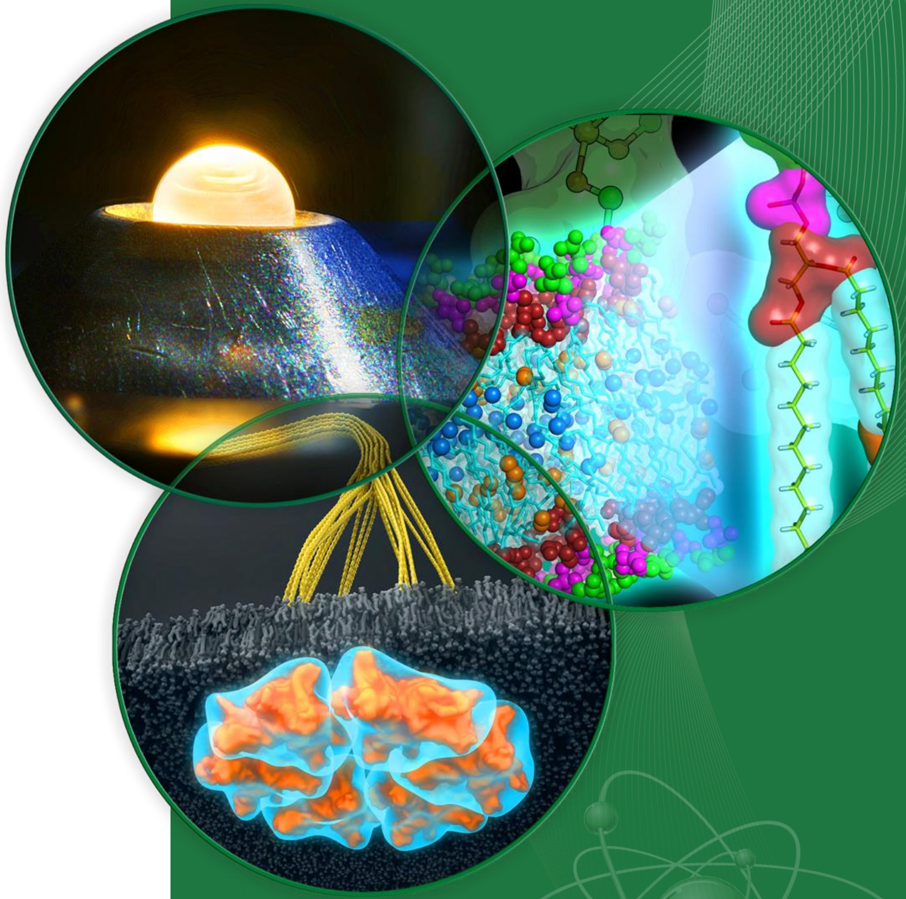
The Path to Reliable 1.4 MW Operation of SNS Targets



Presented to
Neutron Advisory Board

Presented by
Don Abercrombie
Instrument and Source Division Director

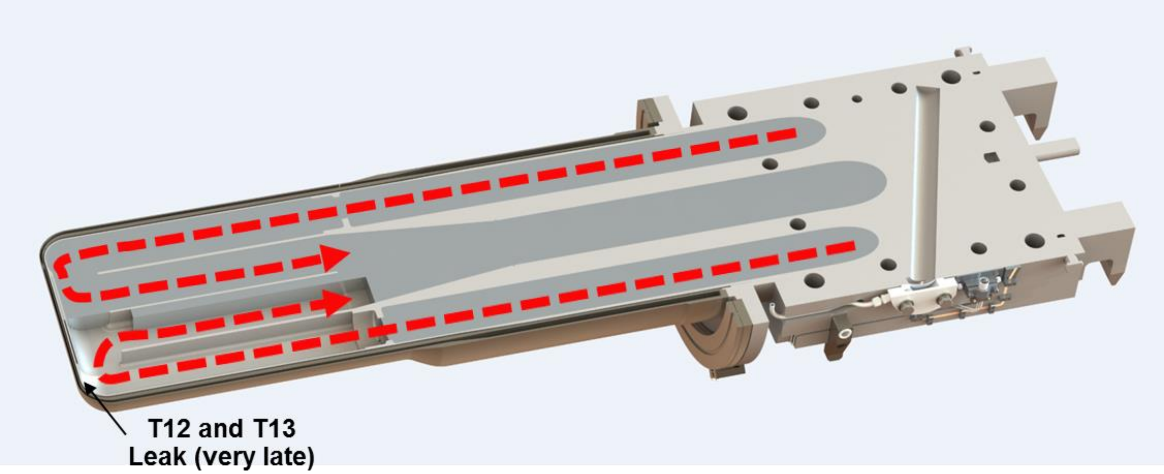
June 30, 2016
Clinch River Cabin
Oak Ridge, Tennessee

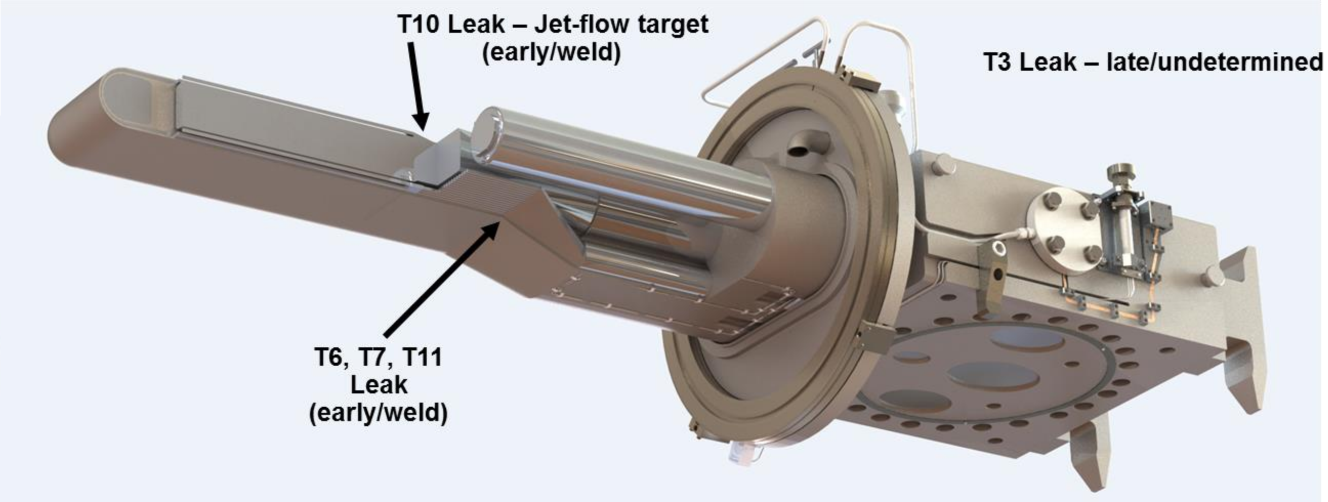
SNS has established a path to reliable target operation at 1.4 MW that is built on a foundation of learning and improvement

- Robust research and experimental programs
  - Seven experiments from 1999-2011 at LANSCE (WNR) utilizing a scaled 2+ MW beam
  - Development of the Target Test Facility at ORNL
- Gaining expertise through experience and collaboration
  - 20 year relationship with JSNS (only other MW-class spallation source with a flowing mercury target)
  - Maintaining international working relationships
  - SNS has available > 100 years of combined experience in mercury target engineering
- Enabling effective learning through operational experience
  - Hot cell, manipulators, and tooling to support post-irradiation examination (PIE) of targets

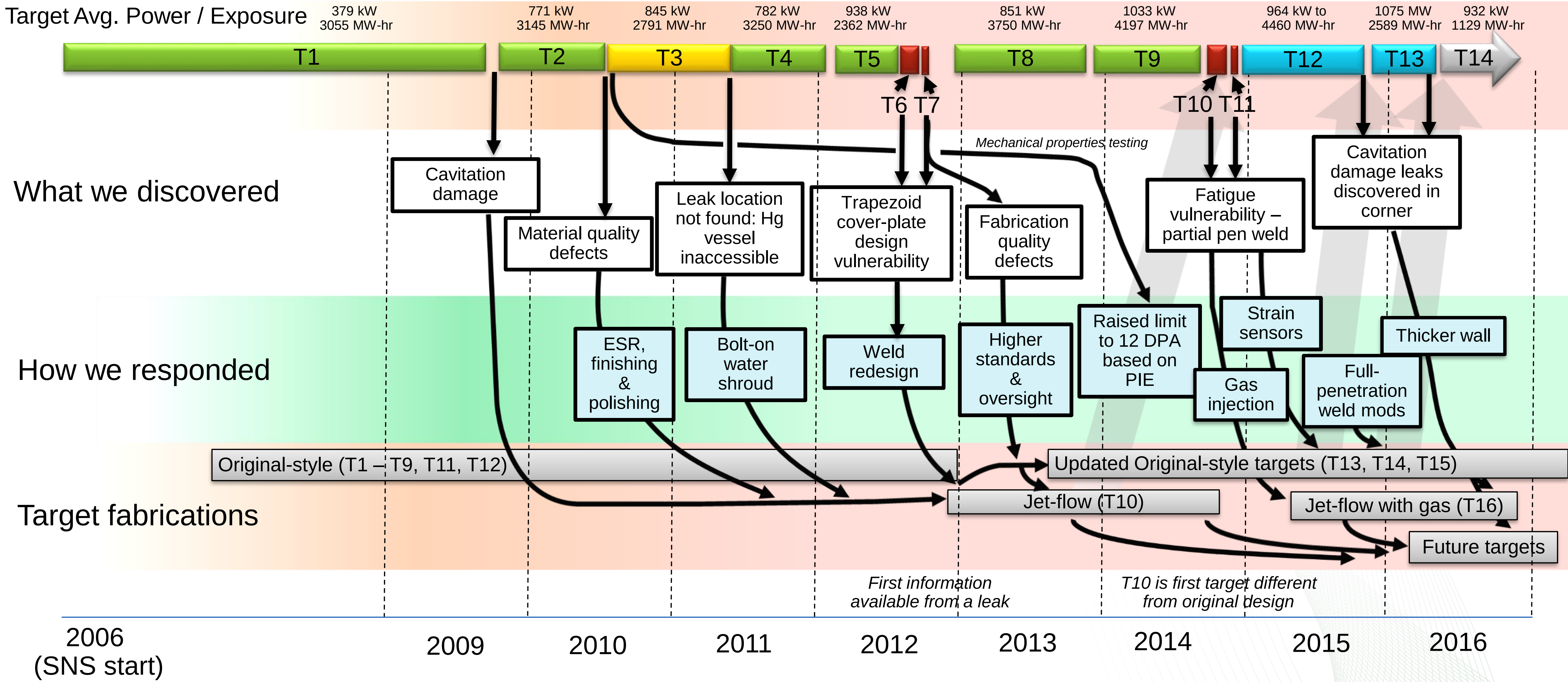
Some of the learning gained through operational experience was associated with premature failures

- Seven of fourteen targets that have operated failed before planned replacement
- Leak locations of all but one were identified
- All identified leaks were associated with two failure modes, both having clear paths to address
  - Fatigue failures at weld locations
  - Cavitation damage erosion (CDE)





Valuable experience gained from T1 through T5 during the early stages of SNS operation



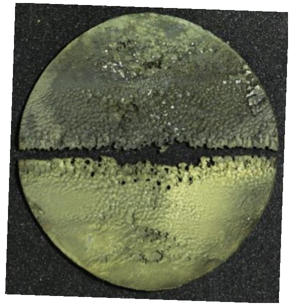
Legend of Timeline Colors

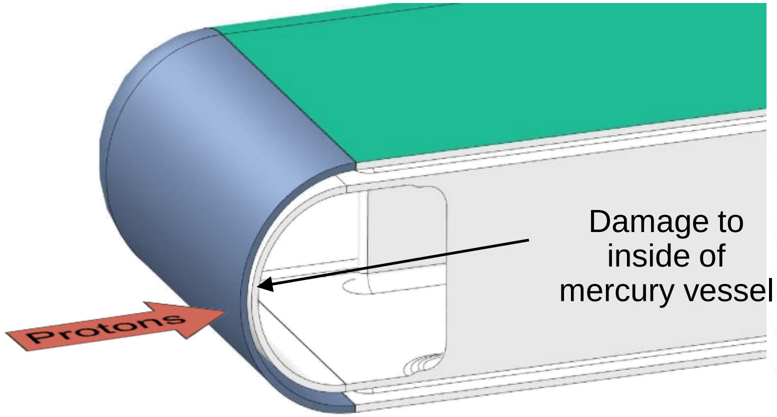
Green – Replaced as Planned Yellow - Leak Unknown Red - Leak at Weld Blue - Leak due to CDE

OAK RIDGE National Laboratory

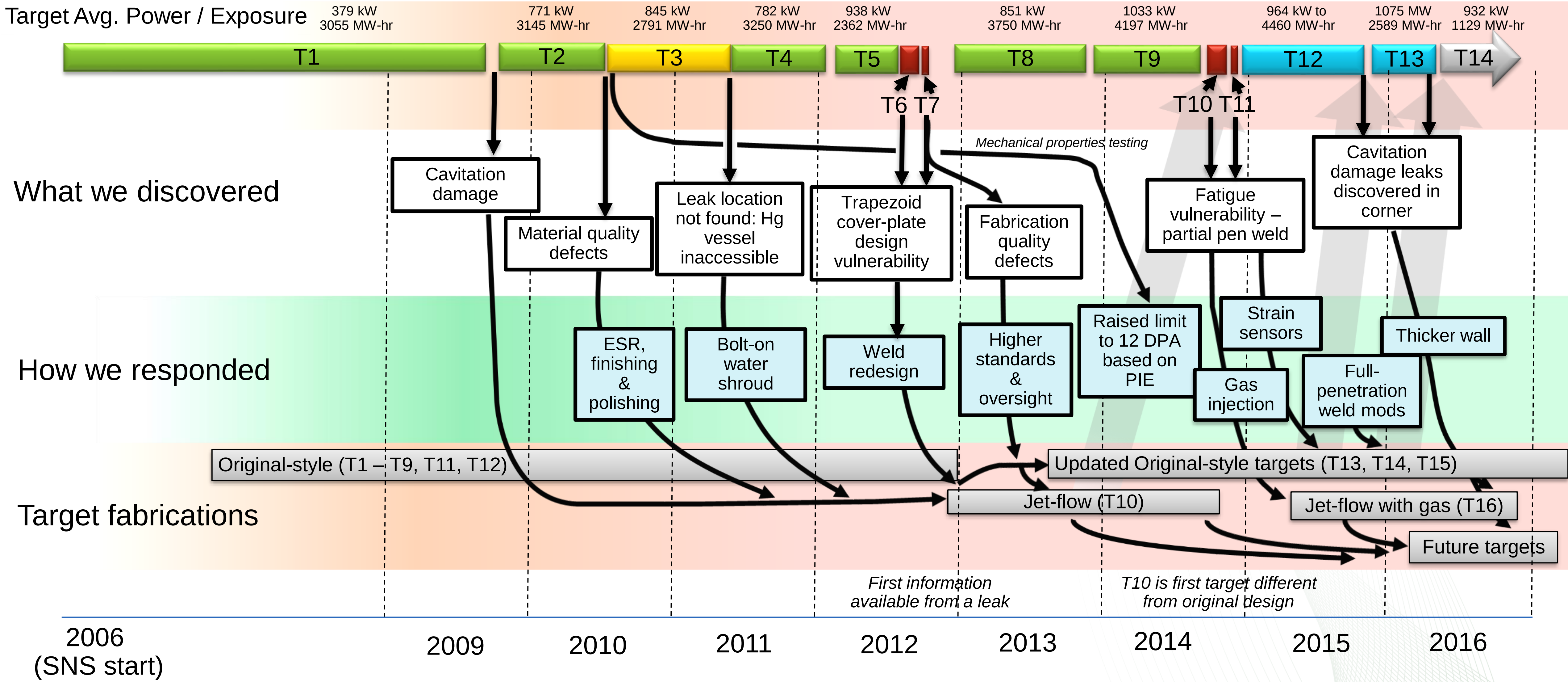
Learning was occurring across several areas during the operation of T1 through T5

- Twelve identical targets were being fabricated using three vendors
  - Vendor oversight consists of an average of one visit per quarter
- LANSCE experiments were examining the impacts of the proton-induced pressure pulse and resultant CDE, and evaluating mitigative options
  - Gas injection was shown to be capable of reducing strain by a factor of five and CDE damage by a factor of 16
  - Unidirectional flow across a surface provided a factor of two reduction in CDE
- Target PIE confirmed the presence of CDE, but found that it was limited to the inner window
  - Considered it possible that the mechanism might be self-limiting
- Target lifetime exceeded expectations
  - Appeared reasonable to pursue implementation of potential improvements less urgently





Operation of T6 through T11 revealed the first identified target failure mode

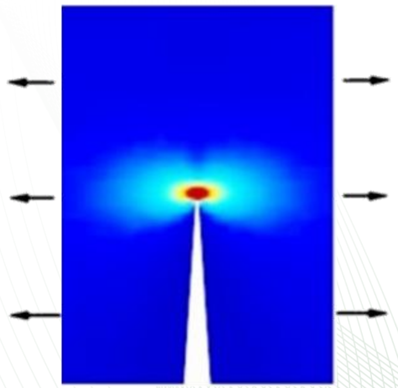


Legend of Timeline Colors

Green – Replaced as Planned   Yellow - Leak Unknown   Red - Leak at Weld   Blue - Leak due to CDE

New information enabled further evaluation to identify a root cause and common failure mode

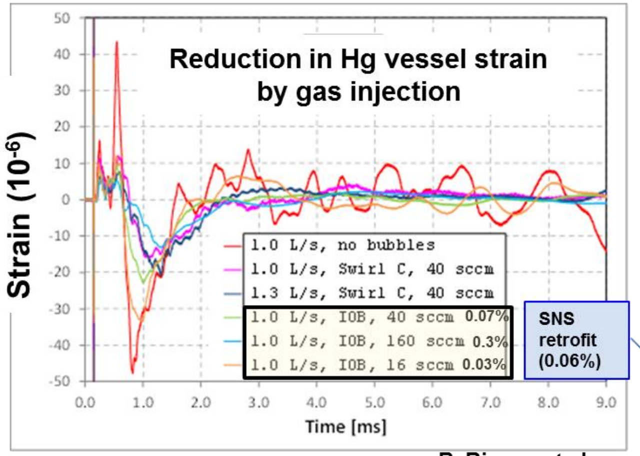
- Following the back-to-back failure of T6 and T7, PIE identified that an inadequate weld at the trapezoidal cover plate failed in both targets
- Actions were taken to re-inspect and repair (as necessary) the same weld on other targets in fabrication, and immediately increase the scale and rigor of vendor oversight
  - Vendor visits increased from one up to ten per quarter
- Designs were completed and procurements initiated for seven more targets that did not utilize the trapezoidal cover plate
- Two targets were operated successfully to extended intervals of replacement, but this was followed again by back-to-back failure of T10 and T11
- Failure of these targets that had been thoroughly inspected for fabrication defects led to the recognition that the targets contained weld design vulnerabilities that made them susceptible to fatigue failure (partial penetration)



SNS developed a DOE-endorsed plan to address target reliability following the February 2015 Meador review

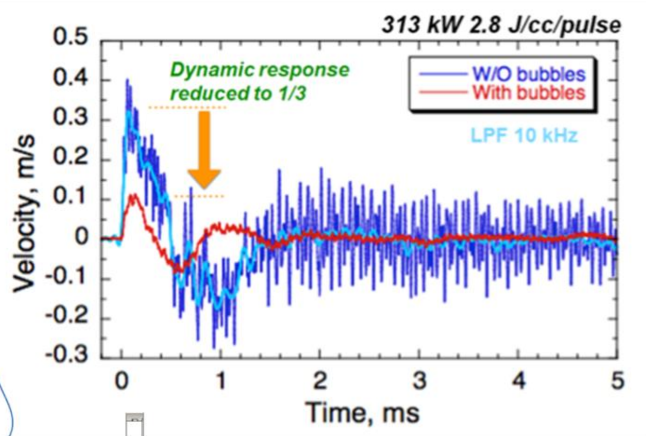
- Plan addresses a broad set of issues relating to target robustness/reliability and included improvements in target analysis and design, PIE capabilities, and issues affecting welding.
- Significant activities included the mitigation of partial penetration weld vulnerabilities, implementation of gas injection, and addition of strain sensor monitoring.

Scaled Experiment at Los Alamos

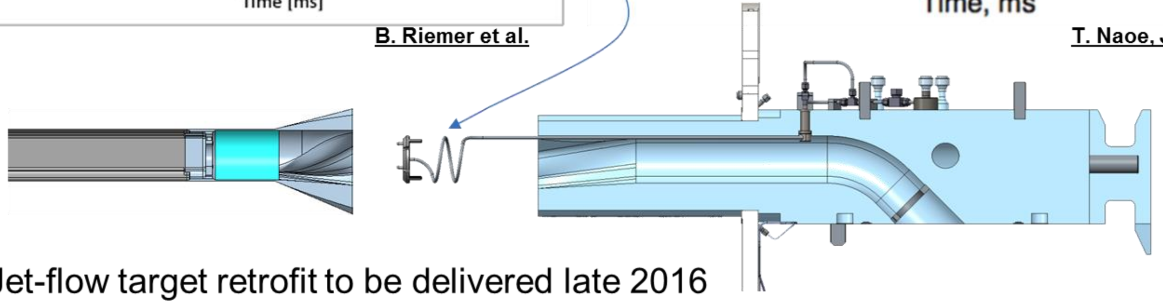


B. Riemer et al.

Vibration measurements at J-PARC

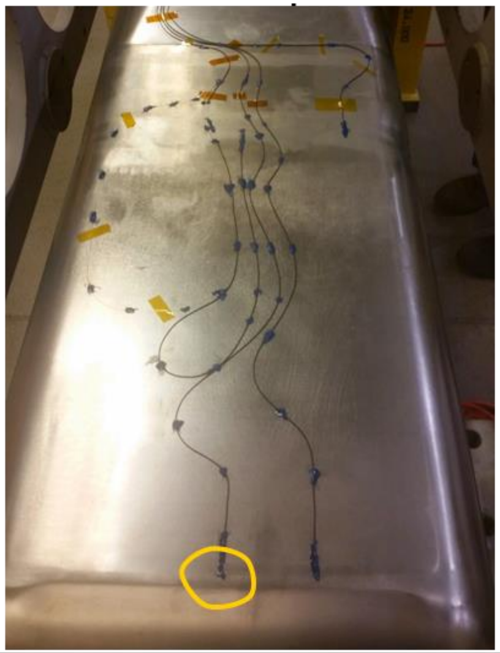


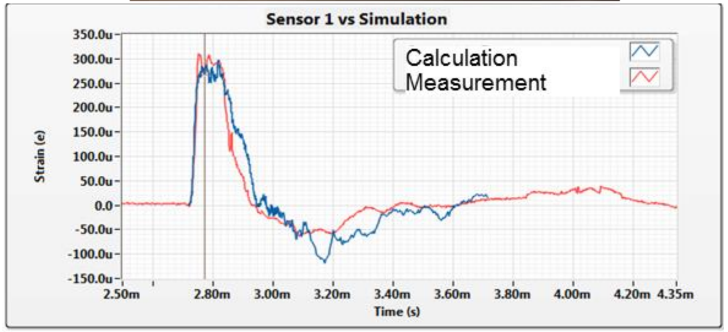
T. Naoe, J-PARC



Jet-flow target retrofit to be delivered late 2016

Strain sensors on target

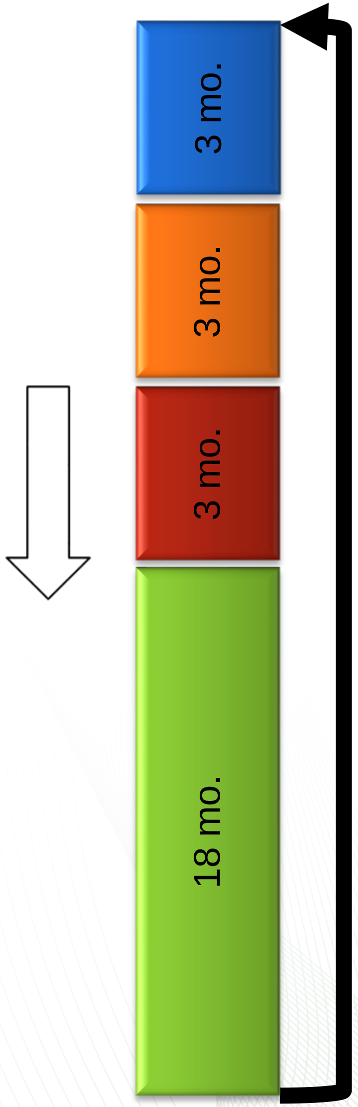




Beam pulse strain measurement showing excellent correlation with model

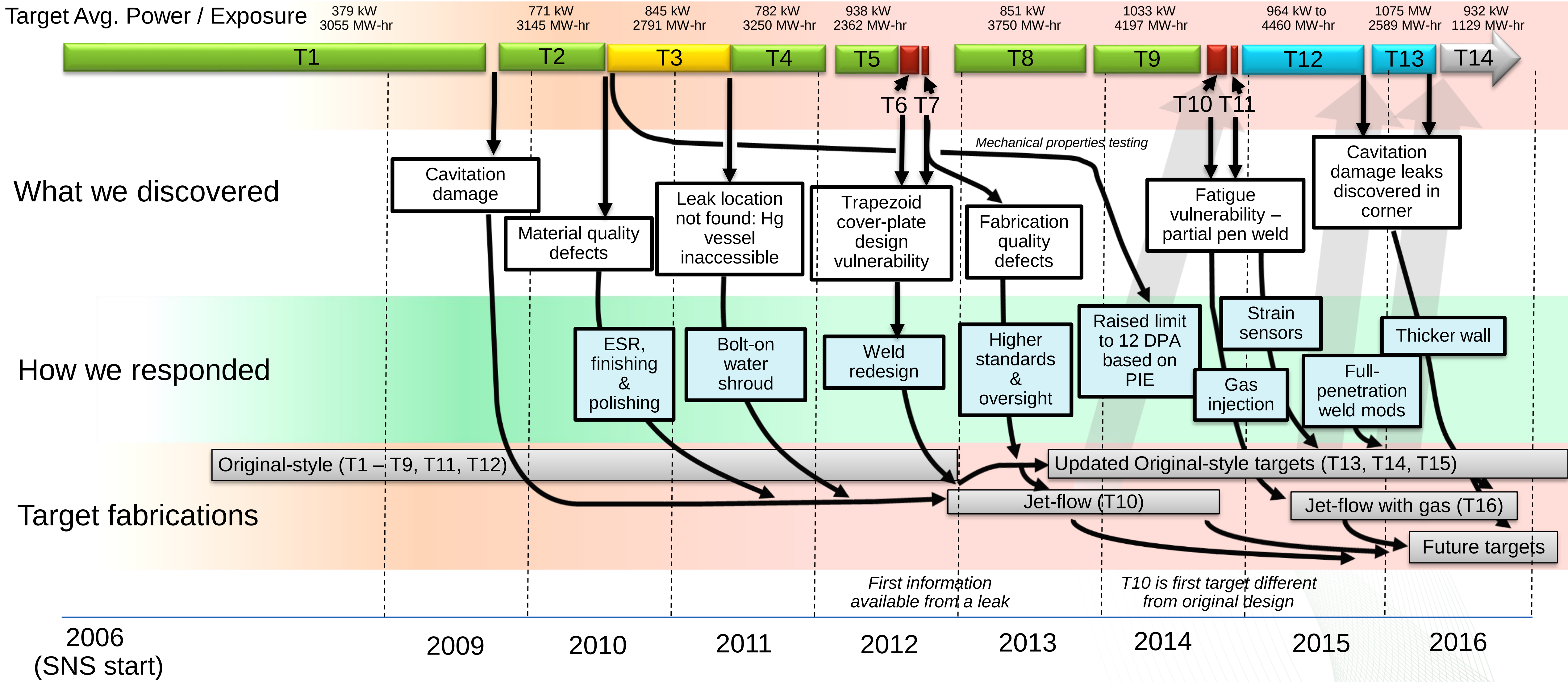
We achieved essential reductions in the cycle time for learning and responding to new information

- Gather information from a used target
- Corroborate with computer models and fab documents
- Develop proposed changes to the design
- Analyze the changes with computer simulation
- Order the target
- Wait at least 18 months for construction of the target
- Wait for the target to be installed and used
- ***This whole process could take 2 – 4 years***



OAK RIDGE National Laboratory

Operation of the last three targets has informed the strategy that enables the path to reliable 1.4 MW operation



Legend of Timeline Colors

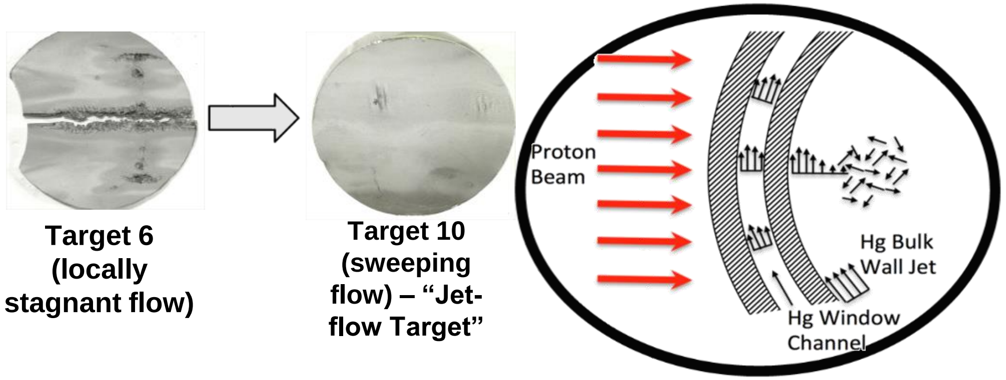
Green – Replaced as Planned Yellow - Leak Unknown Red - Leak at Weld Blue - Leak due to CDE

Oak Ridge National Laboratory

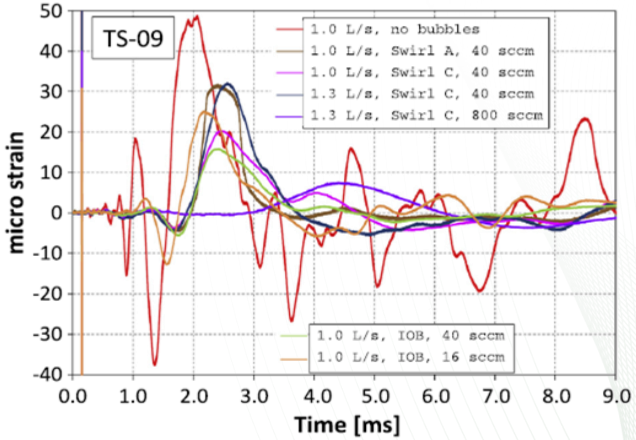
The Path to Reliable 1.4 MW Operation

- Initial target failures were fatigue induced weld failures
  - We are currently operating the third consecutive target that has not failed due to fatigue failures at welds
  - We have addressed this issue
  - Implementation of gas injection and further structural improvements will only increase the margin for fatigue
- Last 2 targets failed due to CDE
  - T12 operated for 24 days >1.3 MW and T13 operated for almost 34 days >1.3 MW
    - By comparison, T9 operated for only 16 days >1.3 MW
  - Cavitation is mitigated by flow and gas injection techniques
  - Thicker walls in vulnerable areas will also provide more time before CDE causes a leak
  - We are implementing these proven techniques

Erosion mitigation with flow



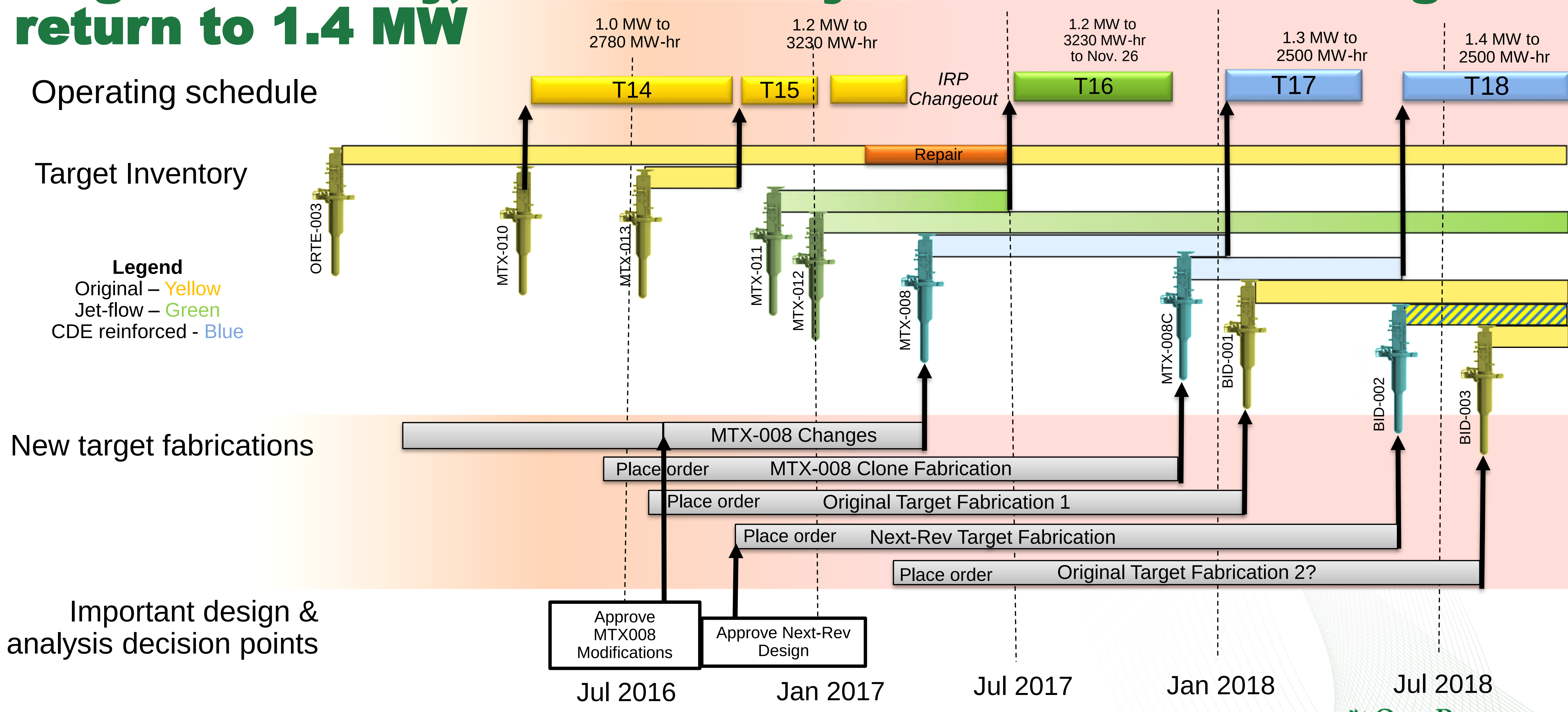
Gas injection mitigates pressure pulse and erosion



Tests in LANSCE beam at WNR show strain mitigation reduction factor of 5 and CDE damage by a factor of 16

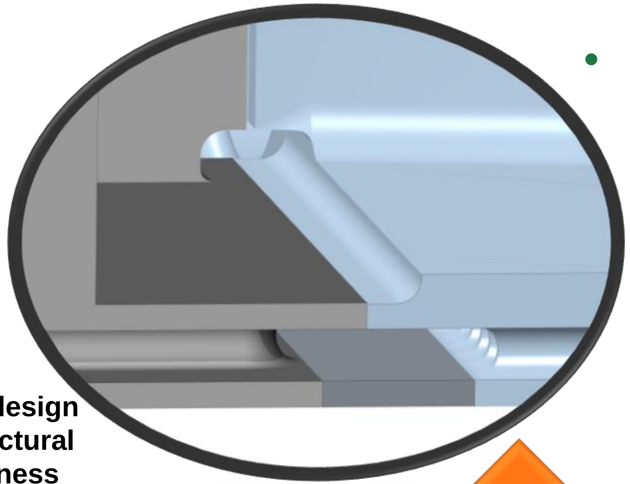
OAK RIDGE National Laboratory

This strategy balances schedule constraints, risks to target inventory, and reliability risks while achieving return to 1.4 MW



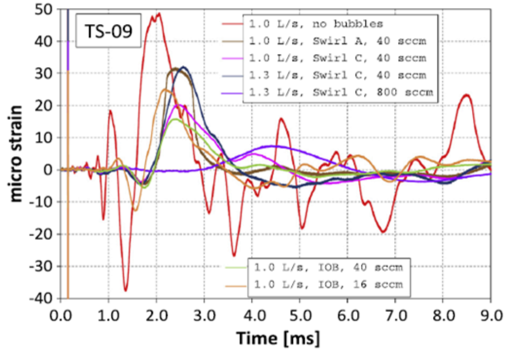
We are implementing a DOE-endorsed plan using proven techniques that provides a path to reliable 1.4 MW target operation in 2018

- Structural Improvements
  - Removal of stress concentrations
  - Increasing wall thickness where possible



Weld redesign for structural robustness

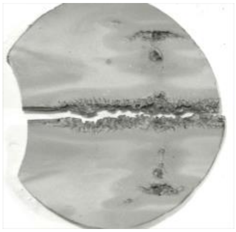
- Gas Injection is shown to reduce stress and cavitation damage



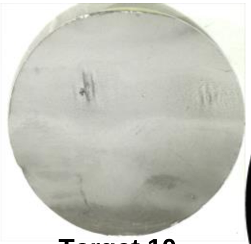
Tests in LANSCE beam at WNR show strain mitigation reduction factor of 5 and CDE damage by a factor of 16

Target solutions

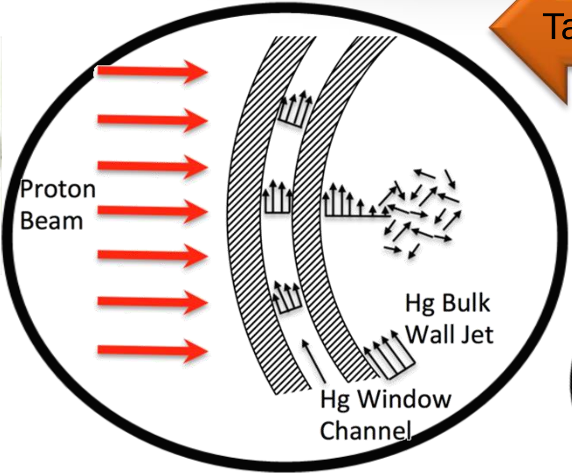
- Flow redistribution within the target can reduce local damage

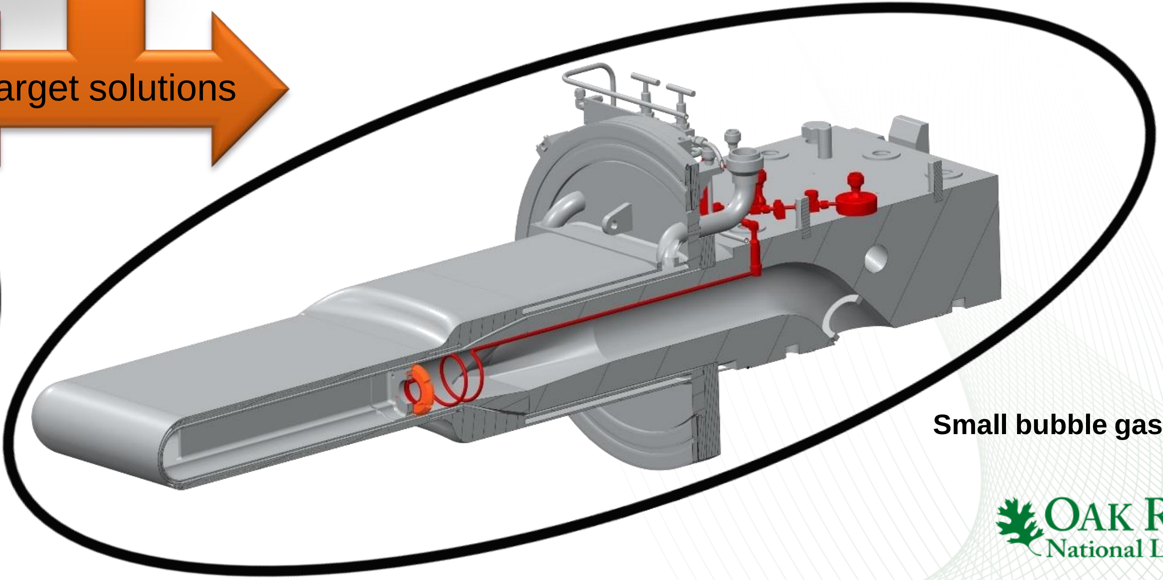


Target 6 (locally stagnant flow)



Target 10 (sweeping flow) – “Jet-flow Target”



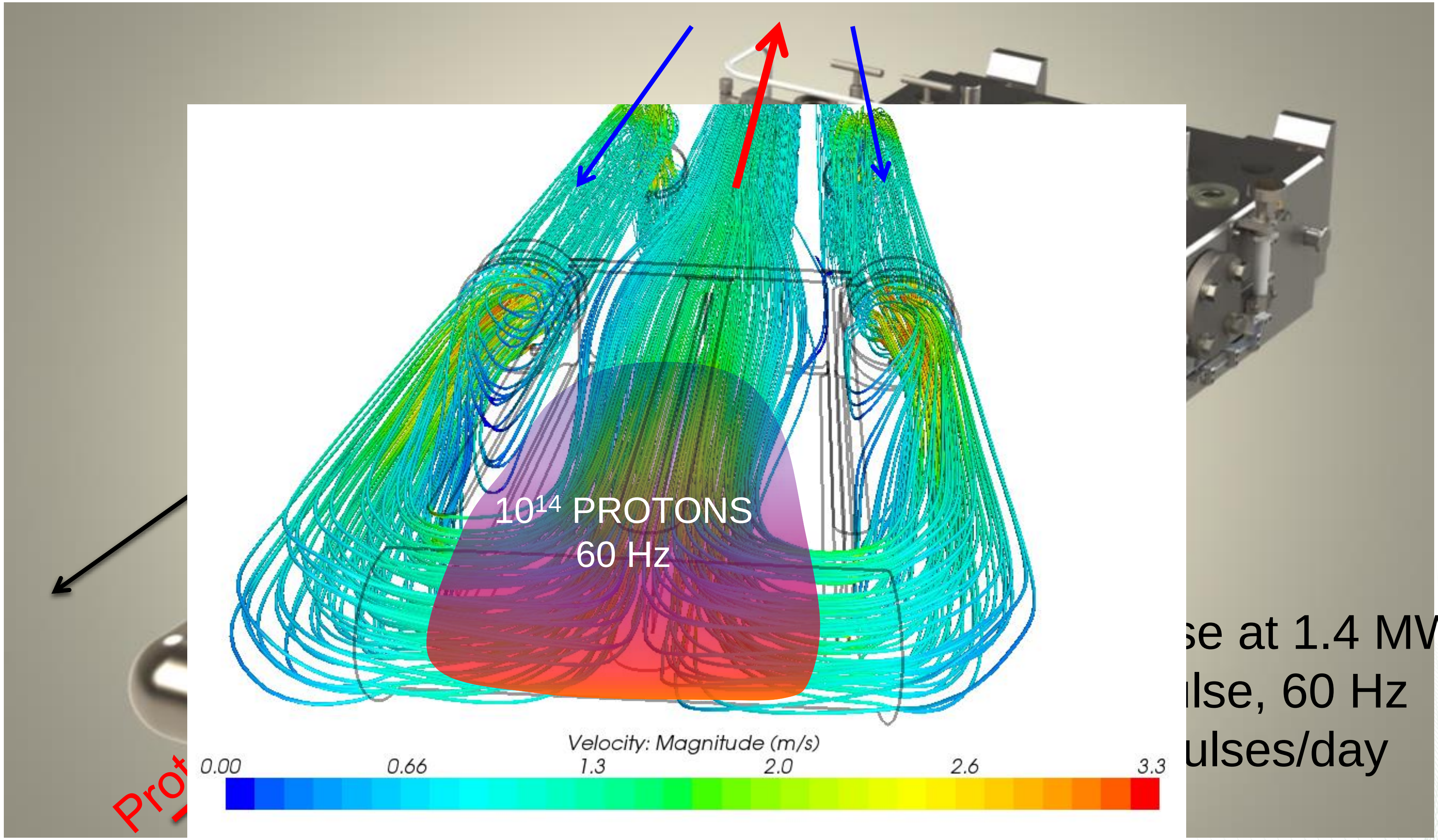


Small bubble gas injection

OAK RIDGE National Laboratory

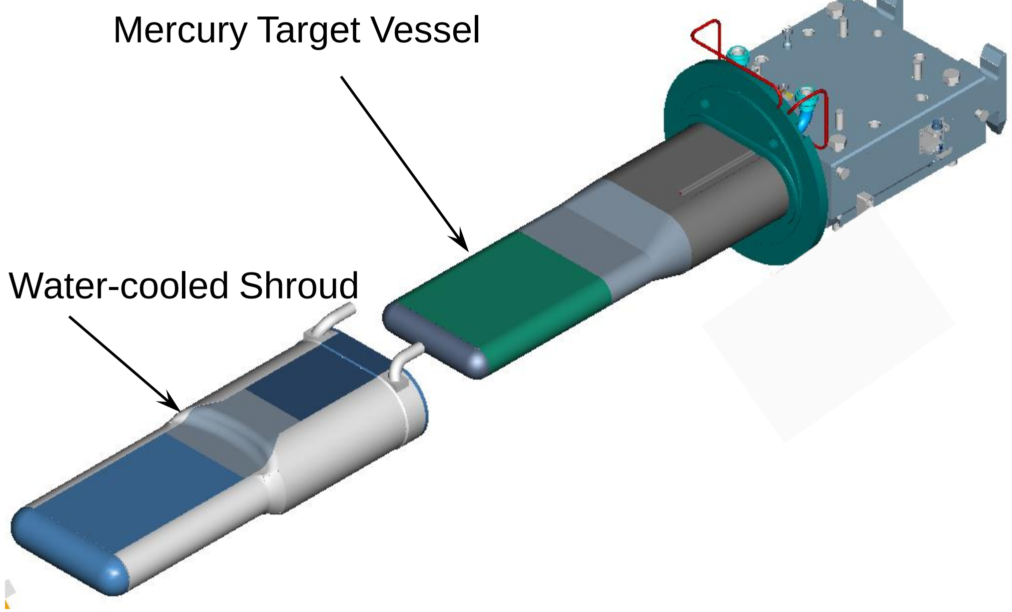
Backup slides

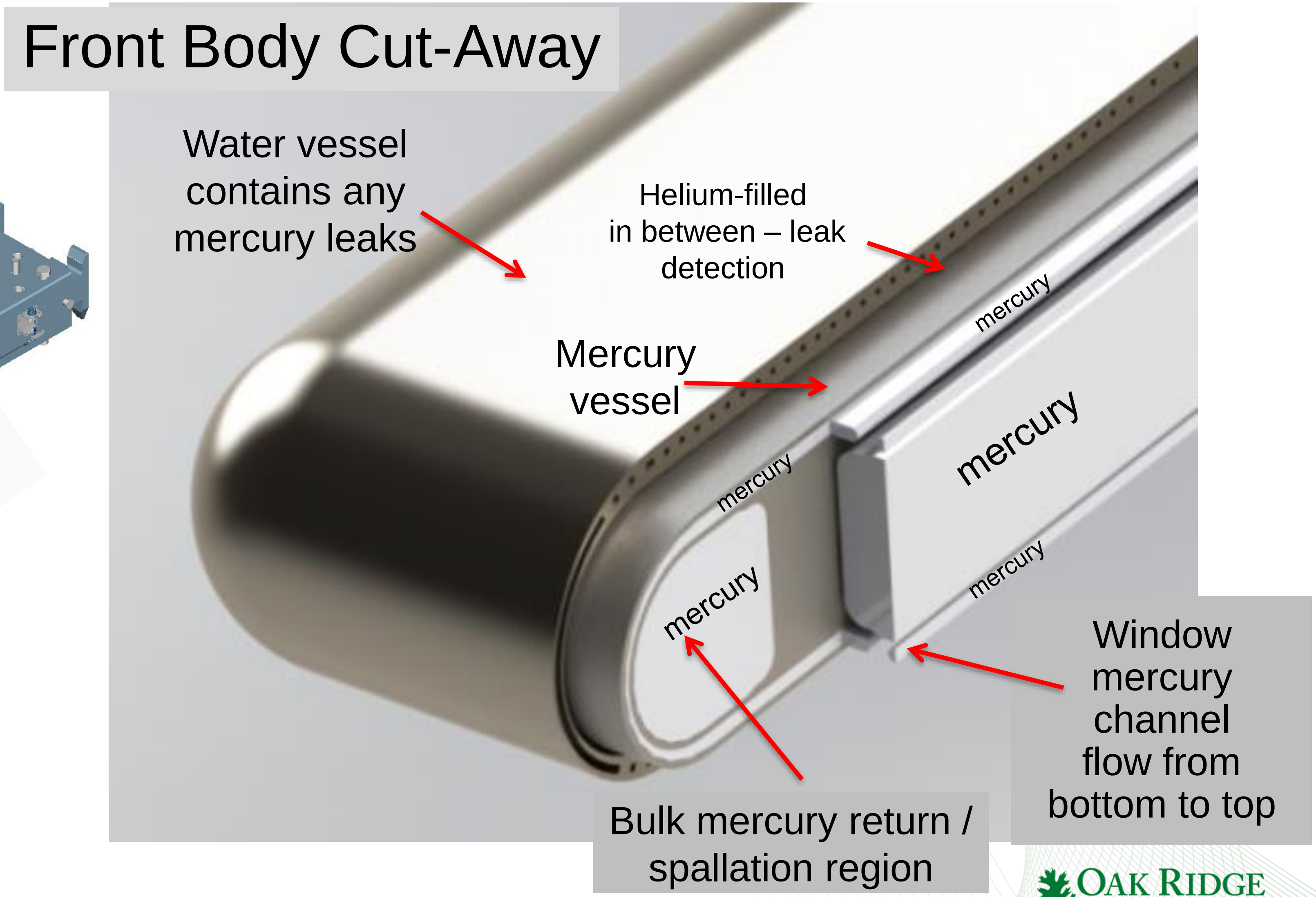
The target module is a stainless steel vessel that holds the mercury flow



se at 1.4 MW
lse, 60 Hz
ulses/day

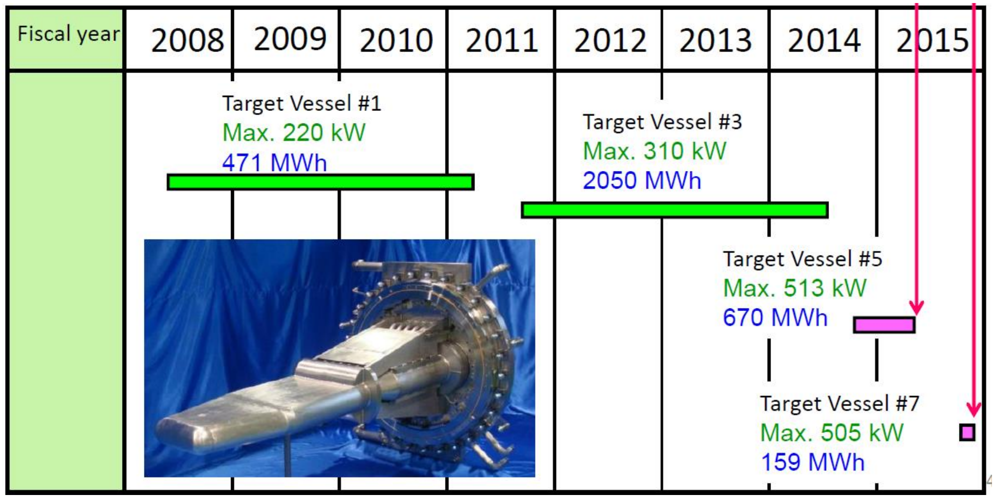
The target module is multilayered and consists of two separate vessels



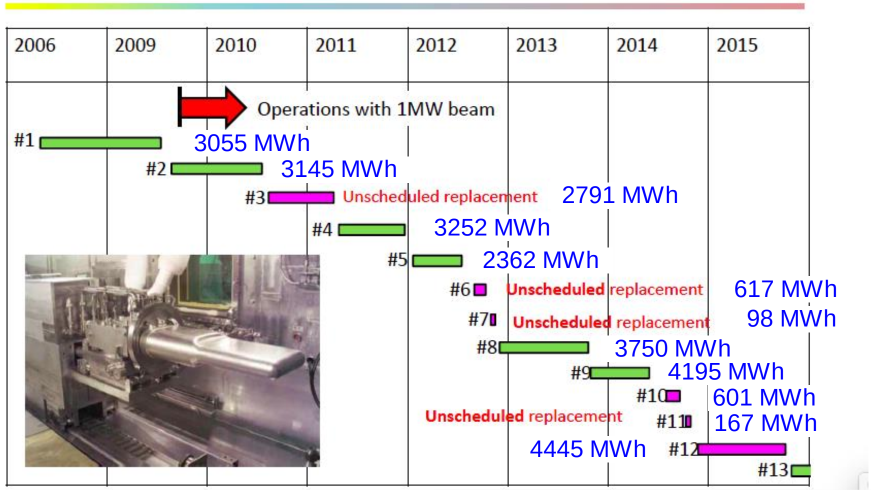


The SNS leads the world in high-powered spallation target technology

J-PARC has recently had to decrease power due to target issues

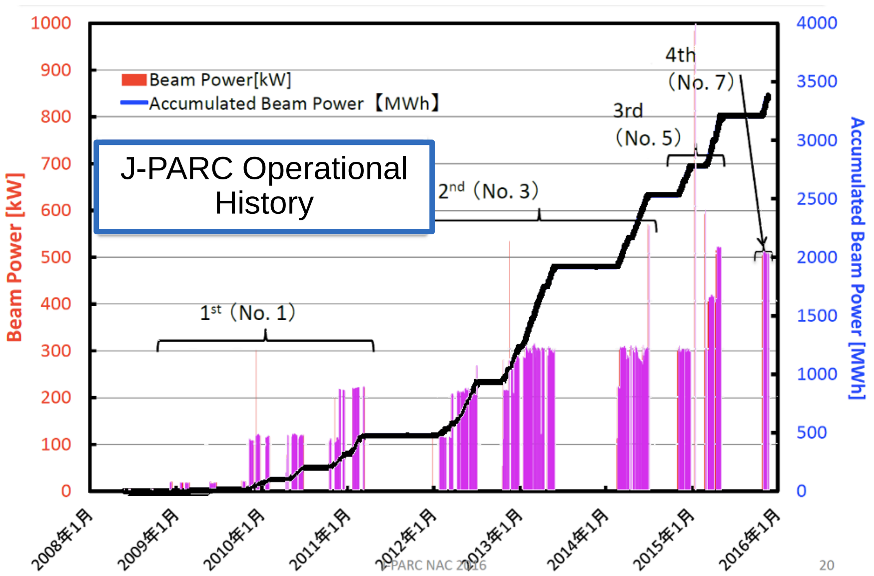


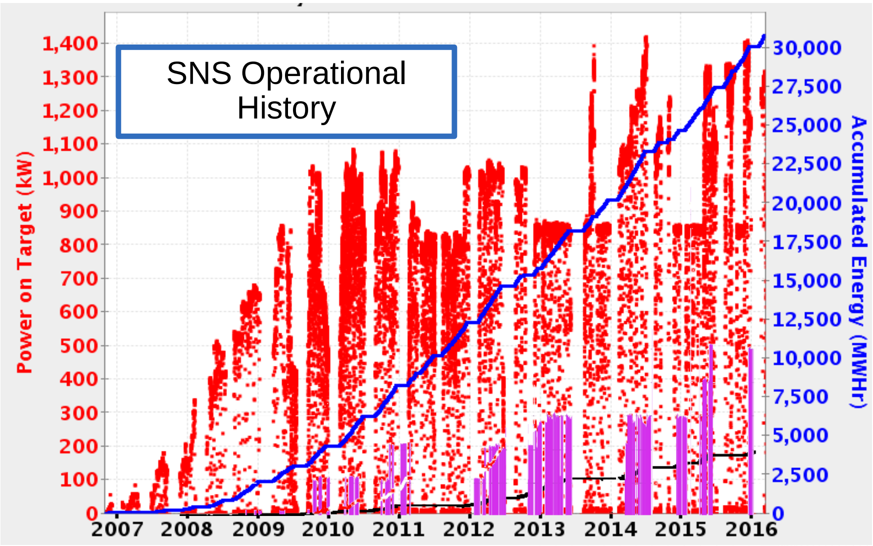
SNS has been operating above 1 MW since 2009



Source: Hiroshi Takada, J-PARC Center

The SNS leads the world in high-powered spallation target technology





Of the nineteen target modules that have been (are being) manufactured…

- **Six** have been operated and removed from service before they reached their administratively controlled radiation damage limit - with no indication of a leak
  - Avoid interrupting the user program
- **Seven** have been operated and removed from service due to a mercury leak
  - Four leaked early (< 617 MW-hr)
  - Three leaked much later
- **Five** have not yet been used yet
  - One is on site
  - Four are in construction
- **One** is in service now (>1100 MW-hr)

Current status toward our goal of 1.4-MW reliable operation

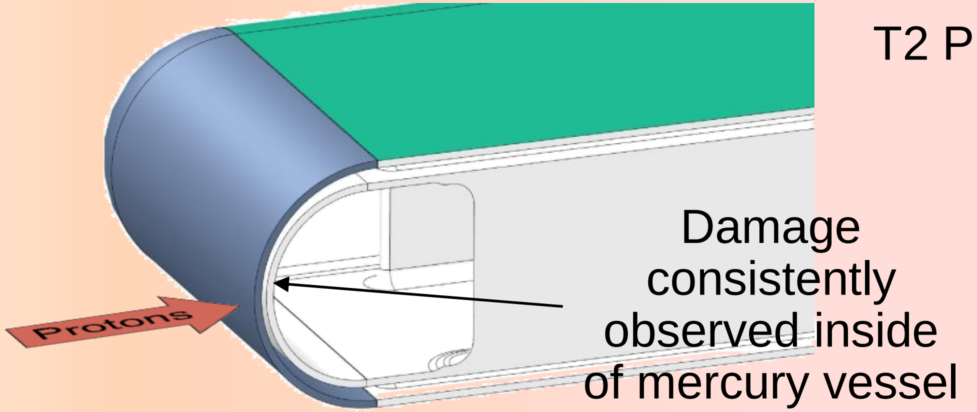
- Operated 4 targets for some time between 1.3 – 1.4 MW
  - T8 for 1 cumulative-day* (removed from service without a leak)
  - T9 for 15 cumulative-days (removed from service without a leak)
  - T12 for 25 cumulative-days before a leak (cavitation damage)
  - T13 for 30 cumulative-days before a leak (cavitation damage)
- T9 was operated
  - 6 months above 1 MW
  - 3 months above 1.2 MW
  - did not leak mercury
- New “improved” designs are on their way
  - T14 (in service) has improvements over T13 and T12
  - T15 will be identical to T14
  - Planned measurements of erosion rate as a function of power (T14 & T15)
  - T16 will be an improved jet-flow model with gas injection

*208 cumulative-days of operation in a (5000-hr) year

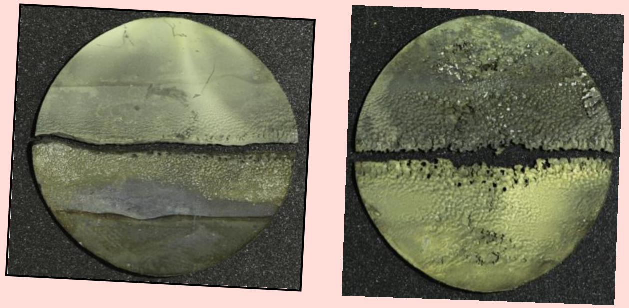
OAK RIDGE National Laboratory

Post-irradiation examination (PIE) cavitation damage erosion (CDE) degrades the target structure

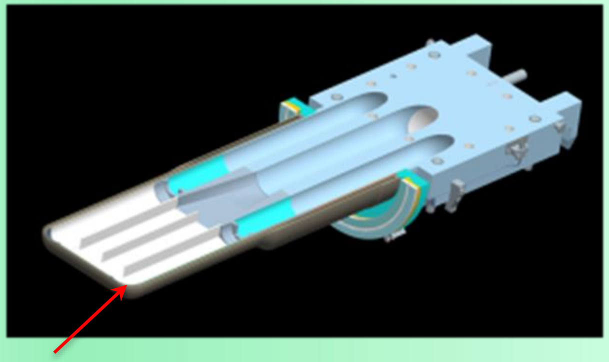
Despite significant CDE, before September 2015 leaks were caused by weld failure (with T3 cause undetermined)

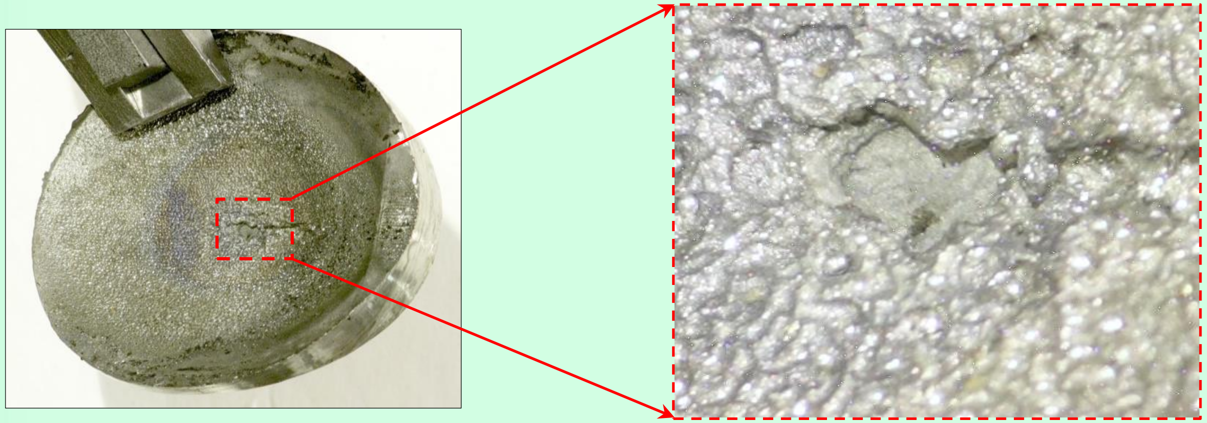


T2 PIE – Inner window which is typical for original target design



First leaks determined to be caused by CDE found in T12 and T13 (2016)

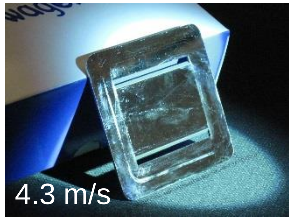




T12 PIE – Front corner leak which occurred in the same location for T13

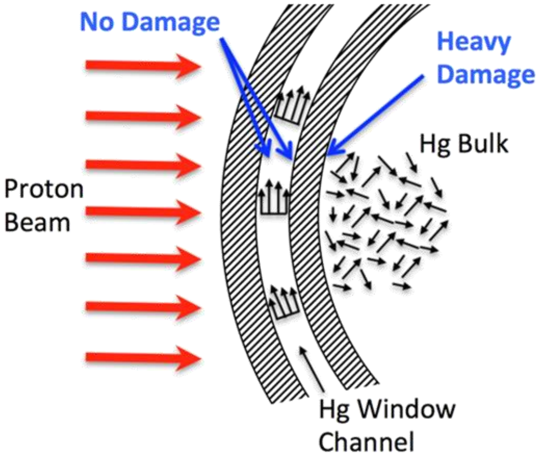
Uni-directional mercury flow near the surface of the target protects the surface from beam-induced cavitation damage erosion (CDE)

- LANSCE scaled experiments showed CDE was significantly reduced (factor of 2) by uniform flow

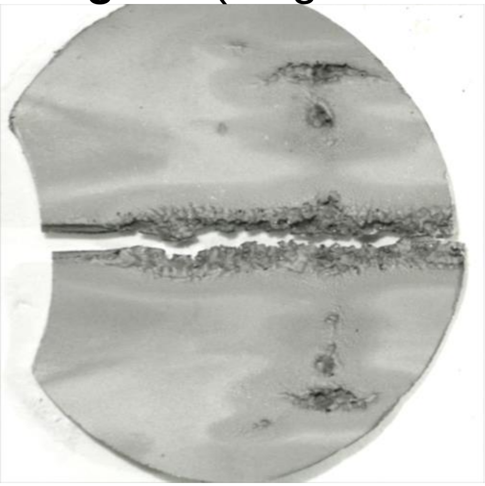


- Results at SNS proved even better than expected, with almost no damage

Original SNS Target

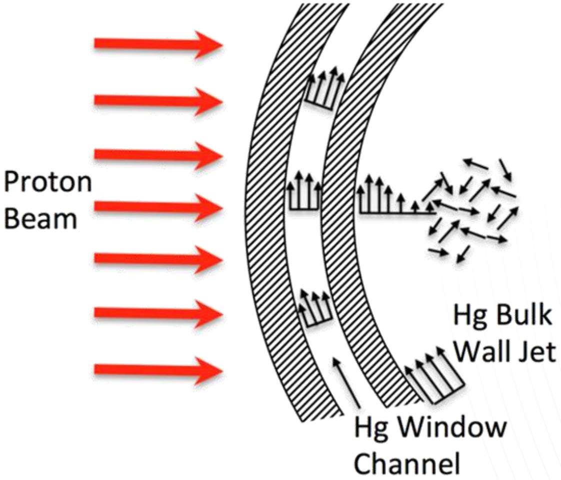


Target 6 (Original flow)



1.1 MW for 6 weeks

Jet-flow Target



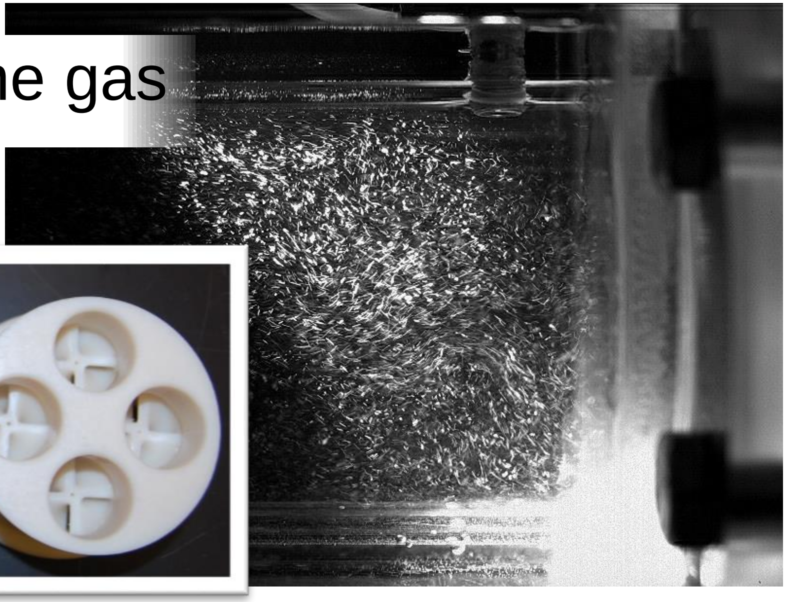
Target 10 (Jet-flow)

1.1 MW for 6 weeks

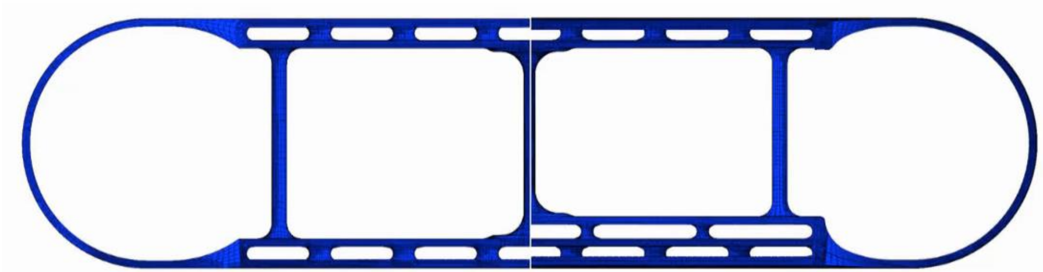
OAK RIDGE National Laboratory

Systematic Path to 2 MW Target involves more extensive changes

- High-volume gas Injection



- Design optimization



- Increased Knowledge
  - In-beam measurements of target
  - Post-irradiation examination

Current plan for target supply and consumption…

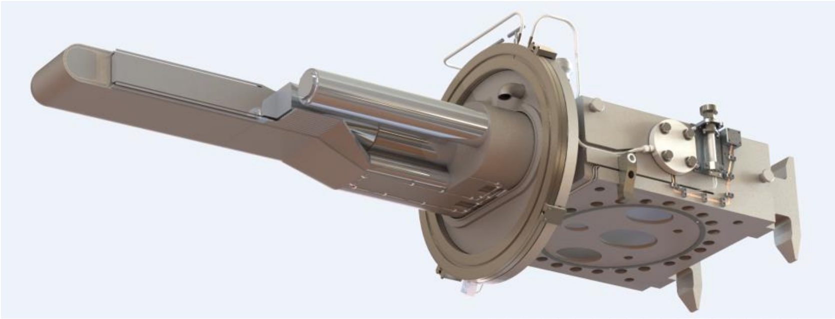
- Supporting user program is the highest priority
  - Operational reliability without unexpected interruptions
  - Increasing flux of neutrons
    - Heavy water
    - Aluminum proton beam window
    - Power on target must come up to 1.4 MW
- Balance operational risk with running at higher power
- Build inventory to three spare targets

Summary

- Target reliability is essential to the neutron science user program at SNS.
- Mercury leaks have occurred in several targets which shortened target lifetime.
- We are continuously improving in response to target operational experience.
- We are implementing a plan that balances continuous improvement and maintaining target inventory.

While we order targets with existing technology, current initiatives should help reach the reliability goal

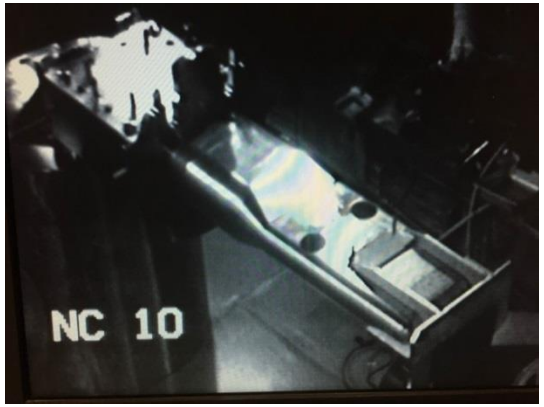
- Improving PIE capabilities
- Measuring the target response during operation
- Changing the design of the targets
- Improving our fabrication methods
- Increasing the pump speed
- Adding gas injection

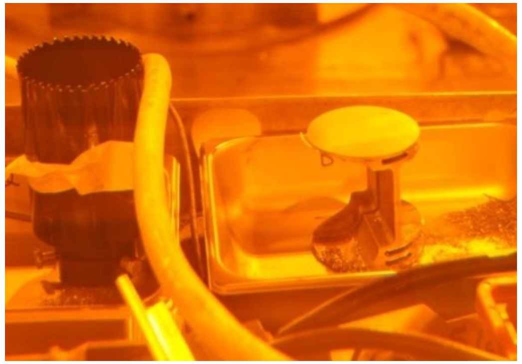


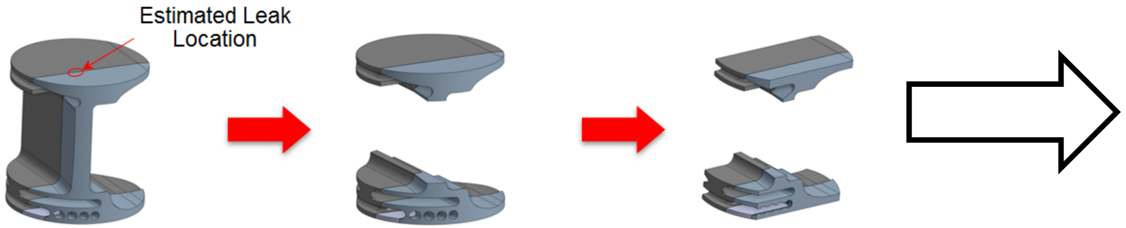
OAK RIDGE National Laboratory

Improving PIE Capabilities

- *Benefit:* Truest source for design guidance
- *Highlight:* T10 leak sample extracted with new tool
- *Developing:* Characterization of specimens







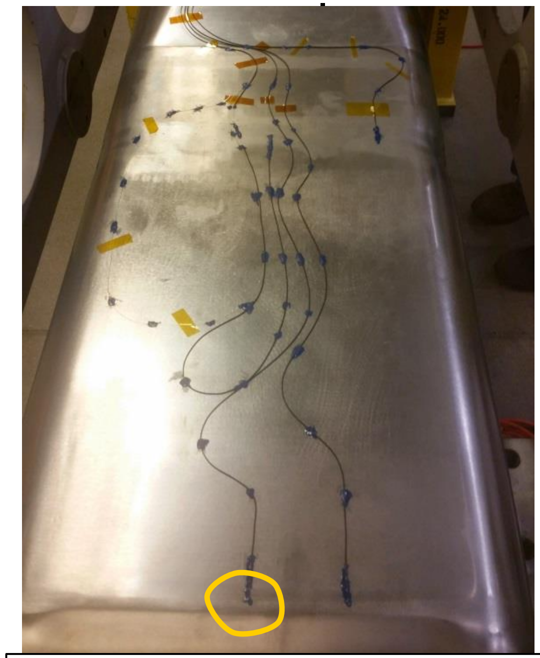
Microscopy and metallurgical testing

Oak Ridge National Laboratory

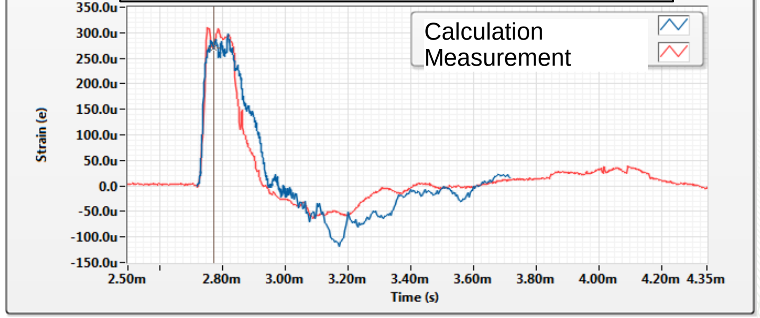
Measuring the target response

- *Benefit:* Direction for design
  - Calibration of analysis
  - Diagnostic for gas injection and other design changes
- *Highlight:* Strain data already collected
- *Developing:* More extensive data (time and space)

Strain sensors on target



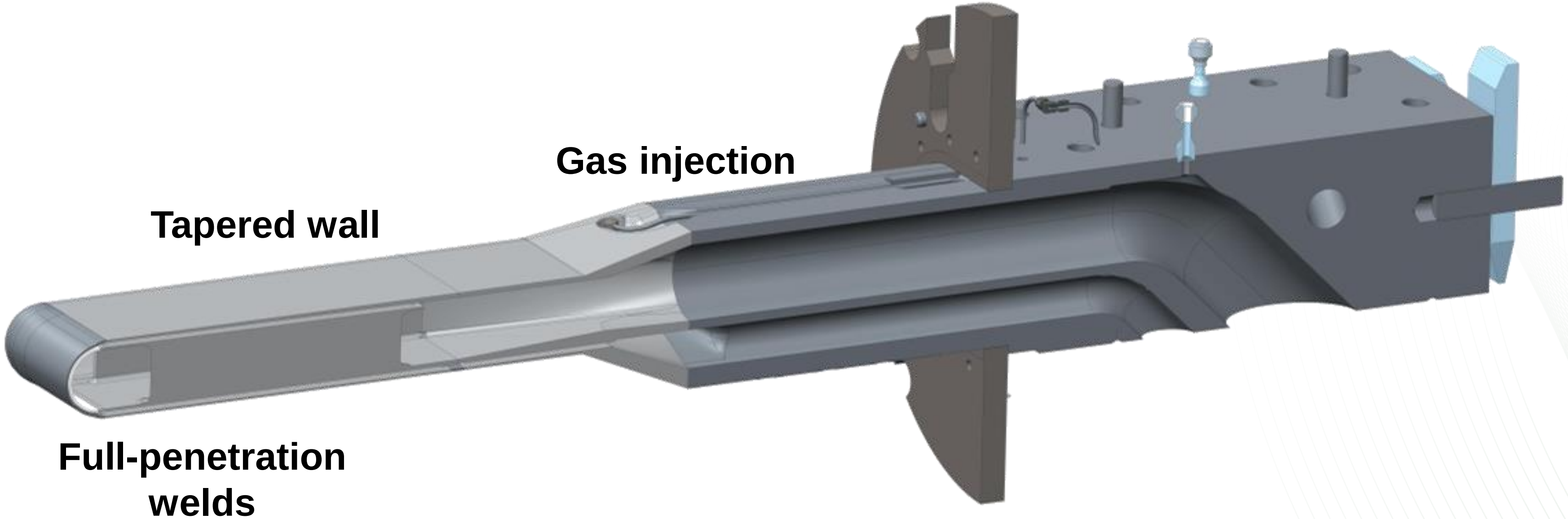
Beam Pulse Strain Measurement



OAK RIDGE
National Laboratory

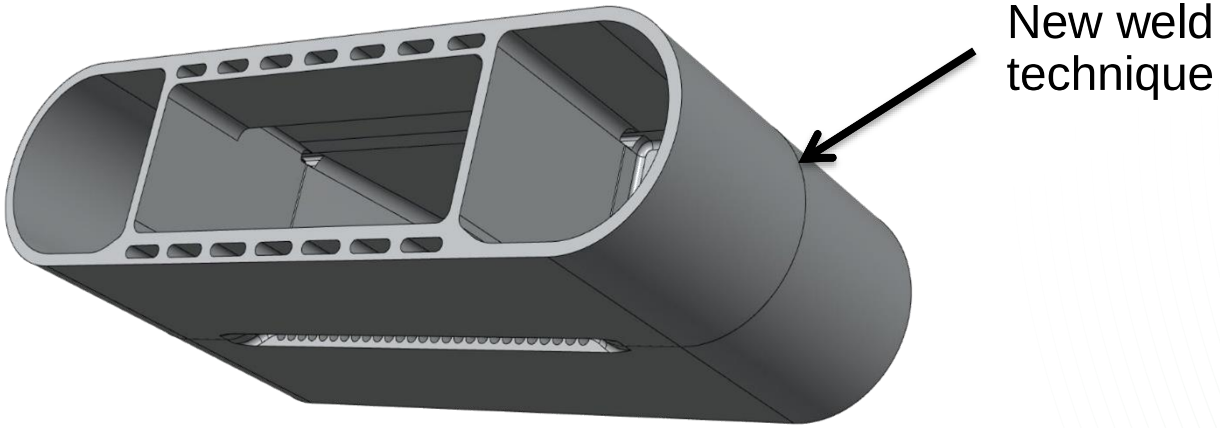
Changing the design of the targets

- *Benefit:* Structure is made more robust to applied loads
- *Highlight:* Four targets already modified, including one “on deck”
- *Developing:* Next generation design



Improving fabrication methods

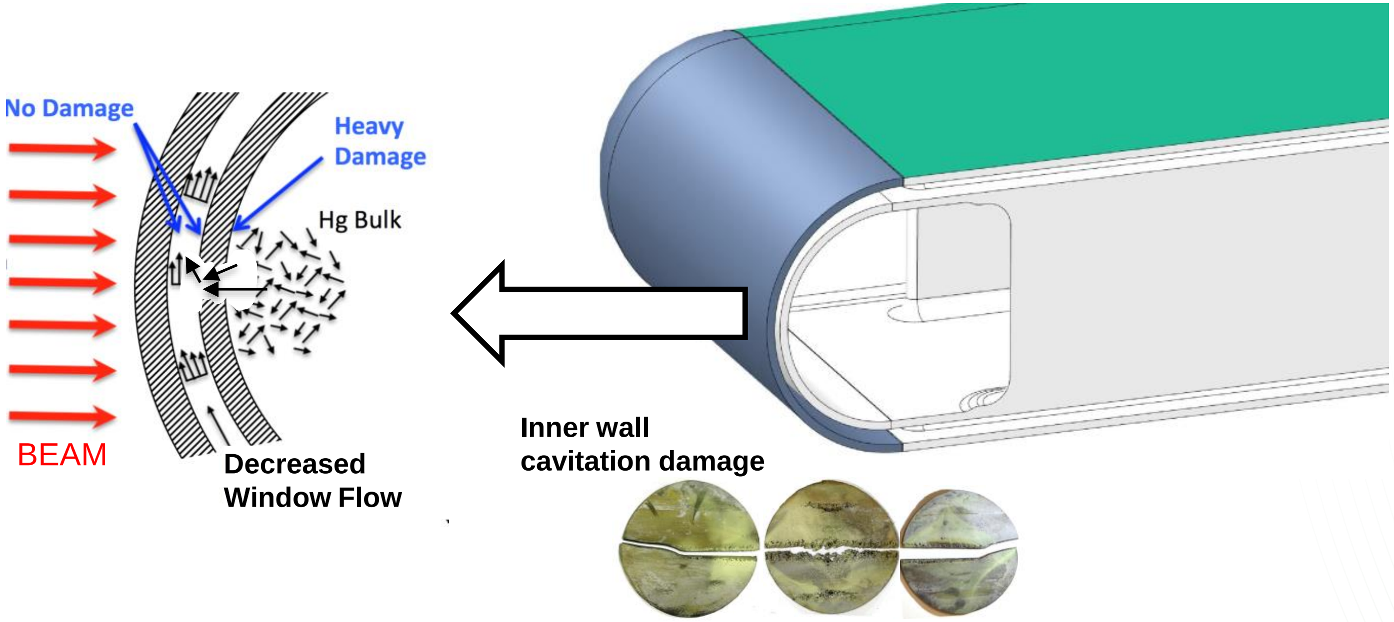
- *Benefit:* Reduce fabrication vulnerabilities
- *Highlight:* TIG vs. E-beam welding mock-up
- *Developing:* Weld distortion test, fabrication specification update



Weld mockup for weld distortion test

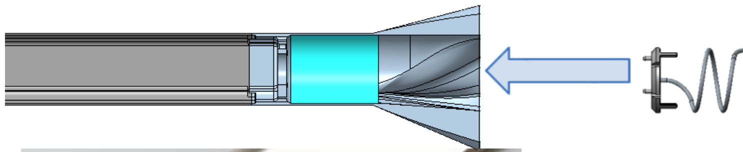
Increased pump speed

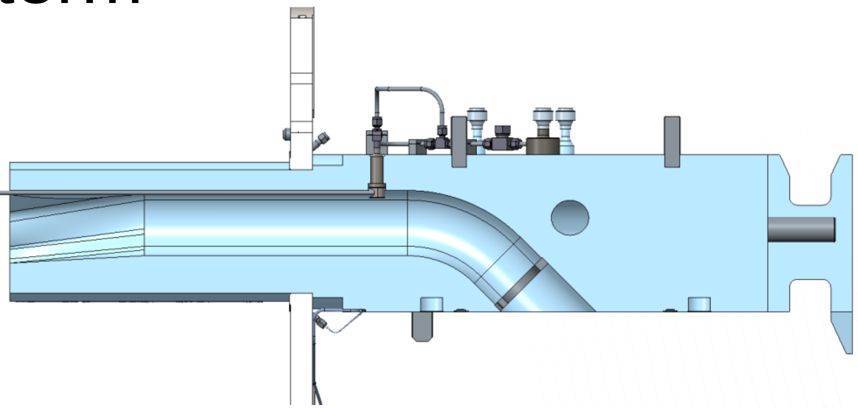
- *Benefit:* Lower thermal stresses and reduced beam-pulse induced cavitation
- *Highlight:* Running successfully at 350 RPM
  - Past 10^8 cycles at 1.4 MW
  - Unexpected improvement of window flow



Adding gas injection

- *Benefit:* Reduction of pulsed structural loads and cavitation erosion
- *Highlight:* Target retrofit fabrication begun
- *Developing:* Gas supply, longer-term implementation

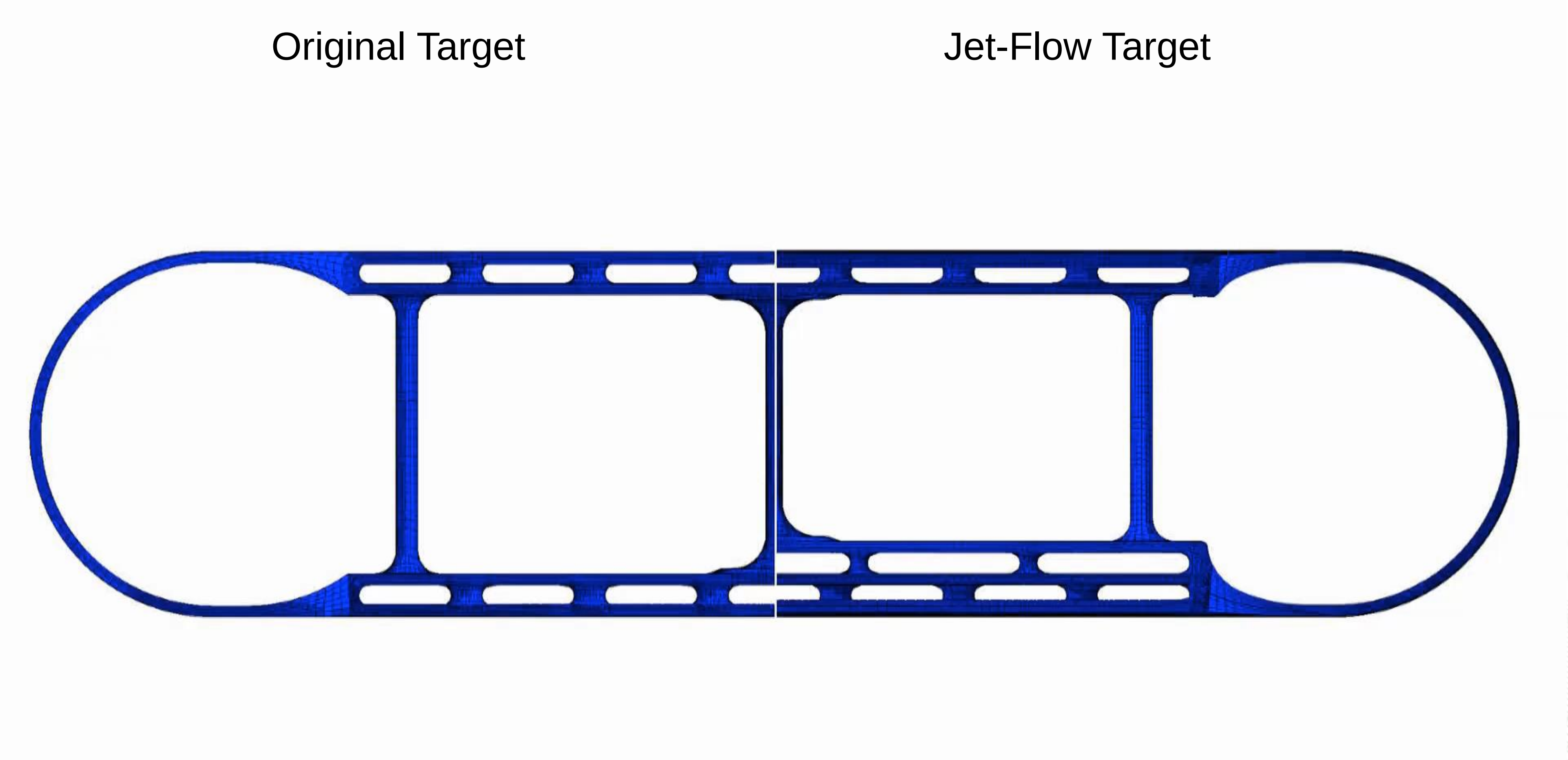




Envisioned: gas bubbles inside mercury

Example of computer simulation

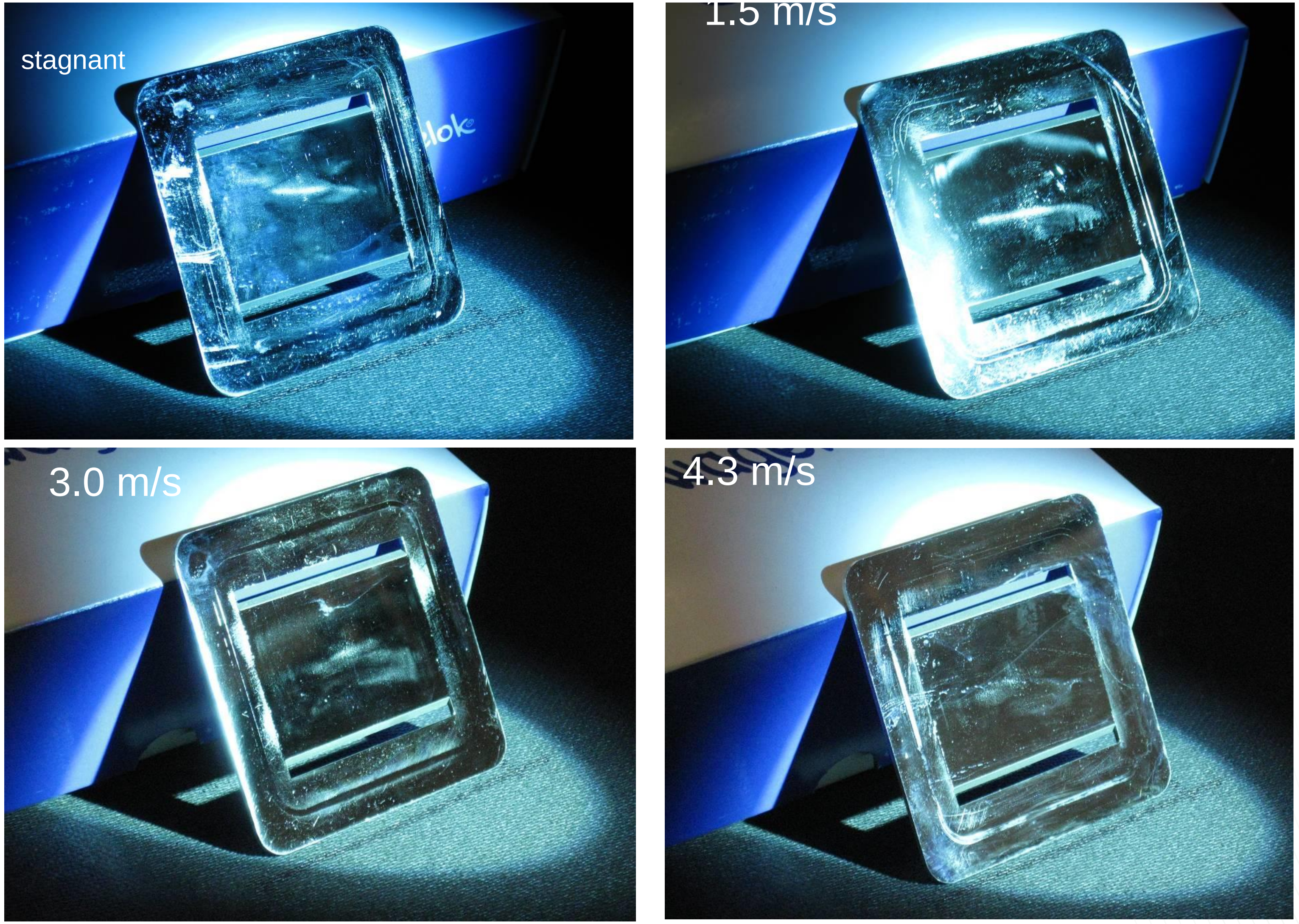
- Simulations used to determine if new design is suitable for use



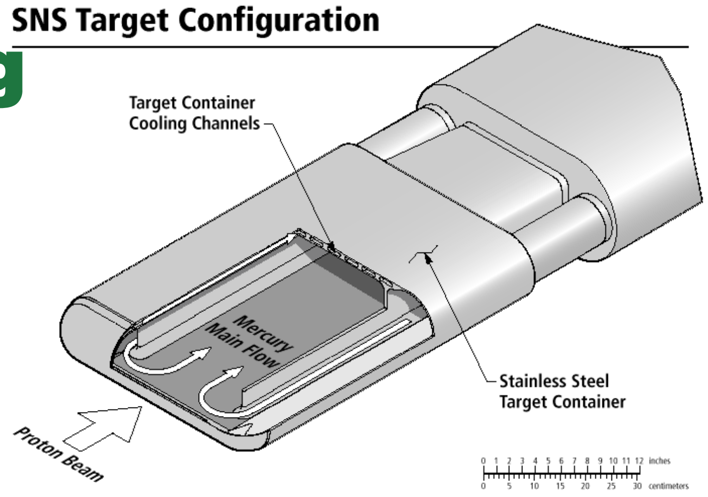
Deformation is scaled up 300X

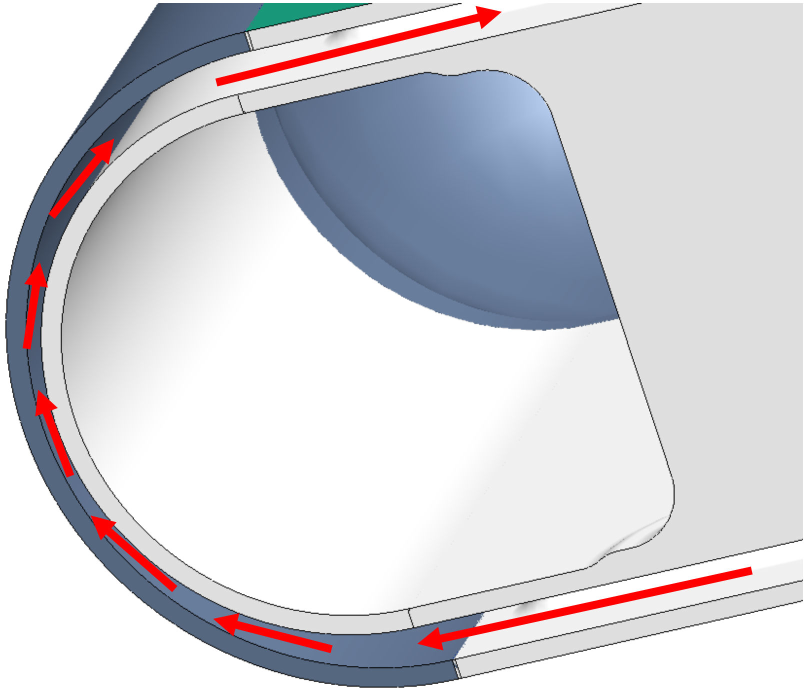
LANSCE/WNR tests at 2.7 MW level showed a factor of 2 reduction of CDE by directed flow

100 pulses per test condition

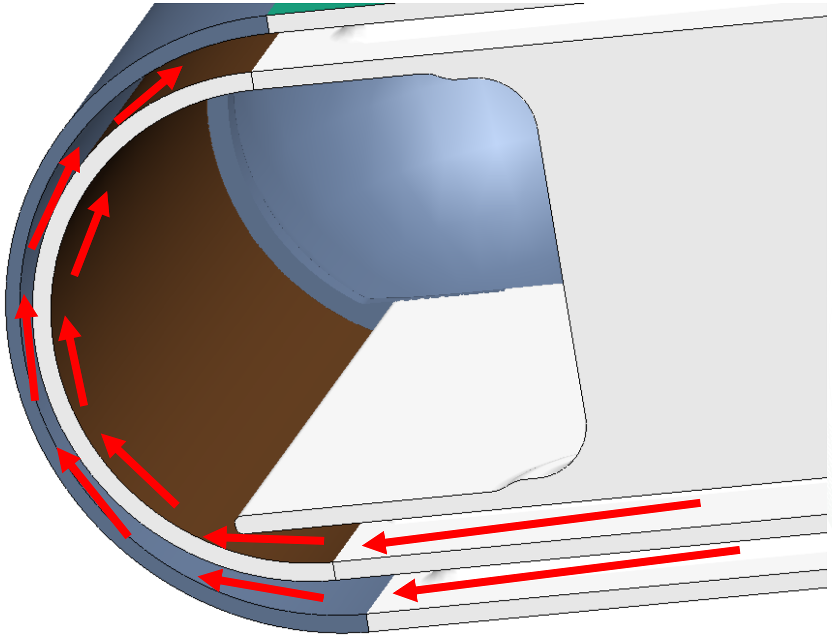


Mitigate Damage Via Flowing Hg



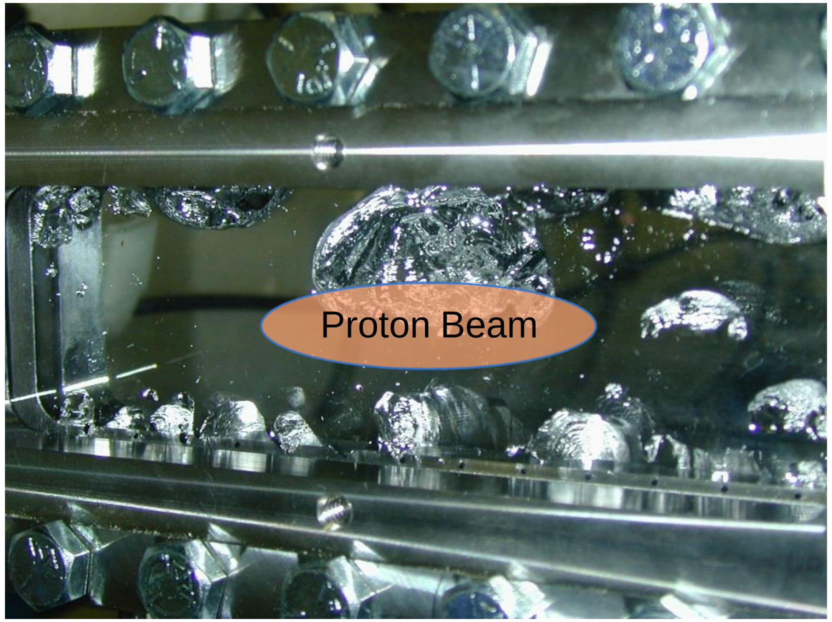


Original Configuration



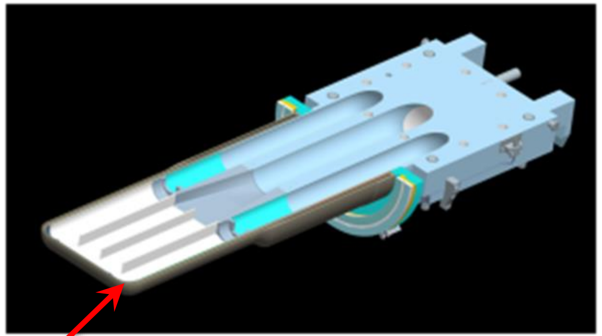
Jet-flow Configuration

Gas injection at the wall has reduced CDE damage by a factor of 16 in LANSCE WNR tests



Target 12 and 13 leak locations were identified during Post Irradiation Examination (PIE)

- The leak locations in Targets 12 and 13 were identified using an articulating videoprobe
- The leaks in Target 12 and 13 were in the same location – at the end of the “driver side” supply passage
- The Target 12 and 13 leaks are thought to be caused by cavitation-induced erosion – the first time targets have failed from cavitation



Target 12 & 13 Leak location

Bubble emanating from T13 leak (submerged under mercury)

Top of target

Driver side flow baffle

Bottom of target

Cracked T12 inner wall

Oak Ridge National Laboratory

These five current initiatives provide layers of improvement

1. Higher flow rate
   – *Already implemented on T13*
2. Incremental changes to materials and geometry
   – *On-deck for installation (T14)*
3. Modified jet-flow target to arrive in August 2016
4. Early gas injection at low flow rate
   – *Should be ready in CY2017*
5. Future design changes that directly address failure modes (e.g. recent results from T12)