Feasibility of a radiation-cooled scraper for PXIE MEBT

- Scrapers in PXIE MEBT
- Radiation- cooled scraper
- Test stand
- Calibration and analysis
- Data analysis
- Estimations for PXIE
- Summary

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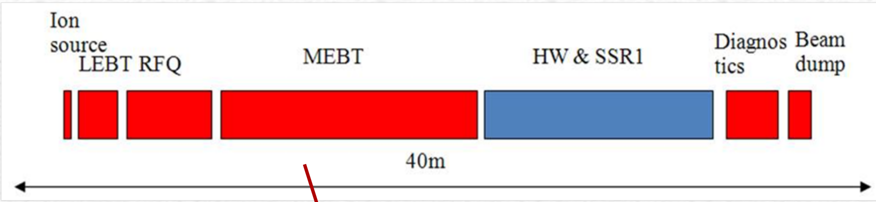
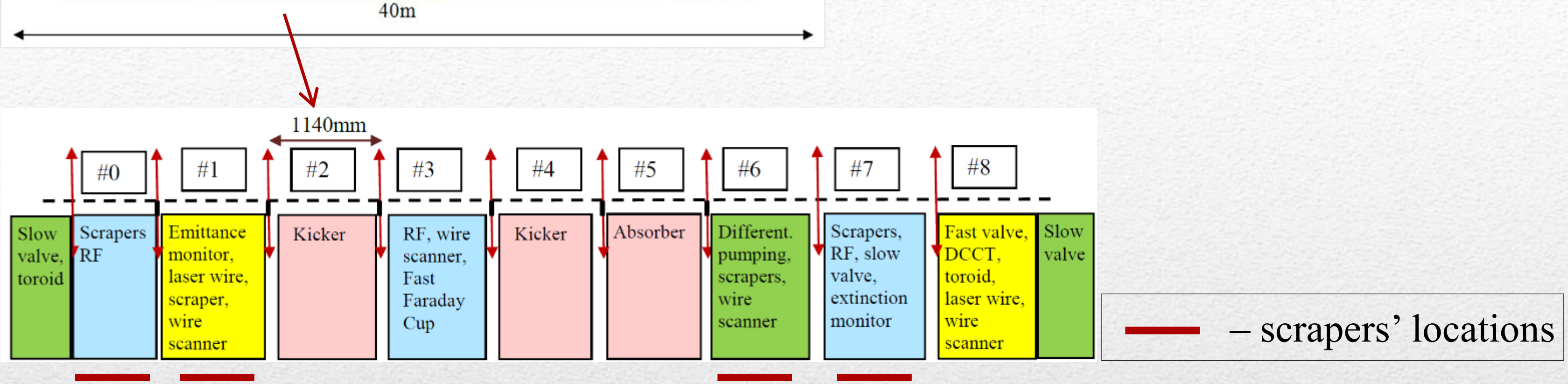
Scrapers in PXIE MEBT



PXIE is being developed to test critical concepts of the Project X front end



A system of scrapers will be used in MEBT to protect MEBT components and downstream SRF cavities

- 2 locations
- 2 sets of scrapers separated by 90º of betatron phase advance in each location
- 4 electrically isolated, movable scrapers in each set

Beam input parameters

Ion type	**H^-**
Beam current\energy	10mA \ 2.1MeV
RMS beam radius	2 mm

Number of scrapers	**16**
Maximum average power per scraper	20-200 W (0.1-1%)
Electrically isolated	

The least expensive solution: a radiation- cooled scraper

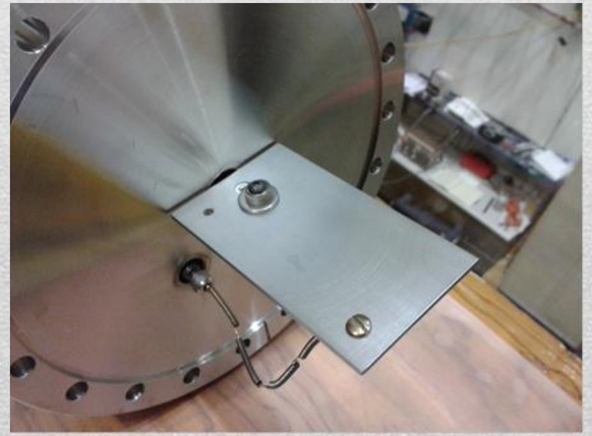
A rough estimation of a steady state temperature: $W_{absorbed} = \varepsilon\sigma T^4 \cdot 2S$

ε – emissivity, $S = 45\ cm^2$ – scraper area

$W_{absorbed} = 100\ W$
$\varepsilon = 0.1$
$\Rightarrow$ In steady state: $T_{ss} = 1200\ K$

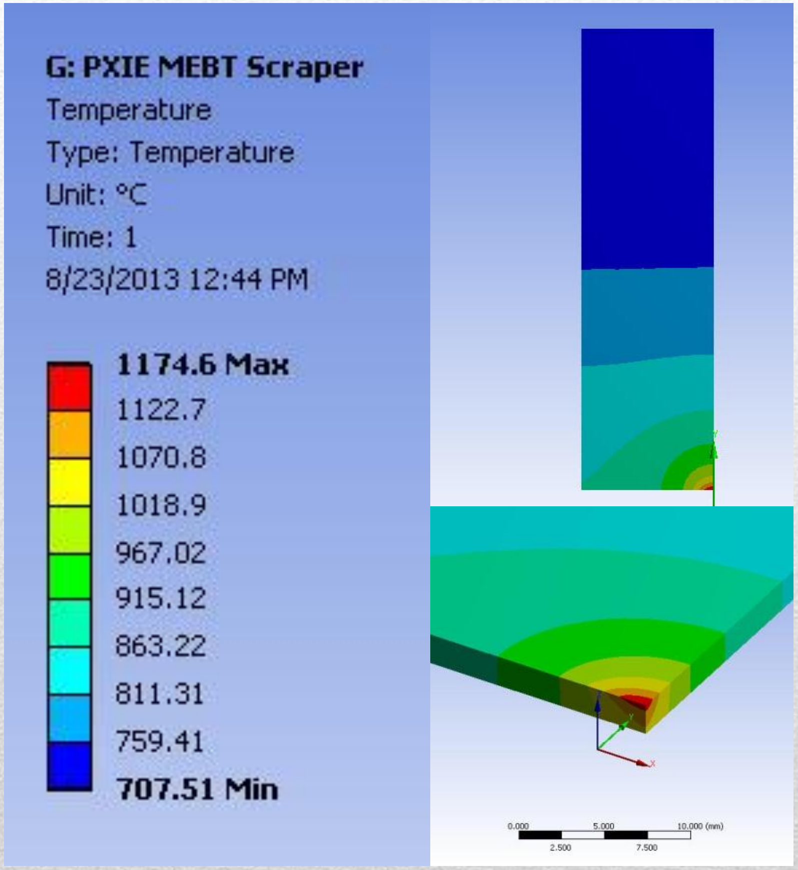
Might be feasible to use such scraper in PXIE

The biggest uncertainty: emissivity
- Can range from 0.05 to 0.2 depending on temperature and surface preparation



For estimations, dimensions of a TZM plate installed at the e-beam test stand are used (3.5”x 2”x0.08”).

Scraper thermal regime for the PXIE case was simulated in ANSYS by Curtis Baffes.



Simulated temperature distribution.
Half of a plate is shown. 3D.

Simulation parameters:

- Beam current: 10 mA
- Beam energy 2.1 MeV
- $\sigma_x = \sigma_y =$ $2\ mm$
- Distance between the beam center and scraper edge 2.75σ = 5 mm
- Emissivity 0.1
- Power absorption 100%
  - absorbed power 63 W
  - Peak power density ~18 W/mm^2

Results:

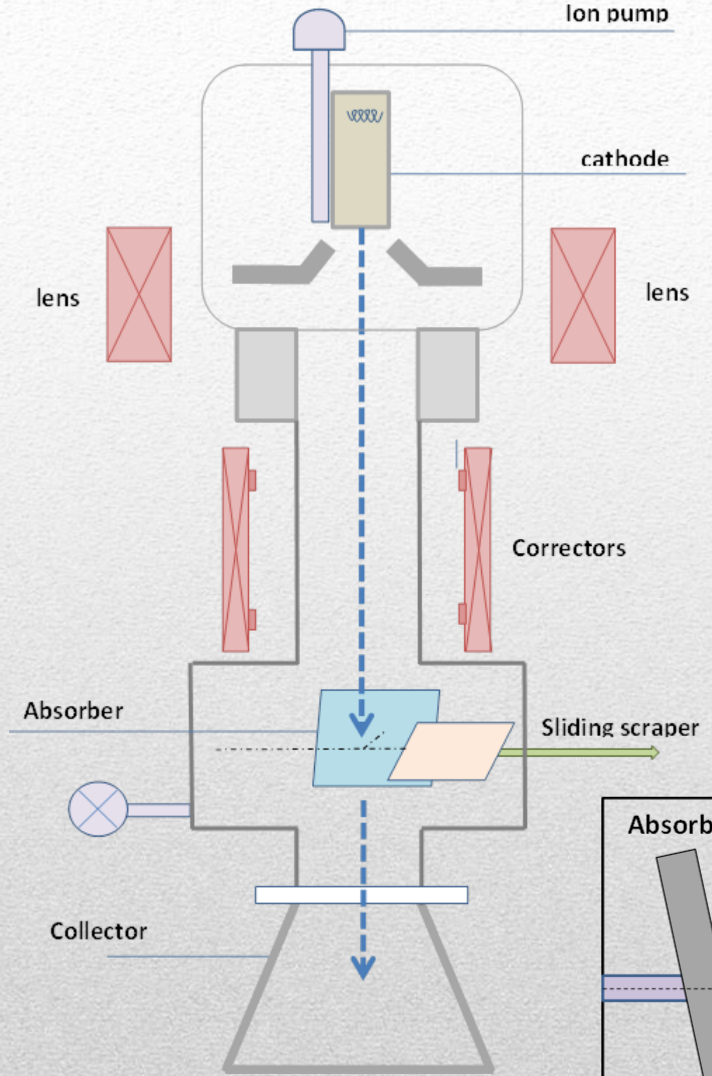
- Maximum temperature is ~1200 ºC
  - The softening point of TZM is ~1300°C; we shouldn’t go much higher
- Mechanical stresses are low in the beam interaction region

ANSYS simulation for PXIE case

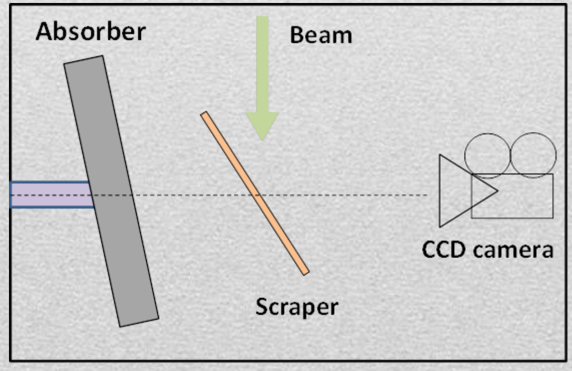
- The scraper prototype was tested at the electron beam test stand
  - Developed for testing of the absorber prototype
  - 27.5 keV, 0.1 – 200 mA DC electron beam
  - Capability to adjust the beam size and position at the scraper location
- Reasoning
  - Attempt to estimate emissivity from experimental data
  - Get “feels” for scraping of a high power density beam
  - Develop diagnostics tools suitable for using at PXIE
- Difficulties
  - Power absorption coefficient for electron beam is unknown
  - No direct temperature measurements

- A C++ code was written for simulations of the thermal regimes in 2D
  - Good agreement (~10K) with ANSYS (performed by C. Baffes) at large beam radius
  - Allows fast estimations at various emissivity values
- A MathCad code for 1D (axially-symmetrical) initial estimations

Testing with an e-beam



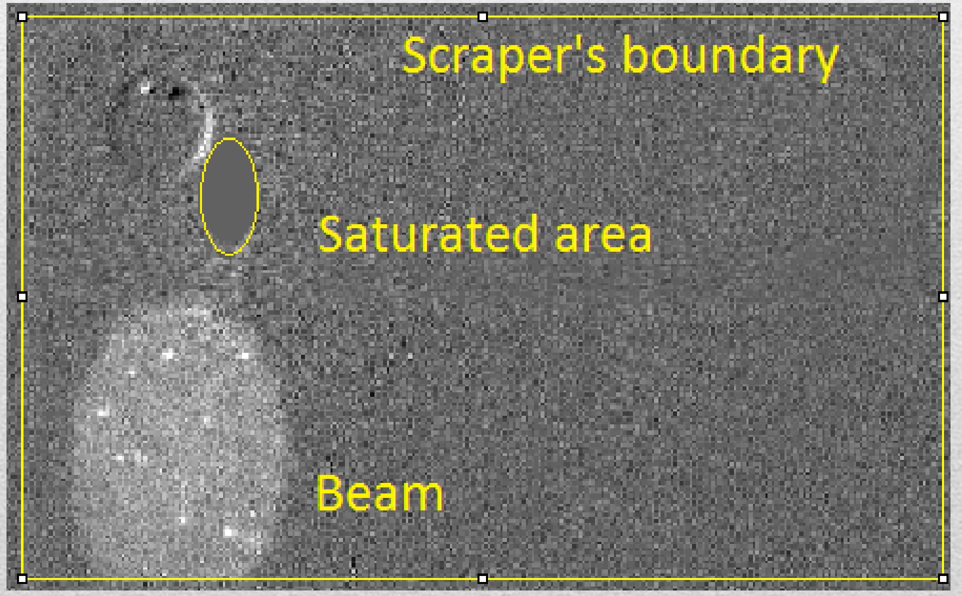
- E-beam
  - Can be moved and focused with two solenoids and a pair of dipole coils
- Absorber prototype
  - Water cooled; equipped with thermocouples
  - Angle between surface and beam is ~9°
  - Molybdenum alloy TZM
- Scraper
  - 88.9 X 50.6 X 2mm TZM plate
  - Angle between surface and beam is ~30°
  - Electrically isolated to measure the current
- CCD camera
  - Image is a combination of Optical Transition Radiation (OTR) and thermal radiation



  - Program for the camera was provided and modified by R. Thurman-Keup, and filters by V. Scarpine

Test stand

- The first set of measurements was made to estimate the emissivity
  - Large-size, low-power beam
- At low power density and short (~seconds) exposure time, the image is dominated by OTR
  - Used to estimate the angle between the surface and the beam
  - Measurement of the beam size and position
- Unexpected difficulty: a high-intensity light from the cathode
  - Saturates the image
  - Makes less reliable a background subtraction
  - Had to move the beam as far as correctors allowed



OTR image of a low-power beam.
27.5 keV, 5 mA. Beam exposure time ~1 sec. The measured beam diameter is ~8 mm. The peculiarity in the left upper corner is a SS screw for electrical connection. Background with no beam is subtracted. No filters.

The surface temperature can be reconstructed from the thermal radiation using Planck's law. In its short-wavelength limit, the Wien's distribution, the light intensity is $I(\nu,T) = \frac{2h\nu^3}{c^2} e^{\frac{-h\nu}{kT}}$

To exclude dependence of camera's sensitivity on wavelength, a narrowband red filter was installed, so that the camera reading is

$$I_C(T) = I_0 e^{\frac{-T_{eff}}{T}} \quad \text{with} \quad T_{eff} \equiv \frac{h\nu}{k_B} = 20350\,K$$

- I_0 is difficult to calculate directly
  - Has been deduced from previous measurements with the absorber prototype, which is equipped with multiple thermocouples. However, inconsistencies found later in the camera program created significant uncertainty in the value.
  - In analysis below was used as a fitting parameter

Image at steady state at the same beam parameters. Background with no beam is subtracted. The image is recorded with a narrow-band (40nm) red filter (707nm).

- Two types of data were compared with simulations by the C++ code
  - Spatial distribution of temperature in a steady state
  - Temporal dependence of light intensity during cooling after turning the beam off
  - Distributions were analyzed at beam currents of 5mA and 4mA
- Heat loss through the holder was neglected in simulations
  - Upper estimation (assuming the holder temperature of 300K and the plate's ~1000K) gives the heat flow ~7 W
  - Modifications of the temperature distribution in area accessible to optical measurements are negligible

Data analysis

Simulated scraper thermal regime

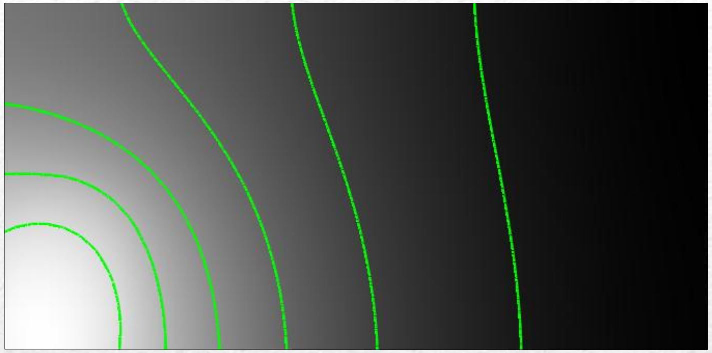
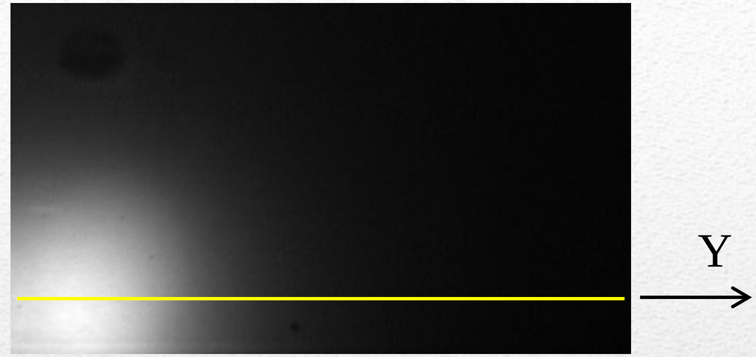
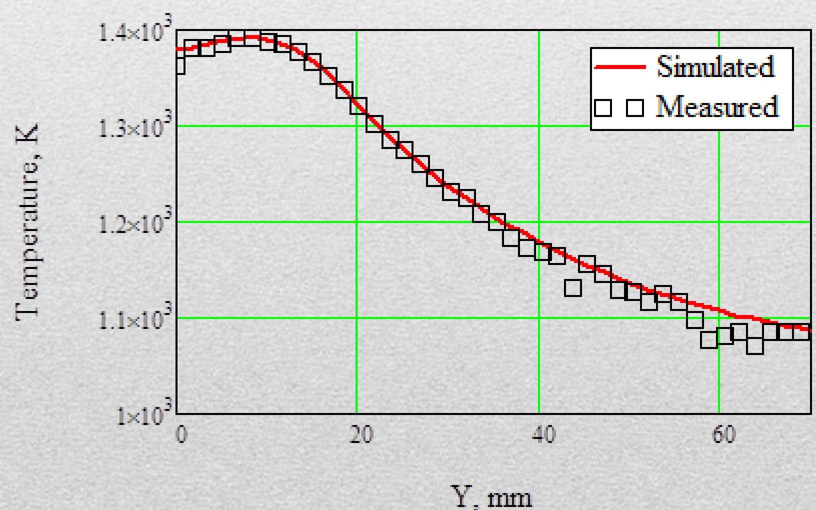


Image recorded for the same parameters



- The intensity distribution was taken along the yellow line

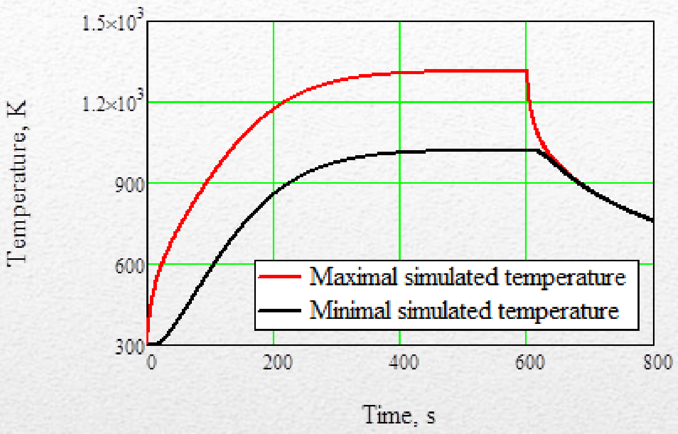


Measured curve was converted into the temperature and compared with simulated one using as fitting variables the power reflection coefficient, emissivity, and intensity calibration coefficient I_0.

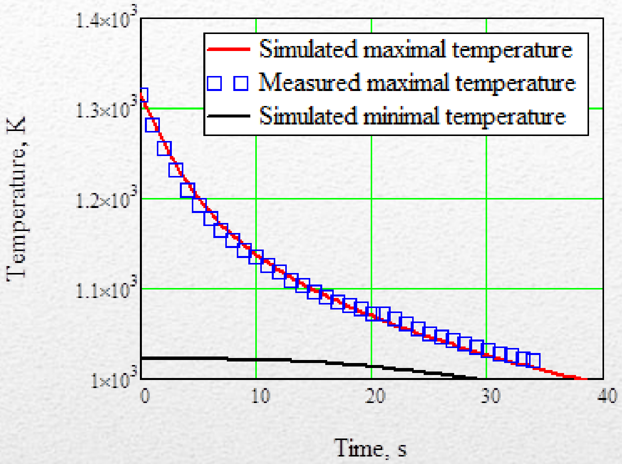
Fitting of intensity measured in steady state to temperature distribution simulated with a C++ code. Red filter; 5mA, 8 mm beam. Case of emissivity of 0.11 is shown.

Spatial distribution

Comparison of simulated and measured curves



Comparison of simulated and measured curves



27.5 keV, 5 mA.
Beam diameter is ~8 mm.
Emissivity: 0.12
Power reflection: 0.2

- The intensity was measured in a small rectangle inside the beam where the temperature is maximal and nearly constant across that area.
- Several sets of the variables produce similar fitting.

k **(power reflection)**	0.0	0.1	0.2	0.3
ε	0.11	0.12	0.13	0.14
T_{max}, K	1446	1368	1292	1215

- The measured secondary emission is ~50 %, hence it's reasonable to expect power reflection < 0.5
  - C. Baffes' simulation with CASINO code for 30º: ~0.3. Note that for the absorber prototype (9°), the code predicted the value higher that was measured

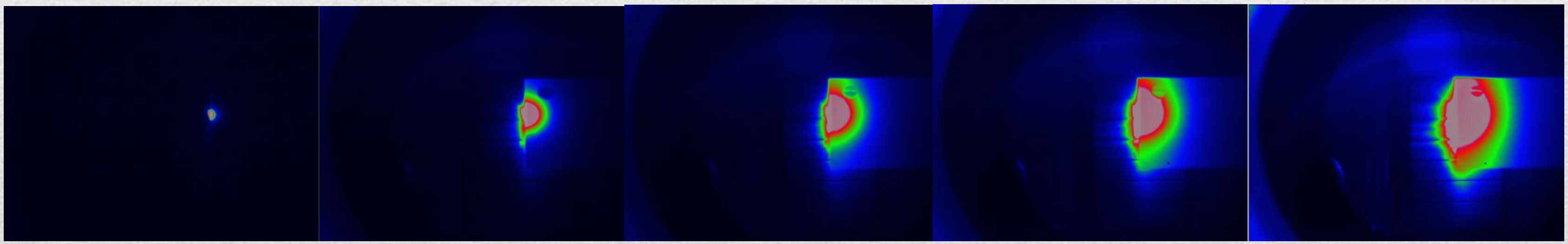
- For power reflection of 0.2 – 0.3, fitting gives emissivity of 0.13 – 0.14

- This fitting gave significantly higher temperatures than using calibration found in the absorber prototype measurements
  - May be related to modification of the program recording the images from camera

Preliminary summary

- To model scraping of a high-power beam, electrons were focused into ~ 2mm radius spot, and the scraper was moved into the beam
  - 27.5 keV, 80 mA
  - Cutting out up to 6 mA; steady state recorded at 5mA, i.e. ~140 W of incident power
  - Manual adjustments of the beam position were used to compensate the thermal expansion
- No visible damages were observed at the plate

Scraper heating

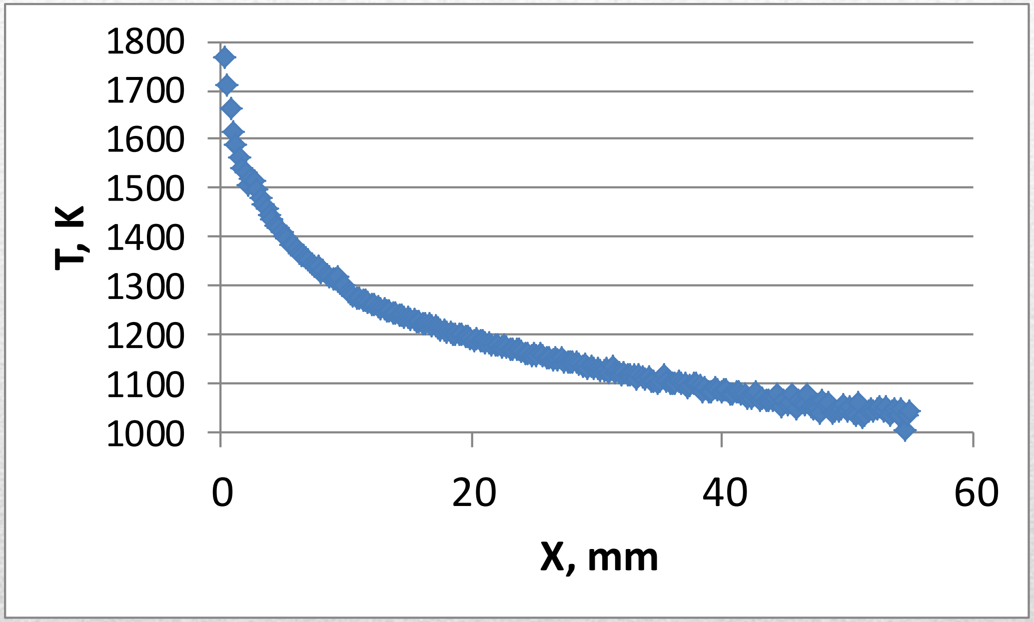


0 1 2 4 7 minutes

- The heating process takes several minutes ⇒
- The scraper seems to be stable against unpredictable current fluctuations

Modeling a scraping regime

- To reconstruct the light intensity distribution, images were recorded at the same beam parameters and three filter combinations
  - Red filter; red filter + 10% neutral filter; red filter + 1% neutral filter
  - Extends the small dynamic range of the camera



Reconstructed temperature distribution along the center of the plate. Digitization of images with three filter combinations. Calibrations are taken for the case of emissivity of 0.13 and power reflection coefficient of 0.2.

- Complication in using a radiation – cooled scraper: thermal expansion
  - Scraper edge moves into the beam when temperature increases
  - Was observed in measurements

Thermal expansion coefficient:	$5.3 \cdot 10^{-6} - 5.7 \cdot 10^{-6}\ K^{-1}$
Scraper length:	$88.9\ mm$
Temperature change:	$\sim 1000\ K$
Expansion:	$\sim 0.5\ mm$

In ANSYS simulation made by Curtis Baffes for the PXIE case (63W scraping), the thermal expansion is 0.4 mm.

- Can be counteracted by a feedback system moving the scraper according to intercepted current
  - For PXIE parameters and 0.1 mm step size used at the test bench, results in ~20% uncertainty of the scraped current
- May be addressed by a more complicated design of the holder

Thermal expansion

- Estimations and numerical simulations show that a radiation – cooled scraper is feasible for PXIE MEBT parameters
- Tools to analyze the surface temperature by intensity of thermal radiation were developed
  - The work helped to reveal inconsistencies in the camera program
  - There is a disagreement of a found calibration coefficient with the previous data from the absorber prototype. The absorber measurements will be repeated with the corrected program
- Developed 2D simulation code helped with fitting the data
- Data are consistent with the emissivity of 0.12 – 0.14
  - Corresponding power reflection coefficient 0.2 – 0.3
- In tests with scraping of a high-power density beam, ~100W was intercepted by the beam edge with no visible damage
  - Uncertainty with scraper edge position caused by thermal expansion should be addressed in the design of the scraping system
  - The scraper is error – tolerant. Long heating time (minutes) and high melting point allow wrong beam steering without damaging the scraper
- A radiation – cooled TZM plate is a plausible candidate for PXIE MEBT scrapers at the absorbed power ~50W

Summary

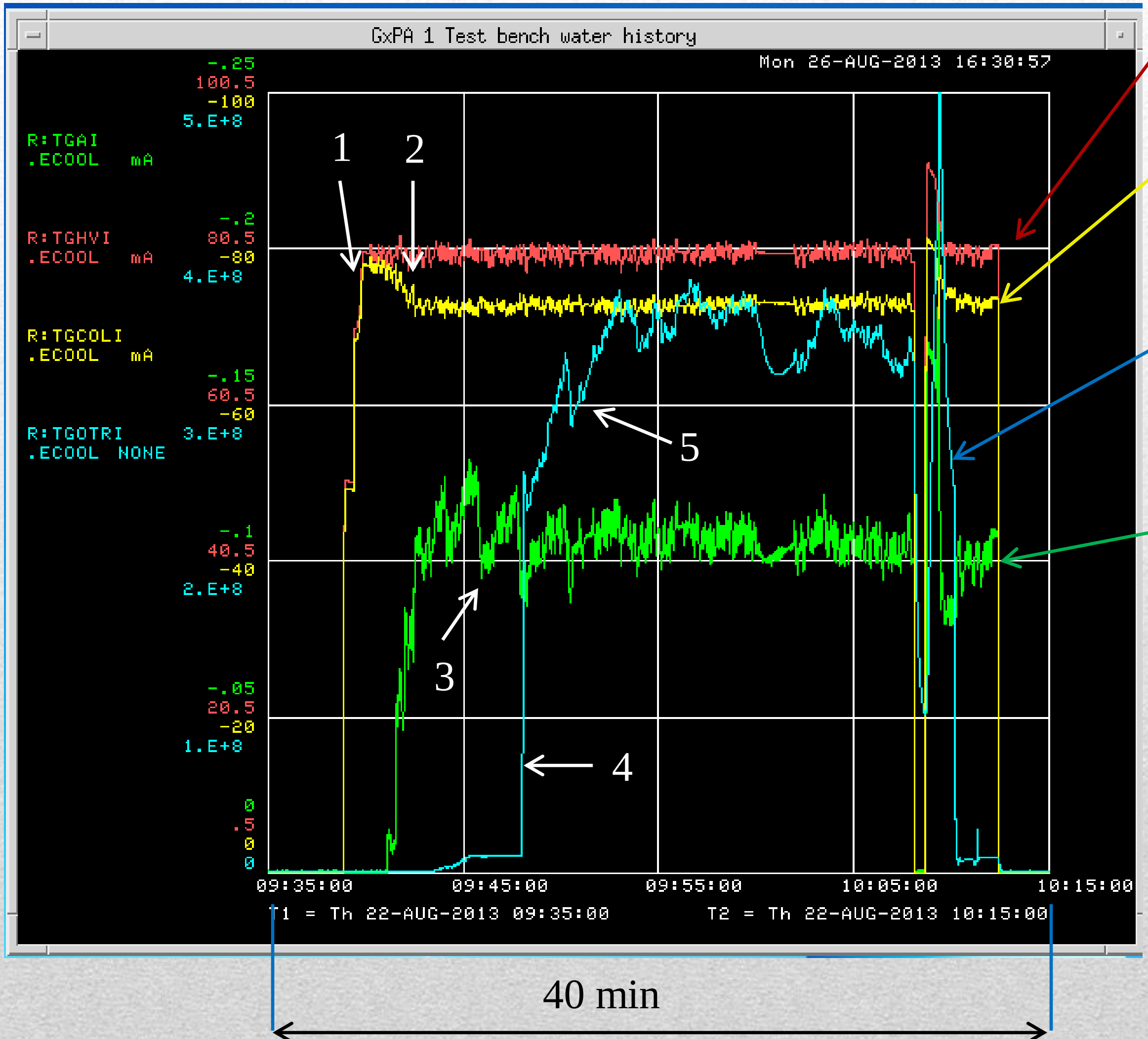
- Thanks to people who contributed to this work:

- Curtis Baffes
  - discussions of the concept and results
  - design, manufacturing, and assembling of the TZM plate
  - ANSYS simulations
- R. Thurman-Keup
  - Setting up his image – recording program and adjusting it to needs of this test
- L. Prost and B. Hanna
  - Participation in part of measurements
- V. Scarpine
  - Sharing optical filters and information about camera
- Many people who set up and helped maintaining the test stand

Acknowledgments

Example of a run with scraping of a high power density

1- beam is turned on; FSM starts to regulate the beam current
2- scraper is moved in
3- beam position is adjusted to keep the scraped current at ~4 mA
4- rectangle is adjusted to enclose the entire scraper
5- light intensity increases due to heating



D44 data. 27.5kV, 80mA. Scraped current~4mA. Red filter.

Example of a run