Positron Beam Application to Materials Science and Intense Accelerator or Reactor based Positron Beam Facilities in Germany

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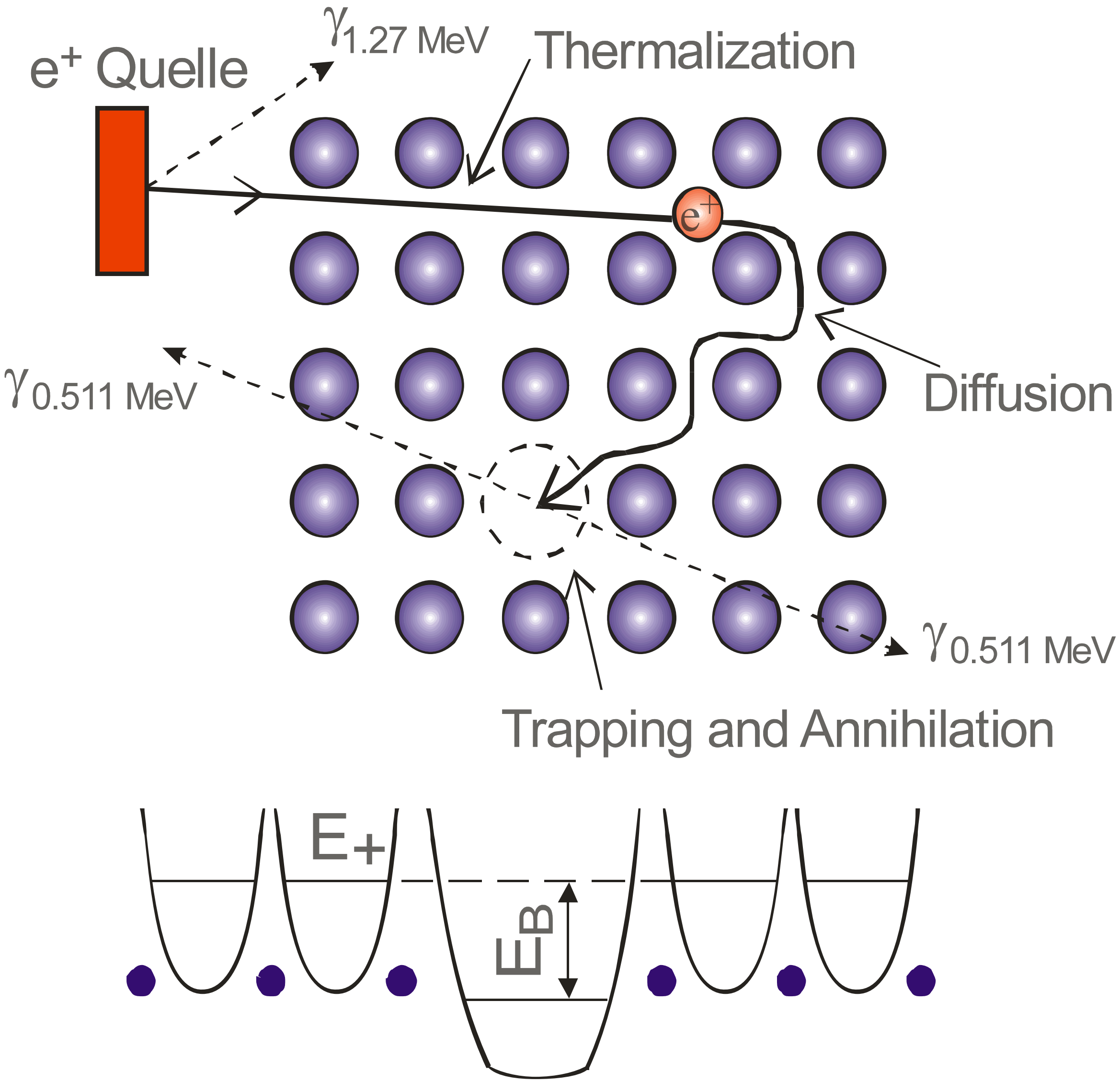
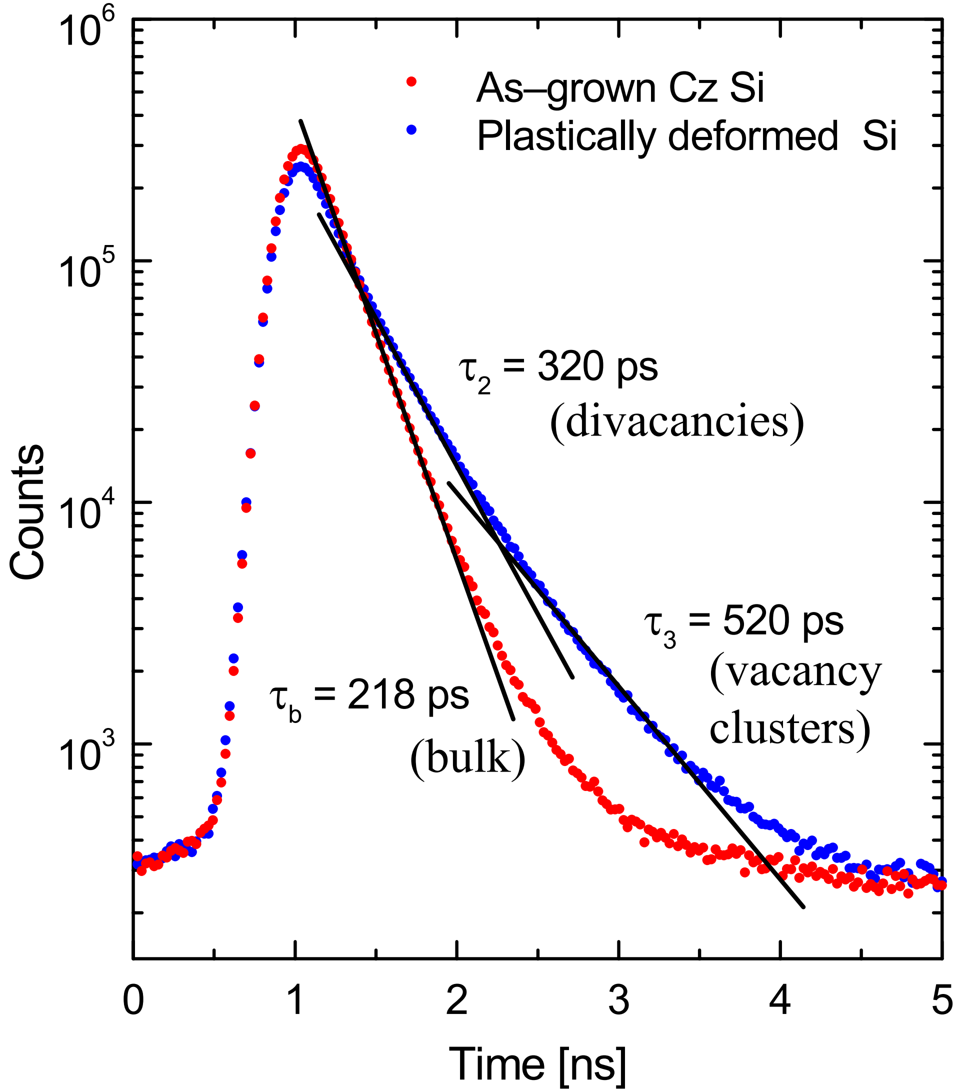
- Introduction: Positrons detect lattice defects
- Examples:
  - new getter centers in Si after high-energy self-implantation ($R_p/2$ effect)
  - study of defects in GaAs
- Large Positron Facility Projects in Germany
- Conclusions

The positron lifetime spectroscopy



- 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 1.27 and 0.51 MeV quanta
- defect identification and quantification possible

Positron lifetime spectroscopy

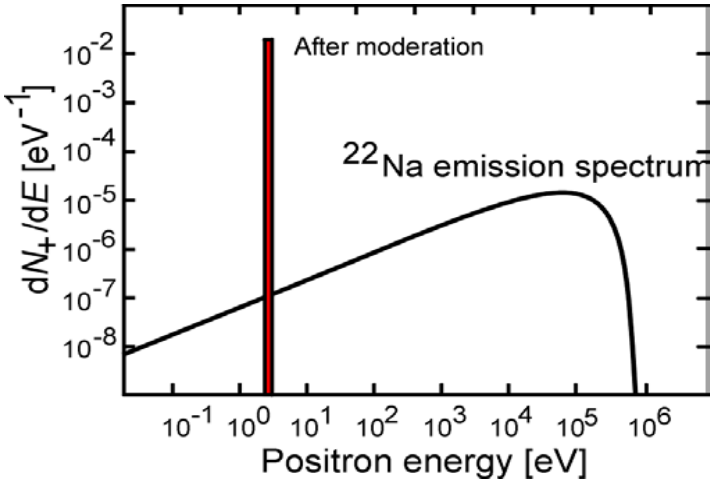


- positron lifetime spectra consist of exponential decay components
- positron trapping in open-volume defects leads to long-lived components
- longer lifetime due to lower electron density
- analysis by non-linear fitting: lifetimes τ_i and intensities I_i
- positron lifetime spectrum: $$N(t) = \sum_{i=1}^{k+1} \frac{I_i}{\tau_i} \exp\left(-\frac{t}{\tau_i}\right)$$
- trapping coefficient
  $$\boxed{\kappa_d = \mu C_d} = \frac{I_2}{I_1}\left(\frac{1}{\tau_b} - \frac{1}{\tau_d}\right)$$
  trapping rate
  defect concentration

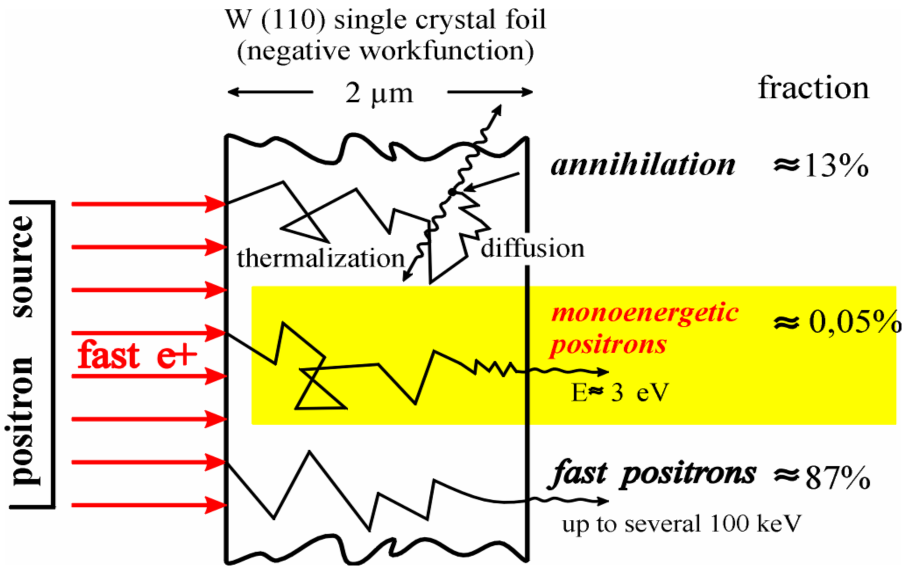
Monoenergetic positron beam by moderation

- positron annihilation was very successful in defect identification in last decades
- semiconductor technology: thin layers (epitaxy, ion implantation)
- broad energy distribution due to β^+ decay
- some surfaces: negative workfunction ⇒ moderation (but rather inefficient)

Energy distribution after β^+ decay

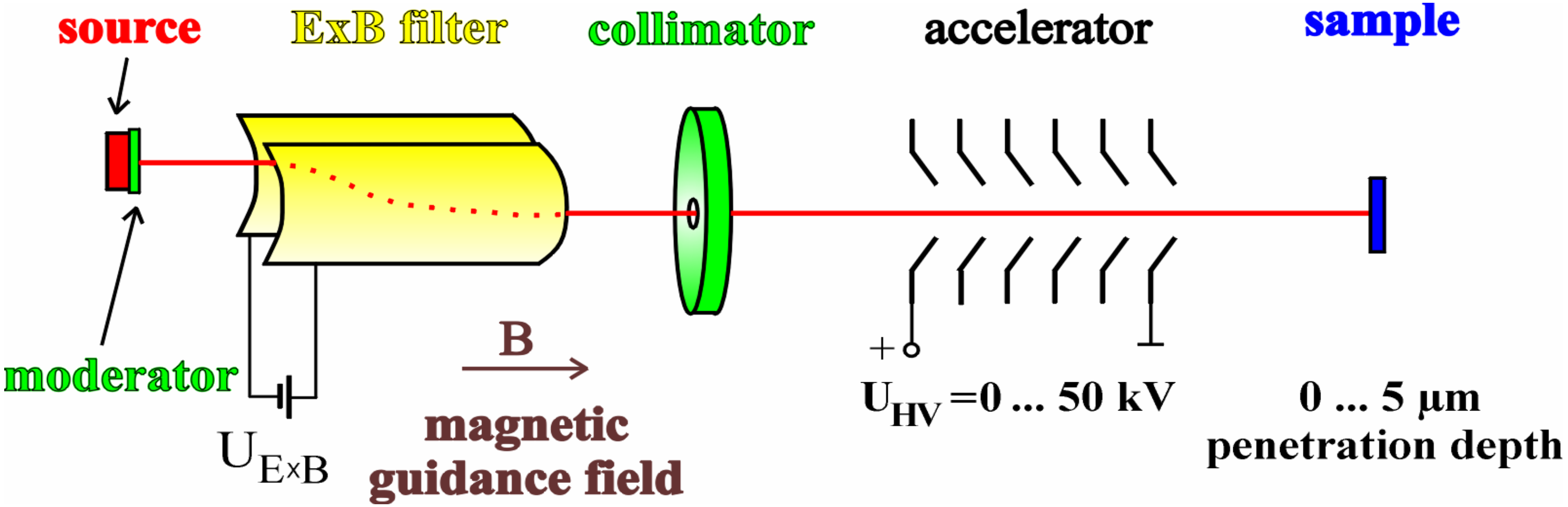


Effect of moderation



Conventional positron beam technique

- positron beam can be formed using mono-energetic positrons
- often: magnetically guided for simplicity

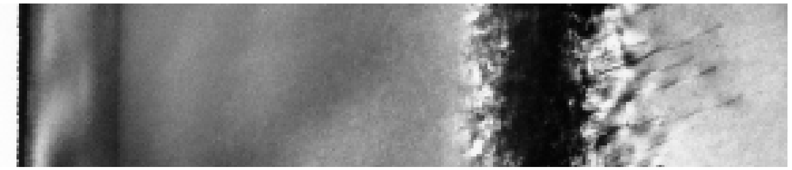


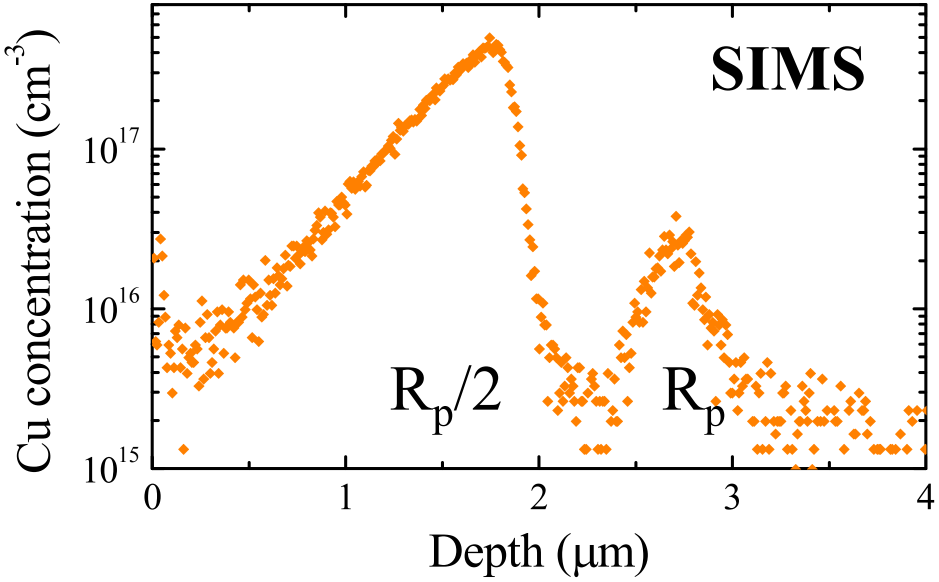
- defect studies by Doppler-broadening spectroscopy
- characterization of defects only by line-shape parameters or positron diffusion length
- for positron lifetime spectroscopy: beam can be bunched

Defects in high-energy self-implanted Si — The $R_p/2$ effect

- after high-energy (3.5 MeV) self-implantation of Si (5×10^{15} cm^{-2}) and RTA annealing (900°C, 30s): two new gettering zones appear at R_p and $R_p/2$ (R_p = projected range of Si^+)
- visible by SIMS profiling after intentional Cu contamination

TEM image by P. Werner, MPI Halle





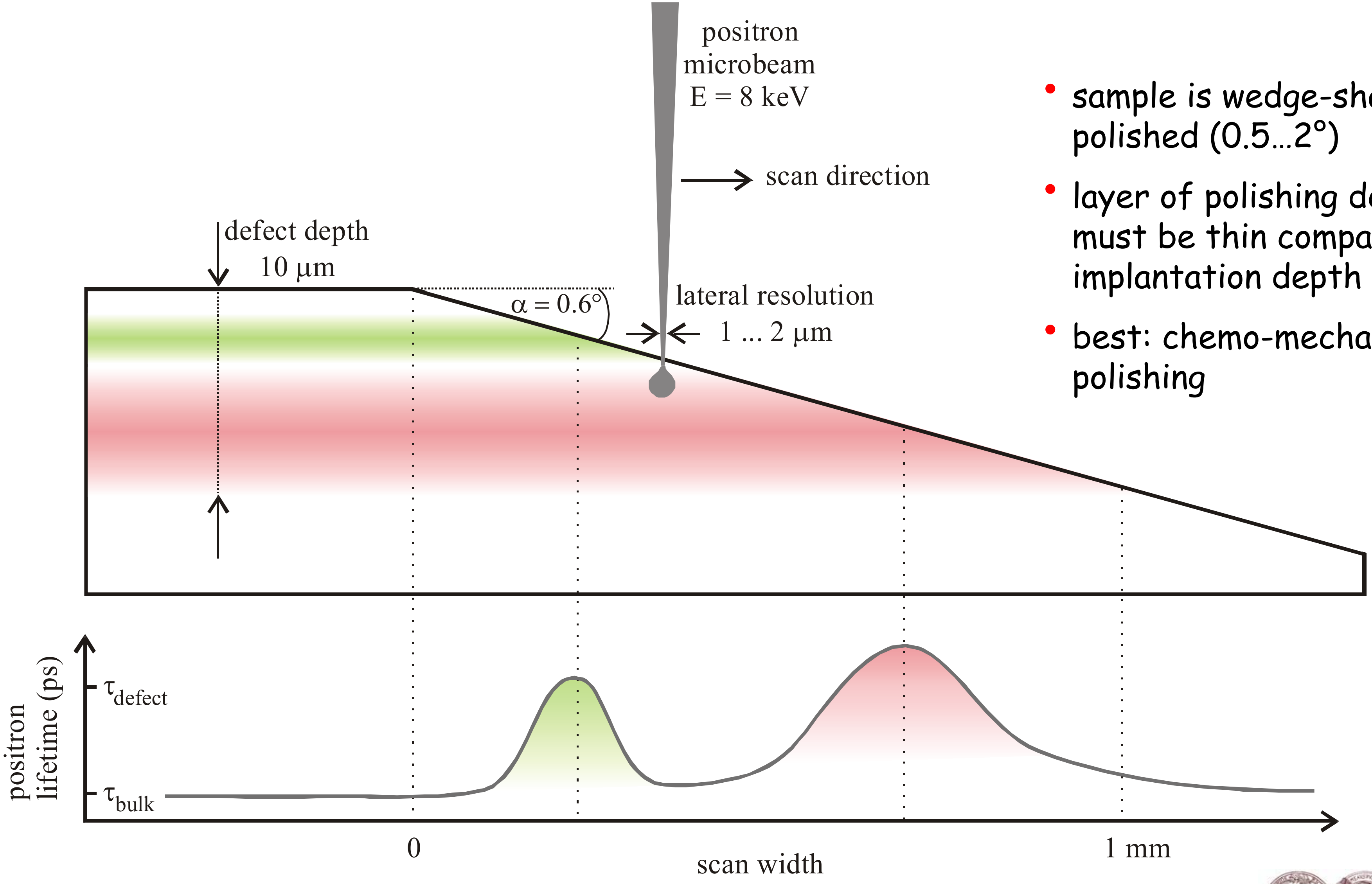
- at R_p: gettering by interstitial-type dislocation loops (formed by excess interstitials during RTA)
- no defects visible by TEM at $R_p/2$
- **What type are these defects?**

Interstitial type
[3,4]

Vacancy type
[1,2]

[1] R. A. Brown, et al., J. Appl. Phys. **84** (1998) 2459
[2] J. Xu, et al., Appl. Phys. Lett. **74** (1999) 997
[3] R. Kögler, et al., Appl. Phys. Lett. **75** (1999) 1279
[4] A. Peeva, et al., NIM B **161** (2000) 1090

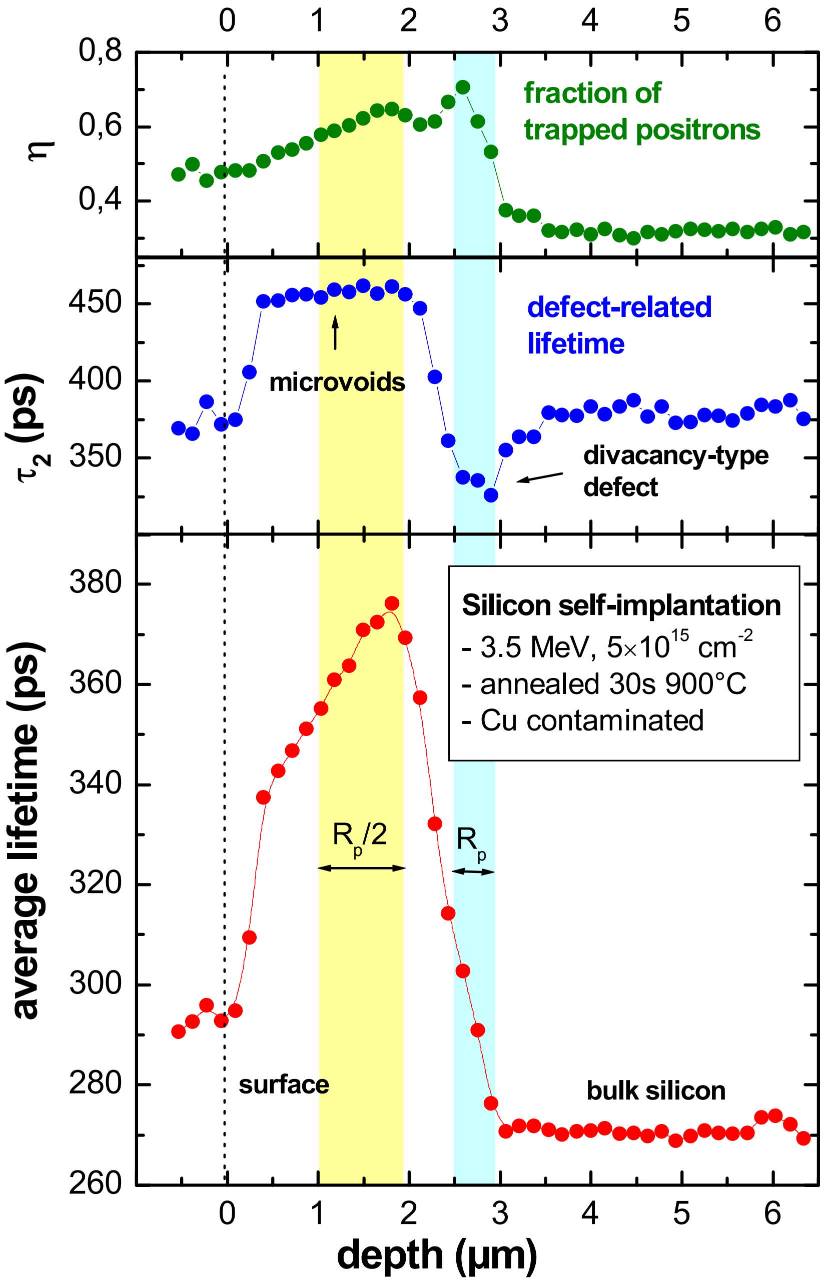
Enhanced depth resolution by using the Munich Scanning Positron Microscope

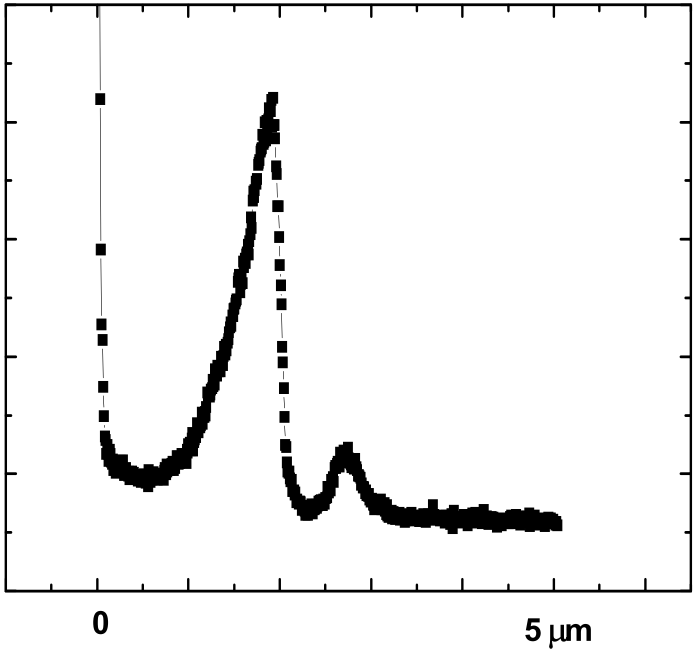


- sample is wedge-shaped polished (0.5…2°)
- layer of polishing defects must be thin compared to e^+ implantation depth
- best: chemo-mechanical polishing

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

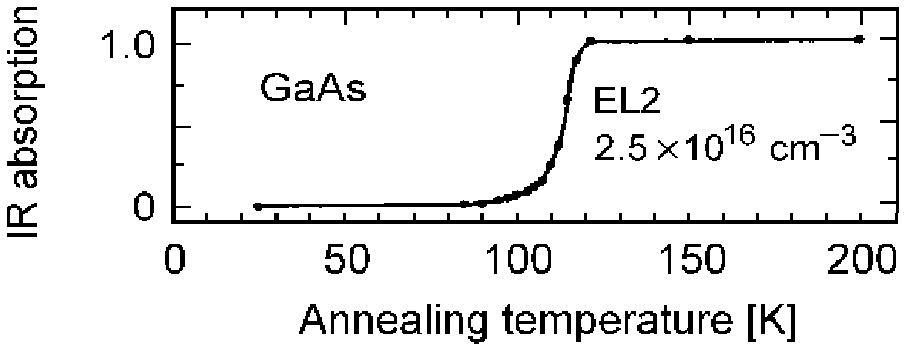


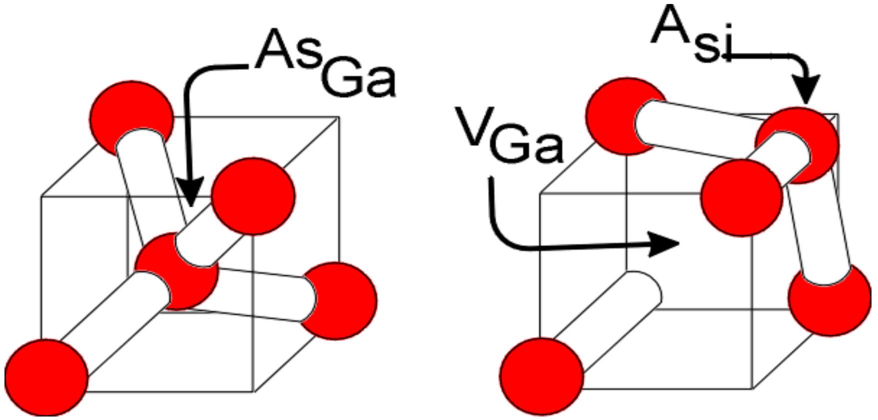


SIMS profile of Cu

The Nature of the EL2-Defect in GaAs

- one of the most frequently studied crystal lattice defects at all
- responsible for semi-insulating properties of GaAs: large technological importance
- is deep donor, compensates shallow acceptors, e.g. C^- impurities
- defect shows metastable state after illumination at low temperatures
- IR-absorption of defect disappears during illumination at T < 100 K
- ground state recovers during annealing at about 110 K
- many structural models proposed
- Dabrowski, Scheffler and Chadi, Chang (1988): simple As_{Ga}-antisite defect responsible
- must show a metastable structural change



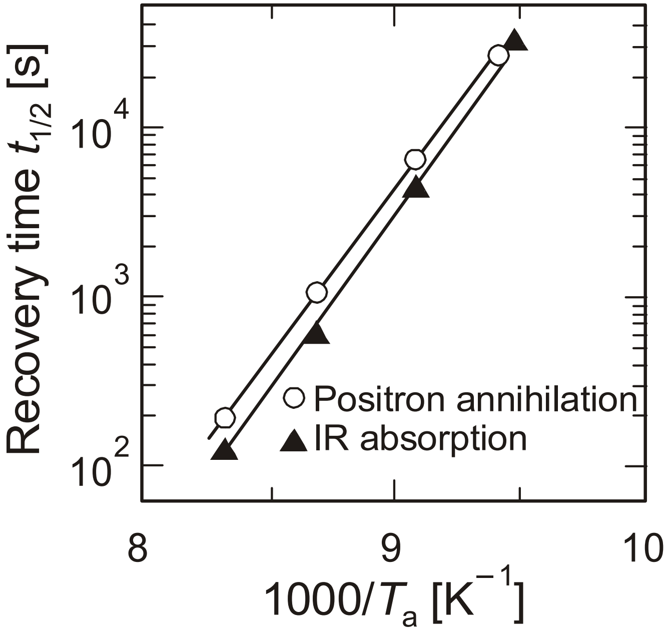


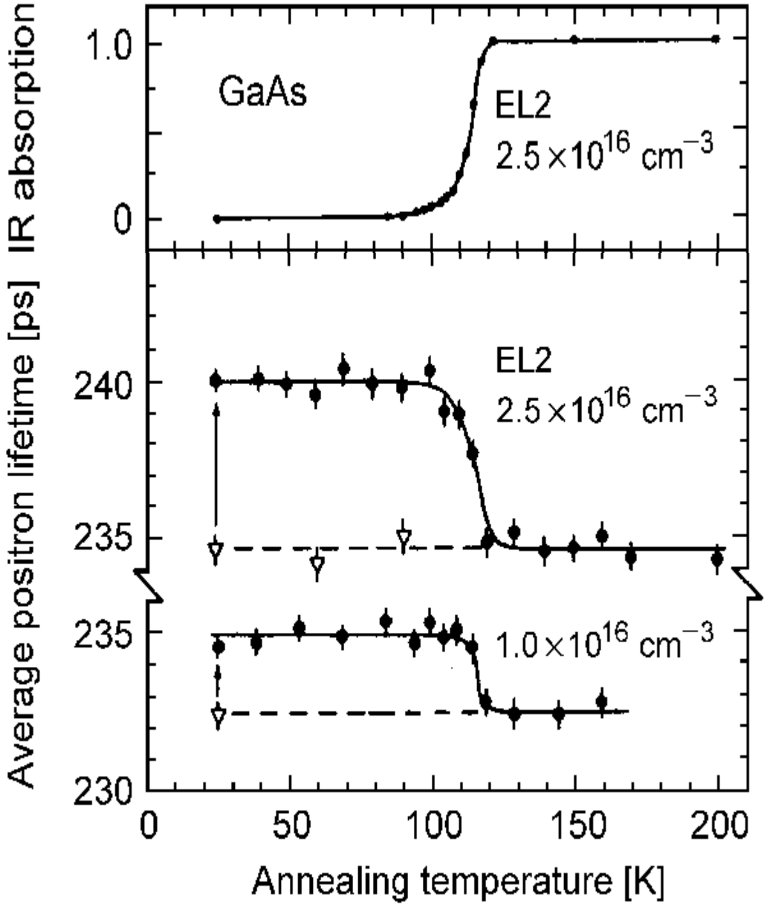
stabil metastabil

(Dabrowski 1988, Chadi 1988)

The Nature of the EL2-Defect in GaAs

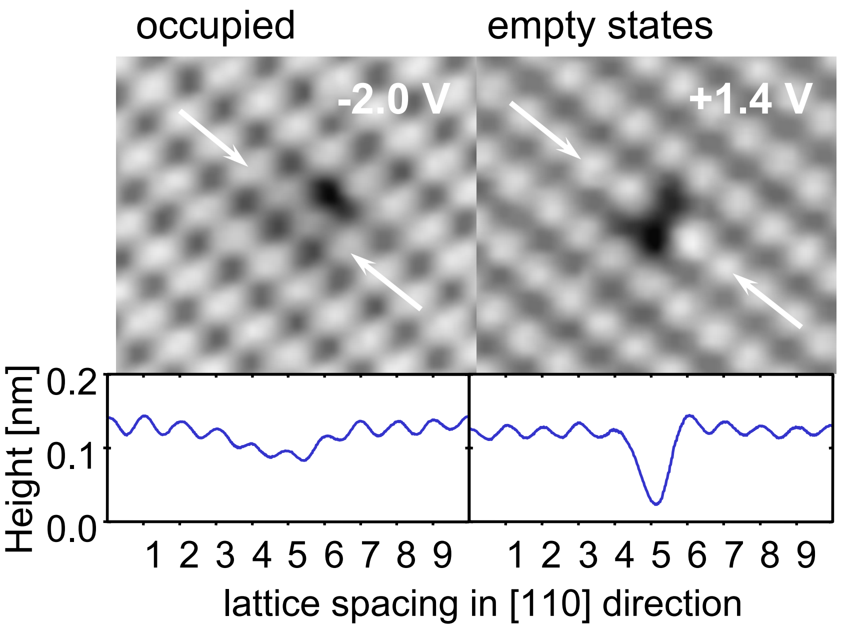
- in metastable state at low temperature: Ga vacancy
- should disappear during annealing at about 110 K
- confirmed by positron lifetime measurements
- kinetics of recovery of ground state is identical for IR- und positron experiment: $E_A = (0.37 \pm 0.02)$ eV
- evidence of the vacancy in metastable state confirms the proposed structural model

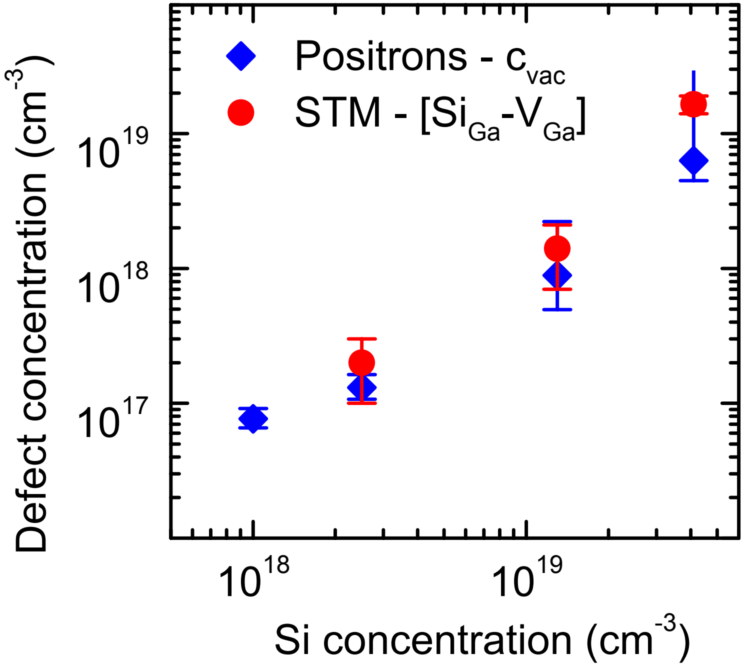




Krause et al., Phys. Rev. Lett. **65** (1990) 3329

Identification von V_{Ga}-Si_{Ga}-Complexes in GaAs:Si





- Scanning tunneling microscopy at GaAs (110)-cleavages planes (by Ph. Ebert, Jülich)
- Defect complex identified as **V_{Ga}-Si_{Ga}**

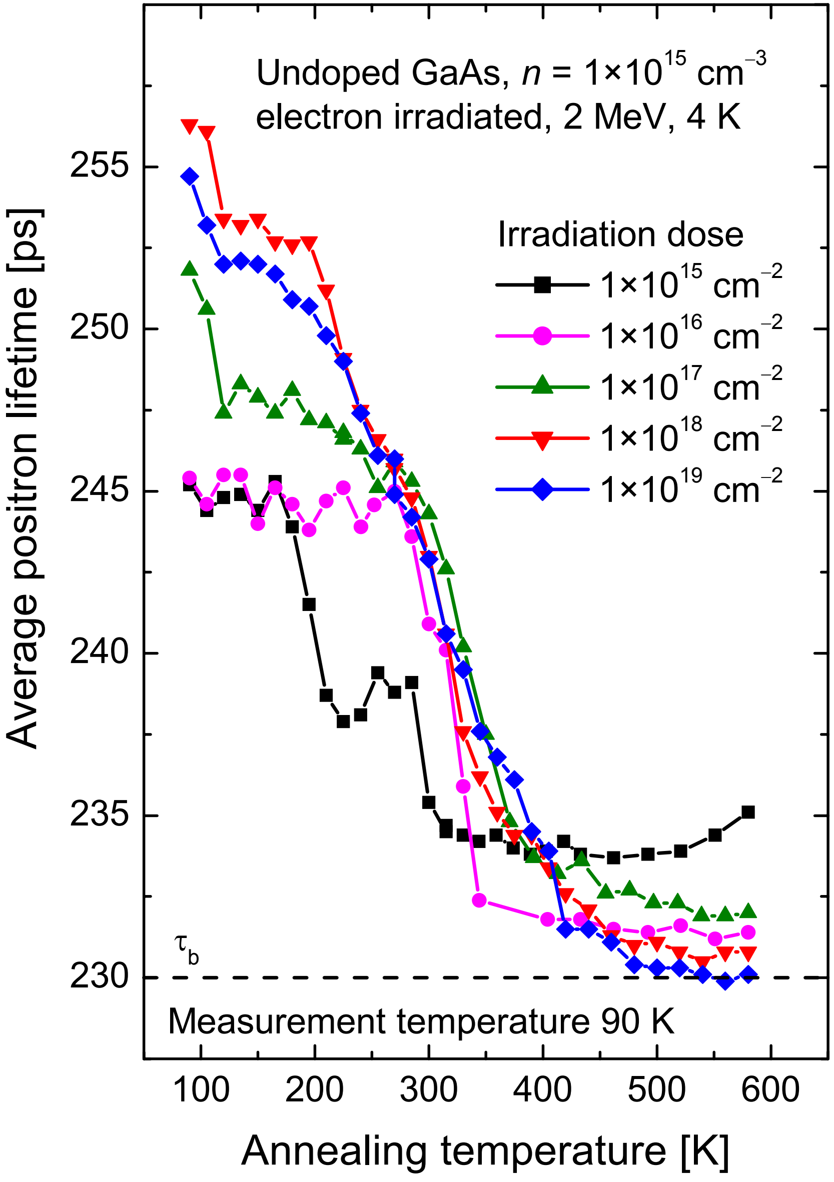
- Quantification → Agreement

Mono-vacancies in GaAs:Si are V_{Ga}- Si_{Ga}-complexes

Gebauer et al., Phys. Rev. Lett. **78**, 3334-3337 (1997)

electron-irradiated GaAs

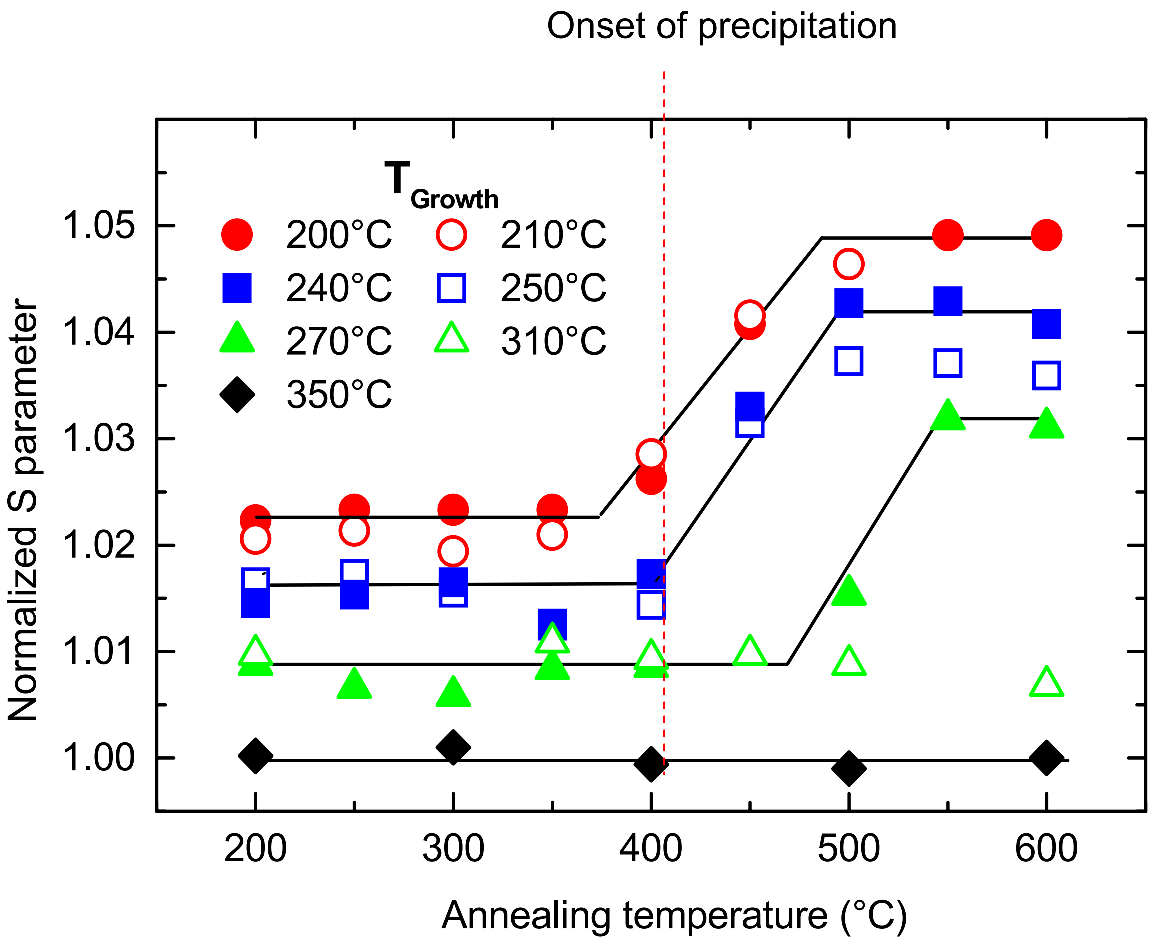
- electron irradiation generates vacancies in both sublattices
- very complex annealing behavior
- main annealing stage at 300 K
- similar annealing stage found for doped GaAs



A. Polity et al., Phys. Rev. B **55** (1997) 10467

Defects in epitaxially grown LT-GaAs-Layer

- MBE-Growth of GaAs can be performed at 200°C
- thickness of layer ≈ 1 µm
- has unique properties, e.g. very short recombination time
- layer extremely rich of defects
- up to 1% As-excess is compensated by As_{Ga} und V_{Ga}
- Ga vacancies are seen by positrons
- during annealing: As-precipitation starts at 400°C
- positrons detect then small vacancy clusters
- clusters are probably bound to precipitates

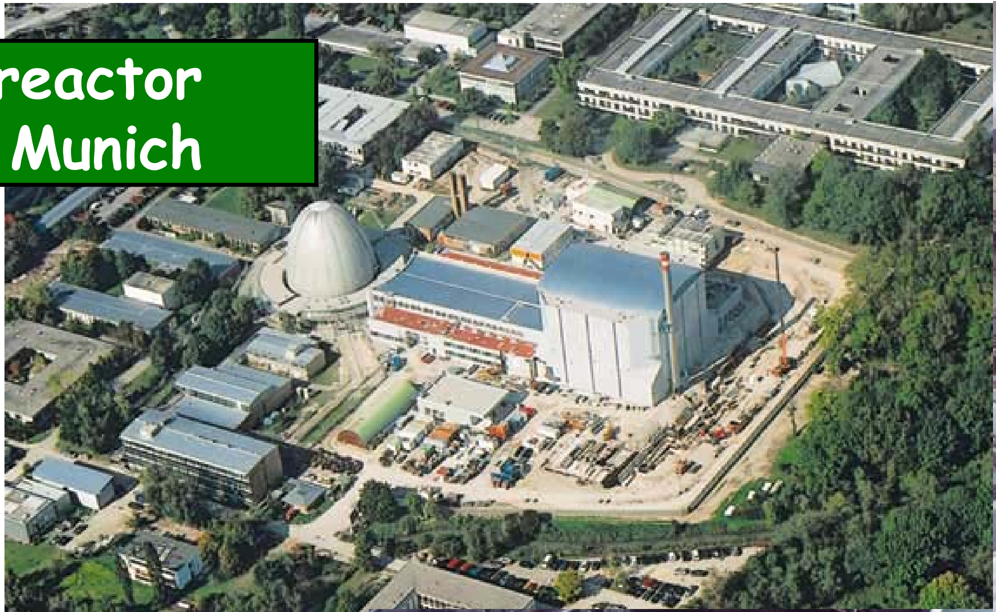


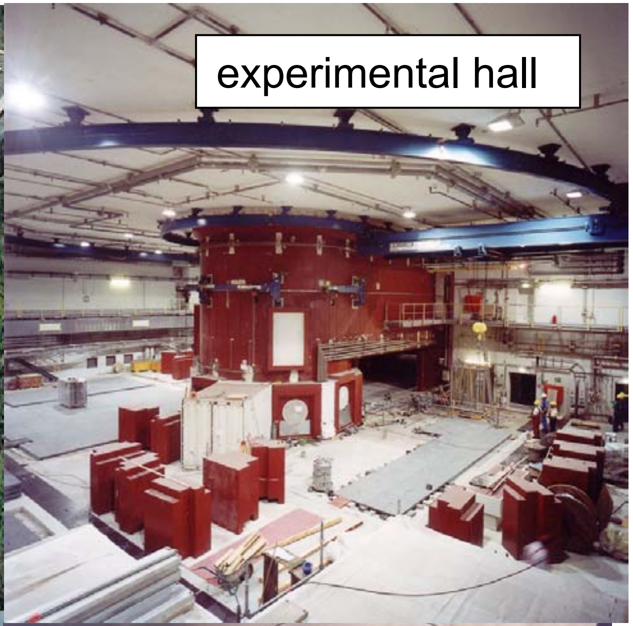
Gebauer et al., Appl. Phys. Lett. **71**, 638 (1997)

Large Positron Facility Projects in Germany

- **FRM-II** (Positron source at Research Reactor-II in Garching near Munich)
  - continous positron beam for different experiments, mainly for:
- **Scanning Positron Microscope** at "Universität der Bundeswehr", Munich
  - system already working using 22-Na source
  - positron lifetime measurement; lateral resolution about 2 µm
- **EPOS** – European Positron Source for applied Research (project at Research Center Rossendorf, near Dresden)
  - positron source for materials research at superconducting 40 MeV-FEL in Rossendorf
  - primary time structure suitable for positron lifetime spectroscopy

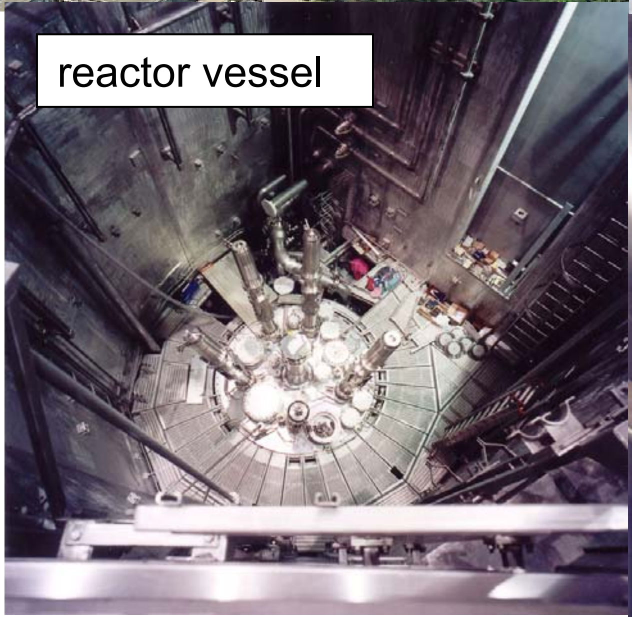
Research reactor FRM-II, Munich





experimental hall

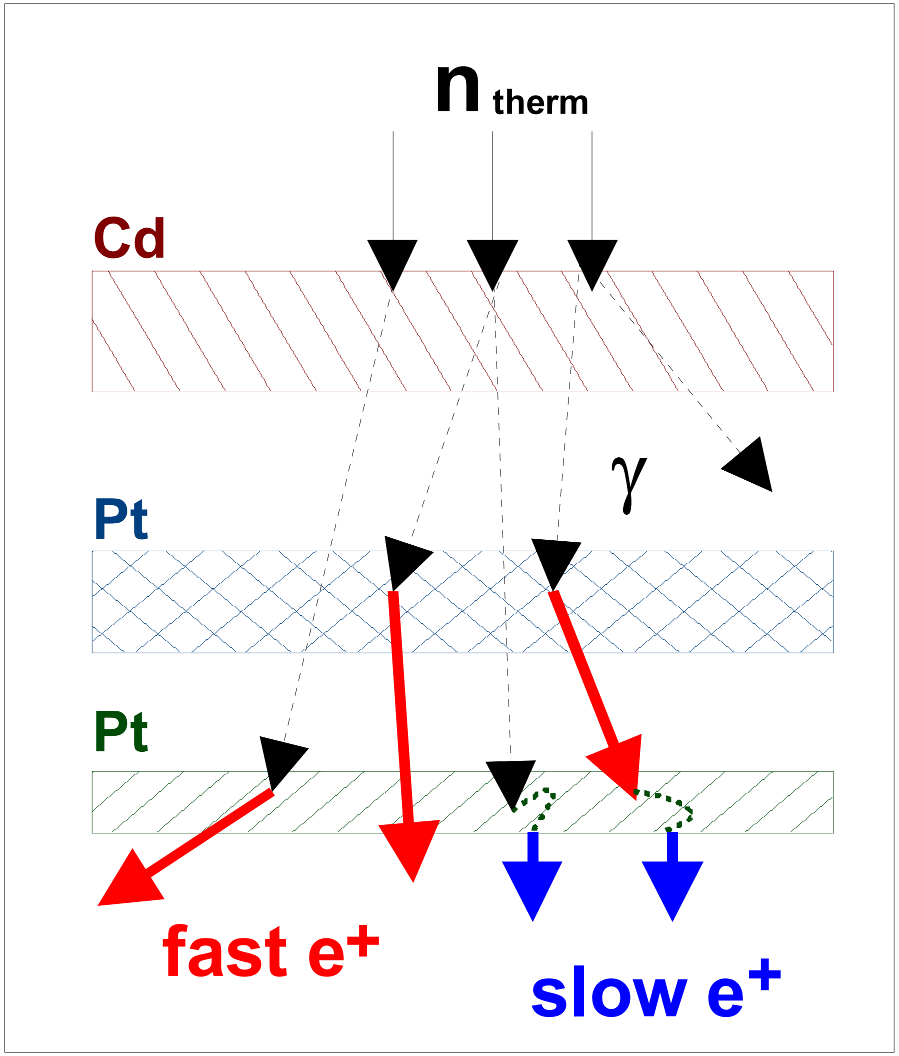
- positron generation by a nuclear reaction: $^{113}Cd(n,\gamma)^{114}Cd$
- three γ rays → pair production
- continuous positron beam
- $\approx 10^{10}$ slow e^+/s expected



reactor vessel

moderator tank

Principle of the Positron Source at FRM-II



n - capture

γ - emission

$\gamma \rightarrow e^+e^-$

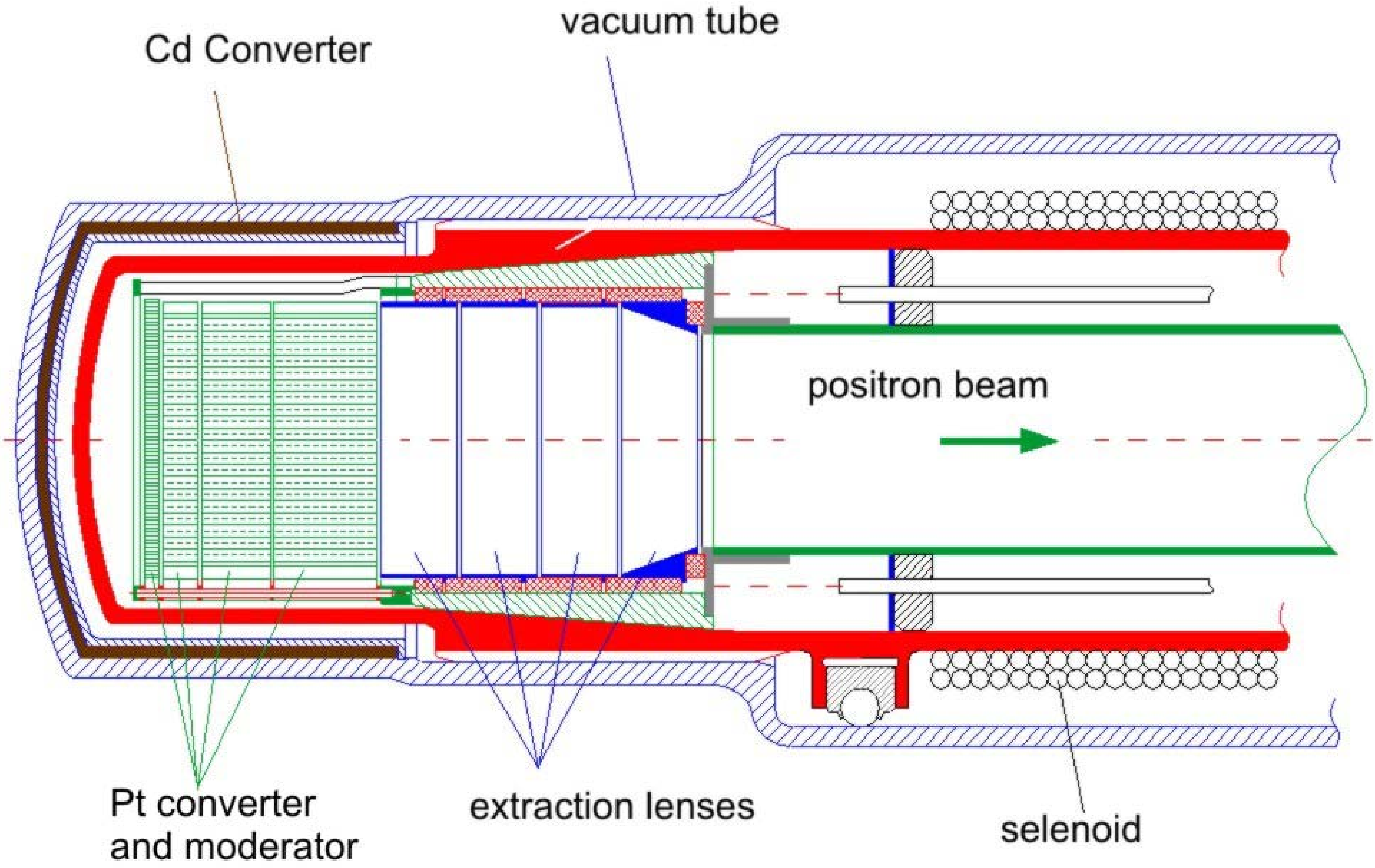
$\gamma \rightarrow e^+e^-$

e^+ - moderation

e^+ - emission

C. Hugenschmidt, 2002

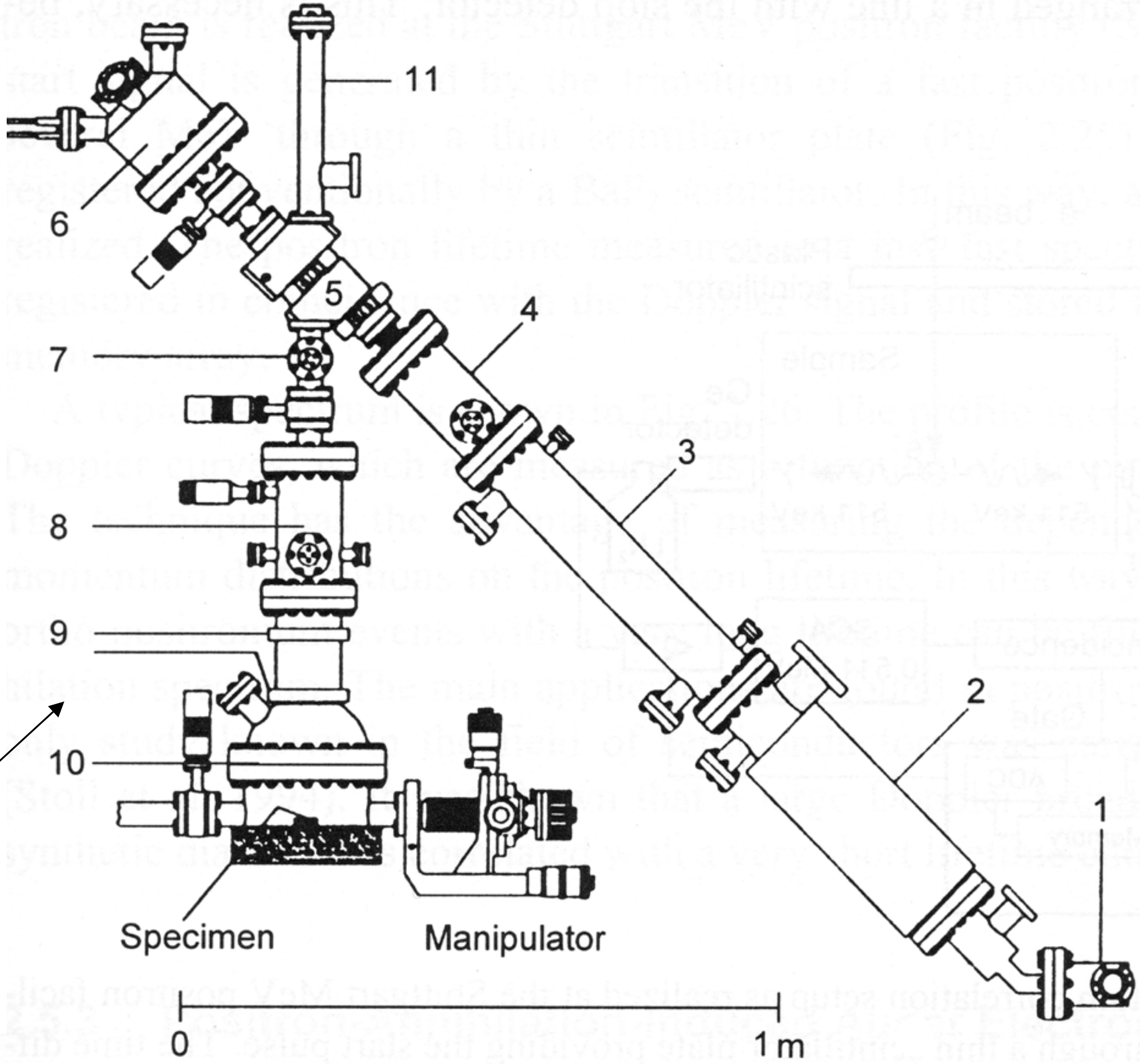
Design of the Positron Source at FRM-II



C. Hugenschmidt, 2002

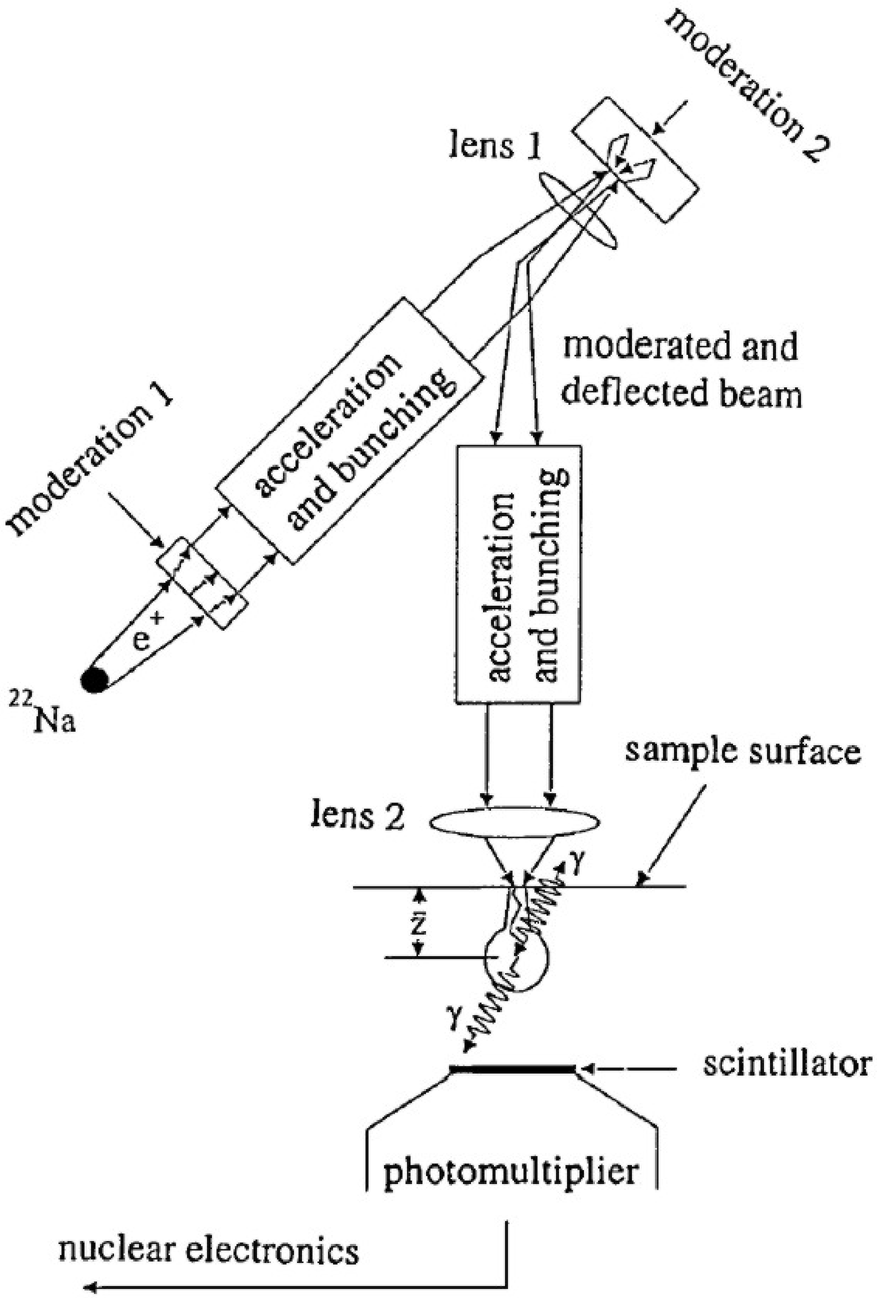
Scanning Positron Microscope in Munich

- Semiconductor devices nm-sized ⇒ Positron microprobes required
- images show directly distribution of positron traps, i.e. nanoscopic lattice defects
- However: positron diffusion length is fundamental limit for lateral resolution
- no sense to improve resolution much below 500 nm
- first instrument was realized at Univ. Bonn (20 μm; Doppler spectroscopy)
- first realization of scanning positron microscope for lifetime spectroscopy: in Munich

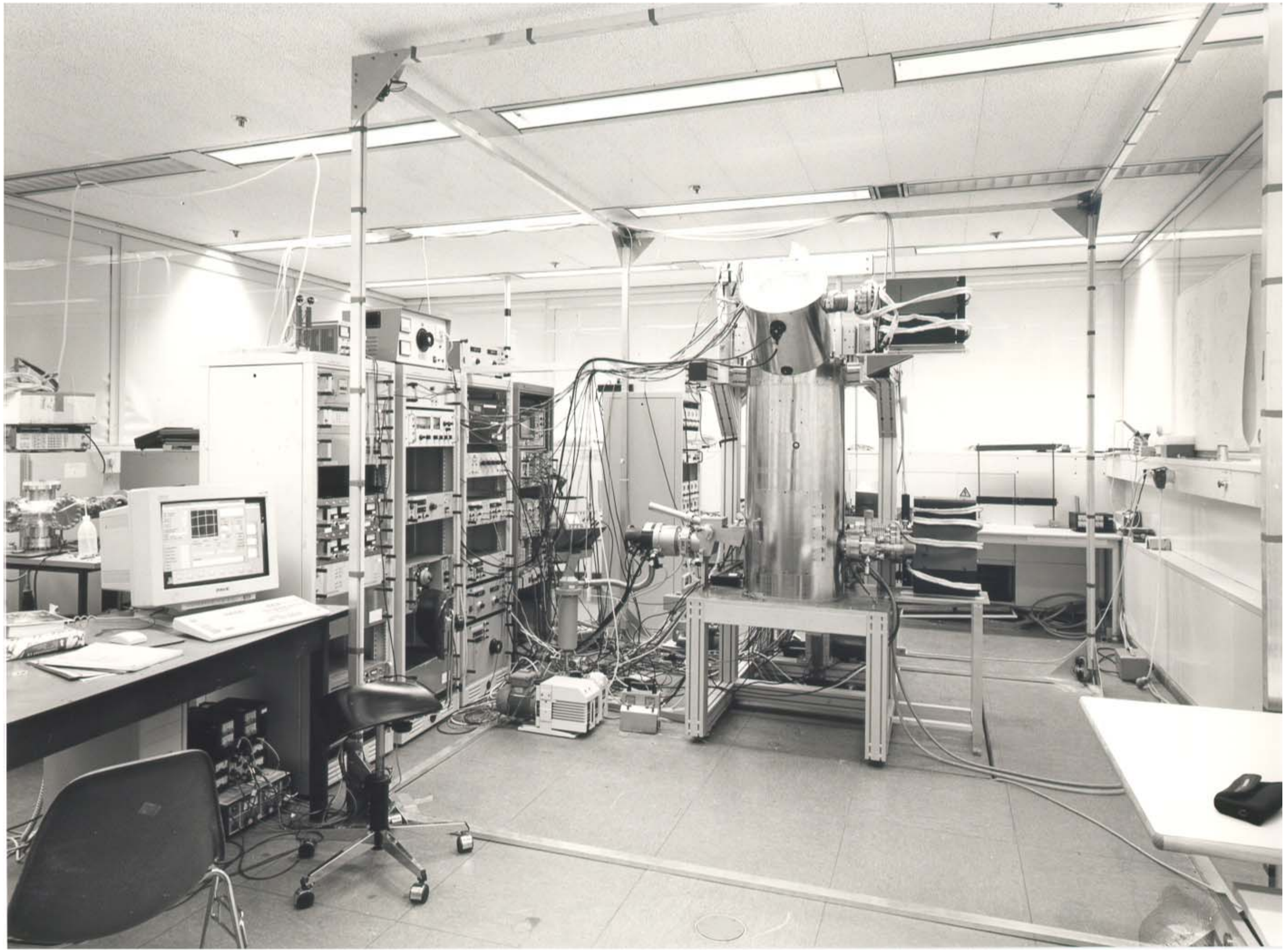


Scheme of the Munich Microscope

- moderated positrons are electrostatically focused, choppered and bunched
- second moderator stage allows focus down to about 2 µm
- positron penetration energy adjustable for depth information
- instrument shall be adopted to the FRM-II positron source when available

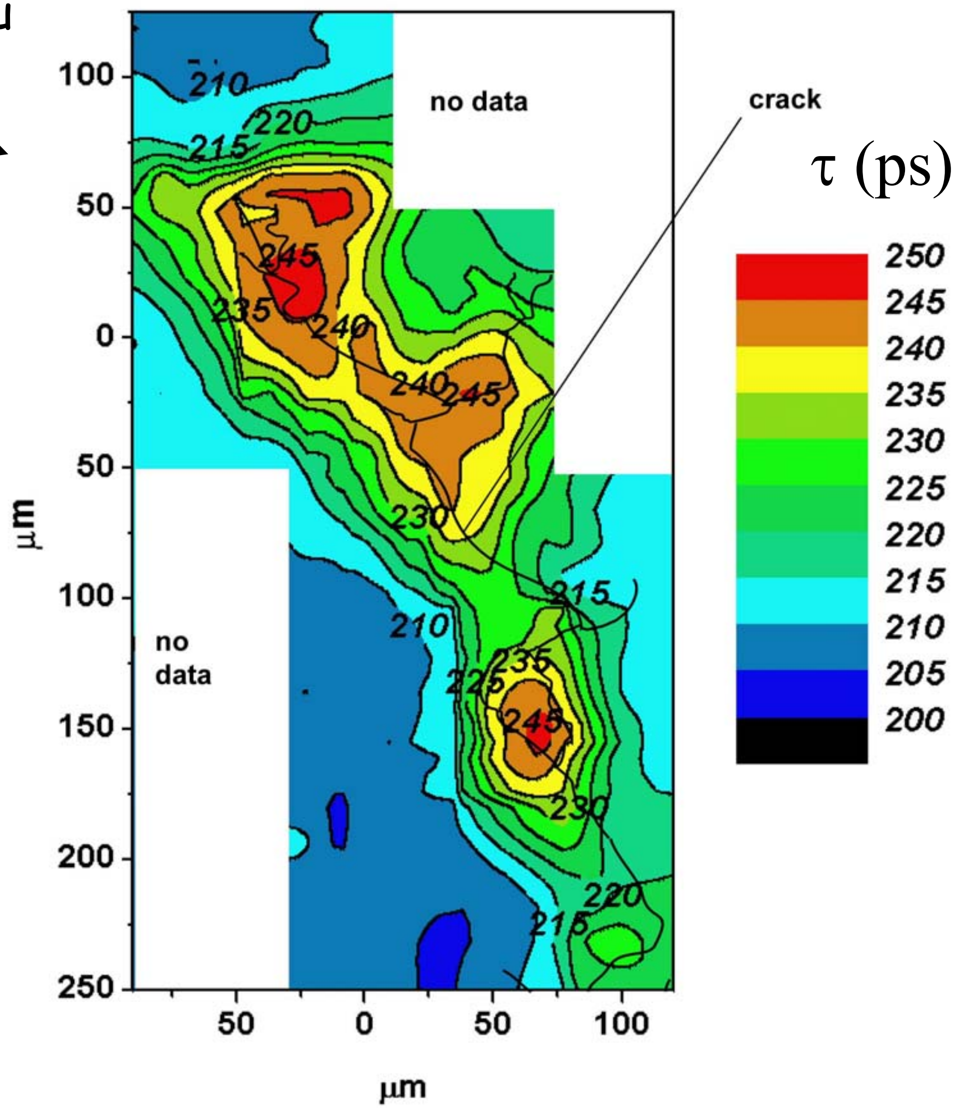


Scanning Positron Microscope in Munich

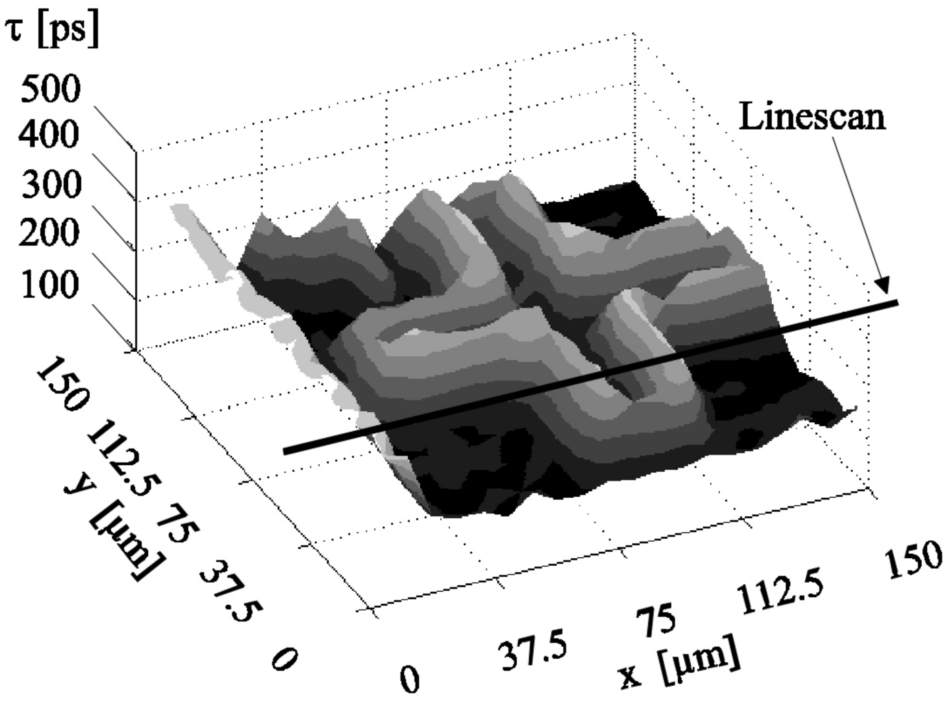


Scanning Positron Microscope in Munich

- defects near a crack in fatigued Cu

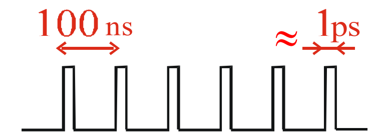


- Semiconductor test structure



Nature **412** (2001)764
Phys. Rev. Lett. **87** () 067402

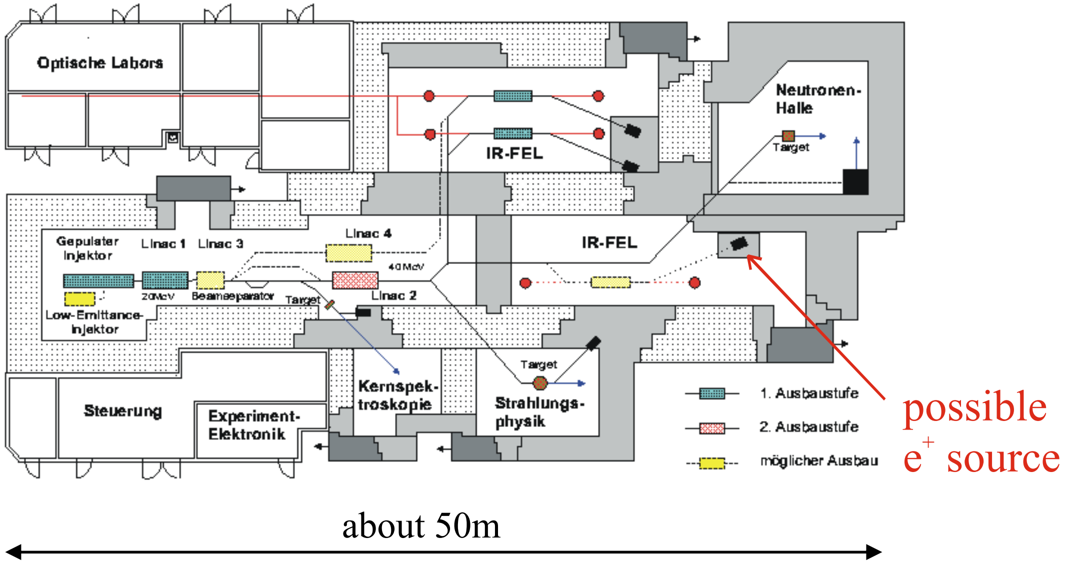
EPOS - Positron source at the Free-Electron Laser at ELBE



electron bunches

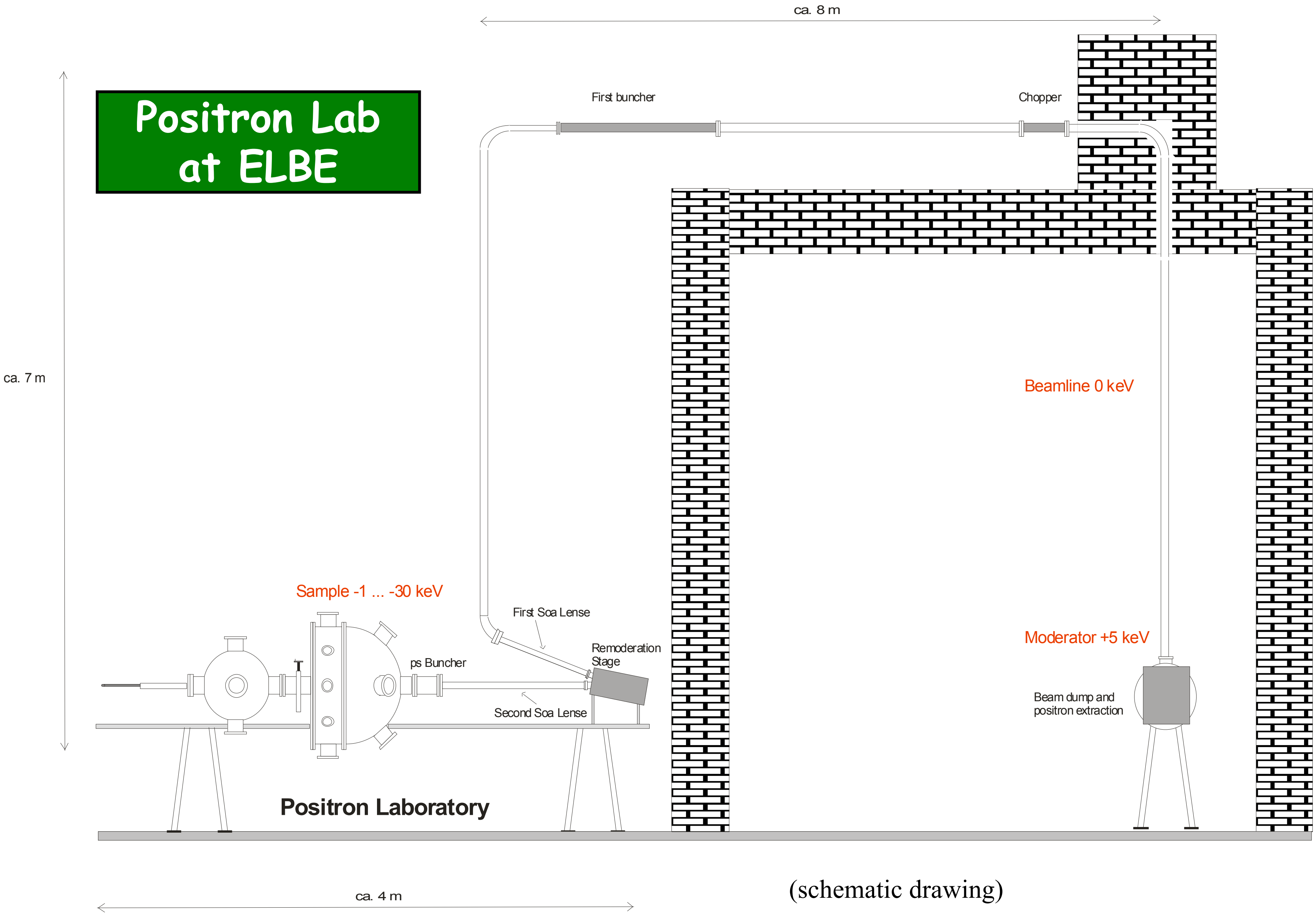
- electron beam at ELBE FEL is bunched

  (length: ≈ 1 ps, repetition time: ≈ 100 ns, cw-mode, up to 10^8 e^-/bunch)
- beam energy: 40 MeV   power: 40 kW
- FEL-system in Rossendorf under construction (ELBE)
- primary electron beam already available



- direct positron lifetime measurement using time structure of e^- beam possible
- about 2…5 x 10^8 slow e^+/s; multidetector system for high counting rate
- combination with Doppler-coincidence spectroscopy (DOCOS) and Age-momentum correlation (AMOC)

Positron Lab at ELBE



(schematic drawing)

Conclusions

- vacancy-type defects can be detected in solids by means of positron annihilation
- method very sensitive for early stage of vacancy agglomeration
- tools for thin layers (mono-energetic positron beams)
- scanning positron microbeams available
- intense positron sources under construction in Germany too

This presentation can be found as pdf-files on our Website:
http://www.ep3.uni-halle.de/positrons

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