Recent Progress on Laser-Plasma Accelerators

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LOASIS Program, Lawrence Berkeley National Laboratory

My Thanks: Many colleagues who provided material

My Apologies: Many results are not included - see talks and working group

Advanced Accelerator Conceprts Workshop, 17 July 2006
Supported by DoE

Outline

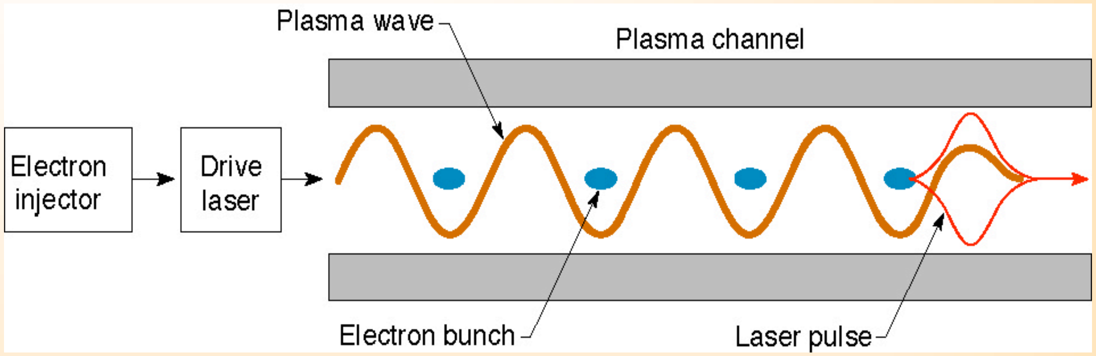
- Brief Review: Status Prior to 2004
  - Self-modulated laser wakefield accelerator regime
  - 100% energy spread, max energy > 100 MeV, nC's of charge
  - Few TW, few-mm gas jet, "high" plasma densities 10^{19}-10^{20} cm^{-3}
- High quality e-beam production at 100 MeV-level (2004)
  - Narrow energy spread, small divergence, 100 MeV, 100's pC
  - Few - 10 TW, few-mm gas jet, "lower" plasma densities 10^{18}-10^{19} cm^{-3}
  - With and without plasma channel guiding
- High quality e-beam production at 1 GeV-level (2006)
  - Narrow energy spread, small divergence, 1 GeV, 100 pC
  - Tens of TW, "lower" plasma densities 10^{18}-10^{19} cm^{-3}
  - Few-cm long plasma channel guiding (capillary discharge)

Outline (continued)

- Laser injection methods
  - Stable, reproducible, high quality beams
  - Experiments underway
- Prospects for acceleration > 1 GeV
  - Staging (injector + channel)
  - Modeling and scaling laws
- Diagnostics and radiation generation
  - Measure laser, plasma, and e-beam properties
  - Use laser probes and radiation generated by e-beam
- Summary

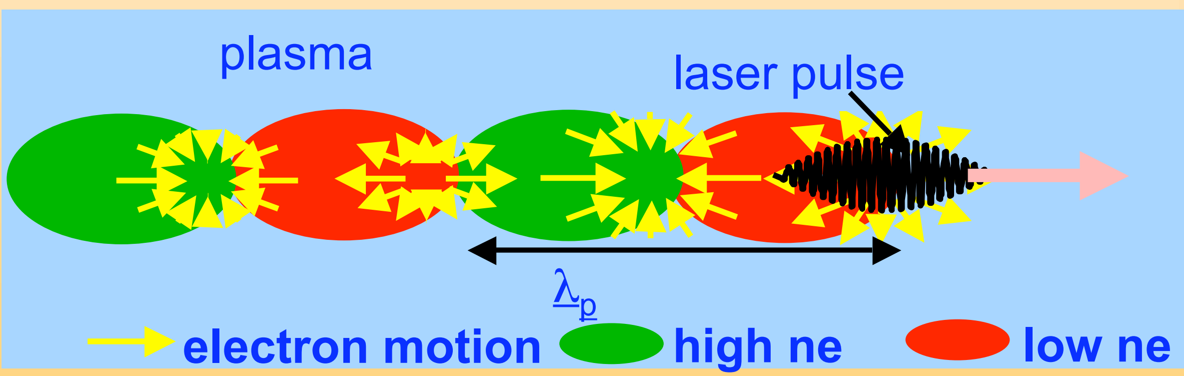
Laser driven excitation of plasma waves: Laser wakefield accelerator

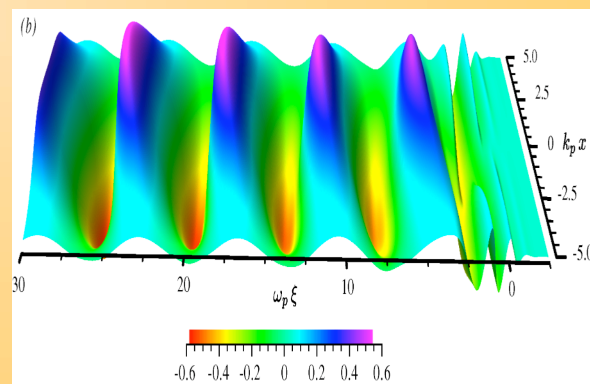
Standard regime (LWFA): pulse duration matches plasma period



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

Radiation pressure of intense laser pulse excites plasma wave (wakefield)





B.A. Shadwick et al., IEEE PS. 2002

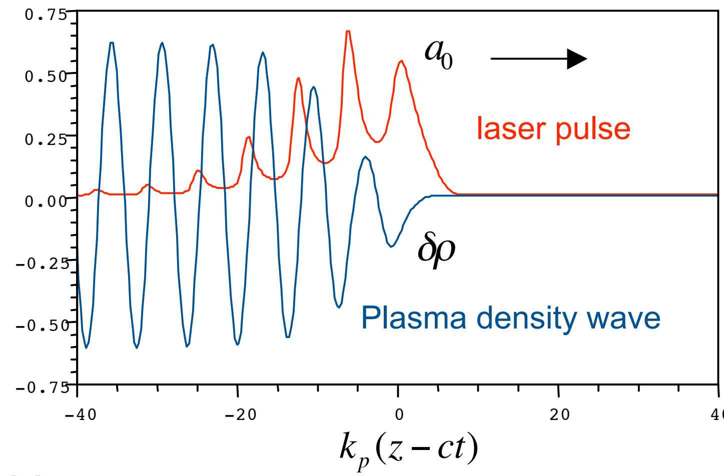
Tajima, Dawson (79); Gorbunov, Kirsanov (87); Sprangle, Esarey *et al.* (88)

State-of-the-Art Prior to 2004:
Self-Modulated Laser Wakefield Accelerator (SM-LWFA)

Self-modulated regime:

- Laser pulse duration > plasma period
- Laser power > critical power for self-guiding
- High-phase velocity plasma waves by
  - Raman forward scattering
  - Self-modulation instability

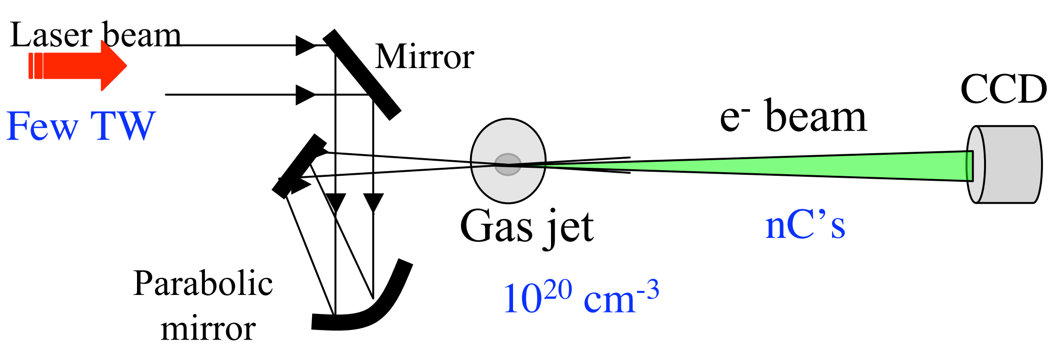
Sprangle *et al.* (92); Antonsen, Mora (92); Andreev *et al.* (92); Esarey *et al.* (94); Mori *et al.* (94)

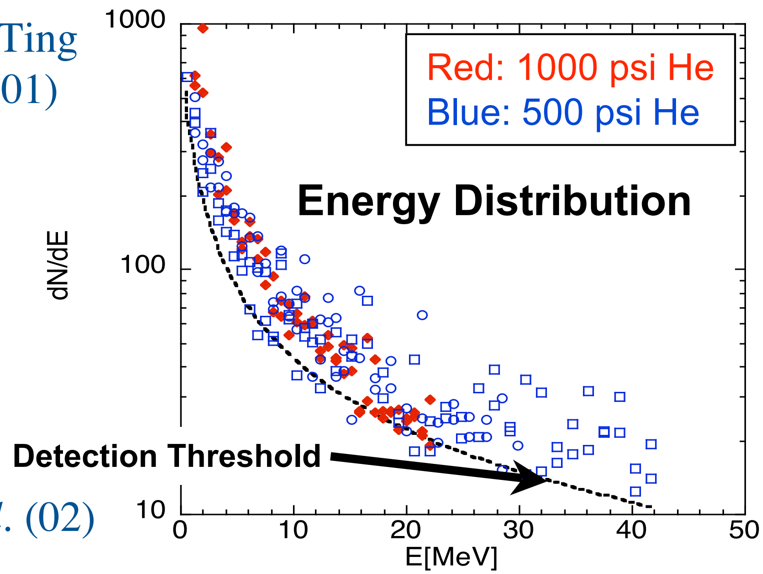


SM-LWFA experiments routinely produce electrons with:

1-100 MeV (100% energy spread), multi-nC, ~100 fs, ~10 mrad divergence

Modena *et al.* (95); Nakajima *et al.* (95); Umstadter *et al.* (96); Ting *et al.* (97); Gahn *et al.* (99); Leemans *et al.* (01); Malka *et al.* (01)





Leemans *et al.* (02)

High quality e-beam production at the 100 MeV-level

Breakthrough Results: High Quality Bunches

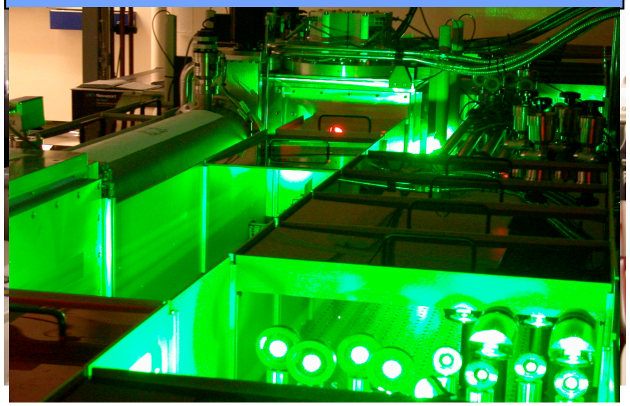
30 Sep 2004 issue of *nature*:

Three groups report production of high quality e-bunches

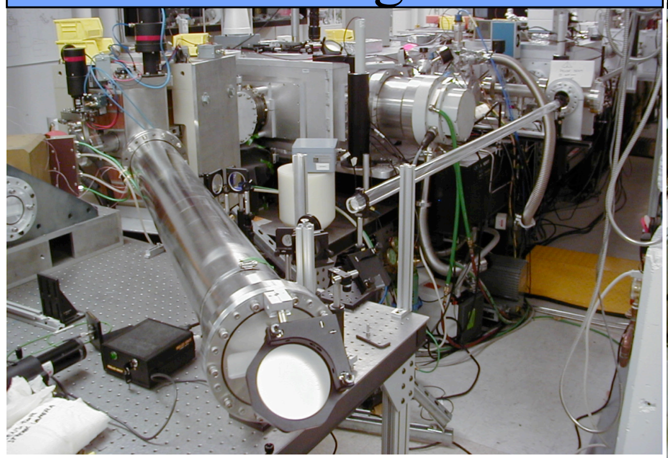
- LBNL/USA: Geddes et al.
  - Plasma Channel: 1-4x10^{19} cm^{-3}
  - Laser: 8-9 TW, 8.5 μm, 55 fs
  - E-bunch: 2×10^{9} (0.3 nC), 86 MeV, ΔE/E=1-2%, 3 mrad
- RAL/IC/UK: Mangles et al.
  - No Channel: 2×10^{19} cm^{-3}
  - Laser: 12 TW, 40 fs, 0.5 J, 2.5×10^{18} W/cm^{2}, 25 μm
  - E-bunch: 1.4×10^{8} (22 pC), 70 MeV, ΔE/E=3%, 87 mrad
- LOA/France: Faure et al.
  - No Channel: 0.5-2x10^{19} cm^{-3}
  - Laser: 30 TW, 30 fs, 1 J, 18 μm
  - E-bunch: 3×10^{9} (0.5 nC), 170 MeV, ΔE/E=24%,10 mrad

LOASIS Lab at LBNL:
high rep rate, high peak power Ti:sapphire system

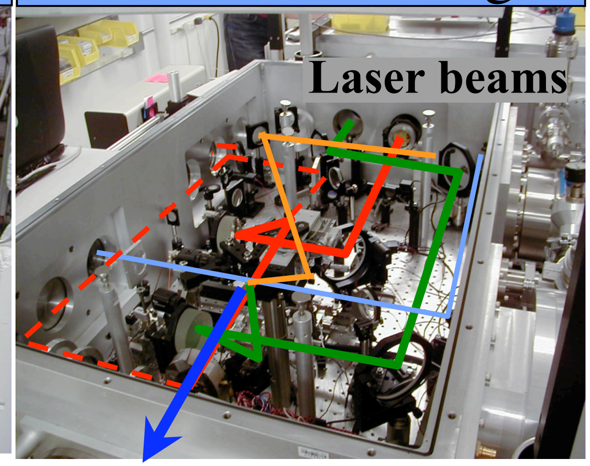
10-100 TW Ti:sapphire



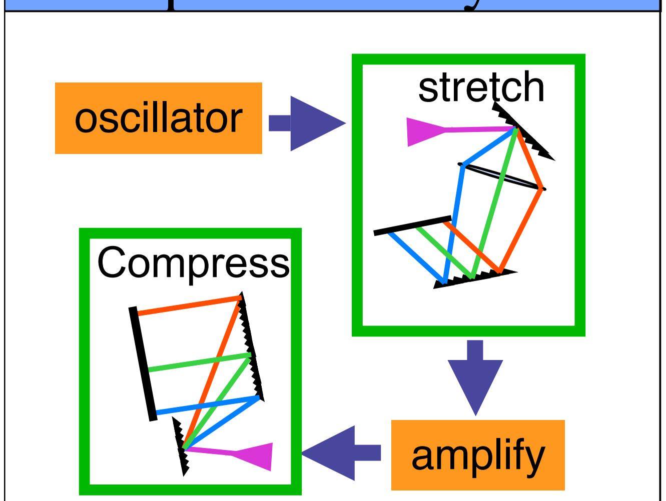
Shielded target room



5+ Beams on Target



Chirped Pulse System



100 TW Ti: sapphire laser system:

3-4 J/pulse

30-50 fs

10^{20} W/cm^2

10 Hz

6 μm spot size

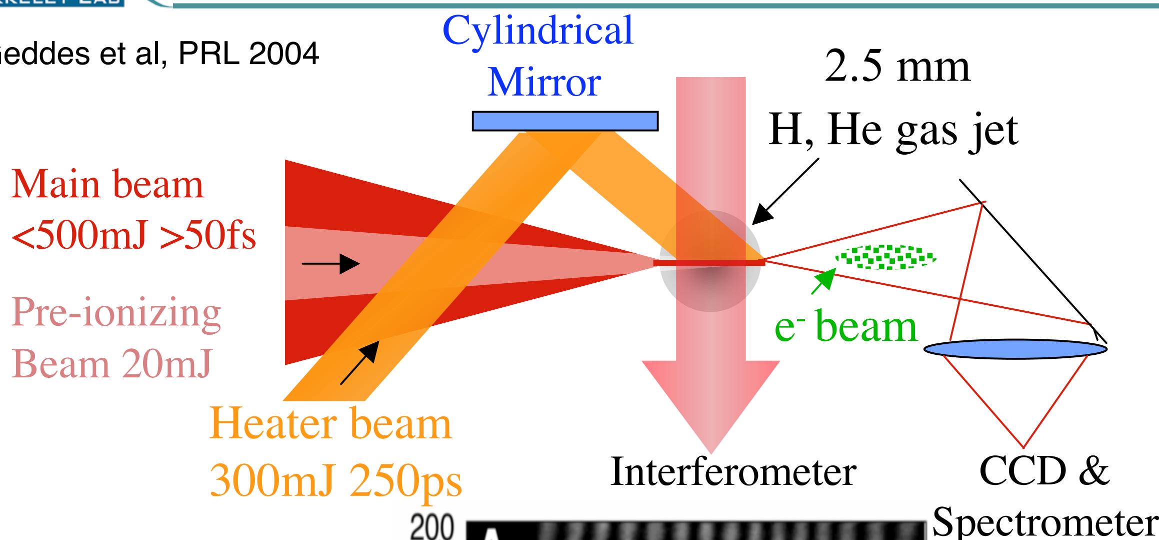
Multiple beams

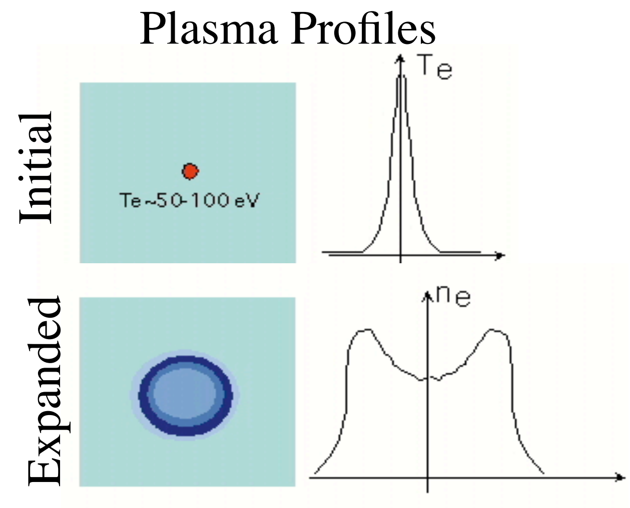
Shielded caves

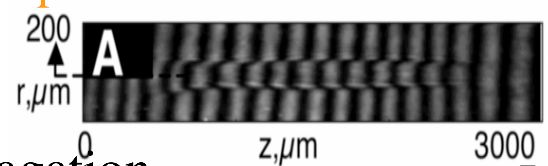
Control Room

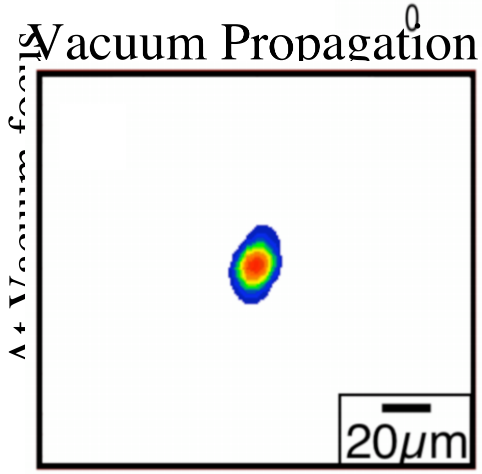
Guided Unaberrated Modes at Relativistic Intensity

Geddes et al, PRL 2004

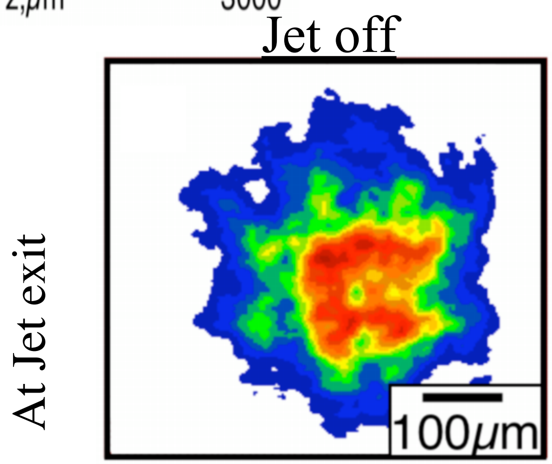




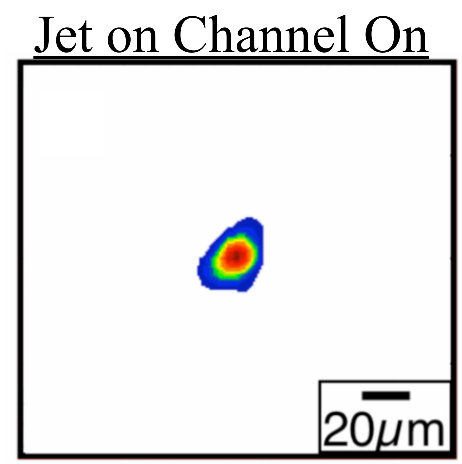




100% within ±16μm
2.5e18 input (7e18)



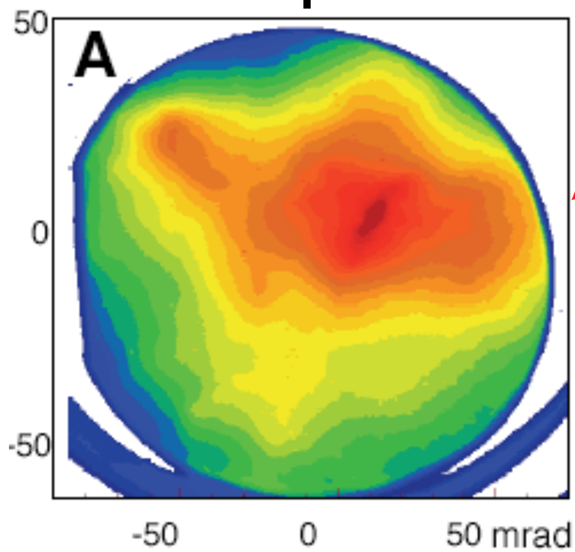
2% within ±16um
Peak@Output ~1.6e16W/cm^2



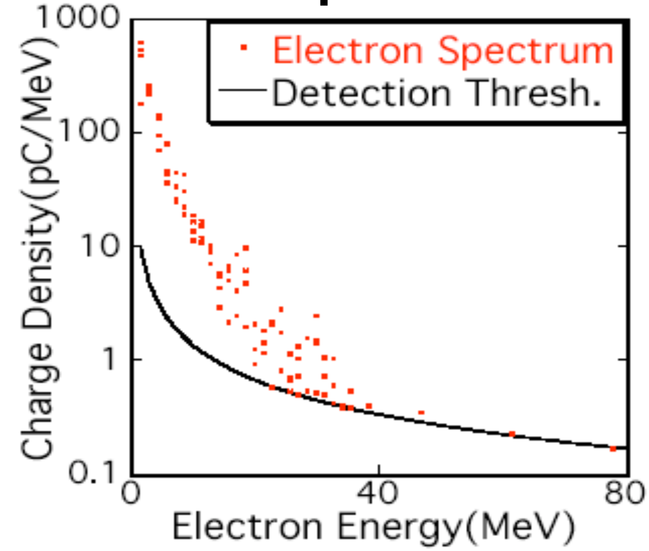
35% guided within ±16μm
Peak@Output >1e18W/cm^2

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

Beam profile

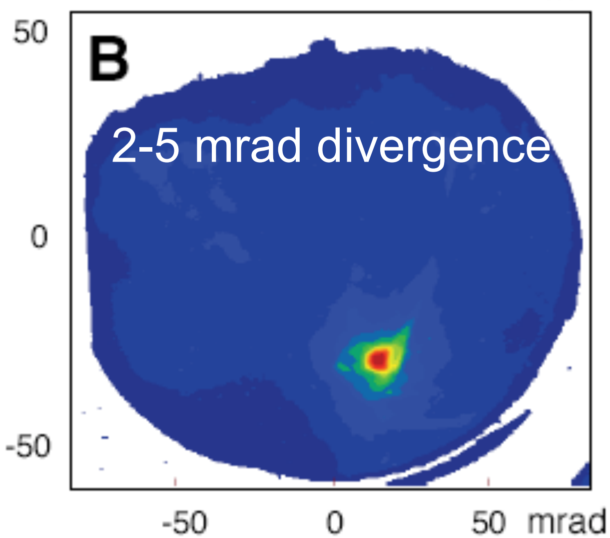


Spectrum

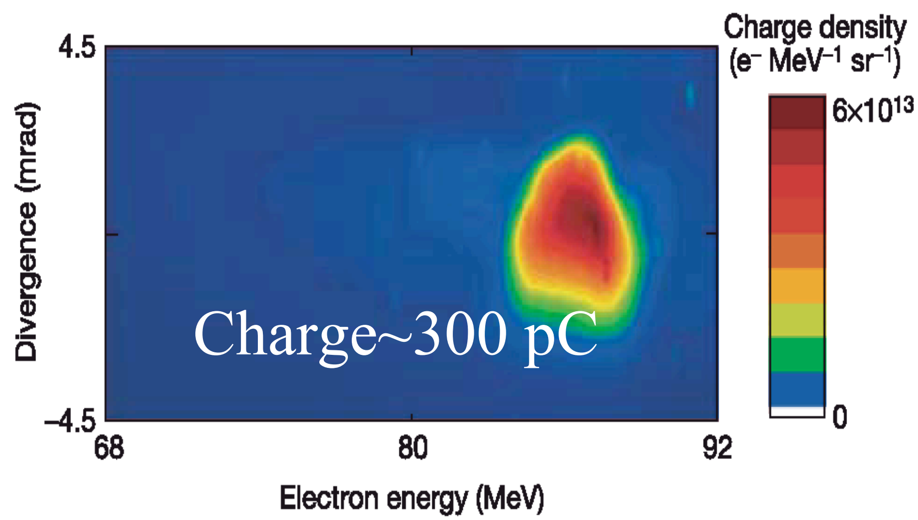


Unguided

Guided

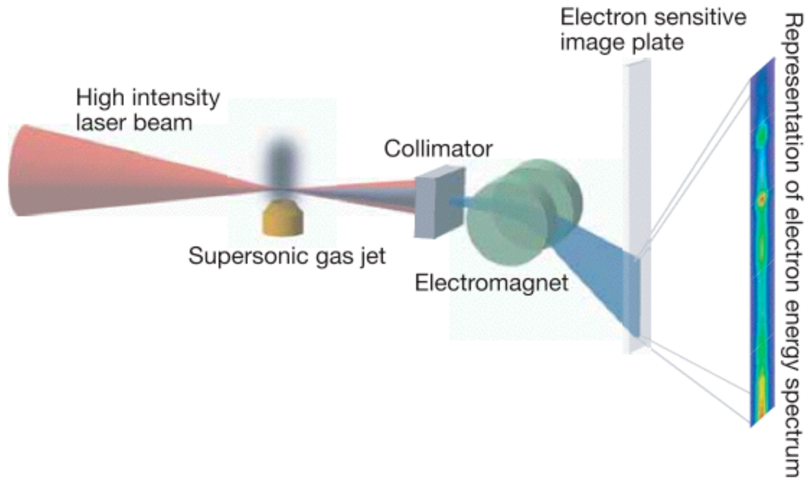


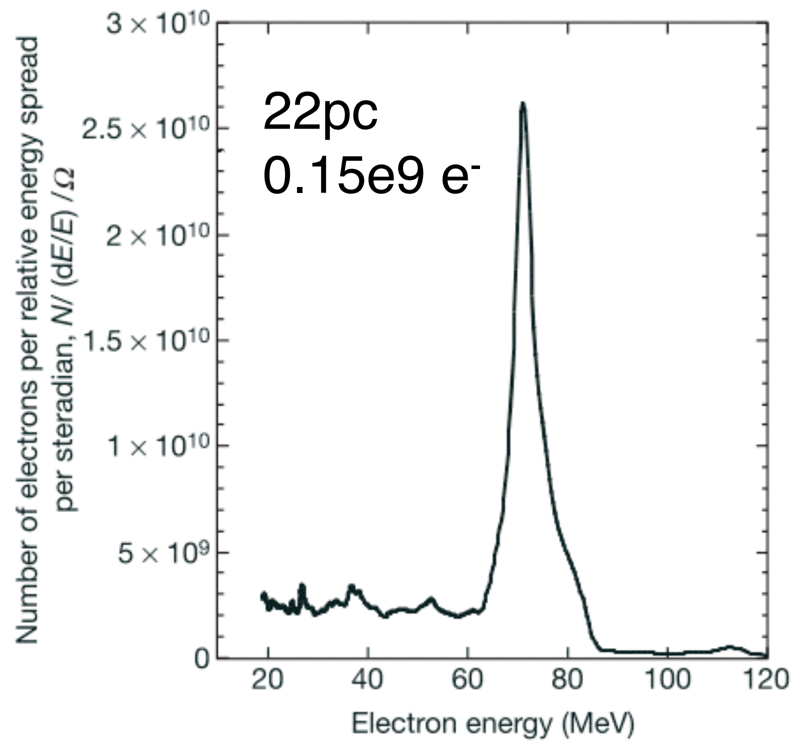
9 TW
50 fs
1.8e19 cm^{-3}
1.7 mm
2e9 electrons
3 mrad
$\Delta E < 4$ MeV



C.G.R Geddes *et al*, Nature, Sept 30 2004

Imperial/RAL Experiments - Mononoenergetic Beams From Unchanneled Accelerator





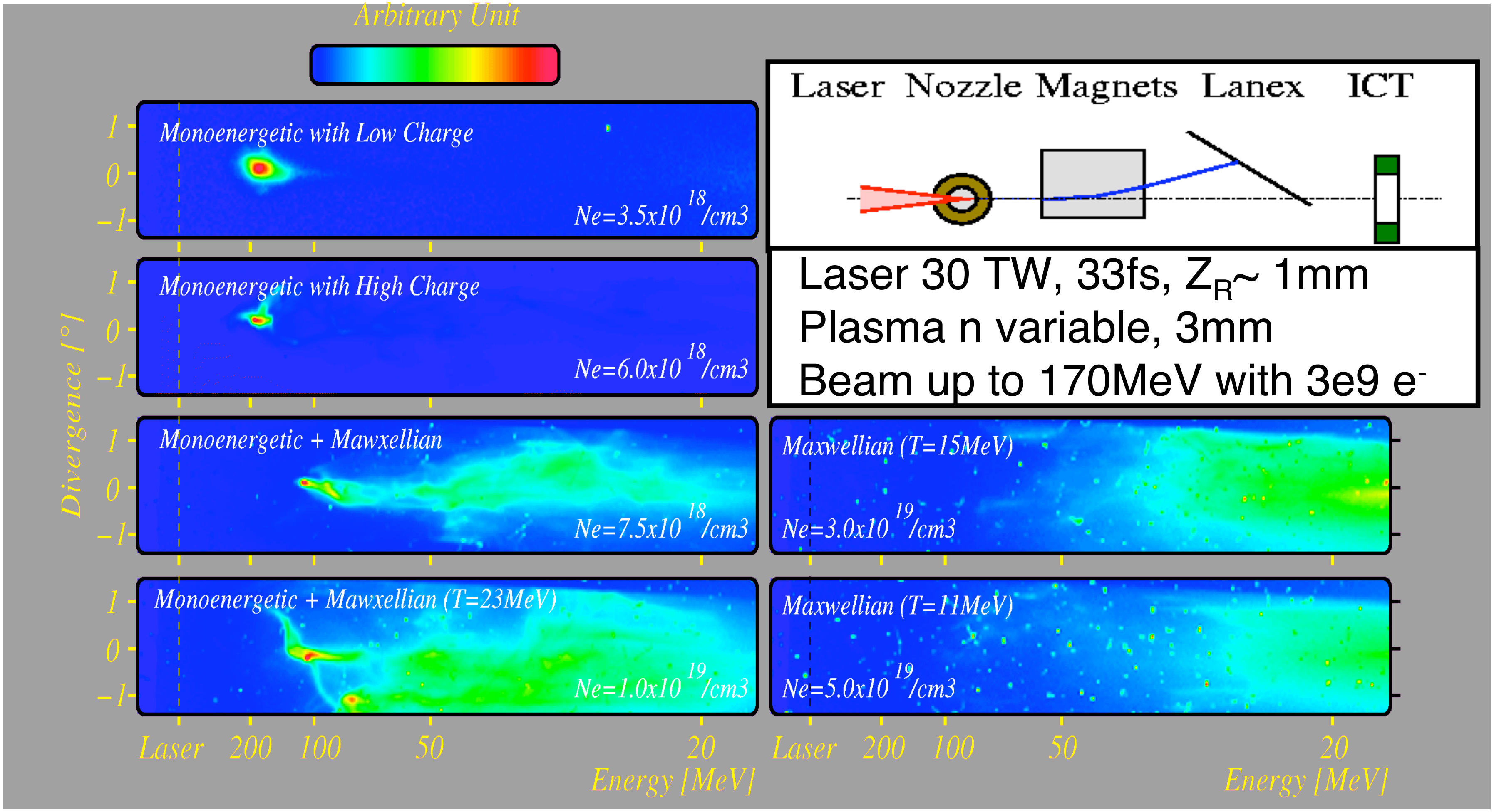
Laser: 12 TW, 40fs, Z_R~ 1mm
Plasma: n ~ 2e19, 2mm
Beam: up to 80MeV with 0.15e9 e^-

Density scan shows monoenergetic beams only at n=2e19 cm^{-3}

Data and figures from Mangles,et al, Nature 2004

LOA

Recent results on e-beam : From Mono to maxwellian spectra Electron density scan



Laser 30 TW, 33fs, Z_R~ 1mm

Plasma n variable, 3mm

Beam up to 170MeV with 3e9 e^-

V. Malka, et al., PoP 2005

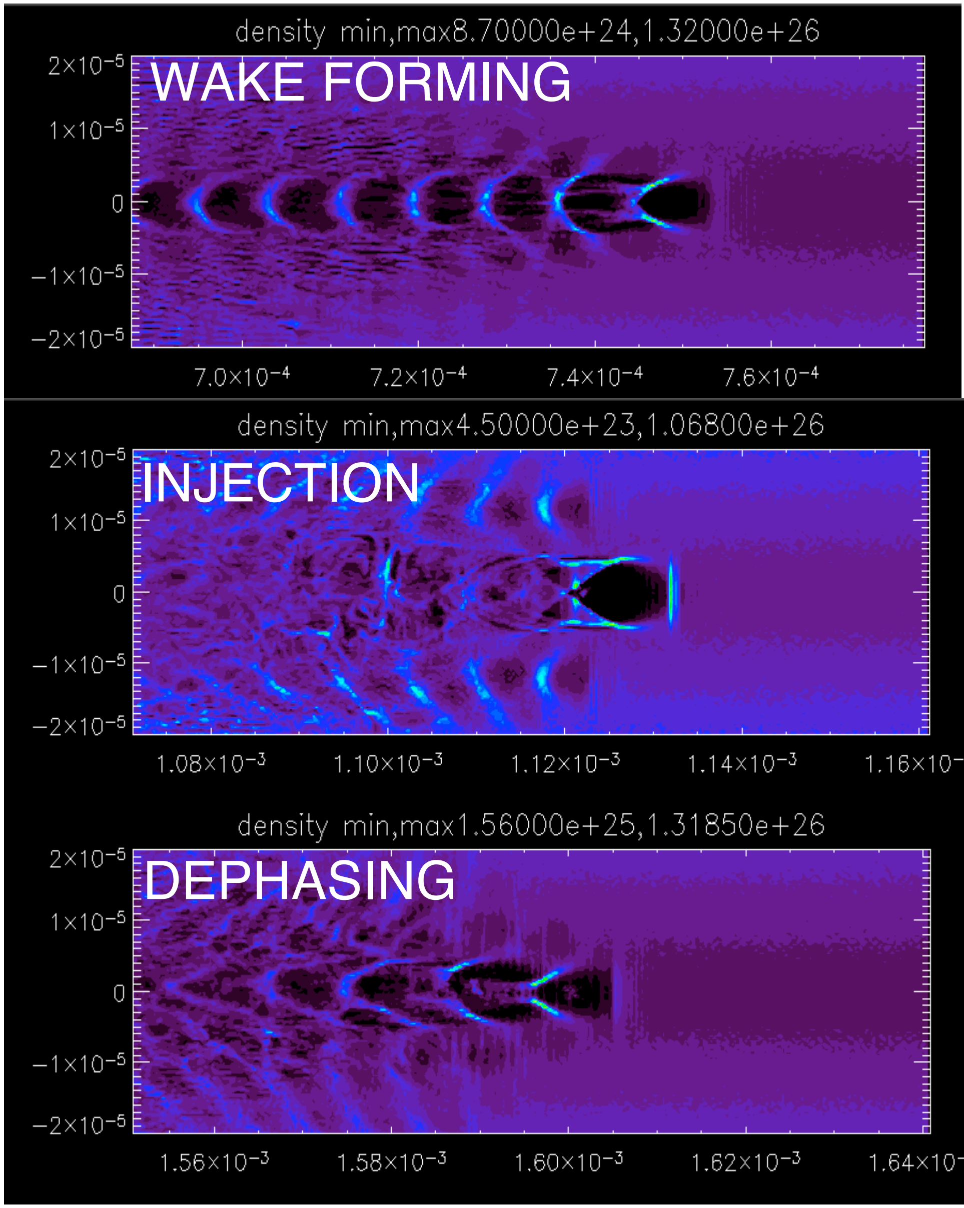
Faure,et al, Nature 2004

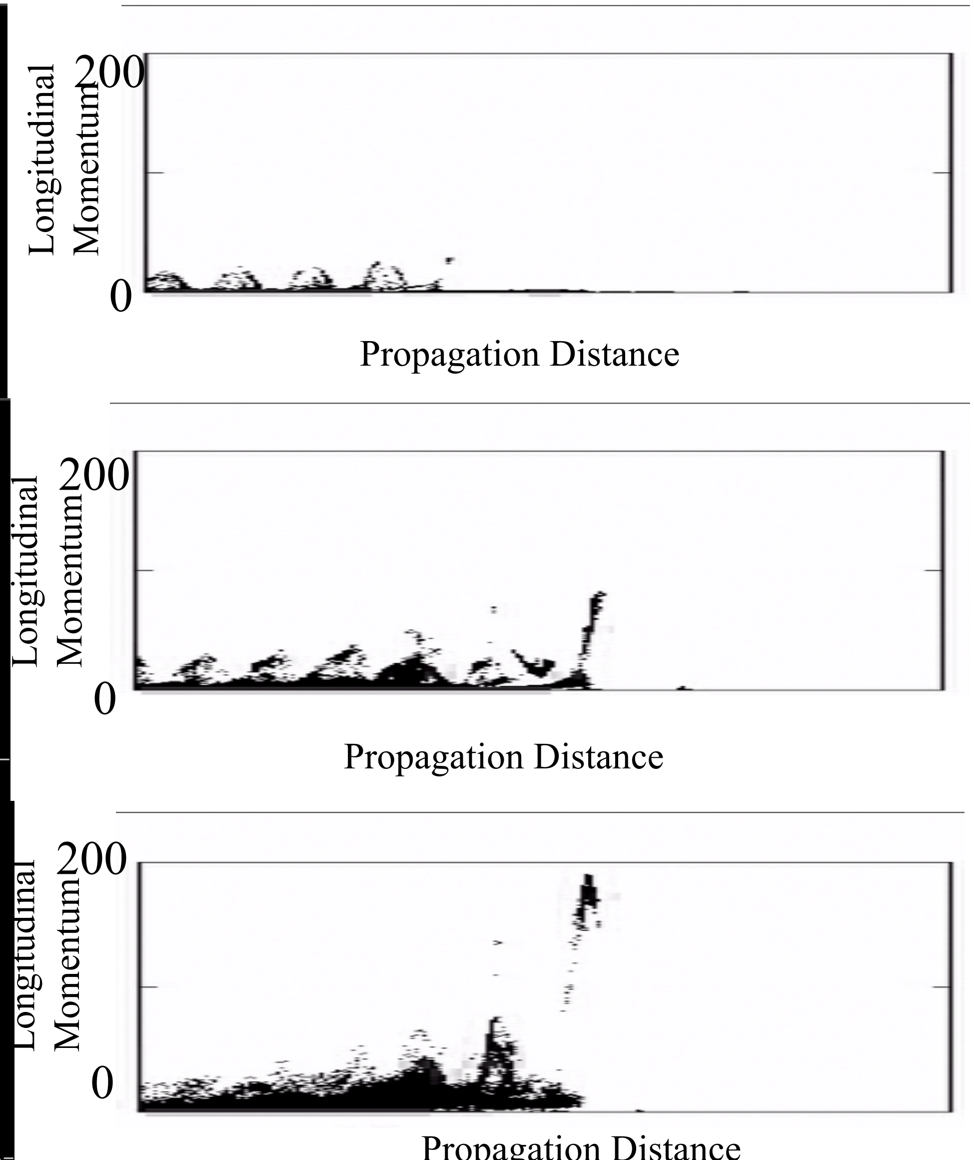
ENSTA POLYTECHNIQUE CNRS

Physics of Narrow Energy Spread

Self-Injected E-Beams

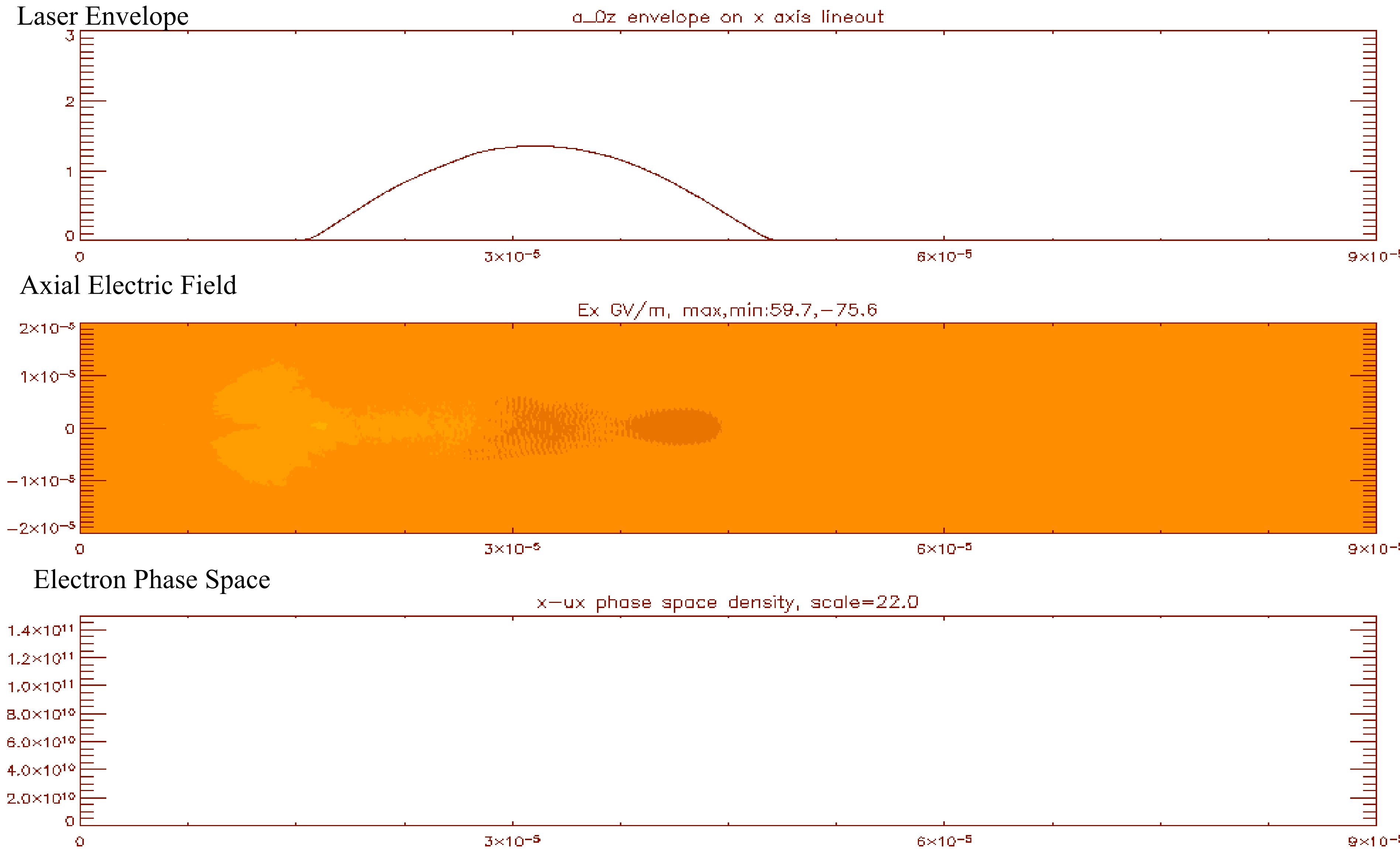
Wake Evolution and Dephasing Yield Low Energy Spread Beams in PIC Simulations





Geddes et al., Nature (2004) & Phys. Plasmas (2005)

Simulations using VORPAL PIC Code: Wake Evolution & Dephasing Yield Low Energy Spread



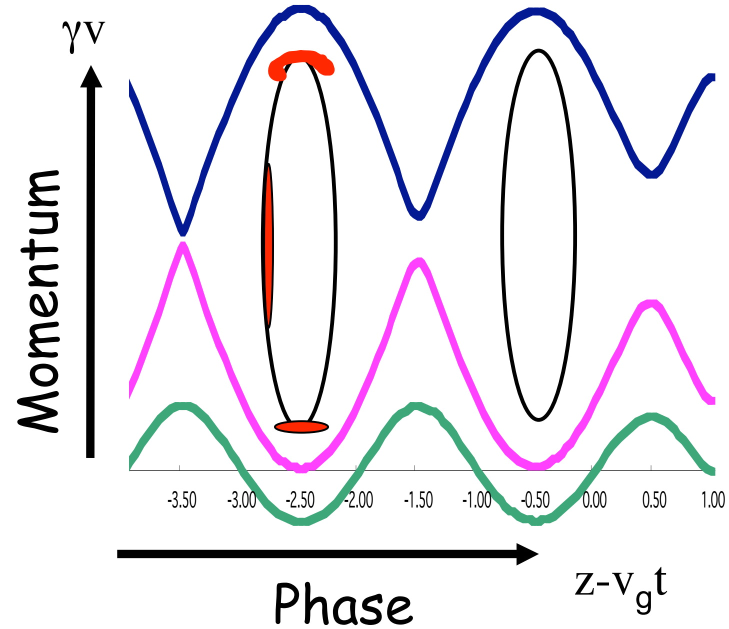
VORPAL: Cary, Nieter, Bruhwiler et al., CU & Tech-X

LWFA: Production of a Monoenergetic Beam

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

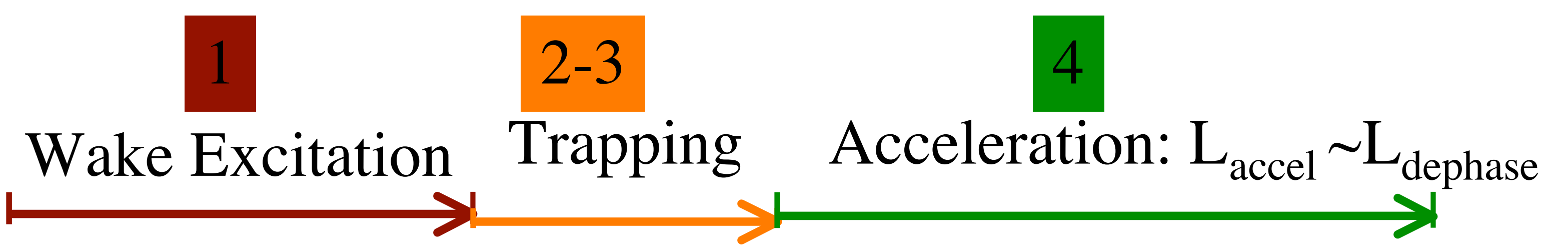
   If > dephasing length: large energy spread

   If ≈ dephasing length: monoenergetic



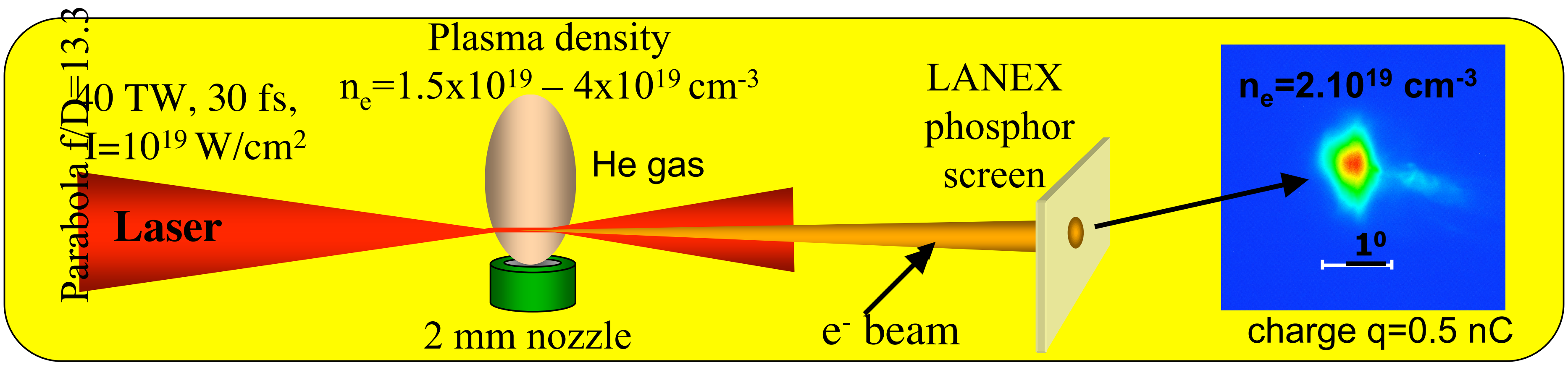
- Dephasing distance:

$$L_{dph} \approx \left(\lambda_p^3 / \lambda^2\right) \propto n_e^{-3/2}$$

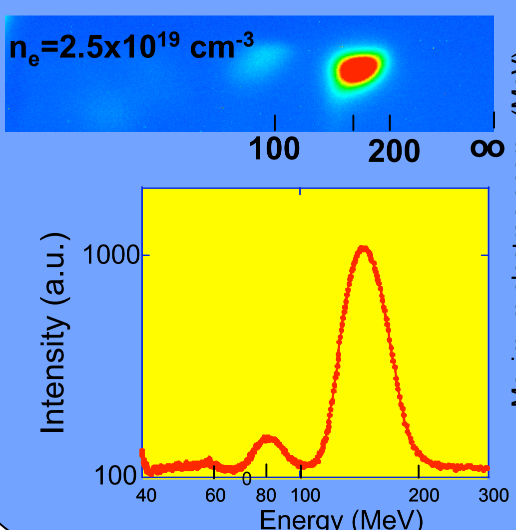


More experiments at the 100 MeV-level

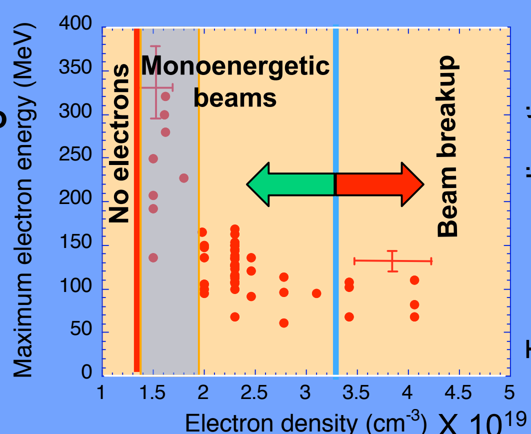
Generation of 300 MeV Quasi-Monoenergetic Electron Beams from Laser Wakefield



Spectrum

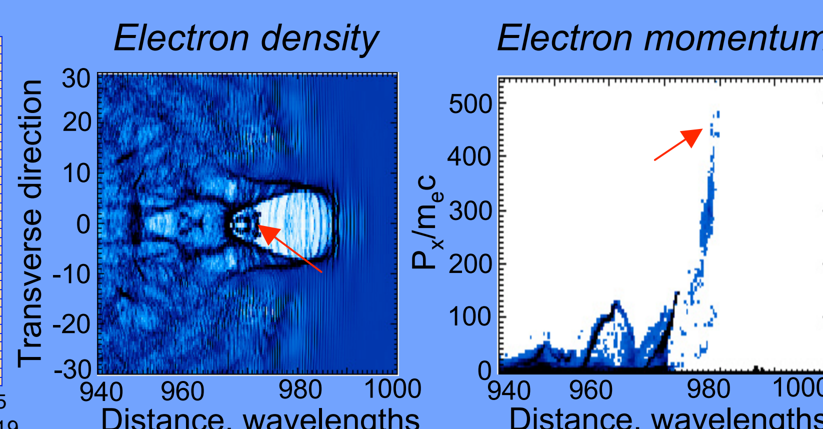


Scaling



Low (2 pC) charge but high (10 mrad) angular stability of e^- beam

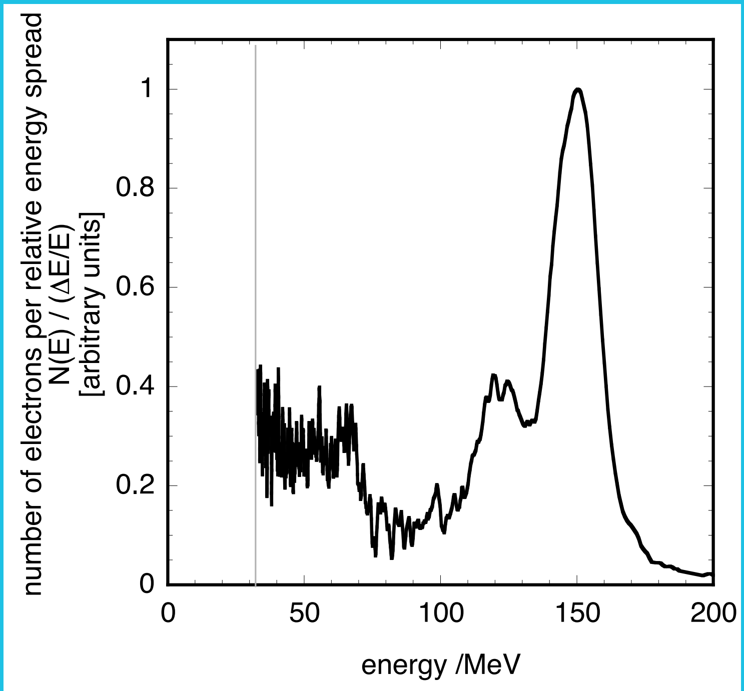
2D PIC simulation

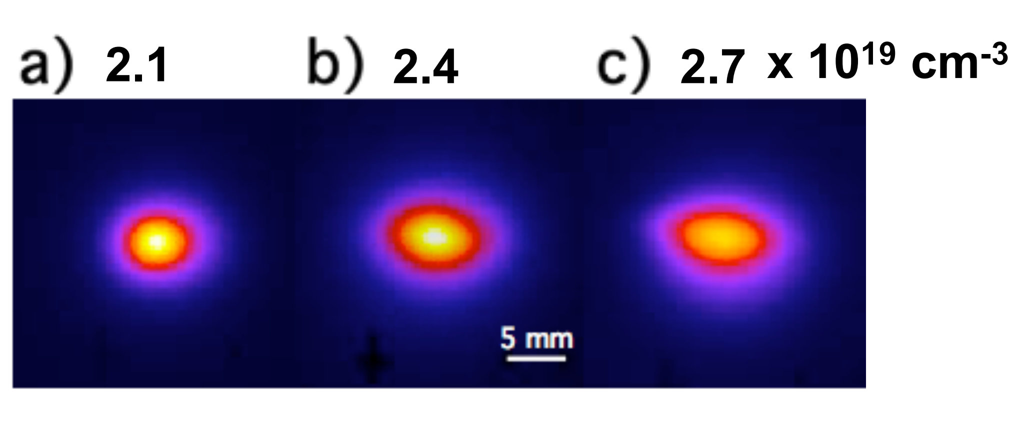


$a_0=2$, $\tau=10T$, $D=20\lambda$, $\omega/\omega_p=10$

A. Maksimchuk et. al. submitted to Phys. Rev. Lett. (2006).

Monoenergetic Electrons come from back of first plasma wave period





- Imperial College / Lund Institute of Technology Collaboration
- 35 fs, 650 mJ, f/10 focusing, 2 mm gas jet

- ~150 MeV, few % energy spread electron beam when $c\tau \sim \lambda_p$
- Elliptical Beam profile due to interaction of electrons with laser field
  - **i.e. electrons are injected within first plasma wave period**
- Beam becomes more circular at lower density
  - **i.e. electron bunch is less than 1 plasma wavelength long - < 25 fs**
- Good agreement of ellipticity, divergence with OSIRIS PIC simulations

SPD Mangles et al,PRL, **96**, 215001 (2006)

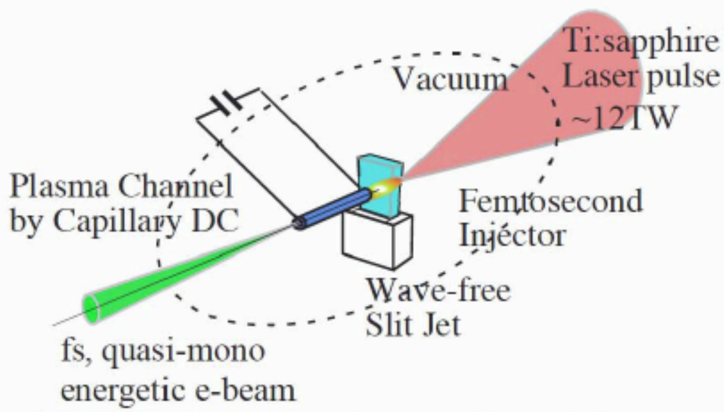
Related: SPD Mangles et al, Nature (2006)

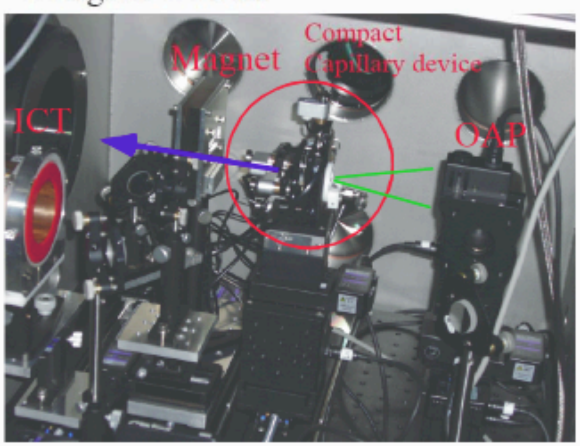
Laser Plasma Cathode Studies @ Univ. Tokyo

T.Hosokai[1,2], K.Kinoshita[1], A.Zhidkov[3], A. Yamazaki[1], A.Maekawa[1], K.Kobayashi[1], R. Tujii[1], and M.Uesaka[1]

1.Nuclear Professional School, School of Engineering, University of Tokyo
2. Department of Energy Sciences, Tokyo Institute of Technology
3.EPERL, Central Research Institute of Electric Power Industry

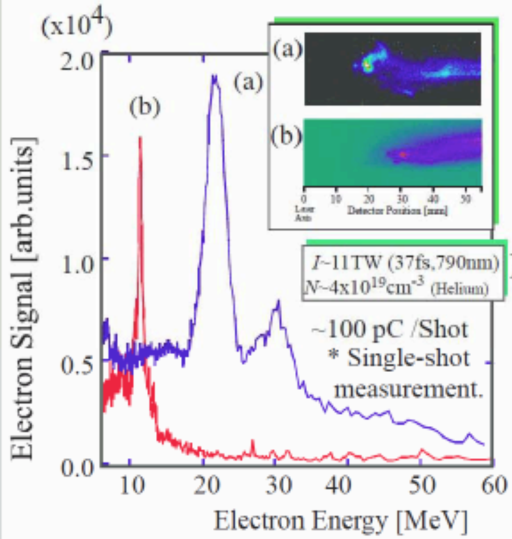
2-staged Acceleration scheme





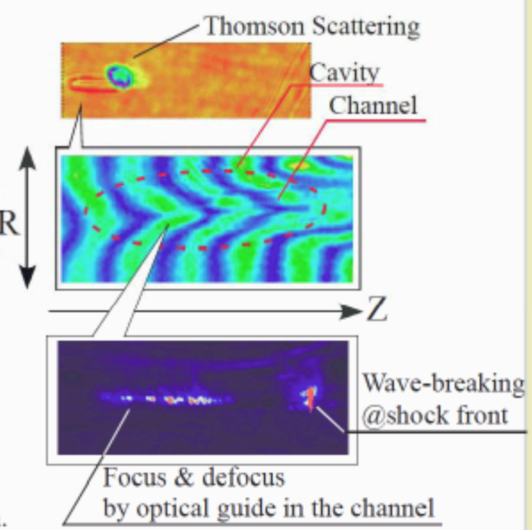
Femtosecond Injector Study

Quasi-mono energy spectra



(a),(b): Different pre-pulse condition.

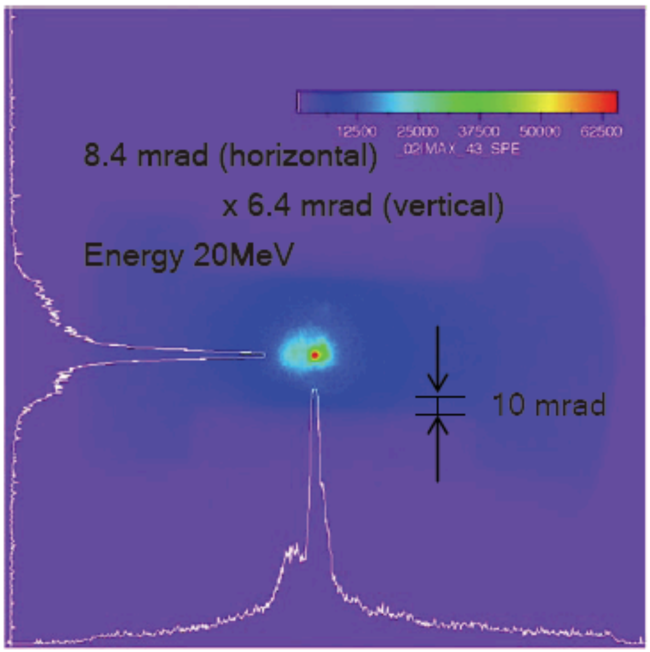
Strong correlation between QME and laser optical guiding.

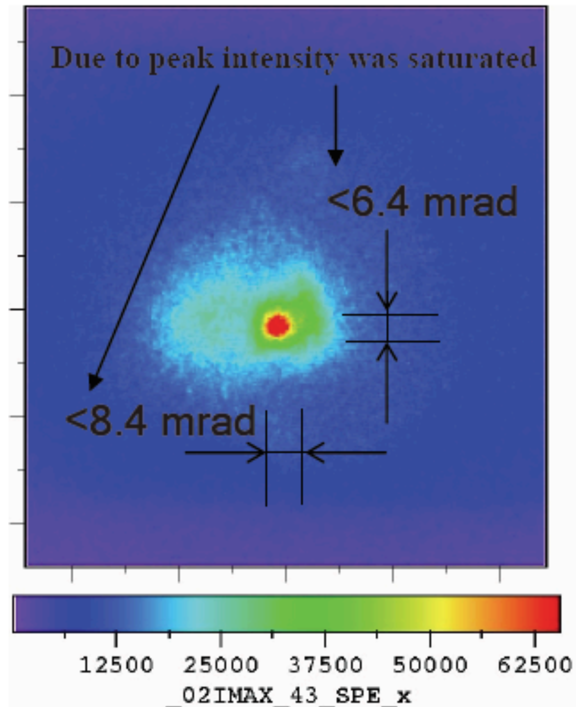


Ref. T.Hosokai,*et al.*,Phys Rev.E **73**,036407 (2006)

Mono-energetic electron beam image obtained by a phosphor screen

Angular distribution of an electron beam





We have been successfully observed the electron beam image by using CCD camera coupled with a phosphor screen

M. Mori et al. Phys. Lett. A (in press)

Recent Results on SM-LWFA Experiments at AIST

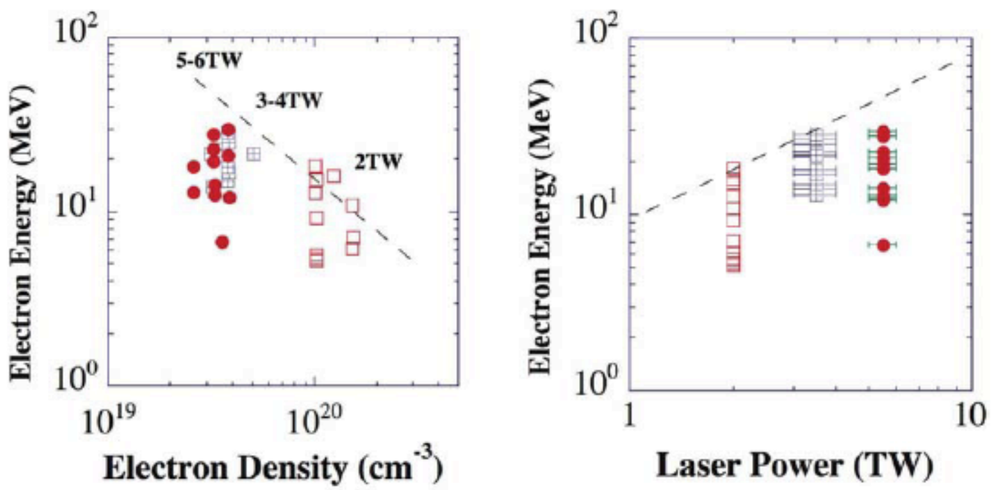
National Institute of Advanced Industrial Science and Technology
AIST

	AAC04	AAC06
Plasma Density	1-1.5x10^{20} cm^{-3}	2-5x10^{19} cm^{-3}
Laser Power	2 TW	2.5-6TW
Pulse Width (FWHM)	50 fs	50 fs
Rayleigh Range $2Z_R$	70 μm	300 μm
Mono-Energy	7-15 MeV	10- 35 MeV*
Acceleration Scheme	SM-LWFA	SM-LWFA

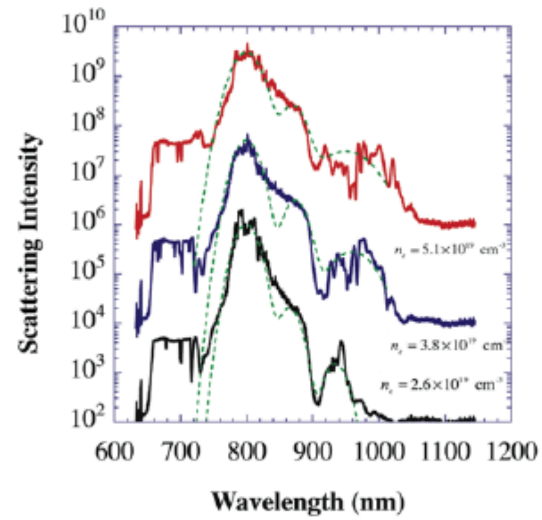
* Limited by a plasma length,

Laser System in a New Lab.
(under construction)

Density and Laser-Power Dependence of
Acceleration Energies of Mono-Energetic Peaks

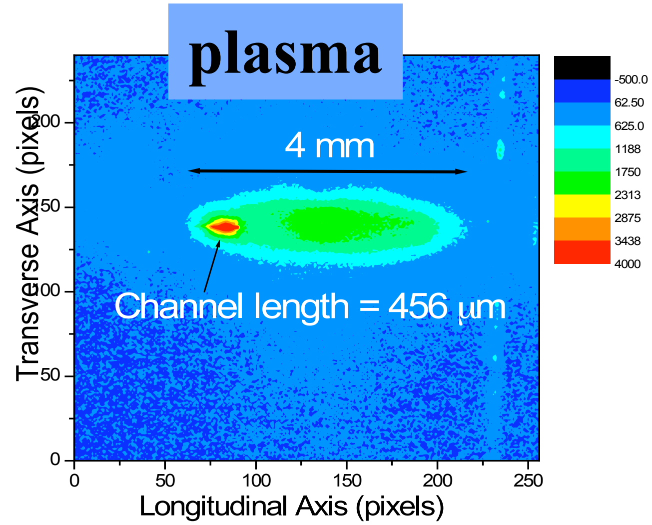


Forward Scattering Spectra

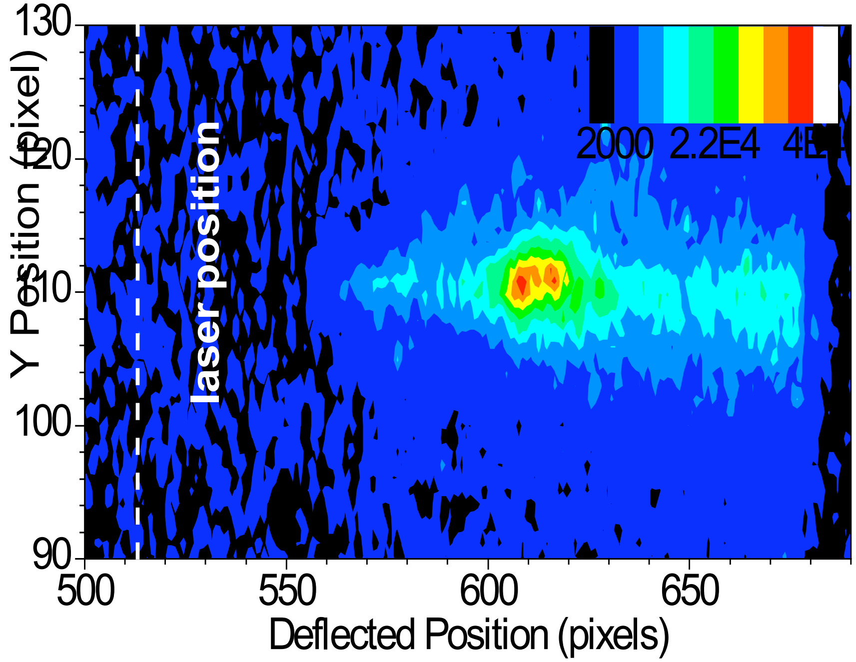


Preliminary Result from KERI-APRI Experiment

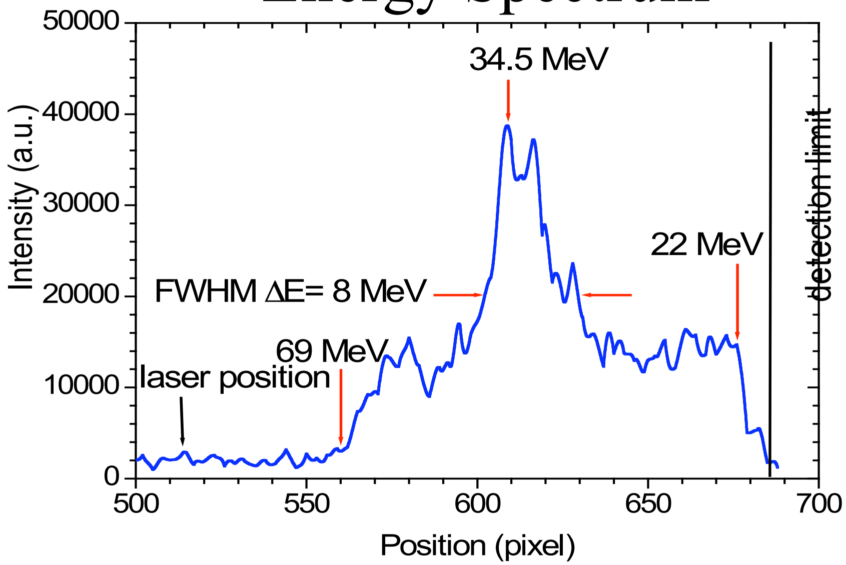
Ti:sapphire laser power=20 TW
Pulse duration=30 fs
Spot size=15 um
Plasma density=2.7*10^19
Gas = He



Electron beam image deflected by a permanent magnet

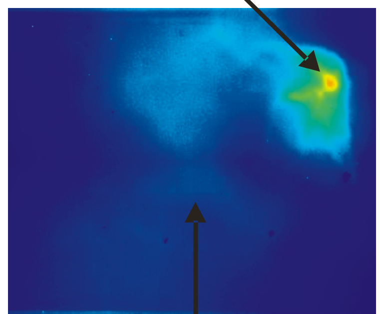


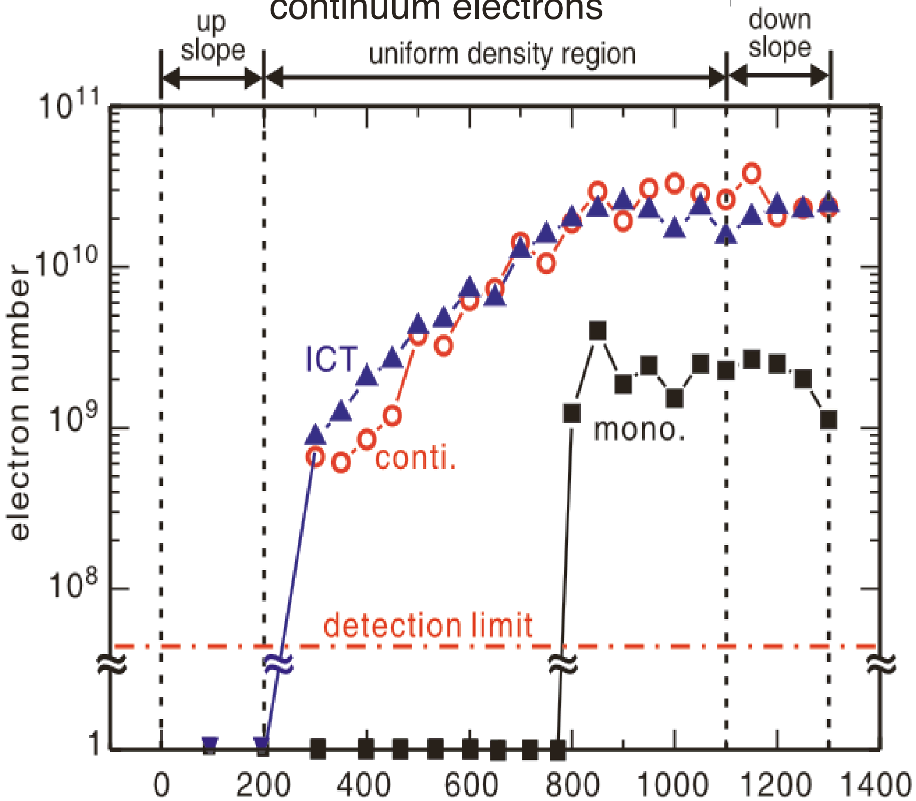
Energy Spectrum



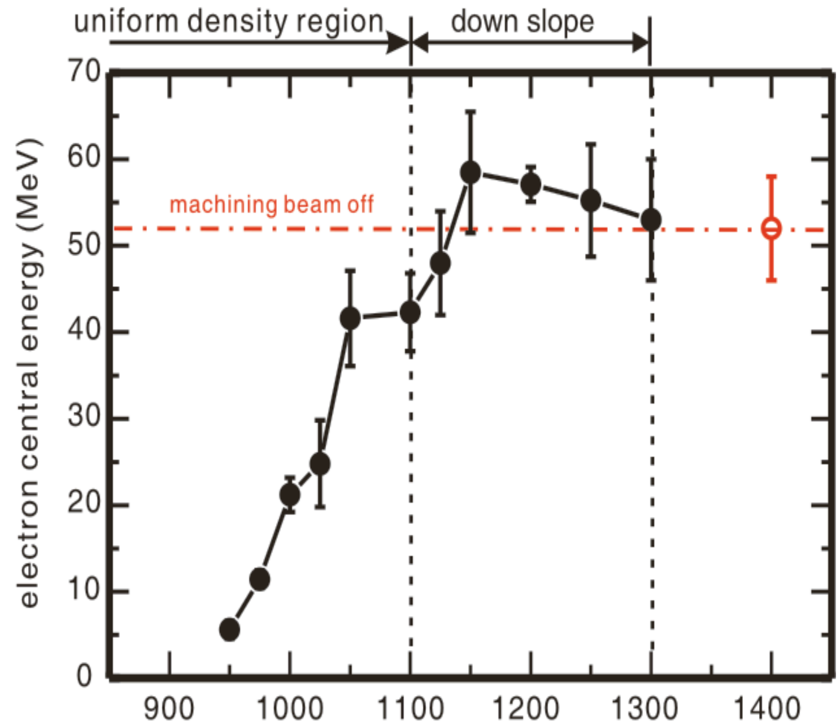
Szu-yuan Chen, NCU, Taiwan

Energy and charge of the monoenergetic electron beam at various positions





230 mJ, 45 fs pump pulse
4×10^{19} cm^{-3} plasma density



The energy of the monoenergetic electron beam increases roughly linearly from 5 MeV at 950-μm position to 55 MeV at 1150-μm position, corresponding to an acceleration gradient of ~2.5 GeV/cm.

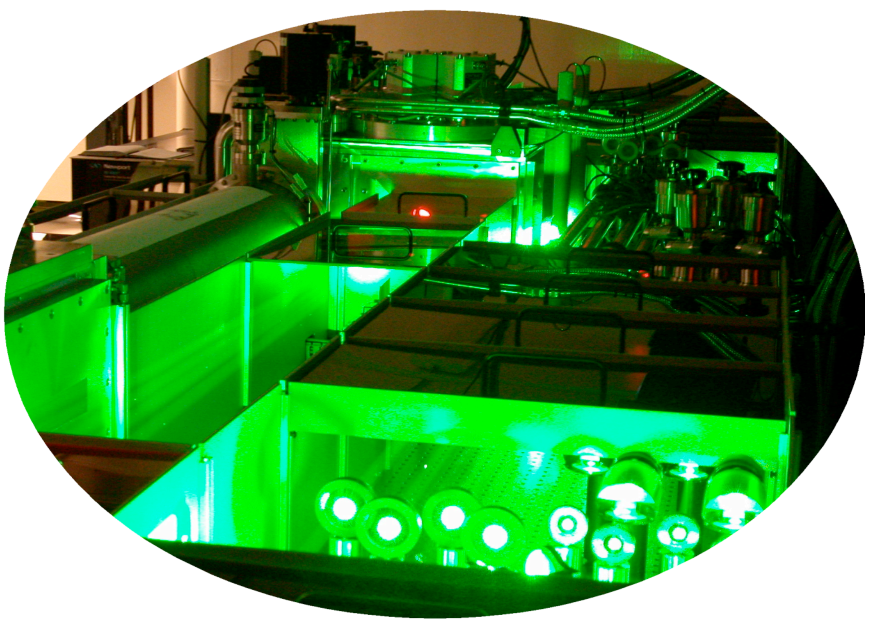
E-beams beyond 1 GeV

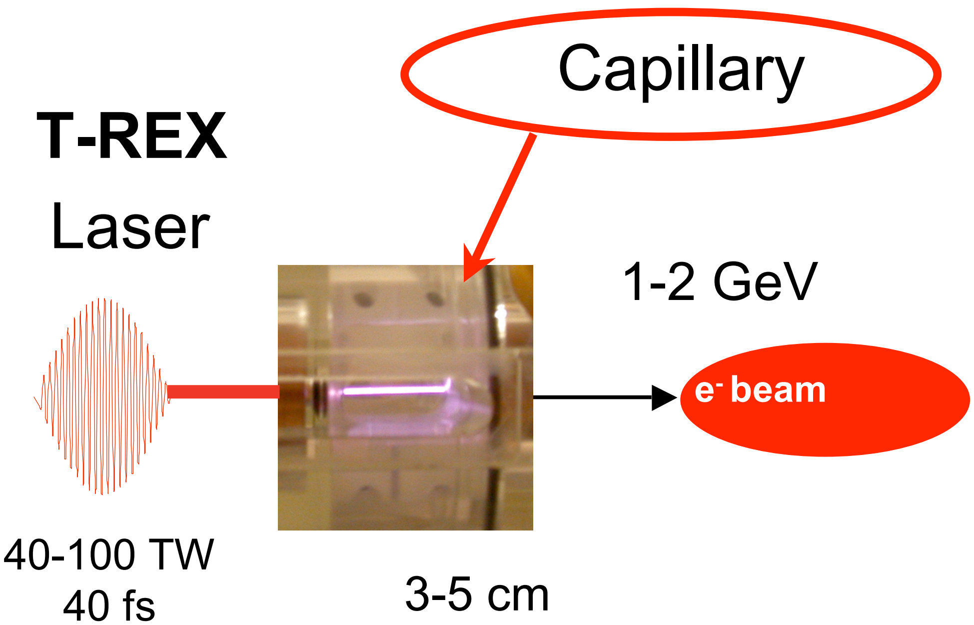
GeV laser accelerator: channeling over cm-scale

- Increasing beam energy requires increased dephasing length and power:

$$\Delta W_d[\mathrm{GeV}] \sim a^2 \lambda_p^2 \sim I[\mathrm{W/cm^2}]/n[\mathrm{cm^{-3}}]$$

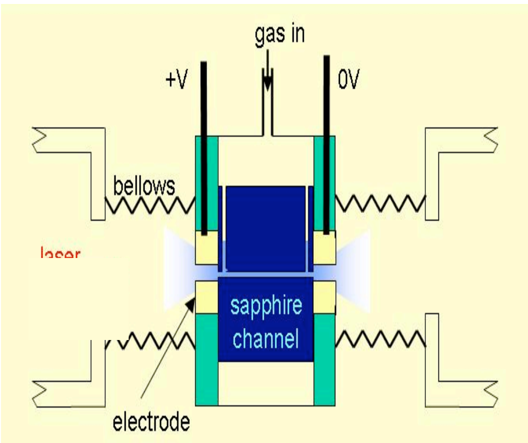
- Scalings indicate cm-scale guide at ~ 10^{18} cm^{-3} and 40-100 TW laser for GeV
- Laser heated channel formation inefficient at low density
- Use capillary channels for cm-scale guides driven by upgraded laser



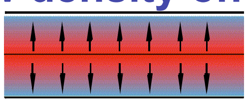


Capillary channel guiding: set-up

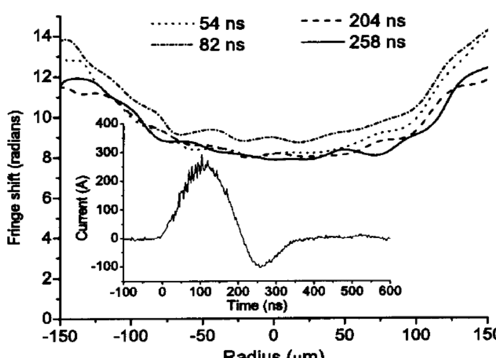
Discharge Capillary



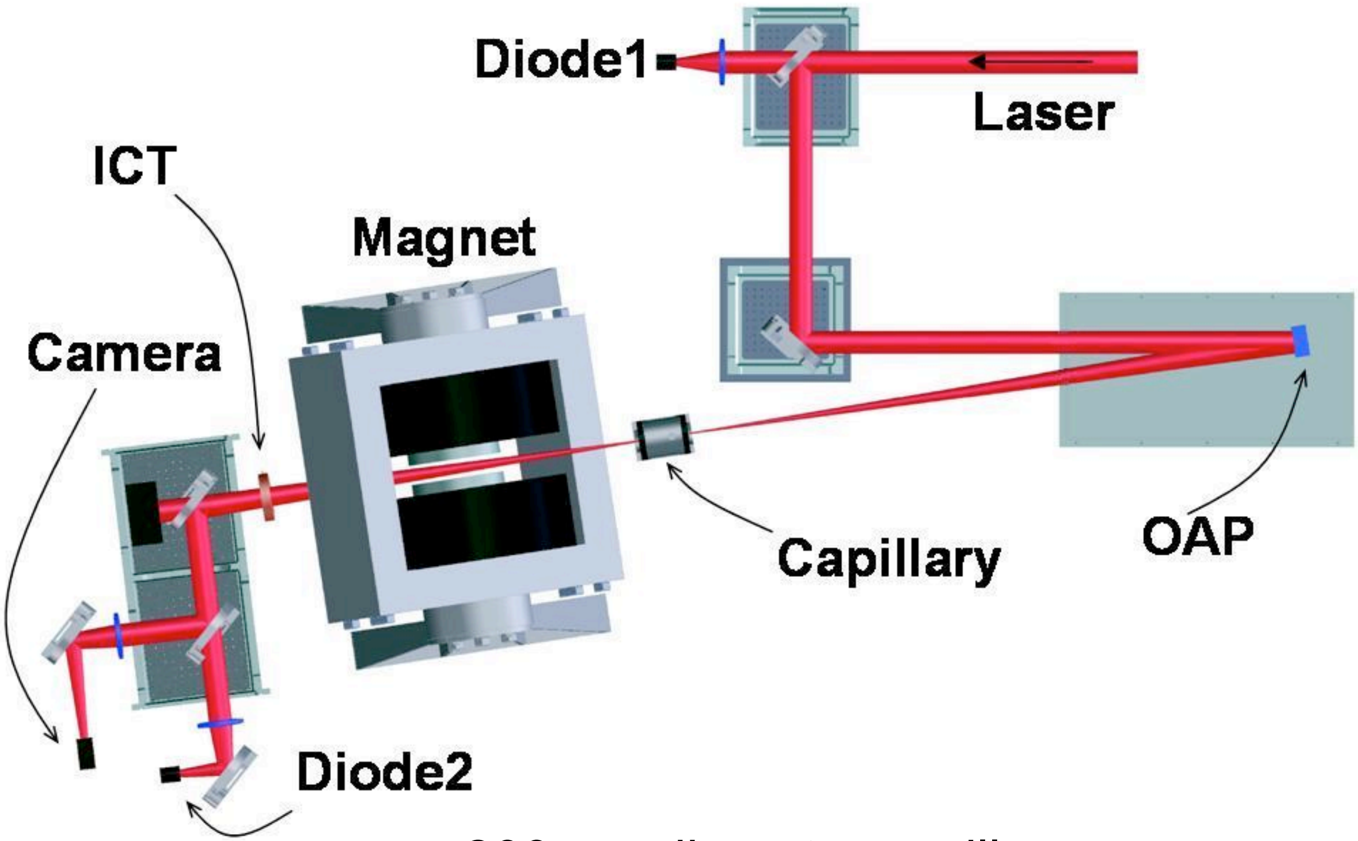
Pressure Balance-> low density on axis



Channel Profile

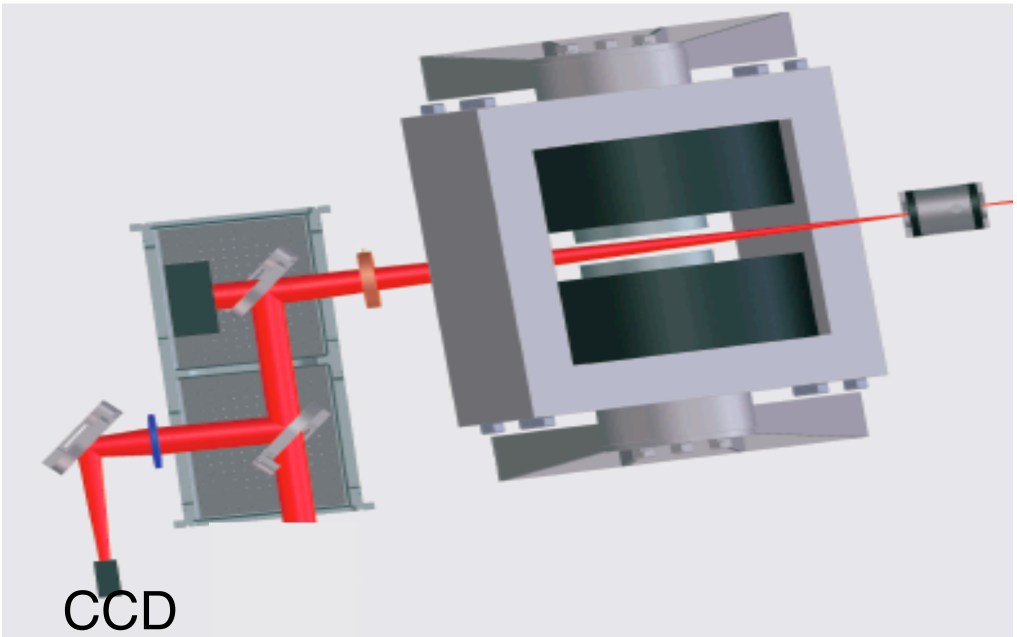


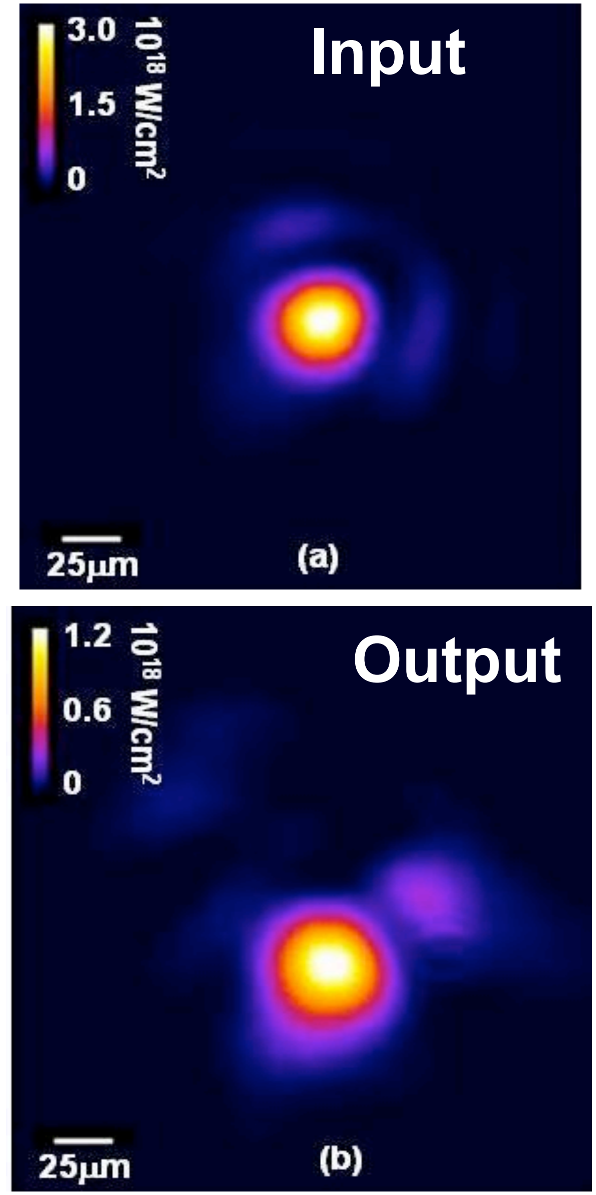
From: Spence et al, JOSA-B, **20**,p138, 2003



- 209 μm diameter capillary
- 85 mbar initial pressure
- $n_0 = 8.5 \times 10^{17}\ cm^{-3}$
- 32 micron matched spot

40 TW laser pulse guided over > 3 cm





P = 0.1-40 TW in 40 fs, 10 Hz

$w_{x,in} = w_{y,in} = 26\ \mu m$

$w_{x,out} = w_{y,out} = 33\ \mu m$

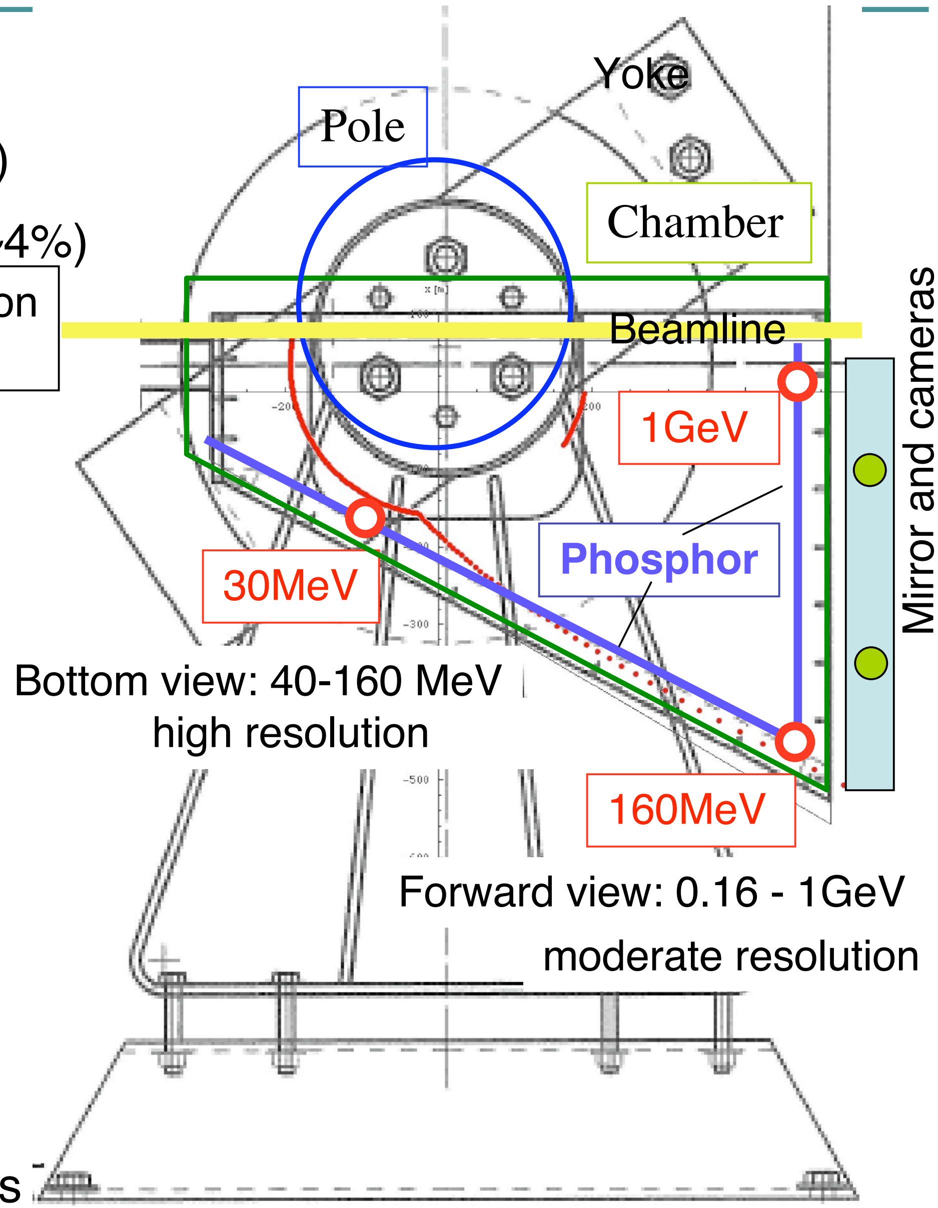
LOASIS GeV Spectrometer

- Maximum resolving energy: ~1.1 GeV
- Large momentum acceptance (>factor 35)
- High resolution (bottom: <1%, forward: 2~4%)

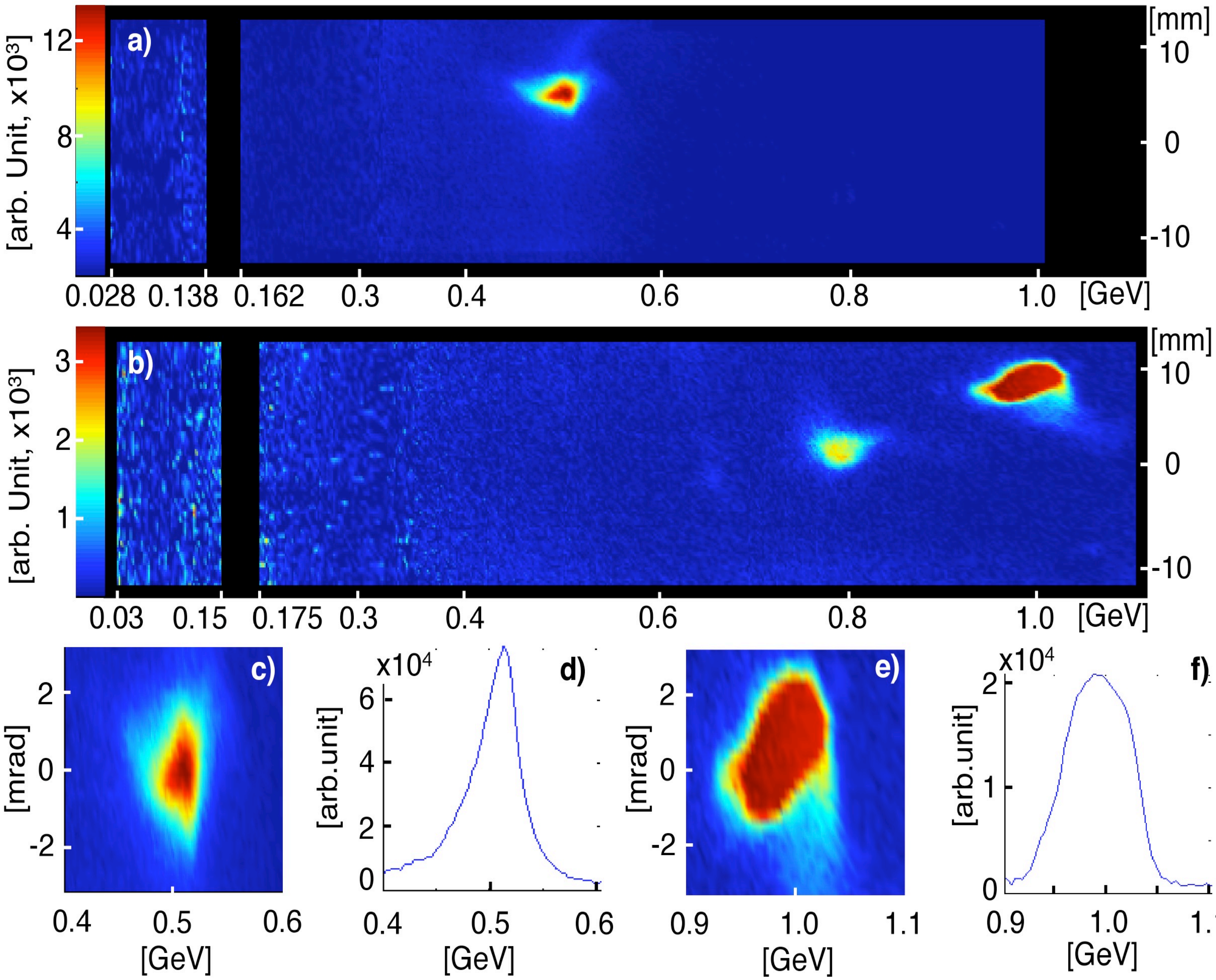
Capillary

Chamber   Shielded mirror and cameras

Interaction point



1 GeV bunches with narrow energy spread achieved with 40 TW laser pulses



25 TW

E<0.6 GeV

Q~50-300 pC

40 TW

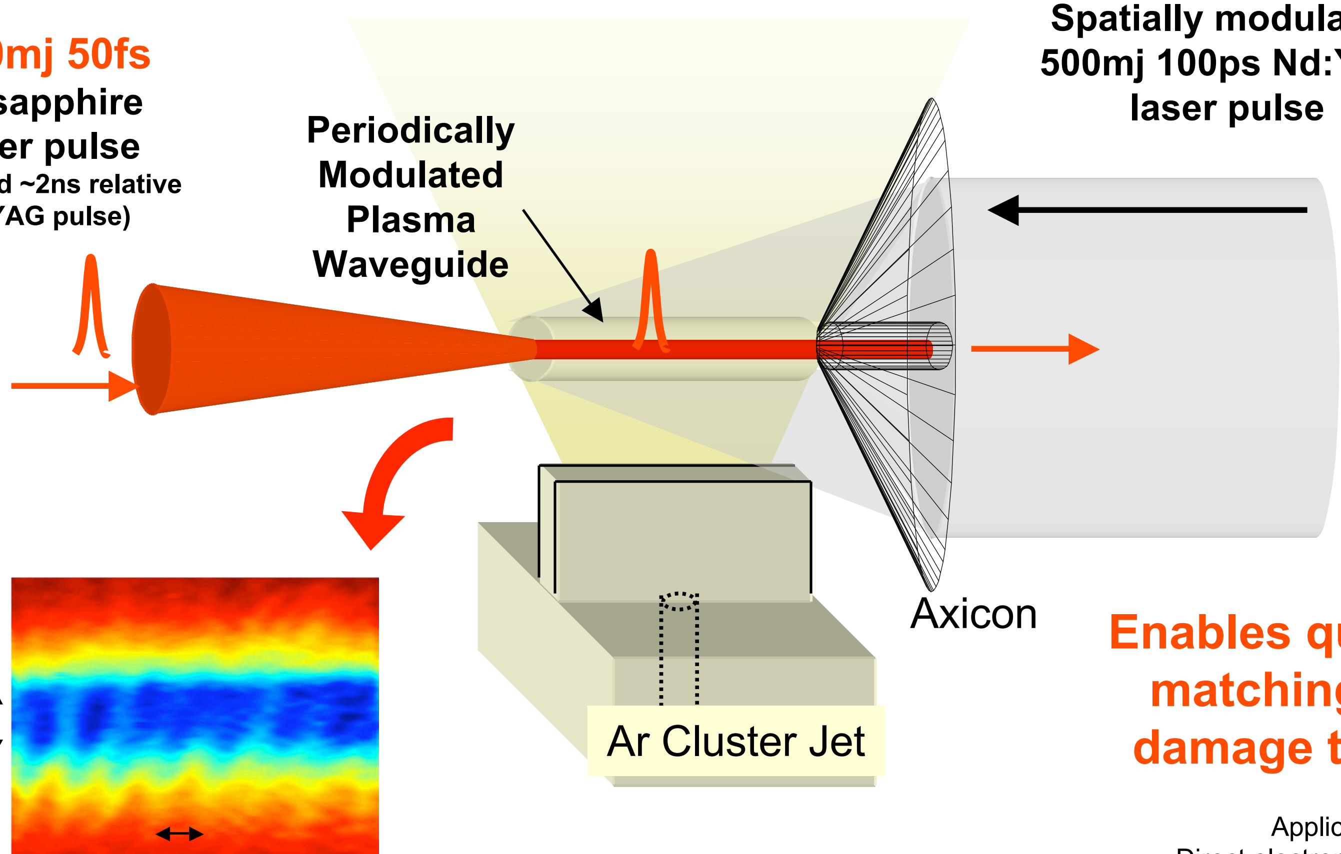
E< 1.1 GeV

Q~50-100 pC

Energy spread at spectrometer resolution

Leemans et al, submitted

A periodically modulated preformed plasma channel for quasi-phase matched guiding

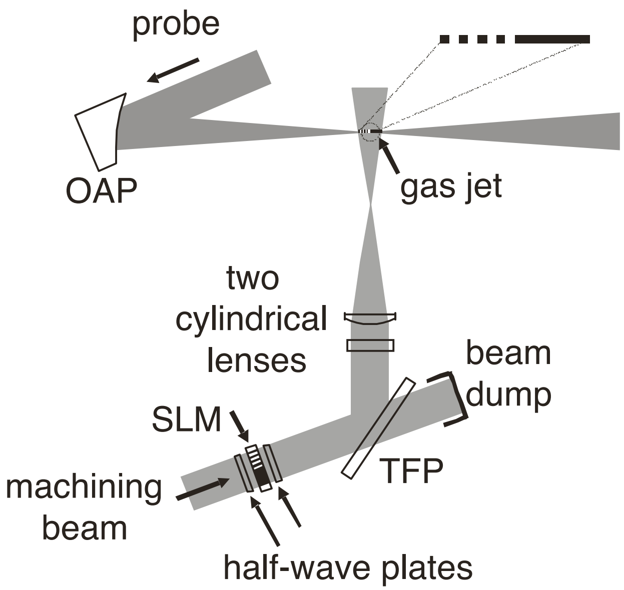


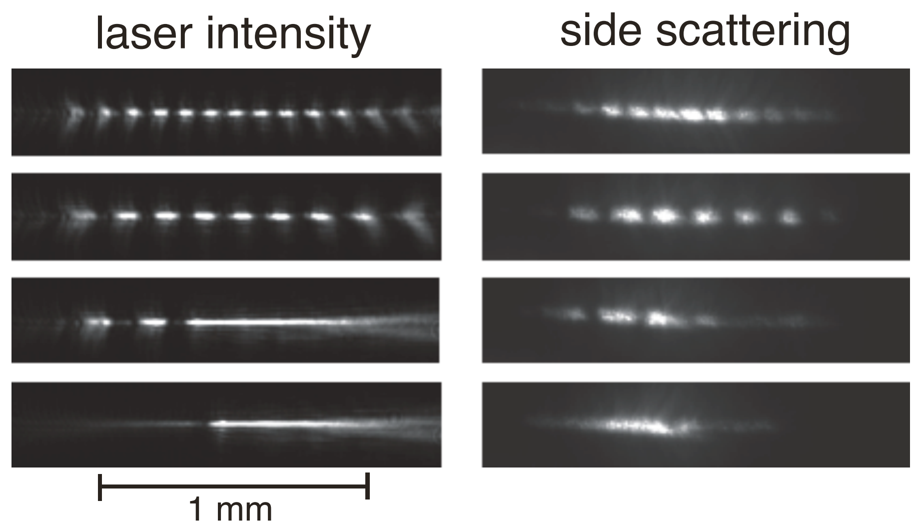
Extracted phase from 60fs transverse probe
(200 consecutive shot average, 1ns delay)

Enables quasi-phase matching with no damage threshold!

Applications:
- Direct electron acceleration
- Wakefield acceleration
- High harmonic generation
- Terahertz generation

Programmable fabrication of longitudinal density structures





- By replacing the patterned mask with a liquid-crystal spatial light modulator (SLM), programmable fabrication of longitudinal density structures can be achieved.
- The SLM also allows fine adjustment of the intensity at each pixel to compensate for effects such as diffraction and B-integral or to obtain wide-range uniformity, which cannot be achieved by using hard masks.

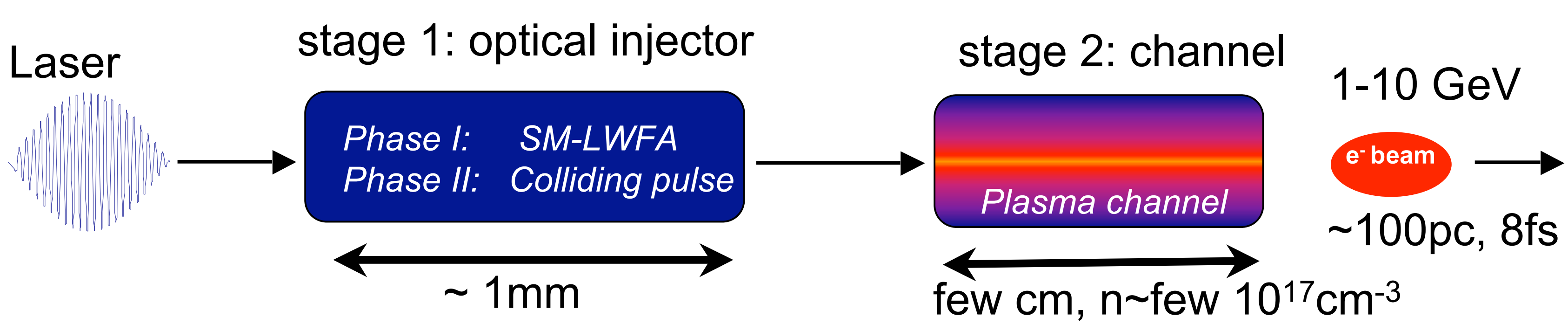
Laser-Plasma Accelerators Beyond 1 GeV

Staging and controlled injection for next generation accelerators

- GeV experiments: Scaling law in mildly nonlinear regime

$$\Delta W_d[\mathrm{GeV}] \sim a^2\lambda_p^2 \sim I[\mathrm{W/cm^2}]/n[\mathrm{cm^{-3}}]$$

- Energy spread limited measurement
- Bunches may be percent energy spread
- Staging ~ preserves ΔE
  - stage a low energy injector injector and 1-10 GV accelerator modules
  - 10 GeV using ~ PW of laser energy and m-scale plasma



Physical picture

basic formulas

The accelerating structure needs to remain as stable, for this purpose we choose the laser spot size and intensity from the condition :

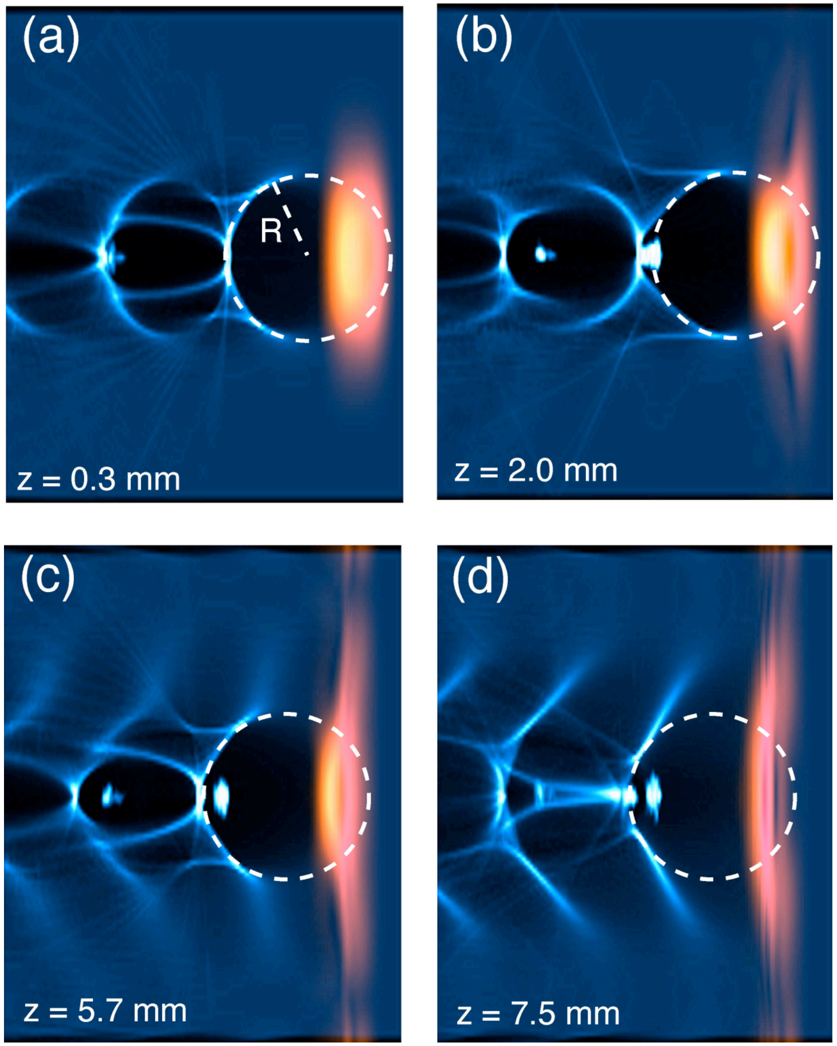
$$\begin{bmatrix}\text{Matched}\\ \text{profile}\end{bmatrix}: \; k_p w_0 \approx k_p R_b \approx 2\sqrt{a_0} \Rightarrow a_0 \approx 2\left(\frac{P}{P_c}\right)^{1/3}$$

The accelerating field in the ion channel decreases linearly from the front reaching minimum value with magnitude:

$$\begin{bmatrix}\text{Maximum}\\ \text{field}\end{bmatrix}: \; \frac{eE_M}{mc\omega_p} \approx \frac{1}{2} k_p R_b \approx \sqrt{a_0}$$

The acceleration process is limited by dephasing:

$$\begin{bmatrix}\text{Acceleration}\\ \text{distance}\end{bmatrix}: \; \begin{matrix} a_0 > 1 \\ L \approx R_b \end{matrix} \Rightarrow L_{etch} \ge L_\phi \approx \frac{4\sqrt{a_0}}{3k_0}\left(\frac{k_0}{k_p}\right)^3$$



Scaling laws

The energy obtained by a group of particles is:

$$\Delta E \approx e\overline{E}_w L_\phi \approx mc^2 \left(\frac{P}{P_r}\right)^{1/3} \left(\frac{n_c}{n_p}\right)^{2/3}$$

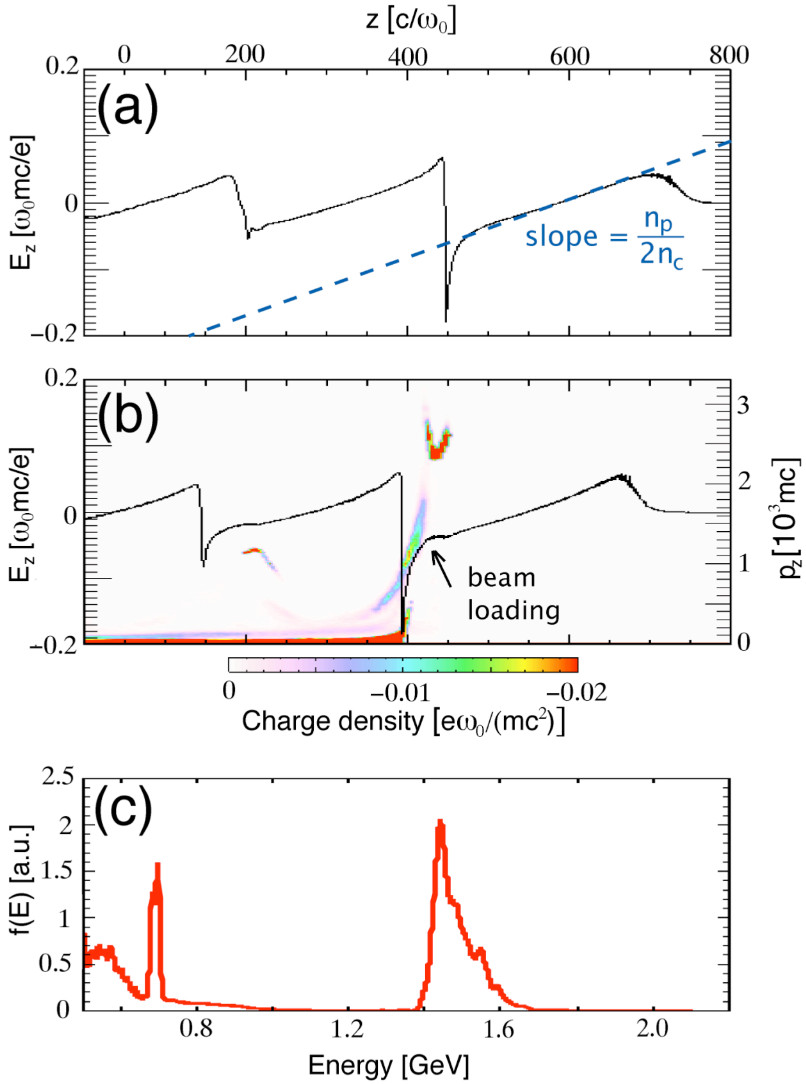
$$\Rightarrow E[GeV] \approx 1.7 \left(\frac{P[TW]}{100}\right)^{1/3} \left(\frac{10^{18}}{n_p[cm^{-3}]}\right)^{2/3} \left(\frac{0.8}{\lambda_0[\mu m]}\right)^{4/3}$$

Energy balance yields the maximum # of particles that can be accelerated:

$$N \approx \frac{8/15}{k_0 r_e} \sqrt{\frac{P}{m^2c^5/e^2}}$$

$$\Rightarrow N \approx 2.5 \times 10^9 \frac{\lambda_0[\mu m]}{0.8} \sqrt{\frac{P[TW]}{100}}$$

3D full PIC simulation with OSIRIS for a 200TW, 30fsec yields 300pC at 1.5GeV in agreement with the theory.



Parameter design for GeV and beyond

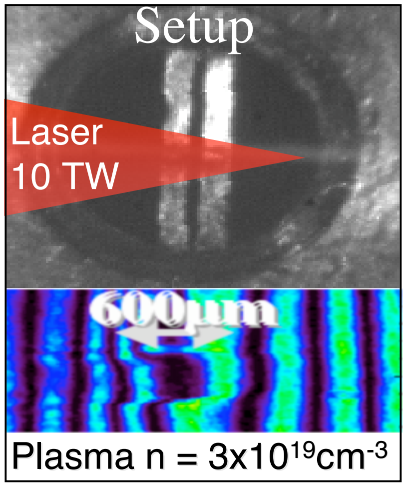
P(PW)	τ(fs)	n_p (cm^{-3})	w_0 (μm)	L(m)	a_0	$\Delta n_c/n_p$	Q(nC)	E(GeV)
0.020	30	1×10^{18}	14	0.016	1.76	60%	0.18	0.99
0.040	30	1.5×10^{18}	14	0.011	2.53	40%	0.25	0.95
0.100	30	2.0×10^{18}	15	0.009	3.78	0%	0.40	1.06
0.200	100	1.0×10^{17}	45	0.52	1.76	60%	0.57	9.9
2.0	100	3.0×10^{17}	47	0.18	5.45	0%	1.8	10.2
2.0	310	1.0×10^{16}	140	16.3	1.76	60%	1.8	99
40	330	4.0×10^{16}	146	4.2	7.6	0%	8	106
20	1000	1.0×10^{15}	450	500	1.76	60%	5.7	999
1000	1000	6.5×10^{15}	460	82	12.1	0%	40	1040

Note: Channel guiding: 60% and 40%; Self-guiding: 0%; external injection: 60%; self-injection: 40% and 0%
P/Pc=0.7 for 60% case, and 2 for 40% case

Stable e-beams: Laser injection

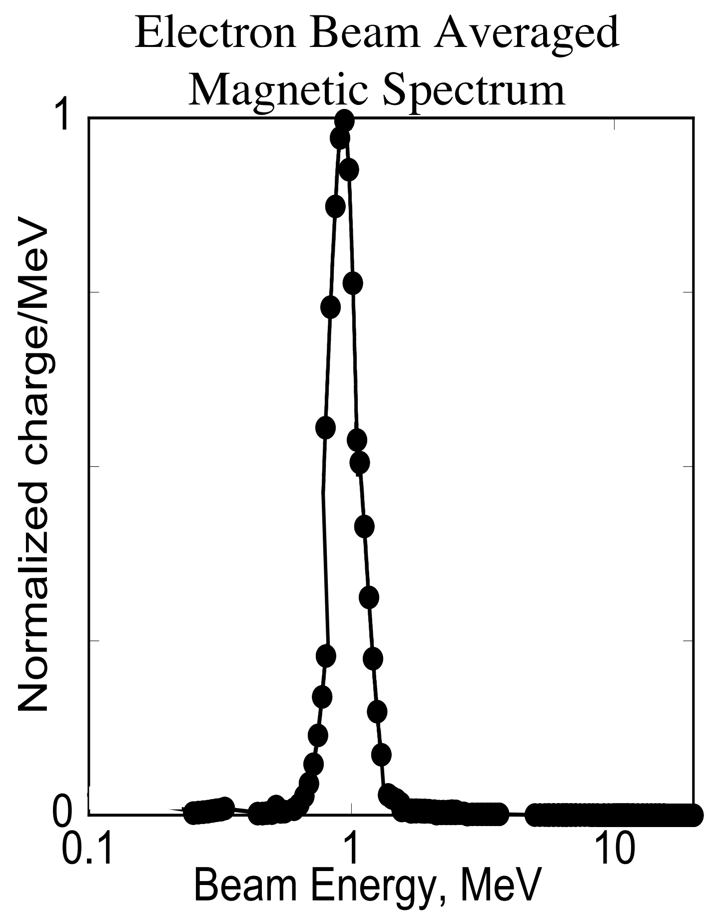
LILAC: D. Umstadter et al., PRL (1996)
Colliding Pulse: E. Esarey et al. PRL (1997)
LIPA: C.I. Moore et al., PRL (1999)

Stable self trapped beams near 1 MeV with nC charge observed in LOASIS experiments



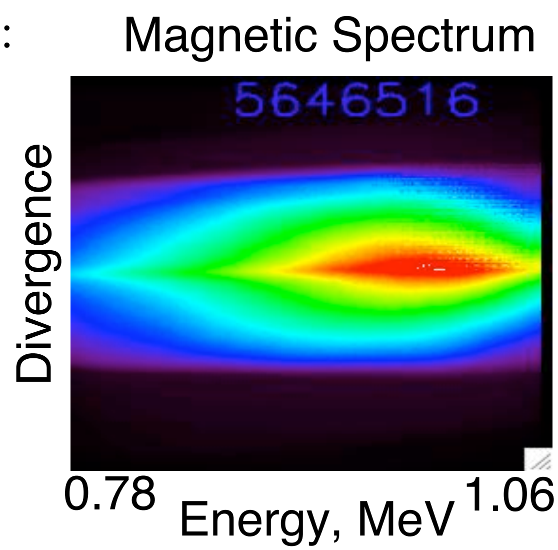
Laser focused downstream of a thin Hydrogen plasma

Mechanism: Trapping on plasma down - ramp (PIC)



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

- stable > 1 hour.
  (as long as observed)
- repeated > 10 run days



Geddes et al., submitted

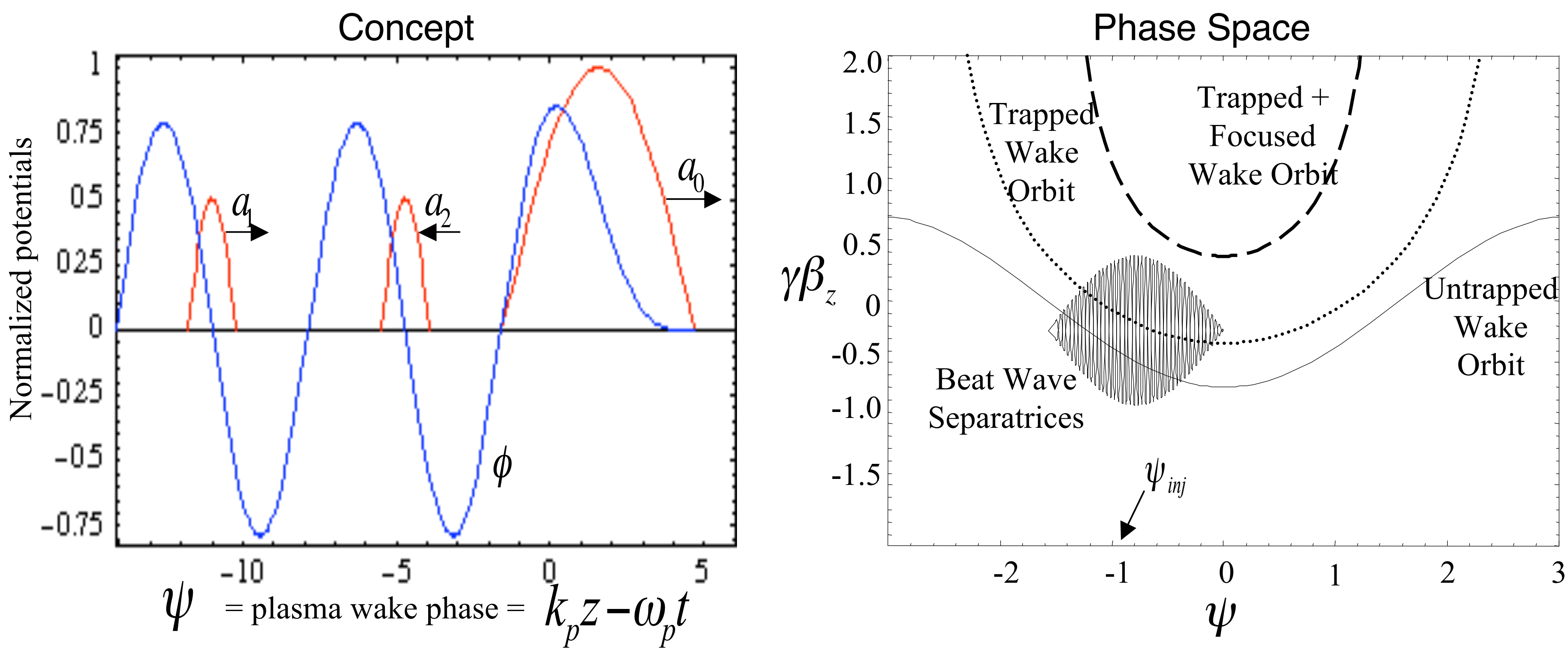
Repeatable Small Energy Spread Beams: Colliding Pulse Injection

Self trapping produces (so far) unstable beams: reliance on beam loading limits flexibility

Control over electron load phase and number is needed for higher quality beams

Use the beat between two counter-propagating laser pulses to give particles a momentum and phase ‘kick,’ allowing control over trapping

Linearly sensitive to laser parameters -> superior stability



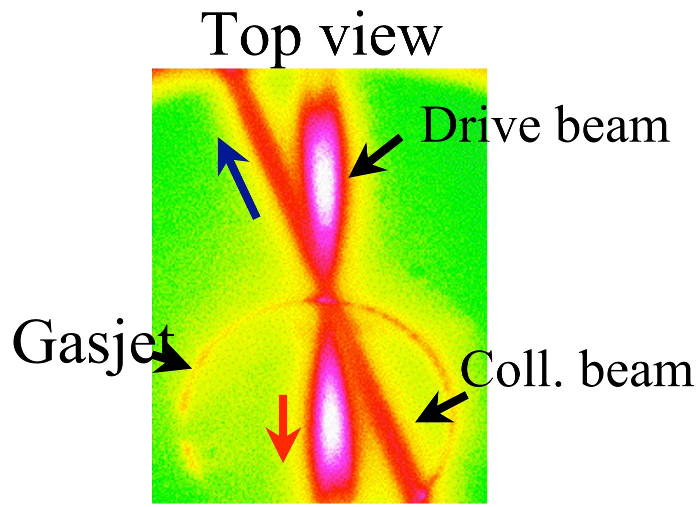
Esarey *et al.*, PRL (97); Schroeder *et al.*, PRE (99), Fubiani *et al.* PRE (04)

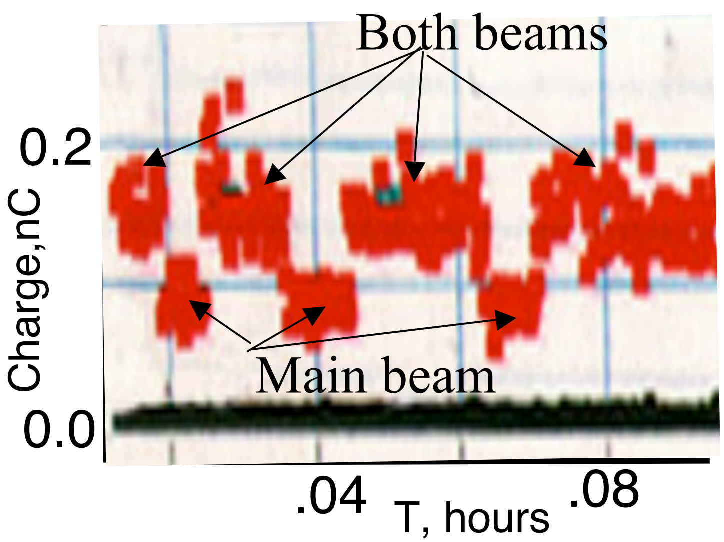
Experiment: colliding 2 pulses

K. Nakamura et al., Proc. AAC (2004)
W. Leemans et al., Femto Beam Sci, M. Uesaka, Ed. (2005)

✓Implemented 2-pulse, 30˚ crossing angle

- Expected bunch properties
  - Femtosecond bunches
  - %-level energy spread
  - > 10 pC charge





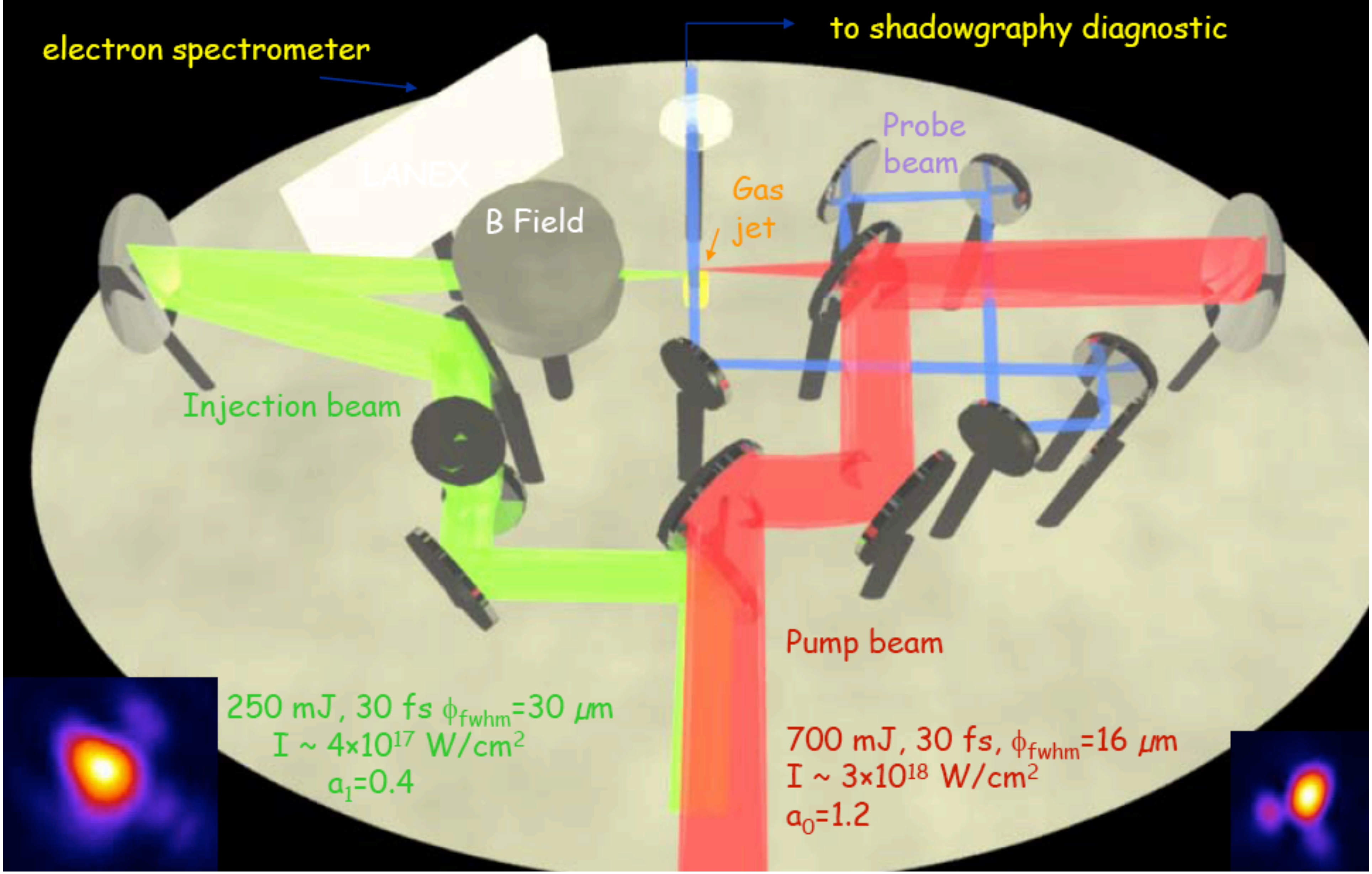
Physics entangled due to dark current
no clear sensitivity to timing scan

Experiment now under way in channel -> no dark current, long structure.

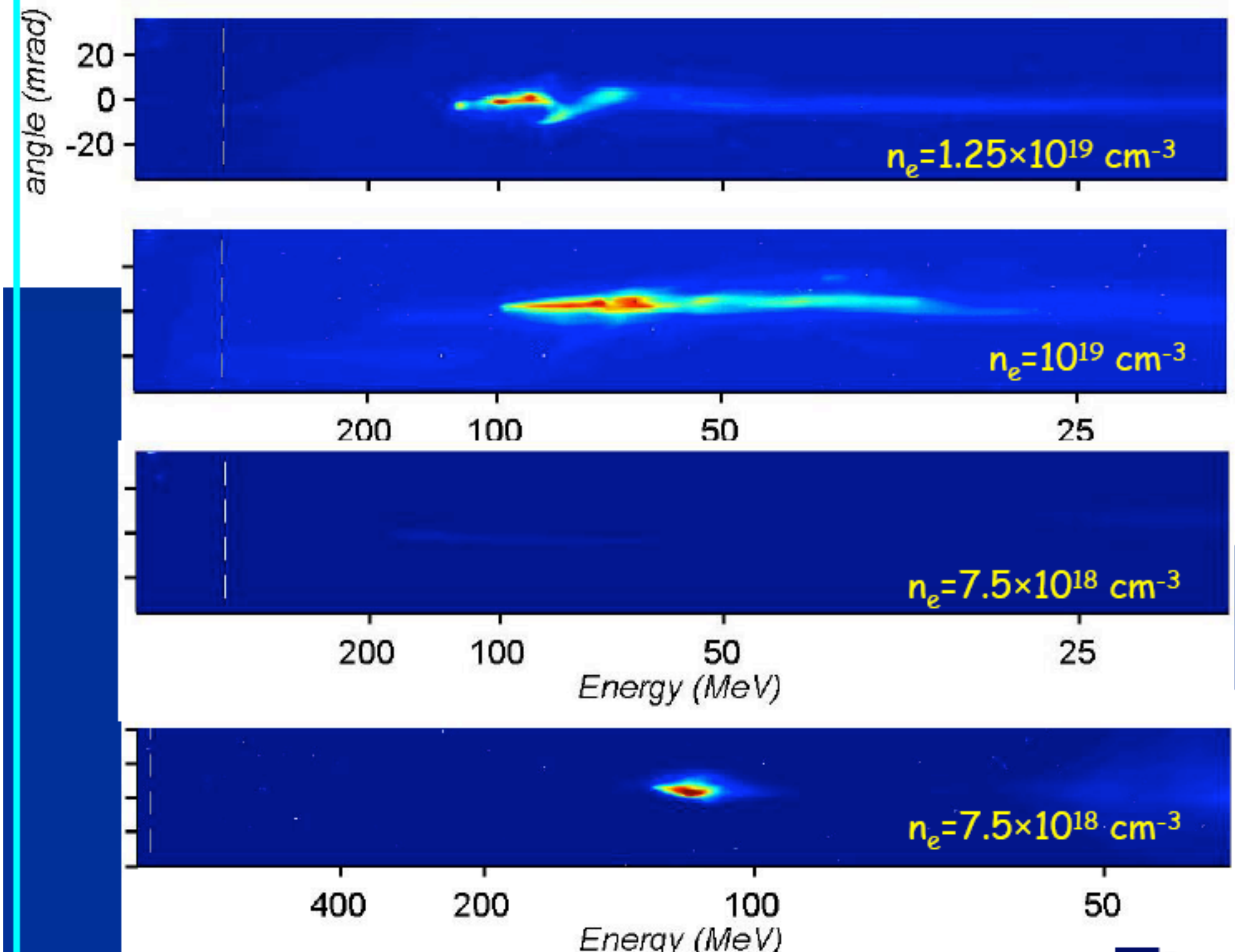
Use as injector into long, channeled stage

- Other experiments underway, e.g., LOA, NRL two-gasjet experiment

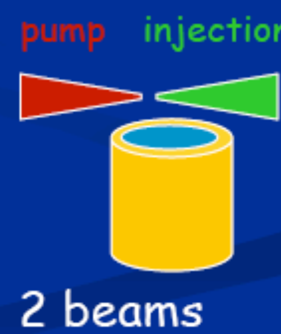
Experimental set-up



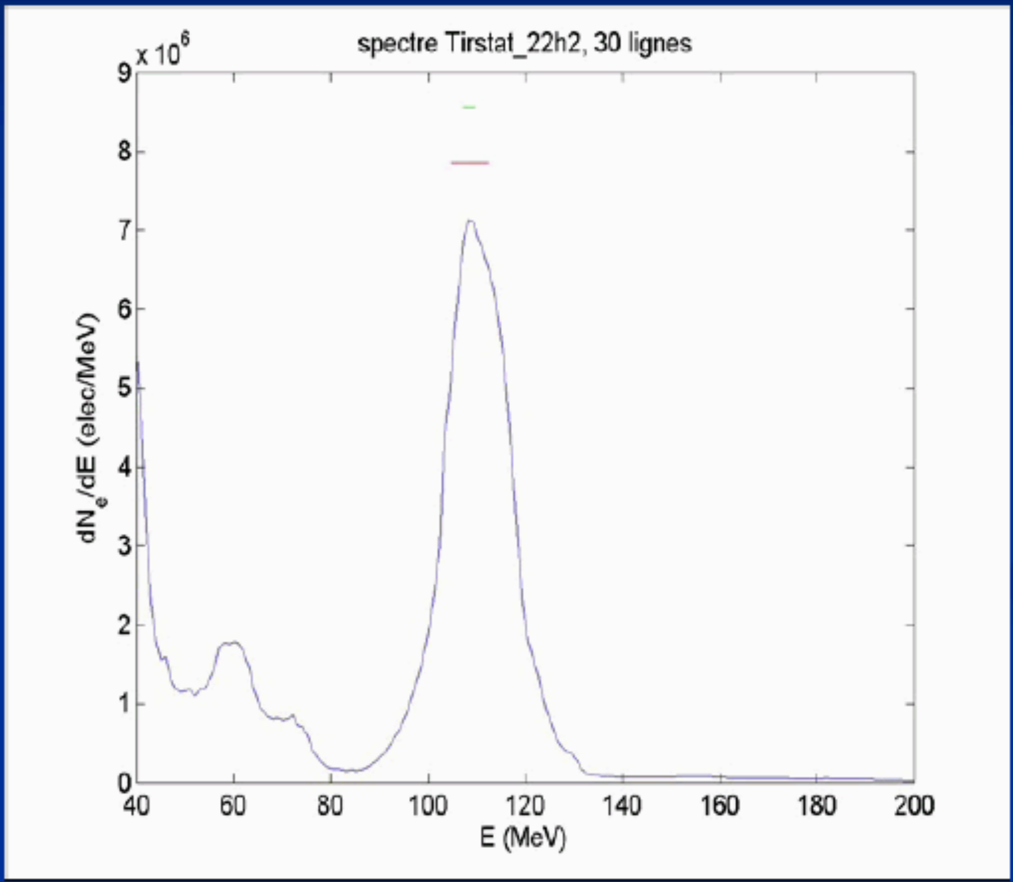
From self-injection to external injection



Self-injection Threshold



Optical injection by colliding pulses leads to stable monoenergetic beams

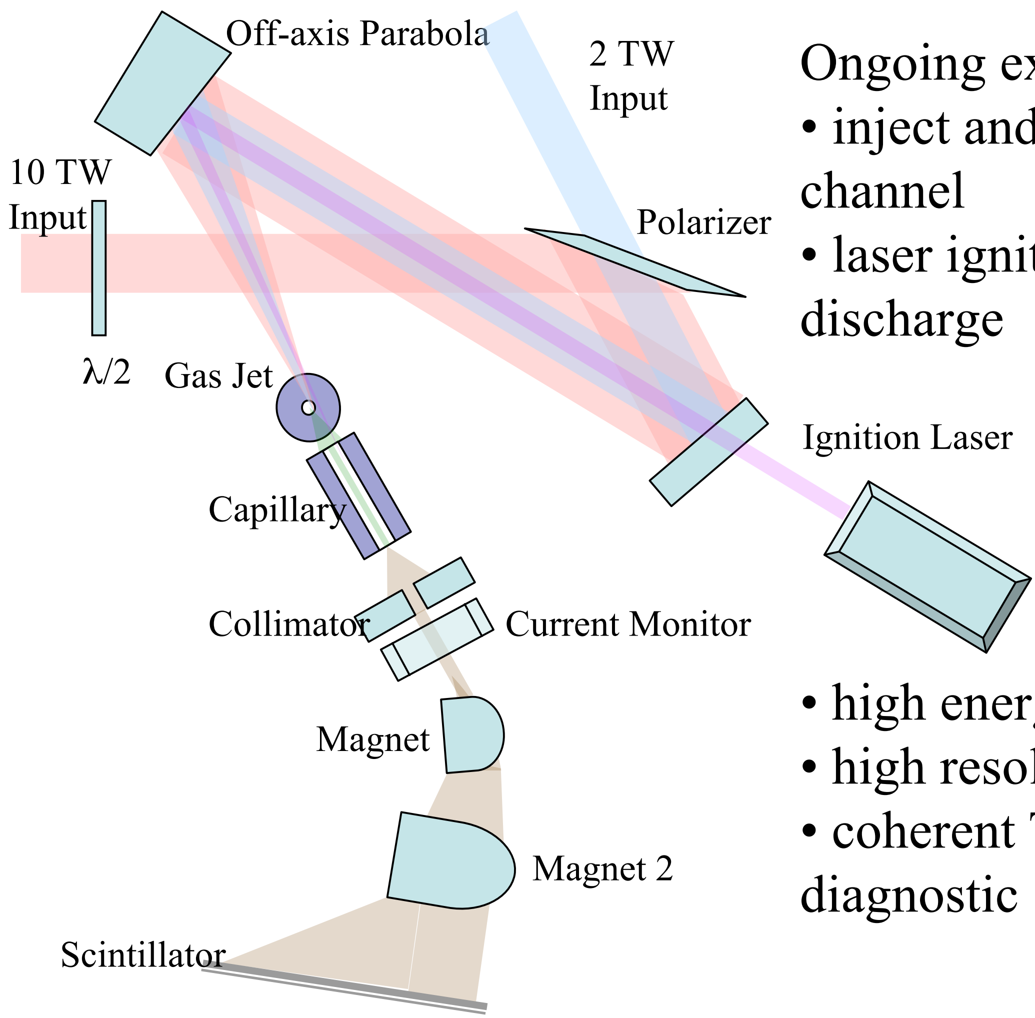


STATISTICS
value and standard deviation

Bunch charge= 19pC, σ = 6.8 pC
Peak energy= 117MeV, σ = 7 MeV
ΔE= 13MeV, σ = 2.5 MeV
ΔE/E= 11 %, σ = 2 %
Divergence= 5.7 mrad
Pointing stability= 1.8 mrad

Laser Injector/Guided Acceleration Experiment

LIPA: Laser Ionization and Ponderomotive Acceleration



Ongoing experiment:

- inject and accelerate electrons in a plasma channel
- laser ignition for ablative capillary discharge

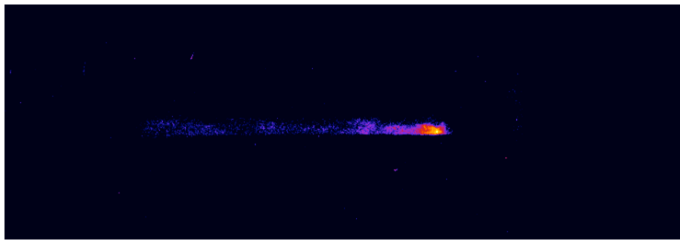
- high energy electron spectrometers
- high resolution gated optical imager
- coherent Thomson scattering as wakefield diagnostic

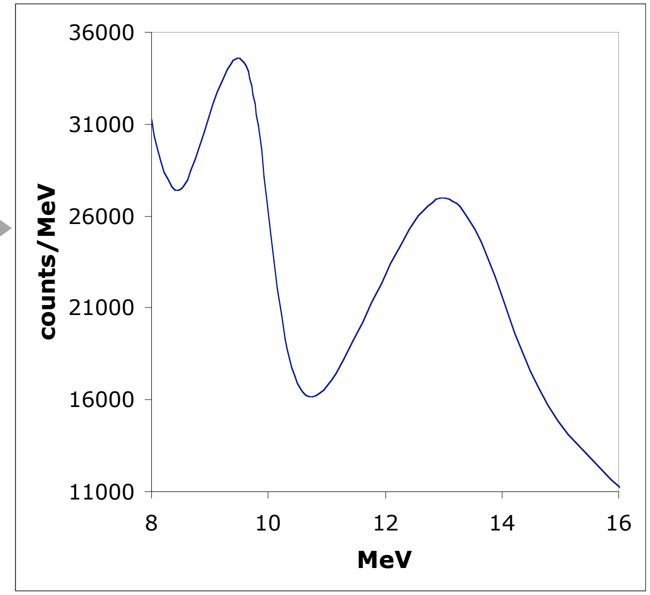
Quasi-monoenergetic Electrons from He and N_2

Two Gas Jet Experiment

Energy spectrum from He gas jet

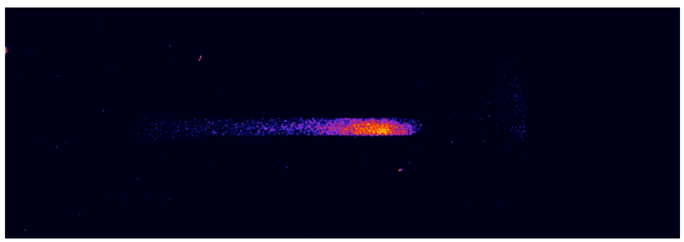
Wakefield jet





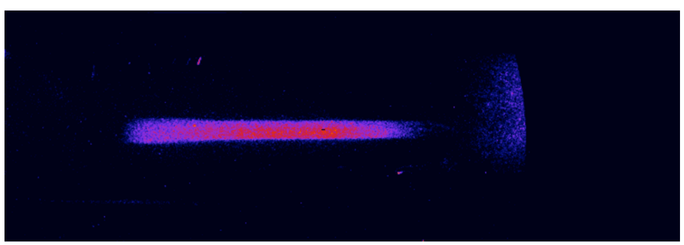
Energy spectrum from N_2 gas jet

LIPA jet



HD-LIPA
From N_2

Both jets



Laser parameters:
50 fs, 8 TW, 5×10^{18} W/cm^2 intensity at focal spot

Gas jet 1 mm long. 10^{19} cm^{-3} plasma density.

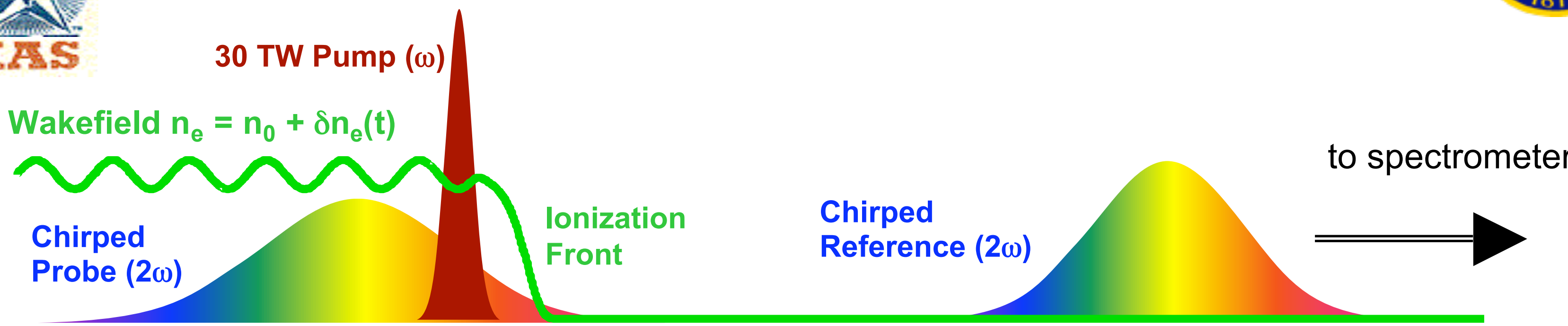
D. Kaganovich et al., Phys. Plasmas (2005)

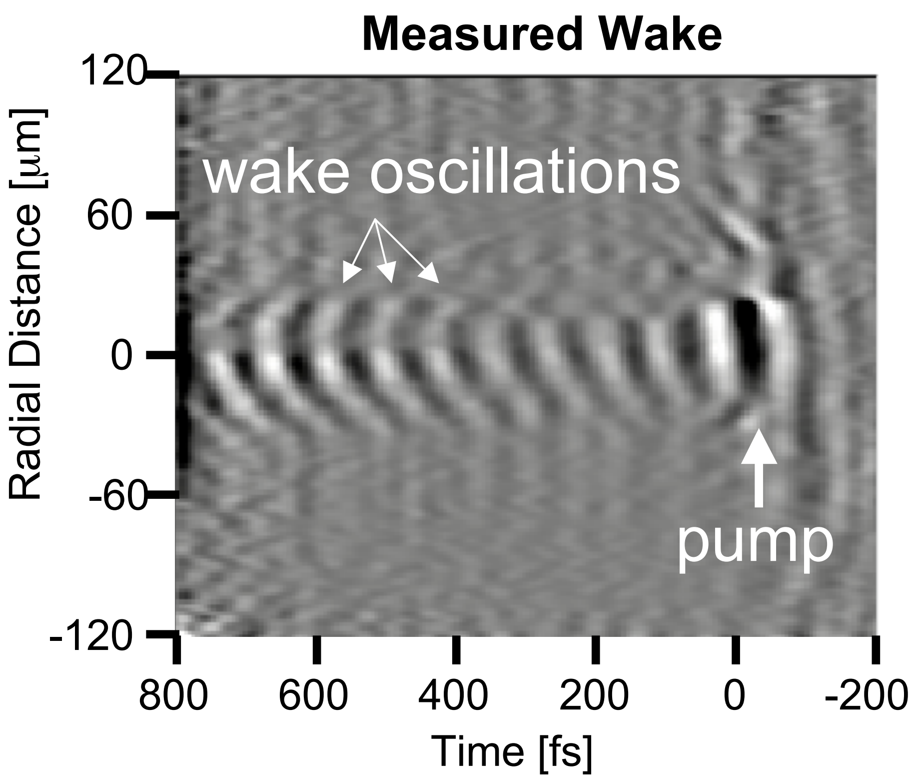
Radiation Production:

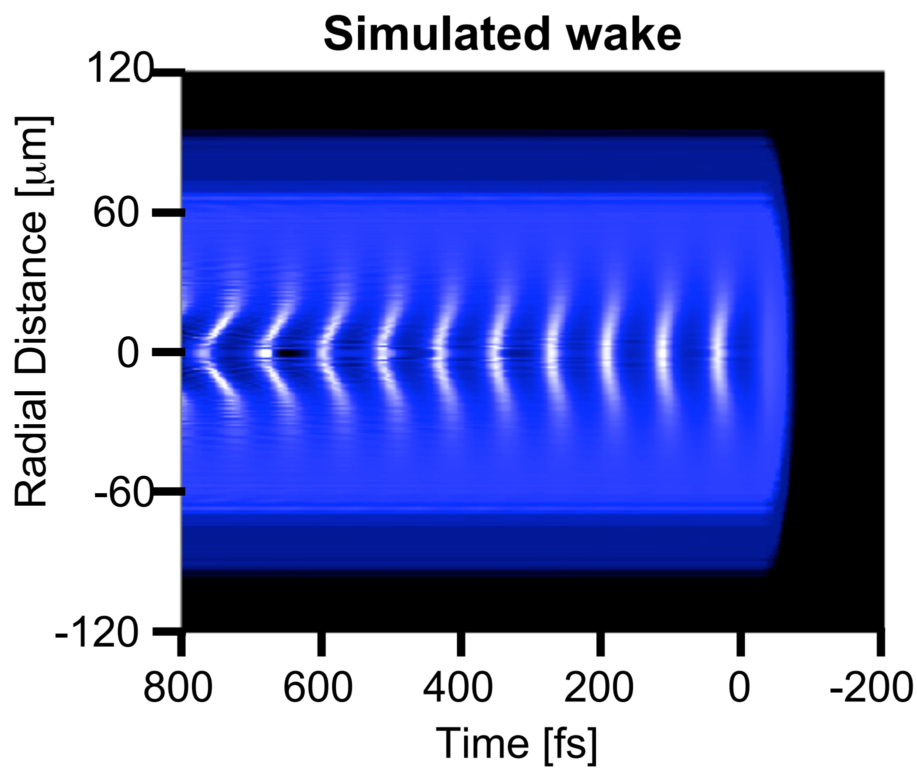
Sources and Beam Diagnostics

Wakefield Snapshots using Frequency Domain Holography enrich experiment-theory dialog

N. Matlis *et al.*, submitted to Nature Physics (2006)







will be discussed in N. Matlis' plenary talk at 3:30pm, Monday

Next generation radiation sources rely on coherence

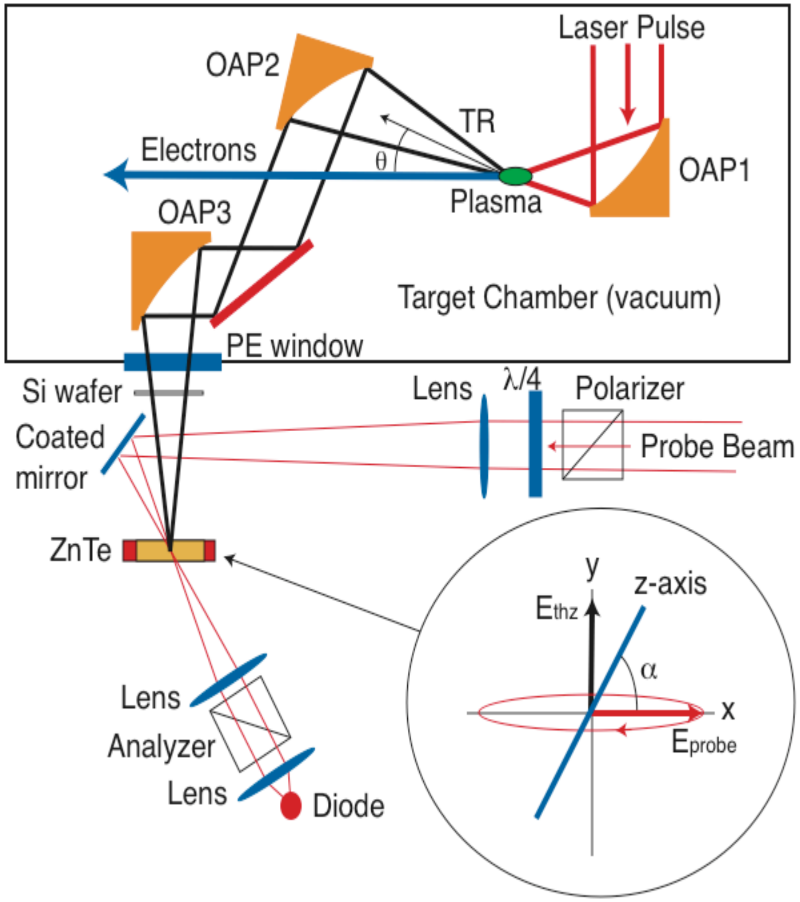
$$I_{total}(\omega) = \left\{ N + N(N-1)\left|g(k)\right|^2 \right\} I_e(\omega)$$

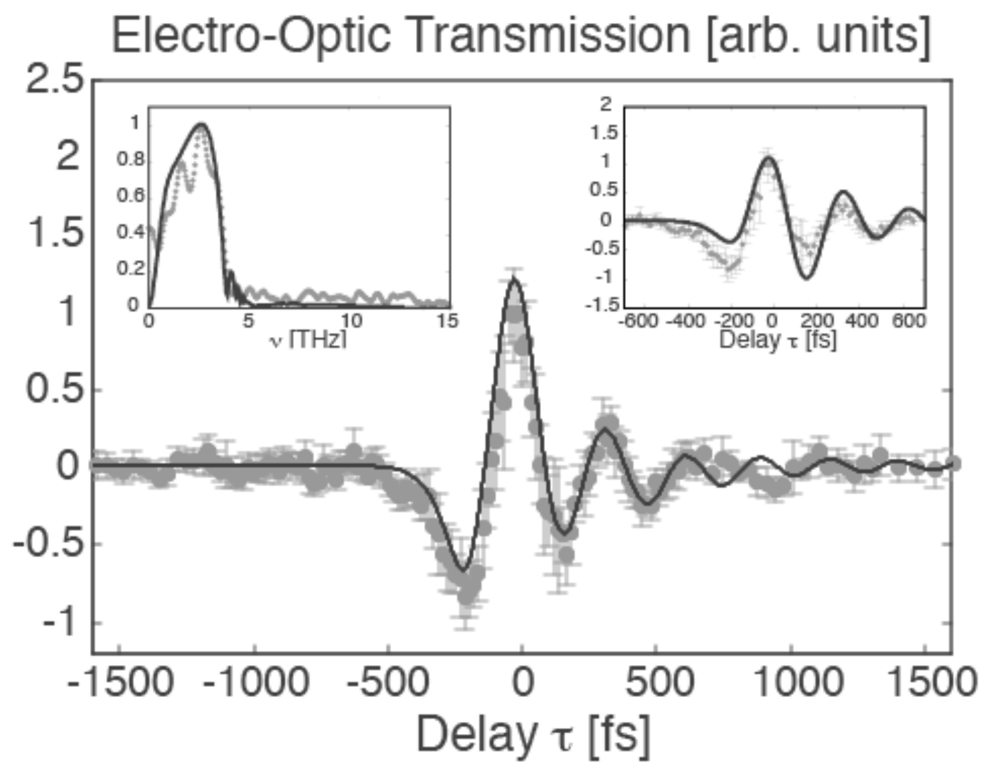
$$g(k) = \int_{-\infty}^{\infty} \rho(z) e^{ikz}\, dz$$

Dominates if $\sigma_z < \lambda$

- **Coherence => FEL, Optical manipulation of beams**
- **Femtosecond bunches from advanced accelerators**
  - **100 MeV, 1 mm-mrad normalized emittance, %-level energy spread ?**
    - **Will emittance be preserved at higher energy ?**
    - **Will relative energy spread reduce ?**

Coherent THz from LWFA: pump-probe experiments





- Relies on transition radiation from plasma vacuum boundary

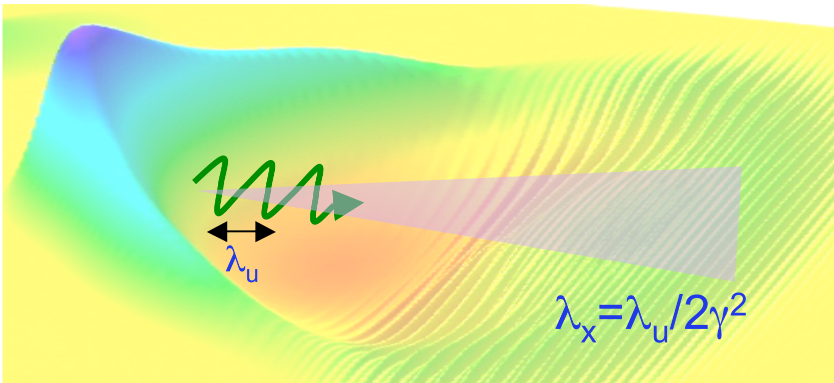
W.P. Leemans et al., PRL 2003
C.B. Schroeder et al., PRE 2004
J. Van Tilborg et al., PRL 2006

- Spectrum consistent with <50 fs bunch
- Charge and bunch shape stability
- Intrinsic synchronization
- MeV/cm reachable
- Non-linear dynamics in semiconductors
- High field superconductors

Incoherent x-ray sources developed for first experiments

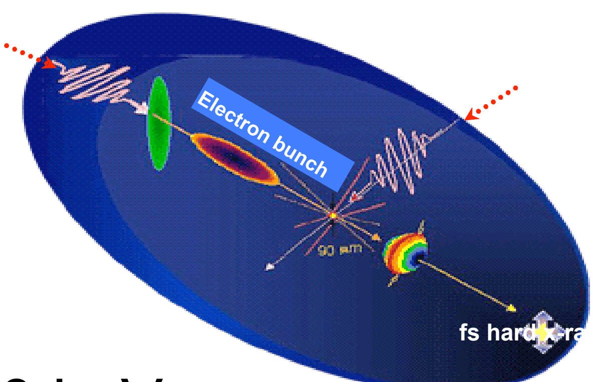
Electron beam driven wake
Wang et al., Phys. Rev. Lett. ***88****, 135004 (2002)*

- Betatron (synchrotron) radiation:

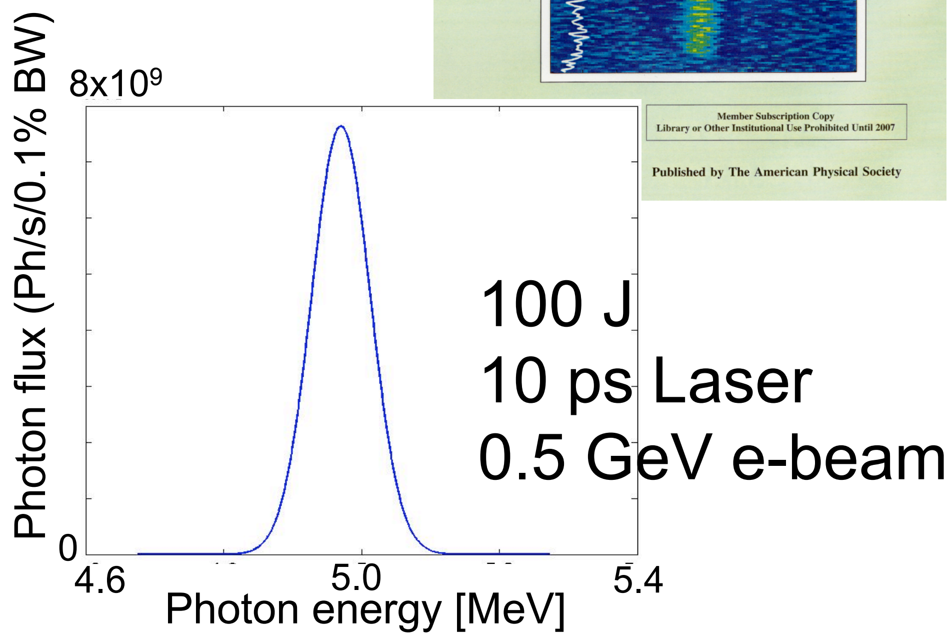


E. Esarey et al., PRE 2002
A. Rousse et al., PRL 2004

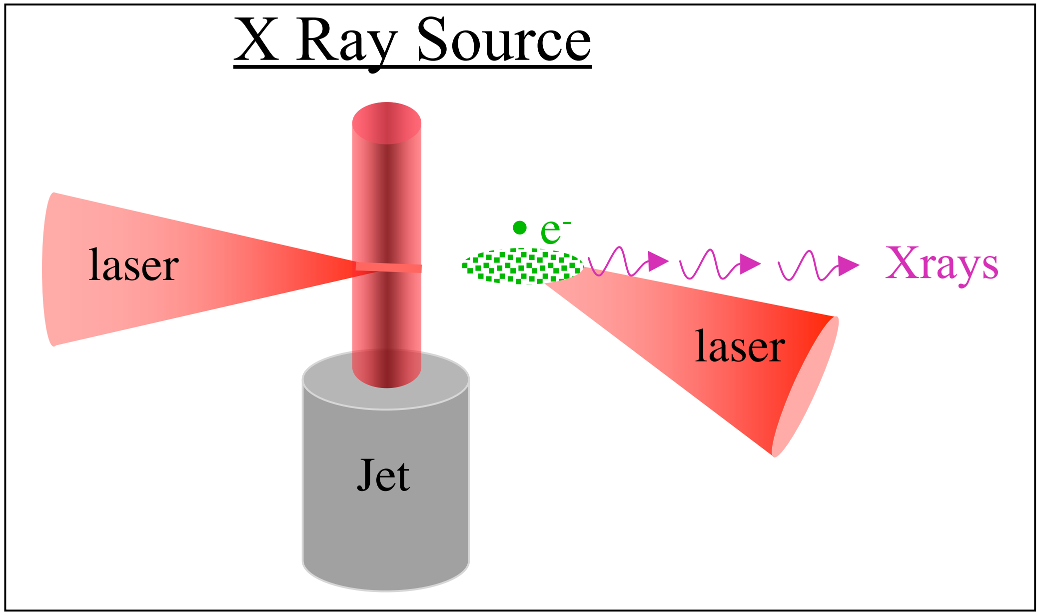
- Thomson scattering radiation:



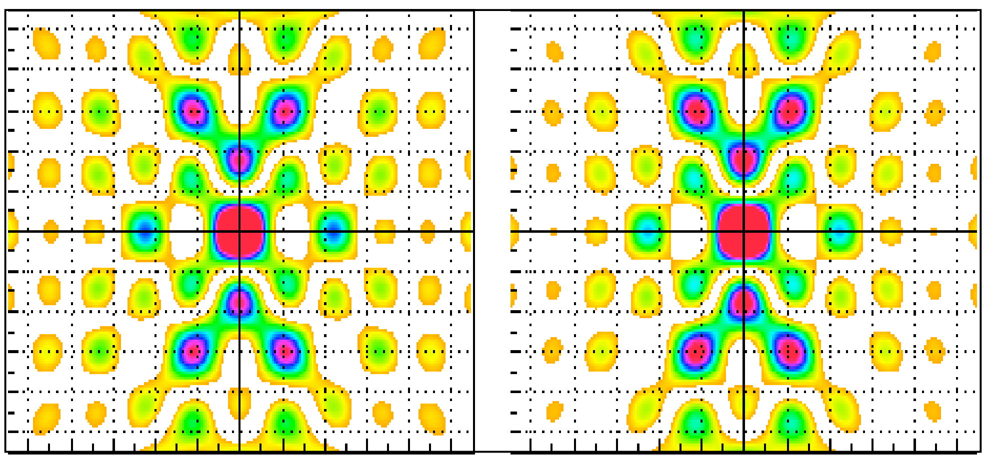
1-50 keV xrays



Thomson Scattering X-ray Source/Beam Diagnostic



X ray Diffraction Shows Changes In Structure



Electrons see laser as undulator

Demonstrated with RF accelerator limited by charge density

Radiation upshifted by $2\gamma^2$
80MeV electrons ~ 100keV photons

Laser accelerators offer intense, short electron beams.

10^8 photons/shot*

10^4-10^5 ph/shot/0.1%BW*

10fs pulse

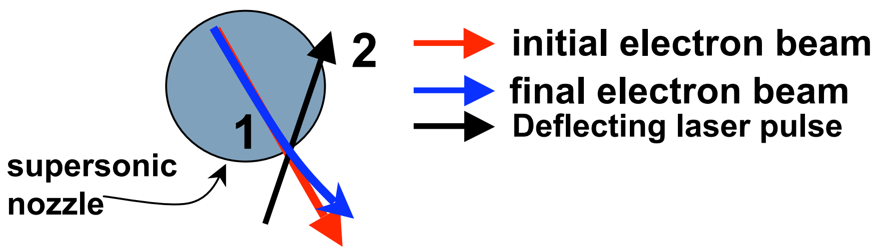
Time resolved X ray diffraction, imaging

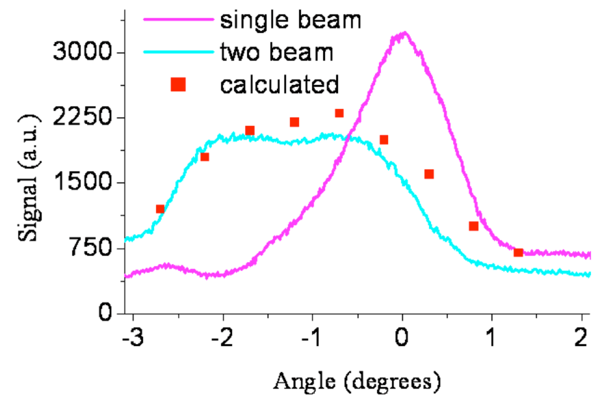
Possible resolution of beam evolution over propagation

*Following Catravas et al, Meas. Sci. Tech. 2001

Optical deflection and conditioning of femtosecond MeV electron bunches

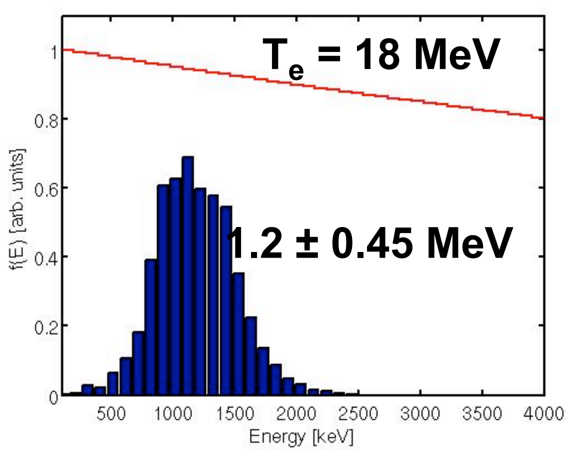
Colliding an ultra-intense laser pulse and a relativistic electron beam leads to energy and intensity dependent deflection.





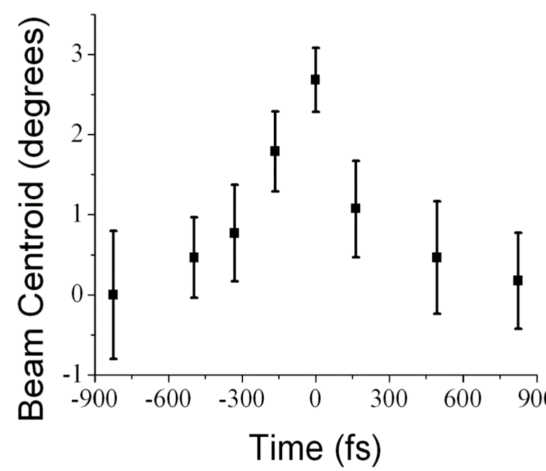
1st laser pulse – accelerates electron beam
2nd laser pulse – deflects electron beam

Conditioned Electron Beam



Higher intensities condition MeV electron beams

a_0	E ± ΔE (MeV)	e^-/5 nC (10^8)
2.5	1.20±0.45	9.02
5.6	2.35±0.45	7.03

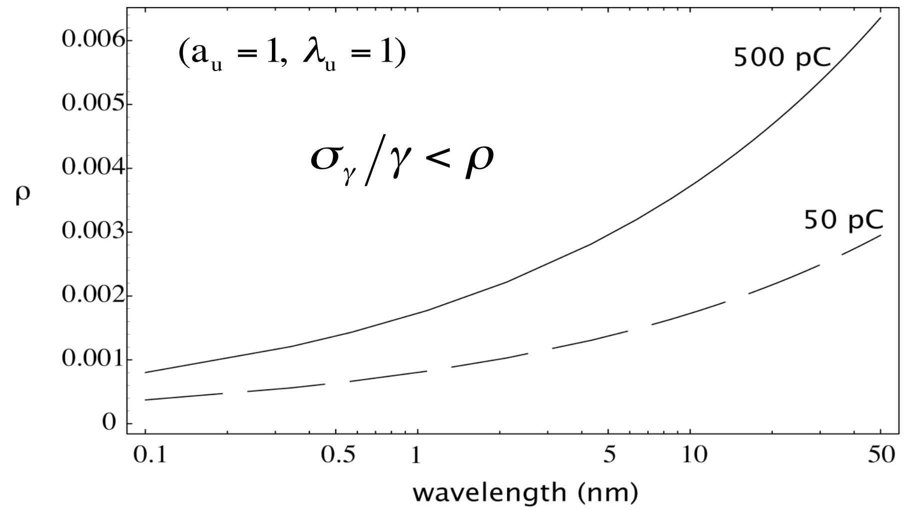


S. Banerjee *et al.*, Phys. Rev. Lett. **95**, 035004 (2005)

Ultraintense laser pulses optically select, near-monochromatic femtosecond MeV electron bunches without space-charge broadening.

An LWFA based FEL ?

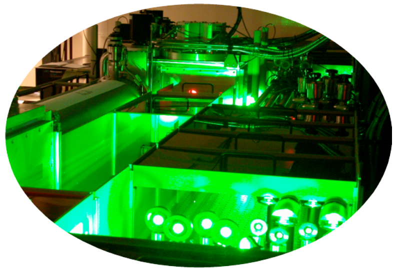
LWFA beam parameters	
Normalized energy, γ	2000
Normalized emittance	1 mm mrad
FWHM duration	20 fs
Charge	0.5 nC
Peak current	25 kA
Energy spread (projected)	0.01



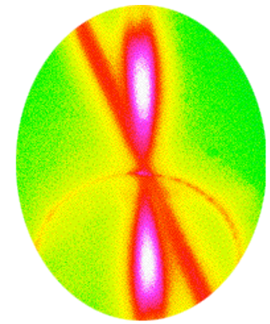
FEL parameters	1 GeV LWFA	0.25 GeV LWFA
Normalized beam energy	2000	500
Undulator wavelength	1 cm	1 cm
Undulator strength	1	1
Radiation wavelength	2 nm	30 nm
FEL parameter	$2{\cdot}10^{-3}$	$5{\cdot}10^{-3}$
Saturation length	4.7 m	1.8 m
Photons/pulse at saturation	10^{13}	10^{14}
Beak brightness (ph./s/mm^2/mrad^2/0.1%BW)	$5{\cdot}10^{30}$	10^{29}

- Will emittance be preserved?
- Will ΔE/E be low enough ?
- European and Asian efforts underway

Scaling to Future Laser Driven Accelerators



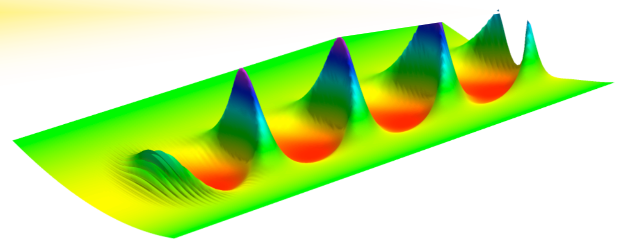
Lasers at > 300 TW, > 300 W
High rep-rate, high average power



Staging of modules: ΔE, phase
Stable injection

Challenges

10 GeV, low energy spread & emittance
Guiding over meter scale

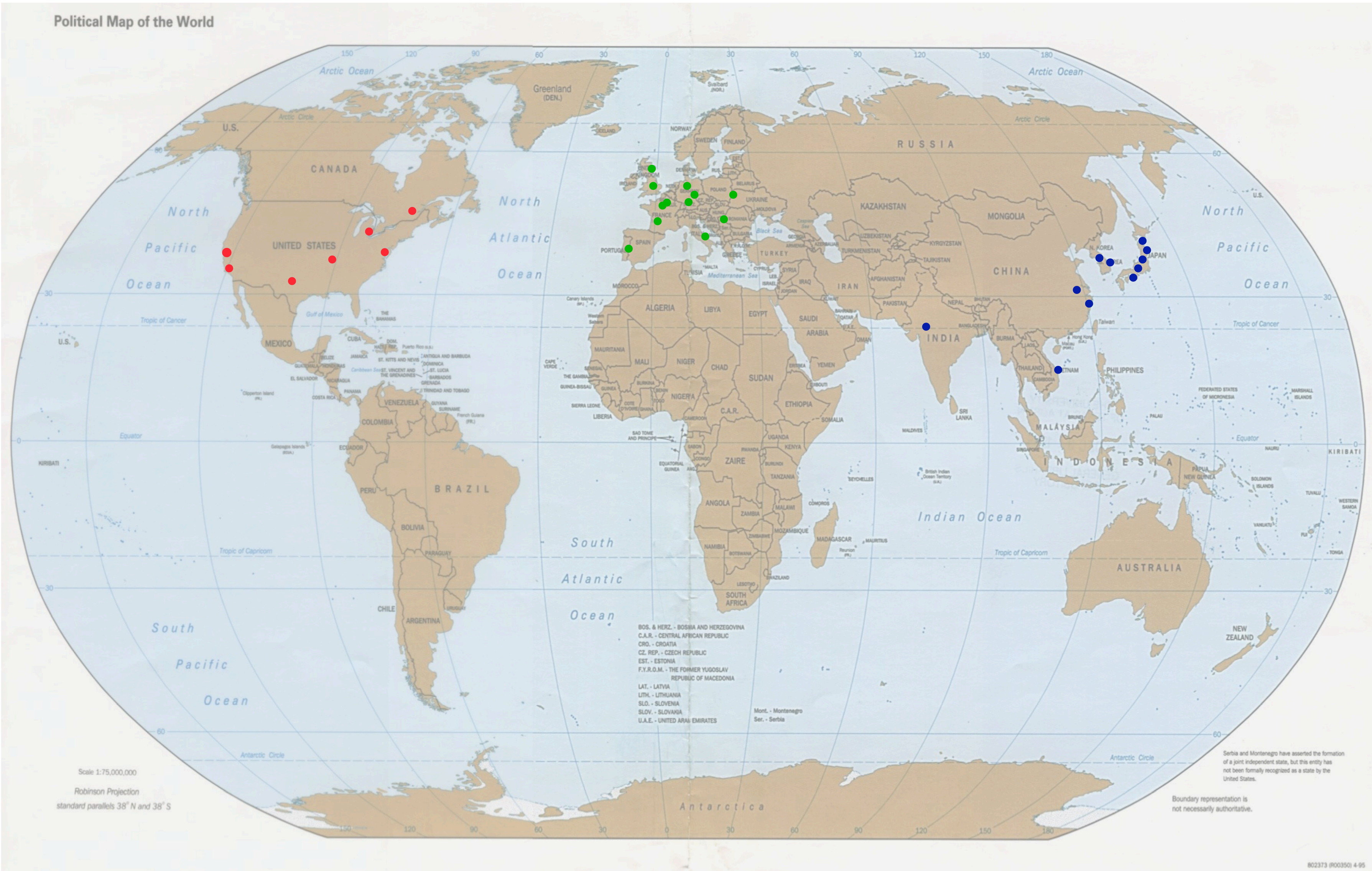


3-D modeling, improved algorithms
Reduced models

Understanding of:

- Laser evolution, shaping, depletion, spectral shifting
- Bubble regime, self-trapping, self-guiding experiments
- Beam dynamics, applications, optimization (THZ, X-rays, FEL's)

Advanced accelerator research worldwide



Map courtesy V. Malka

Summary

- High quality e-beams
  - Few percent energy spread, few mrad, 100 pC
  - Accelerate over dephasing length, “tune” on power and density
  - 100 MeV: 10 TW, few-mm gas jet, densities 10^{18}-10^{19} cm^{-3}
  - 1 GeV: 40 TW, few-cm plasma channel, densities 10^{18}-10^{19} cm^{-3}
- Laser injection methods
  - Stable, reproducible, high quality beams
  - Experiments underway: LOA, LBNL, others…
- Prospects for acceleration > 1 GeV
  - Staging (injector + dark-current-free channel)
  - Modeling and scaling laws
- Challanges
  - Optimization: Tailor laser and plasma parameters
  - Diagnostics: Wakefield, laser, e-beam (emittance, fs-resolution)
  - Verify physics: Nonlinear evolution, pump depletion, dephasing
  - Staging: Long channels, laser+e-beam transport
  - Stability: Laser injection, feedback
  - Modeling: Reduced (time-averaged, quasi-static) codes
  - Applications: High-average power lasers