PAUL SCHERRER INSTITUT

PSI

Manuel A. Pouchon :: Laboratory Head :: Paul Scherrer Institut

LNM: Labor für Nukleare Materialien

NES Information Event, 24.10.2017

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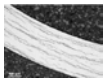
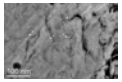
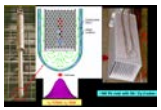
Mission of LNM

- **CENTRE OF EXCELLENCE:**
  The LNM is national centre of excellence in Switzerland in the domains of (irradiated) **materials behaviour** and **ageing** in **nuclear installations**.

- **ACADEMIC R&D & SCIENTIFIC SERVICE**
  Sustainability of **current** and **future nuclear installations** for electricity & heat generation as well as to the performance of **nuclear facilities**.
  A special emphasis is placed to the **safety** & **safe long-term operation** of the CH NPPs.


  - **Material ageing** in the primary circuit and its impact on **integrity, safety** & **lifetime**
  - **Performance** and **safety** of **LWR core materials** in **service** and storage
  - **Radiation damage** in structural and core/target materials of advanced nuclear and accelerator systems.
  - **Material irradiation program at SINQ** in co-operation with the Spallation Neutron Source Division.
  - **Post-irradiation examinations** and **failure analysis** in close cooperation with the Hotlab Division AHL.

Mission of LNM

- **KNOWLEDGE MANAGEMENT:**
  Academic **teaching** and **education** as well as in **knowledge transfer**
  → contributing to the education of the future nuclear specialists and
  → preservation of expertise & excellence

- **INDEPENDENT EXPERTISE:**
  Independent expertise and **excellence** for
  → **Swiss safety authority**, e.g. for expertise's and consulting (TSO)
  → **industry**, e.g., for material examinations and failure analysis.

- **STATE OF THE ART INFRASTRUCTURE:**
  State-of-the-art **lab & computing infrastructure** and **modelling tools** for:
  → **characterization** of **(radioactive) materials**
  → **analysis & prediction** of the **material behavior, integrity, safety & lifetime**
  (strongly benefiting from PSI's unique large scale facilities:
  hotlab, SLS, SINQ, SwissFEL)

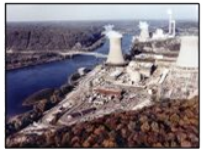
Background - Programs

Today in CH

LWRs

Generation I

Early Prototype Reactors



- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors

- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs

- ABWR
- System 80+
- AP600
- EPR

Near-Term Deployment

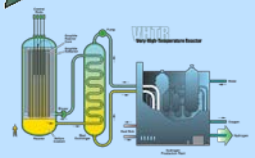
Generation III+ Evolutionary Designs Offering Improved Economics

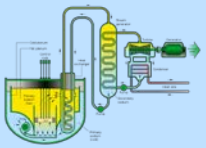
.....

High T
Fast n

Generation IV

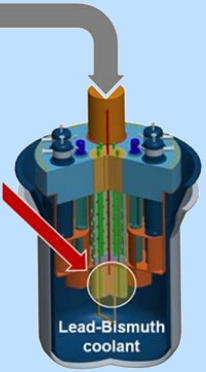
- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant





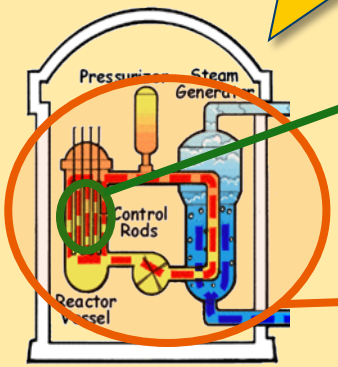
ADS

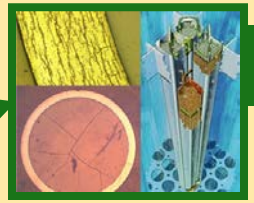
Spallation



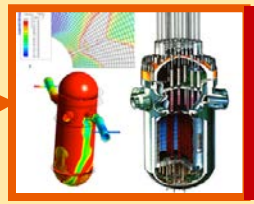
Gen I | Gen II | Gen III | Gen III+ | Gen IV

1950 1960 1970 1980 1990 2000 2010 2020 2030

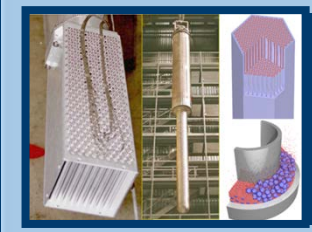




Nuclear Fuels



Component Structural Integrity



Advanced Nuclear Materials

Projects overview

ANM:

- MeAWaT - ETH competence center CCEM
- 3D Printing - ETH scientific focus area – additive manufacturing
- MatISSE, SOTERIA, INSPYRE, M4F - European projects
- STIP irradiation program / PIE - CAS, JAEA, USTB, Beijing University, HFUT

NF:

- Cladding Mechanical Behavior and Influence of Hydrogen (dry storage, …) - swissnuclear, ESB
- Hydrogen uptake - swissnuclear, MUZIC
- ATF - CARAT, swissnuclear, KKG
- Fuels - swissnuclear, Areva, Westinghouse, NFIR
- FIB – R'Equip

INTEGER:

- PISA-II & -ext, PARENT, NORA-II, SAFE-II → LEAD, PROBAB, NORA-III - ENSI
- PLiM-VI - swissnuclear
- Helium FM - fusion/STIP-V
- SOTERIA, INCEFA+, NOMAD, MEACTOS, M4F - European projects
- YUMOD (KKL), SCC Alloy 52 (KKL), BWRVIP-233(EPRI), EAF LAS (EPRI)

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SCC in Ni-Alloys and Weldments in LWRs

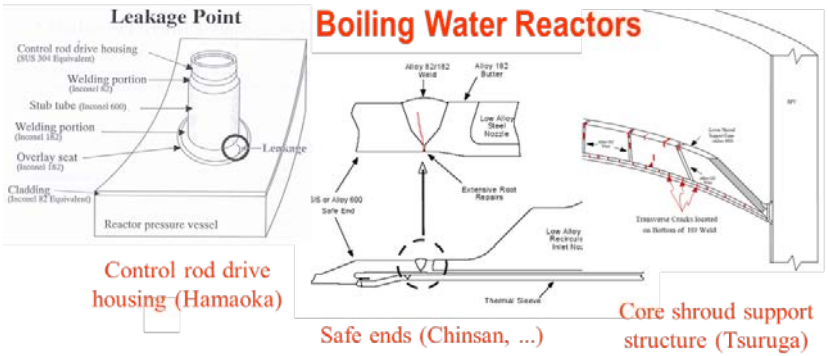
Current activities:

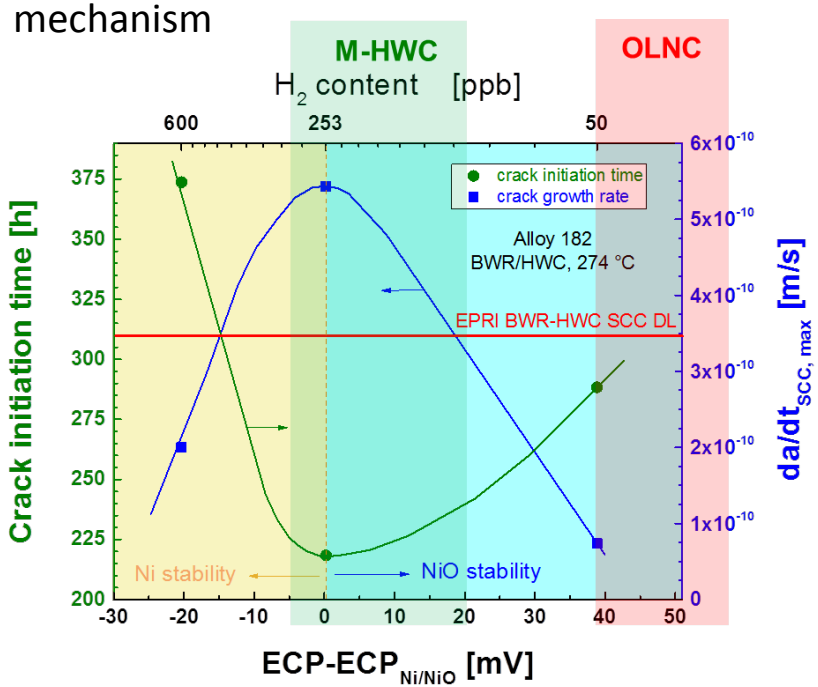
- **SAFE-II (ENSI):** Subproject-I: PhD thesis of J. Bai on the Effect of hydrogen on SCC initiation in Alloy 182 under BWR/HWC conditions @ 274 °C
- **MICRIN+ (EU-7 /NUGENIA+):** Accelerated screening test method for SCC initiation studies
- **ICG-EAC Round Robin (in-kind):** SCC initiation study in Ni-alloys under constant load
- **MEACTOS (H2020 EURATOM):** Mitigating environmentally-assisted cracking through optimisation of surface condition
- **ECG-COMON Round Robin (in-kind):** Effect of hydrogen on the corrosion behaviour and oxide films in Ni, Alloy 600 and Alloy 182
- **Overlay repair weld with Alloy 52M (KKL, service project):** Characterization of SCC resistance and fracture toughness on mock-up weld

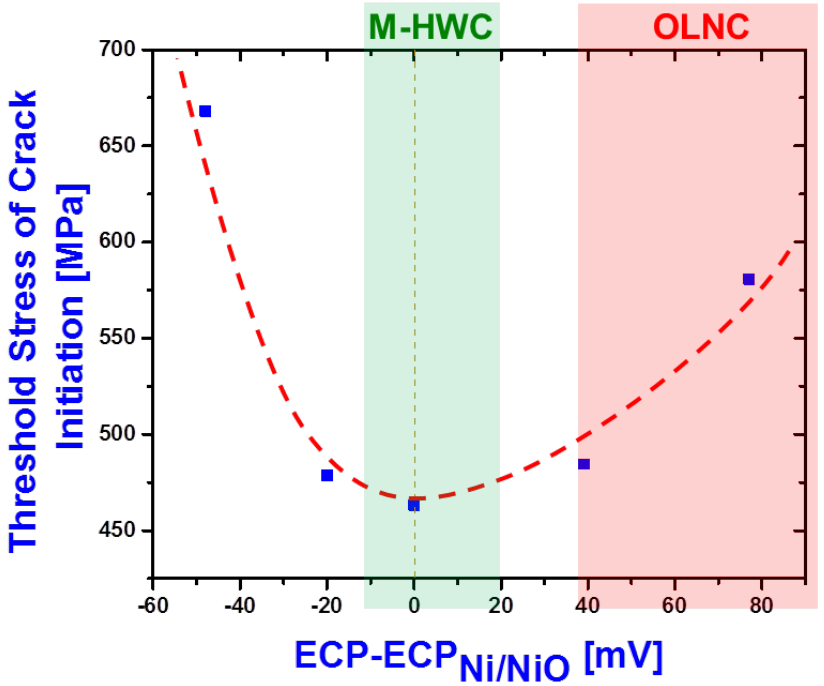
SAFE-II SP-I: SCC Initiation in Alloy 182 Dissimilar Metal Welds

PhD project of J. Bai:

- Background: SCC incidents in Alloy 182 DMWs in BWRs
- Effect of H_2 on SCC initiation & short crack growth in Alloy 182 under BWR/HWC conditions @ 274°C
- Identification of optimal mitigation conditions
- Tentative mechanistic interpretation on mechanism

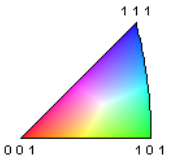


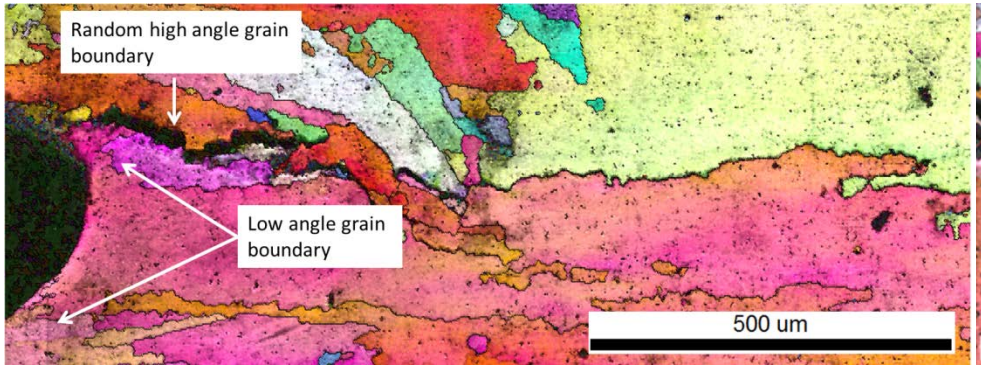


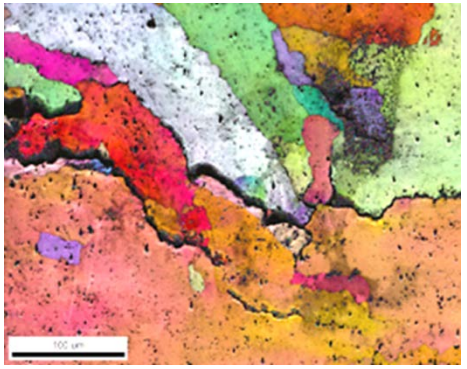


Maximum in SCC initiation susceptibility & SCC crack growth rate at Ni/NiO phase boundary!

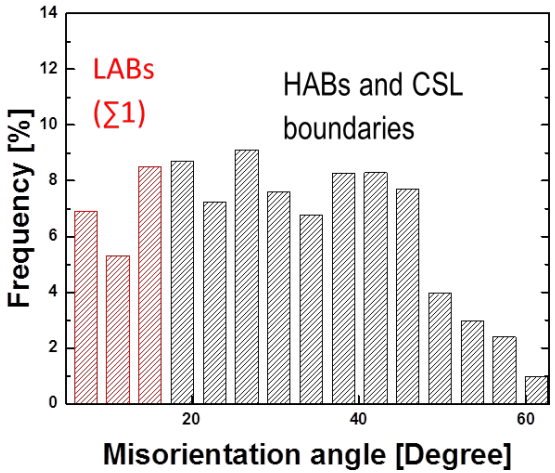
EBSD Analysis of IGSCC Initiation & Propagation



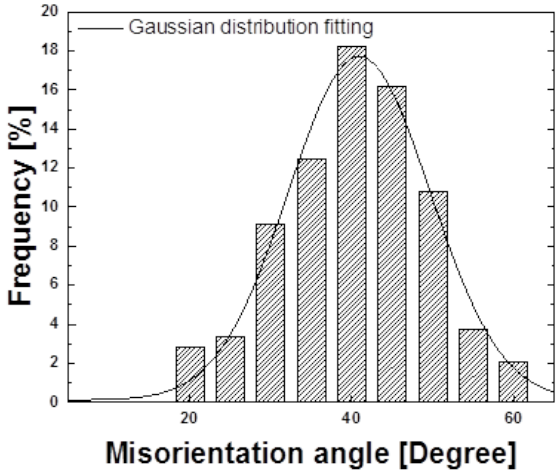




All grain boundaries in original material



All cracked grain boundaries

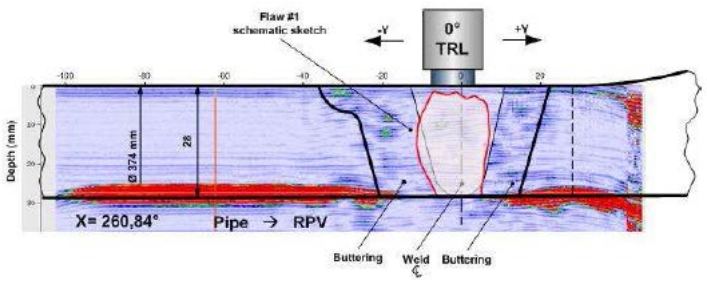


- **Low angle grain boundaries** seem to be **resistant to SCC**.
- Random **high-energy, high-angle grain boundaries** (HABs) with higher number of **Schmid factor mismatch** between the adjacent grains are **prone to SCC**

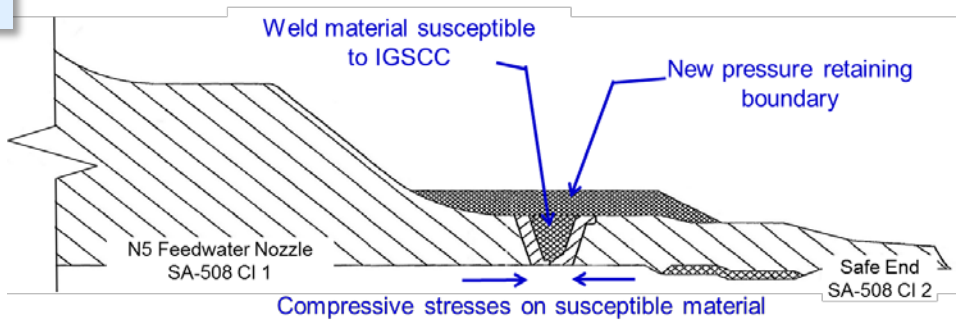
→ **strain/deformation incompatibility** plays a key role in crack initiation & propagation

Material Characterization on Alloy 52 for KKL

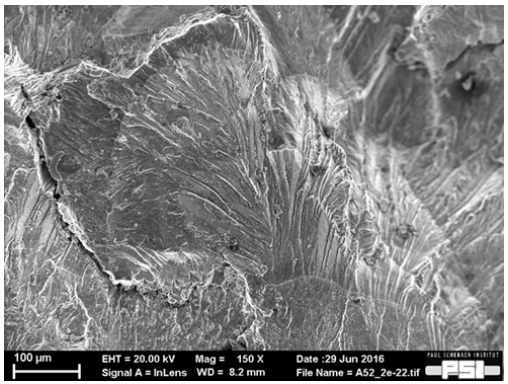
Axial SCC crack in N5 RPV FW nozzle
~ 93 % of wall thickness

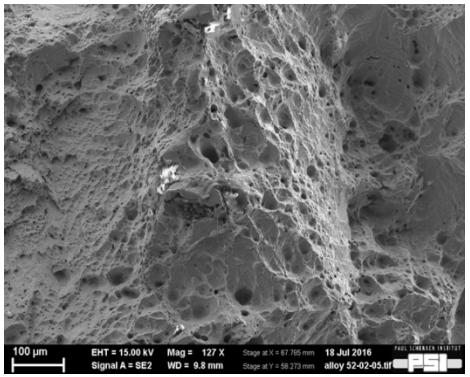


Full structural overlay repair weld with Alloy 52M



- Request of ENSI for additional material tests with Alloy 52M to confirm the assumptions of the performed integrity assessment
- Tensile and EPFM tests in air, SCC test in high-temperature water
- Very high SCC resistance & high toughness confirmed
- KKL & ENSI were highly satisfied by professional PSI work





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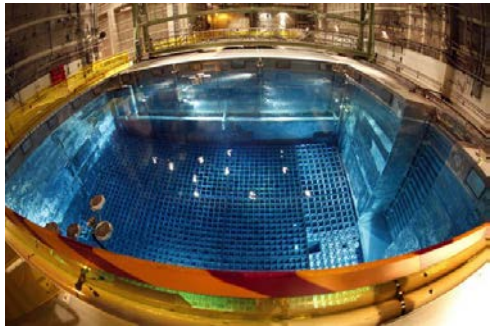
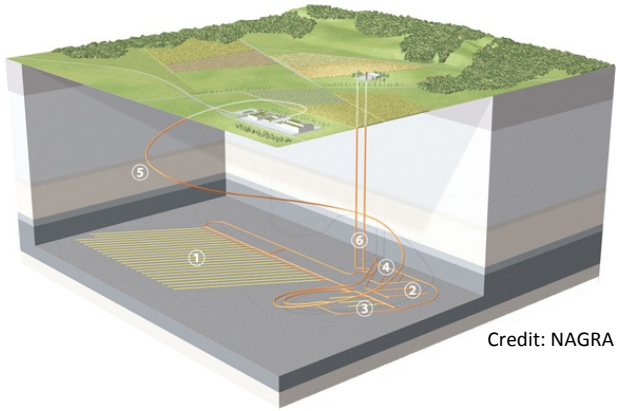
Transportation of spent fuels, dry storage

Cladding fatigue risk



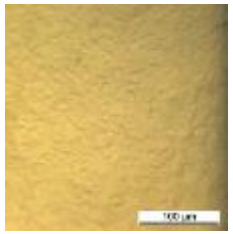
Credit: Zwilag

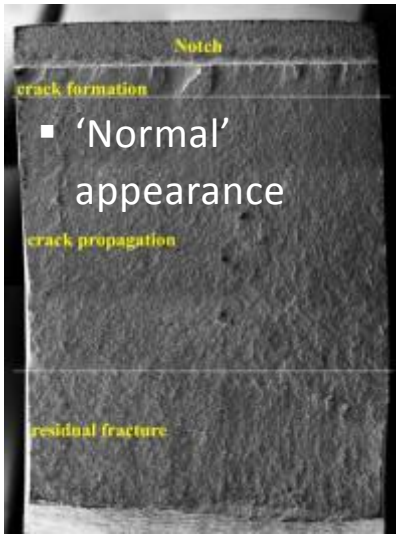


Credit: NAGRA

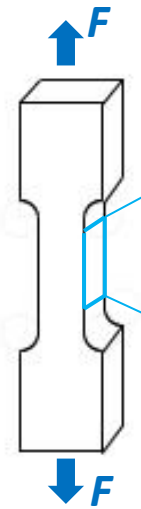
Hydride (Re-)Orientation – Impact on Fatigue

H-free, as-received

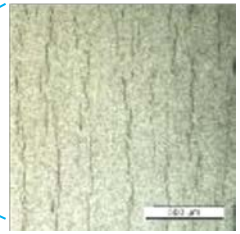


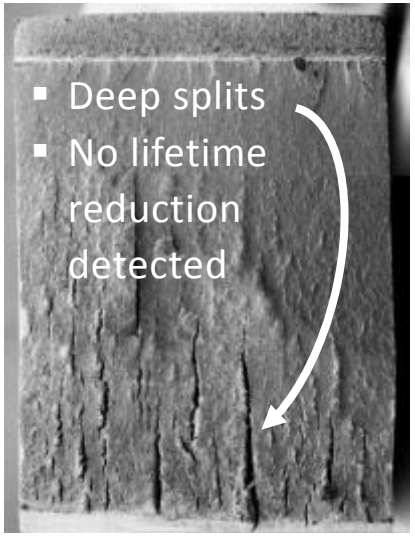


- 'Normal' appearance



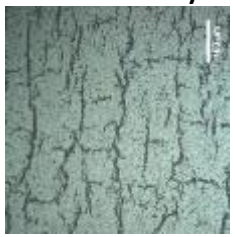
In-plane hydrides

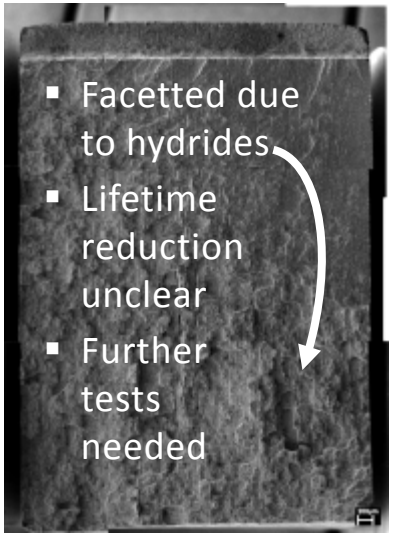




- Deep splits
- No lifetime reduction detected

Reoriented hydrides



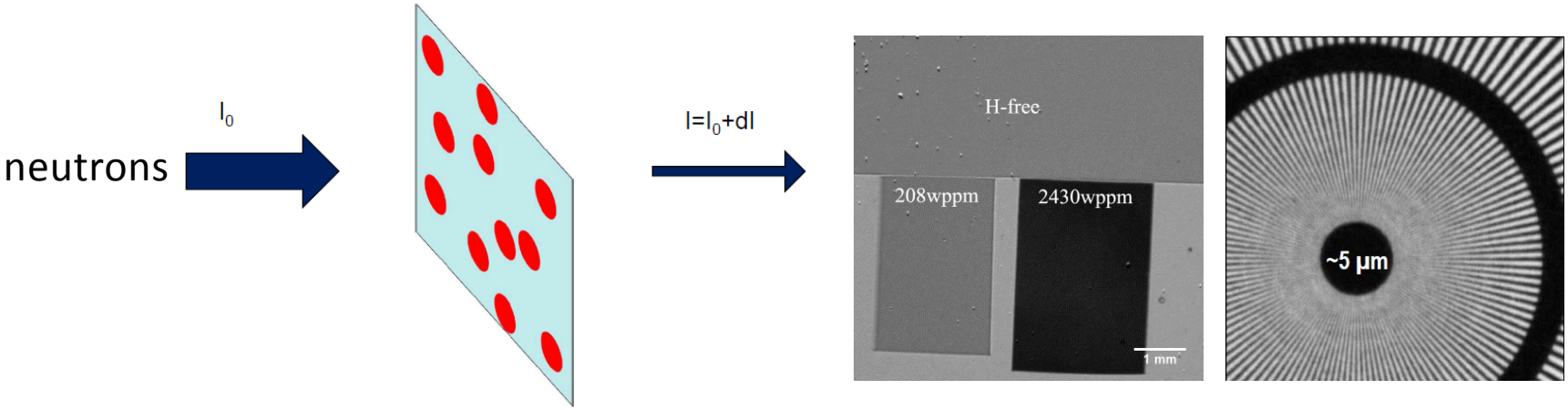


- Facetted due to hydrides
- Lifetime reduction unclear
- Further tests needed

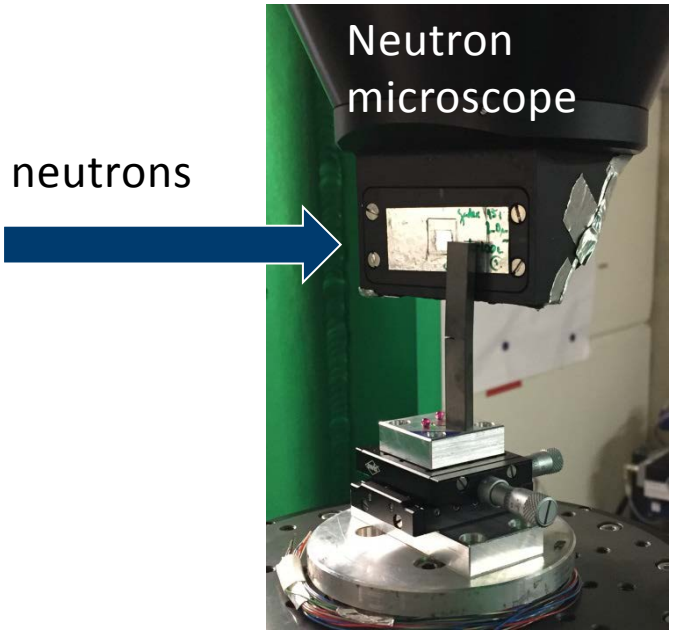
W. Gong, A. Brenin, R. Zubler, J. Bertsch, Hydrides Impact on Zircaloy Fatigue Properties, , WRFPM, Sep. 10-14, 2017, Jeju, Korea

Neutron Radiography at PSI SINQ

Spatial resolution

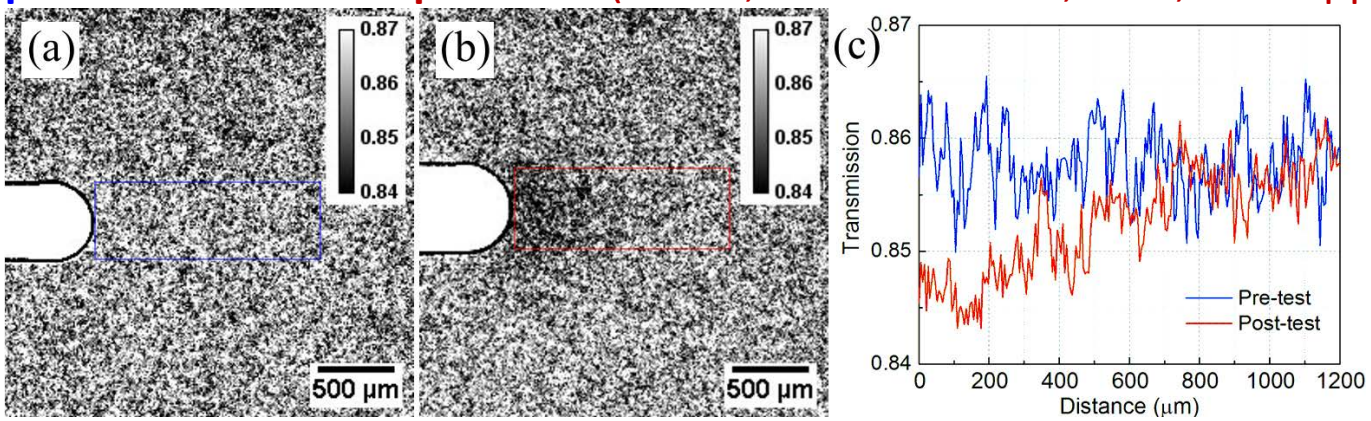


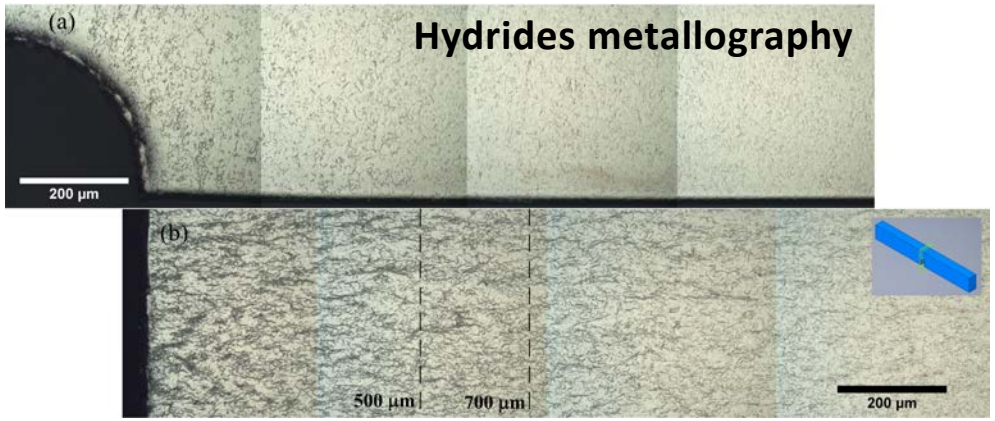

SINQ spallation neutron source

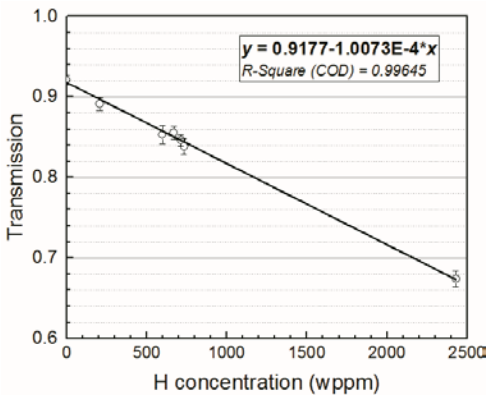


Ex-situ Measurements – H & Stress

pre-test **post-test** (350°C, 120 MPa nom., 10 h, 240 wppm H)





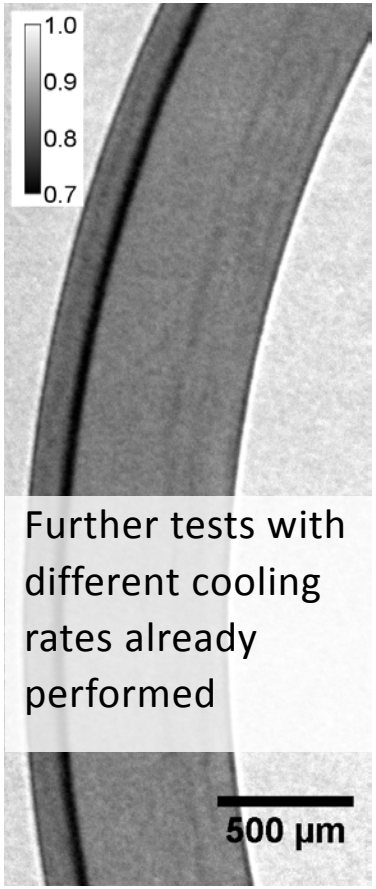


H concentration Calibration

0.016 transmission increase ➡ **~160wppm H elevated by stress**

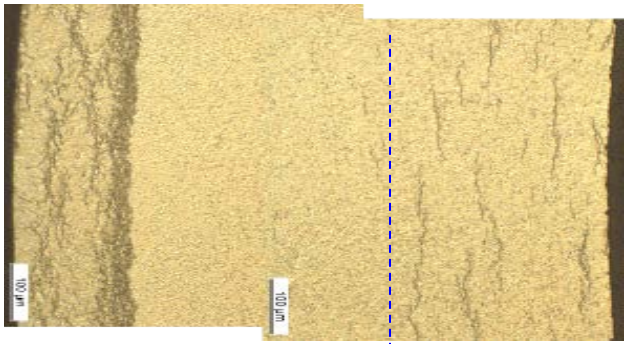
Liner Cladding – Quantification H content

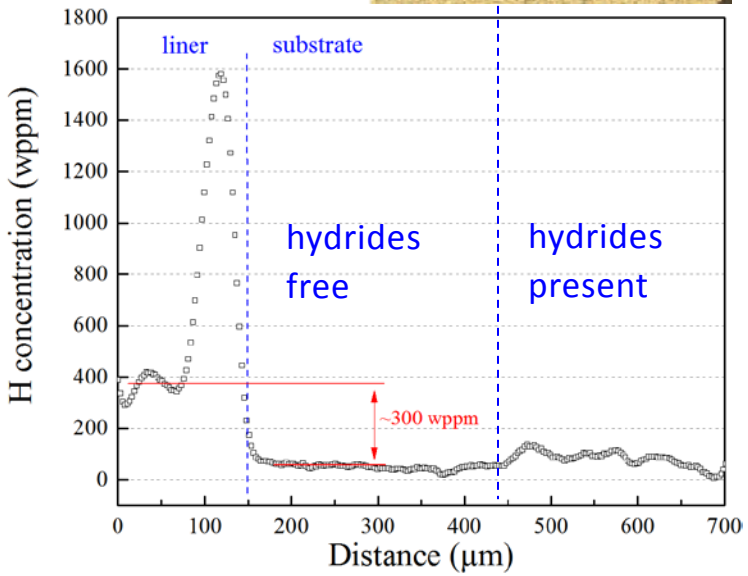
- DX-D4 outer liner cladding, ~200 wppm H
- 4.5 mm segment // neutron beam
- POLDI thermal neutron beamline, exposure 3 min x 100



Neutron image

Further tests with different cooling rates already performed





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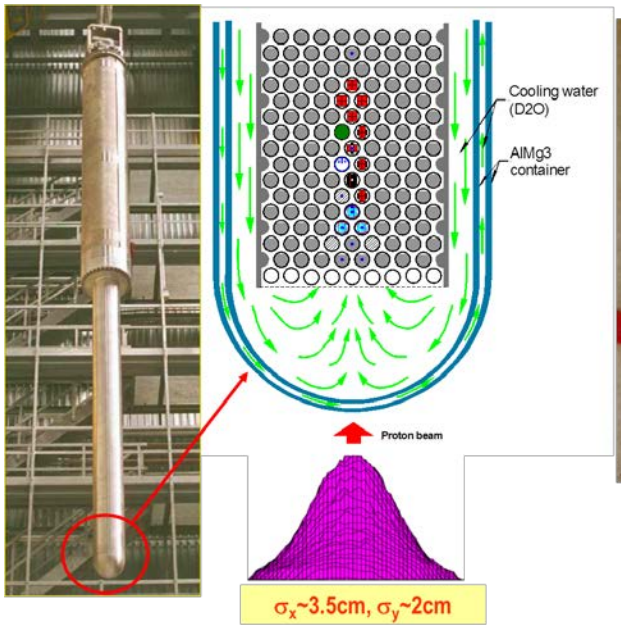
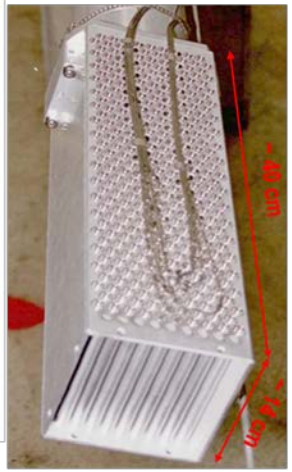
    - SCC in Ni-Alloys and Weldments in LWRs
    - … effect of hydrogen on SCC initiation in Alloy 182
    - … SCC resistance and fracture toughness on mock-up weld on Alloy 52M
  - Cladding & Fuel ***(Nuclear Fuels)***
    - Hydride (Re-)Orientation
    - … under fatigue
    - … investigation using neutrons
    - … liner cladding and H distribution
  - Advanced Systems ***(Advanced Nuclear Materials)***
    - Spallation material investigations (from STIP)
    - … material flow using new sample preparation box and FIB
    - … example using atom probe tomography

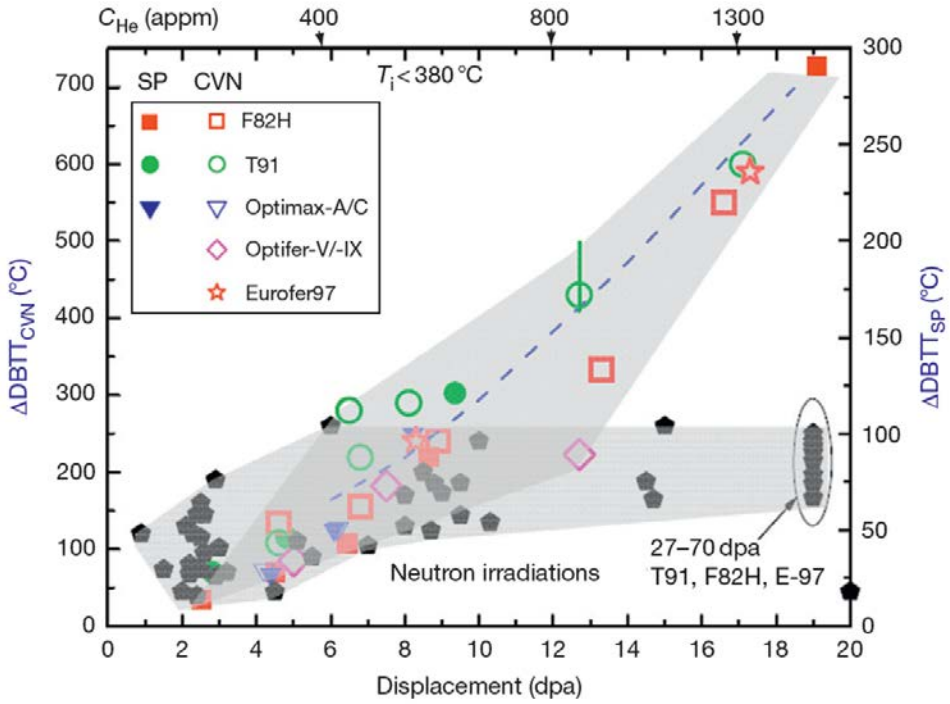
STIP program – Materials in Spallation Target





Embrittlement of FM Steels

(high He production)



Analysis Tools – Connection Through FIB

Spallation Materials

Hot Cells

NPPs

Hotlab

Preparation box

Hotlab-FIB

Mechanical Testing

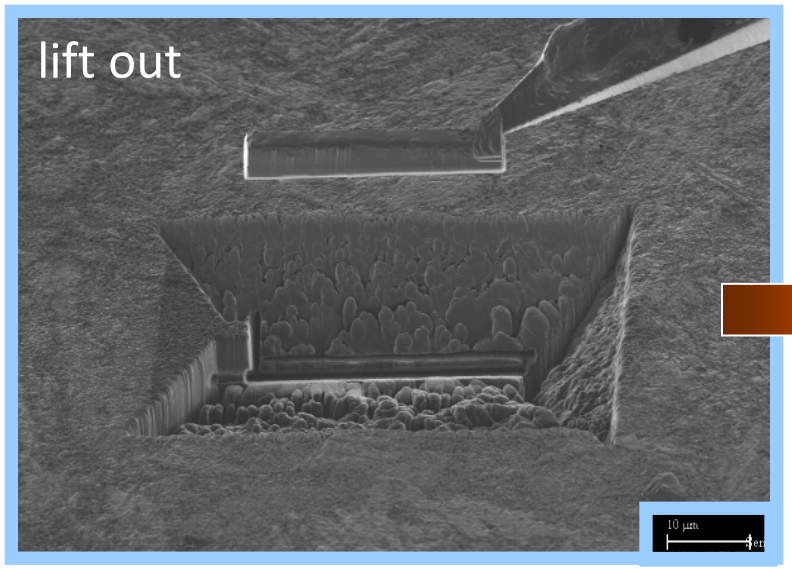
nm - µm - mm

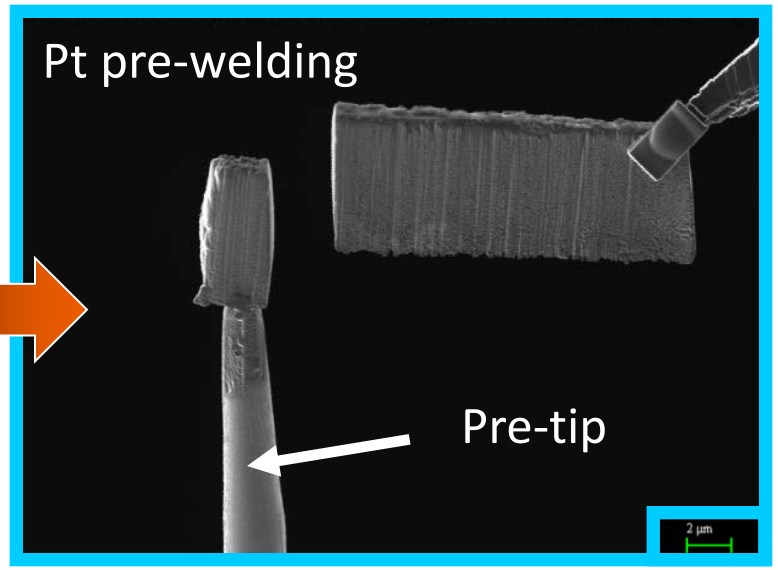
Microscopy / APT

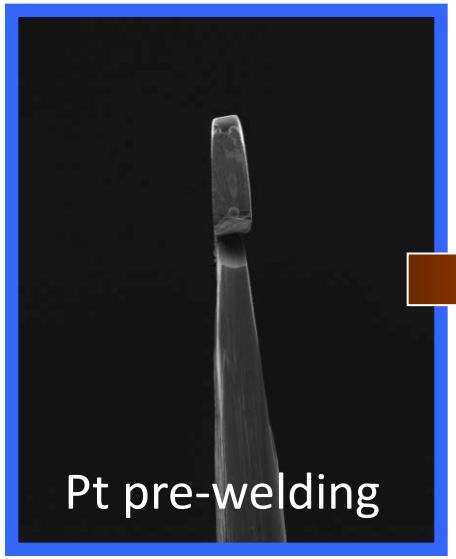
Beam Line Techniques

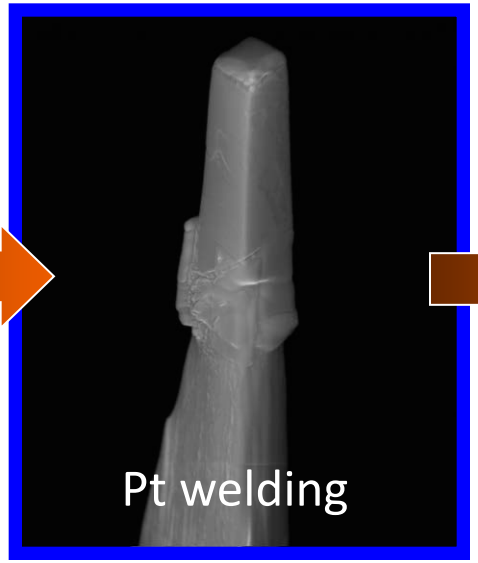
APT – Sample prep.

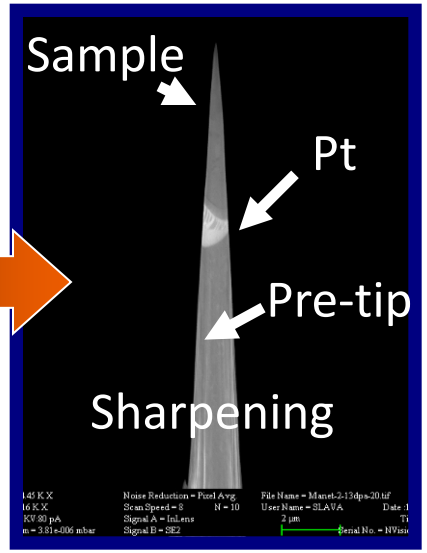
Activity for a TEM sample: · 10^6 Bq











Activity for APT sample: $1.4 \cdot 10^{-3}$ Bq

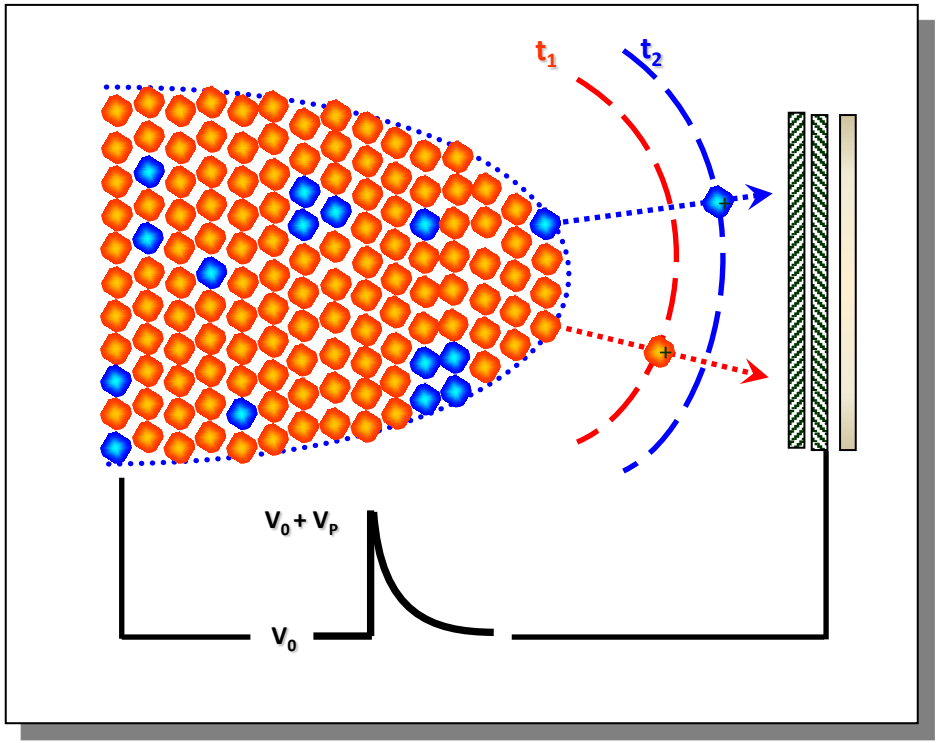
APT - Background

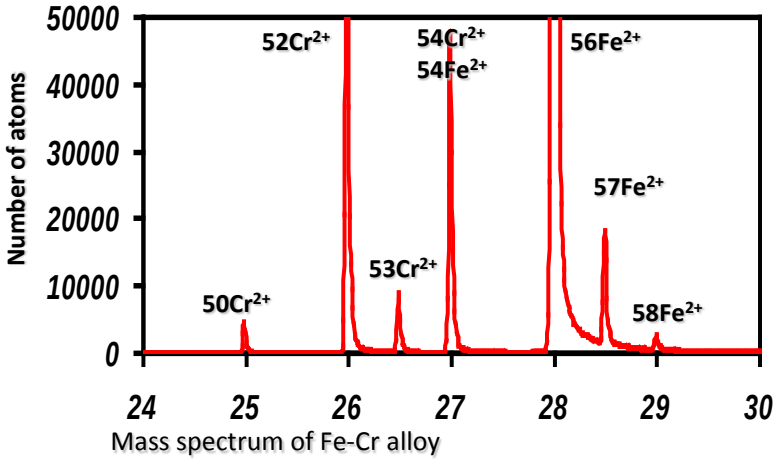
electric field is induced at the apex of a tip

$$E \approx 10...30 \frac{V}{nm}$$

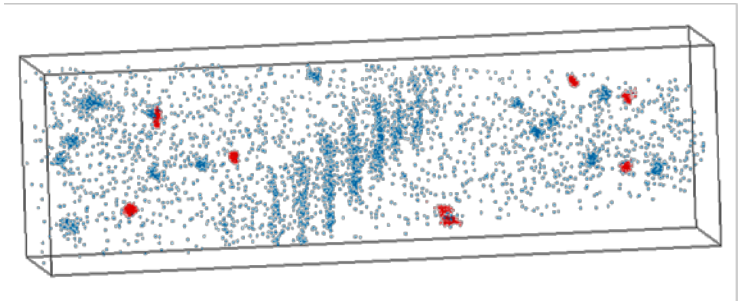
mass to charge ratio of the ions allows to determine their chemical nature

$$\frac{m}{n} = 2 \cdot e(V_O + V_P) \cdot \left(\frac{t}{L}\right)^2$$





30×30×100nm^3

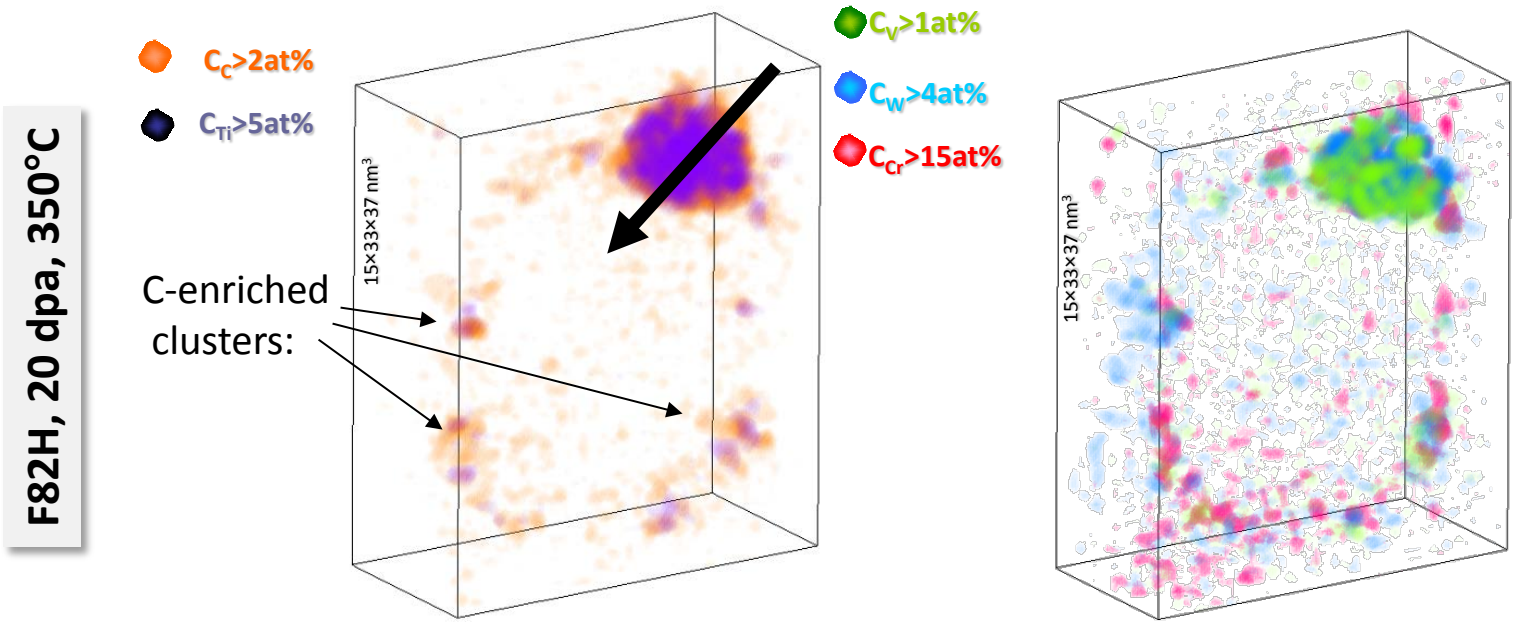


few Mega atoms

APT Results - Example

Material: Fe-8Cr-2W-0.1C-0.2V-0.04Ta martensitic steel F82H
Japanese reduced activation steel, fusion structural material, also candidate for GenIV

Exposure: Irradiation in SINQ target (STIP II), to 20 dpa at 350°C



C-enriched clusters:

- on the loops or in its neighborhood
- (Cr, W, V, Ti and Fe) to C ratio ≈ 17 to 1, M18C carbide Chi (χ) -phase?
- But: no data about such phases in F82H

← radiation induced

Wir schaffen Wissen – heute für morgen

Nuclear Materials Research at PSI is active…

… serving the authorities and industry with safety investigations.

… helping the industry with performance optimizations.

… contributing to education and training.

… contributing to the next generation research.

My thanks go to

- All the members of LNM for their great efforts & performance
- AHL / SU / NES / NUM
- All external partners like ENSI, swissnuclear, CCEM, SNF, …


LNM & Friends