The 12th

Advanced Accelerator Concepts Workshop

Grand Geneva Resort, Lake Geneva, Wisconsin, USA

Organized by: Argonne Wakefield Accelerator Group and Northern Illinois University

July 10-15, 2006

WG 6 Summary

Wim Leemans, Mike Downer, Craig Siders

Apologies to those whose results we are not showing…

Overview

- Attendees: ~ 80; 32 talks
- Joint sessions with WG1&WG6
- Topics:
  - Acceleration
  - Guiding
  - Injection
  - Simulations
  - Scaling laws
  - Diagnostics
  - Laser systems

Some of the questions:

-To guide or not to guide?

-Will simulations <u>ever</u> catch up with experiments?

-How big should the laser be?

AAC2004 Results: High Quality Bunches

30 Sep 2004 issue of *nature*:

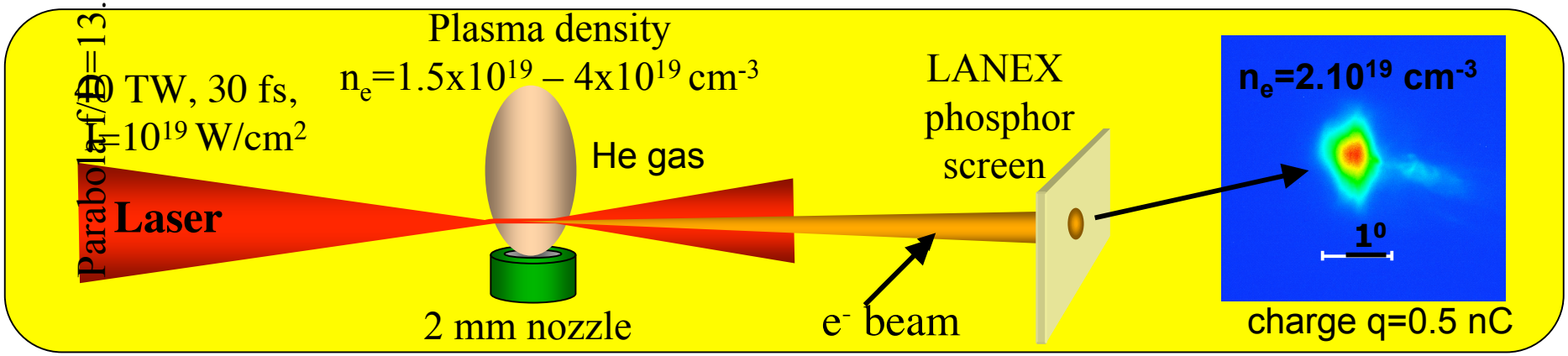
Three groups report production of high quality e-bunches

- 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, $\Delta E/E$=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, $\Delta E/E$=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, $\Delta E/E$=24%,10 mrad

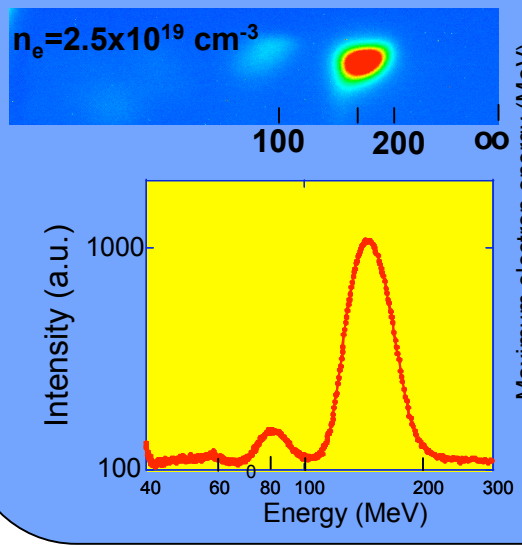
Quasi mono-energetic beams widely observed

- Results reported from:
  - Michigan (S. Reed et al.)
  - Taiwan (S.Y. Chen et al.)
  - Japan (T. Hosokai et al., Kando et al., T. Reiko, K. Koyama)
  - NRL (Kaganovich et al.)

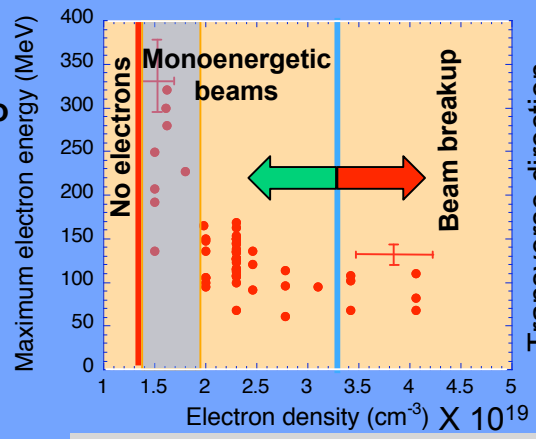
Generation of 300 MeV Quasi-Monoenergetic Electron Beams from Laser Wakefield



Spectrum



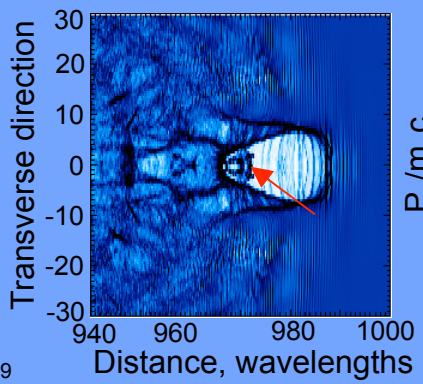
Scaling



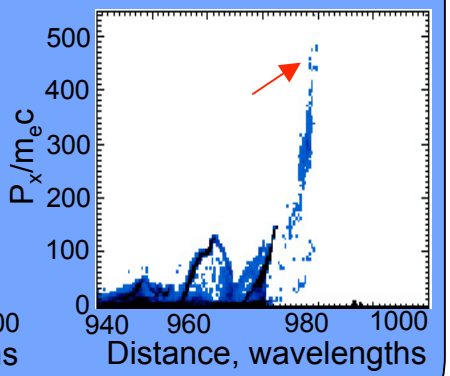
Low (2 pC) charge but high (10 mrad) angular stability of e^- beam

2D PIC simulation

Electron density



Electron momentum



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

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

The agreements between simulation and experiment is good

RAL/IC 2004

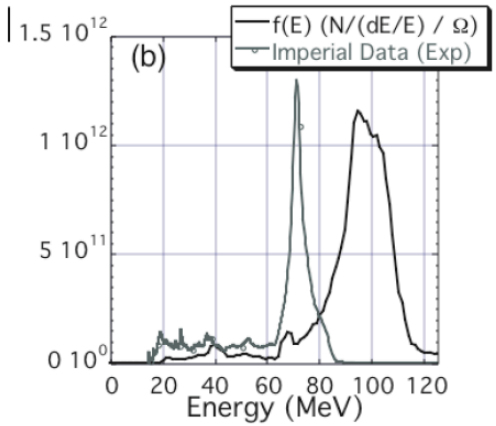
Total # of electrons: 2.3 10^8 (2.0 10^8 reported in *Nature*).

Average Energy ~95 MeV (*Nature* reports [50,80] MeV).

Normalized Emittance:

3.51 μm (in b)

7.61 μm (in e)



AAC-2006

Agreement between simulation and experiment is good in this case

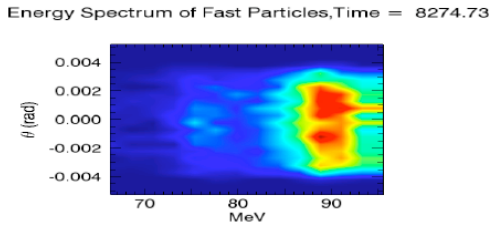
LBNL/2004

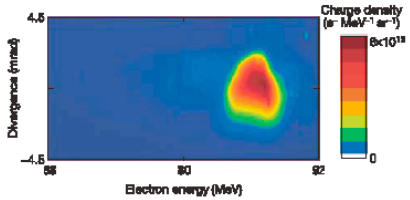
Total # of electrons: 1.76 10^9 (2.0 seen in experiments)

Normalized Emittance:

14.23 μm along b

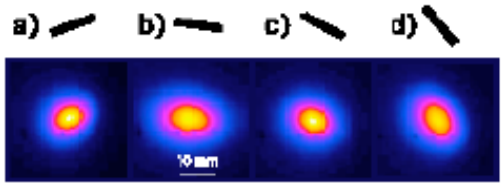
17.44 μm along e



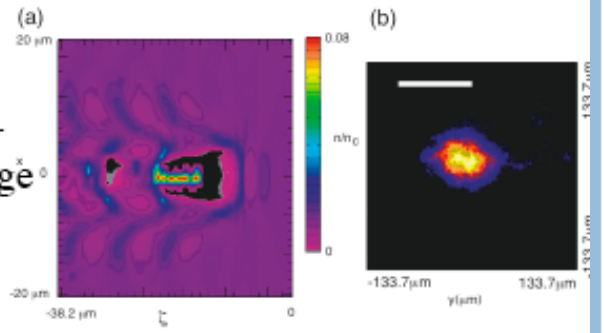


E-Beam profile depends on laser polarization

CCD Images from Experiment



3D OSIRIS Output + Synthesized CCD Image



Reported by Z. Najmudin

Experimental and Simulation Results -- LOA Parameters

LOA/2004

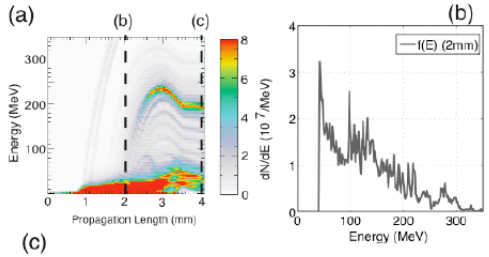
Simulation yields:

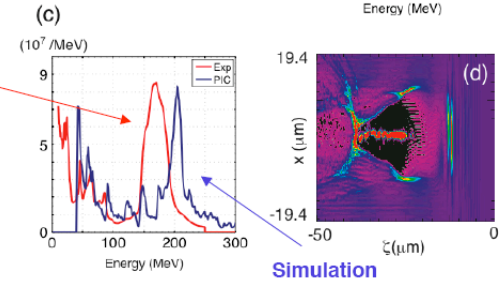
2.25×10^9 *electrons*

Experiment yields:

Experiment

3.13×10^9 *electrons*





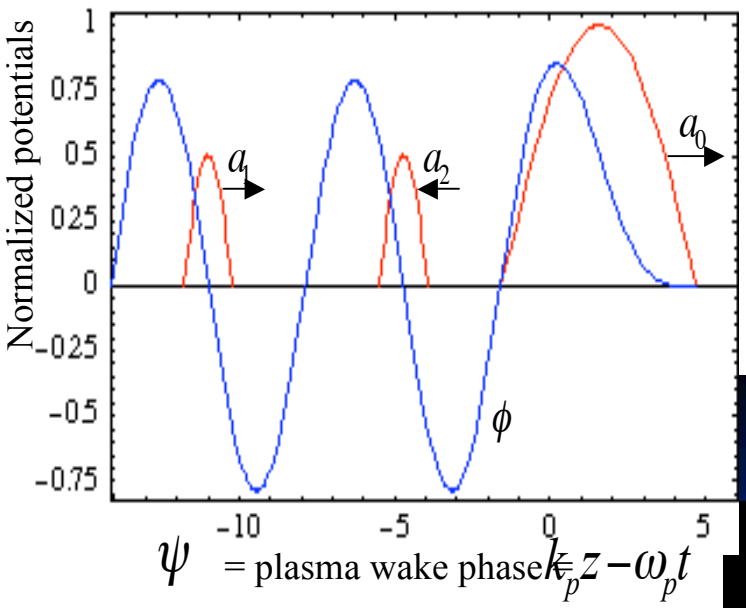
Simulation

AAC-2006

New trends in the field

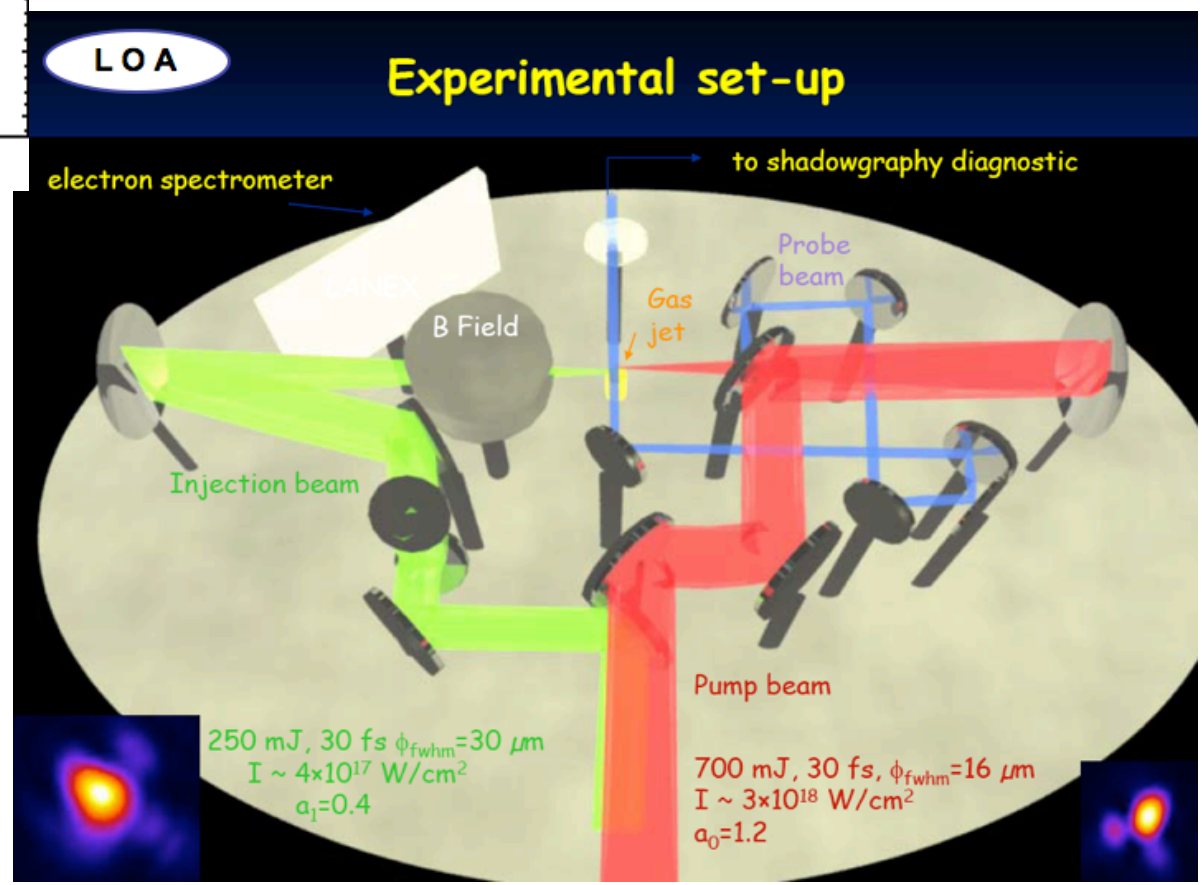
- Stability:
  - e.g. Pre-plasma control
- Injection control:
  - Laser triggered
  - Density transition
  - Self-trapped with parameter control
- Sophisticated diagnostics
  - Optical wake field diagnostics
  - Bunch duration measurements in THz and optical regime
- Engineered/machined plasmas
  - Transverse -> guiding structures, optical element
  - Longitudinal ->quasi-phase matching
- GeV channel guided accelerator

Repeatable Beams: Colliding Pulse Injection



Concept:
- slow wave structure to trigger trapping
- fast wave structure to accelerate

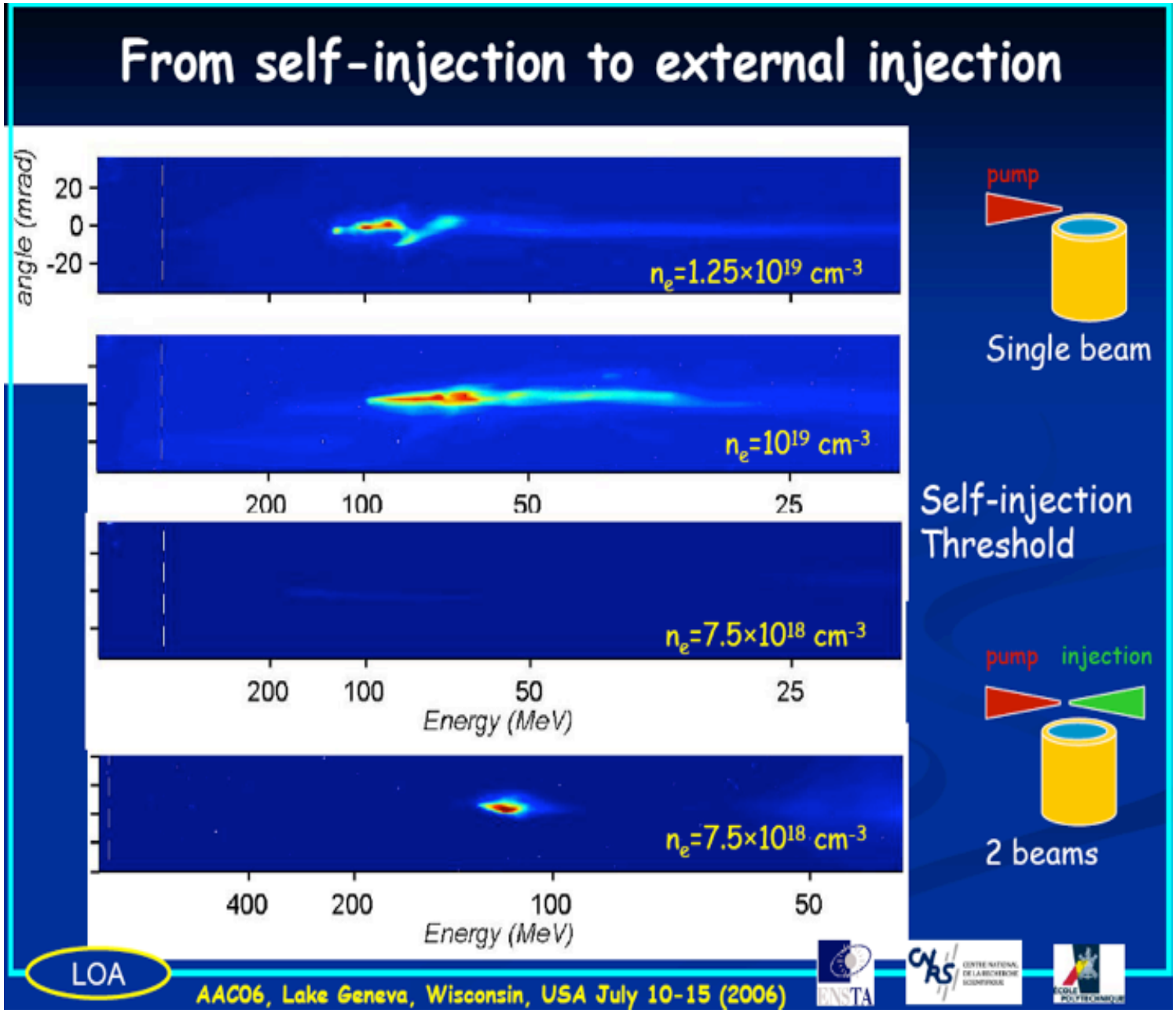
Two-pulse implementation-LOA



Esarey *et al.*, PRL (97)

Schroeder *et al.*, PRE (99)

Fubiani *et al.* PRE (04)



Courtesy: V. Malka

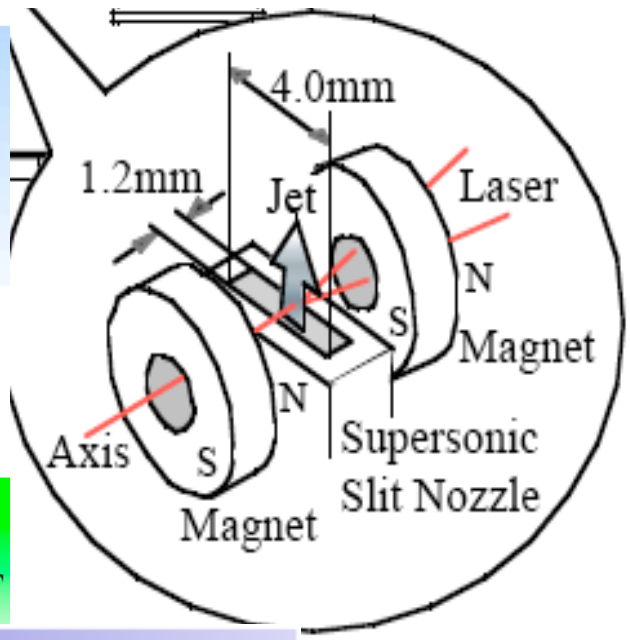
Repeatable Beams: Pre-plasma control

Pre-plasma manipulation by external magnetic field on gas jet injector

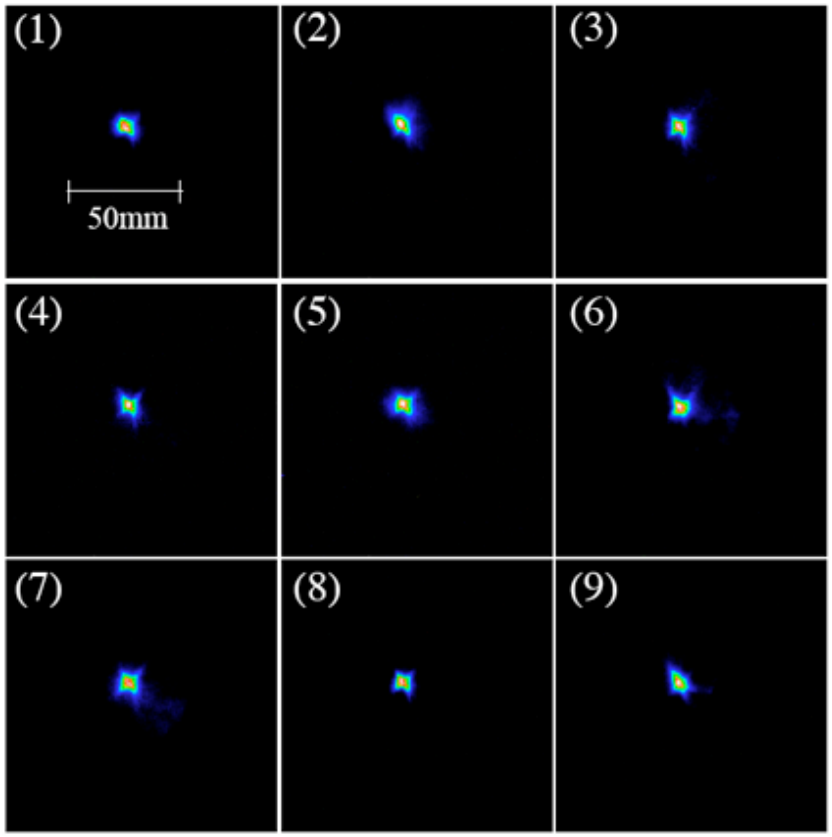
$F^{\#}$=3.5 (f= 178mm)

He Gas: $4 \times 10^{19} cm^{-3}$

Laser : 6 ~ 12 TW



Axal B-field:
0.18, 0.22, 0.20T



- Narrow-cone beam
- Remarkable stability
- Not so sensitive to focus position
- Not so sensitive to ns-prepulse level
- e-beam profile: Star shape

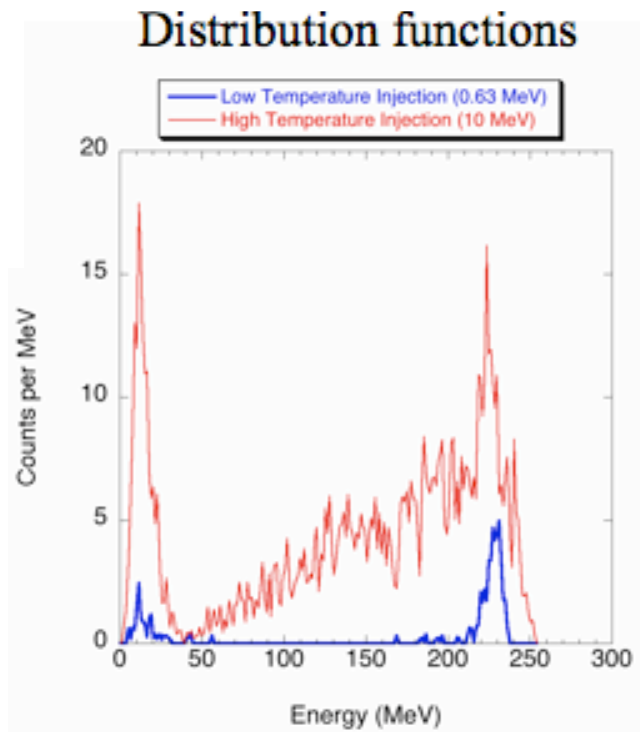
T.Hosokai,*et al.*,Phys Rev.Lett (submitted)

Repeatable Beams: External injection&density transitions

External Injection

UNPHASED, WARM BUNCH INJECTION*
TurboWAVE Simulation, $ct = 3.3$ cm
*R. Hubbard, *et al.*, IEEE Trans. Pl. Sc. **33**, 712 (2005)

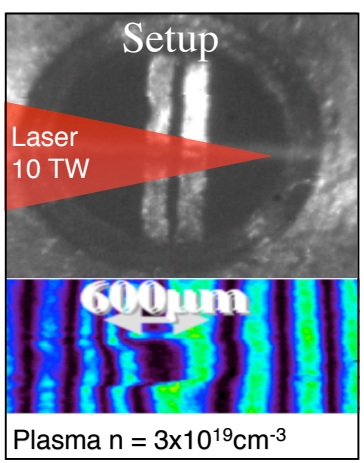
$P_0 = 8$ TW, $\tau_L = 67$ fs,
$r_0 = 30$ μm, $n_0 = 5\text{x}10^{17}$ cm^{-3}



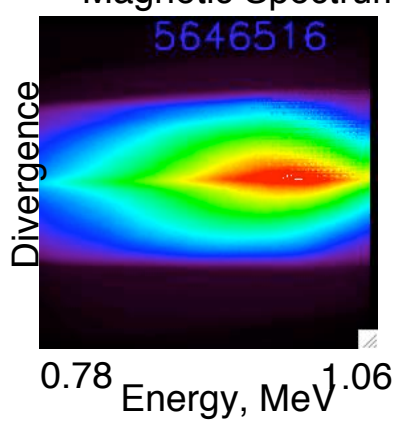
Also: S. Kalmykov, UT Austin

Density transitions

Stable 1 MeV beam: LBNL; Geddes et al., submitted
focusing on plasma down-ramp

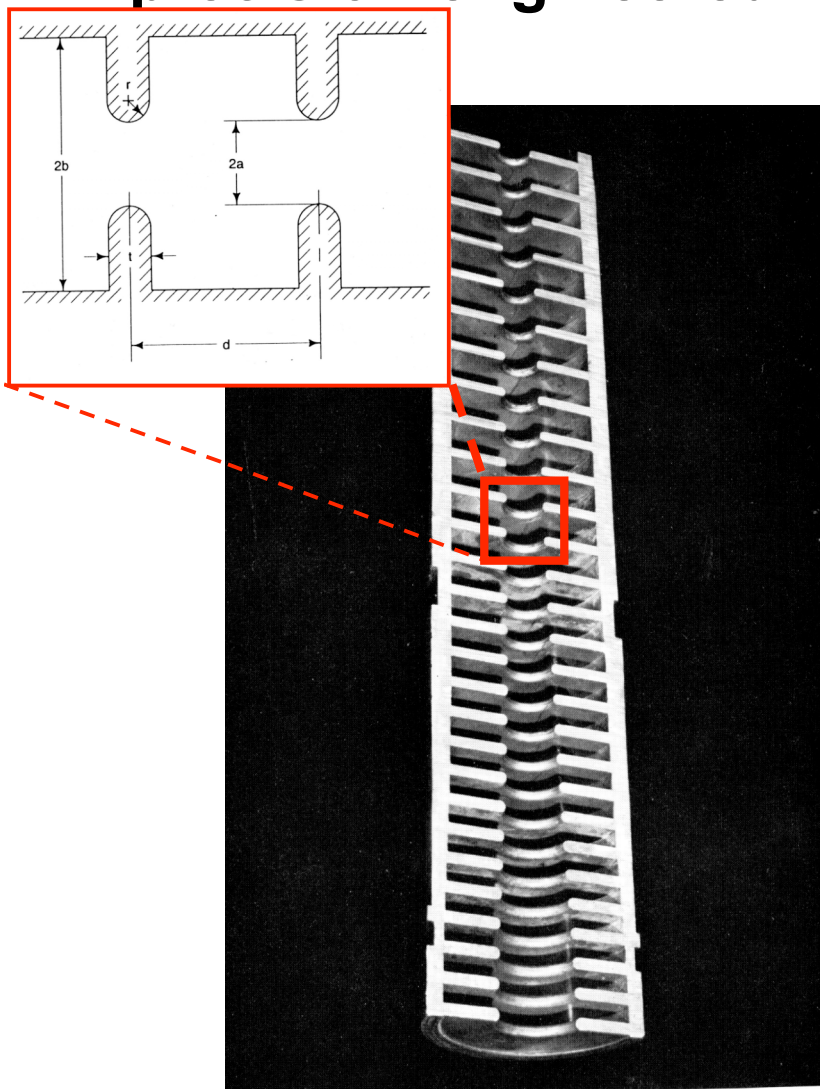


Magnetic Spectrum



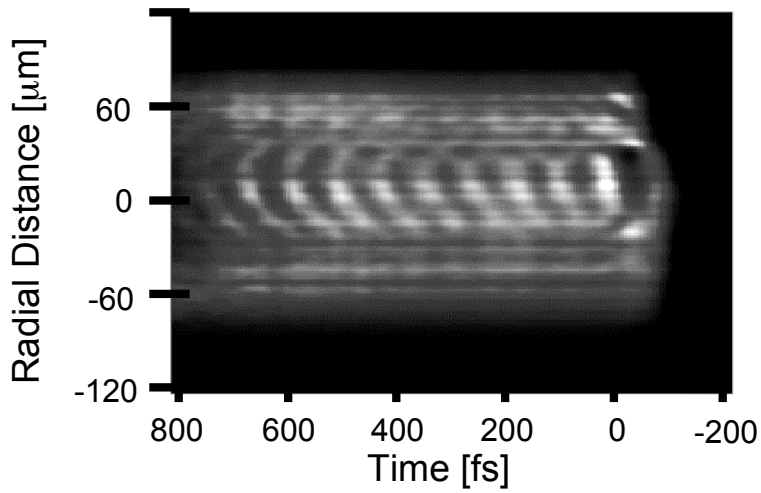
Controlling the ramps:
- plasma machining

Copper RF accelerator cavities must be precision-engineered

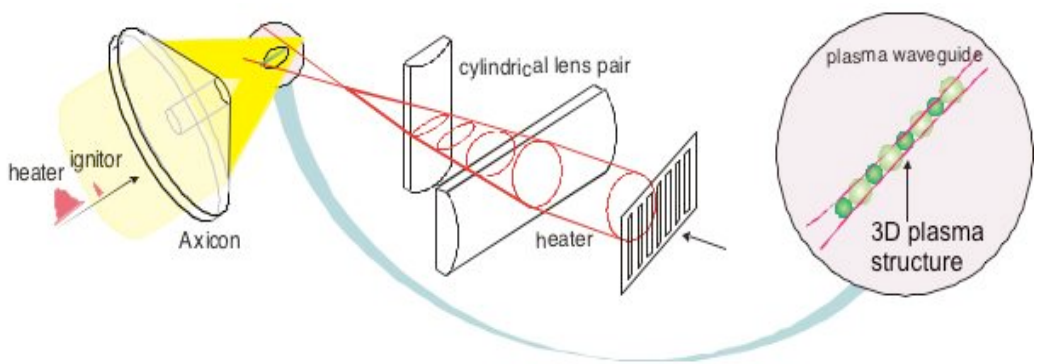


Since 2004, we have learned to see[1] and engineer[2] plasma accelerating structures

[1]Frequency Domain Holography



[2] Plasma Tomography & Channeling



Guiding techniques continue to improve
Next "frontier" is 0.5-1m long, low density channels (10^{17} cm^{-3})

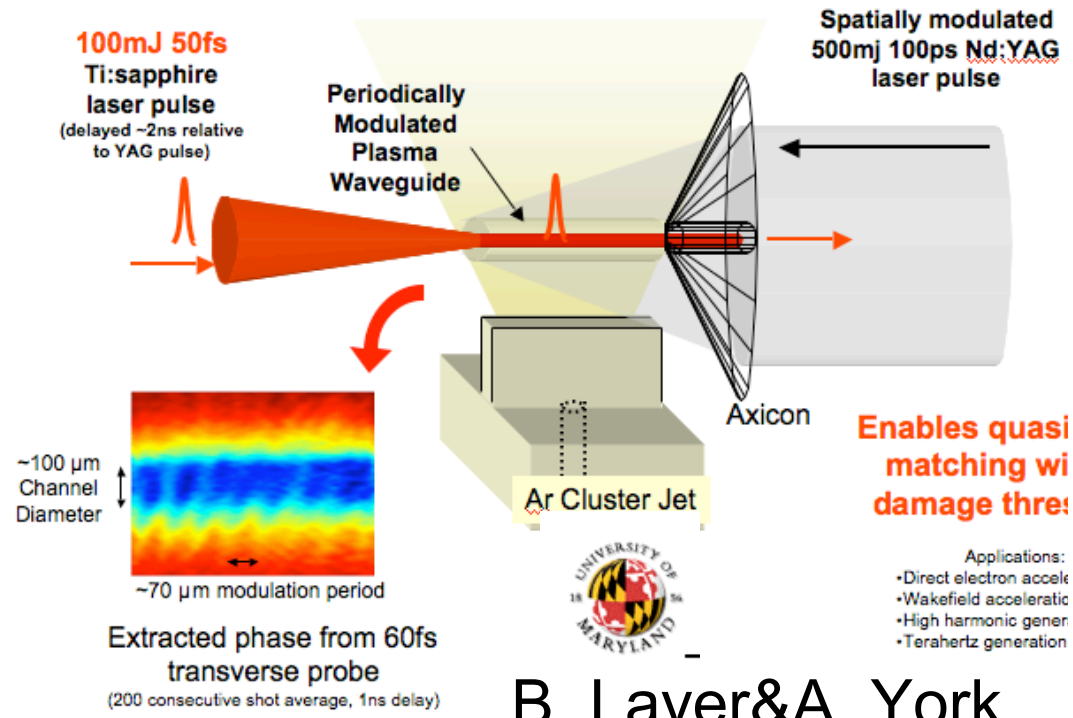
Technique	Density (cm^{-3})	Length (mm)	Intensity (W cm^{-2})	Advances	Issues
Monomode capillary	0 – 10^{17}	100	10^{17}	Guiding through gas demonstrated	Short capillary lifetime
Hydro-dynamic expansion	10^{18} - 10^{19}	15	$5x10^{18}$	Lower densities Longitudinal structure	Auxiliary laser system reqd. Energy of laser increases with channel length
Hydro-dynamic compression	10^{17}	100	10^{17}	High-intensity guiding	Plasma fully ionized? Timing jitter
Discharge-ablated capillaries	10^{18} - 10^{19}	120	10^{17}	Reduced jitter Longitudinal uniformity measured	Partially ionized plasma Low capillary lifetime
Gas-filled capillaries	10^{18} - 10^{19}	50	10^{18}	Guiding @ 10^{18} Wcm^{-2} Generation of GeV e-beam	Able to scale to low densities?

Courtesy:
S. Hooker

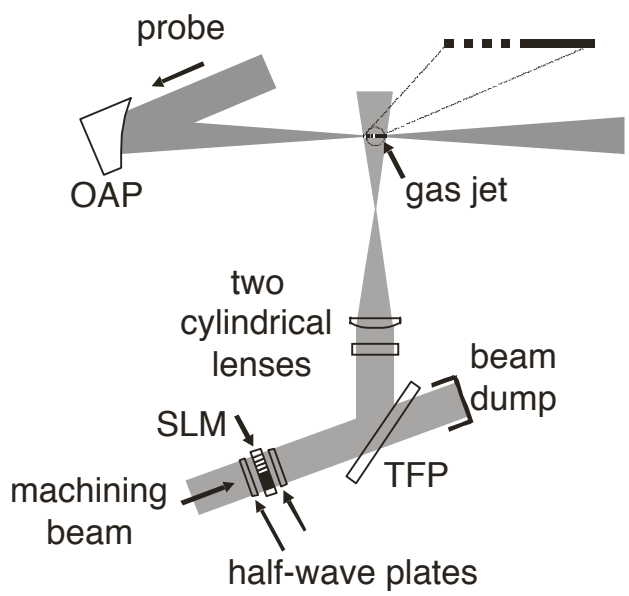
Machining the plasma structure

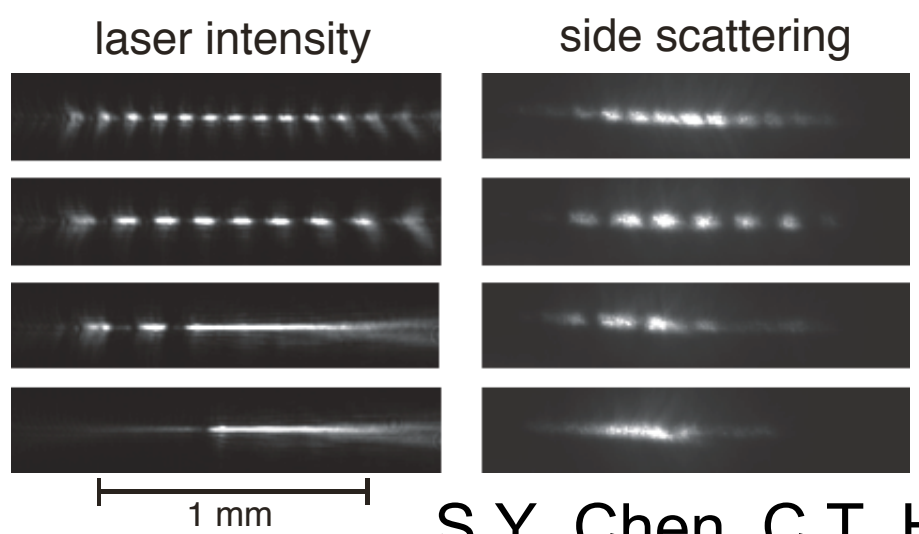
Machining the plasma:

- Transverse: channels, guiding
- Longitudinal: modulated density, quasi-phase matching
- U-Maryland
- Taiwan



B. Layer&A. York





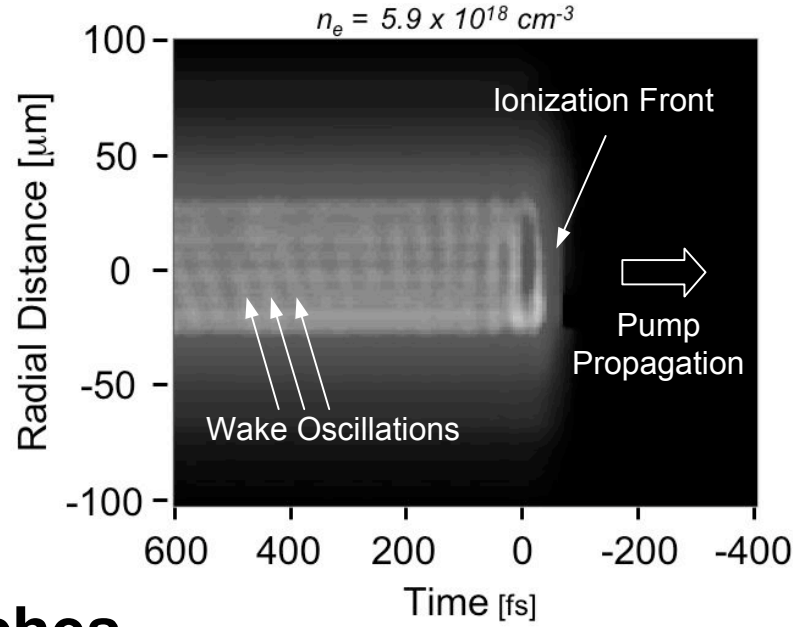
S.Y. Chen, C.T. Hsieh

Diagnostics Highlights

- **Laser Wake structure**
  (presented by Nicholas Matlis - U. Texas)

Holographic Snapshots of Laser Wakefields

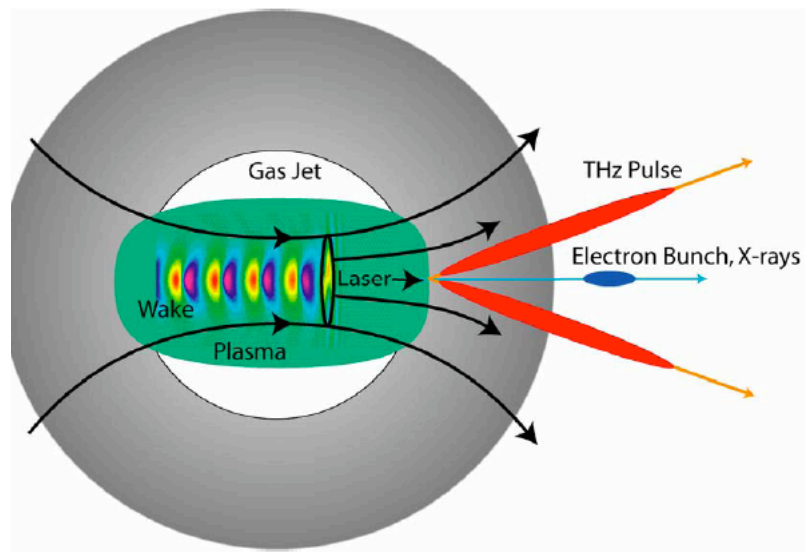
- immediate experimental feedback
- new point of contact with simulations



- **Femtosecond Electron Bunches**
  (summarized by Mitsuru Uesaka - U. Tokyo)

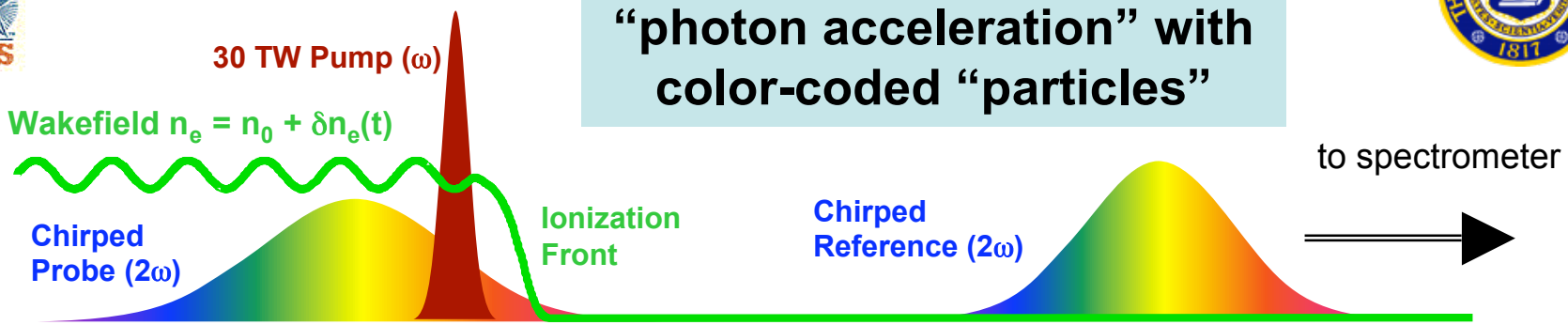
-50-200 fs bunches measured using Coherent Transition Radiation (CTR) & Electro-Optic techniques

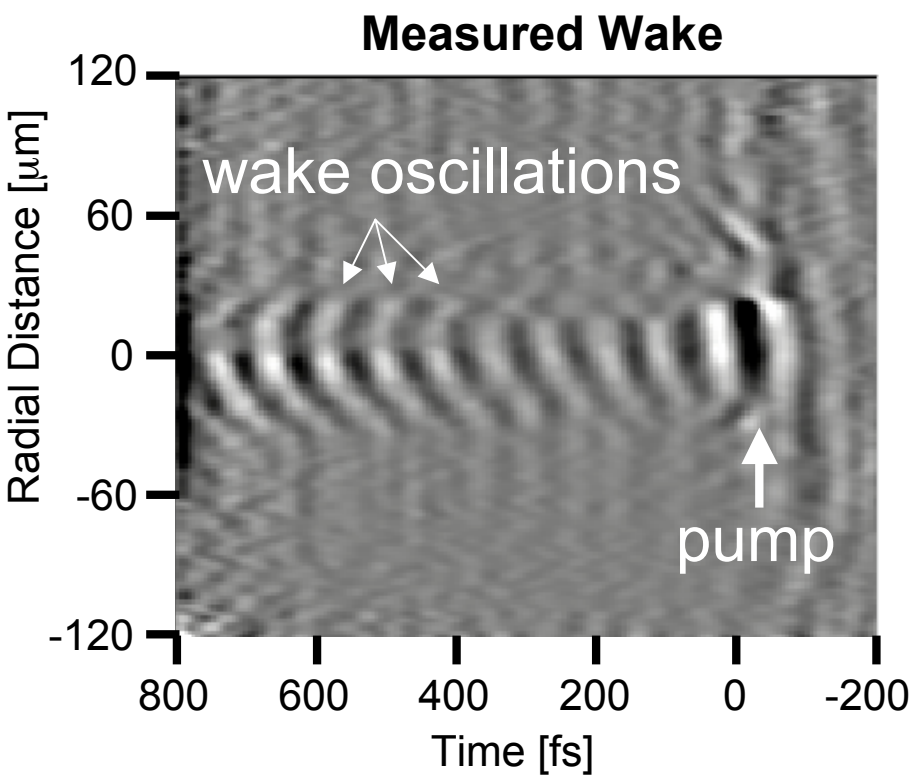
Single-shot THz CTR from plasma-vacuum boundary (LBNL-van Tilborg)

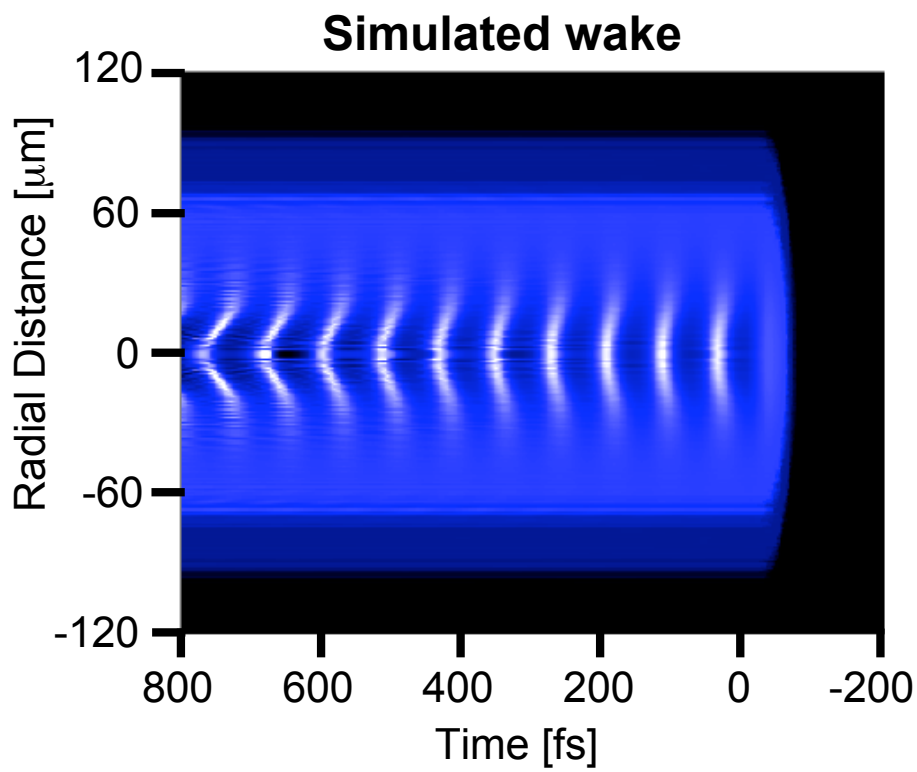


Wakefield Snapshots using Frequency Domain Holography enrich experiment-theory dialog:

"photon acceleration" with color-coded "particles"







Laser-plasma accelerators produce femtosecond electron bunches: we have made progress in characterizing them

courtesy M. Uesaka - U. Tokyo

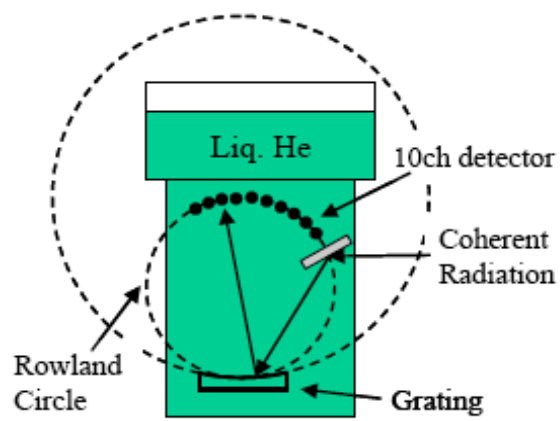
Measurement Methods of Femtosecond Electron Bunches

Methods	Radiation	Time resolution	Single-shot
Streak camera	Cherenkov radiation	200 fs	○
Michelson Interferometer [2]	Transition radiation	No limit	×
Electro-Optic method [3]	Transition radiation	No limit	○
Polychromator [2]	Transition radiation	No limit	○

[2] T. Watanabe et al, Nucl. Instr. and Meth. A 480, 315 (2002)
[3] J. van. Tilborg et al, Phys. Rev. Lett. 96, 014801 (2006)

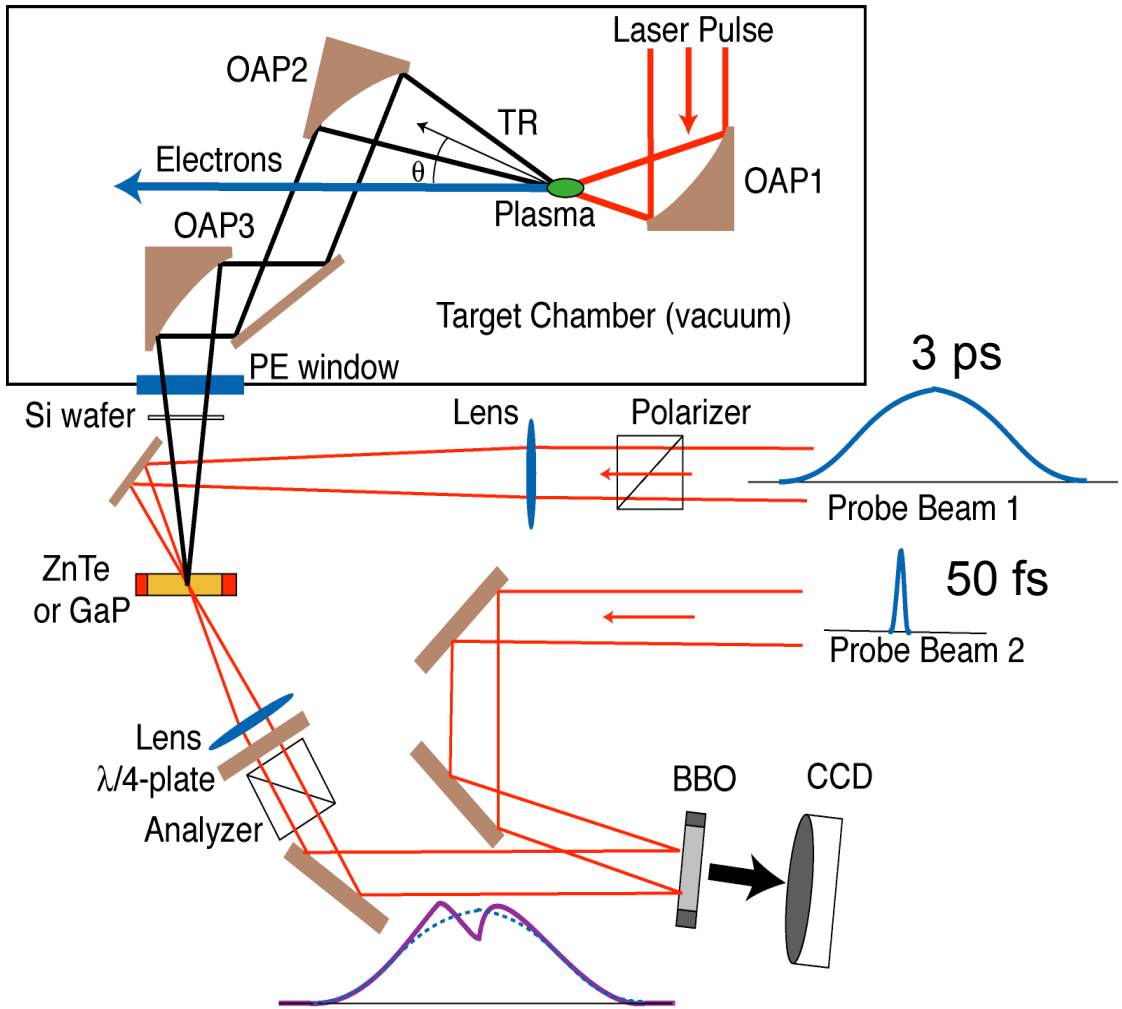
Bunch duration measurement by spectrum measurement of coherent transition radiation (CTR)

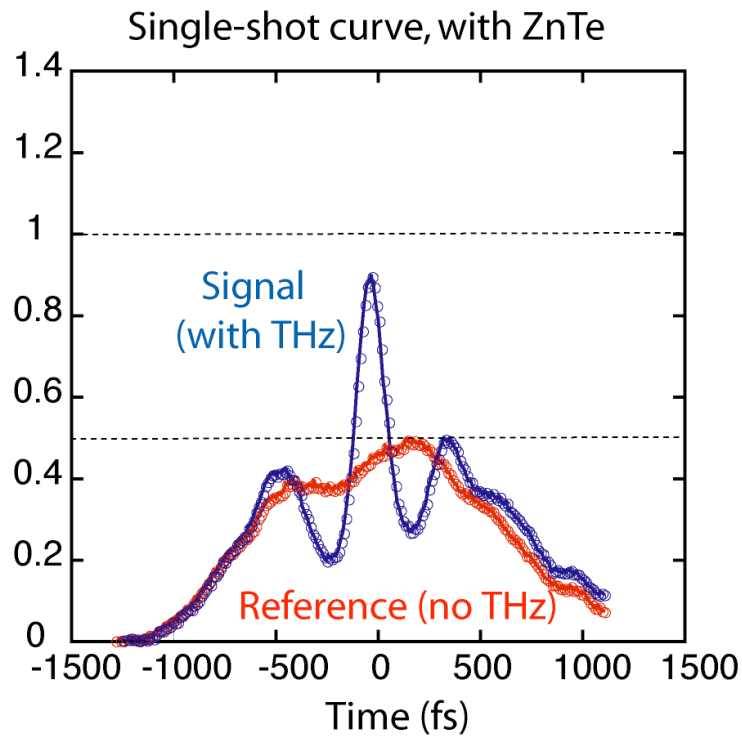
- Time-resolution is no limitation theoretically. (<100 fs in experiments?)
- Single-shot measurement is possible with 10-channel polychromator.



10ch polychromator

Single-Shot Technique for EO detection of THz pulses: Information on every bunch





< 50 fs bunches

J. van Tilborg et al., PRL 2006

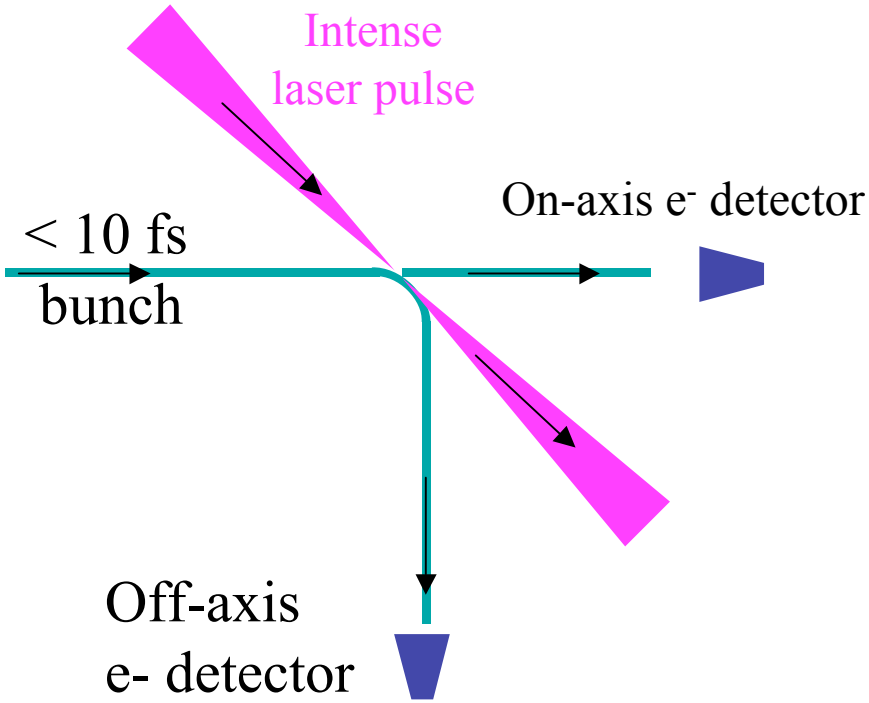
G. Berden et al., Phys. Rev. Lett. 93, 114802 (2004)

Talk by C. Geddes, LBNL

Methods were proposed for measuring < 10 fs bunches

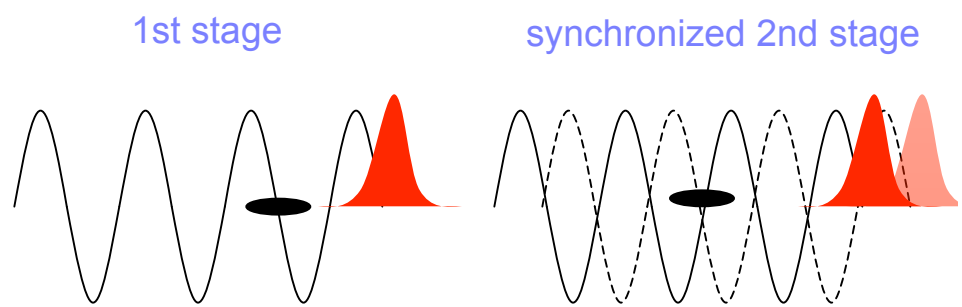
Laser deflection

(D. Kaganovich NRL)



Staged laser acceleration

(V. Yakimenko - BNL)



2nd stage spectrum characterizes bunch length

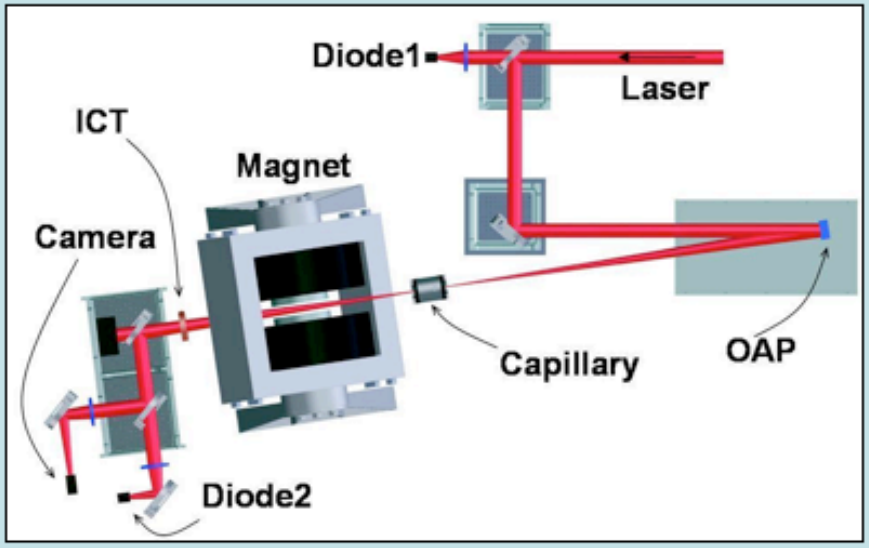
Optical CTR (Y. Glinec - LOA)

- spectrum: modulations observed in optical spectrum consistent with fs-bunches
- time profile
- harmonics

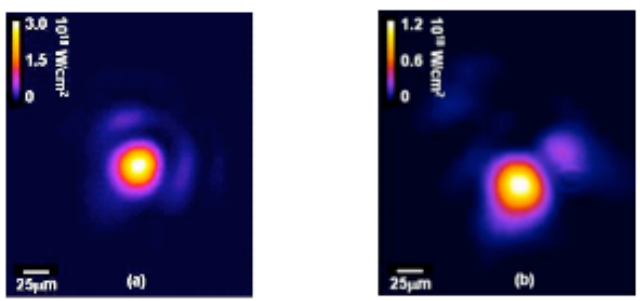
Electron acceleration in a capillary discharge waveguide

Lawrence Berkeley National Lab:
W. Leemans, B. Nagler, C. Tóth, K. Nakamura, C. Geddes, E. Esarey, C. Schroeder

Oxford University:
S. M. Hooker and A. J. Gonsalves

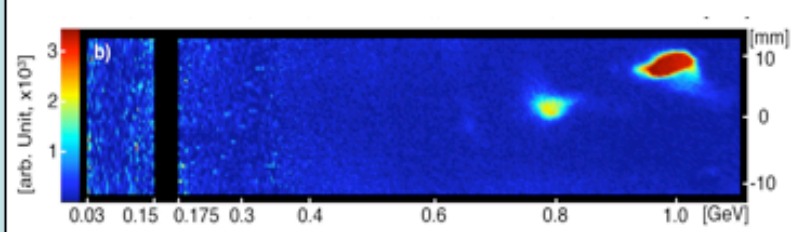


Waveguide:
Guiding of 40 TW laser pulses:
- in capillary discharge waveguide
- over 33 mm of plasma



Input spot Exit spot

Electron acceleration:
Generation of e-beams with:
- %-level energy spread
- mrad divergence
- Energy up to 1 GeV



Talks from B. Nagler, K. Nakamura; also D. Dimitrov on coupling

Stable 0.5 GeV Beam Generation

225 μm diameter and 33 mm length capillary

Density: 3.0~3.4x10^{18}/cm^3

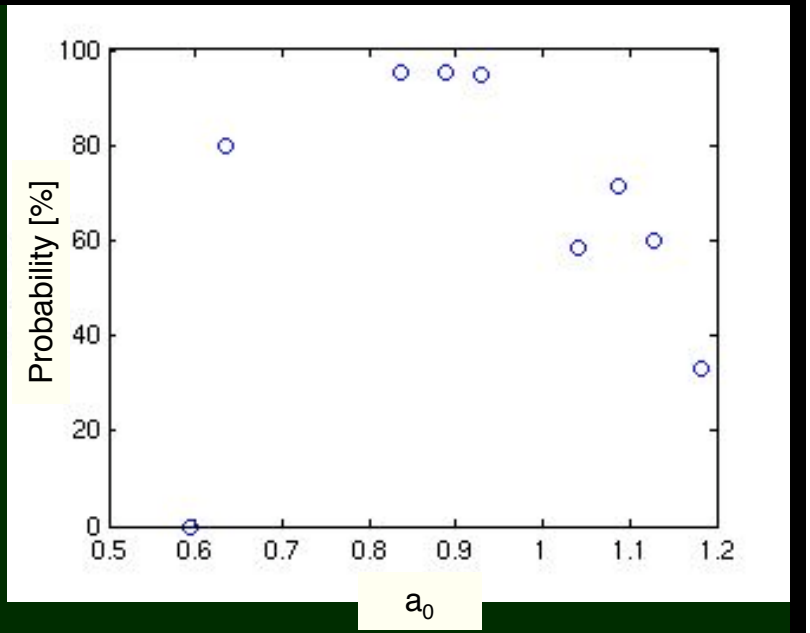
Laser: 950(+-15%) mJ/pulse (compression scan)

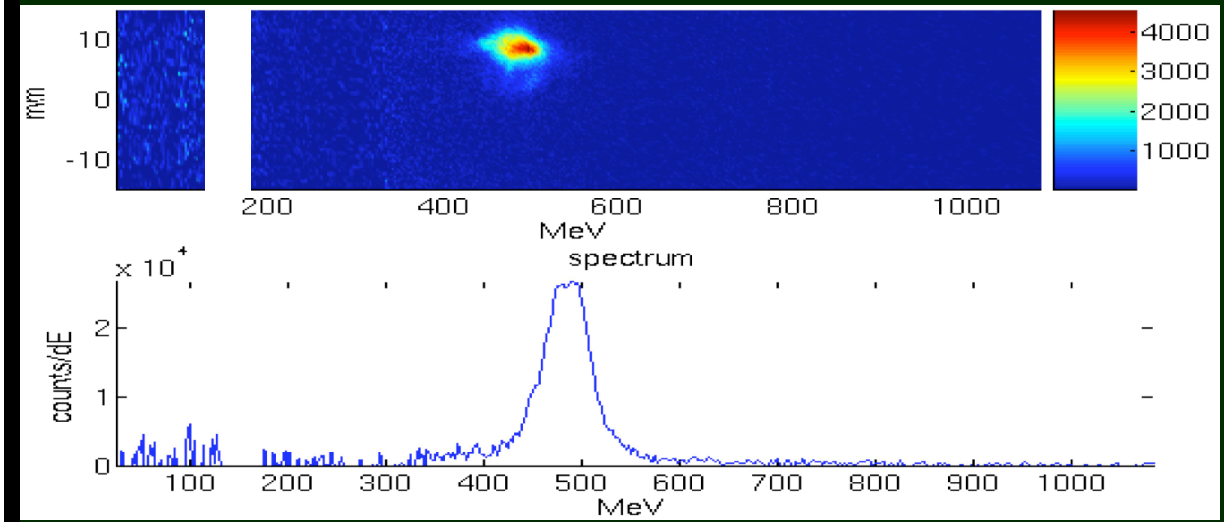
Injection threshold: a_0 ~ 0.65 (~9TW, 105fs)

Less injection at higher power

-Relativistic effect

-Self modulation





Courtesy: K. Nakamura

Stable operation

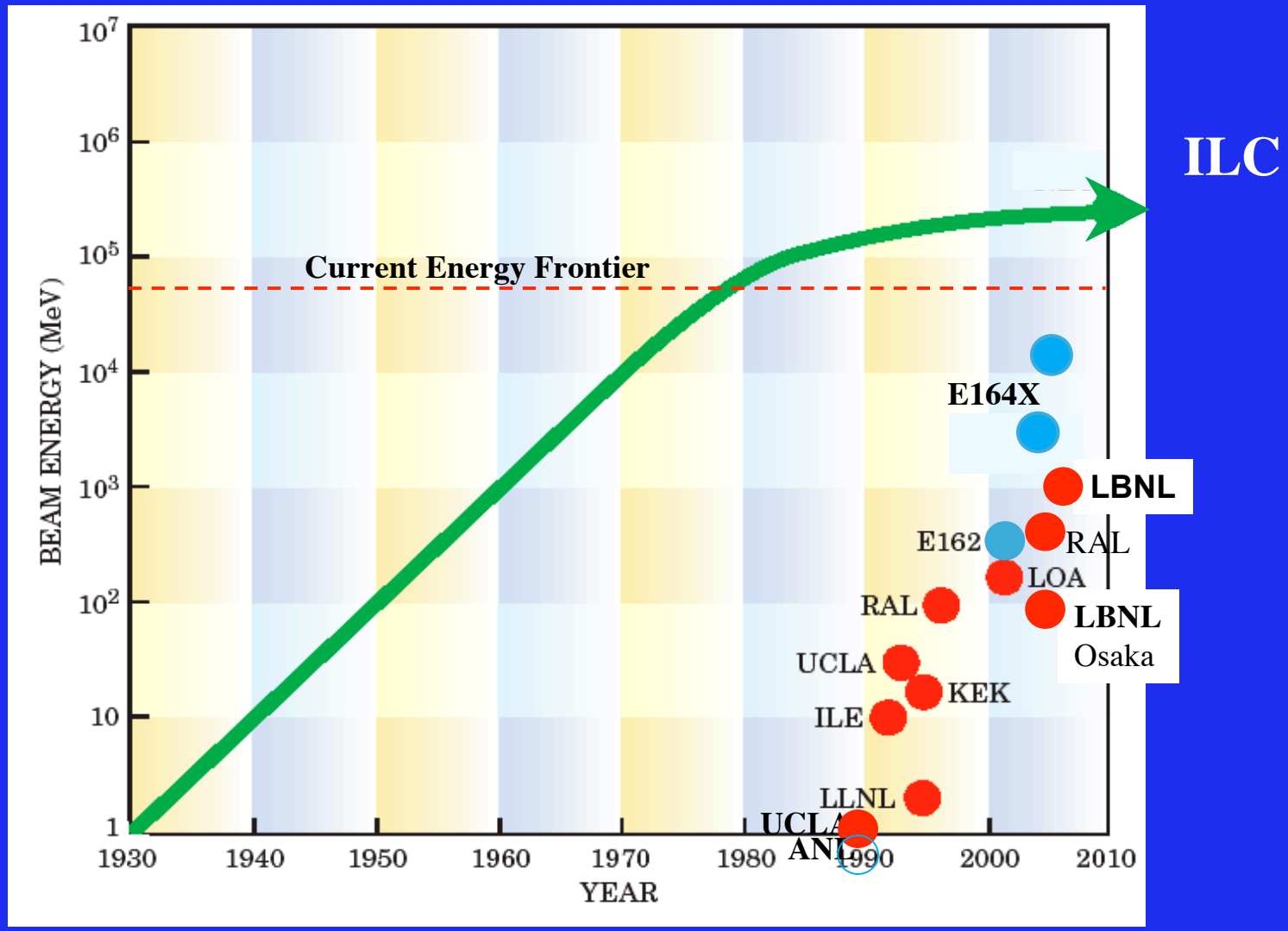
500 MeV Mono-energetic beams:

a_0 ~ 0.75 (11 TW, 75 fs)

Peak energy: 490 MeV
Divergence(rms): 1.6 mrad
Energy spread (rms): 5.6%
Resolution: 1.1%
Charge: ~50 pC

Plasma Accelerator Progress

"Accelerator Moore's Law"



From: T. Katsouleas -APS-DPP 2005 + new LBNL 1 GeV result

When will experiments catch up with simulations ?

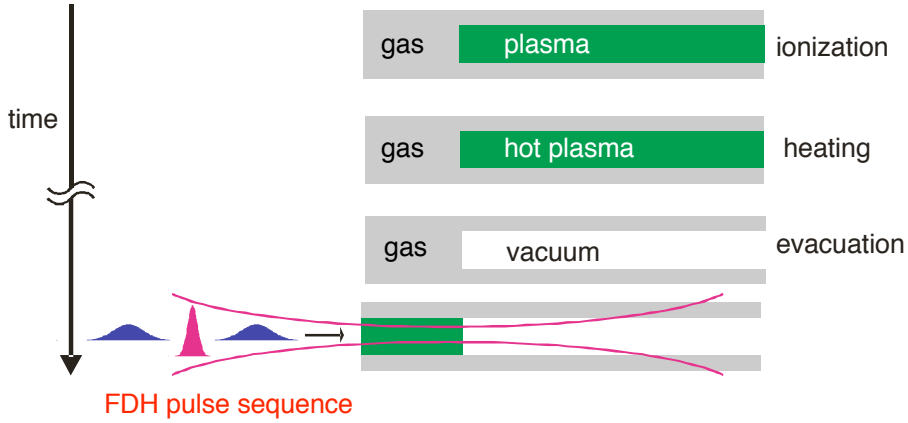
- Previously simulations have been benchmarked against the “end” observables: e- energy, number, divergence

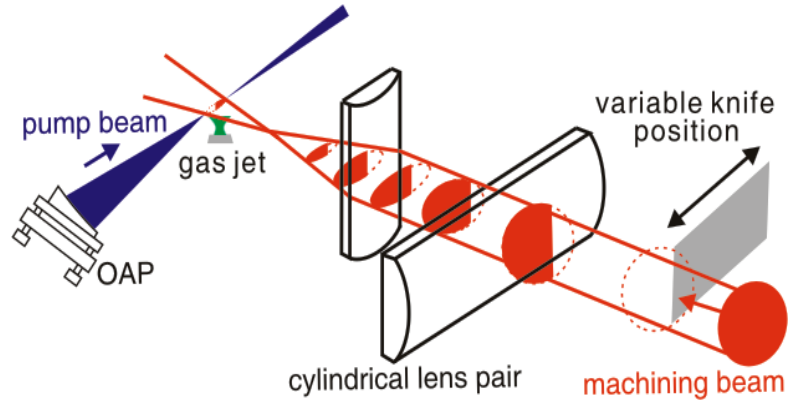
- Now single-shot holographic measurements of wake structure provide an earlier point of contact between expt. & theory

“Lake Geneva” Convention on Experiment-Computational Enemy Combatants

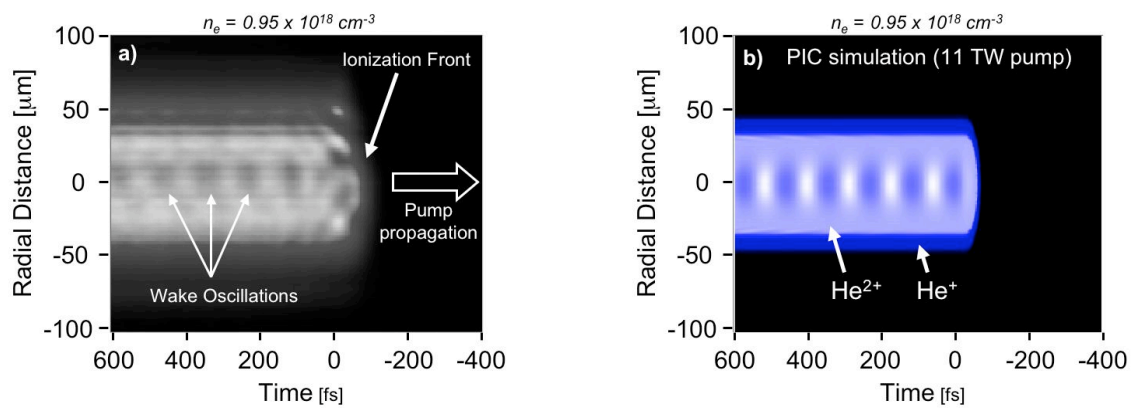
Rec^n for 2008: Benchmark Simulations by “Differential” FDH

a) Slice out short sections of plasma by laser micro-machining (SY Chen-Taiwan)



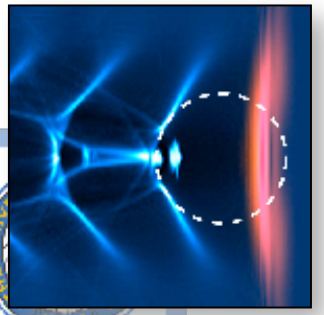


b) Measure wake structures with engineered laser pulses & plasmas



c) Embed computationalists in experimental groups; threaten Guantanamo internment unless they reproduce the measured structure

UCLA Bubble-Regime Scalings



Parameter design for Gev and beyond

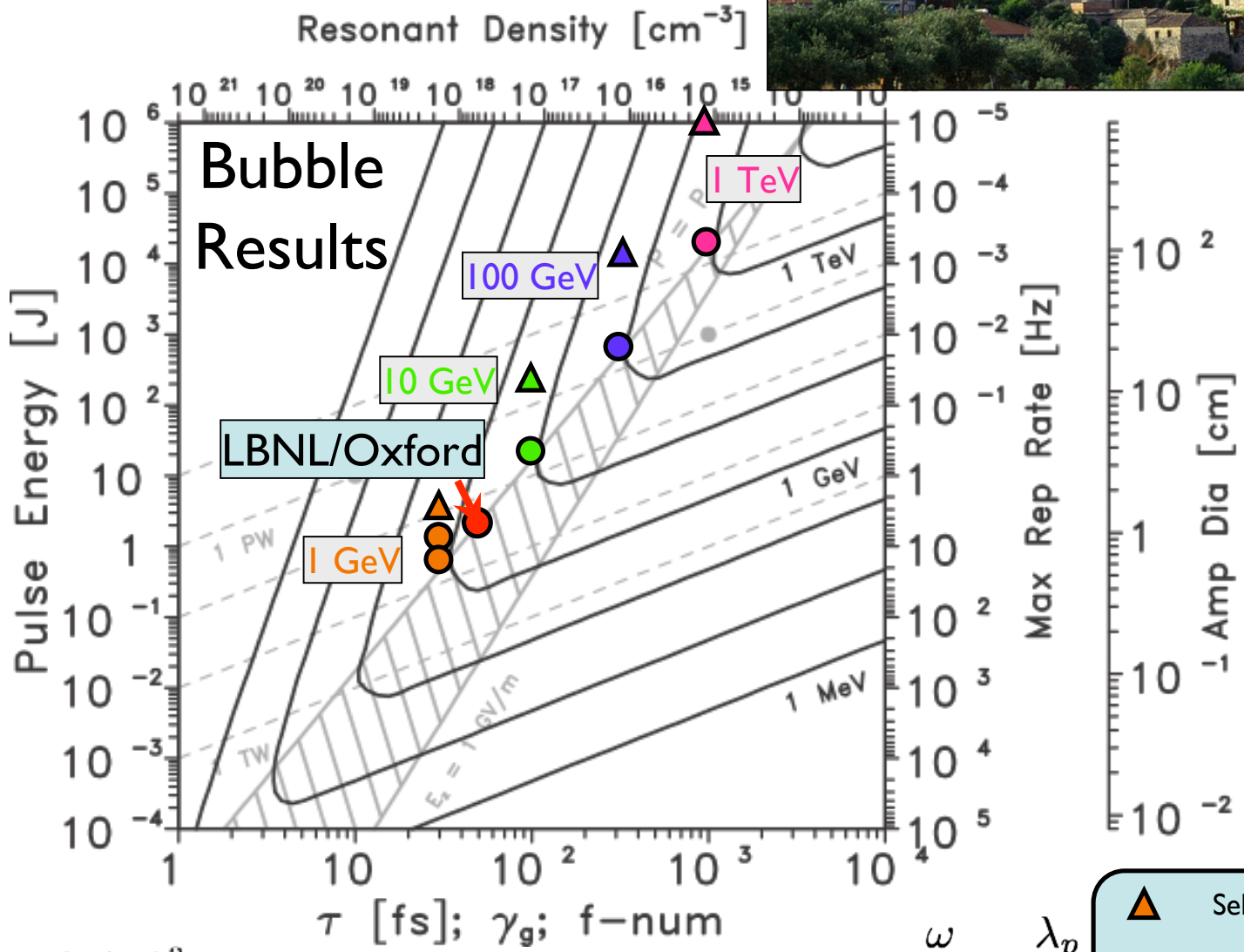
P(PW)	τ(fs)	n_p (cm^{-3})	w_0 (μm)	L(m)	a_0	$\Delta n_c/n_p$	Q(nC)	E(GeV)
0.020	30	1×10^{18}	14	0.016	1.76	60%	0.18	0.99
0.040	30	1.5×10^{18}	14	0.011	2.53	40%	0.25	0.95
0.100	30	2.0×10^{18}	15	0.009	3.78	0%	0.40	1.06
0.200	100	1.0×10^{17}	45	0.52	1.76	60%	0.57	9.9
2.0	100	3.0×10^{17}	47	0.18	5.45	0%	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

W.Mori, F. Tsung, W. Lu, M. Tzoufras

Plasma Guiding and Wakefield Generation for Second-Generation Experiments

W. P. Leemans, *Member, IEEE*, C. W. Siders, E. Esarey, N. E. Andreev, G. Shvets, and Warren B. Mori

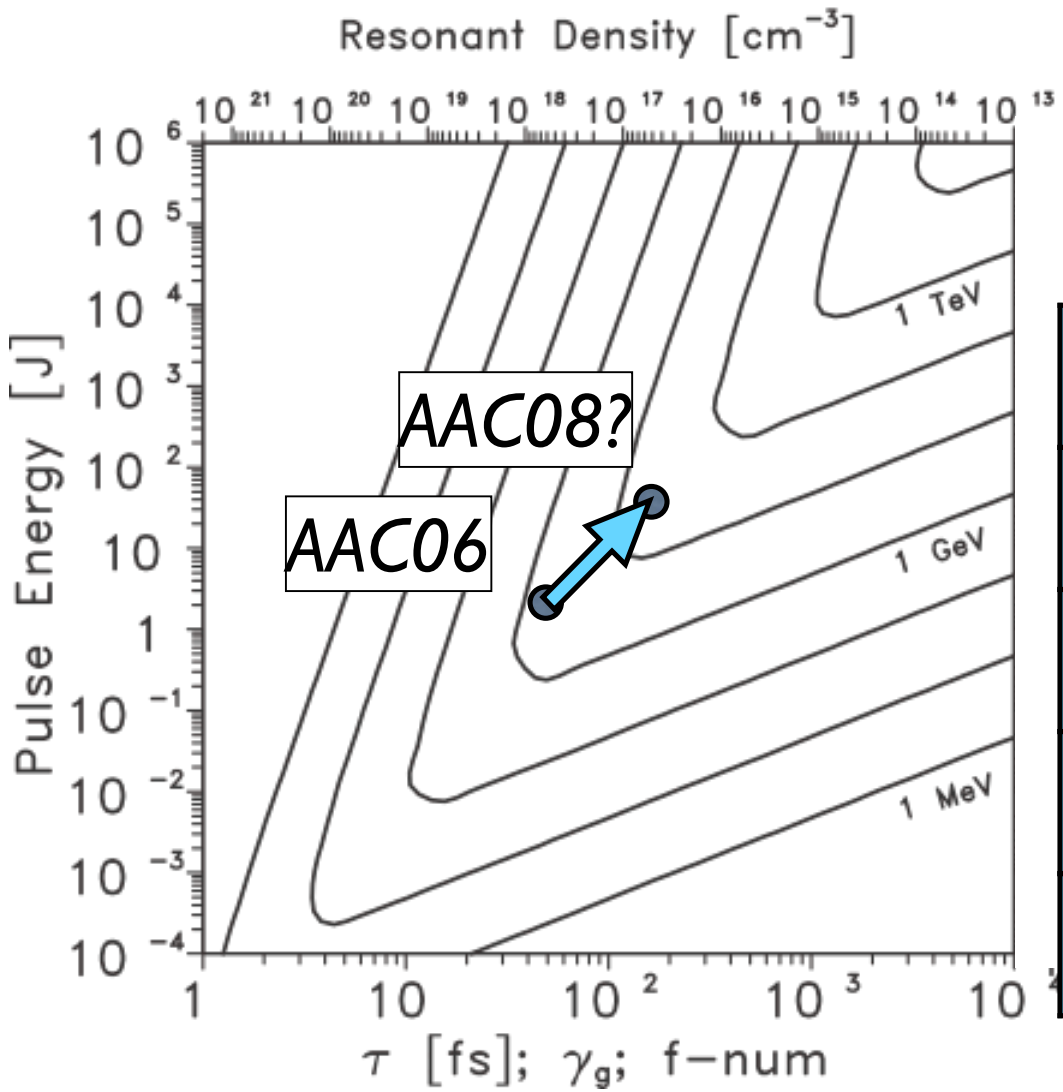


$$P_c[\mathrm{GW}] \cong 17(\omega/\omega_p)^2$$

$$\gamma_g \approx \frac{\omega}{\omega_p} = \frac{\lambda_p}{\lambda}$$

Self-Guide

Channel-Guide



10 GeV Conceptual Design

Spot Size	50-um
Channel Length (capillary or cluster jet?)	0.5-1.0 meter
Density	few x 10^{17} cm^{-3}
Laser Energy	10-100 J
Pulse Width	~100-fs

Lasers for >10 GeV Accelerators

1 nC, 10 GeV = 10 Joules

10% Laser-Electron Coupling

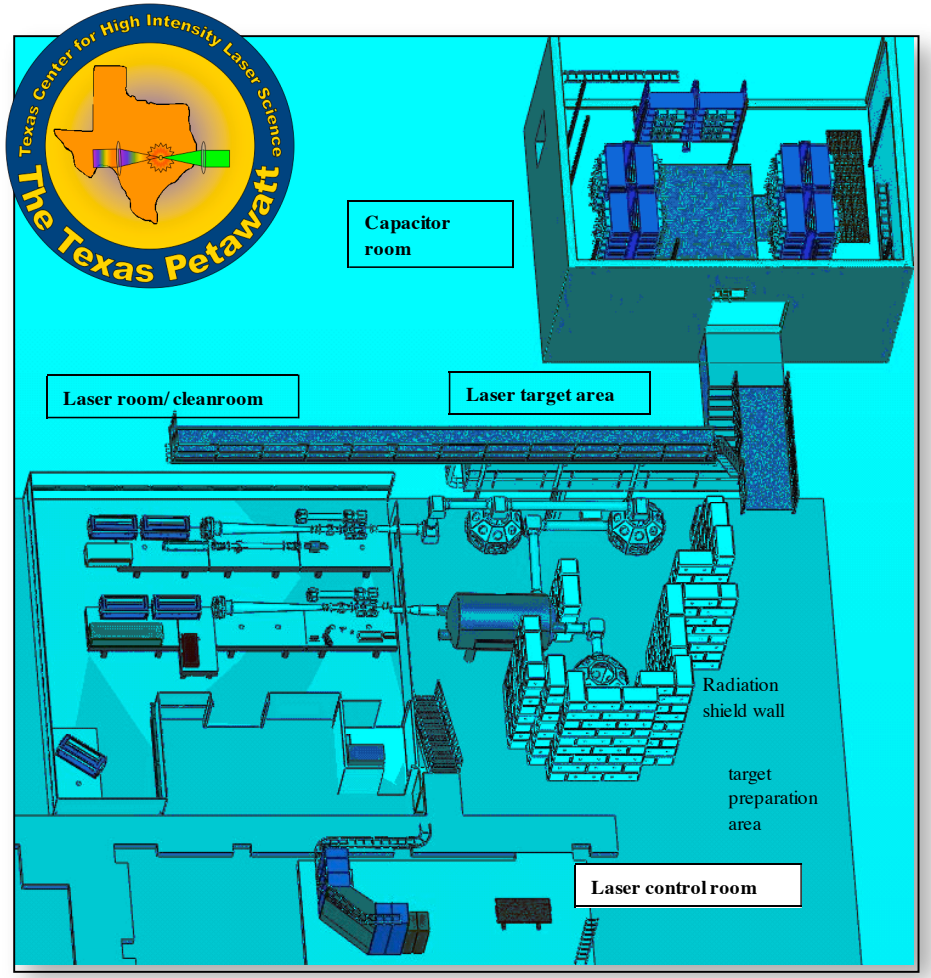
100 J / 100 fs = 1 PW

Rep-Rated High-Energy PW Lasers are a key enabling technology for 10-GeV high luminosity experiments.
(hint hint)

Working Group Talk/Discussion:

- 10-GeV Class lasers nearing completion
- Upgrade path for future: fiber-based kHz kJ Petawatts

Erhard Gaul, UT Austin



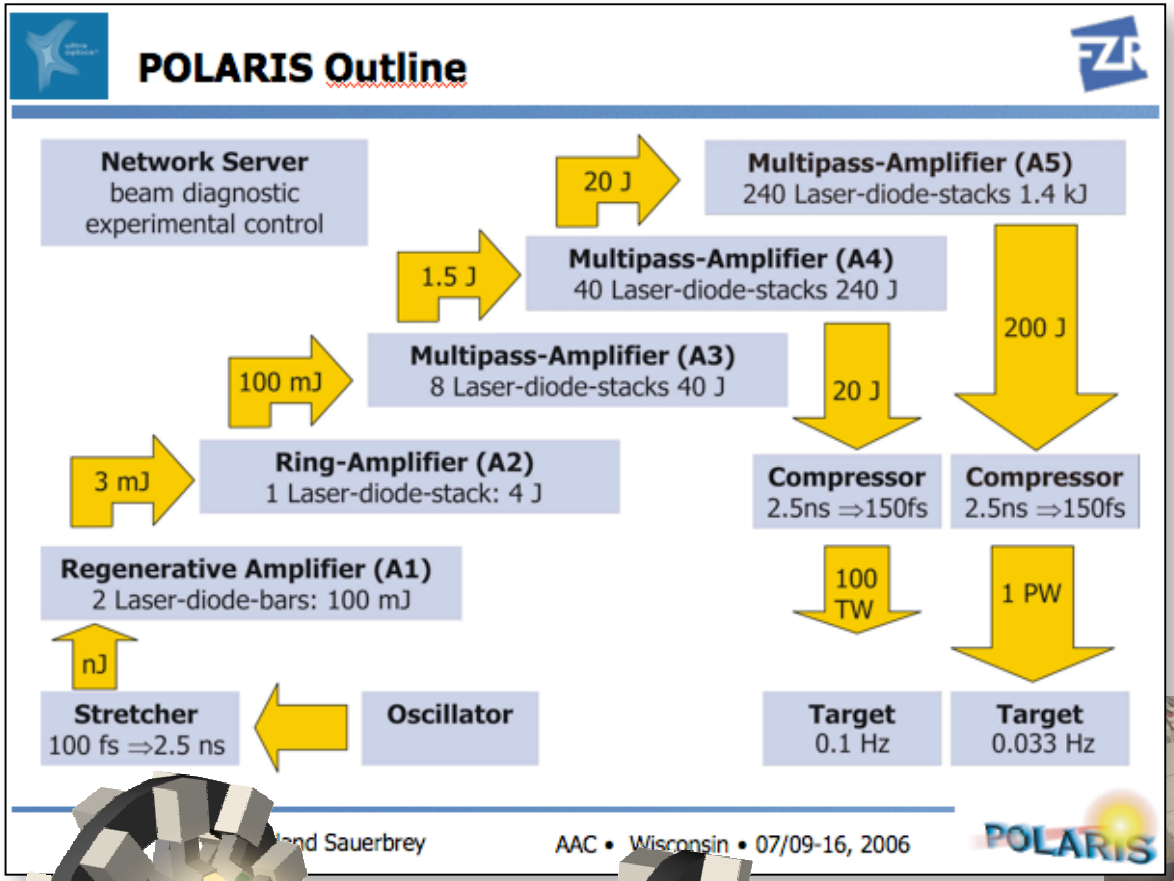
200 J / 150 fs, "Single Shot" OPCPA + NOVA Amps

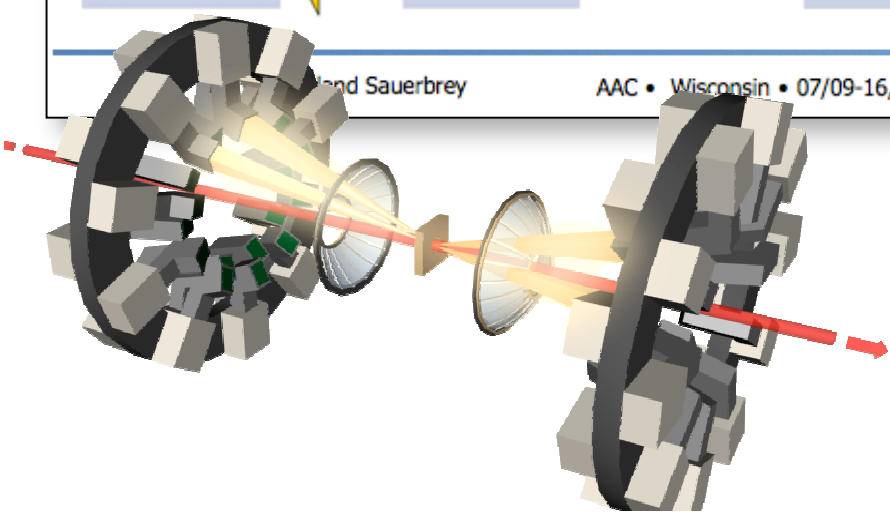
"Dinosaur" technology on PW fast-track.

Key limiters:

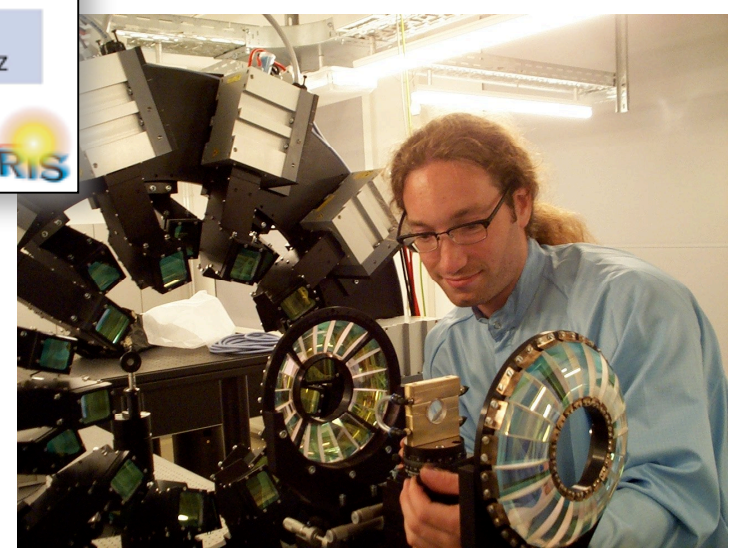
- Inefficiency (quantum defect)
- Heat removal (glass)
- Compressor Size (damage)
- Long Focusing

Roland Sauerbrey, FZR/Jena

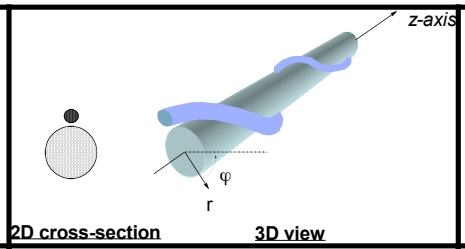
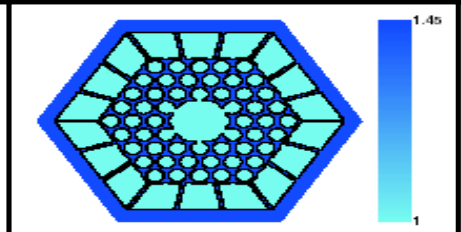
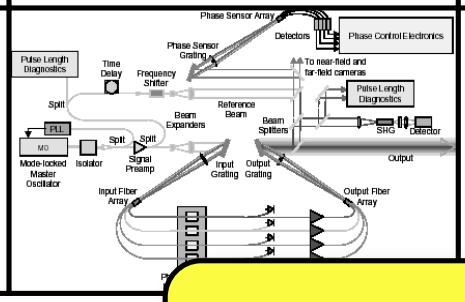




- Significant new technology development
- Diode-pumped Yb:glass
- Efficient (low quantum defect)
- Rep-rated PW's
- Spin-off: pump lasers for few-cycle OPCPA PW



Almantas Galvanauskas, UMich

Single Fiber	Solid Core		10-100 mJ kHz TW's
Single Fiber	Vacuum-Core Photonic Crystal Fiber		0.1-1 J kHz 10's TW's
Fiber Combining	Coherent Phased Wavelength Multiplexing		kJ ps kHz PW's

What are the possible scaling paths?

- Pulse duration scaling in CPA
  - (1-10-ns, could it be >100-ns?)
- Core size of solid core
- Core size of hollow core
- Multiple fiber combining

kHz kJ PW

0.1-1 B$

30-50% Wallplug

Summary

- Another banner year for Advanced Acceleration R&D
  - 1 GeV electron beams using a cm-scale capillary discharge channel guided laser accelerator (LBNL/Oxford)
  - Colliding pulse injection - two-pulse, counter-propagating (LOA)
  - Single shot measurement of laser excited plasma wakes (UT Austin)-Fourier domain holography
  - Laser machined plasmas - transverse and longitudinal (U Maryland, Taiwan)
  - Single shot measurement of the duration of laser accelerated bunches <50 fs (LBNL)
- Next steps:
  - Stability and control: injection, staging, diagnostics, plasma machining
  - 10 GeV with Petawatt laser
  - High fidelity simulations - benchmarking against experiments

THE "LAKE GENEVA CONVENTION" WILL BE UPHELD