Die Positronenannihilation in der Materialforschung

R. Krause-Rehberg[1], G. Dollinger[2], W. Egger[2]

C. Hugenschmidt[3], A. Wagner[4], T. Cowan[4]

1. Universität Halle, Inst. für Physik
2. Universität der Bundeswehr München
3. Technische Universität München, FRM-II
4. Forschungszentrum Dresden-Rossendorf

Martin-Luther-Universität Halle-Wittenberg

Universität der Bundeswehr München

Technische Universität München

Forschungszentrum Dresden Rossendorf

- Geschichtliches
- Techniken der Positronenannihilation
- Anwendungen
  - Kristalldefekte
  - weiche Materie
  - Porosimetrie
- Positronenmessplätze in Deutschland

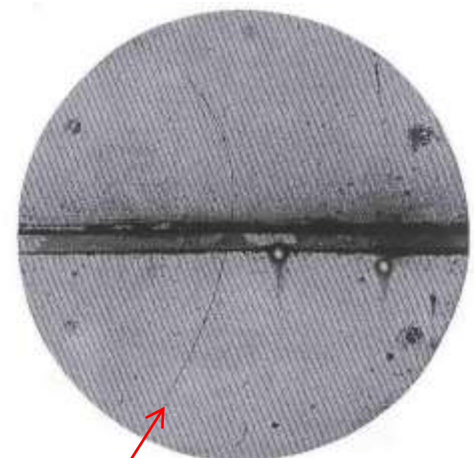
Discovery of the Positron

- Positron was predicted in 1928 by Paul A.M. Dirac
- Discovery in 1932 in cloud chamber pictures by C.D. Anderson

P.A.M. Dirac

C.D. Anderson

- Positronium as bound state of e^- and e^+ lightest atom was predicted (1934) and discovered (1951)
- Annihilation in matter was studied beginning in the 40^s
- Positrons can be obtained by
  - pair production from gamma radiation (E_γ > 1022 keV)
  - β^+ decay from isotopes (mostly ^{22}Na)



- first Identification of a positron in a cloud chamber
- 5 mm lead plate
- photo taken by C.D. Anderson

Electron structure of solids can be discovered

- during annihilation: conservation laws must be fulfilled (energy, momentum)
- positron cools down to thermal energies ->
- energy of annihilating electron-positron pair = energy of electron
- electron momentum distribution can directly be measured

MARCH 1 AND 15, 1942 PHYSICAL REVIEW VOLUME 61

The Angular Distribution of Positron Annihilation Radiation

ROBERT BERINGER* AND C. G. MONTGOMERY
Sloane Physics Laboratory, Yale University, New Haven, Connecticut
(Received January 7, 1942)

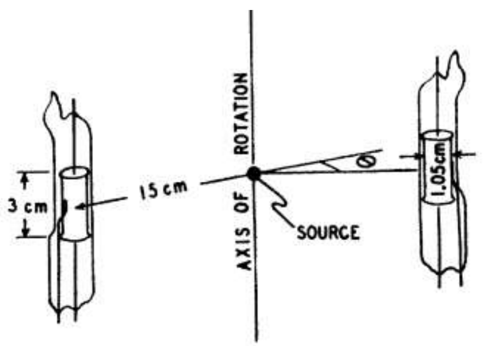
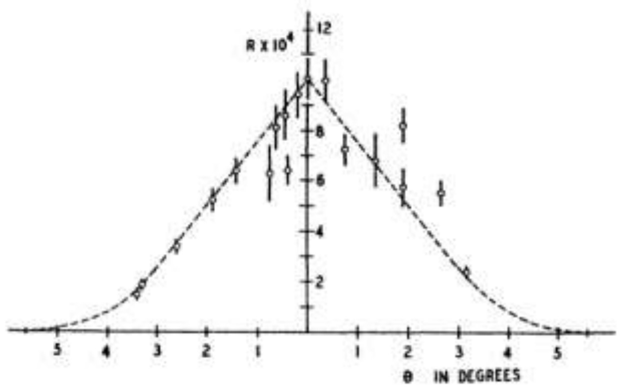
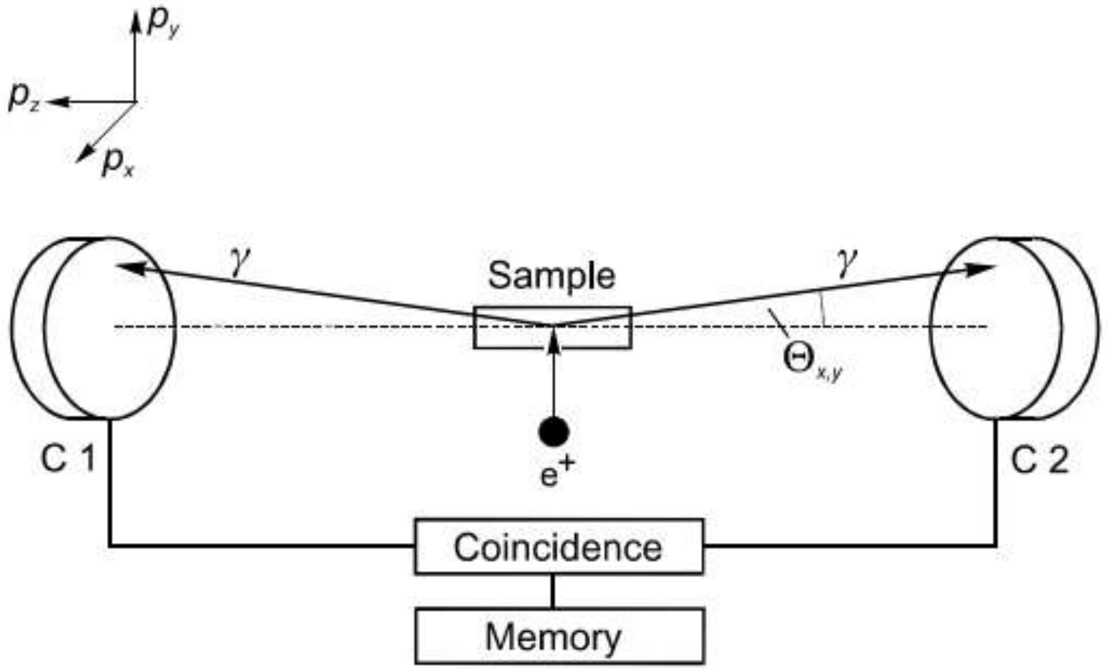


FIG. 1. Schematic arrangement of counters for observing coincidences from annihilation radiation.



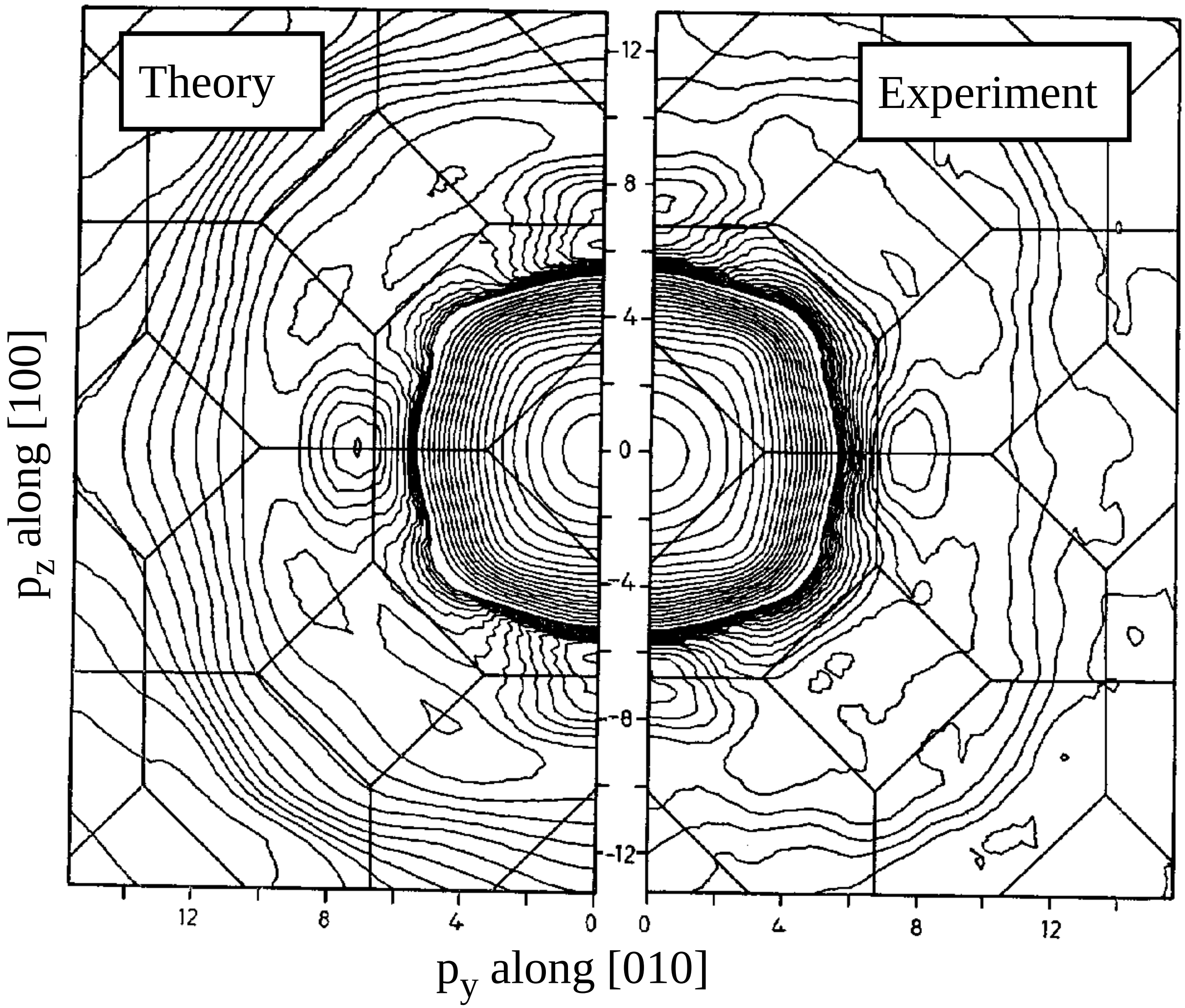
2D – ACAR (Angular Correlation of Annihilation Radiation)

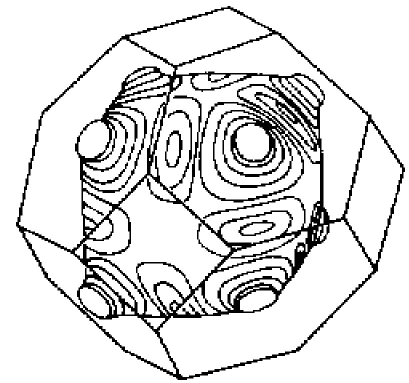
- now: two-dimensional (position-sensitive) detectors
- measurement of single crystals in different directions:
- reconstruction of Fermi surface possible



$$N_c(\Theta_x,\Theta_y) = A_c \int_{-\infty}^{\infty} \sigma(\Theta_x m_0 c, \Theta_y m_0 c, p_z)\,\mathrm{d}p_z$$

2D-ACAR of Copper





Fermi surface of copper

(Berko, 1979)

Positrons are sensitive for Crystal Lattice Defects

- 1950…1960: in addition to ACAR -> different experimental techniques were developed
- Positron lifetime spectroscopy and Doppler broadening spectroscopy
- end of 60s: lifetime is sensitive to lattice imperfections
  - Brandt et al. (1968): **vacancies in ionic crystals**
  - Dekhtyar et al. (1969): **plastically deformed semiconductors**
  - MacKenzie et al. (1967): **vacancies in thermal equilibrium** in metals
- Positrons are localized (trapped) by open-volume defects

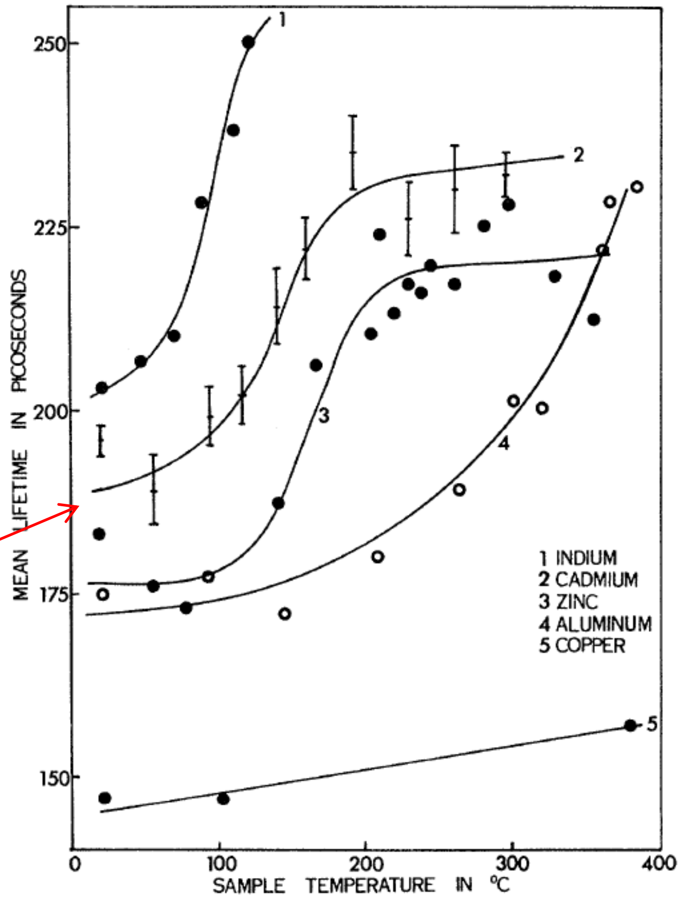
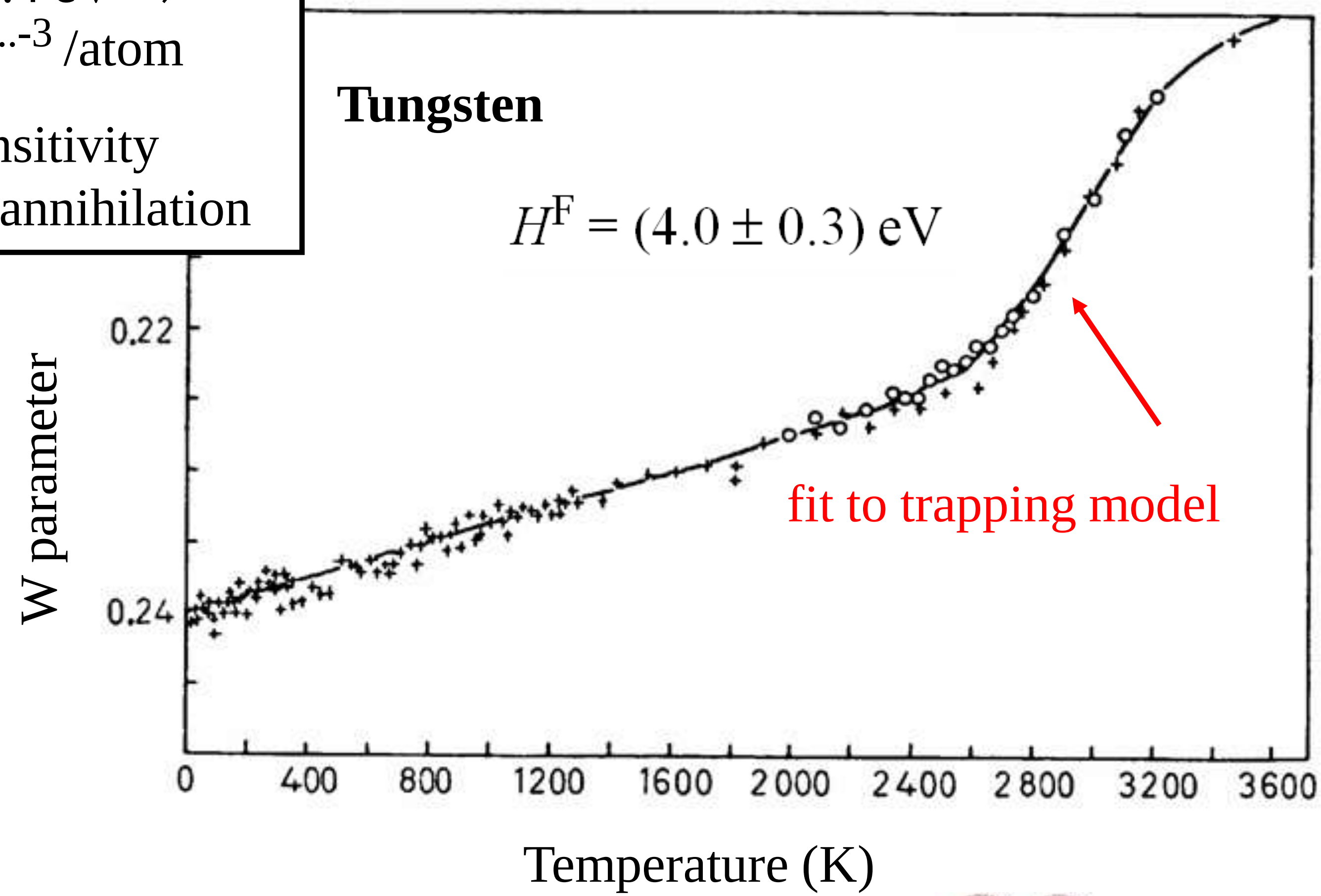


FIG. 1. Positron mean lifetimes in several metals as a function of temperature.

Vacancies in thermal Equilibrium

- Vacancy concentration in thermal equilibrium:
- in metals $H^F \approx 1 \ldots 4$ eV $\Rightarrow$ at T_m [1v] $\approx 10^{-4 \ldots -3}$ /atom
- fits well to the sensitivity range of positron annihilation

$$C_{1v}(T) = \exp\left(\frac{S_{1v}^F}{k}\right)\exp\left(\frac{H_{1v}^F}{kT}\right)$$



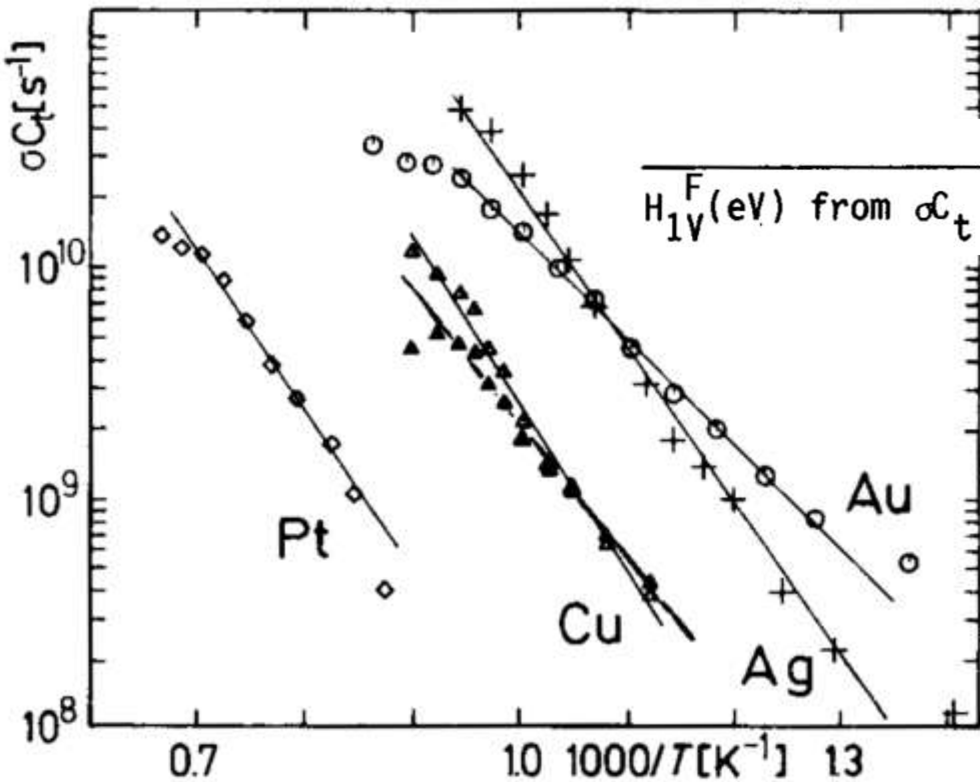
(Ziegler, 1979)

Determination of Vacancy Formation Enthalphy

THERMAL VACANCIES IN THE NOBLE METALS Cu, Ag, Au, AND IN Pt STUDIED BY POSITRON LIFETIME SPECTROSCOPY

H. E. Schaefer[1], W. Stuck[1], F. Banhart[2], and W. Bauer

[1]Universität Stuttgart, Institut für Theoretische und Angewandte Physik, Pfaffenwaldring 57, D-7000 Stuttgart 80,
[2]Max-Planck-Institut für Metallforschung, Institut für Physik, Heisenbergstr. 1, D-7000 Stuttgart 80, Fed. Rep. of Germany



	Cu	Ag	Au	Pt
H^F_{1V}(eV) from σC_t	1.13±.04*	1.31±.07	.89±.02	1.35±.09

- Arrhenius-Plot delivers H_{1V}
- was performed for many alloys

Study of non-equilibrium Defects

PHYSICAL REVIEW B VOLUME 25, NUMBER 2 15 JANUARY 1982

Vacancies and carbon impurities in α-iron: Electron irradiation

A. Vehanen, P. Hautojärvi, J. Johansson, and J. Yli-Kauppila
Laboratory of Physics, Helsinki University of Technology, SF-02150 Espoo 15, Finland
P. Moser
Section de Physique du Solide, Département de Recherche Fondamentale, Centre d'Etudes Nucléaires de Grenoble, 85 X, 38041 Grenoble Cédex, France

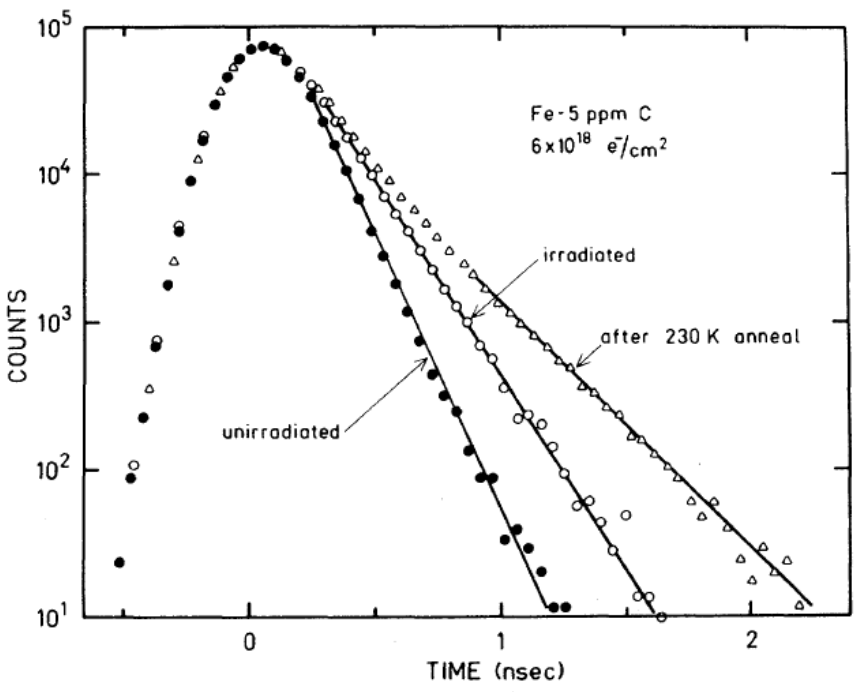
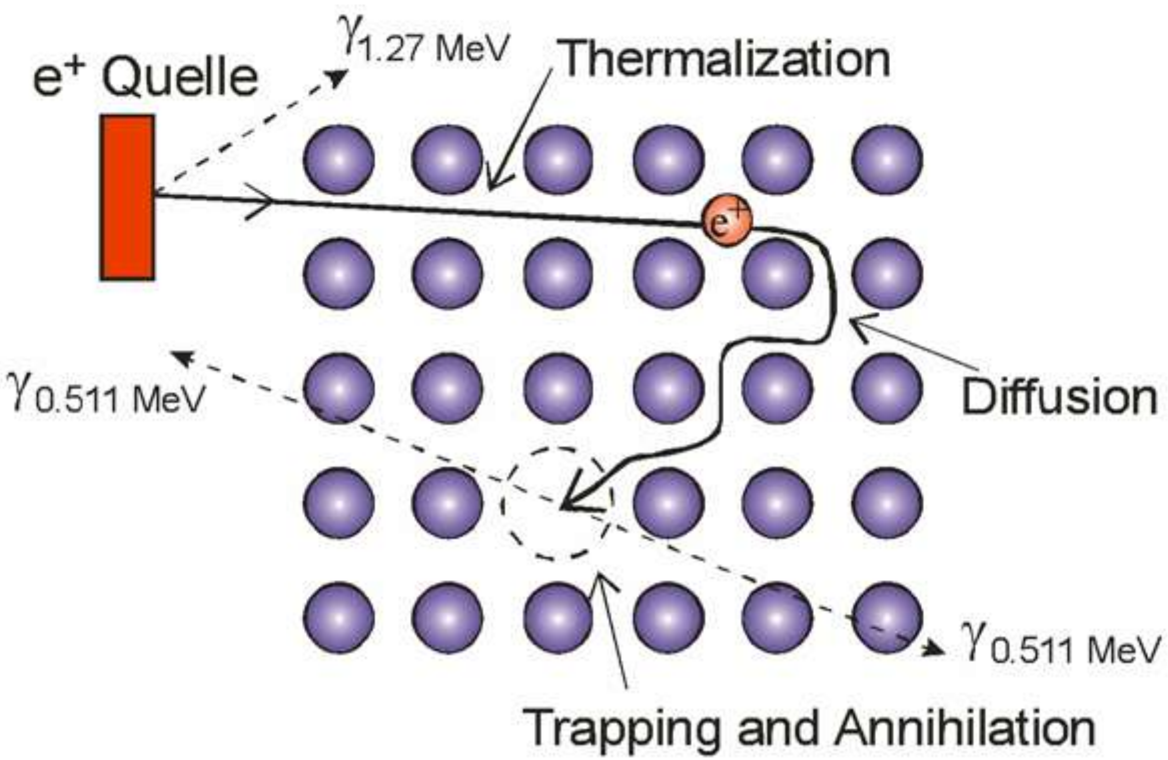


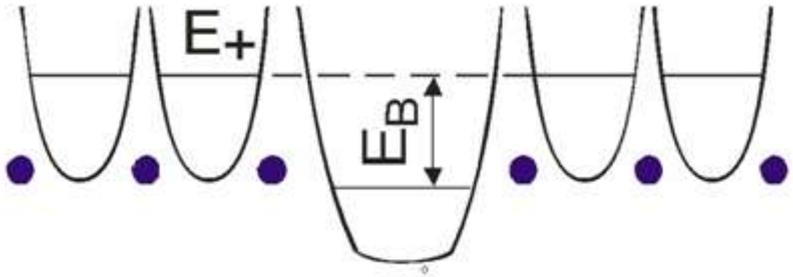
FIG. 1. Positron-lifetime spectra after source-background subtraction in electron-irradiated (6×10^{18} e^-/cm^2) high-purity iron at various stages of isochronal annealing. The dramatic occurrence of a long-lifetime component after 230 K annealing is clearly visible.

- positron lifetime is very sensitive for vacancy-type defects
- here: lifetime increases after irradiation
- and further increase after first annealing: vacancy clustering

The positron lifetime spectroscopy

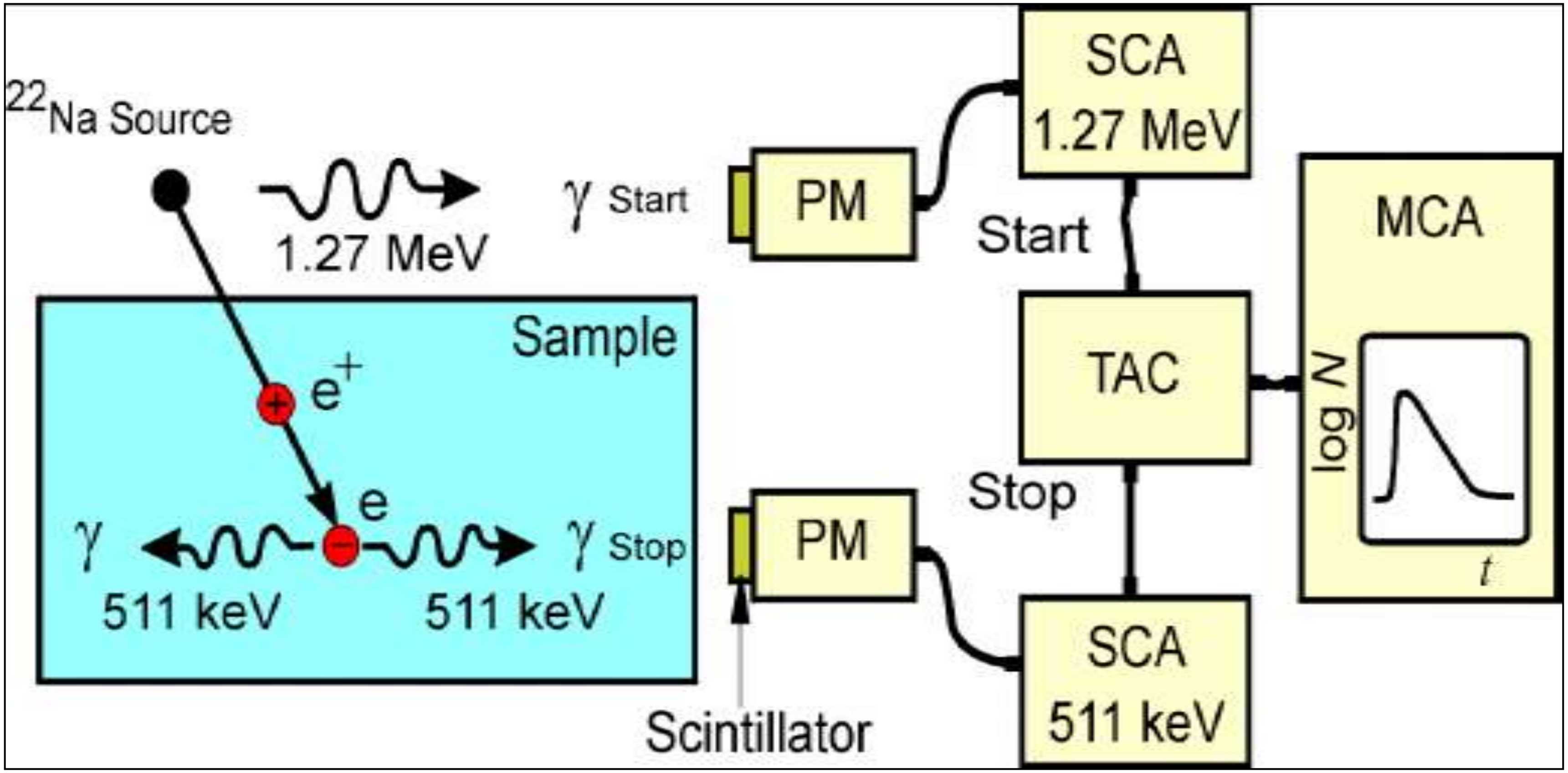
^{22}Na





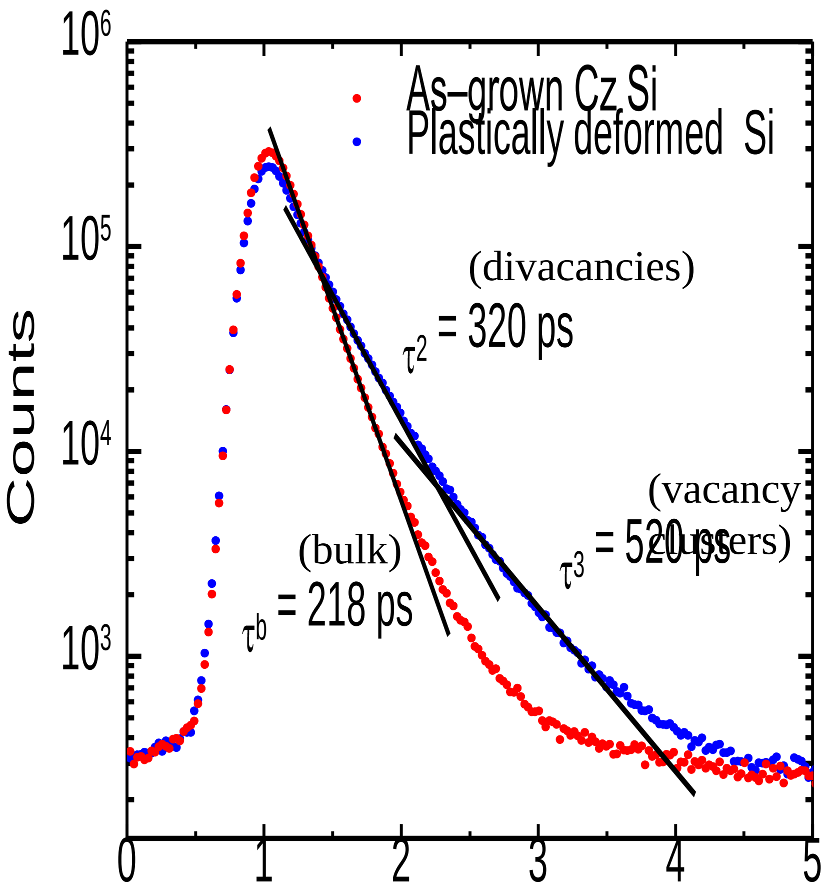
- positron wave-function can be localized in the attractive potential of a defect
- annihilation parameters change in the localized state
- e.g. positron lifetime increases in a vacancy
- lifetime is measured as time difference between appearance of 1.27 (start) and 0.51 MeV (stop) quanta
- defect identification and quantification possible

Positron lifetime spectroscopy



Positron lifetime: time between 1.27 MeV and 0.511 MeV quanta

Positron lifetime spectroscopy



- positron lifetime spectra consist of exponential decay components
- positron trapping in open-volume defects leads to long-lived components
- longer lifetime due to lower electron density
- analysis by non-linear fitting: lifetimes τ_i and intensities I_i

positron lifetime spectrum:

$$N(t) = \sum_{i=1}^{k+1} \frac{I_i}{\tau_i} \exp\left(-\frac{t}{\tau_i}\right)$$

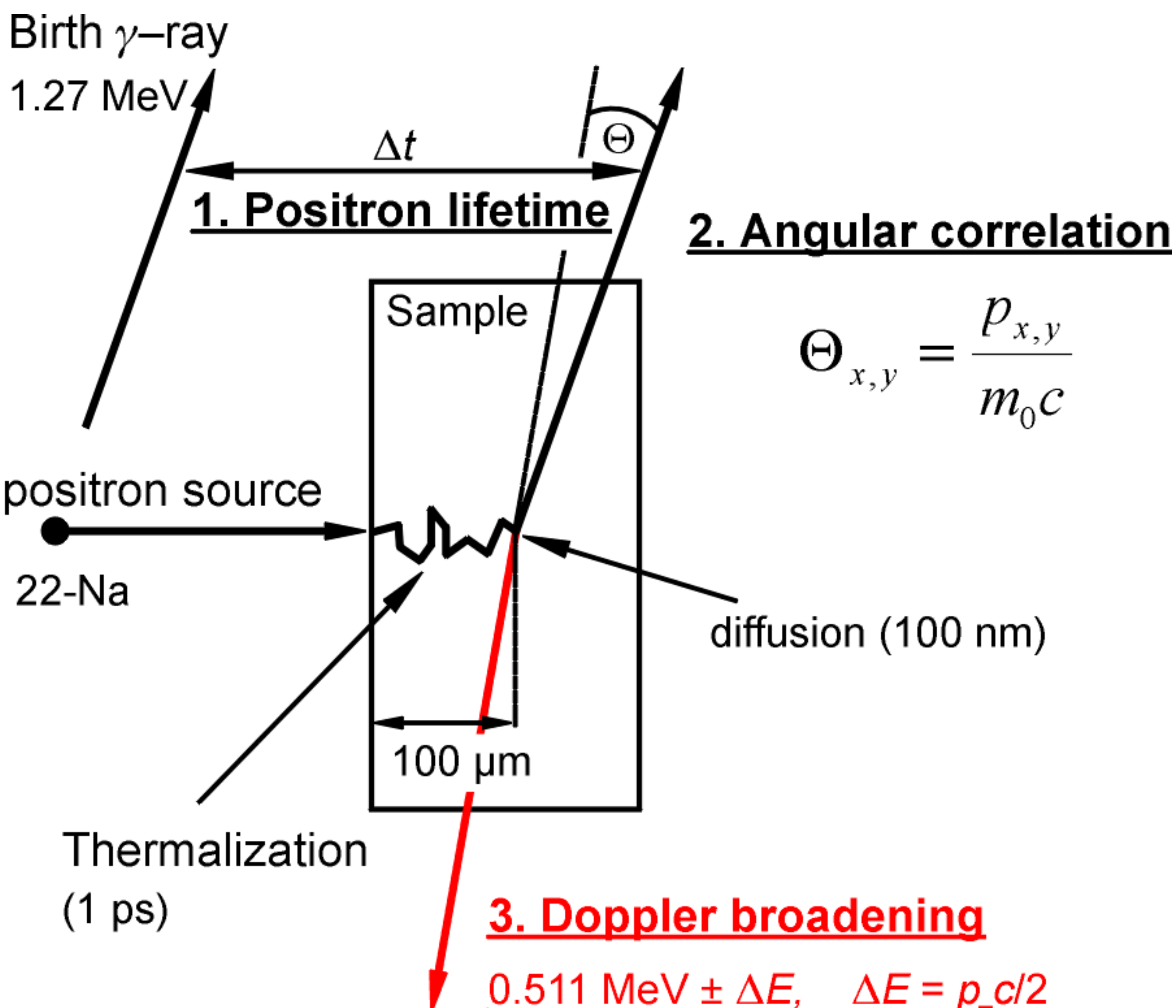
trapping coefficient

$$\kappa_d = \mu C_d = \frac{I_2}{I_1}\left(\frac{1}{\tau_b} - \frac{1}{\tau_d}\right)$$

trapping rate

defect concentration

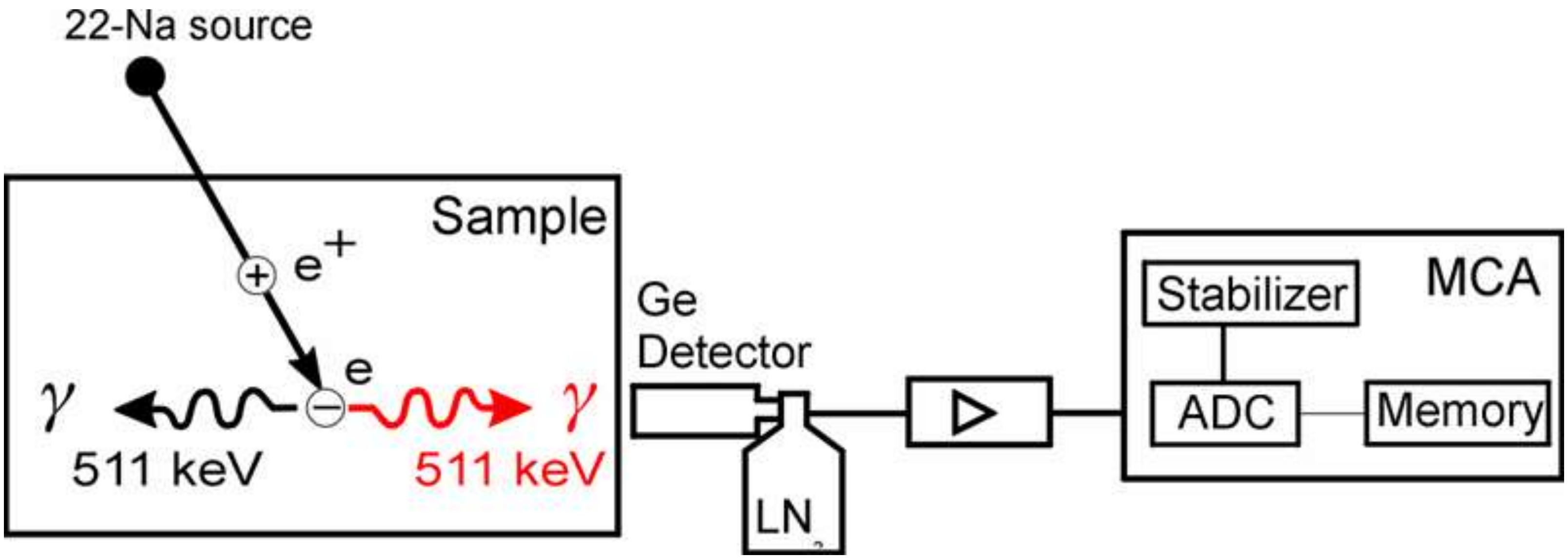
Doppler Broadening Spectroscopy



$$\Theta_{x,y} = \frac{p_{x,y}}{m_0 c}$$

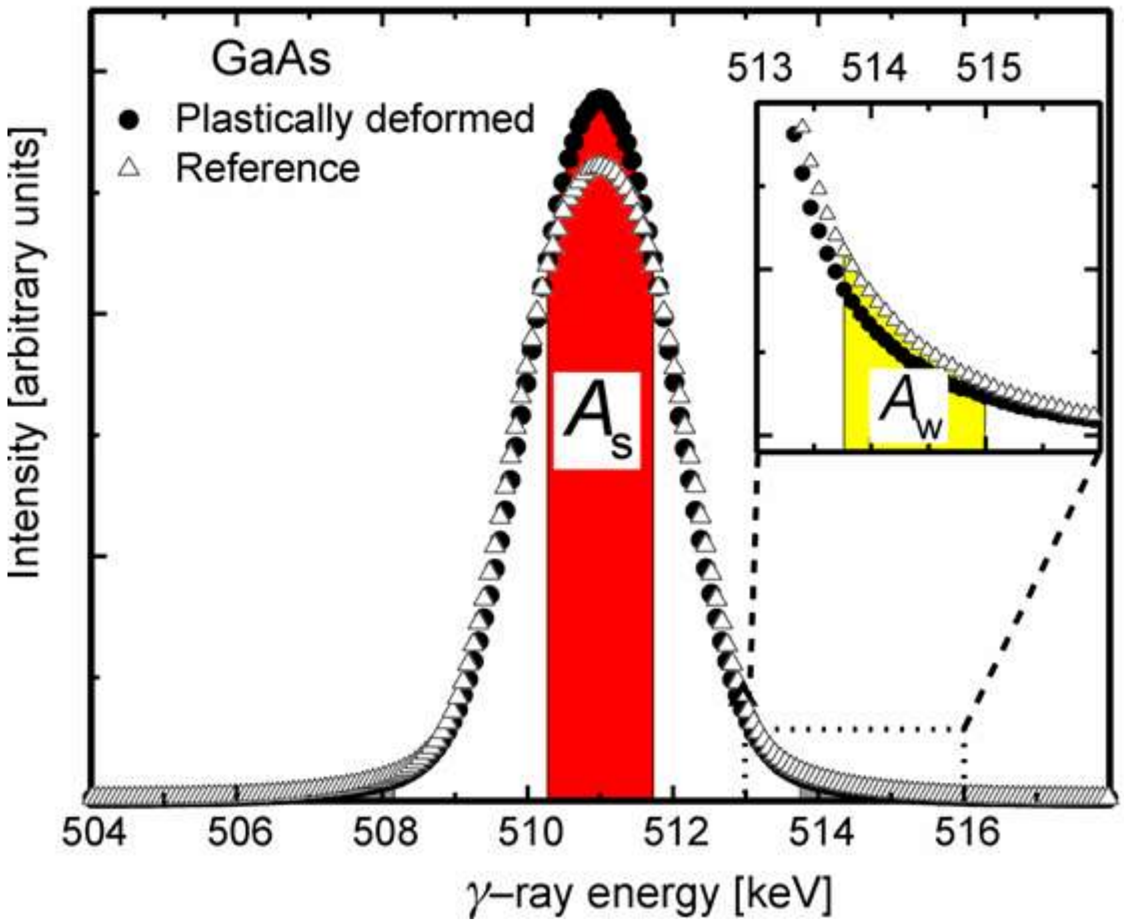
0.511 MeV ± ΔE, $\Delta E = p_z c/2$

Measurement of Doppler Broadening



- electron momentum in propagation direction of 511 keV γ-ray leads to Doppler broadening of annihilation line
- can be detected by conventional energy-dispersive Ge detectors and standard electronics

Line Shape Parameters



S parameter:

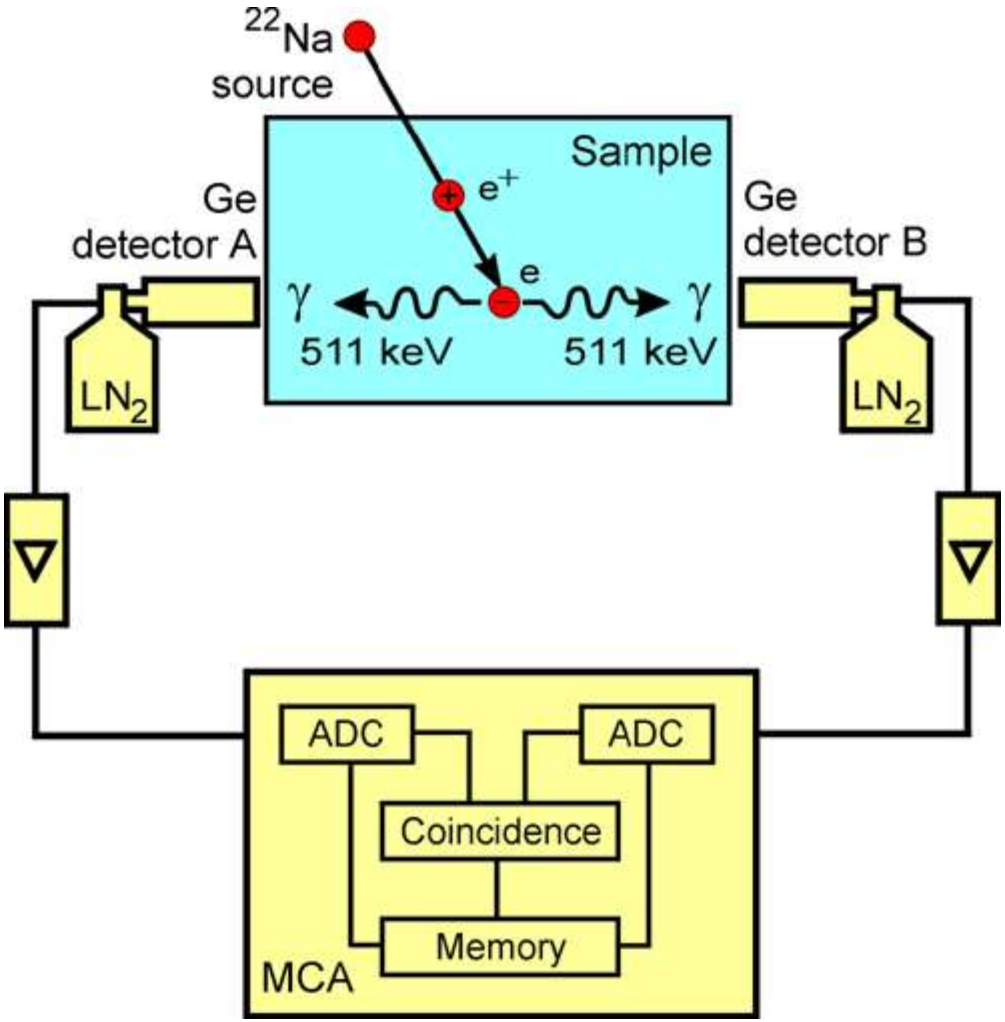
$S = A_S / A_0$

W parameter:

$W = A_W / A_0$

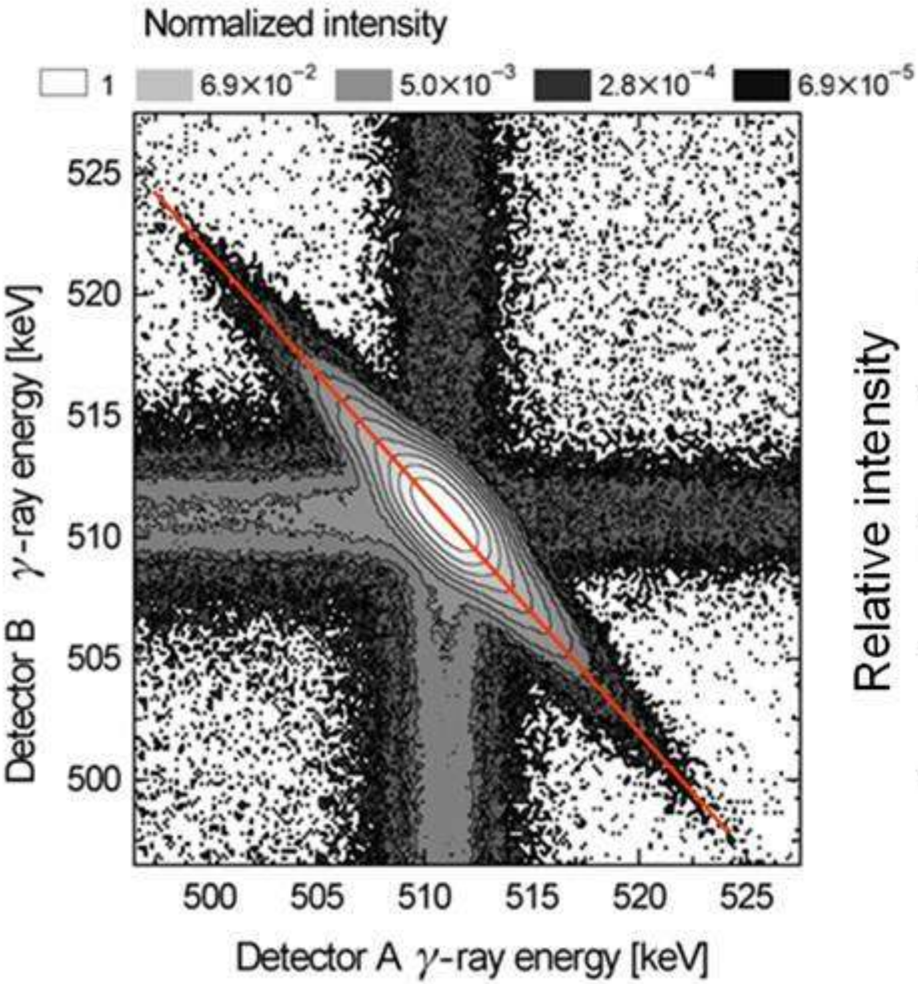
W parameter mainly determined by annihilations of core electrons (chemical information)

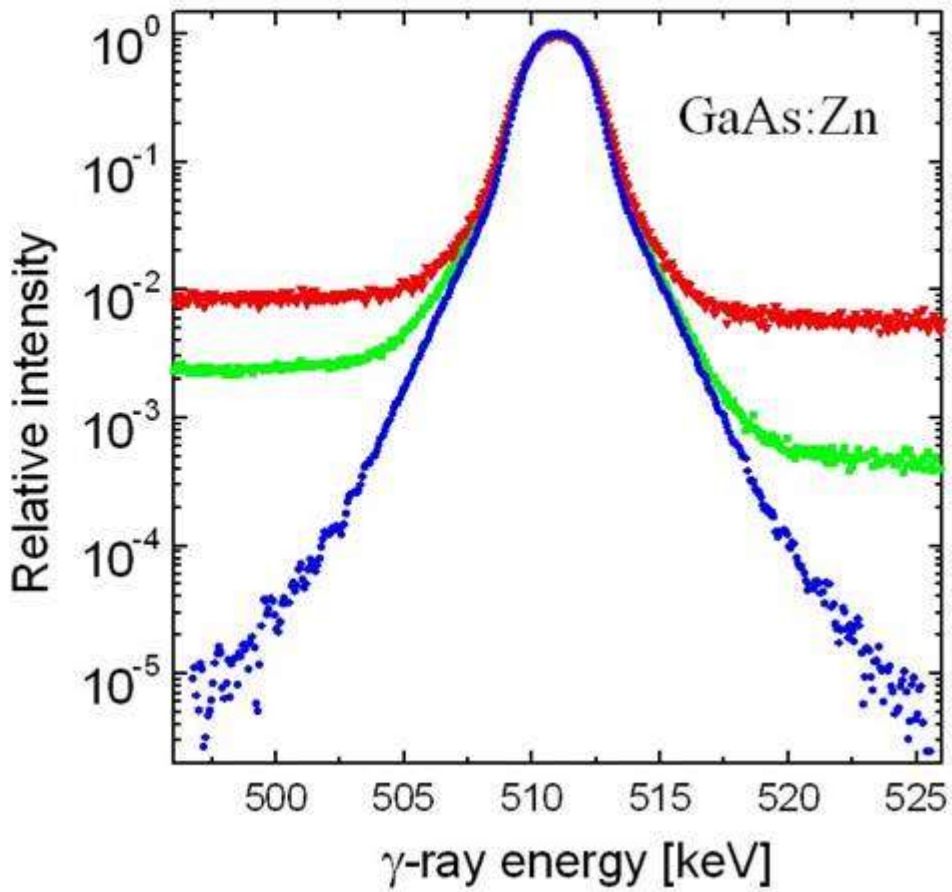
Doppler Coincidence Spectroscopy



- coincident detection of second annihilation γ reduces background
- use of a second Ge detector improves energy resolution of system

Doppler Coincidence Spectra

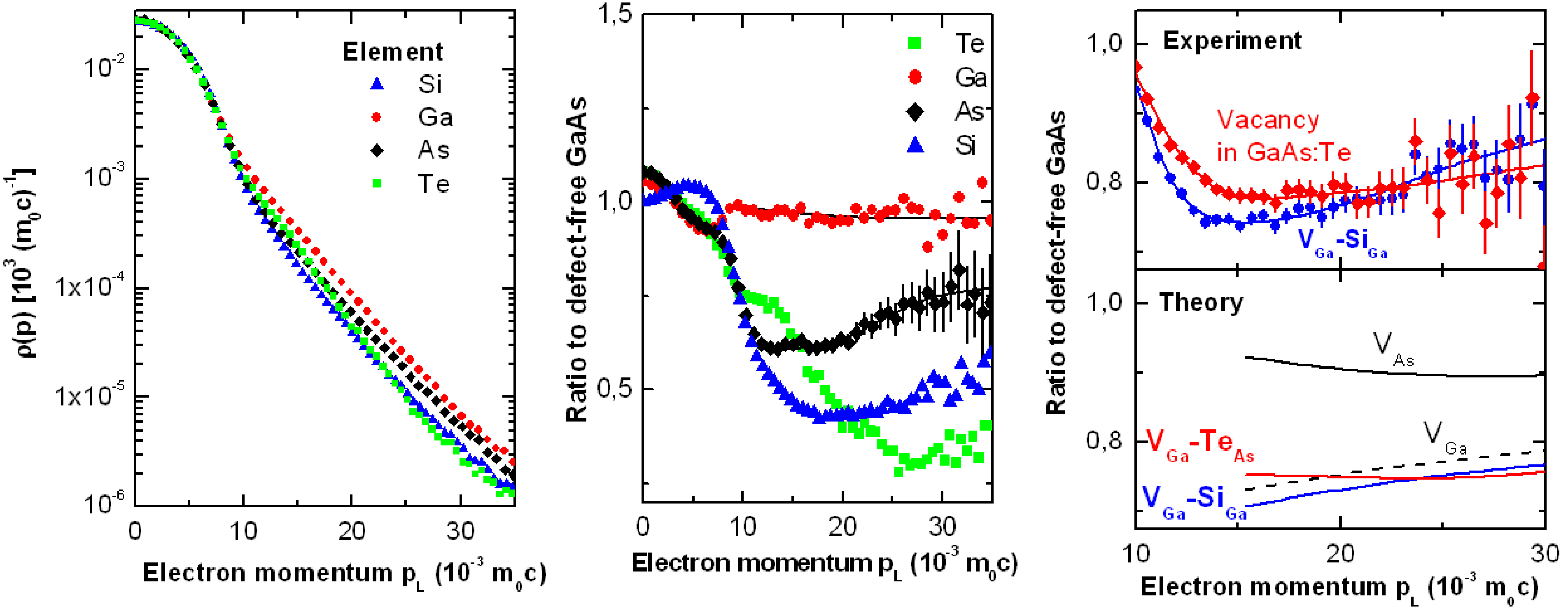




$$E_1+E_2= 2\ m_0\ c^2 =1022\ \text{keV}$$

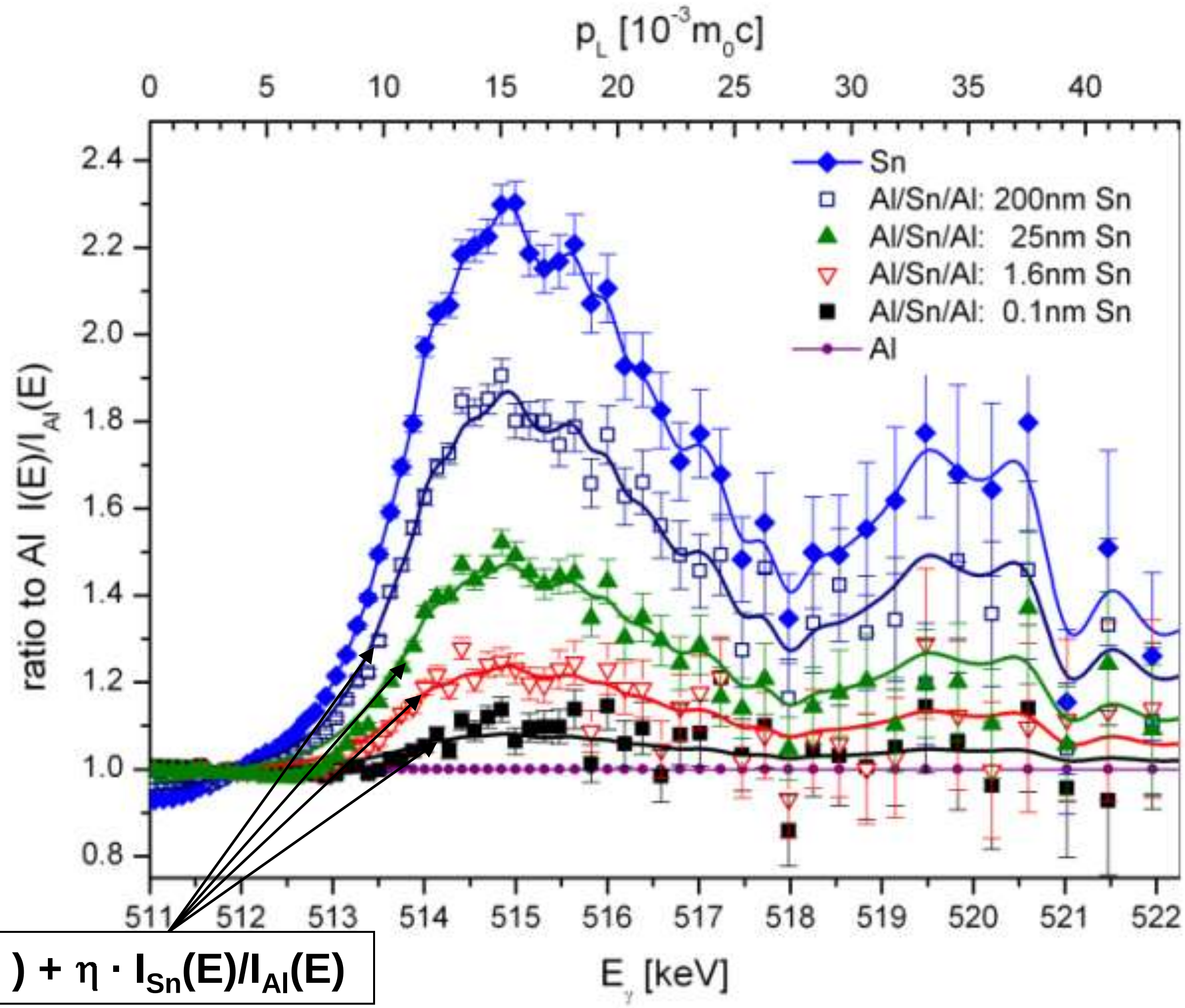
Doppler-Coincidence-Spectroscopy in GaAs

- Chemical sensitivity due to electrons at high momentum (core electrons)
- a single impurity atom aside a vacancy is detectable
- examples: V_{Ga}-Te_{As} in GaAs:Te



J. Gebauer et al., Phys. Rev. B **60** (1999) 1464

High Sensitivity of CDBS for thin Layers

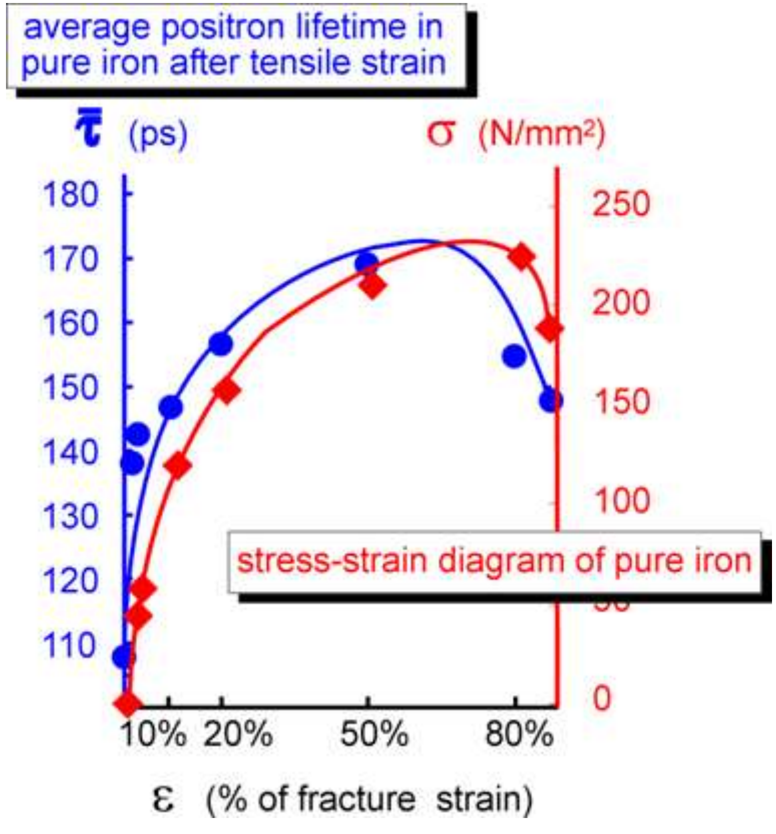


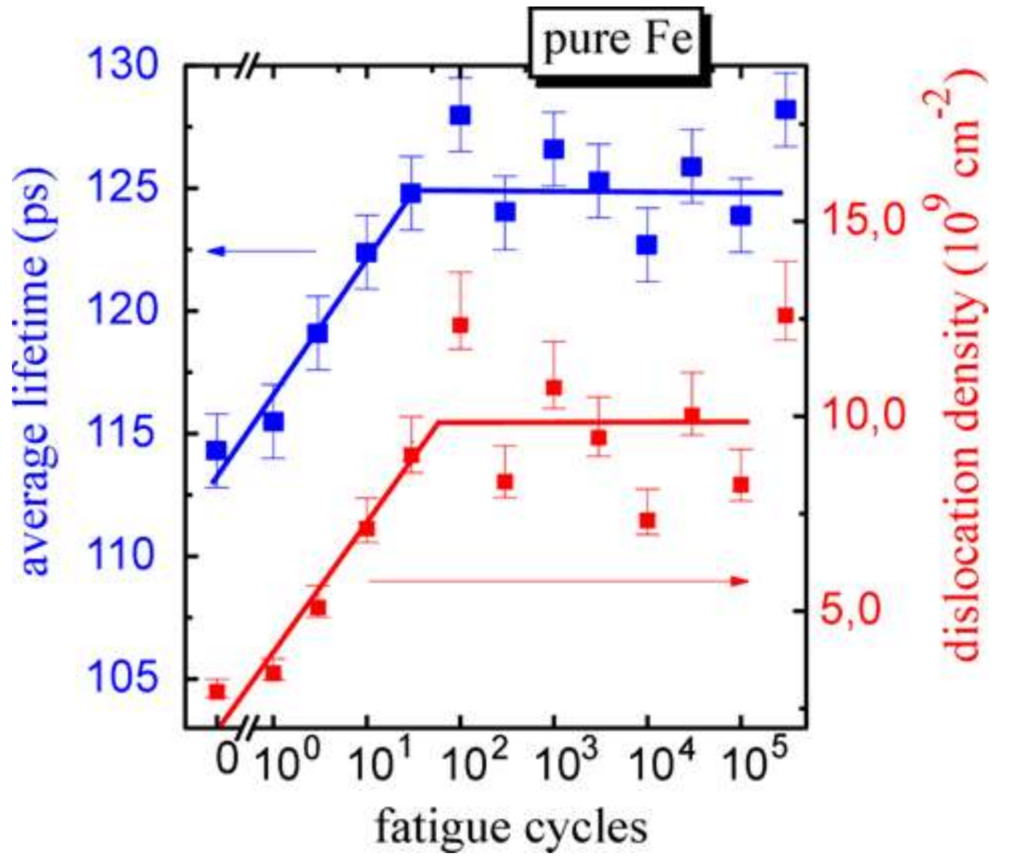
$$I_{ratio}(E) = (1 - \eta) + \eta \cdot I_{Sn}(E)/I_{Al}(E)$$

C. Hugenschmidt et al. PRB 77 (2008) 092105

Defects in Iron after tensile strength and fatigue treatment

- We performed an extensive study of defects in mechanically damaged iron and steel
- Positrons are very sensitive: detection of defects already in the Hooks range of the stress-strain experiment
- Vacancy cluster and dislocations are detectable in both cases

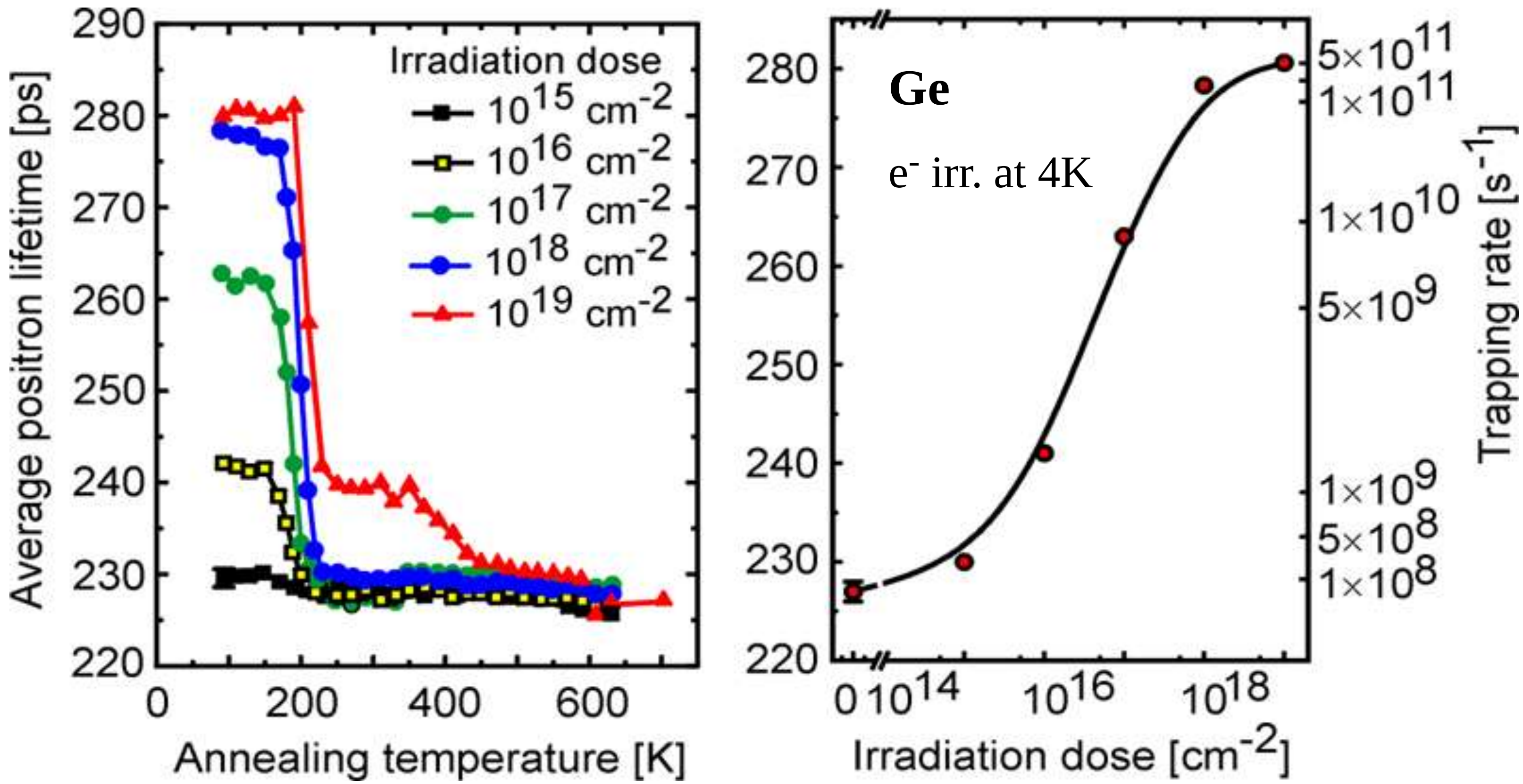




Somieski et al., J. Physique IV 5, C1/127-134 (1995)

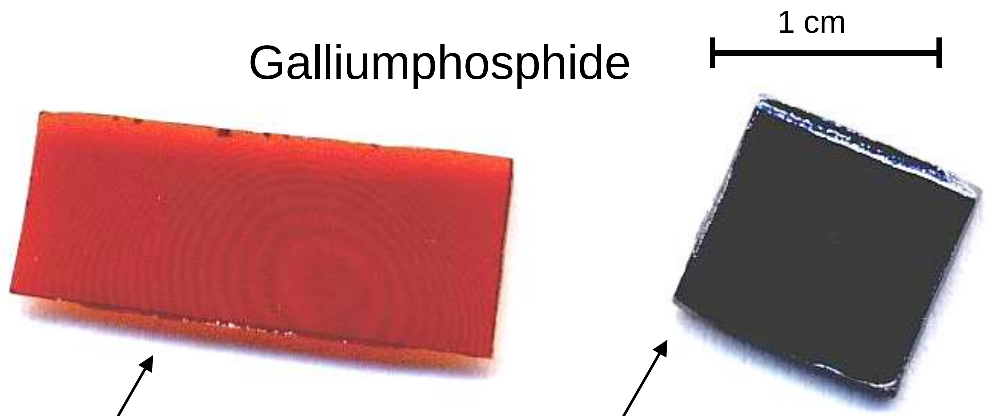
Defects in electron-irradiated Ge

- Electron irradiation (2 MeV @ 4K) induces Frenkel pairs (vacancy - interstitial pairs)
- steep annealing stage at 200 K
- at high irradiation dose: divacancies are formed (thermally more stable)



(Polity et al., 1997)

Point defects determine properties of materials



without vacancies
transparent

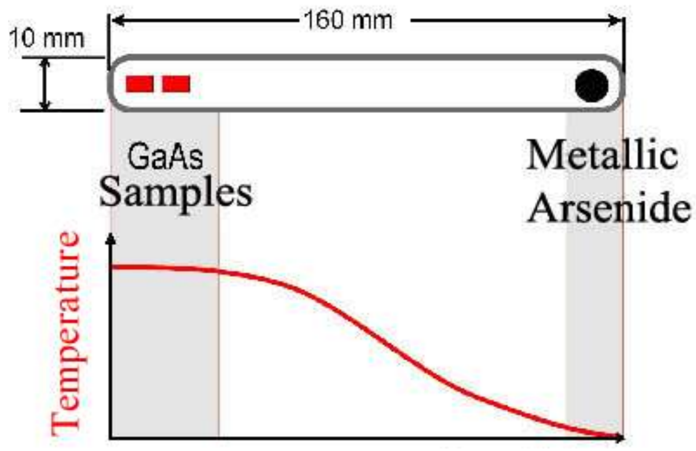
with 0.001% vacancies
opaque
1 vacancy in 100000 atoms

- Point defects determine electronic and optical properties

- Point defects are generated by irradiation (e.g. cosmic rays), by plastic deformation or by diffusion, …
- Metals in high radiation environment -> formation of voids -> embrittlement

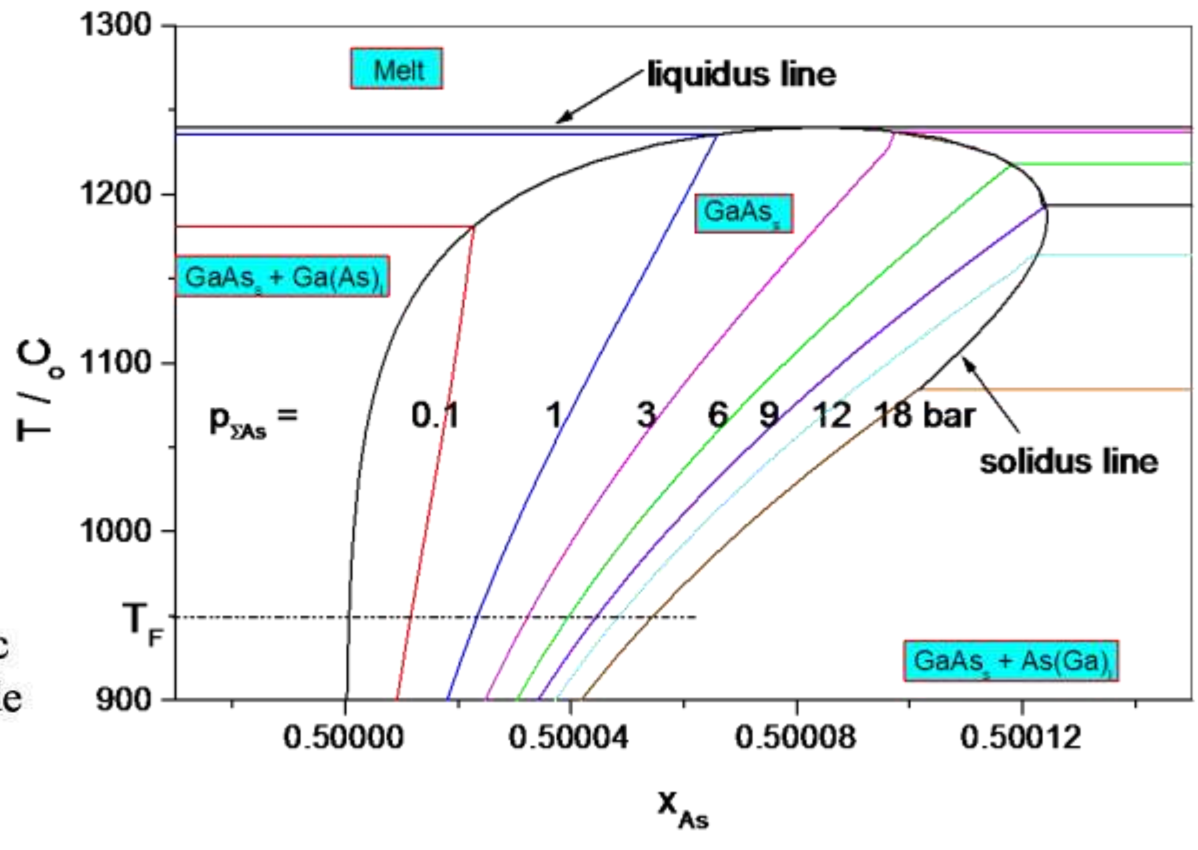
GaAs: annealing under defined As-partial pressure

- two-zone-furnace: Control of sample temperature **and** As partial pressure allows
- T_{As}: determines As-partial pressure
- navigate freely in phase diagram (existence area of compound)



T_{sample}: 1100° C

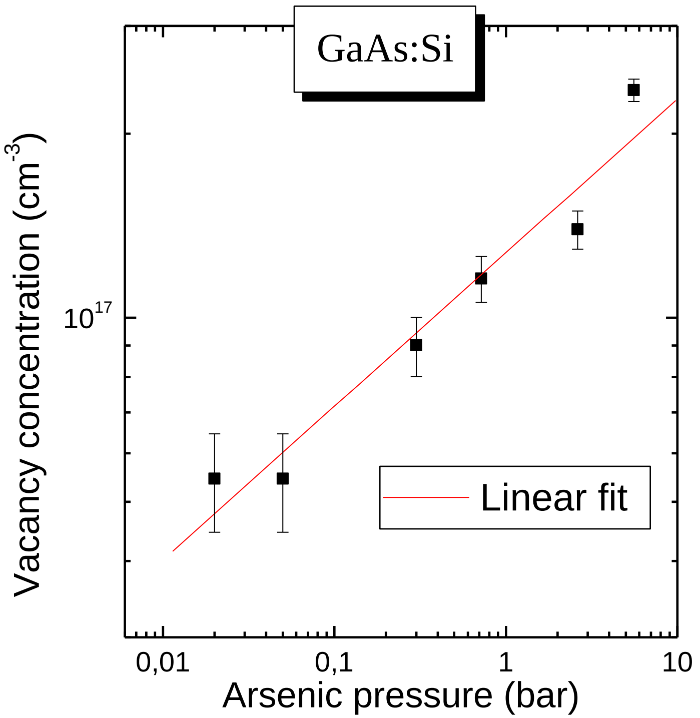
Equilibrium Phase Diagram of GaAs



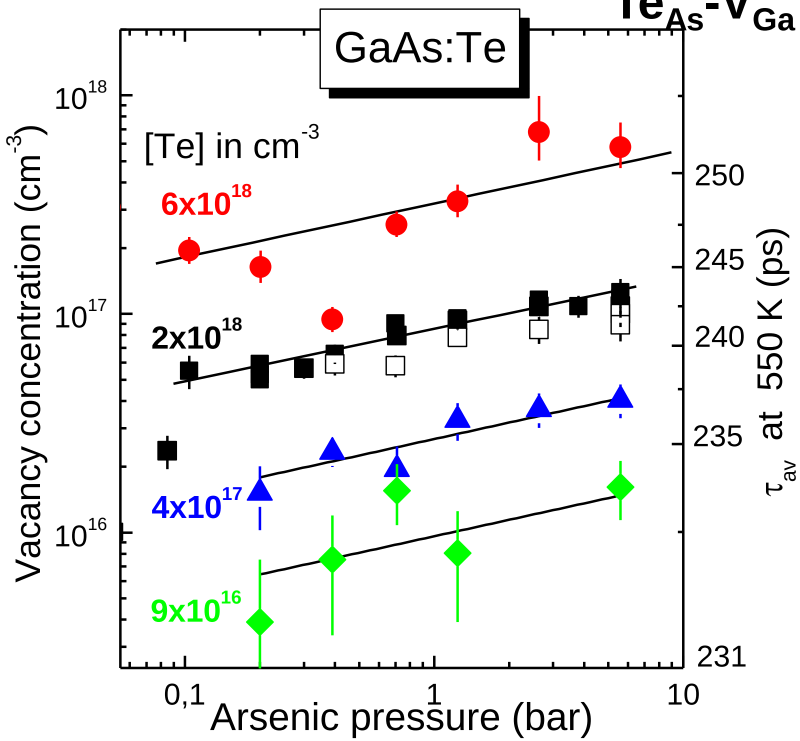
Jurisch, Wenzl; 2002

GaAs: Annealing under defined As pressure

Si_{Ga}-V_{Ga}



Te_{As}-V_{Ga}



Thermodynamic reaction:

$1/4\ As_4^{gas} \leftrightarrow As_{As} + V_{Ga}$

Mass action law:

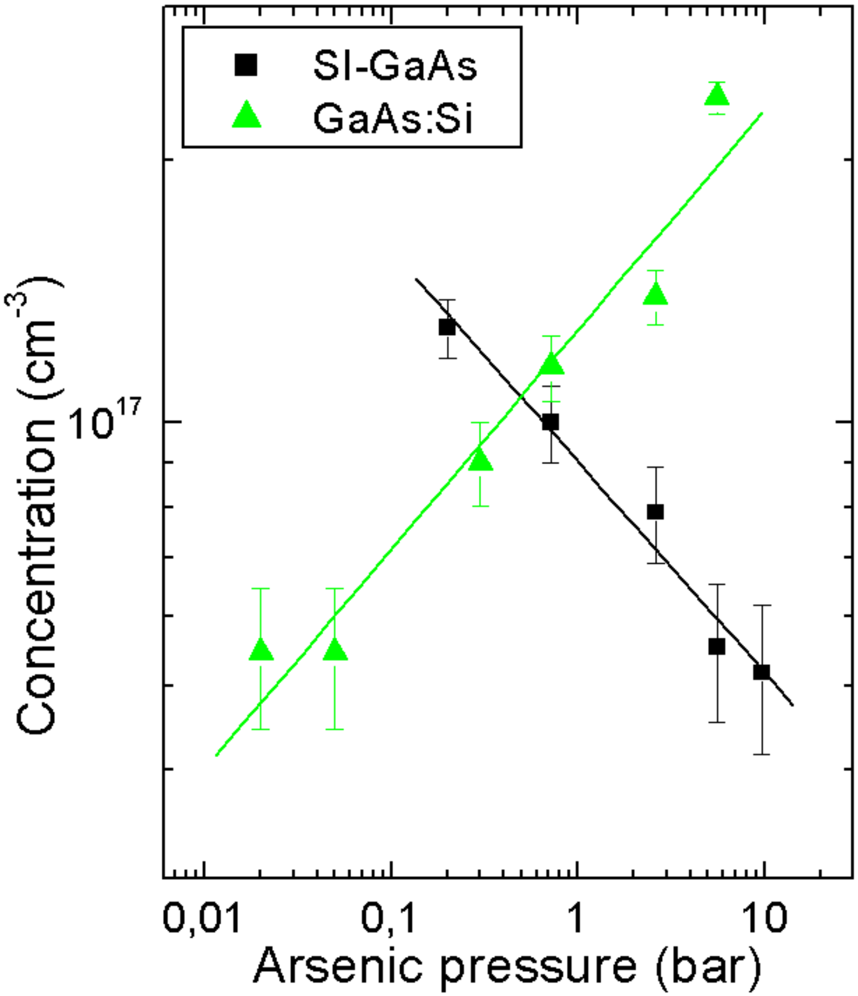
$[V_{Ga}] = K_{VG} \times p_{As}^{1/4}$

J. Gebauer et al.,
Physica B 273-274, 705 (1999)

Fit: $[V_{Ga}\text{-Dopant}] \sim p_{As}^{n}$

$\rightarrow n = 1/4$

Comparison of doped and undoped GaAs



Thermodynamic reaction:

$$As_{As} \leftrightarrow V_{As} + 1/4As_4^{gas}$$

Mass action law:

$$[V_{As}] = K_{VAs} \times p_{As}^{-1/4}$$

Fit: $[\text{V-complex}] \sim p_{As}^{n}$

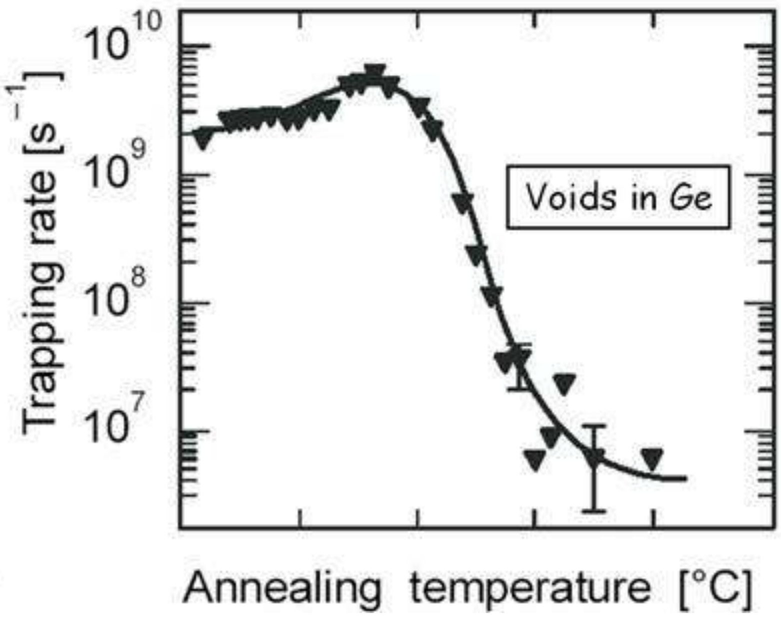
$\rightarrow n = -1/4$

undoped GaAs: As vacancy

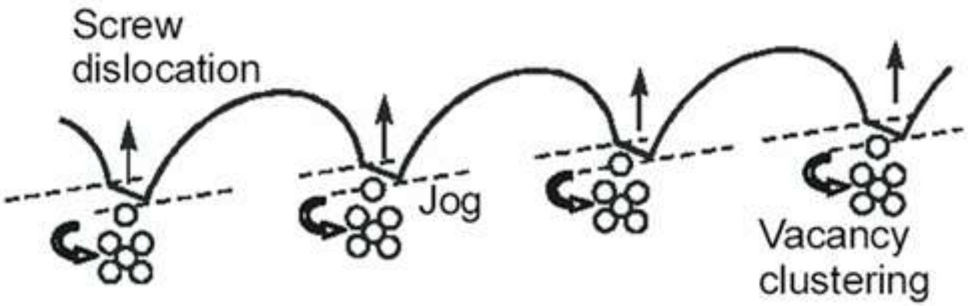
Bondarenko et al., 2003

Vacancy clusters in semiconductors

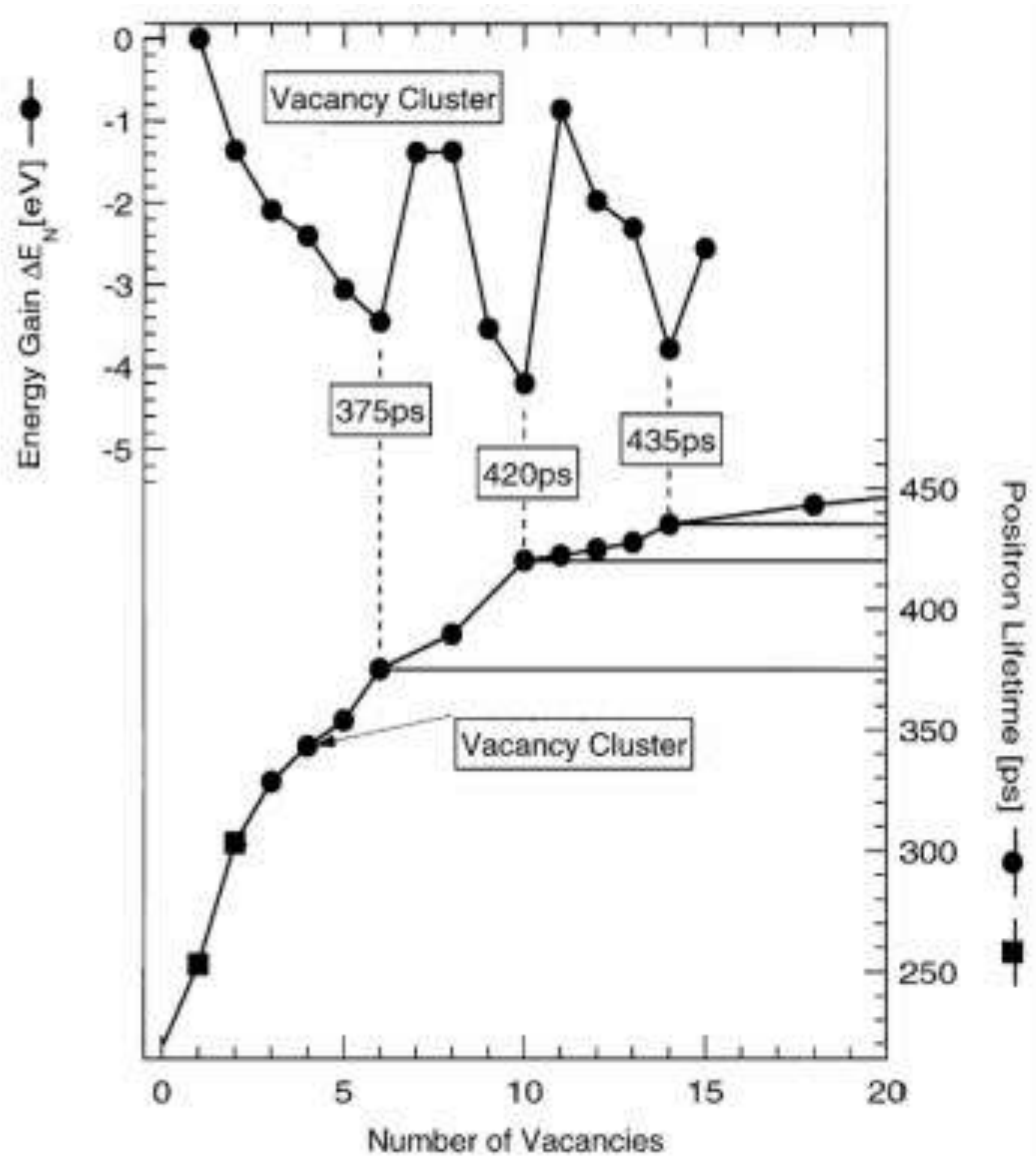
- vacancy clusters were observed after neutron irradiation, ion implantation and plastic deformation
- due to large open volume (low electron density) -> positron lifetime increases distinctly
- example: plastically deformed *Ge*
- lifetime: τ = 525 ps
- reason for void formation: jog dragging mechanism
- trapping rate of voids disappears during annealing experiment



Krause-Rehberg et al., 1993



Theoretical calculation of vacancy clusters in Si



- there are cluster configurations with a large energy gain
- „Magic Numbers" with 6, 10 und 14 vacancies
- positron lifetime increases distinctly with cluster size
- for n > 10 saturation effect, i.e. size cannot be determined

T.E.M. Staab et al.,
Physica B 273-274 (1999) 501-504

Vacancy clustering during defect annealing

- electron irradiated Fe
- clustering in early stage can be observed
- very sensitive: formation of divacancies and small clusters (n < 10)

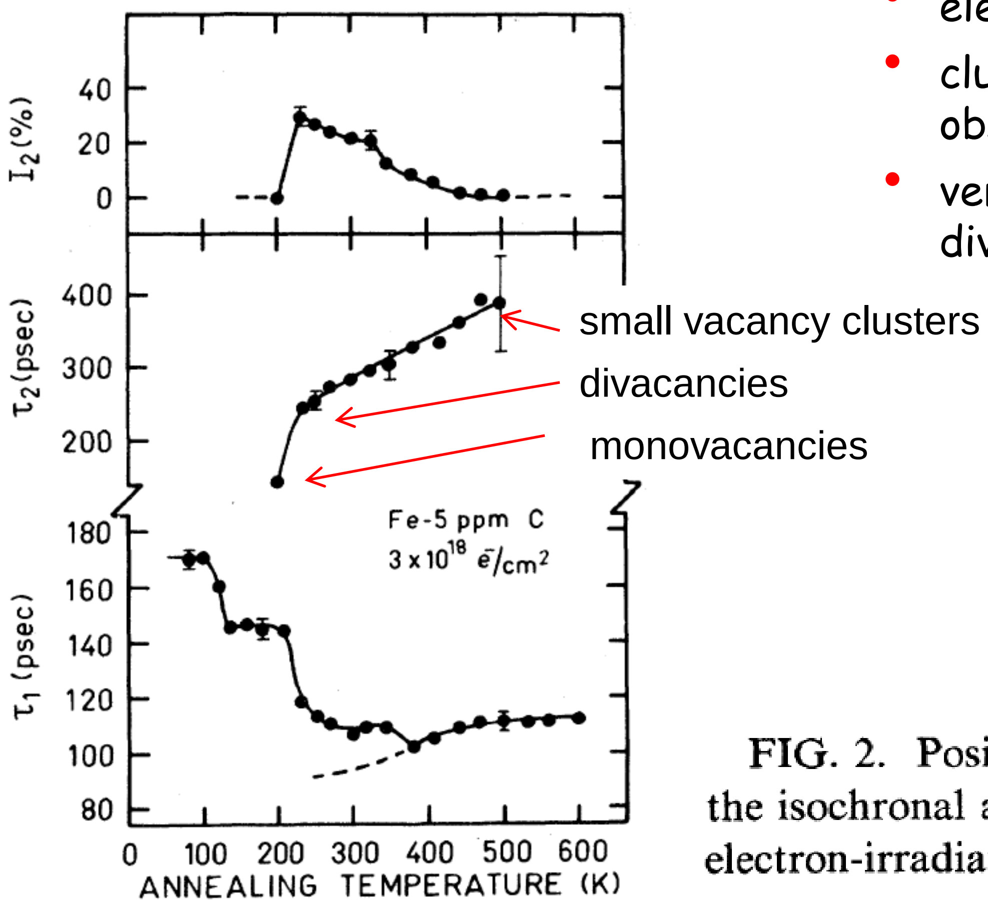
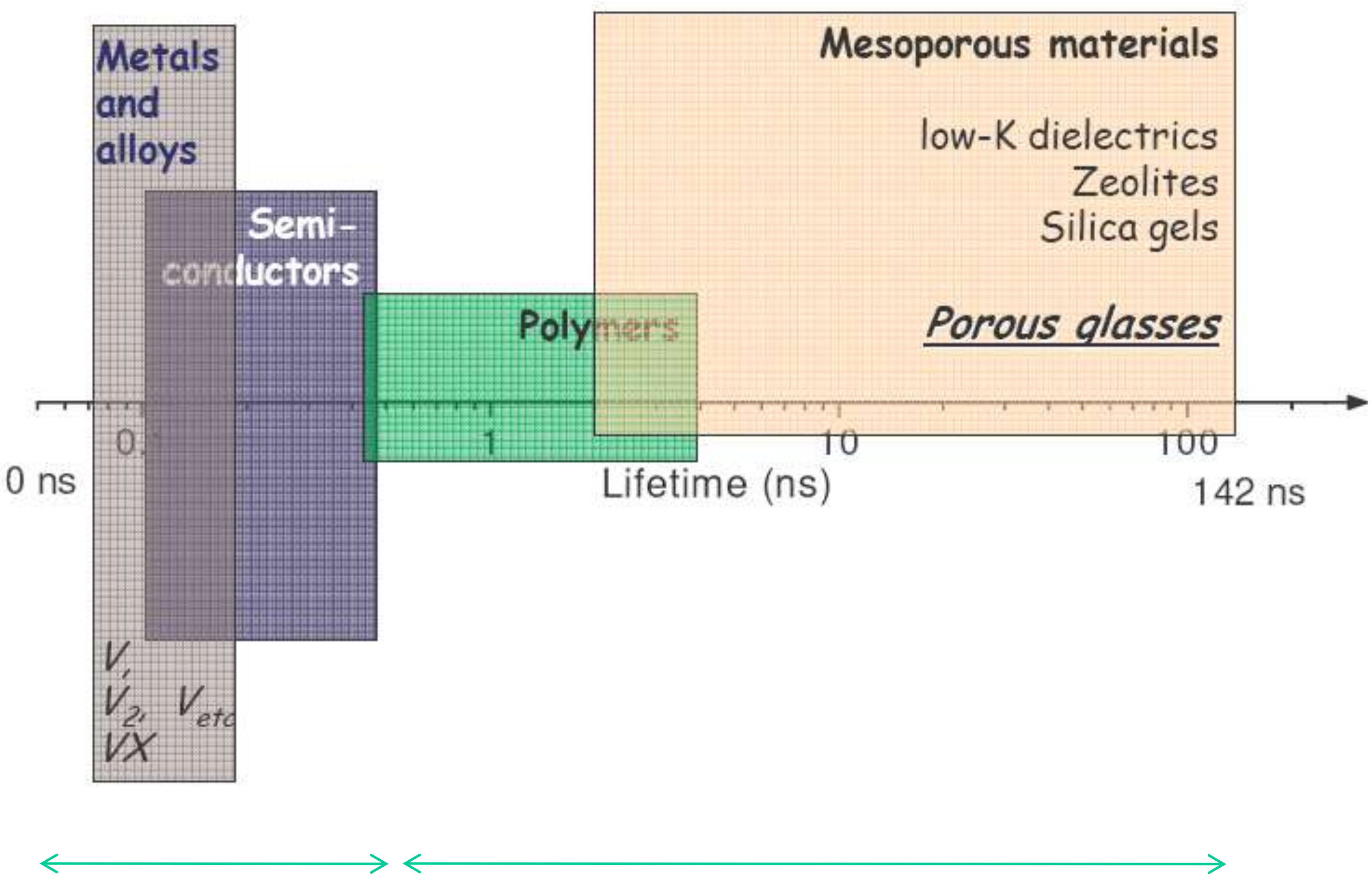


FIG. 2. Positron-lifetime parameters as a function of the isochronal annealing temperature in the low-dose electron-irradiated pure iron.

Vehanen et al., Phys. Rev. B 25, 762–780

Typical Lifetimes

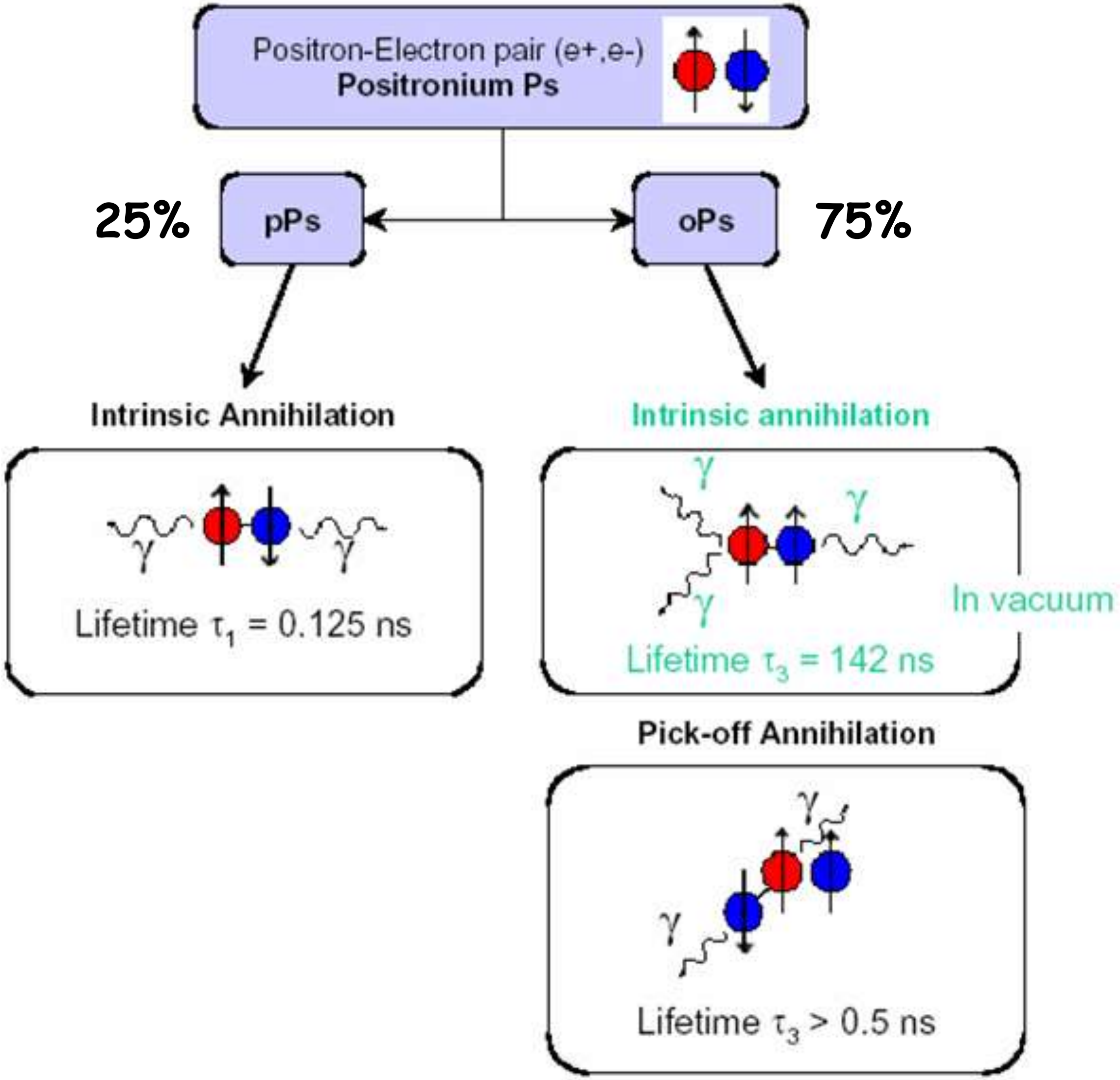


Positron

Positronium

o-Positronium Lifetime allows Porosimetry

- In materials without free electrons Positronium may be formed (Polymers, glass, liquids, gases)
- p-Ps annihilates without interaction with host material
- o-Ps lifetime in vacuum 142 ns
- in matter: positron may pick off another electron with opposite spin -> fast annihilation with two gammas

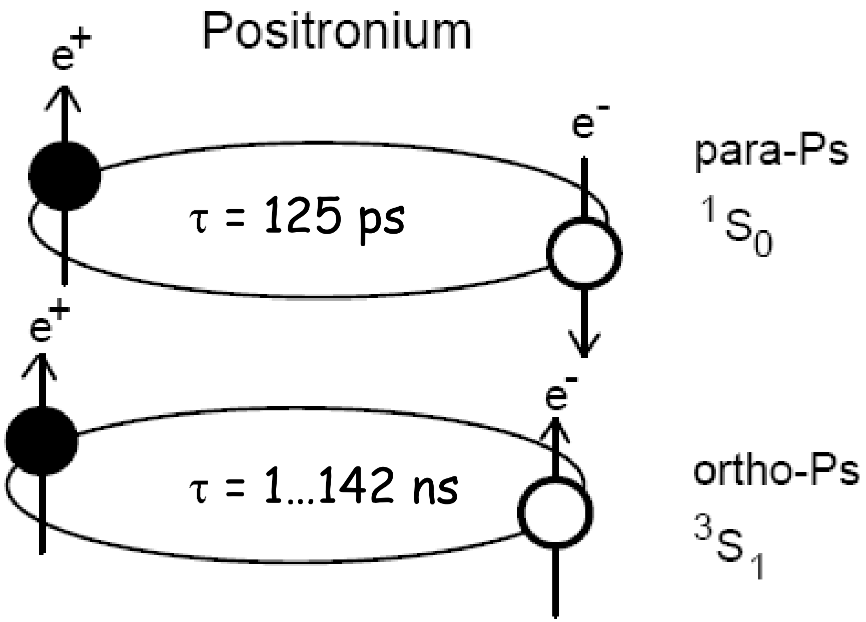


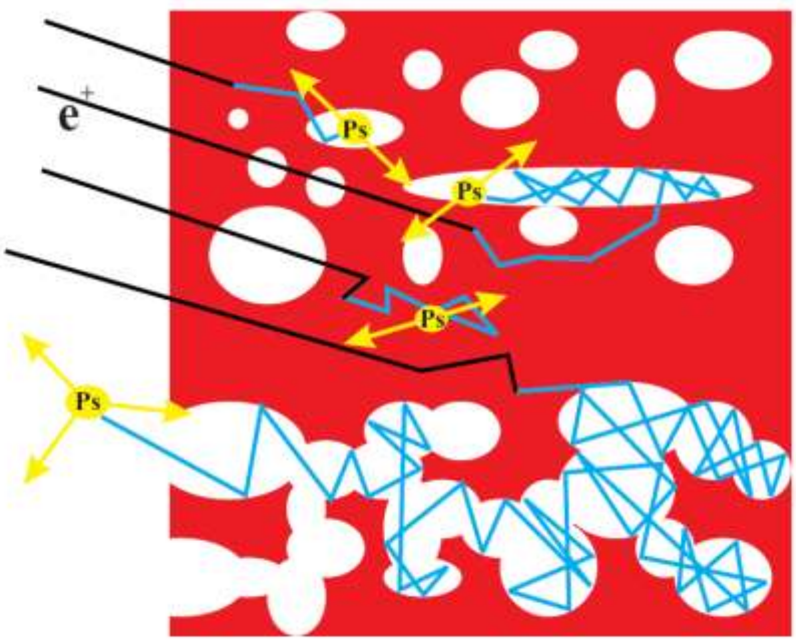
Pick-off Annihilation

positrons form Ps

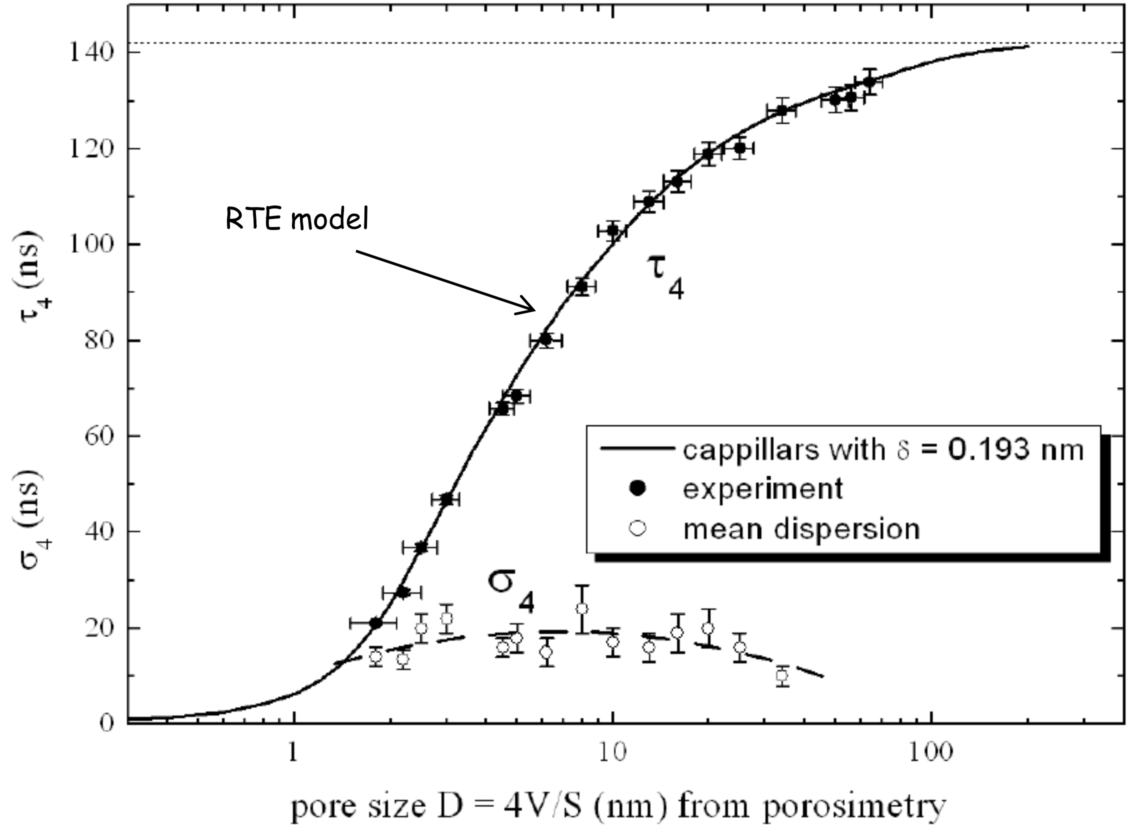
pick-off annihilation:

- o-Ps is converted to p-Ps by capturing an electron with anti-parallel spin
- happens during collisions at walls of pore
- lifetime decreases rapidly
- lifetime is function of pore size 1.5 ns to 142 ns



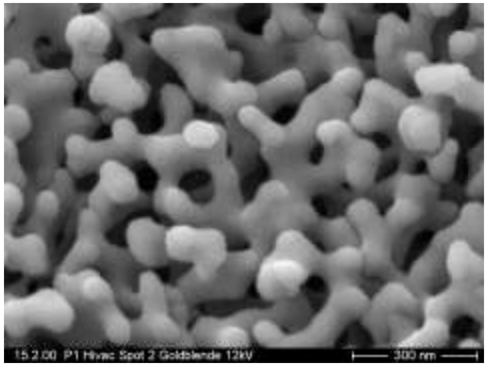


o-Ps lifetime τ_4 versus pore size in CPG Glass



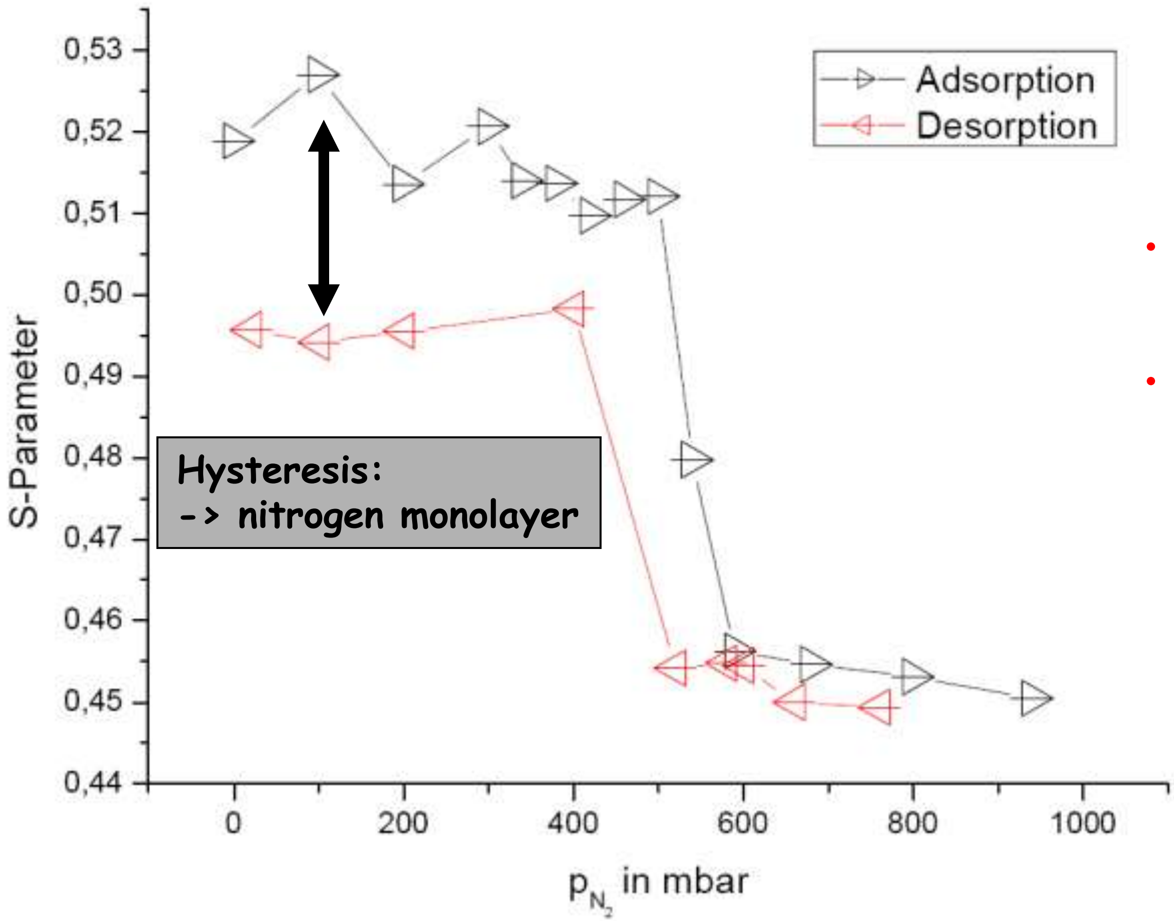
S.Thränert, Dissertation, MLU Halle 2008

- we measured porous CPG glass in a broad pore size range



- given pore size obtained by N_2-adsorption and/or mercury intrusion technique
- for T=300 K fair agreement to the RTE model

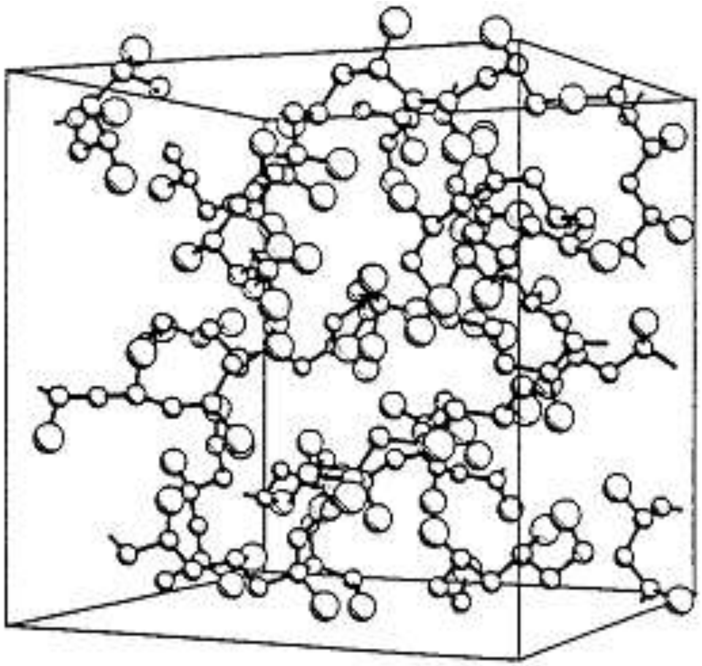
Cryo-condensation in nano-pores



- N2-Adsorption at T = 80 K and d = 16 nm
- study of phase transitions under confinement conditions possible

Structure of the free Volume in Soft Matter

- free volume due to structural, static or dynamic, disorder
- important for several macroscopic properties of these materials,
- viscosity, molecular transport, structural relaxation, and physical aging
- Positron Annihilation: Detection of subnanometric local free volumes (holes):
- mean size and size distribution

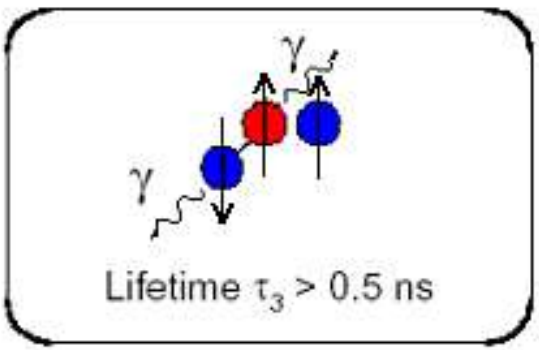


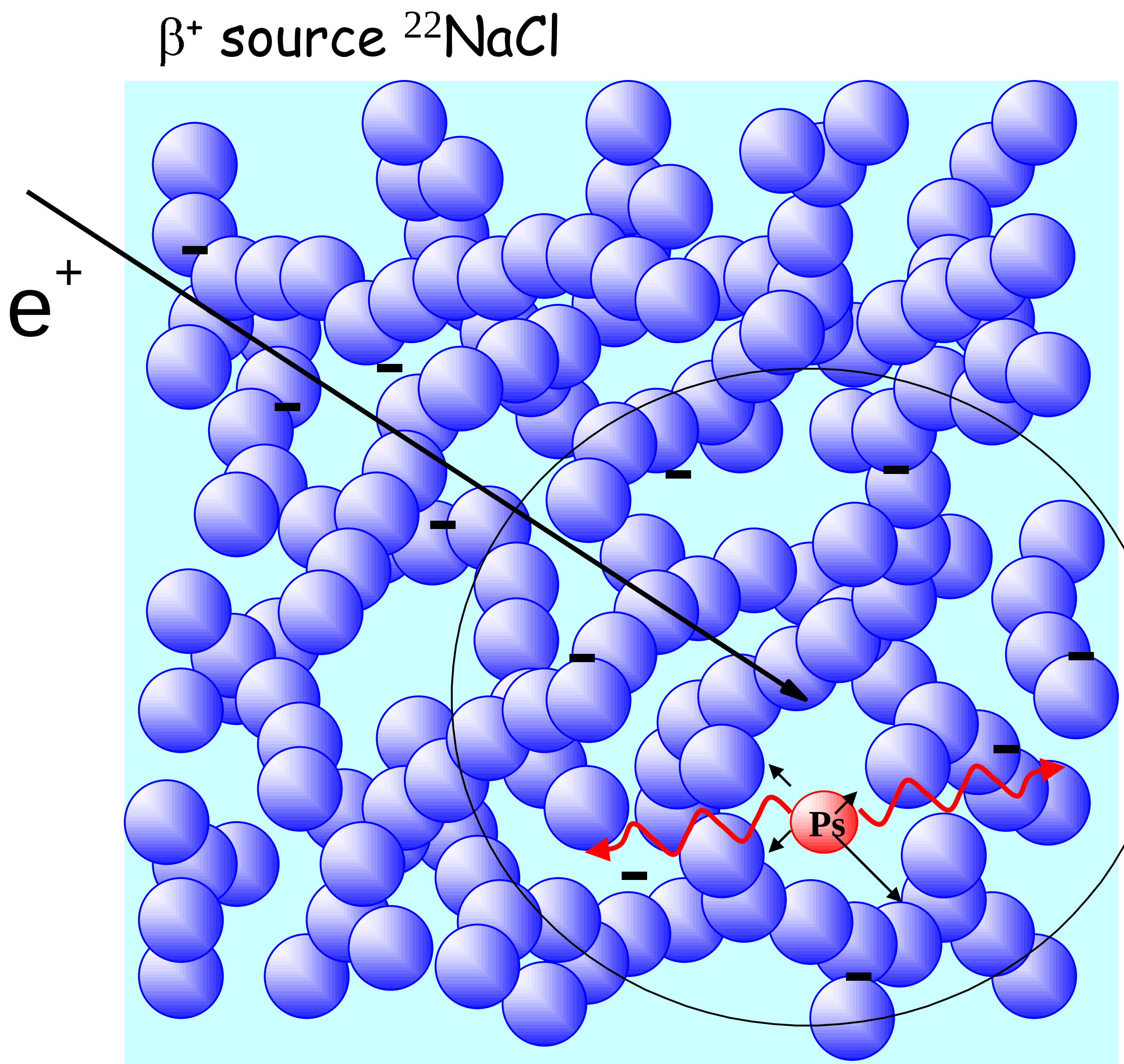
Schematic representation of the Polypropylene microstructure

(Simulation, Theodoru et al. 1985)

Ps Formation in Polymers

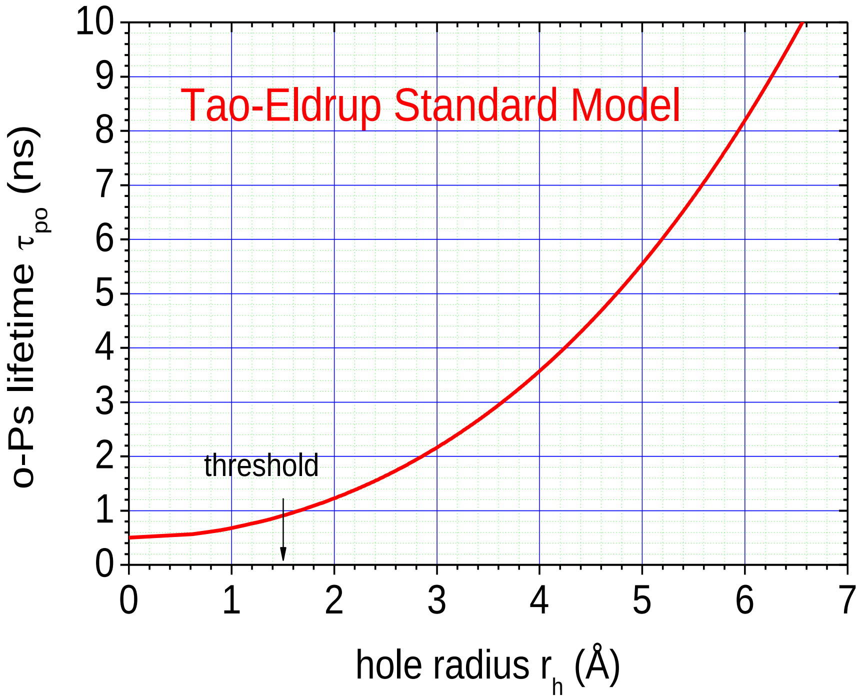
Pick-off Annihilation

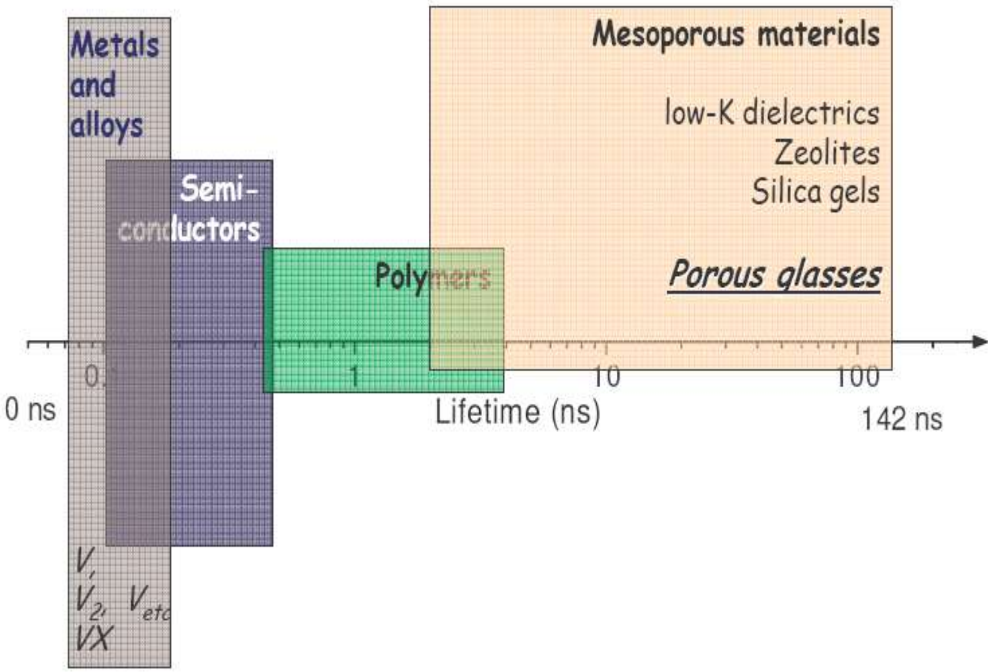




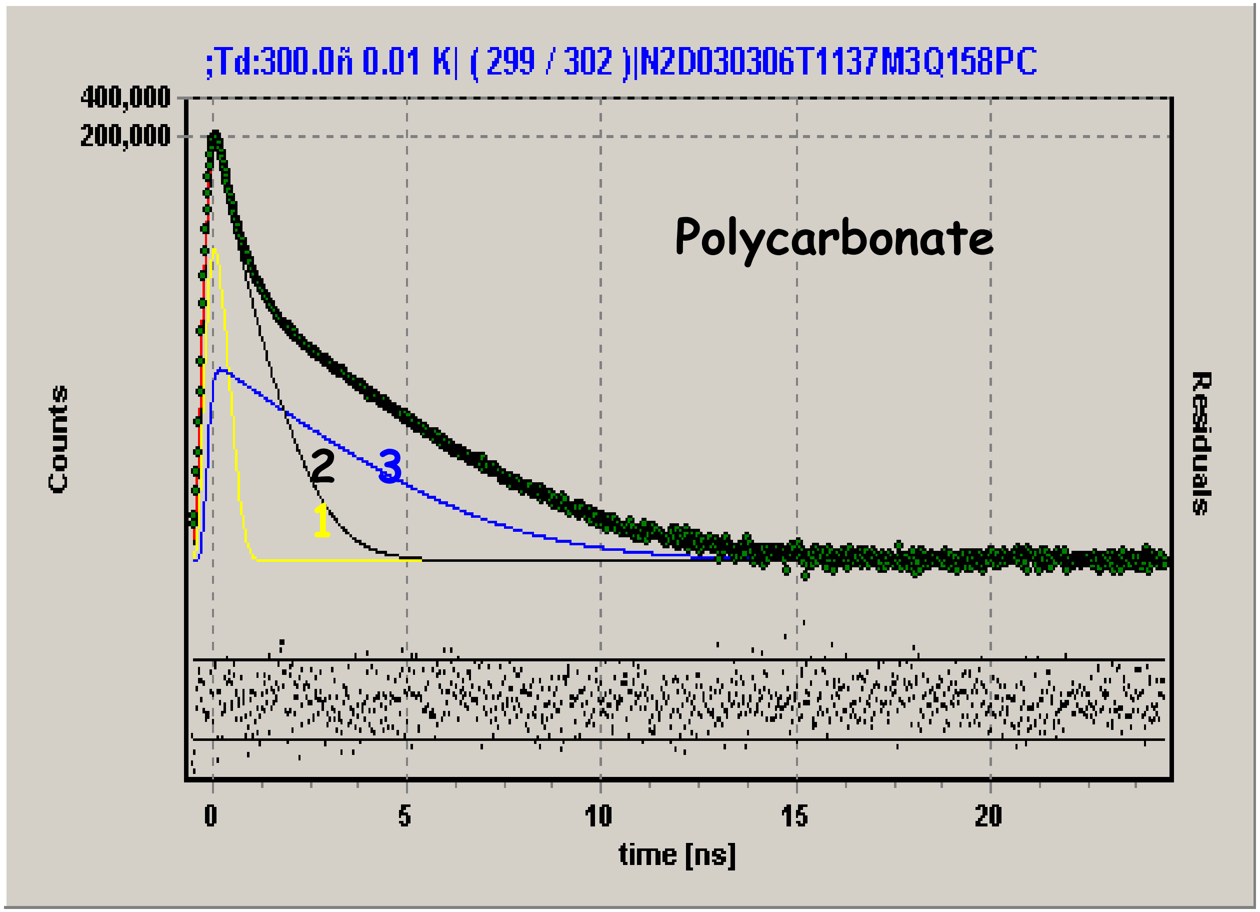
The o-Ps Lifetime as a Function of the Hole Size

$$\tau_{o-Ps\ pickoff} = \frac{0.5ns}{\left[1 - \frac{r_h}{r_h + \delta r} + \frac{1}{2\pi} Sin\left(\frac{2\pi r_h}{r_h + \delta r}\right)\right]}$$





Typical PALS Spectrum



p-Ps

$\tau_1 \approx 0.125$ ns

free positrons

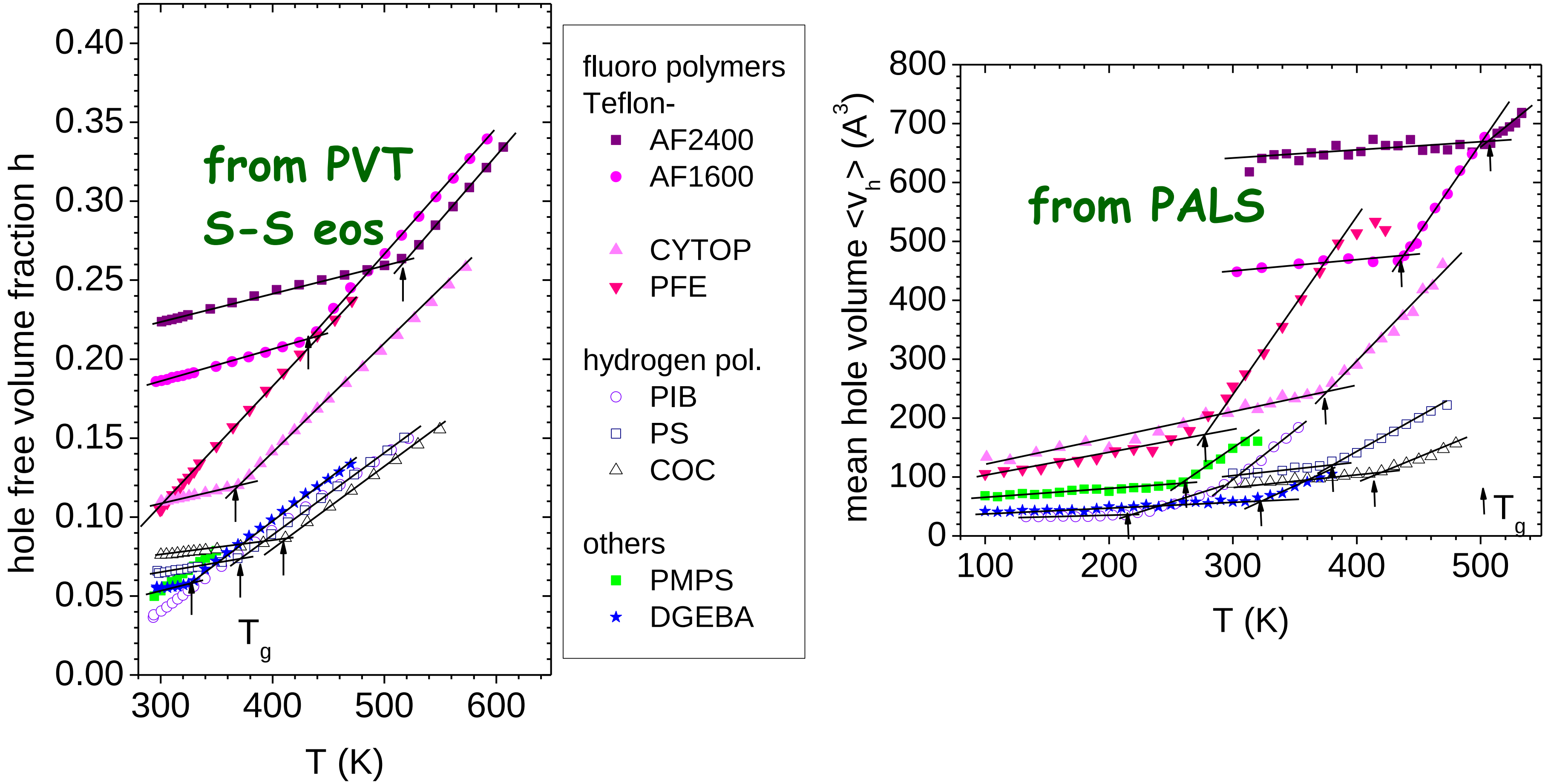
$\tau_2 \approx 0.35$ ns

o-Ps (pick-off annihilation)

$\tau_3 = 1 - 8$ ns

$$n(t) = I_1 \exp(-t/\tau_1) + I_2 \exp(-t/\tau_2) + I_3 \exp(-t/\tau_3)$$

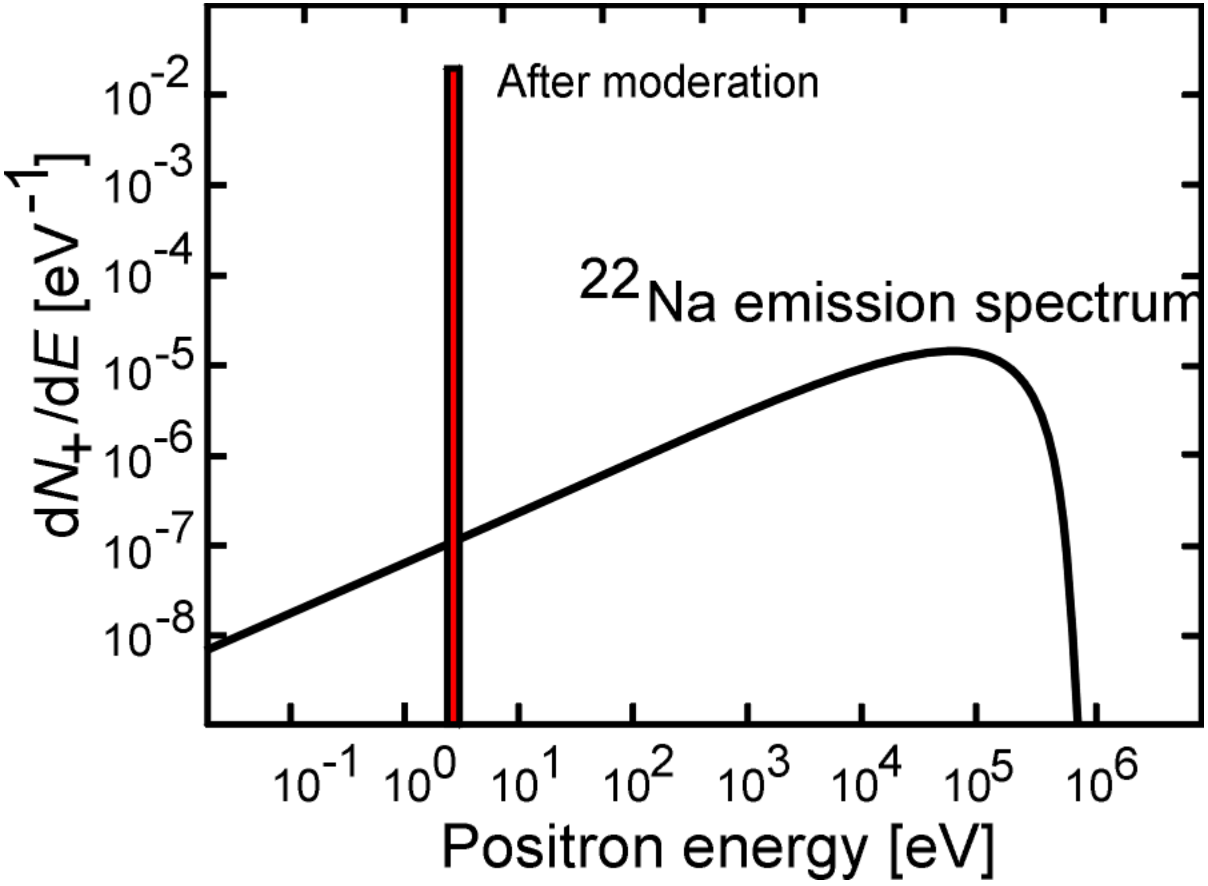
Temperature Dependence of the Hole Free Volume



Dlubek et al., *Macromolecules*, 41 (2008) 6125

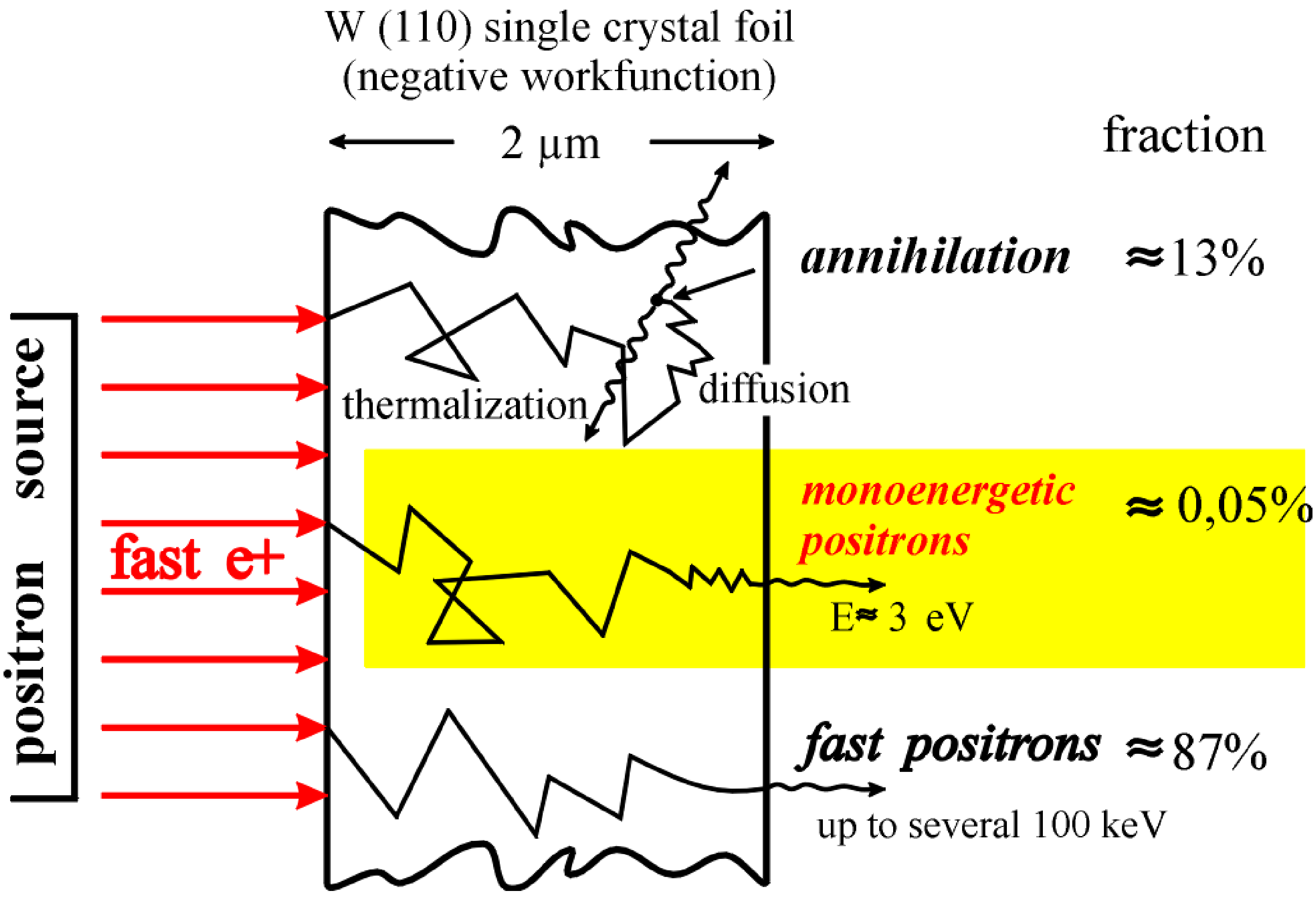
Moderation of Positrons

Mean (maximum) implantation depth of un-moderated positrons from a isotope ^{22}Na source (1/e 0.999): Si: 50μm (770μm)



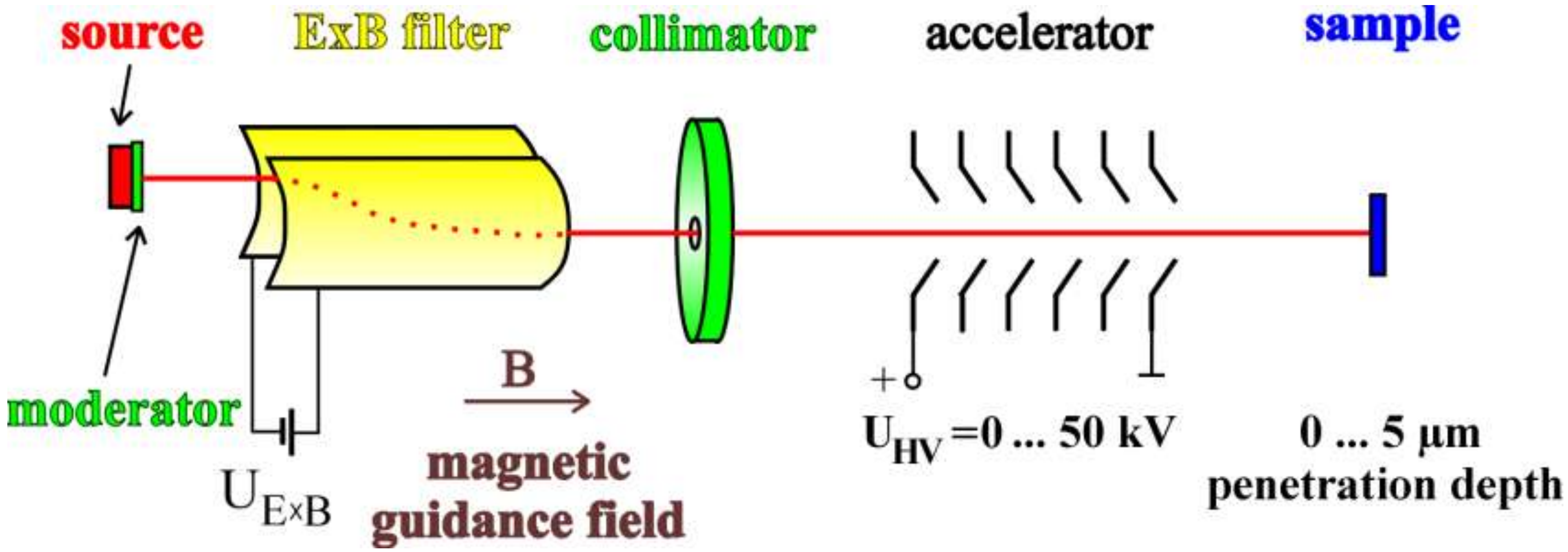
- broad β^+ positron emission spectrum
- deep implantation into solids
- not useful for study of defects in thin layers
- for defect depth profiling: moderation necessary
- monoenergetic positrons can be implanted to different depth

Moderation of Positrons



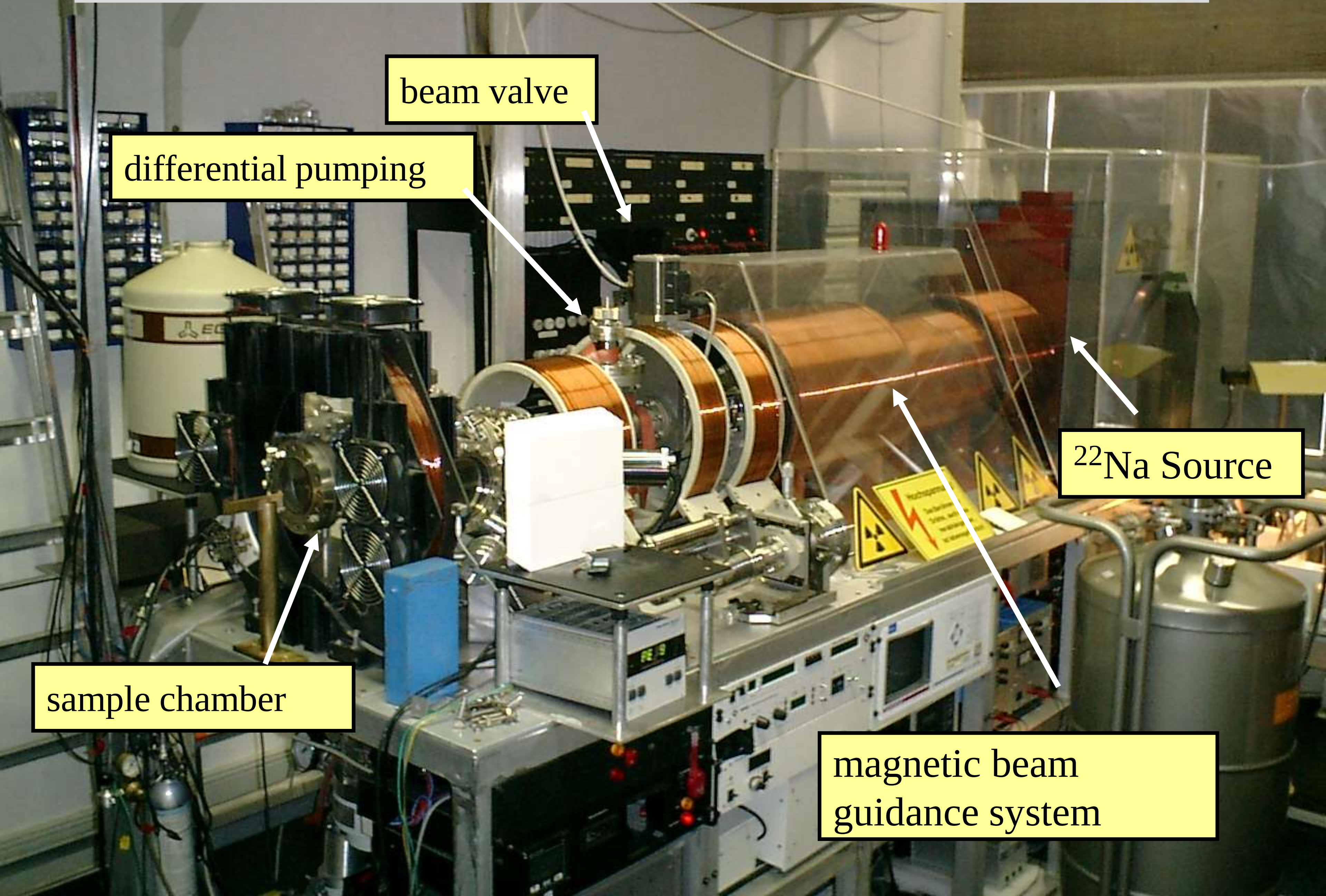
moderation efficiency: $\approx 10^{-4}$

The Positron Beam System at Halle University



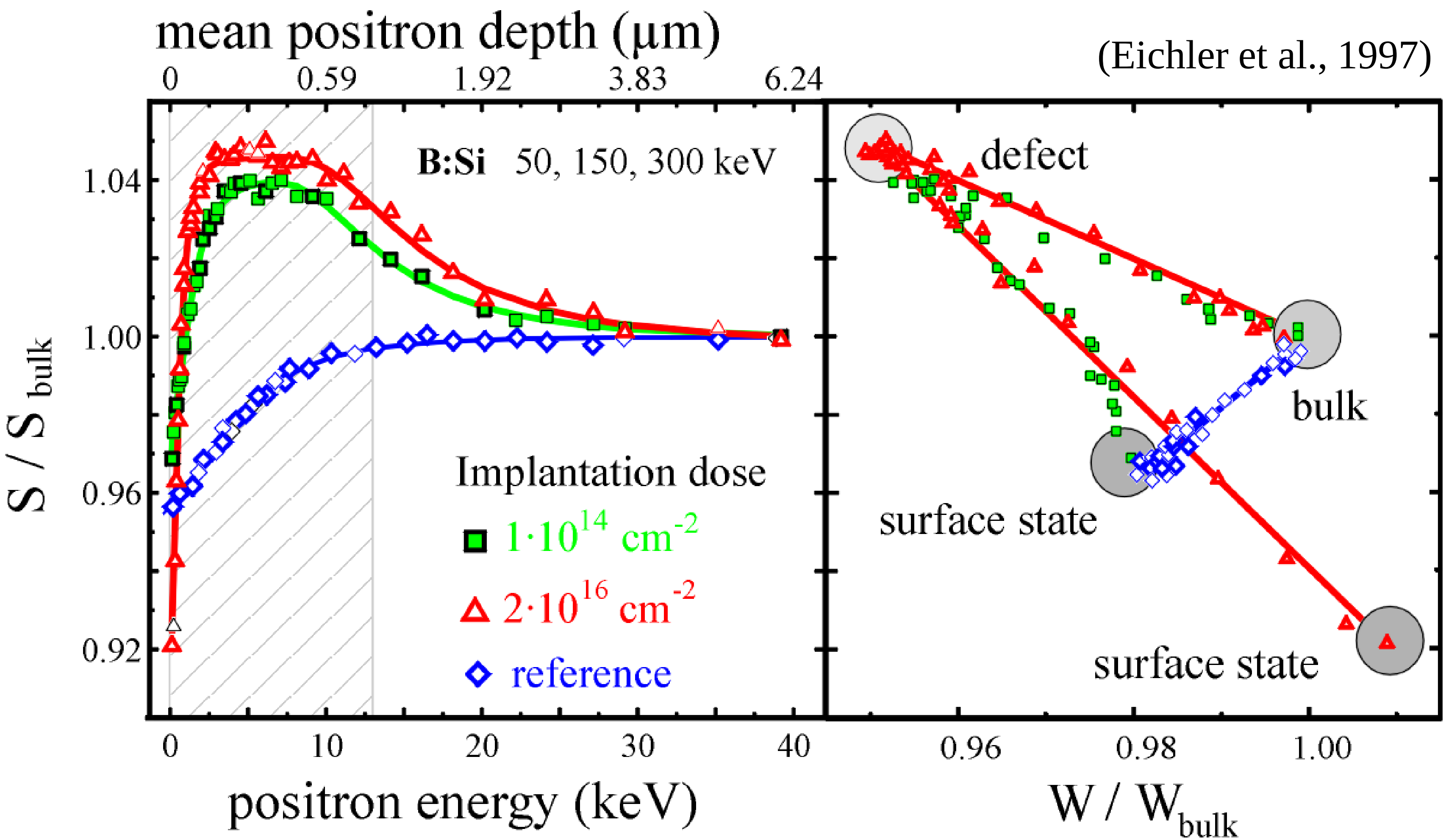
- spot diameter: 5mm
- time per single Doppler measurement: 20 min
- time per depth scan: 8 hours

The positron beam system at Halle University



Defects in Si induced by Ion Implantation

- ion implantation is most important doping technique in planar technology
- main problem: generation of defects ⇒ positron beam measurements

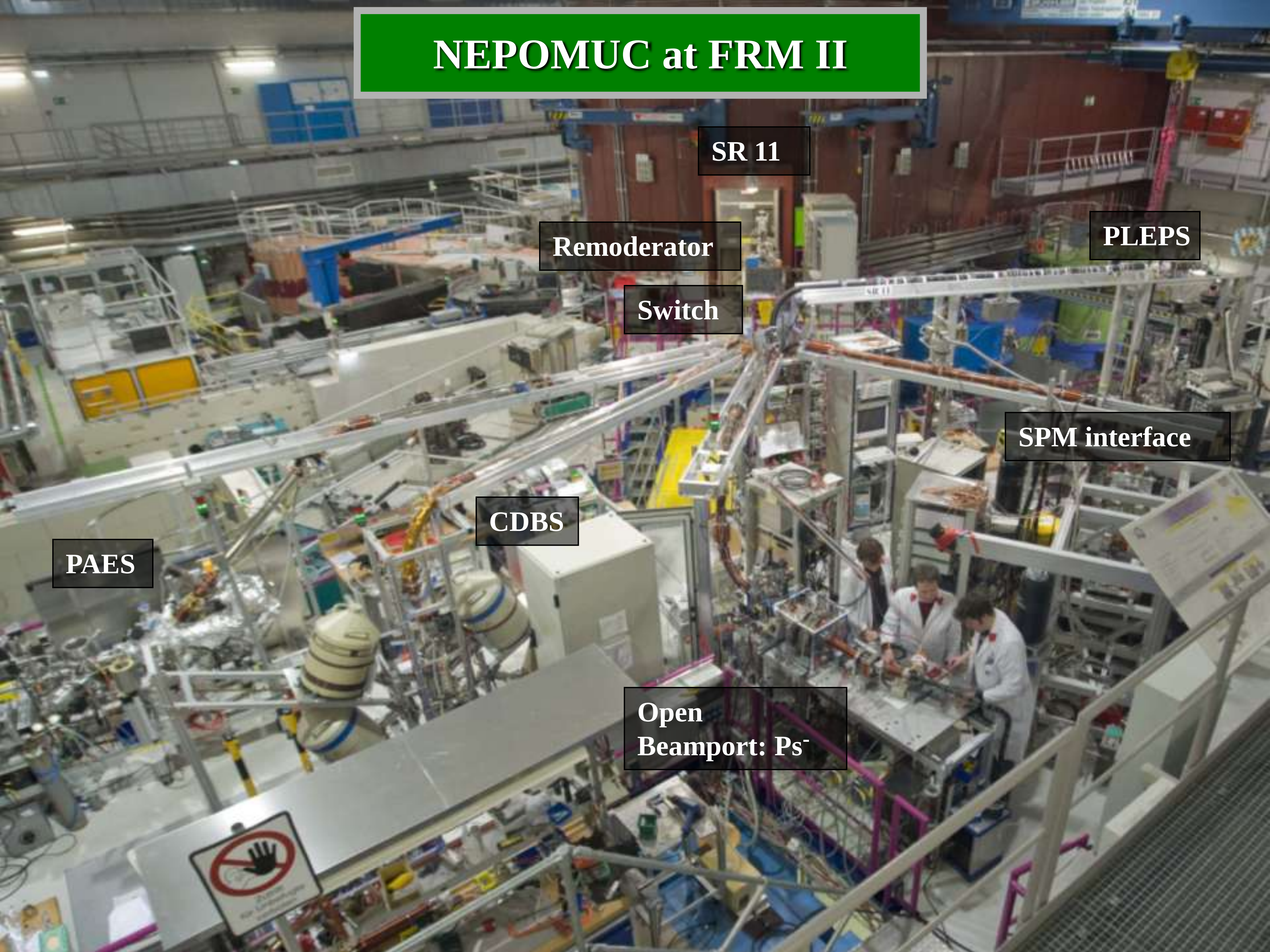


User-dedicated intense Positron Sources in Germany

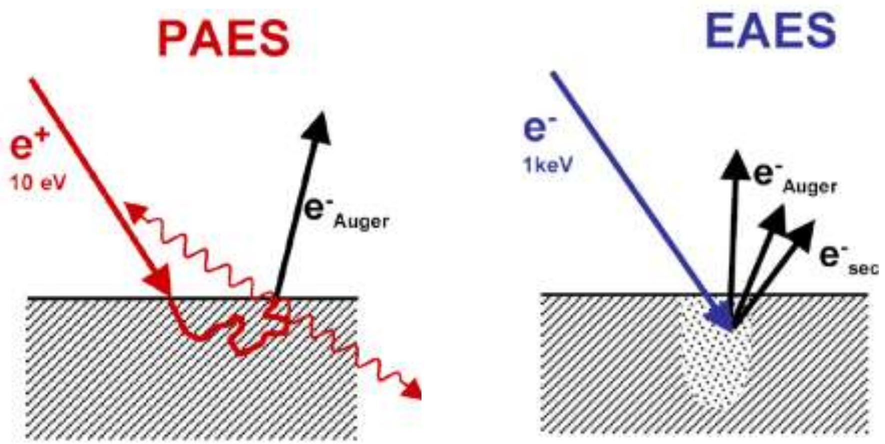
- Two intense positron sources available (positrons by pair production)
- **NEPOMUC** (NEutron induced POsitron Source MUniCh) at FRM-II
  - PLEPS (monoenergetic positron lifetime system)
  - PAES (Positron-induced Auger Electron Spectroscopy)
  - CDBS (Coincidence Doppler Broadening Spectroscopy)
  - SCM (Scanning Positron Microscope)
  - user beam line
- **EPOS** (ELBE Positron Source) at Research Center Dresden-Rossendorf
  - MePS (Mono-energetic Positron Spectroscopy)
  - GiPS (Gamma-induced Positron Spectroscopy)
  - CoPS (conventional setup using 22Na sources)

- at both sites: web-based application system for beam time

NEPOMUC at FRM II



Positron Annihilation Induced AES

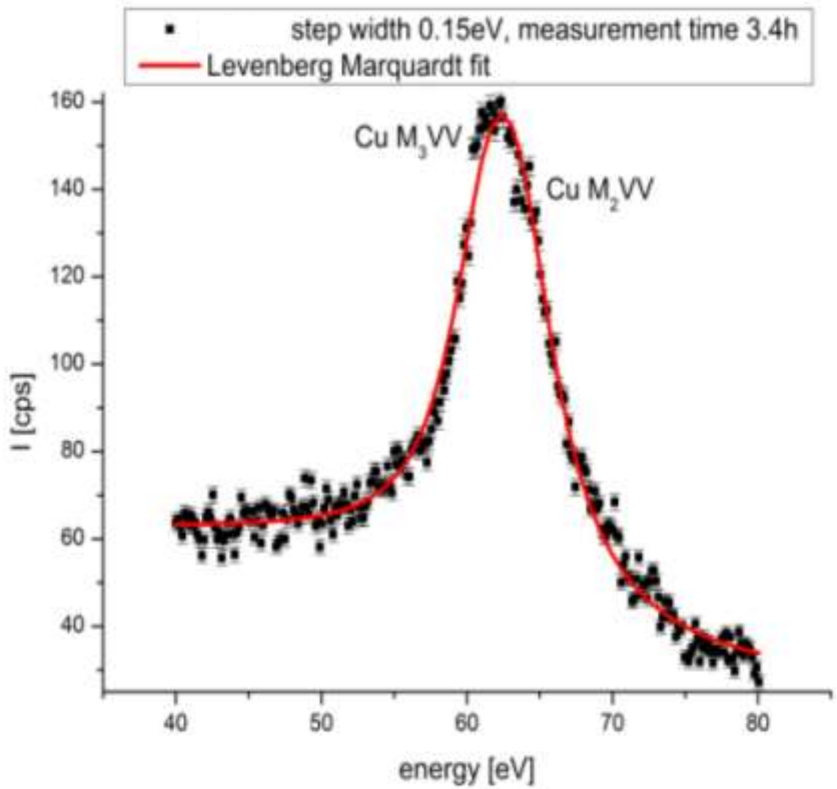


e+ induced emission of Auger e$^-$:

- e^+ diffusion
- e^+ trapping in surface state
- annihilation with core e$^-$
- emission of Auger e$^-$

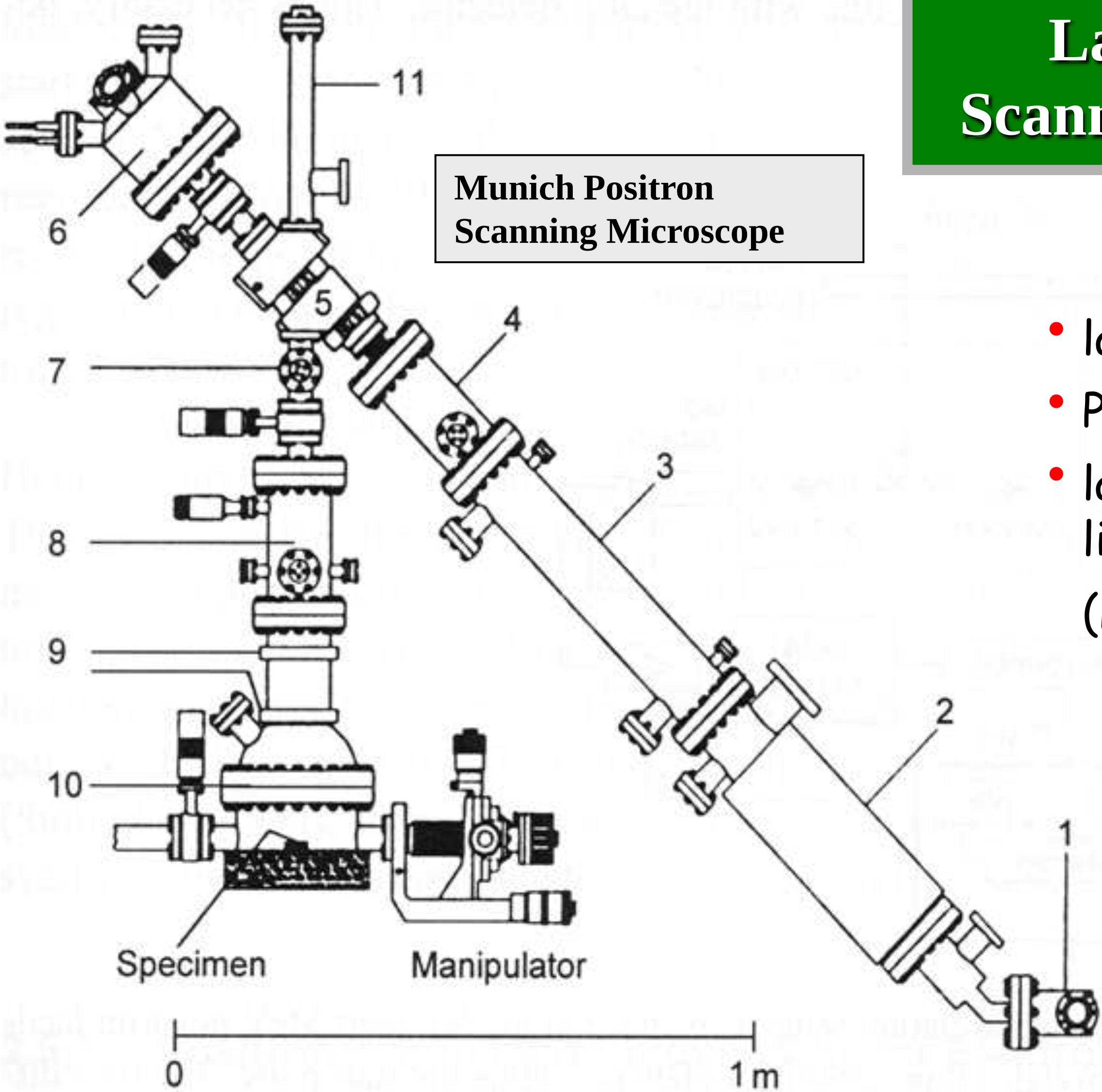
Features PAES:

- no e^-_{sec} background
- non-destructive
- topmost atomic layer



Contact: Dr. Chr. Hugenschmidt

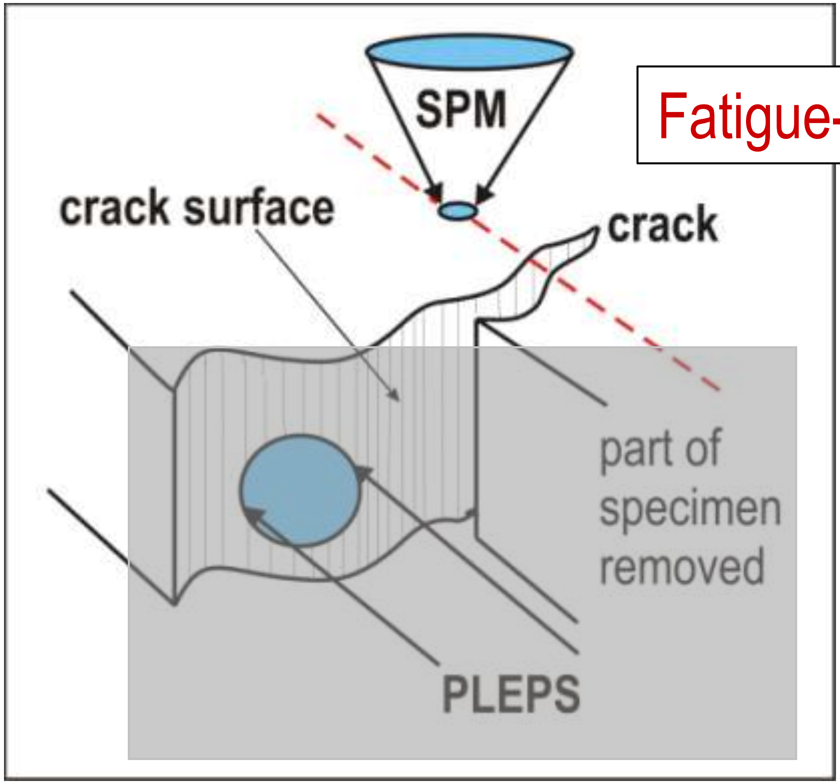
Lateral Resolution with Scanning Positron Microscope



W. Triftshäuser et al., NIM B **130** (1997) 265

- lateral resolution 1…2 μm
- Positron lifetime spectroscopy
- lateral resolution principally limited by positron diffusion ($L_{+} \approx$ 100nm)

SPM on top of cracked sample

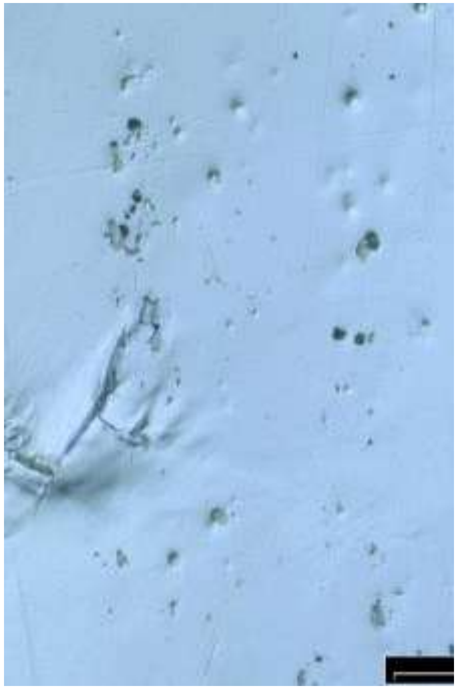


Fatigue-Crack in Al 6013

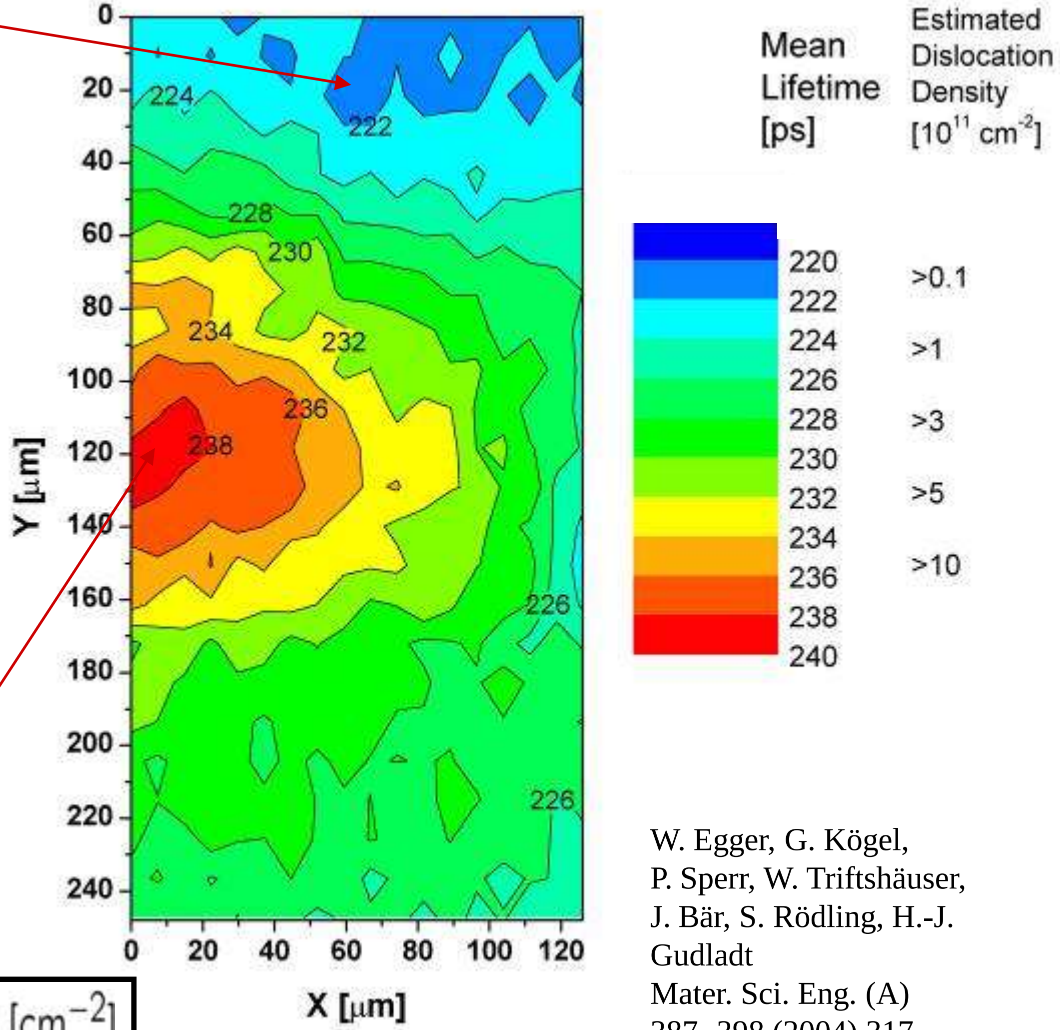
SPM: Lifetime-Image of Fatigue-Crack in Al 6013

resolution 5μm; step-size 10 μm

Trapping at Mg / Si-clusters!



Only dislocations close to crack-tip !



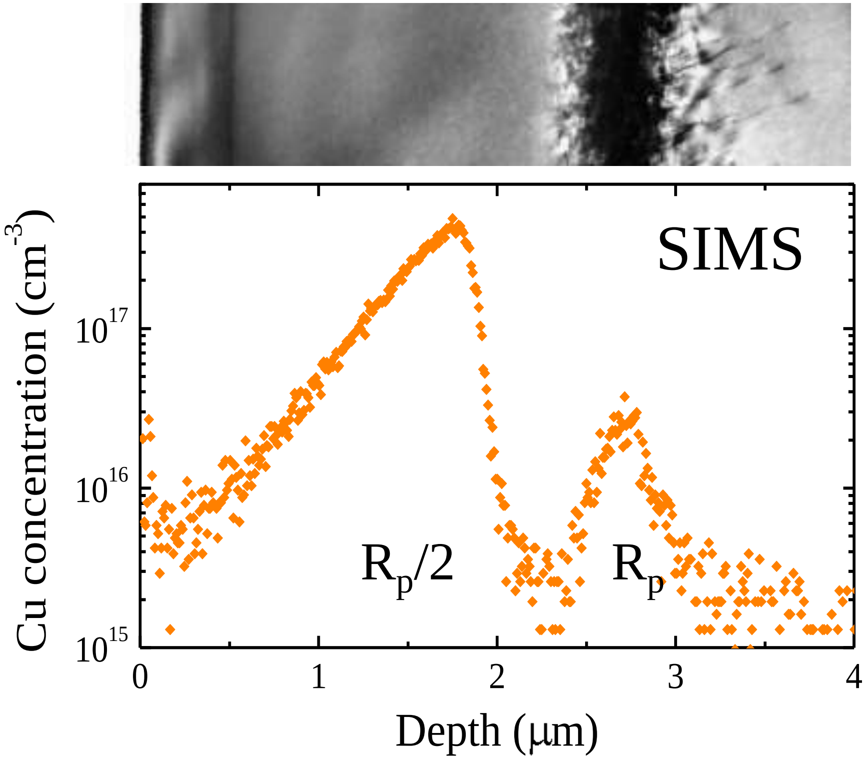
$$c_{disl} = 4 \cdot 10^{11} (\tau - 220\,\text{ps})/(240\,\text{ps} - \tau)\ [\text{cm}^{-2}]$$

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

Defects in high-energy self-implanted Si: The Rp/2 effect

- after high-energy (3.5 MeV) self-implantation of Si ($5x10^{15}$ cm^{-2}) and RTA annealing (900°C, 30s): two new gettering zones appear at Rp and Rp/2 (Rp = projected range of Si^+)
- visible by SIMS profiling after intentional Cu contamination

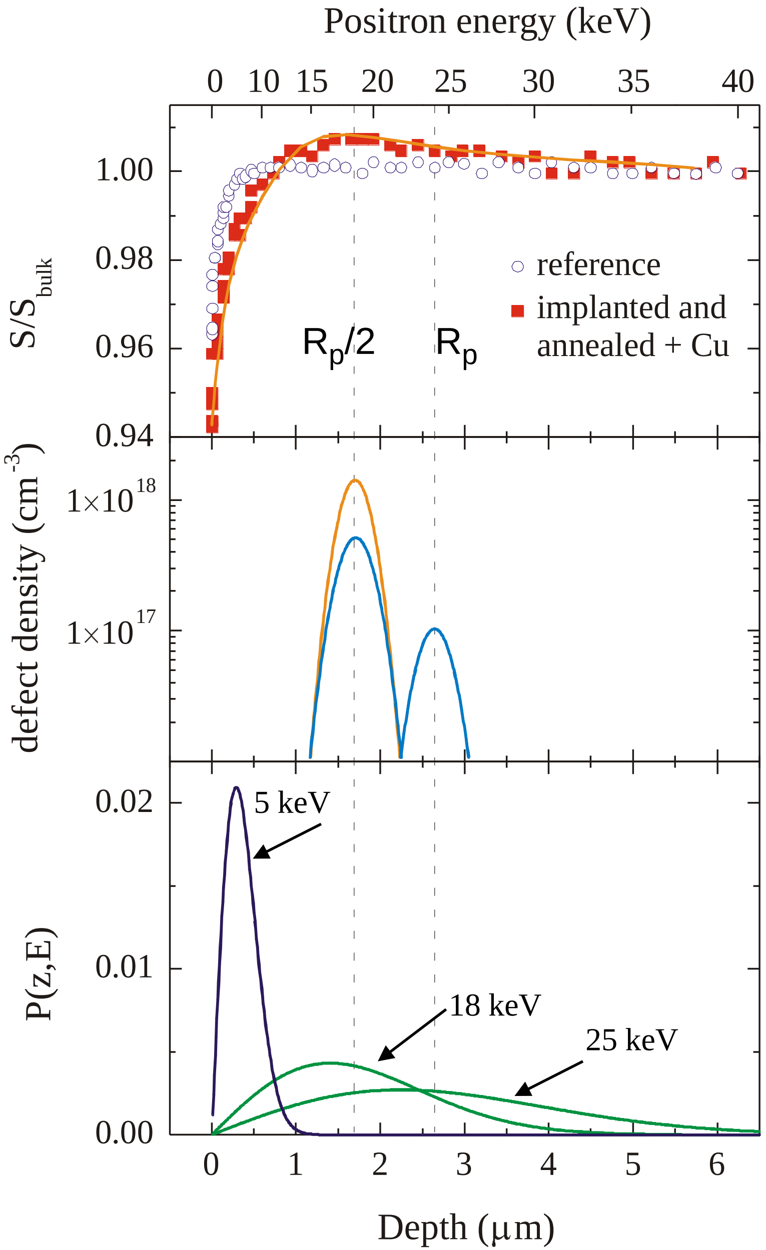
TEM image by P. Werner, MPI Halle



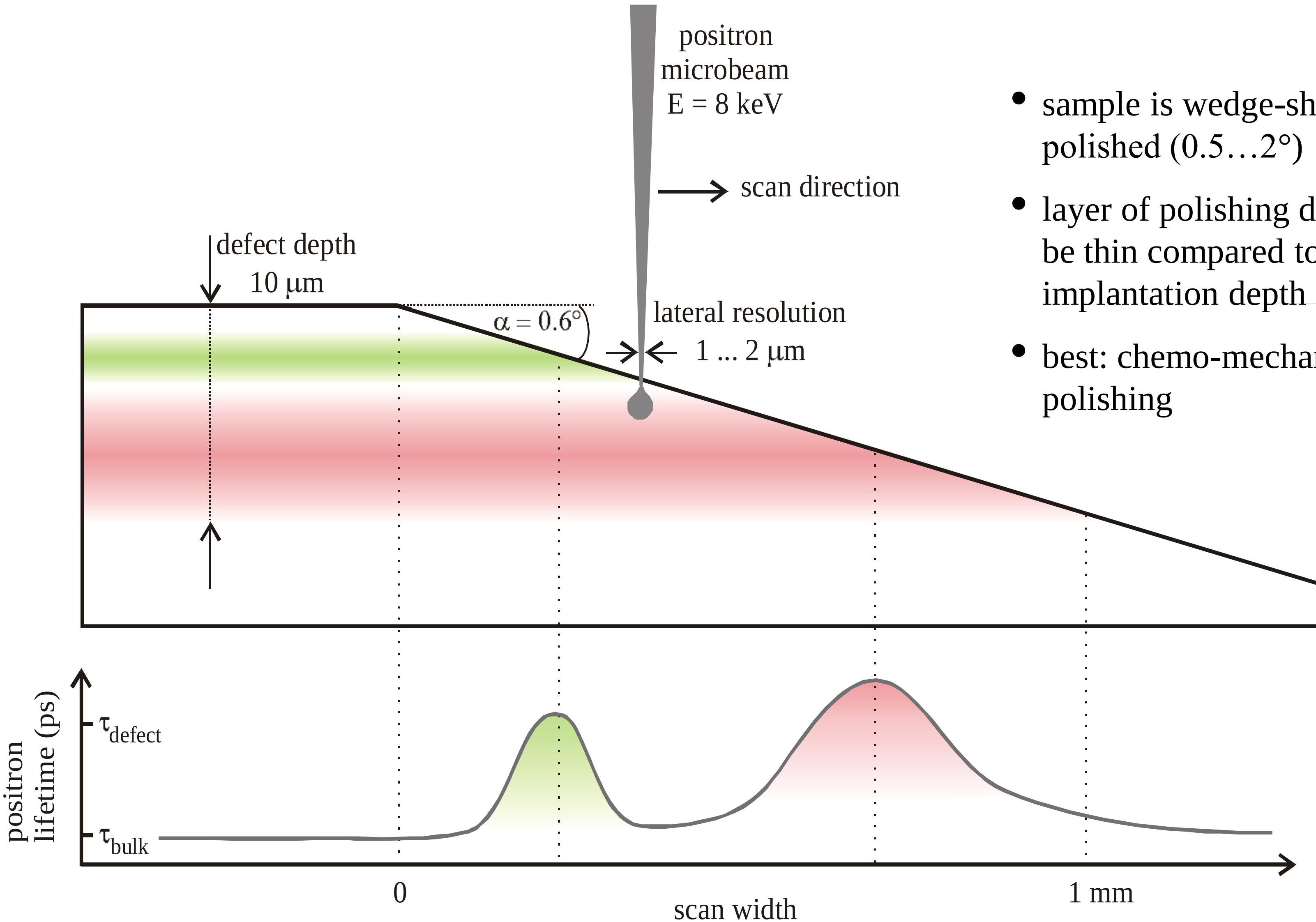
- at R_p: gettering by interstitial-type dislocation loops (formed by excess interstitials during RTA)
- no defects visible by TEM at Rp/2
- What type are these defects?

Investigation of the Rp/2 effect by conventional VEPAS

- the defect layers are expected in a depth of 1.7 mm and 2.8 mm corresponding to E^+ = 18 and 25 keV
- implantation profile too broad to discriminate between the two zones
- simulation of S(E) curve gives the same result for assumed blue and yellow defect profile (solid line in upper panel)
- furthermore: small effect only
- no conclusions about origin of $R_p/2$ effect possible



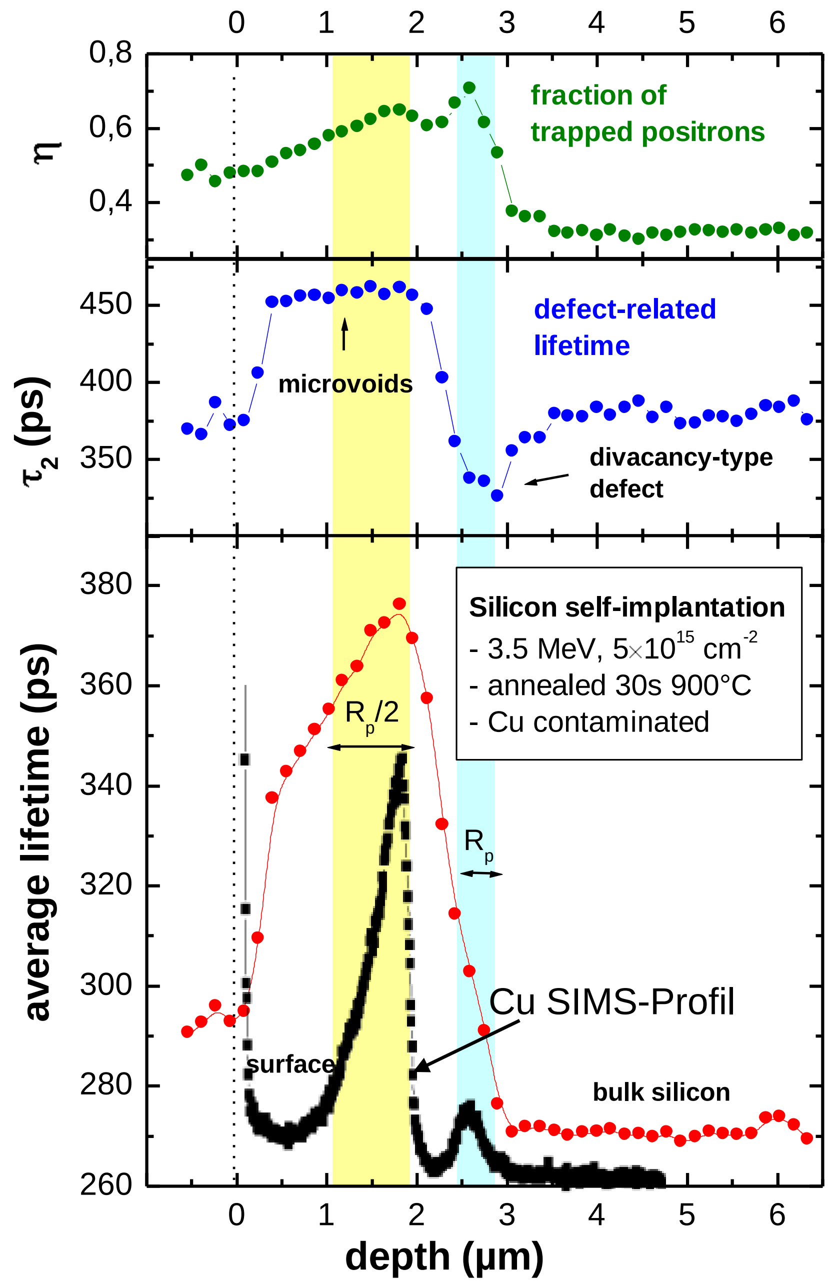
Enhanced depth resolution by using the Positron Microscope



- sample is wedge-shaped polished (0.5…2°)
- layer of polishing defects must be thin compared to e^+ implantation depth
- best: chemo-mechanical polishing

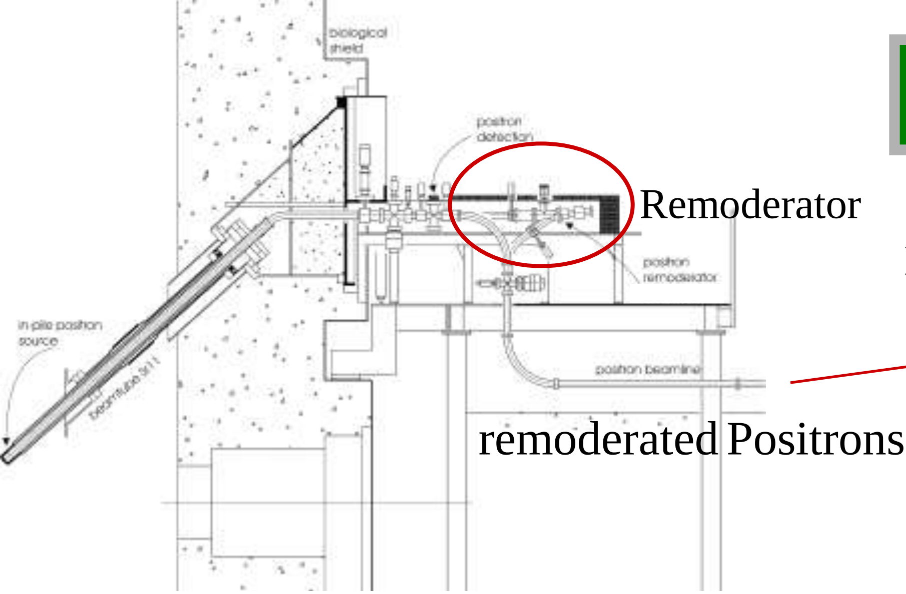
First defect depth profile using Positron Microscopy

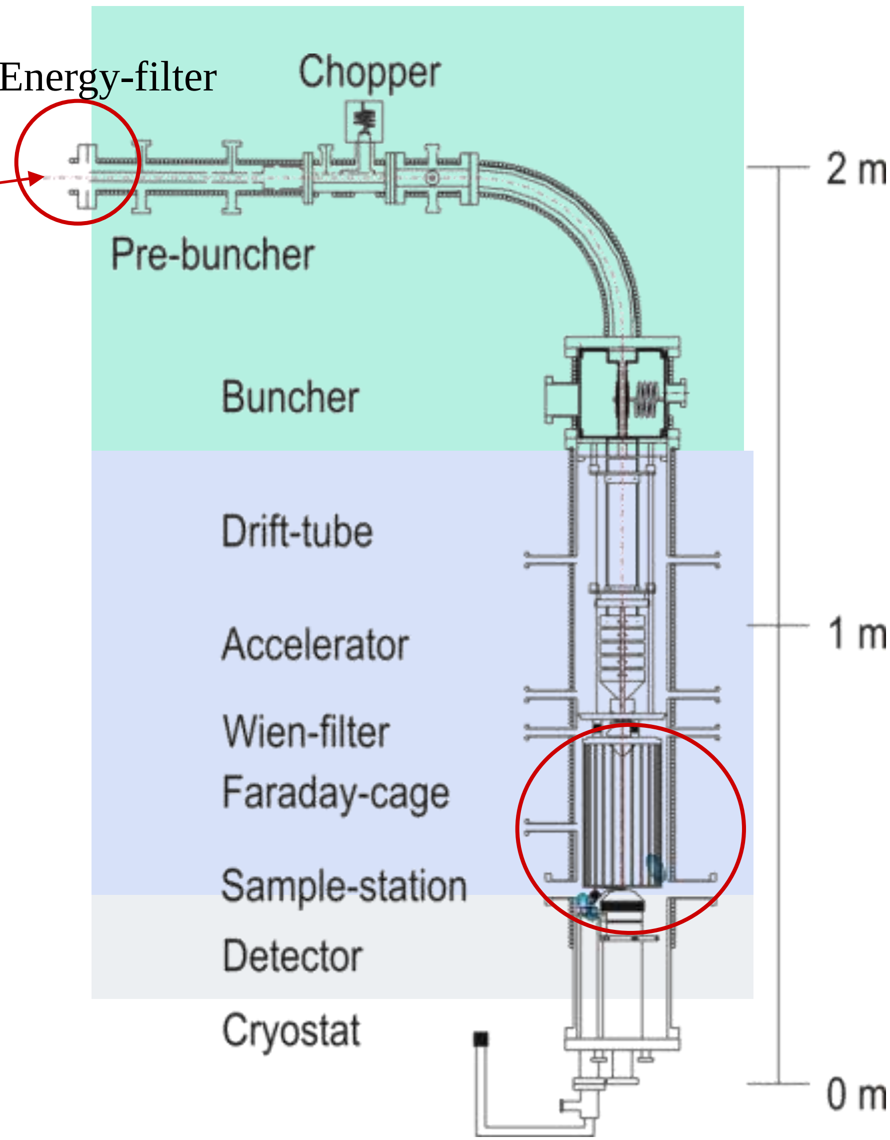
- 45 lifetime spectra: scan along wedge
- separation of 11 µm between two measurements corresponds to depth difference of 155 nm (α = 0.81°)
- beam energy of 8 keV: mean penetration depth is about 400 nm; represents optimum depth resolution
- no further improvement possible due to positron diffusion: L_+(Si @ 300K) » 230 nm
- both regions well visible:
  - vacancy clusters with increasing density down to 2 µm ($R_p/2$ region)
  - in R_p region: lifetime τ_2 = 330 ps; corresponds to open volume of a divacancy; must be stabilized or being part of interstitial-type dislocation loops
- excellent agreement with gettered Cu profile

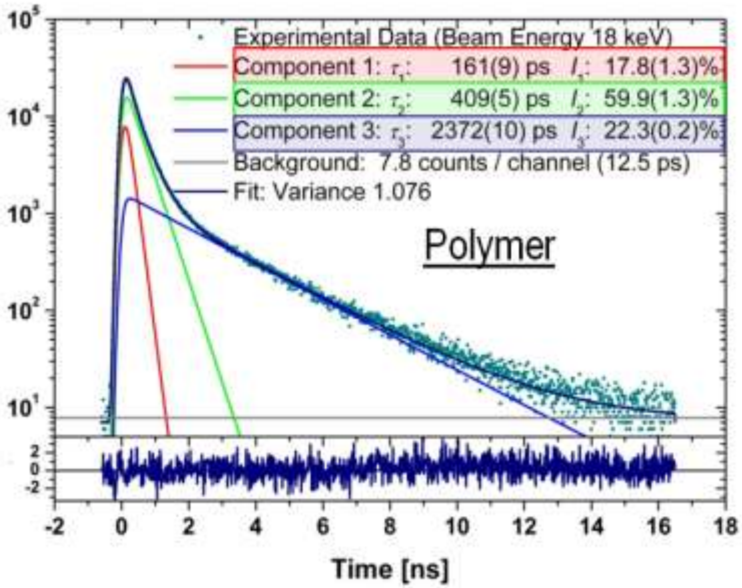


R. Krause-Rehberg et al., Appl. Phys. Lett. 77 (2000) 3932

PLEPS at NEPOMUC







- Measurement-time at 5000 cps: 600 s / spectrum (> 3 × 10^6 counts)
- 3h-4h / depth –profile (15 spectra)
- up to 4 lifetimes resolvable

PLEPS at NEPOMUC

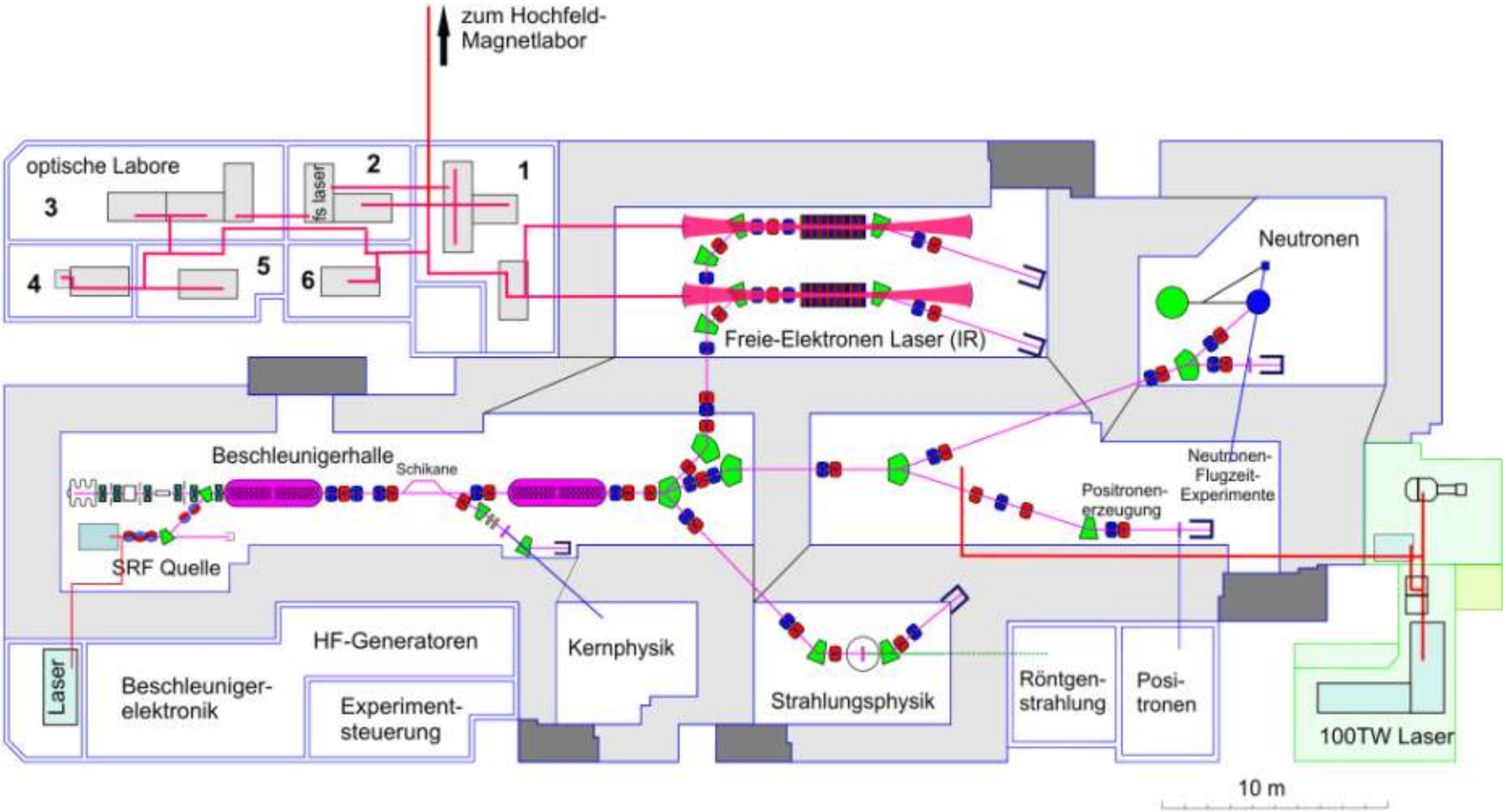
NEPOMUC user since June 2008

Z. Kajczos	KFK Budapest	Al_2O_3
V. Slugen	TU Bratislava	Fe-Cr-Legierungen
R. Brusa	Universita` di Trento	SiO_2, Mg-Nb (H)
J. De Baerdemaeker	Universität Ghent	Ge, Polymere
A. Gentils	CSNSM CNRS	SiC
M.-F. Barthe	CERI Orleans	W
D. Keeble	University of Dundee	$SrTiO_3$, Polymere
J. Cizek	Universität Prag	ZnO
F. Tuomisto	HUT Helsinki	InGaN
S. Eijt	TU Delft	Mg-Ti (H)
A. Dupasquier	Politecnico Milano	STO/YSZ/STO
O. Moutanabirr	MPI Halle	AlN
R. Krause-Rehberg	Universität Halle	GaN
H.J.-Gudladt	UniBw München	Ferrit. / Austen. Stähle
P. Iskra	UniBw München	Si
G. Brauer	FZR Rossendorf	ZnO
A. Ulbricht	FZR Rossendorf	Fe-Cr-Legierungen
K. Schmidt	IPP München	W
K. Rätzke	TU Kiel	Polymere
M. Krause	GSI	Graphit
A. Nix	Universität Göttingen	ta-C

EPOS = ELBE Positron Source

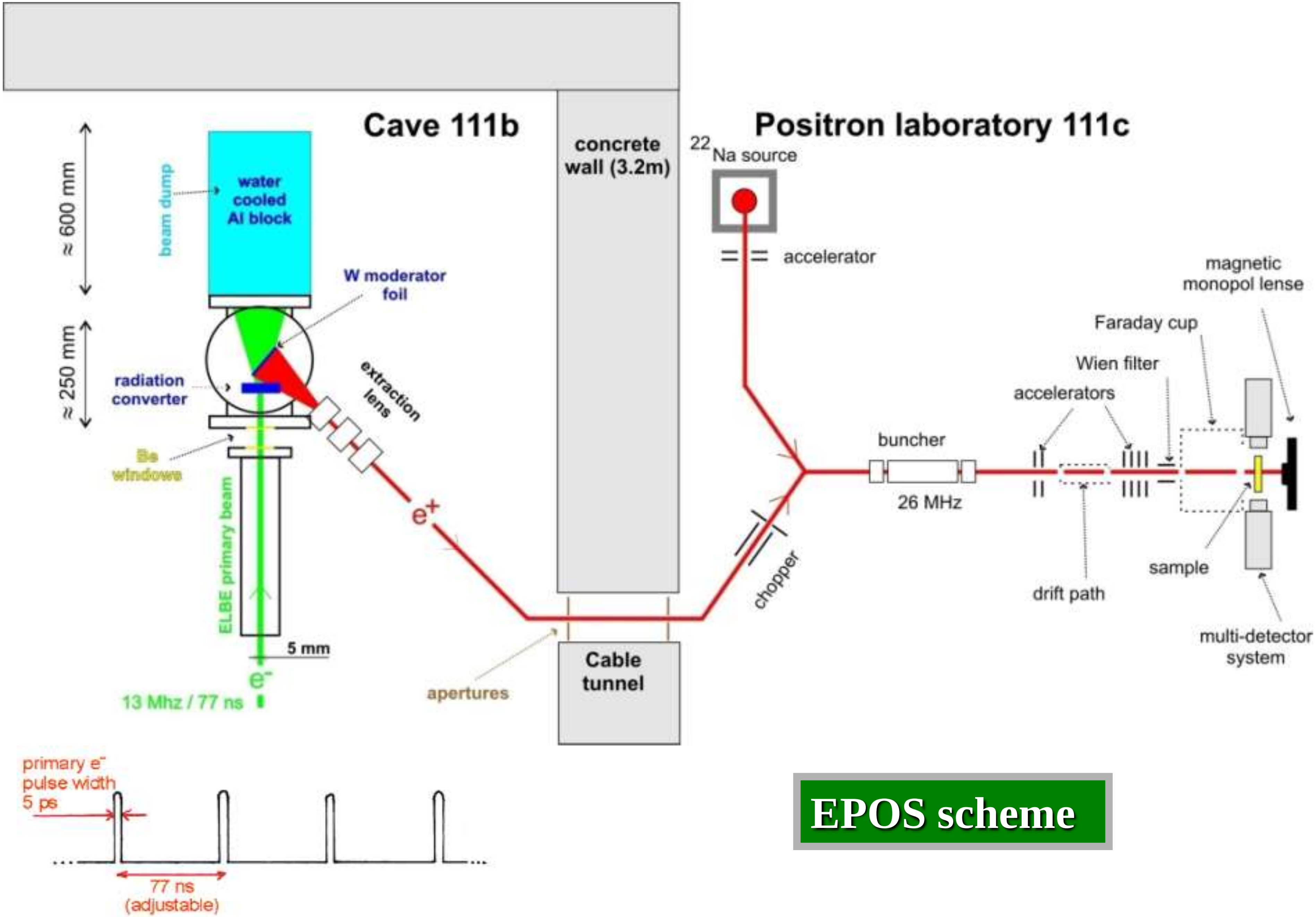
- ELBE -> electron LINAC (40 MeV and up to 40 kW) in Research Center Dresden-Rossendorf
- EPOS -> collaboration of Univ. Halle with FZD
- EPOS will be the combination of a positron lifetime spectrometer, Doppler coincidence, and AMOC
- User-dedicated facility
- main features:
  - high-intensity bunched positron beam (E_{+} = 0.5…30 keV)
  - very good time resolution by using the unique primary time structure of ELBE
  - digital multi-detector array
  - fully remote control via internet by user

Ground plan of the ELBE hall

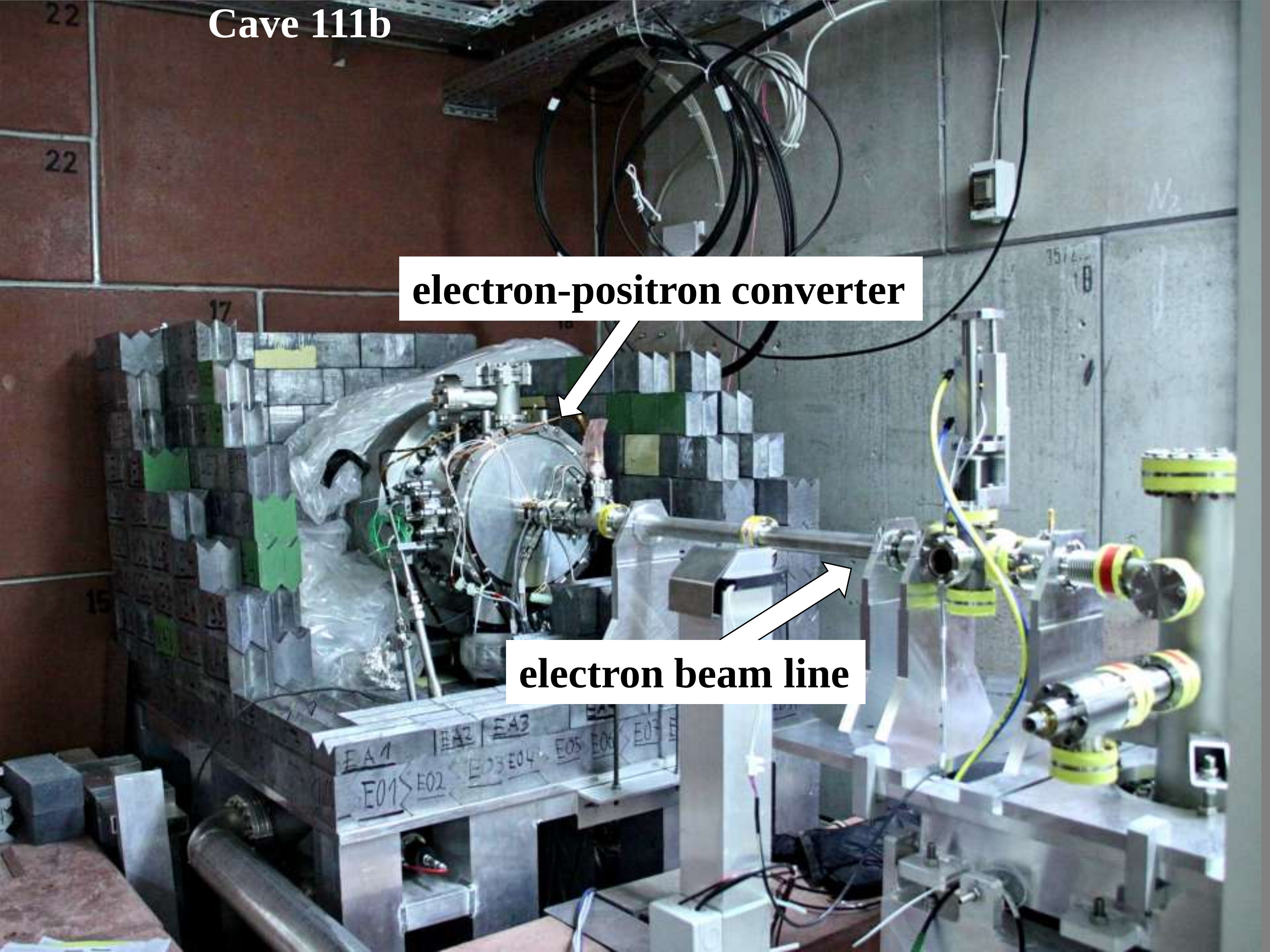


1: Diagnosestation, IR-Imaging und biologische IR Experimente
2: Femtosekundenlaser, THz-Spektroskopie, IR Pump-Probe Experimente
3: Zeitaufgelöste Halbleiter-Spektroskopie, THz-Spektroskopie

4: FTIR, biologische IR Experimente
5: Nahfeld und Pump-Probe IR Experimente
6: Radiochemie und Summenfrequenz-Erzeugung, photothermische Spektroskopie

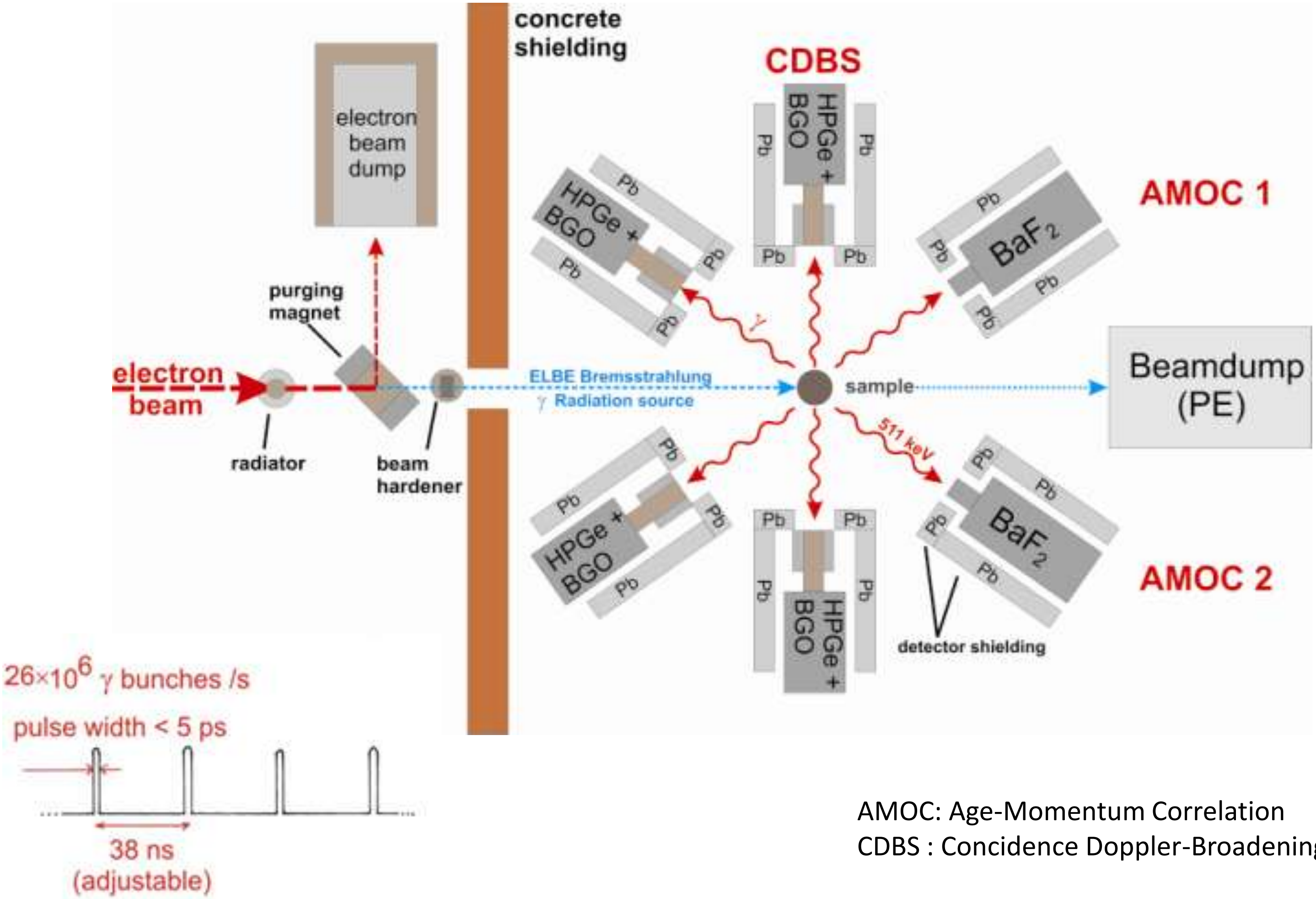

Cave 111b
Positron laboratory 111c
concrete wall (3.2m)
22Na source
accelerator
beam dump
water cooled Al block
W moderator foil
radiation converter
extraction lens
Be windows
ELBE primary beam
5 mm
e-
13 Mhz / 77 ns
e+
apertures
Cable tunnel
chopper
buncher
26 MHz
accelerators
Wien filter
Faraday cup
magnetic monopol lense
drift path
sample
multi-detector system
≈ 600 mm
≈ 250 mm
primary e- pulse width 5 ps
77 ns (adjustable)

EPOS scheme



Cave 111b
electron-positron converter
electron beam line

GiPS: Gamma-induced Positron Spectroscopy

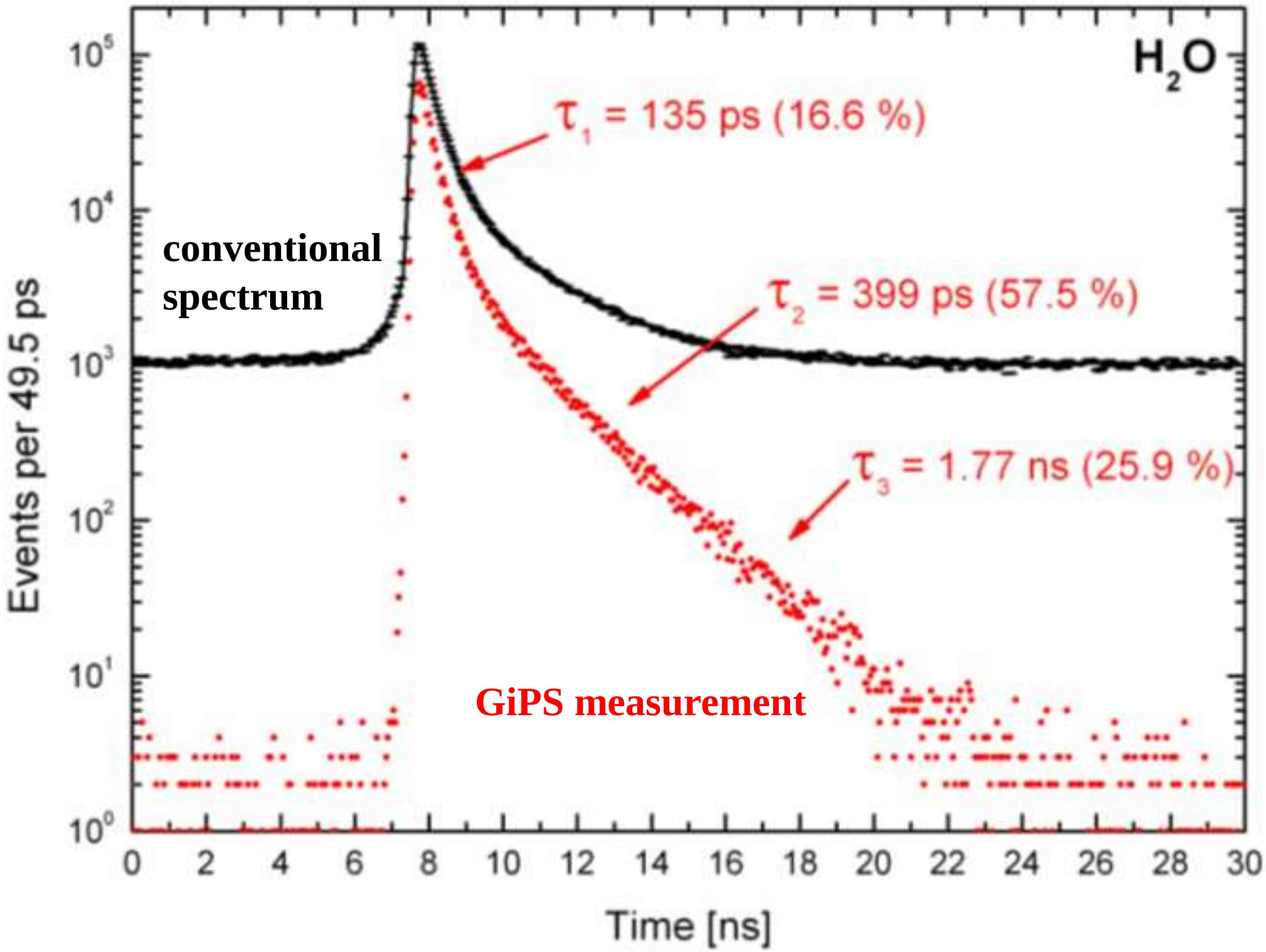


AMOC: Age-Momentum Correlation
CDBS : Concidence Doppler-Broadening Spectroscopy

- 3 coincident setups were used: 2 AMOC and 1 CDBS spectrometer
- only coincident detection ensures high spectra quality

Example: Water at RT

- total count rate in spectrum: 12×10^6



- Black spectrum: conventional measurement by Kotera et al., Phys. Lett. A 345, (2005) 184

Applications of GiPS since begin of 2009

- neutron irradiated Fe-Cr alloys (highly activated up to 50 MBq ^{60}Co)
- Reactor pressure vessel steel samples from Greifswald nuclear power station
- Iron samples after mechanical damage (LCMTR-ISCSA-CNRS, Frankreich)
- set of Zircony alloys (Collaboration Mumbai/India)
- porous glass (Chem. Department/Univ. Leipzig)
- biological samples
- liquids

Positron Annihilation Spectroscopy: Applications

Variety of applications in all fields of materials science:

- defect-depth profiles due to surface modifications (ion implantation; tribology)
- soft matter physics (open volume; interdiffusion; …)
- porosimetry (e.g. low-k materials - highly porous dielectric layers)
- bulk defects in semiconductors, ceramics and metals
- epitaxial layers (growth defects, misfit defects at interface, …)
- fast kinetics (e.g. precipitation processes in Al alloys; defect annealing; diffusion; …)
- radiation resistance (e.g. space materials)
- many more …

This presentation can be found as pdf-file on our Website:
http://positron.physik.uni-halle.de