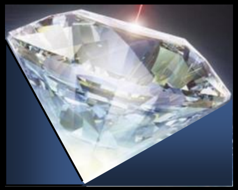
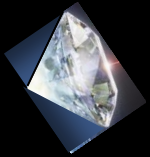
INTERACTIONS OF ACCELERATED

CHARGE PARTICLES WITH DIAMOND







Prof. Elias Sideras-Haddad
University of the Witwatersrand
Johannesburg

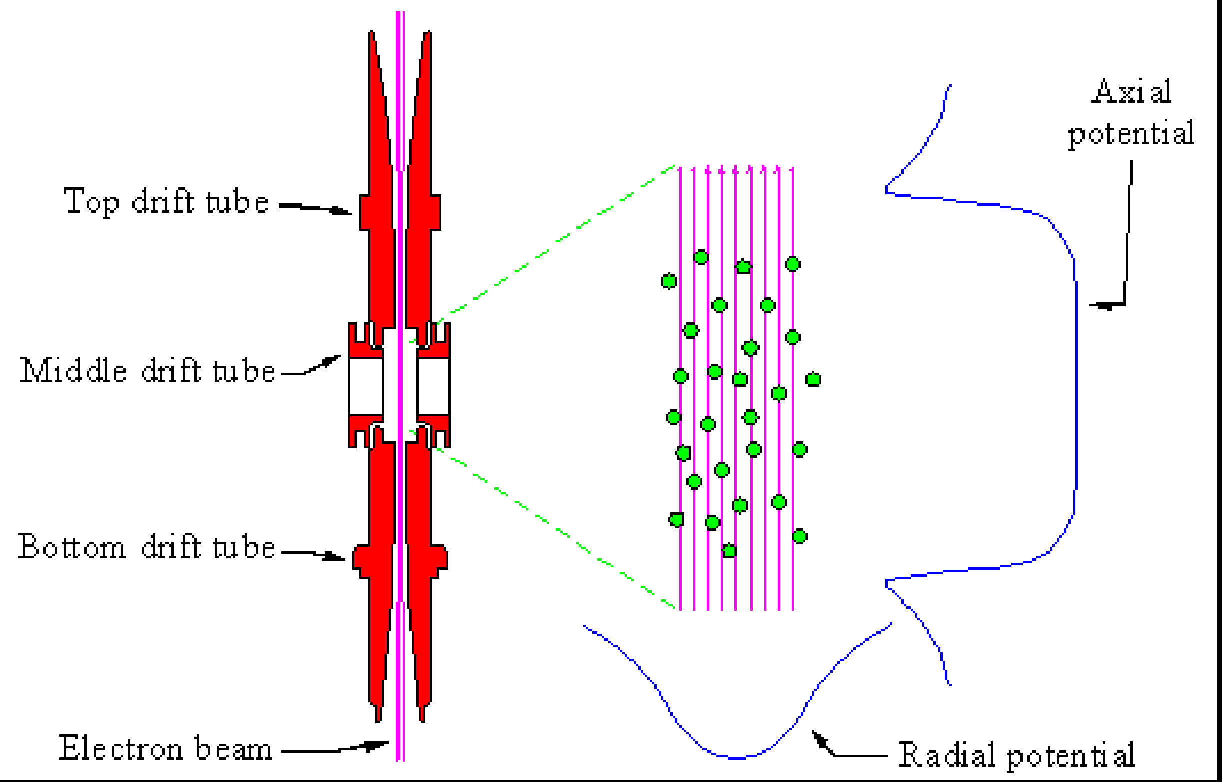

Most of the Universe consists of Highly Ionized Matter

Highly Ionized Matter : Ions with very few electrons

Laboratory Access to such ions only recently possible :

- **Large nuclear accelerator facilities (GSI) / LARGE VELOCITIES**
- **EBIT (Electron Beam Ion Trap) SLOW HIGHLY CHARGED IONS**

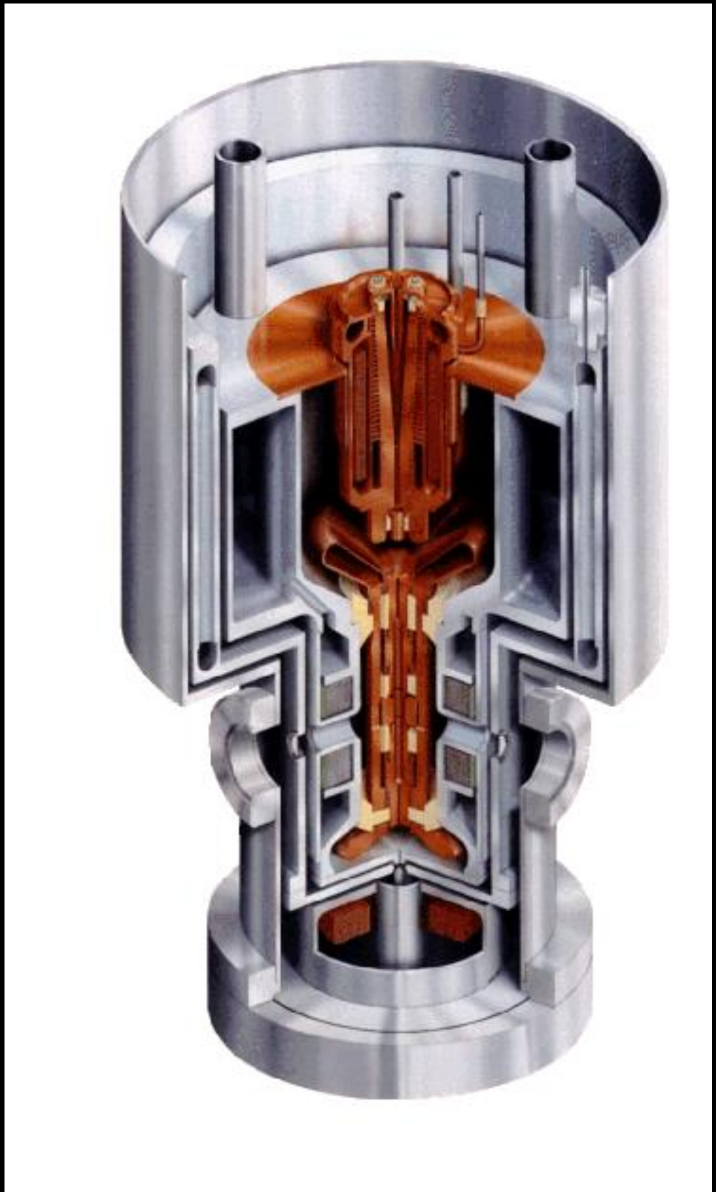
How EBIT Works



High-current-density electron beam (up to 5000 A/cm^2) passing through a series of three drift tubes.

Ions are trapped radially by the space charge of the electron beam itself, and axially by voltages applied to the end drift tubes.

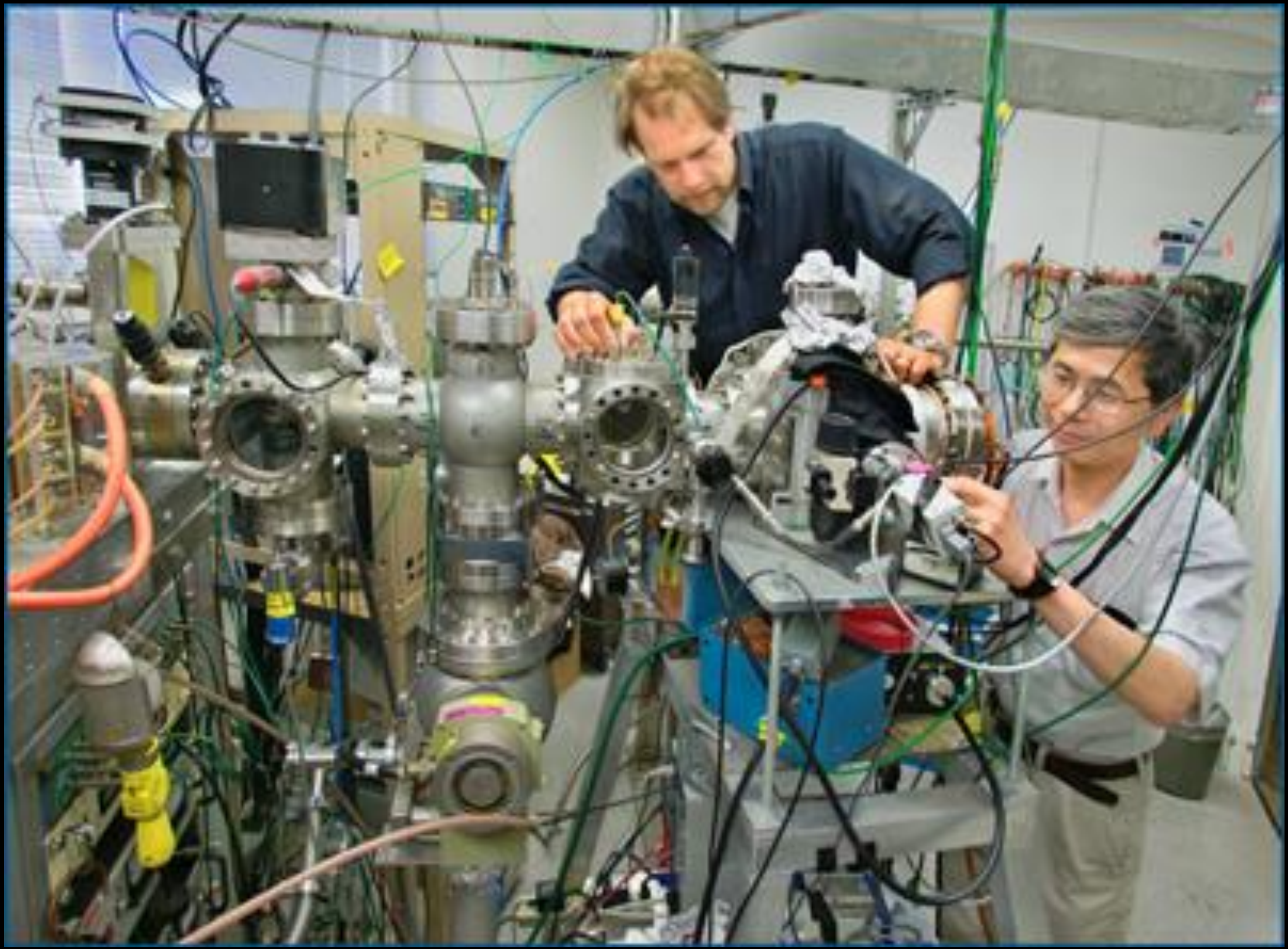
The electron beam is magnetically compressed by a high magnetic field from a pair of superconducting Helmholtz coils.



As electrons collide with the ions in the beam, they strip off electrons until the energy required to remove the next electron is higher than the beam energy.

The LLNL/EBIT is capable of an electron beam energy of about 200 keV, enough to make Bare Uranium (U92+, a uranium nucleus with no electrons around it).

The EBIT facility used in the present studies is located at Lawrence Berkeley National Lab (LBNL)



SHCI -Surface Interactions

The outstanding property of a multiply charged ion:

high potential energy.

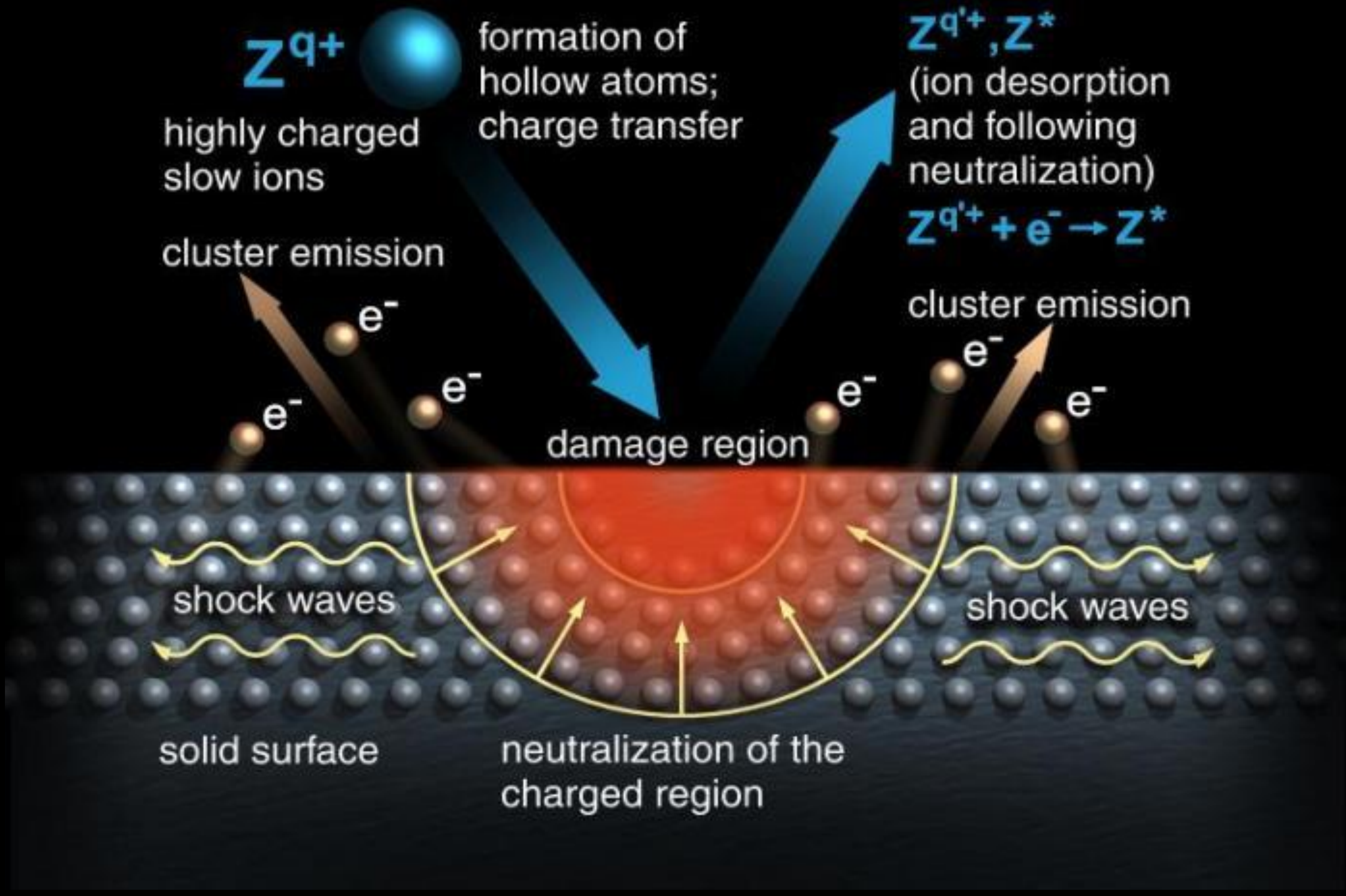
The potential energy of a SHCI is the sum of ionization potentials of the ion. (Xe^{54+} has 202 keV)

Power densities of the order of ***$\sim 10^{14}$ W/cm^2.***

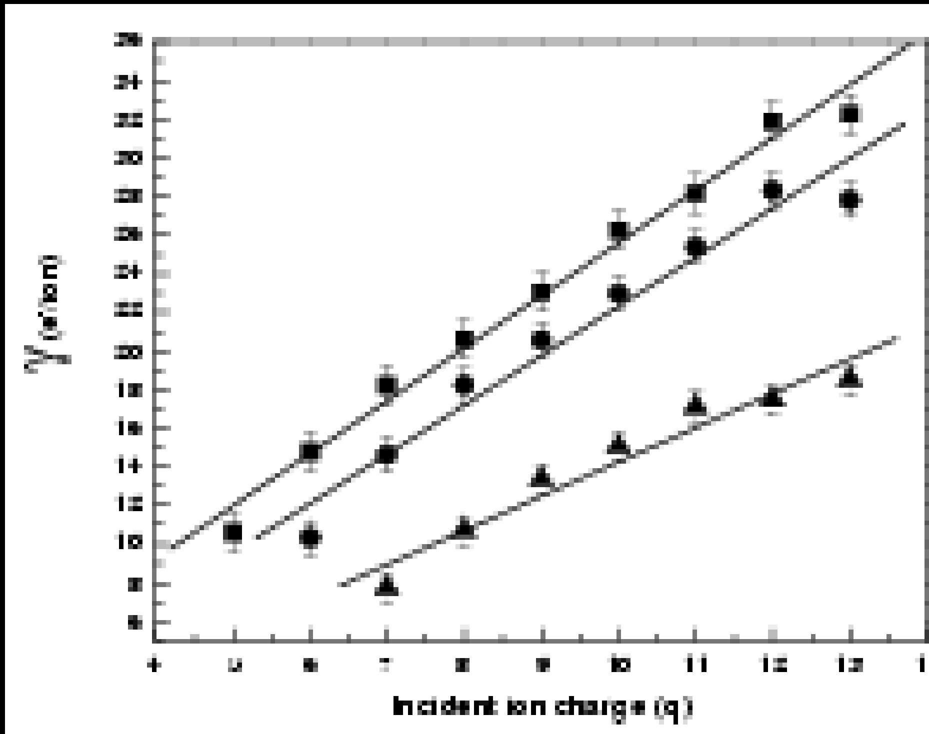
Key Questions

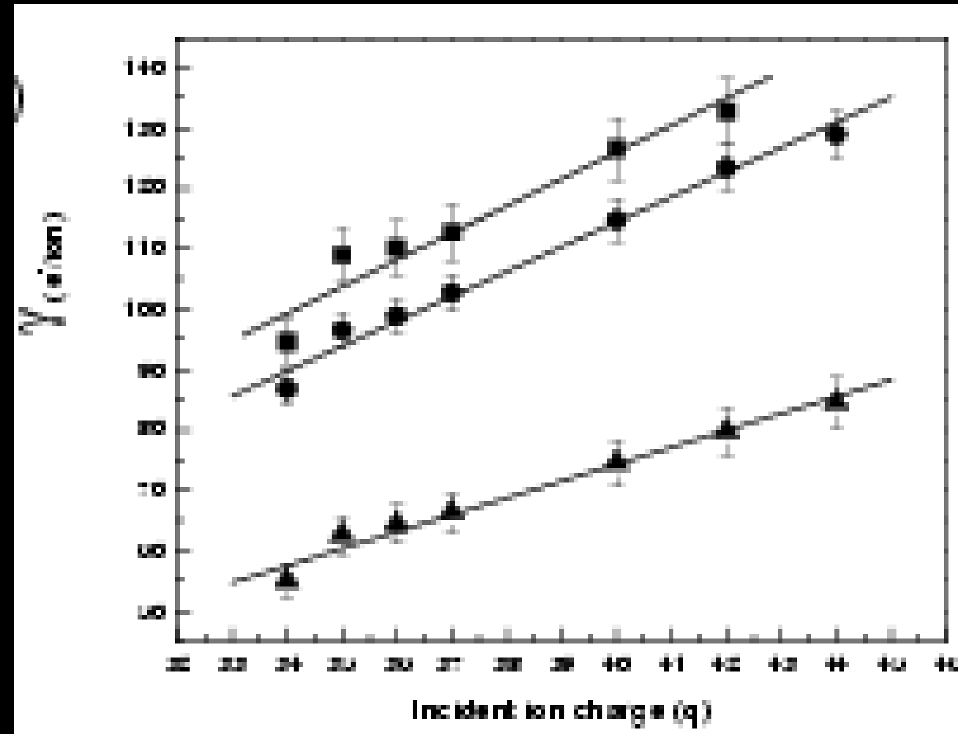
•how does the solid surface respond to transfer of such enormous potential energy in interactions with SHCI

•what are the applications of the surface response.



Z^q+
highly charged slow ions
formation of hollow atoms; charge transfer
Z^q'+, Z*
(ion desorption and following neutralization)
Z^q'+ + e⁻ → Z*
cluster emission
cluster emission
e⁻
damage region
shock waves
shock waves
solid surface
neutralization of the charged region



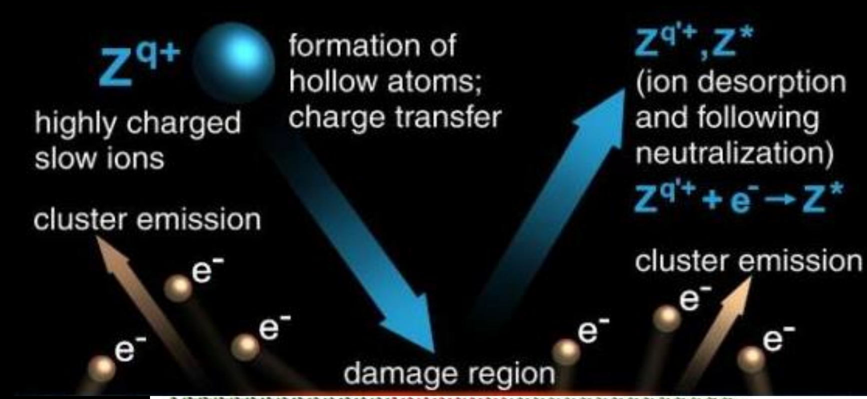


Phosphorous Ions

Xenon Ions

■ **IIa Diamond**
● **IIb Diamond**
▲ **Aluminium**

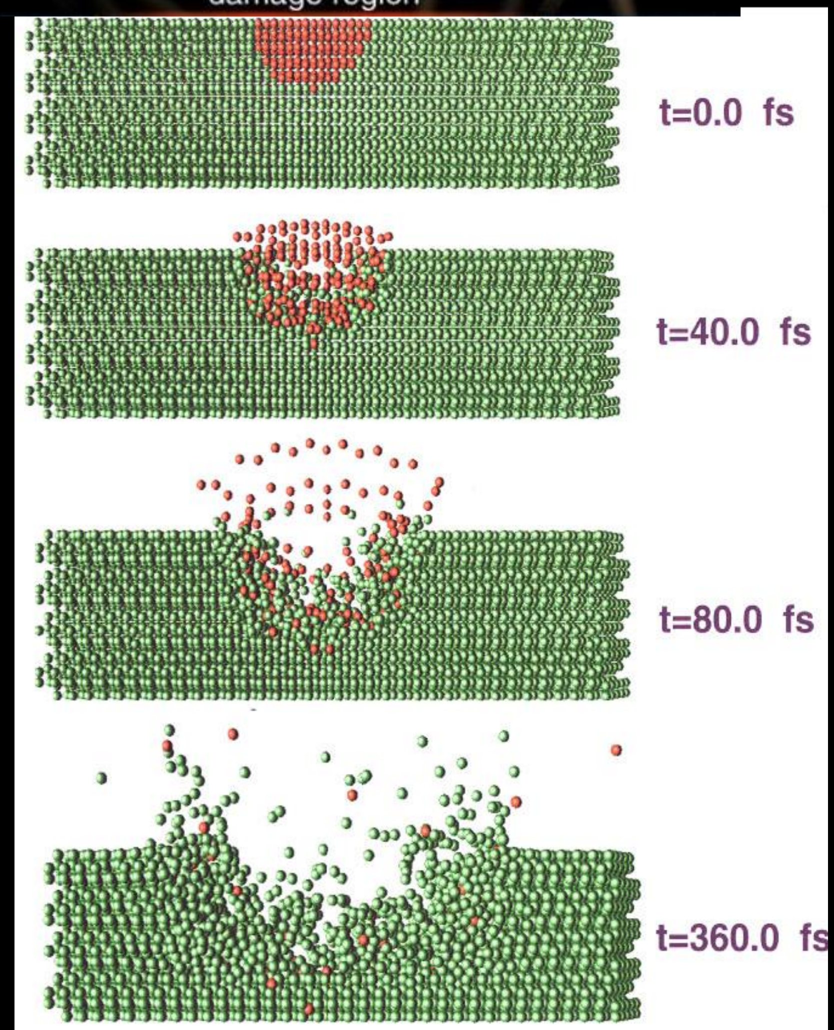
The largest electron emission yields ever observed!!!



Impacts with SHCI:

High spatial and temporal localization of the energy deposition that opens a new regime of ion-solid interactions where femtosecond effects can be induced on a nanometer scale.

<u>COULOMB EXPLOSIONS !</u>



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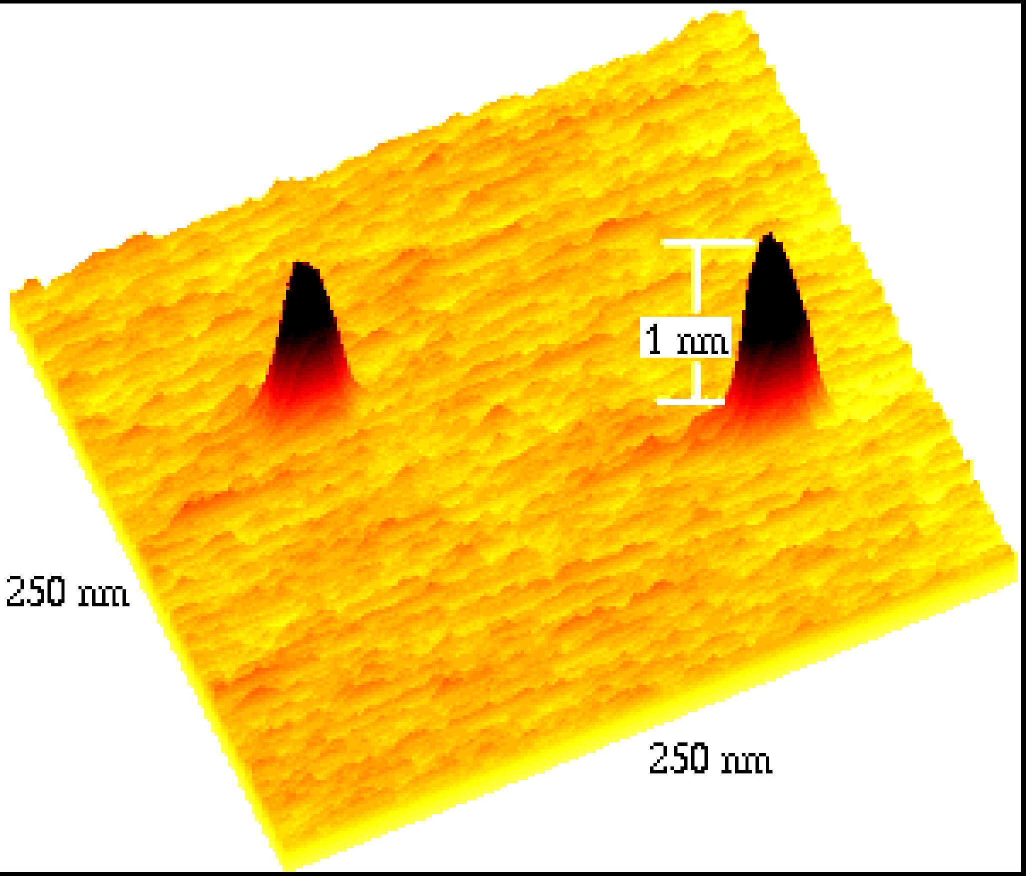
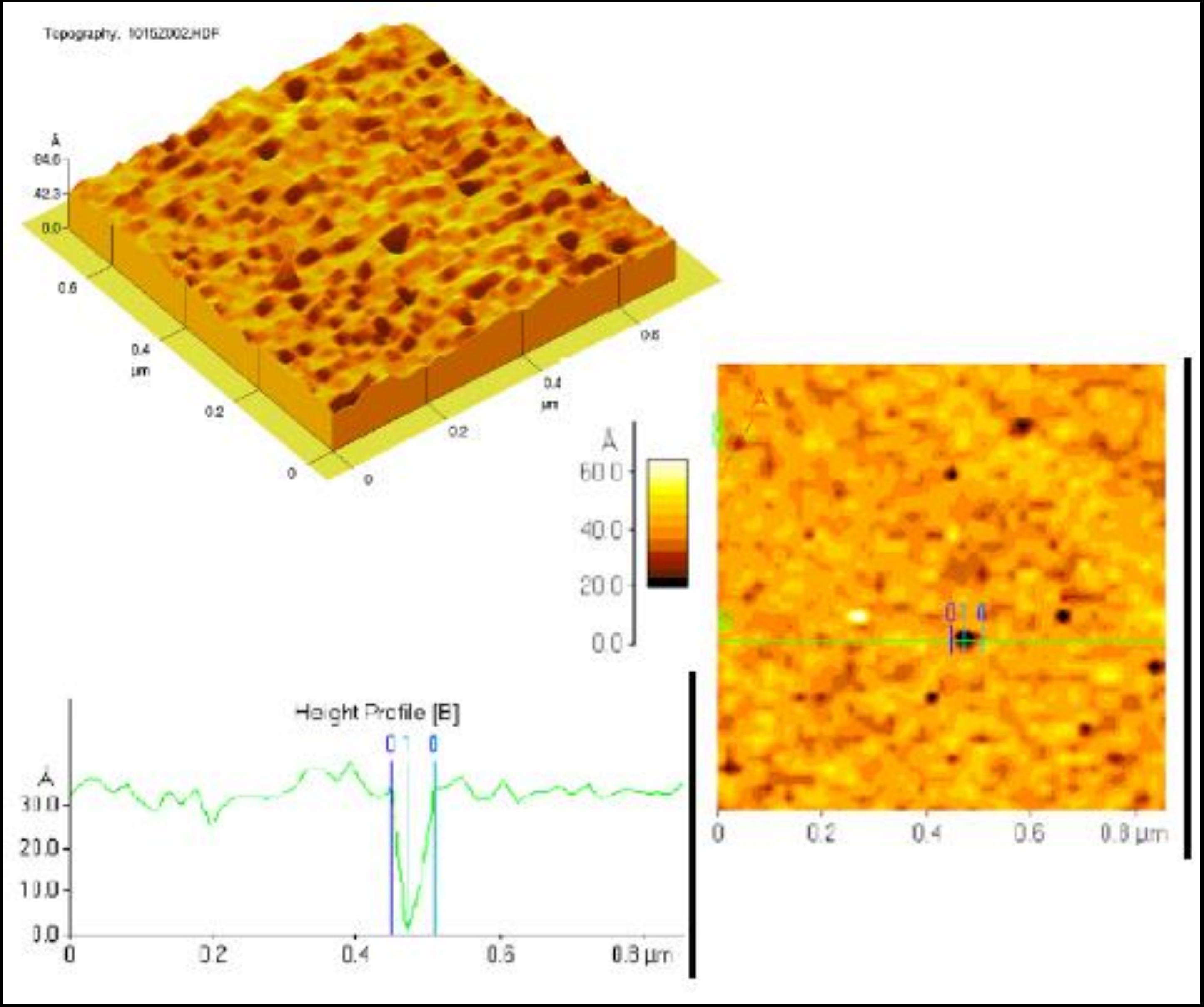


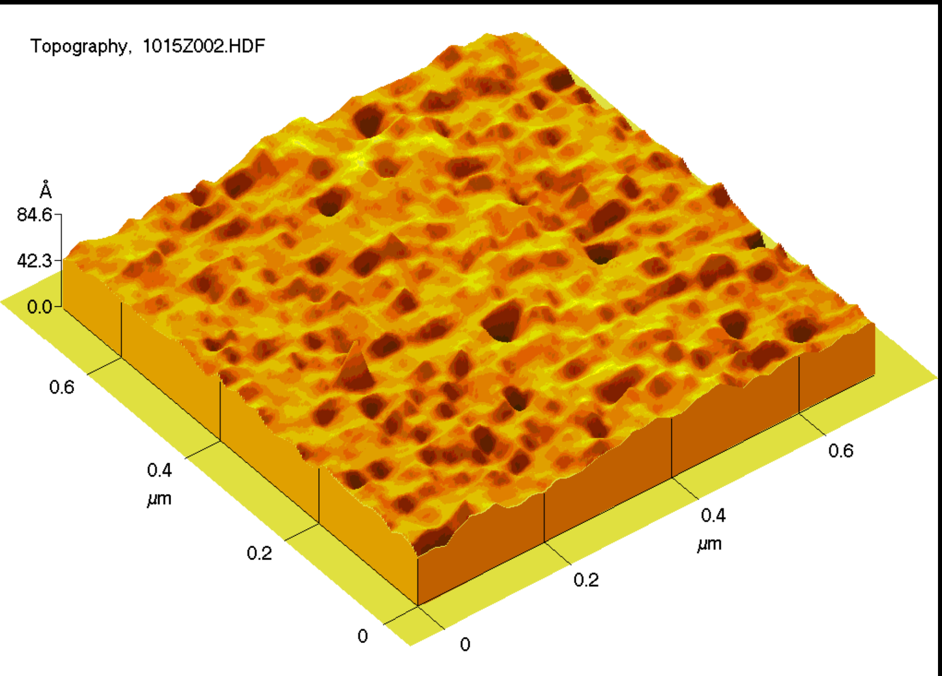
Coulomb Explosions !

AFM Images of structures on mica from EBIT at NIST - USA

Nanostructuring of atomicly flat diamond IIA surface (111) with Xe $^{44+}$ from the EBIT at LBNL



The intense electronic excitation induced by the highly charged ions leads to motion of the atoms in the surface, which can freeze in a unique manner into metastable geometric nano-structures with different electronic properties.



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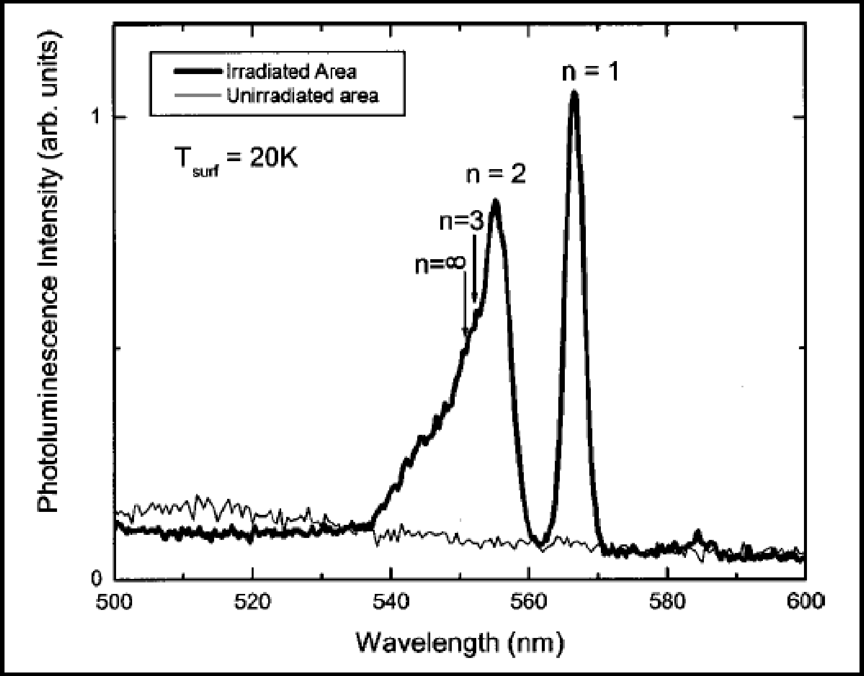
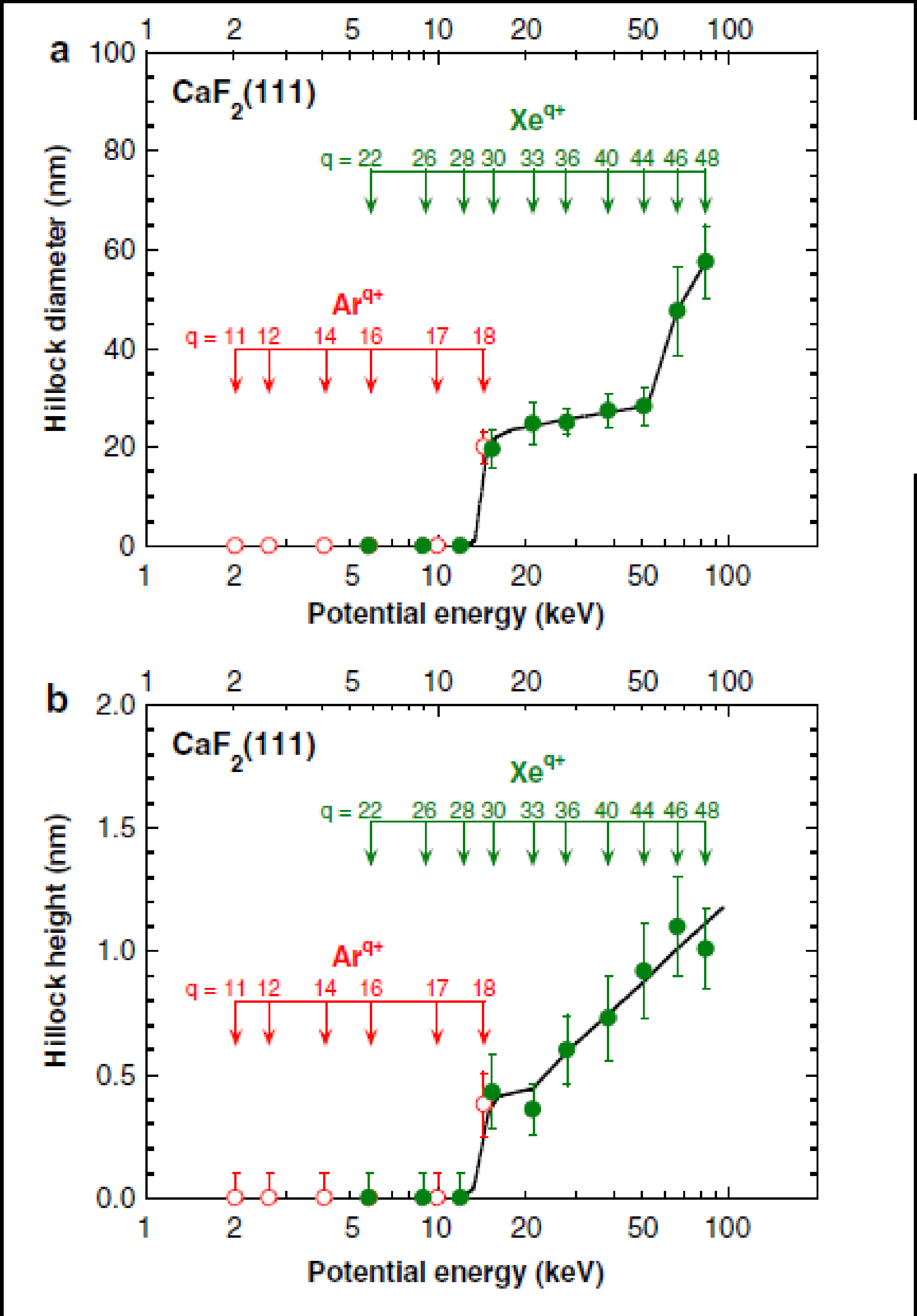


Photoluminescence at 20 K from Si (100) irradiated with Xe^{+44} reveals excitonic signatures



Mean diameter (top) and height (bottom) of hillock-like nanostructures as a function of the potential energy of Ar^{q+} (open symbol) and Xe^{q+} (full symbol) projectiles.

Hillocks are found only above a potential energy threshold of about 14 keV.

SHCI a Tool for Fabrication of Single Atom Devices

and ….

Quantum Computing….???

The application that has many researchers excited is

Quantum Spintronics,

which could lead to practical quantum information systems and possibly to quantum computer.

THE DIAMOND AGE OF SPINTRONICS

Quantum electronic devices that harness the spins of electrons might one day enable room-temperature quantum computers—made of diamond

By David D. Awschalom, Ryan Epstein and Ronald Hanson

2007 SCIENTIFIC AMERICAN

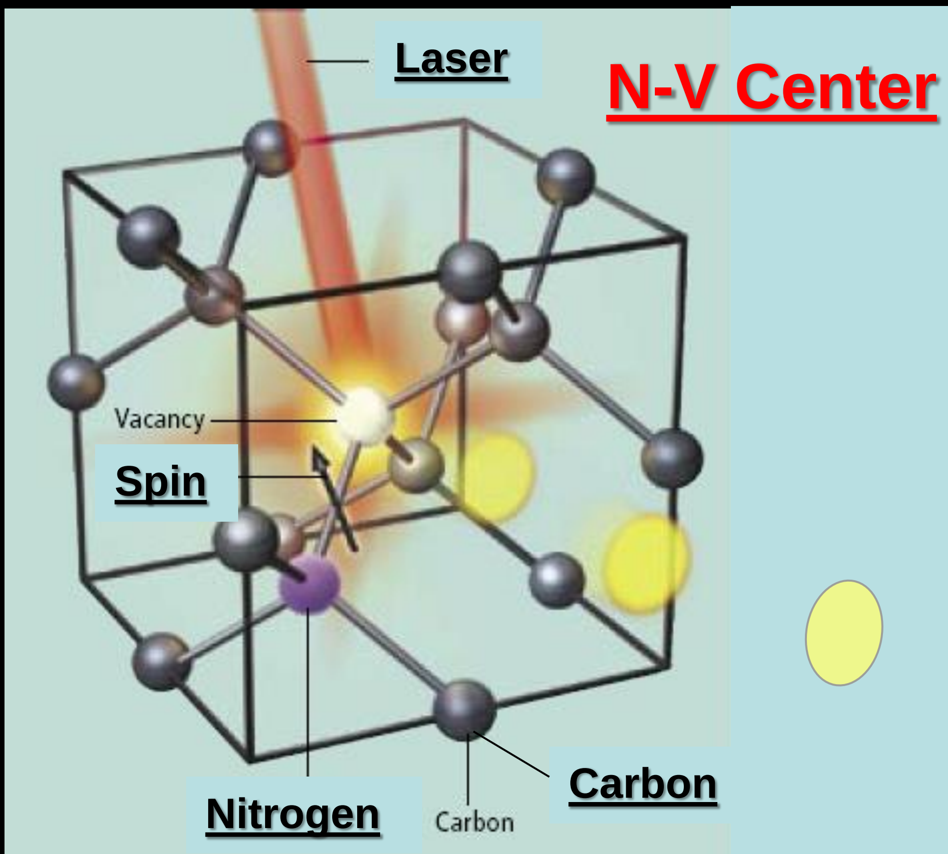
The most advanced quantum information-processing units to date are spins of ions trapped in electromagnetic fields.

Still impractical……

Why not Qubits, which reside directly in a solid substrate ?

- **Can spins in solids be individually addressed and controlled?**
- **Can scientists come up with suitable interactions to implement quantum logic gates reliably?**
- **Can spins in solids maintain quantum information long enough to perform a useful number of operations on that information?**

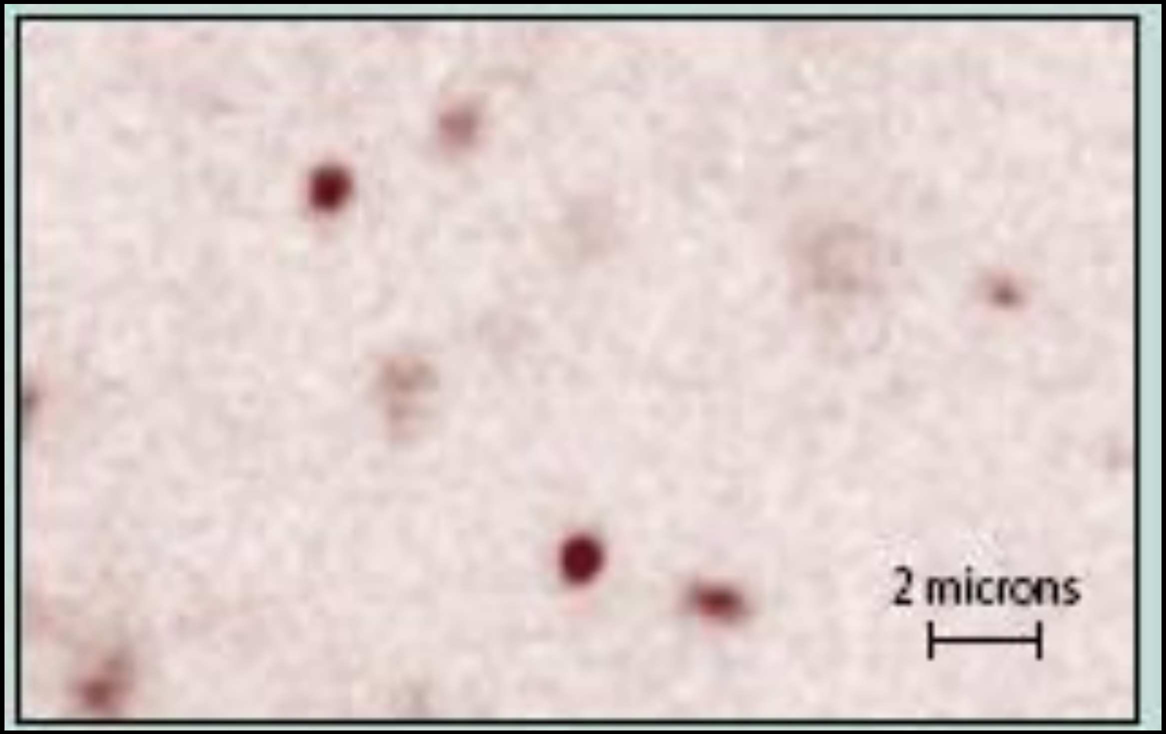
Surprisingly, one of the most promising host materials for spins turned out to be ... DIAMOND !!!



A laser can repeatedly excite an electron at the N-V center, which each time emits a single photon in a specific quantum state when it decays back to its ground state.

Centers whose spin is in state 1 are much brighter than centers whose spin is in state 0.

Radio-frequency waves tuned to a precise frequency change the N-V centers back and forth between 0 and 1, passing through transitional states that are quantum superpositions of the two.



Diamond has been used in this way to demonstrate quantum cryptography prototypes, which rely on a steady supply of single photons.

Observation of Coherent Oscillations in a Single Electron Spin
F. Jelezko, T. Gaebel, I. Popa, A. Gruber, and J.Wrachtrup, Phys.Rev. Let. Vol 92 (2004), 7

- The N-V center exhibits quantum behaviour even at room temperature.

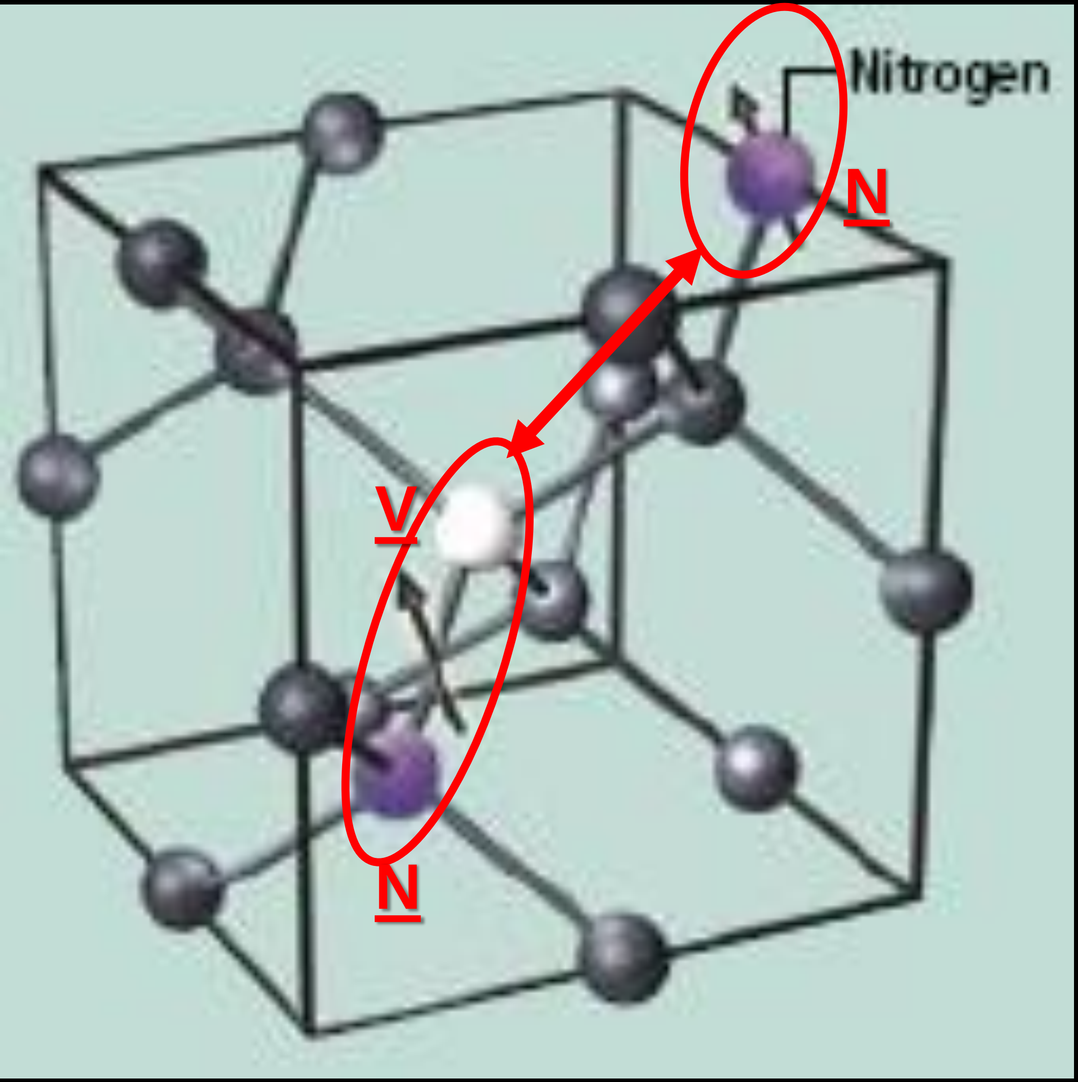
- Spins in solid materials typically suffer from two problems:

    - an interaction called spin-orbit coupling, which involves the electron's spin and its orbital motion.

    - magnetic interactions with other spins, such as the spins of the nuclei that make up the lattice.

In diamond, both these effects are very weak!

For example, the nuclei of carbon 12, which makes up 99 percent of natural carbon, have zero spin and thus no effect on the spin of an N-V center.



"Dark-Spins" in Diamond

[N-V] – N

INTERACTIONS

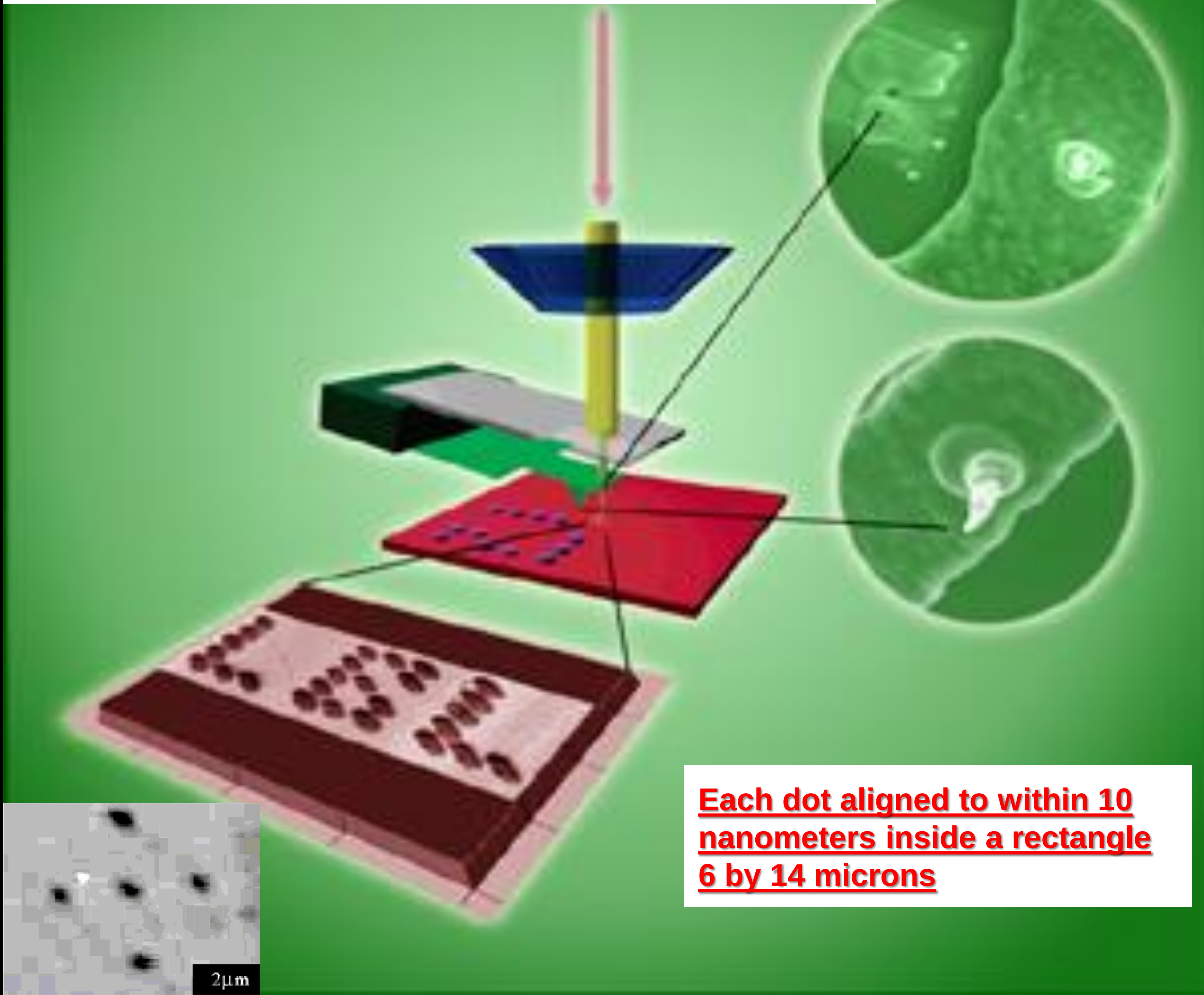
R. Hanson, F. M. Mendoza, R. J. Epstein, D. D. Awschalom, Phys. Rev. Lett. 97, 087601 (2006)

The fabrication of qubit arrays requires the placement of individual atoms with nanometer precision and high efficiency.

WE USE EBIT TO :

- **MONITOR SINGLE ION IMPLANTATION**
- **CREATE THE QUANTUM DEFFECT AT THE SAME TIME**
- **IN SITU AFM GUIDES IMPLANTATION**

AFM Assisted Single Ion Implantation

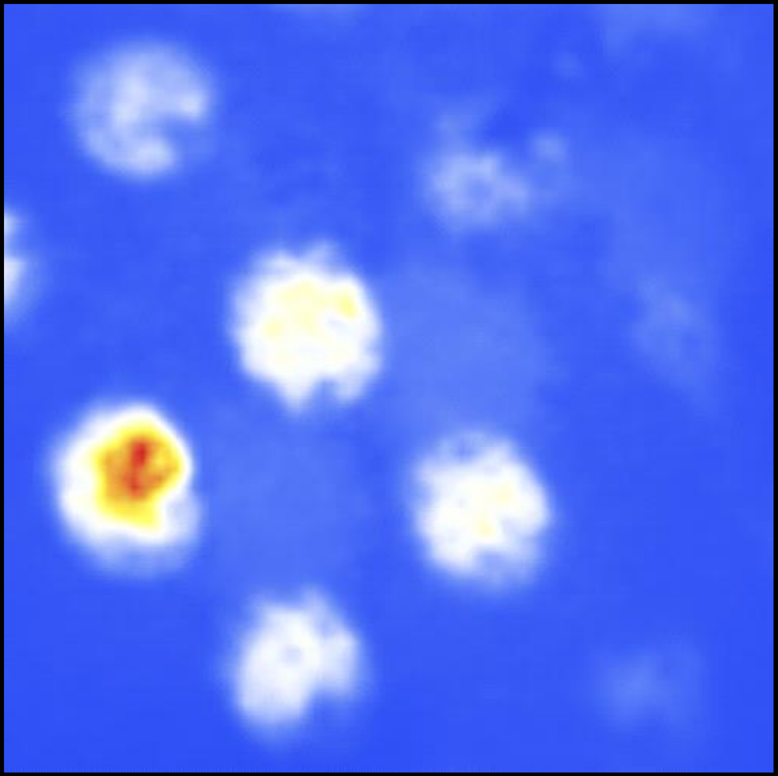


Each dot aligned to within 10 nanometers inside a rectangle 6 by 14 microns

Single-atom doping for quantum device development in diamond and silicon

C. D. Weis, A. Schuh, A. Batra, A. Persaud, I. W. Rangelow, J. Bokor, C. C. Lo, S. Cabrini, E. Sideras-Haddad, G. D. Fuchs, R. Hanson, D. D. Awschalom, T. Schenkel

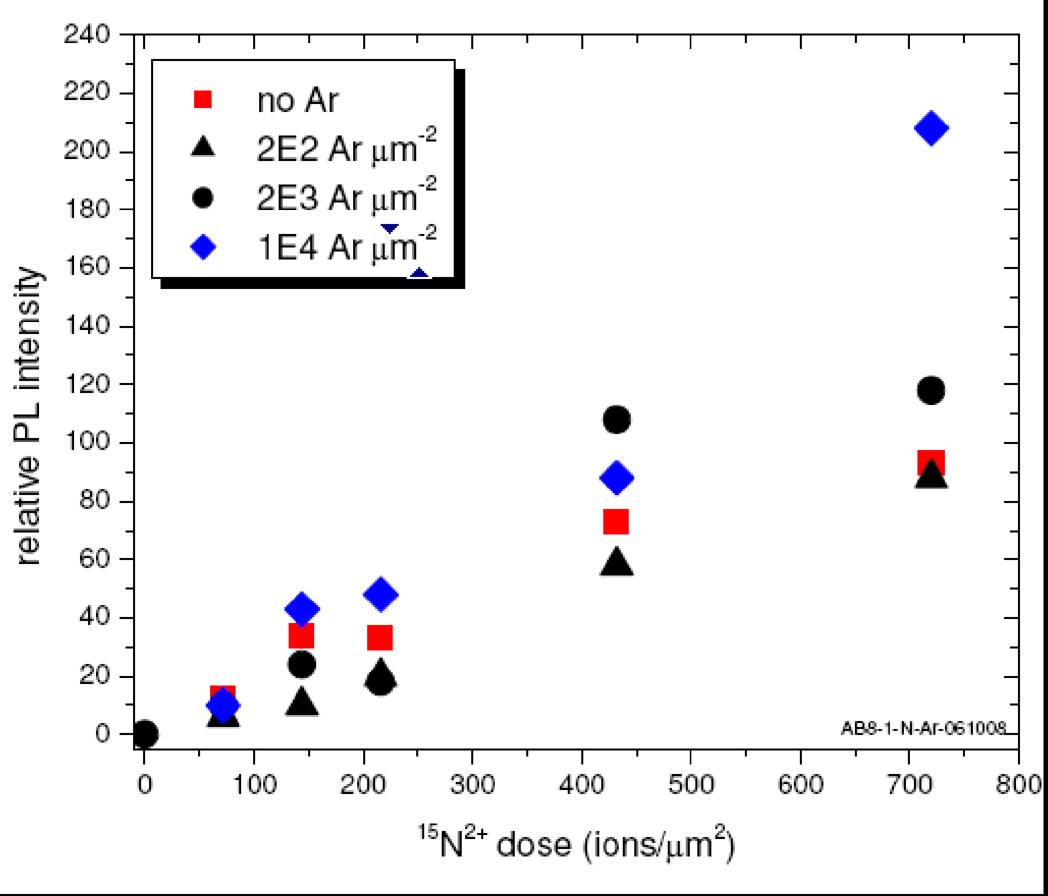
(Submitted on 12 Jun 2008)



Map of photoluminescence N-V intensities at RT of implanted nitrogen (^{15}N) ions. Used long pass filter (>630 nm) to suppresses light from NV^0 centers.

Micron scale spots with ensembles of $^{15}NV^-$ centers were formed (^{14}N <10 ppb) by implantation of atomic $^{15}N^{2+}$ after thermal annealing (800º C, 10 min., in Ar). The background signal from naturally occurring ^{14}N forming $^{14}NV^-$ centers in random locations is very low in these samples.

[^{15}N – V] - V INTERACTIONS



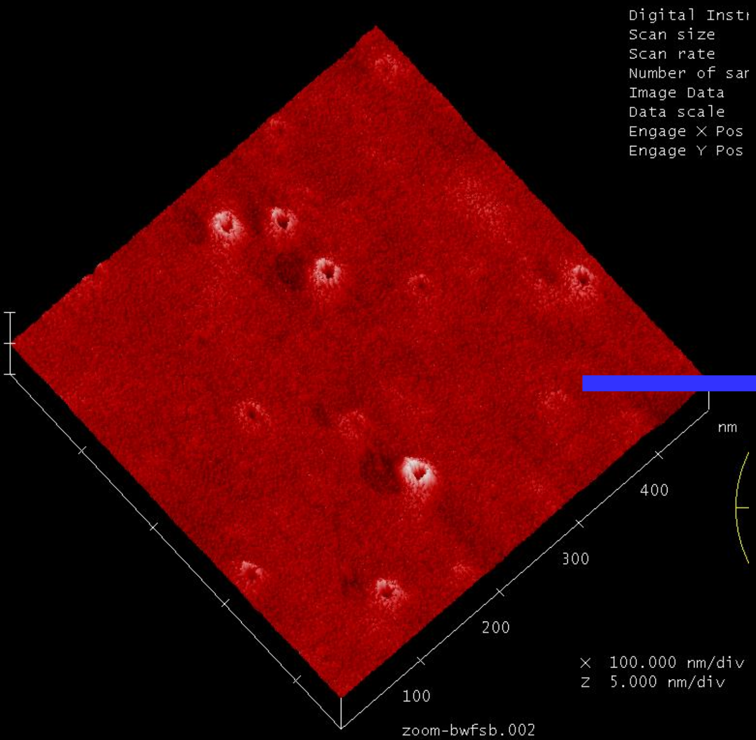
Try to achieve center formation with high efficiency Nitrogen doses and Argon ion (28 keV) co-implant doses were varied across the dot pattern to identify optimal local vacancy densities for $^{15}NV^-$ center formation.

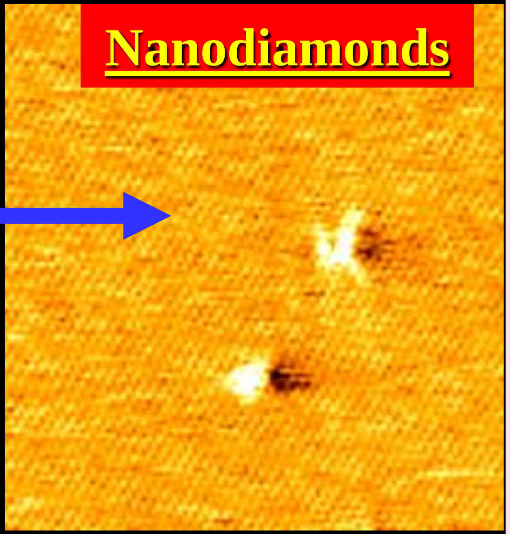
The PL intensity increases with increasing nitrogen implantation dose.

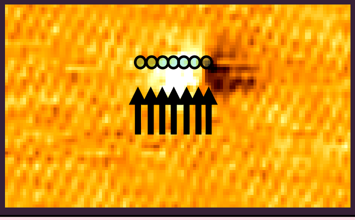
No PL from $^{14}NV^-$ centers was observed for implantation of only argon ions at a dose of $2x10^{11}cm^{-2}$. Co-implantation of argon ions ($2x10^{11}$ to 10^{12} cm^{-2}), together with implantation of nitrogen ions yields increased PL from a given nitrogen implant dose.

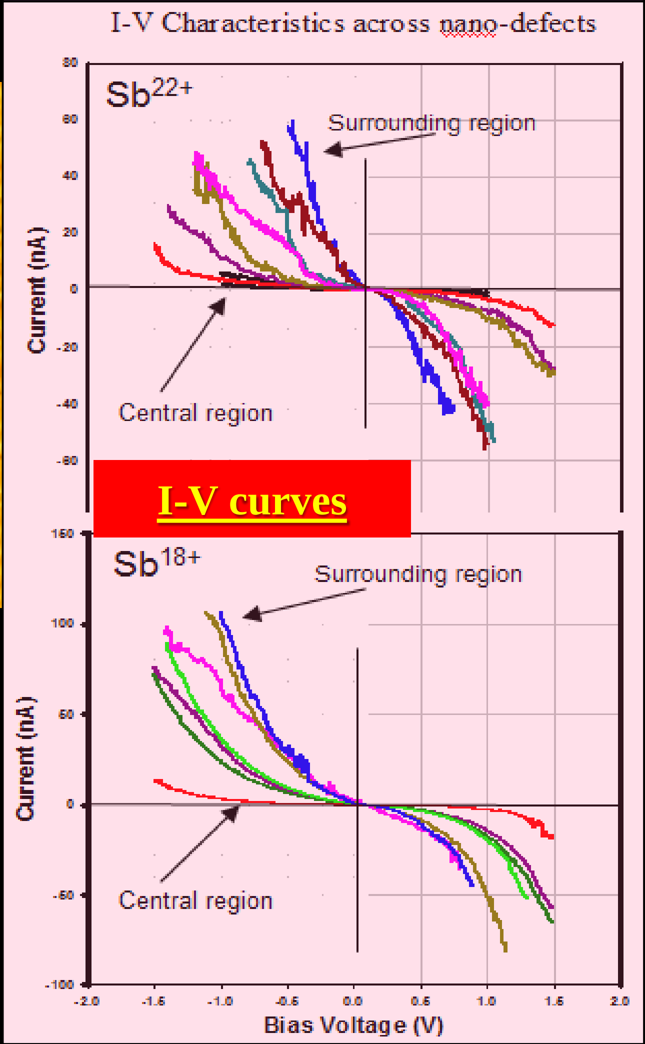
So, the presence of vacancies from the argon co-implant enhances NV- formation and opens a path to optimization of NV- formation

Diamond-Like Nano-Structures Induced by Highly Charged Ions on HOPG (WITS Team)







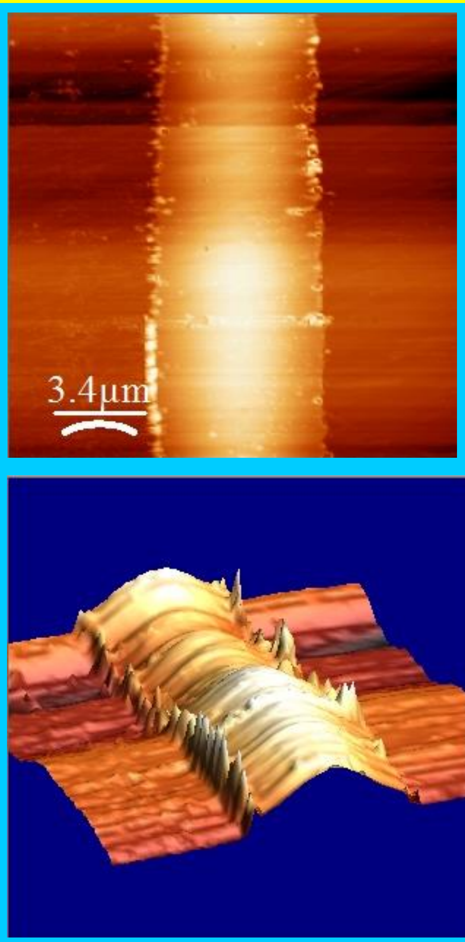


AFM image of nanodefects formed on HOPG after bombardment with Sb 18+

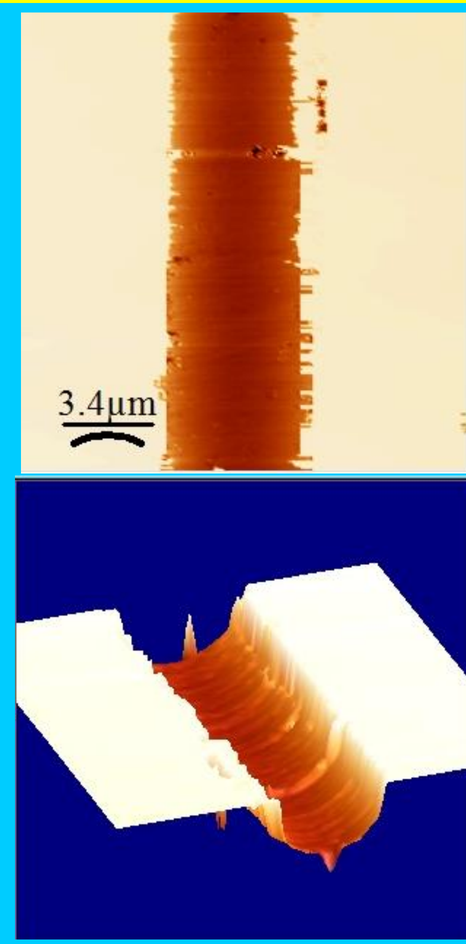
AFM image of nanodiamonds formed on HOPG after annealing in H2 atmosphere

Magnetic Ordering in Diamond after Proton Irradiation
(WITS – Ithemba LABS Team)

Topographical AFM



Magnetic Image MFM



Diamond Nano-Magnetic Domains for Diamond Spintronics