3 MW Solid Rotating Target Design

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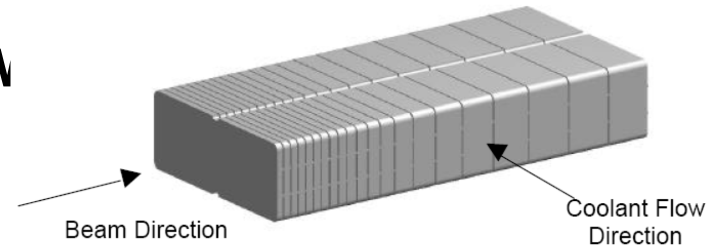
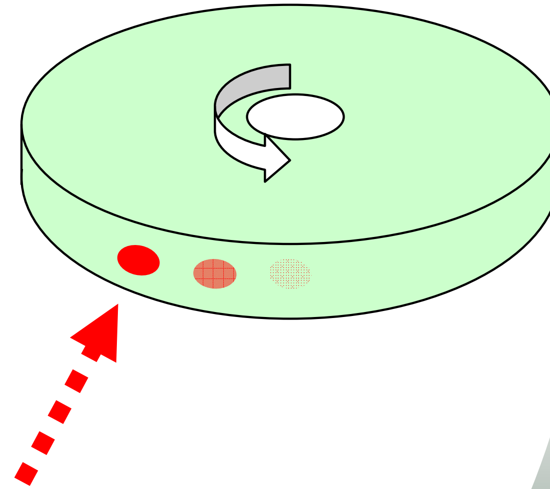
Outline

- **Justification for a Rotating Spallation Target**
- **Study Parameters**
- **Neutronic Analysis**
- **Finite Element Thermal/Stress Analysis**
- **Mechanical Design**
- **Development**

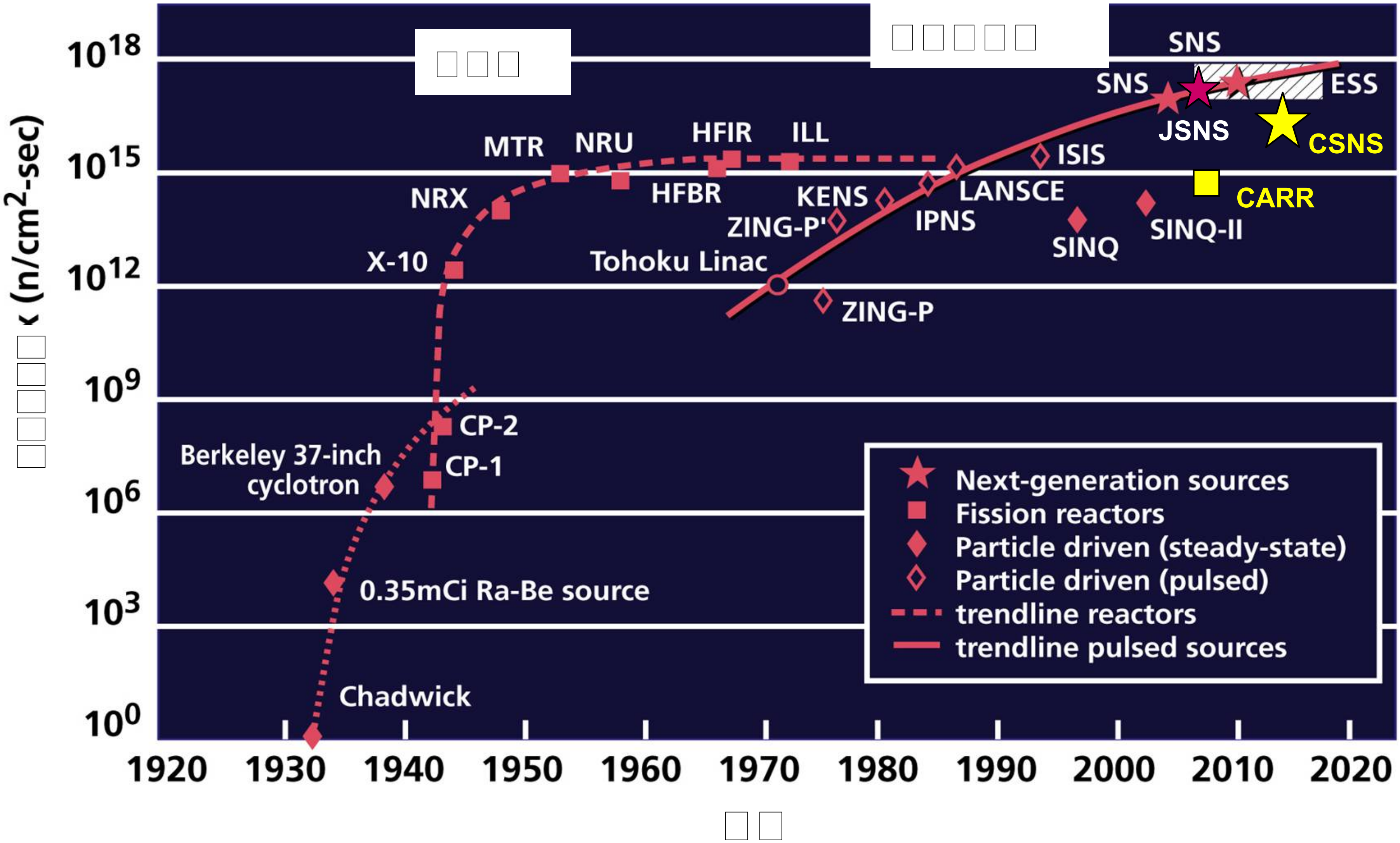
Justification for a Rotating Spallation Target

- **High Power Spallation targets to date have been based on stationary water solid metal or flowing liquid metal designs.**
- **Both concepts have life-time difficulties in the MW range**
  - **Solid targets need more water cooling in the active zone which reduces performance**
  - **Liquid metal targets may develop cavitation erosion and shortened life, particularly for short pulse operation**
- **Rotating solid target designs offer the potential of better neutronic performance because of higher target density and longer lifetimes**
- **Recently there has been a renewed interest in such a concept for the SNS second target station.**
- **China and ESS Bilbao are also developing rotating target proposals. China has begun to build a full-scale mockup.**





Future Accelerator Based Spallation Sources



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

Hokkaido , Japan Oct 19-24, 2008 Presented by Jia Xuejun At IWSMT-9

Study Parameters

- The initial rotating target study goal was to develop a configuration suitable for 3 MW, 1.3 GeV beam at 20 Hz, long pulse based on assumed SNS second target station (STS) configuration. As the STS design advances the target design parameters will be refined.
- Target life-time goal is > 3 years.
- Tantalum clad tungsten assumed for initial evaluations:
  - ISIS, and KENS experience have shown very good performance in beam operation
  - R&D for other clad materials should be investigated since it may be possible to significantly reduce the long term (week +) decay heat produced by tantalum
  - Tantalum assumed so that a decision could be made to baseline a rotating target without being dependent on R&D results
- Segmented target blocks encased in a 316L SST water shell.
- Target diameter (1.2 m) determined by radiation damage time limits on the 316L shell.
- Rotating target configured for integration into the overall STS layout (access, maintenance, moderator positioning, and etc.)

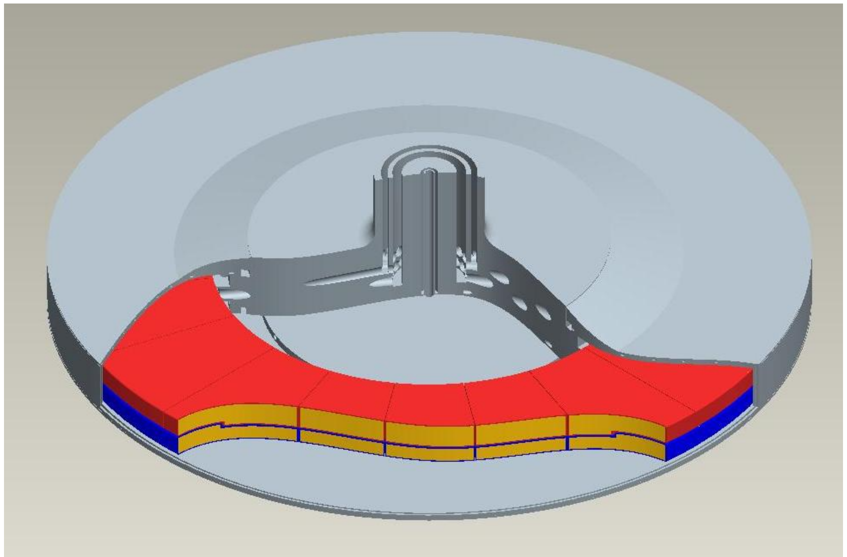
Neutronic Analysis

- **MCNPX models were used to generate an initial target configuration:**
  - **single pulse energy distribution,**
  - **decay heat,**
  - **optimized coupled moderator configuration, and**
  - **performance for the second target station**
- **MCNPX data was used directly in the finite element thermal/stress models.**

Target & Beam Assumptions in MCNPX model

Initial analysis configurations developed based on 2D parametric studies

Target Configuration	
Tungsten & Ta clad height	7 cm
Outside radius	60 cm
Target Segments	20 x 2
Tungsten & Ta clad radial depth*	25 cm
D_2O Channel heights	1.5 mm
Steel shroud thickness	1 cm



Proton Beam Profiles

Double Gaussian:

- **Vertical Sigma - 1.5 cm**
- **Horizontal Sigma - 4.5 cm**

Flat:

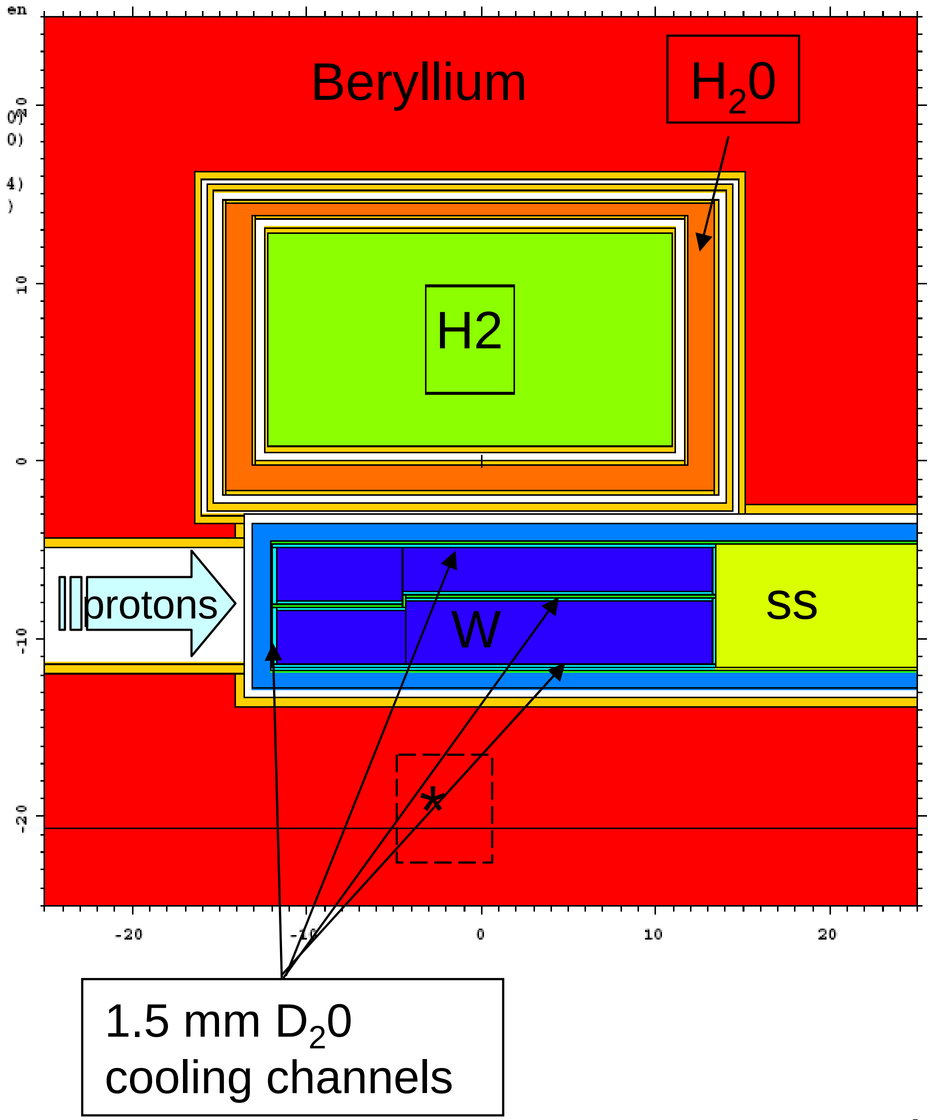
- **Vertical: 6 cm**
- **Horizontal: 18 cm**

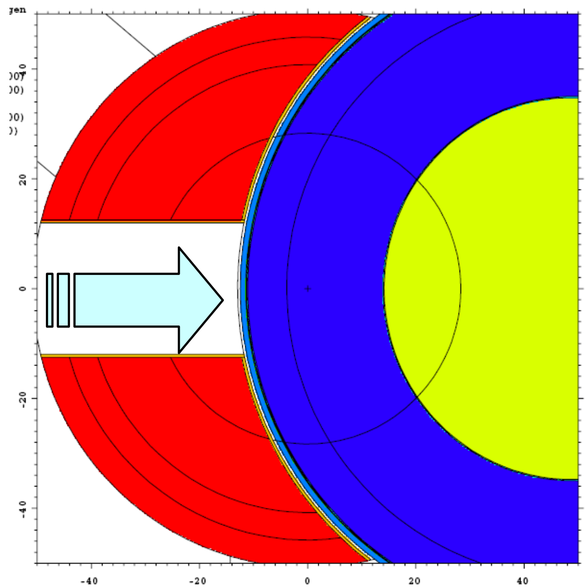
Power: 1MW – results scaled for 3 MW
Proton Energy: 1.3 GeV
Repetition rate: 20 Hz (long pulse)

* 1-2% neutronic performance loss accepted to make fabrication easier

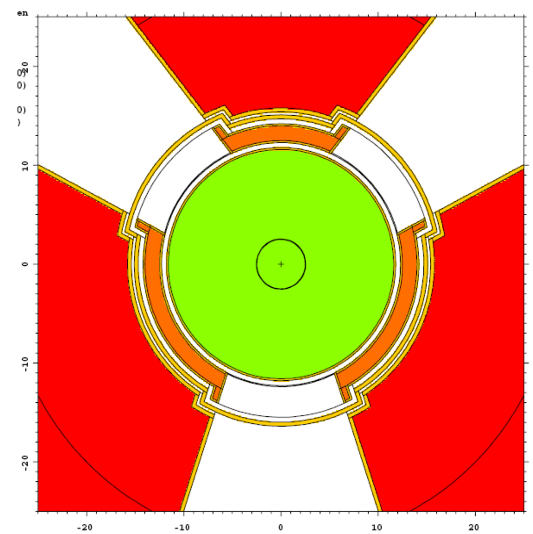
TMR Configuration: Cylindrical para-H2 moderator in wing configuration

Vertical cut





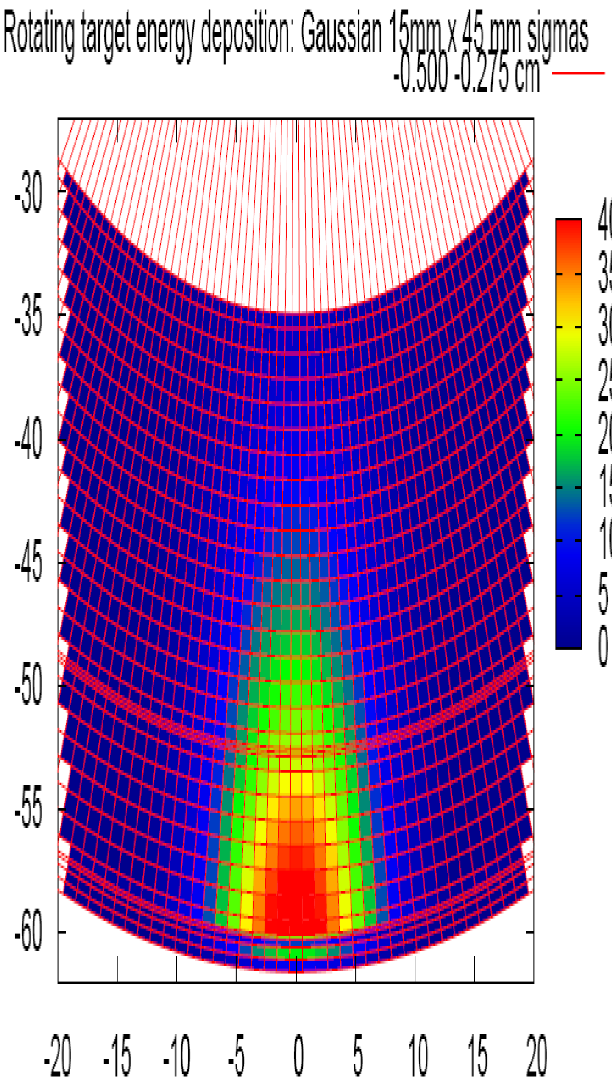
Horizontal cut
On mid-plane



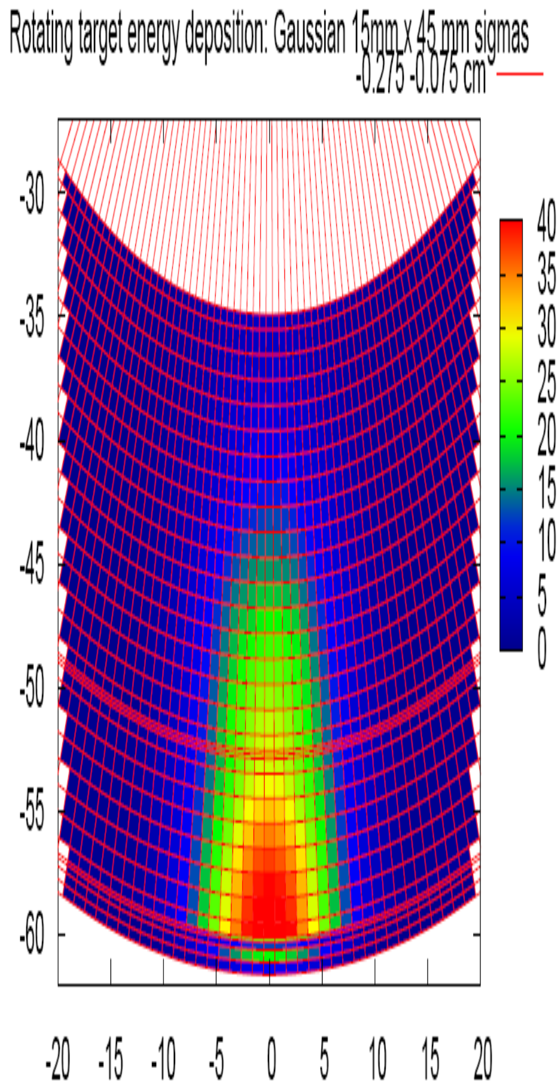
Horizontal cut
Through moderator

* Lower moderator not modeled

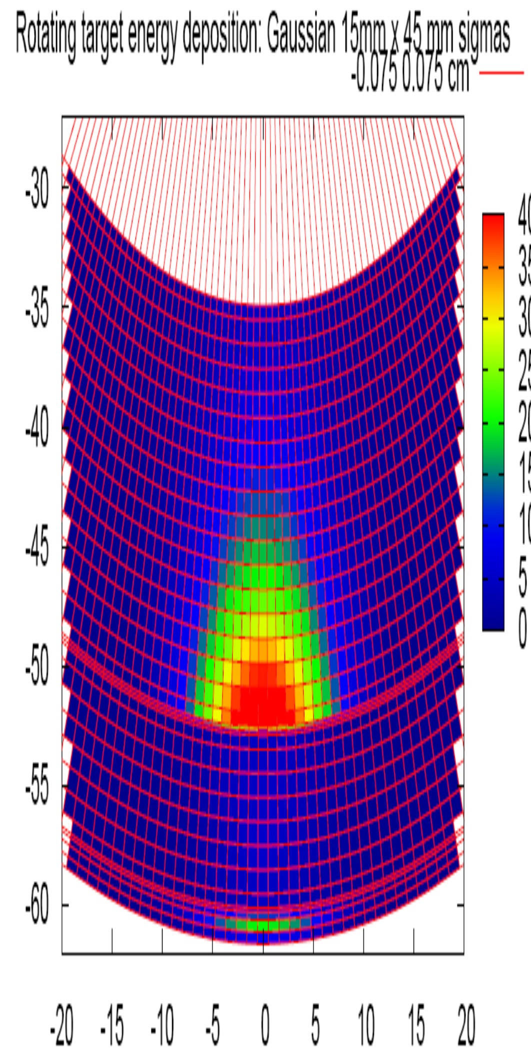
Energy Deposition (J/cc) per Pulse: Gaussian profile



Bulk tungsten



Central Tantalum Cladding



Central D2O Channel

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Optimized Neutronic Configuration

An optimized Para-hydrogen moderator configuration and center cooling channel step location in the target was calculated with MCNP for maximum moderator brightness

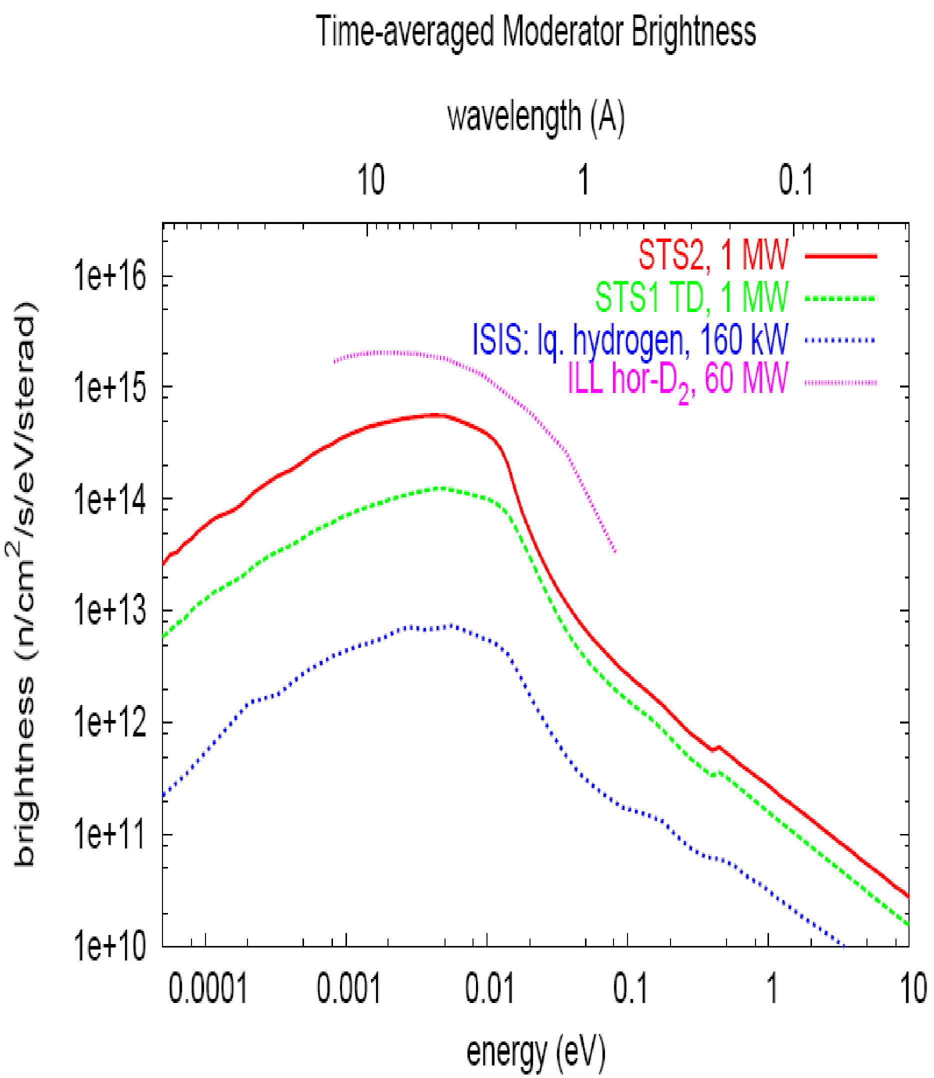
- H_2 radius 11cm
- H_2 height 12 cm
- Pre-moderator
  - Bottom 1.3 cm
  - Top 0.68 cm
  - Radial 0.68 cm
- Pre-moderator extension:
  - Length 0.65 cm
  - PM thickness 0.65 cm

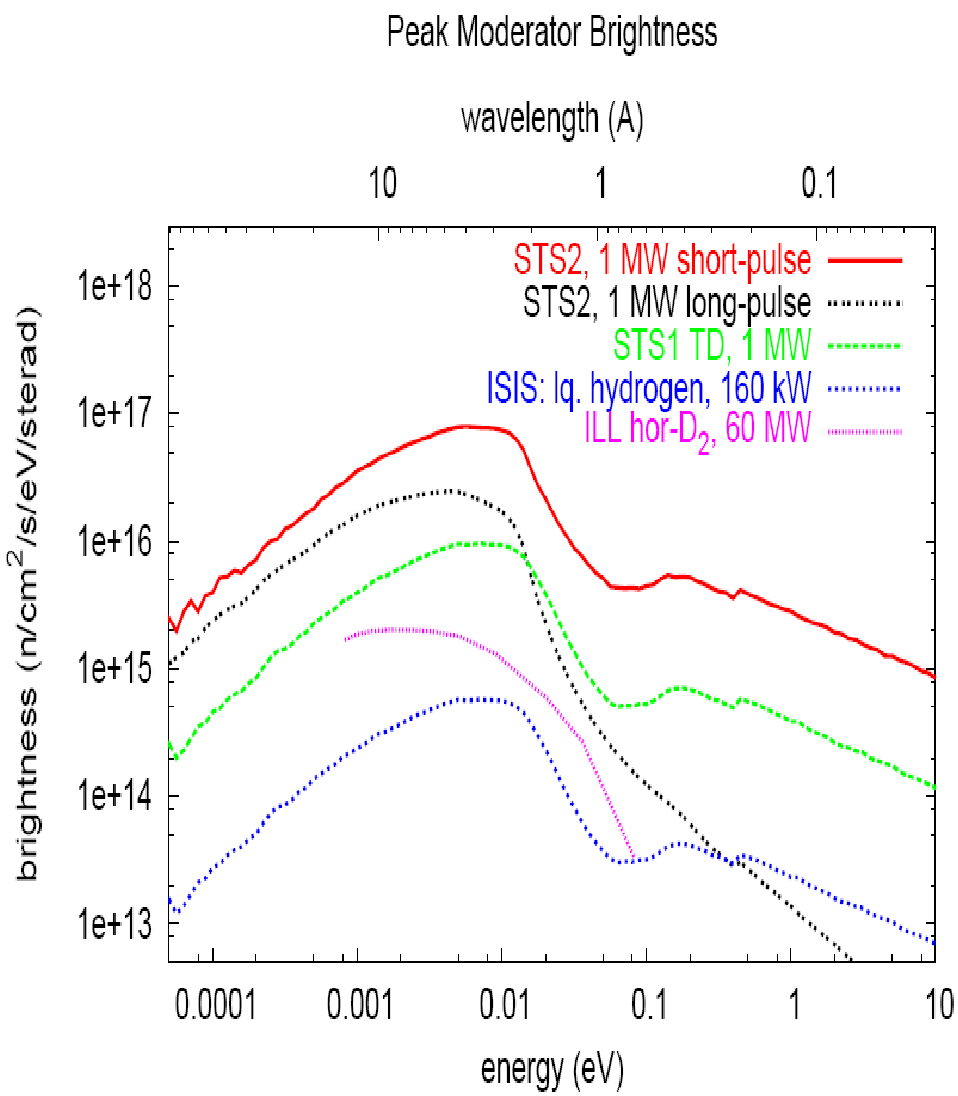
- Moderator axis with regard to target nose: 11 cm
- Target height*: 7 cm
- Step Location of central cooling channel: 7.5 cm

* Minimum to allow for offset beams

Neutron Performance:

Charts compare STS performance with other facilities. The rotating target configuration gives slightly better neutron performance as STS mercury target (+ 7% for flat profile, + 3% Gaussian profile).





Peak Material Damage at 3MW:

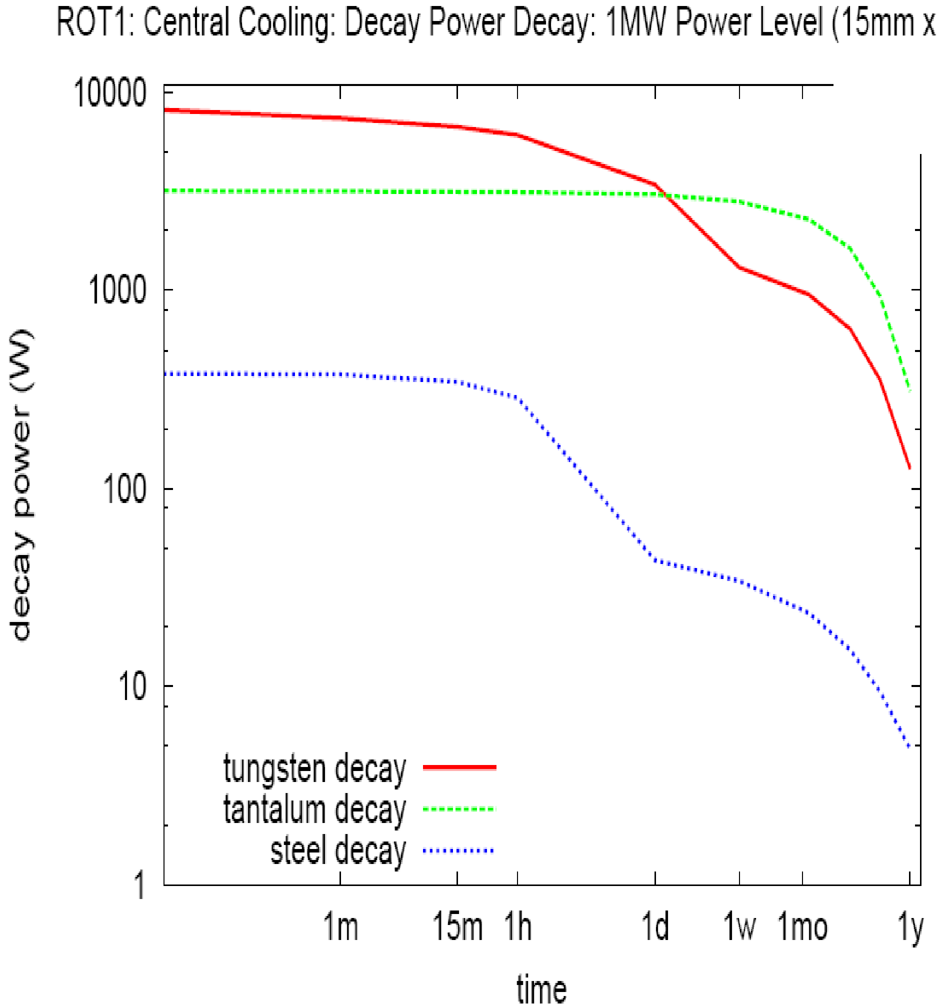
5000 Beam Hours = 1 year

Component	Gaussian beam	Flat beam	Hg Target
Target vessel (SS316)	1.95 dpa/yr	1.6 dpa/yr	30 dpa/yr
Tantalum cladding	2.7 dpa/yr	1.8 dpa/yr	-
Tungsten bulk	3.1 dpa/yr	2.2 dpa/yr	-
Moderator structure (Al6061)	21 dpa/yr	18 dpa/yr	10 dpa/yr

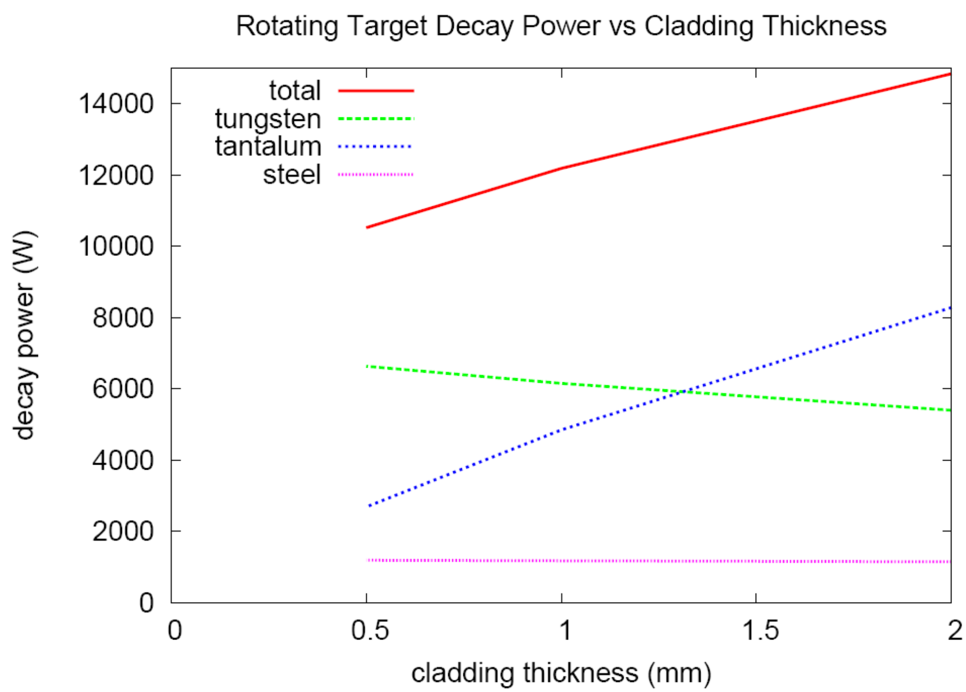
NOTES:

1. **The stationary moderators have a higher change-out rate than the rotating target.**
2. **The stationary target shell has a significantly shorter life than the rotating target shell.**

Afterheat ~ 36 kW @ 3 MW for 1 mm Ta clad



.5 mm clad



1 MW

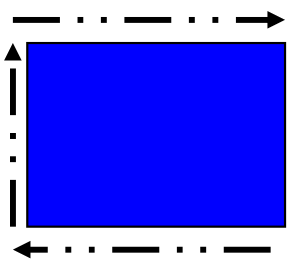
NOTE: Long and short term control of decay heat is a significant solid target design and operating issue

Design Implications of Afterheat

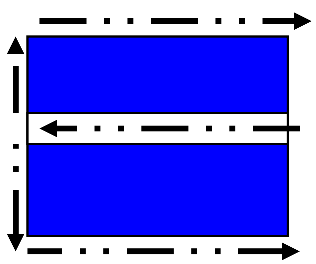
- **Long and short term control of decay heat is a historical solid target design and operating issue,**
- **Tantalum cladding alone generates substantial afterheat therefore it is desirable to either use a different cladding or make the cladding as thin as reasonably possible.**
- **Afterheat control is important in all operating scenarios, short-term cooling failures, maintenance shut-downs, target replacement operations and long-term target storage. Backup and redundant cooling systems and channels are required.**
- **Uncontrolled afterheat drives the safety case studies.**

3 MW Cooling Configuration: External vs. Center Cooling

- **External Cooling preferred from standpoint of neutronics and mechanical simplicity**
- **Center Cooling provides much lower peak temperatures and stresses - half thickness and cooling close to peak heating zone**



External Cooling



Center Cooling

Comparison for Gaussian Beam with 25 l/s flow

	Peak Temperature (C)	Peak Stress MPa
External Cooling	**320**	**380**
Center Cooling	**170**	**110**

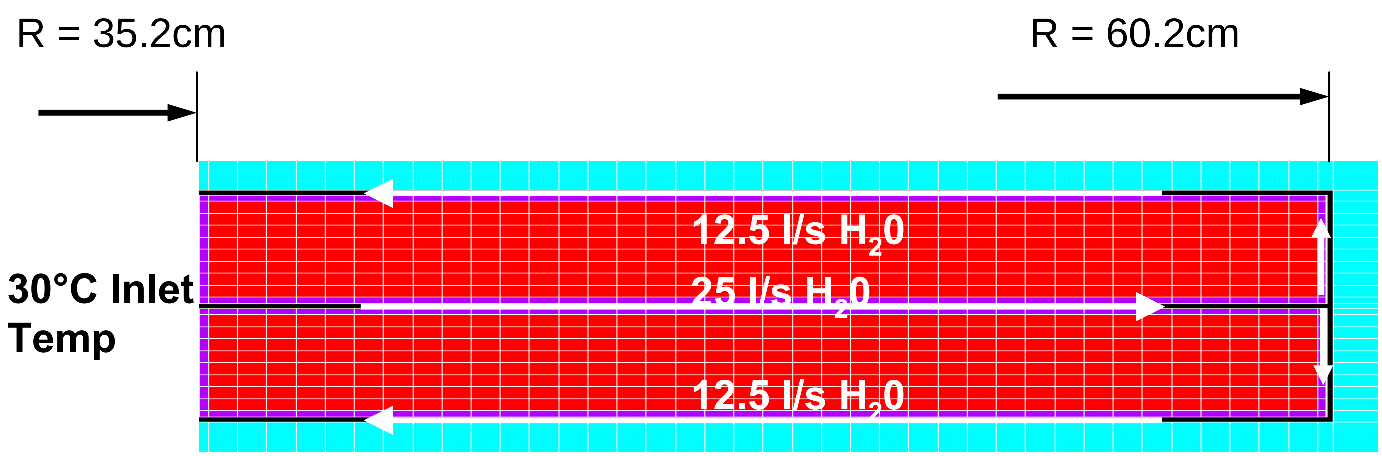
Neutronic Performance loss with center cooling < 3%

Finite Element Thermal/Stress Analysis

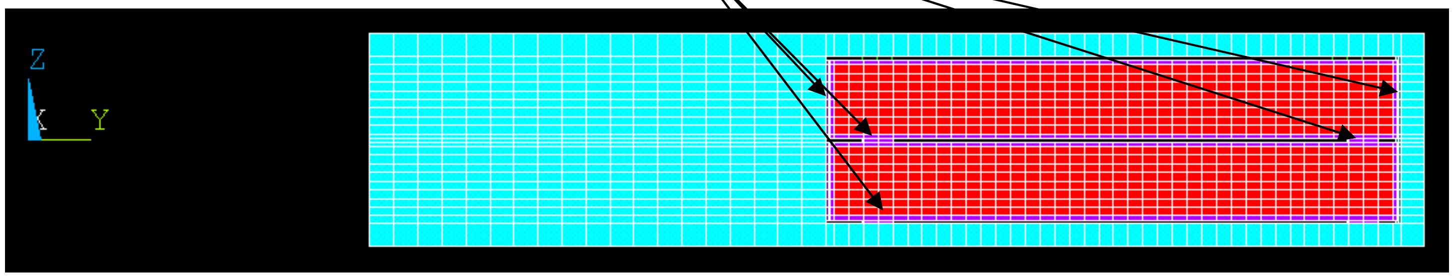
- **Detailed finite element modeling began after completion of the initial neutronic and 2D thermal/stress analyses.**
- **ANSYS analysis software was used to refine the design of the shroud and target segments. Particular focus was given to cyclical loading.**
- **Neutronic energy deposition data imported from MCNPX directly into ANSYS.**

Boundary Conditions – Initial ANSYS models

- **3 MW beam power in a Gaussian or flat profile**
  - 3D heat deposition profile from MCNPX analysis rotated around the target at 30 rpm with 20 Hz pulse frequency and 1 ms pulse length
  - 1 of 20 double wedges (18^0)
  - 10 mm thick 316 SS shroud
  - Non-constant convection coefficients from Dittus-Boelter correlations.



Radial Springs and Ta spacers between target wedges and SS shell



Design Implications of Distributed Water Cooling

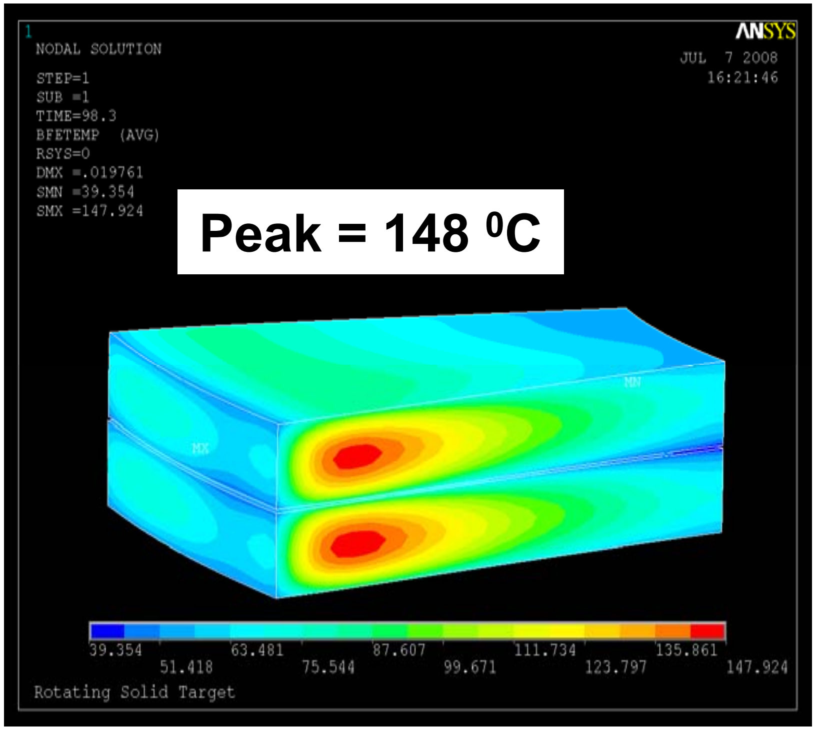
- **Analysis assumes the maintenance of consistent water cooling gaps.**
  - **Swelling of target segments over time must be limited.**
  - **Shroud cannot bend significantly,**
  - **Springs and spacers must be used to allow segments to thermally change. These elements must not significantly interfere with the flow of the cooling water.**
  - **Compliant channeling guides must be used to direct water flow over the top and bottom surfaces with a minimal bypass.**
- **A solid, conductive and highly reliable bond must be maintained between the Tungsten and the cladding. HIP bonded Tantalum has been proven to be very effective. Ta has a closely matched coefficient of thermal expansion, high density, excellent corrosion resistance and good weldability.**

Summary of Quasi-Steady State Response

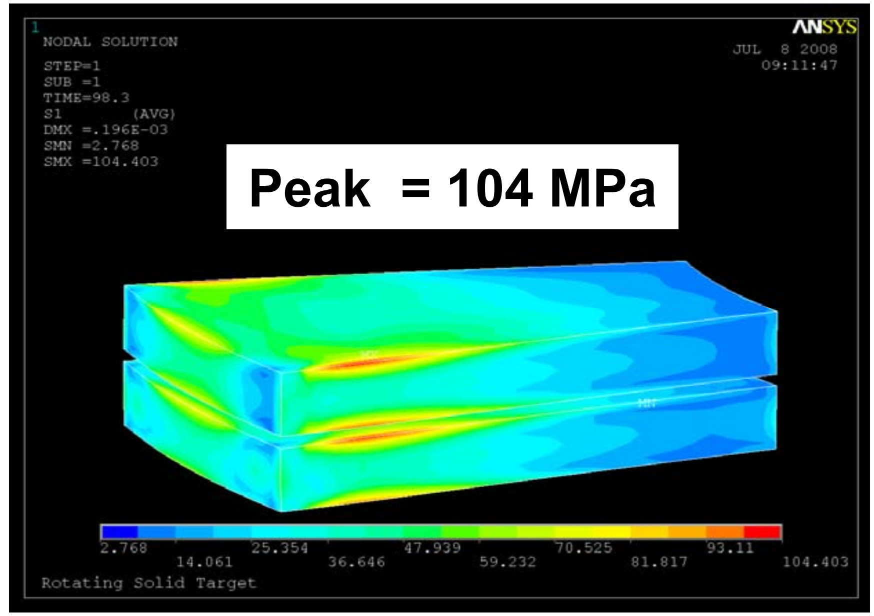
Beam Shape	Rotation Speed (rpm)	Maximum Temp. (°C)	Maximum 1st Principal Stress in W (MPa)	Maximum 1st Principal Stress in Ta clad (MPa)
Gaussian	30	170	119	59
1cm Off Gaussian	30	208	128	76
Flat	30	160	110	53
Flat	60	148	104	50

All stress levels are well below 500 MPa unirradiated tungsten yield or 180 MPa Tantalum yield and have margin for fatigue and irradiation effects

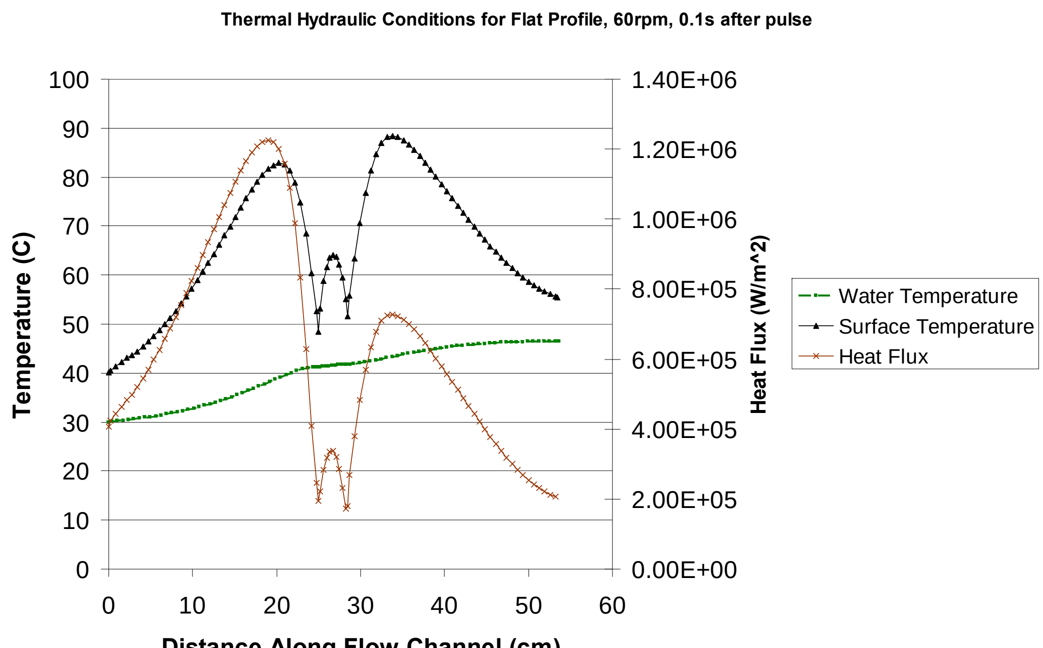
Flat Beam Profile 60 rpm



Thermal



1st Principal Stress (MPa), $T_{reference}$ = 20°C



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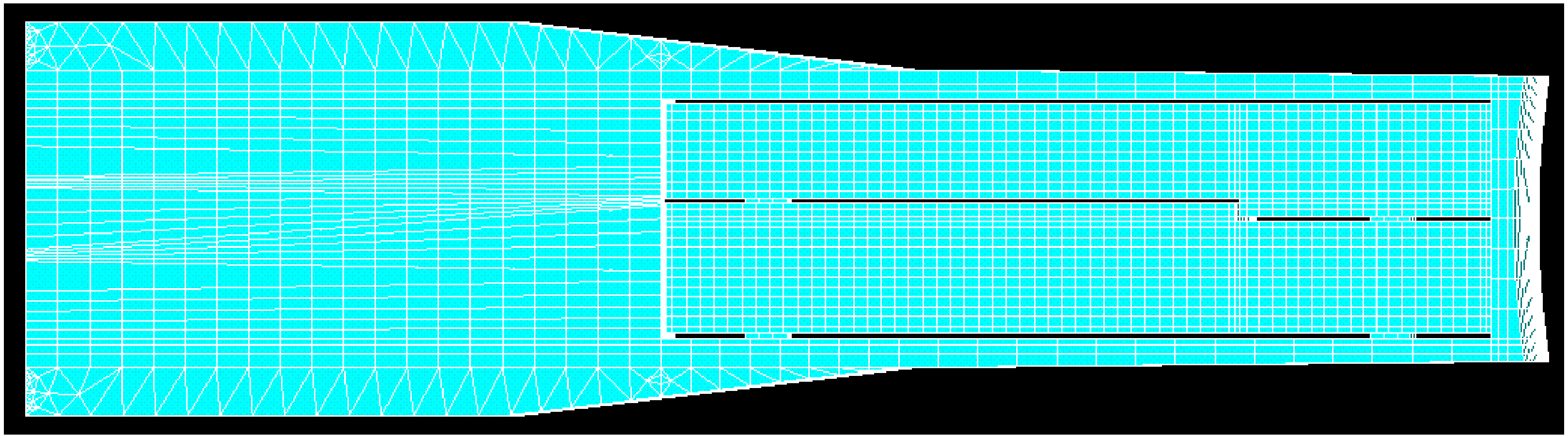
Design Implications of Cyclical and Periodic Energy Input to the Target Segments

- **Thermal flexing of the Tungsten segments results from both the intermittent nature of proton beams and the cyclical loading of a rotating target.**
- **Stresses in the segments must be minimized by shaping the beam and optimizing the cooling.**
- **Ta clad W segments have been successfully used in ISIS when exposed to a real world proton accelerator source.**
- **Significant development work aimed at improving the toughness of Tungsten alloy in beams is underway in Japan.**

Detailed Shroud Study

- **3 MW beam power in a Gaussian or flat profile**
  - 3D heat deposition profile from MCNPX analysis rotated around the target at 30 rpm with 20 Hz pulse frequency and 1 ms pulse length
  - 1 of 20 double wedges (18^0) with stepped flow channel for improved neutronics
  - Optimized shroud design with non-constant thickness and concave radius at nose
  - Non-constant convection coefficients from Dittus-Boelter correlations.
  - 3mm cooling channels spaced 3° apart in shroud with 10gpm total flow
  - 5 bar internal pressure, centripetal forces from rotation, and gravitational forces included



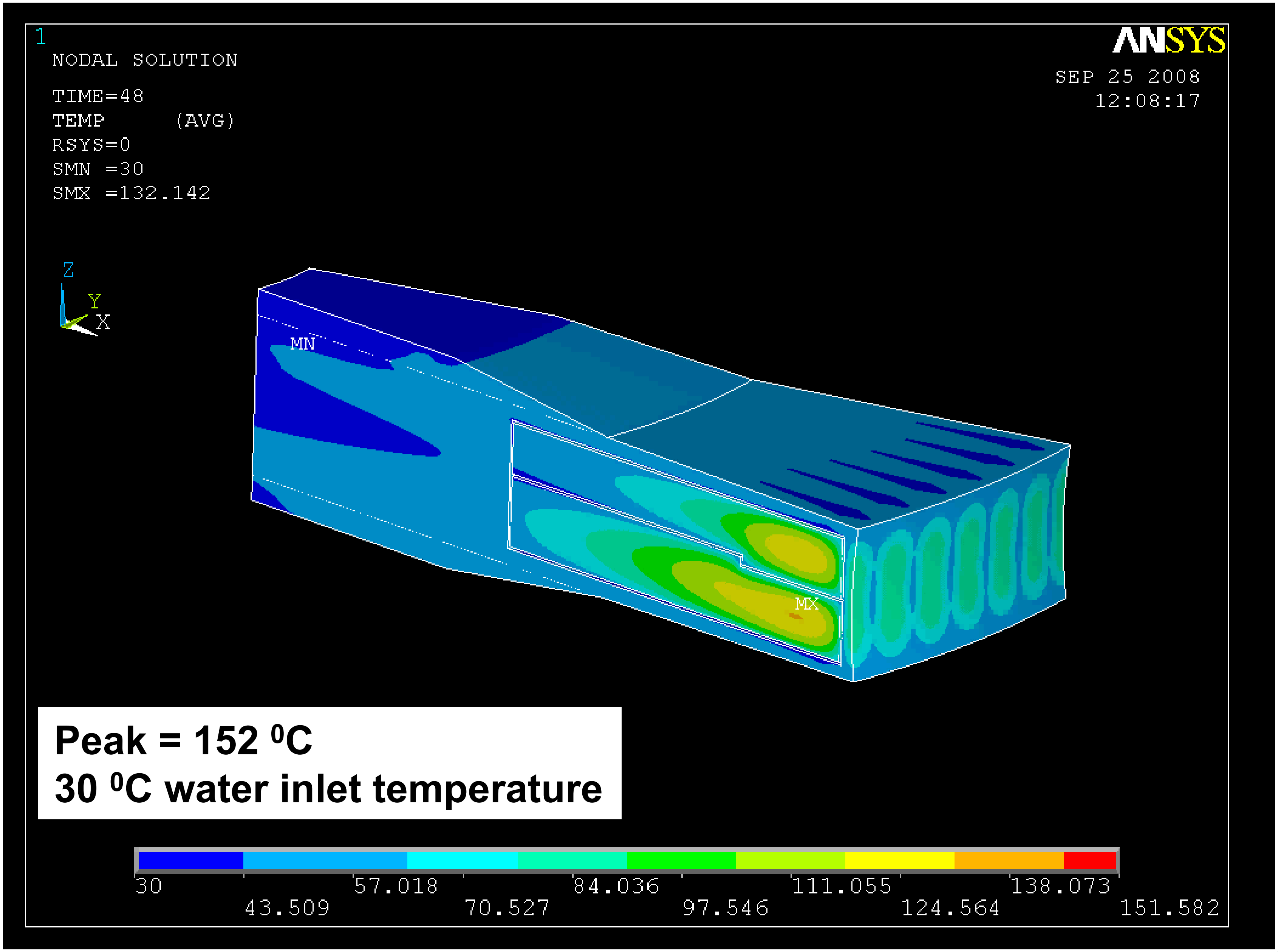
Detailed Shroud Study Results Summary

Beam Profile	Rotation Speed (rpm)	Maximum Shroud Temp. (°C)	Max. Von Mises Stress in Shroud (MPa)
Gaussian	30	Nose – 115 Hub - 62	Nose – 290 Hub - 219
Flat	30	Nose – 95 Hub - 59	Nose – 200 Hub - 211
Flat	60	Nose – 92 Hub - 58	Nose – 181 Hub - 210

When just internal pressure, rotational inertia, and gravity are applied, resulting Max. Von Mises are 123 MPa in nose and 166 MPa in hub.

In all cases, Shroud stresses are below ASME BPVC allowable for thermally induced stresses in 316 SS (413 MPa). Additionally, the non-thermally induced stresses are below the linearized stress limit of 207 MPa.

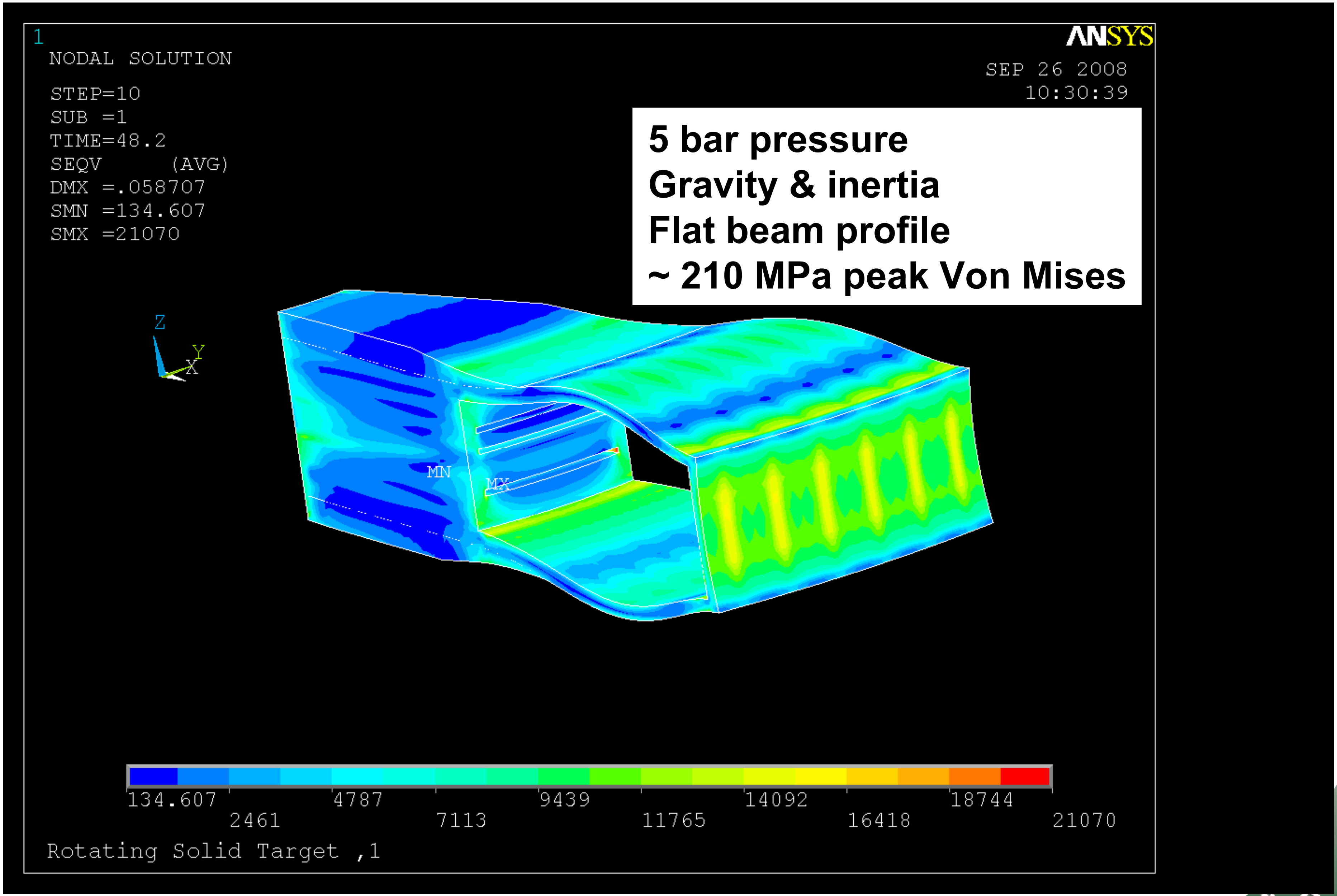
Target and Shroud with Flat Beam Profile 30rpm



Peak = 152 ^{0}C

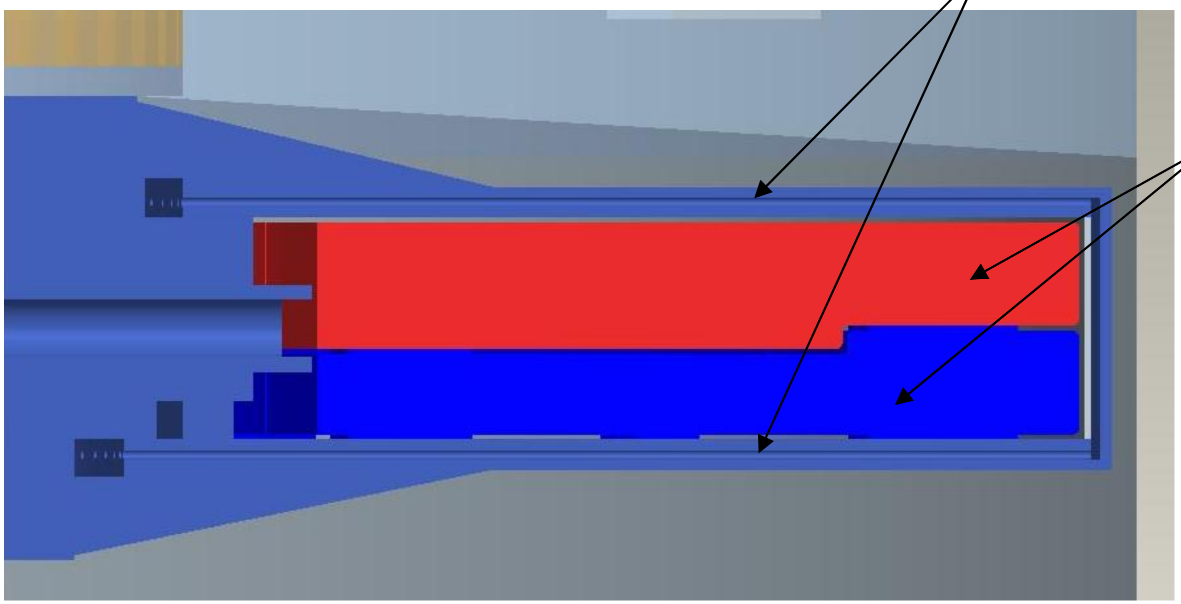
30 ^{0}C water inlet temperature

Shroud with combined loads



36 kW Decay Heat Removal

- **The proposed SNS target includes several layers of defense:**
  - **Seismic qualification for core vessel components and target**
  - **Primary cooling system with UPS low flow capability**
  - **Independent backup (UPS) cooling within structural shell**
    - **3 mm diameter holes on 3^0 spacing**
    - **1 m/s water flow (~ 10 gpm total)**
  - **Passive radiation and gas conduction to reflector assemblies**
    - **5 mm gaps to reflector/shielding assemblies**
    - **0.8 emissivity coating on target and reflectors**



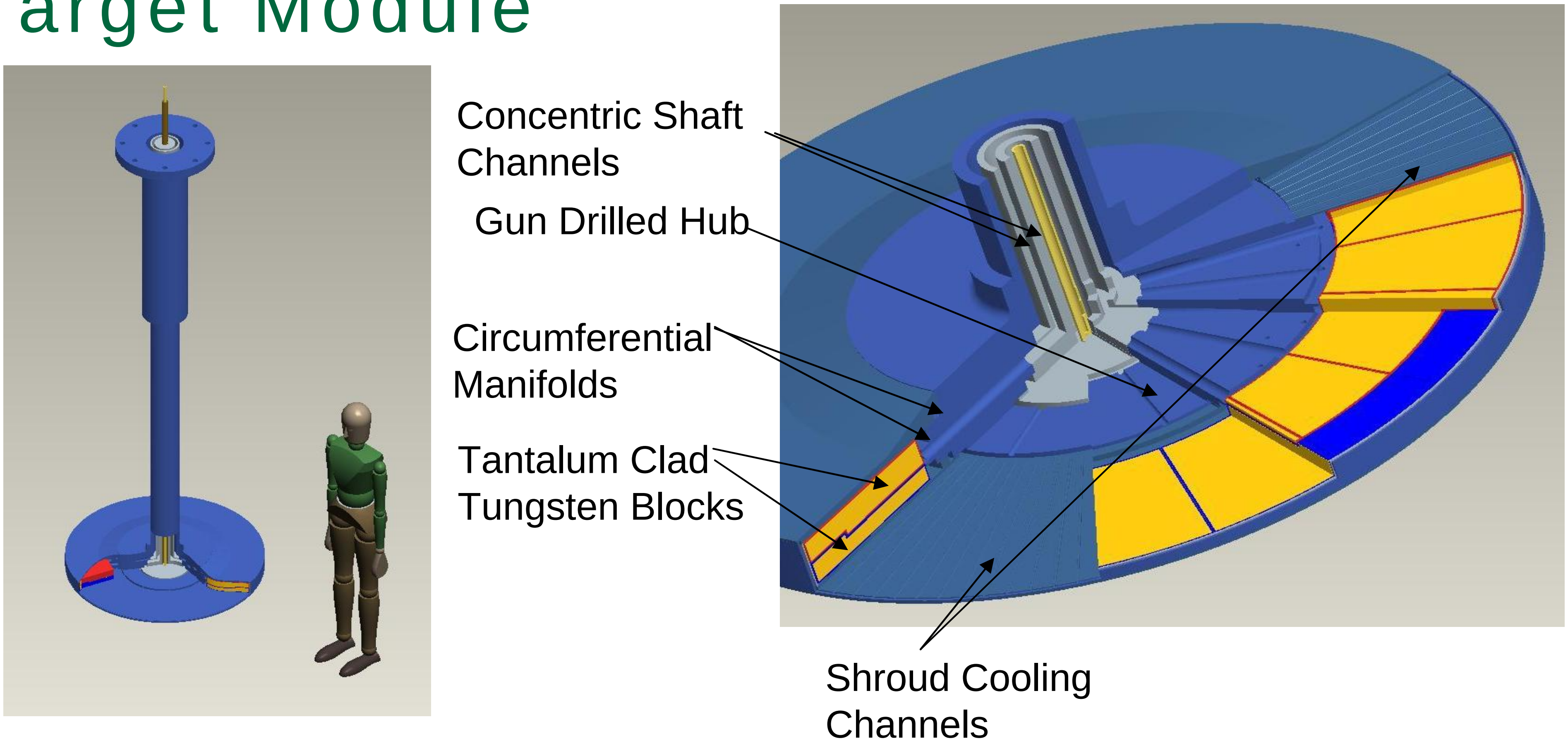
Off Normal modes with decay heat

- Secondary loop cooling within shell structure operating, stagnant primary cooling water in gaps within shell
  - Target wedges stay below water saturation temperature
- Helium in all gaps and reflector assemblies at 50 C. Simulates failure of primary and secondary loops but intact Core Vessel.
  - Maximum tungsten temperature ~ 400 C
- Air in all gaps and no active target cooling – reflector plugs maintained at 50 C – Simulates a major failure of both cooling systems and also the core vessel helium containment.
  - Maximum tungsten temperature ~ 700 C
- Tungsten/steam interaction threshold ~ 800 C
  - No vaporization of the target material should occur
  - Possible air-tantalum interaction above ~ 500 C
- We believe the safety case will be acceptable but further studies are planned for STS conceptual design

Mechanical Design

- **The design of the STS rotating target progressed in concert with the analysis**
- **Layouts of the rotating target in an STS facility were completed to confirm feasibility and define limitations.**
- **A preliminary failure mode analysis was completed to support the safety case and assist with understanding the necessary support facilities.**

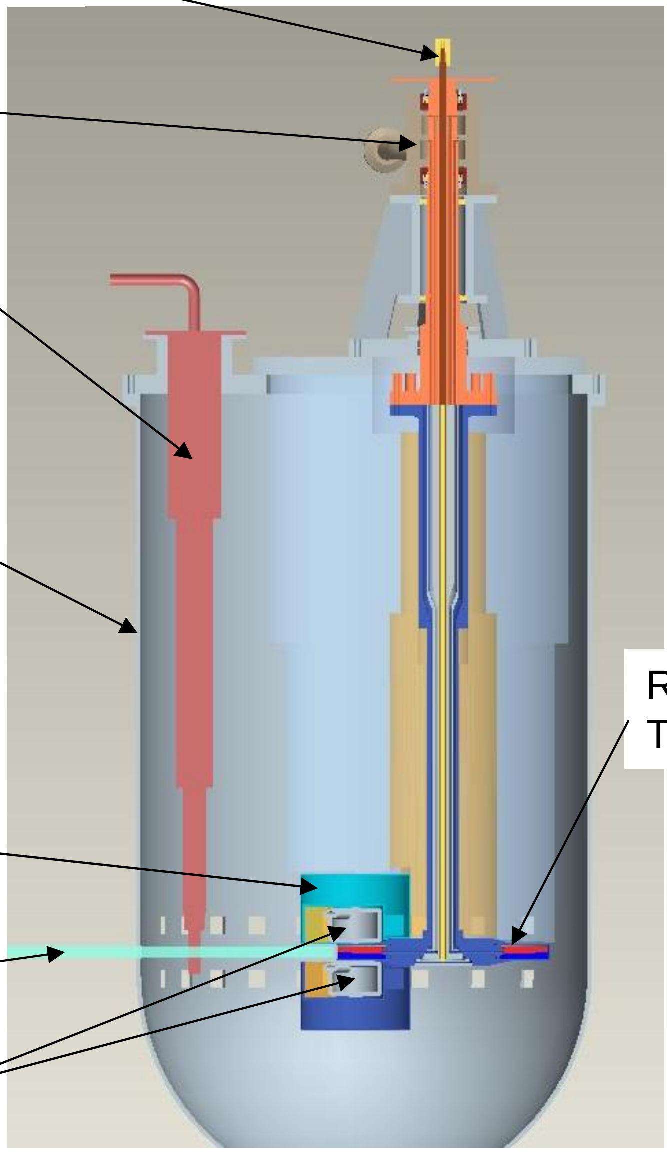
Target Module



- **The target module includes the clad segments, shroud and axle.**
- **The joint between the target and drive modules must be very precise. This joint also includes a significant water seal assembly.**
- **Concentric pipes inside the axle will require differential thermal expansion capability.**

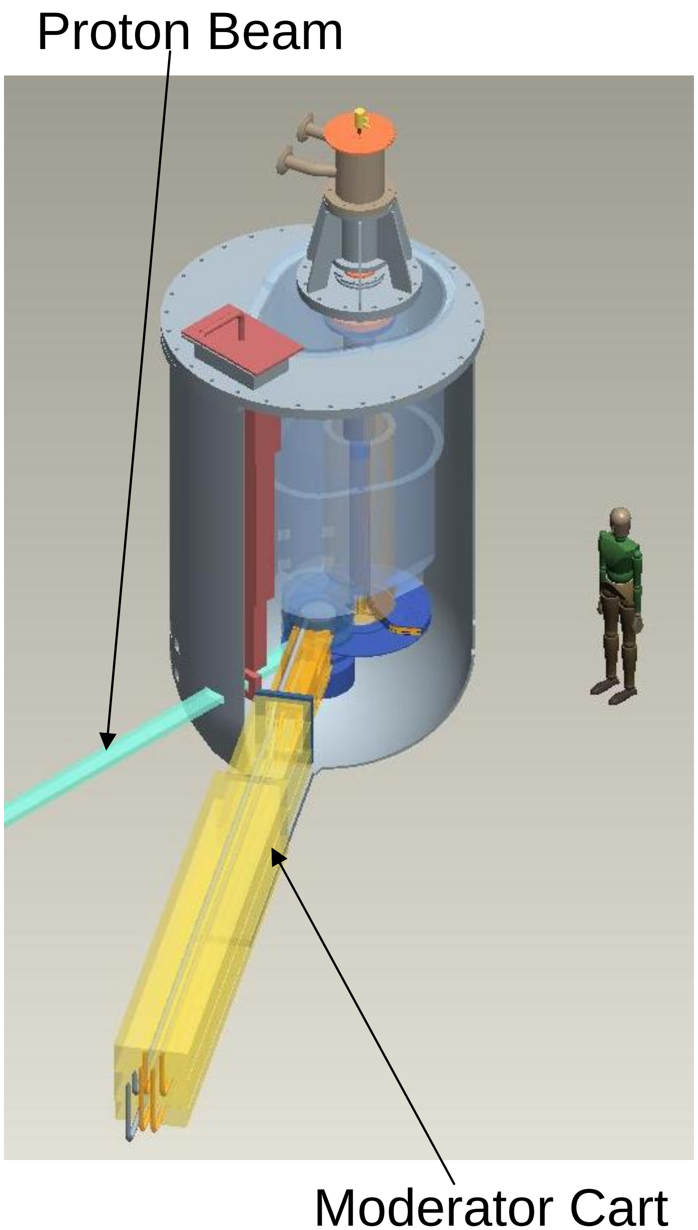
Target Axle and Drive Configuration

- **Optimization studies of drive and axle positions resulted in a basic layout of an overhead drive system located outside the core vessel.**
- **This arrangement provides for hands-on maintenance access after a few days of decay time.**
- **The drive, seal and bearings are located away from the high radiation area. Activated target cooling water is expected to generate approximately 1 G/hr in the drive enclosure during beam-on operations.**
- **The drive module will have extensive power, temperature and vibration monitoring to provide advance warning of bearing and seal deterioration and failures.**

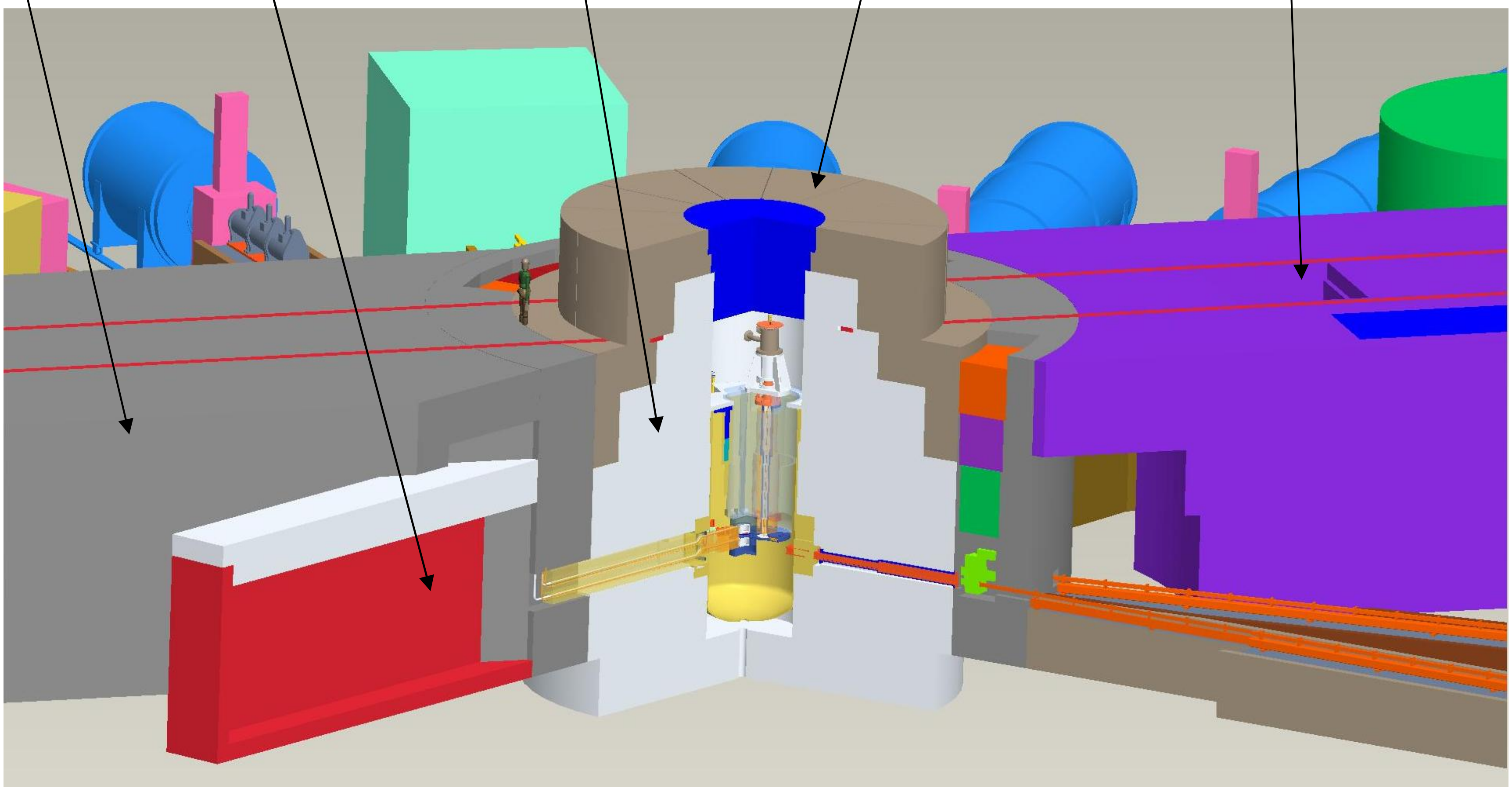


Moderator Interface

- **The life expectancy of the target is 5 to 6 years for 10 dpa in the front window.**
- **The expected life of the moderators is ~ 1 year (20 dpa); thus it is important to separate the maintenance access of the two assemblies.**
- **The lower moderator is trapped under the rotating target**
- **An optimization study resulted in the selection of a horizontal, cart mounted moderator assembly positioned up-stream of the target.**
- **This configuration supports individual moderator change-out and maintenance without interfering with the target.**



Second Target Station

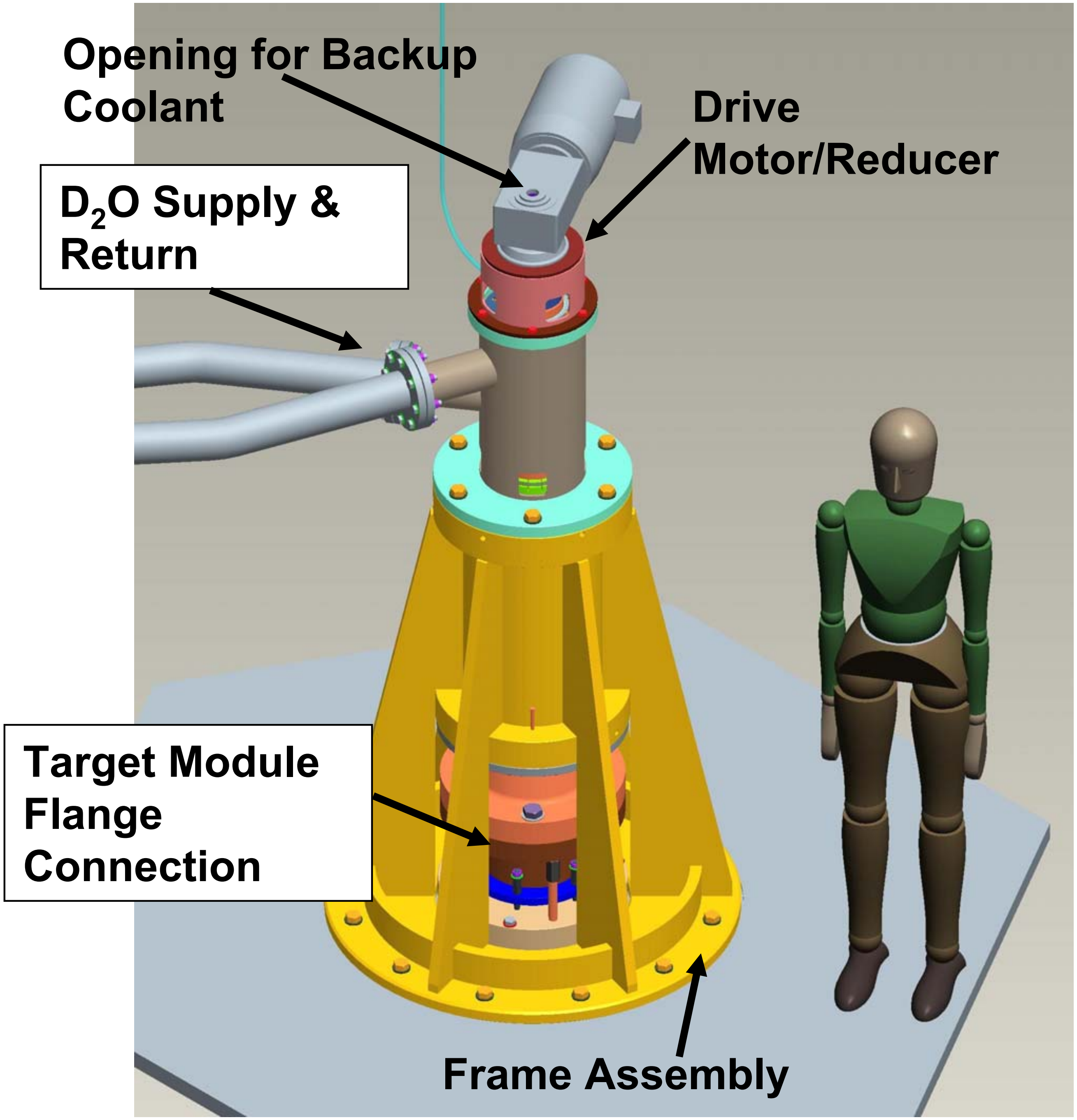


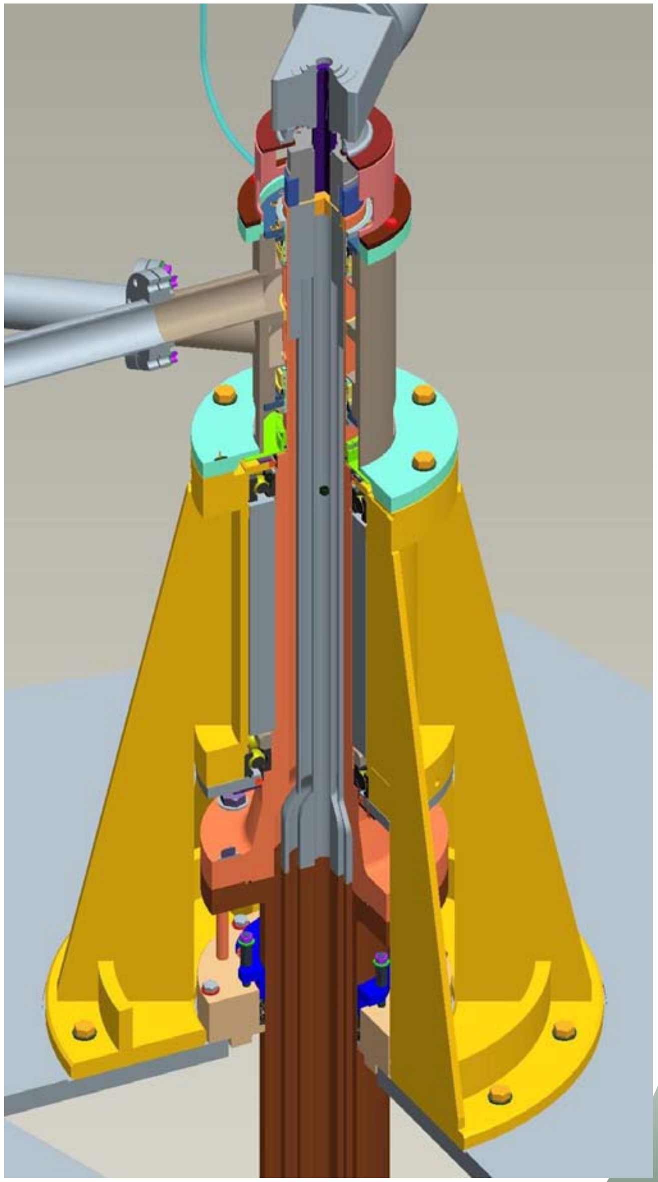
The use of curved beam guides is expected to eliminate the need for primary vertical shutters within the monolith

Basic Drive Module Configuration

- **The minimum size of the drive shaft (.165 m) was determined by the predicted water flow requirements.**
- **The maximum shaft size (.172 m) at the seals was determined by the available mechanical face seal. The resulting wall thickness is sufficient to transmit the rotary drive torque but not a significant bending force.**
- **The drive reducer assembly is located on top for accessibility.**
- **The bearing assembly is placed beneath the water coupling so the drive shaft wall thickness can be increased to handle bending and bearing loads.**
- **Space is left beneath the bearing assembly to permit access to the drive shaft/target axle interface and vessel seal.**
- **The backup cooling system is inserted, independently through the drive module.**

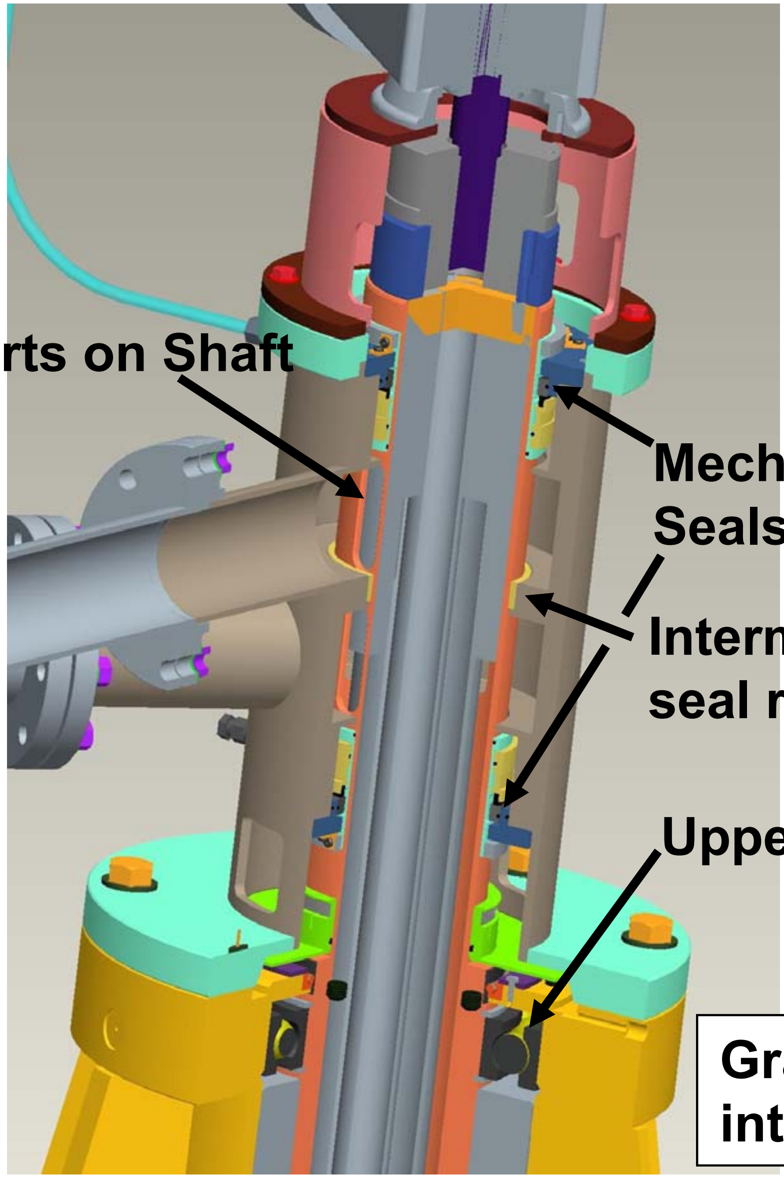
Drive Module Configuration



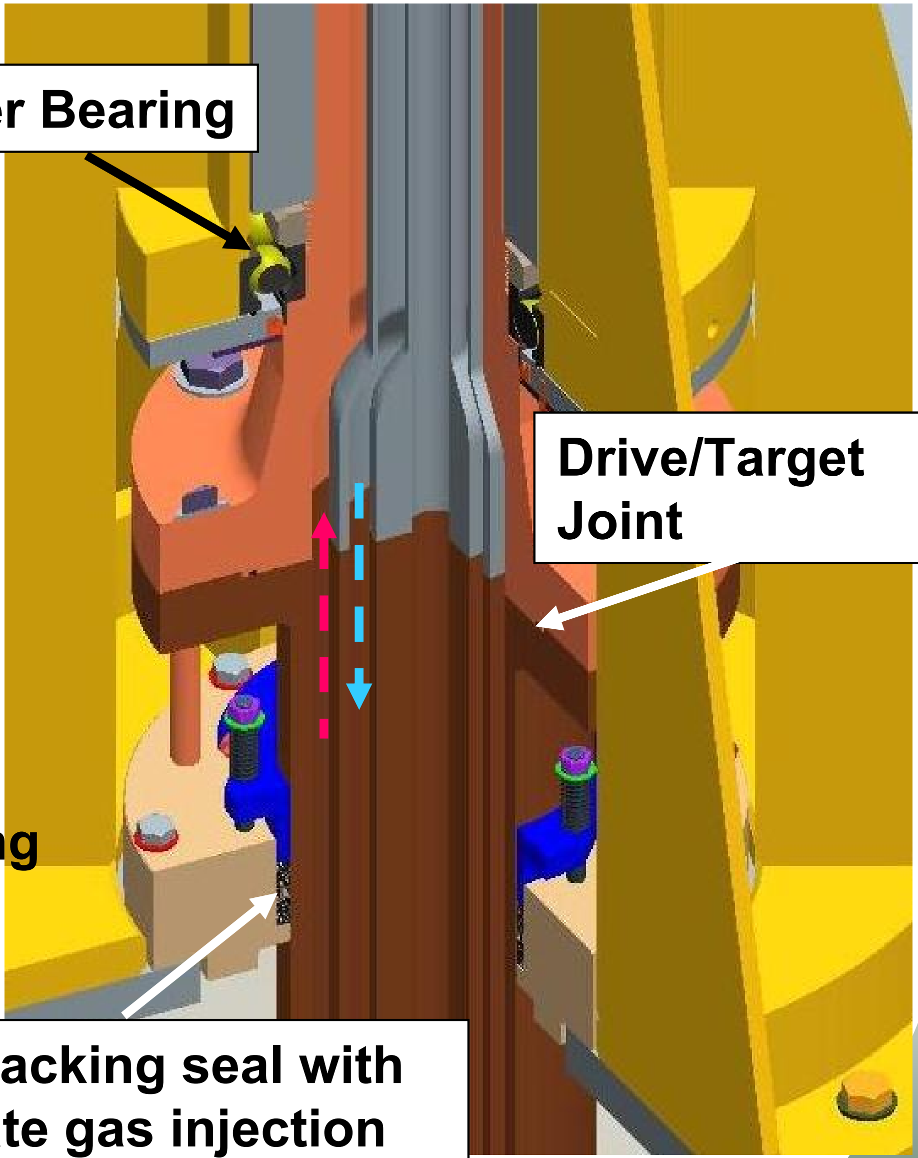


Section View

Upper and Lower Drive Unit Sections



Upper Section



Lower Section

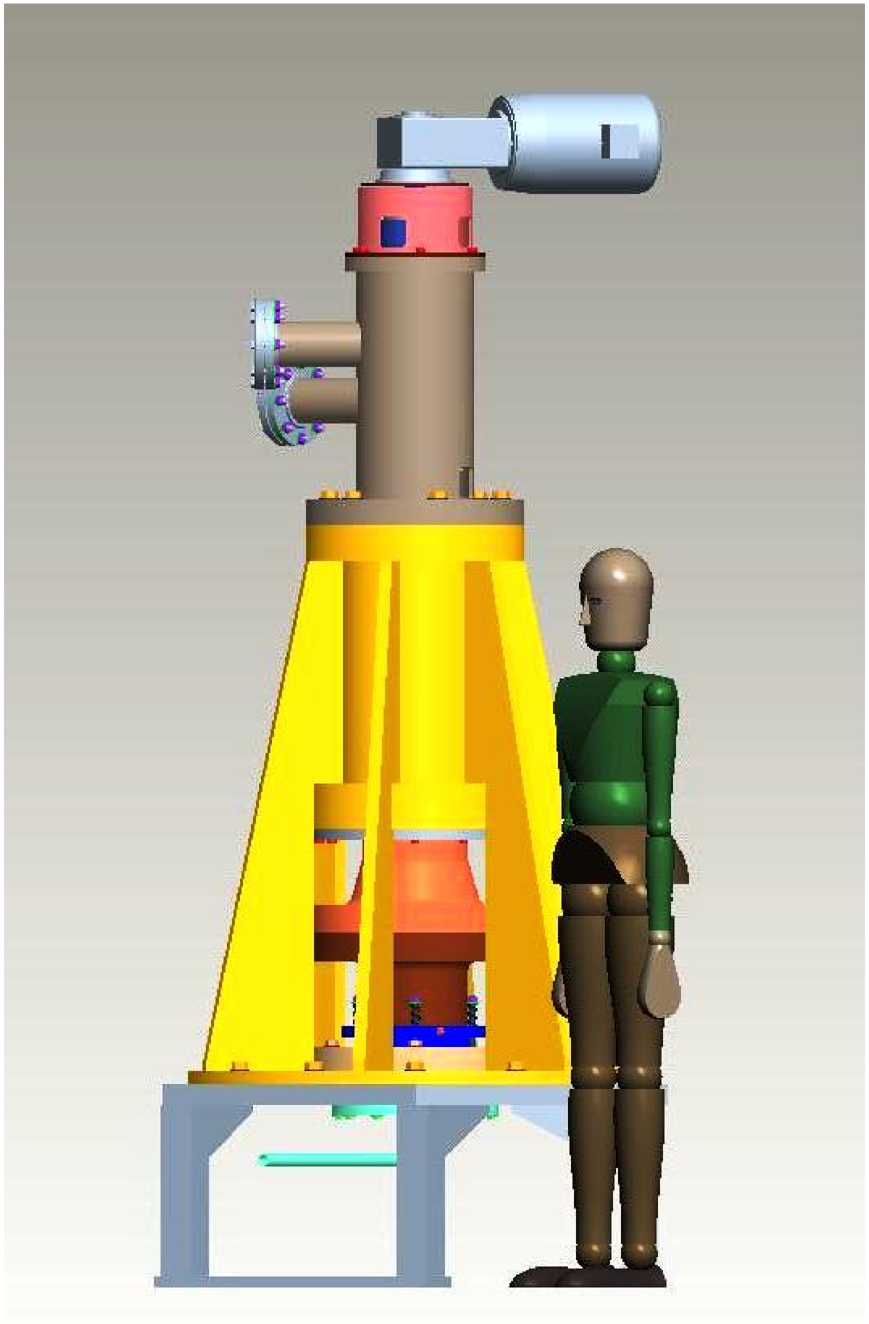
Rotating Target Development

Rotating target development work is proceeding in China, Japan, Europe and the US.

- **Significant Development Milestones:**
  - **Develop configurations suitable for the next generation of accelerator based spallation sources.**
  - **Build and test precision drives based on the proposed configurations,**
  - **Build and test cooling water flow test apparatuses,**
  - **Develop data on the metallurgical properties of Tungsten after exposure to proton beams,**
  - **Evaluate alternative cladding materials,**
  - **Develop a thorough understanding of the fabrication requirements for large Tungsten segments,**
  - **Resolve all safety issues; particularly those related to the water/Tungsten interaction,**
  - **Develop target handling and operating concepts which address the control of after heat.**

ORNL 2009 Mockup Test

- **The phase one mockup will test the drive, seals and bearings in a prototypical assembly**
- **It will be designed for inclusion in a larger assembly which includes a mockup target to be added later**
- **Reliability and durability are the key features to be demonstrated in testing this year**



Summary

- **Preliminary results for a 3 MW rotating target appear encouraging and no "show stoppers" have been identified**
  - **Equivalent neutronic performance compared to a mercury target and much longer life,**
  - **Further safety studies are planned,**
  - **Hub design requires flow channel layout refinement,**
  - **Water channeling around wedges needs to be developed**
  - **Tungsten wedge fabrication issues including cladding, HIPing and welding need to be discussed with vendors.**
- **Mockup Testing of the drive, bearings and seals this year should give confidence and basis for future incorporation and testing of a target module**