INFLUENCE OF FLUX AND COMPOSITION ON LOOP'S NATURE IN NICKEL DURING ION IRRADIATION

Lisa Lefort[1], Brigitte Décamps[2], Guilhem Sagnes[1], Thomas Jourdan[1], Marie Loyer-Prost[3]

[1]Université Paris-Saclay, CEA, Service de Recherche en Corrosion et Comportement des Matériaux, SRMP, 91191 Gif-Sur-Yvette

[2]Laboratoire de Physique des 2 infinis Irène Joliot-Curie (IJCLab), CNRS/IN2P3, Université Paris-Saclay, 91400 Orsay, France

[3]Université Paris-Saclay, CEA, Service de Recherche en Matériaux et procédés Avancés, 91191 Gif-Sur-Yvette

Industrial context

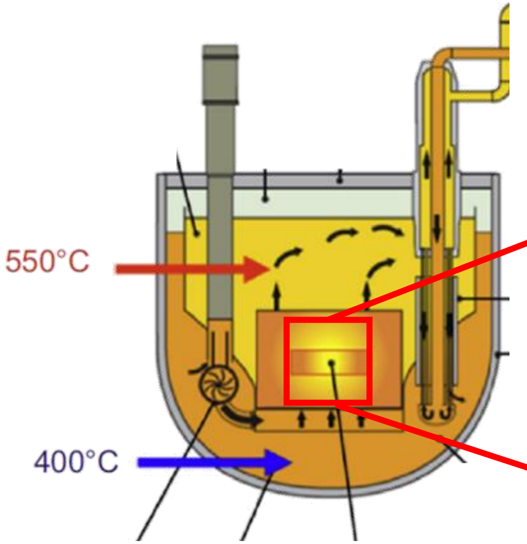
Development of next generation reactors (Sodium-cooled Fast Reactor, SFR-Gen IV)

Huge challenge for fuel cladding materials = harsh environmental conditions

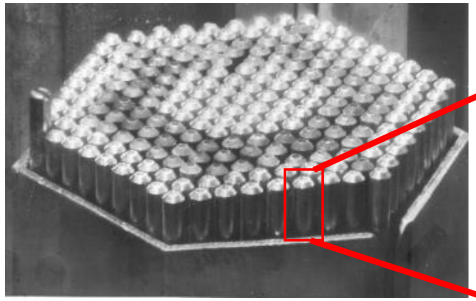
- High irradiation > 100 dpa (displacement per atom)
- High temperature 450-600°C

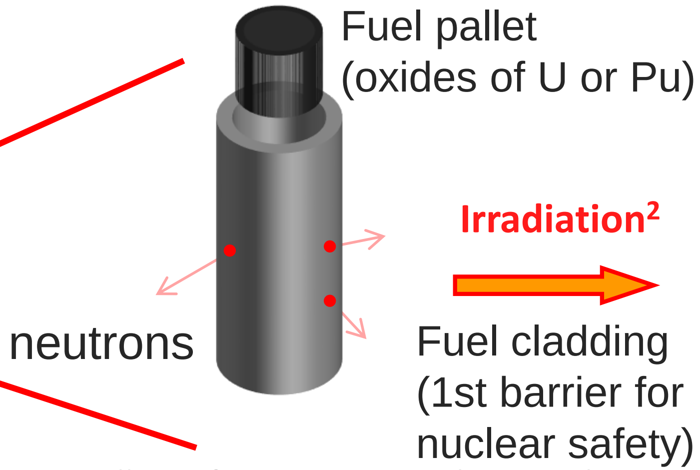
Austenitic Materials

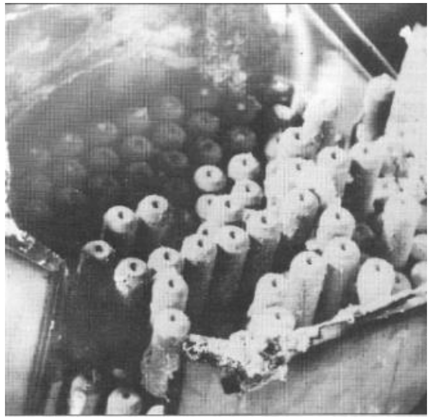
- Foreseen as the first candidate for fuel cladding of SFR-Gen IV
- Well-known major issue : 3D volume extension => irradiation-induced void swelling



Typical SFR diagram with nominal temperature[1]





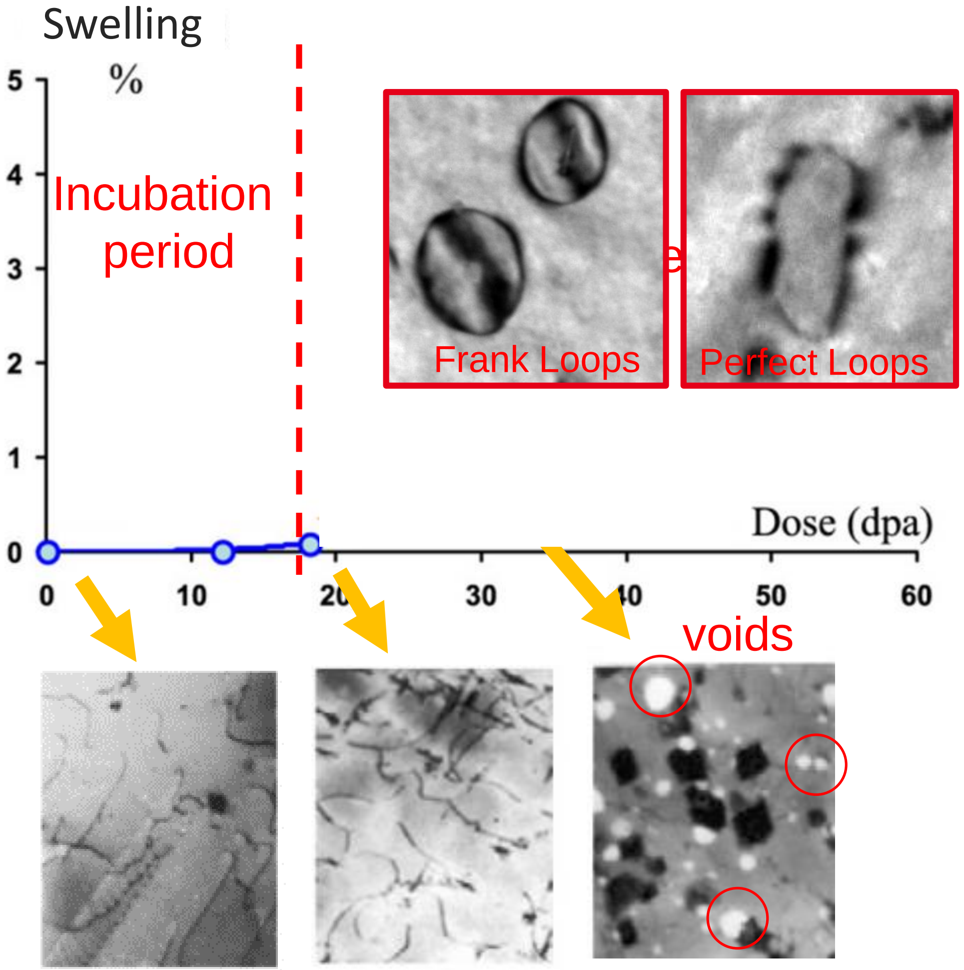


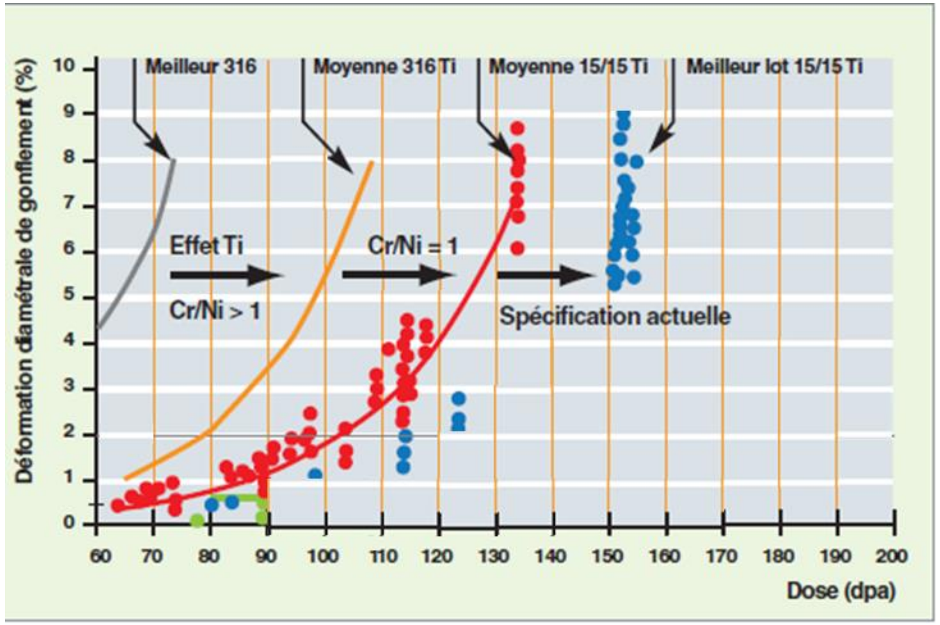
Swelling of austenitic stainless steels in SFR[2]

[1]S. Dubiez-Le Goff et al., Proceedings of ICAPP'12, 12053 (2012) [2]P. Dubuisson, Revue de métallurgie 108, 33-37 (2011)

Radiation-induced void swelling in austenitic steels

Swelling of 316 ASS in function of irradiation dose at 600°C in Phénix[1].





Swelling of different cladding candidates of Gen-IV reactors[3]

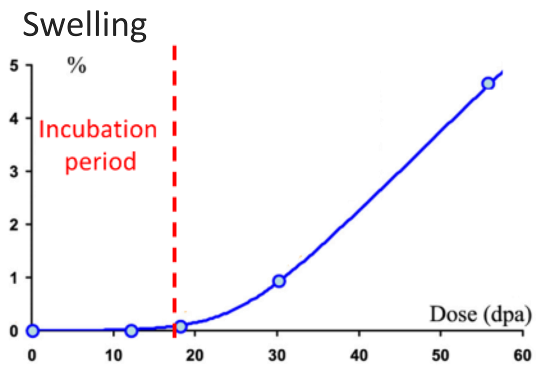
- **Influence of composition ?**

[1] P. Dubuisson, Revue de métallurgie 108, 33-37 (2011);
[2] F.A. Garner, Radiation Damage in Austenitic steels (2012); [3] J.-L. Seran, NT DMN, Nuclear Energy Division Monograph (2015)

Approach

1. Objective

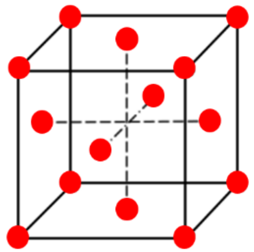
Better understand the mechanisms governing the early-stage irradiation behavior of austenitic structure (FCC) structure



2. Approach

- **Simplification of studied materials**

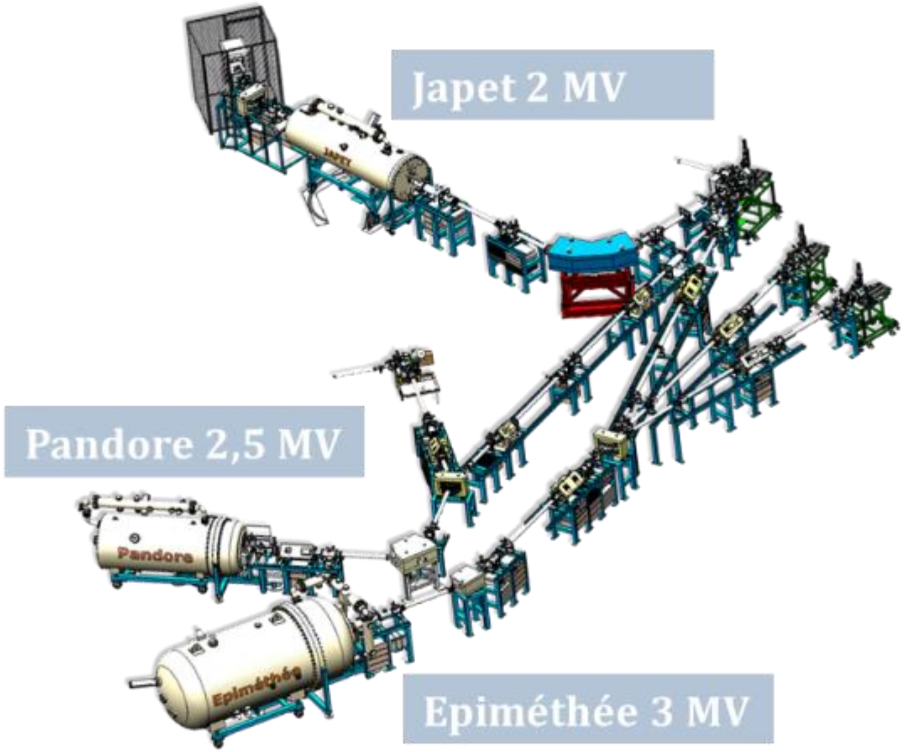
Ni and nickel alloys (Ni0,8Ti)
→ FCC structure



Face-centred cubic lattice
(FCC)

- **Simplification of experiment conditions**
  - Ion irradiations on **JANNuS** platforms
  - Good control of various flux and irradiation temperatures

→ Influence of flux ?

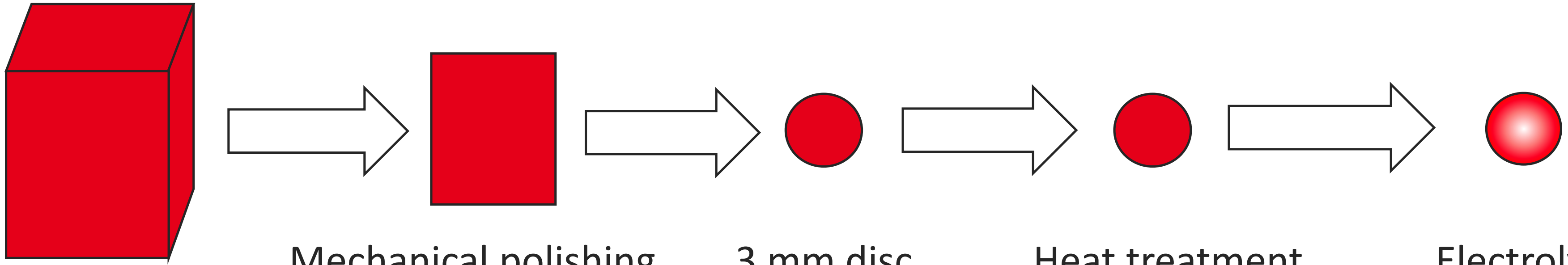


Approach – sample preparation

Ni - Prepared at Ecole des Mines St. Etienne

Element Wt%(ppm)	C	S	O	N	Ti/Cr	Ni
Ni	8	2	3	2	\	Bal.

Ni0,8Ti (99,2% Ni + 0,8% Ti) - Prepared in CEA Saclay

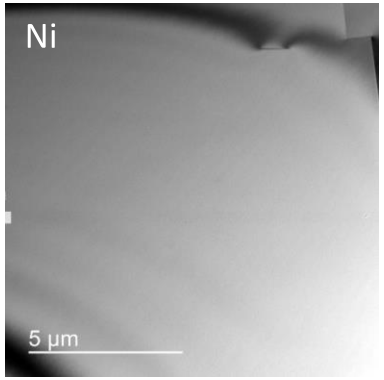


Mechanical polishing 100 µm

3 mm disc punching

Heat treatment (annealing 1000°C)

Electrolytic polishing



Microstructure characterization before irradiation

Irradiations

Observations by TEM,
Thin foil characterization

Approach – irradiations

JANNuS facilities Saclay and Orsay

Material	Platform	Temperature	Flux
Ni	JANNuS Orsay ARAMIS Ni2+ 2MeV	450°C	**High** 3.10-4 dpa/s
Ni	JANNuS Saclay Japet Ni2+ 5MeV	450°C	**Intermediate** 6.10-5 dpa/s
Ni	JANNuS Saclay Epiméthée Fe9+ 22,5MeV	450°C	**Low** 6,7.10-6 dpa/s
Ni 0,8 Ti	JANNuS Orsay ARAMIS Ni2+ 2MeV	450°C 510°C ; 560°C	**High** 3,1-3,5.10-4 dpa/s

Iradina:

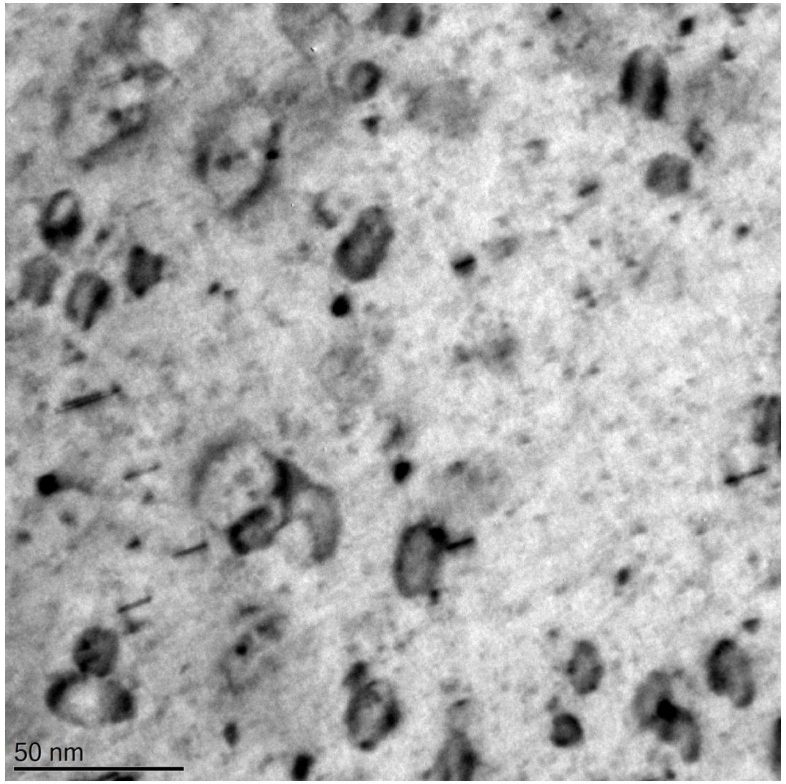
- SRIM like, quick calculation, $E_{displacement}$ = 40 eV

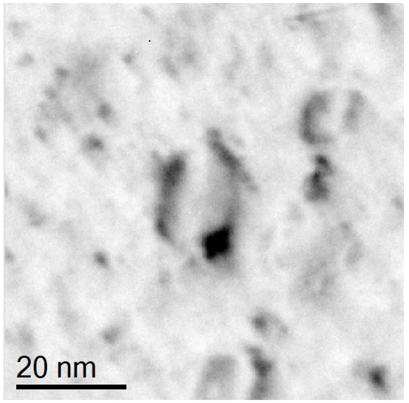
1. Influence of flux

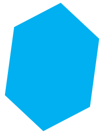
High flux

Ions = Ni^{2+} 2MeV (JANNuS Orsay)
Ion flux = 4e11 ions/cm^2/s ⬄ **G = 3.10^{-4} dpa/s**
T = 450°C
Dose = 0.18 dpa

$g = [0\bar{2}0]$







→ Vacancy type loops

↓

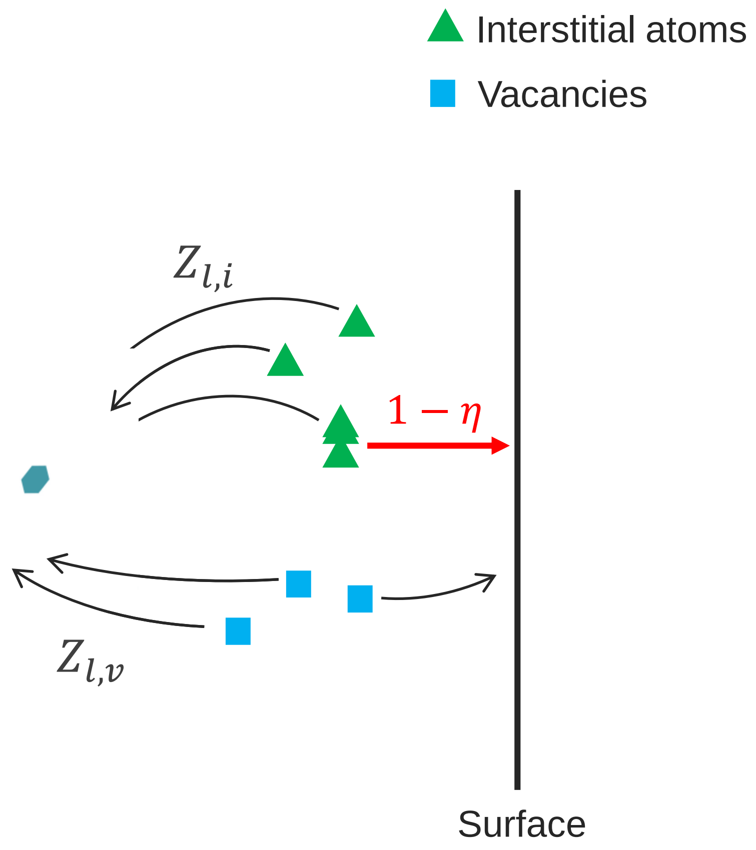
?

High flux

- At steady state, **standard rate theory** predicts a radius variation of a vacancy loop :

$$\frac{dR}{dt} = \frac{\Omega}{b}\left(Z_{l,v} - Z_{l,i}\frac{k_v^2}{k_i^2}\right)D_v C_v \ \mathbf{< 0}$$

  - **Vacancy-type loops should not grow**



- Introduction of production bias $\mathbf{1-\eta}$ (surface effect)

$$\frac{dR}{dt} = \boxed{\frac{\Omega}{b}\left(Z_{l,v} - Z_{l,i}\frac{k_v^2}{k_i^2}\right)D_v C_v} + \boxed{\frac{\Omega}{b}\frac{Z_{l,i}}{k_i^2}\boldsymbol{G}(\mathbf{1-\eta})}$$

Dislocation bias term < 0 | Production bias term > 0

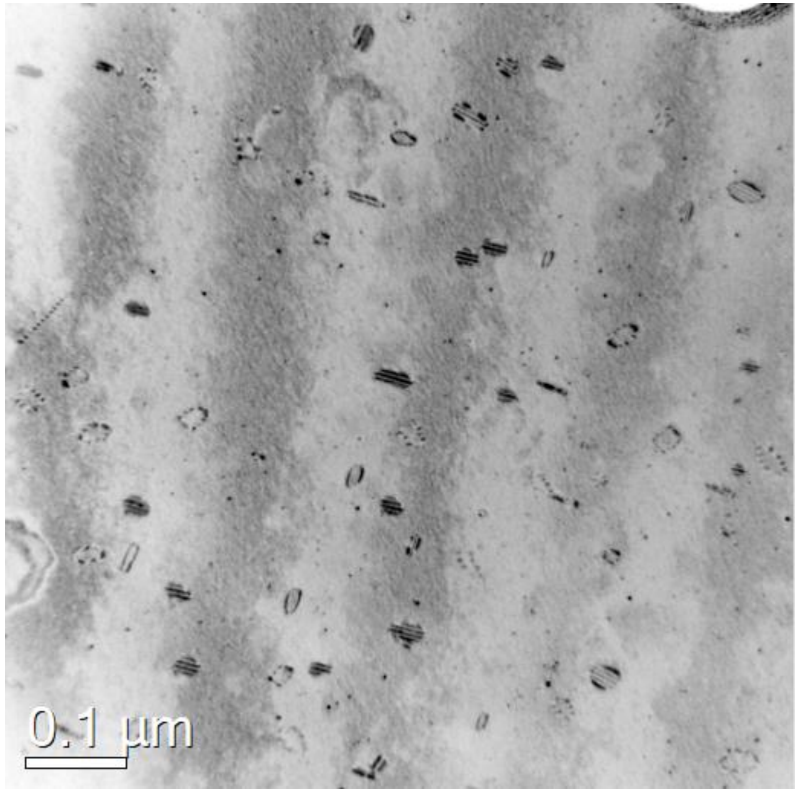
$$\frac{dR}{dt} > \mathbf{0}$$

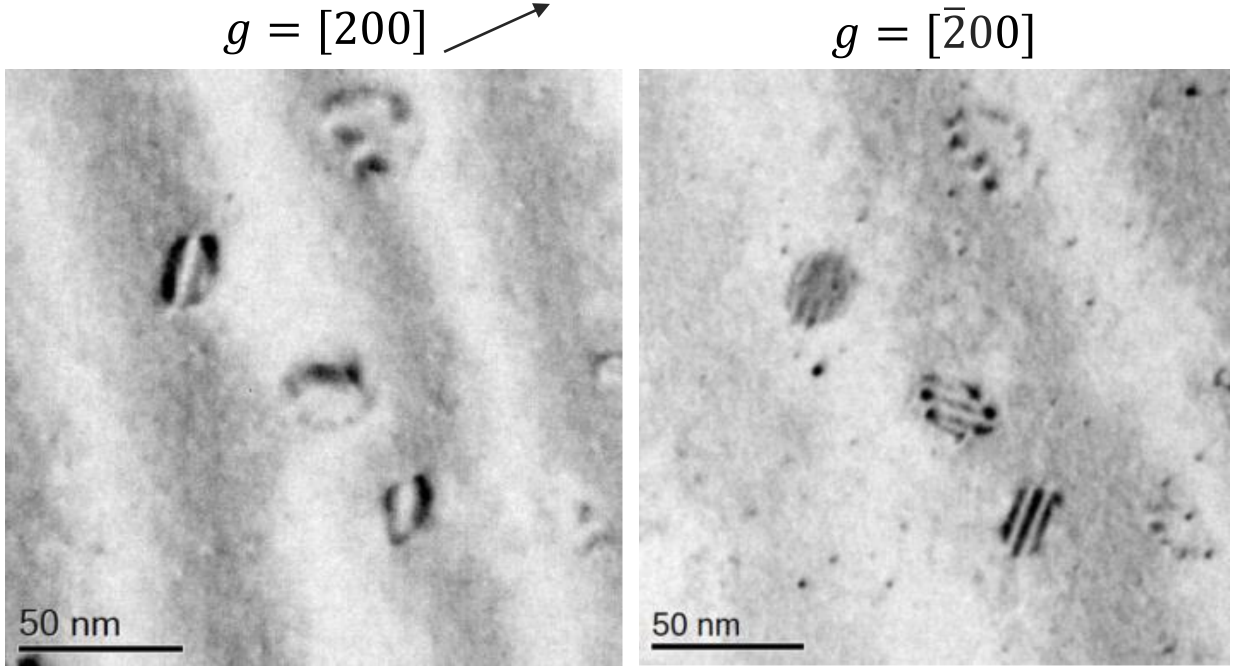
*K. Ma, B. Décamps, T. Jourdan, M. Loyer-Prost & al., Acta Materialia 212 (2021)**

** https://doi.org/10.1016/j.actamat.2021.116874*

Low flux

Ions = Fe^{9+} 22,5 MeV (JANNuS Saclay)
Ion flux = 7.93e10 ions/cm^2/s ⇔ **G = 6,7.10^{-6} dpa/s**
T = 450°C
Dose = 0.06 dpa



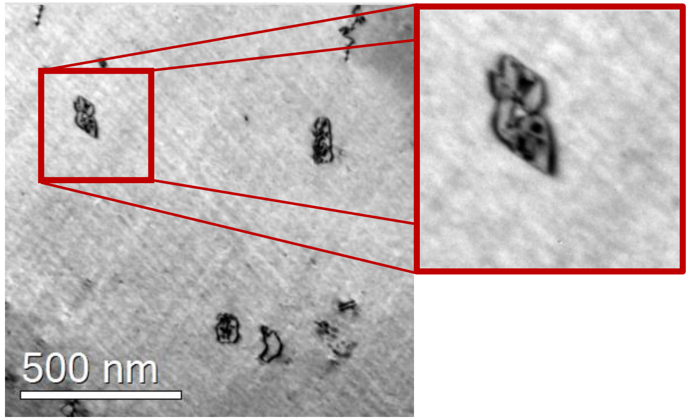


→ Interstitial type loops

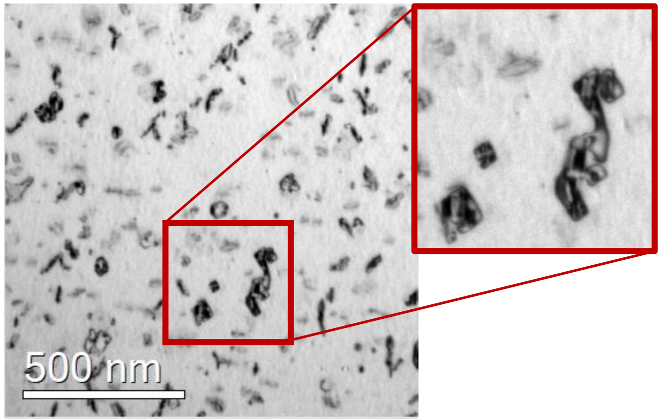
Intermediate flux

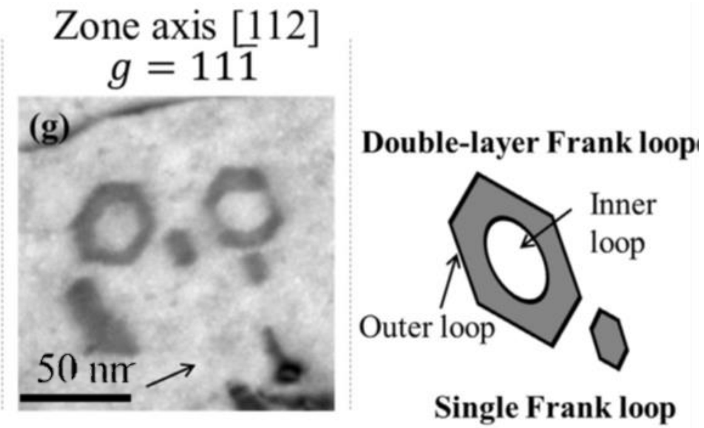
Ions = Ni^{2+} 5MeV (JANNuS Saclay)
Ion flux = 2.2e11 ions/cm^2/s ⇔ **G = 6.10^{-5} dpa/s**
T = 450°C

Dose = 0.06 dpa



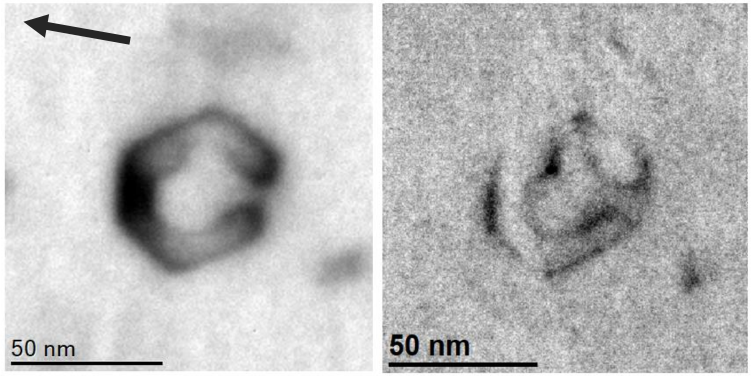
Dose = 0.7 dpa



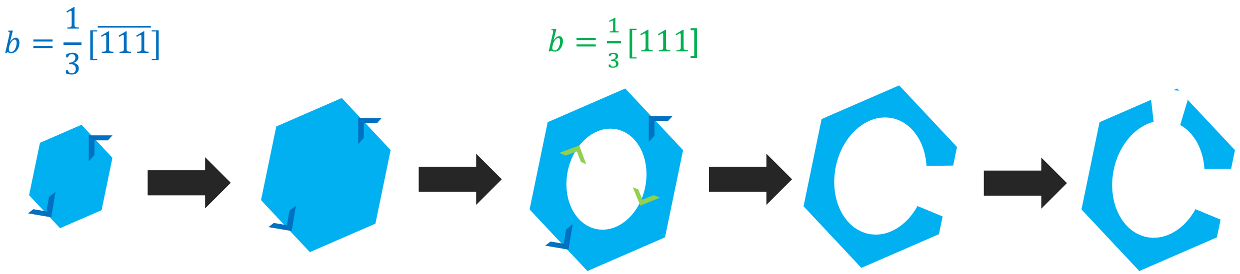


K. Ma & al., Inversion of dislocation loop nature driven by cluster migration in self-ion irradiated nickel. Scripta Materialia 208 (2022).

$Z = [121], g = [1\bar{1}1]$



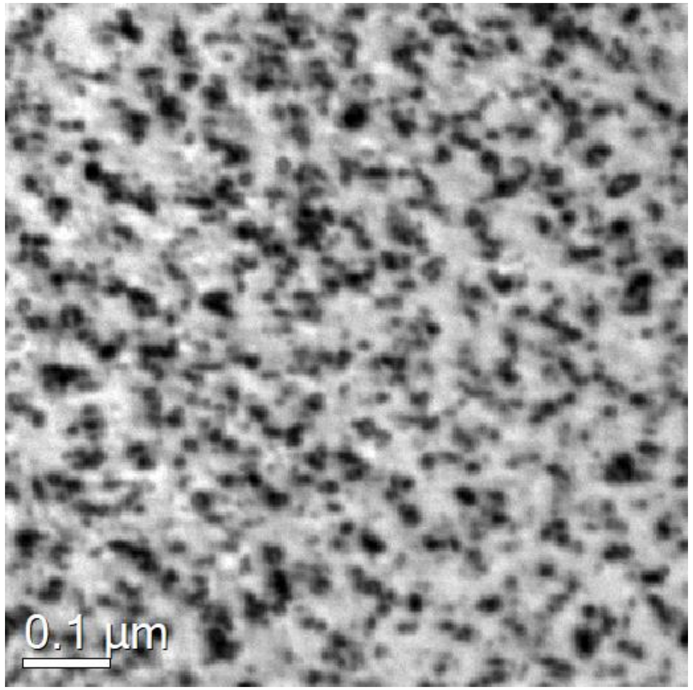
→ Vacancy type loop



To sum up

0.06 dpa, 450°C

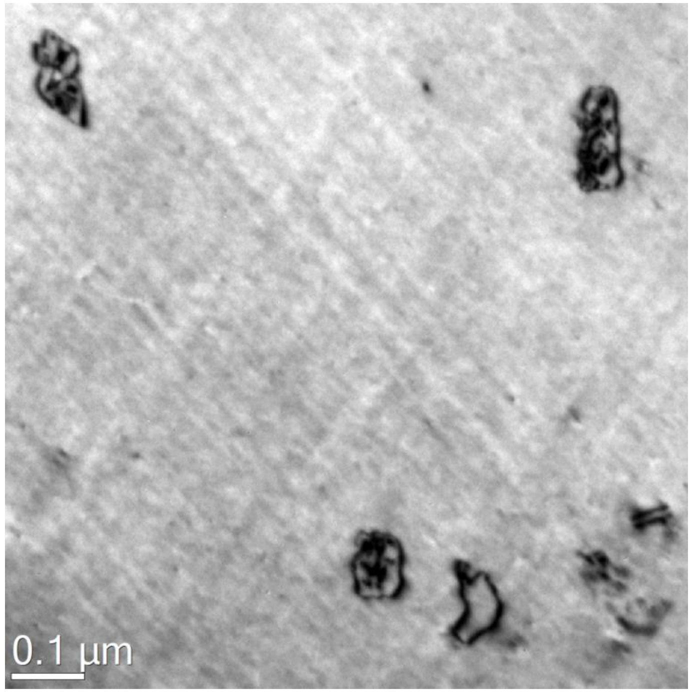
High flux
3.10^{-4} dpa/s



t ~ 200 nm

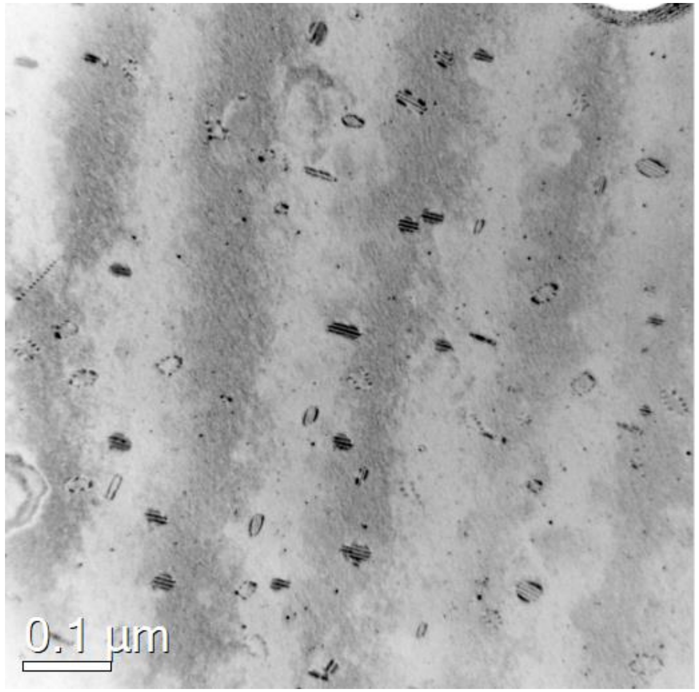
Vacancy type

Intermediate flux
6.10^{-5} dpa/s



t ~ 200 nm

Low flux
6.7x10^{-6} dpa/s



t ~ 80 nm

Interstitial type

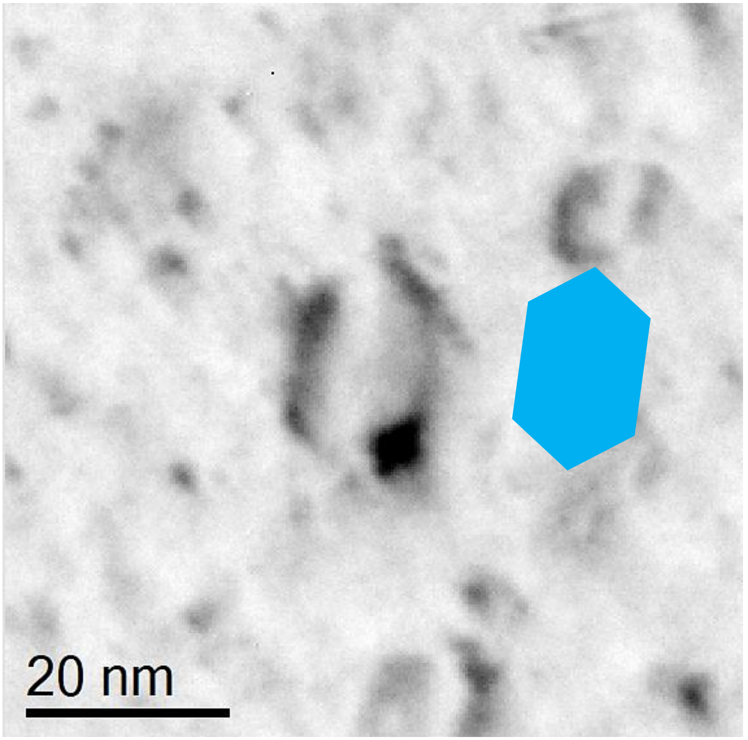
2. Influence of composition

Influence of composition

Ions = Ni^{2+} 2MeV (JANNuS Orsay)
Ion flux = 4e11 ions/cm²/s ⇔ G = 3.10^{-4} dpa/s
T = 450°C

Ni

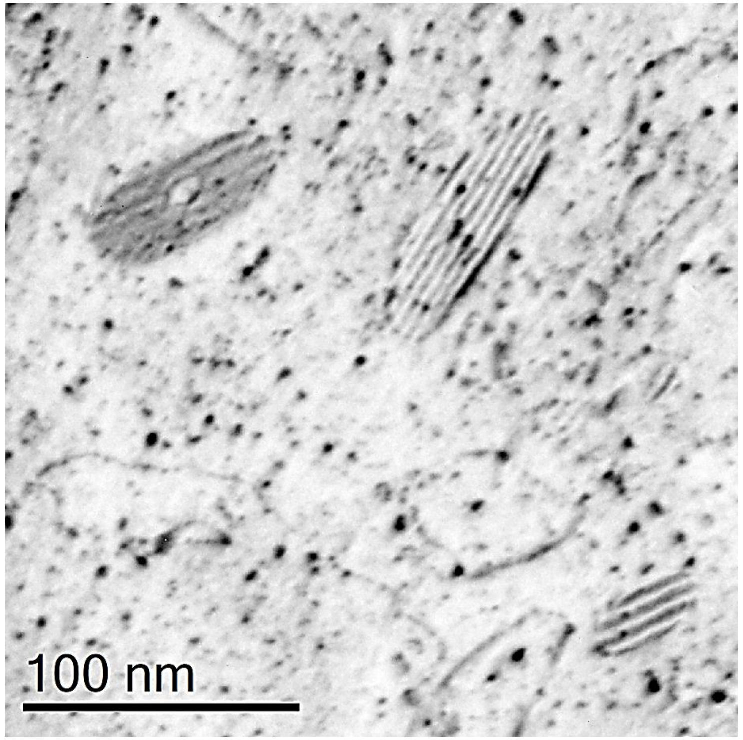
0,18 dpa

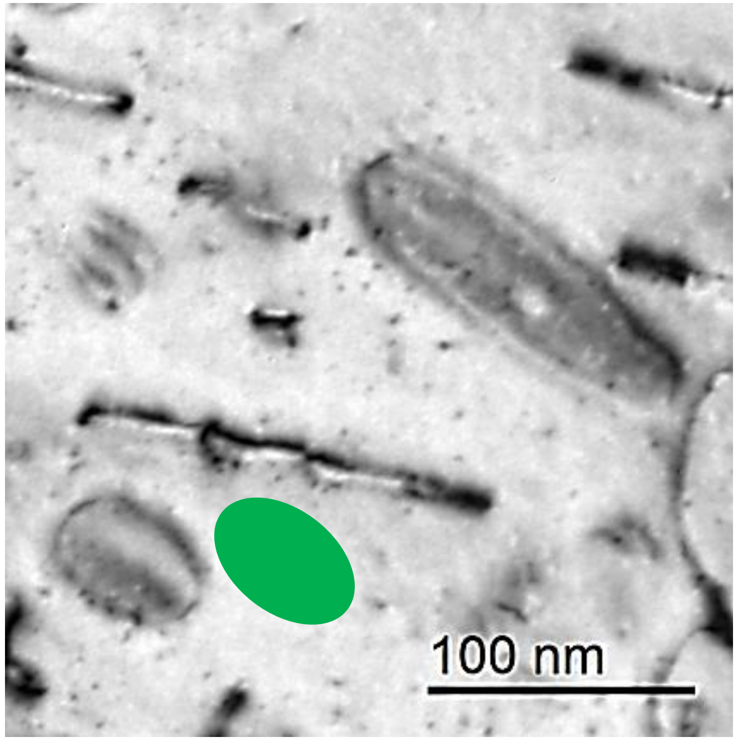


→ Vacancy type loops

Ni0,8Ti

0,66 dpa



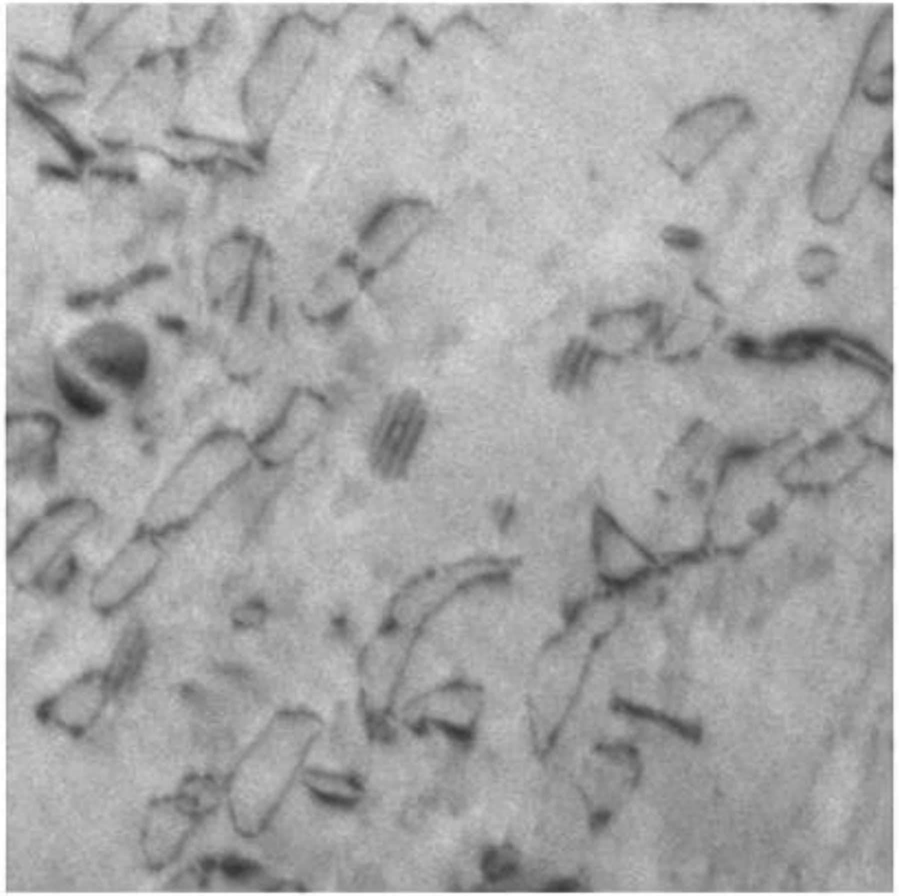


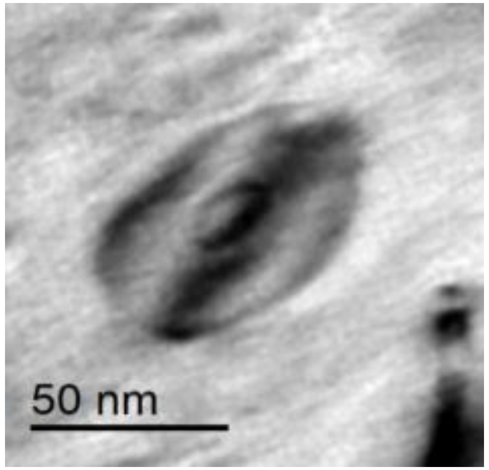
→ Interstitial type loops

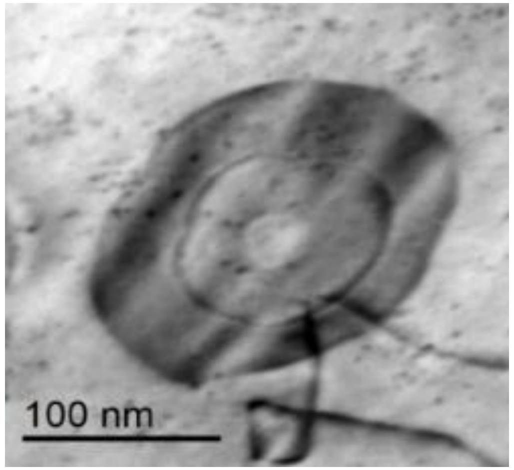
→ 1- η lower in Ni0,8Ti

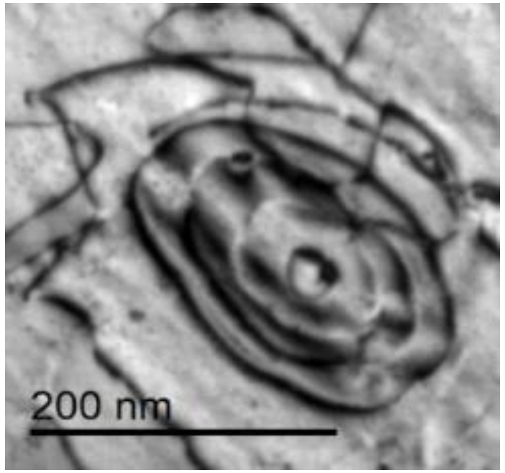
Multi-layer loops

560°C









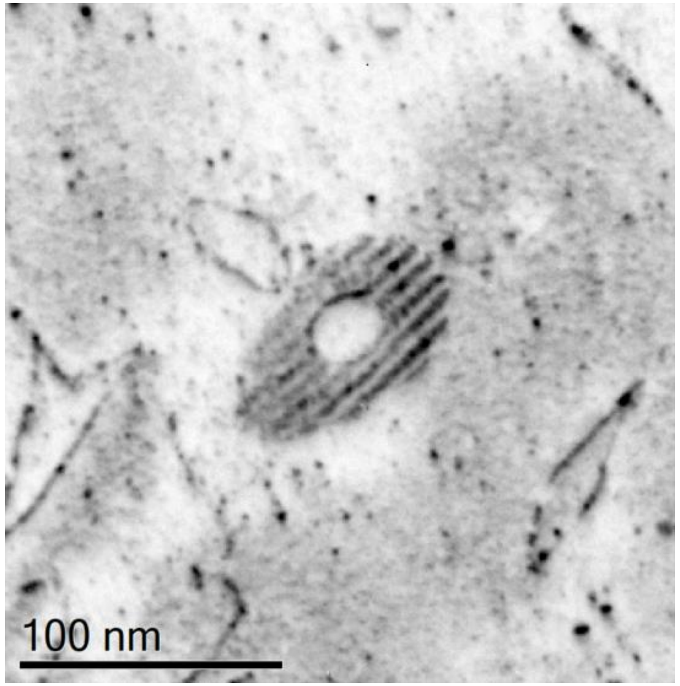
→ Very close to each other

→ Same Burgers

Frank loop with perfect crystal inside

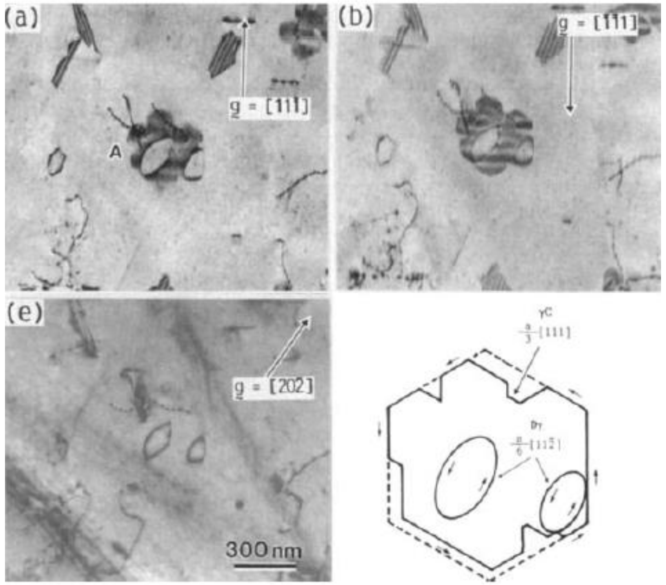
↳ faulted/unfaulted

510°C

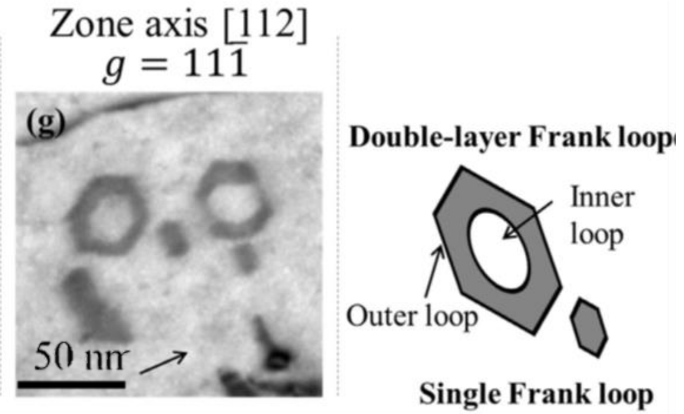


→ Shockley partial ?

→ Inner vacancy loop ?



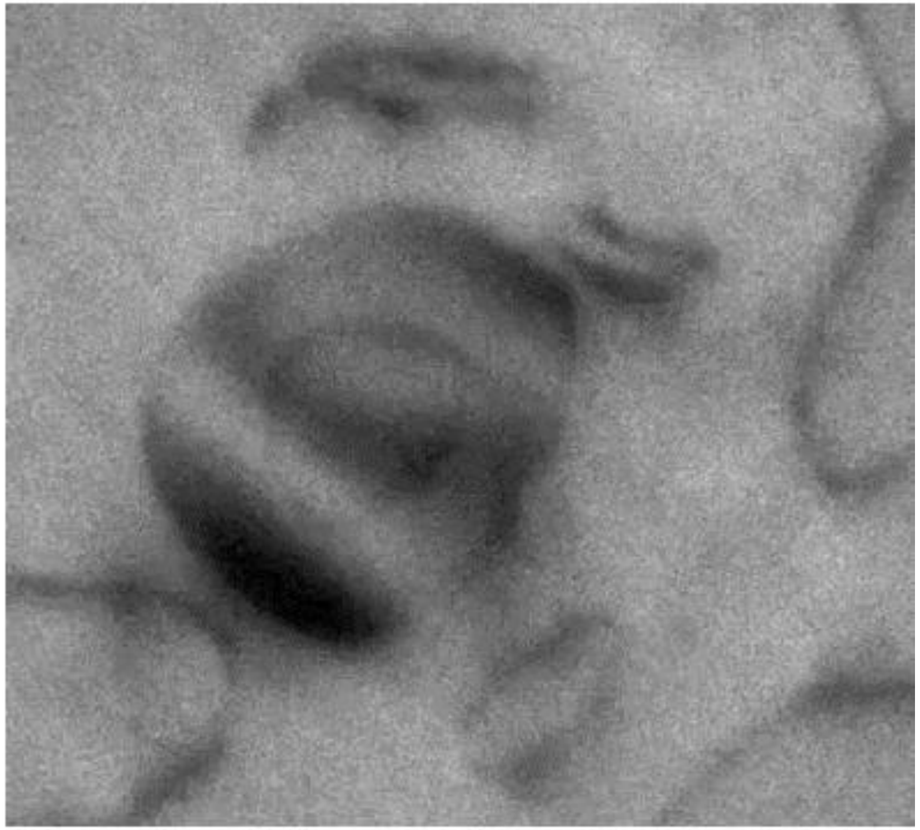
Suzuki et al., Philosophical Magazine A (1992) 1309

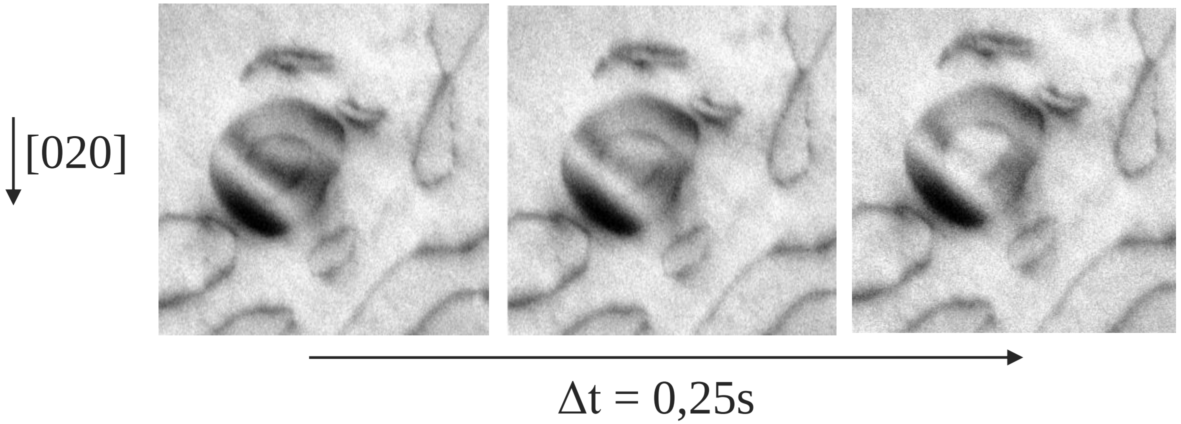


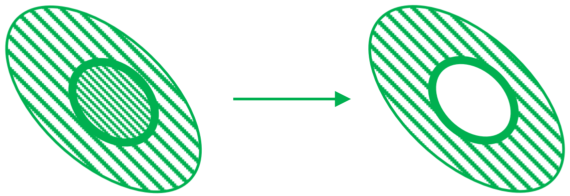
K. Ma & al.,Scripta Materialia 208 (2022).

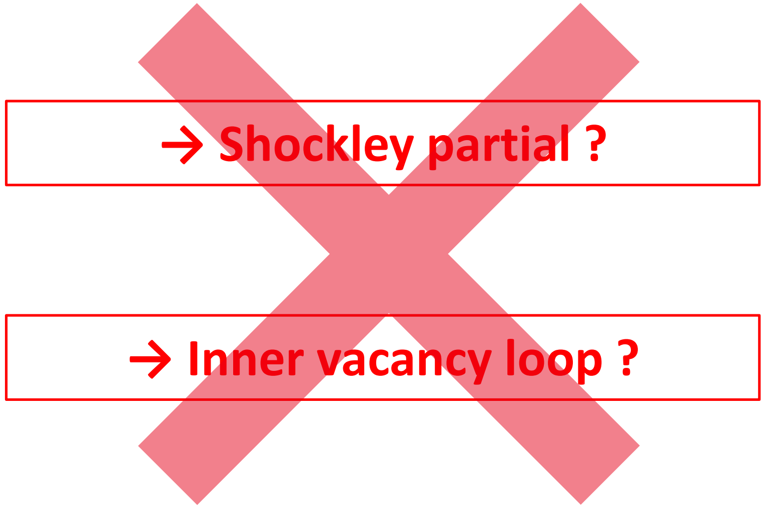
Frank loop with perfect crystal inside

560°C

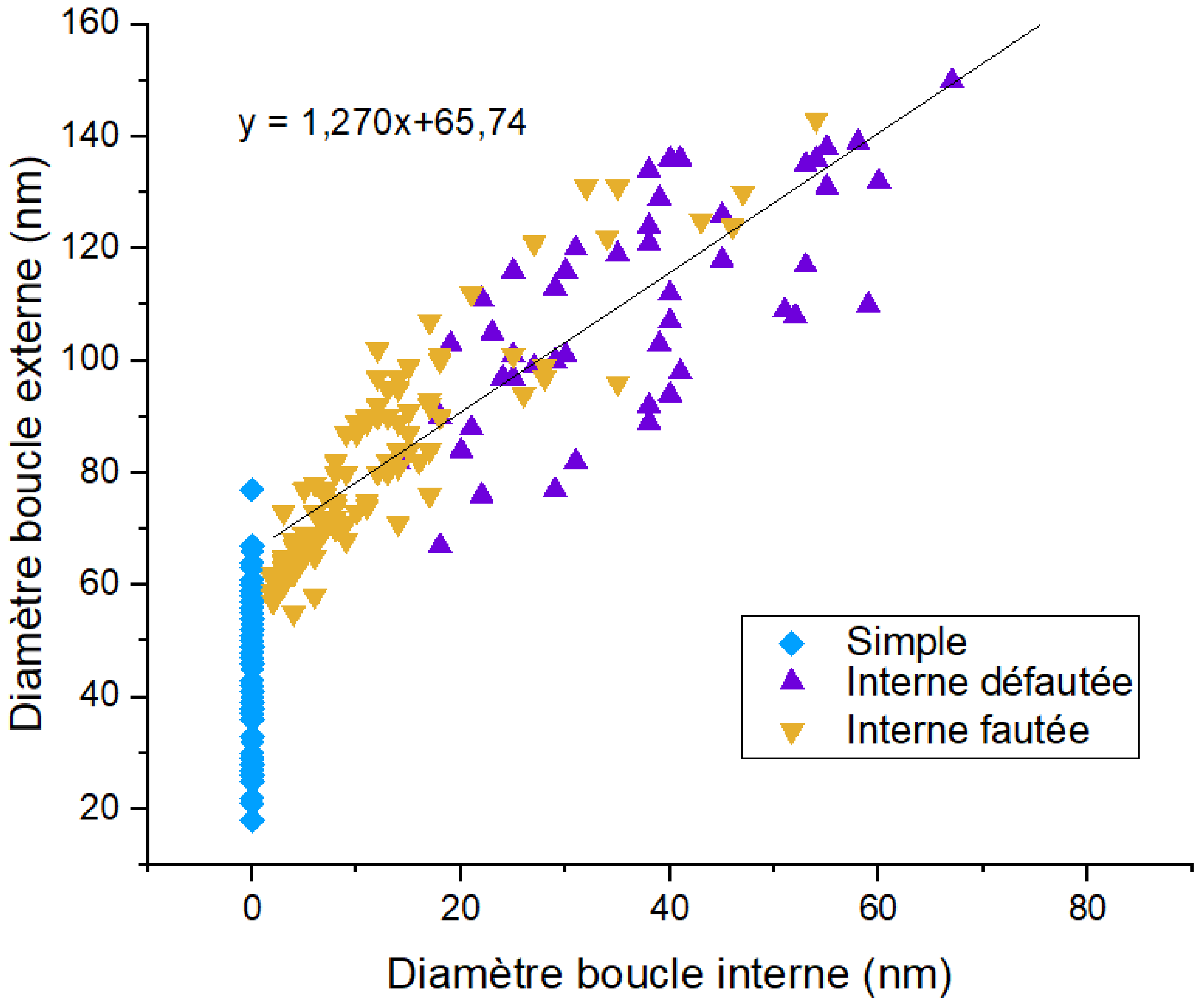








Frank loop with perfect crystal inside

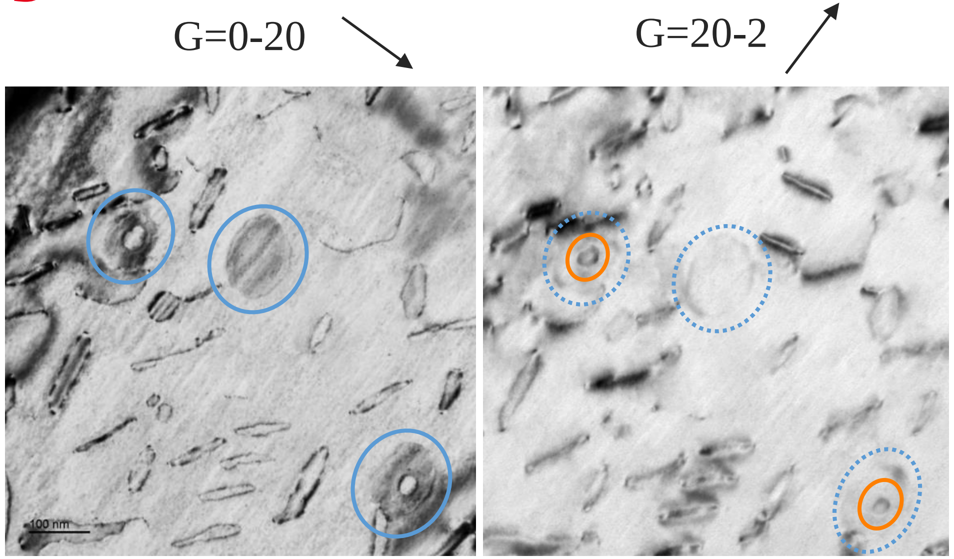


Frank loop with perfect crystal inside

Visibility of external and internal loops (560°C)

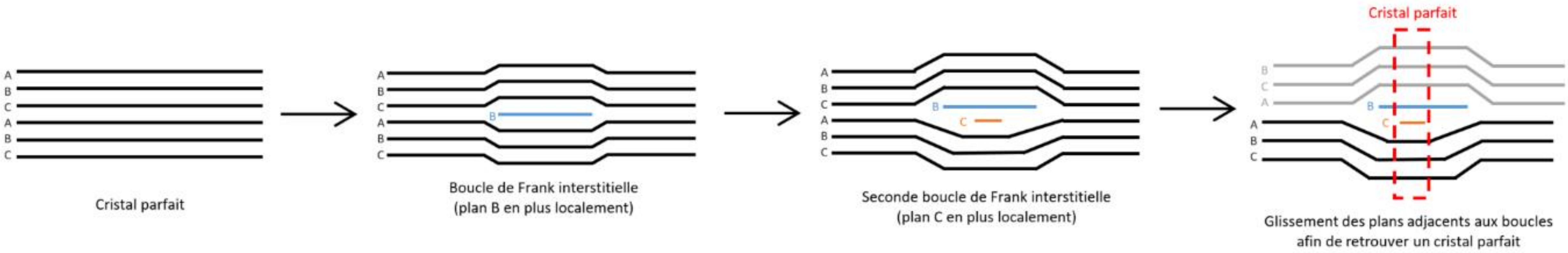
→ internal loop Burger vector = 1/a[1-12]

2/3[1-11] + **1/6[-112]** = ½[1-12]



1/3[1-11]

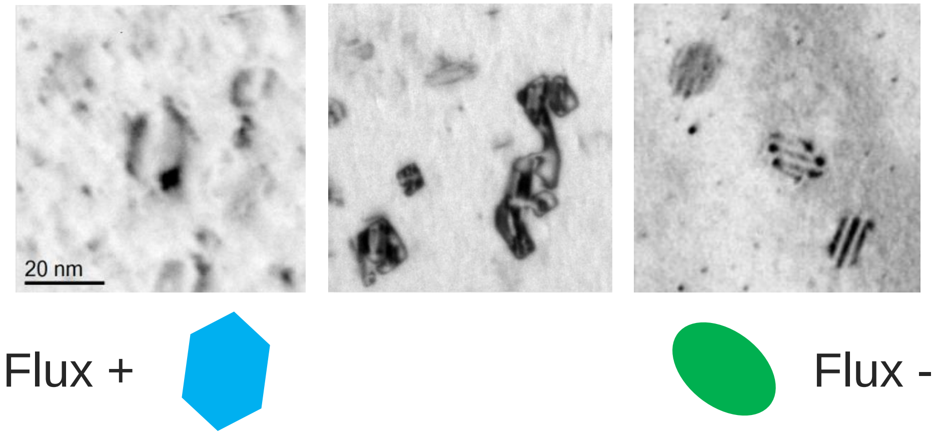
Mechanism of internal loop unfaulting by Shockley partial



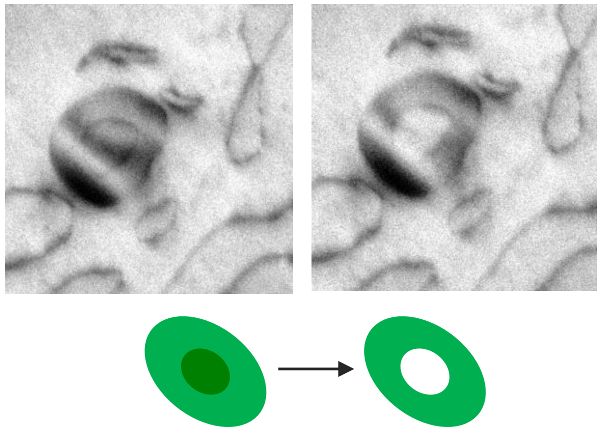
3. Conclusion

Conclusion

- Flux variation can change loop's nature
- Complex microstructure for intermediate flux
- Relation between shape and nature's loop for Frank loop



- Titanium significantly reduces interstitial losses at surfaces
- Multiple loops can unfault partially, becoming faulted/unfaulted



Prospects

- Further study on multiple loops

- Removal of temporal variation of the flux : effect of defocused beam

Thank you

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