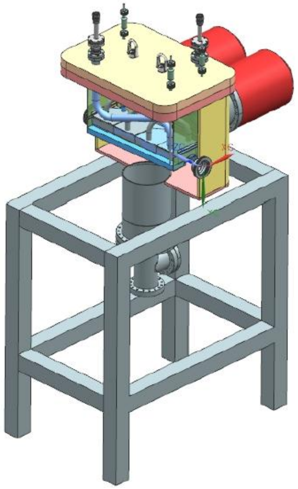
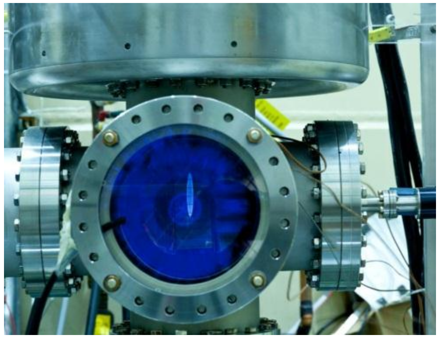


Status of PXIE MEBT absorber development

C. Baffes, A. Shemyakin

APT Seminar, May 7, 2013



Contributors

- B. Hanna – operation and measurements
- V. Lebedev, M. Hassan - first concept
  - grazing angle, slits, steps
- L. Prost – test stand
  - beam simulations, radiation estimations, “hot spots” analysis
- J. Walton – test stand; pre-prototype
  - Design and assembly
- K. Carlson - test stand
  - Electrical, controls
- Yu. Eidelman – material choice
  - Radiation, secondary particles
- A. Chen – absorber vacuum
- R. Thurman-Keup- imaging
  - camera and its software
- L. Carmichael – conditioning program
- A. Mitskovets- test stand commissioning
- C. Exline– prototype assembly

Thanks to

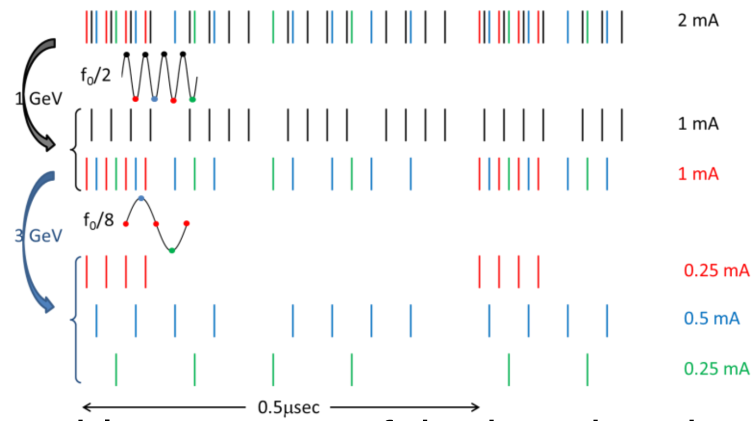
- V. Dudnikov
  - Importance of blistering
- T. Schenkel
  - Large reflected power for H-
- V. Scarpine
  - Help with optical measurements
- A. Lumpkin
  - Discussions
- I. Terechkine
  - Suggestion to use micro-channels

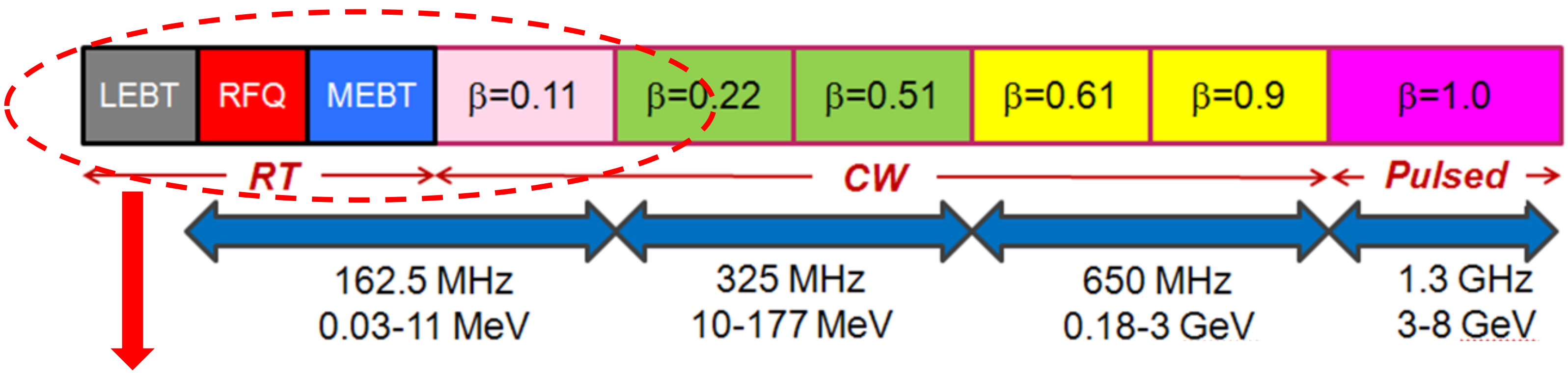
Outline

- Project X and PXIE
- Absorber concept
- Absorber prototype
- Test stand
- Measurements
  - Power balance
  - Temperature measurements
  - Beam imaging
- Summary and plans

Project X and PXIE

- Project X is an Intensity Frontier accelerator providing MW-scale proton beam to many users quasi-simultaneously
  - Acceleration in SRF from low energies
  - Constant power in time scale >µs; adjustable structure of the bunch train
  - Accomplished by bunch-by-bunch chopping in MEBT and RF separation after acceleration to the required energy

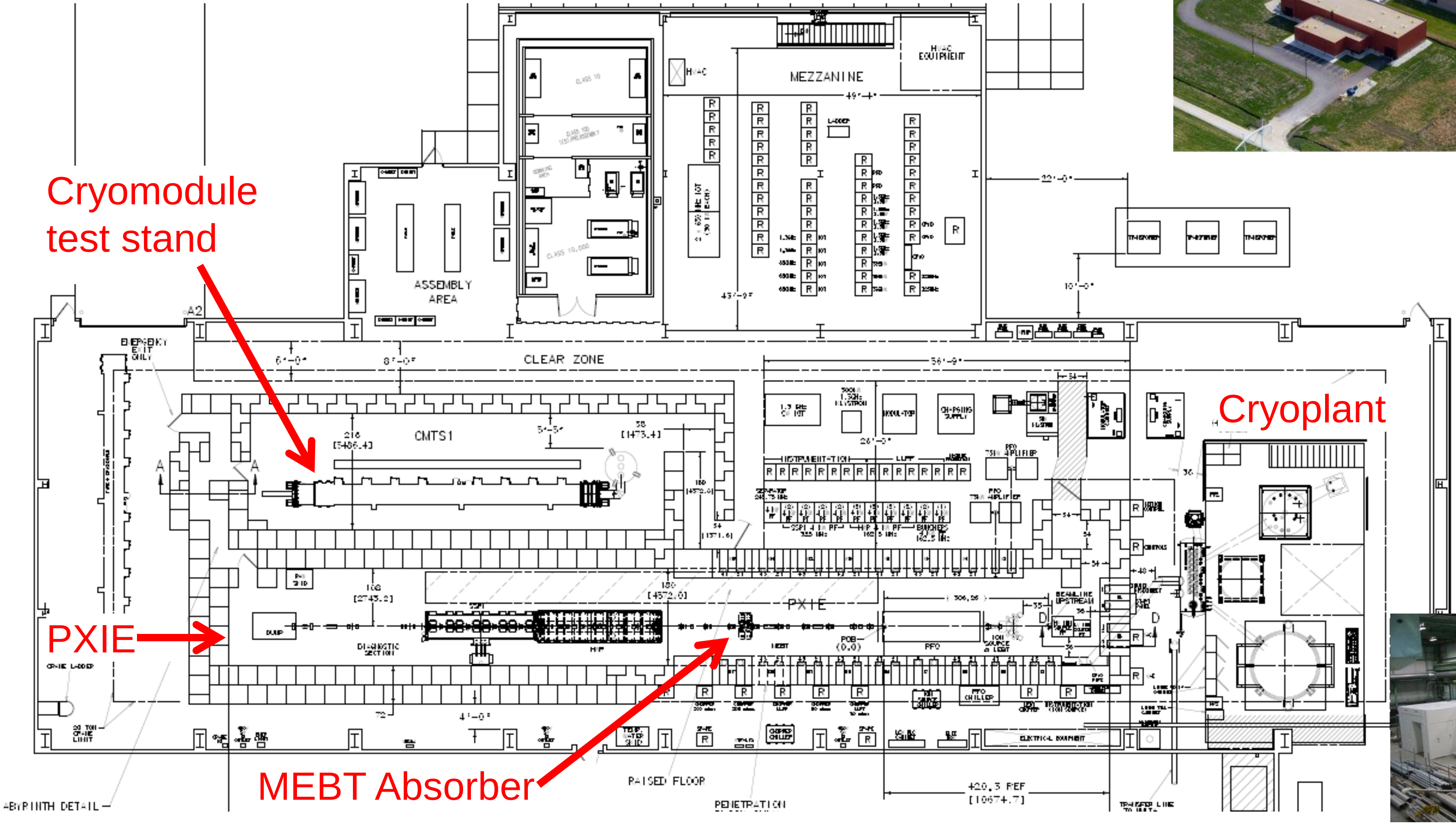




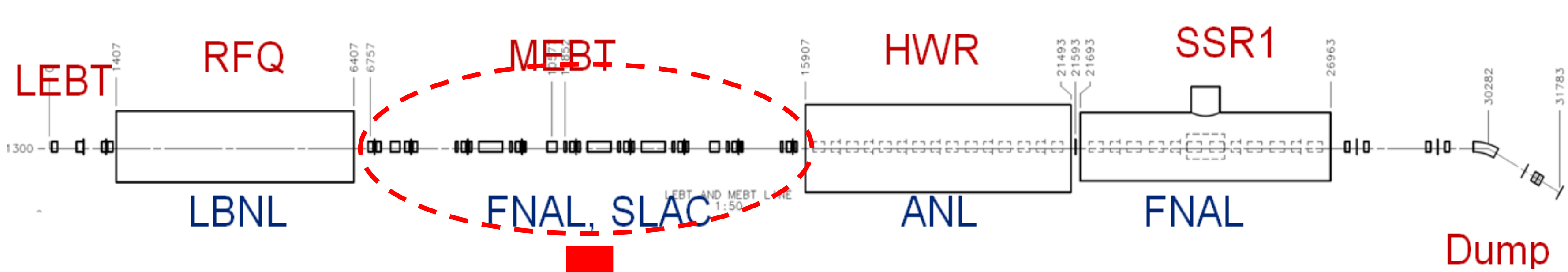
Addressed by the Project X Injector Experiment, PXIE

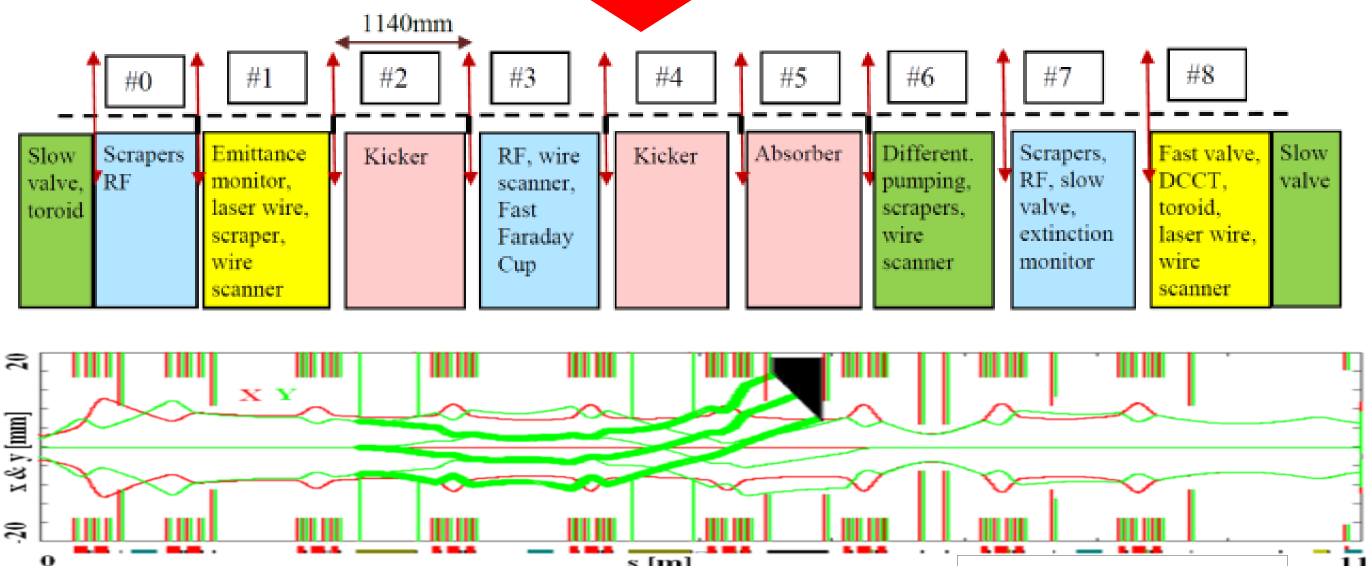
PXIE

- PXIE will be assembled in the existing Cryo Module Test Facility building



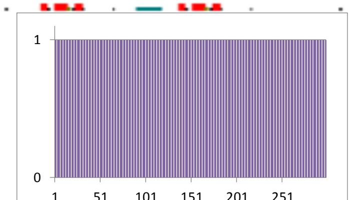
PXIE MEBT

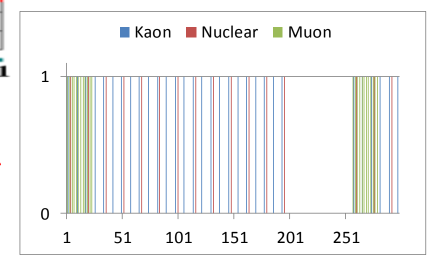




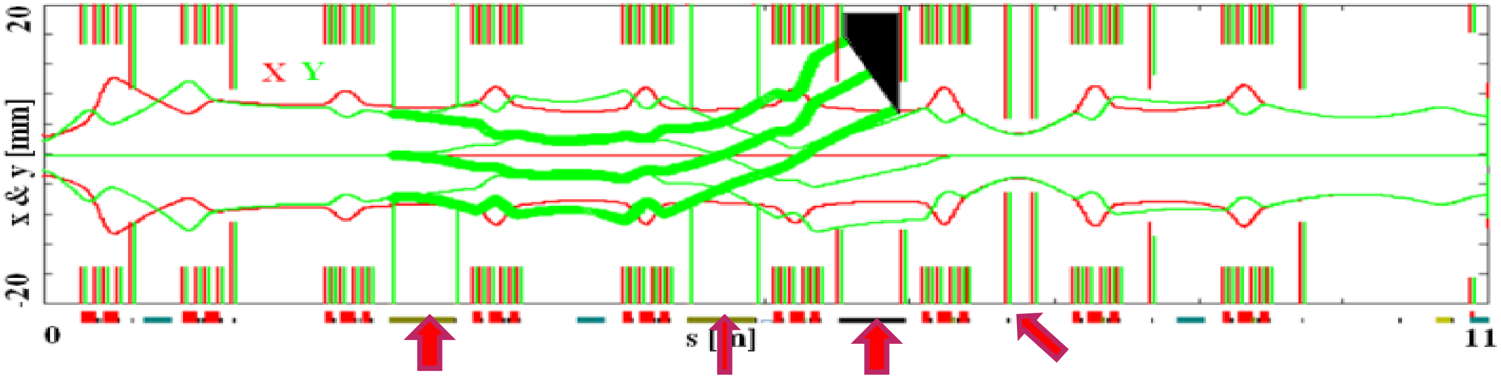
MEBT sections and optics. 3σ envelopes of passing bunches – thin lines, removed bunches- thick lines. Red squares- quads, blue – bunching cavities.

- MEBT chopping system transforms CW, 5 mA beam from RFQ to 1mA "Repetitive Structure"





PXIE MEBT absorber

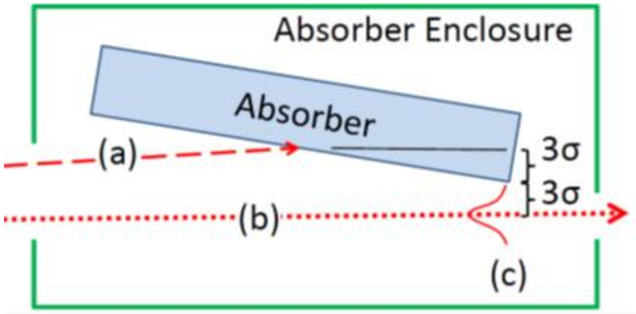


Two kickers separated by 180º

Absorber

Differential pumping

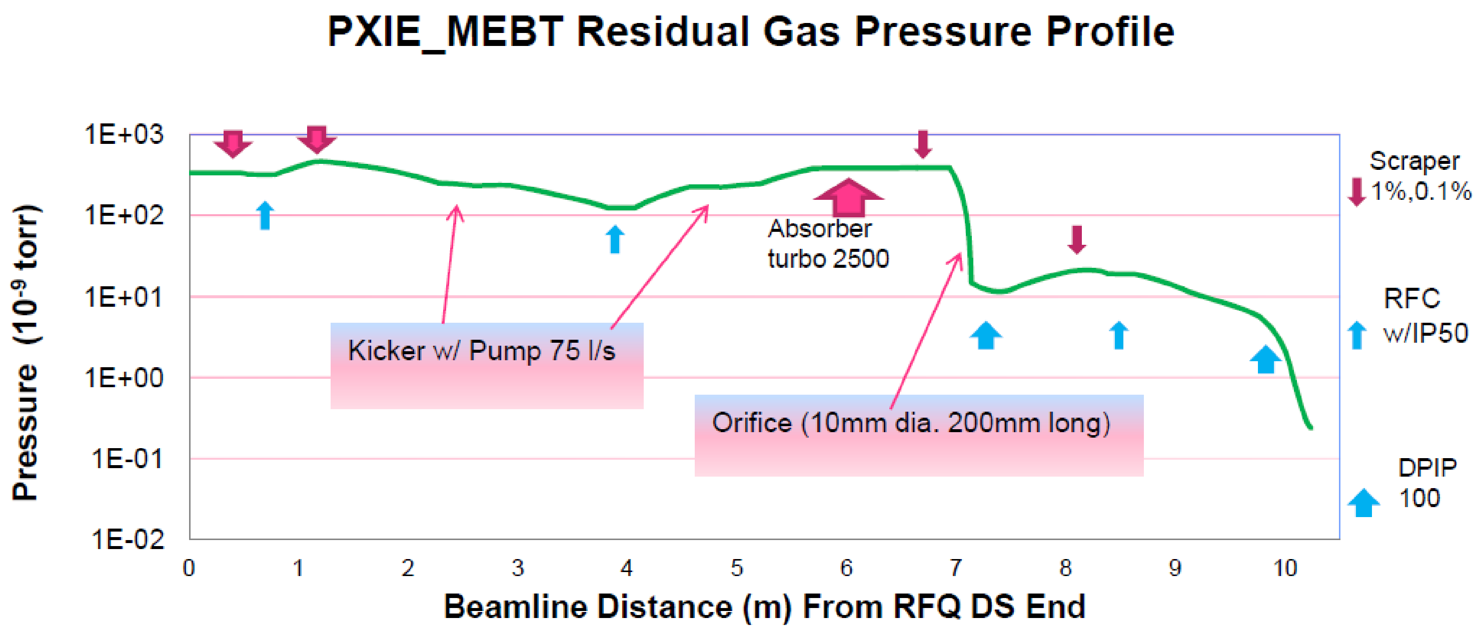
- Absorber requirements
  - Nominal beam power 2.1 MeV x 4mA = 8.4 kW
  - Design beam power 2.1 MeV x 10mA = 21 kW
  - Beam size, x/y, rms 2/2 mm
  - Vacuum with nominal beam < $1\cdot10^{-6}$ Torr
  - Life time ≥ 1 year
  - Number of thermal cycles ≥10,000



Challenges

- High beam power density, up to 1.7 kW/mm^2
  - High temperature and temperature-induced stress
  - Addressed with a small incident angle, ~30 mrad, and the choice of the cooling scheme and materials
- Sputtering: knocking out atoms by H- ions
  - Amount of removed material is tolerable
- Secondary particles (protons, electrons, ions)
  - ~25% of the incident beam energy is reflected
    - Helps with power density at the absorber surface but requires attention to heat management of the vacuum chamber
    - May affect measurements of bunch clearing
- Radiation (neutron production, residual radiation)
  - Choice of low RFQ energy, 2.1 MeV
  - Choice of the absorber material

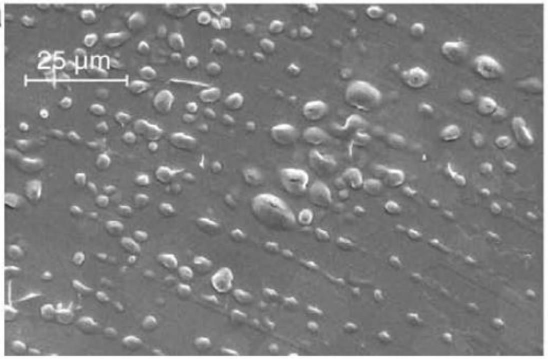
Challenges: vacuum



- Vacuum load
  - Main load is expected to be the hydrogen recombination in absorber
  - 2500 l/s turbo pumping
  - Differential pumping section downstream of the absorber

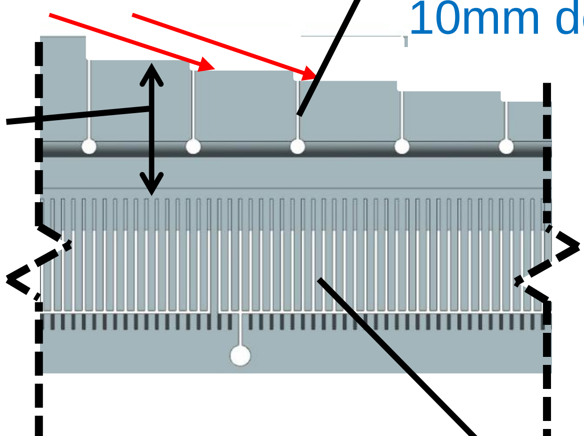
Challenges: blistering

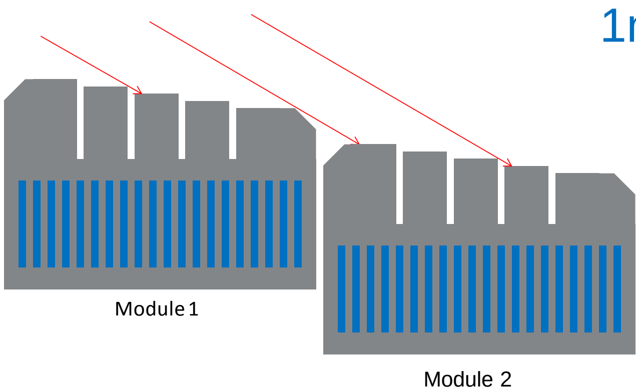
- Process
  - Hydrogen ions are implanted beneath the surface of the metal by the beam, form gas pockets, and rupture
  - Depends on ion fluence and material properties
- Problems
  - Changes roughness of the surface
    - Specially a problem for small grazing angle
  - May generate dust
  - May create bursts of pressure killing the beam
- Motivates the use of Molybdenum alloy TZM
  - attractive combination of blistering resistance, good thermal properties, and reasonable cost



Blisters in Cu irradiated by 190keV proton beam, V.T. Astrelin et al, "Blistering of the selected materials irradiated by intense 200keV proton beam," Journal of Nuclear Materials 396 p43, 2010

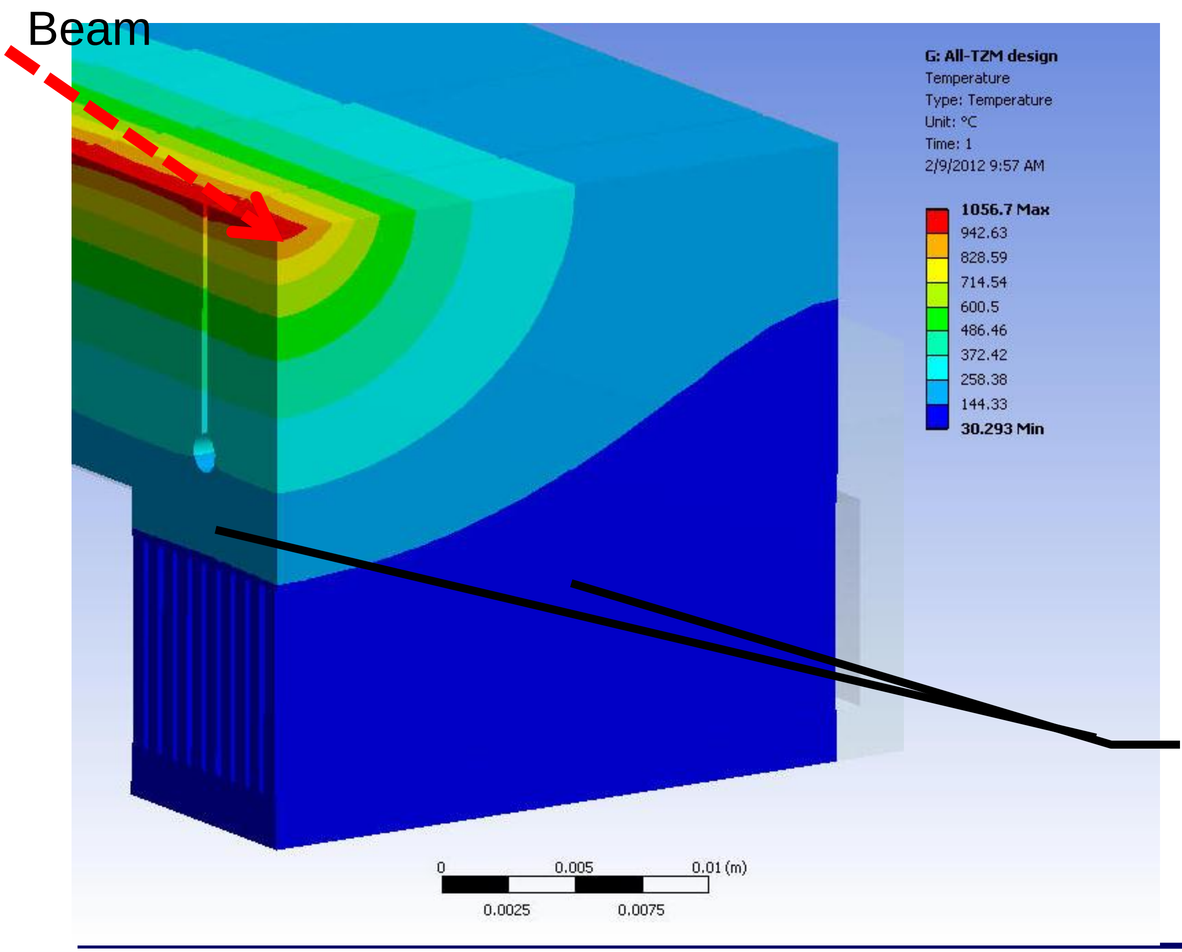
Absorber concept





- 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

Simulations: temperature



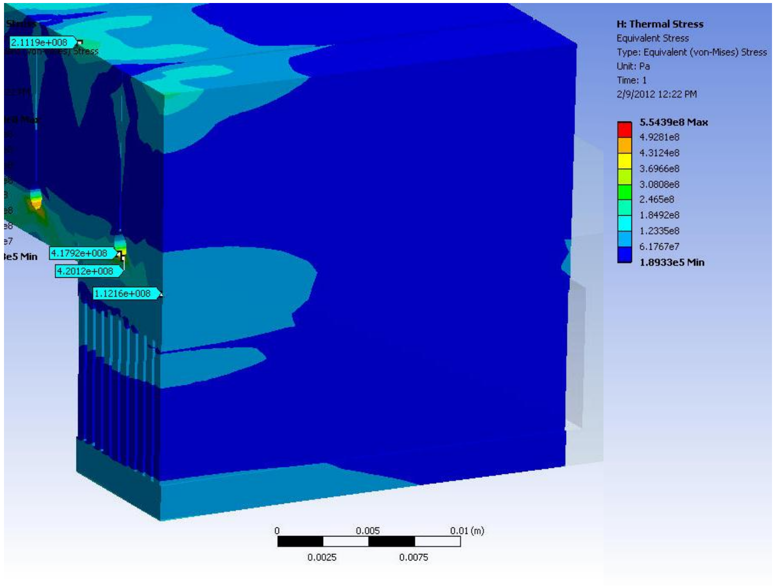
Max temp 1056°C on the beam absorbing surface

21kW of the absorbed power; 20C of water cooling temperature

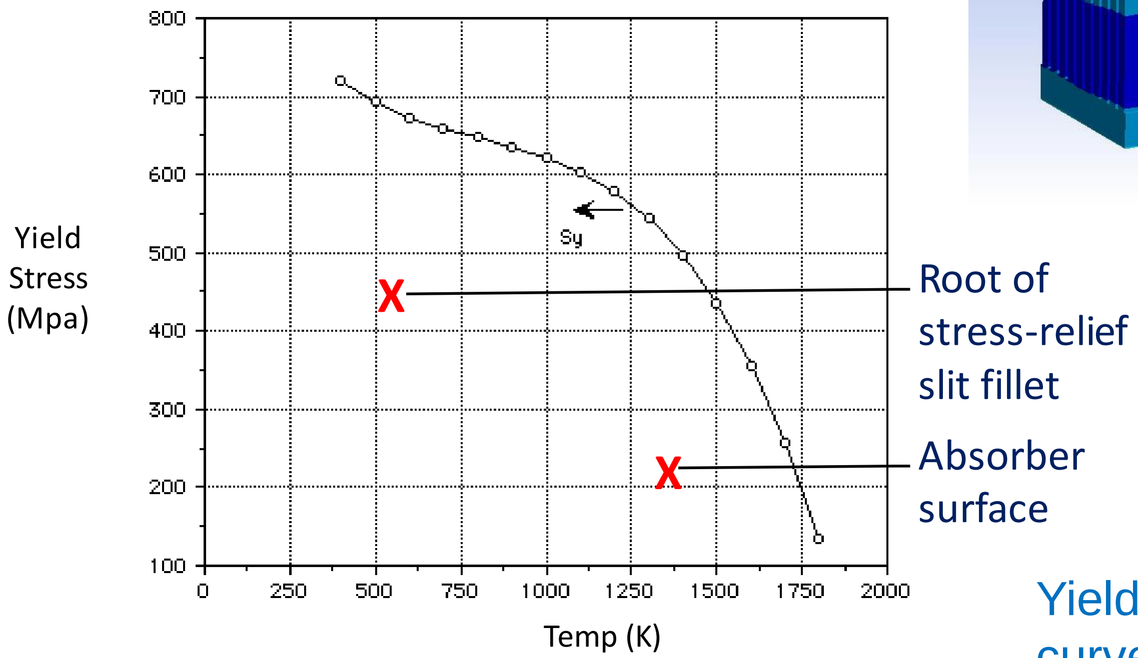
Mid-planes of absorber (symmetry boundary)

Simulations: stress

- Maximum stress is 450 MPa and is localized at the root of the relief slit
- Reasonable safety factor everywhere



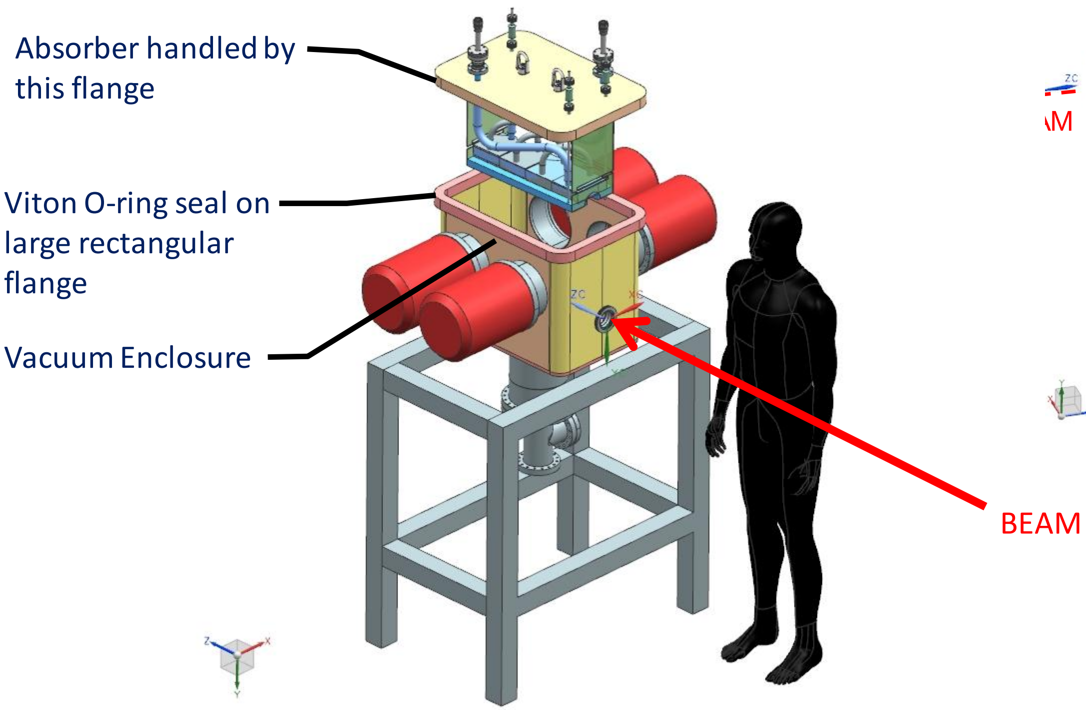
Results of stress simulation in ANSYS

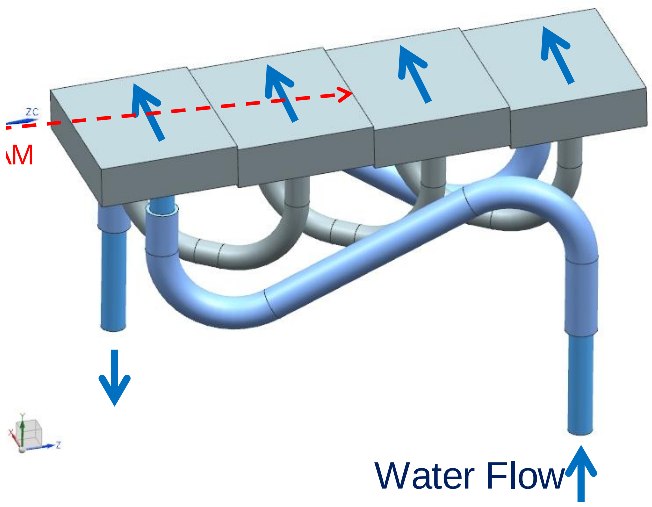


Yield stress – Temperature curve of TZM

Packaging concept

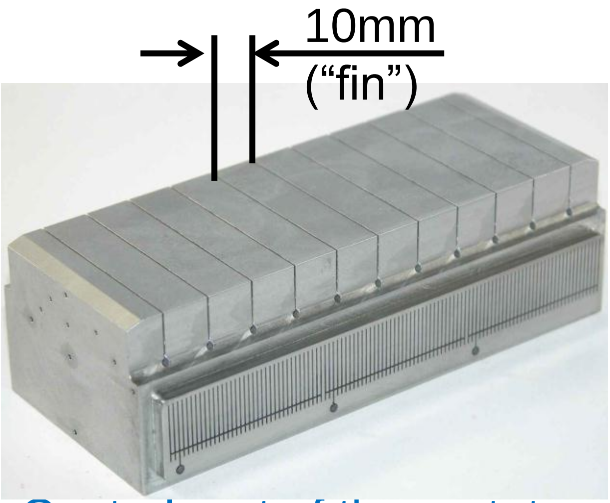
- Four identical modules
  - Simpler manufacturing and repair
- Mounted at the top flange





Absorber prototype

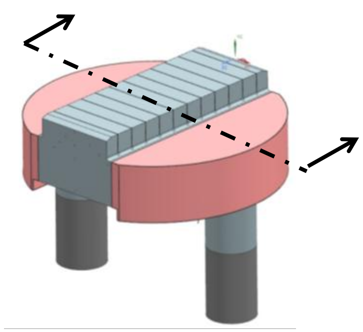
- ¼ - size prototype was designed, manufactures, and is being tested with an electron beam
- Goals
  - Go through the full manufacturing cycle
  - Test thermal properties of the TZM absorber with an electron beam at a comparable power surface density
  - Validate FEA modeling approach, investigate film boiling transition
  - Develop instrumentation
- In tests, the electron beam comes to the surface at a larger angle, ~150 mrad
  - A similar beam surface power density can be created with a significantly lower power
  - Slits suppress the longitudinal heat transfer, and tests with a beam footprint longer than one fin already make sense

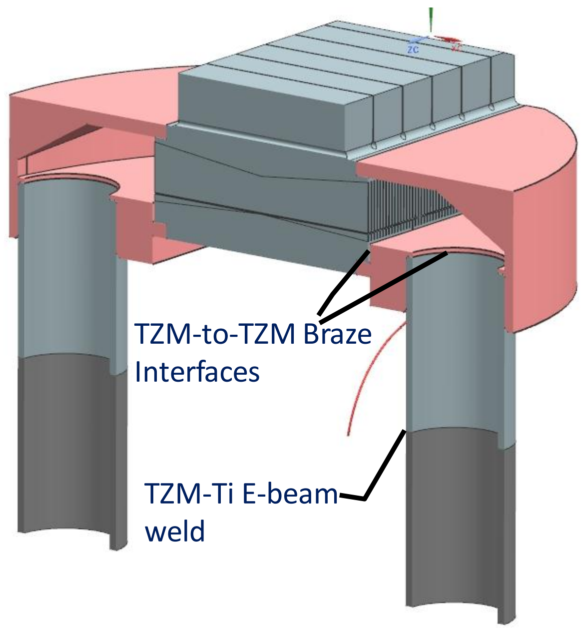


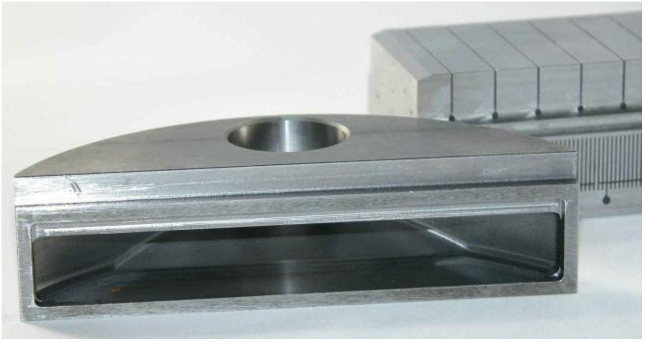
Central part of the prototype

Manufacturing

- Steps
  - Machining of TZM parts (mainly EDM)
  - TZM-to-Ti transitions (e-beam welding)
  - Two-stage brazing of TZM parts (Palcusil 25 and 82Au/18Ni)
  - Ti – to – SS transitions (roll-bonded)
  - final assembly with stainless steel structure and cooling lines



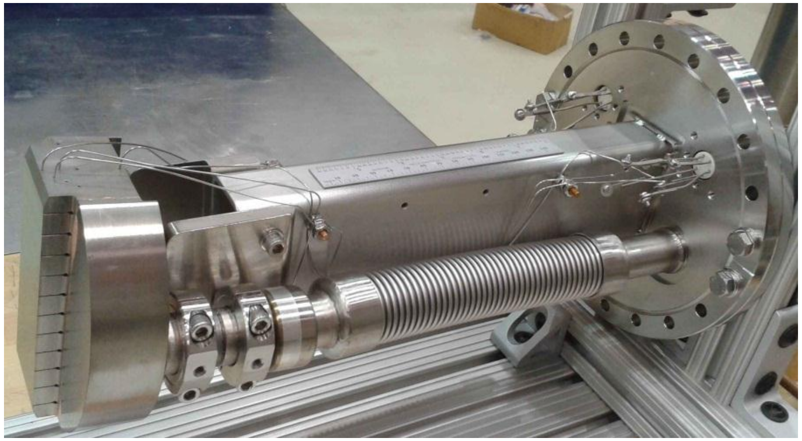


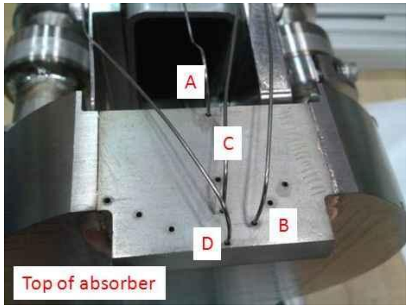


Project X

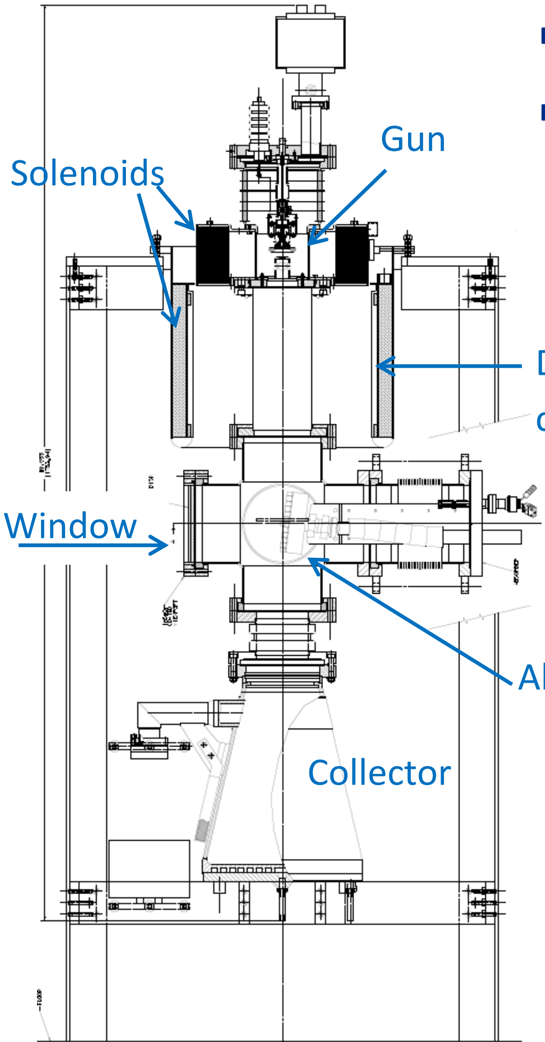
Manufacturing (2)

- Difficulties
  - Comparatively complicated production process
  - TZM is fragile and requires careful handling
  - A leak after first brazing, repaired during the second brazing
- The prototype was assembled and pressure tested
  - 6 Type-K thermocouples installed





Test bench



- Mainly parts from ECool project; in MI-31
- E-beam: 28 keV, up to 0.2A

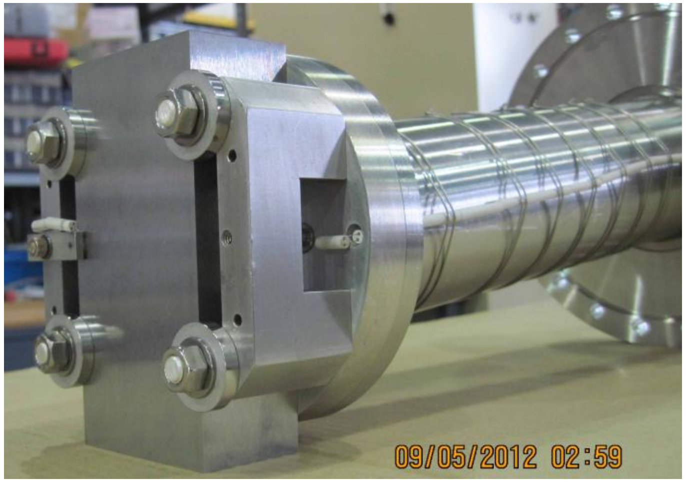
  The prototype can be moved in and out using a long bellow

  - A window gives a view of the entire surface of the prototype
    - Presently a quartz window covered by a lead glass on the air side

Photo: M. Murphy

Test stand commissioning

- The test stand was commissioned with a simple “pre –prototype”
  - A TZM brick bolted to a water-cooled pipe through a carbon foil
- Made normal number of mistakes with necessary corrections
  - Killed the cathode; the initial vacuum window was darkened by radiation; cracked the window by overheating with secondary particles; melted the TZM surface; shorted the control electrode …
  - The biggest oversight was a dramatic underestimation of the portion of the reflected power (~ 50%)
- Main results
  - Stand was commissioned
  - Unexpectedly good performance of the pre-prototype
  - Optical Transition Radiation (OTR) image is clearly visible and very helpful
  - Thermal radiation is detectable well before melting



Instrumentation

- Details on the following slides

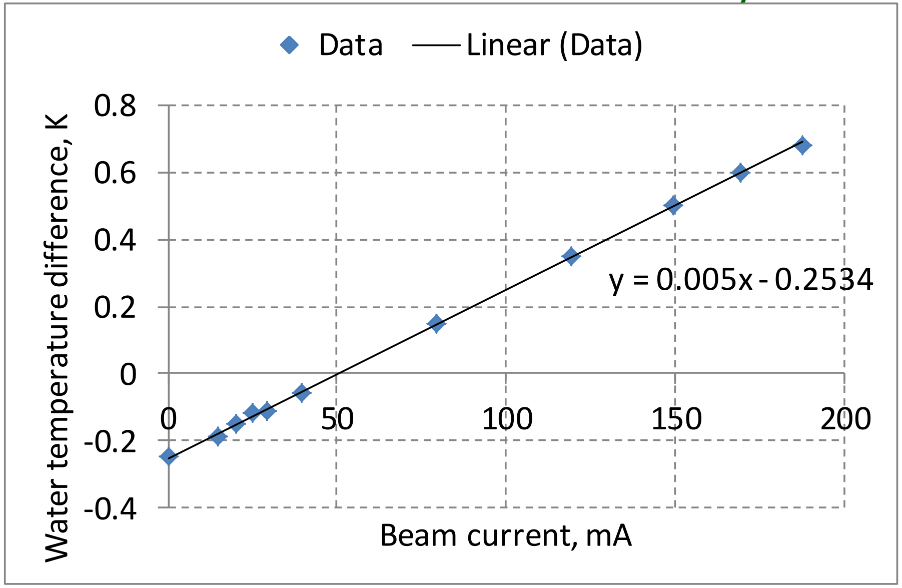
- Temperature
  - Thermocouples in the absorber, at the test chamber, and RTD (resistance thermometers) for inlet/outlet water
- OTR and thermal radiation light
  - TV camera
- Beam energy and current (HV PS readings)
  - Collector current if the beam is sent there
- Cooling water flow
  - Paddle flow meter; a vortex flow meter is being connected
- Test plate
  - Can be inserted instead of the absorber for measurements at low beam currents
  - Was used at the initial stage of commissioning

Work with prototype

- Surface conditioning
  - Cathode emission is dramatically affected by outgassing of the absorber
  - Long runs under control of a program (FSM)
  - Outgassing coefficient dropped by ~5000 times
- Calibration of dimension scaling
  - Started with dipole correctors calibrated with a test plate
  - Now using the image of the prototype with known dimensions
- Power
  - The beam power is known well, U_{PS} x I_{PS}
    - If the beam is sent into the collector, collector current is 98%, as expected due to secondary emission
  - However, power removed by secondary particles decrease the energy deposited to the absorber (“reflected power”)

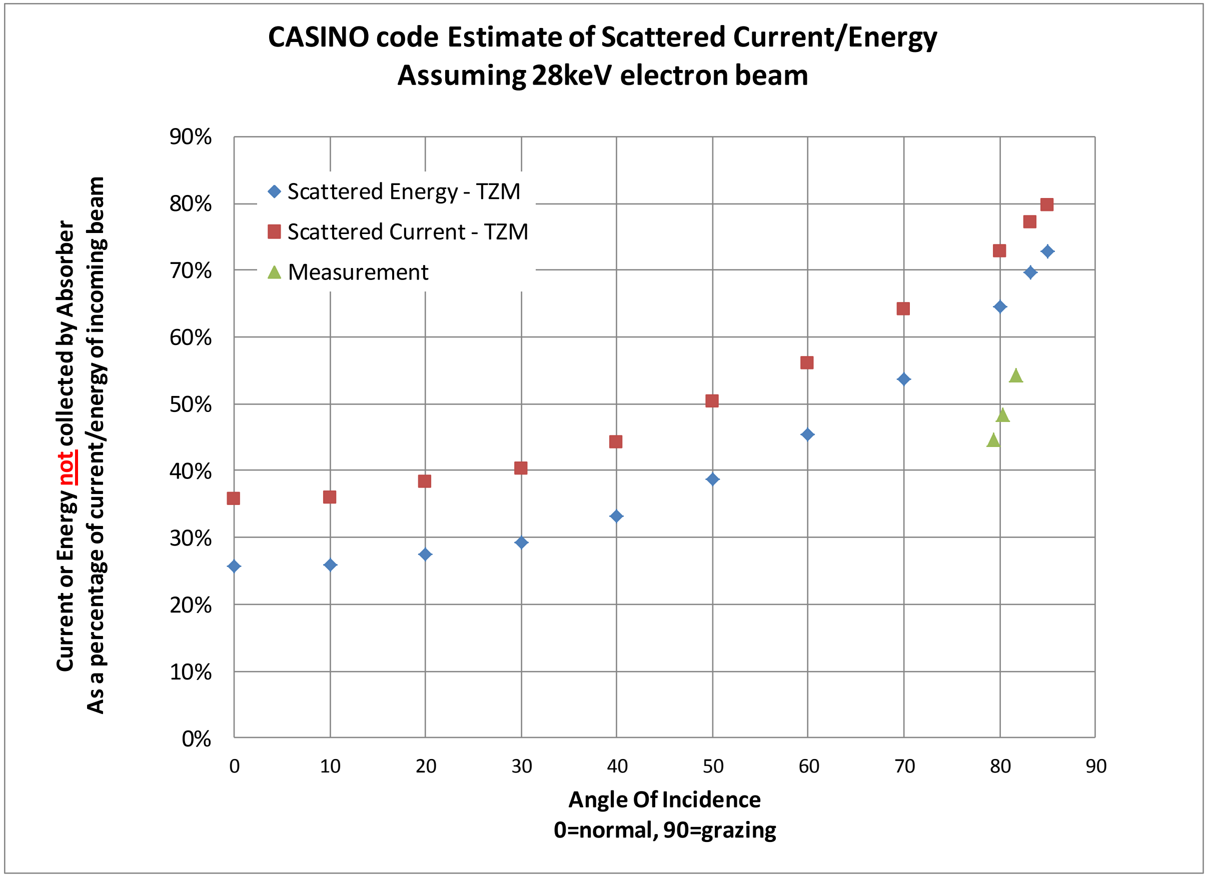
Reflected power

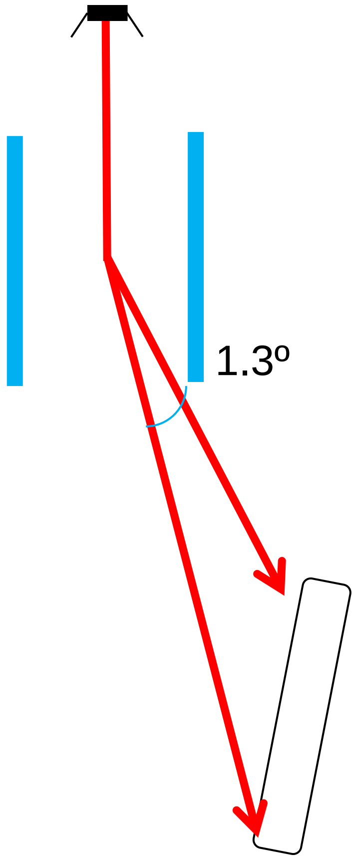
- Absorbed power can be measured from the inlet-to-outlet water temperature rise
  - Statistical and systematic errors of temperature measurements are low
  - However, calibration of the paddle flow meter is unknown and may be off by as much as 50%
    - A new vortex flow meter is installed and is waiting for connection
    - Will cross – check it by sending the beam into the collector



Measured inlet-to-outlet water temperature rise as a function of the beam current. Standard error for the slope is 0.6%.Mar-Apr 2013.

Reflected power estimate





Measurements: 1-Nov-12, 55 mA, 28 keV
Simulations: CASINO (MC code from Université de Sherbrooke, Québec, Canada, http://www.gel.usherbrooke.ca/casino/index.html)

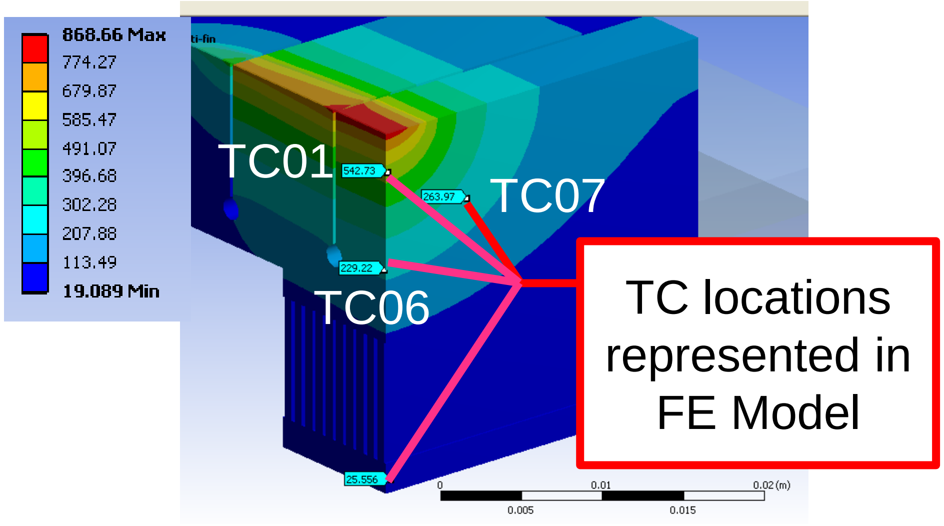
The incident angle depends on the corrector currents

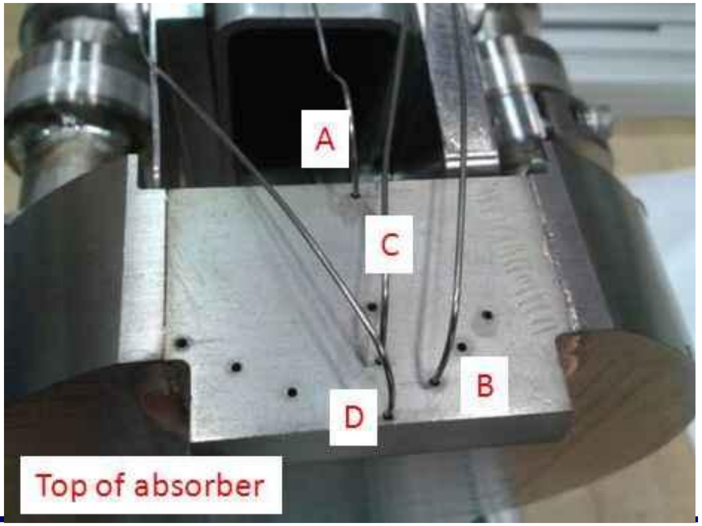
Reflected power: consequences

- Real deposited power is only 30-50% of available 5.5 kW
  - Measuring a real number within ~5% is a high priority
  - Should not be a problem to compensate by decreasing the beam size
    - The footprint is still several times longer than the fin
- Heating the test chamber
  - After installing a blower, Tmax ~ 200C @ 200mA
- Irradiating the window
  - Initially installed borosilicate viewport became brownish
  - Replaced by a quartz window
- Heating the window
  - Cracked the window because of overheating
  - Moved it further from the absorber, made an air gap between the viewport and the lead glass

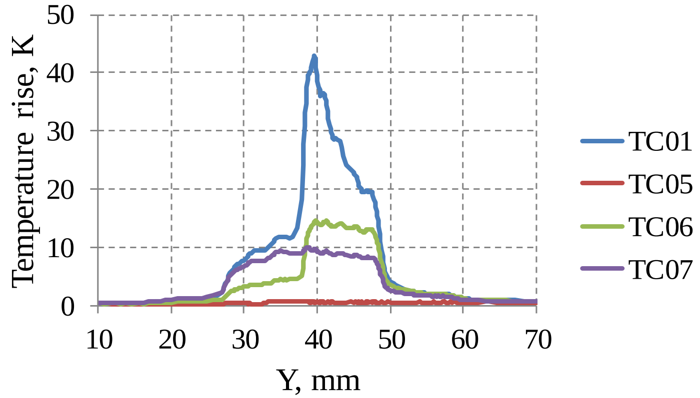
Thermal measurements

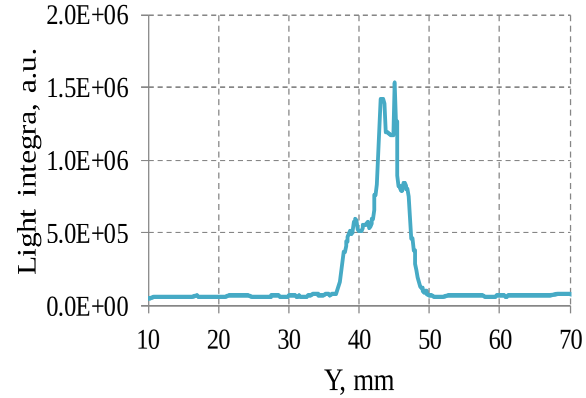
- 6 thermocouples in 3 different fins
  - Most of measurements are for fin #5, which has 4 of them
- For comparison with simulations
  - The beam size is taken from OTR images (see later)
  - Constant power density distribution is assumed





Thermocouples location test





Vertical scan of the fin #5 with a “pencil” beam. In horizontal direction, the beam is centered in the middle plane of the prototype. Left: rise of temperatures with respect to the incoming water. 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. Right: the light integral from a rectangle covering the fin #5. Peak in the center likely corresponds to thermal radiation.

- Thermocouples are in the expected locations
- The temperature reading depends also on temperature of the fin #4
  - Heat conductance along the thermocouples

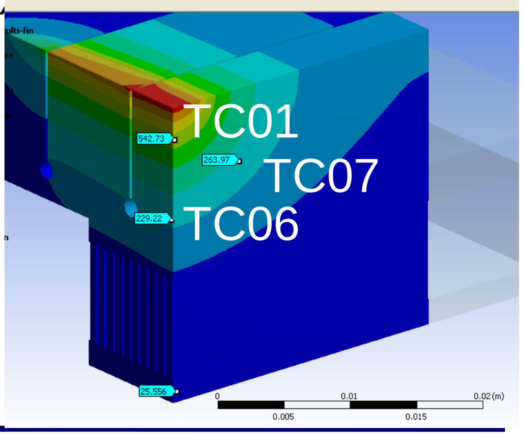
Analysis Correlation

An example correlation (2D Model, Reflection = 0.5, uniform beam, angle=155mrad)

Beam Parameters		Predicted in ANSYS				Observed at Test Bench			Discrepancy (Analysis-Measured)		
Current	Beam Radius	Tsurface	TC01	TC06	TC07	TC01	TC06	TC07	TC01	TC06	TC07
mA	mm	C	C	C	C	C	C	C			
40	1.75	340	204	119	108	216	106	83	-6%	15%	39%
80	2.75	384	250	147	132	254	133	116	-1%	13%	16%
120	4.75	285	208	133	117	196	113	104	7%	21%	15%
170	3.8	550	375	223	196	247	153	132	56%	53%	57%

March 2013 data

- Current challenges to correlation:
  - Uncertainty in absorbed energy ~30% (the driving uncertainty)
  - Uncertainty in beam distribution (primarily at low currents)
  - Thermocouple effects (longitudinal conduction)
- 2D vs 3D: 10-15% discrepancy in peak surface temperature
  - 2D model has a better representation of cooling
  - 3D model takes longitudinal effects into account
    - Thermocouple conduction and beam shape
- Overall uncertainty in surface temperature is ~50%



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

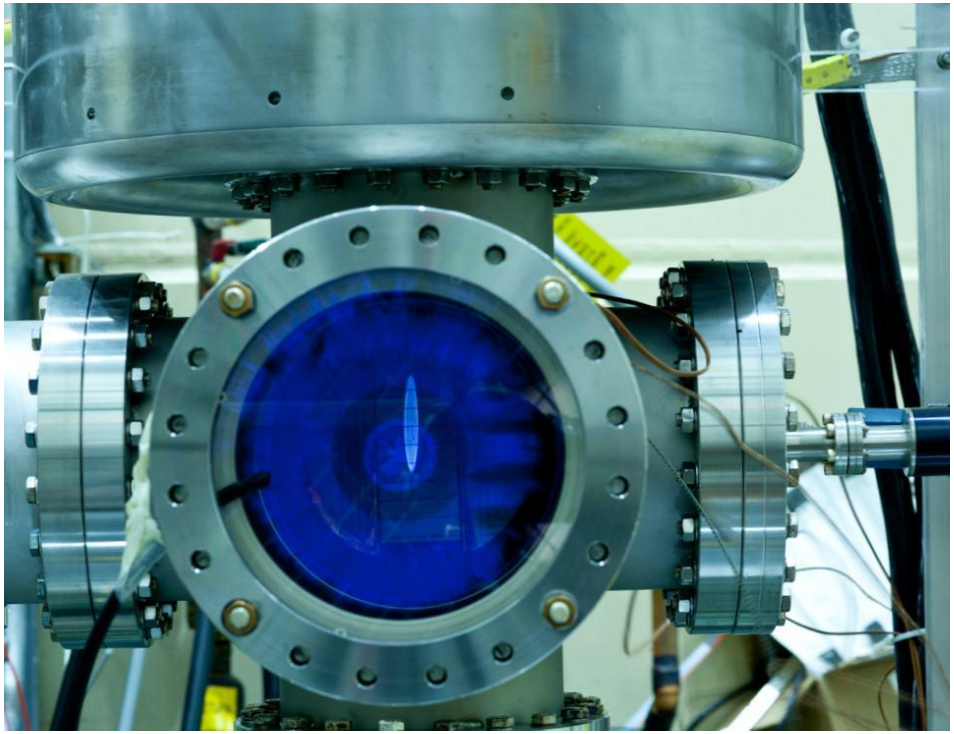
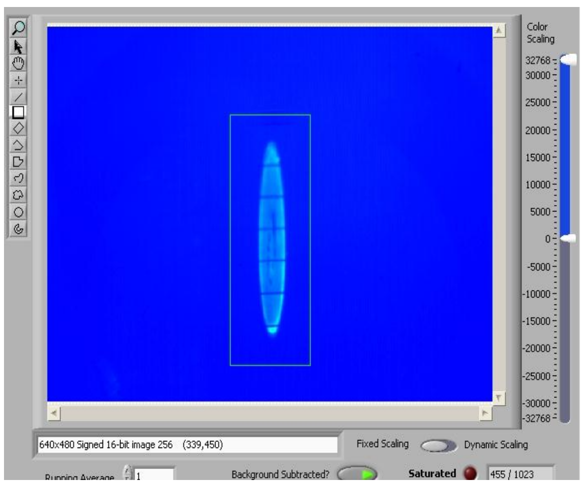
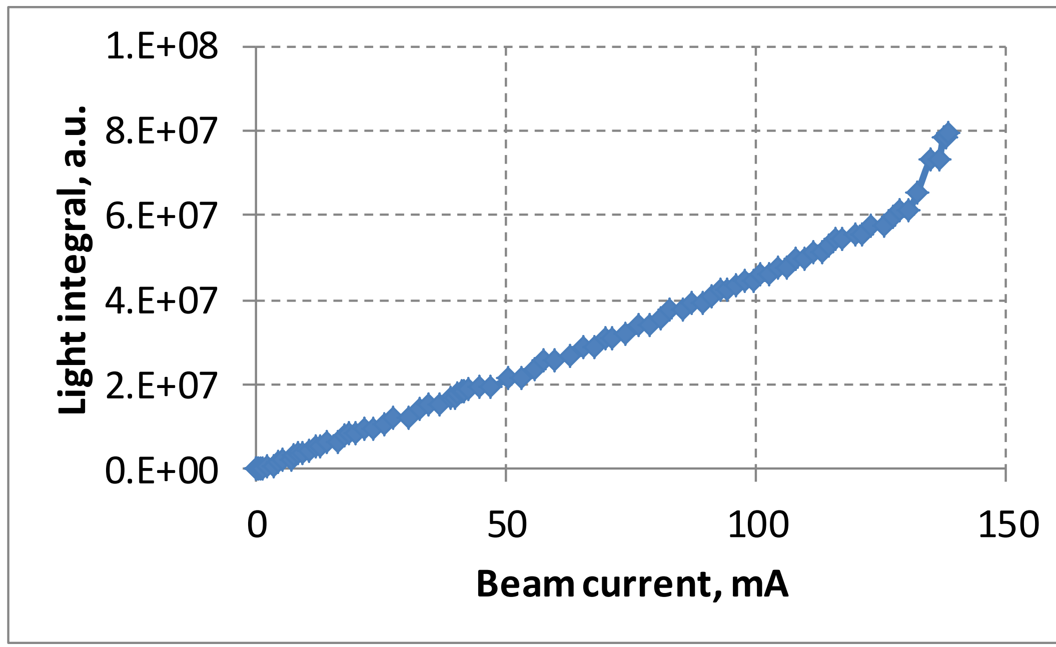


Photo of the beam footprint on the absorber prototype. White ellipse is the beam footprint, and blue is glowing at the quartz viewport.
I_e= 190mA, axes of footprint ellipse are ~50x7 mm. Incident beam power density ~20 W/mm^2.
Photo: M. Murphy

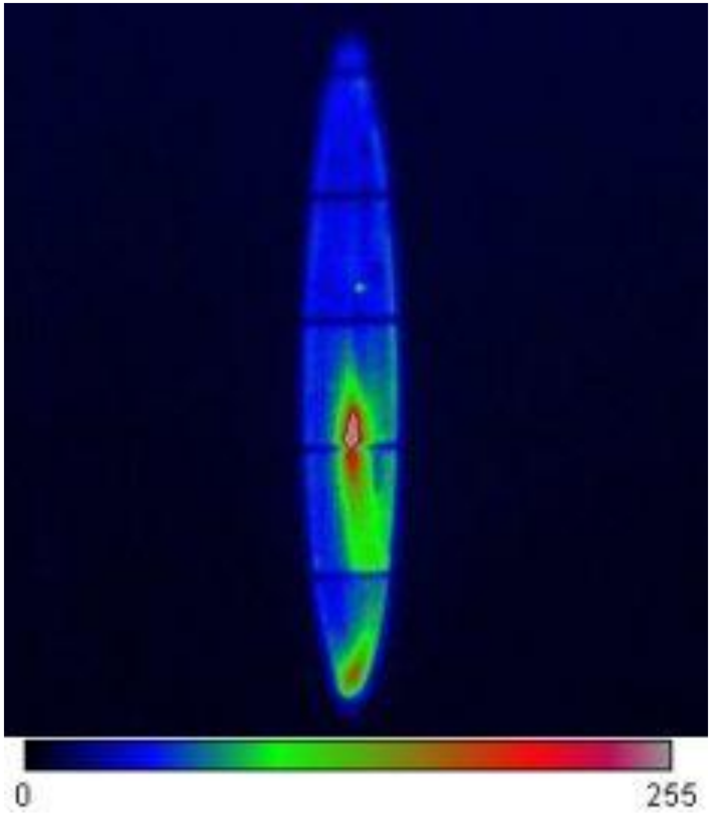
OTR vs thermal radiation

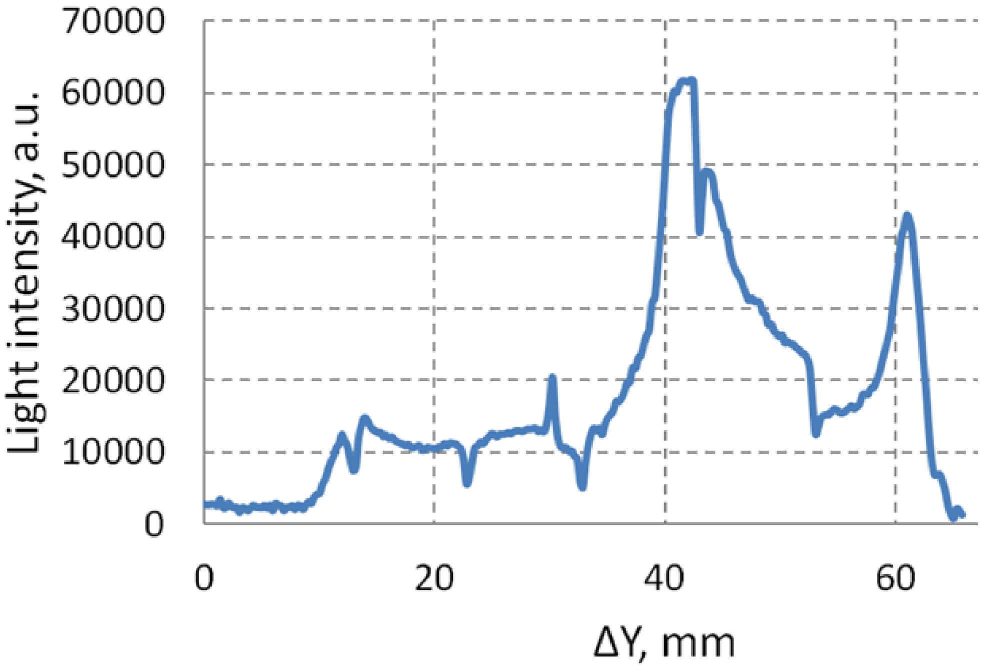
- Amount of light from a rectangle over the beam footprint increases first linearly with the beam current (OTR), then becomes non-linear and quickly saturates (thermal radiation).
  - Part of light comes from reflections





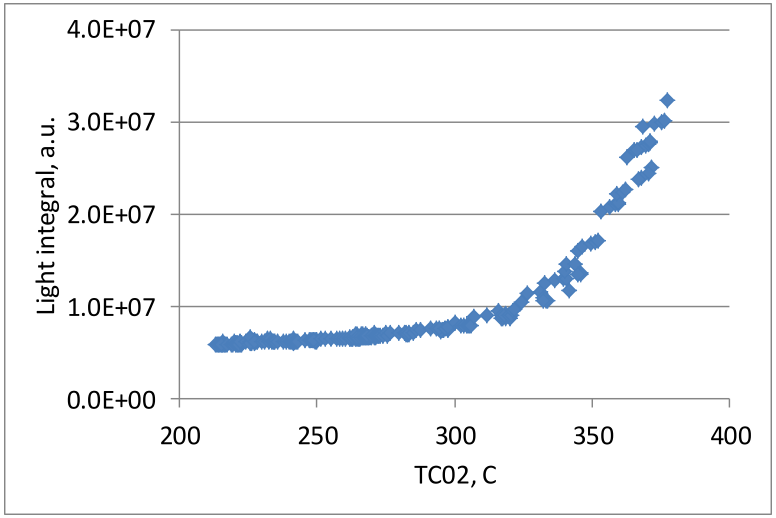
Saturated image





Beam image with saturation. Left – beam image in false colors; beam current 0.2A, beam ellipse axes are 7.4x52mm.   Right – light intensity in vertical midplane.

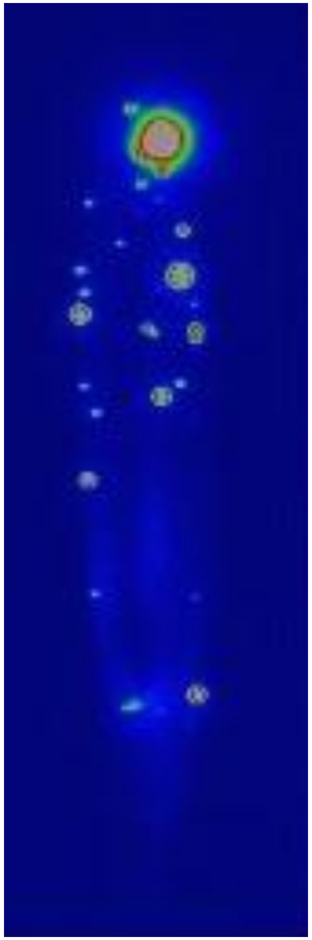
Onset of thermal radiation



Integral of light recorded from a single fin (#8) as a function of the temperature of a thermocouple placed close to the surface . The thermocouple center is located in the middle of the fin, 2.4 mm from the surface. Beam current is 0.19 A. The highest temperature is when the beam footprint ellipse was 6.4x45 mm (incident beam power density 22 W/mm^2). The curve is recorded by changing beam focusing.

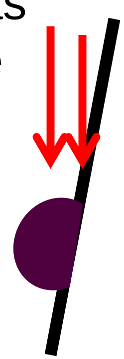
- For a large beam, both the integral of OTR light from a single fin and the temperature of a thermocouple placed close to the surface are approximately linear with amount of current coming to the fin. The resulting linearity between the light integral and the temperature breaks when camera register the thermal light
  - Can’t use to reliably estimate the surface temperature
    - The answer is determined by assumptions about the red end of the camera range
  - Plan to repeat with a narrow-band filter

“Hot spots”

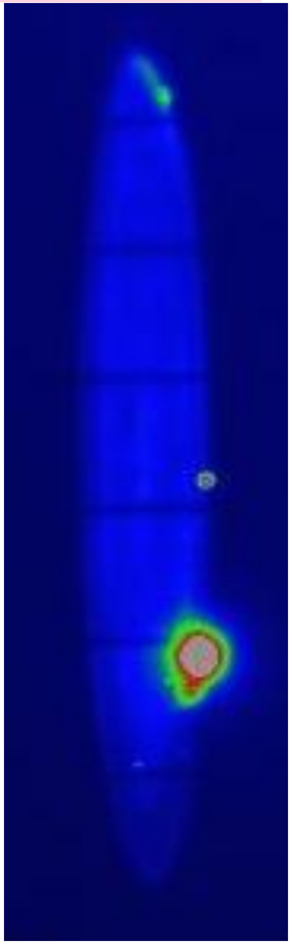


Pre-prototype; 190 mA

- There are spots on the TZM surface that start emitting thermal radiation at much lower current density that the average
  - At least, most of 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 the quality of the surface finish



- A whitish elliptical spot appeared at the prototype surface.
  - Doesn’t look like the melted area at the pre-prototype. We speculate that it might be a result of evaporating one of hot spots.



Prototype; 120 mA

Summary of the tests

- The absorber prototype was exposed to ~10 W/mm^2 and survived
  - Goal for the incident H- power density is 22 W/mm^2 ; ~25% of power is expected to be reflected => ~17 W/mm^2 for 10mA operation
  - If prototype performance is stable at these parameters, it may be used as is at PXIE up to I_{H-}~2mA
  - Hot spots and whiting discoloration are a concern
- No contradiction with thermal simulations
- OTR image is visible and very helpful
- Thermal radiation is detectable and distinguishable from OTR
- Capability of temperature sensing system is adequate for power balance measurements

Plans for the test

- Measure the absorbed energy within ~5%
  - Need a calibrated flow meter
- Make a more careful comparison with simulations
  - Beam image far from thermal emission
  - Better measurement of current density distribution
- Try to estimate the surface temperature from thermal radiation
  - Install a narrow-band filter and correlate the light integral with thermocouple reading
- After having a better idea about parameters, increase the surface temperature to ~1100C
- May decide to make thermal cycling tests
  - A failure with a water leak would kill the test stand
    - Water with glycol

Plans for absorber design

- We hope that the tests will show that this concept can be a solution for the PXIE absorber
  - Choice of TZM looks appropriate
- However,
  - Manufacturing is complex
  - If a dramatic overheating happens, a crack may go all the way to water
  - Realization that secondary particles decrease the absorbed power by ~25% may allow a simpler design
  - Pre-prototype worked better than expected
    - A good thermal contact between the TZM and undelaying water-cooled structure through a carbon foil
- We plan to consider an alternative design
  - Small TZM bricks bolted to a water-cooled body
    - Temperature drop across the contact is less important for a high surface temperature regime (in comparison with a copper absorber)

How to protect the absorber?

- An absorber failure may be catastrophic
- Typical thermal time is long (a part of a second), but how to detect a problem?
  - Water interlocks
  - Vacuum
    - After initial exposure to beam irradiation, ion gauge reading doesn’t depend on the surface temperature
  - Thermocouples
    - Fins are thermally separated; temperatures should be measured in each
    - May a problem for ~50 fins
  - Would be great to image the entire ~50cm length of the absorber
    - Turn off the beam if the integral of light from any fin exceeds a limit due to thermal radiation
    - Successfully tested with the prototype
- Possible design modification
  - Would be great if a water leak doesn’t develop at any surface temperature

Summary

- Absorber concept is progressing
  - Grazing angle, TZM, slits, steps, modular design are to stay
- Designing, manufacturing, and testing of the prototype gave a lot of useful experience and ideas
- E-beam test stand has been commissioned
  - Can be used for testing of other high power density PXIE components
- The absorber prototype is being tested at the absorbed power density comparable with that required for the MEBT absorber
  - Can be used for initial tests at PXIE
- We have a better understanding of possible diagnostics tools, procedures, and necessary protection

- Having the absorber design ready in FY14 seems realistic

List of contributors

Contributors

- B. Hanna – operation and measurements
- V. Lebedev, M. Hassan - first concept
  - grazing angle, slits, steps
- L. Prost – test stand
  - beam simulations, radiation estimations, “hot spots” analysis
- J. Walton – test stand; pre-prototype
  - Design and assembly
- K. Carlson - test stand
  - Electrical, controls
- Yu. Eidelman – material choice
  - Radiation, secondary particles
- A. Chen – absorber vauum
- R. Thurman-Keup- imaging
  - camera and its software
- L. Carmichael – conditioning program
- A. Mitskovets- test stand commissioning
- C. Exline– prototype assembly

Thanks to

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