Ion irradiation studies for novel applications of diamond based materials

M. Tomut

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Team

- **GSI / TU Darmstadt:**

P. Simon, A. Prosvetov, C. Trautmann

- **RHP Technology**:

M. Kitzmantel, E. Neubauer

- **LBNL and The Molecular Foundry:**

J. Schwartz, R.Lake, Th. Schenkel

- **University of Heidelberg**:

S.Dedera, U. Glassmacher

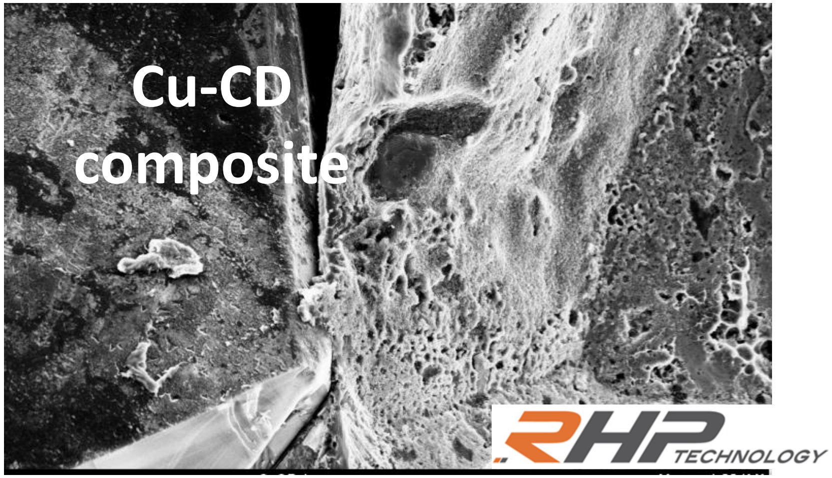
- **University of Stuttgart:**

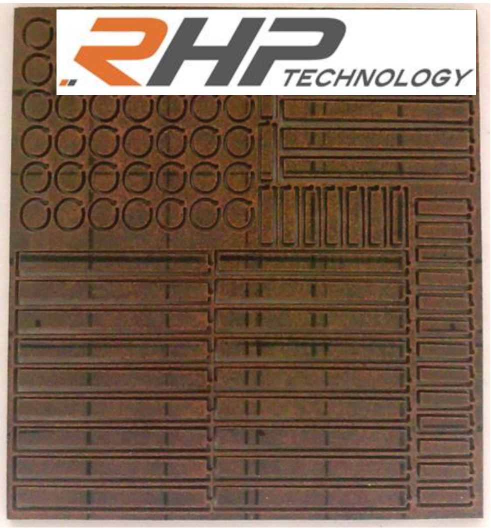
R. Ferhati, W. Bolse

Outline

1. Cu-CD composites developed within EuCARD2
2. Online investigations of Ion beam- induced defects in diamond
3. The Nitrogen – Vacancy center in diamond
4. NV-center formation without thermal annealing
   - Swift heavy ions in nitrogen implanted diamond
   - Swift heavy ions in diamond with nitrogen from growth
5. Biophysics and medical applications
6. Outlook

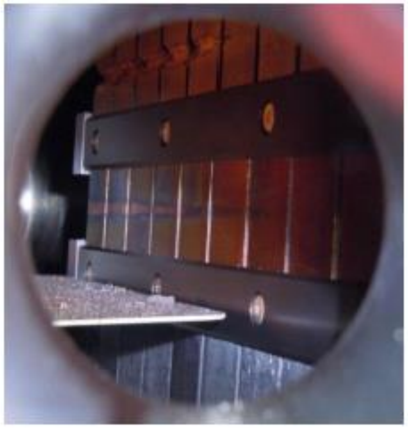
Novel composite materials for LHC collimators upgrade





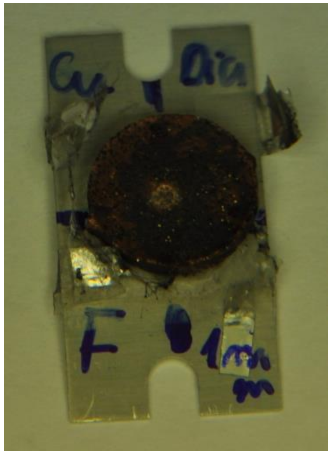
Proton beam high energy deposition-HiRadMat, CERN:

Courtesy:
A. Bertarelli



Laser shock experiment-GSI:

Pulse duration:	0.7-20 ns
energy:	0.3-1 kJ
Max. Intensity:	10^{16} W/cm^2

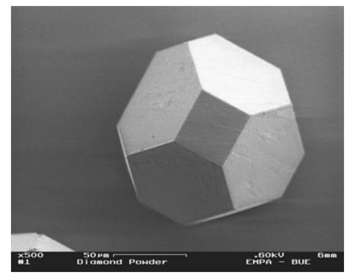


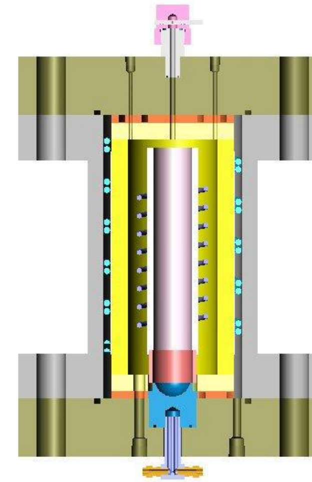
Cu-CD Composite Production and optimization

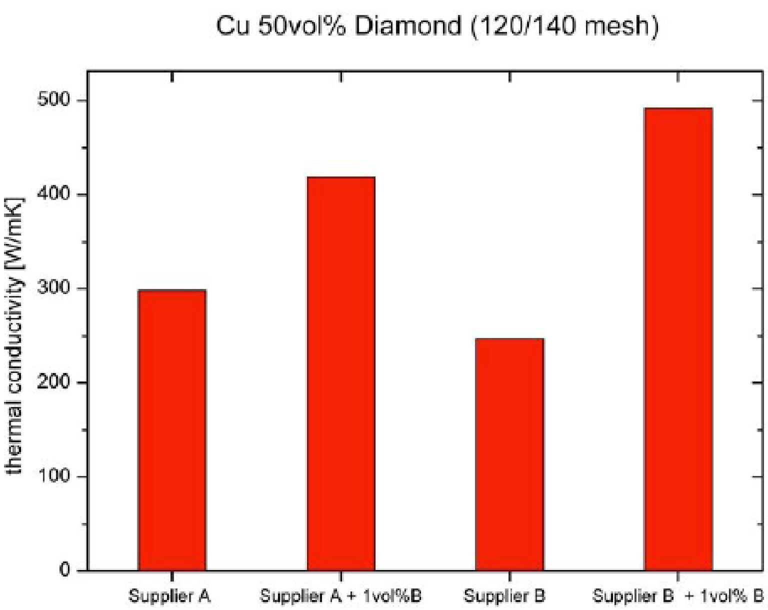
- Developed by **RHP-Technology** (Austria)

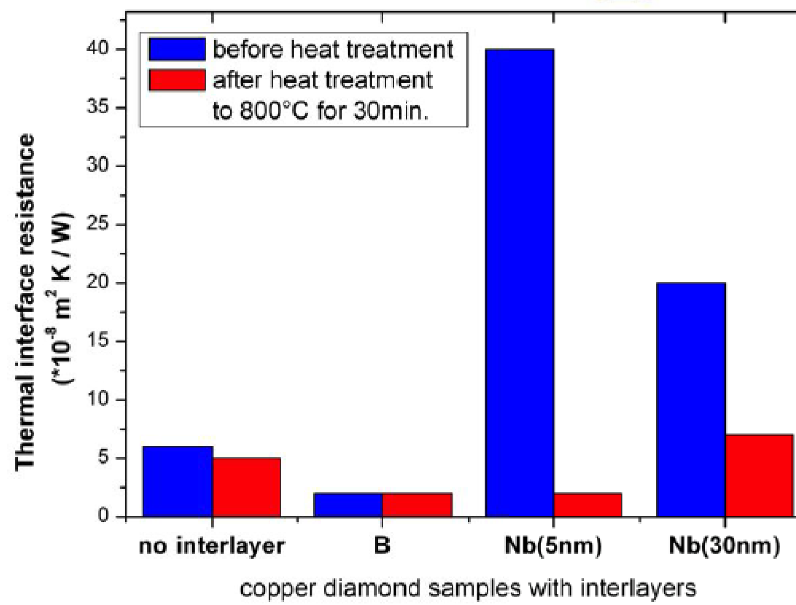
Rapid Hot Pressing for optimized manufacturing

Selected Diamond Grid
- Mono-crystalline diamond
- Low nitrogen level
- Relatively large size (>100µm



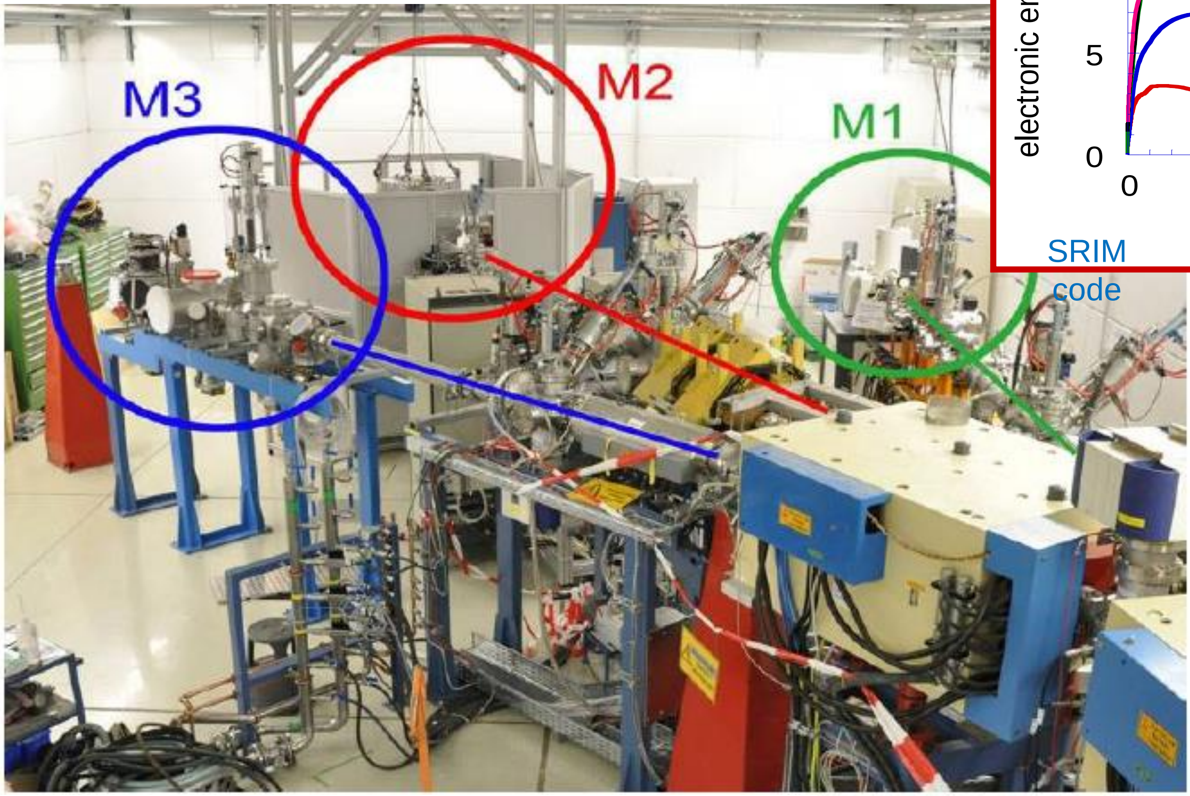


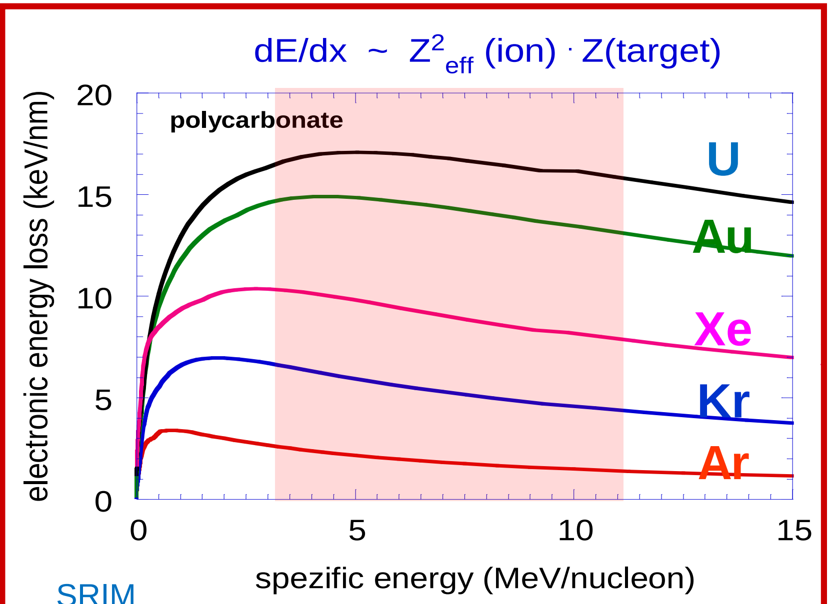




M-branch irradiation facility at GSI
In situ experiments

- energies close to Bragg peak:
  - to maximize energy deposition and damage
  - to avoid activation



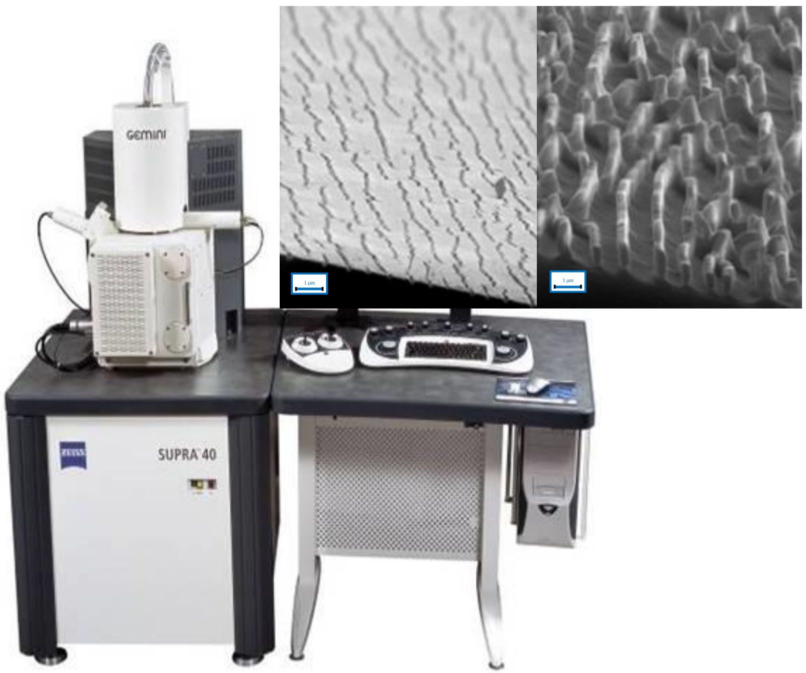


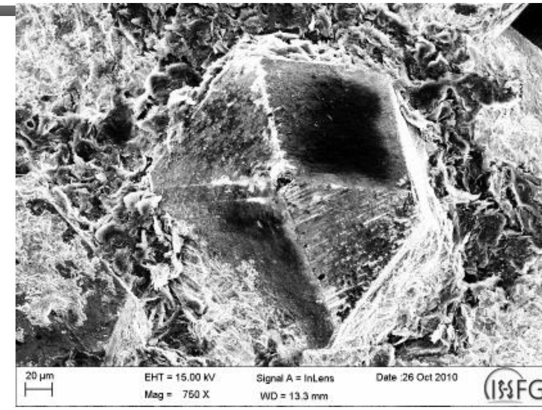
SRIM code

ion species ..C…Xe...U
flux:
up to10^{10} ions/cm^2 s

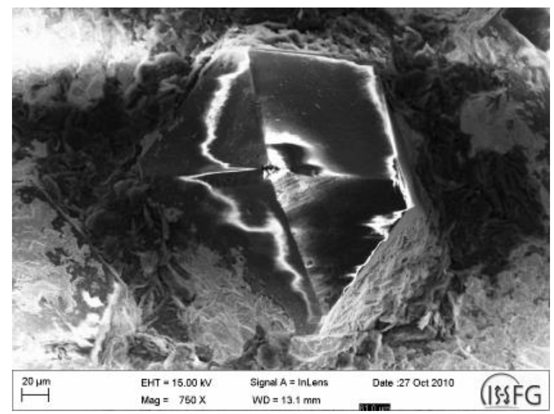
In situ analysis HR-SEM facility at GSI-UNILAC

M1
Electron Microscopy

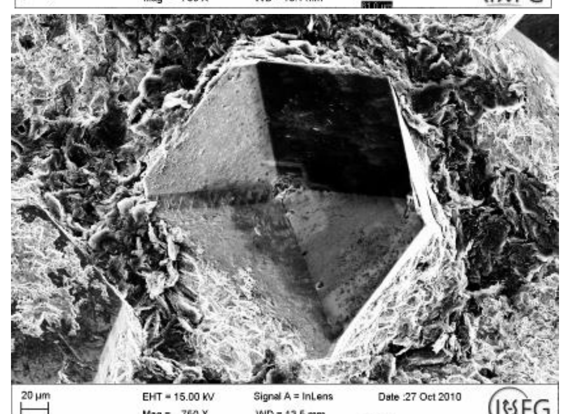




pristine



1×10^{13} i/cm^2

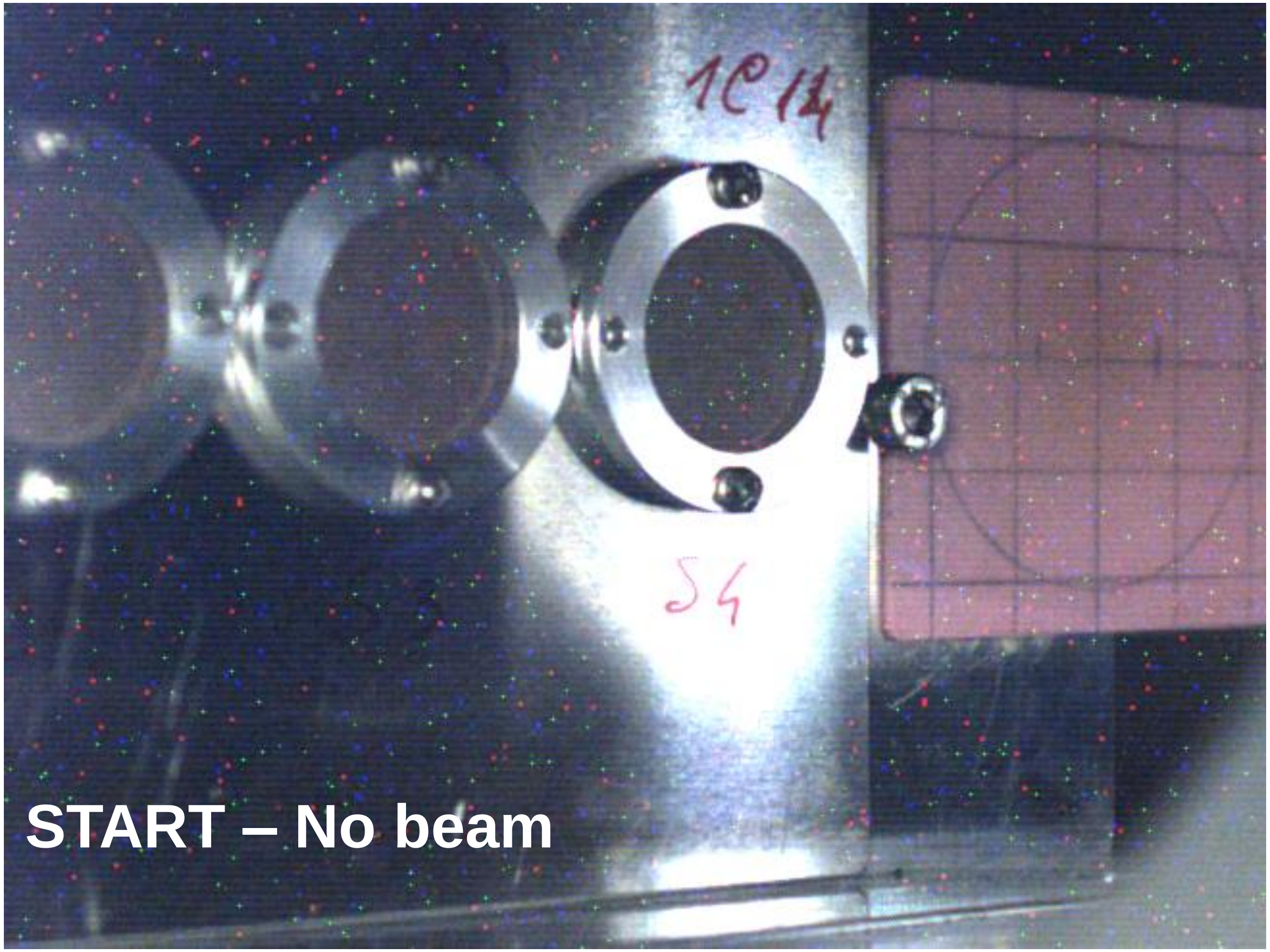


1.7×10^{14} i/cm^2

in collaboration with University of Stuttgart,

M.Tomut, GSI - EuCARD

Evolution of ion induced luminescence in Cu-CD composites with dose



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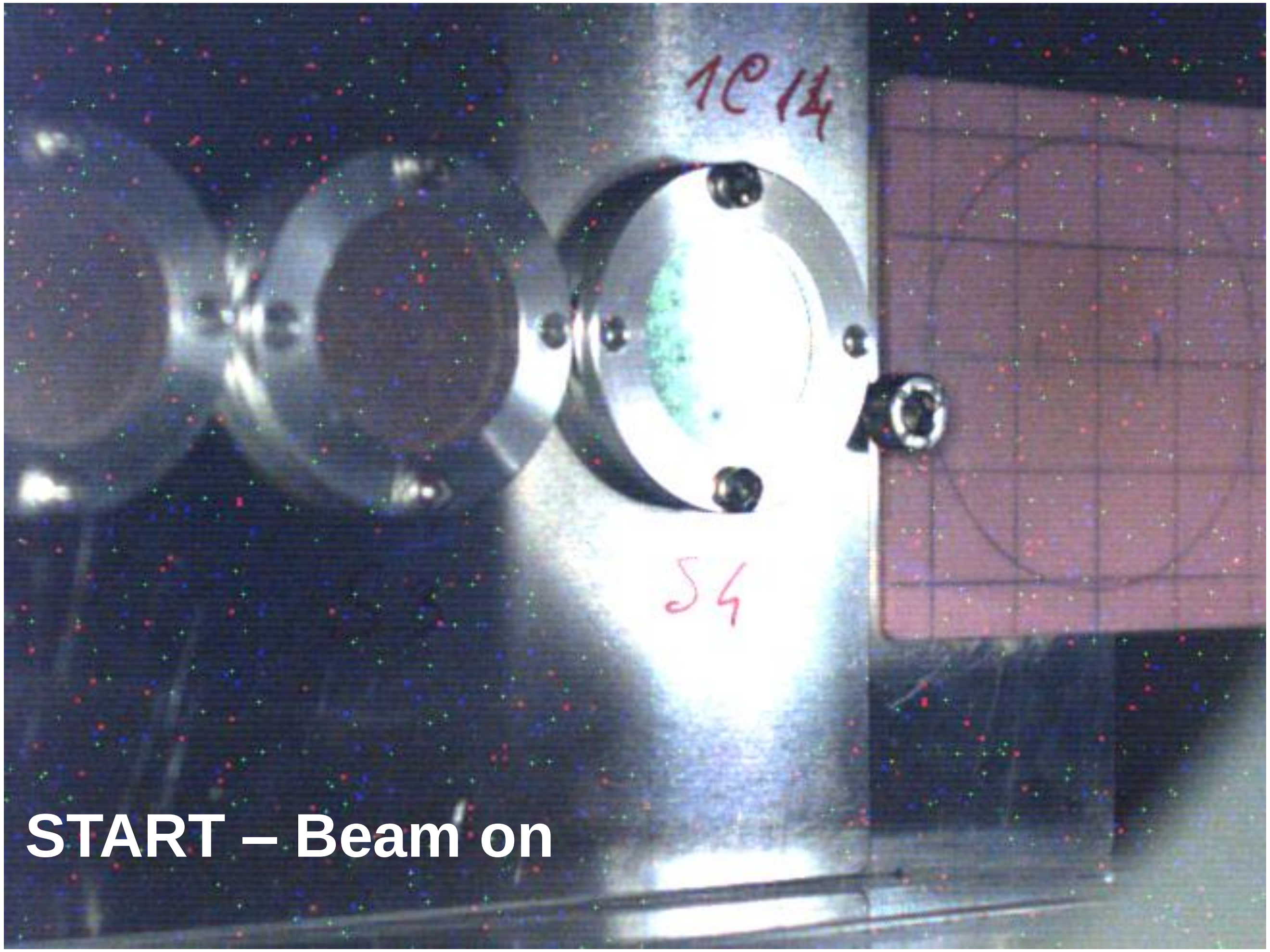

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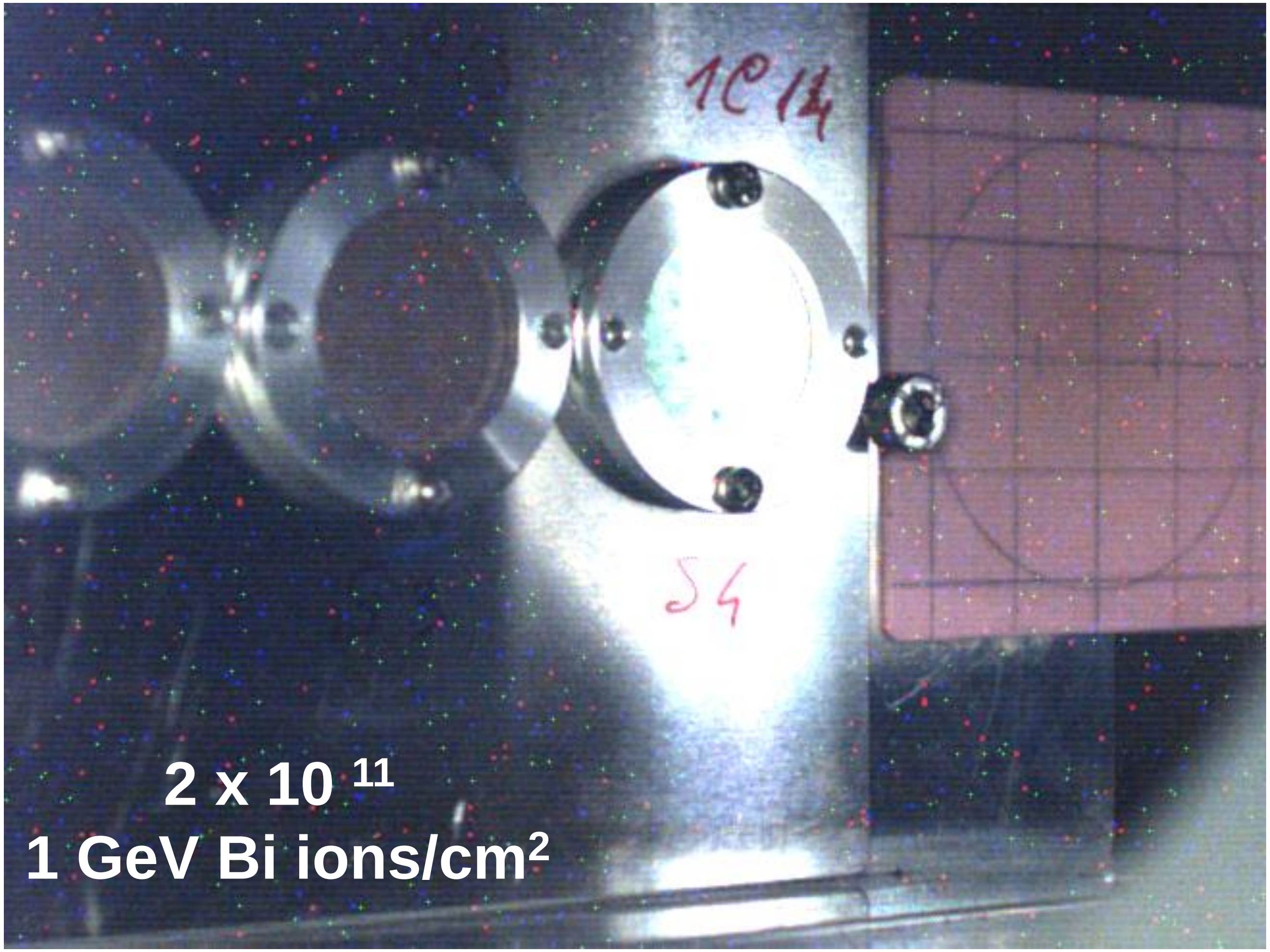

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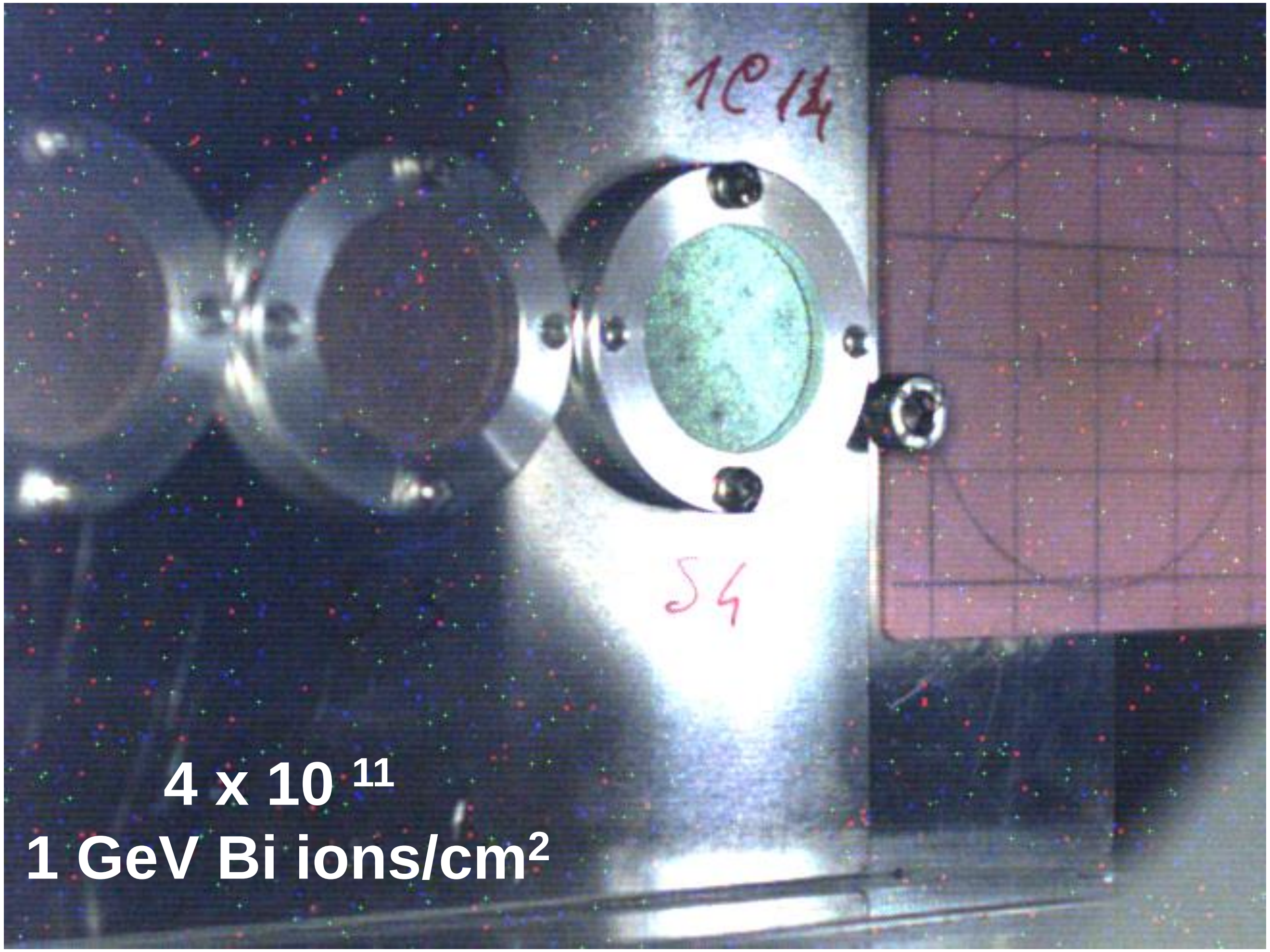

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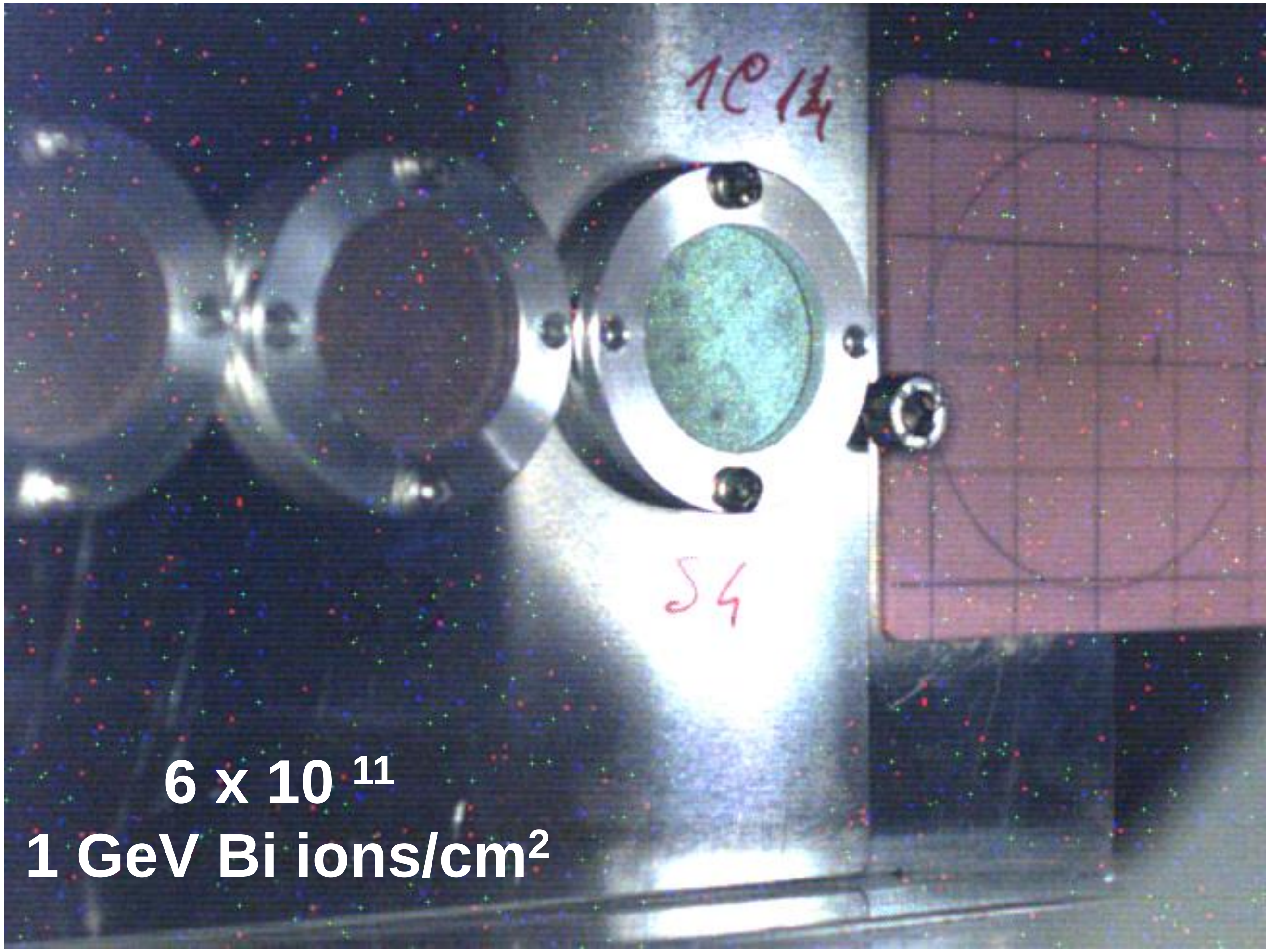

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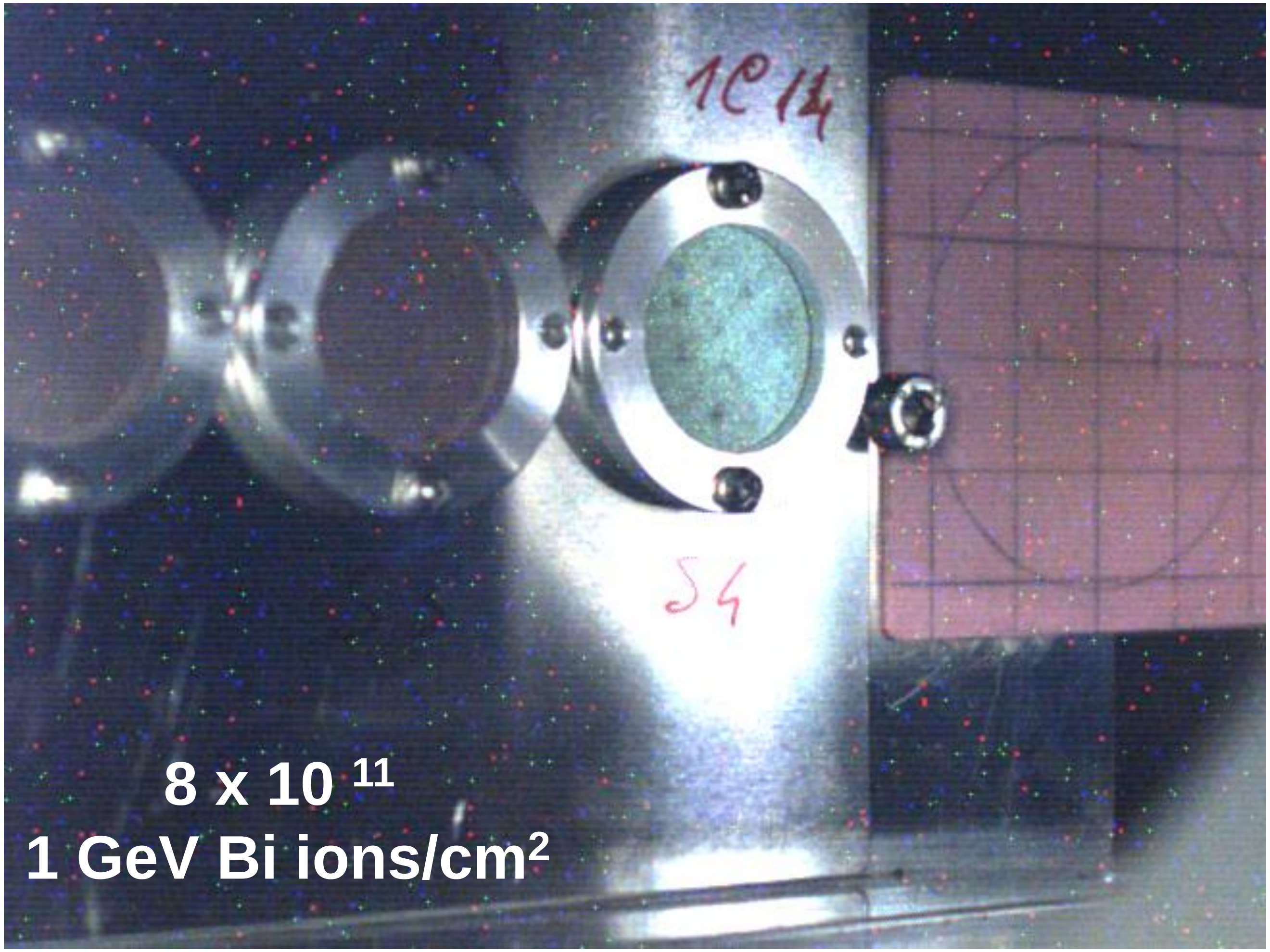

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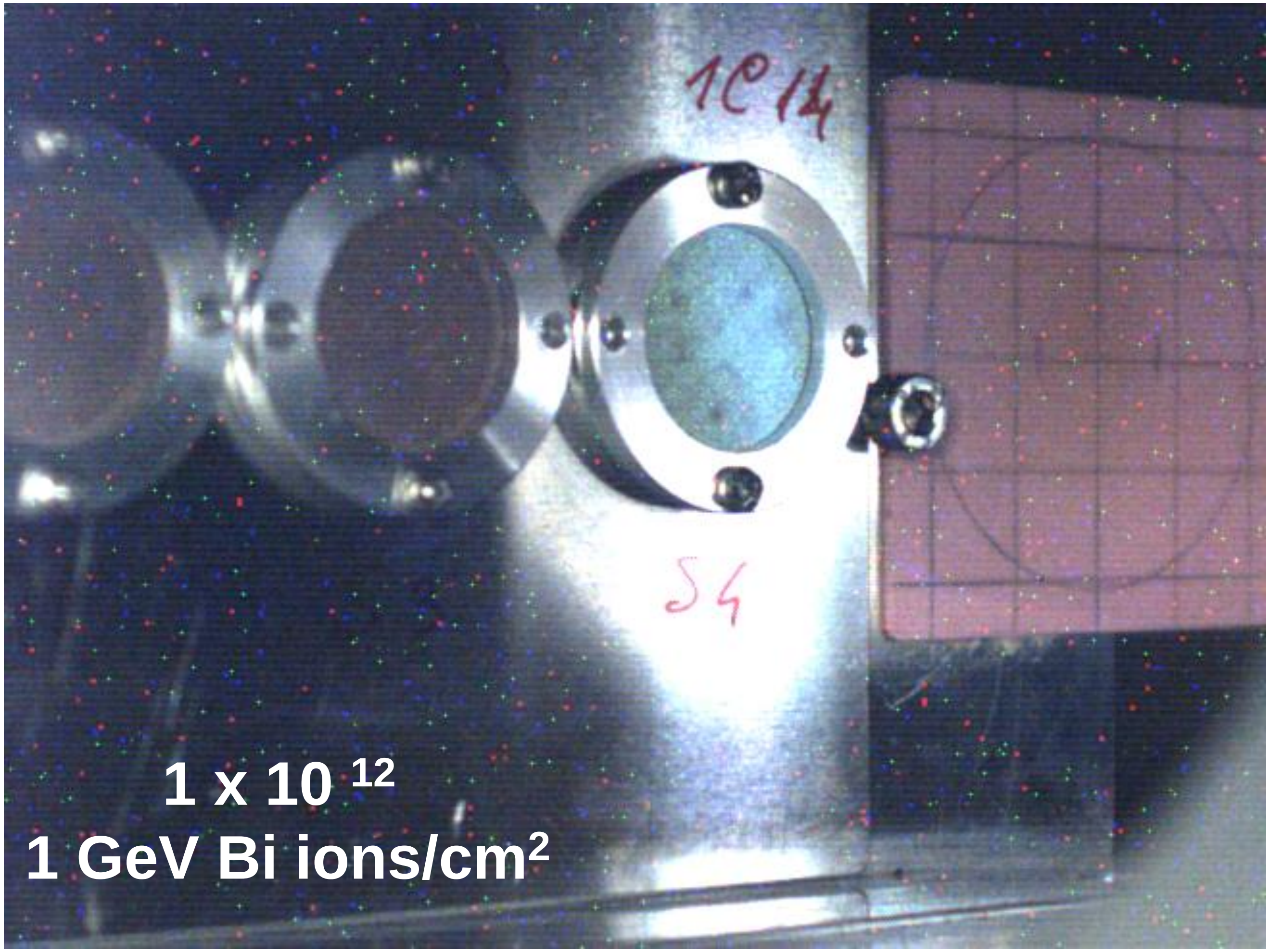

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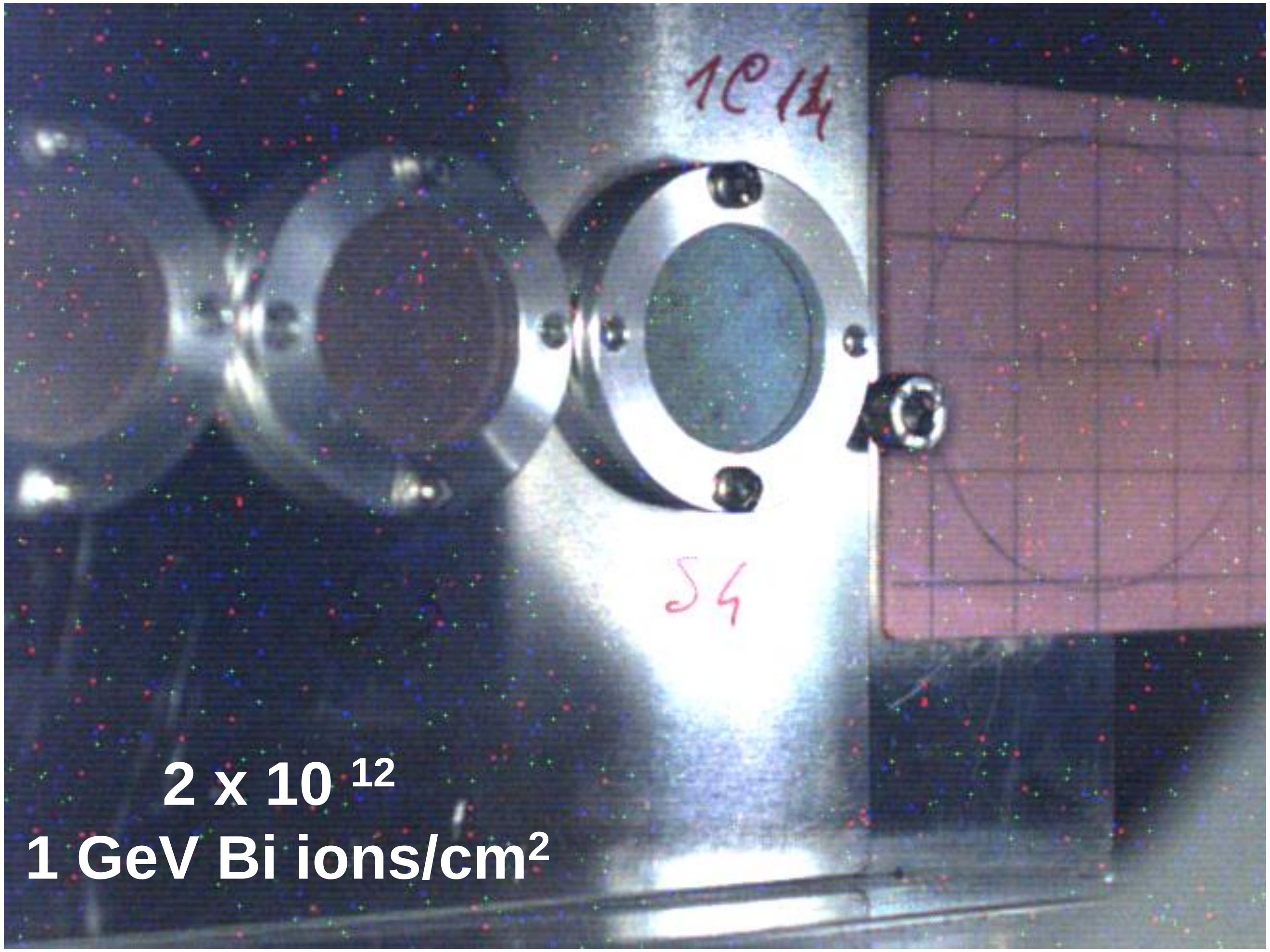
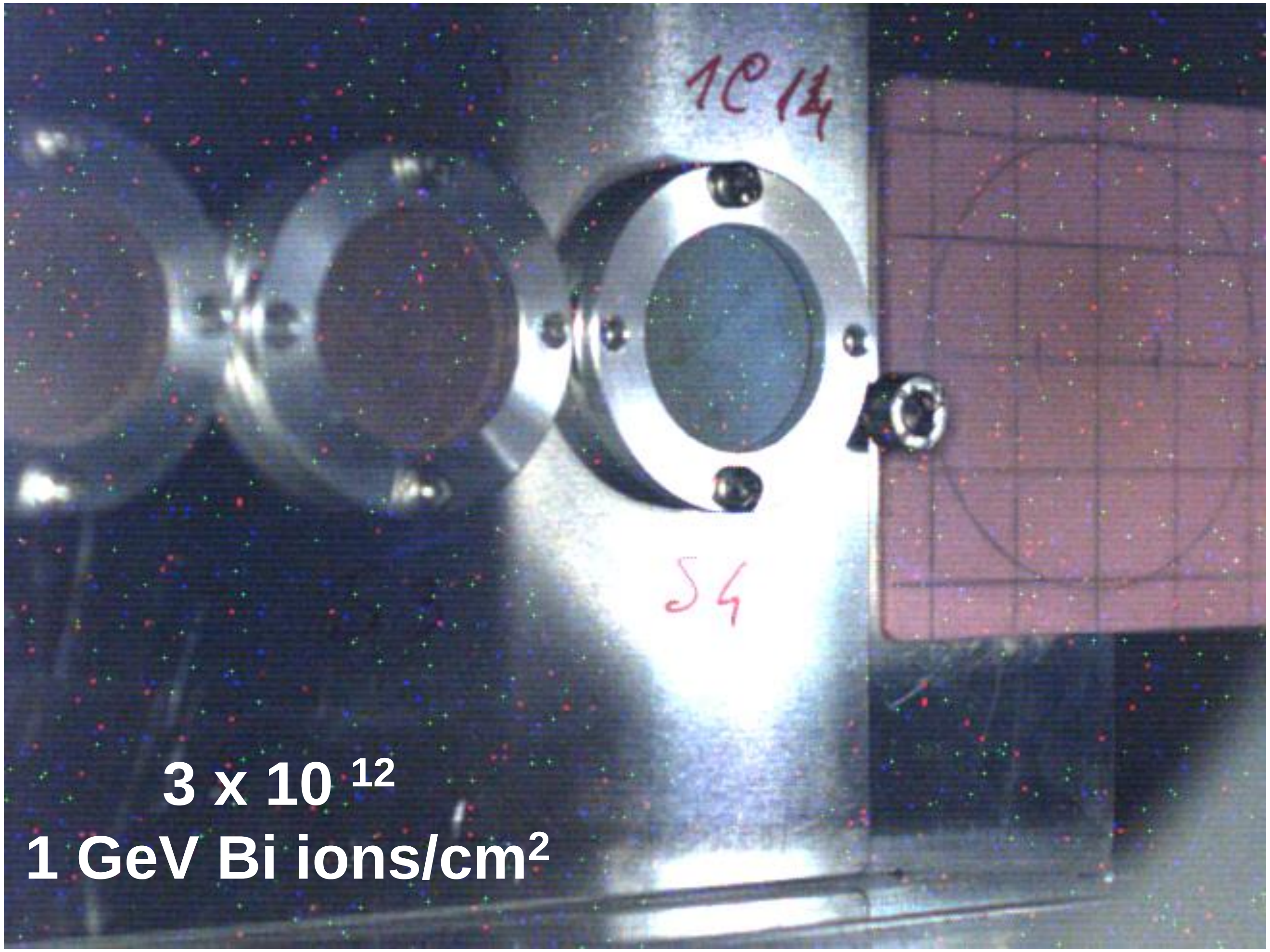
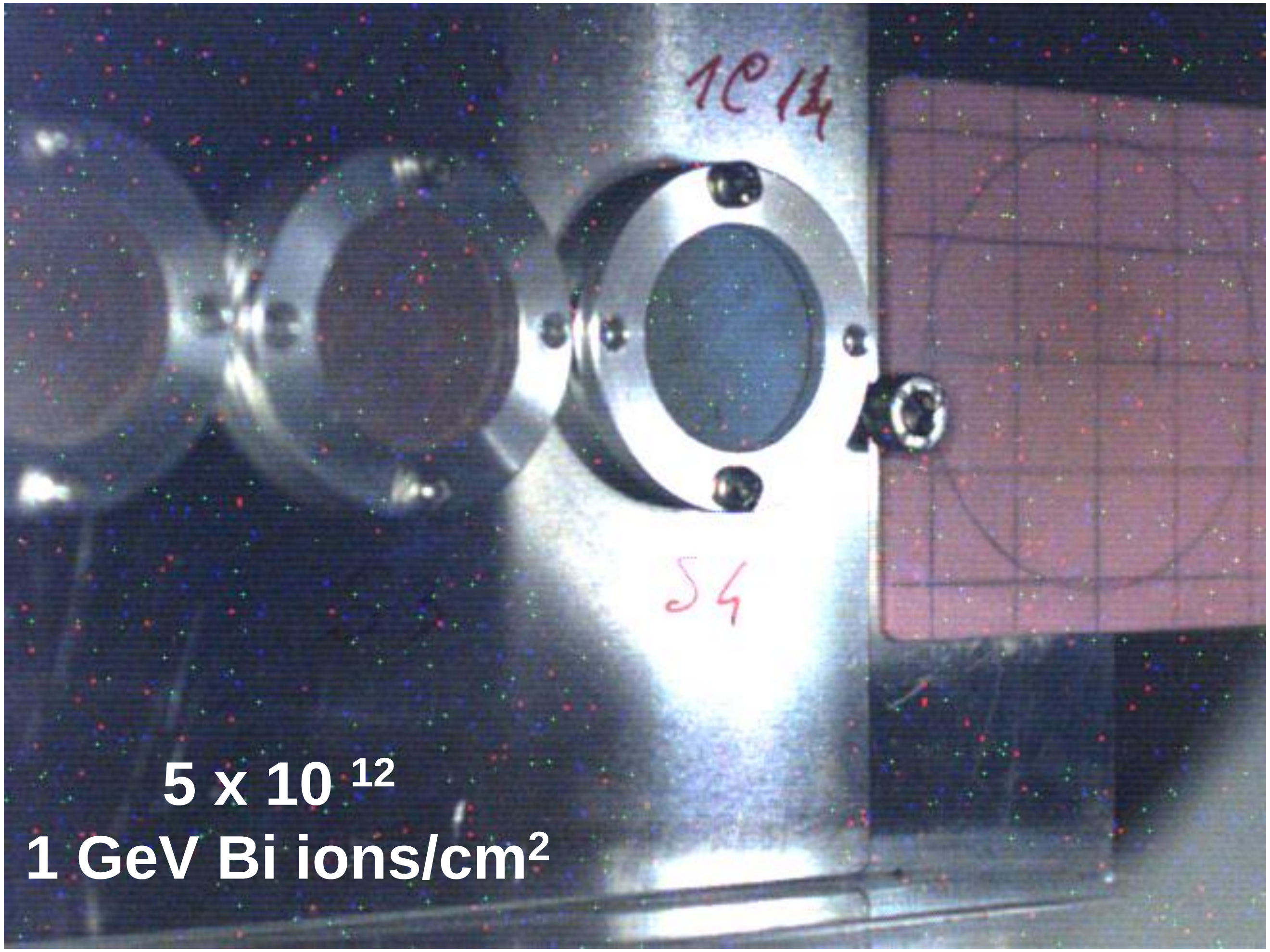


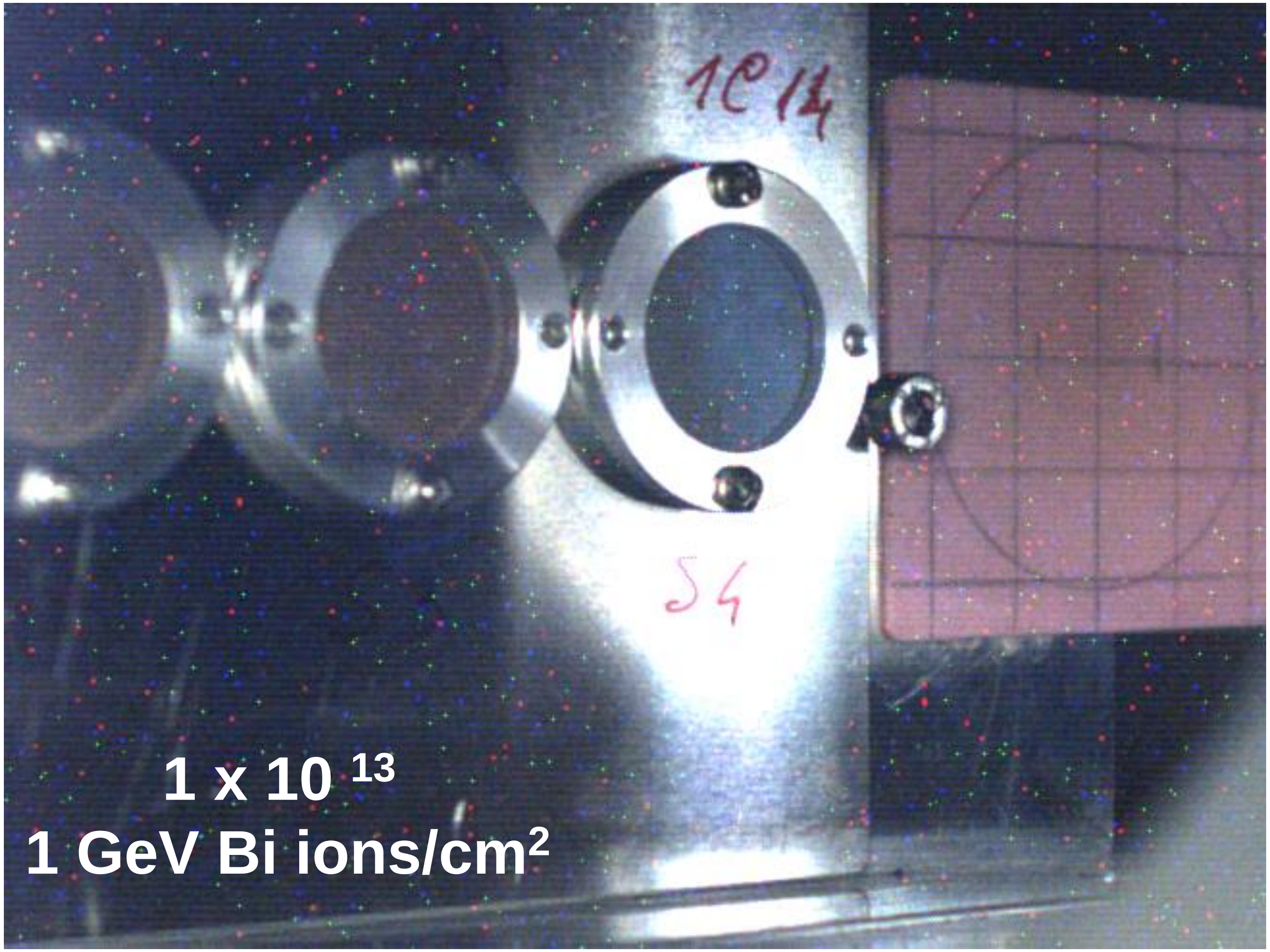
Evolution of ion induced luminescence in Cu-CD composites with dose



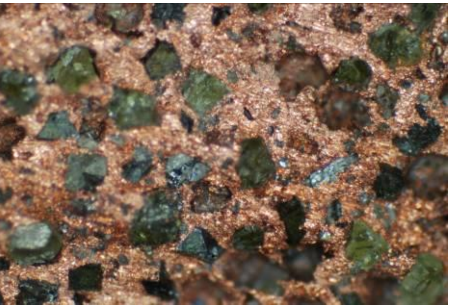
Evolution of ion induced luminescence in Cu-CD composites with dose



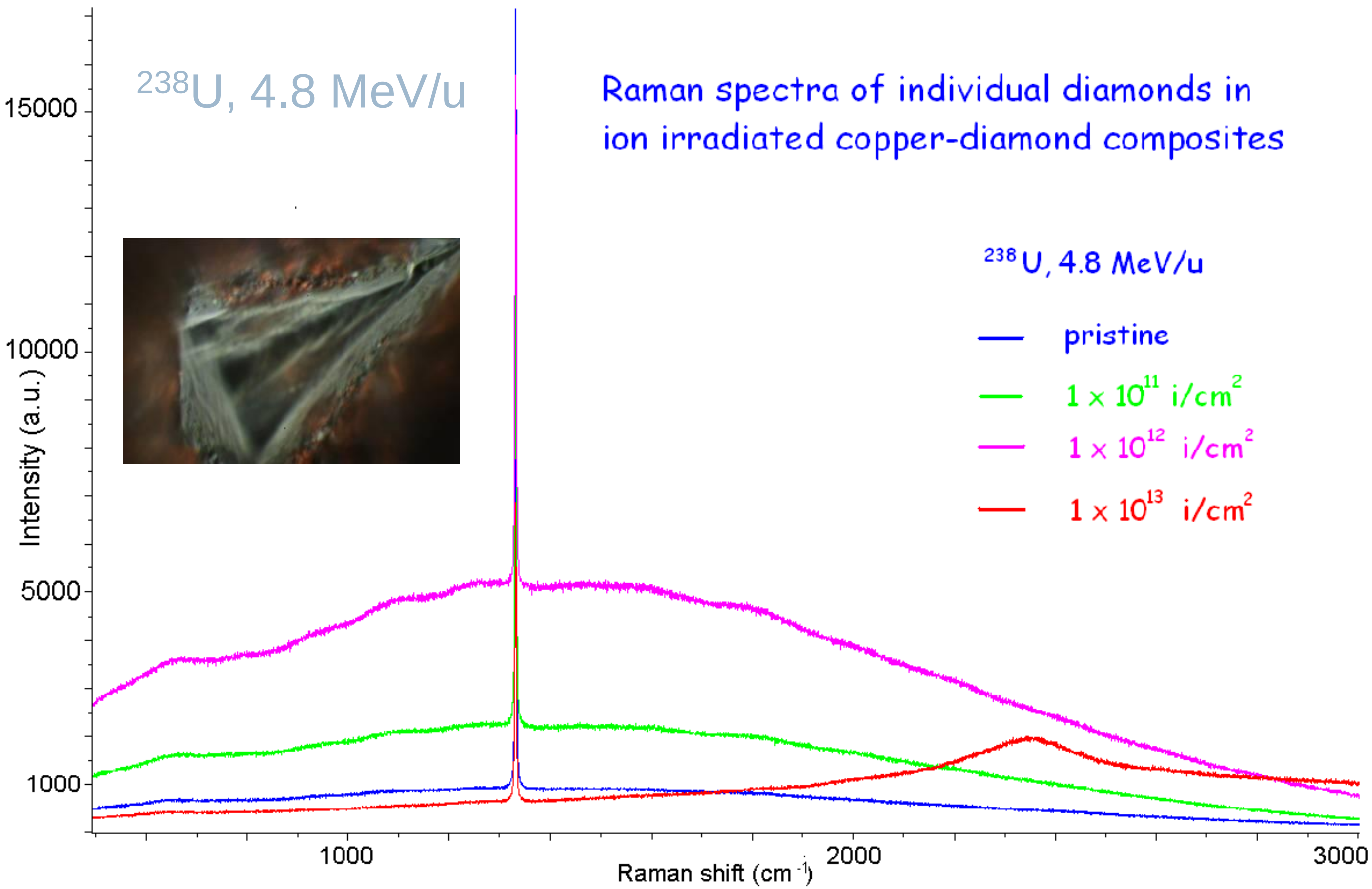
Evolution of ion induced luminescence in Cu-CD composites with dose



Post irradiation Raman spectroscopy – ion induced defects in diamond

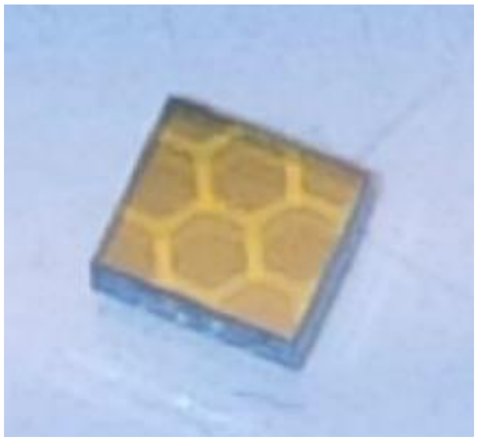


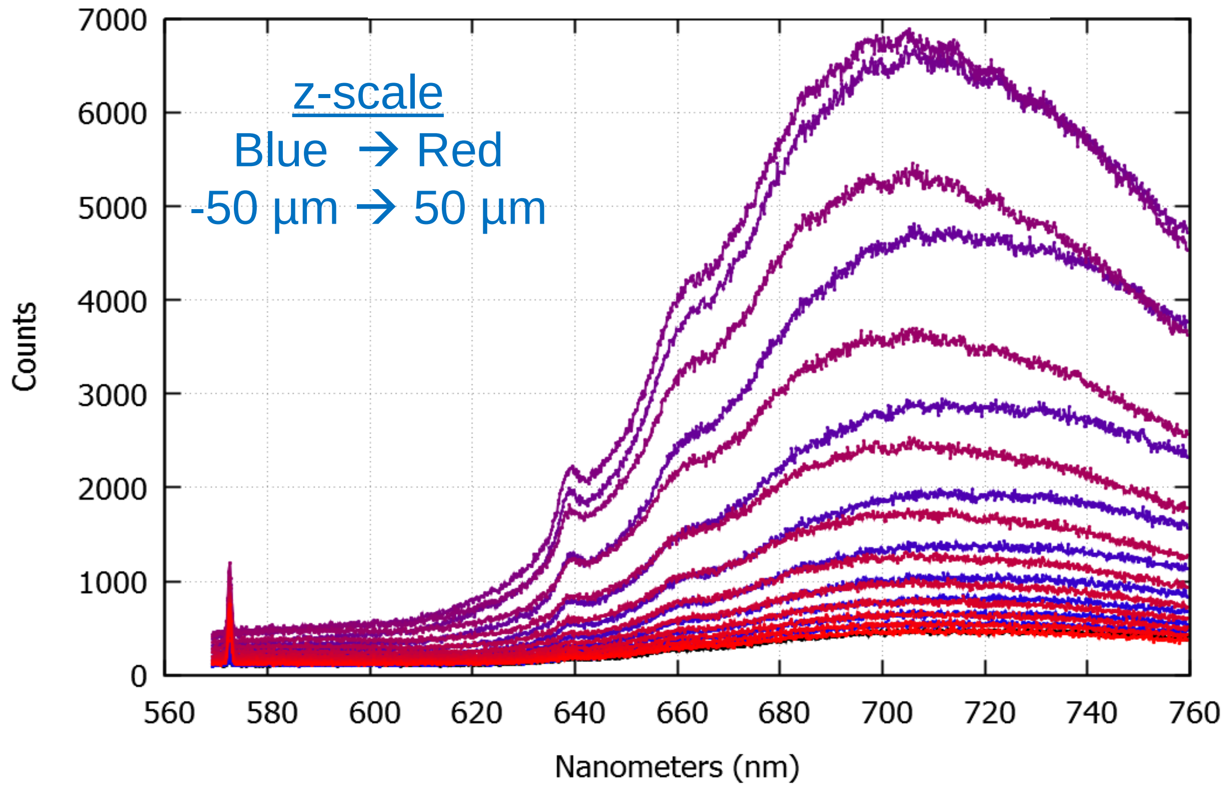
Diamond



Off-line Raman spectroscopy shows:-increasing luminescence background due to ion-induced optical active defects

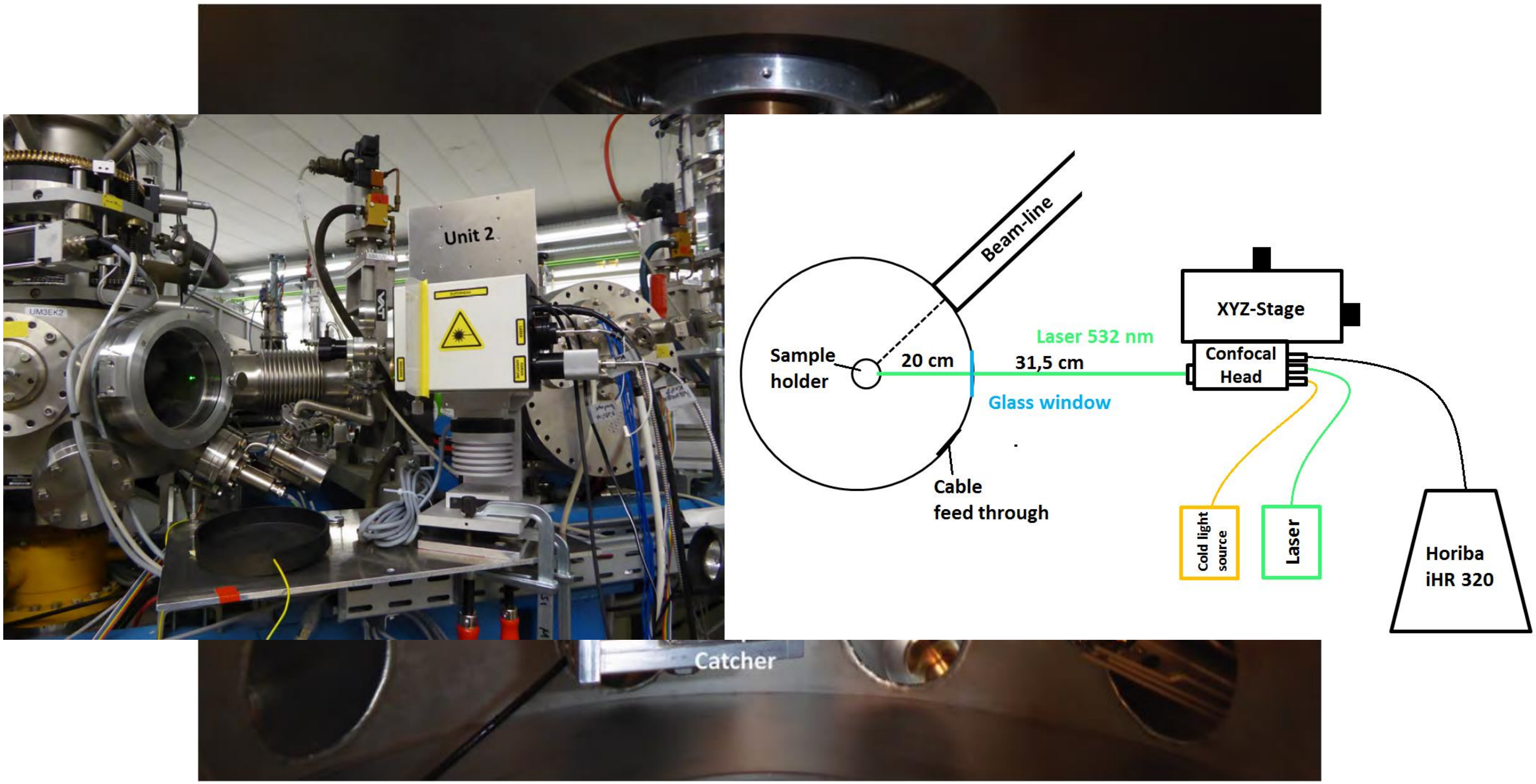
NV-center formation by passage of swift, heavy ions through diamond



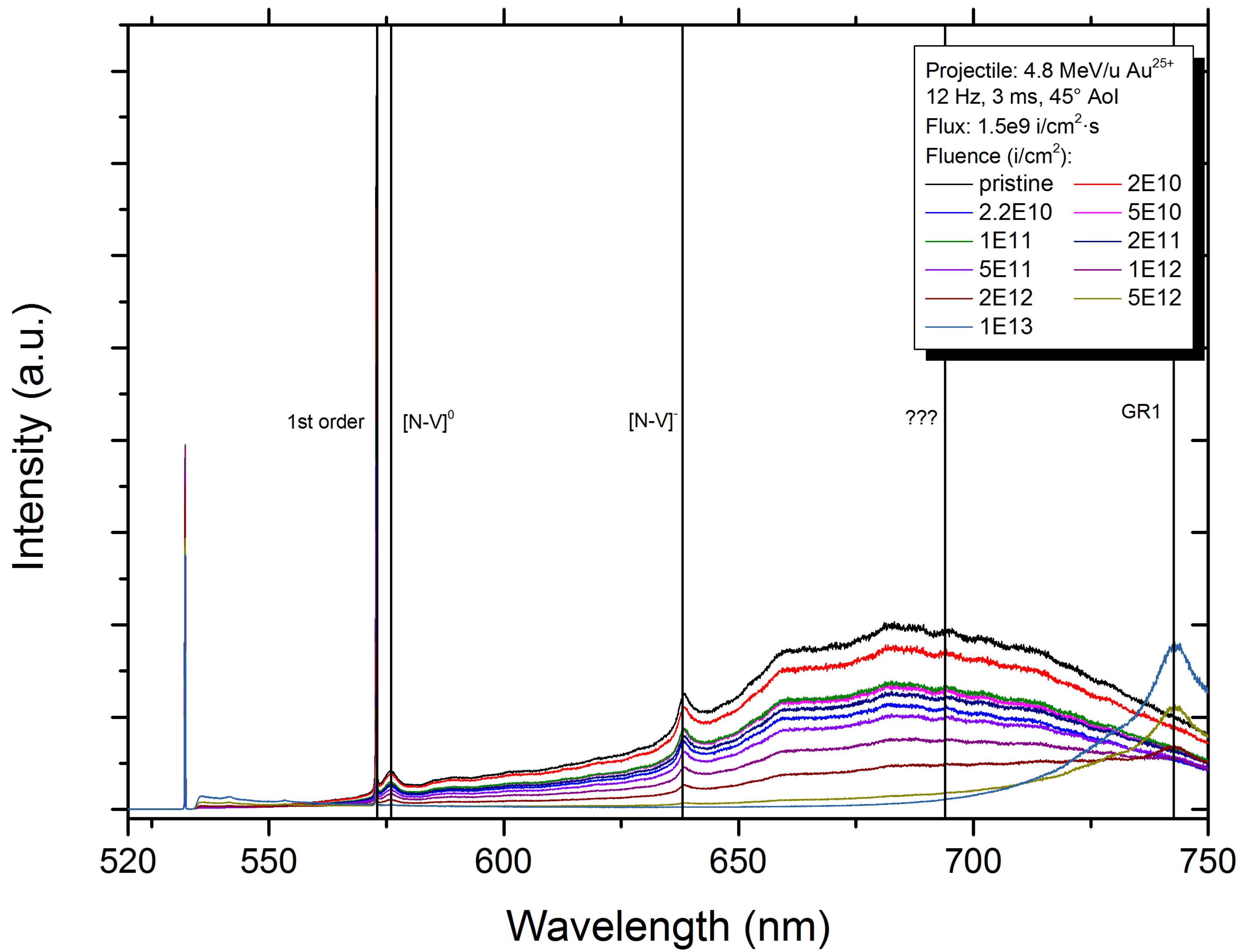


- Nitrogen present as P1 centers from CVD growth
- 1.1 GeV Au ions deliver electronic excitation and displacement damage (3E12 i/cm^2)
- NV centers are formed locally by passage of SHI, without thermal annealing
- mechanism of SHI induced NV-center formation not known

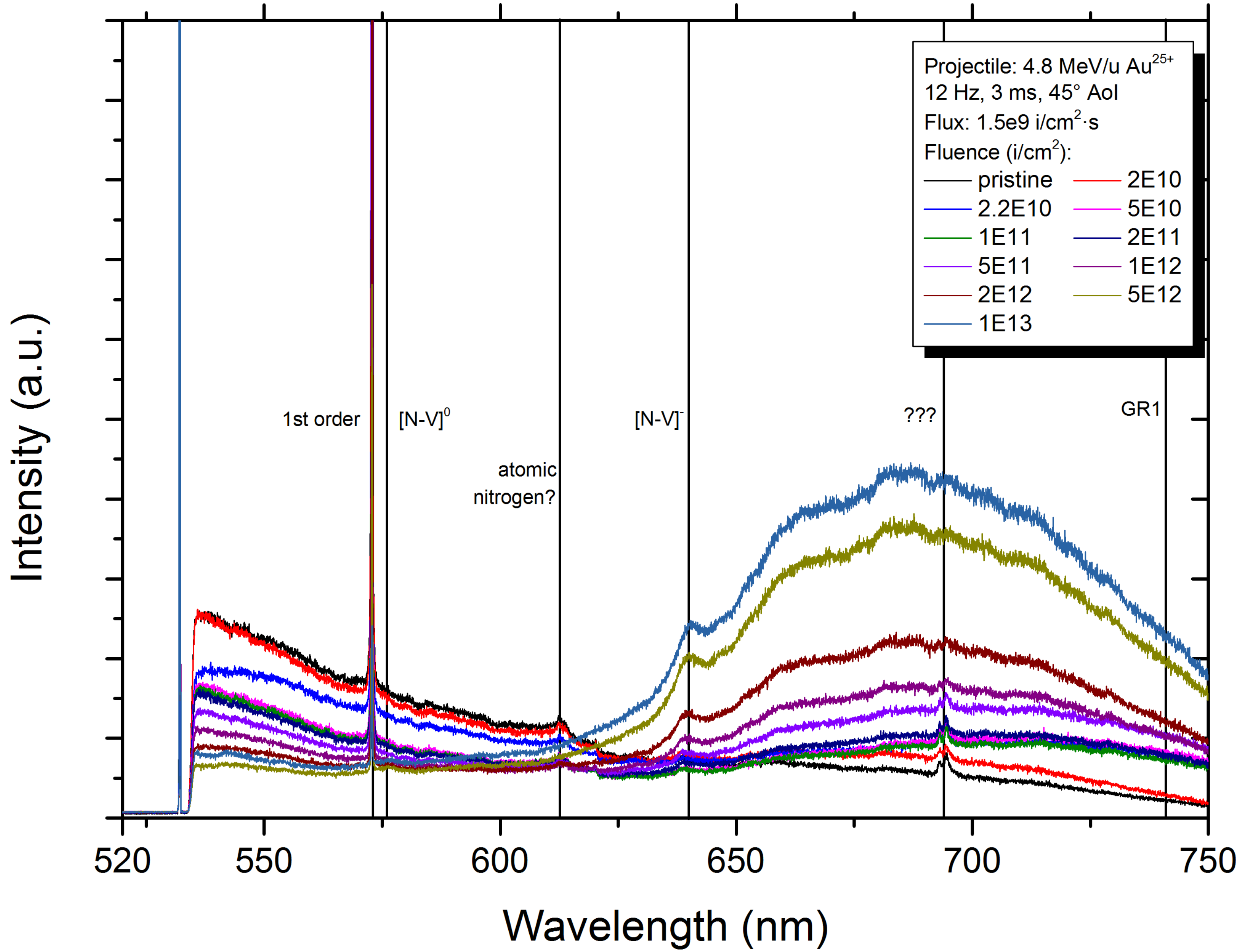
In situ Raman Spectroscopy



Online monitoring of beam-induced color centers – standard E6



Online monitoring of beam-induced color centers –Yellow Diamond



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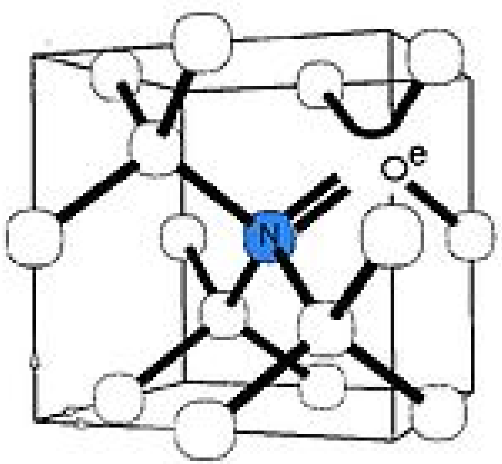
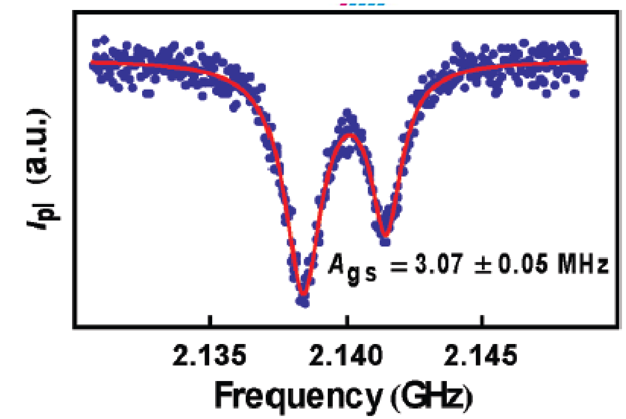
The Nitrogen-Vacancy center in diamond – a color center for magnetometry and quantum computing

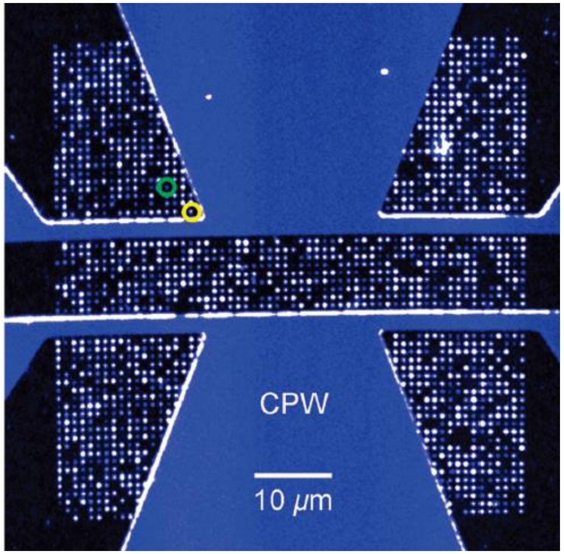


https://en.wikipedia.org/wiki/nitrogen-vacancy center

- up to ms spin coherence time at room temperature
- optical single spin read-out/manipulation (optical detection of magnetic resonance)
- single spin physics, entanglement and few-qubit control has been demostrated with e- and nuclear spins

→ **need for reliabe formation of high quality NV-centers**





D. Toyli, et al., NanoLett. 2010
G. Fuchs, et al., Nat. Phys. 2010
J. Schwartz, et al., NJP, 2012

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

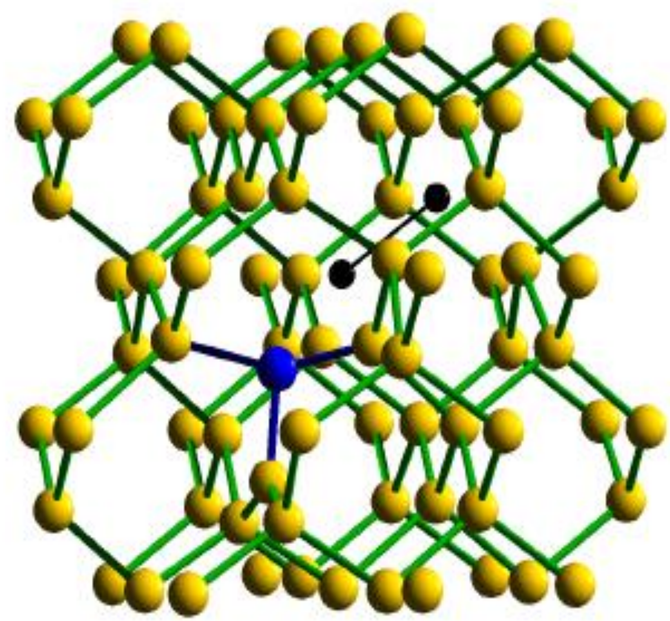
What are mechanisms of NV-formation ?

$N_{substitutional} + V \rightarrow NV^{0,-}$

vs.

$N_{interstitial} + V_n \rightarrow NV^{0,-}$

J. Schwartz, et al., NJP 2012, JAP 2014



- A nitrogen atom on a split interstitial site (blue), close to two vacancies (black). Carbon atoms in yellow. NV's form during annealing at >300°C

J. Adler, R. Kalish, et al., J. of Physics, 2014

- di-vacancy formation favored over NV formation during annealing of N rich diamond after vacancy producing irradiation

P. Deak et al. PRB 2014:

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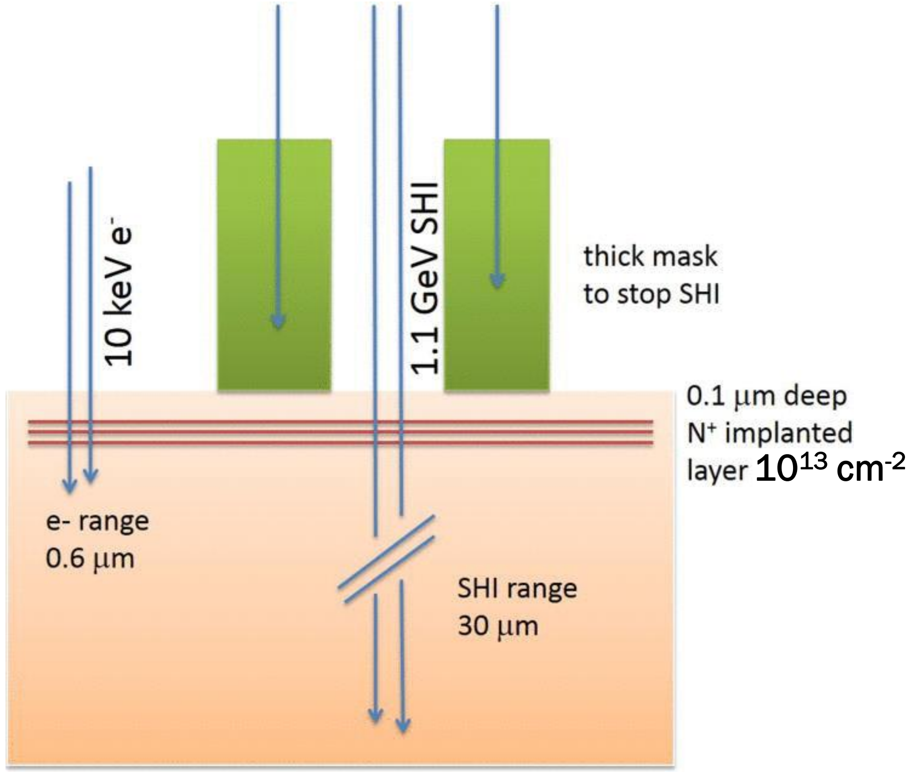
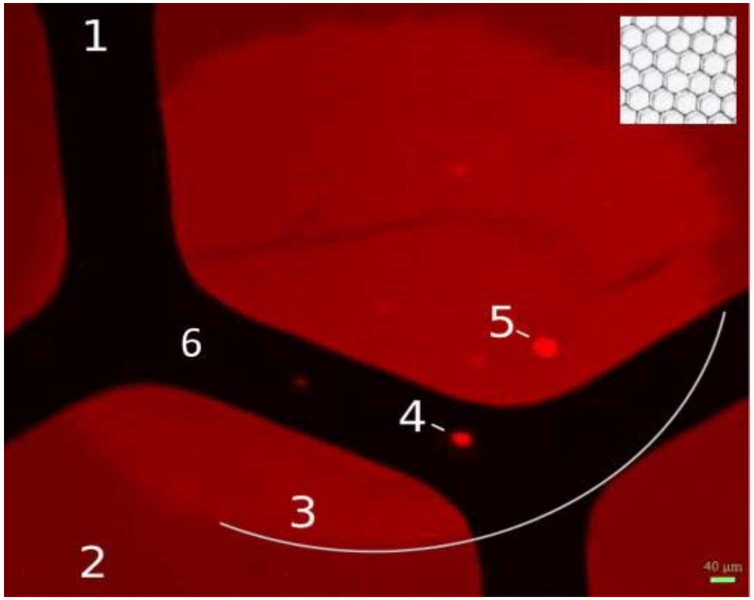
NV formation by electronic excitation from passage of ions through diamond ?





	Nitrogen implant	heavy ions	e- beam	See NVs ?
1	No	No	No	No
2	No	Yes	No	No
3	**Yes**	**Yes**	**No**	**Yes !**
4	Yes	No	Yes	Yes
5	**Yes**	**Yes**	**Yes**	**Yes**
6	Yes	No	No	No

- Swift heavy ions, 5 MeV/u Uranium-ions, 5×10^{11} cm^{-2}
- Electronic stopping power: ~50 keV/nm (Bragg peak)
- delta-electrons up to ~10 keV

J. Schwartz, et al., J. Appl. Phys., 2014

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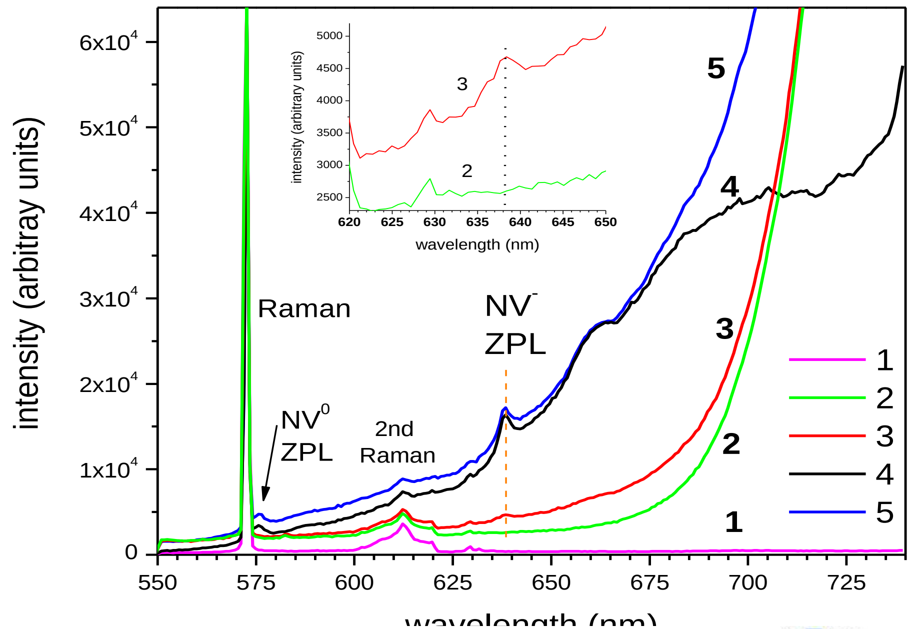
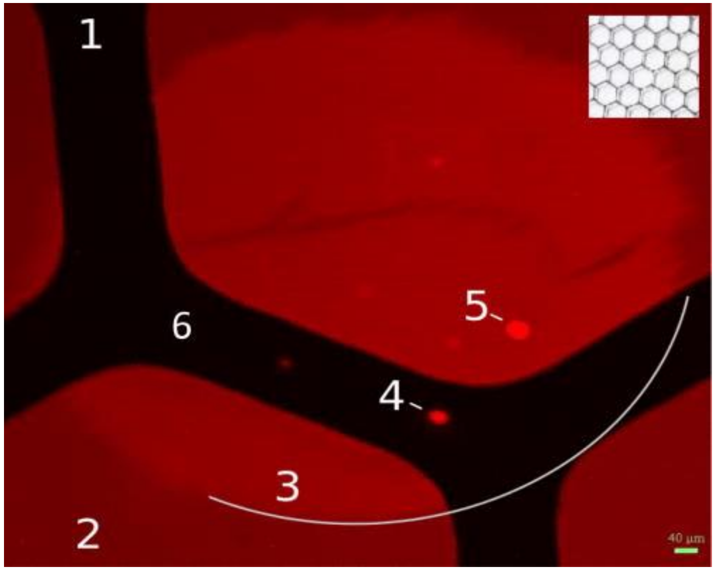
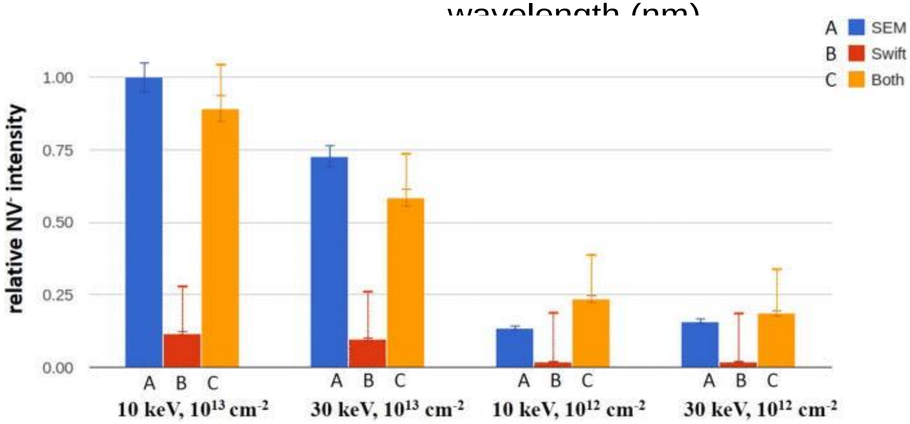
Local NV-center formation by electronic excitation from swift, heavy ions, without thermal annealing







J. Schwartz, et al., J. Appl. Phys., 2014

NV's form in the nitrogen implanted layer during the passage of swift heavy ions

Formation yield is ~0.1 of yield from high fluence e-beam and ~0.02 of yield from thermal annealing

- Low absolute NV/N ~ 10^{-4}–10^{-3}
- Not clear if effects of swifts and e-beam are additive

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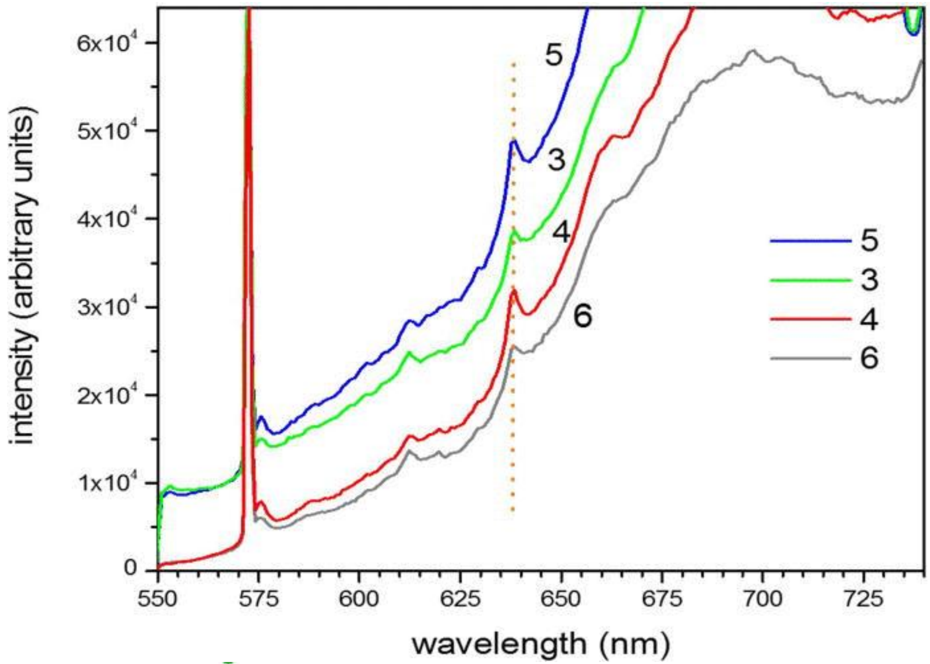
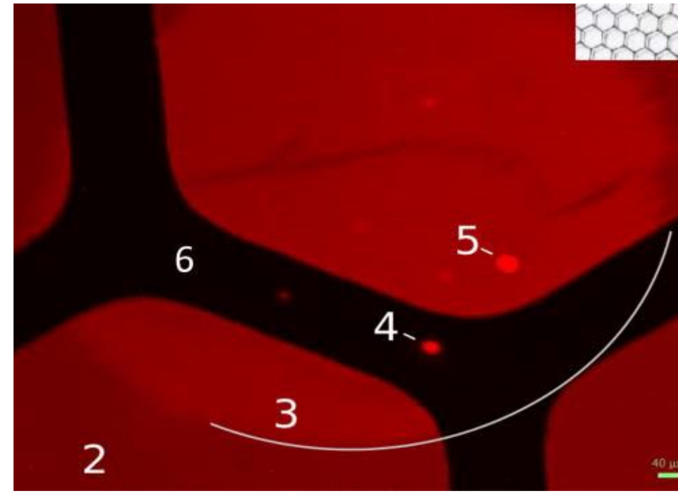
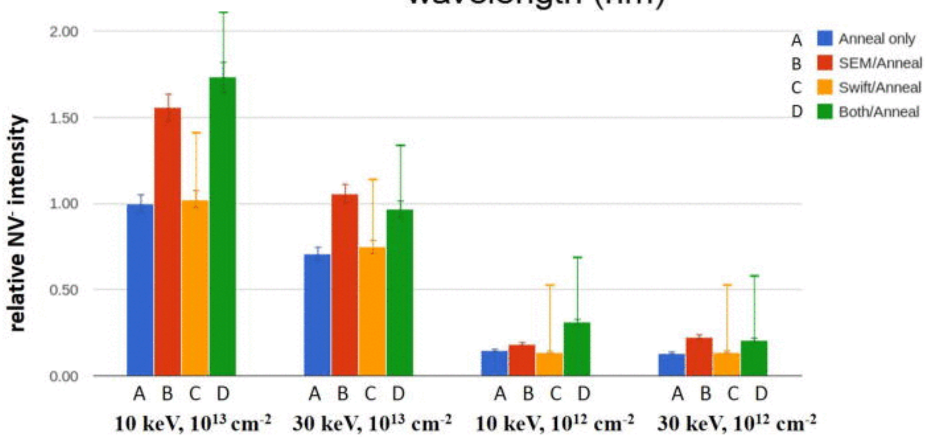
Local NV-center formation by electronic excitation from swift, heavy ions – yields after thermal annealing





J. Schwartz, et al., J. Appl. Phys., 2014



- NV yields higher by factor 1.7x for e-beam and then thermal annealing vs. thermal annealing alone (850 °C, 1 h, in vacuum)
- But no evidence for additive effect of swifts and thermal annealing
- Formation yield is ~0.1 of yield from high fluence e-beam and ~0.02 of yield from thermal annealing
- absolute NV/N ~ 10^{-4}–10^{-3}

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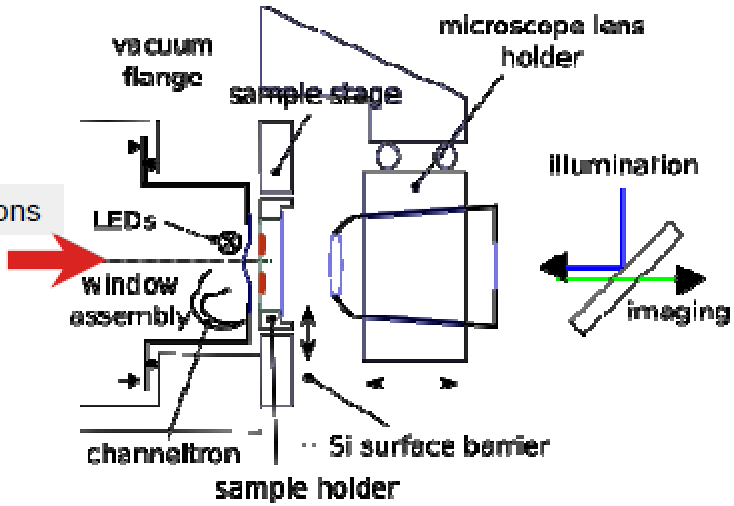
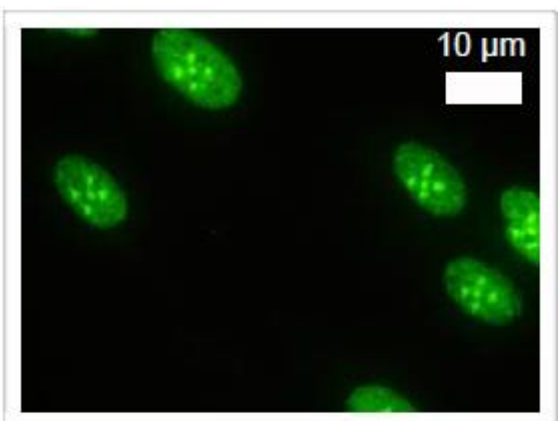
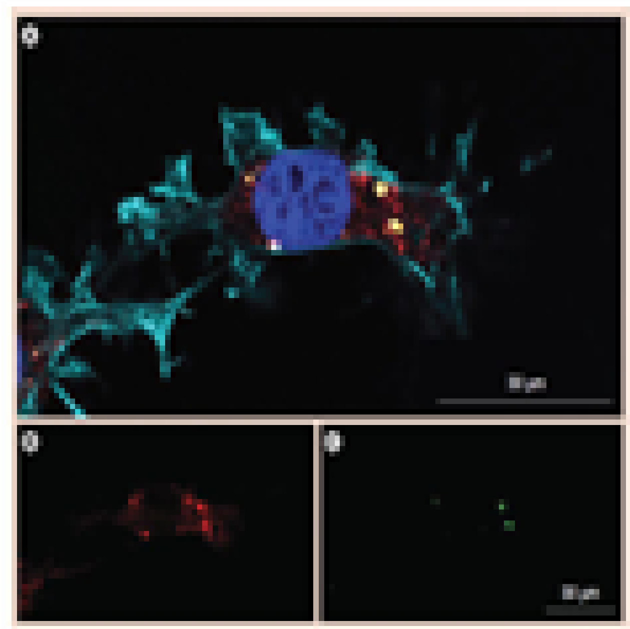
Biophysics and medical applications

Radiation effects in cells- Ion beam microprobe





Functionalized nanodiamond particles for medical imaging



Outloook

WP 17. Materials for extreme thermal management (PowerMat)

1. Optimize metal matrix for better response to fast extracted heavy ion beams

2. Optimize diamond particle sizes and distribution for different applications

3. Optimize color centers in diamond for different applications (luminescence screens, QD’s and medical imaging) - using different doping recipe

4. Explore the use of intense ion pulses for materials processing far from equilibrium


Thank you for your attention!