High Temperature Moderator

High Temperature Moderator Containment:

Advanced Moderator Module (AMM) Concept

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Introduction: Yttrium Hydride based Moderator designs

Advanced neutron moderators are needed for microreactors typically operating with HALEU due to:

- Light weight and compact size requirements.
- High efficiency/high temperature requirements.

Hydrogen is the best moderator, so materials with high H_2 density will be ideal candidates, such as metal hydrides.

- **Yttrium hydride YH_x** (out of all metal hydrides) shows the best potential:
  - Exceptional high H_2 concentration (figure a),
  - Low neutron absorption cross section,
  - Lower H_2 dissociation rate at high temperatures (needed for optimal performance) compared to other hydrides (figure b),
  - Good thermal conductivity and high melting point.
- **However, dissociation rate of YH_x at high operating temperatures (e.g., > 850 ^{o}C) can lead to significant H_2 losses during long term operations, compromising performance**
  - Thus, low H_2 permeability encapsulation of YH_x is essential.
  - Metal based encapsulation solutions are likely to need H_2 barrier coatings
- **Two unique containment designs** are being considered which are:
  - TZM based moderator design (LANL)
  - SiC Composite/Nb-liner based moderator design (ANL)

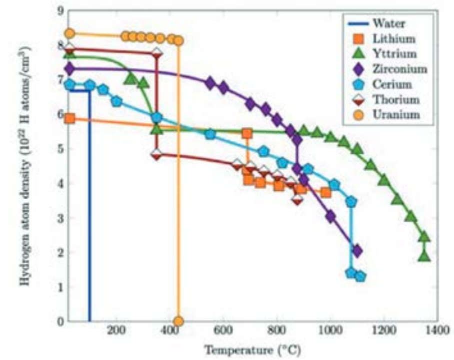

Figure (a)

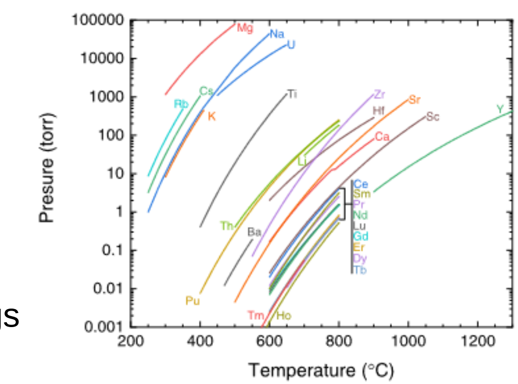

Figure (b)

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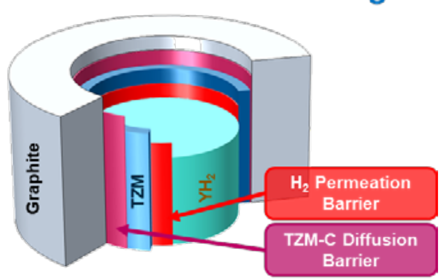
Overview: High Temperature Moderator Containment (ANL contributions)

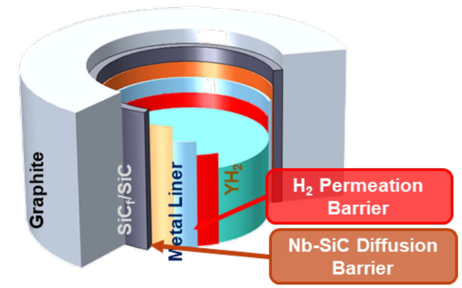
Heat & radiation resistant high temperature barrier coating **(FY-23, completed)**



- ***H_2 permeation barrier and graphite interaction barrier materials and architecture selection:***
  - Metal ceramic multilayer architecture.
  - Cr_xAl_y/Al_2O_3 based design.
  - Optimized individual layer thickness.

- ***Confirmation of desired barrier properties:***
  - Thermal cycling resistant
  - Resistant against radiation damages.
  - Significant reduction in H_2 permeation.
  - Prevents high temperature graphite interactions

Advanced Moderator Module (AMM) concept **(FY-24, ongoing)**



- ***Preparation of AMM modules:***
  - Implementation of developed H_2 barrier design within Nb tubes.
  - Confirmation of mechanical and thermal properties of the implemented barrier coating.
  - Manufacturing outer SiC shells.
  - Shrink fitting SiC shells over coated Nb liners.
  - Hermetic sealing of coated Nb liners (welding).
  - Loading of YH_{2-x} pellets

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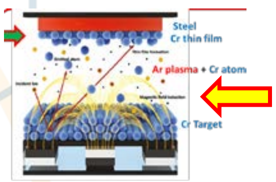
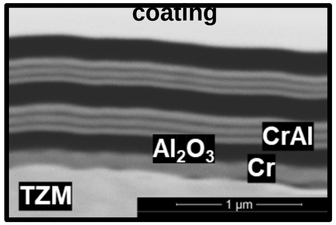
Recap of properties of the developed H_2 permeation barrier in FY 23

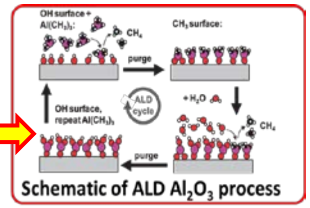
H_2 Barrier Coating (Thermal & Radiation Performance)



Schematic of PVD Cr sputtering

FIB cross section of as prepared coating



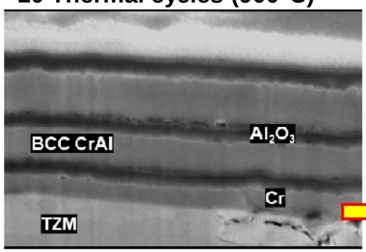


Schematic of ALD Al_2O_3 process

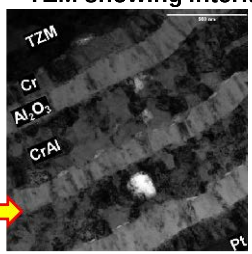
Developed Multilayer Permeation Barrier Design

- Optimal design: thin layers of Al_2O_3 combined with thin Cr_xAl_y most stable.
- Combination of ALD and PVD has been used to generate the metal ceramic architecture.

10 Thermal cycles (900ºC)

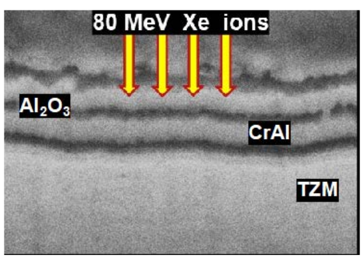


TEM showing interface

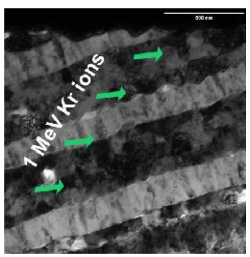


High Temperature Performance of the Functional design

- No surface cracks.
- No separation at the interfaces.
- No interaction between metal/ceramic layers.



~10 dpa (5E16 ions/cm^2), AMIS facility



~11 dpa (4E15 ions/cm^2) IVEM facility

Radiation Tolerance of Developed Permeation Barrier.

- Microstructure and material phases intact
- No observable diffusion & void formation between multilayers

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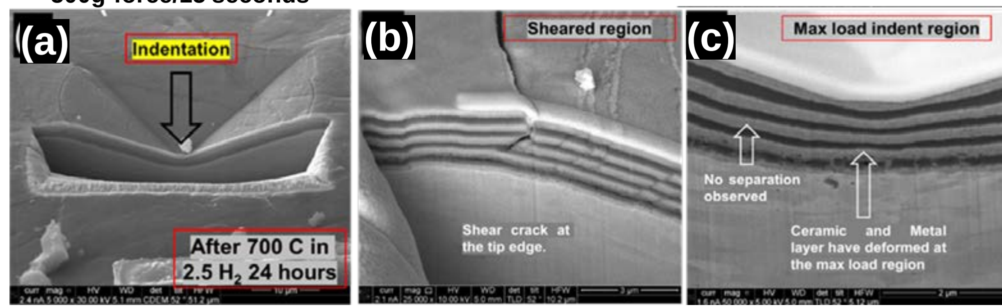
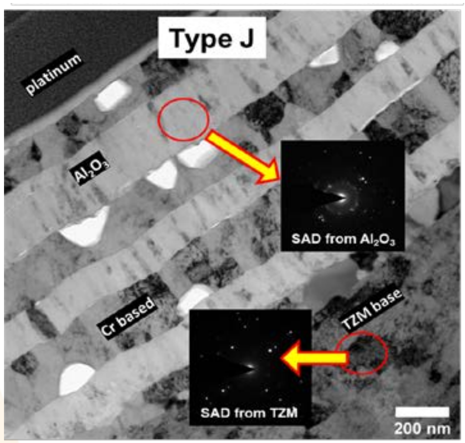
H_2 Barrier coating (Mechanical & Permeation Performance)

500g-force/15 seconds

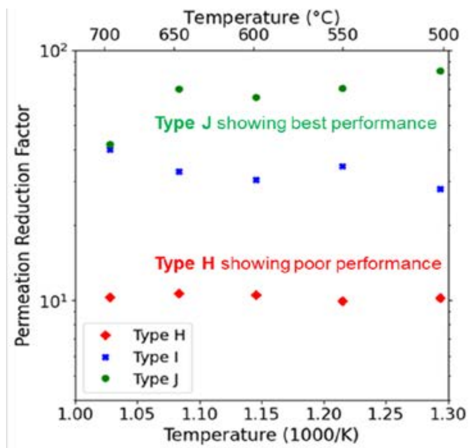


Mechanical behavior (localized deformation via micro indentation)

- At max load region, Al_2O_3 and CrAl deformed, but no layer cracks or separation at other coating regions
- Crack traveled through first few layers, but stopped at one of the CrAl layer



TEM image taken from multilayer cross section after exposure to **pure H_2 (100 Kpa) at 700 ºC**



PRF of best performing coating at different temp.

Static Gas Absorption and Permeation (SGAP) Testing at INL:

- Permeation reduction factor (PRF) quantifies hydrogen permeation reduction, serving as a metric for the coating's success.
- ~50 times PRF is achieved with the multilayer design, measured at 700 ºC, against pure H2 (100 Kpa)

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FY 24 AMM Related Activities

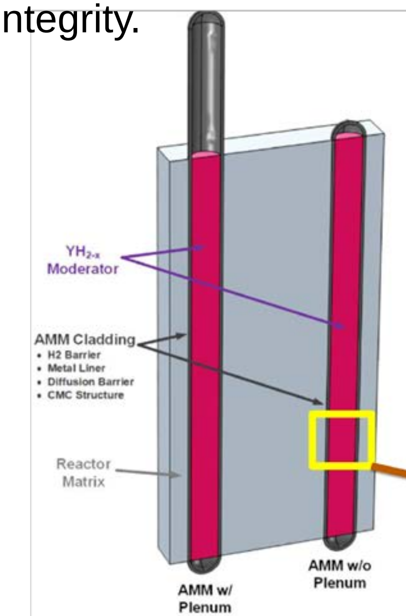
Advanced Moderator Module (AMM) Concept

Argonne National Laboratory is developing an AMM featuring a YH_{2-x} metal hydride, encased in a niobium (Nb) liner with a H_2 barrier to contain hydrogen at high temperatures, and a silicon carbide (SiC) composite cladding for structural integrity.

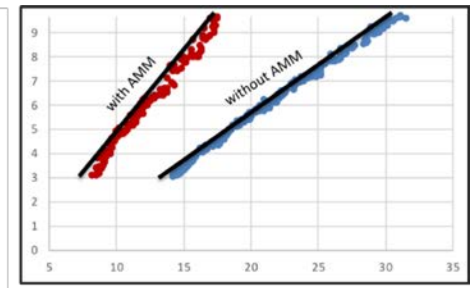
Advantages

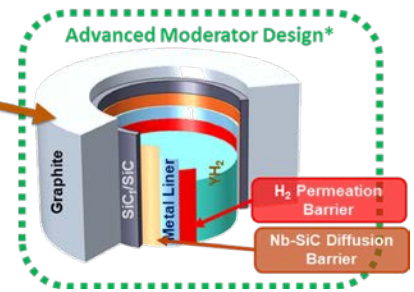
- Utilizing metal hydrides, like YH_{2-x}, allows for optimal moderation.

- AMM's encapsulation method promises an improved performance:
  - Improved H_2 retention.
  - Reduced thermal neutron absorption compared to other approaches (e.g., SS, high temp. alloys, ..)
  - Successful deployment will support small microreactor cores with extended operational lifetimes.



AMM technology with Plenum description [1]





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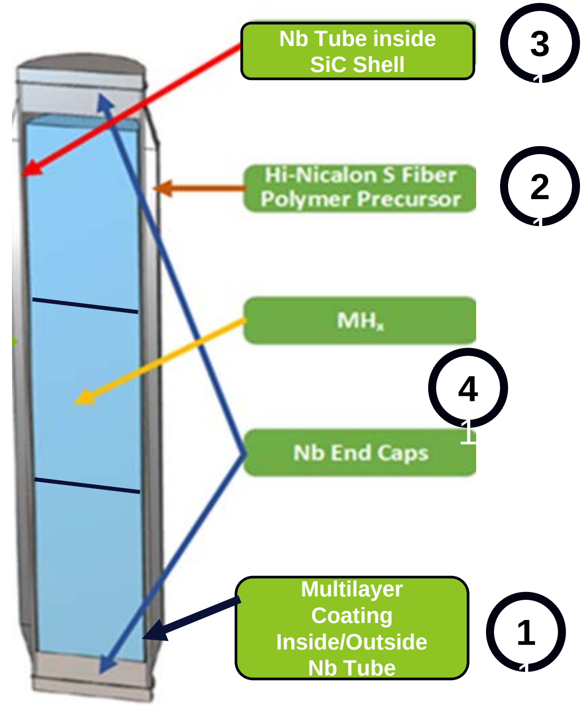
AMM Manufacturing Progress

1. **Implementation of developed H_2 barrier design inside & outside of 10 mm O.D. Nb liners/tubes - completed**
   - Utilizing ALD and PVD coating techniques.
   - Thermal behavior verifications.

2. **Manufacturing outer SiC composite shells via polymer impregnation and pyrolysis (PIP) - completed**
   - In collaboration with ceramic tubular products LLC (CTP).

3. **Form SiC composite shells on Nb tubes - completed**
   - Coated Nb tubing shrank with liquid N_2 to fit into composite shells
   - Other method is being pursued through a GAIN voucher.

4. **Loading of YH_{2-x} pellets & welding end caps - ~ April**
   - 27 mm tall, 9.0 mm dia. YH_{2-x} pellets received from LANL, which will be used to prepare 10 cm long AMMs
   - Initial end caps weld studies were **completed**



Schematic of the AMM Cross section , showing the metal hydride pellet within Nb liner, and enclosed by two Nb caps, welded on both ends.

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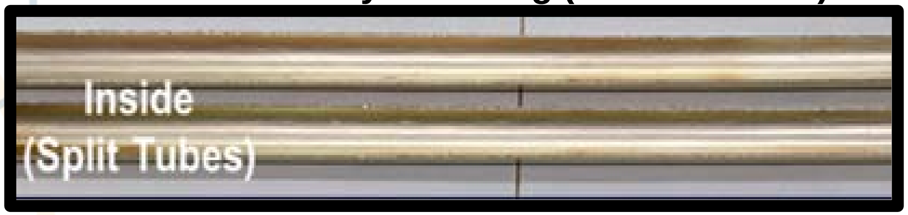
1 - IMPLEMENTING THE COATING WITHIN TUBULAR STRUCTURE

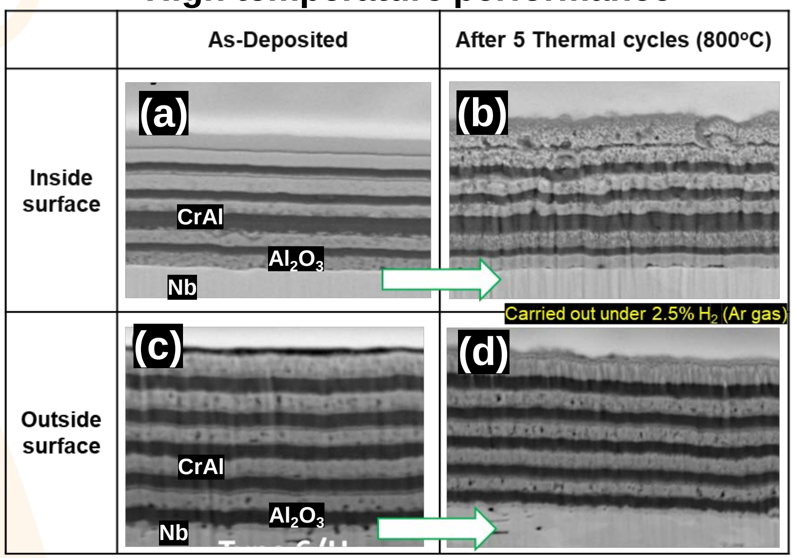
Uniform multilayer coating (Inside surface)



Observations:

- No flakes/cracks
- Uniform color

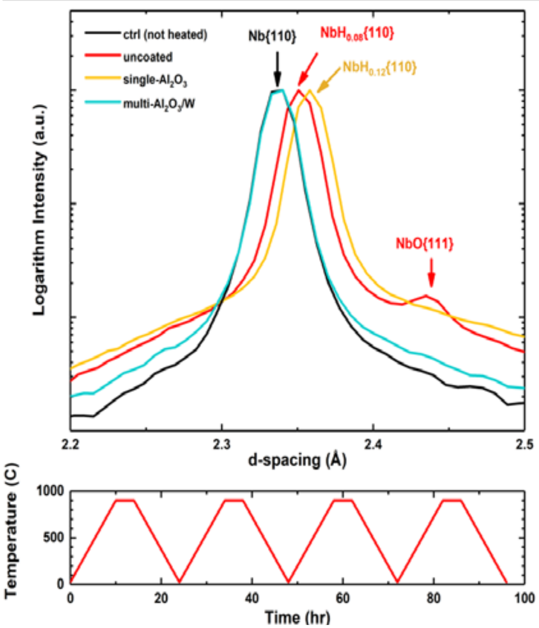
High temperature performance



Observations:

- The multilayer design was implemented within/outside 10 mm OD Nb tubes.
  - Dense
  - Conformal
- Thermal performance of the coating were satisfactory

Synchrotron XRD



No hydridation or oxidation of the Nb substrate with coating present, measured after performing thermal cycling at 900 °C

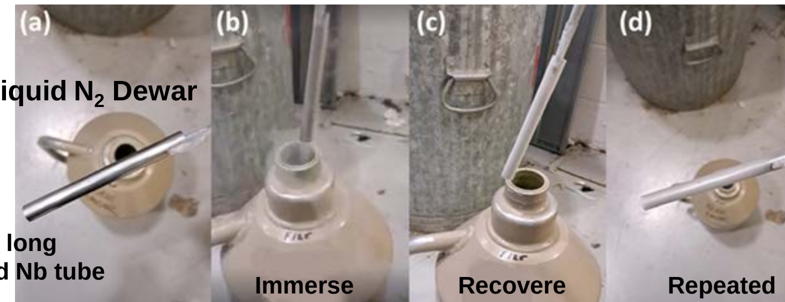
2 - SiC COMPOSITE SHELLS

SiC shells prepared via **PIP technique** where the polymer infiltrated SiC fiber pre-form prepared over graphite mandrel.

In collaboration with Ceramic Tubular Products (CTP)

3 - SHRINK FITTING Nb LINERS

Cryogenic Shrink fitting



Despite extreme low temperatures & stresses of rapid contraction/ expansion, Cr_xAl_y/Al_2O_3 coating remain adherent to Nb substrate.

SiC-coated Nb liners of various lengths were manufactured

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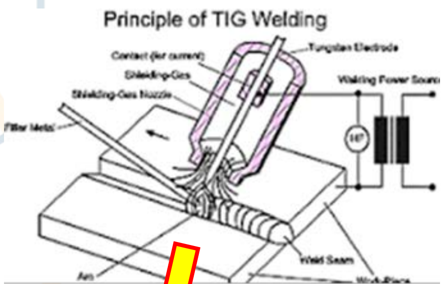
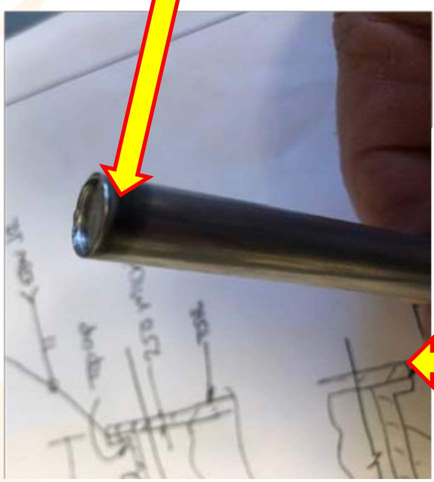
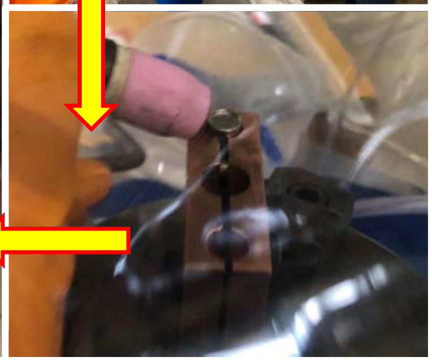
4 - WELDING OF END CAPS





Coated Nb tube with welded end

TIG weld setup at ANL



Copper chillers for reducing Heat Affected Zone (HAZ)

TIG Welding of AMM Nb liners to end caps to generate hermetic seal that contain the YH_{2-x}

- Nb, highly reactive at high temperatures, requires a pristine environment to produce strong, clean, and defect-free welds.
- TIG welding, high-energy density & inert conditions, provides rapid heating & cooling rates (*enhanced with a Cu chiller used for drawing the excess heat out*) that minimize heat-affected zone & reduced residual stresses.
- The welds have been leaked tested (No He response at $1e10^{-10}$ std. He cc/sec). Coating did not affect the weld quality.

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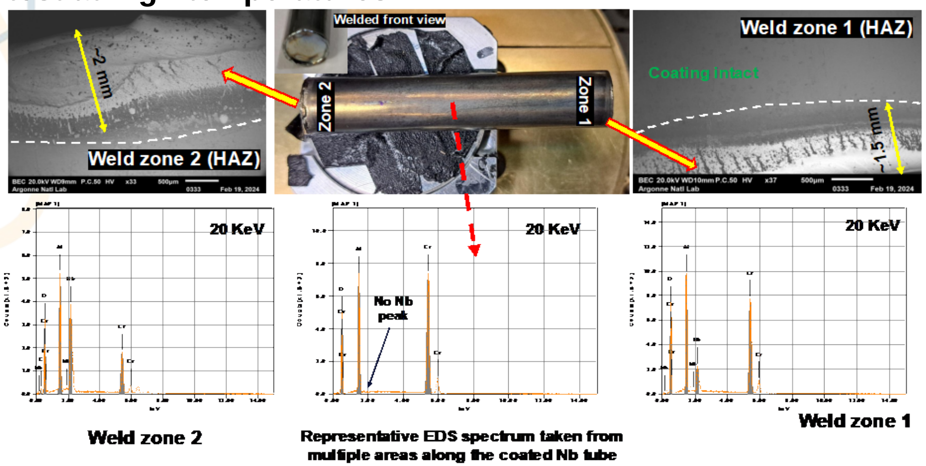
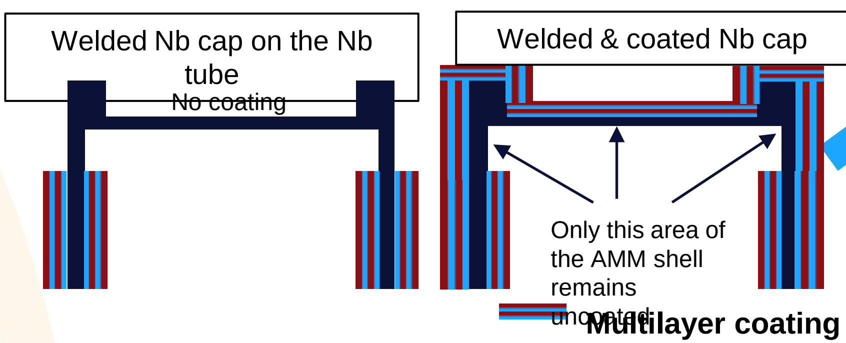
CHARACTERIZATION AND COATING OF THE WELD ZONE

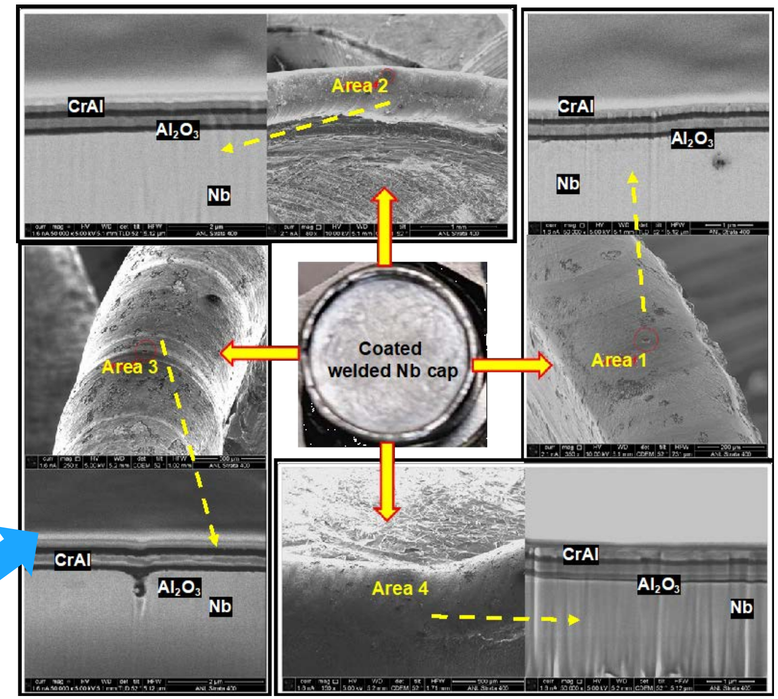
Issue: Affected weld zone can be a H_2 permeation weak spot

Resolution: Apply multilayer coating to end cap areas and test at high temperatures





FIB analysis after welded region has been coated and HT at 800 °C



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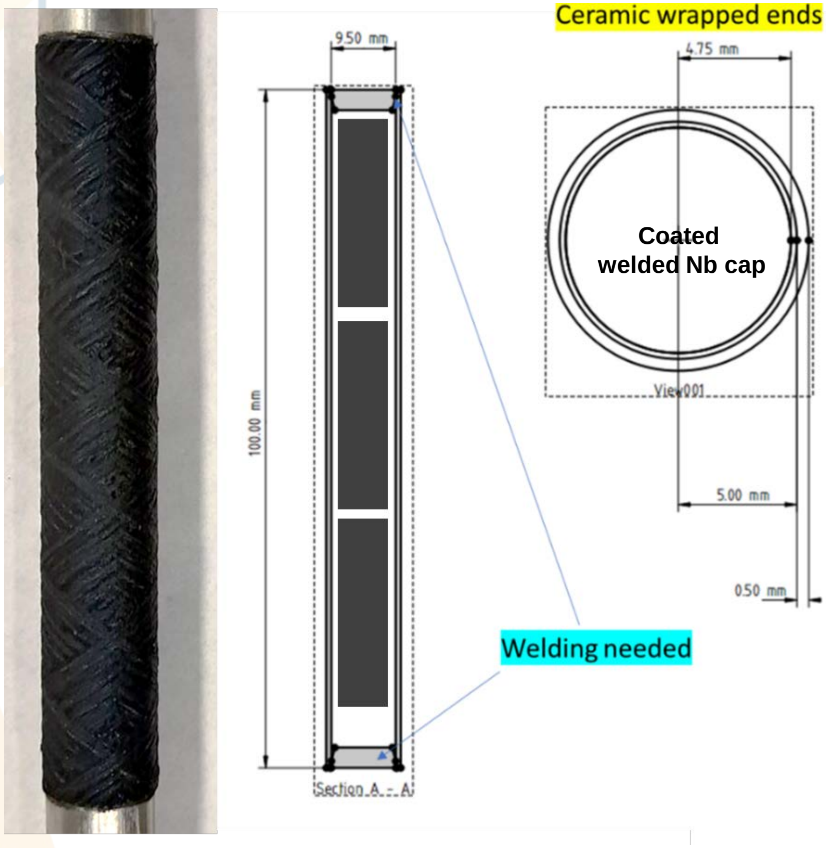
Next steps



Schematic of the final AMM prototype containing YH_{2-x} pellets (3x)

- ***More welding trials:***

(a) Try with pre-coated Nb caps used for welding Nb tub ends.
(b) Perform long term thermal cycling to verify weld joint quality.

- ***Loading YH_{2-x} pellets and welding end caps to complete AMM prototype manufacturing:***

(a) 10 cm long, SiC enveloped coated Nb tubing will be used for the final step.
(b) After welding one end of the AMM shell, three **YH_{2-x} pellets** (~81 mm in total) from LANL will be loaded in the shell.
(c) Followed by welding open end to develop a hermetic seal.

- ***Thermal testing:***

a) 10 thermal cycling at temp. >800 ^{o}C will be done followed by splitting the AMM shell to characterize the YH_{2-x} pellet composition.

- ***H_2 permeation testing at LANL (if possible)***

Summary: Advanced Moderator Module (AMM) Concept

- Different steps and their status for manufacturing AMM is presented in detail.
- We successfully applied the FY-23 developed multilayer H_2 diffusion barrier (**measured ~50 PRF at 700 ^oC, data from INL**) both **on inner and outer surfaces of Nb tubes** with **OD of 10 mm**.
- We have also **verified thermal performance** of the deposited coating.
- Details of the SiC composite shell manufacturing and shrink fitting at cryogenic temperatures in collaboration with Ceramic Tubular Products LLC (CTP) are discussed.
- Ongoing investigations on TIG welding process to hermetically seal AMM tubes have been presented.
  - Based on the studies coated Nb tubes did not affect the weld quality
  - All welds passed the He leak tests.

Final Goal: By end of FY24 demonstrate a working AMM prototype with loaded YH_{2-x} pellets, thermally tested to verify the AMM shell and the coating is surviving the expected operational high temperature exposures as well as testing the module H_2 permeation if possible.

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