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The Surrey Ion Beam Centre

# Ion Irradiation Facilities


## Roger Webb

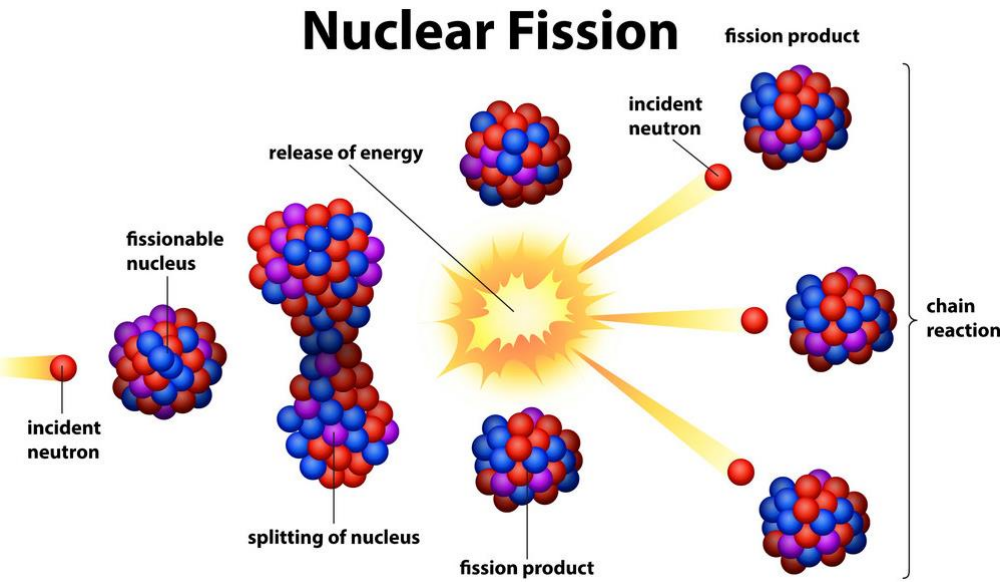
## UK National Ion Beam Centre,

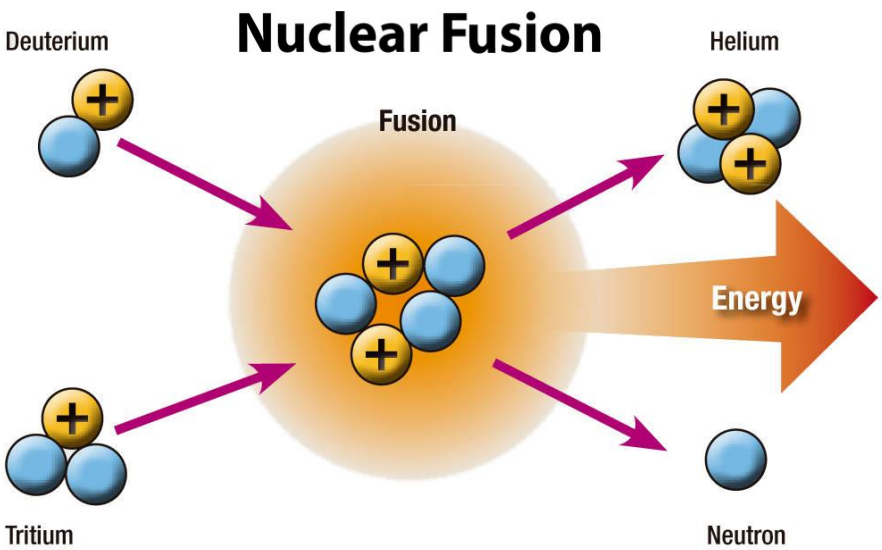
## Universities of Surrey, Manchester & Huddersfield


Tuesday, 18 December 2018

# Contents

# Neutrons are a product of Nuclear Energy

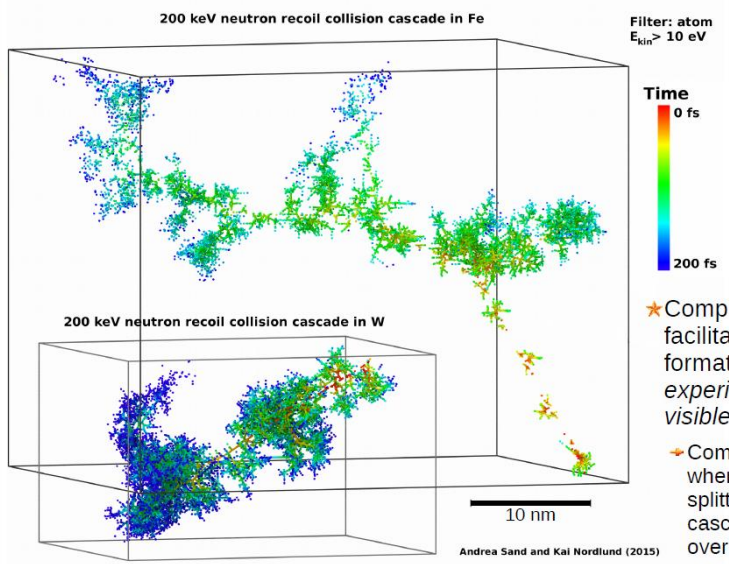



**Fission neutrons have a mean energy <3MeV**

**Fusion neutrons have a mean energy <14MeV**

# Collision cascades: W vs. Fe




- Compact cascades facilitate in-cascade formation of large, *experimentally visible* defects in W
  - Compare to Fe, where subcascade splitting disperses cascade energy over a wider area

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI
Faculty of Science
Department of Physics
Andrea Sand
www.helsinki.fi/yliopisto
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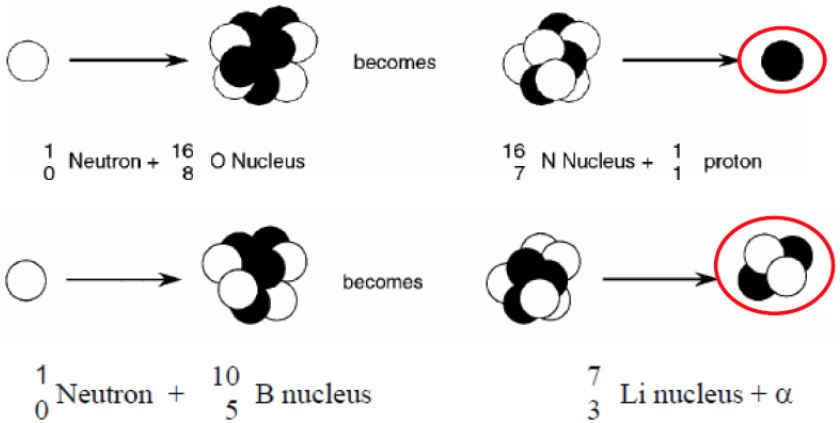
## Transmutation from (n,p) and (n,α) reactions




- **Neutron irradiation causes substantial displacement damage.**
- **Transmutation results in production of H and He particles.**
- **Structural materials often operate at high temperatures >1000°C**
- **High Fluences over time:**
  - **high damage (~200dpa)**
  - **up to 2,000 ppm He**
  - **up to 10,000 ppm H**

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**Some currently available reactor facilities used for materials testing**

mixed-spectrum reactors

fast reactors

**Fast reactor can reach 20-30 dpa per year**

| Facility | Country | Fast Flux $E_n$>0.1 MeV ($10^{18}/m^2s$) | Displacement damage in steel (dpa/yr) | Useful vol ($cm^3$) | Temp Range (°C) | Comments |
|---|---|---|---|---|---|---|
| BR2<br>Core<br>Reflector | Germany | <br>1.5–3.0<br>0.05–1.0 | <br><3/yr<br><1/yr | <br>90<br>250 | <br>50–1000<br>50–1000 | • ~105 days/yr<br>• Caps ϕ: 50–200 mm<br>• In-situ fatigue rigs |
| OSIRIS | France | 2.5 | few/yr | 230 | 50–1000 | |
| HFR<br>Core (C5) | Nether-lands | 2.5 | <7/yr | 1540 | 80–1100 | • 275 days/yr<br>• In situ experiments |
| ATR<br>A and H,<br>B,<br>I-positions<br>Flux traps | U.S. | <br>2.3<br>0.8<br>0.03<br>2.2 | <br>6–10/yr<br>6–8/yr | <br>240<br>1390<br>5560<br>5560 | <br>50–>1500<br><br><br>▪ | • Caps ϕ: <127 mm<br>• Large irrad. volume<br>• Versatile facility |
| HFIR<br>Tgt Pos 37<br>RB pos 8 | U.S. | <br>11<br>5.3 | <br>18/yr<br>5–7/yr | <br>100<br>720 | <br><br>300–1500 | • Very high peak flux<br>• Accelerated testing in smaller volumes |
| JOYO | Japan | 5.7 | ~30/yr | | 300–700 | • Temp. control +4 K<br>• 300 days/yr |
| BN600 | Russia | 6.5 | 20-52 | 350 | 375–750+ | • Very-high dose rate<br>• Only passive instrumentation |
| BOR-60 | Russia | 3.0 | ~20 | 358 | 300–700+ | • Only passive instrumentation<br>• High level PIE |

**Displacement rates not high enough in research reactors for long term testing.**

Heavy Ion irradiation facilities are often used to emulate long term irradiation damage.

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# IAEA Accelerator Database

< 6MV

- 219 Electrostatic Accelerators - 166 Facilities World Wide


Clearly not all are available for ion irradiation experiments, but many are.

BUT, also need to take into account:

**Synergistic Effects**

In simultaneous irradiation of Fe, H and He there is a synergistic effect.

Need for multiple beams – dual and triple.

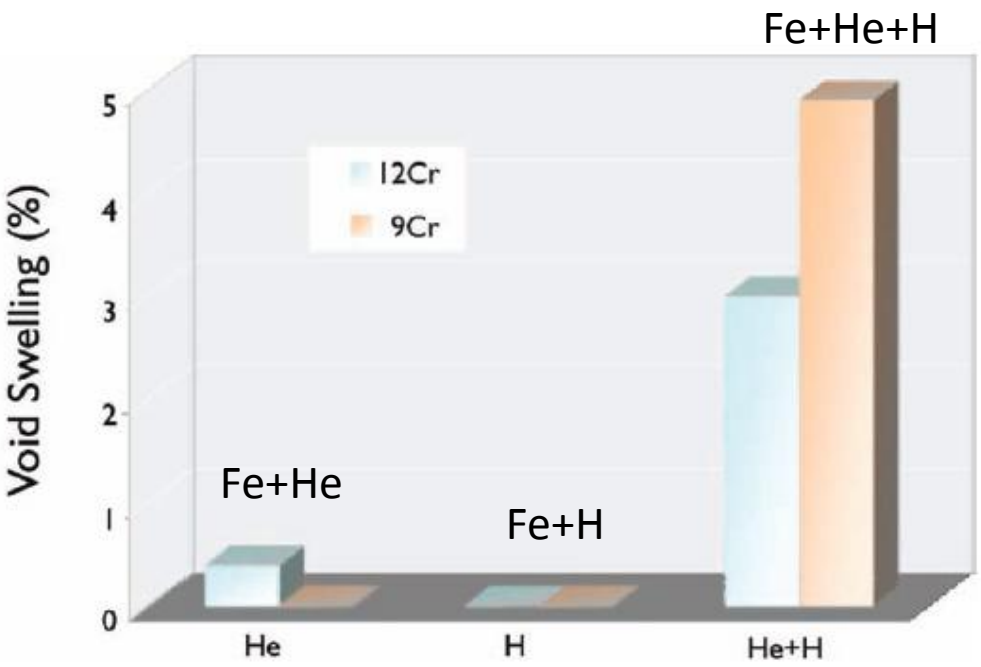



Figure 1. The synergistic effect of He and H was shown clearly in the triple ion ($Fe^{3+}$ + $He^{+}$ + $H^{+}$) irradiation of an FeCr steel.[3]

# DUAL beam Facilities

| Laboratory | Facility 1 | Facility 2 |
|---|---|---|
| MSD, IGCAR, India | 1.7MV Tandem | 30-150keV Implanter |
| HIT, Tokyo, Japan | 3.75MV V de G | 1MV Tandem |
| DNE, Nagoya University, Japan | 2MV V de G | 200kV implanter |
| HZDR, Rossendorf, Germany | 3MV Tandem | 500kV implanter |
| FSU, Jena, Germany | 3MV Tandem | 400kV implanter |
| LANL, USA | 3MV Tandem | 200kV implanter |
| DCF, Manchester, UK | 5MV Tandem | 1.7MV Single ended |
| RBI, Zagreb, Croatia | 6MV Tandem | 1MV Tandem |
| University of Kyoto, Japan | 1.7MV Tandem | 1MV V de G |

# Triple beam Facilities

| Laboratory | Facility 1 | Facility 2 | Facility 3 |
|---|---|---|---|
| IAEA, Takassaki, TIARA, Japan | 3MV Tandem | 3MV V de G | 400kV implanter |
| Jannus, Saclay | 3MV Pelletron | 2.5MV V de G | 2.25MV Tandem |
| Kharkov Inst of Physics, Ukraine | 2MV ESU | 50kV protons | 50kV helium |
| National Tsing Hua Univ, Taipei | 500kV implanter | 2MV Tandem | 1MV V de G |
| Oak Ridge National Lab, USA? | 5MV V de G | 2.5 MV V de G | 400kV V de G |
| Lawrence Livermore, USA? | 10MV Tandem | 2MV Tandem | 1 MV Tandem |

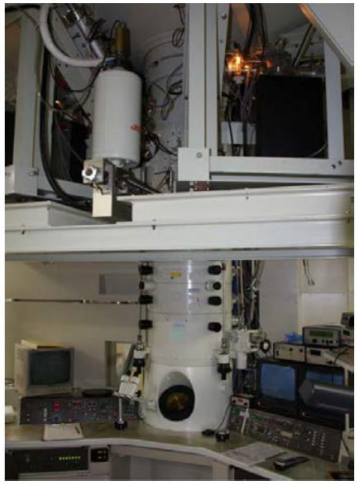
# In-situ TEM / ion accelerator facilities

Kyushu, Japan

Argonne, USA

Hokkaido, Japan

Tsukuba, Japan

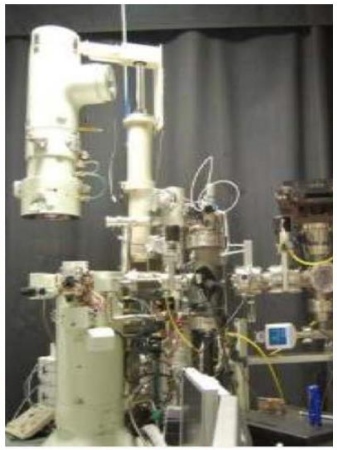


Shimane, Japan

Huddersfield, UK


Orsay, France

Wuhan, China



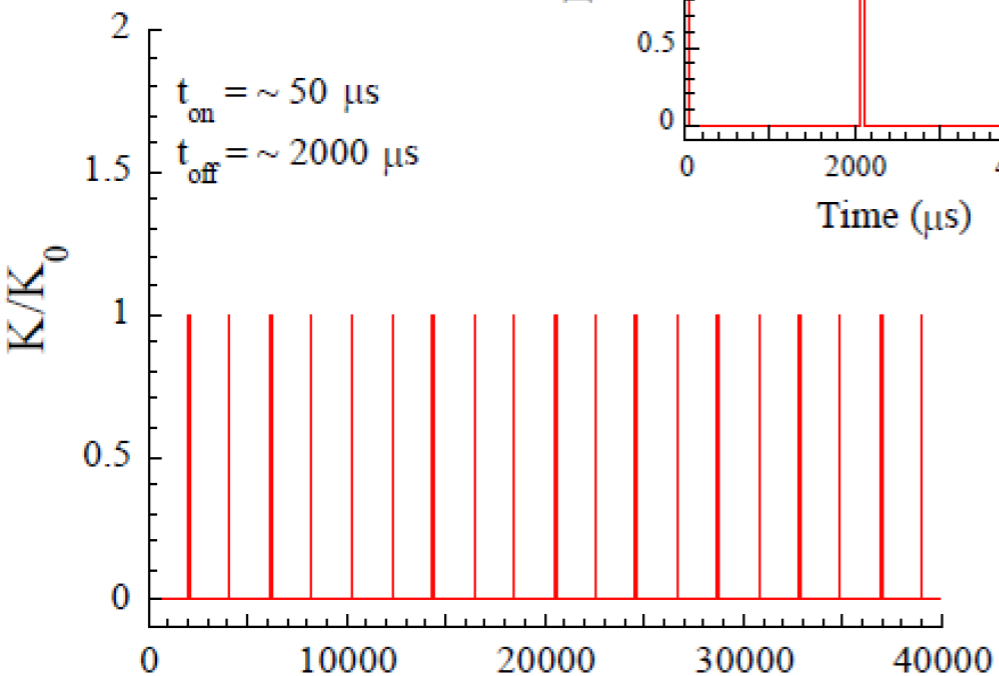
Sandia.USA

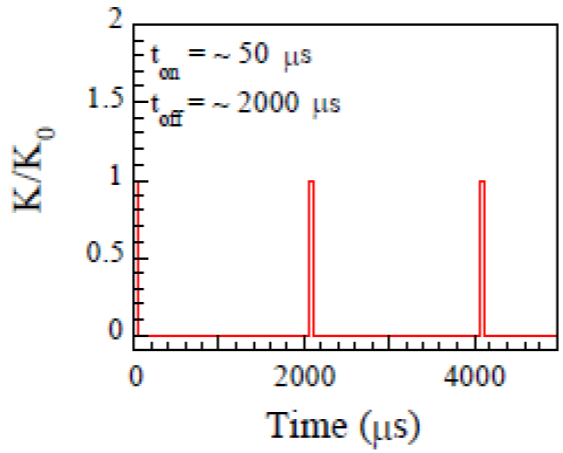
Shao & Garner et al – Texas A&M

# Rastering (beam sweeping) is not suitable to simulate non-pulsed neutron irradiation.

**rastered at**
**255 Hz horizontally**
**2061 Hz vertically**

**Duty factor of 2.5%**




**ASTM E521-83. Standard Practice for Neutron Radiatio Damage Simulation by Charged-Particle Irradiation**

**"It is recommended that a rastered beam be avoided fo the simulation of a constant neutron flux."**

Shao & Garner et al – Texas A&M

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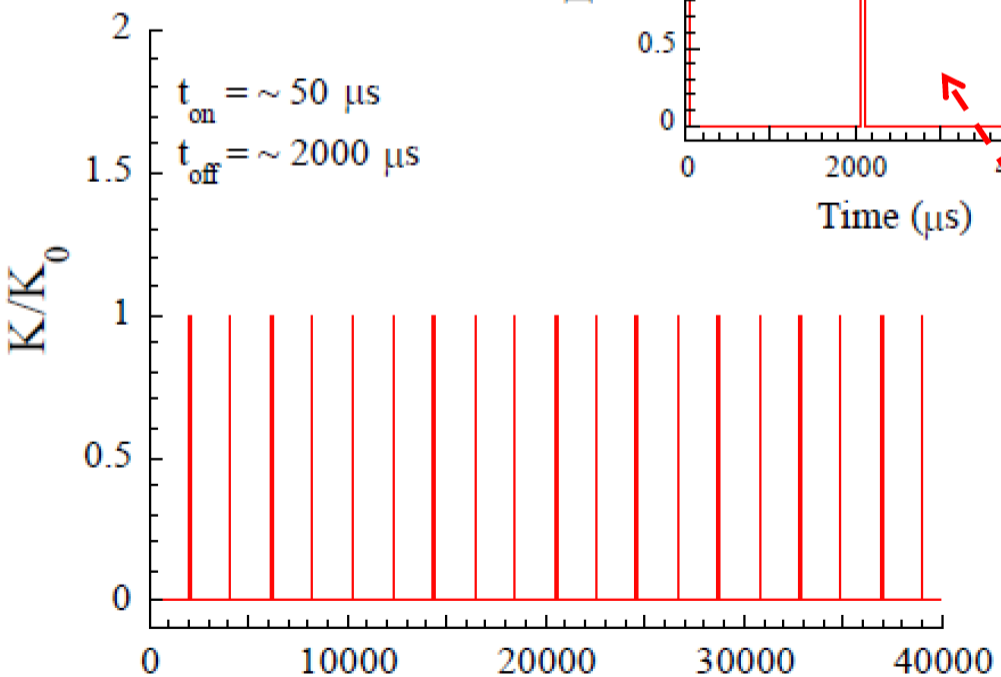


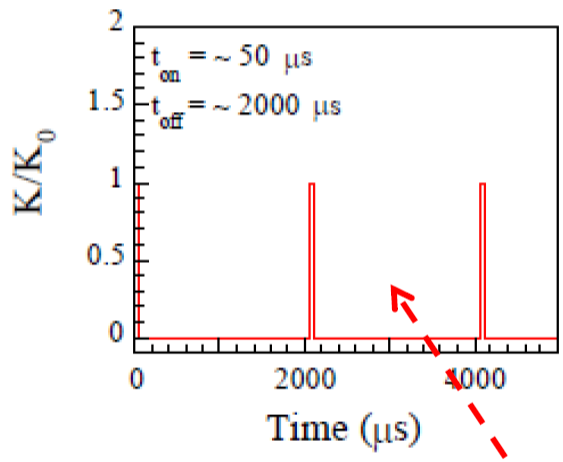


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**Void nuclei tend to dissolv during the between-pulse periods.**

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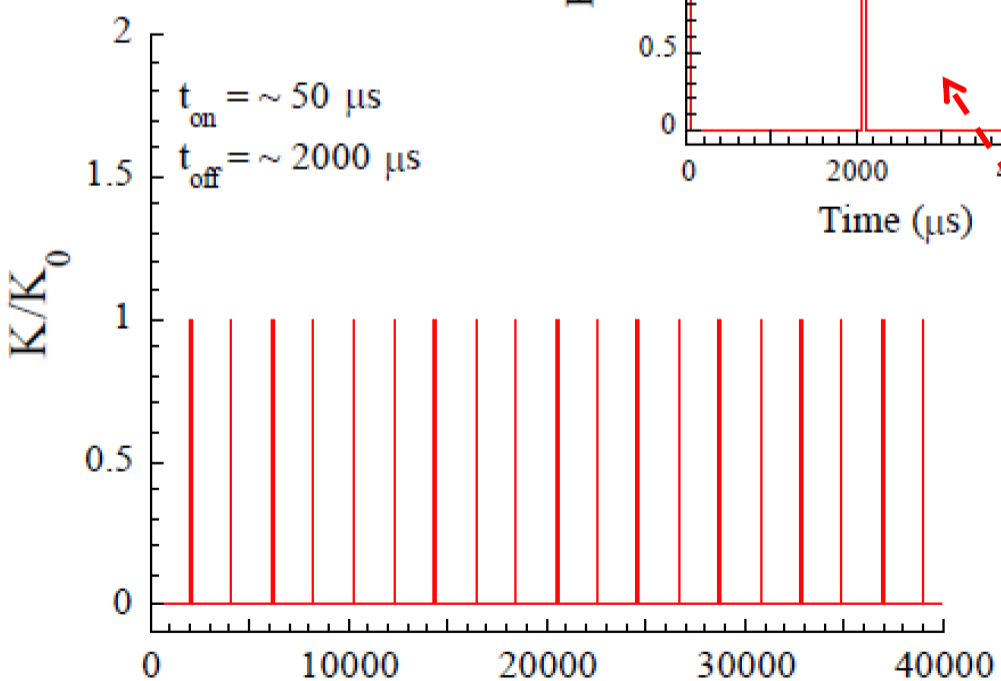


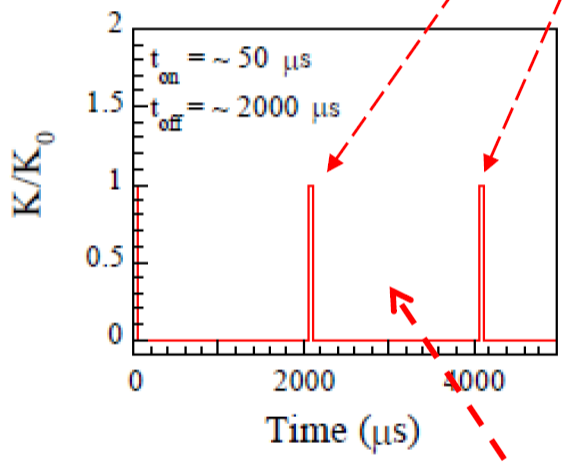


**At 40 times the average dpa rate, the injected interstitial suppression effect will be supercharged, suppressing void nucleation during the beam-on period.**

**ASTM E521-83. Standard Practice for Neutron Radiatio Damage Simulation by Charged-Particle Irradiation**

**"It is recommended that a rastered beam be avoided fo the simulation of a constant neutron flux."**

**Void nuclei tend to dissolv during the between-pulse periods.**

**See papers by Getto and**

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# The UK National Ion Beam Centre

## Bringing together 3 ion beam facilities in the UK

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Ion Beam Centre

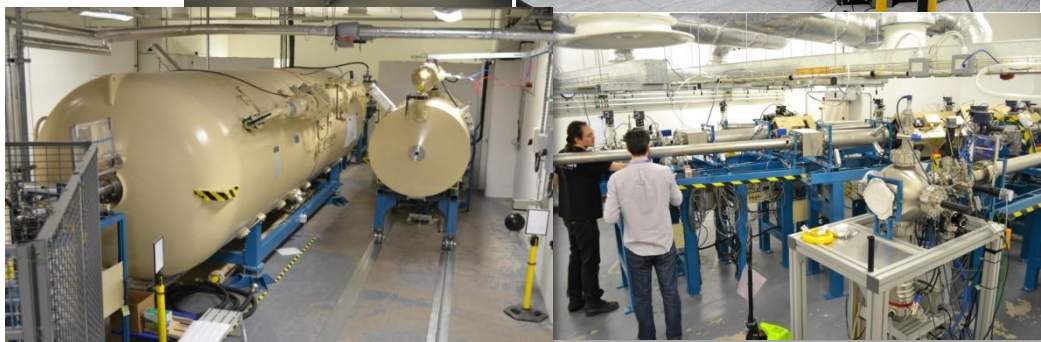
Surrey Ion Beam Centre

University of HUDDERSFIELD
Inspiring tomorrow's professionals

MIAMI dual beam in-situ TEM
and
MEIS Facilities

MANCHESTER 1824
The University of Manchester

Dalton Cumbrian Facility



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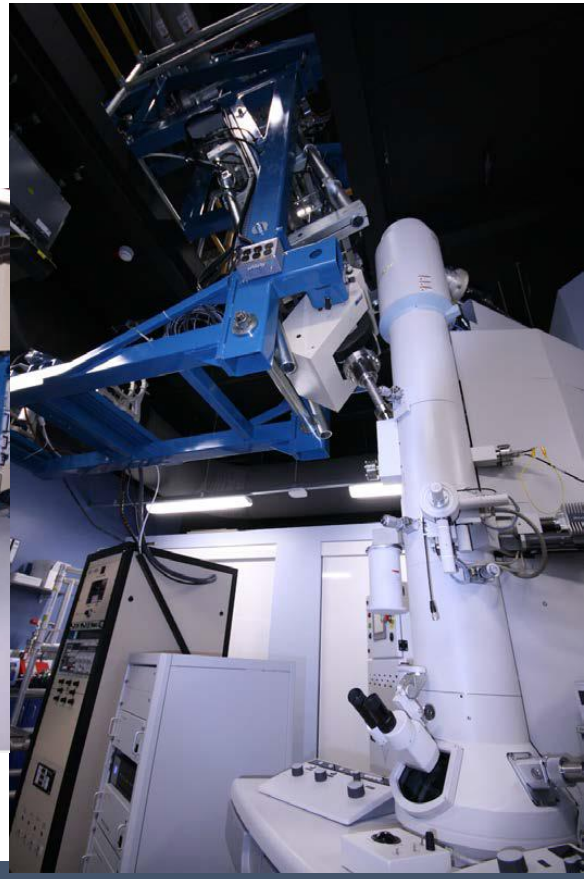
# Huddersfield MIAMI Facility



## Implanter with In situ TEM

- **Facilities**
  - JOEL 2000FX TEM
  - 2-100keV Implanter
  - Temperature stage -173-1000$^{o}$C
  - Dual beam arrangement
- **Applications**
  - Nuclear Radiation damage
  - Ion Implantation
- **Staff**
  - Steve Donnelly
  - Johnathan Hinks
  - Graeme Greaves

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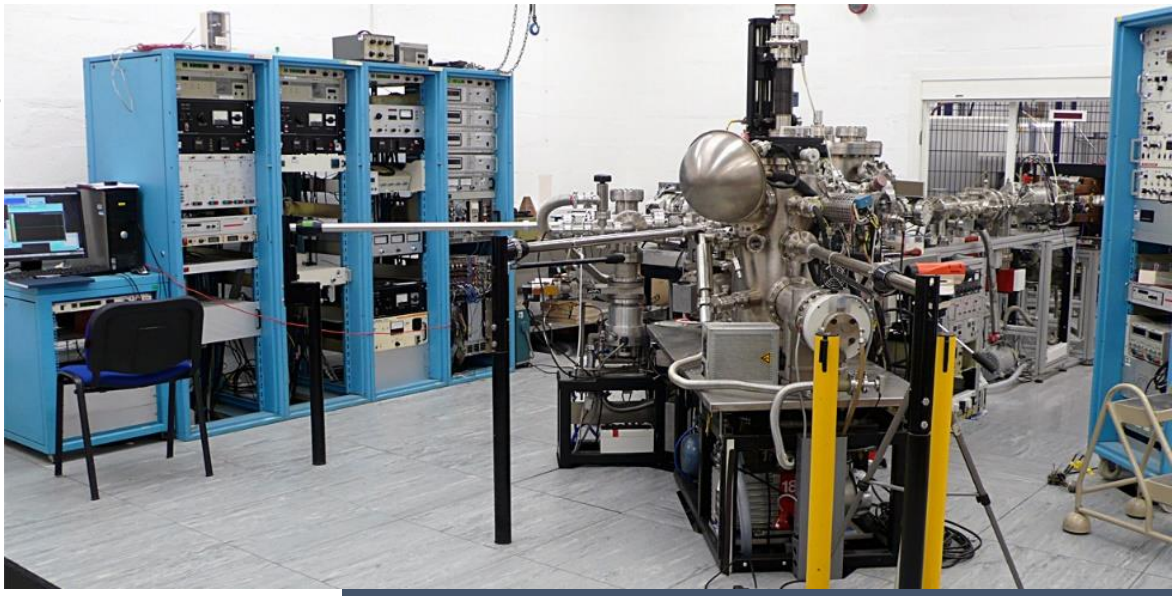

**Medium Energy Ion Scattering**

- **Facilities**
  - 50-200keV Accelerator
  - LEED Auger
  - Temp range 300-1300K
- **Applications**
  - High Resolution Depth Profiling
  - Channelling for damage studies
- **Staff**
  - Jaap Van Den Berg

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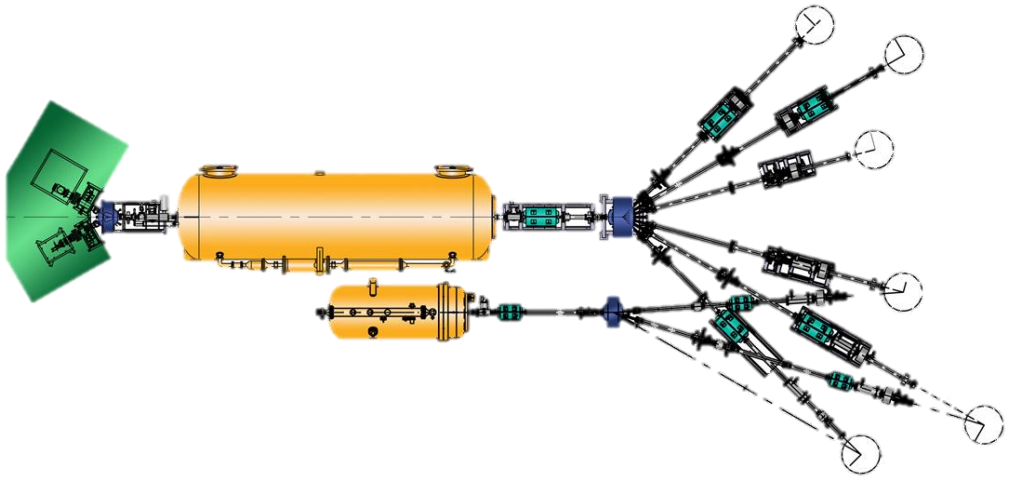
# Manchester Dalton Institute

**Cumbrian Nuclear User Facility**

- **Facilities**
  - 5 MV Tandem – 10MeV $^{1}H^{+}$ up to 100µA;
    15 MeV $^{4}H^{2+}$ up to 15µA
    35 MeV $^{12}C^{6+}$ ~150nA
  - 2.5MV single ended for dual beam work (under construction)
- **Applications**
  - Radiation Damage Studies
  - Nuclear Irradiation
- **Staff**
  - Andy Smith
  - Nick Mason



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# Manchester Dalton Institute

## Cumbrian Nuclear User Facility

High beam energy/high beam current experiments

- Beam line “hot cell” to allow higher penetration & higher damage rate studies
- Equipment for the handling, storage & onward transport of activated samples

Ion beam analysis : PIXE, RBS, NRA & ERDA

In-situ measurements : High temperature & pressure corrosion loop, Raman spectroscopy

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# Surrey Ion Beam Centre

- **Controllable Materials Modification**
  - 0.4-2MV High Energy Implanter
  - 2-200kV High Current Implanter
  - Implantation 2keV⇒4MeV (up to 10mA)
  - Sample size $mm^2$ to 40cmx40cm
  - Hot (700°C) or cold (~10K)
  - Sample Chambers in class 100 clean room

**Available Implanted Species**

- 2 - 2000kV
- Not Available
- Call

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | | | | | | | | | | | | | | | | | He |
| Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| Na | Mg | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |
| Cs | Ba | Lu | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | Po | At | Rn |
| Fr | Ra | Lr | Rf | Db | Sg | Bh | Hs | Mt | Ds | Rg | Cn | Uut | Uuq | Uup | Uuh | Uus | Uuo |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| La | Ce | Pr | Nd | Pm | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |
| Ac | Th | Pa | U | Np | Pu | Am | Cm | Bk | Cf | Es | Fm | Md | No | Lw |

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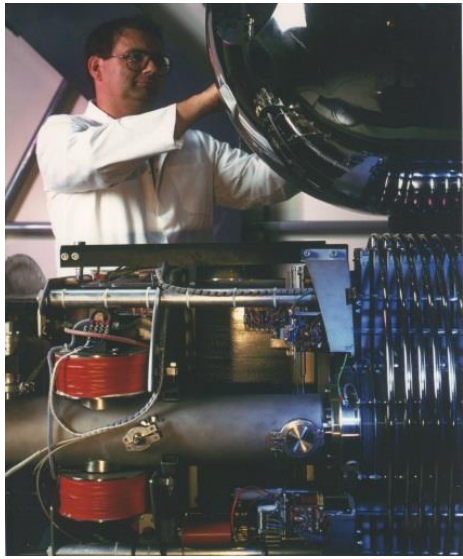

- **Advanced Materials Analysis**
  - 2MV Tandem
  - Techniques include RBS, ERD, PIXE, PIGE, NRA, IBIL, IBIC, MeV SIMS
  - Channelling Spectroscopy for damage analysis
  - Fully automated collection and analysis
  - External Beam for vacuum sensitive samples (~2um)
  - Horizontal nanobeam (~500nm)
  - Implantation line – heavy ion irradiation up to ~10MeV

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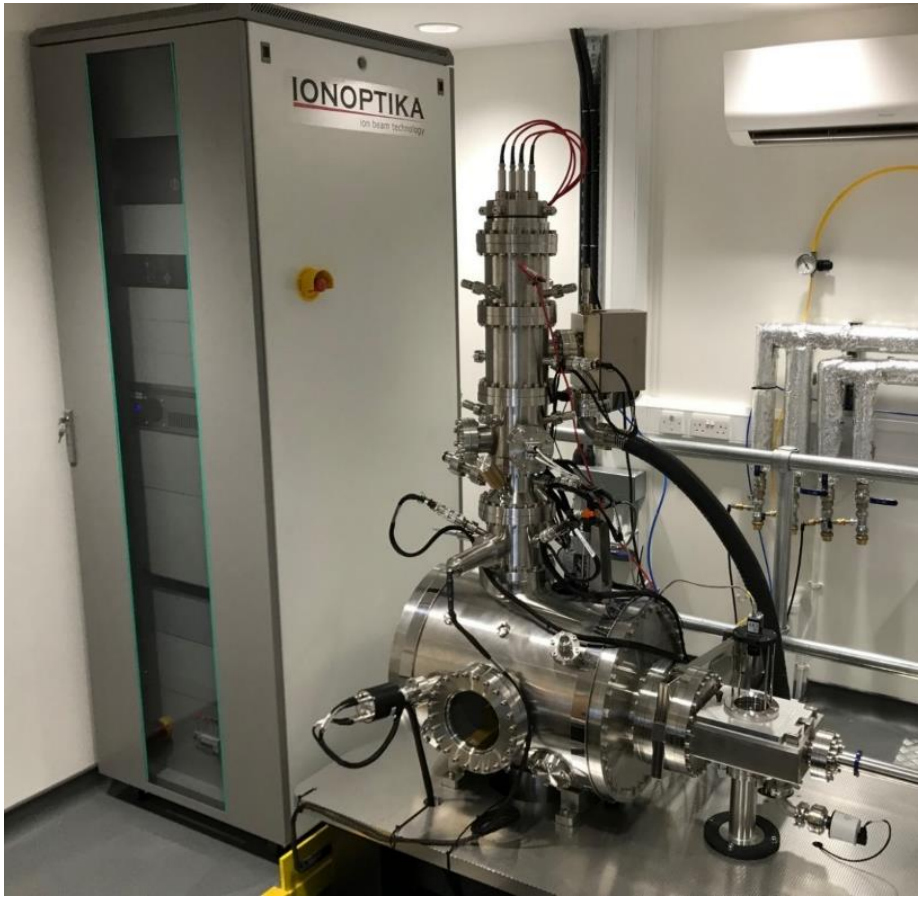
Simple

# Deterministic Ion Implantation




**Aim to support QT applications:**
to be able to place **two atoms** such that they are **within 20nm of each other**.
**Not one, and not three.**
**Repeat for a 100x100 array < 1hour**

| Capability | SIMPLE01 |
|---|---|
| Ion species | **Si, P, Mn, Se, Er, Bi**, Ge… |
| Isotope selection | ✓ |
| Spatial resolution | <20 nm |
| Ion energy | 5kV – 20kV |
| Deterministic doping | ✓ (single ion) |

| Capability | SIMPLE02 |
|---|---|
| Ion species | **N, O**, He, Ne, Ar… |
| Isotope selection | ✓ |
| Spatial resolution | <40 nm |
| Ion energy | 5kV – 25kV |
| Deterministic doping | ✓ (single ion) |

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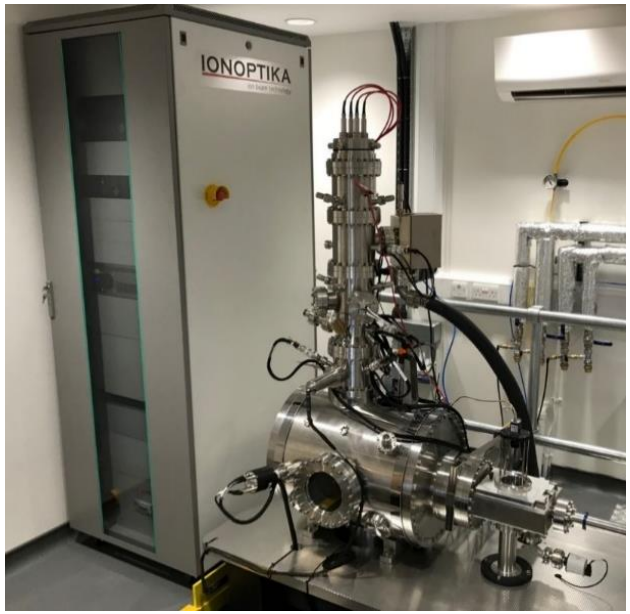
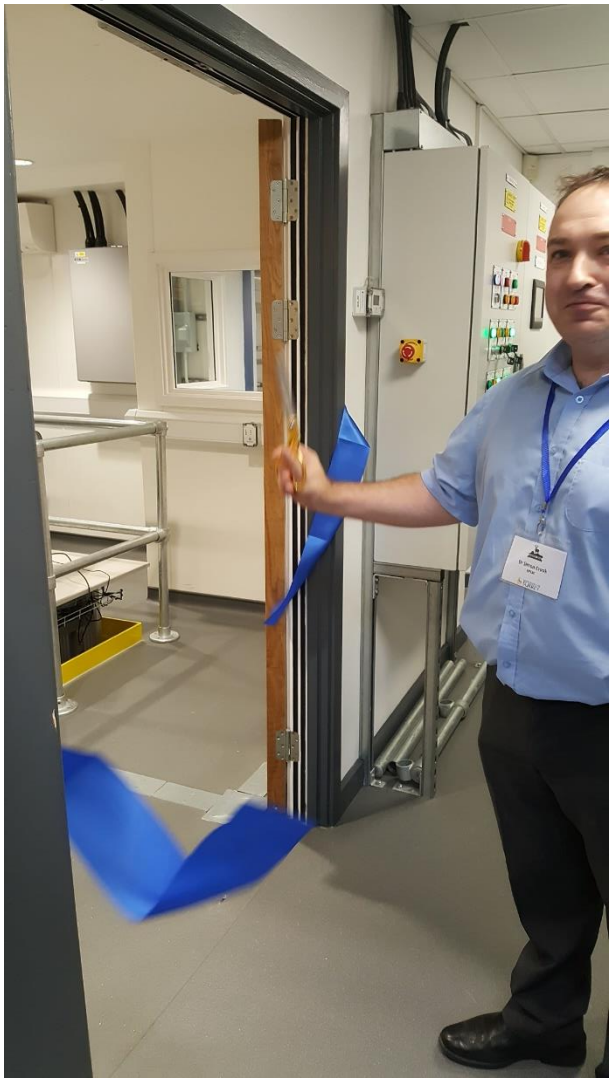
# Installation of SIMPLE01 at the Surrey Ion Beam Centre



# Access to the UKNIBC

- Currently open to support National projects at UK Universities.
- Commercial access for anyone.
- Surrey is certified at ISO9001:2015

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# New EU H2020 I3 grant starting 1/1/19:

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**R**esearch **a**nd **D**evelopment with **I**on Beams – **A**dvancing **T**echnology in **E**urope

**18 partners across Europe:** Following on from SPIRIT (11 partners) under FP7

**Offering TNA**

**HZDR – Dresden-Rossendorf, Germany**
Atomki - Hungary
CAEN – Italy
**CNRS – France**
**ETHZ – Switzerland**
IMEC – Belgium
**INFN – Italy**
Ionoptika – UK
Ionplus – Switzerland

**Surrey - UK**
IST – Portugal
**JSI – Slovenia**
**JYU – Finland**
**KUL – Leuven, Belgium**
Orsay Physics – France
**RBI – Croatia**
**University Bundeswehr – Munich, Germany**
**University of Vienna**

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14 National & Regional Ion Beam Centres

Providing TNA for ion beams of all stable elements from a few eV up to GeV

Table 1.2: TA access distribution listed by categories, topics and methods

| TNA topic distribution | | | HZDR | CNRS | ETHZ | INFN | JSI | JYU | KUL | RBI | UBW | UKNIBC | UW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Category | Topic | Method | 1 | 4 | 5 | 9 | 11 | 12 | 13 | 15 | 16 | 17 | 18 |
| Analysis | Elemental Analysis & Depth Profiling | RBS | | | | | | | | | | | |
| | | ERDA | | | | | | | | | | | |
| | | NRA | | | | | | | | | | | |
| | | PIXE / PIGE / PES | | | | | | | | | | | |
| | | MEIS | | | | | | | | | | | |
| | Ultrahigh Sensitivity | Cosmogenic dating AMS | | | | | | | | | | | |
| | | High-energy AMS | | | | | | | | | | | |
| | | Environmental tracer AMS | | | | | | | | | | | |
| | Lateral Imaging | External microbeam IBA | | | | | | | | | | | |
| | | (ambient) MeV SIMS | | | | | | | | | | | |
| | | PIXE (μ-beam, camera) | | | | | | | | | | | |
| | | He-Ne microscopy | | | | | | | | | | | |
| | | H microscopy | | | | | | | | | | | |
| | | IBIC | | | | | | | | | | | |
| | Defect Analysis | RBS/PIXE-C | | | | | | | | | | | |
| | | In-situ TEM | | | | | | | | | | | |
| | Real-time in-situ Analysis | Dynamic / high-T IBA | | | | | | | | | | | |
| Implantation & Irradiation | Broad Beam | Implantation / Doping | | | | | | | | | | | |
| | | Multi-beam | | | | | | | | | | | |
| | | Clean environment | | | | | | | | | | | |
| | Local | Non-Ga FIB, He/Ne microscope | | | | | | | | | | | |
| | | Single ion implantation | | | | | | | | | | | |
| | | Cell irradiation | | | | | | | | | | | |
| | Deep | MeV ions | | | | | | | | | | | |
| | | Swift heavy ions | | | | | | | | | | | |
| | Shallow | Low-energy ions | | | | | | | | | | | |
| | | Highly charged ions | | | | | | | | | | | |

Primary Provider  Secondary Provider

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# New EU H2020 I3 grant starting 1/1/19:

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**R**esearch **a**nd **D**evelopment with **I**on Beams – **A**dvancing **T**echnology in **E**urope

**18 partners across Europe:** Following on from SPIRIT (11 partners) under FP7

**Offering Irradiation**

**HZDR – Dresden-Rossendorf, Germany**
Atomki - Hungary
CAEN – Italy
**CNRS – France**
**ETHZ – Switzerland**
IMEC – Belgium
**INFN – Italy**
Ionoptika – UK
Ionplus – Switzerland

**Surrey - UK**
IST – Portugal
**JSI – Slovenia**
**JYU – Finland**
**KUL – Leuven, Belgium**
Orsay Physics – France
**RBI – Croatia**
**University Bundeswehr – Munich, Germany**
**University of Vienna**

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# HZDR – Dresden-Rossendorf, Germany

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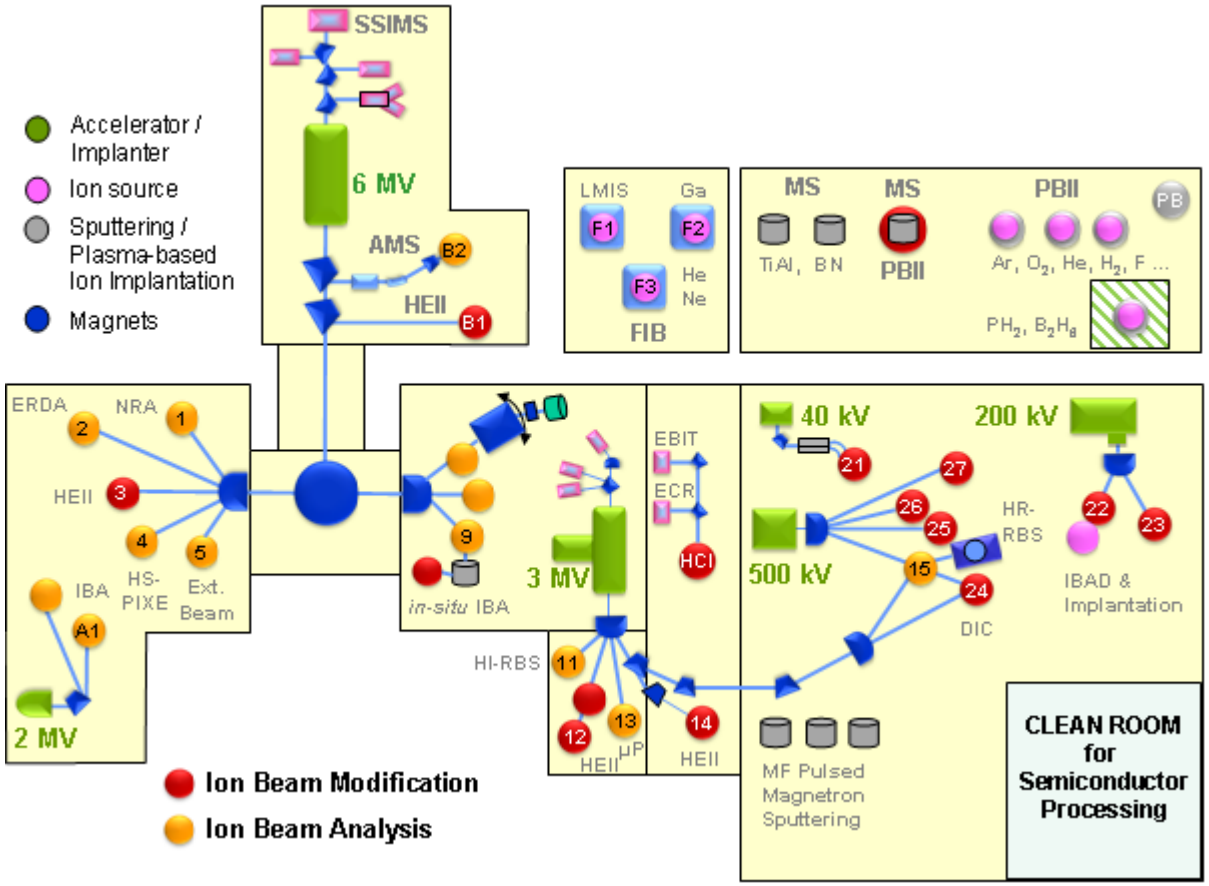
Dual beam capability:

- 3MV tandem
- 500keV implanter

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CNRS, CEA, – France

cea DSM/IRAMIS
cnrs Institut de Physique
ENSICAEN
UNICAEN Université de Caen Normandie

CIMAP
Ciril
Centre Interdisciplinaire de Recherche avec les Ions Lourds
User Facility for Interdisciplinary Research at GANIL

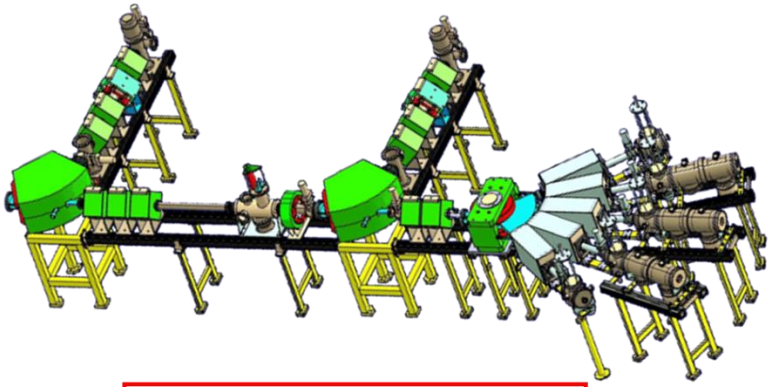
LABORATOIRE D'EXCELLENCE EMC

# Irradiation conditions

Wide range of **temperature**
10 K, 77K up to 1200°C
1100°C for nuclear materials ($UO_2$)
Different **angles** down to grazing incidences

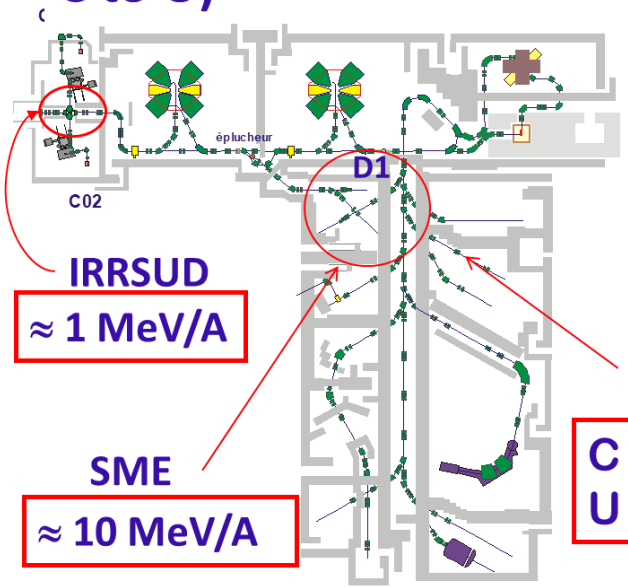
**+++ On line experiments for dense materials**

## ARIBE
## Low Energy Beam Line



de $He^{+}$ à $Xe^{31+}$ ; 18 kV

## High Energy Beam Lines (from C to U)




IRRSUD
≈ 1 MeV/A

SME
≈ 10 MeV/A

HE
C à 95 MeV/A
U à 24 MeV/A

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# RBI - Croatia

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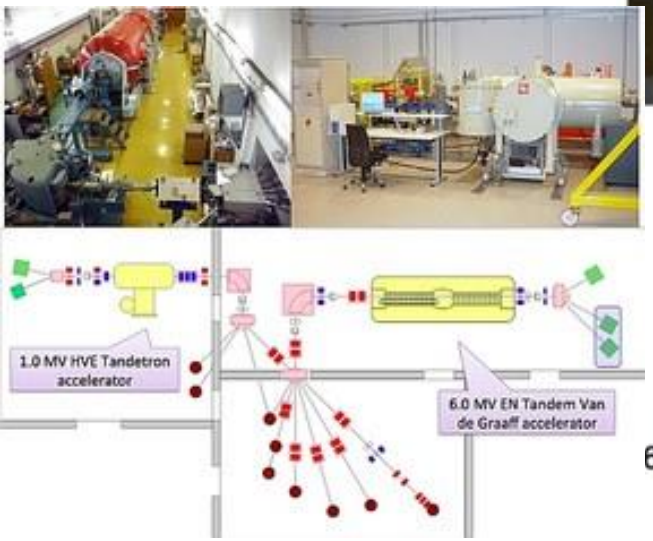
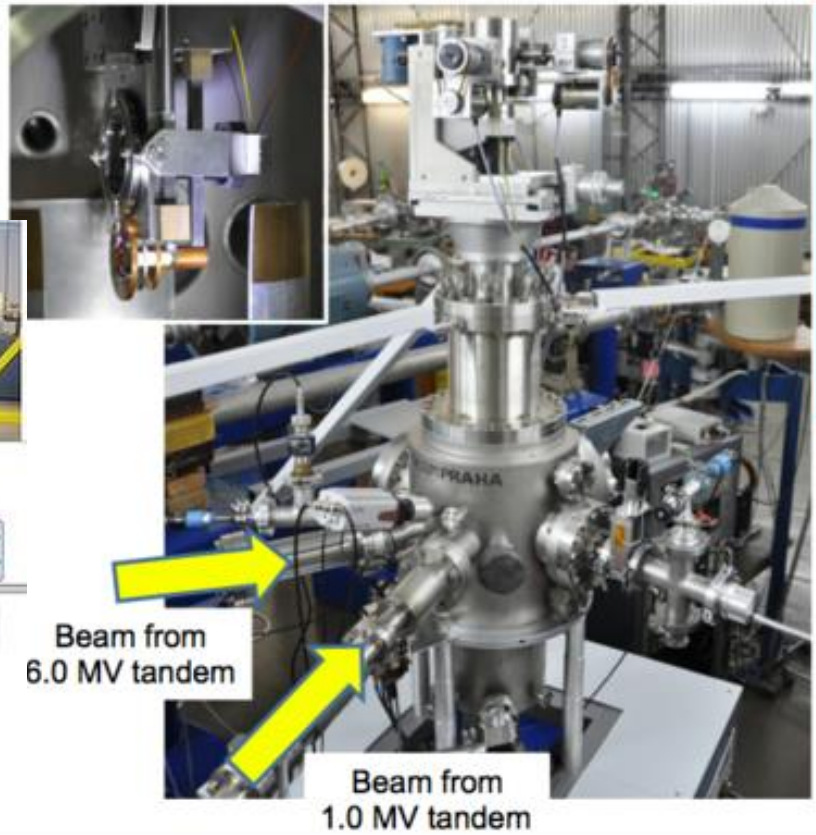
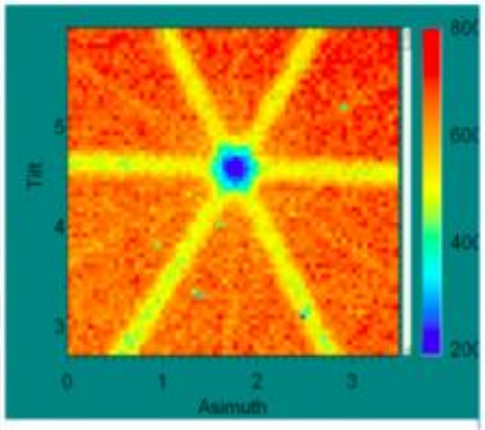
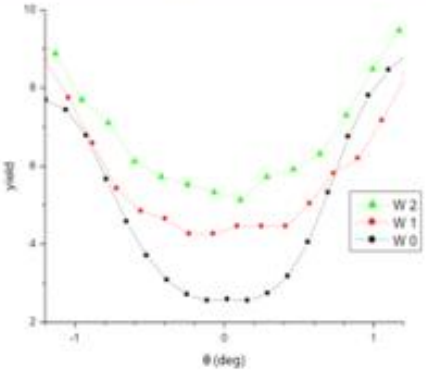
Dual beam capability:

- Irradiation
- Ion Beam Analysis



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# University Bundeswehr – Munich, Germany

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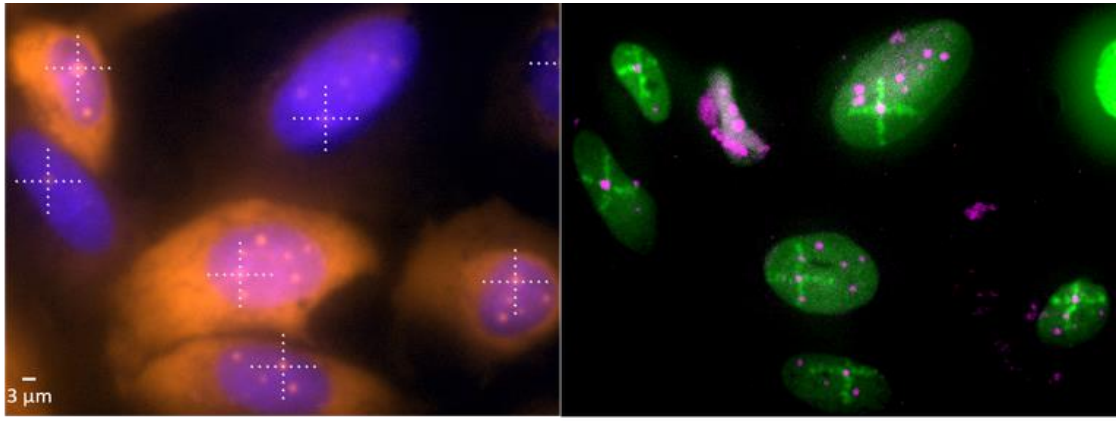
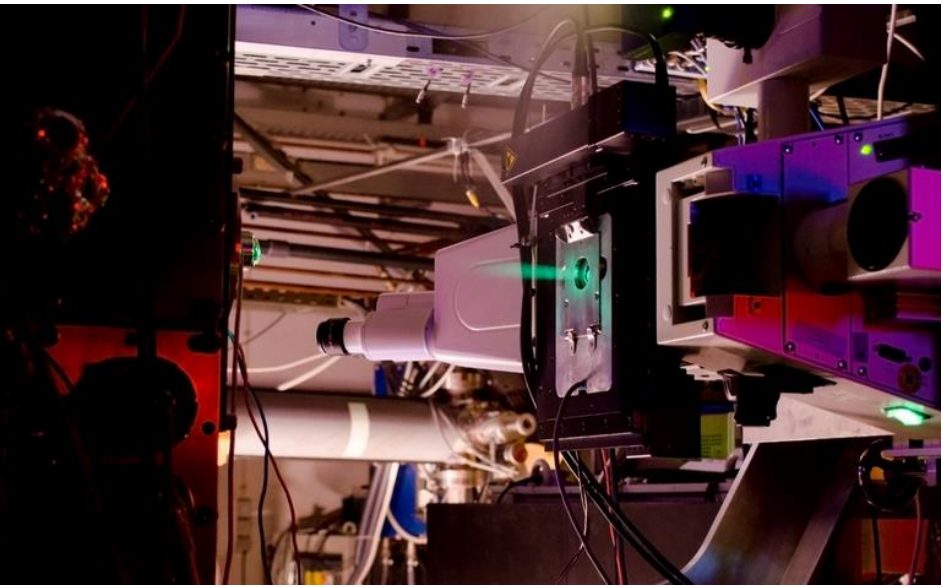
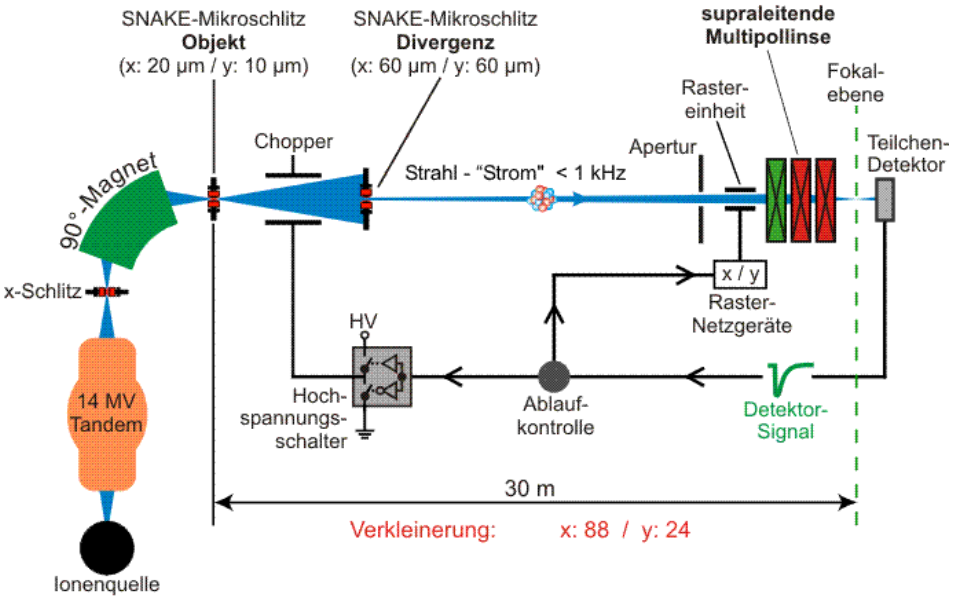
S·N·A·K·E

Irradiation of Single Biological Cells





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11 National & Regional Ion Beam Centres
Providing TNA for ion beams of all stable elements from a few eV up to GeV

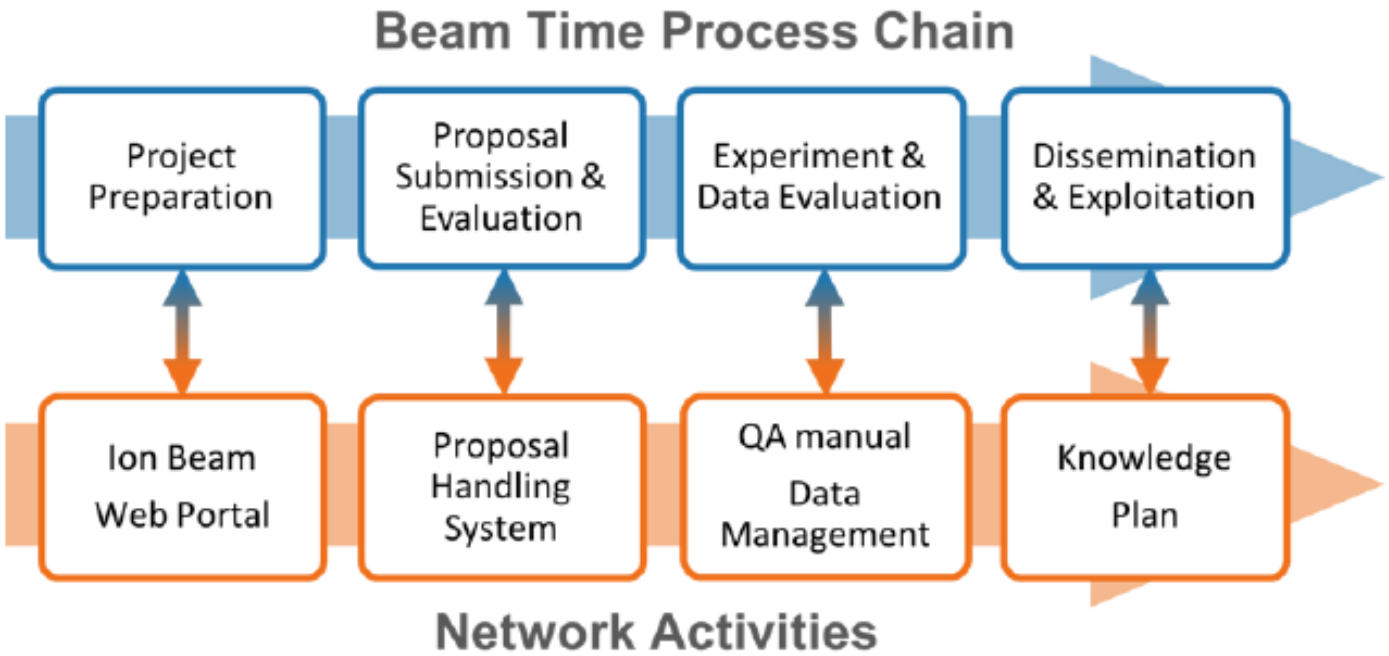


Figure 1.1: Illustration of the process chain of an experimental campaign and the corresponding Network Activities.

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Previous TNA activity under SPIRIT

16,000 hours of TNA were provided across the consortium over 4 years

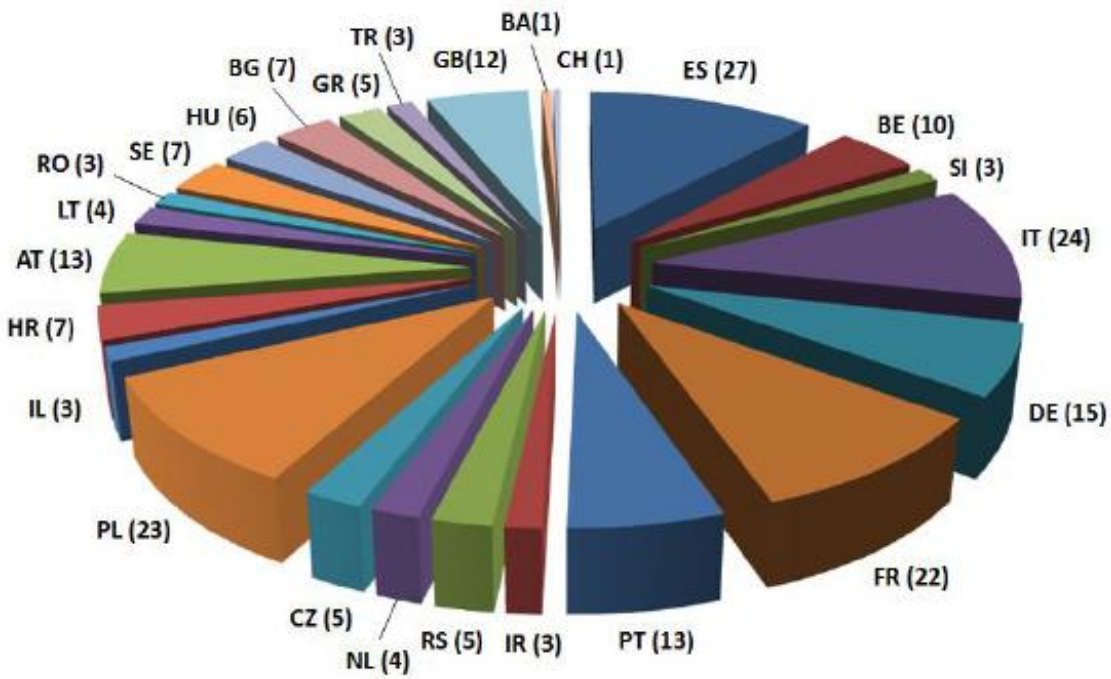


Figure 1.2: Country distribution of SPIRIT TA proposals received.

# Access to the RADIATE

- Process will be via web based portal
- Process will be quick
- Contact the facility rep and prepare short proposal
- Proposal submitted – call always open
- Proposal reviewed – 2 week turn around
- If accepted, book the time!