Compact Laser Plasma Accelerators for ultrafast electrons, X-rays and THz

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LOASIS Program
http://loasis.lbl.gov/

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Office of Science
U.S. Department of Energy

National Nuclear Security Administration
Office of Nonproliferation and Verification R.&D.

Defense Threat Reduction Agency

Laser Plasma Accelerators have attractive qualities for applications

- Accelerator is ***COMPACT*** (mm to cm)
  I. Gradient ~ 100 MeV/mm

- LPAs produce **multiple forms of radiation**
  I. Electrons (1 MeV to 4 GeV @ LOASIS)
  II. THz (1 – 10 THz)
  III. VUV (30nm) from undulator
  IV. X-Ray (1 – 20 keV)
  V. Gamma-Ray (MeV – GeV, simulated): Inverse Compton Scattering

- Laser, e^-s, THz, VUV, X-Rays & γ-Rays are
  I. intrinsically synchronized
  II. ultrashort (few fs)

- LPAs are **highly configurable**
  I. Accelerator is dynamically created every shot
  II. Density profile can be dynamically modified
  III. Laser can be split and is easily configurable (energy, focal length)

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  III. Charge, divergence

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- THz as Coherent Transition Radiation (Source & Diagnostic)

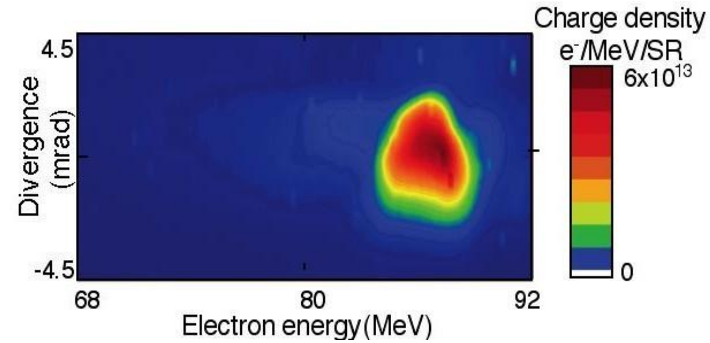
- Applications
  I. Electron diffraction

Laser Plasma Accelerators put electrons on the table

$E_{Wakefield} \sim 10,000\ E_{SLAC}$

Typical University Lab

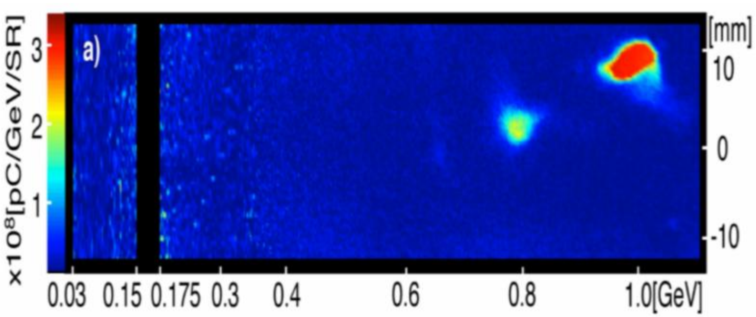
9 TW: E = 86 MeV, ΔE/E = 4.7%



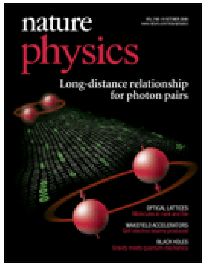
2004

*Geddes et al., Nature **431**, 538 (2004)*
*Faure et al., Nature **431**, 541 (2004)*
*Mangles et al., Nature **431**, 535 (2004)*

40 TW, E=1 GeV, ΔE/E = 2.5%

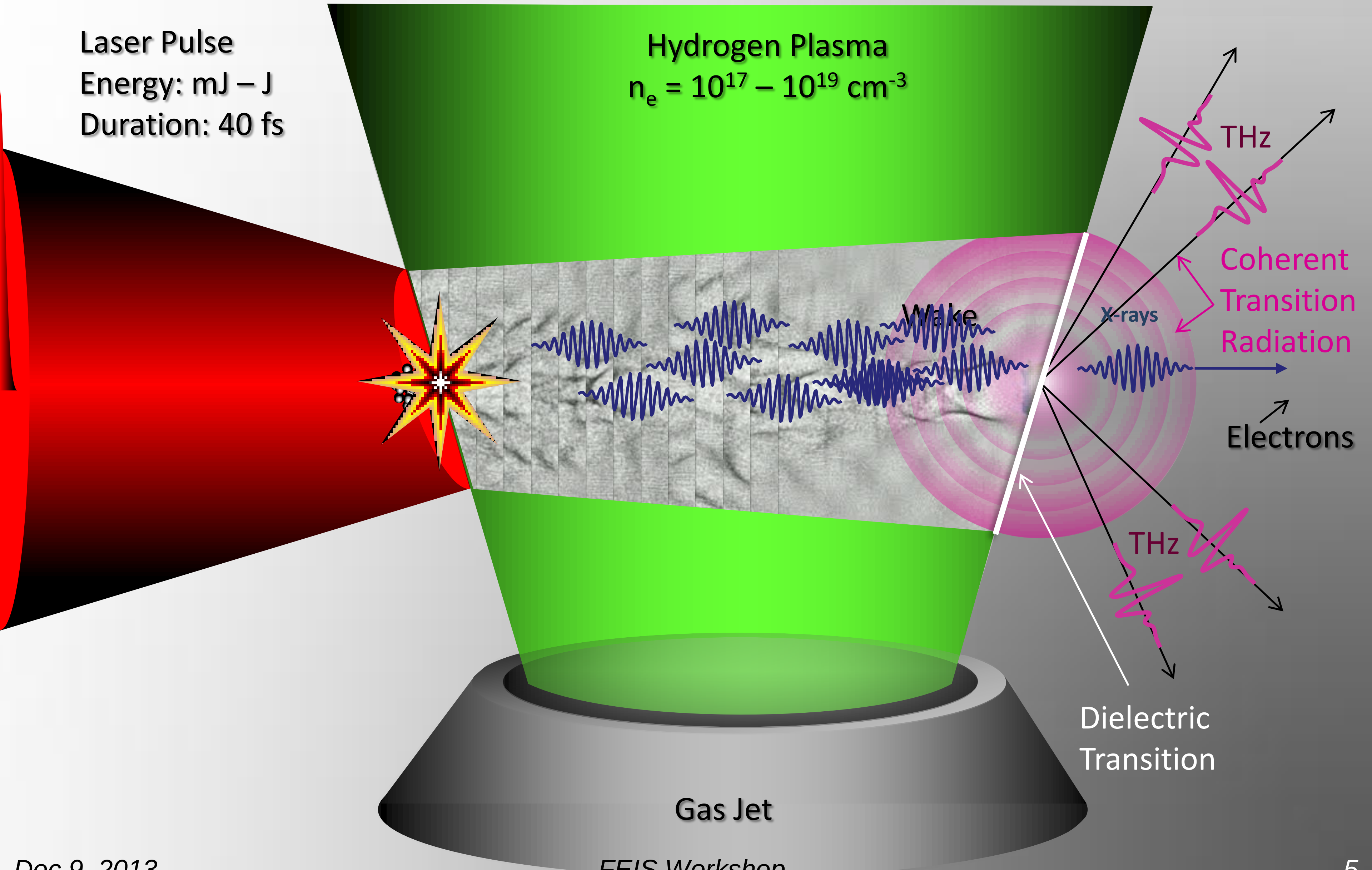


2006

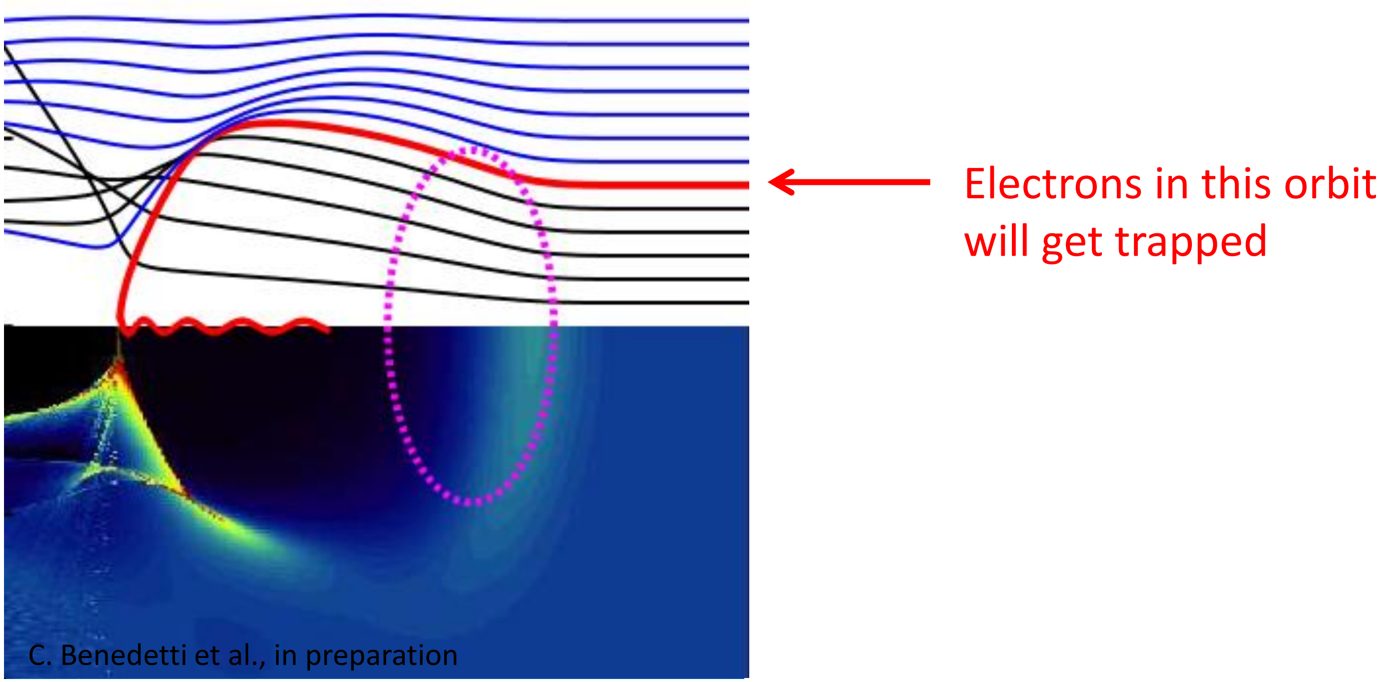


*Leemans et al., Nature Physics **2**, 696 (2006)*

Laser-Plasma Interaction



Plasma Acceleration structure generated by laser ponderomotive force

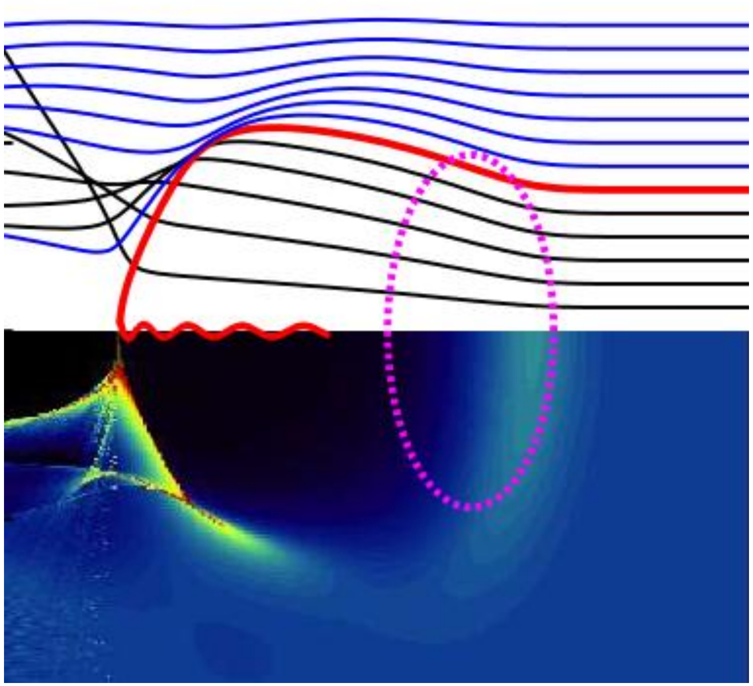


$$F_{pond} \propto -\vec{\nabla} I_{Laser}$$

<u>Theory of Bubble Regime</u>:

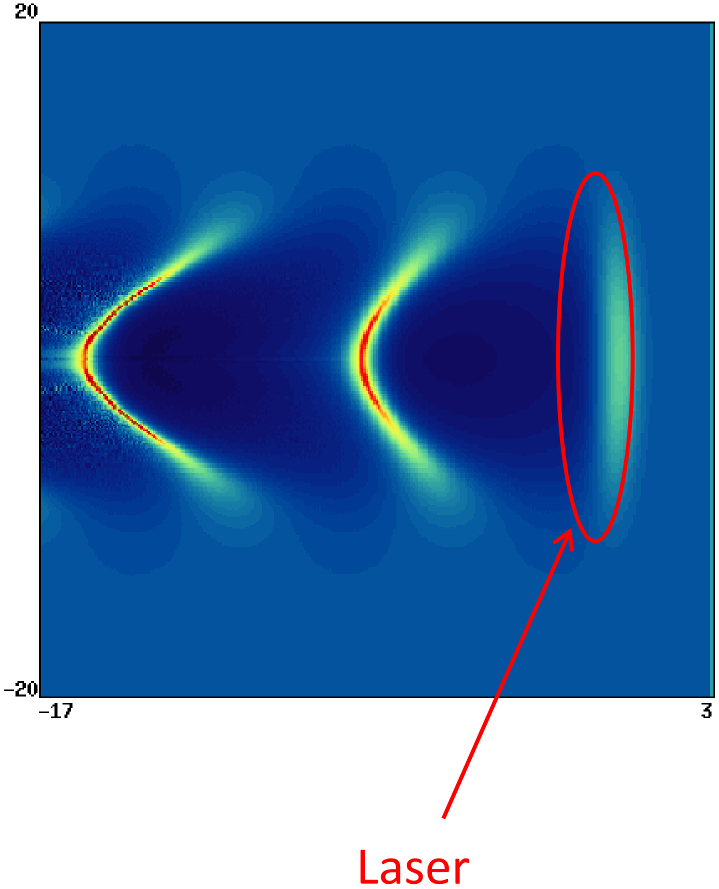
- Pukhov et al., Appl. Phys. B **74,**355 (2002)
- Esarey et al., Rev. Mod. Phys. **81**,1229 (2009)

In Single-beam accelerators, Self-Injection occurs in "Bubble" Regime



C. Benedetti et al., in preparation

Animation of Injection Process

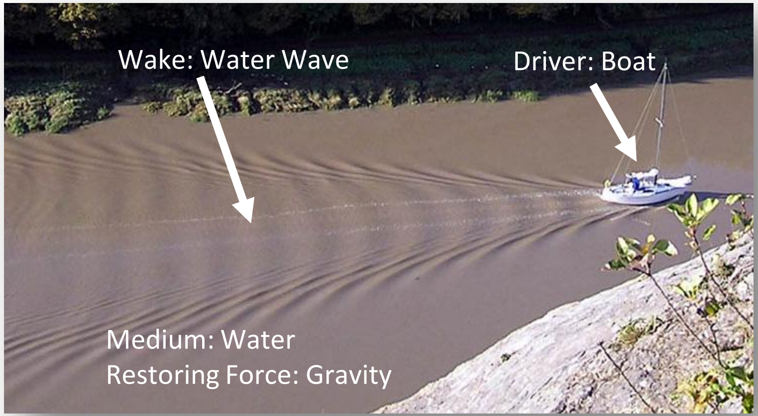


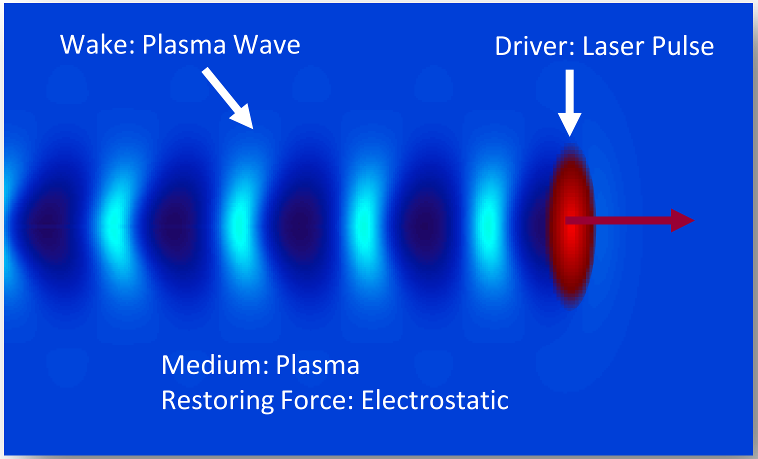
Theory of Bubble Regime:

- Pukhov et al., Appl. Phys. B **74,**355 (2002)
- Esarey et al., Rev. Mod. Phys. **81**,1229 (2009)

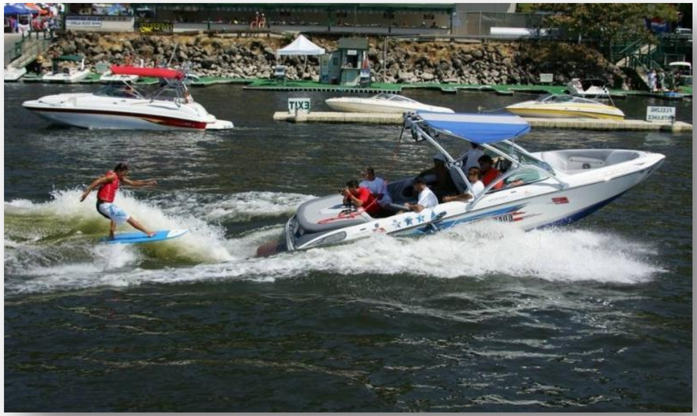
Laser Plasma Accelerator analogy

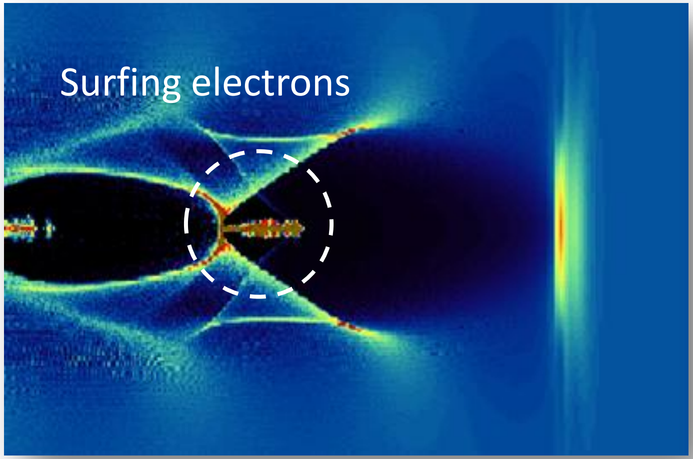
Wake Generation



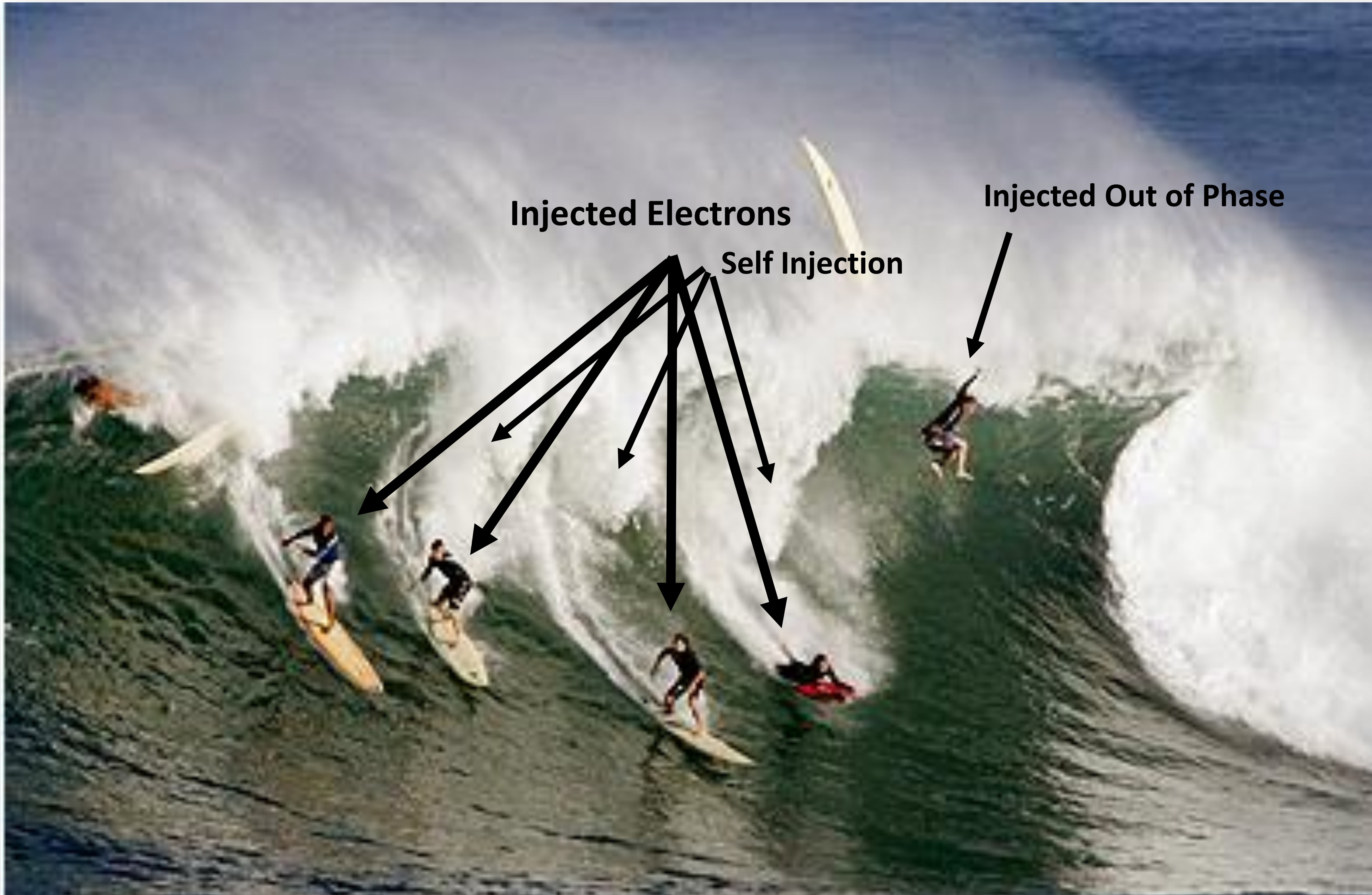


Electron Acceleration





Electrons surf on a plasma wave



Overview

- Introduction to laser plasma accelerators (LPAs)

- Electrons from LPAs
  - I. Electron energies from MeV to GeV
  - II. Electron bunch temporal properties
  - III. Charge, divergence

- X-rays from LPAs
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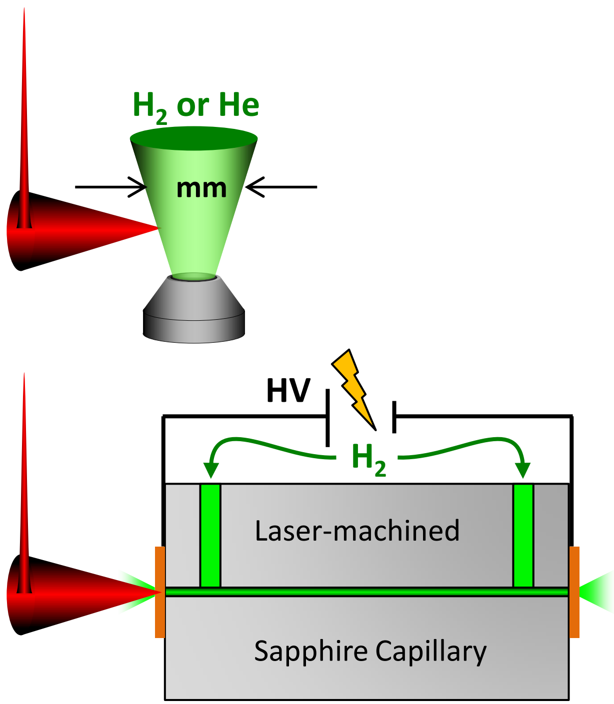
- Applications
  - I. Electron diffraction

Quasi-monoenergetic electron beams from MeV to GeV generated at LOASIS

	Electron Energy	Laser Peak Power	Target Type	Interaction Length	Name of system
1	1 MeV	10 TW	Gas Jet	< 0.6 mm	Godzilla
2	100 – 300 MeV	10 TW	Gas Jet	1 – 3 mm	Godzilla
3	0.3 – 1.1 GeV	50 TW	Capillary Discharge	3 cm	T-Rex
4	4+ GeV	1 PW	Capillary Discharge	9 cm	BELLA

Laser – Plasma Accelerator Tuning Knobs

1. Laser Intensity/Energy
2. Interaction Length
   - Laser focal length
   - target density profile
3. Plasma Electron density
4. Injection method



Gas Jet

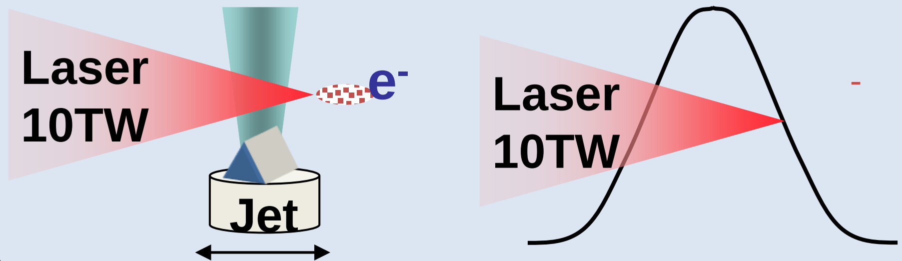
Capillary Discharge (Guiding Structure)

Generation of 1 MeV electrons

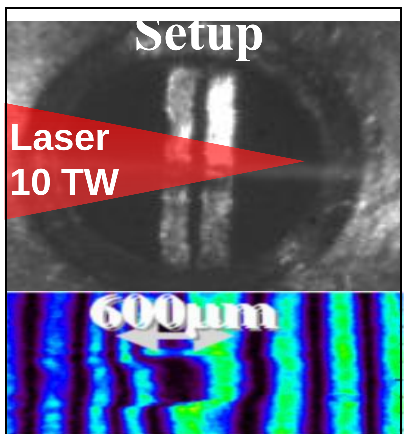
Geddes et al., PRL (2008)

- Plasma down ramp decreases wake phase velocity (Bulanov, Suk): plasma wavelength increases as the laser propagates

Laser focused on downramp of gas jet density profile

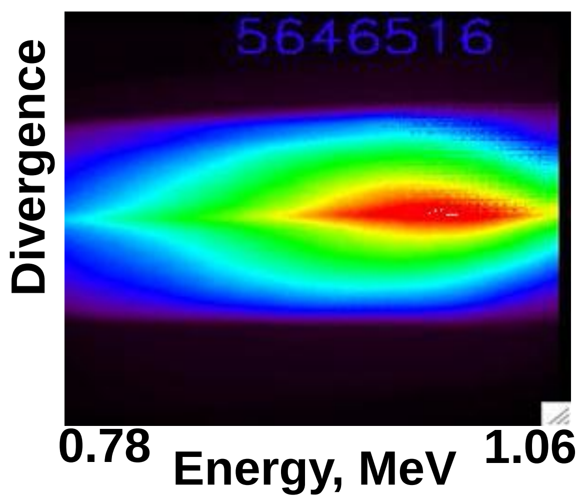


$L_{interaction} < 0.6$ mm

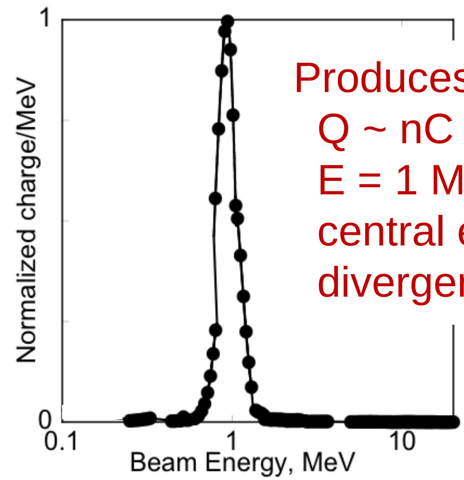


Plasma n = $3 \times 10^{19} cm^{-3}$

Energy Spectrum



Averaged Spectrum



Produces stable beams:
- Q ~ nC
- E = 1 MeV ± 10% FWHM
- central energy stable ±5%
- divergence : 10-80 mrad

Downramp injector produces stable beams

Fig. 2 (Run A) Leemans et al., Compt Rendu Physique **10**,130 (2009)

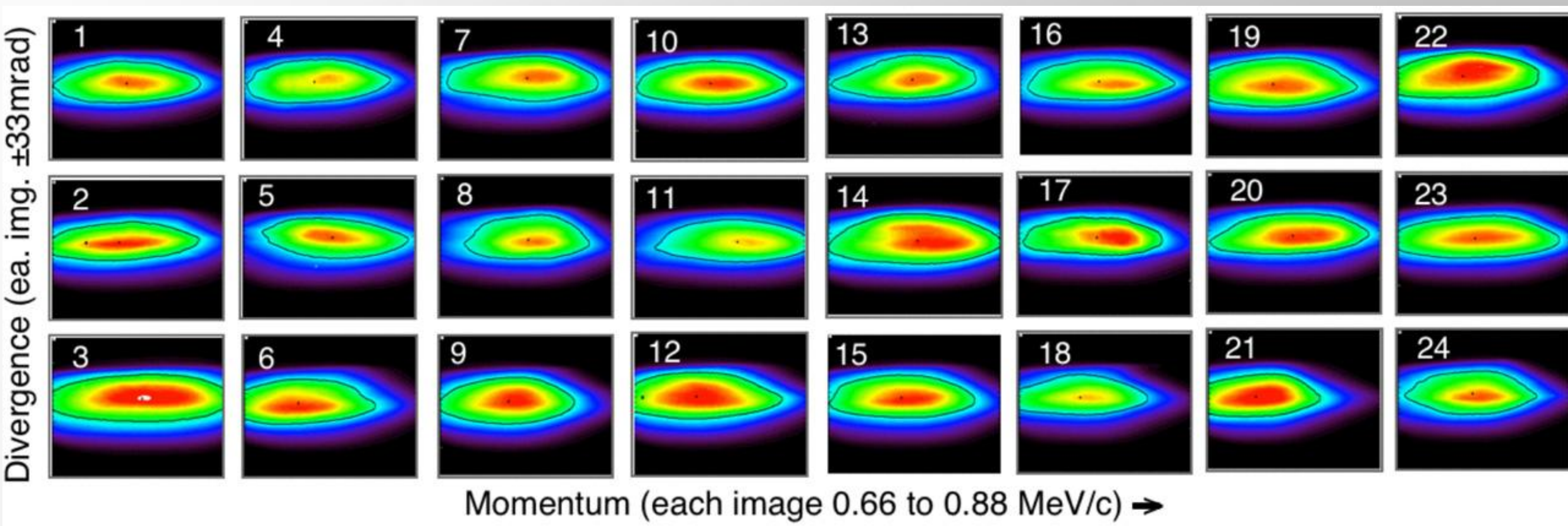
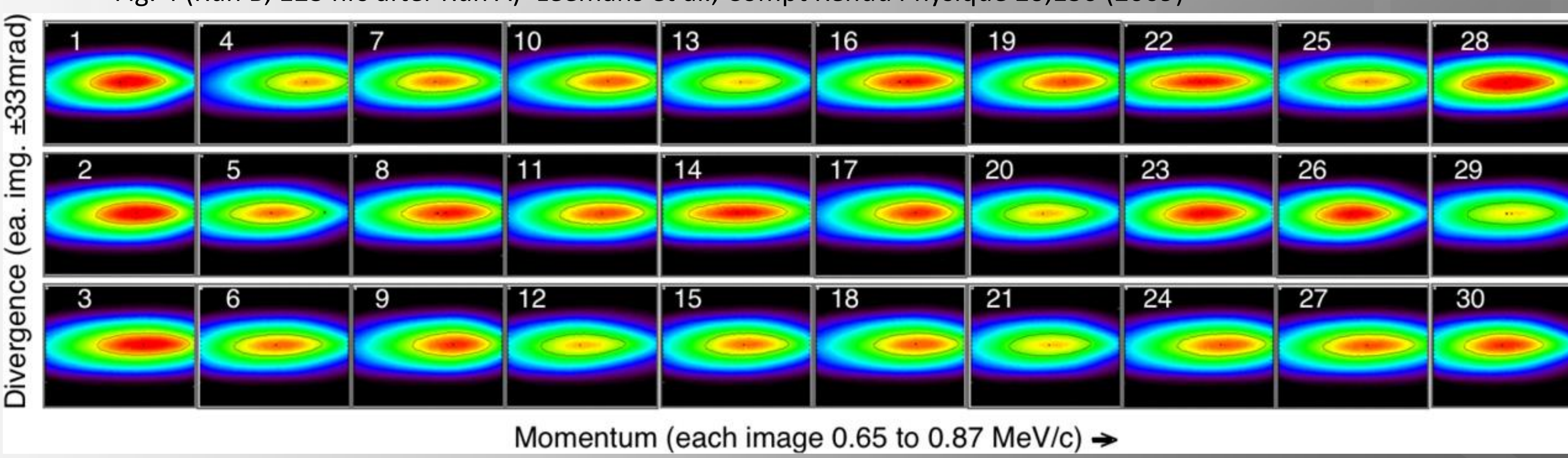
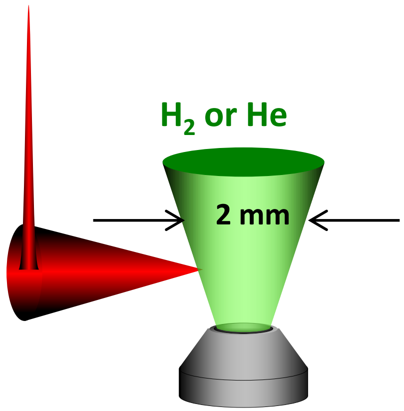


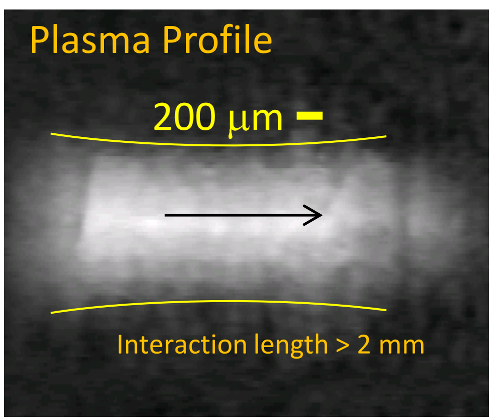
Fig. 4 (Run B, 123 hrs after Run A) Leemans et al., Compt Rendu Physique **10**,130 (2009)

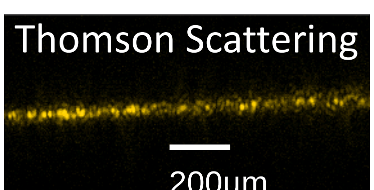


Increasing interaction length to 2mm results in > 200 MeV electrons

Interaction Length > 2 mm

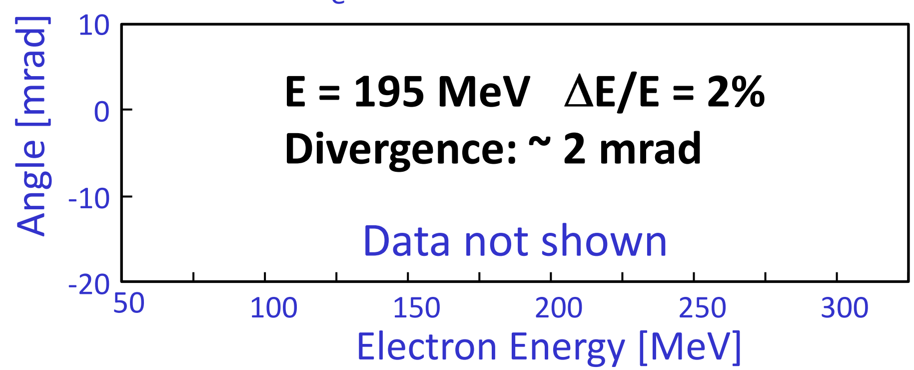






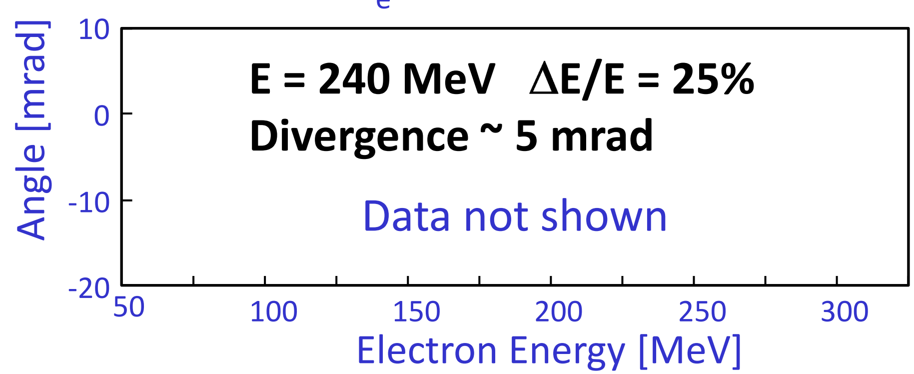
Regime I: High quality, but unstable

$n_e = 1.0 \times 10^{19}\ cm^{-3}$



Regime II: High quality, but stable and large ΔE

$n_e = 4.3 \times 10^{18}\ cm^{-3}$



Stable Beams at 200 – 300 MeV

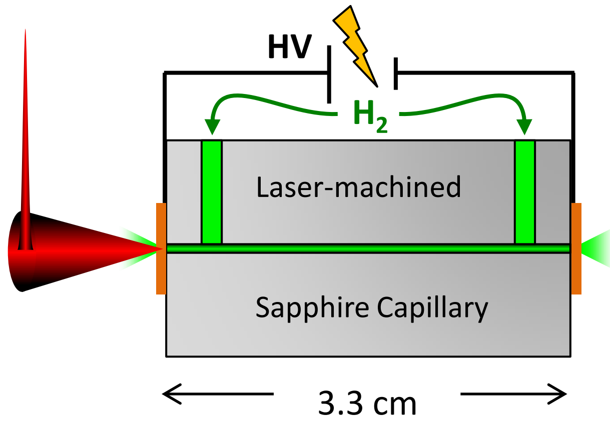
4e18 cm^-3	4.3e18 cm^-3	4.7e18 cm^-3	5.0e18 cm^-3

Data not shown:

Multiple Beams
Energy 250 MeV
DE/E = 25%
Divergence: ~ 5 mrad

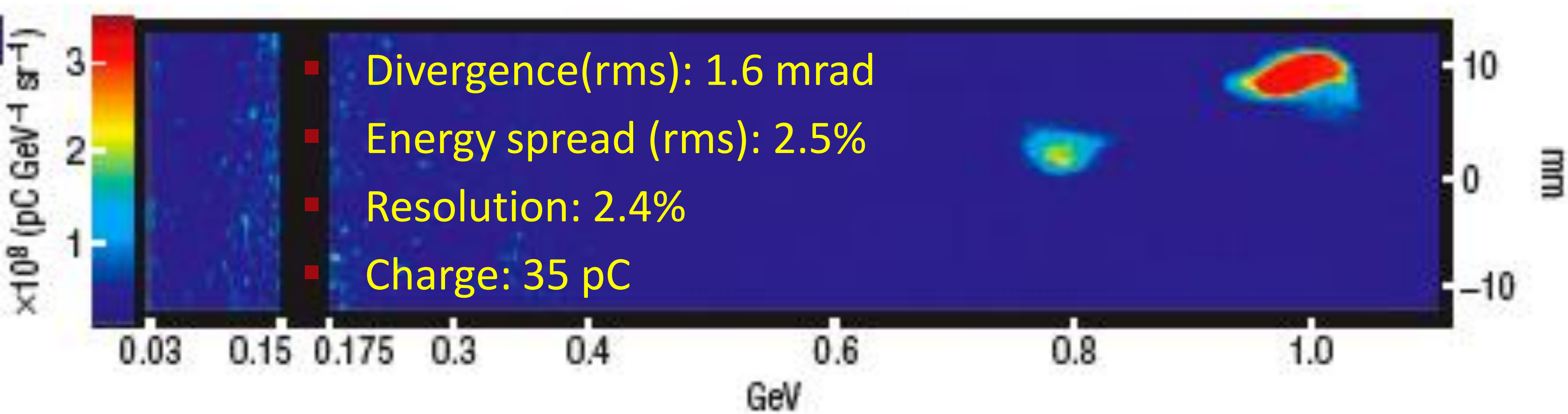
- Beam produced on nearly 100% of shots
- Energy spread is large
- Low energy component present
- Only one knob (pressure) & tuning range is small

Increasing interaction length to 3cm results in > 1 GeV electrons



Capillary Discharge (Guiding Structure)

- a_0 ~ 1.46 (40 TW, 37 fs)
- n_e ~ 10^{18}cm^{-3}, P_{crit} ~ 7TW

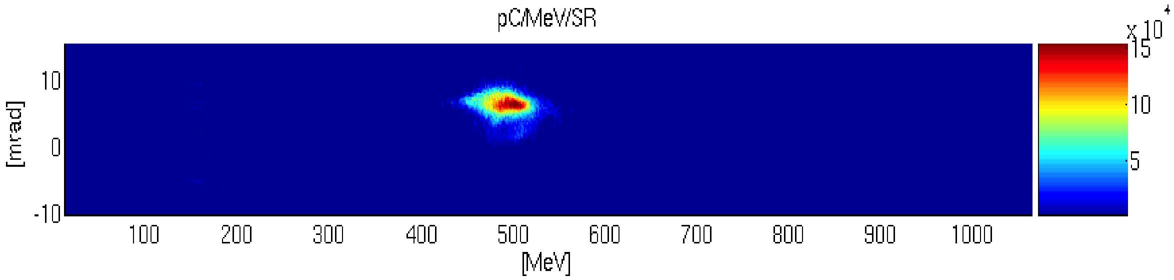


W.P. Leemans et. al, *Nature Physics* **2**, 696 (2006)

Stable Regime Produces 500 MeV Beams

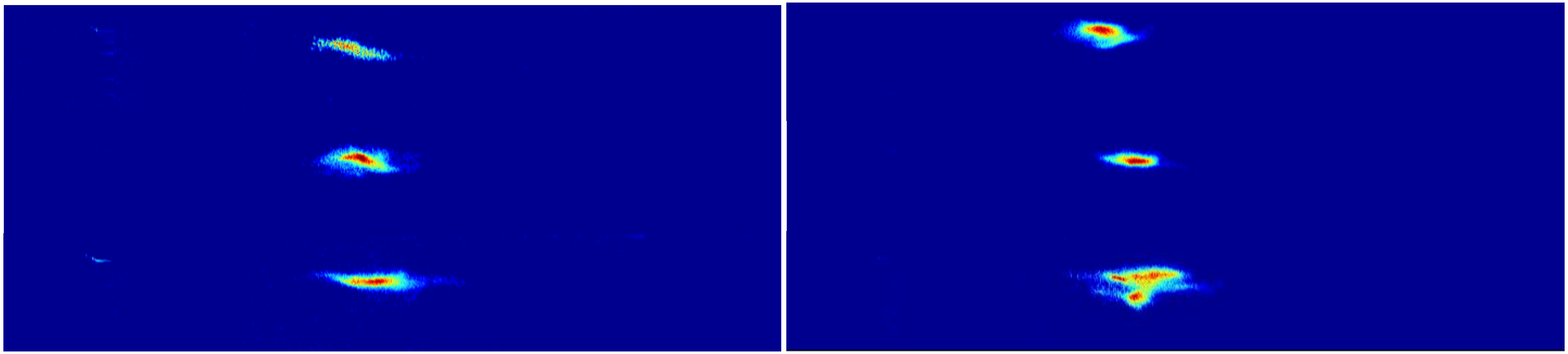
- Laser: $a_0 > 0.77$ (12 TW, 80 fs)
- Capillary: 225 μm diameter and 33 mm length
- $n_e \sim 3.5\text{x}10^{18}$ cm^{-3}, $P_{crit} \sim$ 9TW

500 MeV beam



- Divergence(rms): 1.6 mrad
- Energy spread (rms): 5.6%
- Resolution: 1.1%
- Charge: 50pC

Charge=32±14pC, Energy=456±45MeV, dE/E= 6±3%



W.P. Leemans et al., *Nature Physics* **2**, 696 (2006); K. Nakamura et al., *Phys. Plasmas*, **14** 056708 (2007)

Increasing Interaction length to 9 cm …

BELLA (1Hz, 1 Petawatt) = 4+ GeV

More to come…

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  I. Electron energies from MeV to GeV
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  I. Undulator radiation
  II. Betatron radiation
  III. Inverse Compton Scattering

- Transition radiation
  I. THz as Coherent Transition Radiation (Source & Diagnostic)

- Applications
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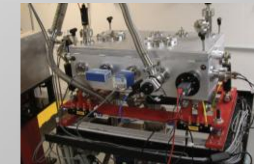
Single-shot undulator spectra from broad-band LPA e-beams observed!

First demonstrations

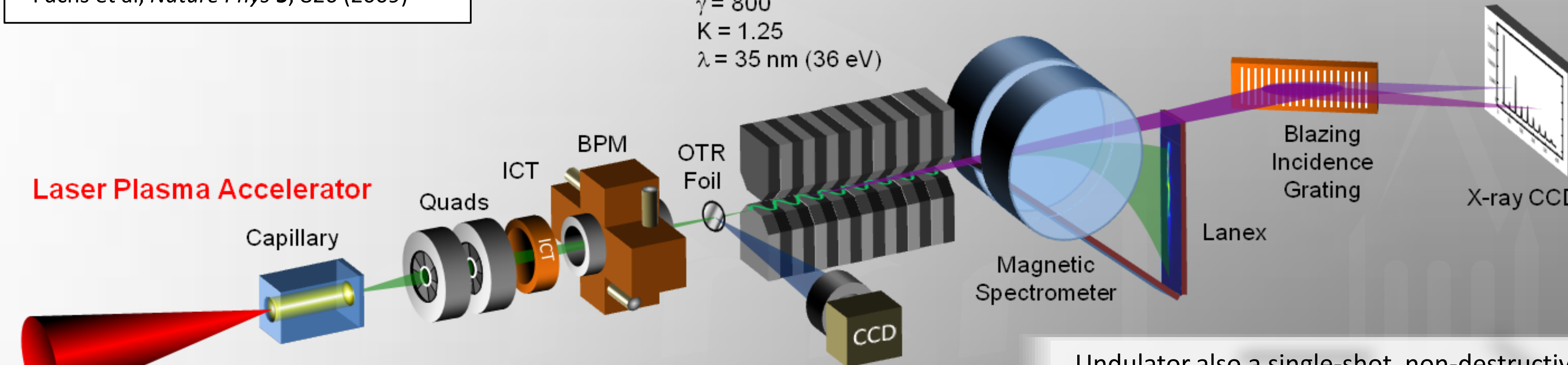
- VISIBLE Light (Jena)
  Schlenvoigt et al, *Nature Phys* **4**, 130 (2008)
- VUV Radiation (MPQ)
  Fuchs et al, *Nature Phys* **5**, 826 (2009)



Also supported by: DTRA Defense Threat Reduction Agency

Single-shot EUV Spectrometer

Thunder Undulator
L = 1.5m (66 periods)
λ_{und} = 2.2cm
γ = 800
K = 1.25
λ = 35 nm (36 eV)



Undulator also a single-shot, non-destructive e-beam diagnostic

Electron energy: 300 – 500 MeV

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Graph not shown: 30 nm spectrum

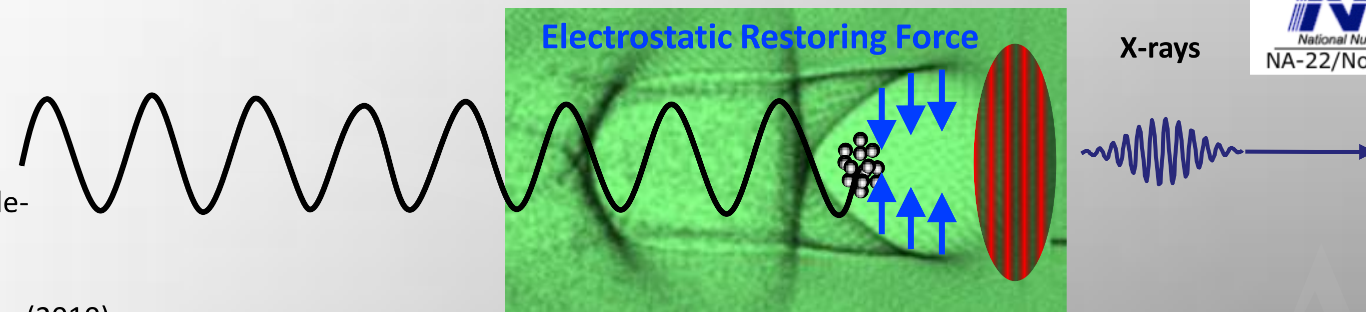
K. Robinson et al, IEEE Quant Elect (1987)

$10^4 – 10^5$ photons from 275 MeV Beam with 100% energy spread

keV X-rays produced in LPAs by Betatron oscillations

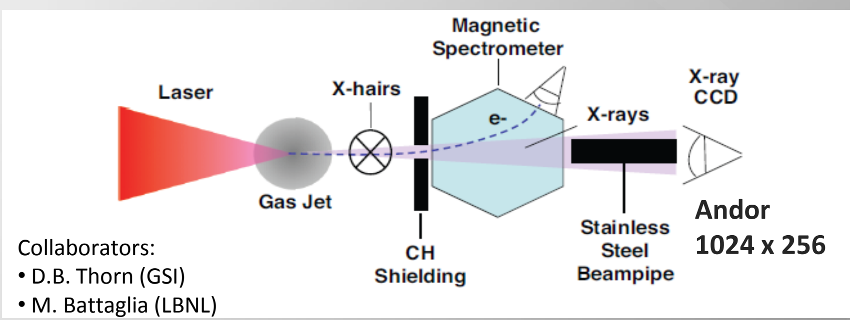
Esarey et al *Phys Rev E* **65**, 056505 (2002)

NA-22/Nonproliferation R&D

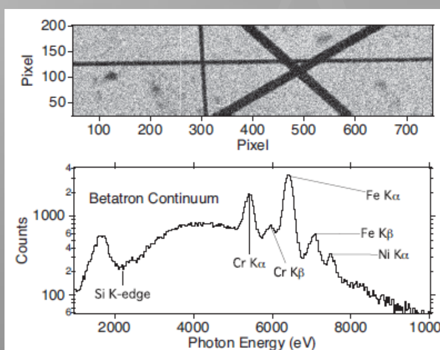


related experiment include-
Rousse et al.,PRL,
Phuoc et al., PoP (2005)
Kneip et al., Nature Physics (2010).

Gas Jet Experiment



Collaborators:
- D.B. Thorn (GSI)
- M. Battaglia (LBNL)



Single shot image ~2e5 photons on camera

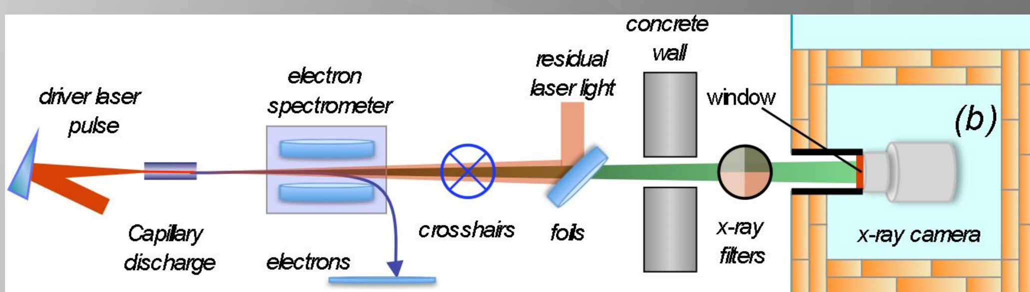
<u>Experiments on LOASIS capillary-based LPA[1]</u>

Laser: 1.3J, τ_p = 60fs, w_0= 24μm

Plasma: $n_e = 5\times10^{18}$ cm^{-3}

e-beams ~ 0.5 GeV, mrad divergence

[1] Leemans et al, Nature Physics 2006

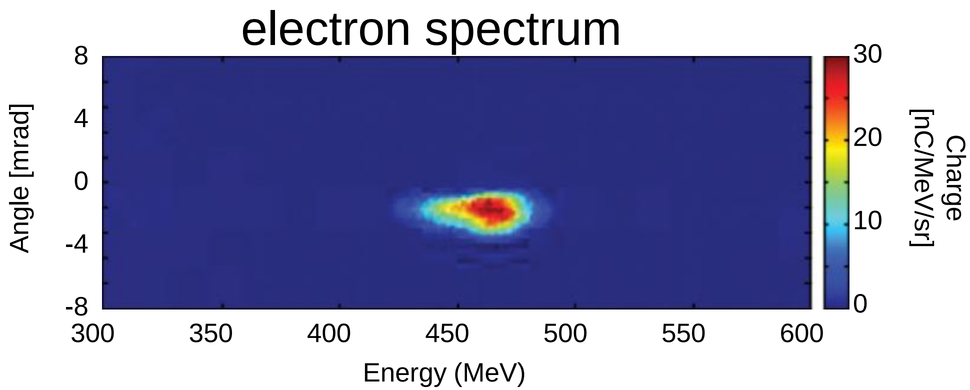


Single-shot Matching theory / data indicates beam size & emittance of 0.1 μm

- $n_e = 5\times10^{18}\ e^-/cm^3$

Single-shot spectra

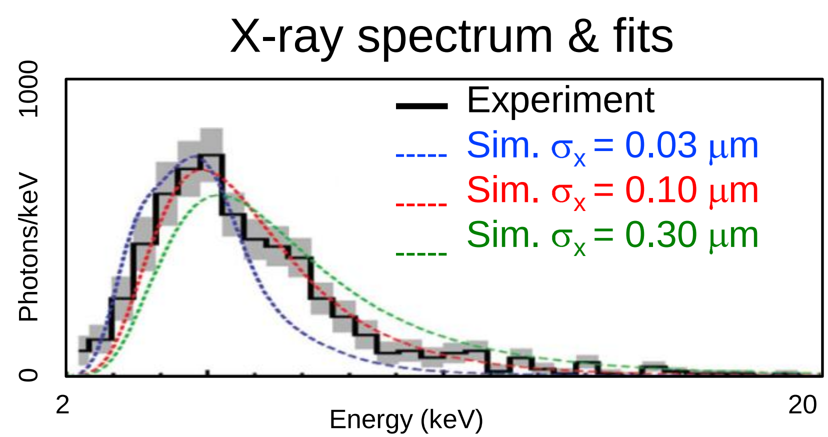
- E_0 ~ 463 MeV, ΔE ~ 6.6%
- Q ~ 0.4 pC,
- σ_θ ~ 1.2 mrad



$a_\beta \propto r_\beta (\gamma\, n_e)^{1/2}$

X-ray spectrum constrains emittance:

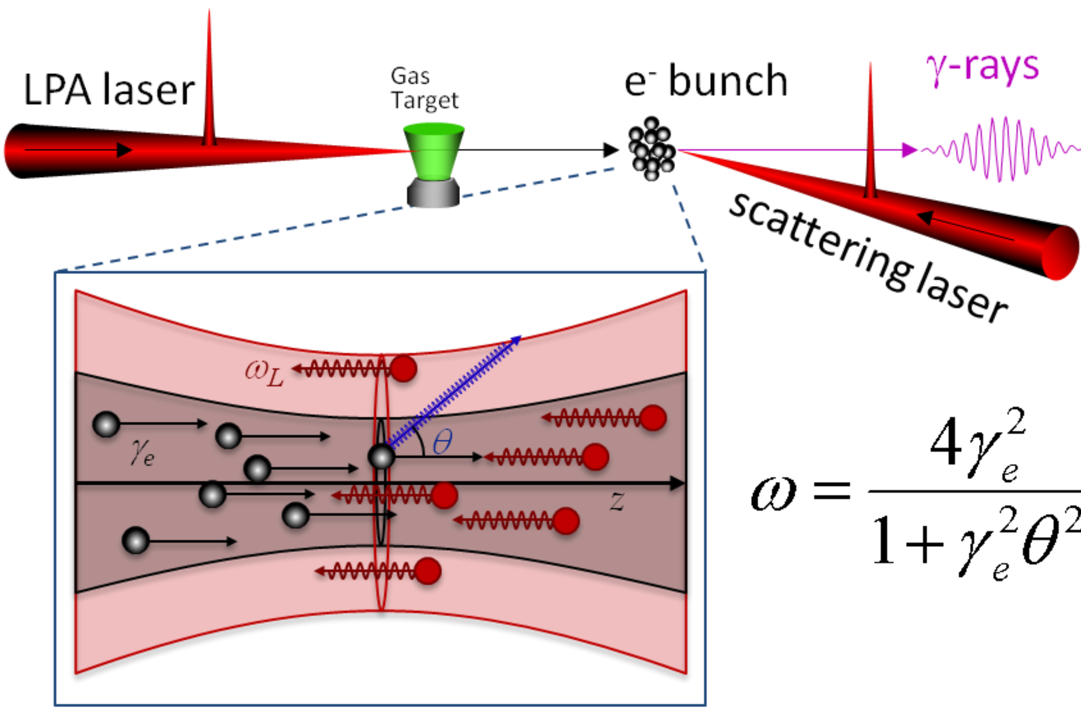
- σ_x~ 0.1 μm
- $\varepsilon_x \approx \gamma\sigma_x\sigma_\theta \approx 0.1$ mm-mrad



Simulations: Virtual Detector of Synchrotron Radiation (VDSR)
M. Chen et al., PRSTAB **16**, 030701 (2013)

[1] E. Esarey et al., Rev. Mod. Phys. 81, 1229 (2009). [2] Esarey *et al.*, Phys. Rev. E **65**, 056505, 2002 [3] Chen et al, in prep
Plateau et al, PRL 2012

LPA beams can be used to produce gamma sources



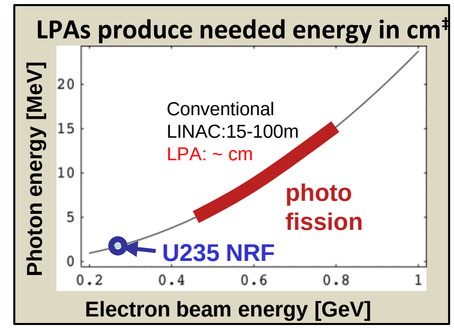
$$\omega = \frac{4\gamma_e^2}{1+\gamma_e^2\theta^2}$$

Inv Compton Scattering ~ Undulator radiation

- Optimized yield ~ 1 γ/e$^-$ (6.2x10^6 γ/pC)
- 1 GeV e-beam → 25 MeV γ-rays
- 10 GeV e-beam → 2.5 GeV γ-rays

γ-rays suitable for Special Nuclear Material (SNM) detection

- 1-20 MeV γ's from 0.3-1 GeV e-
- 1% level gamma ΔE achievable
- Low divergence: standoff possible



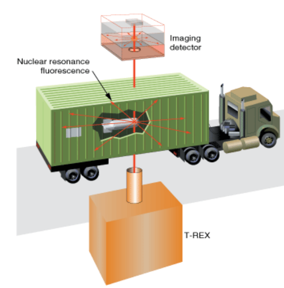


Image from LLNL TREX project using conventional accelerator: https://lasers.llnl.gov/programs/psa/advanced_radiography/t-rex.php

References

Thomson Scattering from Conventional accelerators:
- P. Sprangle et al, J.Appl. Phys 1992
- W.P. Leemans et al., PRL 1996
- R.W. Schoenlein et al., Science 1996
- Albert et al PoP2012

Thomson scattering from an LPA:
- Leemans TPS 2005;

Detection of SNM using LPA-based Thomson scattering:
- Geddes et al., CAARI 2008

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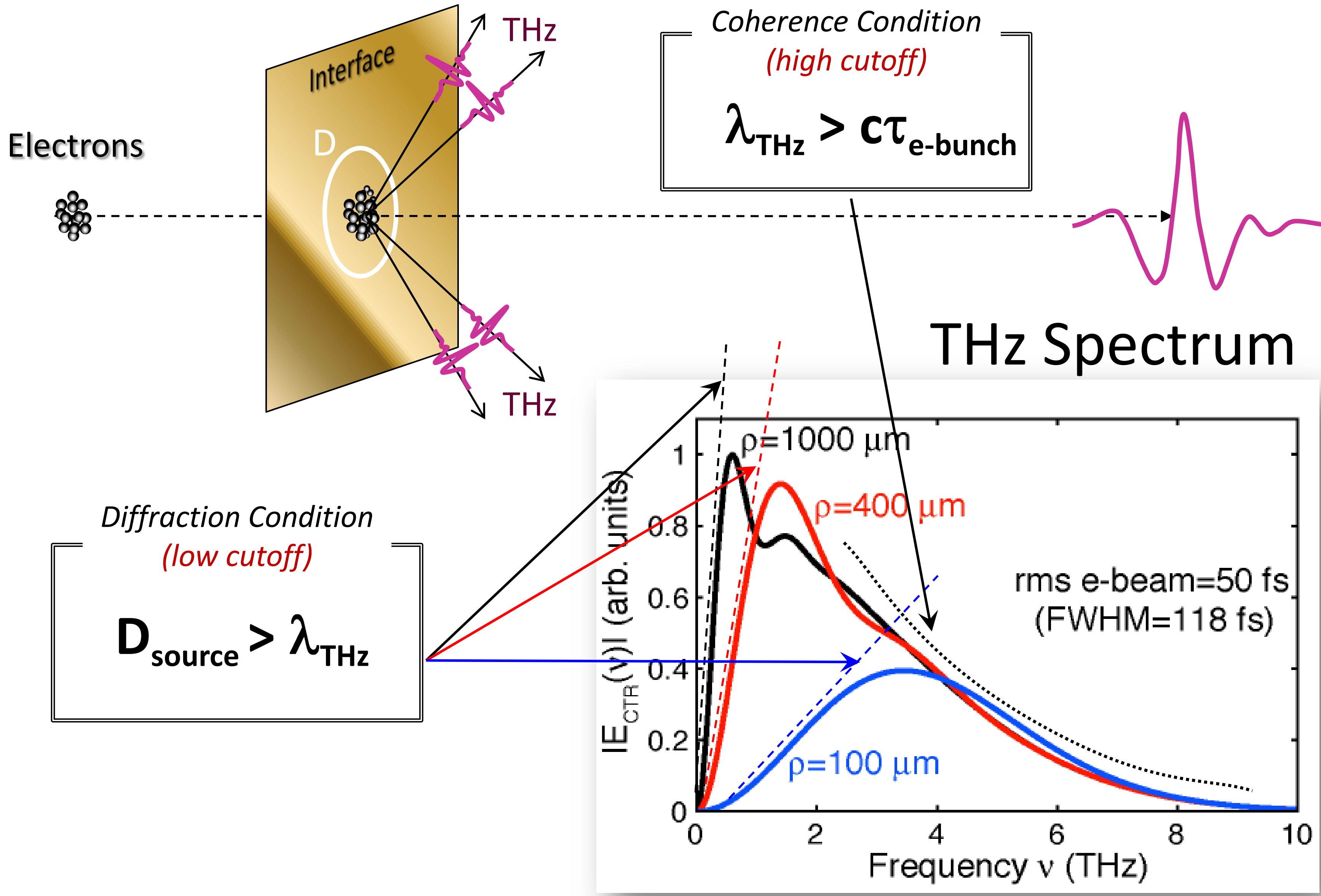
  III. Charge, divergence
  IV. Controlling injection

- X-rays from LPAs
  I. Undulator radiation
  II. Betatron radiation
  III. Thomson Scattering

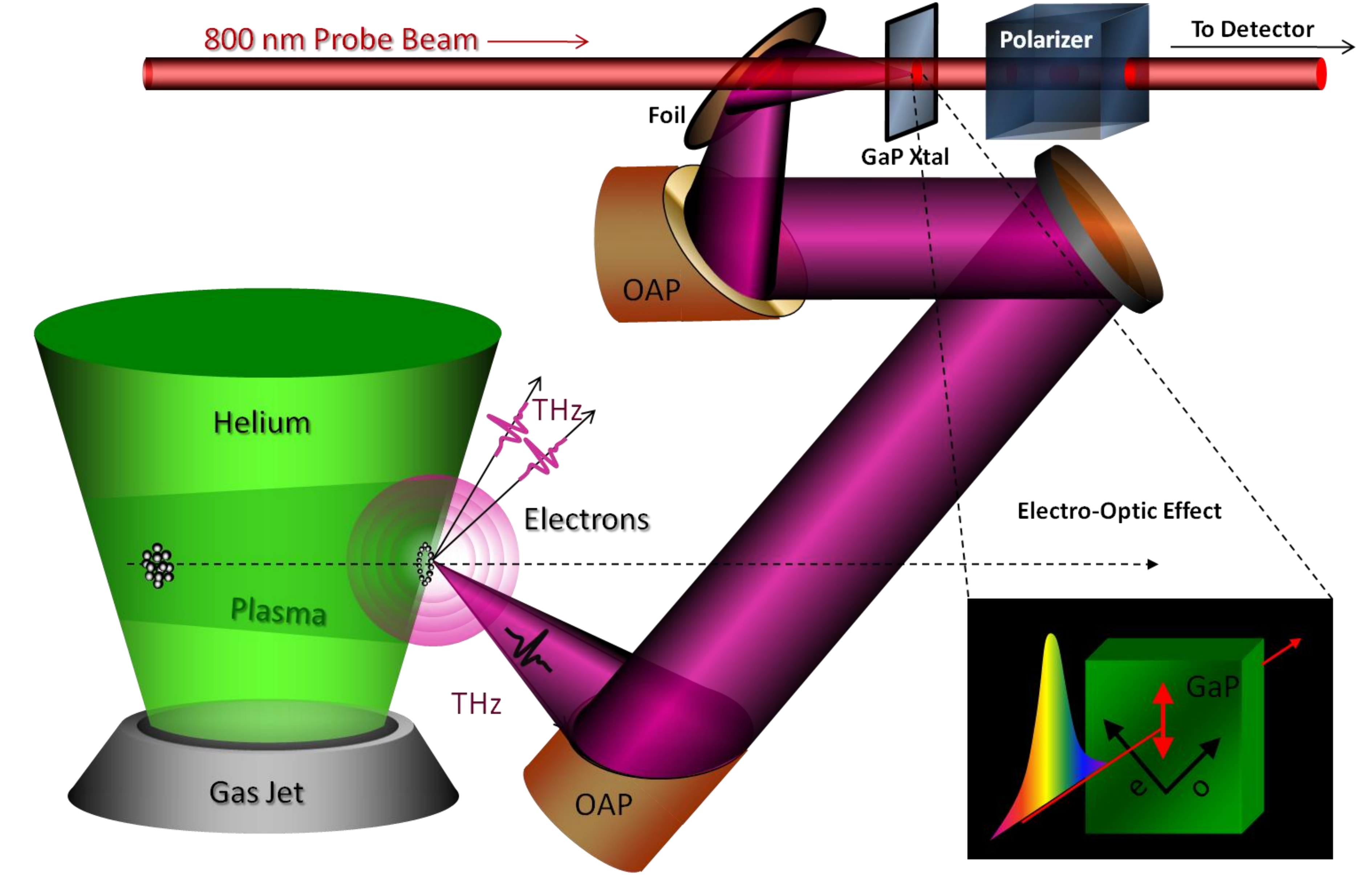
- Transition radiation
  I. THz as CTR

- Applications
  I. Electron diffraction
  II. Pump-probe: ultrafast magnetic switching
  III. App 3

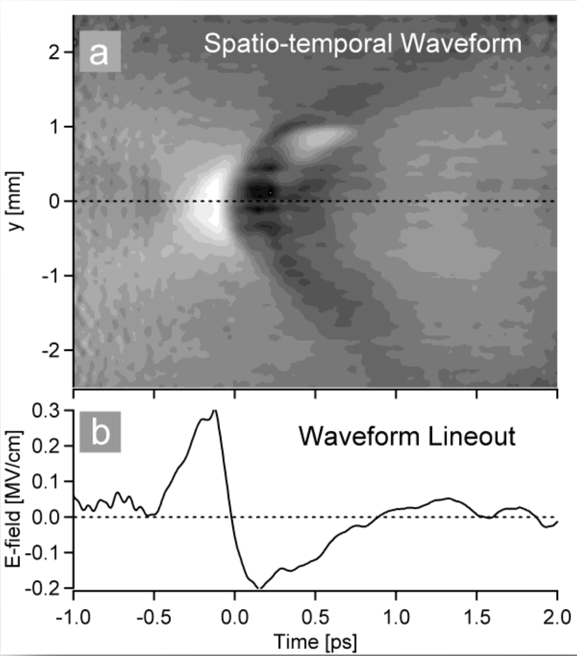
Transition Radiation is Emitted by electrons passing an Interface

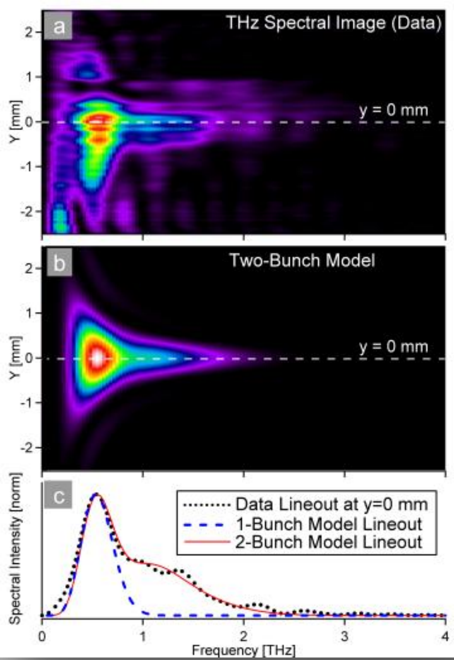


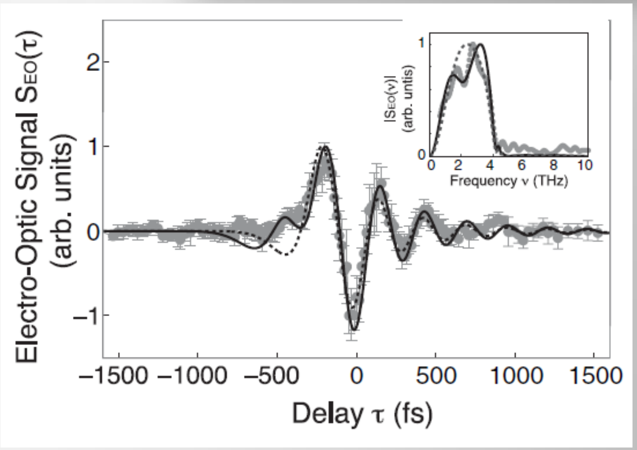
THz Collection Geometry



Bunch properties can be inferred from spatio-temporal model





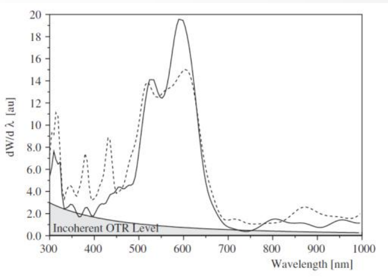


Analysis of THz waveforms confirms bunch durations < 50 fs

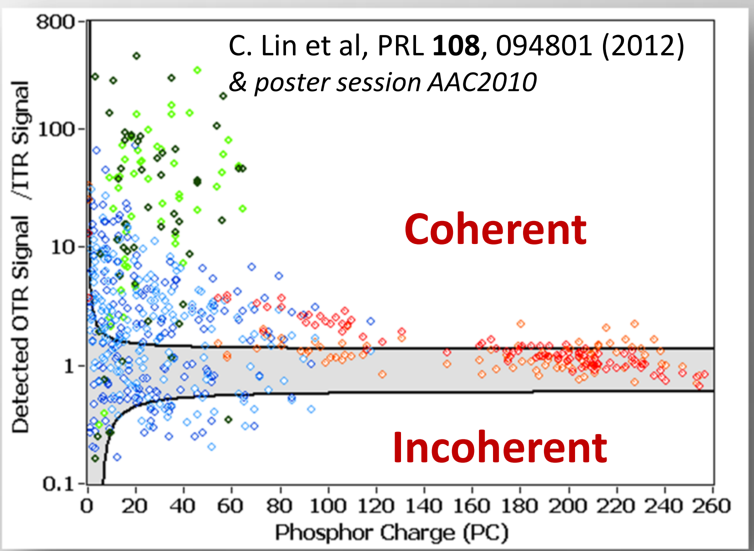
J. Van Tilborg PRL 96, 014801 (2006)

Evidence for Coherent OTR at 3m

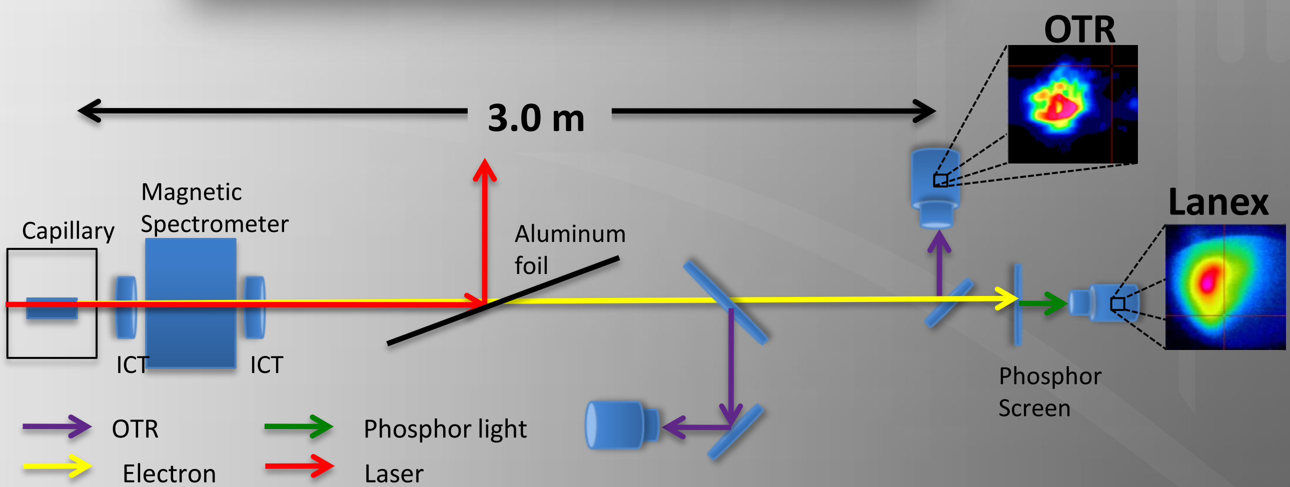
Glinec et al, PRL **98,** 194801 (2007)



Coherent OTR at
1.5 - 140 mm



- **First observation of Coherent OTR at meter distances**
- **Laser completely blocked**
- **Indicates presence of micro-bunching (fs level)**



LOASIS Experiment

Conclusions

❖ LPAs generate electron beams with energies from MeV to GeV

	Electron Energy	Laser Peak Power	Target Type	Interaction Length	Name of system
1	1 MeV	10 TW	Gas Jet	< 0.6 mm	Godzilla
2	100 – 300 MeV	10 TW	Gas Jet	1 – 3 mm	Godzilla
3	0.3 – 1.1 GeV	50 TW	Capillary Discharge	3 cm	T-Rex
4	4+ GeV	1 PW	Capillary Discharge	9 cm	BELLA

❖ Charge ~ pC – nC, bunch duration: few fs

❖ LPAs also generate other forms of radiation

I. Electrons (1 MeV to 4 GeV @ LOASIS)
II. THz (1 – 10 THz)
III. VUV (30nm)
IV. X-Ray (1 – 20 keV)
V. Gamma-Ray (MeV – GeV, simulated)

❖ Outputs are intrinsically synchronized

The END