An Update on SNS STS with Emphasis on the Target Activation

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Outline

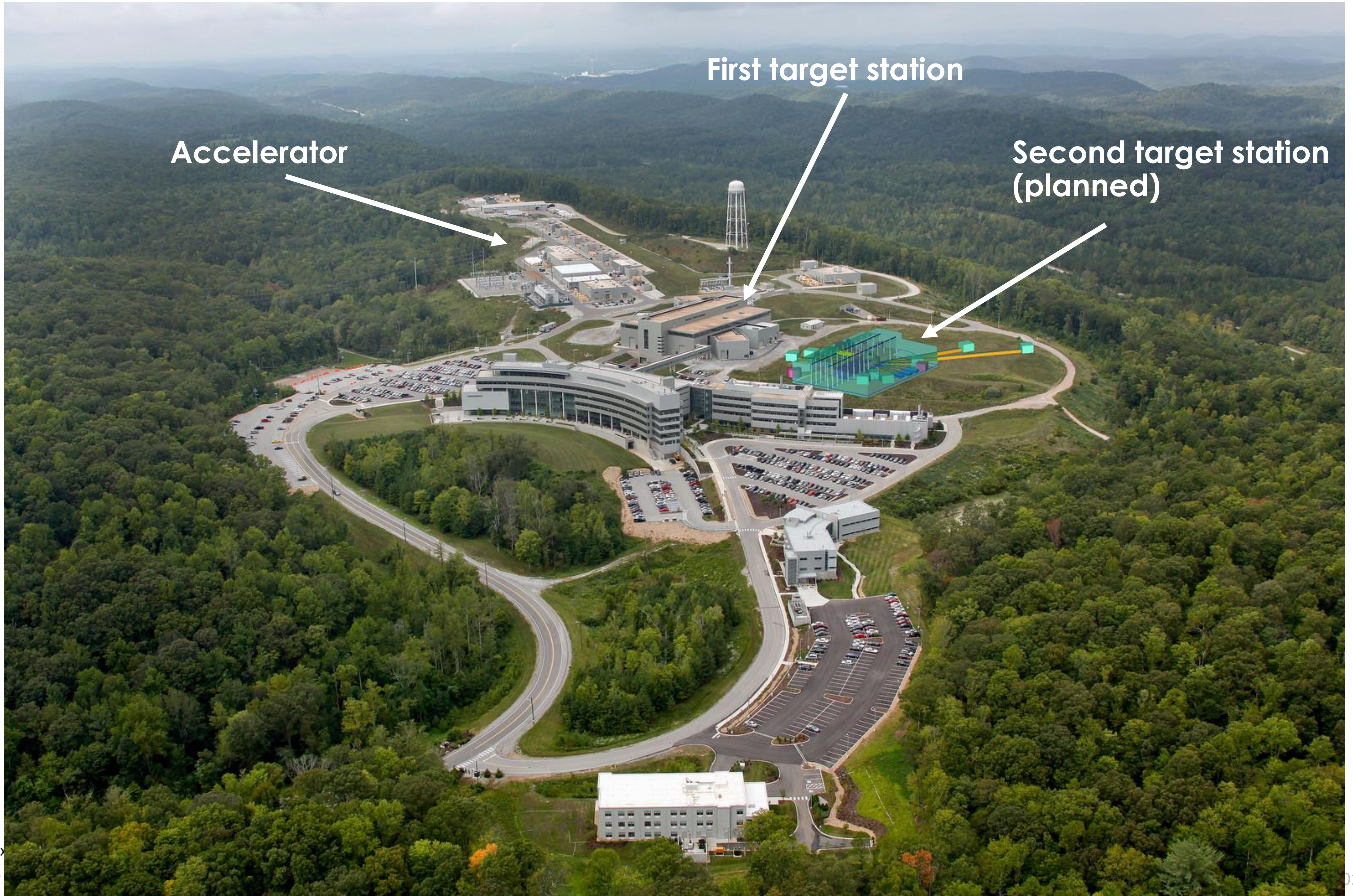
- Short overview of the SNS
- Second Target Station (STS)
  - STS objectives
  - STS target evolution
  - Activation and decay heat
  - Effects of proton beam footprint size
  - Expected STS performance
- Conclusion

SNS

Accelerator Driven

Pulsed

Spallation Neutron Source



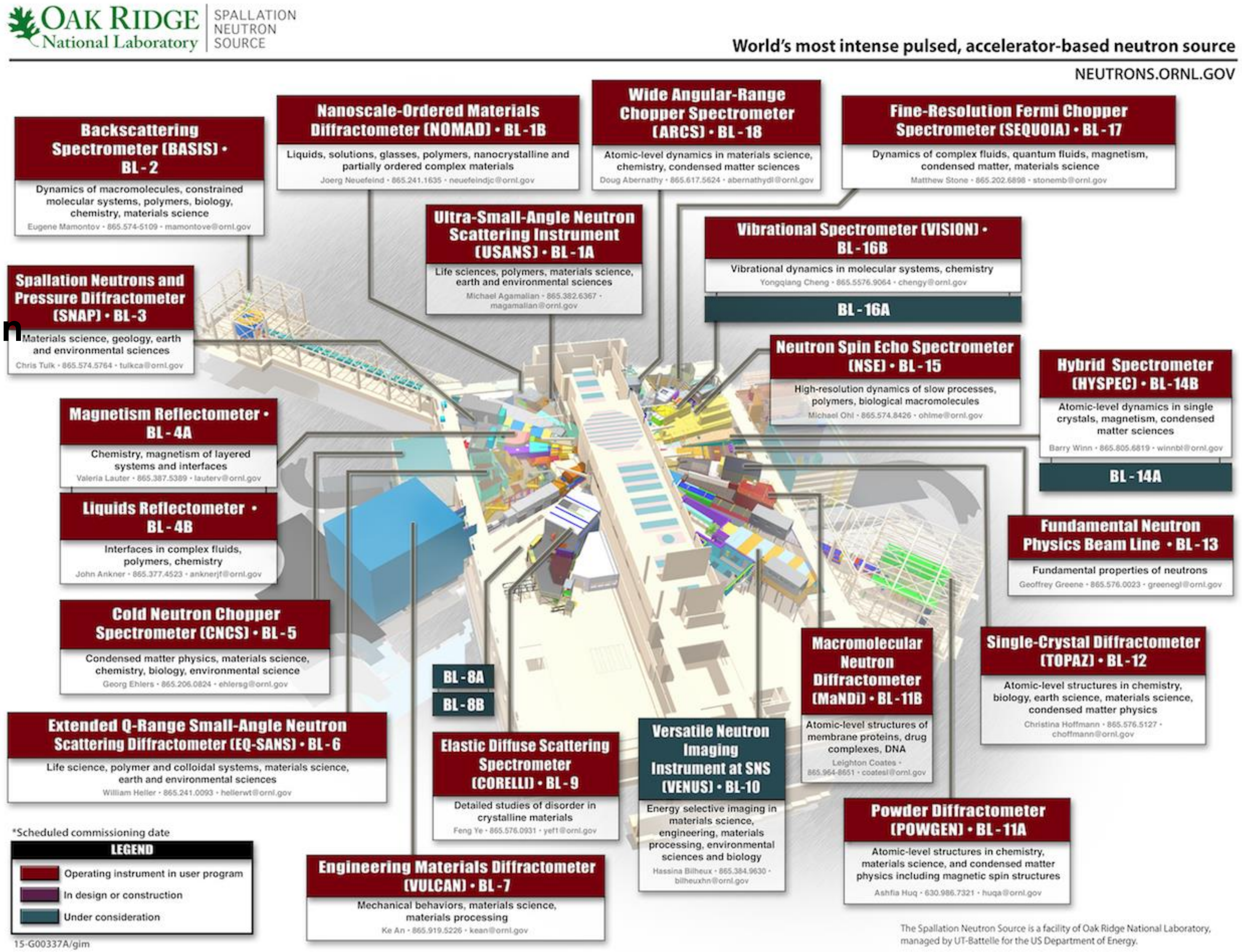
Overview

STS FTS

Total 22 beamlines

19 beamlines in operation with instruments

One under construction



SNS STS history

- **Since 2006: SNS FTS in operation, designed to allow two major upgrades:**
    - **PPU:** proton power upgrade, doubling the SNS beam power
    - **STS:** adding second target station
- **Jan. 2009: DOE approved STS scientific mission need (CD-0)**
- **2010-2012: long (1 ms) and short (< 1μs) pulse options explored**
- **2013-2014: pre-conceptual design effort**
- **Jan. 2015: published Technical Design Report**
- **Sept. 2015: rotating target recommended for the baseline configuration**
- **Oct. 2015: STS workshop conducted to seek the community's input on all aspects of the project with the emphasis on the instruments**
- **Jan. 2016: Funded to start the conceptual design work on rotating target**
- **April 2017: STS updated, rotating target, short pulse (< 1μs)**
- **June 2017–Sept. 2018: STS work largely on hold, priority given to PPU**
- **Sept. 2018: STS work resumed**
- **Feb. 2019: performed STS Target Systems Conceptual Design Review**
- **August 2019: STS project office established at ORNL**
- **June 2020: potential for DOE CD-1 review of STS**

Upgrading SNS to a world-leading fourth-generation neutron source

SNS-PPU

- Increases power of accelerator from 1.4 MW to 2.8 MW
- Increases proton energy from 1GeV to 1.3 GeV
- Increases power delivered to the FTS to 2 MW
- Increases neutron flux on existing FTS beam lines
- Provides platform for construction of STS
- Received DOE CD-1 approval 4/4/2018
- DOE/SC CD-3A approved 10/5/2018
- DOE/SC CD-3B approved 9/3/2019 (long lead procurement)

SNS-STS

- Rotating tungsten target, water cooled
- Will receive 700 kW proton beam power
- Short pulse (< 1μs), 15 Hz repetition rate
- Will accommodate 22 beam lines
- Optimized for cold neutron pulses with the highest peak brightness
- Currently preparing for DOE CD-1 review projected in June 2020

FTS/STS parameters

FTS (upgraded)

- Short (<1 μs) proton pulses
- 1.3 GeV protons
- 45 pulses/second
- 2 MW beam power
- 44.4 kJ per proton pulse
- Large beam footprint:
  ~ 140 cm^2
- Hg target

STS

- Short (<1 μs) proton pulses
- 1.3 GeV protons
- 15 pulses/second
- 700 kW beam power
- 46.7 kJ per proton pulse
- Smaller beam footprint:
  ~ 60 cm^2 (90% of the beam)
- W target (Ta clad, water cooled, segmented, sync.)

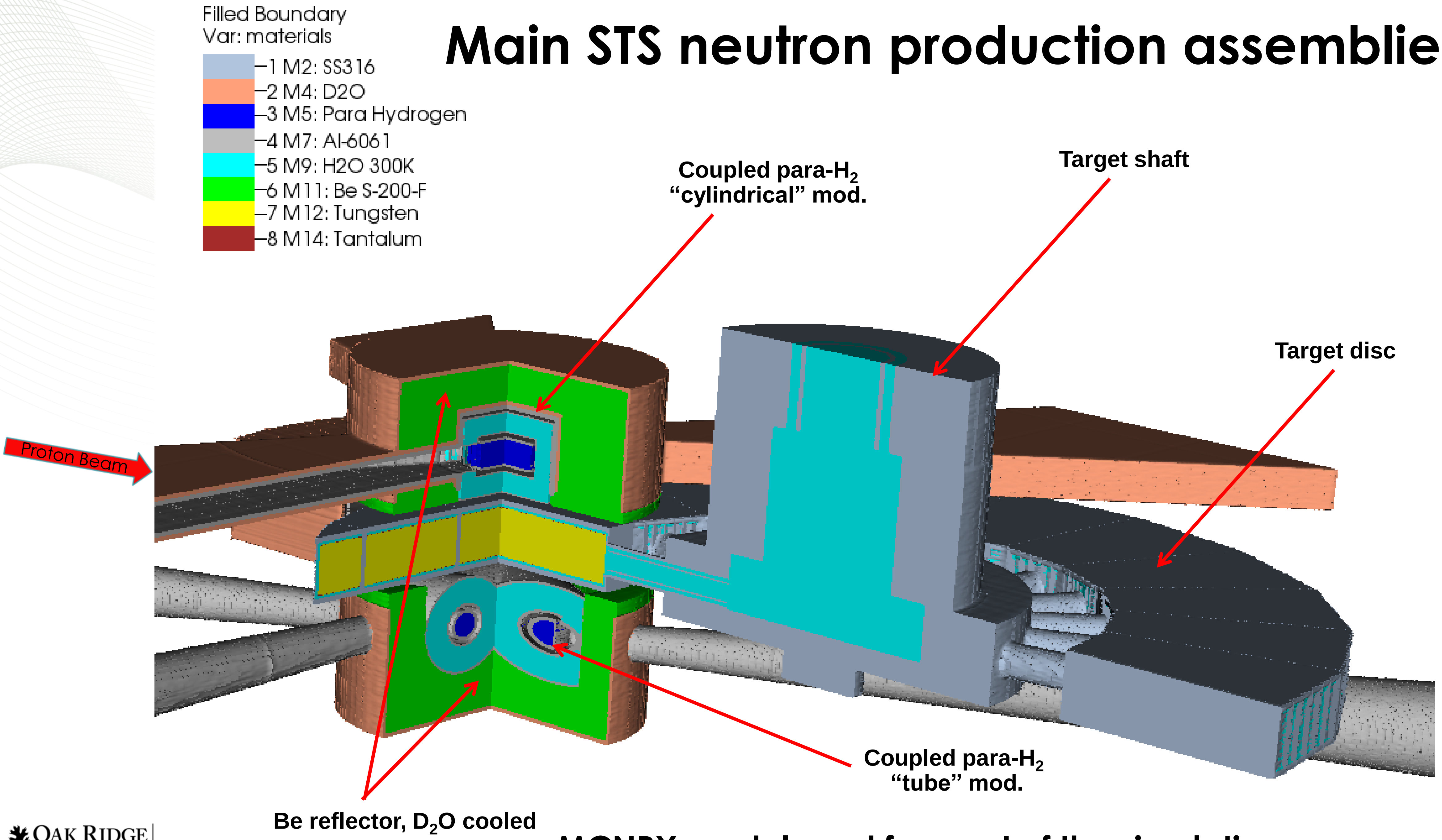
STS requirements

- **Provide high peak brightness at long neutron wavelengths**
- **Accommodate 22 instruments**

STS neutronic design

- **The STS design requirements lead to:**
  - Compact target design
  - Small beam footprint with compact high intensity neutron production zone
  - Tight moderator-to-target coupling
  - Optimization of target/moderator/reflector design
- **Constraints include:**
  - Dimensions of the viewed areas of the moderators as required by the instruments/beamlines
  - Target peak heating rates below limits imposed by cooling capabilities
  - Radiation damage rates low enough to allow for sufficient target and moderators lifetime
- **Stationary and rotating target options considered**
- **Current baseline is rotating target**

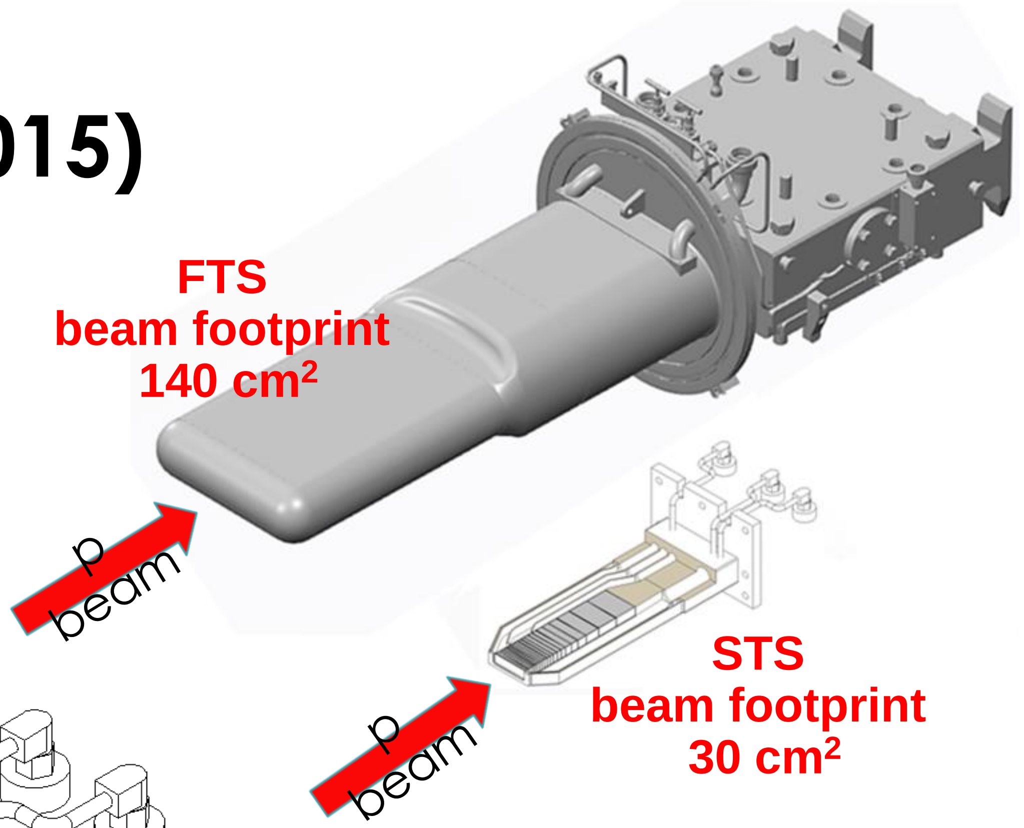
Main STS neutron production assemblies

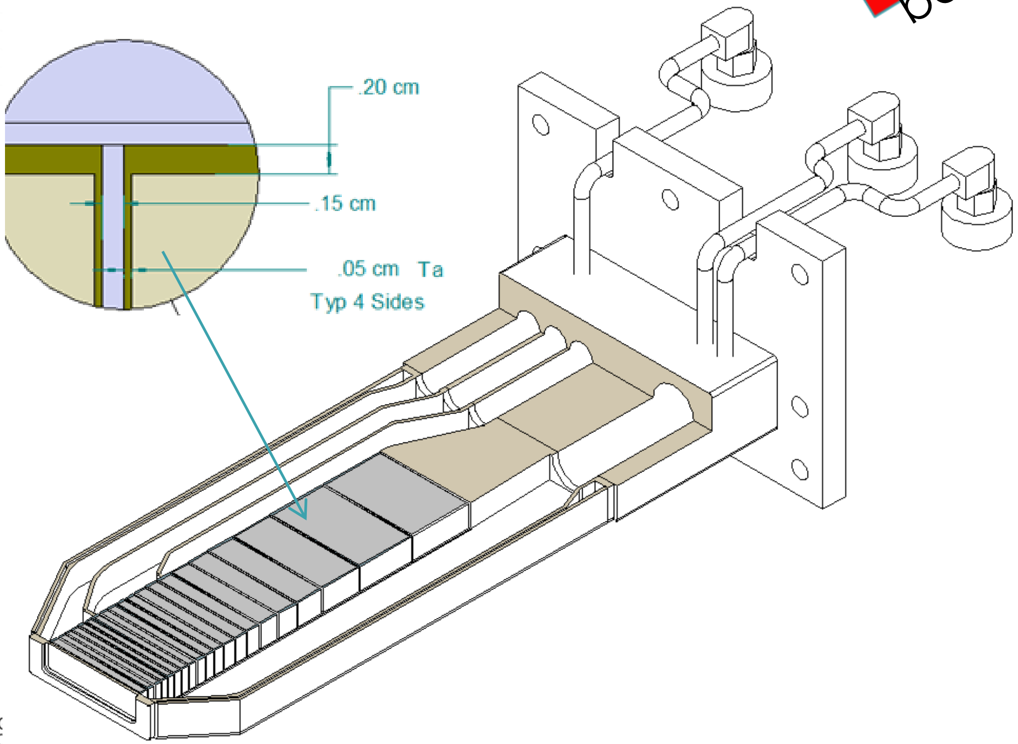


MCNPX model used for most of the simulations

STS evolution: stationary target layout (2015)

- 17 W plates clad with Ta
- 30 cm total length
- Cooled with D_2O

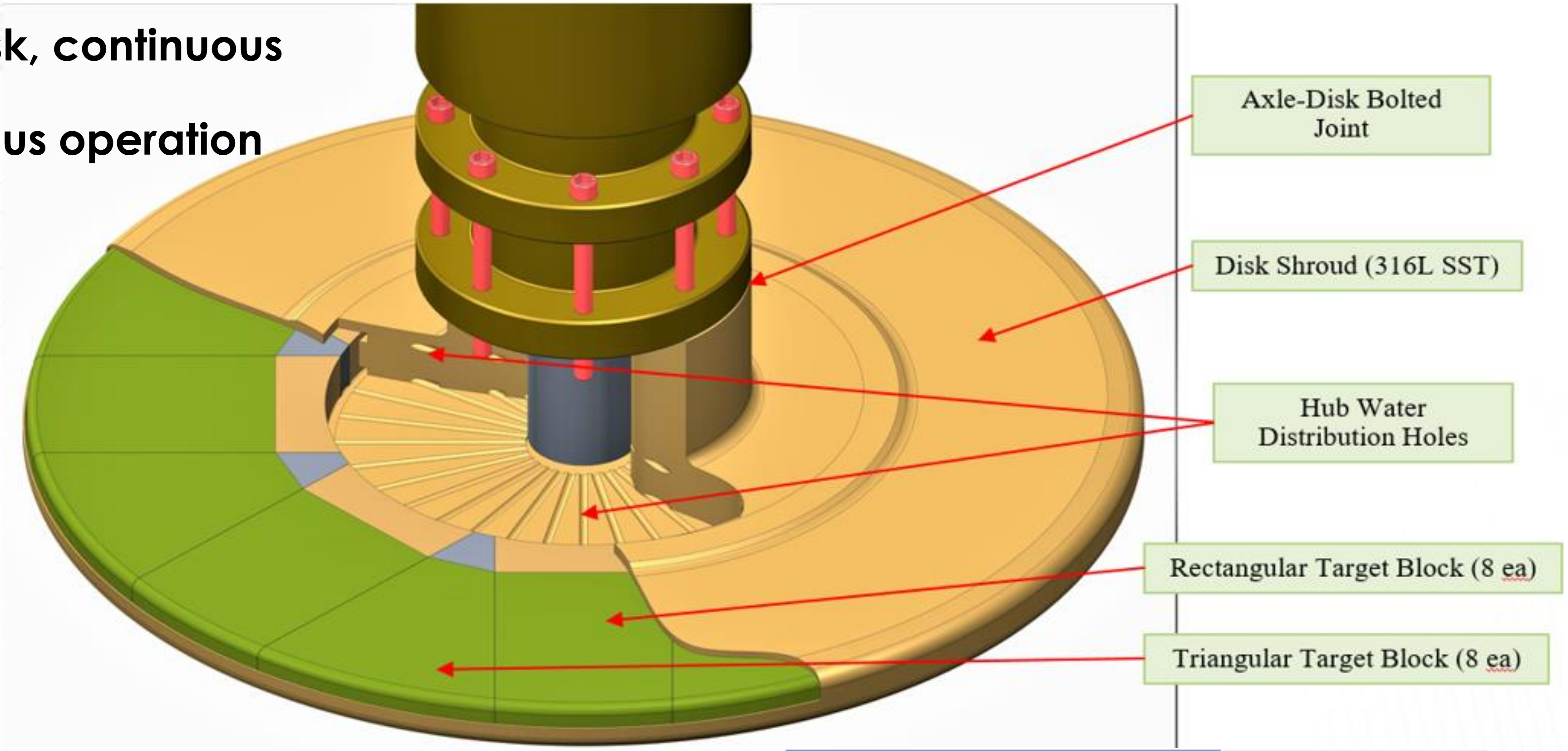




- Plate thicknesses vary to limit peak temperature in plate < 250°C, peak surface temperature < 110°C
- 1.5 mm cooling channels between plates

STS evolution: rotating target, previous design (April 2017)

- tungsten disk, continuous
- Ta clad,
- asynchronous operation
- D_2O cooled



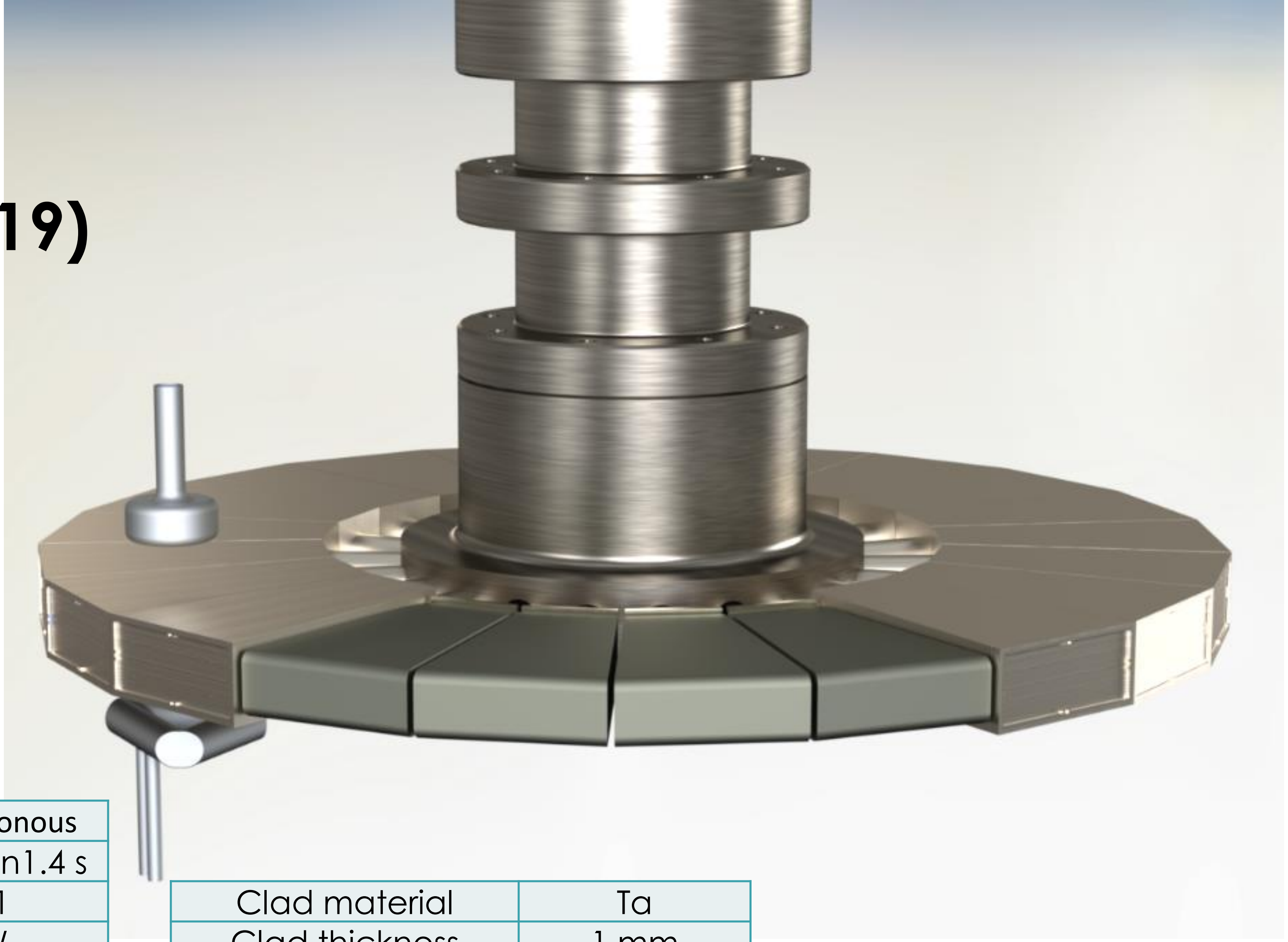
Target diameter	1.14 m
Tantalum clad thickness	1 mm
Tungsten/Ta plate thickness	5 cm
Plate radial depth	25 cm
Beam spot area (90%)	7.5 cm x 4 cm

Beam frequency	15 Hz
Beam Power	700 kW
Rotation speed	20 RPM
Timing	Asynchronous
Shell material	316L
Coolant	D_2O

Cooling: D_2O, 30^oC, 3 m/s nominal

STS evolution: rotating target, current design (2019)

- **21 tungsten segments,**
- **Ta clad,**
- **Synchronous operation**
- **H_2O cooled**



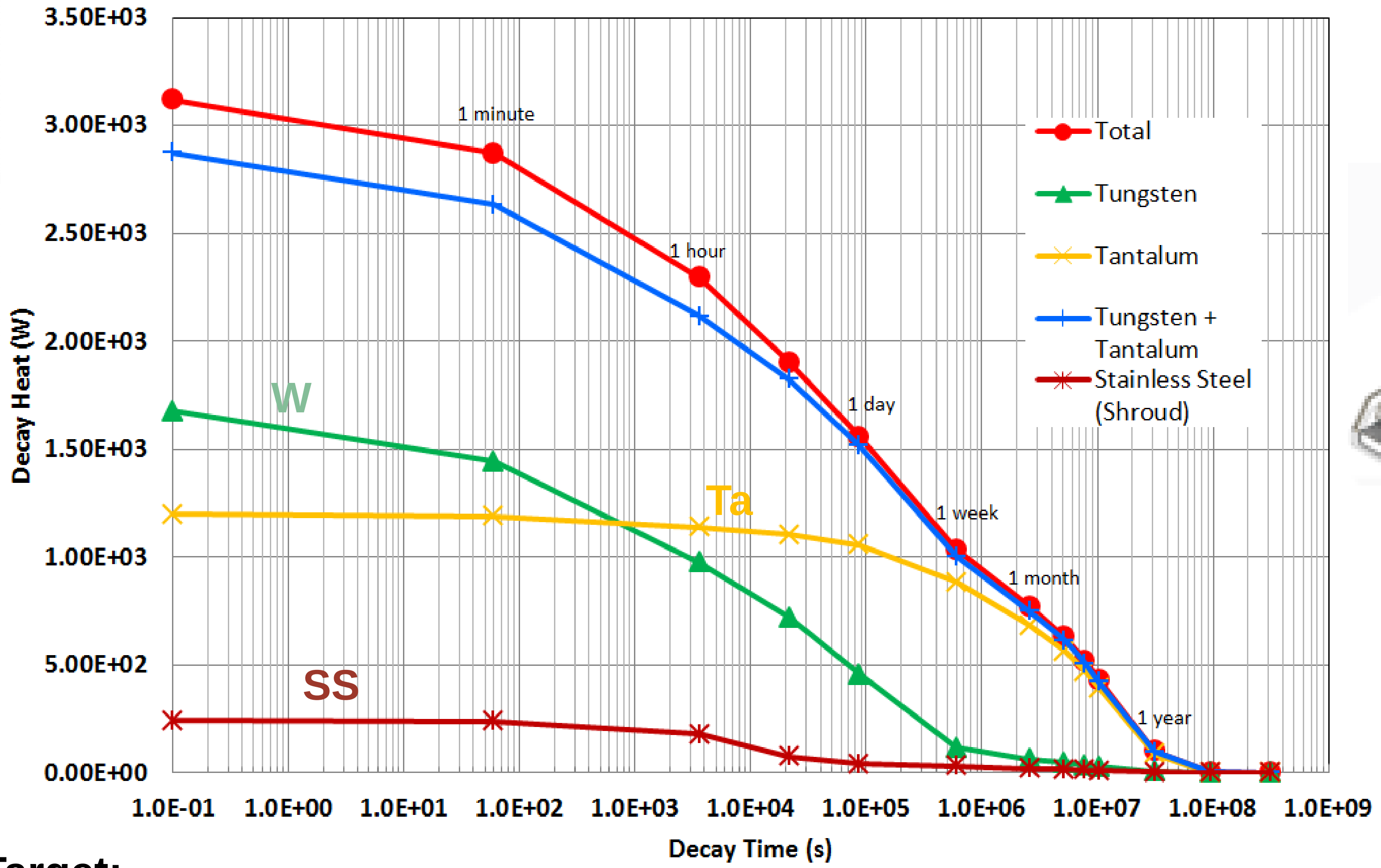
Rotating target	Synchronous
Rotational speed	1 turn in1.4 s
Number of segments	21
Target Material	W
W width	163.7 mm
W height	58 mm
W length	250 mm

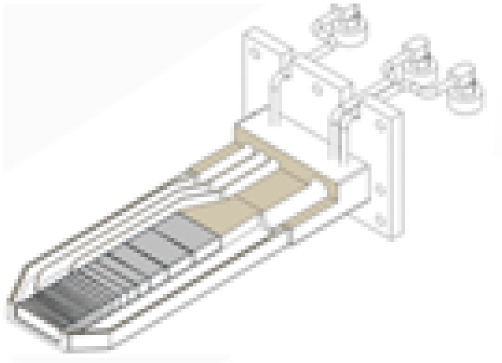
Clad material	Ta
Clad thickness	1 mm
Disk diameter	1156 mm
Shroud material	316L SS
Cooling	H_2O

Stationary target decay heat rate versus decay time

Decay heat is high, dominated by tantalum at t > ~12 minutes;
at 1day decay time ~ 75% of decay heat from Ta comes from Ta-182 ($t_{1/2}$ =114.4 d)

After 1 year of operation (5000 h/y), at 0.5 MW

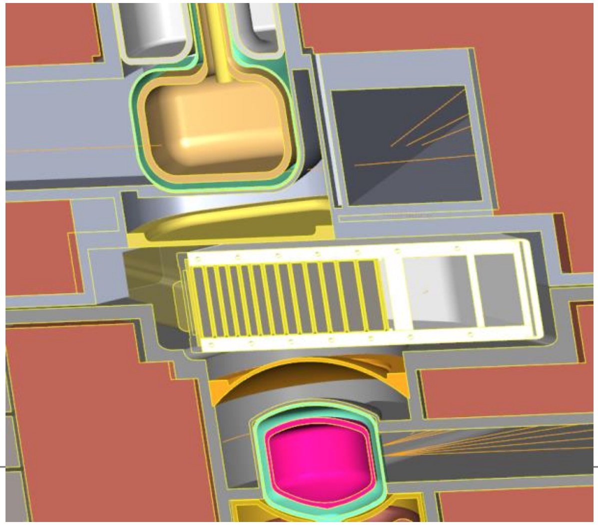




Target:
- **tungsten 23.6 kg**
- **SS 17.1 kg**
- **tantalum 2.7 kg**

Decay heat:
- **500 W at ~ 97 d**
- **300 W at ~ 220 d**

Stationary target : loss of cooling accident with beam trip

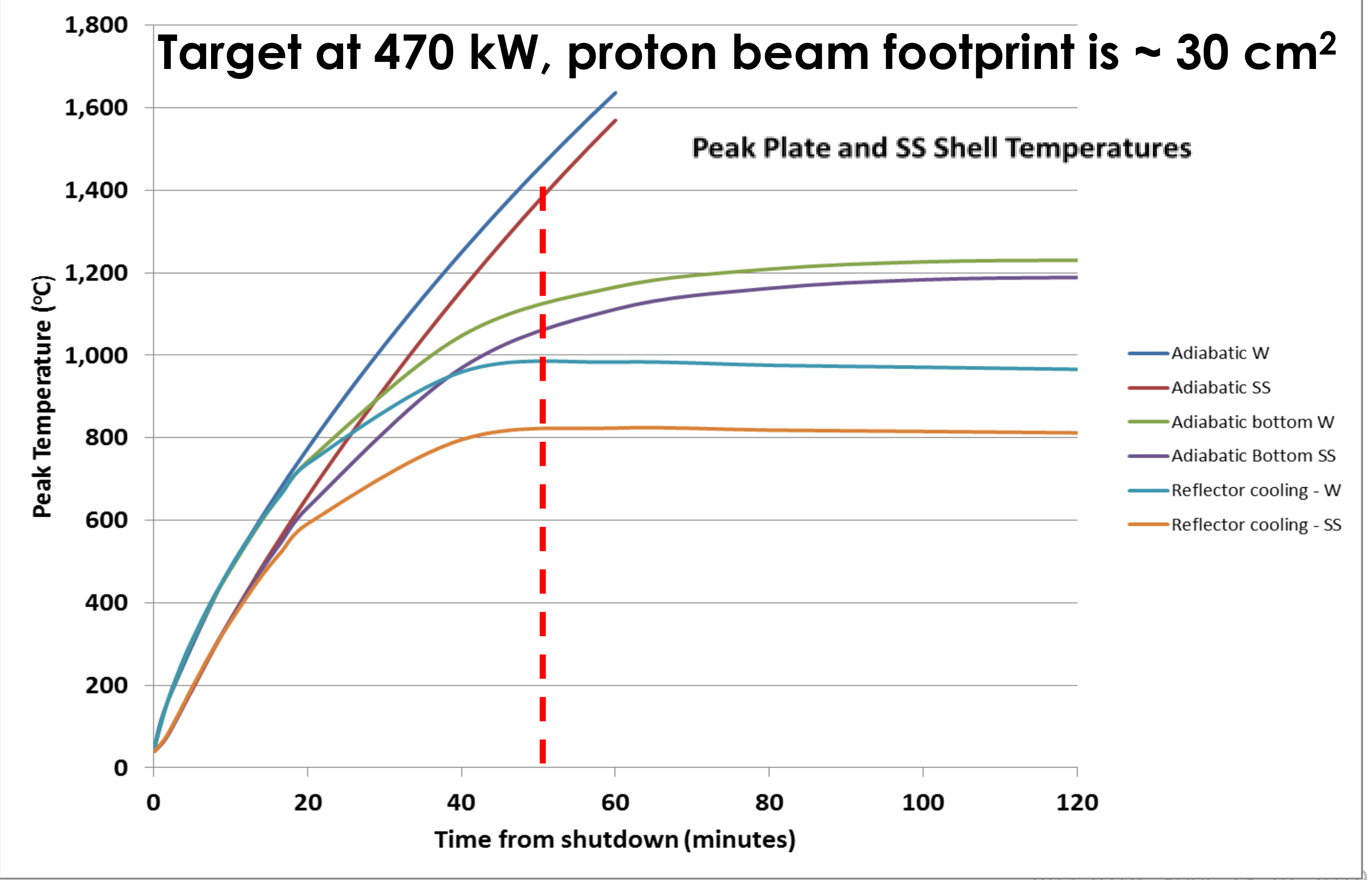


- **100 °C IRP heat sink above and below the target**
  - thermal radiation and gas conduction keeps the peak shell temperatures below ~ 825 °C and structural integrity would be maintained
  - Tungsten vaporization rate will be very low assuming tantalum integrity is lost.
- **100 °C IRP heat sink above and dry pre-moderator below the target**
  - Peak SS shell ~ 1200 °C and structural integrity may be lost due to softening
- **Target and IRP fully dry**
  - Target shell melting point near front reached in ~ 50 minutes
  - vaporization starts after ~ 20 minutes

Conclusion:

- **Irrecoverable facility impacts;**
- **unmitigated safety impacts of the loss of cooling with a dry target and IRP were deemed not acceptable.**

Operation at 700 kW would make the consequences more severe.



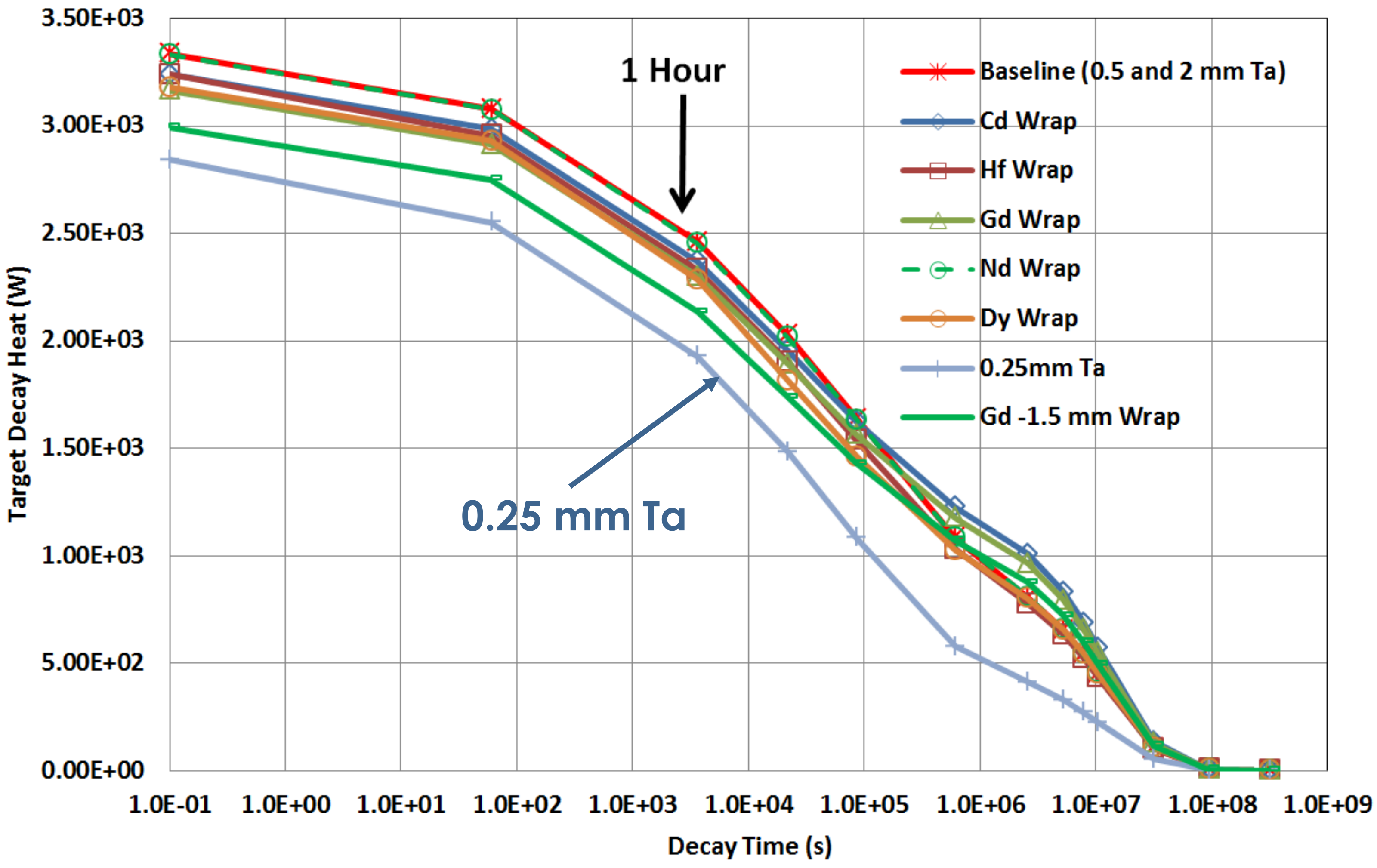
Stationary target: can decay heat be reduced ?

- **Add thermal absorber "wrap" around the target: a** 0.3 to 1.5 mm poison wrap does not significantly reduce residual heating

- **Reducing Ta clad thickness to 0.25 mm** (0.01 in) on all tungsten surfaces reduces the Ta decay heat by more than 50%, but increases W decay heat by 10 -12%, so full target decay heat is reduced by only 20% in the 8hour time range considered for the safety analysis.

- **Reduced tantalum clad thickness would only increase the time to reach unacceptable temperature levels but would not change the basic safety issues**.

- It is also important to note that the thin clad welds would be more difficult to perform with the high level of reliability required for the STS target.



Transition from stationary to rotating target

After the review In Sept. 2015 the rotating tungsten target was selected as the STS target design option.

The stationary target was abandoned due to:

- irrecoverable facility impacts during loss of coolant accidents,
- unacceptable on-site consequence to workers during worst-case accident scenarios,
- and the likely extent of infrastructure required to address these risks

Decay heat as an accident initiator was a driving factor to abandon stationary target

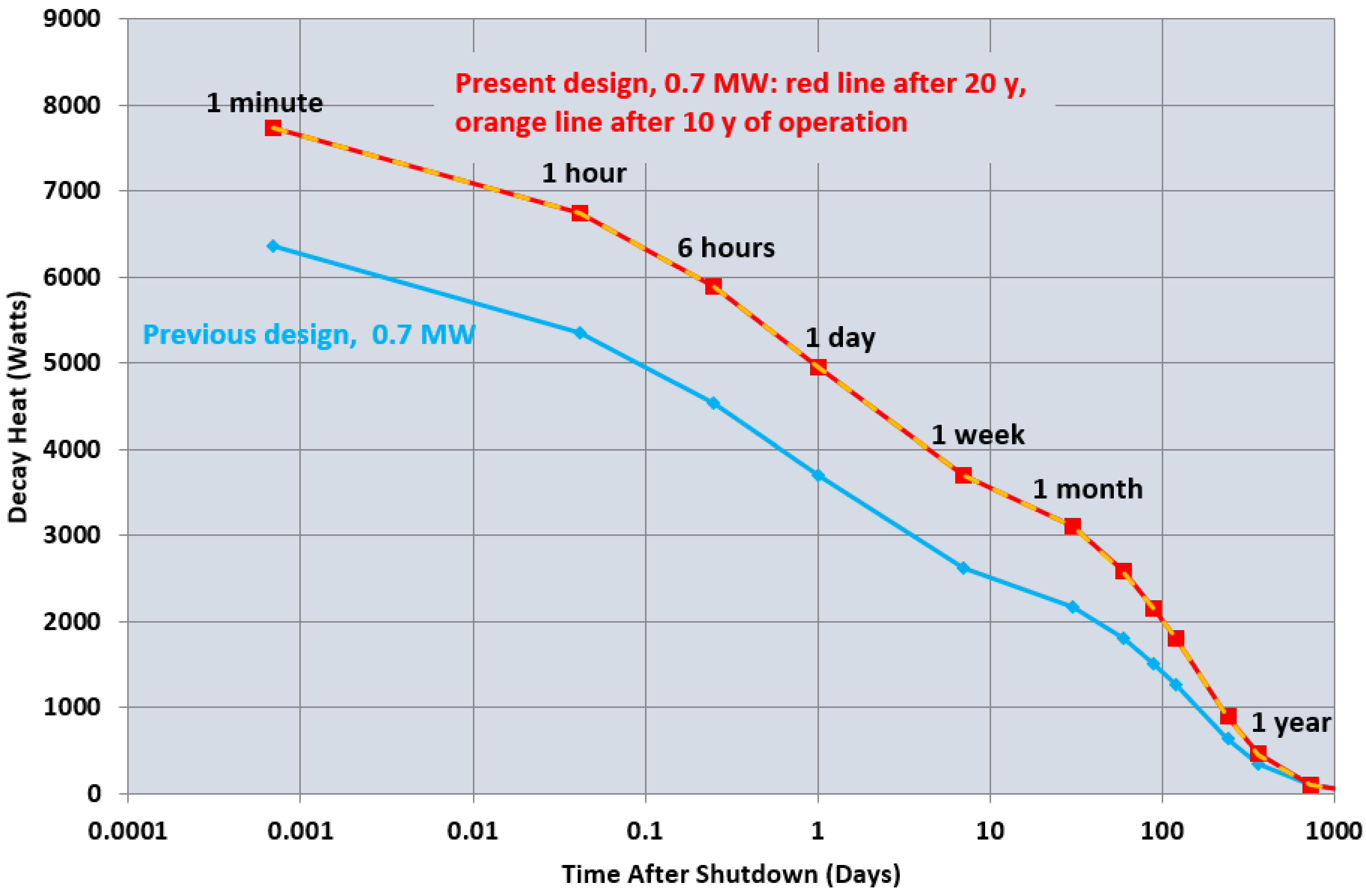
Rotating target was selected because:

- delivered the desired brightness,
- possessed acceptable worst-case accident consequences,
- eliminated decay heat as an accident initiator,
- possessed a multi-year lifetime
- the drive mechanism concept had been partially validated through successful operation of a full-scale mock-up at 60 rpm for 5,400 hours

Rotating target decay heat

Rotating target, present design:
after 20 y and
10 y of operation
(5000 h/y), at 0.7 MW

Rotating target, previous design:
after 20 years of
operation (5000 h/y),
at 0.5 MW and 0.7 MW

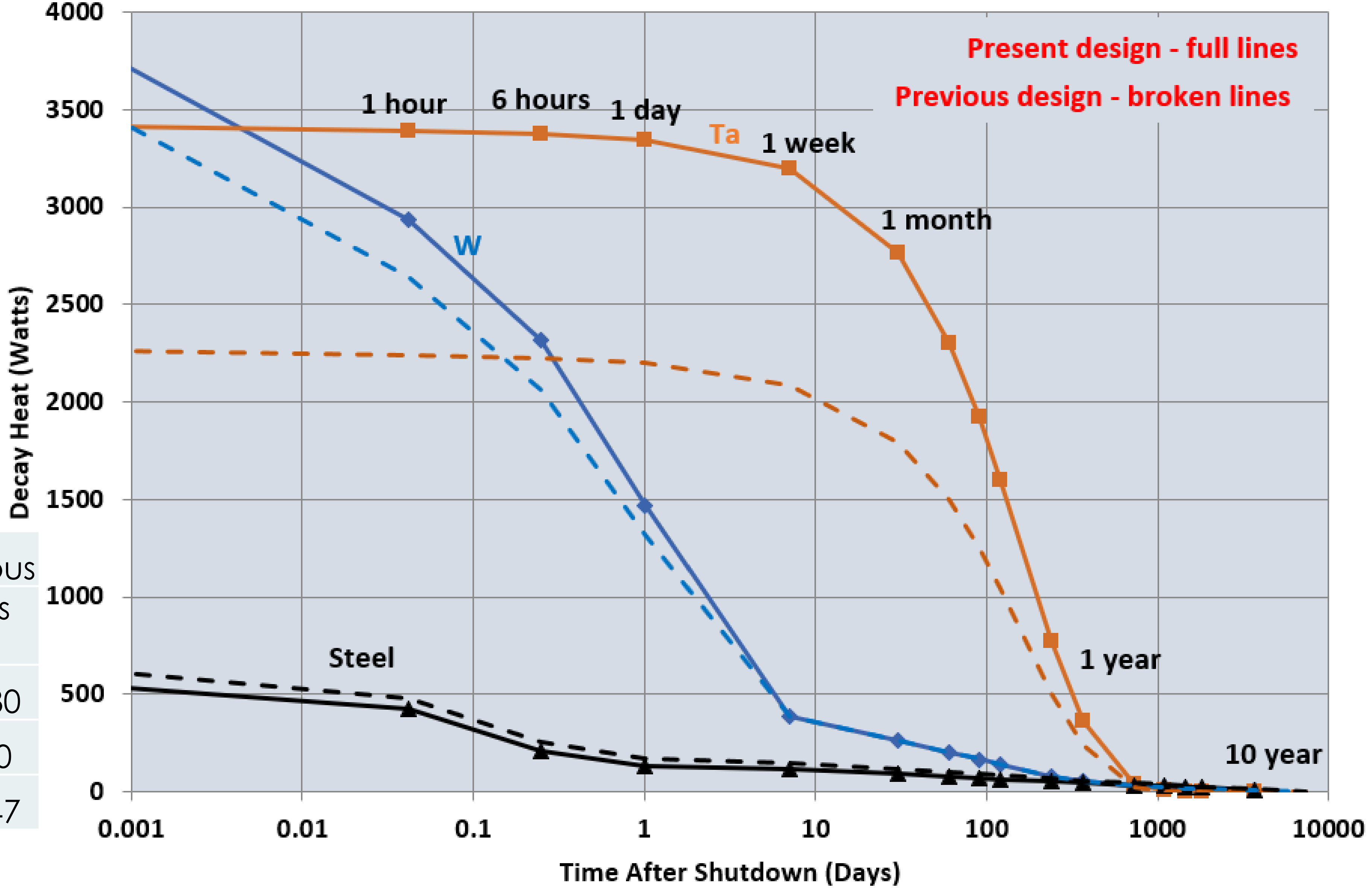


Rotating target decay heat, by material

20 years of beam-on operation (5000 h/y); 0.7 MW, 15 Hz

Ta contribution is dominant over long period of time.

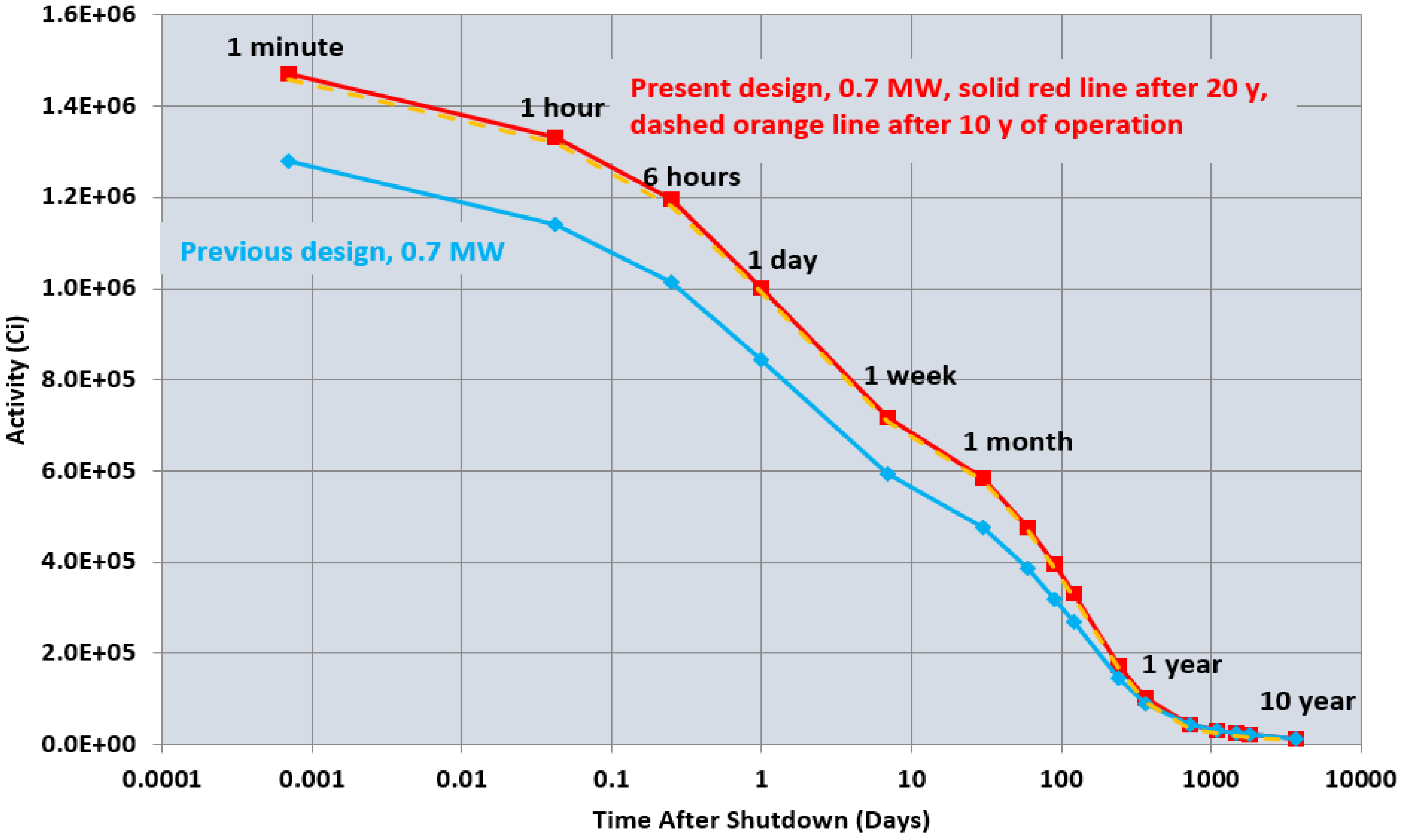
	Current Mass (kg)	Mass Ratio	Previous Mass (kg)
W	743.60	0.98	757.80
Ta	38.03	1.18	32.20
Steel	562.40	1.22	462.47



Rotating target activity

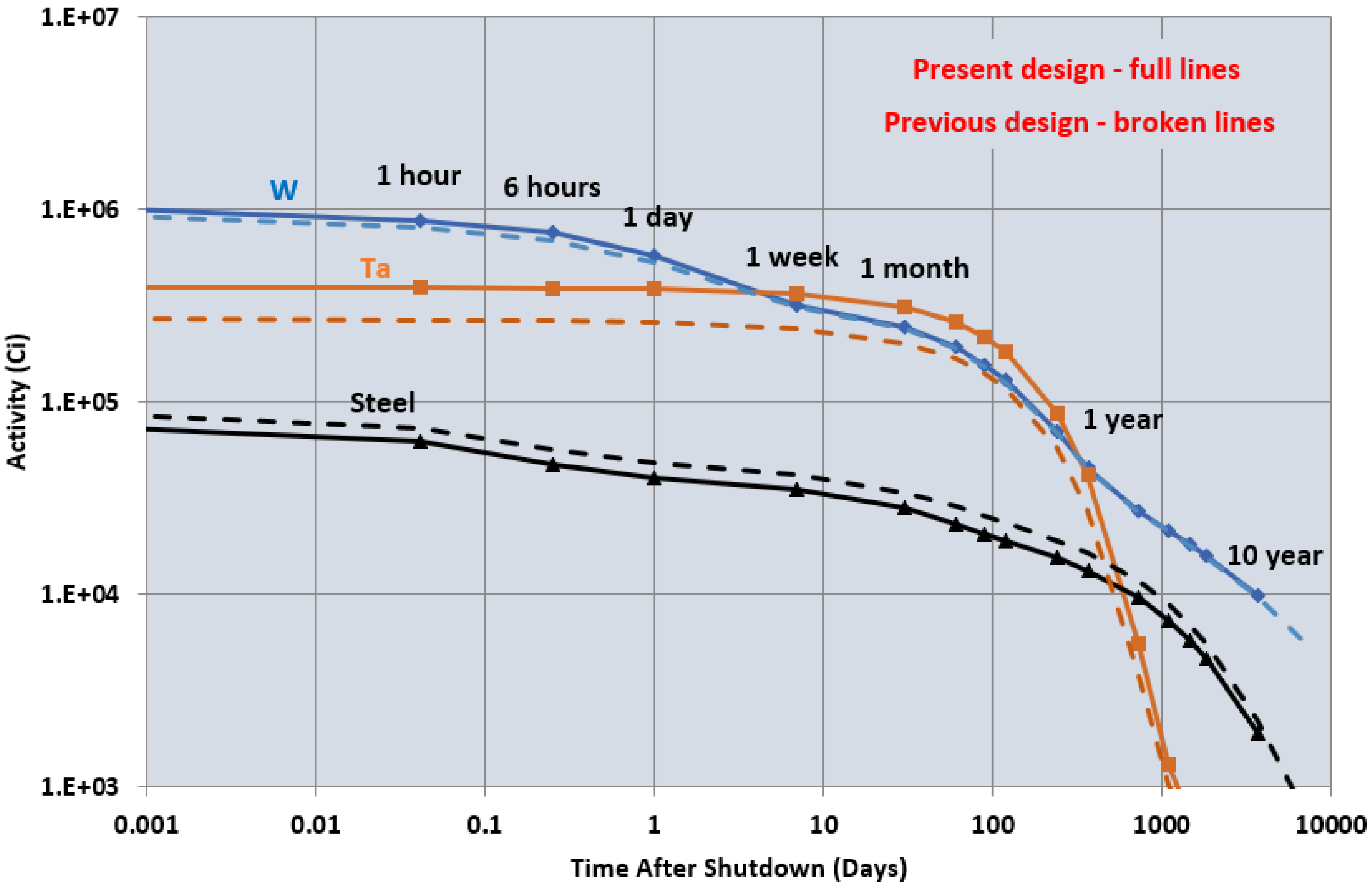
Present design: activity after 10 years and 20 years of operation (5000 h/y), at 0.7 MW.

Previous design, 20 years of operation



Rotating target activity, by material

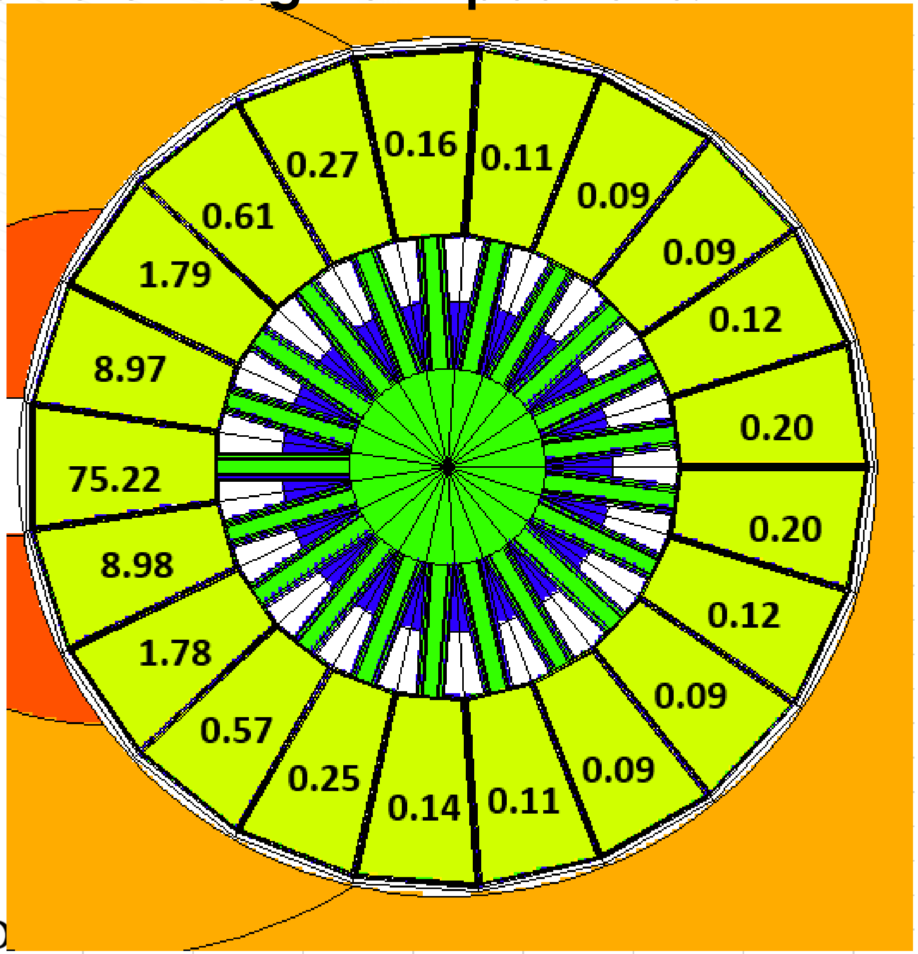
Activity after 20 years of operation (5000 h/y), at 0.7 MW, Ta clad

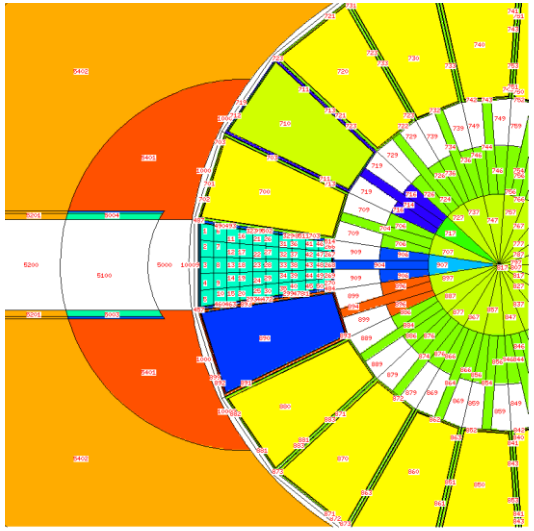


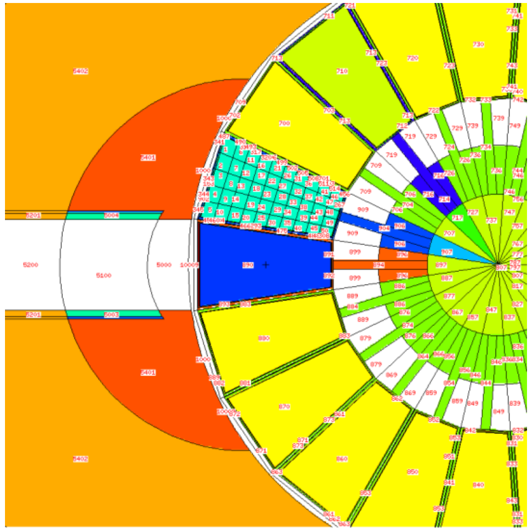
Decay heat for synchronous target

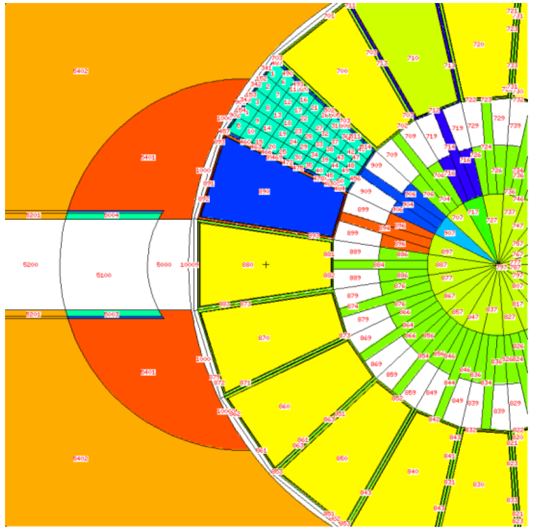
In segmented, synchronous target the activation is not uniformly spread around the target disk circumference. This introduces significant complexity in the activation analysis.

Contributions (in %) to the W decay heat (at 1 week after shutdown) from different segment positions.









To obtain decay heat distribution in the segment, contributions from different segment locations were calculated and summed.

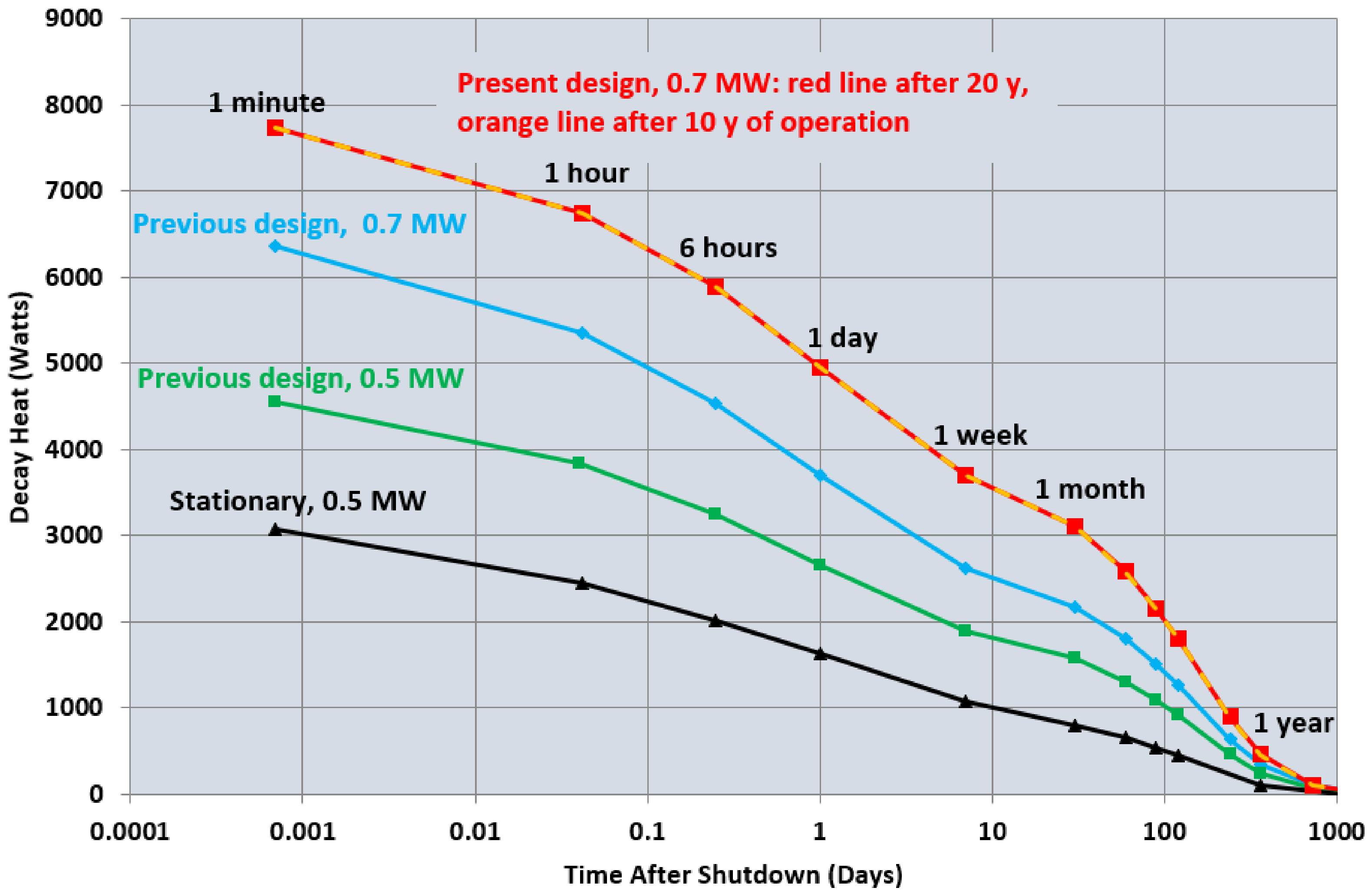
To obtain spatial distribution the segment was subdivided in ~ 500 cells.

Target decay heat

Rotating target, present design:
after 20 y and
10 y of operation
(5000 h/y), at 0.7 MW

Rotating target, previous design:
after 20 years of
operation (5000 h/y),
at 0.5 MW and 0.7 MW

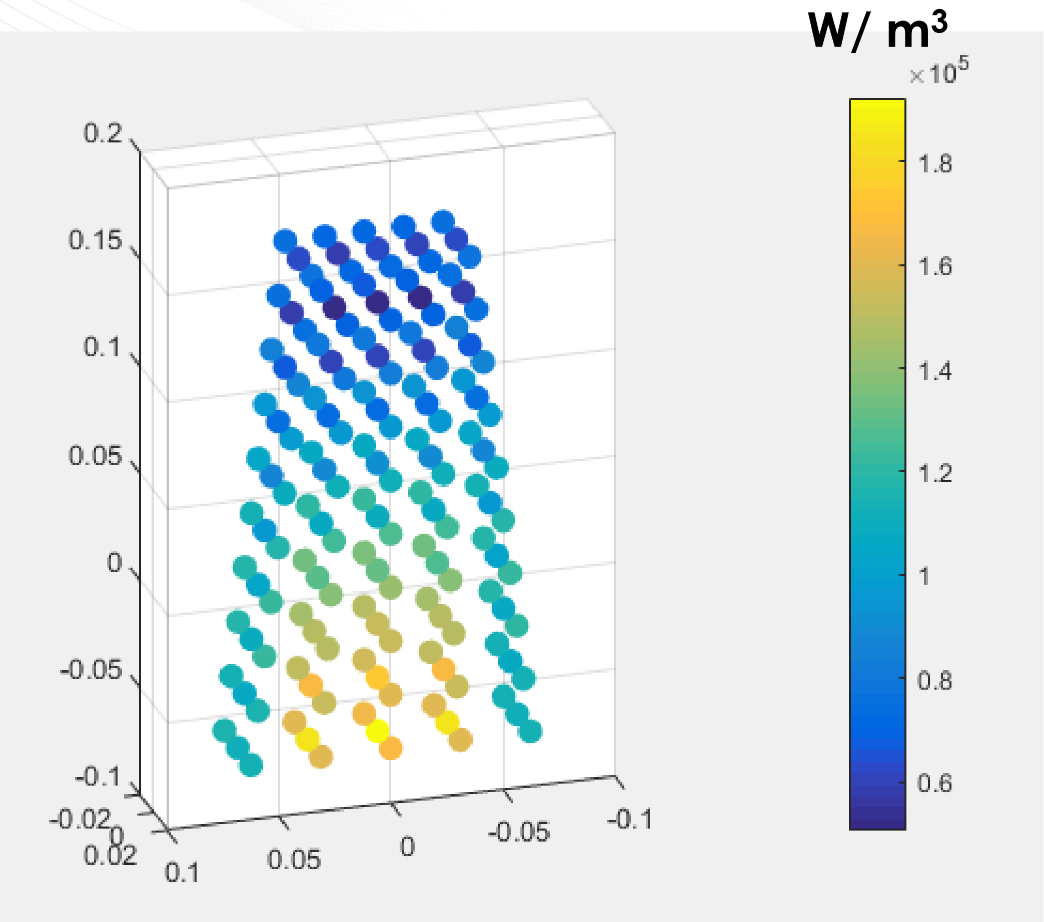
Stationary target:
after 1 year of
operation (5000 h/y),
at 0.5 MW



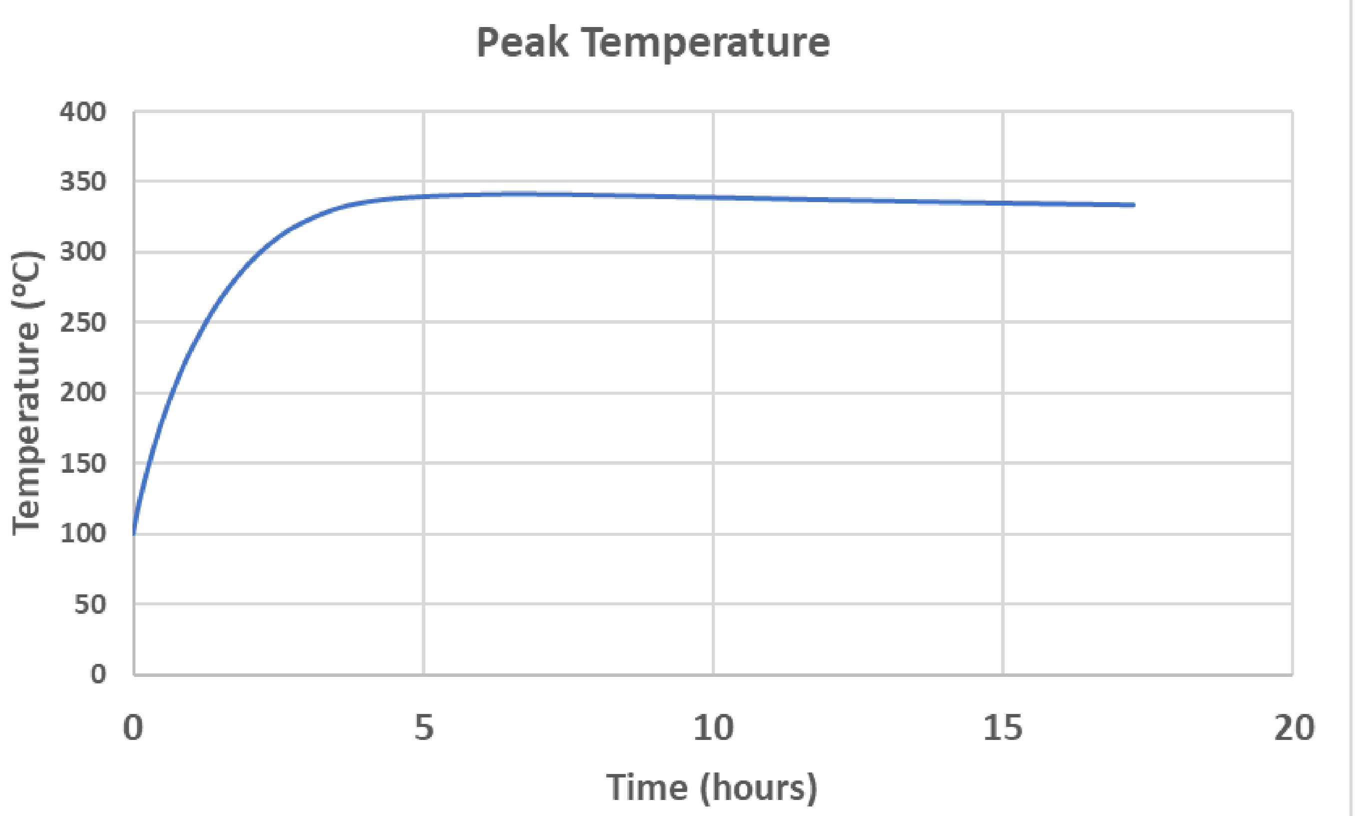
Total decay heat for the rotating target is much higher than for the stationary target.
But in the rotating target the decay heat is distributed over large volume and does not cause prohibitively high temperatures in the case of the loss of active cooling.
The average decay heat density in W and Ta at shutdown is 2.1 W/cc for stationary target and 0.18 W/cc for rotating target.

Rotating target: decay heat removal by thermal radiation to shielding after loss of cooling and beam trip

Tungsten heating at shutdown t=0

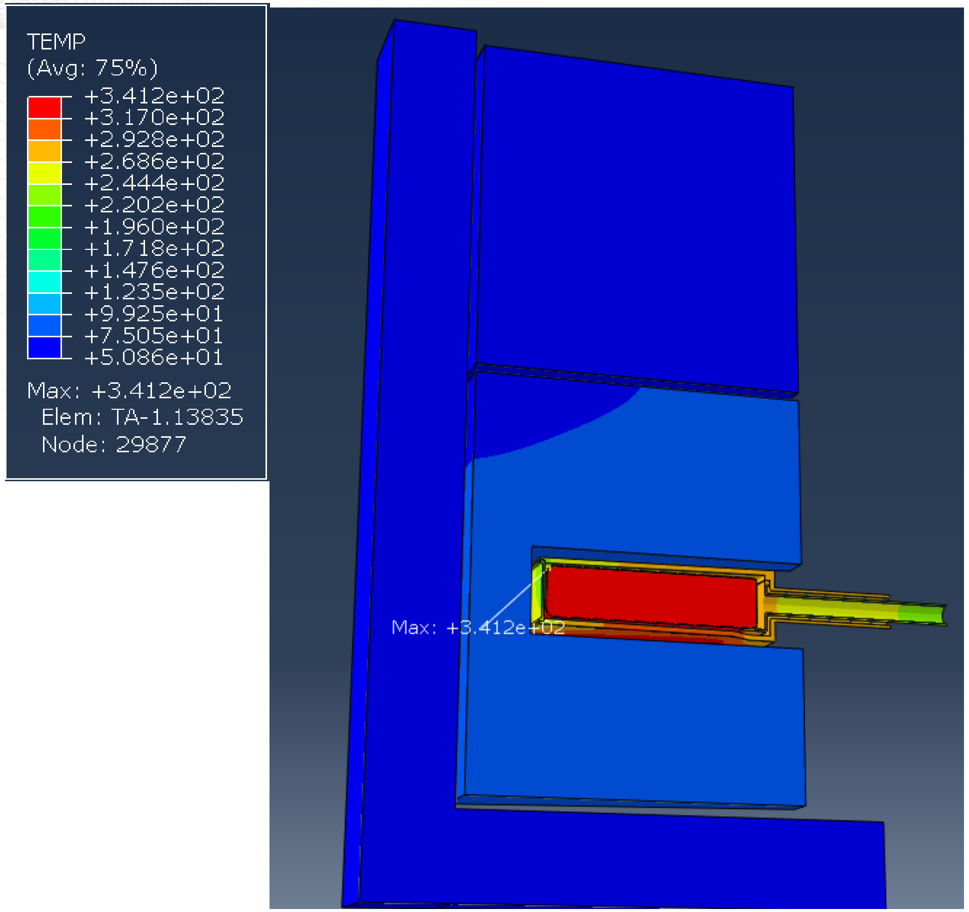


Target peak temperature 341°C at 6.1 hours



Decay heat can be passively removed without catastrophic damage to the target.

Rotating target: decay heat removal by thermal radiation to shielding after loss of cooling and beam trip



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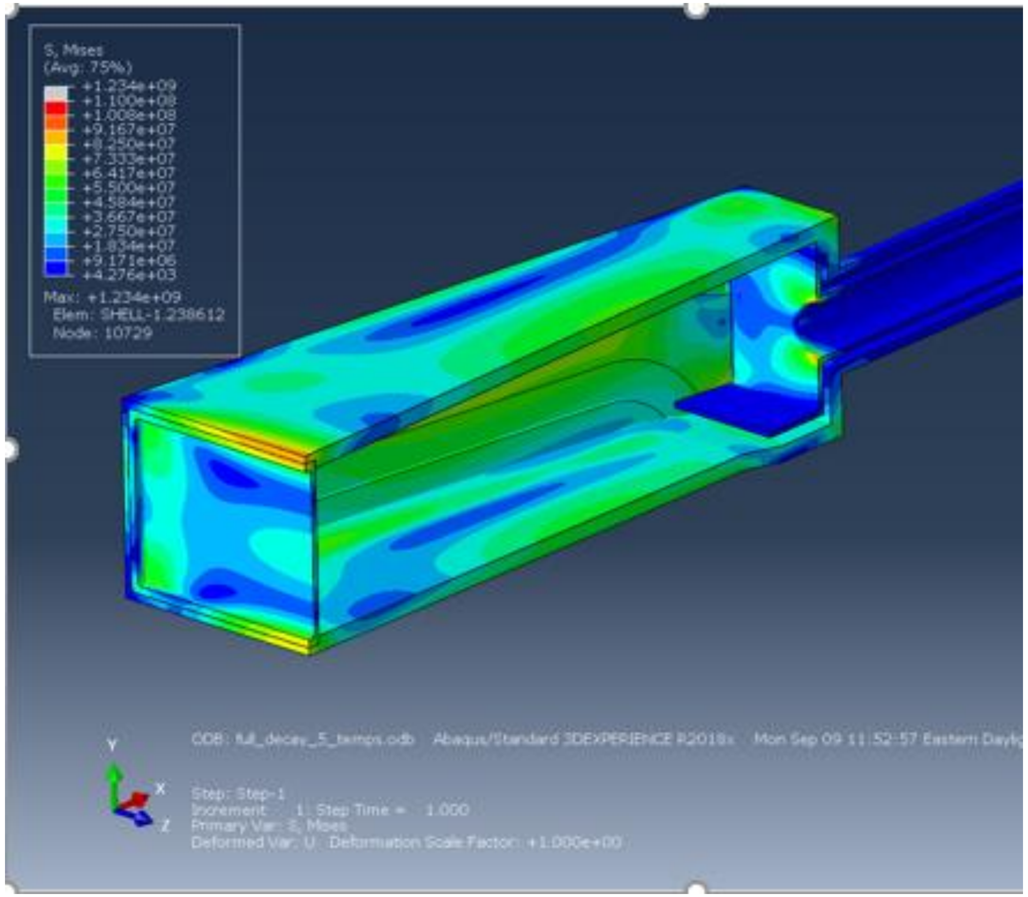


Stainless steel shroud peak Von Mises stress ~ 95 MPa at 6.1 hours

Decay heat can be passively removed without catastrophic damage to the target.

Rotating target prelim. acc. analysis (STS with Ta clad)

- **Loss of cooling with proton beam trip**
  - No target damage is expected
  - No radiological consequences

- **Loss of cooling, proton beam on target, target rotates**
  - Stainless steel shroud peak temperature 1567°C in 10 minutes
  - W/Ta block peak temperature 1648°C in 10 minutes
  - Steel shell will likely fail between 800°C – 1400°C, 4 to 5 minutes into the accident
  - Equivalent of the FTS Target Protection System is likely to be needed for loss of cooling events
  - The STS design will assure that for a high-consequence, low-probability design basis accident, the dose to a maximally exposed individual would be less than 1 rem in an uncontrolled area and less than 25 rem for a worker in a controlled area.

Target radionuclide inventory (with Ta clad)

Activities by isotopes after 20 years of operation (5000 h/y) at 0.7 MW, Ta clad

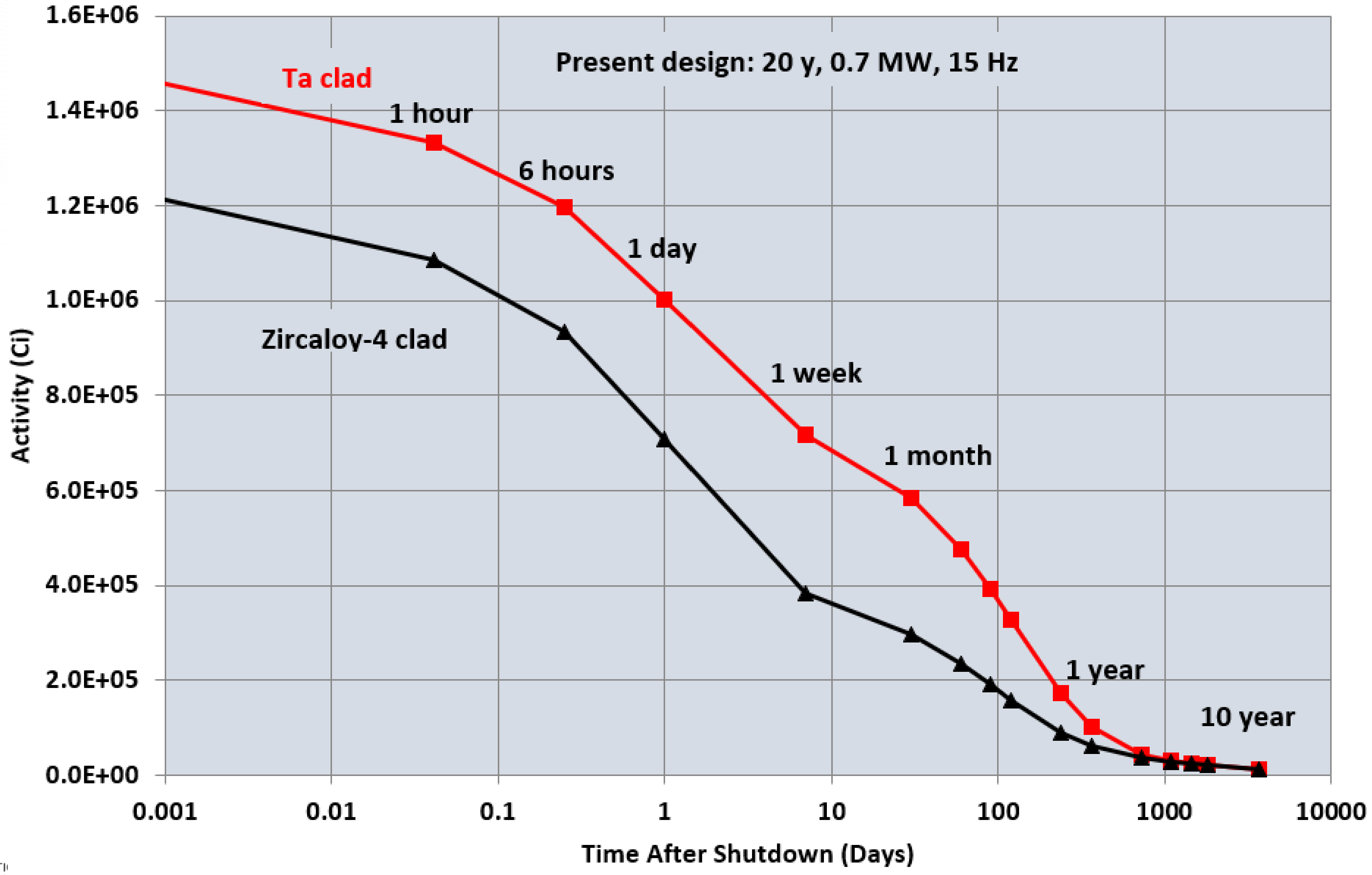
Detailed isotopic inventories were produced for accident analyses and waste management planning.

At Shutdown
Top 20 nuclides sorted by activity

Isotope	Half-life (s)	Activity (Ci)
W -187	8.54E+04	3.86E+05
TA-182	9.89E+06	3.75E+05
W -183*	5.20E+00	3.08E+05
W -185	6.49E+06	1.78E+05
TA-182*	2.83E-01	1.70E+05
W -181	1.05E+07	4.44E+04
MN- 56	9.28E+03	2.35E+04
TA-183	4.41E+05	1.87E+04
W -179	2.25E+03	1.69E+04
H - 3	3.89E+08	1.60E+04
TA-178	5.59E+02	1.60E+04
TA-179	5.74E+07	1.51E+04
TA-177	2.04E+05	1.29E+04
W -178	1.87E+06	1.24E+04
CR- 51	2.39E+06	1.21E+04
W -185*	1.00E+02	1.07E+04
TA-176	2.91E+04	9.56E+03
FE- 55	8.62E+07	9.47E+03
HF-175	6.05E+06	8.03E+03
TA-175	3.78E+04	7.51E+03
Target total		**1.97E+06**

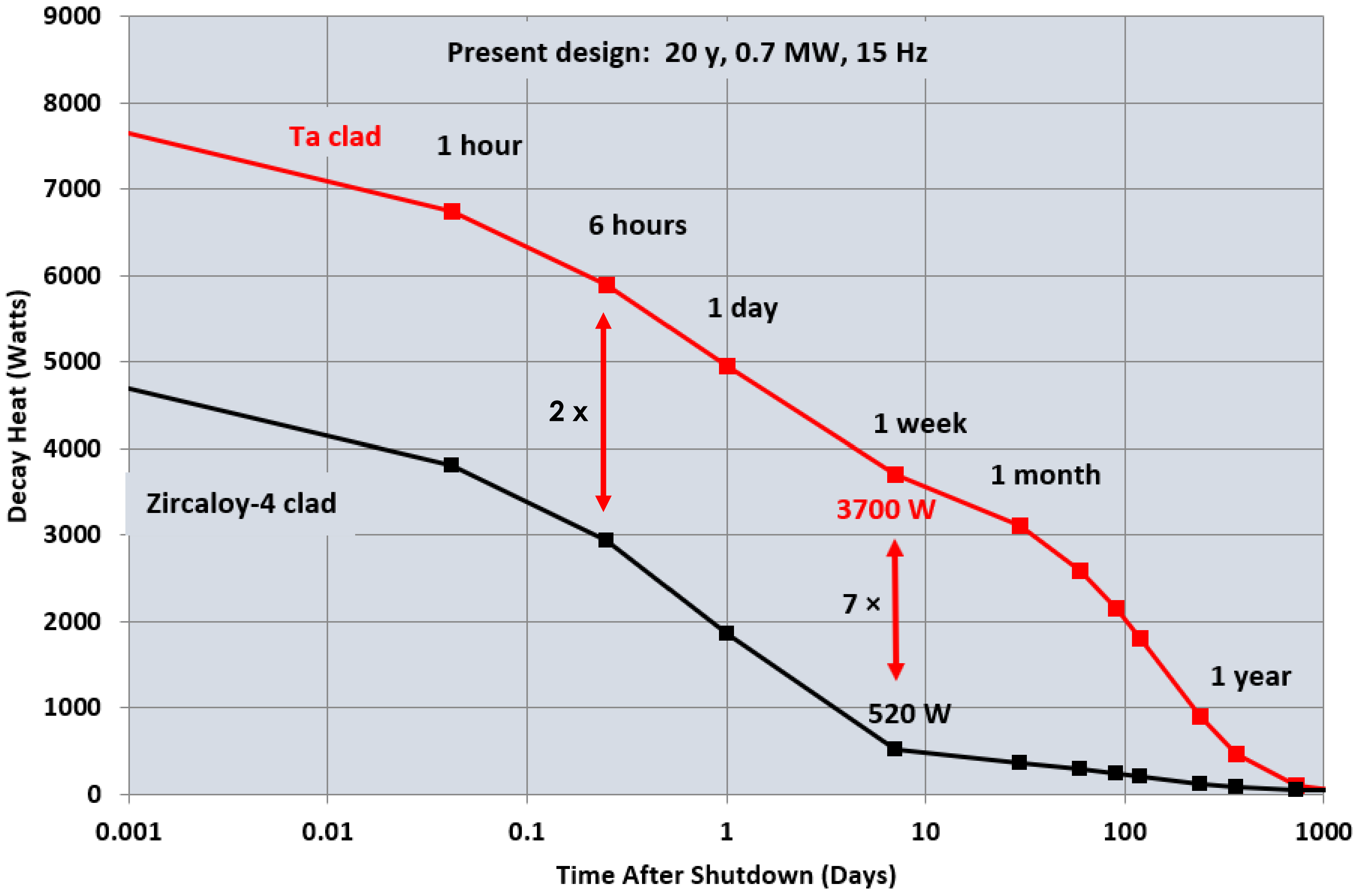
Target radionuclide inventory remains high and motivates search for the ways to lower it.

Reducing target activity: Zircaloy-4 clad replacing Ta clad

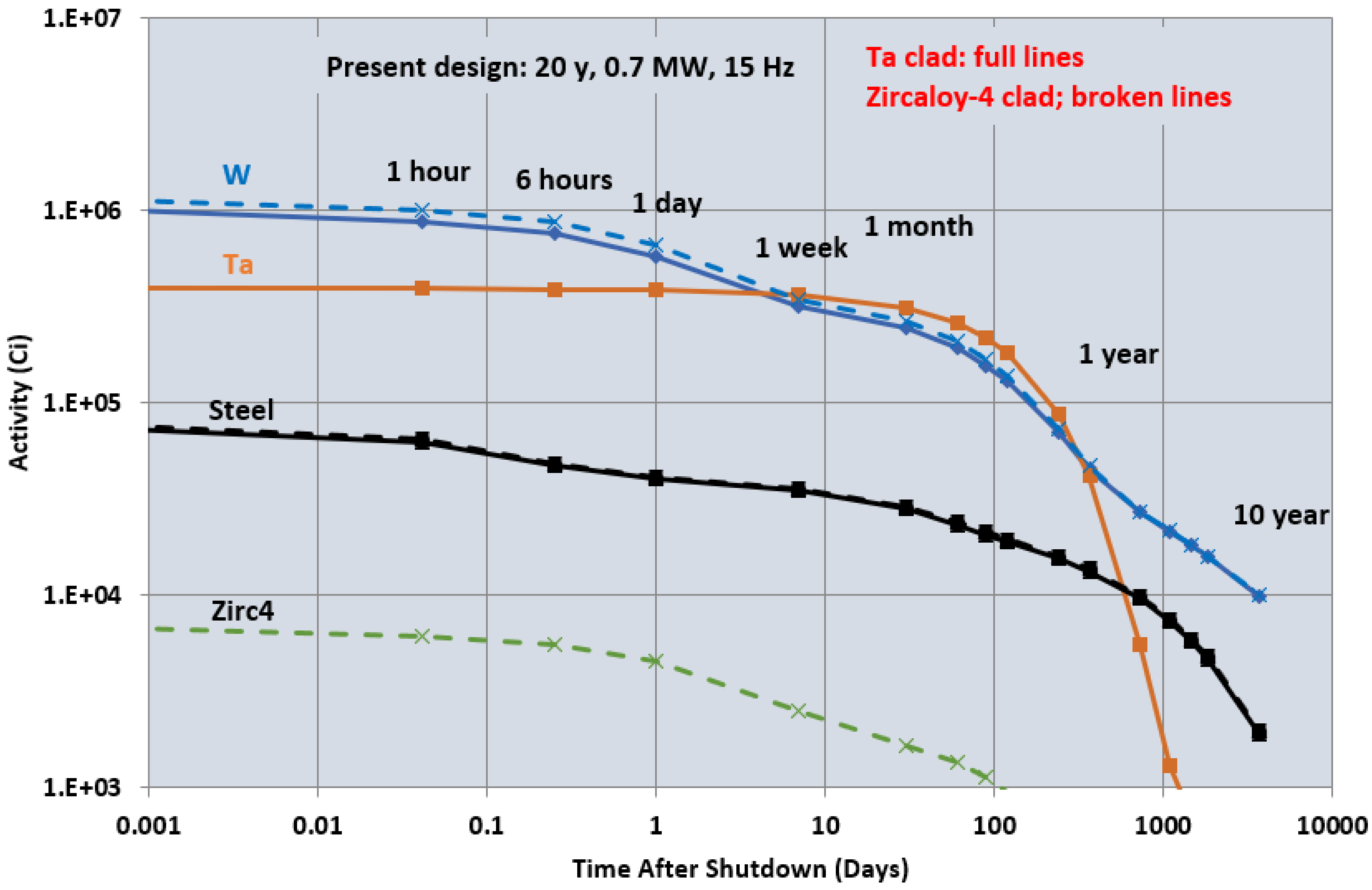


Reducing target decay heat: Zircaloy-4 clad

By replacing Ta with Zircaloy-4 a significant reduction in decay heat and activity can be obtained.



Target activity by material: Ta vs. Zircaloy-4 clad



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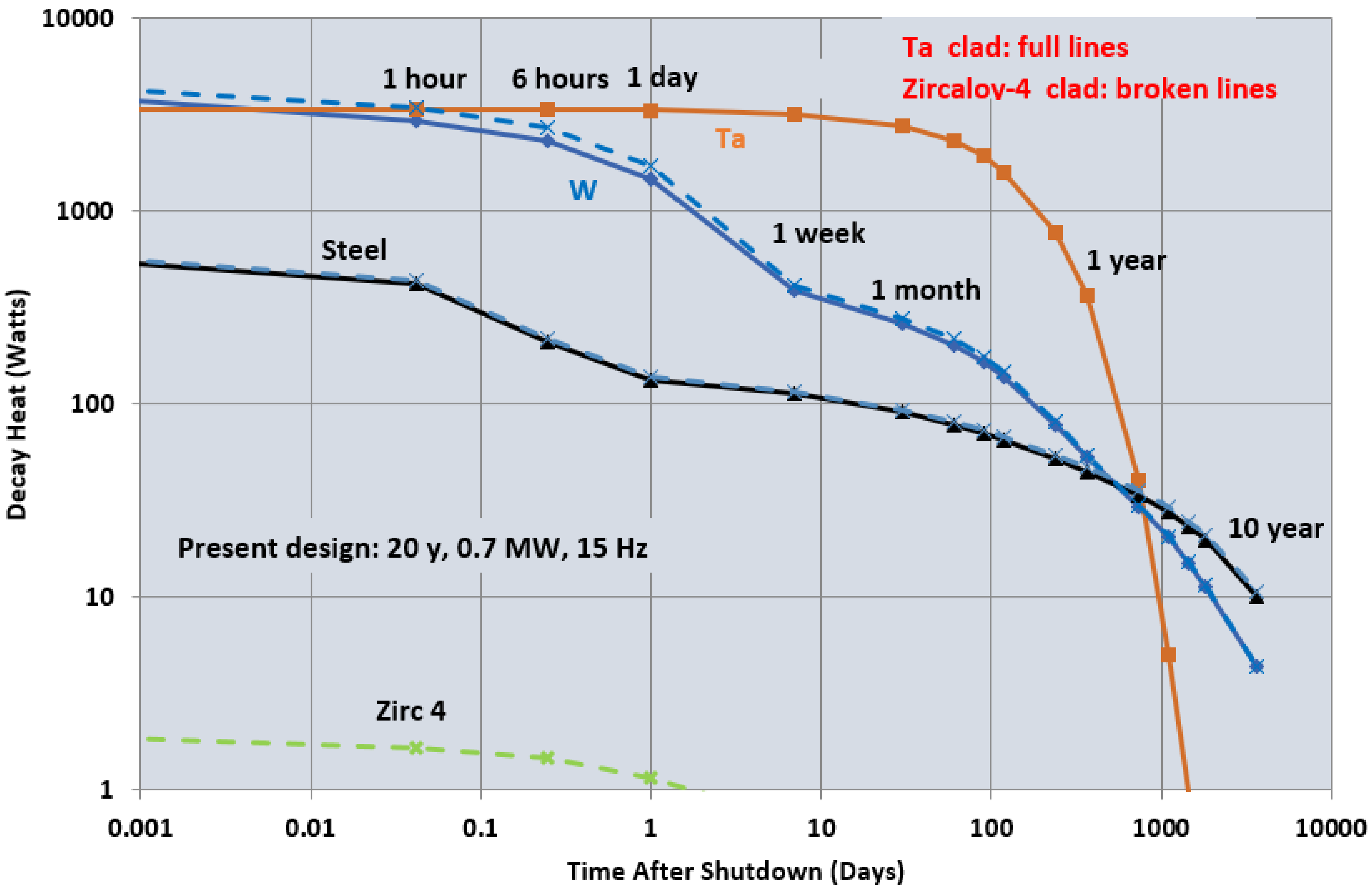

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Rotating target modifications

Transition to rotating target resolved problems with decay heat.

Further modifications were necessary to reduce peak stresses in the target induced by pulsed proton beam operation.

Proton beam footprint was enlarged to reduce peak energy deposition and "instantaneous" temperature rise.

Larger proton beam footprint required larger tungsten block.

Proton beam size/ profile

Proton Beam Profile	σ_x	σ_y	Vert. Extent 95 % Beam	Horiz. Extent 95 % Beam	~Area of 90 % Beam	Max. Heating	Max. dT
	(cm)	(cm)	(cm)	(cm)	(cm^2)	(J/cc/ pulse)	(deg. C)
1.0-1.0	1.65	3.04	4.0	7.6	30.4	77.9	30.12
1.2-1.0	1.98	3.04	4.8	7.6	36.5	65.1	25.17
1.2-1.2	1.98	3.65	4.8	9.2	44.2	54.8	21.06
1.2-1.7	1.98	5.17	4.8	13.0	62.4	39.0	15.00

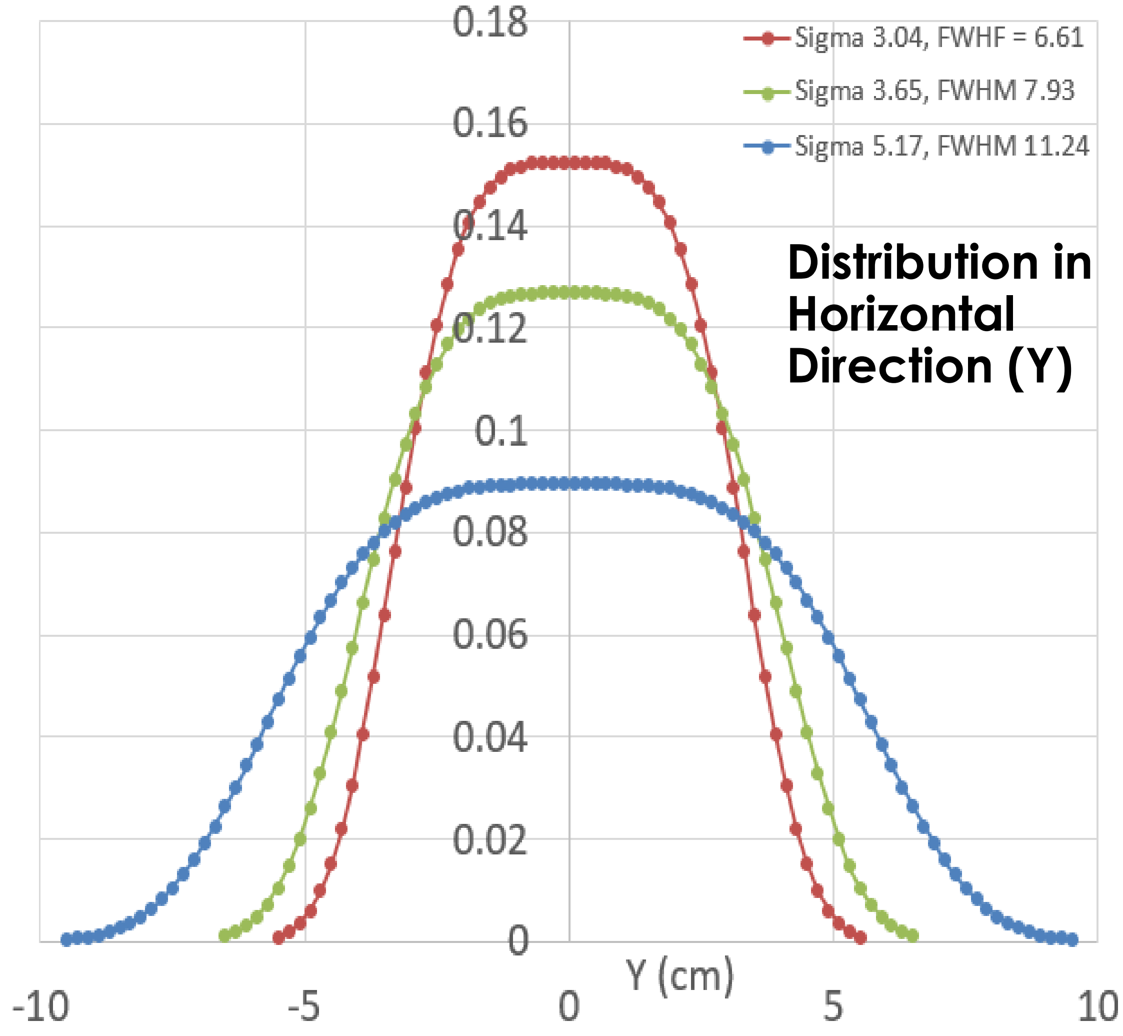
Footprint	30 cm^2	→	62 cm^2
Peak Dynamic Von Mises Stress	134 MPa	→	69 MPa

Super-Gaussian distribution of proton beam current

$$p(x,y) = NF \times e^{-\frac{1}{2}\left(\frac{|x-x_0|}{\sigma_x}\right)^4} \times e^{-\frac{1}{2}\left(\frac{|y-y_0|}{\sigma_y}\right)^{3.9}}$$

FWHM = 2.18 * σ

Doubling the proton beam footprint (from ~ 30 cm^2 to ~ 60 cm^2), causes only modest decrease in moderator performance: ~ 2 – 5 %.



Expected STS performance

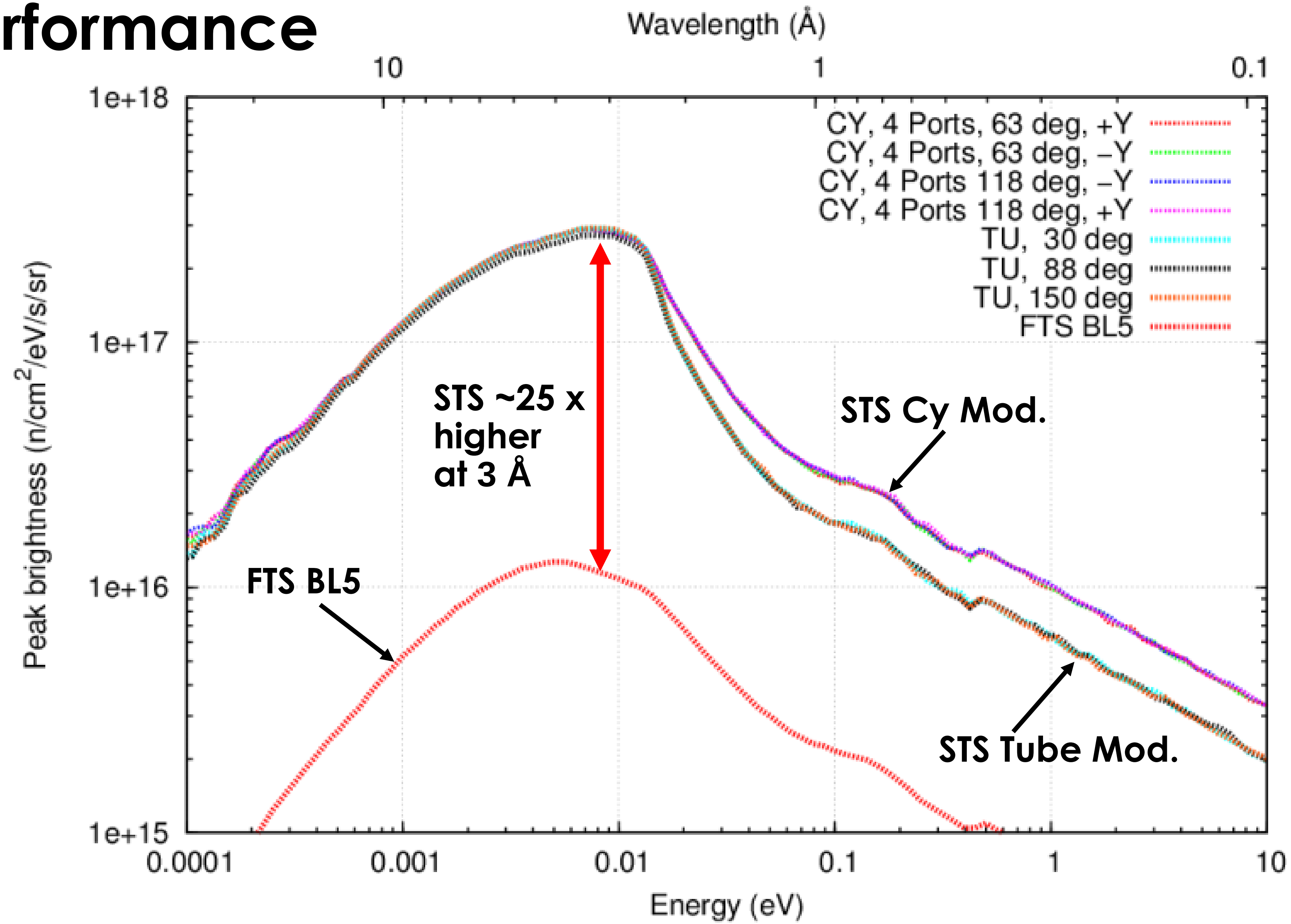
Peak moderator brightness

STS:

0.7 MW, 15 Hz, 1.3 GeV

FTS "as is":

1.4 MW, 60 Hz, 1.0 GeV, Al proton beam window, IRP2 with D_2O cooling, 20% loss due to power-induced degradation



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Expected STS performance

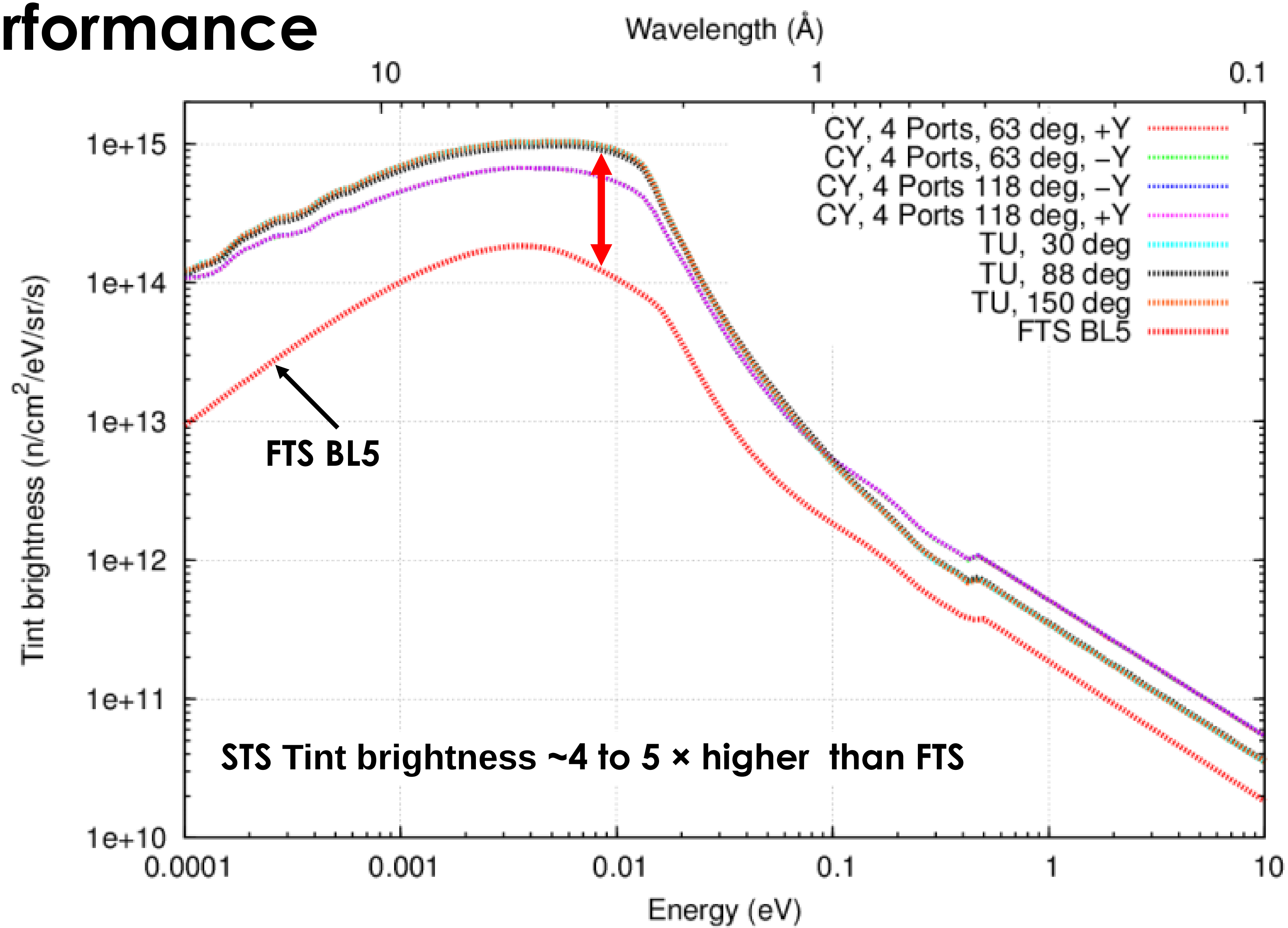
Time integrated brightness

STS:

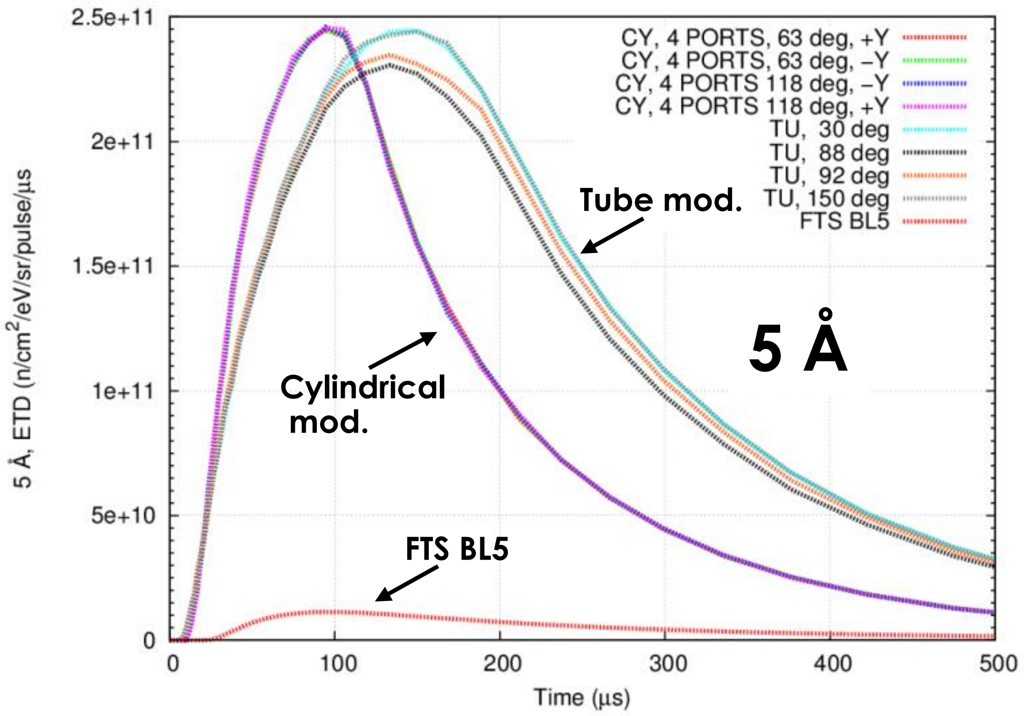
0.7 MW, 15 Hz, 1.3 GeV

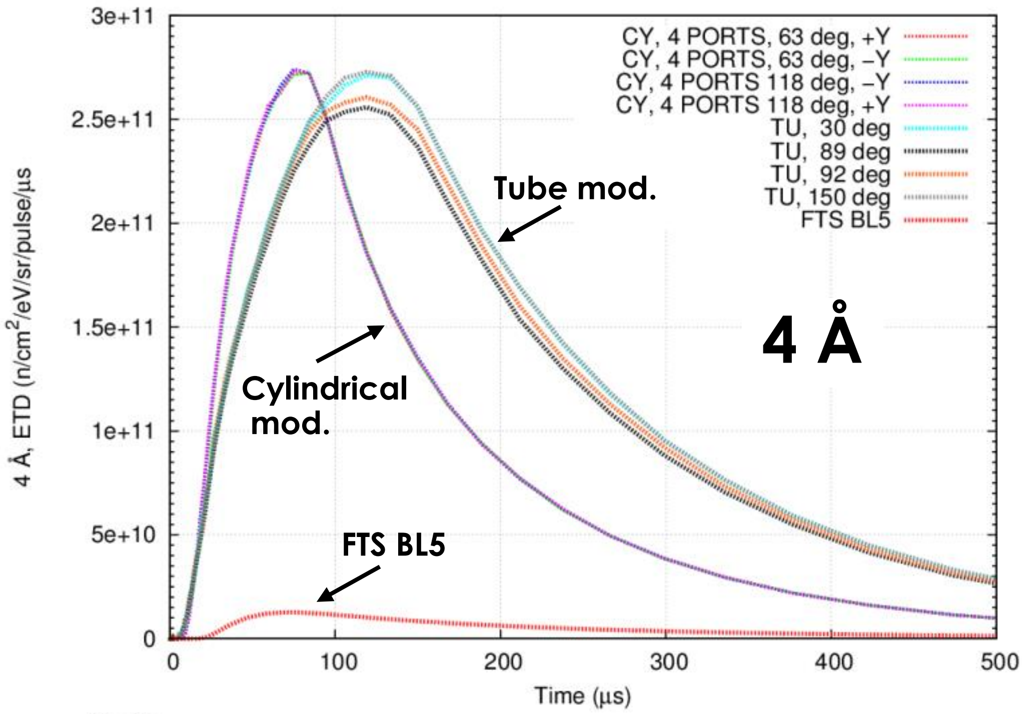
FTS "as is":

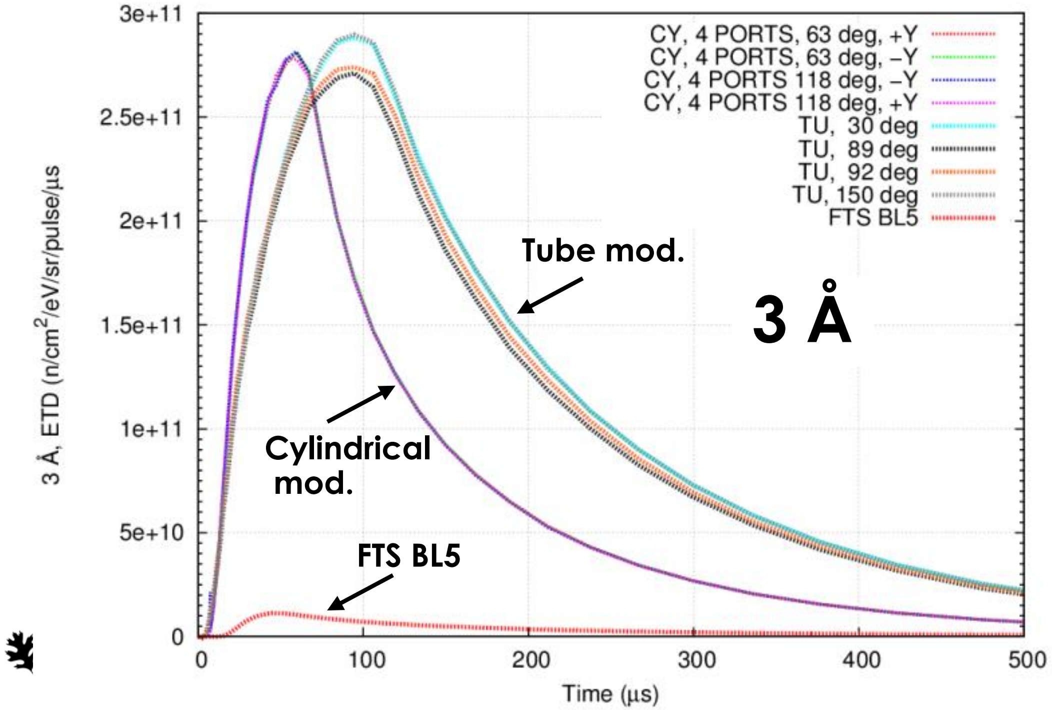
1.4 MW, 60 Hz, 1.0 GeV,
Al proton beam window,
IRP2 with D_2O cooling,
20% loss due to power-induced degradation

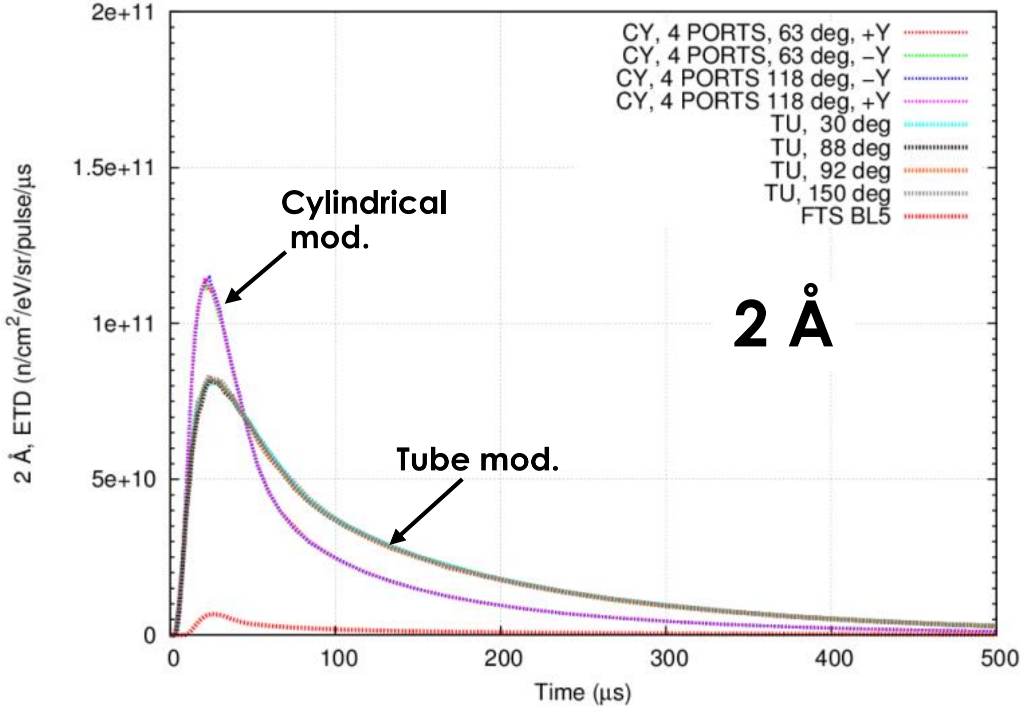


STS pulse shapes









Conclusions

- In 2019 STS reached the status of a project; conceptual design work continues.
- For the STS stationary target high decay heat concentrated in a small target volume was found to be important accident initiator and was a driving factor to abandon stationary target.
- Rotating target, with much larger target volume and surface area for thermal radiation, resolved this problem.
- Target radionuclide inventory is high and motivates search for the ways to lower it. Replacing Ta clad with Zircaloy-4 can is promising but requires development.
- STS will deliver short pulses of long wavelength neutron beams with exceptional brightness.