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Plasma-Wall Interaction with Irradiated Tungsten and Tungsten Alloys in Fusion Devices

Effect of high energy ion irradiation damages on deuterium permeation and retention in tungsten

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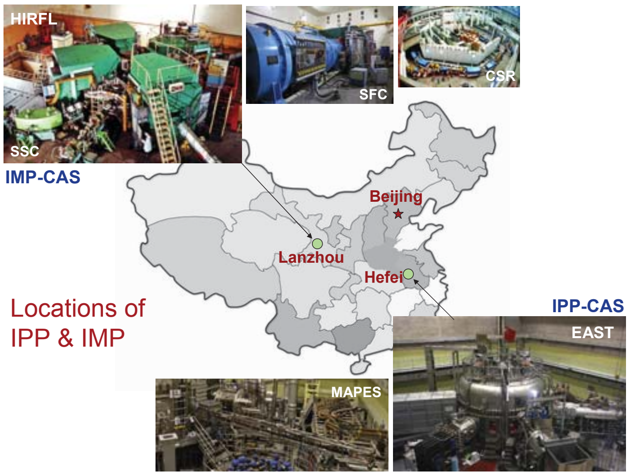

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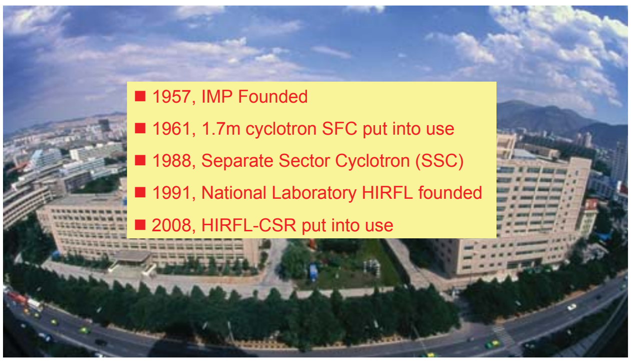
- HIRFL ion accelerators and Irradiation chambers
- Irradiation experiment with W at HIRFL and Test plan of irradiated W
- MAPES and other test facilities
- Radiation damage in steels by using HIRFL ion beam – an example

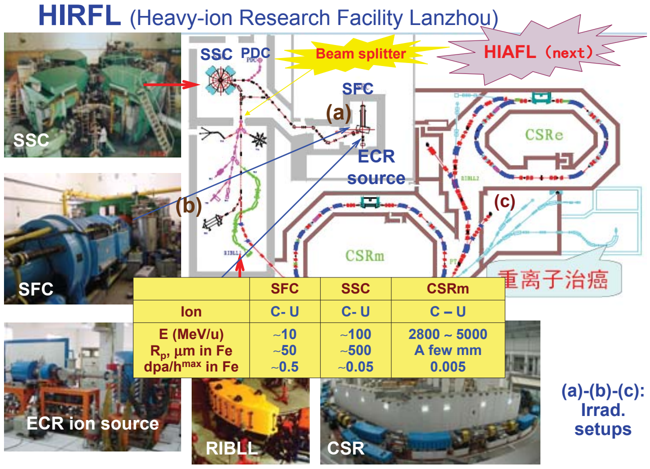
1. HIRFL ion accelerators & Irradiation chambers



Heavy-ion Research Facility in Lanzhou (HIRFL)

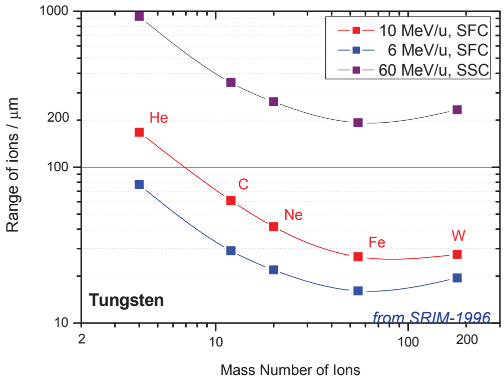
兰州重离子加速器国家实验室

HIRFL (Heavy-ion Research Facility Lanzhou)



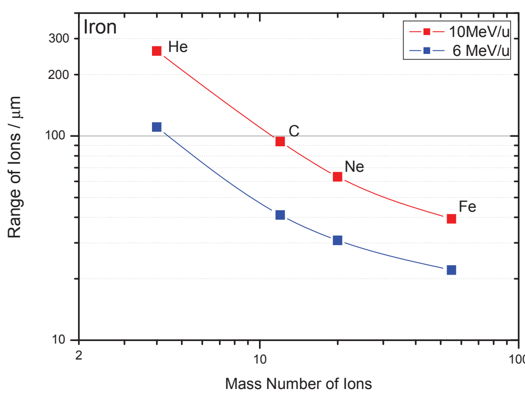
	SFC	SSC	CSRm
Ion	C- U	C- U	C – U
E (MeV/u) R_p, µm in Fe dpa/h^{max} in Fe	~10 ~50 ~0.5	~100 ~500 ~0.05	2800 ~ 5000 A few mm 0.005

Range estimation of ions in pure W, corresponding to SFC / SSC energies



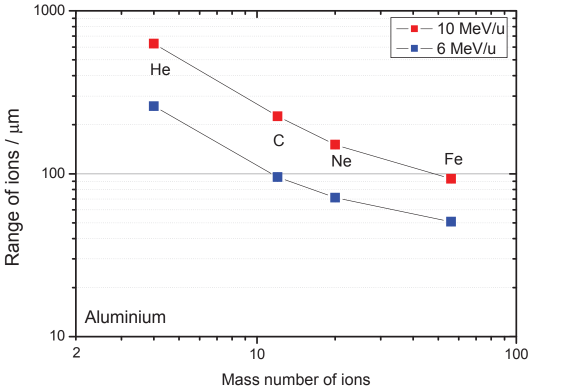
Using SFC heavy ions, a minimum thickness of 40 µm, and a maximum of 0.12 mm can be penetrated. While the minimum thickness increases to 0.4 mm using SSC ions.

Range estimation of ions in pure Fe, corresponding to SFC



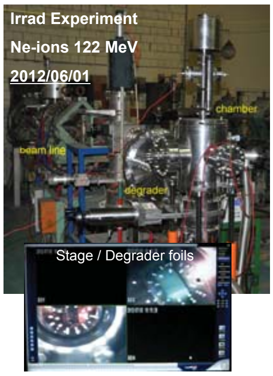
from SRIM-1996

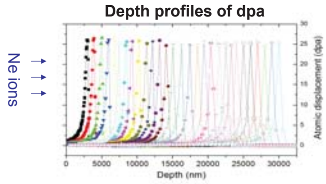
Range estimation of ions in pure Al, corresponding to SFC



from SRIM-1996

Irradiation chamber at HIRFL-SFC terminal (site a)

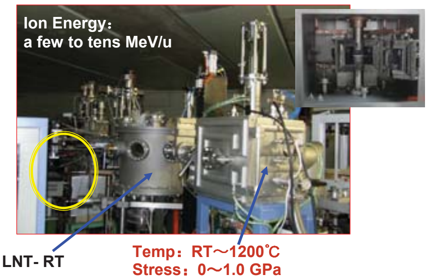




- Energy degrader：a uniform distribution of damage (useful for TEM & mechanical properties)
- Cold/Heating stages：temperature control of specimens.
- Irradiation area: Φ15 mm

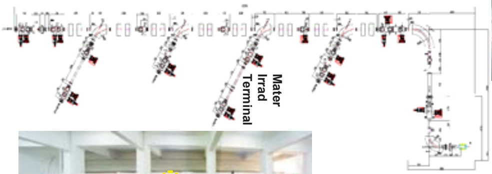
Irradiation chamber at HIRFL-SSC terminal (site b)

High temperature & Stress (HTS) Materials Research Terminal



- A new LN-cooling stage and an energy degrader was recently developed.
- An on-line irradiation creep test chamber is being designed.

320 kV High-voltage Platform



- Ion Energy: 10 keV – several MeV → R_p:1-2 μm
- Ion species: H, He, O up to $^{209}Bi^{q+}$
- X-Y beam Scanning: 25mm x 25 mm area impl.
- RT / Heating stages (600°C)

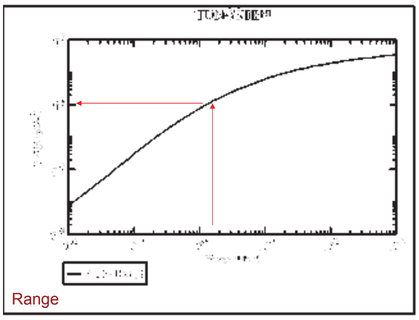
High Power EB Accelerator

1) 1.2 MV @ 40 mA

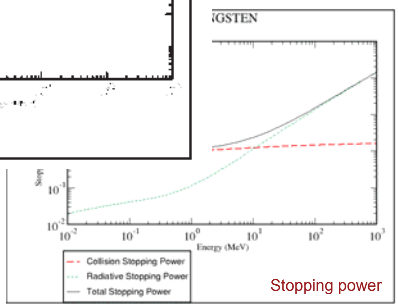
2) 1.5 MV @ 300 mA

- 1x10^{-3} dpa per hour
- Max. area: 15 cm x 40 cm

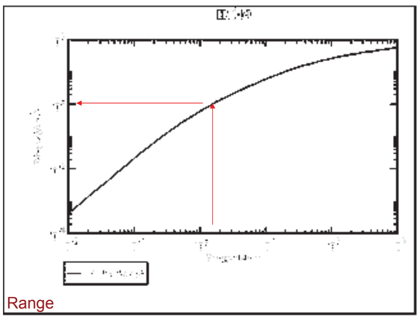
Overview of EB Accelerator made at IMP



Range & stopping power of high-energy electrons in Pure Tungsten
—a calculation

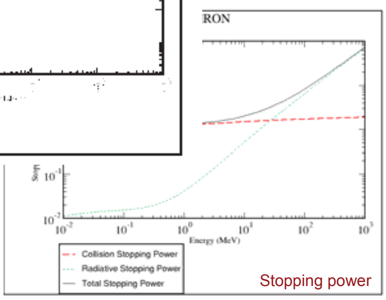


* Arrows show Range corresponding to IMP e-beams



Range & stopping power of high-energy electrons in Pure iron

—a calculation



* Arrows show Range corresponding to IMP e-beams

2. Irradiation experiment of W with HIRFL ions

Irradiation Experiments

Conditions of ion irradiation (@ HIRFL-SFC terminal)

Ion species：122 MeV $^{20}Ne^{4+}$, 84 MeV $^{12}C^{4+}$

Doses / Temperature：100 appm (Ne) / 0.1 dpa (Ne, C), @360-400°C, 12 hours

* Energy degrader was used to produce defects through the depth 50-80 μm

Materials：Pure W (99.95% , supplied by AnTai Company , China), steels annealed @ 1200°C for 2 hours in vacuum

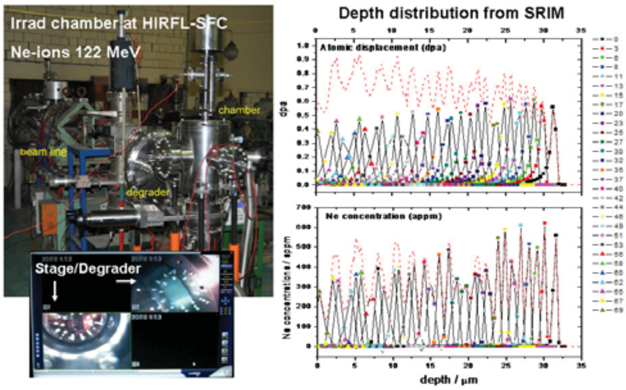
Tests: (undergoing)
- Positron annihilation spectrometry (PAS) : defects configuration
- GDP, PDP: retention and permission behavior (Sealing technique!)
- TEM: microstructures
- Small punch test (SP) : mechanical properties
- SEM/EDS: fracture features after small punch

Conditions of high-energy e-beam irradiation (1.5 MeV)
Dose: 0.1 dpa (100 hours), Irradiated area: 10 cm x 40 cm

–Ne are similar with Helium in bubble growth

Marokov, Goodhew et al, ***J Nucl Mater*** 158 (1988) 81

SRIM estimation of depth distribution of dpa / Ne-concentration in Fe-8Cr

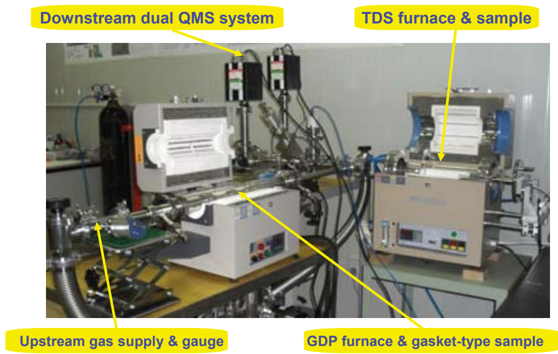


corresponding to a fluence of 9x10[16] ions/cm² under irradiation with 122 MeV ^{20}Ne ions (E_d=40 eV), SRIM-2012 code

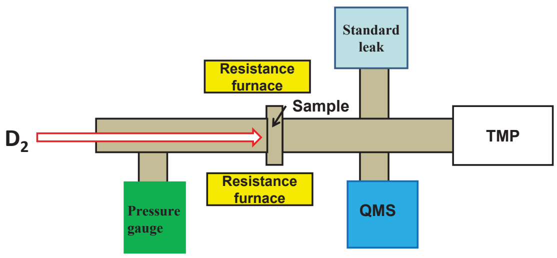
3. Test facilities in IPP

GDP, TDS,
Plasma exposure in EAST

GDP + TDS device @ ASIPP



Experimental method - GDP



TMP: turbomolecular pump
QMS: quadrupole mass spectroscopy

Schematic diagram of the setup for GDP

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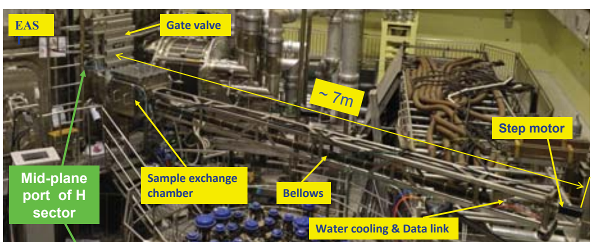
MAPES

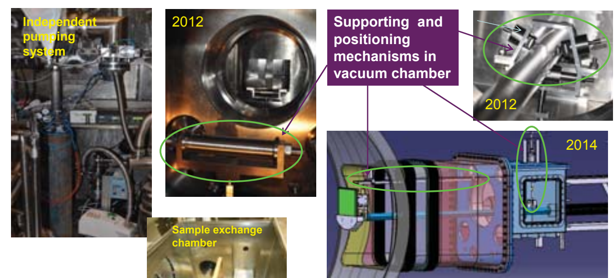
(Material and Plasma Evaluation System)

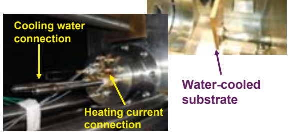
MAPES configuration and features



- ✓ Gate valve (DN500mm)
- ✓ Maximum sample weight: 20kg, to be up to 30kg
- ✓ Sample holder moving velocity: 1-15 mm/s
- ✓ Sample travel distance: max. 2.5m, beyond the LCFS

MAPES accessories





- ✓ Independent pumping system
- ✓ Remote control system
- ✓ Sample water cooling&heating system (2014)
- ✓ Gas puffing system (2014)

4. Radiation damage in materials by using HIRFL ion-beams

Void swelling in steels

Irradiation chamber

X-TEM sample

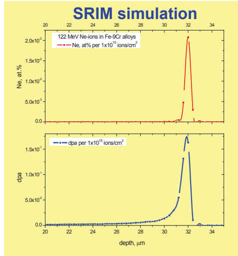
Irradiation conditions

Ions: $^{20}Ne^{6+}$ (122MeV)

Peak dpa: 1, 5, 10 (@ 0.5 dpa/h)

Peak C_{Ne}: 1200, 6000, 12000 appm

T_{irr}: 440, 510, 570 °C

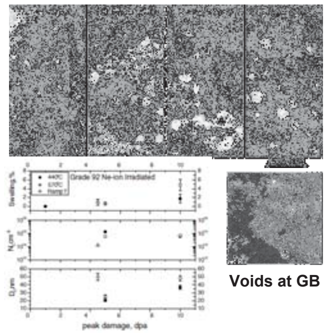


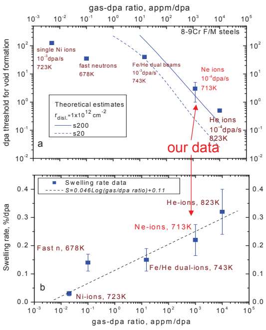
- **F/M steel:T92B, ODS ferritic**
- **Austenitic steel: 316L, FeCrMn alloy**
- **High-Ni alloy: 800H**

Zhang et al, ***J.Nucl.Mater.*** ***283-287***(2000)259; ***375***(2008)185;***386-388***(2011)457)

Void swelling in Ferritic/Martensitic steel (T92)

122MeV Ne ions Irradiation



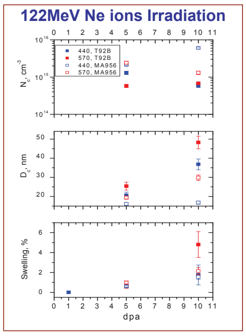


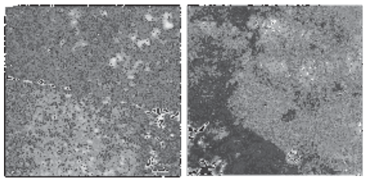
Strong dependence of void swelling on Temperature and Irradiation dose. Fast void growth at grain-boundaries at high doses / temperature (⩾ 5 dpa/6000 appm@570°C) –showing a significant embrittlement at GB.

Correlation with other ion irradiations (He beam, He/Fe dual beam, etc) is found, indicating that Ne can be used to simulate He effects under simultaneous atomic displacement.

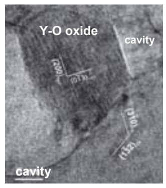
C.H.Zhang, J.Jang et al, ***J Nucl Mater*** 375(2008)185-191

Void swelling in ODS ferritic steels (MA956)





(a) ODS steel (MA956) (b) F/M steel (T92B)



Lower void swelling rate, and less significant void growth at grainboundaries in the ODS steel – a higher resistance to void swelling and helium embrittlement

C.H.Zhang et al, ***J Nucl Mater*** 386-388(2009)457-461

HIRFL-SFC Ion Irradiation Experiments (Recent work)

Conditions of ion irradiation:

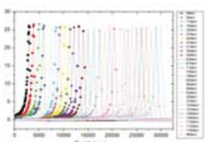
Ion species: 122 MeV $^{20}Ne^{4+}$

Doses / Temperature: 300-1300 appm (Ne) / 0.3-1.3 dpa, @360-400°C

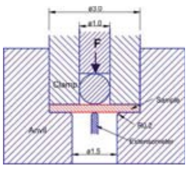
Materials: F/M steel (T91、T122)、ODS ferritic steel（3 kinds, Al/Ti/Zr added）

Tests: Small-punch test（SP）@RT & 500°C;

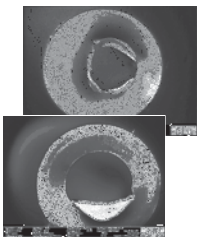
Fractures: SEM/EDS



dpa profiles in Fe-16Cr alloys (from SRIM)



Small-punch (Schematic)

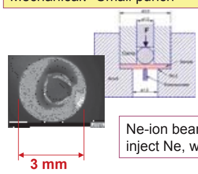


Ne, Ar are similar with Helium in bubble growth

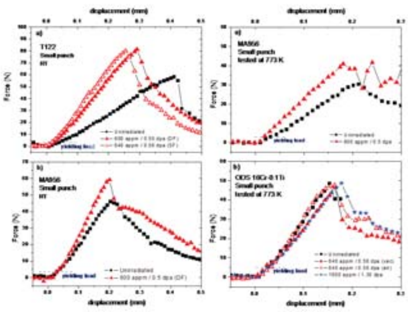
Marokov, Goodhew et al, ***J Nucl Mater*** 158 (1988) 81

Small punch test of the Ne-ion-irradiated specimens

Materials:
19Cr-4Al-ODS steel (MA956)
16Cr-0.1Ti-ODS steel
F/M steels (T91, T122)
Irradiation conditions:
122MeV Ne-ions
600-1300 appm Ne
0.5-1.3 dpa
713 K
Test:
Microstructures: SEM, TEM
Mechanical: Small punch



3 mm



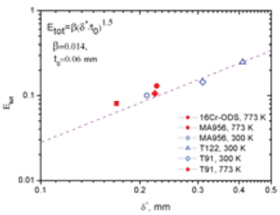
RT-test 500°C test

Load-displacement curves before/after irradiation

Ne-ion beam was used to produce collision cascade damage meanwhile to inject Ne, which has similar behavior with He in steels.

Zhang et al, ***ICFRM-16***, Beijing, Oct. 2013

Data analysis and Results discussion

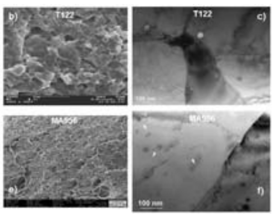


There is a 3/2-power law correlation of the total elongation E_{tot} from tensile tests with the displacement to fracture δ_f from small punch tests

$$(E_{tot}^{irr}/E_{tot}^{v})=(\delta_f^{irr}/\delta_f^{v})^{3/2}$$

Loss of ductility after irradiation

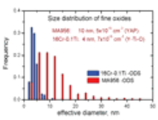
Material	16Cr-ODS	MA956(ODS)		T122
appm Ne	600-1300	600		600
$\Delta E_{tot}/E_{tot}$ (T_{test})	0 (500°C)	22% (500°C)	19% (20°C)	41% (20°C)



A microstructural interpretation:

Large cavities were observed at grain-boundaries in the conventional F/M steel, while only small bubbles were observed at oxide/matrix interfaces in ODS steels after irradiation.

The Al-free Ti-added ODS steels contains finer oxides in higher density –supply high concentration of sites trapping gas atoms.



Thank you !