Webinar for LMC staff
SAND2013-3842P
May 16, 2013

Sandia's
High Heat Flux Facility

HHFF
SANDIA NATIONAL LABORATORIES

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Sandia National Laboratories
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- **High Heat Flux Facility**
  - *- electron beams*
  - *- cooling loops*
  - *- diagnostics*

- **Thermo-mechanical and Thermo-fluid modeling specializing in One-sided Heating**
  - *- Abaqus*
  - *- Star CCM+*
  - *- Fluent*
  - *- Comsol*
  - *- Catia*
  - *- SolidWorks*

“HHFF is the only fully-equipped **HIGH** heat flux facility in the western hemisphere”

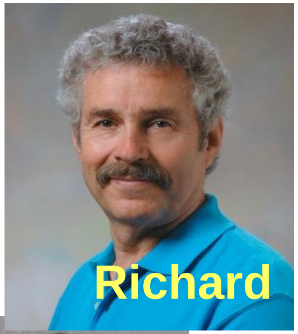
“We can put 1.2 MW on a dime!”

Sandia expertise on fusion PFCs

[*Advanced Electrical & Electromagnetic Systems*](), DMTS & PE (nuclear eng)

thermal analysis, CFD, code development, e-beams

high heat flux testing, diagnostics, D.O.E., admin.



Hydrogen & Metallurgy Science (Livermore)

- **Richard Nygren**
  PFC design, thermal analysis, HHF testing
- **Dean Buchenauer**
  edge physics, fueling (compact toroids)
- **Rob Kolasinski**
  H/D/T in metals, lab plasma experiments*

**Includes Tritium Plasma Experiment, built by Sandia, now at INL*

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A unique set of capabilities support our PFC research for fusion.

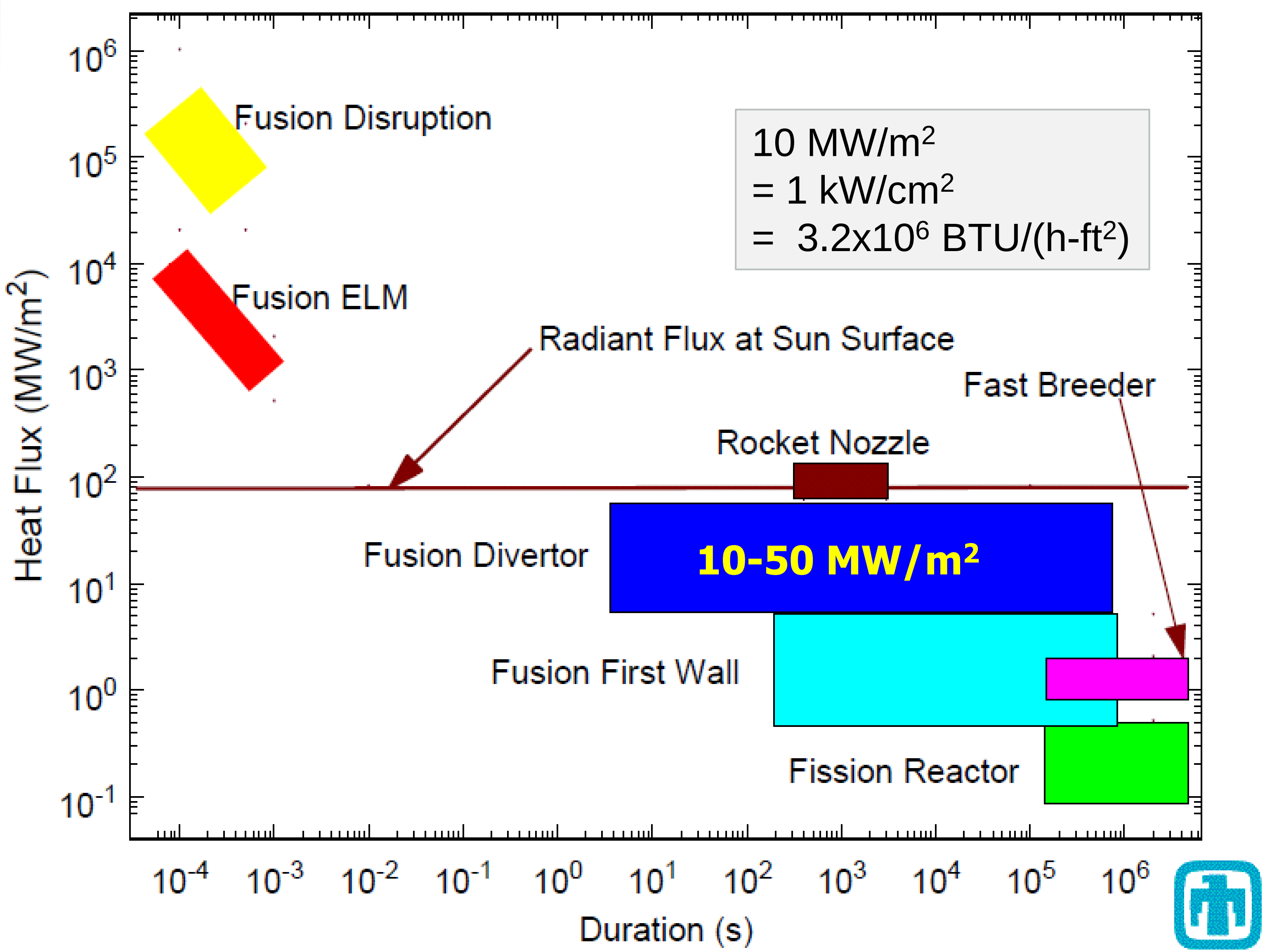
Surface analysis for Plasma Surface Interactions

- Plasma sources for tritium PSI studies: Deuterium Plasma Experiment (DEP) and TPE, now at INL in Idaho.
- Low-energy ion beam probes for LEIS, DRS & SIMS
- MeV ion beam analysis of surface modification and T trapping.
- Traditional surface analysis (Auger, Raman AFM, and XPS).

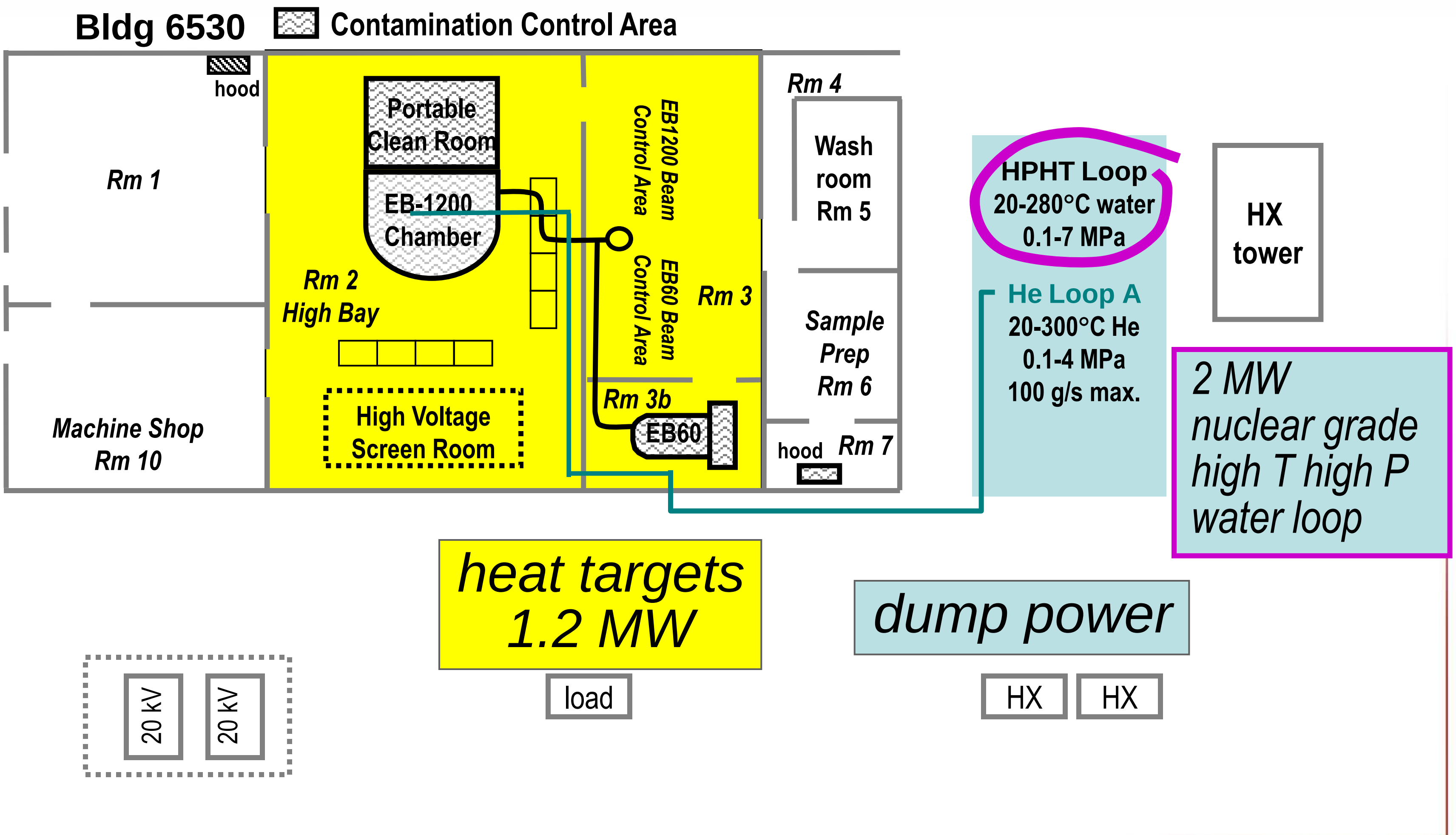
High Heat Flux Testing (High Heat Flux Facility)

- Electron beams: EB60 & EB1200
- Coolants: high temp & press water, helium, liquid metal
- Diagnostics: IR, pyrometers, thermocouples, calorimetry
- Beryllium handling facility
- Large sample SEM
- Codes: magnetic fields, thermal & stress distributions, computational fluid dynamics

What are high heat fluxes?

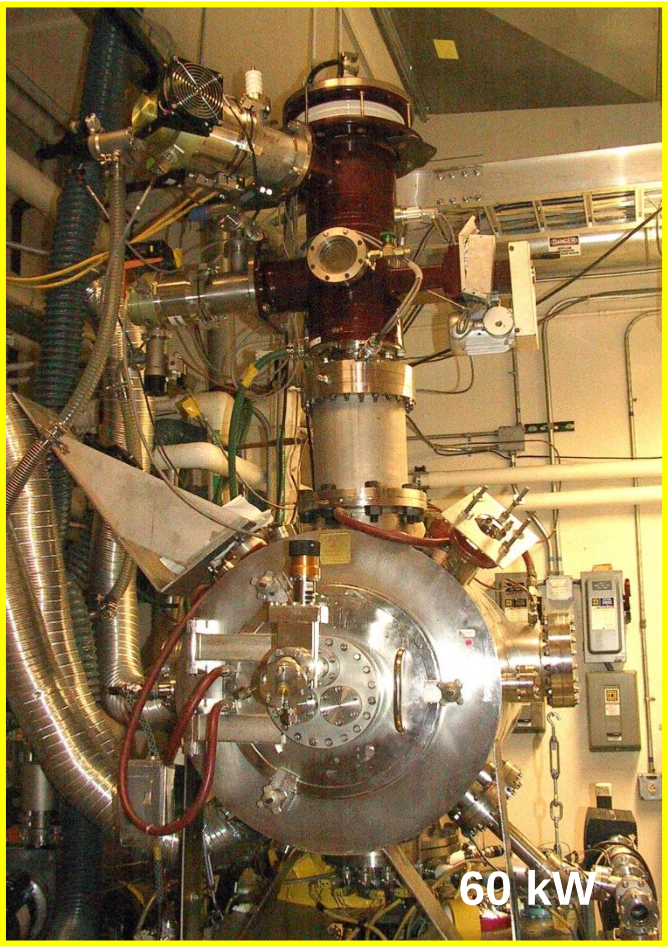


HHFF Layout
(High Heat Flux Facility)



HHFF e-beams

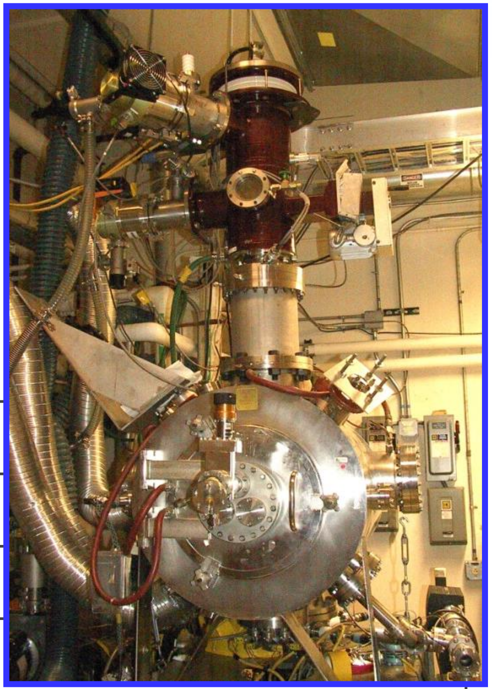
EB-1200



EB-60

- e-beam testing gives complete access to the heated surface for optical, IR and pyrometry measurements
- low thermal conduction losses
- requires 10 mTorr or better vacuum
- RGA, OES and LIF possible
- Fiberscopes, borescopes

EB-60

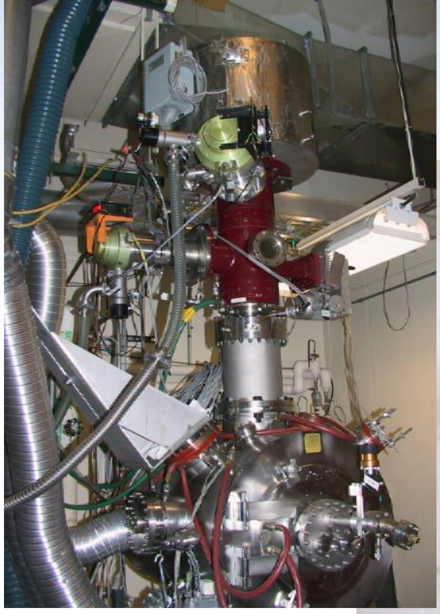


Beam power	60,000W (60kW)
Accelerating voltage	30,000V (30kV)
Beam current	2A
Beam spot	2mm FWHM at target plane
Target area	0.1-10,000mm^2
Pulse length	From 2ms to continuous
Chamber pressure	~6 x 10^{-4} Pa, cold-trapped diffusion pump
Gun pressure	~1 x 10^{-6} Pa, turbopump

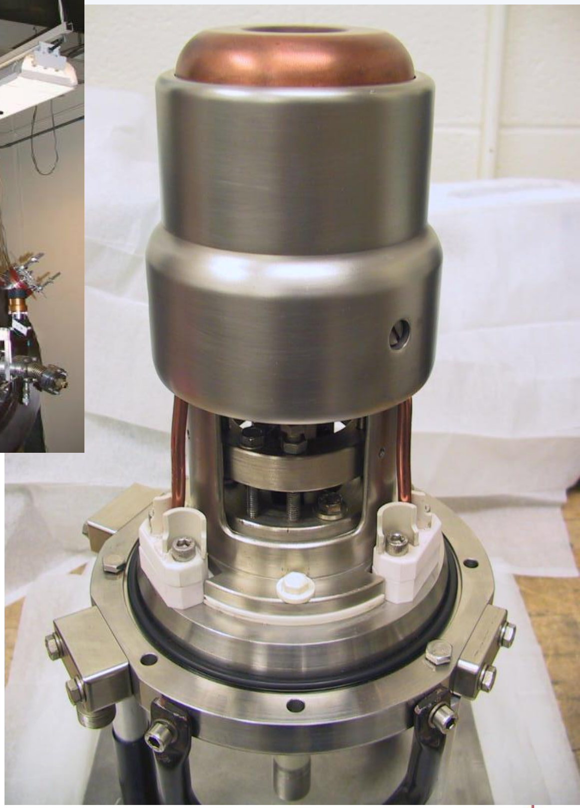
Gun Control

Our 60 kW gun had operated at 30kV and 2A but had been controlled by setting the voltage to achieve a desired power level.

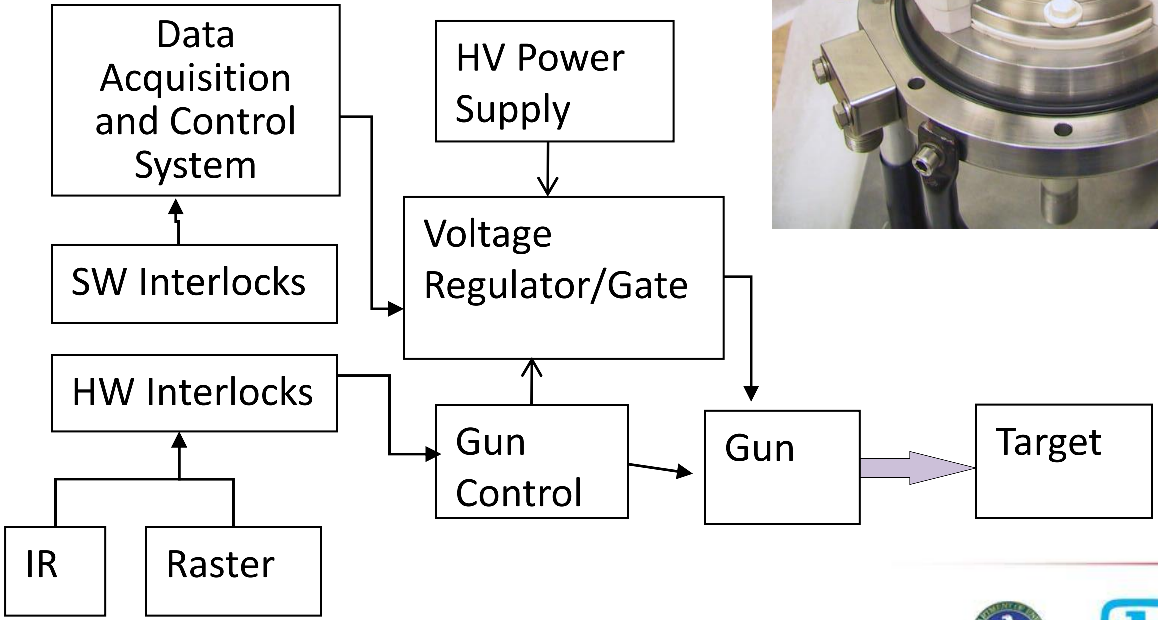
For our testing, regulating the current to set the power is more appropriate.   We either gate the accelerating voltage to the gun (EB1200) or use a suppression grid (EB-60)



EB60 source with modifications



- isolated focus electrode that normally operates at the cathode potential
- applied a negative suppression bias
- gap dimensions based on analysis



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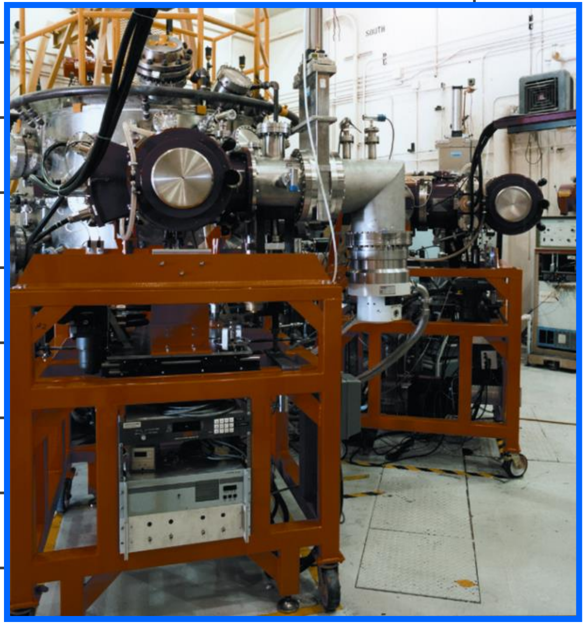
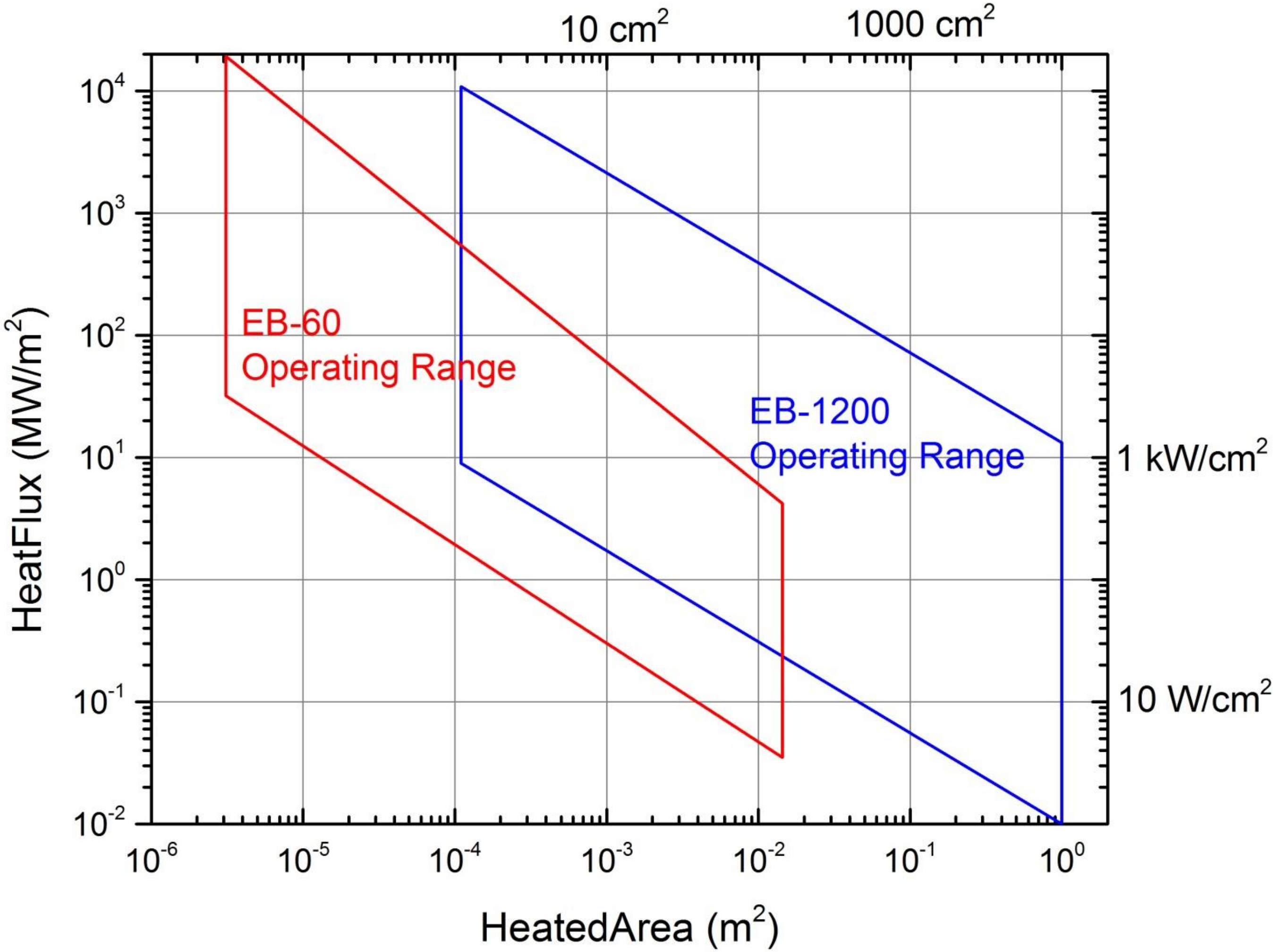
EB-1200

Beam power	0-0.6MW(cw) each gun; 0-1.2MW(cw) total
Accelerating voltage	0-40,000V (40kV)
Beam current	0-15A each gun
Magnetic lenses	2 coils
Spot diameter at 600kW, 1.5m	35mm
Magnetic deflection	2 yokes(orthogonal)
Max raster frequency	10,000Hz (10kHz)
Max. angle beam deflection	±7°, 10kHz; ±30°, <200Hz
Max. heat flux (unrastered)	>1000MW/m^2
Max. heated area at 10kHz	370mm x 370mm at 1.5m
Heat flux at maximum area	8.7MW/m^2
Max. pressure in chamber	<3Pa
Cooling water consumption	2.2m^3/h

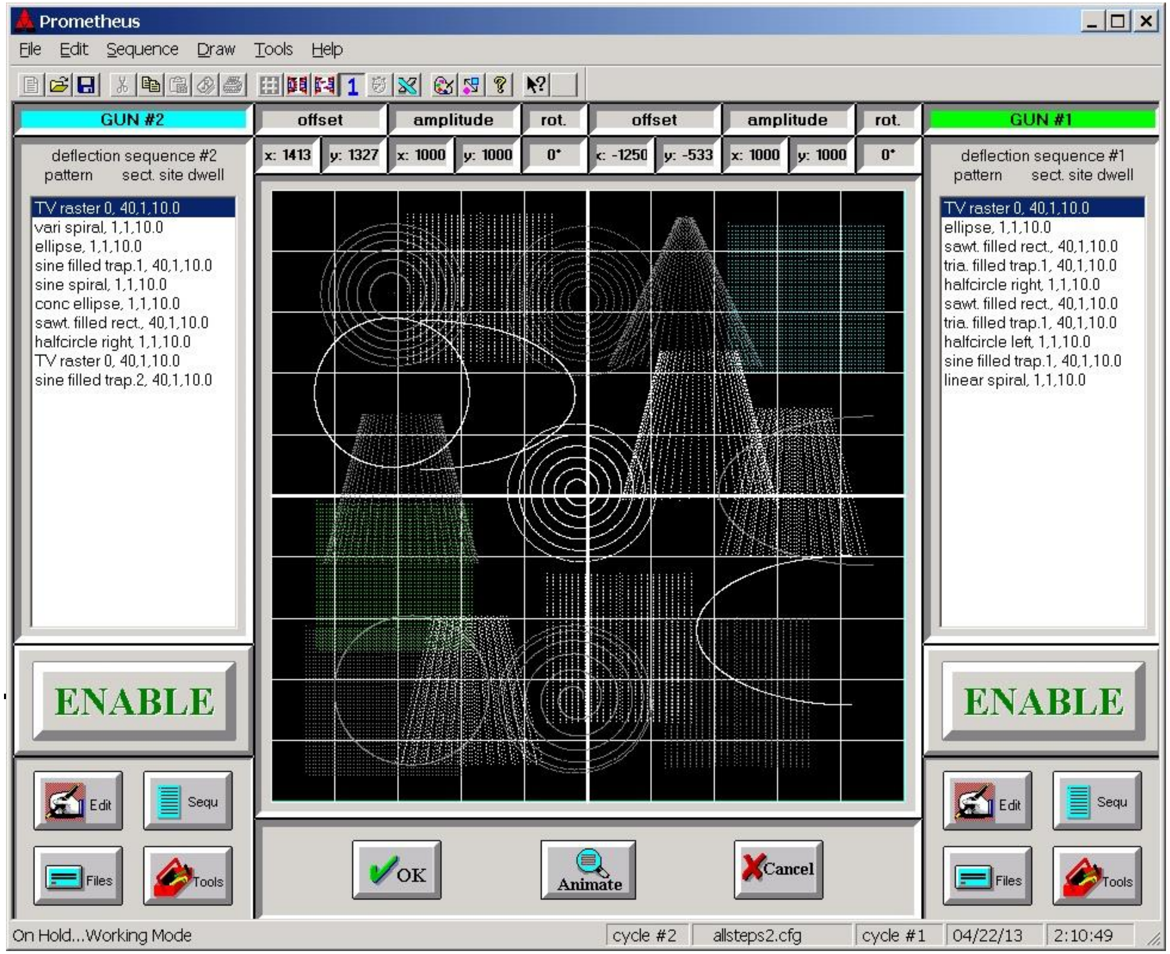


Our e-beams cover an amazing range of areas and flux levels.



Exotic raster patterns and high-speed pattern switching make complex spatial and temporal heat loading possible.

- E-beams are equipped with digital rastering.
- The “Prometheus” program can raster at 10 kHz and pattern switch at 1kHz from one area to another.
- Exotic patterns can be input
  Native, Excel, or Drawn
- Size, position rotation and aspect ratio can be controlled.
- 40 sections, 32 sequences, 10 steps.
- Different dwelltimes can be set for each section.



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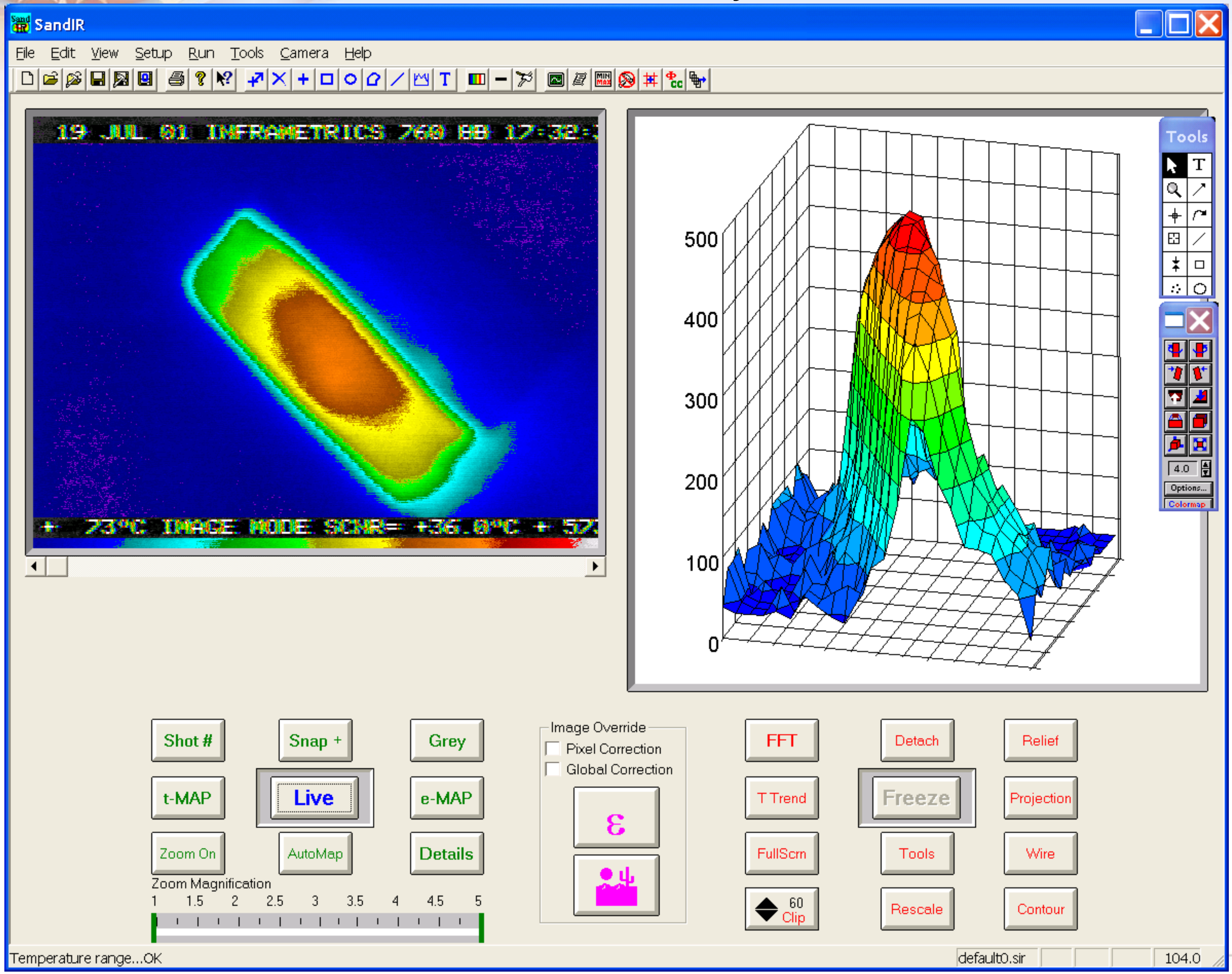
Sandia Infrared Analysis Software



SandIR Features

- Acquires, calculates & plots real temperatures for each camera frame (at >247,000 points per frame, 30 Hz) 7 Million temperature calculations/second
- Very visual interface with Zoom, SNL owned
- Hi-res display compatible (1280x1024 etc.)
- 32-bit, 5-thread C++ OOP Windows application >30,000 lines of C++ code
- Origin plotting support - 3-d relief & contour
- DT3132 Hi-res Framegrabber - PCI Bus, dual-channel, WinXP, latest device drivers (DirectDraw)
- Reads FLIR camera VIR info in real time
- Uses camera calibration files (pre-interpolates)
- Provides for detailed emittance mapping over entire image pixel by pixel
- Corrects for background reflections using T-bkgd map over entire image pixel by pixel
- Automapping feature for complete emissivity and T-bkgd mapping of “unknowns.”
- Permits manual User input of emissivity and T-bkgd maps or constants
- Vectorized, requires >2 GHz multiple processors
- Windows2000, WindowsXP compatible
- Sandia COE/security compliant
- Complete image toolkit: spots, ellipses, rectangles, profiles, lines, cursor probes
- Real-time image correction for spatially varying emissivities and reflections
- Save IR images and maps or export Origin projects
- Image format translators for JPG, TIFF, GIF, PNG, and BMP formats
- Temporal tool plots
- Exports data directly to Excel or Origin spreadsheets

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Many new HX technologies were tested at the HHFF.

• Gyrotrons	Thermacore and Varian (2)
• RF Mirrors	PPPL (1)
• Magnetrons	Jaycor and CPI (2)
• Klystron Source	Thermacore (1)
• Porous metal HX	Thermacore (3)
• RF Faraday Shield (He)	Thermacore (3)
• Divertor Module (dual) (He)	Thermacore (2)
• Vanadium He-cooled HX	General Atomics (1)
• Tungsten Divertor (dual)	Thermacore (1)
• Tungsten Foam HX	Ultramet (1)
• Micro-channel He-cooled HX	General Atomics (2)
• Normal Flow He-cooled HX	Creare (2)
• BNCT photon beam stop	Lawrence Berkeley (1)
• BNCT target	Linac Systems (2)
• PEP-II photon beam stop	Stanford Linear Accelerator Center (1)
• Beryllium windows	General Electric (3)
• EUV Plasma source electrodes	Thermacore (3)
• C-C Heatpipe Space Radiator	AllComp (1)
• Hypervapotron Divertors	ITER (3) and Boeing (3)
• Single-channel He-cooled Mo HX	Ultramet (3)
• Multichannel He-cooled W HXs	Ultramet (3)

Continuation of non-DOE HHF Testing

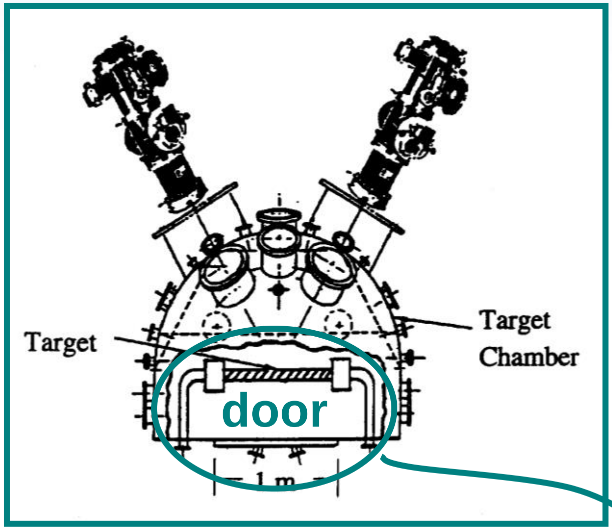
DIII-D Graphite Tiles	GA (5)
W Lamellae Tiles	MIT (2)
TPX & Kstar CFC Tiles	PPPL (2)
NSTX CFC Tiles	PPPL (1)
FRIB Accelerator Targets	MSU (2)
Nanowire Enhanced HXs	Technova (2)
He/He Refractory Regenerator	Ultramet (1)
Li/He Refractory HX	Ultramet (1)
Be Armored Heatsinks	NGK (1)
PS Be Armored Heatsinks	LANL (2)
Be ITER FWQ Mock-ups	ITER (6)
W-coated Graphite Mock-ups	NIFS (2)
Swirl Tube or Finned Heatsinks	JAEA (8)
Swirl Tube Divertor Heatsinks	CEA (2)
W and CFC Armored Divertors	IPR (2)
Lithium jets	ALPS/APEX (4)
Lithium Emissivity	ALPS/APEX (2)
Molten Salt (FLiBe and FLiNaBe)	ALPS/APEX (2)

FWQM Tests in EB1200

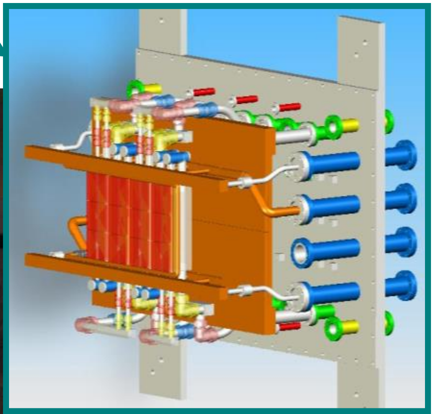
- We can test four FWQ mockups at one time using 2 e-guns. We completed testing of 6 FWQMs.
- 2 IR cameras
- 48 TCs, 4 flow, 4 ΔP

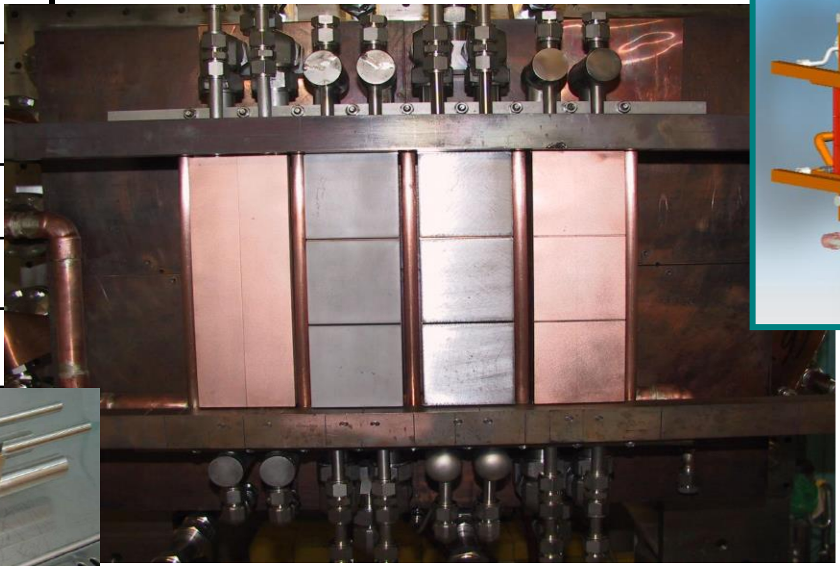
  4 calorimeters, 4 pyrometers

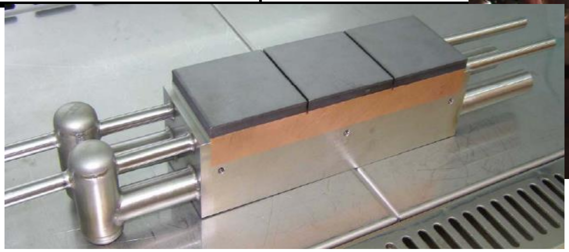
Heat flux (absorbed)	**0.7 MW/m^2**
$P_{absorbed}$/cycle	**13.4 kW**
Water	**100 C** **1 m/s**
Water T_{out}-T_{in}	**~20C**
Number of cycles	**12,000**
Full cycle (on/off)	**96 s**



EB1200 Electron Beam



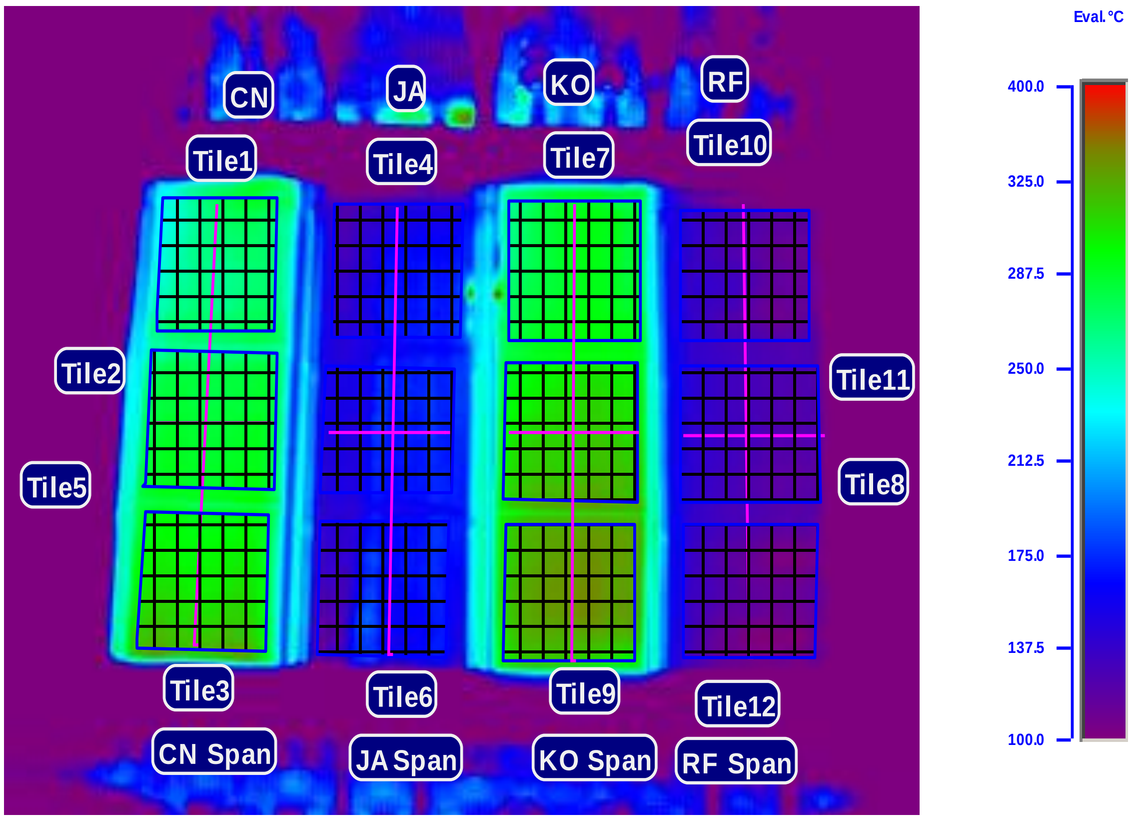




Monitoring/measuring surface temperature

Temperature-based shot triggers

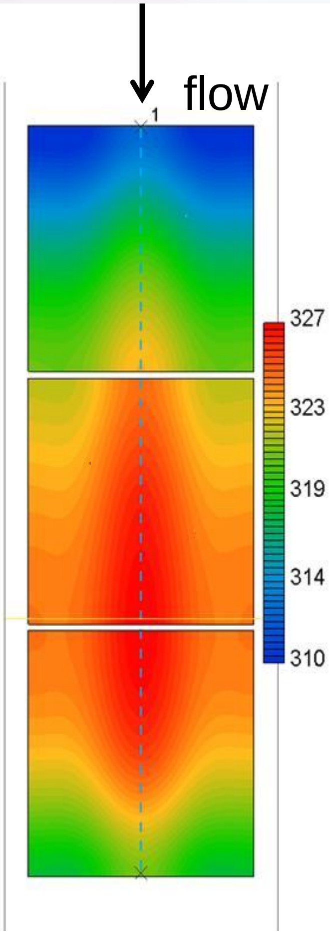
Another concern for failure resulting in significant melting of the beryllium armor is the breakdown of the armor tile bond to the cooled copper alloy substrate. Our IR camera systems monitor the temperature and control an interlock to the electron gun control



In addition to SandIR, we use IRControl developed by Automation Technology, GmbH.

Using IRControl, and interface hardware from National Instruments, we defined multiple trigger points based on the peak and average temperatures of multiple areas.

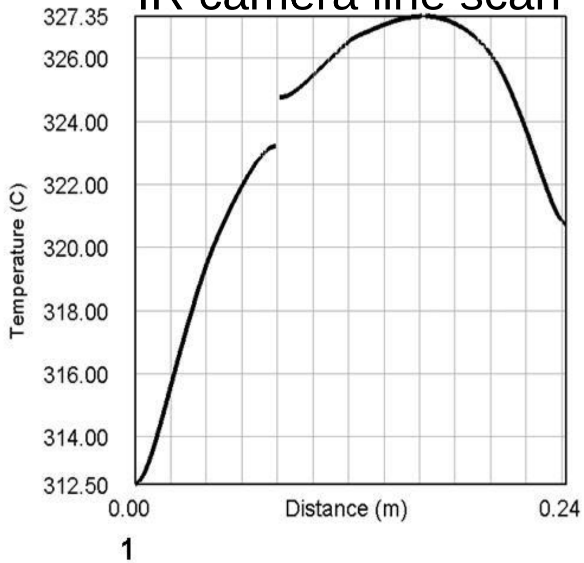
E-gun calibration



calculated surface temperature distribution

FWQM cyclic heat test calibration run-
0.875MW/m2 (uniform on all tiles)
5GPM per mockup at 100C inlet conditions

IR camera line scan



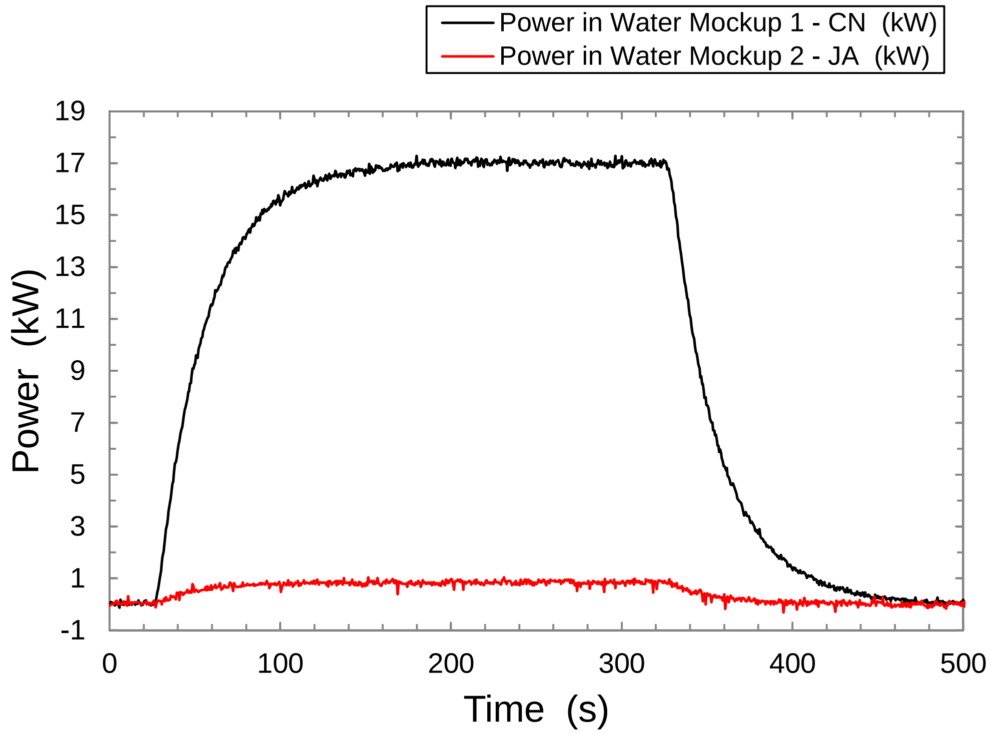
We calibrate the gun operating level and the raster patterns to provide the proper uniform heat loading on each of the mockups.

To do this we run long shots on a single mockup to determine the proper settings for the gun to achieve the required steady state absorbed power in the cooling water

As part of this procedure we also adjusted the beam raster pattern to provide uniform full coverage of the beryllium armor front surface while minimizing overspray onto adjacent mockups. We often use thermal modeling results as a guide for this process.

Real Time Calorimetry

We monitor the power absorbed by the target(s) during the shots through water calorimetry and also monitor the surface temperature.



Power absorbed in the water is used to compute the heat flux absorbed through the heated area. Electron reflection coefficients vary depending on the Z of the target, geometry and even surface temperature.

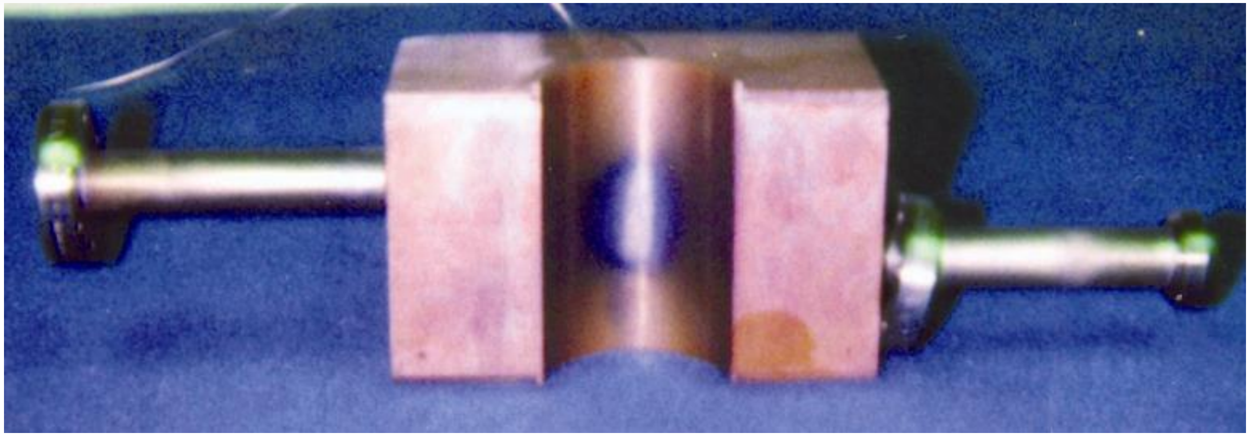
We adjusted the gun settings as necessary to maintain the peak absorbed power levels within 5% of the level observed at the beginning of cycling just after the steady state calibrations.

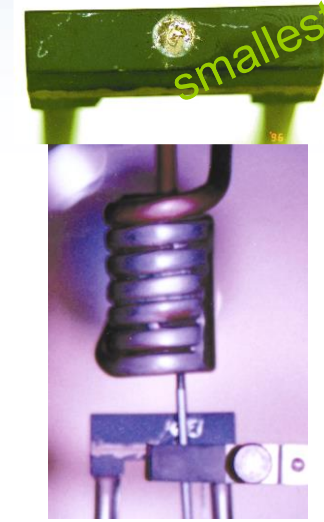
Several HX performance records achieved at the HHFF.

• Varian microchannel gyrotron (3800 cycles at 22 MW/m^2)	141 MW/m^2
• Thermacore porous metal gyrotron (10,000 cycles at 27 MW/m^2)	109 MW/m^2
• Thermacore He-cooled RF Faraday shield	10 .3 kW
• Thermacore porous metal HX	74 MW/m^2
• Vanadium He-cooled HX test	6 MW/m^2
• LBNL BNCT Al beam stops for cancer treatment (6.6 MW/m^2, 7.5 MW/m^2 max)	50,000 cycles
• Magnetron vane tips	78 MW/m^2
• Microwave Cross-Field Amplifiers	80 MW/m^2
• Helium Cooled Foam Divertor	22 MW/m^2

Gyrotrons: copper porous metal HX using water cooling

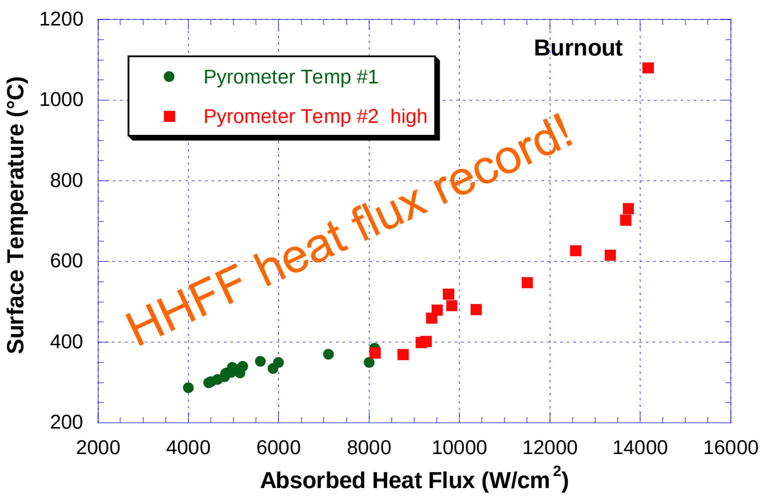
Magnetron Vanes

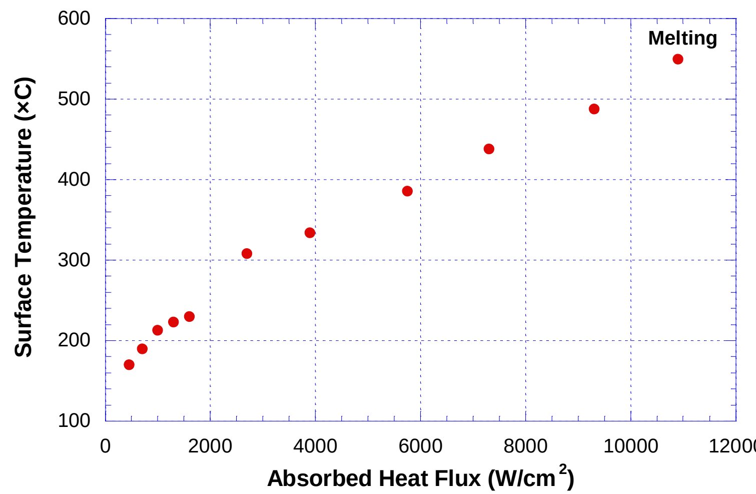




Varian Microchannel Gyrotron Cavity

Thermacore Porous Metal Gyrotron Cavity





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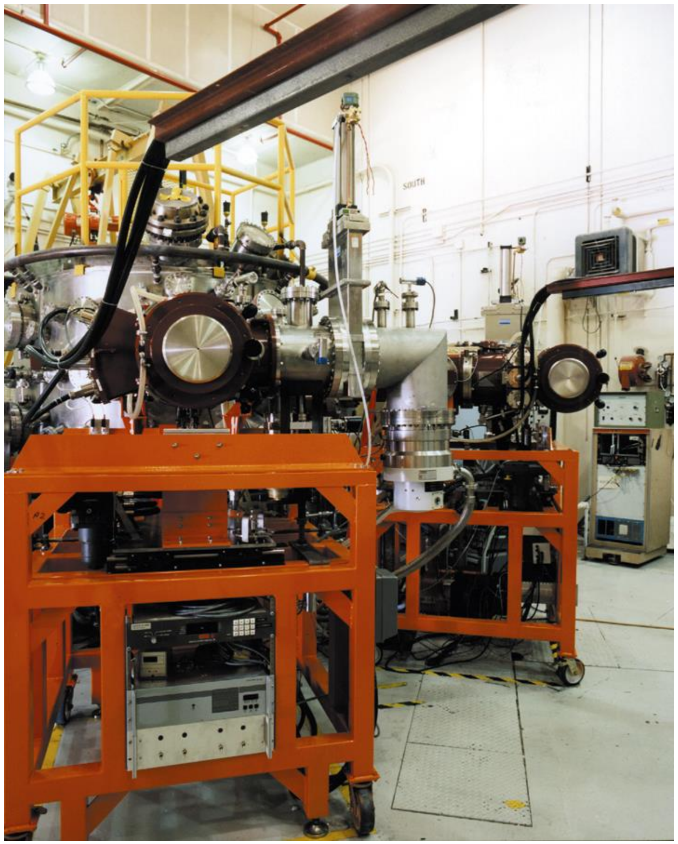
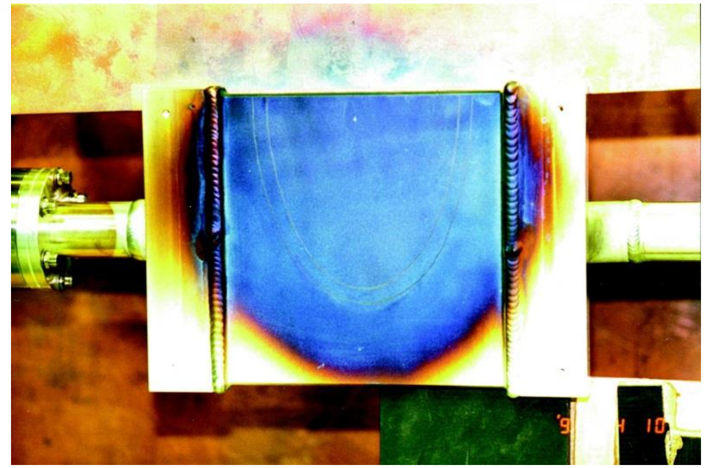
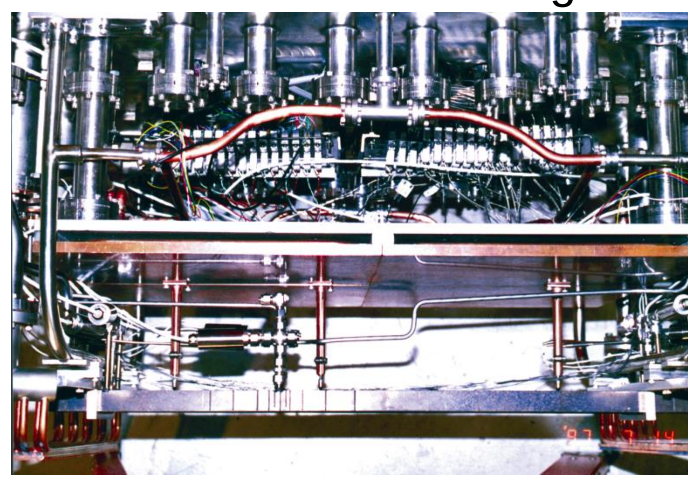
The EB-1200 can test full-scale components.

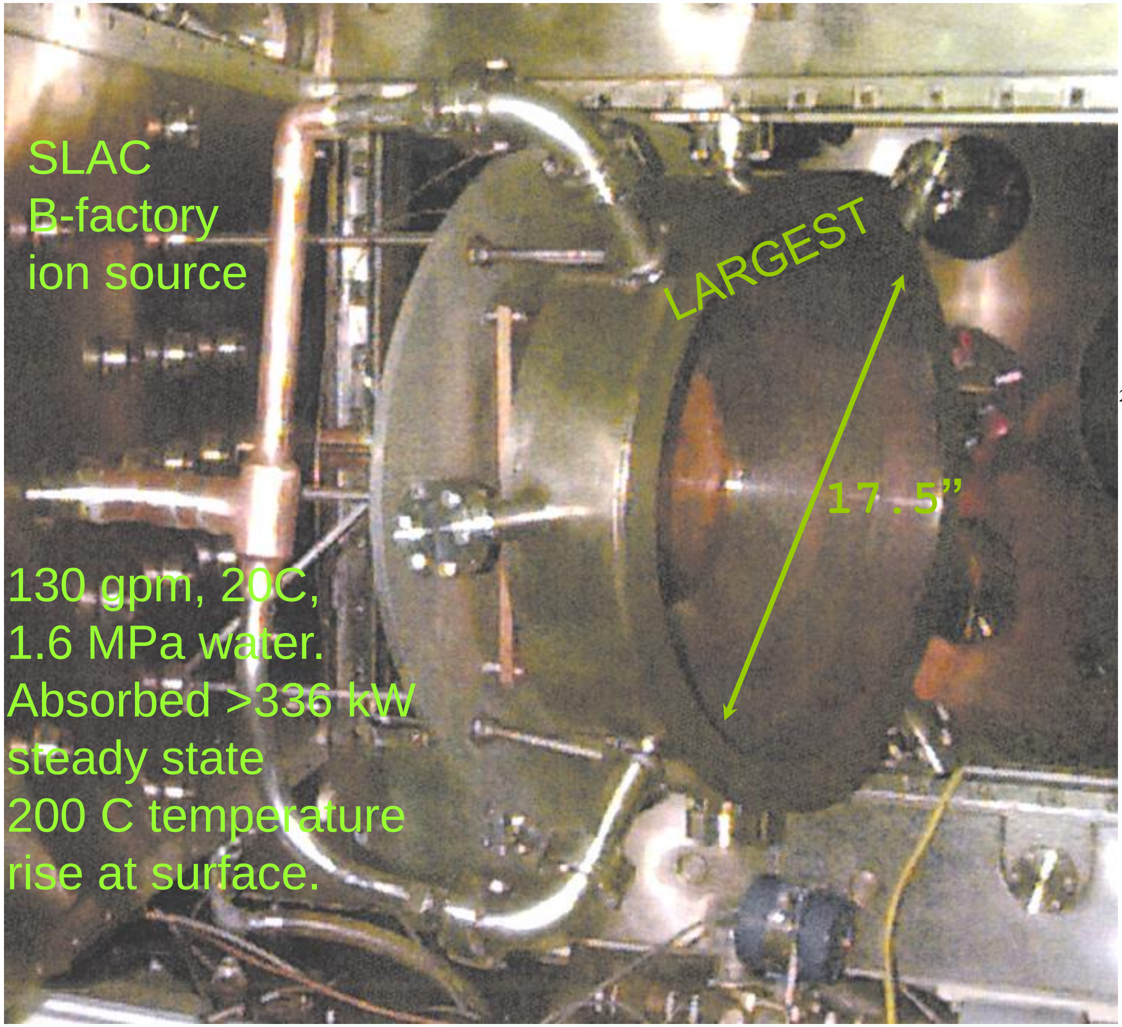


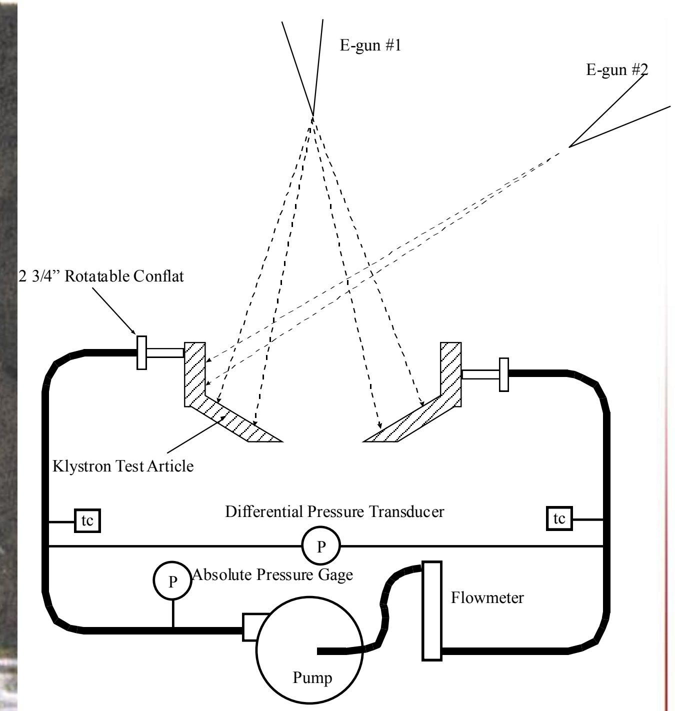


Aluminum BNCT target



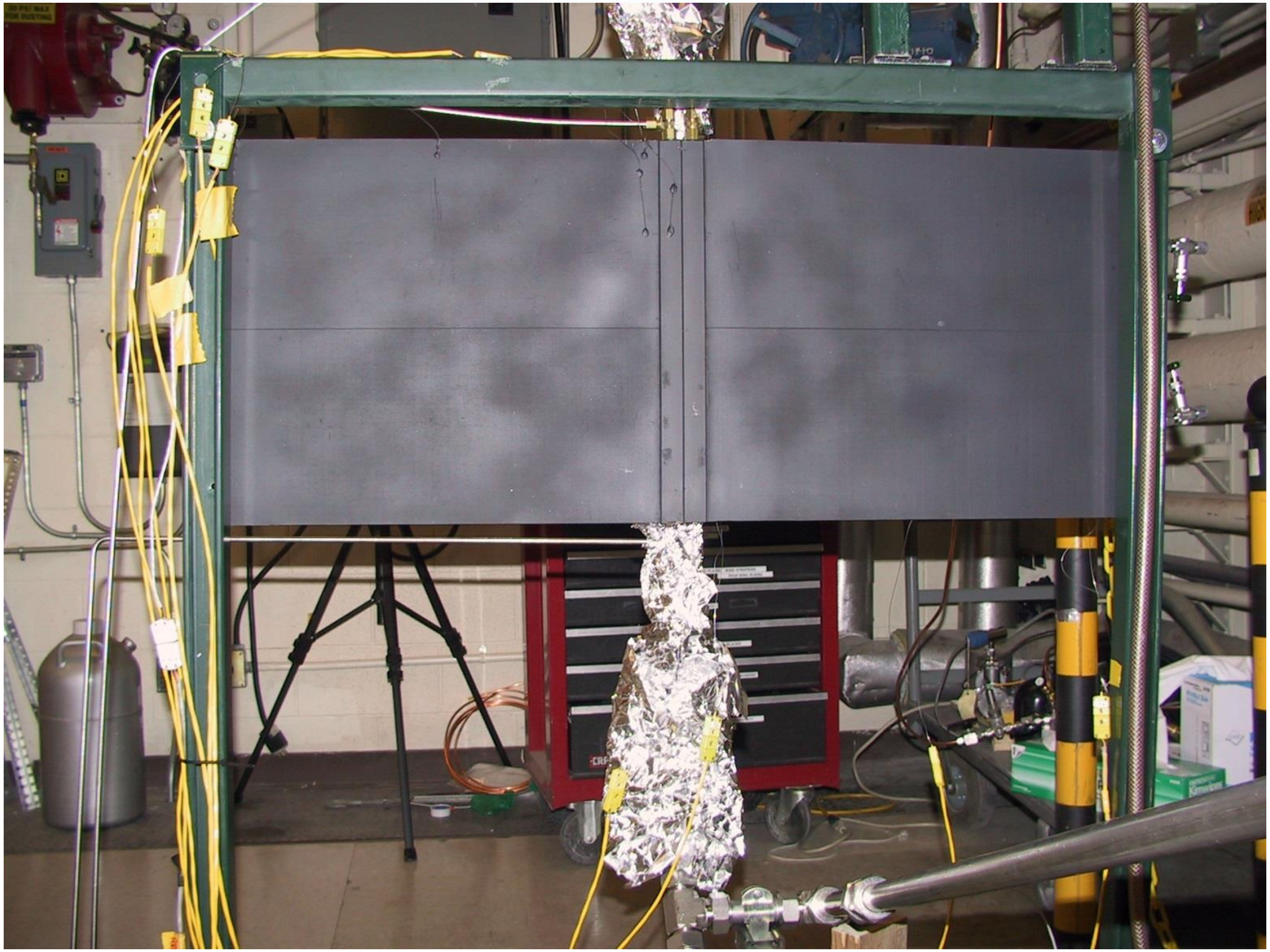
Thermacore phase II SBIR project
Klystron collector: copper porous metal HX using water cooling





Max q"=31 MW/m^2
15 MW/m^2, 10,000 cycles
2s ON/2 s OFF

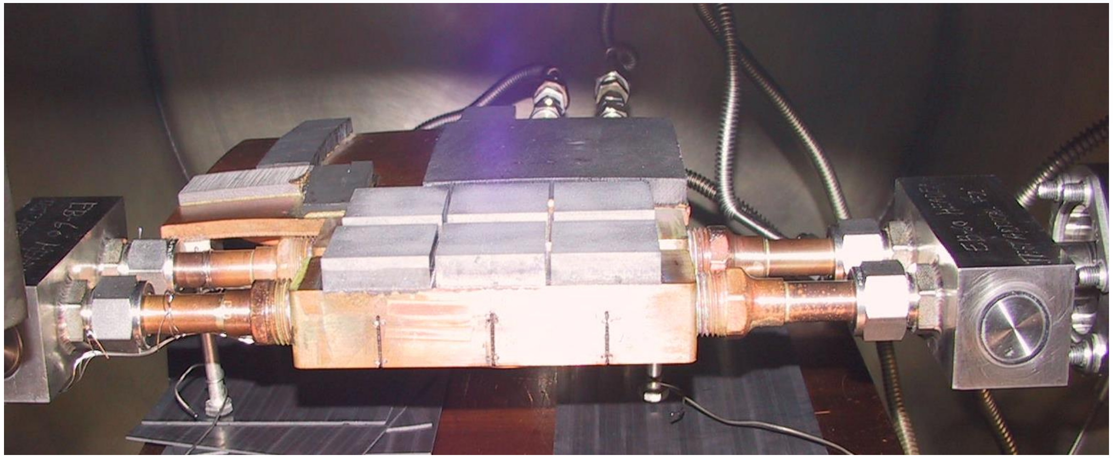
C-C Heatpipe Space Radiator – Used HPHT loop and Diagnostics

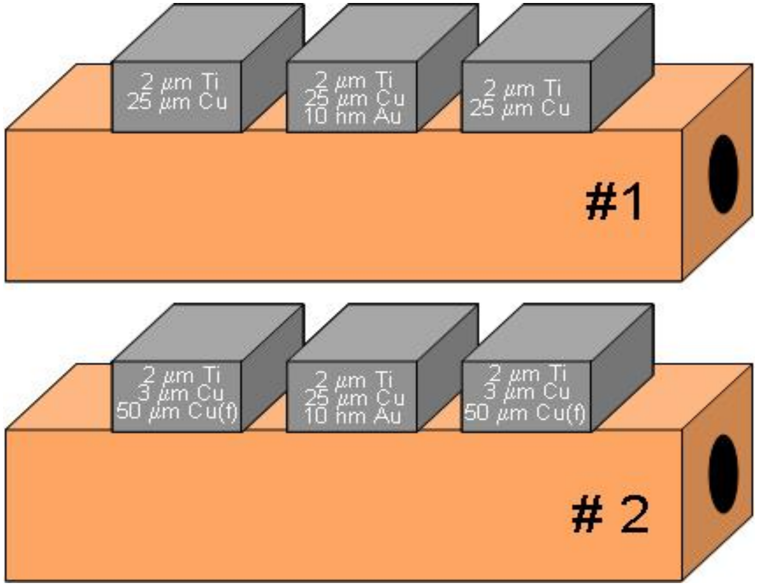


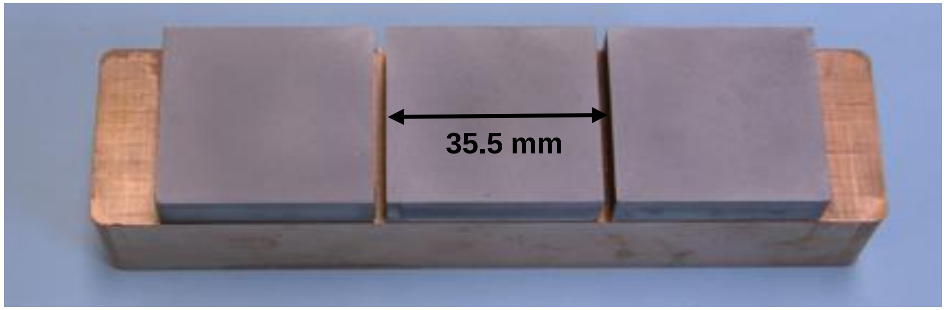
Testing in EB60

In EB60 we test smaller samples than EB1200. A typical size is 30 mm wide by 80 mm long.

For ITER, smaller mockups with variations in joining were precursors to the larger First Wall Quality Mockups tested later in EB1200.

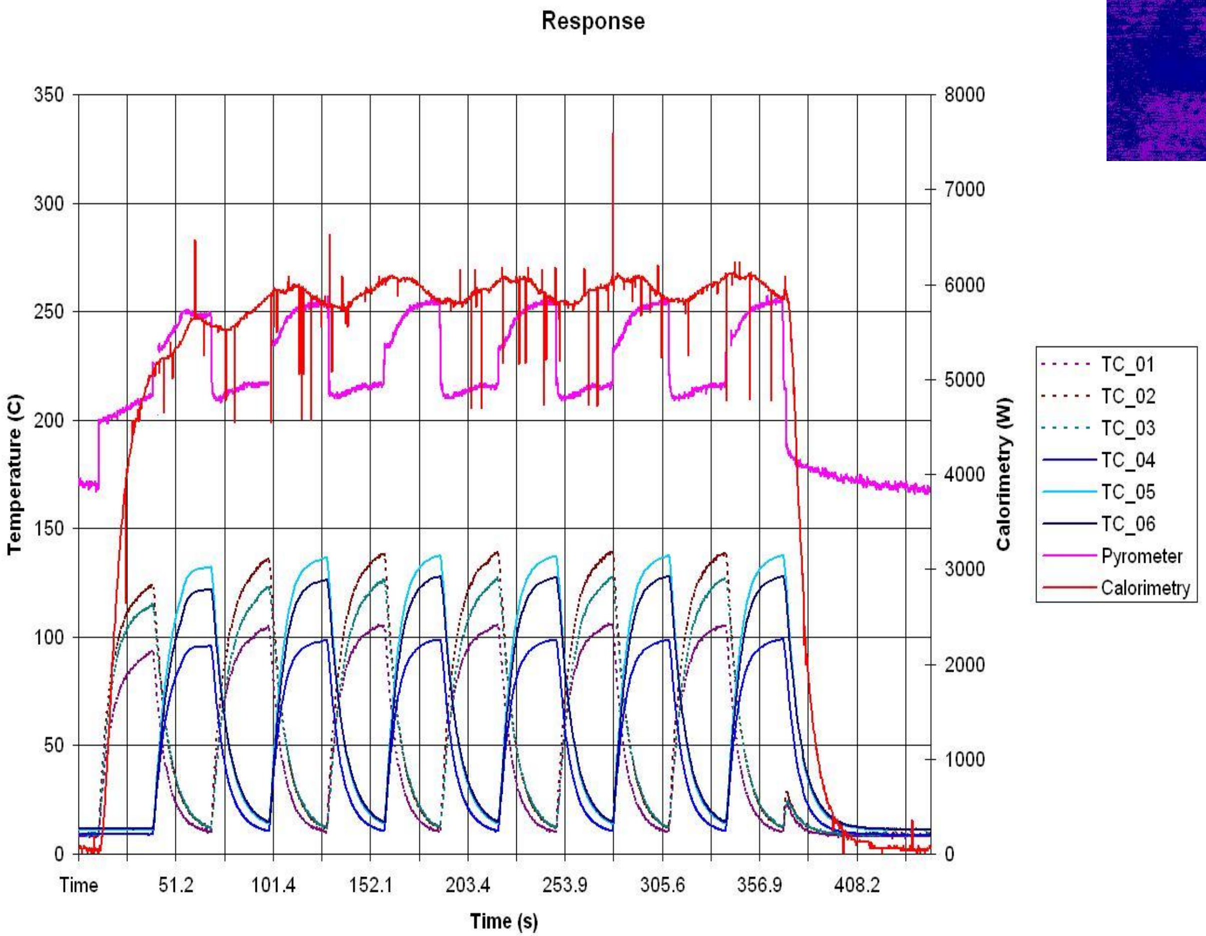


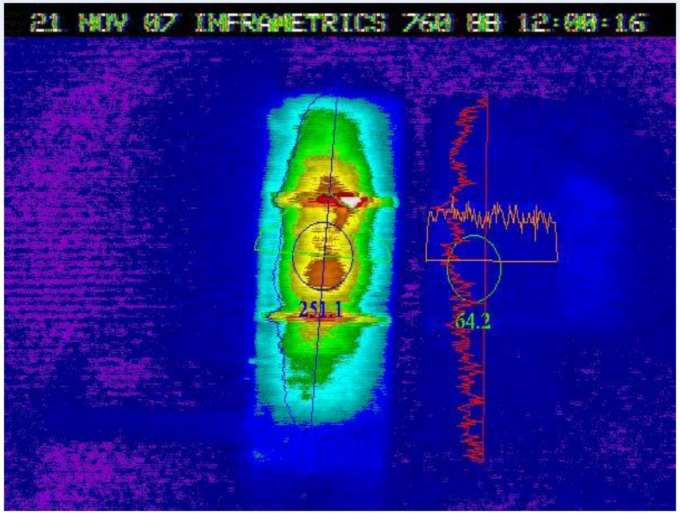




Testing in EB60

Both mock-ups survived 1000 cycles with no significant changes in their response. The temperature of the top surfaces reached 254 ˚C; while the center TCs reached 136 ˚C and 139 ˚C for each mock-up, respectively.





IR temperature of mockup #1, end of 30s heating cycle.

The thermogram above shows the temperature distribution on mock-up #1 at the end of the 30-s on-cycle.

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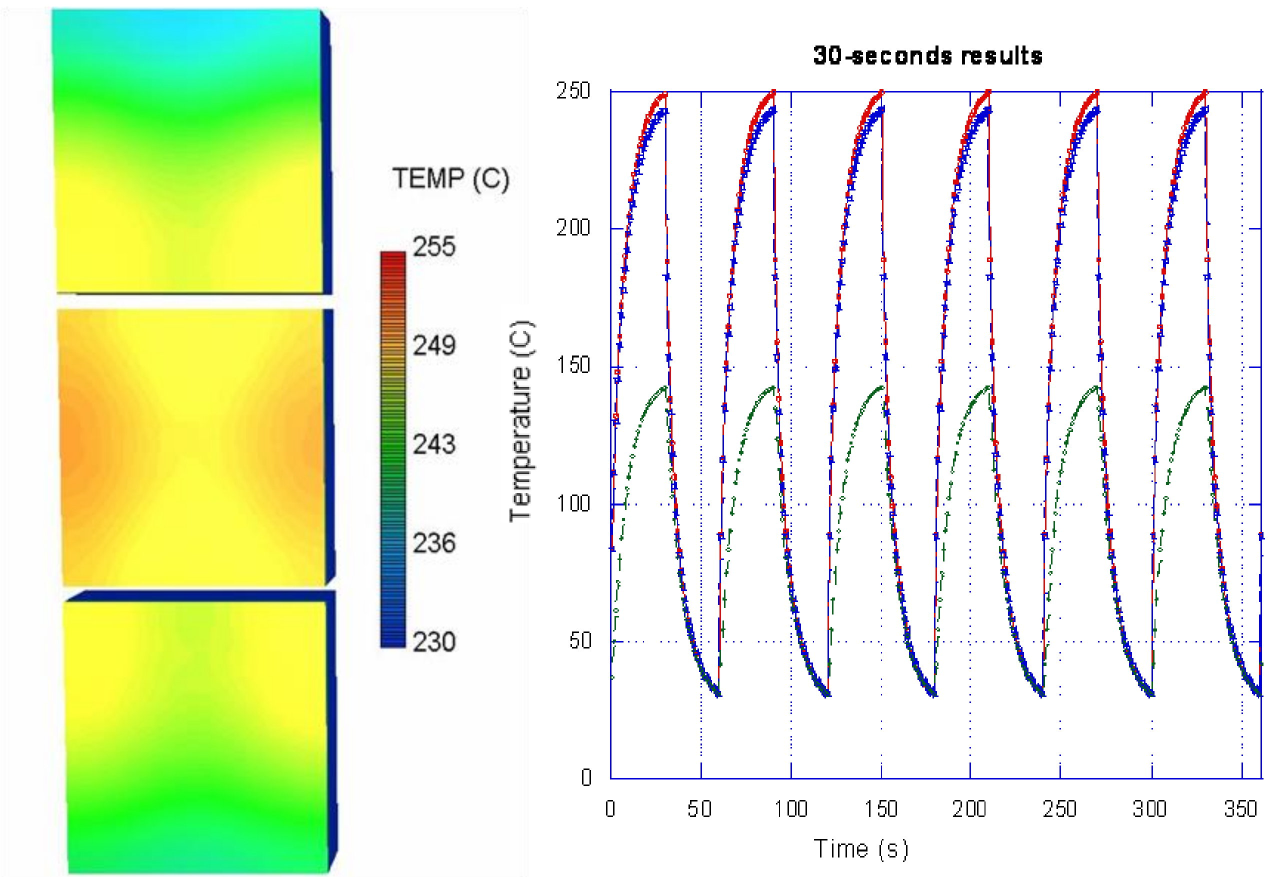
Testing in EB60

CFD computations predicted the Be surface temperatures at end of a 30 s shot. We also predicted the time-dependent average surface temperature integrated over the tile area (solid curves) and the temperature of the thermocouple in the center tile (dashed curve) over six cycles.



(a) (b)

The test results and the CFD predictions agreed well.

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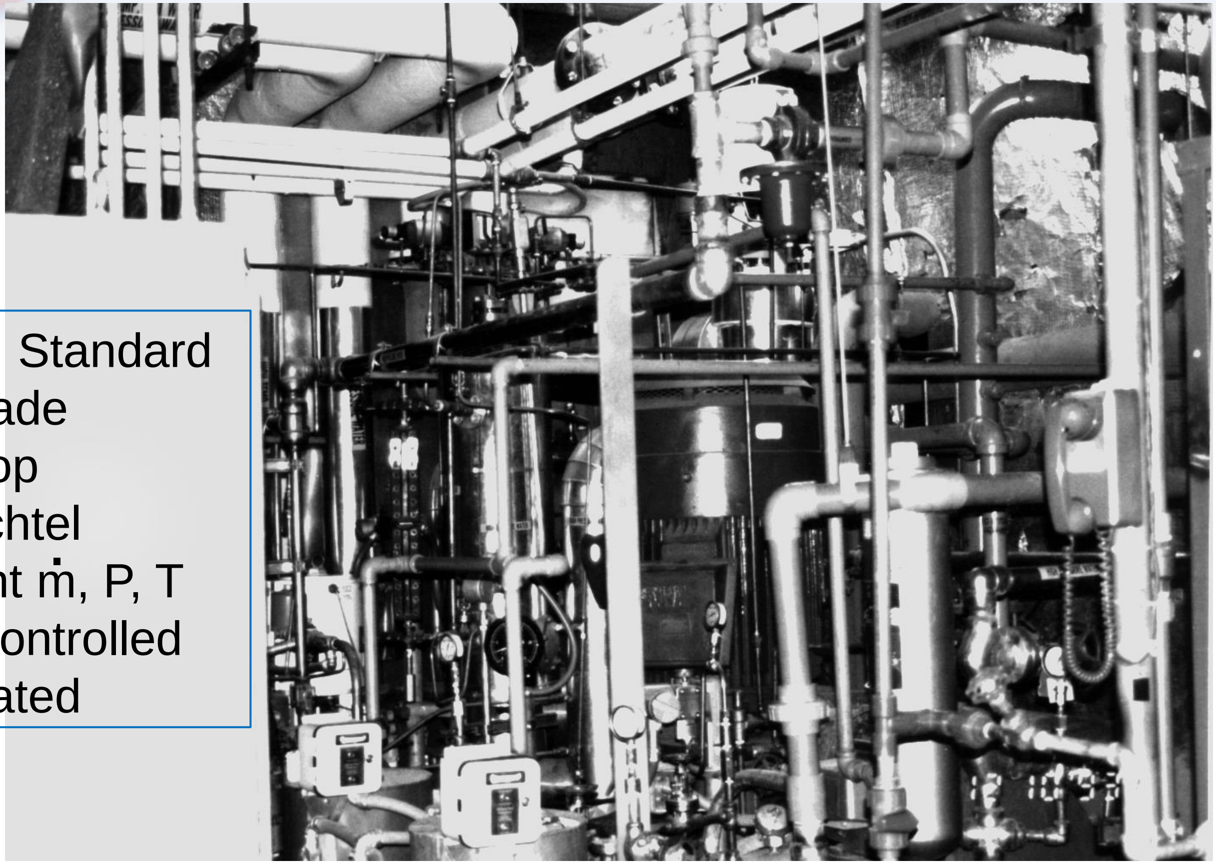
High Pressure High Temperature Water Loop (HPHT)

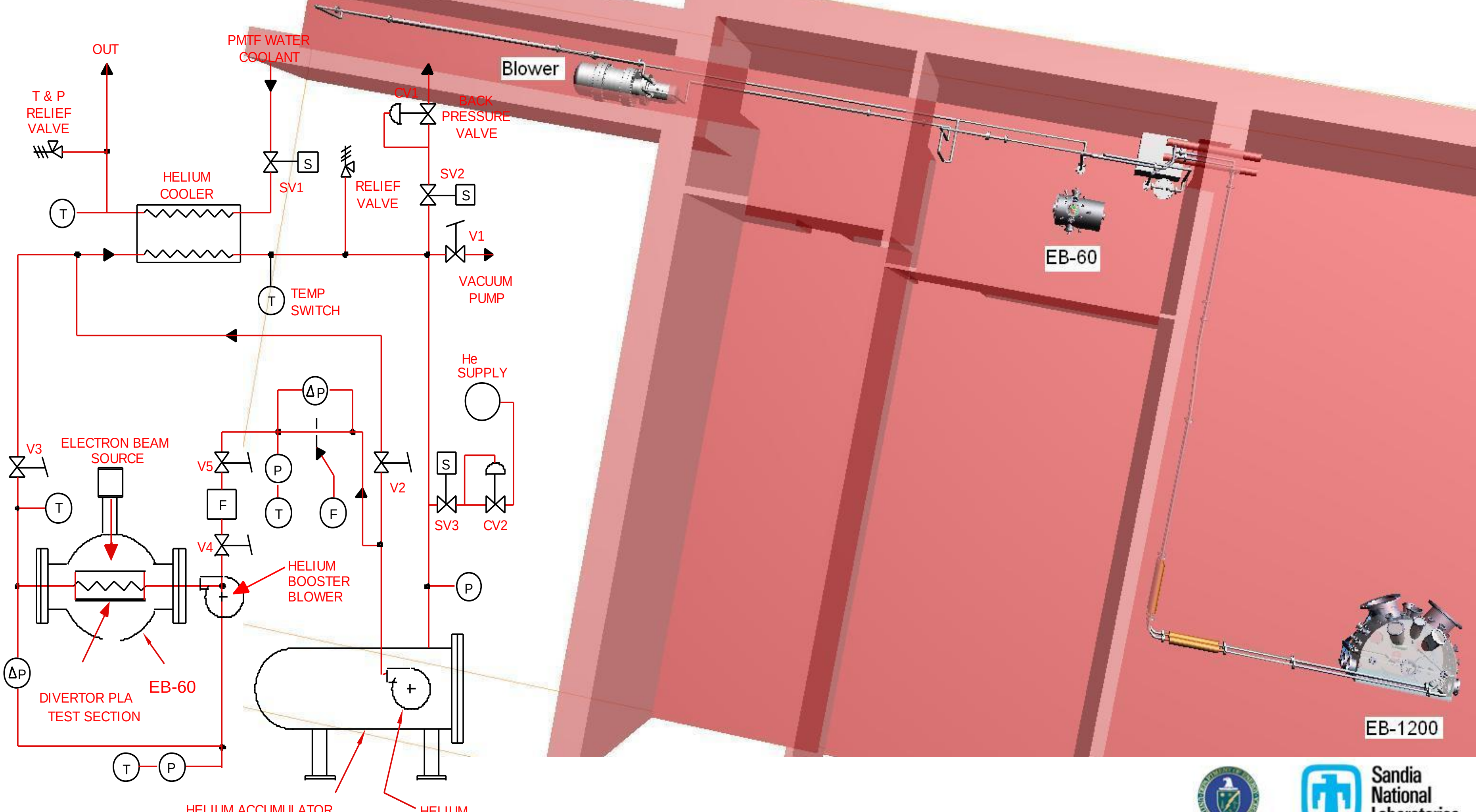


2 MW ANSI Standard
Nuclear Grade
Cooling Loop
built by Bechtel
Independent $\dot{m}$, P, T
chemistry controlled
fully automated

	Metric	English
Flow	3 to 30 l/s	50 to 500 gpm
Temperature	40 to 280 °C	100 to 540 °F
Pressure	0.1 to 7.0 MPa	15 to 1000 psi
Target Pressure Drop	0.01-1.4 MPa	1 to 200 psi
pH	7 to 11	7 to 11
Oxygen	200 ppb max.	200 ppb max

Helium Flow Loop (HeFL)

100 g/s, 4 MPa, 60C helium
Max Delta-P ~ 186 kPa (27 psi)
Largest closed helium flow loop in US



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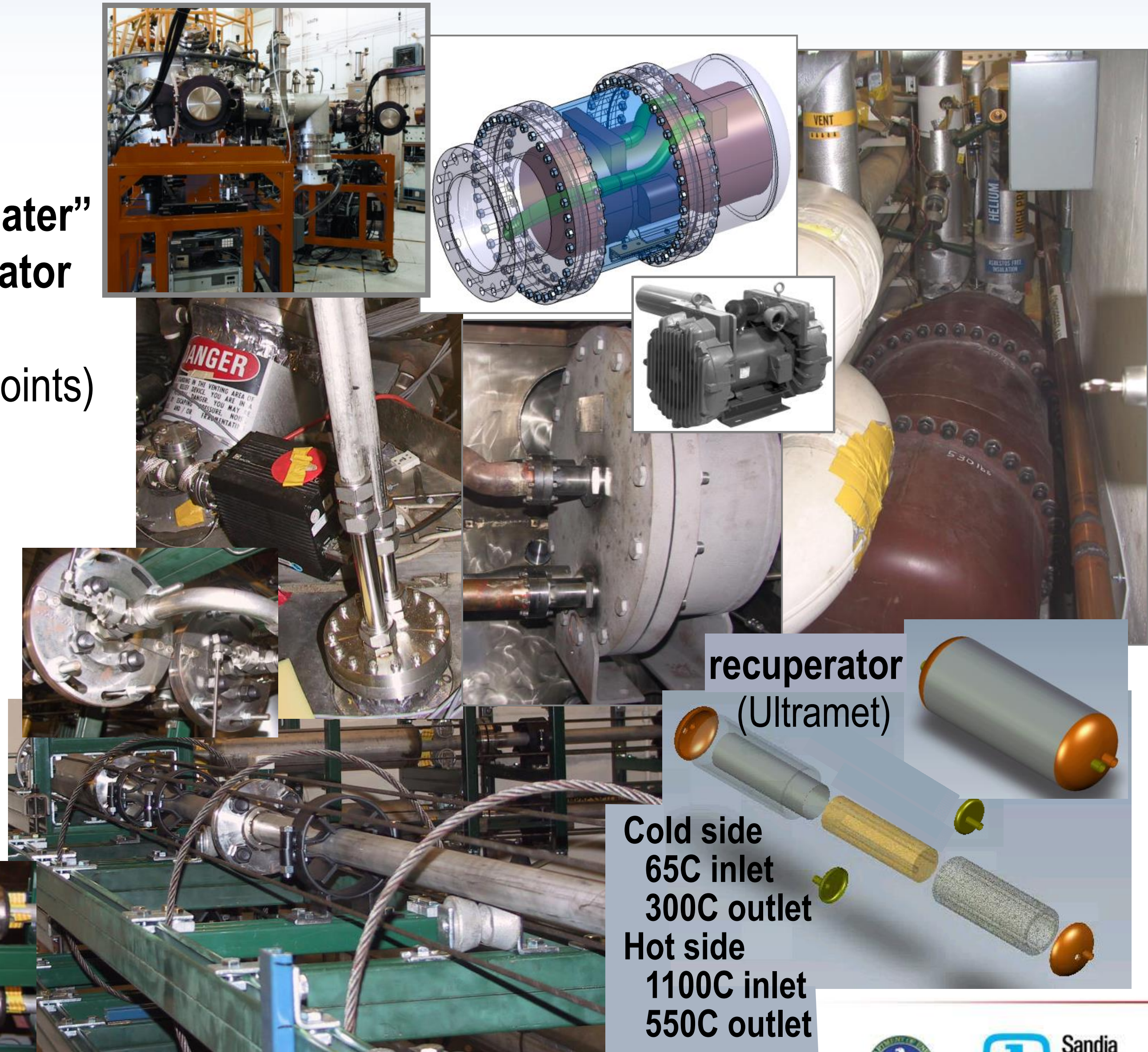
Basic Elements of He Flow Loop Upgrade for EB-1200
(via Ultramet CRADA)

- **dual stage 30 hp blower & pressure vessel**
- **e-beam powered "He heater"**
- **refractory foam recuperator**
- **He/water spiral HX**
- **piping** (hi-T valves, exp. joints)

- **~100 g/s, 4 MPa He**
- **275 kPa (40 psi)**
- **testing to 1100 C** *(heater & regenerator)*
- **37x74 cm^2**
- **multiple channels** *(flow instabilities)*
- **200+ kW heat removal**



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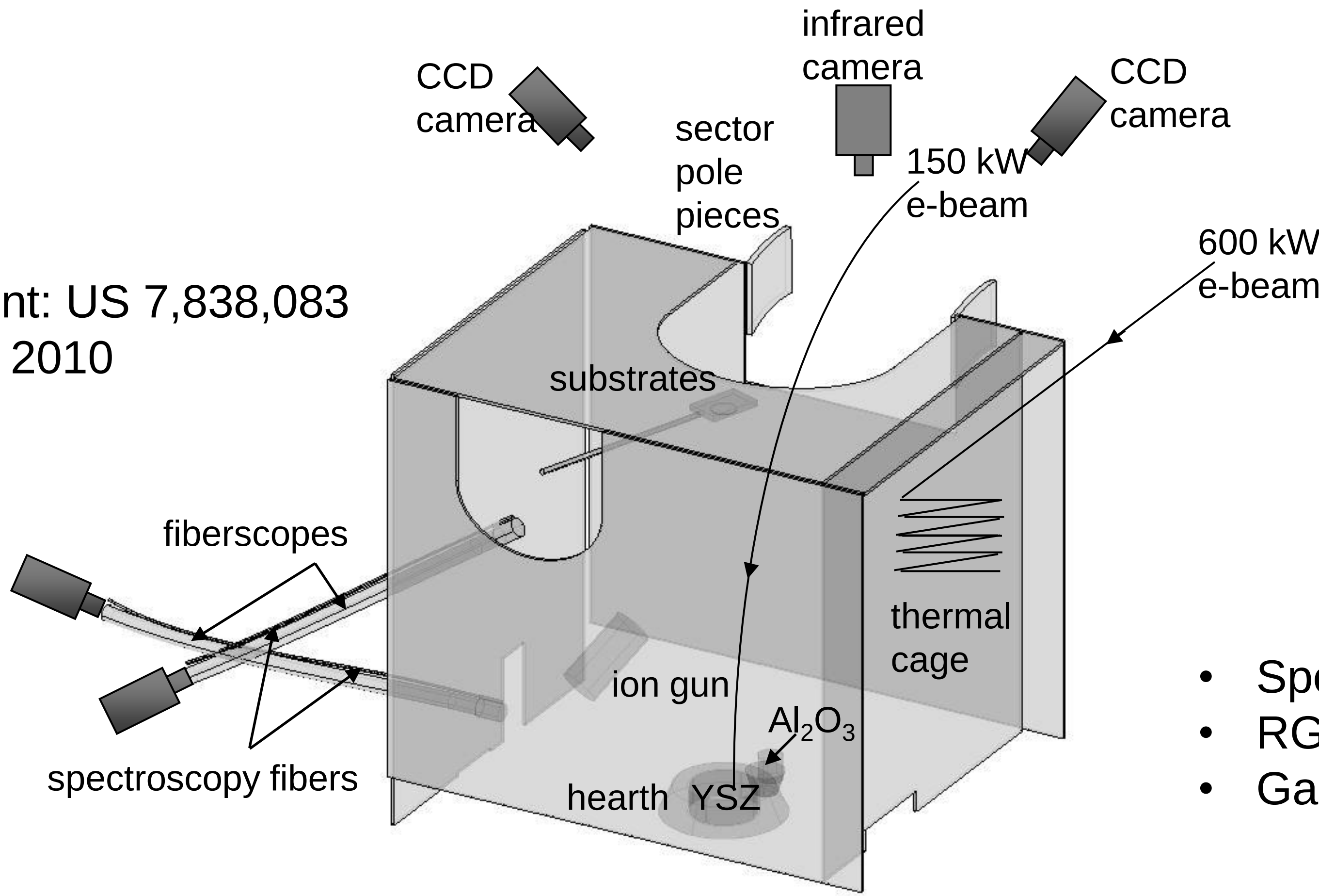
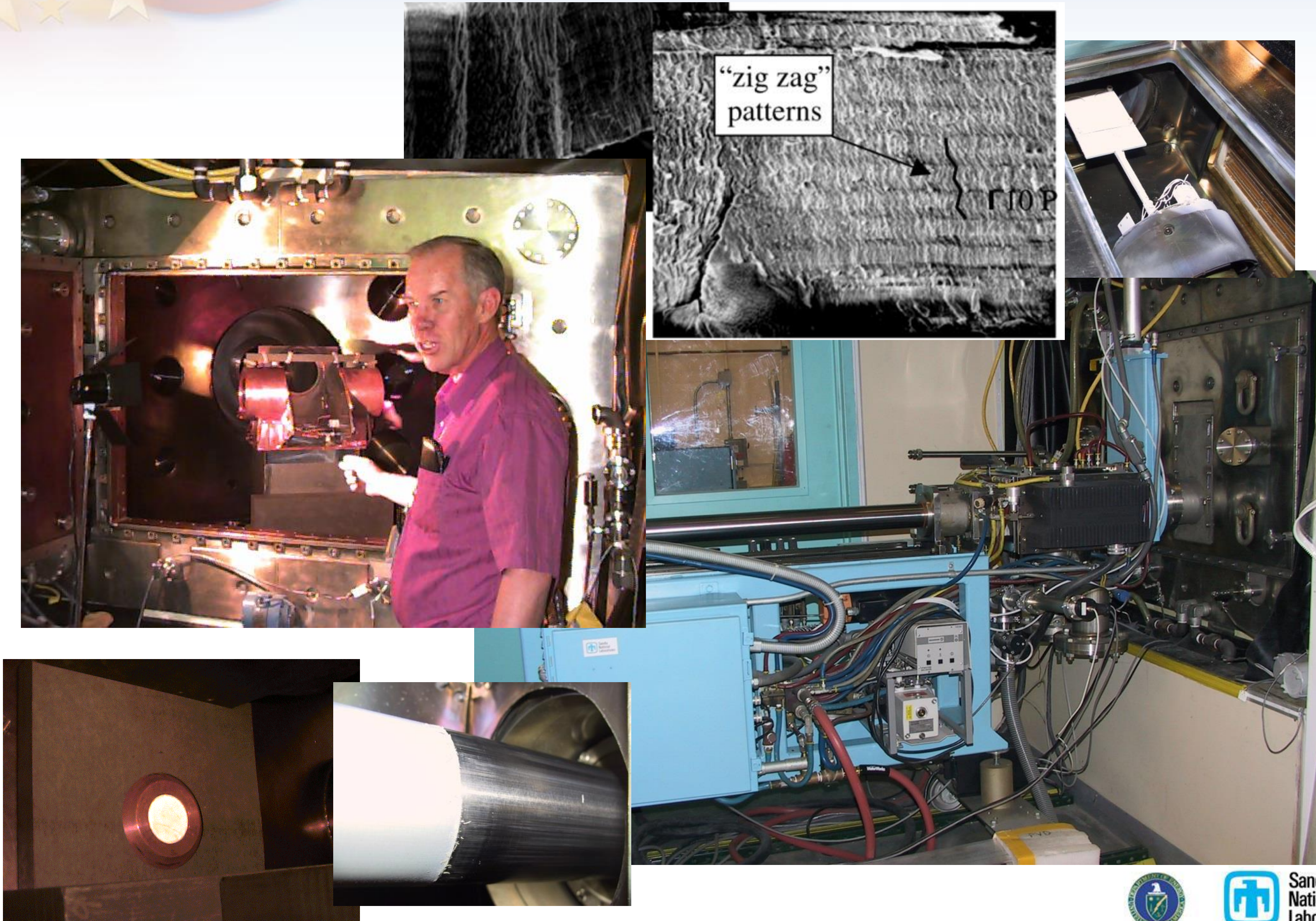
Materials Processing: IBA-PVD of YSZ
- versatility of a dual-gun system – vapor phase alloying

Patent: US 7,838,083
Nov. 2010



- Spectroscopy
- RGA Analysis
- Gas injection

Materials Processing: IBA-PVD of YSZ



The High Heat Flux Facility collaborates with Sandia's National Solar Thermal Test Facility

Solar Power Tower

Central receiver tower and heliostat field. Field contains 216 heliostats, each with 37 m^2 of reflective area. Field provides 6 MW_{th} to the tower, which includes three test bays and the roof for component or subsystem testing.

Solar Furnace

Provides 16 kW_{th} and peak flux of 600 W/cm^2 with 3 cm spot size at the focus.

Molten Salt Loops

Three parallel loops for component and subsystem testing. Up to 585°C, 40 bar (max), and 50 kg/s flow conditions.

Dish Systems

Flexible dish test platforms provide 40-80 kW_{th} to test articles and receivers at fluxes up to 12,000 suns

Trough Concentrators

Accurate elevation and azimuth sun tracking for testing of trough concentrators

- *Heat testing of space shuttle tiles*
- *Aerodynamic heating simulations on NASA ablator samples*
- *Missile nose cone heat testing*
- *Satellite sensor calibrations using heliostats*
- *Thermal nuclear pulse simulations using the central tower and heliostats*

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Analysis Capabilities

Engineering

- Catia and SolidWorks
- Abaqus – structural mechanical FEM
- Star CCM+ - CFD analysis
- Comsol Multiphysics
- Dag-mcnp - neutronics
- ANSYS Mechanical and Fluent
- Opera Suite – E&M

Data Reduction

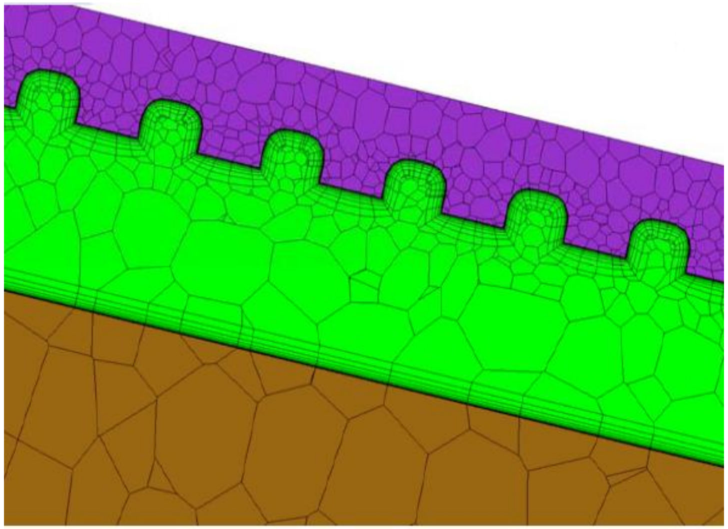
- SandIR – IR analysis
- IRControl – IR monitoring
- FLIR Researcher – IR analysis
- Origin, Kaleidagraph – plotting
- Multiple in-house DAC codes
- In-house spectroscopy codes
- Leybold RGA code

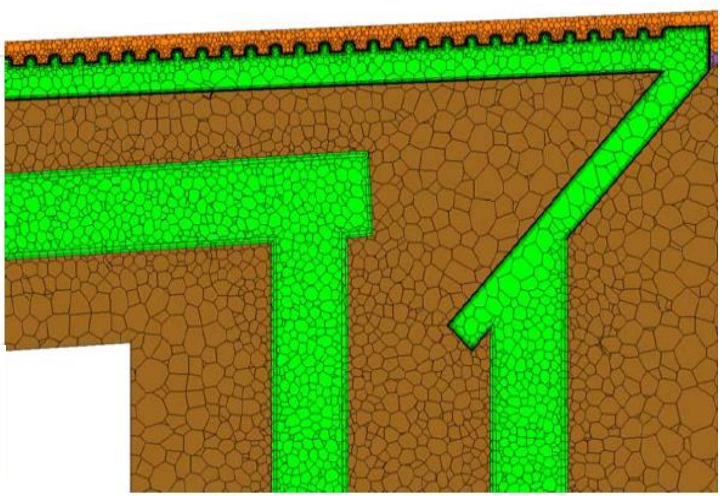
Technology leaders:

1) two-phase flow analysis
2) gas cooling – porous media, jets
3) joining, hydrogen and refractory alloys
4) High temperature heat exchangers

Star-CCM+ 560 k polyhedra mesh

Switches from Eulerian multi-phase mixture to VOF for film boiling.



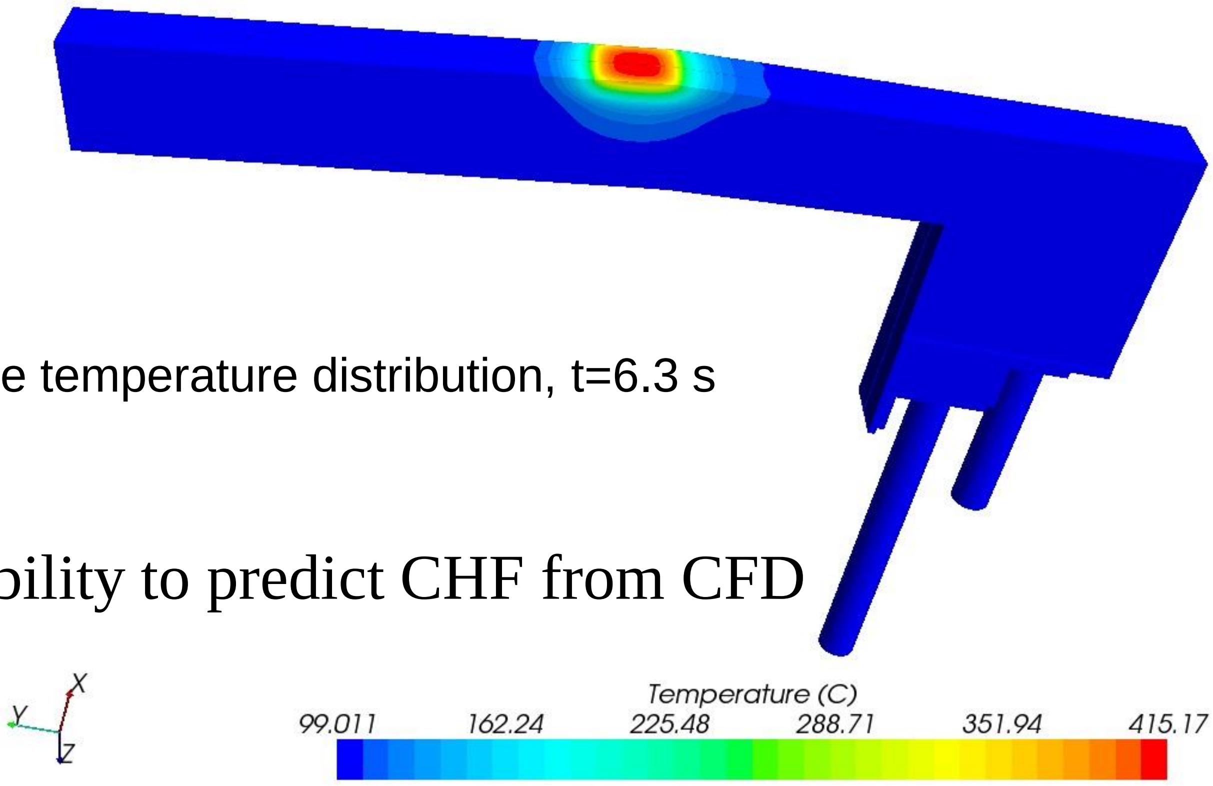


- Three Dimensional
- Stationary
- Implicit Unsteady
- Multi-phase mixture
- VOF
- Turbulent (k-e realizable)
- Surface Tension
- Gravity
- Segregated Flow
- Boiling

Star-CCM+ Results

Case analyzed is a hot "stripe" on a section of the ITER first wall.

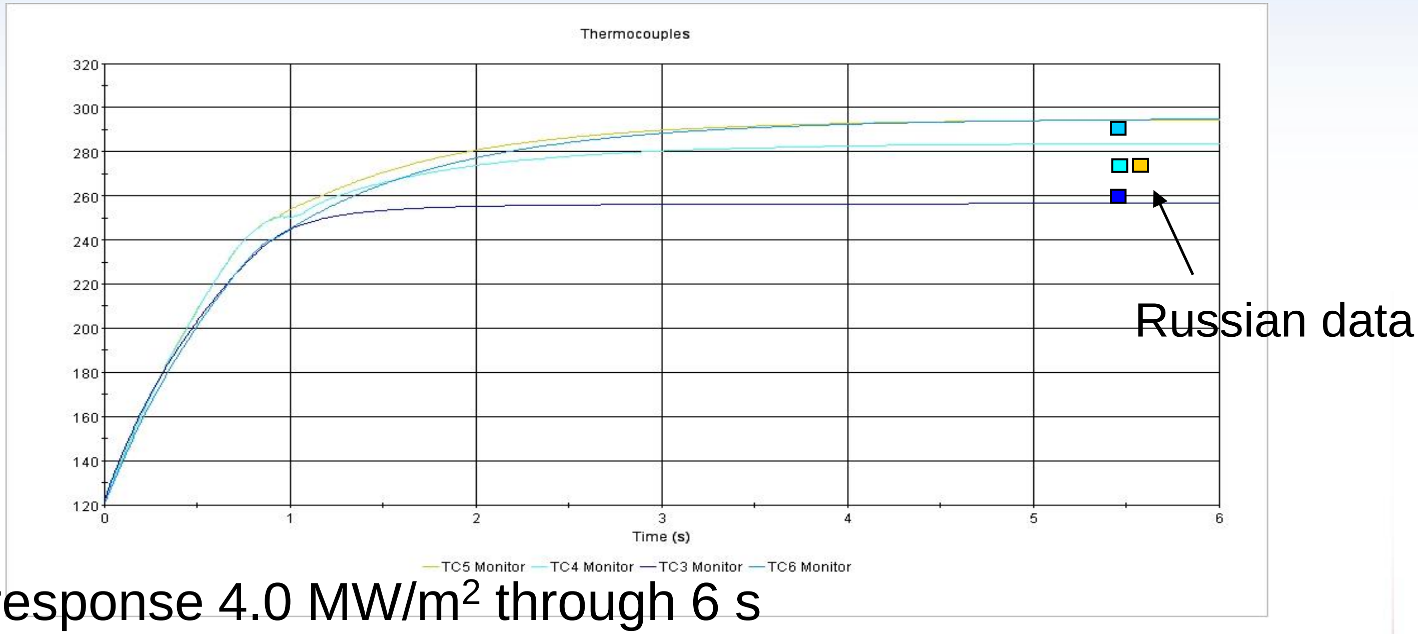
CCM+ boiling models were benchmarked against US and Russian test data for rectangular channels and hypervapotrons to within 10^{o}C.



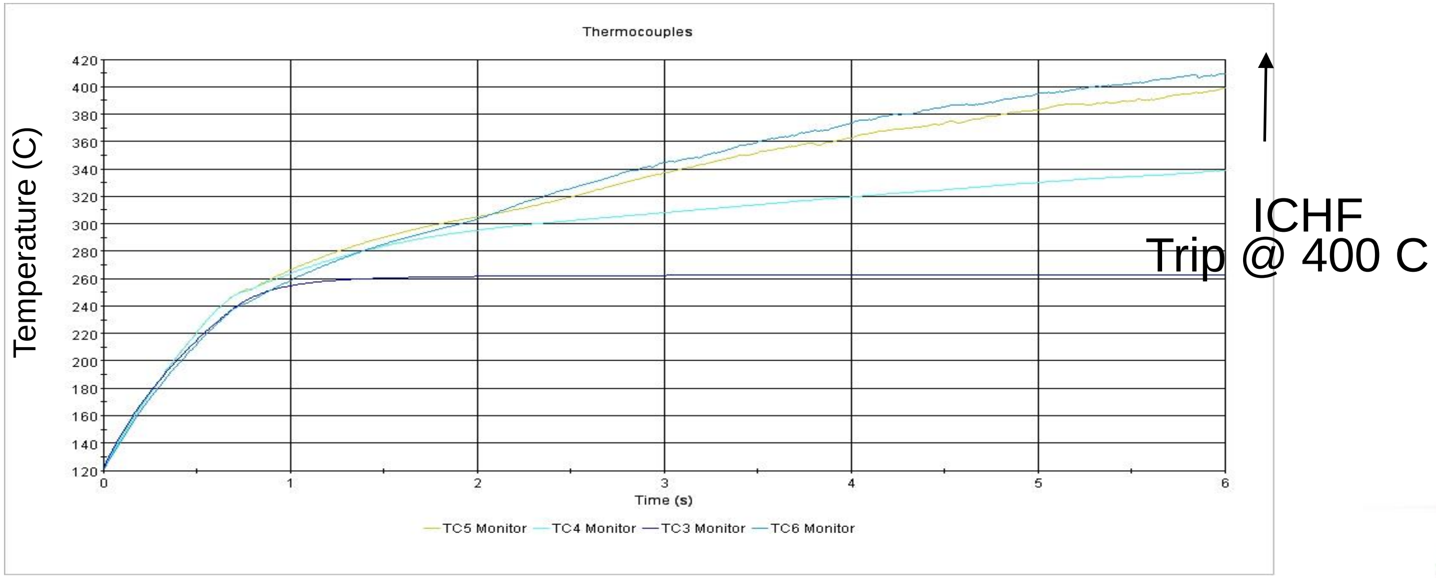
Surface temperature distribution, t=6.3 s

→ capability to predict CHF from CFD

Thermocouple response 3.5 MW/m^2 through 6 s



Thermocouple response 4.0 MW/m^2 through 6 s



Not ss yet!

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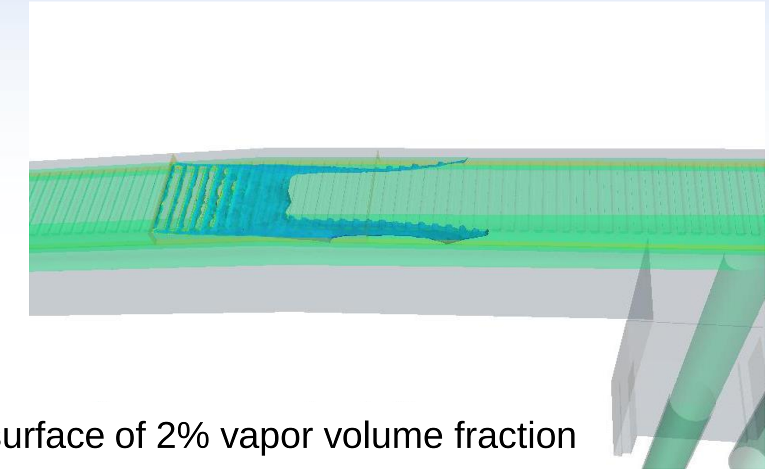
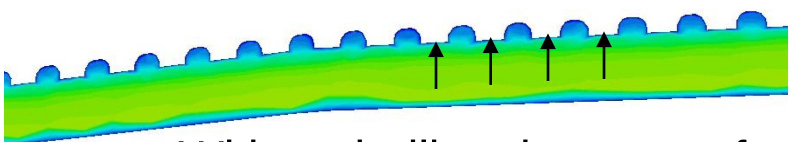
Star-CCM+ Results

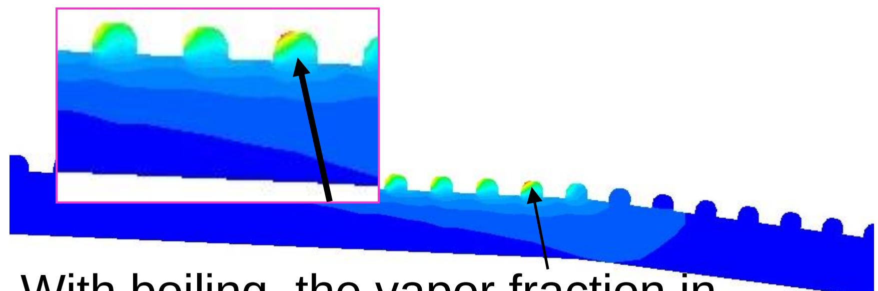


Case analyzed is a hot “stripe” on a section of the ITER first wall.

The details of the heat transfer change dramatically as boiling ensues.

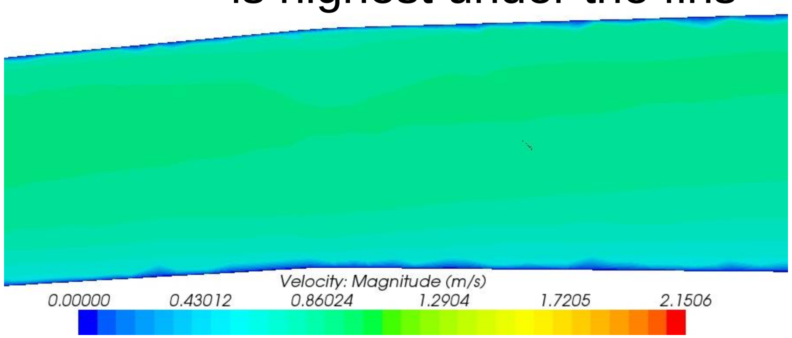
Iso-surface of 2% vapor volume fraction



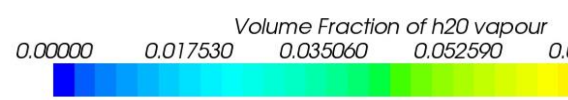


With no boiling, heat transfer is highest under the fins

With boiling, the vapor fraction in grooves is 4%-6% on average



t=6.3 s



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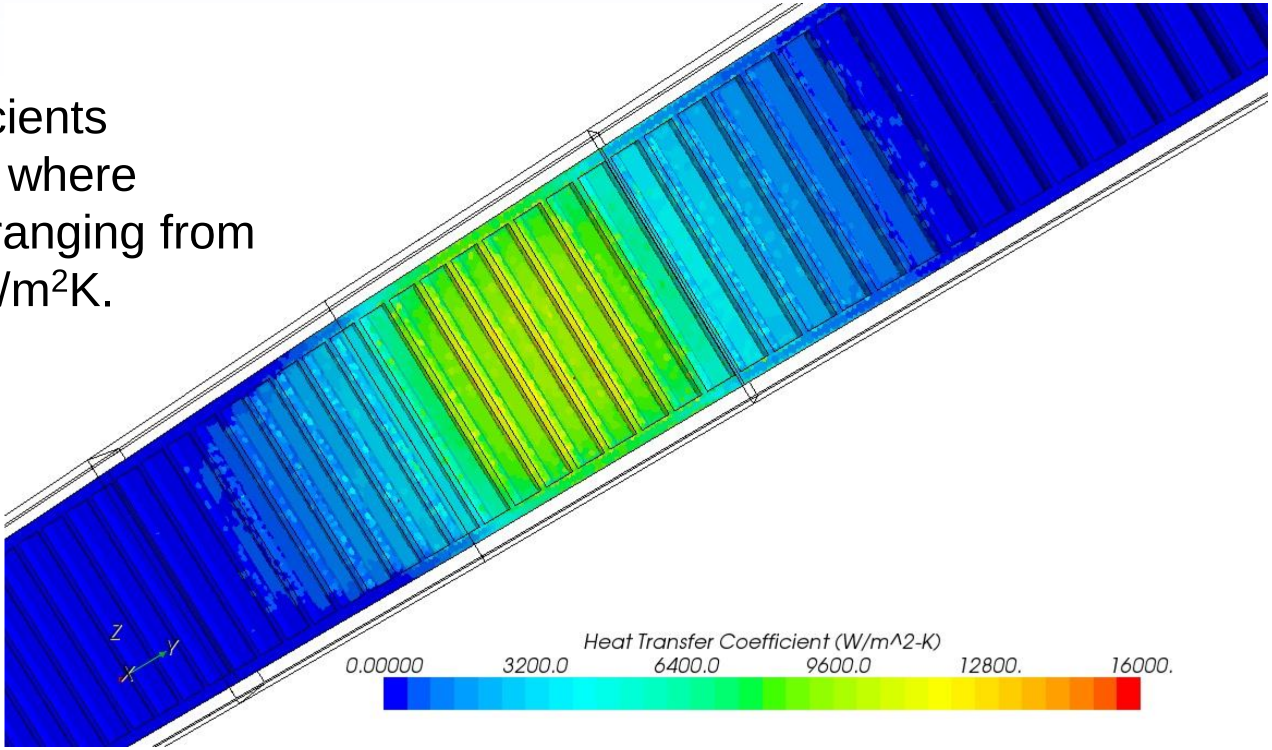
Star-CCM+ gives same h as Fluent for nucleate boiling.

Heat transfer coefficients increase in grooves where boiling takes place ranging from 12,000 to 13,000 W/m^{2}K.



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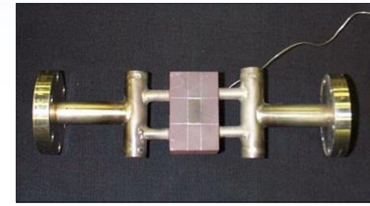
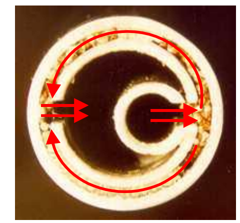
Helium-cooled modules for PFCs

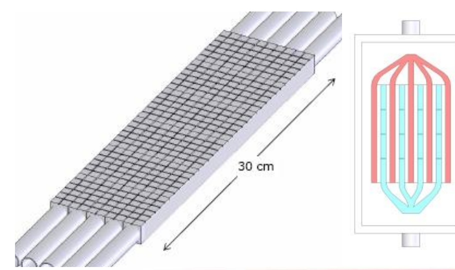
TR3

year	*Type of Test Article*	*fabricator*
1993	Cu Micro-channel HX (~100μ channel size)	Creare, Inc.
	Cu Divertor mockup A (0.46mm channels)	General Atomics
	Cu Porous (40%) metal HX (0.43mm dia.)	Thermacore, Inc.
1994	Cu Dual channel porous metal HX	Thermacore, Inc.
	Cu Div. mockup A retest, higher heat loads	General Atomics
1996	Cu Phase-II porous metal HX	Creare, Inc.
	Vanadium spiral-tube HX	General Atomic
1997	Cu Faraday shield A	Thermacore, Inc.
	Cu Divertor mockup B	Thermacore, Inc.
1998	Cu Faraday 2nd shield B	Thermacore, Inc.
	Cu Divertor 2nd mockup C	Thermacore, Inc.
1999	Div. mockup B retest, added diagnostics	Thermacore, Inc.
2000	W tubes with W foam	Ultramet, Inc.
2000	W FW module with W porous medium	Thermacore, Inc.
2001	VPS W tube with VPS porous medium	Plasma Processes
2006	W tube with W foam in axial flow	Ultramet, Inc.
2008	Sq. Mo w/ Mo foam, circumferential flow	Ultramet, Inc.
2010	4-Channel, Larger Area Mo panel	Ultramet, Inc
2011	Li/He Heat Exchanger	Ultramet, Inc
?	W Tee-tube Jet impingement	Plasma Processes
?	FZK 9-finger HEMJ	FZK, IEA
?	Phenix	JA/US

TR4



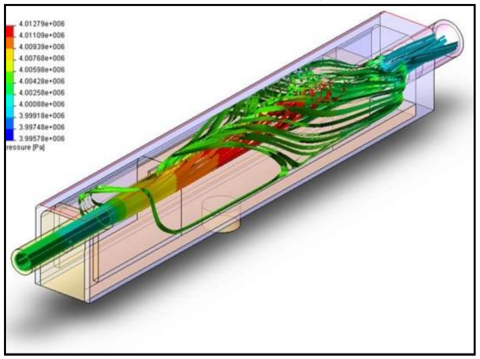


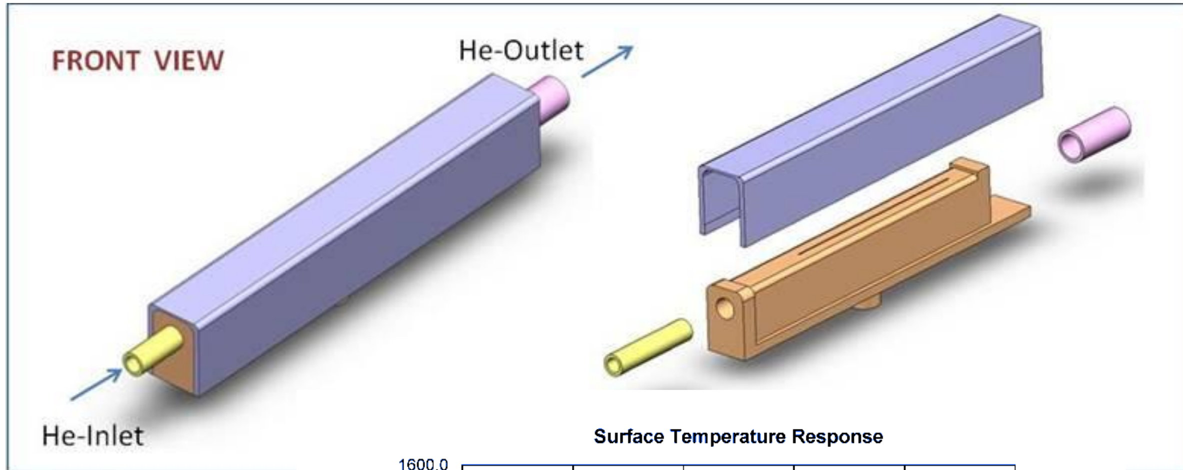


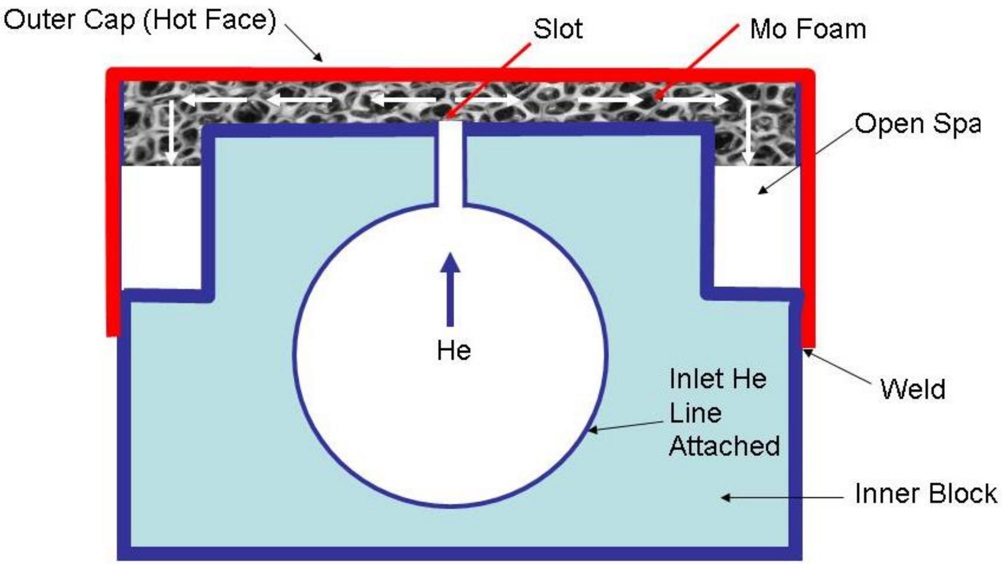
4 Single-Channel Heat Exchangers Tested in EB-60

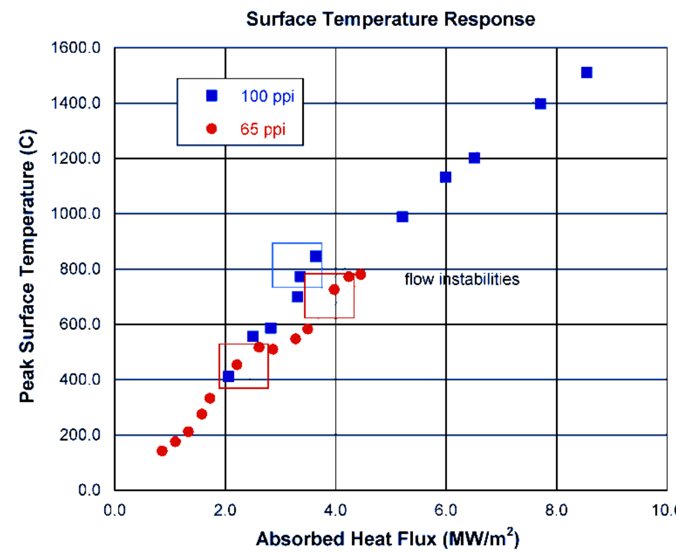
- All Molybdenum -

1. No foam
2. 45 ppi 77% porosity
3. 65 ppi 77% porosity
4. 100 ppi 77% porosity









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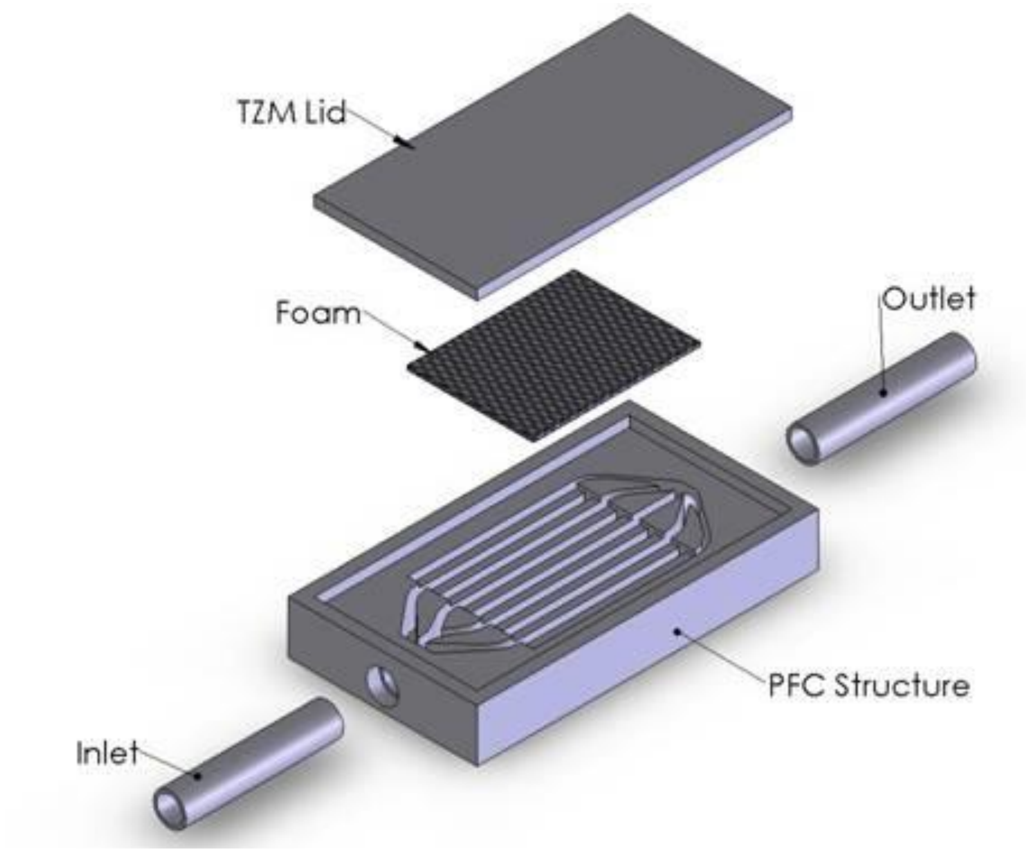
Larger panels ready for testing.

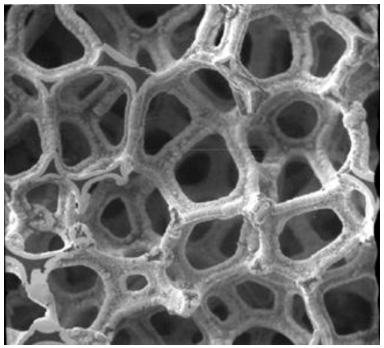


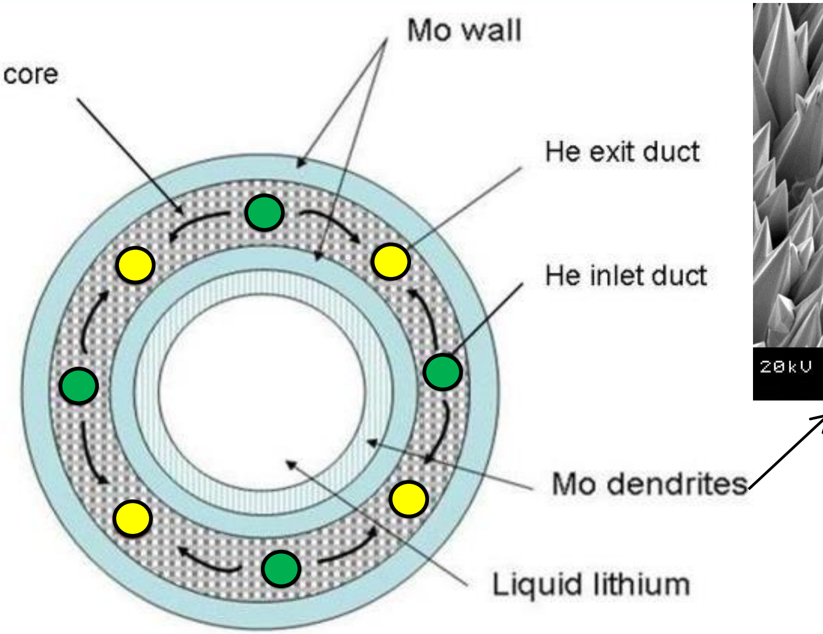
•Multiple channel (4)
•Flat surface
•All refractory
•Short flow paths
•600 C inlet temps

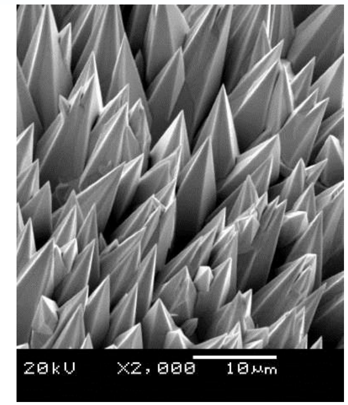
Investigate:
•Larger heated areas
•Flow instabilities

Li/He Prototype Heat Exchanger

With Circumferential Flow







The heat contained in liquid lithium, flowing through the ID of the structure, is transferred to a molybdenum tube with the assistance of a high surface area dendritic molybdenum layer grown on the tube inner surface.

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END

Questions?