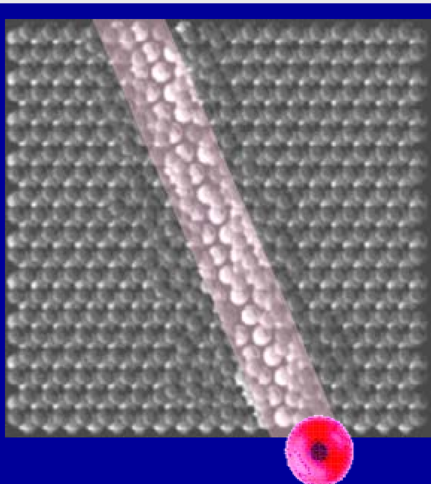
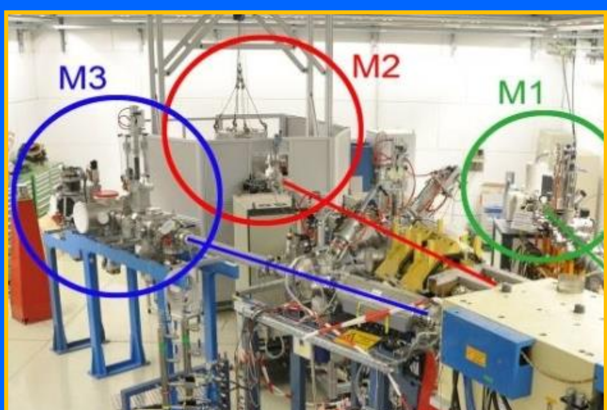
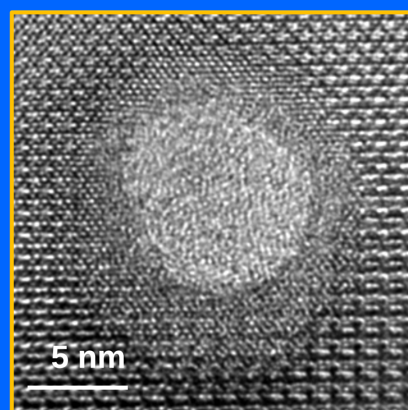
Material science and nanostructures produced with GeV heavy ions

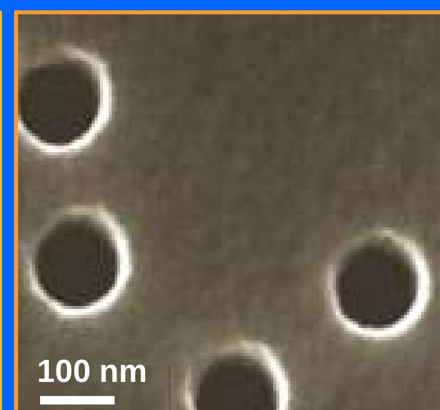
FAIR GSI

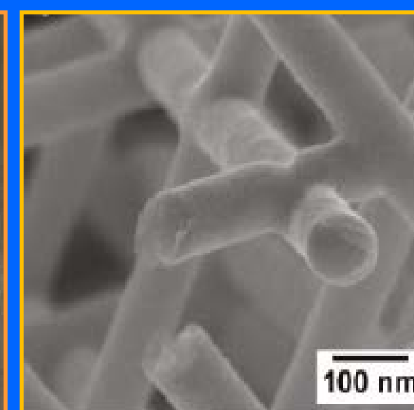


- Facility for high-energy ions
- Ion - solid interaction at high energies
- Beam-induced surface effects
- Ion-track nanotechnology





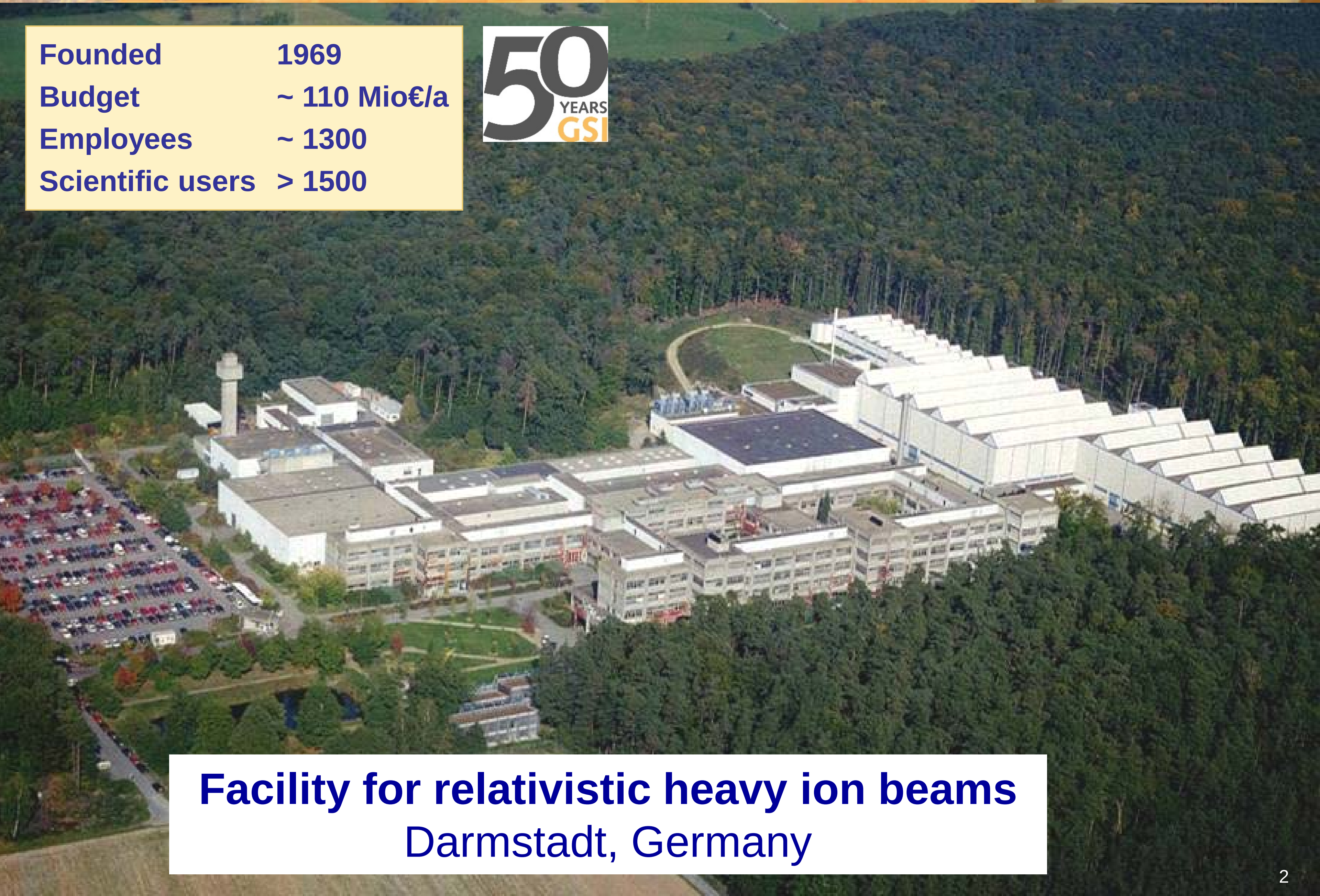




Christina Trautmann, GSI Helmholtzzentrum & Technische Universität Darmstadt, Germany

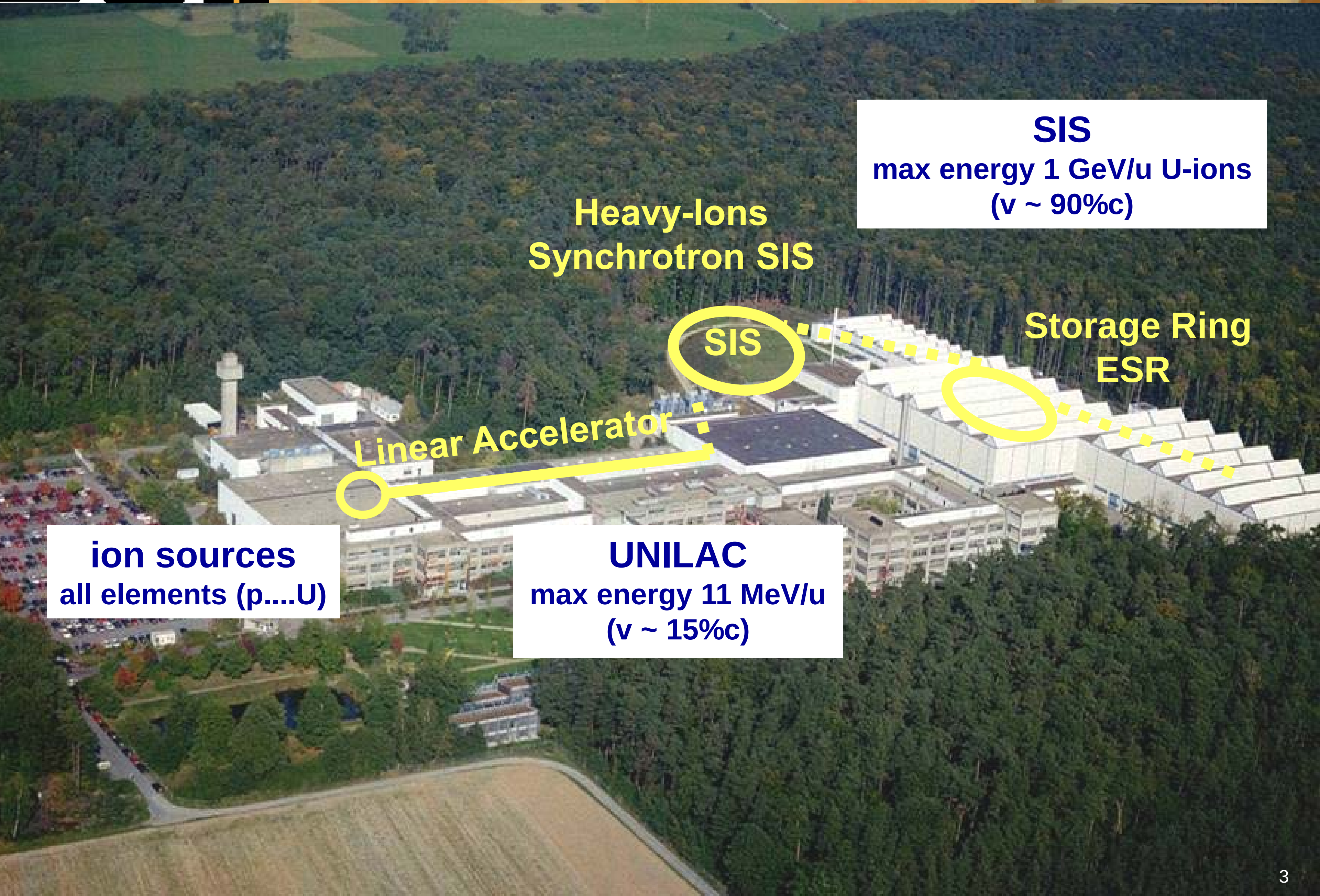
Helmholtz Centre for Heavy Ion Research

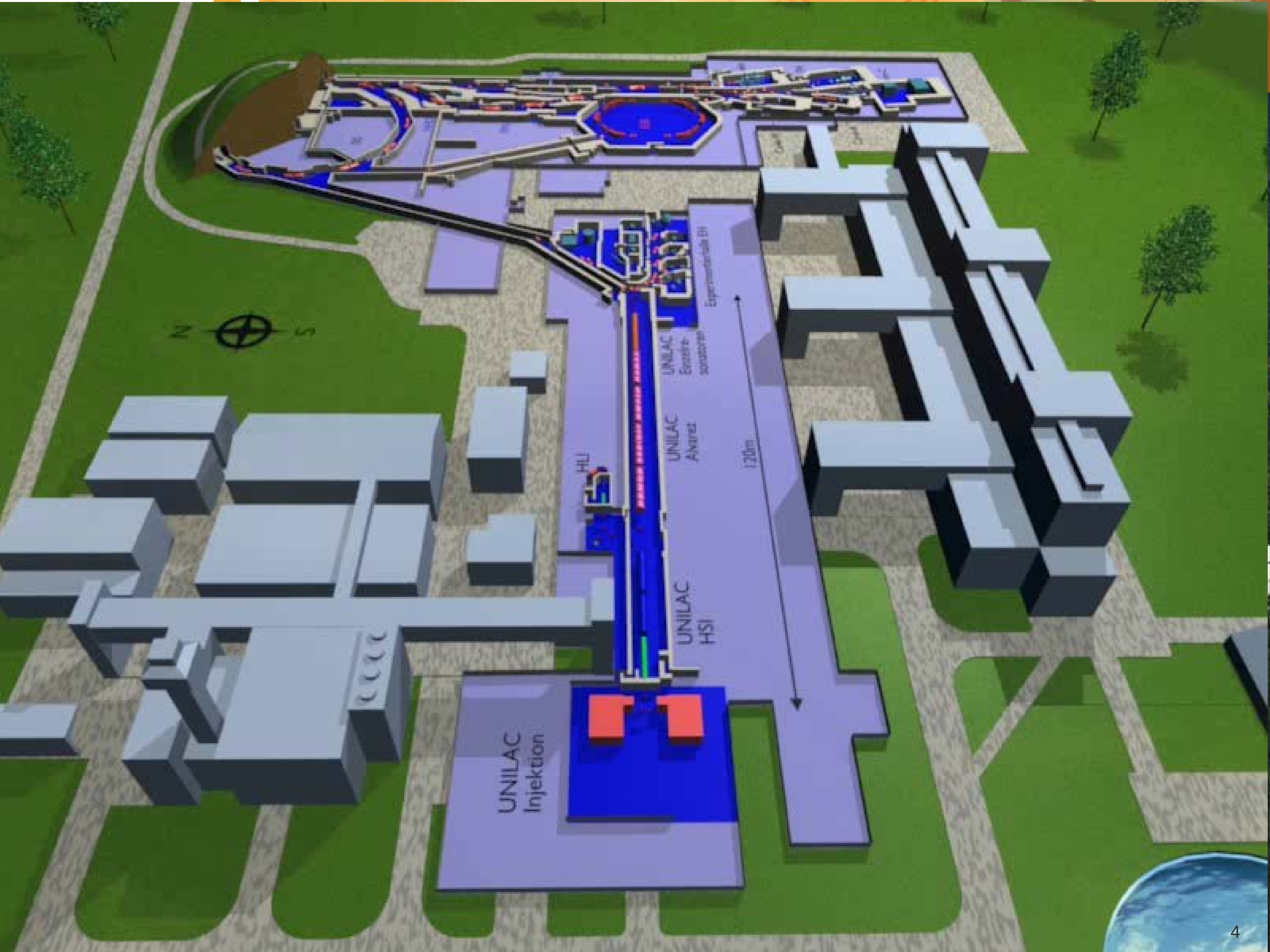
Founded	**1969**
Budget	**~ 110 Mio€/a**
Employees	**~ 1300**
Scientific users	**> 1500**



Facility for relativistic heavy ion beams
Darmstadt, Germany

Helmholtz Centre for Heavy Ion Research




UNILAC
Injektion
UNILAC
HSI
UNILAC
Alvarez
UNILAC
Einzelresonatoren
HLI
120m

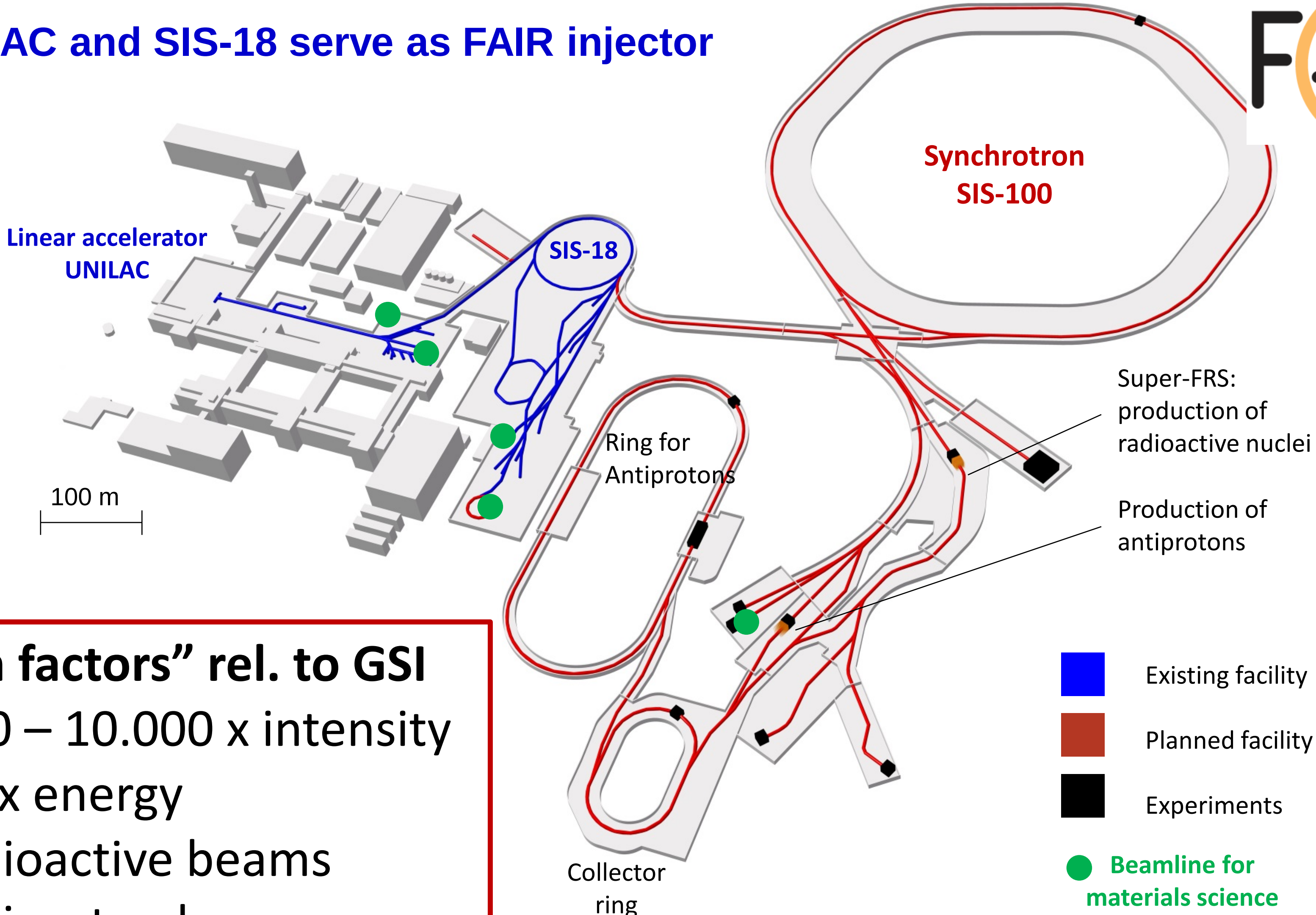
Facility for Antiproton and Ion Research

- **international facility**
- **1600 Mio Euro**
- **2018 – 2025 construction**
- **first beam expected 2025**

GER FL F IN PO RO RU SE SLO UK

Facility for Antiproton and Ion Research

UNILAC and SIS-18 serve as FAIR injector



"Gain factors" rel. to GSI

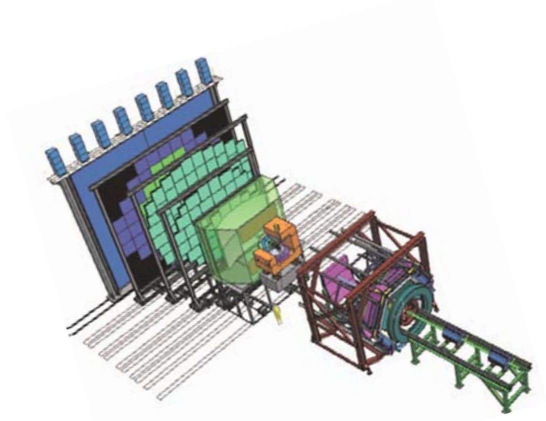
- 100 – 10.000 x intensity
- 10 x energy
- radioactive beams
- antiproton beams

FAIR Construction Site

- SIS100:
  1.1 km circumference
  20 m deep in ground
- 1400 pillars drilled 60 m into ground for subsoil stabilization

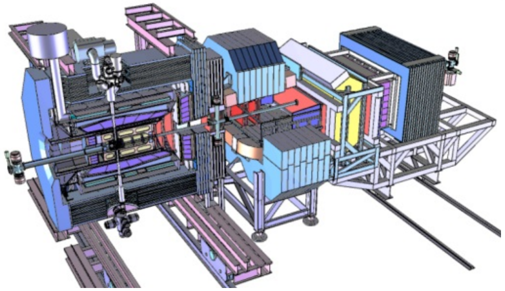
- **total area > 200 000 m^2 (30 soccer fields)**
- **area buildings ~ 98 000 m^2**
- **24 buildings (vol ~1 Mio m^3)**
- **0.6 Mio m^3 of concrete**

GSI/FAIR Research fields – 4 physics pillars



CBM
- Dense and Hot Nuclear Matter

NUSTAR
- Nuclear Structure far off stability
  Physics of Explosive Nucleosynthesis



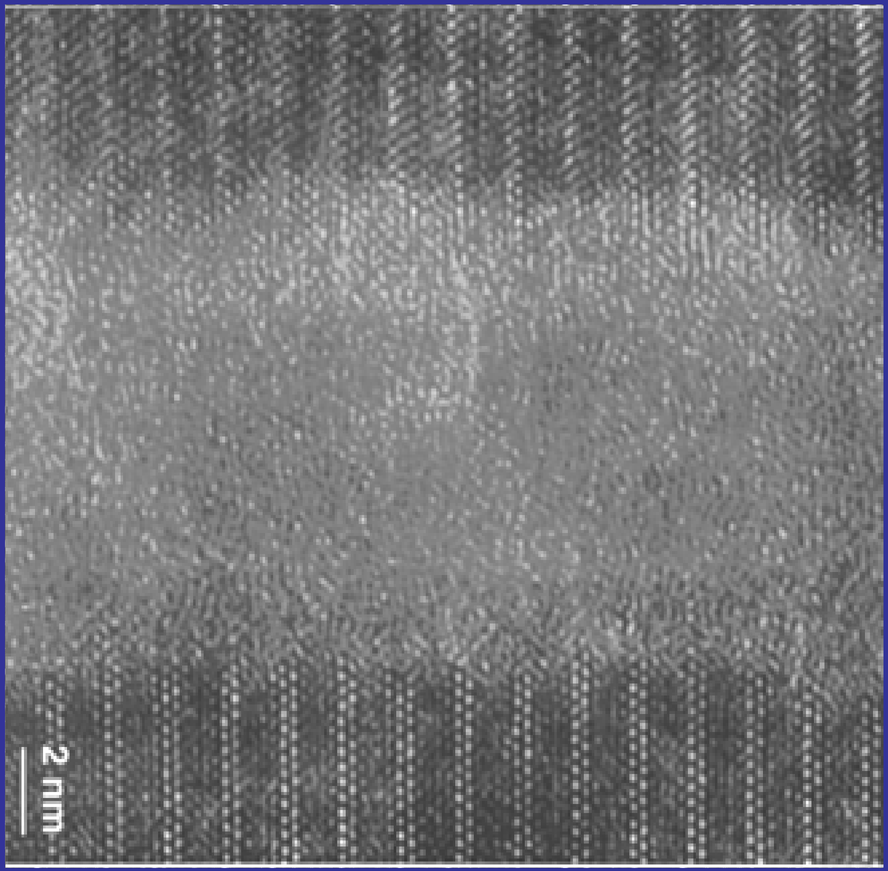
PANDA
- Hadron Structure & Dynamics with cooled antiproton beams

APPA
- Atomic Physics and Fundamental Symmetries
- Plasma Physics
- **Materials Research** ← **~5% activity**
- Radiation Biology and hadron cancer therapy

Ion irradiation of solids

2-GeV Au projectile → high-T_c superconductor

15% velocity of light

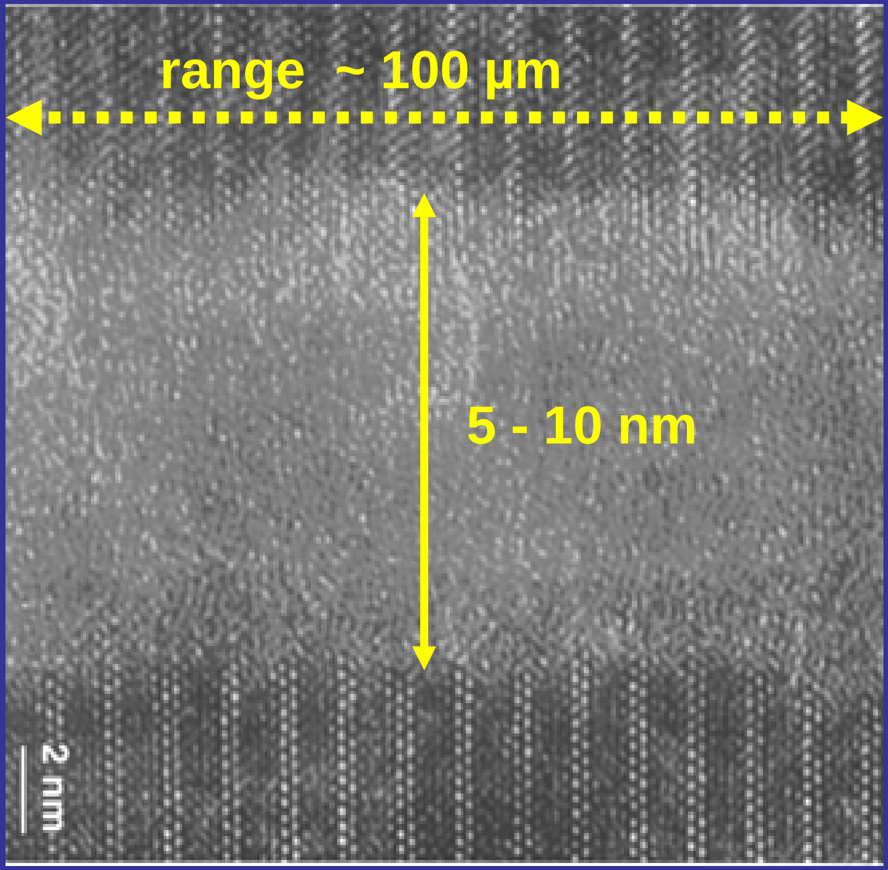


Ion irradiation of solids

each projectile produces damage trail = ion track

disorder

amorphous



broken bonds

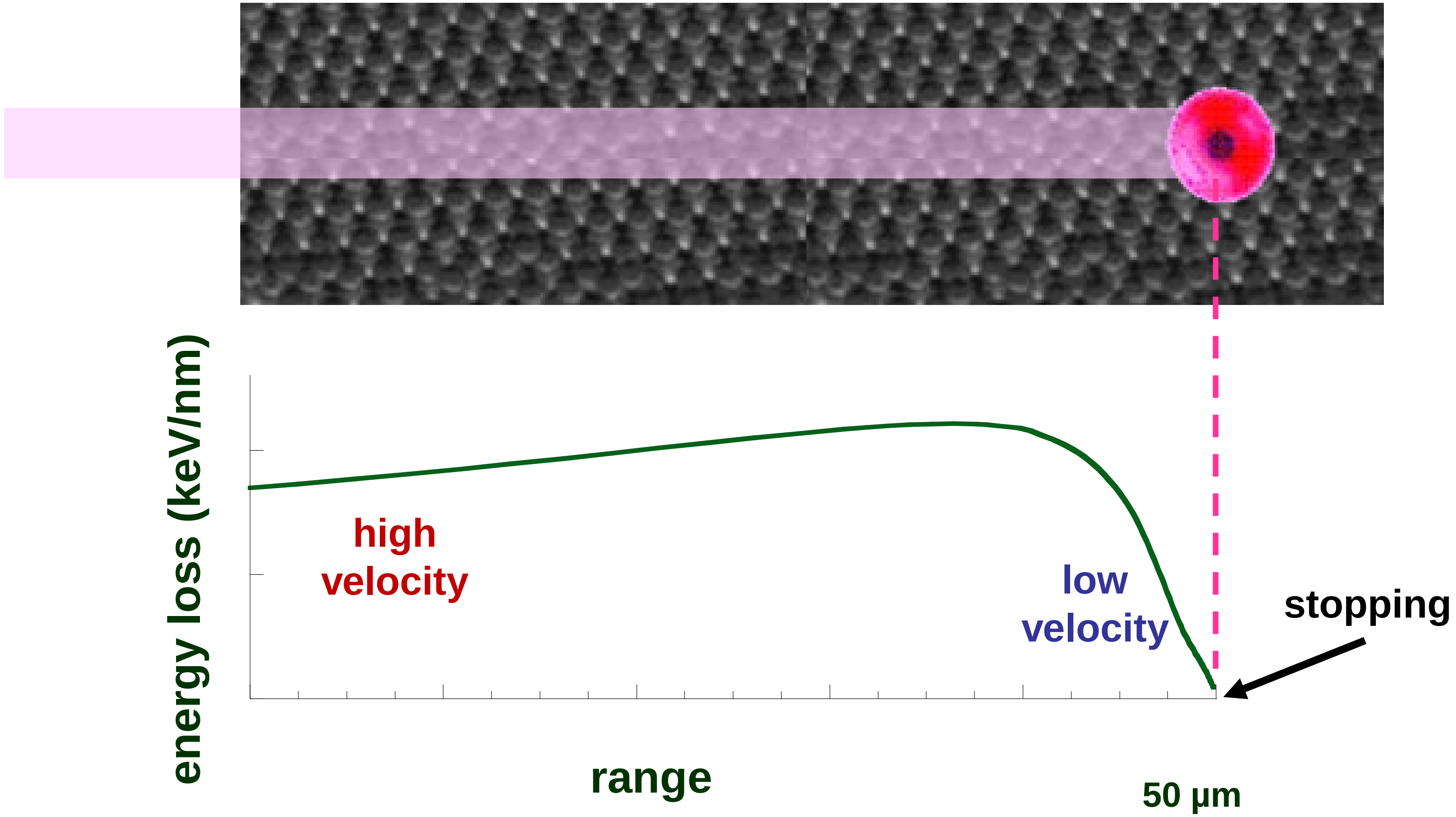
simple defects

defect clusters

Wiesner et al, Physica C (1996)

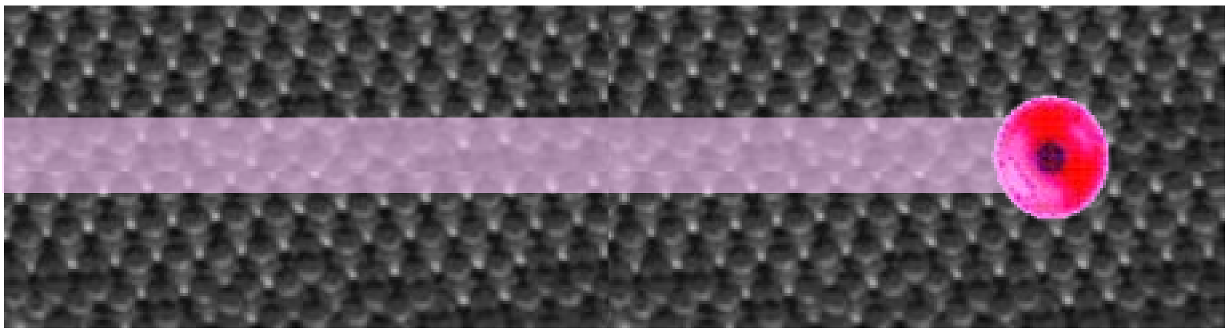
Ion - solid interaction

1-GeV ion **v = 10% c** **range ~50 µm**



Ion - solid interaction

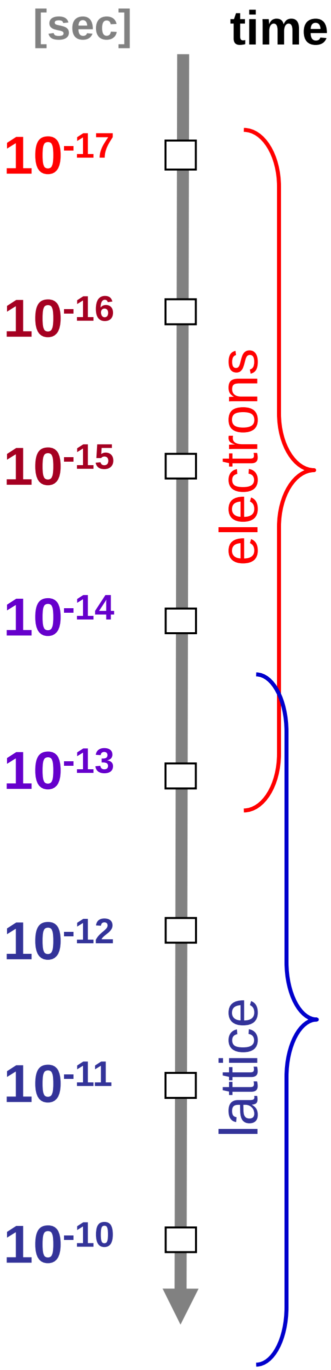
1-GeV ion   v = 10% c   range ~50 µm



49 µm
collisions with electrons
excitation and ionization

1 µm
elastic collisions
with atoms

electron cascade



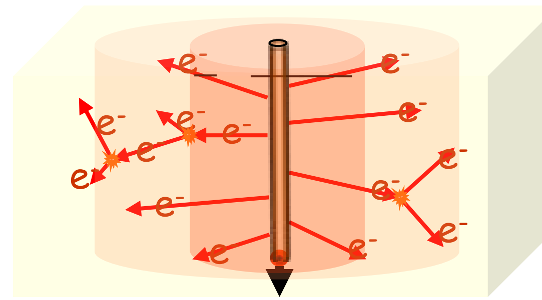
track formation process

stage 1: $10^{-17} – 10^{-16}$ s

generation of δ-electrons

stage 2: $10^{-15} – 10^{-14}$ s

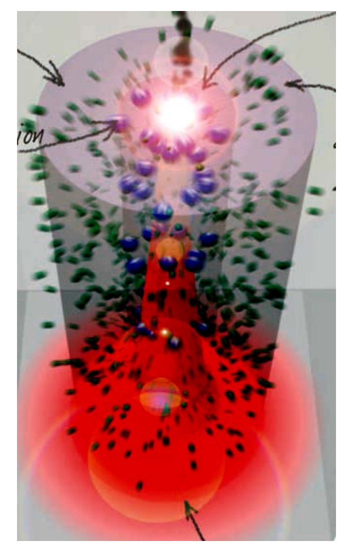
electron cascade



stage 3: ~ 10 fs - 1 ps electron-phonon coupling

stage 4: ≥ 1 ps lattice processes

thermal spike, defect creation...



track formation process

[sec] time

10^{-17}

10^{-16}

10^{-15}

10^{-14}

10^{-13}

10^{-12}

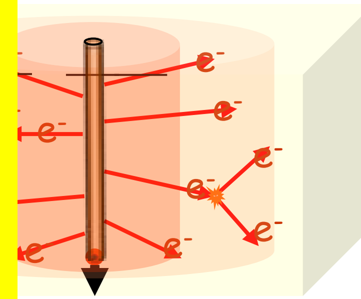
10^{-11}

10^{-10}

electrons

lattice

stage 1: $10^{-17} – 10^{-16}$ s



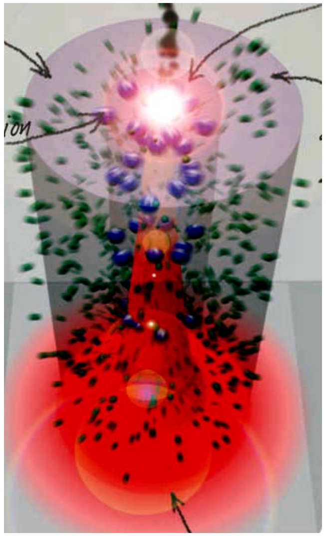
- **extremely fast**
- **non-equilibrium process**
- **two step process:**

  (i) electron → (ii) atom system

non

stage 4: ≥ 1 ps lattice processes

thermal spike, defect creation...



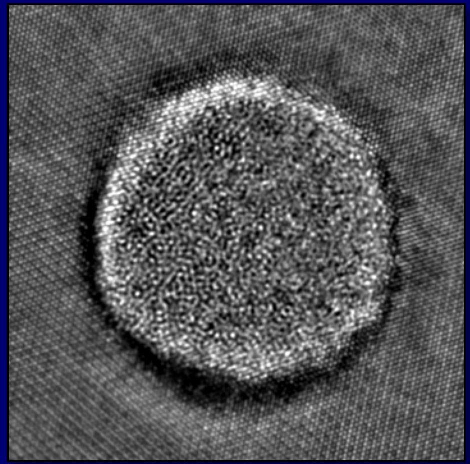
Track size depends on many parameters

pyrochlor

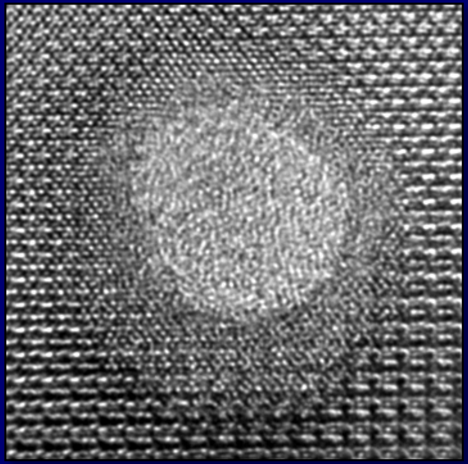
$Gd_2Ti_2O_7$

2.2-GeV ^{197}Au

40 keV/nm; RT



changing
composition



$Gd_2Ti_1O_5$

2.2-GeV ^{197}Au

40 keV/nm; RT

J. Zhang, J. Mater. Res. (2010)

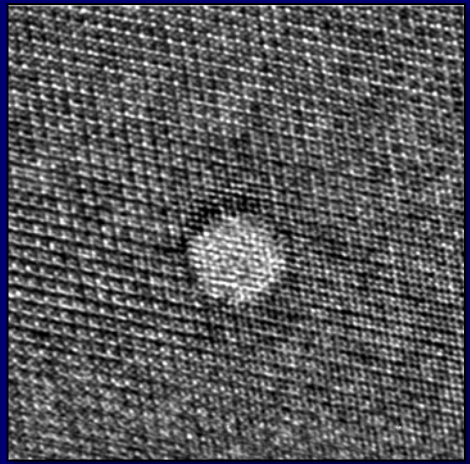
decreasing
energy density

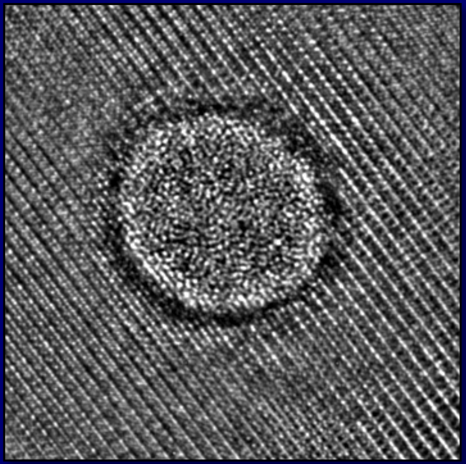
decreasing
temperature

$Gd_2Ti_2O_7$

1.1-GeV ^{101}Ru

20 keV/nm; RT





$Gd_2Ti_2O_7$

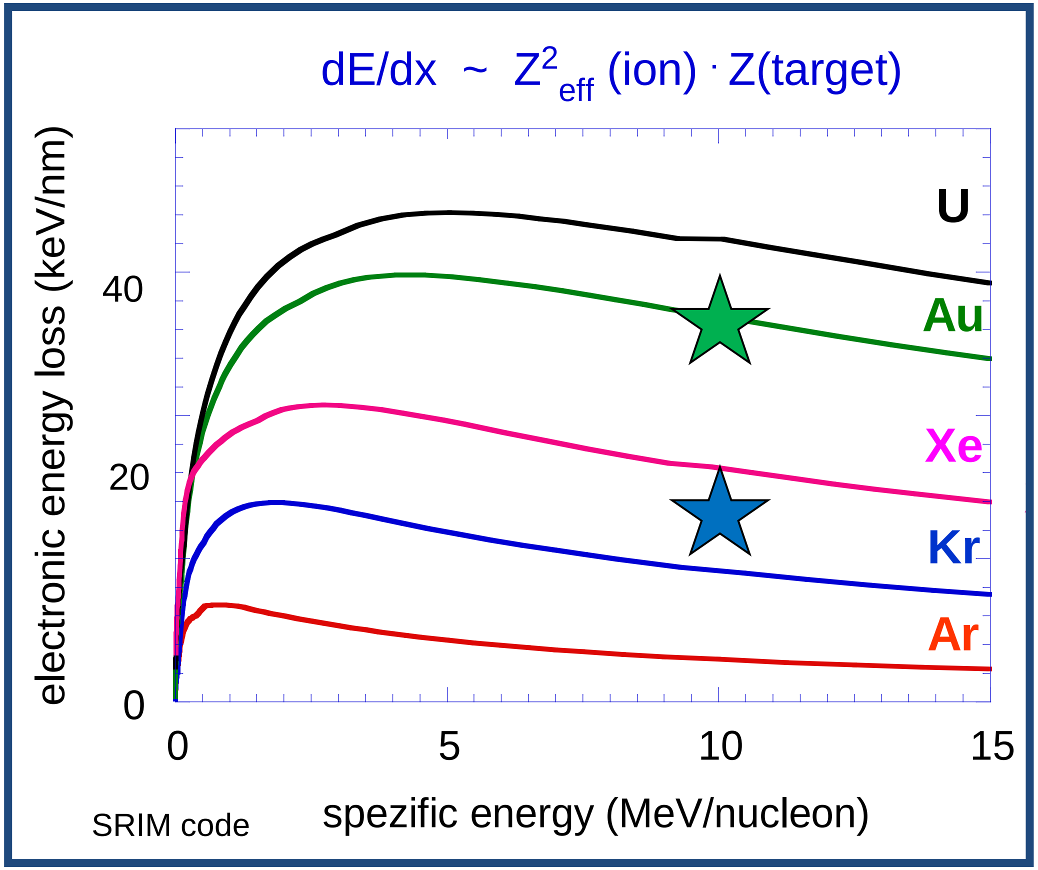
2.2-GeV ^{197}Au

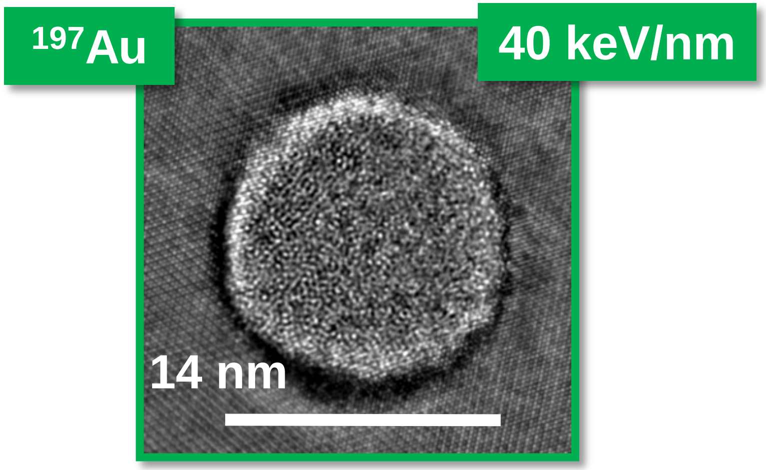
40 keV/nm; **8 K**

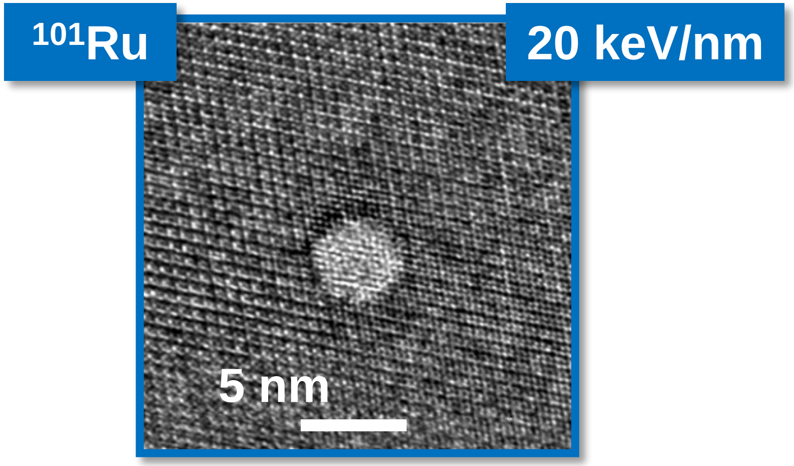
5 nm

most important parameter = energy loss of ions

energy loss of different ions

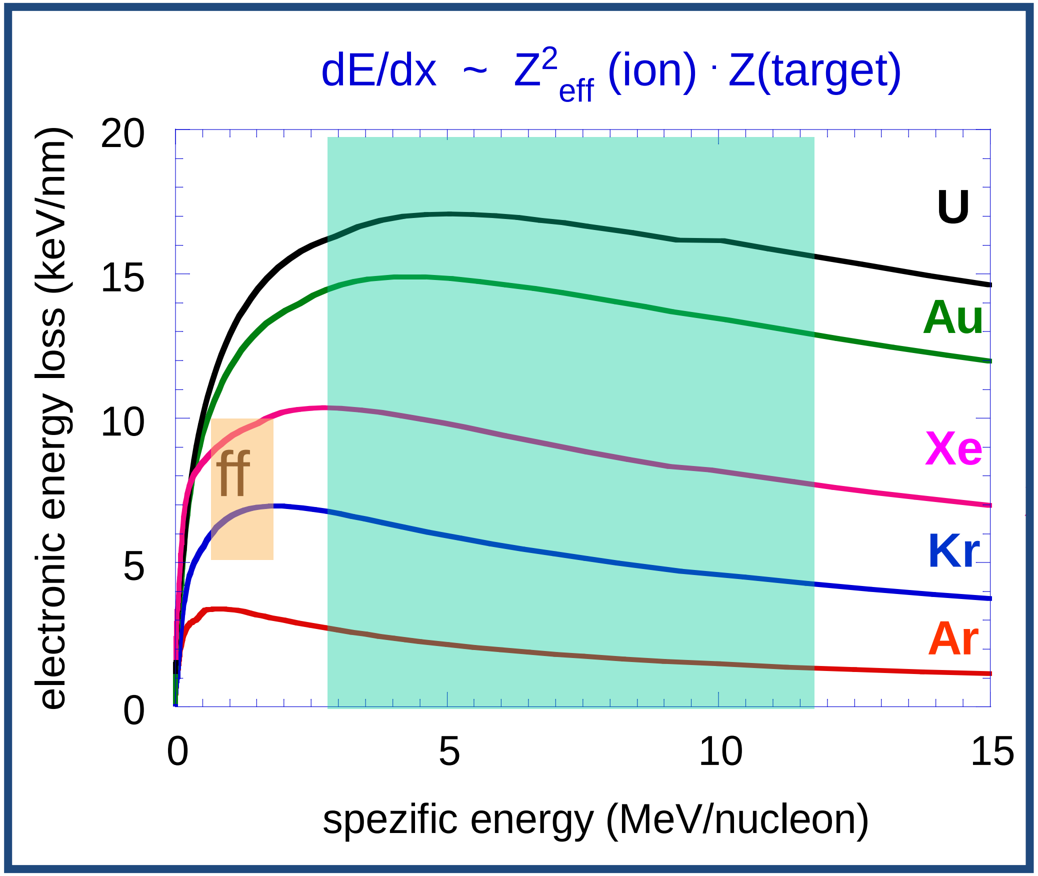




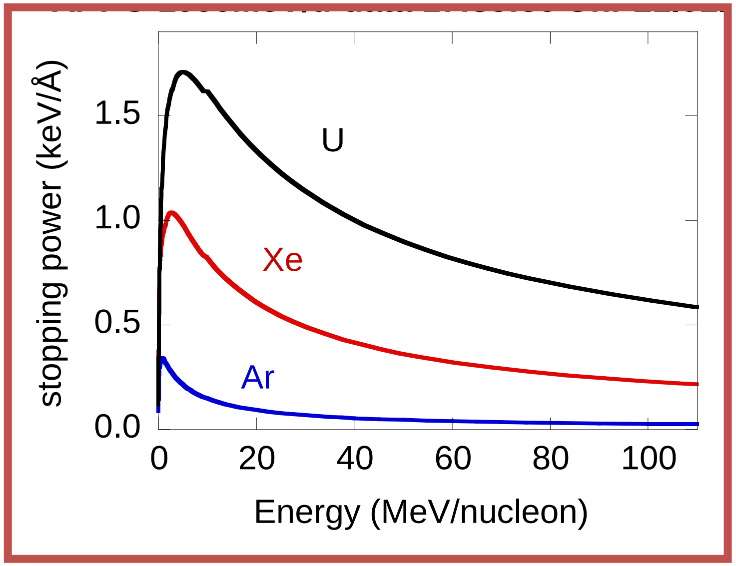


most important parameter = energy loss of ions

UNILAC energies



higher energies → lower energy loss

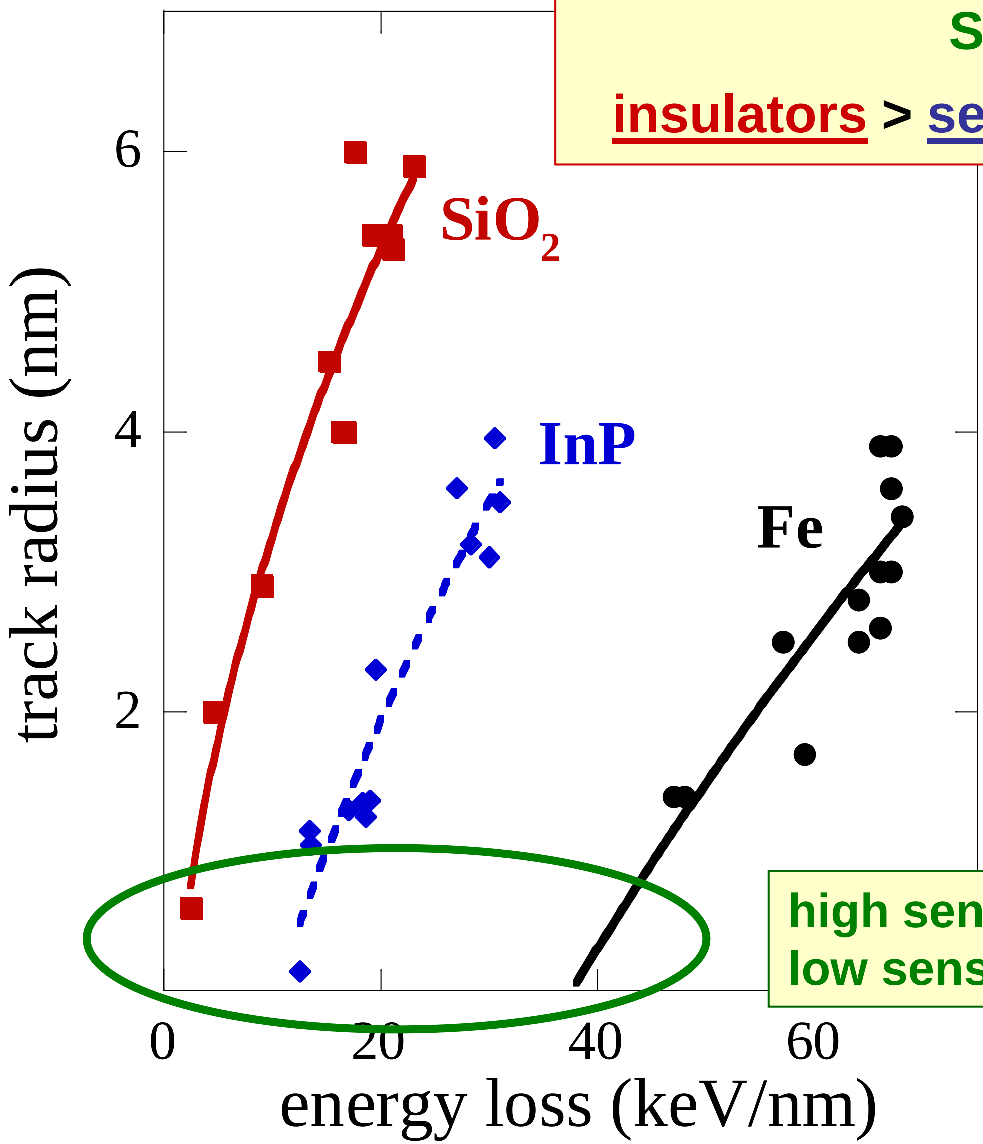


specific energy = 10 MeV/nucleon

^{40}Ar → 10 x 40 MeV = 400 MeV

^{238}U → 10 x 238 MeV = 2380 MeV

Sensitivity of materials for ion track formation



Sensitivity:

insulators > semiconductors > metals

high sensitivity → low threshold
low sensitivity → large threshold

Track formation depends on materials nature

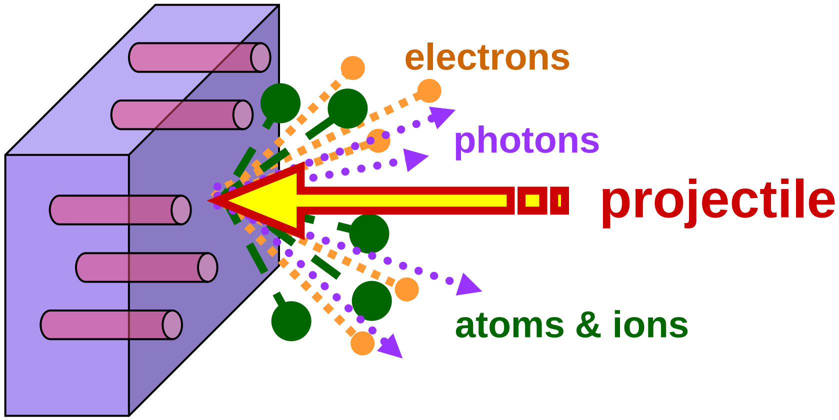
high sensitivity		low sensitivity
dE/dx threshold ~1 keV/nm	~20 keV/nm	~50 keV/nm

insulators	semi-conductors	metals
- polymers	- amorphous Si, Ge	- amorphous alloys
- oxides, spinels	- GeS, InP, $Si_{1-x}Ge_x$	- Fe, Bi, Ti, Co, Zr
- ionic crystals	- ~~Si, Ge~~	- ~~Au, Cu, Ag,~~
- ~~diamond~~		

~~no tracks~~

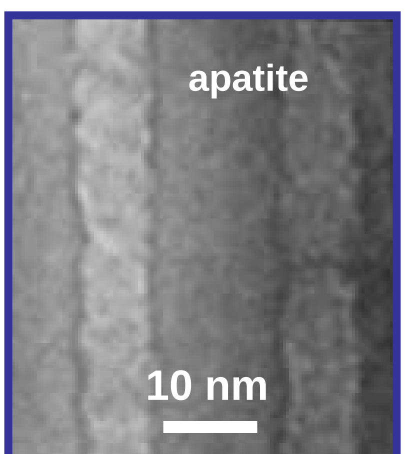
Materials science with swift heavy ions

destructive power



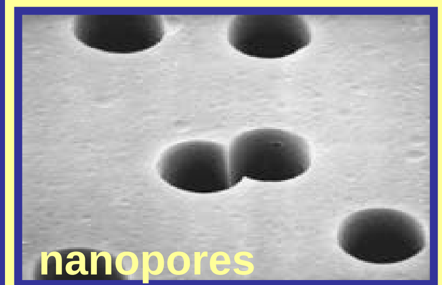
track formation & degradation

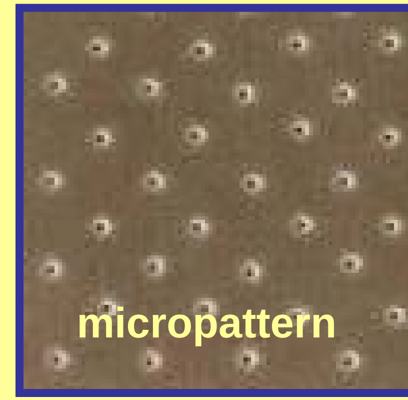
microscopic

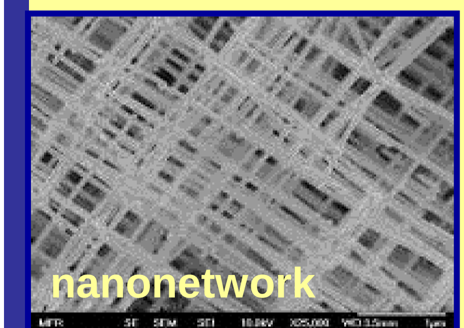


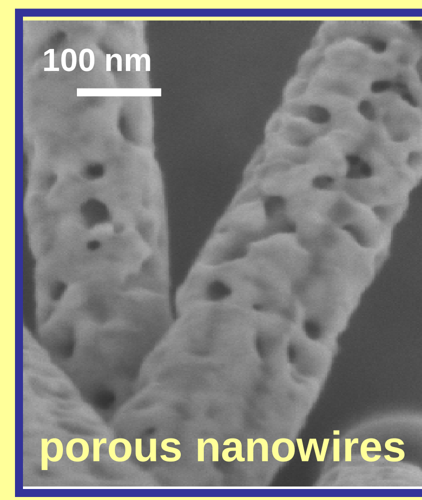
macroscopic

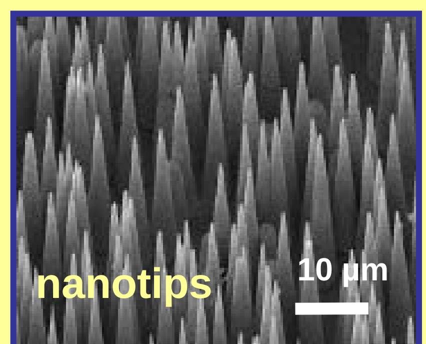
structuring tool



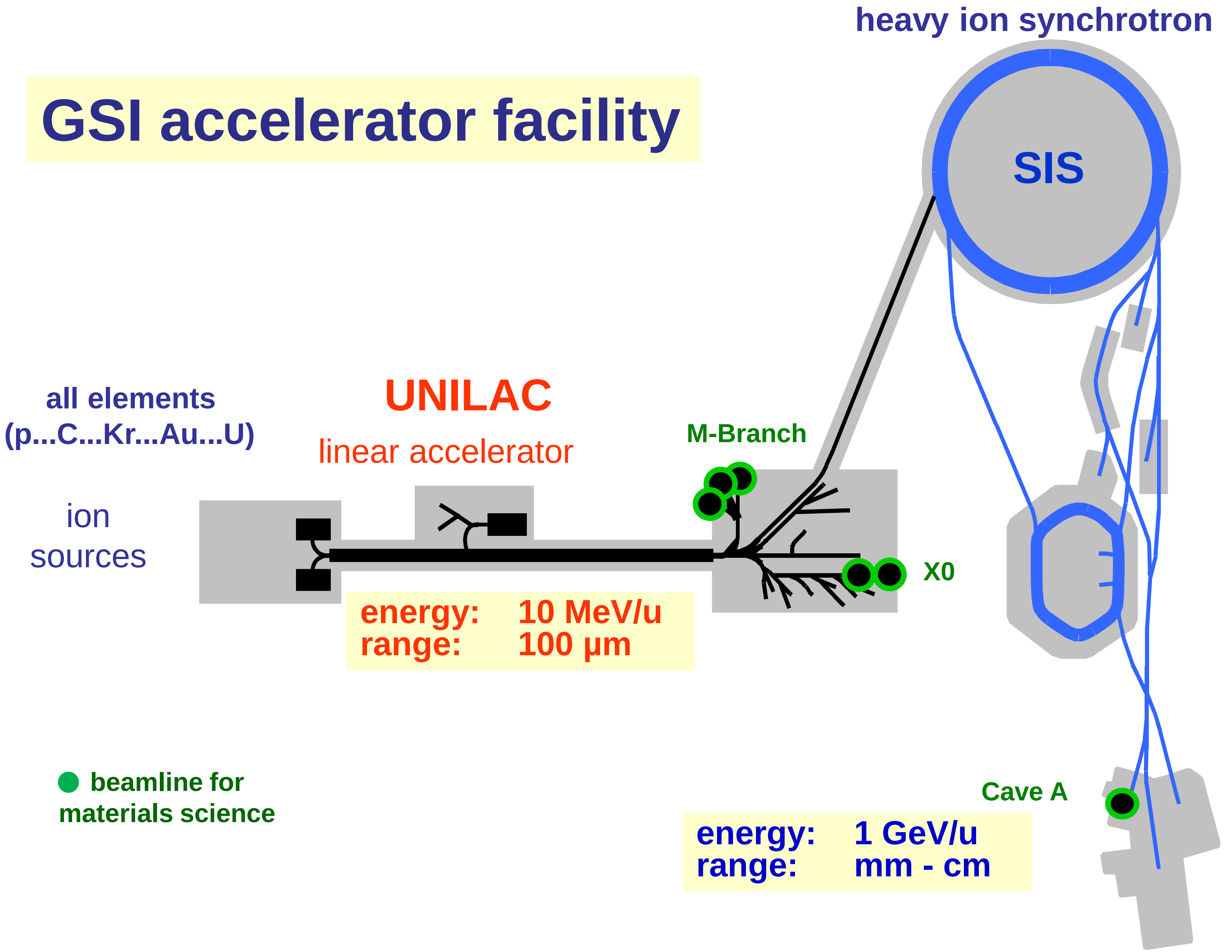




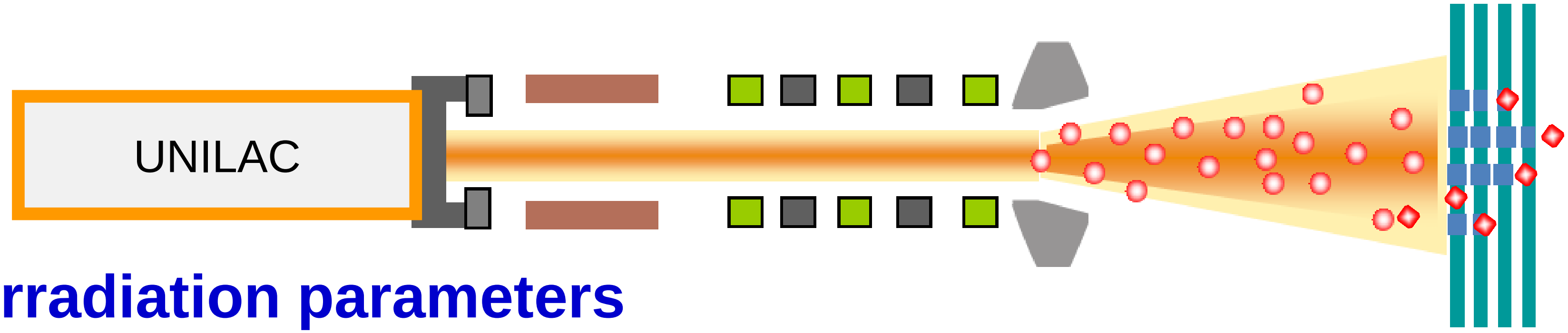




GSI accelerator facility

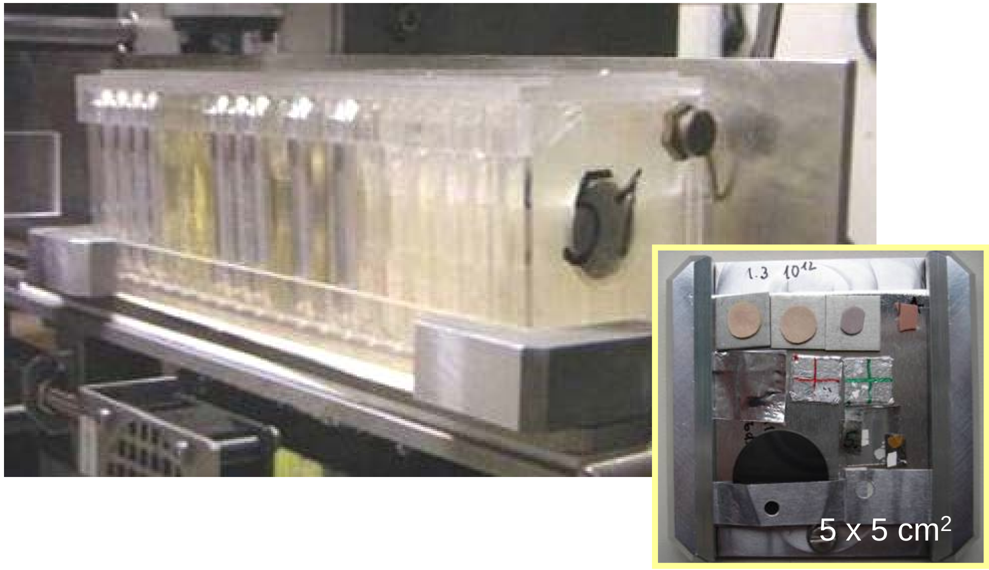


User facility for materials science



Irradiation parameters

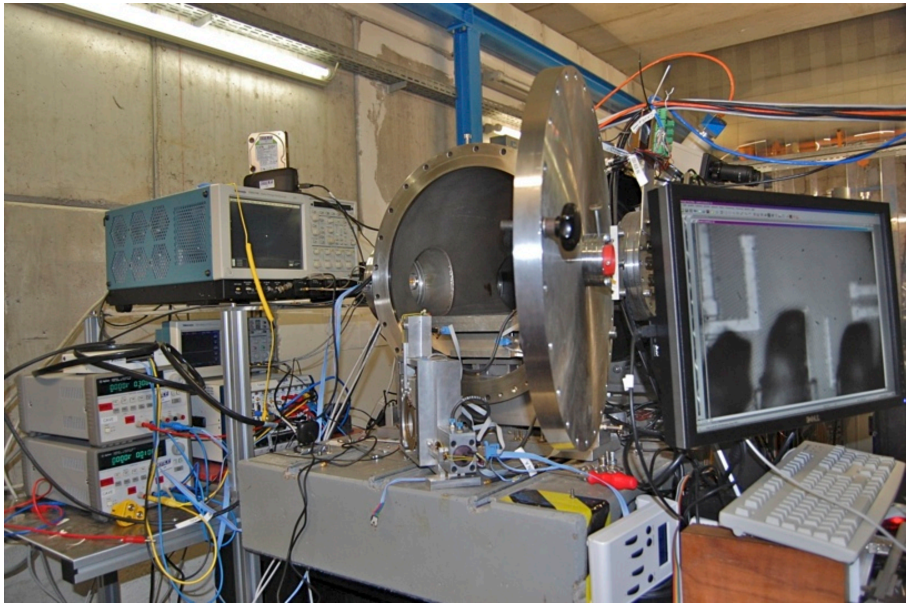
- ion species: C ... U
- energies: 4 – 11.4 MeV/u
- max range: ~100 µm
- fluence range: 1–10^{14} ions/cm^2
- variable temperature conditions

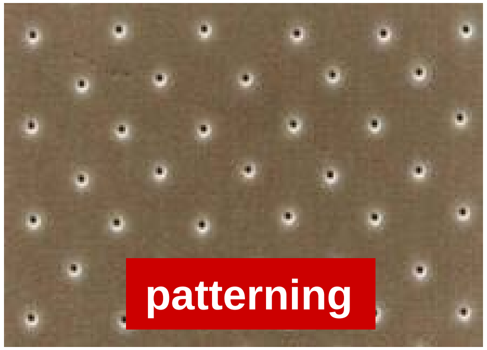


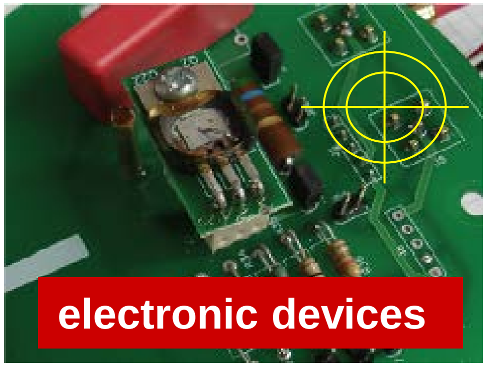
Proposal required

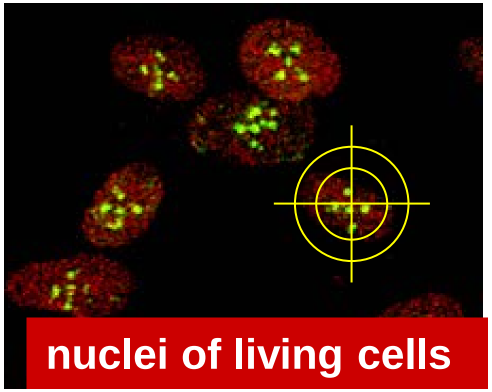
Users are organized in MAT collaboration
Registration via GSI webpage
https://www.gsi.de/work/forschung/appamml/materialforschung/mat_collaboration.htm

Microprobe for targeting with single ions



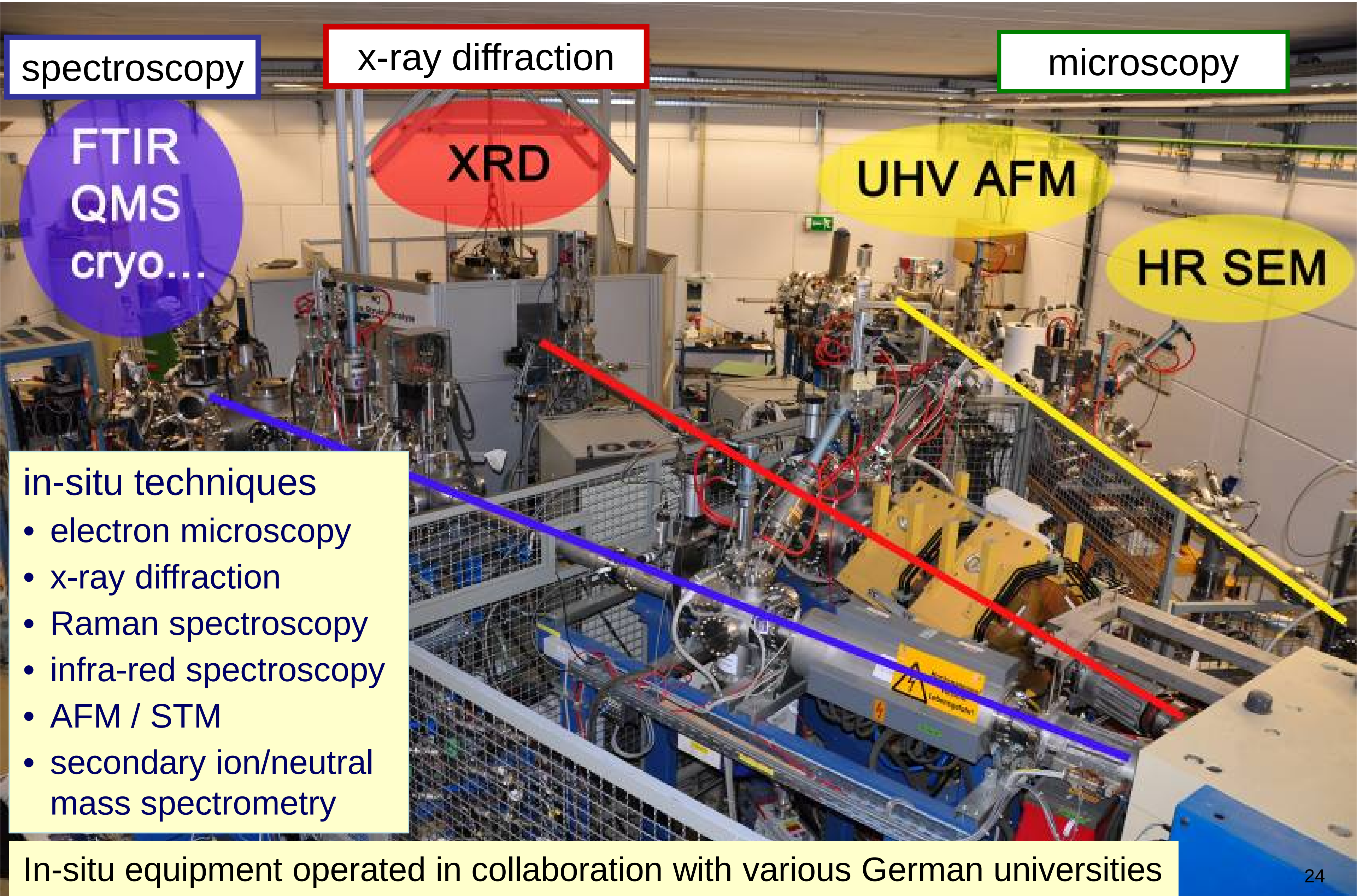






- **protons – U ions**
- **E_{max} 11.4 MeV/u**
- **absolute targeting accuracy < 1µm**
- **targeting rate 1000 ions/s**

M-branch: Irradiations combined with in situ analysis



in-situ techniques

- electron microscopy
- x-ray diffraction
- Raman spectroscopy
- infra-red spectroscopy
- AFM / STM
- secondary ion/neutral mass spectrometry

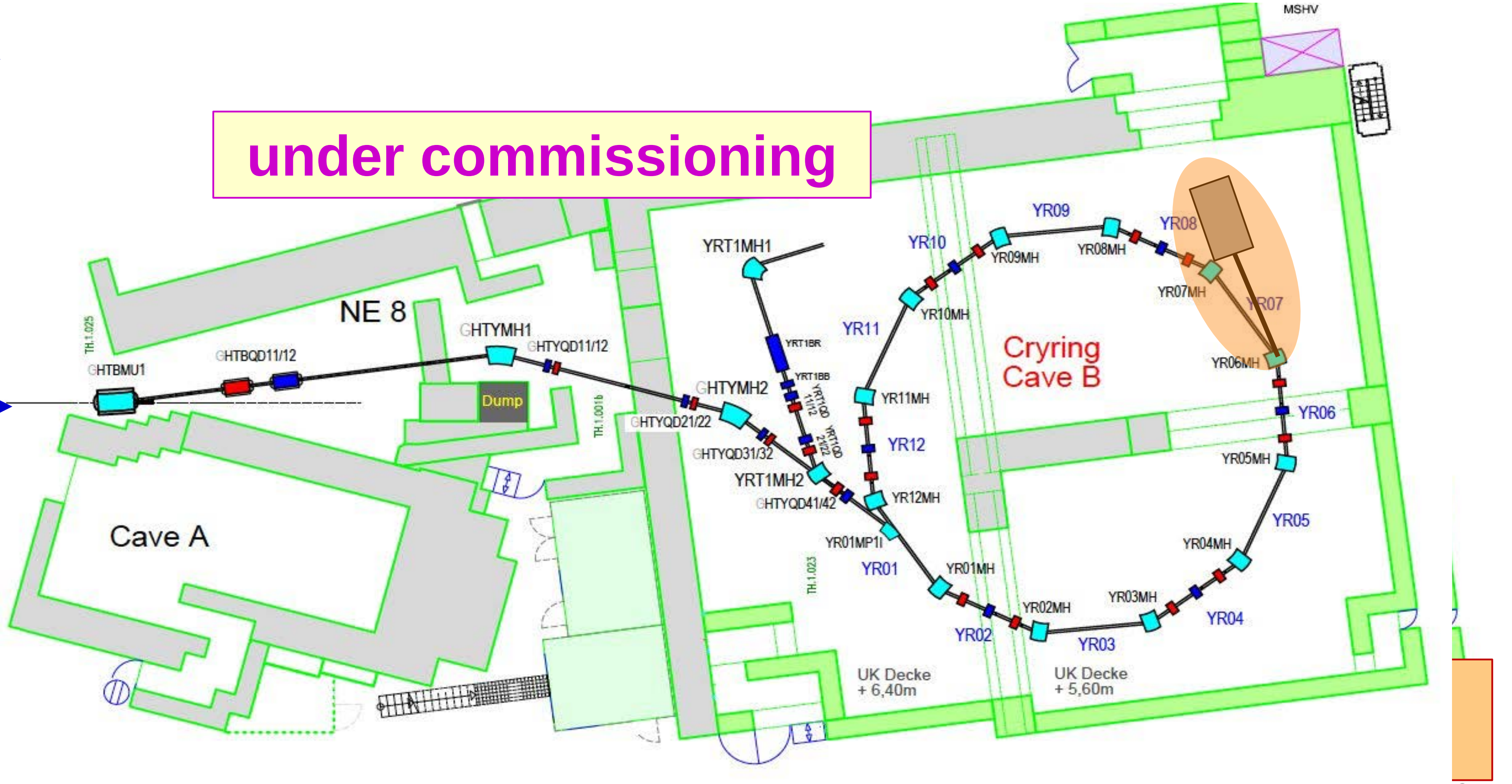
In-situ equipment operated in collaboration with various German universities

CRYRING – BIOMAT station

Irradiation experiments with highly-charged or fully-stripped ions (e.g. 10 MeV/u U^{92+})

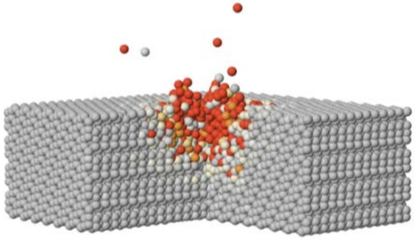
UNILAC → SIS18 → ESR →

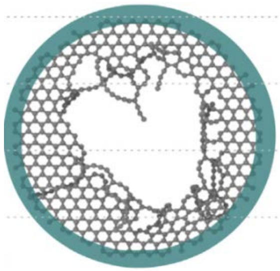
under commissioning

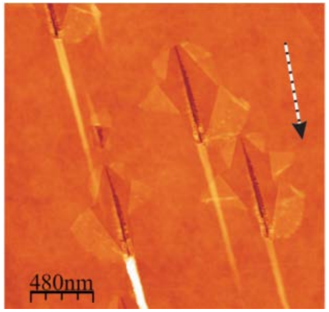


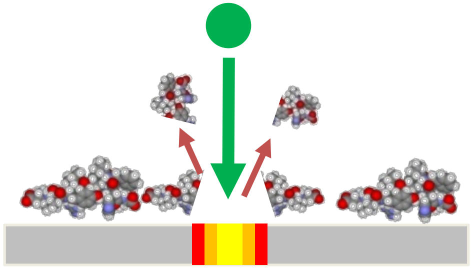
Topics of interest at CRYRING

- Slow highly-charged or fully-stripped ions
  - tune potential energy (charge state)
  - tune kinetic energy (up to ~10 MeV/u)
- Surface processes far from thermal equilibrium
- Deposition of highest energy densities
- Tailored nanostructures with individual ions









Ion-track nanotechnology

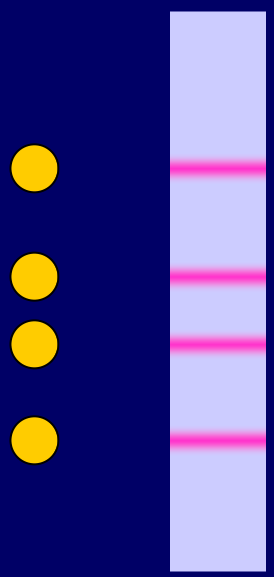
Part 1

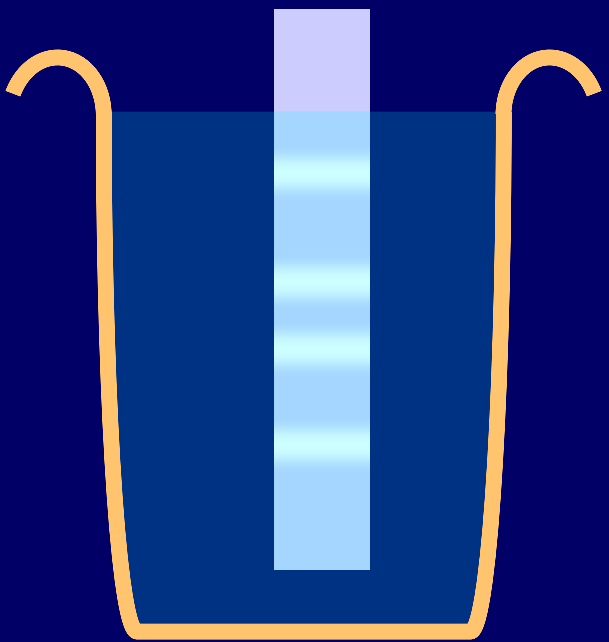
drilling holes ....

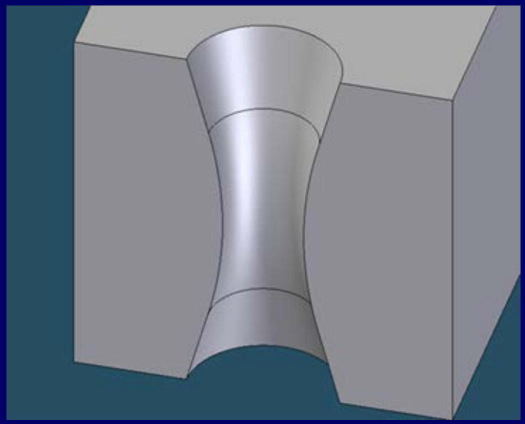
Part 2

.... filling holes

Ion-track nanotechnology

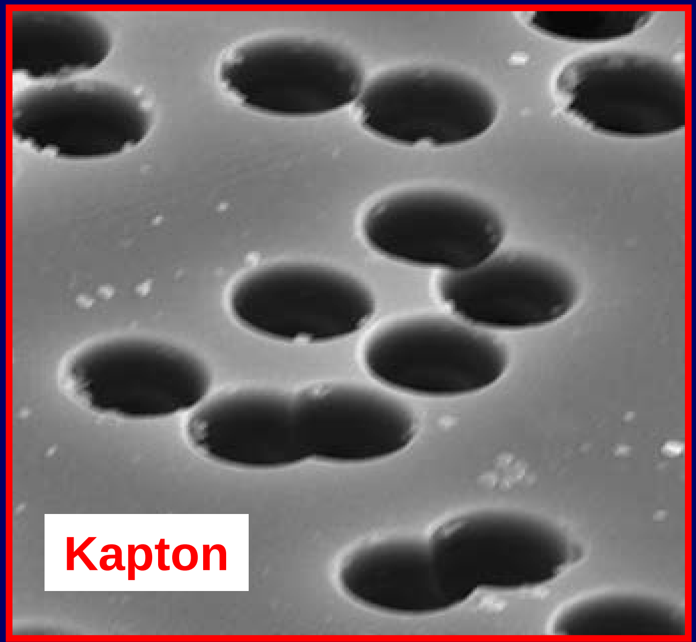






ion
irradiation

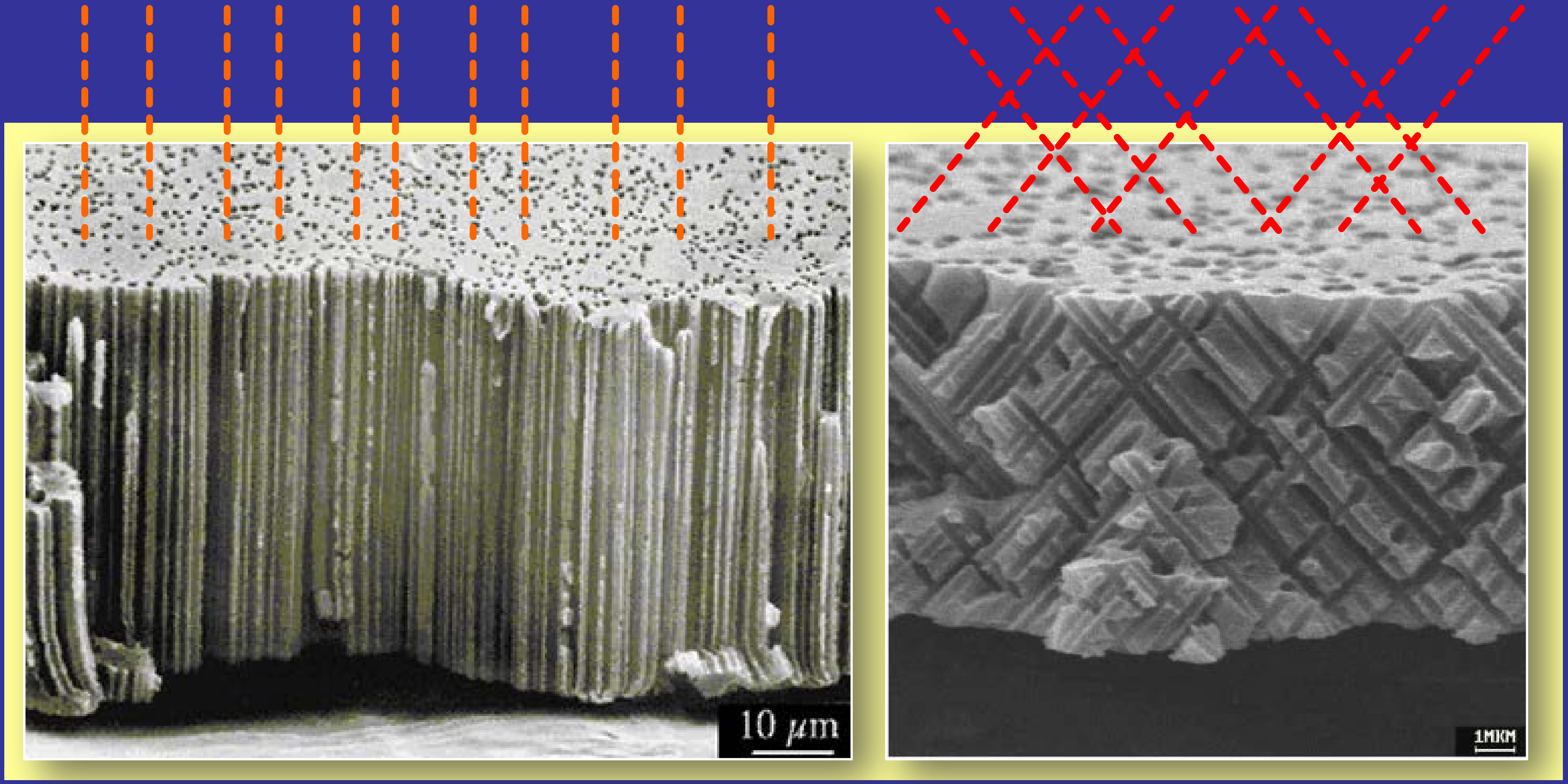
etching bath
(e.g. NaOH)



Ion-track nanotechnology

fluence (ions/cm^2) determines number of pores

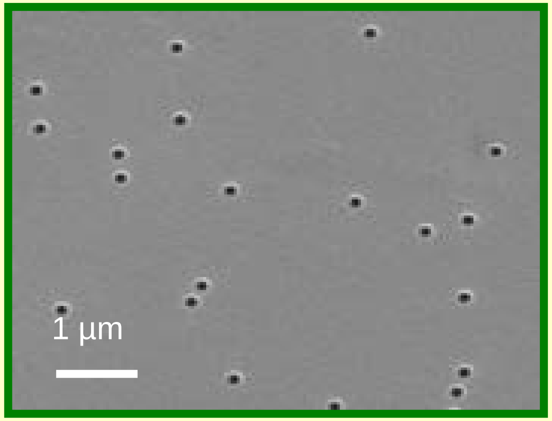
irradiation angle defines pore orientation

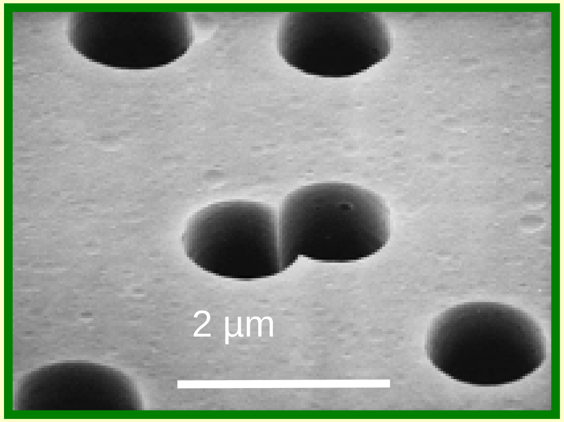


Ion-track nanotechnology

etching process defines

pore size: 15 nm – few µm



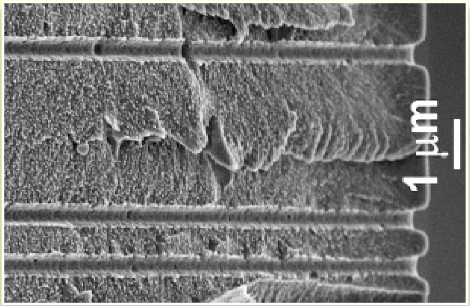


short etching **long etching**

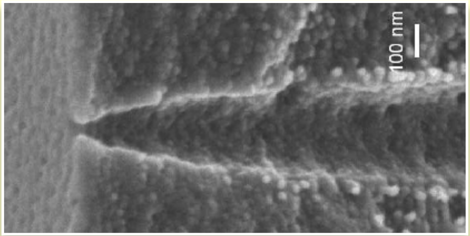
aspect ratio > 1000 possible

pore geometry

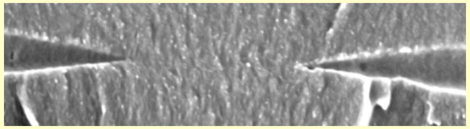
cylindrical



tapered



double-conical



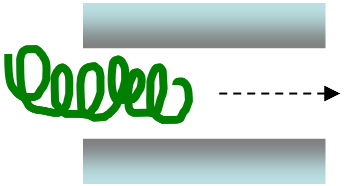
Apel *et al.*, NIMB 267 (2009)

most suitable polymers

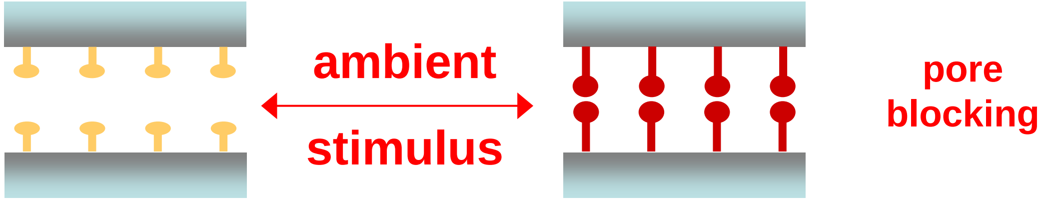
PET	polyethylene terephthalate (e.g., Mylar)
PC	polycarbonate (e.g., Lexan, Makrofol)
PI	polyimide (e.g., Kapton)

Building bio-inspired smart nanochannels

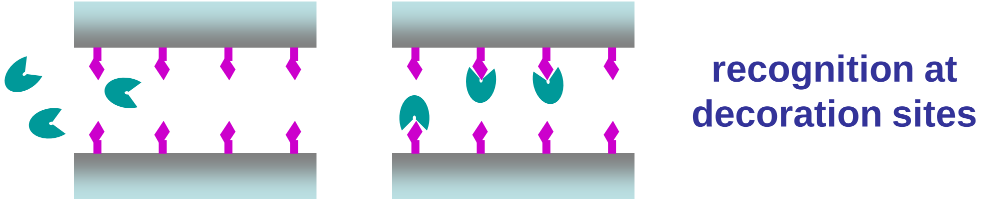
transport of biomolecules



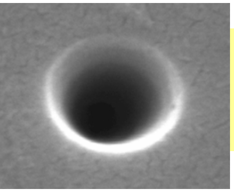
responsive channels



biosensor

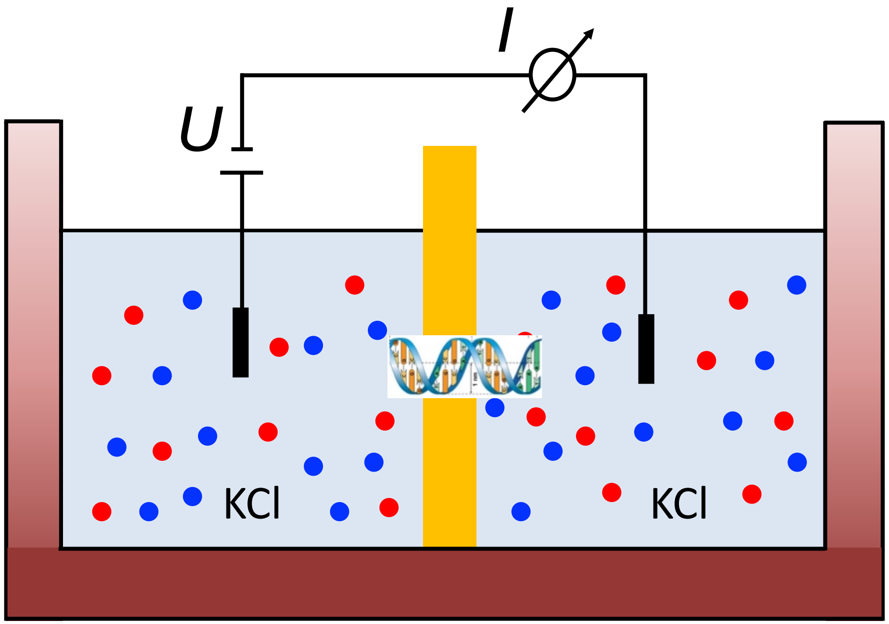


ligand binds to receptor

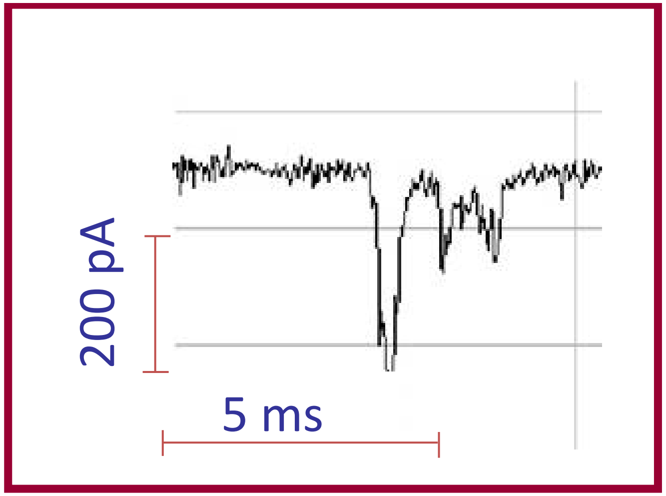


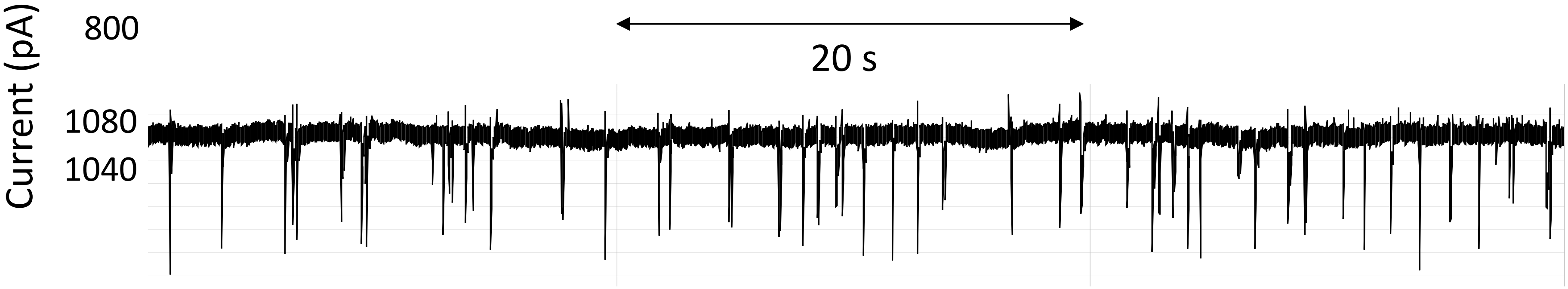
Sensors based on single nanopores

Translocation of particle through nanopore



current signal during DNA translocation

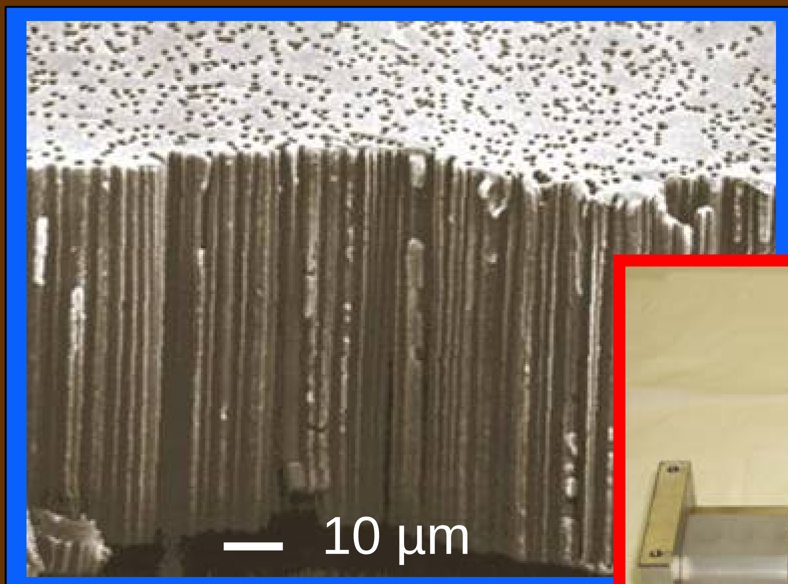




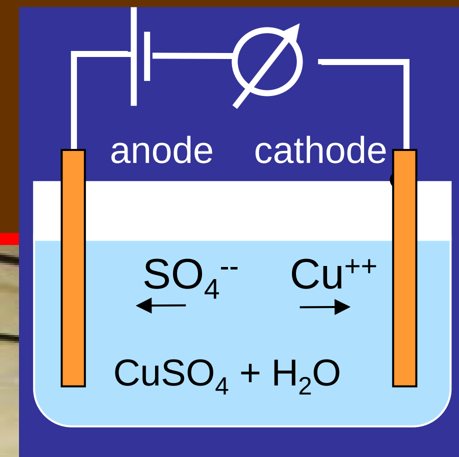
Part 2

.... filling of holes .....

Ion track membranes as templates

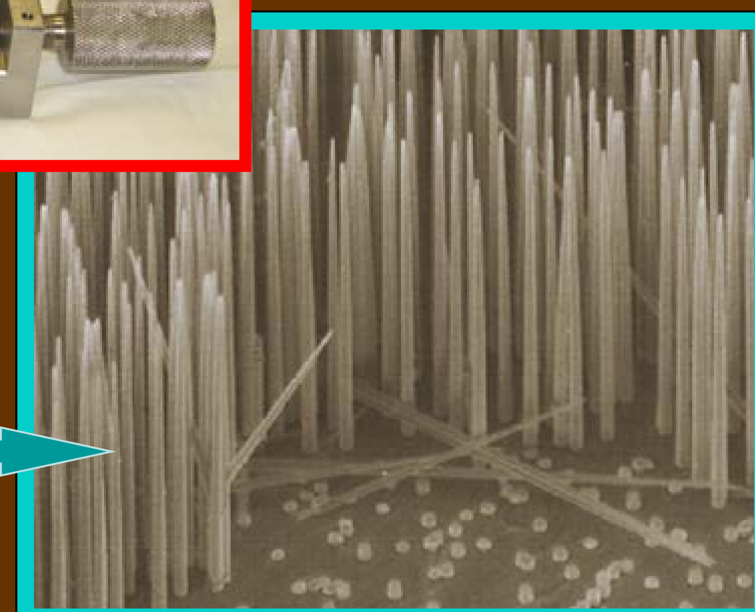


ion track membrane



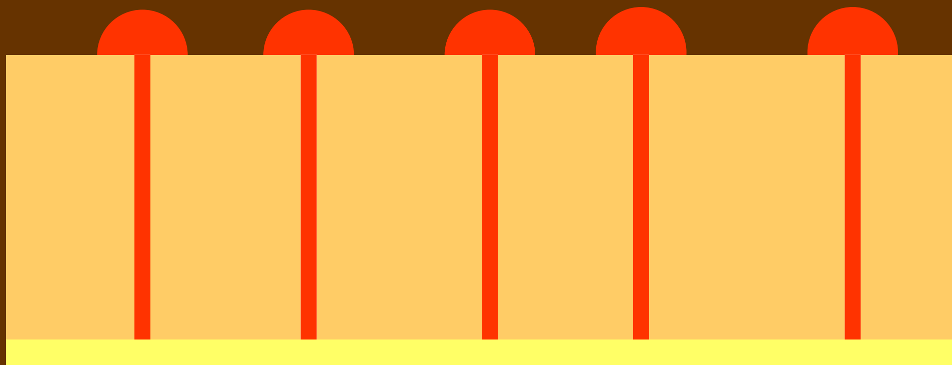
filling of pores in galvanic cell

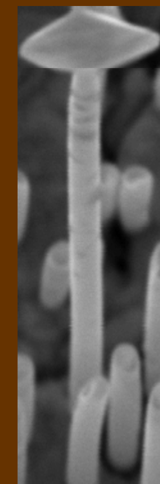
dissolution of polymer



free-standing metal needles

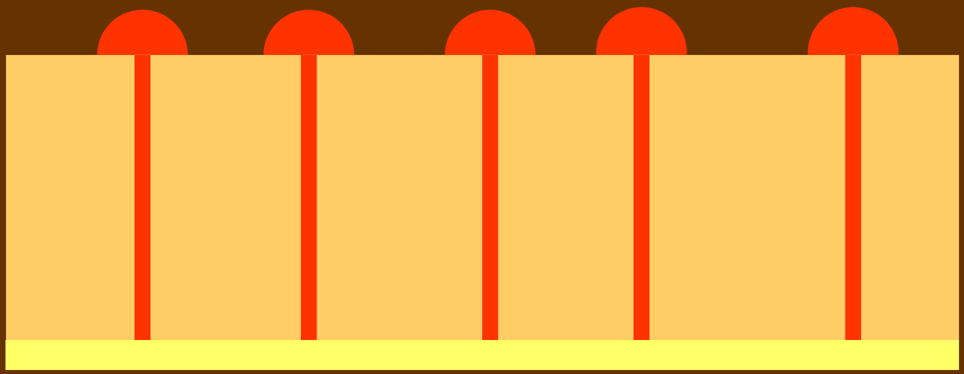
Electrochemical deposition

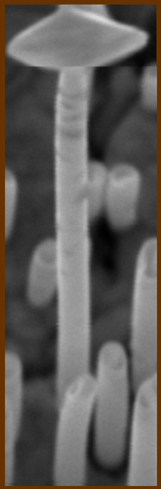


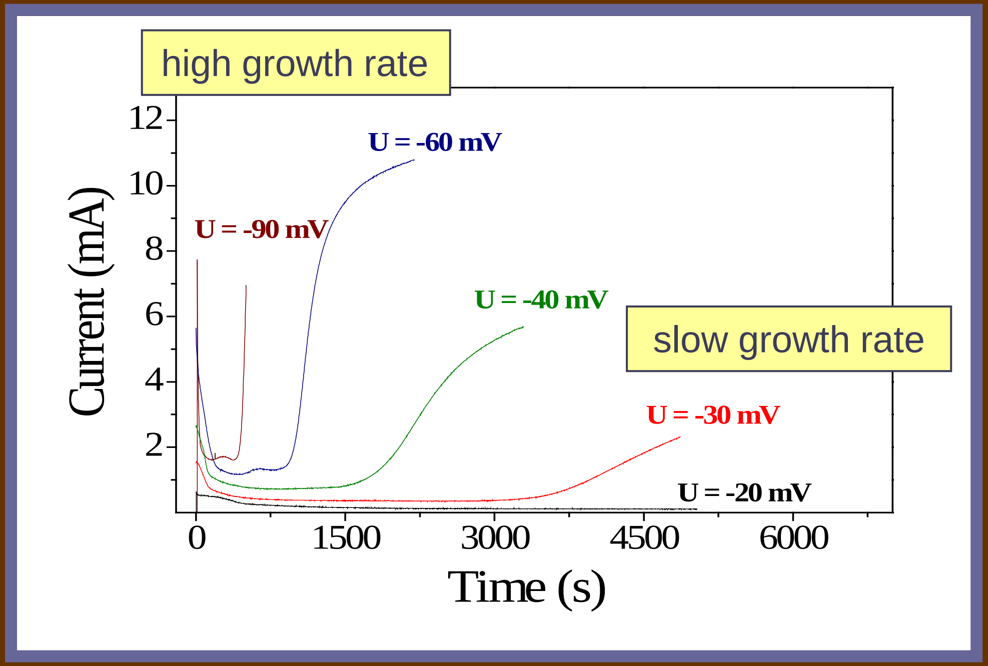


Electrochemical deposition

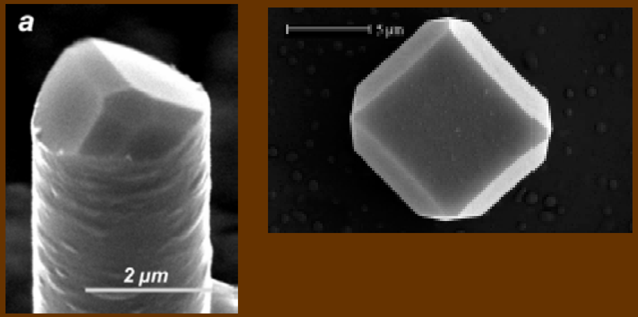
Cu, *T* = 50 °C







single-crystalline growth favored at
- low voltage
- high temperature

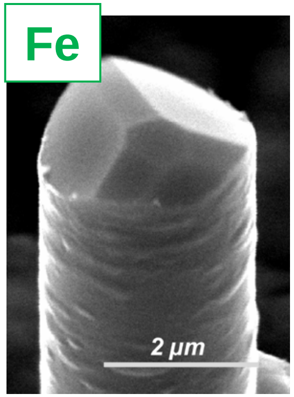


Toimil Molares, Adv. Mater 13 (2001)

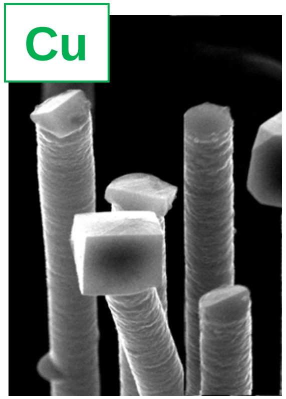
Micro- and Nanowires

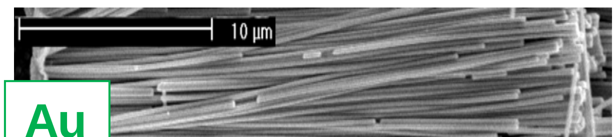
Metals

Fe



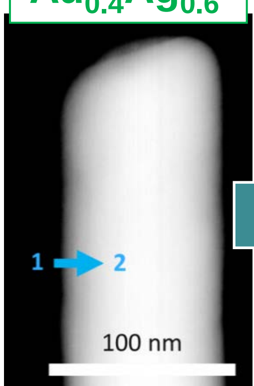
Cu





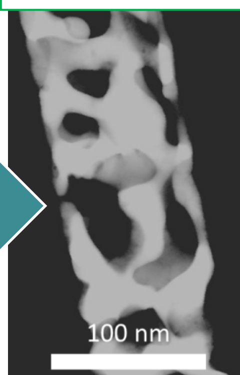
Au

$Au_{0.4}Ag_{0.6}$



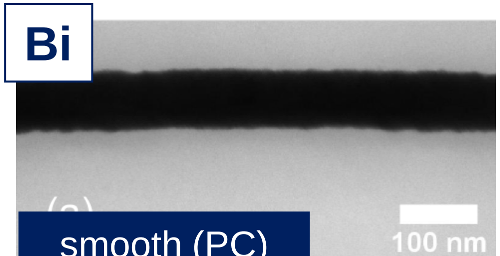
HNO_3

Porous Au



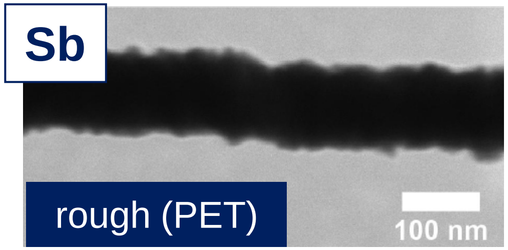
Semimetals

Bi



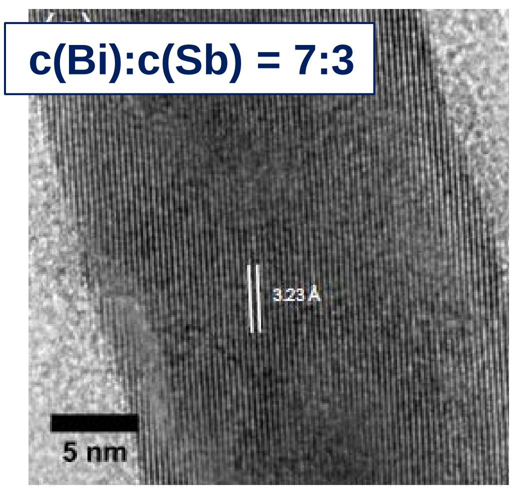
smooth (PC)

Sb



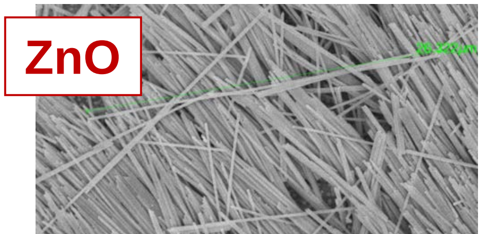
rough (PET)

c(Bi):c(Sb) = 7:3



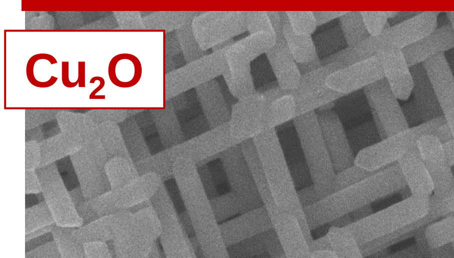
Semiconductors

ZnO



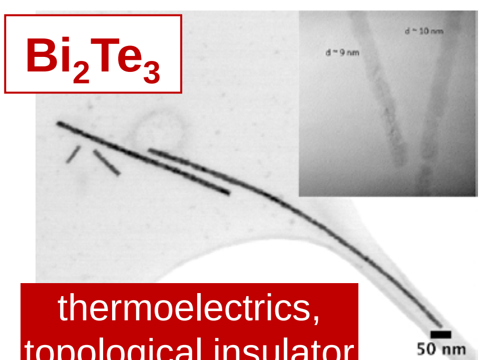
sensors, piezoelectric

Cu_2O



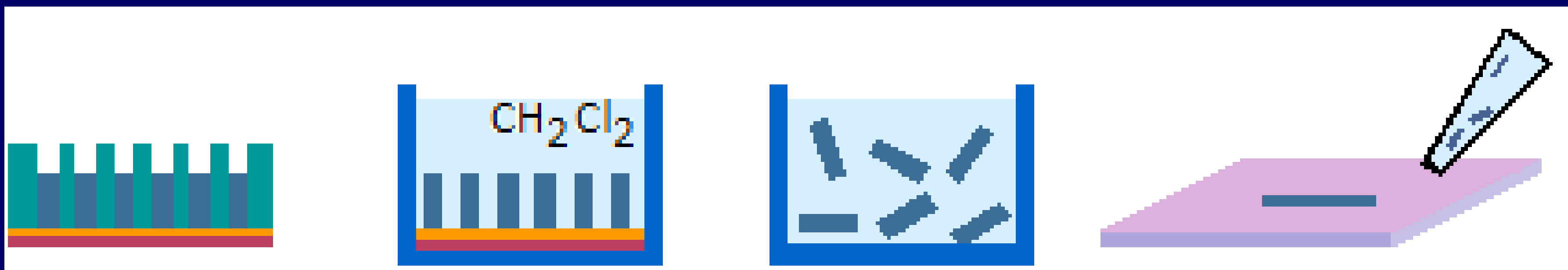
photoelectrodes, catalysis

Bi_2Te_3



thermoelectrics, topological insulator

Nanowire release and manipulation

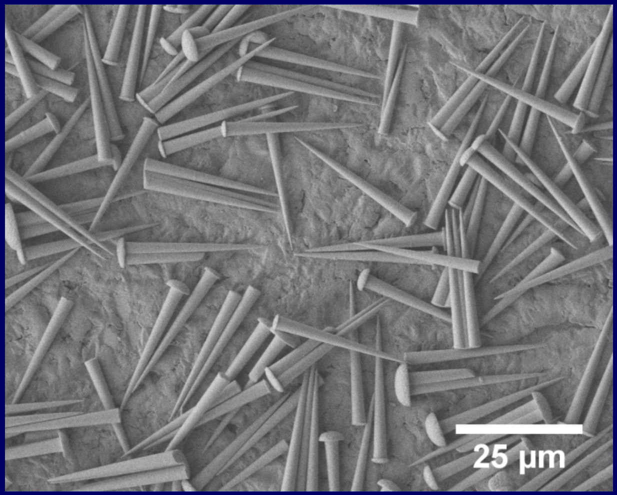


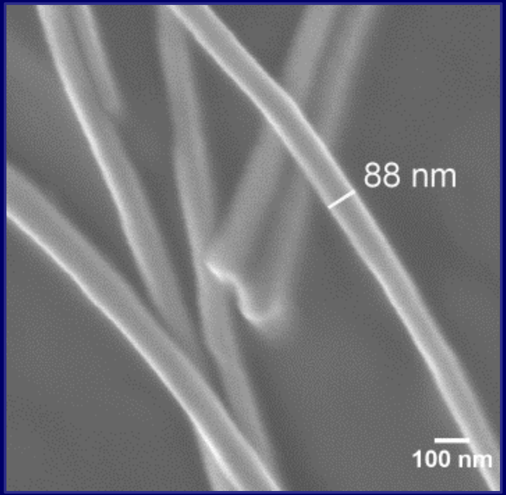
embedded nanowire

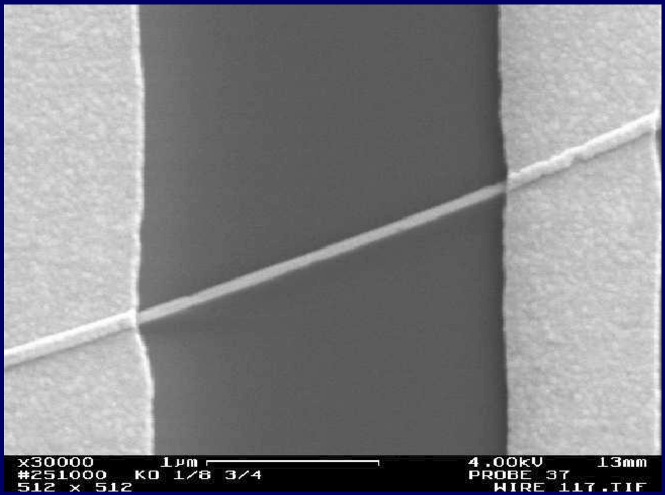
template dissolution

nanowire in solution

drop nanowire on substrate

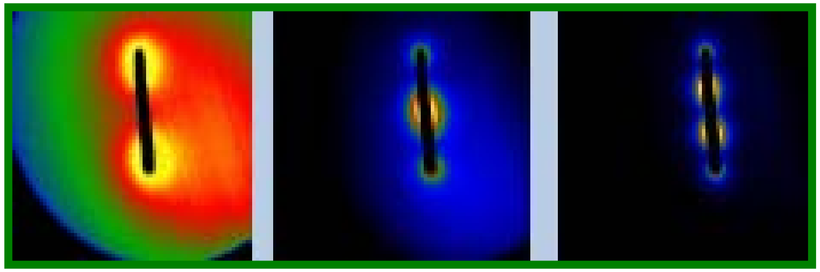




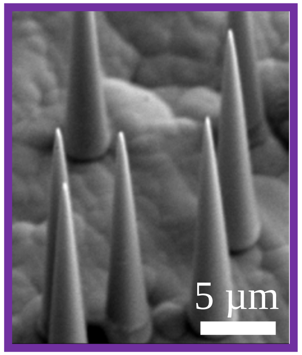


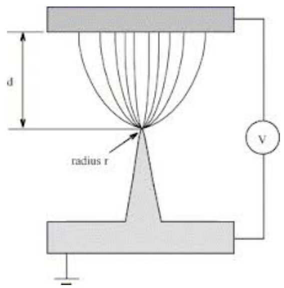
Nanowire properties due to small-size effects

- plasmonic properties

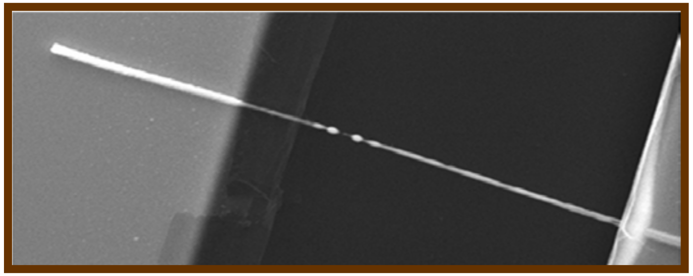


- field emission





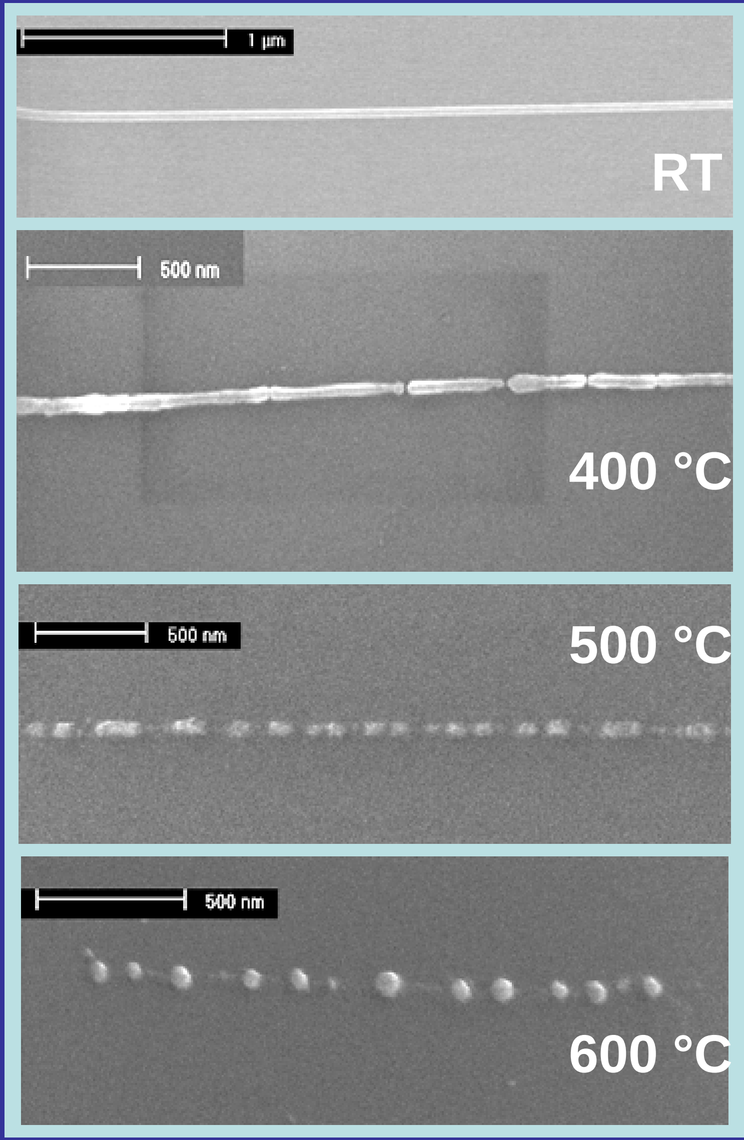
- electrical resistivity
- thermo-electrical
- thermal stability



Rayleigh instability at T << melting

Thermal stability of Cu nanowires

water jet

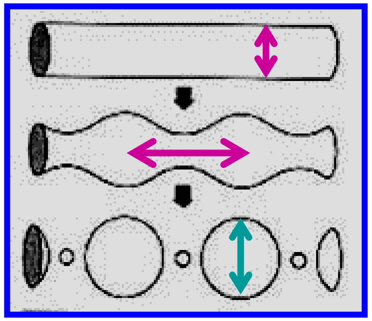


30-nm Cu wire on SiO_2 substrate
30 min annealed in vacuum

Cu: T_{frag}(400 °C) << T_{melt} (1083 °C)

Au: T_{frag}(300 °C) << T_{melt} (1064 °C)

Rayleigh instability: $\lambda = 8.89\ r$



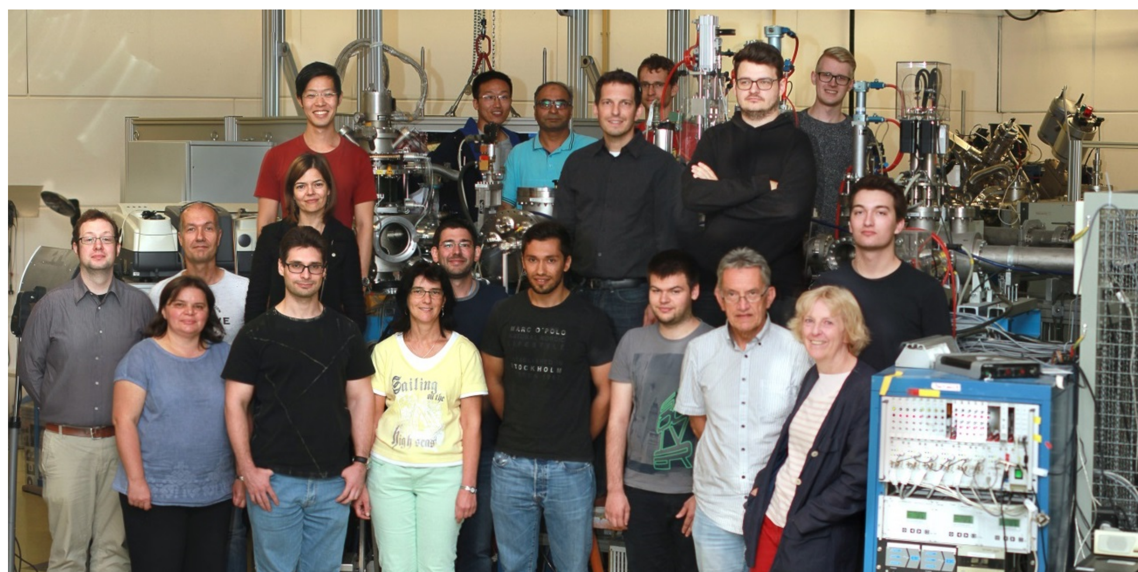
surface diffusion

$d_s = 3.78\ r$

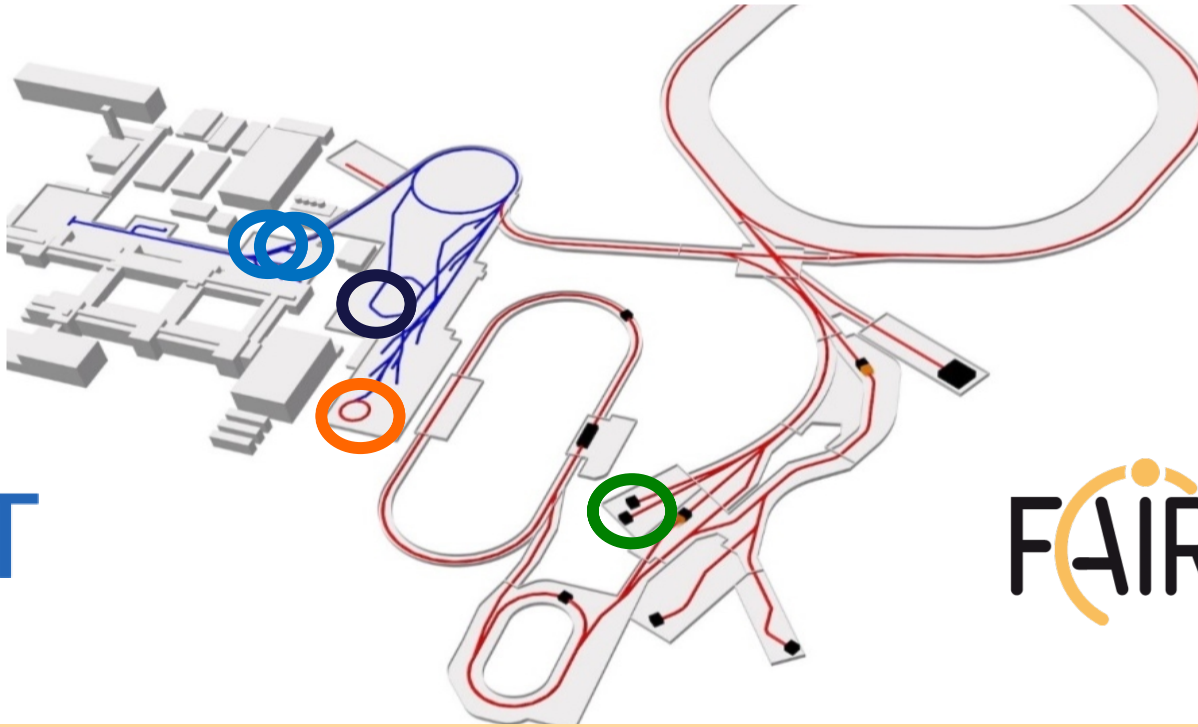
Cu: Toimil et al, APL 85 (2004)
Au: Karim et al., Nanotechn *17* (2006)

Material science user platform

- ion species
- beam energy – energy loss
- efficient sample irradiation system
- in-situ beam monitoring
- in situ analysis (outgassing, spectroscopy....)
- user support



Existing and future MAT User platform



UNILAC 3-11 MeV/u	SIS-18 80-1000 MeV/u	CRYRING 0.3-14 MeV/u	SIS-100 0.1–10 GeV/u
M-Branch beamline X0 microprobe	**Cave A high energy cave**	**BIOMAT station low energy highest charge states**	**APPA Cave FAIR high energy cave**
		beam >2020	**beam >2025**

Thank you