Solar Energy from Space
Power Beaming and Self-focusing in Atmosphere

Presentation to

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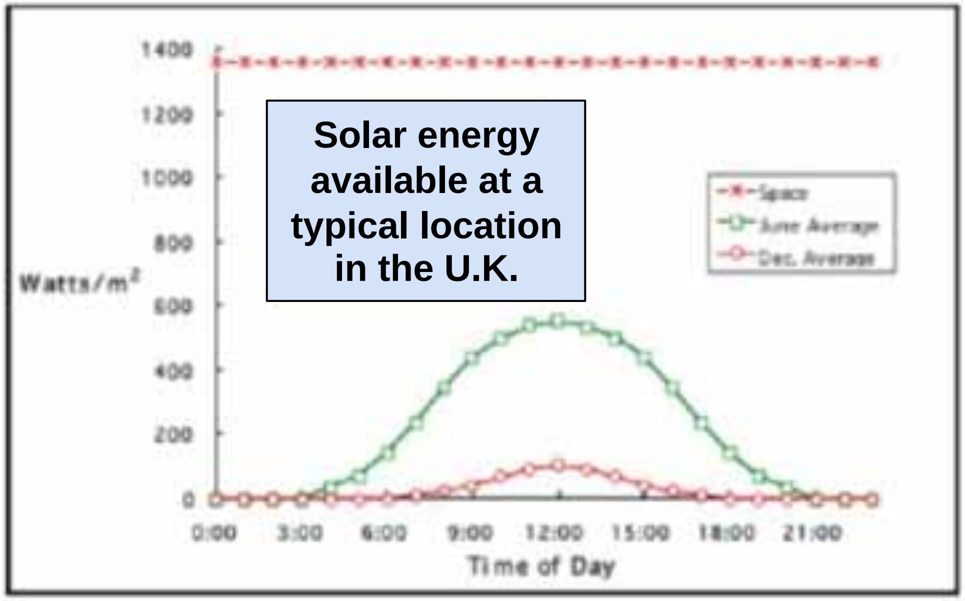
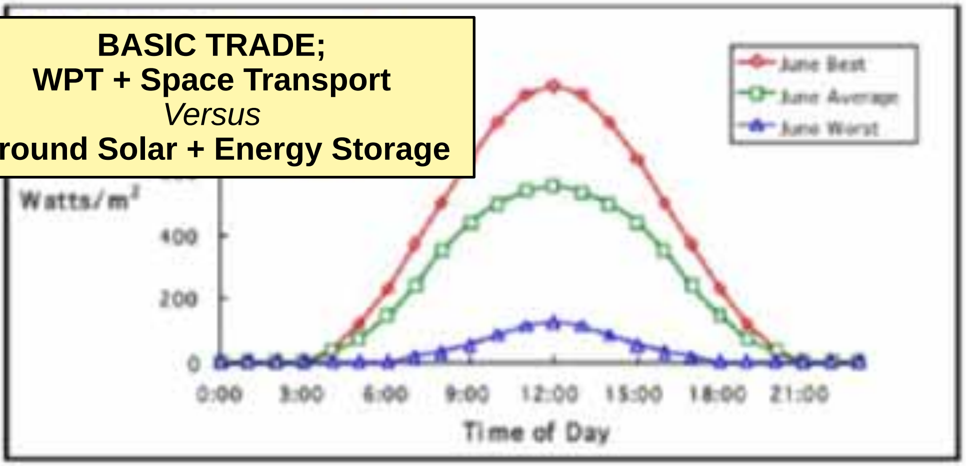
Another false dichotomy:
Terrestrial versus space solar power?

- There must be terrestrial solar
- For baseload power, however, the challenges facing ground solar power are in many ways harder than those for space-based systems
- The total solar energy available at a typical site on the Earth’s surface is much less than in space
- Moreover, the energy available varies widely — seasonally and daily
- “Baseload” using ground solar requires substantial over-capacity and costly large-scale energy storage or global distribution networks…



Solar energy available at a typical location in the U.K.

BASIC TRADE;
WPT + Space Transport
Versus
Ground Solar + Energy Storage



What is space-based solar power?

- Peter Glaser, a VP at Arthur D. Little, invented the “Solar Power Satellite” circa 1968 — with the original patent issued in 1973
- In an SPS, Sunlight is captured in space where a solar array is up to 24-times more cost-effective in providing continuous power, compared to a solar array on the Earth
- The Solar Energy is converted to a coherent beam and transmitted to a receiver on Earth where it is converted into either electric power or synthetic fuels
- SSP has been studied by DOE, NASA, ESA, and JAXA, but has generally “fallen through the cracks” because no organization is responsible for both Space Programs and Energy Security

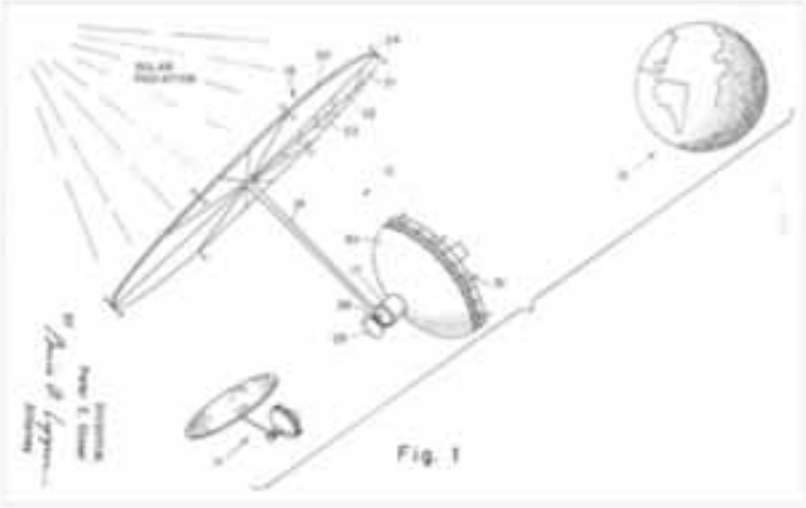
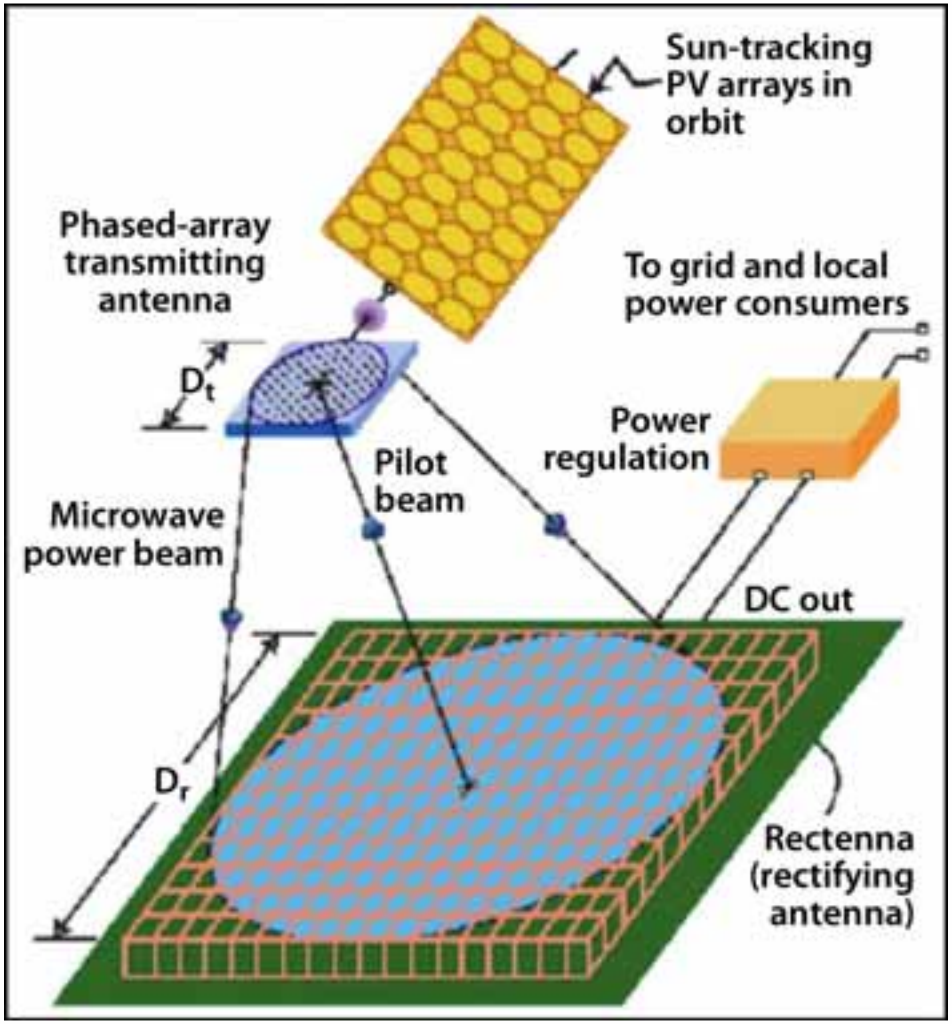


Fig. 1

Solar electricity from orbit — Useful properties of space and enabling technologies

- Mean solar flux in orbit outside Earth’s shadow cone is ~8 times higher than long-term mean solar radiation at surface
- Earth’s atmosphere is relatively transparent to microwave and optical wavelengths, permitting relatively efficient line-of-sight wireless power transmission (WPT) with ~100% duty cycle from GEO for electrical baseload
- “Zero g” permits low mass inflatable-rigidizable structures
- Enabling technologies are low-mass and laser power beamers, thin-film PV & low-cost access-to-orbit launch vehicles and (long-term) space elevator. But SSP can proceed now with existing technologies.

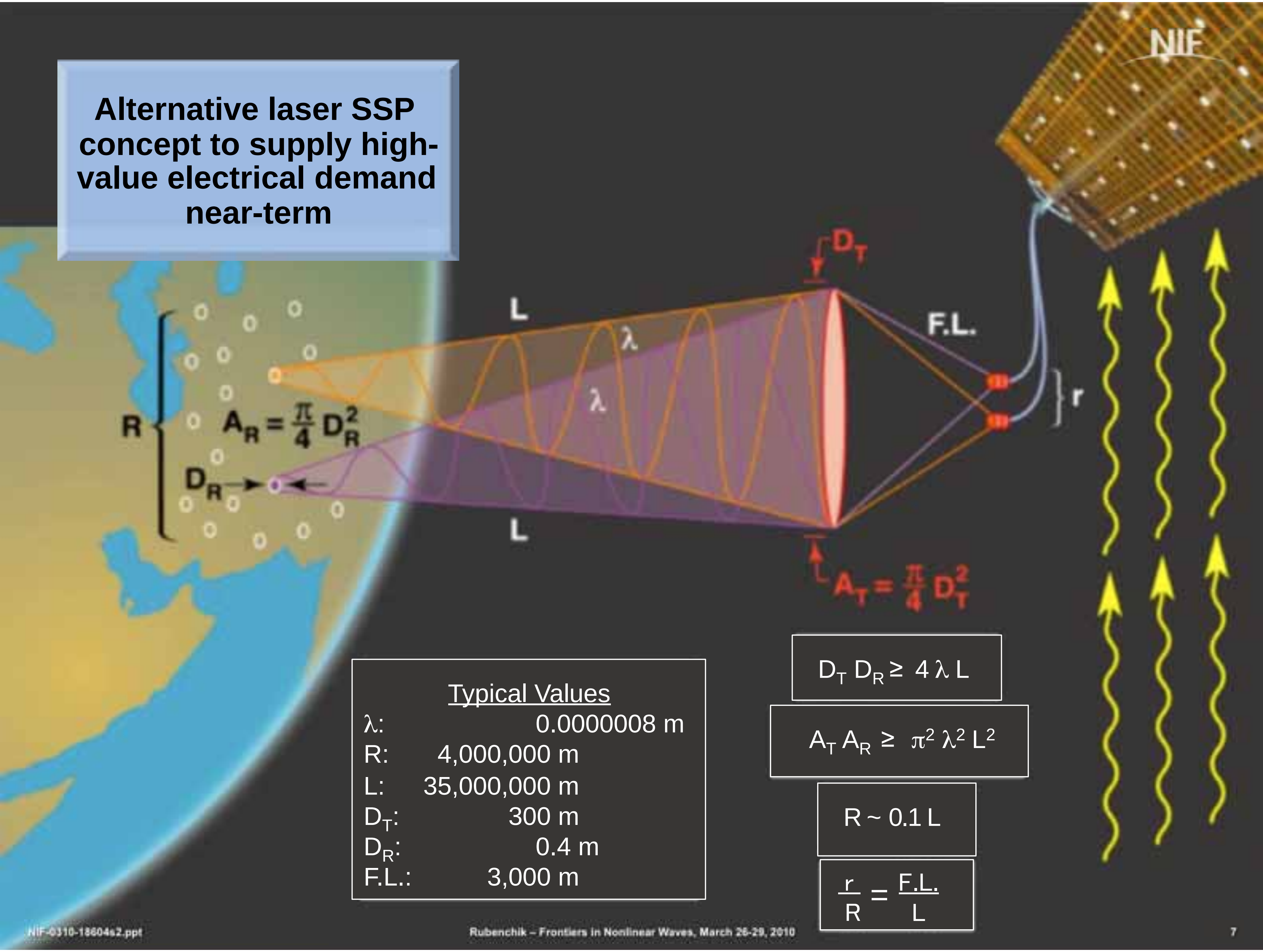


Transmission of solar energy from space to the earth's surface is a significant challenge

- First proposals used microwave transmission
  - Advantage: high efficiency conversion of electricity to microwaves in space and on the earth's surface
  - Advantage: microwaves have good transmission characteristics through the earth's atmosphere, even during periods of heavy cloud cover
  - Challenge: microwave receiver on earth must have a huge collection area
  - Challenge: the focusing system used to direct the microwaves from space to earth must be extremely accurate

- Using a laser for transmitting the energy from space to earth reduces the required size of the receiver on earth by more than a thousand times and relaxes the focusing requirements of the transmission system

Alternative laser SSP concept to supply high-value electrical demand near-term



Typical Values

λ:	0.0000008 m
R:	4,000,000 m
L:	35,000,000 m
D_T:	300 m
D_R:	0.4 m
F.L.:	3,000 m

$$D_T D_R \geq 4 \lambda L$$

$$A_T A_R \geq \pi^2 \lambda^2 L^2$$

$$R \sim 0.1 L$$

$$\frac{r}{R} = \frac{F.L.}{L}$$

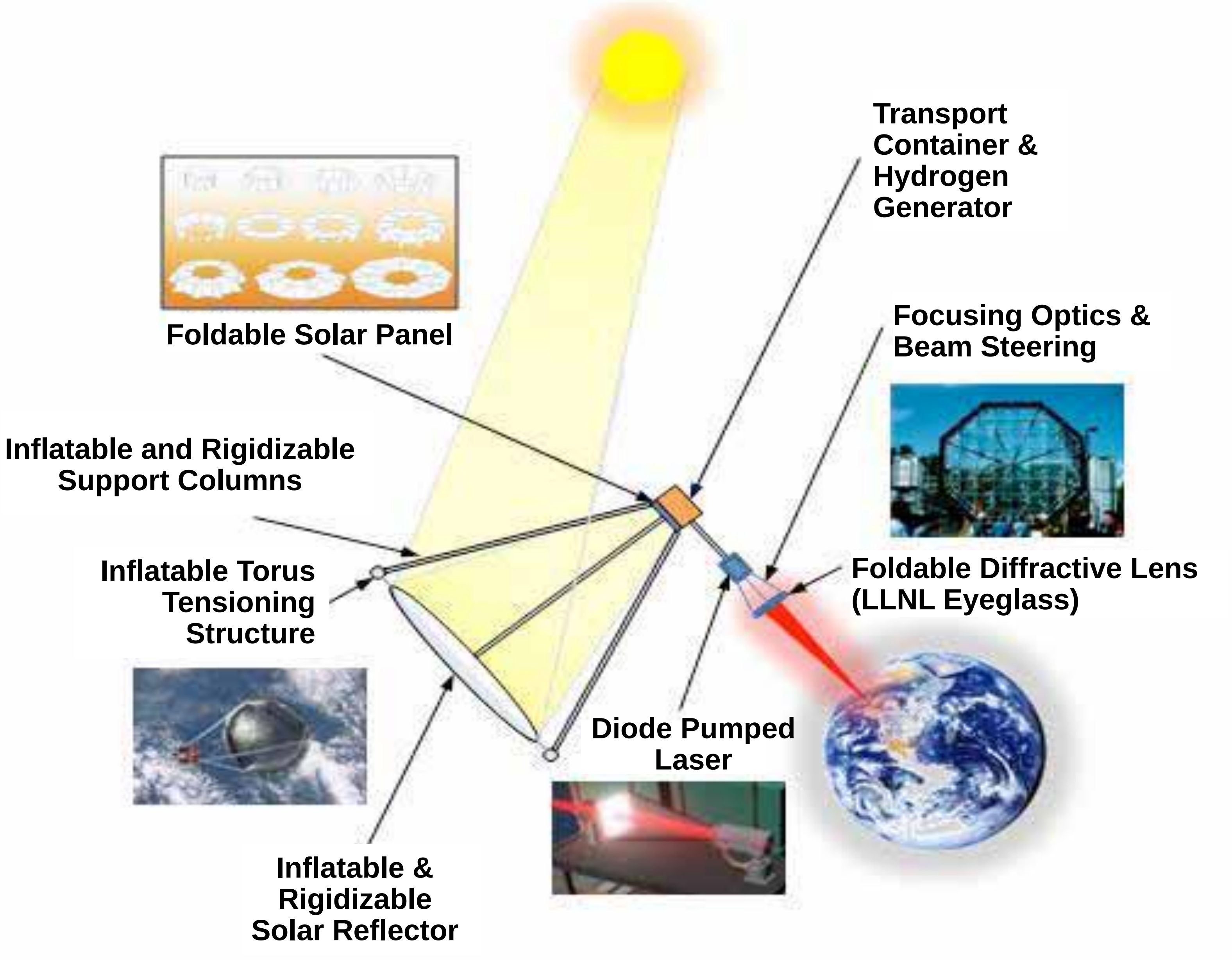
Recent advances in laser technology and optics are game changers

- Laser efficiency is now comparable with the efficiency of microwave devices
- The weight/power ratio of the laser system is greatly reduced
  - — The delivery of the laser system to orbit is greatly simplified due to the significant reduction in mass and volume
- Inflatable, light weight mirrors were developed by industry to concentrate light of the collected solar energy, which reduces the area and weight of the solar panels in space
- Lightweight diffractive optics can be used to collect solar energy
  - — This technology has been developed by LLNL (Eyeglass)
- These recent advances in laser and optical technology makes possible the deployment of the complete system into orbit with only one un-manned commercial launch

Comparison of low and GEO orbit systems

GEO	LEO
• Delivery is expensive	• Delivery is less expensive
• Focusing optics are big	• Focusing optics are smaller
• Aiming accuracy is high	• Aiming accuracy is relaxed
• No need for continuous steering	• Continuous steering is required
• Less time in Earth shadow	• More time out of operation

Notional Architecture (Solar Power Beaming)



Transport Container & Hydrogen Generator

Foldable Solar Panel

Focusing Optics & Beam Steering

Inflatable and Rigidizable Support Columns

Inflatable Torus Tensioning Structure

Foldable Diffractive Lens (LLNL Eyeglass)

Diode Pumped Laser

Inflatable & Rigidizable Solar Reflector

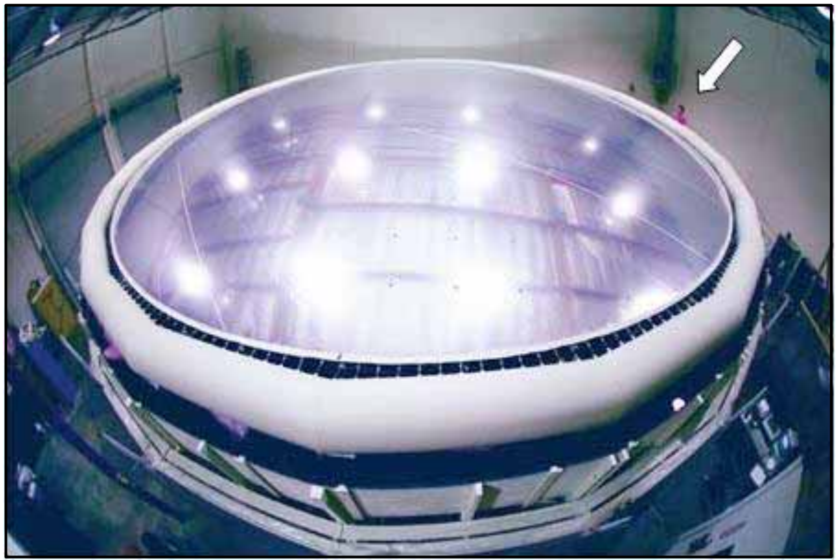
Progress in Laser Development

- Diode-pumped , electrical lasers with efficiency ~50% and multi-KW output are commercially available now

- Electrical, diode-pumped laser systems with weight power ratio ~5kg/kw are under development now. High Energy Laser Area Defense System (HELLADS); http://www.globalsecurity.org/military/systems/aircraft/systems/hellads.htm

L'Garde has deployed in space a version of an inflatable solar collector

- Inflatable Antenna Experiment (IAE) in May 1996.
- 14 meter diameter version shown.
- Solar reflector is packaged by systematic folding to accommodate the sequence of deployment in space.
- Still camera image of the IAE in orbit during testing in space, taken from the space shuttle Endeavour.



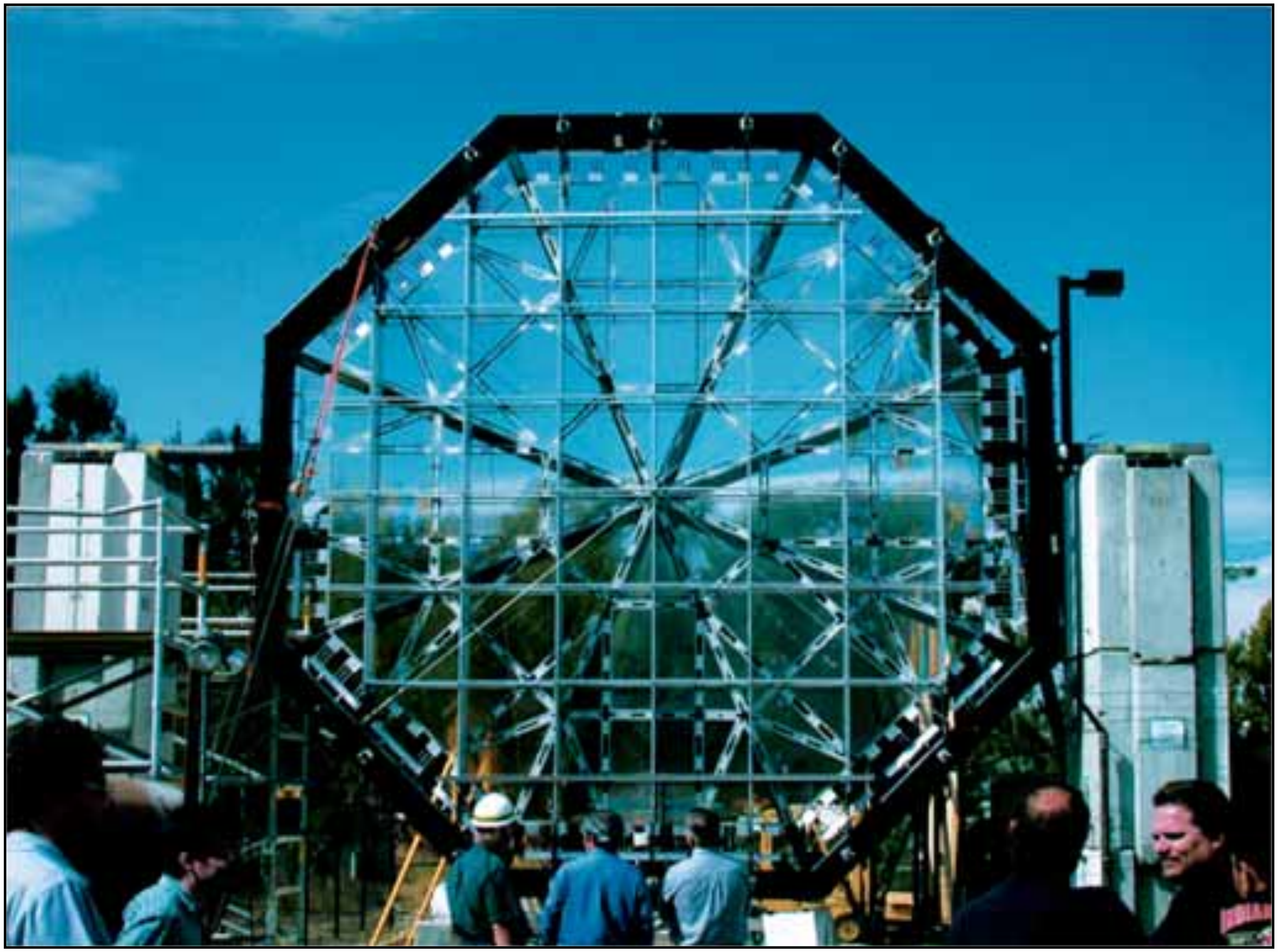
- IAE reflector during ground tests; for scale, note the person on the right wearing a red shirt.
- Our packaged structure is designed to fit within a 2m x 2m x 1m deployment volume.

Solar cells progress

- Concentrator Photovoltaic (CPV) multi-junction cell concept of the National Renewable Energy Laboratory (NREL), was developed for space applications. This thin, lightweight cell will transform (300 X) concentrated solar radiation into electricity with an efficiency of approximately 40%. (Photonics Spectra December 2008 pp.40)

- Solar power required to pump 1MWt laser is~5MWt (laser efficiency 50% and cell efficiency 40%). The area of inflatable concentrator must be ~3600 m^2 and solar cell area~120 m^2

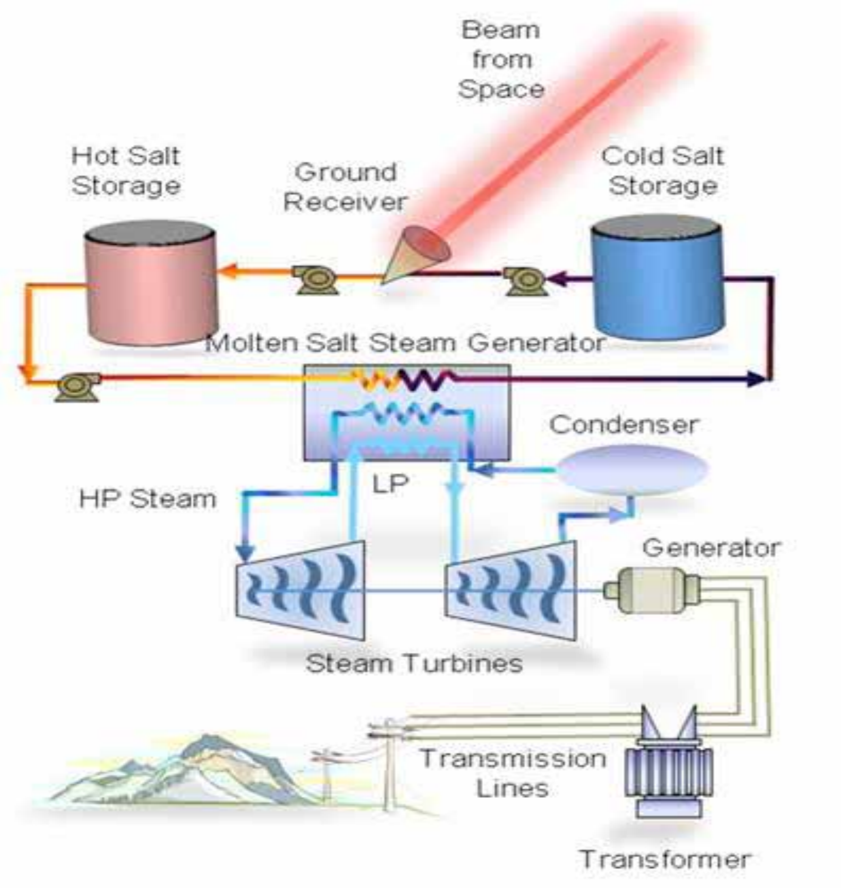
Focusing optics and beam steering utilizes large size diffractive optics technology developed at LLNL



5 meter “Eyeglass” diffractive lens prototype, shown mounted in a steel and aluminum frame, ready for optical testing at LLNL

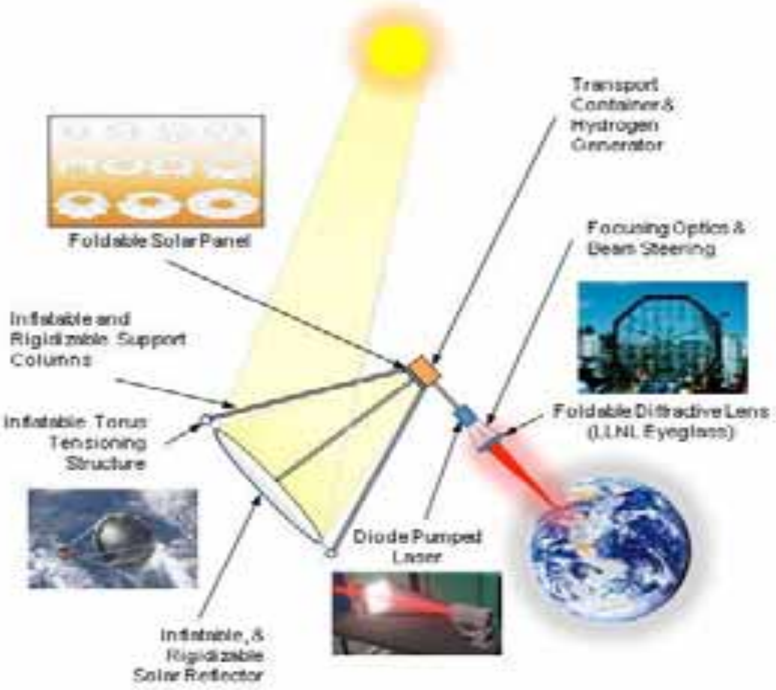
Solar power beaming system and terrestrial power generation station

Solar power beaming system and terrestrial power generation station



Molten salt generator station configuration, capable of 70% electricity transformation efficiency

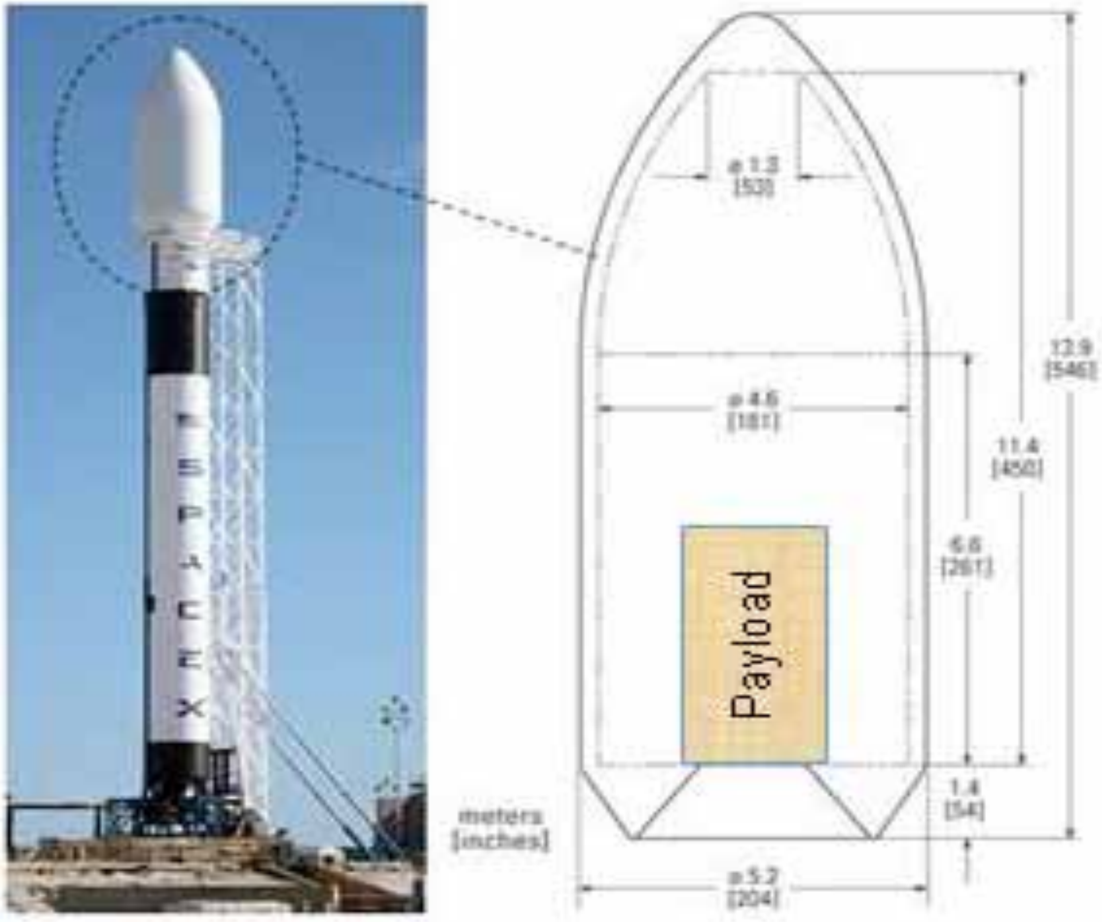
Overview of solar power beaming system



Subsystem	Weight (kg)
Solar Reflector	3425
Solar Collector	300
Packaging Container w/Utilities	450
Diode Pumped Laser System	4550
Focusing and Beam Director System	400
Total System Weight	**9125**
Total Packaged Volume	**2m square x 4m tall**

The entire system can be deployed into space using a single, unmanned commercial launch vehicle

- LEO (low earth orbit) mass to orbit maximum payload: $\leq$10,450 kg
- LEO mission pricing: $36.75M (SpaceX est.)
- Cape Canaveral launch site



Space X Falcon 9 Launch Vehicle

Overview of major subsystems

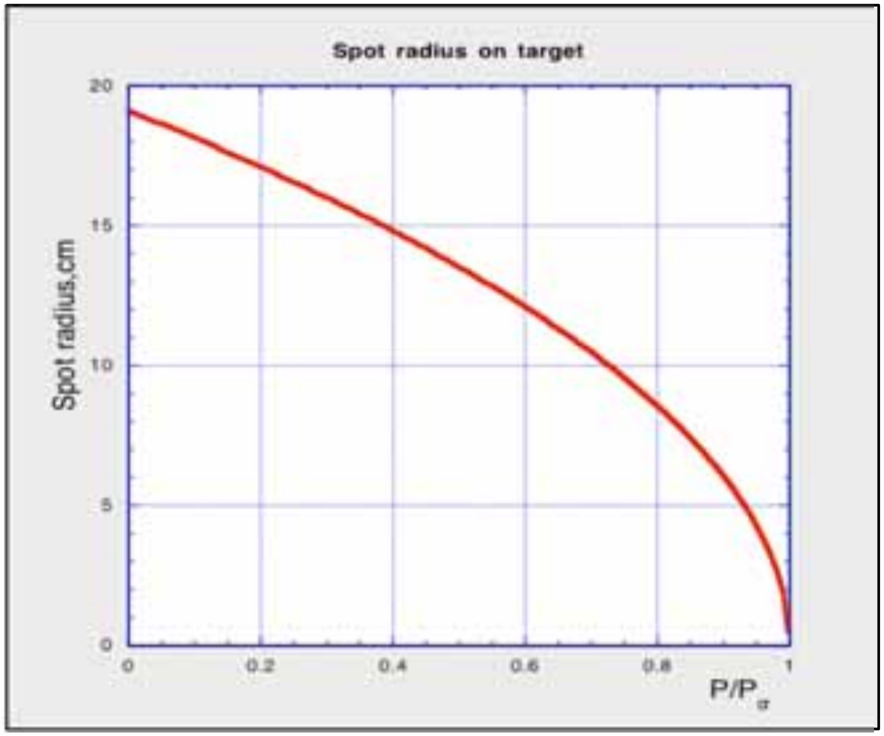
- Launch vehicle is the commercially available Space X Falcon 9
- Solar Reflector and inflatable membrane system manufactured and demonstrated by L'Garde, Inc.
- Solar Collector uses the concentrator photovoltaic (CPV) multi-junction cell concept, developed at the National Renewable Energy Laboratory (NREL) and commercially manufactured by EMCORE Corporation
- Focusing optics utilizes large diameter mirrors based on the use of diffractive optics developed at LLNL under the Eyeglass program
- Power generation station on earth uses molten salt/steam generator technology

Self-focusing in atmosphere can compress the beam

- For beam power well above Pcr beam breaks in filaments with P~Pcr.

$$P_{cr} = 11.68\lambda_0^2/(8\pi^2 n_0 n_2) = 0.93\lambda_0^2/(2\pi\, n_0 n_2)$$

- To compress the whole beam the power must be comparable with Pcr. The compression place even for P<Pcr



Numerical modeling demonstrates beam focusing as a whole up to P ~ 0.7Pcr in uniform media, about 2 times compression.

Turitsyn et al. Op.Express 15, 14750, 2007

Atmosphere in homogeneity helps to suppress beams filamentation

- The nonlinear refractive index is proportional to density. The density can be interpolated as exponential (isothermal atmosphere) with density scale h~6km.

$$n_2(z) = n_2(0)\frac{\rho}{\rho_0}; \rho = \rho_0 e^{-\frac{z}{h}}$$

- Critical power on the ground Pcr~1.7 Gwt for 0.8μm light. The length of the self-focusing L for the beam with the radius a is

$$L \sim \frac{ka^2}{\sqrt{\frac{P}{P_{cr}} - 1}}$$

- For L comparable with the atmosphere height one can expect the self-focusing suppression

Basic equations

$$i\frac{\partial U}{\partial z}+\frac{1}{2n_0k_0}\Delta_\perp U+k_0n_2(z)\,|U|^2\,U=0 \qquad n_2(z)=n_2\exp[-\frac{z}{h}]=n_2\exp[g_0z]$$

Substitution $\Psi=\exp[g_0z/2]\times U$

- **Propagation in amplifier**

$$i\frac{\partial\Psi}{\partial z}+\frac{1}{2n_0k_0}\Delta_\perp\Psi+k_0n_2\,|\Psi|^2\,\Psi=i\frac{g_0}{2}\Psi$$

- **Propagation in amplifier-> <- propagation in non-uniform atmosphere**

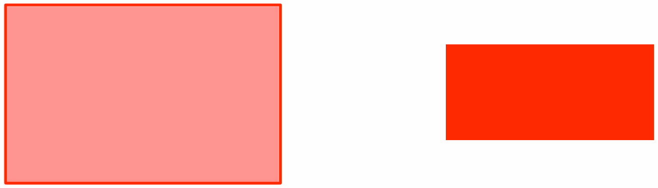
- **Steady-state solution**

$$U=U_0\exp[ik_0\,|U_0|^2\int n_2(z')dz']$$

Instability suppression

- **Uniform media: Most unstable mode during self-focusing always about the beam radius.**

$$K_\perp^2 \propto n_2 A^2 \propto \frac{1}{a^2}; A^2 a^2$$



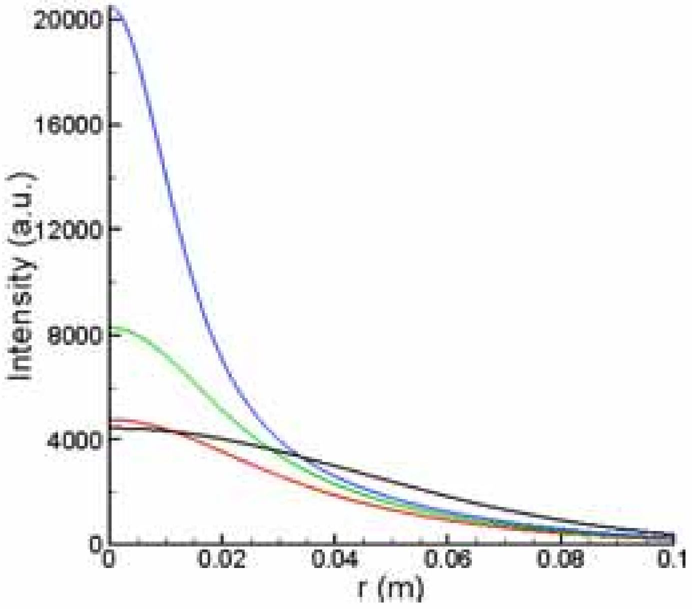
- **Non-uniform media: Most unstable mode during self-focusing smaller then the beam radius. Initial perturbations amplitude is smaller and the growth slow down.**

$$K_\perp^2 \propto n_2(z) A^2 \propto \frac{n_2(z)}{a^2}; A^2 a^2$$

Modeling demonstrates strong beam compression without filamentation

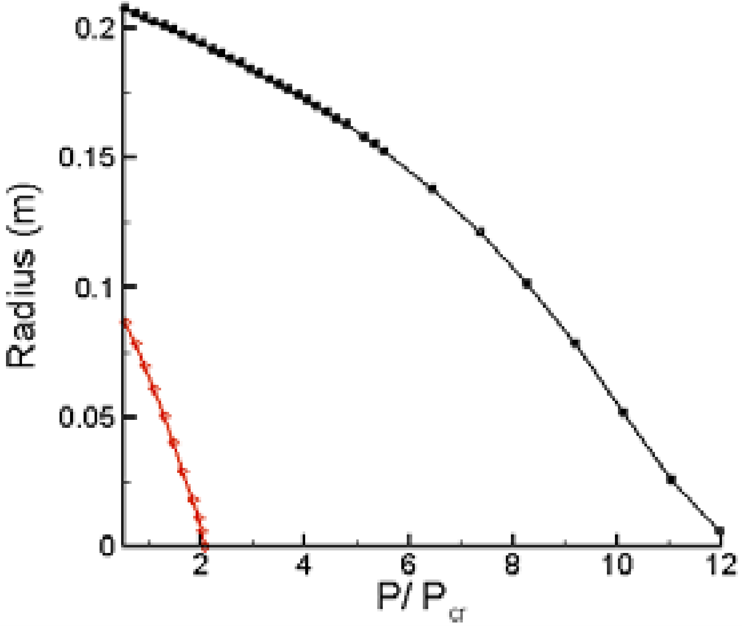
- Laser beam propagates from the height 500 km , focused by 1 m mirror

Intensity distribution on the ground



Beam intensity distribution on the ground the red line - P/Pcr=1, the green line - P/Pcr=1.29, the blue line - P/Pcr=1.66 The black line represents the linear theory for P/Pcr=1.66.

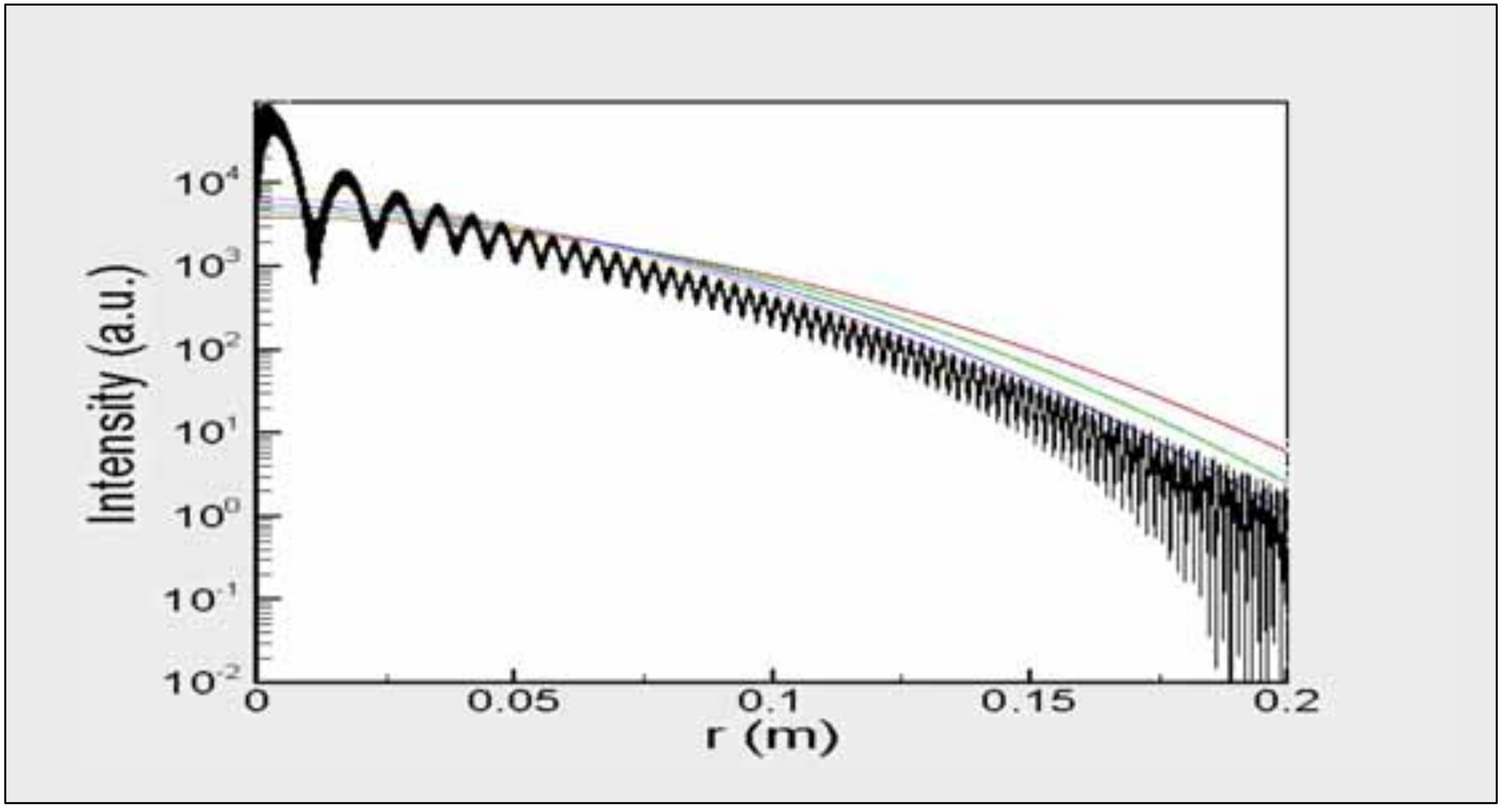
Beam radius vs height



The beam radius versus power for the mirror radius R=1m(red line) and R=0,5m (black line)

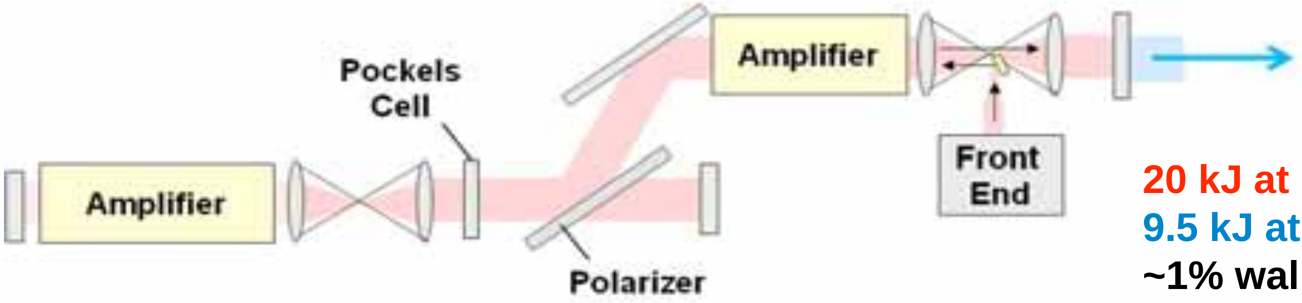
The power increase produce beam filamentation

- Laser beam propagates from the height 500 km , focused by 1 m mirror. P= 1.13Pcr on the height 10 km. Intensity distribution on the different heights. Red-line-25 km, green-20 blue-15km yellow-5km, black-intensity distribution on the ground. The complete filamentation takes place below 5 km.



The National Ignition Facility (NIF) at LLNL uses a 192-beam Nd:glass laser to initiate fusion implosions

- NIF's laser is the world's largest optical instrument
- Ignition is anticipated in 2010-2011
- NIF beam power for 4MJ of 1w light and 3 nsec pulse P~4MJ/ 192*3nsec ~7TWt~1700000 P_{cr}
- NIF's multi-passed beamlines use flashlamp-pumped Nd:glass amplifiers



20 kJ at 1w
9.5 kJ at 3w
~1% wallplug efficiency
1 shot every 3-4 hours
40cm x 40cm apertures

Description of instability

- **Equations for small perturbations** $U(z,r) = (U_0 + a + ib) \times \exp[ik_0 \, |U_0|^2 \int n_2(z')dz'$

$$\frac{\partial a}{\partial z} + \frac{1}{2n_0k_0}\Delta_\perp b = 0$$

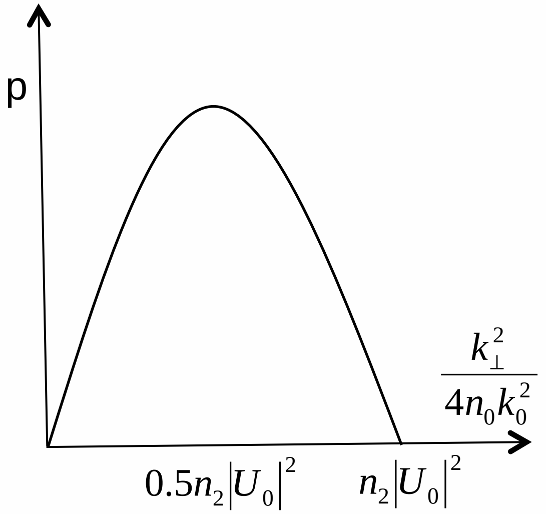
$$-\frac{\partial b}{\partial z} + \frac{1}{2n_0k_0}\Delta_\perp a + 2k_0 n_2(z)\,|U_0|^2\, a = 0$$

-> $$\frac{\partial^2 a}{\partial z^2} + \frac{1}{2n_0k_0}\Delta_\perp\{\frac{1}{2n_0k_0}\Delta_\perp + 2k_0 n_2(z)\,|U_0|^2\}a = 0$$

- **Passive optics n_2=const (Bespalov-Talanov instability)**

$$a \;\propto \exp[ik_z z + i\vec{k}_\perp \vec{r}_\perp]$$

$$k_z^2 = \frac{\vec{k}_\perp^2}{2n_0k_0}[\frac{\vec{k}_\perp^2}{2n_0k_0} - 2k_0 n_2\,|U_0|^2]$$



- **Unstable solution at** $n_2|U_0|^2 > \frac{k_\perp^2}{4n_0k_0^2}$

P=Imk$_z$, p$_{max}$ = $kn_2|U_0|^2$

What is the size of unstable perturbations

- At power P~P_{cr} the size of most unstable perturbation is about beam size. For fused silica P_{cr}~ 4 MWt. NIF beam power for 4MJ of 1w light and 3 nsec pulse P~4MJ/192*3nsec ~7TWt~1700000 P_{cr}

- The size of most unstable mode l

$$l \sim a\sqrt{\frac{P_{cr}}{P}} \sim 0.001a$$

- For beam size a ~40cm l~0.4 mm

Instability in amplifiers. What was done.

- **The transversal modulations grow up exponentially**

$$\delta I(z) \propto e^{pz}, p^2 = \frac{\vec{k}_\perp^2}{2n_0k_0}[2k_0n_2I - \frac{\vec{k}_\perp^2}{2n_0k_0}]$$

- **The spatial growth rate p is maximal at**

$$\frac{\vec{k}_\perp^2}{2n_0k_0^2} = n_2I, \; p = k_0n_2I$$

- **Initial perturbation increases after distance L**

Exp(pL)=Exp(k_0n_2IL) = ExpB

- **Intensity modulation** $\frac{\delta I}{I} = \frac{2\delta U*U}{I} = 2ExpB$

- **Usual requirement- B<2-3 Typically most stringent restriction is an optical damage** $\rho(F) \sim F^m; m \sim 6-9$

Exact solution

- **Basic equation** $$\frac{d^2a}{dz^2}+\frac{q^2\omega^2g_0^2}{4}(\omega^2-\exp[g_0\,z])a=0$$

- **The important parameters**

$$q=4\;k_0\,n_2(0)|U_0|^2\;/g_0 \qquad \omega^2=\frac{\vec{k}_\perp^{\,2}}{4n_0k_0^2n_2(0)\,|U_0|^2}, \quad \nu=q\omega^2=\frac{\vec{k}_\perp^{\,2}}{2n_0k_0g_0},$$

- **The exact solution**

$$a(z)=\frac{i\,f_0g\omega\pi}{2\sinh[\nu\pi]}\times\left\{I'_{-i\nu}(g\omega)\times I_{i\nu}(g\omega e^{g_0z/2})-I'_{i\nu}(g\omega)\times I_{-i\nu}(g\omega\,e^{g_0z/2})\right\}+$$
$$\frac{i\,f_1\pi}{g_0\sinh[\nu\pi]}\times\left\{I_{i\nu}(g\omega)\times I_{-i\nu}(g\omega e^{g_0z/2})-I_{-i\nu}(g\omega)\times I_{i\nu}(g\omega e^{g_0z/2})\right\}$$

- **The analogue of the increment of the spatial growth rate in our situation will be the value =ln[a(L)/a(0)]. For a large ratio a(L)/a(0), this value is practically independent of boundary conditions**

Instability in amplifiers. What was done.

- The effect of intensity growth was taken into account in 2 ways.
  - B integral was substituted by
    Conservative estimate

$$B' = \int k n_2 I(z) dz$$

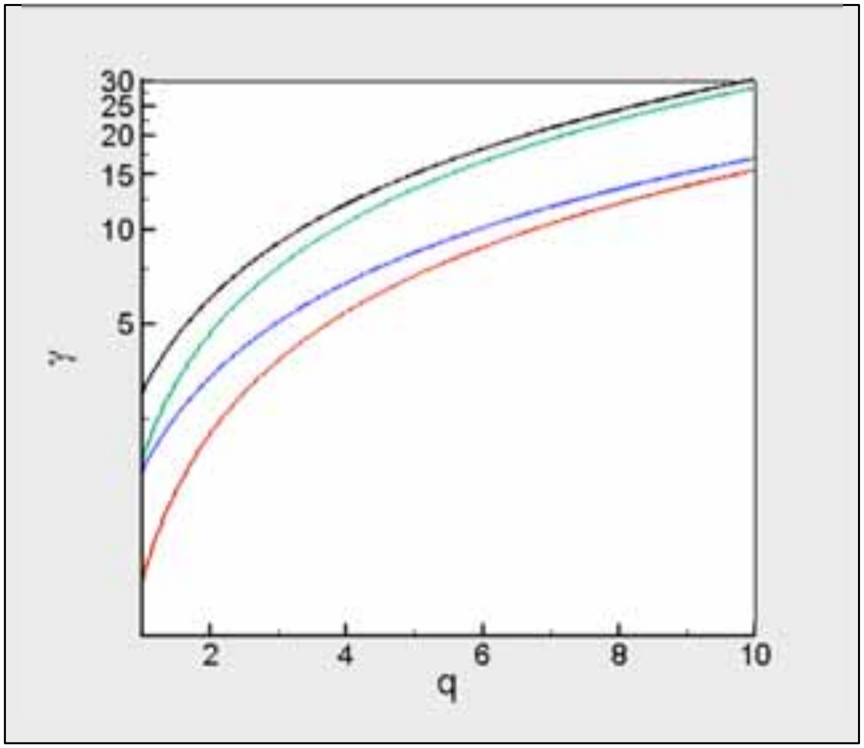
  - Adiabatic approximation (AA). We assume that locally we have B-T growth.
    The overall amplification factor

$$\gamma_a = \int_0^L \operatorname{Im} k_z dz = \int_0^L p(z) dz; p^2 = \frac{\vec{k}_\perp^2}{2n_0k_0}[2k_0n_2I - \frac{\vec{k}_\perp^2}{2n_0k_0}]$$

- Accuracy of AA is not clear.

Results

- Expansion of exact solution for big values of Bessel function index coincides with AA. But convergence takes place at unpractically big growth of perturbations



γ as function γ for ω =0.5 (red line – exact solution, blue – adiabatic approximation) and For ω =1 (green line – exact solution, black – adiabatic approximation), $g_0L=3$.


NIF