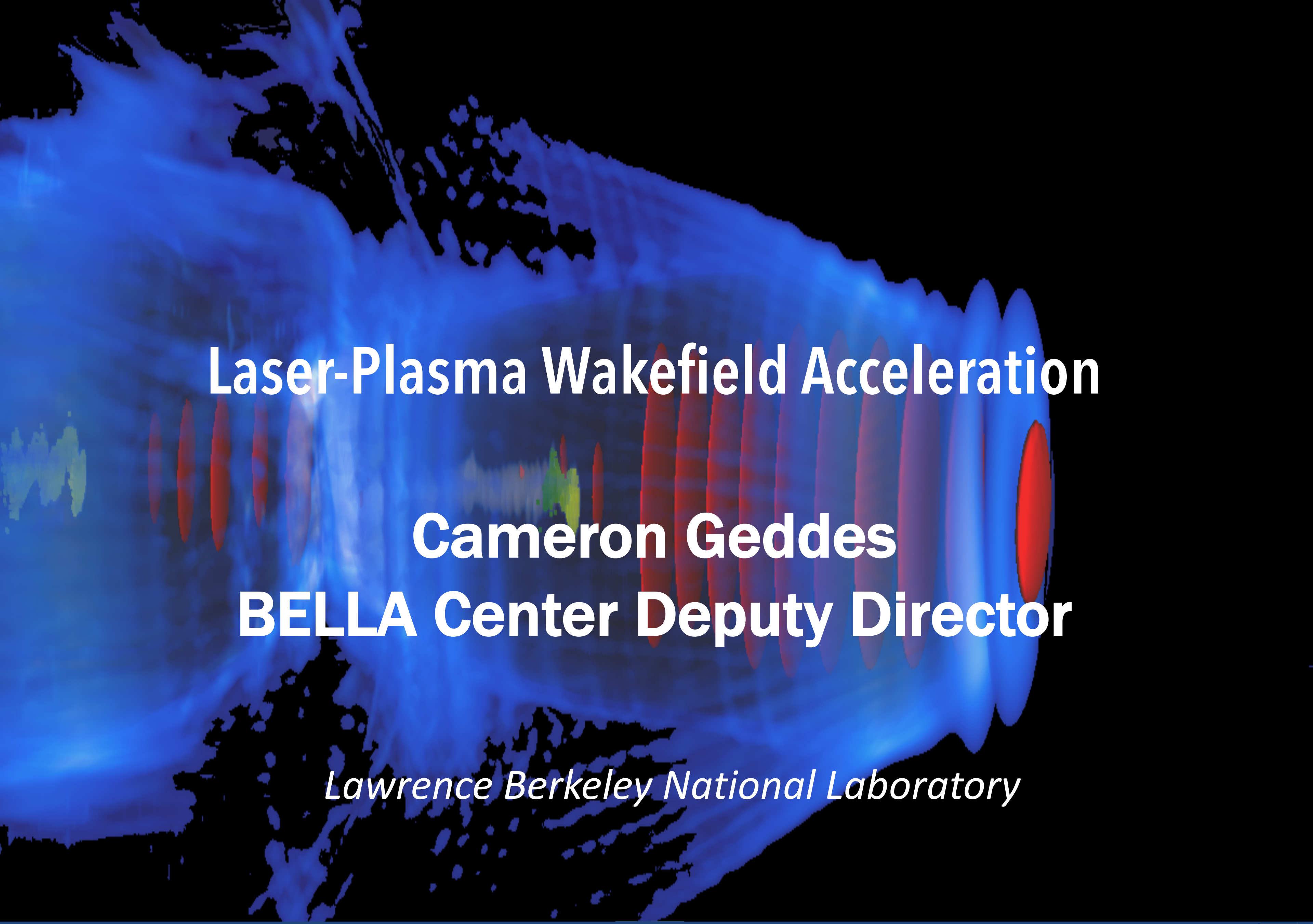
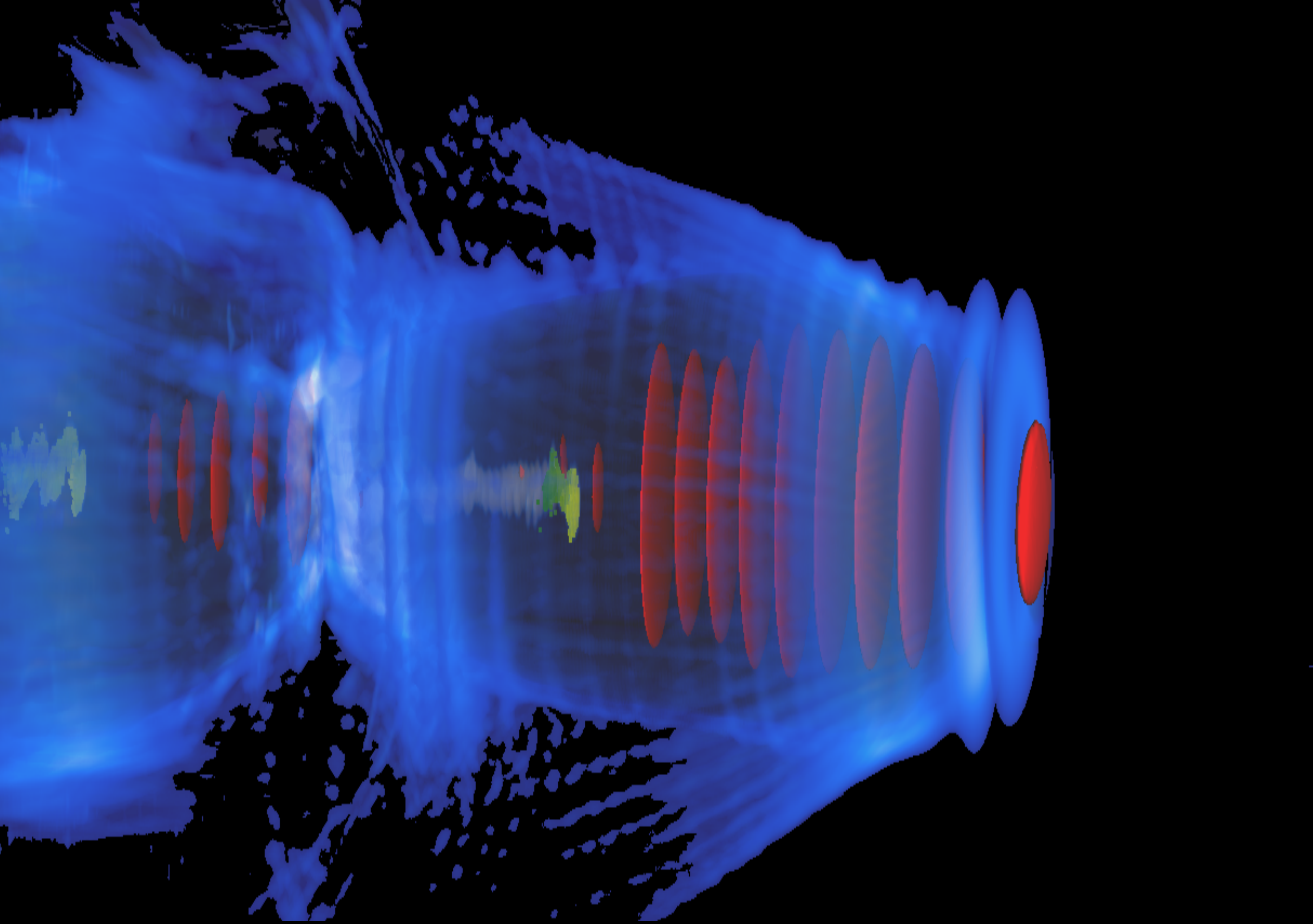


Laser-Plasma Wakefield Acceleration

Cameron Geddes

BELLA Center Deputy Director

Lawrence Berkeley National Laboratory



With thanks to colleagues at LBNL

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

With thanks to the Laser-Plasma Accelerator Community

Advanced Accelerator Concepts Workshop

- 37 presentations and 21 posters

Summary of Working Group 1: Laser-Plasma Wakefield Acceleration

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Abstract**—Advances in and the physics of the acceleration of electrons and positrons using underdense plasma structures driven by lasers were the topics of presentations and discussions in Working Group 1. Such accelerators have demonstrated gradients several orders beyond conventional machines, with quasi-monoenergetic beams at MeV-GeV energies, making them attractive candidates for next generation accelerators and photon sources. The status, future direction, and research outlook are summarized and references given to group presentations.**

Keywords—laser-plasma accelerators, laser wakefield acceleration, positron acceleration, staging, injection, laser guiding

I. Introduction

Working Group 1 (WG1) focused on the acceleration of electrons and positrons using laser-plasma wakefield accelerators (LPAs). Workshop discussions included advances in control over injection and laser guiding to further improve beam quality and stability; techniques for accelerator efficiency, beam quality preservation and staging; detailed diagnostics; radiation generation as a photon source and diagnostic; and beam manipulation. Paths from current results towards achieving parameters required for applications, particularly high energy physics (HEP) colliders at the TeV scale and compact photon sources (such as MeV Thomson sources and free electron lasers) were discussed.

The working group hosted eight oral sessions with 37 presentations and 21 posters. The roles of both plasma wakefield acceleration driven by lasers and of direct laser acceleration were discussed. The working group, including three joint sessions, was organized around six themes:

- Controlled particle injection into the wake for beams that are stable and of higher quality and charge.
- Diagnostic techniques including radiation sources as well as accelerator controls to improve operability.
- Acceleration with preservation of beam quality (special focus on hosing) and efficient transfer of laser energy to realize performance goals.
- Staging multiple plasma elements, including beam manipulation, for high beam energies in colliders and beam disposal (deceleration) in photon sources.
- Guiding of the drive laser pulses to extend the lase plasma interaction/acceleration length.
- Novel regimes in driver duration, driver wavelengtn, or plasma density that open new capabilities.

This summary paper presents highlights from each of the themes on progress in laser-plasma acceleration physics and towards meeting the needs of applications. Detailed results and references may be found in the respective papers in these proceedings. Presented results build on past work in these and related techniques, as reviewed in [1-3].

II. Controlled Particle Injection

Injection control is the first key element to obtaining high quality beams. Injection of the appropriate charge and longitudinal bunch shape is required such that acceleration (including beam loading and dephasing) will produce narrow energy spread and high flux. Transverse emittance should also be minimized for focusability of the beam and photon source performance. Progress was presented on ionization, multi-pulse, and external injection techniques. Posters and presentations in Working Group 7 (Radiation Generation and Advanced Concepts) and Working Group 4 (Beam-Driven Acceleration) additionally addressed plasma density transition or 'downramp' injection and 'self' injection. While self-trapping, which occurs when the wake reaches an amplitude sufficient to trap electrons from the plasma through which it propagates, is simple, it offers very limited control. Separate control over electron injection into a wake driven to an amplitude below the self-trapping threshold is hence important so that injection and wake can be tuned independently. Progress was made on several such techniques.

Ionization can be used to control injection into the wake if a gas or gas mixture is used which has ionization states near the peak intensity of the wake drive laser. The leading edge of the driver at low intensity ionizes the bulk states producing a plasma in which the wake is driven. The last state(s) are ionized near the peak of the laser pulse, injecting electrons at near-zero velocity, which are therefore trapped by the wake where the bulk plasma is not. For high-quality beams, injection must be localized and residual ionization momentum addressed. High peak currents from an ionization-injected

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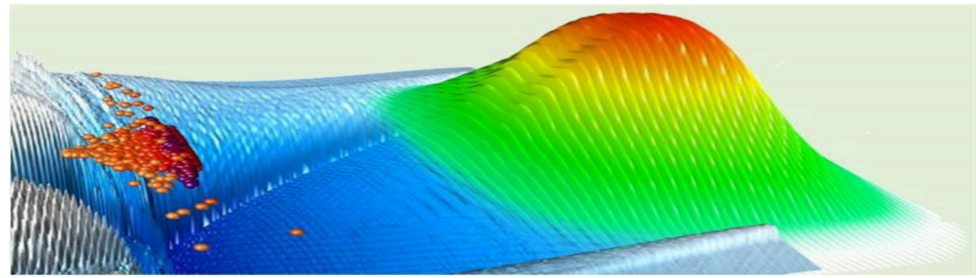


EAAC 2019

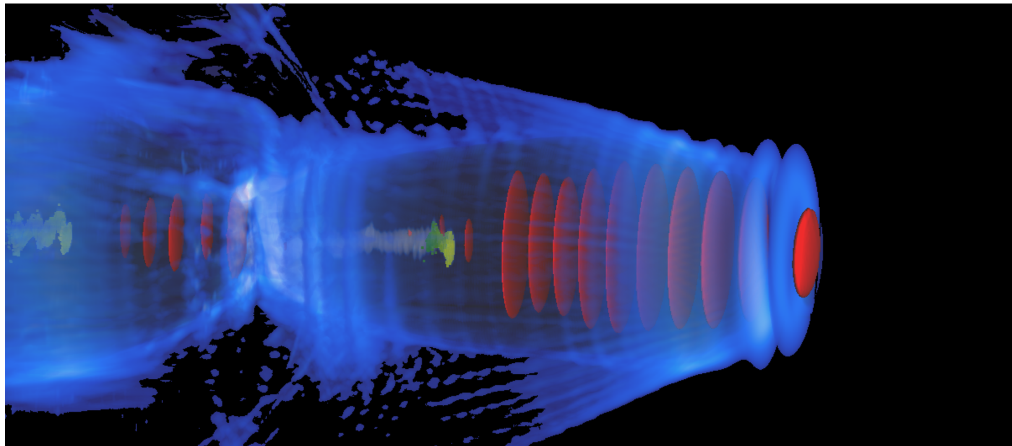
4th European Advanced Accelerator Concepts Workshop

15-21 September 2019
Hotel Hermitage, La Biodola Bay, Isola d'Elba, Italy

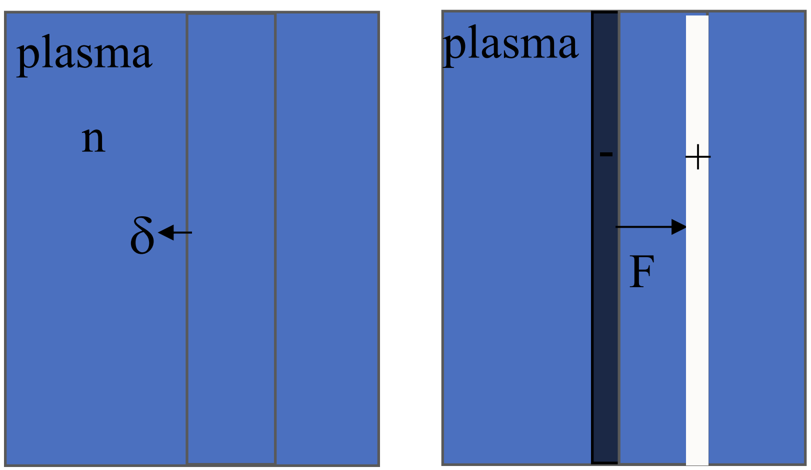
Plasma wave accelerator – GeV/m using Terawatt, femtosecond lasers

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

Wake



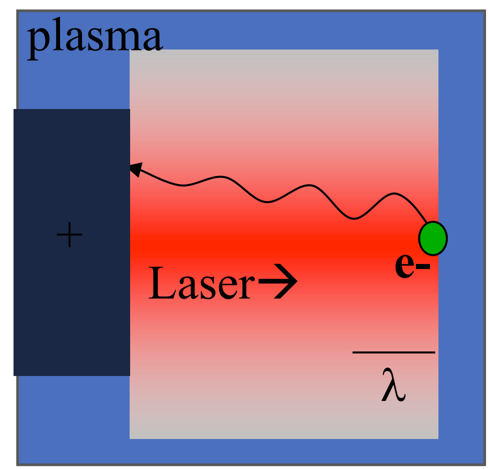
Plasma Oscillation



Displaced electrons induce electric field

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

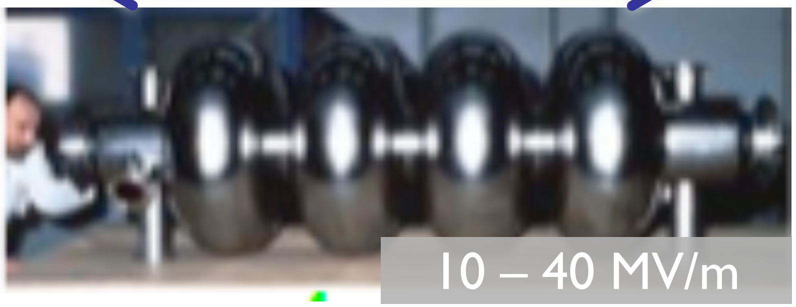
Ponderomotive Force



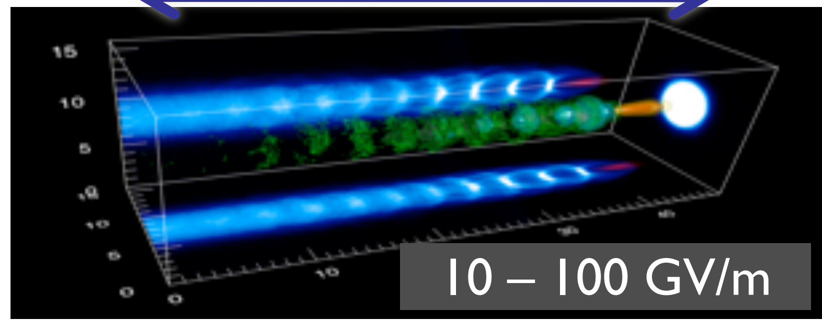
Laser radiation pressure displaces electrons

Laser plasma acceleration (LPA/LWFA) enables compact accelerators

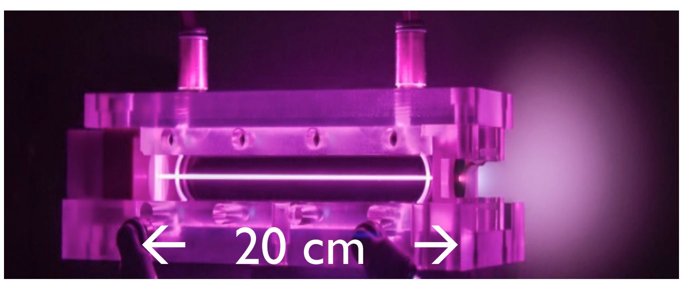
meter-scale

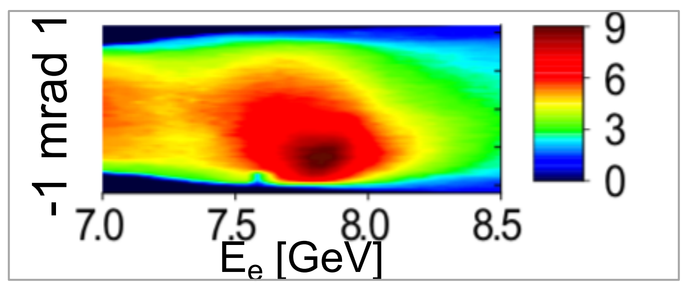


100 micron-scale



7.8 GeV electron beam from 20 cm accelerator

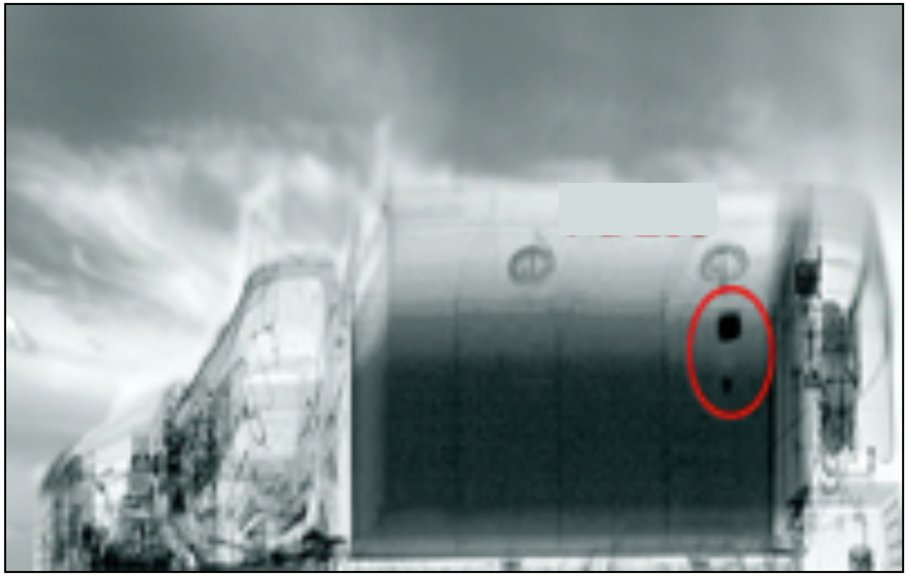


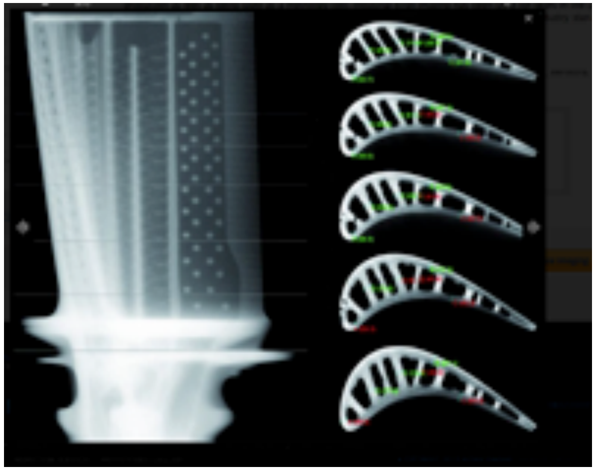


Outline

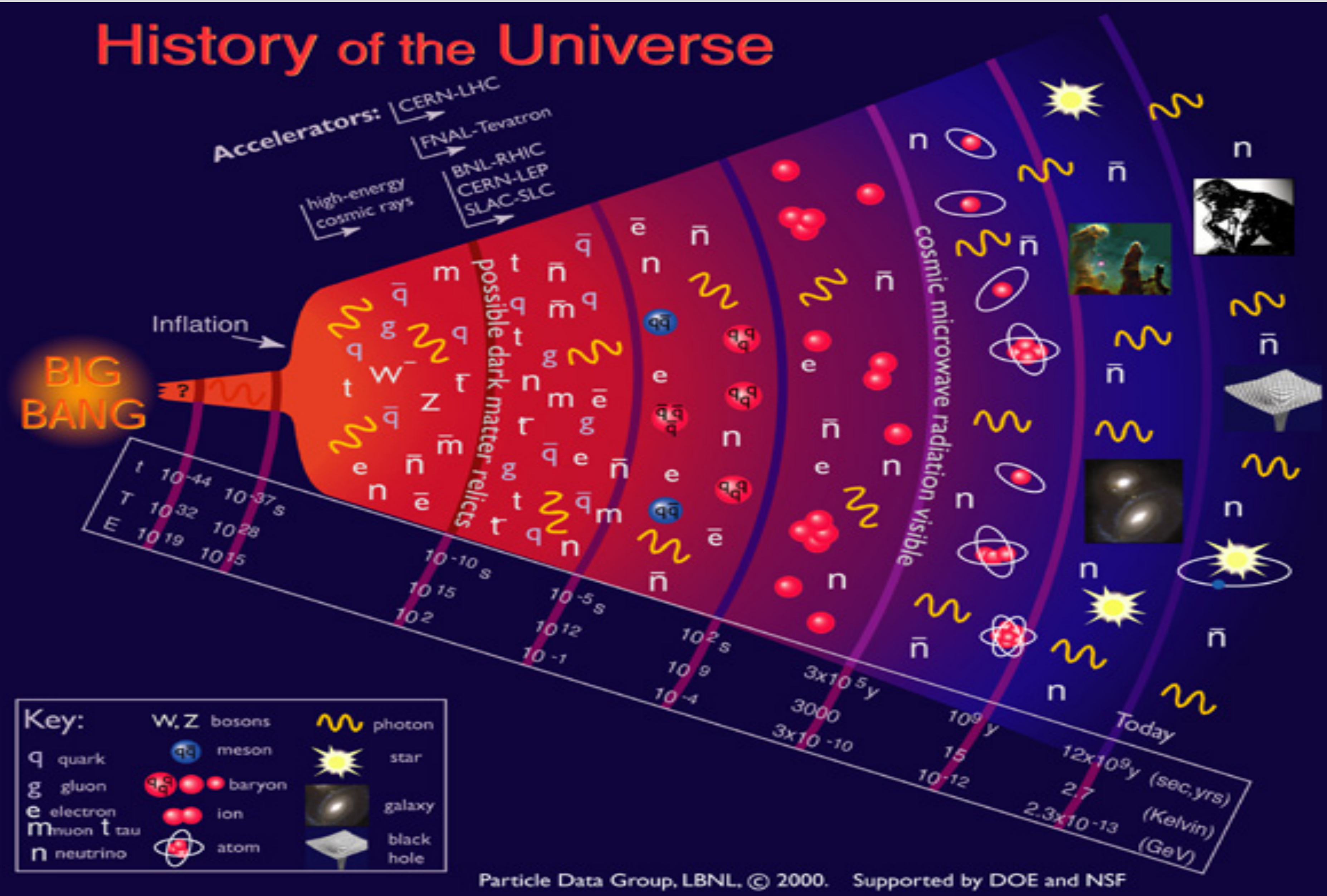
- Accelerator applications, compactness
- Physics of Laser-Plasma wakefield Acceleration
- Simulation considerations
- Experimental review & examples
- Outlook
- Personal perspectives

High energy particles/photons probe the concealed

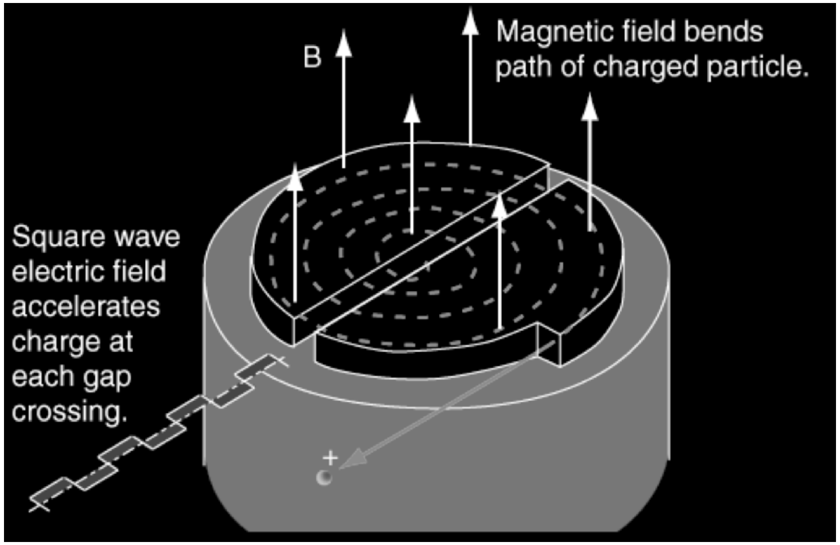


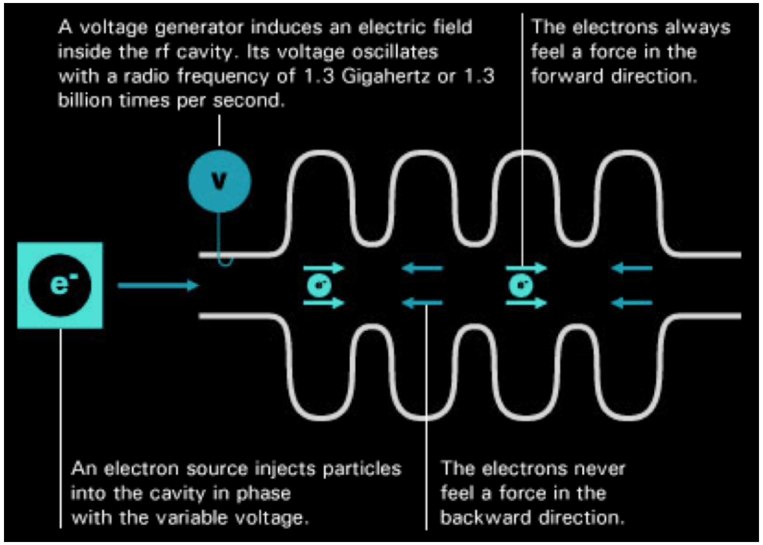


High energy particles/photons probe the origins of the universe

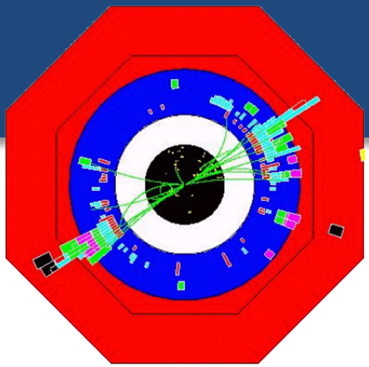


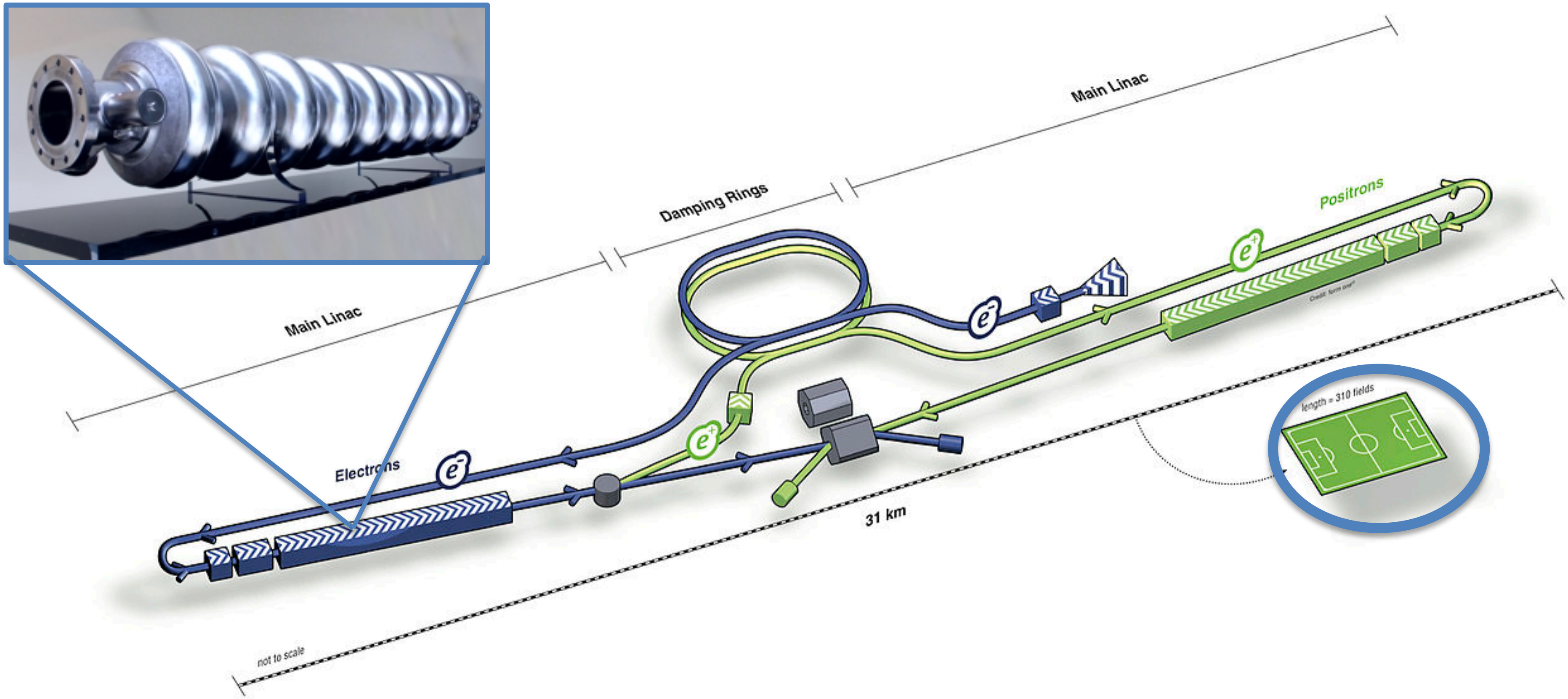
Particle accelerators are successful but large because limited to ~10's MV/m





High energy particle physics is accelerator size/cost limited





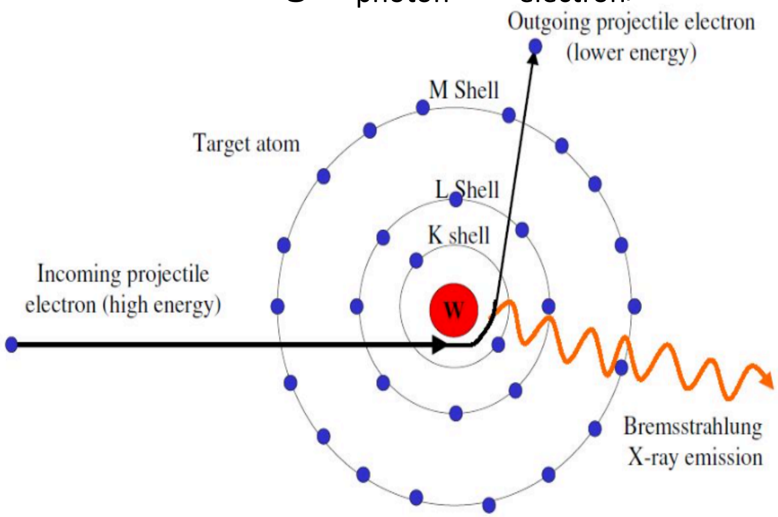
TeV electron accelerator in ~ a soccer field length?

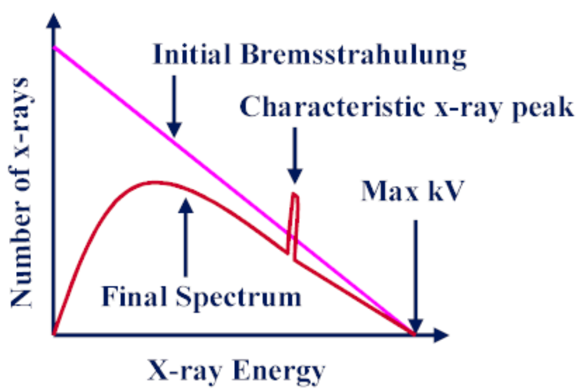
Precise high-energy photon sources also rely on accelerators

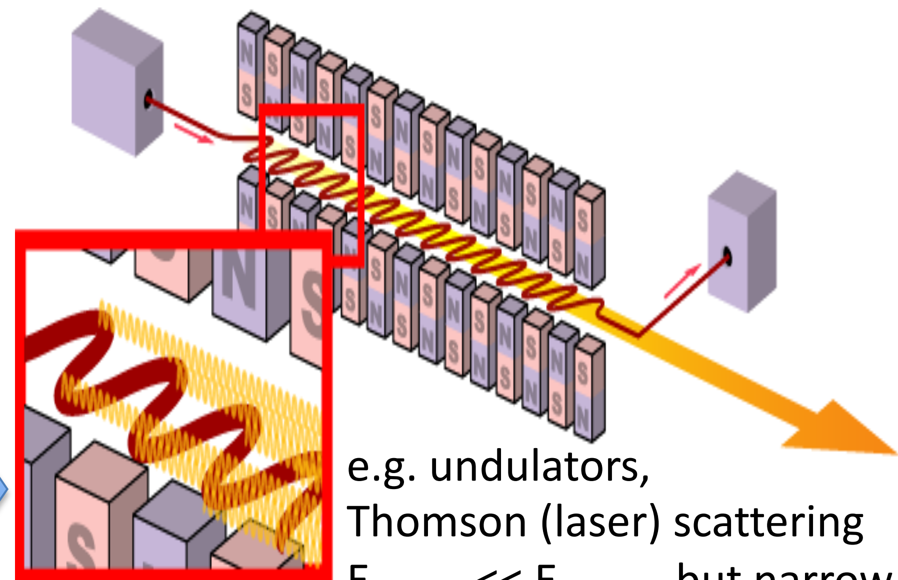
Simple, Low E_e

Lower dose, higher resolution

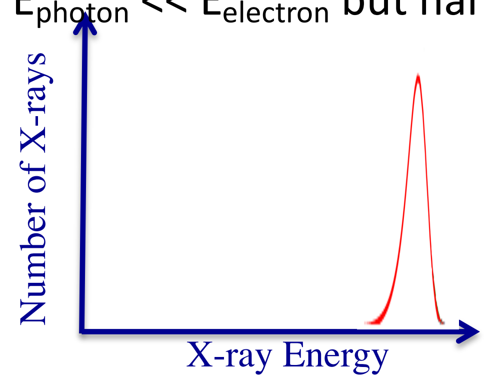
Bremsstrahlung: E_{photon} ~ $E_{electron}$, broad







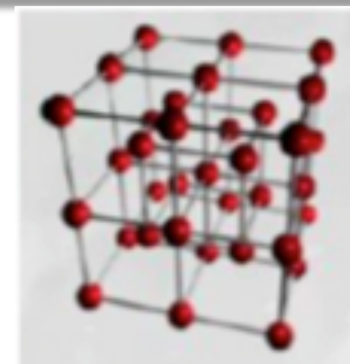
e.g. undulators,
Thomson (laser) scattering
E_{photon} << $E_{electron}$ but narrow



keV photons require keV electrons

keV photons require MeV - GeV electrons

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



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

Outline

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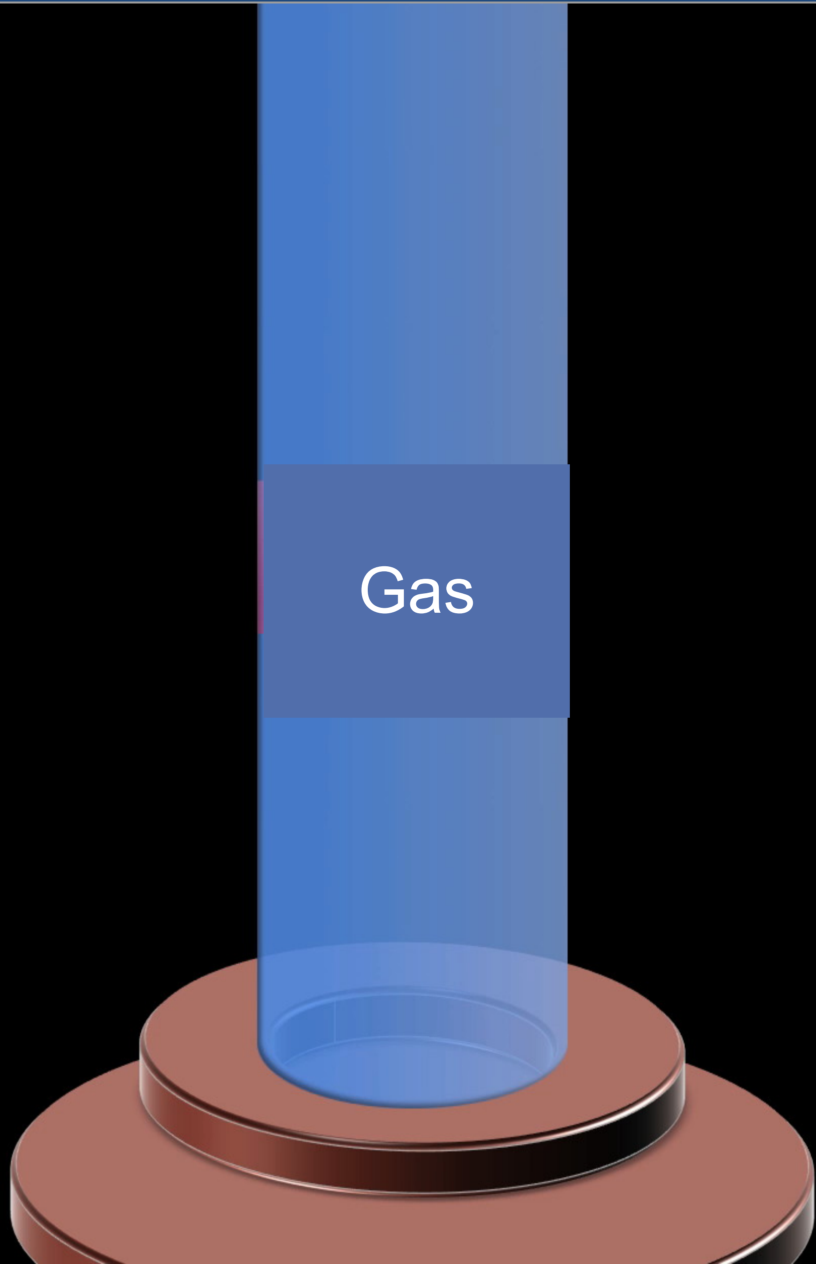
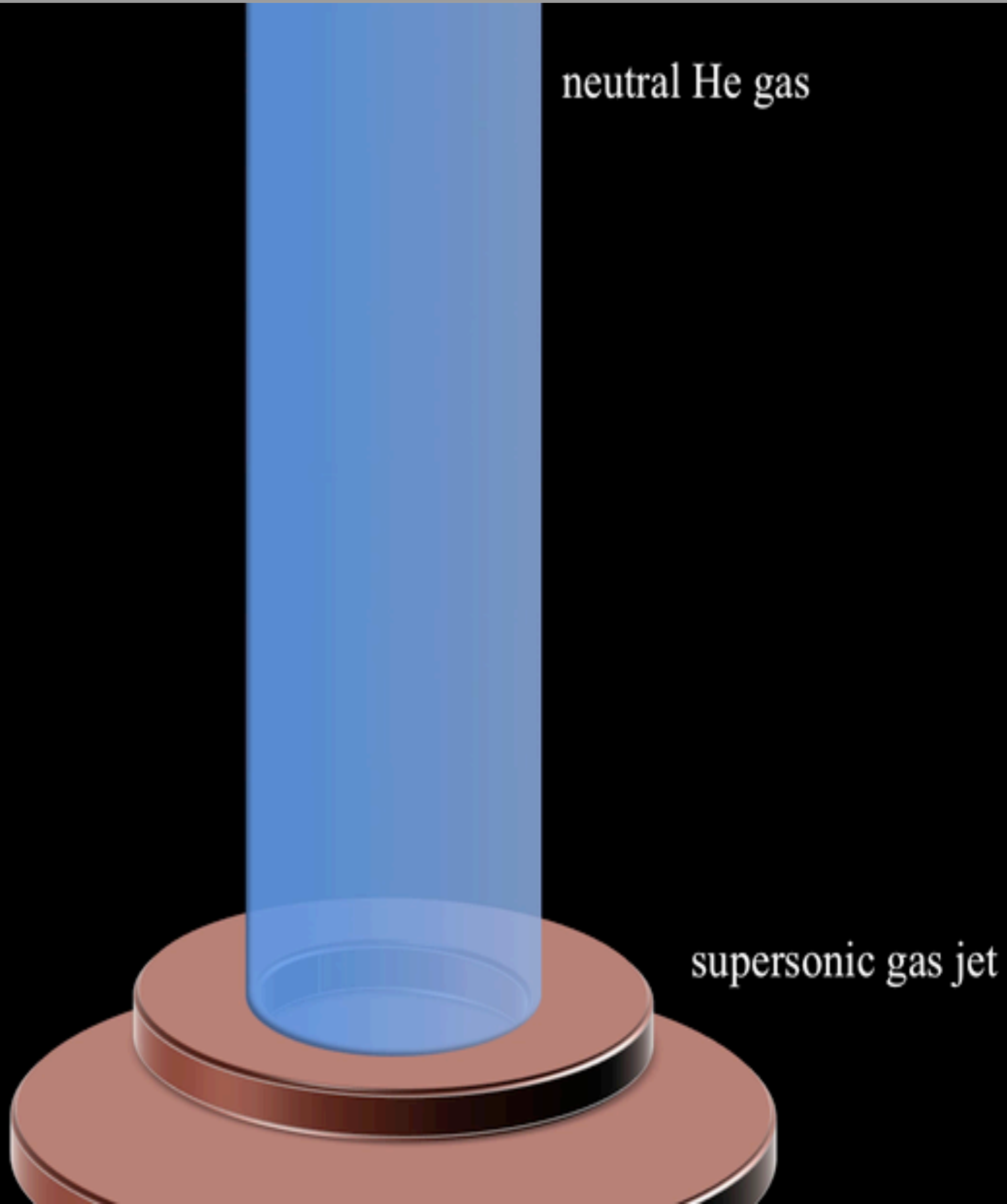
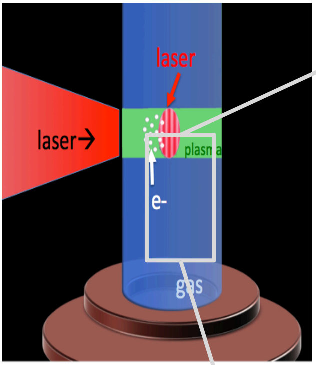
Intense femtosecond laser drives a plasma for Laser Plasma Acceleration (LPA)

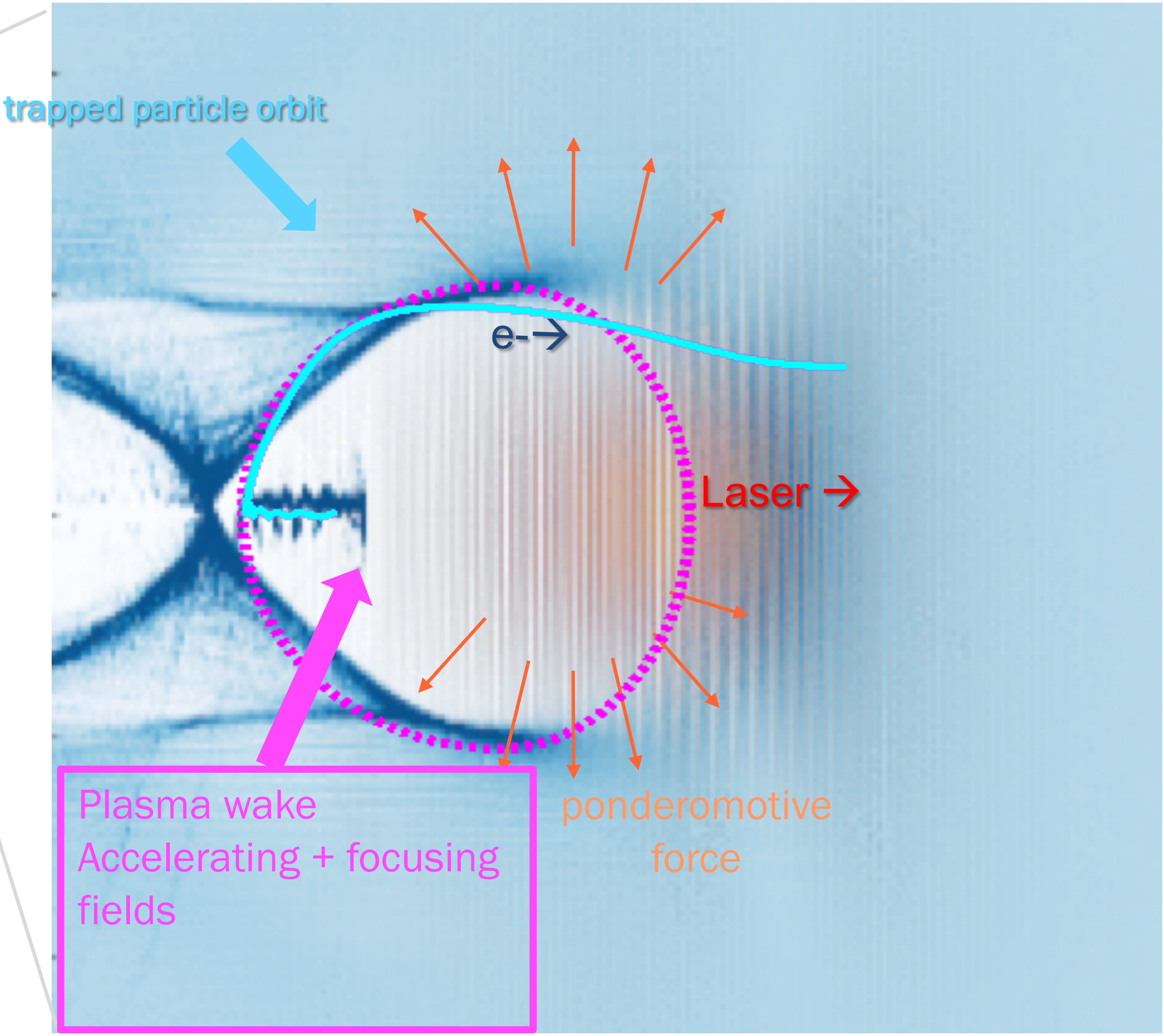


Intense femtosecond laser drives a plasma for Laser Plasma Acceleration (LPA)



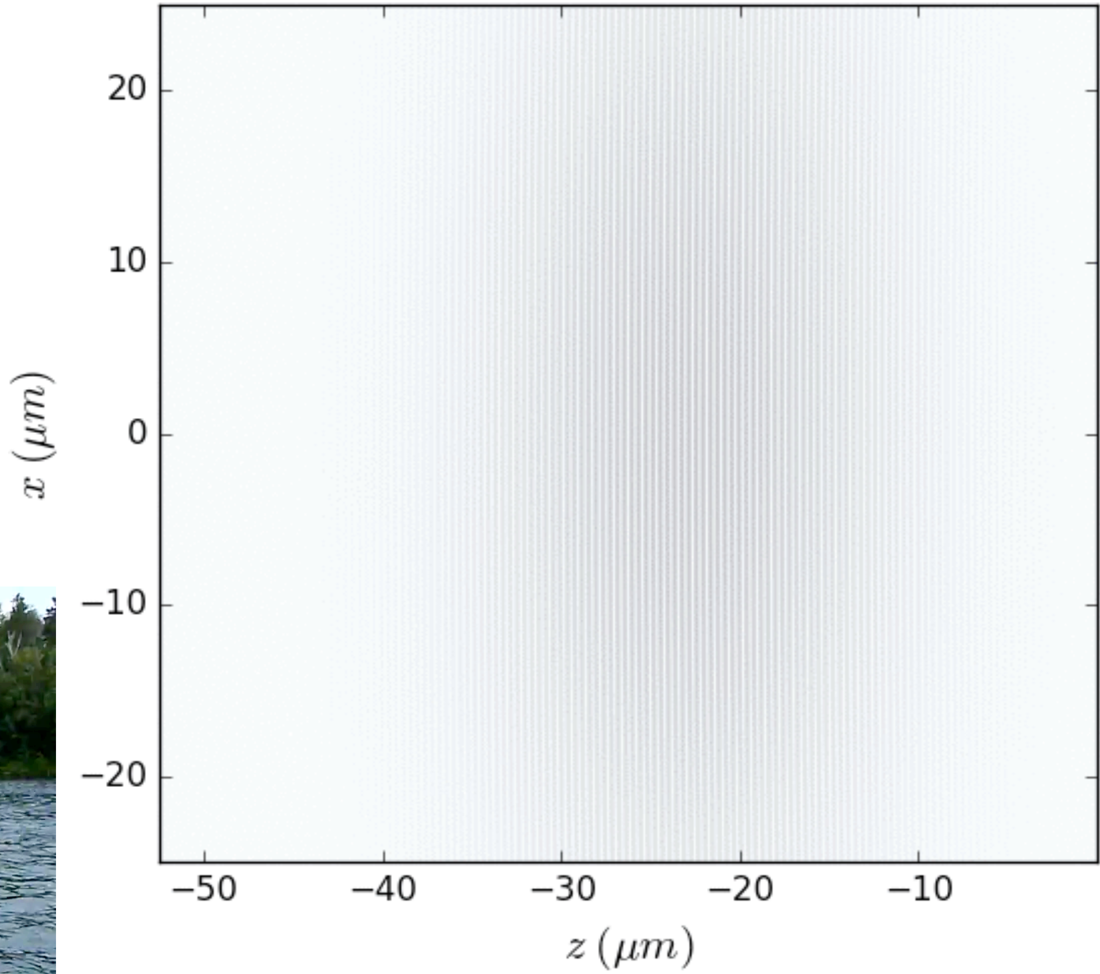
Plasma wave driven by radiation pressure of TW, fs laser





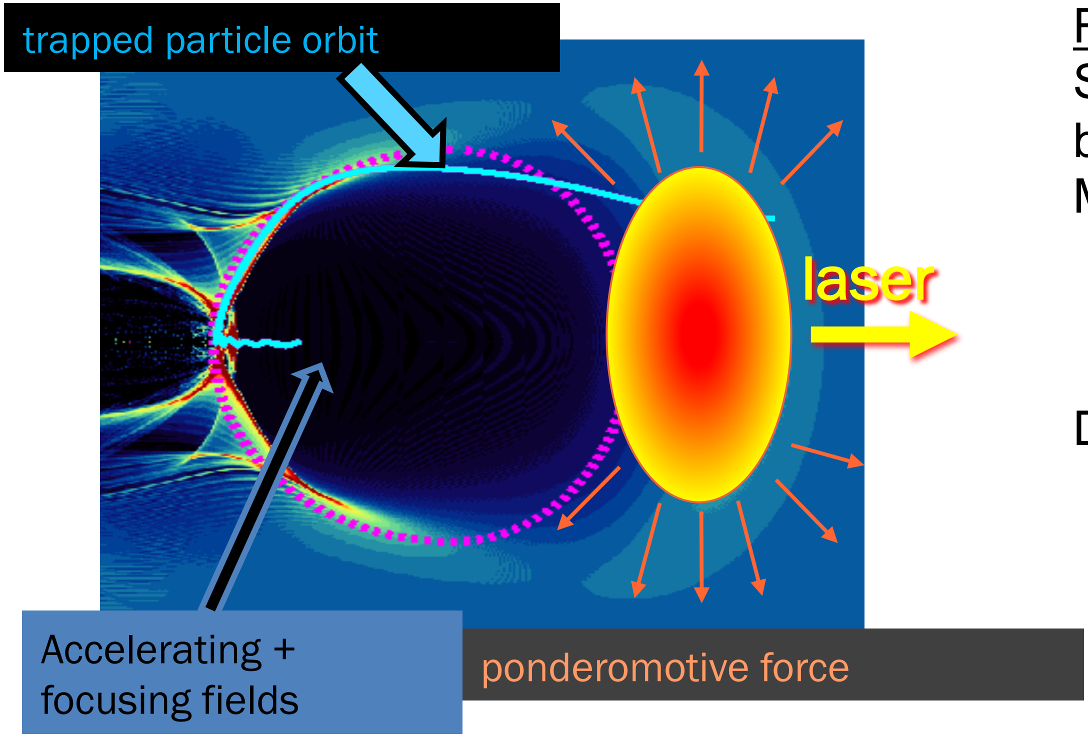
1: W.P. Leemans, Phys. Plasmas 1998, 2: C. Geddes et al., Nature 2004. 3: W.P. Leemans et al., PRL 2014, 4: S. Steinke et al., Nature 2016

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

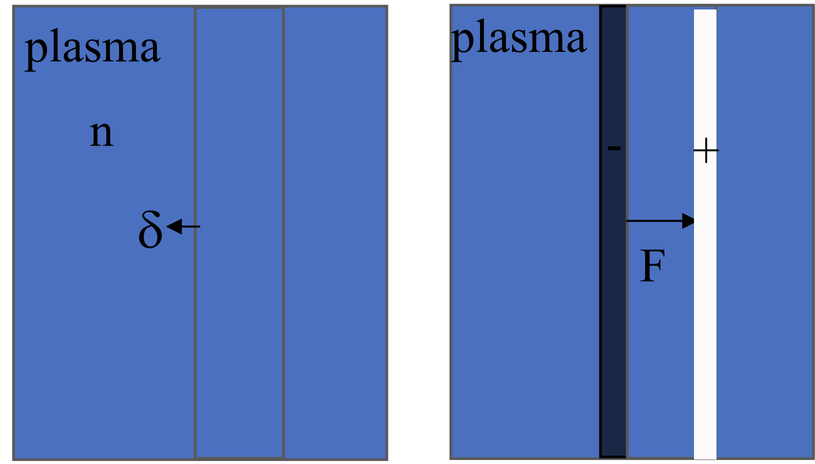
Direct laser acceleration?

- 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

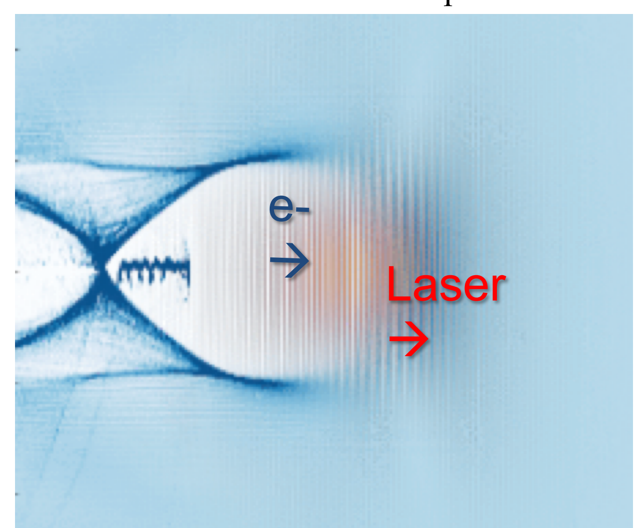
Plasma Oscillation



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.

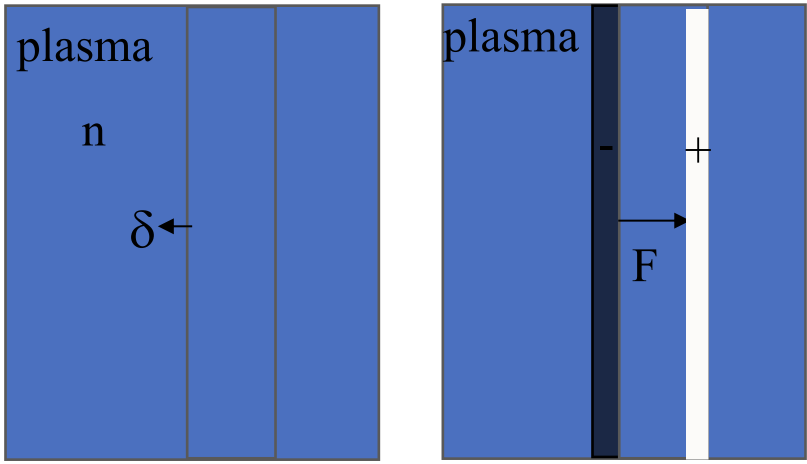
    3D - easier trapping

    Relativistic- harder trapping

  - Note: hot particles trap easily:

    Cold plasma ~10 eV << E_{trap}

Plasma Oscillation



Displaced electrons induce electric field

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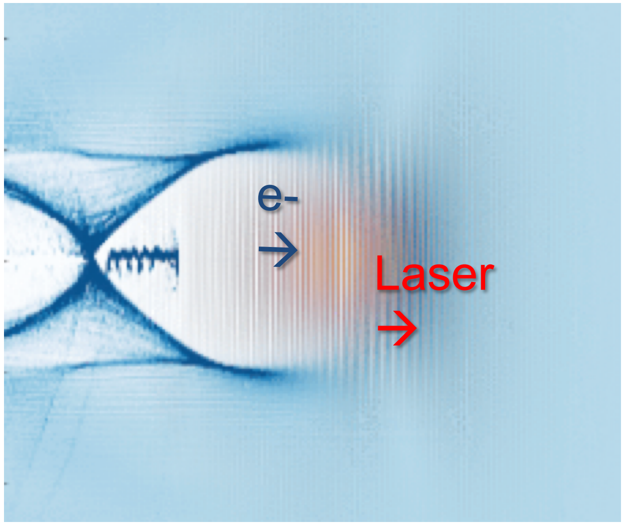
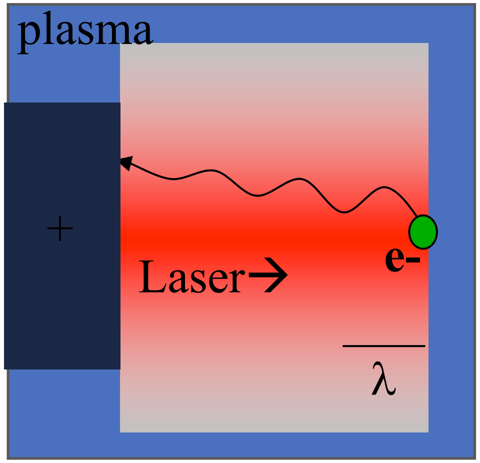


Plasma wave driven by radiation pressure of TW, fs laser: Ponderomotive force

- 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

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

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

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

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

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

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

  - $\Phi_p = mc^2a^2/4e$

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

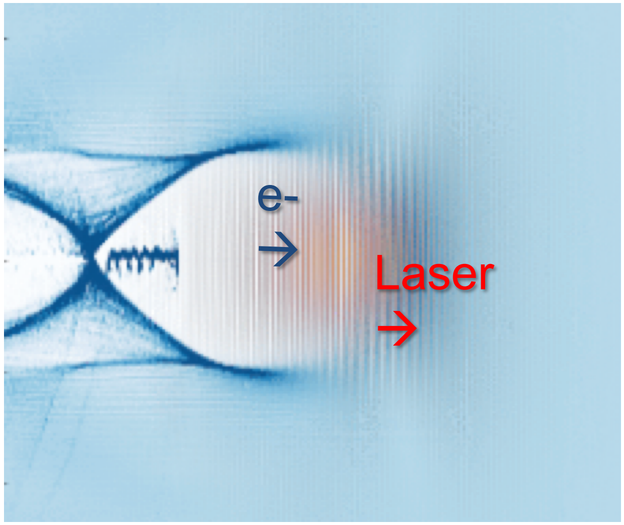
- Intensity to achieve Gradient limit:
  wake potential is order of ponderomotive potential

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

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

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

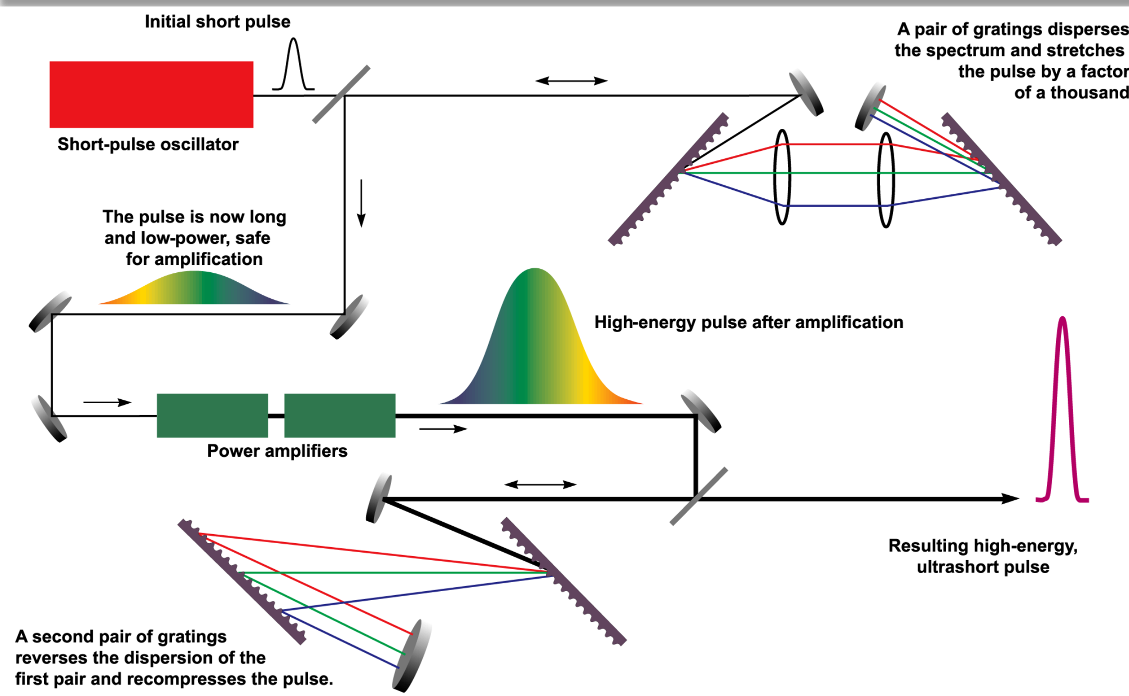
  electron motion in laser field is relativistic



- 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}

LPA 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, resonant LPA

2018 Nobel Prize: Strickland and Mourou

KUNGL. VETENSKAPS-AKADEMIEN
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LPA a key scientific application

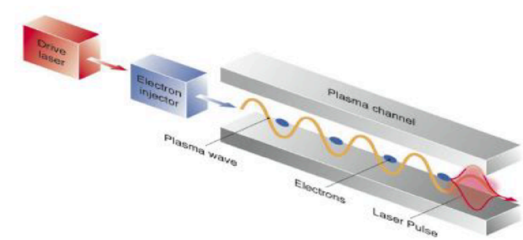


***Figure** 7. Schematic illustration of laser-plasma acceleration. An intense laser pulse drives a plasma wave (wake) in a plasma channel, which also guides the laser pulse and prevents diffraction. Plasma background electrons injected with the proper phase can be accelerated and focused by the wake. (Reproduced from W.P. Leemans (2010), White Paper of the ICFA-ICUIL Joint Task Force – High Power Laser Technology for Accelerators, http://icfa-bd.kek.jp/WhitePaper_final.pdf.)*

At Lawrence Berkeley National Laboratory in California, a petawatt-class laser at the Berkeley Lab Laser Accelerator (BELLA) facility is used to accelerate electrons to 4.2 GeV over a distance of 9 cm [78]. This is an acceleration gradient of at least two orders of magnitude higher than what can be obtained with RF technology.

Very different plasma physics regime:

Cold

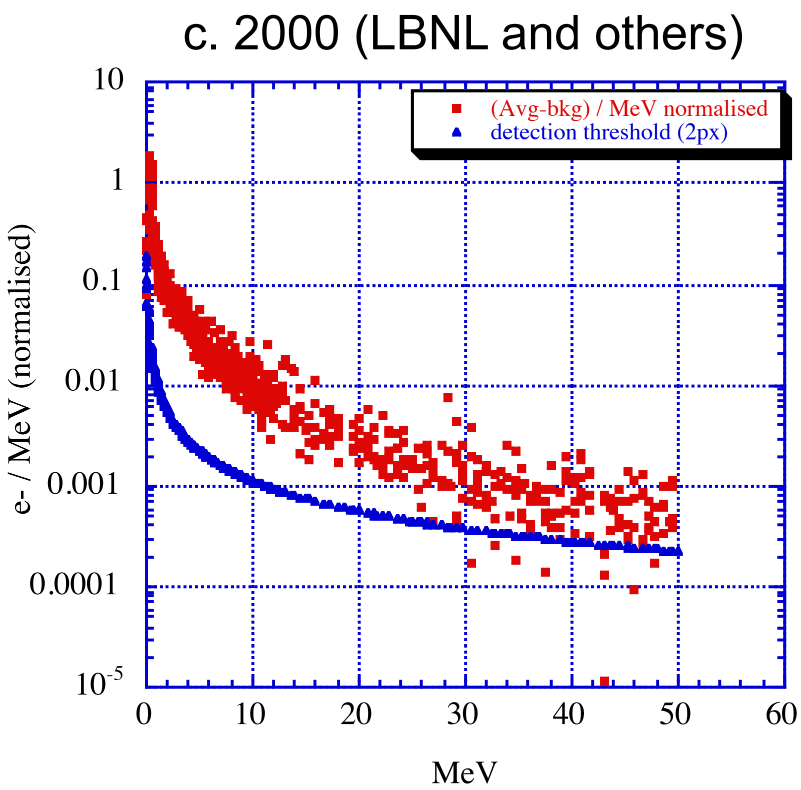
Unmagnetized

Collisionless

Single cycle electron oscillation

Is there anything interesting here?

First results approached GeV/cm but: non-resonant, broad energy spread



Pulse length too long

Interaction length & injection not controlled

Very different plasma physics regime:

Cold

Unmagnetized

Collisionless

Single cycle electron oscillation

Is there anything interesting here?

Relativistic motion

EM wave – plasma coupling/propagation

Wave and beam-plasma coupling

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 $\mathbf{v} = \mathbf{v}_0 + \tilde{\mathbf{v}}$, and discard quantities that are higher order in $\tilde{\mathbf{v}}$. This is suitable for considering small departures from stasis:

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

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

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 $\tilde{\mathbf{v}} = \mathbf{v}_s + \mathbf{a}c$ 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

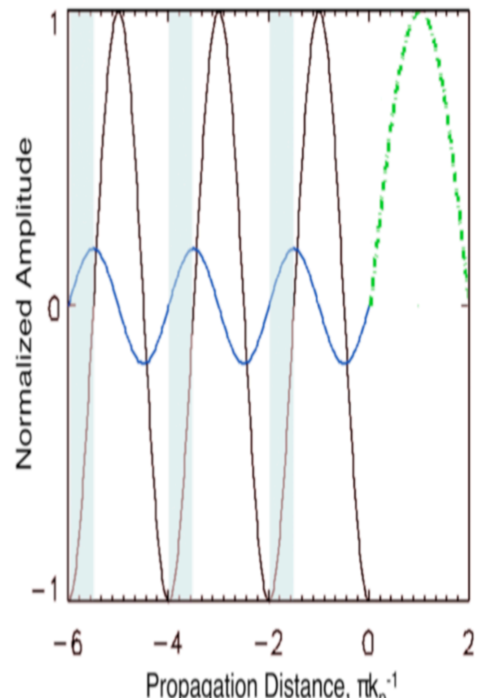
If the wake is not one-dimensional, the radial wake can be derived from the Panofsky-Wenzel theorem [3, 16, 75, 76]. This will be most important for laser spot size (and hence wake radial dimension) $\lesssim \lambda_p$. We make use of:

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

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:

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

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 $w_0 \sim \lambda_p$.

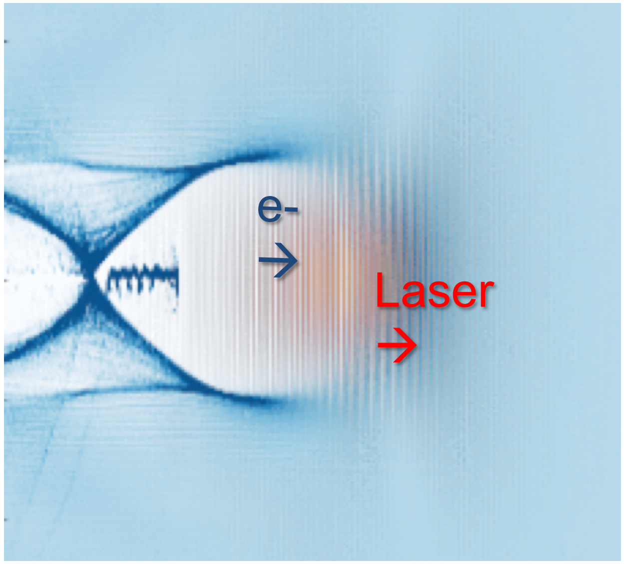
Shaded regions: radial field is positive and longitudinal field negative, are both accelerating and focusing for electrons.

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

Laser-propagation:
EM dispersion in unmagnetized plasma

- Laser velocity, from dispersion

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



- 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:

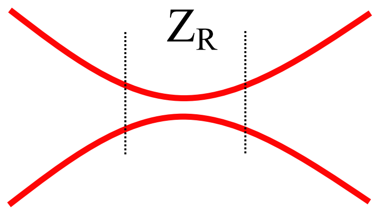
$$\begin{aligned} \nabla^2\mathbf{E} + \frac{\omega^2}{c^2}\epsilon\mathbf{E} &= 0 \\ k^2 + \epsilon\frac{\omega^2}{c^2} &= 0 \\ \omega^2 = \omega_p^2 + k^2c^2 & \end{aligned} \tag{2.28}$$

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:

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

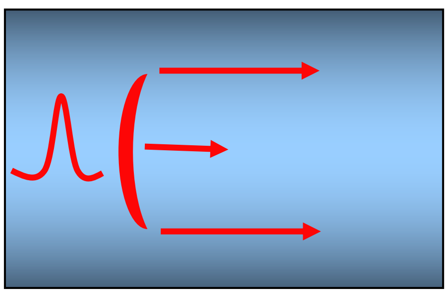
Laser-plasma acceleration: Laser guiding enables high energies

- cm-scale acceleration > 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

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

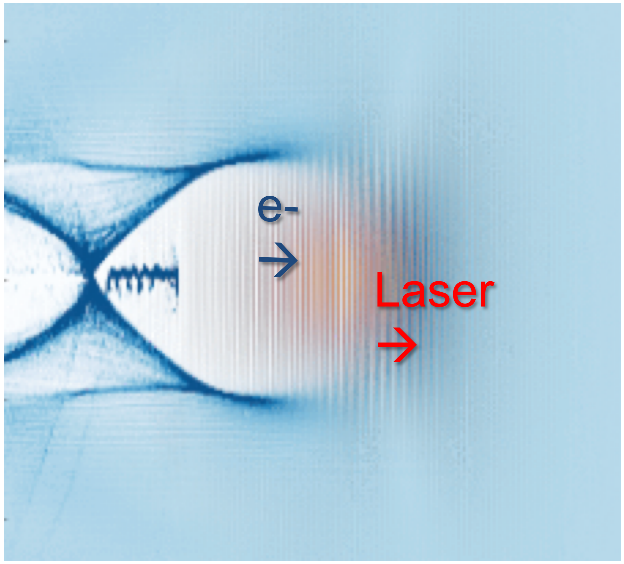
$$E_z^2 L_p = E_L^2 L_L$$

Linear wakefield: $a_0^2 \ll 1$

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

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

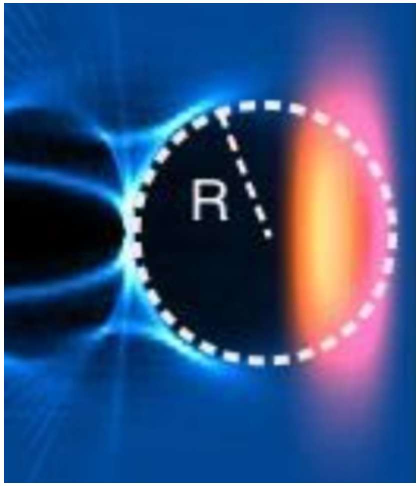
$L_{pump} = 4\, L_d/a^2$ → a ~ 1-2 efficient



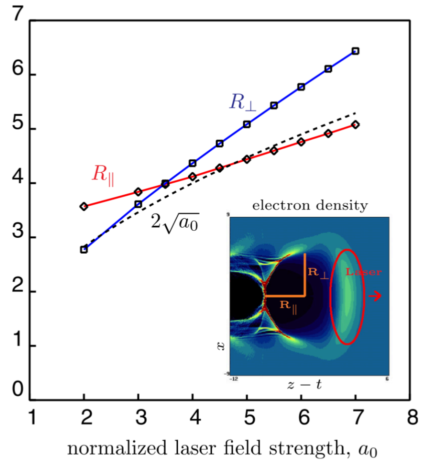
- Energy gain: $E_{wake}\, L_{d,pump} \sim a^2\, \lambda_p^2/\lambda_0^2$

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

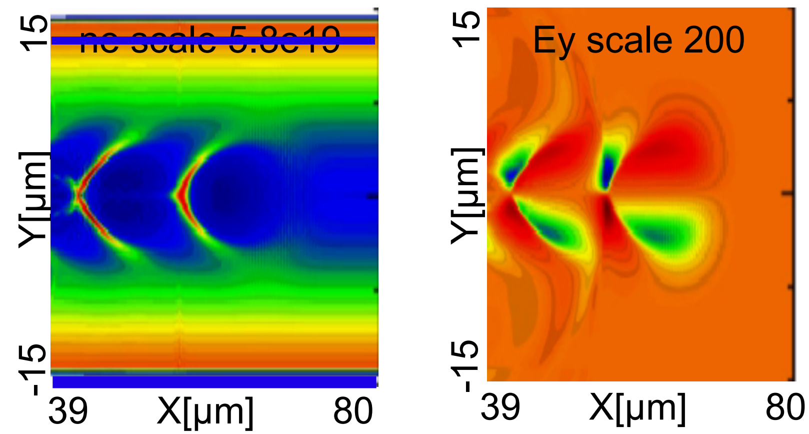


Benedetti et al, Phys Plasmas 20, 103108, 2013

- 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

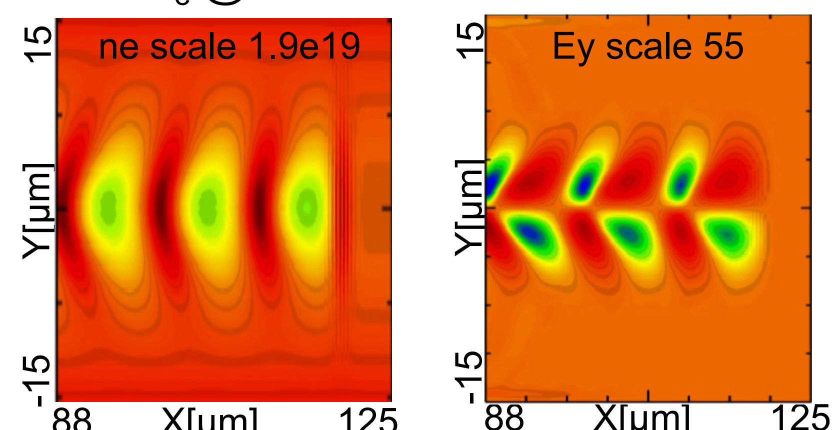
a_0=2 nonlinear

scaled n_e @ 1.3×10^{19} - Ex = 230-550 GV/m



a_0=1 quasilinear

scaled n_e @ 1.3×10^{19} - Ex = 135-165 GV/m



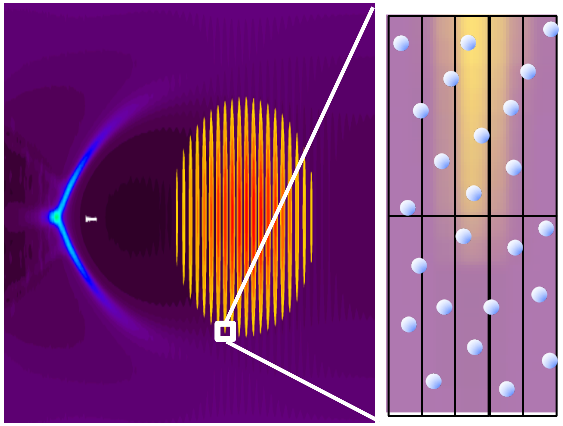
Remarkably, scalings with plasma parameters remain the same
detailed changes but similar general acceleration

Outline

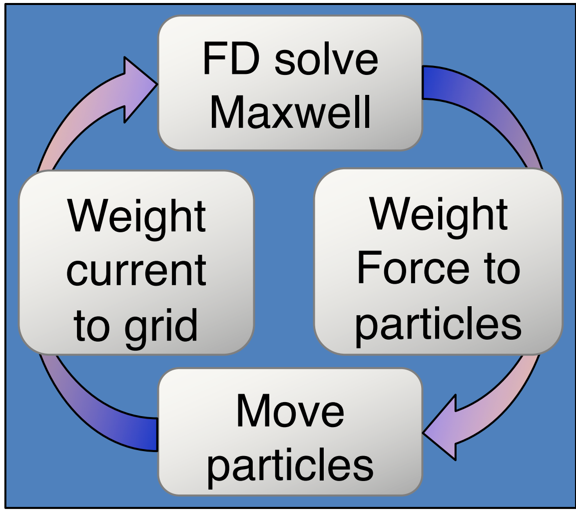
- Accelerator applications, compactness
- Physics of Laser-Plasma wakefield Acceleration
- Simulation considerations
- Experimental review & examples
- Outlook
- Personal perspectives

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

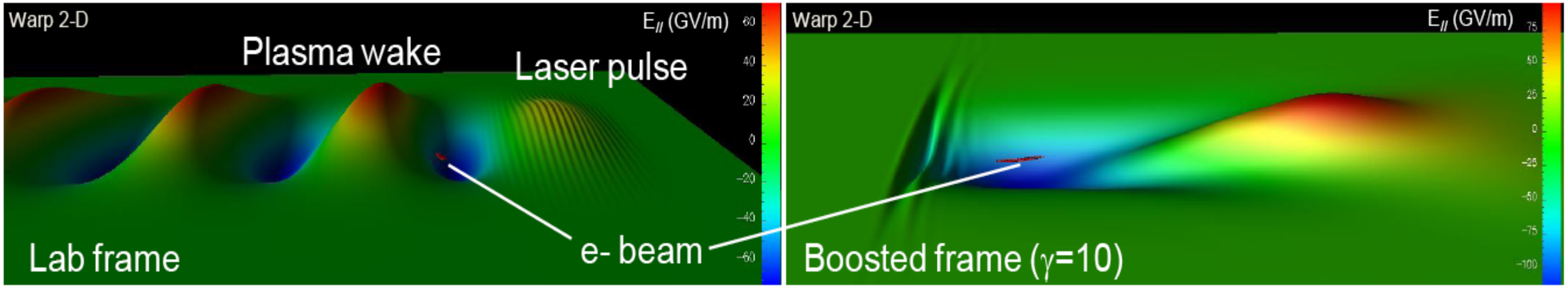
Problem-specific techniques are essential: Lorentz boost, Gallilean boost, envelope

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

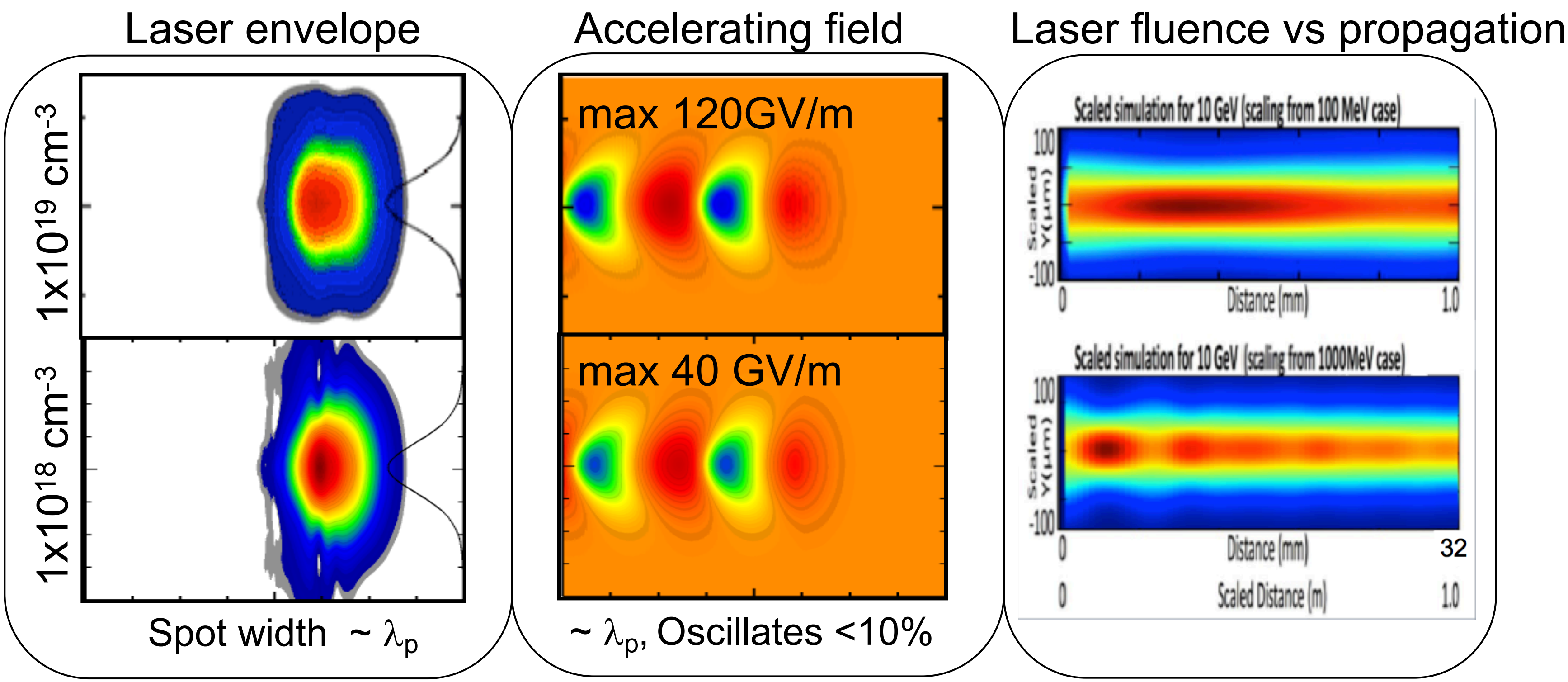
Suitable when trapping not important

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 $1x10^{19}$

1120 MeV at $1x10^{18}$

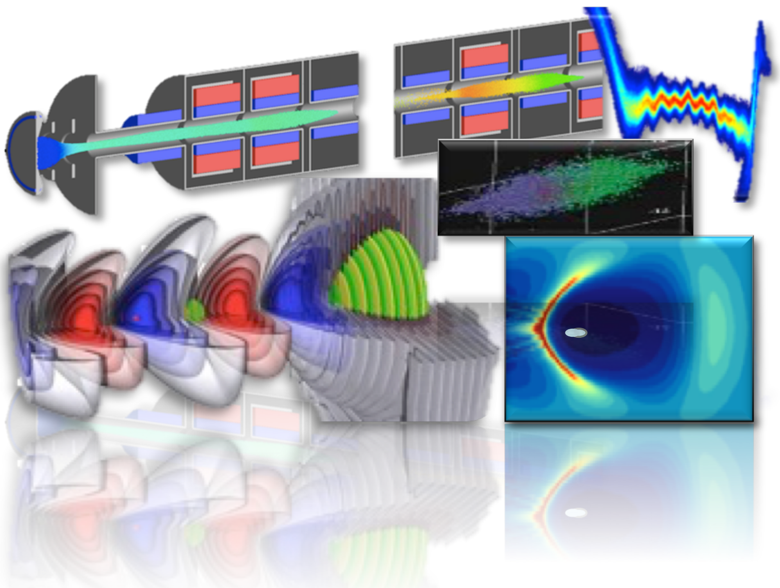
Laser evolution & multi- dimensional physics included – transverse osc. does not scale

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.

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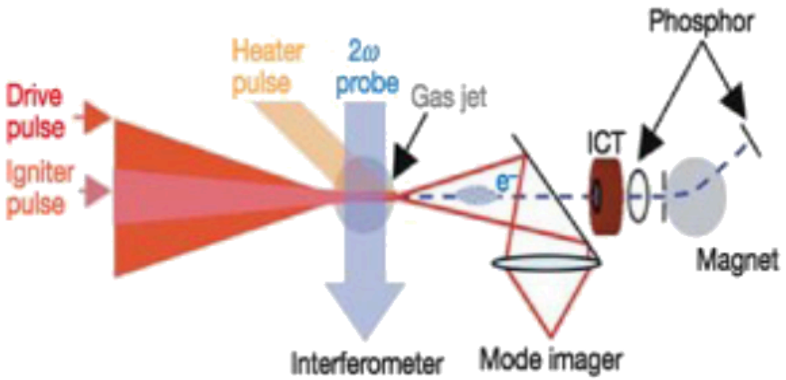
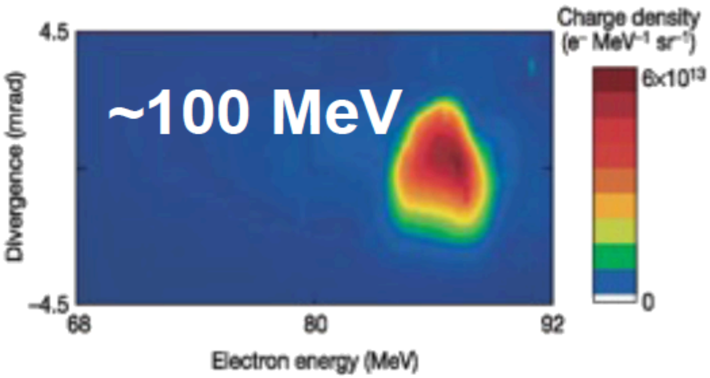
Guided, self injected experiments at lower density: high energy, lower energy spread

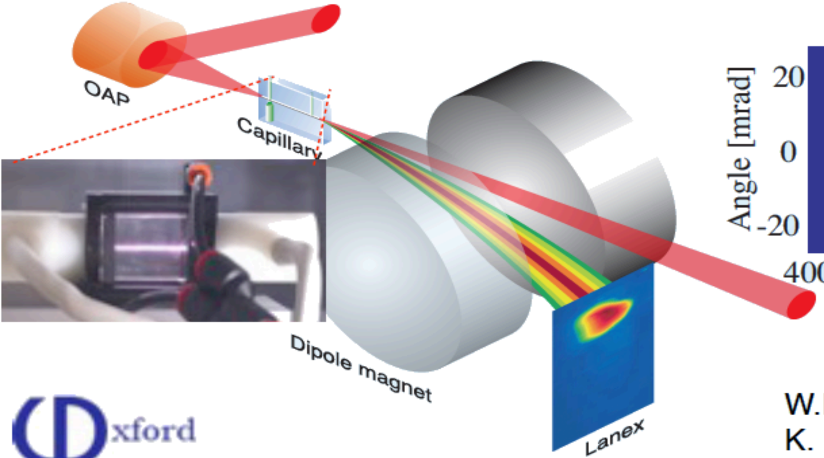
2004 result: 10 TW laser, mm-scale plasma

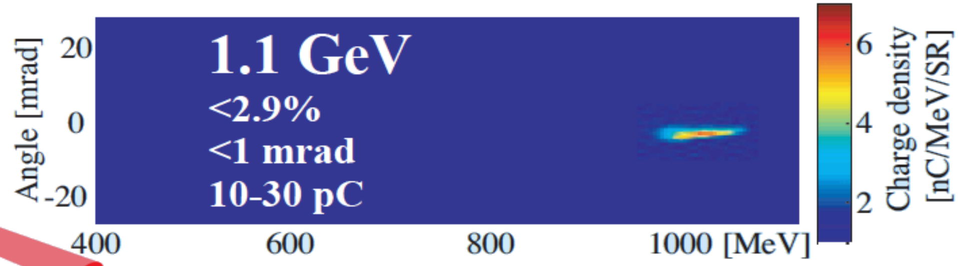


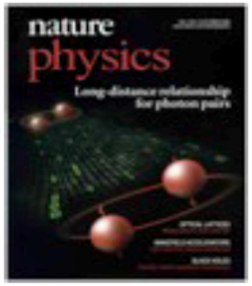


C. G. R. Geddes,et al, Nature,**431**, p538 (2004)
S. Mangles et al., Nature **431**, p535 (2004)
J. Faure et al., Nature **431**, p541 (2004)

2006 result: 40 TW laser, cm-scale plasma



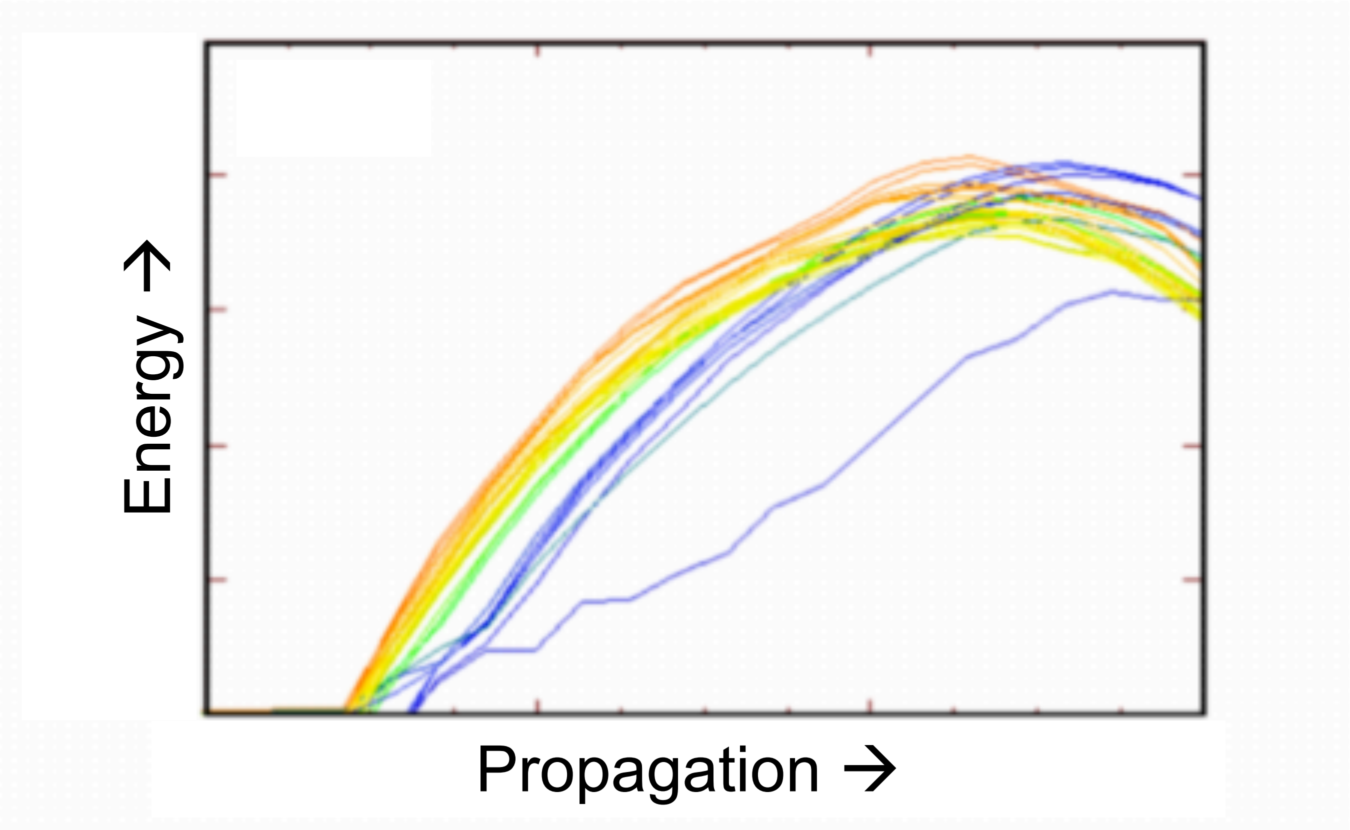




W.P. Leemans et. al, *Nature Physics* **2**, p696 (2006)
K. Nakamura et al., Phys. Plasmas **14**, 056708 (2007)

Oxford Physics

High quality self trapped beams can result from dephasing



bunches energies

Grand challenges for LWFAs to address

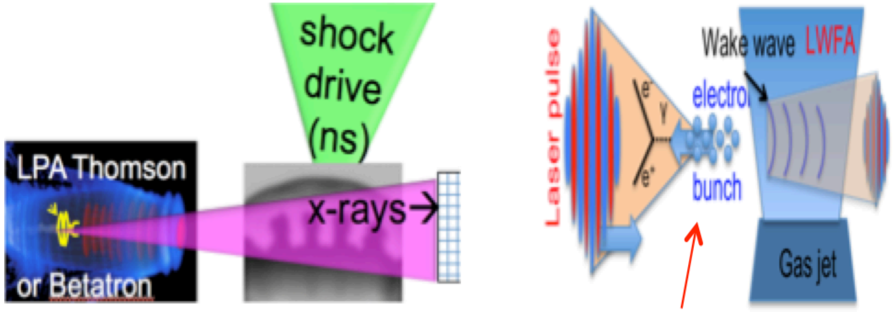
-- small accelerators with big capabilities --

sub-µm resolution, reduced dose x-ray characterization

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

< 1 µm emittance

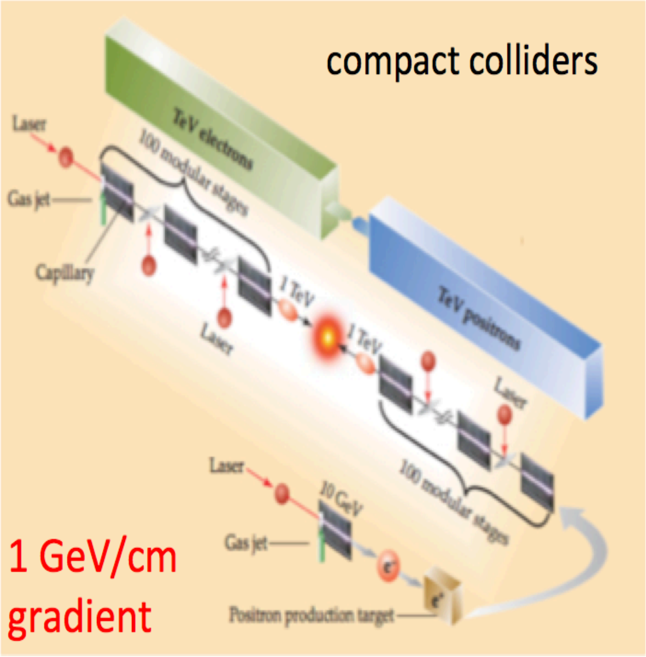
femtosecond dynamic probes



fs e-bunches

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

compact colliders



1 GeV/cm gradient

Leemans & Esarey Physics Today 2009

multi-species material characterization (1-stop shopping)

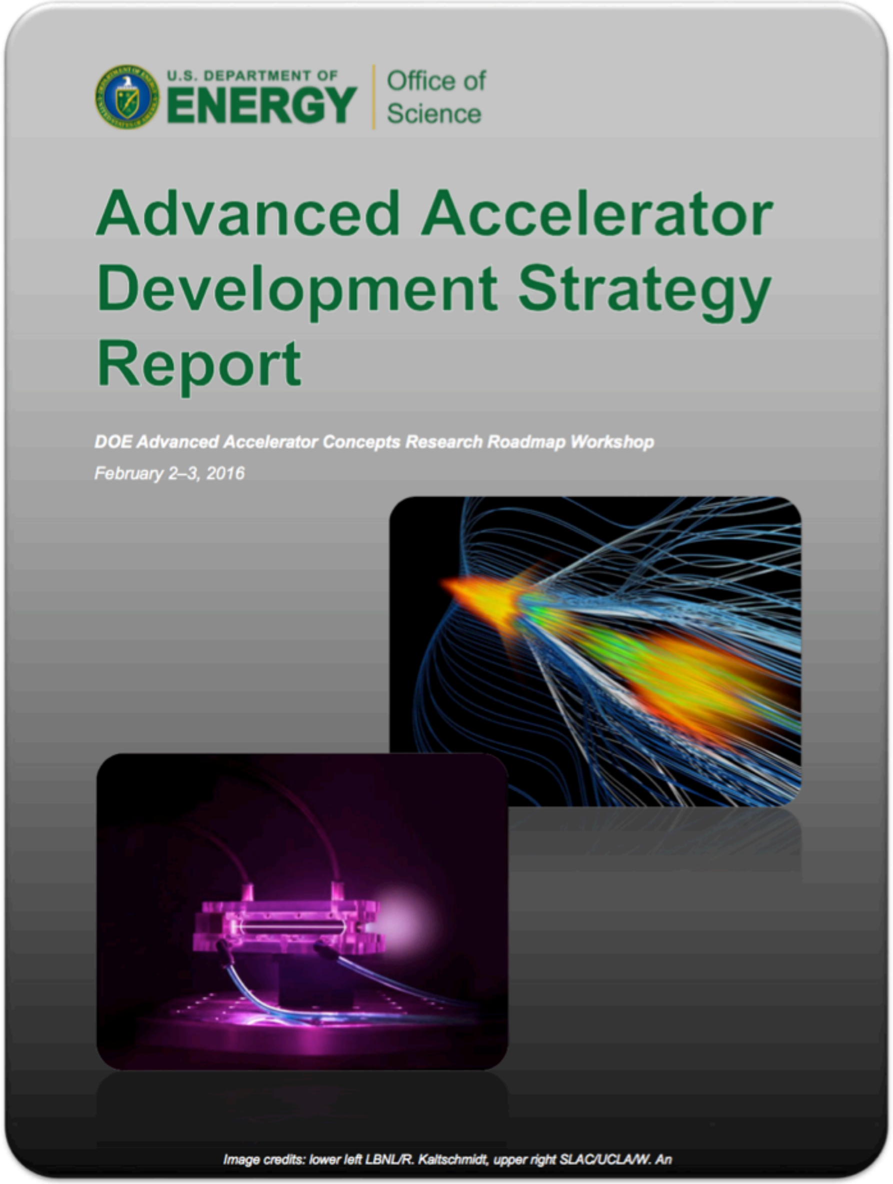
- Basic Science
- Medical
- Industrial
- Military

electrons, positrons, photons, hadrons using one laser

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+

Roadmap for Laser Plasma Accelerators has been developed



Strategy for future particle colliders

DOE Office of Science HEP
General Accelerator R&D program

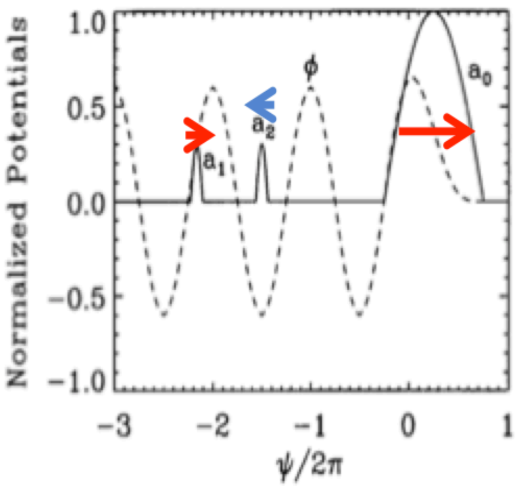
TeV to multi-TeV in 100's of meters
- nC class charge
- 50kHz class rate
- nm emittance
- percent energy spread

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

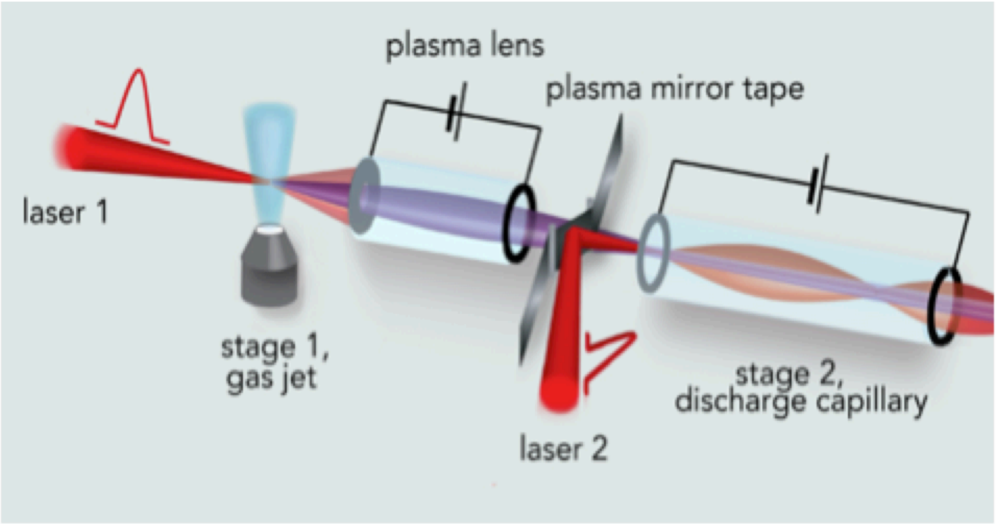
GeV-class, ≥ kHz, 10-100pC
Stepping stone and early application

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

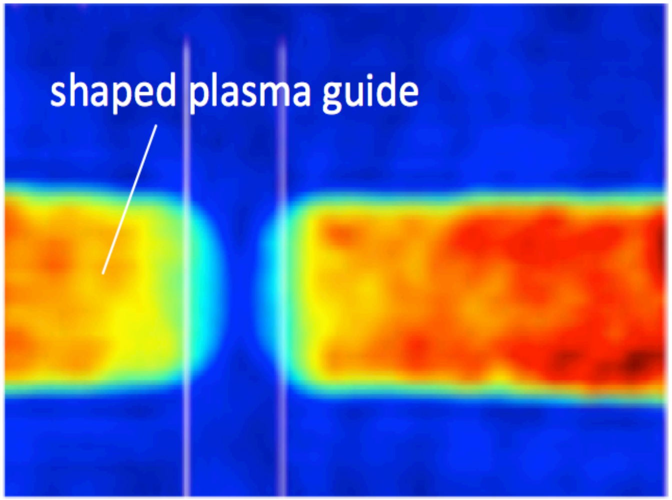
Injection: brighter 6D, shaped bunches



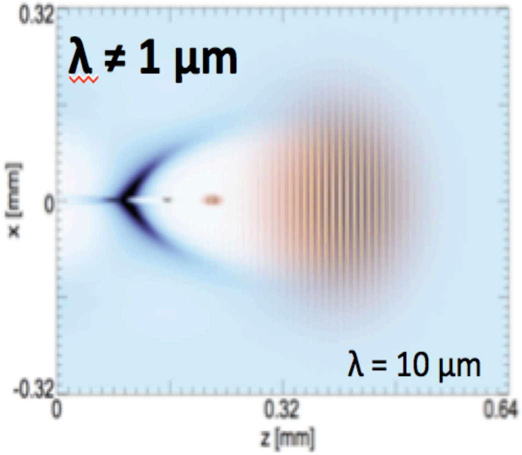
Acceleration: preserve emittance, stage efficiently

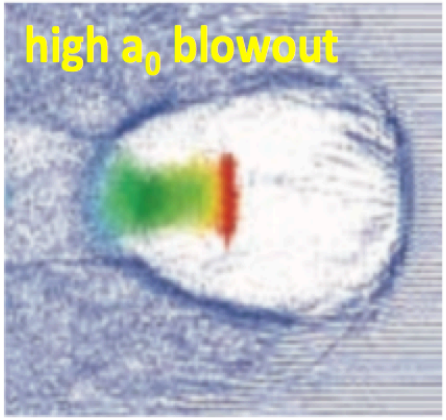


Guiding: reach depletion limit, tailor waveguide & laser

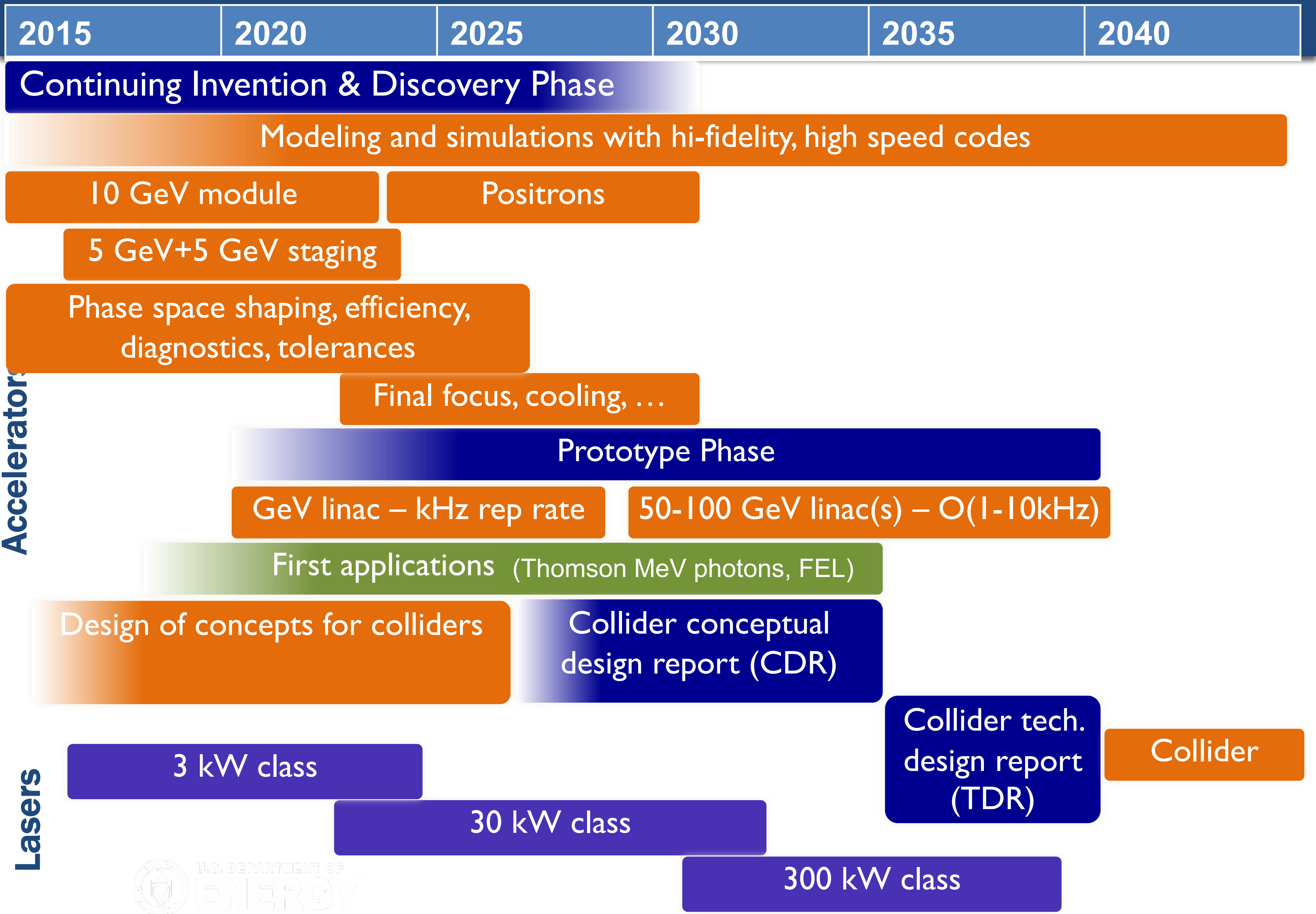


Optimization: scaling with *λ*, a_0, *etc.*



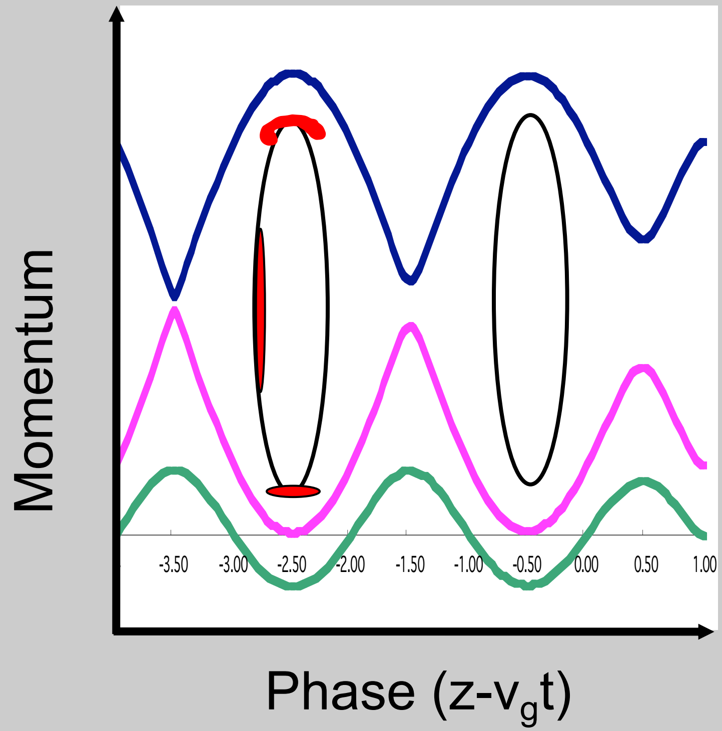


Roadmap for Laser Plasma Accelerators has been developed



Control trapping for stable high quality beams

I. Control electron phase & spread – ΔE

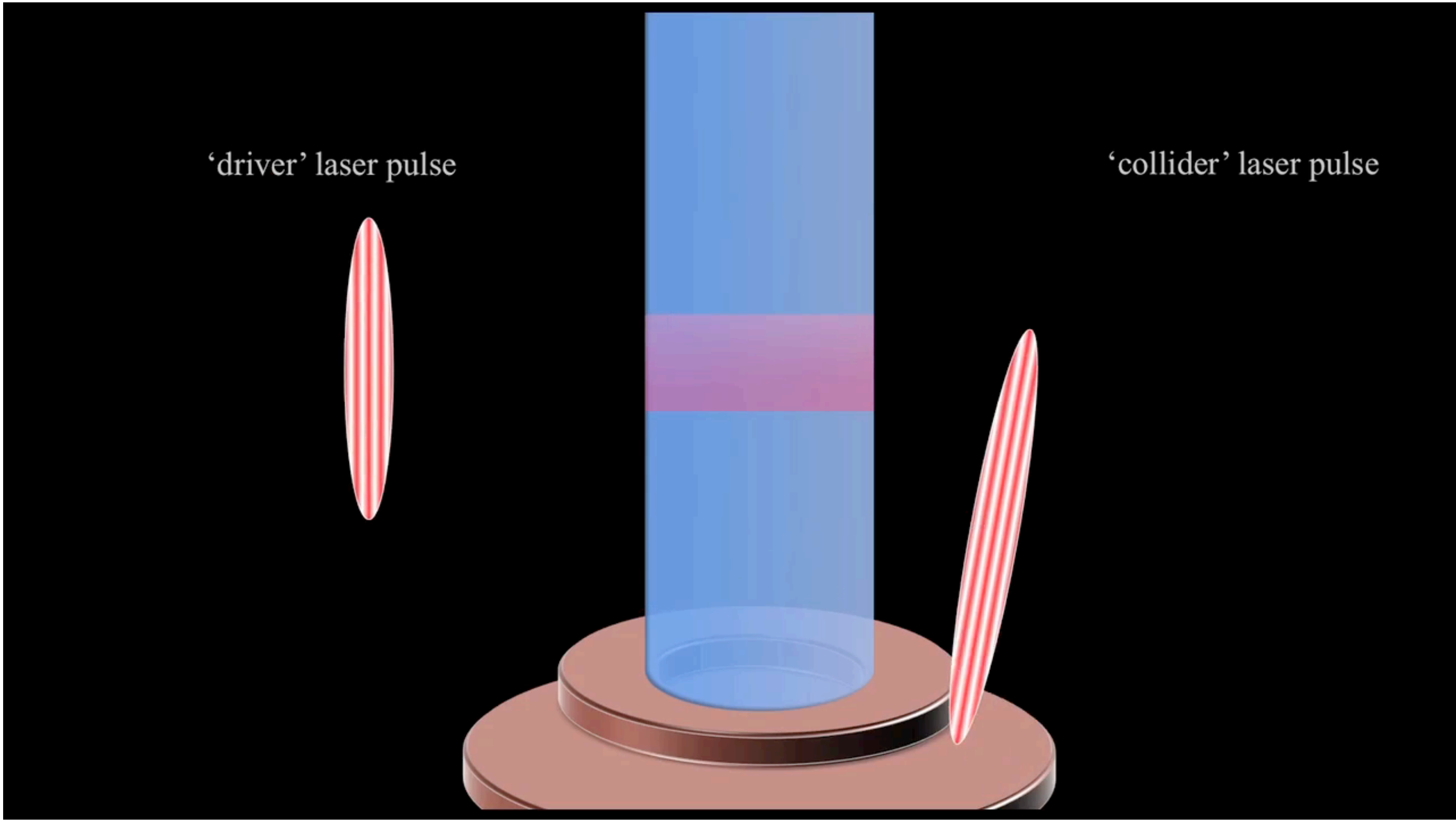


II. Control trapping orbit - emittance

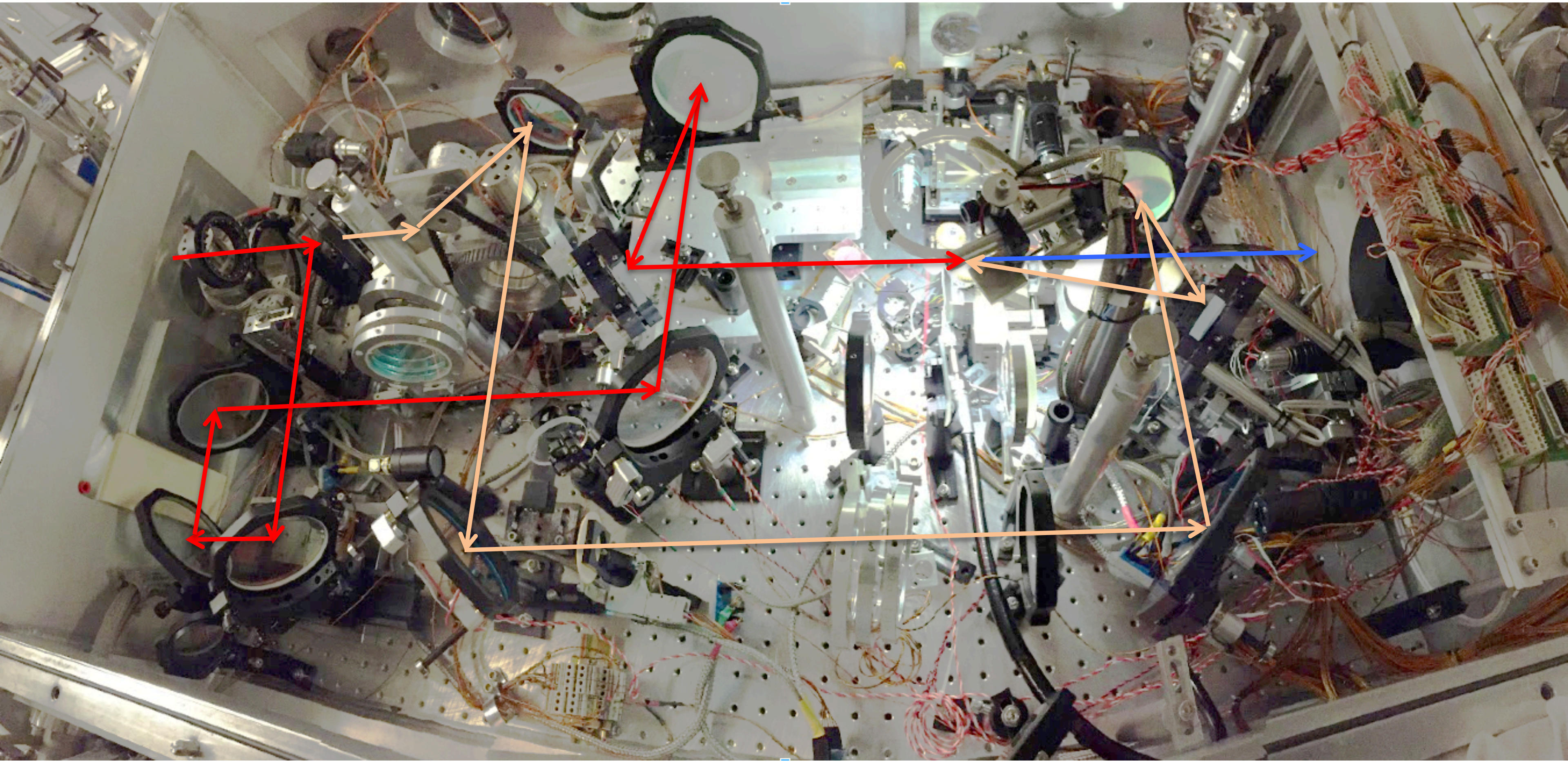
Techniques:

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

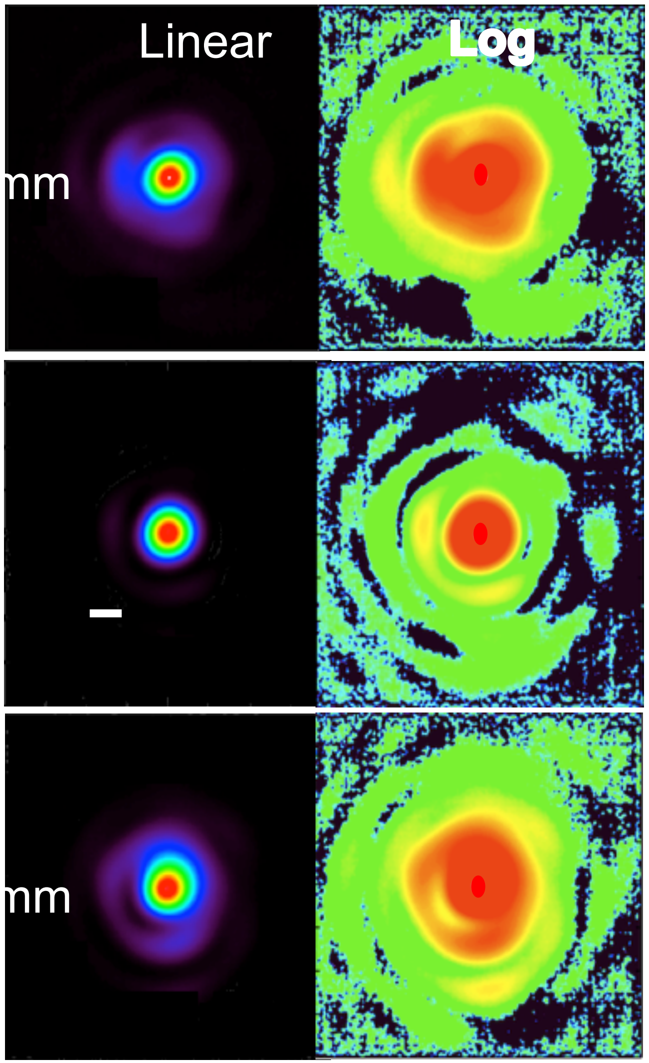
Controlling injection:
additional laser pulses or plasma shaping



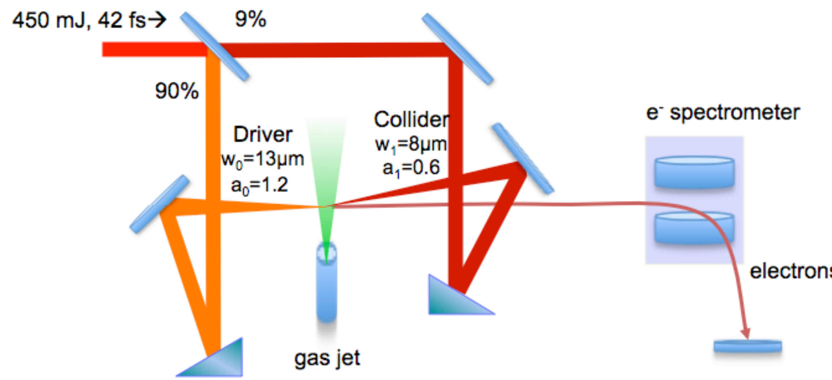
µm pointing & fs timing enable control



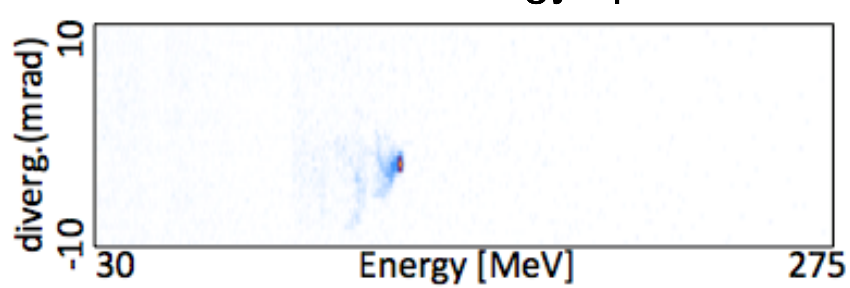
Control of laser mode and injection precise beams at ~0.2-1 GeV



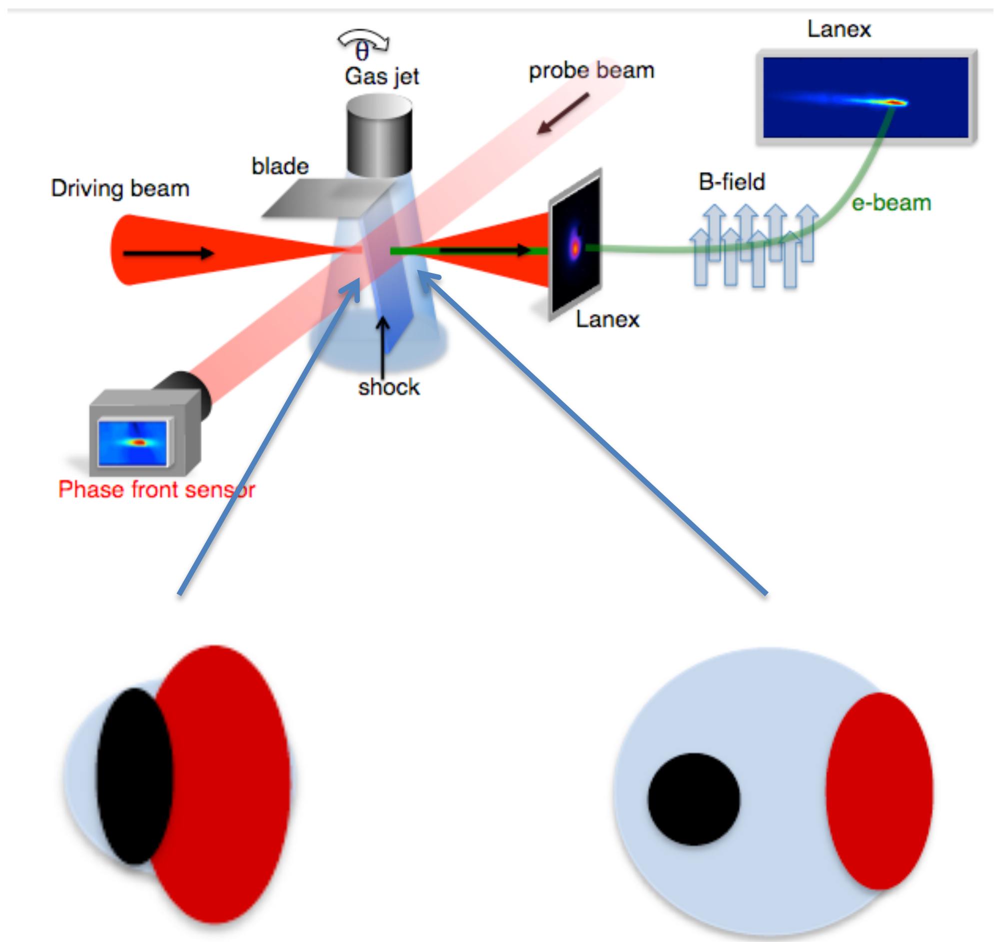
Same 10 TW laser pulse that previously generated 80 MeV, few % energy spread…

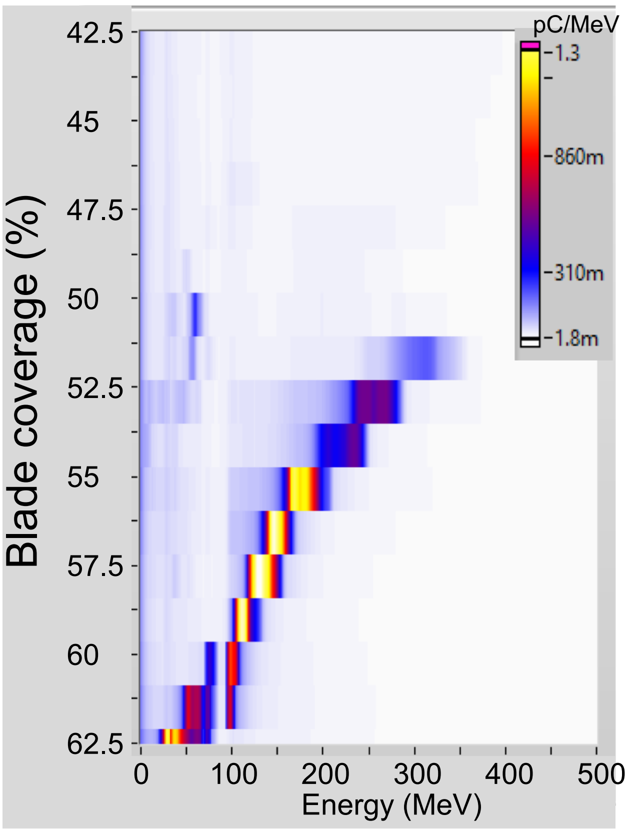


Precise control: 100-250 MeV,
Energy spread ~ 1%



Highly reproducible 0.3 GeV using density ramp injection

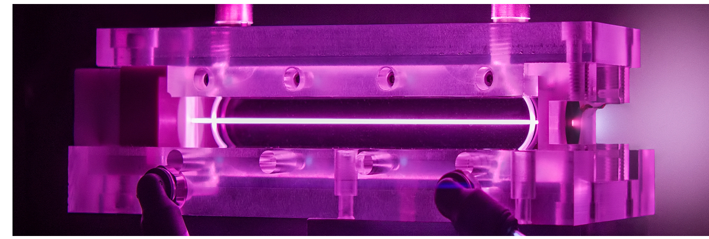




Capillary discharge allows long waveguides (several cm) Up to 4.2GeV using 300TW

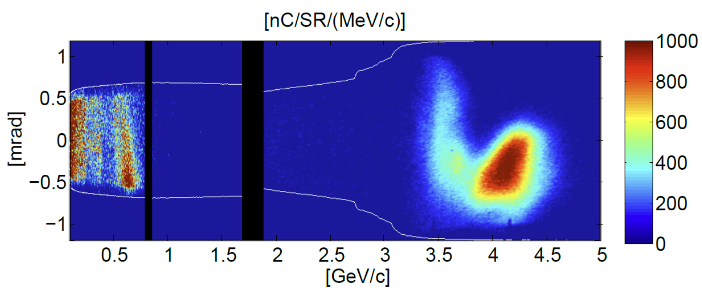
Capillary discharge forms plasma channel

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

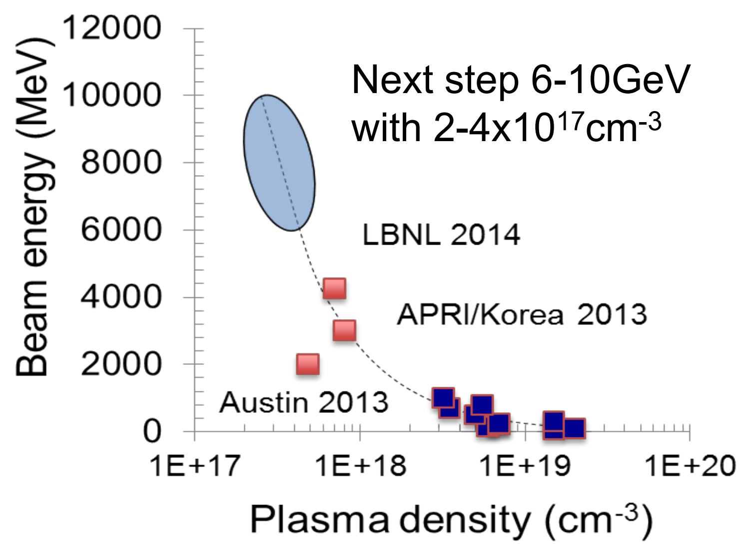
2014 Record LPA energy



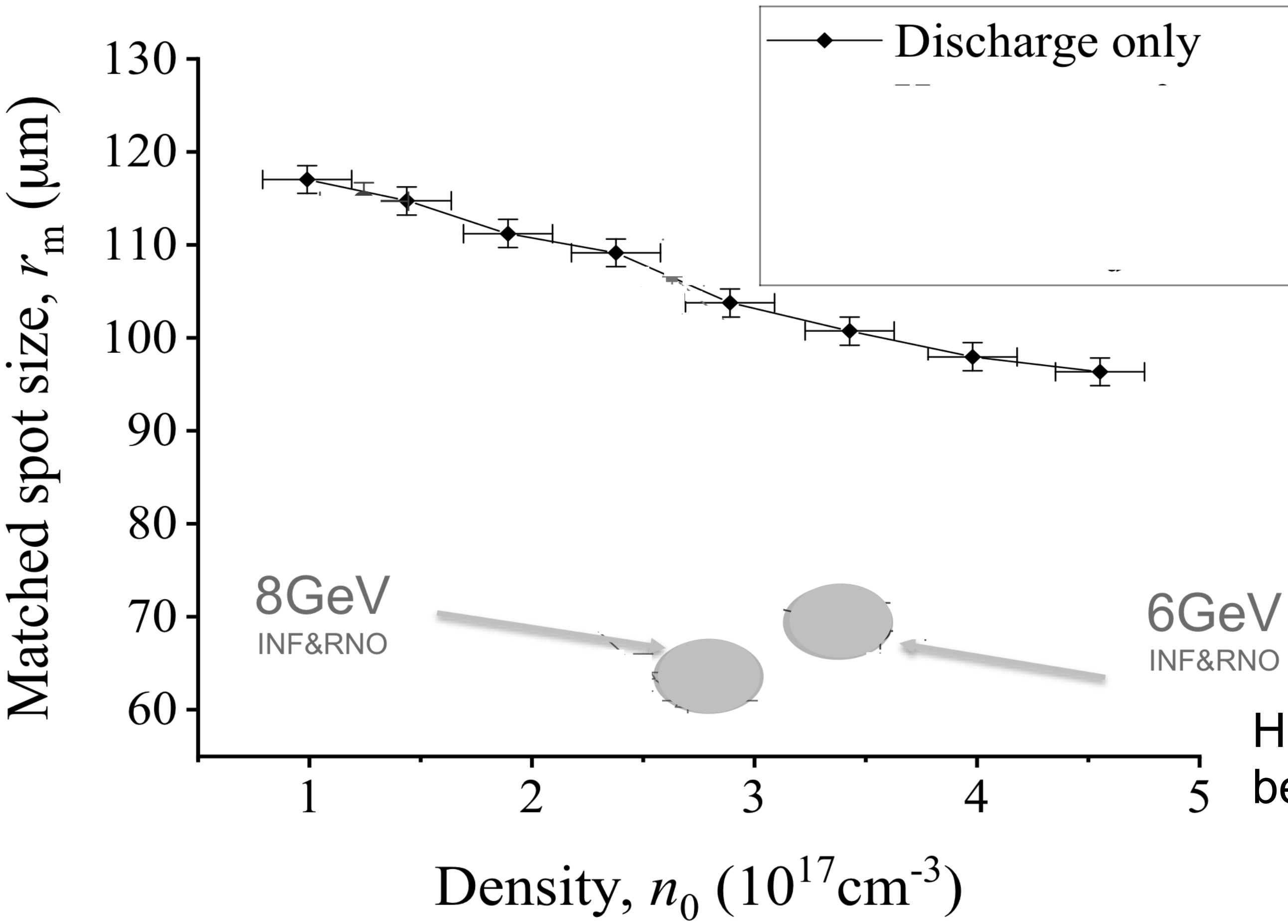
- 300 TW
- Up to 4.2 GeV ($7x10^{17}$ cm^{-3})
- Stable 2.7 GeV beams ($8.5x10^{17}$ cm^{-3})
- Up to 200 pC ($1.1x10^{18}$ cm^{-3})

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



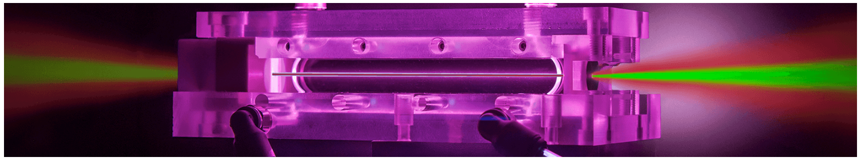
$D_{capillary}$= 800μm

Hotter discharge? no – before desired spot:
- Melt wall
- Undesired injection

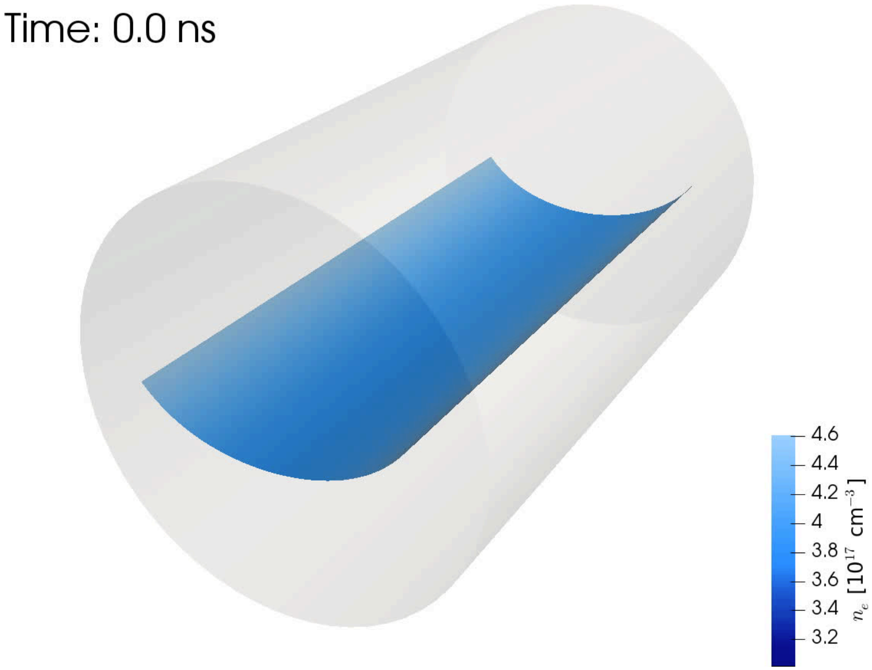
Magnetic field? Difficult
- High B: rep rate & effic.

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

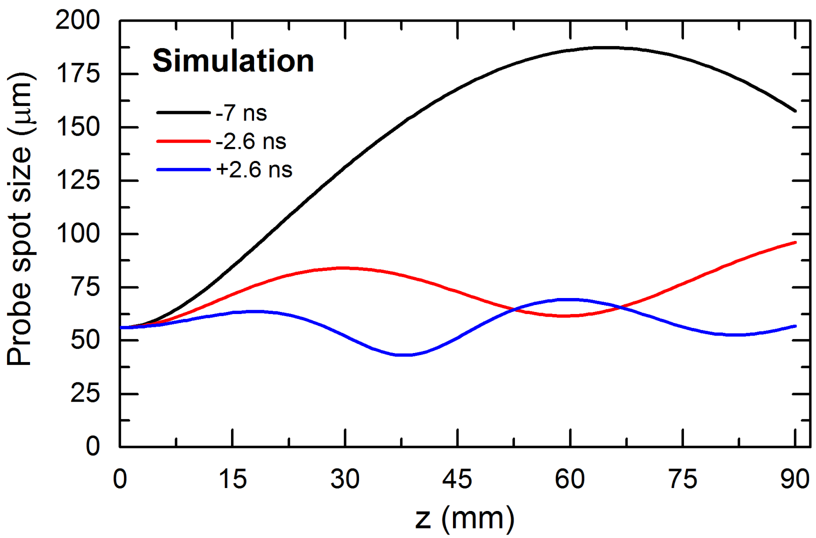
"Heater" laser increases channel strength & guides laser pulses at lower density



MARPLE simulation

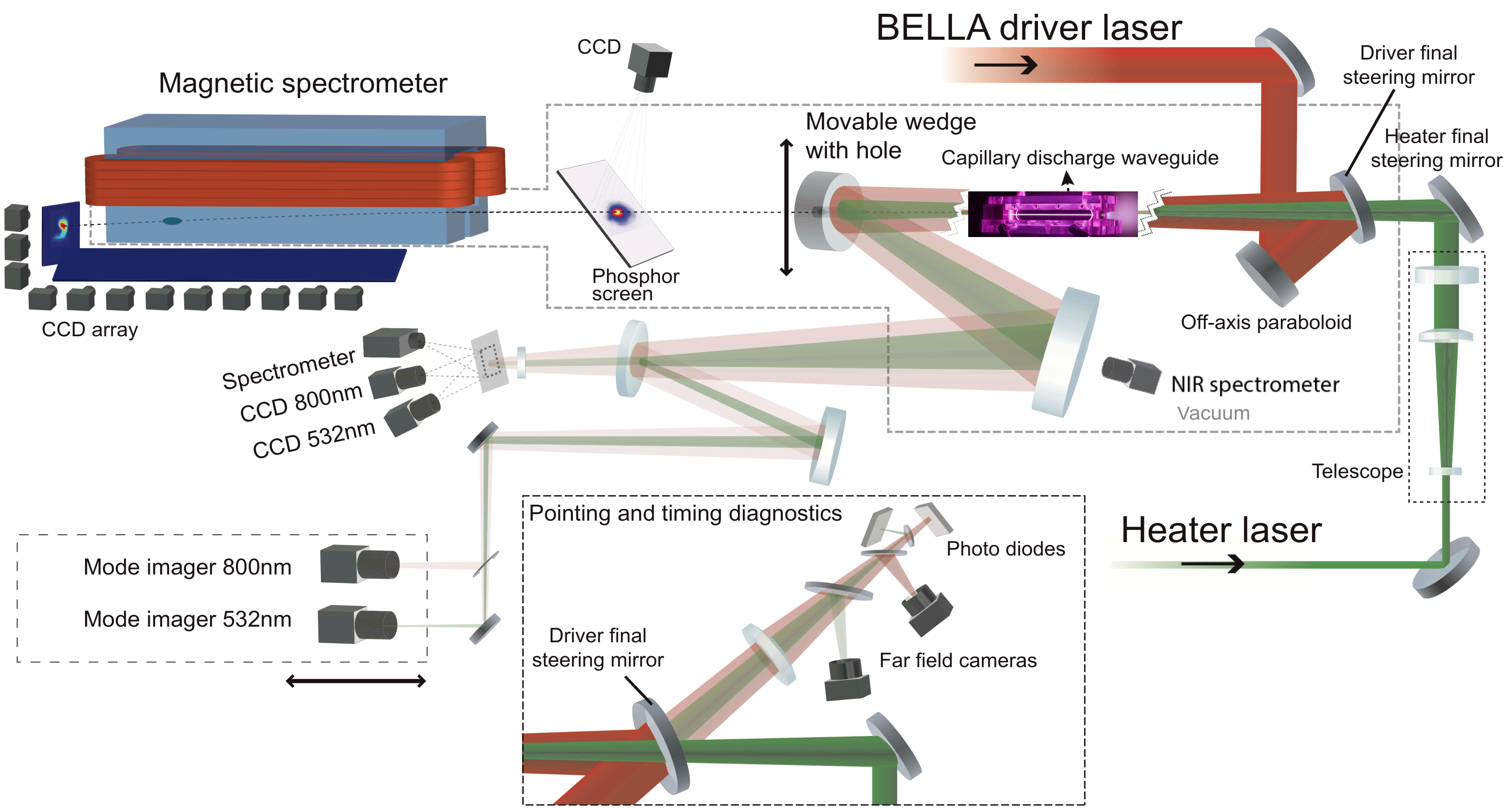


- Nanosecond pulse <u>locally</u> heats plasma through Inverse Bremsstrahlung
- Electron density distribution is changed
  - n_0 reduces
  - w_m reduces locally (faster rise of density from axis)

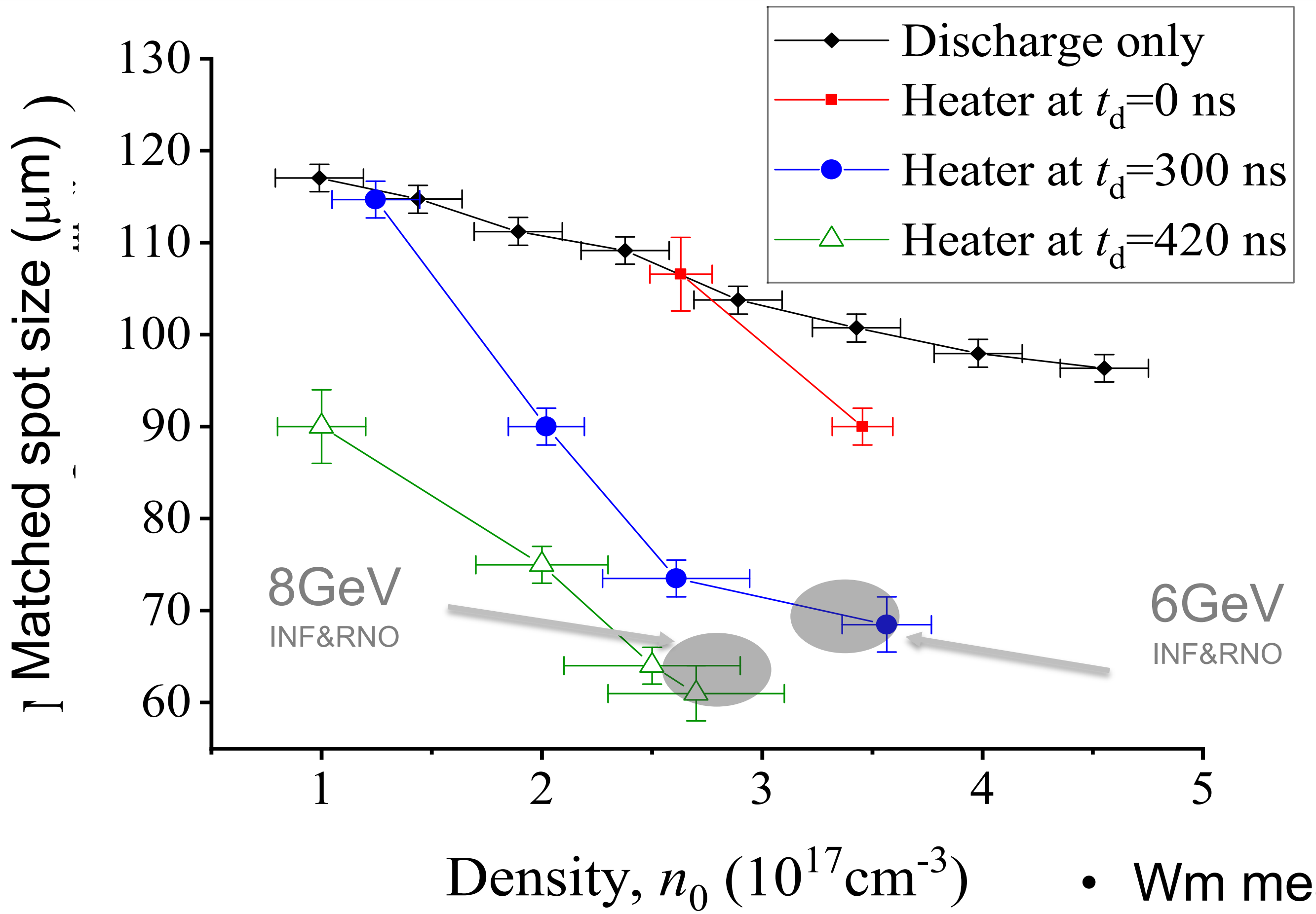


Gonsalves et al., PRL (2019); Bobrova *et al.*, *POP* 2013; Durfee *et al.*, *PRL* 1993; Volfbeyn *et al.*, *POP* 1999

Heater laser added to BELLA petawatt beamline



Heater laser significantly lowers matched spot size



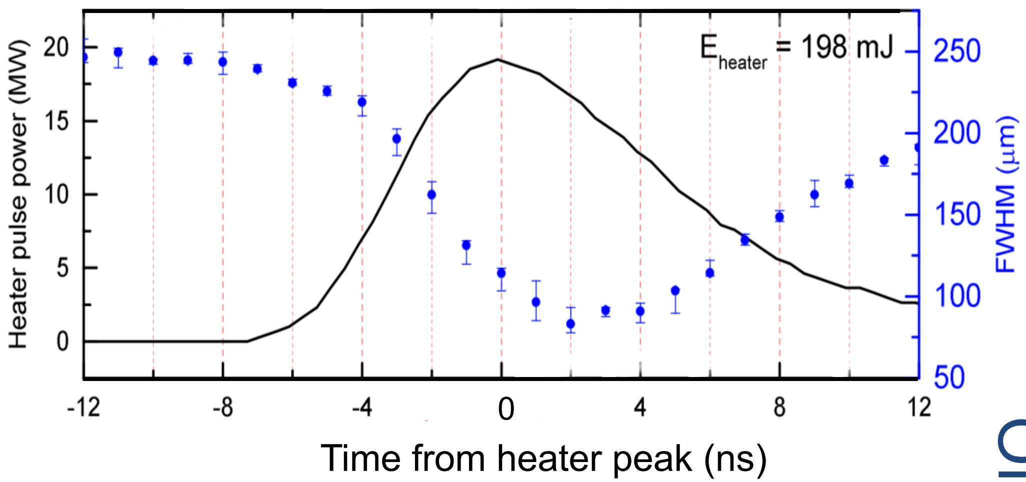
U_{Heater} = 300mJ
$D_{capillary}$= 800μm
$W_{0heater}$=80μm

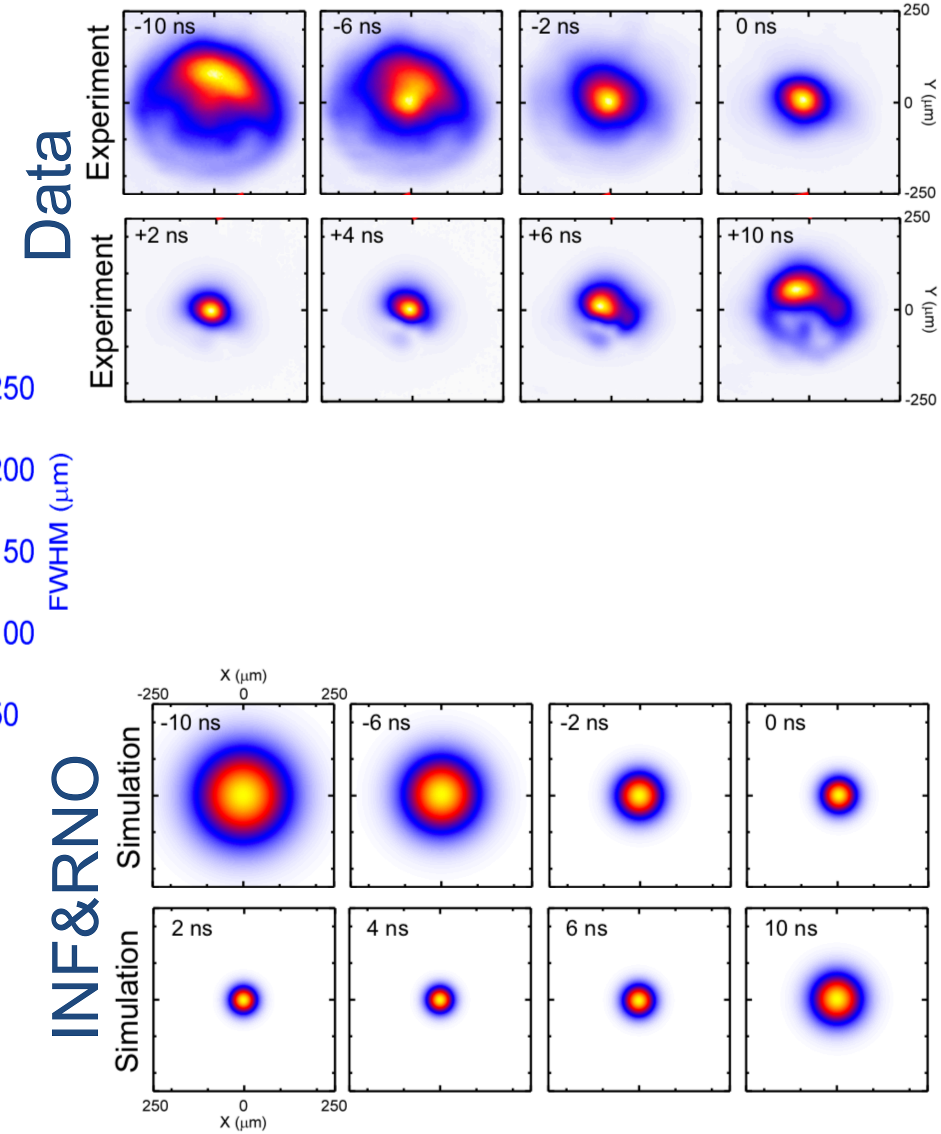
- Wm measured with centroid, spot size, and divergence oscillations
- Density from group velocity measurements

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

Guided low-power laser modes indicate plasma channel enhancement

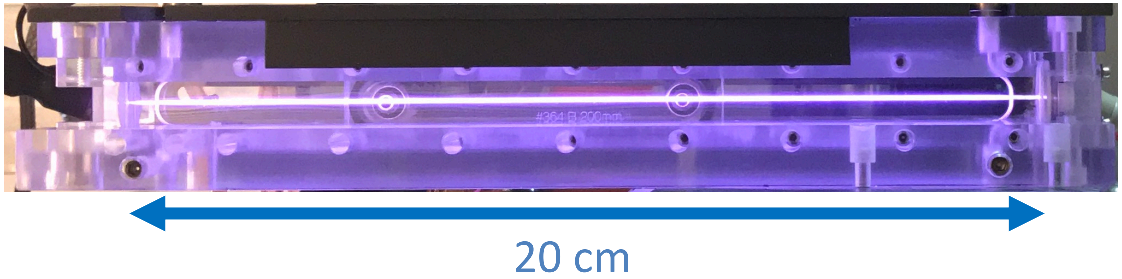
L_{cap}=6cm; W_{0probe}=60μm; n_e=0.4×10^{18} cm^{-3}



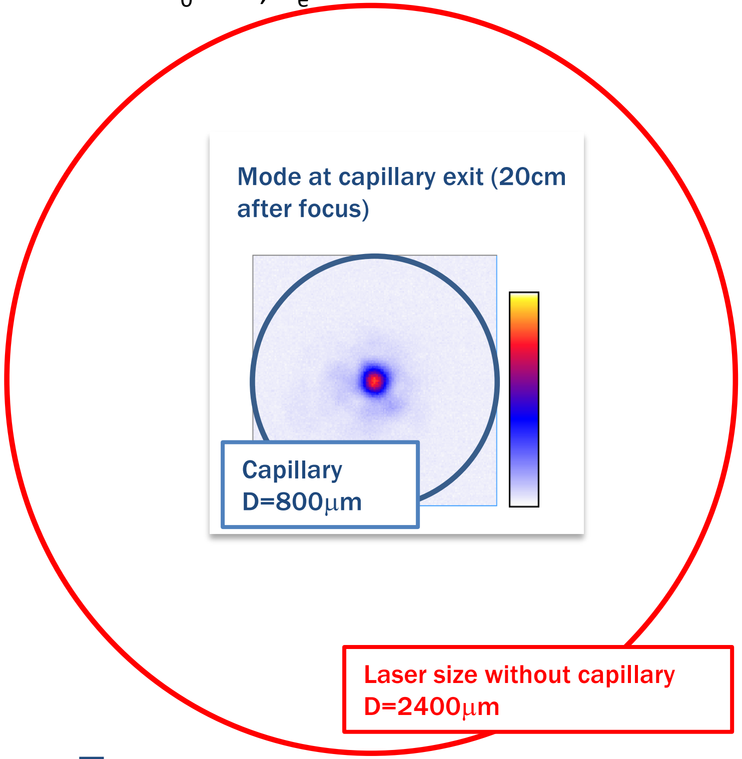


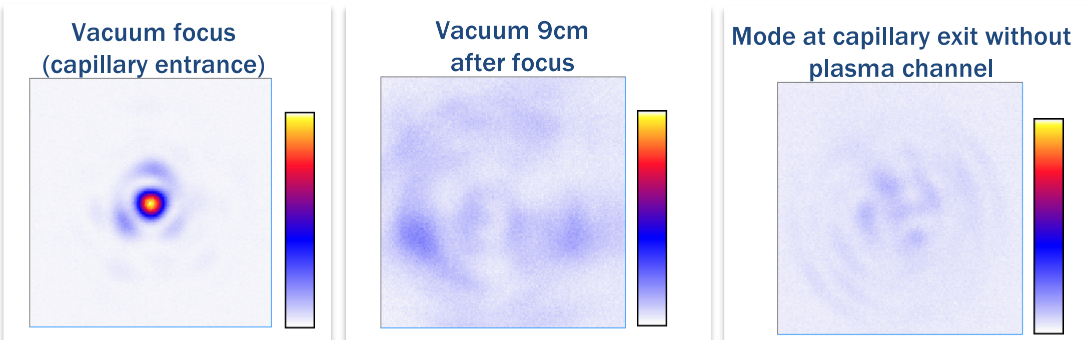
A. J. Gonsalves et al., Phys. Rev. Let. 2019

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



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

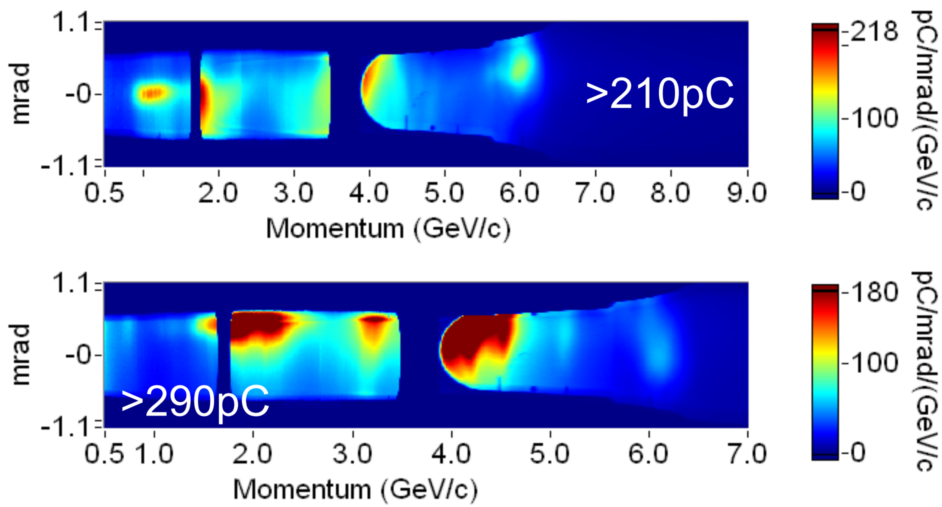


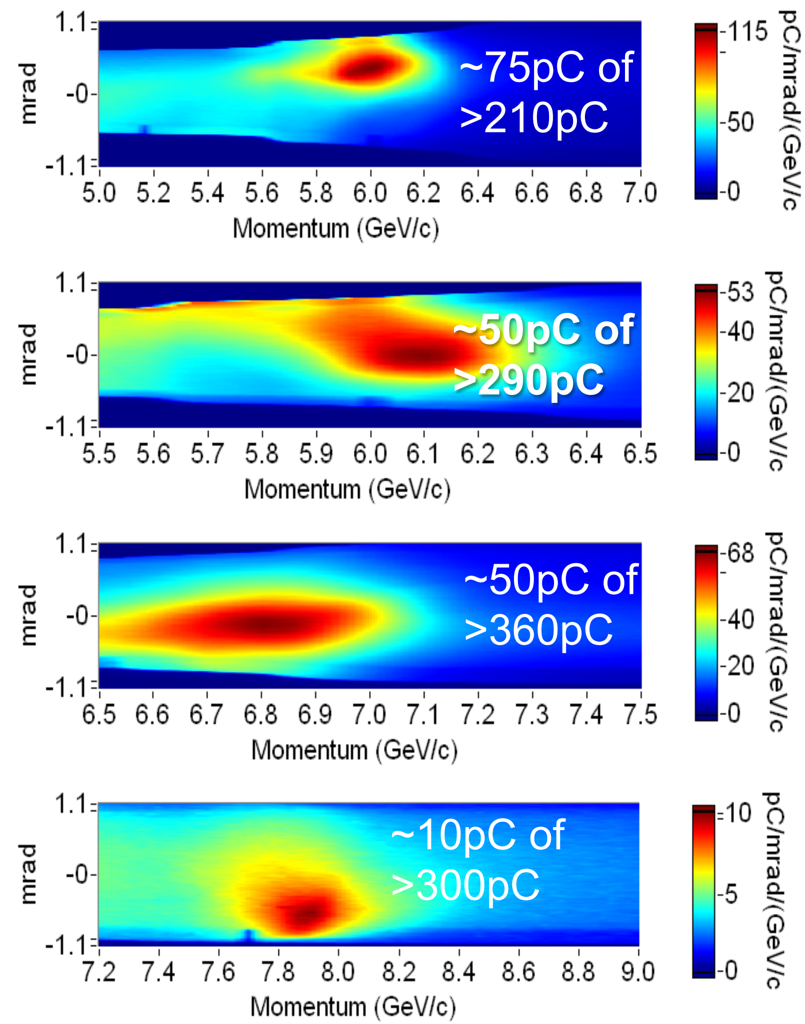


Spot size w_0 increased from 53μm to 60μm to increase Z_R

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

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



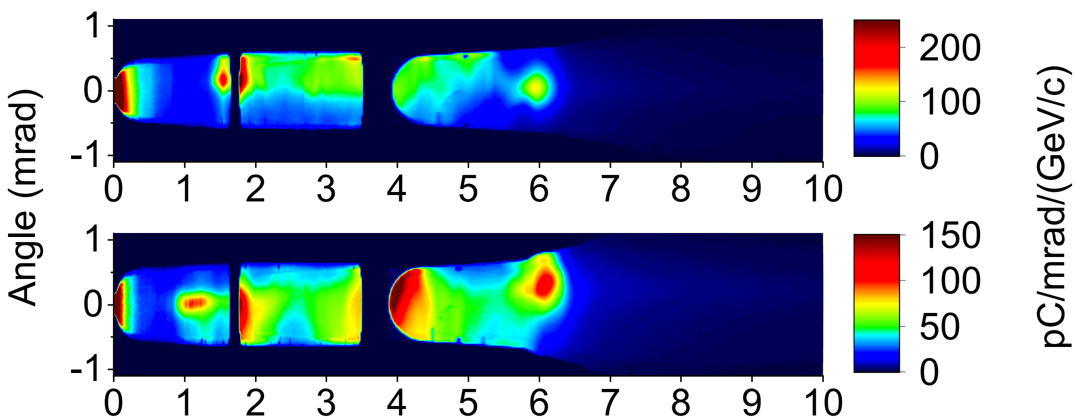


- Non-localized injection produces energy spread
- Highest energy bunches dE/E~10%
- Beam divergence down to 150urad FWHM
- 0.5-1 joule energy in e beam

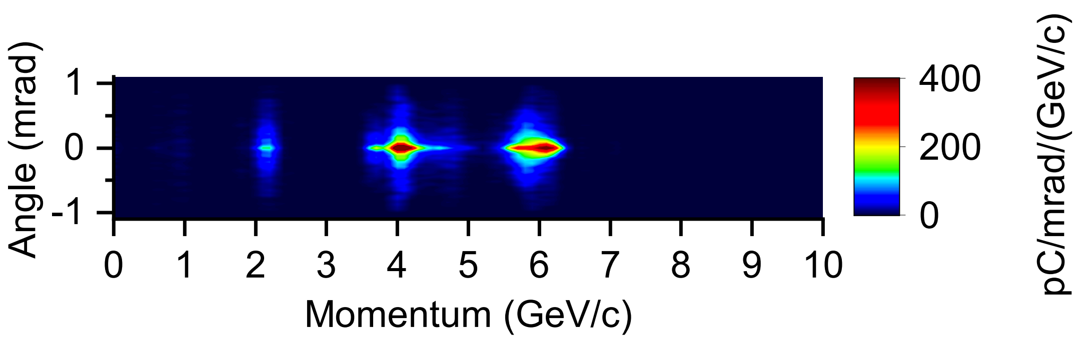
A. J. Gonsalves et al., Phys. Rev. Let. 2019

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

Experiment



Simulation

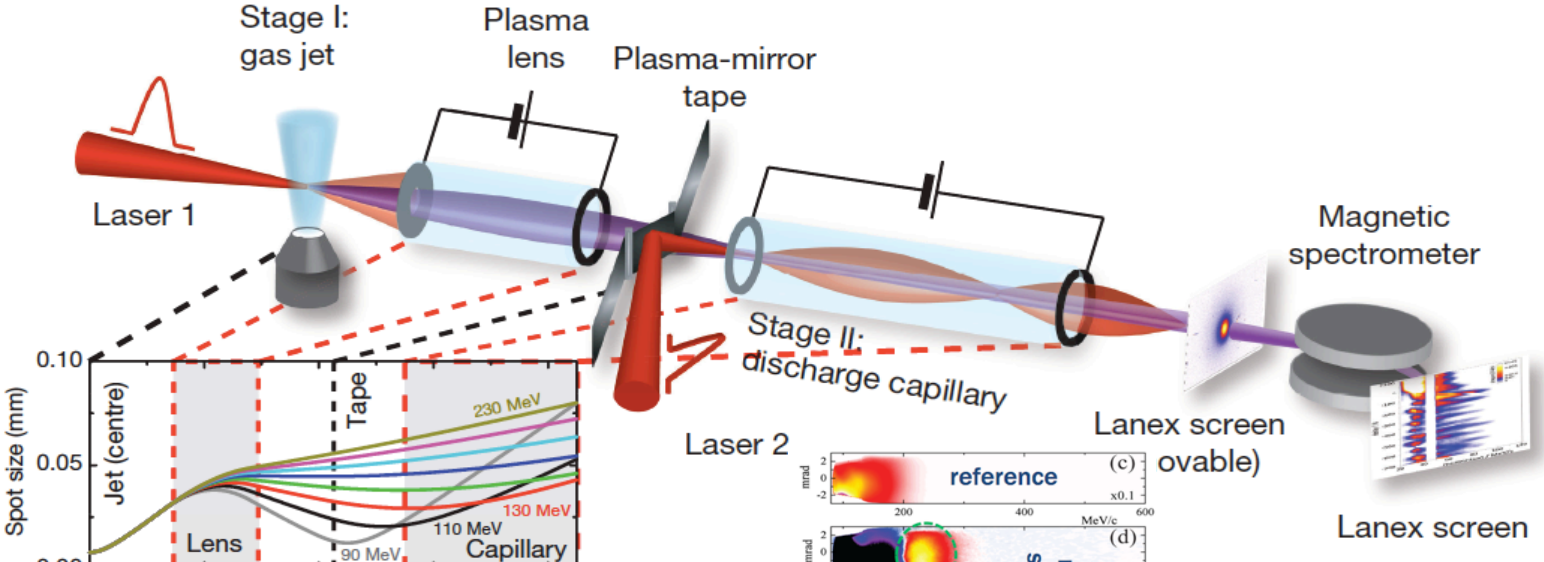


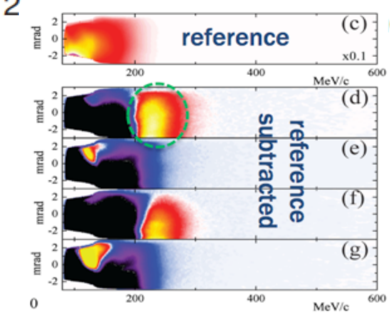
Next:

- Further optimization of channel strength at density ~$2\text{x}10^{17}\text{cm}^{-3}$
- 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

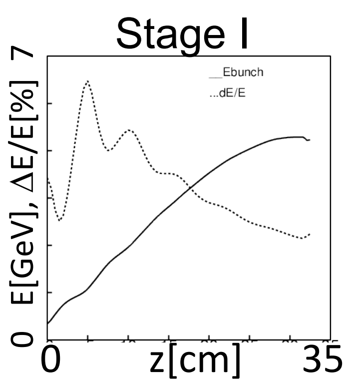
Staging experiment successful at 100 MeV
2nd beamline at PW needed for multi-GeV

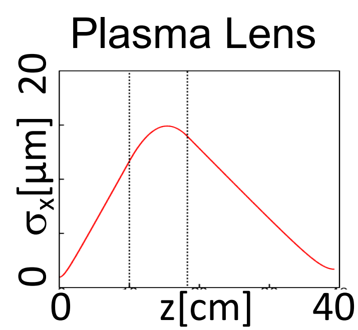


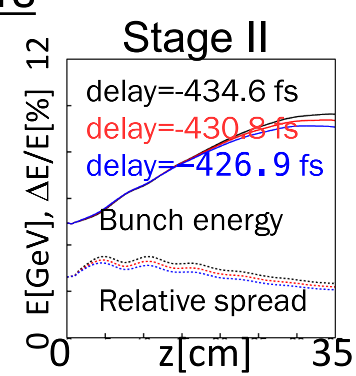


stage
t laser-
plasma accelerators” Nature 530, 190 (2016).

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



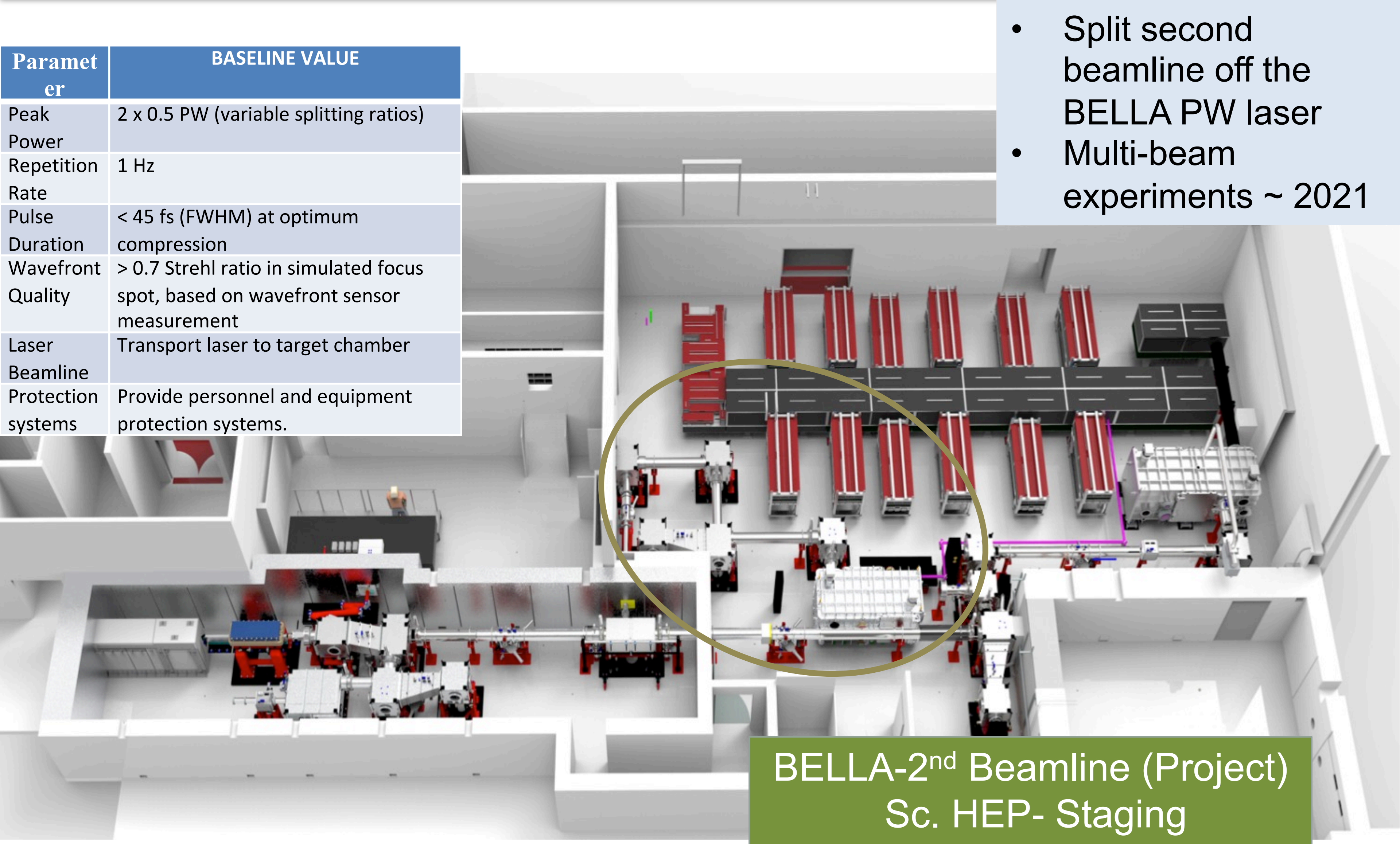




Second beamline on BELLA is under way for multi-GeV staging: Enables e+ and multi-beam high intensity experiments

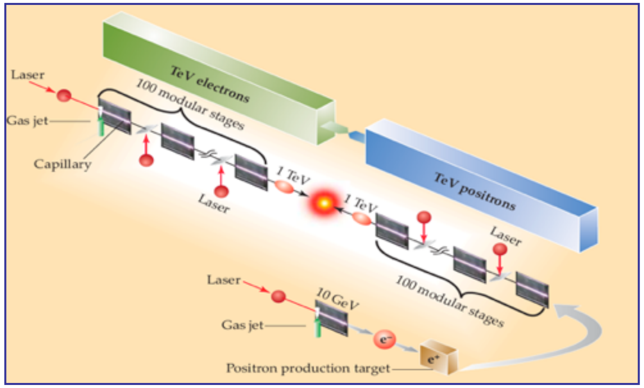
Parameter	BASELINE VALUE
Peak Power	2 x 0.5 PW (variable splitting ratios)
Repetition Rate	1 Hz
Pulse Duration	< 45 fs (FWHM) at optimum compression
Wavefront Quality	> 0.7 Strehl ratio in simulated focus spot, based on wavefront sensor measurement
Laser Beamline	Transport laser to target chamber
Protection systems	Provide personnel and equipment protection systems.

- Split second beamline off the BELLA PW laser
- Multi-beam experiments ~ 2021



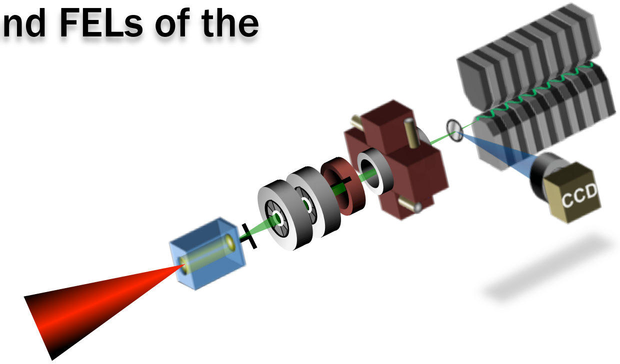
BELLA-2nd Beamline (Project)
Sc. HEP- Staging
Multi-GeV staging

Broad applications open to LPAs
Require both development and increased repetition rate



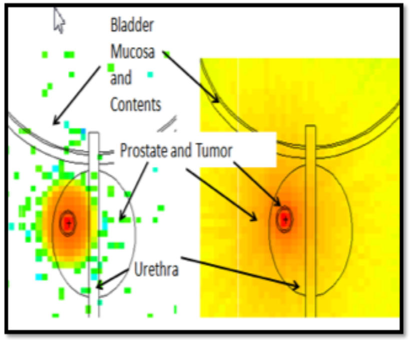
Leemans & Esarey, Physics Today (2009)

Colliders and FELs of the future



C. B. Schroeder et al. FEL Proc (2013)

Arthroscopic accelerator for biomedical/security applications



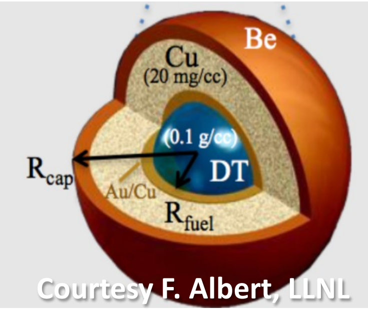
US Patent –LBNL/VARIAN

Compact MeV Thomson gamma ray source

Laser based, narrow-bandwidth, tunable

S. G. Rykovanov, C.G.R. Geddes et al., J. Phys. B, 47 234013 (2014)

MeV radiography

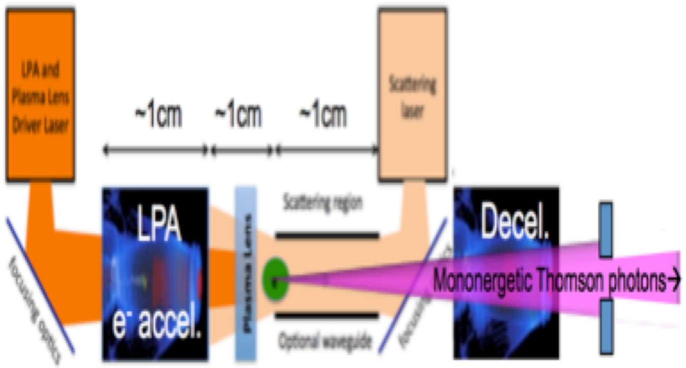


Betatron based x-ray source—phase contrast imaging

MPQ: J. Wenz et al., Nature Comm. (2014)

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

Thomson source

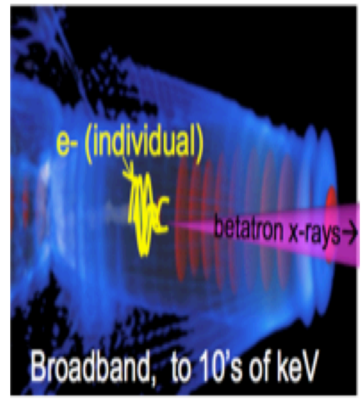


Narrow ΔE, keV to MeV, femtosecond, mrad

NNSA Defense Nuclear Nonproliferation R&D — National Nuclear Security Administration

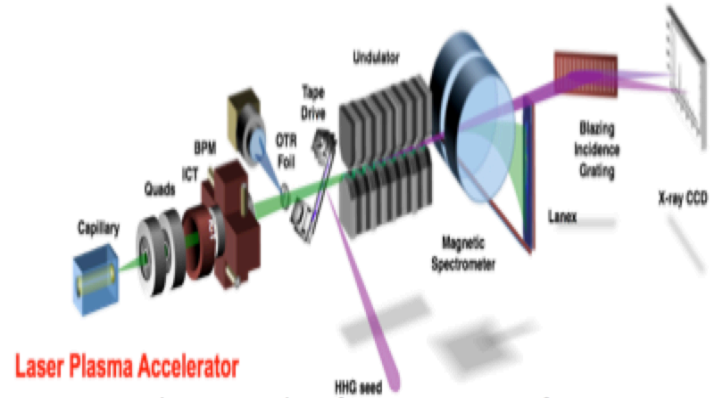
DHS/DNDO

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…

Outline

- Accelerator applications, compactness
- Physics of Laser-Plasma wakefield Acceleration
- Simulation considerations
- Experimental review & examples
- Outlook
- Personal perspectives

Strong and growing community driving LPA progress

Advanced Accelerator Concepts Workshop

- 37 presentations and 21 posters

Summary of Working Group 1: Laser-Plasma Wakefield Acceleration

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***Abstract*—Advances in and the physics of the acceleration of electrons and positrons using underdense plasma structures driven by lasers were the topics of presentations and discussions in Working Group 1. Such accelerators have demonstrated gradients several orders beyond conventional machines, with quasi-monoenergetic beams at MeV-GeV energies, making them attractive candidates for next generation accelerators and photon sources. The status, future direction, and research outlook are summarized and references given to group presentations.**

***Keywords*—laser-plasma accelerators, laser wakefield acceleration, positron acceleration, staging, injection, laser guiding**

I. Introduction

Working Group 1 (WG1) focused on the acceleration of electrons and positrons using laser-plasma wakefield accelerators (LPAs). Workshop discussions included advances in control over injection and laser guiding to further improve beam quality and stability; techniques for accelerator efficiency, beam quality preservation and staging; detailed diagnostics; radiation generation as a photon source and diagnostic; and beam manipulation. Paths from current results towards achieving parameters required for applications, particularly high energy physics (HEP) colliders at the TeV scale and compact photon sources (such as MeV Thomson sources and free electron lasers) were discussed.

The working group hosted eight oral sessions with 37 presentations and 21 posters. The roles of both plasma wakefield acceleration driven by lasers and of direct laser acceleration were discussed. The working group, including three joint sessions, was organized around six themes:

- Controlled particle injection into the wake for beams that are stable and of higher quality and charge.
- Diagnostic techniques including radiation sources as well as accelerator controls to improve operability.
- Acceleration with preservation of beam quality (special focus on hosing) and efficient transfer of laser energy to realize performance goals.
- Staging multiple plasma elements, including beam manipulation, for high beam energies in colliders and beam disposal (deceleration) in photon sources.
- Guiding of the drive laser pulses to extend the laser-plasma interaction/acceleration length.
- Novel regimes in driver duration, driver wavelength, or plasma density that open new capabilities.

This summary paper presents highlights from each of the themes on progress in laser-plasma acceleration physics and towards meeting the needs of applications. Detailed results and references may be found in the respective papers in these proceedings. Presented results build on past work in these and related techniques, as reviewed in [1-3].

II. Controlled Particle Injection

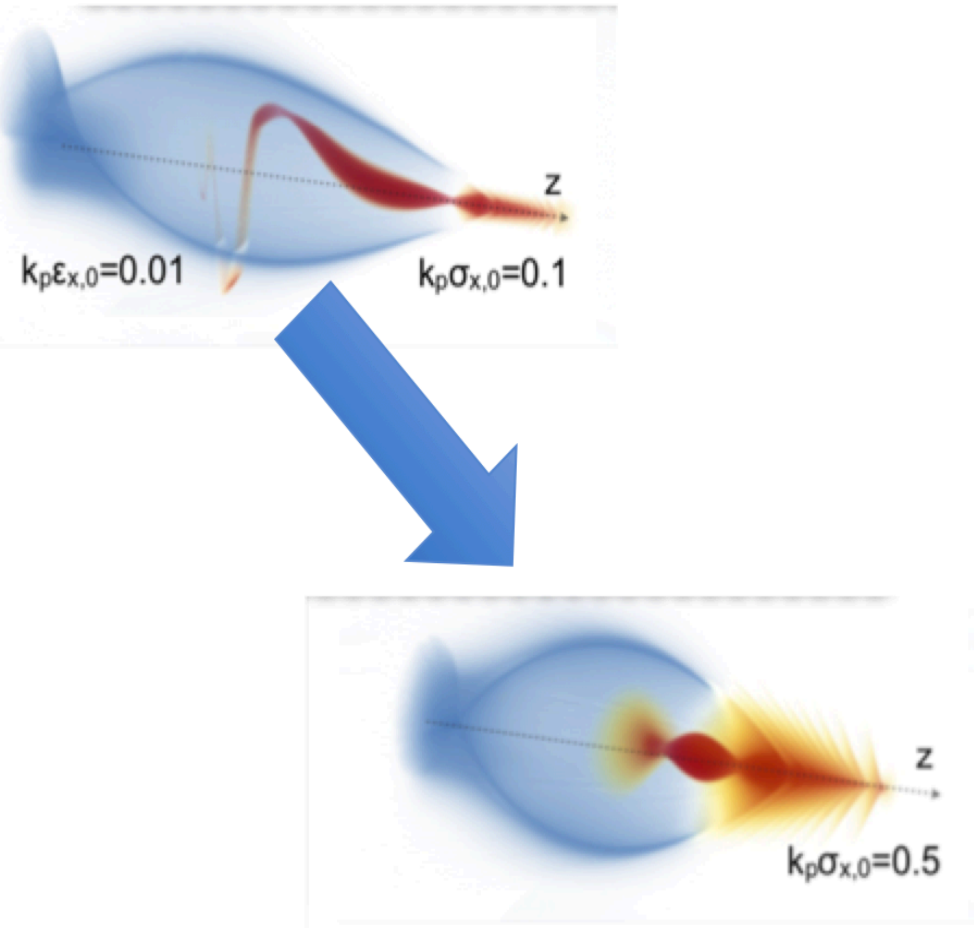
Injection control is the first key element to obtaining high quality beams. Injection of the appropriate charge and longitudinal bunch shape is required such that acceleration (including beam loading and dephasing) will produce narrow energy spread and high flux. Transverse emittance should also be minimized for focusability of the beam and photon source performance. Progress was presented on ionization, multi-pulse, and external injection techniques. Posters and presentations in Working Group 7 (Radiation Generation and Advanced Concepts) and Working Group 4 (Beam-Driven Acceleration) additionally addressed plasma density transition or 'downramp' injection and 'self' injection. While self-trapping, which occurs when the wake reaches an amplitude sufficient to trap electrons from the plasma through which it propagates, is simple, it offers very limited control. Separate control over electron injection into a wake driven to an amplitude below the self-trapping threshold is hence important so that injection and wake can be tuned independently. Progress was made on several such techniques.

Ionization can be used to control injection into the wake if a gas or gas mixture is used which has ionization states near the peak intensity of the wake drive laser. The leading edge of the driver at low intensity ionizes the bulk states producing a plasma in which the wake is driven. The last state(s) are ionized near the peak of the laser pulse, injecting electrons at near-zero velocity, which are therefore trapped by the wake where the bulk plasma is not. For high-quality beams, injection must be localized and residual ionization momentum addressed. High peak currents from an ionization injected

Invented in US
Now larger efforts in Europe / Asia

- Controlled particle injection: stable and reproducible, low energy spread and emittance, and higher in charge.
- Efficient transfer of the laser energy to the wake structure and to the particle beam for applications.
- Staging, multiple plasma elements to reach high beam energy for HEP applications with quality/charge preservation
- Guiding of the drive laser to extend the interaction/acceleration length.
- Regimes of operation in driver duration, density or wavelength that open new capabilities
- Compact beam manipulation techniques: radiation cooling, focusing systems, and beam property exchanges
- Diagnostic techniques to better understand the electron beam properties – including radiation sources
- Target formation: gas and plasma hydrodynamics for structuring, repetition rate; kHz 'solids' – dedicated research area

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



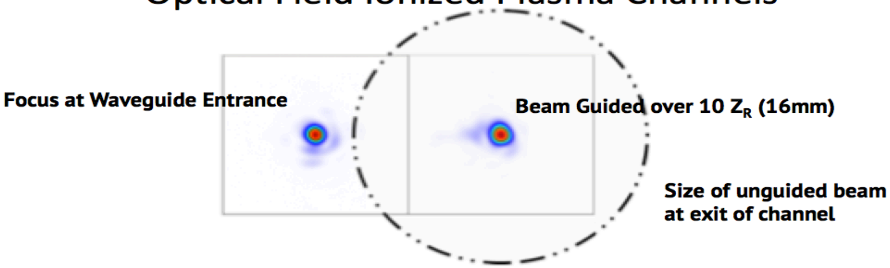
- Important for collider concepts
- Substantial collaboration and cross-fertilization of ideas among presentations
  - Nagaitsev (FNAL)
  - Hildebrand (UCLA)
  - Mehrling (LBNL)
  - Lehe (LBNL)

- 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

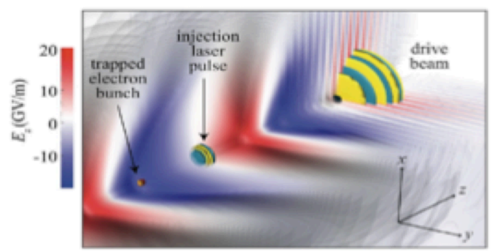
Simon Hooker, Robert Shalloo, et al. Oxford
High-Intensity Guiding in Axicon Formed Hydrodynamic Optical Field Ionized Plasma Channels



- 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}

<u>Requires additional laser pulses & stability, shaping for facilities</u>

Carl Schroeder, LBNL
Two-Color Laser-Ionization Injection

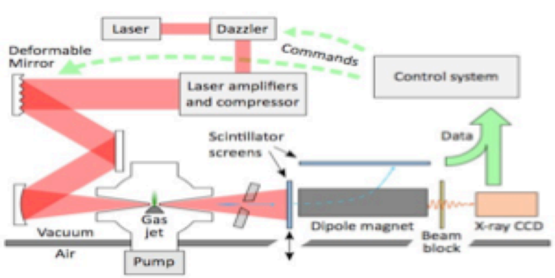


Thermal emittance from ionization-induced trapping in plasma accelerators" PR ST-AB 17, 101301 (2014).

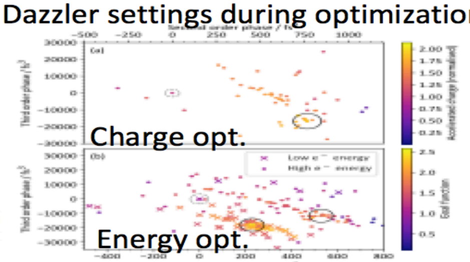
- Long wavelength driver: leaves inner states un-ionized
- Short wavelength tight focus injection pulse ionizes inner states
  - potential for 10nm-class emittance

<u>requires fine control of beam centering, & additional beam</u>

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

<u>need for kHz lasers to enable fine control and fluctuation suppression</u>

Concepts for high average and high peak laser power are emerging and will enable applications demanding high average fluxes of beams

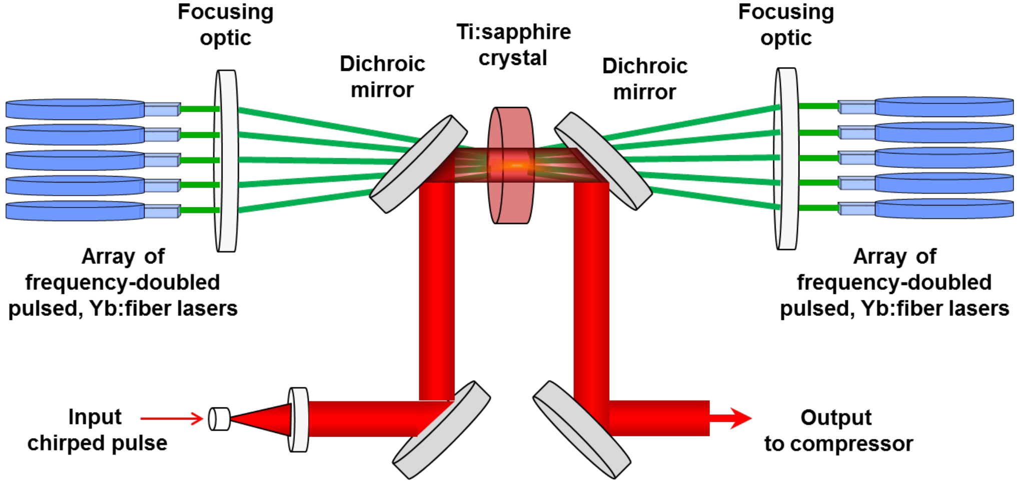
High **peak** power,
low average power

1 Hz, PW BELLA laser

High **average** power,
low peak power

100 kW average power, industrial lasers, 35% wall plug efficiency

High average and peak power lasers
Demonstration available near term



Several options for construction: commercial coming soon

Coherent combining schemes with fiber lasers offer path to collider-class

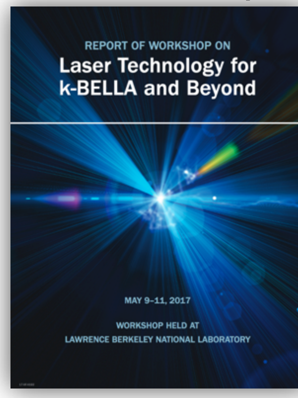
Facility concept: near term LBNL project

k-BELLA kHz rep rate LPA enables high flux and efficiency
kHz stabilized, shaped few-Joule 30fs laser pulses

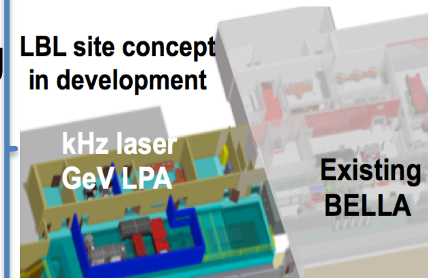
Develop stable, efficient accelerator system based on laser-plasma wake

- 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 accelerato



- 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

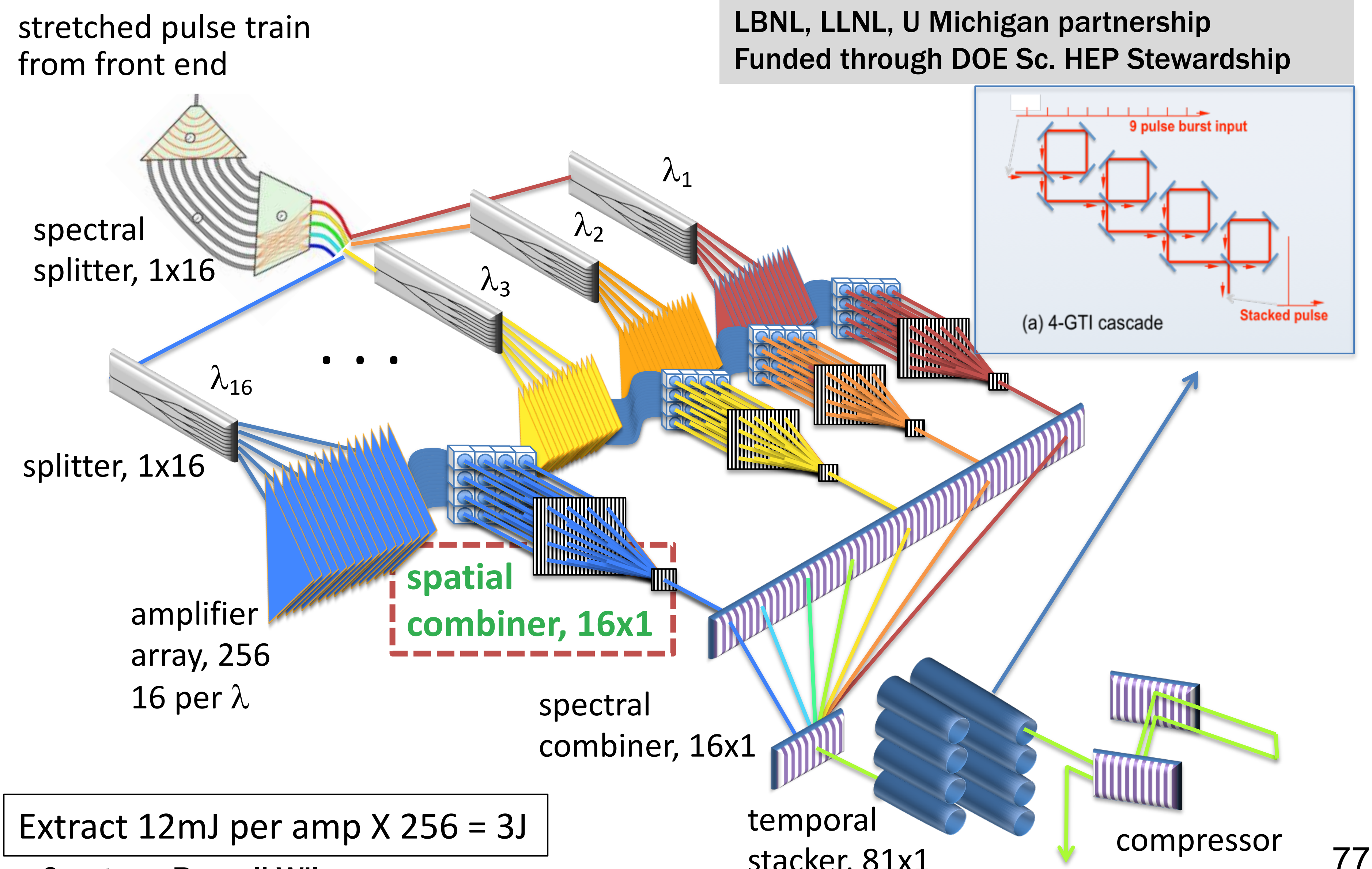
LPA control using shaped laser pulses beyond current limits of fluctuation

Collider, nuRadio, 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

Novel Architectures are being explored for k-BELLA: 3J, 30fs, 1kHz Fiber Laser – 3 kW average power at 100 TW

LBNL, LLNL, U Michigan partnership
Funded through DOE Sc. HEP Stewardship



Extract 12mJ per amp X 256 = 3J

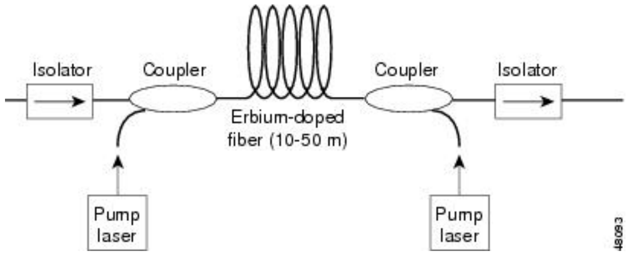
Courtesy: Russell Wilcox

Outline

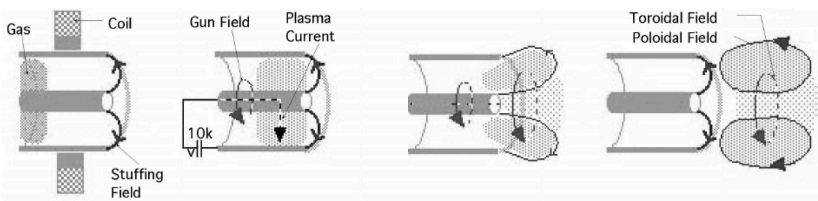
- Accelerator applications, compactness
- Physics of Laser-Plasma wakefield Acceleration
- Simulation considerations
- Experimental review & examples
- Outlook
- Personal perspectives

Plasma physics offers many interconnected opportunities for exciting team research

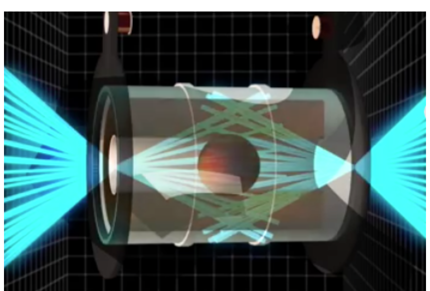
1992-1994: Swarthmore fiber lasers



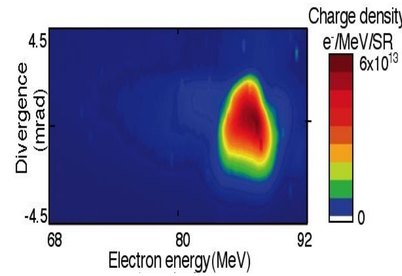
1995: PPPL NUF & UW tokamak
1995-1997: Swarthmore Spheromak

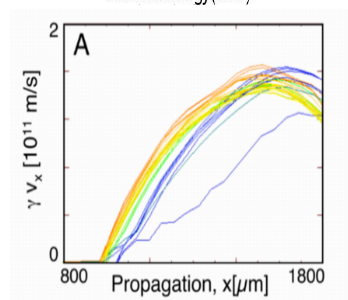


1997-2000: LLNL, LLE, Polymath
ICF Laser-plasma interactions



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

Community wide planning opportunity now for future of plasma physics

Two ongoing activities – be active!

APS-DPP Community Planning Process

Identifying scientific and technological opportunities in the fields of Plasma Physics and Fusion Energy Science

2019 National Academies Plasma Decadal

- Broad plasma science
  - Burning plasma in previous study
- Multi-agency
- http://nas.edu/plasma

2019 National Academies Plasma Decadal

- Fusion & burning plasmas, Discovery plasma science, HED & Acceleration
- DOE Sc. FES
- https://sites.google.com/pppl.gov/dpp-cpp/home

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

Critical opportunity for plasma physics
Long term planning and coordination is essential to our field
Charges posted on web sites
Great resources for you: white papers, past studies, town halls…

Resources for more information

- 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.

- Laser-plasma textbook (not wakefield, but strong link)
  - Kruer, Physics of Laser-Plasma Interactions
- US Particle Accelerator School
  - Periodic advanced accelerator classes
  - http://uspas.fnal.gov
- Contact me: cgrgeddes@lbl.gov

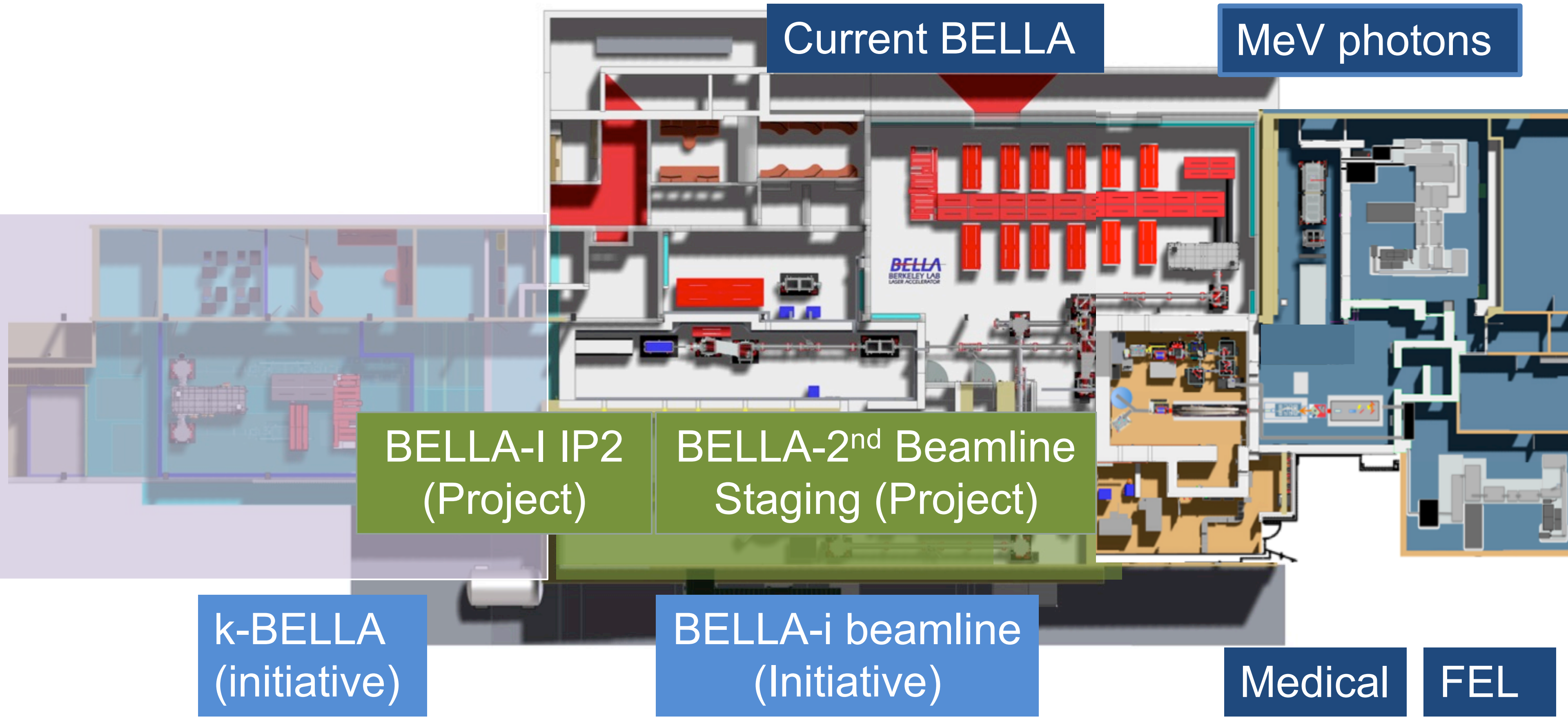
Summary

- Laser plasma accelerators becoming important to DOE, beyond
- Roadmap established for TeV – class LPA based collider
  - DOE High Energy Physics supported
  - Intermediate applications:
    - MeV photons (NNSA DNN R&D),
    - FEL (BES, Moore)
- 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

The BELLA center: world-leading capabilities driving LPA technology for high energy physics and applications

Exisiting and planned laser facilities in Building 71 at LBNL

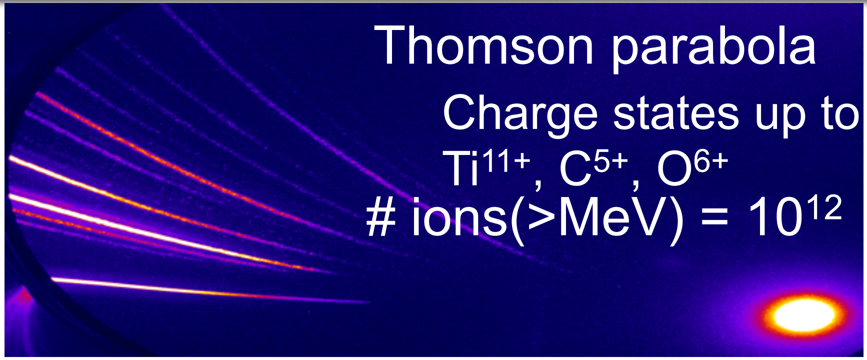


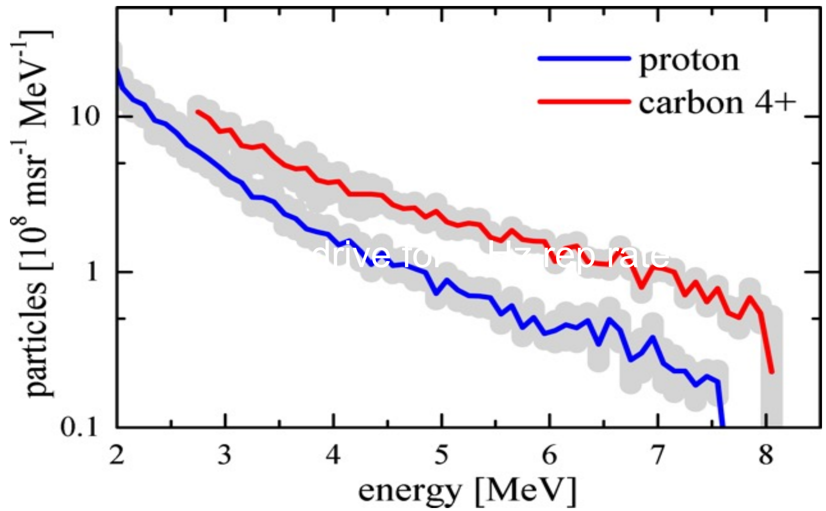
Unique resource of and for the DOE and beyond

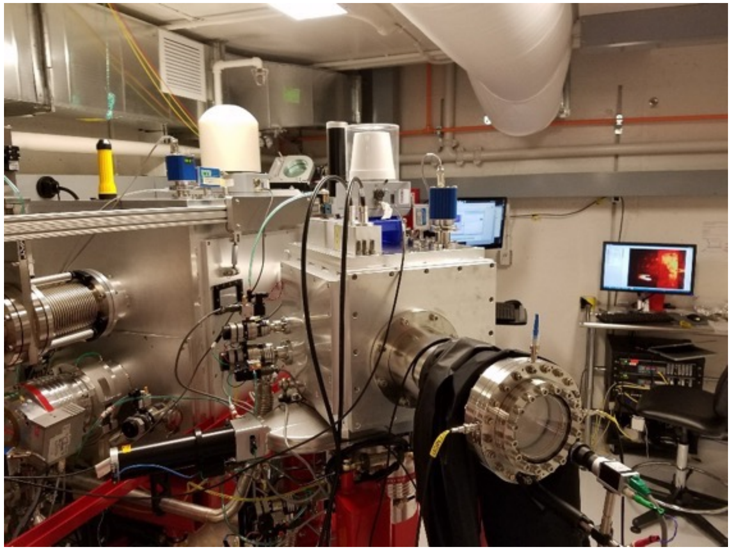
Proton/ion experiments have started on BELLA
To date: TNSA, sets stage for future advanced methods

DOE Sc. FES

TNSA: 100 micron spot:
10^{12} protons, <250 mrad



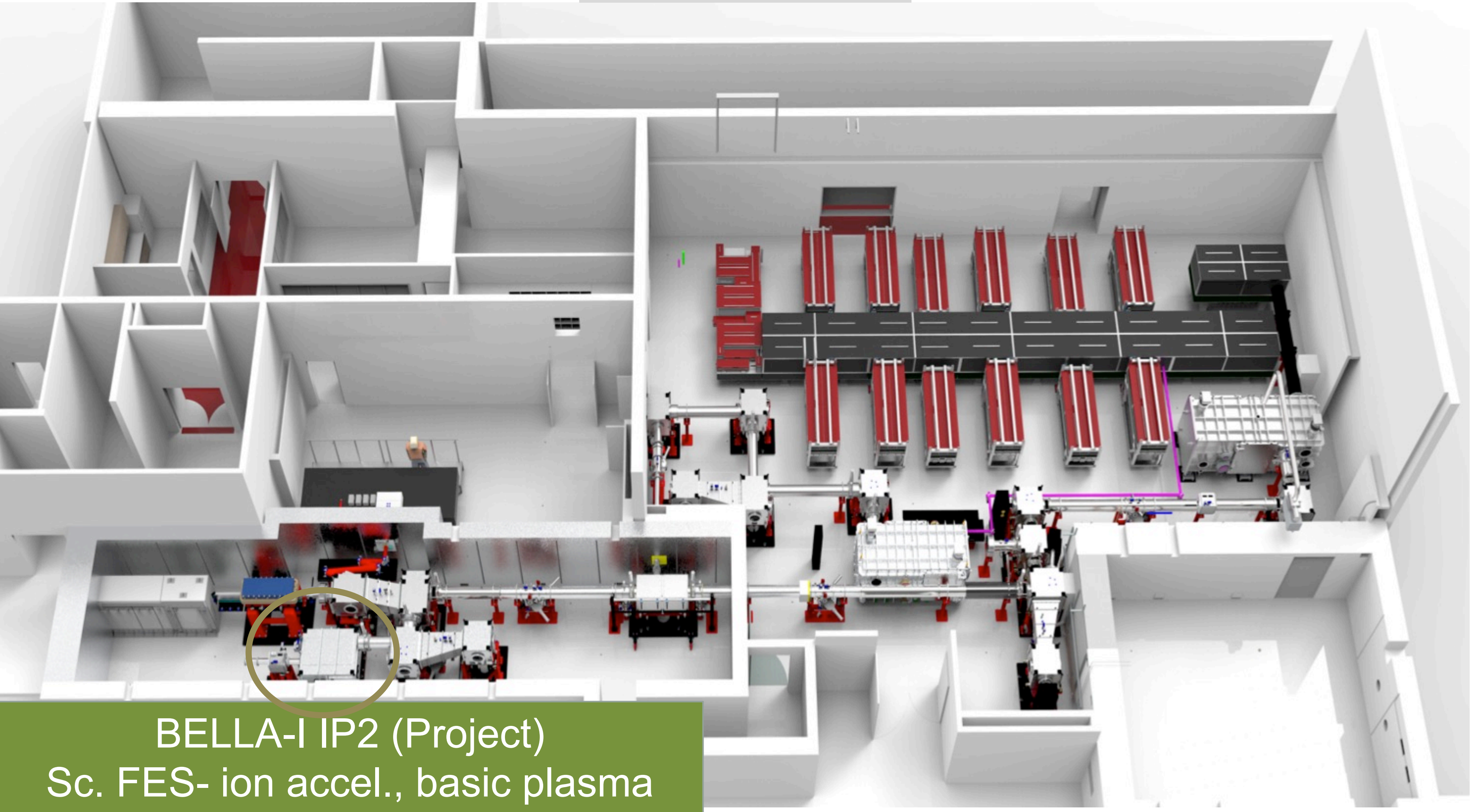




- **BELLA PW, long focal length beamline**
  - $2 \cdot 10^{19}$ W/cm^2
  - laser-plasma interactions, ion acceleration for users in LaserNetUS
  - 1 Hz shot rate and 1 Hz targets
  - intense ion pulses, ~10^{12} ions/shot, low divergence

Second interaction point project in progress to enable ultra-high intensity experiments

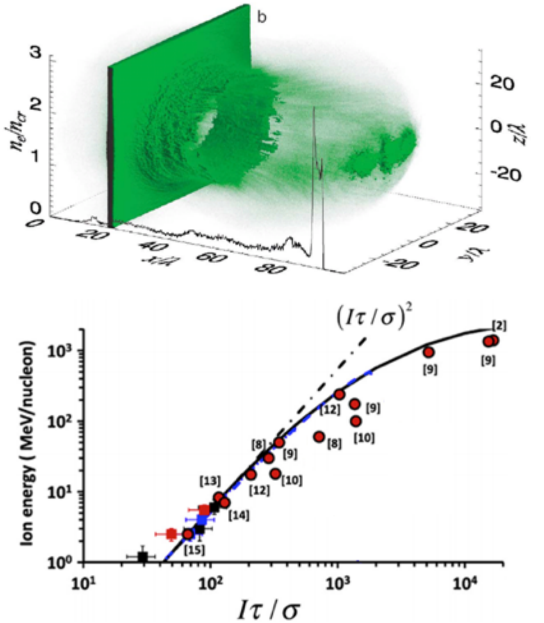
DOE Sc. FES



BELLA-I IP2 (Project)
Sc. FES- ion accel., basic plasma
Ion acceleration

Fundamental Physics of Relativistic Plasmas
High precision at 1Hz, set scaling to large facilities

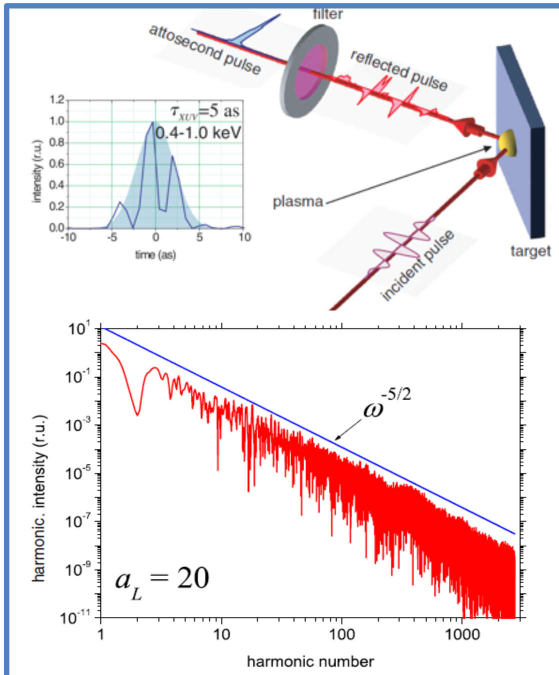
Game changing demonstration of RPA



- More favorable scaling prop to laser intensity
- High efficiency (~10%)
- Ion energies of 200 MeV/u suitable for bio/ medical applications

Esirkepov, et al., PRL ***92,*** *175003 (2004)*

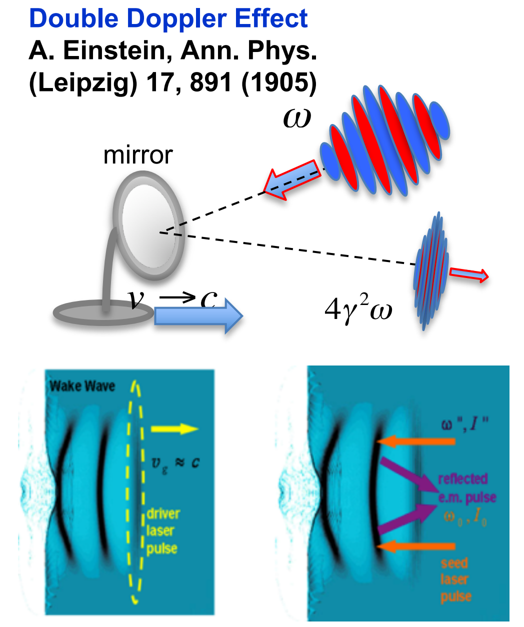
Generation of attosecond (as)-light pulses



- Relativistic plasma oscillations generative high harmonics
- Polarization gating for single as-pulse

Tsakiris et al., NJP ***8****, 19 (2006)*

Relativistic flying mirror

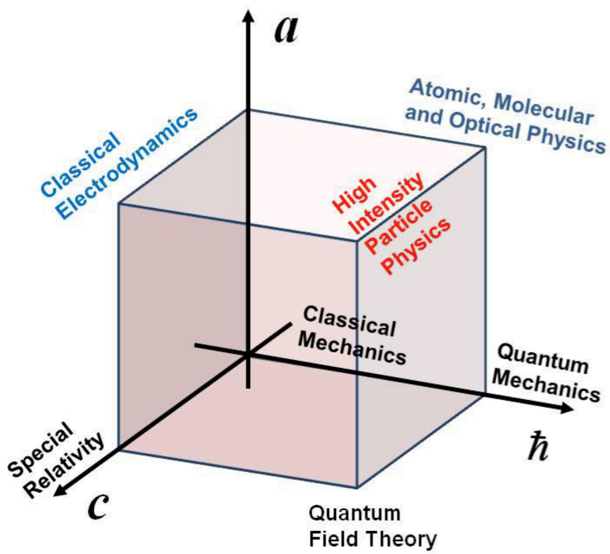


Parabolic relativistic mirrors are formed by the wake behind the laser pulse

Bulanov et al., PRL ***91****, 085001 (2003)*

High repetition rate high field experiments

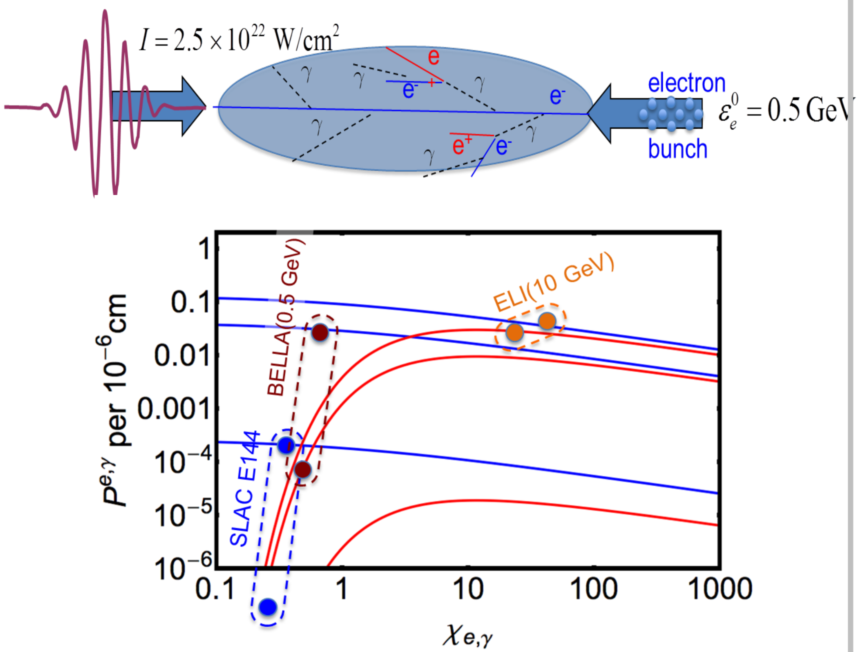
High Intensity Particle Photon Interaction



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

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

Electromagnetic Cascades have high event rates for PW laser colliding with e- beams

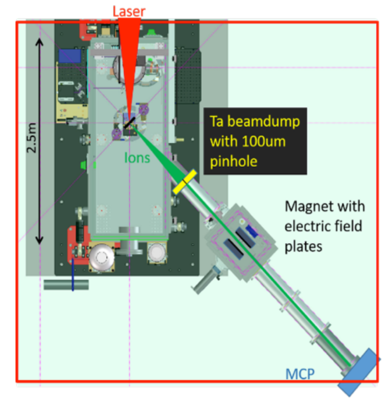


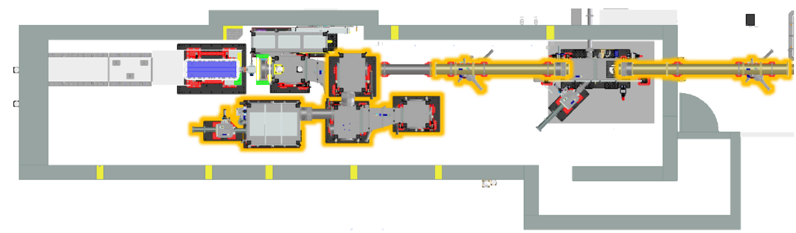
Bulanov et al., PR A ***87****, 062110 (2013)*

Electron –Positron Pair creation: Multiphoton Compton & Breit-Wheeler effects with improved event rates

LaserNet via DOE Sc. FES
User access to BELLA capabilities

- **BELLA PW, long focal length beamline**
  - $2 \cdot 10^{19}$ W/cm^2 available now
  - laser-plasma interactions, ion acceleration
  - Multi-beam in 2021 pending staging experiment
- **BELLA PW, short focal length beamline**
  - $>10^{21}$ W/cm^2 available in 2019
- **100 TW laser**
  - 5 Hz, laser-plasma interactions
  - development of secondary beams
- **Complements high energy/lower rate systems**
- **Joint development of capabilities of interest**
  - **Scaled experiments**
  - **Targets (thin films, micro/nano-fab, …)**
  - **Diagnostics**
  - …





MOLECULAR FOUNDRY

ALS
ADVANCED LIGHT SOURCE