Ehrenkolloquium für Herrn Prof. J.R. Niklas:

Antimaterie in der modernen Materialforschung

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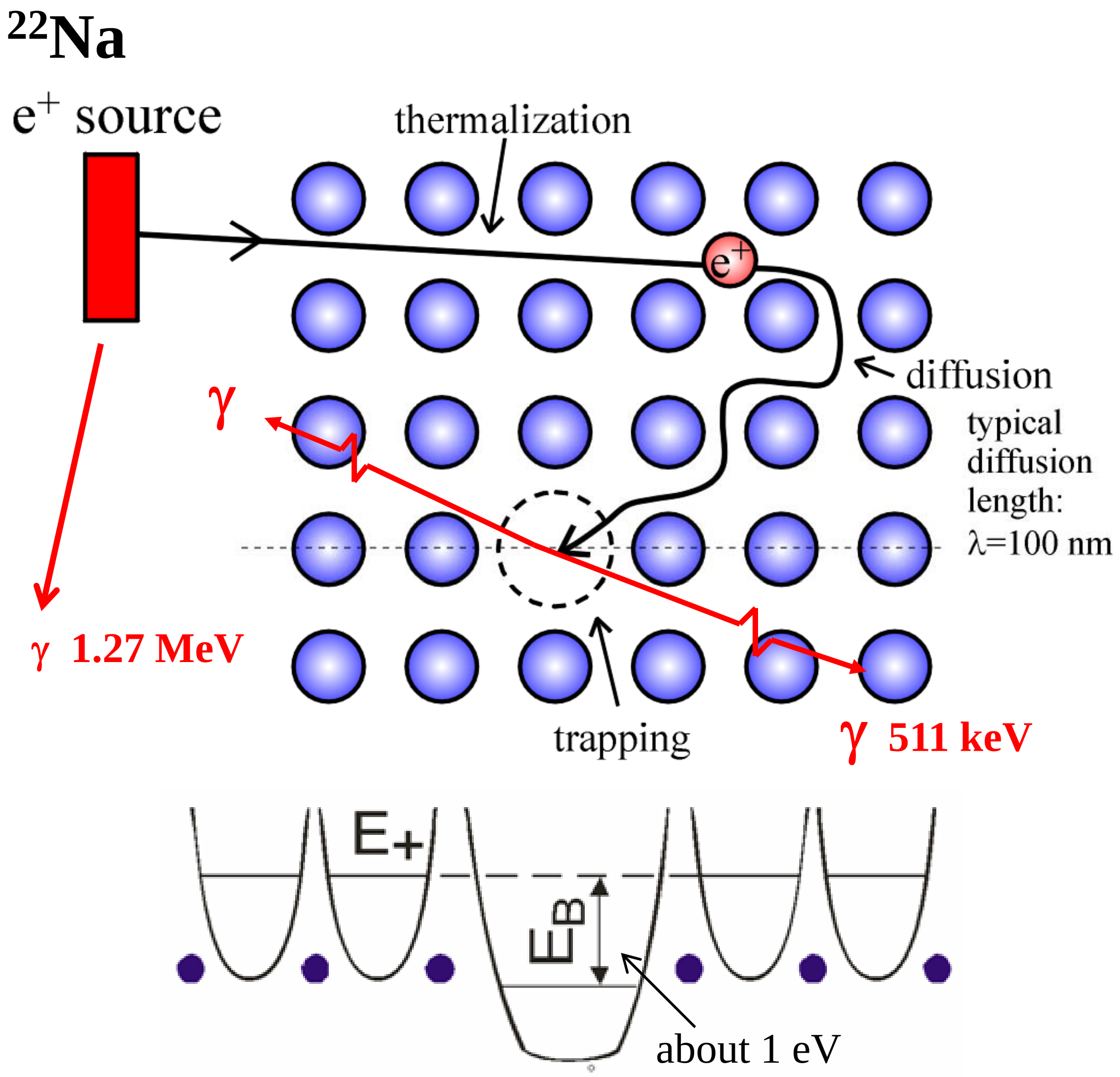
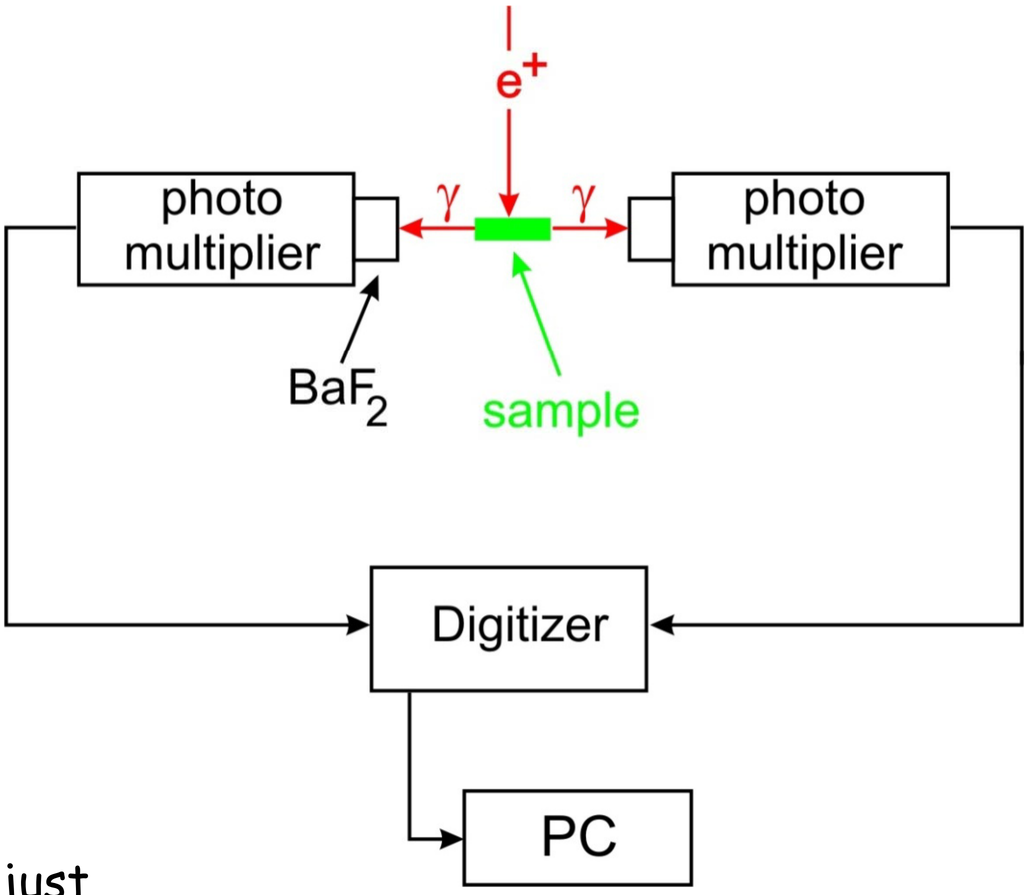
- Technik der Positronenannihilation
- Anwendungen
- Gepulste, intensive Positronenquelle EPOS an ELBE (FZ Dresden-Rossendorf)

The positron lifetime spectroscopy



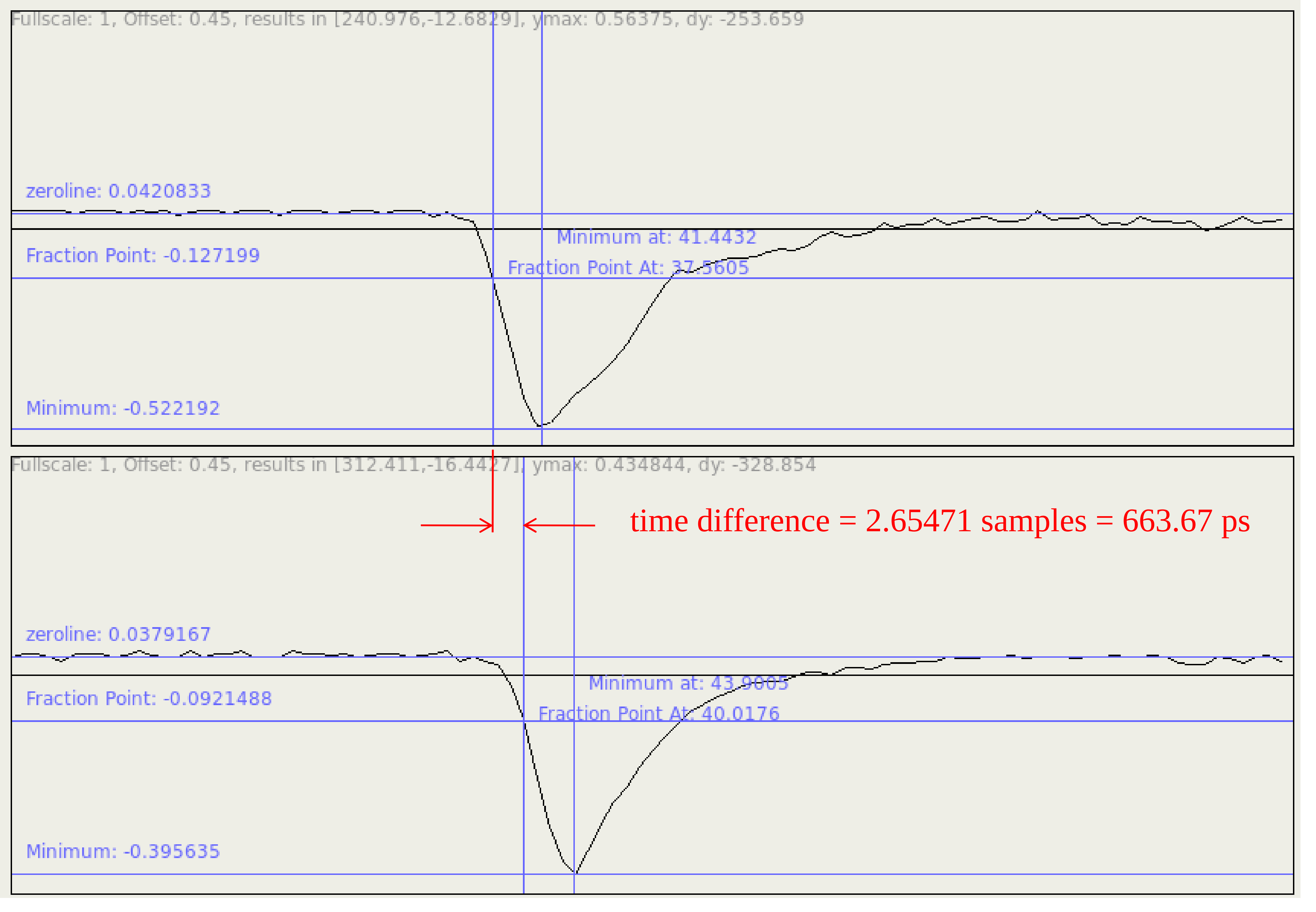
- positron wave-function can be localized in the attractive potential of a defect
- annihilation parameters change in the localized state
- e.g. positron lifetime increases in a vacancy
- lifetime is measured as time difference between appearance of 1.27 (start) and 0.51 MeV (stop) quanta
- defect identification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

Digital lifetime measurement

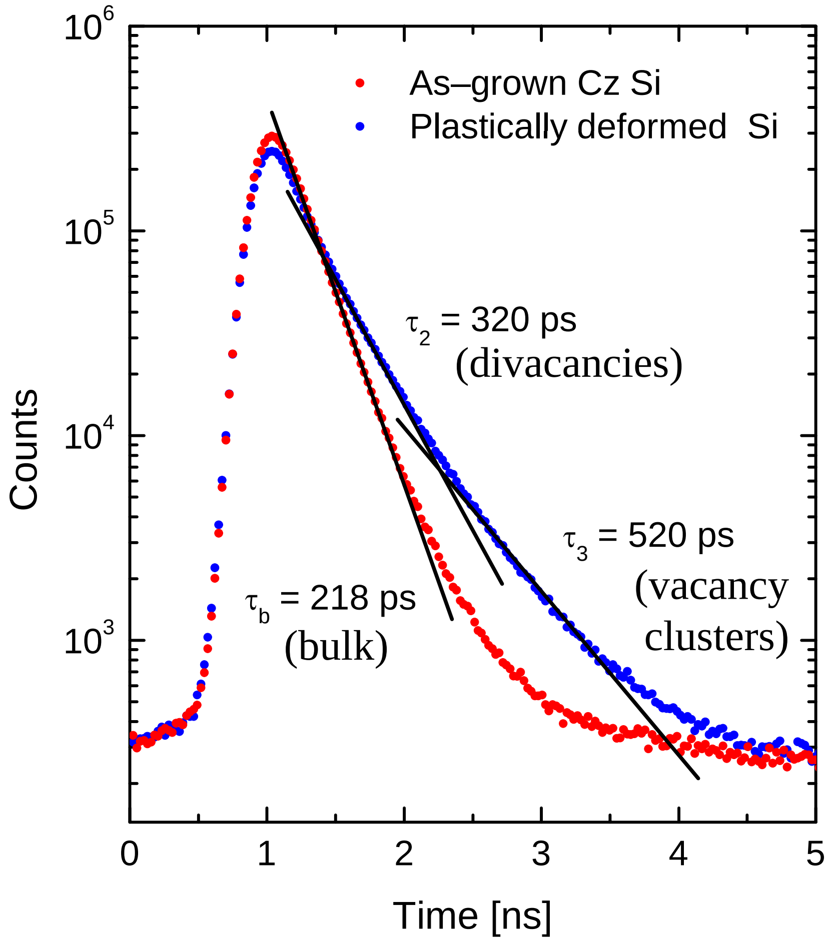


- simple setup
- nothing to adjust
- timing very accurate (accuracy 10^{-6})
- pulse-shape discrimination (suppress "bad pulses")
- each detector for start & stop (double statistics)

Screenshot of two digitized Anode Pulses



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

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

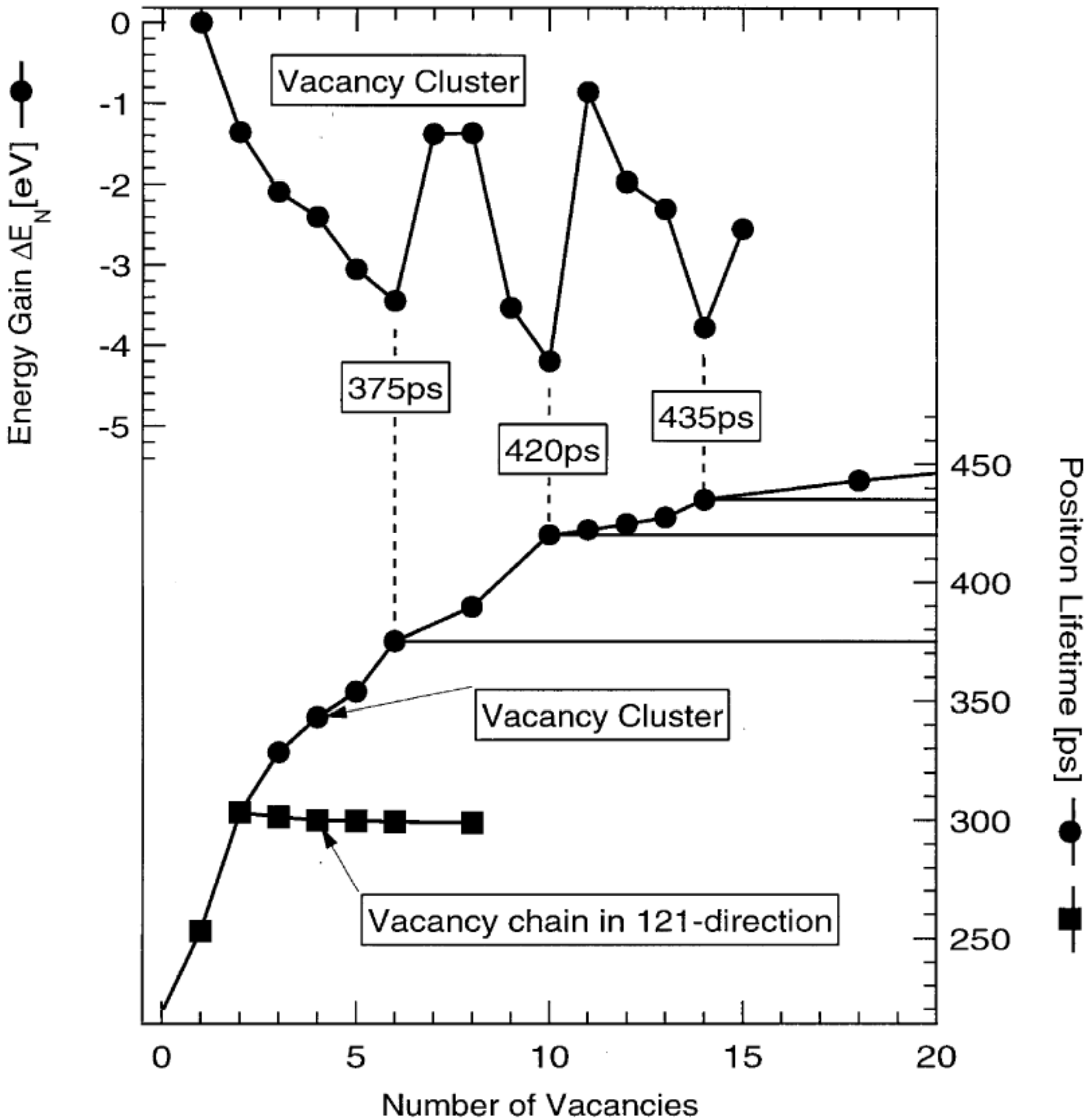
trapping rate

defect concentration

Detection Range of different Defects

Defect Type	Sensitivity range detection limit ... saturated trapping
neutral vacancies	5×10^{15}... 10^{19} cm^{-3}
dislocations	10^{8} ... 5×10^{11} cm^{-2}
precipitates (r=2 nm)	10^{14} ... 10^{17} cm^{-3}
grain boundaries	5 μm ... 200 nm (particle size)
microvoids (>50 atoms)	10^{14} ... 5×10^{17} cm^{-3}

Theoretical Calculation of Vacancy Clusters in Si

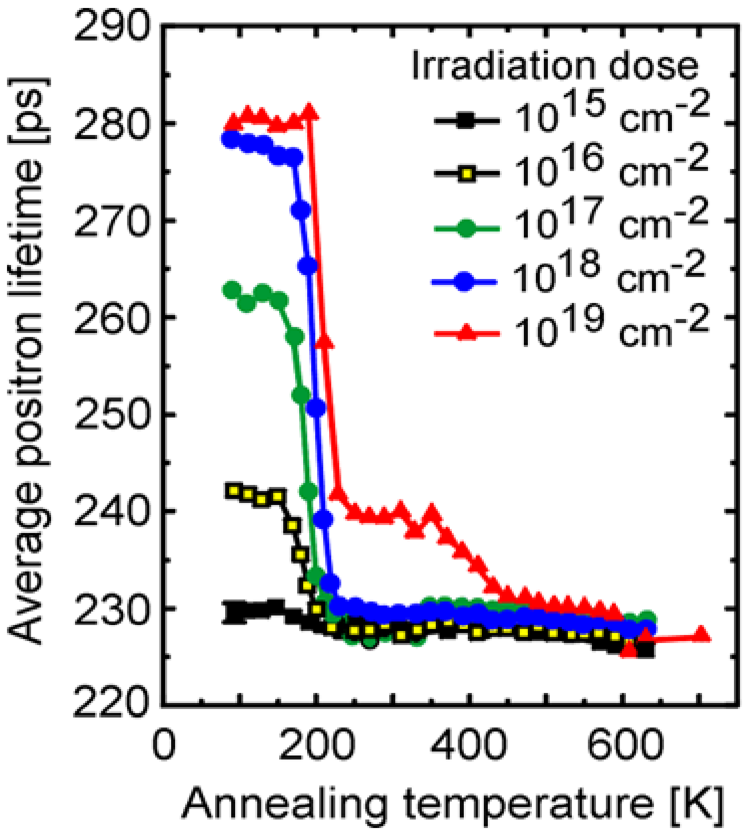


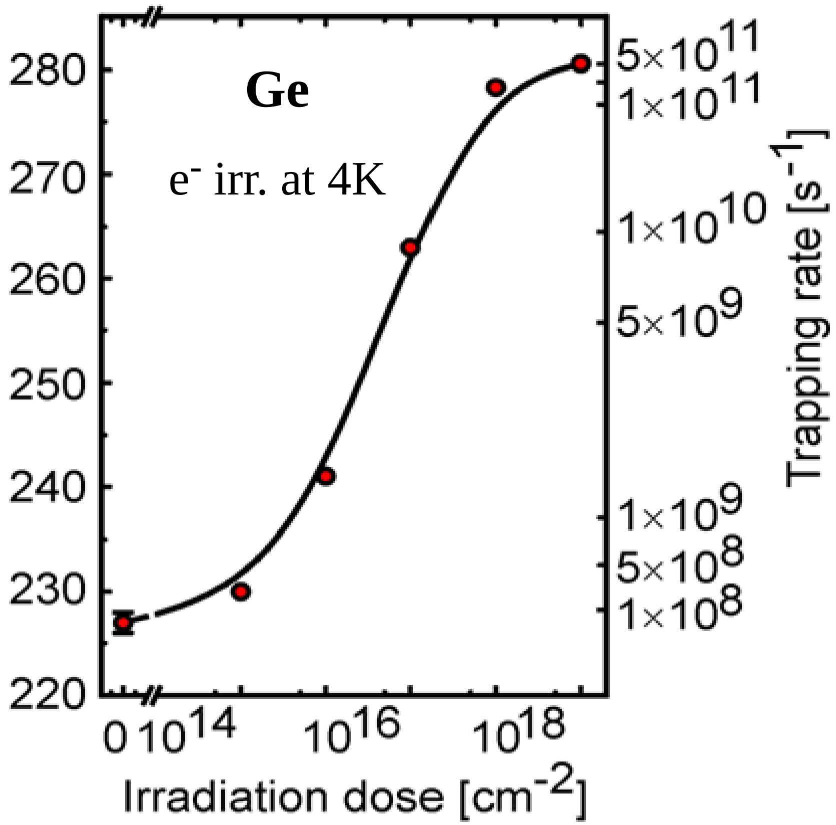
- there are cluster configurations with a large energy gain
- „Magic Numbers" with 6, 10 und 14 vacancies
- positron lifetime increases distinctly with cluster size
- for n > 10 saturation effect, i.e. size cannot be determined

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

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 stable up to 400 K)

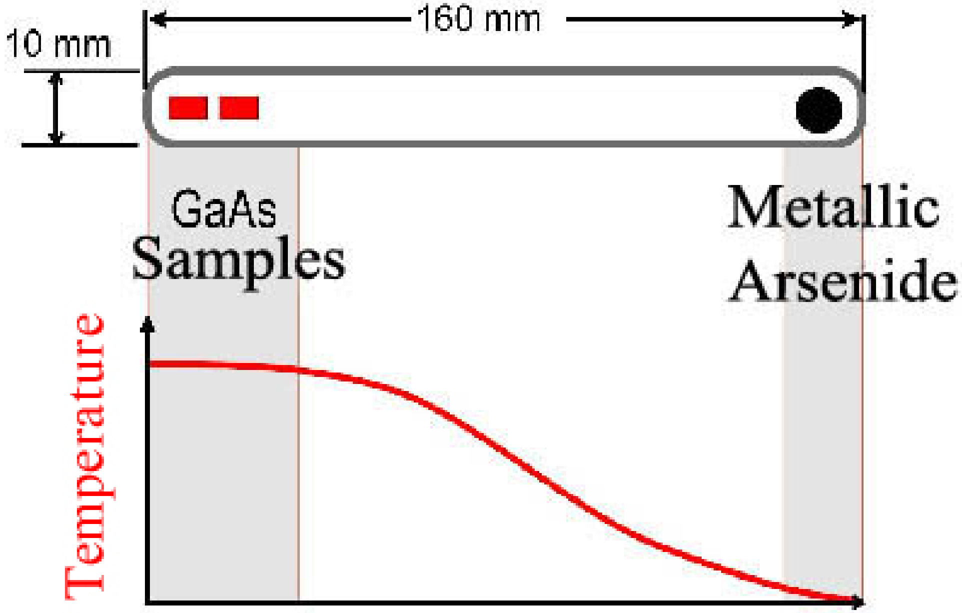




(Polity et al., 1997)

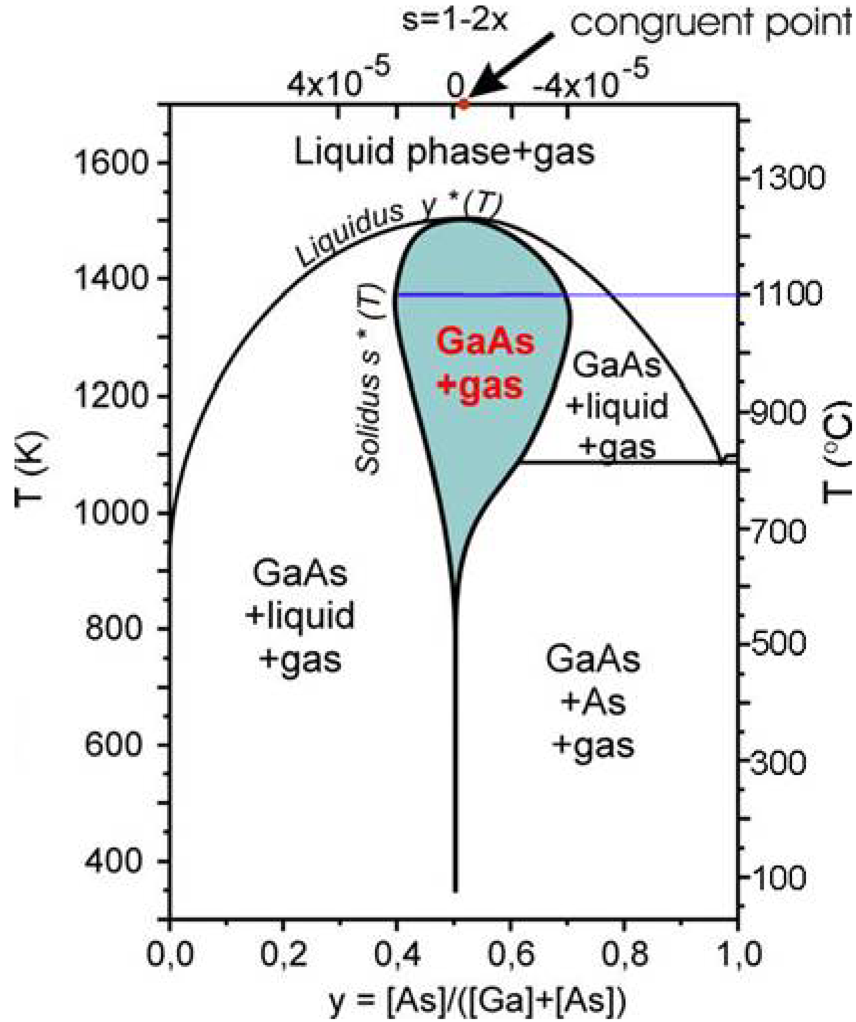
GaAs: annealing under defined As-partial pressure

- two-zone-furnace: Control of sample temperature **and** As partial pressure allows to navigate freely in phase diagram (existence area of compound)
- Measurements near equilibrium after quenching of samples



T_{sample}: 1100° C

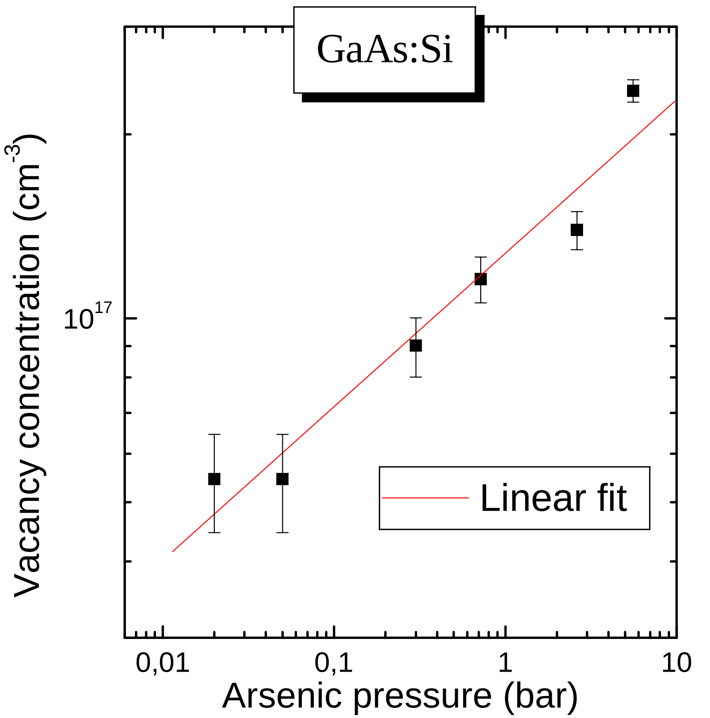
T_{As}: determines As-partial pressure



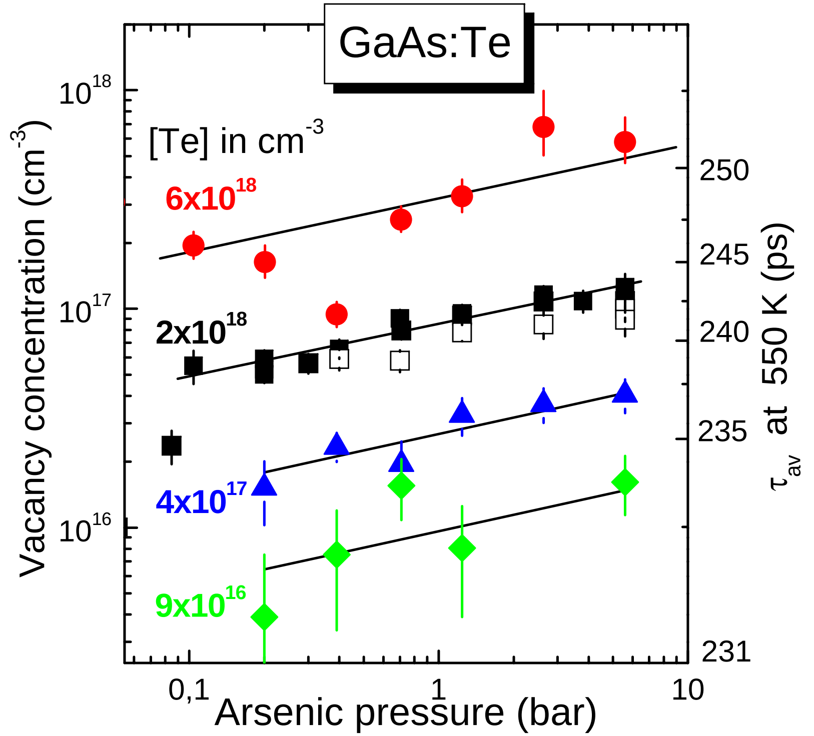
H. Wenzl et al., J. Cryst. Growth **109**, 191 (1991).

GaAs: Annealing under defined As pressure

Si_{Ga}-V_{Ga}



Te_{As}-V_{Ga}



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

Thermodynamic reaction:

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

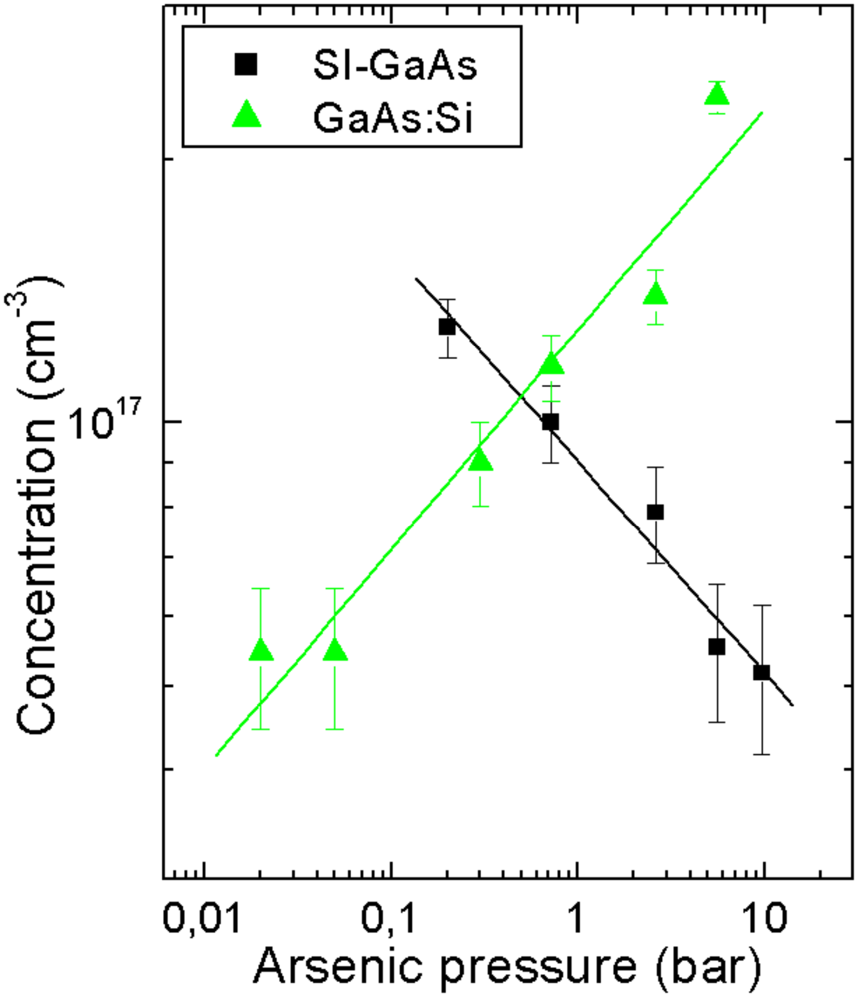
Mass action law:

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

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

$\rightarrow n = 1/4$

Comparison of doped and undoped GaAs



Bondarenko et al., 2003

Thermodynamic reaction:

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

Mass action law:

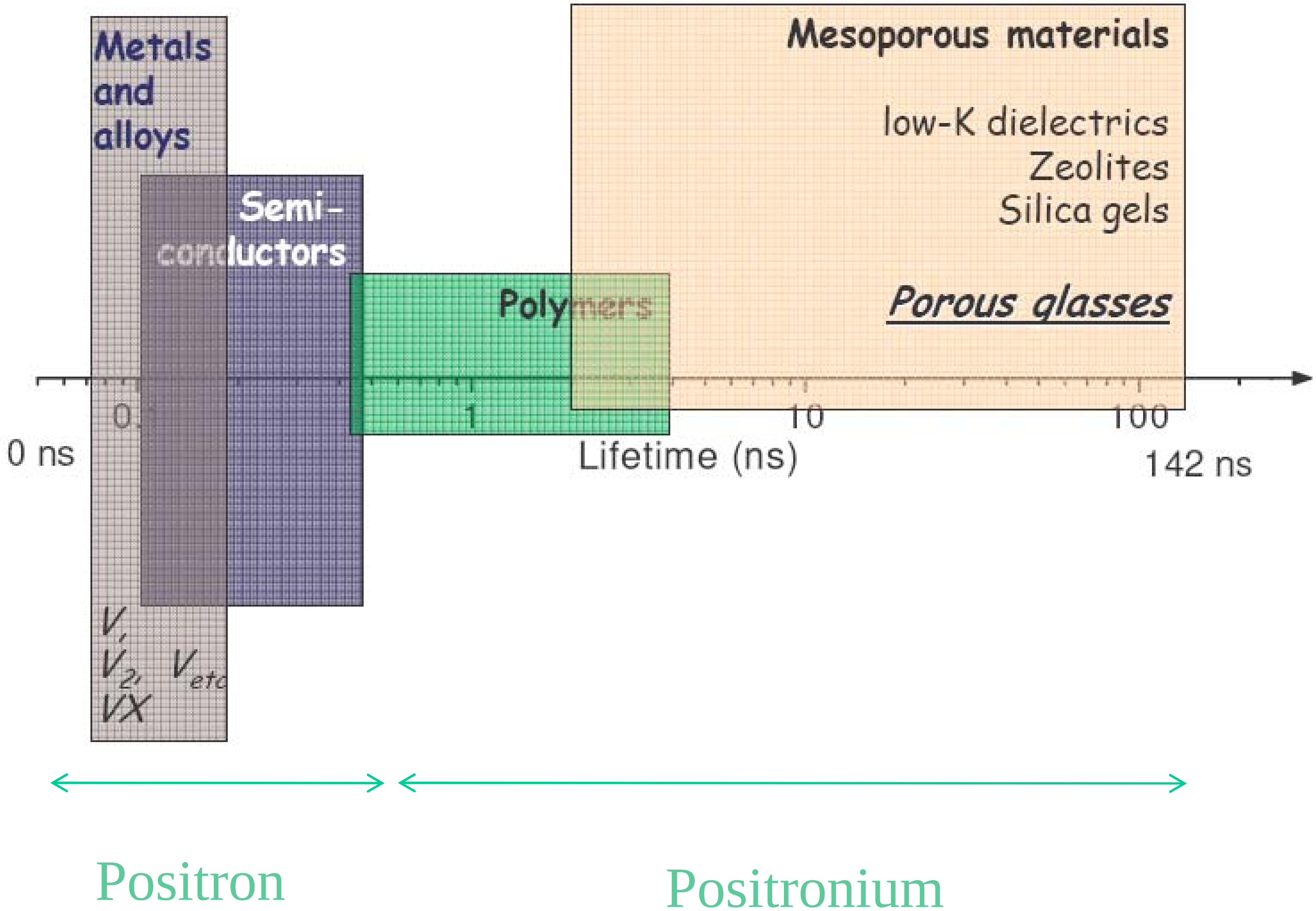
$$[V_{As}] = K_{VAs} \times p_{As}^{-1/4}$$

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

$\rightarrow n = -1/4$

undoped GaAs: As vacancy

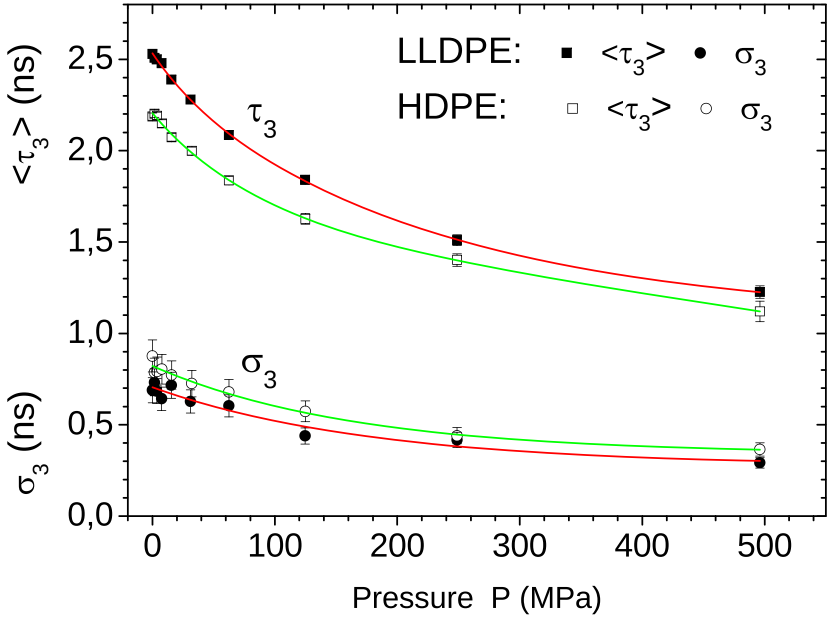
Typical Lifetimes

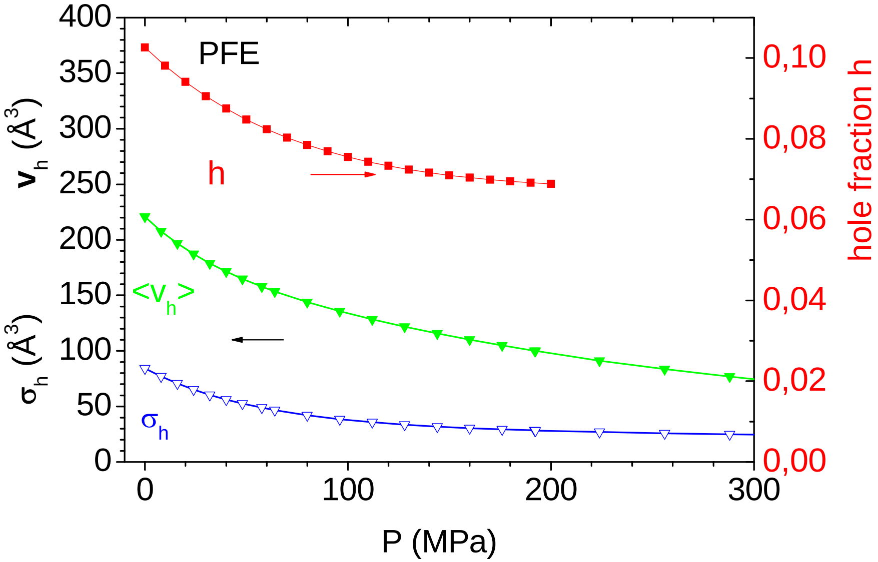


Polymers under Pressure

- The open volume V_h between polymer molecular chains can be determined from the ortho-positronium lifetime τ_3
- Also its size dispersion σ_h and the hole fraction h

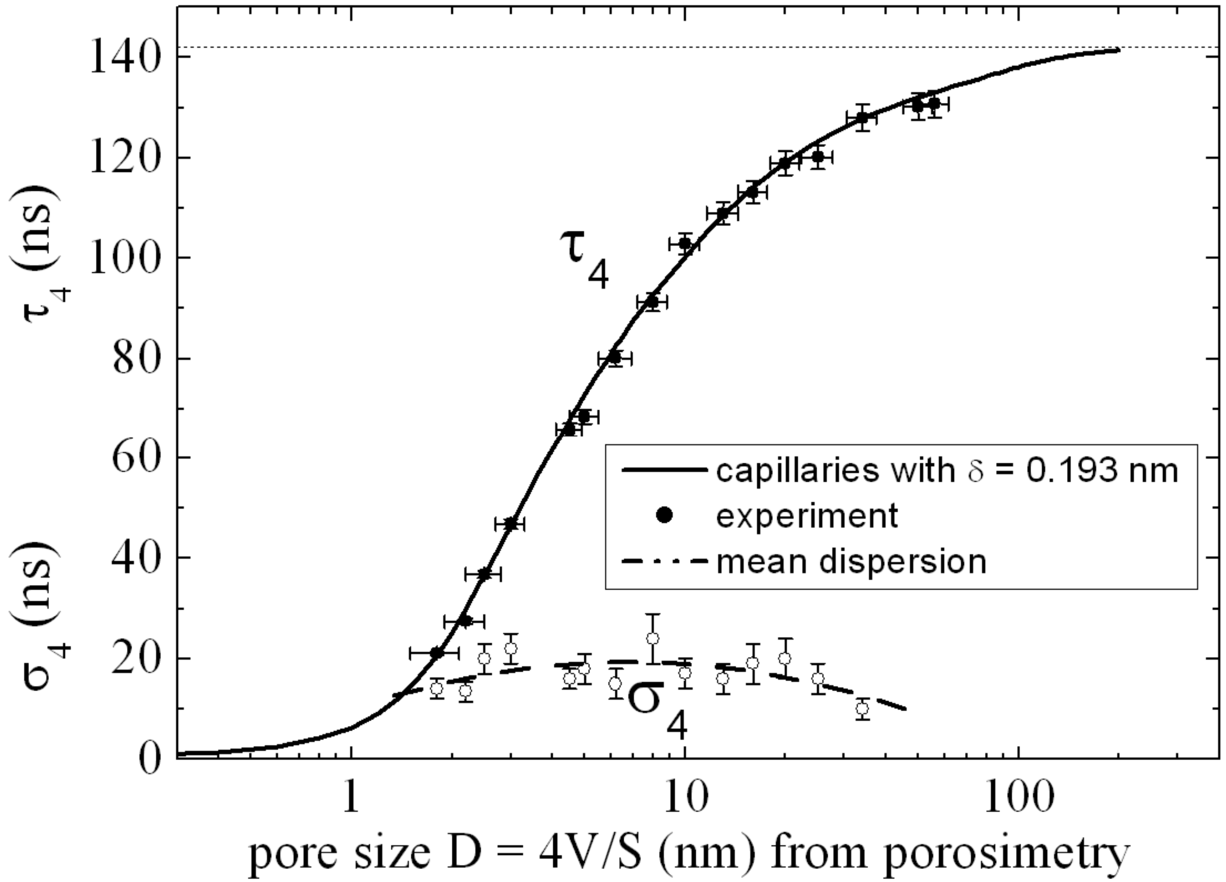
LLDPE: low-density polyethylene HDPE: high-density polyethylene PFE: perflourelastomer

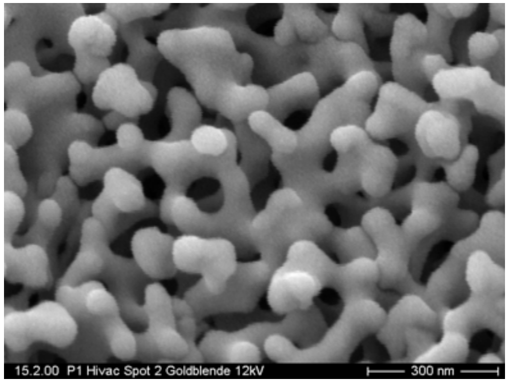




Porosimetry by Positronium

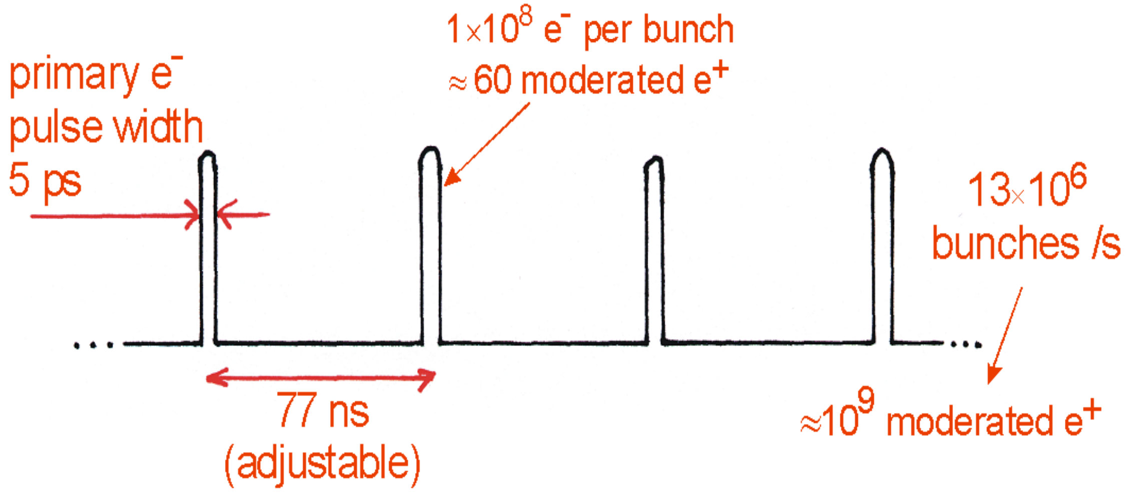
- Controlled pore glass: pore diameter 1…100 nm
- Best sensitivity of positrons: 1…10 nm
- Pore size distribution can be determined





The EPOS positron source at Research Center Dresden-Rossendorf

- Radiation source ELBE = **E**lectron **L**inac with high **B**rilliance and low **E**mittance
- Primary electron beam (40 MeV x 1 mA = 40 kW)
- Main goal: Infrared Free-electron Lasers
- Very interesting time structure: cw-mode of short bunches with 13 MHz

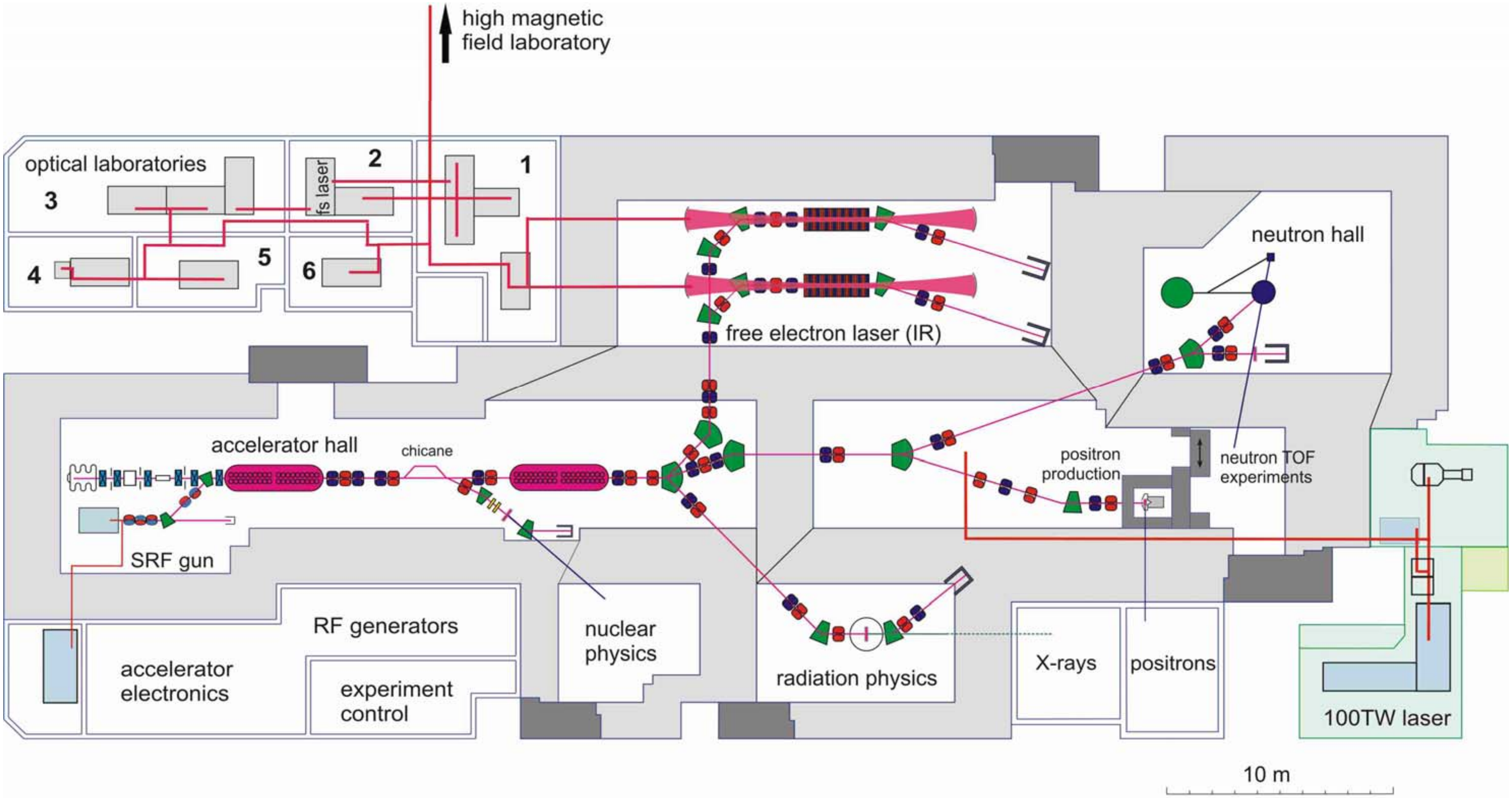


electron bunches

EPOS = ELBE Positron Source

- Intense, pulsed beam of slow (monoenergetic) positrons
- All relevant positron techniques for materials research (positron lifetime, Coincidence Doppler broadening, AMOC)
- EPOS is external facility of Martin-Luther-University Halle in collaboration with Research Center Dresden-Rossendorf (FZD)
- User-dedicated facility
- Remote controlled via internet
- Financing by University Halle, Land Sachsen-Anhalt, European Community, and FZD

ELBE Layout



high magnetic field laboratory
optical laboratories
3
fs laser
2
1
4
5
6
free electron laser (IR)
neutron hall
accelerator hall
chicane
positron production
neutron TOF experiments
SRF gun
RF generators
nuclear physics
radiation physics
X-rays
positrons
accelerator electronics
experiment control
100TW laser
10 m

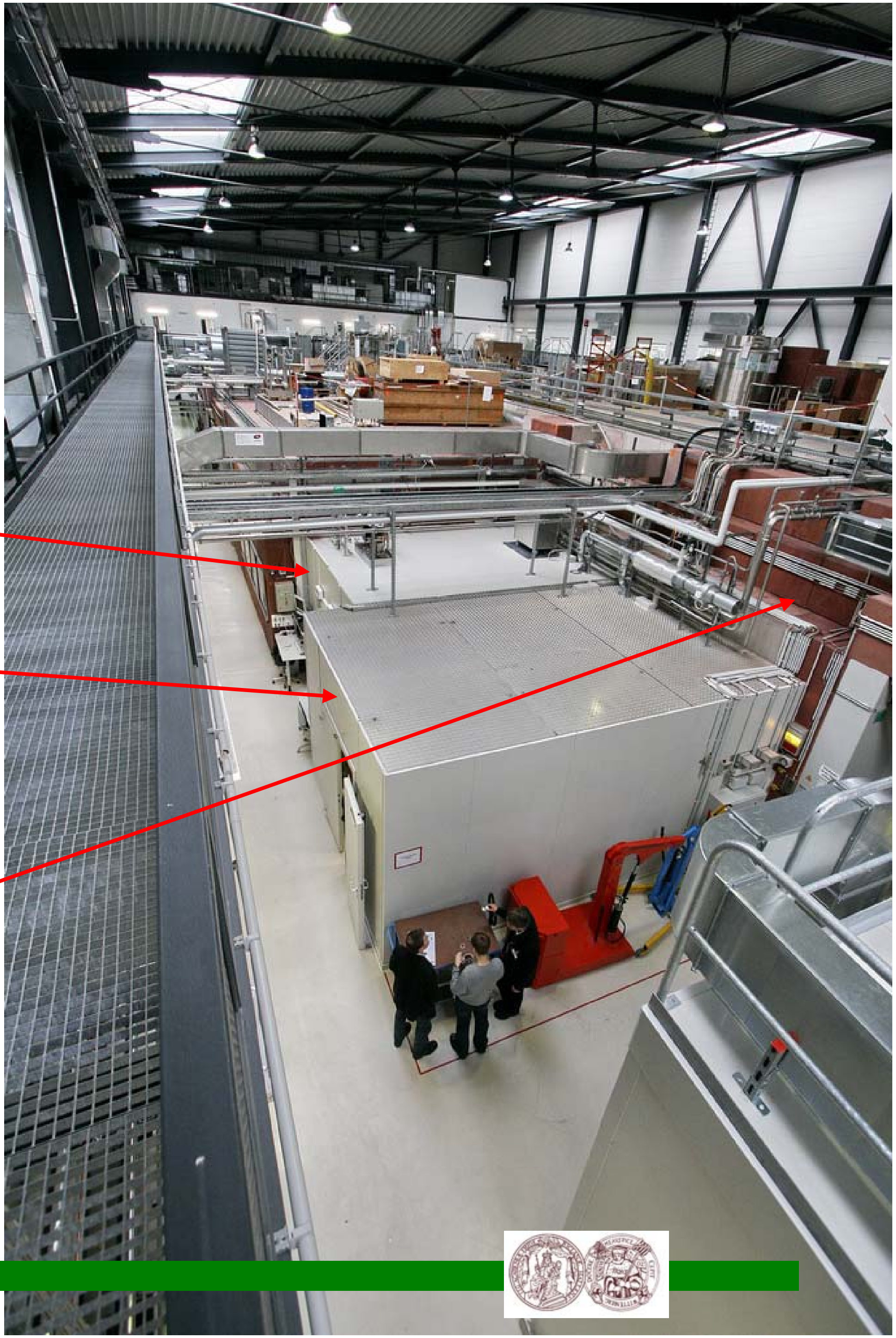
Positron Lab

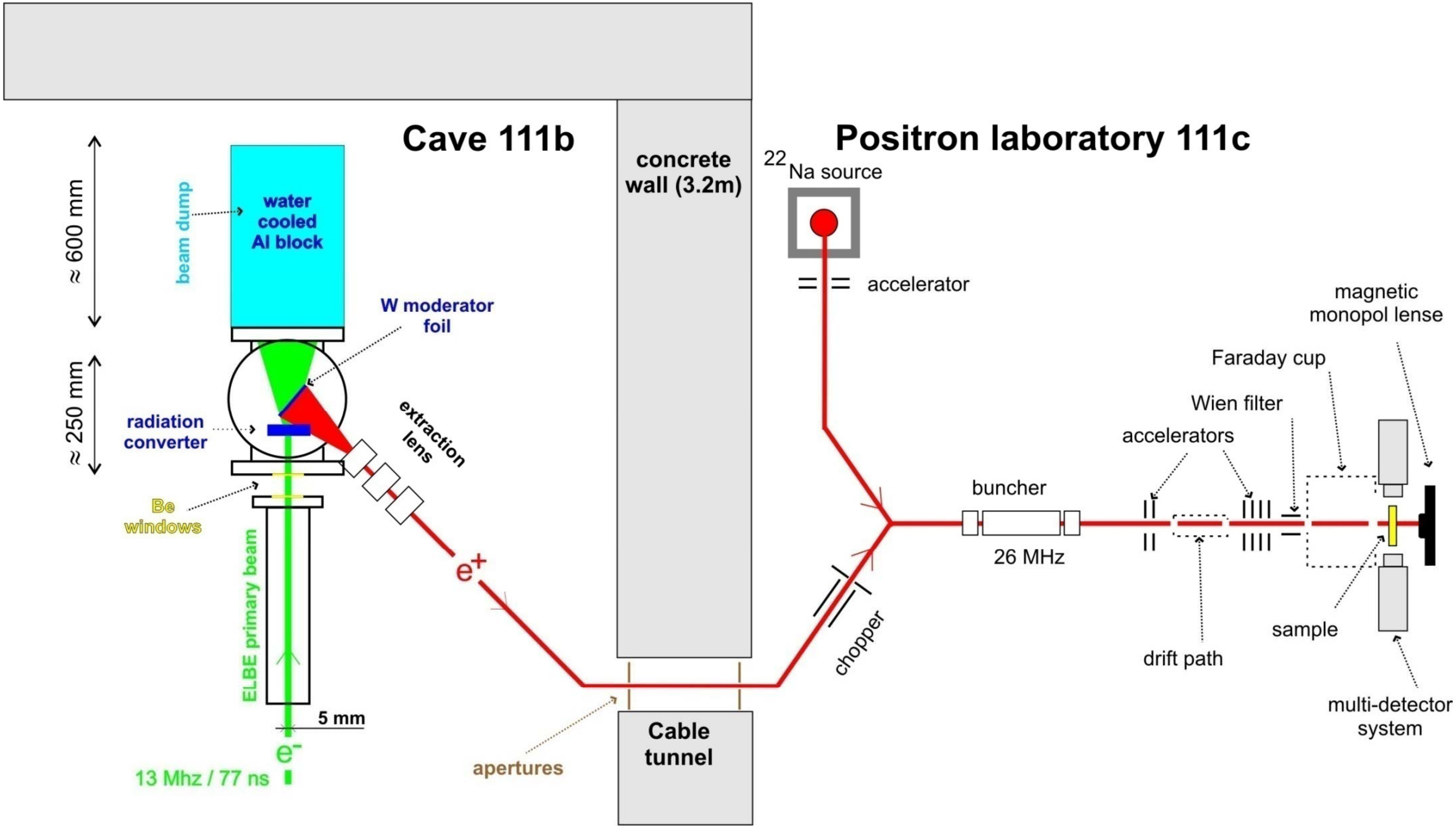
- positron lab in ELBE hall

X-ray Lab

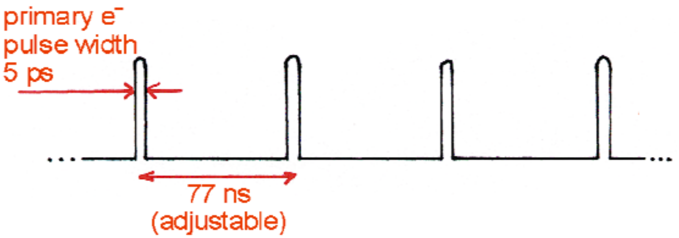
Positron Lab

concrete screening of Cave 111b
(location of e^+ converter)





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

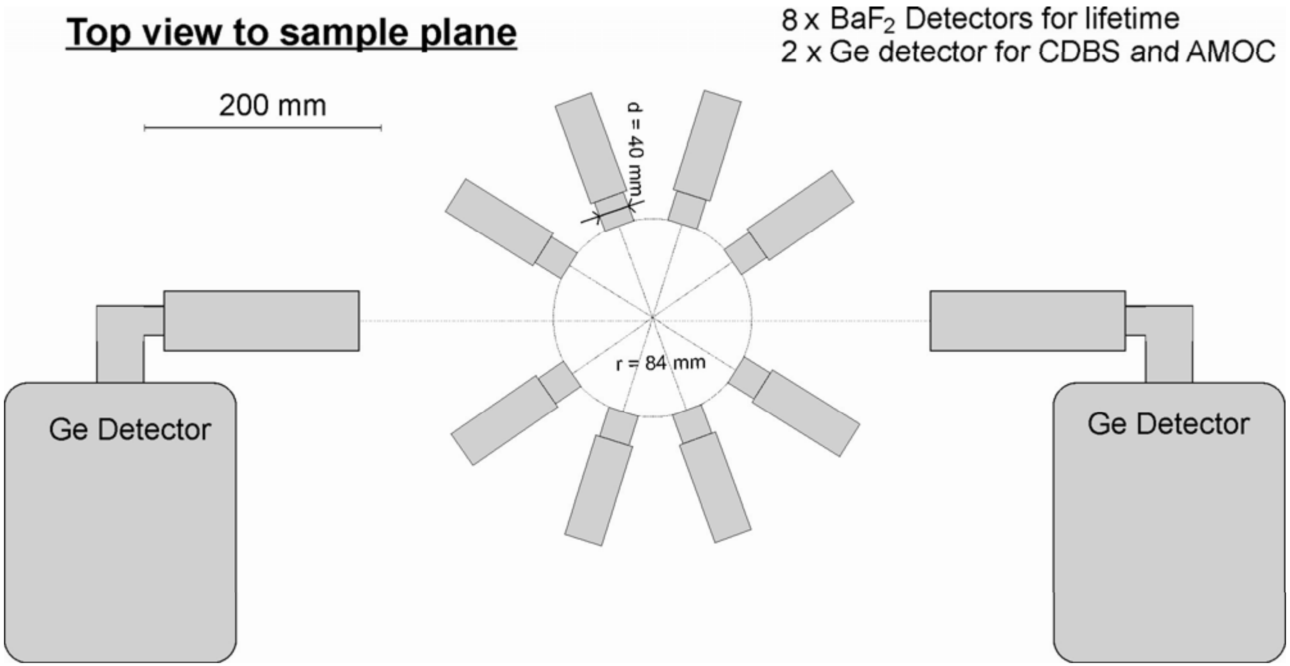


primary e- pulse width 5 ps
77 ns (adjustable)

EPOS scheme

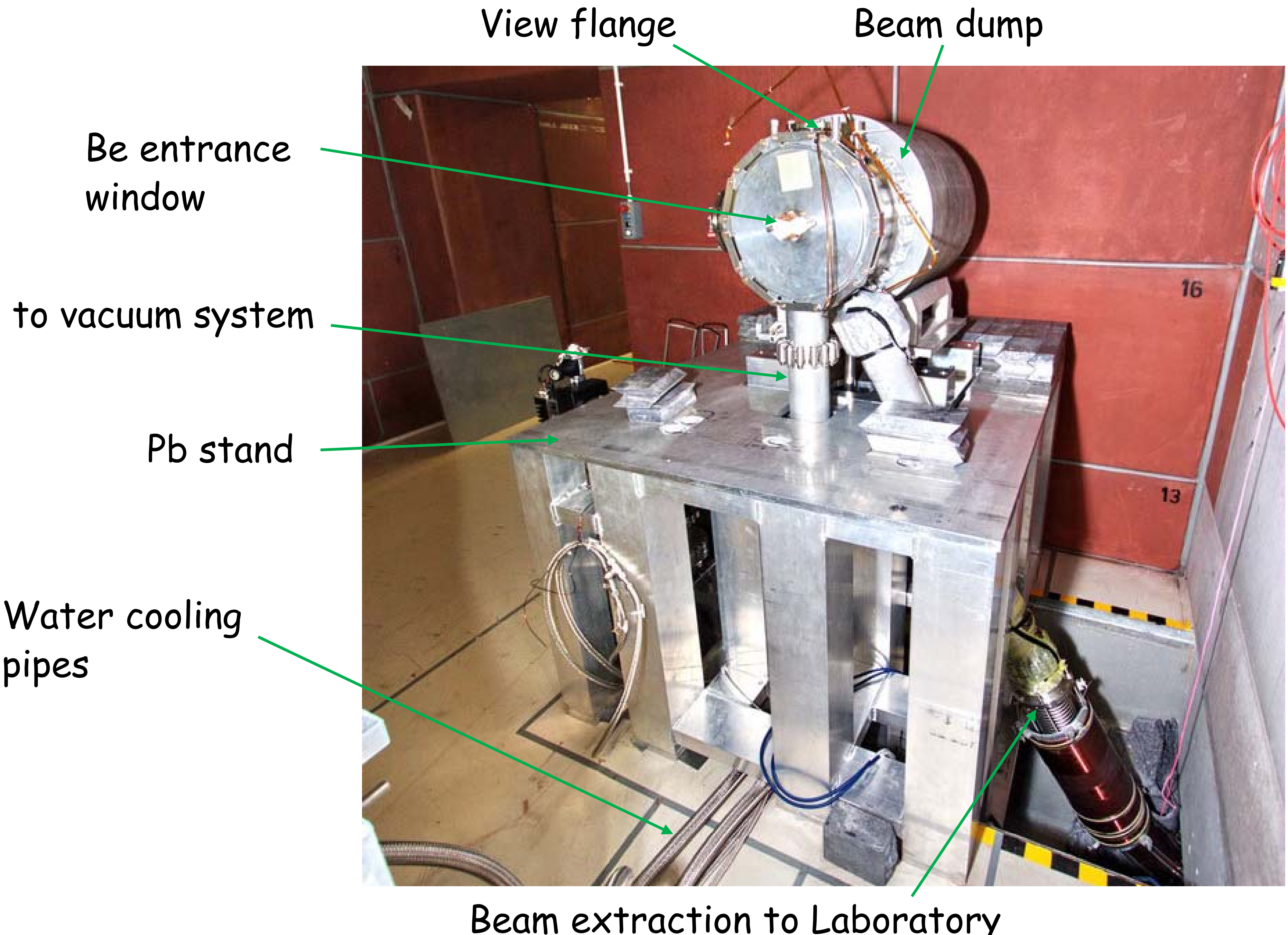
Detector system

- **3 experiments**: lifetime spectroscopy (8 BaF_2 detectors); Doppler coincidence (2 Ge detectors), and AMOC (1 Ge and 1 BaF_2 detector)
- **digital detection system**:
  - lifetime: almost nothing to adjust; time scale exactly the same for all detectors; easy realization of coincidence
  - Doppler: better energy resolution and pile-up rejection expected
  - pulse-shape discrimination improves spectra quality

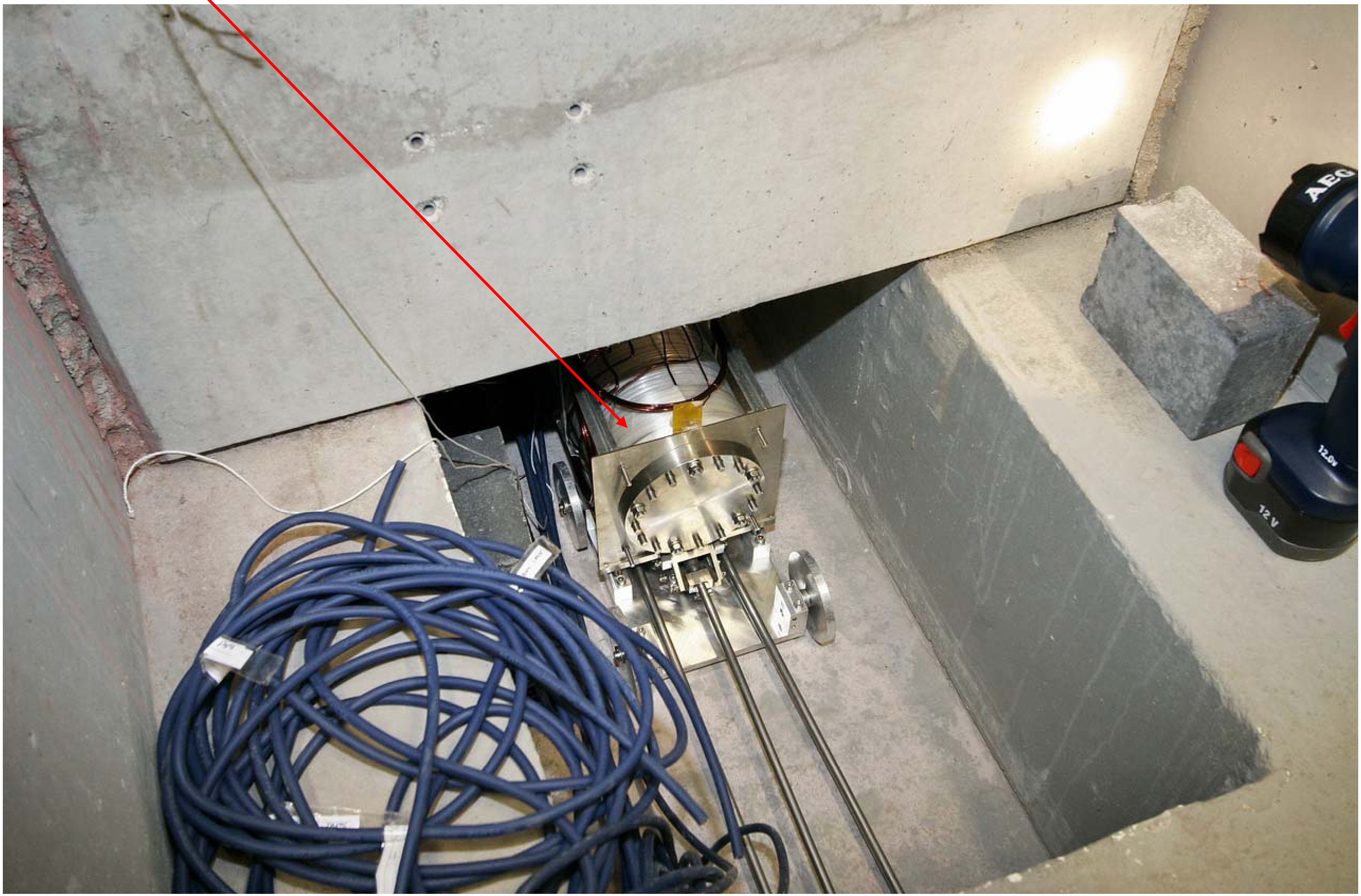


First Projects of EPOS

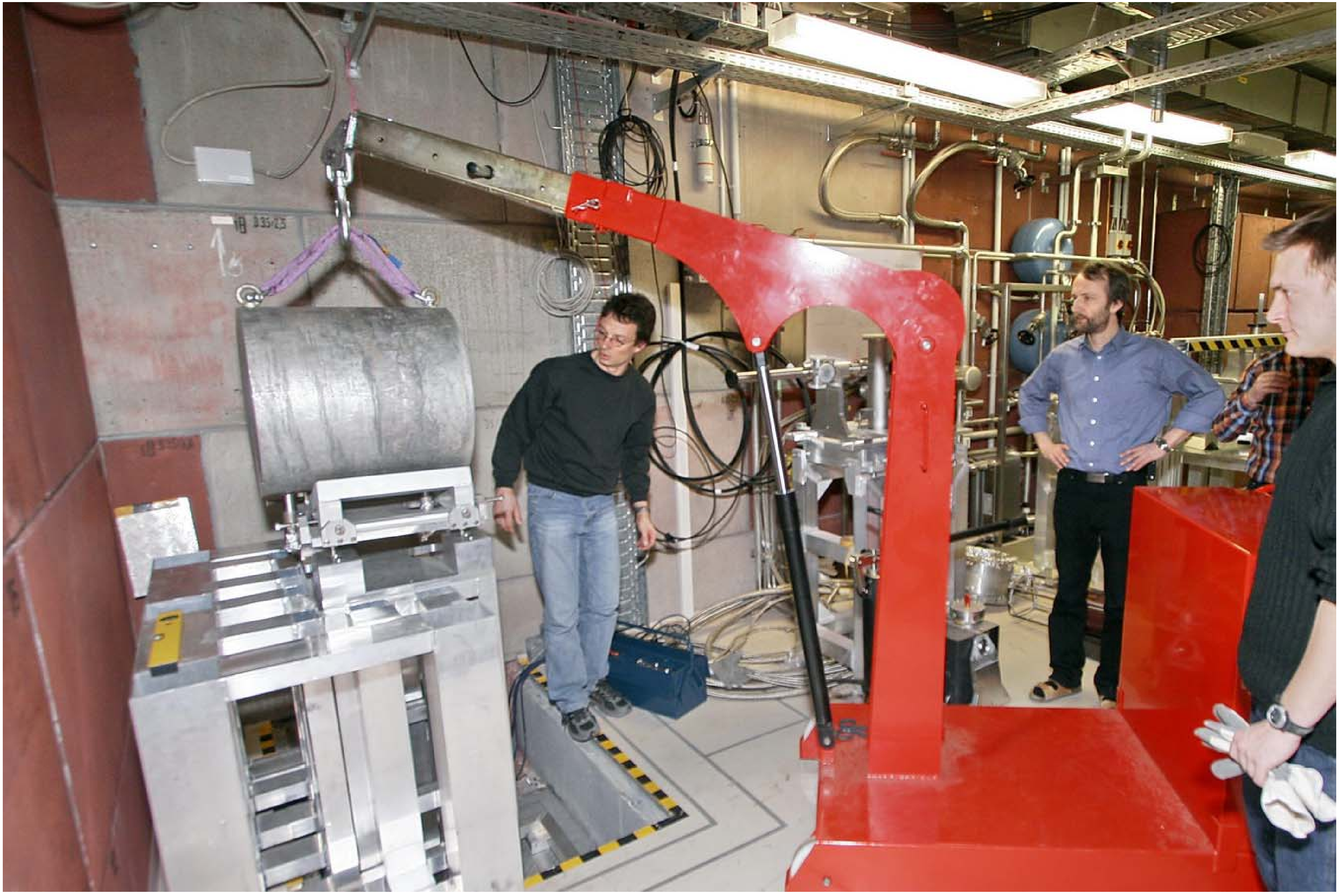
- Irradiation-hard Steel of Fission Reactors (FZD)
- Defects in ZnO (FZD & Uni Leipzig; IKZ Berlin)
- Low-k dielectrics for microelectronics (AMD Saxony)
- Smart cut of wide band-gap semiconductors – GaN, ZnO, AlN (MPI Halle)
- Rp/2 effect in Si (FZD)
- Abnormal diffusion of Zn and Cu in III-V-compund semicondutors (Uni Halle)
- Pore size distribution on micro- and mesopores (Uni Halle)
- Defects in “dirty” Si for photovoltaic (Fraunhofer Inst. Halle)
- Thin polymer layers on top of metallic substrate (Uni Kiel)
- Hydrogen in defects in metals (Uni Prague, FZD)
- Defects after tribological treatment of surfaces (Academy Inst. Krakow)
- …


View flange
Beam dump
Be entrance window
to vacuum system
Pb stand
Water cooling pipes
16
13
Beam extraction to Laboratory

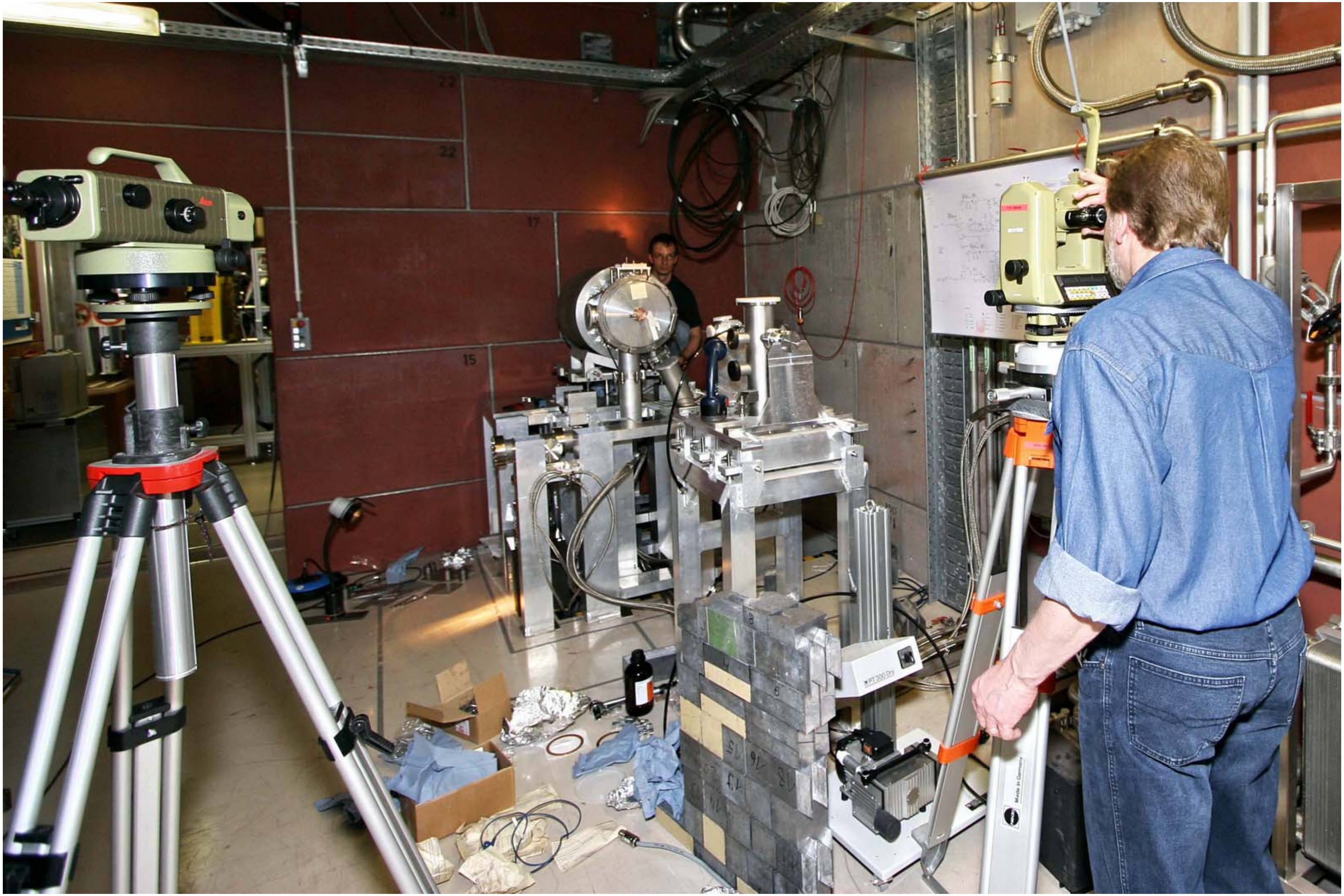
Beam line through cable channel under 3.2 m concrete



Electron beam dump is put onto the stand



Adjustment of Be windows: deviation 0.17mm (y-direction) and 0.10 mm (x-direction)



Pb screening almost complete

Heavy concrete radiation screening started