MEBT Absorber
Prototype Status Update

Project X Meeting, 15-Oct-2013

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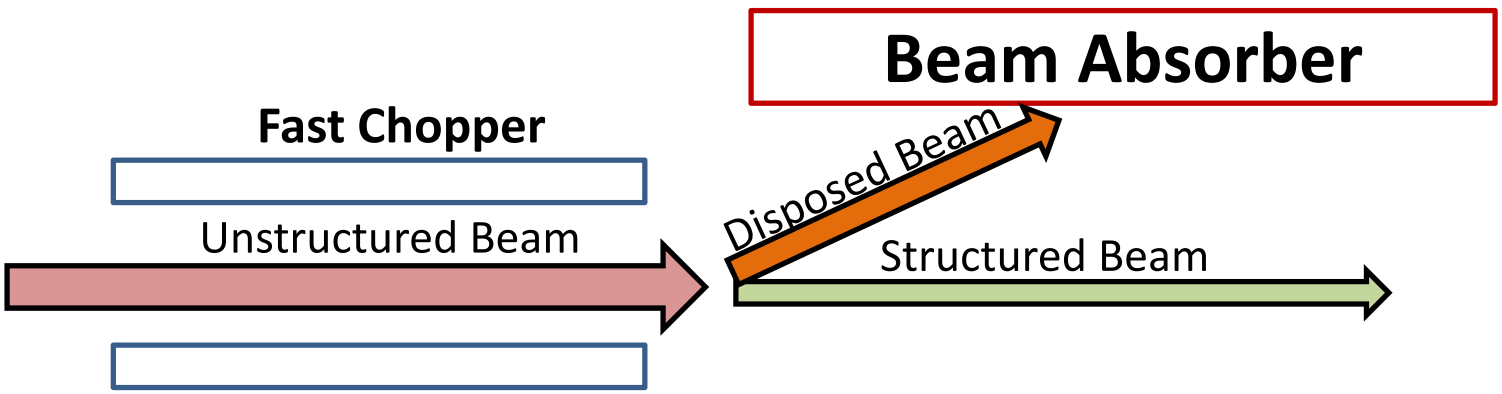
PX Doc DB ID: Project X-doc-1226

MEBT Prototype Absorber Update

- Background
- Test Results
- Implications to PXIE Design
- Proposed Next Steps

Background:
Absorber Configuration



Functional Specifications Document:

https://projectx-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=964

Key Driving Absorber Requirements

- 2.1MeV Ions
- 21kW maximum incident power (~75% absorbed / ~25% reflected)
- Beam size: $\sigma_x = \sigma_y = 2mm$
- 650mm maximum length

Key Derived Parameters

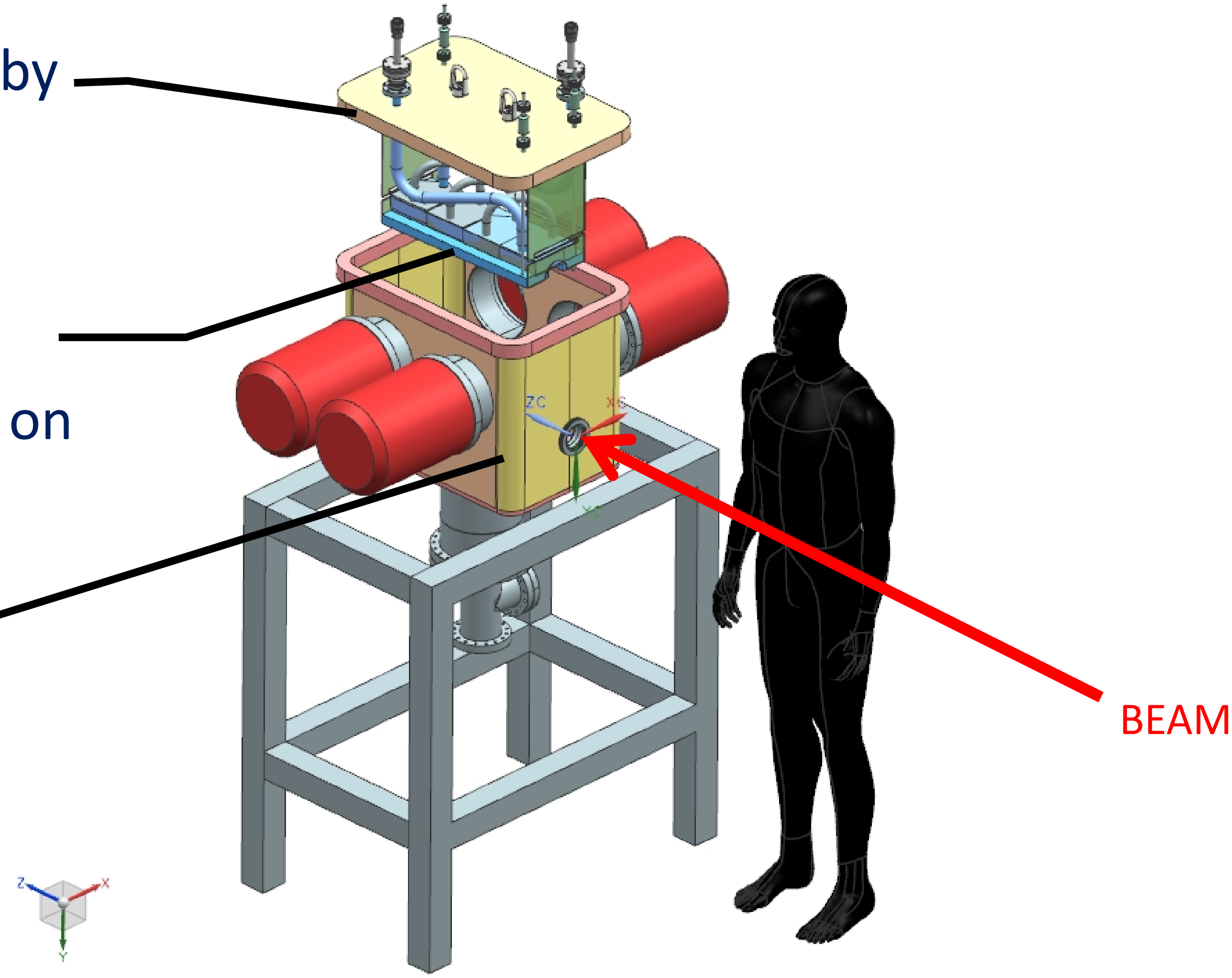
- 0.029rad grazing angle
- ~17 W/mm^2 maximum absorbed power density of the face of the absorber

2011 Preliminary PXIE Concept

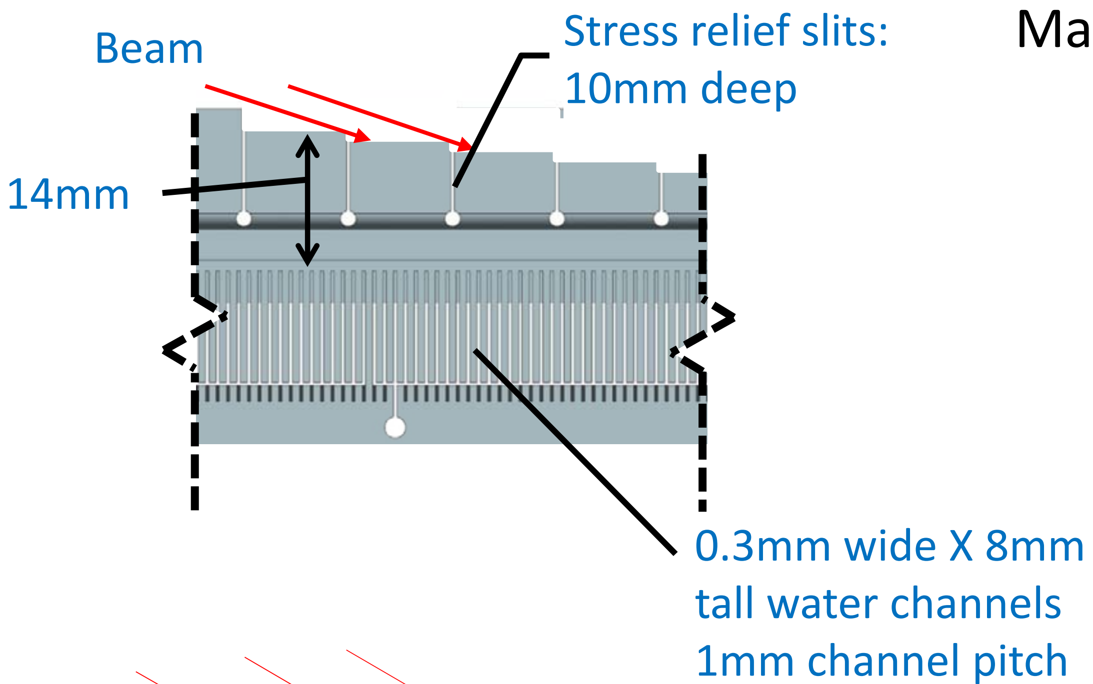
Absorber handled by this flange

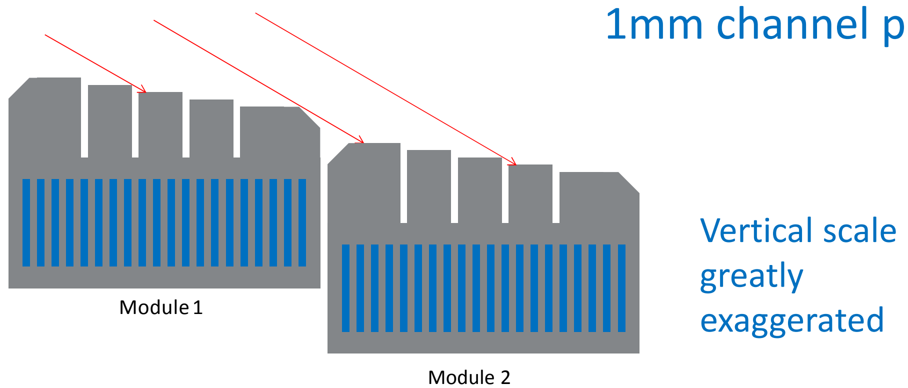
Qty. 4 absorber modules mounted on common structure

Vacuum Enclosure



2011 Preliminary PXIE Concept





Main design features

- Grazing incident angle of 29 mrad to decrease the surface power density
- TZM to address blistering
- Stress relief slits
- Steps to shadow the slits from beam
- narrow transverse channels for water cooling
- The total ~0.5m length divided to 4 identical modules to simplify manufacturing

2011 Concept Design Risks

Key risks of this specific design include:

- Manufacturing processes
  - Machining of Mo TZM
  - TZM-to-stainless transition
- Flow characteristics and heat transfer
- High temperatures in absorber material
- Module-to-module and global alignment stability
- Blistering/Sputtering of TZM material in H- Beam

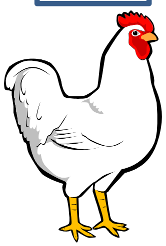
Addressed by prototype testing

Prototype Approach

- Prototype a single absorber module
  - 116mm length
  - Single-pass water cooling
- Test in an E-beam test stand
- Angle of incidence between absorber and beam 120mrad
  - 4X greater (more normal) than PXIE plan
  - Allows us to replicate peak power deposition within limited length of test module

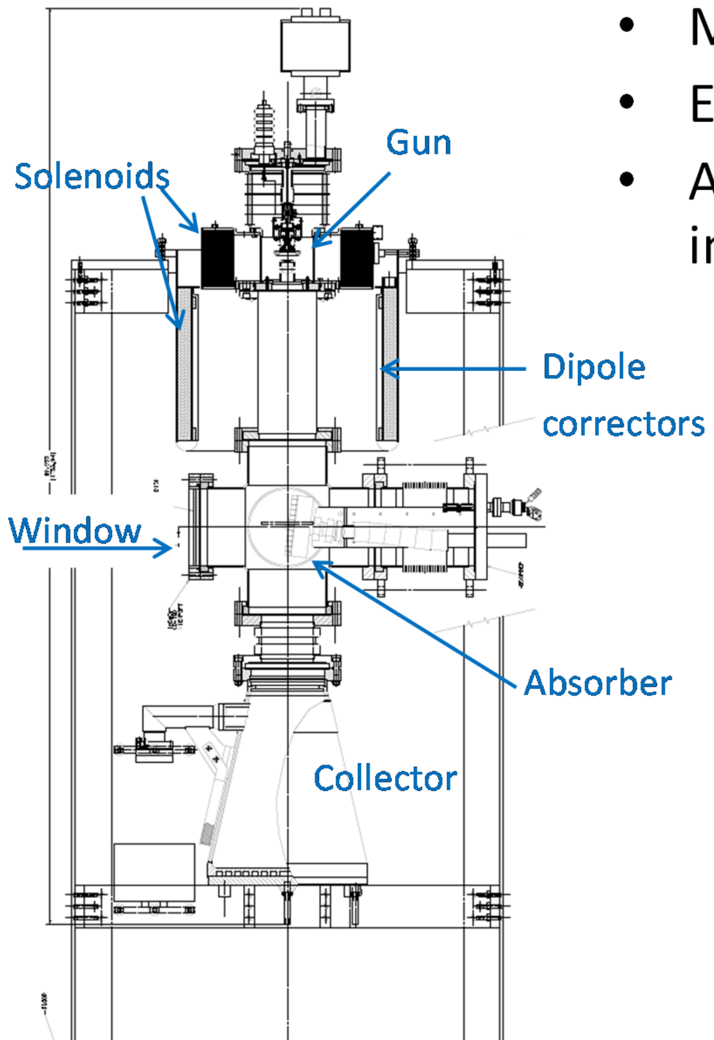
Goals of Prototype Testing

- Investigate areas of fabrication risk
- Study OTR as a diagnostic technique
- **Test ability of absorber to survive expected power density**

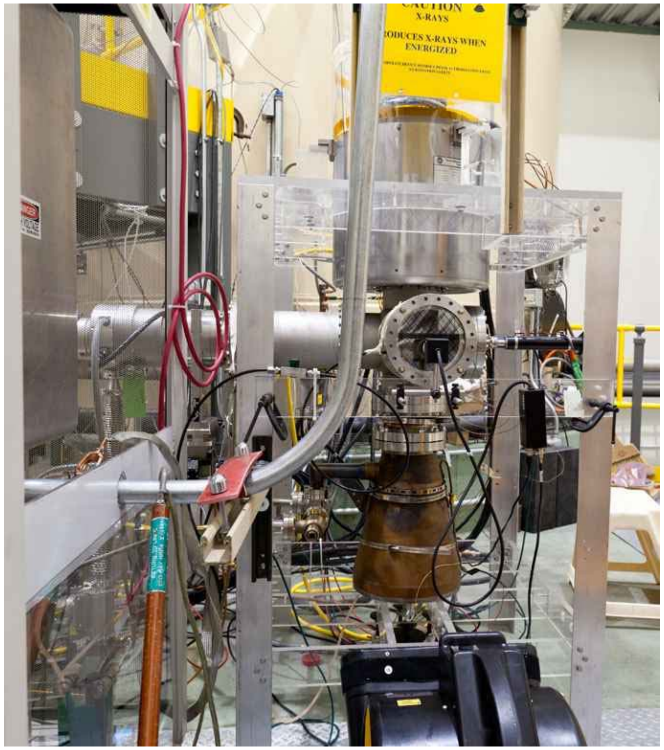


- Test ability of absorber to survive thermal cycling
- Correlate temperatures to improve modeling
- Investigate cooling performance in different flow regimes

Test bench



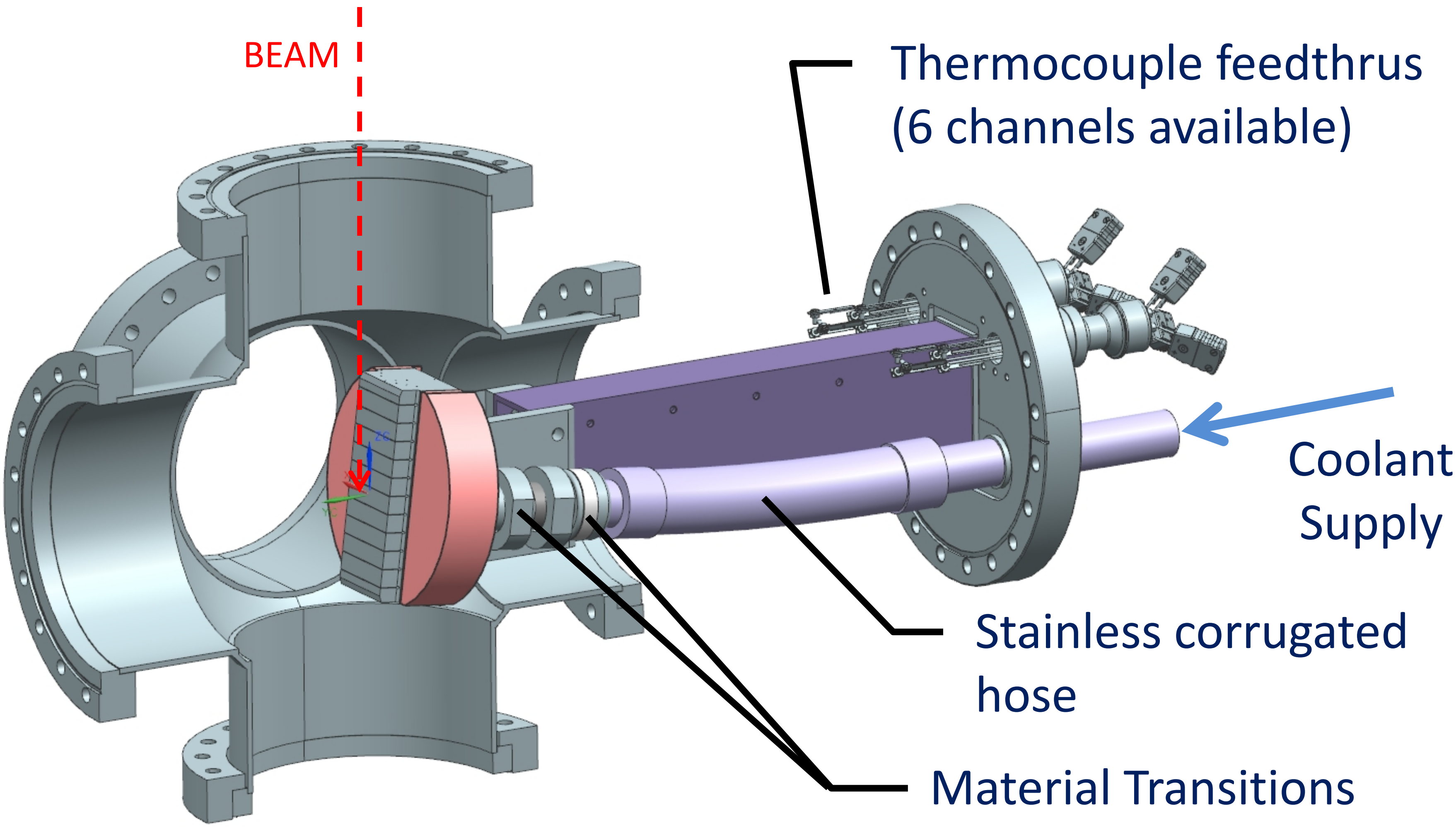
- Mainly parts from ECool project
- E-beam: 27.5 keV, up to 200mA, 5.5kW max
- Absorber and scraper prototypes may be moved into the beam



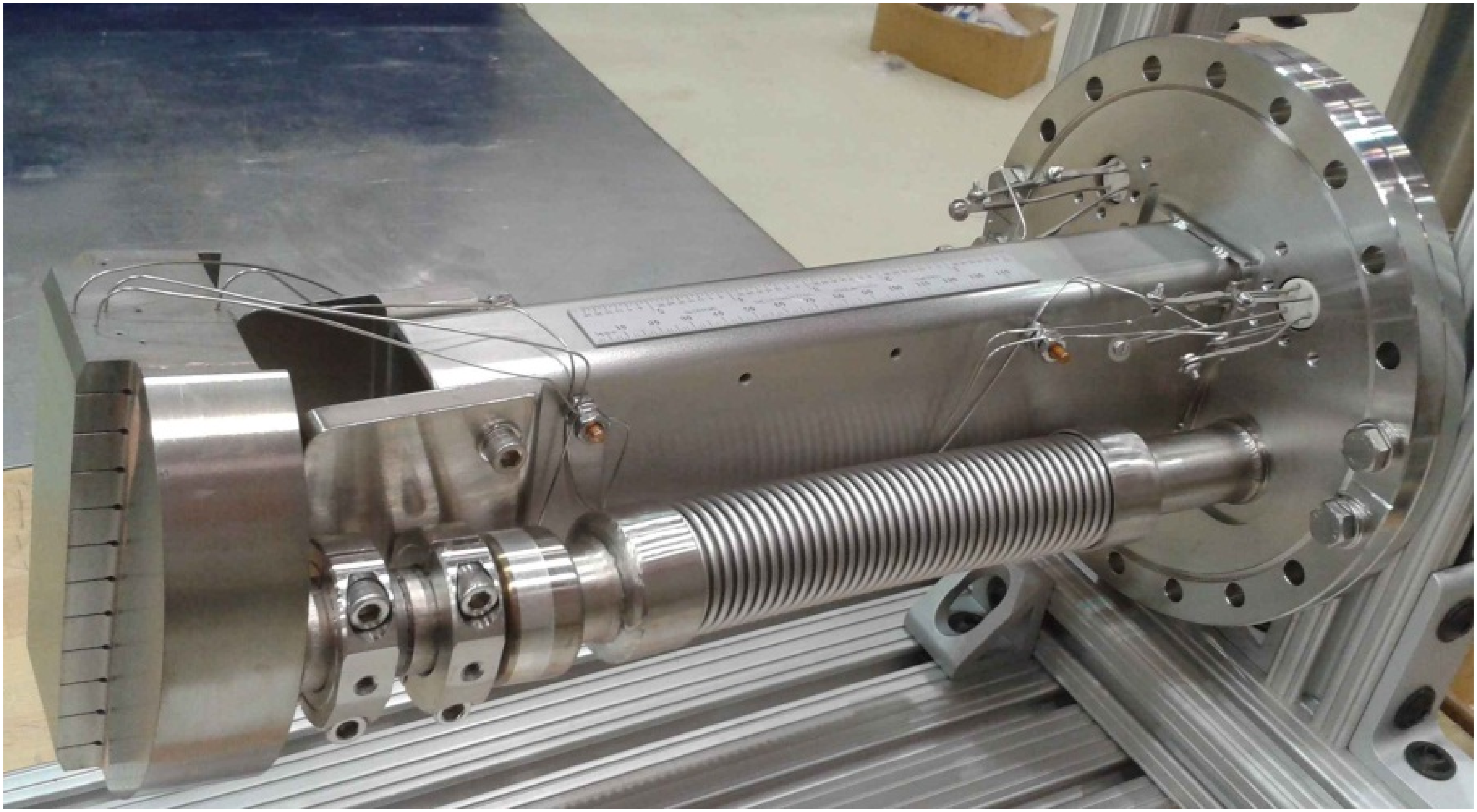
Test Implementation: K. Carlson, B. Hanna, L. Prost, J. Walton

Photo: M. Murphy

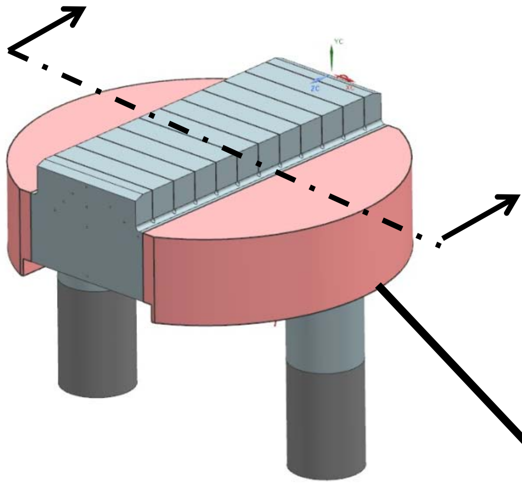
Prototype In Test Bench Cross

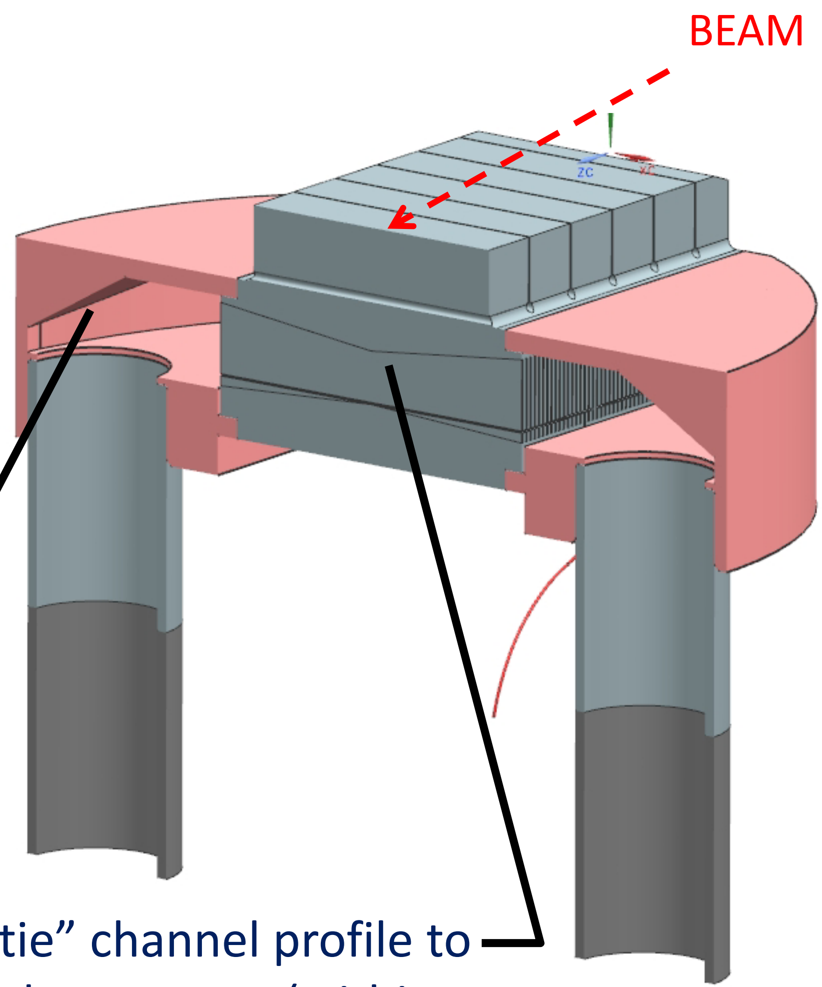


Prototype Absorber



Cooling Geometry





Circular external shape to fit within commercial cross in e-Beam Test

Manifold profiling to control longitudinal (between channels) coolant velocity distribution

"Bowtie" channel profile to control transverse (within channel) velocity distribution

MEBT Prototype Absorber Update

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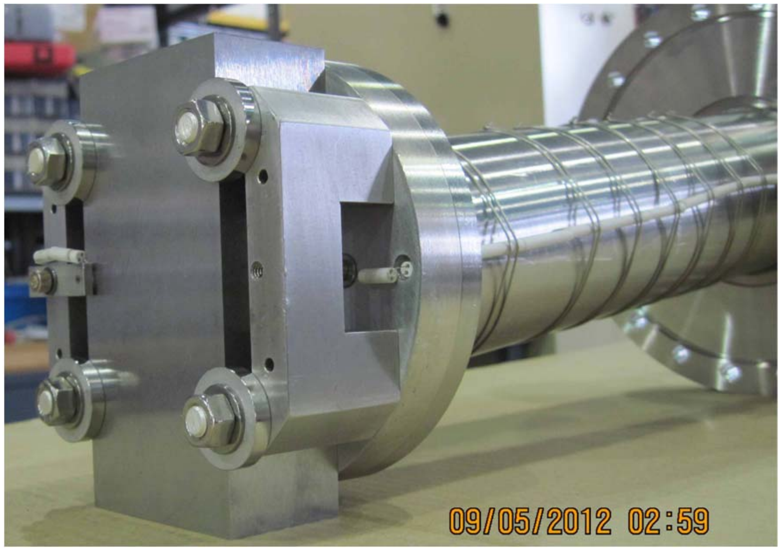
- Test Results
  - Pre-Prototype and Scraper
  - Prototype
    - Fabrication
    - Power Deposition
    - Beam Profile and OTR Diagnostics
    - Optical Surface Temperature Measurement
    - Thermometry and Analysis Correlation
    - Cooling Regime
- Implications to PXIE Design
- Proposed Next Steps

Test stand commissioning With "Pre-prototype"

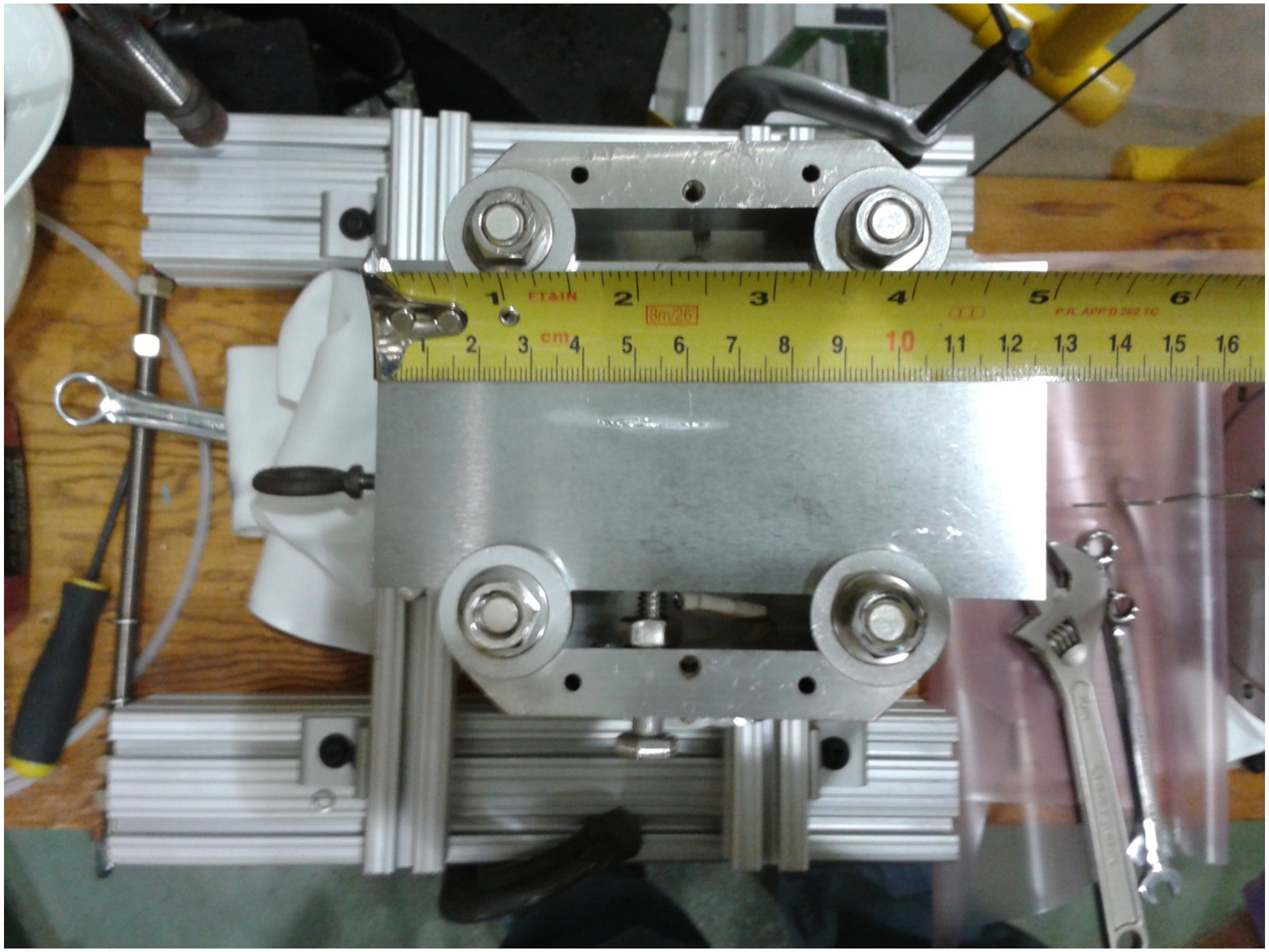
- The test stand was commissioned with a simple "pre –prototype"
  - A TZM brick bolted to a water-cooled pipe through a graphite foil

- Main results
  - Stand was commissioned
  - Pre-prototype absorbed up to 2kW (with low power density)
  - TZM/graphite/aluminum thermal contact estimated and found to be better than expected (~4W/m^2K)
  - Surface was damaged at high power density (before addition of graphite foil)



Designed and built by J. Walton

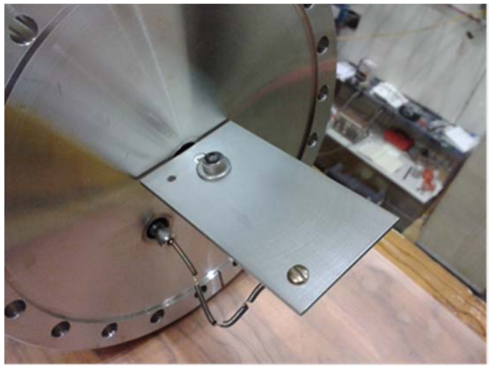
Test stand commissioning With "Pre-prototype"



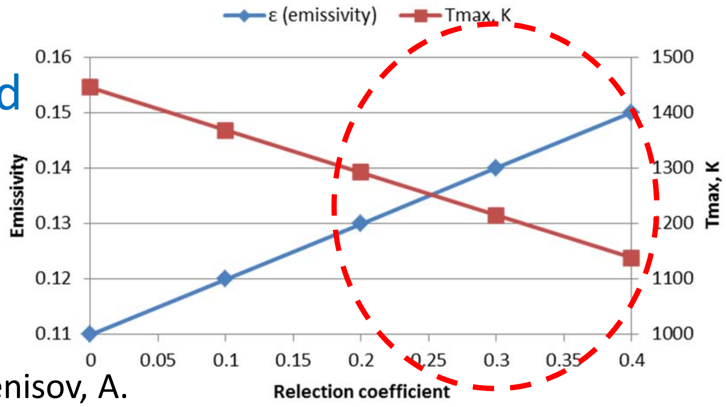
Surface Damage

Scraper measurements

- Summer'13: a TZM plate was irradiated by an electron beam (at the same test stand)
  - As a prototype of a radiation-cooled scraper
  - Intensity of thermal radiation measured by a camera with a red (707 nm) narrowband filter was correlated with numerical simulations
  - Several spatial and temporal measurements
  - Fitting parameters:
    - Power reflection coefficient, emissivity, and calibration of image intensity vs Temp
  - Comparison gave correlation between 3 parameters rather than a unique solution



Scraper prototype: an electrically isolated TZM plate, 3.5"x 2"x0.08".



Range of solutions

Feasibility of a radiation-cooled scraper for PXIE MEBT, by C. Baffes, A. Denisov, A. Shemyakin, http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1221

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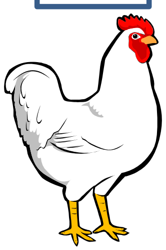
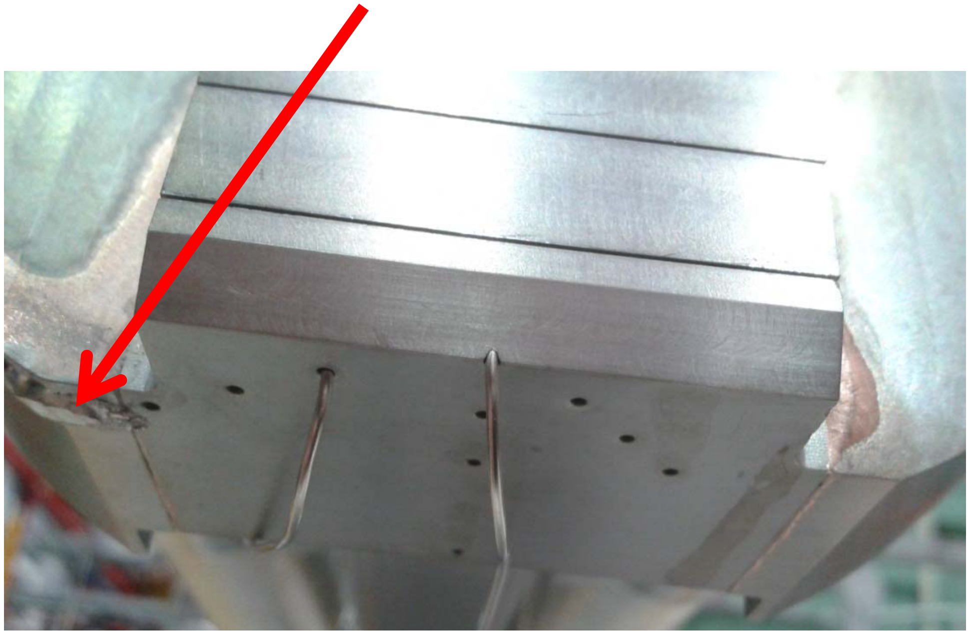


- Test ability of absorber to survive thermal cycling
- Correlate temperatures to improve modeling
- Investigate cooling performance in different flow regimes

Lessons Learned: Fabrication General Impressions



Leak through TZM bulk required braze rework

- Challenging fabrication was completed successfully, albeit with brazing rework
- Quadrupling of this process for a 4-module PXIE design is doable, but not particularly attractive

Lessons Learned: Fabrication Details

Project X

Fracture of unpolished TZM tube during in-process testing

The Good…

- TZM 364 (PM variety) worked adequately
- Brittle-as-glass TZM was successfully machined with cutting tools and an acceptable level of edge chipping.
- TZM-to-Ti e-beam welding worked, weld embrittlement was less than the inherent brittleness of TZM
- Multi-step multi-alloy brazing process worked

The Bad…

- Brittle fractures in development testing point to a need for better surface preparation (i.e. polishing)
- Electropolishing was not particularly effective on TZM

…And the Ugly

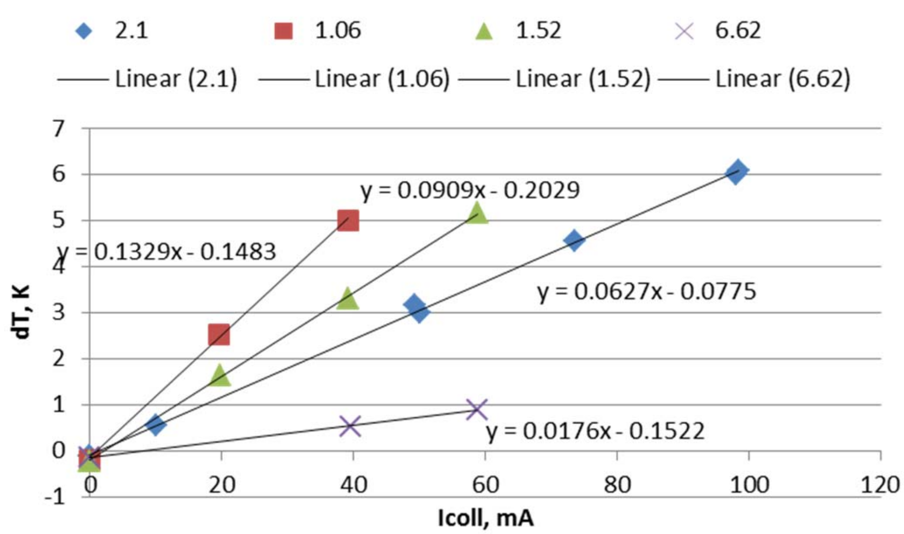
- Leak through TZM bulk is disconcerting

Power deposition

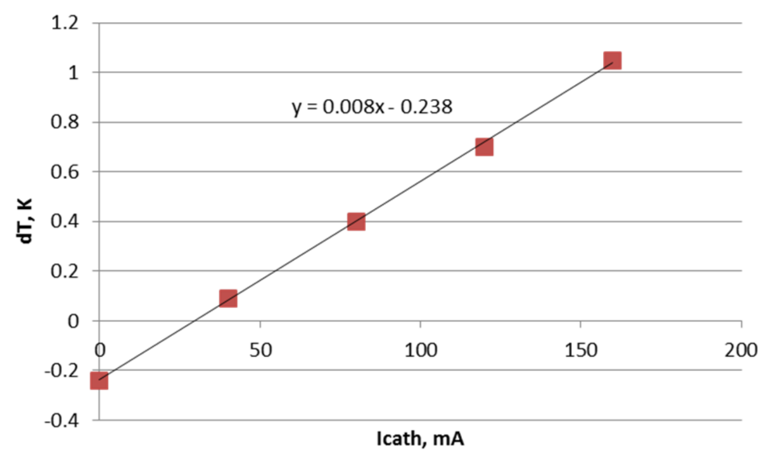
- The beam power is known well, U_{PS} x I_{PS}
  - If the beam is sent into the collector, collector current is 98% of cathode's, as expected due to secondary emission
  - However, power removed by secondary particles decreases the energy deposited to the absorber ("reflected power")
- Absorbed power can be measured from the inlet-to-outlet water temperature rise, *power=ΔT·(thermal capacitance)·(flow)*
  - Statistical and systematic errors of temperature measurements are low
  - Flow read by a vortex flow meter is stable, but systematic error due to non-linearity can be as much as 15%
  - The cooling liquid is water with glycol of unknown proportion
    - Separate measurement by heating/cooling rates: 0.9 of water thermal capacitance

Power deposition (cont.)

- For reliable calibration, the beam was directed into the collector with the same flow meter and thermocouples
  - Agreement within ~5% with assumption than the entire beam power is deposited at the collector and removed by water
- Final result: absorbed power in the prototype is 45%



Water temperature rise in collector and in absorber prototype (at 6.54 gpm).



Beam imaging

- Two types of radiation: OTR and thermal
  - The camera is sensitive to both
  - OTR is linear with beam current and gives information about the beam shape, position, and current density distribution
  - Thermal radiation depends on temperature and is highly non-linear with the beam current
- Images were recorded with camera
  - Several filters to distinguish between OTR and thermal radiation
  - Support from Instrumentation Dept.

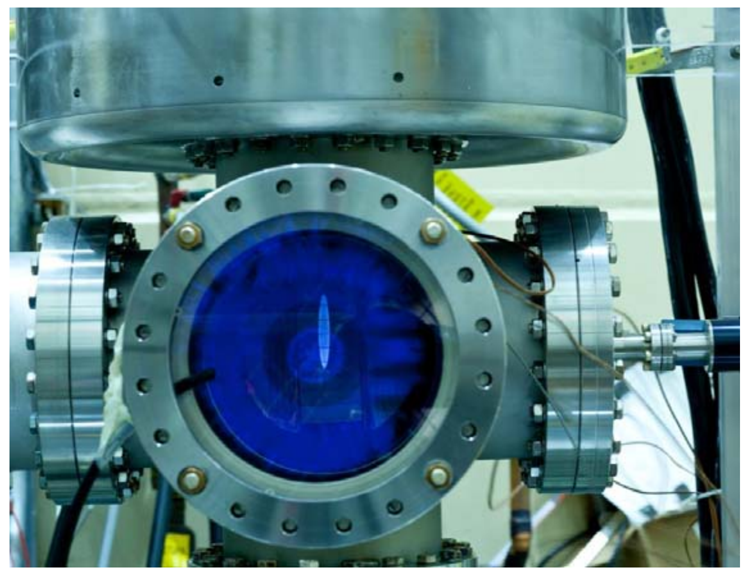
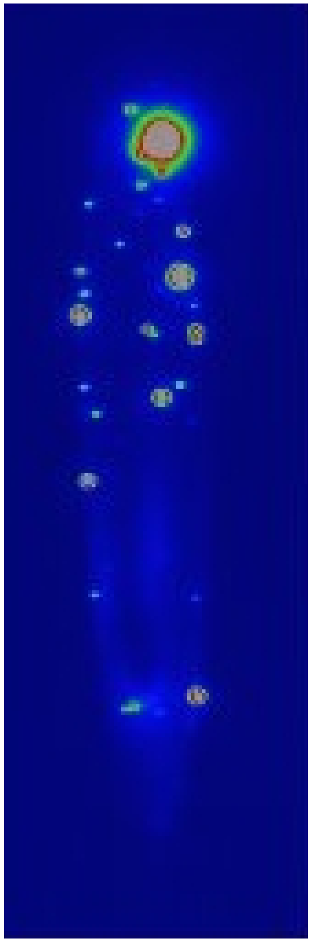


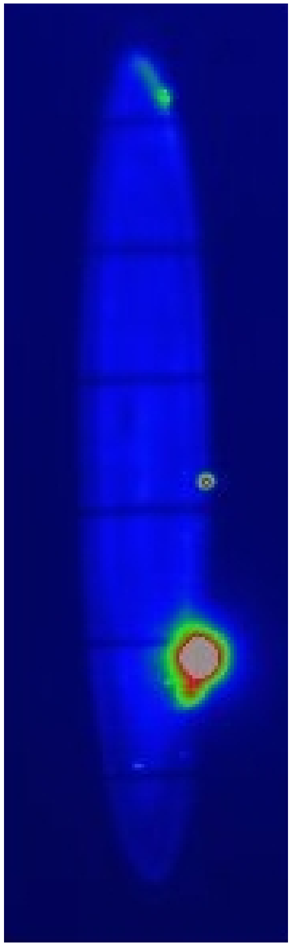
Photo of the beam footprint on the absorber prototype (white ellipse). I_e= 190mA, axes of footprint ellipse are ~50x7 mm. Incident beam power density ~20 W/mm^2. Photo: M. Murphy

Surface Characteristics

- There are spots on the TZM surface that start emitting thermal radiation at much lower current density that the average
  - Most spots stay at the same location when the beam is moved
  - Density of spots at the pre-prototype was significantly higher than at the prototype
- May be related to particulate contamination and/or quality of the surface finish
- A whitish elliptical spot appeared at the prototype surface early on, at low power density
  - Doesn't look like melted area at the pre-prototype. We speculate that it might be a result of evaporating one of hot spots



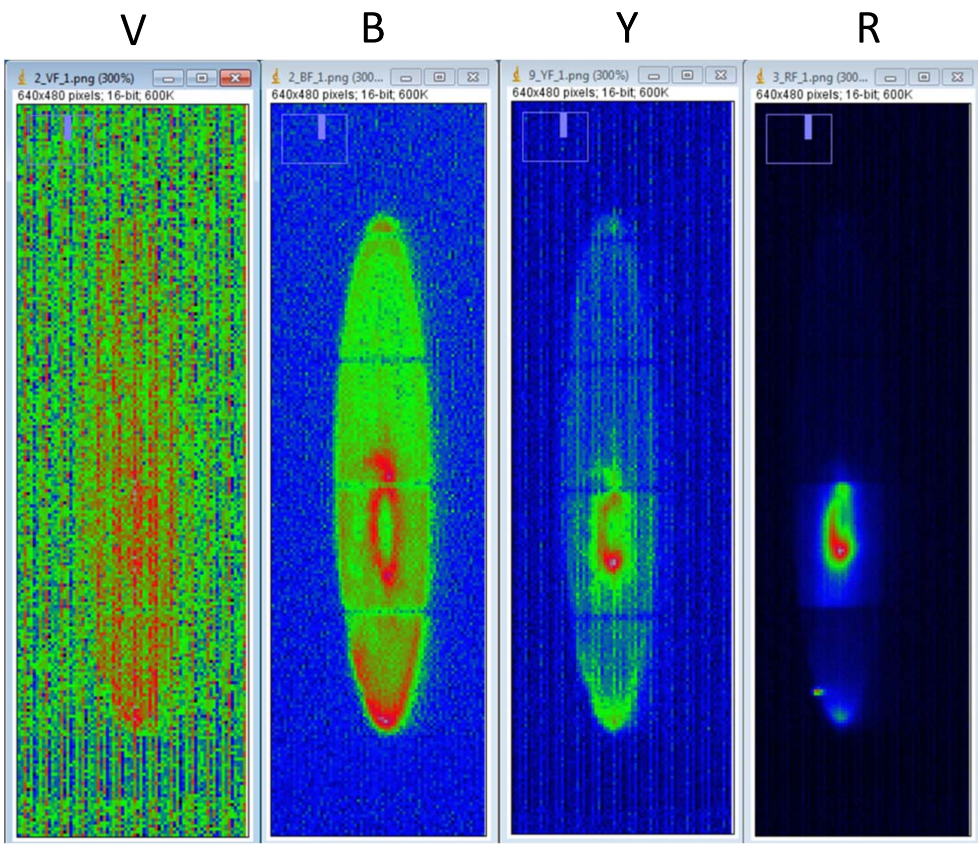
Pre-prototype
190 mA



Prototype
120 mA

Beam Profile

- A short-wavelength filter suppresses thermal radiation, while OTR is supposed to be flat over the optical region



- Violet filter doesn't provide enough light
  - likely restricted by lead glass
- Blue (wider) filter picks up thermal radiation at highest temperatures
  - Still reasonable information about the current density distribution

Images of the beam footprint with different filters, in false colors. Color/intensity map differs between images. L to R: Violet (center 407.6 nm, 50% bandwidth 37 nm); Blue (452 nm, 87 nm), Yellow (605nm, 35nm), and Red (707nm, 38nm). I_e= 190mA.

Lessons Learned: Optical Diagnostics

- OTR was extremely valuable for commissioning and diagnosis
  - PXIE H- OTR will be much less bright, but we need to try
- Capturing thermal radiation equally important
  - Need temperature calibration procedure for PXIE
  - Could implement a filter wheel
- We should require ourselves to image the full surface of the PXIE absorber (machine protection)

Electron OTR on the prototype surface
I_e= 190mA, axes of footprint ellipse are ~50x7 mm.
Incident beam power density ~20 W/mm^2.
Photo: M. Murphy

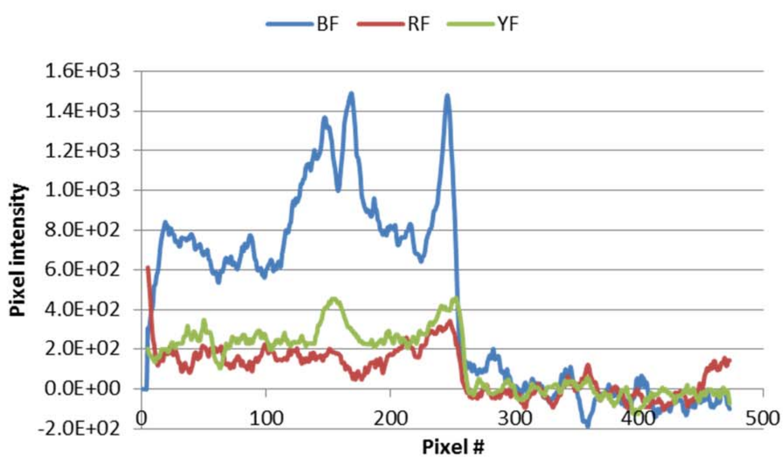
Optical Measurement of Surface temperature

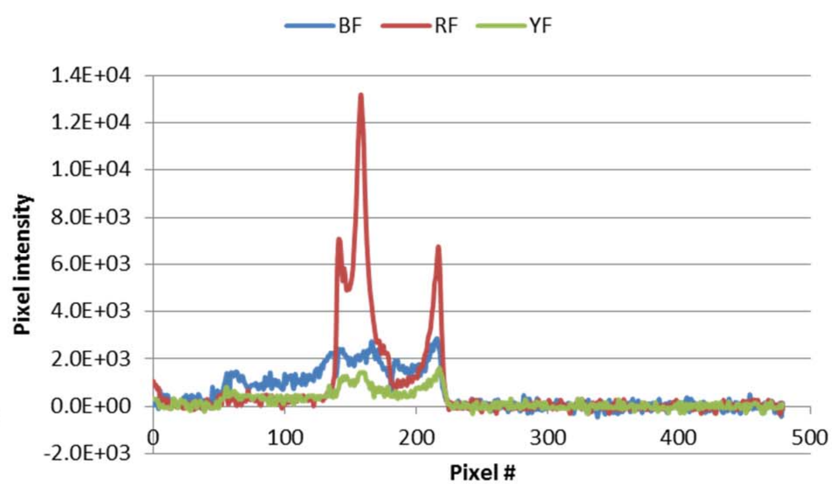
- At the beam footprint's power density corresponding to what is required for PXIE, the beam image with red and yellow filters is dominated by thermal radiation
  - The light intensity can be used to estimate the surface temperature

- The relationship between the camera readouts and light intensity is affected by camera sensitivity and by optical characteristics of windows and filters
  - One possibility is to use the calibration found in scraper measurements (same material, same distance)
  - Another way is to compare the images with red and yellow filters, assuming the OTR spectrum to be white in optical region

Procedure

- Focus the beam so that the OTR signal is above the noise but dominates over thermal and record images with B/Y/R filters
  - Calculate intensity integrals and their ratios
- Record images with 3 filters for a more tightly focused beam
  - Adjust Yellow intensity using the found ratio
  - Subtract the Blue image from Red and Yellow with proper coefficients

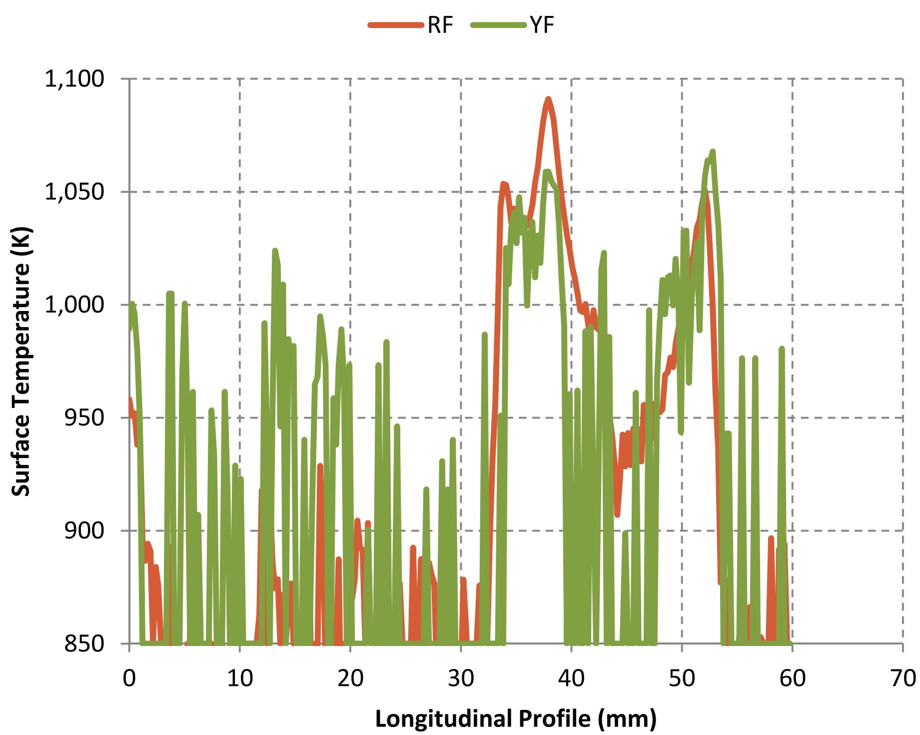




Distribution of light intensity along the vertical central line for two focusing cases. 3 curves correspond to 3 filters. The left curves are shown with 10-point averaging. I_e= 190mA.

Surface Temps at Intermediate Power Density

- The signals are too noisy to reconstruct the calibrations better than predictions from scraper measurements
  - Corresponding temperature uncertainty ~150K



$$I_R(T) = I_{0R} \cdot \exp\left(-\frac{T_R}{T}\right)$$

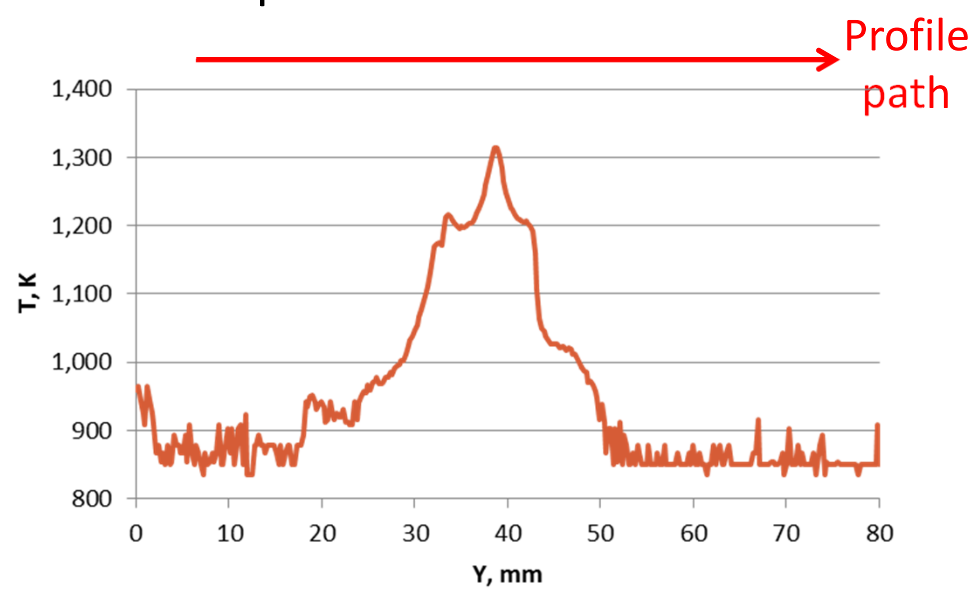
$$I_Y(T) = k_{YR} \cdot I_{0R} \cdot \left(\frac{\nu_Y}{\nu_R}\right)^3 \exp\left(-\frac{T_R}{T} \cdot \frac{\nu_Y}{\nu_R}\right)$$

$$T_R = \frac{h\nu_R}{k_B} = 20350K$$

Temperature calculated from Red and Yellow distributions with the calibration coefficient found in scraper measurements for emissivity of 0.15. I_e= 190mA.

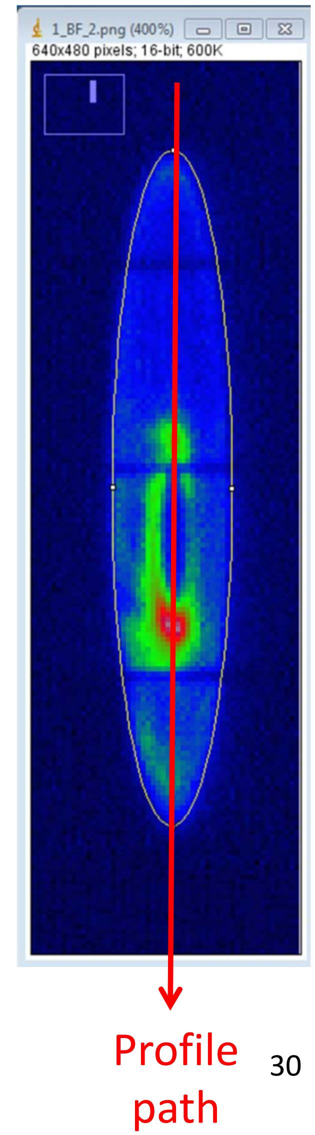
Surface Temps at High Power Density

- Images were recorded with Red and Red+neutral density filtering (for dynamic range)
- The Blue image was used to reconstruct the current density across the footprint



Temperature profile along the central vertical line calculated from combined RF and RF+10%NF data. I_e= 190mA. Average absorbed power density is 17 W/mm^2.

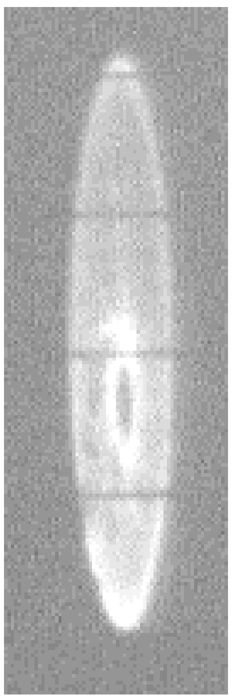
Blue image in false colors. The ellipse drawn in ImageJ shows the area used for calculating the average power density. The axes are 32mm x 5.5mm. The red spot is likely affected by thermal radiation.



Correlation Analysis: Beam Profile Mapping

Project X

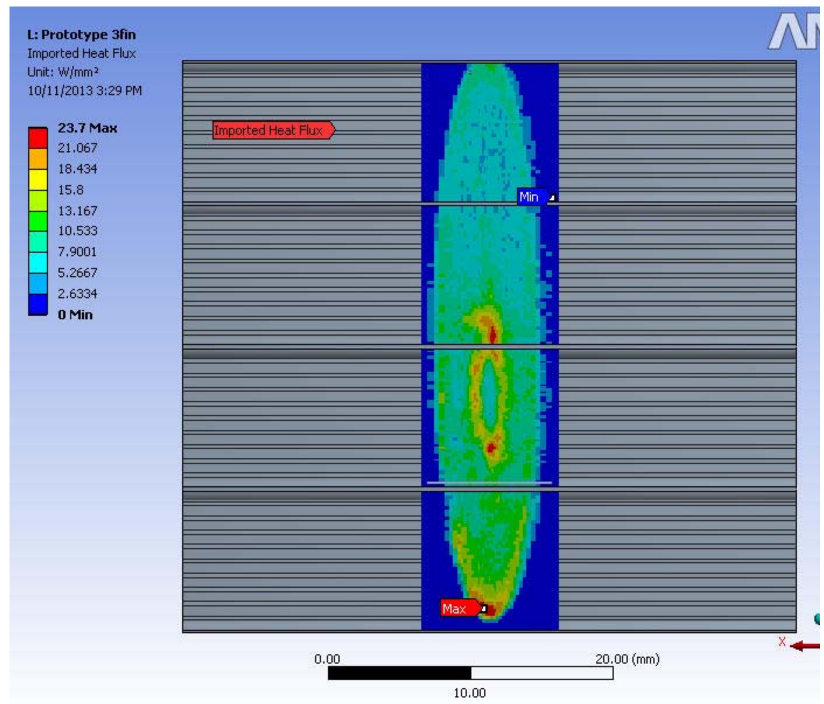
- Initial correlation efforts were hampered by beam profile uncertainties
- Eventually, we used OTR at an intermediate focusing to map the beam profile



Blue-filter beam image
Dominated by OTR

Mapping to FEA

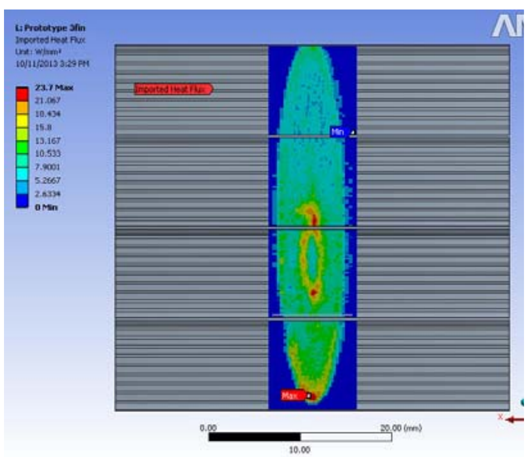
OTR intensity proportional to power



Analyzed beam profile: intermediate focusing
Power Density on Fin 5”
10W/mm^2 average 25W/mm^2 peak

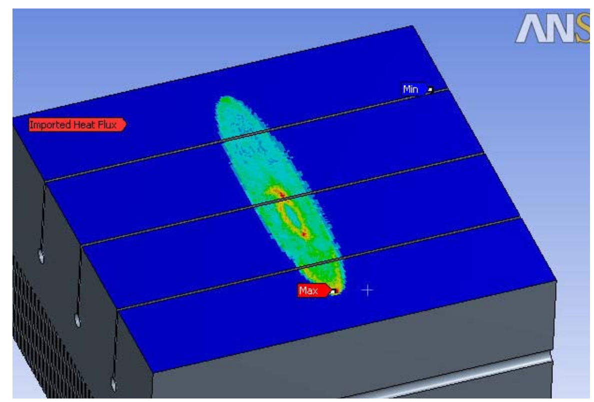
Correlation Analysis: Beam Profile Mapping

- Direct mapping did not work for the tightly focused beam, some blue thermal radiation (λ<520nm) passes the filter
- We scaled the 10W/mm^2 beam profile down to the known focused size
  - Power density scales up
  - Known deficiency in this method: beam "hole" changes with focusing



Scaling

Scaling by size
Beam power unchanged
Power density increases

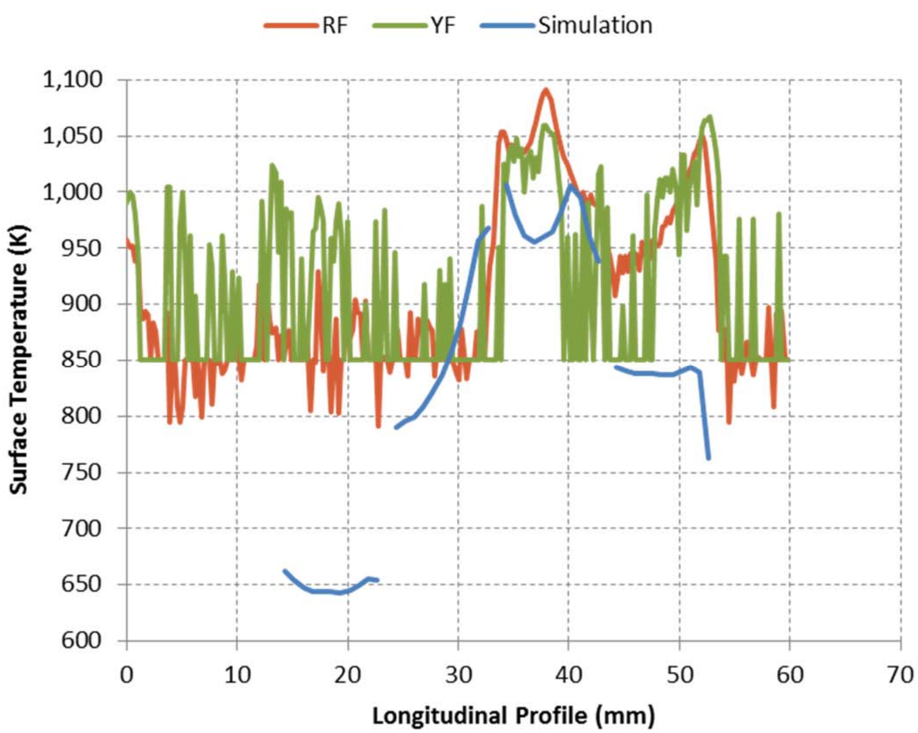


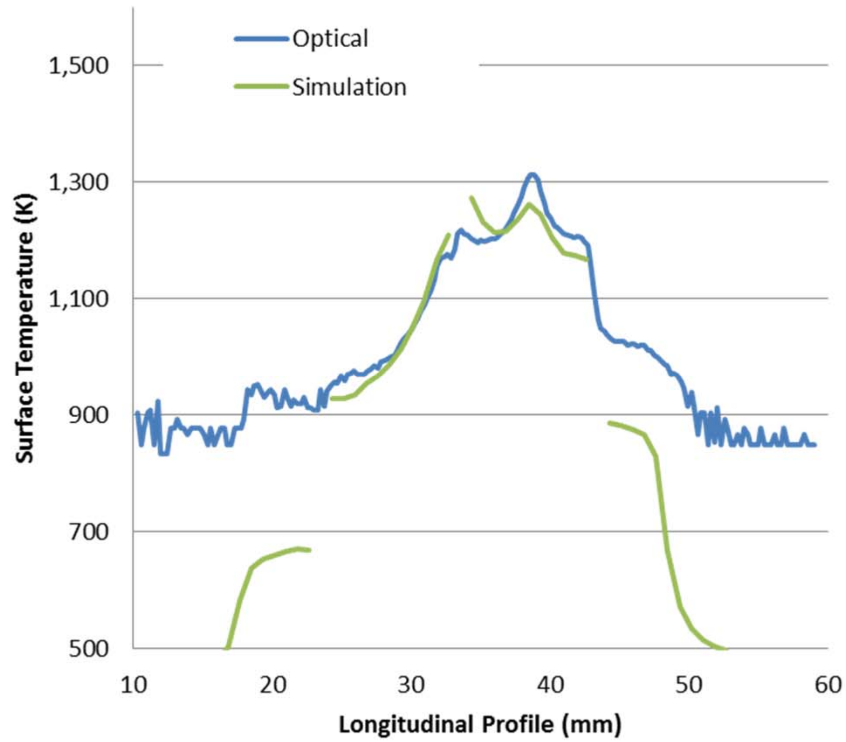
Analyzed beam profile: intermediate focusing
Power Density on Fin 5:
10W/mm^2 average, 25W/mm^2 peak

Analyzed beam profile: strong focusing
Power Density on Fin 5:
17W/mm^2 average, 40W/mm^2 peak

Correlation Analysis

- Predicted temperatures are close to optical measurement of surface temps if the calibration coefficient corresponding to largest possible reflection in the scraper measurements is chosen

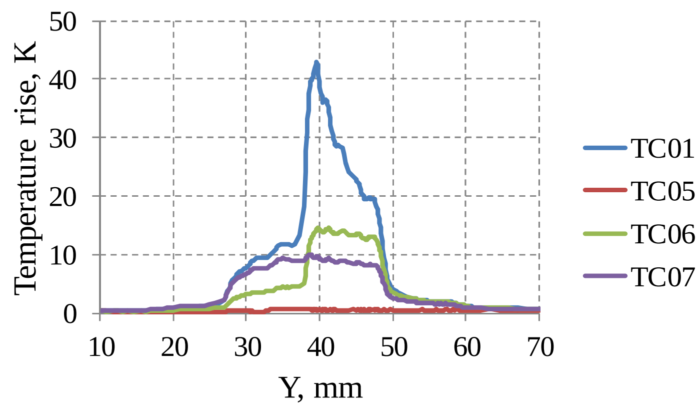




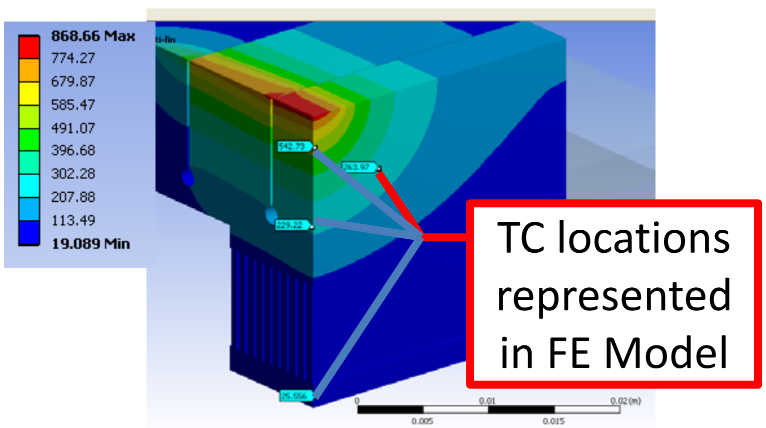
Comparison of temperature profiles along the central vertical line for two focusing cases.

Thermometry in fins

- 6 thermocouples in 3 different fins
  - Most of measurements are for fin #5 (4 TCs)
- Readings are affected by thermal conductivity of thermocouples
  - Corrected based on measurements with a "pencil" beam



TC readings in the vertical scan through fins #3-6 with a "pencil" beam. Thermocouple depths, in mm, are 2.65, 6.15, 9.15 for TC01, TC06, and TC07, correspondingly; TC05 is below the water channels. TC06 is shifted by 6 mm from the transverse midplane, and others are in the middle.



Correlation Analysis

Analysis Correlation Results		Tsurface [1] K	TC01 C	TC06 C	TC07 C
Strong Focusing [5]	Predicted Temp [2]	1218	575	298	261
~17W/mm^2 on Fin 5	Observed Temp [3]	1226	596	322	270
	Prediction Error [4]	**<10%**	**-3.6%**	**-7.8%**	**-3.5%**
Intermediate Focusing	Predicted Temp [2]	974	464	258	227
~10W/mm^2 on Fin 5	Observed Temp [3]	1004	500	287	233
	Prediction Error [4]	**<10%**	**-7.4%**	**-10.7%**	**-2.9%**

Notes:

[1] Average temperature in longitudinal trace over center of fin 5
Errors of order 20% in the cooler areas of the surface

[2] Predicted in FEA, with thermocouple conduction effect compensated

[3] Surface observation from optical measurement, all others from thermocouples

[4] calculated as [dT predicted - dT observed] / [dT observed]
where dT is change relative to water temperature

[5] Beam profile is a scaling of the OTR-dominated intermediate focusing profile

Conclusions: Analysis/Capability/Durability

The Good…

- The prototype survived 17 W/mm^2 average, 40 W/mm^2 peak
  - This meets requirement for PXIE @ 10mA (17 W/mm^2 peak)
- The absorber survived a modest number (~1E2) of thermal cycles
- Independent temperature measurements and estimates coincide within reasonable error bars

The Bad…

- We do not know whether we should be worried about the observed changes on the absorber surface

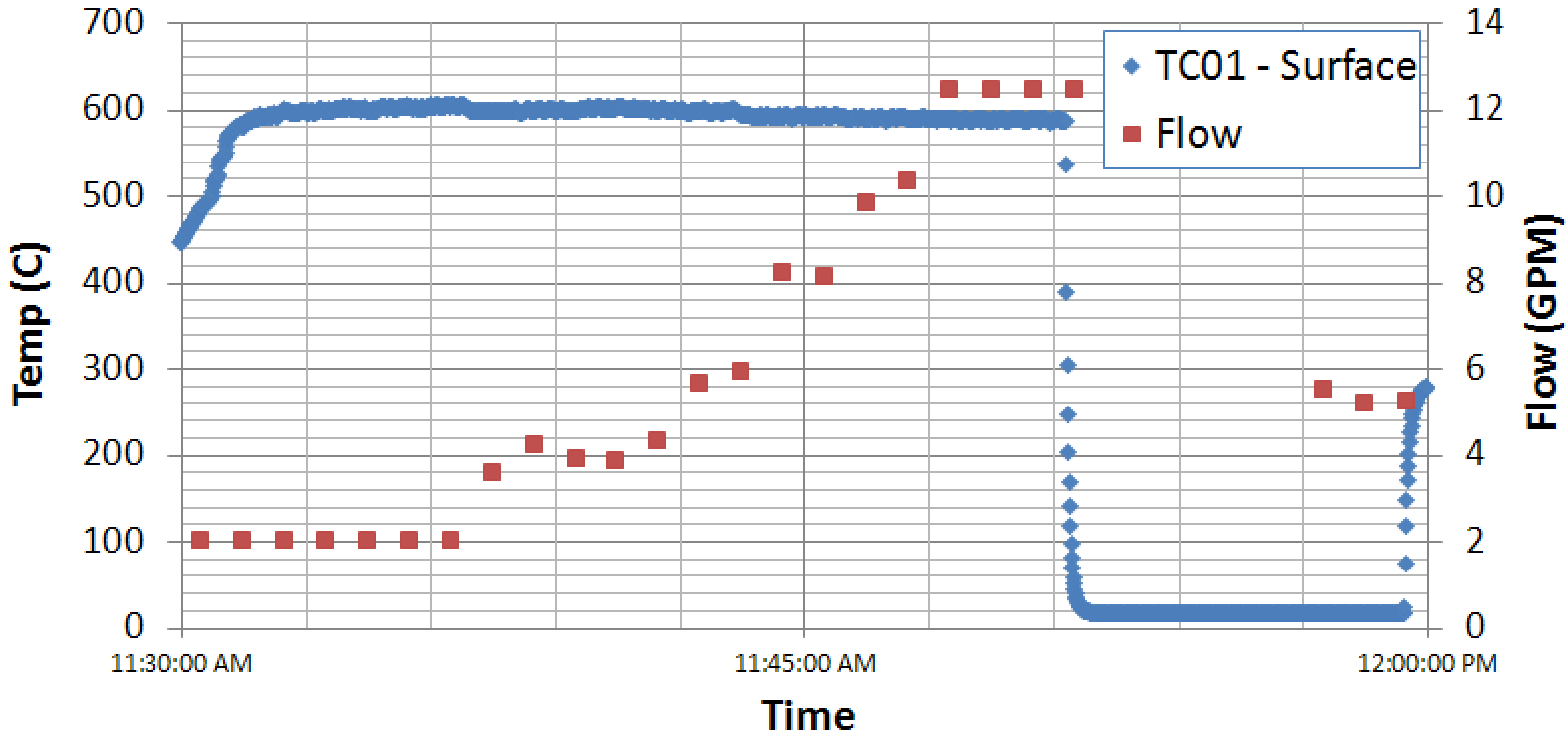
…And the Ugly

- We are afraid to do the planned thermal cycling tests. A coolant-to-vacuum leak will kill the test bench, precluding any further testing
- This is a valid fear for PXIE as well

Investigation of Cooling Regime

Project X

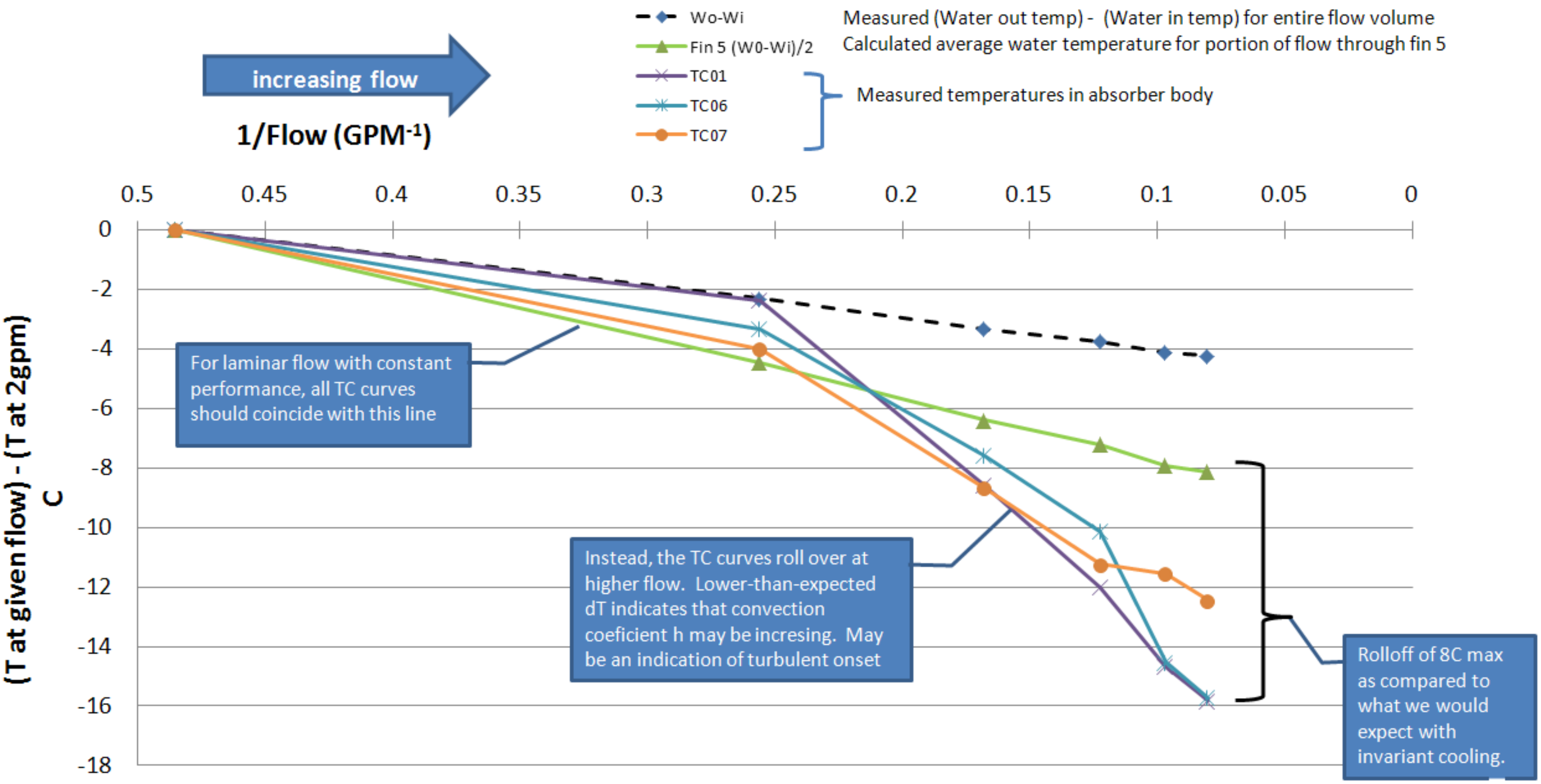
- With constant beam conditions, we increased flow from 2gpm to 12 gpm
  - All thermocouples were monitored
  - Any transitions (e.g. boiling, laminar→turbulent) would result in inflections
  - Instead, temperatures were relatively insensitive to flow



Investigation of Cooling Regime

Project X

- We expected fully laminar flow, with dT inversely proportional to flow
  - Instead, we see a slight improvement with higher flow rates
  - This suggests the onset of the turbulent transition (helpful!)



Lessons Learned: Cooling Scheme

The Good…

- The understanding that ~25% H- energy and ~50% of e- energy is reflected moves the cooling design into a more comfortable regime
- For this reason, we don't need glycol at 2°C, water at 20°C is fine
- Prototype module could run with low flow rates of 2gpm, permitting us to consider single-pass designs for PXIE
- No evidence of local film boiling
- Evidence suggests we may be benefitting from some amount of turbulent transition behavior

The Bad…

- We'd like to get away from wetted material transitions in vacuum

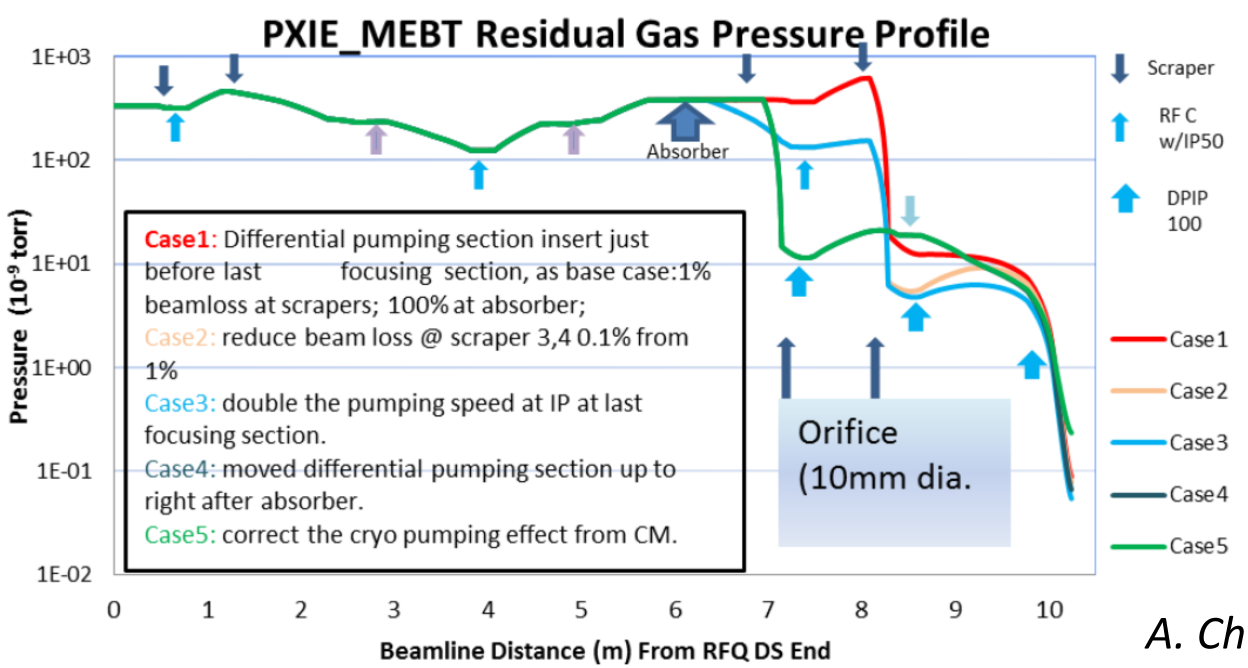
…And the Ugly

- Property and flow measurement uncertainties for water/glycol mixtures are a mess. We'll consider avoiding glycol in PXIE

Lessons Learned: Vacuum

Project X

- The test bench absorber volume operates at or below the 1E-7 Torr
- The PXIE absorber will operate in the mid E-7 Torr range
- For the better vacuum of the test bench:
  - graphite interface layer did not spoil vacuum (cold vacuum ~E-9 Torr)
  - After conditioning*, outgassing of the hot absorber did not spoil vacuum



*PXIE absorber to be high power vacuum conditioned before valving in SRF components

A. Chen

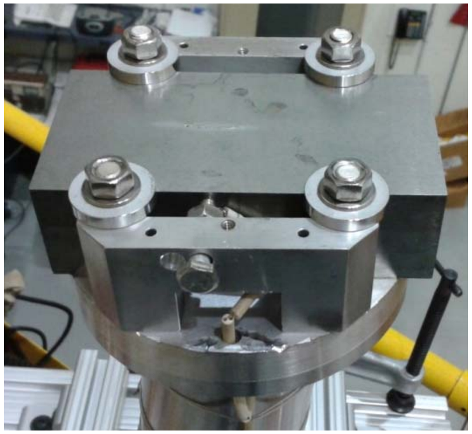
MEBT Prototype Absorber Update

- Background
- Test Results
- Implications to PXIE Design
- Proposed Next Steps

PXIE Design Drivers

- We now understand the following
  - 25% of the incident energy is reflected
    - This makes absorber cooling easier
    - …but requires ~5kW of energy to be absorbed elsewhere
  - A coolant-to-vacuum leak is scary
    - Given that the cooling design is not at the hairy edge of working, we can design to minimize this risk
  - The J. Walton pre-prototype scheme worked better than expected
    - A contact interface is an option for PXIE
    - Addition a graphite thermal interface layer improved thermal contact, didn't kill the vacuum

J. Walton's Design



PXIE Design Philosophy

- Use the following tested design features
  - TZM material
  - Stair-step surface geometry for stress relief and shadowing
  - mm-scale cooling channel geometry
  - Graphite thermal interface layer with compressive preloading
- Design to accomplish the following:
  - Reduce the likelihood of water-to-vacuum failure mode by going to a non-monolithic thermal contact design
    - Failure of TZM less likely to propagate
    - Fab complex cooling features in a conventional material
  - Capture some of the reflected energy at the absorber
    - Minimize area of vacuum enclosure that needs blistering-resistant and/or actively cooled features
    - Maintain optical view of the surface for diagnostics

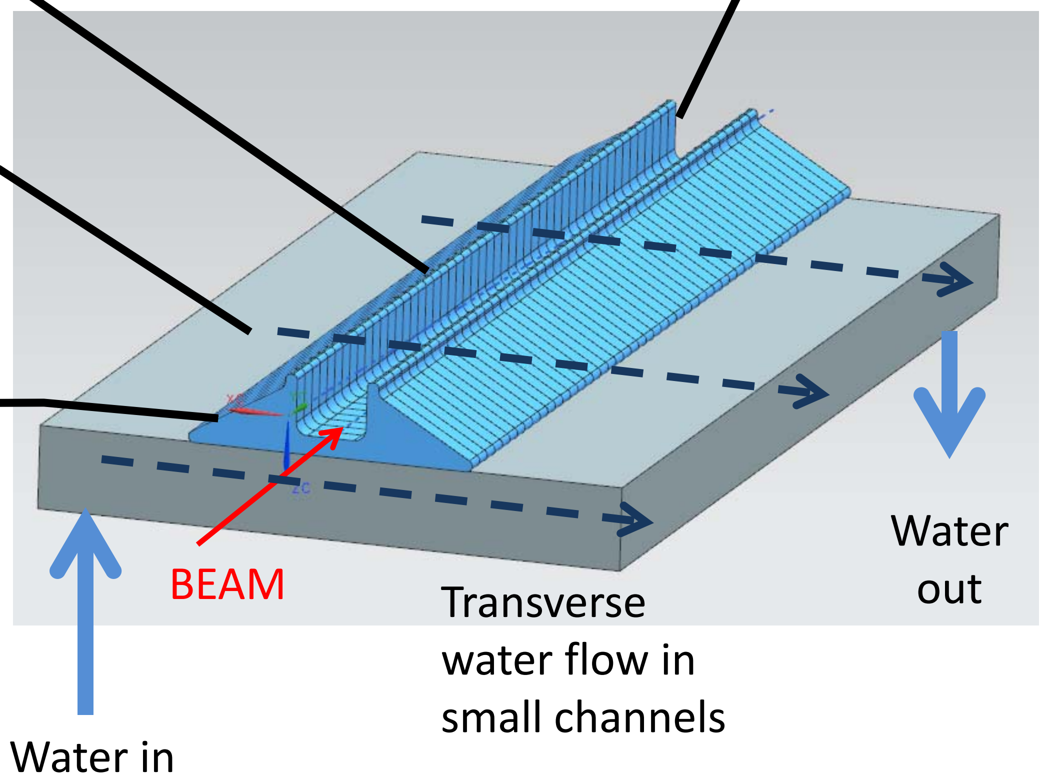
PXIE Absorber Cartoon

TZM absorbing fins
1cm thick
Stack Qty. ~50 of these
Beam incident in “valley”

Side walls absorb some of the reflected energy and shadow preload structure

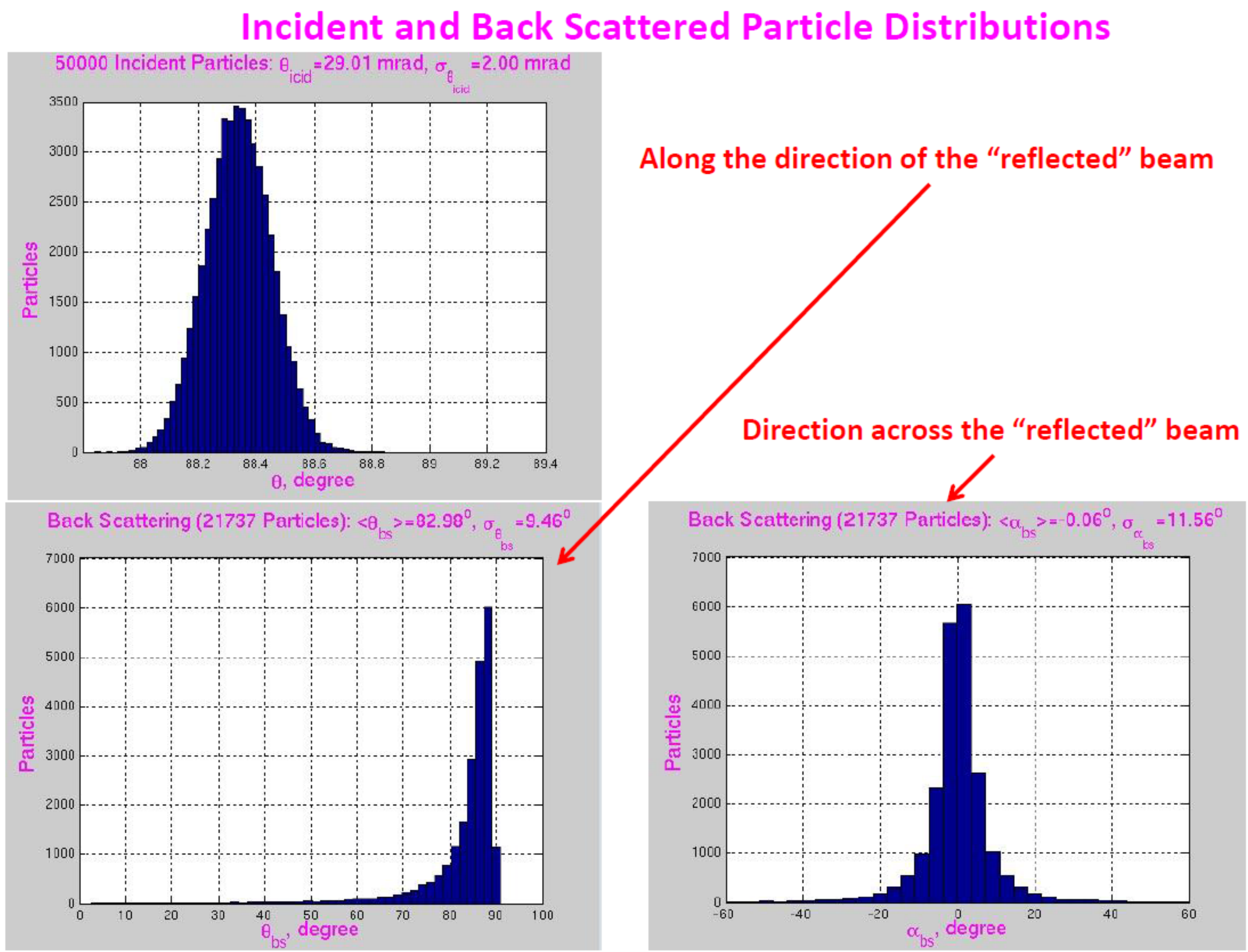
Cooling Strongback
Same channel design as prototype
monolithic, likely Aluminum

(Not shown) Preload structure
Pushes individual TZM fins down
into graphite thermal interface layer



Reflected Energy Distribution:

Project X



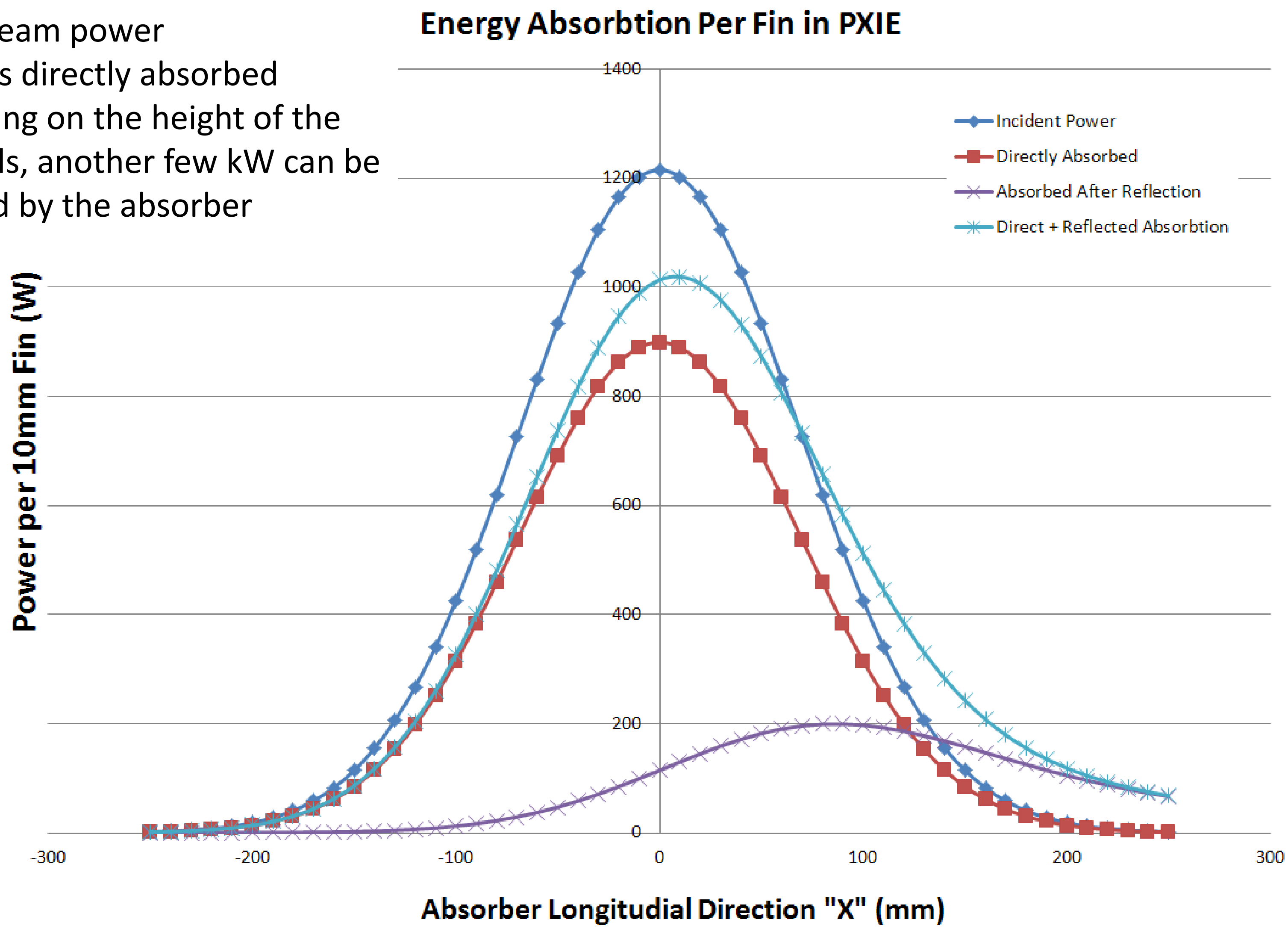
Y. Eidelman

Reflected Energy Reabsorbed by Absorber

Project X

For 21kW beam power

- ~16kW is directly absorbed
- Depending on the height of the side walls, another few kW can be captured by the absorber

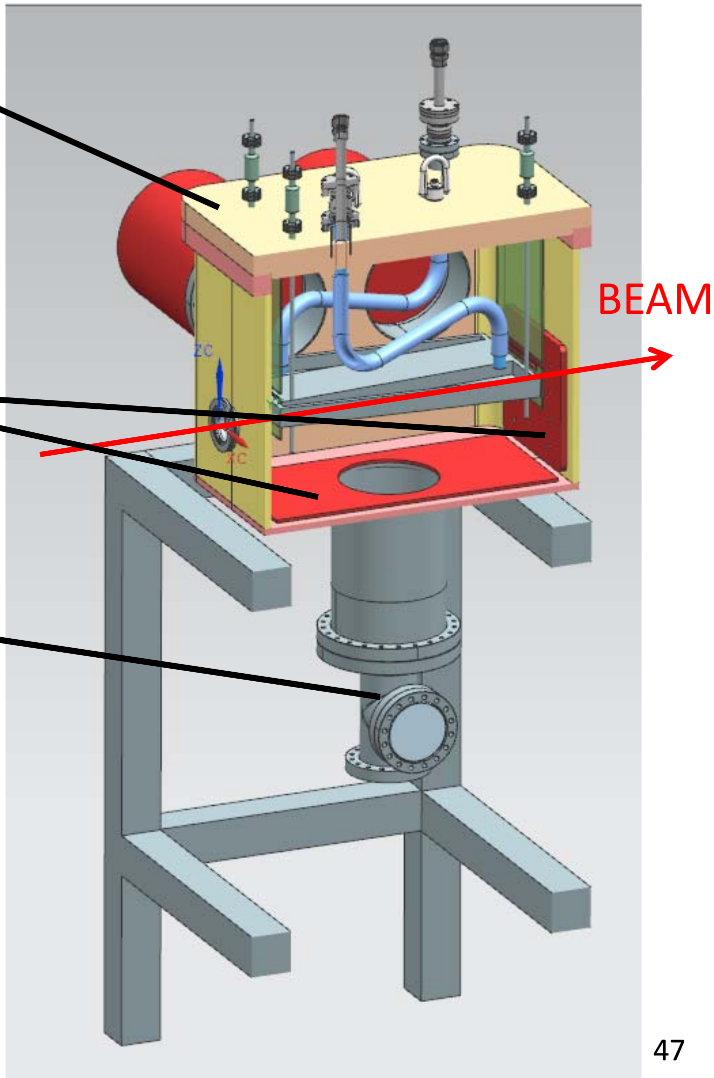


Assembly Cartoon

Absorber kinematically mounted on handling flange
Absorber is electrically isolated

Secondary absorbing plates
Intercept reflected particles

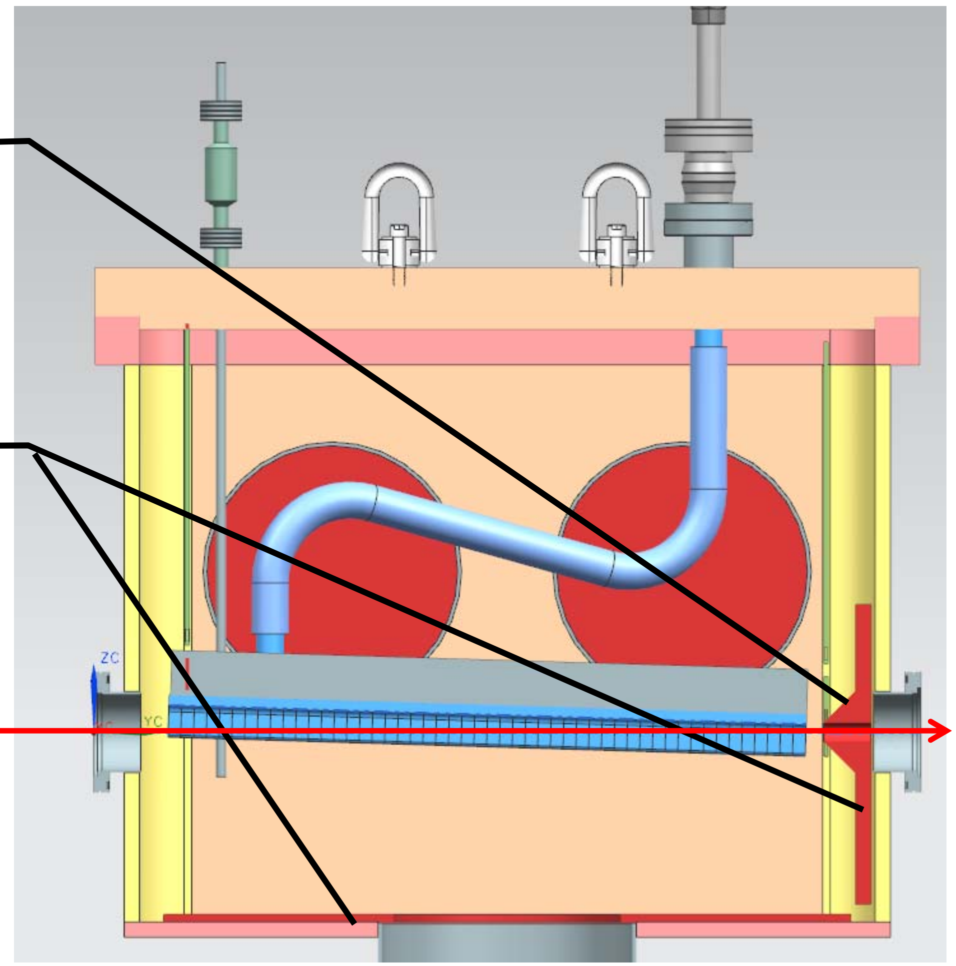
Placeholder for imaging system
Periscope arrangement
Inadequate as shown
(can't image the full absorber surface)



Assembly Cartoon

Option to implement an orifice here
Limits propagation of reflected particles
Aids in vacuum separation

Cooling of secondary absorber plates is likely required. This is envisioned as being implemented on the outside of the vacuum enclosure



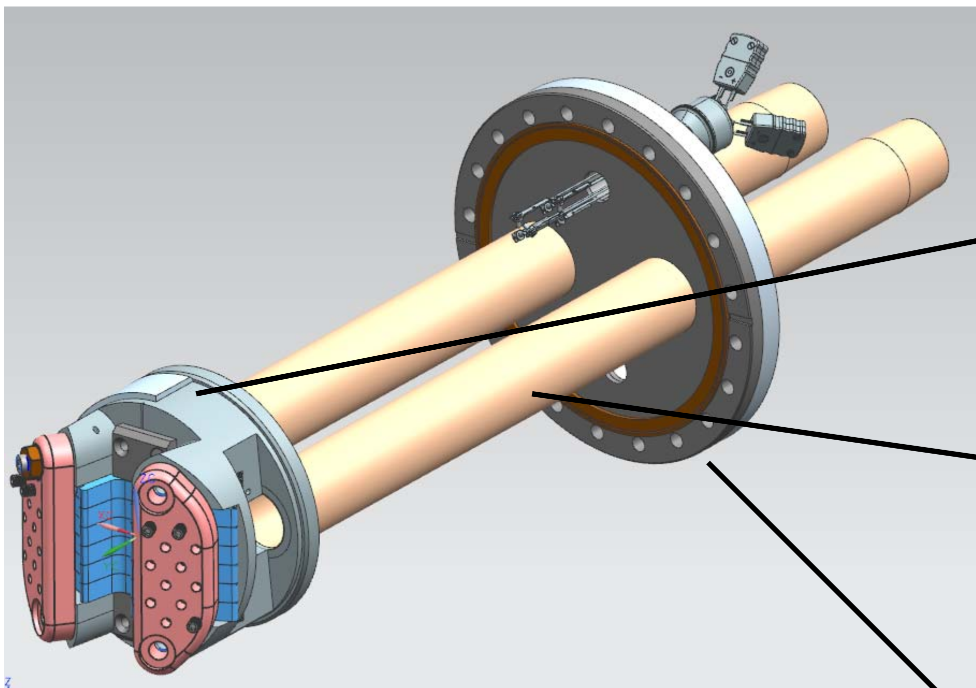
MEBT Prototype Absorber Update

- Background
- Test Results
- Implications to PXIE Design
- Proposed Next Steps

Proposed Next Steps:

- Proposed PXIE design has its own risks
  - Implementation of thermal contact
  - Temperature/time stability of thermal contact
  - Management of reflected energy
- Much effort was invested in the test bench. It is a significant resource for PXIE in general and this task in particular
- We suggest building a next iteration of the prototype
  - Use in the same test bench
  - Retire thermal contact risks
  - M&S funding was included in MEBT FY14 request

Prototype 2 Concept

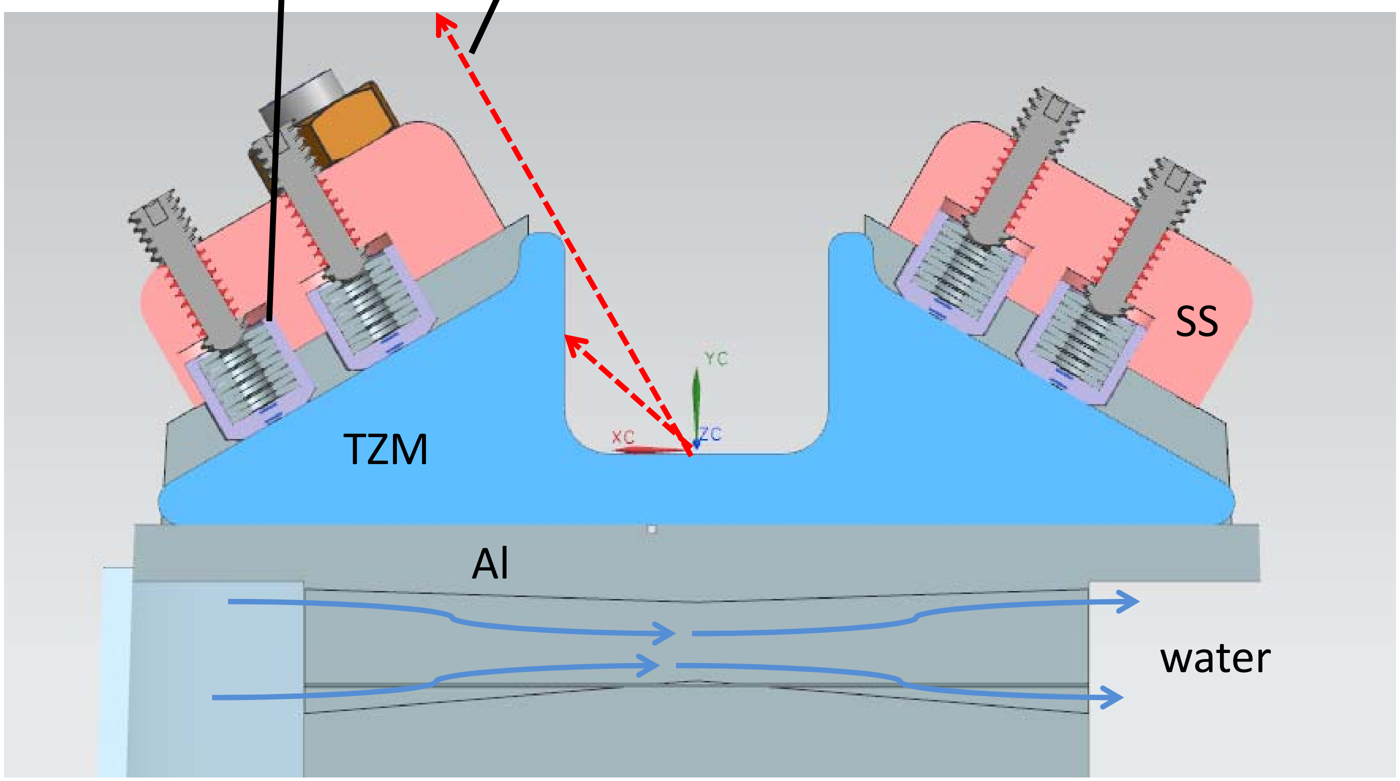


- 6 PXIE-like TZM fins
  - Graphite thermal contact
  - Individually preloaded
- Aluminum cooling strongback
  - Transverse cooling channels
- Aluminum plumbing to air
  - No in-vacuum material transitions
- ATLAS Aluminum/SS flange interfaces to test bench

Prototype 2 Concept

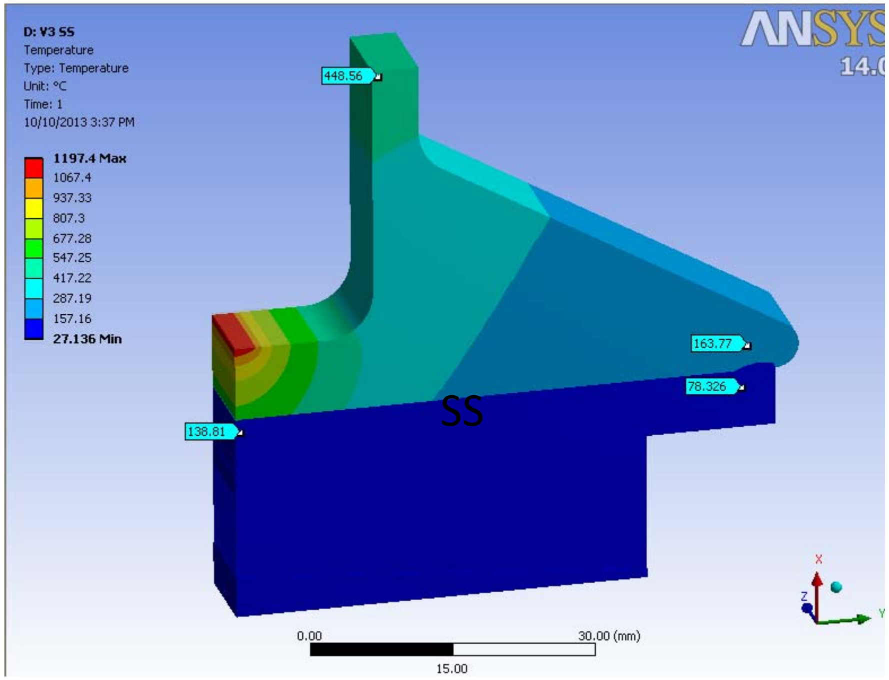
Structure (mostly) shielded from reflected energy by TZM

Compliant preloading with disk springs



Prototype 2 Thermal Analysis (Preliminary)

- 1.1kW per 1cm fin
- Assumed thermal contact 4E3 W/m^{2}K, as suggested by Pre-prototype testing
- Peak predicted surface temps of 1200°C are ~25% higher than Prototype 1 peak *predicted* surface temps, still within capabilities of TZM
- Prototype 1 testing results encourage us to go down this design path, but the hit to thermal performance motivates further testing

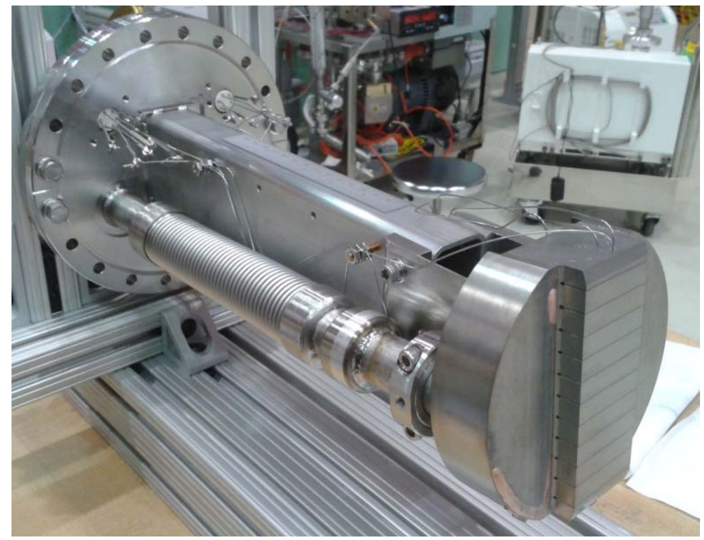


Prototype 2 Nuances

- Reflection of the H- beam in PXIE is somewhat specular (i.e. mirror-like) (per Y. Eidelman result)
- Reflection of the e- beam in the test bench is likely much more diffuse (from first principals, also seen in a CASINO simulation)
- It will be challenging to deposit a representative energy profile on the incident surface and the side walls of the absorber at the same time
  - In general, we expect "extra" energy to be deposited in the side walls by the test bench. This should yield a conservative test
  - Calorimetry should allow us to understand what level of side wall energy deposition we achieve

Summary

- A prototype has been built and tested to the power density of PXIE@10mA, and has survived
- Temperature measurements and analysis agree to within measurement uncertainty, and we are building confidence in the design methodology



- We're satisfied with material choice, vacuum properties, and fluid dynamics
- Learning from the prototype recommends design improvement to a simpler thermal-contact design for PXIE
- Uncertainties in the revised design concept motivate an iteration of the prototype process

Contributors

Contributors

- B. Hanna – operation and measurements
- V. Lebedev, M. Hassan - first concept
- L. Prost – test stand, simulations
- J. Walton – test stand, pre-prototype
- K. Carlson - test stand electrical
- Yu. Eidelman – material choice
- A. Chen – absorber vacuum
- R. Thurman-Keup- imaging
- A. Mitskovets- test stand commissioning
- C. Exline– prototype assembly
- A. Denisov – Scraper Measurements

Thanks to

- V. Dudnikov
  - Importance of blistering
- T. Schenkel
  - Large reflected power for H-
- V. Scarpine
  - Help with optical measurements
- A. Lumpkin
  - Discussions
- I. Terechkine
  - Suggestion to use microchannels