Laser Accelerated Plasma Propulsion System (LAPPS)

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- Recent Experiments at The University of Michigan and elsewhere have shown that Ultra-short Pulse [Ultrafast] Lasers can accelerate charged particles to relativistic speeds

- They have accelerated electrons and protons to more than 1 MeV

- They have accelerated Deuterons (in clusters) for Fusion Applications and for Nuclear Activation Applications such as $B^{10}(d,n)\,C^{11}$. Also induced photon fission such as $Au^{197}\,(\gamma,n)\,Au^{196}$

- Expect to accelerate protons to rest mass energies, i.e. to

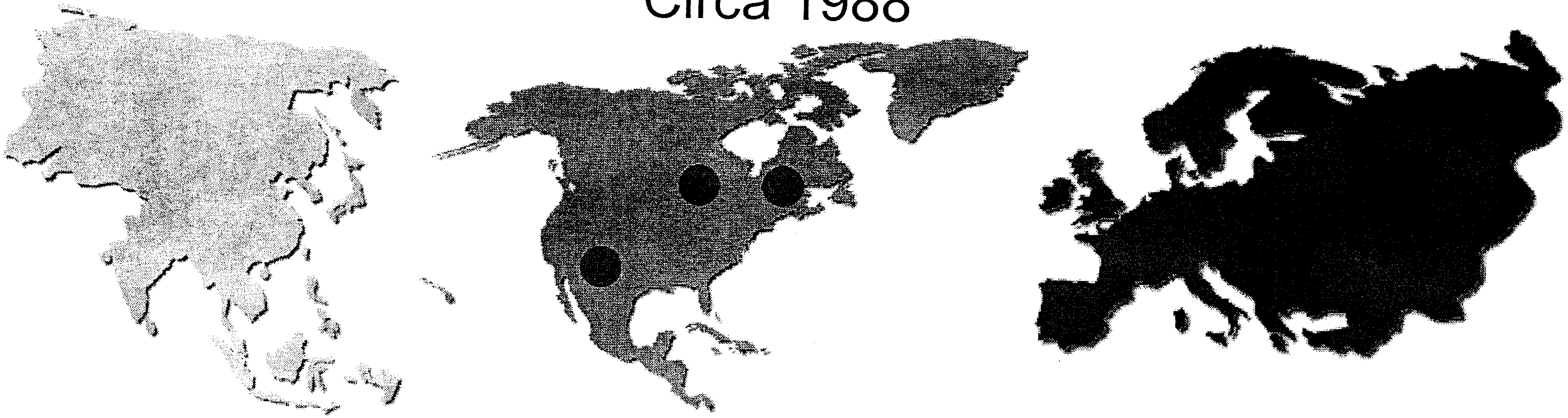
  $$v=0.866c$$

  Which would translate to

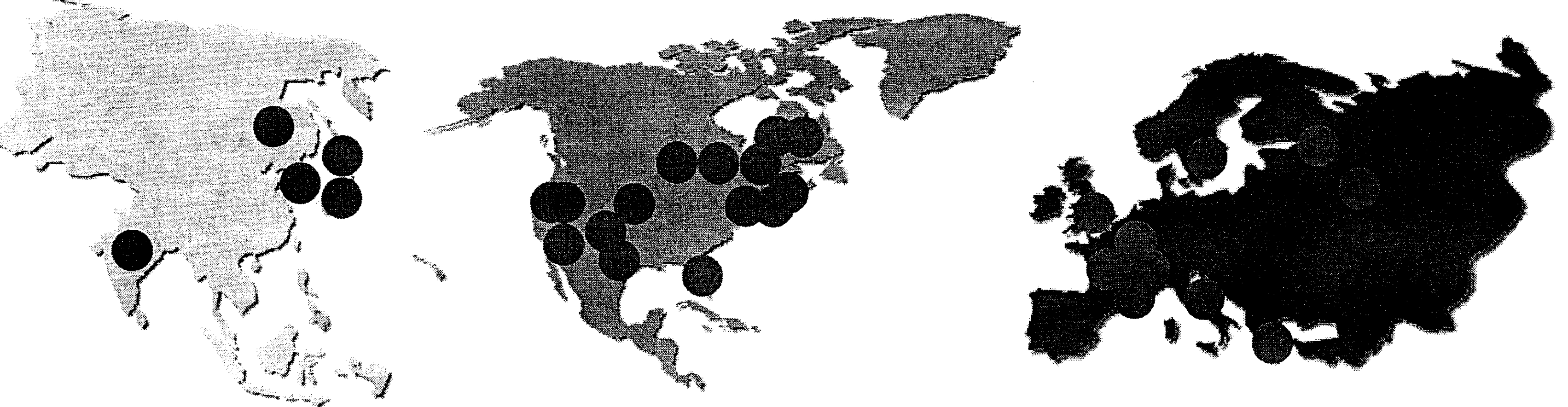
  $$\mathrm{Isp}=10^7\ \mathrm{s}$$

Ultra-High-Intensity Laser Labs

Circa 1988



Circa 2000



A ultrashort laser pulse with only 1 Joule of energy can accelerate an electron to an MeV in just a few microns

$$\frac{energy}{time} = power$$

$$\frac{power}{area} = intensity$$

$$\frac{1\ \text{joule}}{\text{sec}} = 1\ \text{watt}$$

→

$$\frac{1\ \text{terawatt}}{(10\ \text{micron})^2} = 10^{18}\,\text{watt/cm}^2$$

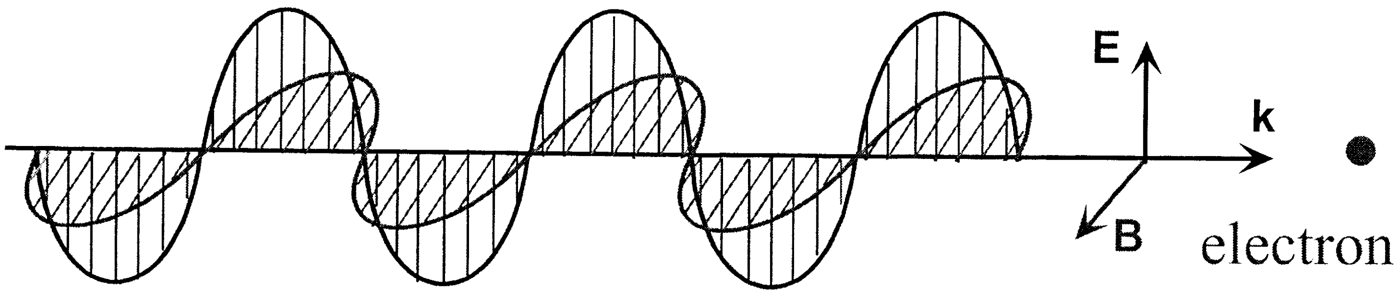
$$\frac{1\ \text{joule}}{\text{picosecond}} = 1\ \text{terawatt}$$

$$electric\ field\ (\text{V/cm}) = (intensity)^{1/2}$$

↓

$$(10^9\ \text{V/cm})\ \text{X}\ (10\ \text{microns}) = 1\ \text{megavolt}$$

Relativistic Electron Motion



electron $v_o = 0$

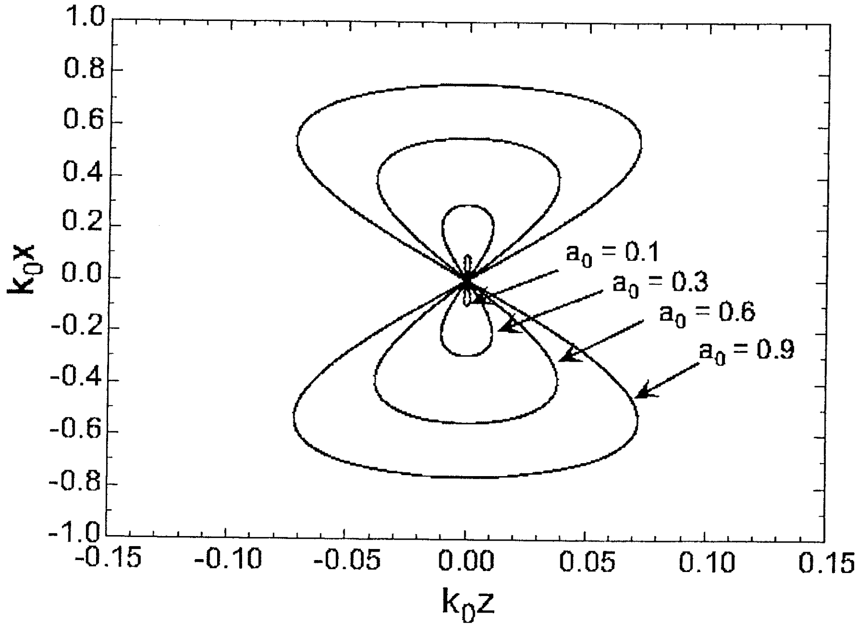
$$\mathbf{k}=k\hat{\mathbf{z}},\quad \mathbf{E}=E_0\cos(kx-\omega t)\hat{\mathbf{x}},\quad \mathbf{B}=B_0\cos(kx-\omega t)\hat{\mathbf{y}}$$

$$\boxed{\frac{d\mathbf{p}}{dt}=\frac{d(\gamma m_0\mathbf{v})}{dt}=q\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right),}$$

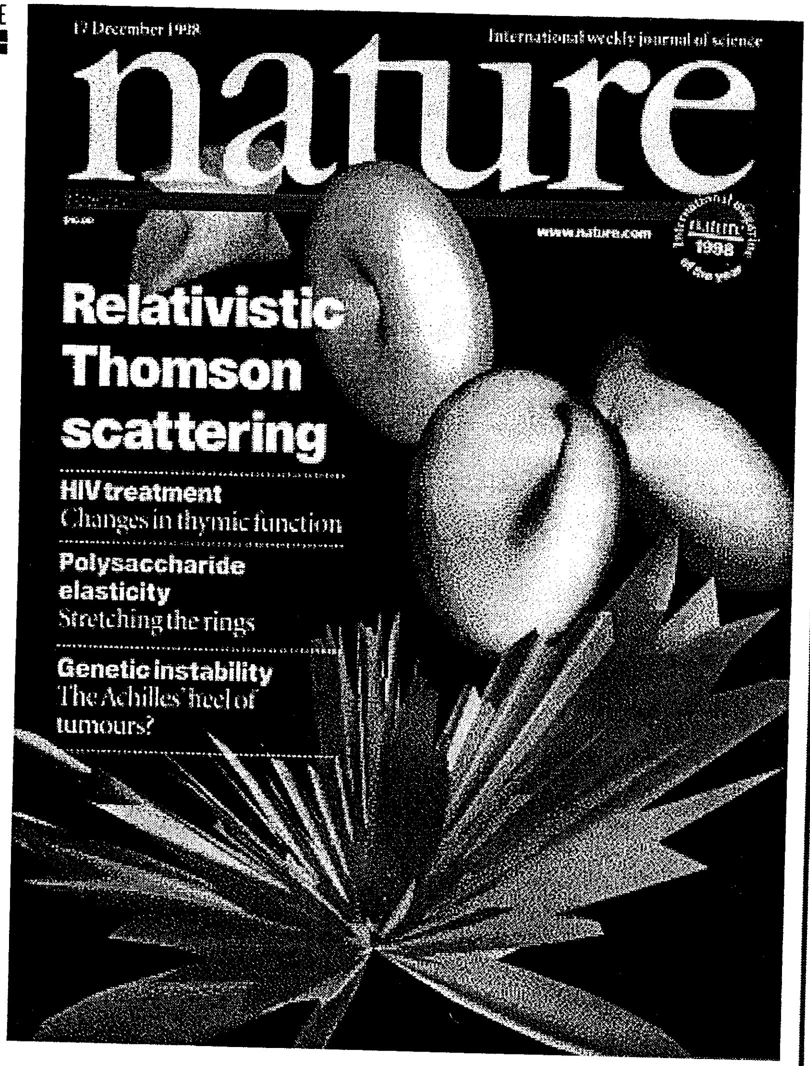
$$\gamma_\perp\equiv\left(1-(v_\perp/c)^2\right)^{-1/2}=\left(1+a_0^2/2\right)^{1/2}$$

$$a_0=\frac{eA}{m_0c^2}$$

$$=0.85\times10^{-9}\sqrt{I\left(\mathrm{W/cm^2}\right)}\lambda(\mu\mathrm{m}).$$



Experimental Confirmation



17 December 1998

International weekly journal of science

nature

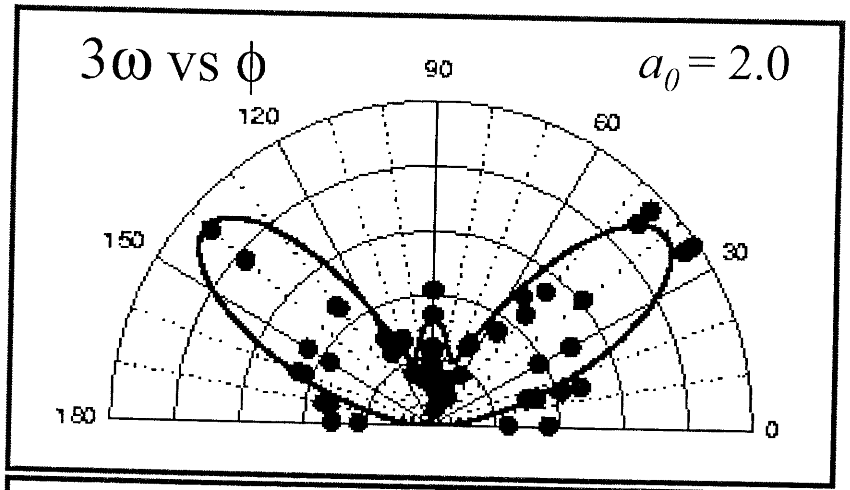
www.nature.com

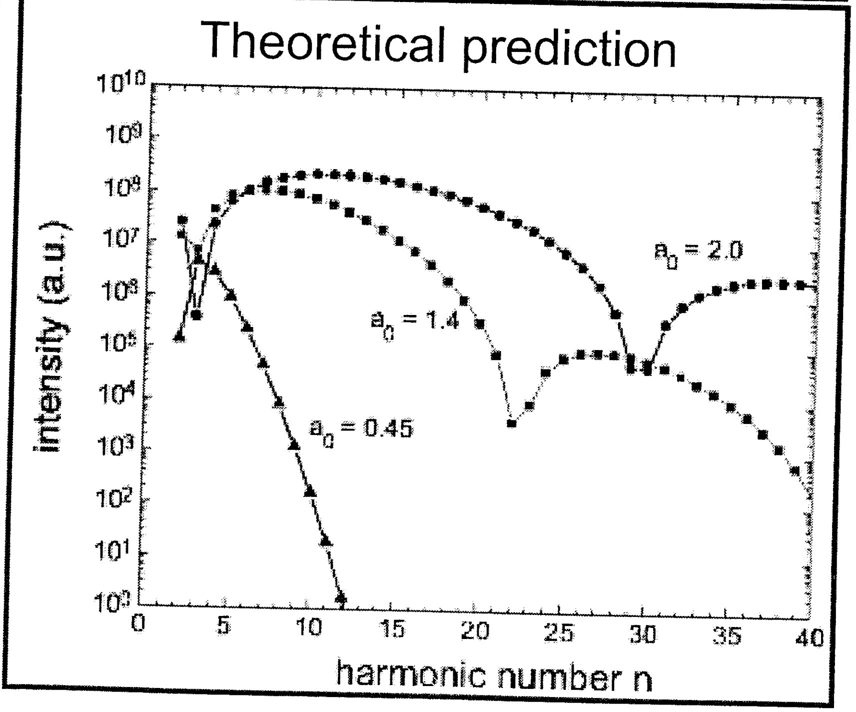
Relativistic Thomson scattering

HIV treatment
Changes in thymic function

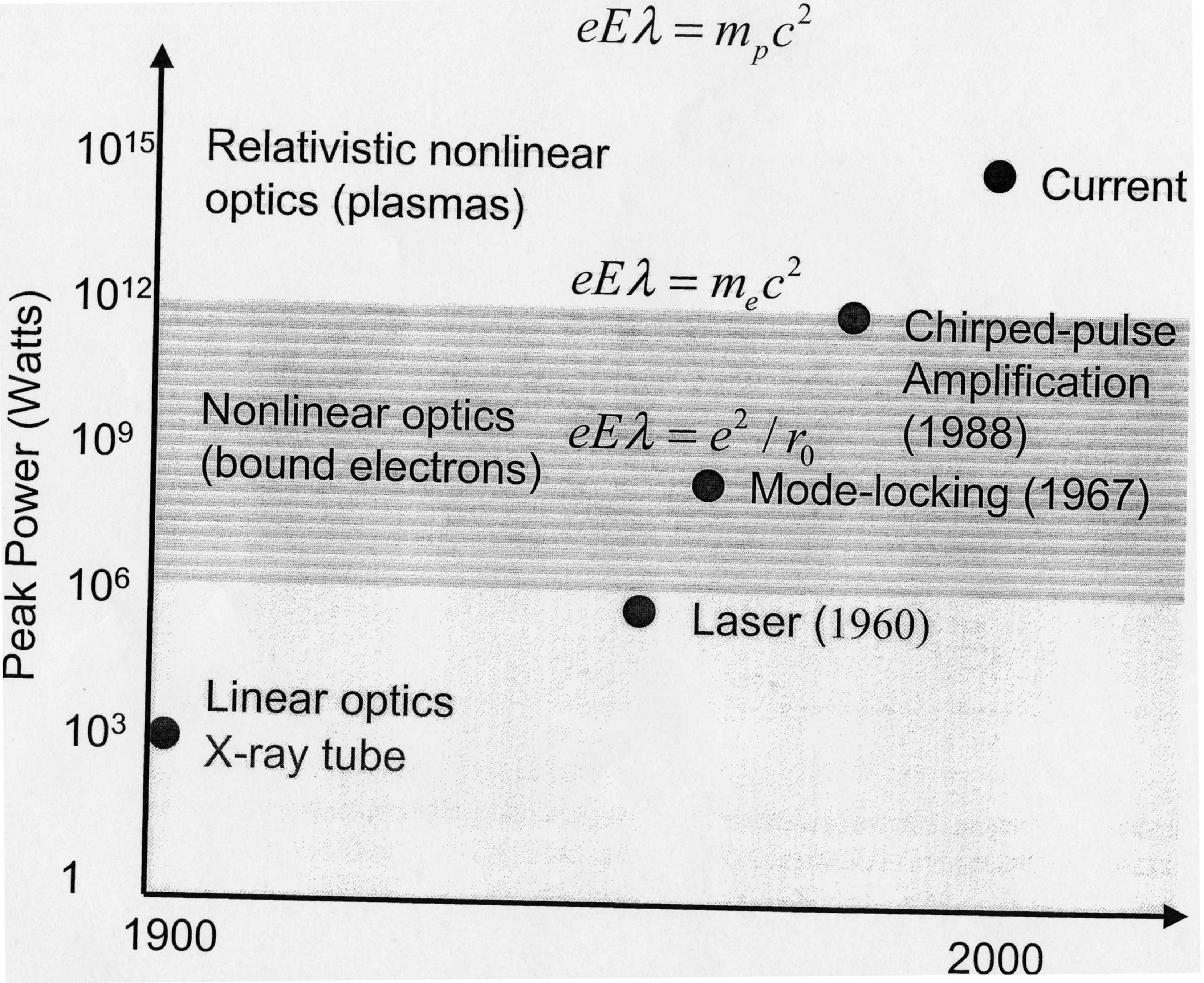
Polysaccharide elasticity
Stretching the rings

Genetic instability
The Achilles' heel of tumours?

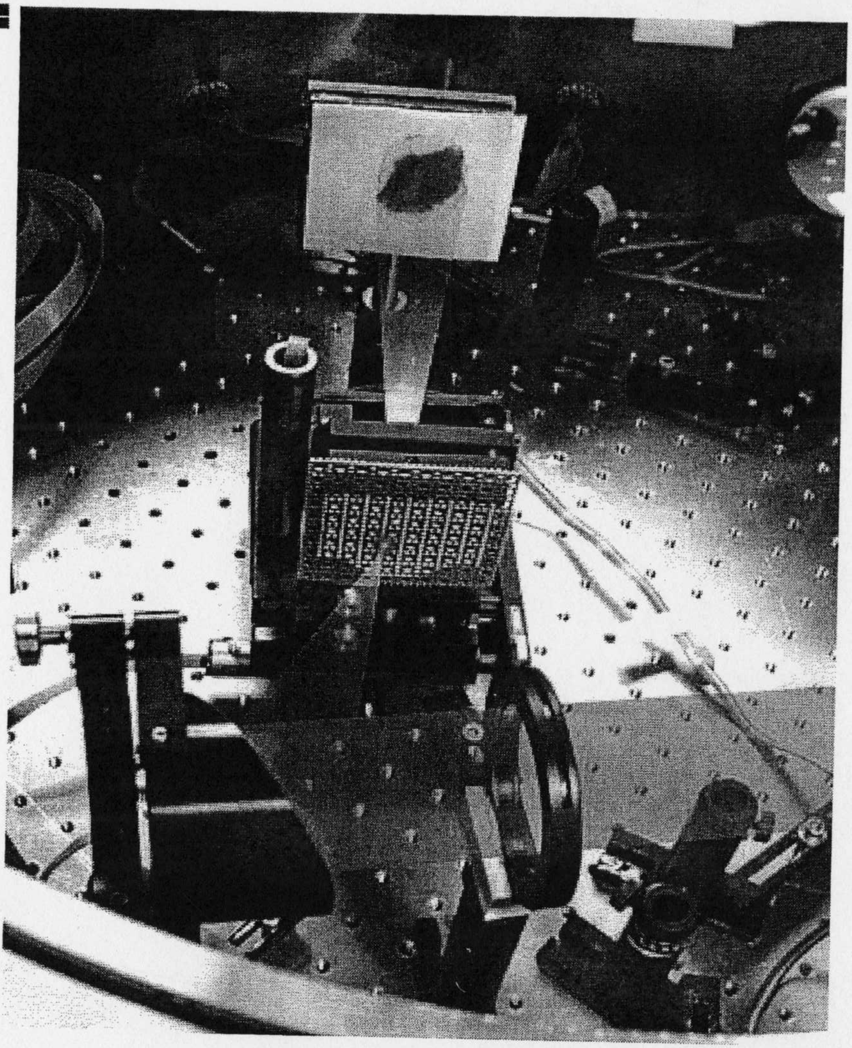




S. Chen *et al.*, " *Nature,* **396**, 653 (1998).


$eE\lambda = m_p c^2$
Peak Power (Watts)
10^{15}
Relativistic nonlinear optics (plasmas)
Current
$eE\lambda = m_e c^2$
10^{12}
Chirped-pulse Amplification (1988)
Nonlinear optics (bound electrons)
$eE\lambda = e^2 / r_0$
10^9
Mode-locking (1967)
10^6
Laser (1960)
Linear optics X-ray tube
10^3
1
1900
2000

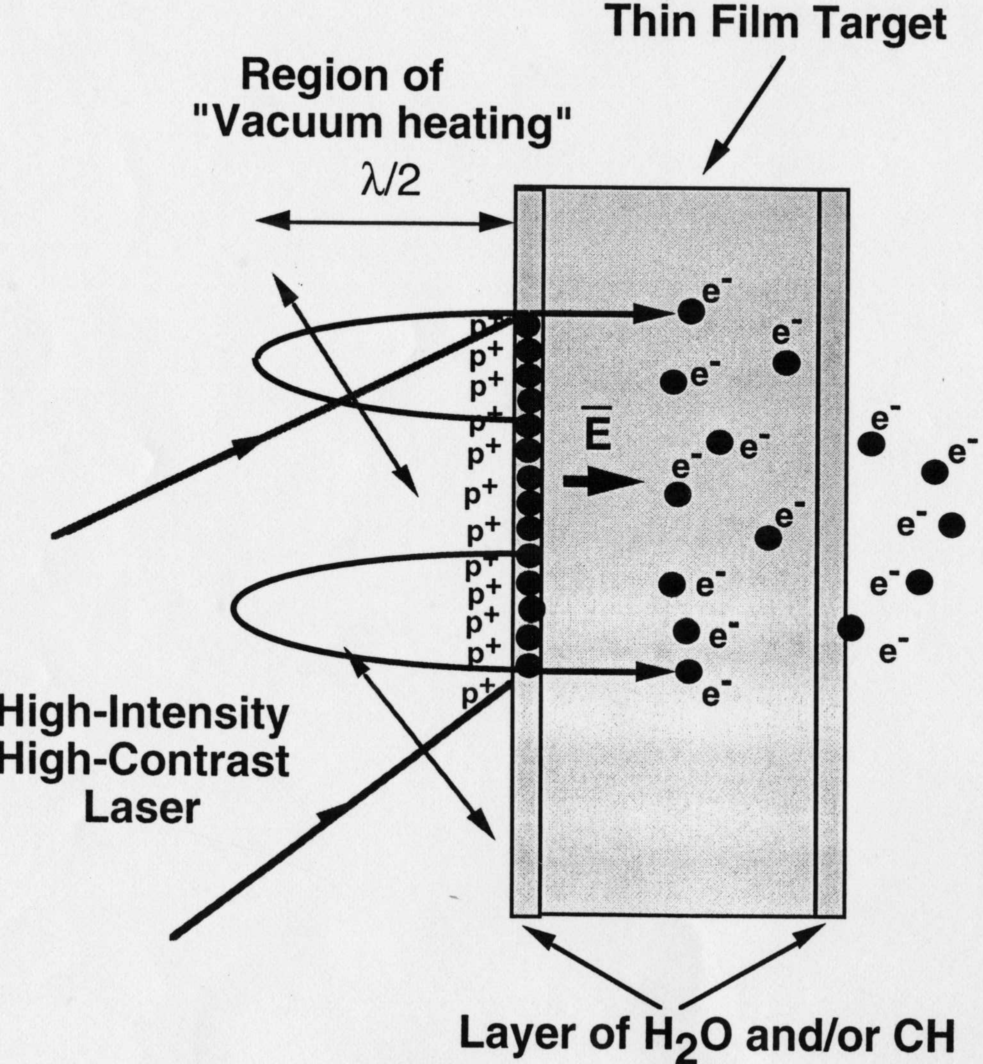
A Beam of MeV Protons



- $a_0 = 3.0$
- Cone angle = 40°
- Always normal to the target
- Front side origin
- 2π mm-mrad
- $E \sim 10$ GeV/cm
- $N > 10^{10}$ p
- $J = 10^8$ A/cm^2

A. Maksimchuk, K. Flippo, D. Umstadter, V.Y Bychenkov, *Phys. Rev. Lett.* **84**, 4108 (2000).

Mechanism for proton acceleration



ion acquire an electrostatic energy:

$$\varepsilon_i \approx Ze\phi \approx Z\varepsilon_e$$

Solving equation for energy balance and Coulomb energy we can estimate:

characteristic electron density

$$n_e \approx n_c(a/2\pi)\sqrt{\eta 2\lambda / R}$$

and electron energy

$$\varepsilon_e \approx \pi a m c^2 \sqrt{\eta R / 2\lambda}$$

Then characteristic ion energy is

$$\varepsilon_i \geq Z\sqrt{\eta I R \lambda}$$

Comparison of Recent Results

Institute	**Energy (MeV)**	**Yield**	**Laser**			**Target**	**Reference**
			(W/cm^2,	**J,**	**ps)**		
U of Michigan	1	10^8	3×10^{18}	4	0.4	He	PRE 56,7042 (1999)
Rutherford	6		5×10^{19}	50	0.9	Ne	PRL 83 737 (1999)
Rutherford	20	10^{12}	5×10^{19},	50	1.0	Al	PRL 84, 670 (2000)
	420	----	“”	“”	“”	Pb	PRL 85, 1654 (2000)
U of Michigan	1. 5 (2ω)	10^{10}	3×10^{18}	1	0.4	Al	PRL 84, 4108 (2000)
	10	10^{10}	6×10^{18}	4	0.4	CD	APS-DPP (2000)
LLNL petawatt	50	10^{10}	1×10^{20}	60,	0.4	CH & Au	PRL 85, 2945 (2000)
LLNL JanUsp	20		1×10^{21}	5	0.05		APS-DPP (2000)

– Relativistic Self-Focusing

For a focused laser beam with higher intensity on axis and lower intensity off axis in a plasma, the *Index of Refraction*, n

$$n = \sqrt{1 - \frac{w_P^2(\gamma)}{w_0^2}} = \sqrt{1 - \frac{w_{P0}^2}{\gamma w_0^2}}$$

Where $w_{P_0} = \frac{4\pi n_n e^2}{m_e} =$ plasma frequency

Wo= Laser Frequency

Will be higher on axis and lower off axis and plasma acts like a “lens”. Hence what is known as “Relativistic Self-Focusing”

– Ponderomotive Self-Channeling

For a focused laser pulse with transverse laser *intensity gradient*, the transverse Ponderomotive force will push electrons outward and that results in a depression in electron density on axis. This makes *Index of Refraction,* n, higher on axis and once again the plasma acts like a positive lense and leads to self-focusing of the laser pulse. This is referred to as “Ponderomotive Self-Channeling”

Relativistic Mass Shift Affects Light Propagation in Plasma

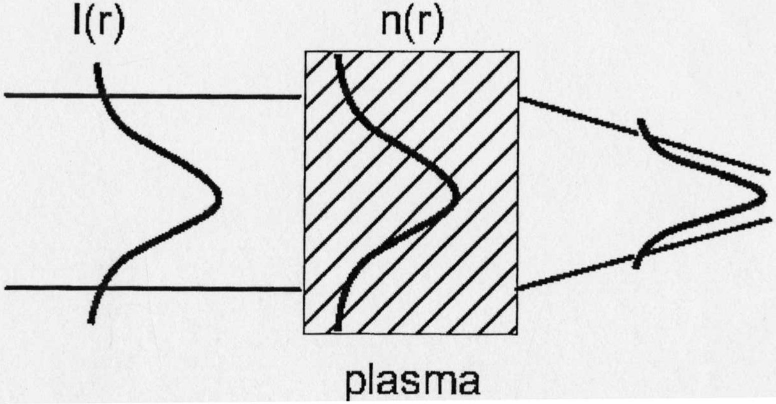
Plasma frequency: $\omega_p = \sqrt{\dfrac{4\pi n_e e^2}{m_0}}$

Index of refraction for light waves: $\eta \equiv \sqrt{1 - \dfrac{\omega_p^2}{\gamma_\perp \omega_0^2}} \cong 1 + \dfrac{1}{2}\dfrac{\omega_p^2}{\omega_0^2}\dfrac{\left\langle a^2 \right\rangle}{2}$

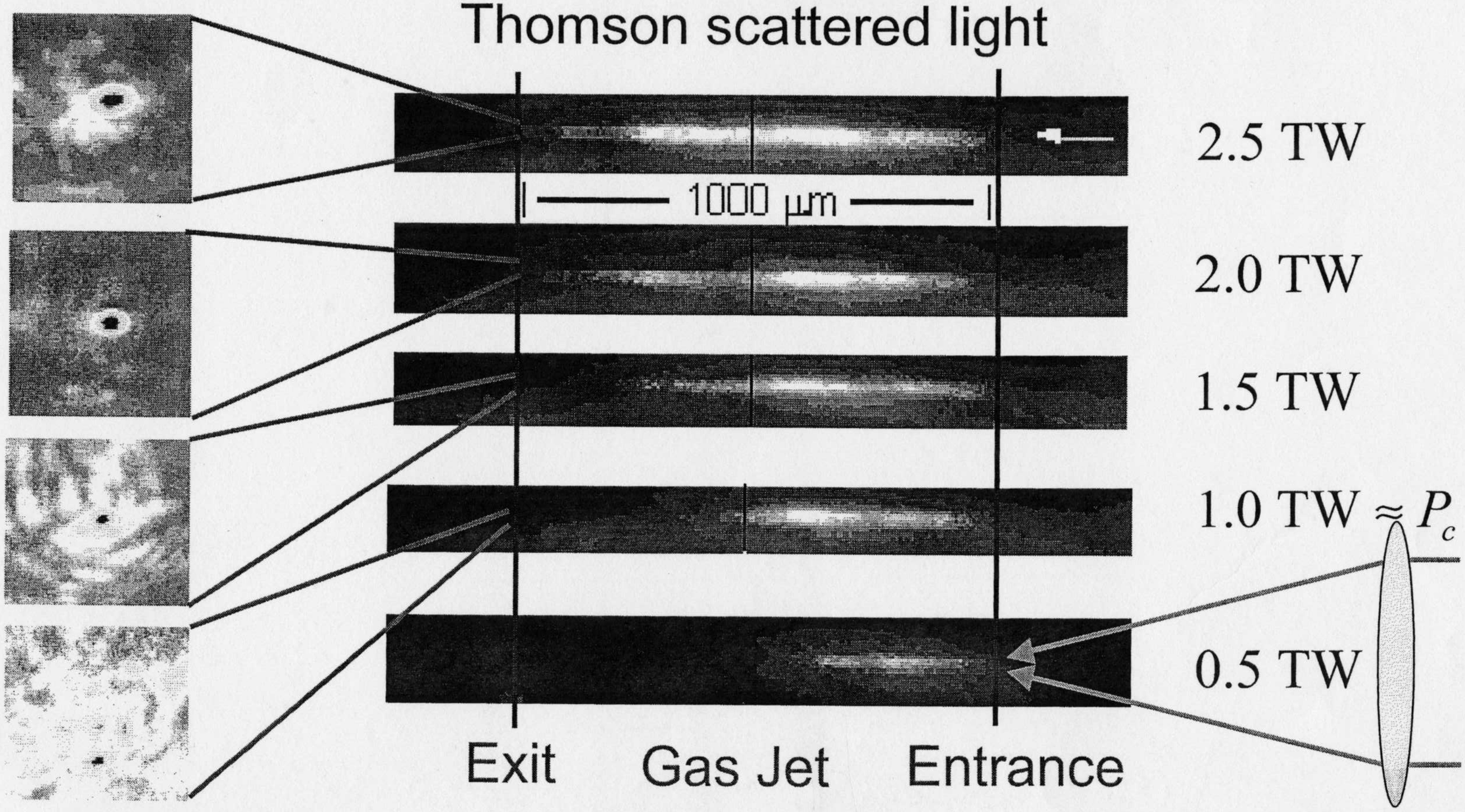
$\Rightarrow$ Phase velocity, $v_\varphi = c\eta^{-1} \propto I$

Relativistic self-focusing:

$P_c = 17\left(\omega_0^2 / \omega_p^2\right)$ GW



Experimental Evidence of Relativistic Self-Guiding



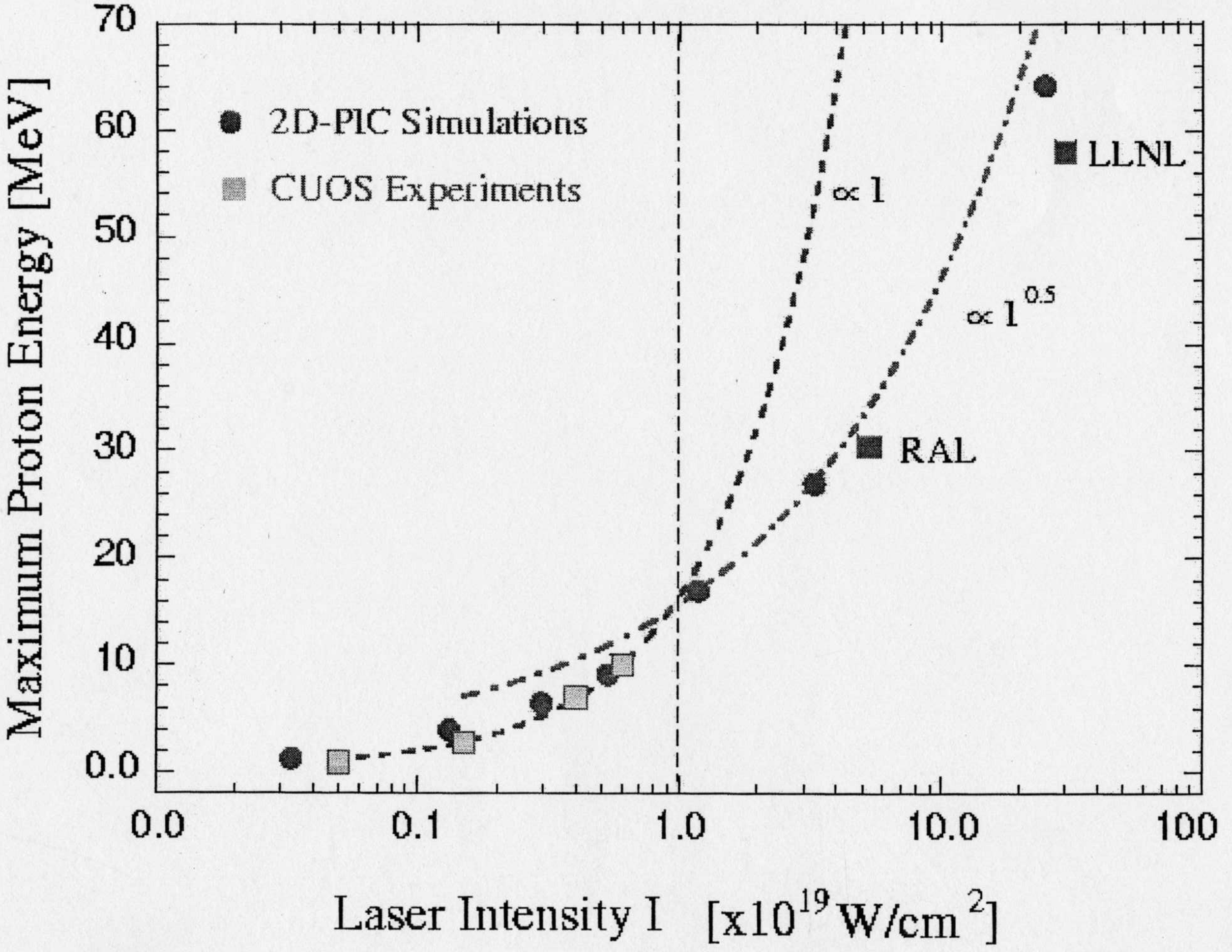
Axial-imaging

Side-imaging of Thomson scattered light

Exit Gas Jet Entrance

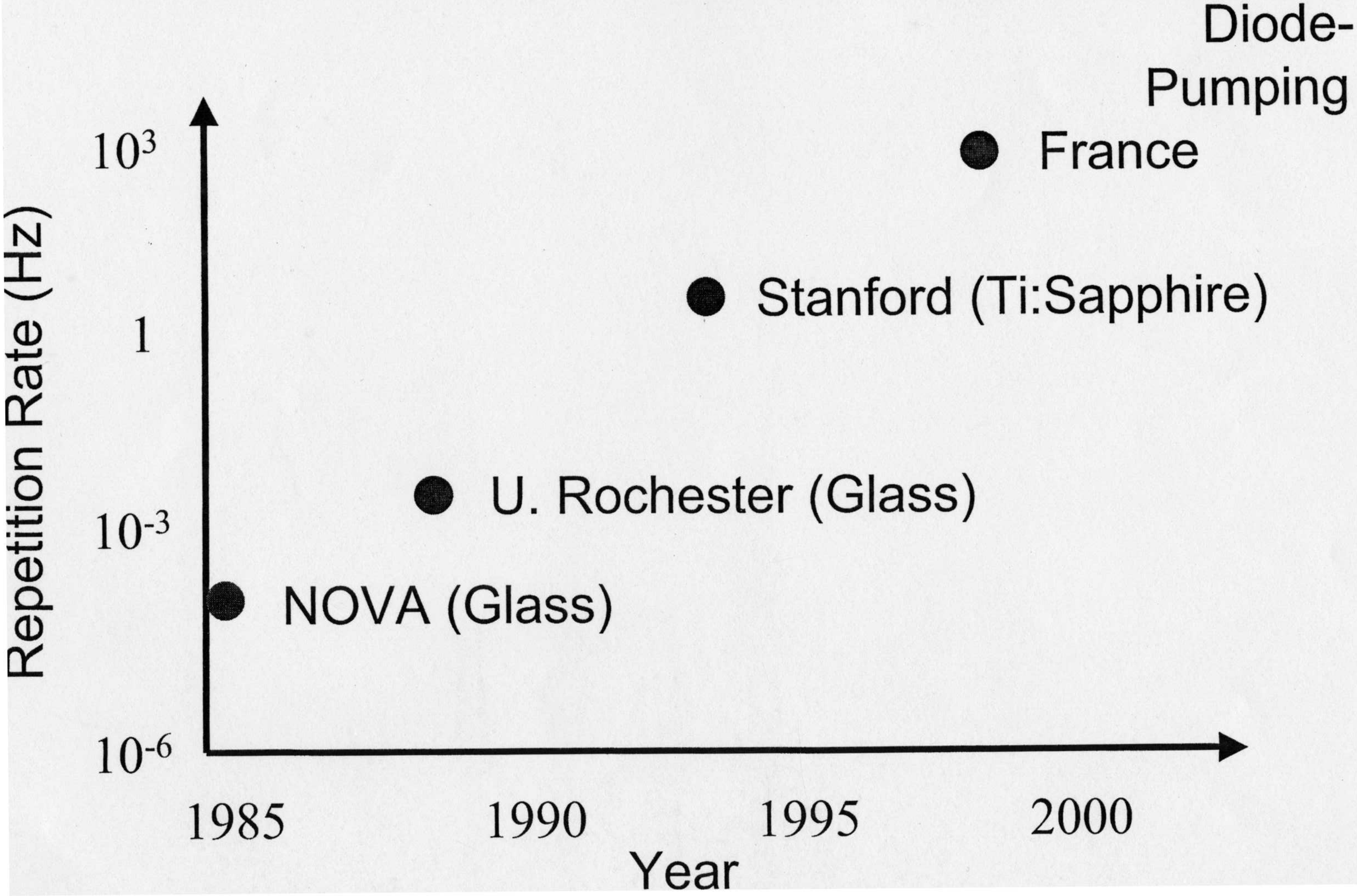
S.-Y. Chen *et al.*, Phys. Rev. Lett., **80**, 2610 (1998).

Scaling of maximum proton energy with laser intensity at λ=1 μm



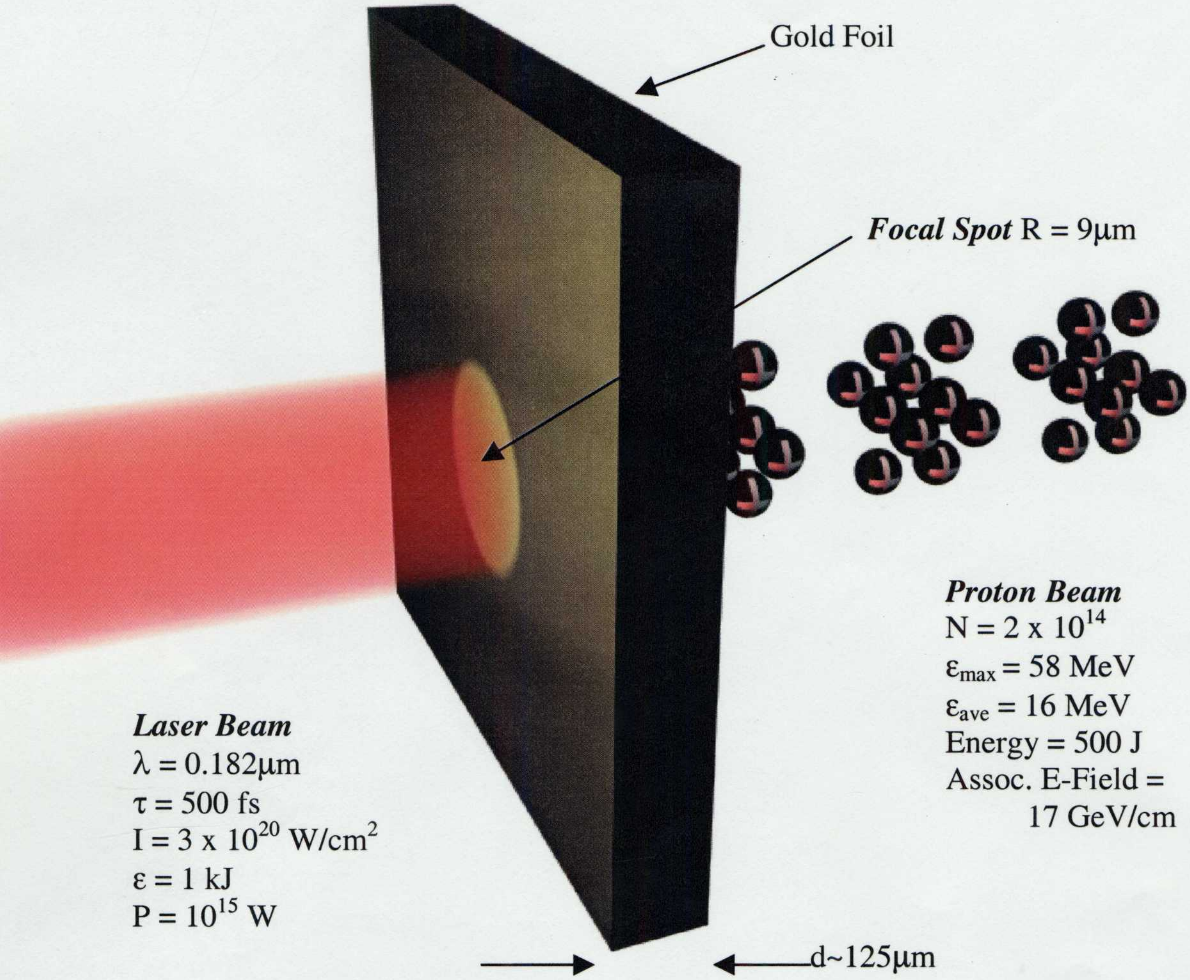
Sentuko *et al.* (2000).

Higher Duty-Cycle Terawatt Lasers: Better Signal Averaging



Laser Accelerated Plasma Propulsion System
(LAPPS)

Recent Experimental Results – R.A. Snavely et al, Phys. Rev. Lett., 85, 2945 (2000)

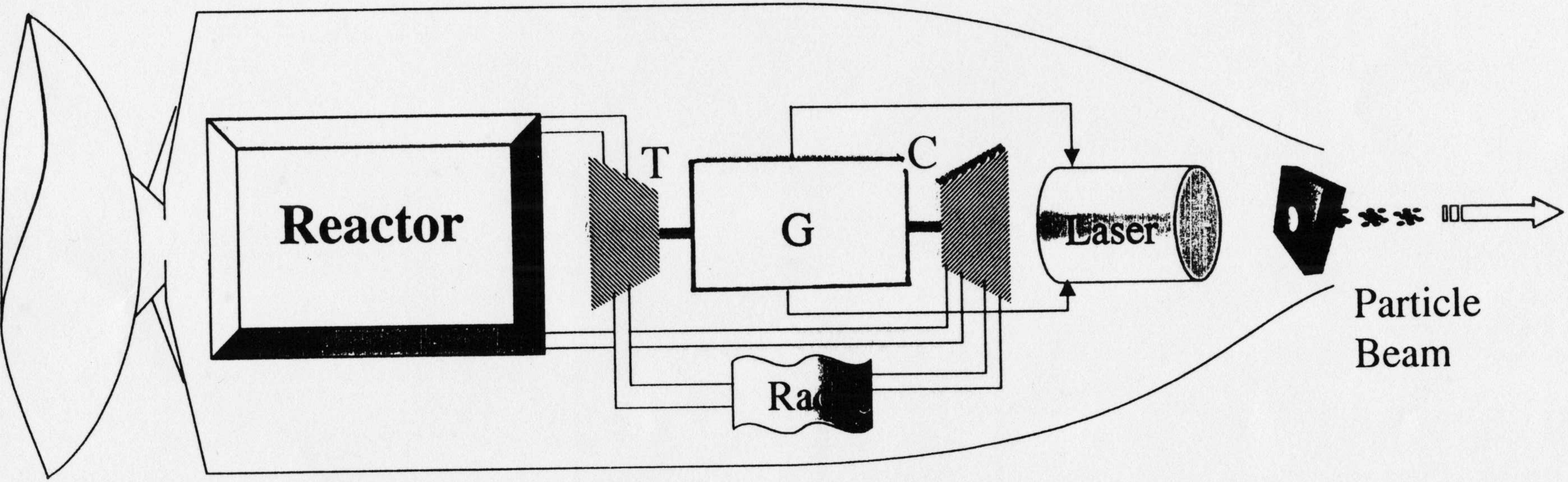


Proton Beam
$N = 2 \times 10^{14}$
$\varepsilon_{max} = 58$ MeV
$\varepsilon_{ave} = 16$ MeV
Energy = 500 J
Assoc. E-Field =
17 GeV/cm

Laser Beam
$\lambda = 0.182\mu m$
$\tau = 500$ fs
$I = 3 \times 10^{20}$ W/cm^2
$\varepsilon = 1$ kJ
$P = 10^{15}$ W

LAPPS Propulsion System
Rep Rate $\omega = 10^3$
$I_{sp} = 5 \times 10^6$
Thrust $F = 1.83 \times 10^{-2}$ N
Driver = Nuclear Reactor ~ 1 MW$_e$
$M_f = 5 \times 10^3$ kg

Fly-By Missions with Above LAPPS	LAPPS with F ~ 1 N
Pluto ~ 56 Years	Pluto ~ 7 Months
Jupiter ~ 19 Years	Jupiter ~ 2.3 Months
Mars ~ 6 Years	Mars ~ 3 Weeks



Laser-Accelerated Plasma Propulsion System
(LAPPS)

Design of 160 MW$_e$ Nuclear Power System (Brayton)

(Lee Mason, NASA GRC)

Masses in kg

System Sizing	Near Term	Mid Term	Far Term
Reactor/Shielding	121978	102140	79593
(1) Reactor	115307	96163	74399
(1) Inst. Shield	4923	4386	3694
(0) Crew Shield	0	0	0
(1) PHTs	1748	1591	1500
Power Conversion	17433	15513	14749
(10) TAC/Ducts	182	182	181
(10) Recuperators	916	805	775
(10) Coolers	487	424	384
(10) Structures	158	141	134
Heat Rejection	110756	42080	8810
(1) Radiator	110756	42080	8810
(1) Aux. Equip	0	0	0
Power MGMT & Dist.	534155	161079	77157
(1) Electronics	234756	92061	34709
(1) Radiator	83137	28696	25592
(1) PL Rad.	57905	28953	14476
(1) Cabling	158357	11370	2379
Total	784322	320813	180309
Ratio	4.9 kg/kW$_e$ = 4.9 mT/MW$_e$	2.0 kg/kW$_e$ = 2.0 mT/MW$_e$	1.1 kg/kW$_e$ = 1.1 mT/MW$_e$

Conclusions

1. Ultrafast lasers have and can accelerate charge particles to speeds that make them attractive for propulsion applications.

2. Accelerating protons to 70 MeV energies or even rest mass energies is within reach in the not too distance future.

3. Intense lasers propagating in plasmas tend to be self-focused due to (i) relativistic self-focusing and (ii) pondermotive channeling. A desirable characteristic for above applications.

4. Rep rates of kilohertz or higher are also within reach making laser accelerated plasmas especially attractive for propulsion.

5. Advancements in ultrafast laser technology and space nuclear power in the next decade or so would allow for the development of a LAPPS propulsion system that can be operable in the time frame of 10-40 years.

6. Such a system would allow robotic/human missions in the solar system and beyond to be achieved in desirably short times.

PHASE II – NIAC

I. High Specific Impulse readily achievable with Present-day LAPPS

II. Need to Increase Thrust ⇒ $F = \omega n m v$, can either
  - i) increase density in ejected proton beam (n), or
  - ii) increase rep rate (ω), or
  - iii) increase particle energy (~v)

III. Can address above issues by
  - i) increasing focal area in target
  - ii) considering use of "jets" in place of solid targets
  - iii) increasing laser power (and intensity)

IV. At UM, laser power: 10 TW (now) → 100 TW ('02) → petawatt ('03-04)

V. Assess Impact of above issues on the all important quantity
"$I\lambda^2$" where I = laser intensity
λ = laser wavelength

Including
  - i) Relativistic focusing
  - ii) Pondermotive channeling
  - iii) Other laser-plasma interaction phenomena