Bigelow Expandable Activity Module (BEAM) ISS Year-One

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BEAM Project Management and Instrumentation Team

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19-July-2017

Agenda

1. **Project overview**

2. **Crew Ingress**

3. **BEAM General Performance**

    - Microbial Air & Surface Monitoring

    - Deployment Dynamics

    - Thermal

    - MMOD Impact Detection

    - Modal Test

    - Radiation

4. **Future Plans & Summary**

5. **Team Acknowledgements**

BEAM project objectives

BEAM on ISS Node 3 Aft

◆ **Demonstrate a commercial expandable habitat module on ISS in partnership with Bigelow Aerospace (BA)**

◆ **Increase human-rated inflatable structure Technology Readiness Level (TRL) to 9**

◆ **Address key elements of NASA's Space Technology Roadmaps to prepare for future deep space and surface habitat missions**

◆ **Exploit experience from NASA's TransHab design and BA's Genesis I & II pathfinder flights**

BEAM animation by NASA/JSC on YouTube
https://youtu.be/VopaBsuwikk

Expandable Space Module History

Early 1952

Werner Van Braun Space Station Concept with expandable sections
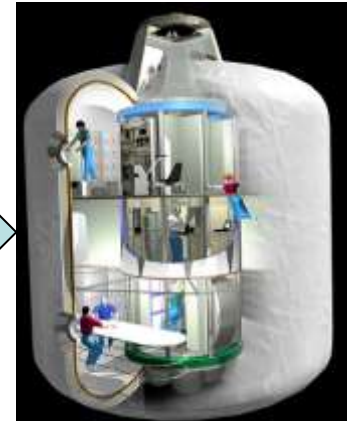
Aug. 12th, 1960

NASA Launched Echo 1

Jan. 25, 1964

NASA Launched Echo 2

1990s

NASA Transhab Concept
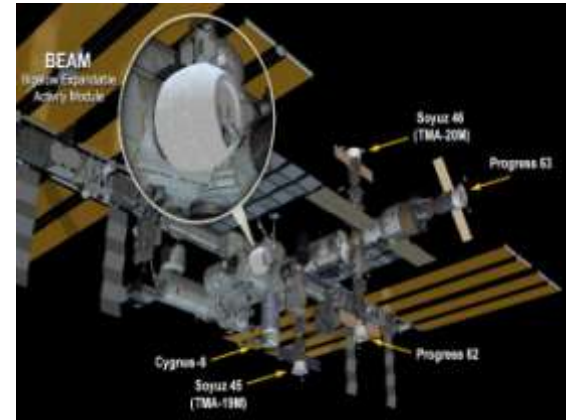
July 12th, 2006

Bigelow Aerospace Genesis 1 Launch

Jan. 30th, 2007

Bigelow Aerospace Genesis 2 Launch

April 8th, 2016

Bigelow Expandable Activity Module (BEAM) launch to ISS on SpX-8
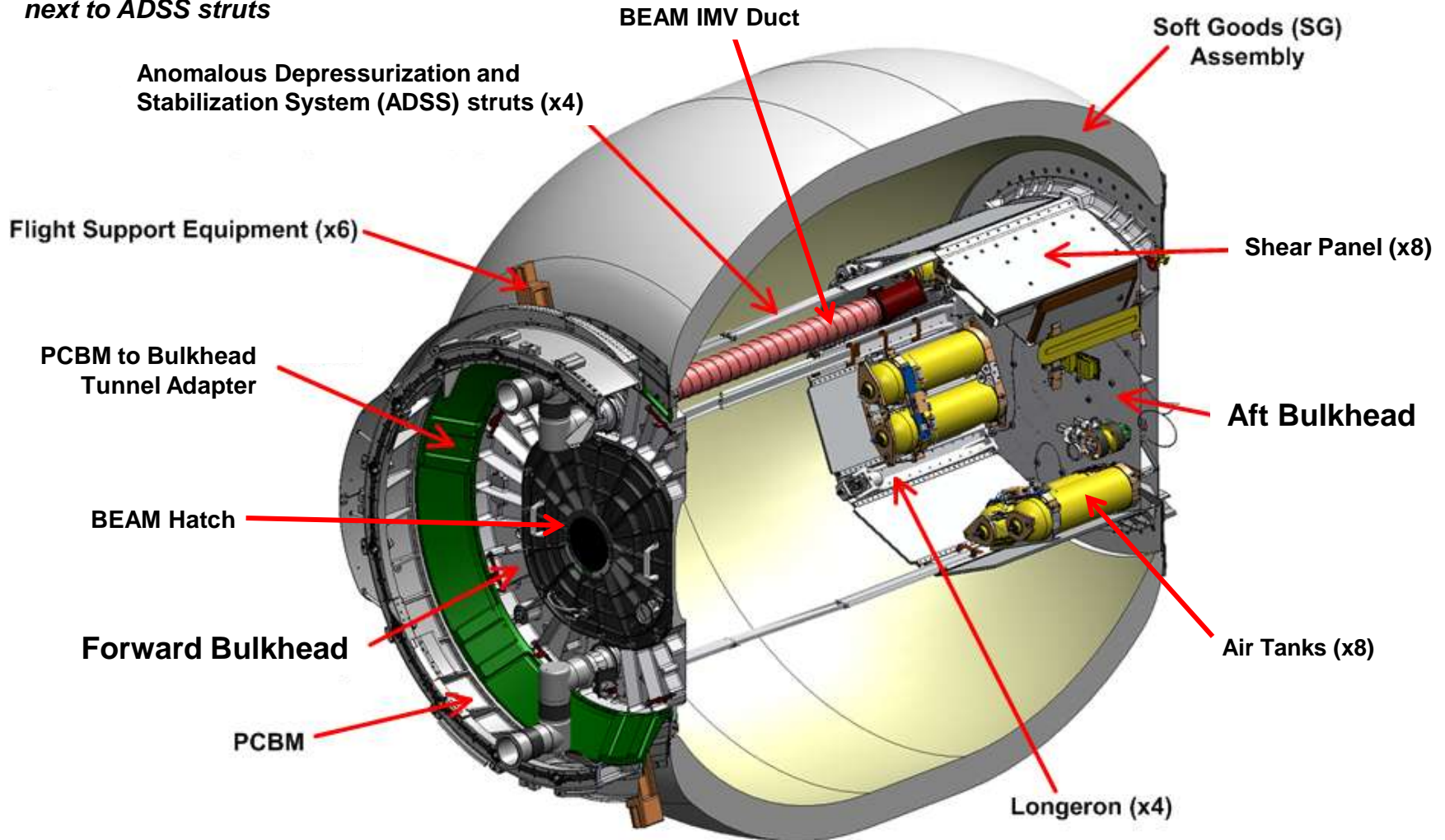
7 hours of deployment in 25 seconds time lapse video

Not shown: Rip-Stitch Straps (RSS) next to ADSS struts

BEAM IMV Duct

Soft Goods (SG) Assembly

Anomalous Depressurization and Stabilization System (ADSS) struts (x4)

Flight Support Equipment (x6)

Shear Panel (x8)

PCBM to Bulkhead Tunnel Adapter

Aft Bulkhead

BEAM Hatch
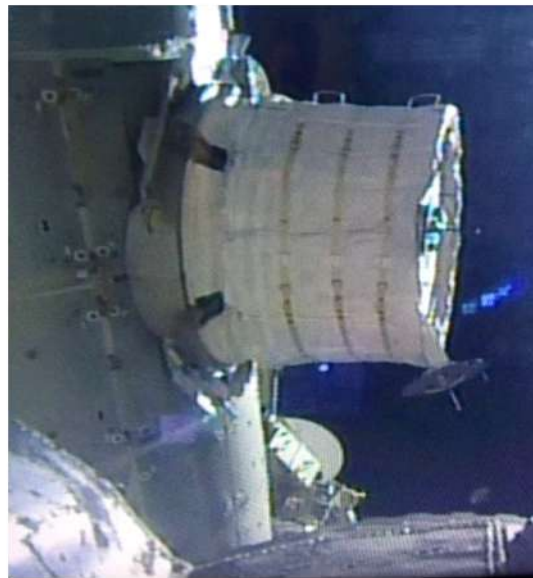
Forward Bulkhead

Air Tanks (x8)

PCBM

Longeron (x4)

BEAM launched, berthed, and deployed on ISS

◆ BEAM launched on SpX-8 (April 8, 2016), Dragon/BEAM arrived Node 2 (April 10th), SSRMS extracted BEAM from Dragon Trunk on Node 2 Nadir, moved it to Node 3, and berthed it on Node 3 Aft port (April 15-16 2016), and fully pressurized on May 28, 2016.

BEAM Project

BEAM Ingress Timeline (Year 1)

Ingress	Date	Operations
1-3	June 6-8, 2016	Outfitted interior, installed sensors, and took microbial air/surface samples
4	5-Sep-16	Replaced DIDS battery packs => DIDS back to nominal ops, reattached 5 accelerometers to shell with Kapton tape, retrieved exposed RAMs for return in Soyuz 46S
5	29-Sep-16	Performed Modal Test; IWIS data not recorded due to bad cable connection, preemptive Kapton-taping of remaining 7 accelerometers
6	24-Oct-16	RAM install and microbial sampling
7	1-Feb-17	2nd Modal Test, RAM swap and microbial sampling
8	22-Mar-17	RAM swap, microbial sampling, accelerometer inspection
9	28-Apr-17	1st REM shield installed (1.1 mm thick)
10	31-May-17	2nd 3D-printed REM shield (3.3mm thick) installation & new RAMs
11	20-Jun-17	3rd (final) 3D-printed REM shield (10mm thick) installation

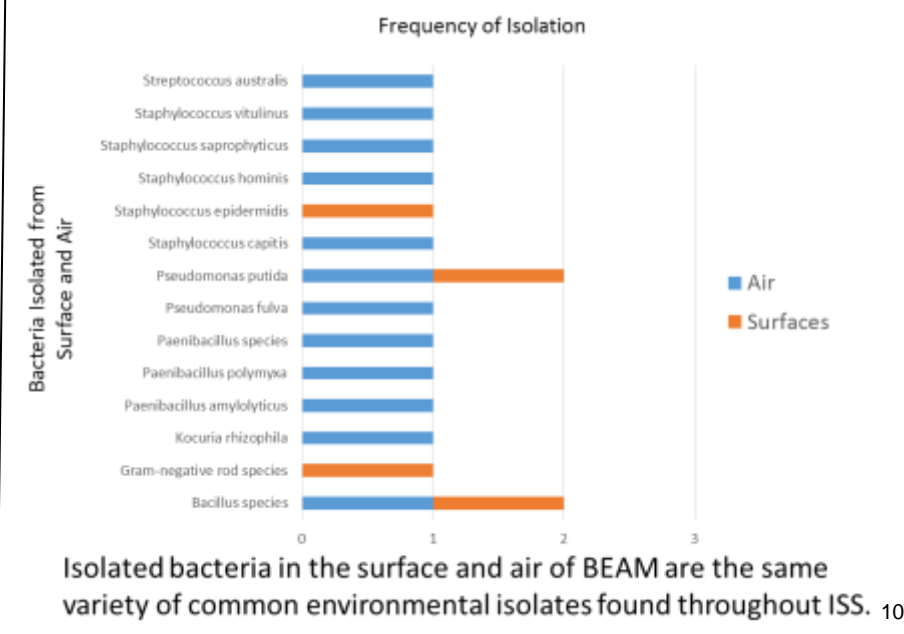Ingress #1-#3

Ingress #4

Ingress #7

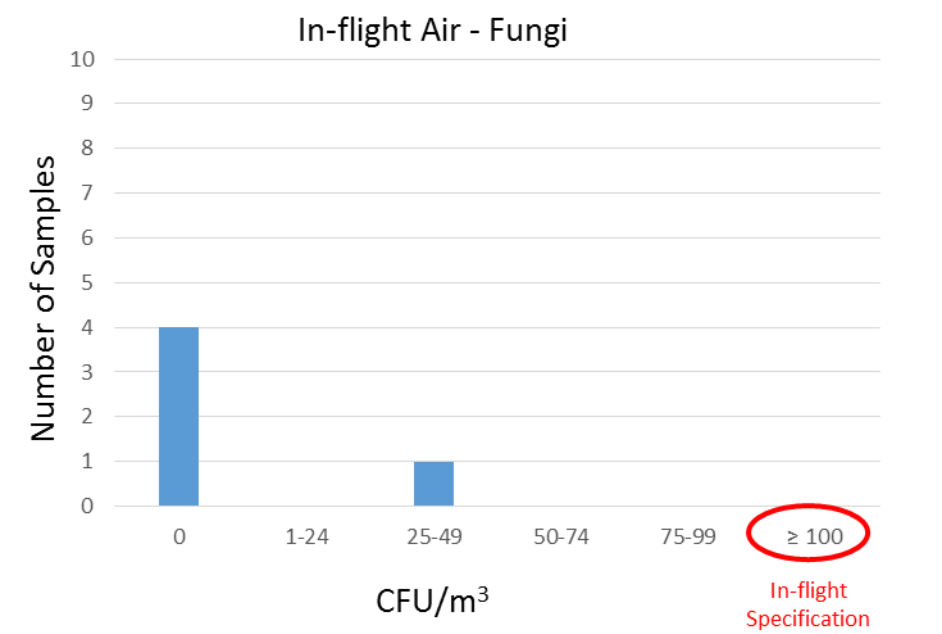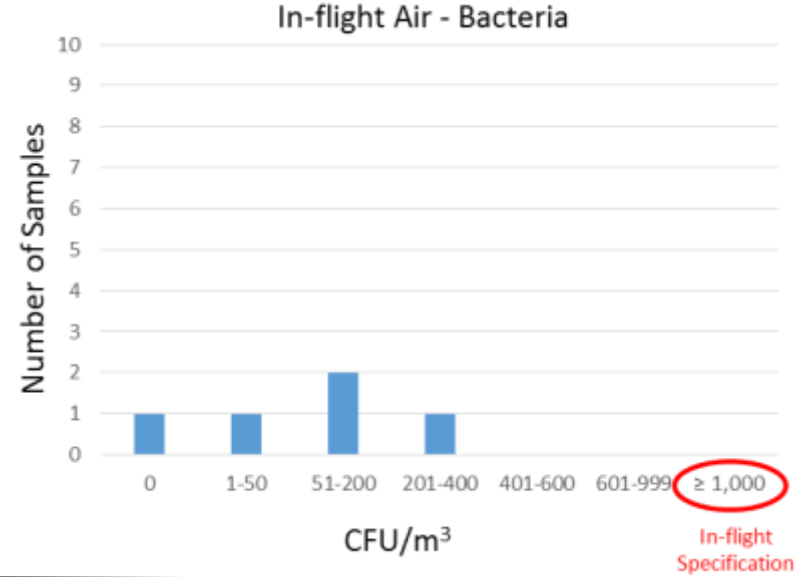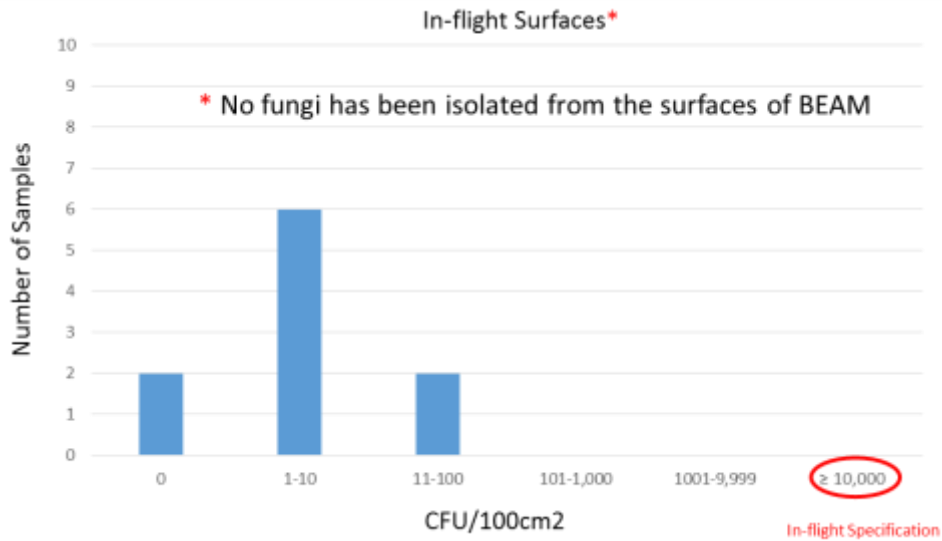# BEAM – Microbiological Monitoring

◆ **Five separate microbiological monitoring sessions occurred on:**

- ▪ June 8, 2016
- ▪ September 5, 2016
- ▪ October 24, 2016
- ▪ March 22, 2017
- ▪ June 20, 2017

◆ **All microbial concentrations from air and surface samples were well below the Medical Operations Requirement Document (MORD) limits. No fungi were isolated from any samples.**

◆ **No medically significant microorganisms were isolated from any samples.**

◆ **Future sampling will be performed in August 2017.**

In-flight Surfaces*

* No fungi has been isolated from the surfaces of BEAM

In-flight Air - Bacteria

In-flight Air - Fungi

Frequency of Isolation

Isolated bacteria in the surface and air of BEAM are the same variety of common environmental isolates found throughout ISS.

BEAM Sensor System Overview

| Sensor	Parameter	Deployment	Data Retrieval	Previous Use
Distributed Impact Detection System (DIDS)	Detects structural impacts to BEAM	Installed pre-launch: •4 transducers on the bulkheads Installed on orbit: •12 transducers on the soft goods •sensor boxes	RF to SSC (closed hatch)	ISS Ultrasonic Background Noise Test SDTO
Deployment Dynamics Sensors (DDS)	Records acceleration loads during inflation stage	3 DDS units and triaxial accelerometers are installed prelaunch	USB to SSC (BEAM ingress)	Shuttle Wing Leading Edge accelerometers and Crew Seat DTO
Wireless Temperature Sensors (WTS)	Monitors temperature of BEAM surface (IVA)	4 WTS units Installed on-orbit (qty 4 RTD channels each)	RF to SSC (closed hatch)	Shuttle Wireless Strain Gauge Instrumentation System
Radiation Environment Monitor (REM)	Monitors radiation environment internal to the BEAM structure	2 REM Installed on-orbit	USB to SSC (closed hatch)	REM SDTO
Radiation Area Monitor (RAM)	Passive radiation monitoring badges	6 RAMs Installed on-orbit	Replaced and returned to ground every Soyuz vehicle cycle	

DIDS

WTS
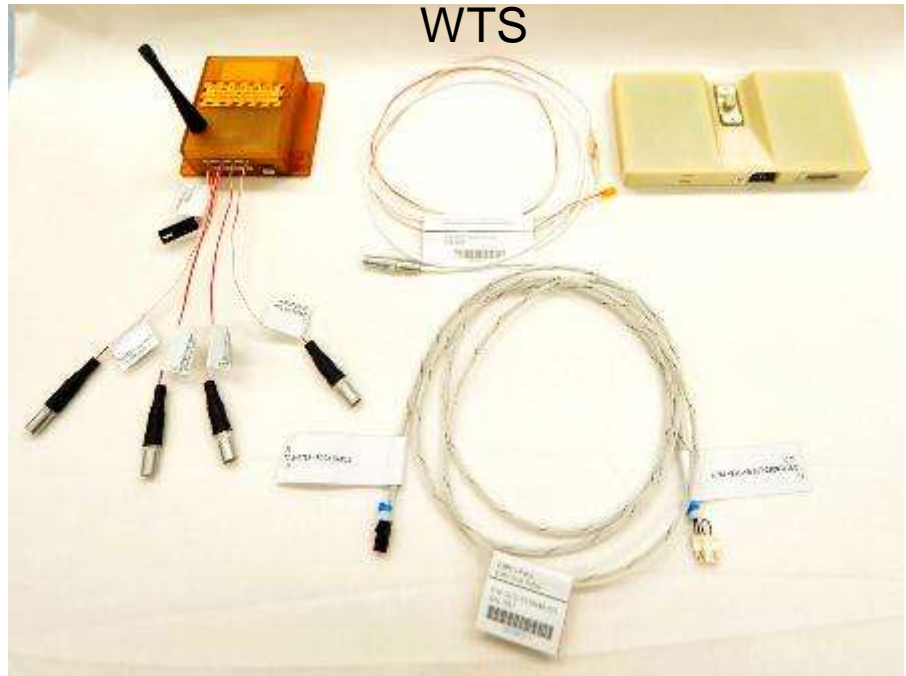
REM

RAM

DDS
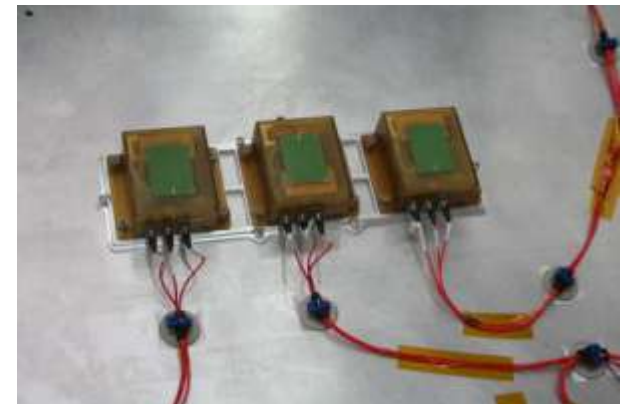
Deployment Dynamic Sensor (DDS)

Purpose: Used as a technology demonstration for characterizing the BEAM Module deployment dynamics with accelerometers on the Aft bulkhead surface.

Deployment: Hardware pre-installed prior to launch on Aft bulkhead.

Qty 3 Deployment Dynamic Sensor (DDS) units
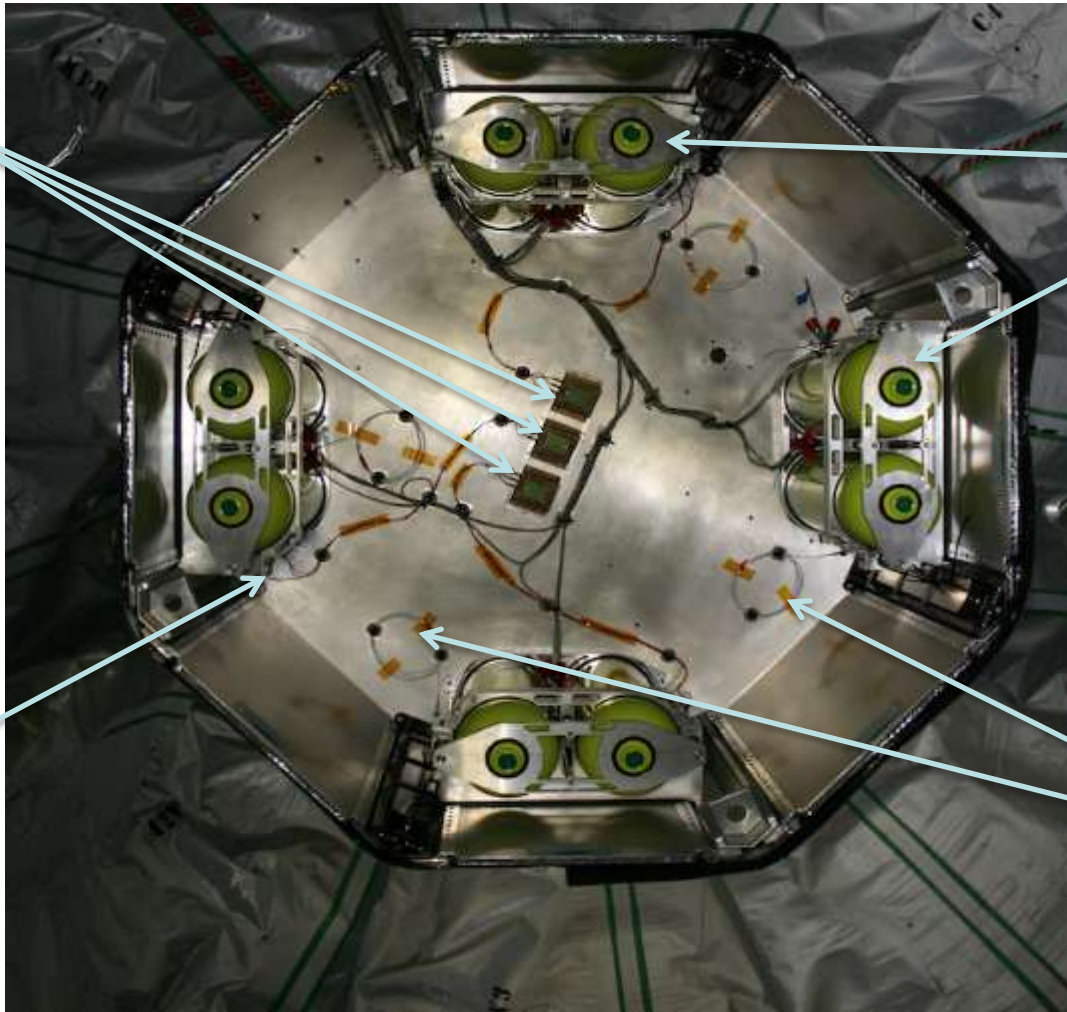
Qty 8 Air Inflation Tanks

Qty 3 triaxial accelerometers

Qty 4 single axis accels with cables for DIDS

DDS Sensor Results for Deployment Monitoring

◆ The DDS successfully recorded 10 hrs of accelerometer data during the BEAM deployment.

- Thousands of impulses were measured from the Rip-Stitch Strap (RSS) stitches popping.

- Max 0.5g peak during initial inflation attempt and max 0.3g during the final inflation.

- No indication of ADSS struts binding or high transient loads on ISS.

Inflation Day 1 (~2.5 hours)

Inflation Day 2 (final hour)
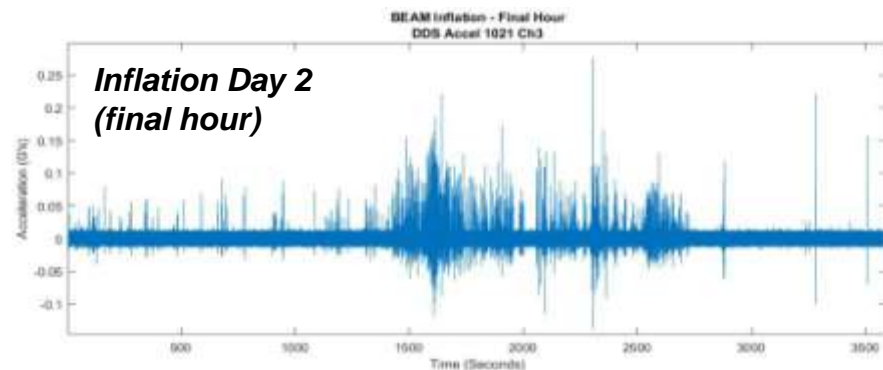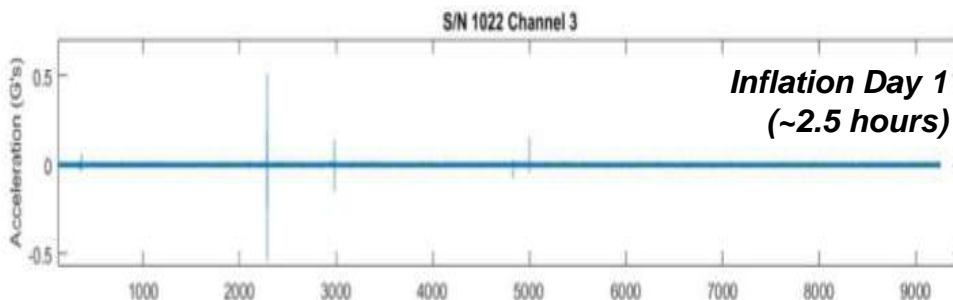
◆ DDS was also used to support Modal testing inside of BEAM.

Purpose: Used as a technology demonstration for characterizing the BEAM Module internal temperature environment during the 2 yr operational phase.

Deployment: Qty 4 Wireless Temp System Kits installed on-orbit

Operations: Each WTS data recorder samples 4 Resistive Temperature Device (RTD) channels once per minute and stores to local memory. Data is downloaded wirelessly ~ 1/month to a laptop in Node 3 and then downlinked to the ground.

Qty 4 Resistive Temp Device Sensor

Qty 1 Extended Life Battery Pack

Qty 1 Wireless Temp Sensor
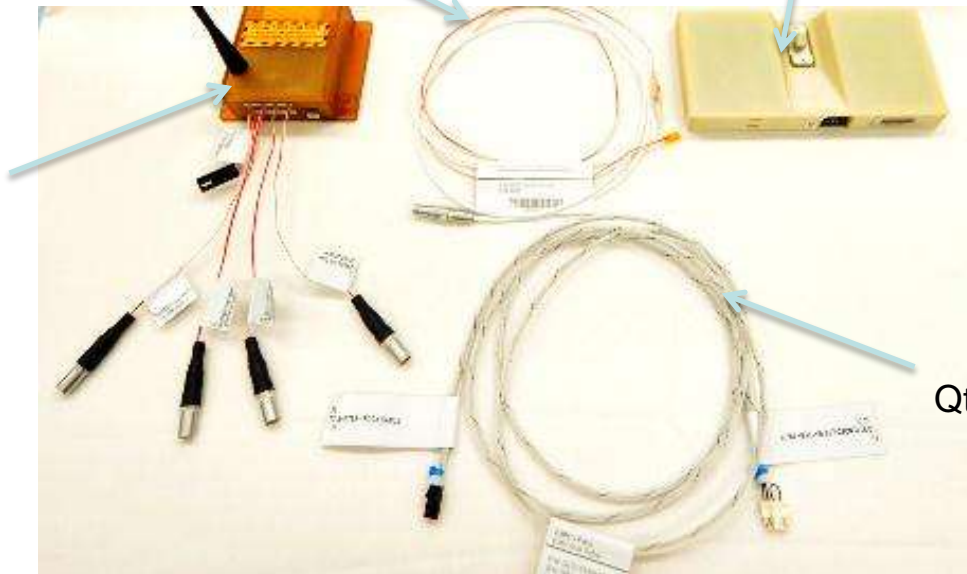
Qty 1 Battery Pack Cable

Wireless Temp Sys Kit Contents

BEAM Thermal Performance

- A total of 16 WTS RTD sensors were installed with tape inside of BEAM.

- 12 sensors were placed radially along the BEAM inner air barrier and 2 sensors on the Forward and Aft bulkhead surfaced respectively. Approximate locations are shown below.

- Initial pre-expansion internal temperatures measured by the DDS system were significantly warmer than predicted analysis temperatures which was likely due to the folded soft goods layer creating an additional thermal isolation not modeled.

- Current model of the Expanded Module tends to under predict the WTS readings. Forward work is required to support model validation which will include re-evaluation of Multi-layer Insulation (MLI) blanket performance, relative isolation of the air barrier from the Debris Protection Assembly (DPA) and higher than expected convective heat transfer from Inter-Module Ventilation (IMV) flow.

- BEAM demonstrated adequate thermal control and condensation prevention with unobstructed ventilation from the ISS IMV, nominally at 22.6 °C and 3.4 m³/min, and ISS atmosphere humidity levels (dew point) from 5.6 to 12.8 °C (Relative Humidity 33 – 54%)
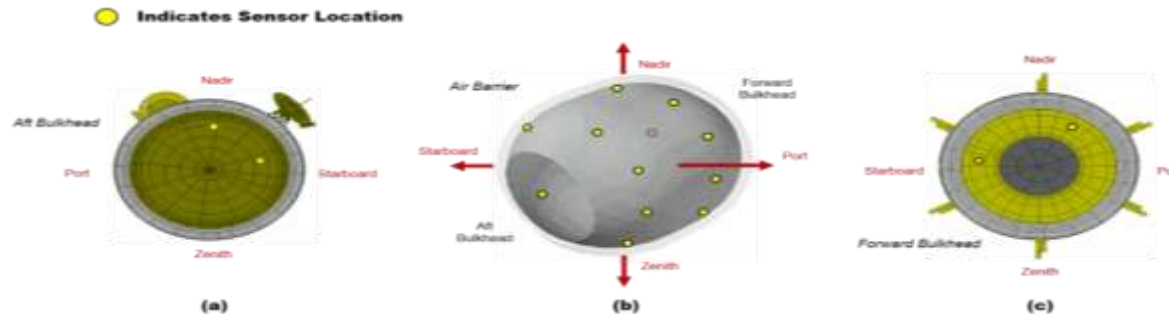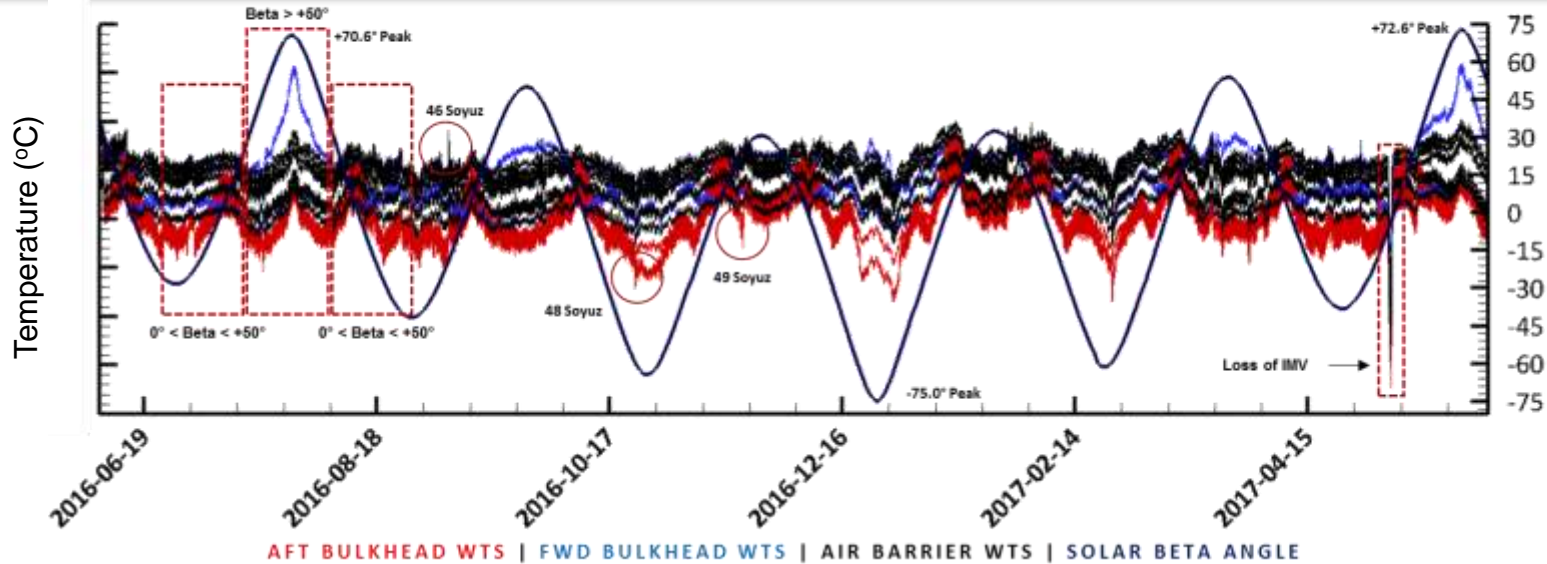

Locations of the 16 WTS sensors (a) BEAM aft bulkhead, (b) air barrier and (c) forward bulkhead*
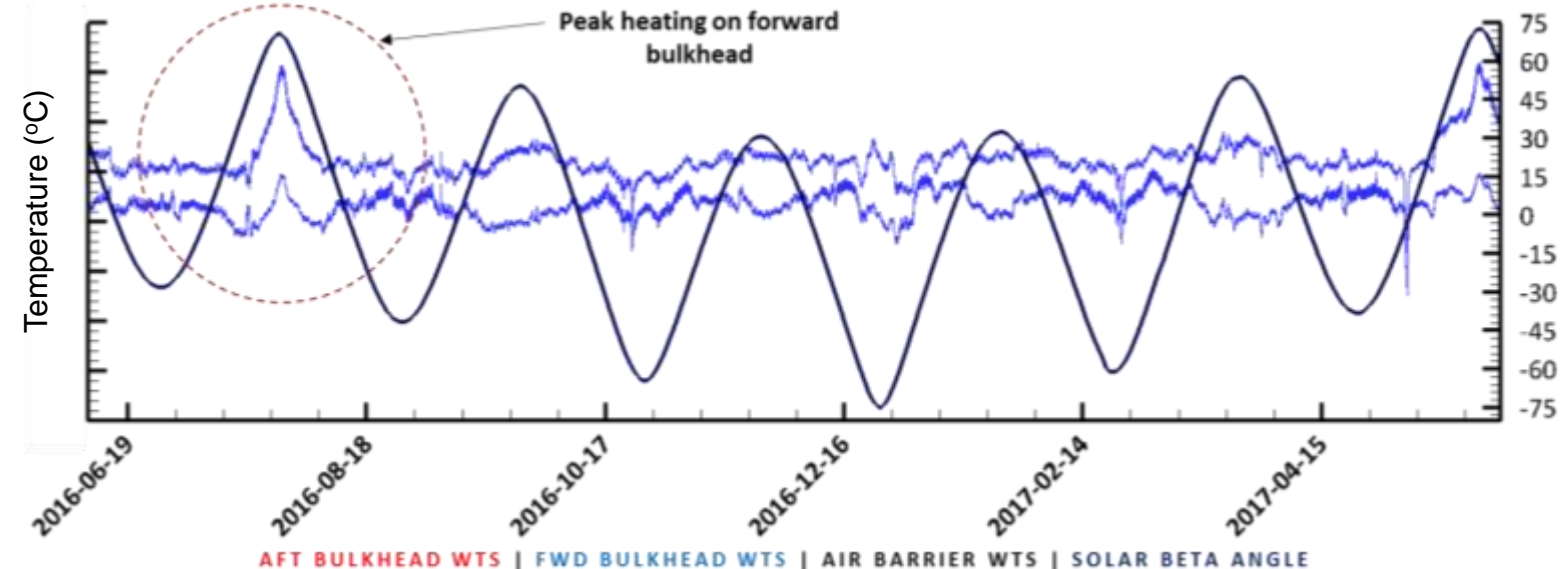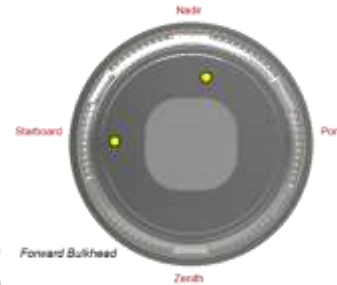
* Graphics and data on this slide and the next were provided by the BEAM NASA/JSC Passive Thermal Principle Investigators John Iovine & William Walker

All WTS

FWD
BlkHD

Aft
BlkHD
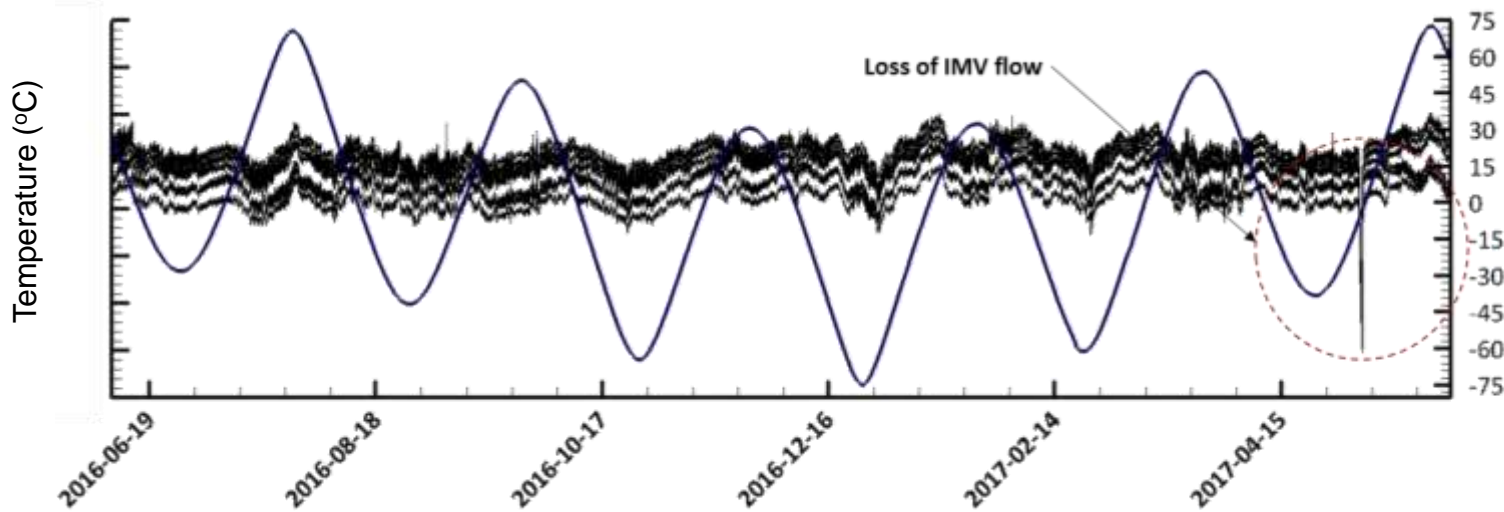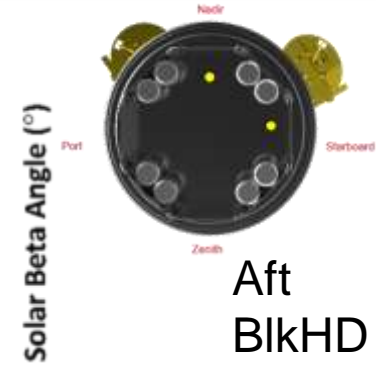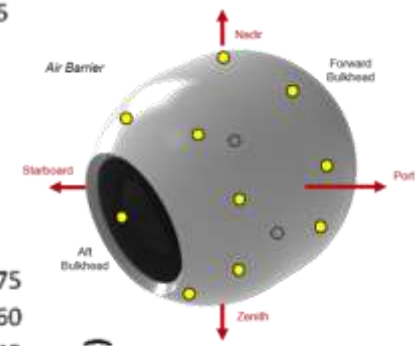
Air
Barrier
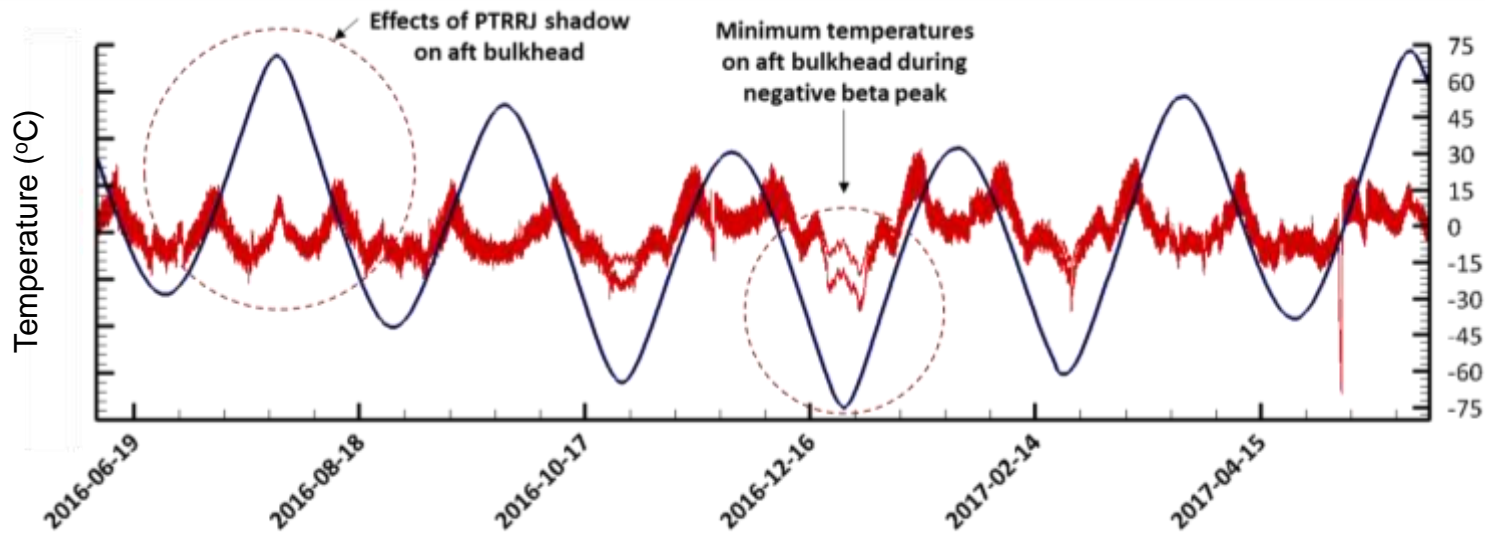
- A pre-flight MM/OD impact detection system feasibility assessment involved performing a variety of tests to ensure the sensor system could be installed onto the softgoods material and detect an impact response.

- Tests included:
    - Instrumented tap testing of Damage Tolerant Test (DTT) inflatable for screening sensor attachment method and standalone data acquisition testing
    - Pull-testing of sensor attachment method to softgoods material
    - Wiring/DAQ hardware attachment mechanism inside of module
    - Hypervelocity Impact Testing with representative coupon of softgoods material w/MM/OD shielding
    - RF communications testing inside of the module
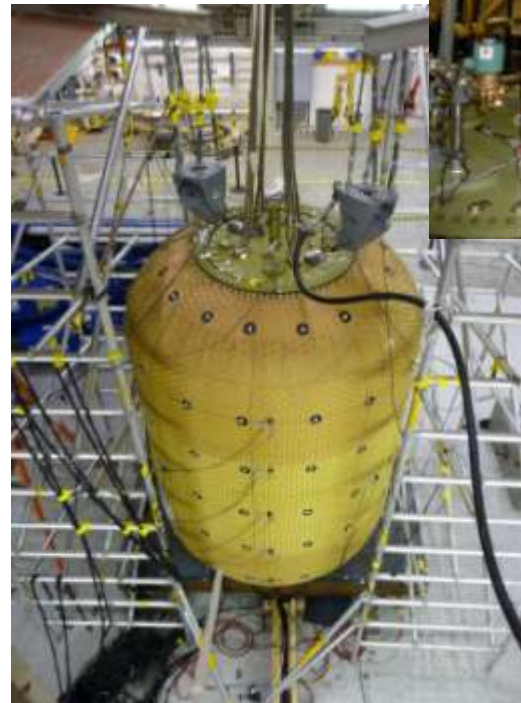
NASA provided inflatable module for initial sensor system feasibility assessment which was <u>NOT</u> part of the BEAM project.

Hypervelocity Impact (HVI) Testing Accomplishments

◆ Demonstrated that the system recorded signal matched accurately with a calibrated data acquisition system at White Sands Test Facility (WSTF).

◆ Verified that adhesive attachment method for accelerometers to smooth surfaces (Bladder) survives HVI impacts.

◆ Velocity behavior of the restraint layer was determined (Anisotropic effects and speed of sound measured).

◆ Most of these HVI tests did not reach the restraint layer, and instead were captured by the shielding layers. Since the shielding system was resting on the restraint layer in these tests, the momentum from those impacts did transfer into the restraint layer via the foam coupling.

Distributed Impact Detection System Overview

Purpose: Used as a technology demonstration for Micro Meteoroid/Orbital Debris (MM/OD) Impact detection system of an inflatable structure for BEAM Module during the 2 yr operational phase.

Deployment: Qty 4 Accel Transducer cables installed pre-launch to Aft Bulkhead and remaining kitted hardware installed on-orbit

Operations: Each DIDS data recorder remains in a low power listening mode until a trigger is recorded above a set g threshold value and records a 270 ms of 30 KHz sampled data window to internal memory for each of its independent 4 channels. New trigger status is downlinked daily and raw trigger can be downlinked on an as needed basis.

Qty 1 Antenna Mount

Qty 1 Battery Pack Cable

Qty 1 Accelerometer Data Recorder

Qty 4 Accel Transducer Cable

Qty 1 Extended Life Battery Pack

Impact Detection Kit Contents

◆ Detects MM/OD and IVA Events

◆ Uses 3 VDC custom designed external Battery Pack, expected operational life of 2 years.

◆ Can store 9999 events on an internal memory card

◆ Verified that adhesive attachment method for accelerometers to smooth surfaces (Bladder) survives HVI impacts.

◆ BEAM air barrier had been pre-marked for DIDS/WTS sensor installation locations.
   ◆ Sensor locations were configured to ensure maximum internal coverage and to monitor pre-flight identified high risk MM/OD impact probability locations.

◆ 12 DIDS piezoelectric accelerometers were adhered to air barrier via pre-applied double-sided transfer tape and Kapton tape by crew

MMOD *impact* risk contours
(red = high risk; blue = low risk)
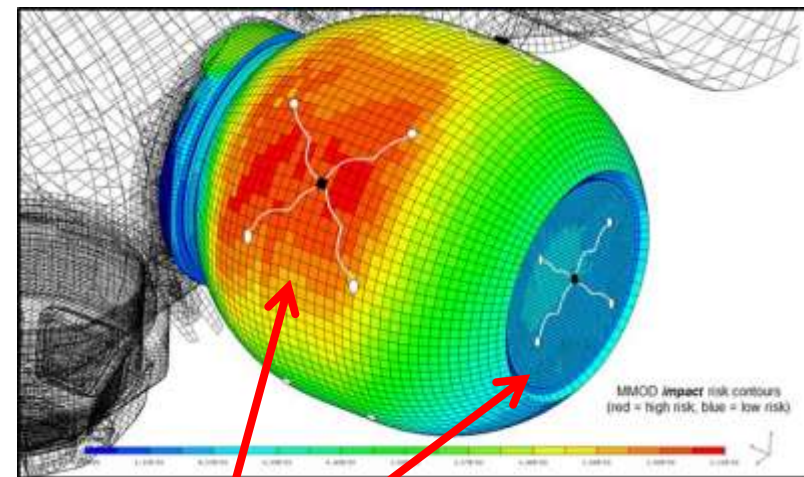
NOTE: NOT Actual sensor location!
DIDS Sensors locations are for illustration purpose only.
DIDS Sensors are Internal to Structure.
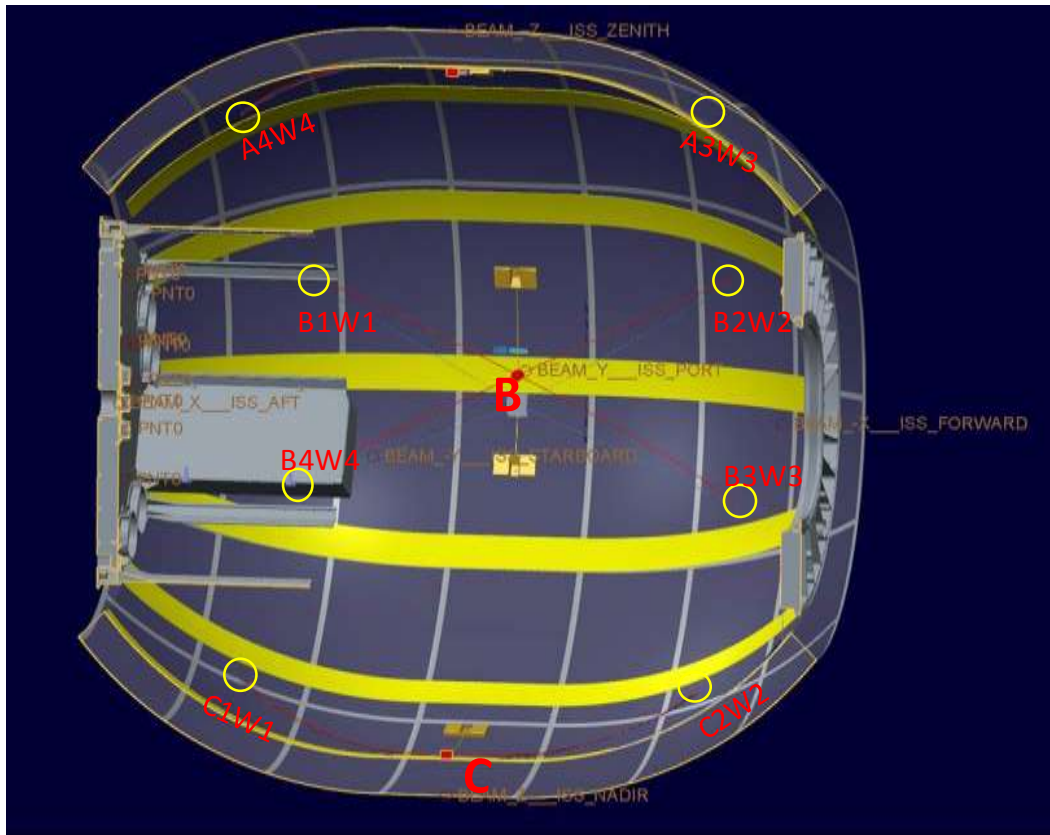
BEAM Sensor 3D Model View

BEAM Mock-up View

Note: Cables attached to inner air barrier with 1 3/8" dia Velcro dots

◆ Initial DIDS operations required engineering to tweak the trigger threshold parameters to ensure DIDS accelerometers would not falsely trigger due to low level ISS background noise being injected into the module structure.

   ◆ Crew activity induced loads to structure have been routinely recorded during previous crew ingresses in the module

◆ DIDS operations had to be adjusted initially to disable an internal amplifier which had been left active and was causing increased power consumption.

◆ On GMT 059 (2/28/17) first likely external impact to BEAM was recorded by all three DIDS units monitoring the internal air barrier surfaces. Recorded signals ranged between 1 - 3 g's acceleration

  ◆ Signal contained high frequency content

  ◆ Triangulated to have impacted on Zenith side (between Channel 2 & 3)

  ◆ Estimated impact amplitude on restraint layer is ~260 g's based on hypervelocity ground test derived models and data suggests the impact would not have penetrated all the way to the restraint layer

  ◆ Pictures of estimated impact location were requested via the ISS External High Definition Camera (EHDC) P1LOOB, however the camera gave very little Zenith surface viewpoint
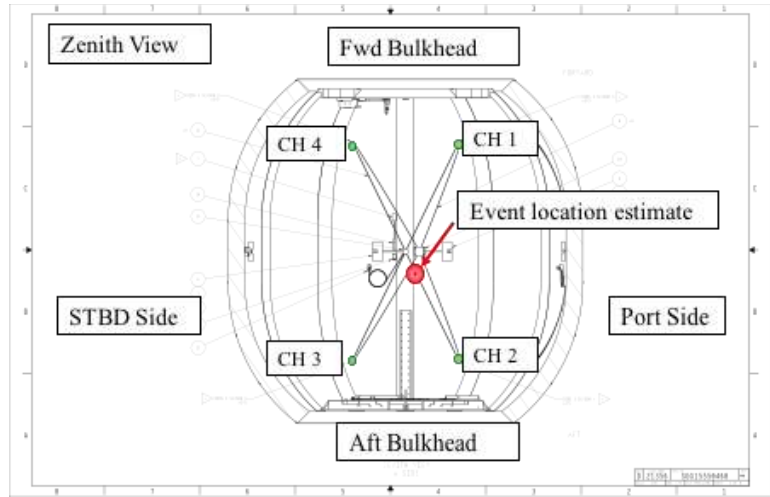
Estimated epicenter location of GMT059 impact
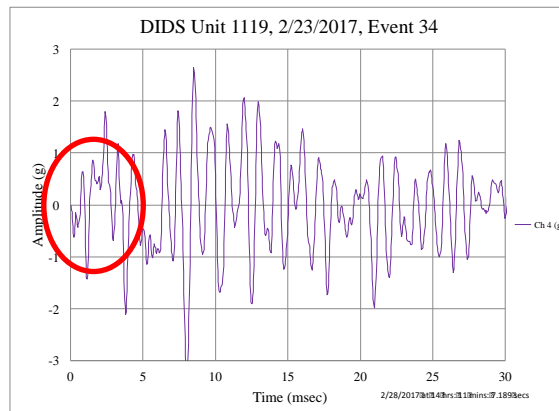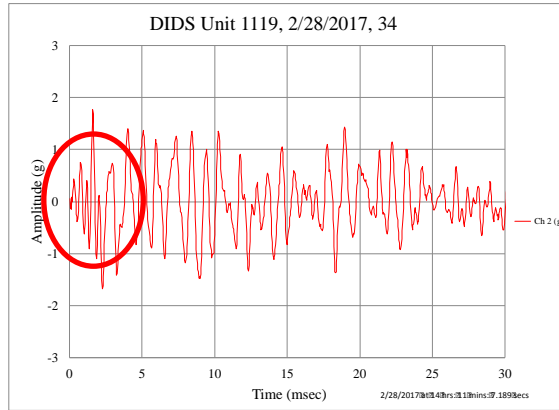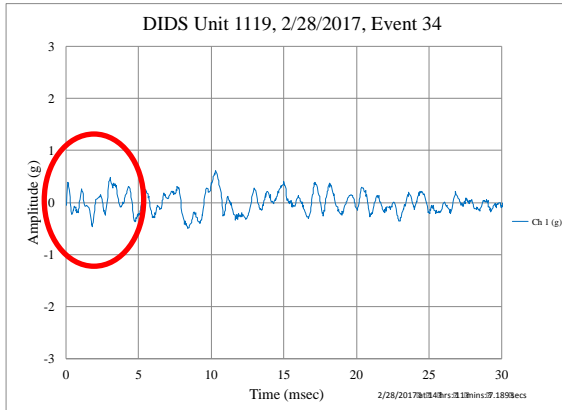
Zenith DIDS Frequency Response

Zenith DIDS Time History (all 4 channels)

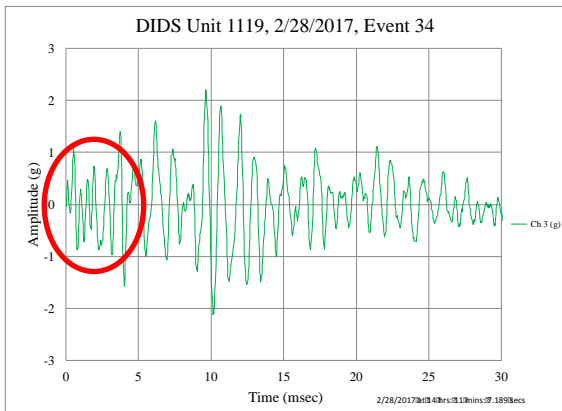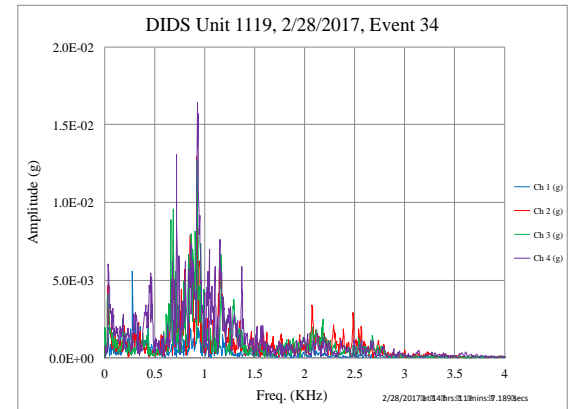- Compare structural modal frequencies of the BEAM on ISS to those measured during BEAM ground testing in 1-G (w and w/o MMOD)
    - Measured w/ Internal Wireless Instrumentation System (IWIS) (primary), DIDS, and DDS
    - Targets 1-3 and 8 (BEAM shell); targets 4-7 aft bulkhead. Adjust computer structural models as necessary to better represent BEAM in micro-G on ISS.
    - 5 impulses at each target x 2 series
    - 3 accelerometer axes x 8 targets x 2 series = 48 total spectra.
    - Multiple ground and on-orbit modal frequencies were correlated based upon accelerometer response, knowledge of the mode shape from ground tests, and impulse excitation location and direction.
    - There is greater confidence in lower frequency modes.

Ground-based sample of Fist Thump Impulse Force

direction

strike with bottom of fist

Frequency Spectrum of Force
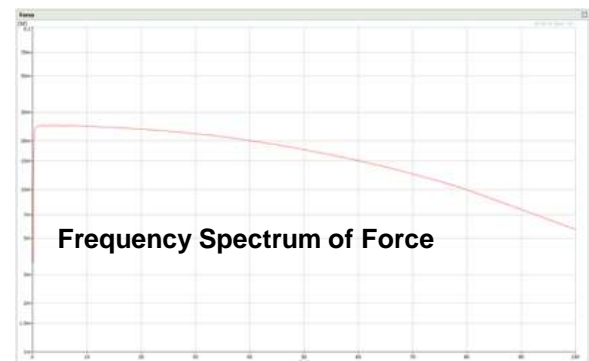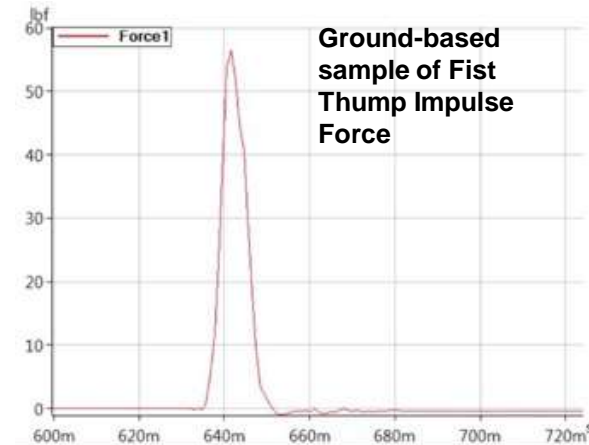
- **Preliminary Results**
  - Large frequency differences between the on-orbit and ground-based tests for the first three modes: the first lateral bending modes are 10 – 14% higher and the first torsion mode is 28% higher on-orbit than in ground tests. Possible reasons for these differences include the following:
    - MMOD layer interaction with the BEAM restraint layer/wall is different on-orbit than under 1-G ground test conditions. Performing ground tests with and without MMOD was valuable for showing this.
    - The spaceflight article and the ground test article have different masses. The first two mode frequencies are higher than in ground-based tests, even without MMOD installed.
    - The ISS interface with BEAM is different from the ground-based test.
- **Forward work**
  - Compare modal frequencies of the ISS-attached BEAM loads model to on-orbit test frequencies.
  - Investigate modelling techniques for attaching MMOD layers
  - Investigate mass differences and perform an operational modal analysis (OMA)
  - Perform a similar analysis on the DDS, DIDS, and Camera Microphone data.

BEAM Radiation Sensors

◆ **A total of 6 Passive and 2 active radiation sensors were installed inside of BEAM via velcro.**

◆ **The Radiation Environment Monitors (REMs) couples small radiation sensor with advanced electronics**

  • Consist of a Timepix read-out chip bonded to a 300 µm thick, 2cm^2 silicon sensor layer.

  • The Timepix provides on-chip data collection and signal digitization within the footprint of each of the individual pixels in the 256 by 256 pixel matrix

  • Power/data provided via USB and connect to Space Station Computer laptop in Node 3

  • Provides spectral information (energy deposition as function of particle type and energy) and radiation dose

◆ **Radiation Area Monitors (RAMs) will come back to ground during nominal ISS Soyuz return cycle for data evaluation.**

Active Instrumentation (REM)

Passive Instrumentation (RAM)

◆ Radiation (REM) initial results

- System has been operating without issues since installation (although GUI needs to be relaunched on a weekly basis due to scheduled laptop reboots.

- Galactic Cosmic Ray (GCR) dose rate similar to other ISS modules

- As expected, REMs measured higher trapped field dose rate — e.g., in South Atlantic Anomaly (SAA) — inside BEAM than in other ISS modules due to thinner shell and lack of equipment racks in BEAM technology demonstrator

- Currently an additional test is underway to determine if the particles being measured inside of BEAM are of low energy and if so, can they be effectively shielded out with 3D printed plastic hemispheres of various thicknesses (1.1mm, 3.3 mm & 10mm.

  ▪ 3D printed hemispheres were printed with the on-board ISS "Made in Space" 3D printer

- BEAM tech demo data will be used to assess shielding requirements for expandable habitat modules configured for human exploration missions

Future Plans

◆ BEAM was originally planned for a 2 yr operational mission to demonstrate and advance the technology with infrequent human ingresses.

- ISS management is evaluating options for using BEAM as a long-term hardware stowage module which would require extending the two year life and reconfiguration of the wireless instrumentation communication & additional batteries.

Summary

◆ Overall BEAM has been performing beyond expectations!

◆ BEAM will help advance the human rated expandable module to TRL 9 and in the future should be considered as a solution for volume/mass savings in future planetary and space exploration applications.

◆ Use BEAM sensor data and lessons learned to fold into future expandable module design

- Evaluate methods to embed sensors into softgoods material during fabrication process that would not risk damage to the module during compression/expansion phases to reduce crew time for installation.

Team Acknowledgements

◆ The authors of this presentation would like to provide a special thanks to the entire BEAM project team and Bigelow Aerospace.

◆ Specifically the authors would like to acknowledge the following people who provided BEAM specific performance data:

- Microbial Monitoring Performance – Ariel Macatangay, William Misek & Melanie Smith
- Deployment Dynamics & Modal Test Results – Michael Grygier
- Thermal Performance – John Iovine & Dr. William Walker
- MM/OD Monitoring Performance – Dr. Eric Madaras
- Radiation Sensor System & Performance – Dr. Dan Fry and the entire Space Radiation Analysis Group (SRAG)

Backup

◆**Why expandables?**

◆**BEAM education & public outreach**

◆**BEAM acronyms**

BEAM Project

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Why Expandables? (1/2)

1. **Lower launch/ascent volume** relative to metallic modules

    • Pro: Reduced size, drag and mass of the launch vehicle (or fairing), or more cargo inside the same fairing

    • Con: Increased complexity for deployment and internal outfitting

BEAM	Packed	Inflated	Inflated/Packed Ratio
Mass (w/ PCBM & FSE)	~1400 kg (~3K lb)		1.0
Volume	**3.6 m³**	**16 m³**	**4.4**
Length (w/ FRGF)	2.16 m	4.01 m	1.9
Diameter	2.36 m	3.23 m	1.4
Pressure	0	14.7 psi	-

Key benefit of inflatables: launch small, then get big in space or on the surface of the moon or Mars

BEAM/Trunk integration

Packed BEAM on ISS N3

Deployed BEAM

2. Less mass for the same volume as metallic modules? Maybe.

- Depends upon mission and design requirements, outfitting, materials, size, etc.
- Current expandable module experience only at low volumes, not mass-optimized
- Small, mass-optimized metallic modules can be less dense than robust BEAM tech demo
- Large expandable module designs *potentially* offer lower density due to much greater specific strength of fabrics vs. metal alloys, though this must be proven in flight
- More experience with expandable modules may reduce mass due to reduced factor of safety (e.g., ISS requires FoS = 4.0 for fabric structures, 2.0 for aluminum)

Quick-Look Module Density Comparison
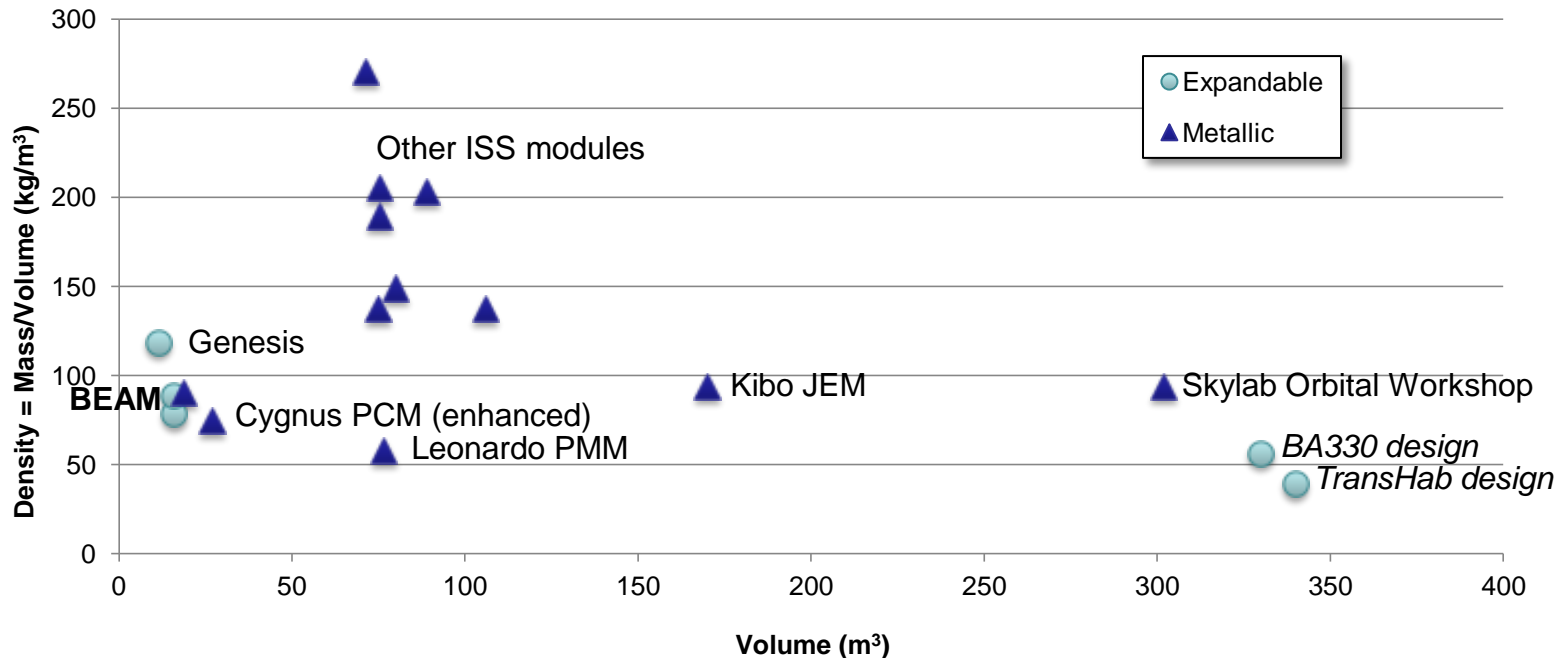
Education and Public Outreach

◆ **BEAM full-size mockup in B.9 at JSC
(publicly visible on the Space Center Houston Red Tour)**

◆ **NASA Twitter & Facebook posts, Facebook Live, Reddit AMA**

◆ **TV, radio and print media interviews and articles**

- NASA TV Space Station Live interview
- Aerospace Daily & Defense Report
- The Economist article, "Pump it up, Scotty", described BEAM as "bouncy castles in space"
- 60 Minutes aired segment with Robert Bigelow and Bigelow Aerospace

◆ **Online articles**

- Bigelow Aerospace BEAM page: http://bigelowaerospace.com/beam/
- NASA Feature: http://www.nasa.gov/mission_pages/station/news/beam_feature.html
- NASA Landing Page: http://cms.nasa.gov/content/bigelow-expandable-activity-module
- NASA Announcement:
  http://www.nasa.gov/home/hqnews/2013/jan/HQ_13-024_Bigelow_ISS_Module.html
- Space News: http://spacenews.com/bigelow-module-ready-to-fly-to-space-station/
- American Airlines magazine: http://magazines.aa.com/content/beam-me

**BEAM installation animation by JSC/IGOAL on YouTube
https://youtu.be/VopaBsuwikk**

BEAM Acronyms

ABH – Aft Bulkhead

ACBM – Active Common Berthing Mechanism (on ISS Node)

ADSS – Anomalous Depressurization Stabilization System

AVV – Ascent Vent Valve

BA – Bigelow Aerospace, LLC

BEAM – Bigelow Expandable Activity Module

CCAFS – Cape Canaveral Air Force Station

CSA – Canadian Space Agency (provides SSRMS)

DCA – Debris Casualty Area

DDS – Deployment Dynamics Sensor

DIDS – Distributed Impact Detection System

DPA – Debris Protection Assembly

EOM – End Of Mission

EVA – Extravehicular Activity

FBH – Forward Bulkhead

FRGF – Flight Releasable Grapple Fixture

FSE – Flight Support Equipment (by SpaceX)

HVI – Hyper Velocity Impact

IMV – Inter-Module Ventilation

IVA – Intra Vehicular Activity

IWIS – ISS Wireless Instrumentation System

MLI – Multilayer Insulation

MM/OD – Micrometeoroid & Orbital Debris

MORD – Medical Operations Requirement Document

MPEV – Manual Pressure Equalization Valve

NSI – NASA Standard Initiators (pyros)

ODAR – Orbital Debris Assessment Report

ODPO – Orbital Debris Program Office

ORDEM – Orbital Debris Engineering Model

ORSAT – Object Reentry Survival Analysis Tool

PCBM – Passive Common Berthing Mechanism (on BEAM)

PPF – Payload Processing Facility (SpaceX/CCAFS)

RAM – Radiation Area Monitor (passive badge)

REM – Radiation Environment Monitor (active)

RSC – Restraint Strap Cutters (w/ NSI pyros)

RSS – Rip-Stitch Straps

SSPF – Space Station Processing Facility (NASA/KSC)

SSRMS – Space Station Remote Manipulator System

SpX – SpaceX

WTS – Wireless Temperature Sensor