Relativistic High Energy Density Physics

Cameron Geddes

BELLA Center Deputy Director

Lawrence Berkeley National Laboratory

With thanks to colleagues at LBNL

Thomas Schenkel
Interim Division Director, ATAP

Carl Schroeder
Deputy Center Director, Theory

Eric Esarey
BELLA Center Director

Cameron Geddes
Deputy Center Director, Experiments

Staff

Csaba Toth

Kei Nakamura

Tony Gonsalves

Jeroen van Tilborg

Sven Steinke

Carlo Benedetti

Stepan Bulanov

Postdocs

Sam Barber
Jianhui Bin
Tobias Ostermayr
Hai-En Tsai
Tong Zhou

Doctoral Students

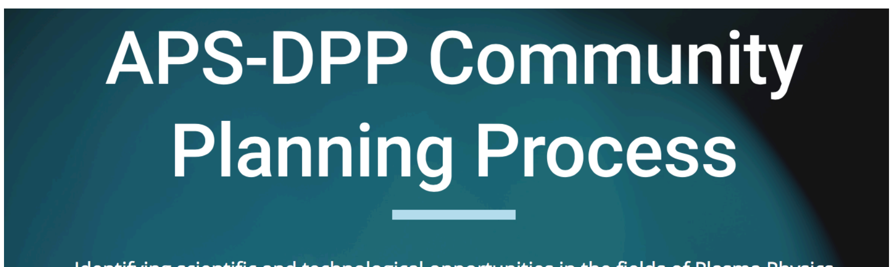
Blagoje Djordjevic,
Fumika Isono
Kelly Swanson
Liona Fan-Chiang
Chris Pieronek

Related: Accelerator Modeling (AMP) and Controls & Instrumentation (BACI) programs

http://bella.lbl.gov

With thanks to the HEDP & Laser-Plasma Accelerator Community

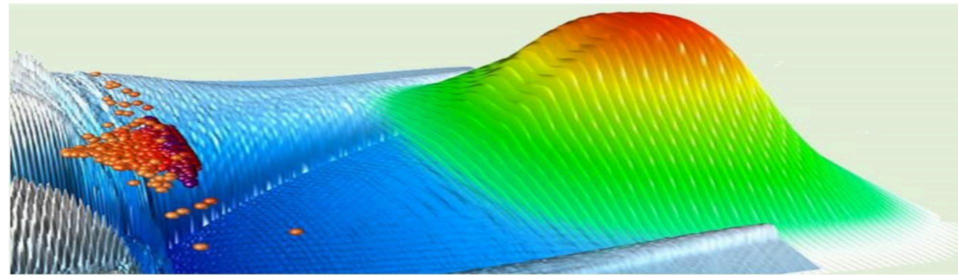
2020 National Academies Plasma Decadal
- Broad plasma science
  - Burning plasma in previous study
- http://nas.edu/plasma

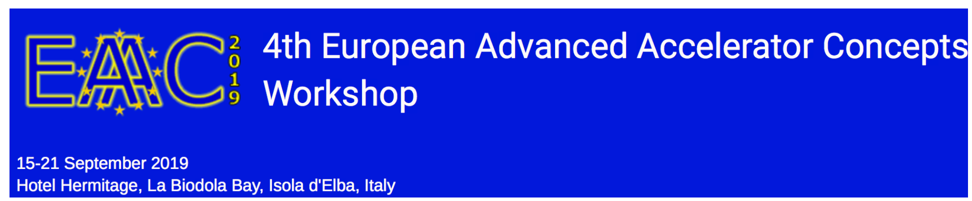


Also: ongoing FESAC Long-Range Planning

2019-20 Community planning process
- Fusion & burning plasmas, Discovery plasma science, HED & Acceleration
- https://sites.google.com/pppl.gov/dpp-cpp/home

2017 Laser Plasma Accelerator Workshop





Additional:
NASEM Brightest Light response,
NSF Plasma Science User Facilities

Great resources for you: white papers, past studies, town halls…

With thanks to the LaserNetUS community

Laser facilities at ten institutions:

University of Texas at Austin,
The Ohio State University,
Colorado State University,
The University of Michigan,
University of Nebraska-Lincoln,
University of Rochester,
SLAC,
Lawrence Berkeley National Laboratory,
Lawrence Livermore National Laboratory,
Université du Québec.

User experiments across HEDP

Student training and experiments

Collaboration and co-development

https://www.lasernetus.org

Outline

- Introduction
- Nonlinear Optics of Plasmas
- Lepton acceleration
- Photon sources
- Ion acceleration
- High field science and nonlinear QED
- Personal perspectives & resources

Relativistic High Energy Density Physics
momentum at or above rest mass

- Consider a particle in a generalized field…
  - Expand electric field about central location r_0

$$\mathbf{E} = \mathbf{E}_s(\mathbf{r})cos(\omega t) = [\mathbf{E}_s(\mathbf{r}_0) + (\delta\mathbf{r}_1 \cdot \nabla)\mathbf{E}_s(\mathbf{r})|_{\mathbf{r}_0} + ...]cos(\omega t) = \mathbf{E}_1 + \mathbf{E}_2 + ...$$

  - First order oscillation

$$m\frac{d\mathbf{v}_1}{dt} = -e\mathbf{E}_1 \Rightarrow \begin{cases} \mathbf{v}_1 = -\frac{e}{m\omega}\mathbf{E}_s(\mathbf{r}_0)sin(\omega t) \\ \delta\mathbf{r}_1 = \frac{e}{m\omega^2}\mathbf{E}_s(\mathbf{r}_0)cos(\omega t) \end{cases}$$

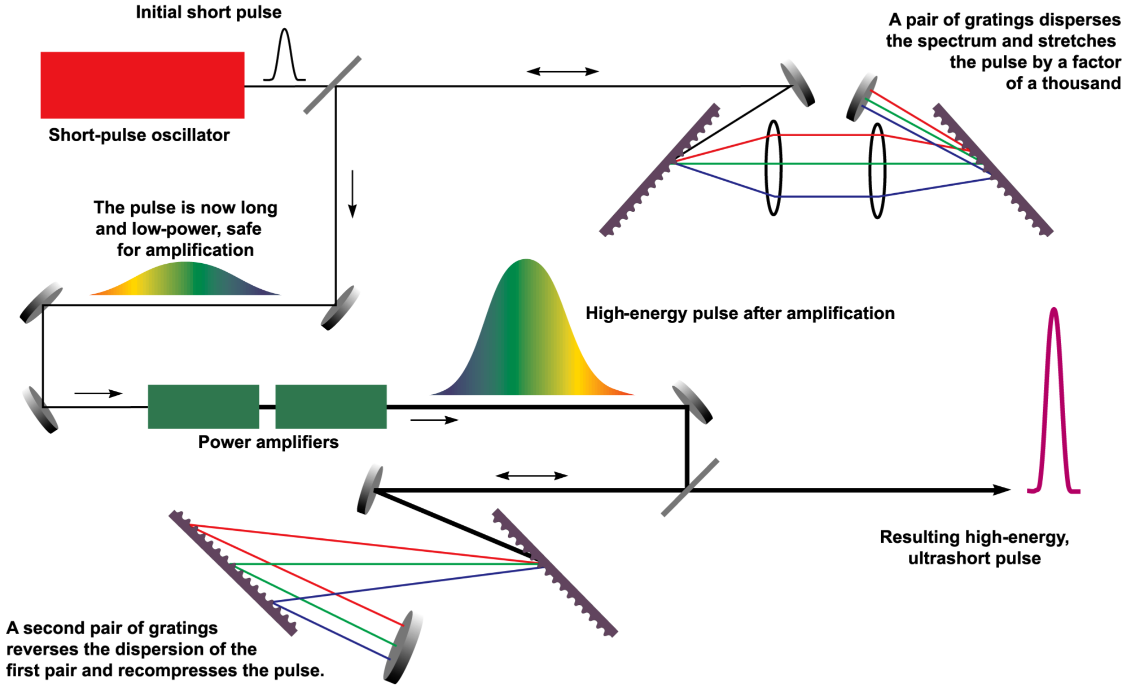
  - v approaches c for

$$a_0 = \frac{eE_s}{\omega mc} \approx 8.5 \times 10^{-10}\lambda[\mu m]\sqrt{I[\frac{W}{cm^2}]} \quad =1$$

  - and high a gives highly relativistic motion $a_0 = \gamma v_\perp / c$

- Laser pressure very strongly shapes plasma, creating unique states

Relativistic intensities enabled by fs, TW lasers: Chirped pulse amplification



1985 Concept

- Generate short pulse
- Stretch
- Amplify
- Compress

Circumvents optic damage

Enables 10's TW – PW systems

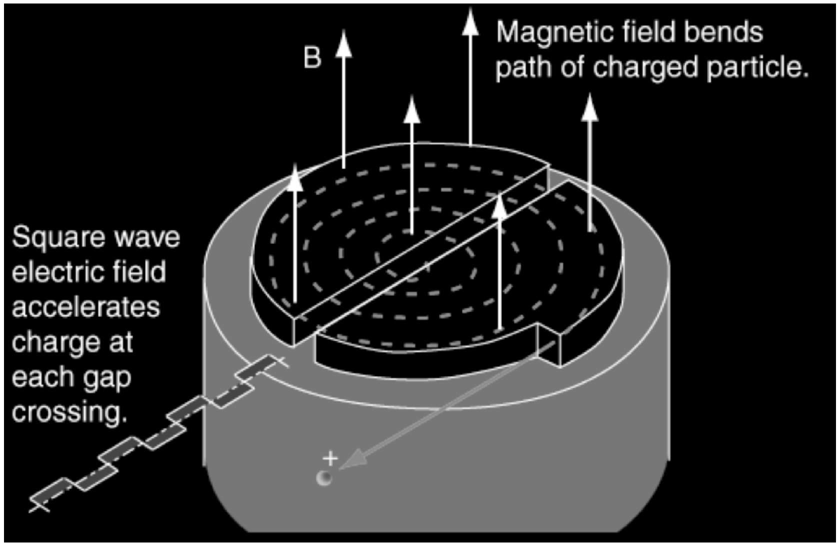
2000's Ti:Sa – 30 fs

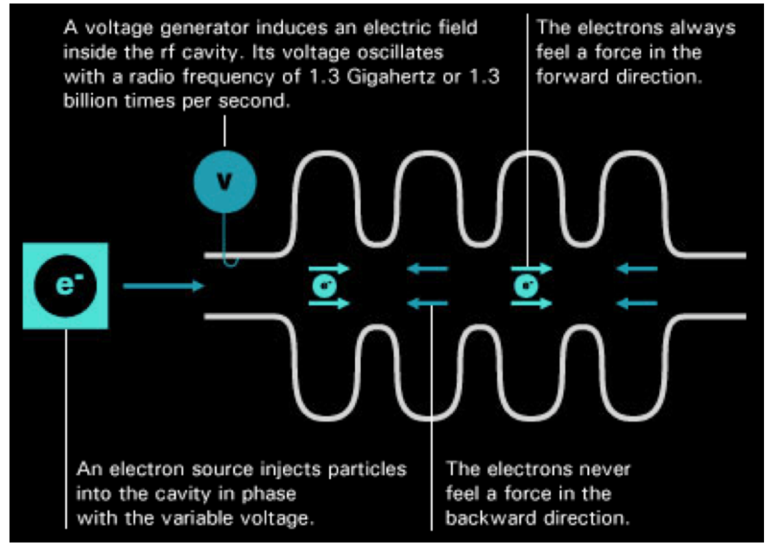
Relativistic intensities > 10^{18} W/cm^2

2018 Nobel Prize: Strickland and Mourou

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Relativistic fields bypass limits on conventional accelerators





Outline

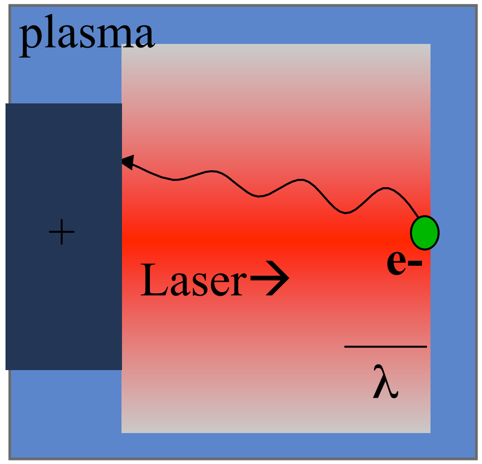
- Introduction
- Nonlinear Optics of Plasmas
- Lepton acceleration
- Photon sources
- Ion acceleration
- High field science and nonlinear QED
- Personal perspectives & resources

Plasma driven by radiation pressure of TW, fs laser: Ponderomotive force

- Laser drive: ponderomotive force

  – Expand electric field about central location r_0

$$\mathbf{E} = \mathbf{E}_s(\mathbf{r})cos(\omega t) = [\mathbf{E}_s(\mathbf{r}_0) + (\delta\mathbf{r}_1 \cdot \nabla)\mathbf{E}_s(\mathbf{r})|_{\mathbf{r}_0} + ...]cos(\omega t) = \mathbf{E}_1 + \mathbf{E}_2 + ...$$



  – First order oscillation

$$m\frac{d\mathbf{v}_1}{dt} = -e\mathbf{E}_1 \Rightarrow \begin{cases} \mathbf{v}_1 = -\frac{e}{m\omega}\mathbf{E}_s(\mathbf{r}_0)sin(\omega t) \\ \delta\mathbf{r}_1 = \frac{e}{m\omega^2}\mathbf{E}_s(\mathbf{r}_0)cos(\omega t) \end{cases}$$

  – Second order; v_1 X B_1 and E_2 terms: average over cycle

$$m\frac{d\mathbf{v}_2}{dt} = -e[\mathbf{E}_2 + \mathbf{v}_1 \times \mathbf{B}_1] = -e[(\delta\mathbf{r}_1 \cdot \nabla)\mathbf{E} + \mathbf{v}_1 \times \mathbf{B}_1]$$

$$\boxed{\mathbf{E}_s \times (\nabla \times \mathbf{E}_s) = \tfrac{1}{2}\nabla E_s^2 - \mathbf{E}_s \cdot \nabla\mathbf{E}_s}$$

$$\partial\mathbf{B}/\partial t = -c(\nabla \times \mathbf{E})$$

$$\mathbf{B}_1 = [\nabla \times \mathbf{E}_s(\mathbf{r}_0)]sin(\omega t)$$

$$\mathbf{F}_p = \langle m\frac{d\mathbf{v}_2}{dt}\rangle = -\frac{1}{2}\frac{e^2}{m\omega^2}[(\mathbf{E}_s \cdot \nabla)\mathbf{E}_s + \mathbf{E}_s \times (\nabla \times \mathbf{E}_s)] = \frac{e^2}{4m\omega^2}\nabla E_s^2(\mathbf{r}) = \frac{mc^2\nabla a_0^2(\mathbf{r})}{4}$$

$$\boxed{a_0 = \frac{eE_s}{\omega mc} \approx 8.5 \times 10^{-10}\lambda[\mu m]\sqrt{I[\frac{W}{cm^2}]}}$$

  – $\Phi_p = mc^2a^2/4e$

Laser-propagation: EM dispersion in unmagnetized plasma

- Laser velocity, from dispersion

$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \quad v_p = \frac{\omega}{k} = \frac{c}{\eta} \quad v_g = \frac{d\omega}{dk} = c\eta$$

- For $n_e \sim 10^{18}$/cc and a 1µm laser, $\omega_p/\omega \sim 1/30$
  - η very close to 1, $v_g \sim c$
- With nonlinearity – electrons more 'massive'

$$\eta \simeq 1 - \frac{\omega_p^2}{2\omega^2} \Longrightarrow \eta \simeq 1 - \frac{\omega_p^2}{2\omega^2}\frac{n}{\gamma n_0}$$

- Laser can be shaped/steered by gradients of:
  - Plasma density
  - Intensity

Laser propagation: EM wave propagation

http://geddes.lbl.gov/papers/Geddes_dissertation.pdf

We begin by considering the propagation of a plane electromagnetic wave in a homogeneous plasma [11, 12]. The plasma affects the laser through its conductivity, which can be modeled by considering the oscillation of the electrons in the laser field. Assuming that $\omega > \omega_p$ (required for propagation, as we shall see), ions can be treated as stationary. Similarly to the ponderomotive force derivation, we take the laser field to be of the form $\mathbf{E} = \mathbf{E}(\mathbf{r})exp(-i\omega t)$ and consider the first order electron motion in the field, yielding:

$$\frac{\partial \mathbf{v}}{\partial t} = -\frac{e}{m}\mathbf{E}(\mathbf{r})exp(-i\omega t) \tag{2.22}$$

$$\mathbf{v} = -\frac{ie}{m\omega}\mathbf{E} \tag{2.23}$$

$$\mathbf{J} = -nev = \frac{i\omega_p^2}{4\pi\omega}\mathbf{E} = \sigma\mathbf{E} \tag{2.24}$$

where $\sigma = i\omega_p^2/(4\pi\omega)$ is the high frequency conductivity of the plasma. By using the non-relativistic mass, we assume a regime where $a_0 << 1$, i.e. the quiver velocity in the laser field is much less than c. If $a_0 \gtrsim 1$, the substitution $m \rightarrow \gamma m$ is made (Eq. 2.30).

Laser propagation:
EM wave propagation

http://geddes.lbl.gov/papers/Geddes_dissertation.pdf

pere's laws. For a wave of the form given above, we find from Ampere's law:

$$\begin{aligned}
\nabla \times \mathbf{B} &= \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} \\
&= (\frac{4\pi}{c}\sigma - \frac{i\omega}{c})\mathbf{E} \\
&= \frac{i\omega}{c}(\frac{\omega_p^2}{\omega^2} - 1)\mathbf{E} \\
&= -\frac{i\omega}{c}\epsilon\mathbf{E}
\end{aligned} \tag{2.25}$$

where $\epsilon = 1 - \omega_p^2/\omega^2$ is the plasma dielectric function. Applying the curl to Faraday's equation and using Eq. 2.25 to substitute $-\frac{i\omega}{c}\epsilon\mathbf{E}$ for $\nabla \times \mathbf{B}$ we obtain the wave equation for $\mathbf{E}$:

$$\begin{aligned}
\nabla \times (\nabla \times \mathbf{E}) = \nabla \times (-\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}) = -\frac{1}{c}\frac{\partial}{\partial t}\nabla \times \mathbf{B} \\
\nabla^2\mathbf{E} - \nabla(\nabla \cdot \mathbf{E}) + \frac{\omega^2}{c^2}\epsilon\mathbf{E} = 0
\end{aligned} \tag{2.26}$$

where the vector identity $\nabla \times (\nabla \times \mathbf{E}) = \nabla(\nabla \cdot \mathbf{E}) - \nabla^2\mathbf{E}$ has been used. Similarly, applying the curl to Eq. 2.25 and using Faraday's equation to eliminate $\mathbf{E}$ we obtain:

$$\nabla^2\mathbf{B} + \frac{1}{\epsilon}\nabla\epsilon \times (\nabla \times \mathbf{B}) + \frac{\omega^2}{c^2}\epsilon\mathbf{B} = 0 \tag{2.27}$$

which is the wave equation for $\mathbf{B}$.

Laser propagation: EM wave propagation

http://geddes.lbl.gov/papers/Geddes_dissertation.pdf

For a plane wave in a homogeneous plasma, $\nabla\epsilon = 0$ and $\nabla \cdot \mathbf{E} = 0$, so that the wave equations become identical. Inserting the spatial dependence of a plane wave $(exp(ik \cdot r))$ into either equation then yields the dispersion relation for electromagnetic waves in a plasma:

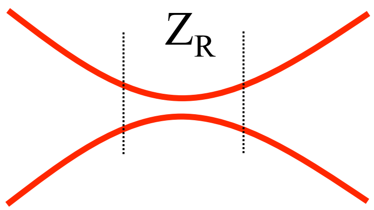
$$\begin{aligned} \nabla^2\mathbf{E} + \frac{\omega^2}{c^2}\epsilon\mathbf{E} &= 0 \\ k^2 + \epsilon\frac{\omega^2}{c^2} &= 0 \\ \omega^2 = \omega_p^2 + k^2c^2 & \end{aligned} \tag{2.28}$$

The group velocity of the laser pulse, v_g, determines the phase velocity of the wake that forms the accelerating structure. Differentiating the dispersion relation Eq. 2.28 we obtain:

$$v_g = \frac{\partial\omega}{\partial k} = \frac{\partial}{\partial k}\sqrt{\omega_p^2 + k^2c^2} = c\sqrt{1 - \frac{\omega_p^2}{\omega^2}} \tag{2.29}$$

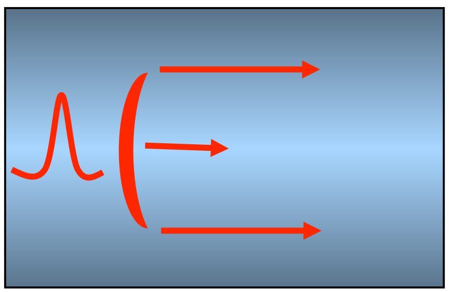
Plasma based laser guiding
Relativistic optical fibers

- cm interactions > Z_R at P <1 PW



$Z_R = \pi w_0^2/\lambda$
a=2→ 200µm @10 TW
2cm @ 1 PW

- Guiding required: refractive index peaked on axis

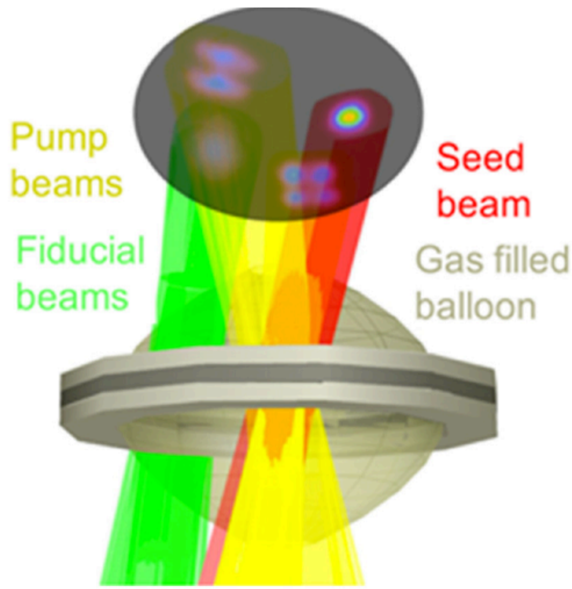


•high plasma density →
high v_p , low v_g

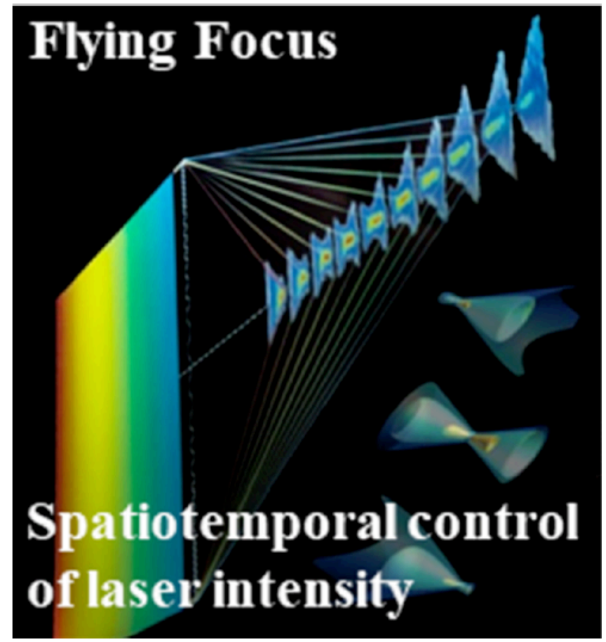
- Guiding due to
  - channel guide with density gradient
  - self guide a >> 1 bubble regime (low a0 part erodes)
  - derivations available: http://geddes.lbl.gov/papers/Geddes_dissertation.pdf

Plasma optics
Light beyond the optic damage limit

Transfer beam energy



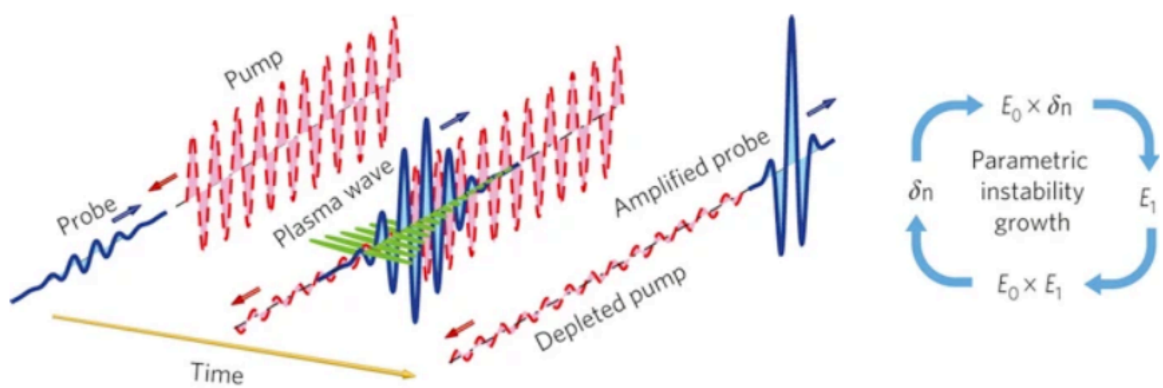
R. K. Kirkwood et al, Nature Physics, 14, 80, (2018).



D Froula et al. Nature Photonics 12, 262 (2018).

Amplify light

Note: illustrative, not necessarily first articles

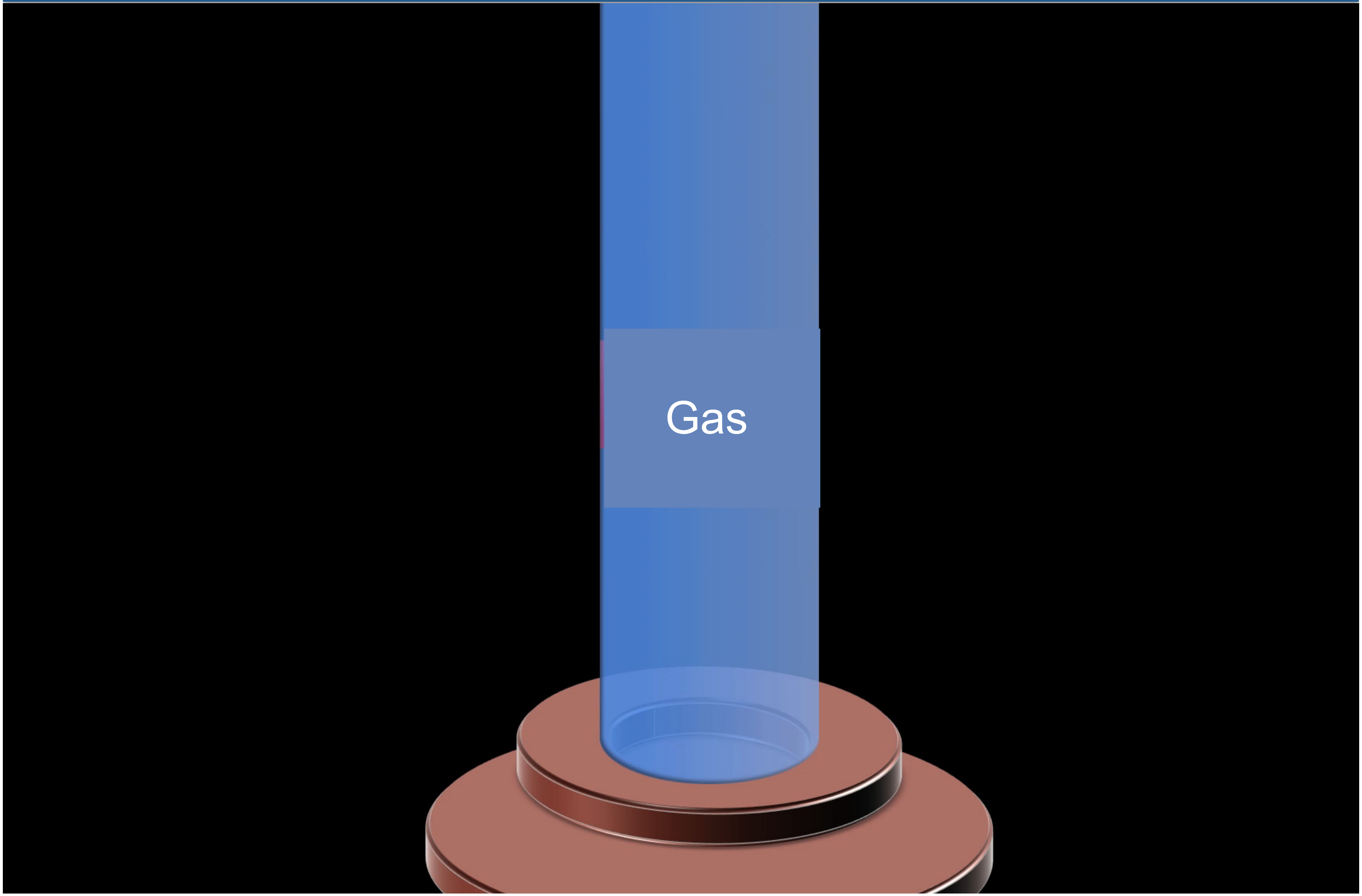


Trines et al., Nature Physics volume 7, pages87–92(2011)

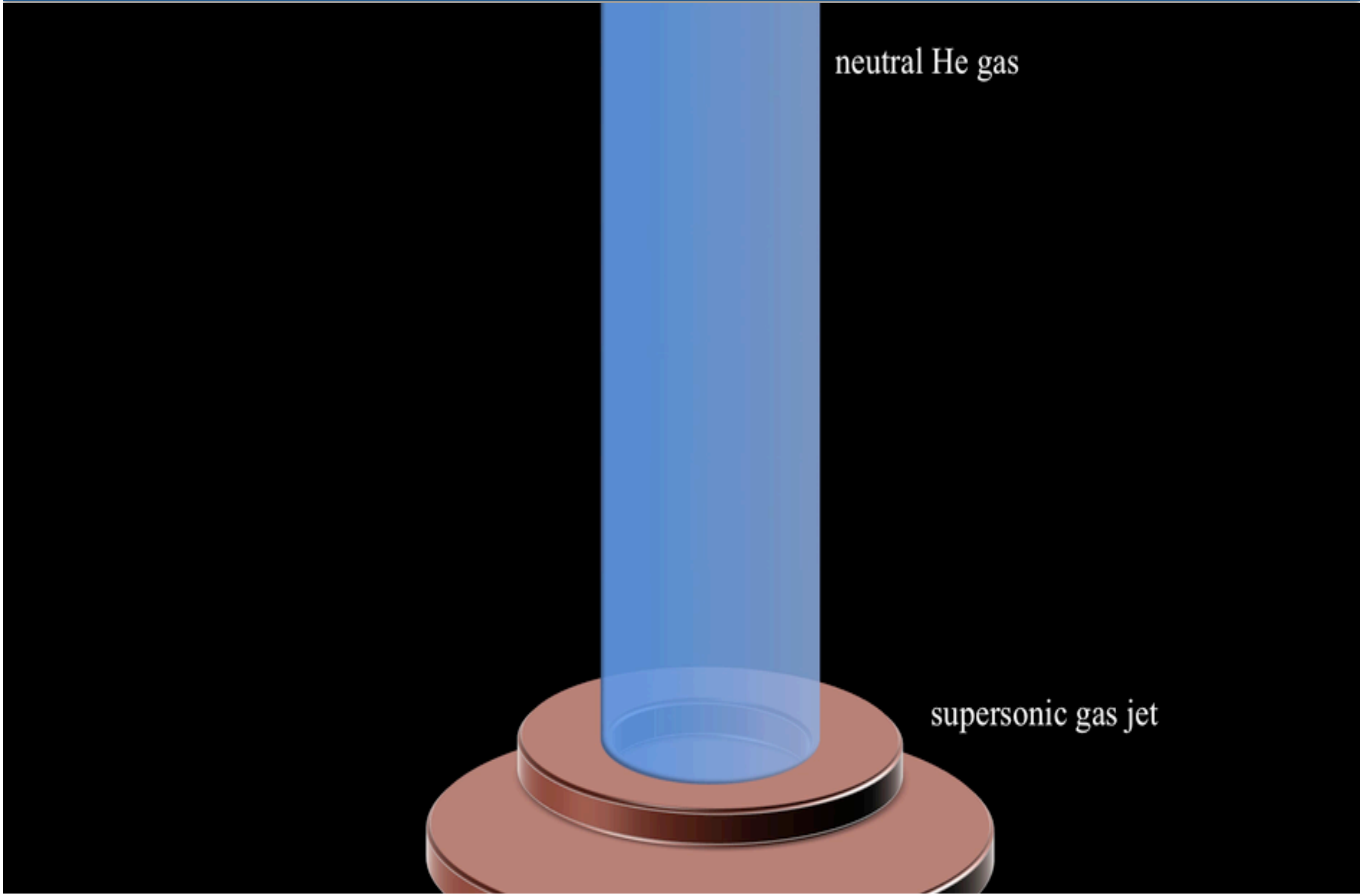
Outline

- Introduction
- Nonlinear Optics of Plasmas
- <u>Lepton acceleration</u>
- Photon sources
- Ion acceleration
- High field science and nonlinear QED
- Personal perspectives & resources

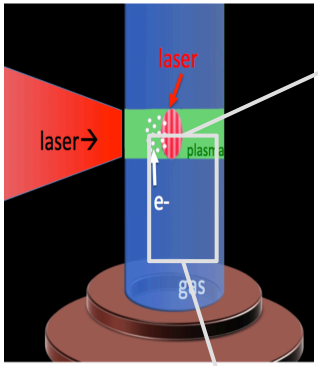
Intense femtosecond laser drives a plasma for Laser Plasma Acceleration (LPA)

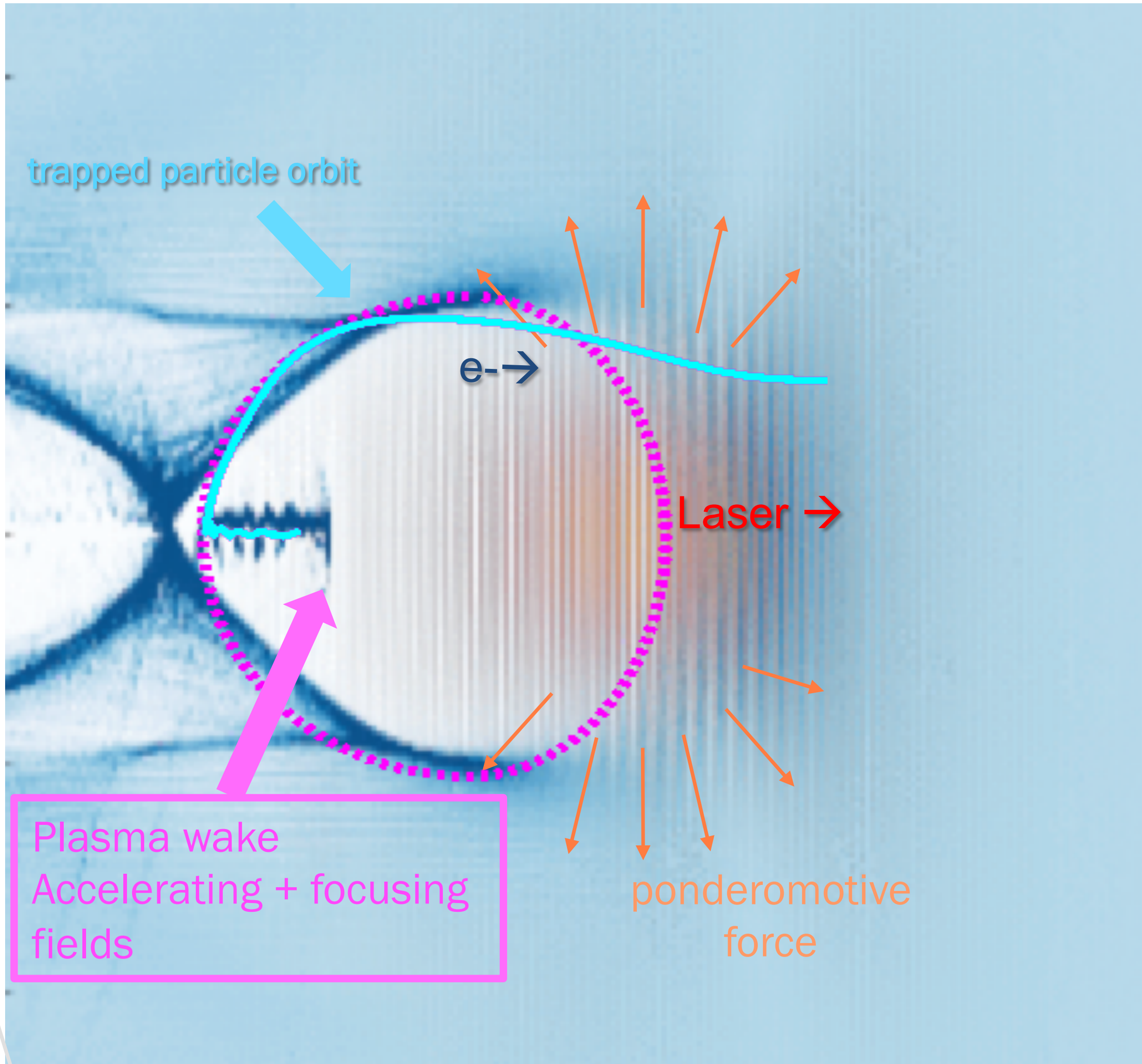


Intense femtosecond laser drives a plasma for Laser Plasma Acceleration (LPA)



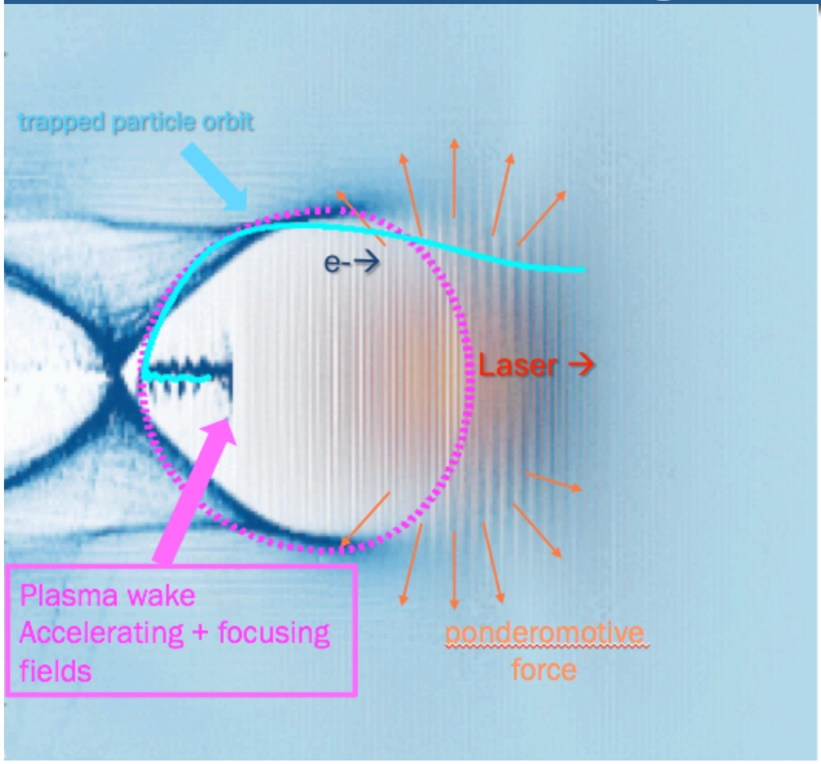
Plasma wave driven by radiation pressure of TW, fs laser





1: W.P. Leemans, Phys. Plasmas 1998, 2: C. Geddes et al., Nature 2004. 3: W.P. Leemans et al., PRL 2014, 4: S. Steinke et al., Nature 2016

Intense laser pulse creates a plasma structure capable of creating strong accelerating fields



Related:
Space charge of a particle
beam can excite similar structure.
Much of physics shared.

- No dephasing
- Nonlocal field
- 'Stiff' driver

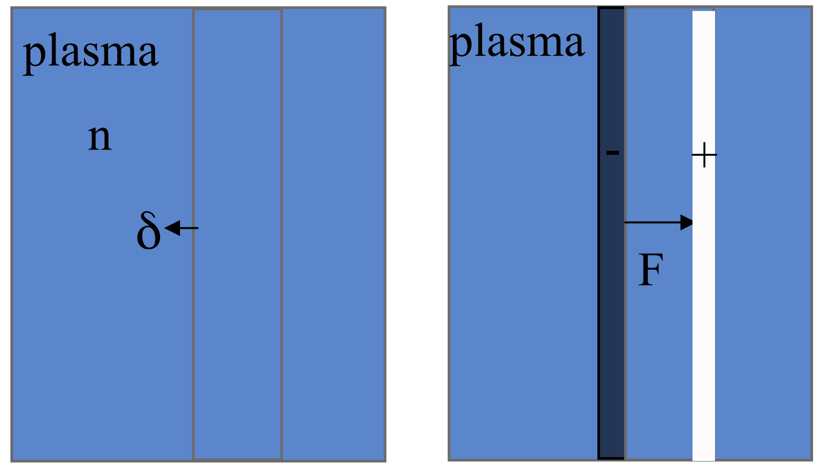
Direct laser acceleration?

- Not in vacuum
- In plasma structure direct can assist: typically low brightness

Plasma wave structure from electron oscillation and driver motion (not EPW dispersion relation!)

- Structure:
  - Oscillation driven by laser
  - Particles return after laser passes, forming wave: $v_\phi \sim v_{g,\ driver}$
  - 'Underdense', $\omega_p << \omega_L$: $v_{laser} \sim c$
  - Period $\lambda_p = 2\pi c/\omega_p \sim 30\mu m$ at $n \sim 10^{18}$/cc
  - scales as $n_e^{-1/2}$: longer period at low density

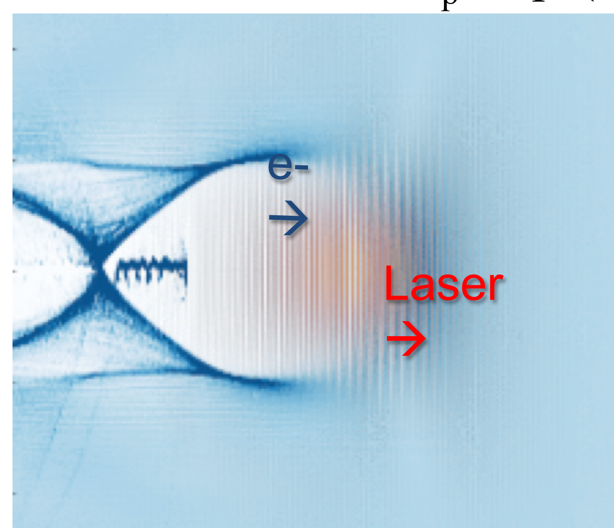
Plasma Oscillation



Displaced electrons induce electric field

$$E \propto n\delta \longrightarrow F \propto n^2\delta \longrightarrow \omega_p \propto \mathrm{sqrt}(n)$$

- Charge: $< e\, N_e\, (\text{wake period})^3 \sim e\, \lambda_p^3 n_e$
  - 10's of pC ($\sim 10^8$- 10^9 e-) at $n \sim 10^{18}$/cc
  - scales as $n_e^{-1/2}$ – higher at low density



Plasma wave offers GeV/cm acceleration

- Gradient – structure
  - 100% amplitude wave – plate charge approx.
  - $E \sim \sigma/\varepsilon_0 = \lambda_p n_e q_e/\varepsilon_0 \sim$ GV/cm at 10^{18}
  - scales as $n^{1/2}$ – high at high density

- Gradient – cold 1D nonrelatvisitic breaking

  $(E_{WB} e/m)*(1/\omega_p) = v_{wake} \sim c$

  $\rightarrow E_{WB} \sim$ GV/cm at $n \sim 10^{18}$

  scales as $n^{1/2}$ – high at high density

  - Corrections approx. balance, close est.

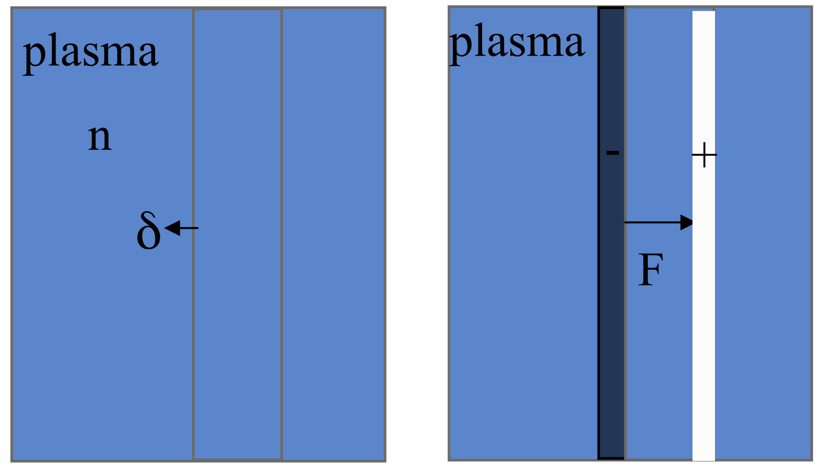
    3D - easier trapping

    Relativistic- harder trapping

  - <u>Note</u>: hot particles trap easily:

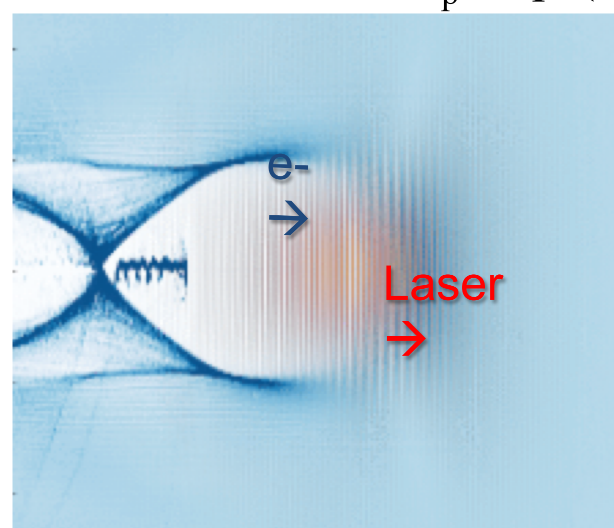
    Cold plasma ~10 eV << E_{trap}

<u>Plasma Oscillation</u>



Displaced electrons induce electric field

$E \propto n\delta \longrightarrow F \propto n^2\delta \longrightarrow \omega_p \propto \mathrm{sqrt}(n)$



Plasma wave driven by radiation pressure of TW, fs laser: GeV/cm acceleration

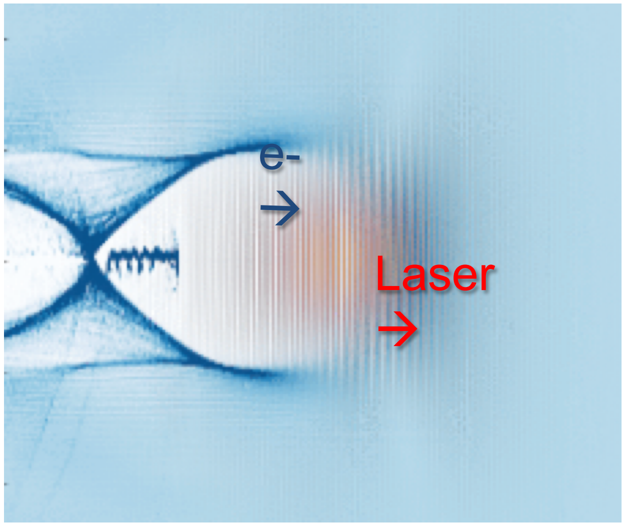
- Intensity to achieve Gradient limit:
  wake potential is order of ponderomotive potential

  $E_{wake} \sim \Phi_p/(0.25\lambda_p) \sim mc^2a^2/e\lambda_p \sim 0.5\ a^2\ E_{WB}$

  → a ~ >1 (~10^{18} W/cm^2) to approach E_{WB}

  $$a_0 = \gamma v_\perp / c$$

  electron motion in laser field is relativistic



- Pulse length for resonant drive ~ $(1/3)\lambda_p$
  - 30 fs for n ~ 10^{18}
- Pulse width ~ λ_p
  - Symmetric structure, efficient field energy partition

    Also: guiding, coming next….
  - Energy ~ λ_p^3: Joules at n~ 10^{18}

Quantitative LPA calculations: Cold fluid model

http://geddes.lbl.gov/papers/Geddes_dissertation.pdf

We begin with the fluid force and continuity equations in one dimension. We write the variables as the sum of a constant background plus a (small) perturbation $\mathbf{v} = \mathbf{v}_0 + \widetilde{\mathbf{v}}$, and discard quantities that are higher order in $\widetilde{\mathbf{v}}$. This is suitable for considering small departures from stasis:

$$\frac{\partial \widetilde{\mathbf{v}}}{\partial t} = -\frac{e}{m}(\mathbf{E}_\perp + \frac{\mathbf{v}}{c} \times \mathbf{B}_\perp + \mathbf{E}_P) \tag{2.9}$$

$$\frac{\partial}{\partial t}\frac{\widetilde{n}}{n_0} = -\nabla \cdot \widetilde{\mathbf{v}} \tag{2.10}$$

where $\mathbf{v}$ is the fluid velocity, n the density, e and m are the electron charge magnitude and mass, and c is the speed of light. $\mathbf{E}_\perp, \mathbf{B}_\perp$ are the (transverse) laser fields and $\mathbf{E}_P$ is the plasma field which is longitudinal: $\mathbf{E}_P = E_z$ for laser propagation along the z axis. Recalling that the high frequency electron motion in the laser field is (Eq. 2.5) $\mathbf{v}_\perp = \mathbf{a}c$ for small $\mathbf{a}$, we write the velocity $\widetilde{\mathbf{v}} = \mathbf{v}_s + \mathbf{a}c$ where $\mathbf{v}_s$ is the slow contribution. Averaging over a laser period, we then obtain for the force equation:

$$\frac{\partial \mathbf{v}_s}{\partial t} = -\frac{e}{m}(\nabla \Phi_P + \mathbf{E}_P) \tag{2.11}$$

where Φ_P is the potential from the ponderomotive force derived in Section 2.1.

Quantitative LPA calculations: Cold fluid model

http://geddes.lbl.gov/papers/Geddes_dissertation.pdf

the time derivative of the continuity equation and $\nabla\cdot$(force Eqn.):

$$\frac{\partial^2}{\partial t^2}\frac{\widetilde{n}}{n_0} = -\frac{\partial}{\partial t}\nabla\cdot\mathbf{v}_s = -\frac{e}{m}(\nabla^2\Phi_P + \nabla\cdot\mathbf{E}_P) \tag{2.12}$$

Then, making use of the Poisson equation $\nabla\cdot E = -4\pi e\widetilde{n}$, we find the response of the plasma to the laser driver:

$$(\frac{\partial^2}{\partial t^2} + \omega_p^2)\frac{\widetilde{n}}{n_0} = -\frac{e}{m}\nabla^2\Phi_P = \frac{c^2}{4}\nabla^2 a^2 \tag{2.13}$$

It can often be useful to take a frame of reference (nearly) co-moving with the laser at $c \approx v_g$. Hence we transform $\xi = z - ct$, $t = t$ and find:

$$(\frac{\partial^2}{\partial \xi^2} + k_p^2)\frac{\widetilde{n}}{n_0} = (\nabla_\perp^2 + \frac{\partial^2}{\partial \xi^2})\frac{a^2}{4} \tag{2.14}$$

The equation is that of a driven harmonic oscillation, with $\widetilde{n}/n$ as the oscillation variable and the ponderomotive potential as the driver, just as one would expect from the discussion of the plasma oscillation and ponderomotive force in Section 2.1. The Green's function solution for such an oscillator is [3, 16, 66]:

$$\frac{\widetilde{n}}{n_0} = \frac{1}{\omega_p}\int_{-\infty}^{t} sin(\omega_p(t-t'))\nabla^2\frac{c^2a^2(\mathbf{r},t')}{4}dt' \tag{2.15}$$

Quantitative LPA calculations: Cold fluid model

http://geddes.lbl.gov/papers/Geddes_dissertation.pdf

Using the Poisson equation to relate density to electric field and potential, the solutions for these quantities are:

$$\begin{aligned} \Phi &= \frac{mc^2\omega_p}{4e}\int_{-\infty}^{t} sin(\omega_p(t-t'))a^2(\mathbf{r},t')dt' \\ E_z &= -\frac{mc^2\omega_p}{4e}\int_{-\infty}^{t} sin(\omega_p(t-t'))\nabla a^2(\mathbf{r},t')dt' \end{aligned} \tag{2.16}$$

Solutions of this equation are obtained by integrating over the laser pulse shape. For a sine pulse ($a_0 \propto sin(\xi/(c\tau_L))$ for $0 \leq \xi/(c\tau_L) \leq \pi$ and $a_0 = 0$ elsewhere) we find that the largest plasma response is obtained for a pulse length $c\tau_L = \lambda_p$, and the plasma wave electric field behind the laser pulse is then:

$$\frac{E_z}{E_0} = -\frac{\pi a_0^2}{8} cos(k_p\xi) \tag{2.17}$$

and as noted above the potential and the density perturbation:

$$\frac{\widetilde{n}}{n} = -\frac{\pi a_0^2}{8} sin(k_p\xi) \tag{2.18}$$

again follow from Poisson.

Quantitative LPA calculations: Multi-dimensional wakes- accelerate & focus

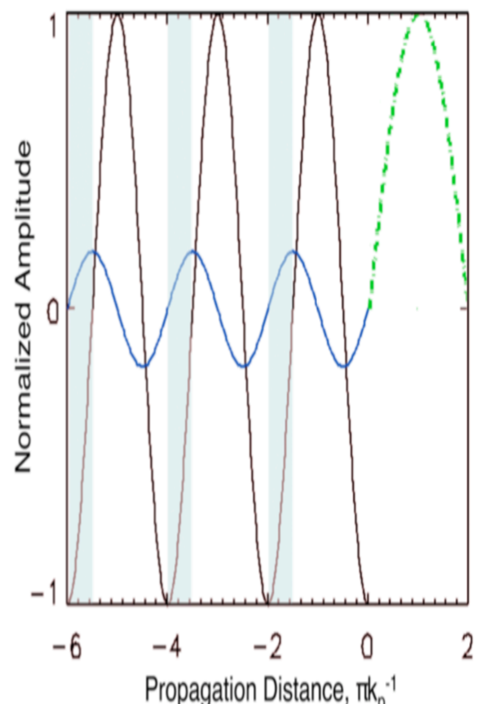
If the wake is not one-dimensional, the radial wake can be derived from the Panofsky-Wenzel theorem [3, 16, 75, 76]. This will be most important for laser spot size (and hence wake radial dimension) $\lesssim \lambda_p$. We make use of:

$$\mathbf{E} = -\nabla\Phi \Rightarrow \frac{\partial E_r}{\partial z} = \frac{\partial^2\Phi}{\partial z\partial r} = \frac{\partial E_z}{\partial r} \tag{2.19}$$

assuming azimuthal symmetry in cylindrical coordinates, as is reasonable for typical round laser driver spots ($\partial\phi/\partial\theta = 0$). For a laser with a Gaussian radial envelope (Section 2.4), the fluid solution (Eq. 2.17) yields:

$$E_z = -\frac{\pi a_0^2 E_0}{8} exp(-2r^2/w_0^2) cos(k_p\xi) \Rightarrow E_r = \frac{\pi a_0^2 E_0}{8}\frac{4r}{w_0^2 k_p} exp(-2r^2/w_0^2) sin(k_p\xi) \tag{2.20}$$

Hence there is a wake region where the fields are both accelerating and focusing: $E_z < 0$ and $E_r > 0$ for $-2\pi < k_p\xi < -3\pi/2$, and this repeats in each wake period.



Wake longitudinal (black) and peak radial (blue) fields behind a laser pulse with a sine envelope (green dotted), from Eq.'s 2.17&2.19 for $w_0 \sim \lambda_p$.

Shaded regions: radial field is positive and longitudinal field negative, are both accelerating and focusing for electrons.

Limited but gets basic scalings: linear 3d and nonlinear 1d also tractable

Laser-plasma acceleration: Acceleration limits (guided)

- Dephasing: v_{driver} < c so particles slip out of phase

$$L_d(1 - v_p/c) = \lambda_p/2$$

$L_d = \lambda_p^3/\lambda_0^2$

- Depletion: energy in wake depletes energy in laser

  - Laser pulse energy: $W_L \propto E_L^2 L_L$
  - Plasma wake energy: $W_P \propto E_z^2 L_p$
  - Pump depletion length: L_p

$$E_z^2 L_p = E_L^2 L_L$$

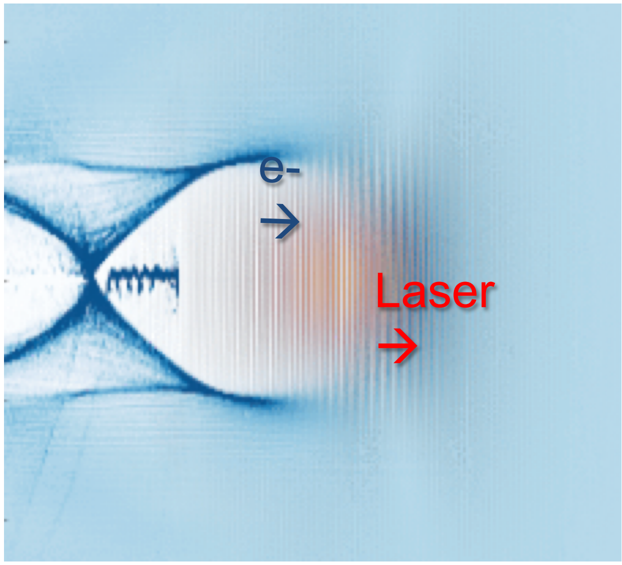
Linear wakefield: $a_0^2 \ll 1$

$$E_L \propto \omega a_0,\ L_L \sim \lambda_p,\ E_z \propto \omega_p a_0^2$$

$$L_p \simeq (\omega^2/\omega_p^2)\lambda_p/a_0^2 = \gamma_p^2 \lambda_p/a_0^2$$

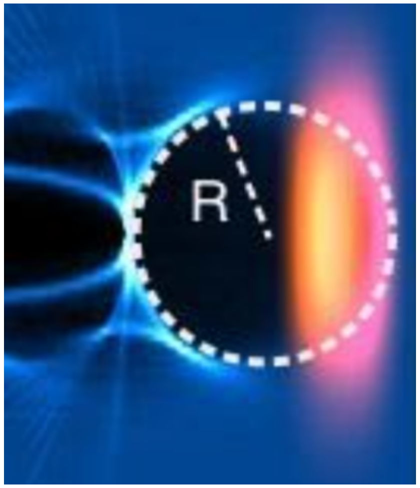
$L_{pump} = 4\, L_d/a^2$ → a ~ 1-2 efficient

- Energy gain: $E_{wake}\, L_{d,pump} \sim a^2\, \lambda_p^2/\lambda_0^2$

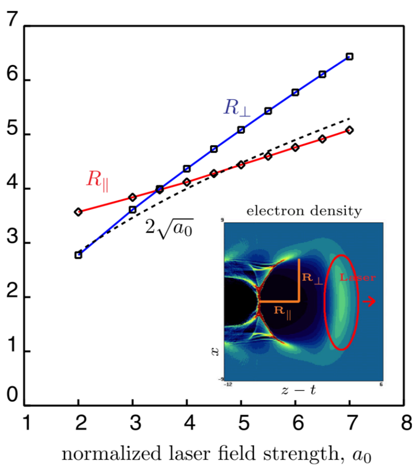


GeV energies in few cm at 10^{18}/cc with few 10^8 e- using Joule-class lasers

Experiments are not 1D or linear: Limited methods for 3D nonlinear 'bubble' wakes



*Lu et al., Phys Rev. Lett 2006 and PR-STAB 2007



Benedetti et al, Phys Plasmas 20, 103108, 2013

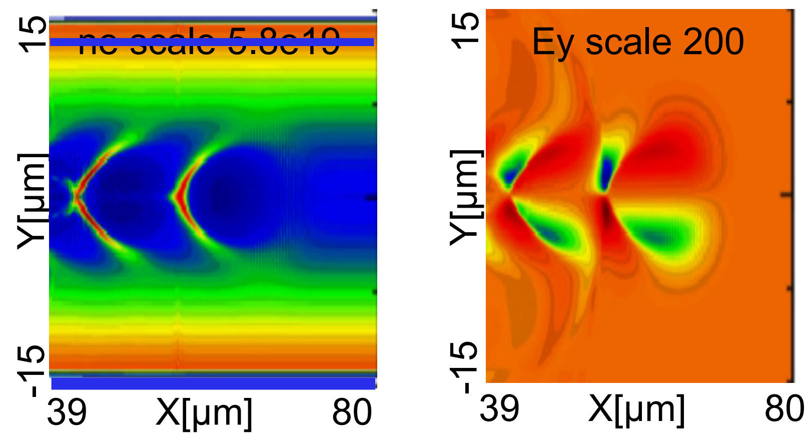
- Nonlinear scalings*
  - $E_{electron\text{-}bunch} \sim 1/n$
  - $P \sim 1/n$
  - $E_{laser} \sim 1/n^{1.5}$
- Similar to linear: coefficients differ

- For a_0=2 10 GeV
  - n_e = 1.3e17
  - vs 1e17 at a=1

- Similar E_{laser}/E_e

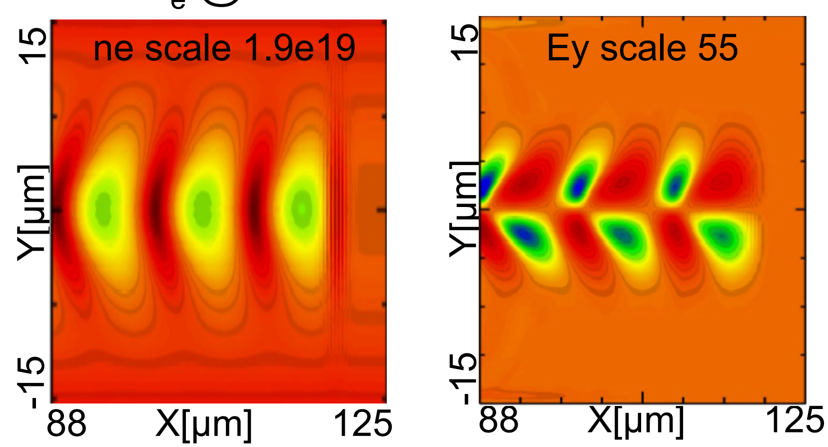
<u>a_0=2 nonlinear</u>

scaled n_e @ $1.3\text{x}10^{19}$ - Ex = 230-550 GV/m



<u>a_0=1 quasilinear</u>

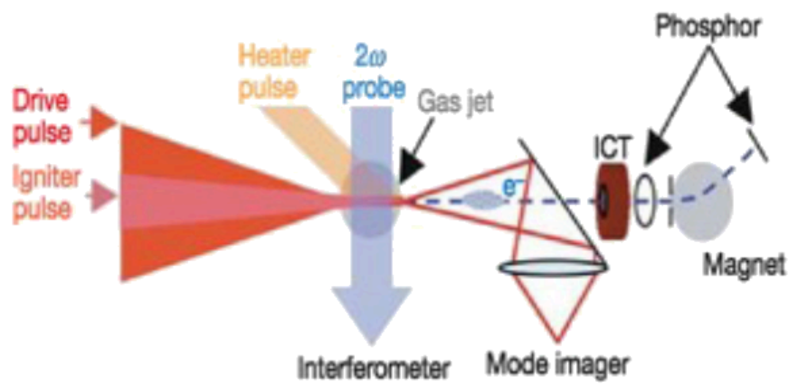
scaled n_e @ $1.3\text{x}10^{19}$ - Ex = 135-165 GV/m

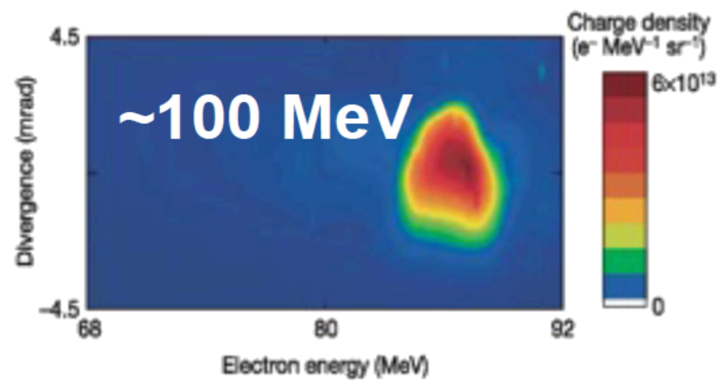


Remarkably, scalings with plasma parameters remain the same
detailed changes but similar general acceleration

Guided, self injected experiments at lower density: high energy, lower energy spread

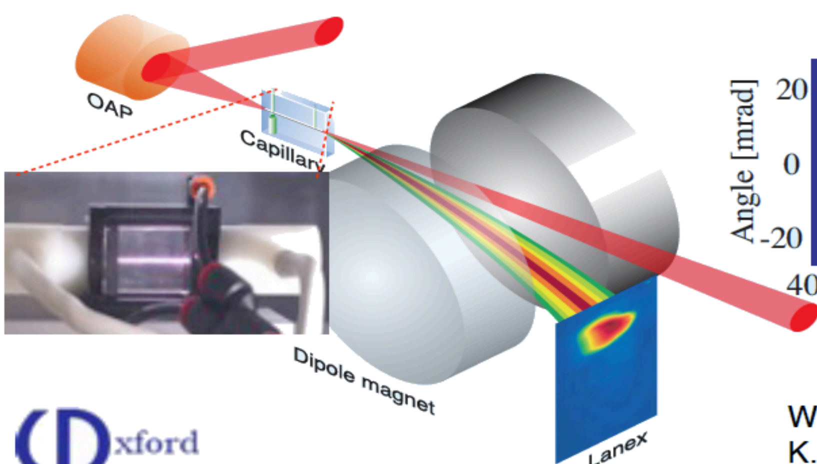
2004 result: 10 TW laser, mm-scale plasma

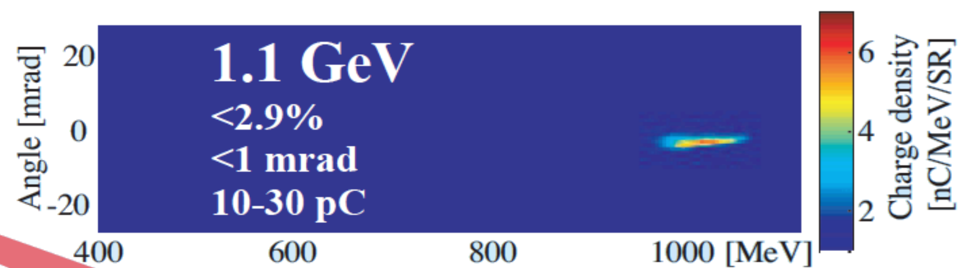


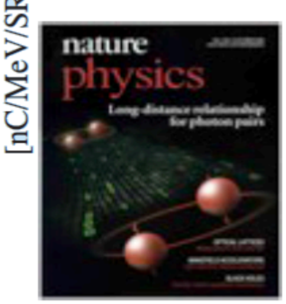


C. G. R. Geddes,et al, Nature,**431**, p538 (2004)
S. Mangles et al., Nature **431**, p535 (2004)
J. Faure et al., Nature **431**, p541 (2004)

2006 result: 40 TW laser, cm-scale plasma



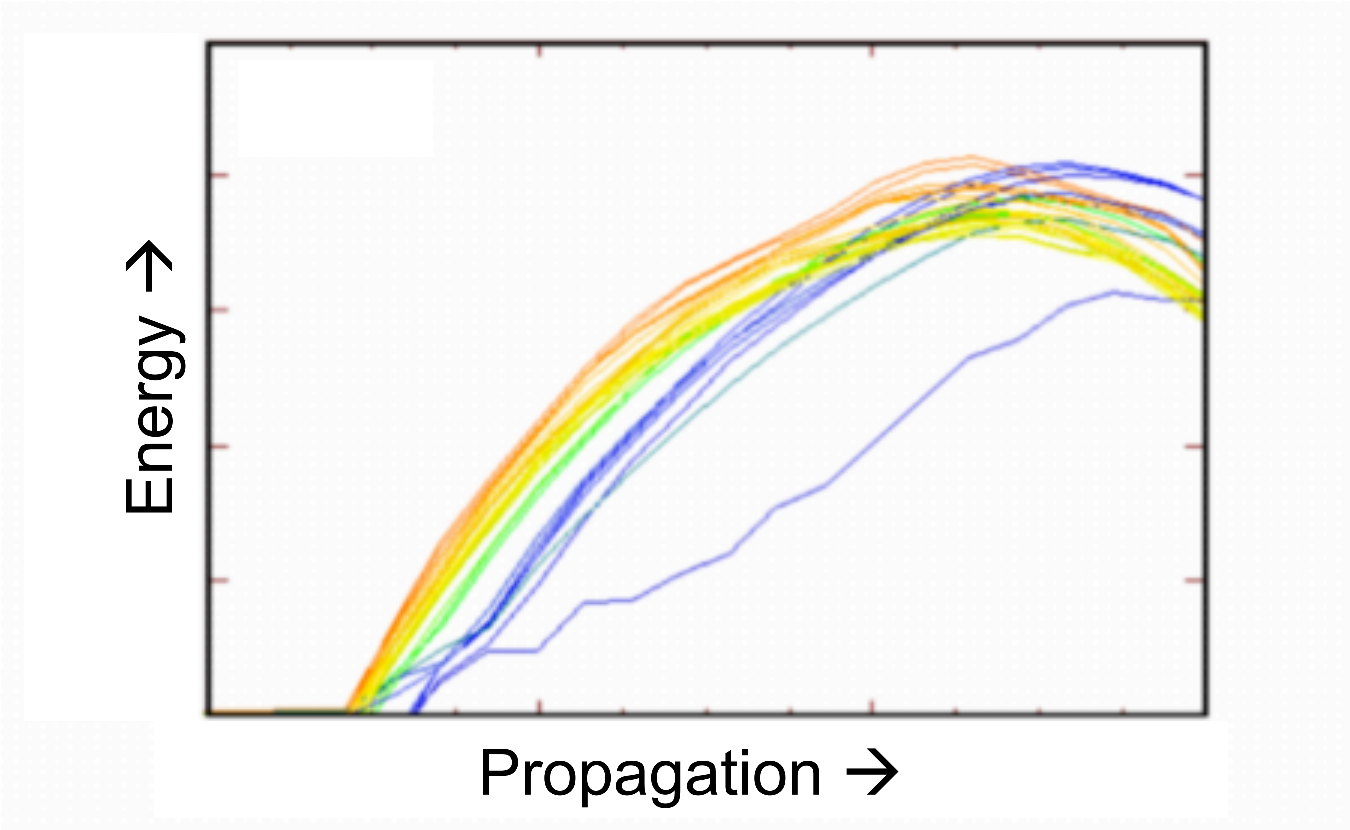




W.P. Leemans et. al, *Nature Physics* **2**, p696 (2006)
K. Nakamura et al., Phys. Plasmas **14,** 056708 (2007)

Oxford Physics

High quality self trapped beams can result from dephasing

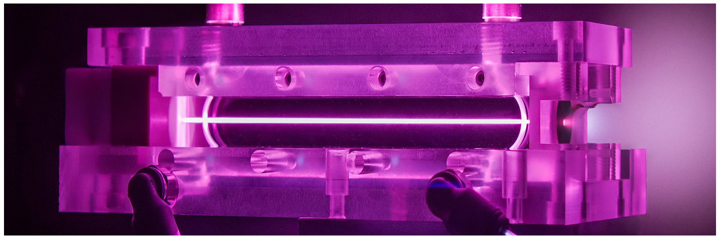


bunches energies

Capillary discharge allows long waveguides (several cm) Up to 4.2GeV using 300TW

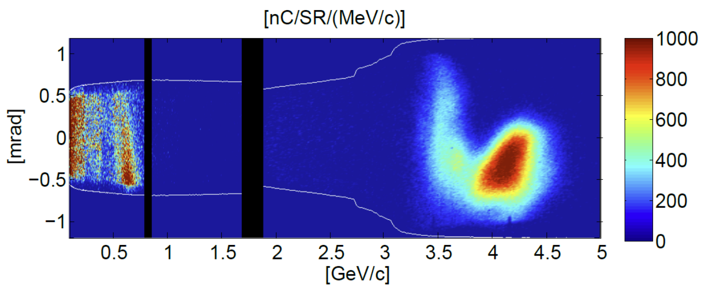
Capillary discharge forms plasma channel

Ohmic heating from current and cold walls form quasi-static parabolic density distribution near axis. MHD physics.



D. J. Spence & S. M. Hooker *PRE* 2001

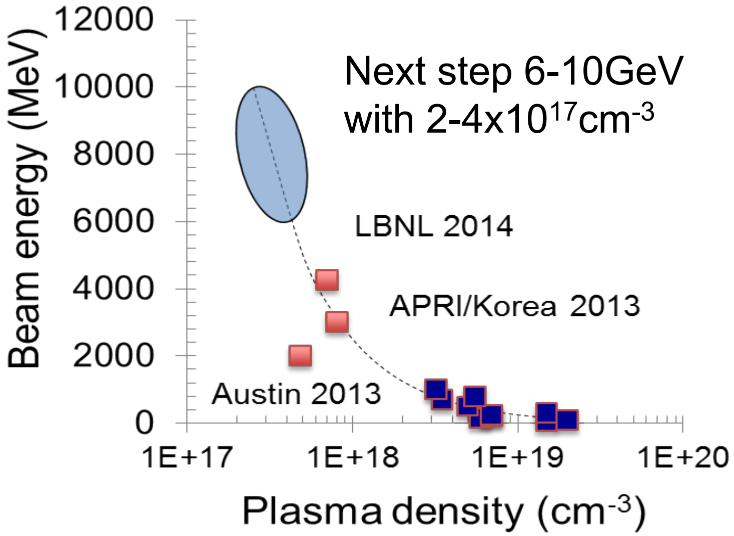
2014 Record LPA energy



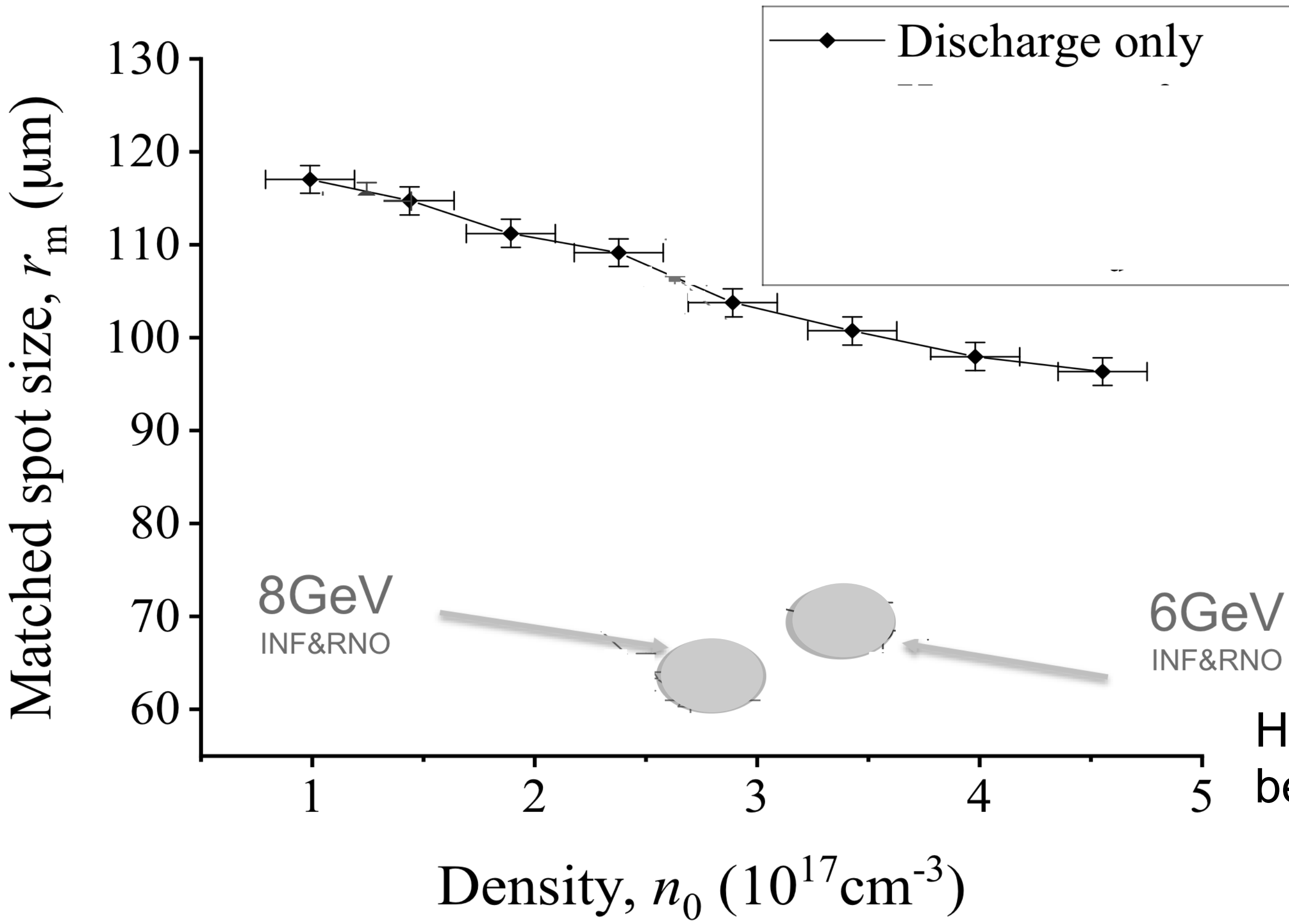
- 300 TW
- Up to 4.2 GeV (7×10^{17} cm^{-3})
- Stable 2.7 GeV beams (8.5×10^{17} cm^{-3})
- Up to 200 pC (1.1×10^{18} cm^{-3})

W. P. Leemans et al., *PRL* 2014;
A.J. Gonsalves et al., *PoP* 2015

Need lower density, higher power



Problem: MHD/heat conduction channel not sufficiently deep at desired density



$D_{capillary}$= 800µm

Hotter discharge? no – before desired spot:

Melt wall

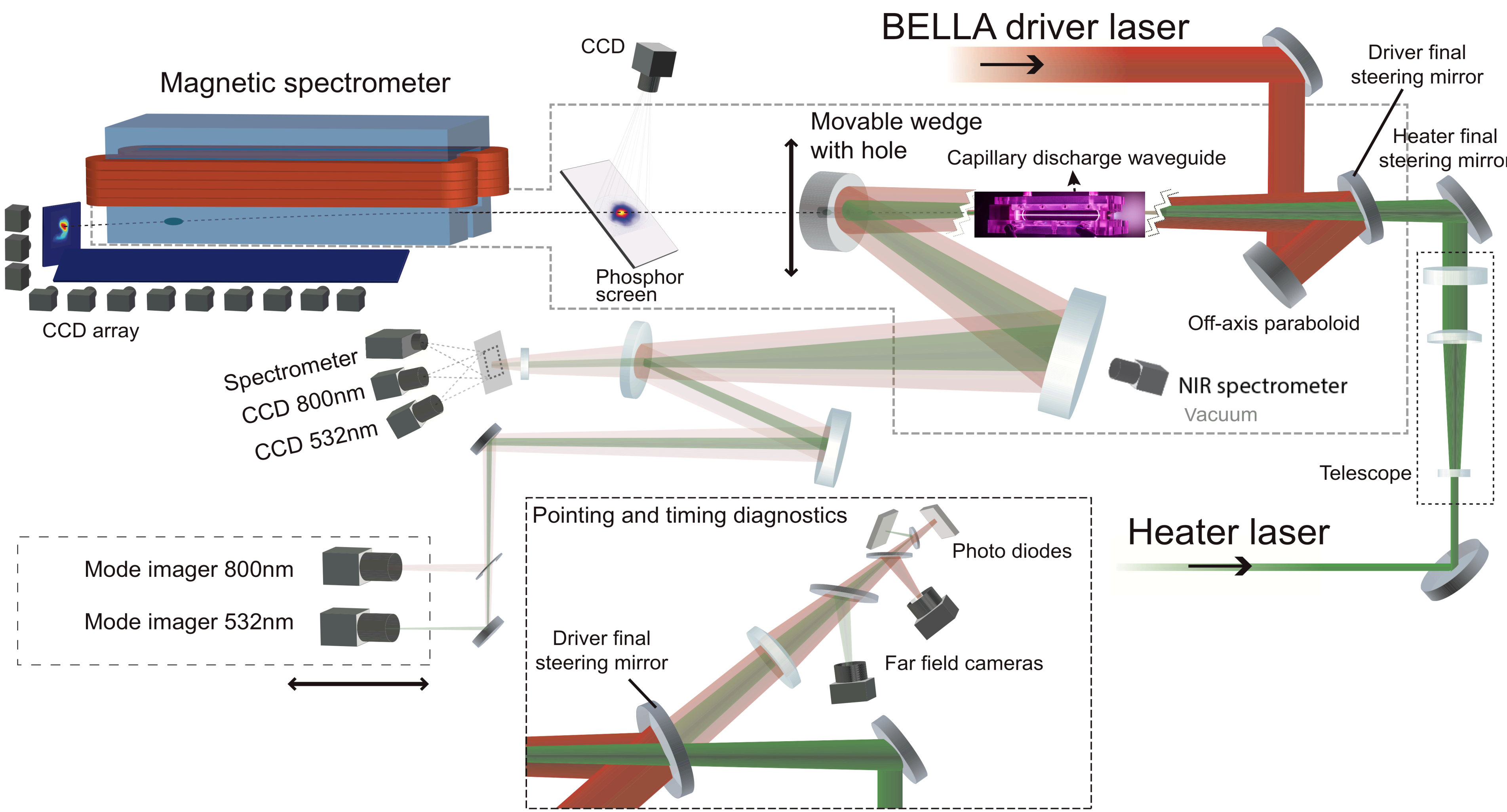
Undesired injection

Magnetic field? Difficult

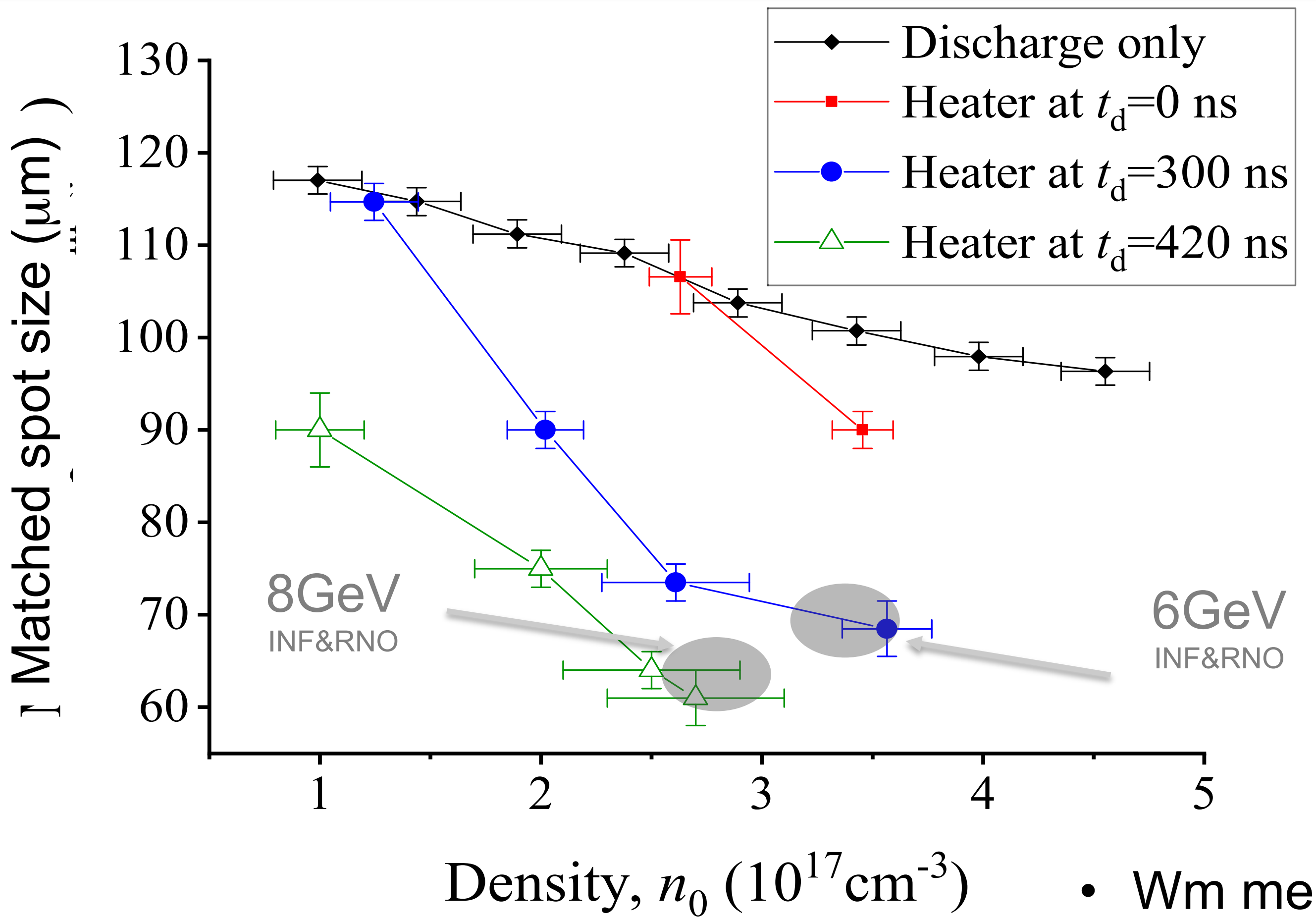
High B: rep rate & effic.

A. J. Gonsalves et al., Phys. Rev. Let. 2019

Heater laser added to BELLA petawatt beamline



Heater laser significantly lowers matched spot size

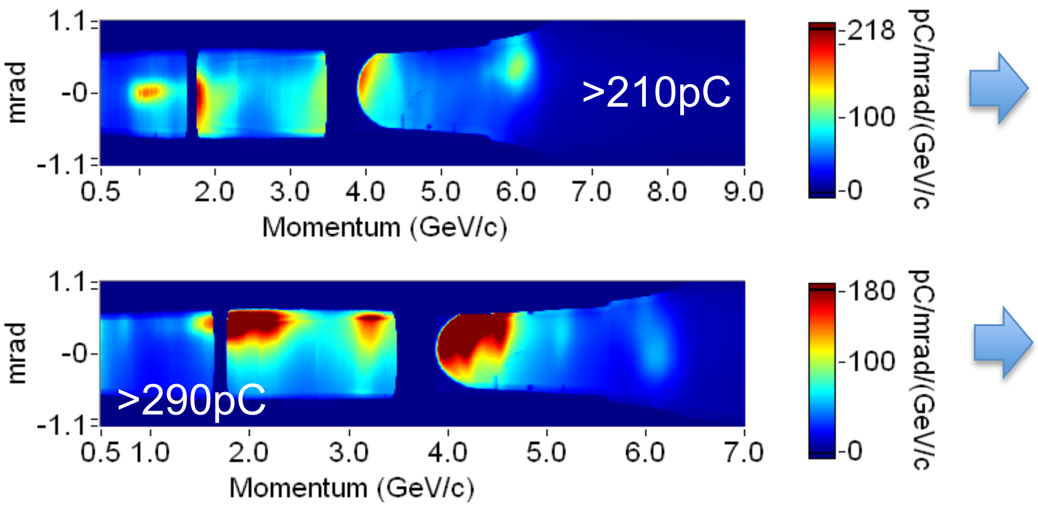


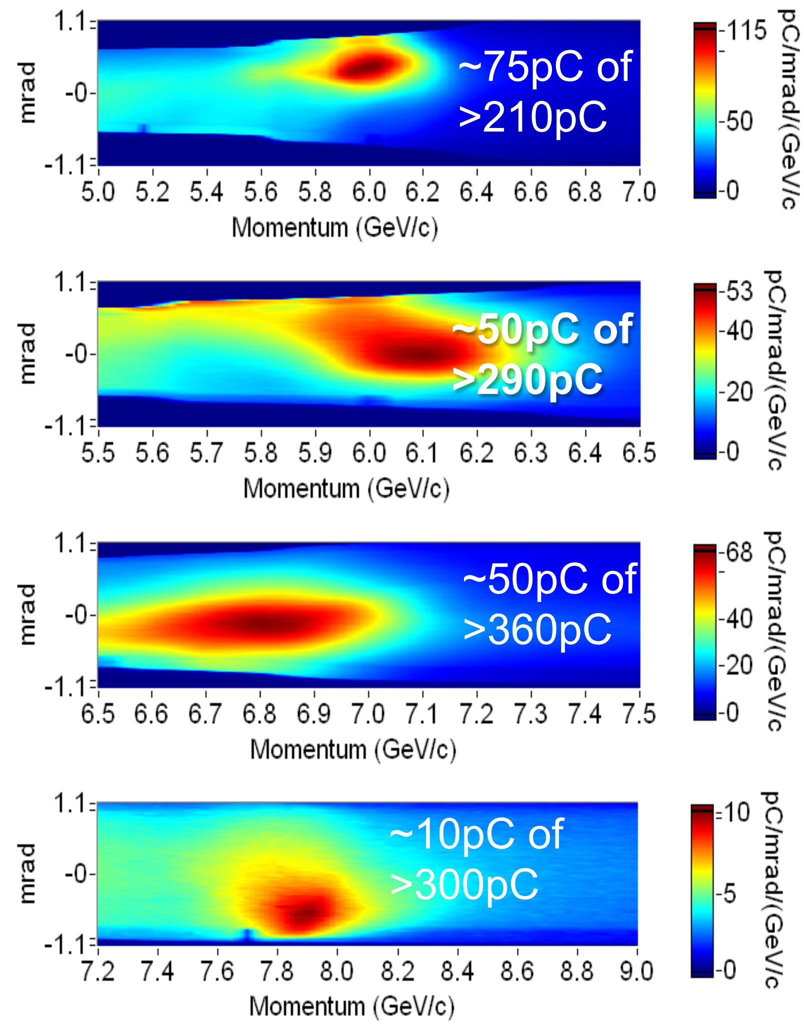
U_{Heater} = 300mJ
$D_{capillary}$= 800μm
$W_{0heater}$=80μm

- Wm measured with centroid, spot size, and divergence oscillations
- Density from group velocity measurements

A. J. Gonsalves et al., Phys. Rev. Let. 2019

Electron beams with energy up to 7.8GeV observed for density 3.4e17/cc





- Non-localized injection produces energy spread
- Highest energy bunches dE/E~10%
- Beam divergence down to 150urad FWHM
- 0.5-1 joule energy in e beam

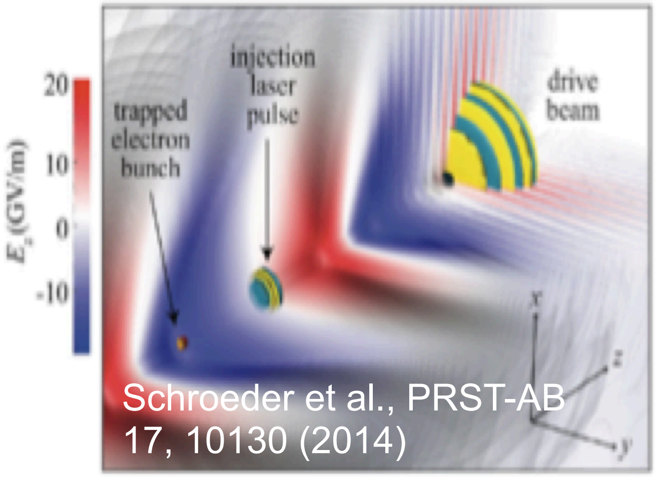
A. J. Gonsalves et al., Phys. Rev. Let. 2019

Important firsts demonstrated, path appears realistic: We are far from optimum, much exciting work to do

Currently	Developing
E: Stable few %	<1%
ΔE: Stable at 10%	<1%
Diverg: ~ mrad	< 0.1mrad
Point: ~ mrad	< 0.1 mrad
Emittance: 0.1 μm	0.01 μm
Charge: ~10 pC	~100pC
Efficiency: few %	~30%
Rate: Hz	≥ kHz
e- only	e-, e+

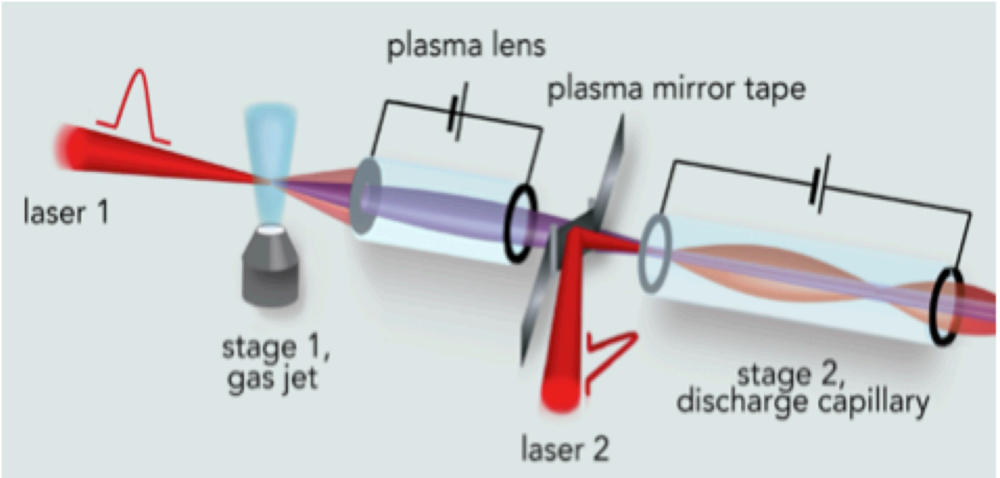
Physics challenge: generate/manipulate ultra-bright beams by precision laser and plasma control/shaping

Injection: brighter 6D, shaped bunches



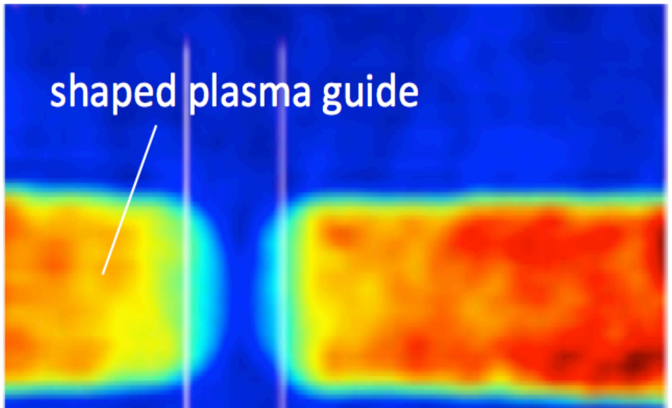
Schroeder et al., PRST-AB 17, 10130 (2014)

Acceleration: preserve emittance, stage efficiently



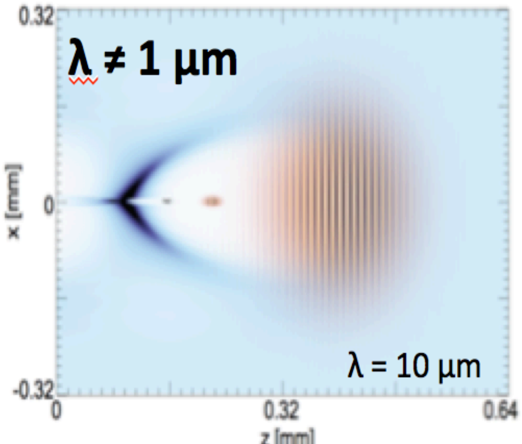
S. Steinke et al., Nature 530, 190 (2016).

Guiding: reach depletion limit, tailor waveguide & laser

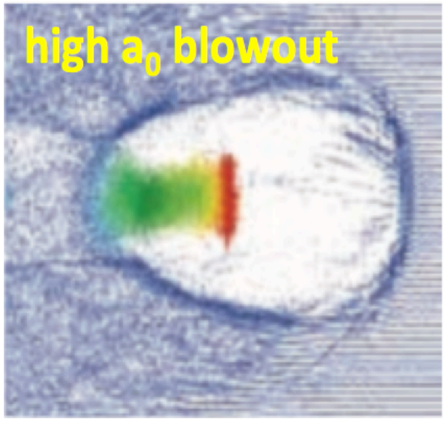


Hine, Michberg et al., Optics Letters 41, 15, p3427 (2016)

Optimization: scaling with *λ*, a_0, *etc.*



Courtesy M. Downer



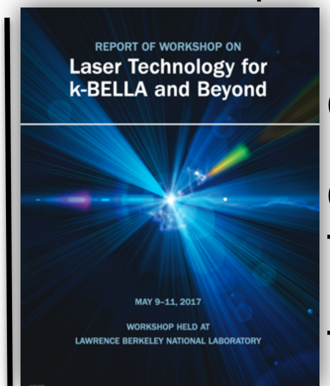
Pukhov et al., Appl. Phys. B 74, 355–361 (2002)

kHz rep rate LPA next for high flux and efficiency stabilized, shaped few-Joule 30fs laser pulses

Develop stable, efficient accelerator system based on laser-plasma wake

- High beam brightness. via advanced injectors, e.g. 2-color ionization
- Efficient acceleration – high charge
- Efficient stage coupling
- Precision photon & positron sources

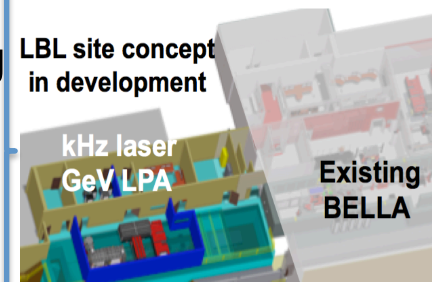
Technical paths available to kHz, GeV accelerator



Fiber Combining

Cryo-DP TiSaph

TmYLF



Two key issues: <u>shot-to shot fluctuation</u>
precision laser shaping

Ground & air motion fall off at O[100Hz]
khz, few-Joule 30 fs system=stable GeV

- Laser pointing: µrad to < 0.1 µrad
- Focus/wavefront: now at fluct. limit
- Near field: currently not well controlled
- Pulse shape, carrier envelope

LPA control using shaped laser pulses beyond current limits of fluctuation

Collider and photon source applications require order[s] of magnitude higher brightness, efficiency

- LPA currently operating at fraction of accessible performance
- Laser control at shot-to-shot limit, stabilization key
- GeV class LPA representative
- Few-joule laser energy at kHz accessible near term – enable progress

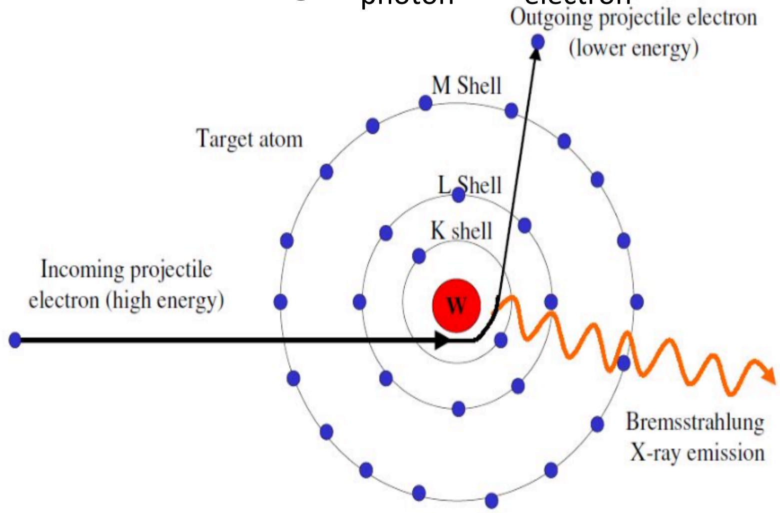
Outline

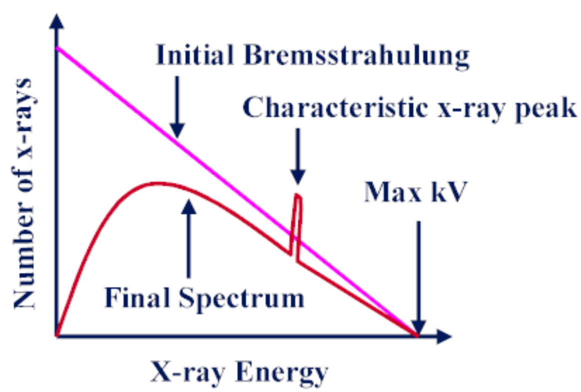
- Introduction
- Nonlinear Optics of Plasmas
- Lepton acceleration
- <u>Photon sources</u>
- Ion acceleration
- High field science and nonlinear QED
- Personal perspectives & resources

Precise high-energy photon sources also rely on accelerators

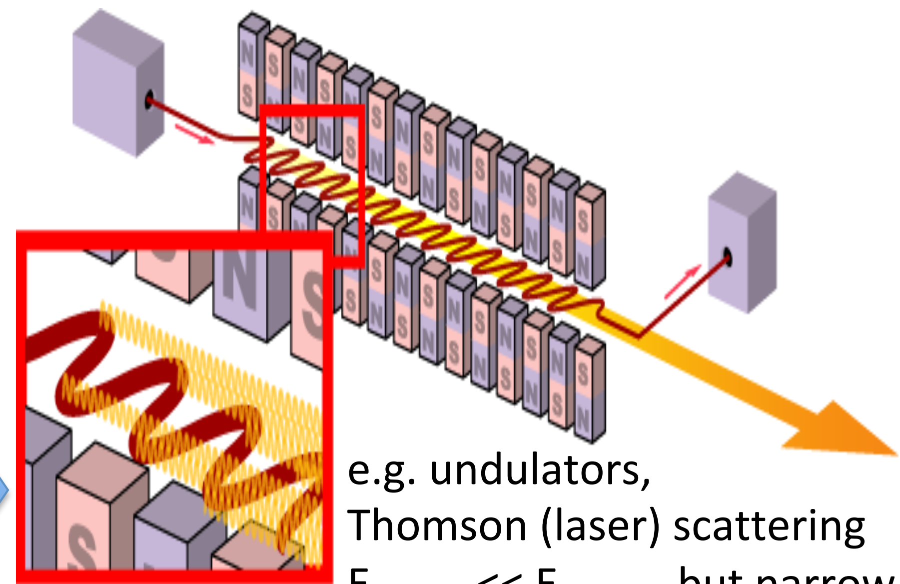
Simple, Low E_e

Bremsstrahlung: $E_{photon} \sim E_{electron}$, broad

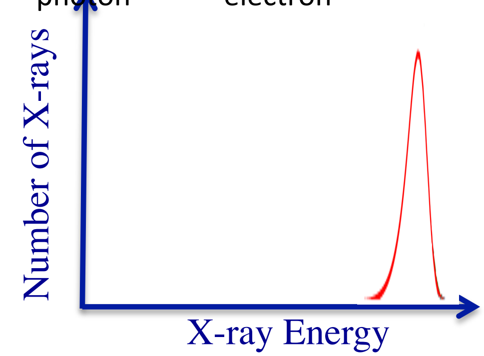




Lower dose, higher resolution



e.g. undulators,
Thomson (laser) scattering
$E_{photon} \ll E_{electron}$ but narrow

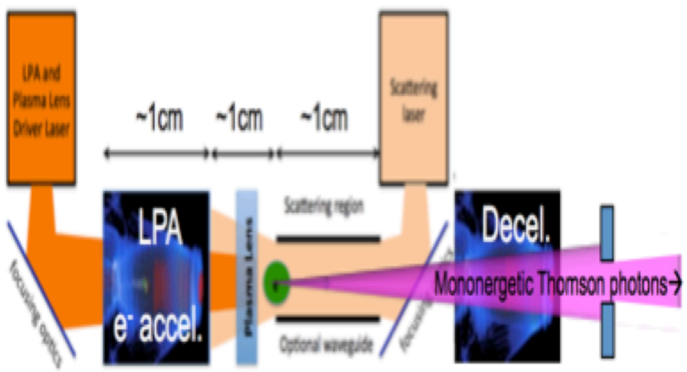


keV photons require keV electrons

keV photons require MeV - GeV electrons

Photon sources: broad benefit, intermediate beam parameters
GeV-class, ≤ μm emittance, ≤ percent energy spread

Thomson source

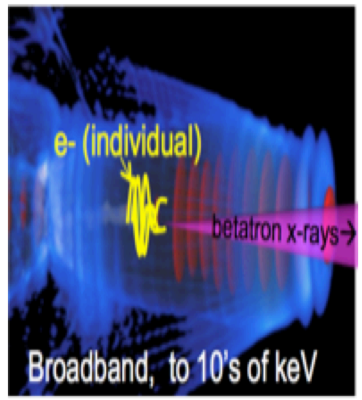


Narrow ΔE, keV to MeV, femtosecond, mrad

NNSA Defense Nuclear Nonproliferation R&D

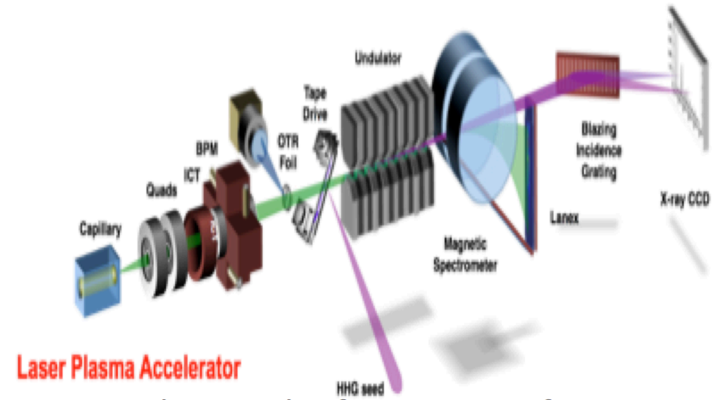
DHS/DNDO

Betatron source



DOE Sc. FES

Free electron Laser



Coherent ultrafast XUV to soft Xrays

Gordon and Betty Moore Foundation

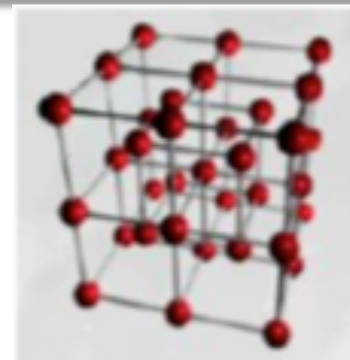
DOE Sc. BES

GeV-class
≥ kHz
10-100pC
≤ μm emittance
≤ percent ΔE

- Monoenergetic keV-MeV photons: Improve radiography, photofission, NRF. New signatures, including backscatter, polarized photofission, nuclear isomers.
- Applications: Nonproliferation and HEDS probes
  - Related: security, medical, industrial, stockpile

- Coherent photons in UV to Xray bands depending on accelerator & beam transport performance
  - Intrinsically bright, femtosecond source
- Applications: material science, biology…

Photon sources are accelerator gradient limited: Enable precision high performance for field applicartions



GeV photon source drivers at truck/lab scale & fs duration?

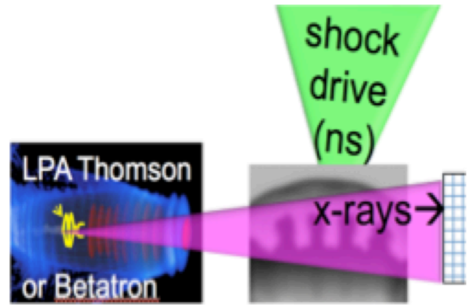
Plasma Accelerators & Photon Sources Could Enable Scientific & Societal Grand Challenges

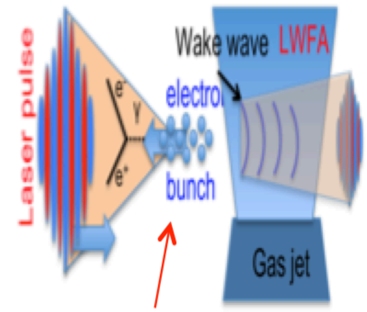
sub-µm resolution, reduced dose x-ray characterization

including:
- narrow ΔE_x
- low $\Delta\theta_x$
- coherent

< 1 µm emittance

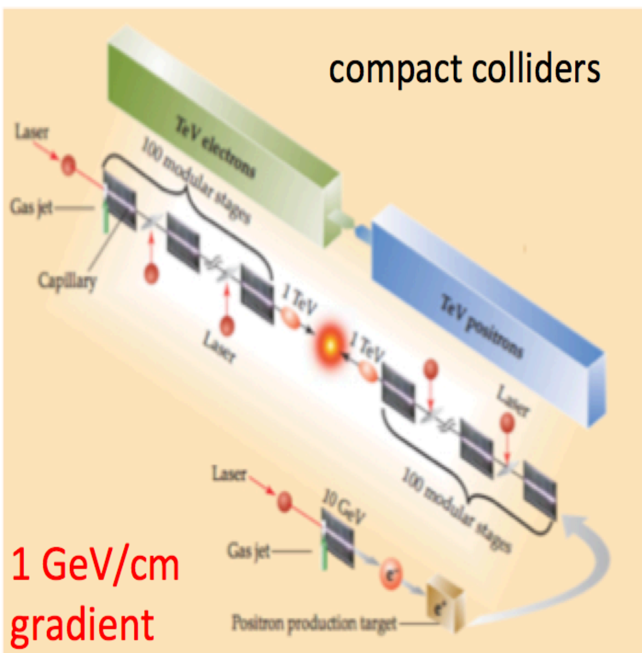
femtosecond dynamic probes





fs e-bunches

$10^{22} - 10^{26}$ W/cm^2



Leemans & Esarey Physics Today 2009

multi-species material characterization (1-stop shopping)

- Basic Science
- Medical
- Industrial
- Military

electrons, positrons, photons, hadrons using one laser

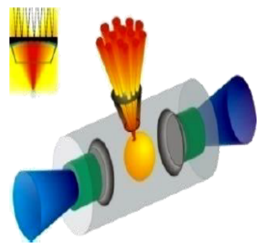
Outline

- Introduction
- Nonlinear Optics of Plasmas
- Lepton acceleration
- Photon sources
- <u>Ion acceleration</u>
- High field science and nonlinear QED
- Personal perspectives & resources

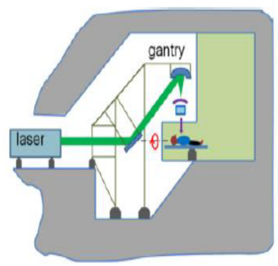
Laser Ion Acceleration has a number of applications

Applications:

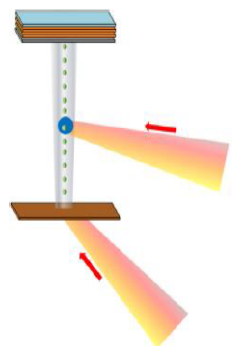
Fast Ignition



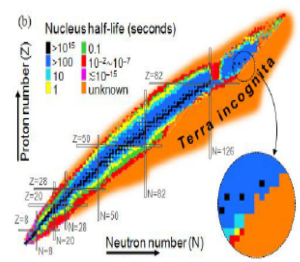
Hadron Therapy



Proton Radiography

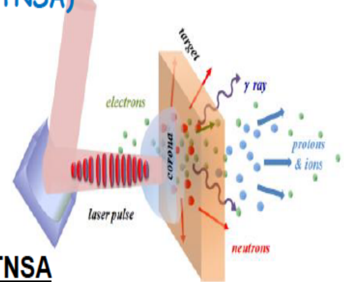


Nuclear Physics



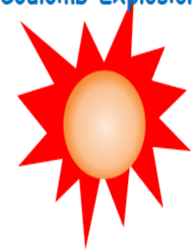
Mechanisms:

Target Normal Sheath Acceleration (TNSA)



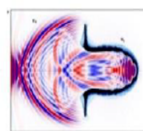
TNSA
Laser: Moderate Intensity
Target: Thick solid density foils
Ion Energy: ~100 MeV

Coulomb Explosion (CE)



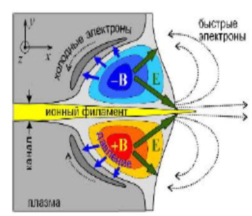
CE
Laser: High Intensity
Target: Clusters-MLT
Ion Energy: MeV - GeV

Radiation Pressure Acceleration (RPDA)



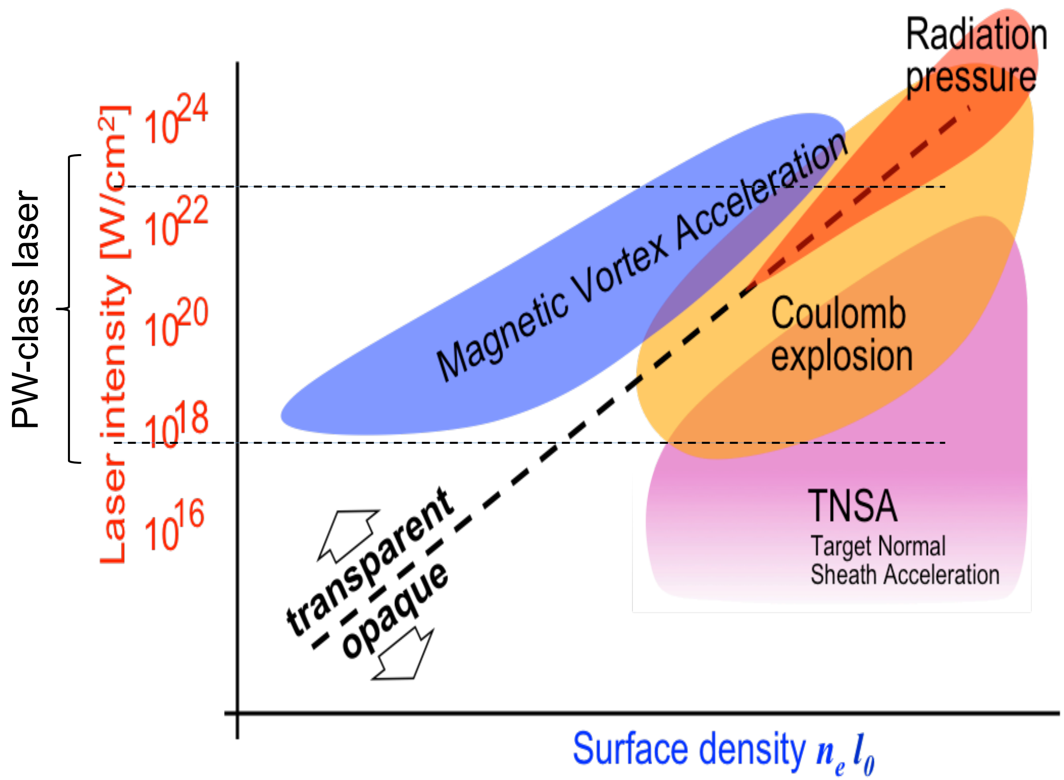
RPDA
Laser: High Intensity
Target: Thin Foil - MLT
Ion Energy: GeV

Magnetic Vortex Acceleration (MVA)



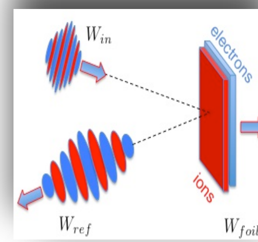
MVA
Laser: High Intensity
Target: Near Critical Density Slab
Ion Energy:100s of MeV to GeV

The Ion Acceleration Mechanism is Determined by Laser Intensity and Target Surface Density



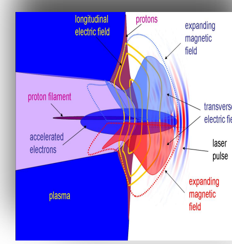
RPA
Laser: High Intensity
Target: Thin solid density foils
Ion Energy: hundreds of MeV

Ion Energy ~ Laser Power



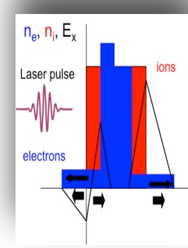
MVA
Laser: High Intensity
Target: Near Critical Density slab
Ion Energy: hundreds of MeV to GeV

Ion Energy ~ Laser Power$^{2/3}$



TNSA
Laser: Low Intensity
Target: Thick solid density foils
Ion Energy: ~100 MeV

Ion Energy ~ Laser Power$^{1/2}$

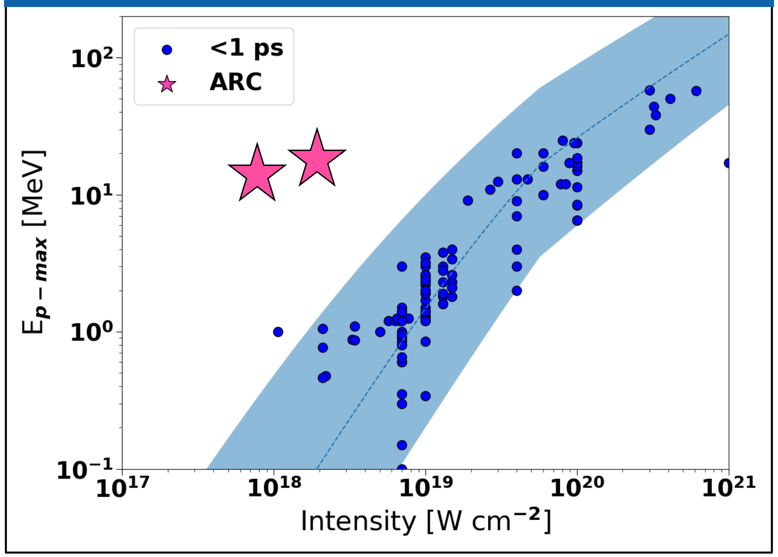


Applications: Radiography, Deflectometry, Cancer Therapy, Injection into conventional accelerators, Fast Ignition, Isochoric heating of matter, Positron Emission Tomography, Nuclear Physics…

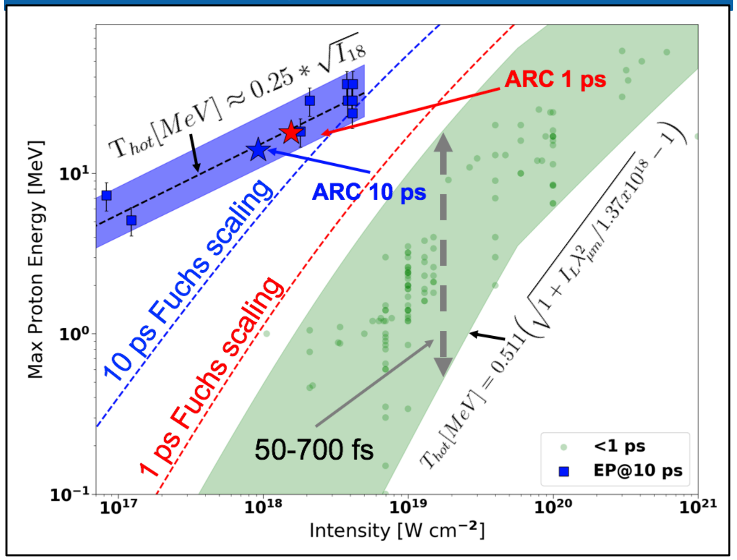
S. S. Bulanov, et al., Physics of Plasmas 23 , 056703 (2016);

Proton maximum energies on ARC exceed conventional scaling by ~5x

Maximum Proton Energy vs. Intensity



A new scaling has been determined



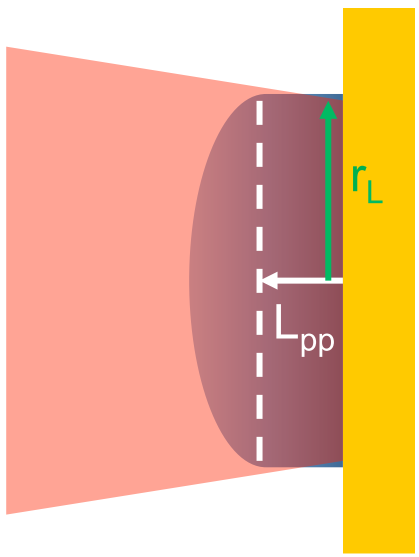
- **A robust proton source has been successfully demonstrated on NIF ARC**
  - Maximum energy of **18 MeV** @ 1 ps
  - **> 50 J** into protons @ 10 ps pulse-length
- **New modeling capability can accurately predict max proton E**
- **Super-ponderomotive electron acceleration → higher than predicted proton energies**

Why can we get such high proton energies at sub-relativistic intensities?

D. Mariscal *et al., Phys. Plasmas,* accepted (2019)
D. Mariscal *et al., PRL,* submitted

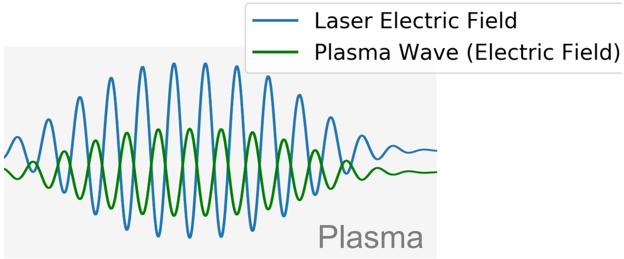
Courtesy, Tammy Ma

Electrons can be accelerated to “super-ponderomotive” energies via multiple mechanism in 10’s of micron scale low density pre-plasma



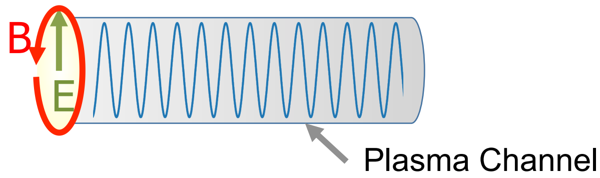
Self-Modulated Laser Wakefield Acceleration (SMLWF)

E. Esarey, et al., Rev. Mod. Phys. (2009)



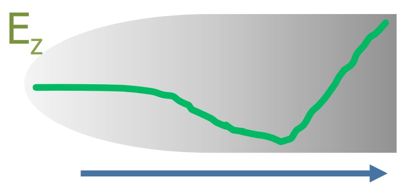
Direct Laser Acceleration

A. Pukhov, et al., PoP ***6*** *(1999);*
A. Arefiev, et al. PoP ***23*** *(2016)*



Potential + Dephasing

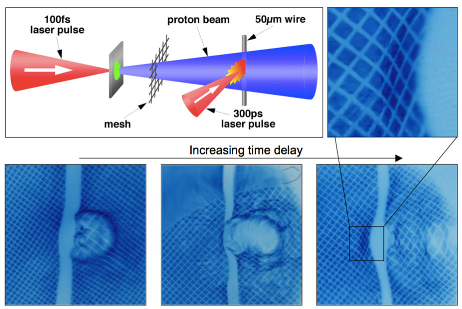
B. Paradkar, et al., PoP ***19*** *(2012); A. Sorokovikova, et al., PRL* ***116*** *(2016)*



These mechanisms can accelerate electrons to energies that are >10x those accelerated from the ponderomotive force

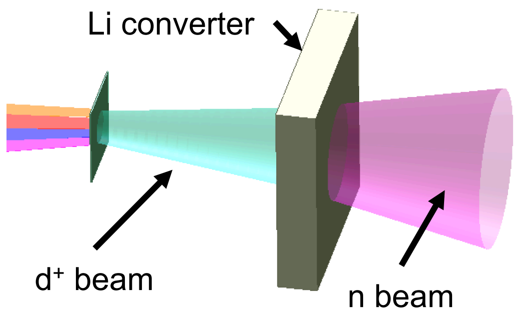
Coupled to NIF, developing ARC's laser-driven particle beam capabilities will enable multiple exciting applications

Proton radiography, deflectometry

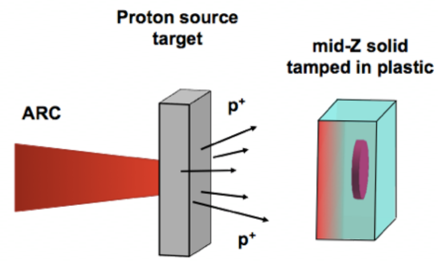


P. Patel

Deuteron/Neutron Sources

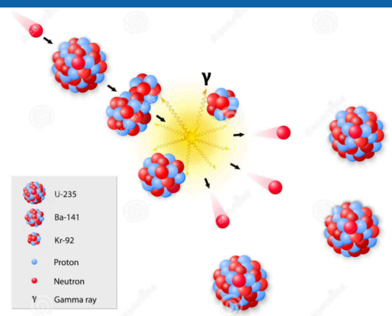


Isochoric heating / Warm Dense Matter

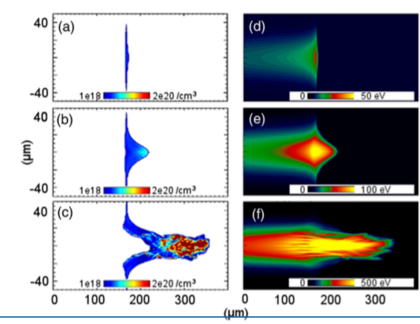


Patel, PRL (2003)

Nuclear reactions in plasmas

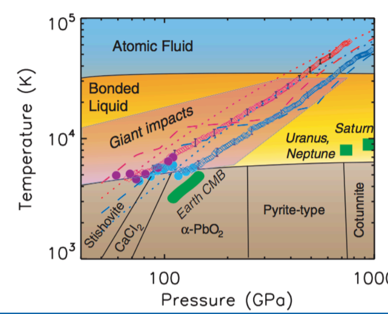


Stopping power investigations



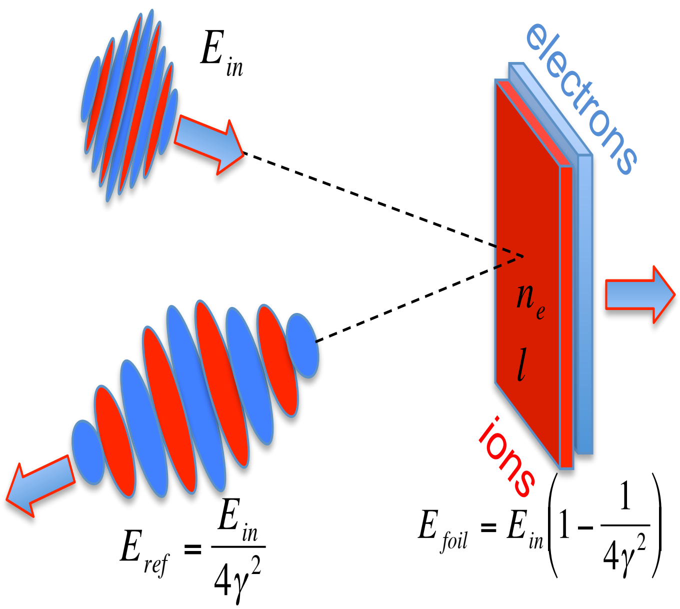
Kim, PRL (2015)

Preheat & Equation-of-State studies



Hicks, PRL (2006)

Radiation Pressure Acceleration is advanced mechanism based on the receding relativistic mirror concept



T. Esirkepov, *et al.*, Phys. Rev. Lett. **92,** 175003 (2004)

- High contrast allows the interaction of non-expanded target with the main laser pulse
- Pulse is reflected by the target
- The target is accelerated by the radiation pressure

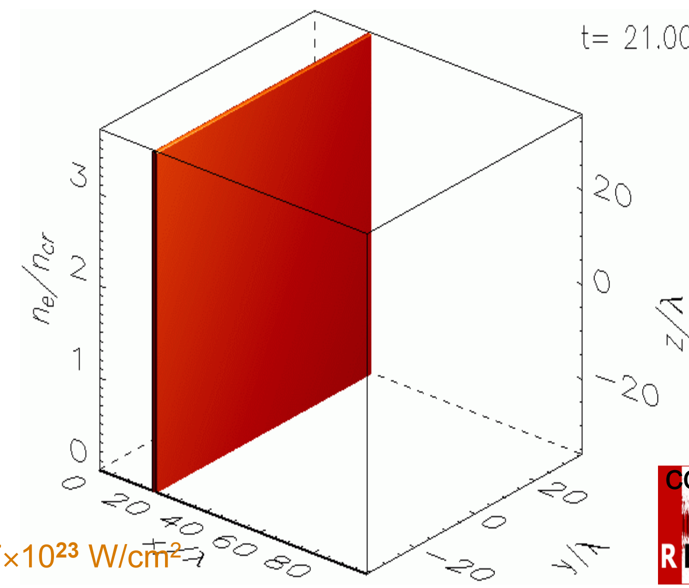
- non-relativistic case: ion energy ~ [laser energy]^2

$$\mathcal{E}_a = 8 \times (10^{11}/N_{tot})^2 (m_p/m_a)(\mathcal{E}_{las}/1\ \mathrm{J})^2\ \mathrm{MeV}$$

- ultra-relativistic case: ion energy ~ [laser energy]

$$\mathcal{E}_a = 6.25 \times (10^{11}/N_{tot})(\mathcal{E}_{las}/100\ \mathrm{J})\ \mathrm{GeV}$$

O. Klimo, et. al., Phys. Rev. STAB 11, 031301 (2008)
S. V. Bulanov, et. al., Comp. Rendus Physique 10, 216 (2009)



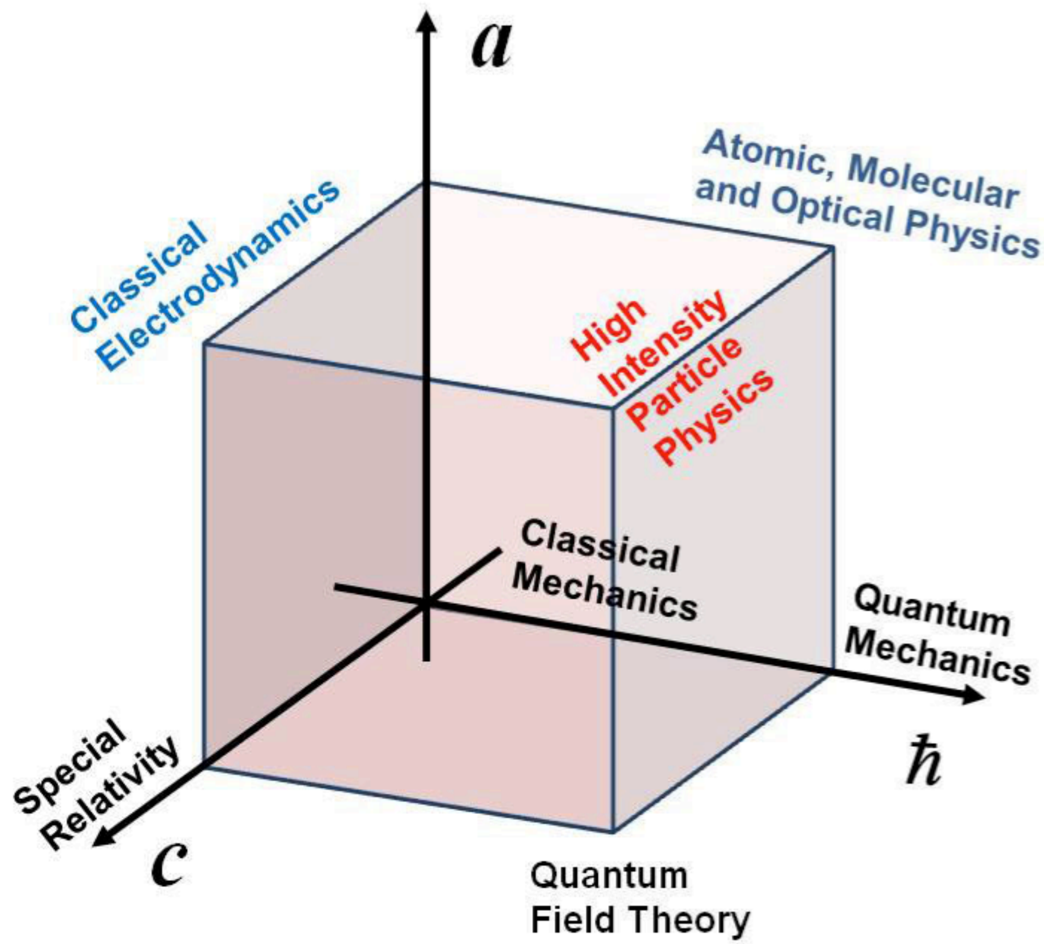
Laser:
I = 1.37×10^{23} W/cm^2

code REMP

Outline

- Introduction
- Nonlinear Optics of Plasmas
- Lepton acceleration
- Photon sources
- Ion acceleration
- High field science and nonlinear QED
- Personal perspectives & resources

High field experiments
Probe the relativistic quantum regime



- Nonpertubative Quantum Field Theory
- Electromagnetic Cascades/ Avalanched
- Ultimate Laser Intensity Limit

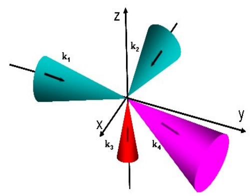
LBNL workshop "Nonlinear QED with ultra-intense PW-class laser pulses" (2012)

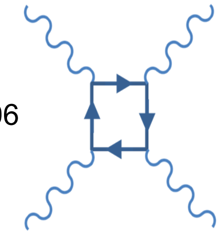
High Intensity Particle Physics

Laser fields may provide both the strong electromagnetic field and generate the high-energy particles and therefore represent a particularly interesting environment for studying a number of High Intensity Particle Physics effects.

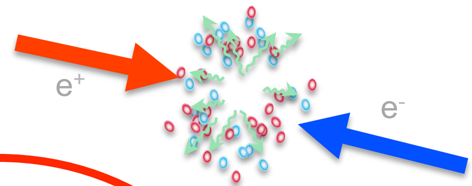
4-wave mixing

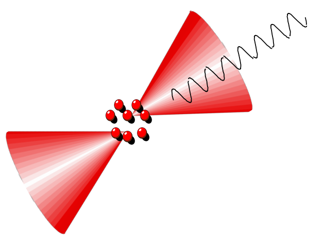
(Lundström et al, 2006



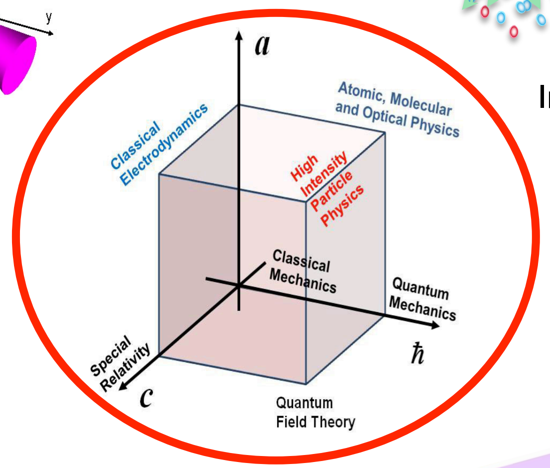


Photon-photon scattering via relativistic mirrors (Koga et al (2012))

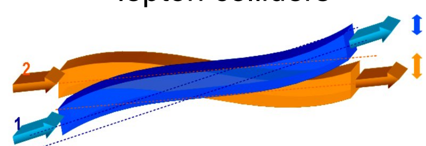




High order harmonic generation (Di Piazza, Hatsagortsyan, C. H. Keitel, 2005 Fedotov & Narozhny, 2006)

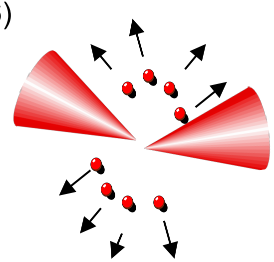


Interaction point physics at future TeV- class lepton colliders

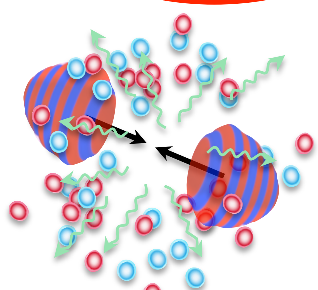


Birefringent e.m. vacuum

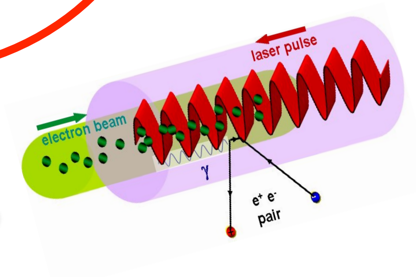
(Rozanov, 1993)



Electron positron pair production from vacuum (Schwinger, 1951)



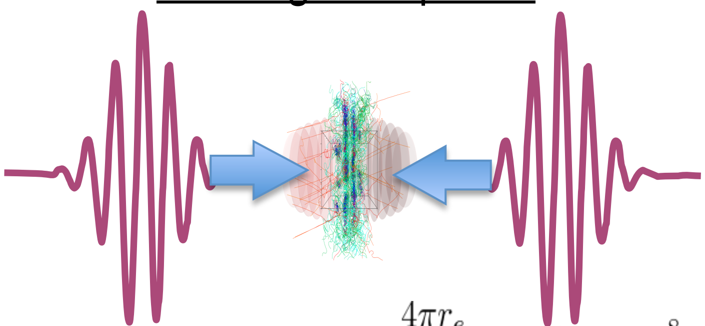
- Electromagnetic avalanches
- Electromagnetic cascades



Mulitphoton Compton and Breit-Wheeler processes
A. I. Nikishov, V. I. Ritus (1964);
Bula et al (1996); Burke et al (1997)

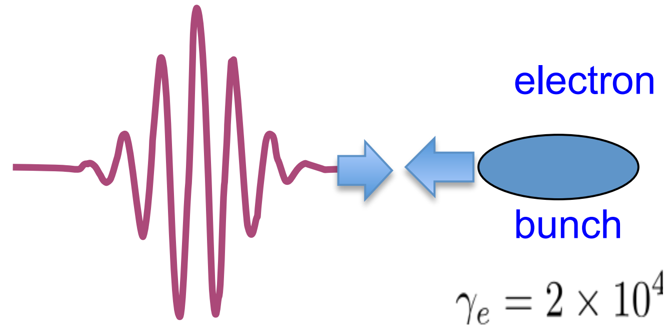
Principal schemes of the experiments for the study of extreme field limits.

Colliding laser pulses



$$\varepsilon_{rad} = \frac{4\pi r_e}{3\lambda_0} = 1.47 \times 10^{-8}$$

Colliding laser pulse and an electron beam



$$\gamma_e = 2 \times 10^4$$

1. Radiation effects become dominant $a > a_{rad} = \varepsilon_{rad}^{-1/3} = 400$

$$I_{rad} = 3.5 \times 10^{23} \quad W/cm^2$$

2. QED effects become dominant

$$a > a_Q = (2\alpha/3)^2 \varepsilon_{rad}^{-1} = 1.6 \times 10^3$$

$$I_Q = 5.5 \times 10^{24} \quad W/cm^2$$

1. Radiation effects become dominant

$$a > a_{rad} = (\omega \tau_{laser} \gamma_e \epsilon_{rad})^{-1/2} = 10$$

$$I_{rad} = 2 \times 10^{20} \quad W/cm^2$$

2. QED effects become dominant

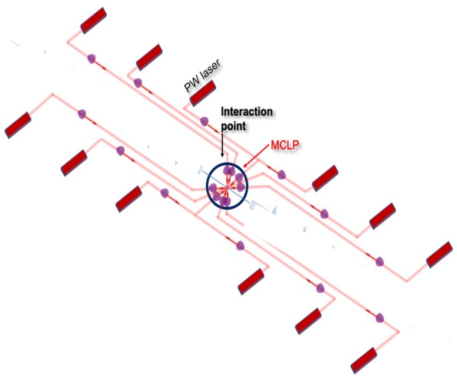
$$a > a_Q = (2\alpha/3) \gamma_e^{-1} \epsilon_{rad}^{-1} = 20$$

$$I_Q = 5.8 \times 10^{20} \quad W/cm^2$$

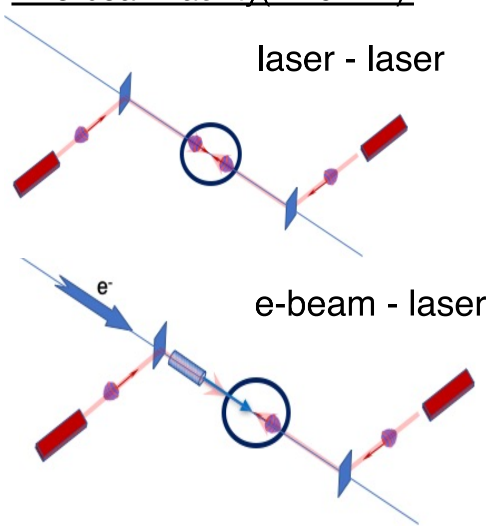
S. V. Bulanov, T. Zh. Esirkepov, Y. Hayashi, M. Kando, H. Kiriyama, J. K. Koga, K. Kondo, H. Kotaki, A. S. Pirozhkov, S. S. Bulanov, A. G. Zhidkov, P. Chen, D. Neely, Y. Kato, N. B. Narozhny, G. Korn, *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 660, 31 (2011)*

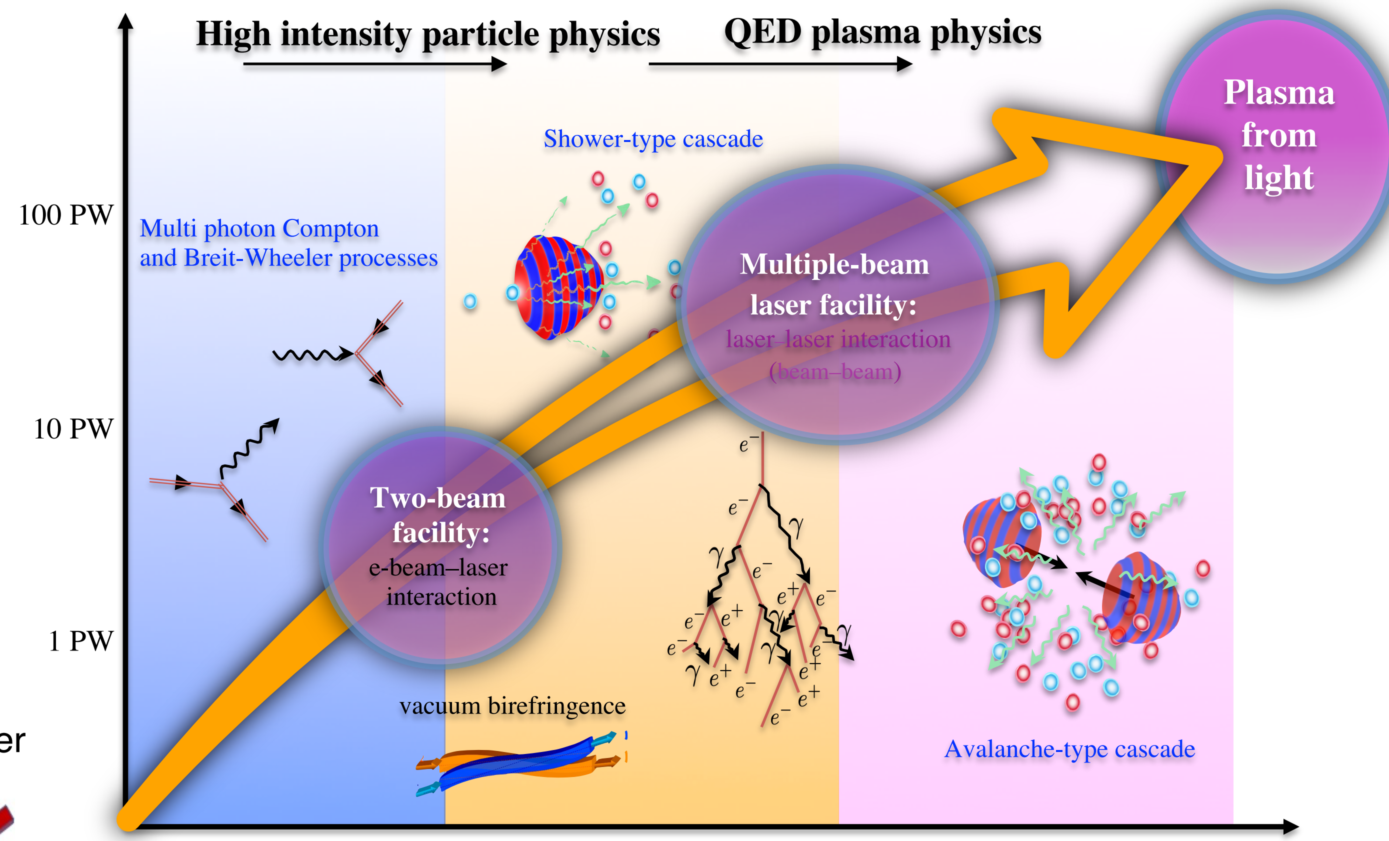
Sequence of Opportunities for the study of high intensity particle physics

Multiple-beam laser facility (100 PW):



Two-beam facility(1-10 PW):



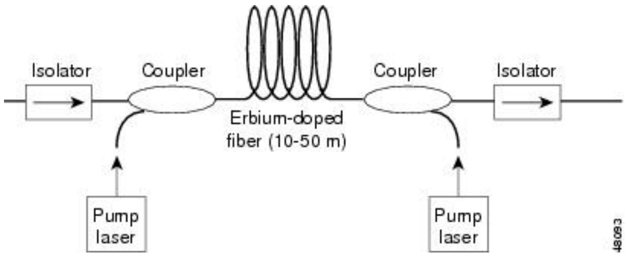


Outline

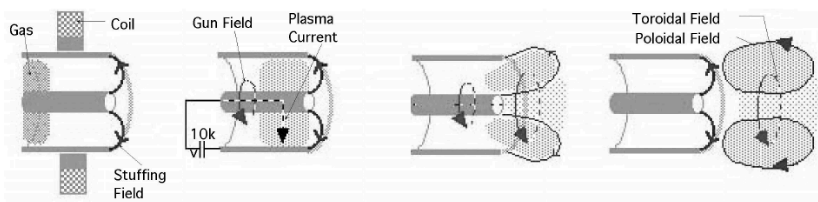
- Introduction
- Nonlinear Optics of Plasmas
- Lepton accelertion
- Photon sources
- Ion acceleration
- High field science and nolinear QED
- Personal perspectives & resources

Plasma physics offers many interconnected opportunities for exciting team research

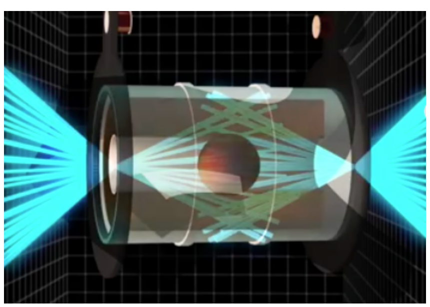
1992-1994: Swarthmore fiber lasers



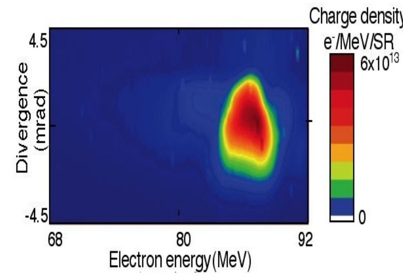
1995: PPPL NUF & UW tokamak
1995-1997: Swarthmore Spheromak

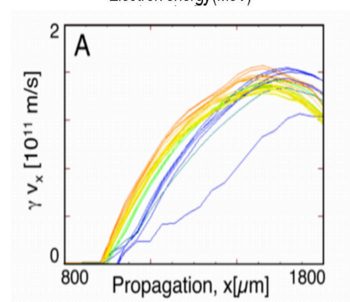


1997-2000: LLNL, LLE, Polymath
ICF Laser-plasma interactions



2000-2019 UCB then LBNL
Laser plasma acceleration





2000-02: gas targets

2002-04: guided LPA

2005-09: simulations

2009-18: light sources

2019- Center

Resources for more information

- Laser-plasma textbook
  - Kruer, Physics of Laser-Plasma Interactions

- Accelerator qualitative review paper:
  - Leemans and Esarey, Physics Today, 2009
- Technical review papers:
  - Esarey, IEEE Trans Plasma Science v24, 1996
  - Esarey et al., Rev. Mod. Phys. v81, 2009
  - Joshi et al., Physics of Plasmas v14, 2007
  - Hooker et al., Nature Photonics 2013

more theory

more expt.

- US Particle Accelerator School
  - Periodic advanced accelerator classes
  - http://uspas.fnal.gov
- Contact me: cgrgeddes@lbl.gov

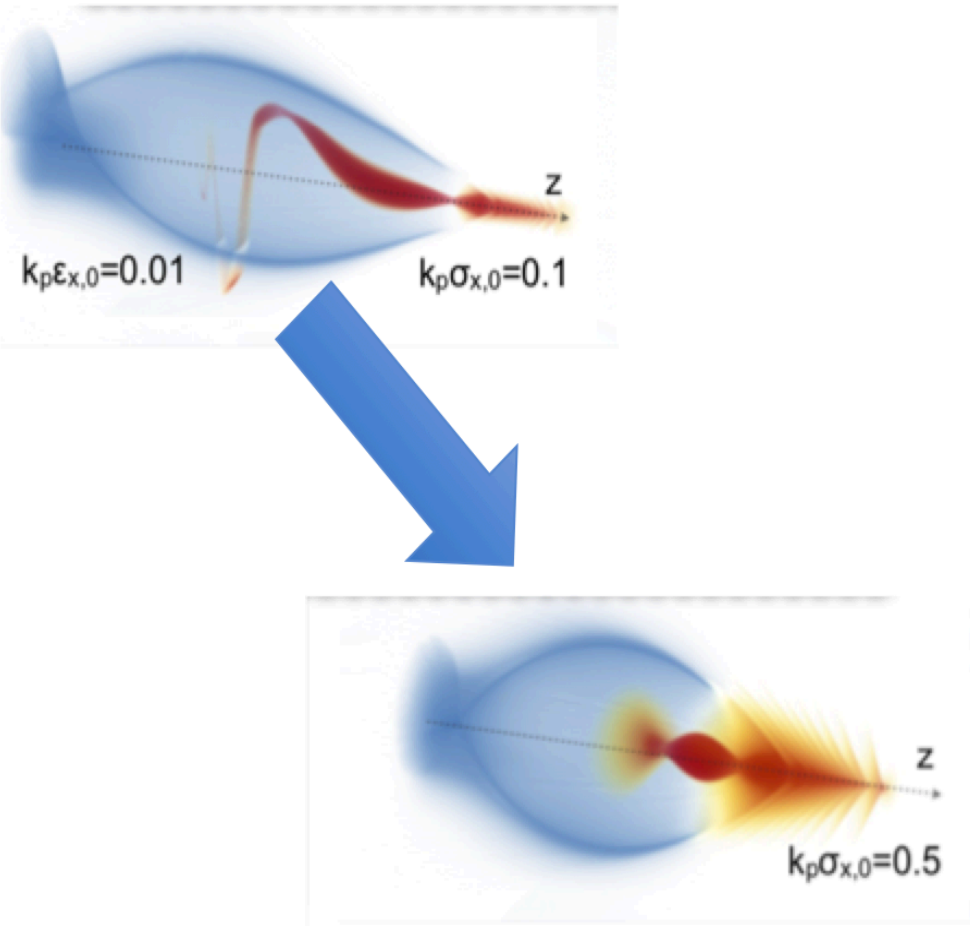
Summary

- Plasma optics allows manipulation & use of extreme fields
- Laser plasma accelerators becoming important to DOE, beyond
  - DOE High Energy Physics for future colliders
  - Photon source & ion applications:
    - MeV photons (NNSA DNN R&D),
    - FEL (BES, Moore)
- Fundamental physics at intersection of quantum, plasma
- High rep rate lasers are key enabler for average flux

- Many opportunities for cross collaboration
  - MHD target formation
  - Gas and plasma diagnostics
  - Wave-particle coupling, beam physics
  - Optics, laser technology development
  - Plasma simulation, scaling

Backup material

Beam Quality Preservation
Hosing, Joint between laser, beam driven communities

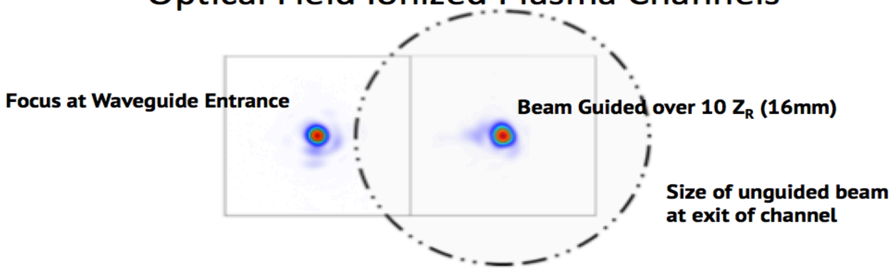


- Important for collider concepts
- Substantial collaboration and cross-fertilization of ideas among presentations
  - Nagaitsev (FNAL)
  - Hildebrand (UCLA)
  - Mehrling (LBNL)
  - Lehe (LBNL)
- Major progress on understanding and in past two years, mitigation via:
  - energy spread
  - focusing strength variation
  - wake structure form
  - drive beam width

<u>Understanding requires fine control of beam centering, profile</u>

Beam Quality Preservation
Hosing, Joint between laser, beam driven communities

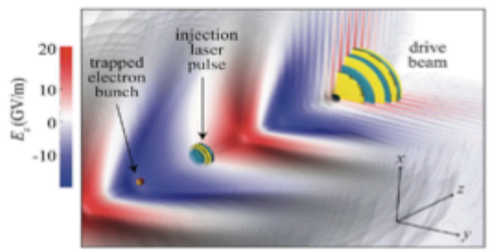
Simon Hooker, Robert Shalloo, et al. Oxford
High-Intensity Guiding in Axicon Formed Hydrodynamic Optical Field Ionized Plasma Channels



- Hydrodynamic expansion of plasma columns heated by OFI can generate long, low-density “indestructible” plasma channels
- 10-50 um matched spot sizes for axial densities of 1-10x10^{17} cm^{-3}

Requires additional laser pulses & stability, shaping for facilities

Carl Schroeder, LBNL
Two-Color Laser-Ionization Injection

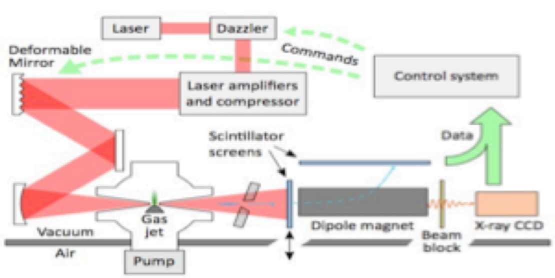


Thermal emittance from ionization-induced trapping in plasma accelerators” PR ST-AB 17, 101301 (2014).

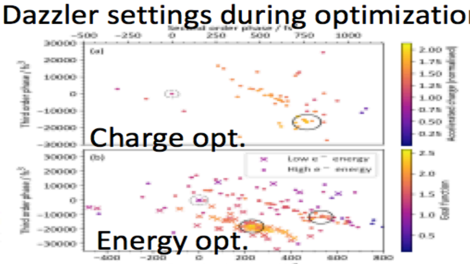
- Long wavelength driver: leaves inner states un-ionized
- Short wavelength tight focus injection pulse ionizes inner states
  - potential for 10nm-class emittance

requires fine control of beam centering, & additional beam

Alec Thomas, et al. U. Michigan
Laser wakefield acceleration with active feedback at 10TW



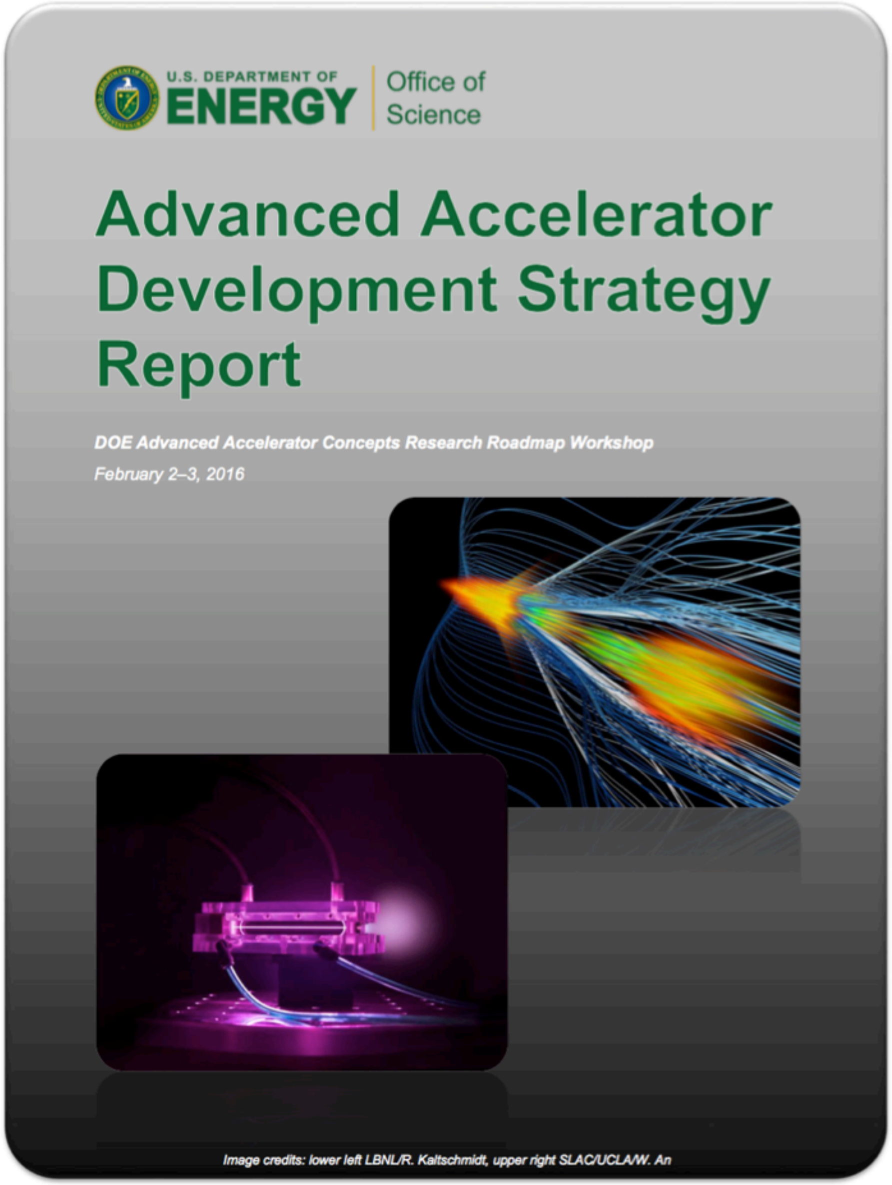
Dazzler settings during optimization



- Feedback routines optimise laser wakefield accelerator performance
- Full spatio-temporal control of the laser pulse
- Started on Hz-class systems

need for kHz lasers to enable fine control and fluctuation suppression

Roadmap for Laser Plasma Accelerators has been developed



Strategy for future particle colliders

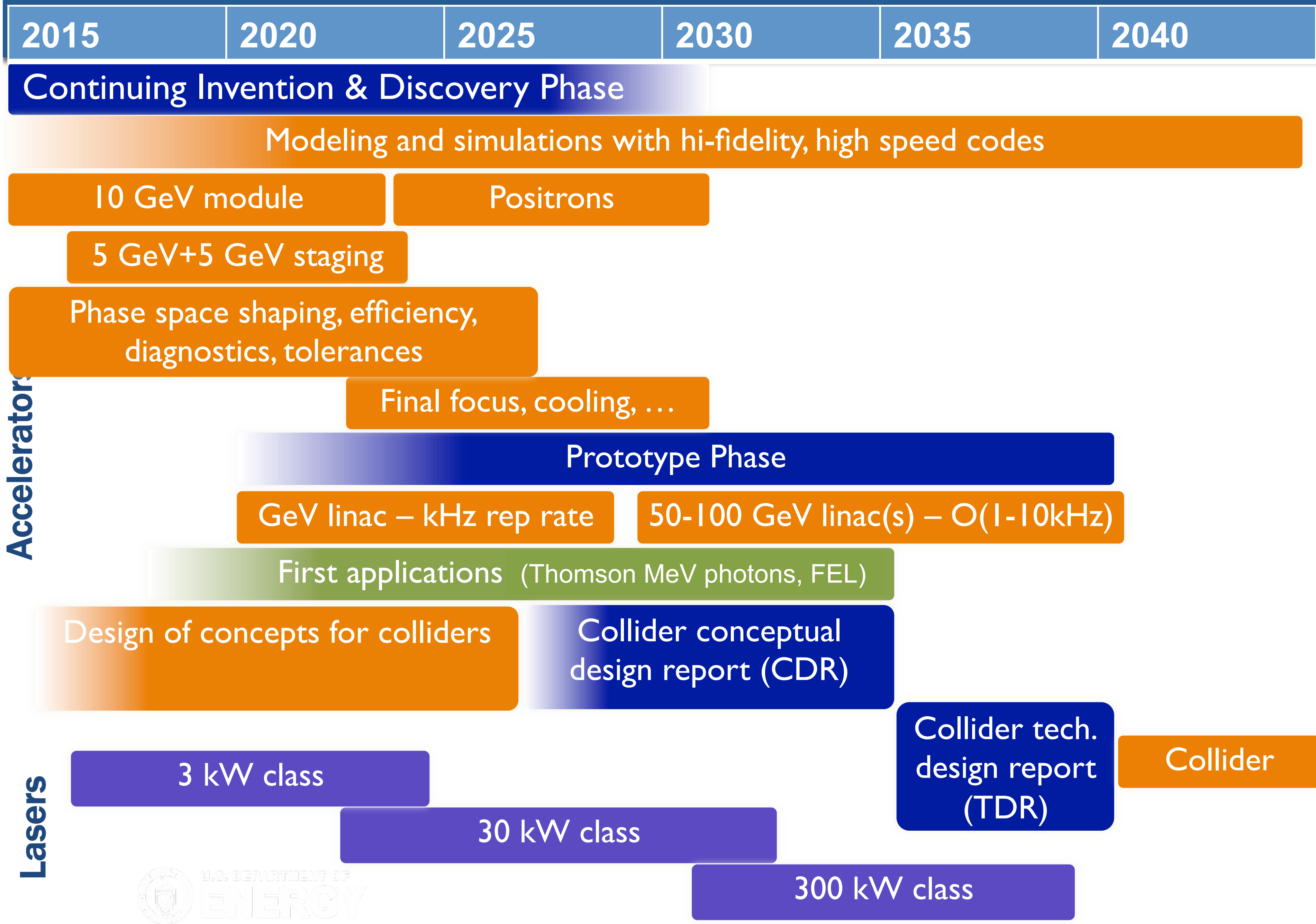
DOE Office of Science HEP
General Accelerator R&D program

TeV to multi-TeV in 100's of meters
- nC class charge
- 50kHz class rate
- nm emittance
- percent energy spread

Intermediate applications: photon sources for nonproliferation, security, basic science, industry, medicine
- Thomson: keV-MeV
- Betatron: keV
- Free Electron Lasers

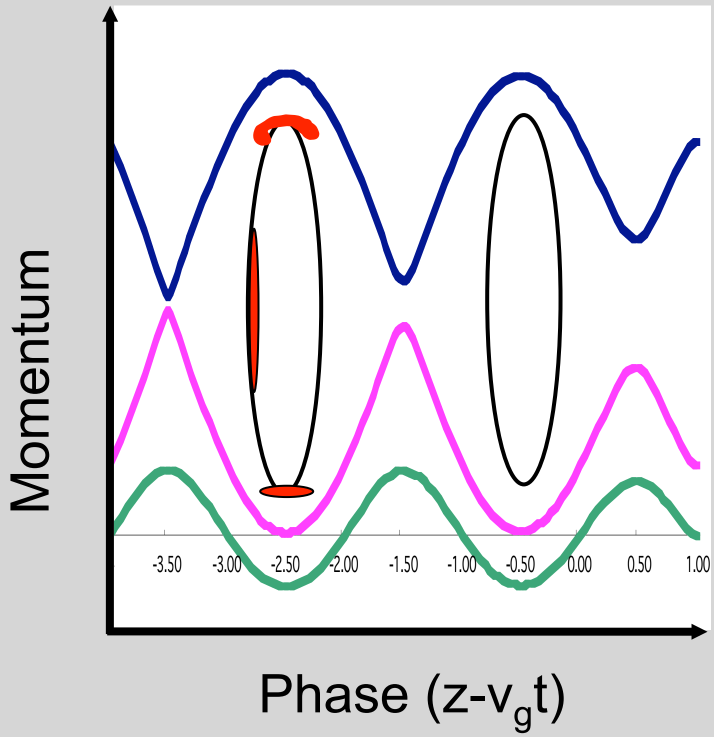
GeV-class, ≥ kHz, 10-100pC
Stepping stone and early application

Roadmap for Laser Plasma Accelerators has been developed



Control trapping
for stable high quality beams

I. Control electron phase & spread – ΔE

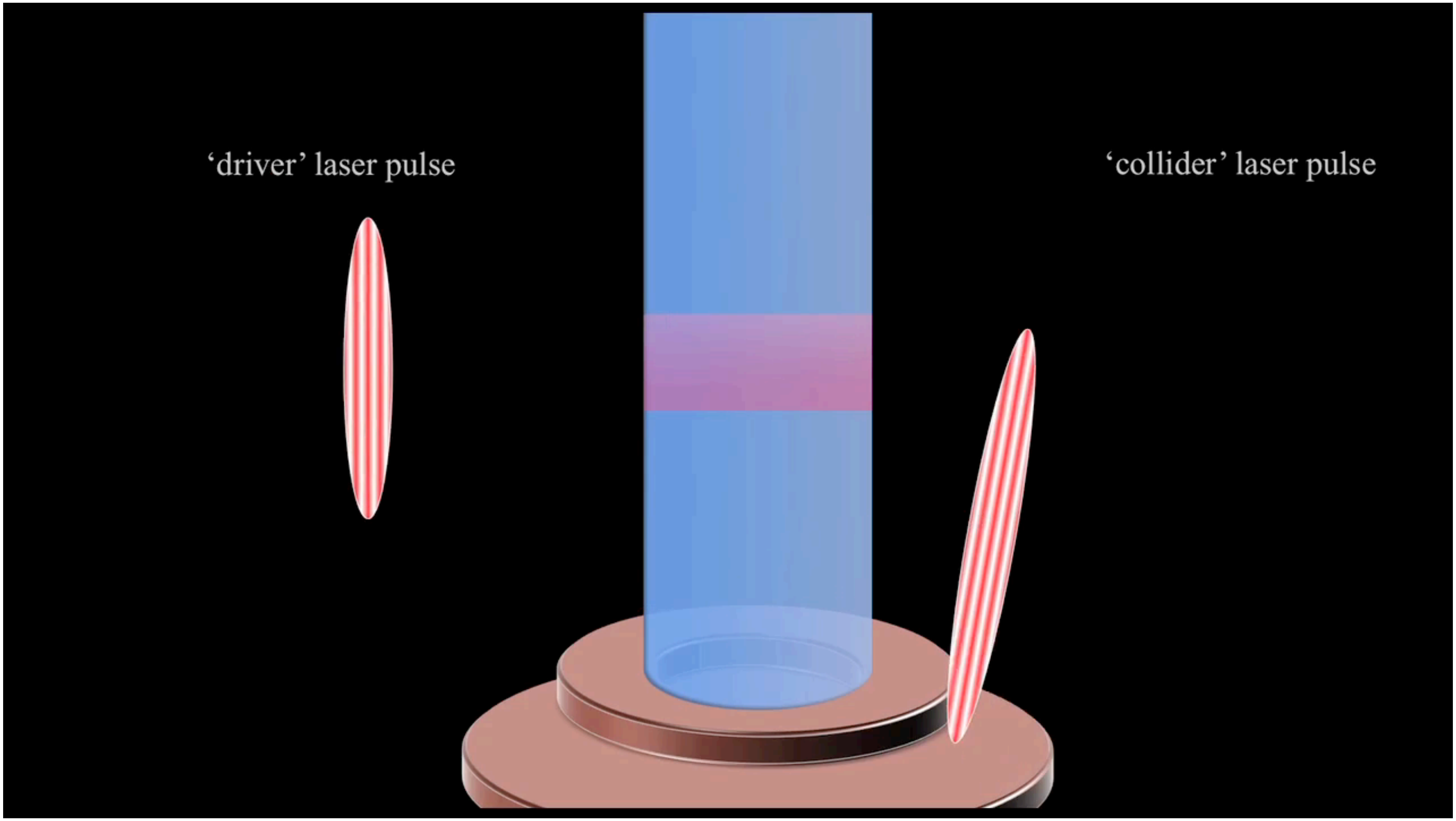


II. Control trapping orbit - emittance

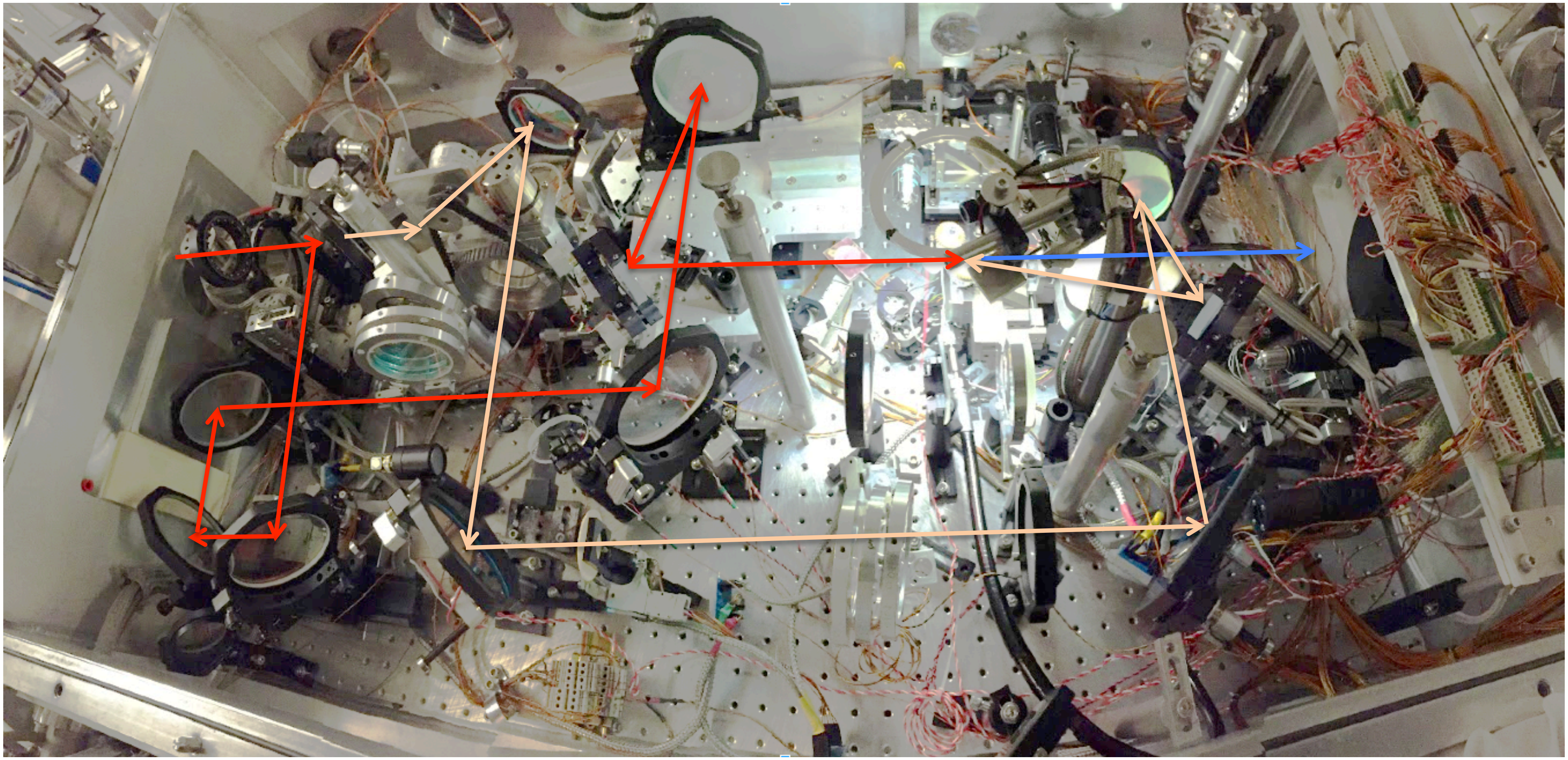
Techniques:

- Controlled self trapping
- Colliding pulses
- Plasma density gradient
- Ionization

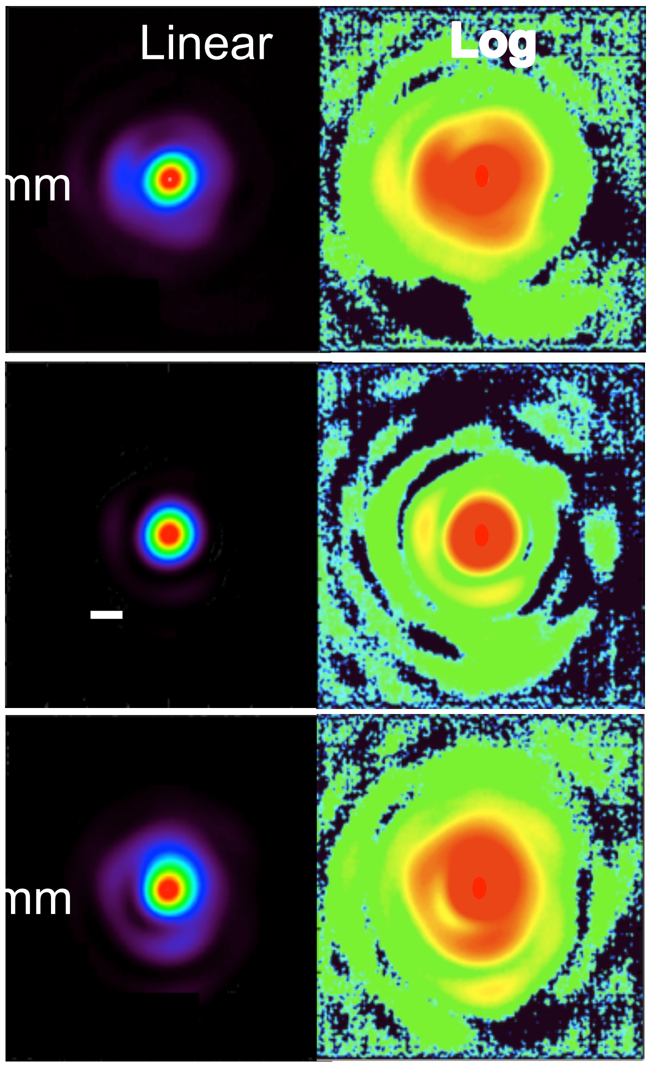
Controlling injection:
additional laser pulses or plasma shaping



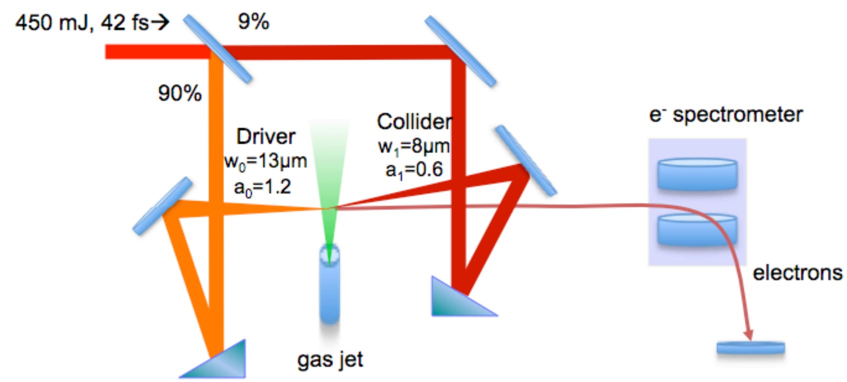
µm pointing & fs timing enable control



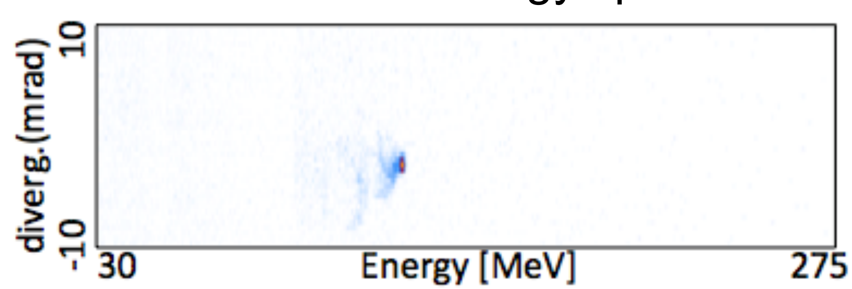
Control of laser mode and injection precise beams at ~0.2-1 GeV



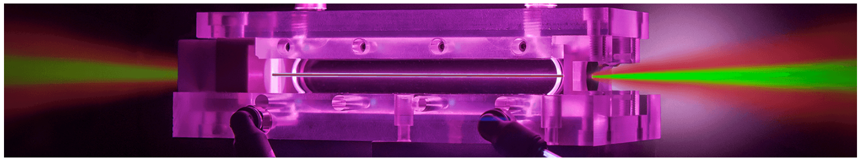
Same 10 TW laser pulse that previously generated 80 MeV, few % energy spread…



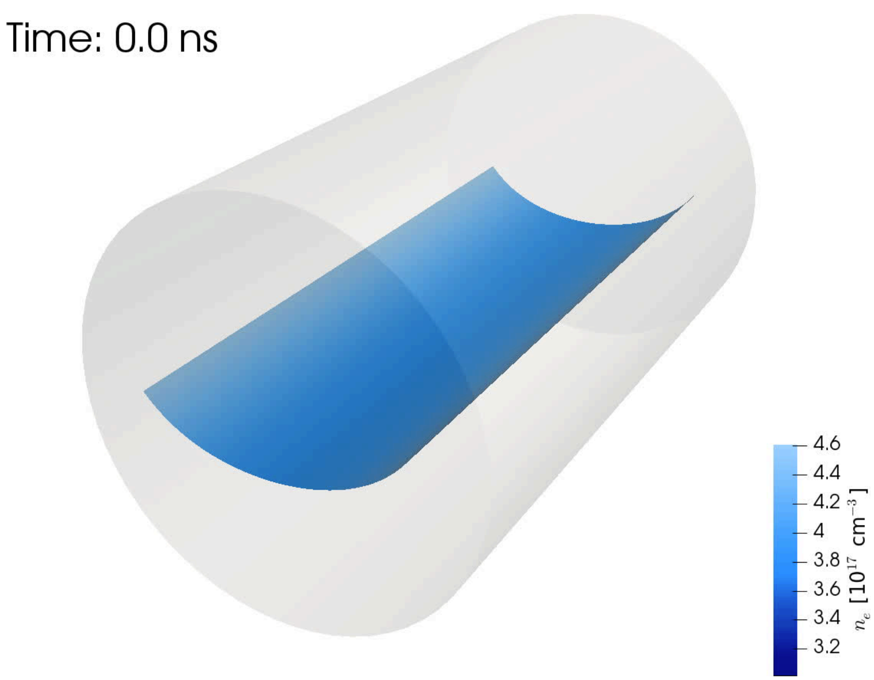
Precise control: 100-250 MeV,
Energy spread ~ 1%



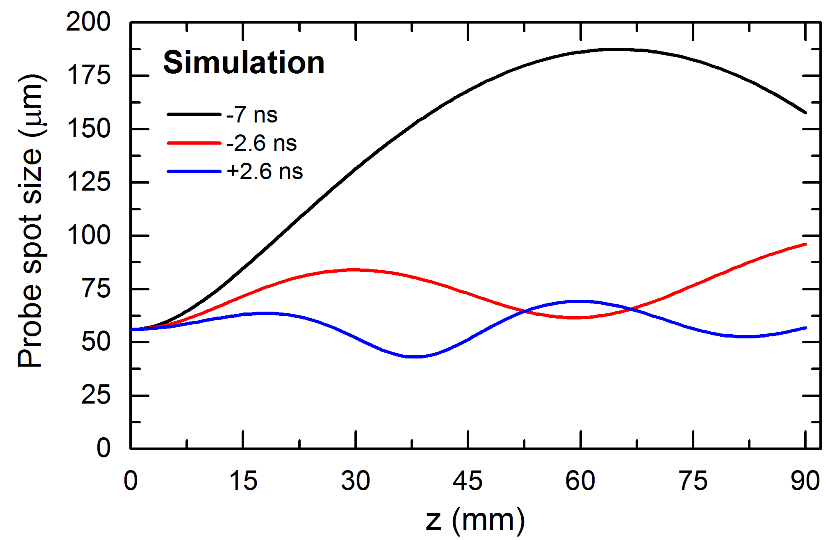
“Heater” laser increases channel strength & guides laser pulses at lower density



MARPLE simulation



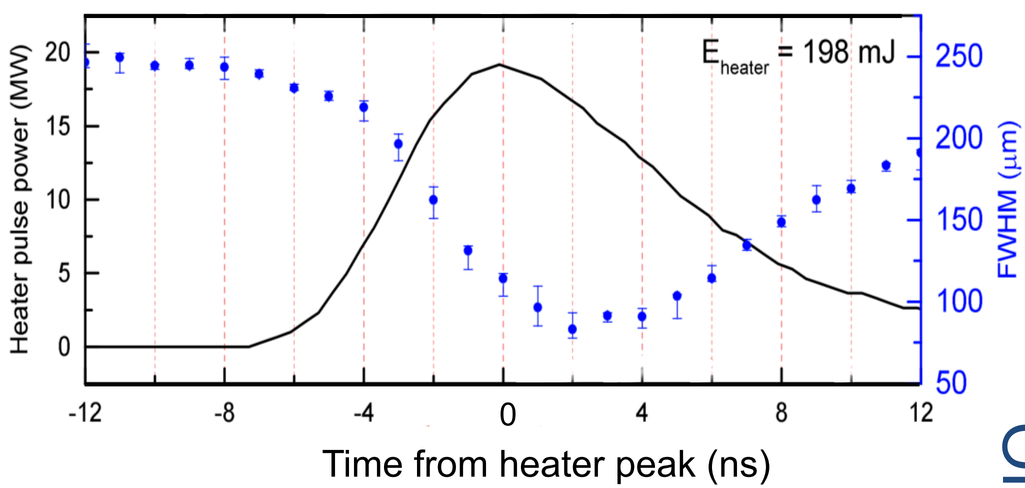
- Nanosecond pulse locally heats plasma through Inverse Bremsstrahlung
- Electron density distribution is changed
  - •n_0 reduces
  - •w_m reduces locally (faster rise of density from axis)

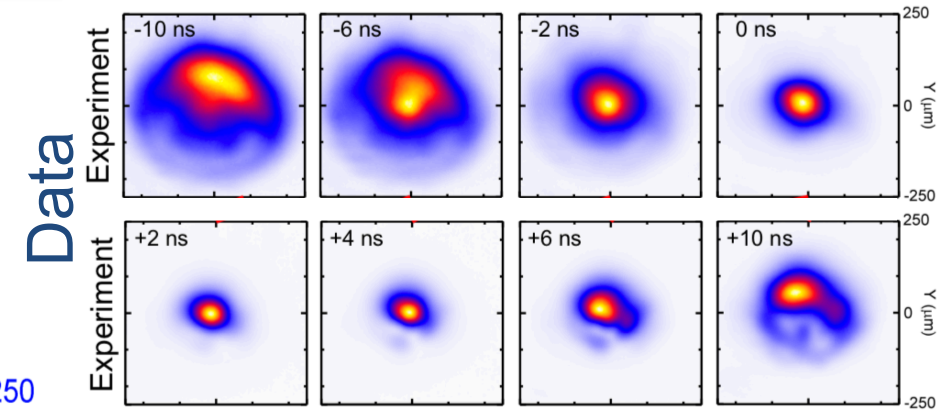


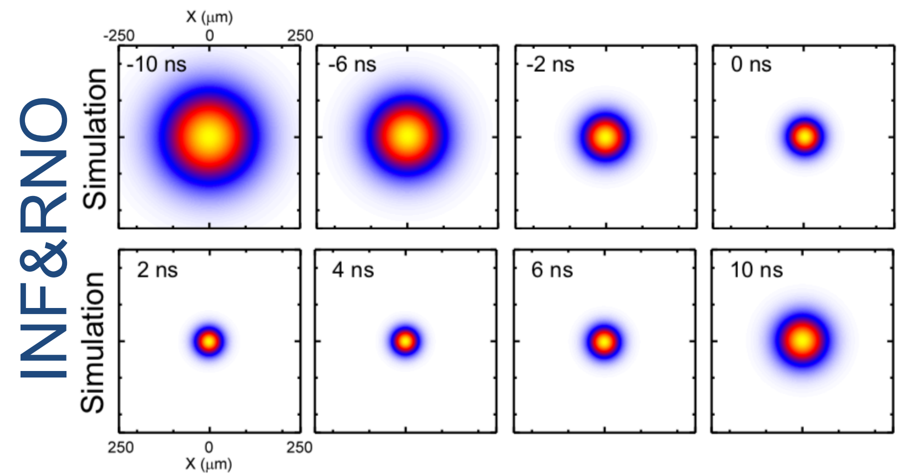
Gonsalves et al., PRL (2019); Bobrova *et al.*, *POP* 2013; Durfee *et al.*, *PRL* 1993; Volfbeyn *et al.*, *POP* 1999

Guided low-power laser modes indicate plasma channel enhancement

L_{cap}=6cm; W_{0probe}=60μm; n_e=0.4×10^{18} cm^{-3}



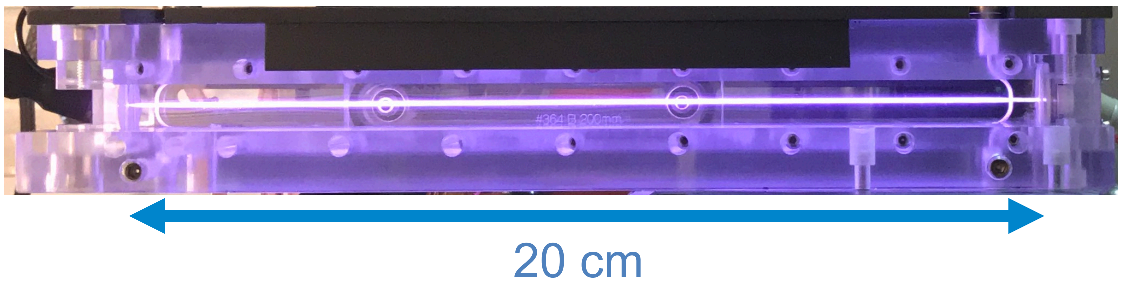


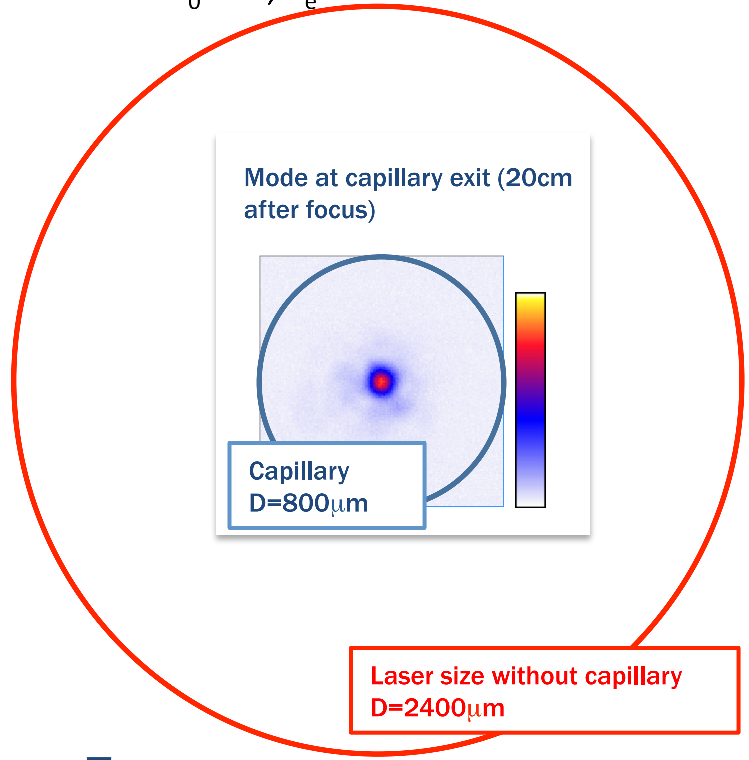


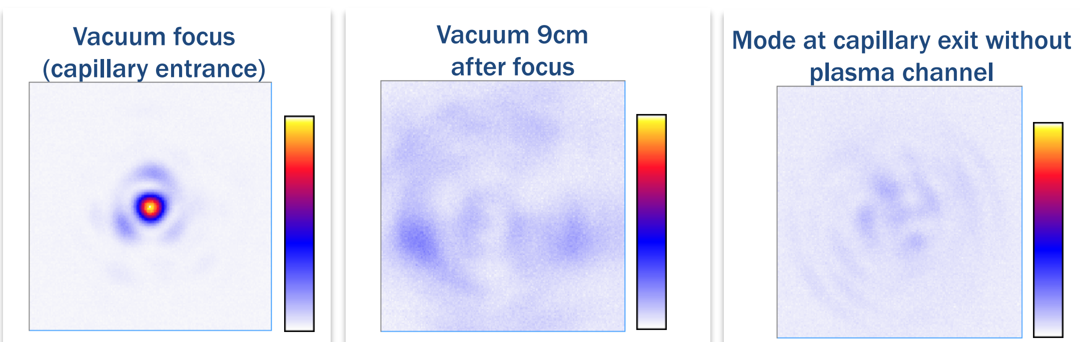
A. J. Gonsalves et al., Phys. Rev. Let. 2019

Petawatt pulses (“driver”) guided by 20 cm long heated discharge channels at 3.4e17/cc

20 cm; 950 TW (~30fs); $1.2\text{x}10^{19}\text{Wcm}^{-2}$;
$a_0=2.4$; $n_e=0.34\times10^{18}\text{ cm}^{-3}$





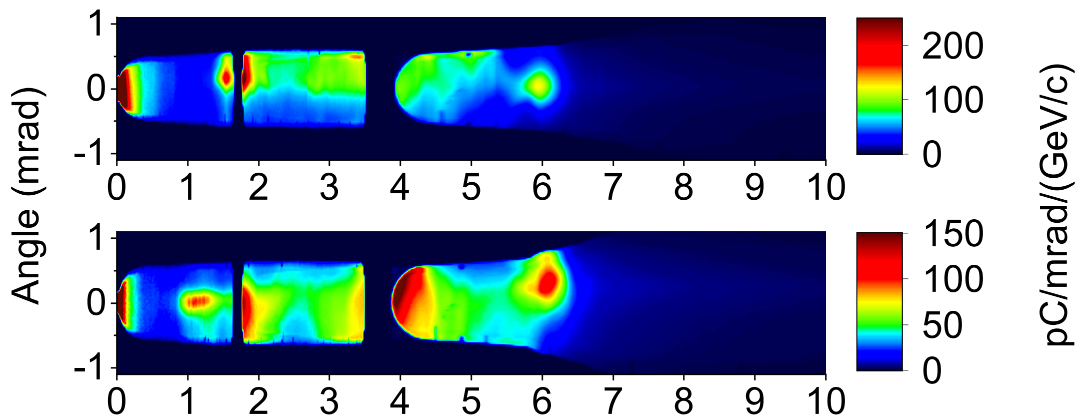


Spot size w_0 increased from 53μm to 60μm to increase Z_R

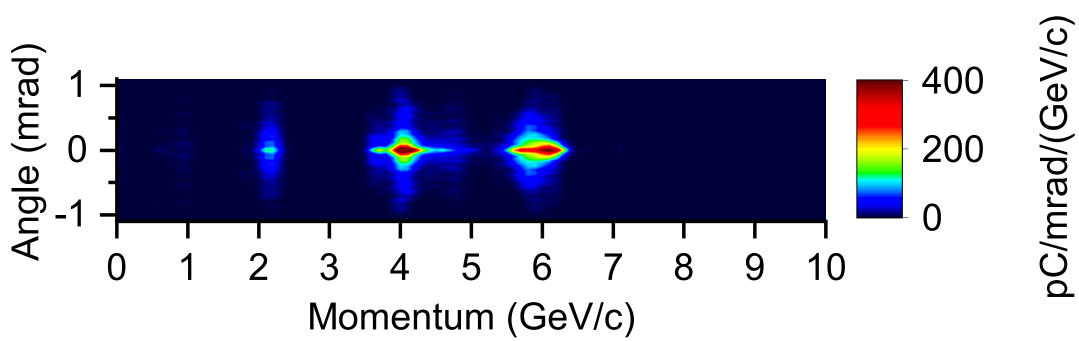
A. J. Gonsalves et al., Phys. Rev. Let. 2019

Simulations capture electron beam parameters; Show path forward to higher energy and quality

Experiment



Simulation

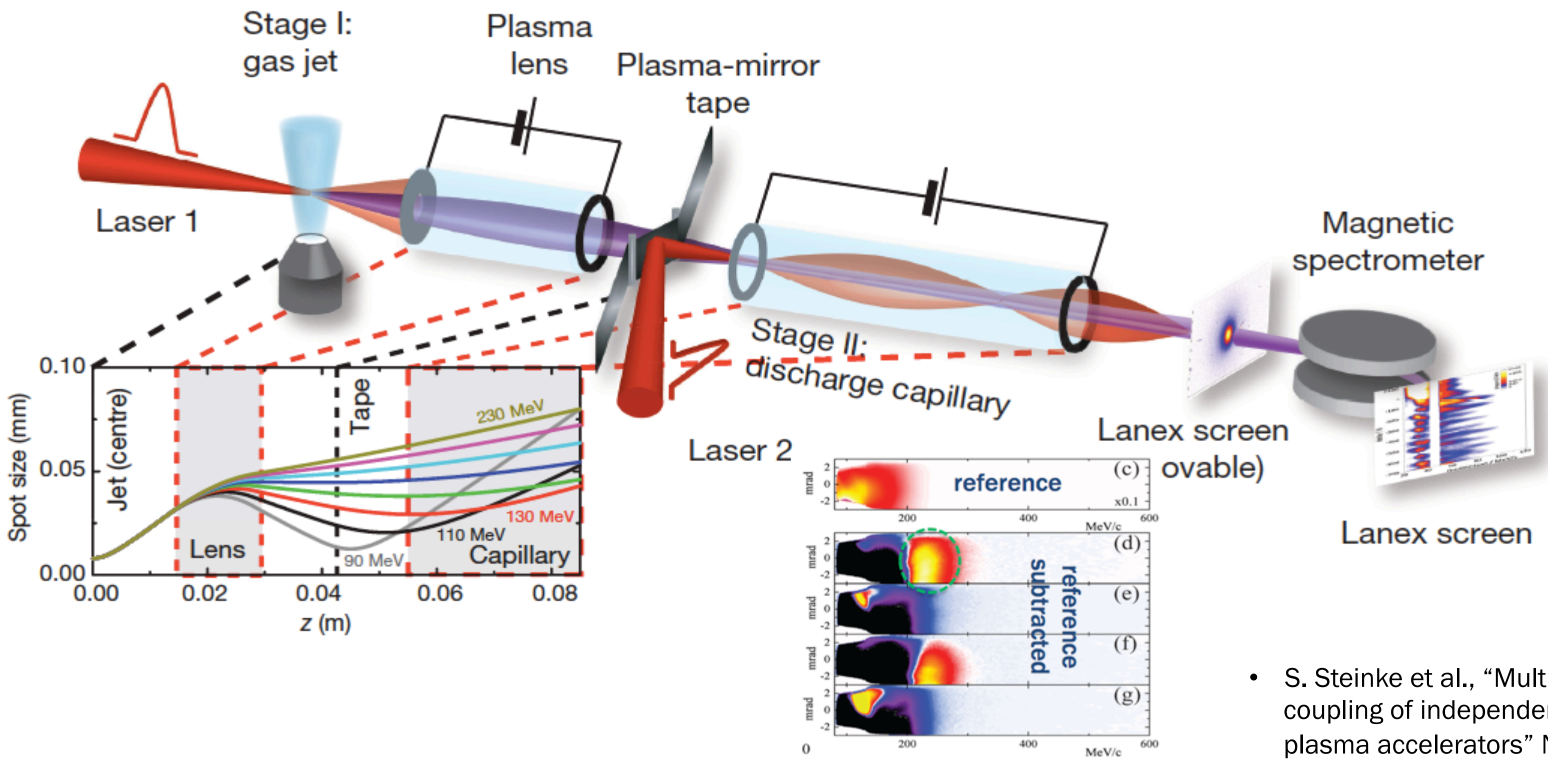


Next:

- Further optimization of channel strength at density ~2×10^{17}cm^{-3}
- Demonstrate localized injection with PW laser power and in longer capillaries (single bunch and reduced energy spread)

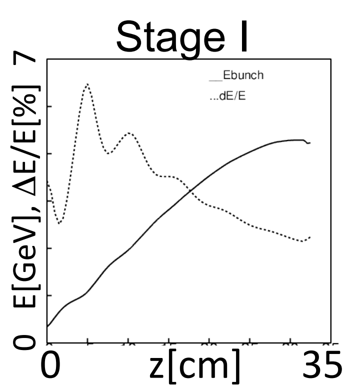
A. J. Gonsalves et al., Phys. Rev. Let. 2019

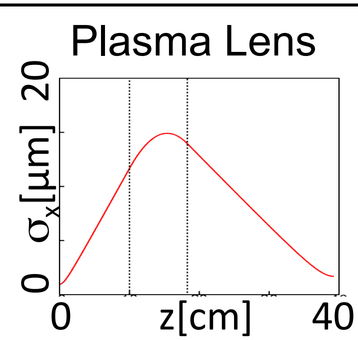
Staging experiment successful at 100 MeV
2nd beamline at PW needed for multi-GeV

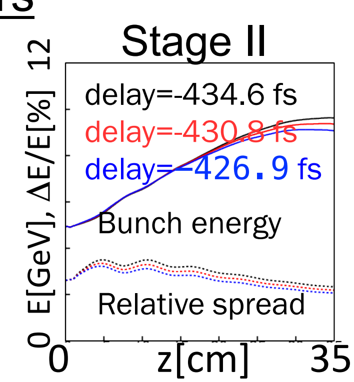


- S. Steinke et al., “Multistage coupling of independent laser-plasma accelerators” Nature 530, 190 (2016).

<u>Scales to multi-GeV at PW powers</u>

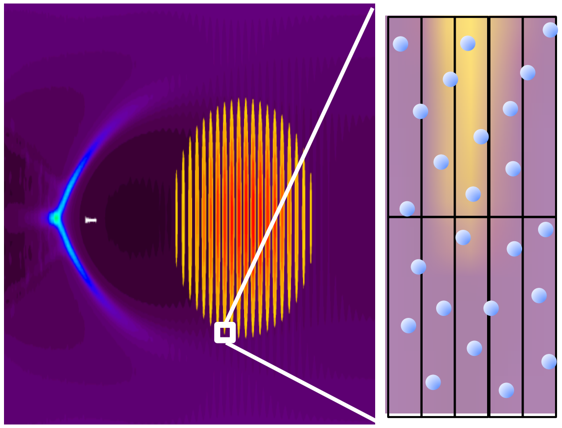






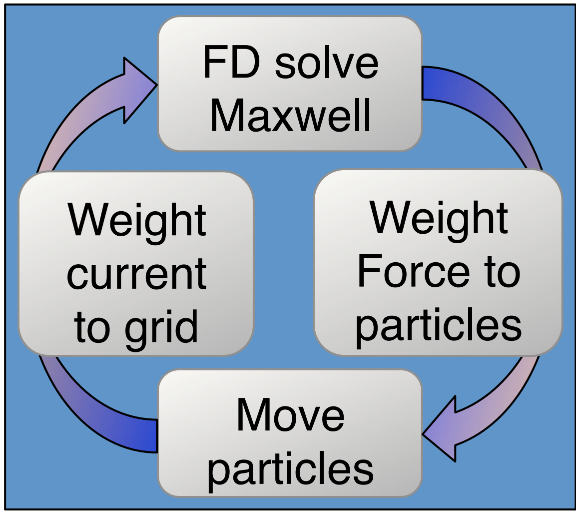
Analytic calculations are limited: Simulate using particle in cell, other methods

- Particle simulations resolve nonlinear wake, kinetics
- Explicit Particle in Cell (PIC) resolves λ_{laser}, σ_{bunch}
  - in space over 100μm^3 ~ 200Mcell
  - in time over 3 cm ~ 1 Mstep
  - few particles / cell ~ Gparticle, TB
- Traditional: Finite difference time domain advance



- Improve accuracy to model collider emittance

- Limited – need for
  - Scaling to many processors
  - Efficient methods



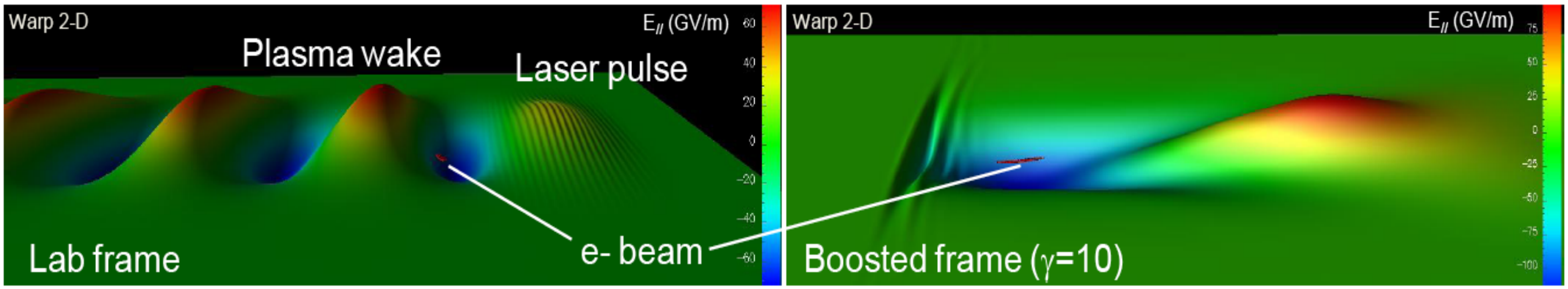
Problem-specific techniques are essential: Lorentz boost, Gallilean boost, envelope

Lorentz boost[1]:

Key issue: micron-scale laser wavelength, 10's of cm plasma

Boost: laser redshifts, plasma shortens

Issue: numerics from plasma flowing over grid → move the grid, special solvers[2]



Envelope codes[2]

Do not resolve fast oscillation of laser

Issue: broadening as laser depeletes requires special methods

Quasi-static codes[2]

Extend time step to evolution scale ~ diffraction depth

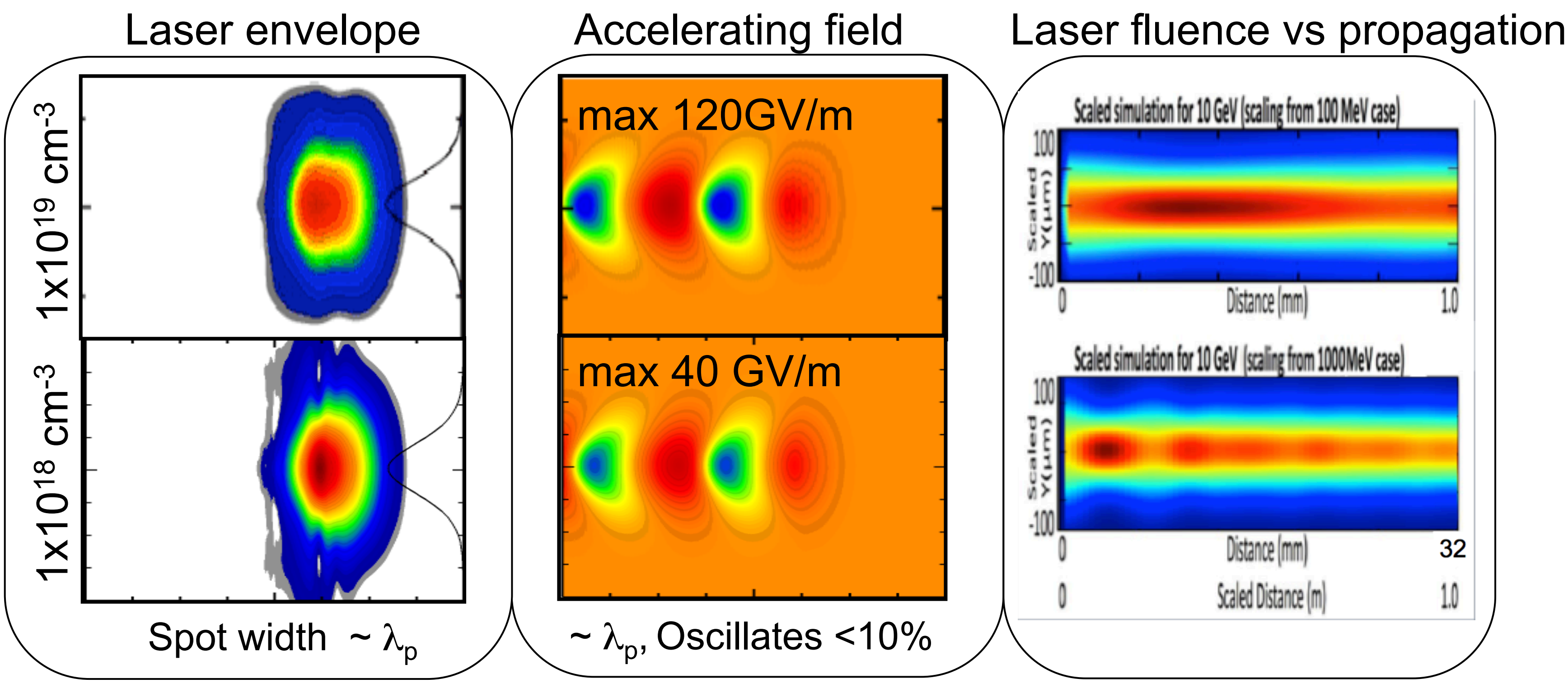
Suitable when trapping not important

And many more…

1: J.-L. Vay, Phys Rev. Lett 2007 and Phys Plasmas 2011; M. Kirchen et al Phys Plasmas 2016; H. Vincenti and J. L. Vay, Comput. Phys. Commun. (2016).
2 pioneered by Antonsen, Gordon *et al*. (NRL,UMD); C. Benedetti, et al., Plasma Physics and Controlled Fusion, (2018), B.M. Cowan et al., J Comp Phys 2007

Combination of calculation, simulation: Best of both worlds? With limits…

- Scaling with density: holding constant L_{laser}/λ_p, w_0/λ_p, a_0



Depletion, dephasing scale as expected

Energy gain ~ λ_p^2

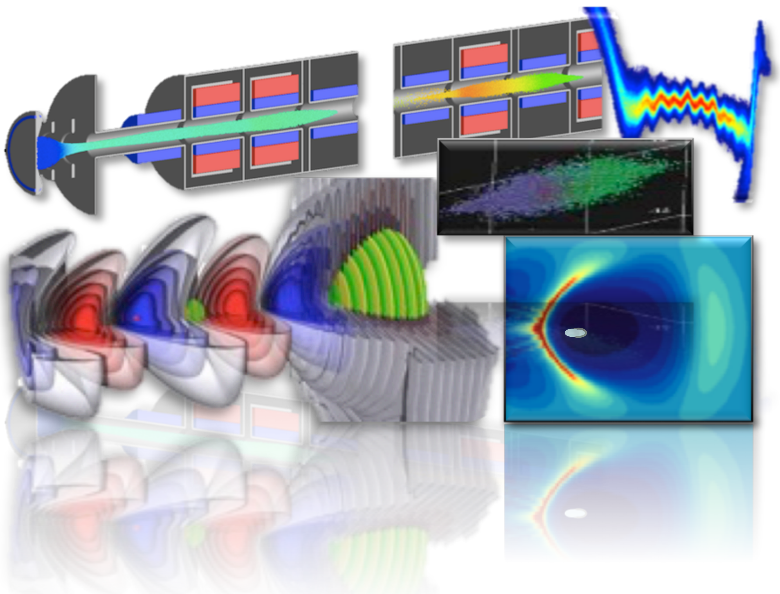
97 MeV at $1\text{x}10^{19}$

1120 MeV at $1\text{x}10^{18}$

Laser evolution & multi- dimensional physics included – transverse osc. does not scale

Laser-plasma accelerators require state of the art simulations

blast.lbl.gov
BLAST
BERKELEY LAB ACCELERATOR SIMULATION TOOLKIT



State-of-the-art simulation tools*:

- ***Multi-physics frameworks*:** IMPACT, Warp.
- ***Specialized codes*:** AMBER, BeamBeam3D, FBPIC, INF&RNO, POSINST.
- ***Libraries*:** PICSAR.

Wide set of physics & components:

- beams, plasmas, lasers, structures, ...
- linacs, rings, injectors, traps, …

At the forefront of computing:

- novel algorithms: boosted frame, etc.
- SciDAC, INCITE, NESAP, DOE Exascale.

*Most codes open source, available at blast.lbl.gov or upon request.