Laser Plasmas at the Irradiance Frontier*

Presented by Daniel Gordon

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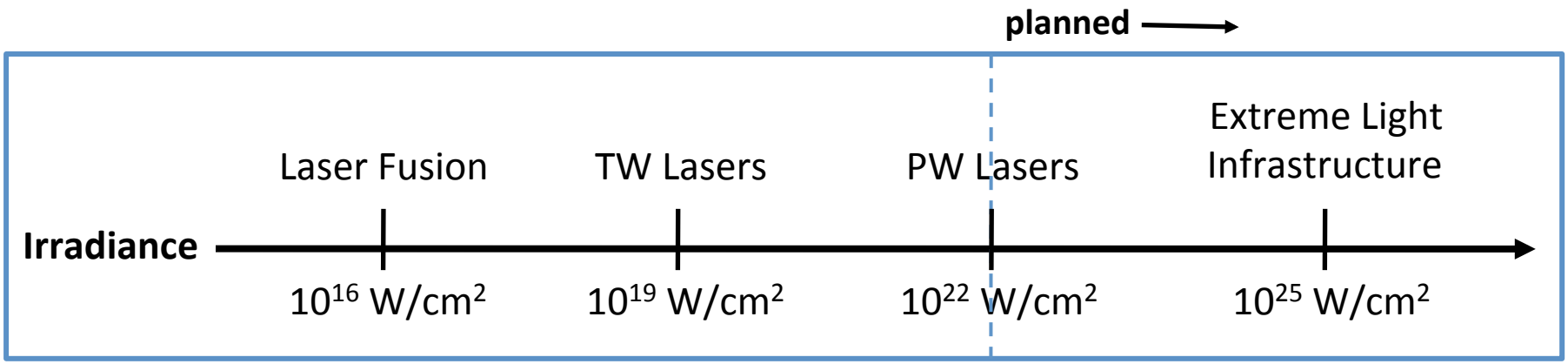
New Physics at Irradiance Frontier

- For $I > 10^{23}$ W/cm^2, new processes appear in laser-plasma interactions
  - Direct response of ions to the optical field
  - Trapping of electrons in the optical wave
  - Ultra-relativistic tunneling
  - Radiation reaction effects



High Power Lasers at Present and in Near Future

- University of Michigan HERCULES facility holds irradiance record of **2×10^{22} W/cm^2**
  - V. Yanovsky et al., Opt. Exp. **16**, 2109 (2008)
- Several PW class lasers
  - LBNL, LANL, Michigan, Nebraska, OSU, Texas, others…
- 10 PW laser projects
  - VULCAN at Rutherford Appleton Laboratories, UK
  - ILE APPOLON at ILE, France
  - 10 PW beamlines at ELI-NP, Bucharest, Romania
- Exawatt scale : European Extreme Light Infrastructure (ELI)
  - Coherent beam combining of several 10 PW beams (speculative)
- Other exawatt proposals: XCELS (Russia) and HiPER (UK)

Program Area Schematic

- Fundamental physics, first observations
  - Radiation reaction, GeV vacuum acceleration, K-shell tunneling from high-Z atoms
- Develop suitable simulation tools
  - Likely that ordinary PIC codes will not do
  - Ab initio ionization modeling challenging
- Develop enabling technology
  - Scaling conventional systems, plasma optics, pulse amplification and compression in plasma
- Develop applications
  - Particle acceleration, light sources, fusion

Charged Particle Dynamics at the Irradiance Frontier

Expect novel regimes of both electron and ion motion in vacuum fields

Time scale for relativistic acceleration: $$\tau_R = \frac{mc}{qE}$$

Usual normalized vector potential is: $$a = (\omega\tau_R)^{-1}$$

Consider *I* = 10^{23} W/cm^2 , *E* ~ 900 TV/m

Electrons: $$\tau_R = 2 \text{ attosec}$$

Relativistic in small fraction of optical cycle
Forward directed (**v**x**B**) and possibly trapped

Protons: $$\tau_R = 4 \text{ fsec}$$

Relativistic in about one optical cycle
Ponderomotive effects significant

Relativistic Tunneling Ionization

- Most work on tunneling non-relativistic
- Relativistic *free* states easy to reach
  - Nitrogen (Z=7) fully stripped for $I \sim 10^{19}$ W/cm^2
  - quiver momentum ~ 3mc
- Relativistic bound states occur for high Z
- Extreme irradiance fully strips heavy elements
  - Krypton (Z=36) fully stripped for $I \sim 10^{23}$ W/cm^2
  - Uranium (Z=92) fully stripped for $I \sim 10^{26}$ W/cm^2
- Ab initio simulation requires resolution of frequencies of order $mc^2/\hbar$
  - Typically $>10^5$ times the optical frequency
  - GPU acceleration is found to be effective

Overview of Radiation Reaction

- Self-force on an elementary particle due to its own emitted radiation
  - Derived by Abraham and Lorentz before modern era
  - Modernized and clarified by Dirac [P.A.M. Dirac, Proc. R. Soc. 167, 148 (1938)]
- Radiation reaction is an unsolved problem of classical electrodynamics

$$mc\frac{du^i}{ds} = \frac{e}{c}F^{ik}u_k + g^i$$

Lorentz force reaction force

LAD reaction force is $$g^i = \frac{2q^2}{3mc}\left(\frac{d^2u^i}{ds^2} - u^i u^k \frac{d^2u_k}{ds^2}\right)$$

- LAD force has pathologies such as runaway solutions.
- Pathologies are eliminated through a perturbative treatment
  - A number of approaches have been suggested, including [Landau and Lifshitz (*Fields*)], [F. Rohrlich, Phys. Lett. A **303**, 307 (2002)], [I.V. Sokolov et al., Phys. Plasmas **16**, 093115 (2009)]

Radiation Dominated Regime

R = reaction force / Lorentz force *R*>1 = radiation dominated

For relativistic electron:

$$R = 1.5 \times 10^{-17} \gamma^2 \sqrt{I[\mathrm{W/cm^2}]}$$

Example:

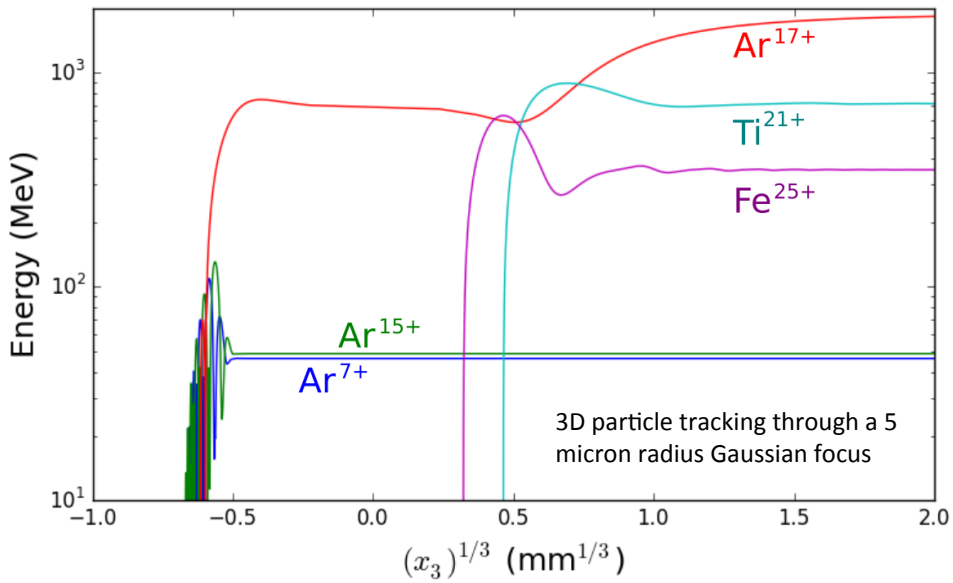
I = 10^{23} W/cm^2 , γ = 1000 gives *R* = 4.7

Possibly accessible with 10 PW technology

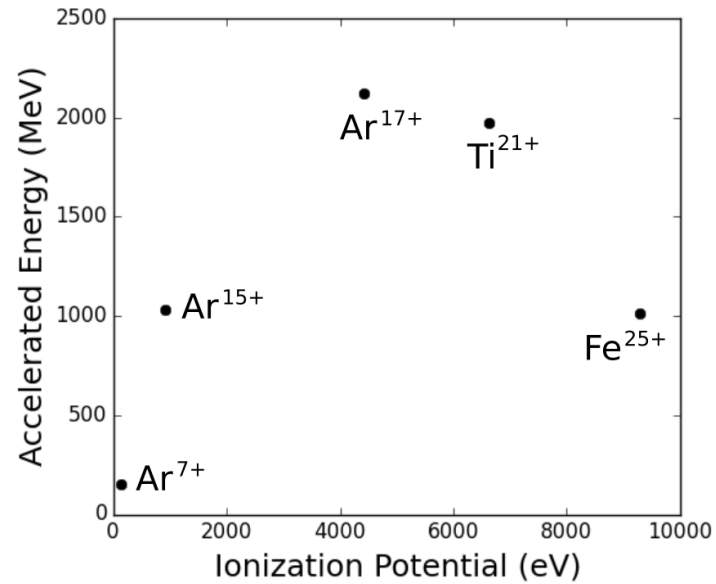
Opportunity: Vacuum Laser Acceleration to GeV Energies[1,2,3]

CAS scheme[1] externally injects into laser focus
xLIPA scheme[2] draws electrons from K-shell of heavy atoms
Other schemes suggested, such as radial polarization[3]

(a) xLIPA orbits for 10 PW laser



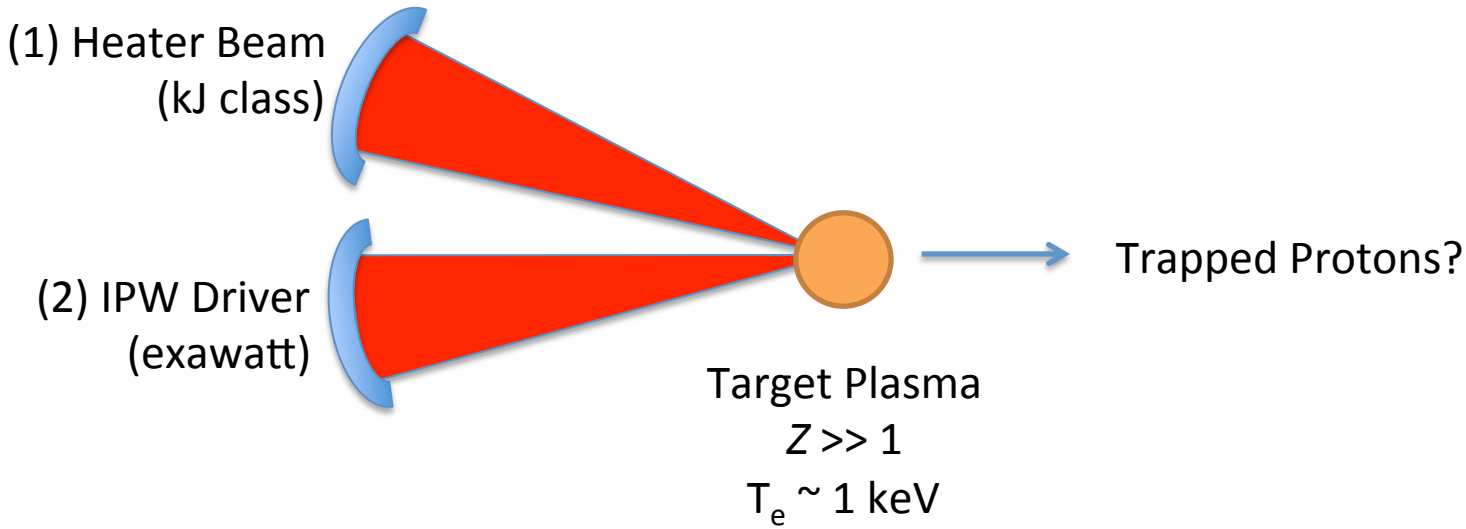
(b) xLIPA Z dependence



1. P.X. Wang et al., Appl. Phys. Lett. **78**, 2253 (2001)
2. D.F. Gordon et al., NRL Memorandum Report, to be published
3. D.N. Gupta et al., Phys. Lett. A **368**, 402 (2007)

Opportunity: Excitation of Ion Plasma Waves

Little explored ion plasma waves (IPW)* can be supported for large T_e and Z, and driven ponderomotively by extreme irradiance light.



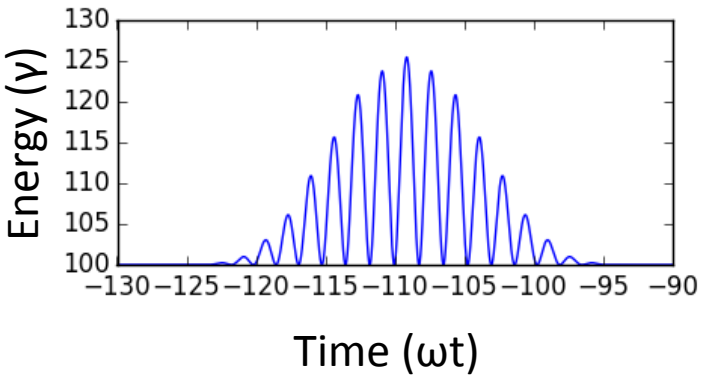
Challenge: exawatt pulse likely far from IPW resonance

* B. Bauer et al., Phys. Rev. Lett. **74**, 3604 (1995)

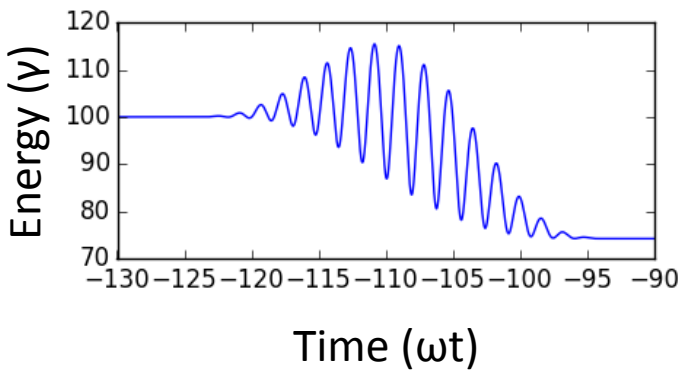
Opportunity: Radiation Reaction Theory vs. Experiment[1,2,3,4]

Consider collision of 50 MeV electron with 0.8 micron planar laser pulse with a=100 [4]

Ordinary Maxwell-Lorentz



Landau&Lifshitz Reaction Force



Reaching a=100 likely requires at least 10 PW laser power
In this example, wavefronts planar (infinite power)

1. Di Piazza et al., Phys. Rev. Lett. **102**, 254802 (2009)
2. M. Chen et al., Plasma Phys. Conrol. Fus. **53**, 014004 (2011)
3. A.G.R. Thomas et al., Phys. Rev. X **2**, 041004 (2012)
4. Y. Kravets et al., Phys Rev. E **88**, 011201 (2013)

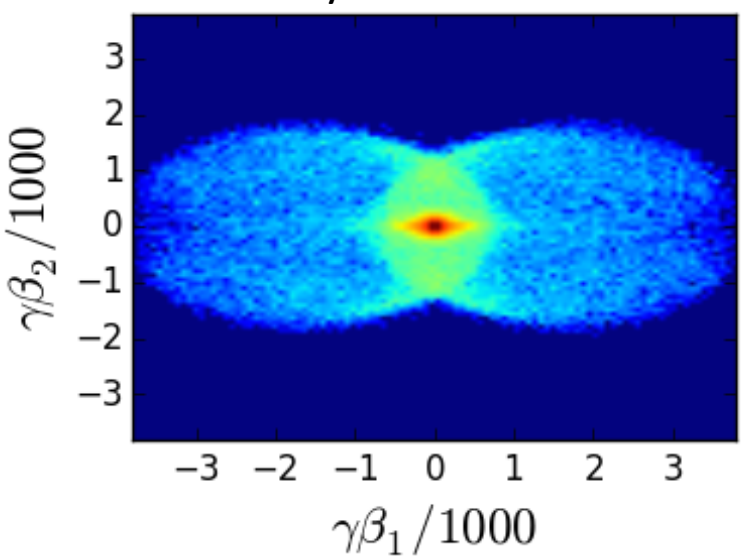
xLIPA with Radiation Reaction[1]

25 exawatts ionizing K-shell of gold

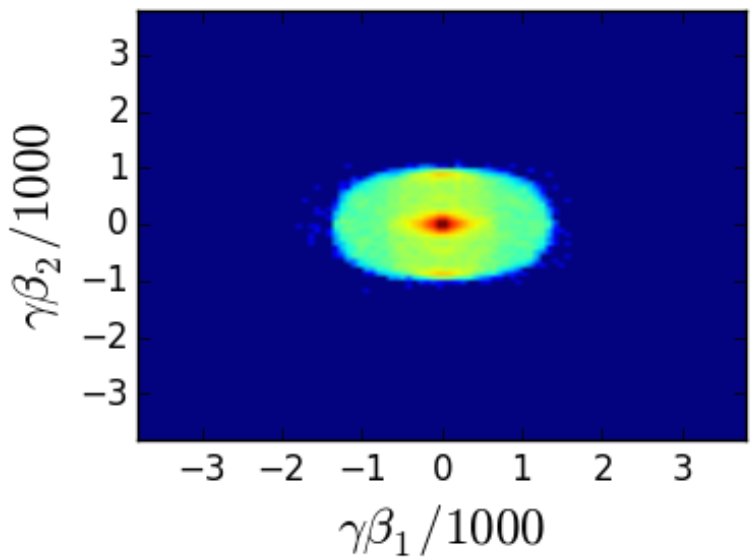
Simulations predict 70 GeV max energy

Effect of RR on transverse phase space particularly striking

Ordinary Maxwell-Lorentz



Landau&Lifshitz Reaction Force

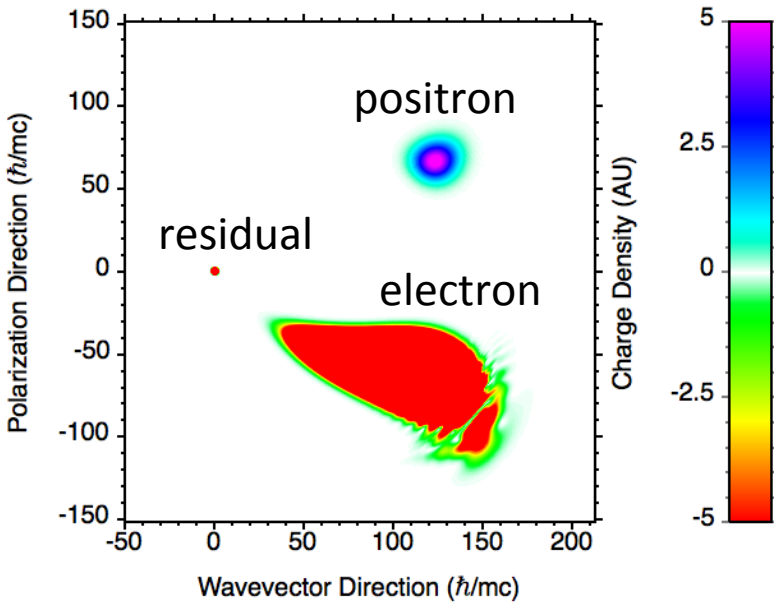


1. D.F. Gordon et al., NRL memorandum report, to be published

Opportunity: Relativistic Tunneling Ionization[1,2,3]

- Theory and simulation not well developed, even for non-relativistic bound / relativistic free scenario
- Fully relativistic problem only recently investigated in some detail

Ionization of a scalar electron with Z=137



- Simulation uses intense x-ray pulse (0.2 nm, E=300000 TV/m)
- Simulations with optical wavelengths lead to extraordinary computational load

1. H. Bauke and C.H. Keitel, Comp. Phys. Comm. **228**, 9092 (2009)
2. M. Klaiber et al., Phys. Rev. A **87**, 023418 (2013)
3. D.F. Gordon et al., J. Comp. Phys. **267**, 50 (2014)

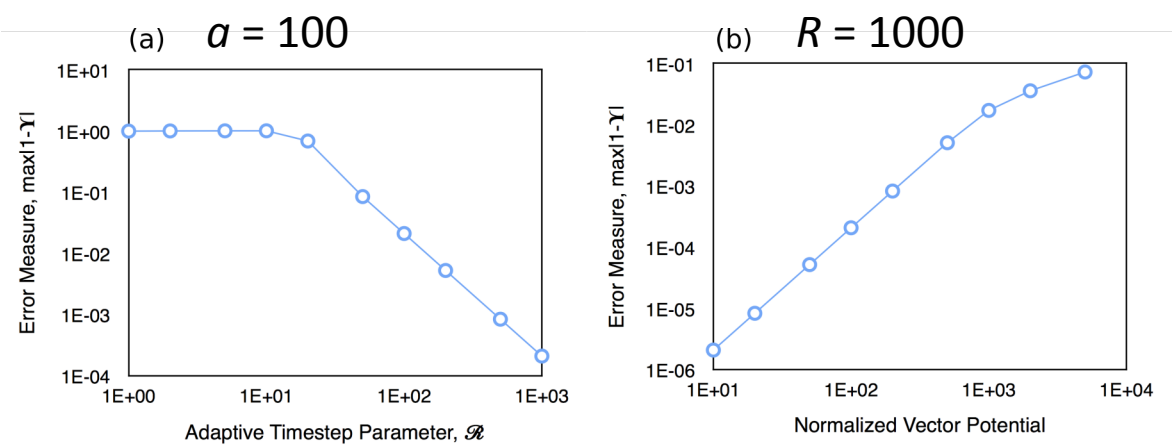
Challenge: Numerical Methods

Conventional PIC codes have excellent track record in "ultra-intense" regime, $1 < a \lesssim 10$

Issues arising in extreme irradiance regime $a \gtrsim 100$

- Accurate tunneling ionization models, including for large Z
- Accurate treatment of radiation reaction effects
- Standard particle pushers struggle at turning points

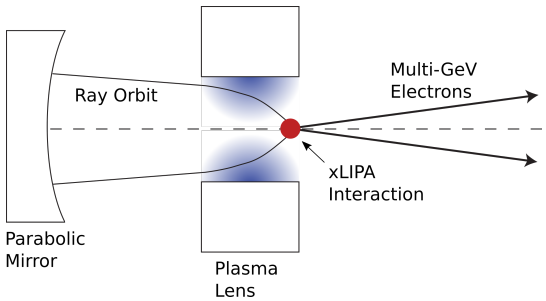
Adaptive time step in proper time: $$\Delta s = \left[\Omega^2 \left(\frac{\omega \Upsilon}{2\pi}\right)^2 + \mathcal{R}^2 \frac{q^2}{2m^2}\left(E^2 + B^2\right)\right]^{-1/2}$$



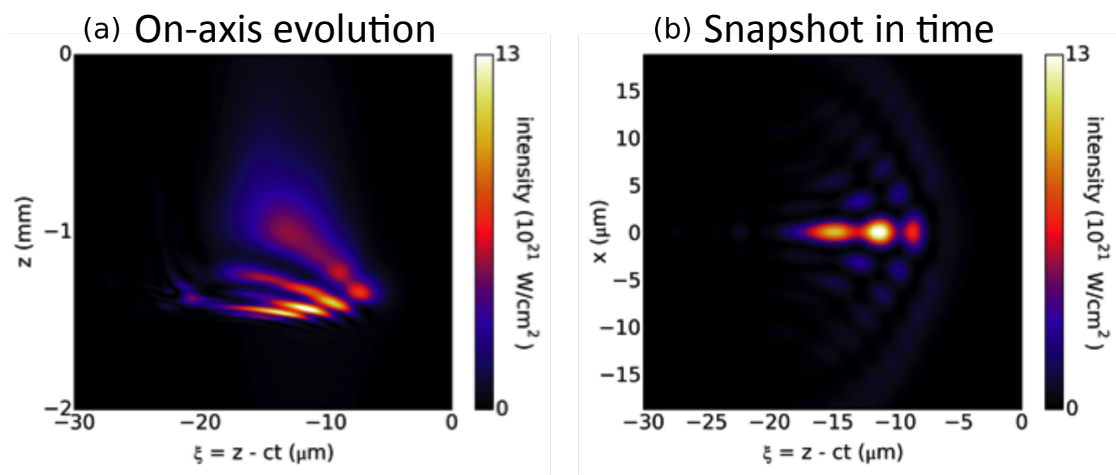
Challenge: Beam Manipulation

Novel beam manipulation techniques such as plasma lenses[1,2,3] may be useful

Example: xLIPA in plasma lens



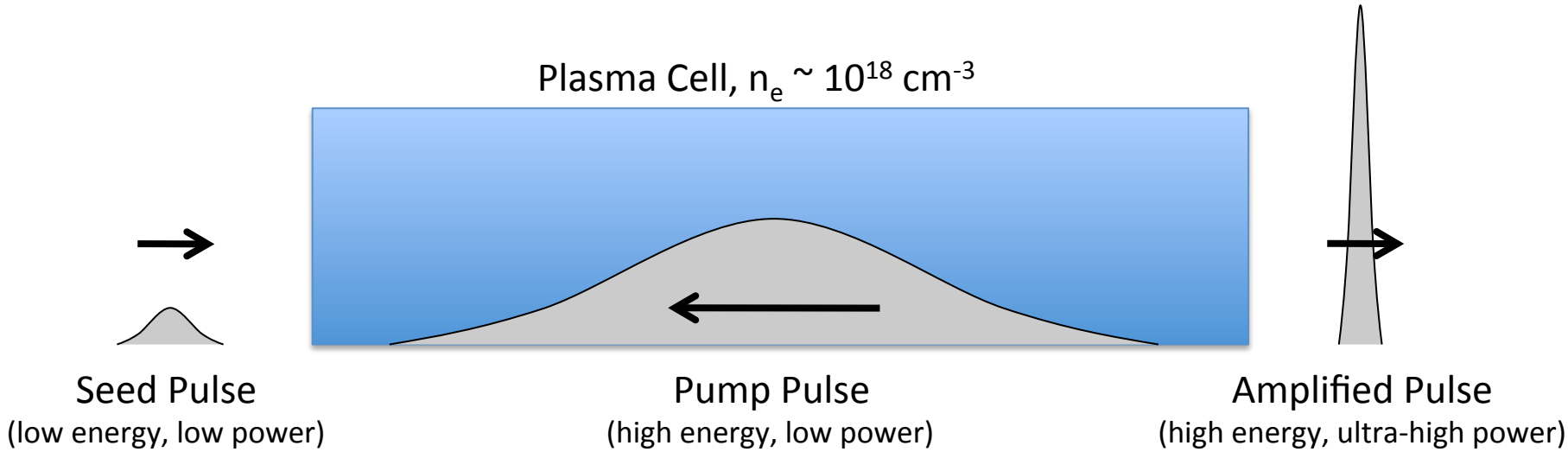
3D PIC Simulation of
10 PW pulse focusing
in a plasma lens



1. C. Ren et al., Phys. Rev. E **63**, 026411 (2001)
2. R.F. Hubbard et al., Phys. Plasmas **10**, 1483 (2003)
3. Y. Katzir et al., Appl. Phys. Lett. **95**, 031101 (2009)

Challenge: Laser Technology

- Nd:glass, long pulse, high energy
- Ti:sapphire, short pulse, lower energy
- Unconventional approaches, e.g., Raman amplifier



- Pump pulse backscatters energy into seed pulse*
- Seed pulse is compressed in time
- Use conventional focusing to obtain high irradiance

* G. Shvets et al., Phys. Rev. Lett. 81, 4879 (1998)

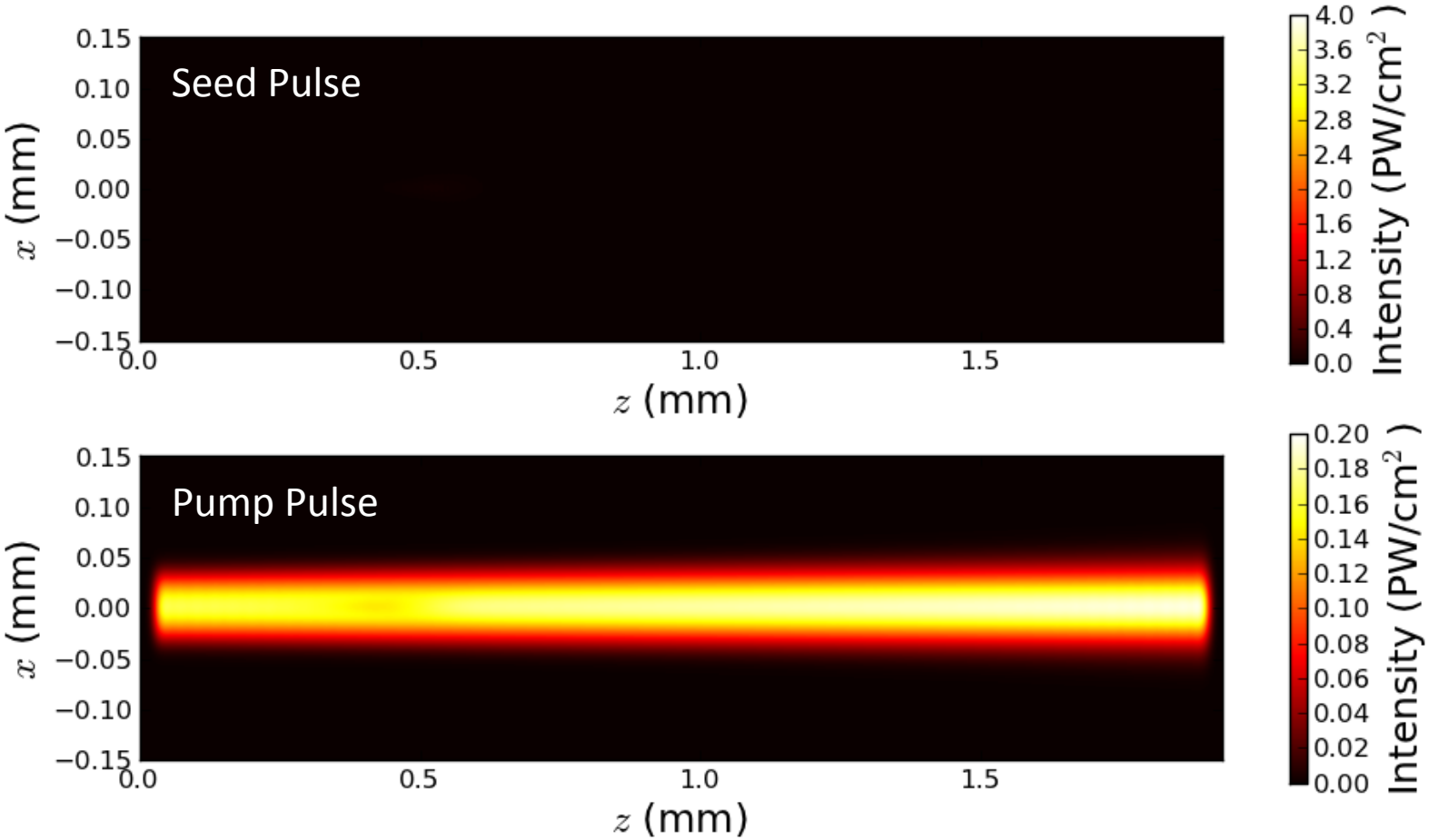
Summary of Irradiance Frontier as a Program Area

- Opportunity for fundamental contributions to laser-plasma interaction physics
  - GeV acceleration by free space fields
  - Bare high Z nuclei from tunneling ionization
  - New regime of direct laser-ion interactions
  - Observation of radiation reaction effects
- Challenges are significant
  - Accessing new regimes stress current laser technology
  - Manipulation of extreme irradiance beams
  - Present computational methods likely inadequate

BACKUPS

NRL Simulations of Raman Amplification

Use Princeton experimental parameters:
pump energy = 1 J , plasma density = 1.3×10^{19} cm^{-3} , λ = 800 nm



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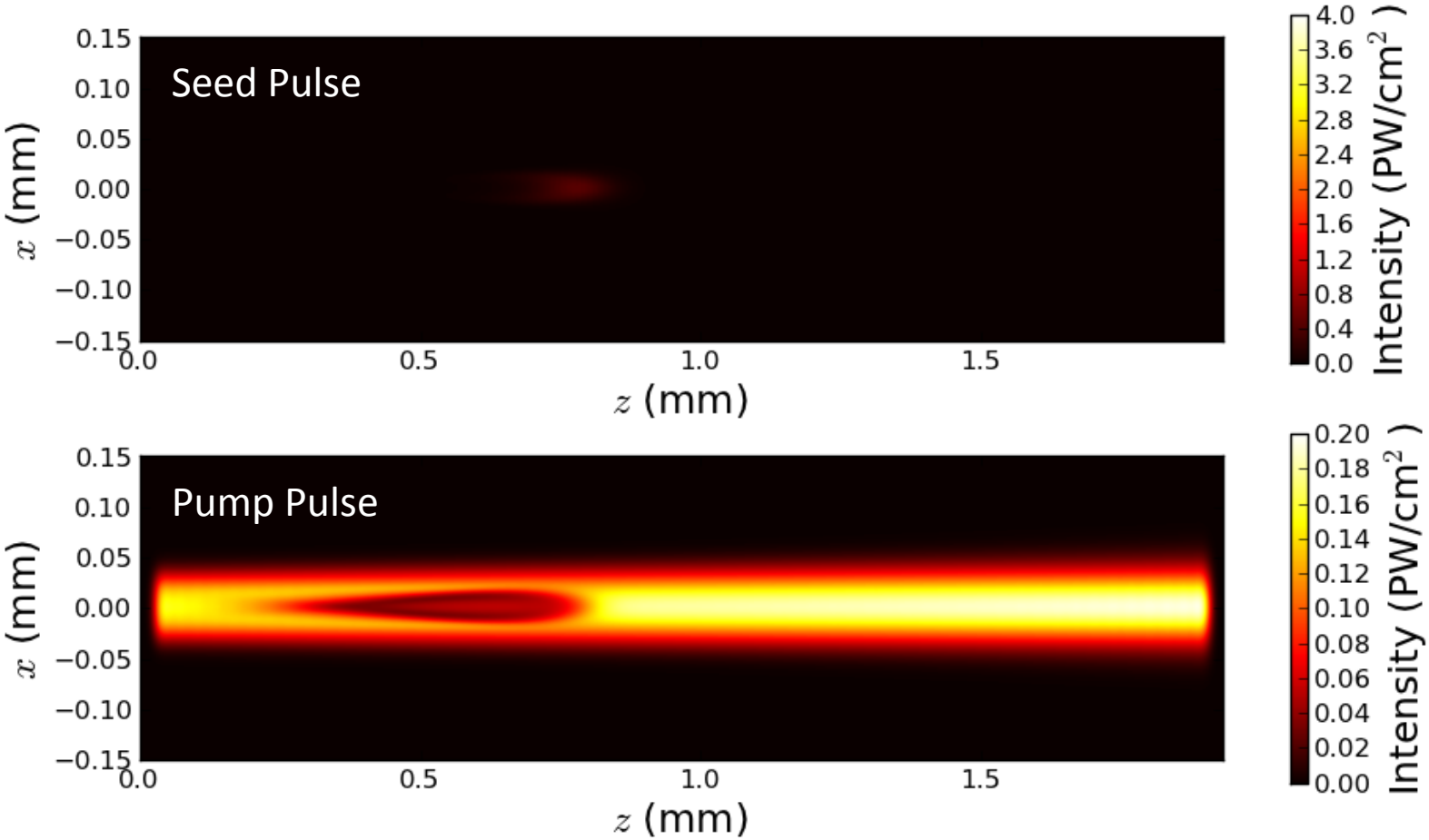

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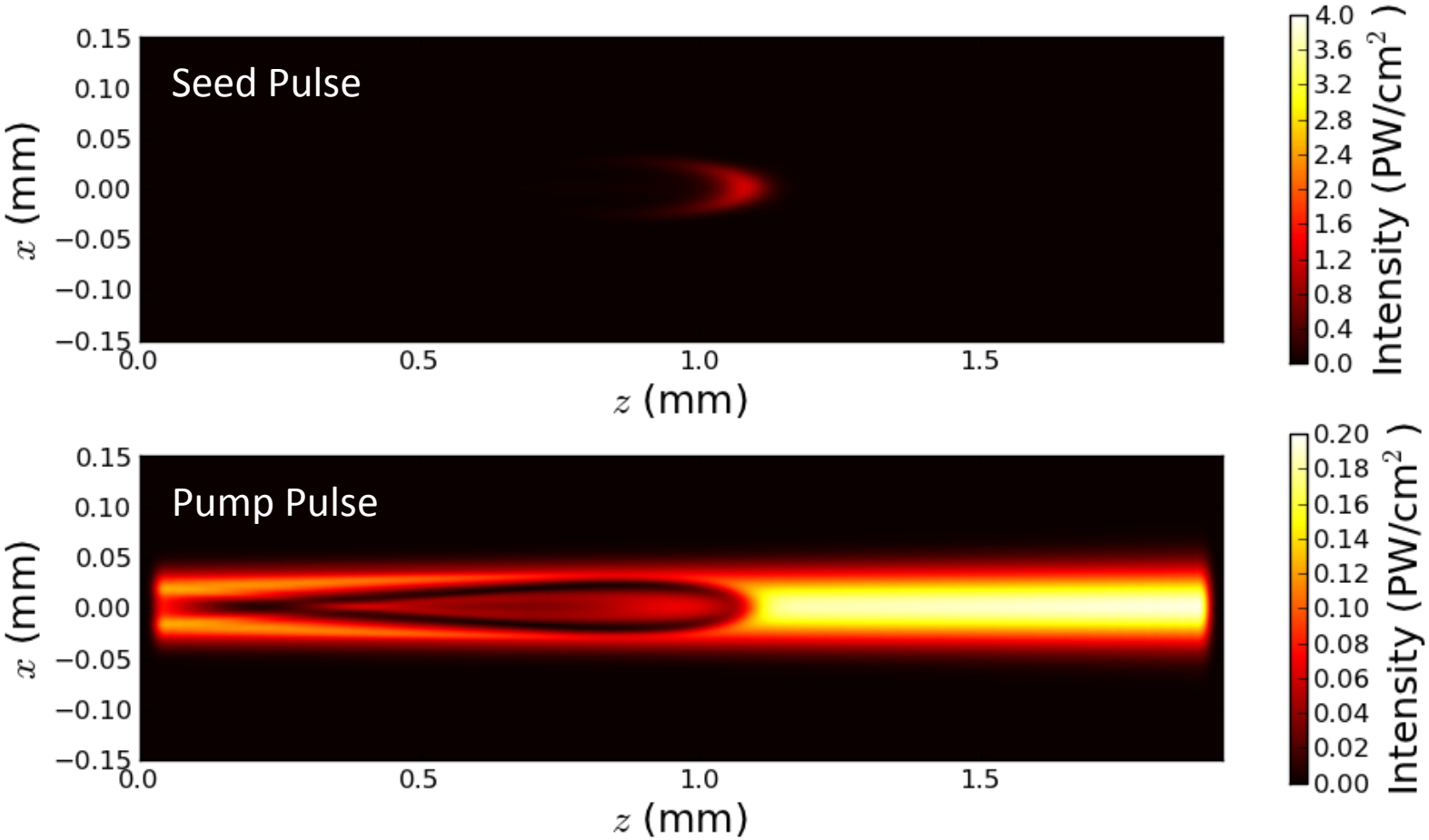

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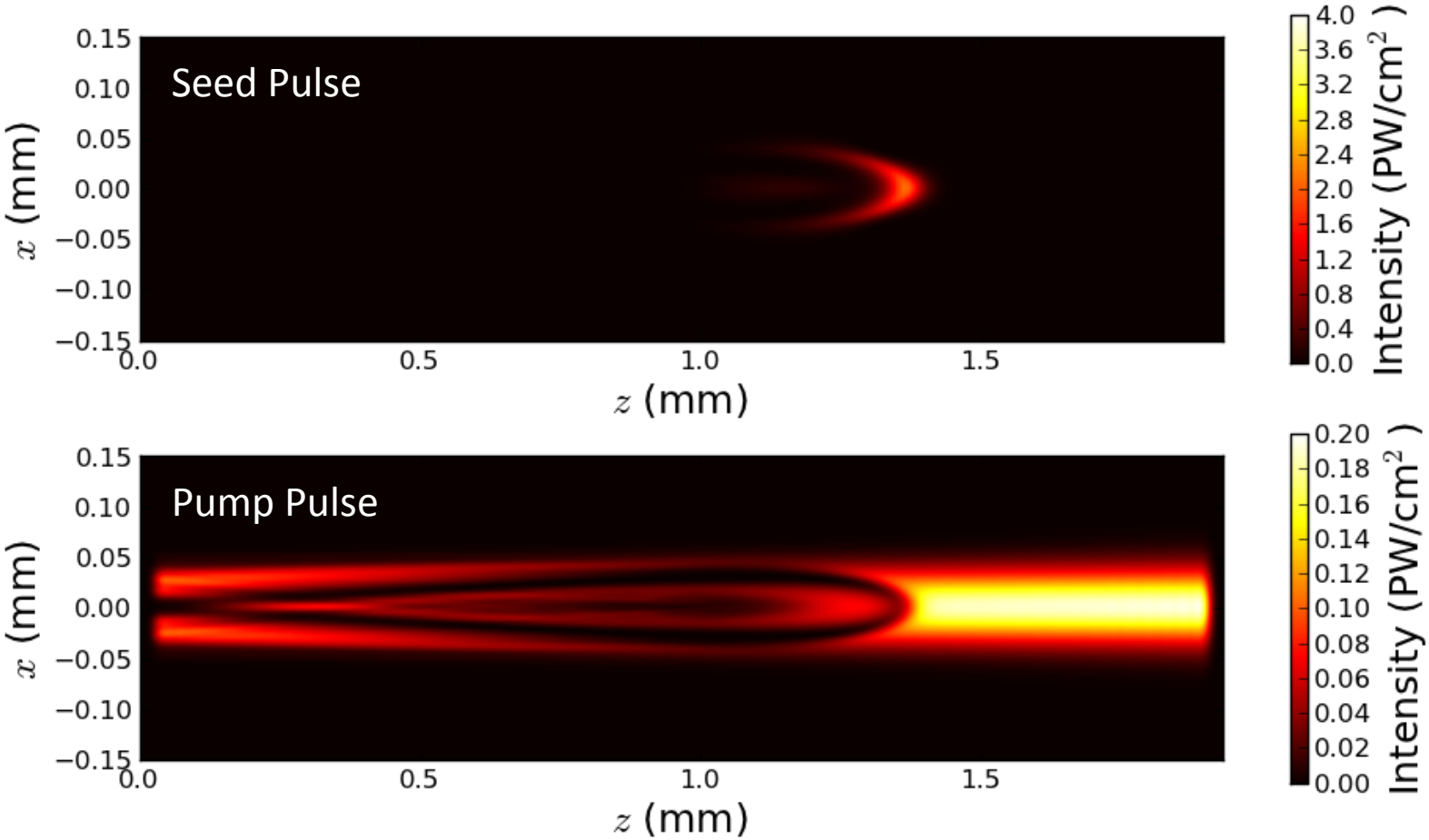

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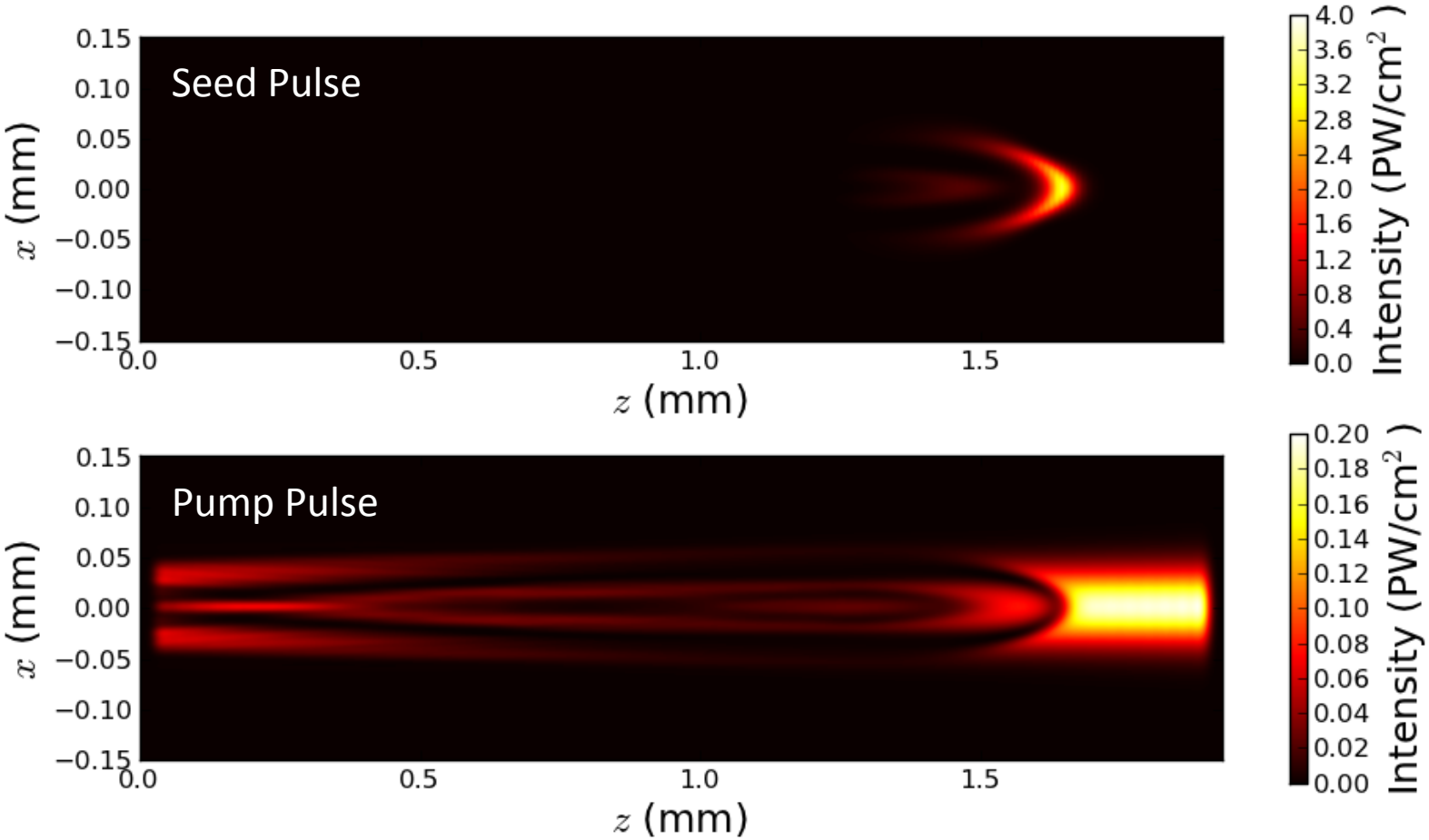

Vacuum Polarization

Atomic Physics

Atomic Field: $E_H = \dfrac{m^2 e^5}{\hbar^4} \approx 5 \times 10^{11}\ \mathrm{V/m}$

$$I \approx 10^{16}\ \mathrm{W/cm^2}$$

Nonlinear effects observable in air for

$$I \approx 10^{11}\ \mathrm{W/cm^2}$$

Energy Scale: $E_H r_H = 27\ \mathrm{eV}$

Vacuum Physics

Schwinger Field: $E_s = \dfrac{m^2 c^3}{e\hbar} \approx 10^{18}\ \mathrm{V/m}$

$$I \approx 10^{29}\ \mathrm{W/cm^2}$$

Nonlinear effects in vacuum may appear for

$$I \approx 10^{24}\ \mathrm{W/cm^2}$$

Energy Scale: $E_s \lambda_c = 510\ \mathrm{keV}$

Laser fields are DC fields!