MEBT Absorber
Design Status Update

Project X Technical Meeting, 14-Feb-2012
C. Baffes, A. Chen, A. Shemyakin
PX Doc DB ID: Project X-doc-991
MEBT Chopper Absorber Design Status Update

• Background and Blistering Concern
• Preliminary Thermal Analysis of a TZM Absorber
• Mechanical Packaging Concept
• Next Steps
Background: Absorber Configuration

Functional Specifications Document:

Key Driving Absorber Requirements
- 2.1MeV Ions
- 21kW maximum absorbed power
- Beam size: $\sigma_x = \sigma_y = 2\text{mm}$
- 650mm maximum length

Key Derived Parameters
- 0.029rad grazing angle
- $\sim 22\text{ W/mm}^2$ maximum power density of the face of the absorber
Background

• In November, we presented thermal analysis for a Copper beam absorber
  

• It was pointed out to us (by V. Dudnikov) that beam-induced blistering could be a concern

• We have investigated blistering, and have found that it is likely a show-stopper for a Copper absorber design

• This has motivated us to change the proposed absorber material to a Molybdenum alloy (Mo TZM)
Blistering Mechanism

- Hydrogen ions are implanted beneath the surface of the metal by the beam
- Ions coalesce into pockets of gas beneath the surface
- High pressure builds up in these gas pockets, and they rupture
  - Surface is roughened and eroded
  - Debris is generated
  - Vacuum bursts occur as individual gas bubbles rupture

Blisters in Cu irradiated by 190keV proton beam, ref [1]
Existing Data

- A literature search was done to look for relevant data
- A list of the most relevant references may be found here: [https://projectx-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=989](https://projectx-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=989)
- Data is most available for beam at normal incidence with $E \leq 200 \text{keV}$
  - Our beam is 2.1MeV incident at a steep angle ($\sim 0.029 \text{ rad}$)
  - Particles will travel of order 20um along the beam direction, and end up at a depth (from the surface) of $\sim 0.6 \text{um}$
  - “Effective energy” with the same implantation depth at normal incidence is $\sim 100 \text{keV}$
- A wide variety of test conditions in the literature makes direct comparisons to existing data challenging
Blistering Trends

• In general, blistering is more severe when...
  • Current density is high
    • Less time for diffusion/desorption to occur
  • Particle energy is low
    • Implantation depth is lower, so imposed gas concentration is higher
    • Blistering effects are well documented in the 1keV-200keV range
  • Hydrogen solubility and diffusion rates of the target metal are low
  • Metal temperature is low
    • diffusion rate of gas increases with temp.
  • Metal surface is smooth
    • less free surface area for gas desorption
Particle Fluence

- For this absorber we expect (at the center of the beam profile):
  - Particle fluence $7.2 \times 10^{19}$ particles/m$^2$/s
  - Current density 11 A/m$^2$
  - (Above is based on Functional Specification values of 10mA max current, $\sigma_x = \sigma_y = 2$mm, derived grazing angle of .029rad)

- Our current density is comparable to what’s in the literature, but our total particle fluence is very high

- Blistering threshold for Cu: $1-4 \times 10^{21}$ particles/m$^2$ [1]
  - We would reach this in less than 1 minute
  - This motivates a search for other materials
## Qualitative Material Comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>Blistering Threshold*: (particles/m²)</th>
<th>Thermal Conductivity (W/m °K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>~2E21 [1]</td>
<td>400</td>
</tr>
<tr>
<td>Tungsten</td>
<td>~3E22 [1]</td>
<td>175</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>&gt;2E23 [3]</td>
<td>140</td>
</tr>
<tr>
<td>Pure Iron</td>
<td>~1E24 [1]</td>
<td>80</td>
</tr>
<tr>
<td><strong>Mo TZM</strong></td>
<td>&gt;1E24 [3,4]</td>
<td>125</td>
</tr>
<tr>
<td>Palladium</td>
<td>~2E24 [1]</td>
<td>70</td>
</tr>
<tr>
<td>Vanadium</td>
<td>&gt;1E24 [1]</td>
<td>30</td>
</tr>
<tr>
<td>Tantalum</td>
<td>&gt;2E24 [1]</td>
<td>57</td>
</tr>
</tbody>
</table>

*This comparison is somewhat dubious, because threshold values shown correspond to a wide variety of test conditions. So it’s apples to oranges, but it does describe the approximate, qualitative trend.
Molybdenum TZM: Benefits

- Mo TZM is a dispersion-strengthened alloy of Molybdenum, containing small additions of Ti and Zr
- Favorable combination of properties for this application
  - Only Ta has unambiguously better blistering resistance
  - Literature blistering limit of >1E24 particles/m² corresponds to >5 hours of beam time. Goal would be to achieve diffusion/desorption steady state within that time
- High thermal conductivity compared to Ta
- High recrystallization temperature of ~1400°C
- High yield strength @ temperature: ~500MPa @ 1000°C
- Reasonable material costs (~$5K), compared to Ta options
Molybdenum TZM: Concerns

- Due to the lower (than Cu) thermal conductivity, a Mo TZM absorber would operate at very high temperature (~1000°C) compared to previous predictions.

- Molybdenum can be brittle at room temperatures – we need to be careful with stresses in the cool portion of the absorber.

- Use of TZM presents tractable manufacturing challenges:
  - Much of the machining would be EDM.
  - Practicing of welding and brazing techniques will be necessary.
Molybdenum TZM: Concerns

- Two Mo isotopes have a neutron production threshold $< 2.1\text{MeV}$
  - $^{97}\text{Mo} (\text{pn})^{97}\text{Tc}$, $1.11\text{MeV}$ threshold, $9.5\%$ abundance
  - $^{100}\text{Mo} (\text{pn})^{100}\text{Tc}$, $0.96\text{MeV}$ threshold, $9.6\%$ abundance

- See Y. Eidelman report on this topic
  

- A Mo absorber will produce more neutrons than a Cu absorber

- In PXIE, it is possible that neutrons streaming back from the main beam dump would be a bigger issue. As such, we may be able to tolerate some neutron production in the absorber
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Preliminary Thermal Analysis of a Mo TZM Absorber

• Though changing material, we will maintain the same overall absorber configuration presented previously:
  • Rectangular geometry, grazing angle of incidence, and axial stress relief slits as proposed in the Hassan et al. concept
  • mm-scale channel water cooling scheme as presented previously

• Dimensions of the stress relief slits and cooling channels have been re-optimized for the lower thermal conductivity of the Mo TZM material
Coordinate System

Detail shown in next slide
Channel Geometry

Stress relief slits: 10mm deep

14mm facesheet thickness

0.3mm wide X 8mm tall water channels
1mm channel pitch
0.7mm fin thickness

Flow transverse to beam direction (into page)

Channel width set at minimum value that can be easily made using wire EDM techniques

Fin and facesheet parameters optimized for a TZM absorber

Two colors are modeling artifact:
This is one piece of material
Channel Flow Parameters

- Maximum single-channel heat transfer = 123W (heat reaction result from iterative analysis)
- Flow of ~2ml/s per channel
- Hydraulic Diameter = 580um
- Re = 840 (fully laminar flow)
- Nu ~ 6 for relevant channel aspect ratio
- $h \sim 6500\ \text{W/m}^2\text{k}$ (average convection coefficient)
- 4-pass system for whole absorber
- 4 gpm total
TZM Absorber @ 21kW Temperature Results

Key Inputs
- 21kW beam
- $\sigma_x = \sigma_y = 2\text{mm}$
- Grazing angle 0.029rad
- TZM with temp-dependant thermal conductivity
- Convective cooling with $h=6500\text{W/m}^2\text{K}$ to $T_f=30\degree\text{C}$

This view shows $\frac{1}{4}$ of the TZM absorber
Max temp 1056°C on the beam absorbing surface

Beam
TZM Absorber @ 21kW
Temperature Results

Max temp 1056°C on the beam absorbing surface

Mid-planes of absorber (symmetry boundary)
In areas of wall super-heating, we may see nucleate boiling

Nucleate boiling will increase heat transfer, up to the onset of transition boiling

With a system bias pressure of < 5atm, we could suppress boiling altogether, or tune system to optimize nucleate boiling heat transfer
Stress Results

- Von Mises stresses shown in MPa, maximum value 450MPa
- Maximum stress very localized at root of relief slit
- Additional relief slit optimization may be warranted
Stress/Temperature Conditions

Yield Stress (Mpa)

Root of axial stress-relief slit fillet

Absorber surface

Temp (K)

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Analysis Conclusions and Next Steps

• TZM absorber would operate at high temperatures and appreciable stresses

• This preliminary analysis shows that predicted operating conditions are within the capability of the material

• Analysis next steps
  • Investigate options to improve mixing in channels
  • Optimize flow parameters in CFD and revisit heat transfer
  • Investigate geometric tweaks to improve stresses
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Motivation for a Modular Design

• The design we’re moving towards has:
  • Complex features, with heavy use of EDM
  • Expensive materials
  • Some amount of risk associated with the fabrication process

• We can minimize this risk by designing a modular absorber

• Benefits of a modular absorber:
  • Lower value-added during machining process
  • Ability to replace modules rather than absorbers
  • Planned electron beam testing can be done on a high-fidelity module prototype rather than a sub-scale mockup
Module Configuration

Envelope representation: details of module not captured

4-pass system

Parallel flow within each module

Serial flow from module-to-module

Water Flow

500mm
Cartoon of Module Shadowing Implementation

Both axial relief slits and modules have step height increments to prevent beam from striking vertical surfaces at low (near-normal) angles of incidence.
Absorbers mounted and co-located by support rails (blue)

Absorbers is built off of an interface flange (peach colored), and is:

- Kinematically mounted
- Adjustable by ~2mm per DOF in tip, tilt and piston. We can adjust angle slightly, we can not move the absorber in and out of the beam
- Electrically isolated relative to flange and vacuum enclosure
Absorber handled by this flange

Viton O-ring seal on large rectangular flange

Vacuum Enclosure
MEBT Absorber
Preliminary Packaging Concept

Absorber enclosure: vacuum vessel, common vacuum with beamline

Pumping:
Qty. 4 Turbos
3000l/s pumping speed total

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Preliminary Packaging Concept

~2.0m
1.7m
(1.3m) beamline

650mm Flange-to-Flange

80-20 Stand
Camera system to monitor OTR

BEAM

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MEBT Absorber
Preliminary Packaging Concept

Detail shown on next slide

BEAM

Absorber suspended above beam axis
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Preliminary Packaging Concept

Absorber supported from large peach-colored flange

Pumping port: no direct view to absorber surface due to sputtering concern

Absorber surface

BEAM
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Next Steps

• Conceptual design and analysis work indicates that a TZM absorber should be feasible within current requirement constraints

• Next steps include:
  • Refine thermal and CFD analysis
  • Do the detailed design of a single, high-fidelity prototype module for use in planned e-beam testing
  • Fabricate and test prototype module to verify thermal and fluid flow characteristics
References


