Fusion and Spallation Irradiation Conditions

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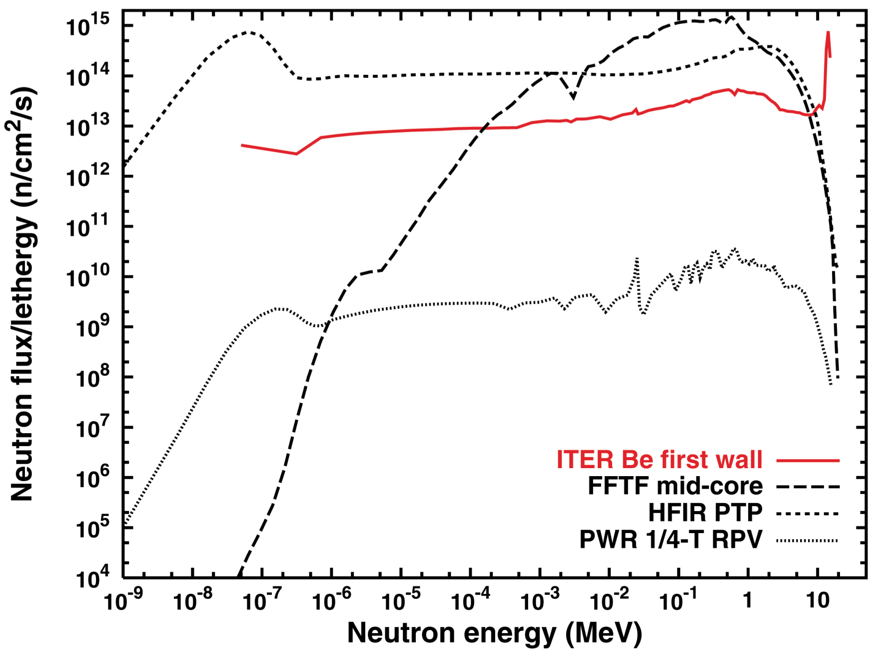
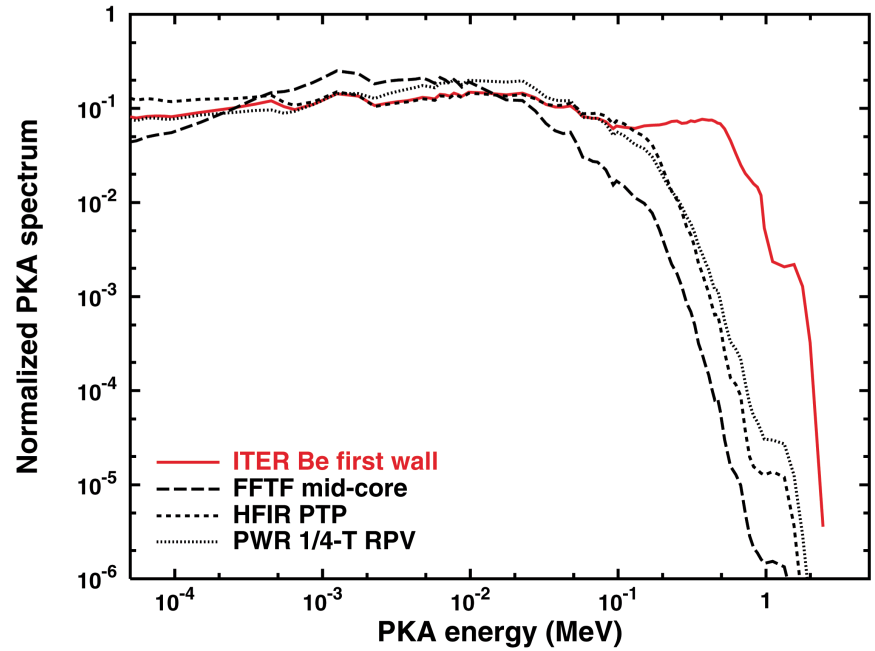
Comparison of fission and fusion (ITER) neutron spectra

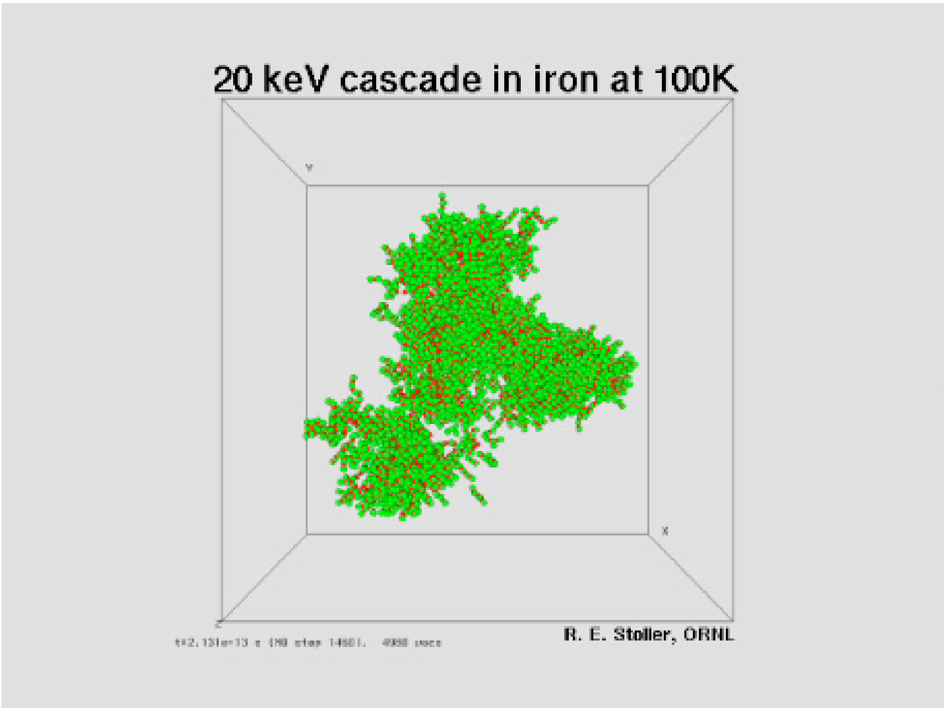
Stoller & Greenwood, JNM 271-272 (1999) 57



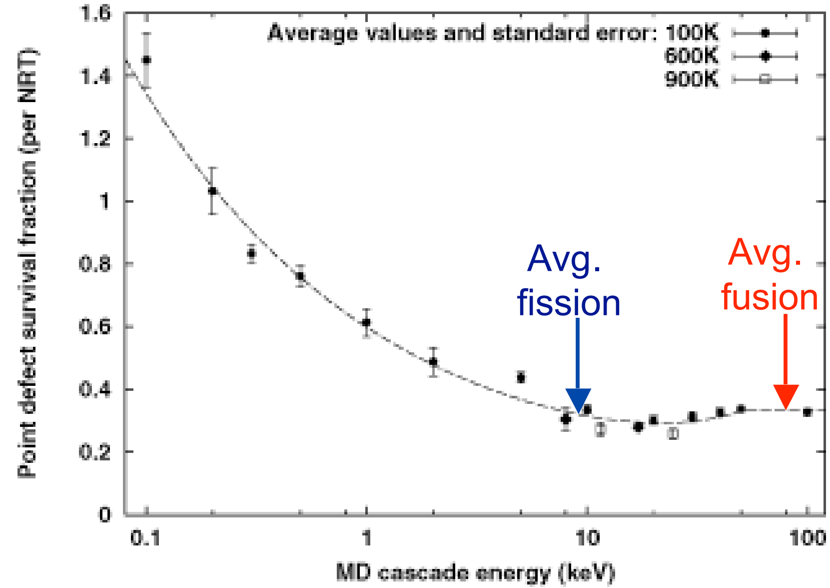


- Main difference between fission and DT fusion neutron spectra is the presence of significant flux above ~4 MeV for fusion
  - High energy neutrons typically cause enhanced production of numerous transmutation products including H and He
  - The Primary Knock-on Atom (PKA) spectra are similar for fission and fusion at low energies; fusion contains significant high-energy PKAs (>100 keV)

Displacement Damage Mechanisms are being investigated with Molecular Dynamics Simulations

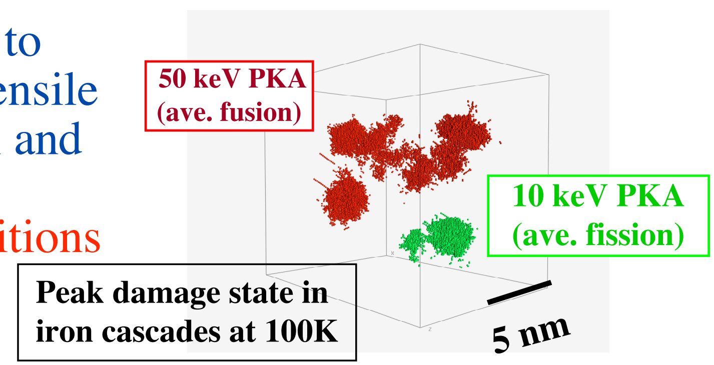


Damage efficiency saturates when subcascade formation occurs



Molecular dynamics modeling of displacement cascades up to 200 keV and low-dose experimental tests (microstructure, tensile properties, etc.) indicates that defect production from fusion and fission neutron collisions are similar

=> Defect source term is similar for fission and fusion conditions



A critical unanswered question is the effect of higher transmutant H and He production in the fusion spectrum

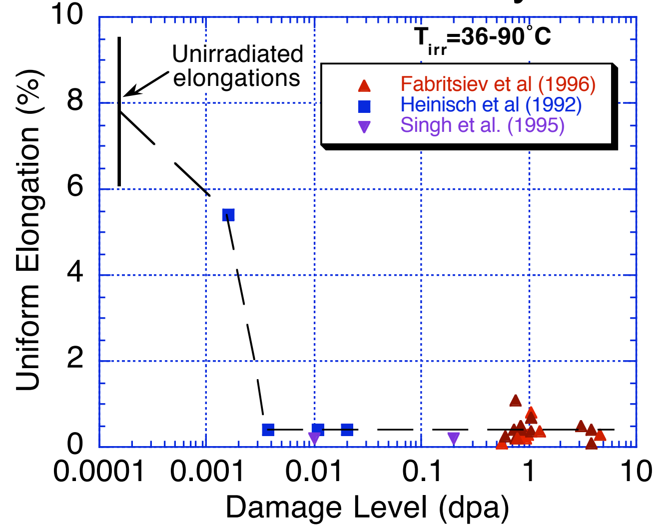
Radiation Damage can Produce Large Changes in Structural Materials

- Radiation hardening and embrittlement (<0.4 T_M)
- Irradiation creep (<0.45 T_M)
- Volumetric swelling from void formation (0.3-0.6 T_M)
- High temperature He embrittlement (>0.5 T_M)

In addition…

- The irradiation environment associated with a D-T fusion reactor is more severe than in fission reactors
  - Higher lifetime dose requirements for structure
  - Higher He generation rates (promotes He embrittlement of grain boundaries, void swelling)

Low tensile ductility in FCC and BCC metals after irradiation at low temperature is due to formation of nanoscale defect clusters



Outstanding questions to be resolved include:

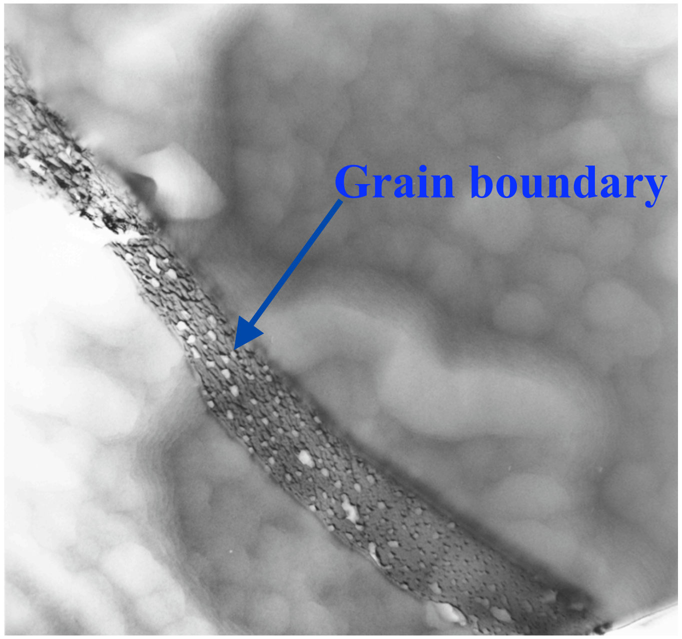
- Can the defect cluster formation be modified by appropriate use of nanoscale 2nd phase features or solute additions?
- Can the poor ductility of the irradiated materials be mitigated by altering the predominant deformation mode?

UT-BATTELLE

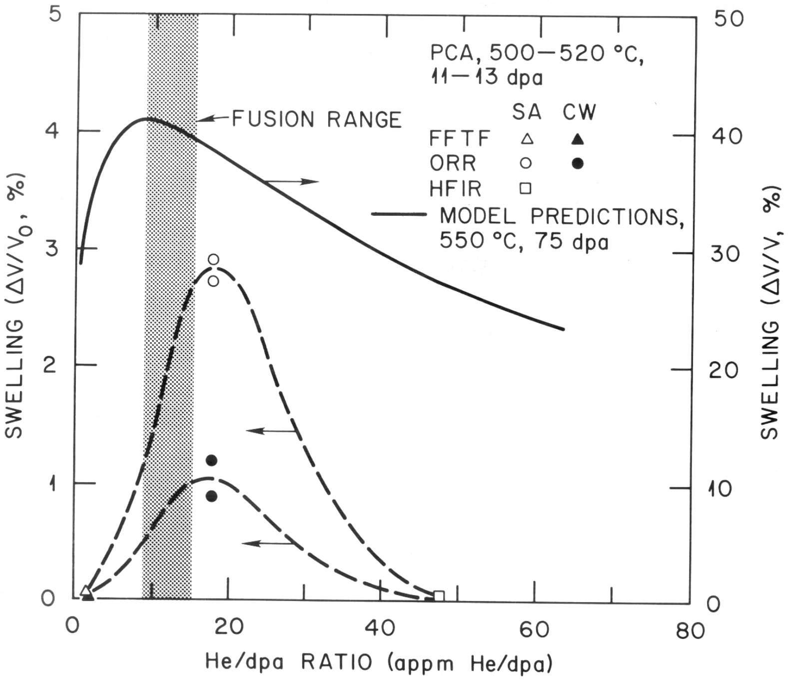
Why is He/dpa ratio an important parameter for fusion materials R&D?

- He generation can alter the microstructural evolution path of irradiated materials (pronounced effects typically occur for >100 appm He)
  - Cavity formation (matrix and grain boundaries)
  - Precipitate and dislocation loop formation

He bubbles on grain boundaries can cause severe embrittlement at high temperatures

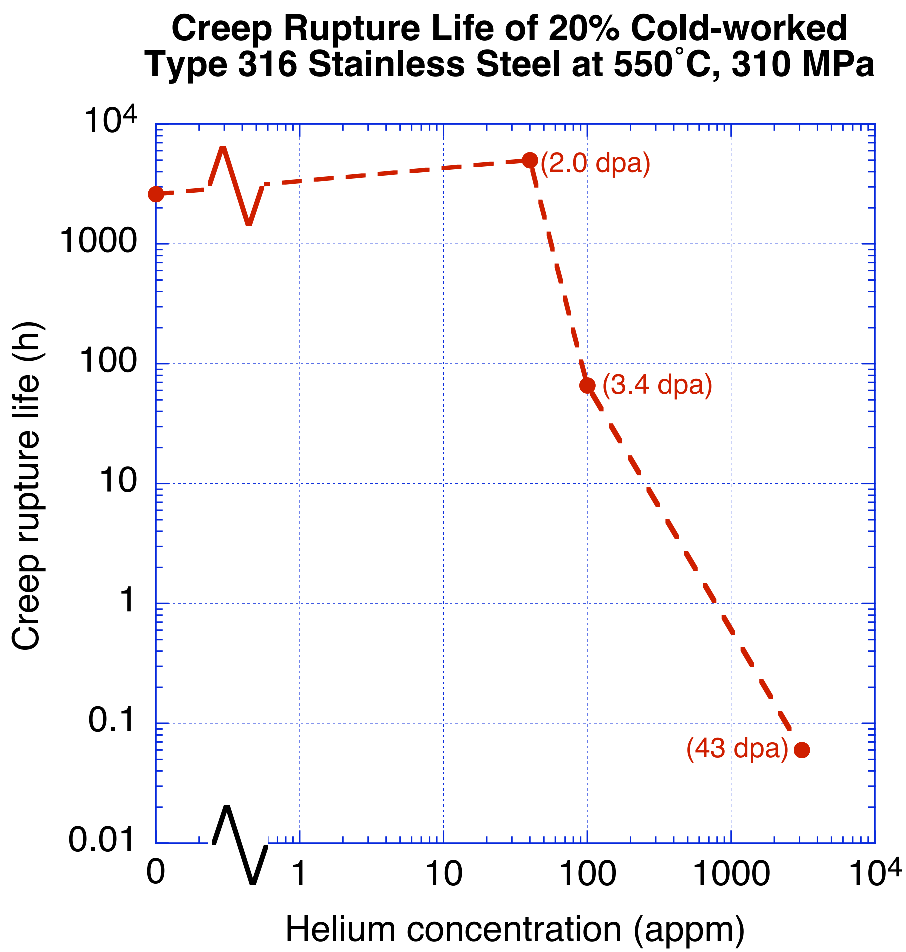


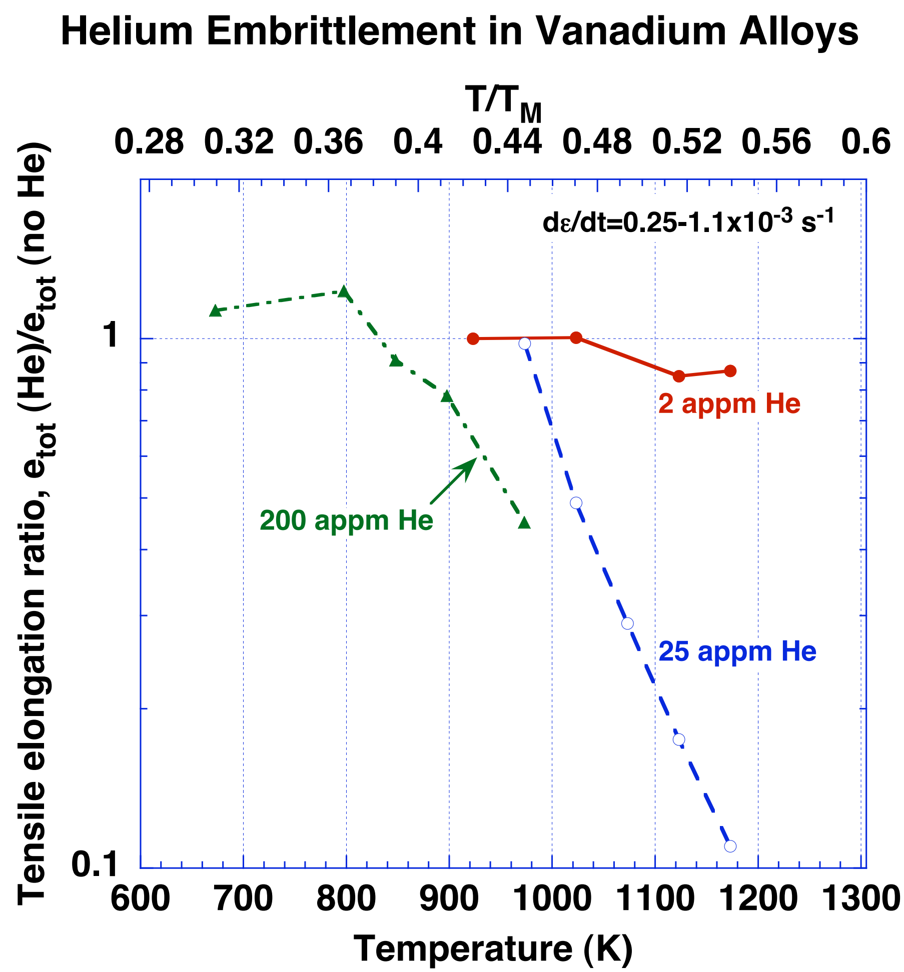
Swelling in stainless steel is maximized at fusion-relevant He/dpa values



Management of He transmutation products (matrix trapping at engineered 2nd phases) is a key factor for fusion materials

Helium embrittlement of grain boundaries occurs at high temperatures for helium concentrations above ~100 appm

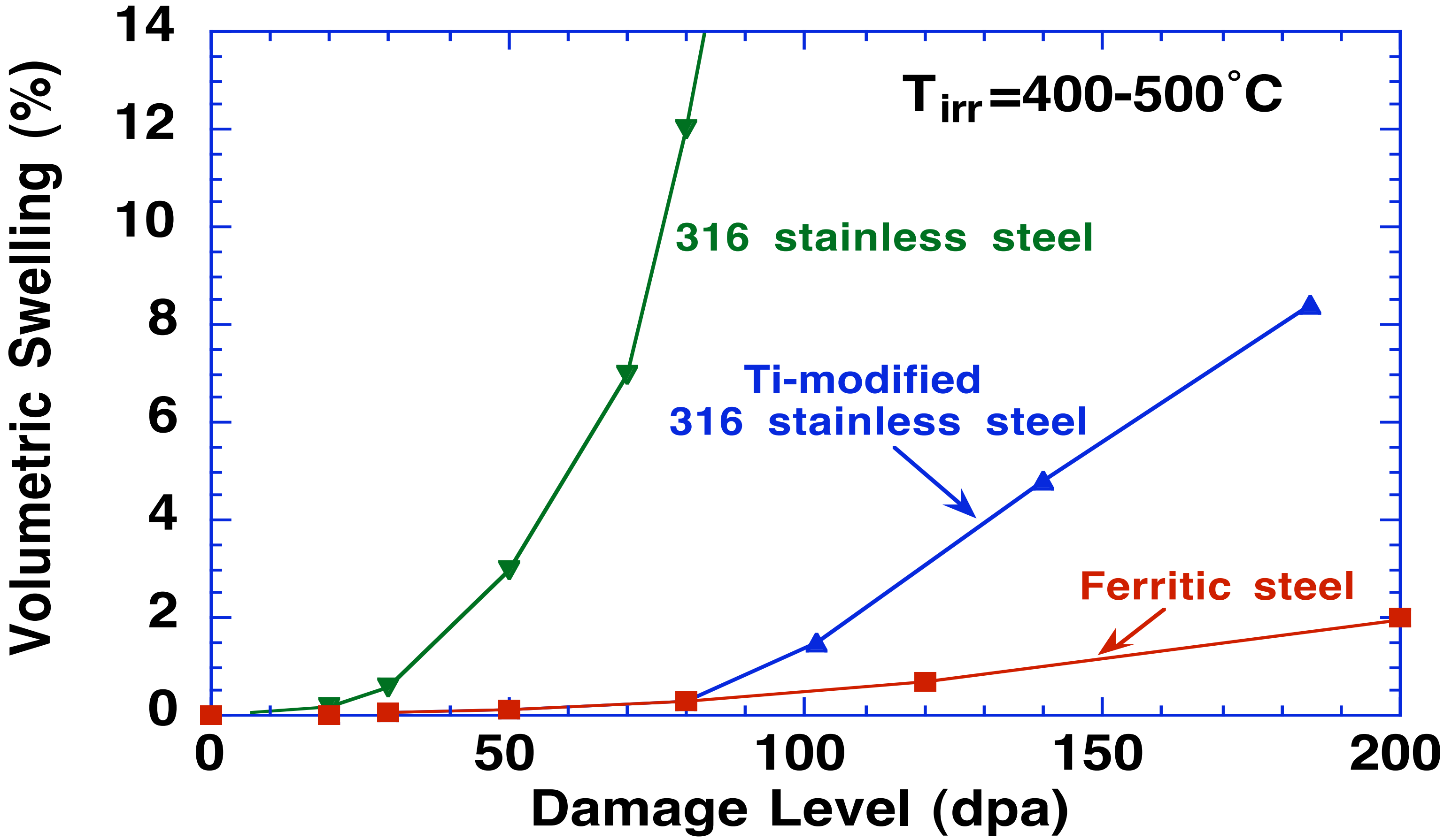




He trapping at nanoscale precipitates within grains is key for inhibiting He embrittlement

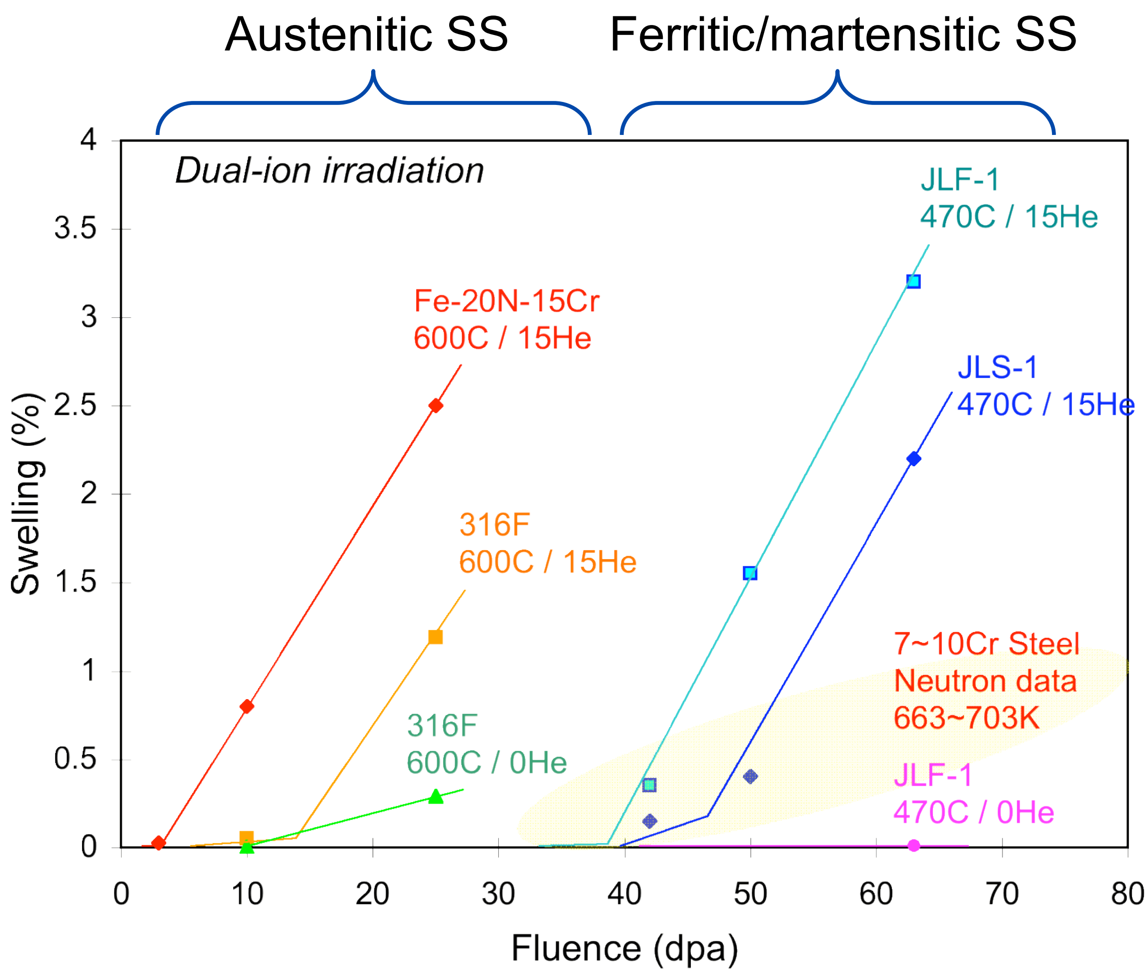
However…….. The formation and microstructural stability of these precipitates is strongly affected by irradiation parameters, in particular the He/dpa ratio

Swelling Resistant Alloys For Fission Reactors Were Successfully Developed



- Lowest swelling is observed in body-centered cubic alloys (V alloys, ferritic steel)
- Materials science strategy used for developing swelling-resistant stainless steel can be applied to new alloys if effects of He on void swelling are understood

Swelling behavior of stainless steels



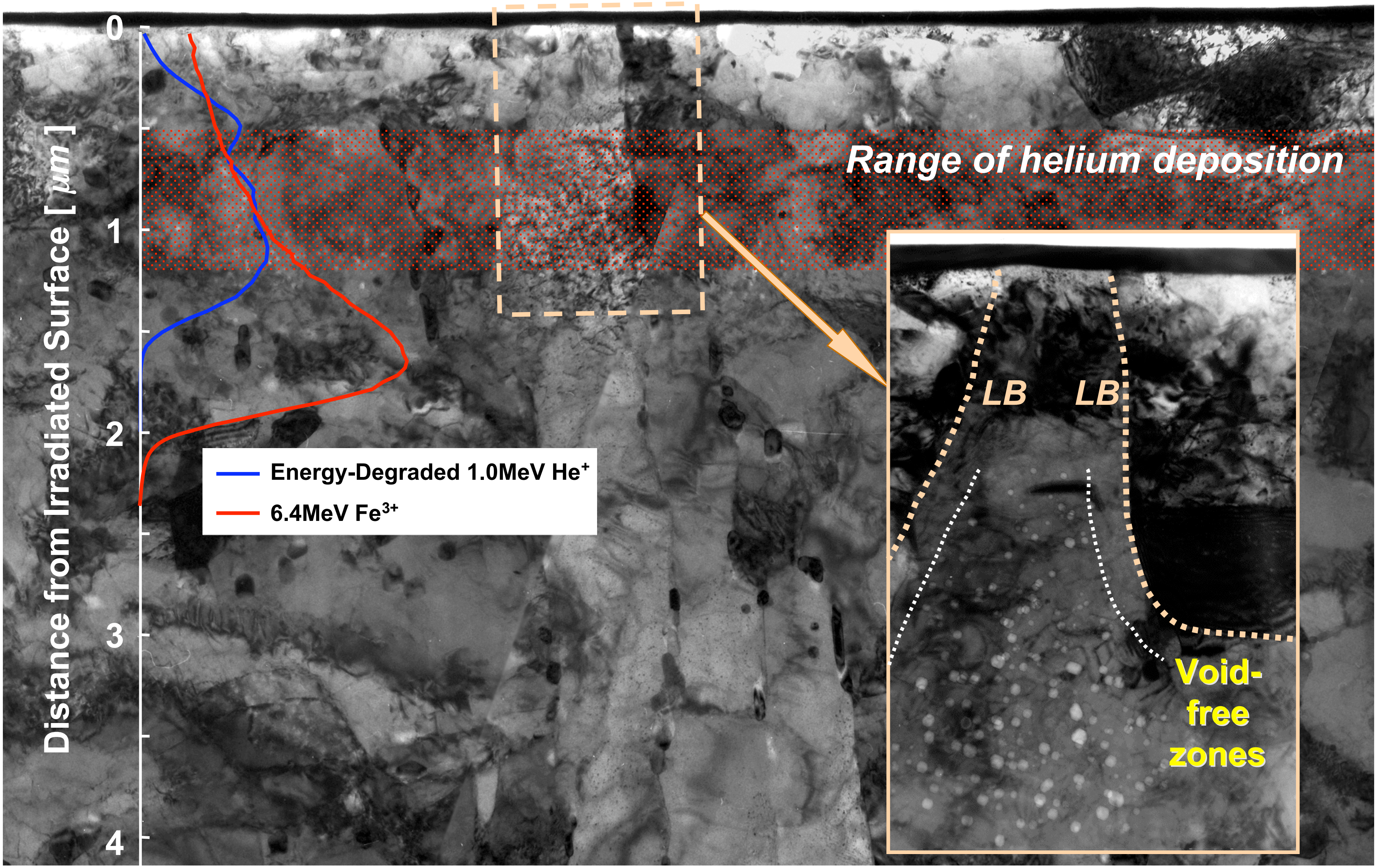
Y. Katoh et al., 2003

- Swelling behavior of RAFMs and austenitics near peak-swelling temperatures are similar in the presence of helium, except for incubation dose.

Cavity formation in JLF-1 by dual-ion beam irradiation

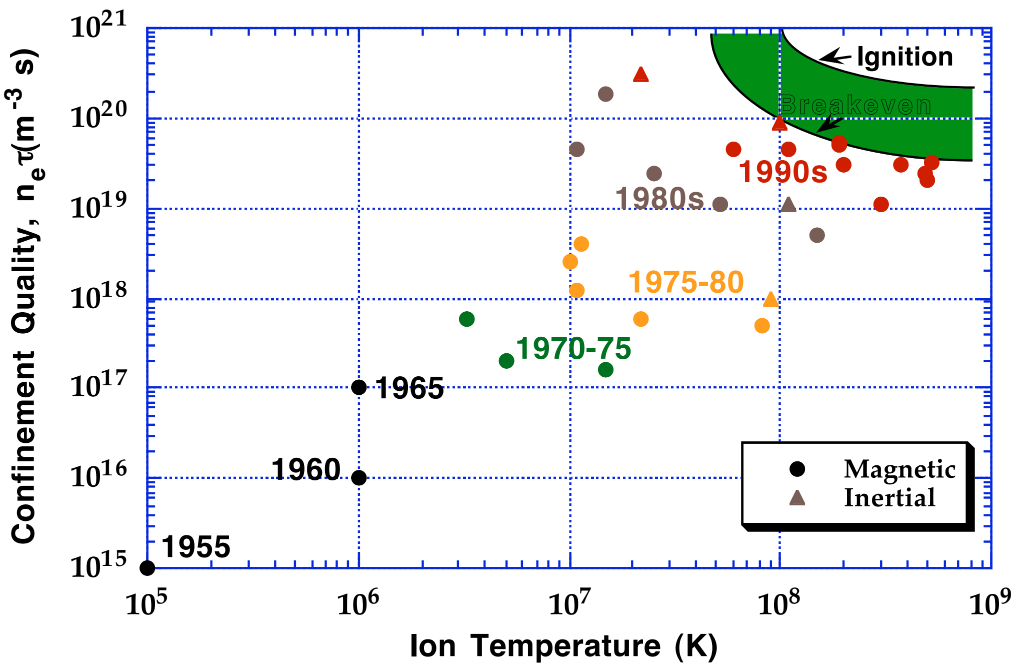
− 6.4 MeV Fe^{3+} + Energy-Degraded 1.0 MeV He^{+}, 20 dpa at 743 K −

Y. Katoh et al., 2003

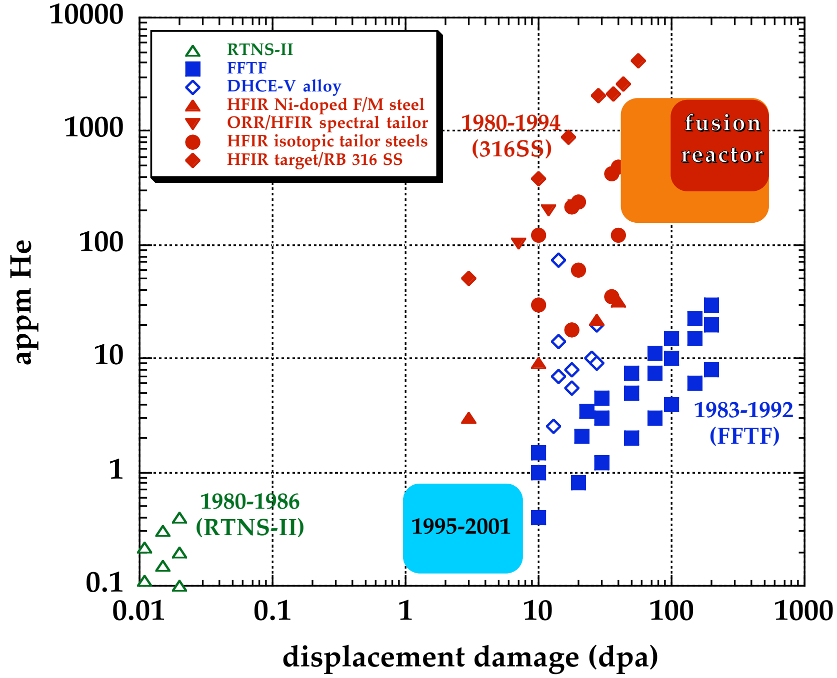


Fusion materials research must rely heavily on modeling due to inaccessibility of fusion-relevant operating regime

- Extrapolation from currently available parameter space to fusion regime is much larger for fusion materials than for plasma physics program
  - Most of He effects data on irradiated materials is based on austenitic stainless steel (FCC); relevance to BCC alloy systems is uncertain
  - Recent fusion materials R&D has focused on low-dose deformation and fracture issues
- An intense neutron source such as IFMIF is proposed to develop and qualify fusion structural materials prior to a construction decision for a fusion Demo reactor



Summary of Helium and Dose Parameter Range
Investigated by the Fusion Materials Program



Spallation Sources

Transmutation of nuclear waste

ADS (F, B...)
ATW/AAA (US)
EA (I, E, F)

Neutrons as probes for condensed matter

ISIS (GB)
LANSCE (US)
SINQ (CH)

SNS (US)
JPARC (J)
ESS (EU)

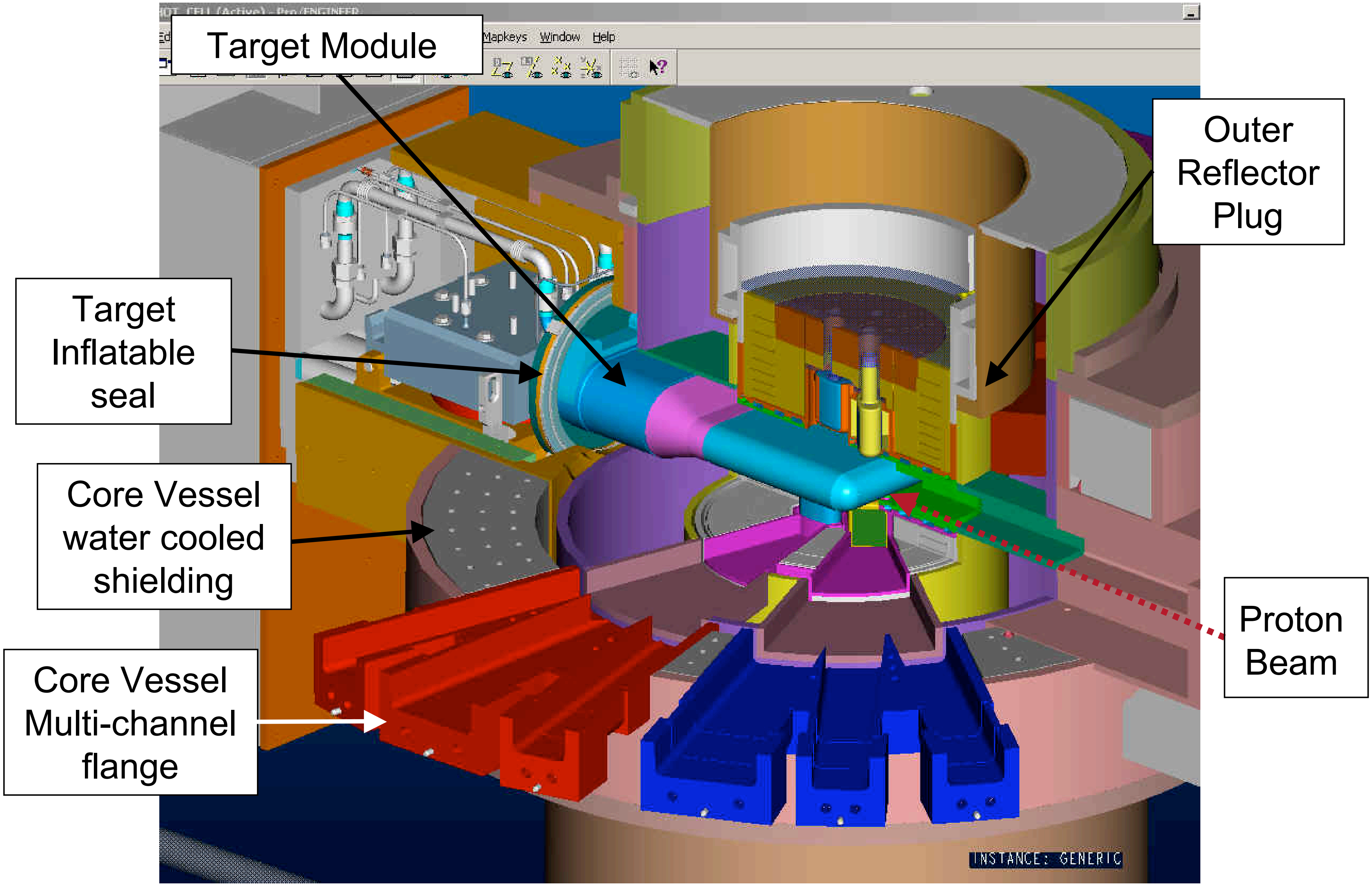
Tritium production

TRISPAL (F)
APT (US)

Typical Parameters:

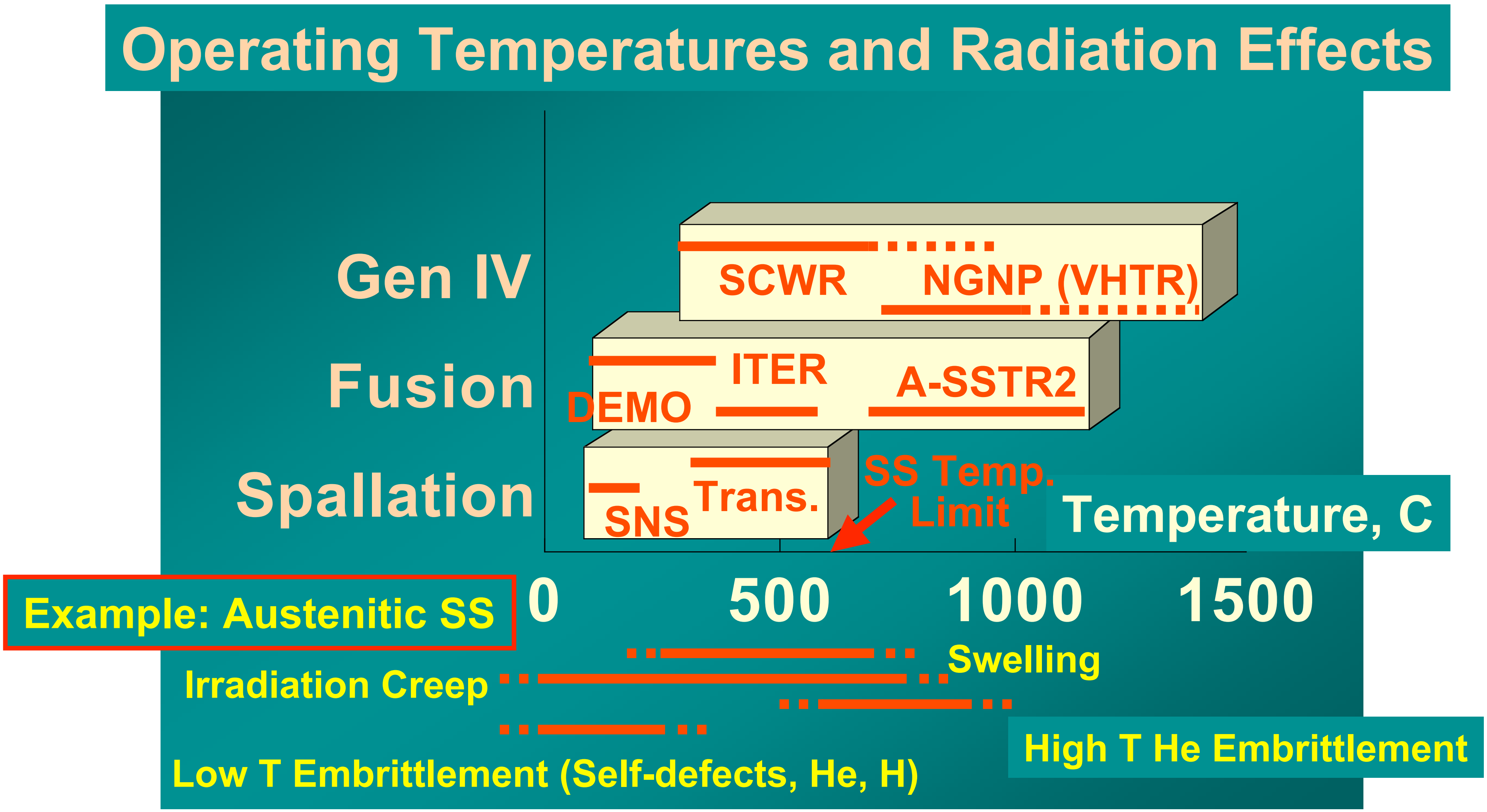
Beam power several MW (~1 GeV protons)
Pulse length ~ 1µs (several 10^{14} p/Pulse ➔ 100 kJ)
Repetition frequency 50/60 Hz
Thermal n-flux up to $7x10^{18}$ $n/m^2 \cdot s$ average
up to $2x10^{21}$ $n/m^2 \cdot s$ in pulse

Design of the SNS



Overlap in Temperature for Fusion, Generation IV Fission Reactors and Spallation Facilities

L.K. Mansur et al. ICFRM-11, J.Nucl. Mater. in press (2004)



Key Operating Conditions for Structural Materials

	Fusion	Fission (Gen IV)	Spallation
Coolant	H_2O, He, Li, PbLi, FLiBe	H_2O(SC), He, Pb, PbBi	Hg, PbBi, H_2O
Particle Energy	< 14 MeV	< 1 - 2 MeV	< 1 GeV (p and n)
Temperatures	300-1000˚C	300-1000˚C	100-500˚C
Max displacement damage	~200	30-150	~20
He/dpa	10 appm/dpa	~0.1 appm/dpa	100 appm/dpa
Stresses	Moderate, nearly constant	Moderate, nearly constant	High, pulsed

Based on L.K. Mansur et al. ICFRM-11, J.Nucl. Mater. in press (2004)

Conclusions

- The structural materials response to exposure to fission, fusion and spallation neutron environments…
- Offers many similarities:
  - Similar defect production source term
  - Radiation hardening and embrittlement (<0.4 T_M)
  - Irradiation creep (<0.45 T_M)
  - Phase stability, radiation induced segregation phenomena (0.3-0.6 T_M)
- And some important differences:
  - Potential for He-enhanced radiation hardening and embrittlement (<0.4 T_M)
  - He and H effects on void swelling (0.3-0.6 T_M)
  - High temperature He embrittlement (>0.5 T_M)
  - He-modified phase stability (0.3-0.6 T_M)

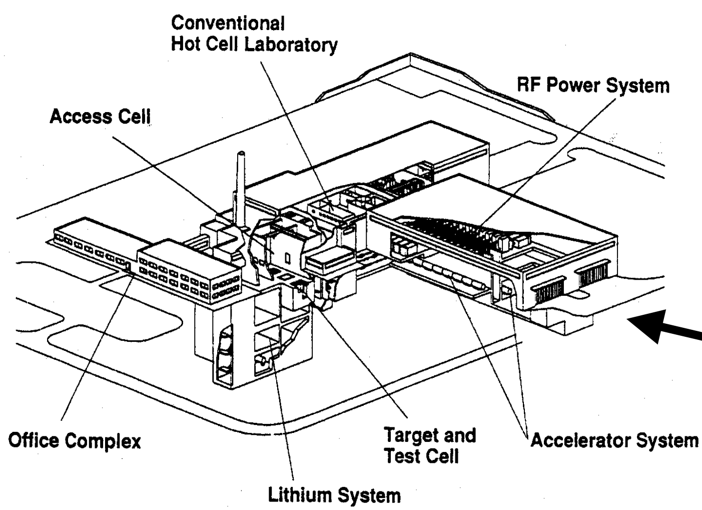
Backup viewgraphs

Fusion Materials Irradiation Facilities

Radiation stability is strongly dependent on exposure temperature, displacement damage (dpa), damage rate, solute transmutation (H, He, ...)

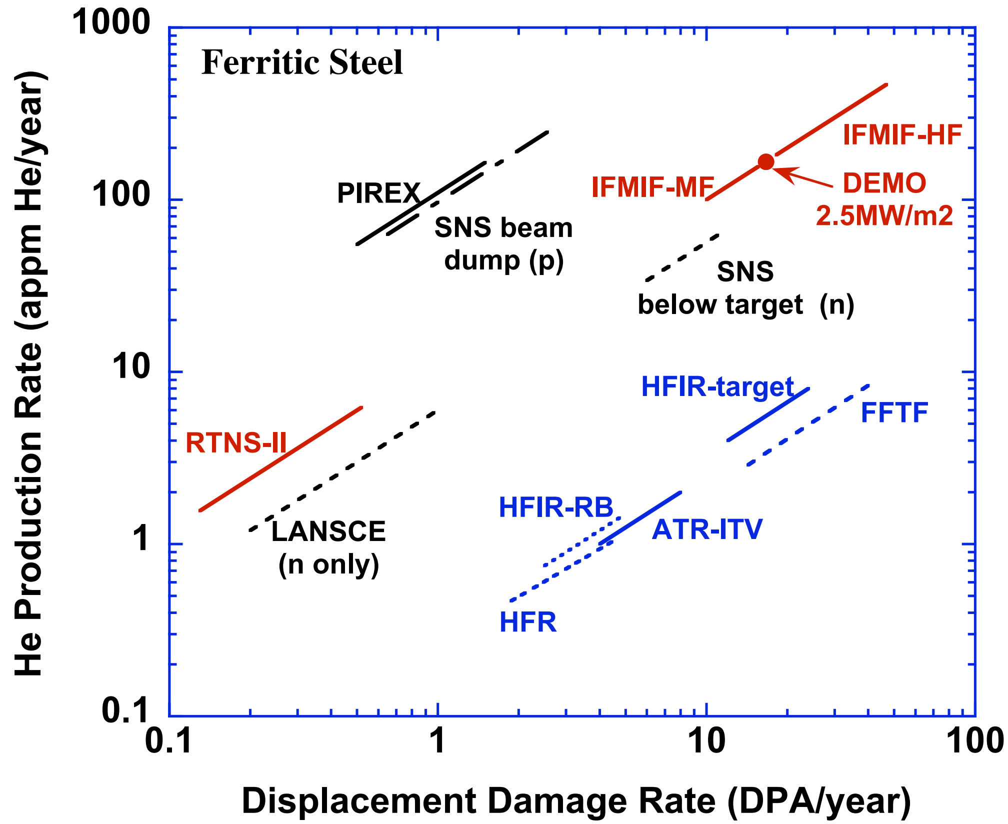
=> He/dpa ratio is a useful radiation effects metric for fusion materials

- Fission sources
  - fusion-relevant displacement damage
  - low He generation (except Ni alloys, etc.)
- Ion accelerators
  - generally limited to microstructural studies
  - typically very high damage rates
- Spallation sources
- D-Li stripping source



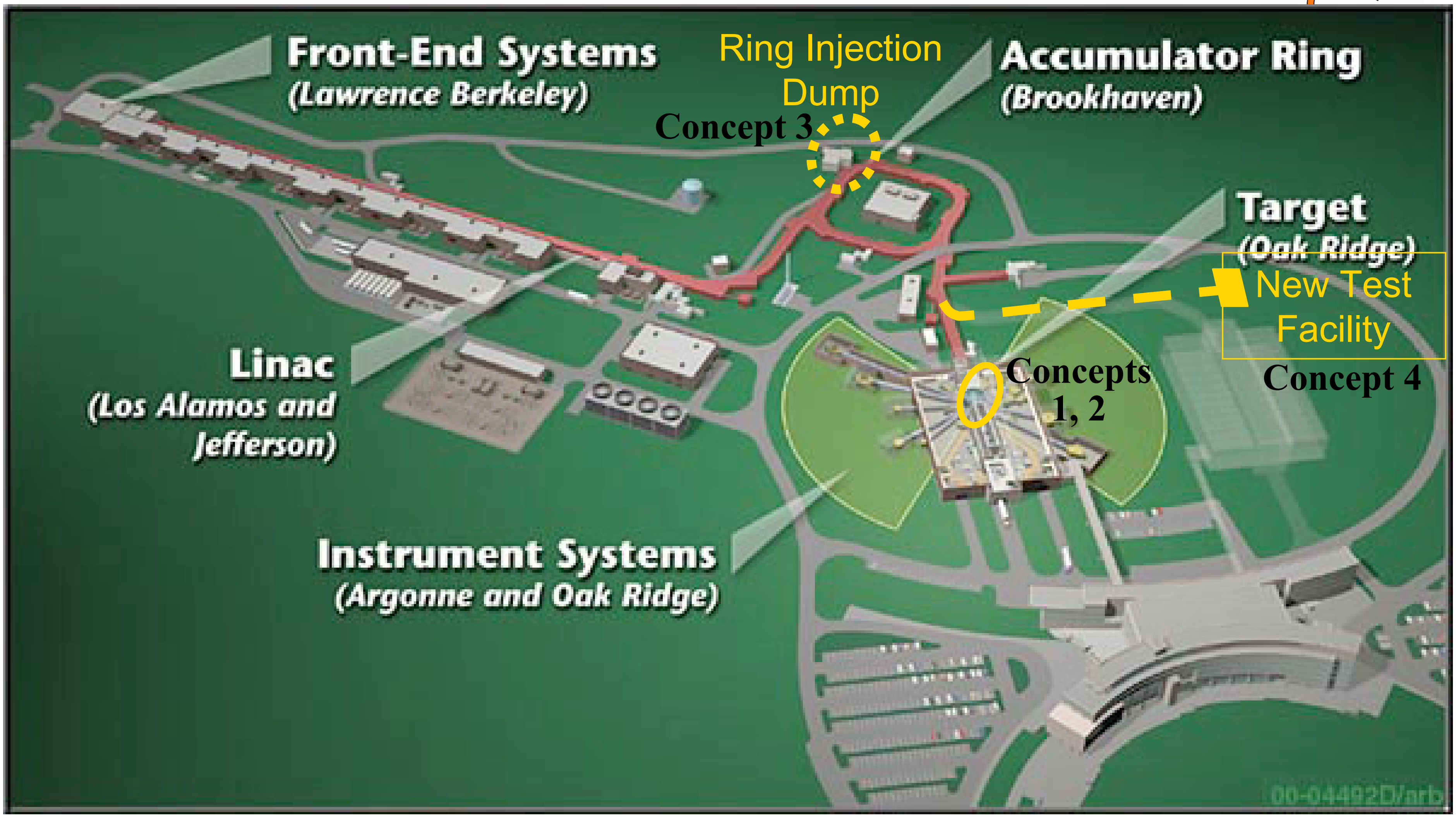
under planning: IFMIF

Comparison of He and Damage Production Rates for Fission, Fusion-relevant and Spallation Neutron Facilities



Modified from H. Bolt (IPP-Garching), 2002

SNS Site Layout



Specific Issues of Common Interest

- No prototype facilities available for Fusion, Gen IV Reactors, or Liquid Metal Pulsed Targets
- All irradiations conducted in few facilities, e.g

HFIR and ATR	JMTR and JOYO
HFR	BOR 60
LANSCE	SINQ

- Common alloys--austenitics, ferritic-martensitics, high nickel alloys, mechanically alloyed steels
- Theory and modeling of radiation response
- Can one technology provide radiation source for other technologies--e.g., spallation for fusion, IFMIF for Gen IV, Gen IV for Fusion
- High transmutation gas effects on swelling and embrittlement--Fusion, SCWR and NGNP (Ni bearing alloys), Spallation

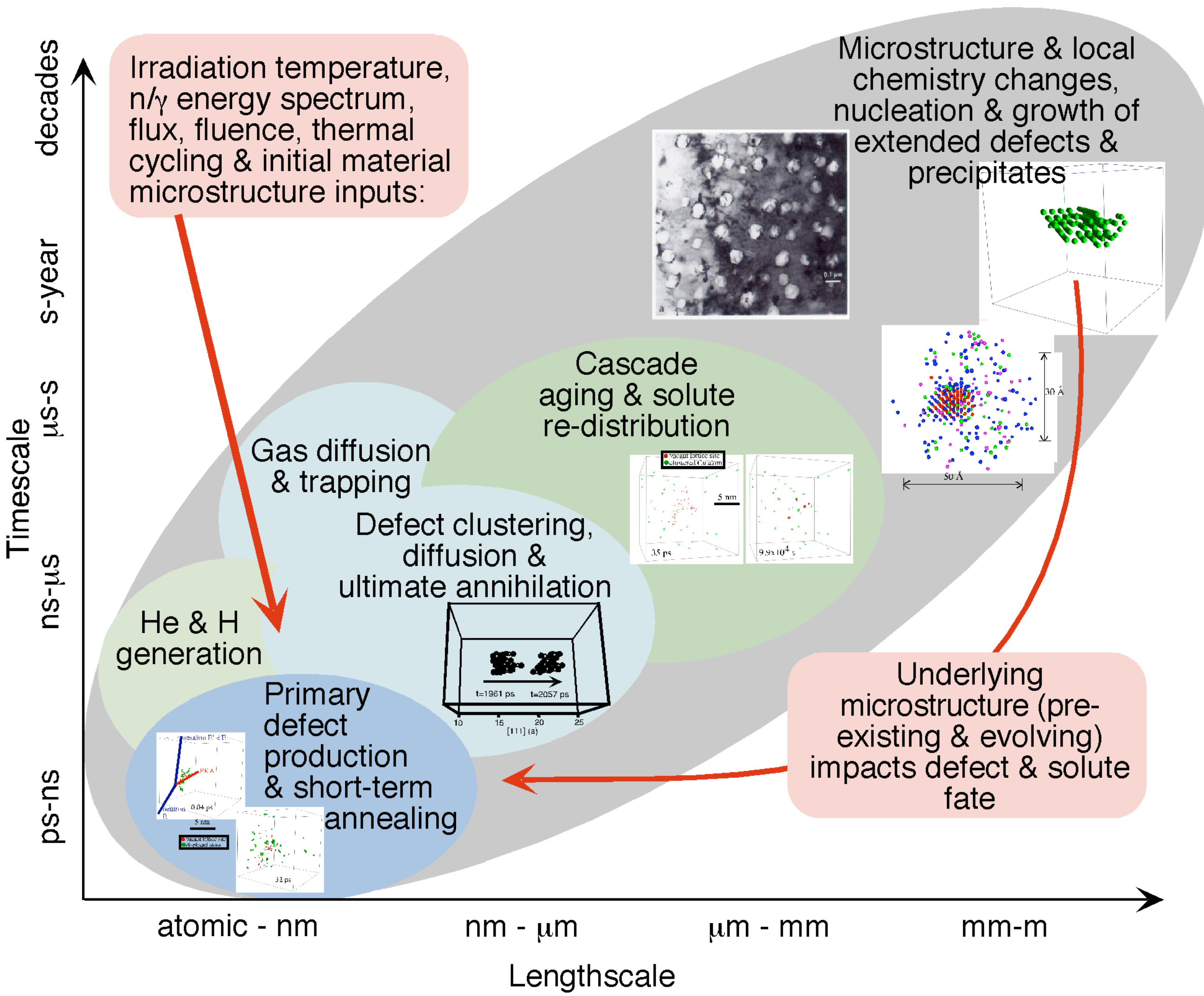
Specific Issues of Common Interest (continued)

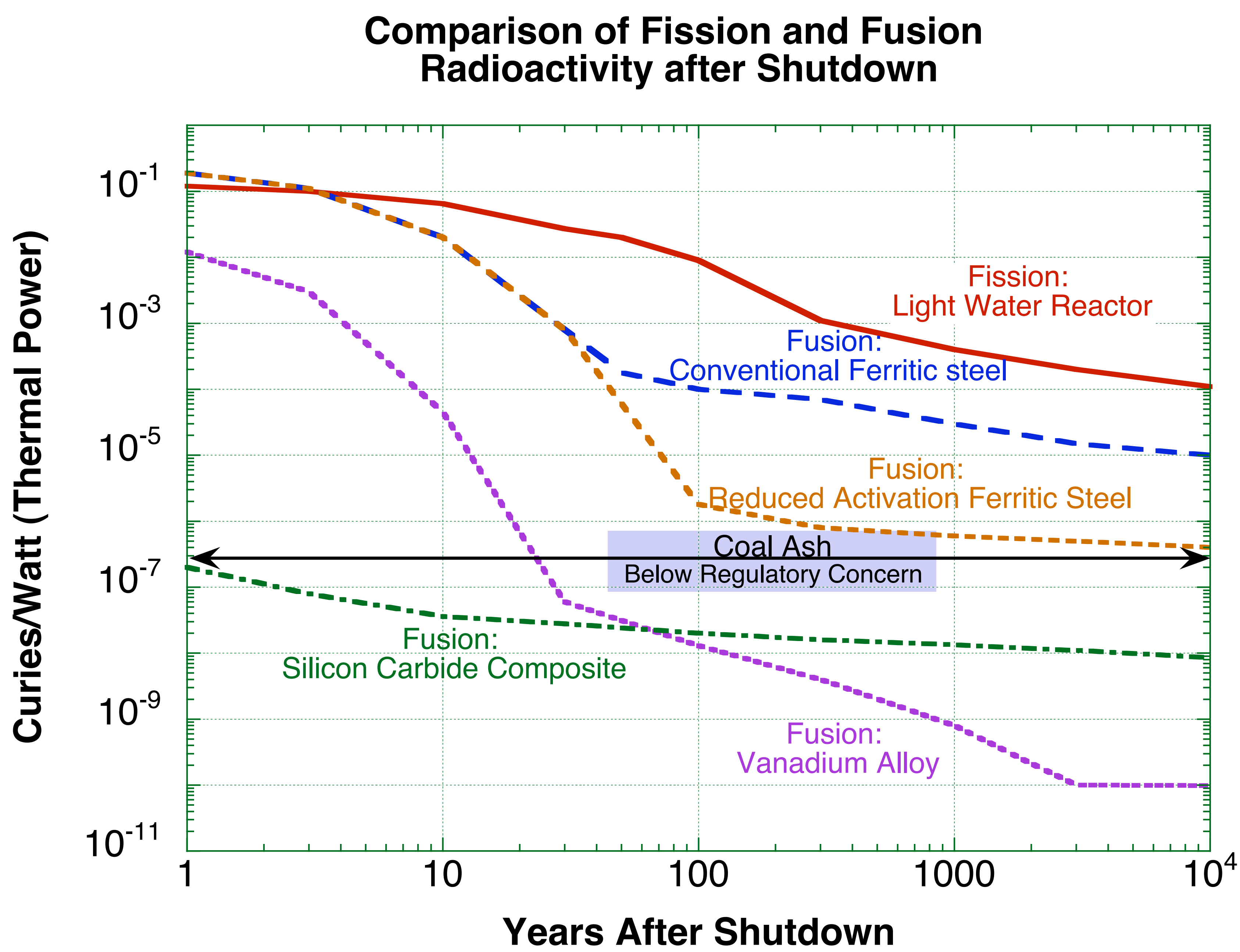
- Very low dose rate, long time exposures
- Wide range of dose rates < 10^{-10} to > 10^{-7}
- High temperature deformation mechanisms—Fusion Demo/Power Plants, Gen IV
- Low temperature flow localization and fracture
- Behavior of structural composites (mechanical properties and structure)--Fusion, NGNP, GFR
- Liquid metals in contact with irradiated structural materials--Fusion, LFR, Spallation
- Water coolant in contact with irradiated structural materials--ITER, SCWR, Spallation
- Gas coolant in contact with irradiated structural materials--Fusion, NGNP, GFR

Key Cross-cutting Phenomena in Theory and Modeling of Structural Materials

- hardening and nonhardening embrittlement including underlying microstructural causes and the effects of helium on fast fracture; low temperatures and all doses
- flow localization, consequences and underlying microstructural causes, low to intermediate temperatures, all doses
- high temperature deformation and fracture, including helium effects; higher temperatures and doses
- irradiation creep and thermal creep; intermediate and high temperatures; intermediate to high doses
- swelling and phase stability, intermediate temperatures; intermediate to high doses
- welding, joining and processing issues
- fatigue and creep-fatigue interactions; dependent on cyclic loading; load level and total cycles
- hydrogen and interstitial impurity effects on deformation and fracture
- chemical compatibility, erosion, bulk corrosion, stress corrosion cracking, impurity and corrosion product transport

Radiation damage is inherently multiscale with interacting phenomena ranging from ps-decades and nm-m




Comparison of Fission and Fusion
Radioactivity after Shutdown
Curies/Watt (Thermal Power)
10-1
10-3
10-5
10-7
10-9
10-11
1
10
100
1000
10^4
Years After Shutdown
Fission:
Light Water Reactor
Fusion:
Conventional Ferritic steel
Fusion:
Reduced Activation Ferritic Steel
Coal Ash
Below Regulatory Concern
Fusion:
Silicon Carbide Composite
Fusion:
Vanadium Alloy