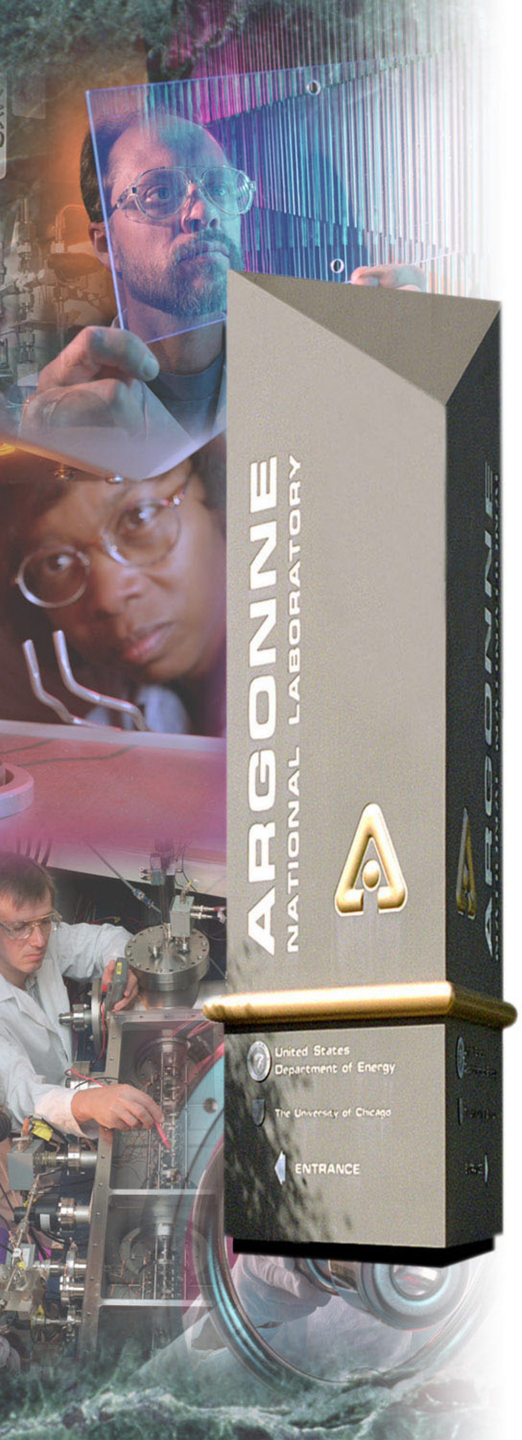

Terawatt Ultrafast High Field Facility: Using Photons to Accelerate Electrons

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Argonne National Laboratory

Office of Science
U.S. Department of Energy

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Outline

- Why? Already covered in numerous workshops/meetings
  D. Bartels will discuss some of these tomorrow
- Physics under extreme conditions
- Terawatt Ultrafast High Field Facility
- Table(s)-Top Terawatt Laser – T^3
- Generation/Characterization of electron pulses
- Future will include coherent fs hard x-rays
- Advantages and disadvantages of our approach

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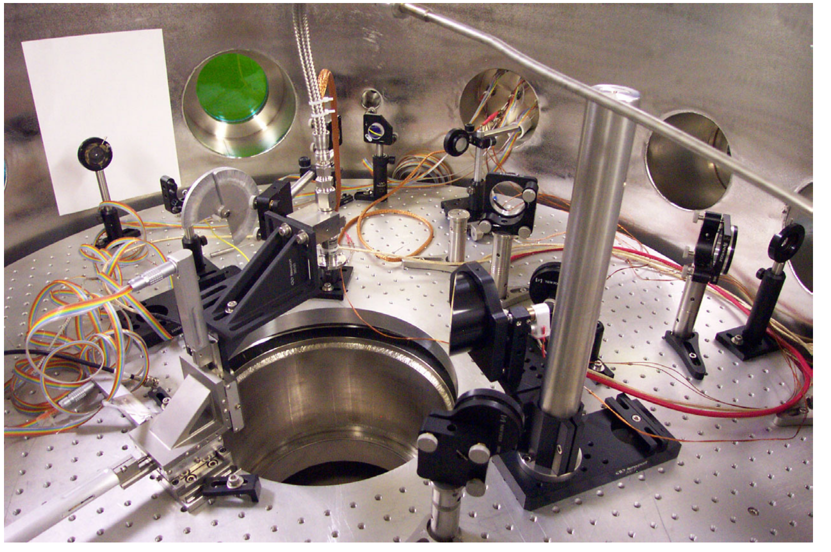
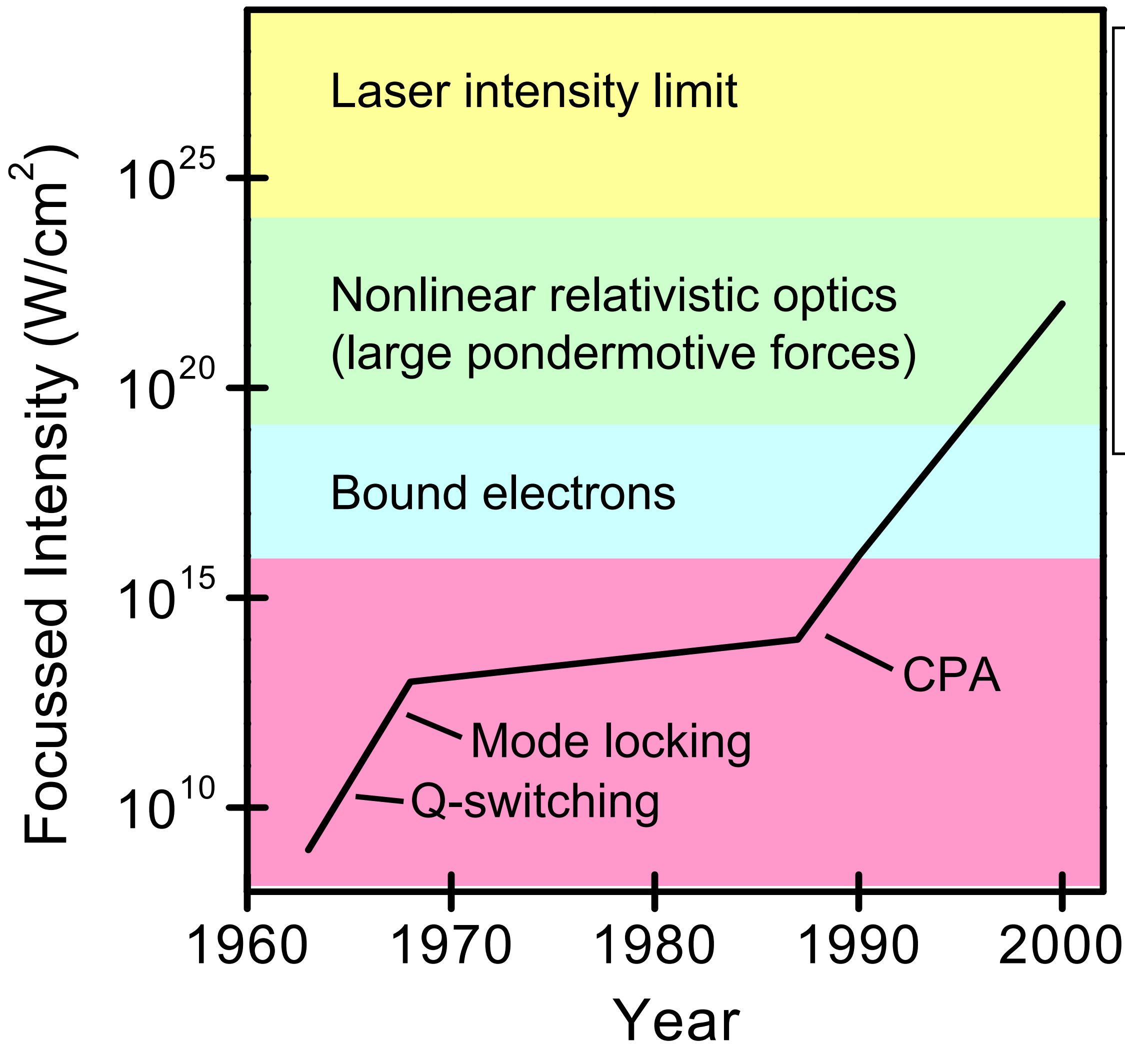
DOE-BES



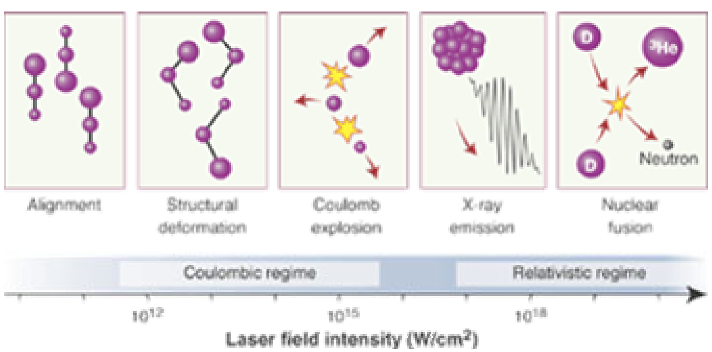
Inside of the TUHFF Target Chamber

Generation of Ultrahigh Peak Powers: Chirped Pulse Amplification

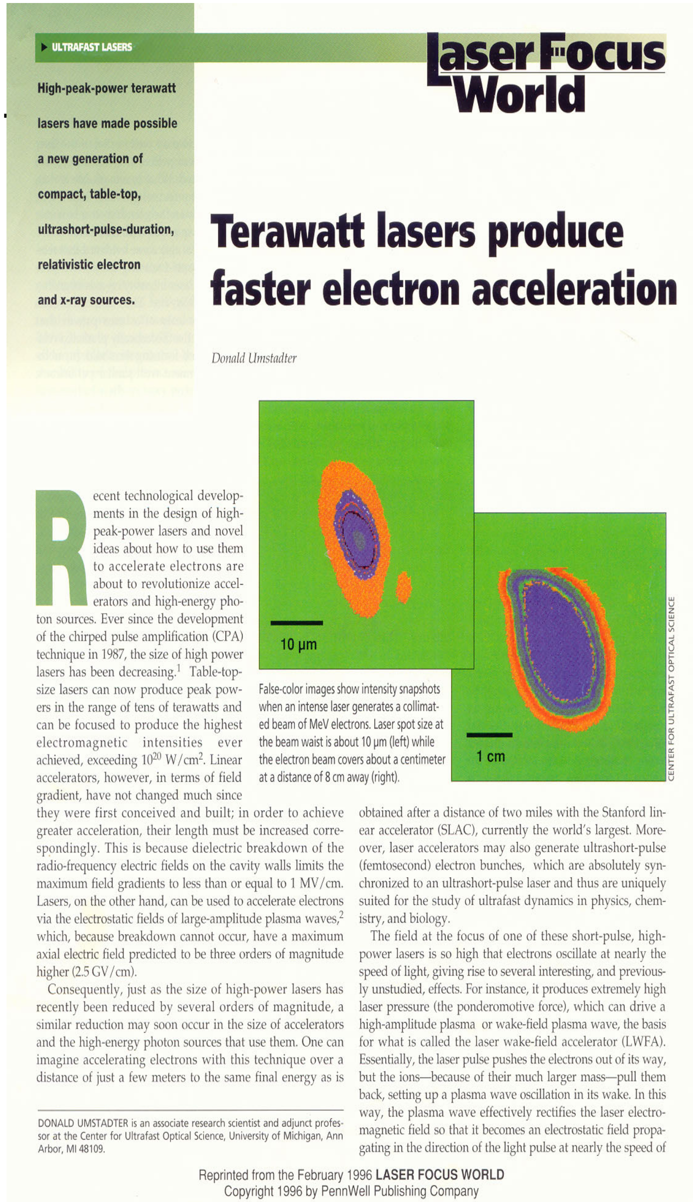


Recent advances in laser technology that have opened up new areas of research in physics and chemical physics

and radiation chemistry?



K. Yamanouchi *Science, 295 1659 (2002)*



ULTRAFAST LASERS

Laser Focus World

High-peak-power terawatt lasers have made possible a new generation of compact, table-top, ultrashort-pulse-duration, relativistic electron and x-ray sources.

Terawatt lasers produce faster electron acceleration

Donald Umstadter

10 µm

1 cm

CENTER FOR ULTRAFAST OPTICAL SCIENCE

False-color images show intensity snapshots when an intense laser generates a collimated beam of MeV electrons. Laser spot size at the beam waist is about 10 µm (left) while the electron beam covers about a centimeter at a distance of 8 cm away (right).

Recent technological developments in the design of high-peak-power lasers and novel ideas about how to use them to accelerate electrons are about to revolutionize accelerators and high-energy photon sources. Ever since the development of the chirped pulse amplification (CPA) technique in 1987, the size of high power lasers has been decreasing.[1] Table-top-size lasers can now produce peak powers in the range of tens of terawatts and can be focused to produce the highest electromagnetic intensities ever achieved, exceeding 10^{20} W/cm^2. Linear accelerators, however, in terms of field gradient, have not changed much since they were first conceived and built; in order to achieve greater acceleration, their length must be increased correspondingly. This is because dielectric breakdown of the radio-frequency electric fields on the cavity walls limits the maximum field gradients to less than or equal to 1 MV/cm. Lasers, on the other hand, can be used to accelerate electrons via the electrostatic fields of large-amplitude plasma waves,[2] which, because breakdown cannot occur, have a maximum axial electric field predicted to be three orders of magnitude higher (2.5 GV/cm).

Consequently, just as the size of high-power lasers has recently been reduced by several orders of magnitude, a similar reduction may soon occur in the size of accelerators and the high-energy photon sources that use them. One can imagine accelerating electrons with this technique over a distance of just a few meters to the same final energy as is obtained after a distance of two miles with the Stanford linear accelerator (SLAC), currently the world's largest. Moreover, laser accelerators may also generate ultrashort-pulse (femtosecond) electron bunches, which are absolutely synchronized to an ultrashort-pulse laser and thus are uniquely suited for the study of ultrafast dynamics in physics, chemistry, and biology.

The field at the focus of one of these short-pulse, high-power lasers is so high that electrons oscillate at nearly the speed of light, giving rise to several interesting, and previously unstudied, effects. For instance, it produces extremely high laser pressure (the ponderomotive force), which can drive a high-amplitude plasma or wake-field plasma wave, the basis for what is called the laser wake-field accelerator (LWFA). Essentially, the laser pulse pushes the electrons out of its way, but the ions—because of their much larger mass—pull them back, setting up a plasma wave oscillation in its wake. In this way, the plasma wave effectively rectifies the laser electromagnetic field so that it becomes an electrostatic field propagating in the direction of the light pulse at nearly the speed of

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In the relativistic regime it becomes possible to generate subps e^- pulses

Requires

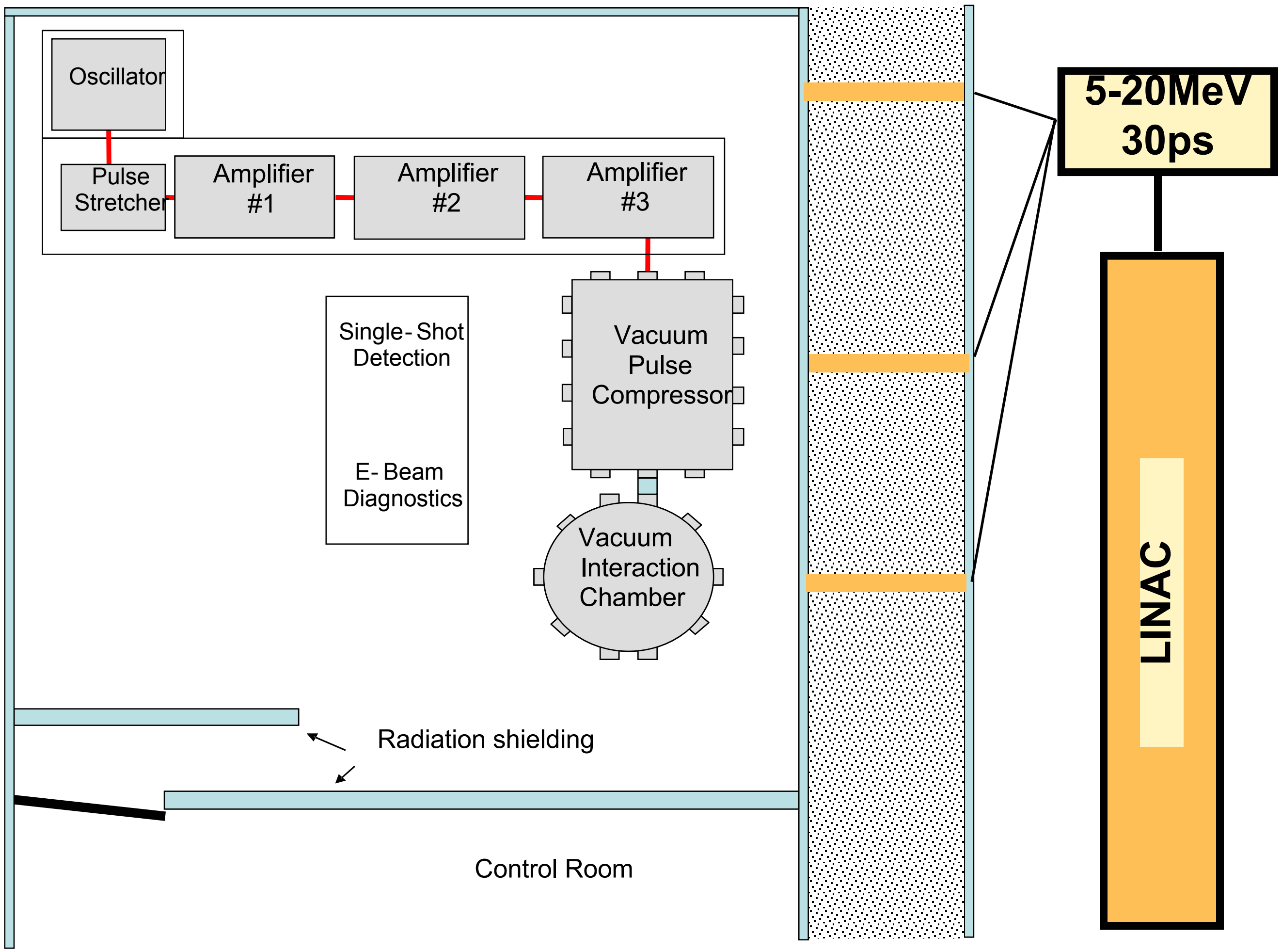
- $>10^{18}$W/cm^2

$\Rightarrow$ terawatt laser system

e.g., .5J in 50fs = 10TW

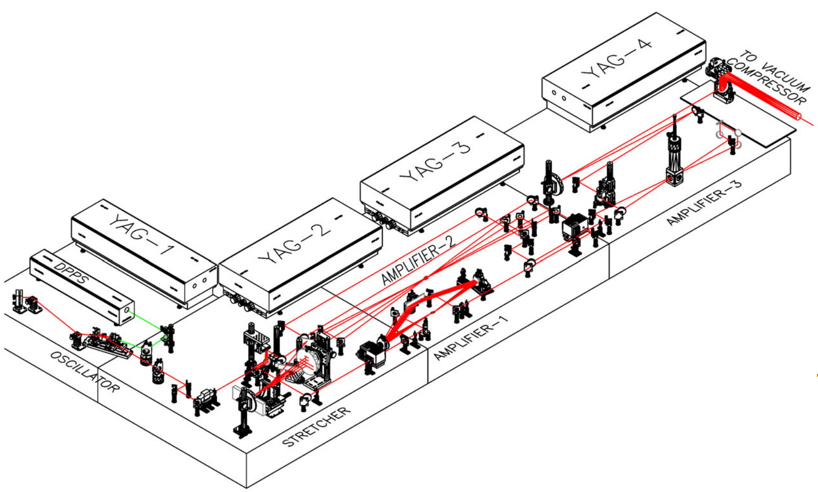
Pulse charges as high as 8nC have been achieved using T^3

Terawatt Ultrafast High Field Facility



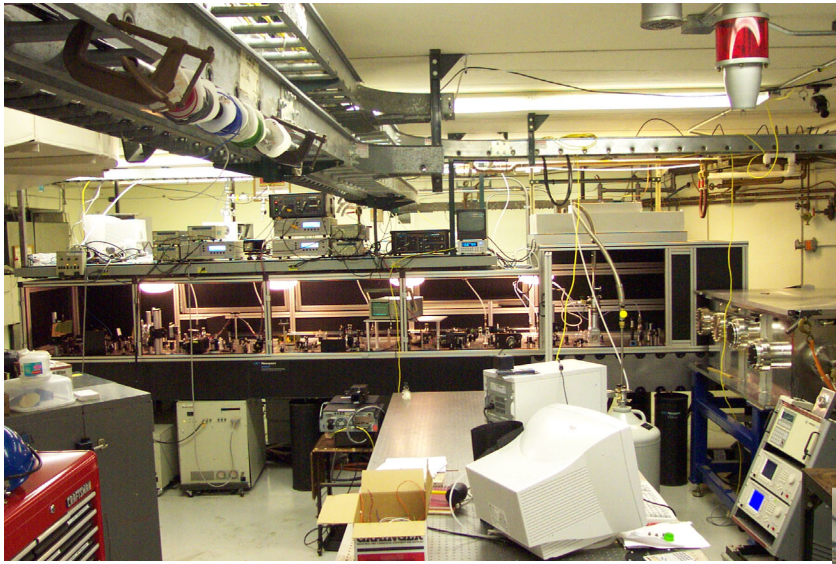
T^3 Specifications

	Wavelength	Rep.	Pulsewidth	Energy
Oscillator	780nm	100MHz	15fs	2nJ
Amp 1	800nm	10Hz	~350ps	2mJ
Amp 2	805nm	10Hz	~350ps	.35J
			30fs	**.15J (5TW)**
Amp 3	805nm	10Hz	~350ps	1.3J
			30fs	**.6J (20TW)**



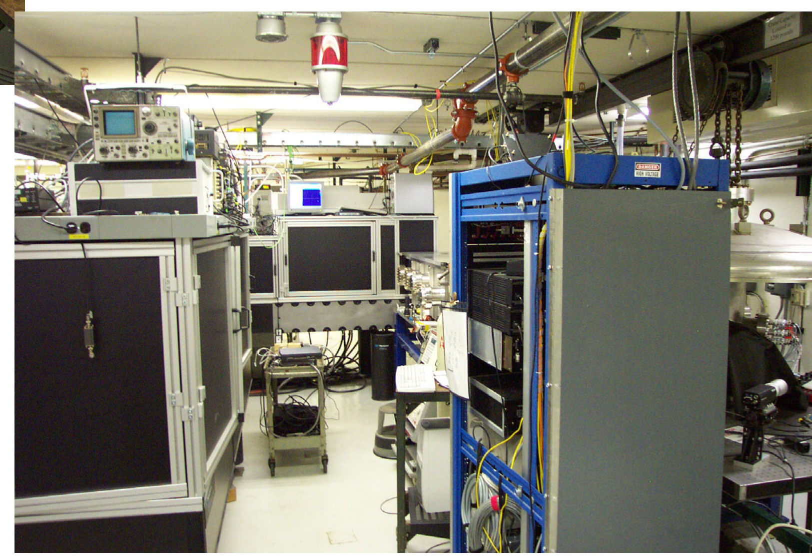
Future upgrade will increase the power to 50TW

T^3

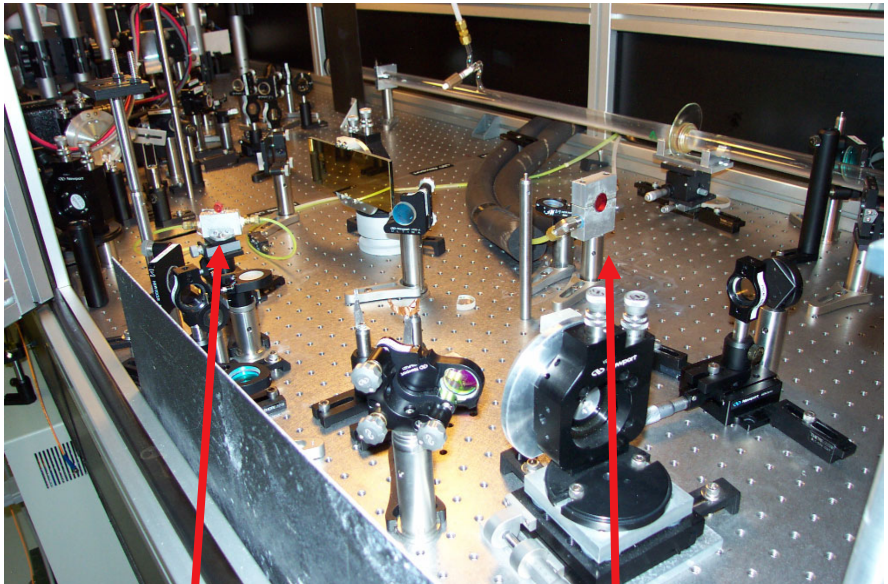


Sometime ago

Present

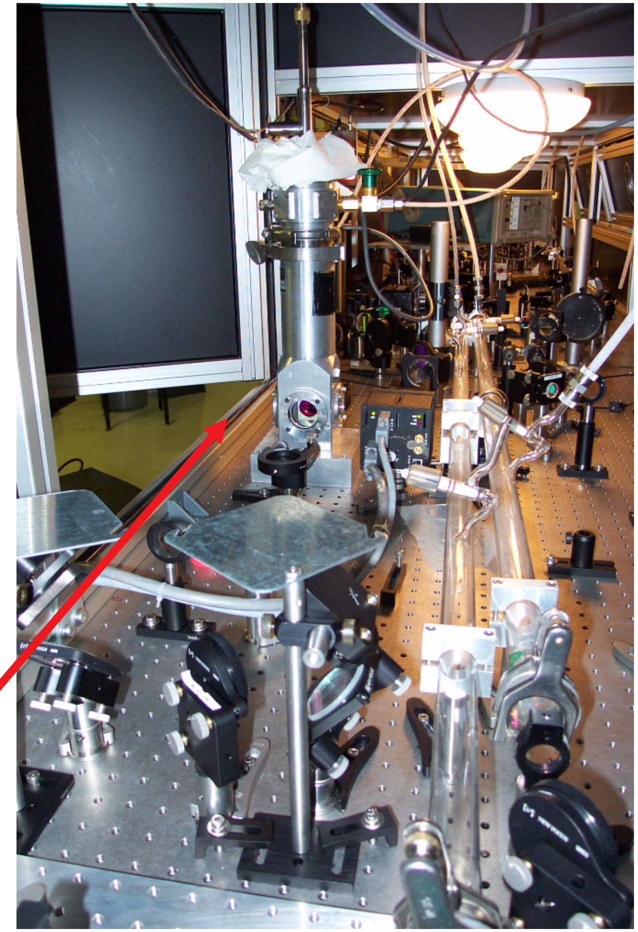


Inside T^3



AMP 1

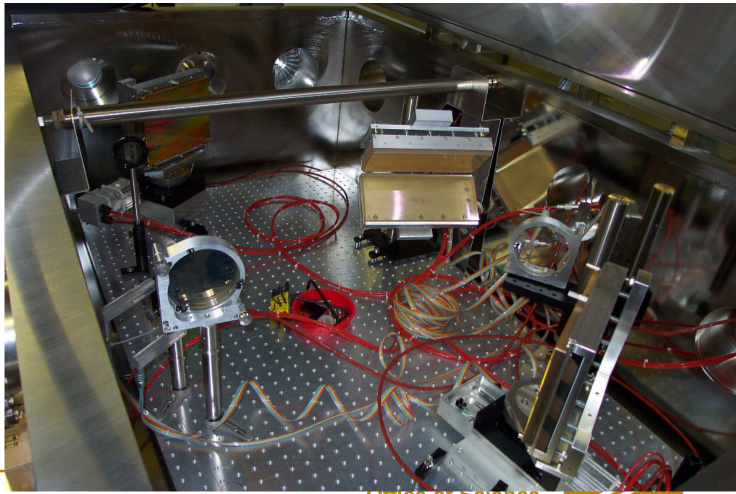
AMP 2



AMP 3

Target Chamber

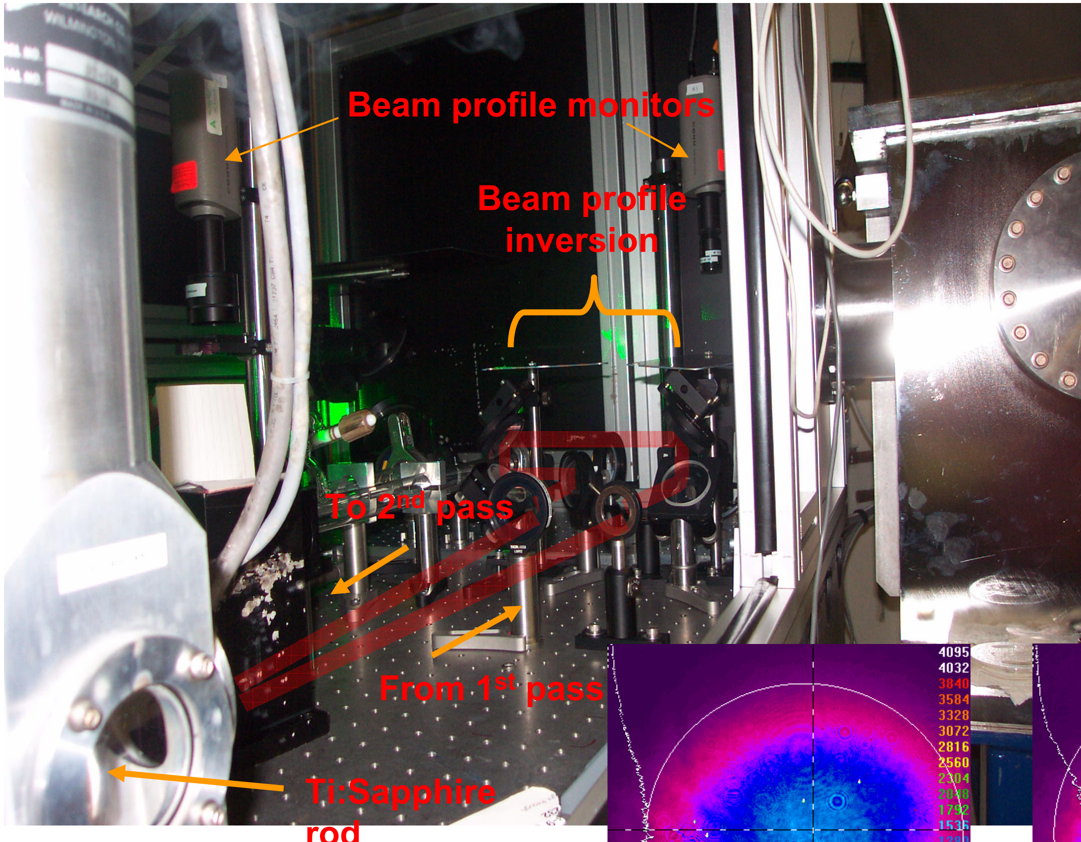
Vacuum Compressor



Unique Aspects of T^3

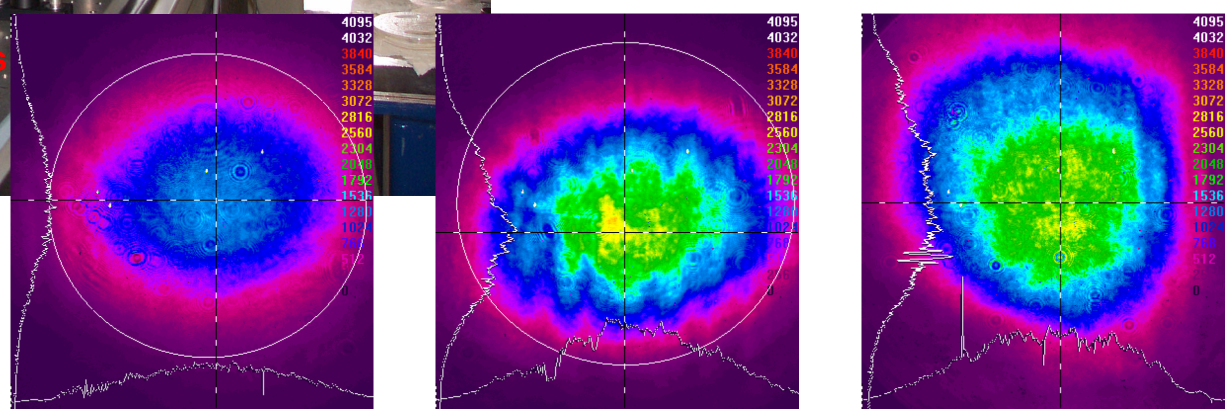
- **Pulse contrast ratio**
  - Need better than $1:10^8$ (10^{12}W/cm^2 in pedestal)
- **Stretcher/Compressor**
  - Very large aperture high quality optics
  - Must compensate for high order dispersive effects
- **Spatial Beam Quality**
  - Critical to prevent catastrophic failure
- **Incorporation of adaptive optics**
  - Continuous real time control over various laser parameters to optimize electron beam and prevent optical failure
  - AOPDF, DM etc.

Correcting for Spatial Aberrations

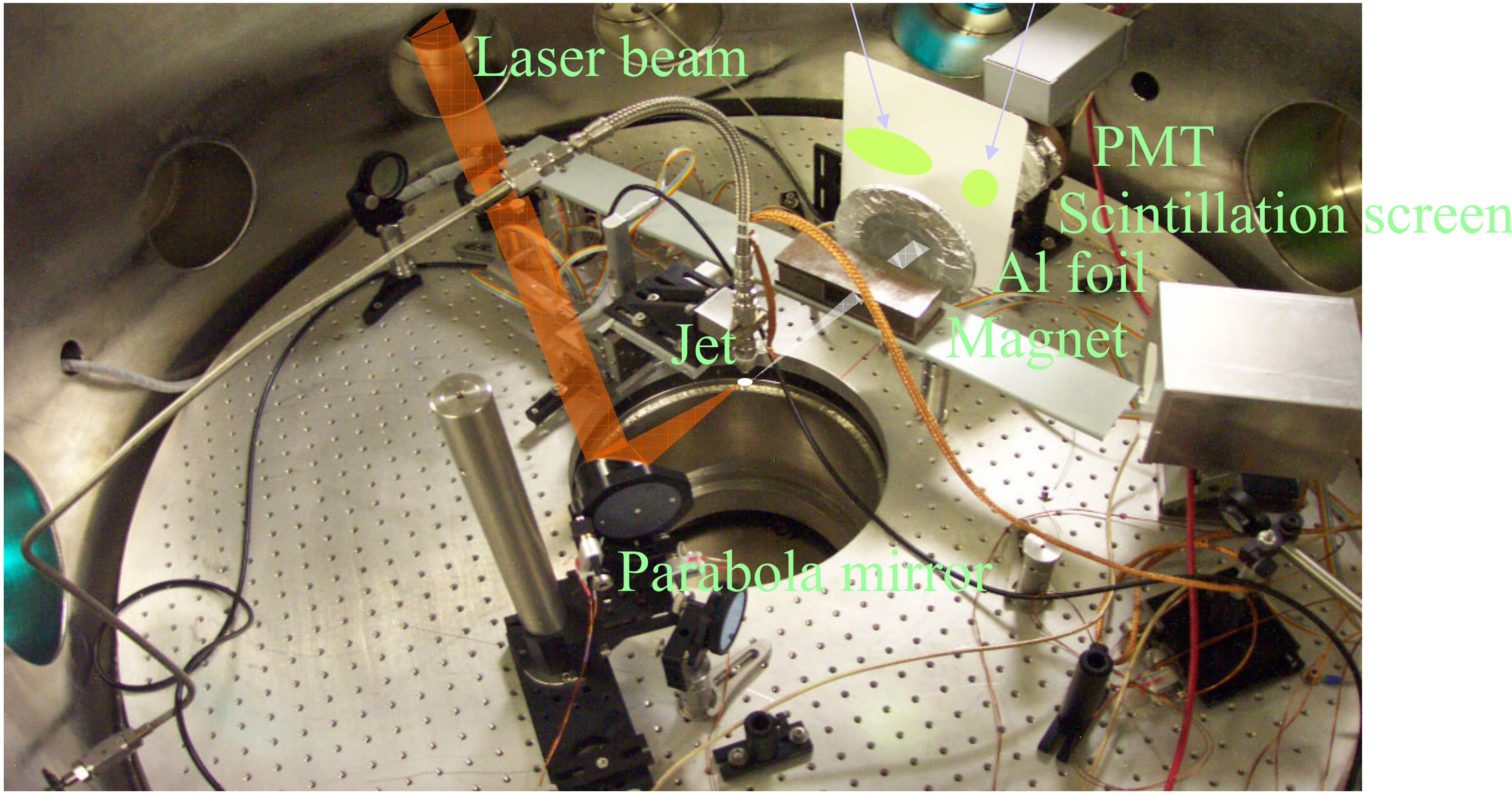


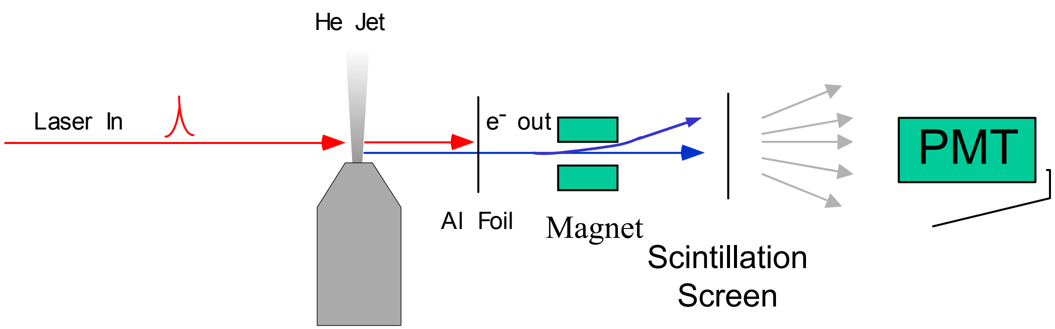
90° Spatial Inversion during amplification offers some relief

Full correction will be realized via deformable mirrors and adaptive learning software



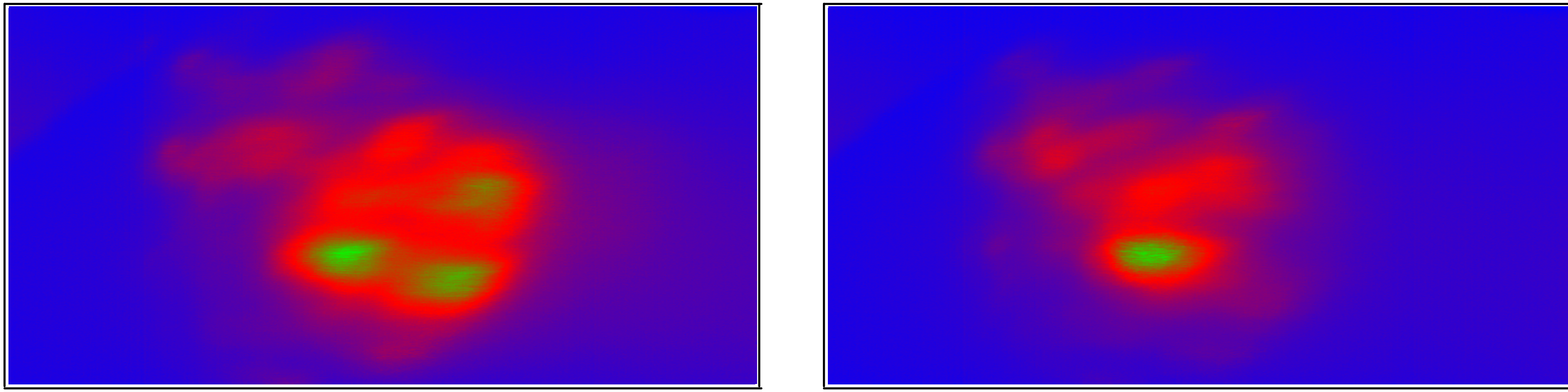
Laser Generation of Electron Pulses





Electron Beam Spatial Profile

2TW 7TW



The full angle beam divergence goes from ~15º at low power (2TW) to ~3º at higher power (7TW). At the highest laser power (23TW) the divergence is expected to be on the order of 1º.

Measurement of Charge

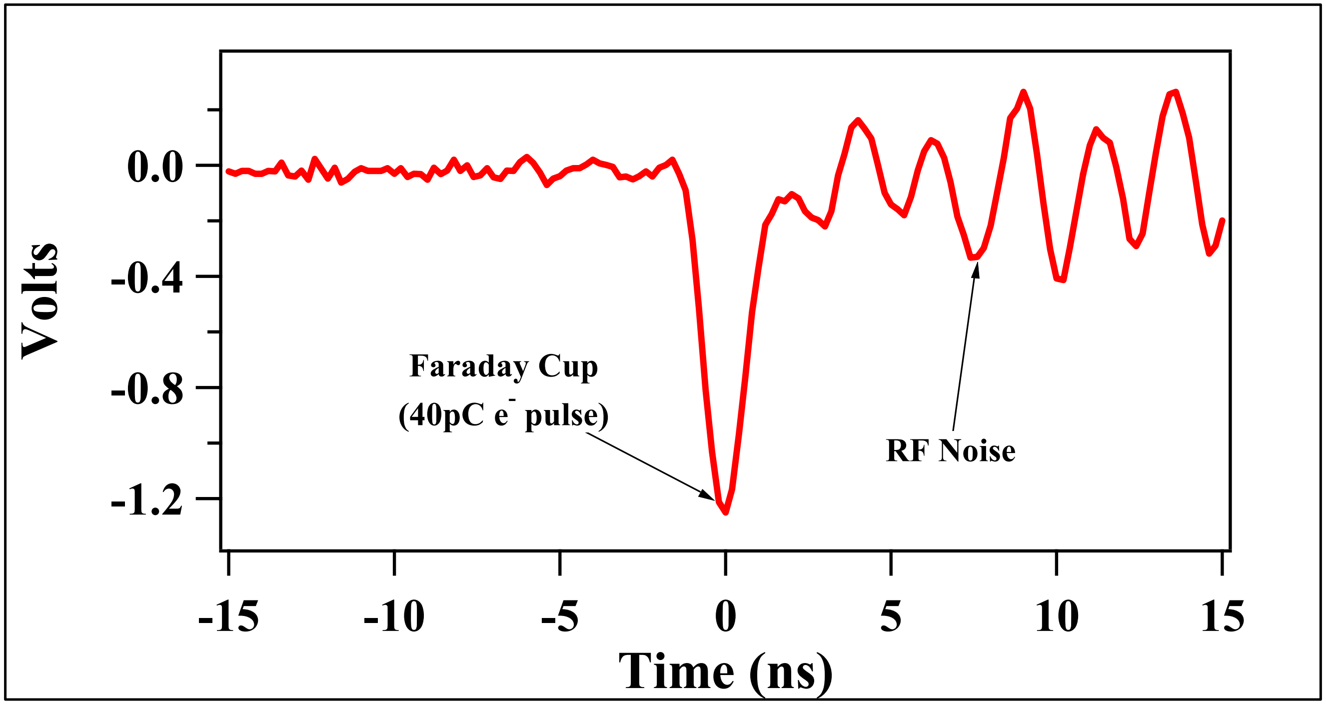
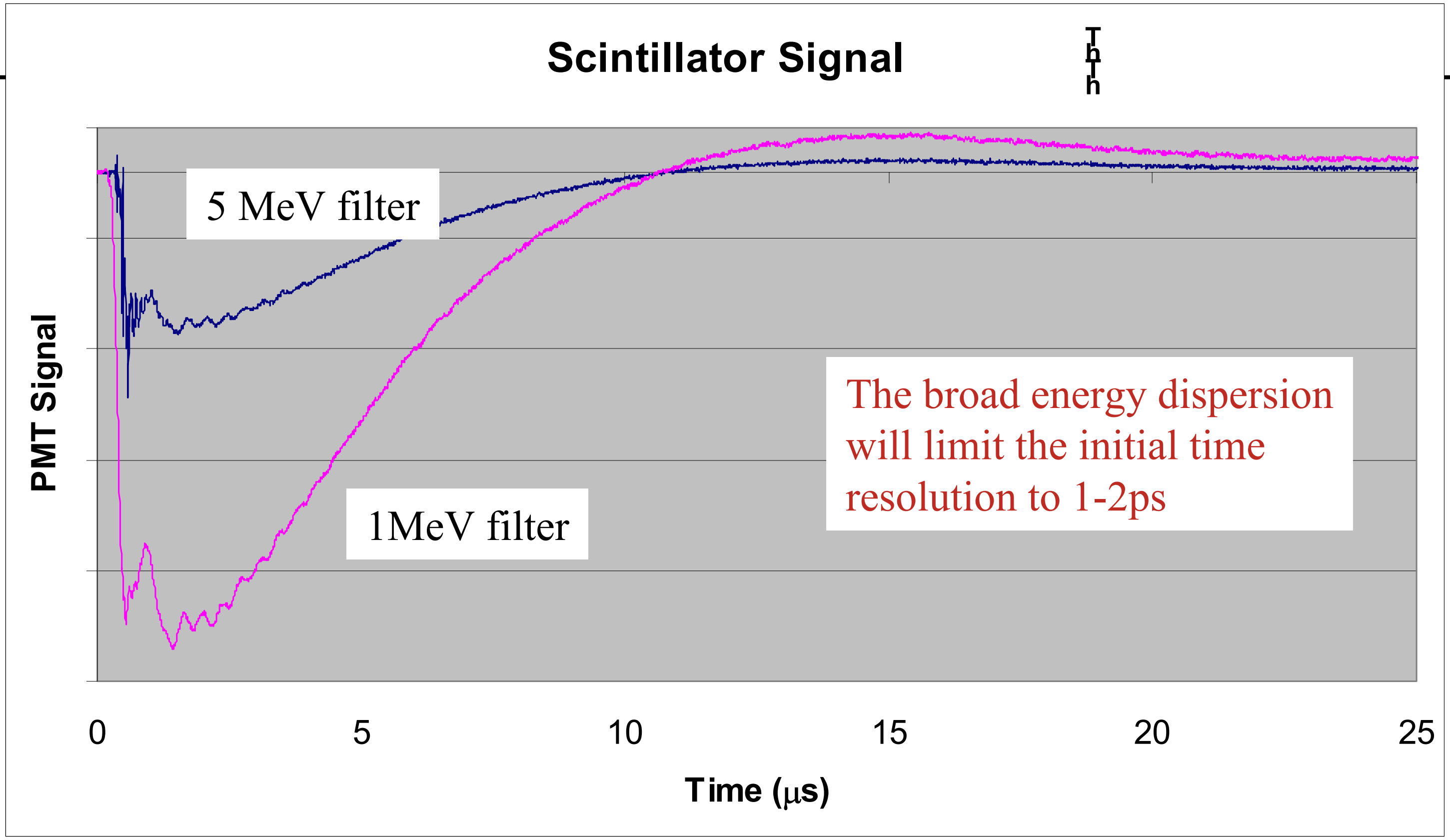


Figure 5. Response of the Faraday cup using 10TW of laser power. From our calibration factor of 21pC/ns·V the charge is estimated to be 40pC

We have measured charges as high as 0.1nC, enough to start experiments with ~5ps resolution!



~30% of electrons >5MeV

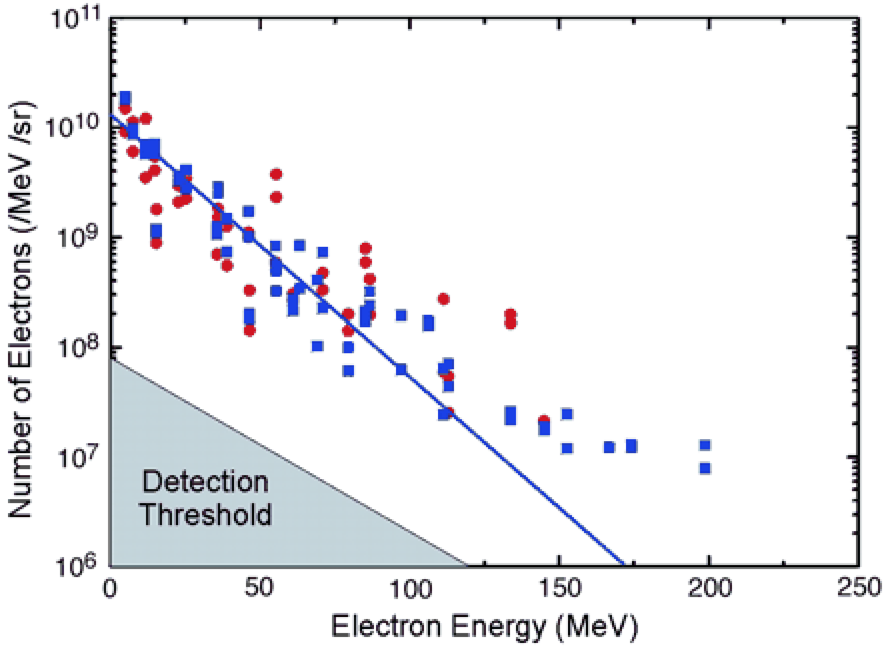
Up to 0.1nC using <10TW

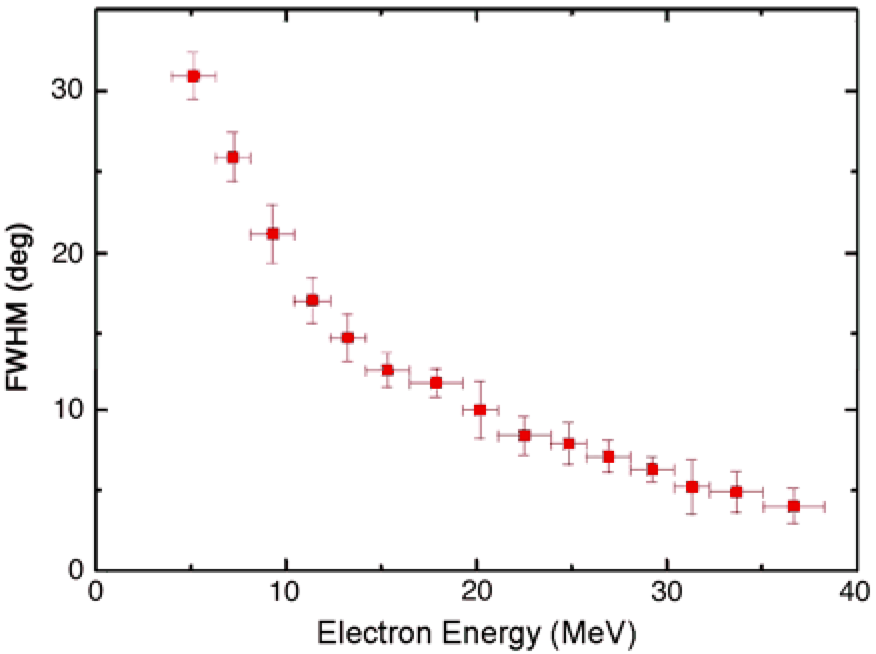
Accelerates electrons to 2MeV in .75mm

=>3GeV/cm acceleration gradient

1MeV/cm traditional accelerator

Energy Spectrum



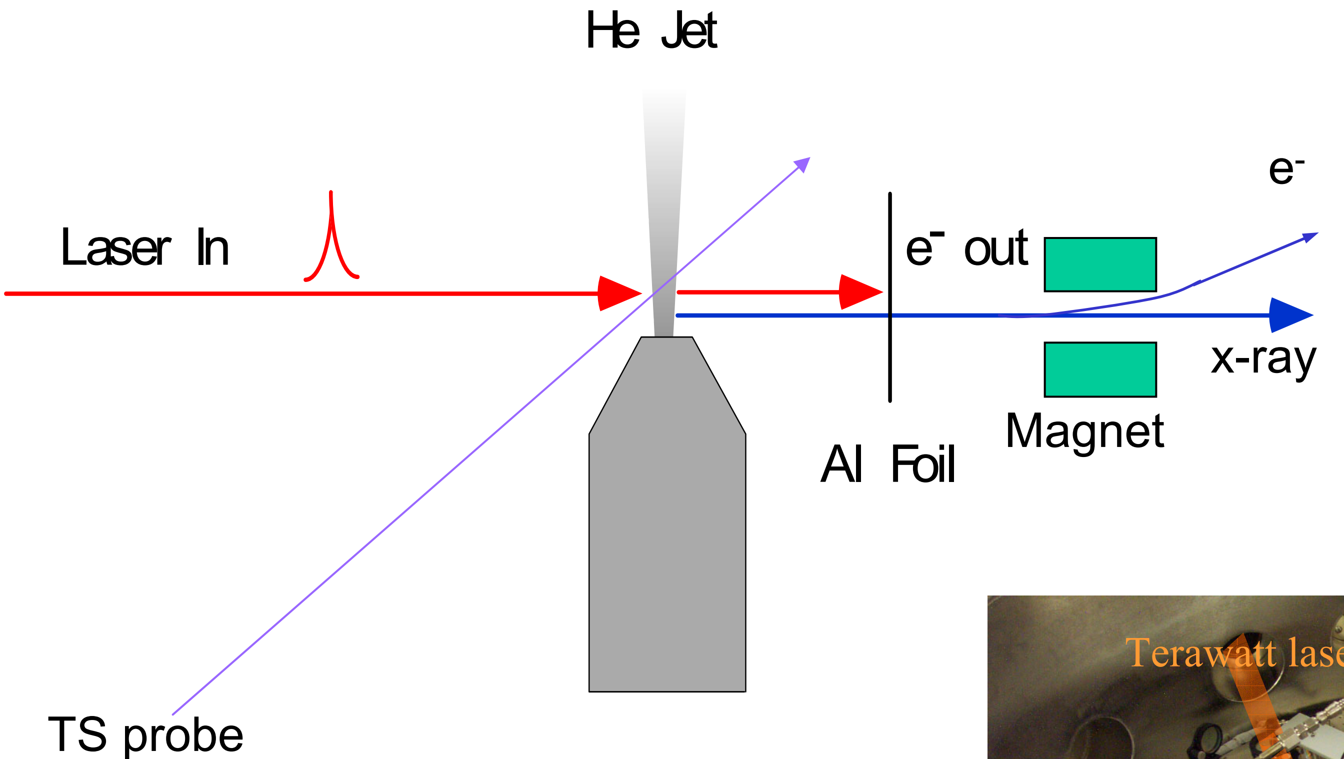


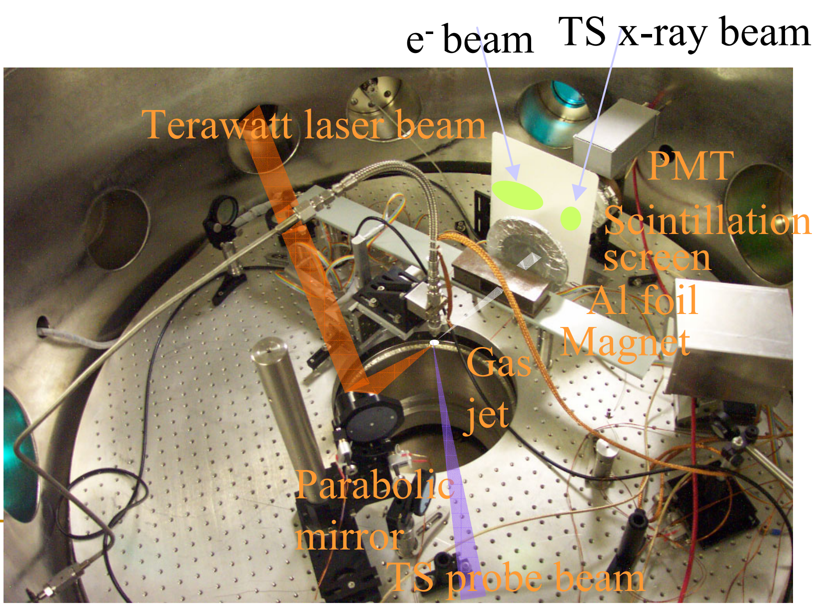
Malka et. Al, Science 298 (2002) 1596

Large energy dispersion is a definite disadvantage
Dispersion = .5ps/cm

Thomson scattering x-ray source in TUHFF

TUHFF = Terawatt Ultra High Field Facility

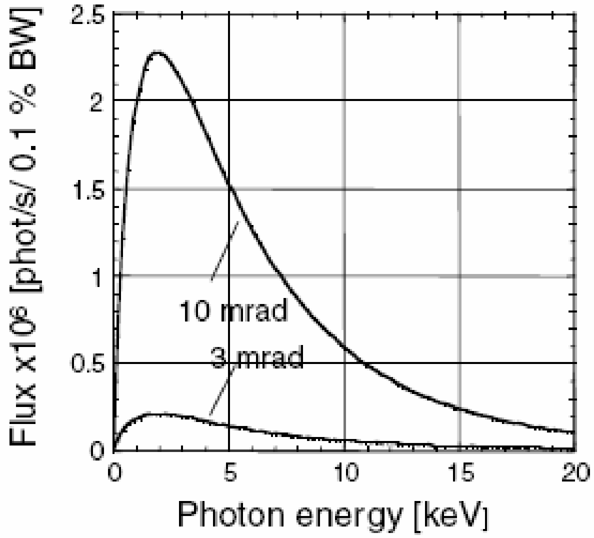


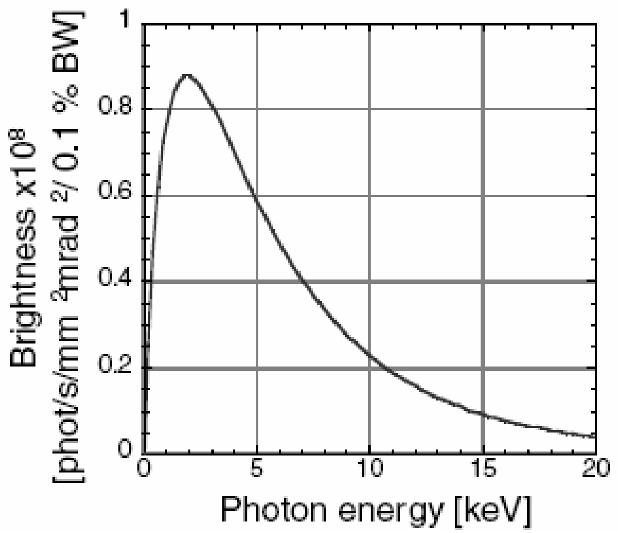


Electron Pulse Longitudinal Profile

?!

*Thomson scattering x-ray source based on laser wakefield accelerators (calculations)**





Has recently been demonstrated, 10^8ph/eV up to 2keV
LOA U. Mich. collaboration

Parameter	SM-LWFA
Laser wavelength λ_L [μm]	0.8
Laser pulse energy U_L [J]	0.6
Laser pulse duration (FWHM) [ps] τ_L	1.4
Electron beam energy γ	Exponential distribution
Number of electrons N_b	3×10^{10}
Electron bunchlength (FWHM) τ_b [ps]	0.1
Electron spot size (FWHM) r_b [μm]	6
Normalized emittance ϵ_N [mm mrad]	1
Bandwidth $\delta\omega/\omega$	10^{-3}
Collection angle [mrad]	3
Repetition rate [Hz]	10
Flux (ph s^{-1}/0.1% BW) in collection angle	2×10^5
Ave. brightness (ps s^{-1} mm^{-2} $mrad^{-2}$/0.1% BW)	9×10^7
Peak brightness (ps s^{-1} mm^{-2} $mrad^{-2}$/0.1% BW)	10^{20}
Total number of photons s^{-1} (all frequencies, all angles)	3×10^{11}
X-ray pulselength [fs]	<100
X-ray photon energy [keV]	Broadband, max at 2–3 keV

* P Catravas, et al Meas. Sci. Technol. 12 (2001) 1828–1834

Summary

- T^3 Version 1 at TUHFF is complete
- Generation of 0.1nC electron pulses achieved
- Next 5ps radiolysis experiments and electron beam temporal characterization
- Continue plans for coherent hard X-ray generation

Advantages/Disadvantages

- More than electron pulses (i.e., physics)
- Can also be used as X-ray source
- Complicated laser system, but…..
- Energy dispersion
- Synchronization
- No linac