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PSI

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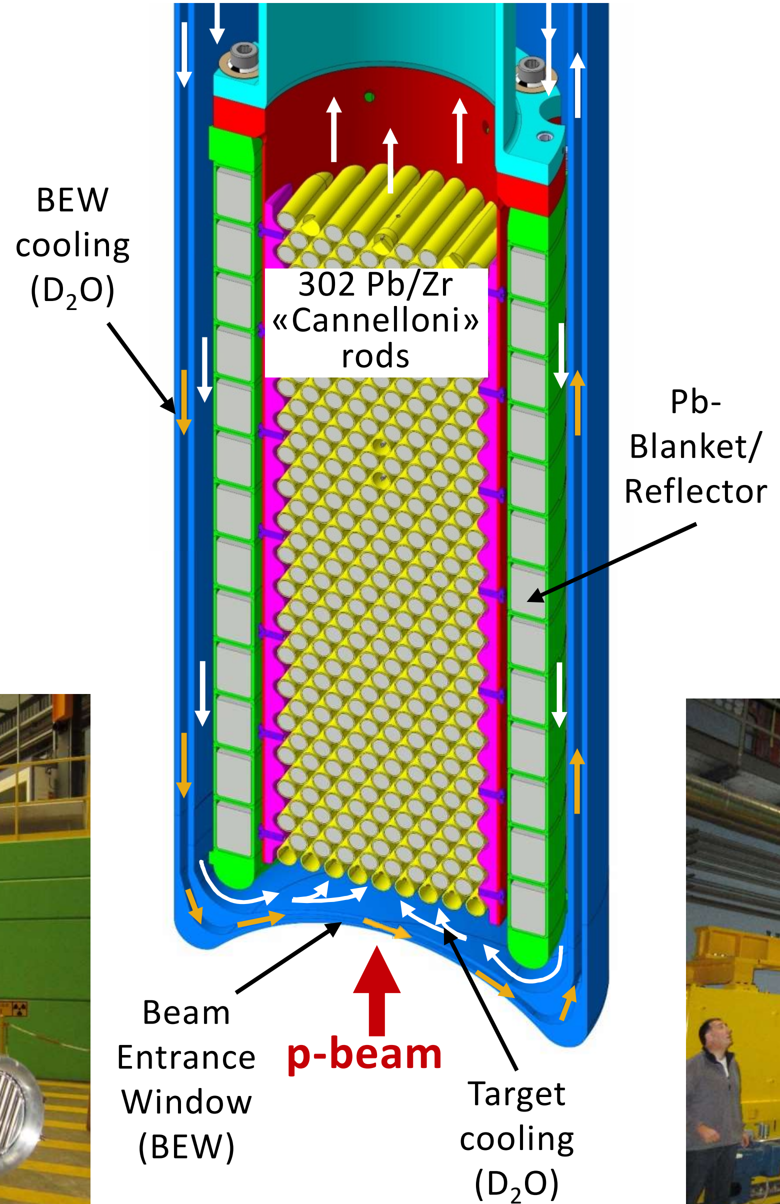
Investigations on the Premature Failure of SINQ Target #11 and its Countermeasures

ICANS XXIII, Chattanooga (TN), USA, 14th October 2019

Outline

- Design of Target #11
- Target Incident
- PIE (visual & metallurgical)
- Possible Failure Scenario
- Improved Design of Target #13
- Performance of Target #13

Assembly of Target #11



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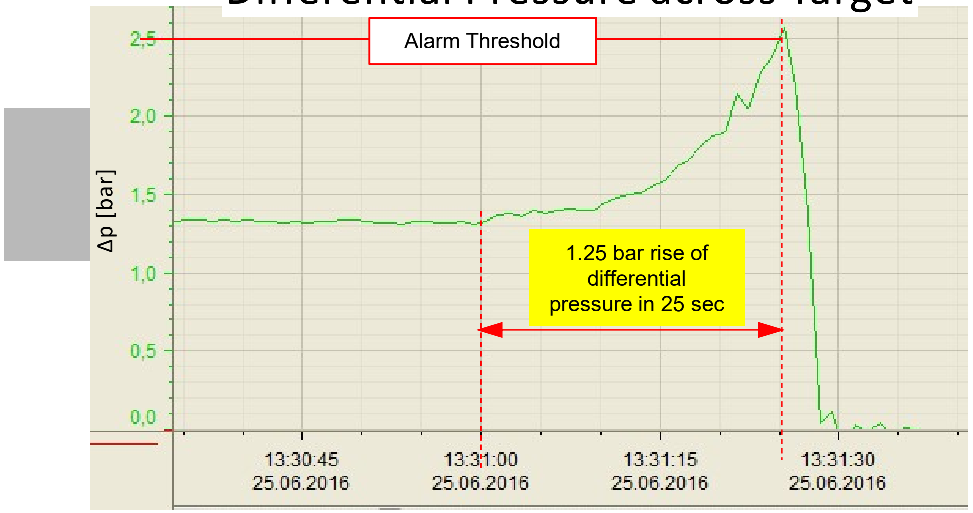
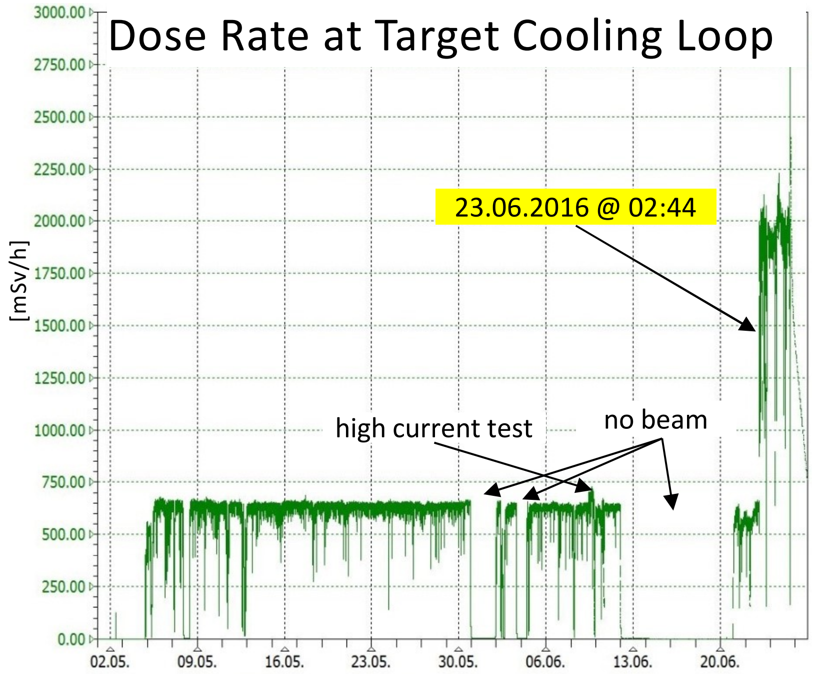
Symptons of the Incident

SINQ

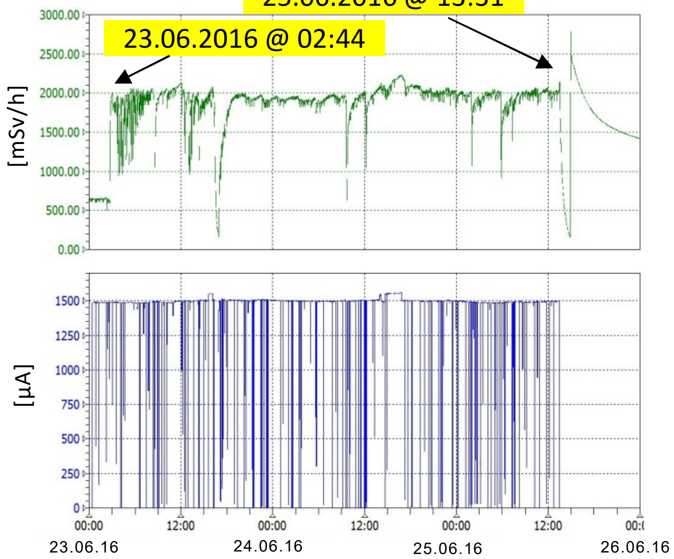
Differential Pressure across Target



Dose Rate at Target Cooling Loop



Dose Rate & p-Current



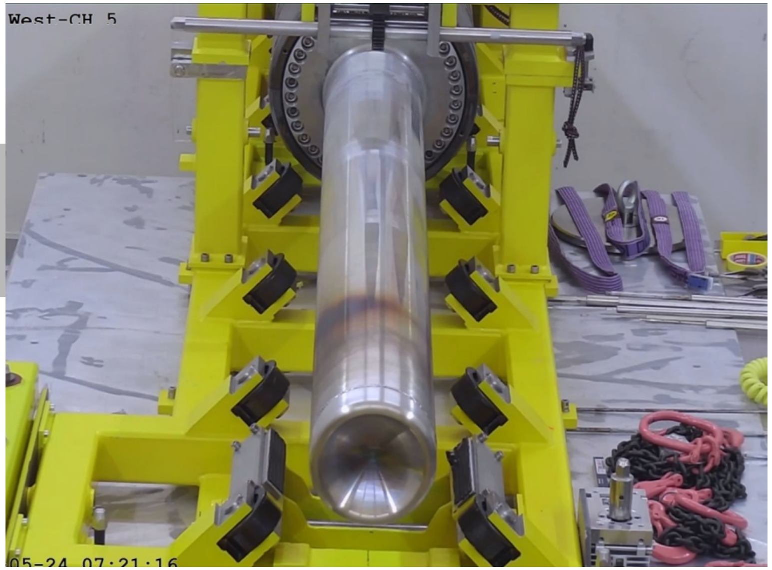
23.06.2016, 02:44

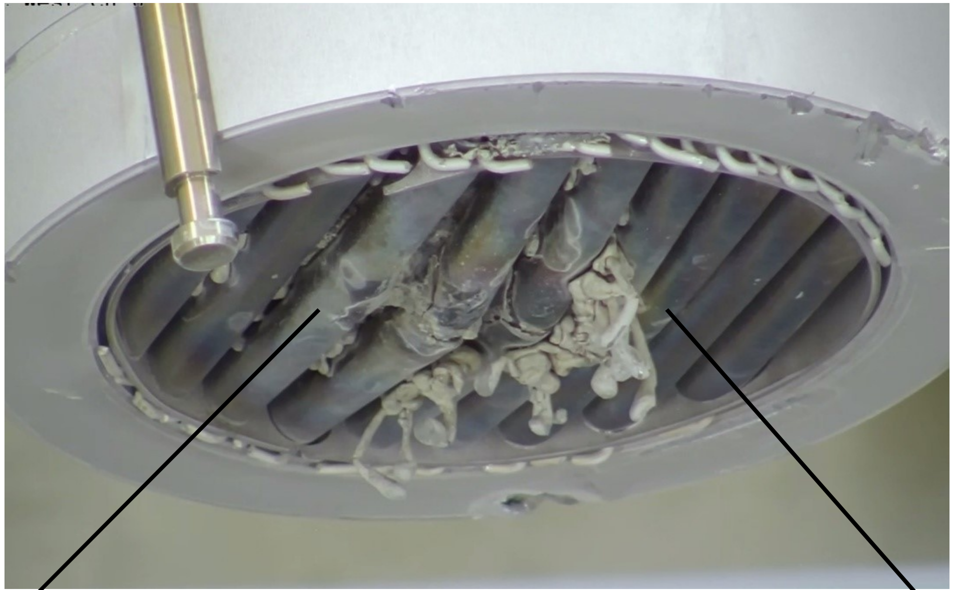
- Sharp increase in dose rate measured close to target cooling pipe
- Overfocussed p-beam

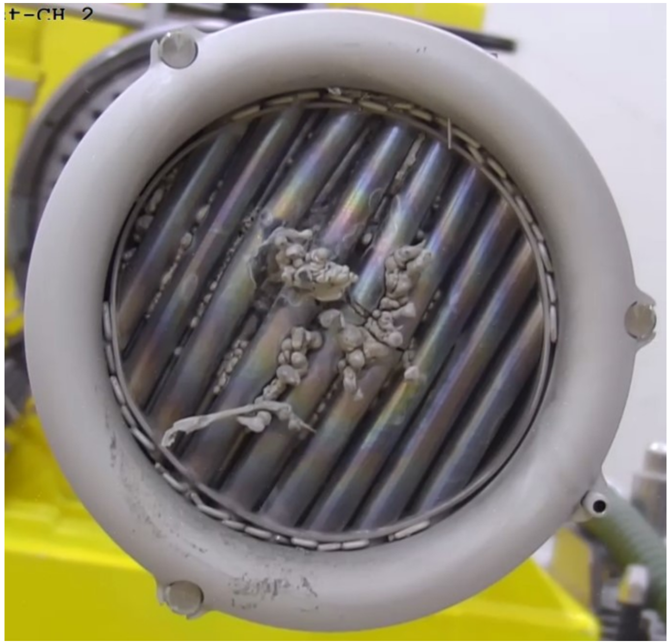
25.06.2016, 13:31

- Sharp rise in differential pressure of cooling water across target => severe blockage of cooling passage
- p-beam switched off

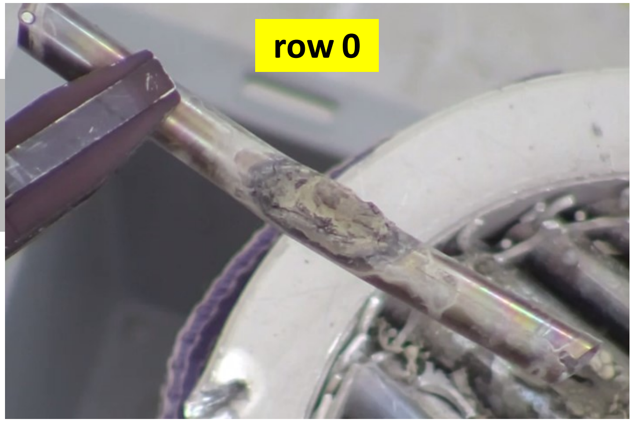
Disassembly and Visual PIE (May 2017)

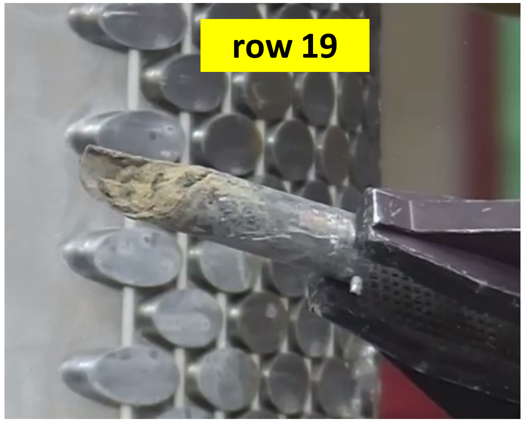


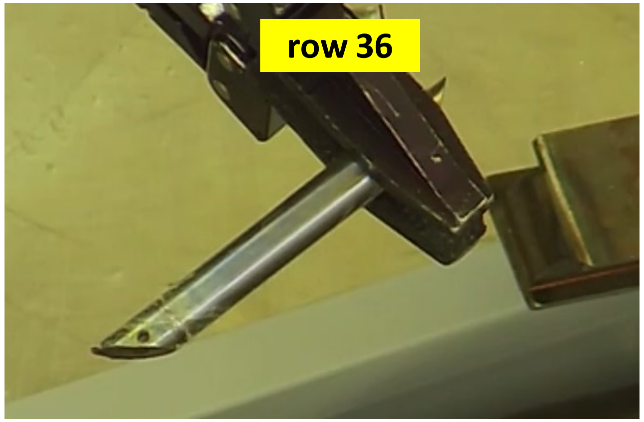


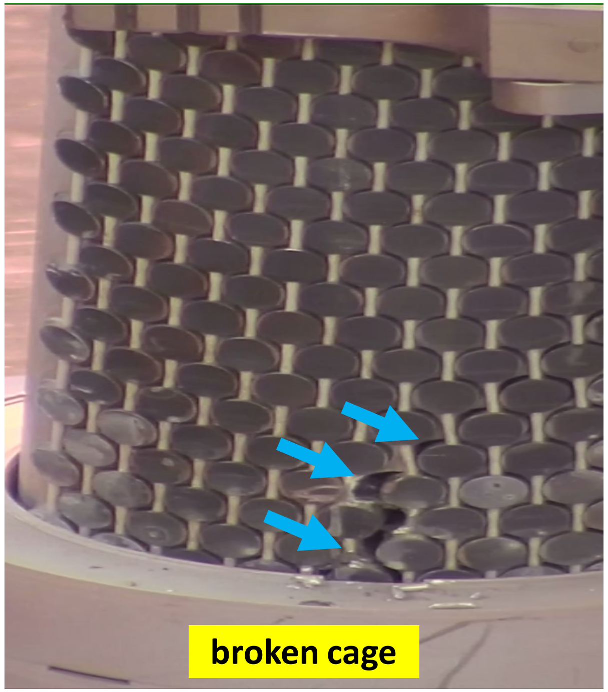


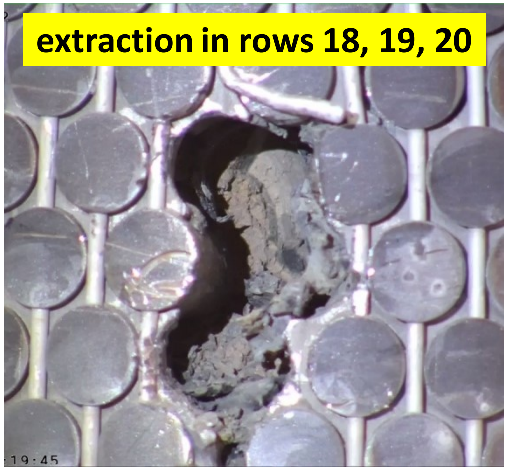
Extraction and Examination





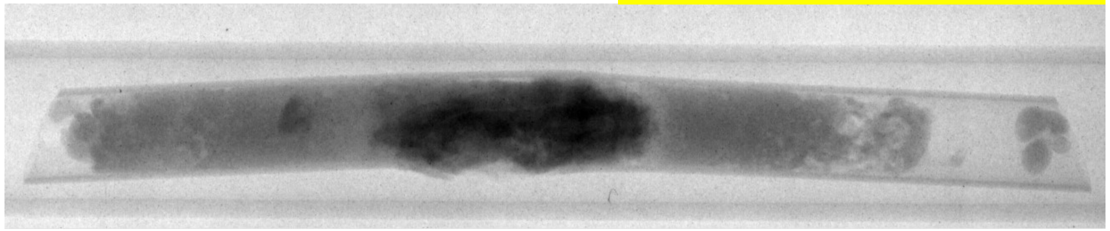




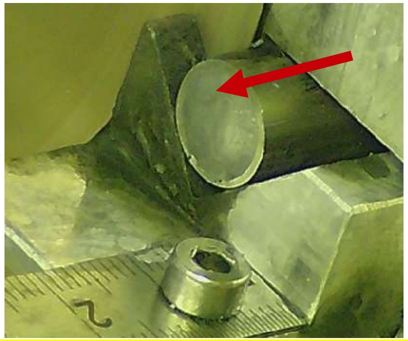


n-radiography of the tube from row 0:

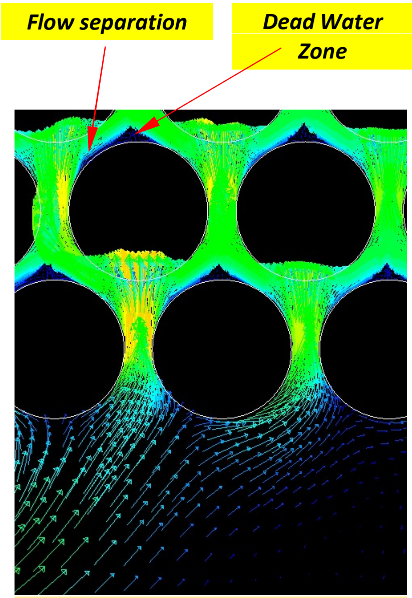
Black spot: probably hydrogen-deposition from p-beam



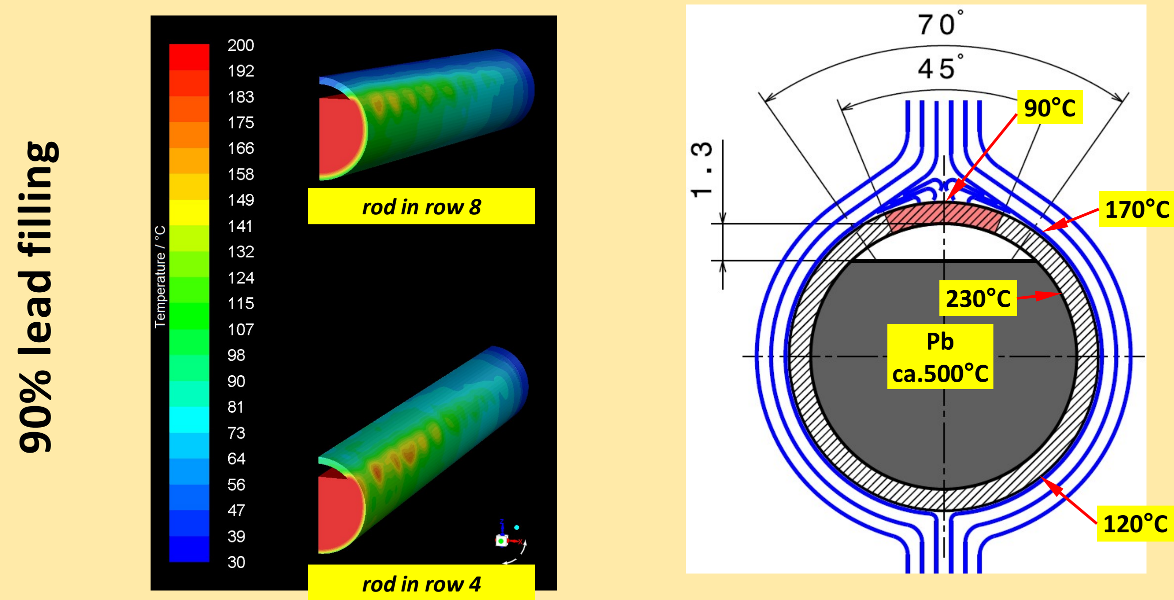
Lead Cross Section & Heat Removal

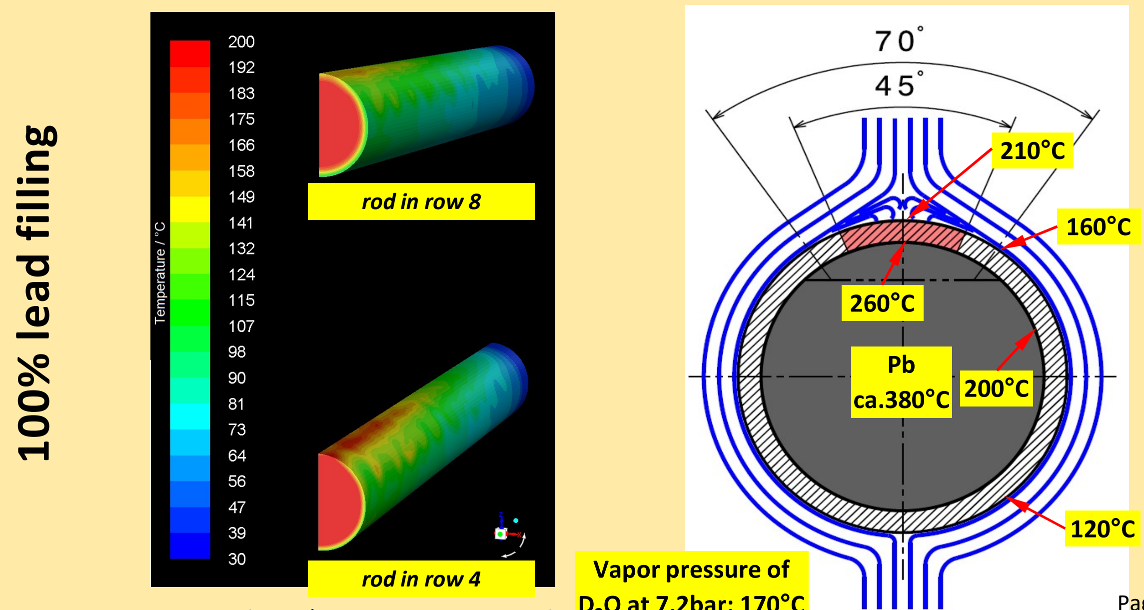


Despite 90% filling in virgin state, tube cross-section appears to be 100% filled after operation



CFD simulation by S. Jollet (PSI)

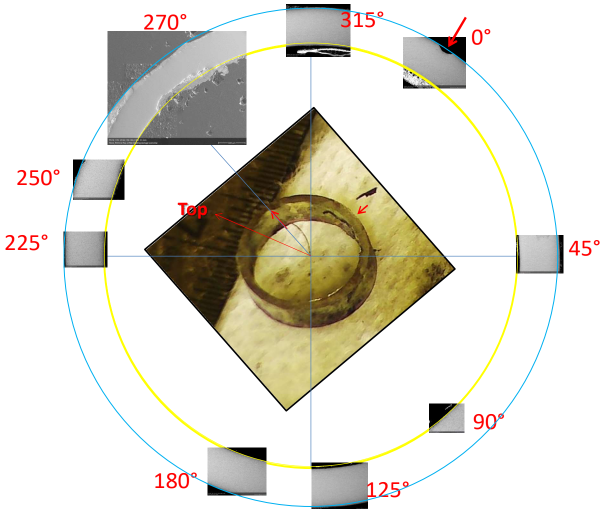




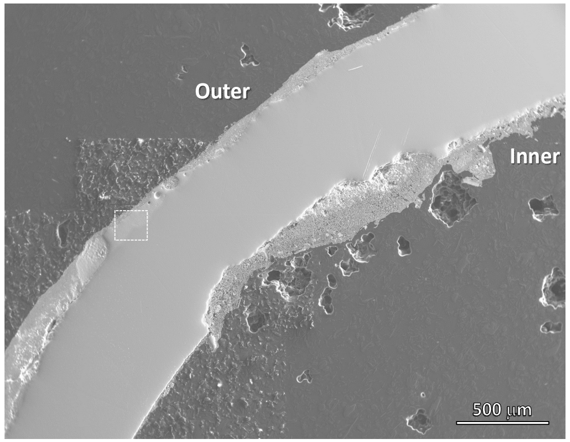
Vapor pressure of D_2O at 7.2bar: 170°C

(FEM/CFD calc. by S. Jollet)

PIE: Electron Probe Microanalysis (carried out by Y. Dai/PSI)

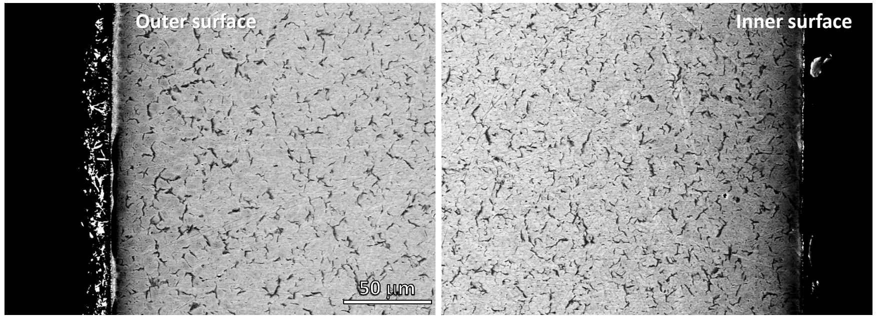


EPMA inspections at different positions of a 3mm slice cut from a sample from row 19
(0° postion is arbitrary)

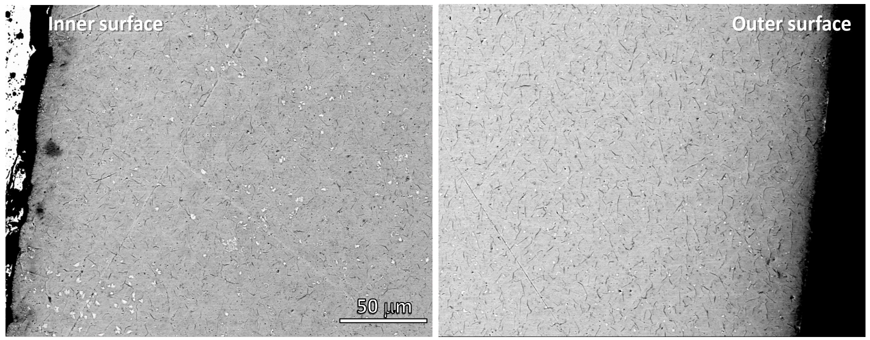


partially melted Zr surfaces => rod experienced extremely high temperatures [$T_m(Zr)$ = 1845°C]

Micrographs showing different hydride structures



Row 19 - 270° position (~9.5dpa)



Row 1 (~18dpa)

Conclusions from PIE

1. Breaking of the empty tubes in the front row and the following intrusion of liquid Pb into them indicates a very violent process had happened – or at least a process where strong forces were involved

2. «Normal» irradiation-induced hardening was detected suggesting that the tube material was getting brittle. In addition, hydrogen embrittlement was observed which could have promoted crack formation

3. In the central zone of target-11 (high p- and n-flux), the Zircaloy tubes experienced very high temperatures during the incident which resulted in partial melting of the Zircaloy tubes and mixing with lead

Most Likely Failure Scenario (Hypothesis)

1. June 23, 2016, brief overfocussing of p-beam ⇒ cracking of one Cannelloni weakened by a combination of irradiation-induced embrittlement and a large number of thermal cycles (approx. 10^5)
2. High temperatures promoted additional invasion of hydrides in crack region causing further embrittlement
3. June 25, 2016, the cracked Cannelloni burst completely (maybe due to high vapor pressure of trapped cooling water) releasing suddenly liquid Pb
4. Liquid Pb immediately solidified and blocked neighboring cooling channels
5. Due to an adverse distribution of coolant paths (broader in outer region) the water was first able to bypass the blockage => no significant pressure drop increase detected yet. Continuation of energy deposition with rate 880kJ/sec
6. Further overheating of badly cooled region. Residual cooling water evaporated quickly. Due to strong local pressures fluctuations in combination with enhanced temperatures more and more rods were breaking («chain reaction»)
7. As the affected blocked region was growing quickly, the pressure drop across the target rose finally till alarm threshold was reached. By switching off the proton beam the heat deposition finally stopped

Target #12 Operation

As target-12 was nearly finished by the time of the failure, it was decided to use it, although it was nearly identical with target-11

- Interstices between rods were optimized in order to con-centrate the main coolant flow through the center region

Special limitations were applied in agreement with the authorities:

- Max. proton charge was limited to 5.0Ah (2/3 of T-11)
- Max. current density was limited to 30μA/cm^2 (40μA/cm^2)
- Max. no. of thermal cycles caused by UCN-TS were limited to 29k (2/3 of what T-11 had experienced)
- Periodic radiologic analyses of target cooling water
- Use of additional p-beam diagnostics
  (see talk by D. Reggiani, Tu 14:50)
- Thoroughly monitoring of dose rate in target cooling loop
- «Soft Kick-back» after UCN pulse 

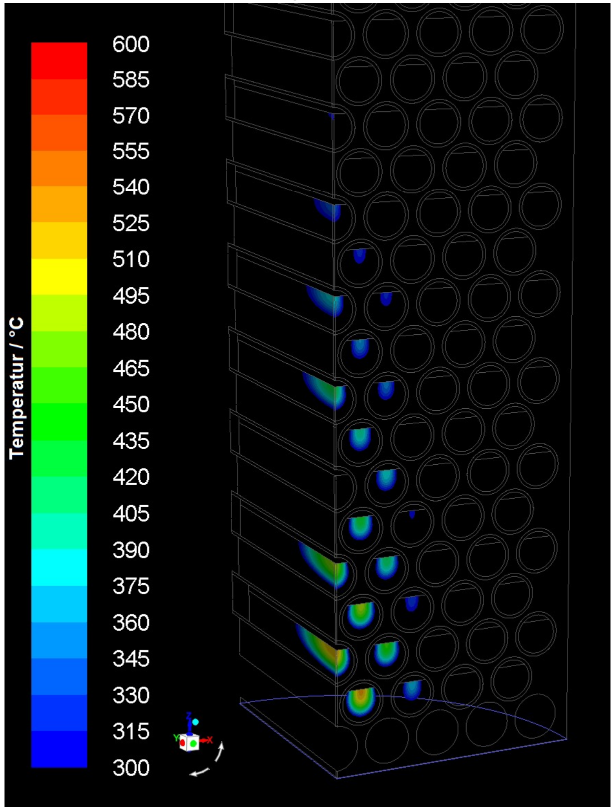
Target-11 failure caused 4 months of unintentional shutdown (restart November 1, 2016)

Design Improvements of Target #13 «Mark V»

Replacement of 33 Cannelloni rods in «hot zone» by solid Zircaloy rods

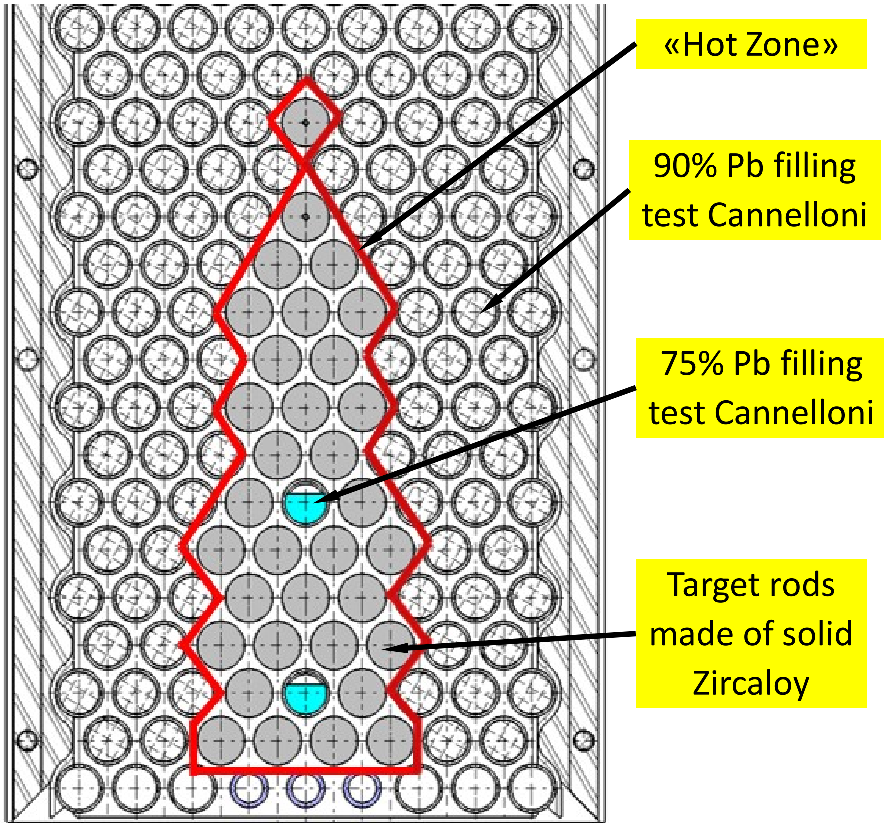
Target temperatures above 300°C from CFD simulation @ nominal current of 1500µA

Melting temperature of lead: 327°C



(CFD simul. by S. Jollet)

Rod distribution



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Design Improvements of Target #13 - continued -

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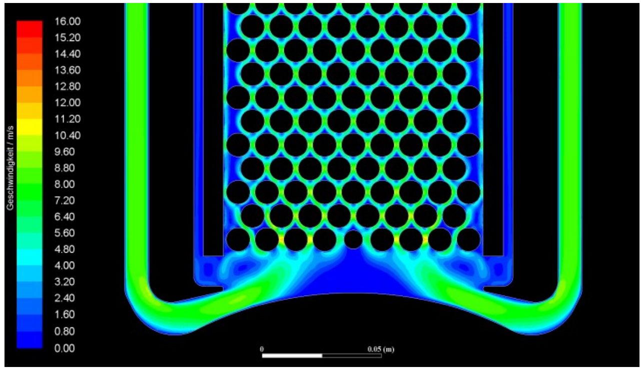
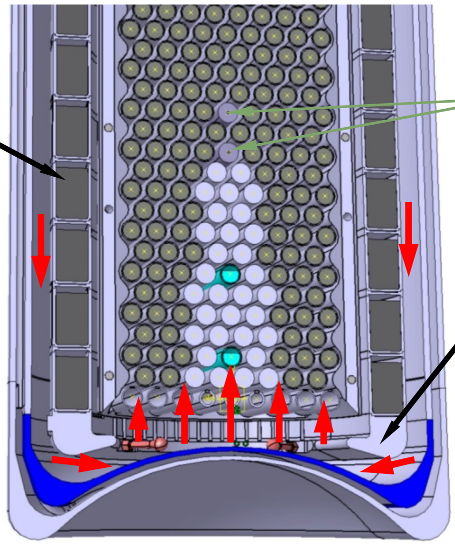
better flow distribution & unique beam positioning system

Coolant flow optimized



(CFD calc. by S. Jollet)

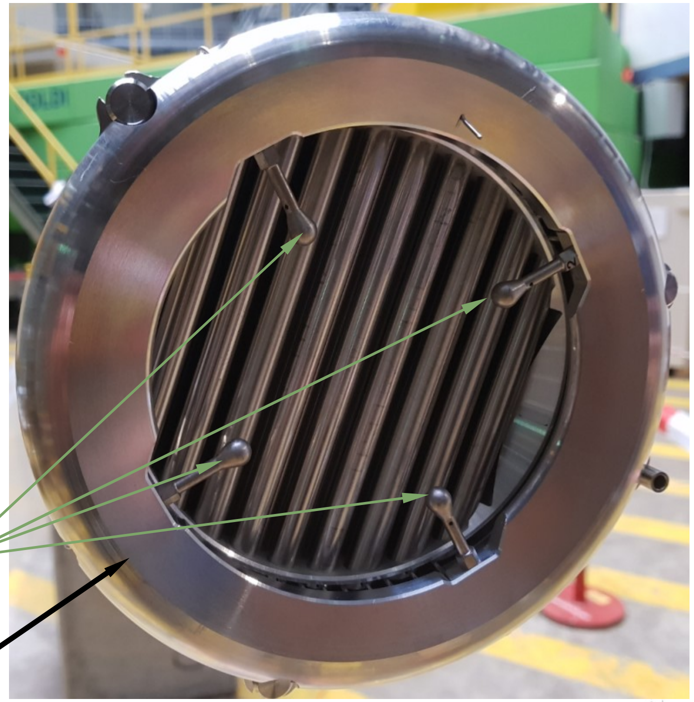
Pb reflector

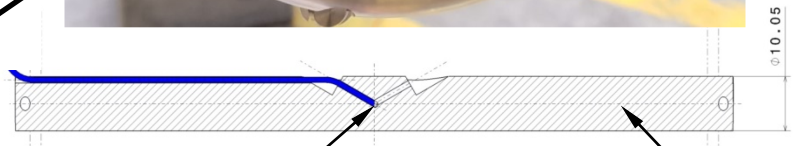


Coolant flow direction

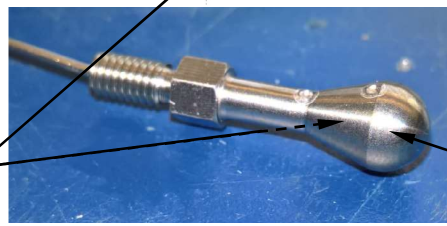
Thermocouples brazed into Zircaloy

Flow guide





Zircaloy rod



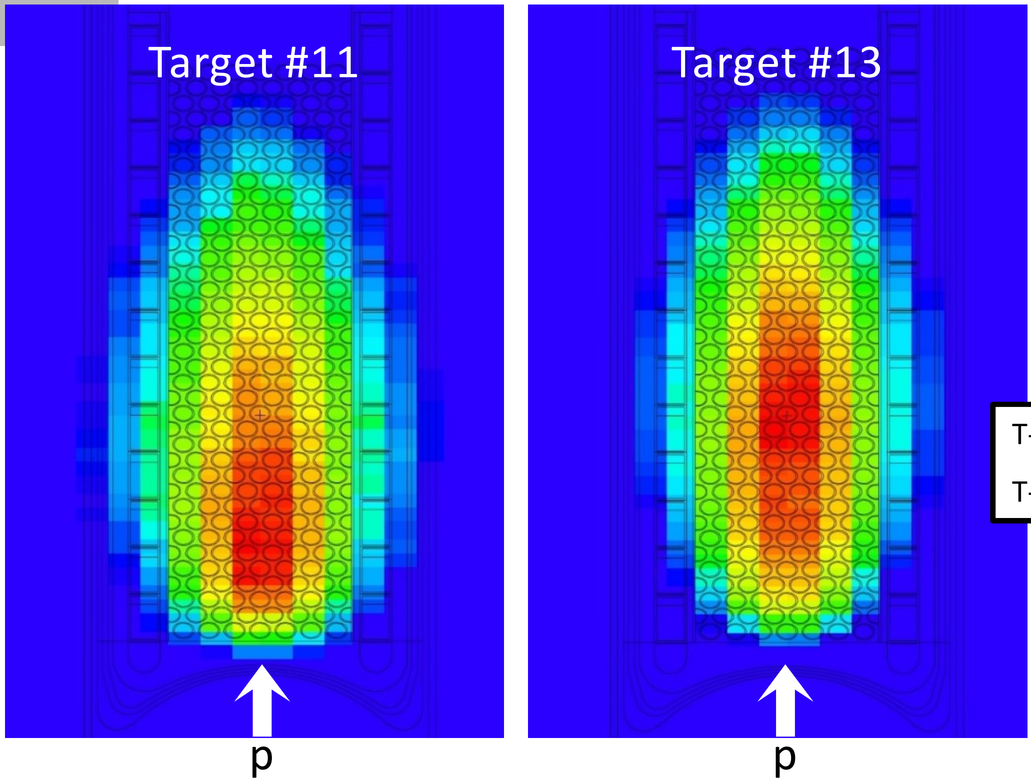
Thermocouples

Zircaloy absorber

First Year of Experience with Target #13

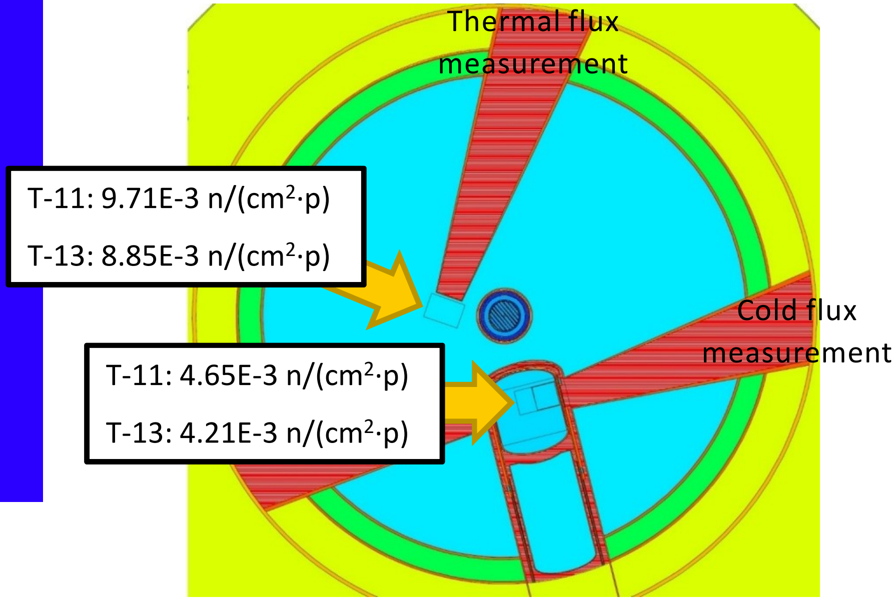
≤ 10% calculated reduction in neutron yield as compared to T-11

calculated neutron flux (with MCNP6.1)



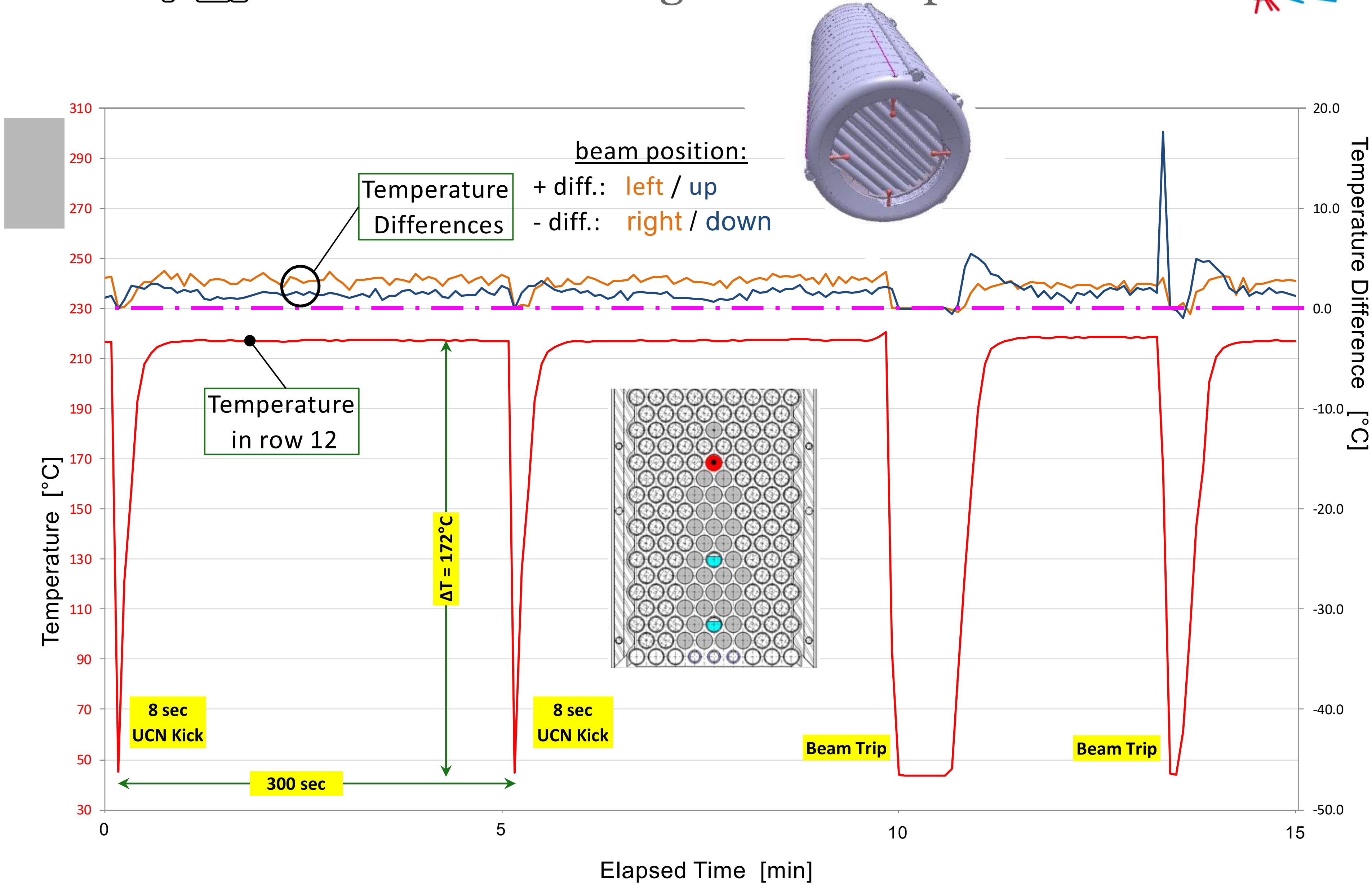
In T-13 the peak of the neutron production rate moves up due to the lower density Zircaloy rods

Gold foil measurements agreed with calculation within measuring accuracy



(all calculations performed M. Wohlmuther)

Monitoring of Heat Deposition



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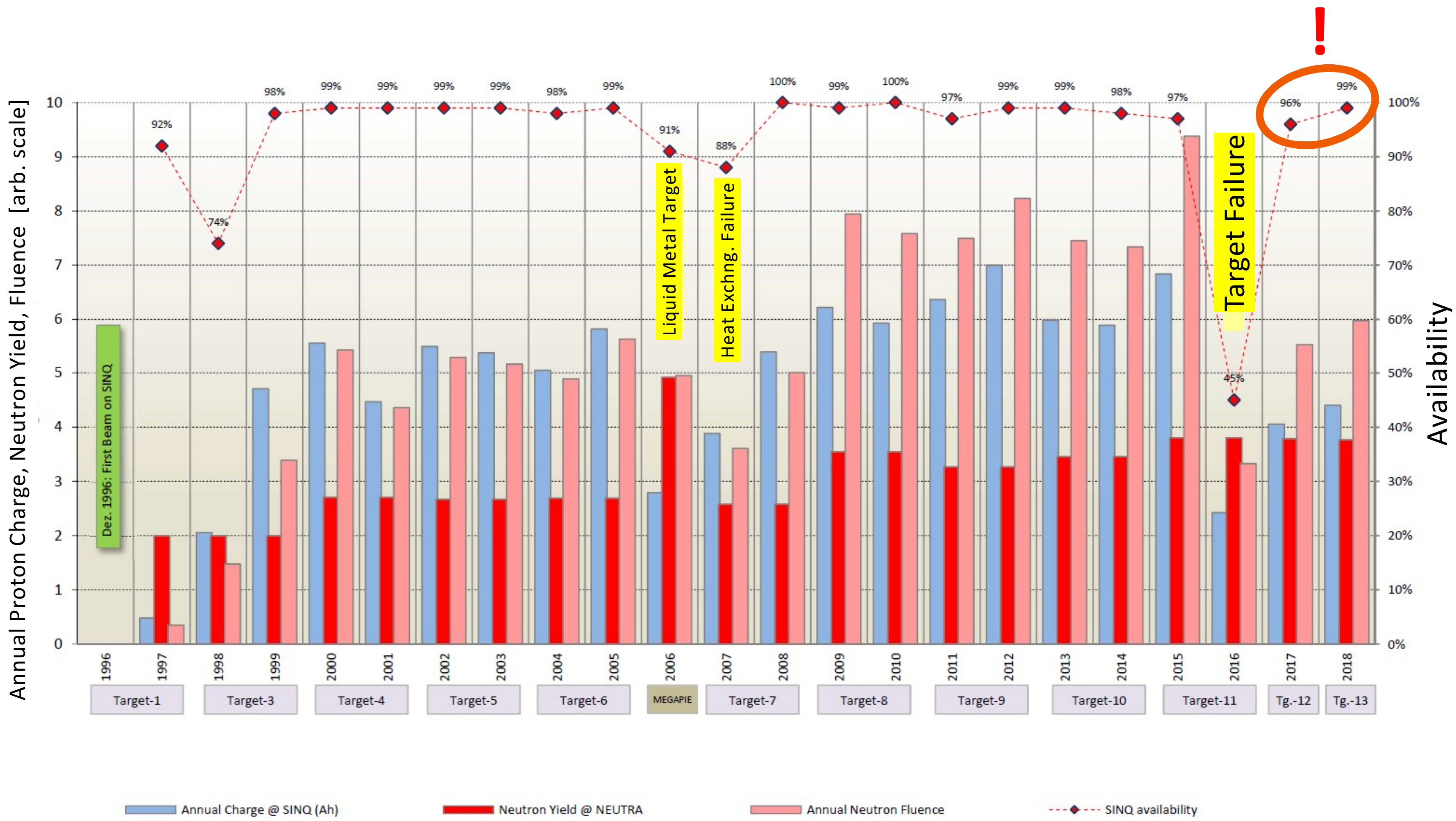
Long Term SINQ Availability

SINQ



Thank you for your attention

… and thanks to my co-authors:

- **J. Welte**
- **Y. Dai**
- **S. Jollet**
- **M. Wohlmuther**
- **A. Ivanov**

Temperatur im Target (Cannelloni-Reihe 2) RNQ01_CT011