Laser-Plasma Acceleration WG

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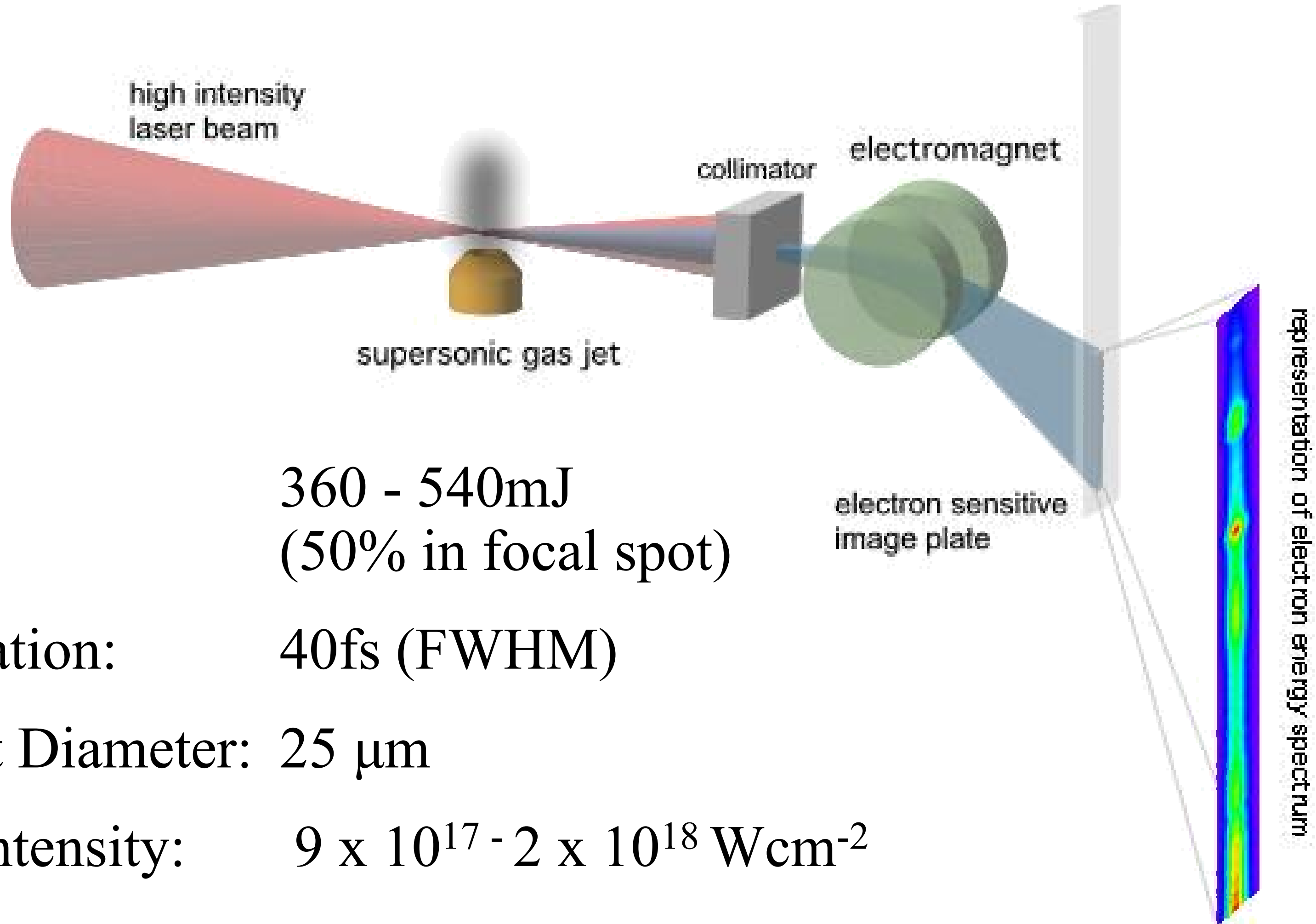
AAC 2004 Experimental Results Laser-Plasma Accelerator WG

	LOA	LBNL	RAL-alphaX	AIST	University of Tokio	Neptune, UCLA	NRL	JAERI	Osaka University	KERI
Scheme	SM(for-ced)LWFA	SM-LWFA	SM-LWFA	SM-LWFA	SM-LWFA	PBWA	SM-LWFA	SM-LWFA	LWFA	SM-LWFA
Laser parrs	30TW 0.8 mkm, 3x1018 W/cm2, W0=18 mkm, 30fs	8TW 0.8 mkm,1x10 19 W/cm2W0 =7 mkm, 55fs	16TW 0.8 mkm ,1x1018 W/cm2W0 =25 mkm,40fs	2TW 0.8 mkm 5x1018 W/cm2W0 =5 mkm,50fs	6TW 0.8 mkm 1x1019 W/cm2W0 =6 mkm,50fs	1TW 10.3+ 10.6.mk	10TW 1.06 mkm3x10 18 W/cm2W0 =12 mkm, 500s	20TW 0.8 mkm2.x10 19 W/cm2W0 =5 mkm,, 23fs	30TW 1.06 mkm	2TW 0.8 mkm
Plasm. Density	$6x10^{18}$ cm^{-3}	$2x10^{19}$ cm^{-3}	$2x10^{19}$ cm^{-3}	$.1.5x10^{20}$ cm^{-3}	$1.8x10^{19}$ cm^{-3}	$1x10^{16}$ cm^{-3}	$1x10^{19}$ cm^{-3}	$1.4x10^{20}$ cm^{-3}	$6x10^{16}$ cm^{-3}	$1x10^{18}$ cm^{-3}
Injector type	Self-trapped	Self-trapped	Self-trapped	Self-trapped	Self-trapped	12 MeV external	Optical Injection ioniz.	Self-trapped	Self-trapped	Self-trapped
Energy Gain	>170±15 MeV, 500 pC,	86 ±2 -150 MeV 300 pC	78 ±2 MeV 20 pC	7 ±1 MeV 2 pC	40 MeV	38 MeV	20 MeV	40 MeV	100 MeV	2 MeV
		Channel		Integrated over 90 shots spectrum		Ponderomotive channel	2 TW beam for LIPA injector		Glass capillary	

Experimental Set-Up



Energy: 360 - 540mJ
(50% in focal spot)

Pulse Duration: 40fs (FWHM)

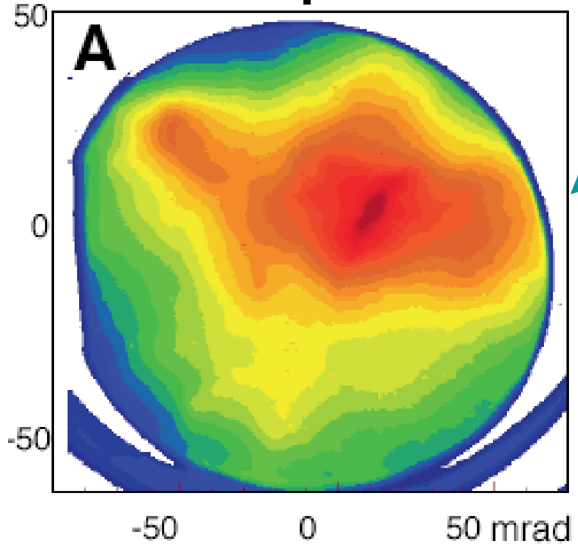
Focal Spot Diameter: 25 μm

Vacuum Intensity: 9×10^{17} - 2×10^{18} Wcm^{-2}

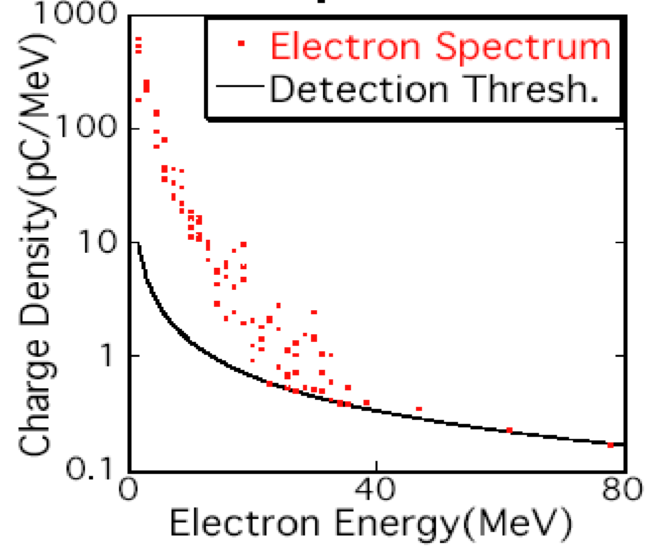
a_0 : 0.7 - 1.0

Breakthrough: 85 MeV e-beam with %-level energy spread from laser accelerator (LBNL)

Beam profile

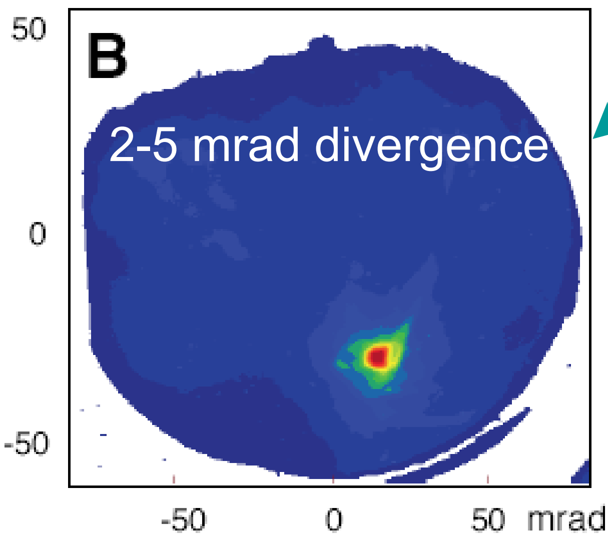


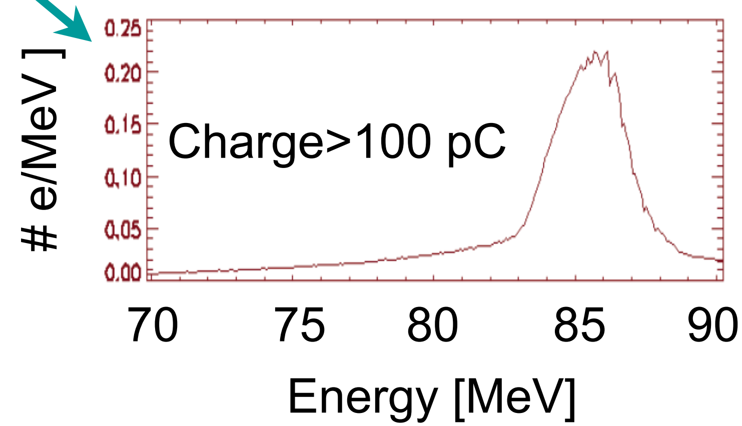
Spectrum



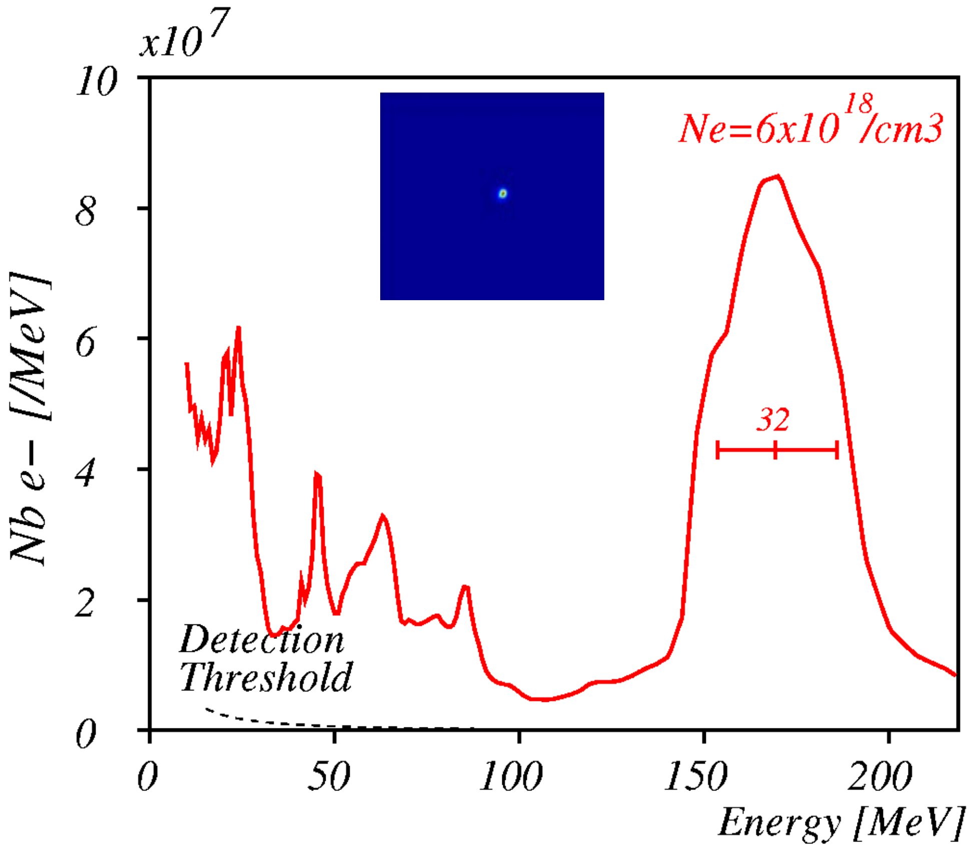
Unguided

Guided

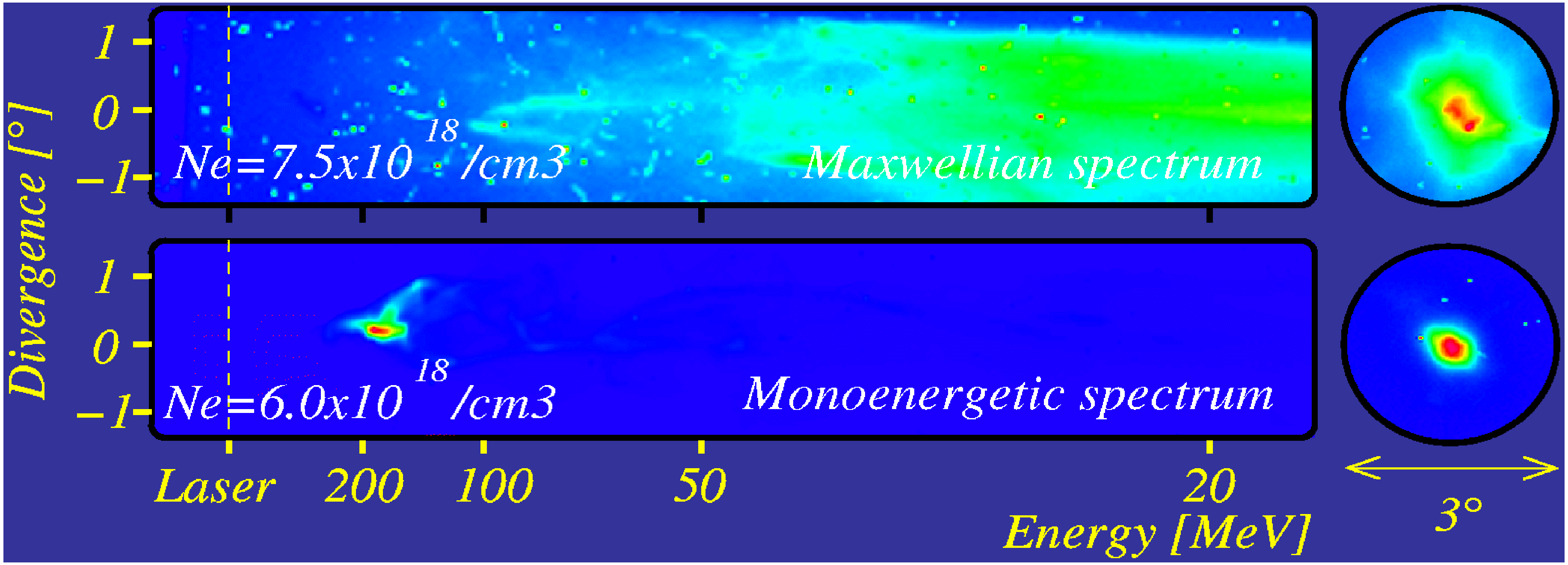




Recent results on e-beam : Energy distribution improvements V. Malka (LOA)



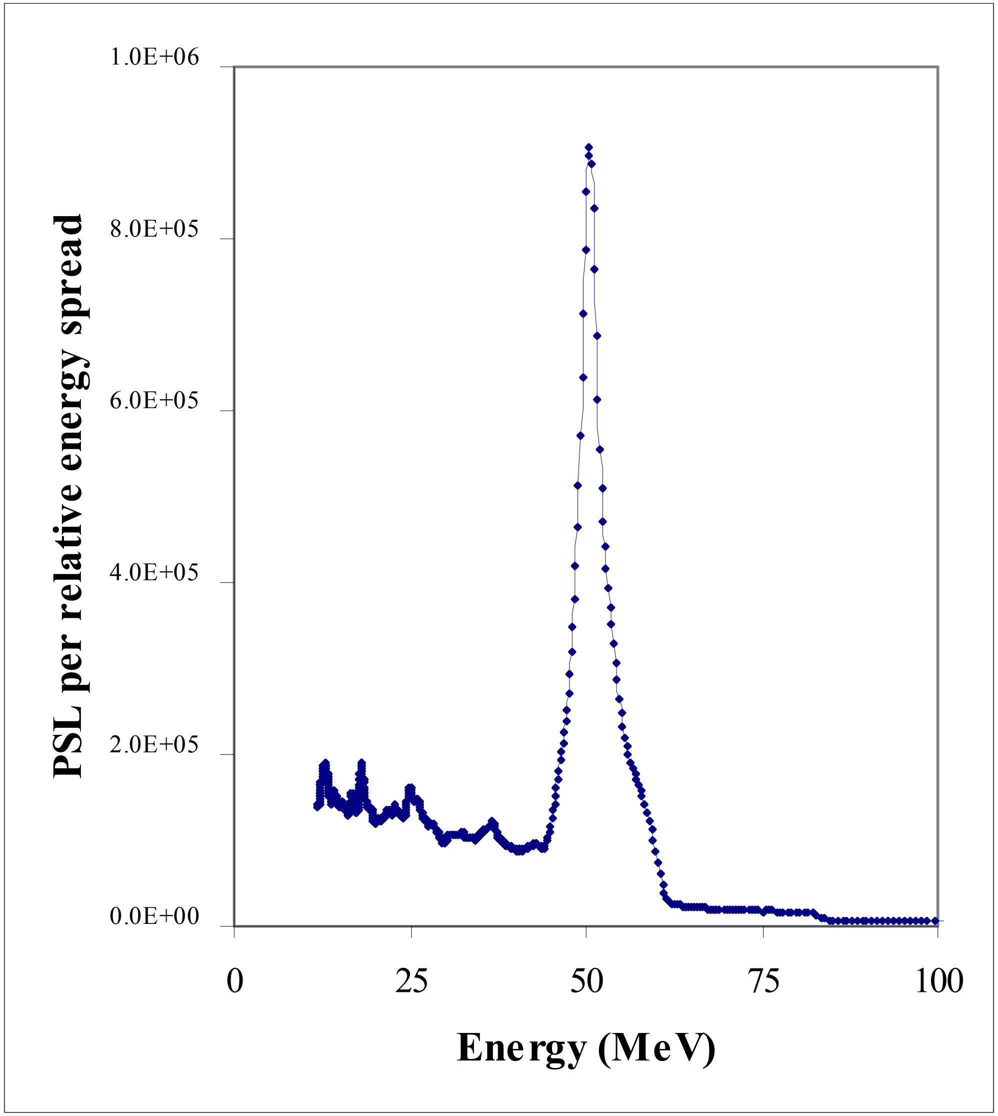
Recent results on e-beam : Energy distribution improvements



N.B. : color tables are different

Results (C.Murphy, IC/RAL)

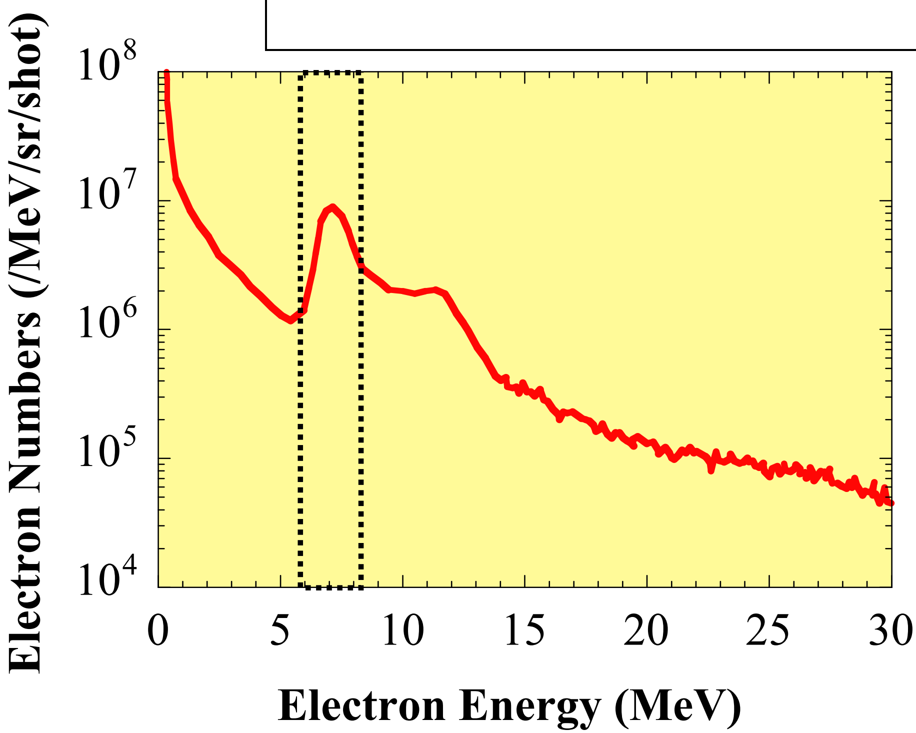
- Electron Spectrum:
  - A single mono-energetic feature over the top of an exponential observed at energies in excess of 50MeV
  - Underestimate of energy due to neglect of fringe fields

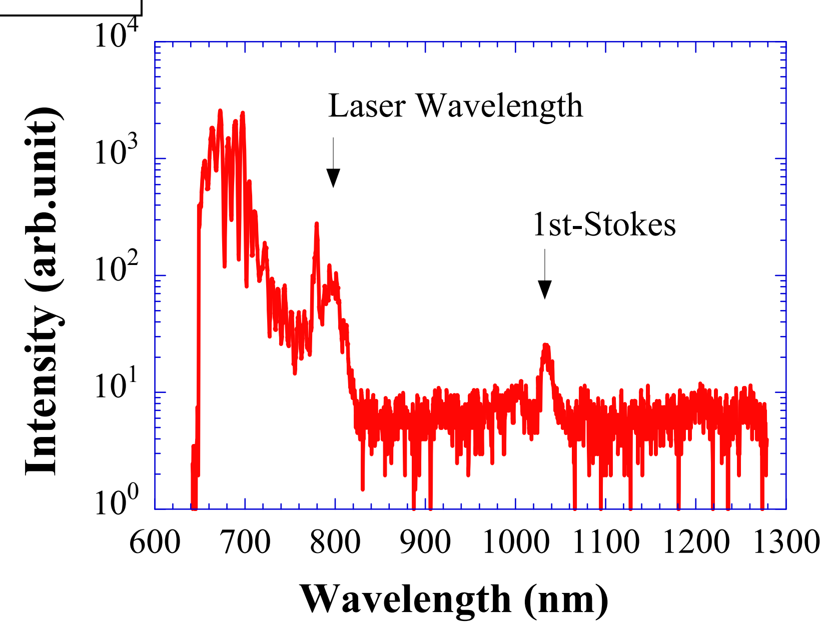


Electron Energy Spectrum including quasi-monoenergetic beam

K.Koyama (AIST, Japan)

Monoenergetic beam was emitted in an narrow divergence angle.



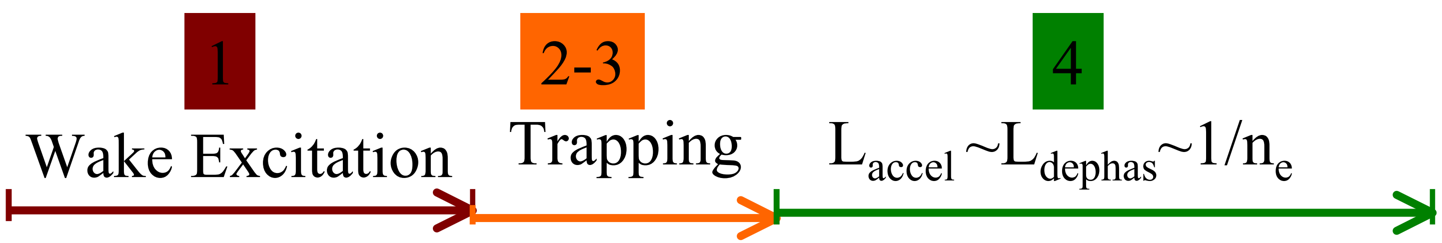


Production of a Monoenergetic Beam

1. Excitation of wake (e.g., self-modulation of laser)
2. Onset of self-trapping (e.g., wavebreaking)
3. Terminatinon of trapping (e.g., beam loading)
4. Acceleration

If > dephasing length: large energy spread

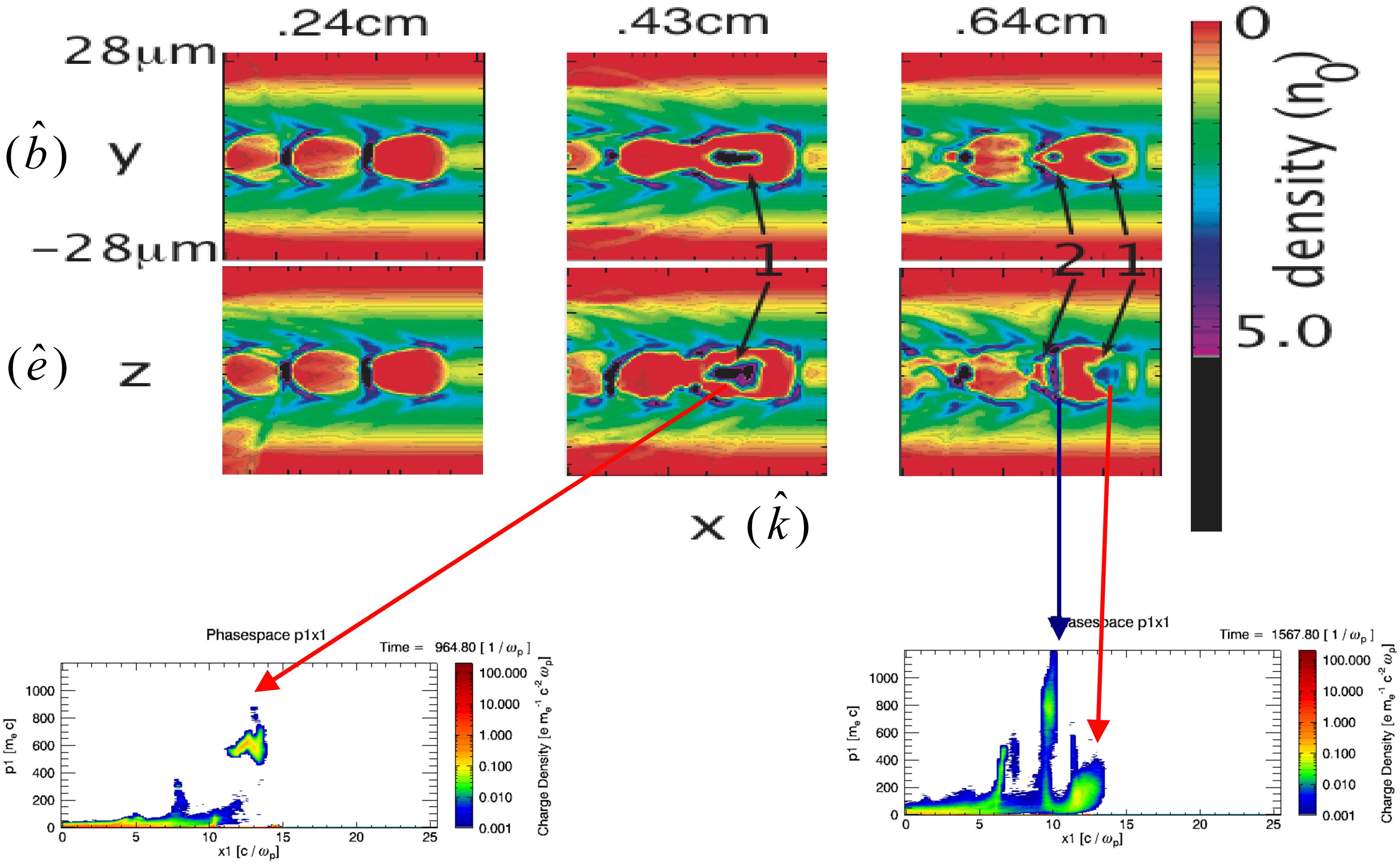
If < dephasing length: monoenergetic



Optimal choice of the plasma density: the smallest possible density
For conditions 1 -4 to be fulfilled.

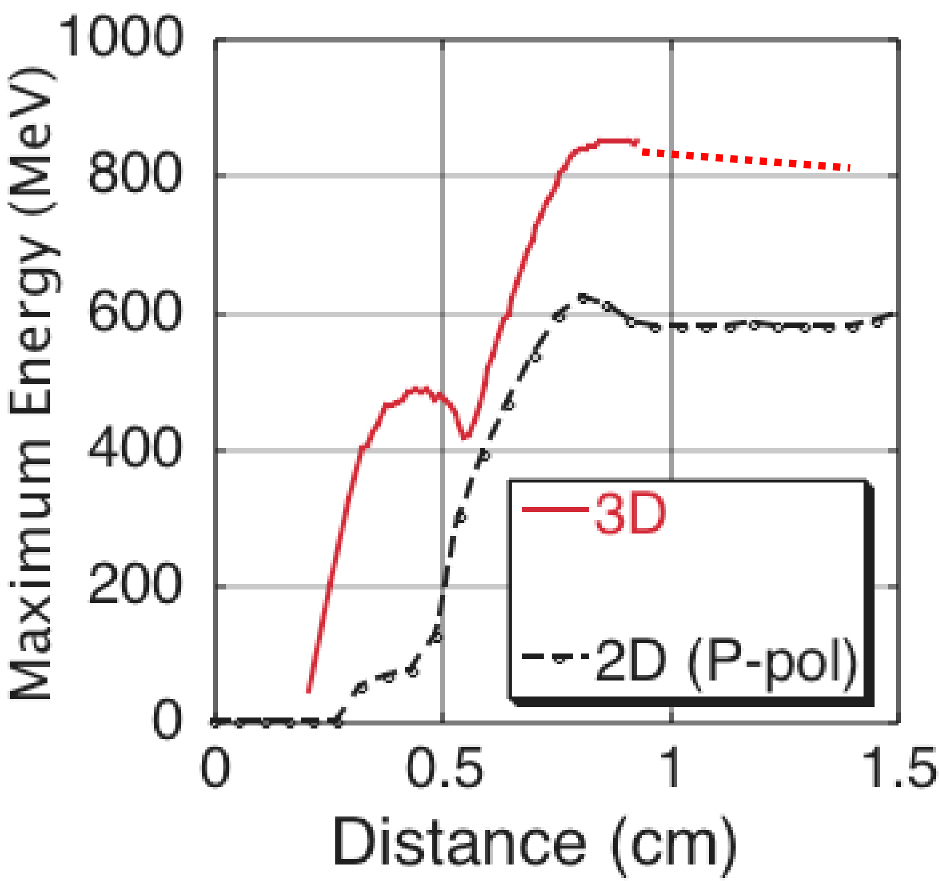
2D PIC Code (W. Mori,UCLA)

Beam loading of first bunch contributes to the generation of a second bunch

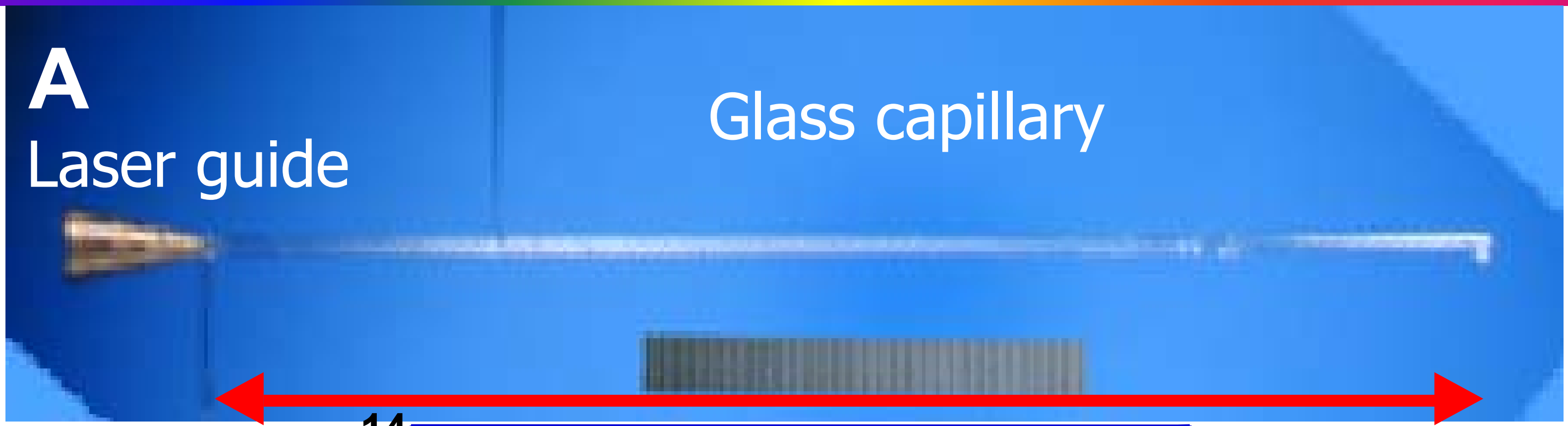


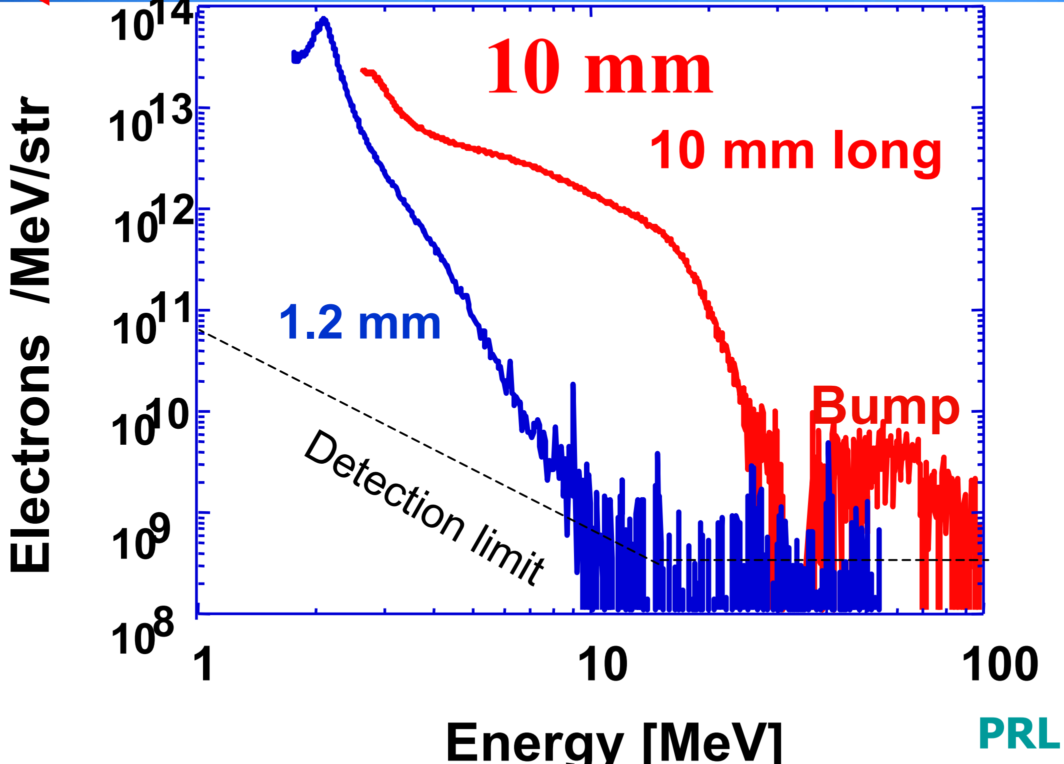
Electron Energy of ~1GeV range observed in our 3D channel simulation

- (3D) Maximum Energy = 840 MeV (over a distance .84 cm)
- 2 acceleration stages, the first bunch reaches ~500MeV then dephases. The second bunch achieves much higher energies (~840MeV)
- 2D Simulations only has 1 group of fast electrons
- 2D simulations underestimate maximum energy gain
- 2D simulations overestimate accelerated charge



Ultra-Intense Laser is illuminated into a glass capillary, which accelerates plasma electrons to 100 MeV
Y.Kitagawa-Osaka





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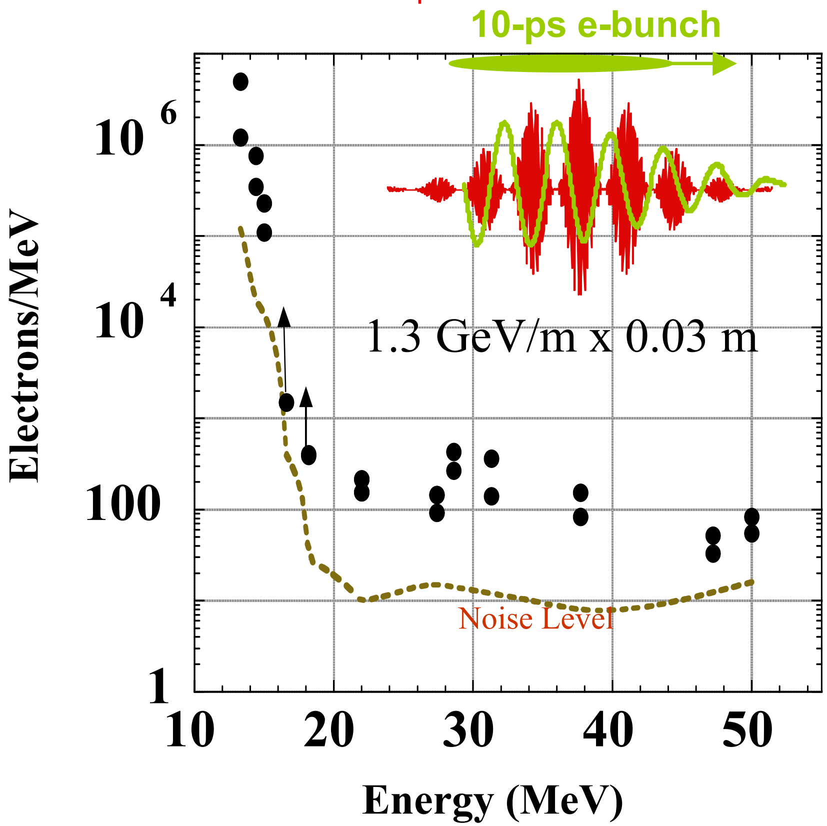
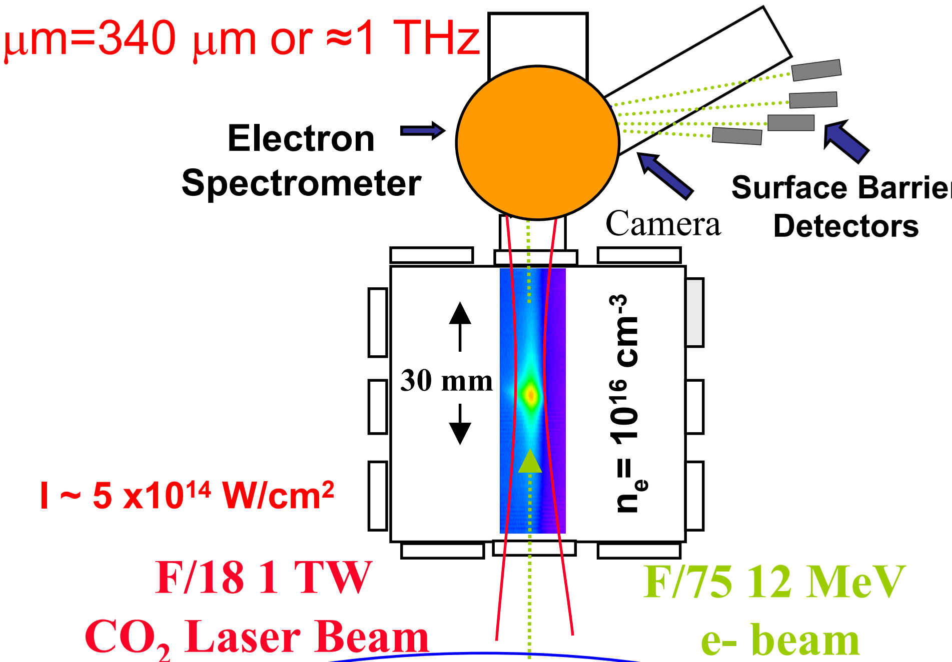
UCLA

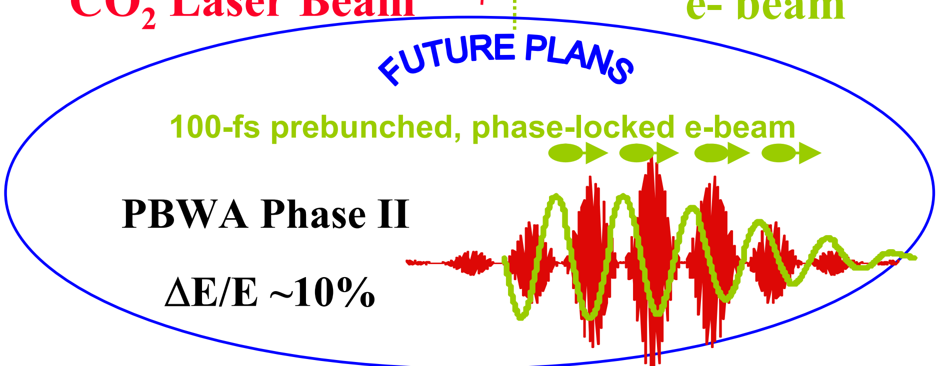
Enhanced acceleration of externally injected electrons in a PBWA

Injection of an electron beam into a 3-cm long ponderomotively formed plasma channel

$\omega_1 - \omega_2 = \omega_{plasma}$ 10.3 μm - 10.6 μm=340 μm or ≈1 THz



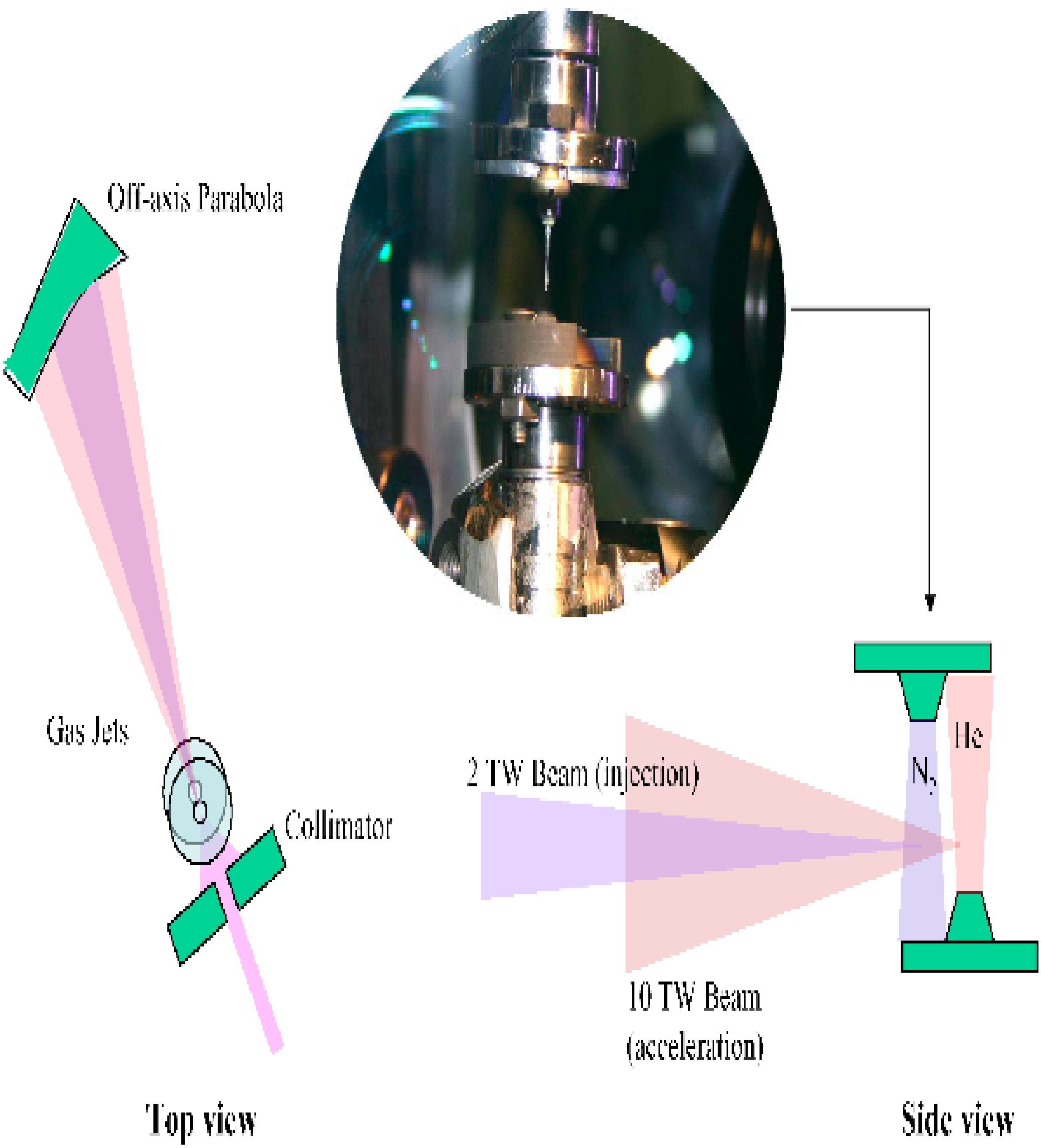




S. Tochitsky et al, PRL, March, 2004

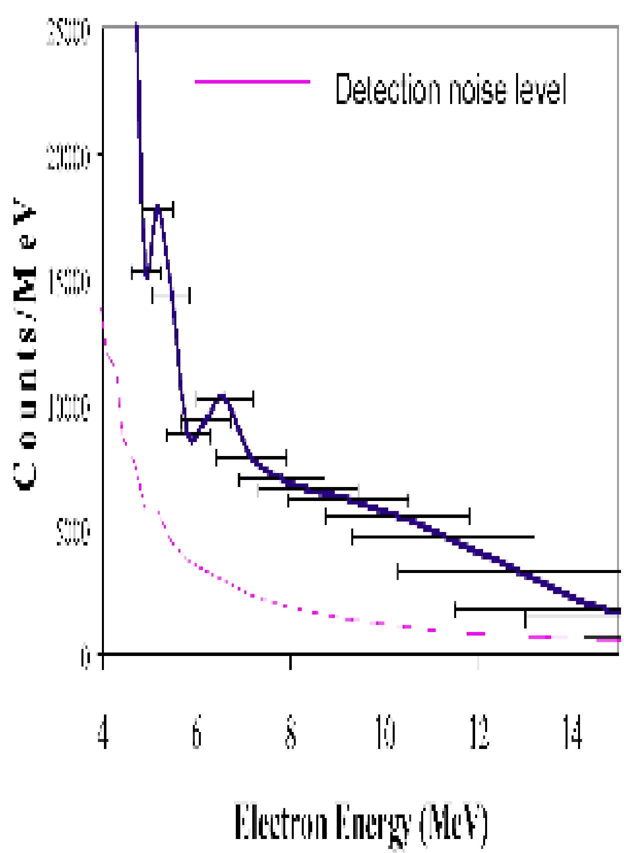
Staged Optical Injection and Laser Wakefield Acceleration

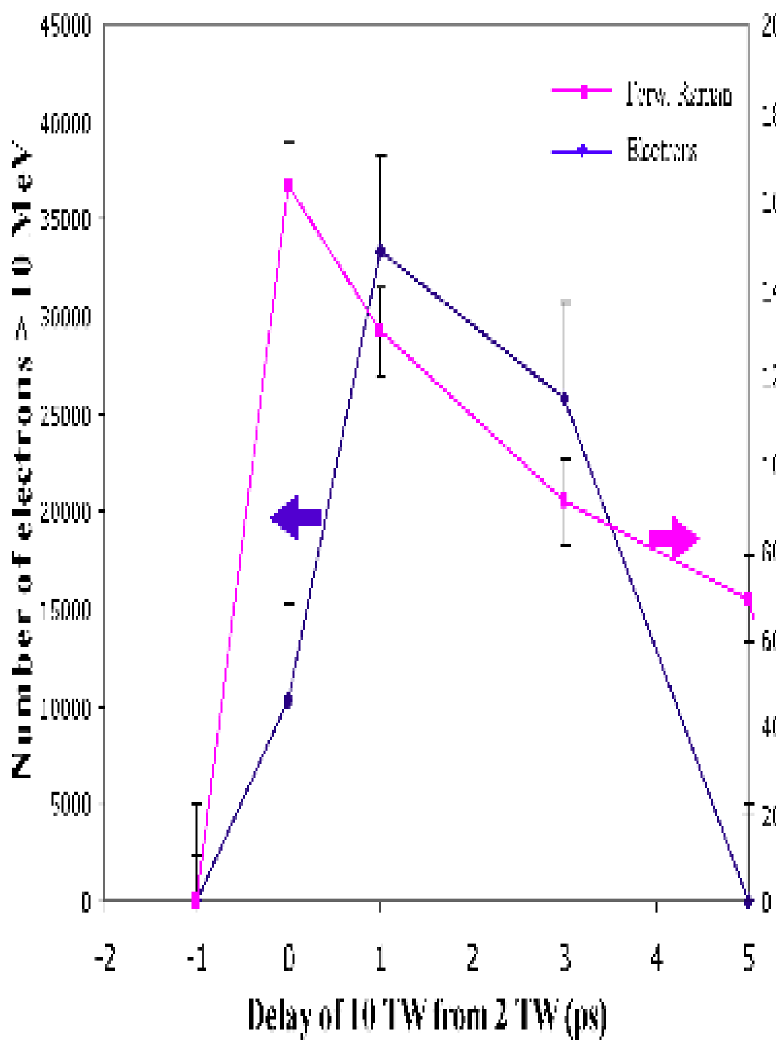
- Synchronized, collinear, two jet, two-beam (2TW/10TW) laser configuration



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 <4 psec
- Delay of electrons from peak forward Raman signal shows:
  - Injection electrons not from background plasma
  - Slippage of injection electrons from laser pulse





Scaling Laws for LWFA

Depletion vs. Dephasing

- Dephasing length

$$L_{dph} = (1/2)(\lambda_p^3/\lambda^2) \times \begin{cases} 1, & a_0^2 \ll 1 \\ (\sqrt{2}/\pi)a_0/N, & a_0^2 \gg 1 \end{cases}$$

- Pump depletion length

$$L_{pd} = (1/2)(\lambda_p^3/\lambda^2) \times \begin{cases} 2/a_0^2, & a_0^2 \ll 1 \\ (\sqrt{2}/\pi)a_0, & a_0^2 \gg 1 \end{cases}$$

- Summary

$$a_0^2 \ll 1 \Rightarrow L_{dph} \ll L_{pd}$$

$$a_0^2 \gg 1 \Rightarrow L_{dph} \sim L_{pd}$$

Energy Gain: $\Delta W = eE_z L_{acc}$

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

$$\Delta W[\mathrm{MeV}] \sim 740(\lambda/\lambda_p)(1 + a_0^2/2)^{-1/2} P[\mathrm{TW}]$$

- Dephasing: $L_{acc} \simeq L_{dph}$

$$\Delta W \simeq (\pi/2)mc^2(\lambda_p^2/\lambda^2)a_0^2 \times \begin{cases} 1, & a_0^2 \ll 1 \\ (2/\pi)/N, & a_0^2 \gg 1 \end{cases}$$

$$\Delta W[\mathrm{MeV}] \simeq 630\frac{I[\mathrm{W/cm^2}]}{n[\mathrm{cm^{-3}}]} \times \begin{cases} 1, & a_0^2 \ll 1 \\ (2/\pi)/N, & a_0^2 \gg 1 \end{cases}$$

- Depletion: $L_{acc} \simeq L_{pd}$

$$\Delta W \simeq \pi mc^2(\lambda_p^2/\lambda^2) \times \begin{cases} 1, & a_0^2 \ll 1 \\ (1/\pi)a_0^2, & a_0^2 \gg 1 \end{cases}$$

$$\Delta W[\mathrm{MeV}] \simeq \begin{cases} 3.4 \times 10^{21}/(\lambda^2[\mu\mathrm{m}]n[\mathrm{cm}^{-3}]), & a_0^2 \ll 1 \\ 400 I[\mathrm{W/cm^2}]/(n[\mathrm{cm}^{-3}]), & a_0^2 \gg 1 \end{cases}$$

One of many 1 GeV scenarios

Energy Gain: Example

- Optimal Regime: Nonlinear $a_0^2 \gg 1$

  Larger energy gain, larger fields, shorter distance
  Dephasing $\sim$ depletion, more energy efficient

- Laser:

  $P = 100$ TW, $a_0 = 3$, $\lambda = 0.8$ μm, $r_0 = 18$ μm
  $I = 1.9 \times 10^{19}$ W/cm^2, 55 fs, 5.5 J

- Plasma: $L_L = \lambda_p/2$

  $\lambda_p = 33$ μm ($n_0 = 10^{18}$ cm^{-3})

- Wakefield

$$E_z = 190 \text{ GeV/m}$$

- Diffraction: Unchanneled

$$L_{acc} = 0.4 \text{ cm}$$

$$\Delta W = 750 \text{ MeV}$$

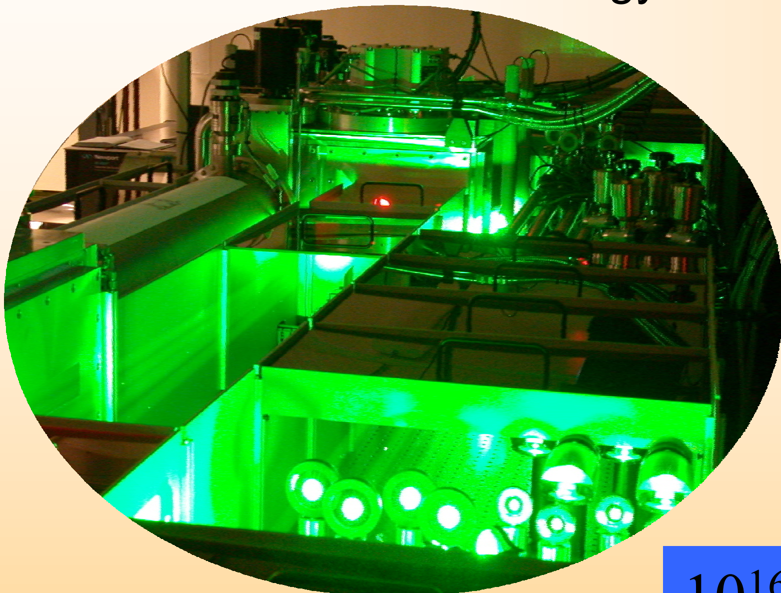
- Depletion/Dephasing: Channeled

$$L_{acc} = 3.8 \text{ cm}$$

$$\Delta W = 7.2 \text{ GeV}$$

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

L'OASIS Laser technology



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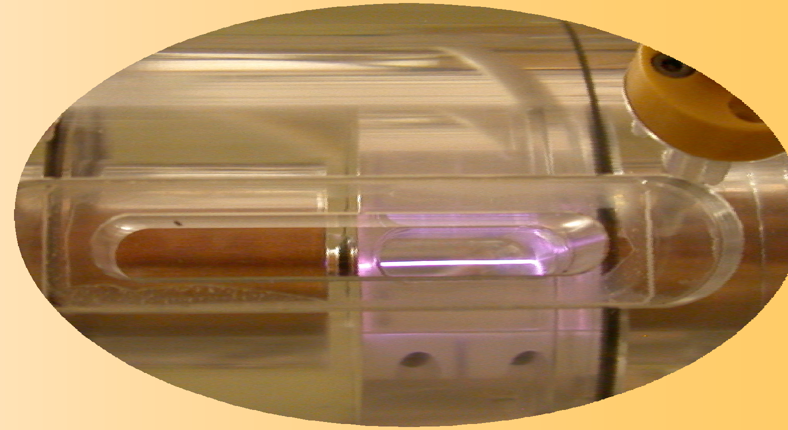
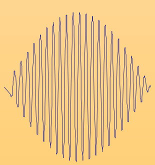
Plasma channel technology



10^{16}-10^{18} cm^{-3}

Laser



100 TW, 40 fs
10 Hz

→ *Electron injector* (< 3mm) → *Plasma channel* (< 10 cm) → 1-3 GeV e^- beam

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