Materials Science with secondary particles generated from an extreme light source

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New source of secondary particles:

Ions

Positrons

Muons

Neutrons

Materials modification

Materials analysis

Unknown states or phases of matter

Laser driven particle sources for materials science

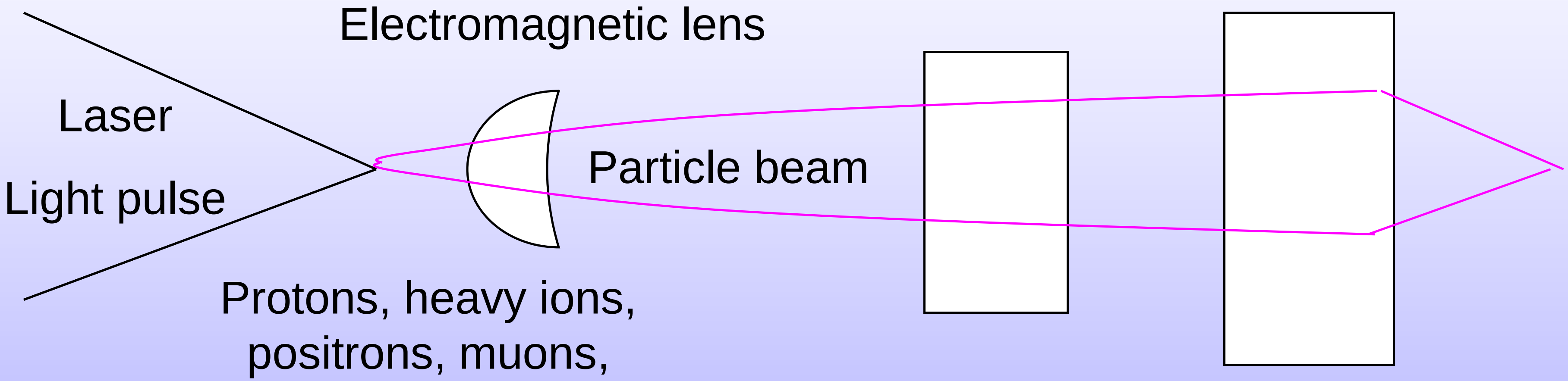
Advantages may be:

- Higher intensities
- Higher brilliances
- Easier or cheaper

$\Rightarrow$ New physics?
$\Rightarrow$ Easier access?
$\Rightarrow$ New applications?

Necessary: Prove of principle of particle production in comparison to existing facilities

Laser generated secondary particle source for materials science



Protons, heavy ions, positrons, muons, (neutrons)

dE/E ~ 10%

High energy, 100 keV – GeV

dt ~ 10 fs

Problem: Velocity spread

Debuncher,

dE/E ~ 10^{-3} – 10^{-5}

Particle selection

Focusing

Deceleration

Moderation

Rebunching

Efficiency?

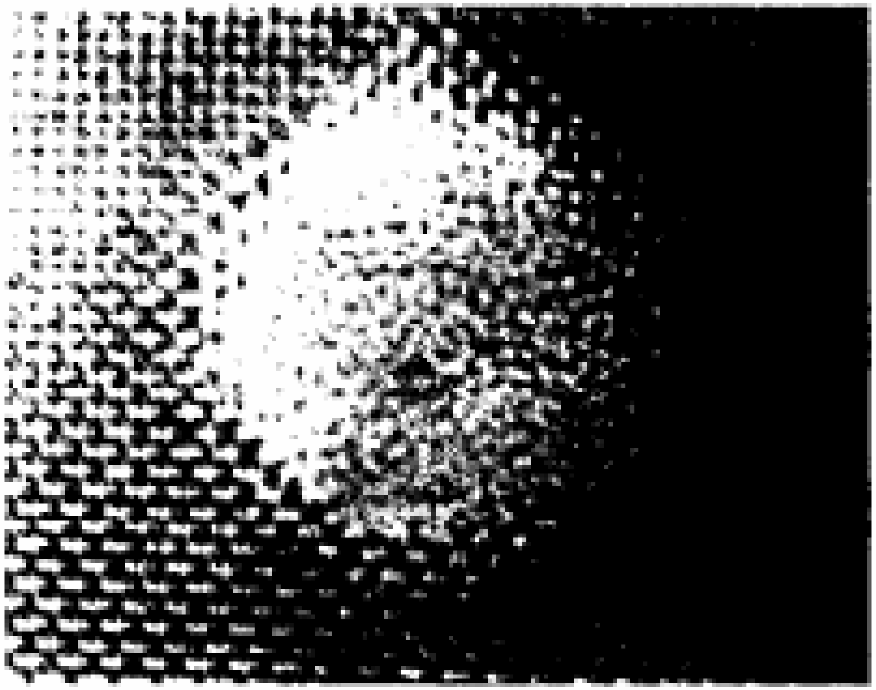
Materials science with laser driven ion beams

- Standard ion beam analysis: no need of Laser driven source

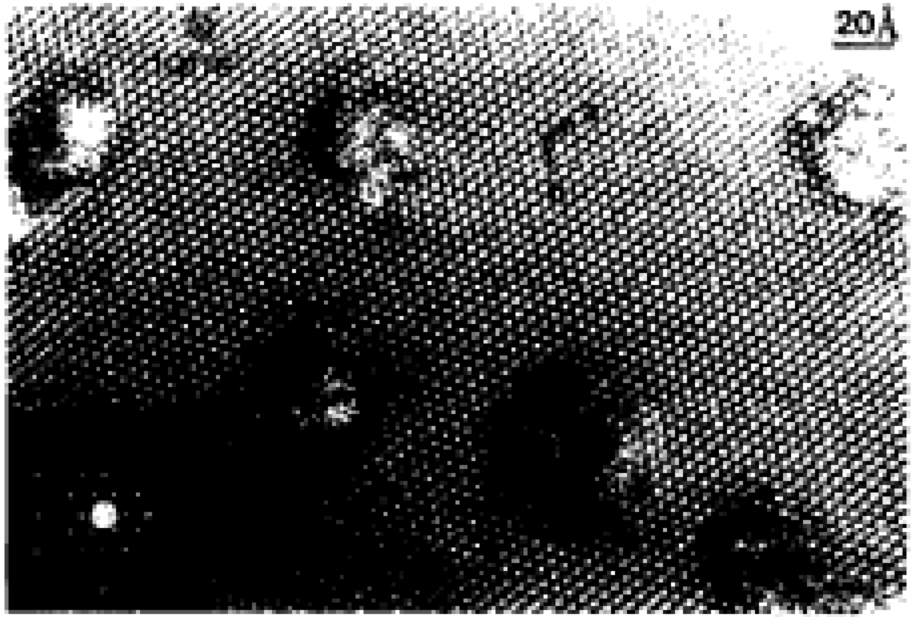
- Materials modification on nanomater scale with secondary particles,
  - i.e. energetic heavy ions (I, Au, U)

    (100 MeV – 1 GeV) : replace big accelerators!
  - Nanofocus of high intensity x-rays, electrons, ions?

Latent ion tracks in solids by thermal spike/Coulomb explosion effects



a



ZrO_2 $BaFe_{12}O_{19}$

Track diameter about 5 nm, dE/dx < 20 keV/nm => nanostructures in insulators

Electron heating within < fs, lattice heating < 100 fs, cooling within ps

F. Studer, M. Hervieu, J.-M. Constantini, M. Toulemonde, Nucl. Instr. and Meth. B 122 (1997) 449

Swift heavy ions from laser pulses

Heavy ion beam (> 100 MeV)

Several ions focused on < 10 nm diameter within ps

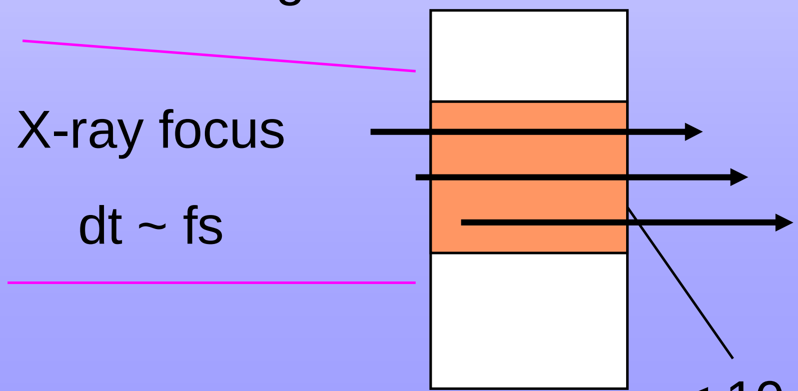
=> latent tracks in metals, simple semiconductors??

=> i.e. nanowires in diamond?

Pump-probe experiments to investigate

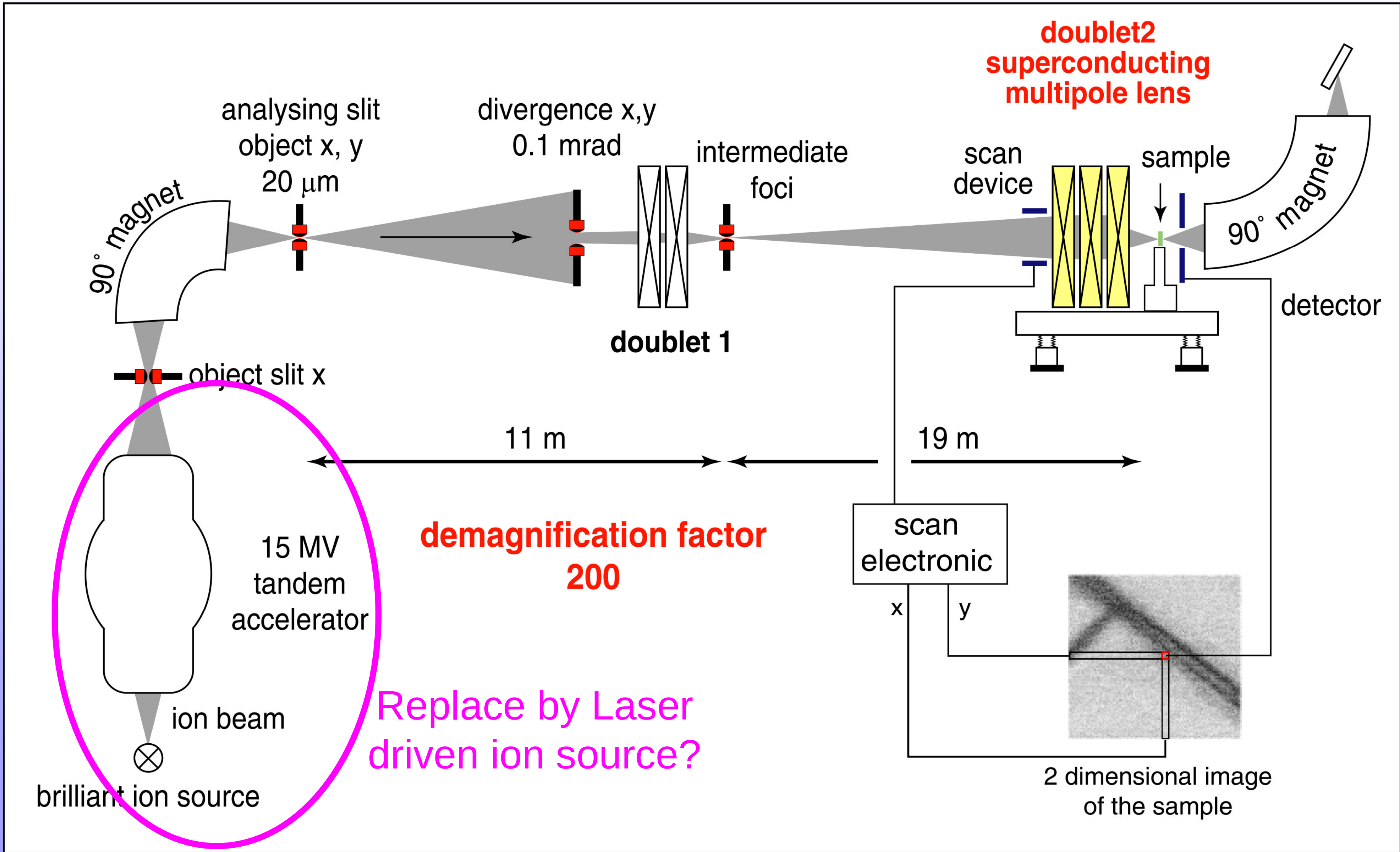
Coulomb explosion / thermal spike phenomena

Direct generation of nm-tracks with focused x-ray pulses?



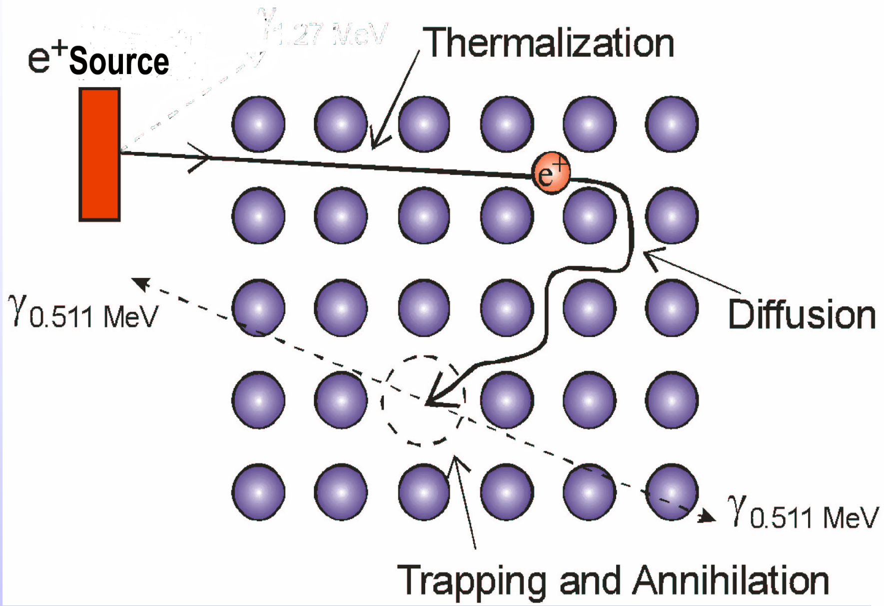
Scheme of SNAKE

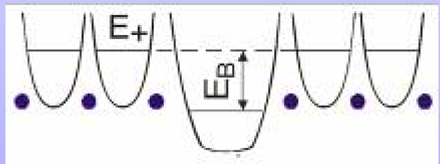
Supraleitendes Nanoskop für Angewandte Kernphysikalische Experimente



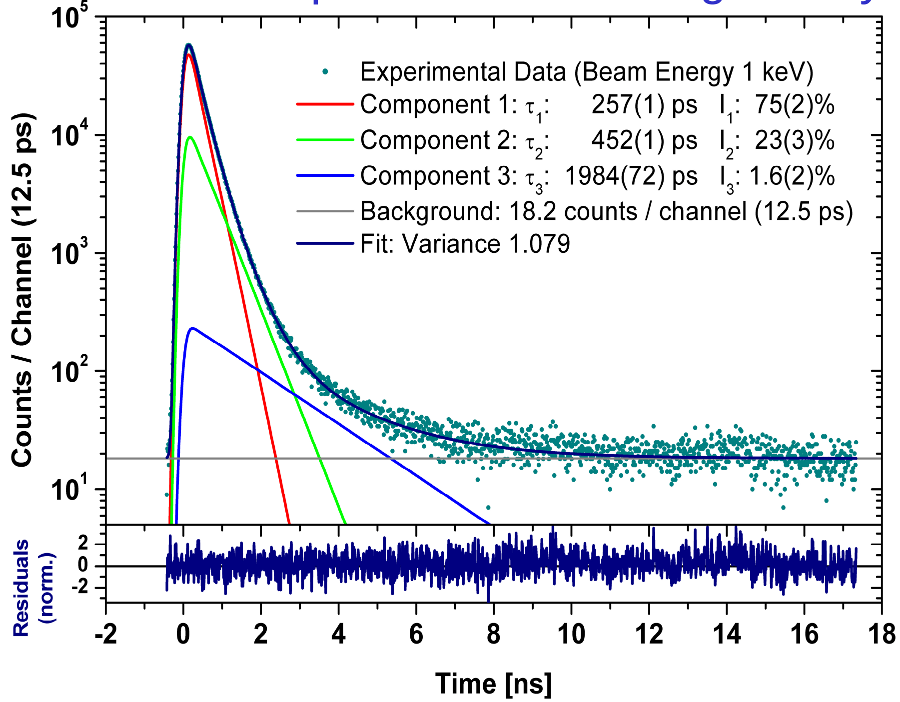
Günther Dollinger

Positron Annihilation Lifetime Spectroscopy (PALS)





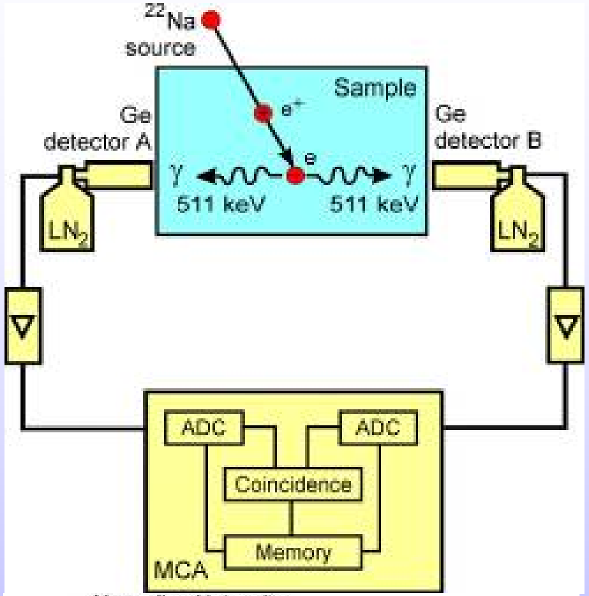
lifetime spectrum of an AlMgSi-alloy

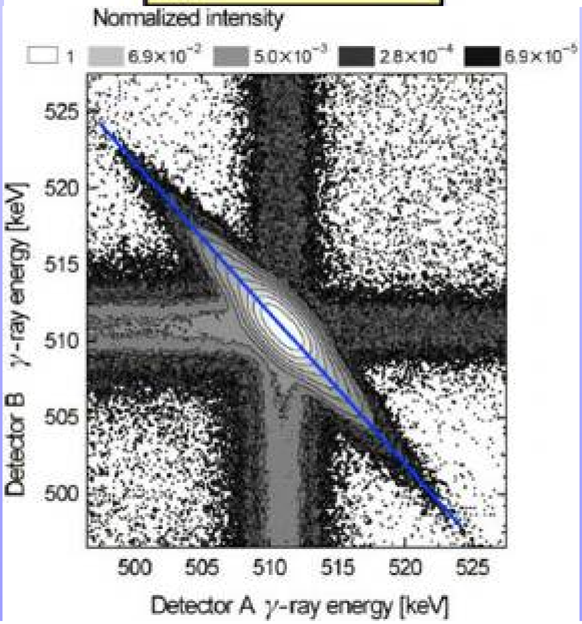


lifetime ∝ (local electron density)$^{-1}$

- defect type from positron lifetime
- defect concentration (≥at ppm) from intensities

Coincident Spectroscopy of Doppler Broadened Annihilation

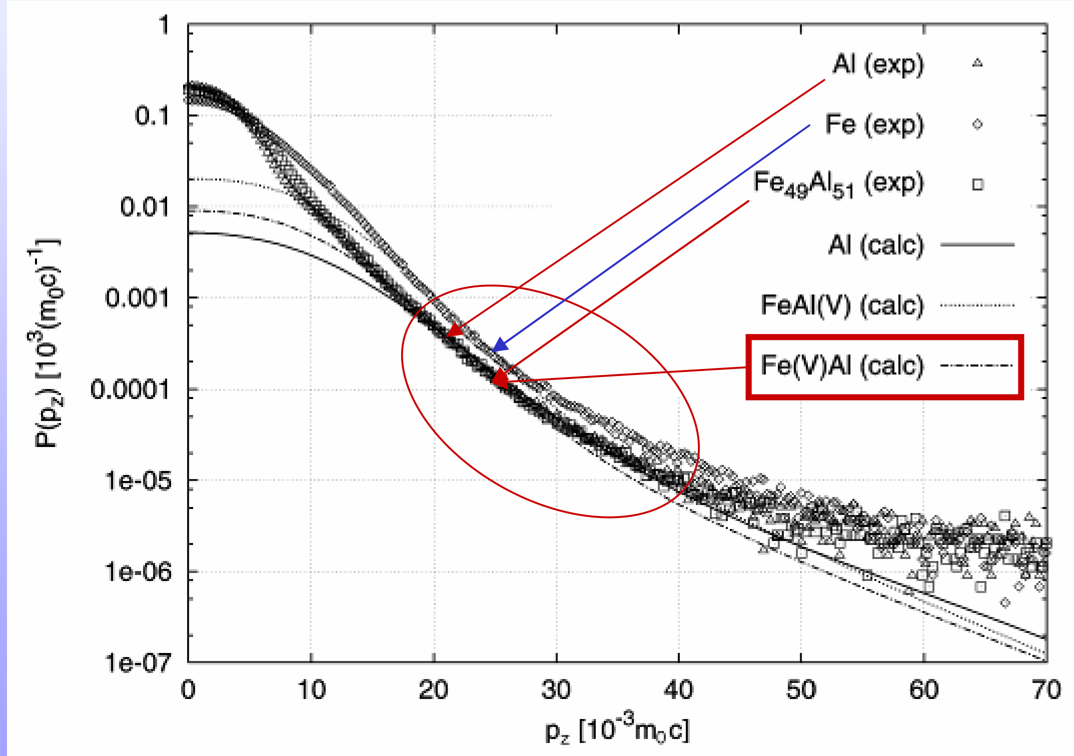




=> Monentum distribution of conduction electrons

=> Chemical information

intermetallic $Fe_{49}Al_{51}$



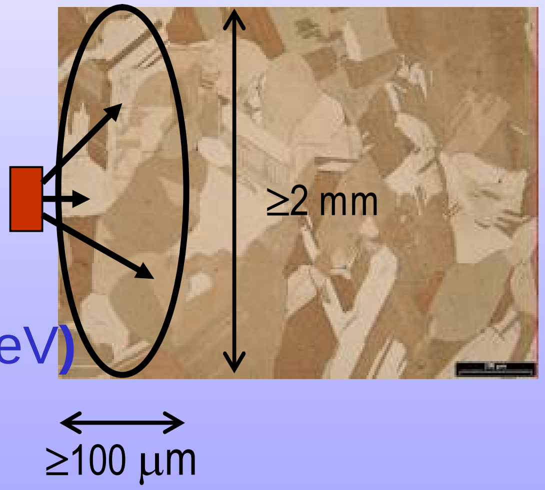
W. Egger, G. Bischof, V. Gröger, G. Krexner
Materials Science Forum 363-365 (2001) 82-84

Monoenergetic Positron-Beams:
=> Depth profile of vacancy type defects

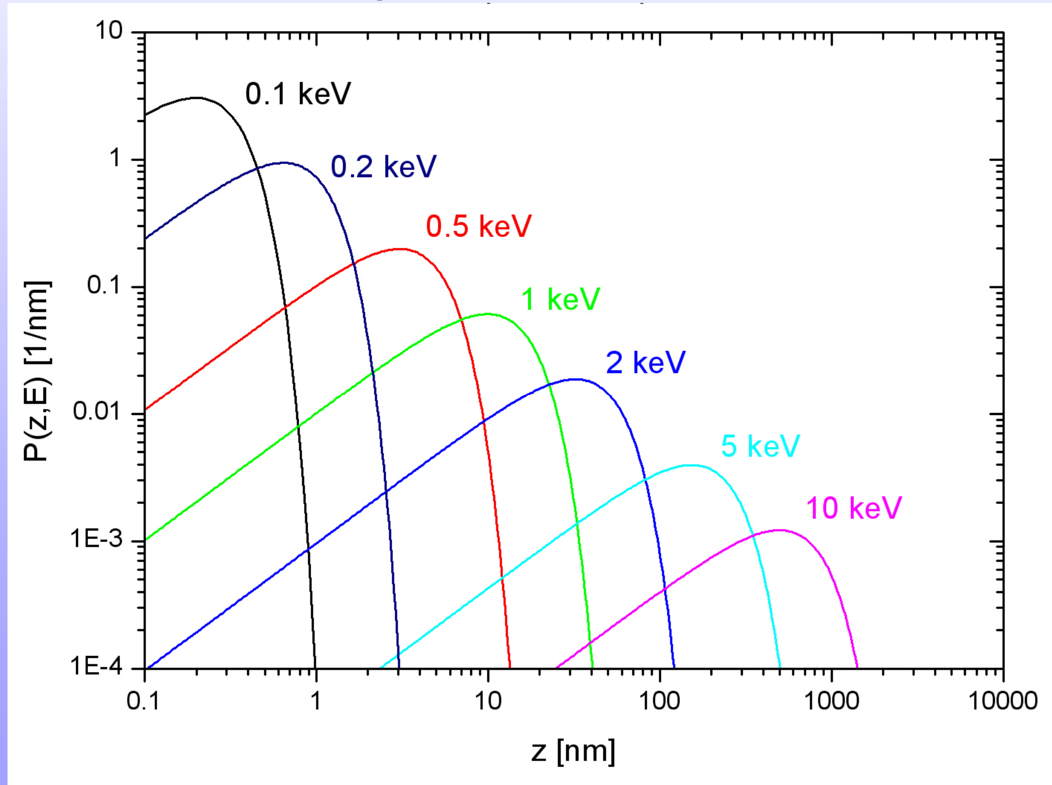
- Conventional method: defect-structure averaged over mm³
- Problem: grain-boundaries, surfaces, precipitates etc. burried in volume signal
- Solution: monoenergetic positron-beams of variable energy

Conventional Method

Source
emits
fast
Positrons
(E≤ 600 keV)



Implantation Profile



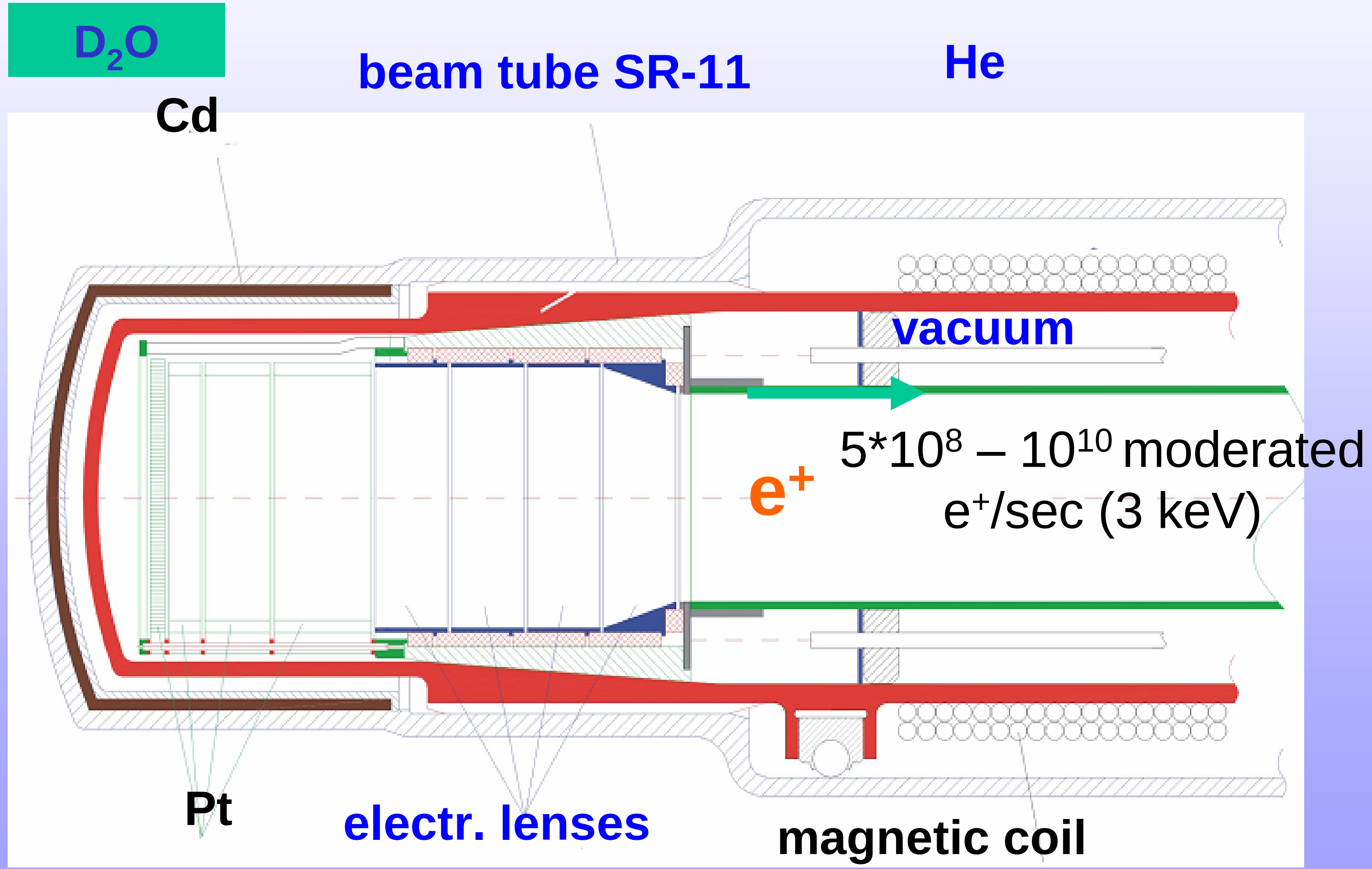
Design of the Positron Source NEPOMUC at the FRM-II:

Most intense slow positron beam

C. Hugenschmidt, K. Schreckenbach, G. Kögel, P. Sperr, W. Triftshäuser Mat. Sci. For. 445-446 (2004)

Neutron flux:

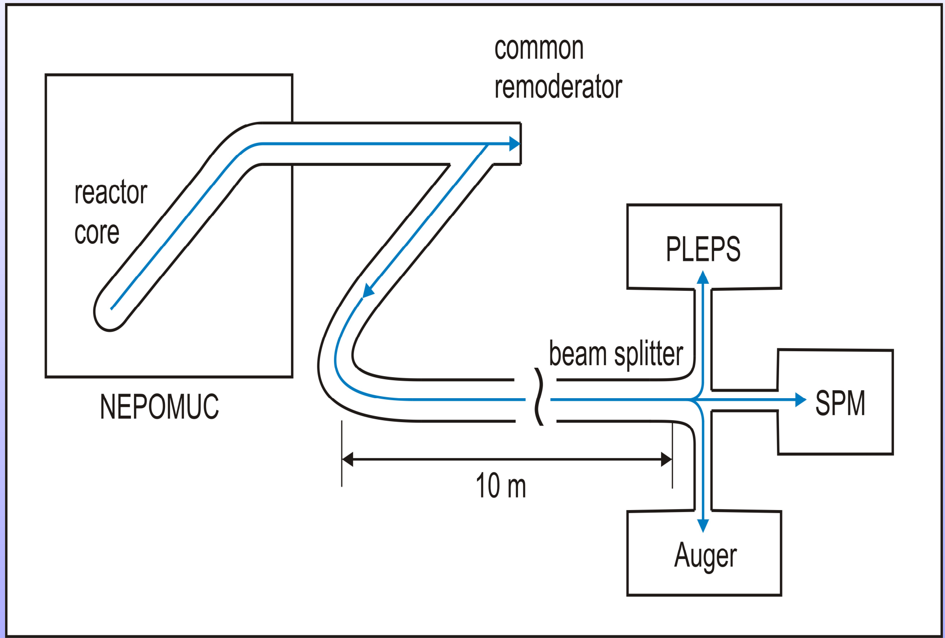
10^{14} n/(cm²sec)

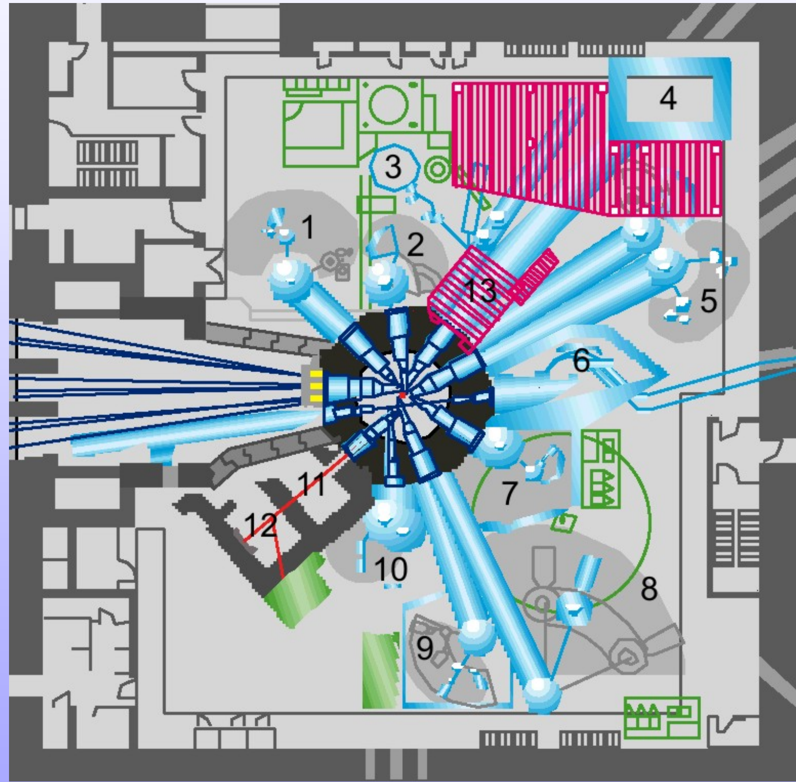


$4*10^{13}$ e^+/sec in Pt-structure

Intense positron source (NEPOMUC) at new Munich research reactor FRM II

C. Hugenschmidt, K. Schreckenbach, G. Kögel, P. Sperr, W. Triftshäuser Mat. Sci. For. 445-446 (2004) 480





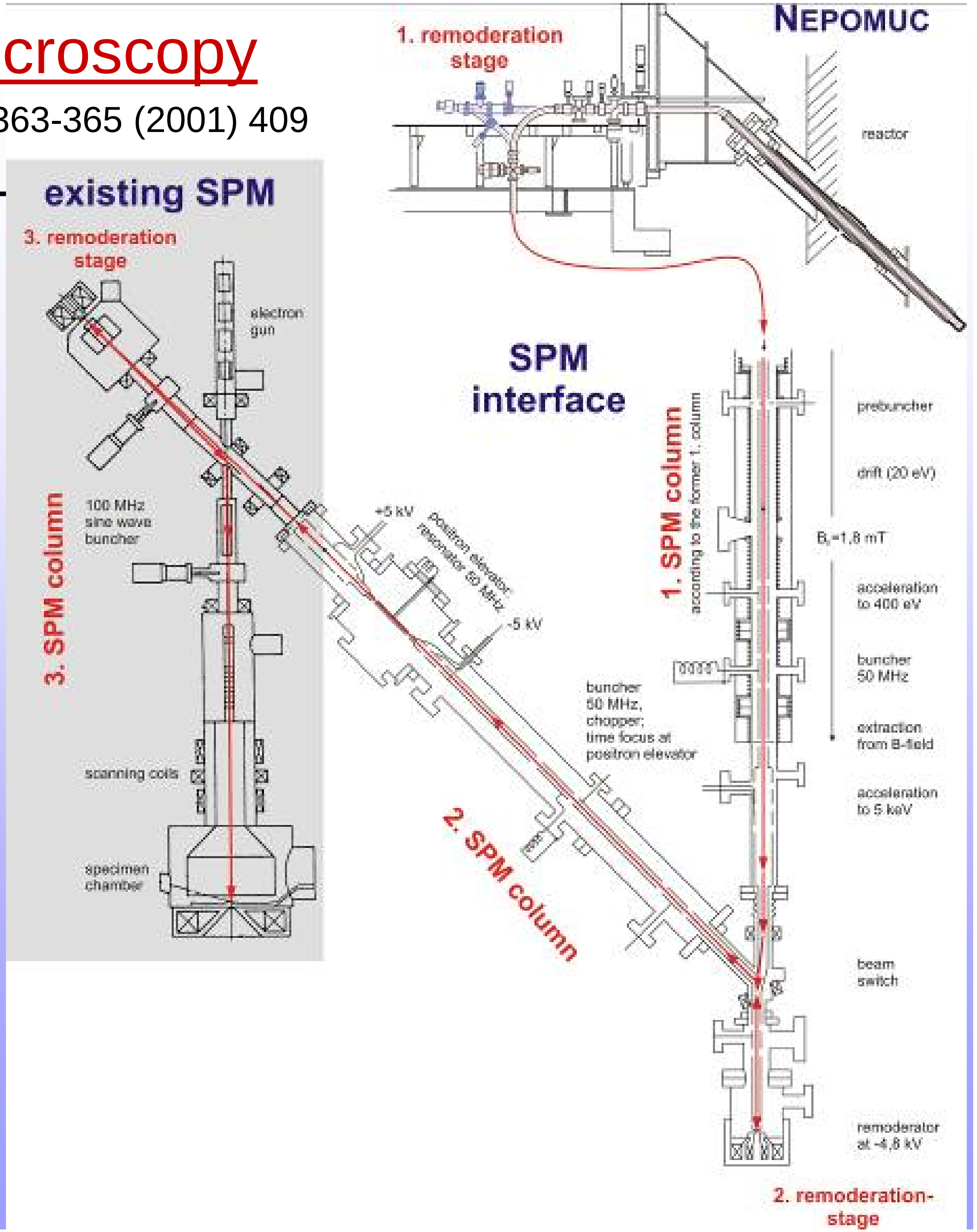
3D positron microscopy

G. Kögel, Mat. Sci. For. 363-365 (2001) 409

- up to 10^6 e^+ / second
- in 100 nm beam spot
- 50 MHz bunches
- dt ~ 100 ps

•=> less than 1 e^+ per bunch

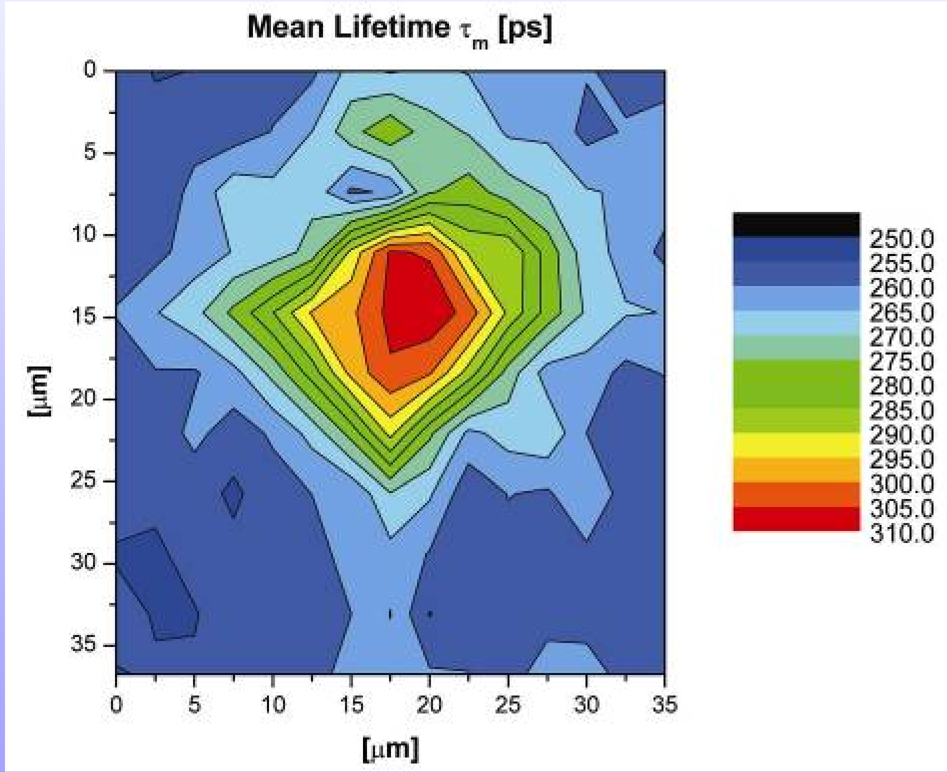
•But about 10 to 1000 defects in the beam spot

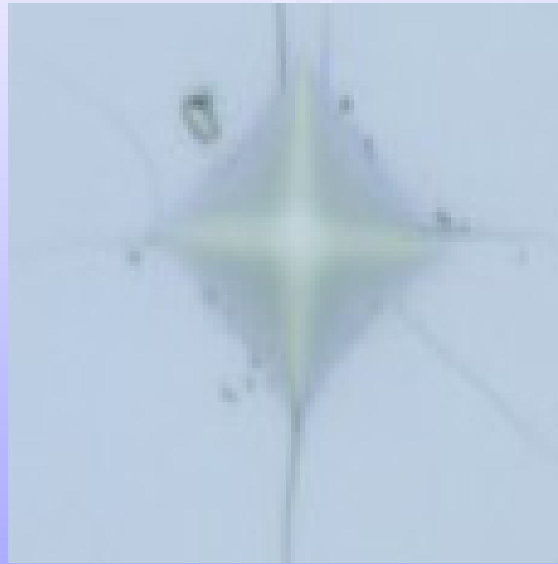


SPM: lateral resolution

Indentation in GaAs:

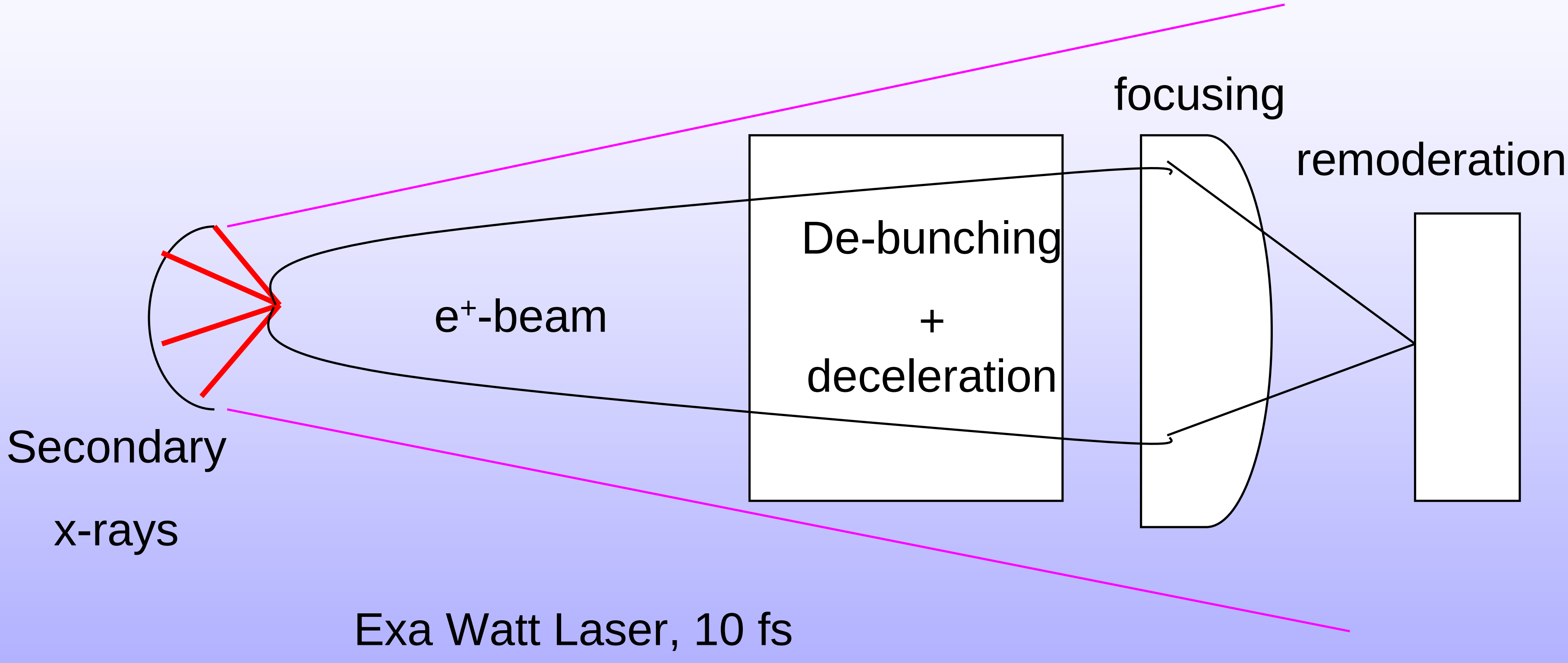
- beam energy 16 keV; mean implantation depth 550 nm; resolution 2 μm; step-size 2.5 μm;
- two lifetimes in the centre: 70% with 365 ps ⇒ vacancy clusters





Optical image

Positrons from Laser driven source



=> 10^4 - 10^{10} e^+ per bunch !

New physics with positron bunches in matter

Do everything as with other sources

plus

Interaction of positrons with matter

1) Quantitative determination of defect densities:

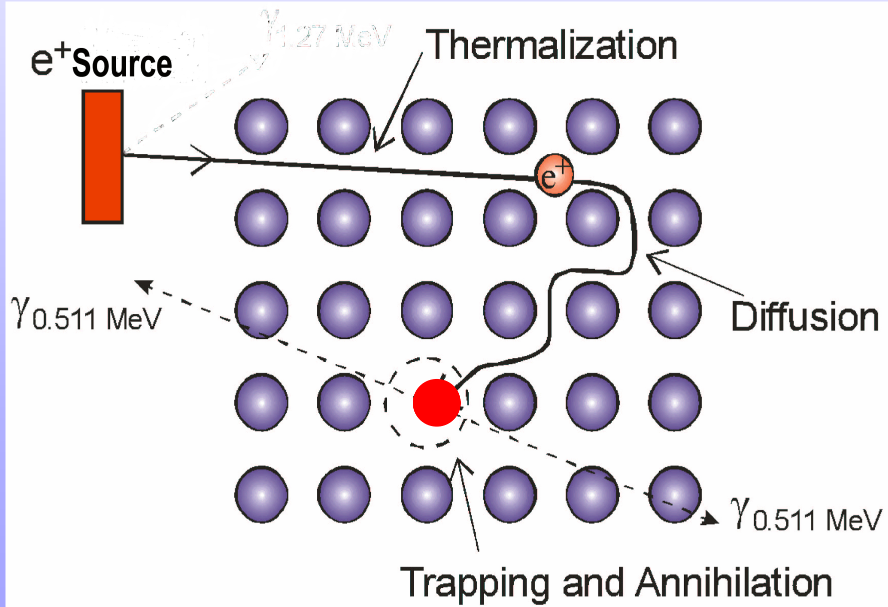
Structural materials => defect density $10^{18}/cm^3$ - $10^{20}/cm^3$

⇒ 10^3 - 10^5 defects in a cube of $100*100*100\ nm^3$

If more e+ per bunch than defects in the spot

⇒ All defects are filled => change of lifetime spectrum at a certain number of positrons

⇒ Quantitative measure of defect density !



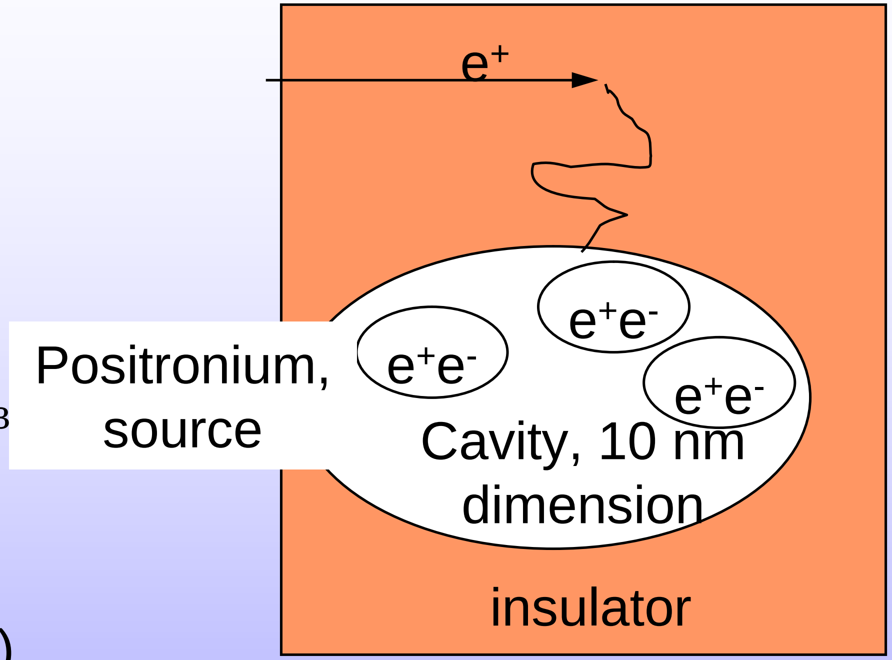
Bose Einstein condensate of positronium in small cavities

e^+e^- are bosons

Interaction of those bosons in the cavity

Above critical density given by

$$\frac{N_{e^+e^-}}{V} = \frac{1.306}{4}\left(\frac{2Mc^2kT}{\pi\hbar c^2}\right)^{3/2} = 8.2\cdot 10^{-2}\,/\,nm^3$$

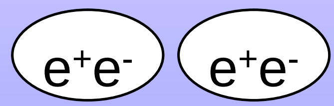


More than 100 positroniums (same spin alignement) in cavity (1000 nm³)

⇒ Bose-Einstein condensate at room temperature

⇒ 10^{10} in cavity, 1 µm diameter 1cm length => 511 keV x-ray laser possible

(Mills et al. Mat. Sci. For. 445-446 (2004)424



Molecule generation, signature: 4.941 eV excitation energy

J. Usukura et. al. Phys. Rev. A 58 (1998) 1918

Conclusion

Questions to solve in future:

Is laser driven particle source competitable to standard sources

Replace accelerators, reactors . . .

Intensities? Brilliances?

i.e. bunched positron beams from reactor source plus e^+-traps?

If competitable to other sources:

than a lot of applications in materials science

Muons

μ^+ as a light version of the proton => diffusion studies

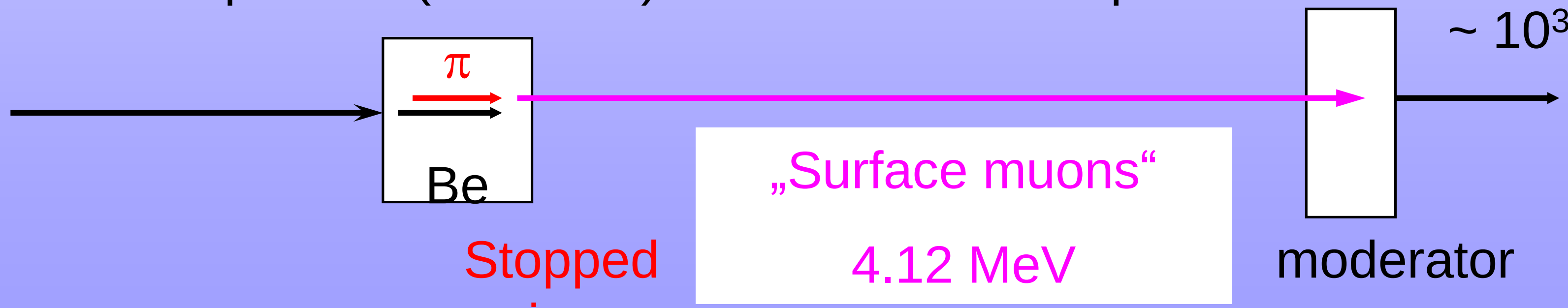
Polarised μ^+: decay assymetry tells about spin direction at decay time

=> spin rotation in magnetic field

=> local magnetic probé

Generation of μ^+ from π^+ -beams or stopped π^+:

e.g. at PSI: 2 mA protons (800 MeV) => ~ 10^6 - 10^9 μ^+/ s



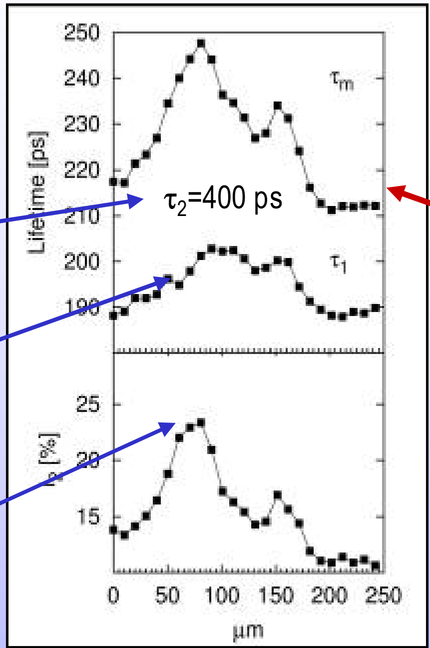
SPM: Lebensdauerbild eines Ermüdungsrisses in Cu

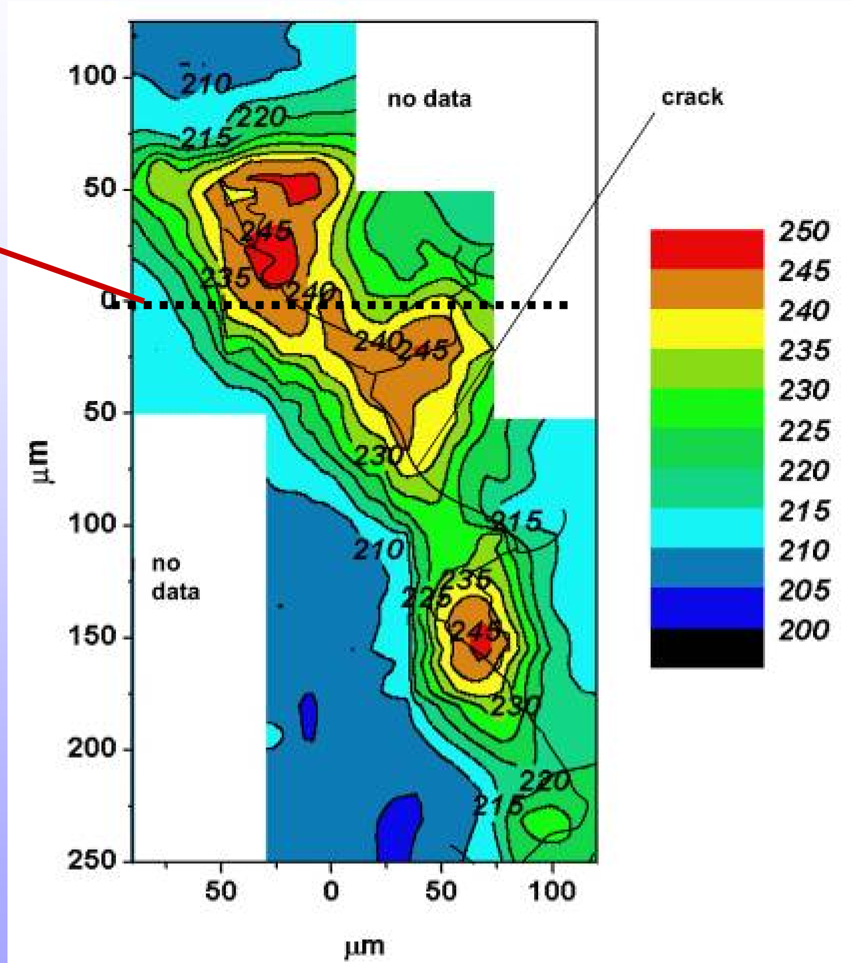
Linescan:
9000 s / Pixel

Leerstellen-
cluster

Versetzungen

Einfangrate
Leerstellencluster
1 / 3 Einfangrate
an Versetzungen





- Strahlenergie: 16 keV
- Auflösung: 5 µm
- Gesamte Messdauer: 200 h !
- Hauptergebnis:

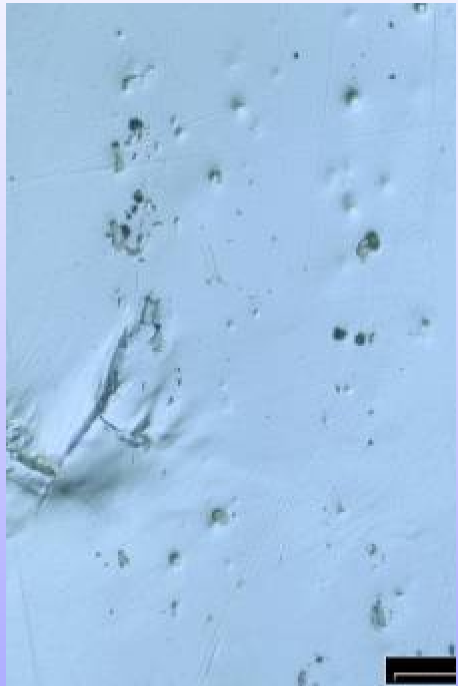
Versetzungen (τ_1) und
grosse Leerstellencluster (τ_2)

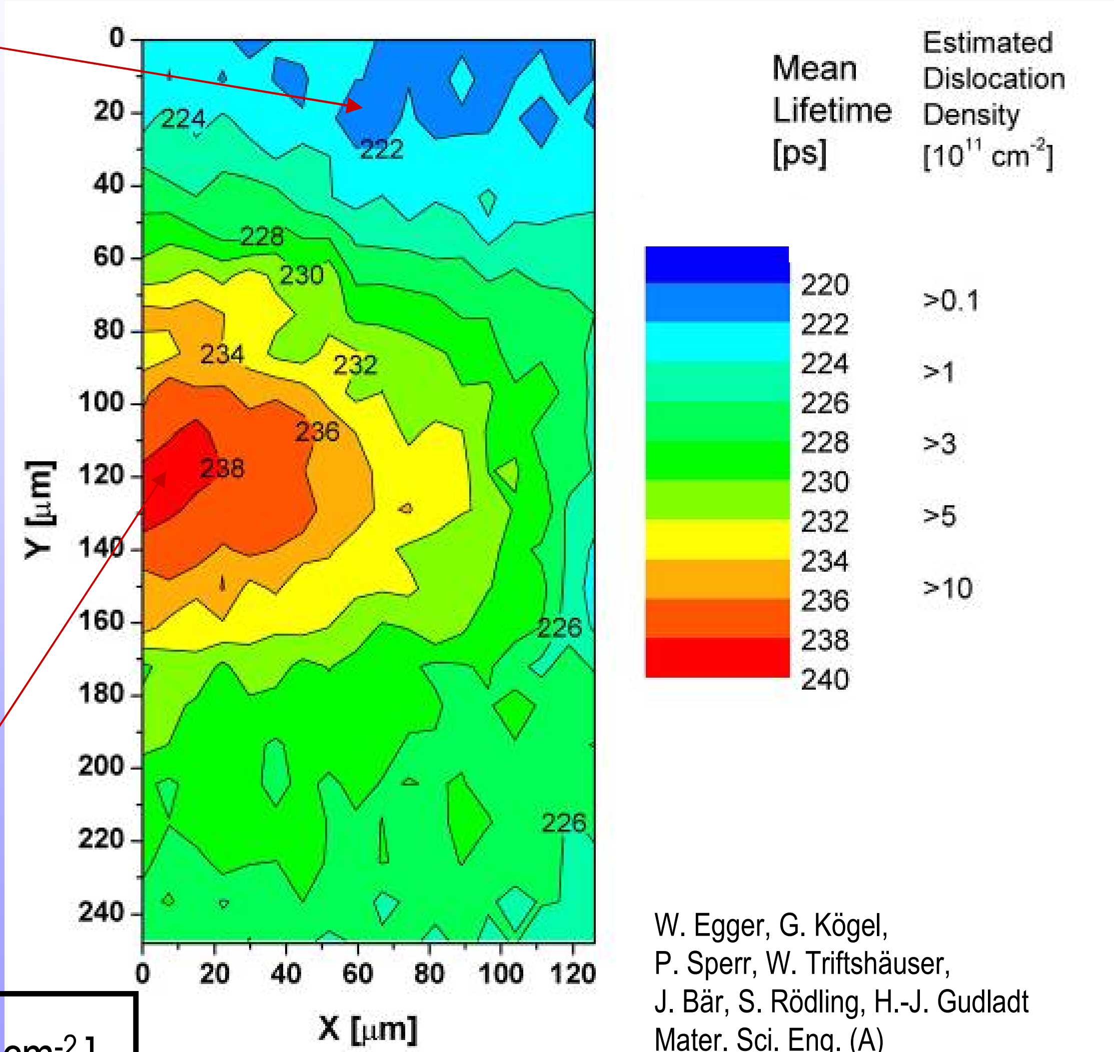
W. Egger, G. Kögel, P. Sperr, W. Triftshäuser,
J. Bär, S. Rödling, H.-J. Gudladt
Applied Surface Science 194 (2002) 214-217

SPM: Lebensdauerbild eines Ermüdungsrisses in Al 6013

• Strahlenergie 12 keV; Auflösung 5µm; Schrittweite 10 µm; $3 \cdot 10^5$ Ereignisse / Pixel

Nur Einfang an Mg / Si-Clustern!



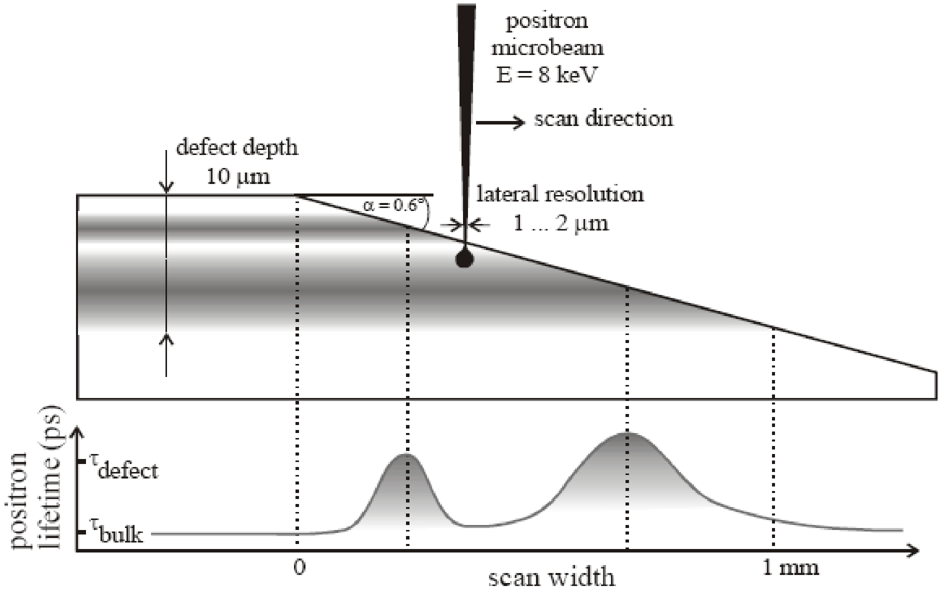


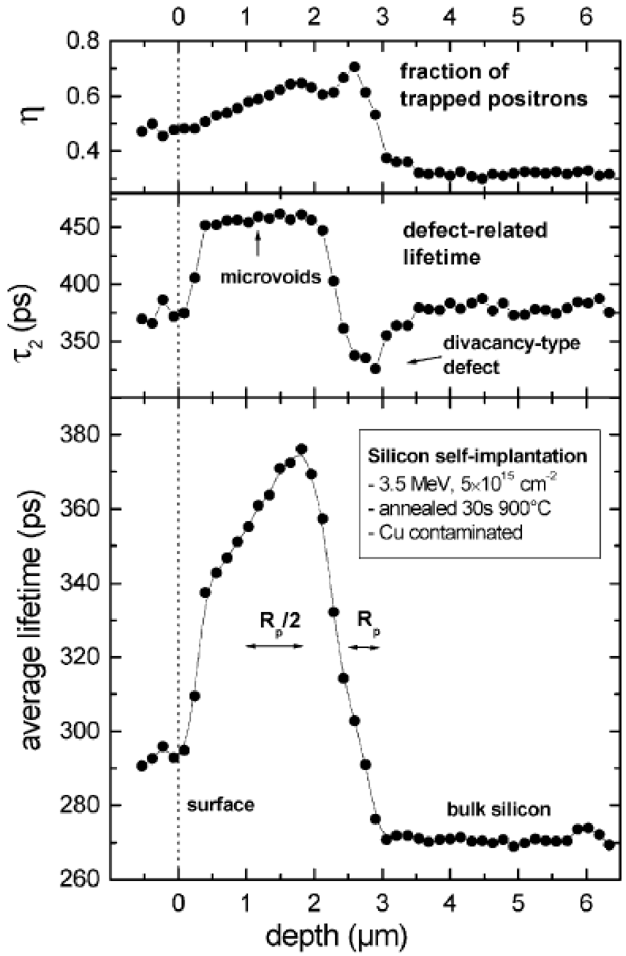
Nur Versetzungen in der Umgebung der Rißspitze!

$$C_{disl} = 4 \cdot 10^{11} \, (\tau - 220) \, / \, (240 - \tau) \; [\,cm^{-2}\,]$$

W. Egger, G. Kögel,
P. Sperr, W. Triftshäuser,
J. Bär, S. Rödling, H.-J. Gudladt
Mater. Sci. Eng. (A)
387- 398 (2004) 317

- Selbstimplantation von Si (3.5 MeV; 5×10^{15} cm^{-2})
  Ausheilung (900° C, 30 s)
- Getterzonen bei Rp und Rp/2
- keine Defekte mit TEM bei Rp/2 sichtbar
- bei Rp/2: Defekte leerstellenartig oder interstitiell?
- Keilschliff zieht Getterzonen auf 1 mm auseinander





- Ergebnis SPM-Messung: Leerstellencluster bei Rp/2

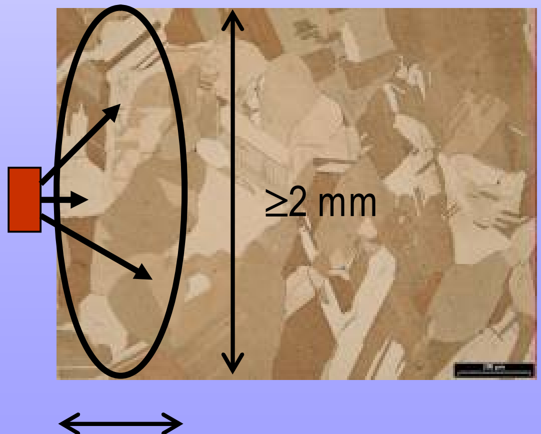
R. Krause-Rehberg, F. Börner, F. Redmann,
W. Egger, G. Kögel, P. Sperr, W. Triftshäuser
Physica B, 308-310 (2001), 442-445

Monoenergetische Positronenstrahlen

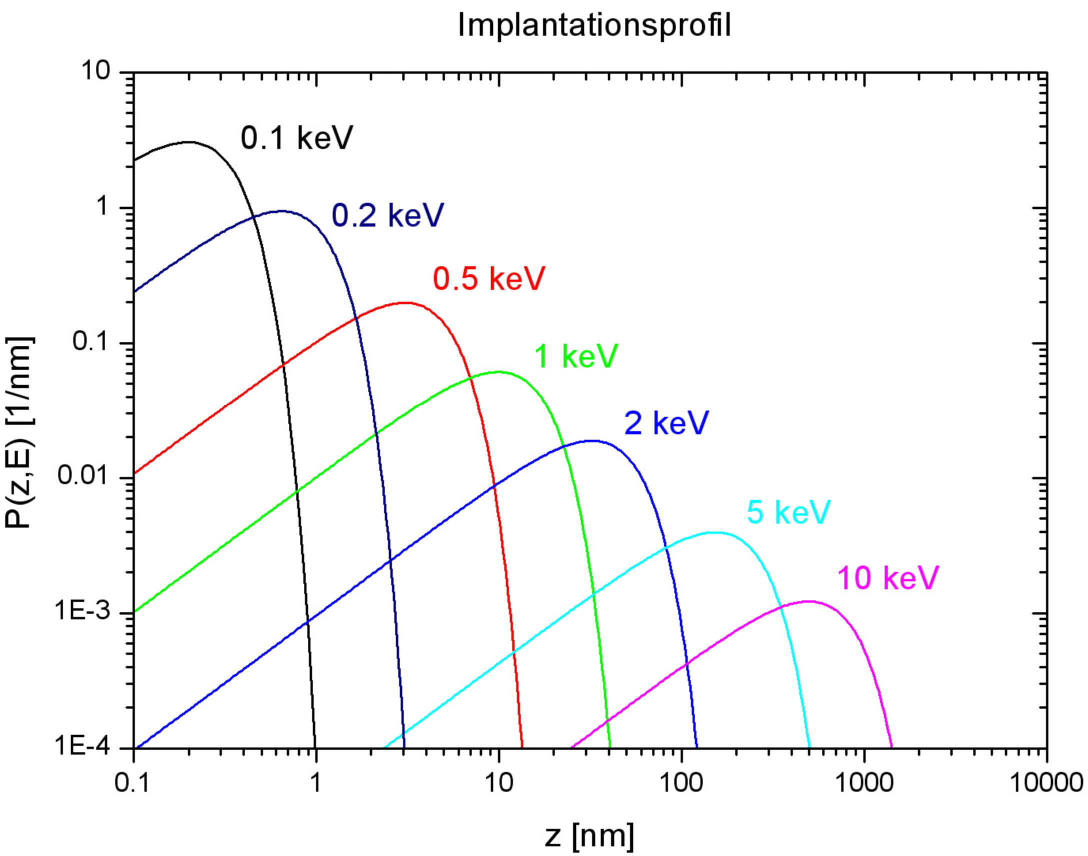
- Konventionelle Methode: Defektstruktur über mm³ gemittelt.
- Problem: Grenzflächen, Oberflächen, Ausscheidungen etc. durch Volumensignal überdeckt
- Lösung: Monoenergetische Positronenstrahlen mit variabler Energie

Konventionell

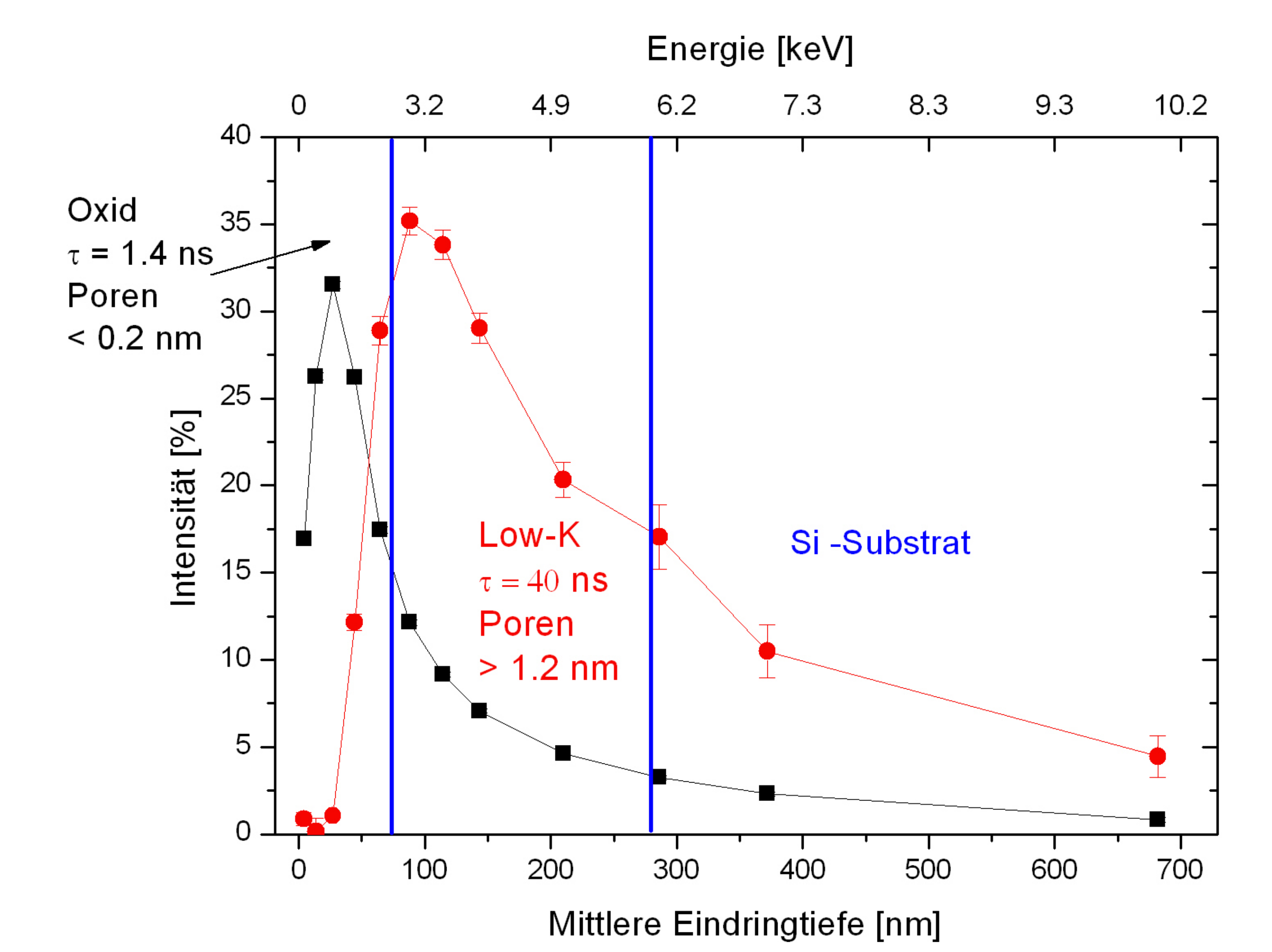
Positronen (E≤ 600 keV)



Günther Dollinger



Tiefenprofil

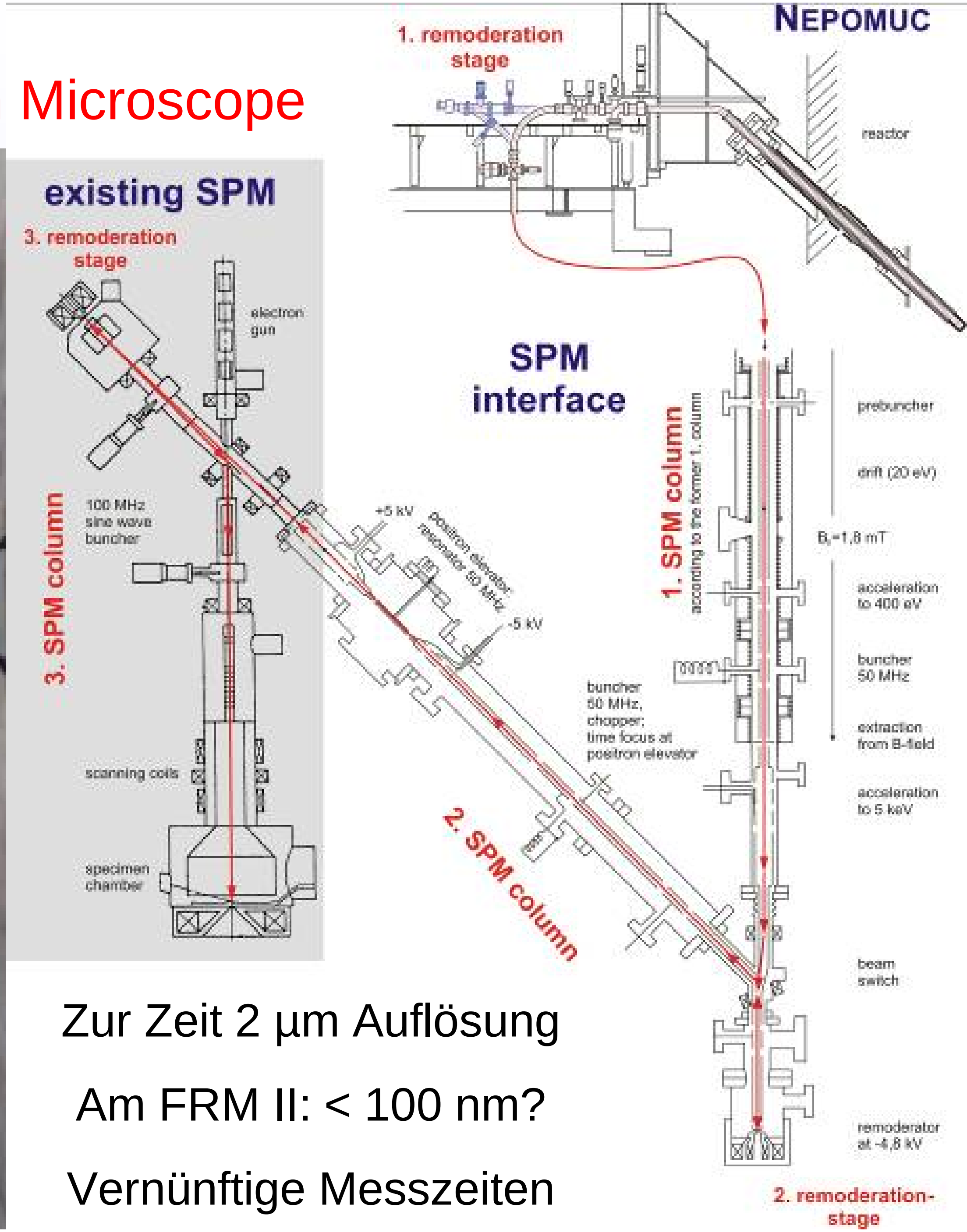


PLEPS: Pulsed Low Energy Positron System

Quelle:	< 30 mCi
Energie:	0.5-20 keV
Pulsung:	50 MHz
Zeitfenster:	20 ns
Zählrate:	500 / s
Pulsbreite:	240 ps
Peak/BG:	10^4
Beamspot:	2-3 mm

Dauer einer Meßreihe (0.5-20 keV): 1d

SPM: Scanning Positron Microscope



Zur Zeit 2 µm Auflösung

Am FRM II: < 100 nm?

Vernünftige Messzeiten

Ziele

Etablierung der Positronenannihilation zur Untersuchung ultradünner Schichten und Grenzflächen:

Sind Monolagen-Schichten im Defekt-Tiefenprofil sichtbar?

Charakterisierung der Defekte, Defektdichte

Elektrische / Optische Beeinflussung der Positronen im Festkörper

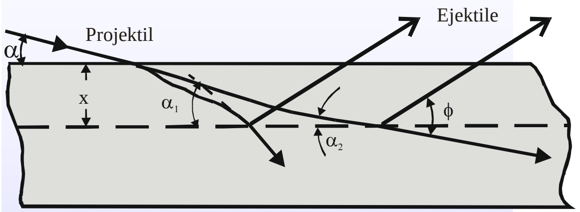
Neuer Zugang zur Untersuchung elektronischer Eigenschaften:

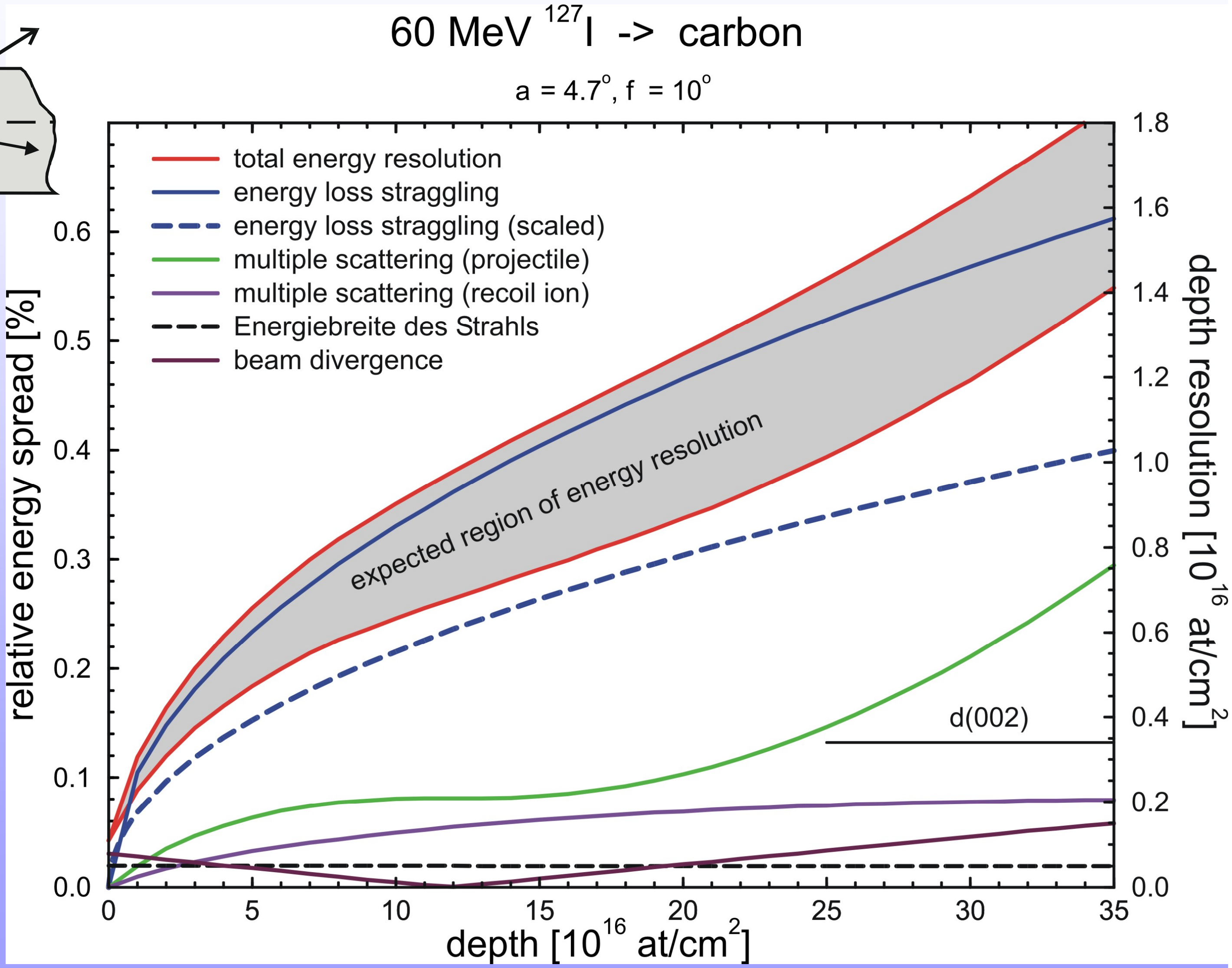
z. B. Untersuchung der Defektdichte an Oxid-Halbleitergrenzfläche eines Feldeffekt- oder Tunneltransistors

Anwendung auf Materialien im Verbund

Depth resolution

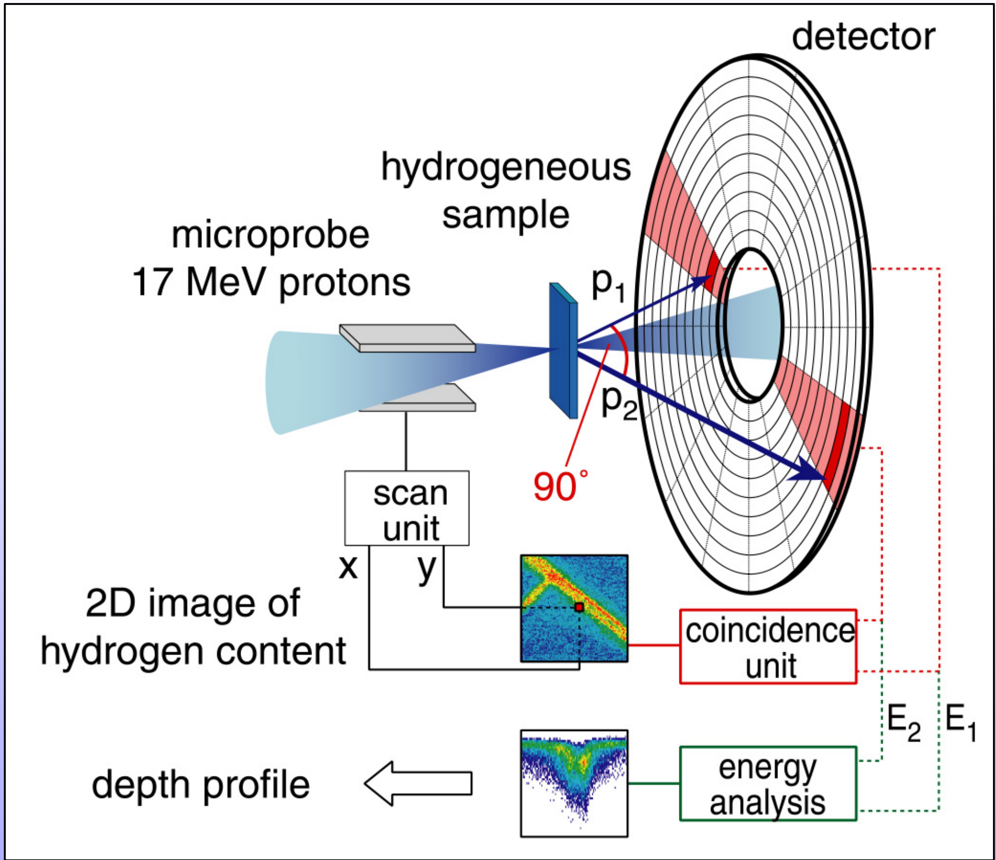
Depth code, E. Szilagy





Ion	Target	Experiment [keV/at/cm²]	Tables (Ziegler) [keV/at/cm²]	Relativer Abstand
40 MeV 197Au	C	7,63E-16	7,40E-16	3,08%
40 MeV 197Au	O	8,14E-16	8,51E-16	-4,50%
40 MeV 197Au	Al	9,49E-16	1,12E-15	-18,12%
40 MeV 197Au	Si	1,29E-15	1,24E-15	4,10%
40 MeV 197Au	Hf	2,25E-15	2,41E-15	-7,16%

3D Hydrogen Microscopy by Proton-Proton Scattering



coincident detection

⇩

sensitivity < 1 at-ppm

spatial resolution

microprobe	strip detector
⇩	⇩
lateral < 1 µm	**depth < 5 µm**

sample preparation

17 MeV protons

⇩

sample thickness 50 µm

Only method for "3D hydrogen microscopy" with ppm-sensitivity quantitative & matrix independent

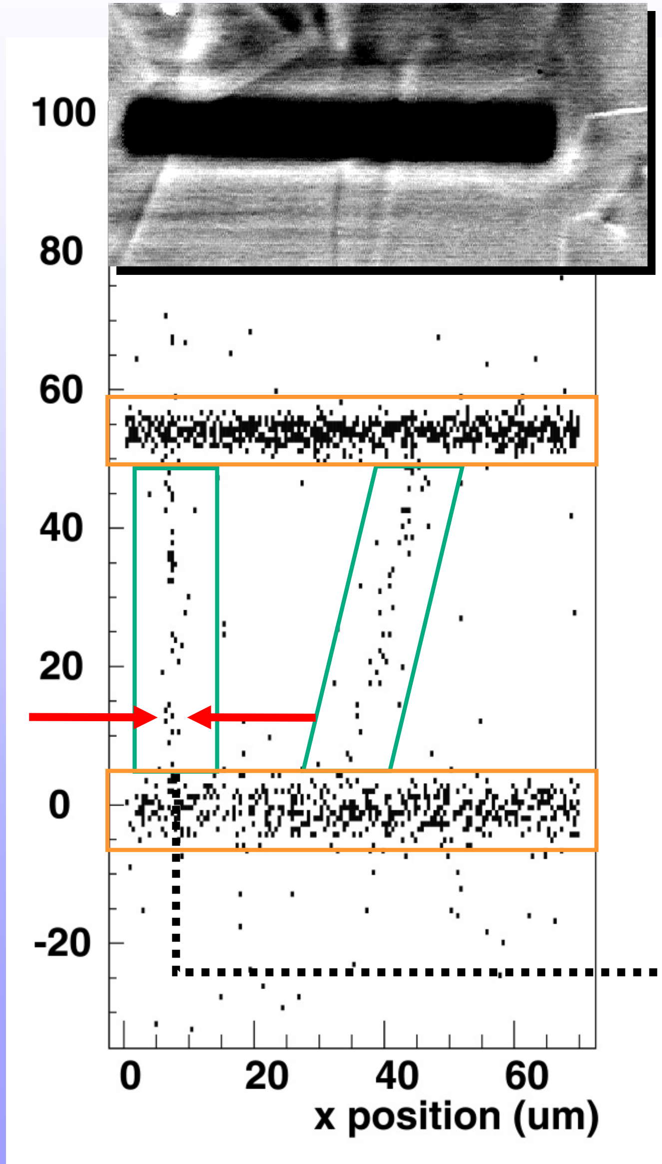
Hydrogen in CVD-diamond

P. Reichart et al. Science, 306 (2004) 1637

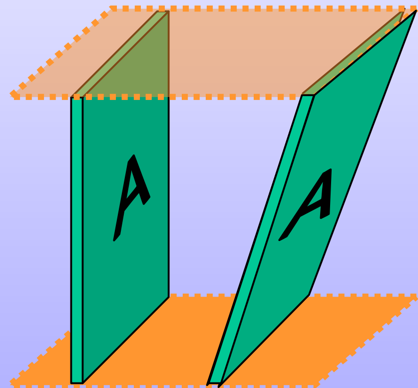
hydrogen on surface

$4.3 \cdot 10^{15}$ at/cm^2

$2.7 \cdot 10^{15}$ at/cm^2



hydrogen on grain boundary



projected to face A

$3.0 \cdot 10^{14}$ at/cm^2

$2.9 \cdot 10^{14}$ at/cm^2

lateral FWHM 0.5 µm

content inside grain
< 0.08 at-ppm

Scanning Positron Microscope (SPM)

source: < 30 mCi

energy: 1-20 keV

pulsing: 50 MHz

time-window: 20 ns

count-rate: 500 / s

timeresolution: 250 ps

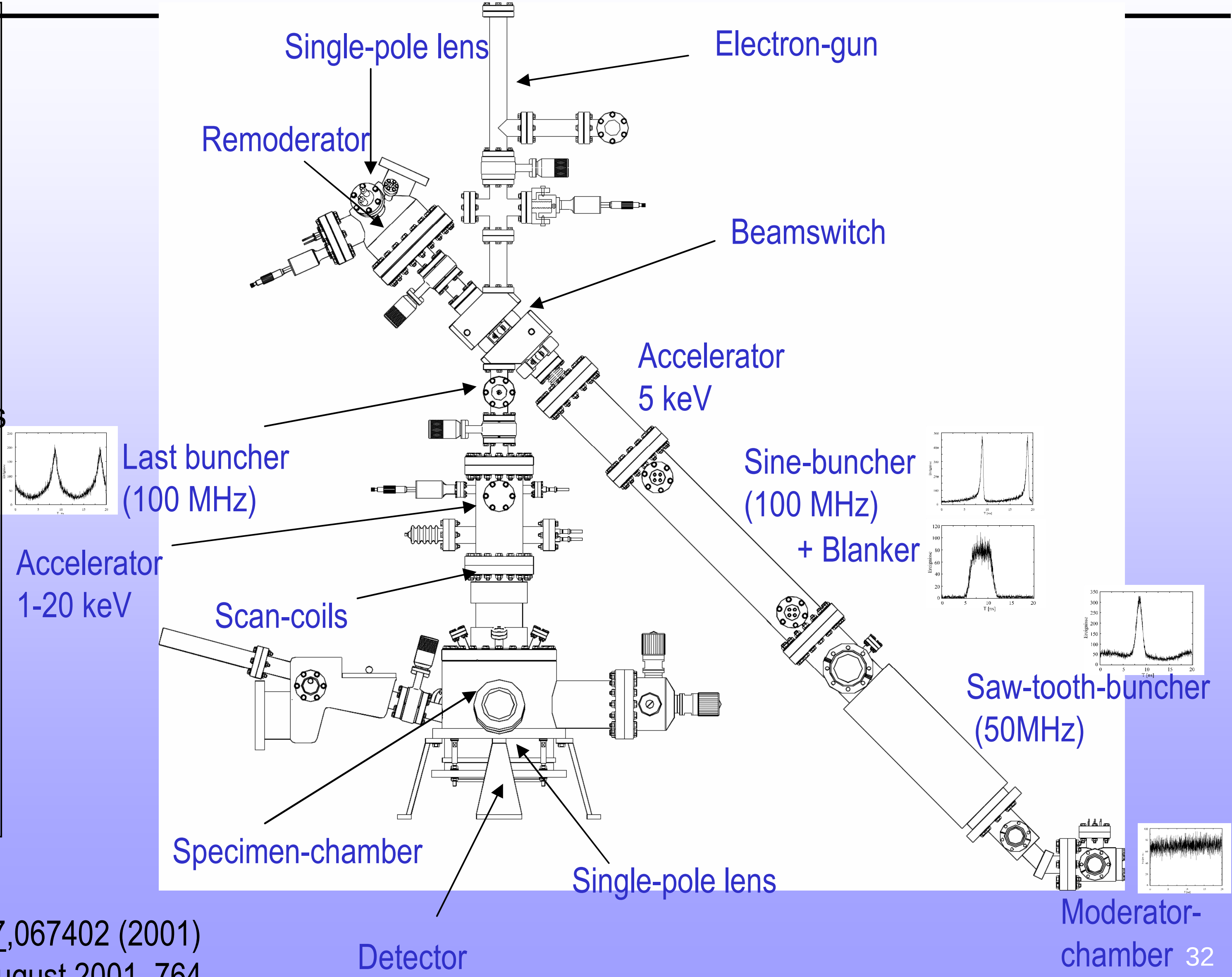
peak / BG: 10^3

beam-spot: $\geq 2\ \mu m$

recording-time

XY scan:

week(s) !



Phys.Rev.Lett. 87,067402 (2001)

Nature 412, 23 August 2001, 764