ASPIC-reloaded

Upgrade of the UHV-system ASPIC for the investigation of surfaces and two-dimensional materials by ultra-low energy implantation and deposition of radioactive probe atoms

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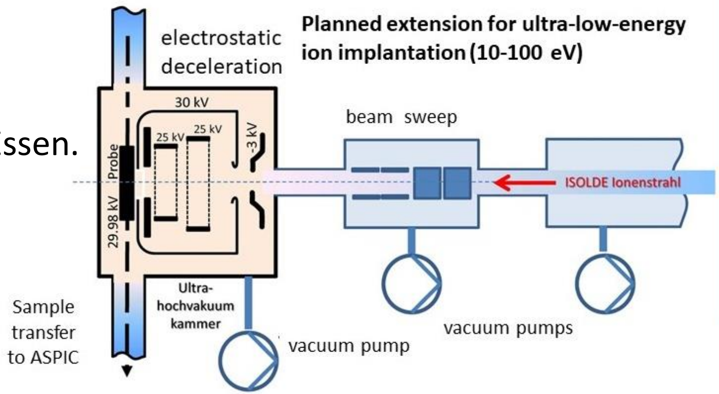
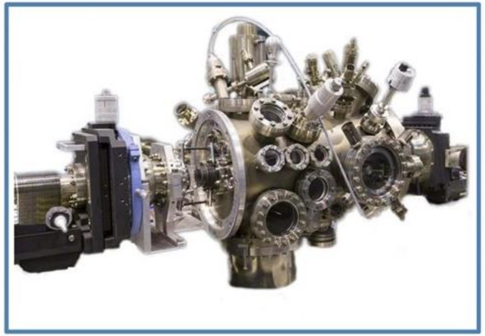
Consortial BMBF Project “Ecomarl”

- Hans Hofsäss from University Göttingen,
- Peter Schaaf from TU Ilmenau
- Doru Lupascu from University Duisburg-Essen.

BMBF 05K19 MG1:
Total budget 2019 - 2022: 483.000 €

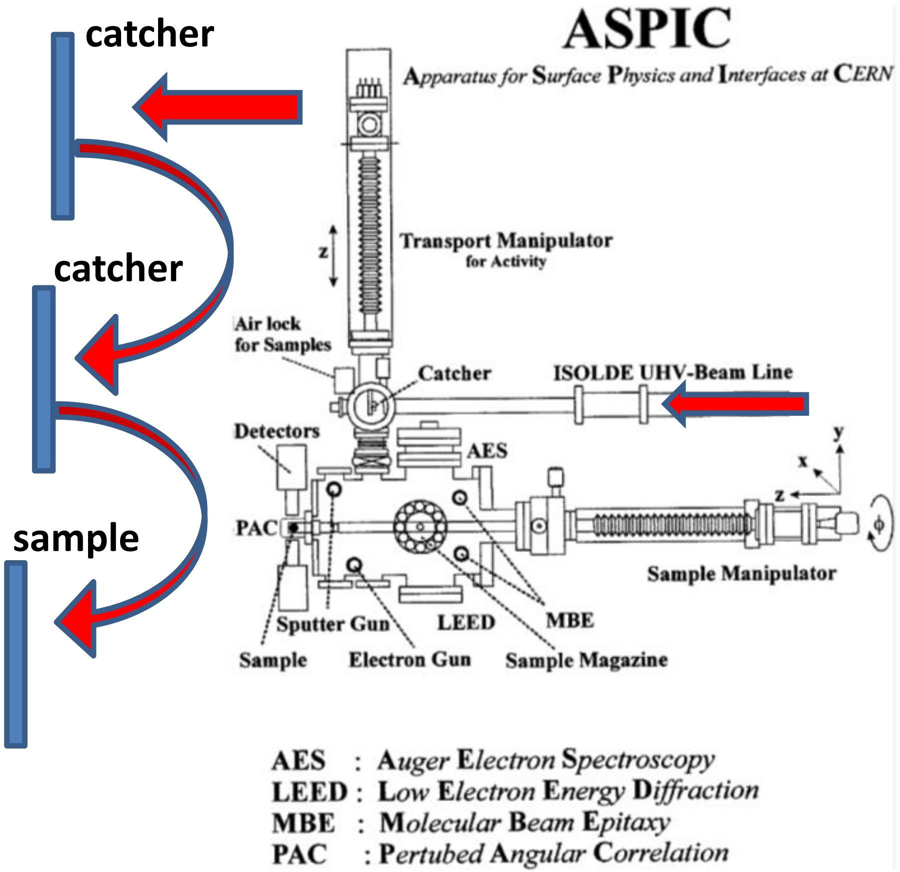




Existing apparatus for surface and interface physics (ASPIC)

History of ASPIC

- 1994 deposition of radioactive atoms on surfaces (H. Haas et al.)
  - Implantation into catcher, 2 stage evaproation onto sample surface
- 1995 Installation of Apparatus for Surface Physics at ISOLDE CERN (**"ASPIC"**)
  - Set up by HMI Berlin, now Helmholtz Center Berlin
  - Used until 2005
- 2014 proposed as UHV system at the beam-line VITO (versatile ion-polarized techniques online)
  - Only a UHV beamline was realized
- 2018 proposal to BMBF for ASPIC reloaded



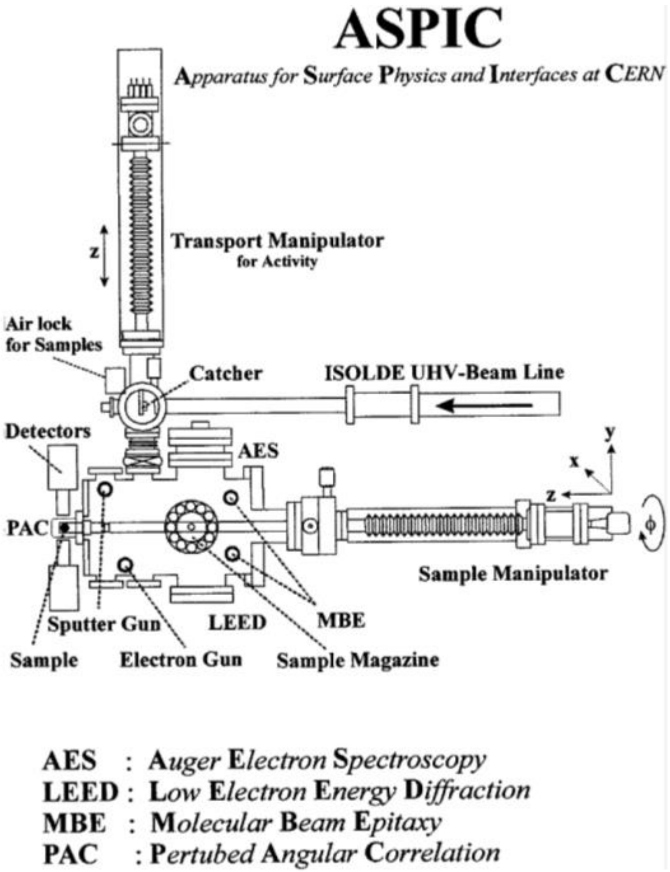
Features of the ASPIC UHV chamber

Versatile UHV chamber for surface physics

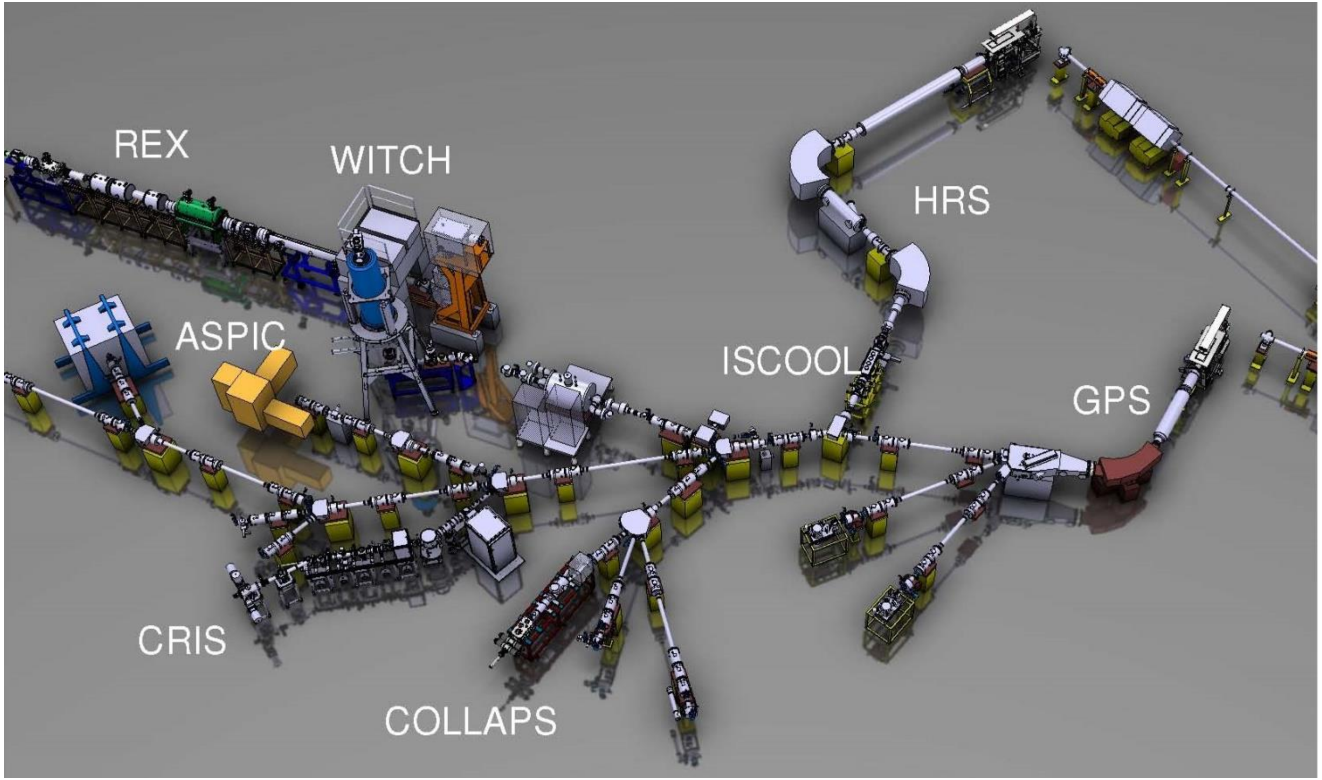
- **Sample surface analysis**
  - Auger electron spectroscopy (AES)
  - Low energy electron diffraction (LEED)

- **Sample preparation and manipulation**
  - Thin film deposition by molecular beam epitaxy (MBE) or vapor phase evaporation
  - Sample cleaning by sputter erosion
  - Sample anealing or cooling (to LN_2 temperature)
  - Electron beam heating

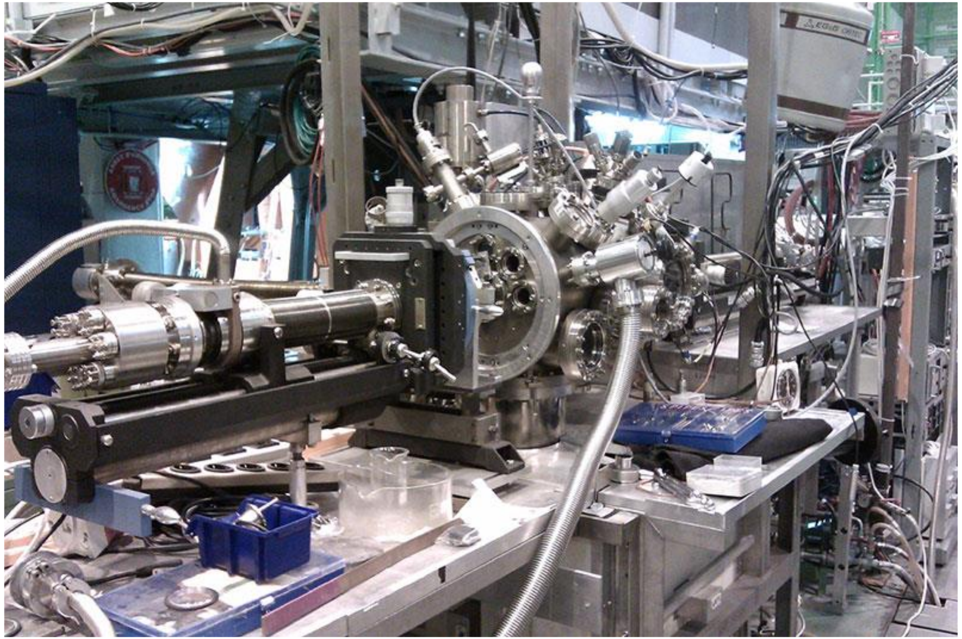
- **Perturbed γγ angular correlation**

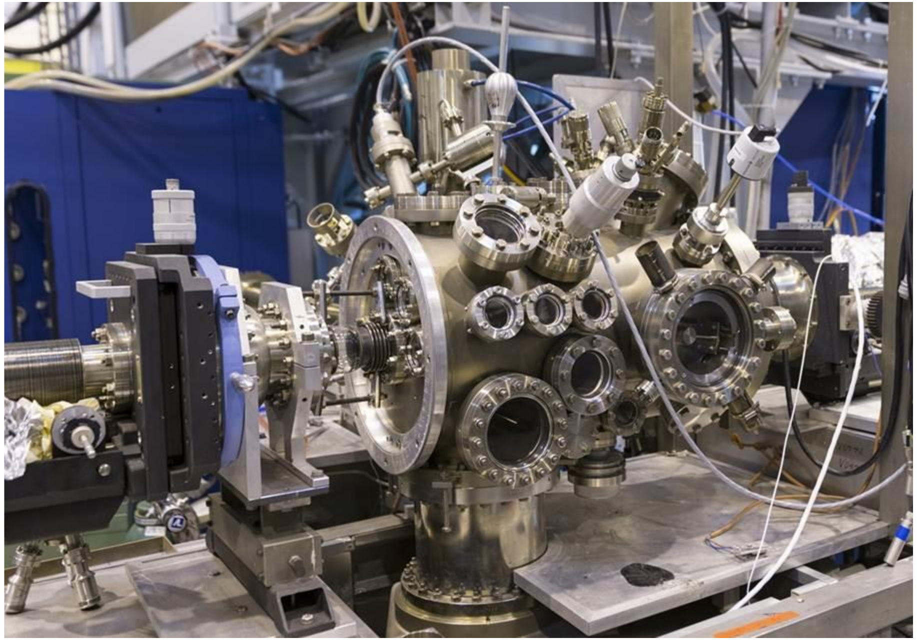


ASPIC at the VITO beamline



ASPIC at the VITO beamline





Example: Adsorbate sites of In on a Ag(100) surface

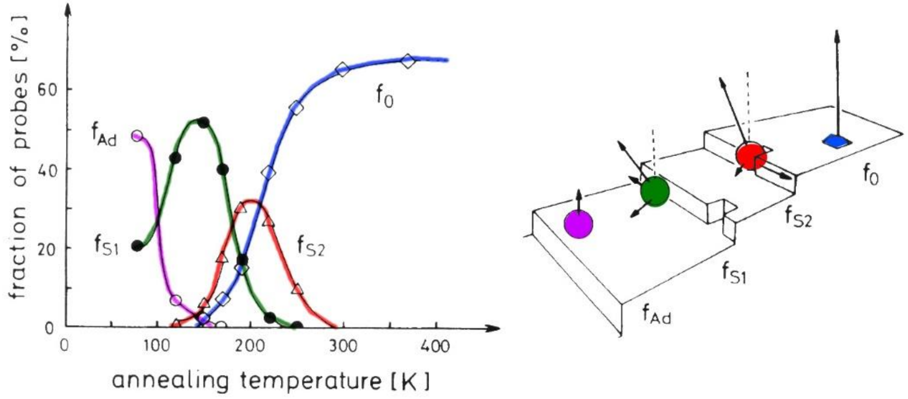


Fig. 5.23 Left side: Fraction of indium probes with different electric field gradients on stepped Ag(100) as a function of annealing temperature. Right side: Surface site model for indium probes suggested by the experimental parameters.

- Analysis of site fraction and electric field gradient orientation

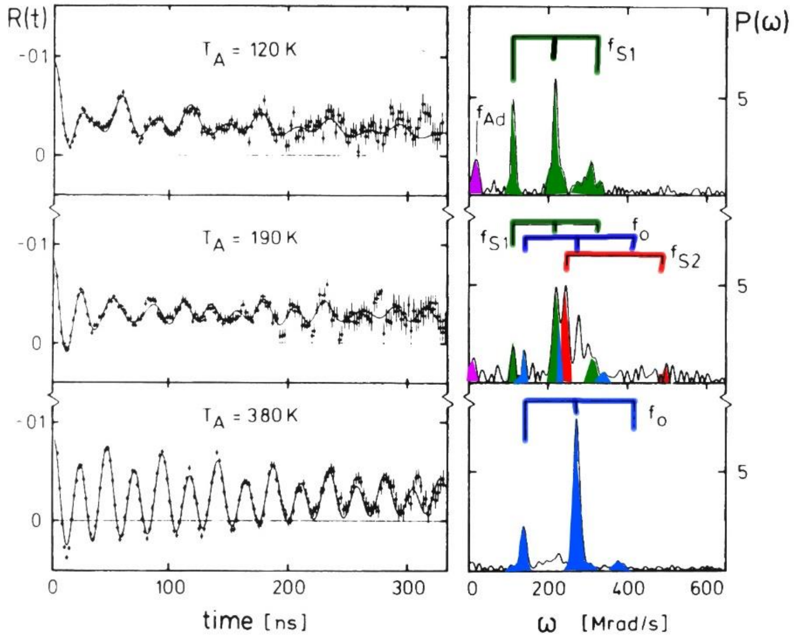


Fig. 5.22 PAC spectra along with their Fourier transforms for ^{111}In on stepped Ag(100) for three different annealing temperatures (annealing time 15 minutes, measuring temperature 77 K). The solid lines were fitted to the experimental points by Eq. (5.41).

R. Fink et al, Surface Science 225 (1990) 331
G. Schatz & A. Weidinger : Nuclear solid state physics

Example: Magnetic hyperfine field for Cd on Ni surfaces

Subsitutional terrace site

$B = 6.6$ T, $V_{zz} = 1.2 \cdot 10^{22}$ V/m^2, $\eta = 0$

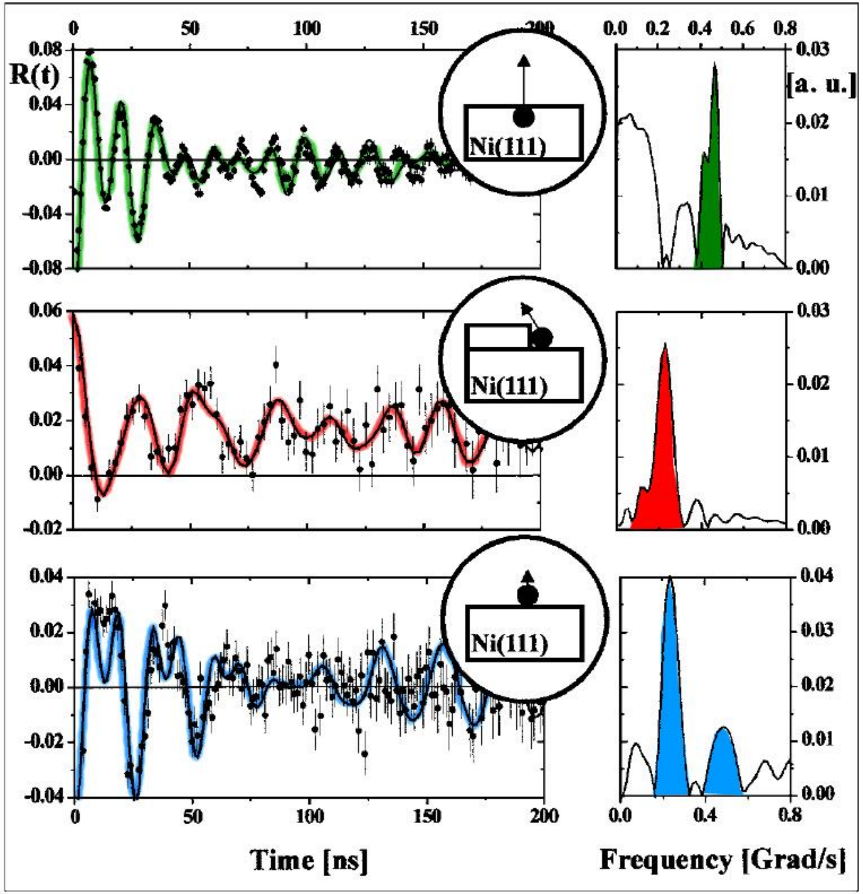
Edges and step sites

$B = 1$ T, $V_{zz} = 6 \cdot 10^{21}$ V/m^2, $\eta > 0$

$B = 4.11$ T, $V_{zz} = 7.3 \cdot 10^{21}$ V/m^2

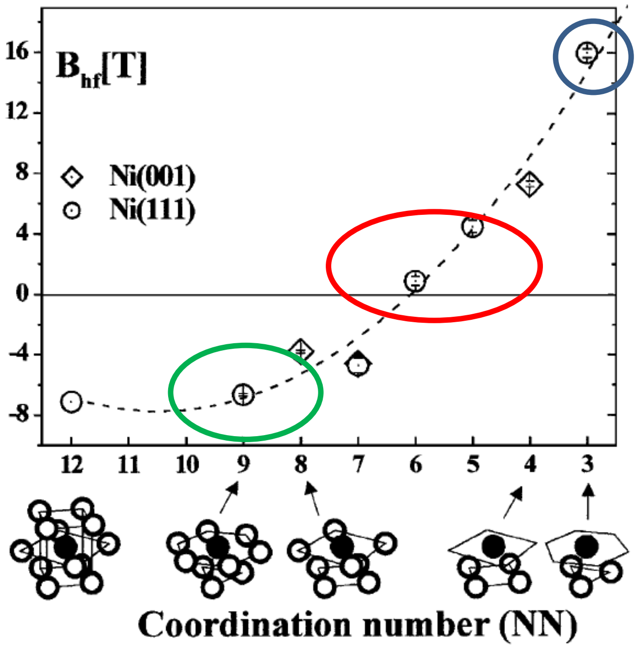
Adatom site

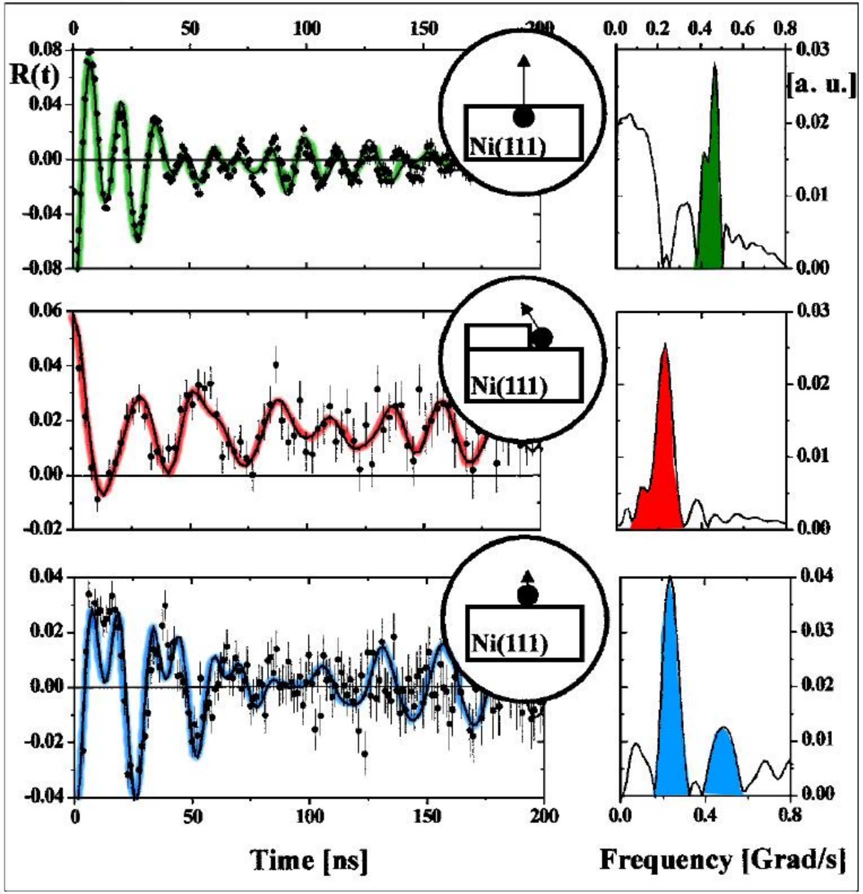
$B = 16$ T, $V_{zz} = 1 \cdot 10^{21}$ V/m^2, $\eta = 0$



Potzger et al. , Phys. Rev. Lett 88 (2002) 247201-1

Example: Magnetic hyperfine field for Cd on Ni surfaces



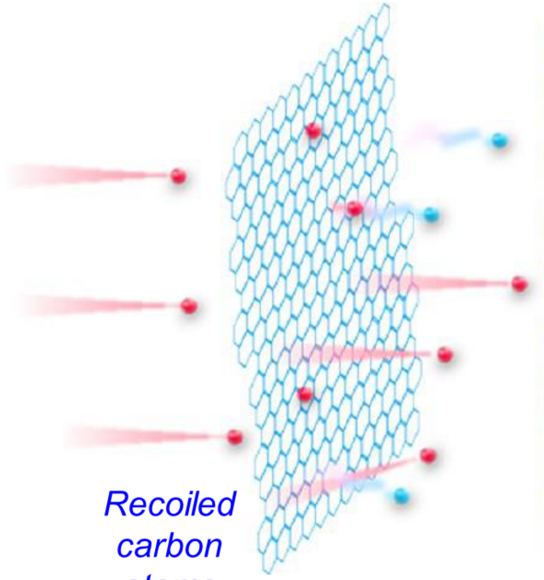


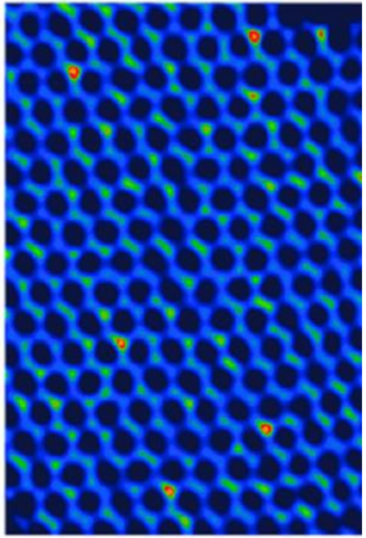
Potzger et al. , Phys. Rev. Lett 88 (2002) 247201-1

Ultra low energy ion implantation of graphene

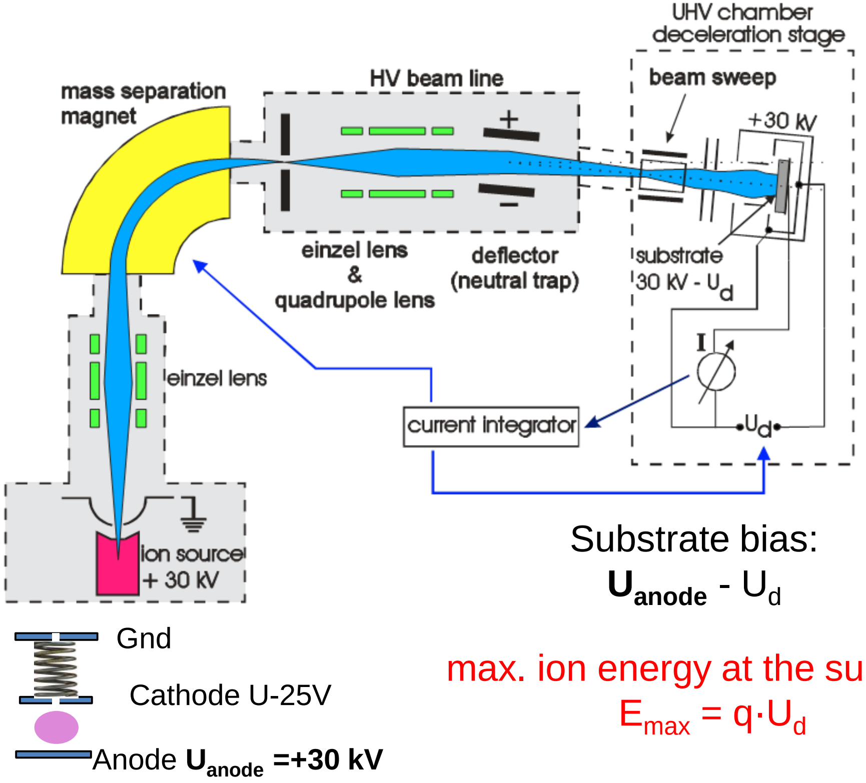
Why not a single binary replacement collision ?

→ **Ultra-low energy, singly-charged mass-selected ion beams**





Mass selected ion beam deposition

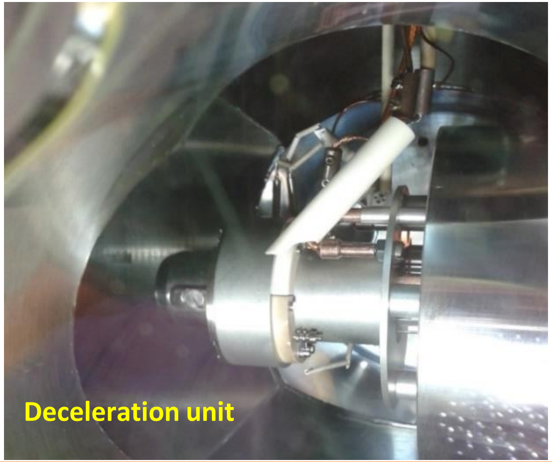


Substrate bias:

$\mathbf{U_{anode}} - U_d$

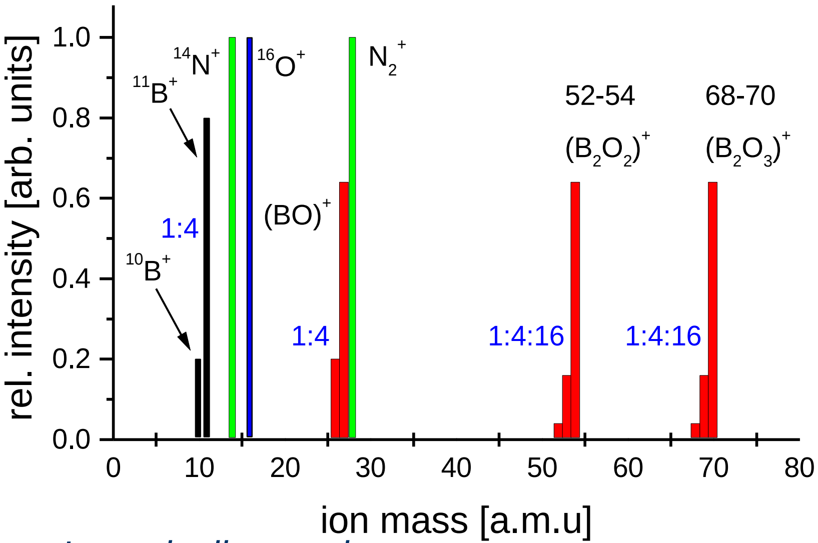
max. ion energy at the substrate

$E_{max} = q \cdot U_d$

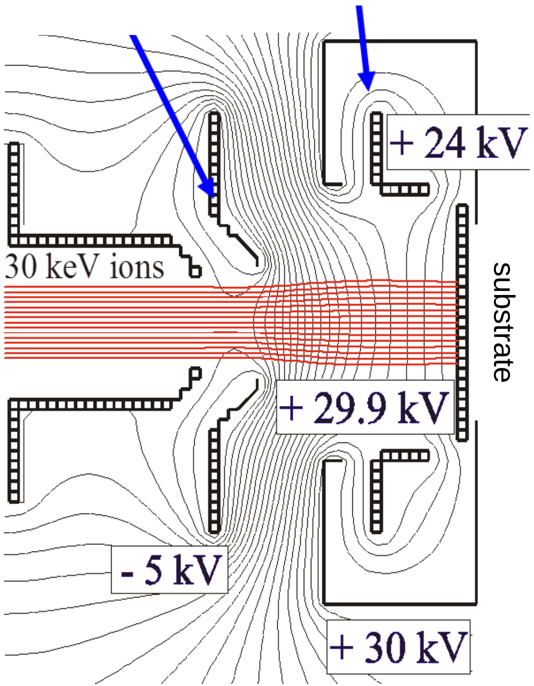


Features of the MSIBD system

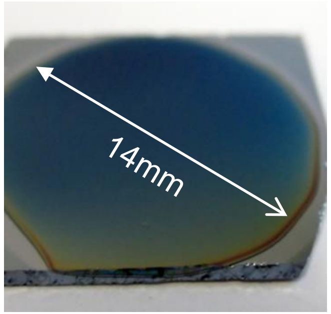
mass spectrum of ionized B_2O_3 vapor + N_2-gas



- *Isotopically pure beams*
- *energy E_{max} down to about 10 eV*
- *Uniform deposition area 12 mm ∅*
- *Precise current measurement*
- *$P \approx 5 \cdot 10^{-10}$ mbar (UHV)*



a-C film from 100 eV C^+ ions



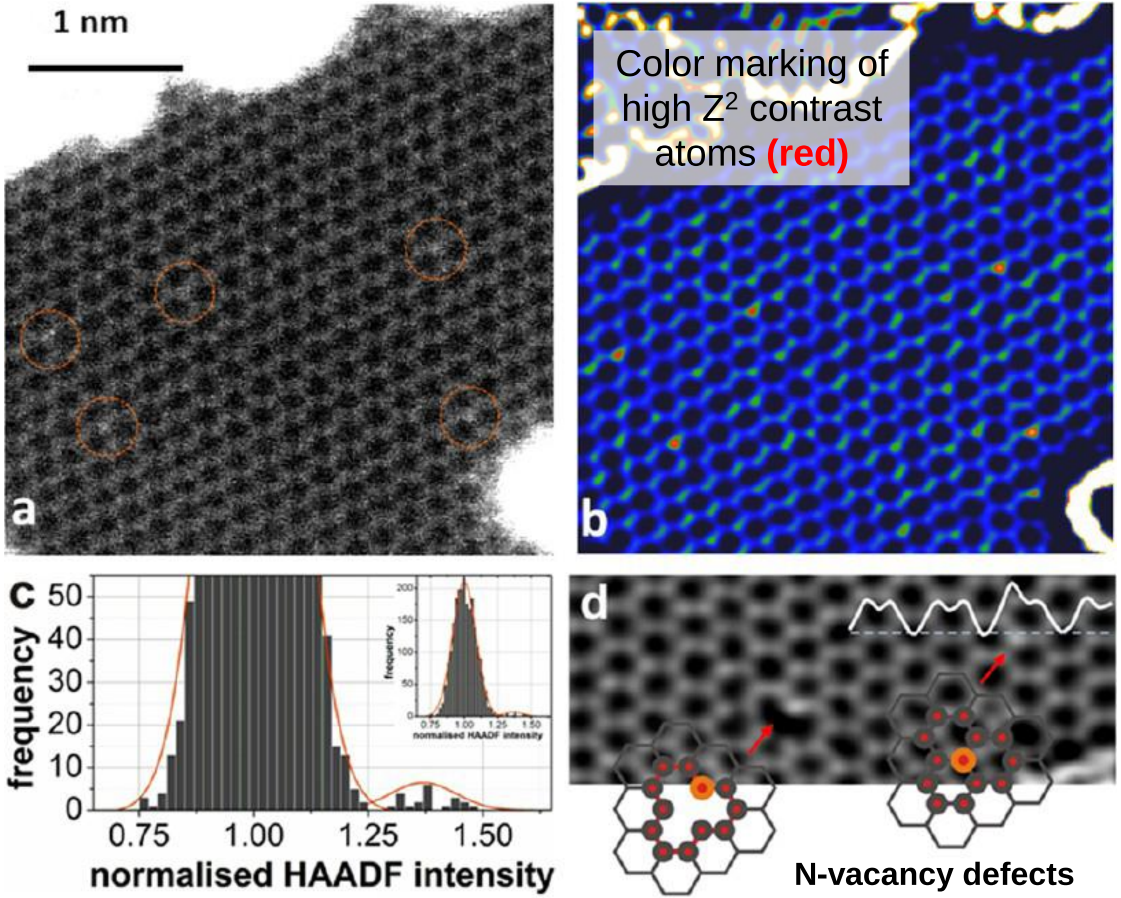
a-C film from 25 eV C^+ ions

Ion implantation doping of free standing graphene

HAADF image of N-doped graphene

(High hangle annular dark field)

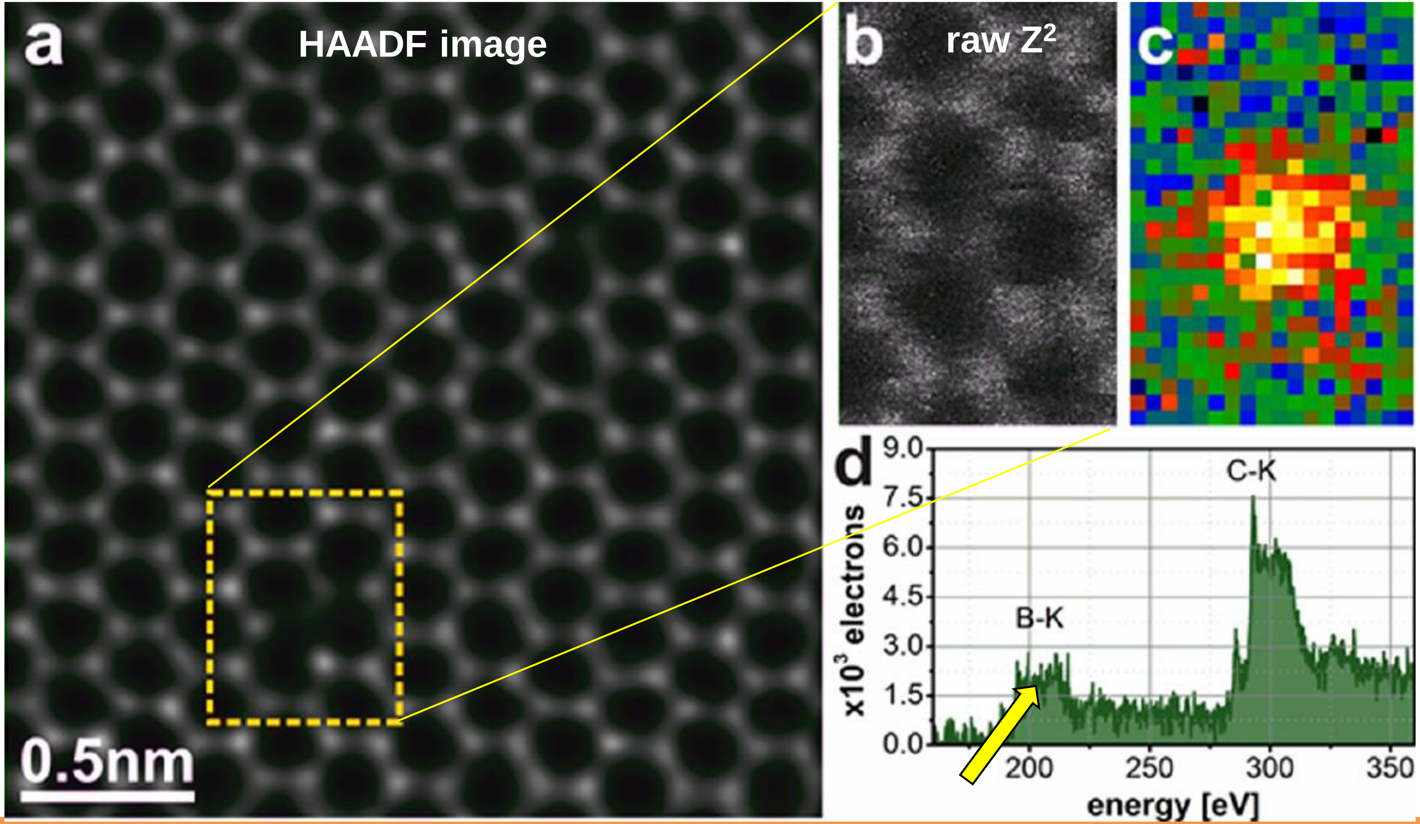
substitutional N-atoms



U. Bangert, W. Pierce, D. M. Kepaptsoglou, Q. Ramasse, R. Zan, M. H. Gass, J. Van den Berg, C. Boothroyd, J. Amani, H. Hofsäss, **Nano Letters 13 (2013) 4902**

Ion implantation doping of free standing graphene

EEL @ 190-220eV

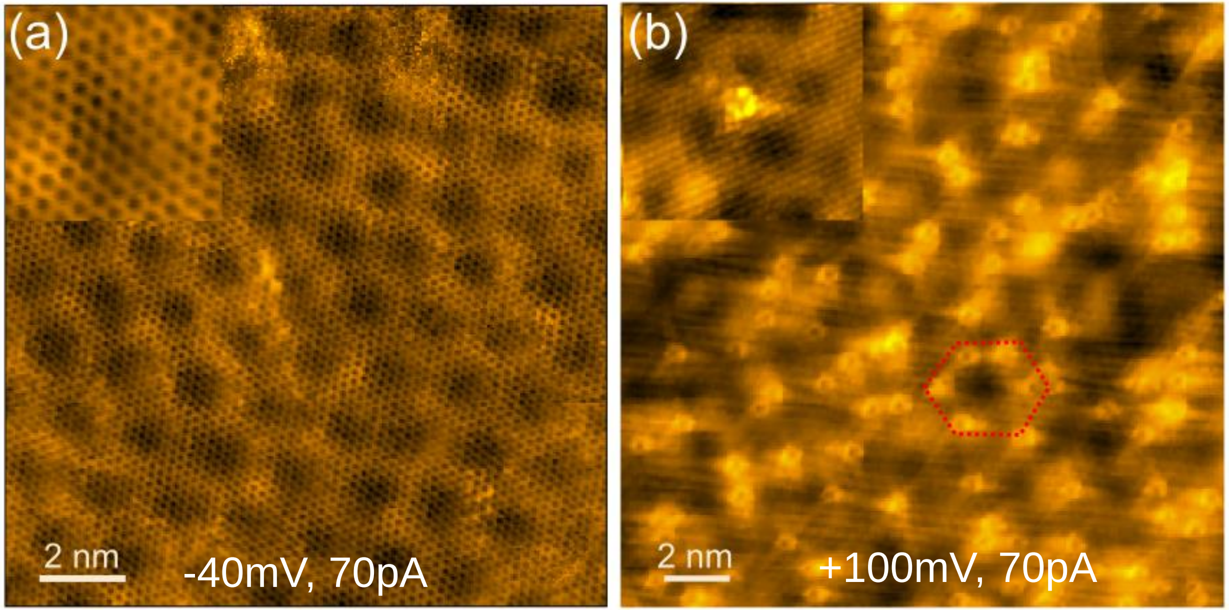


Ion implantation doping of graphene on SiC

Scanning tunneling microscopy

a) pristine graphene on SiC: graphene lattice & 6x6 corrugation

b) N-doped graphene on SiC: N scattering patterns with 3-fold symmetry

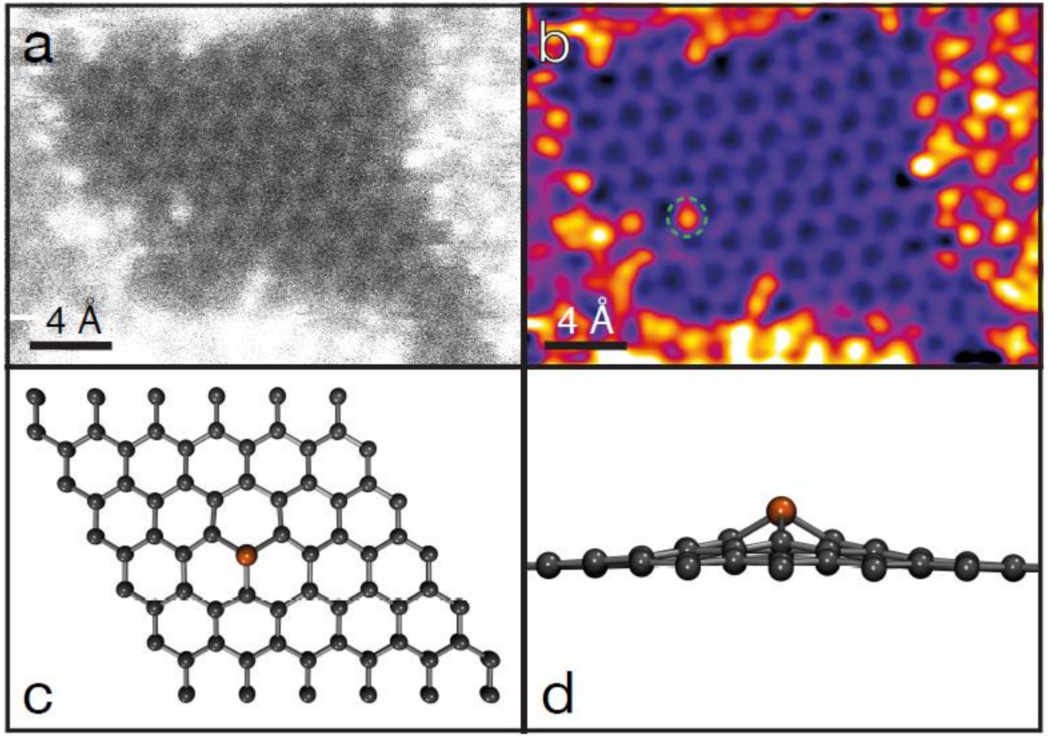


P. Willke, J. A. Amani, S. Thakur, S. Weikert, T. Druga, K. Maiti, H. Hofsäss, and M. Wenderoth, **Appl. Phys. Lett. 105 (2014) 111605.**

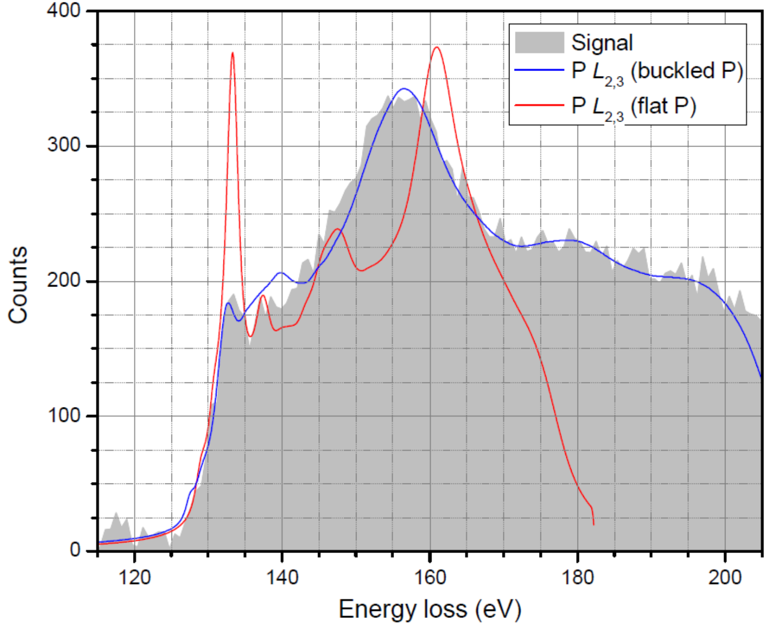
A substitutional P atom in graphene

unprocessed STEM/MAADF image

colored and filtered image



EELS Spectrum & simulations



T. Susi, T. P. Hardcastle, H. Hofsäss, A. Mittelberger, T. J. Pennycook, C. Mangler, R. Drummond-Brydson, A. J. Scott, J. C. Meyer, J. Kotakoski,
2D Mater. 4 (2017) 021013

A substitutional P atom in graphene

EEL spectrum averaged over the substitutional P dopant

energy windows from

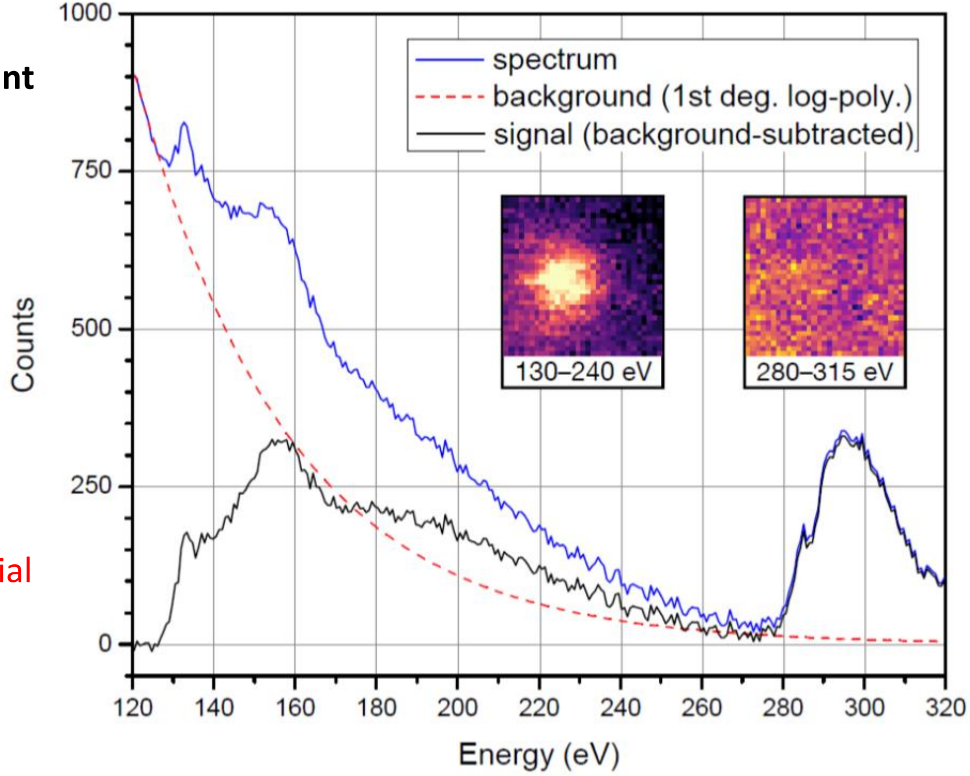
130–240 eV for the P L edge

280–315 eV K-edge.

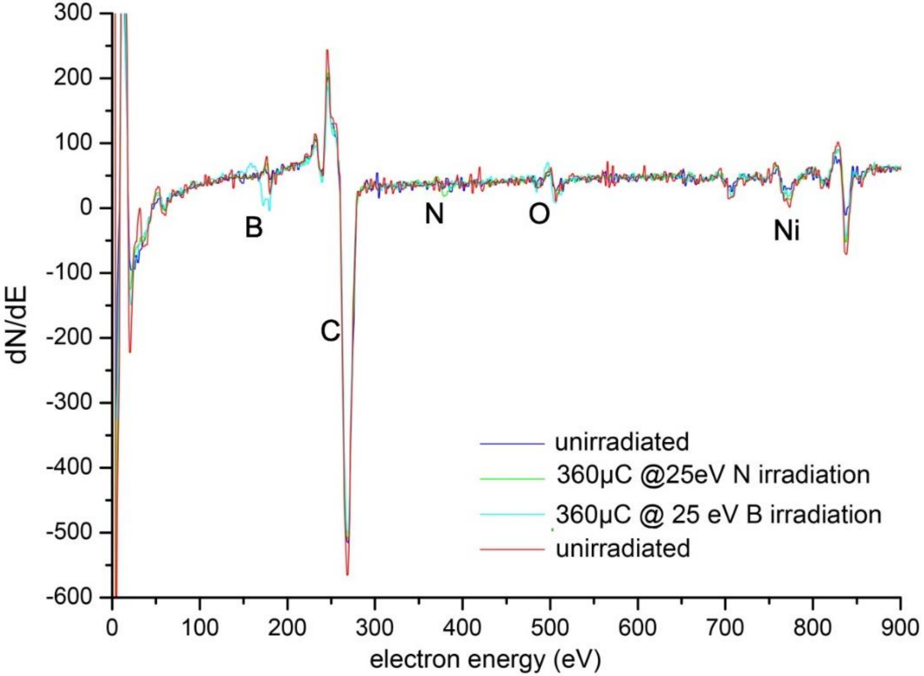
Blue line: original spectrum

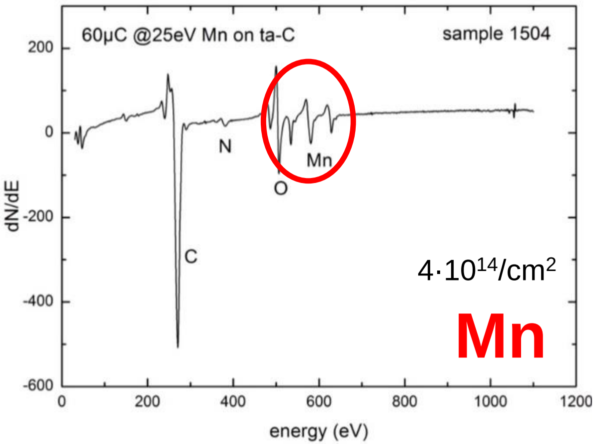
red line: background fit using a 1st degree log-polynomial

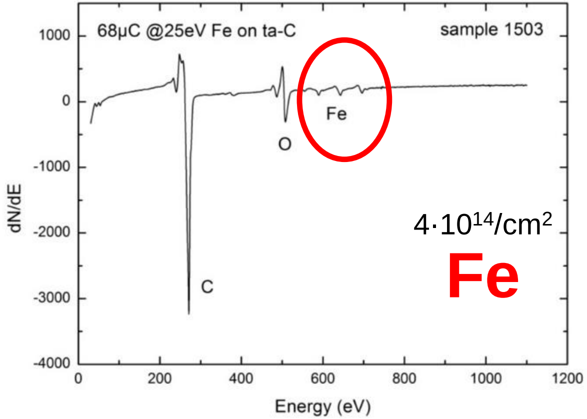
Black line: the resulting signal



Auger spectra of implanted graphene and a-C

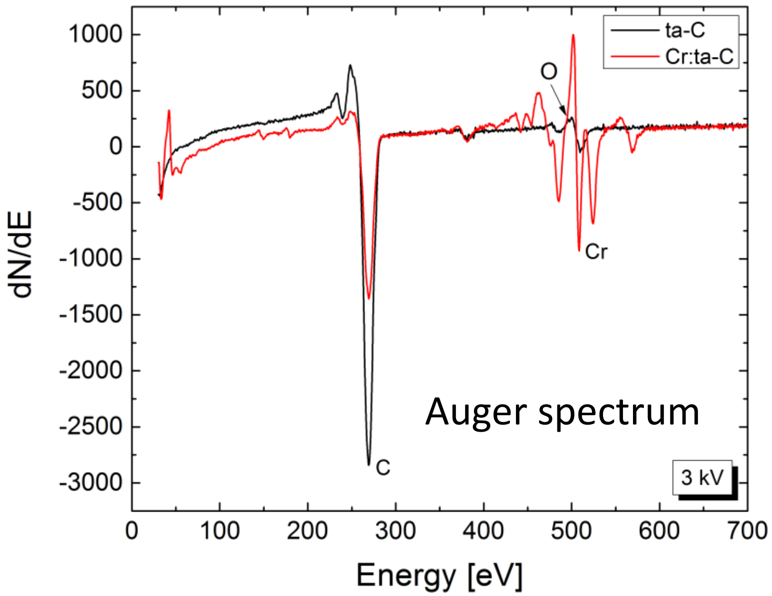


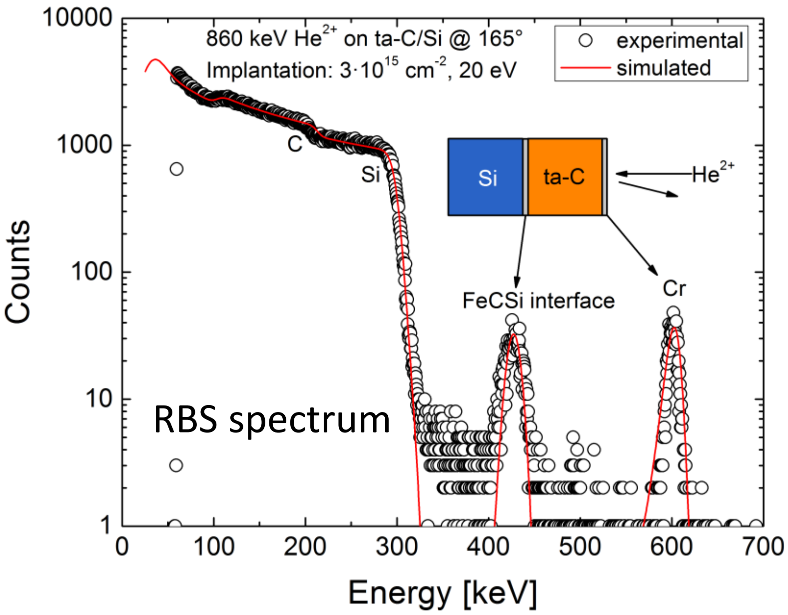




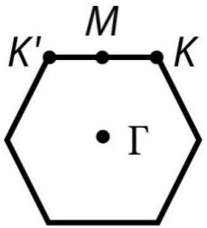
ULE Ion implantation of Cr into graphene and a-C

- **Possible Kondo effect (spin scattering) impurity in graphene**





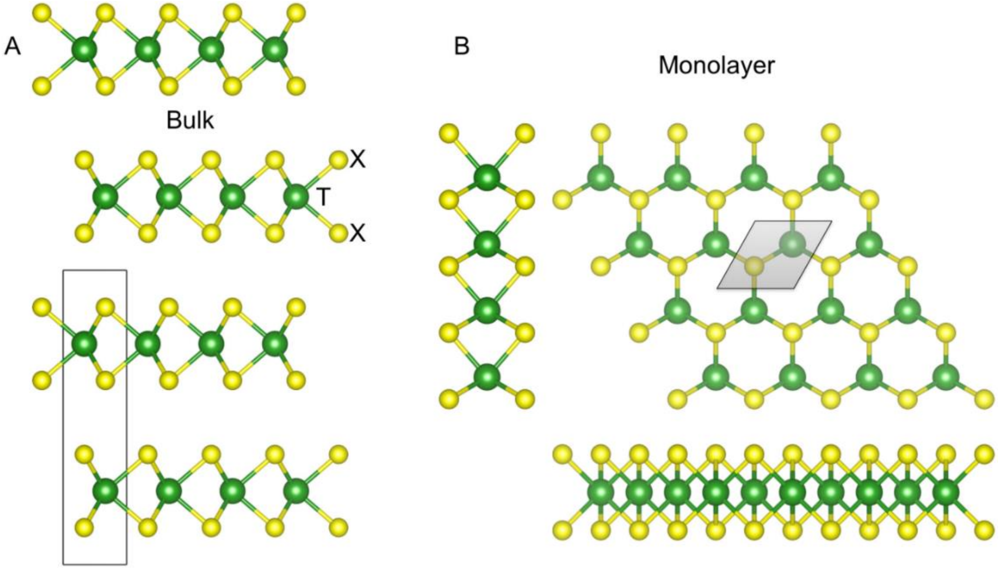
Transition metal dichalcogenides TMDs

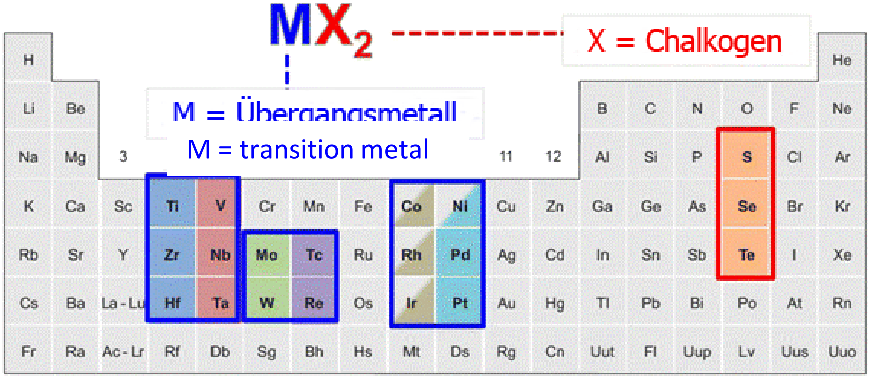


- Van-der-Waals bonds between individual layers
- Existence of a Bandgap in TMDs
  - Parabolic ($E_g = 1.8$ eV)

Bulk

Monolayer



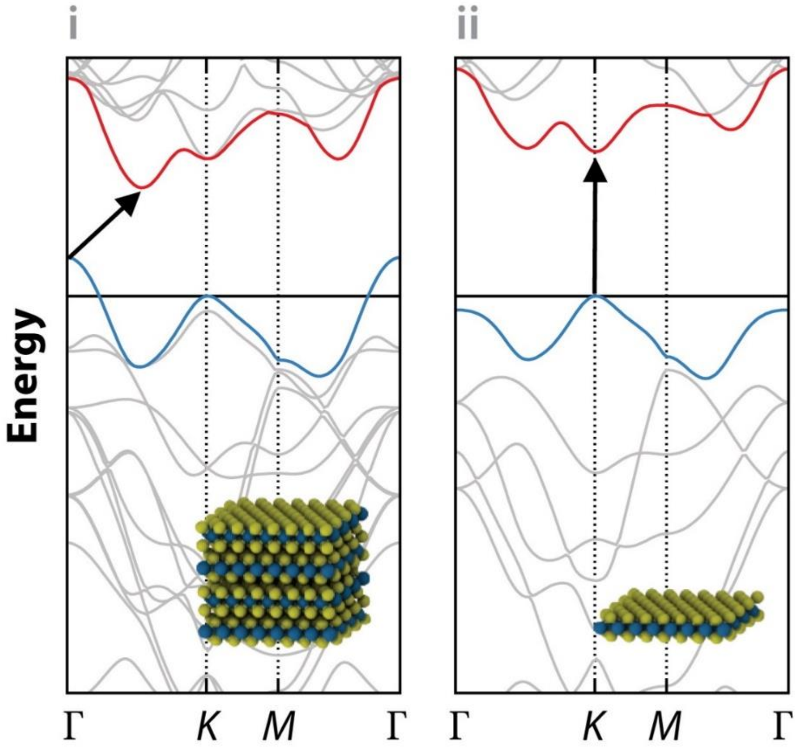


Transition metal dichalcogenides TMDs

- Transition from bulk (i) to ML (ii)

  ➔ transition from indirect to direct band gap
- E_g^{dir} at K-Point of the BZ
- E_g^{ind} at Γ and Γ – K
- 2D TMDs:
  - Photon antibunching
  - Quantum confinement

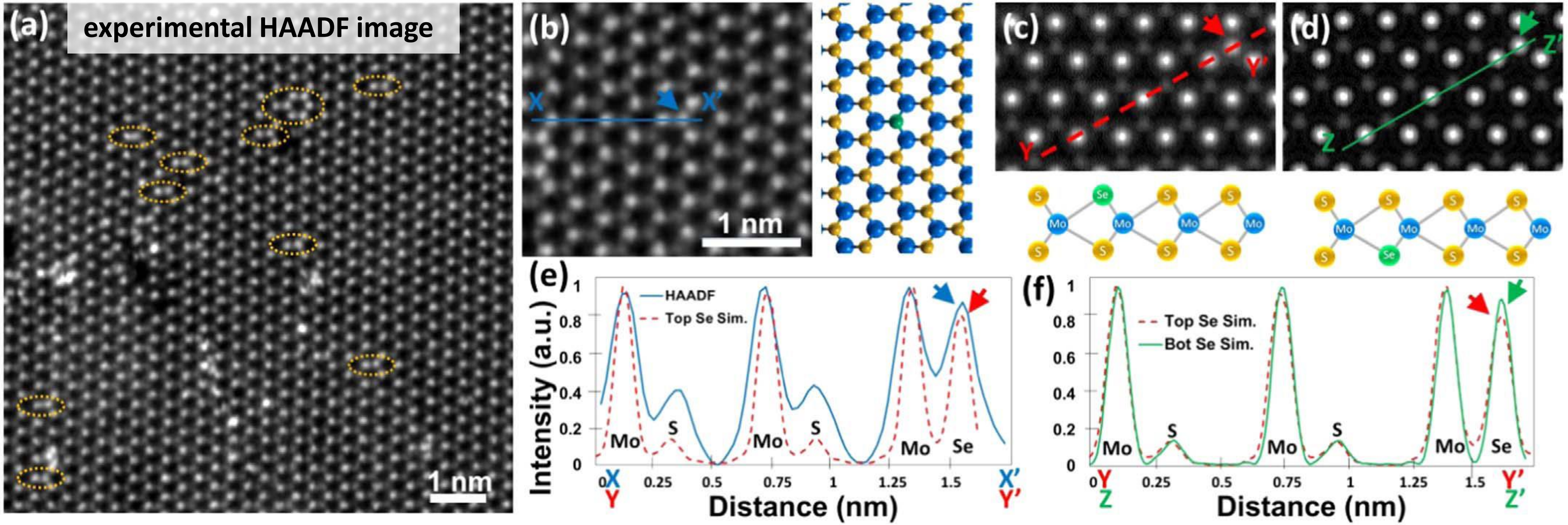
➔ **single photon source**



T. C. Berkelbach and D. R. Reichman, *Annu. Rev. Condens. Matter Phys.* **9** (2018), S. 379

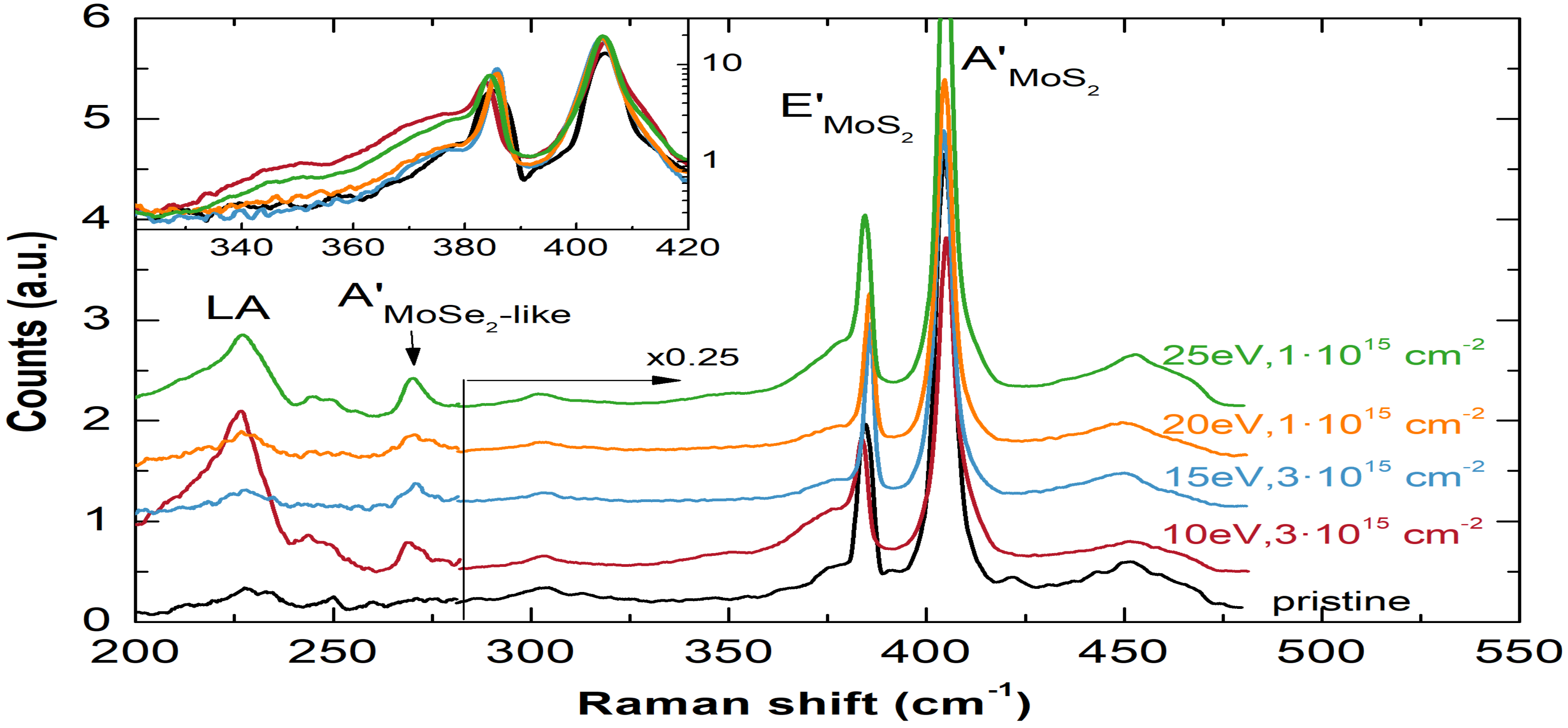
Single layer MoS_2 implanted with Se

HAADF image simulations

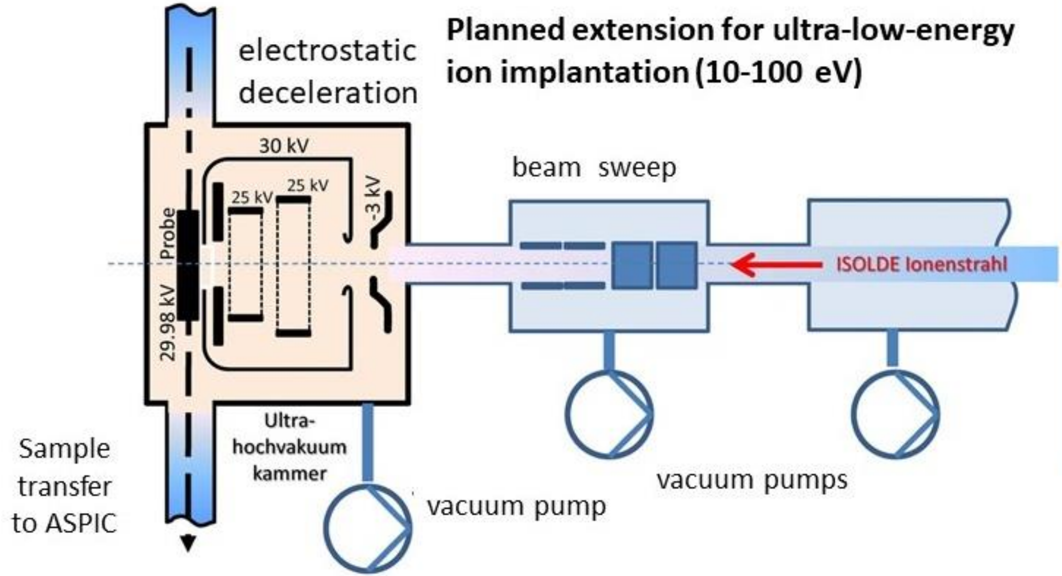


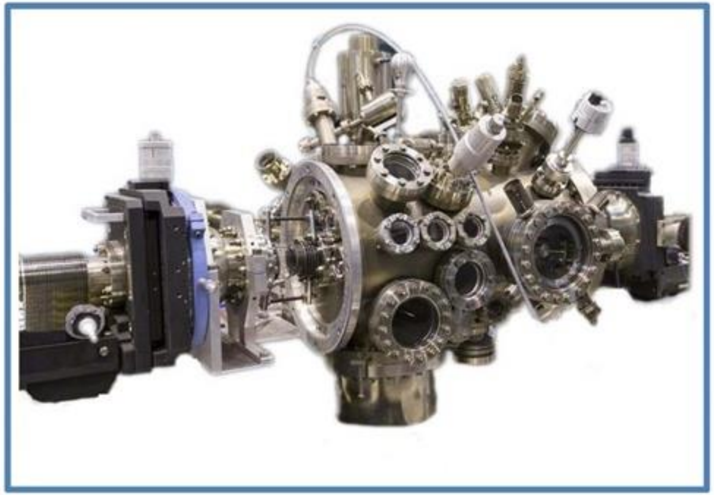
U. Bangert, A. Stewart, E. O'Connell, E. Courtney, Q. Ramasse, D. Kepatsoglou, H. Hofsäss, J. Amani, S. S. Tu, B. Kardynal, **Ultramicroscopy 175 (2017), 021013**

Raman spectra of Se implanted MoS_2



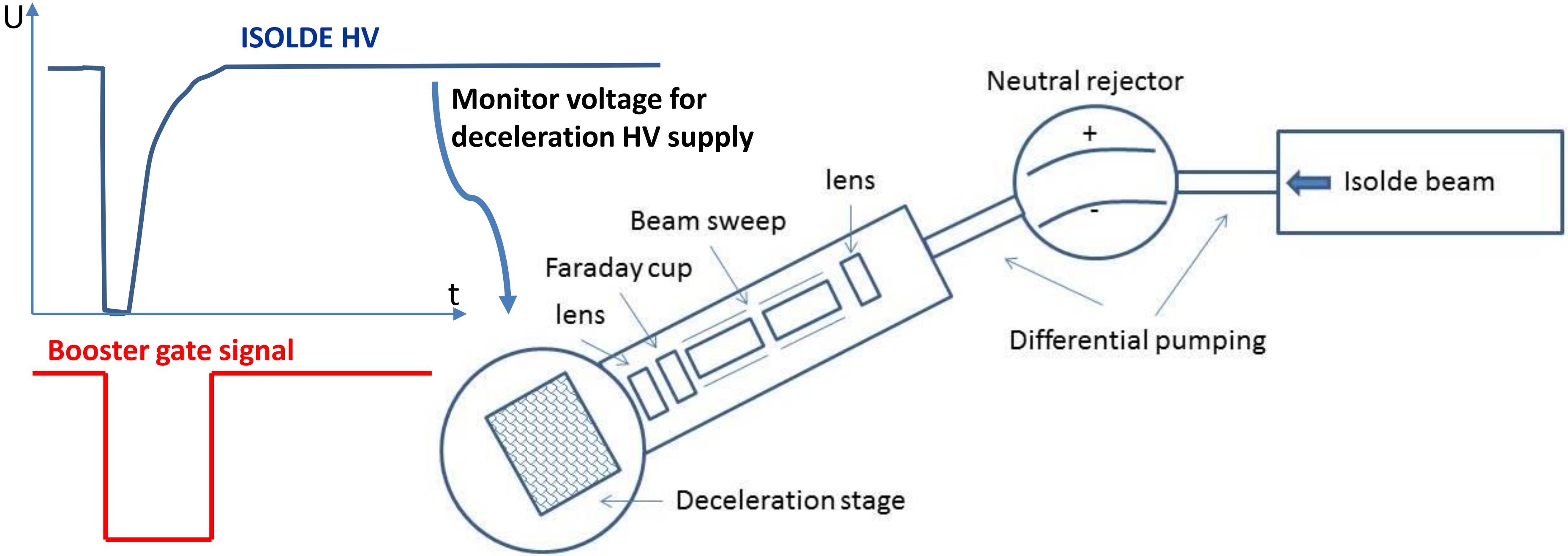
Upgrade of ASPIC for ultra-low energy ion implantation





Existing apparatus for surface and interface physics (ASPIC)

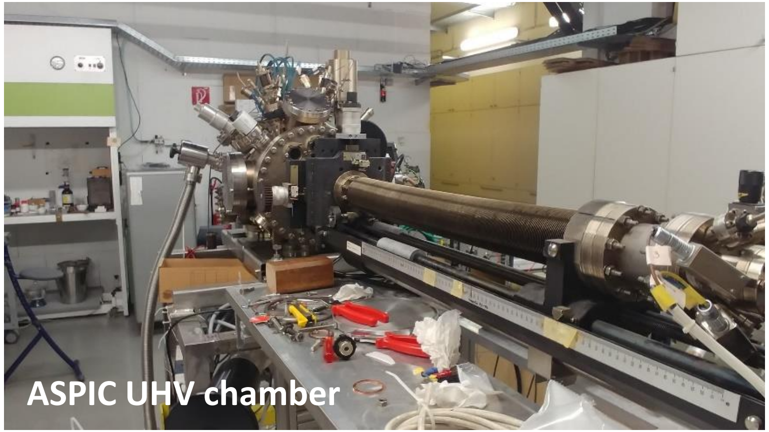
Schematics for deceleration and ion implantation



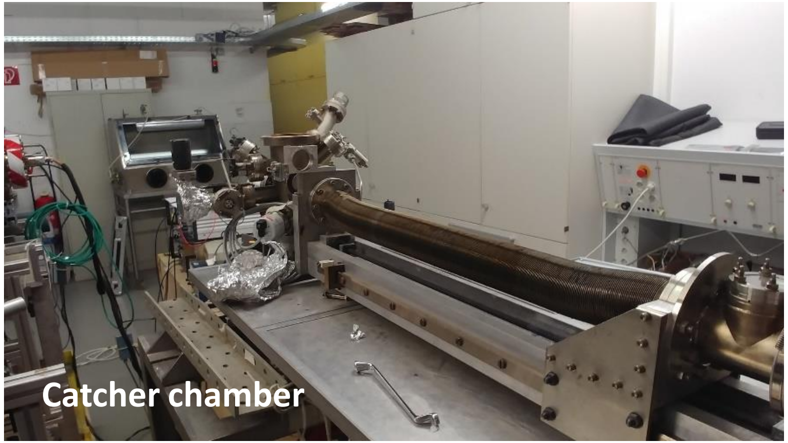
DC deceleration Voltage linked to ISOLDE HV power supply

ASPIC UHV chamber

Catcher chamber

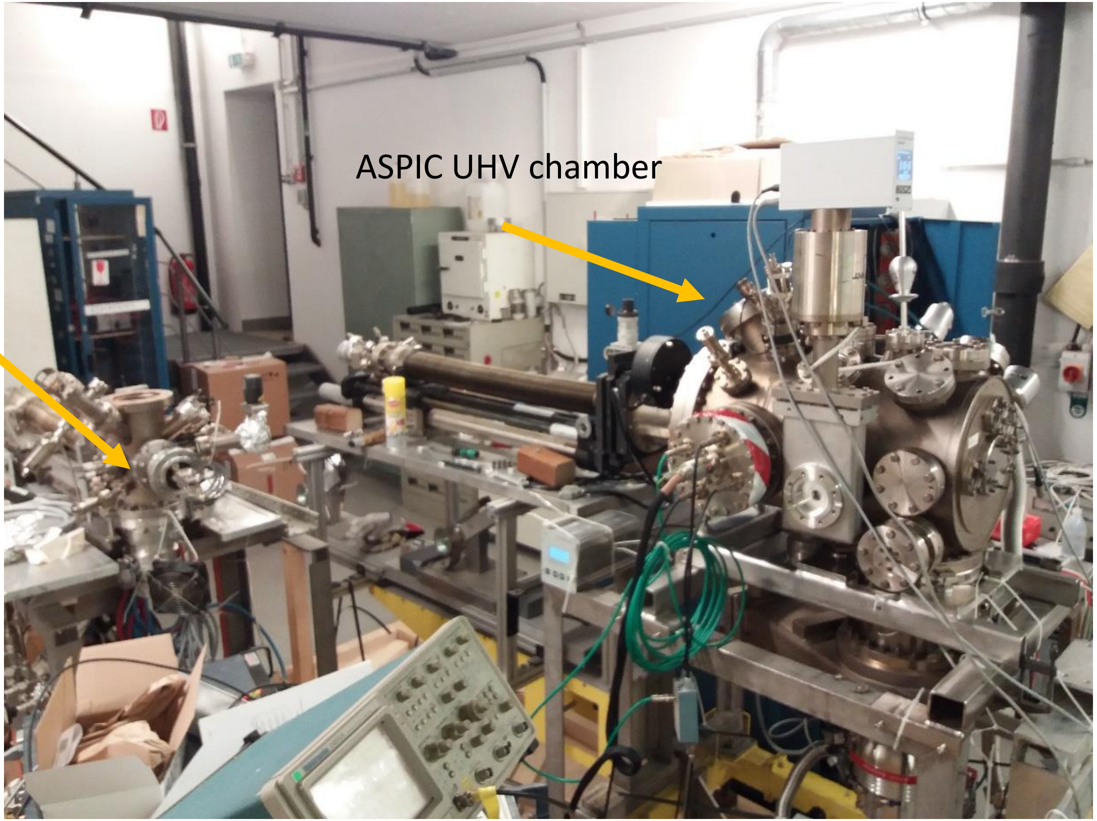


ASPIC UHV chamber



Catcher chamber

Catcher chamber



Power supplies and electronics

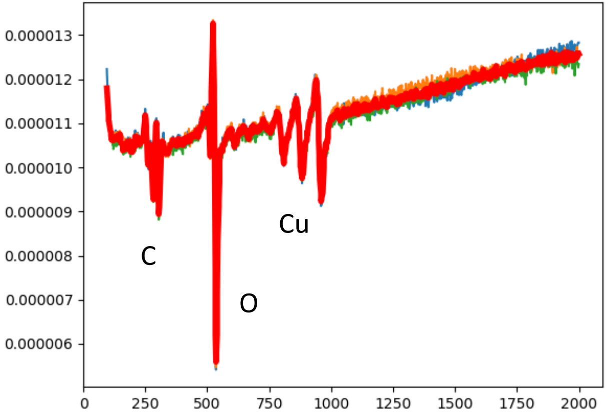
Planned upgrade of ASPIC

Proposal:

- Upgrade with state-of-the-art ion optics for deceleration of ions down to 10-20 eV.
  - Simulation using COMSOL and SIMION
- Renewal of the LEED and Auger Systems
  - **Auger is already working**
  - LEED is getting a new screen
- New and user-friendly sample transfer system
- New sample heating and cooling
- Renewal of the peparation and cleaning systems
- New process control (Lab View)
- Extension for surface Mössbauer spectrometry (SMS)
- Extension for emission channeling?

Disassembled LEED system

1st Auger spectrum



Proposed experiments using ASPIC

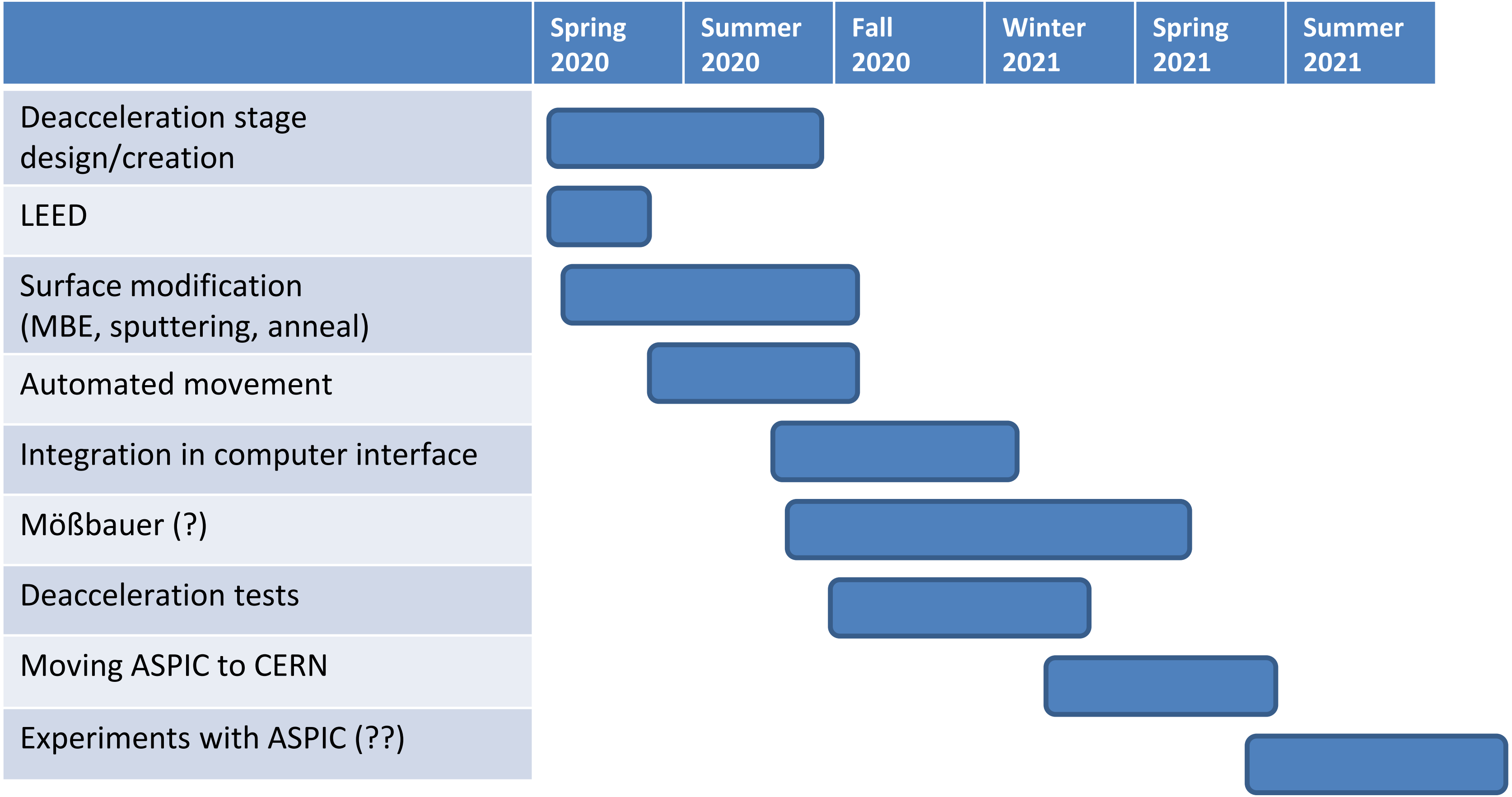
- **PAC and MS studies of 2D materials with very diluted impurities**
  - Cd in graphene and TMDs — ^{111}Ag, ^{111m}Cd, ^{111}In, ^{117}Cd
  - Mn/Fe magnetic impurities in graphene — ^{57}Mn
  - Se in TMDs — ^{77}Br/^{77}Se ; ^{73}Se/^{73}As
  - Rare earth impurities in TMDs — ^{140}Ce/^{140}La ; ^{156}Gd/^{156}Eu, ^{172}Yb/^{172}Lu, ^{158}Gd,^{158}Tb

  - Possible on-line isotopes: ^{28}Mg, ^{48}Cr, ^{62}Zn, ^{111m}Cd, ^{117}Cd, ^{116}Sb,^{118}Sb, …..

- **PAC and MS studies of (crystalline) surfaces**

- **PAC and MS studies of interfaces and very thin films**

See PhD thesis Matthias Nagl, 2014


Spring 2020
Summer 2020
Fall 2020
Winter 2021
Spring 2021
Summer 2021
Deacceleration stage design/creation
LEED
Surface modification (MBE, sputtering, anneal)
Automated movement
Integration in computer interface
Mößbauer (?)
Deacceleration tests
Moving ASPIC to CERN
Experiments with ASPIC (??)