Space Solar Power Technology Flight Demonstrations

SSP TIM at Glenn Research Center
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Guidelines for MSC 1 TFD Definition Studies

- **No fewer than two MSC 1 Points of Departure (POD) will be defined**
- **Guidelines for 1st POD:**
  - Traceable to the ISC MSC 4 concept
    - ISC MSC 4 provided the most cost-effective configuration analyzed to date
    - Characteristics include reflector/concentrator optics, shorter power distribution distances, no power transmission across joints, lightweight structures
  - Capable of accommodating either microwave or laser WPT options
  - Primary mission objective is demonstration of advanced solar power generation, PMAD, and WPT
  - Capable of providing opportunities for several technology experiments on the spacecraft bus
    - Demonstrate applicability to non-SSP missions
    - Including selected space assembly, maintenance and servicing experiments
    - To minimize risk to MSC 1's primary mission objective, technology experiments should not be critical to mission success
- **Guidelines for 2nd POD:**
  - Open to definition
    - Could be new POD that shows promise of being as cost-effective as ISC
  - Must meet established guidelines of MSC 1
  - Can be ambitious, but must be technically feasible

Model System Category 1
[TRL 7 in 2006-2008+ Timeframe]

- **Description:** **Initial SSP-technology space platform with WPT, SPG and PMAD and integral self-transport systems**
- **Primary Function:** **Wireless Power Transmission (Local) and Advanced On-Board Power**
- **Secondary Functions:** **Self-Transporting**
- **Power Level:** **100 kW to 150 kW, total power**
- **Technology:** **Significant advances on the 2000/2001 state-of-the-art**
  - including solar power generation at ~250 W/kg (e.g., with ~30% efficiency if non-thin film)
  - individual arrays @ 25-50 kW
  - WPT with magnetron or relatively modest efficiency solid state for a transmitter that is physically pointed (with limited electronic beam pointing); "pointed" rectenna without high-gain for receiver
  - high voltage SPG and PMAD; etc.

  Laser WPT options are also suitable*

- **Potential Applications:** **On-Board Power; Local Space-to-Space WPT for various Applications; Space Science Radar; Space Transfer Stage for Outer Planet or Other Science Missions; Robotic Mission Primary Spacecraft; Space Transport "Tug"; Space-to-Space or Ground WPT demonstrator**
- **Assumptions:** 5 year lifetime; Minimal on-orbit assembly; Single shuttle launch; 300 V main bus; typical Hall thrusters, Xenon, direct drive

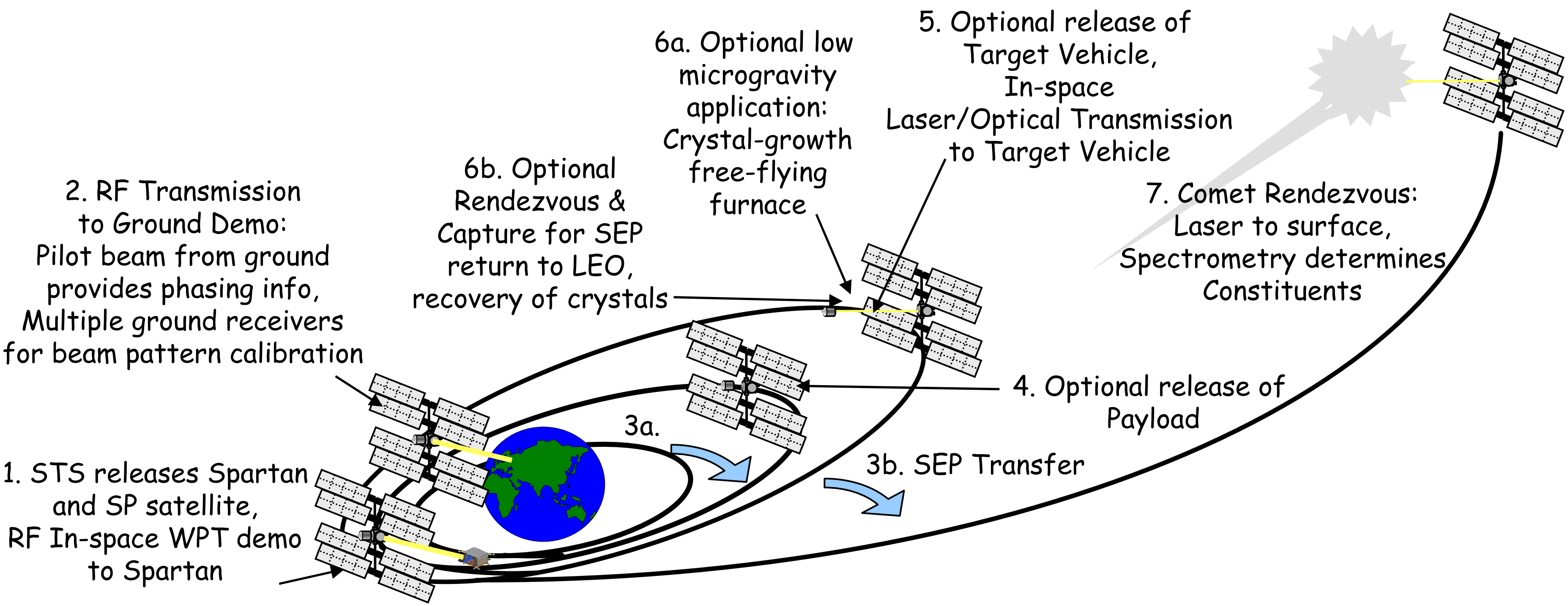
* Added 10/2001

Potential Technology Experiments
(Non-Mission-Critical)

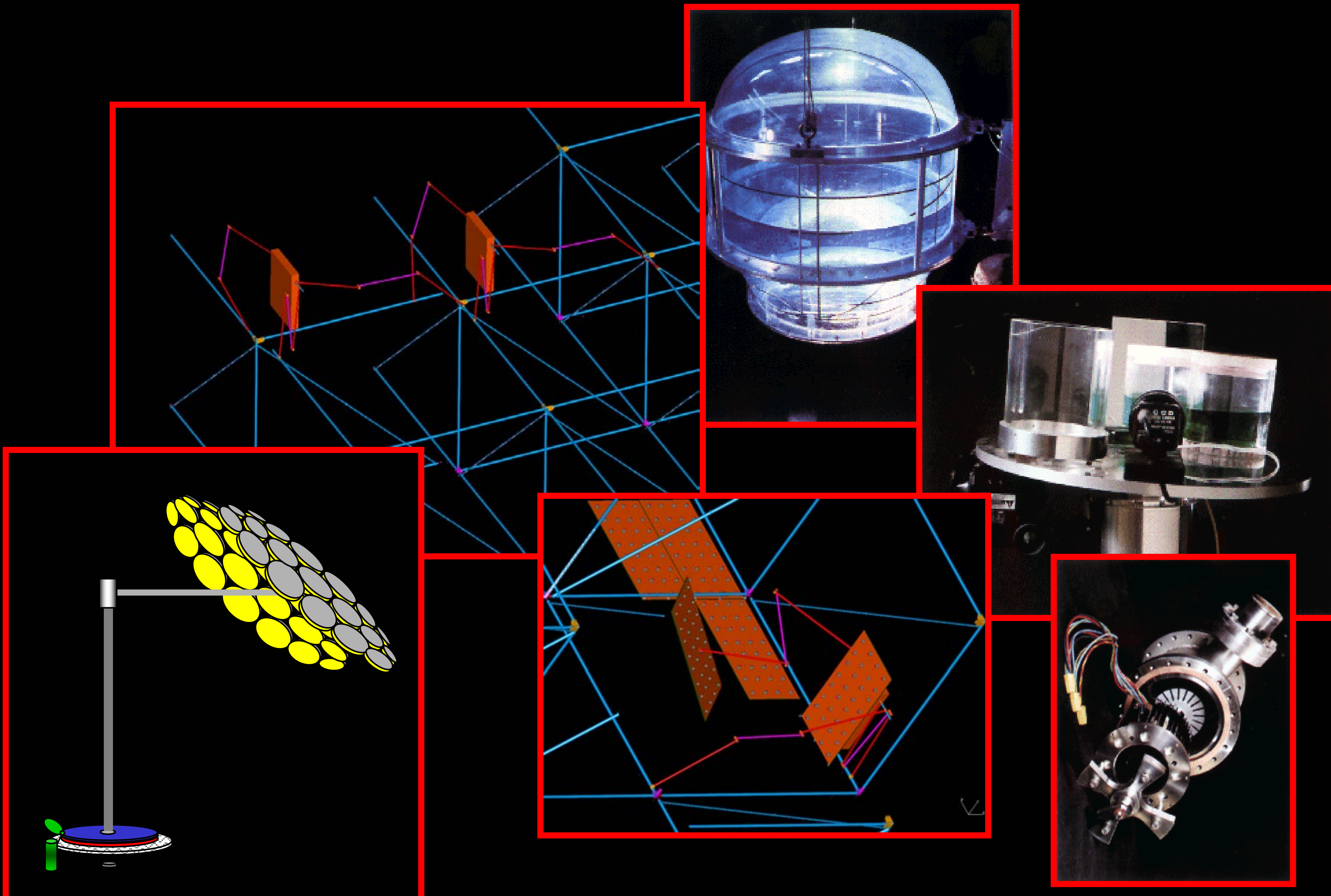
- Space assembly and robotics
- Structures and deployment
- Propulsion technologies, such as electric and solar thermal propulsion
- Very advanced PV systems
- High voltage PMAD
- Energy storage technologies
- Alternative WPT technologies
- Large diameter (5m) RF transmitter
- Advanced materials
- Innovative thermal management technologies
- Attitude control and simulation on smaller spacecraft
- Microgravity manufacturing
- Propellant production and storage

TFD Mission Scenario Options

- 100 kW Technology Demonstrator could perform a variety of mission scenarios
- TFD provides an energy-rich platform for a variety of technology experiments

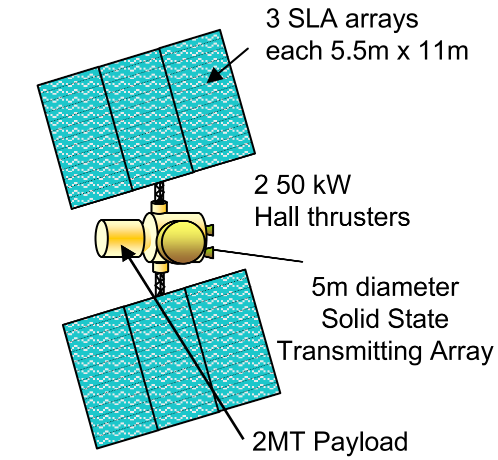


Some Technology Experiment Options



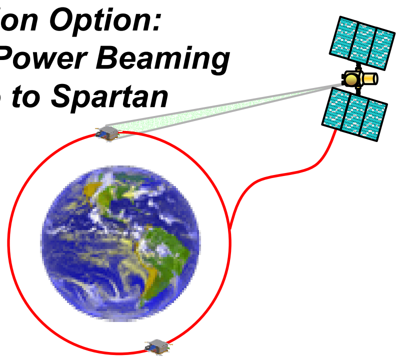
MSC1 Concepts (SERT)
100kW-Class Near-Term Demo

Abacus Concept



7.5MT launched mass
5.9 MT orbited mass

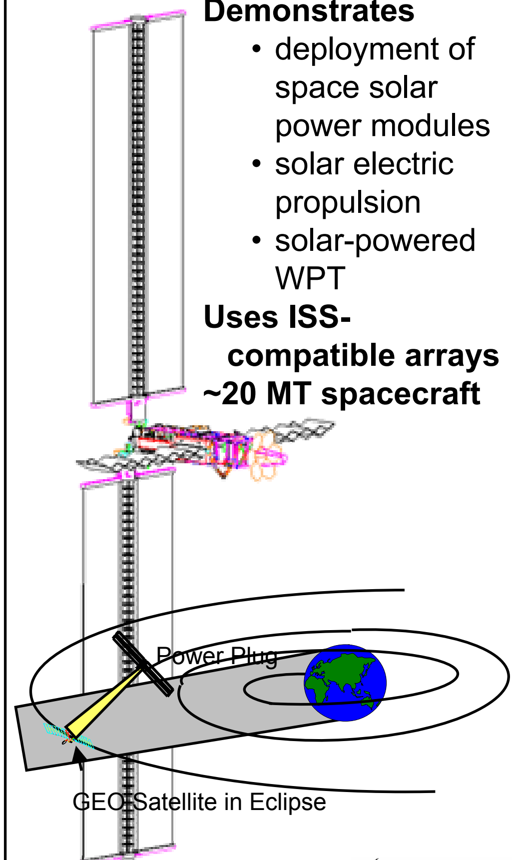
Mission Option:
In-space Power Beaming
Demo to Spartan



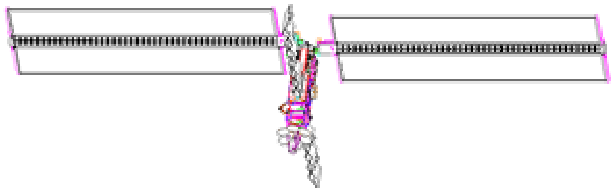
Boeing's MSC 1 / Power Plug
Space-to-Space Power Beamer

Demonstrates
- deployment of space solar power modules
- solar electric propulsion
- solar-powered WPT

Uses ISS-compatible arrays
~20 MT spacecraft



Boeing's MSC 1 / Power Plug
Lunar and Mars Power Spacecraft



- **Objective: provide power or illumination capability at Moon or Mars**
- **100kW arrays based on ISS solar array structure**
- **Could provide ~17kW on Mars surface**
- **Mass Estimates**
  - 5.8MT dry
  - 8.6MT initial mass for lunar mission
  - 10MT initial mass for Mars mission
- **One Delta IV Heavy launch**

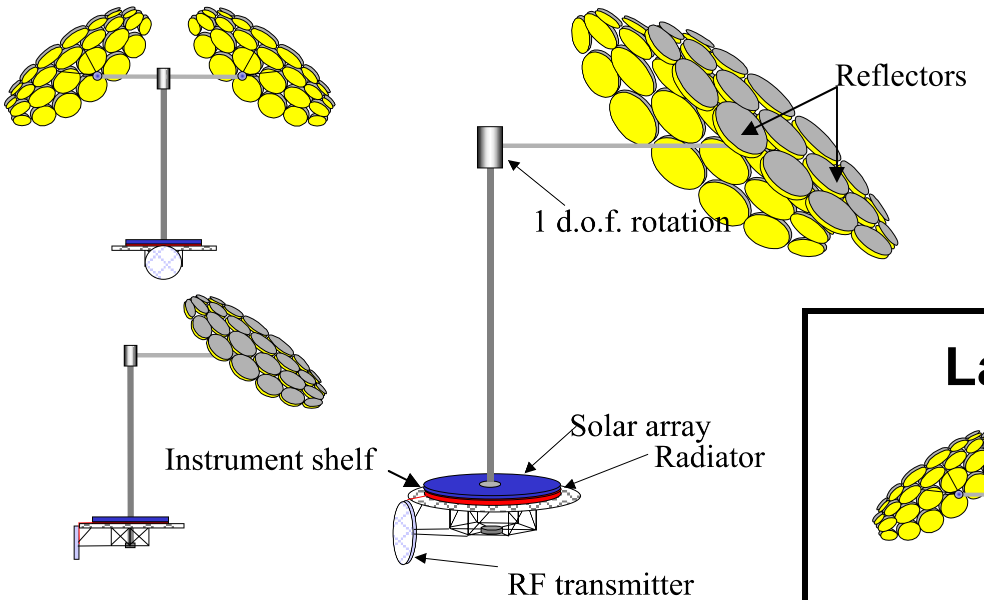
100kW SSP Technology Flight Demonstration

System Design Objectives

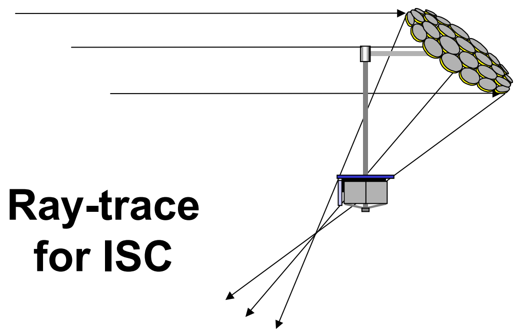
- **Total spacecraft bus dry mass**
  - Approximately 5000 kg
- **Total technology flight experiments dry mass**
  - Approximately 2000 kg
- **Total propellant mass**
  - Approximately 2000 kg
- **Total program/project cost**
  - Less than ~$500M (spacecraft bus)
  - Approximately $250M (technology flight experiments)
  - Approximately $250M (supporting technology development and ground demonstrations)
- **On-board power: 5-10 fold advance on state-of-the-art**
  - 100-150 kW (on-board power)
  - Conversion efficiency: greater than 30%
  - Specific mass: greater than 250 Watts per kilogram
- **Operational voltage: 10-fold advance on state-of-the-art**
  - Approximately 300-500 V

ISC-Derived 100 kW Class Platform

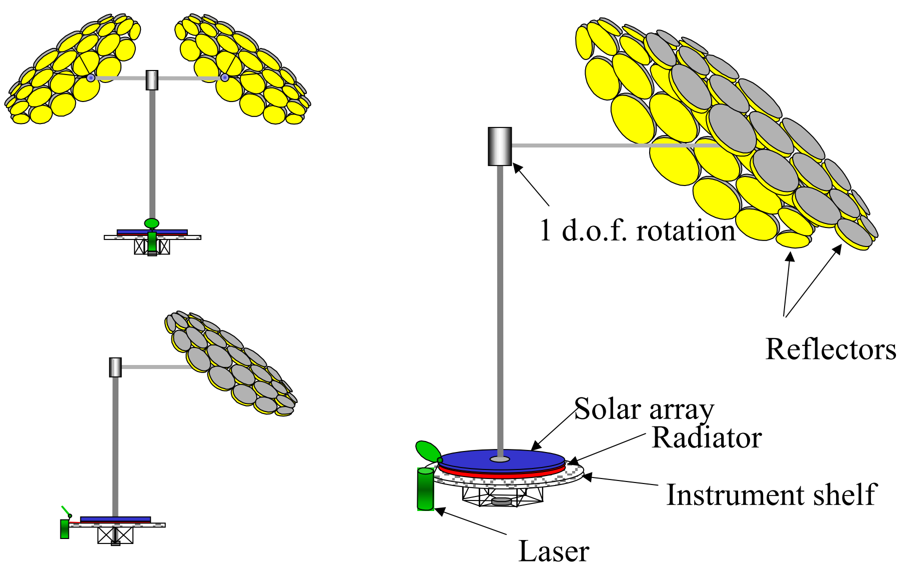
Microwave WPT ISC Configuration



Ray-trace for ISC



Laser WPT ISC Configuration



An Employee-Owned Company

ISC-Derived 100 kW Class Platform
Configuration Assumptions

- Spacecraft orbit is sun-synchronous or geo-synchronous
- Launch package must be compatible with Space Shuttle payload bay dimensions
  - Mirror diameter (minor diameter if elliptical) ~4 m
- Mirrors rigid and not necessarily planar
- Solar arrays and transmitter may be folded
- Transmitter uses heat pipes to eliminate 10:1 center hot spot caused by Gausian power distribution
- Transmitter and solar array temperatures compatible with current state-of-the-art materials
- Laser transmitter an option that could be investigated

Don Perkinson
Sverdrup Corp.
Huntsville, AL

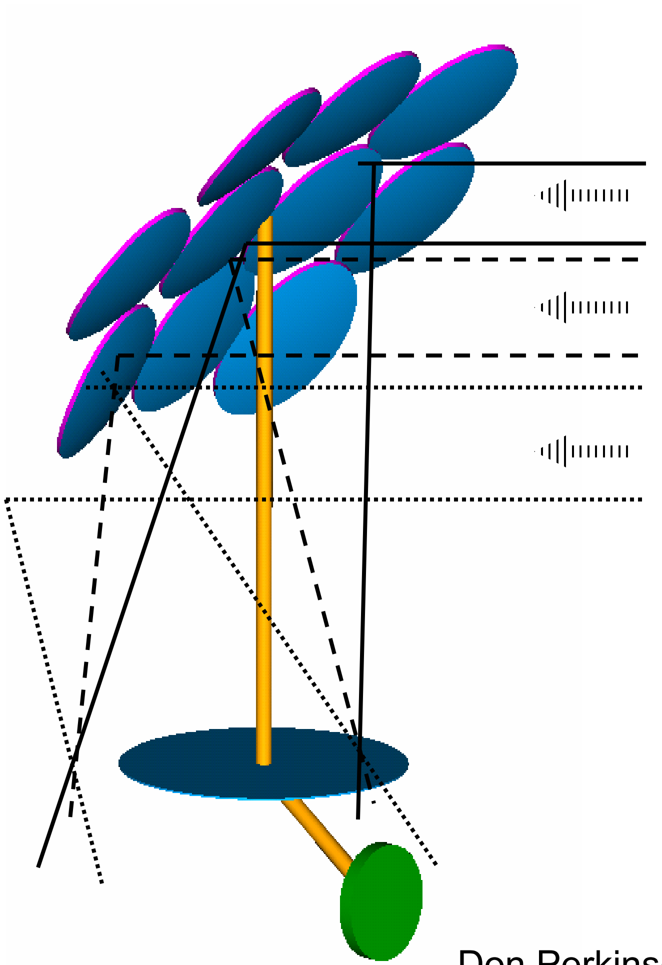
ISC-Derived 100 kW Class Platform
Options for Addressing Uneven Illumination of Solar Arrays

Issue

- Convex mirrors used to produce image size equal to solar array
- Each mirror illuminates entire solar array

Options

- Two options for eliminating elliptical image caused by 45º tilt of mirrors
  - **Use elliptical mirrors with spherical curvature so that image at 45º is circular**
  - **Use circular mirrors with different curvatures vertically and horizontally to spread elliptical source into a circular image (i.e. astigmatic mirrors)**



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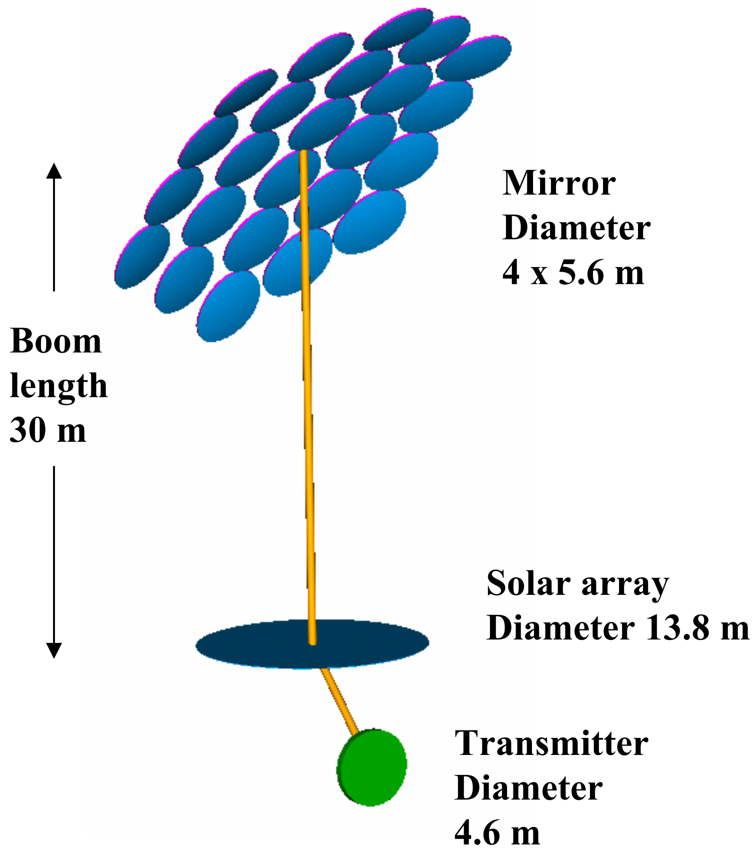
Huntsville, AL

ISC-Derived 100 kW Class Platform
Astigmatic Circular Mirrors Configuration

- Elliptical mirrors (24) with spherical curvature produce circular reflection on array when bending light 90º (i.e. set at 45º), & will fit in STS bay
- Convex mirror produces reflection equal in size to solar array
- Array hot-spots due to partial image overlap eliminated
  - **All images overlap 100%**
  - **Shadow of central post will cause some variation in illumination of array**



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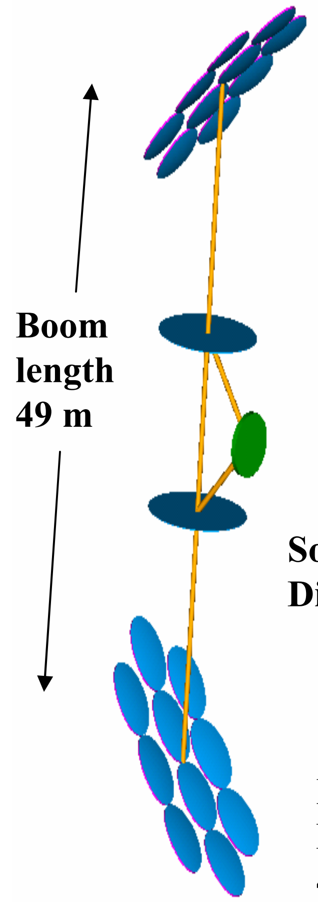
ISC-Derived 100 kW Class Platform
Elliptical Mirrors

- Elliptical mirrors (20) with spherical curvature produce circular reflection on array when bending light 90º (i.e. set at 45º), & will fit in STS bay
- Convex mirror produces reflection equal in size to solar array
- Array hot-spots due to partial image overlap eliminated
  - **All images overlap 100%**
  - **Shadow of central post will cause some variation in illumination of array**



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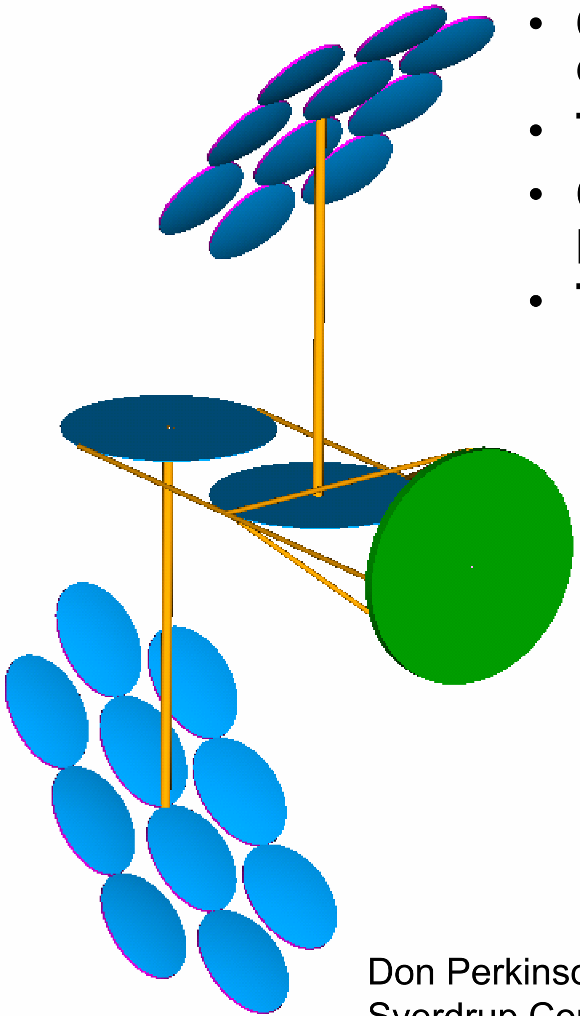
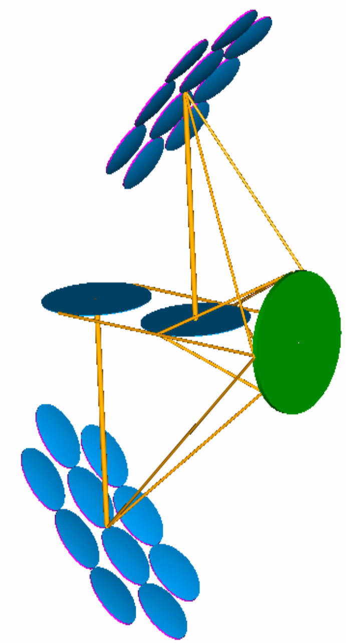
ISC-Derived 100 kW Class Platform
Offset 100 kW ISC



- **Offset solar arrays provide highest heat rejection capability**
- **Transmitter points to earth**
- **Clamshell masts are perpendicular to the orbital plane**
- **Transmitter diameter enlarged**
  - Power density reduced
  - Temperatures lowered
  - Heat pipes eliminate 10:1 power density hot spot due to Gaussian distribution



Mast stabilization brackets added

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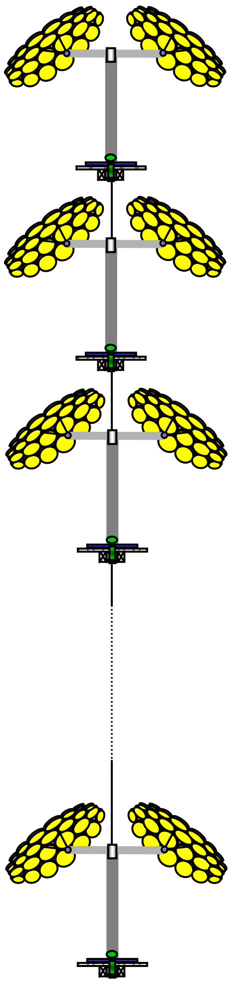
ISC-Derived 100 kW Class Platform
Benefits and Issues

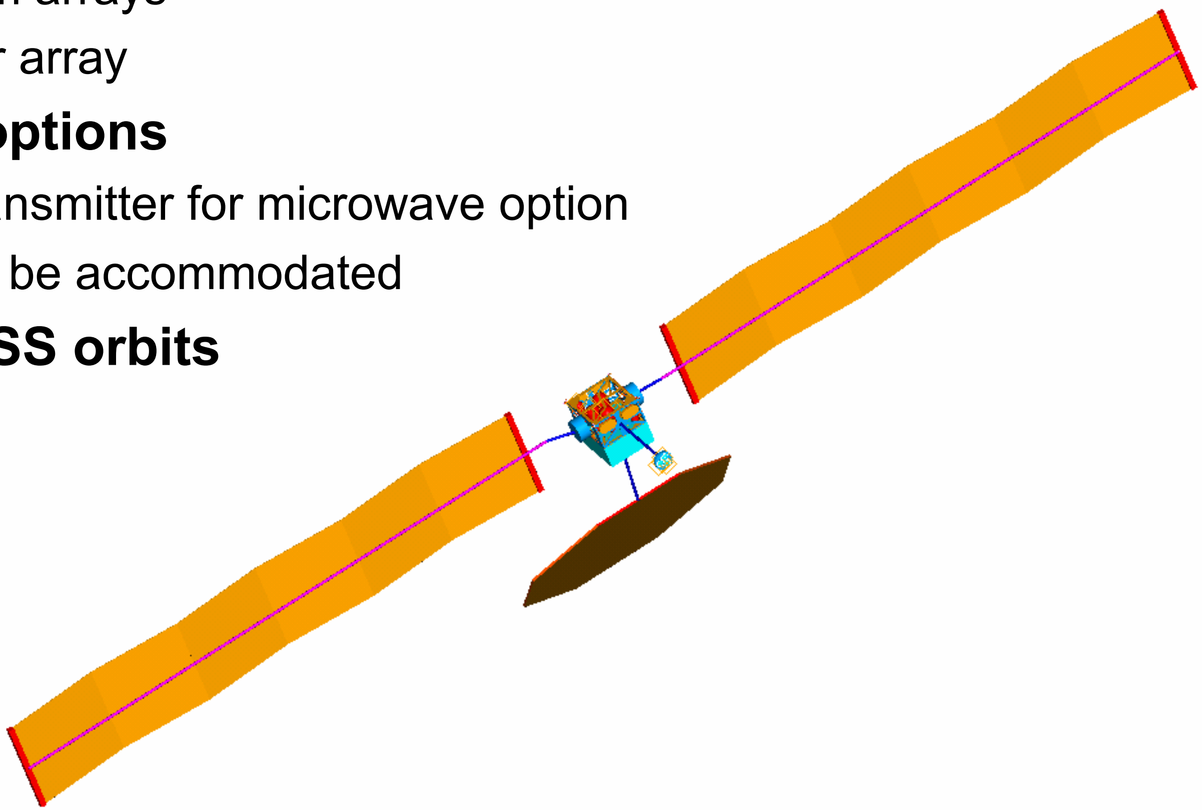


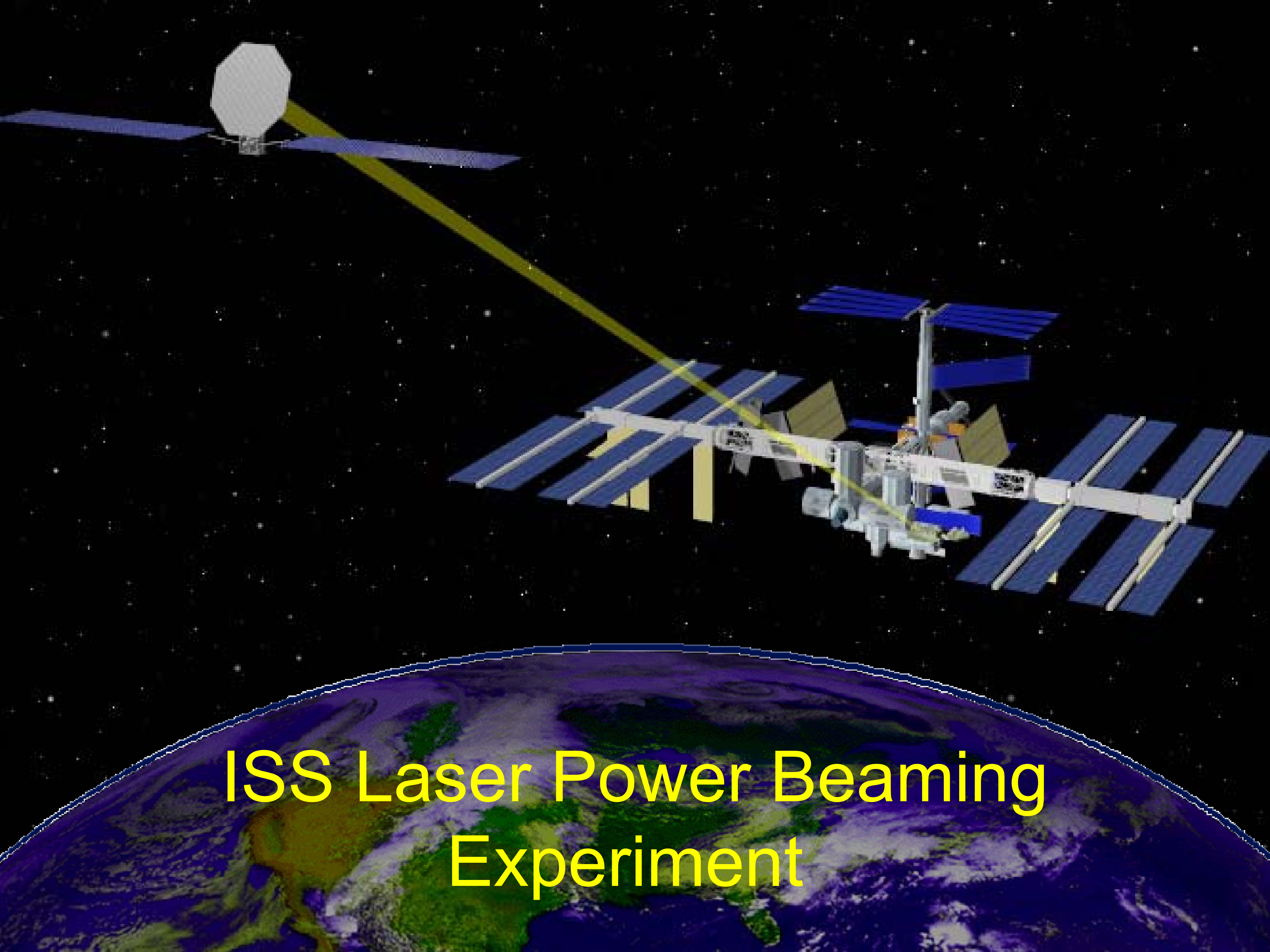
Modular laser configuration

- Benefits
  - Traceability to MSC-4 ISC configuration
  - Laser versions can be stacked to produce MSC-4 configuration
  - Only two inflatable reflectors needed for solar concentration
  - Reflector surface accuracy not particularly critical
  - Provides view to deep space for S/A thermal management
  - Axisymmetric S/A simplifies reflector pointing and control
  - Other ISC attributes: small array, short cabling runs, no slip joint, lightweight structure, etc.
- Issues
  - Conventional S/A's more easily deployed, controlled, and cooled
  - P/L accommodation is challenging (but doable)
  - Possibility for non-uniform illumination of S/A with associated SPG, PMAD and thermal issues
  - Proximity of transmitter to S/A increases cooling problem for both
  - Stacking of systems impedes S/A thermal radiation to space

Planar Array 100 kW Class Platform
Second POD

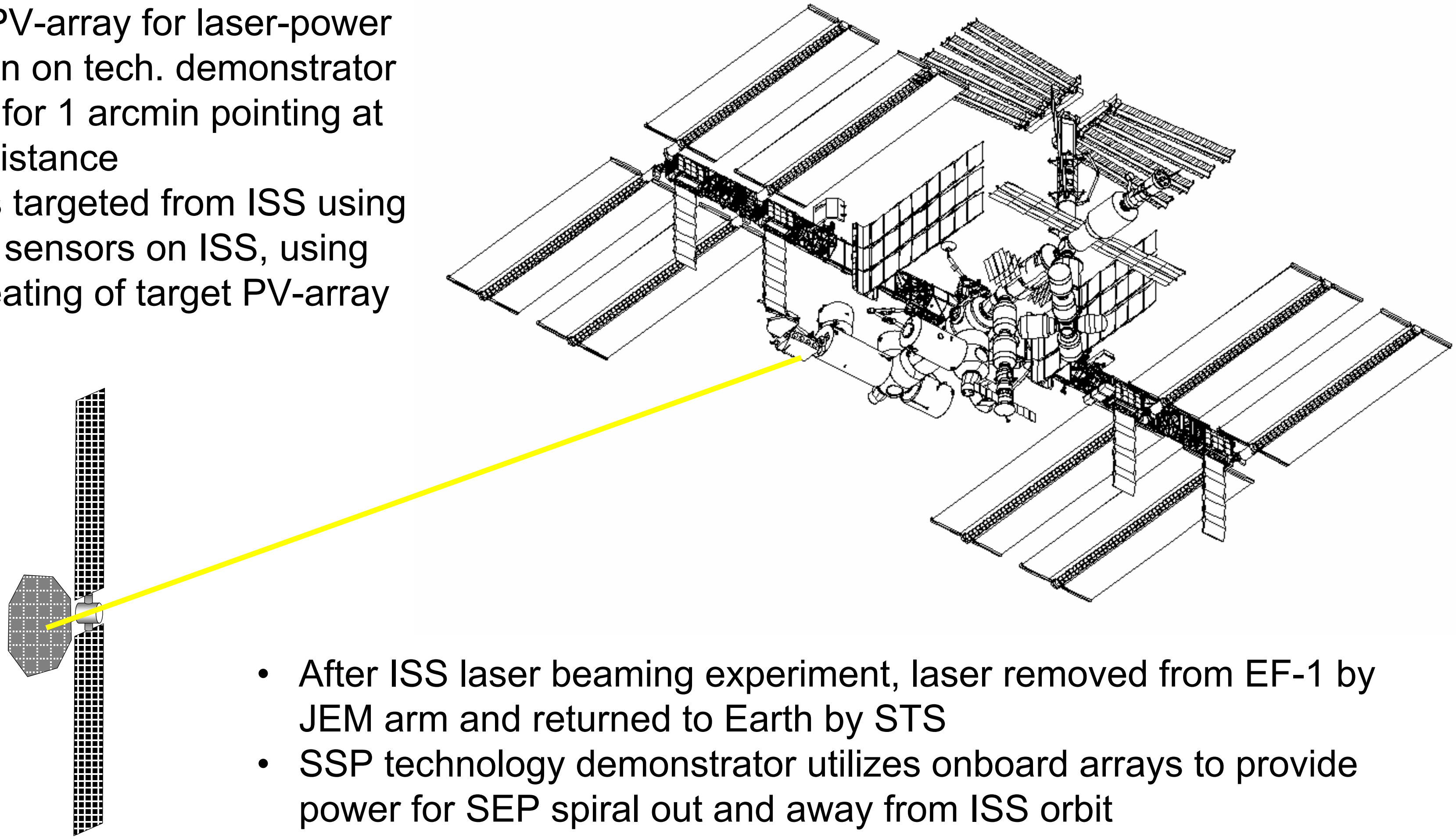
- **Standard spacecraft bus**
  - Higher voltages
- **Advanced planar photovoltaic arrays**
  - Two 5.5 m x 30 m arrays
  - 50 kW output per array
- **WPT technology options**
  - 11m diameter transmitter for microwave option
  - Laser option can be accommodated
- **Compatible with ISS orbits**




ISS Laser Power Beaming
Experiment

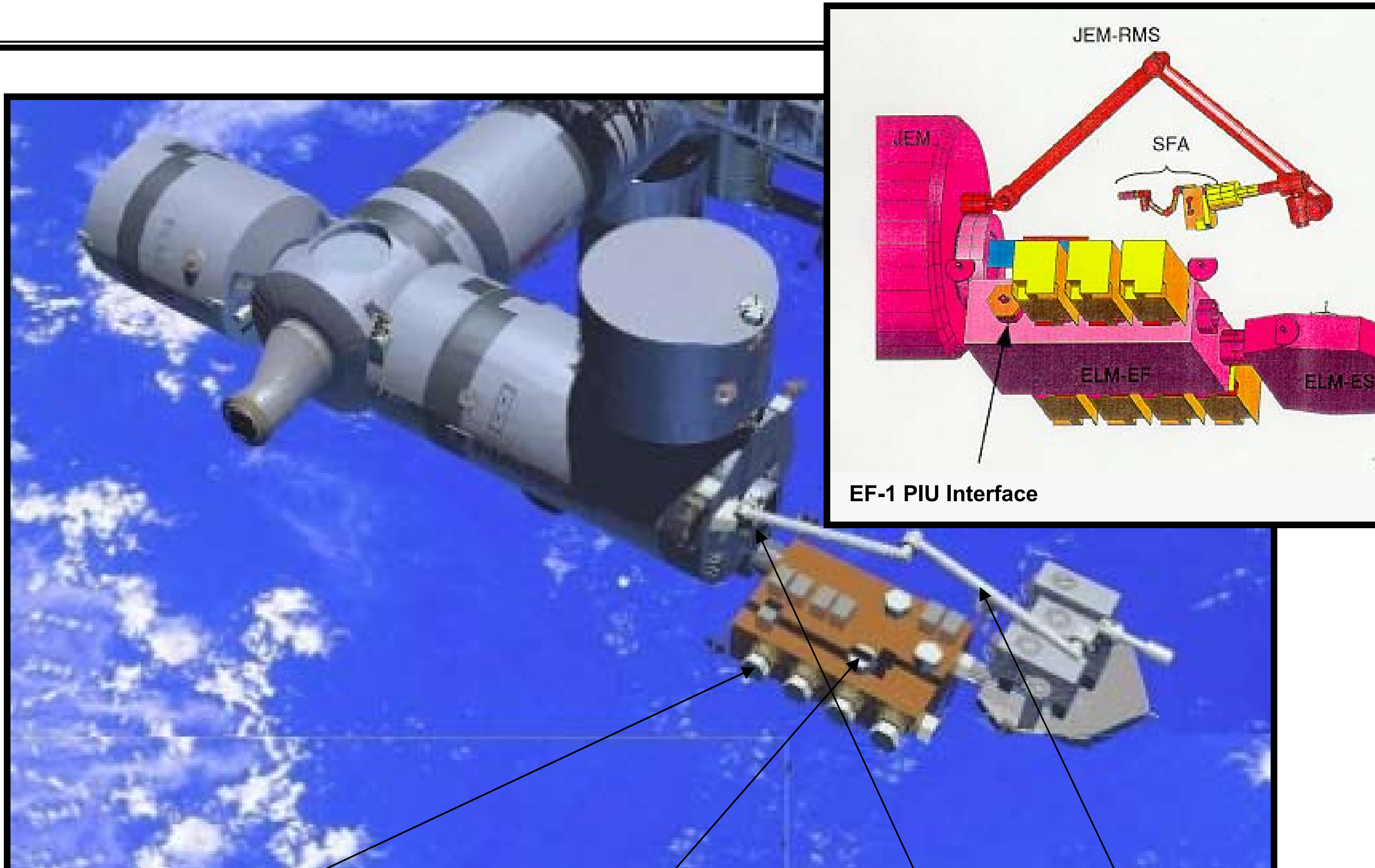
Laser Power Beaming Experiment From ISS to SSP Technology Demonstrator

- JEM-EF site 1 utilized for laser unit on ISS
- 5 kWe power at EF-1 provides ~ 1 kWe beamed energy to co-orbiting SSP tech. demonstrator
- SSP tech. demonstrator orbits ahead of ISS at a distance of 10-20 km
- Tuned PV-array for laser-power reception on tech. demonstrator is sized for 1 arcmin pointing at 20 km distance
- Beam is targeted from ISS using infrared sensors on ISS, using edge heating of target PV-array



- After ISS laser beaming experiment, laser removed from EF-1 by JEM arm and returned to Earth by STS
- SSP technology demonstrator utilizes onboard arrays to provide power for SEP spiral out and away from ISS orbit

JEM-EF Laser Power Beaming Site



EF-1 PIU Interface

EF-1
Laser Beaming Site

EF-11
Temporary Parking Site

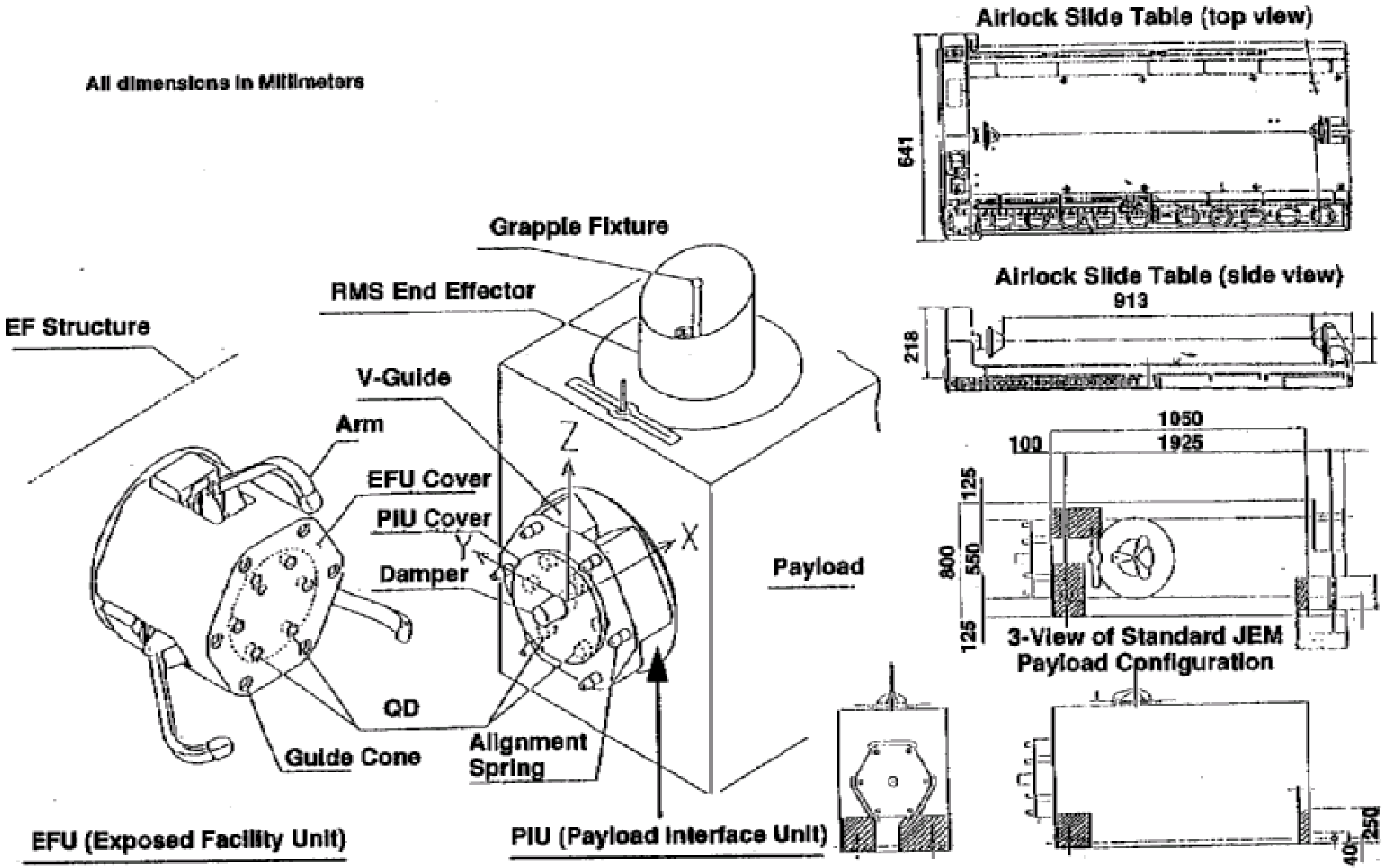
JEM Airlock

JEM RMS

JEM-EF Laser Power Beaming Site

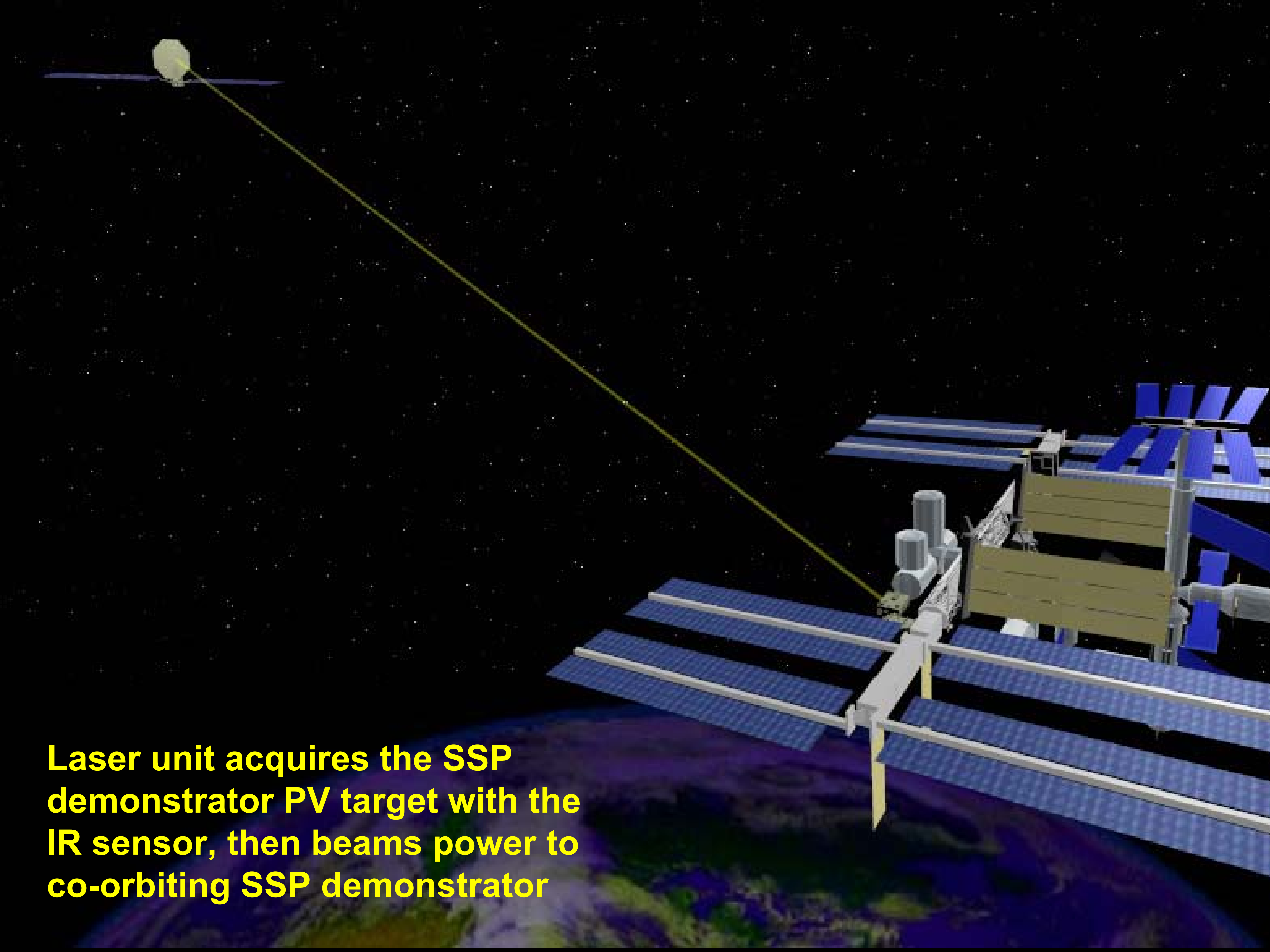
- Forward-oriented EF-1 site selected for wide field of view to co-orbiting SSP demonstrator ahead of ISS, and 5 kWe power and thermal management provided by EFU at site 1
- Slide table interface will be included in laser unit design to enable passage of unit from pressurized volume to the station exterior, without EVA
- JEM grapple fixture will be included in laser unit design to enable transport from slide table to the EFU mounting location
- PIU interface will be included in laser unit design to enable attachment of unit to the JEM-EF platform
- JEM arm will return laser unit through airlock to pressurized interior after beaming experiment
- Mechanical stops will be included in laser pointing mount design to limit regions of laser beaming to field of view in front of ISS
- Laser beaming will be enabled only by IR identification of PV-array edges on tech. demonstrator

Standard JEM-EF Payload Interfaces



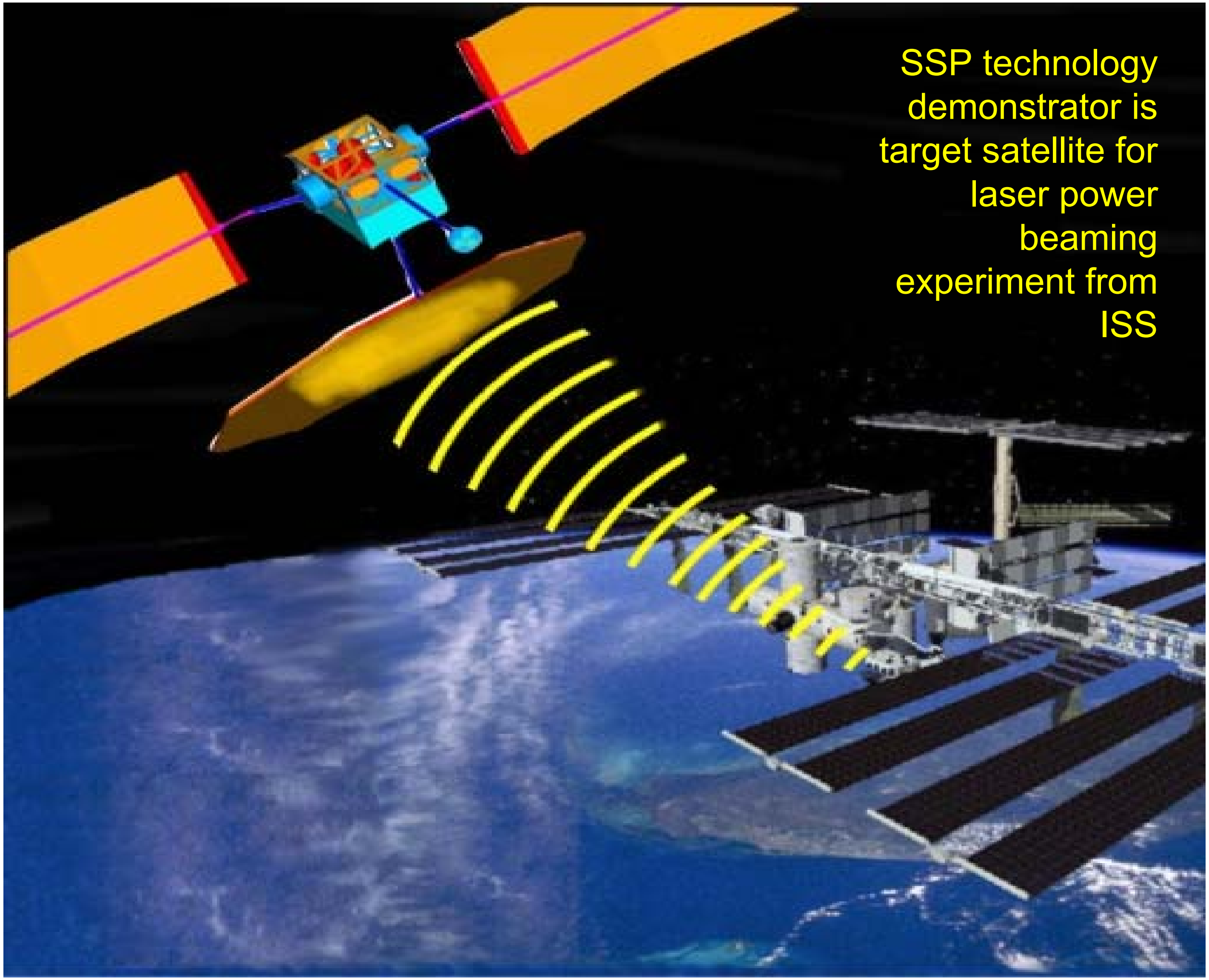
Standard JEM-EF Payload Interfaces

- **Dimensions consistent with airlock volume constraints**
- **Slide Table Capture Mechanism Interface**
  - Mechanical interface only
  - IVA crew member loading and unloading of laser unit with slide table “ski binding” performed manually
  - JEM RMS performs external loading and unloading of payload
- **Grapple fixture for manipulation by JEM main arm**
  - Grapple fixture is smaller than US-Canadian version
  - Used to transport payload between airlock and platform attachment point (EFU)
- **PIU for installation at EFU**
  - Versatile, high capacity structural and utility connection for JEM-EF payloads
  - EFU is “socket’ into which payload’s PIU is “plugged”


Laser unit acquires the SSP demonstrator PV target with the IR sensor, then beams power to co-orbiting SSP demonstrator

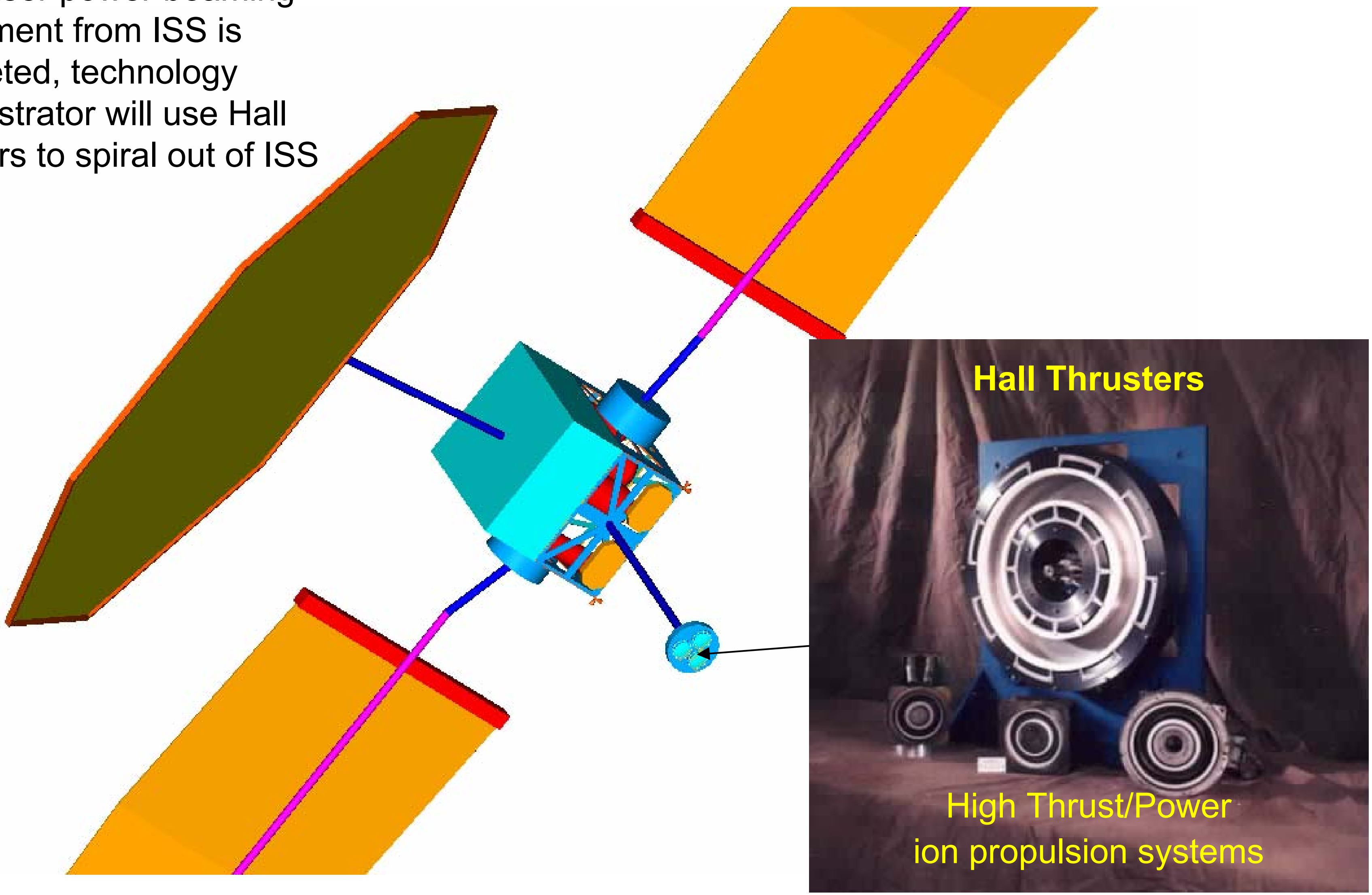
Planar Array 100 kW Class Platform

- 12m diameter tuned PV-array for laser-power reception is sized for 1 arcmin pointing at 20 km distance from ISS
- Beam is targeted from ISS using infrared sensors on ISS, using powered-wire edge heating of target PV-array



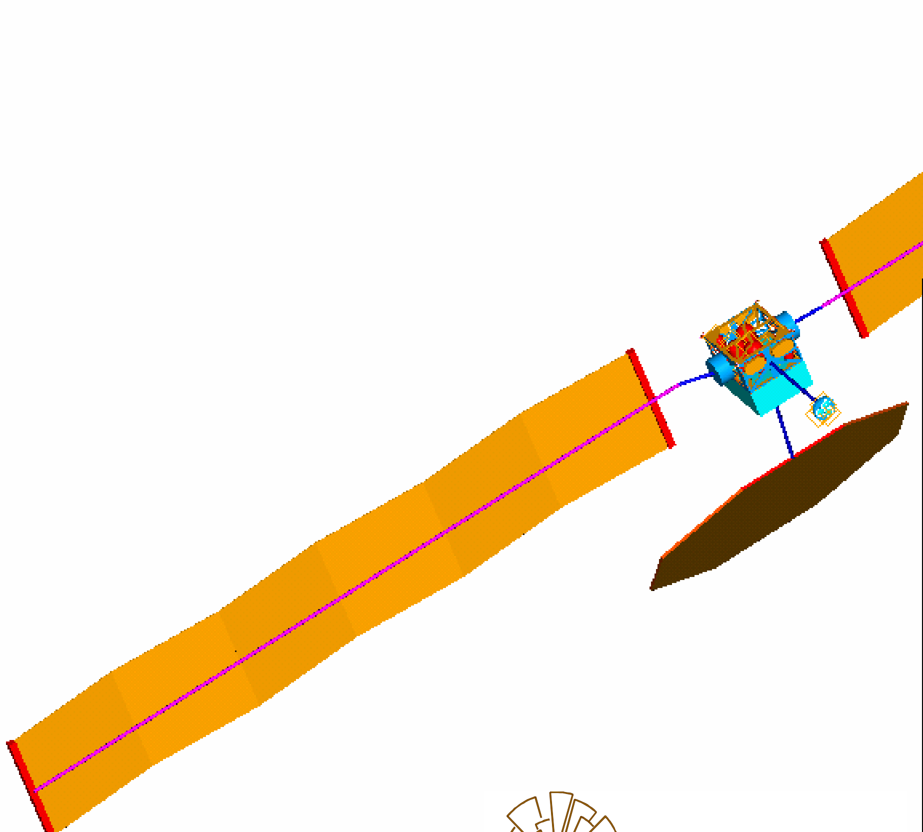
Planar Array 100 kW Class Platform

After laser power beaming experiment from ISS is completed, technology demonstrator will use Hall thrusters to spiral out of ISS orbit

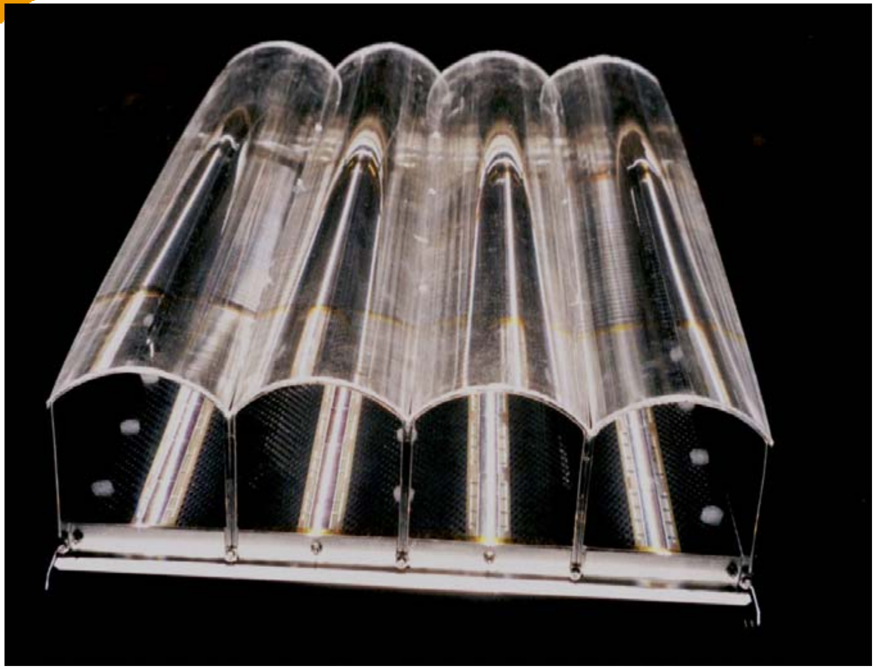


Planar Array 100 kW Class Platform

Two 5.5m x 30m solar arrays populated with Entech stretched lens arrays provide >100 kWe power to direct-drive the Hall thrusters

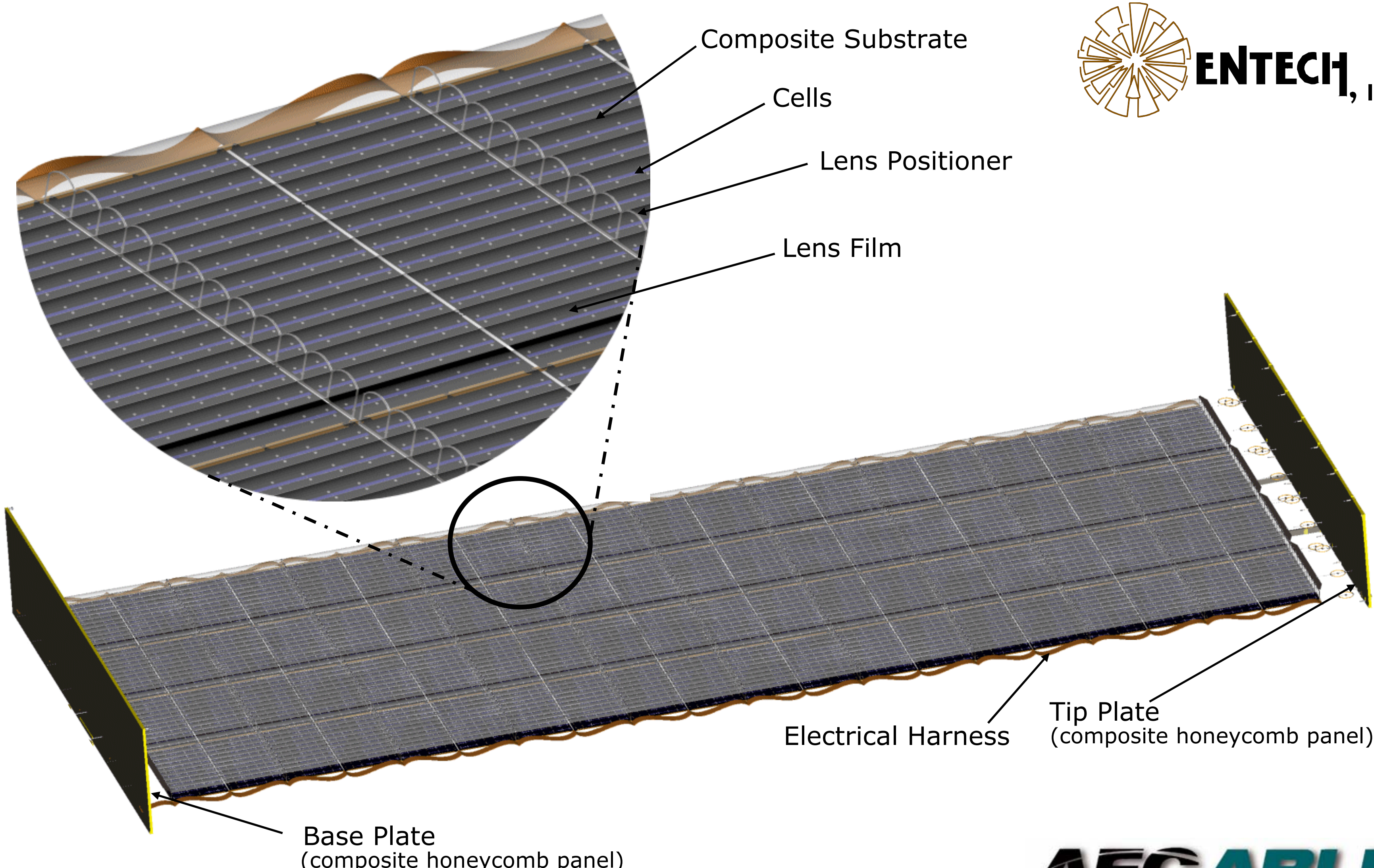


Entech Stretched Lens Arrays

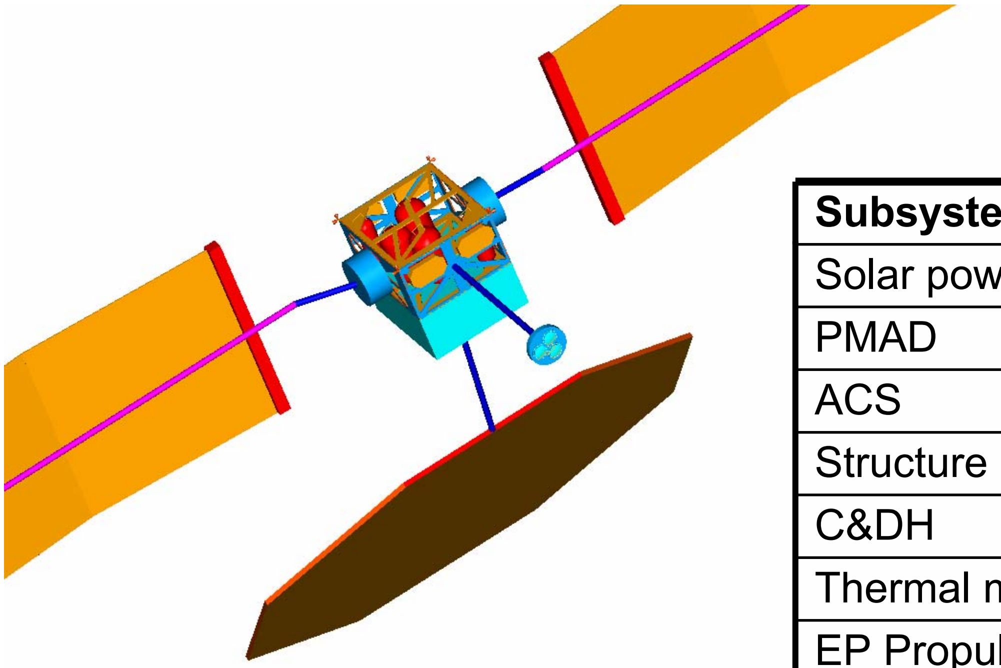


ENTECH, INC.

Stretched Lens Array Mechanical Platform



Technology Demonstrator Mass Estimate



Preliminary

Mass Estimate

Subsystem	Mass (kg)
Solar power collection	252
PMAD	488
ACS	302
Structure	1228
C&DH	259
Thermal management	653
EP Propulsion (dry)	346
Subtotal	3528
Propellant (EP system)	1435
Propellant (AC/orb maint)	70
Experiments	2000
Totals: Initial mass LEO	7033
Orbit mass	5897

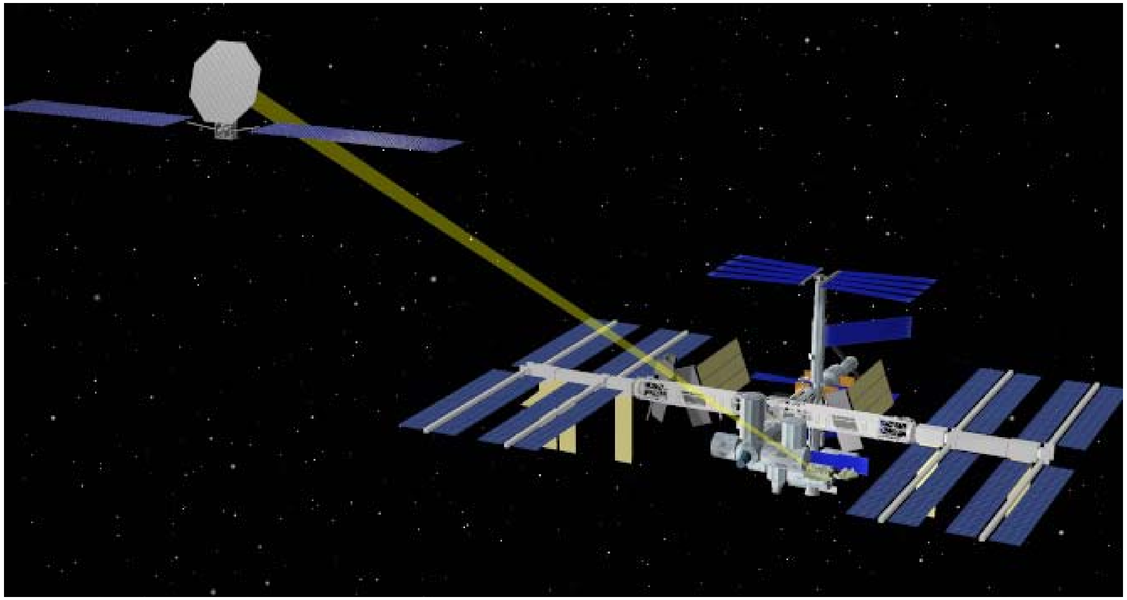
Includes 15% contingency

Assumptions

- 100 kWe from ENTECH arrays (5.5m x 30m each)
- Thermal management for 80 kW
- EP Krypton propellant for 400 km to GEO transfer
- Lifetime in ISS orbit is 40-67 days; depends on arrays attitudes

Summary of ISS Laser Power Beaming Experiment

- ISS JEM EF provides power, thermal management, stable platform for laser power beaming unit
- ISS provides capability to return laser unit to Earth and reuse after flight experiment
- Co-orbiting SSP technology demonstrator spirals out away from ISS after laser power beaming demonstration
- Candidate technologies on SSP demonstrator may also be suitable for testing on ISS



Issues for TFD Planar Array Configuration

- **Thermal management system**
  - May need to manage 80-90 kW of heat
- **Degradation of arrays during spiral through Van Allen belts**
  - Could have >20% loss of solar power generation
  - Need redesign for oversizing of arrays (& thermal management)
- **Energy storage (long times in eclipse)**
- **Solar array α and β joint designs**
  - High power across slip rings
  - ISS-sized rings too large for S/C bus
- **Need suitable PMAD design**
- **Trajectory analyses for EP spiral**
  - Need propellant mass estimates
  - Need thrust vector control / attitude control requirements
  - Need to understand impacts to S/C design, ie, thruster location & directions,…
- **Attitude during ISS co-orbit (do we feather arrays?)**

Questions to Be Addressed by the TIM Working Groups

- **Configurations & Mission Scenarios**
  - Other configuration options & scenarios?
  - What are the benefits & issues?
  - How could the issues already identified be solved (either by configuration modification, or by suitable technology development & implementation)?
- **Technology Experiments**
  - What are suitable technology experiments that could fly on a TFD platform?
  - What is the performance objective for each of these technology experiments?
  - What are the mission scenario requirements for each technology experiment? (orbit, orientation, etc.)
  - What is the technology readiness of each experiment?
  - What is the status of the technology development? (funded current project, unfunded current project, future concept, etc)