Laser-plasma based particle acceleration

Alec Thomas

DOE Townhall on Plasmas

June 30 - July 1 2015

Much credit to many others including: Karl Krushelnick, Louise Willingale, Zhaohan He, Tolya Maksimchuk, John Nees, Victor Yanovsky, Peng Zhang, Chris Ridgers

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Ultrashort Pulse High Field Laser-Plasma Physics

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What does high field mean?

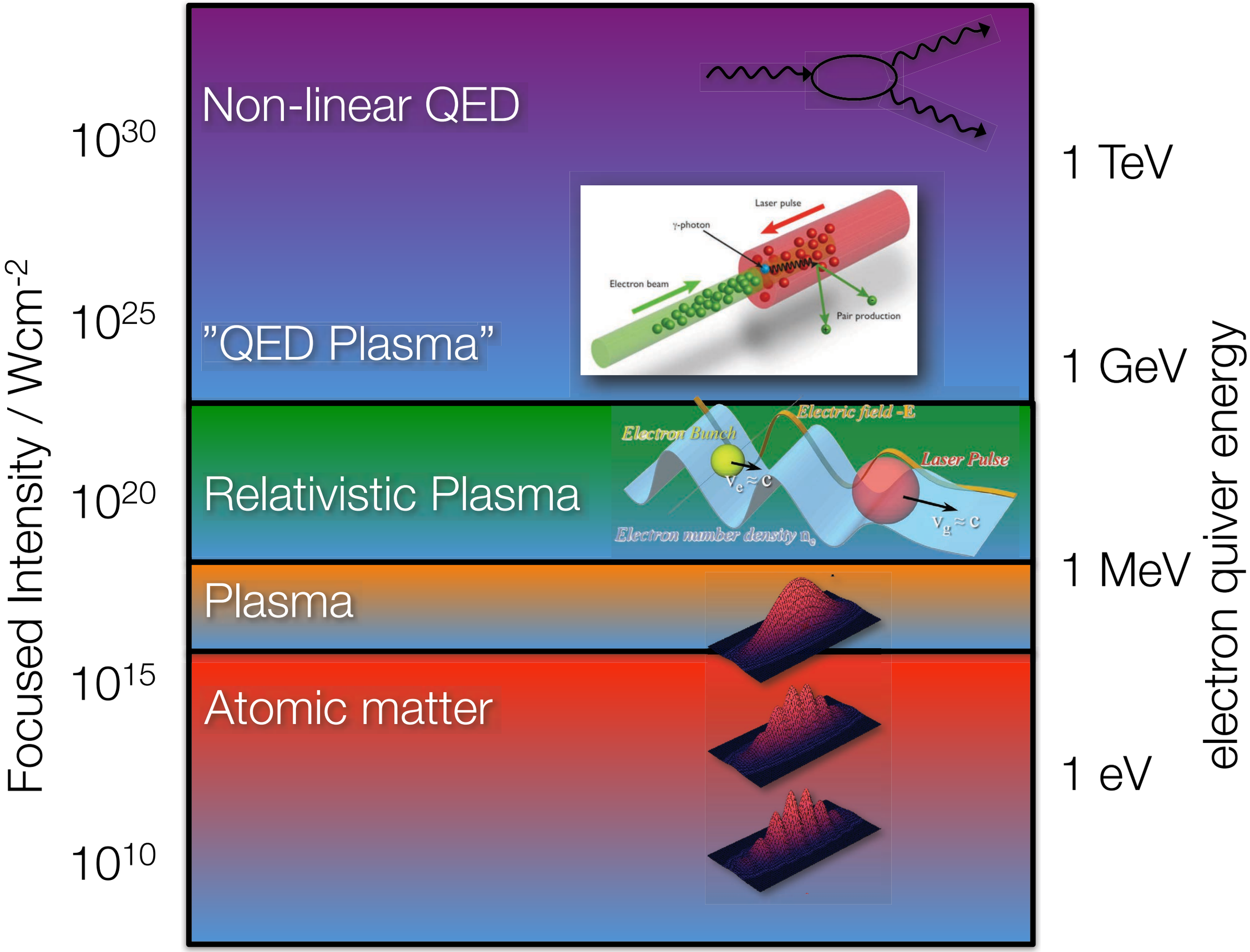
- Could mean one of two things:

1. Electromagnetic Field is large compared to the QED Critical Field:

$$E_S = \frac{m_e^2 c^3}{e\hbar} = 1.3 \times 10^{18}\ \mathrm{Vm}^{-1}$$

2. Electromagnetic Vector Potential is large compared with relativistic threshold

$$A_{rel} = \frac{m_e c}{e} = 17 \times 10^{24}\ \mathrm{Vm}^{-1}\mathrm{s}^{-1}$$


Non-linear QED
"QED Plasma"
Laser pulse
γ-photon
Electron beam
Pair production
Relativistic Plasma
Electric field -E
Electron Bunch
Laser Pulse
$v_e \approx c$
$v_g \approx c$
Electron number density n_e
Plasma
Atomic matter
Focused Intensity / Wcm^{-2}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
1 TeV
1 GeV
1 MeV
1 eV
electron quiver energy

Typical properties of plasma generated in high intensity interaction

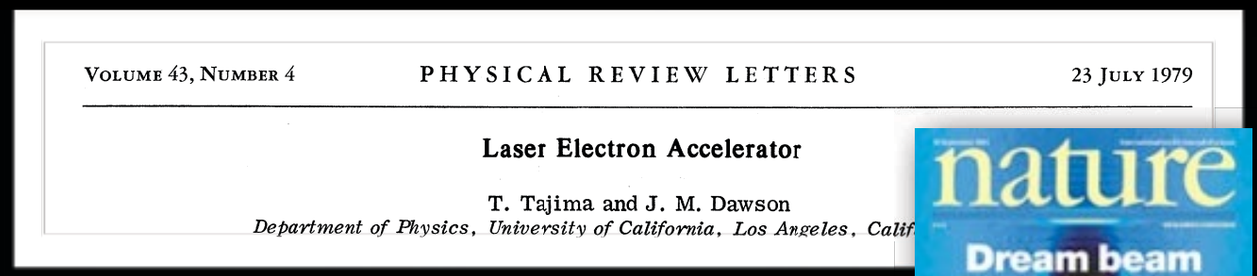
- Laser intensity 10^{22} Wcm^{-2} corresponds to radiation pressure of 10^{17} Pa = 10^{12} Bar!
- Plasma “temperature” may be relativistic - Very far from equilibrium
- May not be quasi neutral - May have system small relative to Debye length
- May not be plasma everywhere - interface between condensed matter and plasma

Typical properties of plasma generated in high intensity interaction

- Generated fields in the plasma are similar strength to applied laser field - i.e. very strong indeed (>TVm^{-1})
- Fields structure controlled by plasma dynamics (either waves or bulk motion)
- **By changing laser and plasma initial conditions we can harness these fields to accelerate charged particles**

Laser Wakefield Acceleration

>1000 papers since Y2000


VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

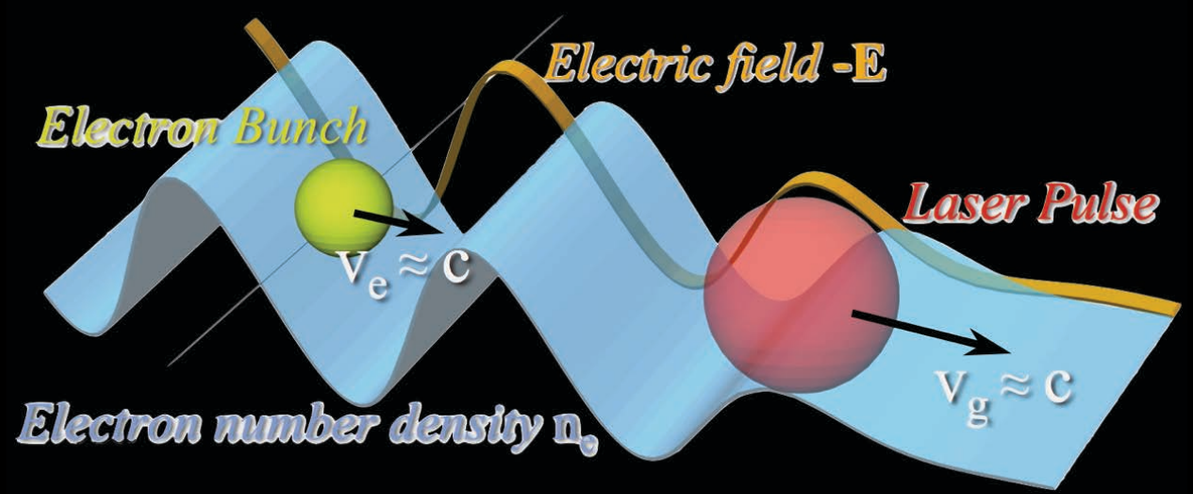
Laser Electron Accelerator

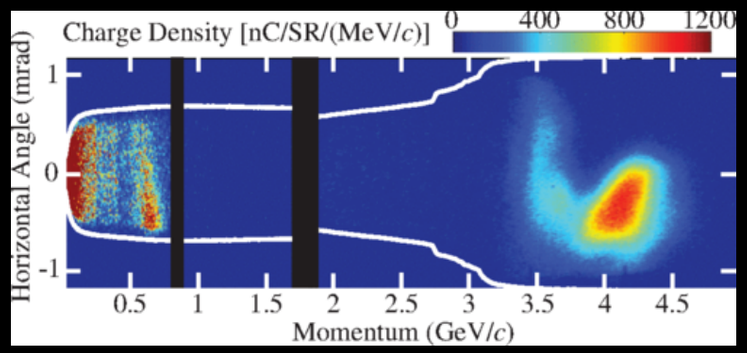
T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, Calif

Mangles Nature (2004)
Geddes Nature (2004)
Faure Nature (2004)

Surfing electrons on an electric wave!





Electron energy spectrum (Leemans, PRL 2015)

Maximum energy gain (limited by dephasing)

$$\Delta T = \frac{2}{3} a_0 \frac{n_c}{n_e} m_e c^2$$

Gordienko and Pukhov, Phys. Plasmas (2005)
Lu et al. PRSTAB (2007)

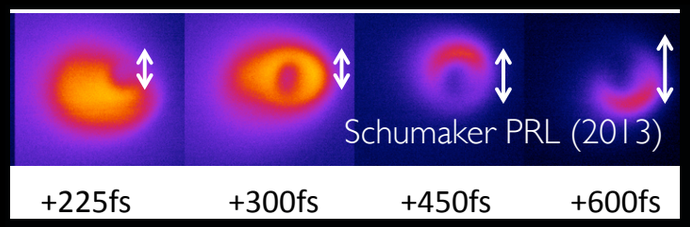
Leemans, Nature Phys (2006)
Kneip, PRL (2009)
Clayton, PRL (2010)
Liu, PRL. (2011)
McGuffey, Phys. Plas. (2012)
Wang, Nature Comms (2013)
Leemans, PRL (2015)

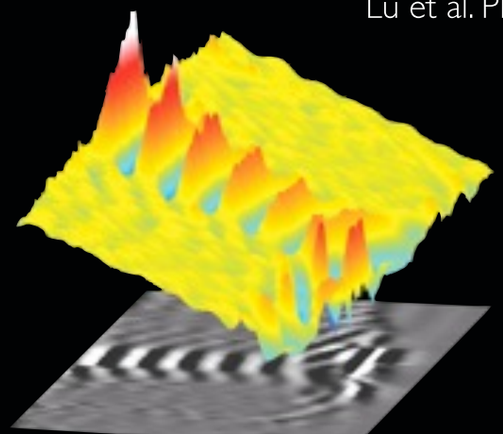
Experiments now demonstrate GeV energies in a cm-scale plasma accelerator

i.e. 100 GeV/m accelerating gradient

Can use electron beam as ultrafast probe

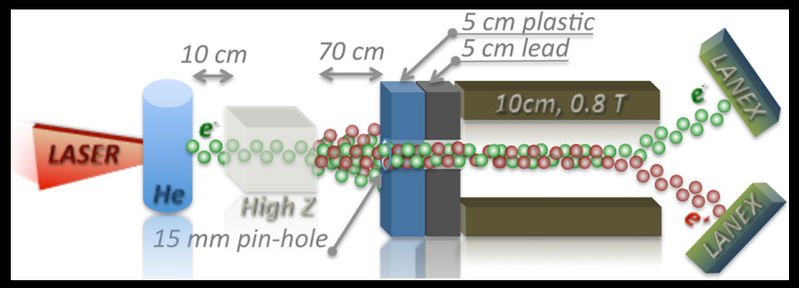
-e.g. magnetic fields





Visualization of wakefield

Matlis et al Nat. Phys. (2006)
Dong et al PRL (2010)



Production of electron positron plasma

Sarri PRL 2013
Sarri Nat Comms 2014

Wakefield based photon sources

Betatron radiation

Electrons in 3D wake structure oscillate with frequency

$$\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$$

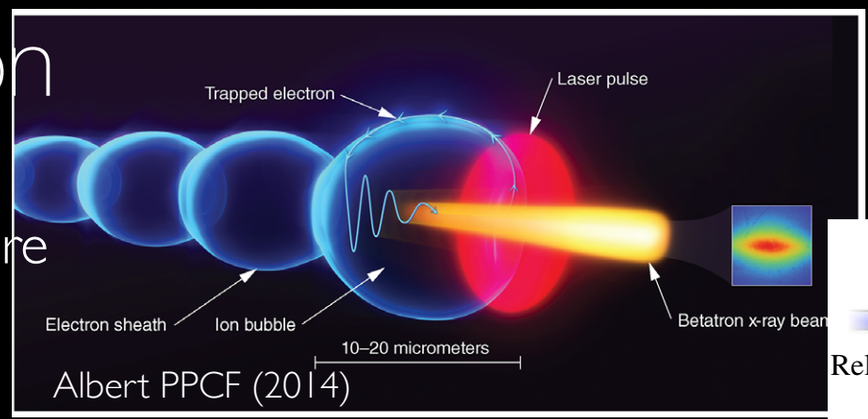
Esarey PRE (2002)

Wang et al PRL (2002)

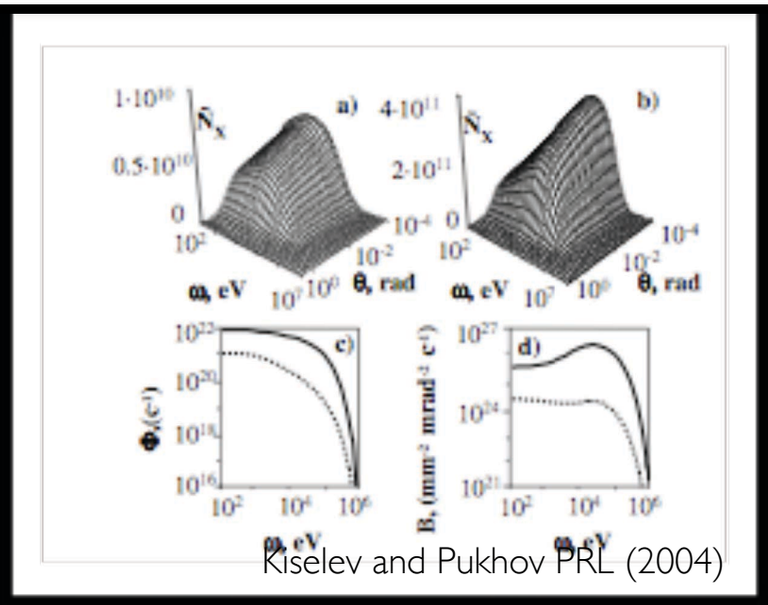
Rousse et al PRL (2004)
Rousse, Ta Phuoc

Kneip et al PRL (2008)

Kneip et al Nature Phys (2010)
Corde et al PRL (2011) x2
Plateau et al PRL 2012
Albert et al PRL (2013)

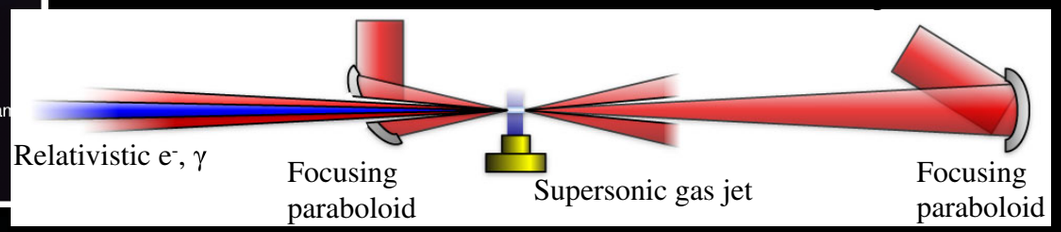


Albert PPCF (2014)



Kiselev and Pukhov PRL (2004)

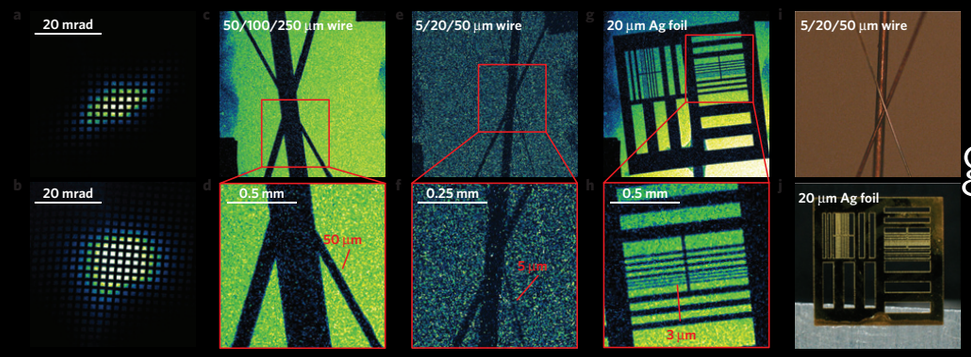
All optical Compton source



Tunable monochromatic gamma ray

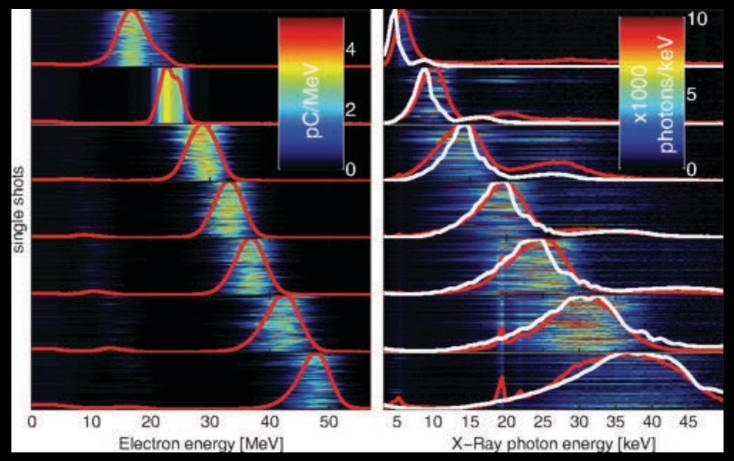
Geddes talk (next)

Ta Phuoc Nature Pho. (2012)
Chen PRL (2013)
Powers Nature Pho (2014)
Sarri PRL (2014)
Khrennikov PRL (2015)



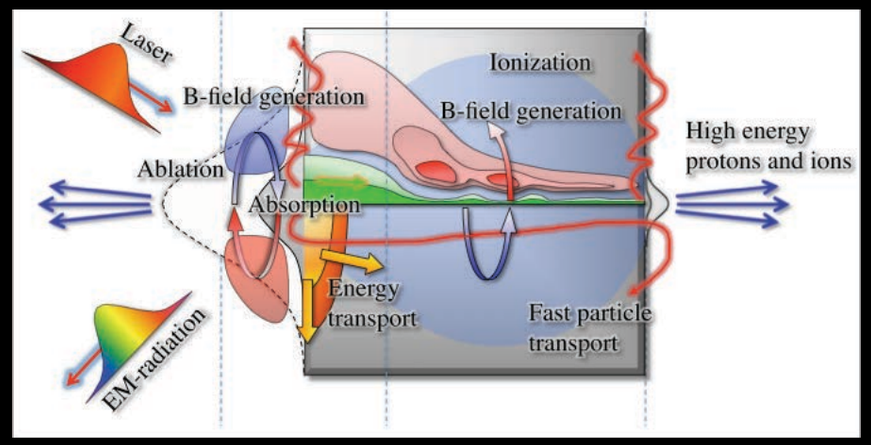
PEAK Brightness comparable to 3rd generation synchrotron

Albert talk (yesterday)



Ion acceleration and HHG

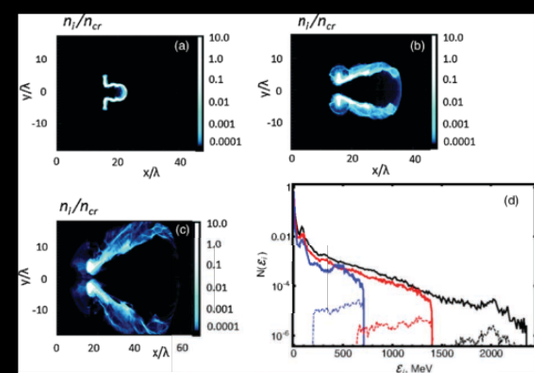
>2000 papers since Y2000



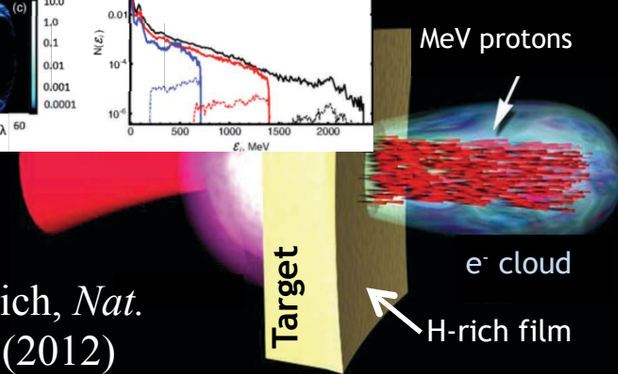
Target Normal Sheath Acceleration

Snavely PRL 2000
Maksimchuk PRL 2000
Zepf PRL 2003
Mora PRL 2003
Kaluza PRL 2004
Wei PRL 2004
Cowan PRL 2006
Albright PRL 2006
Fuchs Nature Phys 2006
Hegelich Nature 2006
Schwoerer Nature 2006
Dollar PRL 2011
Dollar PRL 2012
Veltcheva PRL 2012

Other ion acceleration mechanisms

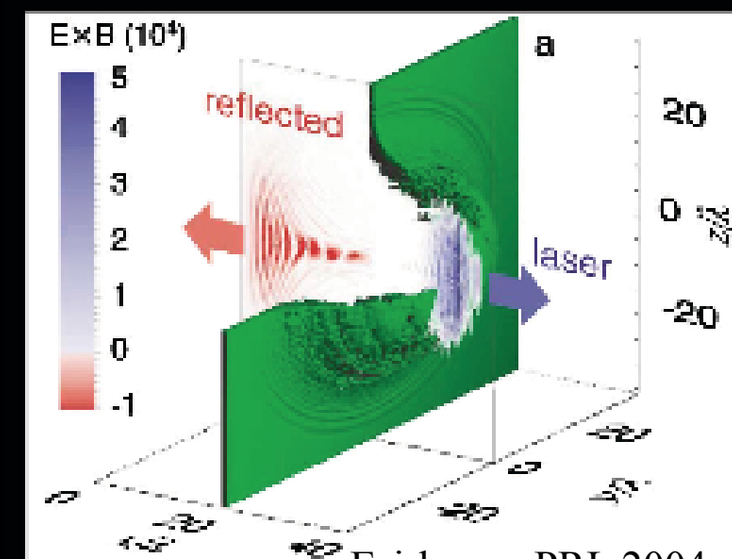


Bulanov et al PRL (2015)

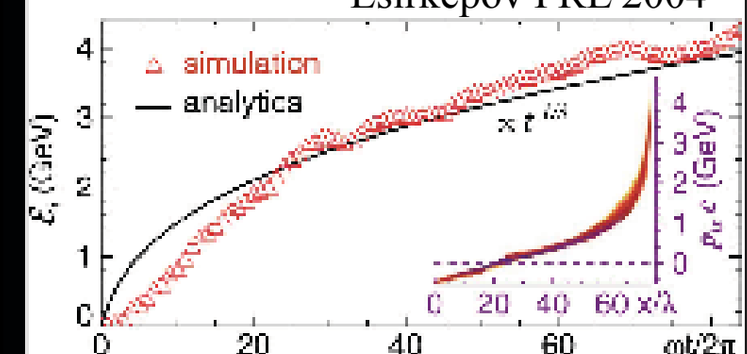


Hegelich, *Nat. Phys.* (2012)

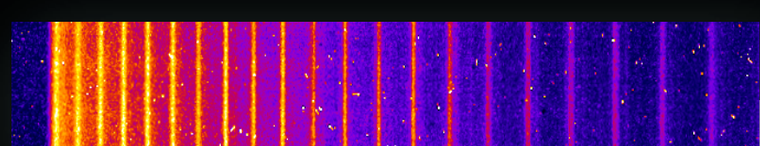
Radiation Pressure Acceleration

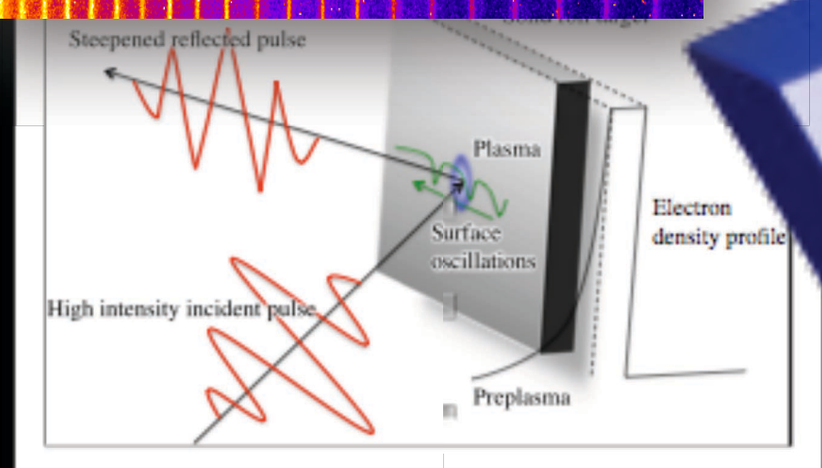


Esirkepov PRL 2004



Esirkepov PRL 2004
Macchi PRL 2005
Robinson PRL 2006
Palmer PRL 2012



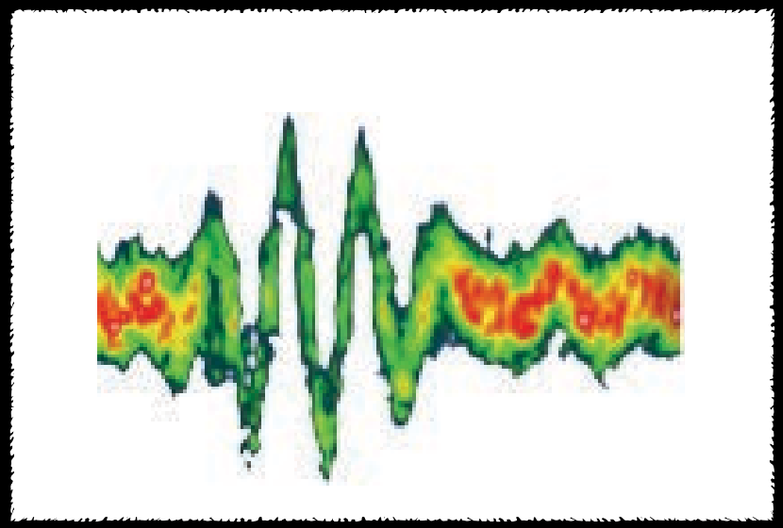


Gordienko PRL 2004
Dromey Nat Phys 2006
Dromey PRL 2007
Dromey Nat Phys 2009
Behmke PRL 2011
Brugge PRL 2012
Rodel PRL 2012
Vincenti PRL 2012
Dollar PRL 2013
Wheeler Nat Pho 2012

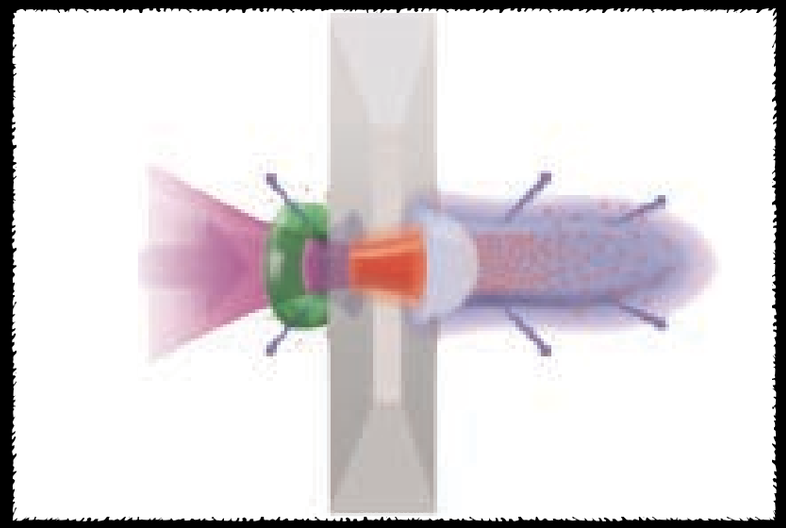
High Harmonic Generation by relativistic oscillating mirror

Relativistic surface motion causes relativistic Doppler shift of incident radiation

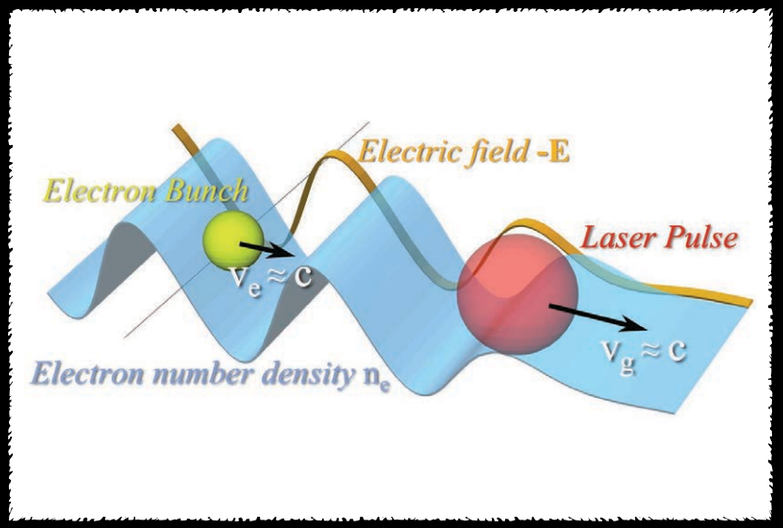
Some applications



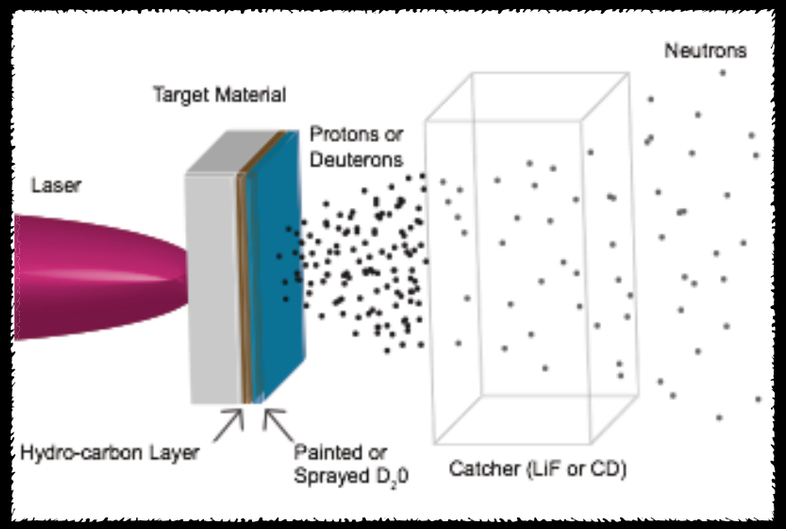
High Order Harmonic attosecond pulse generation for generating atomic "movies"



Laser acceleration of ions for medical hadron therapy applications and advanced fusion schemes



Laser wakefield acceleration for table top sources of energetic electrons



Directional high energy neutron beams for radiography and active interrogation

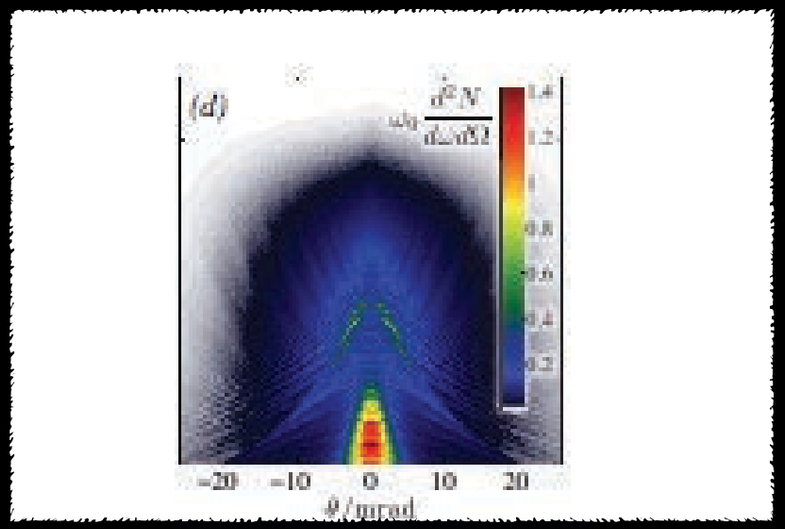
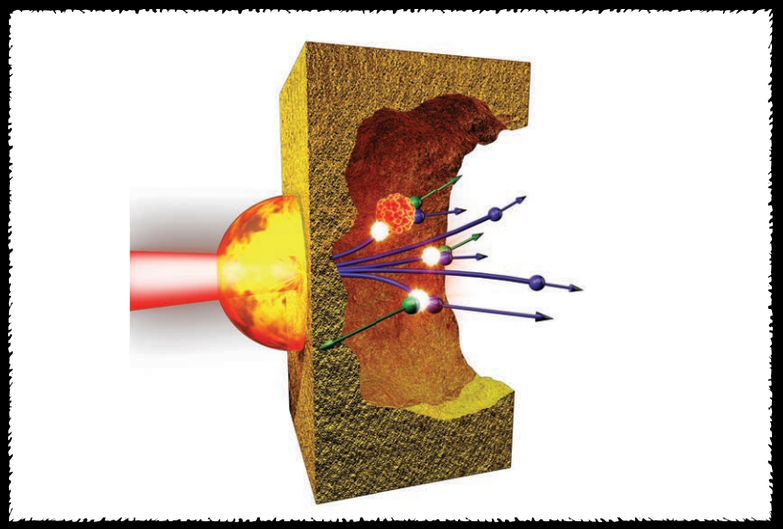


Table-top x-ray and gamma ray sources with high brightness and tunability

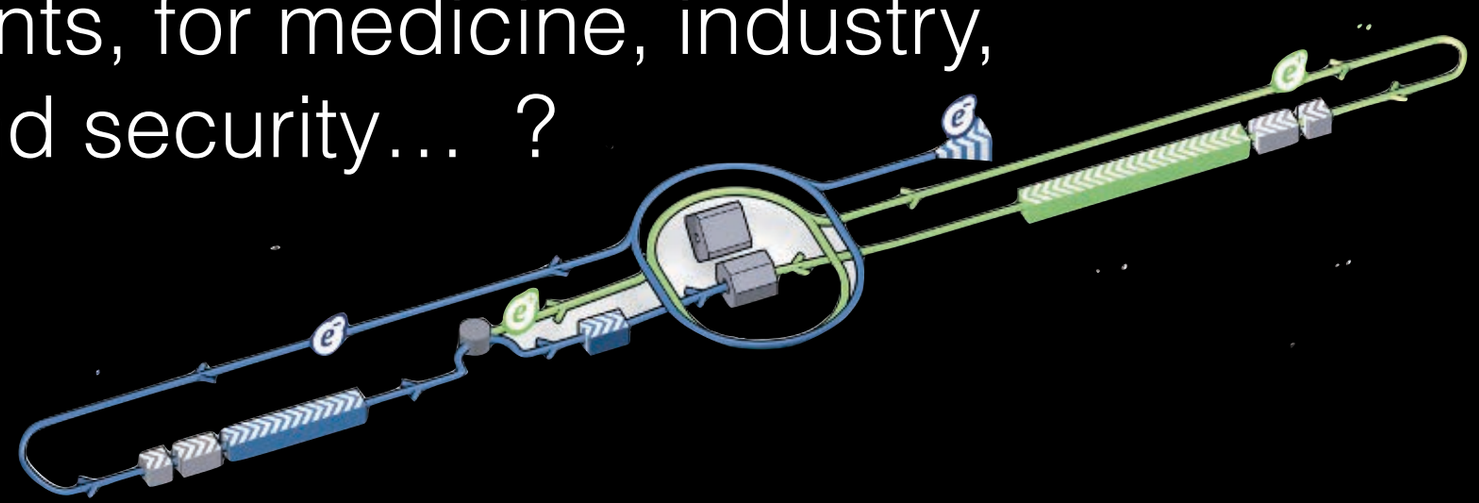


Exotic particle beams for advanced radiography applications

Where is the frontier of *laser-plasma based particle acceleration* / what are the grand challenges?

Where is the frontier of *laser-plasma based particle acceleration* / what are the grand challenges?

- **Can plasma based accelerators realize their potential** to provide charged, neutral particle and photon sources for plasma physics, high energy physics, condensed matter physics etc experiments, for medicine, industry, engineering, homeland security… ?

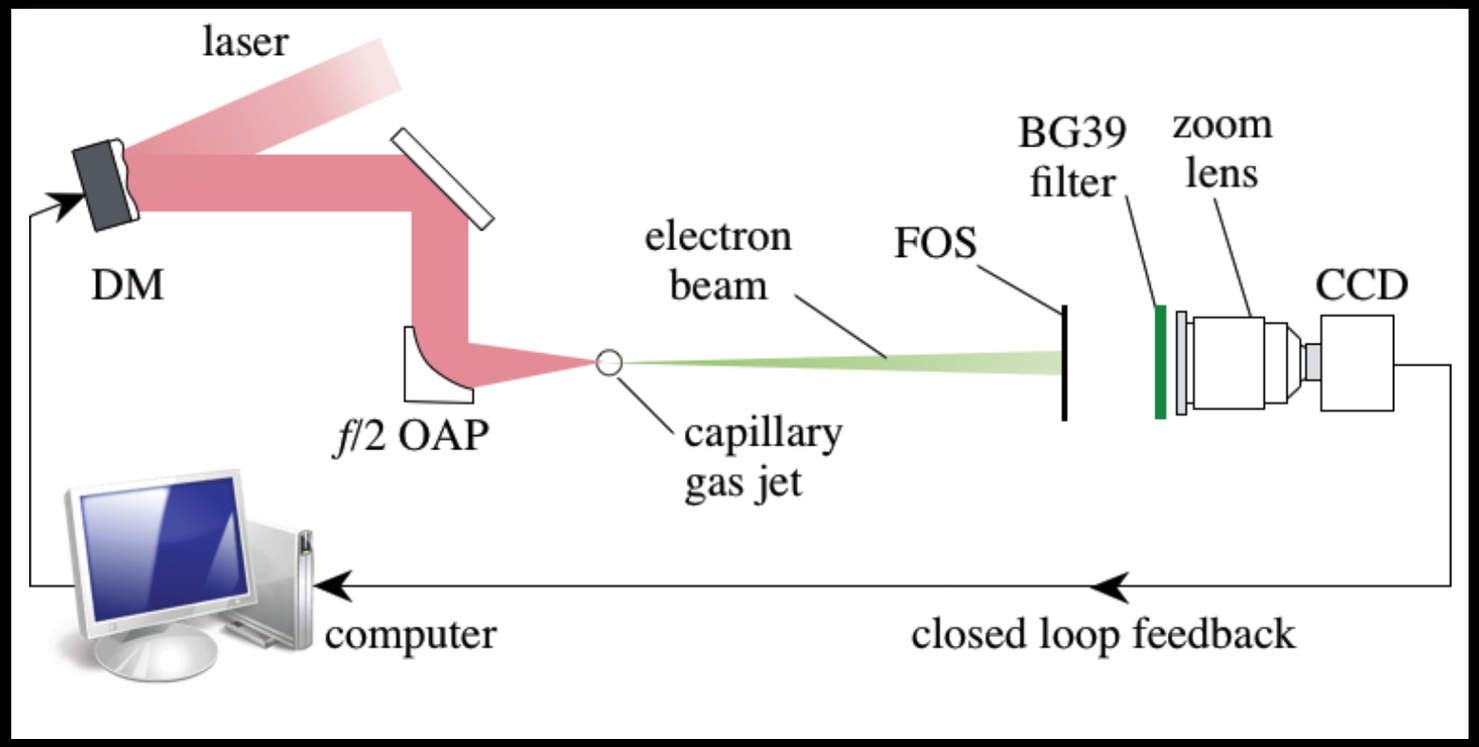


- To what extent can we control plasma behavior?
- What new *plasma* physics arises as the field strength increases?

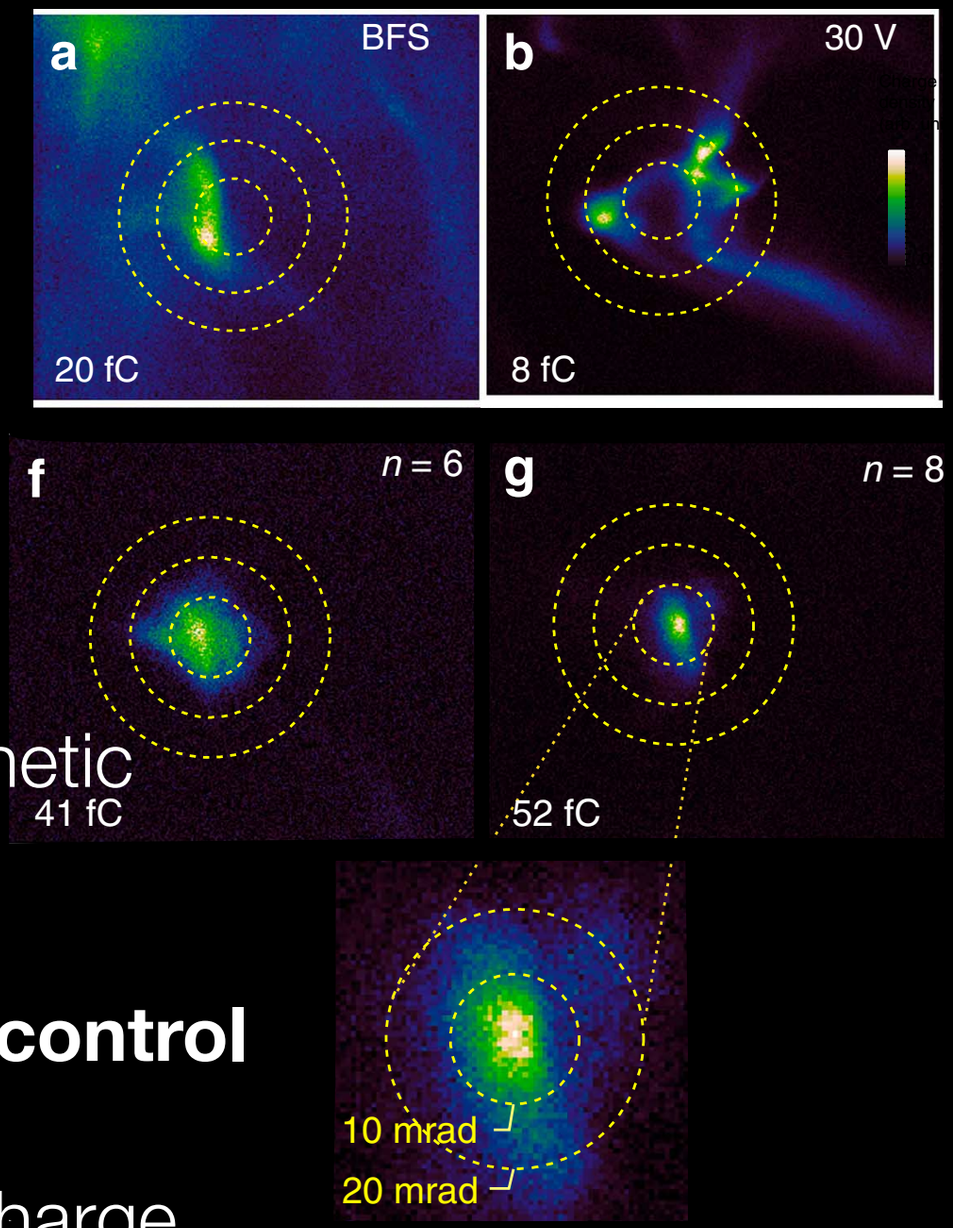
Laser precision…

- fs laser can have pulse duration ~ plasma period
- High field strength means fluid perturbation large compared to fluctuations
- - well established initial conditions, classical dynamics (?) lead to deterministic outcome

LWFA at a kHz



Electron beam profile images (EMCCD)



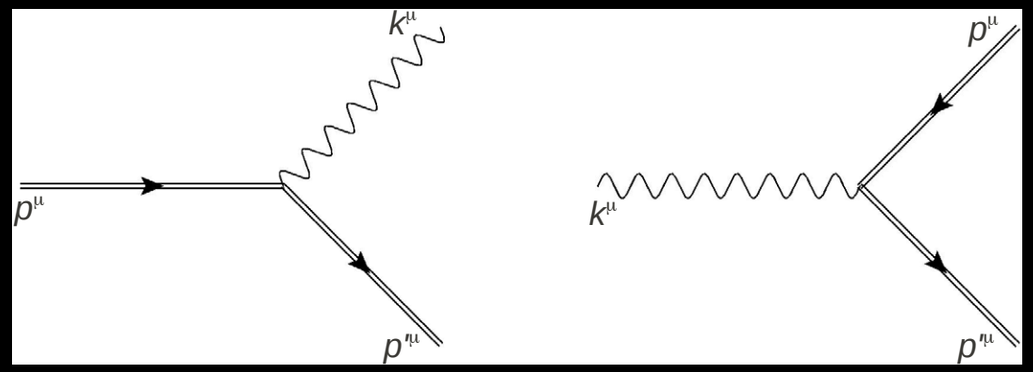
- Feedback-optimized electron beam with genetic algorithm
- Plasma wave structure is reproducible
- **Laser phase manipulated to coherently control plasma dynamics**
- Order of magnitude improvement on peak charge and divergence of LWFA

He *et al.*, *Nat. Commun*. 6 7156 (2015).

- Similar example - control of plasma surface waves in HHG

Strong field QED in plasma

Photon emission by (dressed) electron



Decay of photon to (dressed) pair

$$\chi_e = \frac{||F_{\mu\nu}p^\nu||}{mcE_{cr}} \qquad \chi_\gamma = \frac{||F_{\mu\nu}\hbar k^\nu||}{mcE_{cr}}$$

- This may be important for the next generation of ultra powerful lasers $\chi \sim 10^{-6}\gamma a_0$
- For 10^{23} Wcm^{-2} a_0~300, particles accelerated to $\gamma \sim a_0$
- 4.5 GeV - $\gamma \sim 10^4$

QED plasma state

Relativistic electromagnetic particle kinetics

Radiation reaction affects electron motion, pair production affects macroscopic EM fields

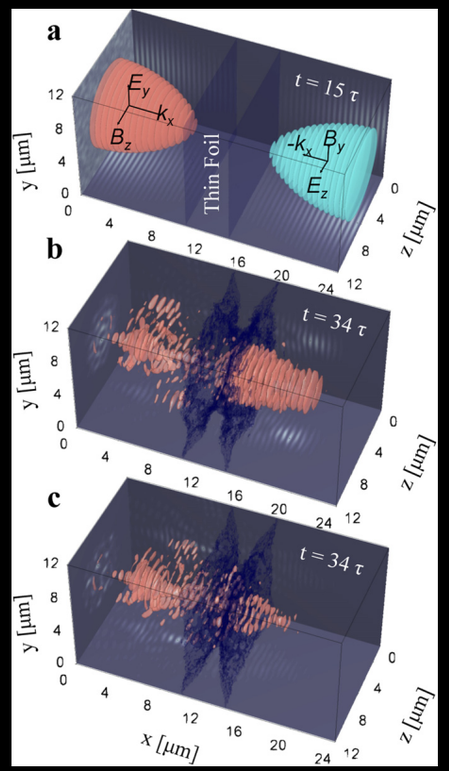
EM fields resulting from particle dynamics affect production rates

QED processes (pair production, radiation reaction)

Bell and Kirk PRL 2008
Fedotov et al PRL 2010
Bulanov et al PRL 2010
Sokolov PRL 2010
Nerush et al PRL 2011
Brady et al PRL 2011
Ridgers et al PRL 2012
Bulanov et al Phys Plasm. 2012
Blackburn et al PRL 2014
Ji etal PRL 2014

Inhibition of relativistically induced transparency by QED processes

Zhang et al New J. Phys 2015



What enabling facilities are / could be made available?

High intensity Laser-Plasma interactions research in US

TW-PW class, ultrashort lasers

Possibly not exhaustive!

ICUIL World Map of Ultrahigh Intensity Laser Capabilities

What enabling facilities are / could be made available?

1. High repetition rate, high power, ultrashort pulse laser systems (e.g. >>TW class, >10 Hz repetition rate)

2. Very high power (>PW) multi beam laser systems

Summary

- High intensity laser plasma interactions
  - are fundamentally interesting - new plasma behavior to explore
    - interface with condensed matter and strong field QED
  - have many applications
- Enabling facilities are very high power, ultrashort pulse lasers
  - Preferably multi-beam, high rep rate