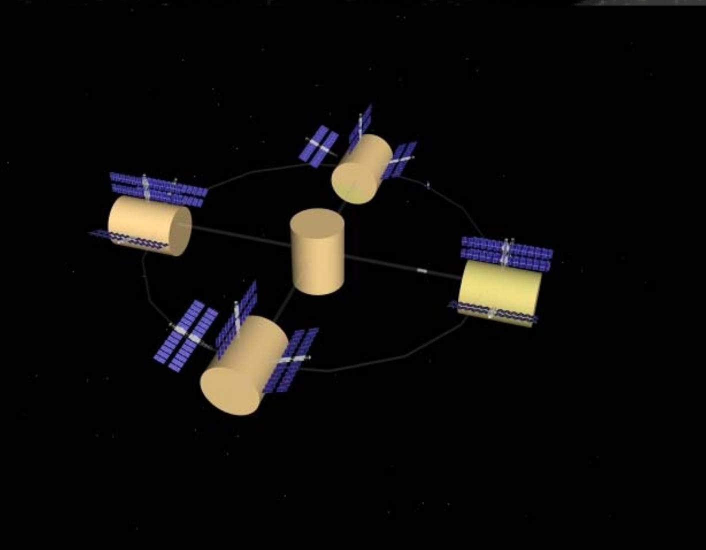
Tailored Force Fields for Construction in Space: Phase 2 1st Year Report



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Georgia Institute of Technology

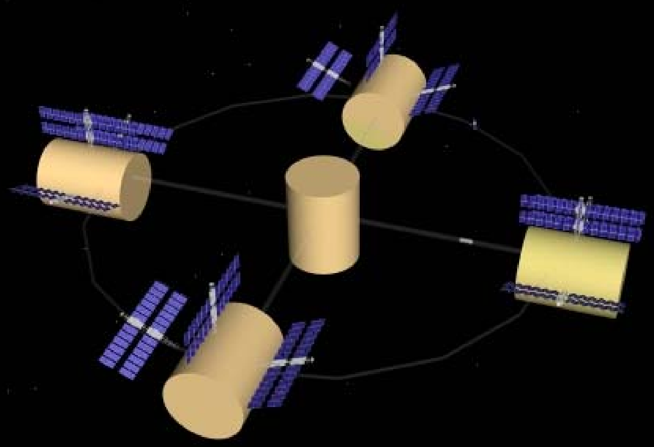
Atlanta, Georgia, USA

Broomsfield, Colorado, October 2005

Long-Term Potential: Enable Permanent Human Habitats in Space

Enable automatic construction of massive structures using extraterrestrial material.

- solve radiation shielding problem
- enable 1-G, spacious, safe shirtsleeves environment
- enable large infrastructure
- enable resource exploitation
- cut dependence on earth-launch costs



Basic Phenomenon

Behavior of a Multitude of Particles in a Standing Wave Field

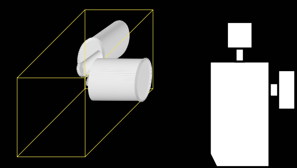
•A multitude of particles in a resonant potential field distribute along nodal surfaces.

•Self-forming walls – flight tests show that the particles fill up vacant spaces in the walls.

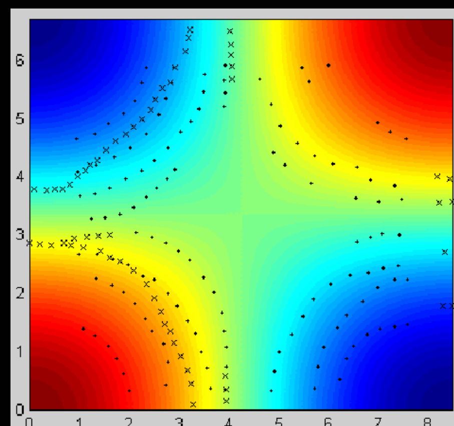
•Forces due to scattering of sound waves known since 1930s.

•Levitation / manipulation of single particle, 1980s.

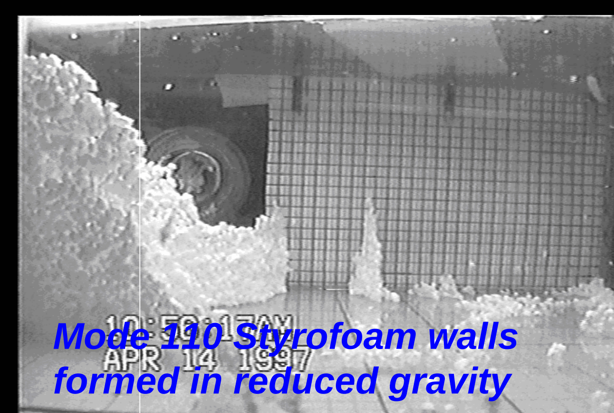
•Behavior of multitude of particles in micro-G, complex wall shapes: Wanis et al, 1997.



Acoustic chamber

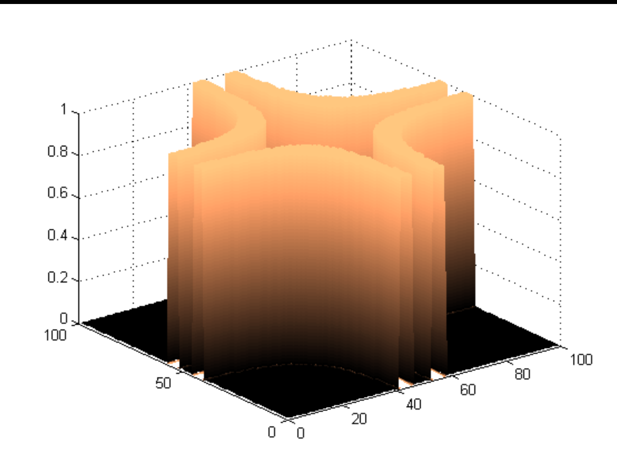


Predicted pressure contours and measured wall locations

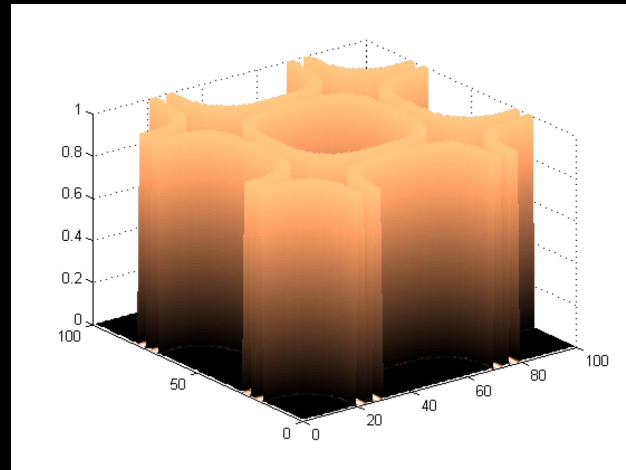


Mode 110 Styrofoam walls formed in reduced gravity

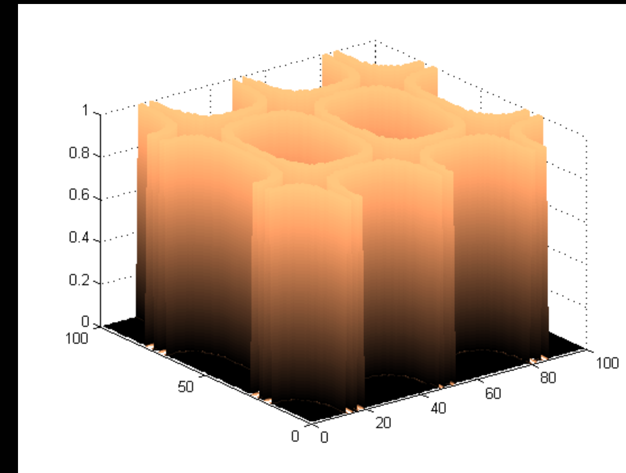
Simulation: Predicted Shapes



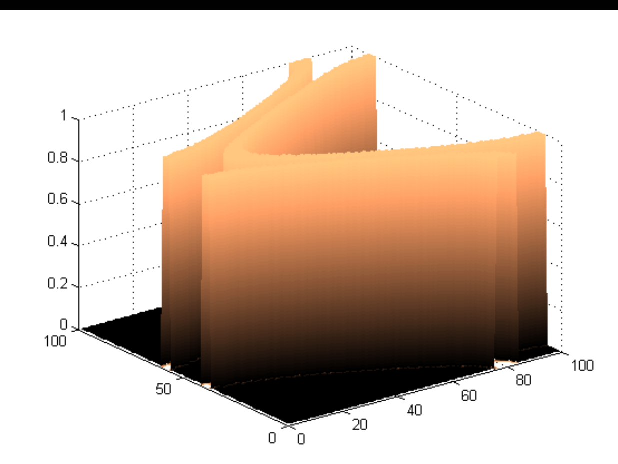
1 1 0



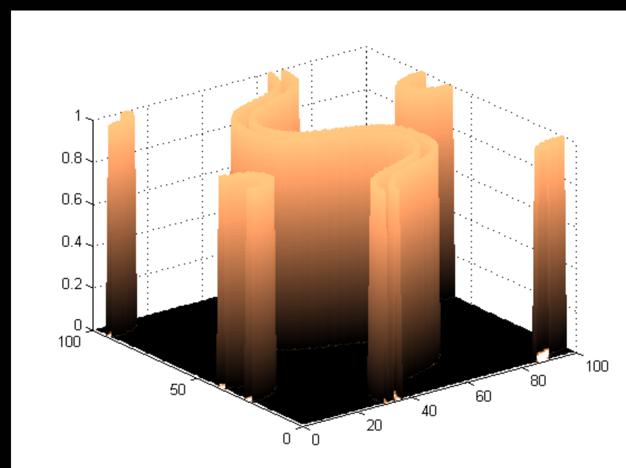
2 2 0



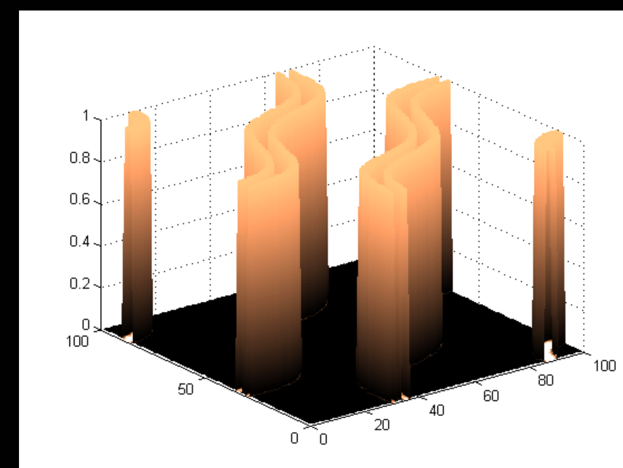
3 2 0



1 0 0 + 0 2 0



2 3 0 + 1 0 0



1 1 0 + 2 2 0

Can this be done with electromagnetic fields?

- *Ashkin*: - manipulated cells and other microscopic particles
  - deformed water/air interface
  - *scattering* forces vs. *gradient* forces

  Note: gradient forces dominant in resonator

- *Zemanek*: calculated force on small particles by Rayleigh scattering formulation which regarded particles as dipoles

- *McGloin*: trapped microscopic beads between counter-propagating laser beams and manipulated them via phase changes

- *Benford*: levitated 10 cm^2 sail in 1g using microwave radiation pressure

Acoustic-Electromagnetic correspondence summary

(1) Conservation Equations

$$\frac{\partial}{\partial t}(density\ of\ \ quantity)+\nabla\bullet(flux\ of\ \ quantity)=\text{sources}-\text{sinks}$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\frac{p^2}{\rho_o c^2}+\frac{1}{2}\rho_o u^2\right)+\nabla\bullet(pu)=work$$

acoustic

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\varepsilon_o E^2+\frac{1}{2}\frac{B^2}{\mu_o}\right)+\nabla\bullet\left(\frac{E\times B}{\mu_o}\right)=work$$

electromagnetic

(2) Force Expressions

acoustic

$$F_{\text{standing}}^{\text{acosutic}}=\frac{5\pi a^3}{6c_o}\left[\left(1-\frac{\rho_o c_o^2}{\rho c^2}\right)+\left(\frac{\rho-\rho_o}{2\rho+\rho_o}\right)\right]\nabla I$$

$$F_{\text{travel}}^{\text{acoustic}}=\frac{11}{8}\pi\frac{I_o}{c_o}k^4a^6\left[\left(1-\frac{\rho_o c_o^2}{\rho c^2}\right)^2+\left(\frac{\rho-\rho_o}{2\rho+\rho_o}\right)^2\right]$$

electromagnetic

$$F_{\text{gradient}}^{\text{emag}}=\frac{2\pi a^3}{c}\left(\frac{m^2-1}{m^2+2}\right)\nabla I$$

$$F_{\text{scatter}}^{\text{emag}}=\frac{8\pi}{3}\frac{I_o}{c}k^4a^6\left(\frac{m^2-1}{m^2+2}\right)^2$$

Experimental Demonstrations

Trapping and moving (by phase control) different size particles in focal region of counter-propagating laser beams

Courtesy of Dr. McGloin, St. Andrews, UK
www.st_andrews.ac.uk/~atomtrap/Research/Beams/beams.htm

DielectroPhoresis:
Chain Formation

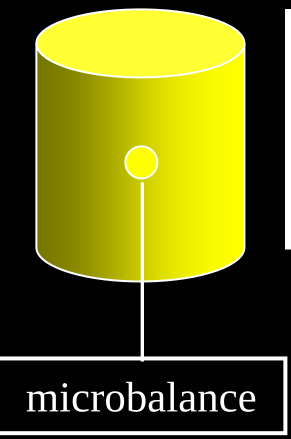
http://www.dielectrophoresis.org/PagesMain/DEP.htm

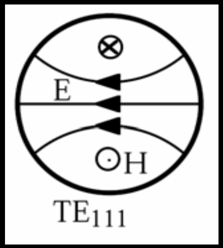
Points made:

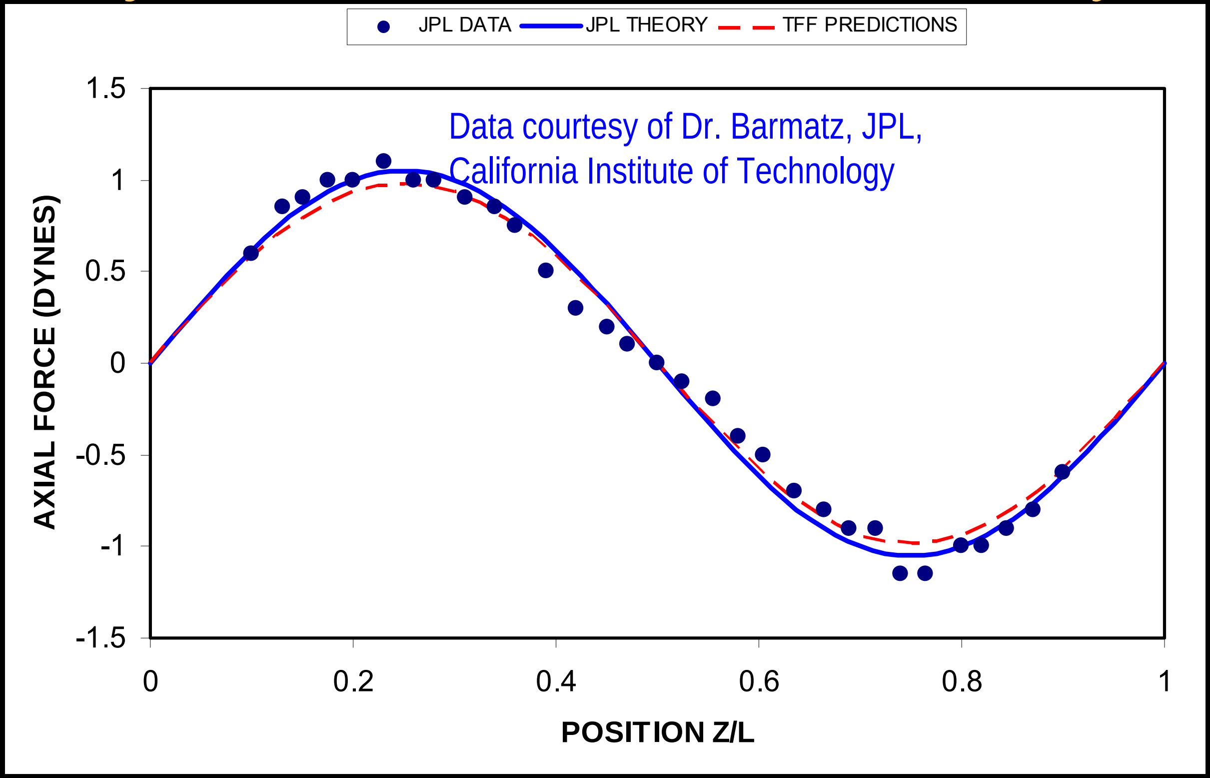
- Force generated in a pair of opposing laser beams (radiation force) on a particle is as predicted.
- Particle-particle interaction in an electromagnetic field is as predicted.
- Chain formation shown under given conditions.

Single Particle Microwave Force Validation

Force on a single object in a resonant microwave cavity







Resonant Mode	TE $_{111}$
Frequency (GHz)	4.84
Source Power (W)	20
Cavity Q-factor	6100
Sphere dia (mm)	9.4
Dielectric constant	11

Points made:

1. Force generated in microwave resonator at Mie/ Rayleigh boundary, agrees with Rayleigh prediction.

2. Scaling holds from acoustics through optics regimes to microwave.

Validation of Wall Formation Using Tailored Force Fields

Will rocks in space move into multilayered cylindrical walls under the influence of a radio wave field?

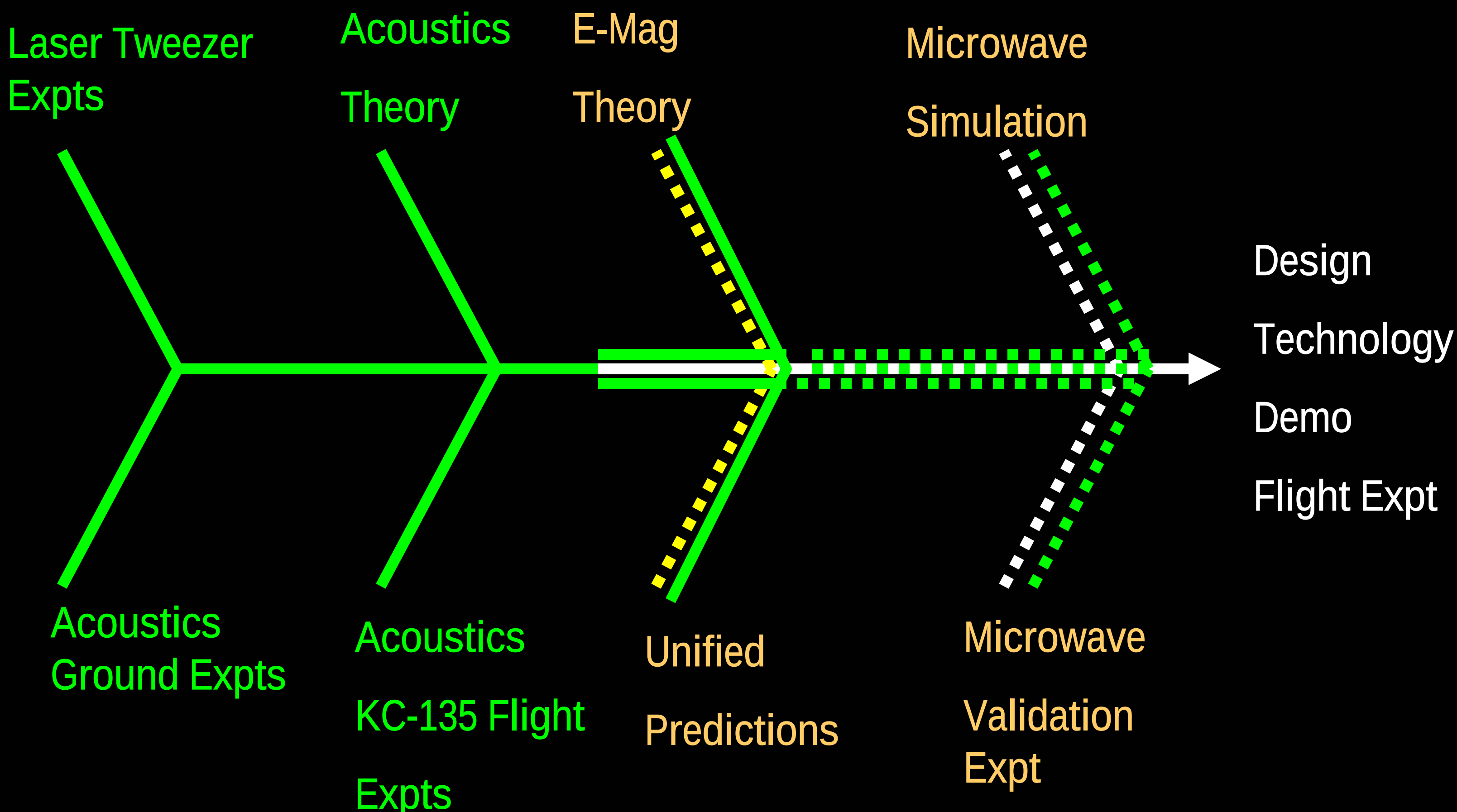
Points made:

- Wall formation confirmed in acoustic field; low-gravity through 1-g.
- Correspondence of acoustics - electromagnetics confirmed from first principles.
- Role of secondary forces (effect of particle on field, and particle on particle) seen to be beneficial in acoustics, known to vary with dielectric properties in electromagnetics
- No direct evidence of wall formation yet in e-mag fields
- No counter-example or reason seen why walls should not form in full-scale problem
- Force mechanisms on single particle confirmed for acoustics, optics, microwave, and matches scaling assumed in conceptual design.

Largest-scale emag validation to-date: JPL data on microwave forces on isolated sphere : millimeter-scale particle, Mie-Rayleigh boundary.

Current efforts: to go to 1 - 10 cm particles, and particle-particle interactions

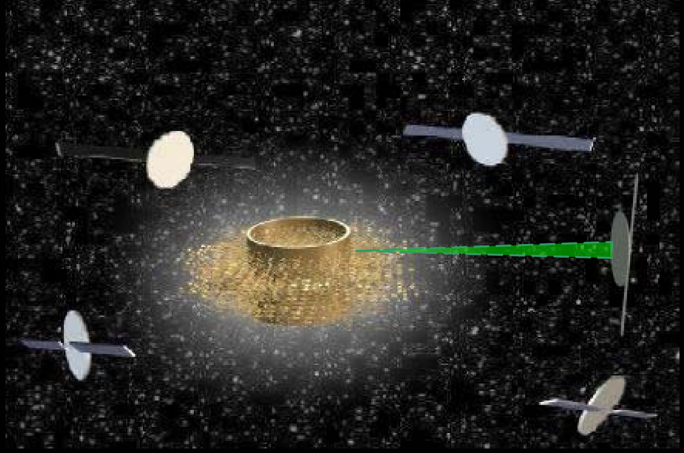
TFF Validation Roadmap: Progress in the Past Year



TFF Reference Case: Massive Construction in Space

- Cylinder: 50 m diameter, 50 m length, 2m thick at Earth-Sun L4
- Construction blocks: 20 cm effective diameter
- Material source: pulverized rock from NEO
- Electromagnetic wave: 3 MHz (radio frequency)
- Heat Curing: 300 MHz and higher (microwave frequency)
- Particle mean acceleration: 1 micro-G
- Resonator Q-factor: 10,000
- Power Input: 258 MW
- Active field time: 13 hrs
- Collector area needed at 10% conversion: 2 sq. km

Implies 10 walls - overkill



L-4 as reference destination

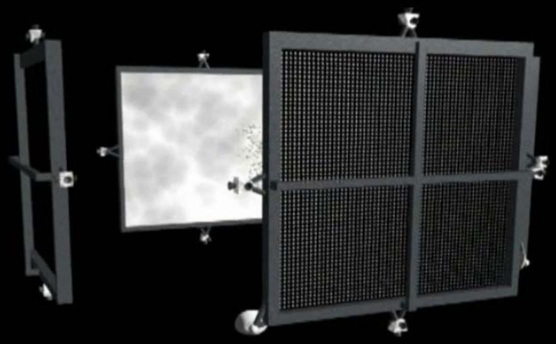
- Known solar intensity
- Low g-jitter
- Known trajectories
- Delta-v comparable to lunar or NEO missions
- Needs robotics
- Good location for future E.T. factories

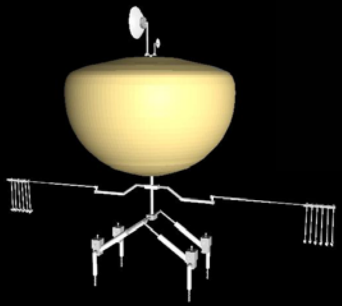
MISSION ARCHITECTURE

Two vehicle designs:

1. TFF craft used for forming walls
2. Resource-extraction “Rock Breaker” craft.

(Names invited for these!)





Requirements:

1. Propulsion to get the craft to the site.
2. Power levels adequate to generate the raw material and build the structure
3. High conductivity radio-wave resonator at least 100m x 100m x 100m.
4. Ability to generate rocks of the size needed for construction
5. Fully robotic operation
6. Ability to fuse the rocks when they reach the desired position

Design Convergence: Solar Collector/ Sail Size

1.2 sq. km of solar collector / sail on each TFF craft:

• Primary solar sail propulsion to reach L4 with a 25,000kg craft.

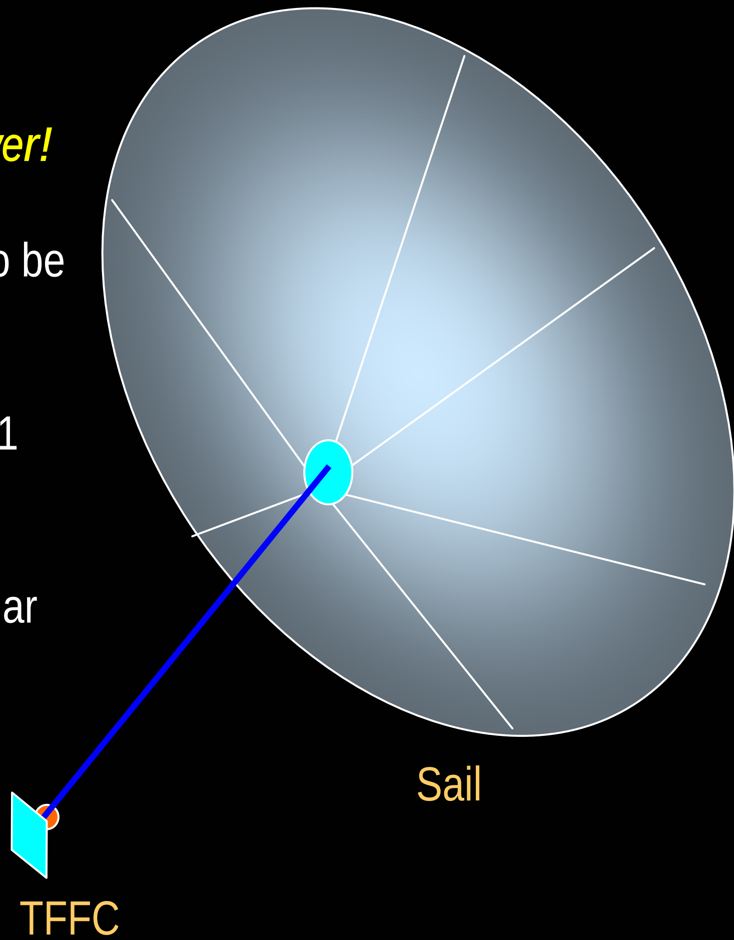
• Plasma / laser – cutting: enough material for one 10-walled cylinder module in 19 days - *limited by cutter mass, not power!*

• TFF Resonator with Q of 2500 is adequate; 10,000 appears to be feasible.

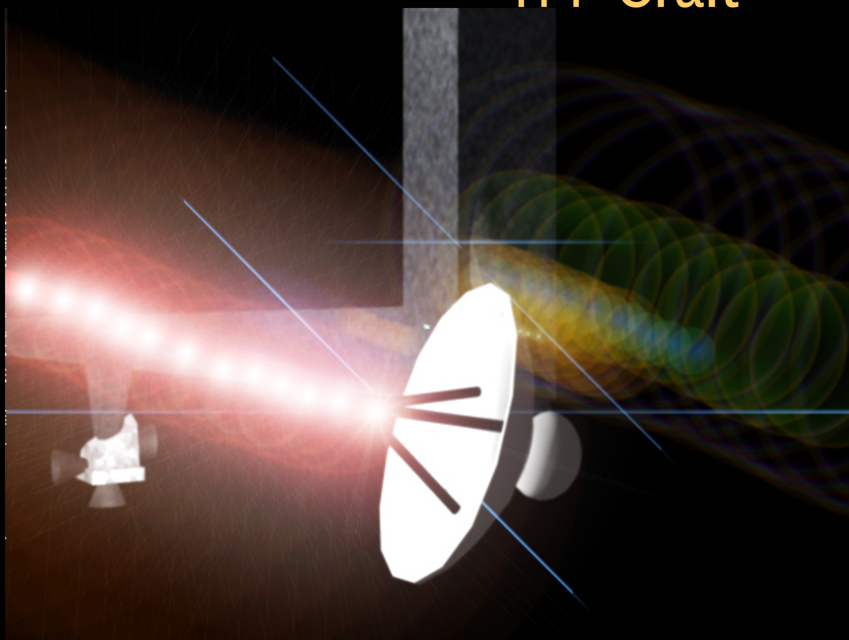
•Simultaneous operation of TFF and sintering beams, forming 1 cylinder wall in 1 hour after system reaches peak intensity

• Sintering & hardening 1 cylinder in 10 hours (2hrs worth of solar energy)

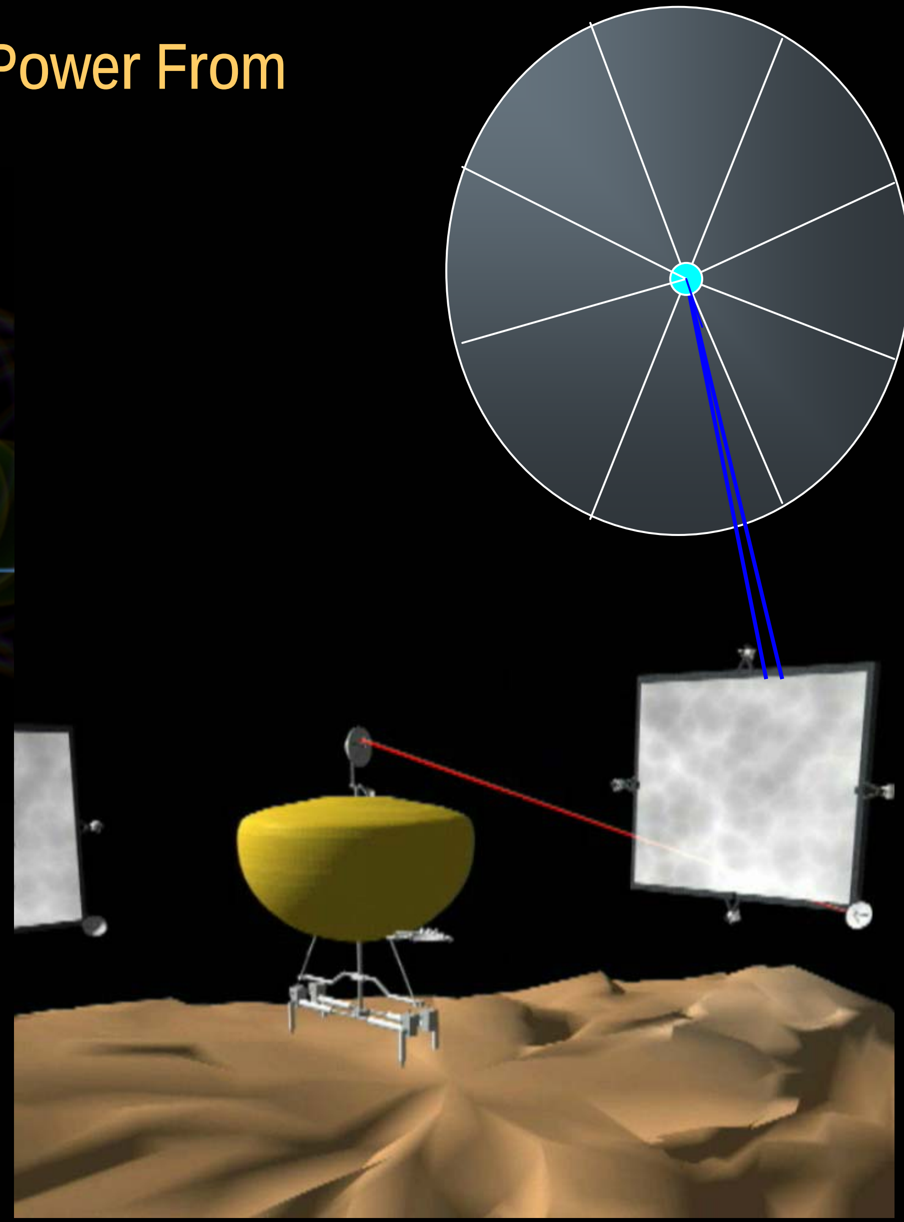
•System suitable for missions as far as Mars



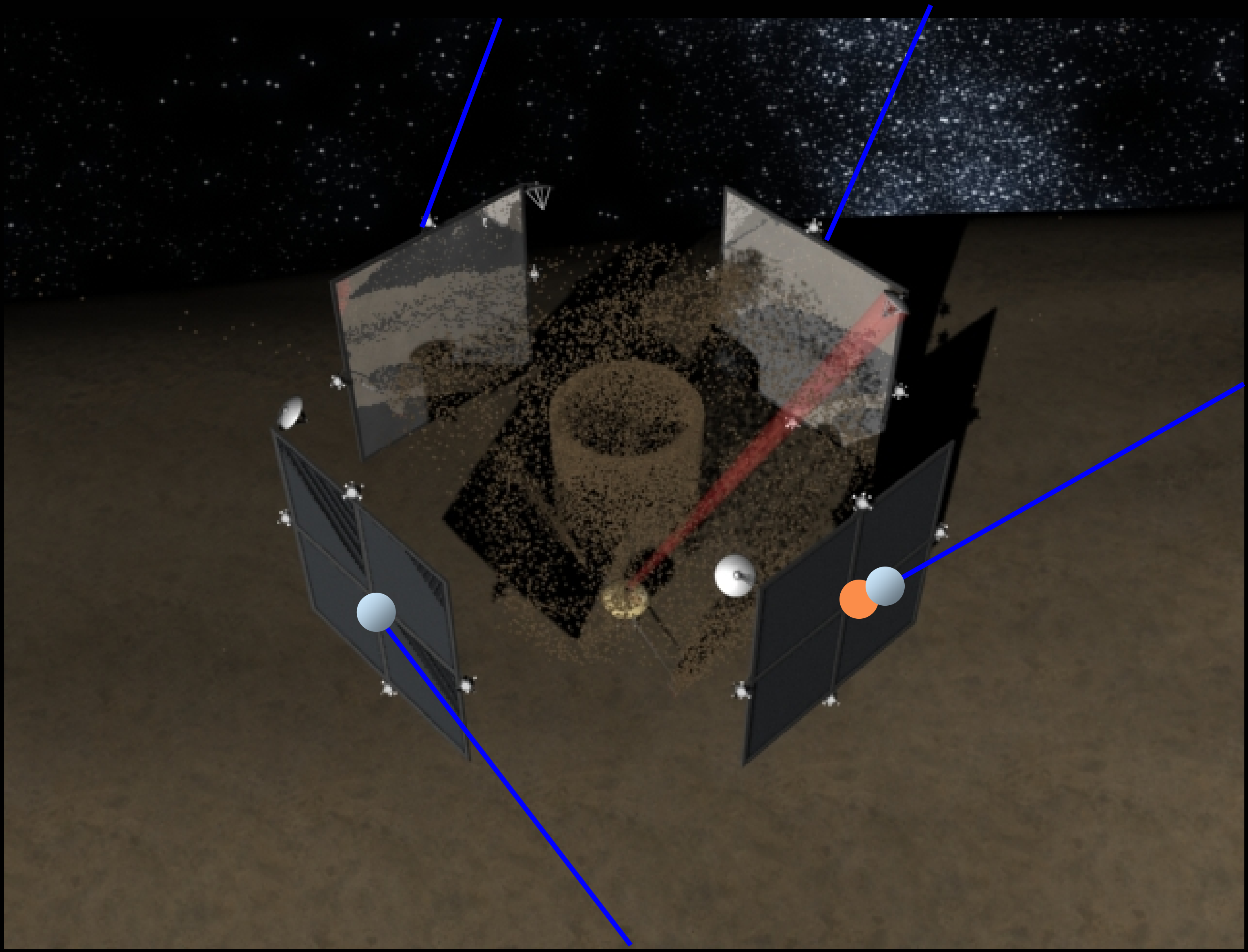
Rock Breaker Gets Beamed Power From TFF Craft



TFF craft beams power to the Rock Breaker

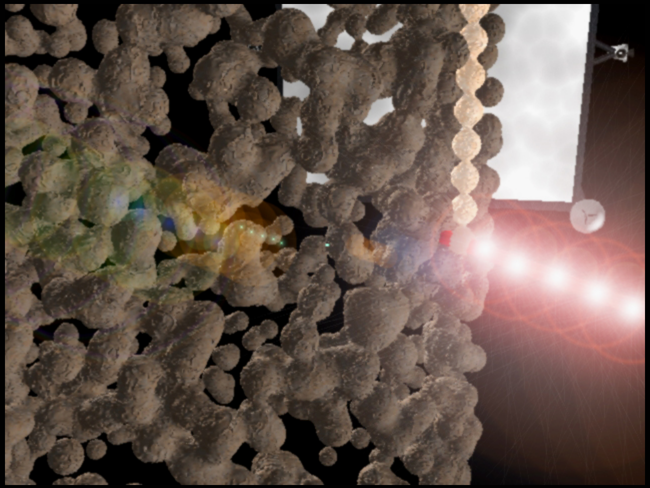


TFF Resonator Cage forms rocks into cylinder



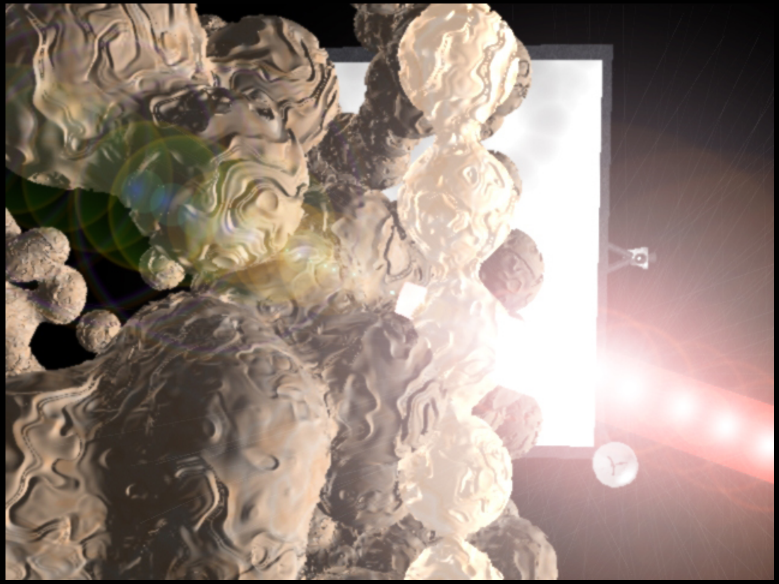
Each wall surface is sintered by beams from RockBreaker or from TFF craft

- Microwave surface sintering forms hard exterior shell for each layer of the cylindrical shell and holds the rubble together.
- The resonator is repositioned to form the next wall layer - - and so on until the desired 2m thickness is formed and sintered in place.

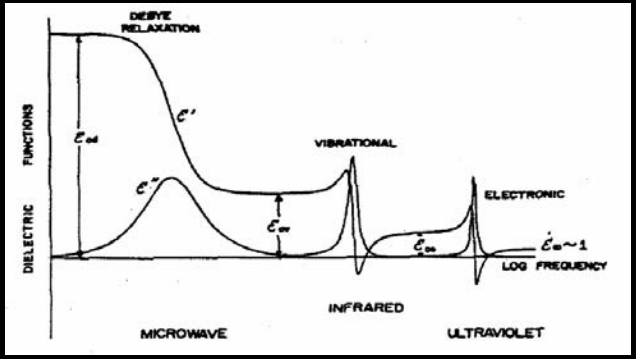


Wavelength Range of Different Processes

Shape formation:	10 - 100m
Refine positioning:	1 - 10m
Beamed power:	1-10 mm
Sintering:	1 - 10 microns



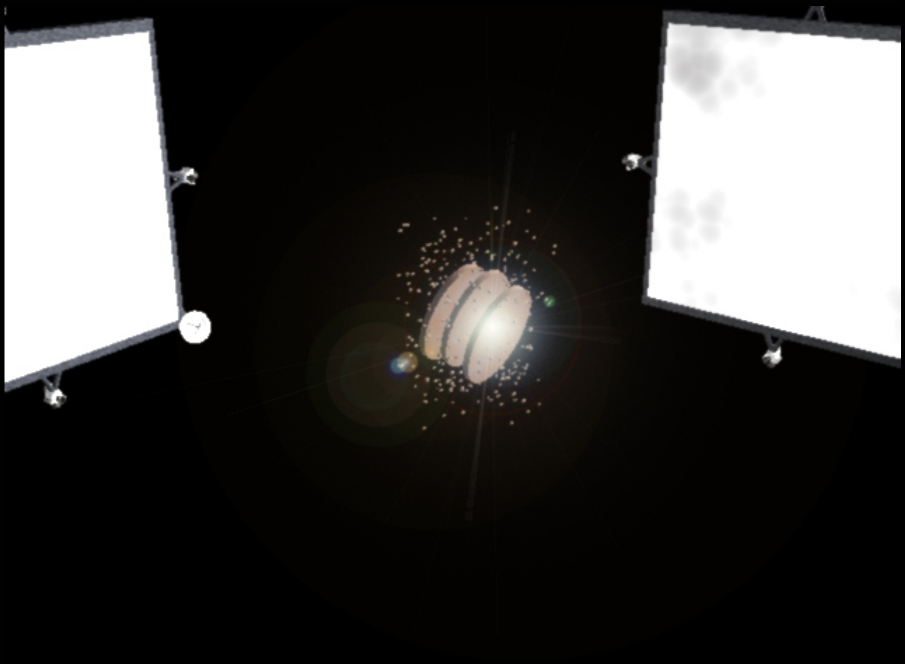
Typical Dielectric Property Variation With Frequency

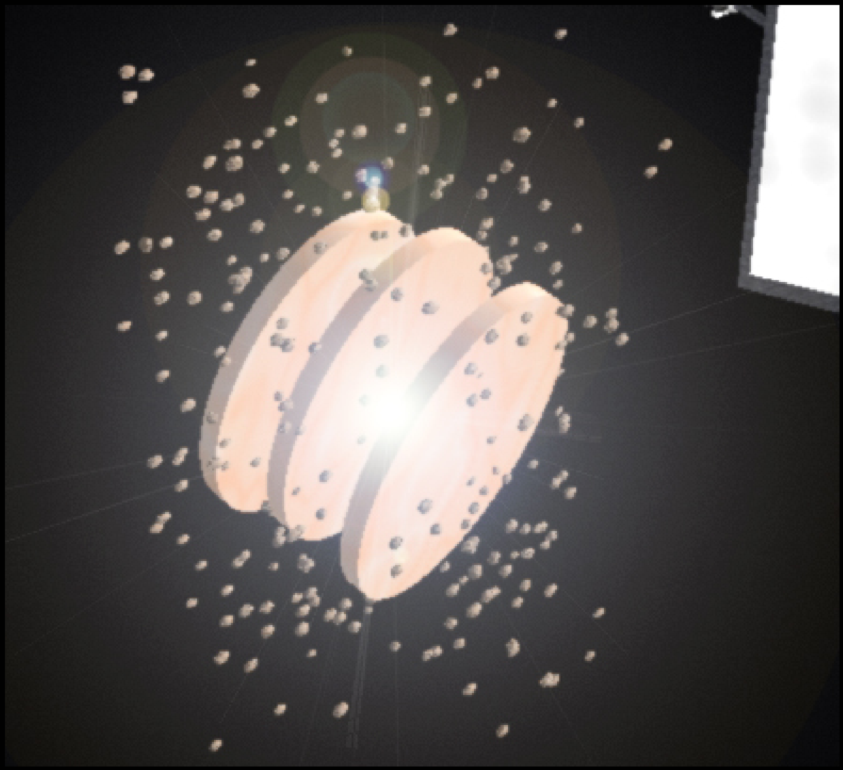


Guggenheim School of Aerospace Engineering, Georgia Institute of Technology

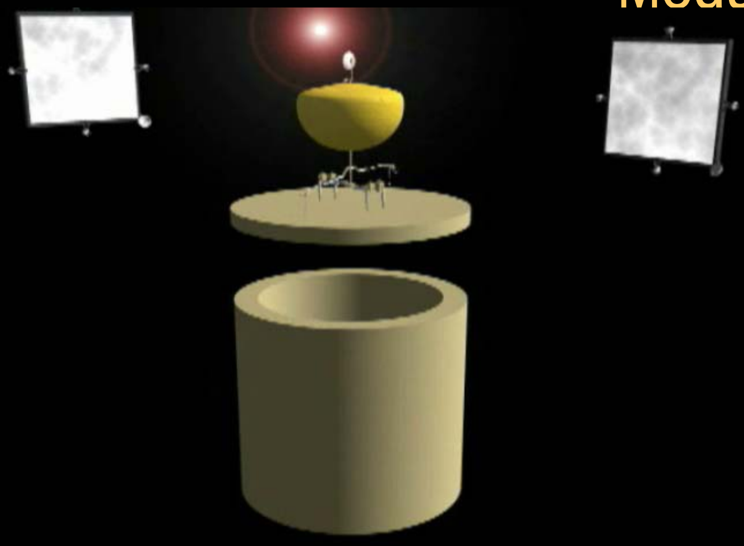
Cap Formation

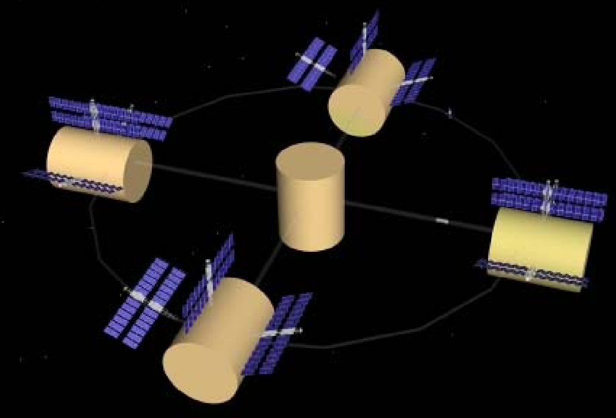
- TFF craft use symmetric mode to form circular endcaps.





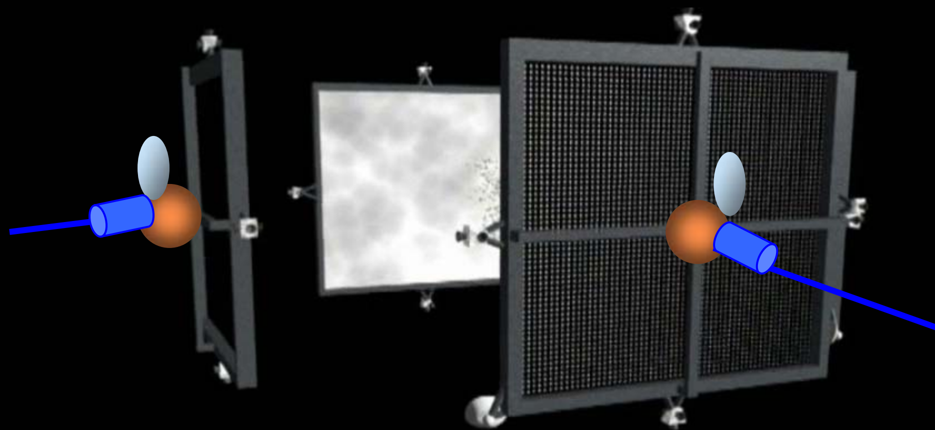
Module Assembly





- Earth-shipped access ports, connecting tubes and solar arrays are installed.
- Rock-breaker moves to form the next rock cloud. TFF system follows.
- The process is repeated for 5 modules.

Systems
1. Antenna Design for full-scale TFF Craft



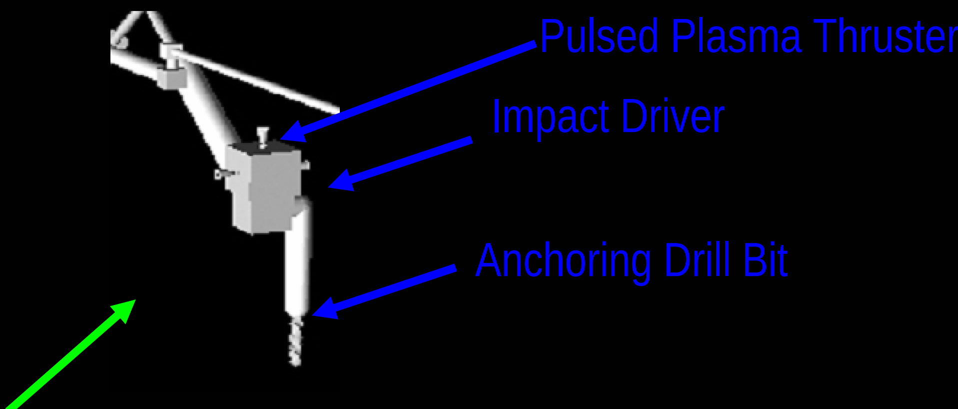
Narrowband oscillator
Resonator walls of 58micron aluminum sheet.
Wire loop transmitters.
Theoretical max Q of 300,0000;
Target operating Q of 10,0000

1.2 sq.km solar sail, reconfigured into collector (not shown).

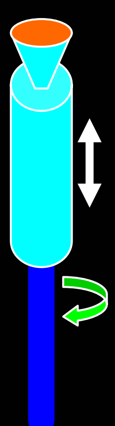
Total package mass target: 25,000 kg at departure from Earth orbit.

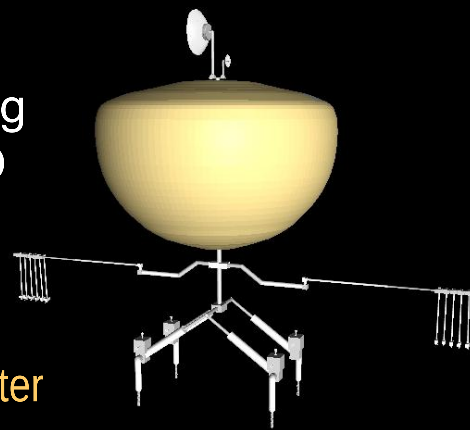
2. Robotic “Rock Breaker” Craft

- Primary power beamed from TFF craft
- Primary solar sail propulsion; plasma thruster maneuvering
- 25,000kg craft + 12,500 kg propulsion package from LEO



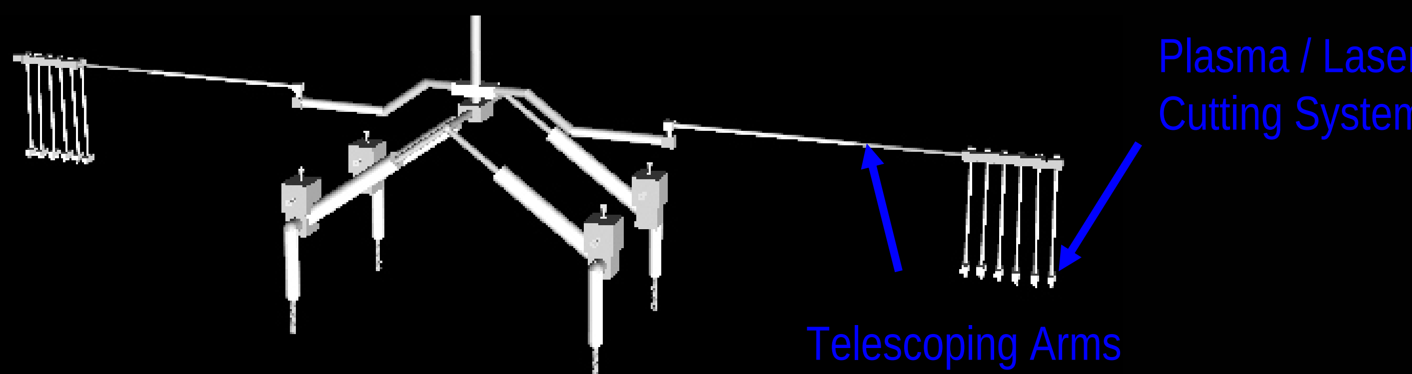
“Impact Screwdriver” Solid-fueled Pulsed Plasma Thruster to attach and disengage craft on NEO.





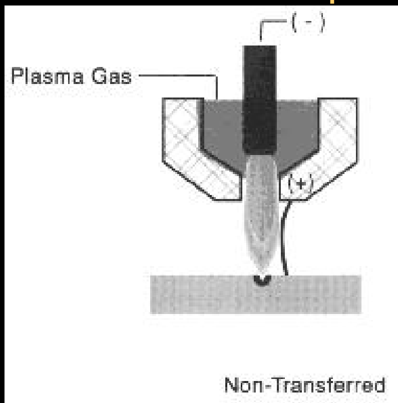
Plasma / Laser Cutter

- 50m radius Telescoping arms.
- 6 cutting arms operating as pairs
- 5 “cutter nozzles” per arm
- Nd-fiber laser beam through Truncated Aerospike plasmajet nozzle



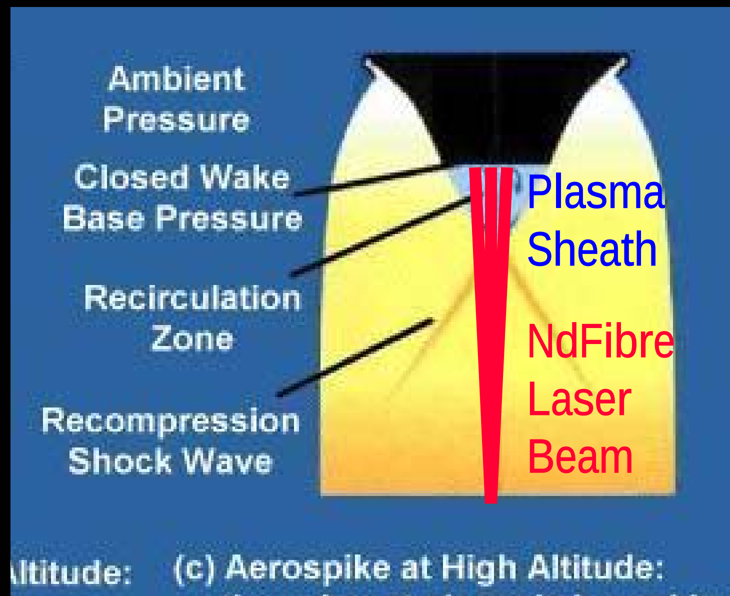
Cutting Method

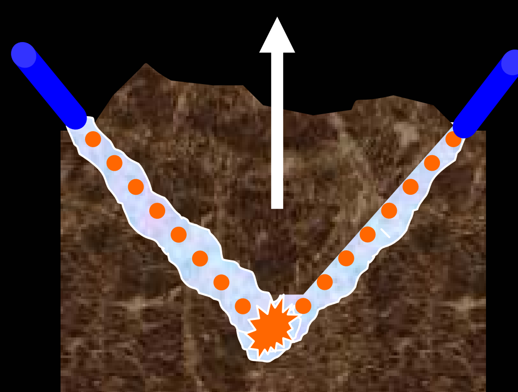
Non-transferred plasma jets



Mainly to provide pressure to
lift & drift cut blocks
to TFF cavity

Truncated Aerospike Nozzle





High Power-Fiber Laser

7kW ytterbium fiber laser

www.twi.co.uk/j32k/ getFile/ar_techgroups.html

Ytterbium fiber lasers

- Cut into rocks faster than most competing teechnologies
- High efficiency
- High power/mass

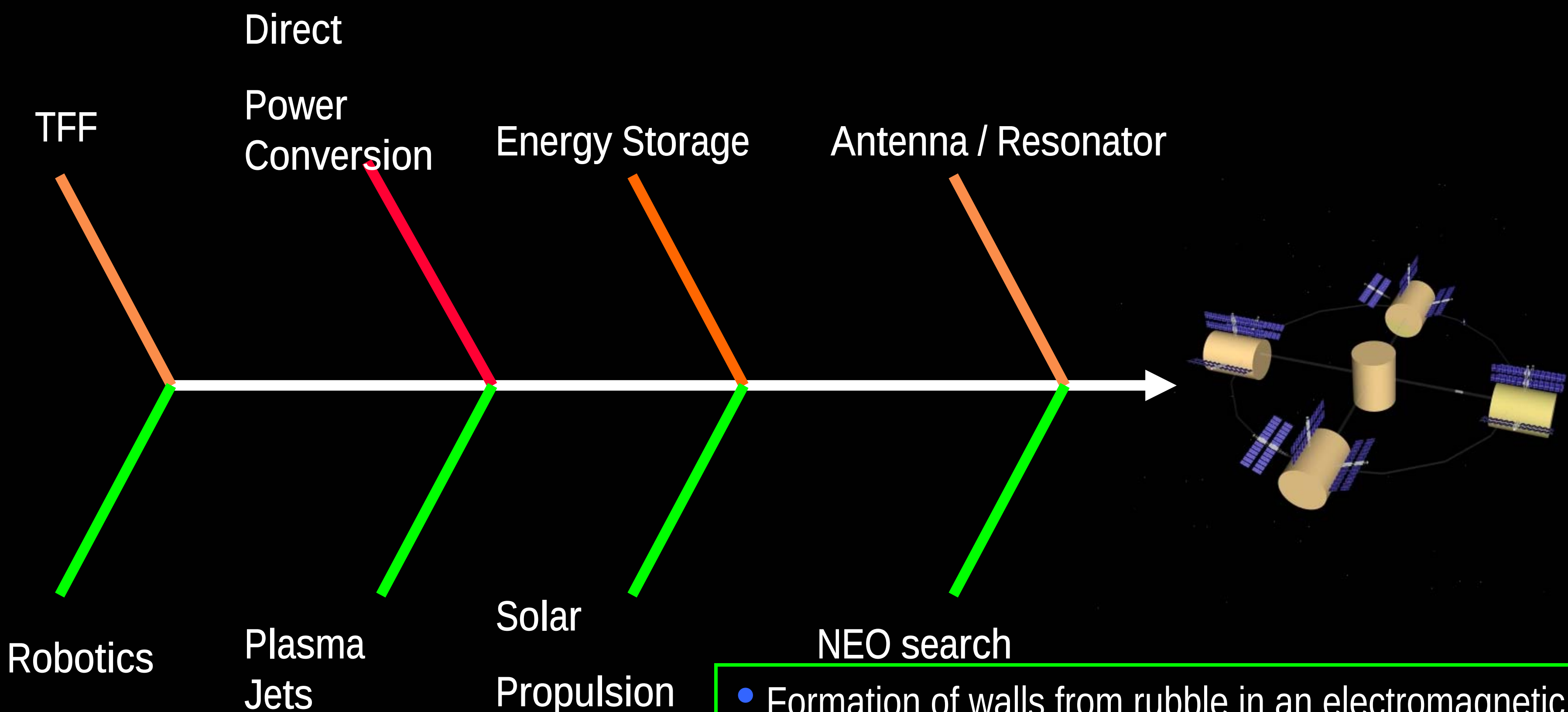
Cost / Complexity Metrics

- Total of 500,000 kg to LEO in ~ 20 cargo launches including mission testing.
  Final Construction System Mass ~ 200,000 kg at LEO. (ISS ~ 187,000 kg to-date)
- NEO Cutting: NEAP mission; Mars drilling eqpt. development.
- Robotics: ISS robotic arm; Mars rovers.
- Final Station assembly: ~ ISS robotic assembly

Impact of Recent Developments on Design Directions

- Opens way for 50,000 kg payloads to LEO
- Opens thinking for lunar-based resources in future steps
- Renewed interest in direct conversion of solar power

Technologies



- Formation of walls from rubble in an electromagnetic resonator
- Rendezvous and material extraction from an NEO
- Power Generation
- Sintering

Mass Estimation: TFF Constructor Craft

Technologies needed in 20 years to get TFF Constructor Craft mass below given delivered mass

Technology	**Present**	**Desired**		**% of total at**	
Desired total mass of one TFFC at L4		**50000 kg**	**25000 kg**	**50000 kg**	**25000 kg**
High-temperature,low-mass solar cell arrays	$3m^2/kg$	$3m^2/kg$	$3m^2/kg$	0.7%	1.5%
Thin-film solar collector	$100m^2/kg$	$250m^2/kg$	$200m^2/kg$	11%	24%
Low-mass power electronics for RF generation	120W/kg	240W/kg	6000W/kg	**61%**	**52%**
Conductors	10m/kg	20m/kg	100m/kg	11%	5%
Struts, braces etc.	0.277m/kg	1.38m/kg	2.77m/kg	16%	18%
Misc. systems, Propulsion + fuel allowance	10000 kg	5000 kg	5000 kg	10%	20%

Application Examples

1998SF36 (Itokawa)

- Diameter: ~500 meters
- Absolute Magnitude: +19.1
- Spectral Type: S(IV)
- Meteorite Analog: LL chondrites (2.7 g/cm^3)
- Size: (490±100)x(250±55)x(180±50) m
- Higher geometric albeido (0.32) suggests a rocky, smoother surface similar to other small near Earth objects
- Metallic iron mixed with iron- and magnesium-silicates?
- Closest Itokawa has been to Earth is 0.32 AU in 2001
- ΔV=1.09 km/s starting from the Earth's orbit (C_3= 0 km^2/s^2)

Dachwald & Seboldt: Solar-Sail Missions to 2000AG6 , 1989UQ, 1999AO1

Estimate ~ 7.6 years with 25,000kg craft and < 0.5 sq. km sail

Mission Architecture Status

Based on concept working as hypothesized:

1. Solar sail propulsion adequate to reach NEOs

2. Sail size dictates collector size: Abundance of power if resonator Q of 10,000 is achieved

3. System reduced to two types of craft

4. Cutting and formation system designs “close” for operation at NEOs
   Cutter time is limiting factor, but adequate for single-walled cylinder

5. Possibility of operating similar design at Mars orbit or near side of asteroid belt - being investigated

6. Uncertainties in power conversion and beaming equipment mass

Team

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Acknowledgments

Support in various forms from

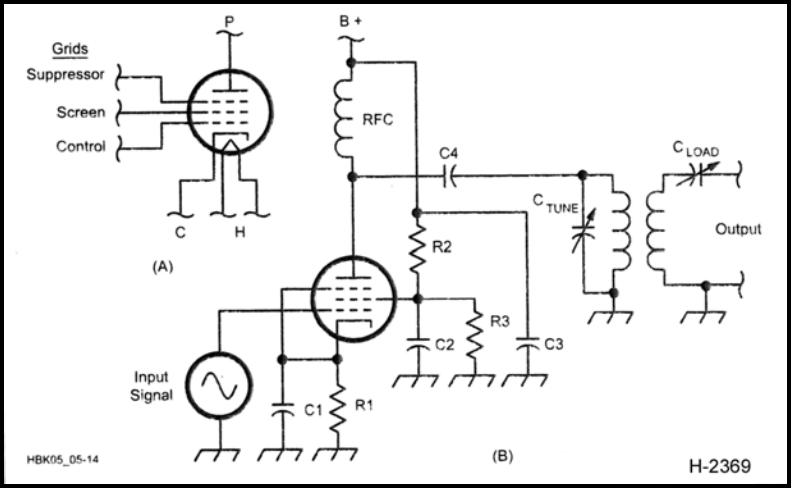
NIAC Phase 1 and Phase 2 grants (Dr. Robert Cassanova, Director)
NASA JSC / Texas Space Grant: Reduced Gravity Student Flight Opportunities Program (Burke Fort, Director)
NASA JSC / Texas Space Grant: ‘NASA Means Business” program
Georgia Space Grant Consortium
Georgia Tech Foundation
Sam Nunn School of International Affairs
G.I.T. and United Technologies student assistantships

Many G.I.T. student team members over the years

Recent / On-going Collaborations:

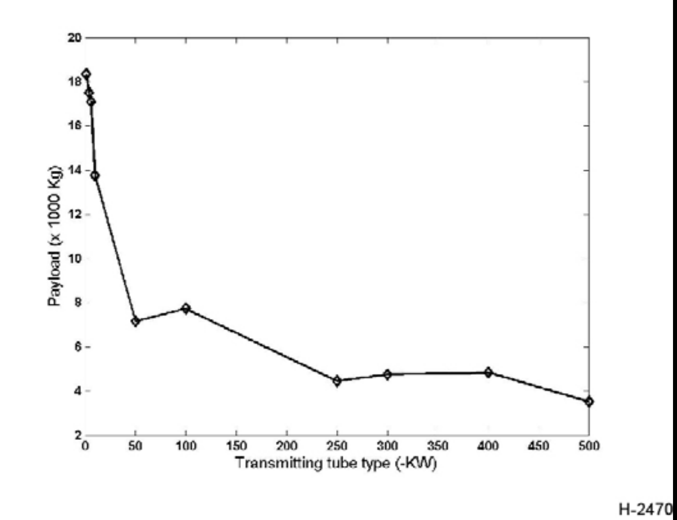
1. NASA Langley (GSRP program) Dr. Sheila Thiebault
2. CalTech/ JPL: Dr. Barmatz

Transmitting Tube



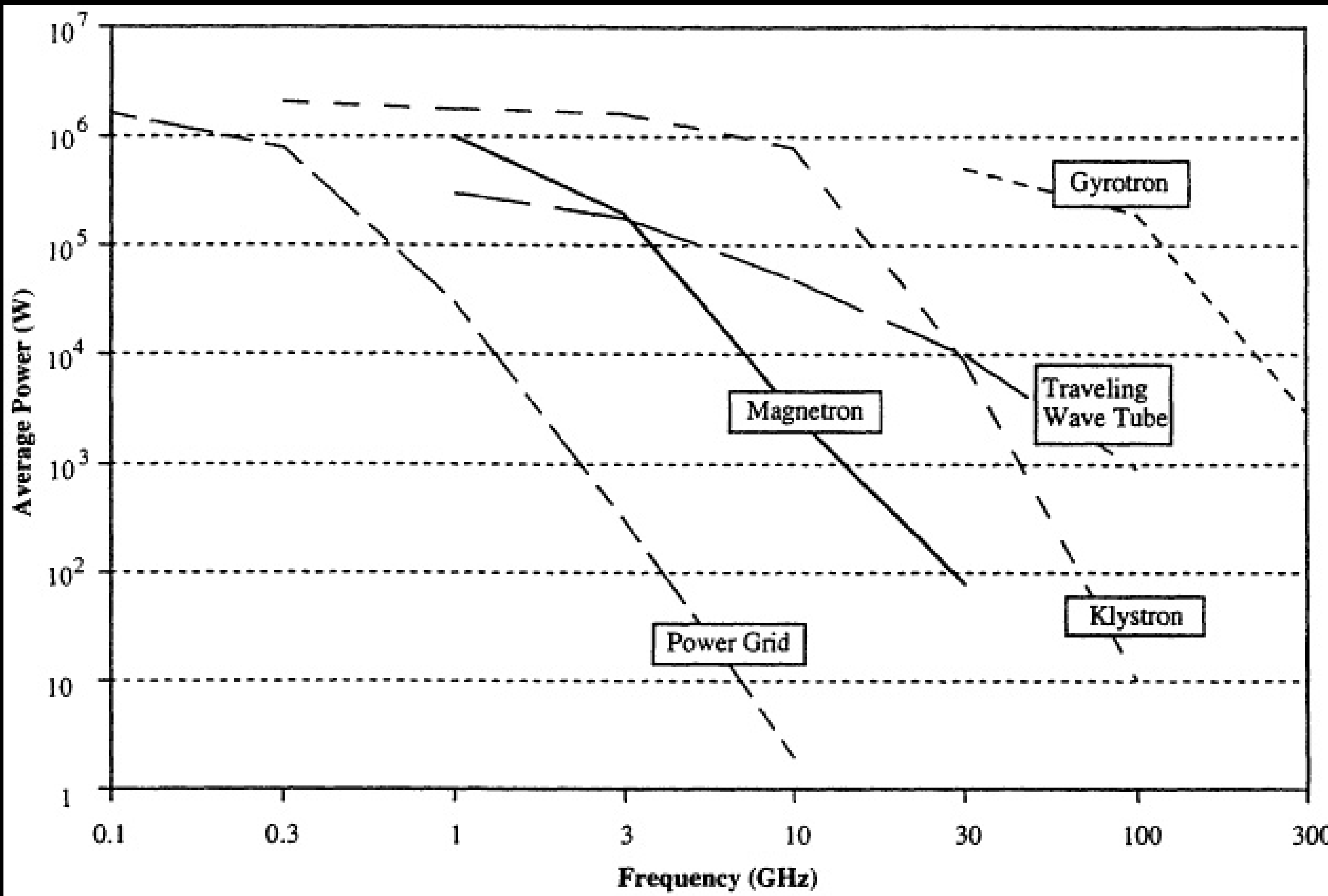
- This approach uses a single vacuum tube to construct a simple amplifier
- Tube designs can produce higher power than semiconductor devices

- Only a few manufacturers still producing tubes
- Weight of tubes needed to produce 25 MW can be predicted from existing tube data



Microwave Sources and power available

Magnetron is the most available source



Source: Microwave Processing of Materials (1994) (books.nap.edu)

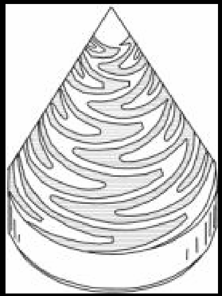
Direct Conversion of Solar Energy to Tuned Radio Frequency

Optical rectennae:

Theoretical conversion efficiencies are only at 48% with conventional heat-engine approaches, but efficiency upto 84.5% is projected using "optical circulators".

Substantial challenges remain in fabricating components at nano-scales needed to capture visible wavelength energy.

- small physical scales
- high frequencies,
- impedance matching of sections
- separation of orthogonally polarised components of power,
- bandwidth requirements



Conical sinuous antenna

References:

"EFFICIENCY OF ANTENNA SOLAR COLLECTION" Richard Corkish, Martin A. Green, Tom Puzzer and Tammy Humphrey, Centre of Excellence for Advanced Silicon Photovoltaics and Photonics, University of New South Wales, Sydney 2052 Australia, 2002

"OPTICAL RECTENNA FOR DIRECT CONVERSION OF SUNLIGHT TO ELECTRICITY".Berland, B., Simpson, L., Nuebel, G., Collins, T., Lanning, B., ITN Energy Systems Inc., Littleton, CO.

Space Solar Power Satellite applications: beamed radio or microwaves.

Defining the Relationship Between Cost, Benefits and Performance: Optimization and Costing Package for TFF

Costing References for Major Program Elements

	Major Element	Reference Projects / Sources
1.	Launches	NASA Return to the Moon program; Heavy-lift program: Delta IV and later.
2.	Antenna / spacecraft	Earth-based spacecraft industry standards
3	R&D costs	Current NASA programs
4.	Lunar solar arrays	Criswell.
5.	RockBreaker system	Earth-based mining industry; NASA Mars drill project
6.	Power Electronics	Earth-based power industry.
7.	Lunar propellants	NASA Return to the Moon; Heavy-lift program.
8.	Mission control	NASA mission control
9.	LEO-NEO tug	Size & cost based on standard propulsion design.

Near Earth Object Region Resources and Materials

NEO region chosen for test case: probable destination for exploration and prospecting. NEO composition is assumed similar to asteroid belt composition

C-type (Carbonaceous):	S-type (Silicaceous):	M-type (Metallic):
Includes more than 75 % of known asteroids	About 17 % of known asteroids	Rest of the known asteroids
Very dark with an albedo of 0.03-0.09.	Relatively bright with an albedo of 0.10-0.22	Relatively bright with an albedo of 0.10- 0.18
Composition is thought to be similar to the Sun, depleted in hydrogen, helium, and other volatiles.	Composition is metallic iron mixed with iron- and magnesium-silicates	Composition is apparently dominated by metallic iron
Inhabit the main belt's outer regions	Dominate the inner asteroid belt	Inhabit the main belt's middle region

Aten	$a < 1.0$ AU, $Q > 0.983$ AU
Apollo	$a > 1.0$ AU, $q < 1.017$ AU
Amor	$a > 1.0$ AU, $1.017 < q < 1.3$ AU

a = semi-major axis

Q = aphelion distance

q = perihelion distance

Specifications of HIRF Lab

Composed of three independent chambers, with the following minimum operational frequencies:

CHAMBER	L	W	H	FREQ
A	47'	23'	9.5'	80 MHz
B	23'	13'	9.5'	150MHz
C	9'	7'	9.5'	250 MHz

Maximizing Length of Cutter Arms

Nitrogen Mass flow rate = 20.016kg/h

Jet exit velocity = 1700-3200m/s

Force exerted on arm = 9.45 - 17.8N

Deflection in Arm:

$I = (\pi/64)*(d_2^4-d_1^4)$

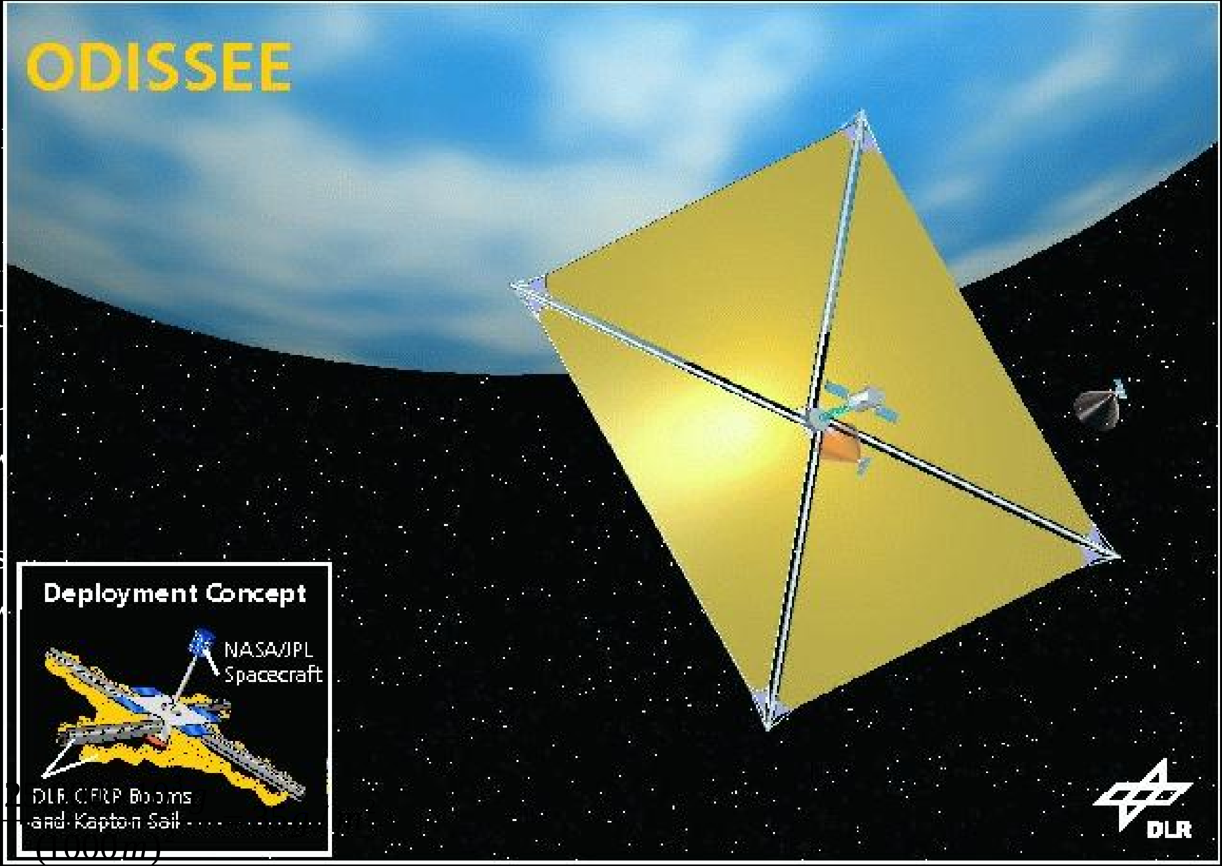
$\sigma = My/I$

$\delta = PL^3/3EI$

Maximum deflection experienced = 12.8cm << yield deflection of 287cm

Solar Sailcraft

- Significant weight reducti
- 85% reflectivity
- Application of carbon sai
  - 200 times thicker than t weighs the same
  - carbon fibers are woven material that is very low
  - Carbon makes sail able to 2500 degrees Celsius
  - Sail loading of 5 g/m² w
- Sailcraft loading



Solar Sail Spacecraft Architecture

Propulsion	Sail Film
Structures	Sail Support; Payload Attachment; Spacecraft Bus
Mechanisms	Sail Deployment
Attitude Control	Cg/Cp Shifters; Sail Vanes
Thermal Control	Active Control; Passive Control
Power & Avionics	Solar Array; Battery; Cables; Avionics

References

- Christou, A.A., 2003. The Statistics of flight opportunities to accessible Near-Earth Asteroids. Planetary and Space Science 51, 221-231.
- Kawaguchi, J., Uesugi, K.T., Fujiwara, A. and Kuninaka, H., 2005. MUSES-C, Its launch and early orbit operations. *Acta Astonautica* In Press, Corrected Proof.
- Dachwald, Bernd., Seboldt, Wolfgang., 2005. Multiple near-Earth asteroid rendezvous and sample return using first generation solar sailcraft, Acta Astronautica, In Press, Corrected Proof.
- Clark, Greg. Space.com - Breakthrough In Solar Sail Technology: http://www.space.com/businesstechnology/technology/carbonsail_000302.html

Hayabusa Mission

- Japanese Space Agency mission to NEA 1998SF36 (Itokawa)
- Launched on May 9, 2003
- Arrived at Itokawa in September and will hover around until November
- Sample extraction will be done at this time
- Will fire a 5 gram metal ball at the surface and collect pieces stirred up from the impact
- Expected return to Earth in 2007

- Selection of Itokawa as target NEO for Tailored Force Fields mission
  - Will gain significant insight into composition through Hayabusa mission

High Intensity Radiation Field Lab (HIRF)

Microwave Force Validation with JPL's 1992 Experiment

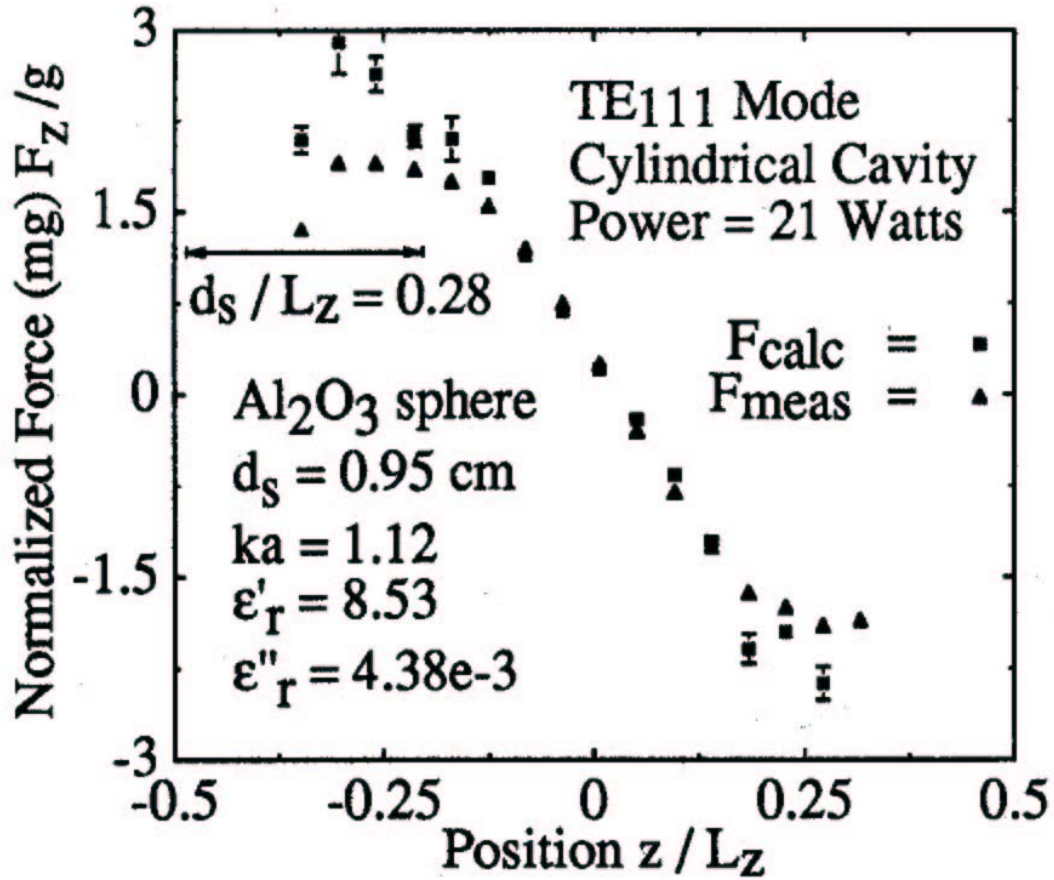
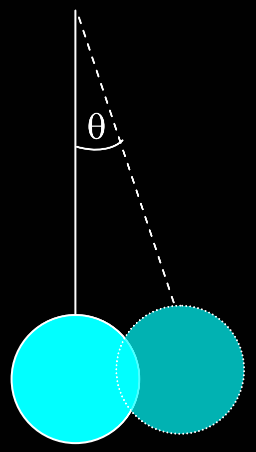


Figure 5. Comparison between measured and predicted axial force as a function of sample position.

JPL measured	18.75 μN
JPL predicted	24.5 μN
we predict	27.8 μN

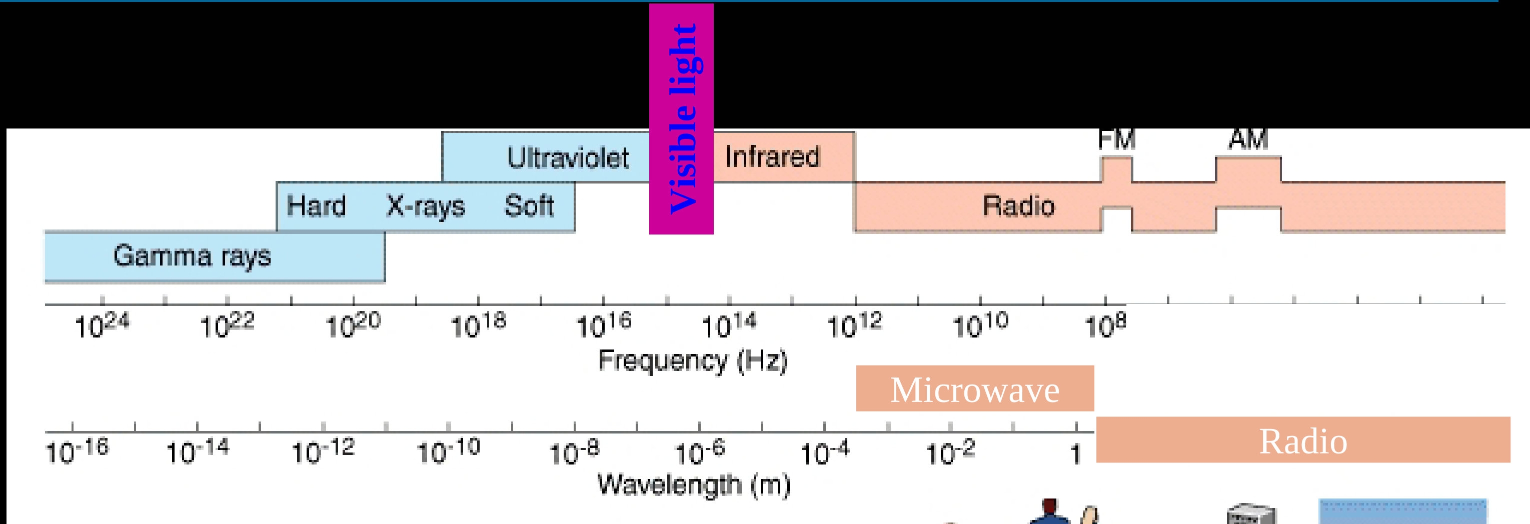
From:
McDonough, C. and Barmatz (1993)

Multiple Particles, Near Full-Scale Validation proposed by using NASA LaRC HIRF Lab



1) 2 particles to examine inter-particle forces
2) Multiple particles examine wall-formation capability
3) Effect of multiple particles on empty cavity field
4) Illuminate 2-particles in close contact held in place by field with high frequency beam to demonstrate surface sintering
5) Use of materials with properties close to Lunar Regolith. Material may be obtained from Dr. Thibeault (already in-discussion)

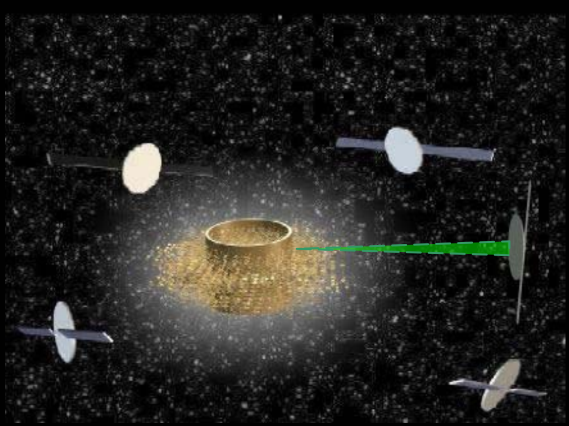
Frequency spacing of each major construction process



Heat curing (sintering)

Refine positioning

Shape formation



Shape formation: 10 - 100m

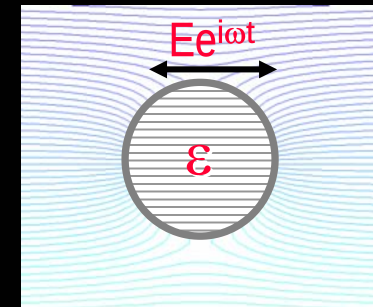
Refine positioning: 1 - 10m

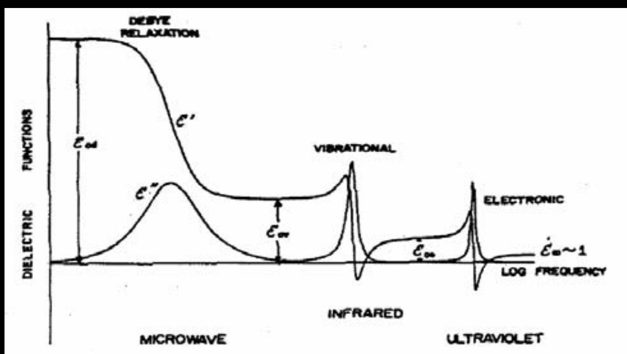
Sintering: 1 - 10 microns

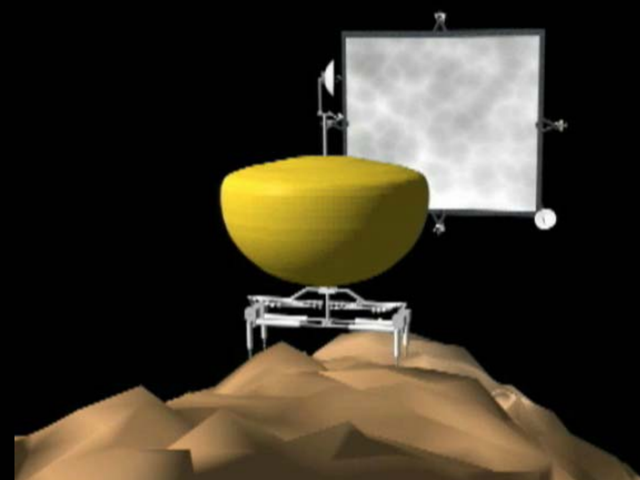
Dielectric Constant, ε

$$\varepsilon = \varepsilon' - i\varepsilon''$$

- ε' ability to penetrate and polarize material
- ε" ability to store energy in material
- ε"/ ε' ability to convert energy penetrated and stored into heat
- Both ε' and ε" are strong functions of frequency

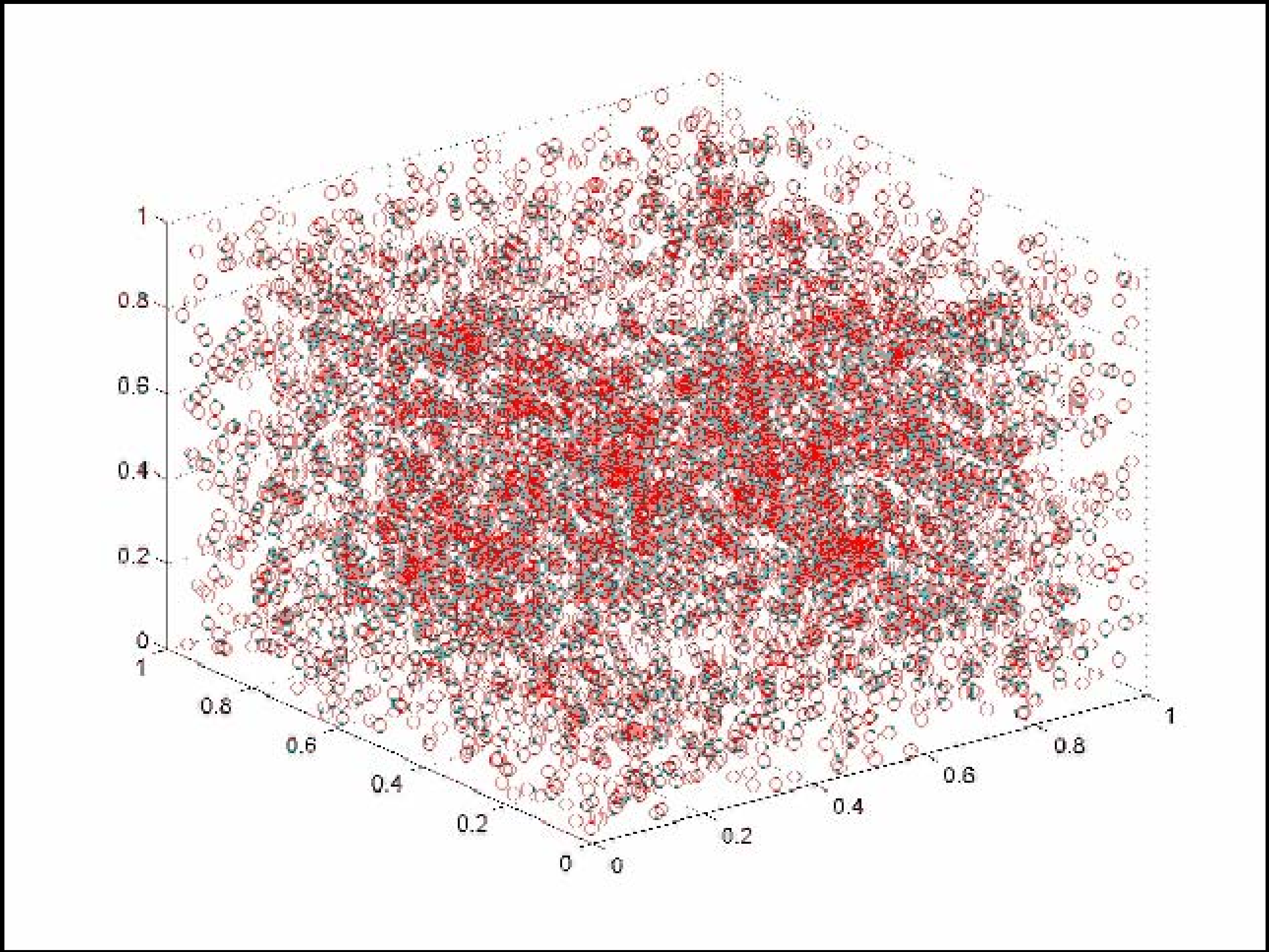






(Bohren and Huffman 1983).

Movement of particles into wall shapes: Matlab 2-d simulation: 110 mode



Electromagnetic Heating development from ε”

$$P_{dis} = \frac{1}{2}\varepsilon_o \varepsilon'' V \omega |E|^2$$ (W/m^3)

$$\rho_o c V \frac{dT}{dt} = P_{dis}$$

A dielectric material’s ability to absorb microwaves depends primarily on ε”

ε” Is a function of frequency and temperature. In some cases high temperatures could lead to thermal runaway.