Progress in Laser Driven Accelerator R&D

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L'OASIS Group

LBNL

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11th Advanced Accelerator Concept Workshop

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Outline

- Introduction
- Single beam laser wakefield experiments
  - Energy spectrum
  - Transverse properties
  - Bunch length
- Laser guiding in plasma channels
  - Narrow energy spread beams: dephasing length
- Plasma based laser triggered injectors
- 1 GeV module: implementation at LBNL
- Summary and conclusion

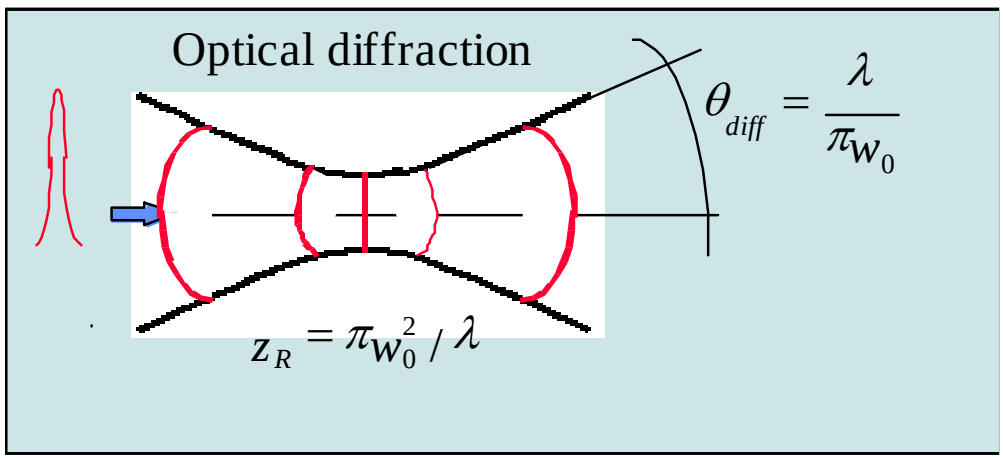
Basic Laser Definitions

- Laser strength parameter: $$a_0 = \frac{eE_L\lambda}{2\pi mc^2} \cong 8.6\times10^{-10}\,\lambda[\mu m]I^{1/2}[W/cm^2]$$

with $$I = 2P/\pi w_0^2$$

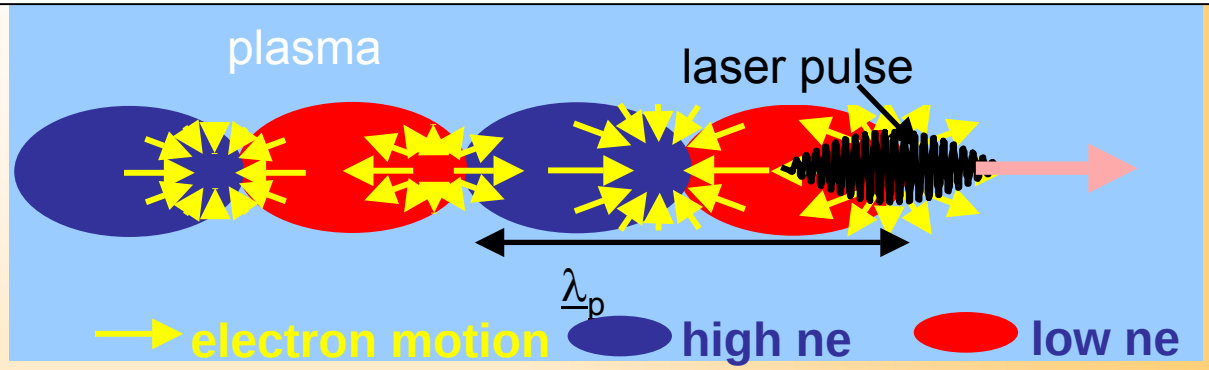
Note: for fixed F-number, $a_0 \sim P$

- Rayleigh length: $$Z_R = \pi w_0^2/\lambda$$

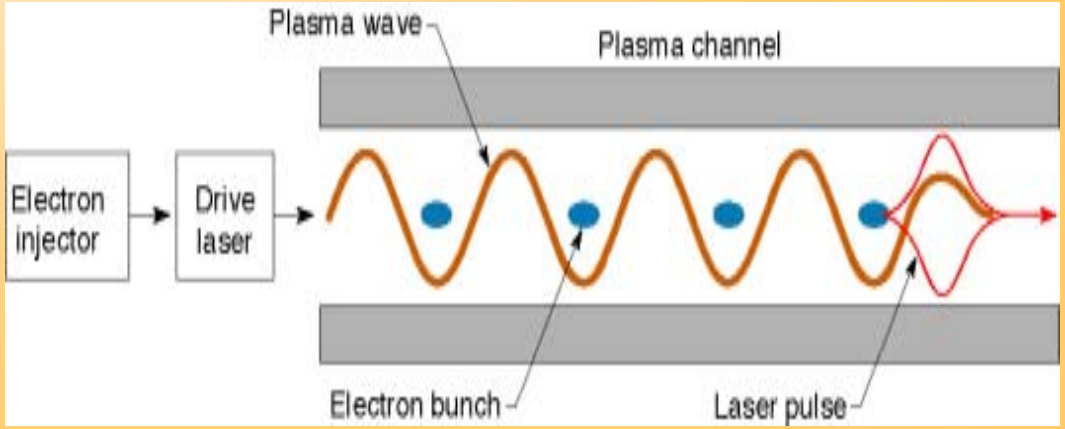


Laser wakefield accelerator: principle

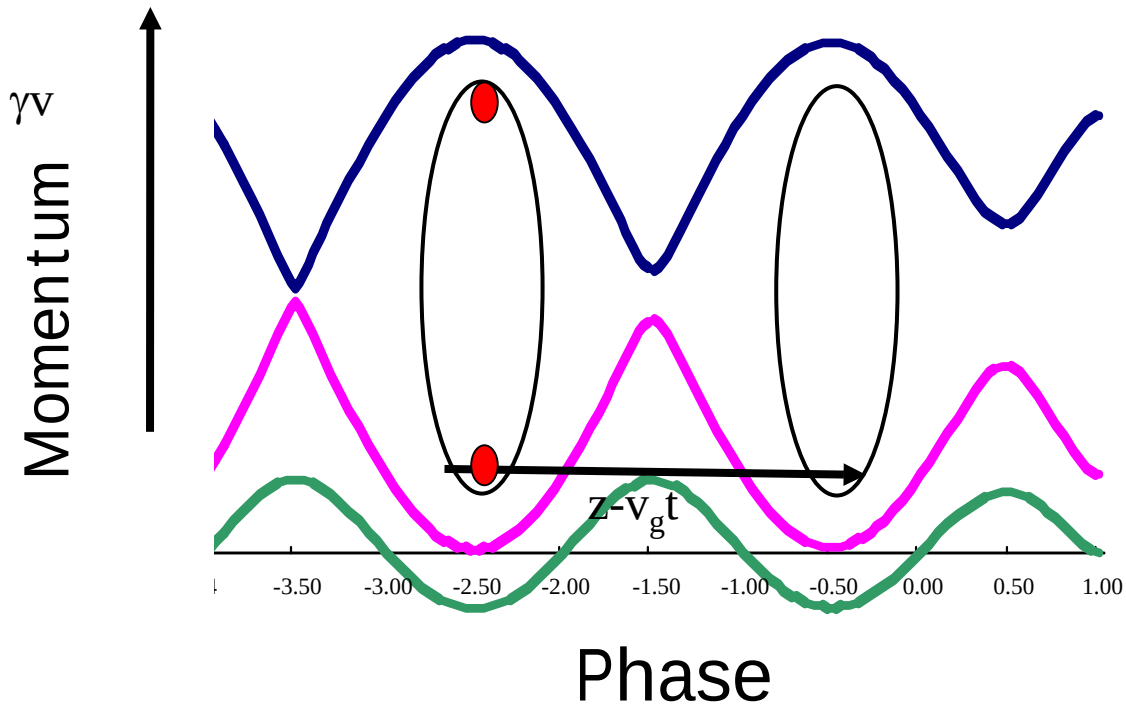
Standard regime (LWFA): pulse duration matches plasma period



Ultrahigh axial electric fields
=> Compact electron accelerators
Plasma wakefields
E_z > 10 GV/m, fast waves
(Conventional RF accelerators
E_z ~ 10 MV/m)
Plasma channel: Guides laser pulse and supports plasma wave



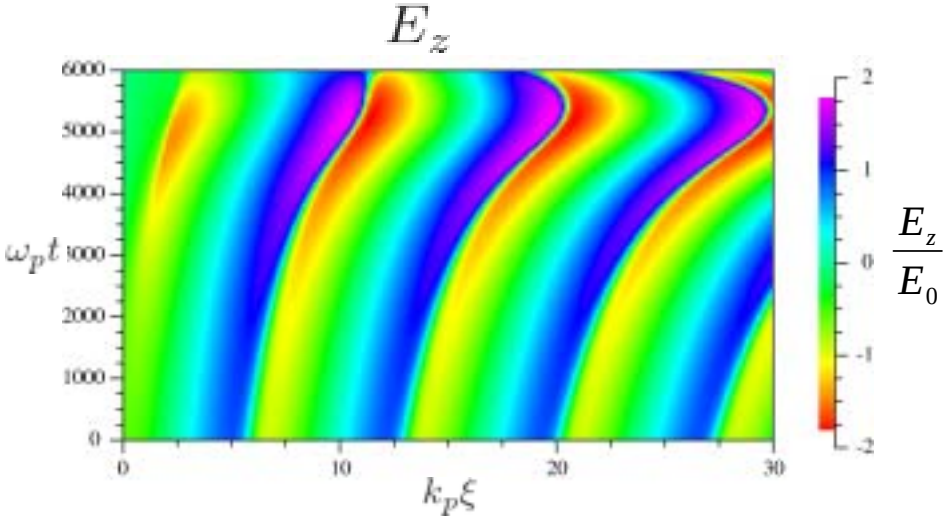
Group velocity of laser < speed of light causes particle dephasing



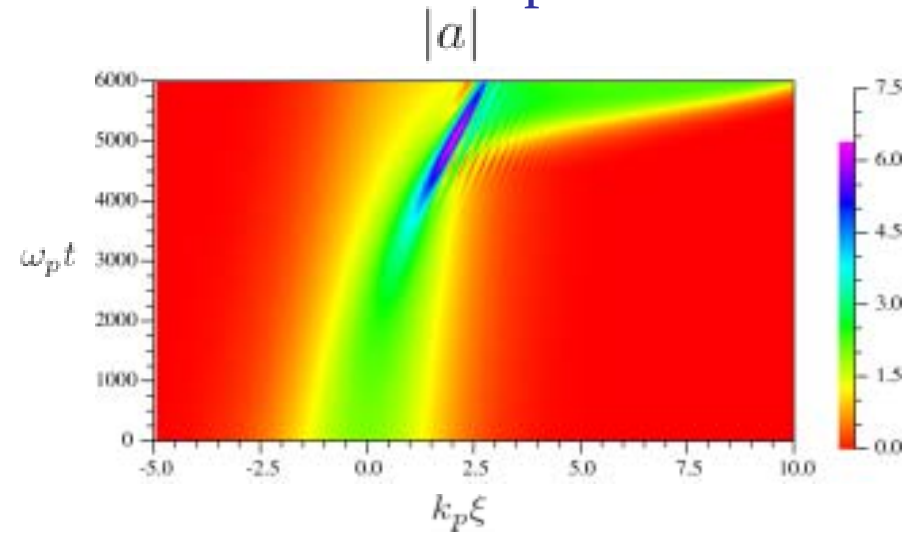
Dephasing length: particle slips in bucket

Verification of scaling laws using fluid numerical studies: 1 GeV example

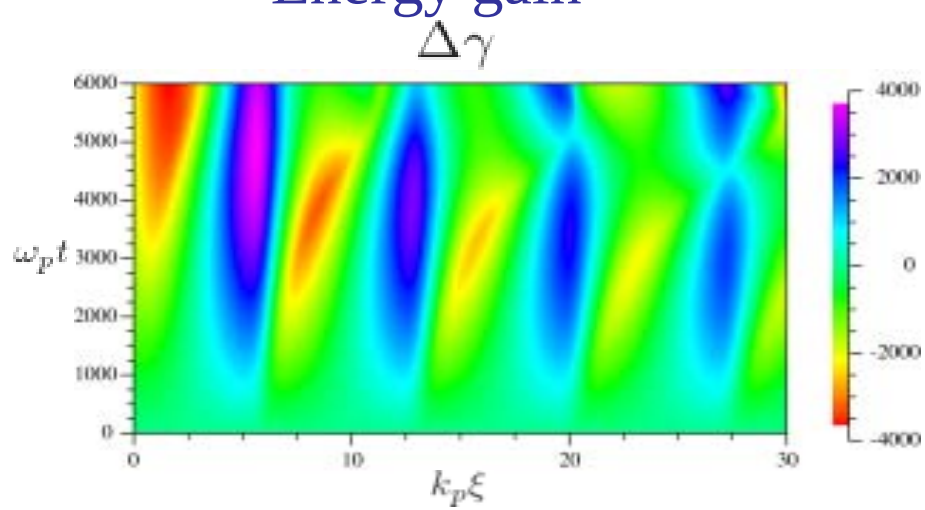
Accelerating wakefield



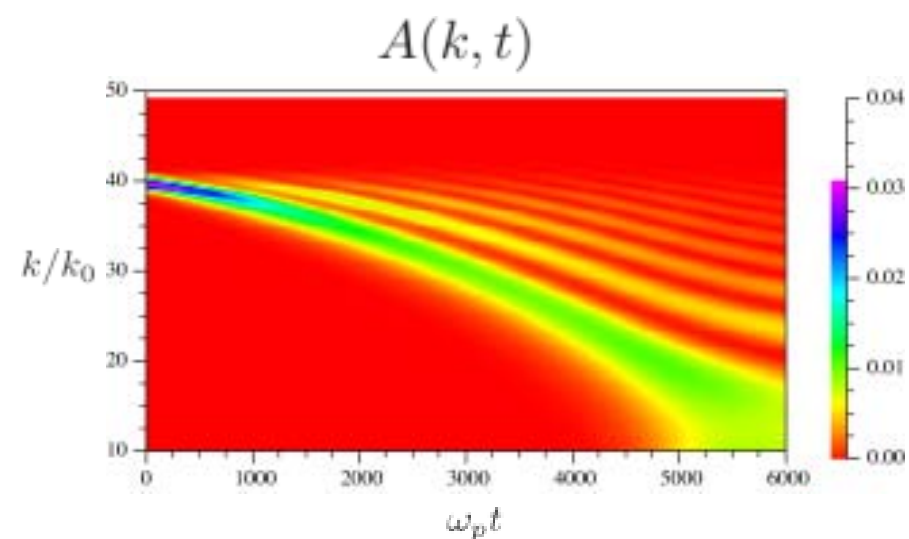
Pulse shape



Energy gain



Frequency spectrum



B.A. Shadwick et al., in preparation

Energy gain $\Delta W = eE_z L_{acc}$

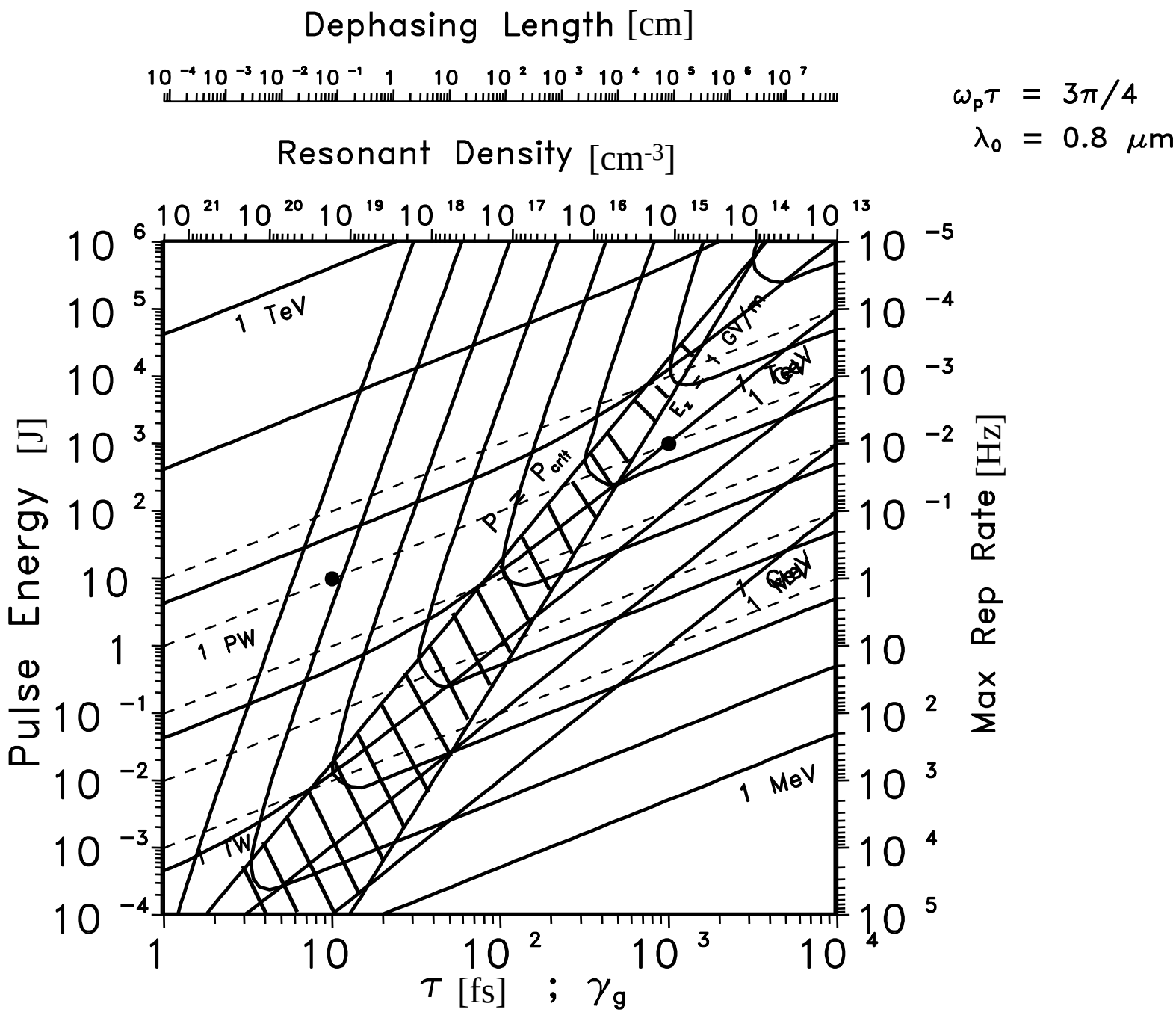
- Diffraction: $$L_{acc} \cong \pi Z_R = \pi^2 r_0^2 / \lambda$$

$$\Delta W_{diff}[MeV] \cong 580(\lambda/\lambda_p)(1 + a_0^2/2)^{-1/2} P[TW]$$

- Dephasing: $$L_{dph} = (1/2)(\lambda_p^3/\lambda^2) \times \begin{cases} 1, & a_0^2 << 1 \\ (\sqrt{2}/\pi) a_0, & a_0^2 >> 1 \end{cases}$$

$$\Delta W_{ch}[MeV] \cong 60(\lambda_p / w_0)^2 P[TW] \times \begin{cases} 1, & a_0^2 << 1 \\ (2/\pi), & a_0^2 >> 1 \end{cases}$$

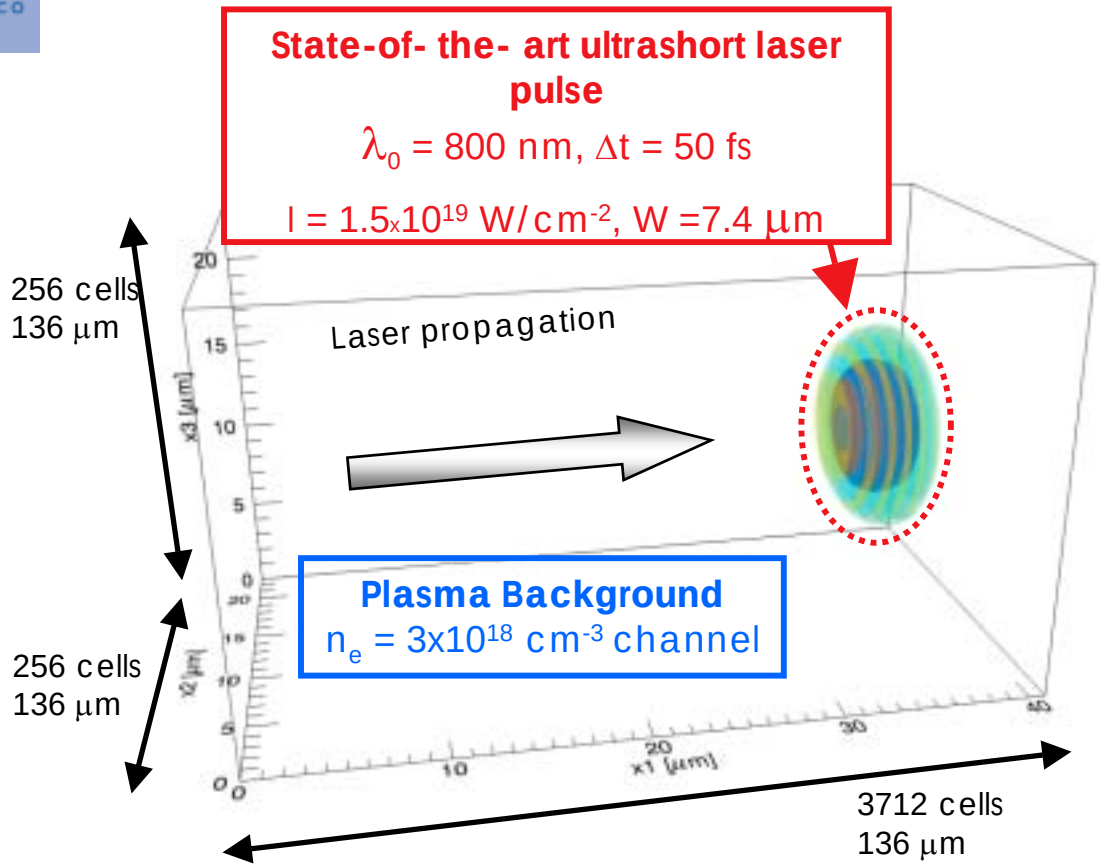
- Depletion: Can be matched to dephasing length in large a_0 limit
  Larger energy gain, shorter distance, more efficient



W.P. Leemans et al., IEEE Trans. Plasma Science, v.24, p. 331, 1996

Full scale 3D LWFA simulation: next experimental frontier - GeV

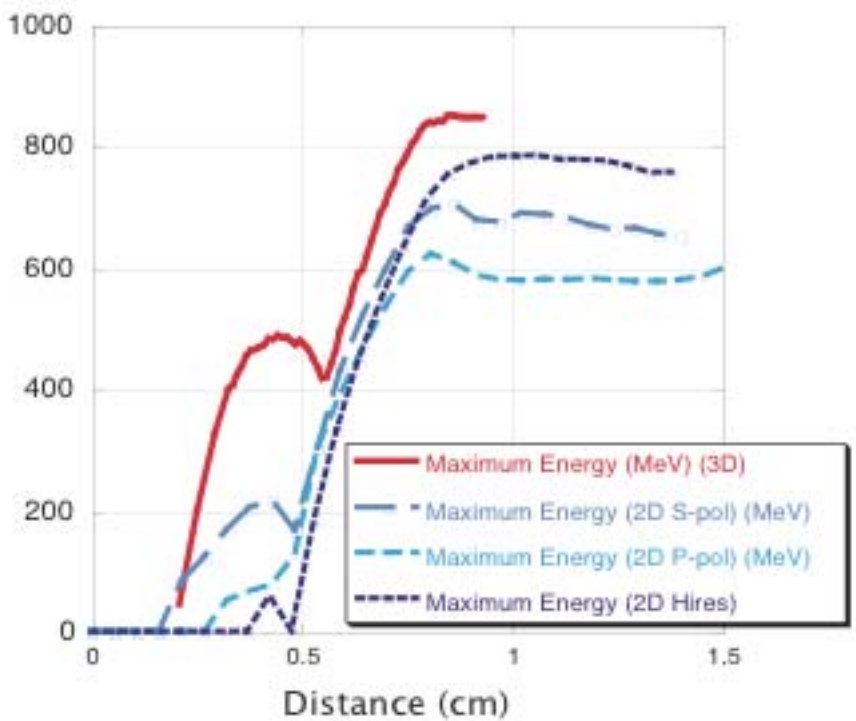
W.B. Mori et al.

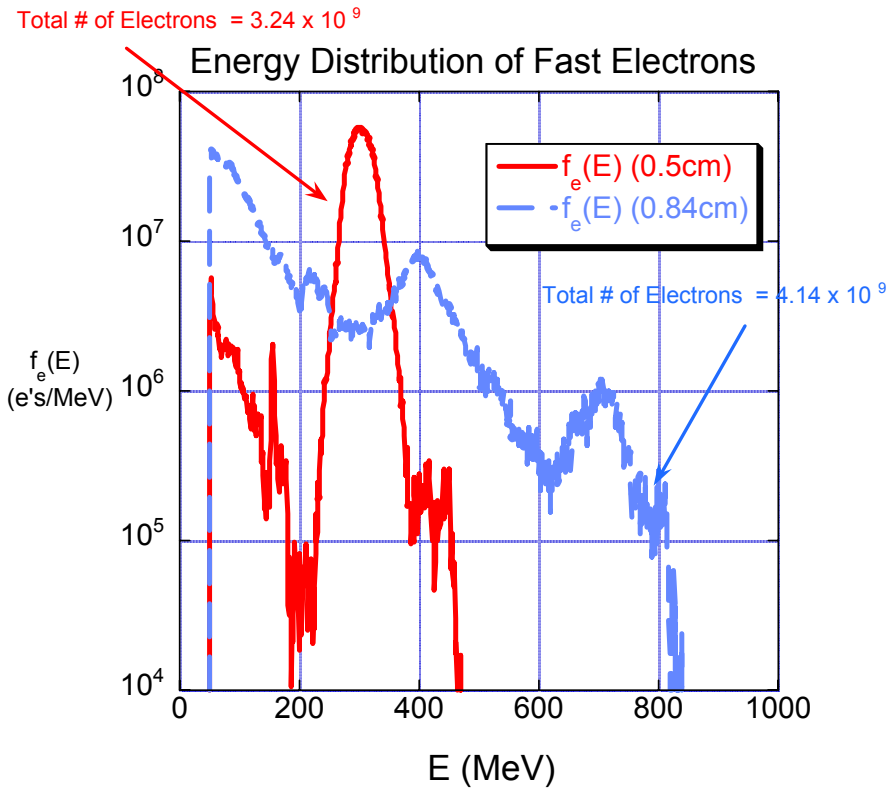


Simulation ran for 300,000 time steps
(~40 Rayleigh lengths)

- Simulation Parameters
  - –Laser:
    - $a_0 = 3$
    - W_0=9.25 λ=7.4 μ
    - $\omega_l/\omega_p = 22.5$
  - –Particles
    - 1x2x2 particles/cell
    - 240 million total
  - –Channel length
    - L=.828cm
    - 300,000 timesteps
- The parameters are similar to those at LBNL except density
- **Operate in blowout regime**

Electron Energy in 1GeV range observed
No external injection required

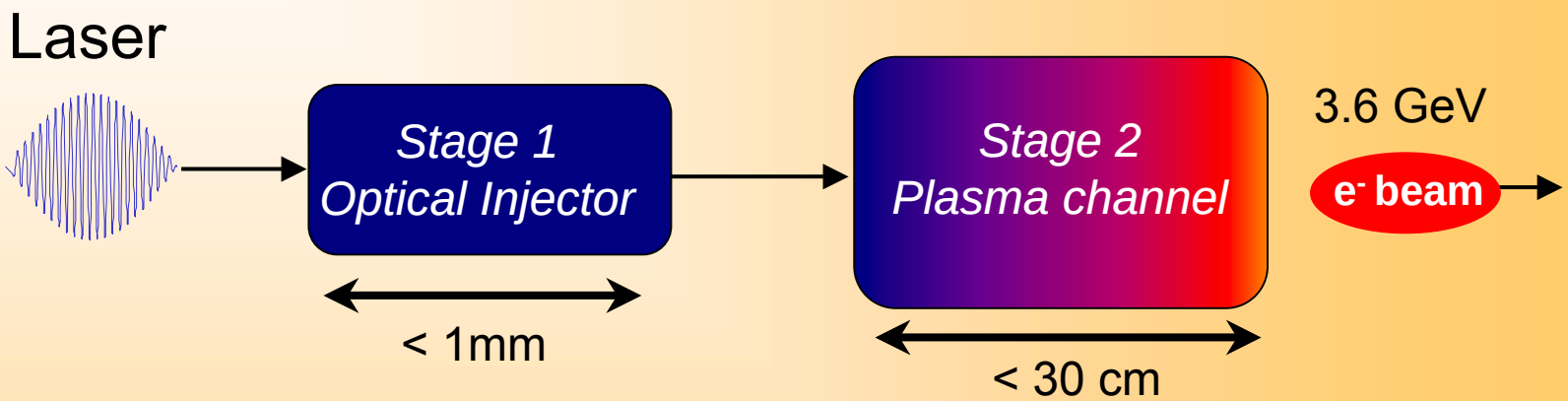




- Electrons originate from channel wall
- Narrow energy peak at 300 MeV after 5 mm
- Maximum Energy = .840 GeV

Development of > 1 GeV module
Concept: two stage module

* A. Reitsma, W. P. Leemans, E. Esarey et al., PRST-AB,5, 051301 (2002)



Example:

Energy Gain: ΔW = **3.6 GeV**, E_{peak} = **23 GV/m**

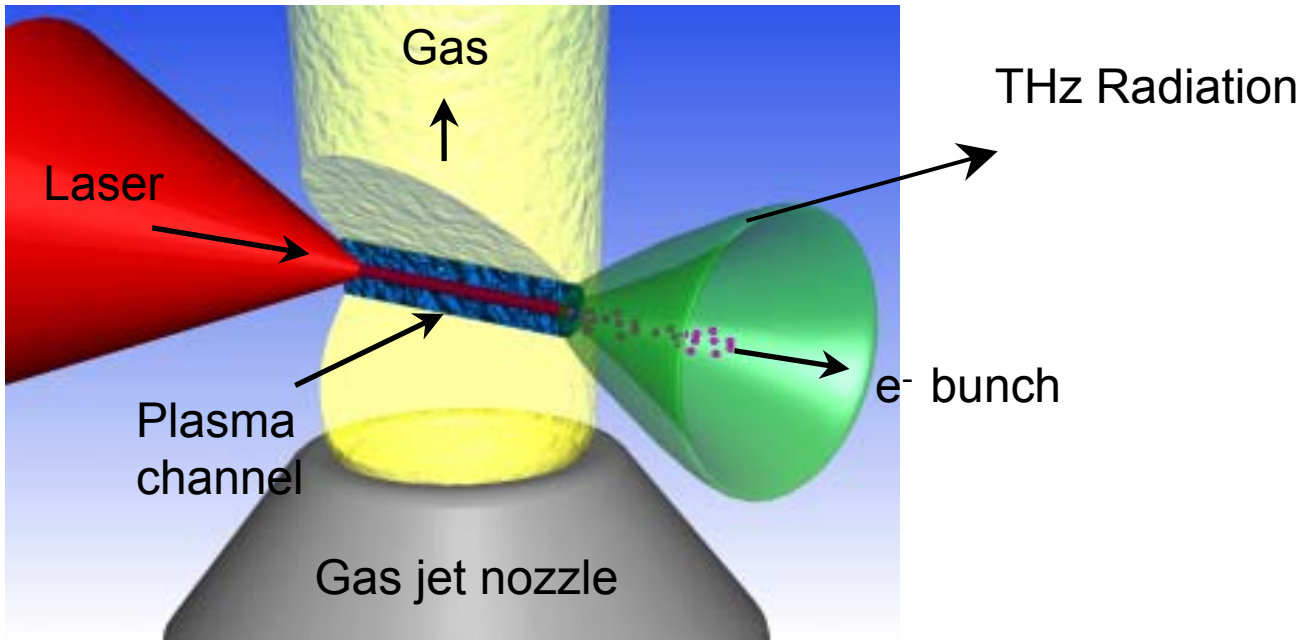
Laser Pulse: **3.9 J**, 44 TW, 90 fs (2×10^{18} W/cm^{-2}, λ = 0.8 μm, r_s = 36 μm)

Plasma: $L_{channel}$ = 29 cm, n = 2.1 x 10^{17} cm^{-3}

Note: 100 pC at 3.6 GeV = 0.35 J

- Challenges:
  - Controlled injection
  - Long scale (10 - 100 cm) length plasma channel + staging + pump depletion
  - Beam properties: energy spread, emittance, charge

Laser wakefield experiments: single drive beam

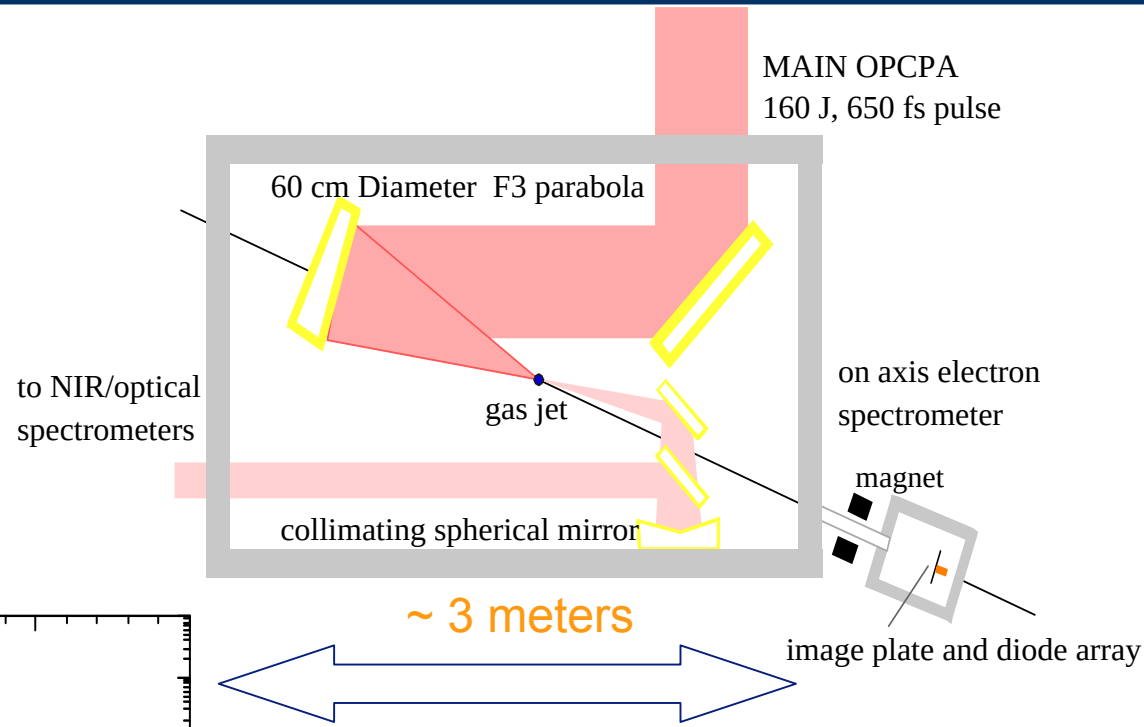


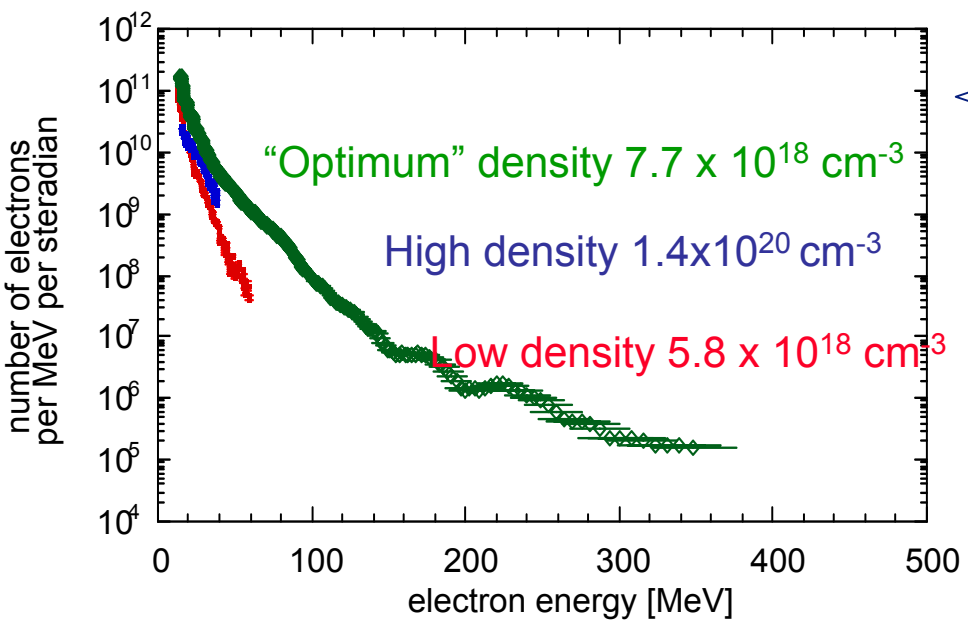
- Properties of e-bunch
  - Energy distribution
  - Spatial distribution
  - Bunch duration

Laser acceleration experiments using the VULCAN PetaWatt

Courtesy of K. Krushelnick et al.

- Vulcan@RAL: 160 J in 650 fs
- Single shot laser



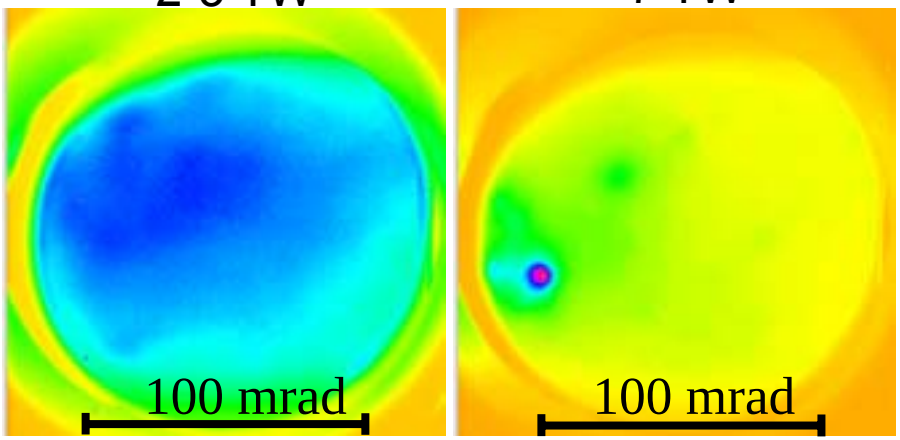


- 350 MeV electrons observed
- Energy spread large

Transverse beam properties

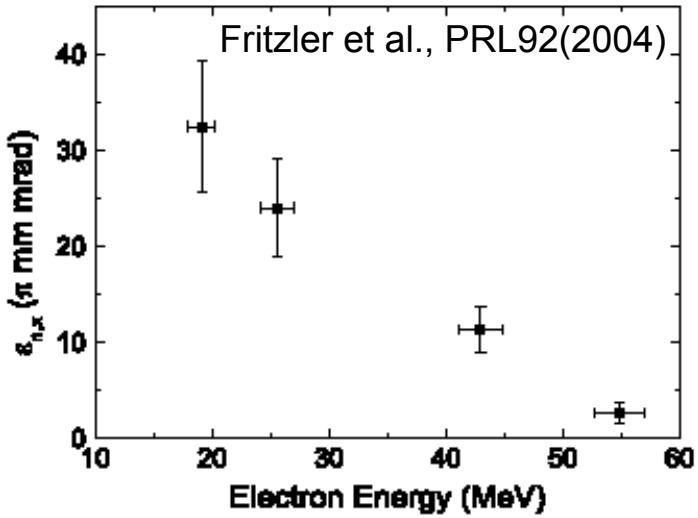
Beam profile 75 cm from jet

2-3 TW > 7 TW



Leemans et al., Phys. Plasmas 11 (2004)

Normalized emittance vs. energy



- Geometric unnormalized "emittance": size(at source) x divergence angle(at screen)
  - 0.01 - 0.1 mm-mrad

Geometric emittance definition: $$\varepsilon_{rms} = \frac{1}{m_0 c \overline{p_z}} \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2}$$

- Significant energy spread: emittance not constant in drift !
  - Correlations develop between transverse position and longitudinal momentum

K. Floettmann, PR-STAB 6, 2003

- Space charge forces:
  - Large stored potential energy in bunch at exit of plasma:Coulomb explosion

G. Fubiani et al., in preparation

Laser pre-pulse affects e-beam

Laser

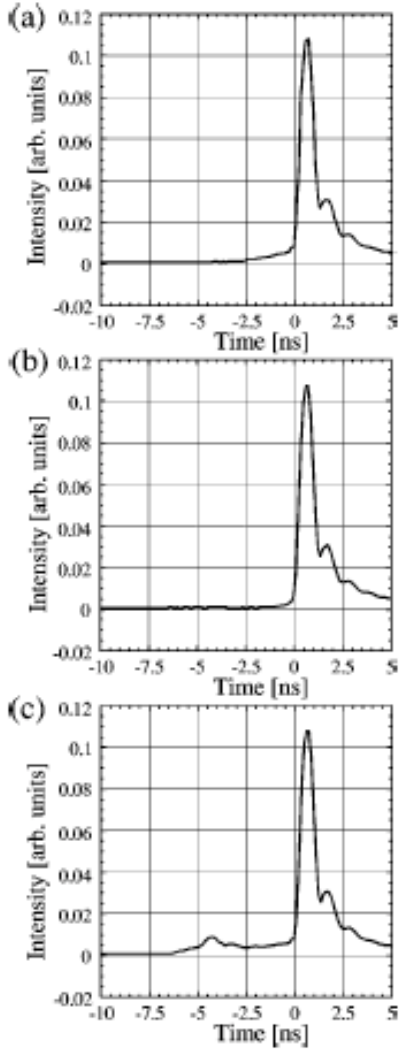


FIG. 4. Typical laser pulse shape detected by a photodiode. (a) ~2.5 ns prepulse, (b) ~1 ns prepulse, (c) ~5 ns nonmonotonic prepulse.

E-beam

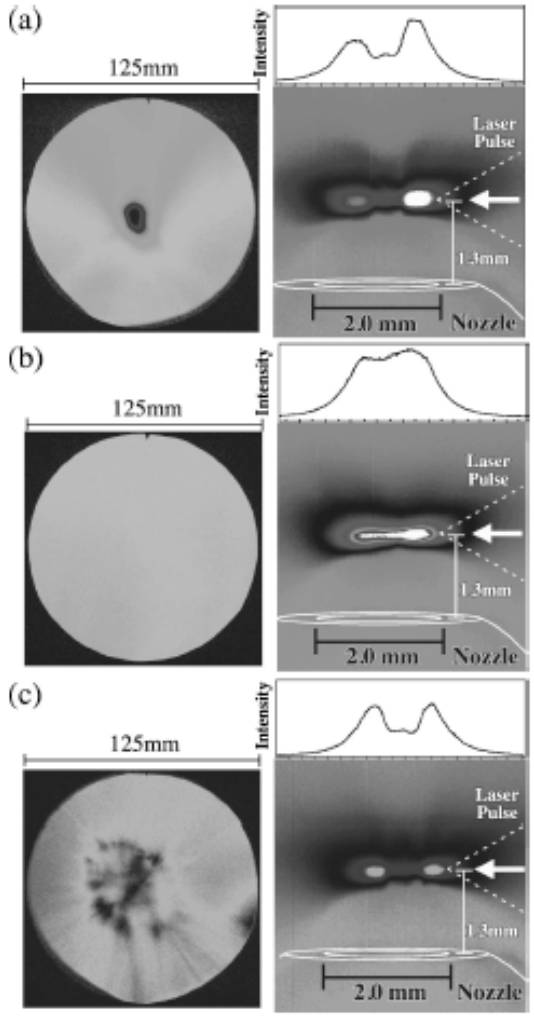


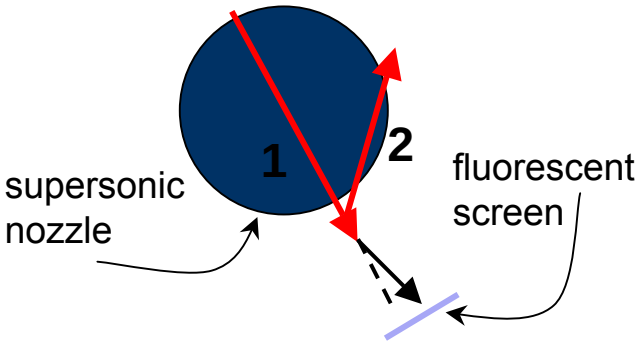
FIG. 5. Typical images of electrons deposited on the bottom plate of the cup-shaped IPs (left hand), and corresponding image of the plasma radiation (right-hand side), and longitudinal profile of the plasma radiation in the direction 90° from the axis (right up) obtained in a density of 2.8×10^{19} cm^{-3} and laser power of 4.8 TW. (a) ~2.5 ns prepulse, (b) ~1 ns prepulse, (c) ~5 ns nonmonotonic prepulse.

T.Hosokai et al., PRE 67 (2003)

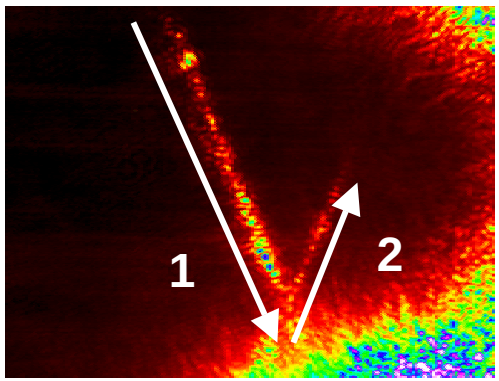
Cross-Correlation of Laser-Wakefield Accelerated Electron Beam

University of Michigan, Ann Arbor

Direct temporal measurement of a sub-picosecond-laser-accelerated electron beam, by use of ponderomotive deflection by an ultraintense laser pulse

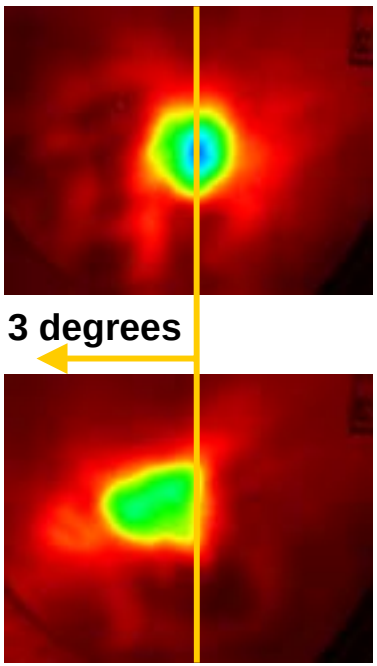


1st laser pulse – accelerates e-beam
2nd laser pulse – deflects e-beam



Channeling of the two laser pulses – the interaction region lies outside the plasma

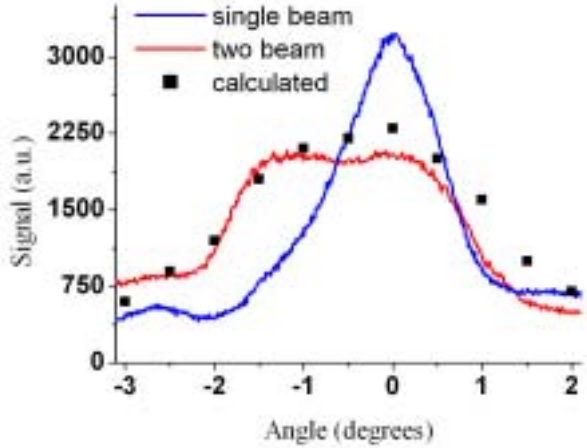
1-beam, undeflected



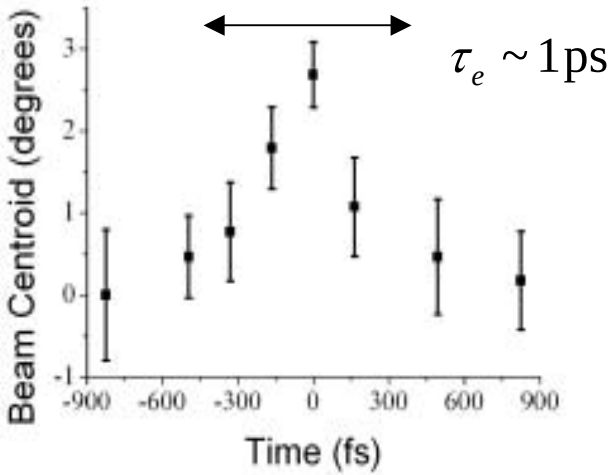
~ 3 degrees

2-beam, zero delay

Ponderomotive deflection of electron beam observed on fluorescent screen



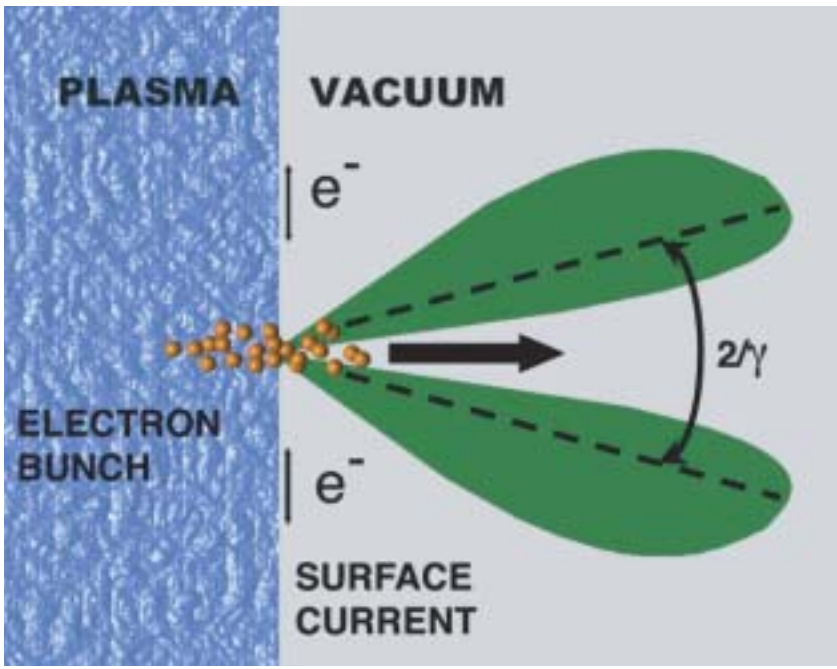
Measurement agrees with calculations that include longitudinal laser fields



Bunch duration measurement via coherent transition radiation

➢ Transition Radiation (THz) from the boundary

Experiment: W.P. Leemans et al., PRL 2003
W.P. Leemans et al., Phys. Plasmas 2004
Theory: C. B. Schroeder et al., PRE 2003
J. van Tilborg et al., Laser and Particle beams 2004



$$I_{total}(\omega) = \{N + N(N-1)|g(k)|^2\} I_e(\omega)$$

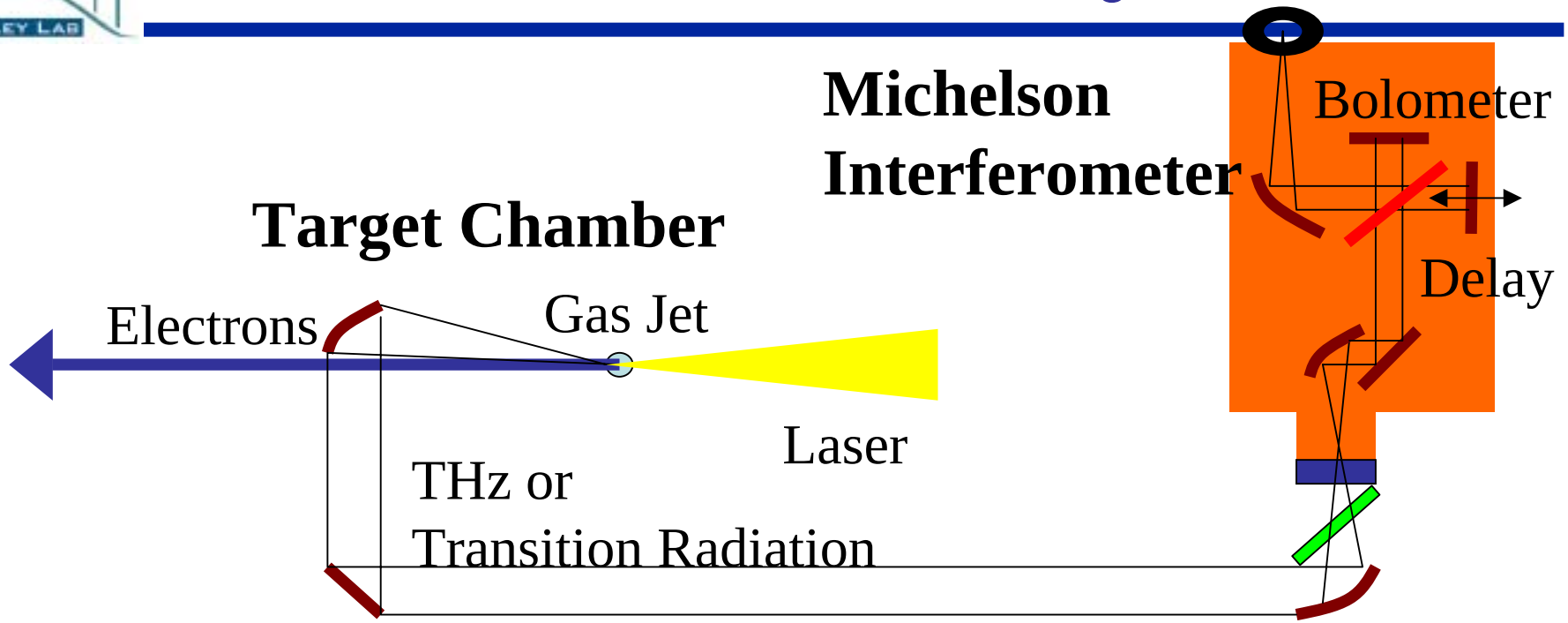
$$g(k) = \int_{-\infty}^{\infty} \rho(z) e^{ikz} dz$$

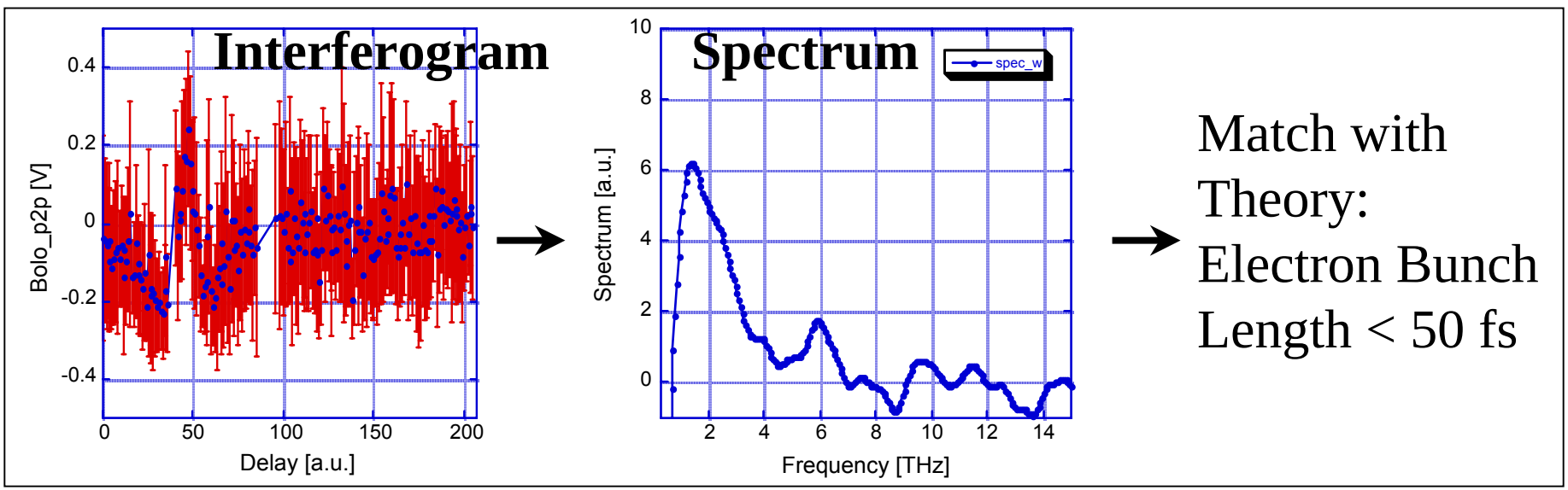
Dominates if $\sigma_z < \lambda$

- Transition radiation
- Diffraction due to finite plasma radius

Measurement of spectrum provides information on bunch duration

Michelson interferometer: bunch length < 50 fs



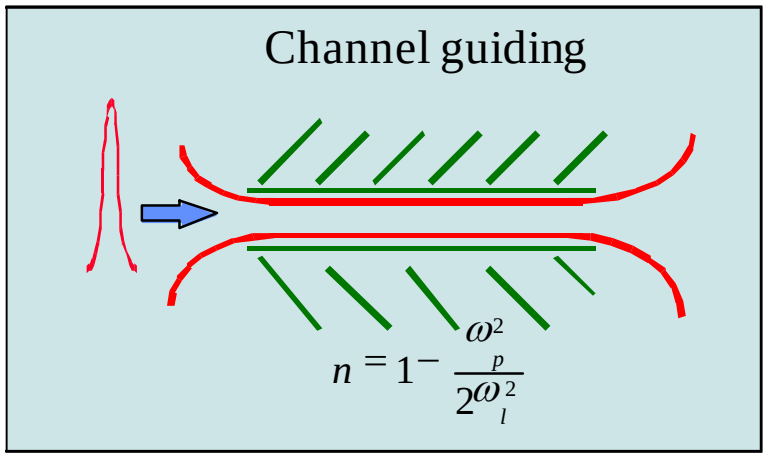


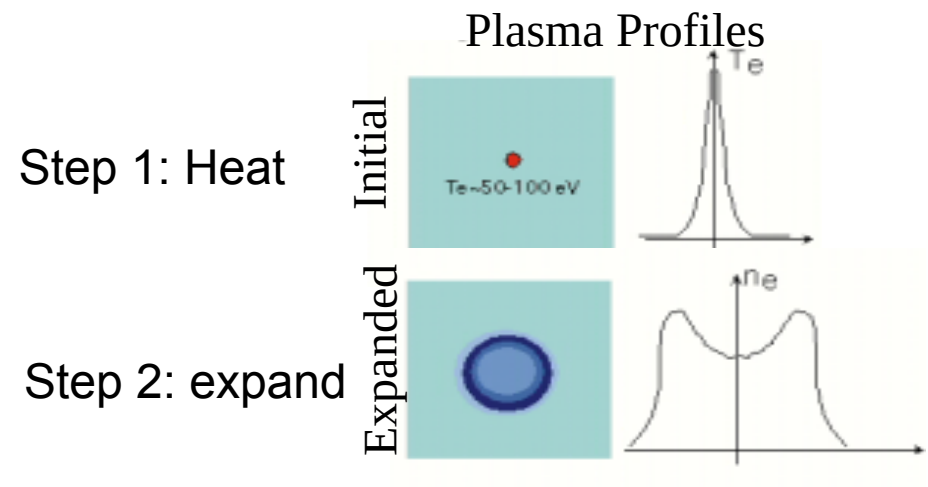
J. Van Tilborg et al., in preparation

Laser guiding in plasma channel

Controlling laser propagation, particle trapping and dephasing

Plasma channel: structure for guiding and acceleration

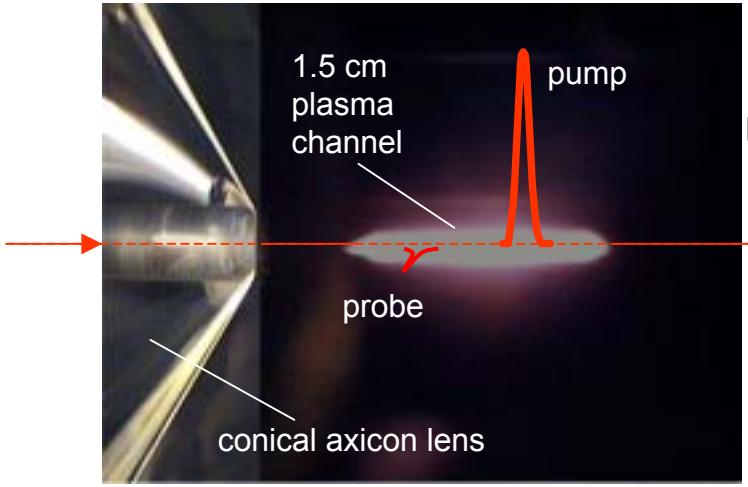


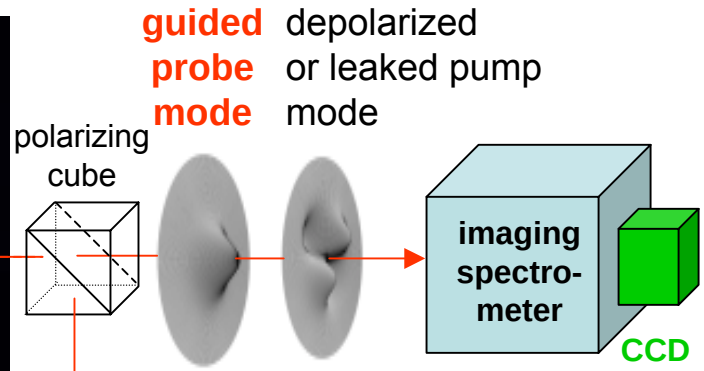


- Hydro-dynamically formed plasma channel
  - On-axis axicon (C.G. Durfee and H. Milchberg, PRL 71 (1993))
  - Ignitor-Heater (P. Volfbeyn et al., Phys. Plasmas 6 (1999))
  - Discharge assisted (E. Gaul et al., Appl. Phys. Lett. 77 (2000))
  - Cluster jets (Kim et al., PRL 90 (2003))
- Discharge ablated capillary discharges (Y. Ehrlich et al., PRL 77 (1996))
- Z-pinch discharge (T. Hosokai et al., Opt. Lett. 25 (2000))
- Hydrogen filled capillary discharge (D. Spence and S. M. Hooker, JOSA B (2000))
- Glass capillaries (B. Cross et al., IEEE Trans. Plasma Science 28(2000))

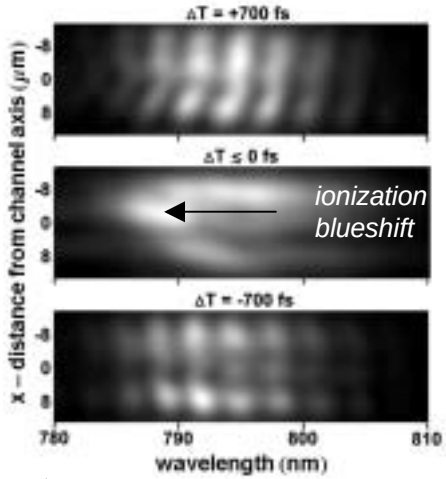
High intensity guiding in fully-ionized He channels

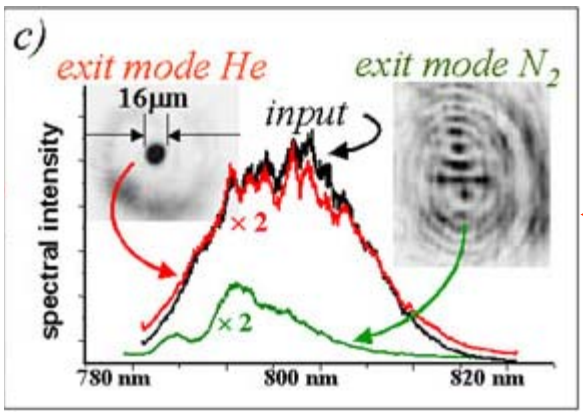
Gaul *et al*., Appl. Phys. Lett. (2000)
Zgadzaj *et al*., J. Opt. Soc. Am. B (2004)





Frequency-Domain Interference Patterns





guided pump properties

Fs pump-probe experiments:

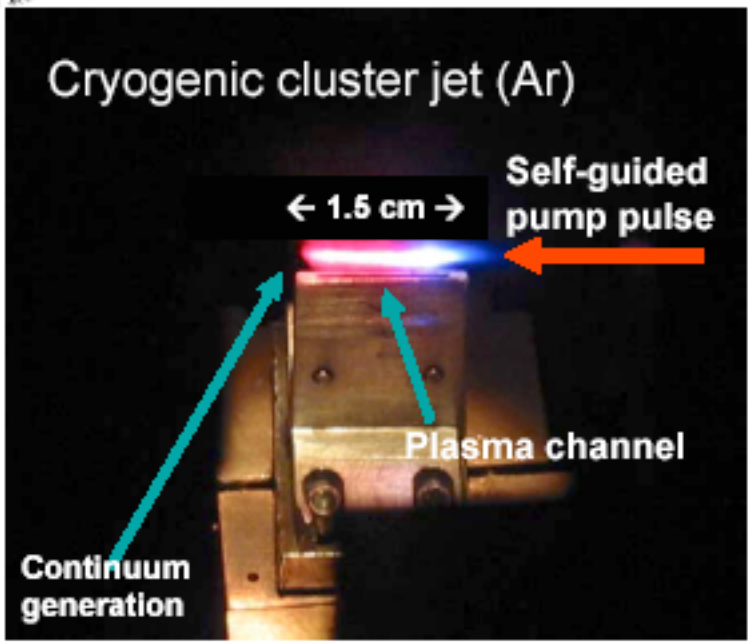
- superior characterization of guiding at 0.2 x 10^{18} W/cm^2
- subtle mode distortions detected via frequency-domain interferometry with depolarized pump
- low level residual un-ionized gas detected via ionization blueshifts at $\Delta T \sim 0$ fs

Essential techniques developed for characterizing channeled LWFAs created by 10^{18} W/cm^2 pump pulses

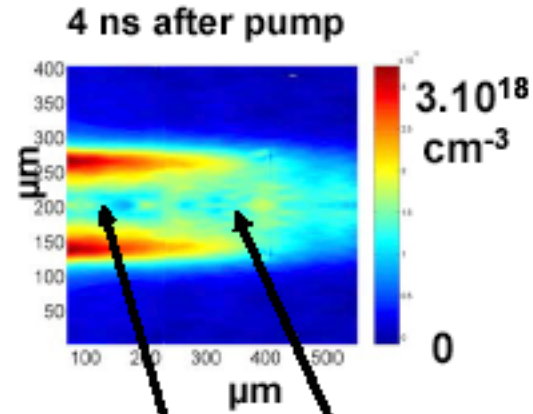
2 x 10^{17} W/cm^2 guided over 1.5 cm (60 z_R) without optical distortion

M. Downer - U. Texas-Austin

Self-guided plasma channel generation in an elongated cluster jet followed by guiding of a secondary pulse



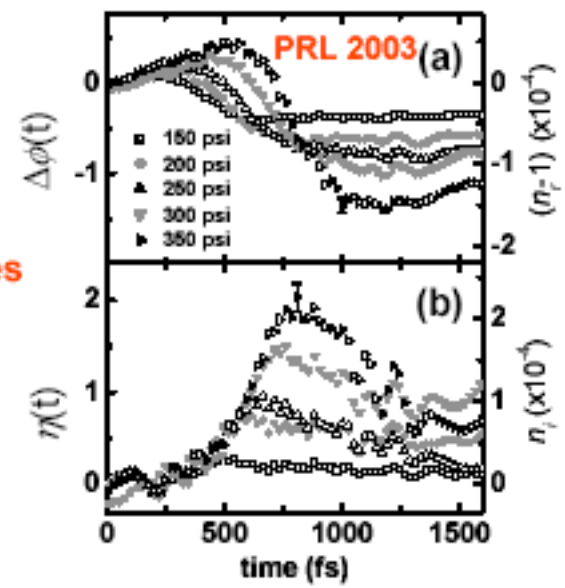
Plasma channel entrance interferometry



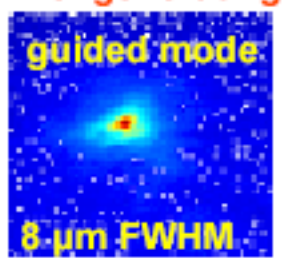
Greatly reduced end taper

10^{18} cm^{-3} density

Polarizability of exploding laser heated clusters makes self-guiding possible



Second pulse injected following self-guided channel-generating pulse



3×10^{17} W/cm^2

H.M. Milchberg et al., U. Maryland

Relativistic intensities (> 10^{18} W/cm^2) guided at LBNL

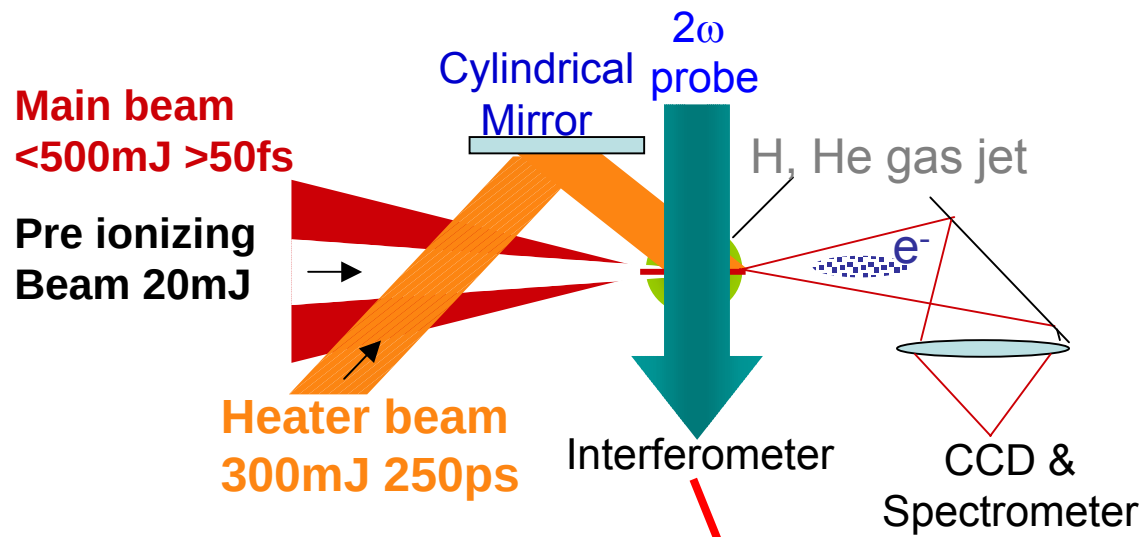
At Vacuum focus

µm

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

I_{in}= 7 x 10^{18} W/cm^2

µm



At Jet exit

µm

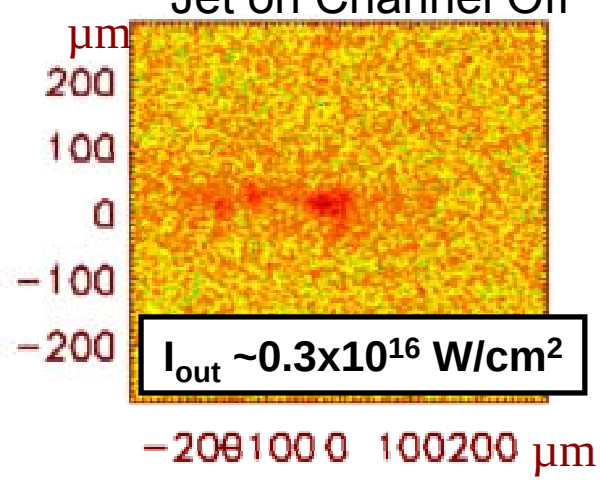
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

I_{out} = 1.6x10^{16}W/cm^2

µm

Jet on Channel Off

µm



I_{out} ~0.3x10^{16} W/cm^2

Jet on Channel On

µm

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

I_{out} ~10^{18}W/cm^2

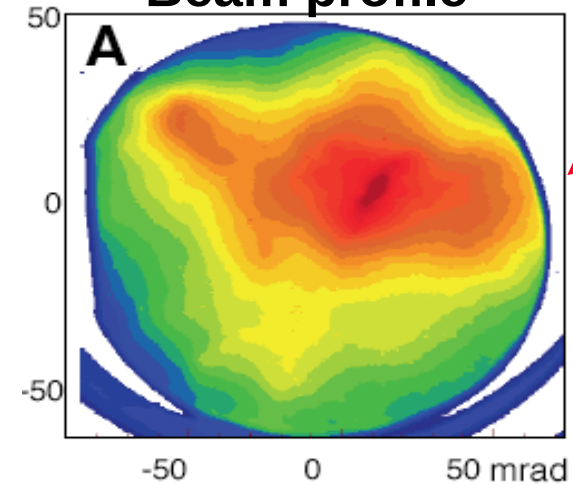
µm

C. Geddes et al., in preparation

Effect on electron beam ?

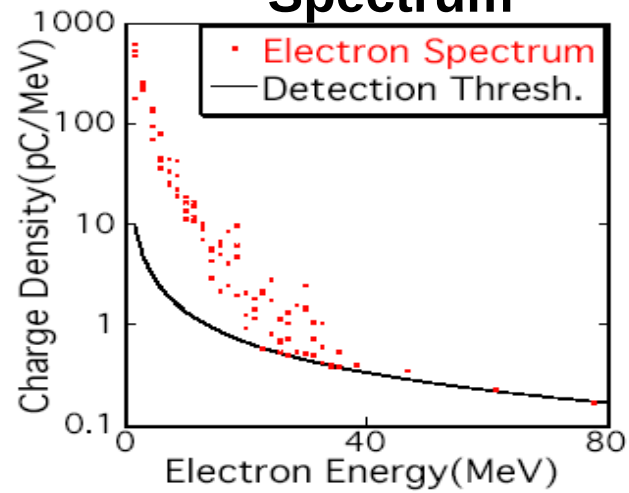
85 MeV e-beam with %-level energy spread observed from laser accelerator

Beam profile

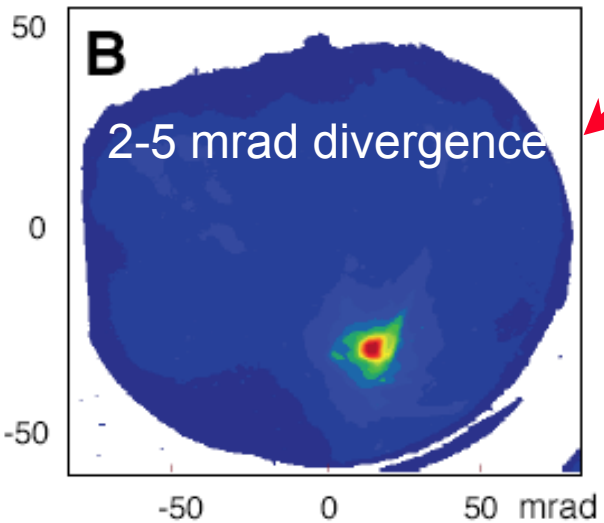


Unguided

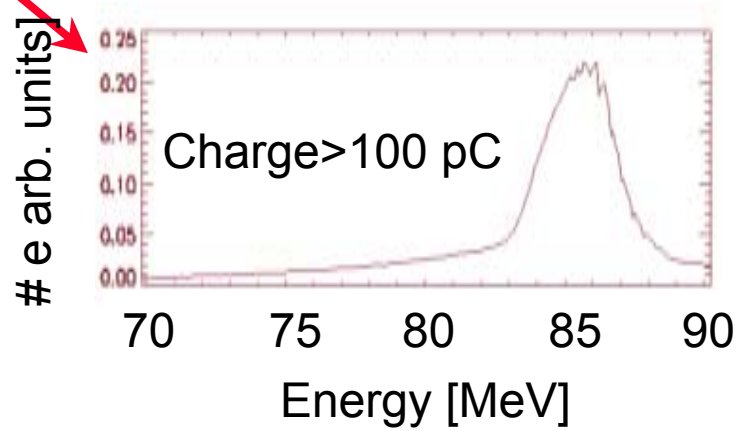
Spectrum



Guided

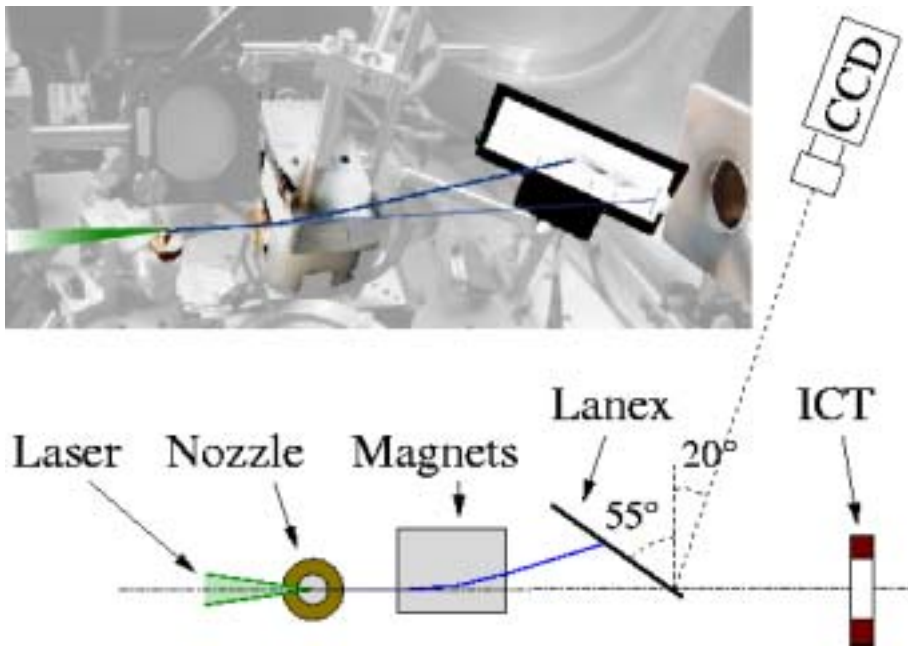


C.Geddes et al., submitted

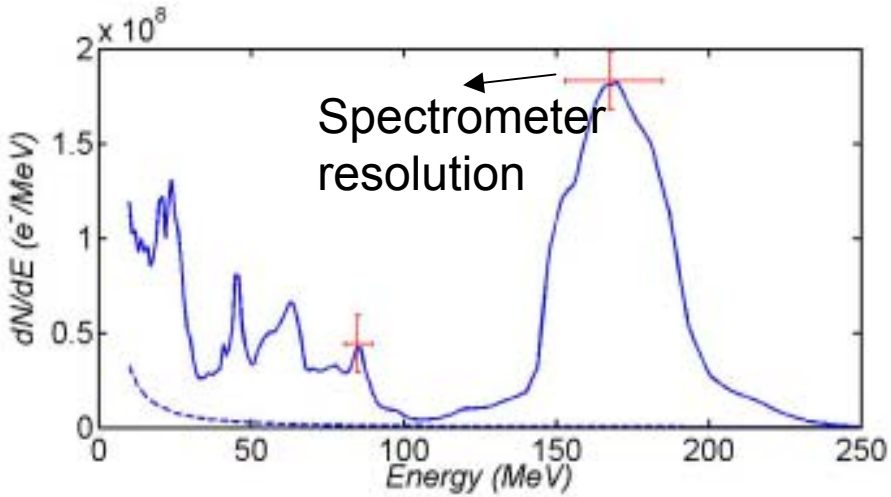


Electrons > 150 MeV observed

High quality electron beams at LOA

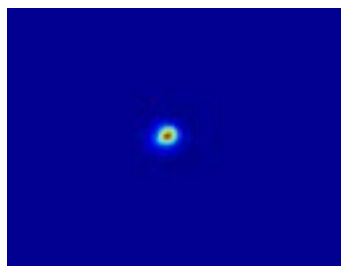


Quasi-monoenergetic spectrum
Hundreds of pC at 170 MeV +/- 20 MeV



Parameters: n_e=6x10^{18} cm^{-3},
a_0=1.3, τ=30 fs P=30 TW
Results obtained with 1 m off-axis parabola:
w_0=18 µm, z_R=1.25 mm

Electron beam profile on LANEX

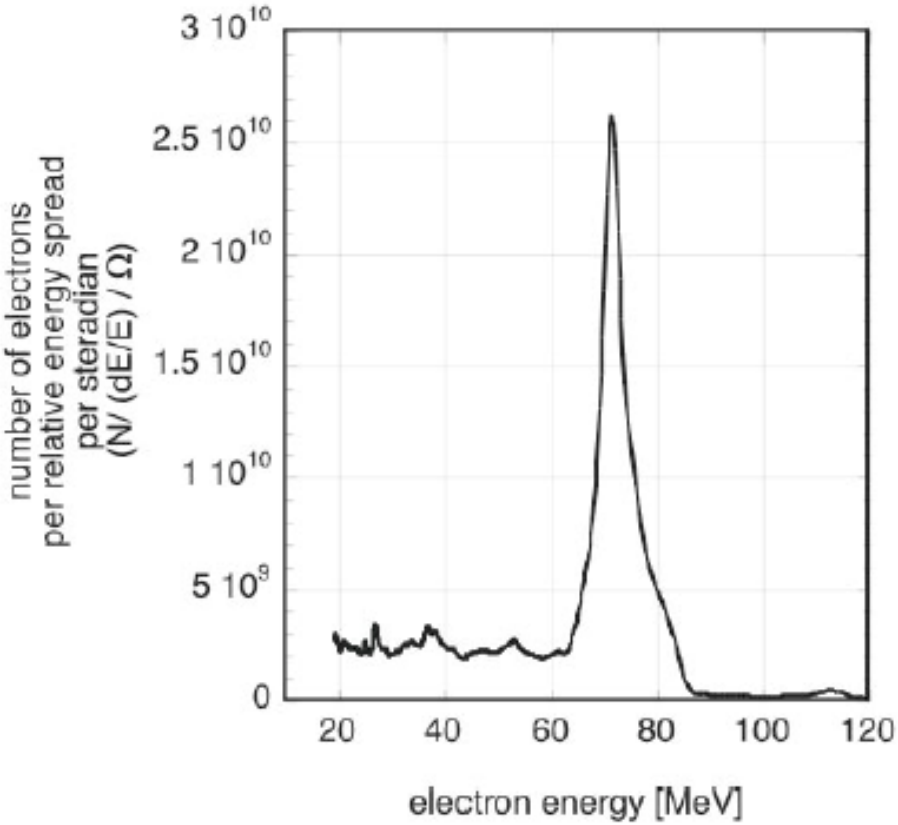


Divergence FWHM = 6 mrad

Courtesy J. Faure, LOA

Imperial College London

Mono-energetic spectra can be observed at higher power ($\Delta E/E$ = 6 %)



E ~ 500 mJ,
pulse duration ~ 40 fsec
Focal spot ~ 25 μm
Density ~ 2 x 10^{19} cm^{-3}

Significant shot-to-shot fluctuations in
a) energy spread
b) peak energy

Careful control of laser and plasma conditions is necessary

Courtesy: K. Krushelnick, RAL

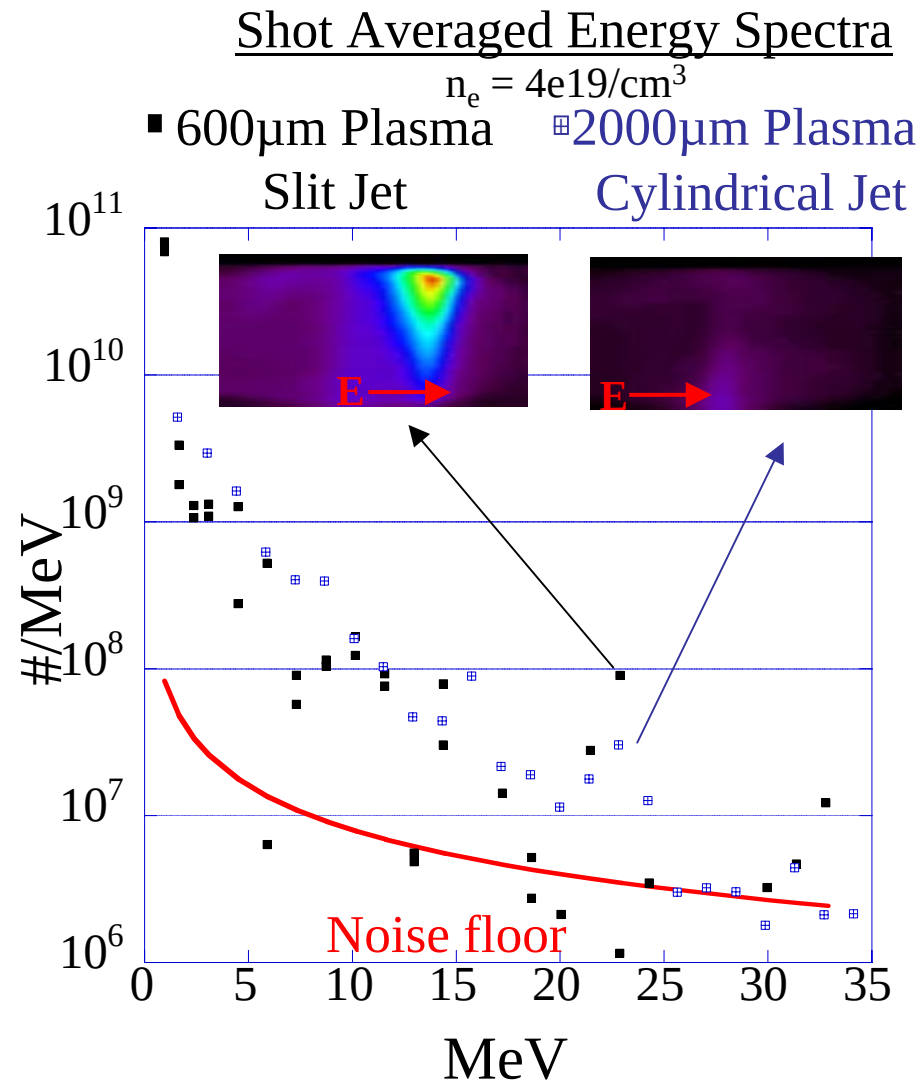
Matching Plasma Length to Dephasing & Depletion Optimizes Performance

2-D VORPAL simulation

Longitudinal Momentum

QuickTime™ and a
PNG decompressor
are needed to see this picture.

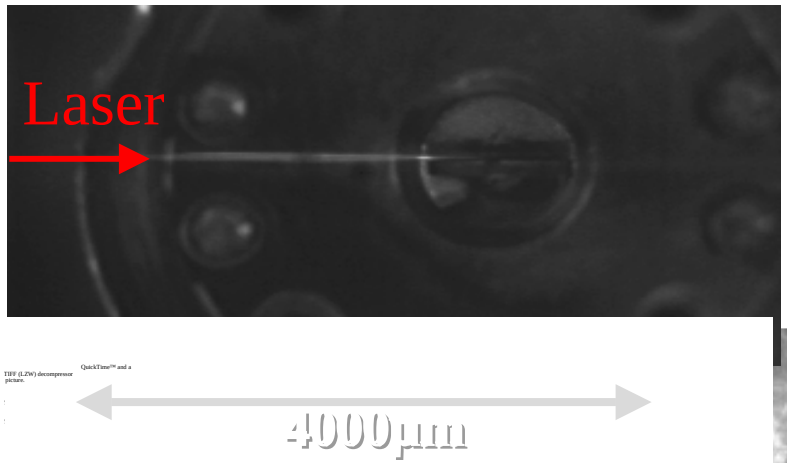
Propagation Distance



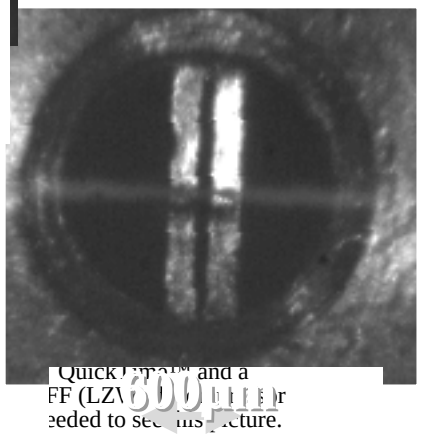
- Optimum: L_{acc} = dephasing length
- Longer distance gains no energy, increases spread

Understanding of Dephasing and Depletion by Variable Plasma Length

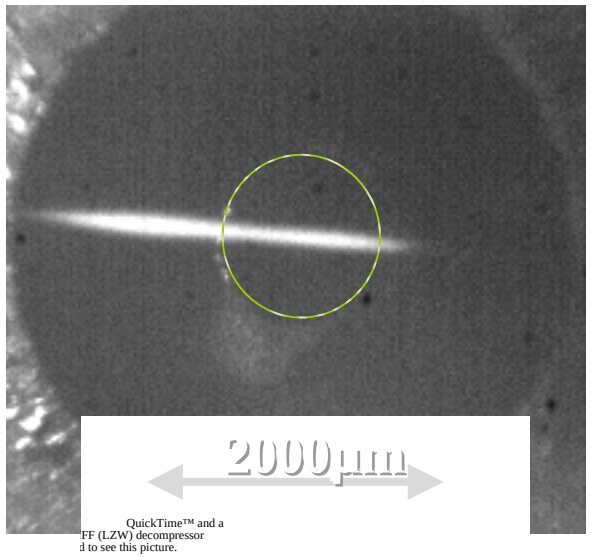
Slit Gas Jet - 4mm x 0.2mm



N_{max} ~ 3e19 -> λ_p ~6μm



Cylindrical Jets ~ 2mm



N_{max} ~ 4e19 -> λ_p ~5μm

N_{max} ~ 4e19 -> λ_p ~5μm

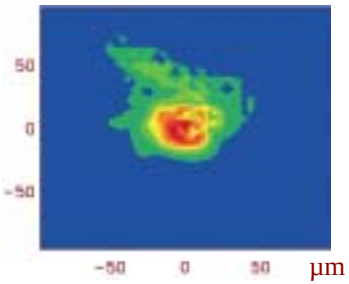
Use of long scale length plasmas in short laser pulse wakefield R&D is enabled by channel technology, especially cluster jets

Input laser mode affects channel coupling and electron yield

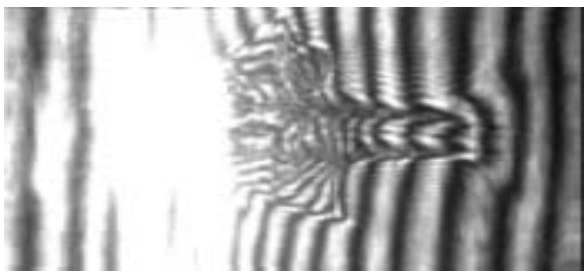
- Thermal loading on grating at 10 Hz operation causes mode distortion. Operation at 1 Hz preserves mode. Need adaptive optic to correct for10 Hz operation

Case 1: Distorted input mode

- Output Mode 10% transmitted. I_{out} ~ 3%I_{in}~3e17



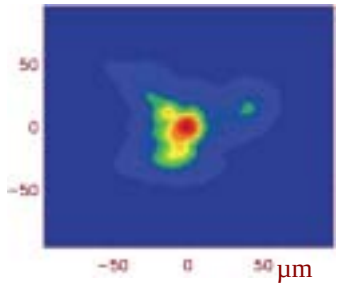
- Side Interferometer



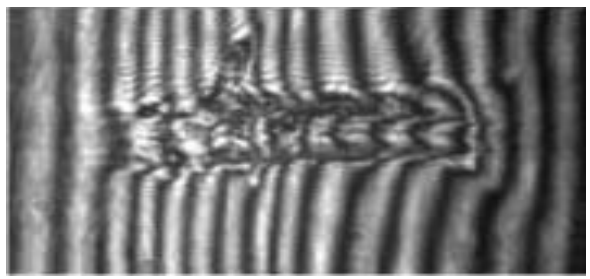
- Observe e-beam, gamma rays
- Large neutron increase over single beam

Case 2: Clean input mode

- Output Mode 10% transmitted. I_{out} ~ 5%I_{in}~5e17



- Side Interferometer



- Clean output mode
- No significant electron output !

Suppression of self-trapping using plasma channel with clean input laser mode

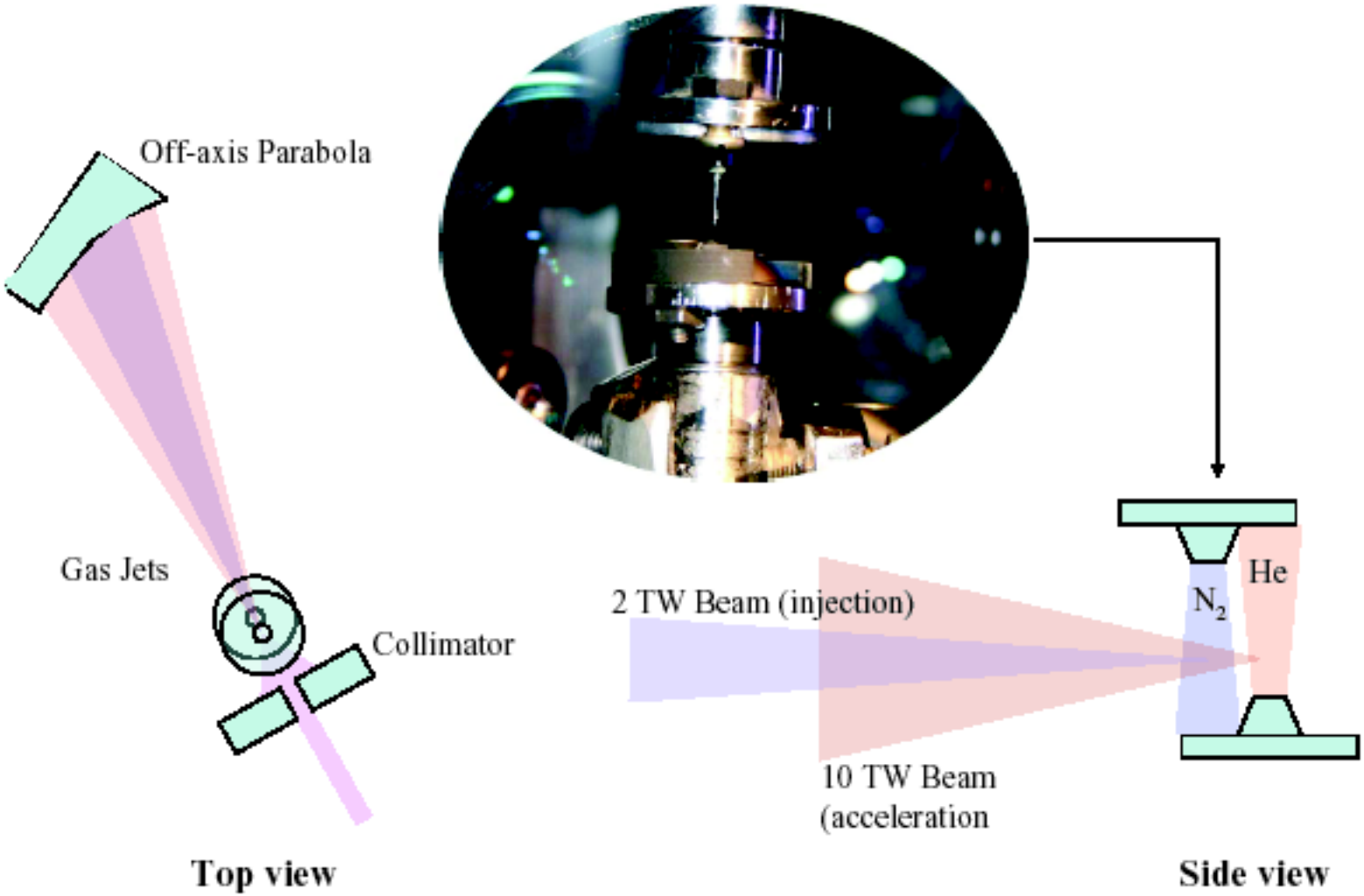
Laser triggered injection

- Use additional laser pulse for control of electron injection process
  - Laser ionization ponderomotive acceleration (LIPA)
  - Laser injection laser acceleration (LILAC)
  - Colliding pulse injection (CPI)
- Alternative: external injection with photo cathode driver
  (e.g. ATF (BNL), AWA (ANL), Neptune (UCLA))

NRL Laser Injection Laser Wakefield Accelerator

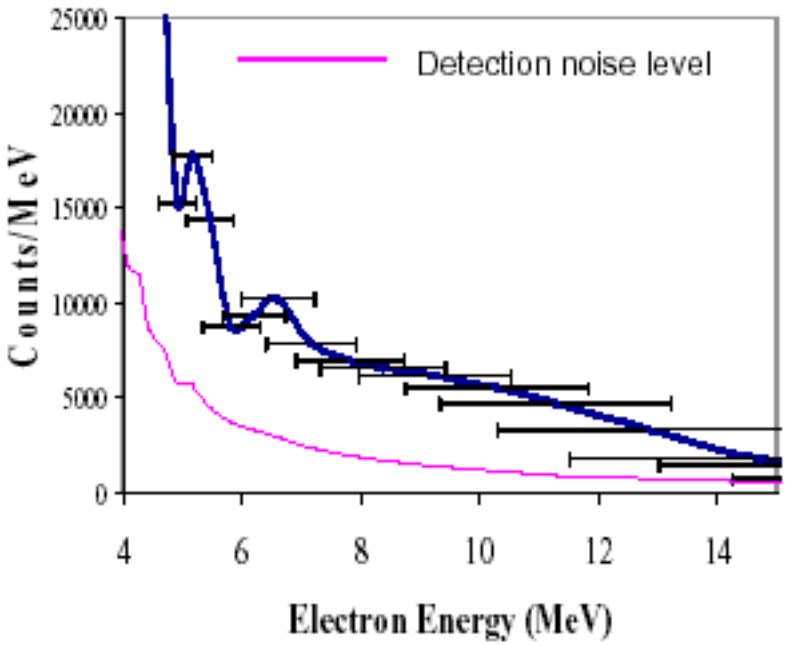
A. Ting, D. Kaganovich, D. Gordon, R. Hubbard and P. Sprangle

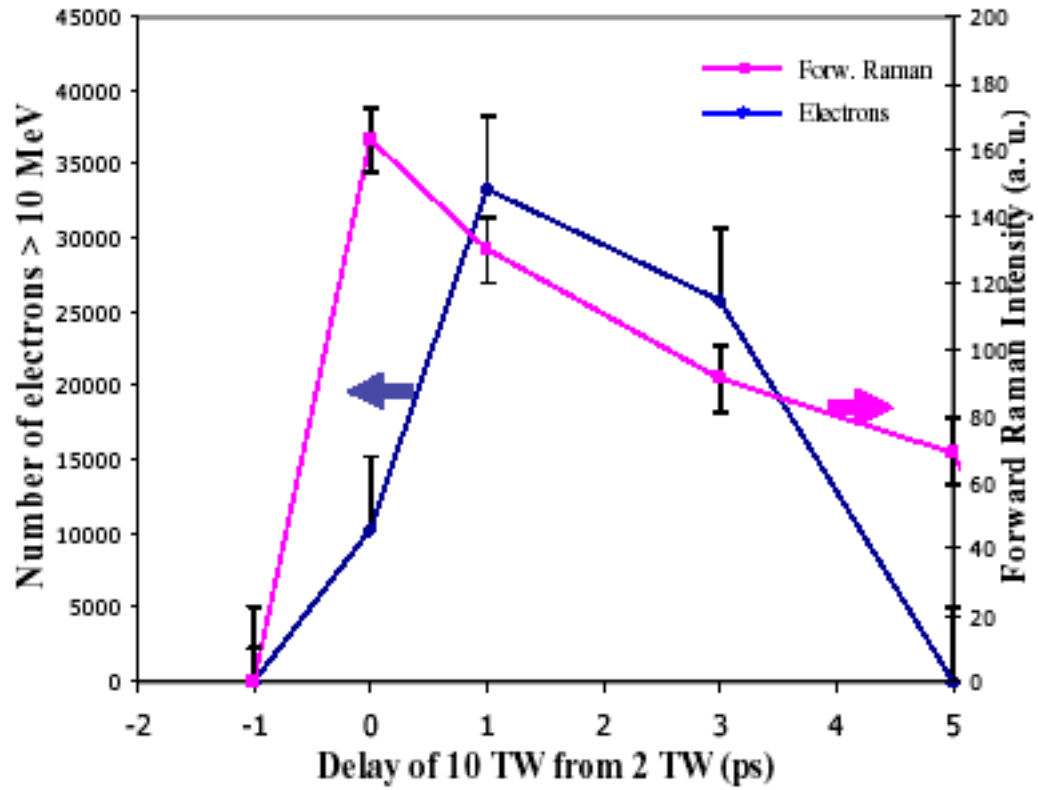
- **Synchronized, collinear, two jet, two-beam (2TW/10TW) laser configuration**



First demonstration of staged optical injection/acceleration LWFA experiment

- Injection electrons <0.5 MeV (high-density LIPA)
- Accelerated electrons >10 MeV
- Injection/Acceleration occurs only for time delays of <3 psec
- Delay of electrons from peak forward Raman signal shows:
  - Injection electrons not from background plasma
  - Slippage of injection electrons from laser pulse





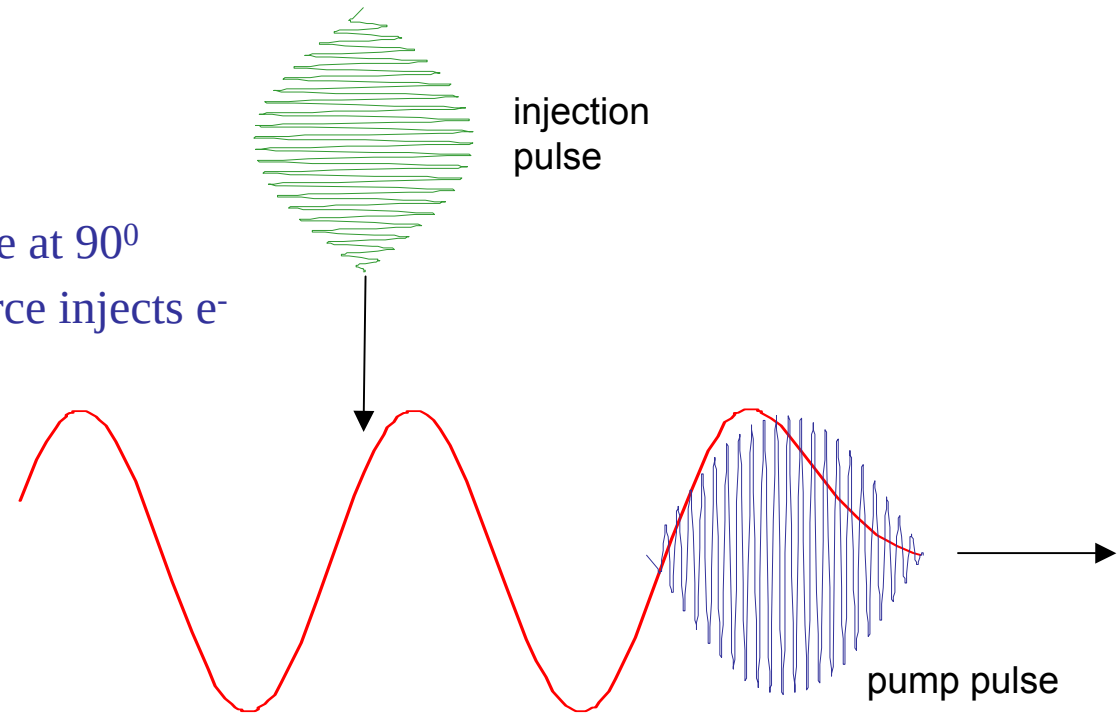
Injector concept: ponderomotive injection-LILAC

Umstadter *et al.*, PRL 96
Hemker et al., PRE 98

- Injection pulse intersects wake at 90^0
- Transverse ponderomotive force injects e^-

$$F_z \propto \nabla a_1^2 \propto a_1^2 / r_1$$

- Requires $a_{inject} \sim a_{pump} \sim 2$

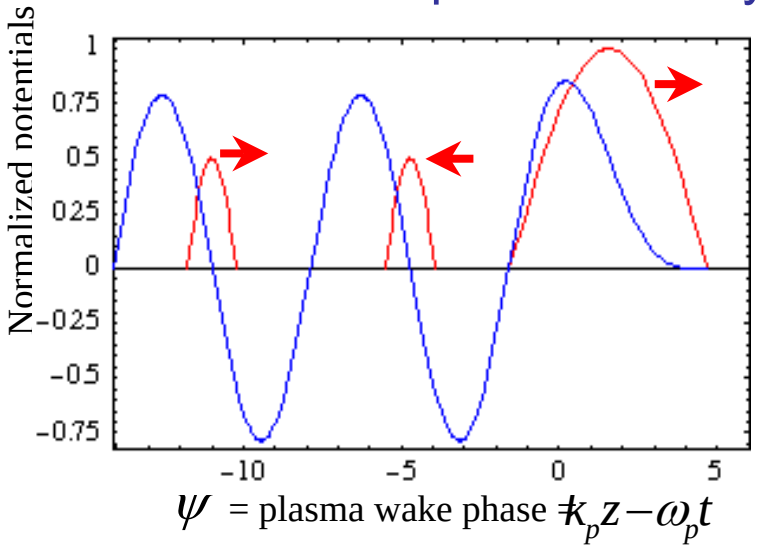


Simulations predict:
- 10 fs bunch
- 6 % energy spread
- 20 MeV in <1 mm

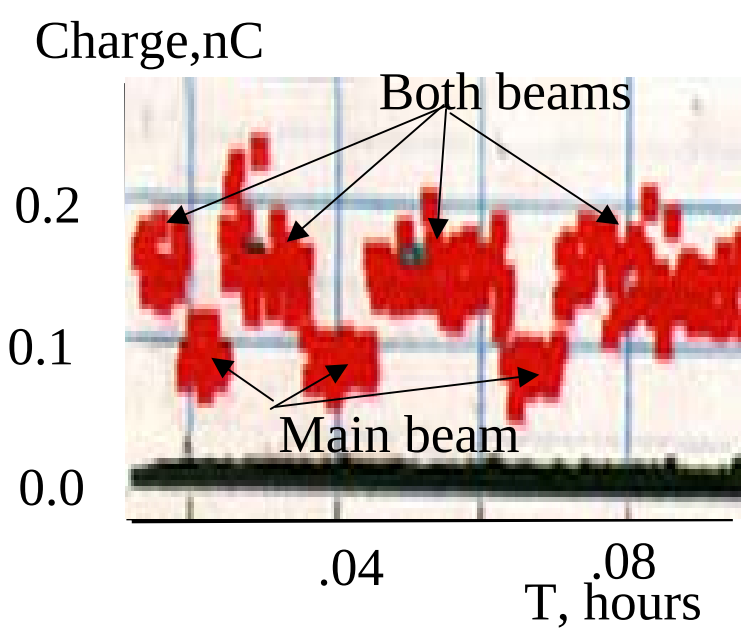
- Experiments at Umichigan: observation of increased temperature of e-beam

Injector concept: Colliding pulse injection

- Fast + slow phase velocity (beat) structure



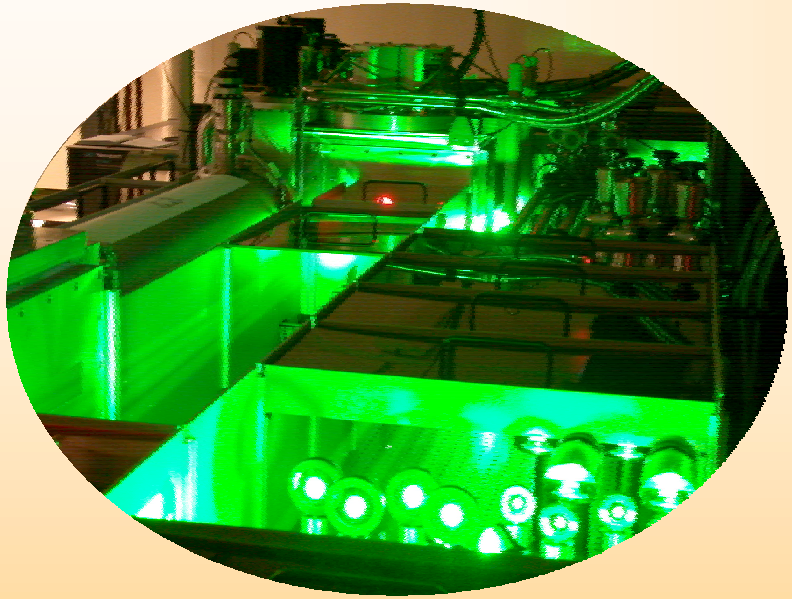
- Time gated injection when pulses overlap
- Lower intensity for trigger pulse then LILAC
- Expected bunch properties
  - 40 MeV in mm
  - Femtosecond bunches
  - %-level energy spread
  - > 10 pC charge



- Preliminary experiment at LBNL (2002)
  - Reduced main drive beam to obtain low "dark current"
  - Observed enhanced e-yield but…
- Physical mechanism:
  - Beat-wave ?
  - Wake-wake interaction ?
  - Heating ?
- Operate in standard wakefield regime
  - Avoids self-trapping
  - Needs guiding to overcome diffraction

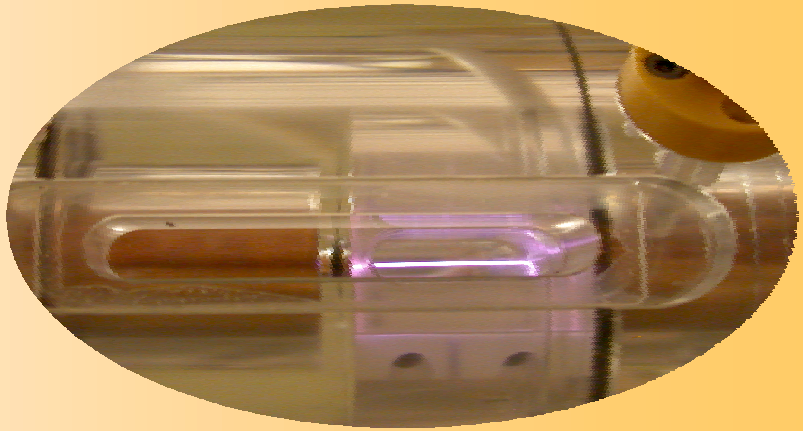
Next step: 1 GeV compact module
100 TW laser + plasma channel

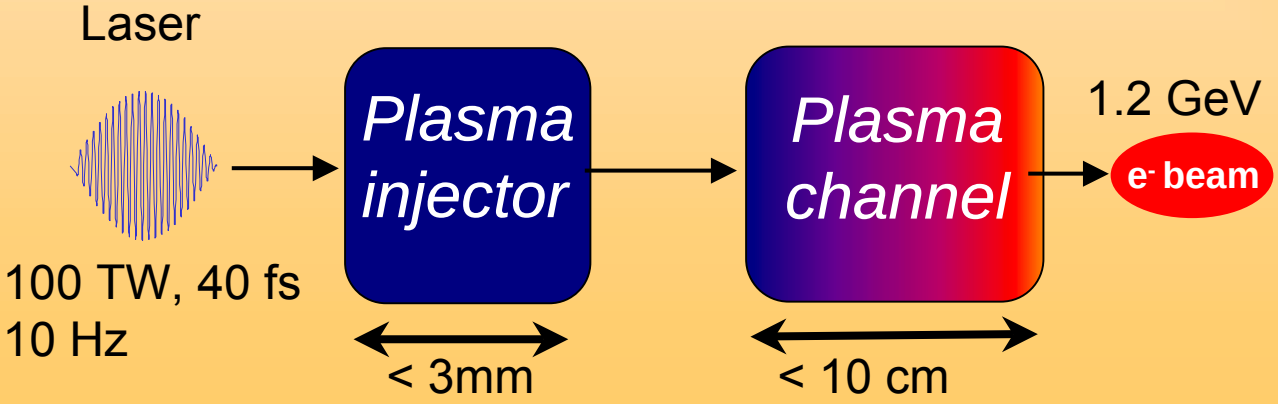
L'OASIS Laser



+

Plasma channel technology





- High energy e-beams
- Femtosecond x-rays
- THz radiation
- Radio-isotopes

Summary

- Ultra-high gradient (10-100 GV/m): > 100 MeV in mm-scale length accelerator ✓
- Femtosecond electron bunches ✓
- High charge yield (multi-nC) but with 100 % energy spread ✓
- Laser guiding at relativistic intensities in preformed channels ✓
- Significantly reduced energy spread observed: acceleration to dephasing length ✓
- Low divergence beams (mrad-level) ✓
- Laser triggered injection experiments underway
- 1 GeV module within reach using 1-10 cm channels
- Laser technology key to success (beam stabilizers, adaptive optics etc…)
- Plasma technology key to success: gas and cluster jets, discharge based systems
- Open questions
  - Stability of accelerator
  - Beam quality: is collider-relevant possible ?
  - Scalability: can plasma channels guide high intensity laser pulses over m-scale?
  - Efficiency: will lasers reach required wall-plug efficiency?

Acknowledgment

Members of l'OASIS team

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DOE -HEP Advanced Accelerator Technology