Ultra-Fast Laser-Driven Plasma for Space Propulsion

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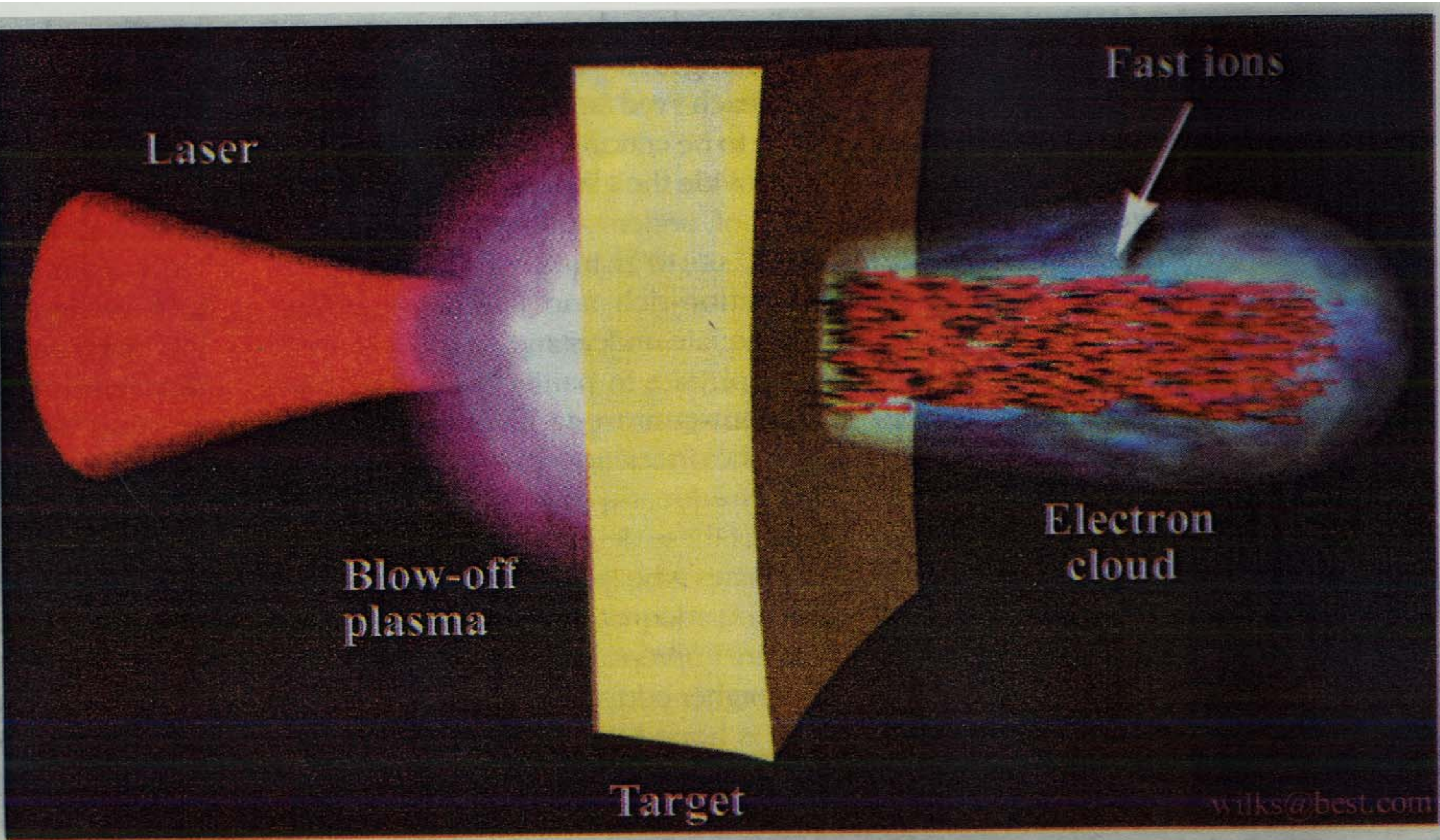


Figure courtesy of Scott C. Wilks of Lawrence Livermore National Laboratory

Demonstrating a technique that may lead to advances in certain forms of radiation therapy and electronics manufacturing, Livermore's Petawatt, the world's most powerful laser, impinges upon a target to generate 30 trillion protons from a tiny spot only 400 microns in size. Two other research groups, in Michigan and the United Kingdom, have demonstrated this technique with smaller-scale lasers.

Presentation Outline

1. Ultrafast lasers and charged particle acceleration
2. Underlying physics
3. Progress in Ultrafast laser research
4. Recent experimental results
5. The LAPPS propulsion concept
6. Phase II objectives
7. Accomplishments thus far
8. Nuclear Reactors for LAPPS
9. Conclusions and Future Investigations

- 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

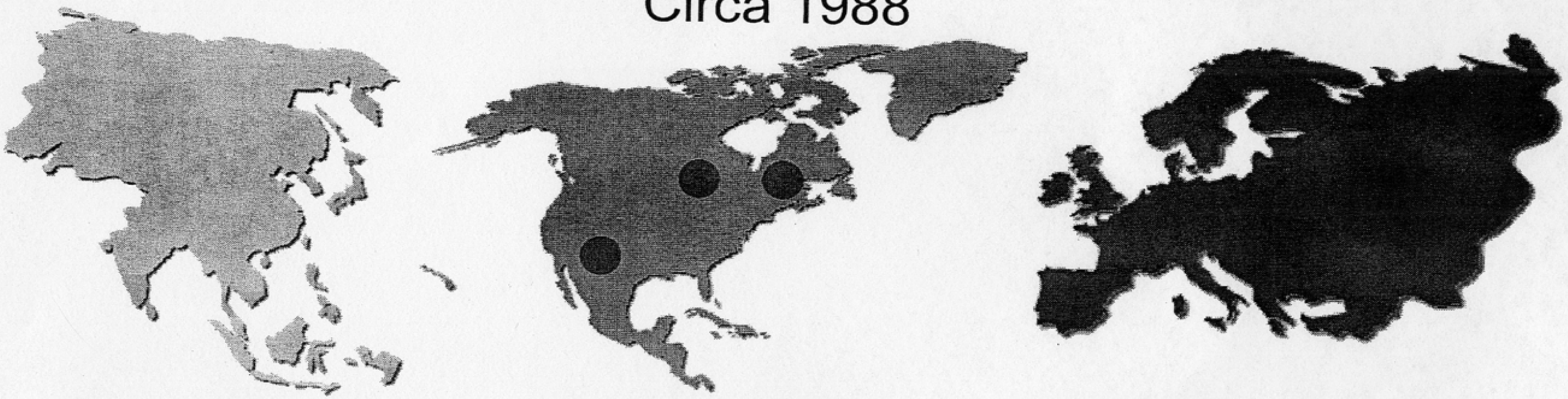
  $$v=0.866c$$

  Which would translate to

  $$Isp=10^7\ s$$

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

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

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

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

$$\rightarrow$$

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

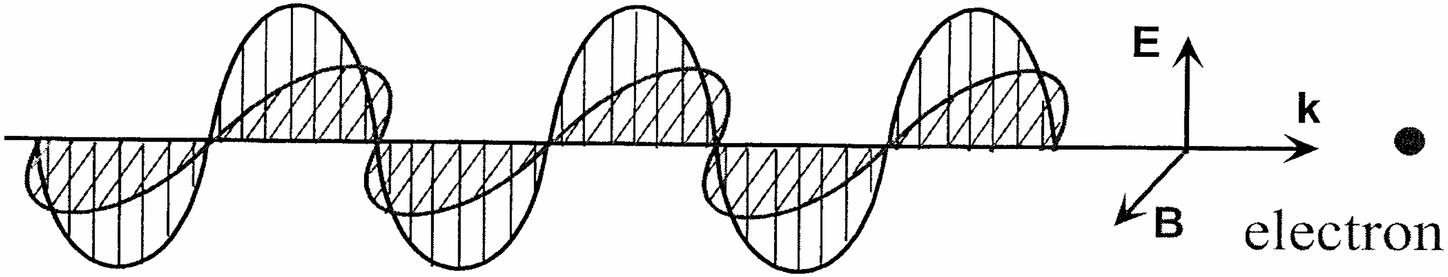
$$\frac{1\text{ terawatt}}{(10\text{ micron})^2} = 10^{18}\text{ watt/cm}^2$$

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

$$\downarrow$$

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

Relativistic Electron Motion



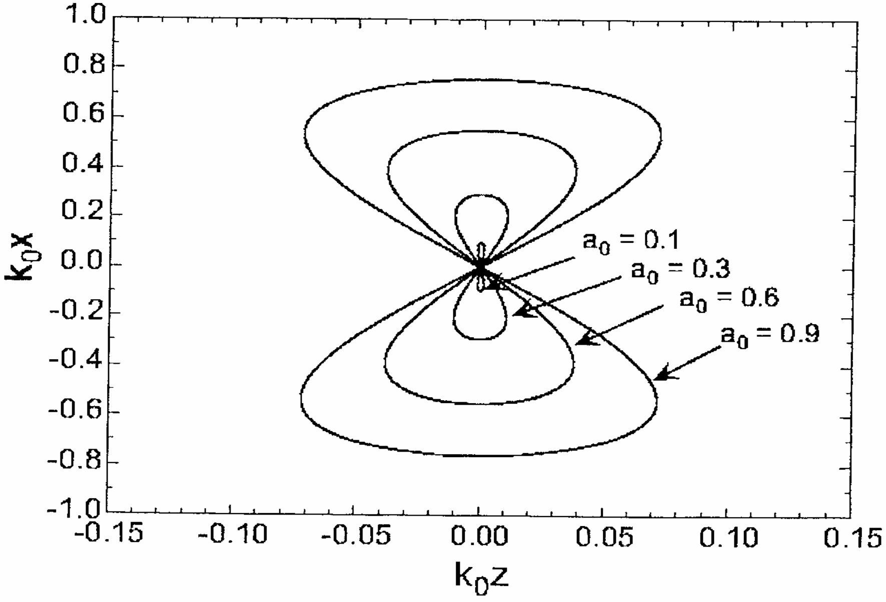
$$\mathbf{k}=k\hat{\mathbf{z}}, \quad \mathbf{E}=E_0\cos(kx-\omega t)\hat{\mathbf{x}}, \quad \mathbf{B}=B_0\cos(kx-\omega t)\hat{\mathbf{y}}$$

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

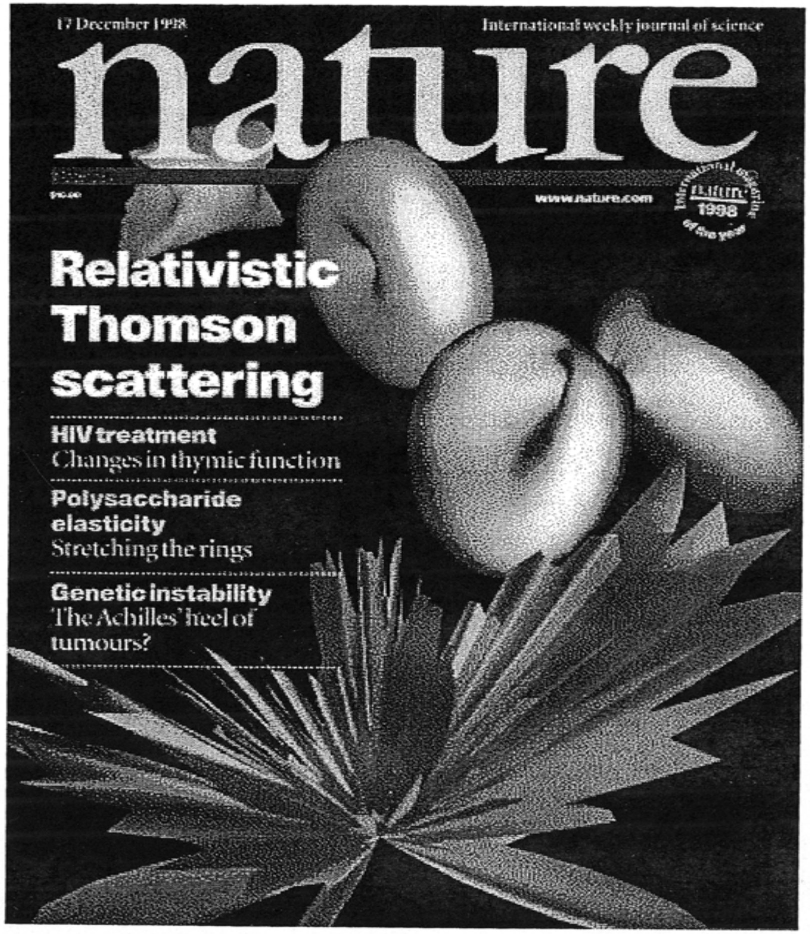
$$\gamma_\perp \equiv \left(1-(v_\perp/c)^2\right)^{-1/2}=\left(1+a_0^2/2\right)^{1/2}$$

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

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



Experimental Confirmation



17 December 1998

International weekly journal of science

nature

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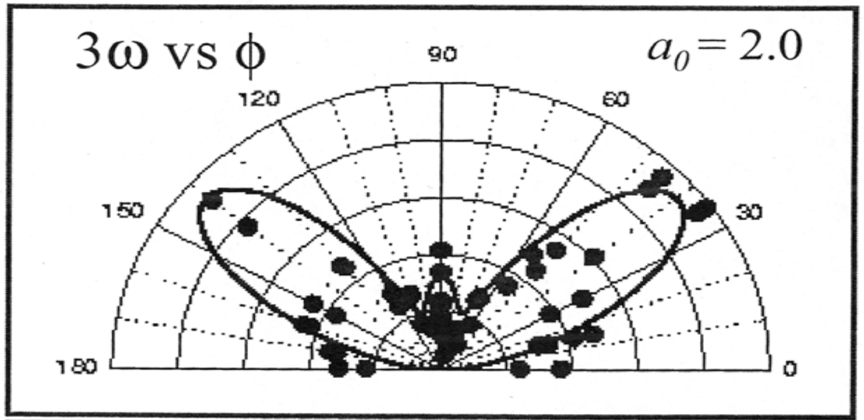
Relativistic Thomson scattering

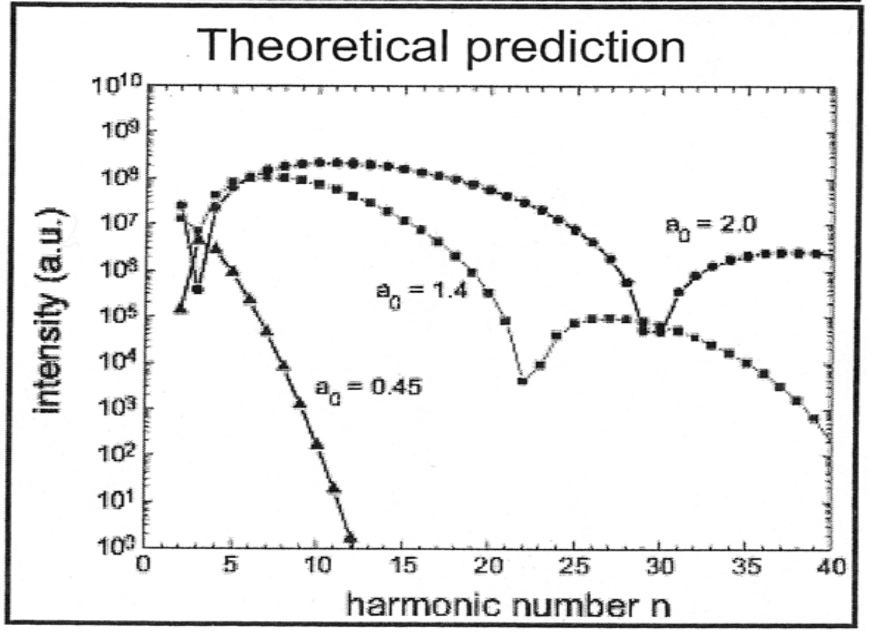
HIV treatment
Changes in thymic function

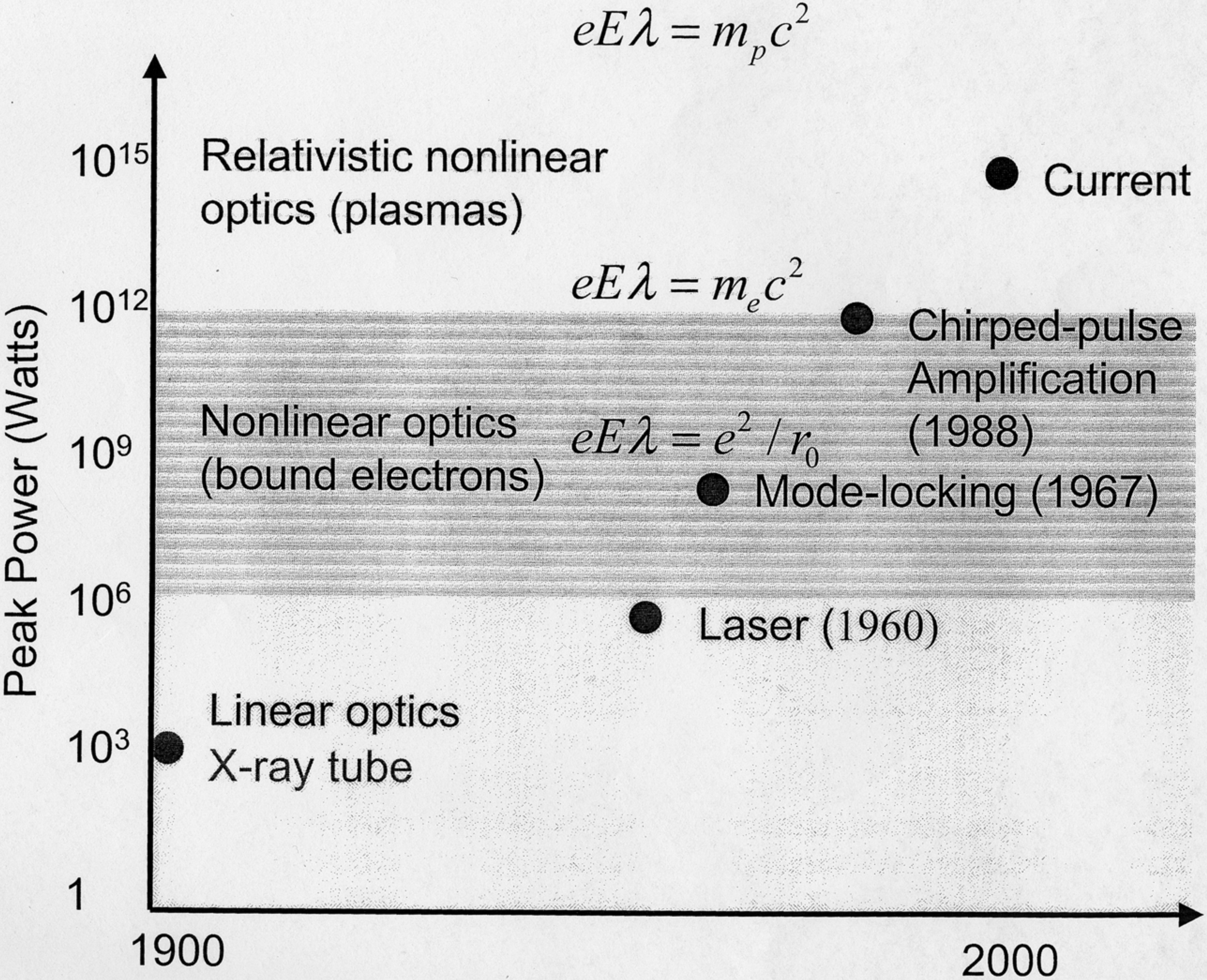
Polysaccharide elasticity
Stretching the rings

Genetic instability
The Achilles' heel of tumours?

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

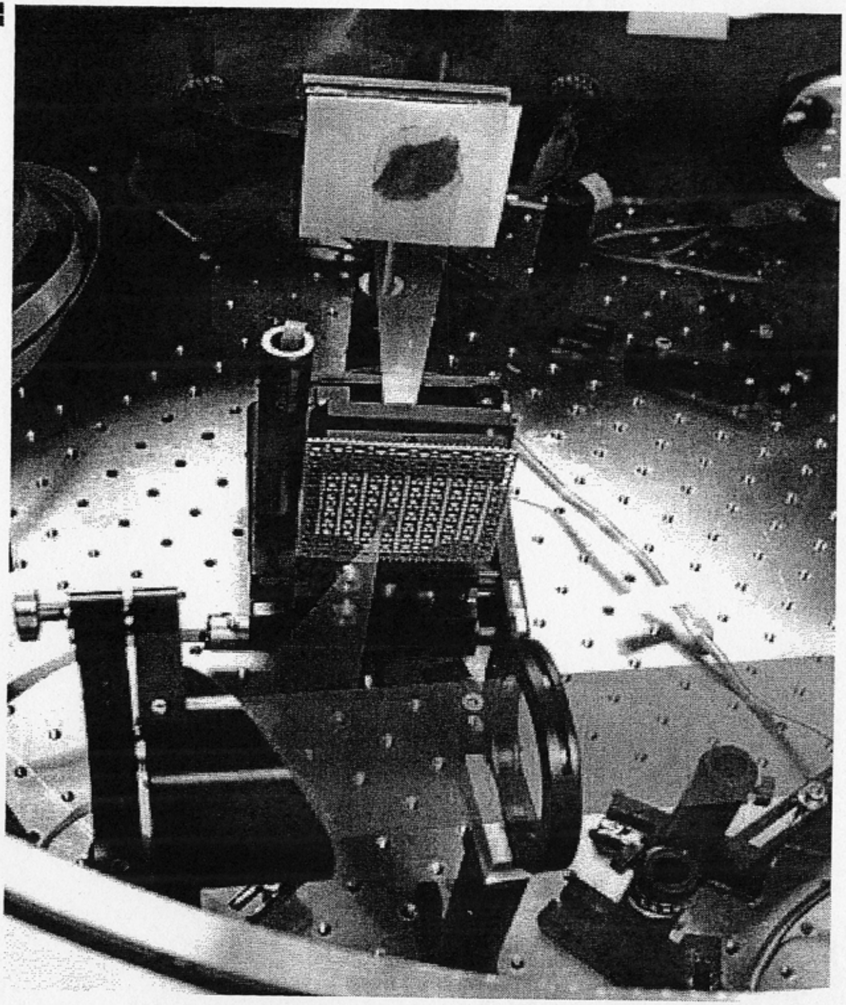



Theoretical prediction



$eE\lambda = m_p c^2$
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

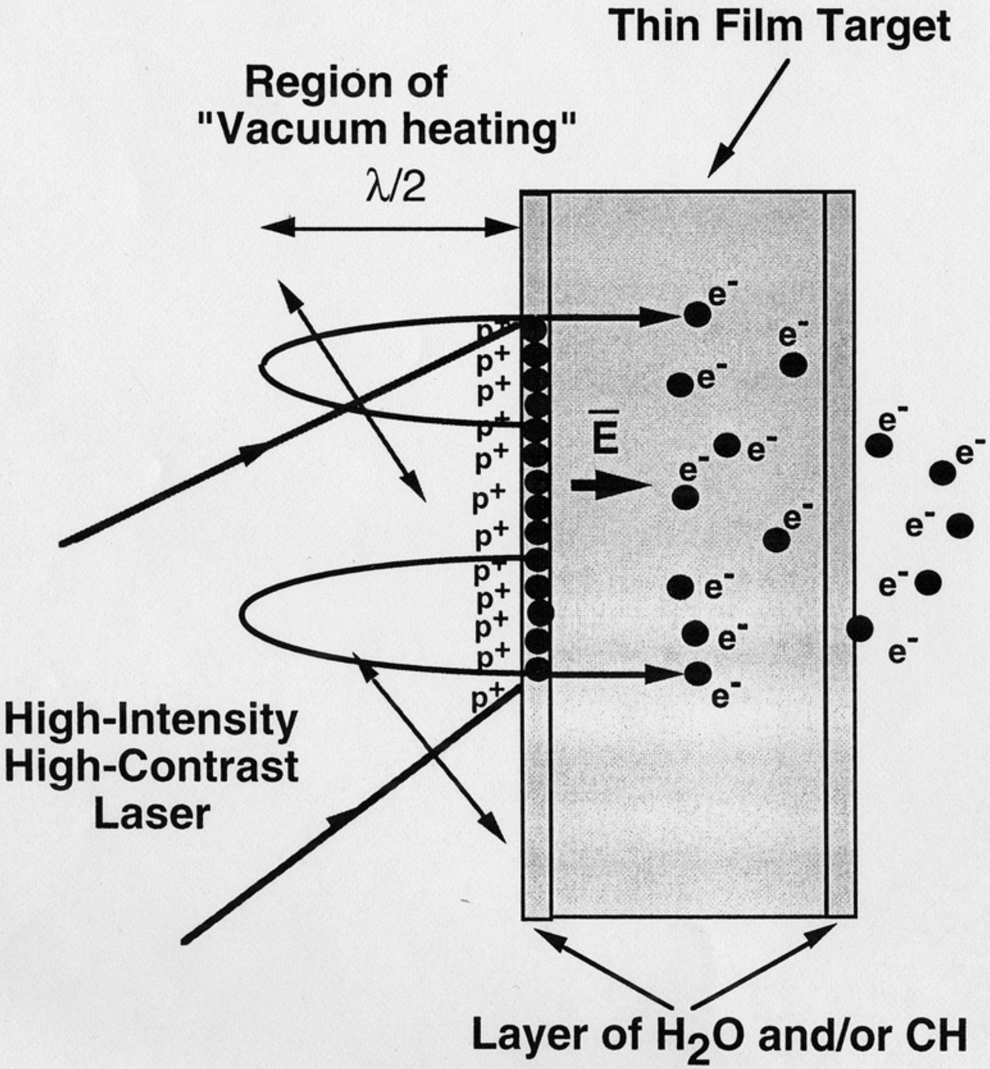
A Beam of MeV Protons



- $a_0 = 3.0$
- 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

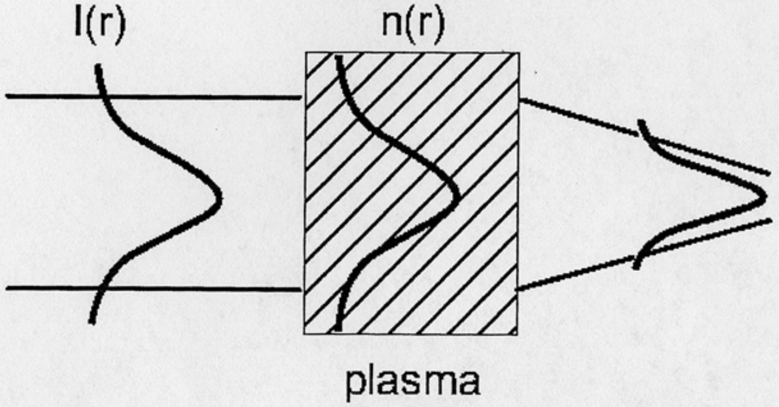
Plasma frequency: $\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_0}}$

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

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

Relativistic self-focusing:

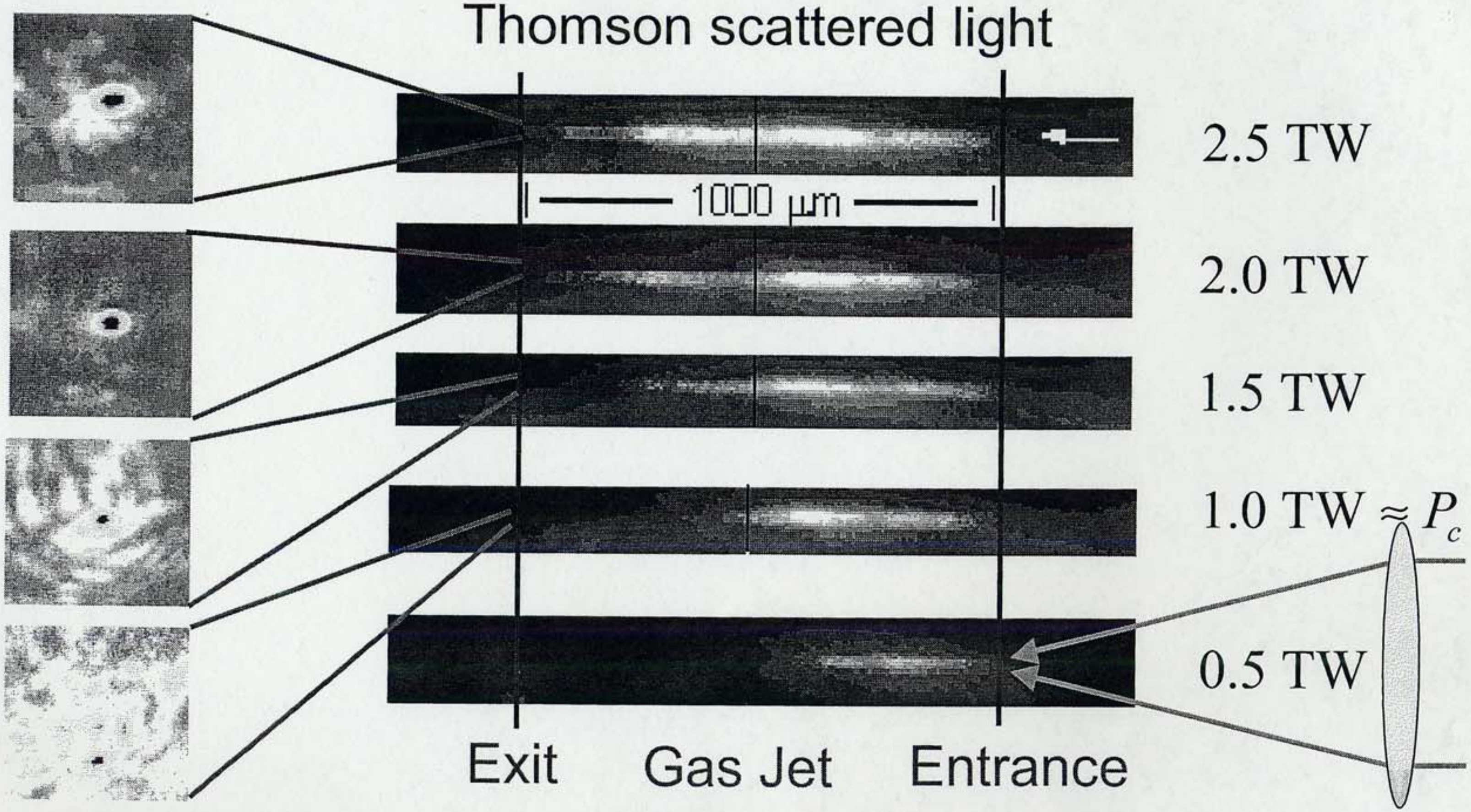
$P_c = 17\left(\omega_0^2 / \omega_p^2\right)$ GW



Experimental Evidence of Relativistic Self-Guiding

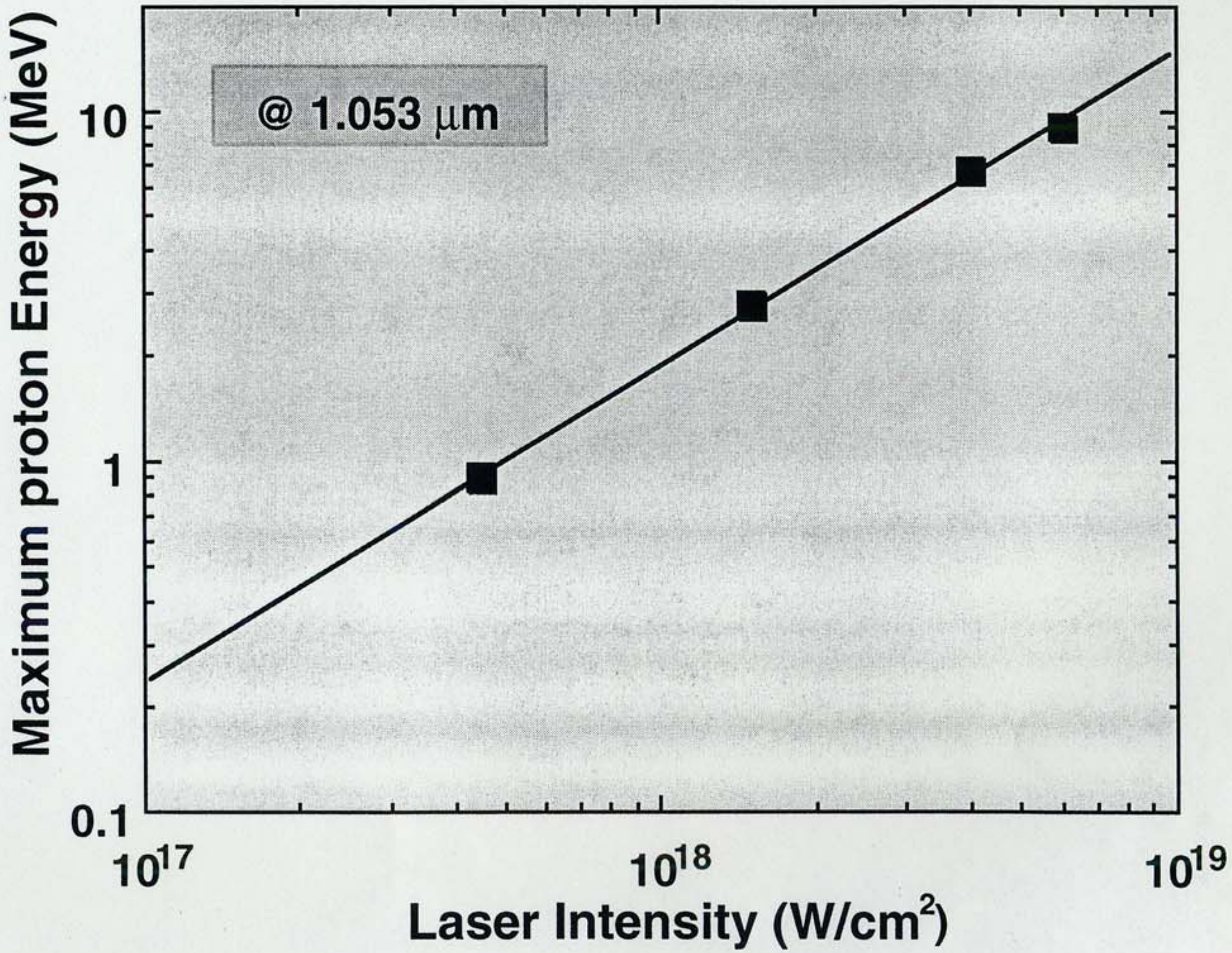
Axial-imaging

Side-imaging of Thomson scattered light

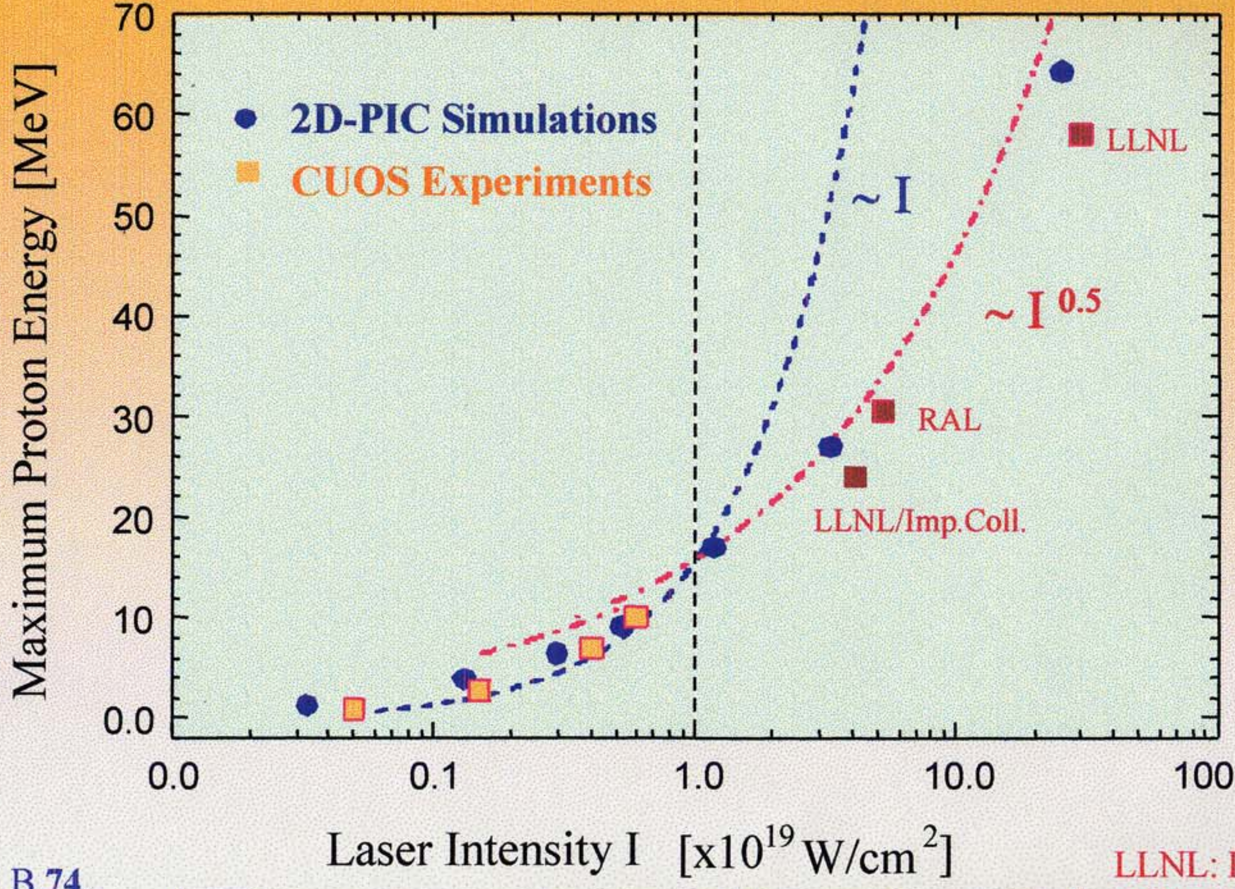


S.-Y. Chen *et al.*, Phys. Rev. Lett., **80**, 2610 (1998).

Maximum Proton Energy Scales Linearly with Laser Intensity



Scaling of maximum proton energy vs. laser intensity

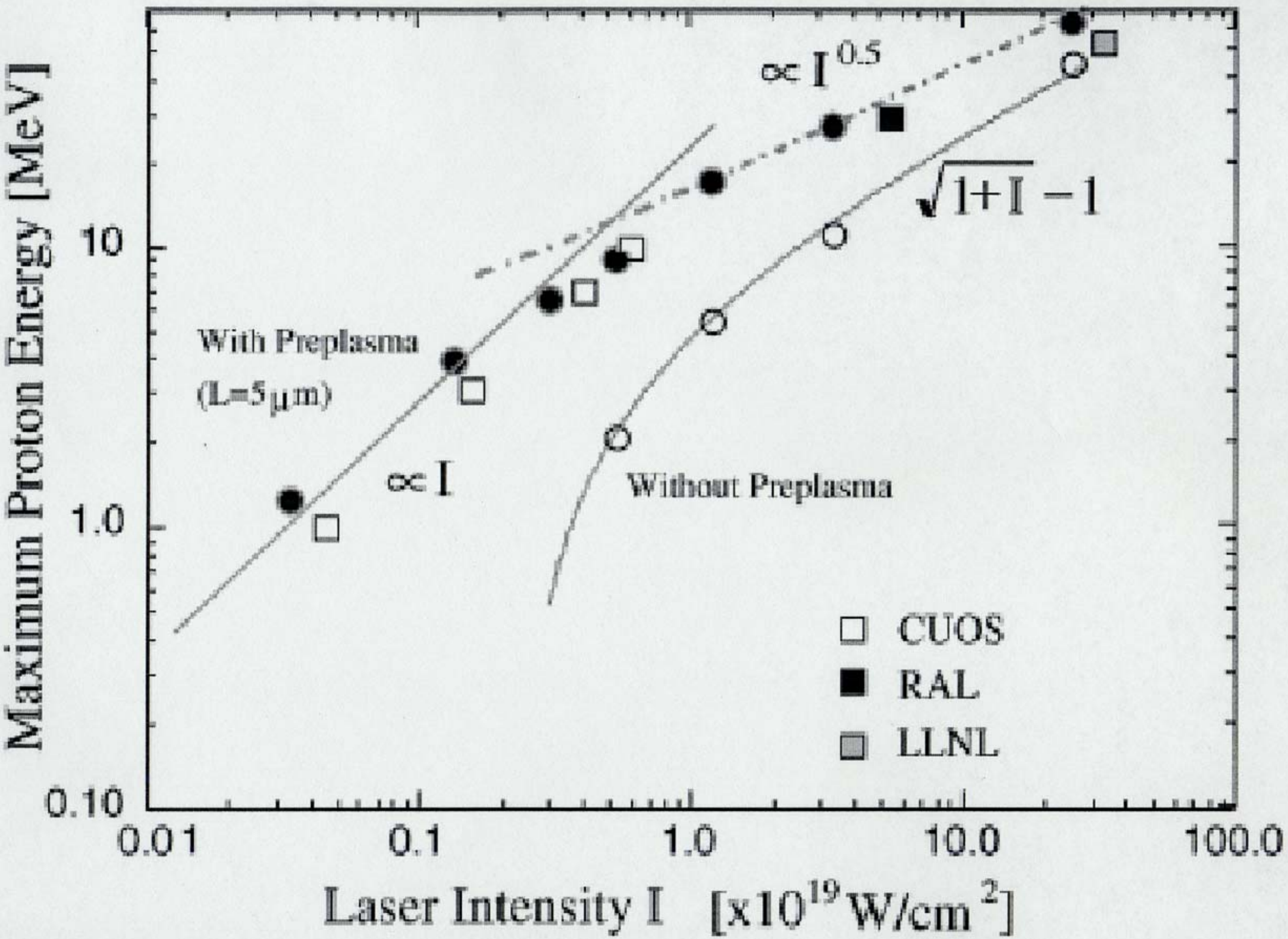


2D-PIC: Appl. Phys. B **74**, 207 (2002)

CUOS: PRL **84**, 4108 (2000); Appl. Phys. Lett. **78**, 595 (2001)

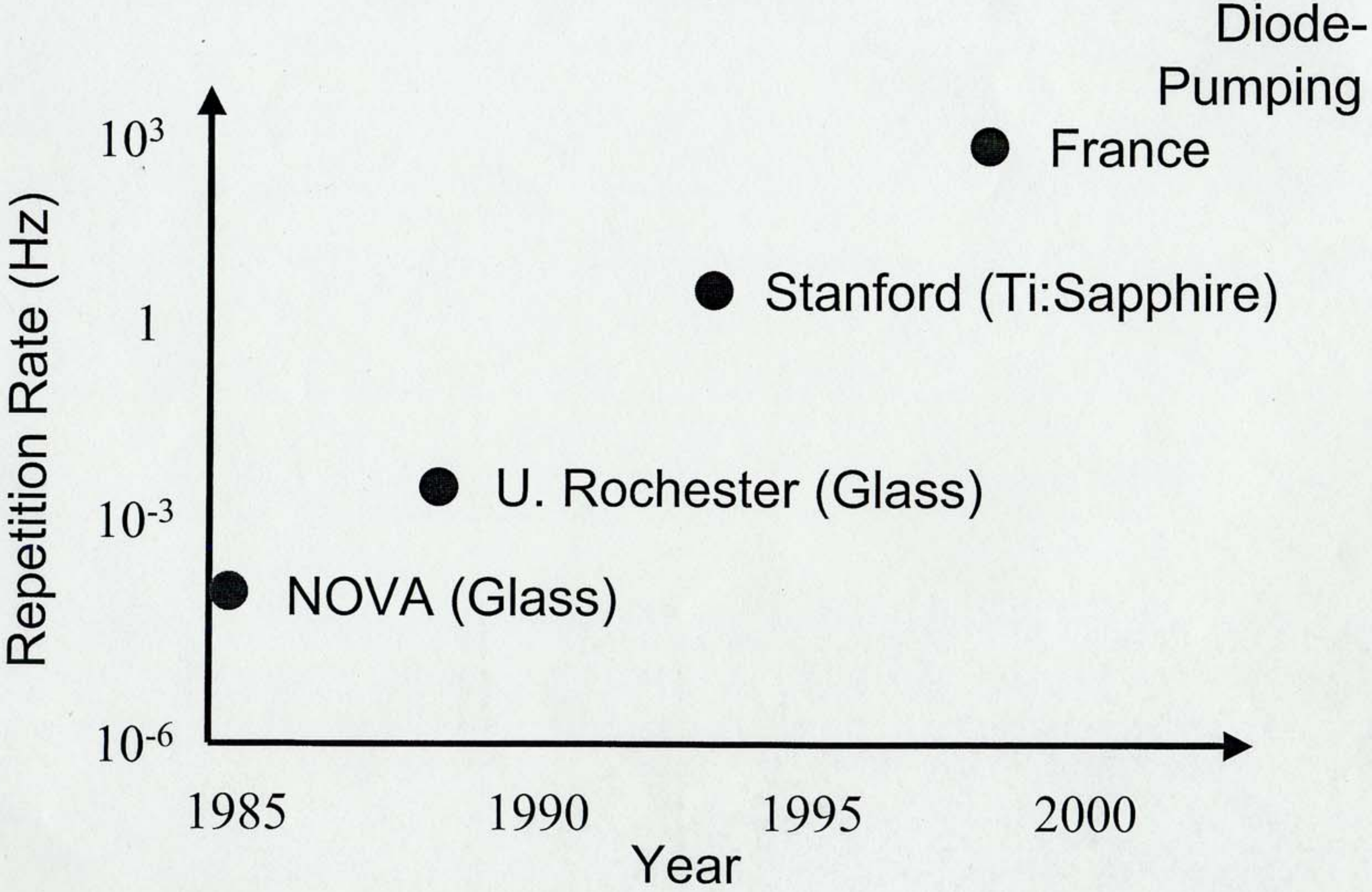
When the laser intensity is higher than 10^{19} W/cm^2 the maximum proton energy grows as $I^{0.5}$.

LLNL: PRL **85**, 2945 (2000)
RAL : PRL **84**, 670 (2000)
LLNL/Imp.Coll.:
PRL **86**, 1769 (2001)



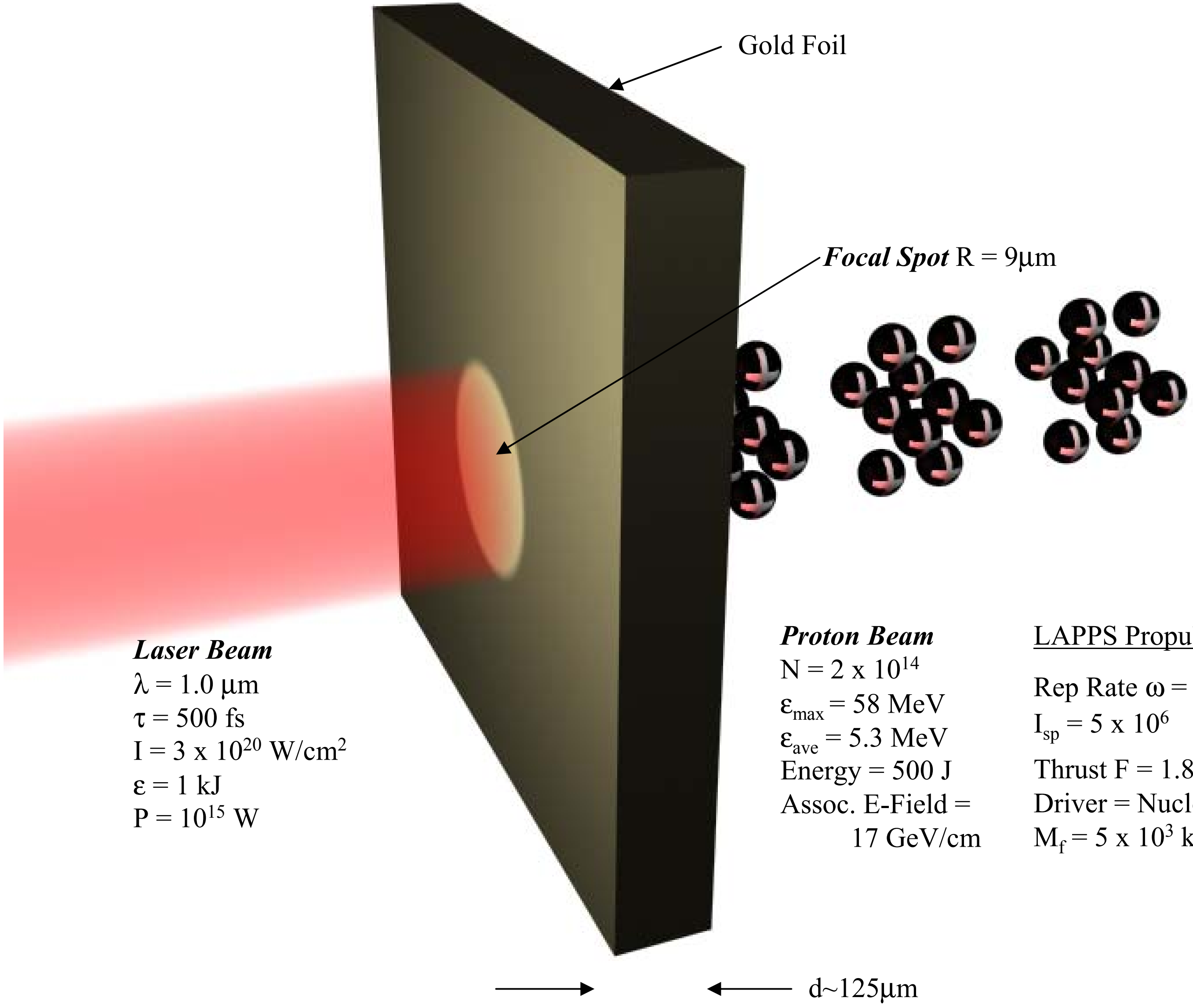
The intensity dependence of the maximum energy of protons (*black dots*) in comparison with the experimental data (*squares*): CUOS – [5], RAL – [13], and LLNL – [3], and simulations without preplasma (*open circles*)

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).

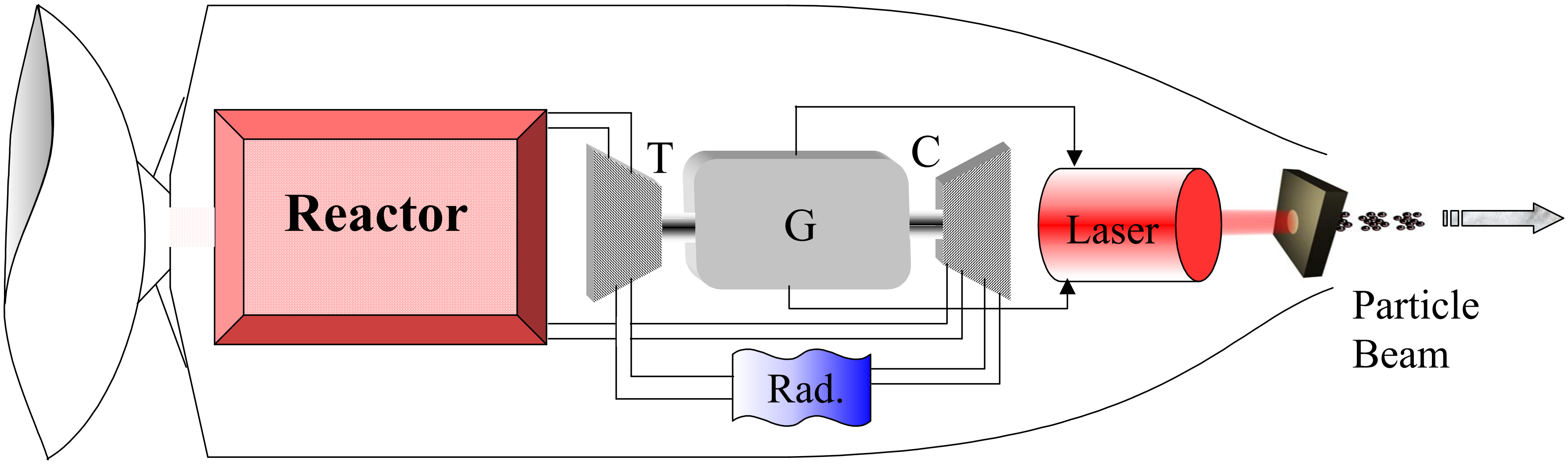


Laser Beam
$\lambda = 1.0\ \mu m$
$\tau = 500$ fs
$I = 3 \times 10^{20}$ W/cm^2
$\varepsilon = 1$ kJ
$P = 10^{15}$ W

Proton Beam
$N = 2 \times 10^{14}$
$\varepsilon_{max} = 58$ MeV
$\varepsilon_{ave} = 5.3$ MeV
Energy = 500 J
Assoc. E-Field =
17 GeV/cm

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



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$_e$

EXAMPLES OF TWO MISSION

1. Fly-By Mission

$$t_f = \frac{M_i - M_f}{F} V_e$$

t_f = travel time to destination

M_i = Initial Mass

M_f = final Mass (Dry Mass)

F = Thrust

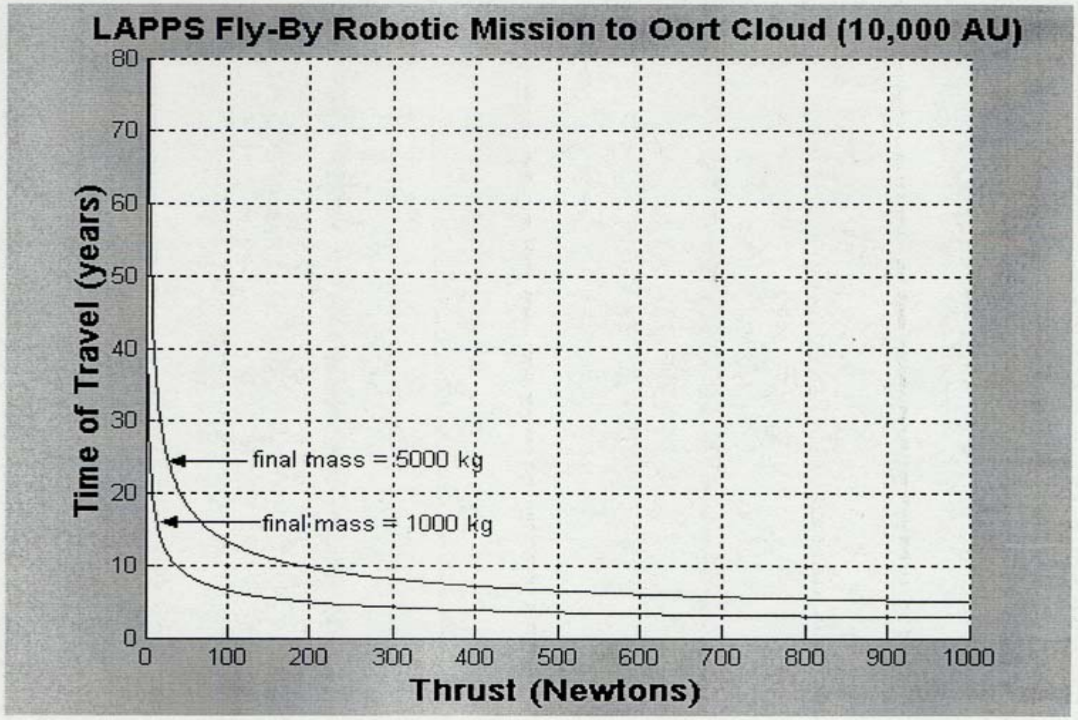
v_e = exhaust velocity

$$S_f = \frac{M_i V_e^2}{F}\left[1 - \frac{M_f}{M_i} + \frac{M_f}{M_i} \ln\left(\frac{M_f}{M_i}\right)\right]$$

S_f = distance to destination

$$V_f = V_e \ln\left[\frac{1}{1 - \frac{F t_f}{M_i V_e}}\right]$$

V_f = final velocity at destination
Assuming starting from rest



Final Mass = 5000 kg:

Thrust (Newtons)	Travel Time (years)
0.031	698.4
25	25.6
100	13.3
500	6.5
1000	4.9

Final Mass = 1000 kg:

Thrust (Newtons)	Travel Time (years)
0.031	312.97
25	12
100	5.5
500	3.4
1000	2.8

2. Constant Thrust, Continuous Burn Acceleration/Deceleration Type of Trajectory

$$\tau_{RT} = \frac{4D}{g I_{sp}} + 4\sqrt{\frac{D M_f}{F}}$$

τ_{RT} = Round Trip time

D = linear distance to destination

g = Earth's gravitational Acceleration

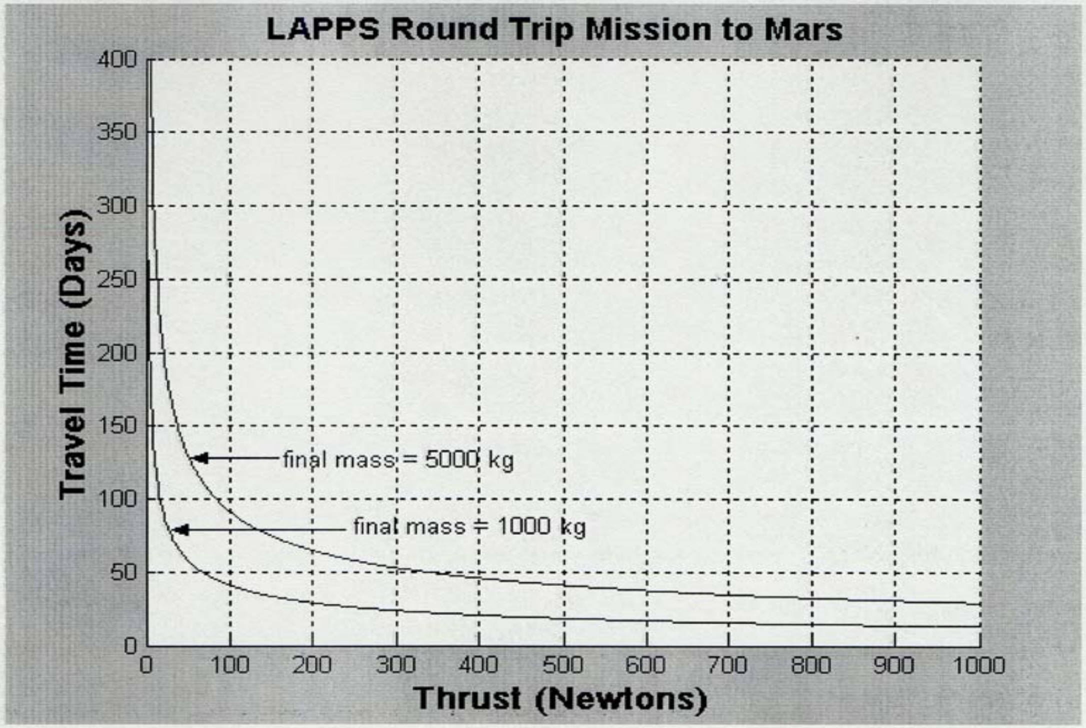
I_{sp} = Specific Impulse

M_f = Dry Mass

F = Thrust

Note the additive effects of the two terms on the right-hand side of Equation

For Optimum τ_{RT}, the two terms must be somewhat comparable!



Final Mass = 5000 kg:

Thrust (Newtons)	Travel Time (Days)
0.031	5193
25	186
100	91.5
500	41
1000	29

Final Mass = 1000 kg:

Thrust (Newtons)	Travel Time (Days)
0.031	2322.5
25	82
100	41
500	18.5
1000	13

Objectives of Phase II

i) Experimentally validate the formula

$$E_i \approx Z_i \sqrt{\eta \, I \, R \, \lambda}$$

ii) Thrust Enhancement Approaches

$F = W N M V$
F = Thrust
W = Rep Rate
N = Number of ions in proton Beam
M = mass of proton
V = velocity of proton

Focus on $N = \Pi R^2 t$
Specificially on $N \sim R^2$
Experimentally Investigate variation of "N" with "R"

iii) Enhance Rep Rate "w" on target side to match that on Laser side
   a. solid target – film spool
   b. liquid jet target – approach steady state

iv) Address issues related to laser-plasma interactions e.g. relativistic focusing and Filamentation Instability

v) Conceptual design of Nuclear reactor for use in LAPPS

Accomplishments Thus Far

i) Experimentally verified $E_i \sim \sqrt{I}$ at high Intensities as would be the case in a propulsion system.

ii) Experimentally verified $E_i \sim \sqrt{\lambda}$, optimum target thickness $t \approx 10\lambda$.

iii) Experimentally established condition for filamentation Instability.

$$P = 5\ P_c = 5\left[17\left(\frac{\omega_o}{\omega_p}\right)^2 \mathrm{G\ W}\right]$$

$$\frac{4\Pi c}{\omega_p a_o} \leq 2 r_o$$

c = speed of light

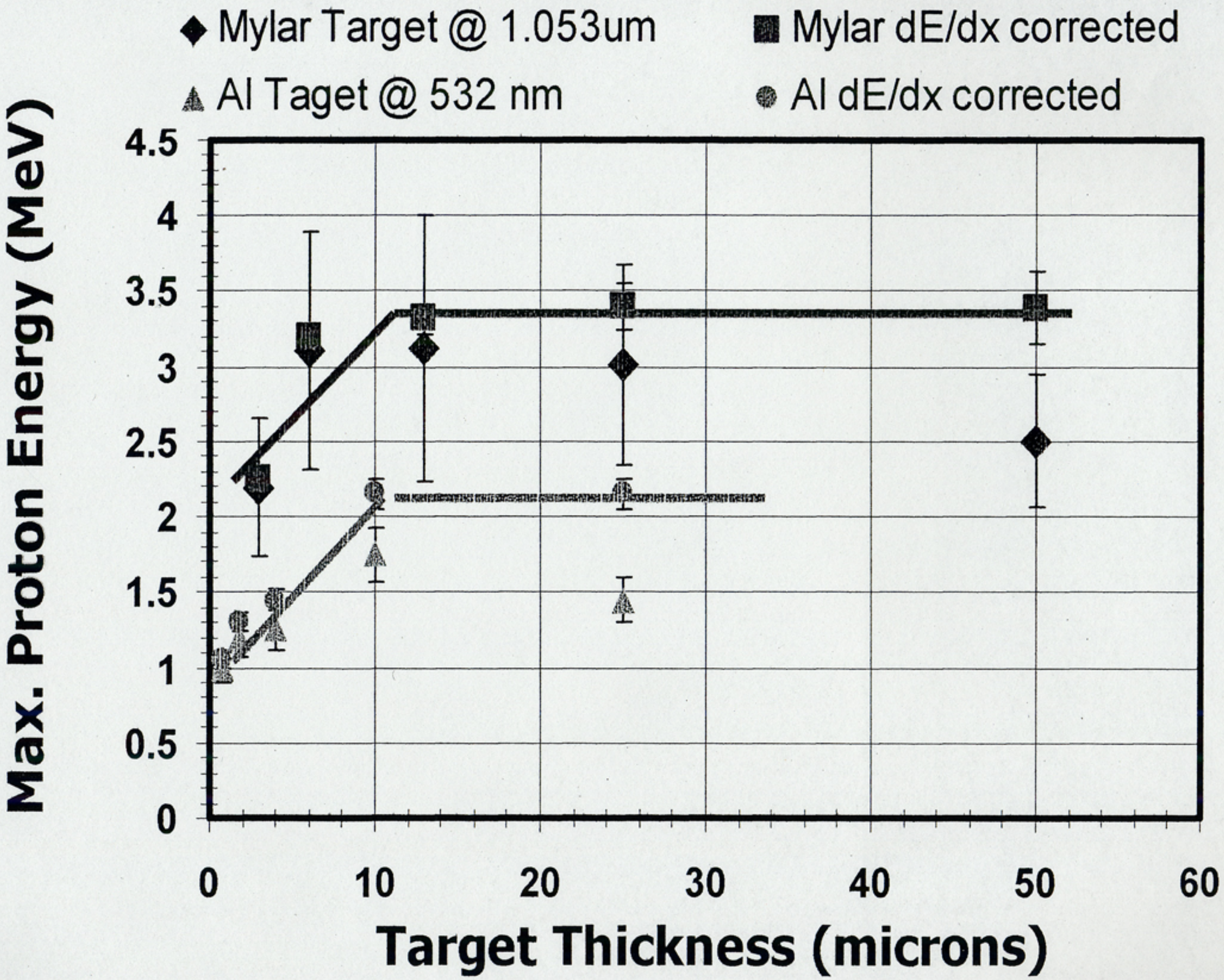
a_o = $8.5 \times 10^{-10}\ \lambda\ [\mu\ \mathrm{m}]\ I^{1/2}\ [\mathrm{W/cm^2}]$

ω_p = plasma frequency

r_o = radius of focal spot

iv) Preliminary Conceptual design of space Nuclear Reactor for use in LAPPS. Likely fuel is cermet fuel with Am (242m) as fissile material due to its large thermal neutron cross section.

Proton Energy vs. Target Thickness



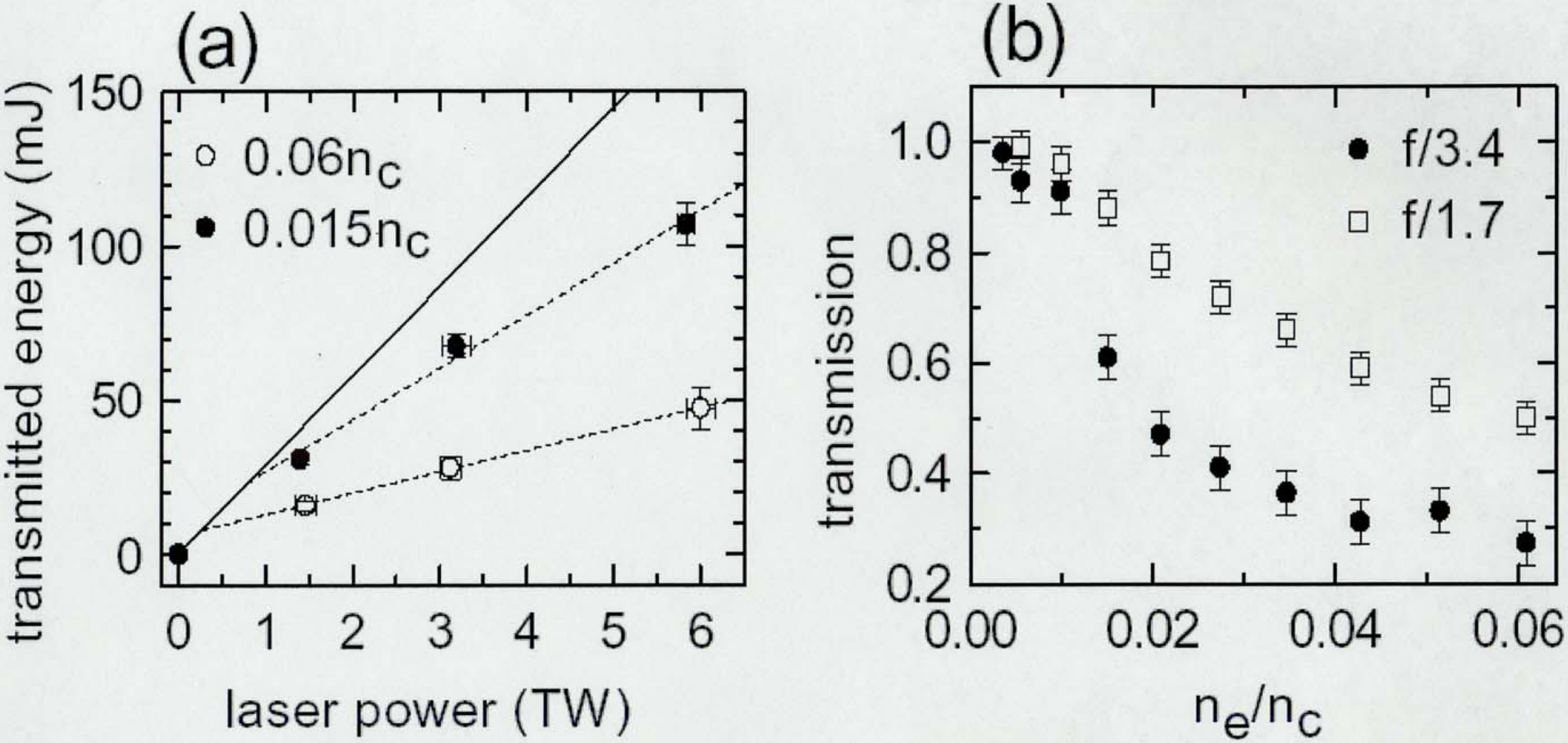
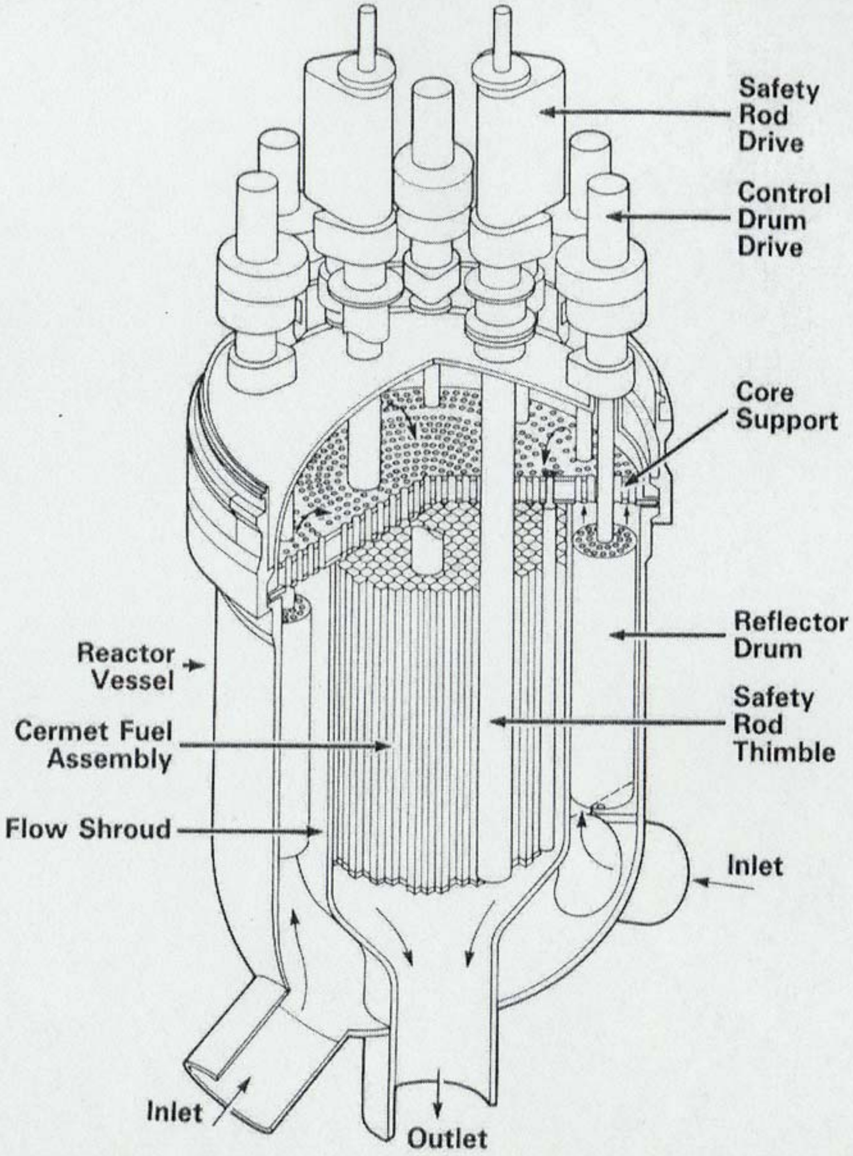
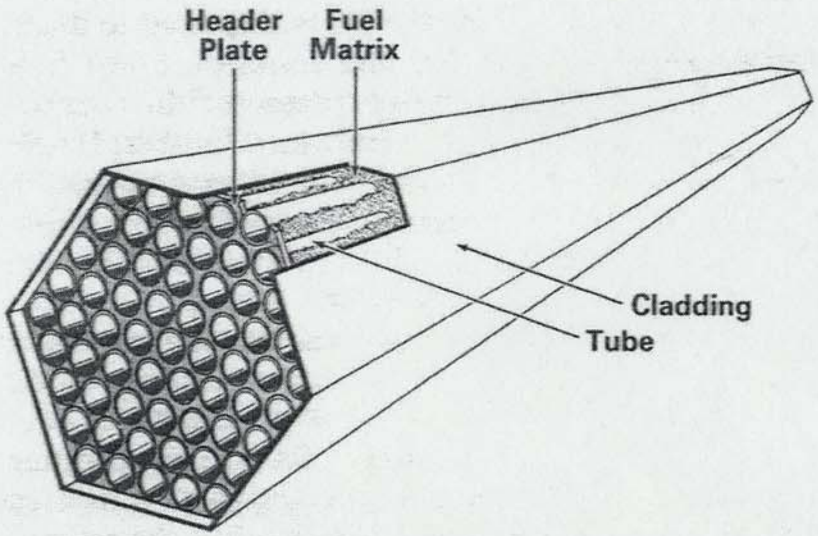


FIG. 1. (a) Energy transmission as a function of incident laser power. The solid line corresponds to 100% transmission. (b) Energy transmission as a function of plasma density for an incident laser power of 6 TW.



REPRESENTATIVE CERMET GAS COOLED CORE (OPEN OR CLOSED CYCLE)



TYPICAL CERMET FUEL ELEMENT SHOWING THE WRAPPER, COOLANT FLOW TUBES, & CERMET MATRIX MADE OF REFRACTORY METAL & FISSILE BEARING CERAMIC.

CERMET REACTOR SYSTEM FEATURES

o--HELIUM-COOLED CLOSED CYCLE REFRACTORY CERMET FUELED SYSTEM

o--BRAYTON CYCLE KNOWN TO PROVIDE 40% OR BETTER THERMAL EFFICIENCIES

o—HELIUM IS A PROVEN WORKING FLUID WITH EXCELLENT HEAT TRANSFER AND MATERIAL (INERT) CHARACTERISTICS

o--CERMET SYSTEMS PROVIDE EXCELLENT SAFETY AND PERFORMANCE FEATURES

o—LARGE MARGIN OF SAFETY DEMONSTRATED FOR LAUNCH, REENTRY, AND TRANSIENT CONDITIONS

o--RUGGED SYSTEM

o--ALLOW EXTREME OPRERATING TEMPERATURES (Hence great efficiencies)

o--EXCELLENT FISSION PRODUCT RETENTION

o--PROMISE OF MANY (10's) YEARS OF OPERATION AT TENS OF MEGAWATTS & AT OVER 70% AVAILABILITY.

ACTIVE CORE MATERIALS COMBINATIONS, ACHIEVABLE TEMERATURES, & SAFETY CONDITIONS FOR CERMET SYSTEMS

Matrix / Clad	Fuel candidates Compatable to Matrix	Performance Characteristics	Peak Coolant Temperature	Basic Features
$W/W-\mathrm{Re}$	UO_2 or $Pu\ O_2$ or $Am^{242m}O_2$	High Temperature compatabilty to 2500K	2250K	Subcritical when immersed in water Or burried. BeO radial reflectors recommended
$Mo/Mo-\mathrm{Re}$	UO_2 or $Pu\ O_2$ or $Am^{242m}O_2$	High Temperature compatabilty to 2250K	2000K	Subcritical when immersed in water Or burried. Be radial reflecors recommended.
$Mo/Mo-\mathrm{Re}$	UN	High Temperature compatabilty to 1900K	1650K	Subcritical when immersed in water Or burried. Be radial reflectors recommended.

REPRESENTATIVE DIMENSIONS AND MASSES OF POTENTIAL CREMET REACTOR SUB-SYSTEMS

ACTIVE CORE MATERIALS	FUEL CERAMIC At (85-92) %td	ACTIVE CORE	REFLECTOR (Be or BeO) shell at 80%td	VESSEL H and D	OVERALL MASS (EST)
Mo or W based	UO_2 (97% enriched)	H=D =(39-40) cm	(10-12) cm	H=75 cm D=60-65 cm	1800 Kg for W and 1600 Kg for Mo
Mo or W based	PuO_2 (95% Pu-239)	H=D =(29-30) cm	(10-12) cm	H=65 cm D=50-55 cm	850 Kg for W and 730 Kg for Mo
Mo or W based	$Am^{242m}O_2$	H=D =(19-20) cm	(10 –12) cm	H=40-45cm D=40-45 cm	410 Kg for W and 320 Kg for Mo

Conclusions and Future Investigations

1. Ultrafast Lasers have been used effectively to accelerate charged particles to relativistic speeds.

2. Experiments at University of Michigan and elsewhere have produced proton beams continuing more than 10^{14} particles at mean energies of several MeV.

3. Laser powers will be reached soon that will accelerate protons to rest mass energies. That translates to a specific impulse, I_{sp}, of about 26 million seconds.

4. A LAPPS (Laser Accelerated Plasma Propulsion System) device based on present day experimental data will produce an $I_{sp} \approx 3x10^6$ seconds albeit at a thrust, F, of $3x10^{-2}$ Newtons. It will require a one MWe nuclear power system to drive it at an approximate mass of 5 mT.

5. If thrust can be enhanced to just 25 Newtons such LAPPS will make a fly-by robotic interstellar mission to 10,000 AU in about 26 years and a round trip to Mars in about 6 months.

6. Increase in thrust can be achieved using larger focal spots. Increase in Laser power will allow this if intensity (and correspondingly proton energy and specific impulse) is to be maintained.

7. For some missions large I_{sp} may not be required if sizable thrust can be produced. Hence, larger focal spots at lower laser power (hence lower in intensity) may be more desirable.

8. Large Rep Rates (~ 1 KH_z) may be necessary. Achieving such rates at the target side may require liquid jet targets or fast moving solid targets.

9. A Nuclear Fission Reactor will be needed to drive a LAPPS propulsion system. A reactor using cermet fuel containing Am (242m) with a half life of 141 years is being considered due to its relatively small size, small mass and safety features.

10. Future investigations will address thrust enhancement approaches, fast moving targets, and nuclear reactor and power conversion systems for use in LAPPS.