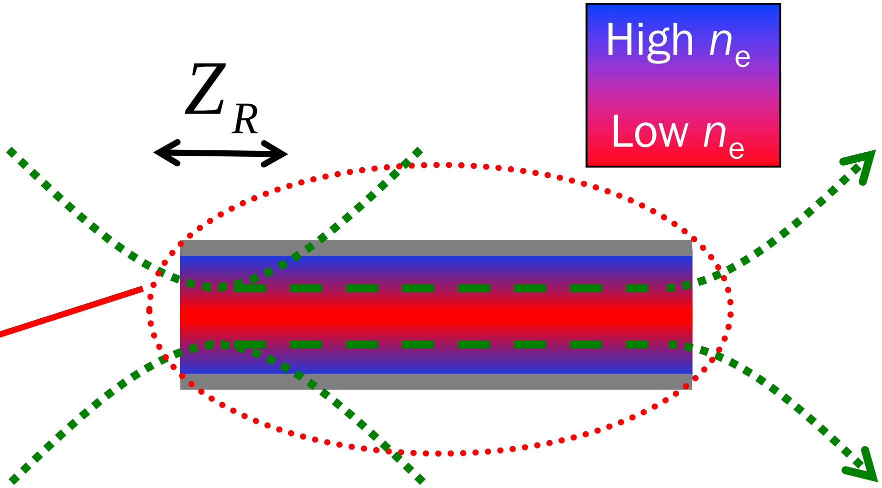
C. G. R. Geddes,et al, Nature,**431**, p538 (2004); S. Mangles et al., Nature **431**, p535 (2004); J. Faure et al., Nature **431**, p541 (2004); Leemans et al., Nature Phys. **2**, 696–699 (2006); Banerjee et al., Phys. Plasmas **19**, 056703 (2012); X. Wang et al., Nature (2012).



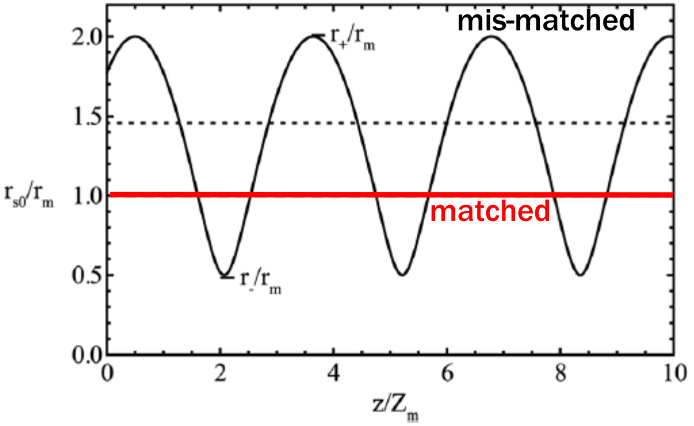
Capillary discharge plasma target mitigates diffraction to increase interaction length & energy gain







$$n(r) \approx n_0 + br^2$$



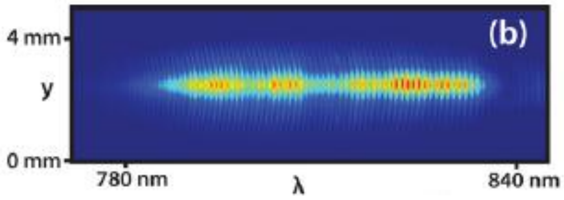
- Gas injected near each end of channel
- $n_e \sim 10^{17}$ - 10^{19} cm^{-3}
- Gas ionized and heated by discharge
- Guiding channel formed by heat conduction to capillary wall

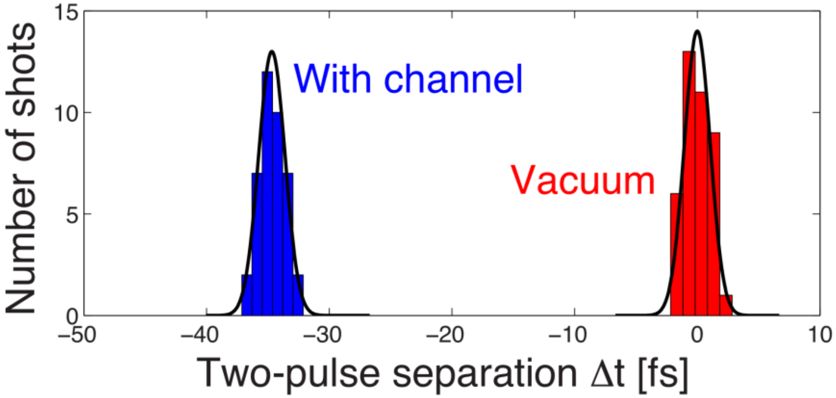
D. J. Spence & S. M. Hooker Phys. Rev. E 63 (2001); A. J. Gonsalves Phys. Rev. Lett. 98 (2007)

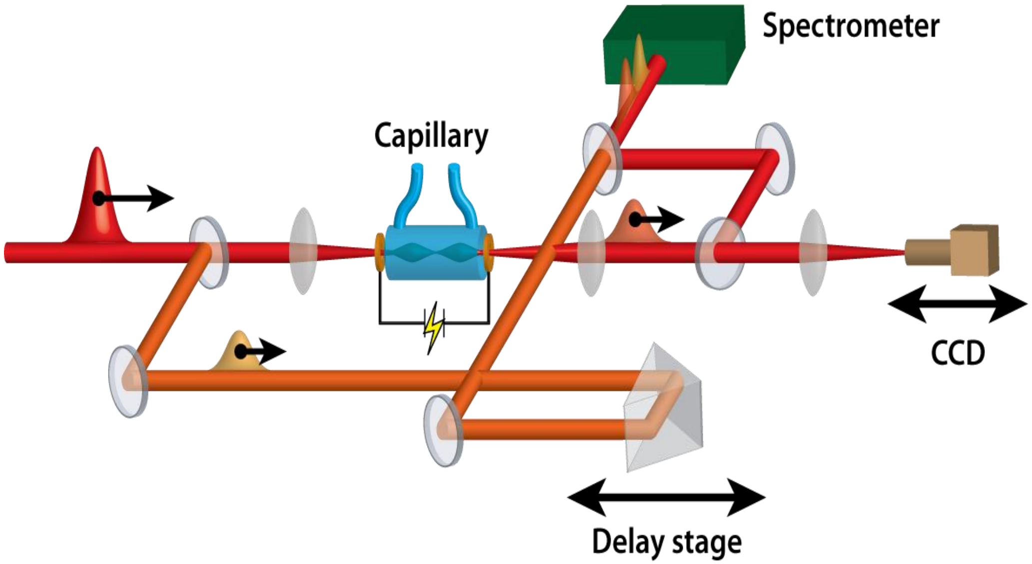
Plasma density inferred from laser group velocity

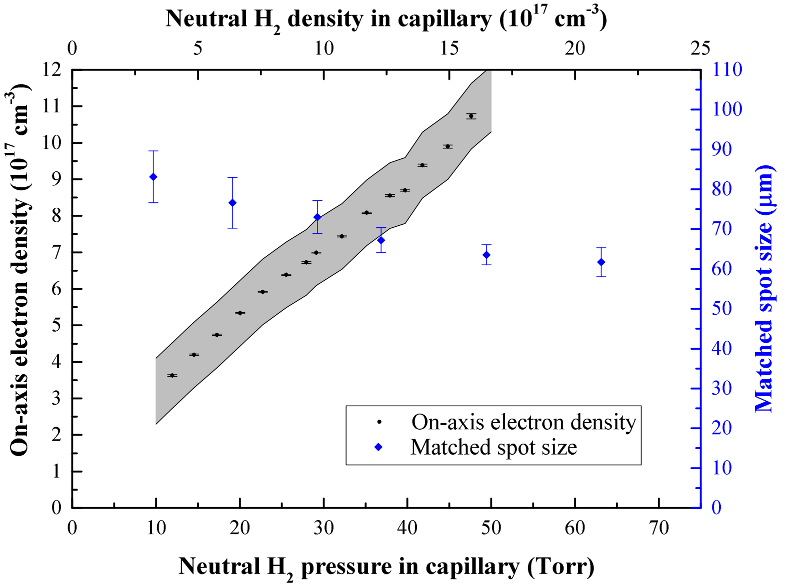
$$n(r) \approx n_0 + br^2$$

$$\frac{v_g}{c} \approx 1 - \frac{k_p^2}{2k_0^2} \qquad with \qquad k_p^2 \sim n_0$$



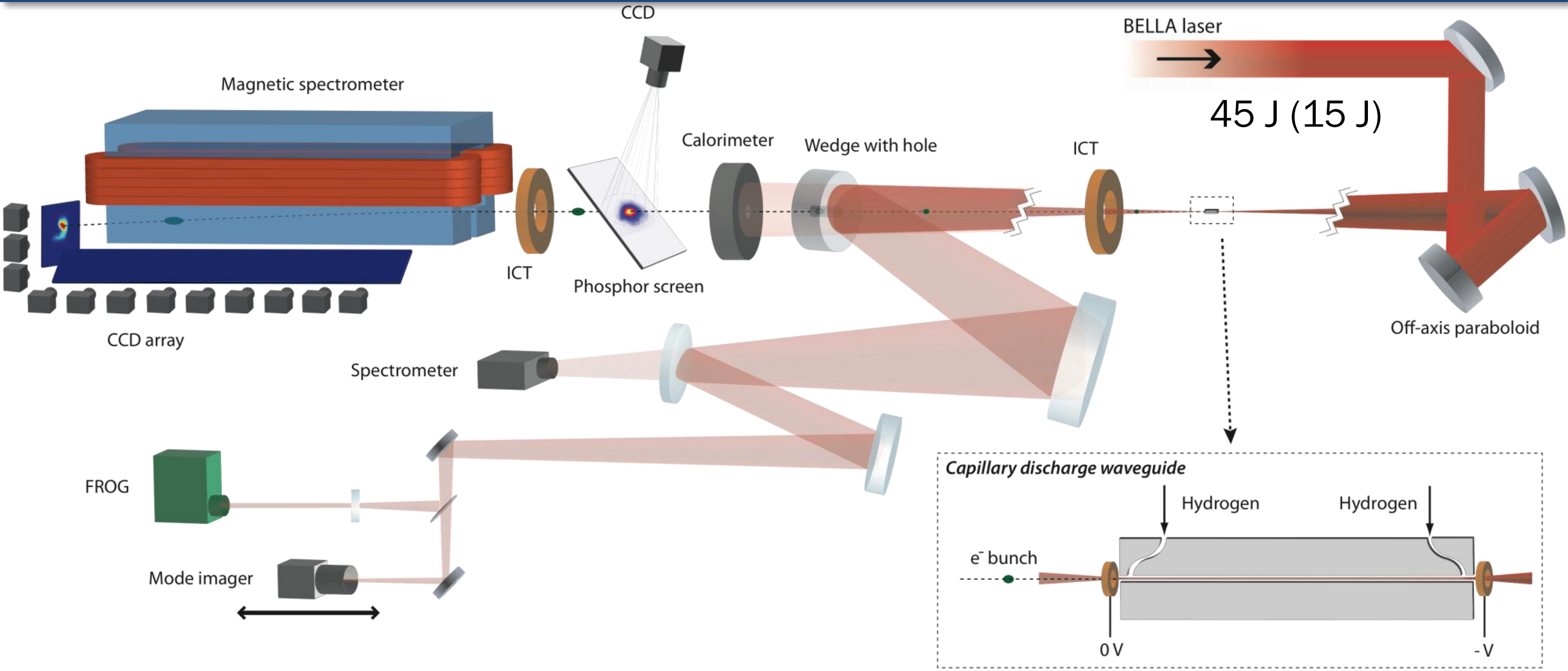






Theory: C. Schroeder *et al.*, Phys. Plasmas 18 (2011)
Experiment: J. van Tilborg *et al.* Phys. Rev. E 89 (2014), J. Daniels *et al.* Phys. Plasmas 22 (2015), Gonsalves et al., Phys Plasmas 17 (2010)

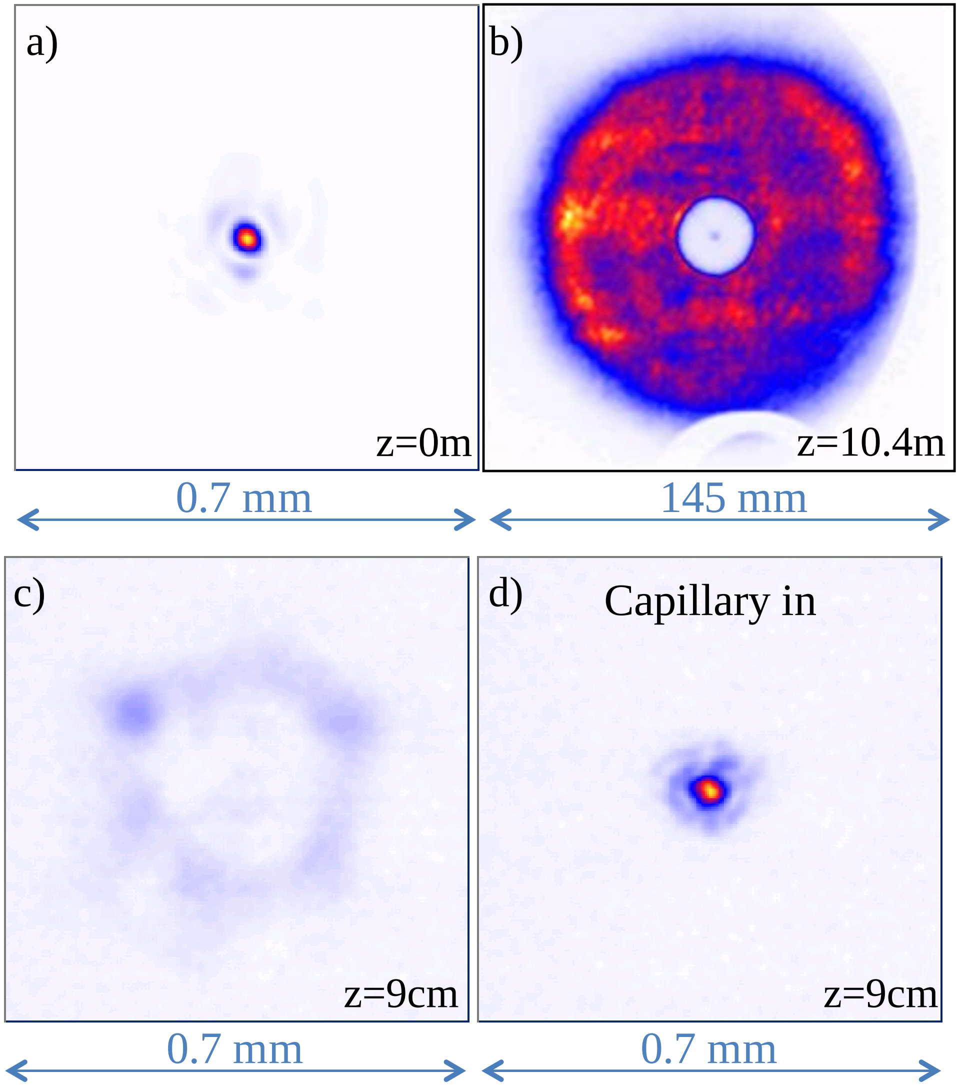
Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets



Mode properties in near field are important in understanding the propagation through the capillary structure

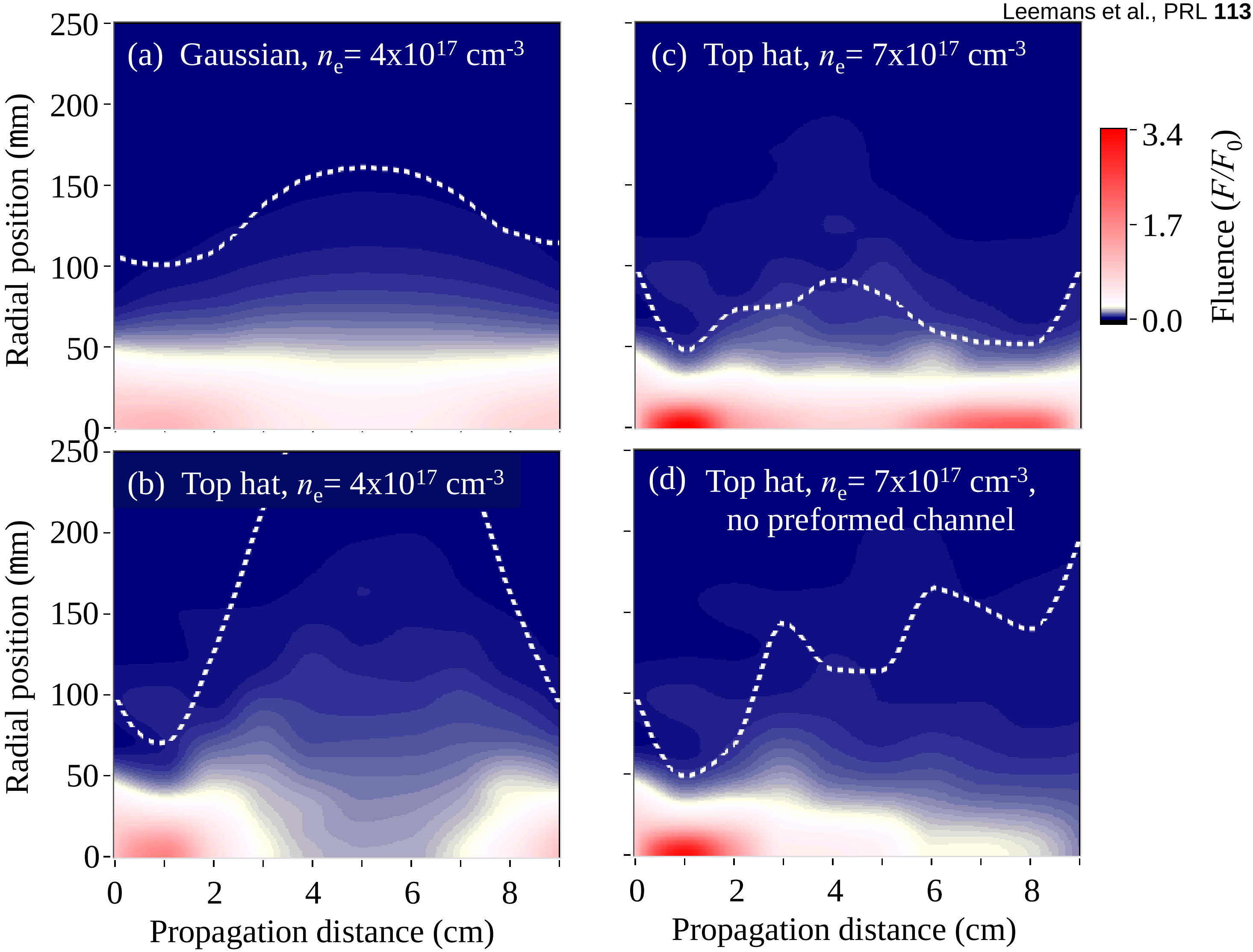
Vacuum mode at focus and 10.4 m away from focus

Mode at 9 cm from focus with and without capillary



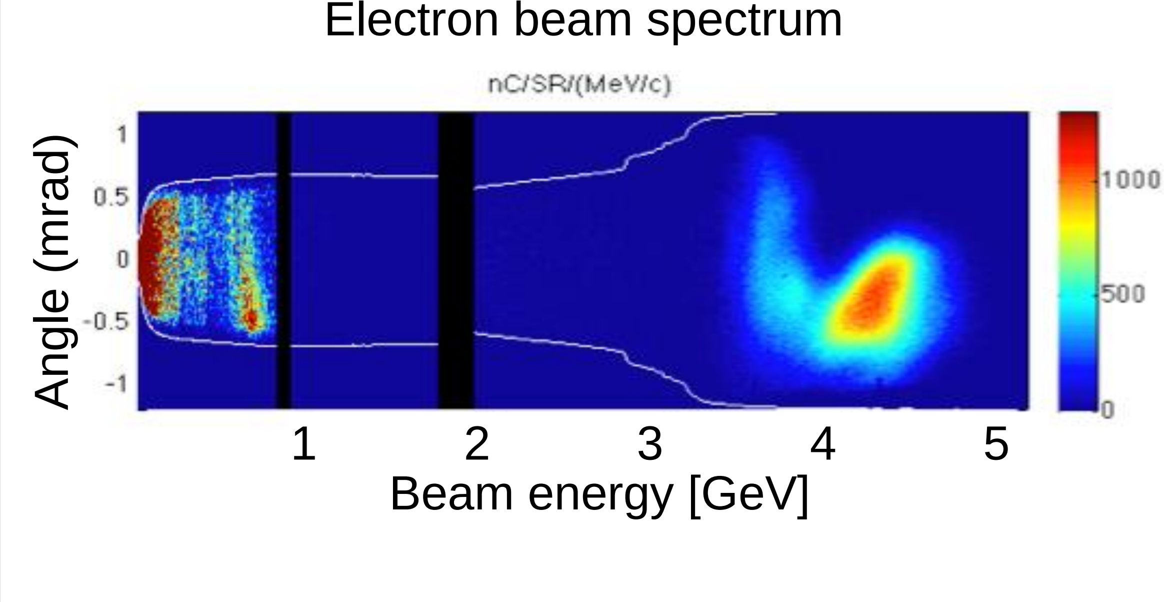
Simulation shows top hat beam gives increased fluence at capillary wall compared to Gaussian , higher density compensates

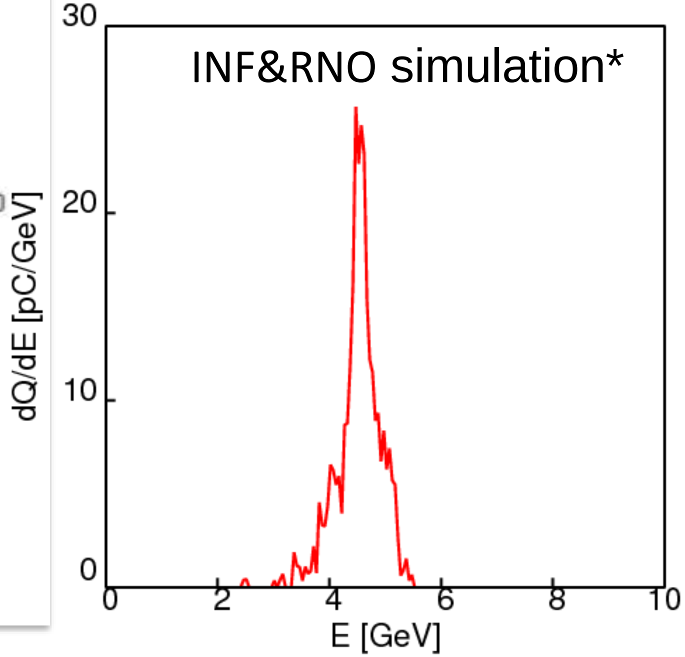
Leemans et al., PRL **113,** 245002 (2014).



4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J)

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012





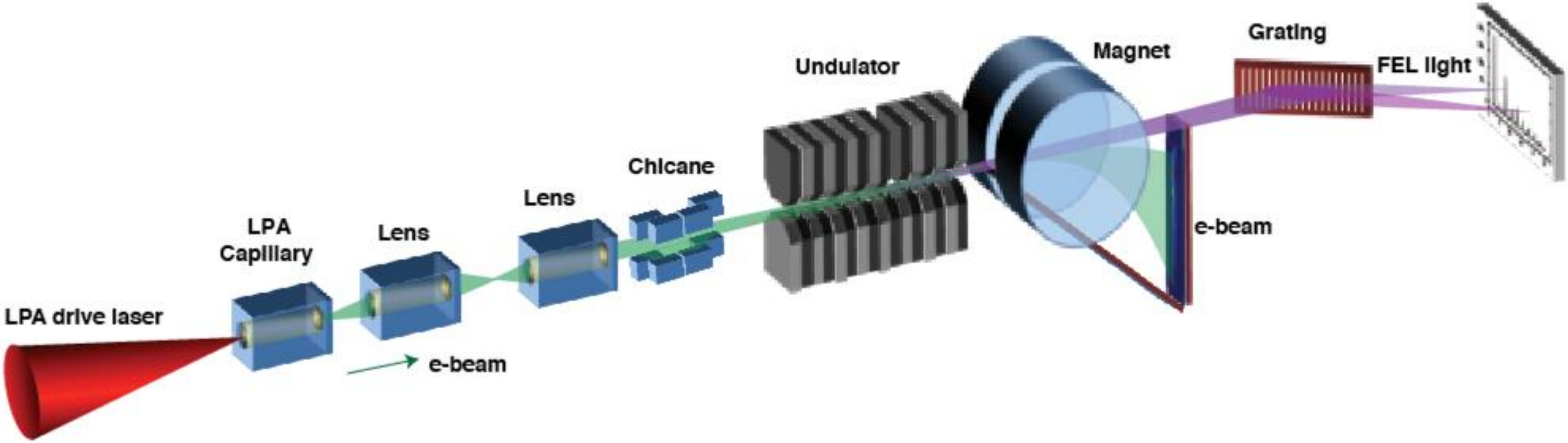
- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 µm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~$6x10^{17}$ cm^{-3})

Gonsalves et al., Phys. Plasmas **22**, 056703 (2015);
Leemans et al., PRL **113,** 245002 (2014).

	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

LPA drives compact undulator light source

For example, $K_0 = 1.5$, λ_u=2 cm, and $\gamma = 1000$ ($\simeq$ 500 MeV), yields $\lambda_r = 21$ nm (60 eV)



$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_0^2}{2} + \gamma^2\theta^2\right)$$

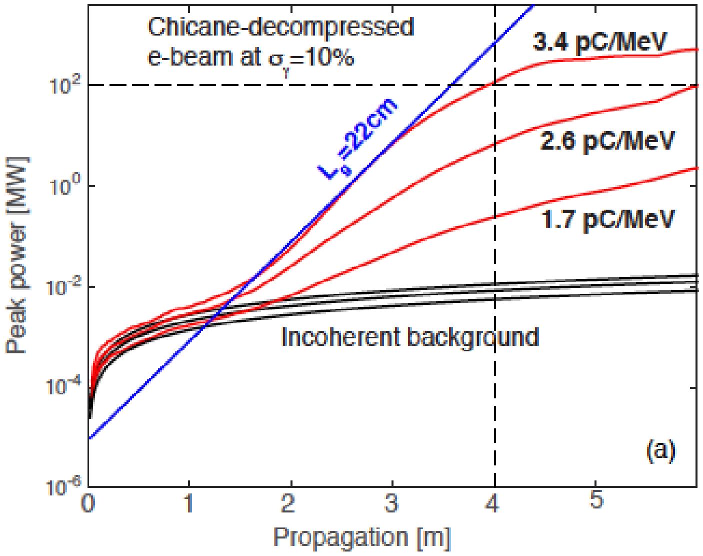
parameters

- λ_u =magnet spacing (undulator period ~1-2 cm)
- γ =Lorentz factor electrons (300 MeV → γ~600)
- K_0 =magnet strength parameter (K_0~1)
- θ =angle of observation (θ<<1)

Number of photons
~ number electrons
~ number periods

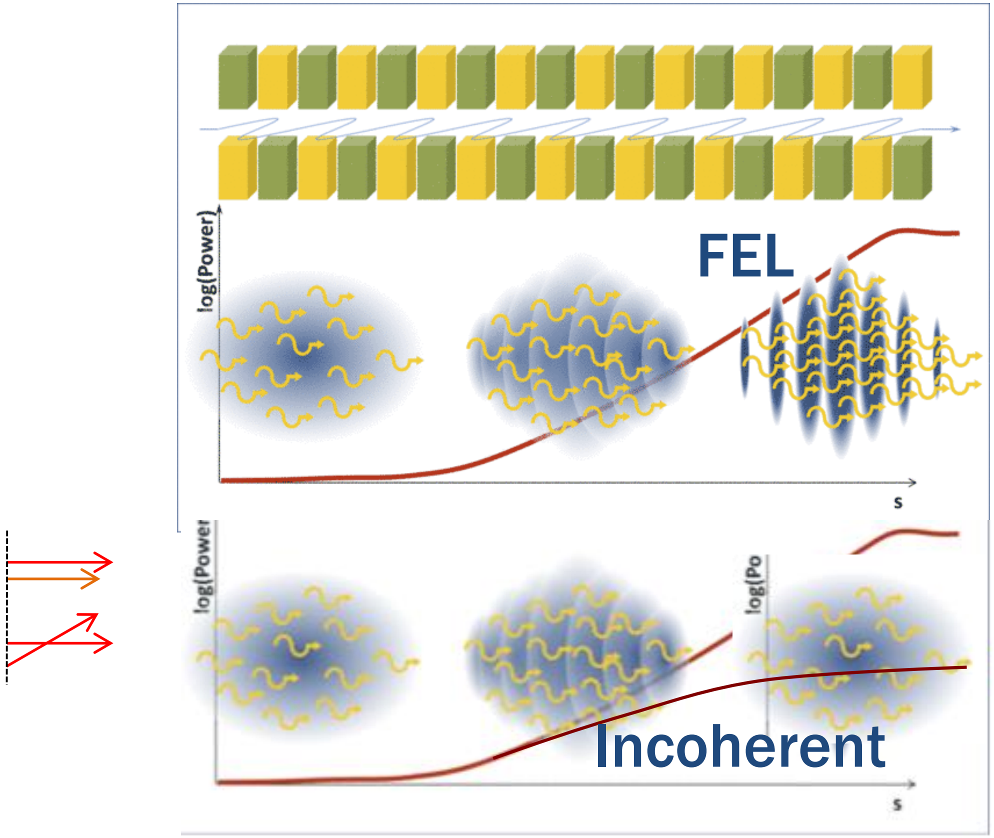
fs source of X-rays
(10^7 photons/shot)

High quality e-beam → coherent Free Electron Lasing

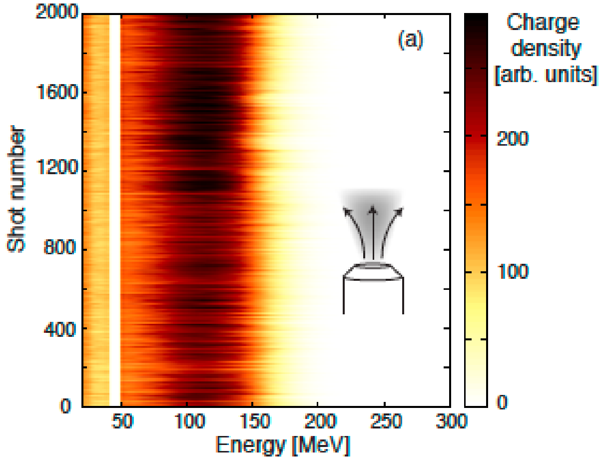


Critical to FEL

- Charge
- Energy spread Δγ (<<1%)
- Emittance ε_n (<<1 μm-mrad)
- Transport: rapid e-beam capture

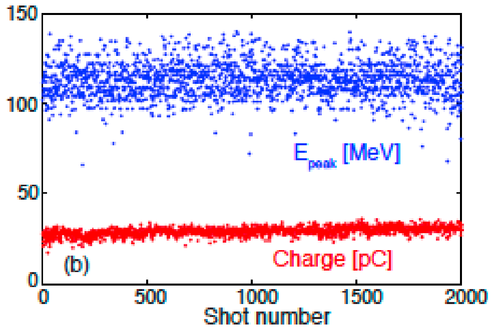


TREX laser system: LPA development (stable damage-free LPA & high charge density LPA)



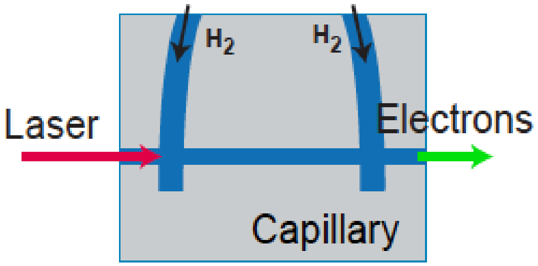
Jet-based LPA: stable, damage-free

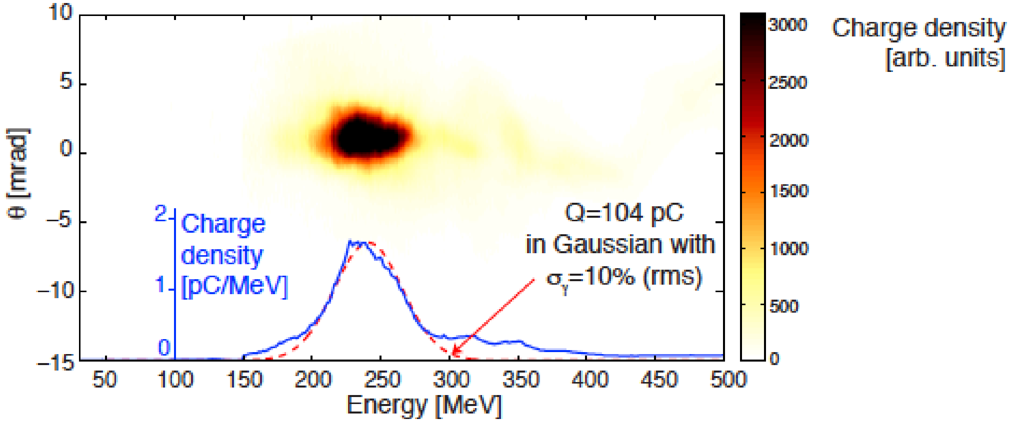
Transport, Diagnostics, UV undulator radiation



Capillary LPA: high energy, high pC/MeV

Soft X-ray FEL

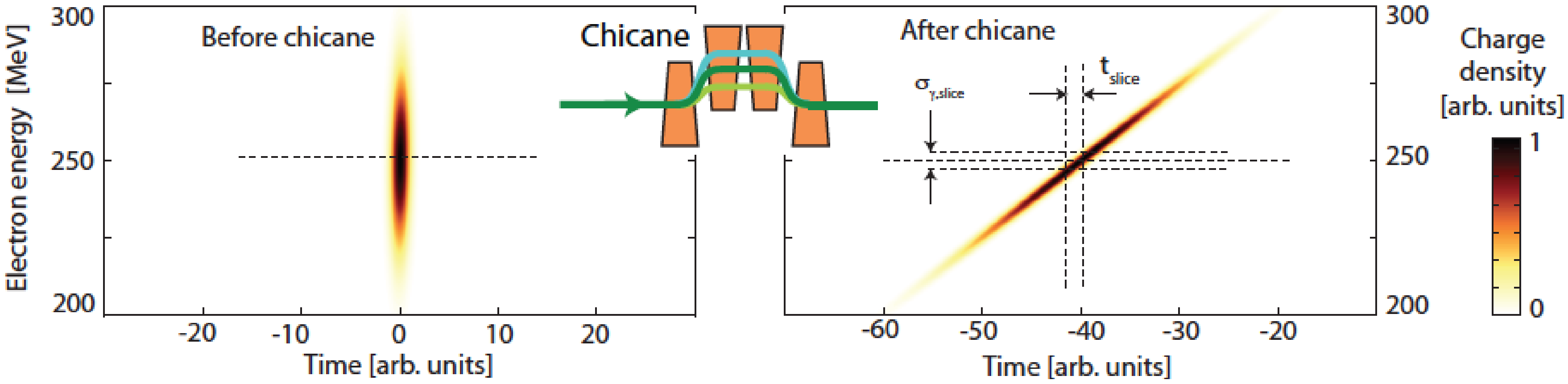




LPA electron beam subject to stringent requirements

Key requirements

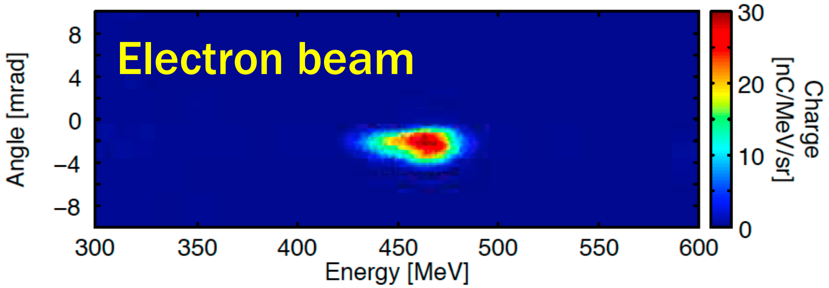
- Sub-% ΔE/E required for lasing slice
- Disperse/stretch electron beam
- Charge 2-3 pC/MeV



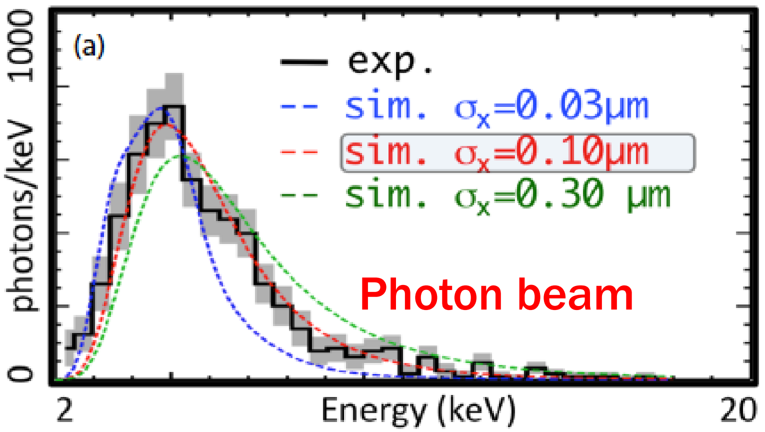
Emittance measurements highlight sub-micron source size

Emittance = Size x Divergence (sub-μm x few mrad)

- Betatron X-ray spectrum ~ size
- Source size ~ 0.1 - 0.5 micron



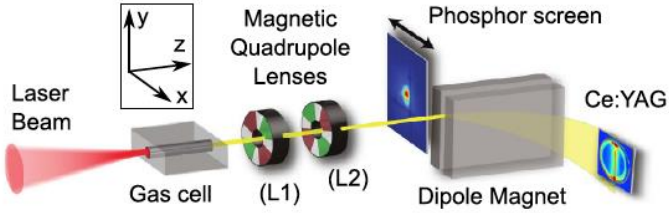
Photon counting X-ray spectrum

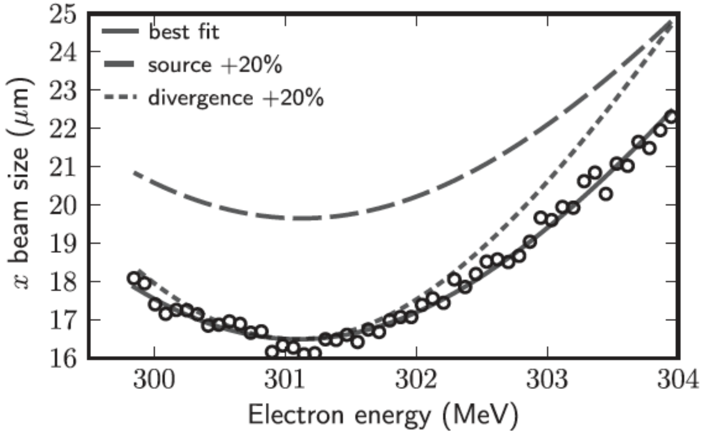


Plateau *et al.* PRL (2012)

Measure e-beam size at image plane

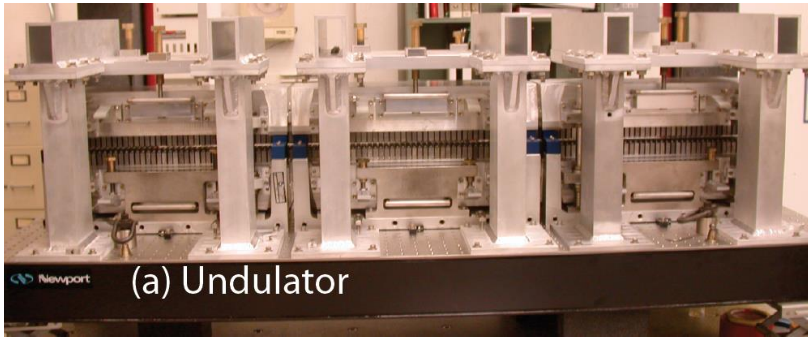
- Source size ~ 0.5 – 1 micron

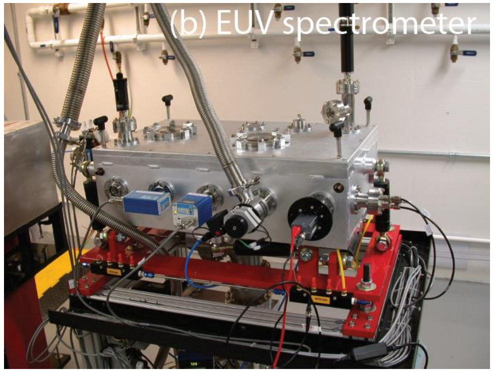


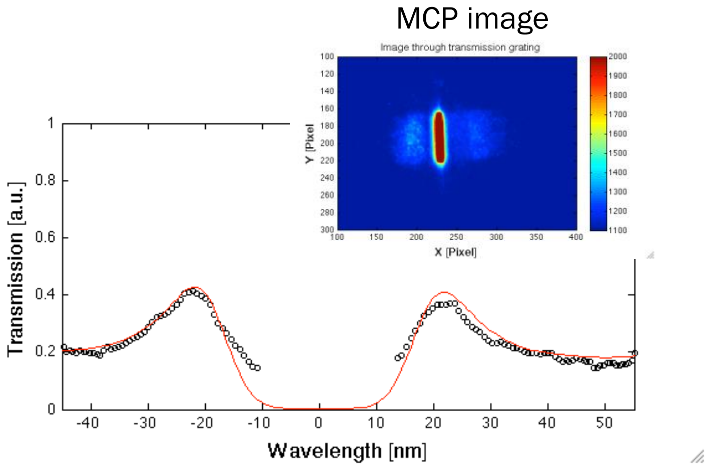


Weingartner *et al.* PRSTAB (2012)

Soft X-rays generated [LPA undulator radiation, tape-based HHG (*seed*)]



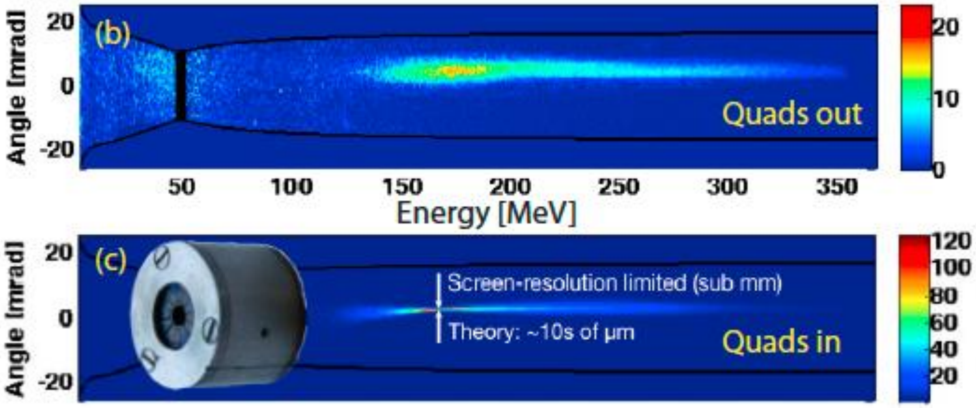




Incoherent X-rays (no designed e-beam transport) from ~400 MeV e-beams

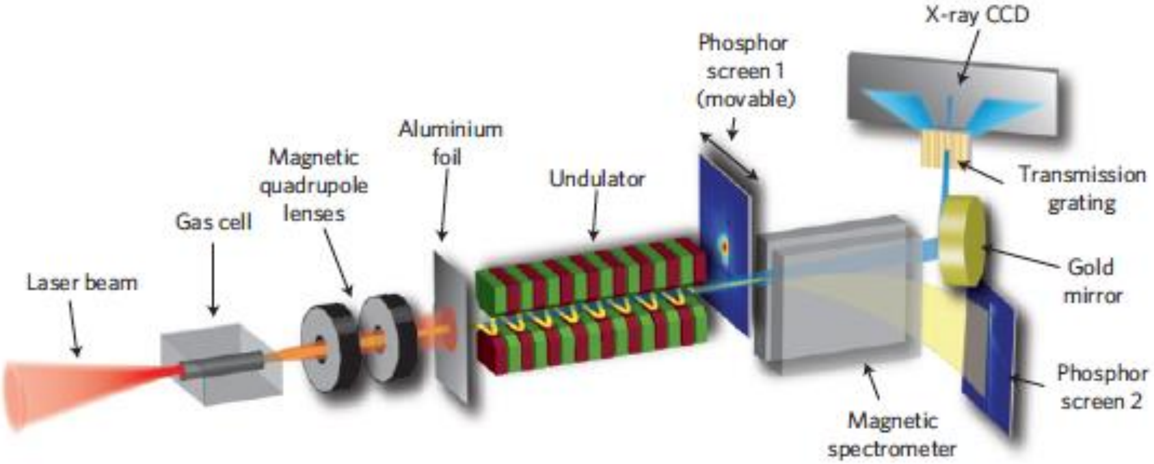
Shaw *et al.* AAC Proceedings 2012

Strong-field miniature quadrupoles have been implemented for LPA beam transport



Quadrupole doublet

- Asymmetric focusing
- Future: triplet (sym. focusing)
- Gradients ~400 T/m
- (not tunable, still too weak)

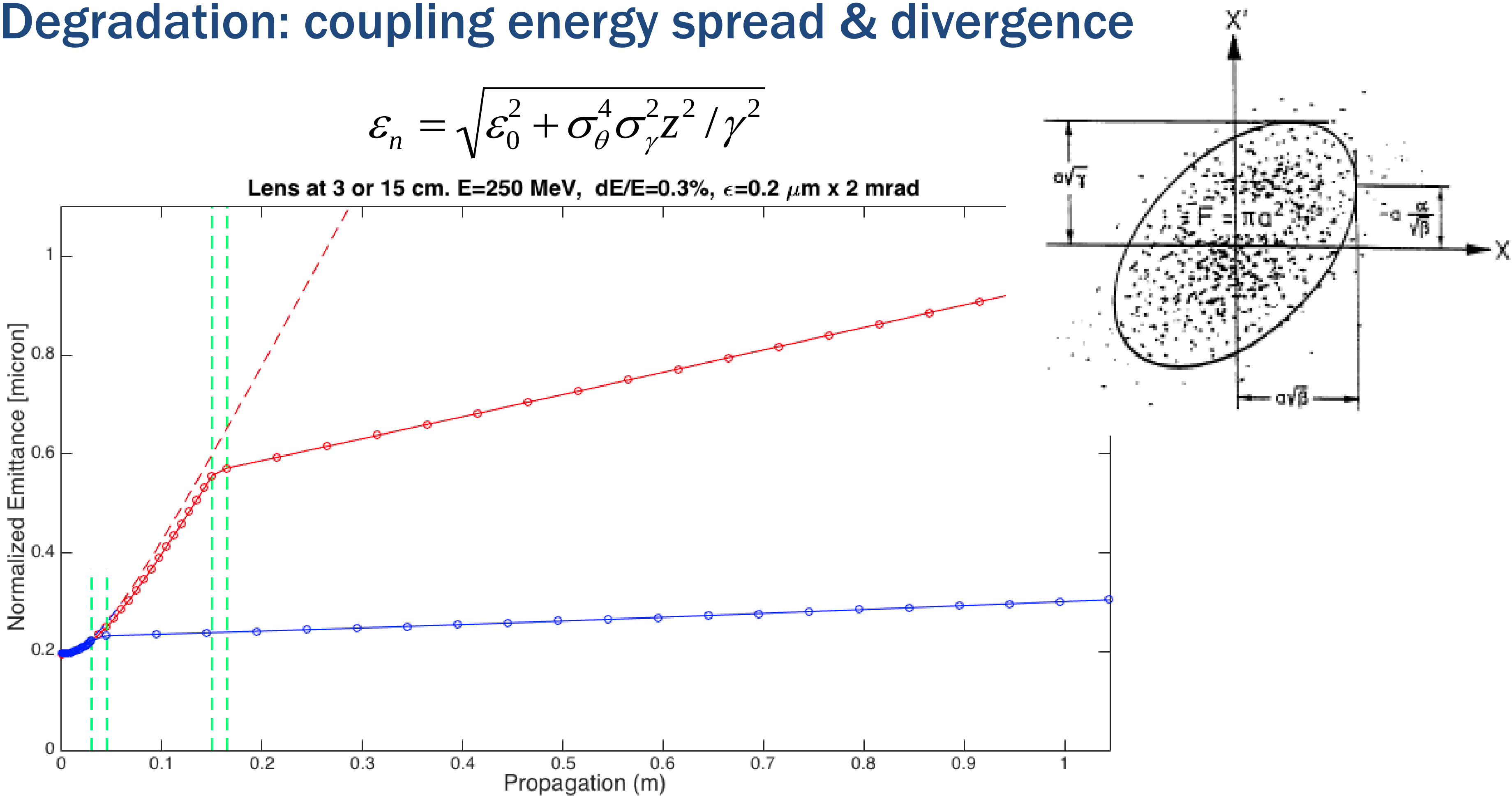


Fuchs *et al.* Nat. Phys. (2009)

Quadrupole technology not capable of rapid capture → emittance increase from energy spread

Degradation: coupling energy spread & divergence

$$\varepsilon_n = \sqrt{\varepsilon_0^2 + \sigma_\theta^4 \sigma_\gamma^2 z^2 / \gamma^2}$$

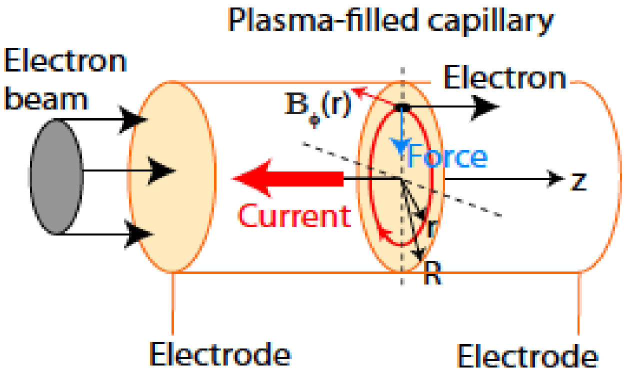

Lens at 3 or 15 cm. E=250 MeV, dE/E=0.3%, ε=0.2 μm x 2 mrad

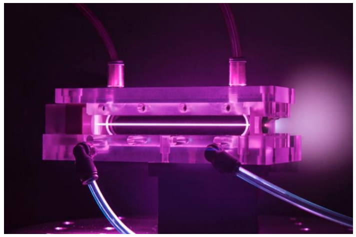
Capillary-discharge active plasma lens successfully demonstrated on LPA line

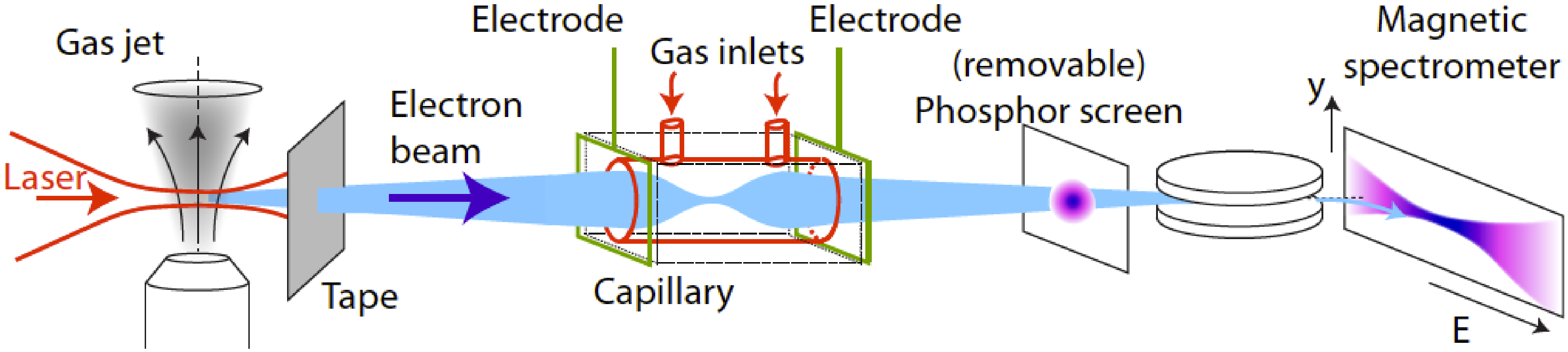
Active Plasma Lens

- Introduced 1950s (ion beams)
- Symmetric focusing
- Tunable
- Gradients >3000 T/m
- Rely on negligible wakefields

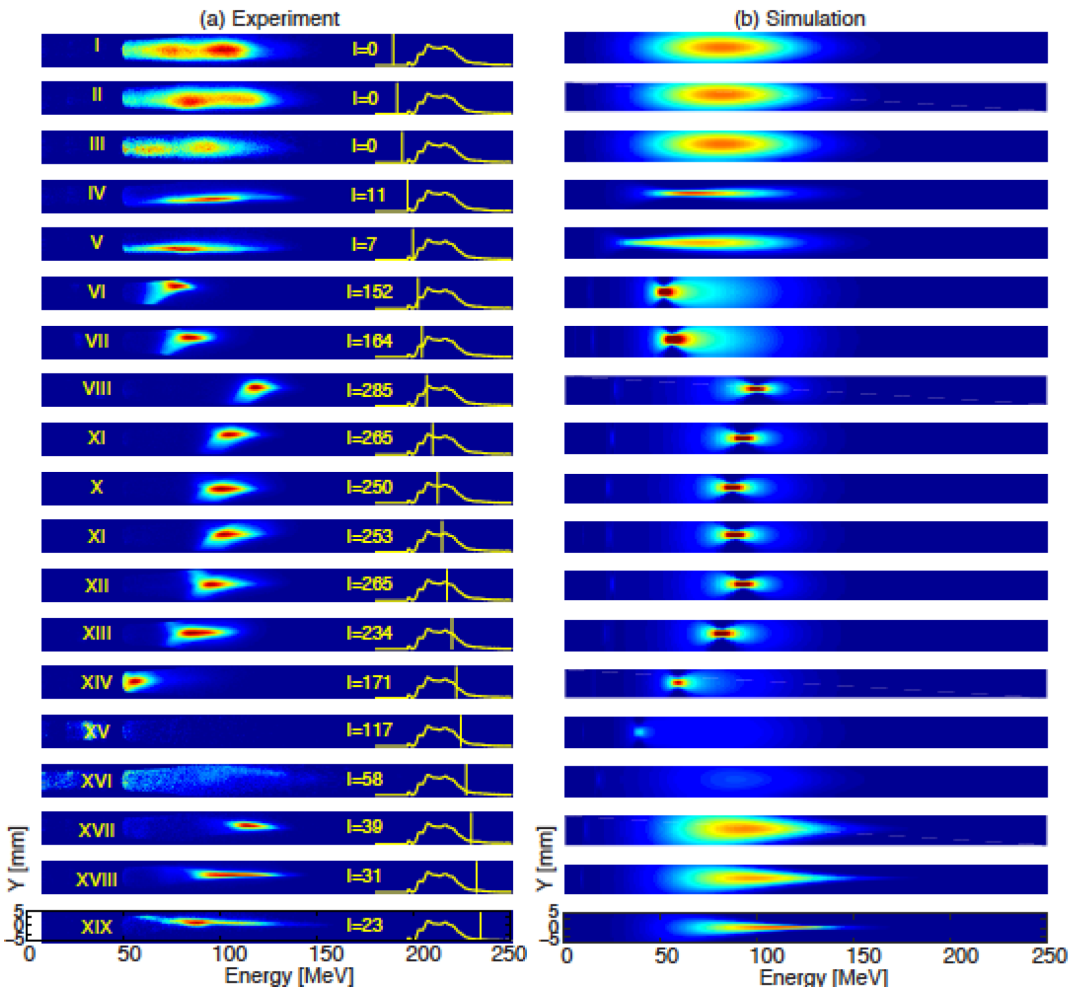
Panofski *et al*. RSI 1950
van Tilborg *et al*. PRL **115**, 184802 (2015)

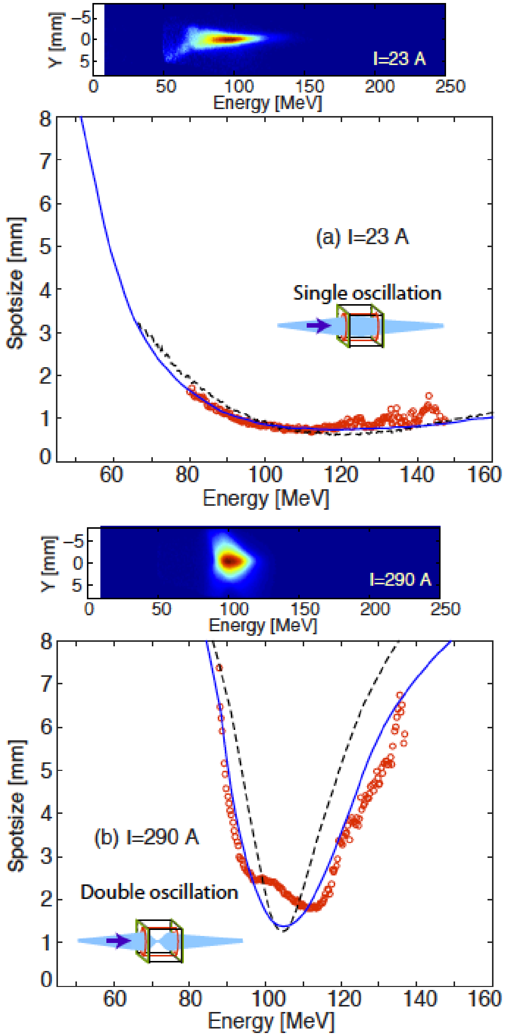






Strong focusing field gradients observed!
Multiple in-lens oscillations increase chromatic dependence

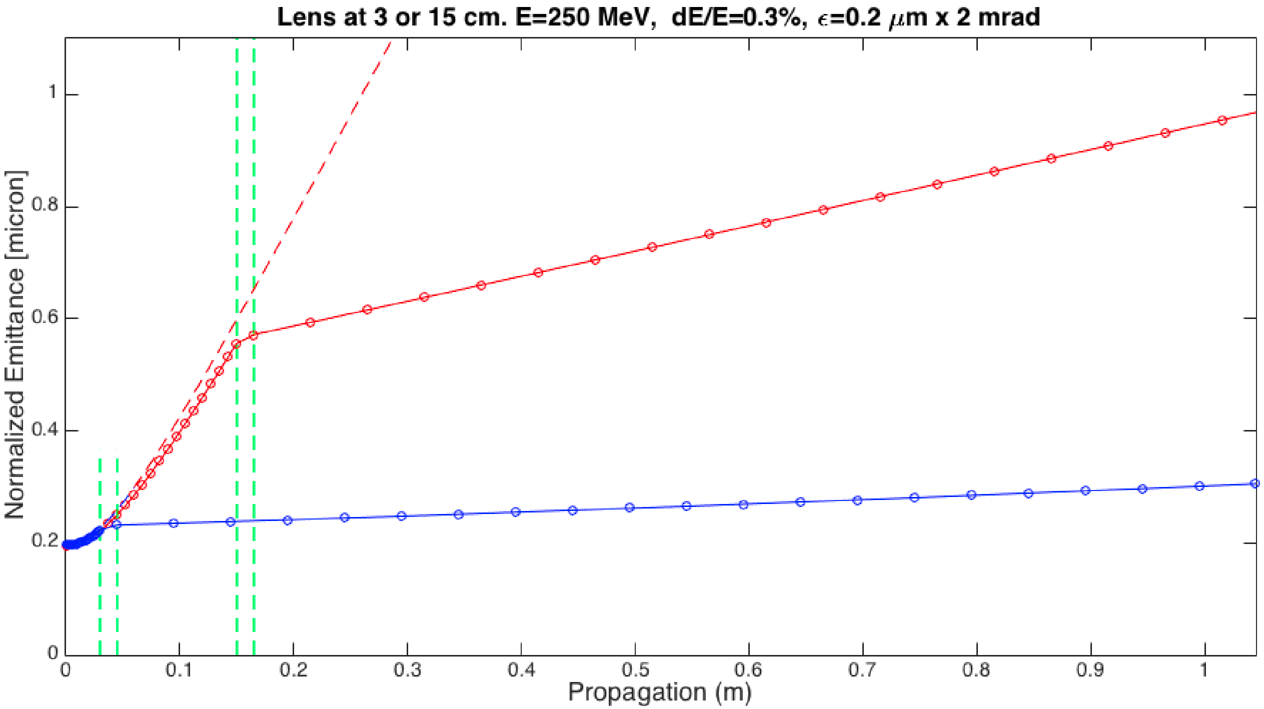




van Tilborg *et al*. PRL **115**, 184802 (2015)

Active plasma lens: capture within few cm → limited emittance degradation

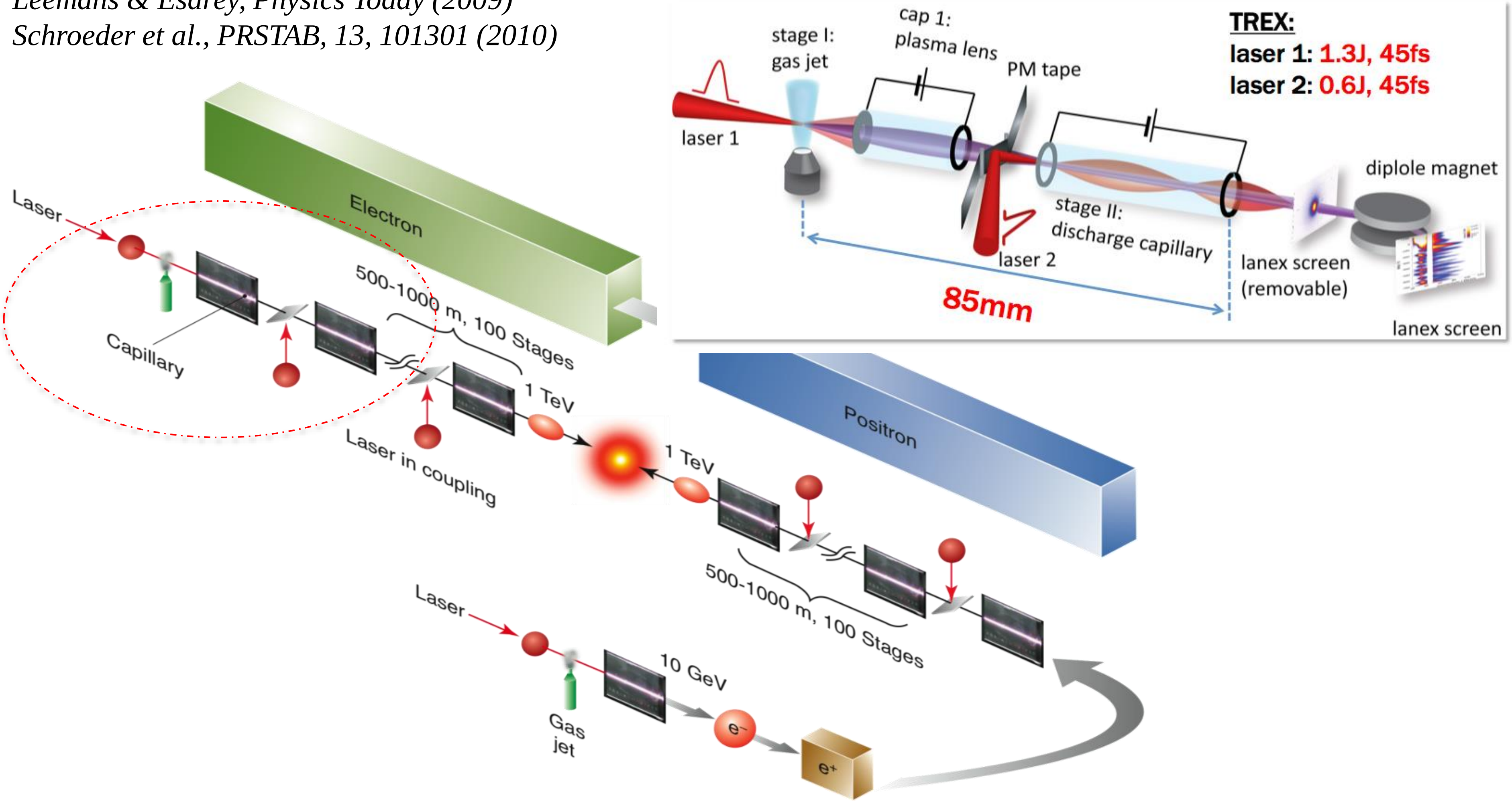
For 300 MeV e-beam
Solenoid (2 T, L=20 cm): F=500 cm
Quad triplet (500 T/m, L=3 cm): F=20 cm
Active plasma lens (2000 T/m, L=3 cm): F=1.7 cm



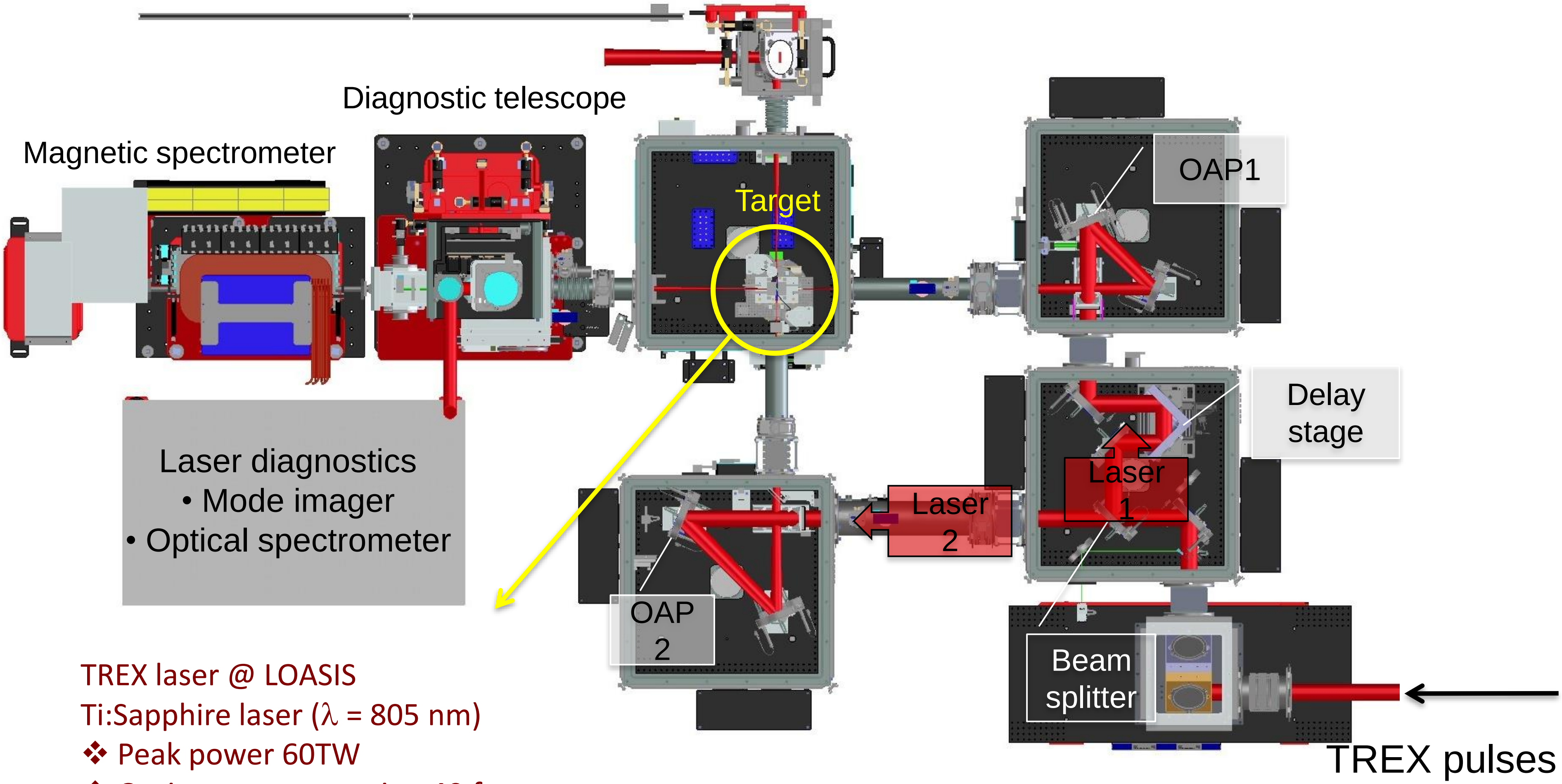
$$\varepsilon_n = \sqrt{\varepsilon_0^2 + \sigma_\theta^4 \sigma_\gamma^2 z^2 / \gamma^2}$$

Staged acceleration setup: the coupling of two independently-driven LPA stages

Leemans & Esarey, Physics Today (2009)
Schroeder et al., PRSTAB, 13, 101301 (2010)



Staged acceleration setup: the coupling of two independently-driven LPA stages

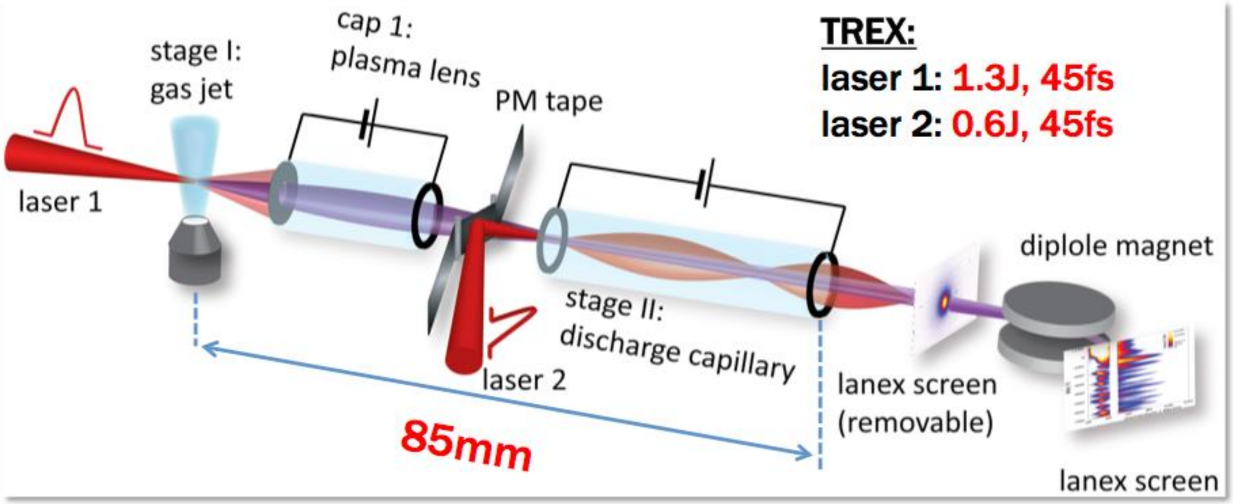


TREX laser @ LOASIS

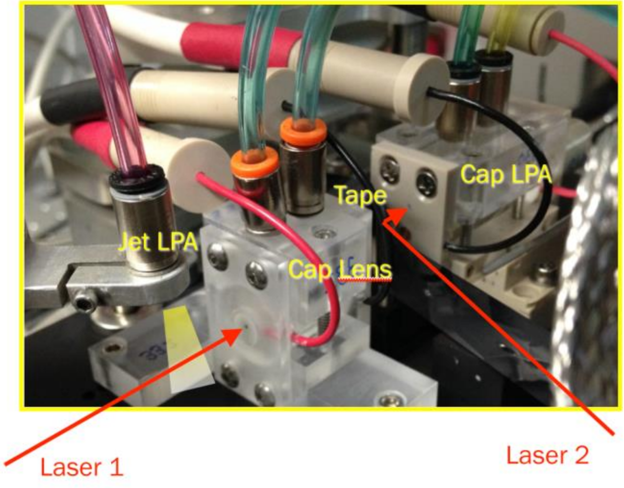
Ti:Sapphire laser (λ = 805 nm)

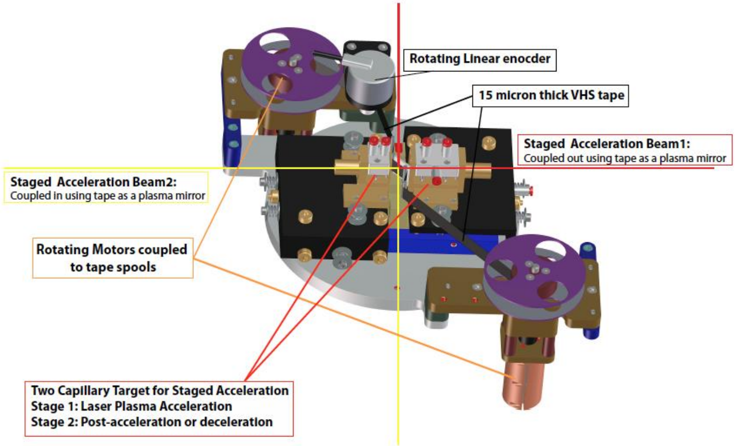
- ❖ Peak power 60TW
- ❖ Optimum compression 40 fs
- ❖ Rep. rate 1-10 Hz

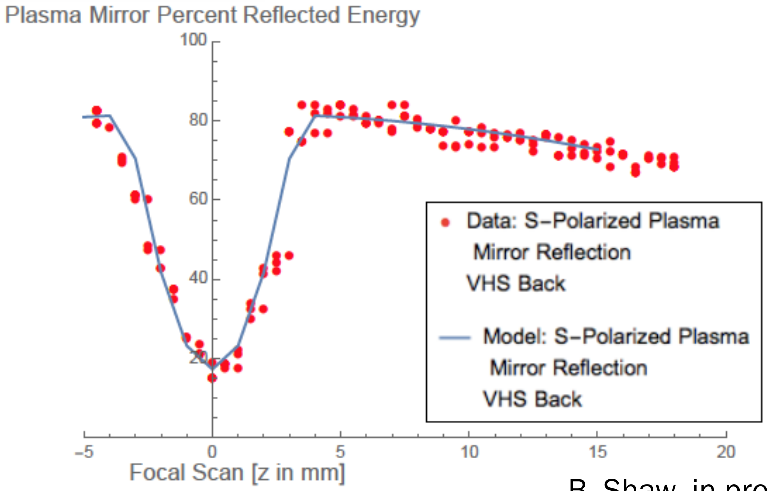
Coupling of “fresh” laser: spooling tape
Coupling of e-beam: active plasma lens



TREX:
laser 1: 1.3J, 45fs
laser 2: 0.6J, 45fs

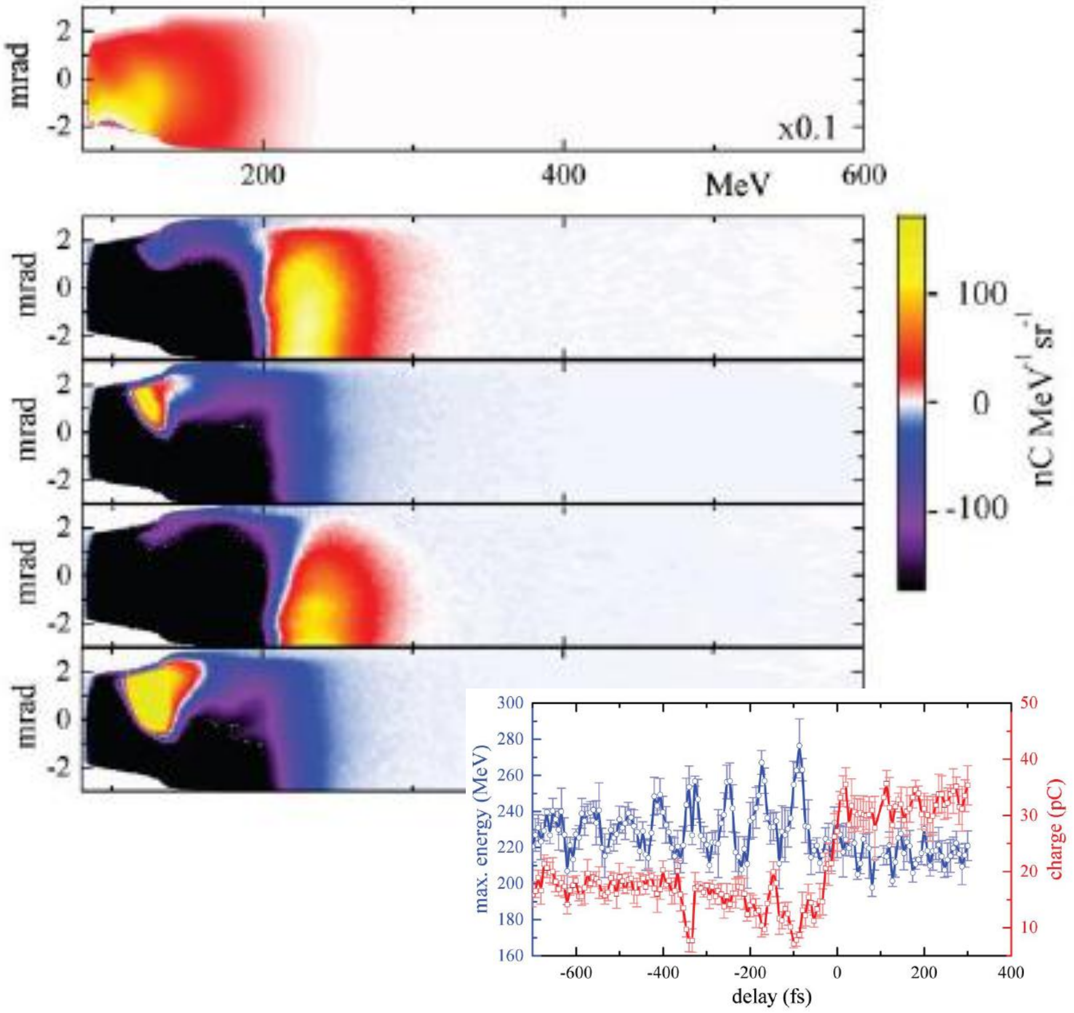


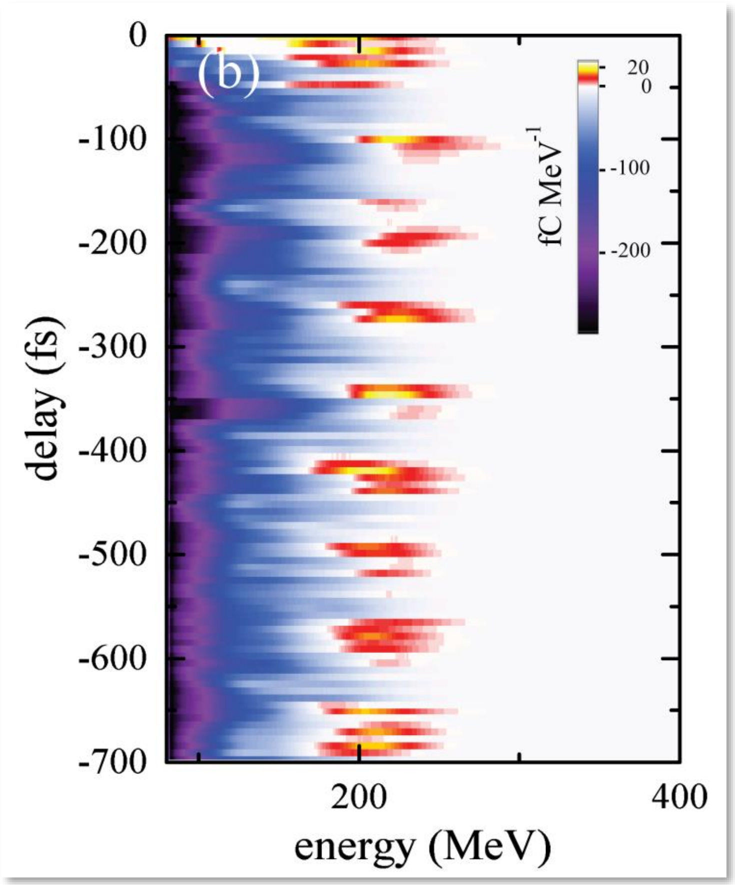




B. Shaw, in preparation

Successful demonstration of staged acceleration. Two independent LPAs coupled with plasma lens & tape

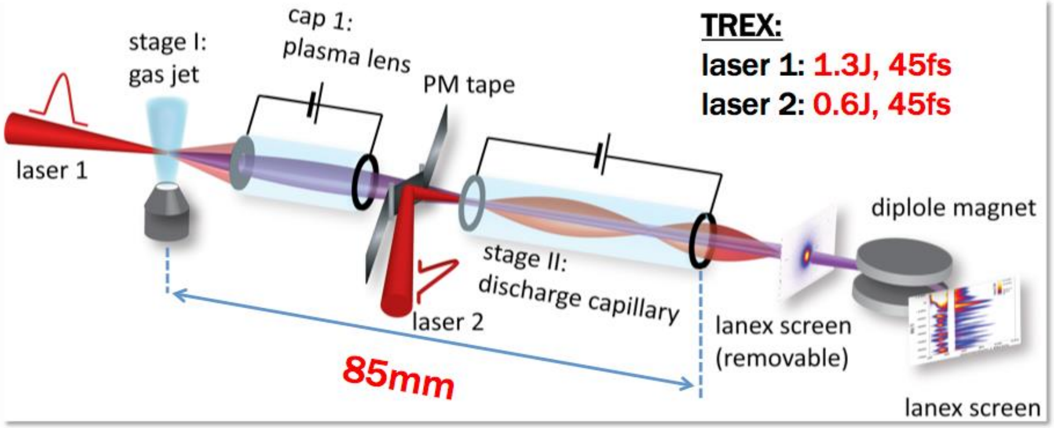




S. Steinke *et al*. Nature 530, 190 (2016)

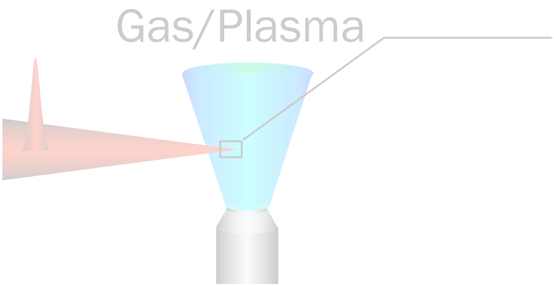
Laser plasma accelerators (LPAs): Wealth of physics and complexities

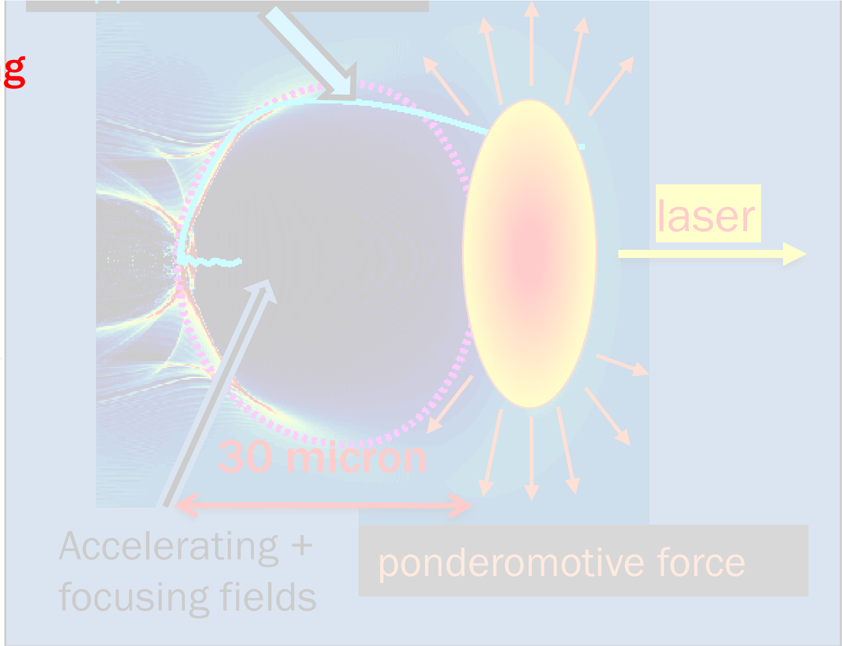
- Setting up the plasma
  - foot laser pulse
  - laser pre-ionization (guiding channel)
  - electrics discharge pre-ionization
- Laser drives strong co-propagating accelerat
  - Transverse laser evolution (diffraction z
  - Longitudinal laser evolution (pulse stee
- Electron injection
  - External injection
  - Transverse wavebreaking
  - Ionization-induced
  - Down-ramp induced
  - Colliding pulse
- Acceleration of injected electrons (10-100 GeV/m)



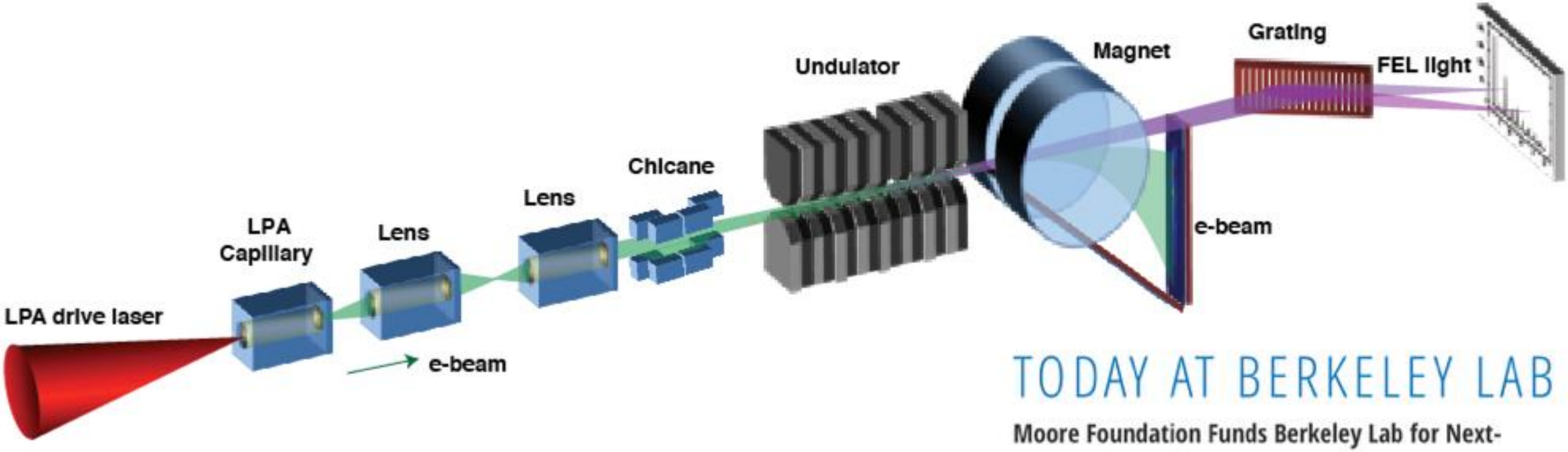
TREX:
laser 1: 1.3J, 45fs
laser 2: 0.6J, 45fs

Femtosecond timing
µm positioning
Future: coupling of
many stages





BELLA Center secured funding from the Moore Foundation to build compact LPA-FEL



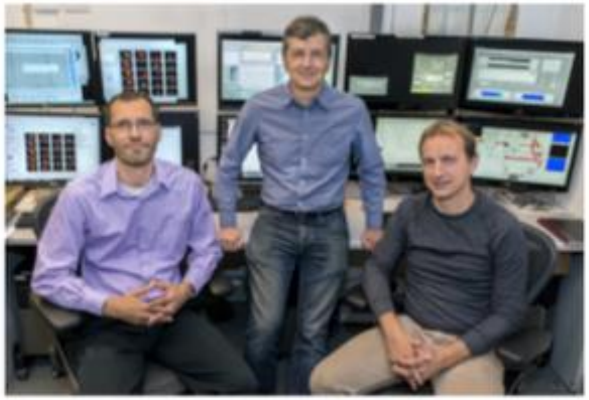
GORDON AND BETTY MOORE FOUNDATION

- New 100TW laser
- One laser room → stable
- Use existing LPA & undulator cave
- Construction started Jan. 2016

TODAY AT BERKELEY LAB

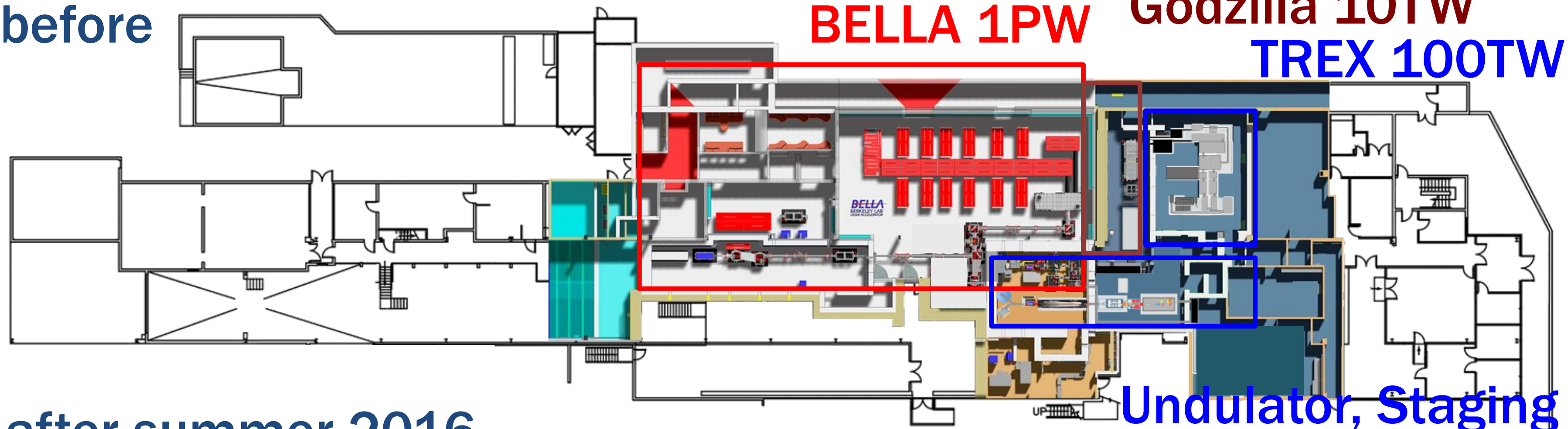
Moore Foundation Funds Berkeley Lab for Next-Generation Accelerators

JANUARY 25, 2016



100 TW labs make-over!

before



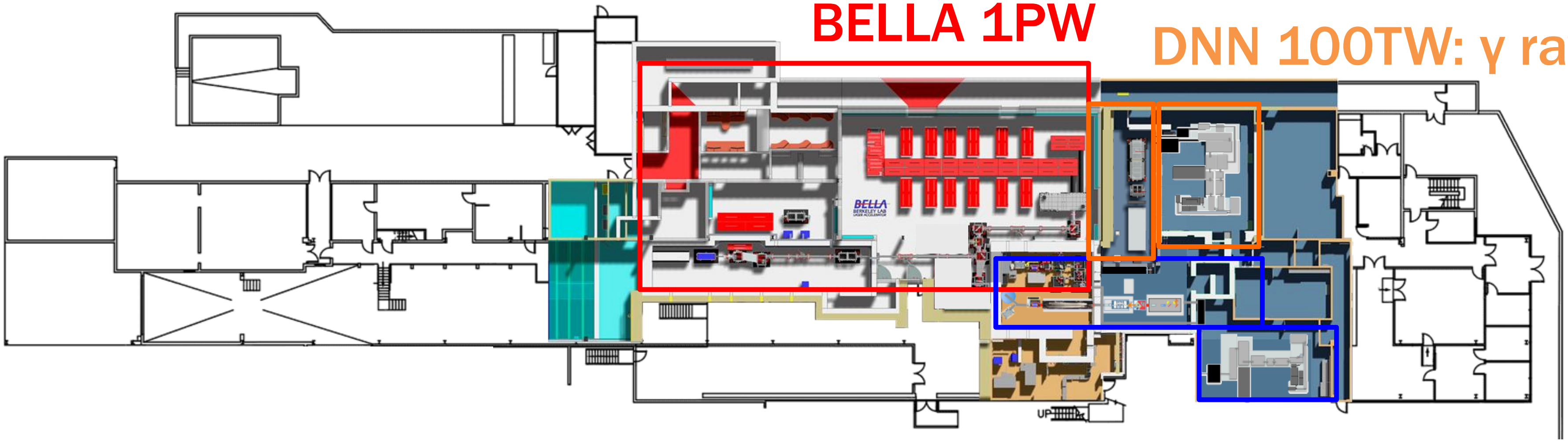
BELLA 1PW

Godzilla 10TW

TREX 100TW

Undulator, Staging

after summer 2016

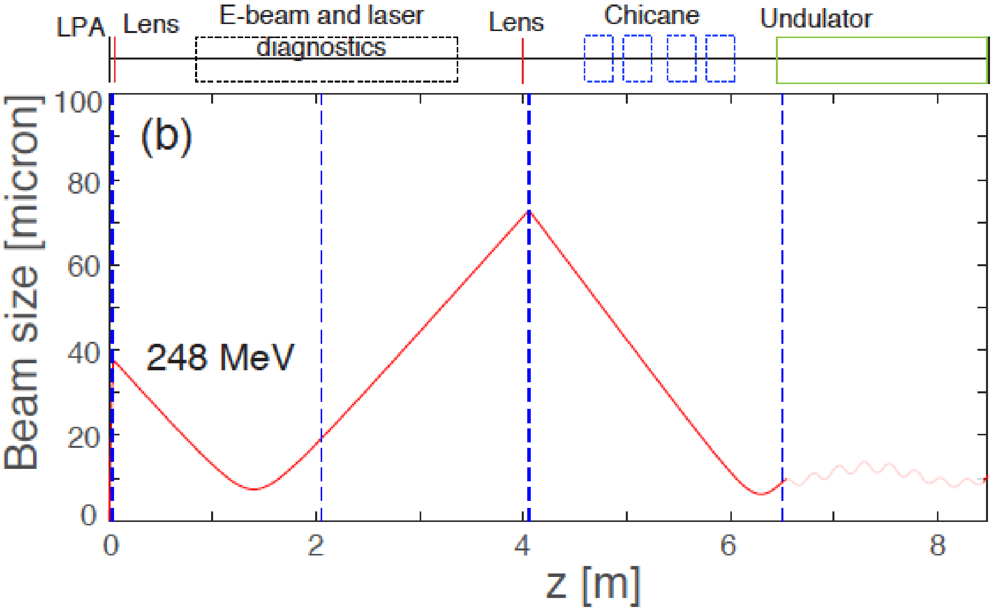


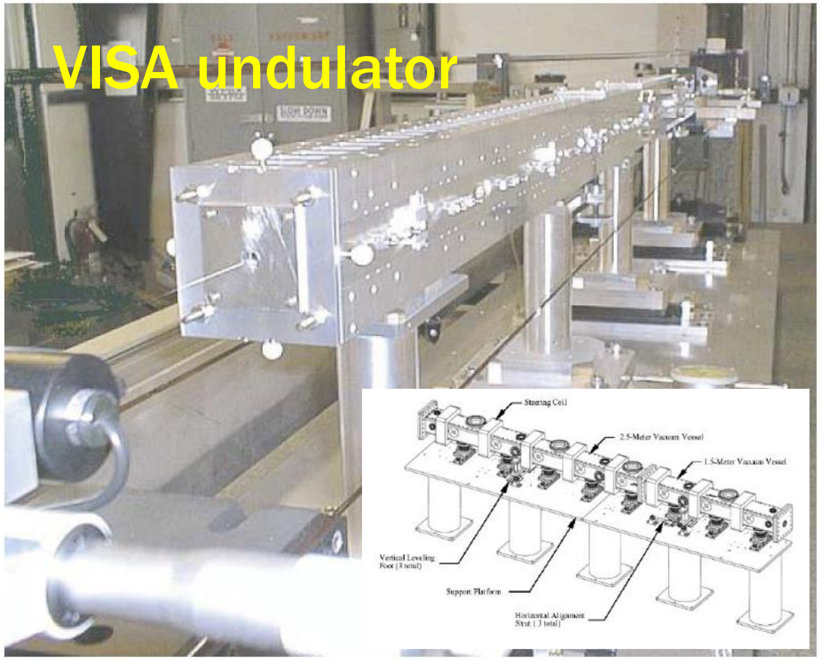
BELLA 1PW

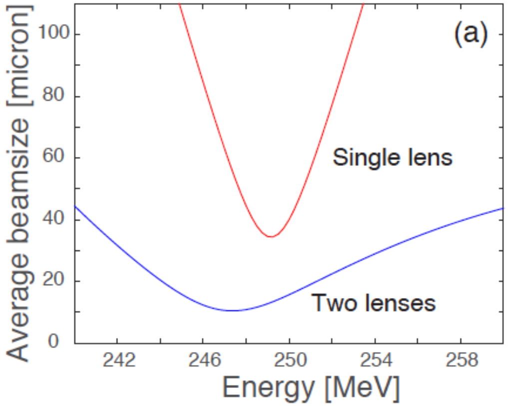
DNN 100TW: γ rays

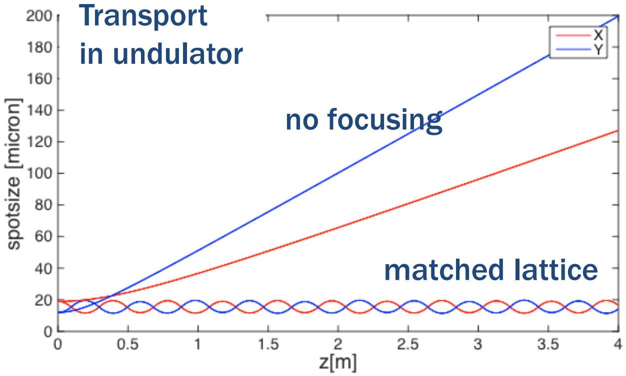
Moore 100TW: Undulator (FEL)

LPA transport optimized
VISA and Kurchatov undulator have embedded strong-focusing

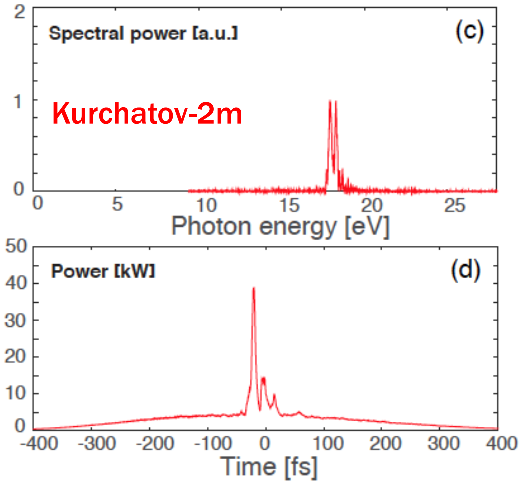


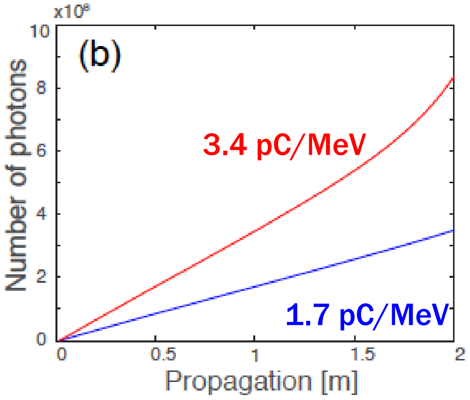






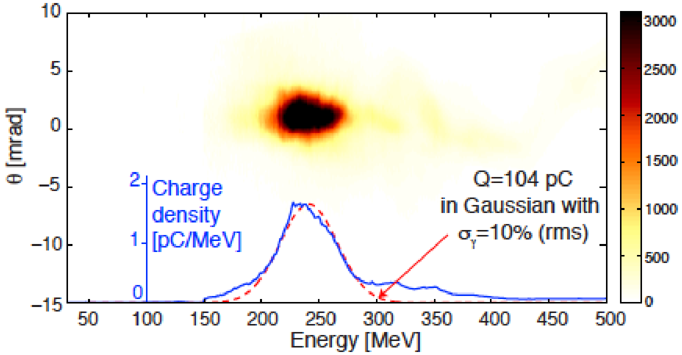
GENESIS simulations predict strong gain for LPA beams

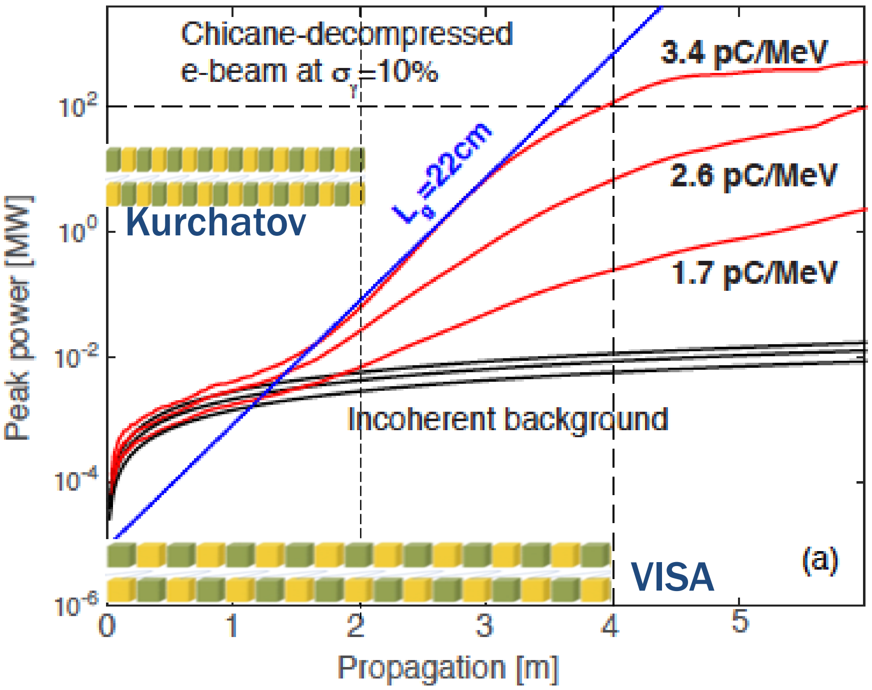




VISA (4m)
220 periods
λ_u=1.8 cm

Kurchatov (2m)
100 periods
λ_u=2.05 cm





E-beam: ε=0.1 μm, σ=10 μm, 1.7/3.4 pC/MeV, 250 MeV (σ_E=10%), D=x64, I_{peak}=200/400 A
VISA Undulator: λ_u=1.8 cm, K=1.26 → λ_r=67.45 nm
Kurchatov: λ_u=2.05 cm, K=1.04 → λ_r=69.67 nm

Summary

- Jet & channel-guiding capillary targets produce MeV-GeV e-beams
- Moore Foundation funding for dedicated single-table 100TW laser system
- Chicane mitigates energy spread
- Active plasma lens as strong e-beam optic
- Compact plasma lens critical to staging of two LPAs
- Several undulators available (Thunder, VISA, Kurchatov)
- Strong simulated photon flux (>1e7-1e8 photons/pulse at 10-50 MeV)
- Kurchatov-2m → onset of FEL lasing, VISA-4m → strong FEL output