Experimental Techniques of Positron Annihilation and the pulsed Positron Source EPOS

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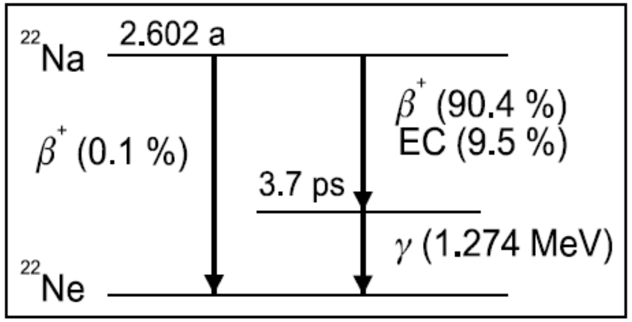
- Techniques of Positron Annihilation
  - Positron Sources
  - Positron Lifetime / Doppler Broadening / Angular Correlation / AMOC
  - The Trapping Model
  - Monoenergetic Positron Beams for near-surface Defect Studies
- The pulsed, intense Positron Source EPOS at ELBE (Research Center Dresden-Rossendorf)

Positron Sources

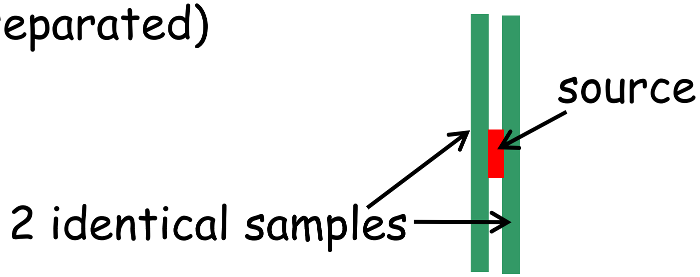
Positrons are usually obtained either by:

- Isotope source: e^+ decay $^{22}Na \rightarrow ^{22}Ne + e^+ + \nu + \gamma$ (1.27MeV)
  (half life: 2.6 years, up to 10^6 e^+/s with "normal" sources)
- pair production using a beam of MeV-electrons onto a target
  (Bremsstrahlung creates positrons; $\approx 10^9$ e^+/s; discontinuous positron beam)

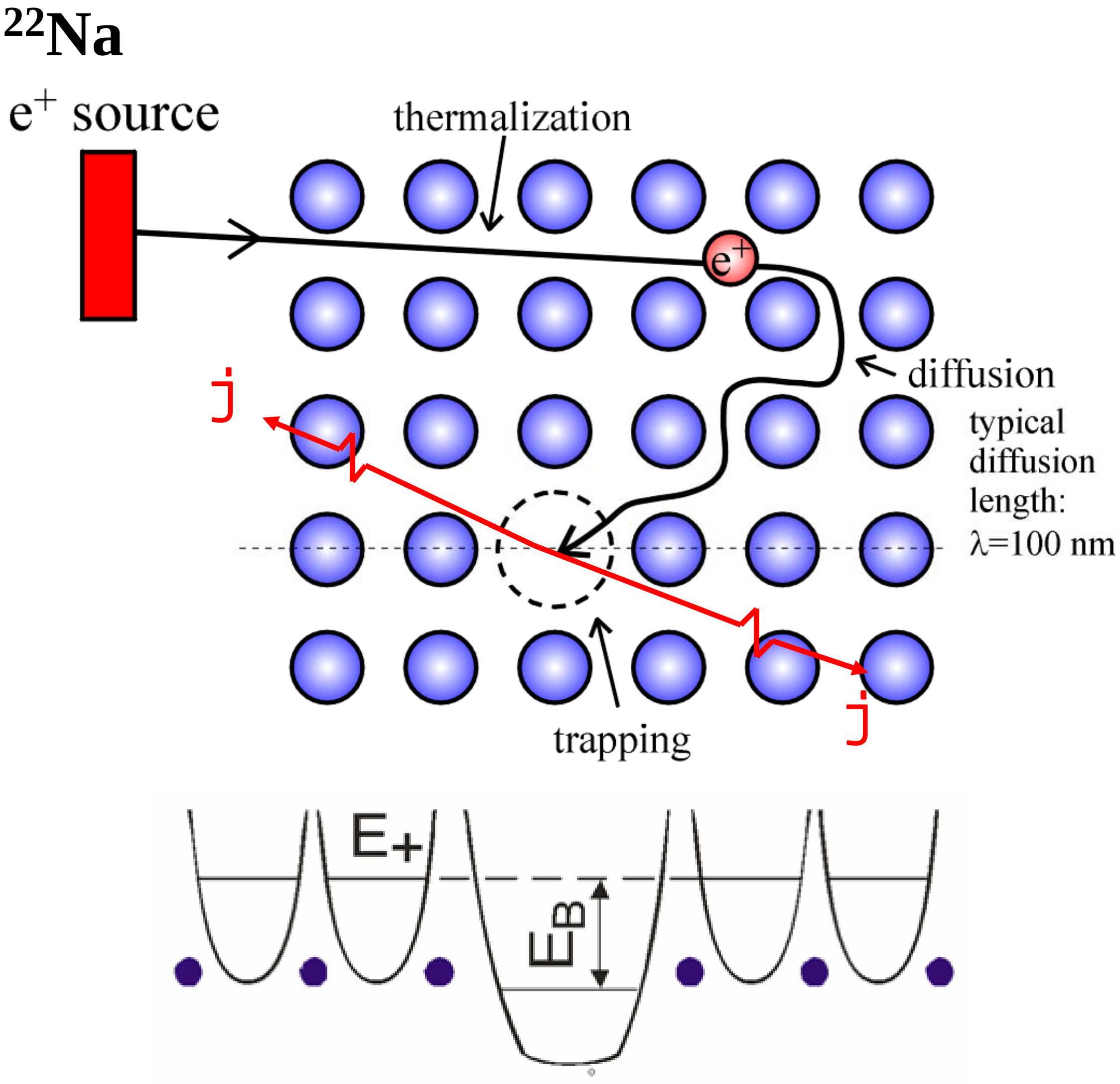


Positrons must hit the sample:

- "Sandwich geometry" (^{22}Na source between two identical samples)
- positron beam (source and sample separated)

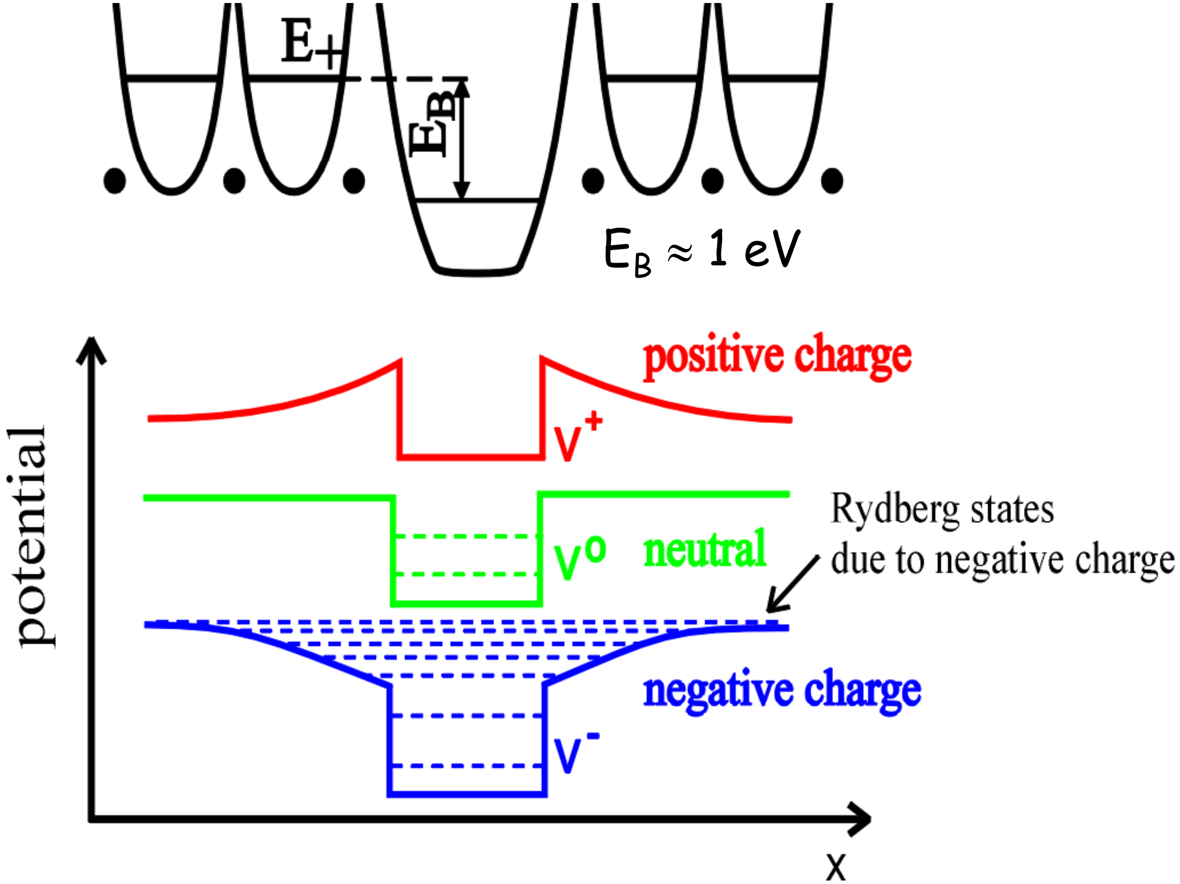


The positron lifetime spectroscopy



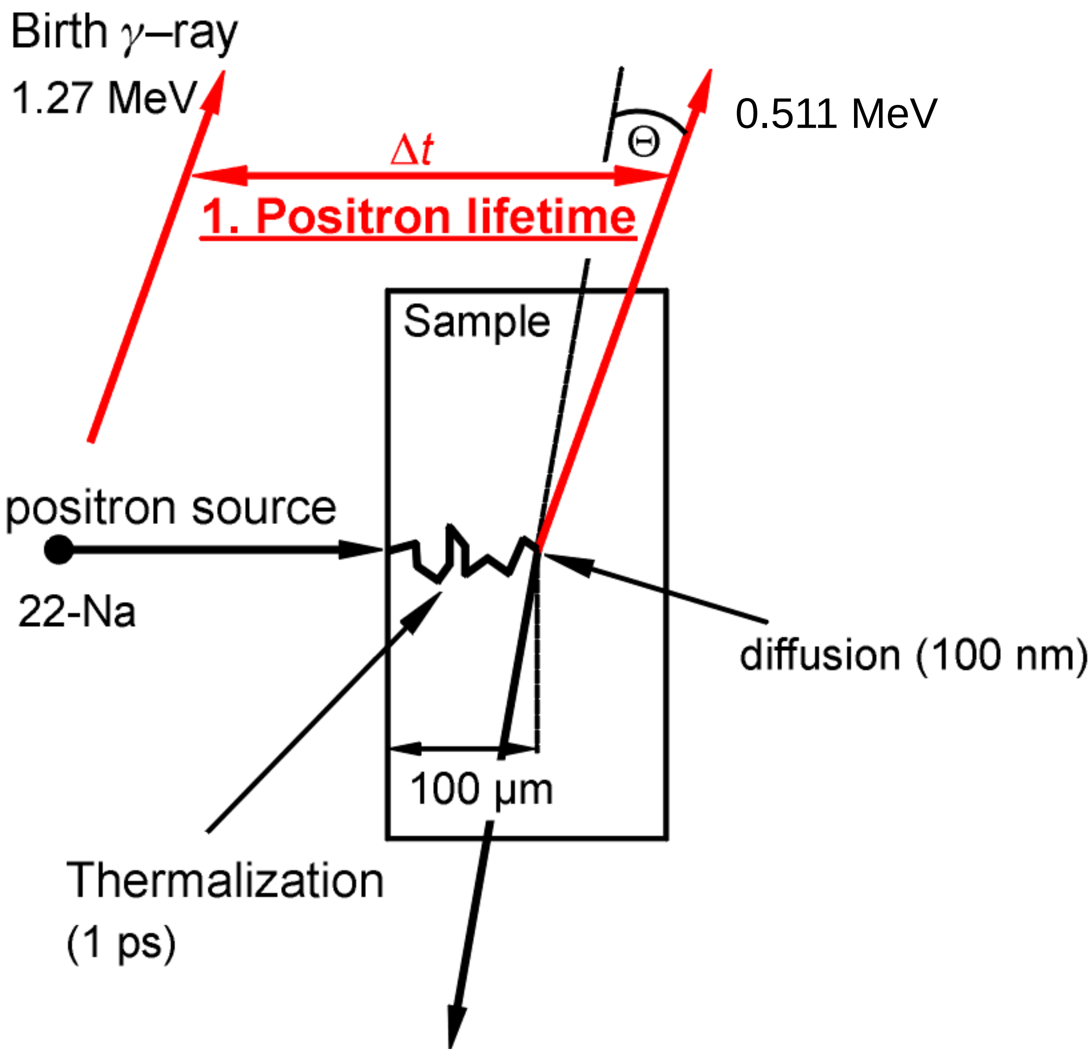
- positron wave-function can be localized in the attractive potential of a defect
- annihilation parameters change in the localized state
- e.g. positron lifetime increases in a vacancy
- lifetime is measured as time difference between appearance of 1.27 (start) and 0.51 MeV (stop) quanta
- defect identification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

Positron Trapping Potential

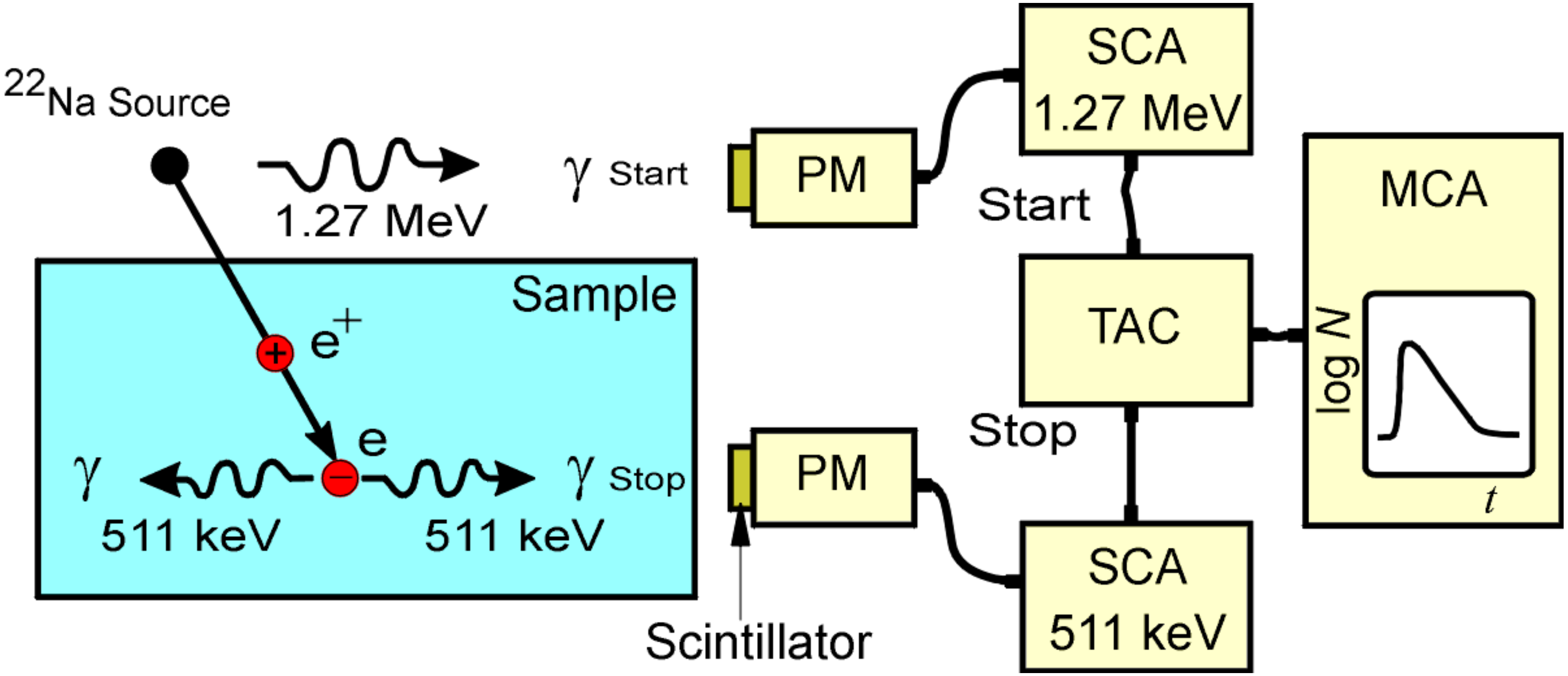


- attractive potential mainly due to missing ion (repelling core is absent)
- in semiconductors: additional Coulomb tails
- no positron trapping by positive vacancies

The Methods of Positron Annihilation



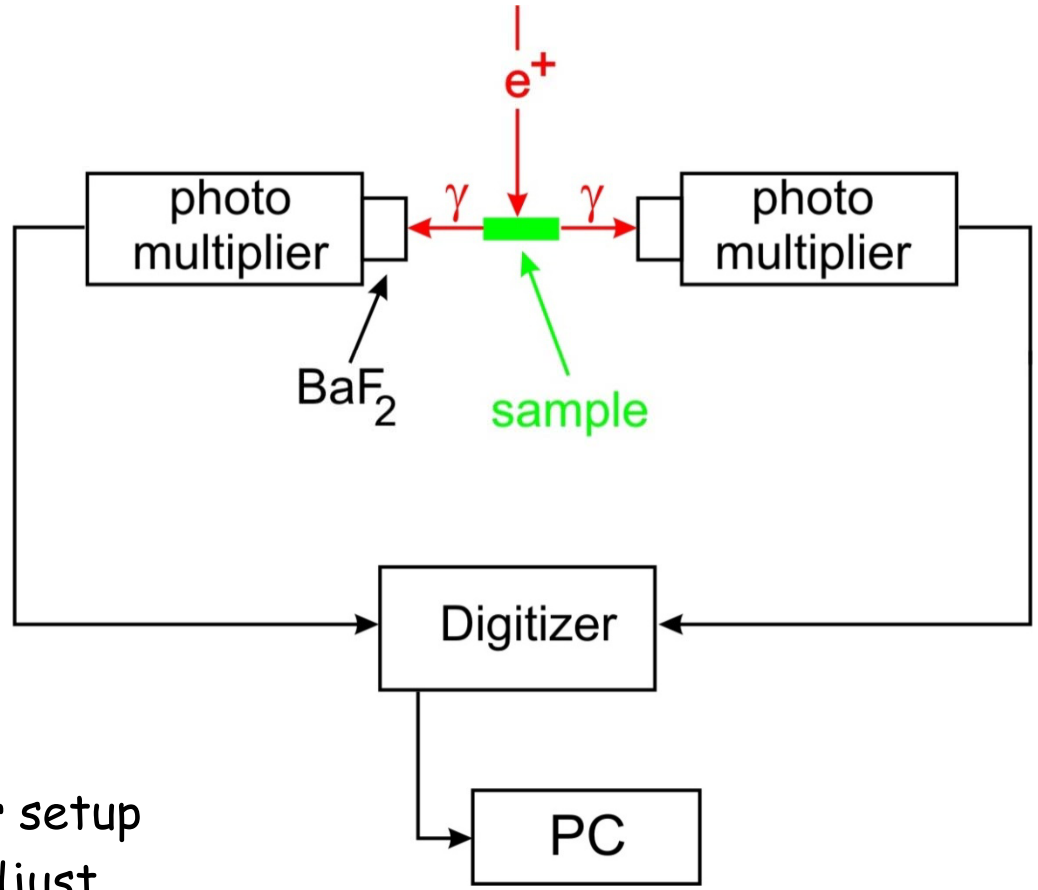
The Positron Lifetime Measurement – Analog Setup



- Positron lifetime is measured as time difference between 1.27 MeV quantum (e^+ decay) and 0.511 MeV quanta (annihilation process)

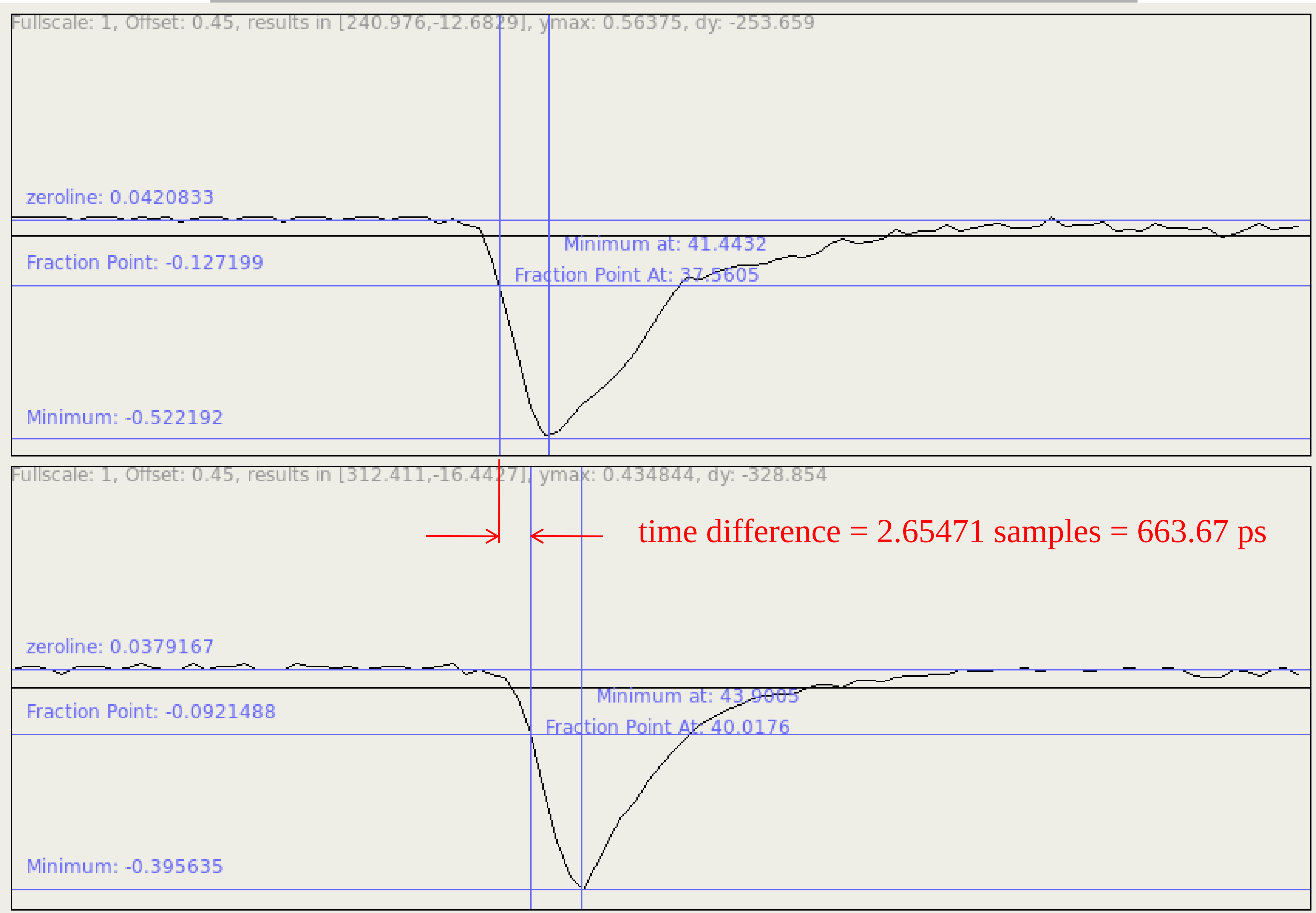
PM=photomultiplier; SCA=single-channel analyzer (constant-fraction type); TAC=time-to-amplitude converter; MCA= multi-channel analyzer

Digital lifetime measurement

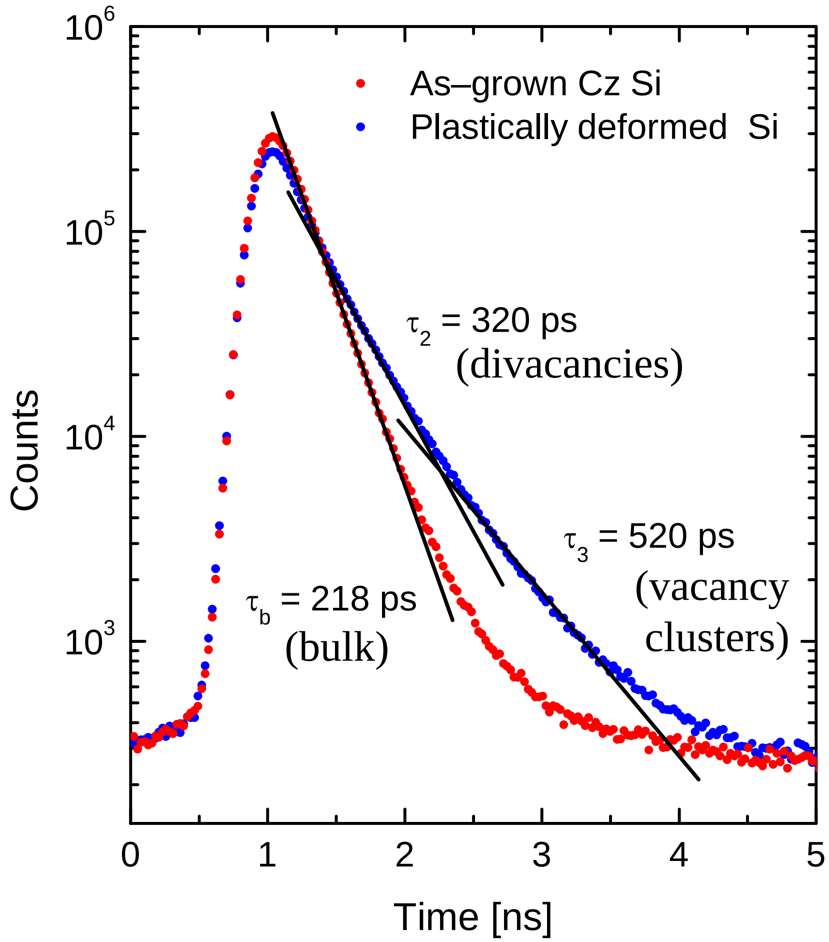


- much simpler setup
- nothing to adjust
- timing very accurate (accuracy 10^{-6})
- pulse-shape discrimination (suppress “bad pulses”)
- each detector for start & stop (double statistics)

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:

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

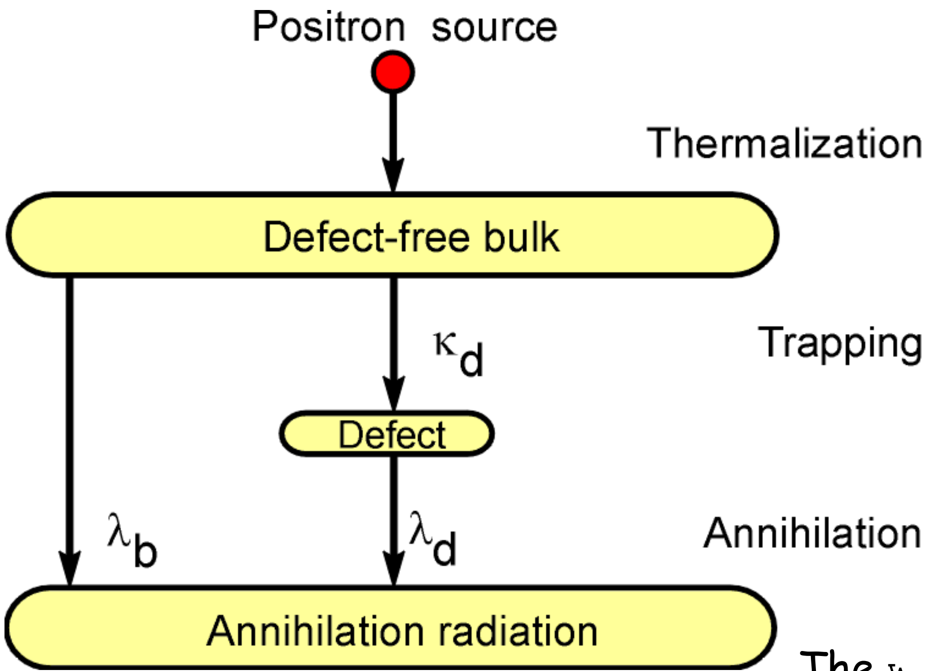
trapping coefficient

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

trapping rate

defect concentration

Analysis of Positron Lifetime Spectra



$$\frac{dn_b(t)}{dt} = -(\lambda_b + \kappa_d)n_b(t)$$

$$\frac{dn_d(t)}{dt} = -\lambda_d n_d(t) + \kappa_d n_b(t)$$

solution: decay spectrum

$$D(t) = I_1 \exp\left(-\frac{t}{\tau_1}\right) + I_2 \exp\left(-\frac{t}{\tau_2}\right)$$

The w_i and I_i are measured and n (trapping rate) is thus obtained. It is proportional to the defect density C_d (μ is trapping coefficient).

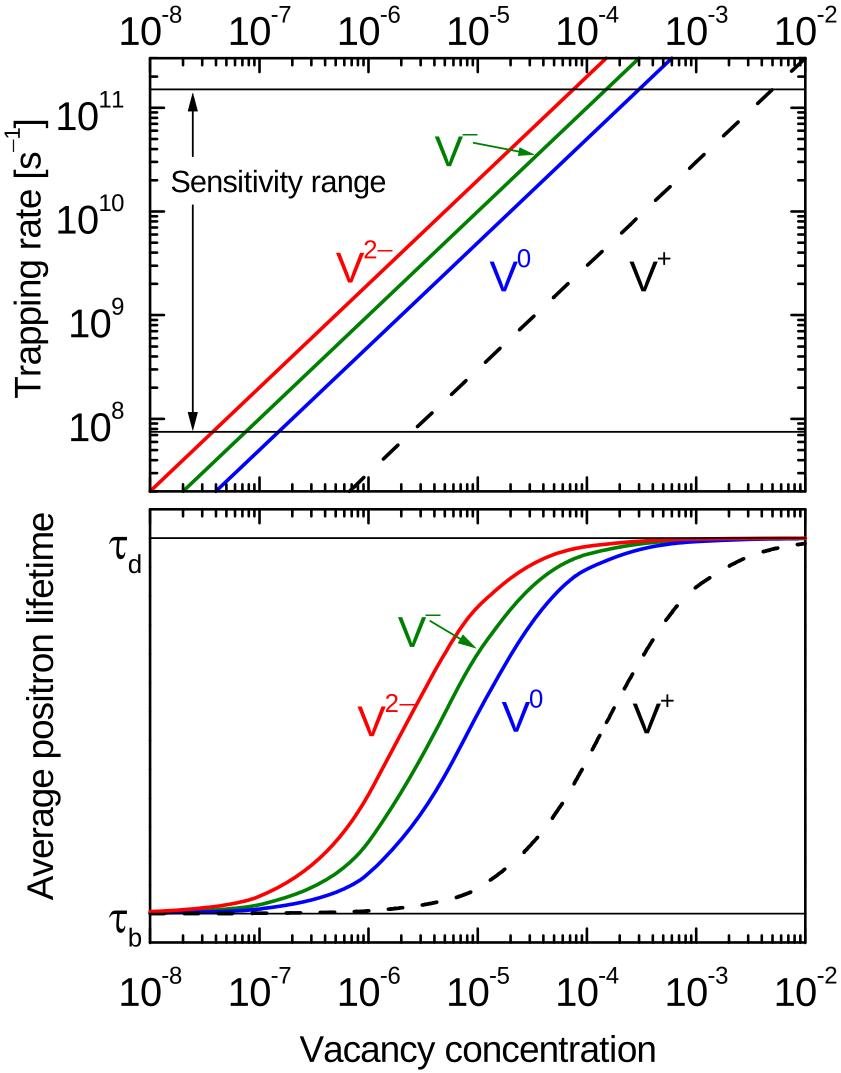
abbreviations:

$$w_1 @ \frac{1}{c_b \,.\, n_d}, \quad w_2 @ \frac{1}{c_d},$$

$$I_1 @ 10 \; I_2, \quad I_2 @ \frac{n_d}{c_b \; 0 \; c_d \,.\, n_d}$$

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

Determination of absolute Defect Densities



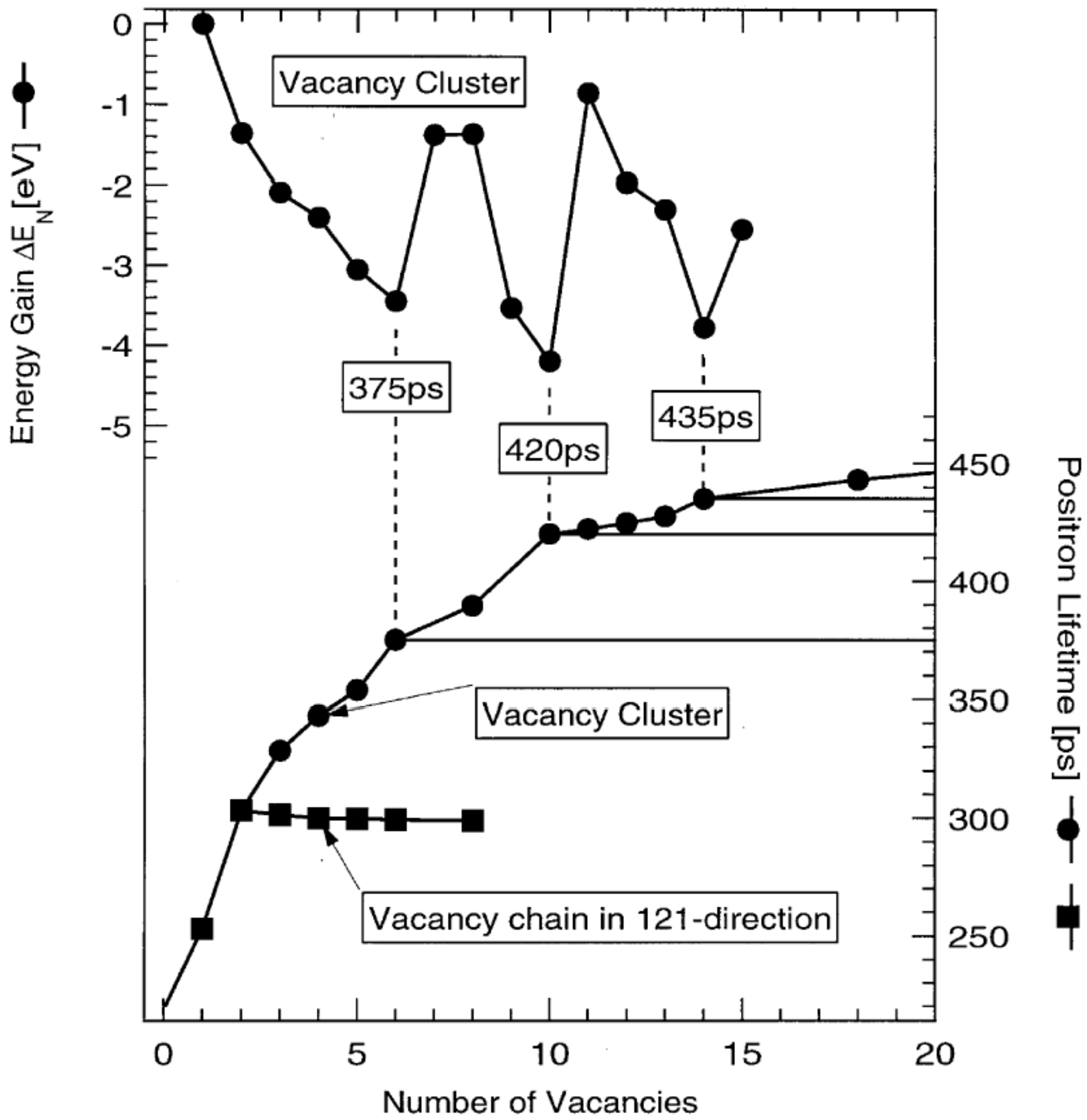
- the trapping coefficient μ $n = \mu C$ must be determined by an independent method
- positron trapping may be strongly temperature-dependent: $\mu = f(T)$

defect in Si_{300K}	μ (10^{15} s^{-1})
V^-	1
V^{2-}	2
V^0	0.5
V^+	< 0.1
dislocation	1 cm^2s^{-1}
vacancy cluster	$n \cdot \mu_{1V}$

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}

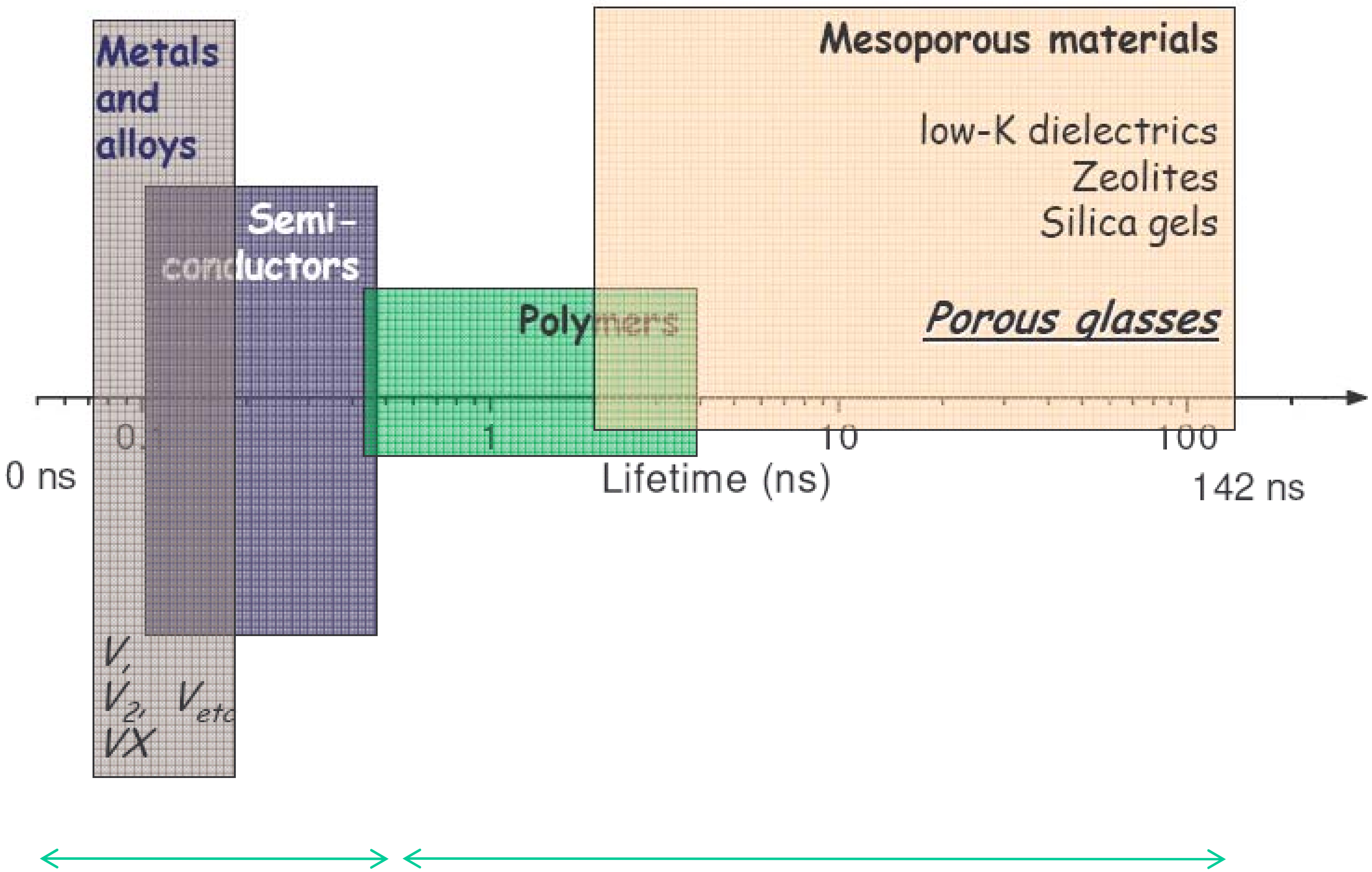
Theoretical Calculation of Vacancy Clusters in Si



- 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

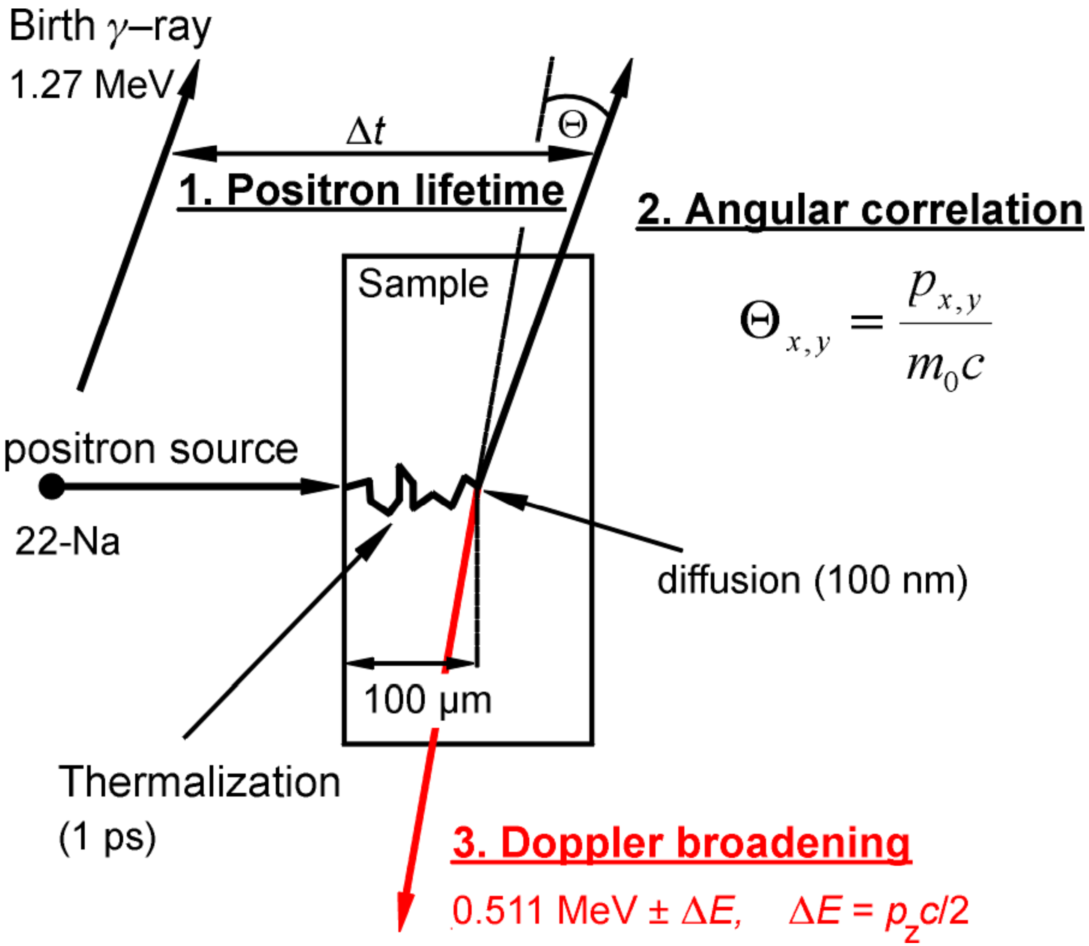
Typical Lifetimes



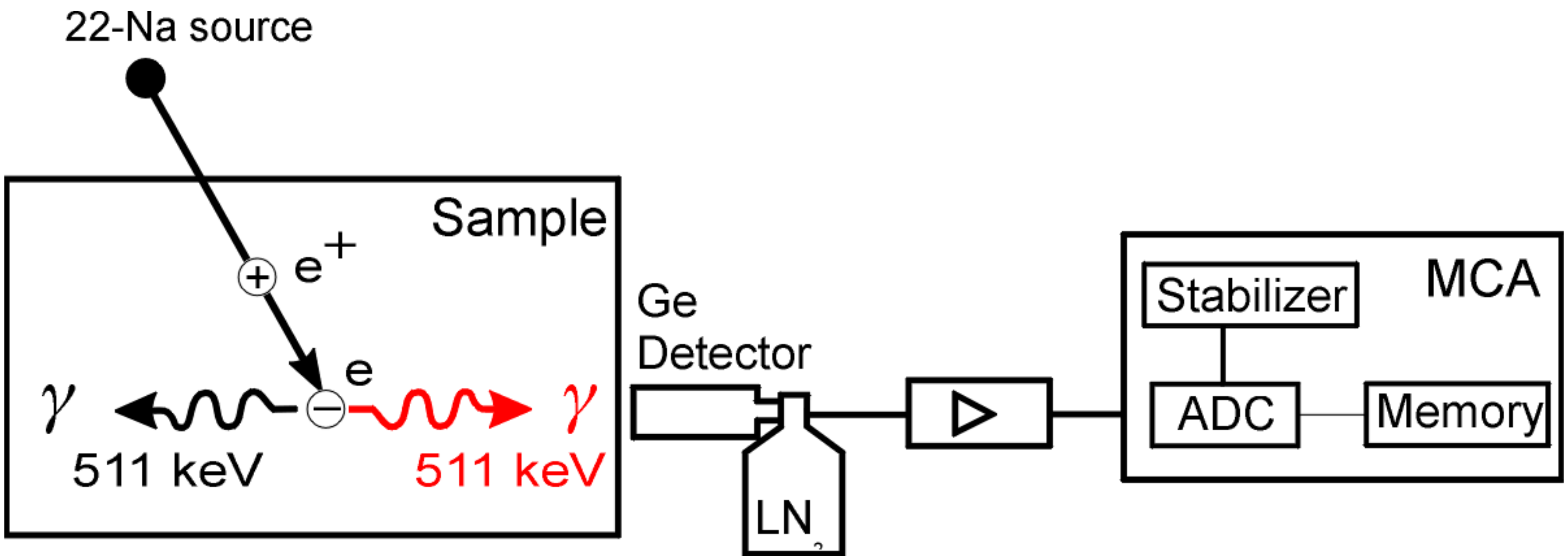
Positron

Positronium

The Methods of Positron Annihilation



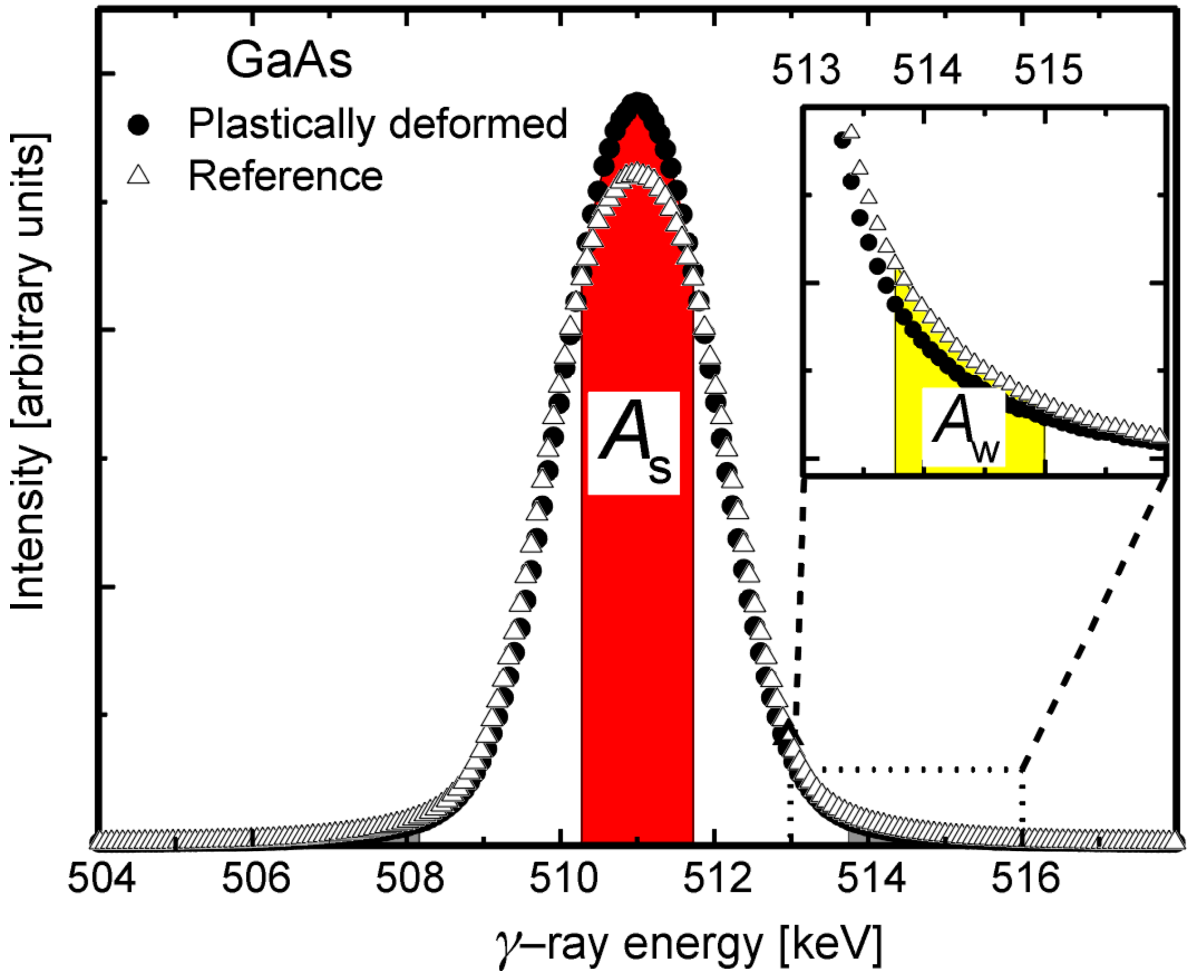
Measurement of Doppler Broadening



$$\Delta E = p_z c/2$$

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

Line-Shape Parameters

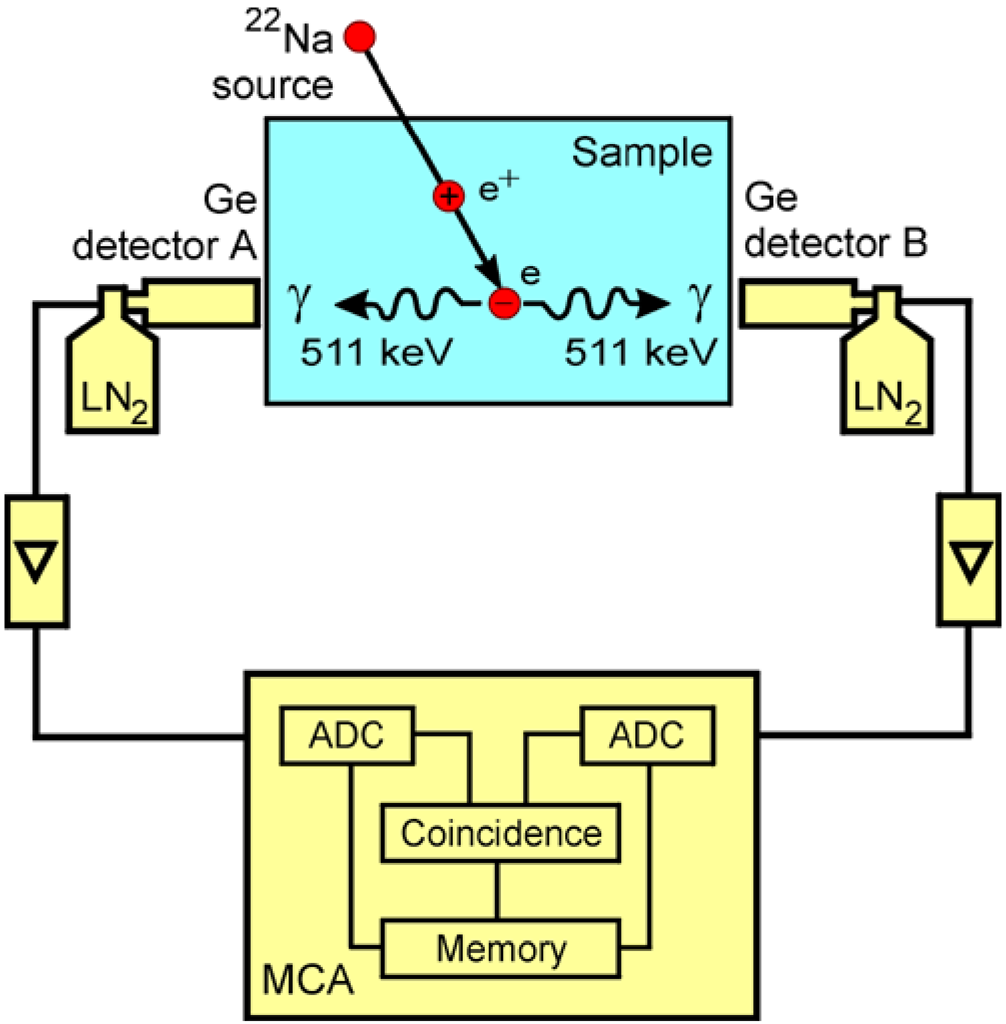


- **S parameter:**
  $S = A_S/A_0$
- **W parameter:**
  $W = A_W/A_0$
- W parameter mainly determined by annihilations of core electrons (chemical information)
- $S = (1\text{-k})S_b \; . \; \text{k}S_d$

$$C_d \; @ \; \frac{1}{\text{p}\,\text{w}_b}\,\frac{S \; 0 \; S_b}{S_d \; 0 \; S}$$

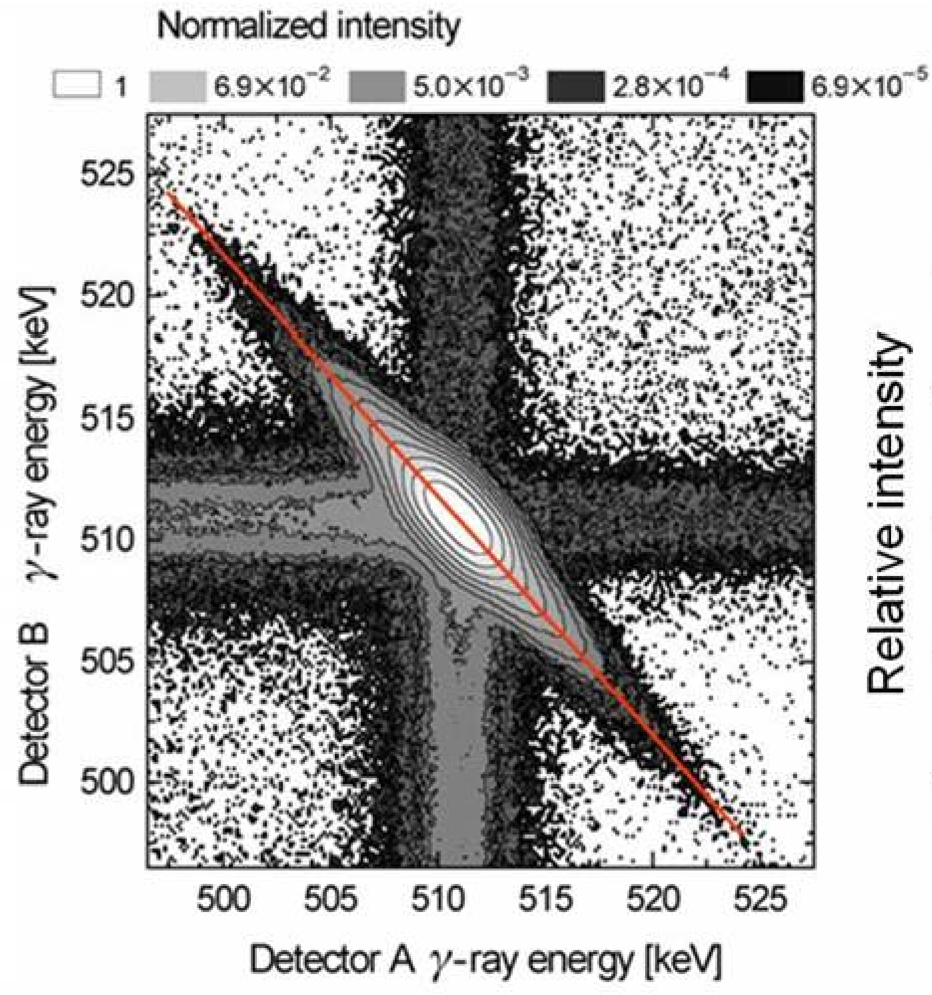
(C_d..defect density, μ trapping coefficient, d..defect, b..bulk, w..lifetime, k..trapping fraction)

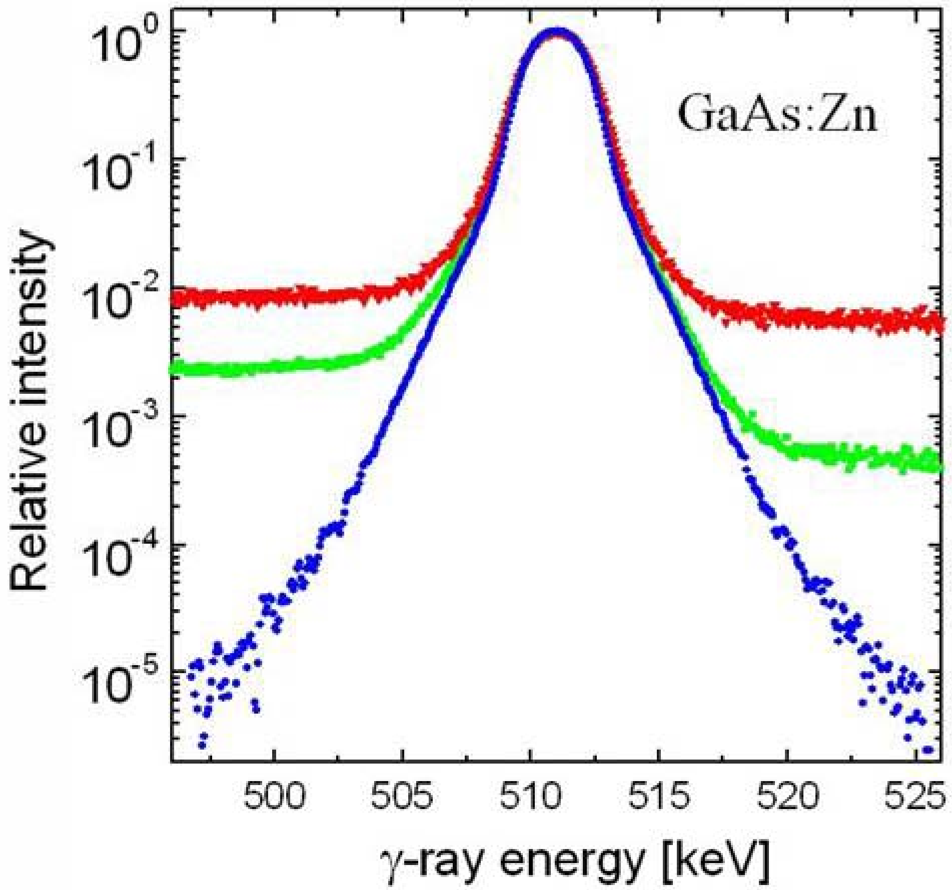
Doppler Coincidence Spectroscopy



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

Doppler Coincidence Spectra

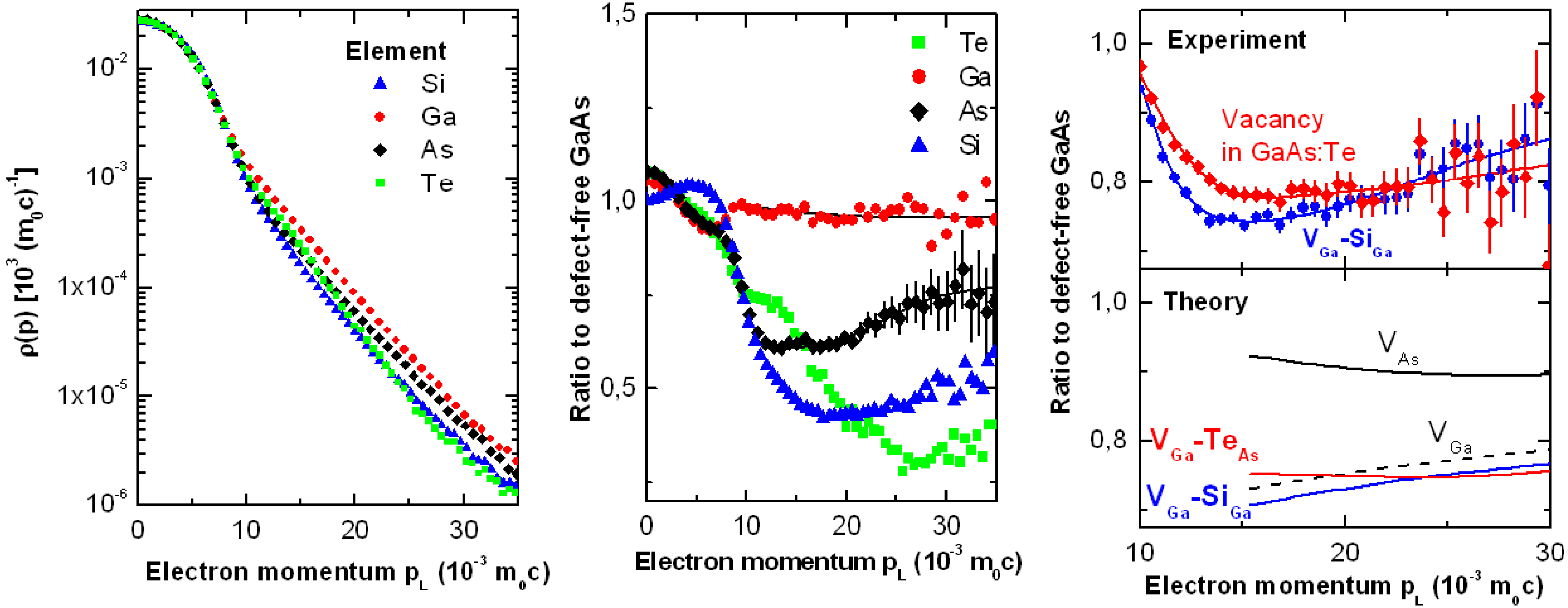




$$E_1+E_2= 2\ m_0\ c^2 =1022\ keV$$

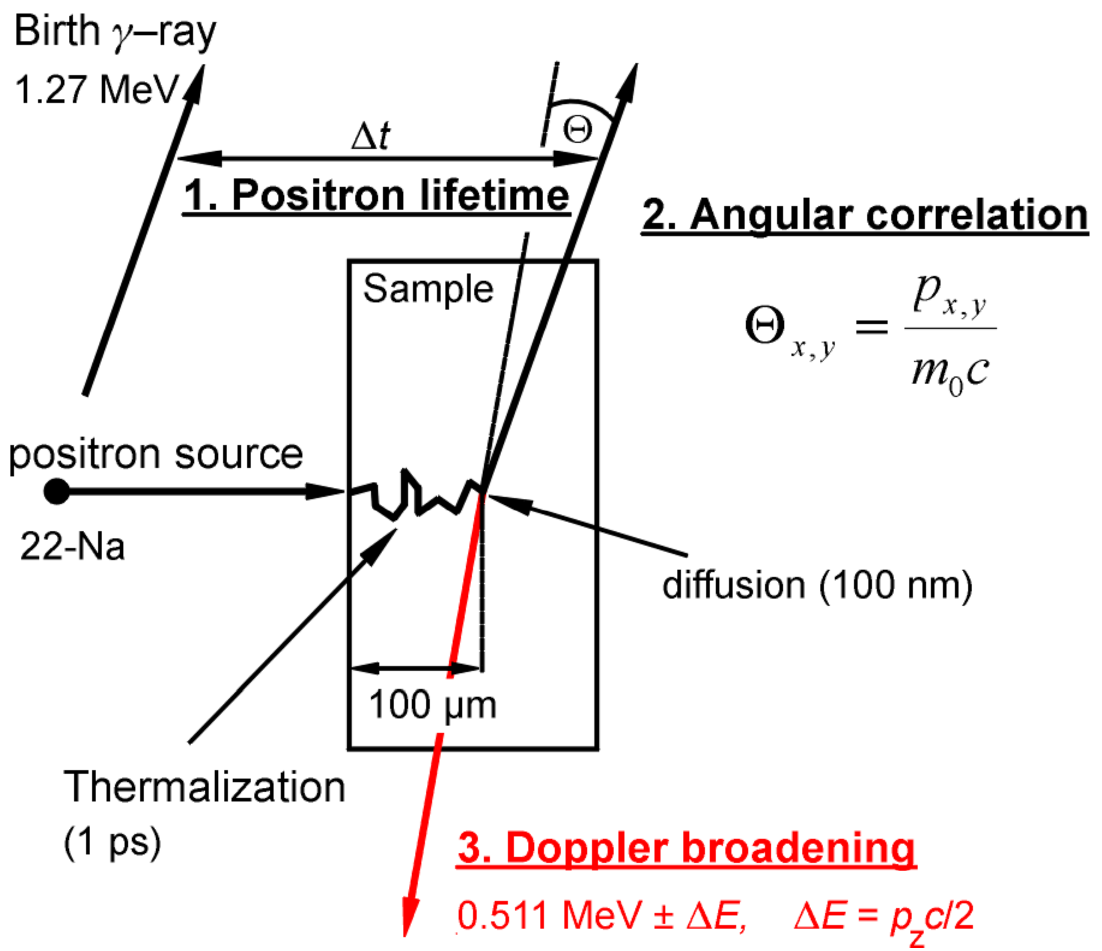
Doppler-Coincidence-Spectroscopy in GaAs

- 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

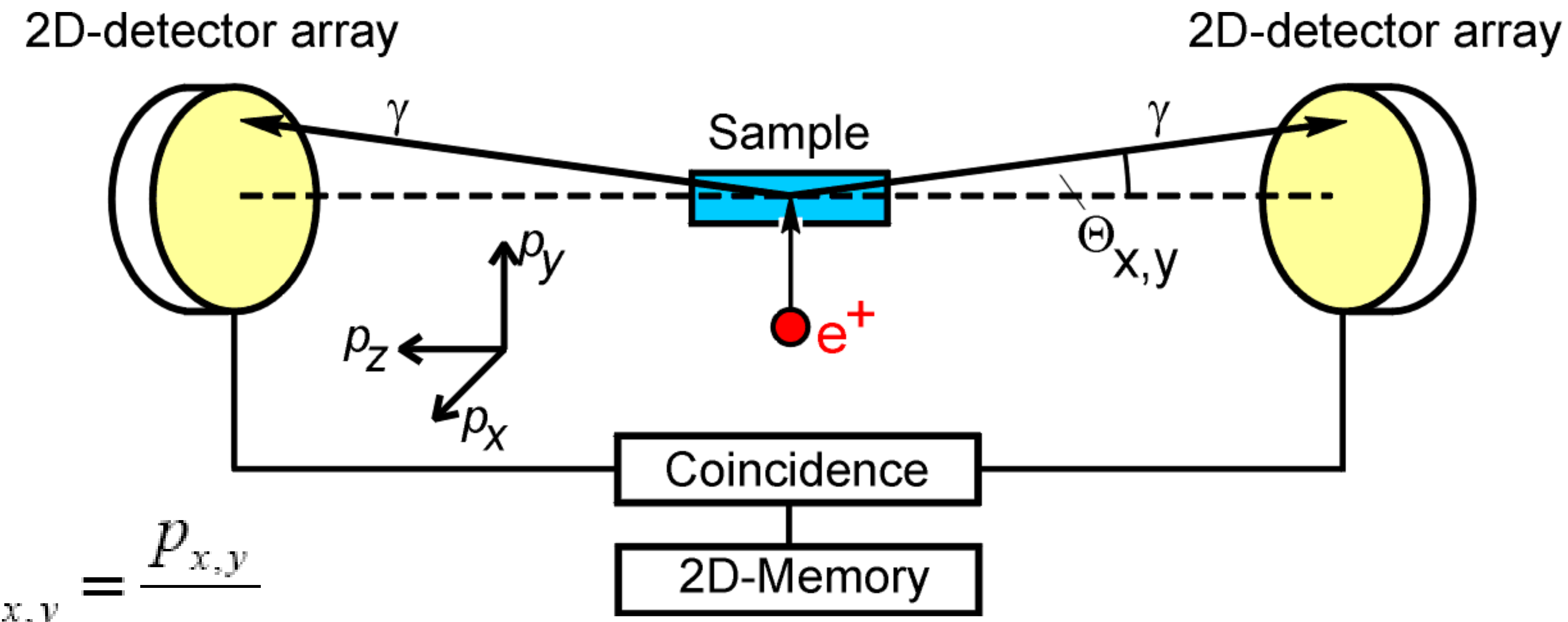


J. Gebauer et al., Phys. Rev. B **60** (1999) 1464

The Methods of Positron Annihilation



Angular Correlation of Annihilation Radiation - ACAR

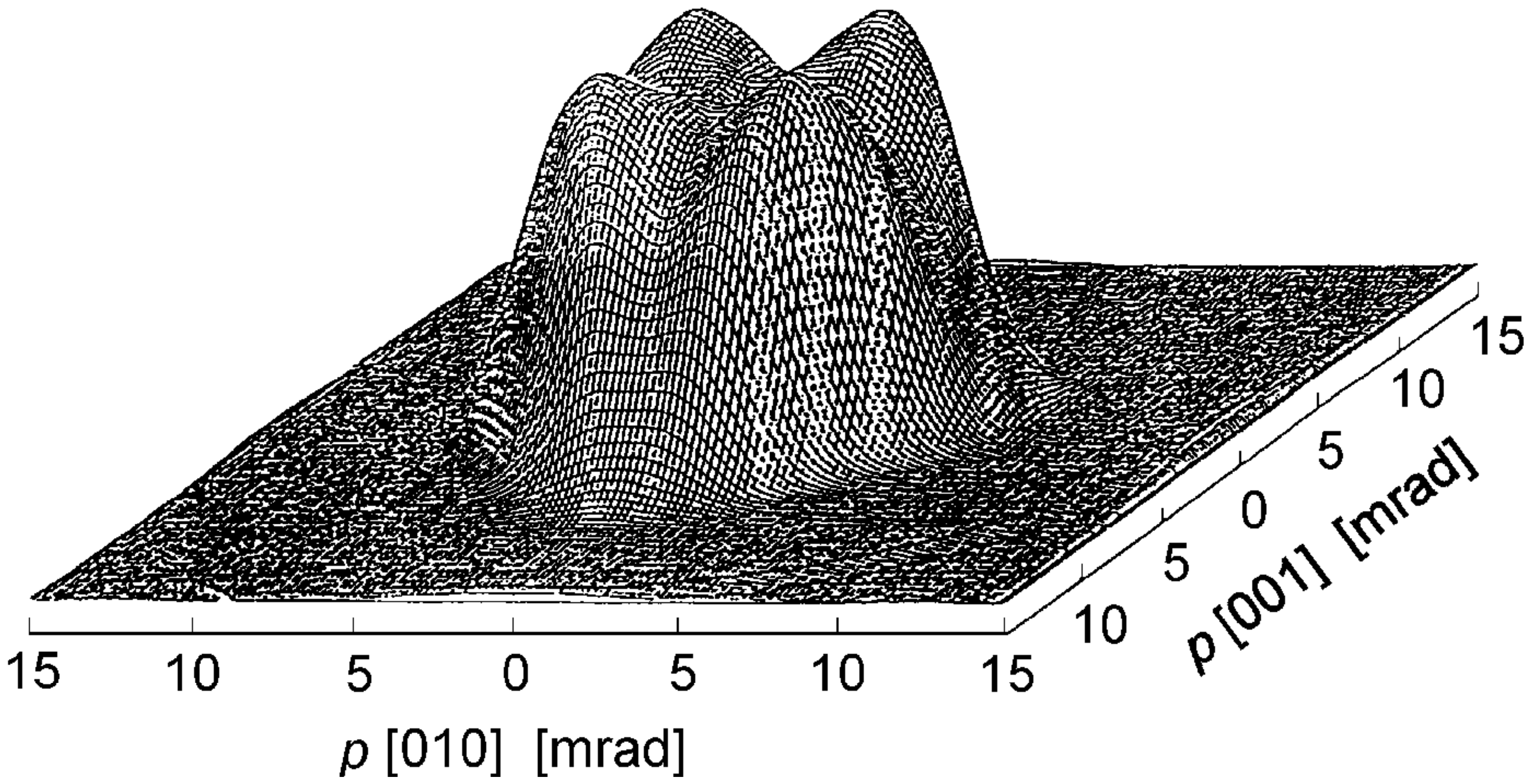


$$\Theta_{x,y} = \frac{p_{x,y}}{m_0 c}$$

Coincidence counting rate N_c:

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

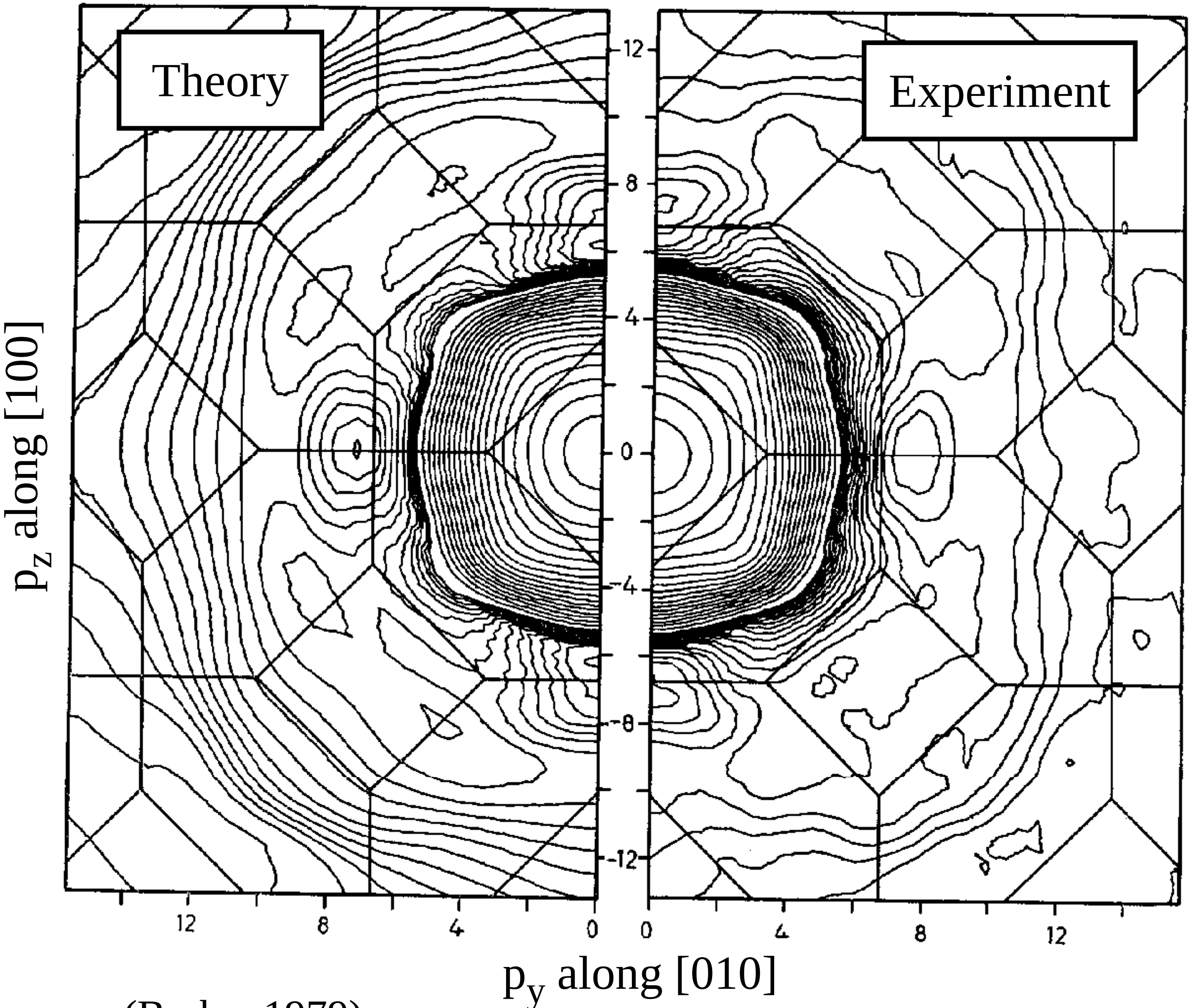
2D-ACAR of defect-free GaAs



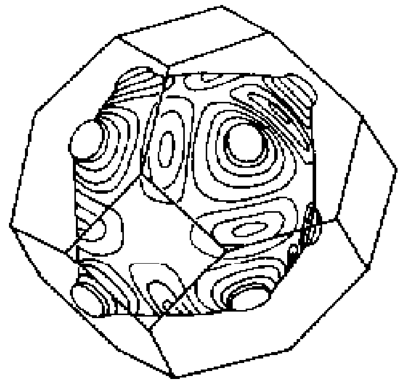
(Tanigawa et al., 1995)

3D-Fermi surface can be reconstructed from measurements in several directions of a single crystal

2D-ACAR of Copper

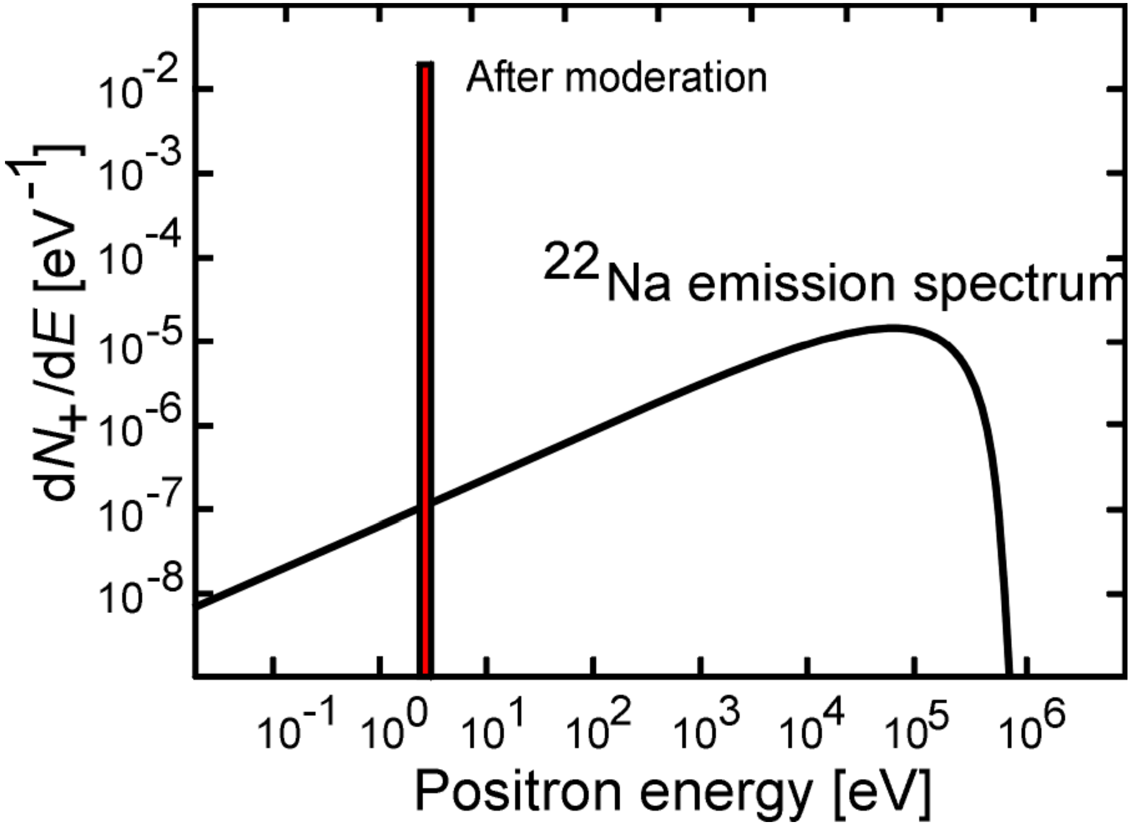


(Berko, 1979)



Fermi surface of copper

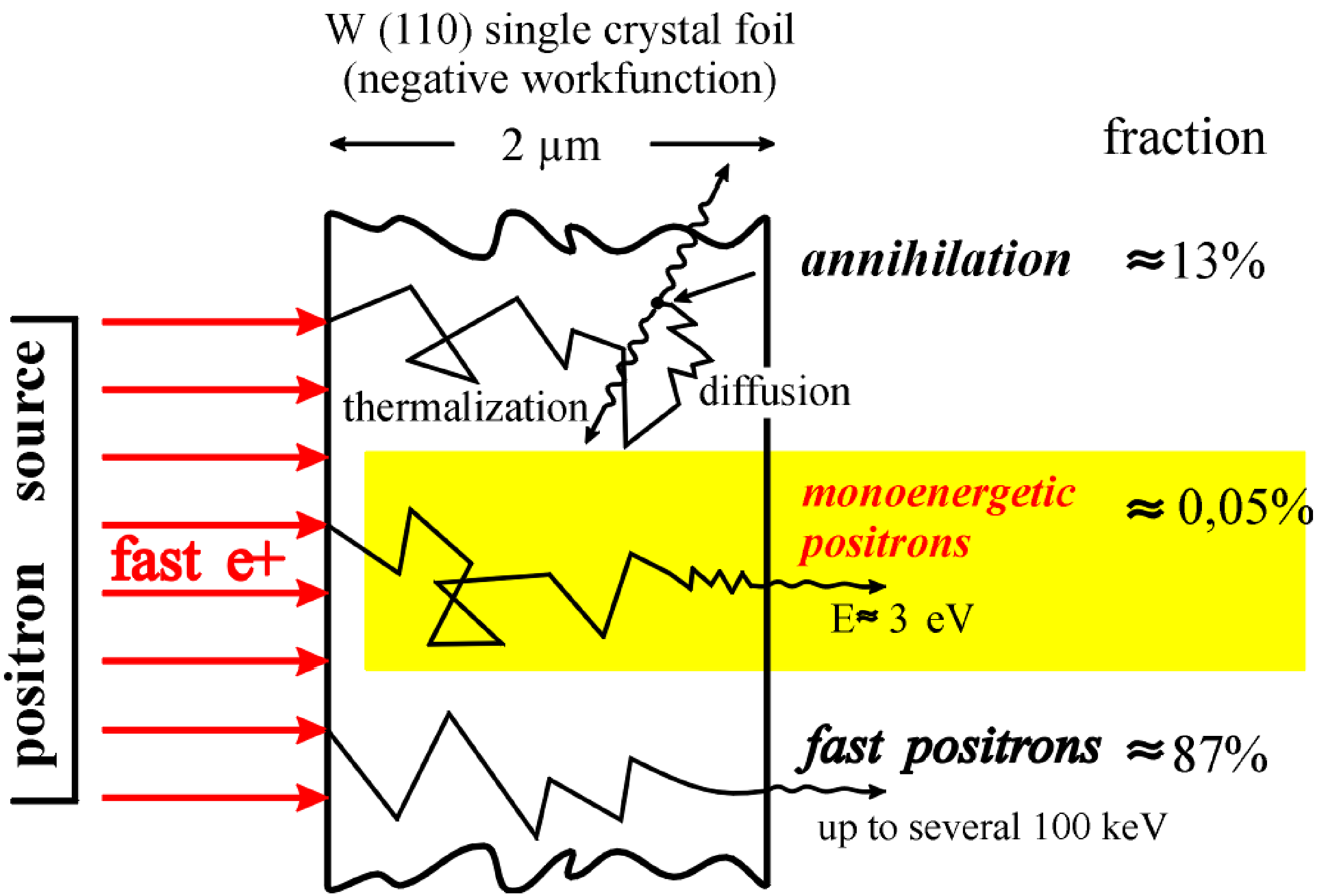
Thermalization in Solids



- broad positron emission spectrum
- deep implantation into solids
- no use for study of defects in thin layers
- moderation necessary

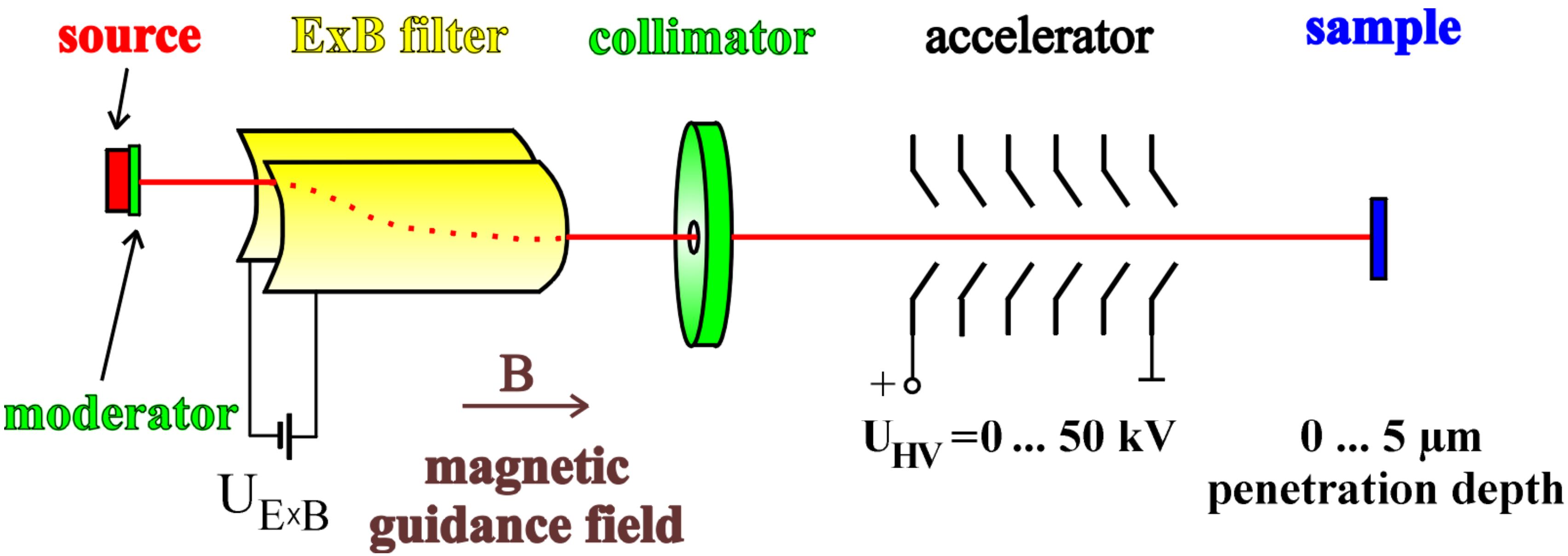
Mean implantation depth of unmoderated positrons (1/e):
Example: Si 50μm

Moderation of Positrons



moderation efficiency only ≈10^{-4}

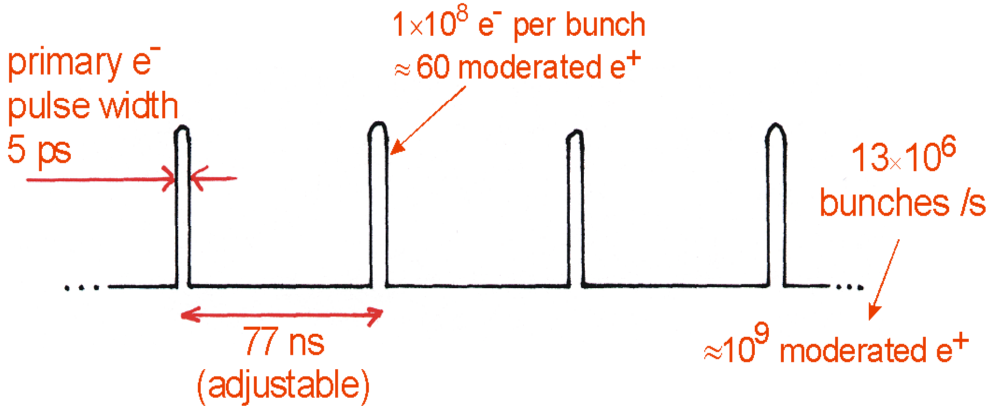
The Positron Beam System at Halle University



- Typical laboratory system (about 40 worldwide)
- spot diameter: 5 mm
- time per single Doppler measurement: 20 min
- time per defect-depth scan: 8 hours
- Drawback: no lifetime spectroscopy possible with this setup

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
- Conventional LINACs: repetition rate in kHz range (positron count rate also in kHz range) – Penning trap required
- Very interesting time structure: cw-mode of short bunches with 13 MHz

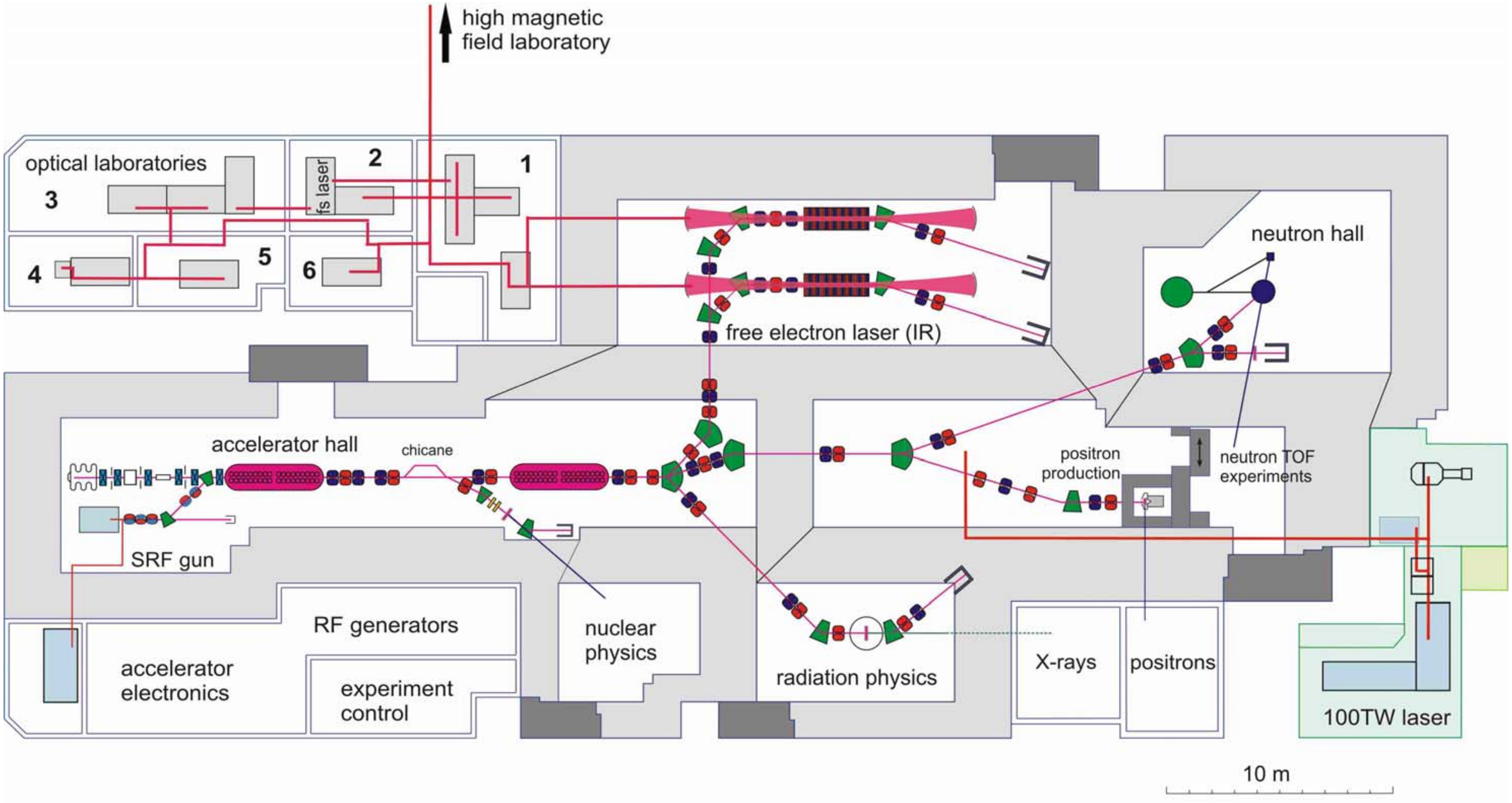


electron bunches

EPOS = ELBE Positron Source

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

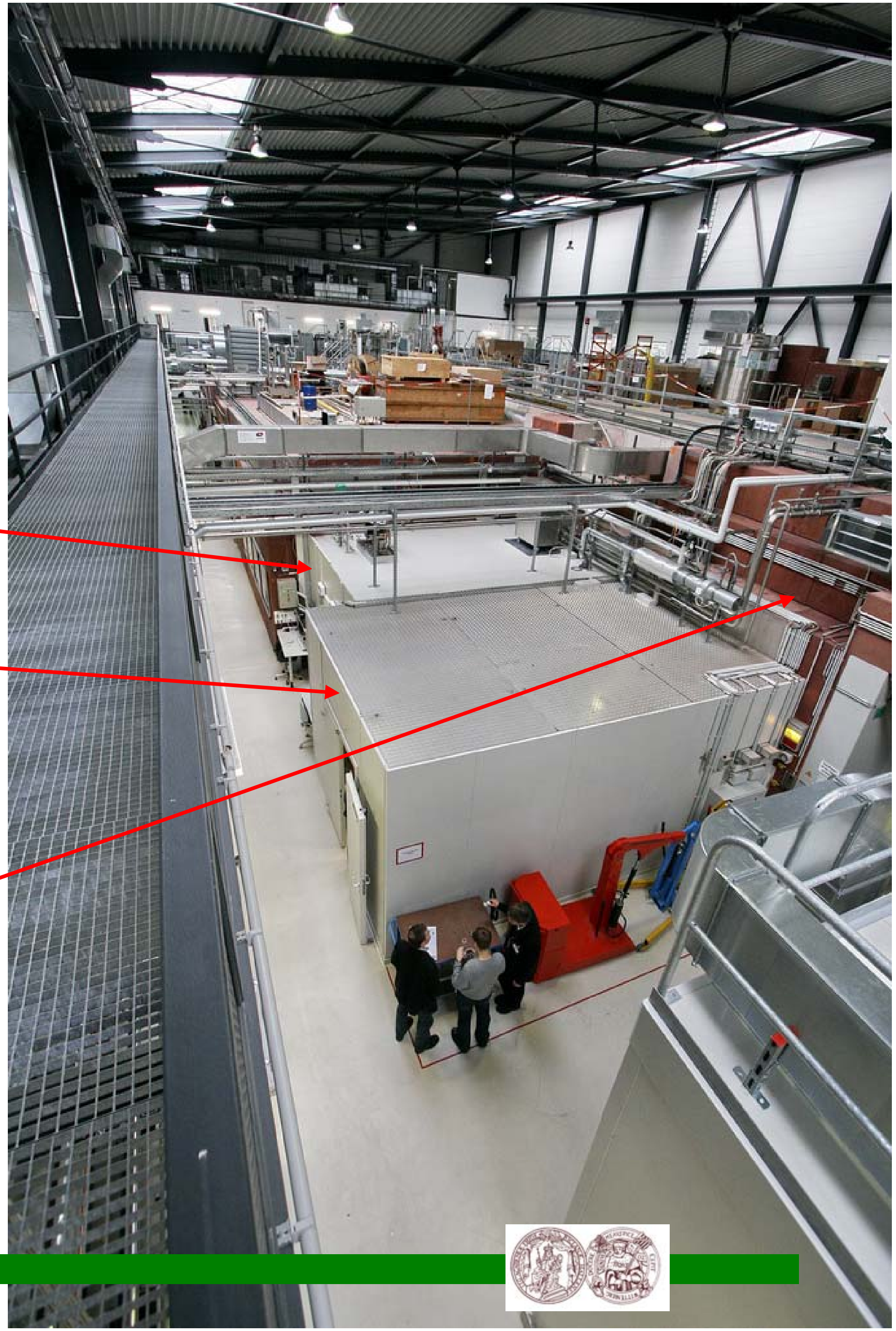
Positron Lab

- positron lab in ELBE hall

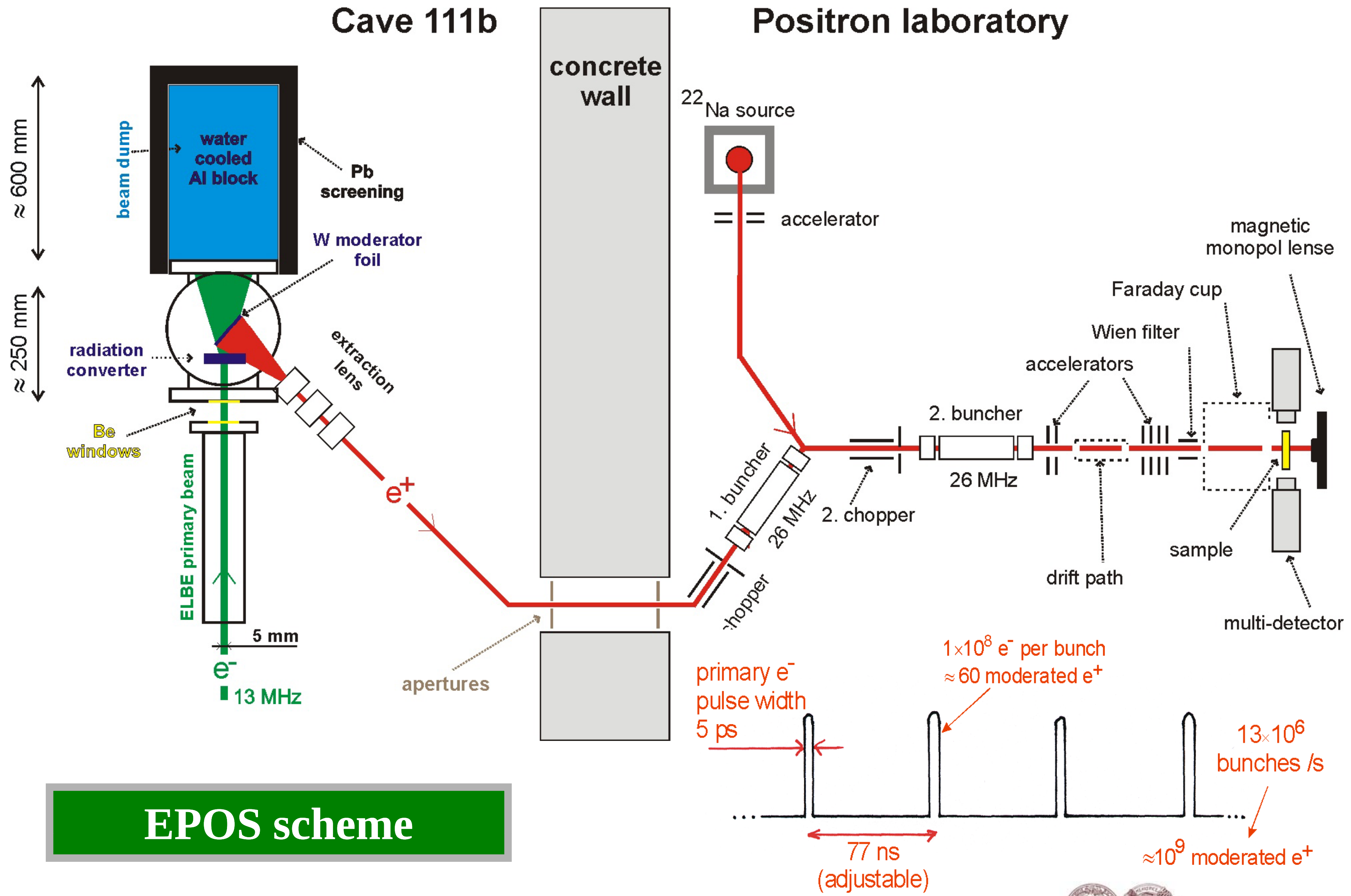
X-ray Lab

Positron Lab

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

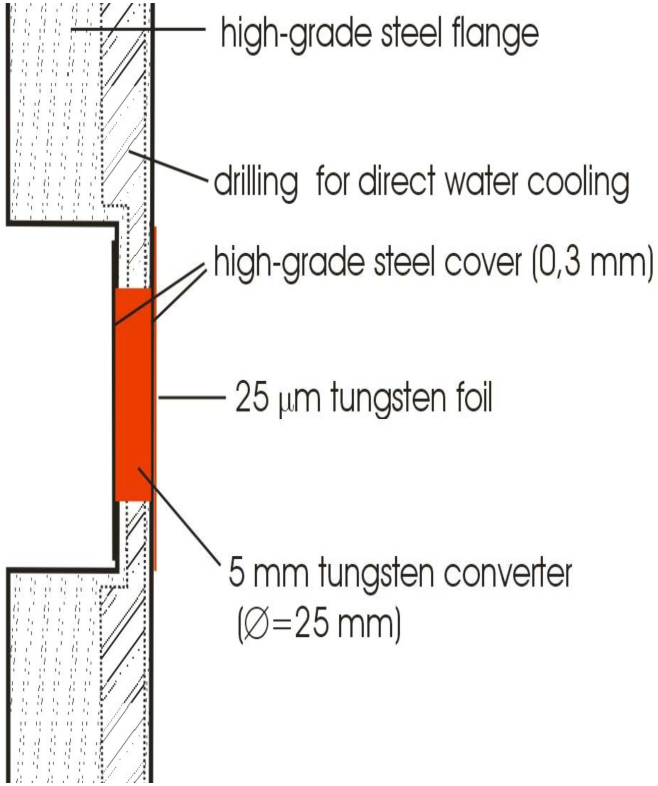


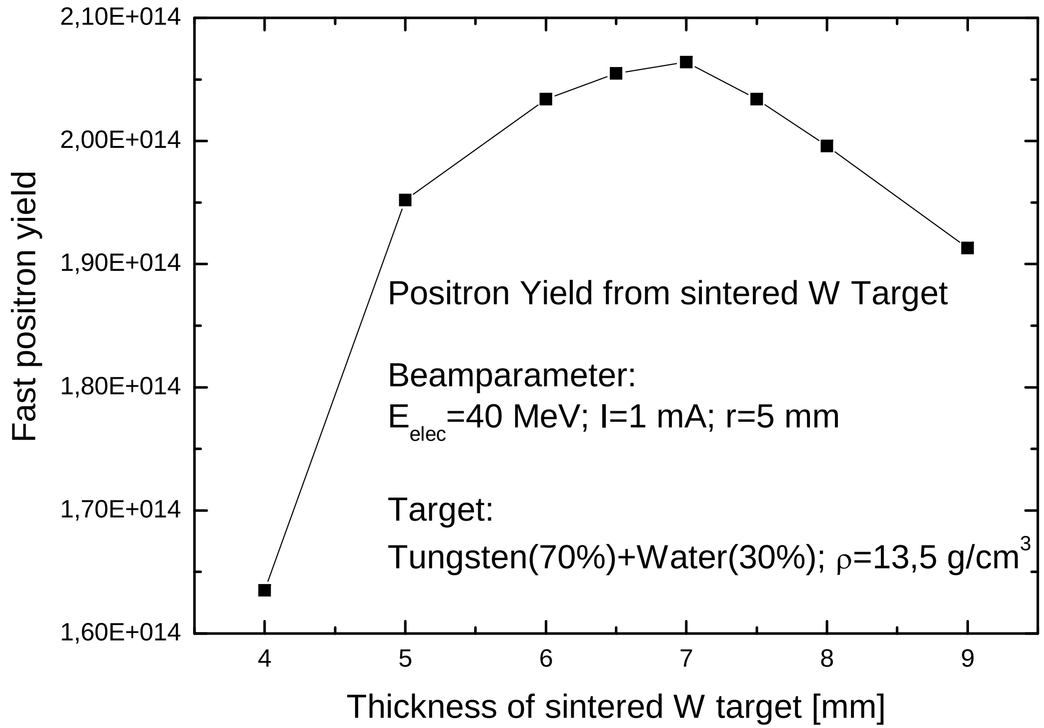
EPOS scheme



Cave 111b
concrete wall
Positron laboratory
≈ 600 mm
≈ 250 mm
beam dump
water cooled Al block
Pb screening
W moderator foil
radiation converter
extraction lens
Be windows
ELBE primary beam
5 mm
e-
13 MHz
e+
apertures
22Na source
accelerator
1. buncher
26 MHz
chopper
2. chopper
2. buncher
26 MHz
accelerators
Wien filter
Faraday cup
magnetic monopol lense
drift path
sample
multi-detector
primary e- pulse width 5 ps
1×10^8 e- per bunch
≈ 60 moderated e+
13×10^6 bunches /s
≈10^9 moderated e+
77 ns (adjustable)

Converter

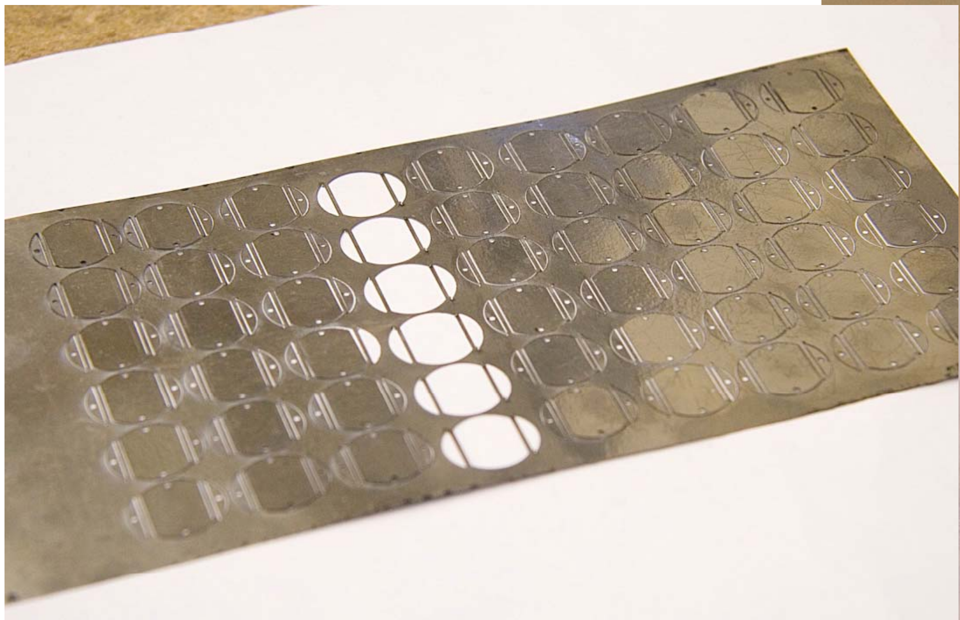


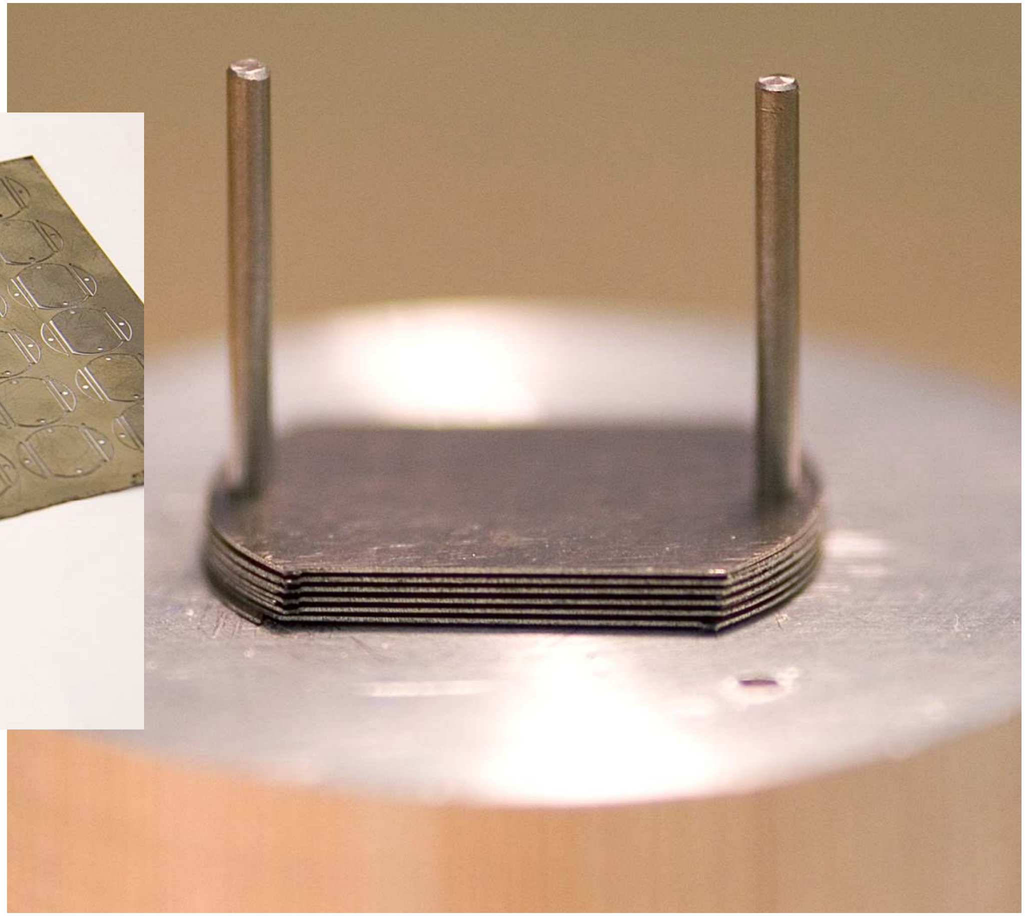


MCNP-Simulationen A. Rogov und K. Noack (FZD)

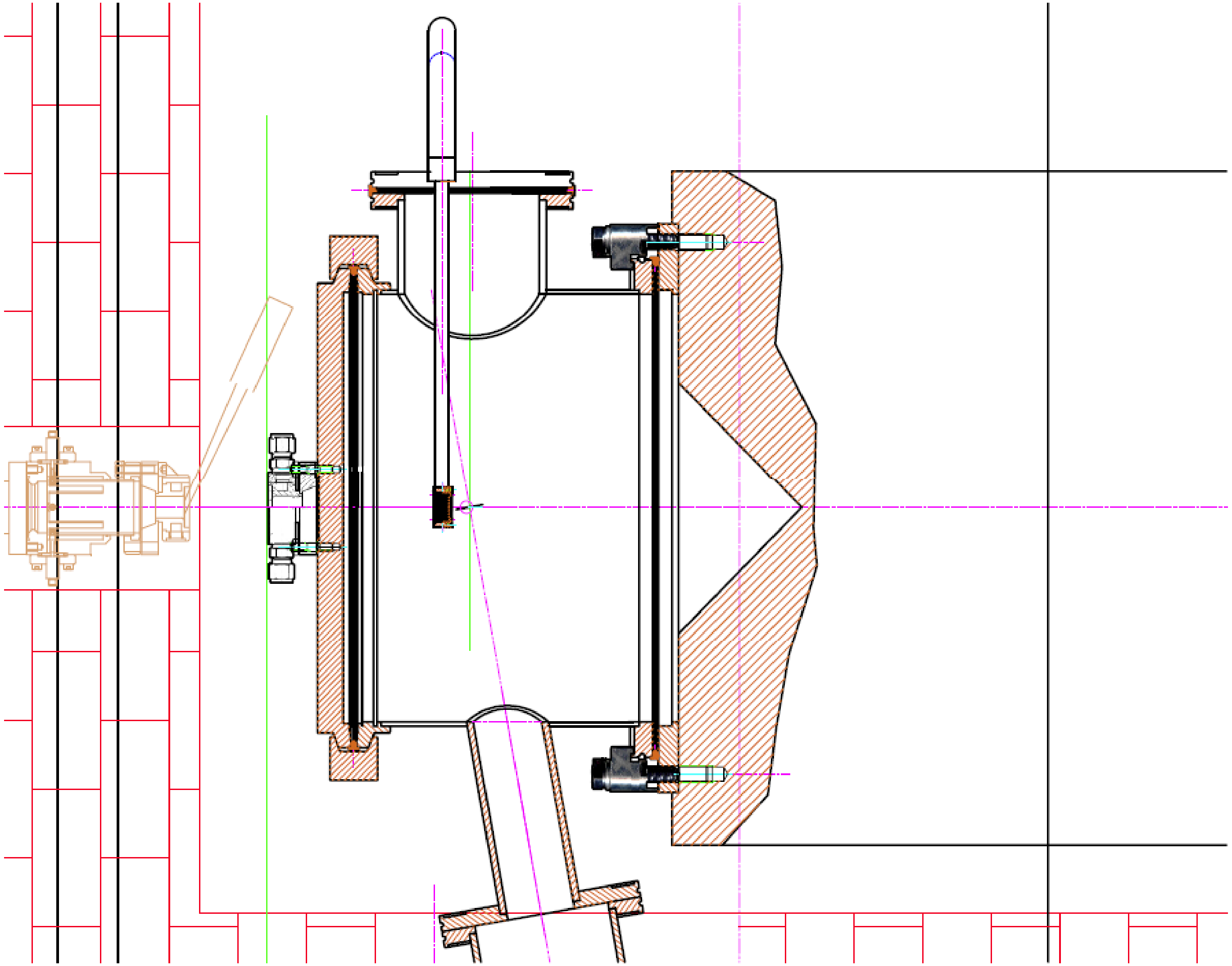
Directly water-cooled Electron-Positron Converter

- stack of 50 pieces W-foils 0,1 mm separated by 0,1 mm -> 13,5 l water at 1,5 bar
- foils cut by IR-laser in our workshop





Converter Chamber



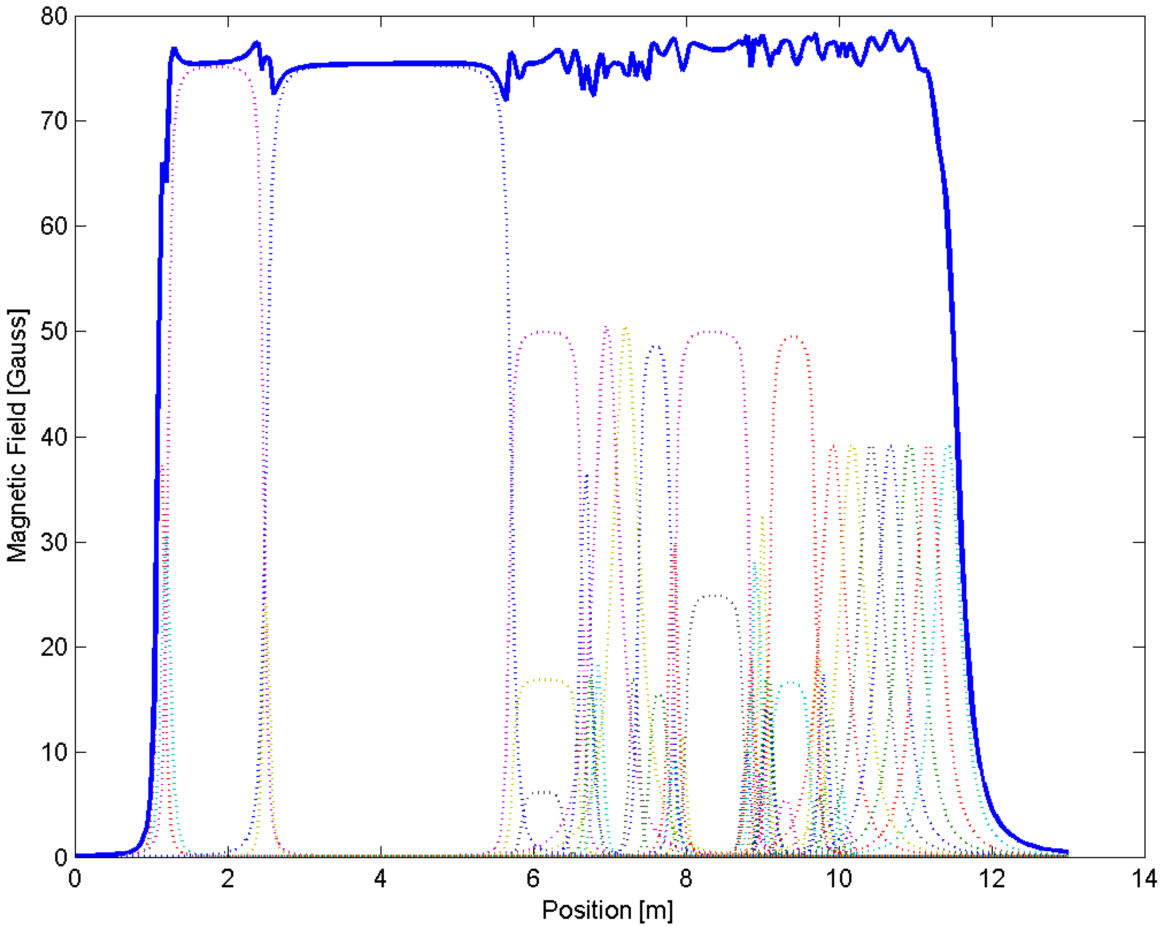
Magnetic Beam Guidance System

Magnetic field of 75 Gauss provides by long coils and Helmholtz coils

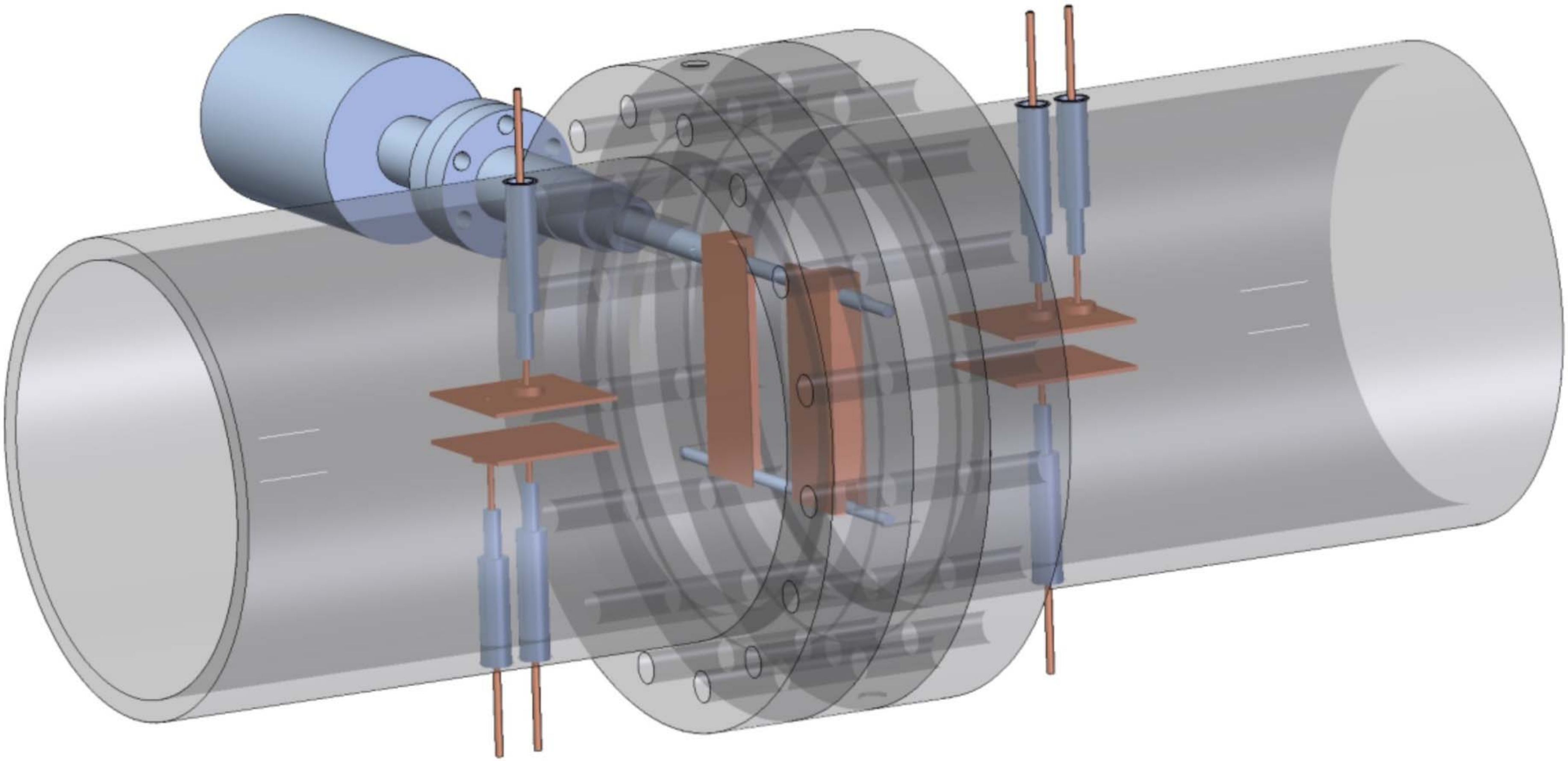
- 45 coils but only
- 5 different currents
- 5 Power supplies

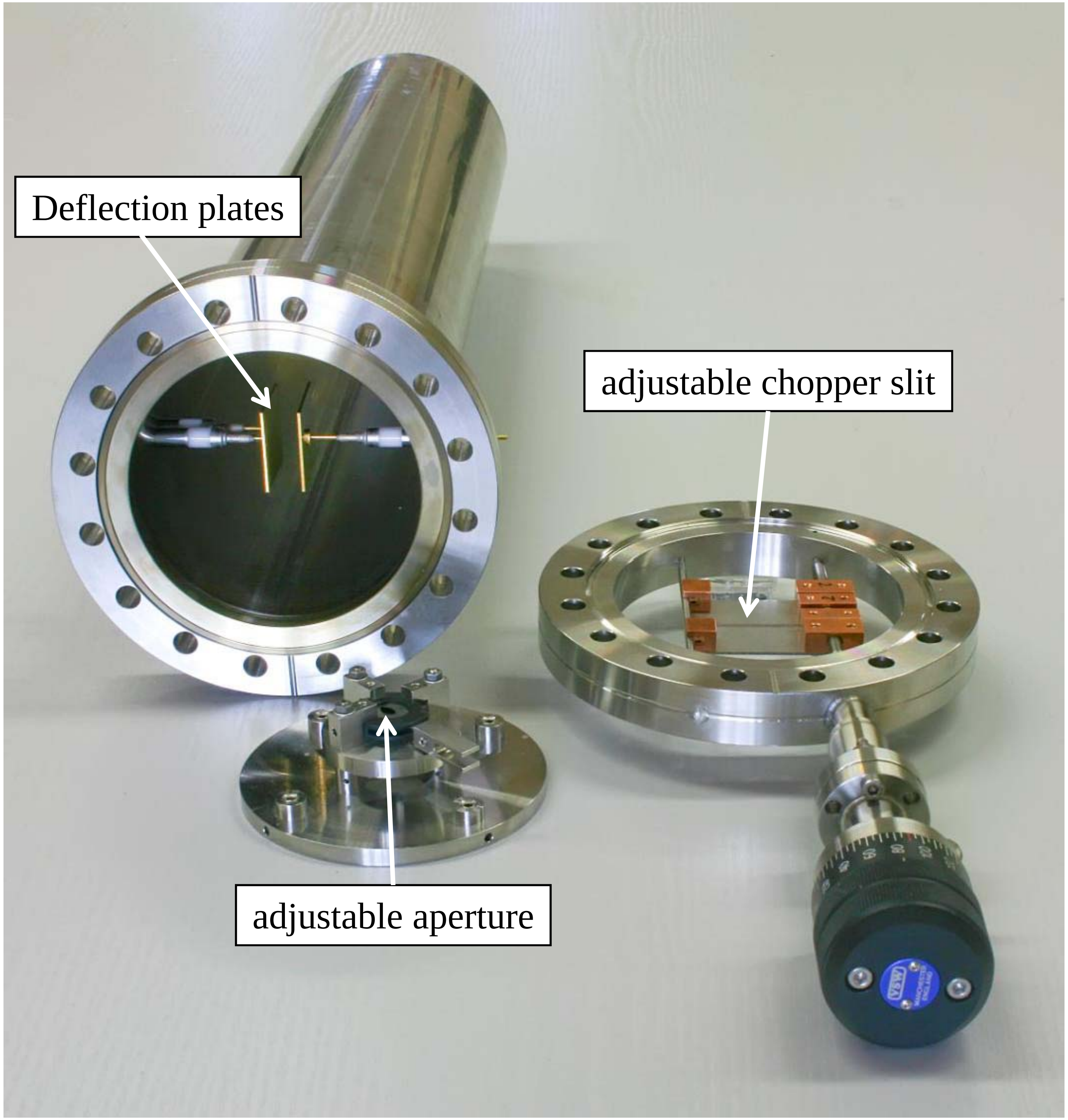
- maximum change 6 G
- gradient < 0.11 G/mm

30 pairs of steering coils with different (computer-driven) current sources

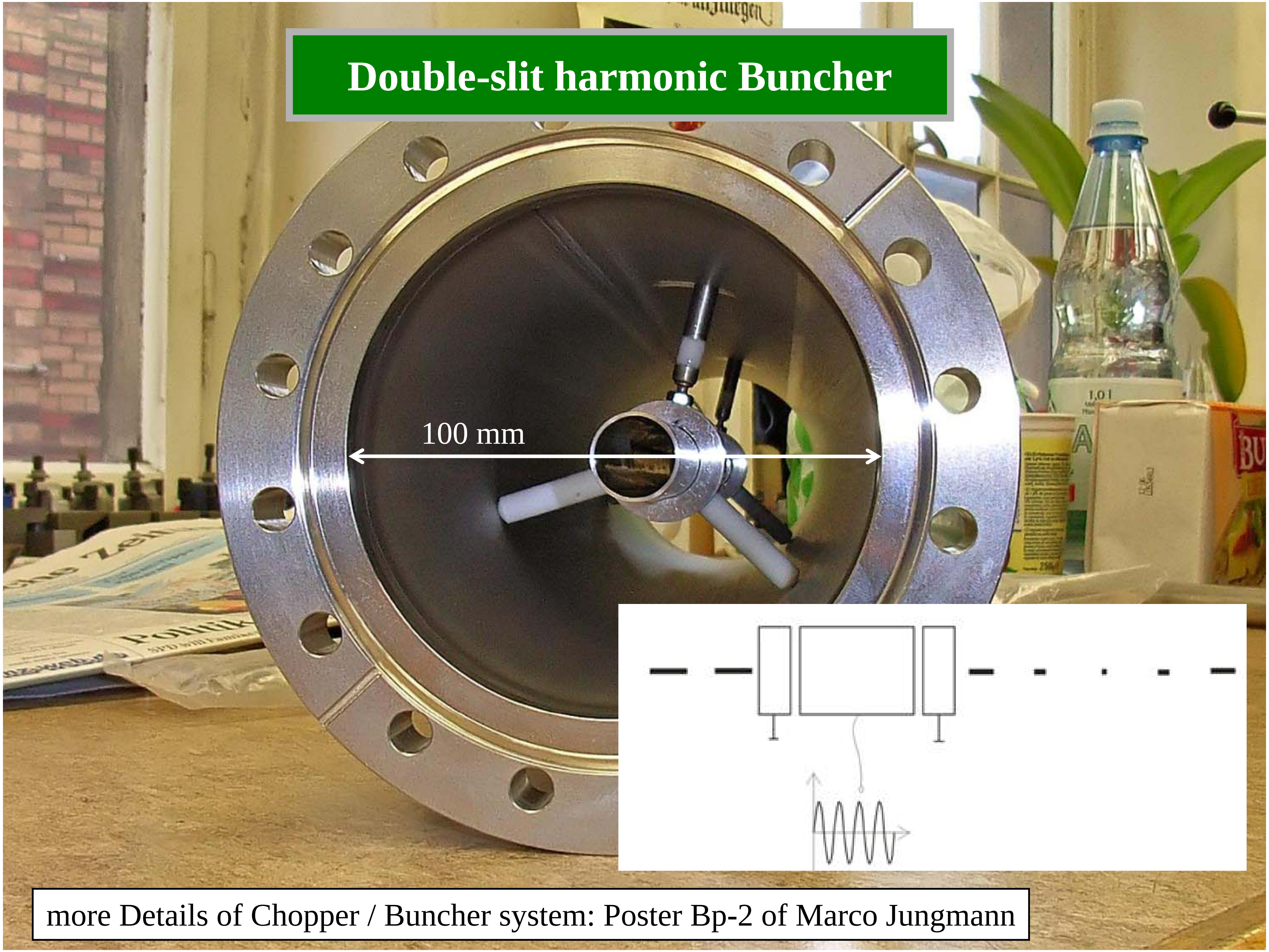


Chopper



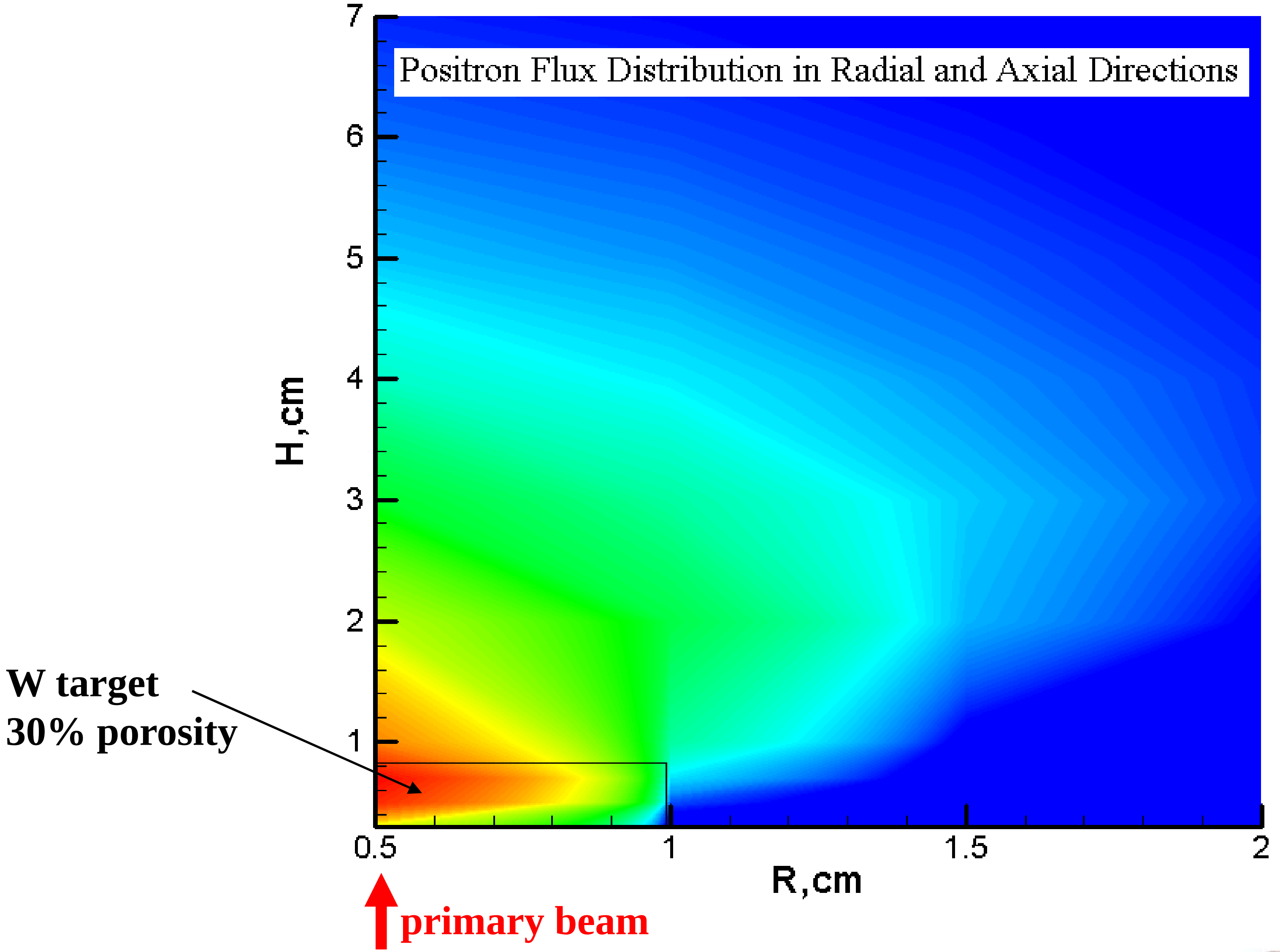

Deflection plates
adjustable chopper slit
adjustable aperture

Double-slit harmonic Buncher



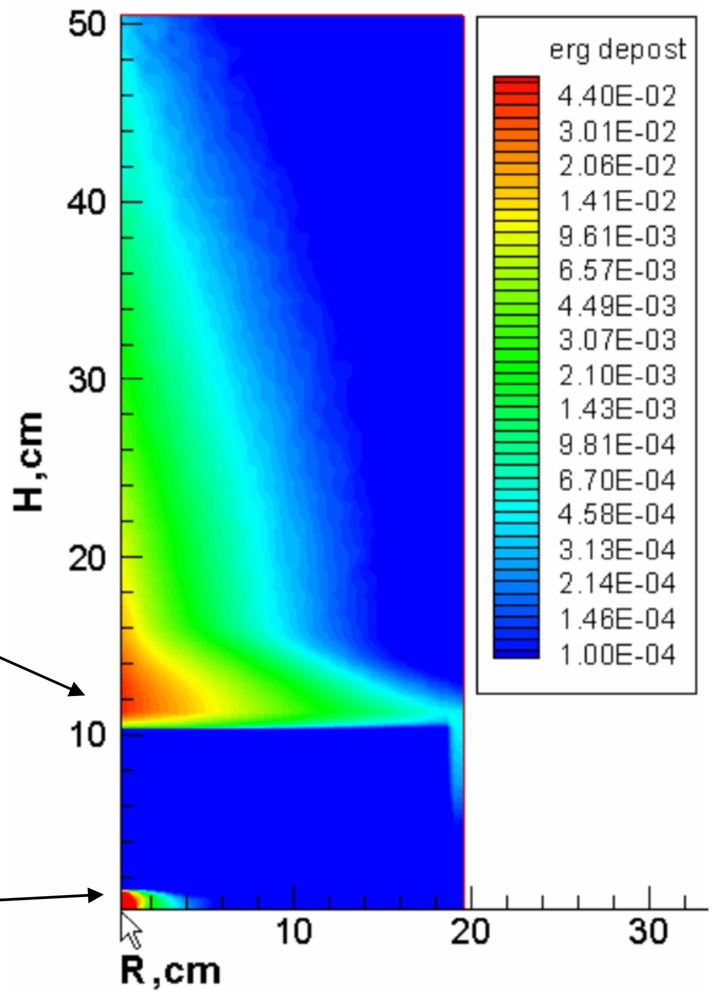
more Details of Chopper / Buncher system: Poster Bp-2 of Marco Jungmann

Simulation of Positron distribution



Simulation of Energy deposition

Al beam dump 21 kW
(made of 5N-purity)

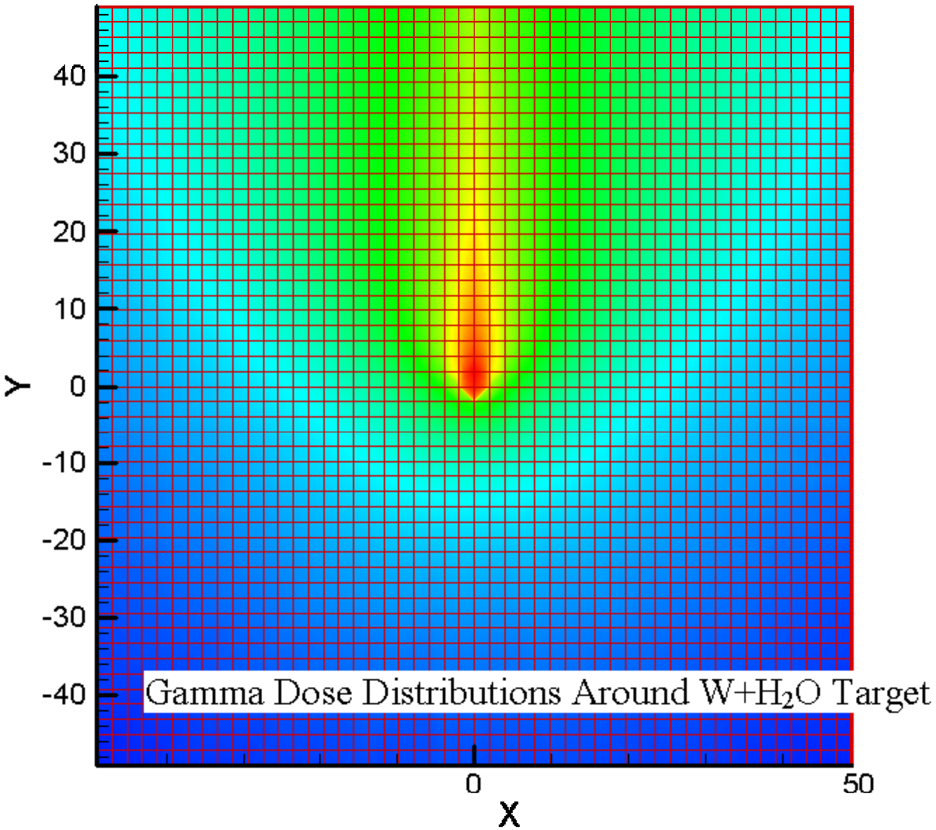


EPOS Density Energy Deposition (in MeV/cm^3) for Distance = 10cm

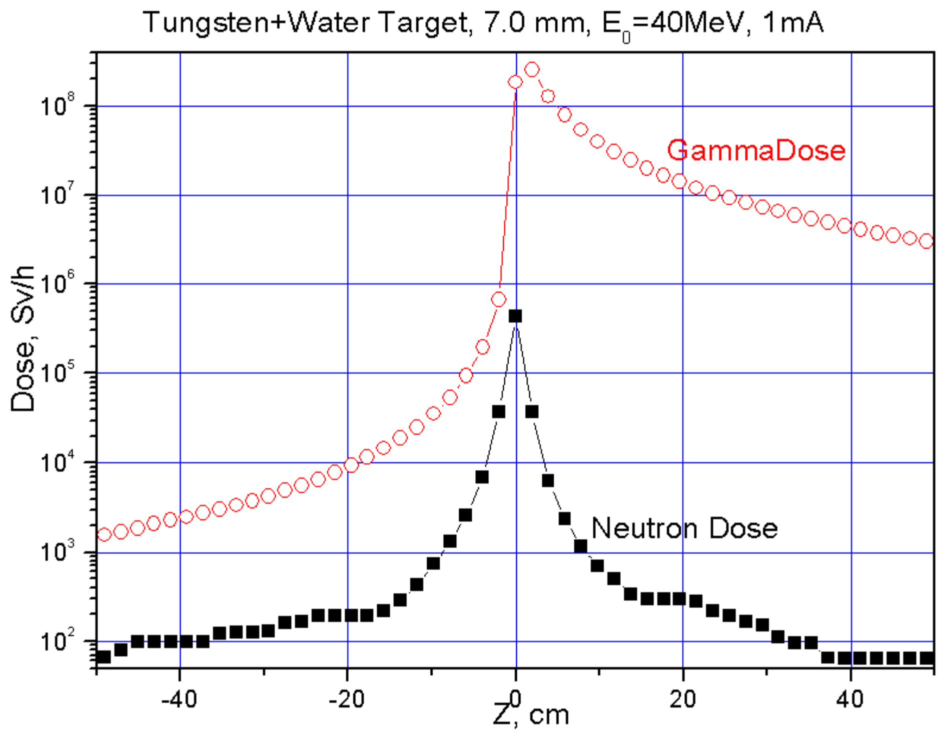
W target
14 kW

primary beam

Simulation of expected γ and n dose



Gamma Dose Distributions Around W+H_2O Target



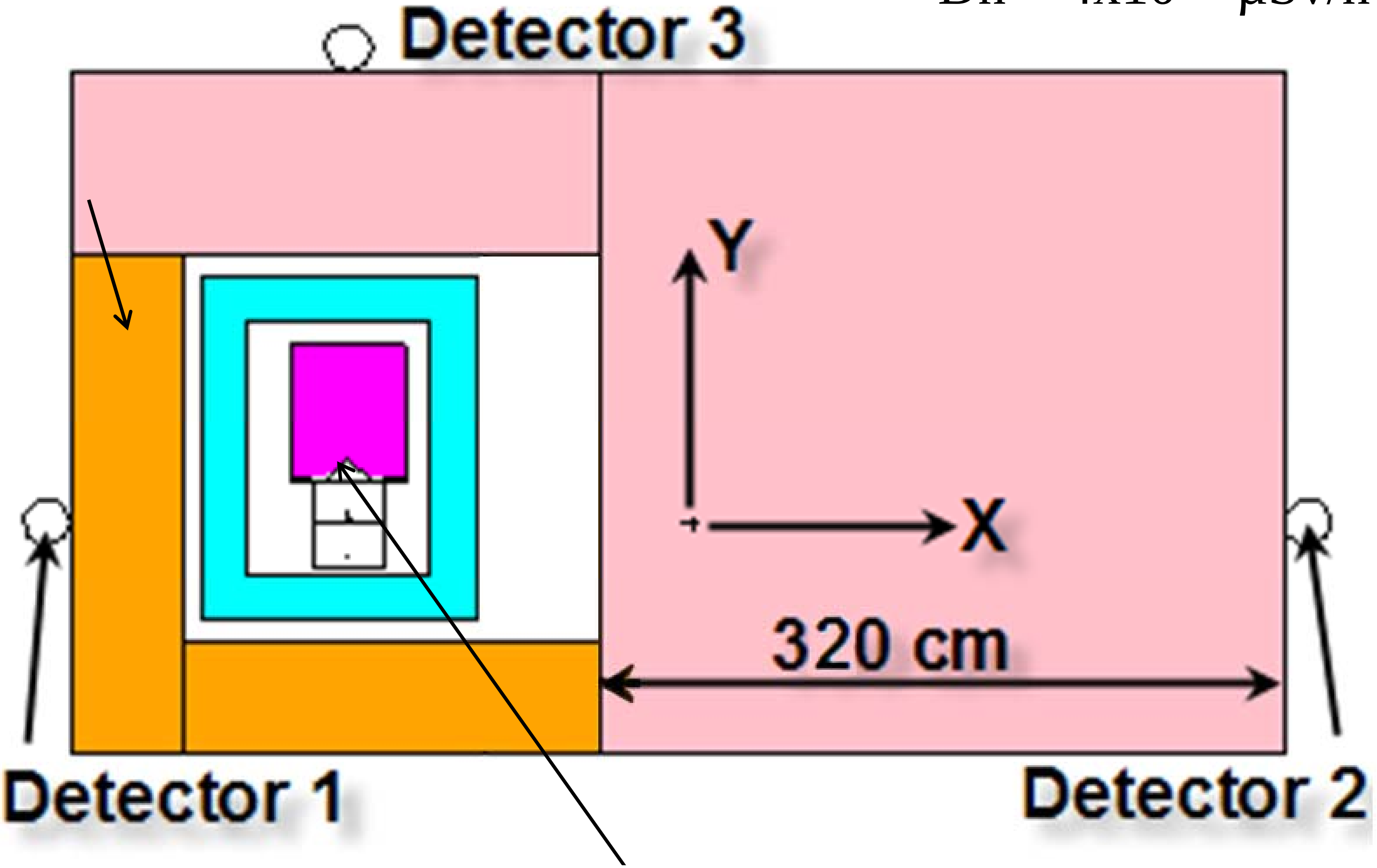
Neutron and Gamma Dose Distributions Around W+H_2O Target in Axial Direction

Screening by lead blocks, Polyethylene bricks and heavy concrete

normal environment
D = 0.15 μSv/h

$D\gamma > 0.25$ μSv/h
$Dn > 0.6$ mSv/h

at ceiling (1.6 m concrete):
$D\gamma = 0.2$ μSv/h
$Dn < 4 \times 10^{-6}$ μSv/h



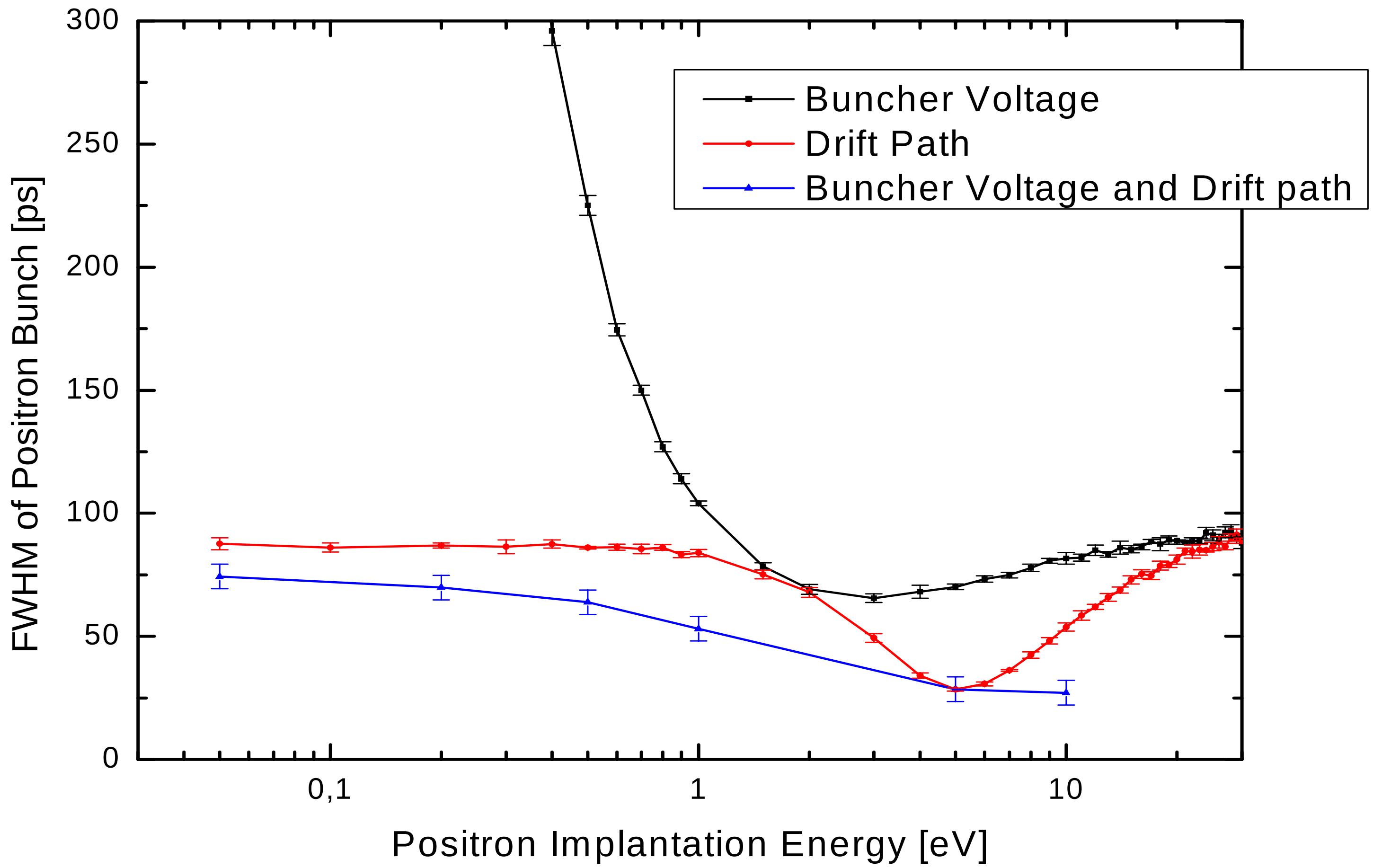
$D\gamma > 0.42$ Sv/h
$Dn > 0.23$ Sv/h

$D\gamma > 10^{8}$ Sv/h
$Dn > 10^{6}$ Sv/h

$D\gamma < 6 \times 10^{-7}$ μSv/h
$Dn < 10^{-18}$ μSv/h

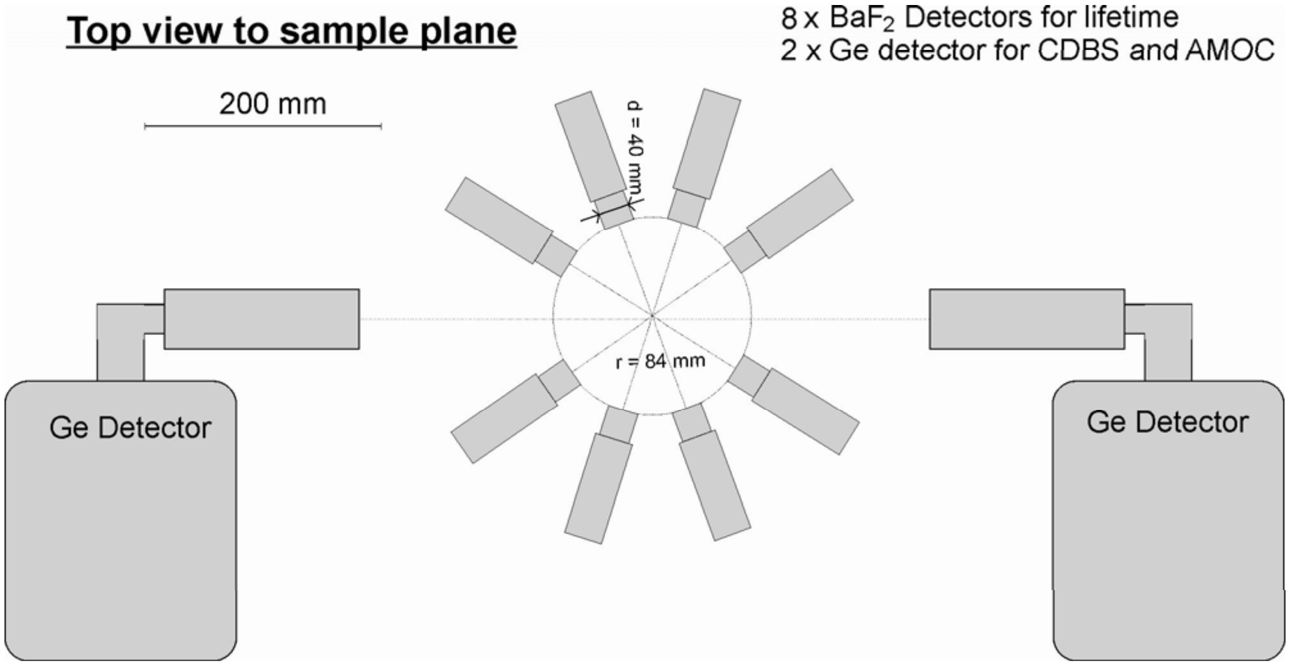
MC-Simulation of Buncher Voltages

Both buncher RF-voltage amplitude and the drift path energy must be adjusted for each beam energy for optimum time resolution at the time focus (sample position)

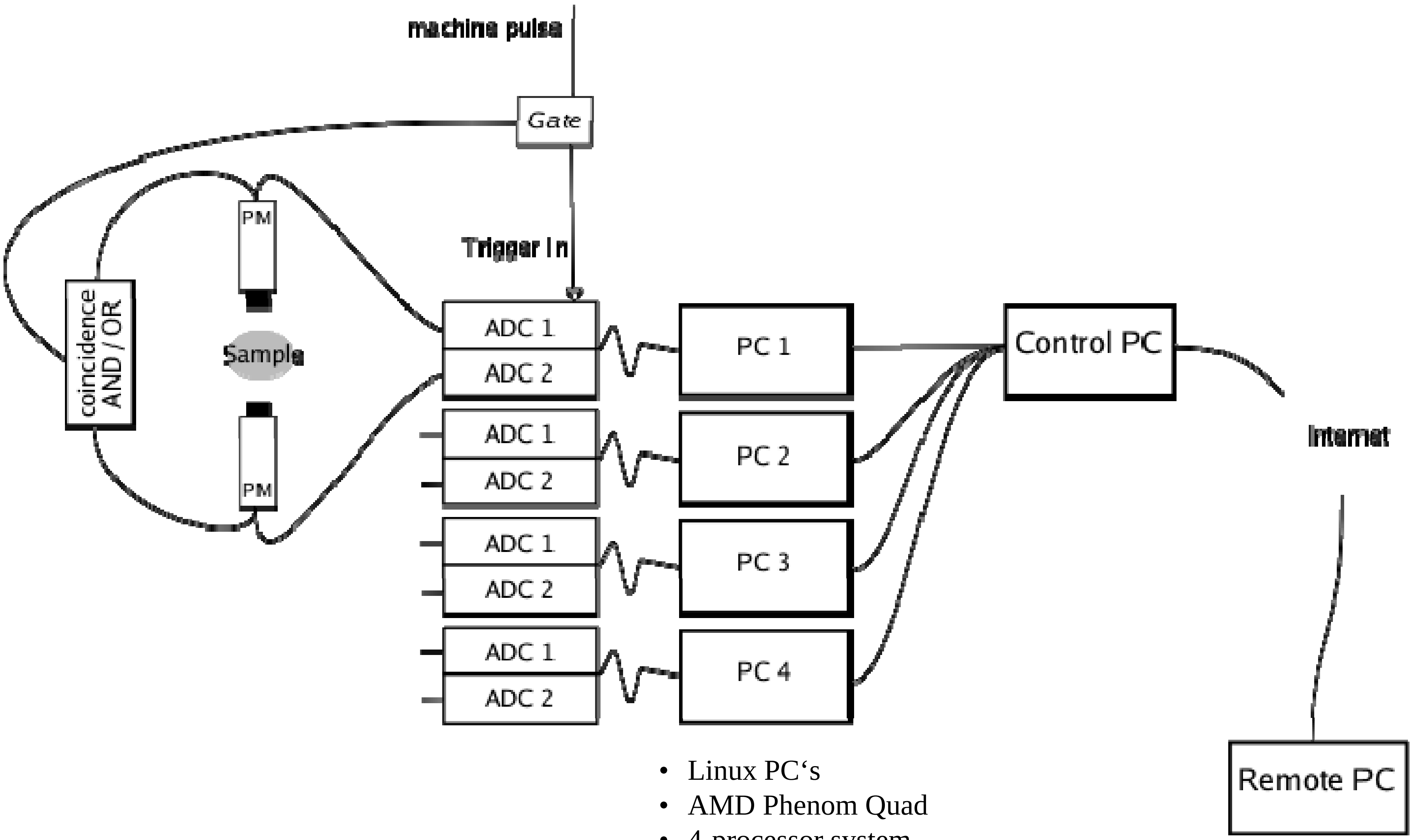


Detector system

- **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



Lifetime detector system



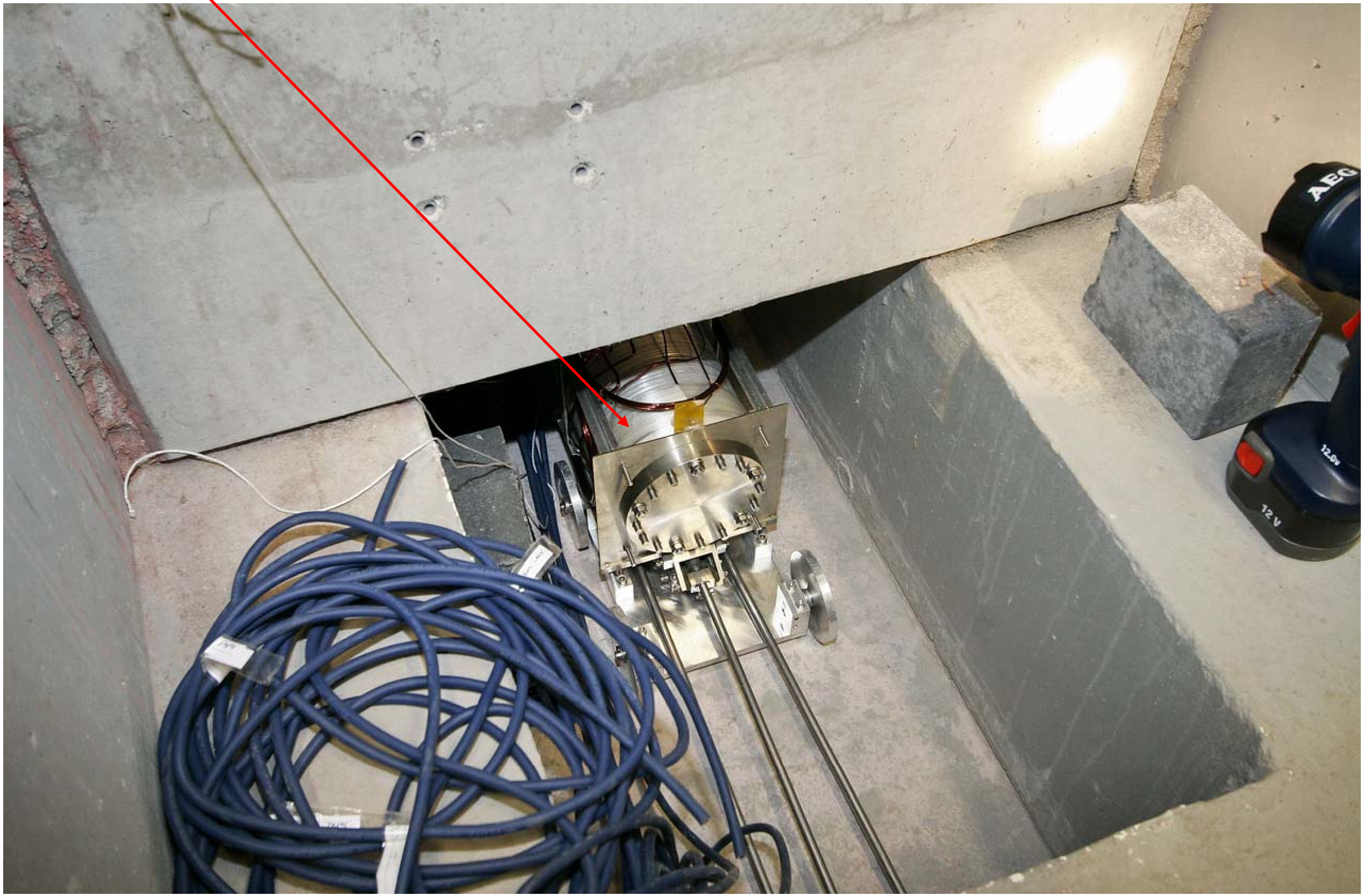
- Linux PC‘s
- AMD Phenom Quad
- 4-processor system
- no monitors, no harddiscs
- 4 GB memory each

EPOS - Applications

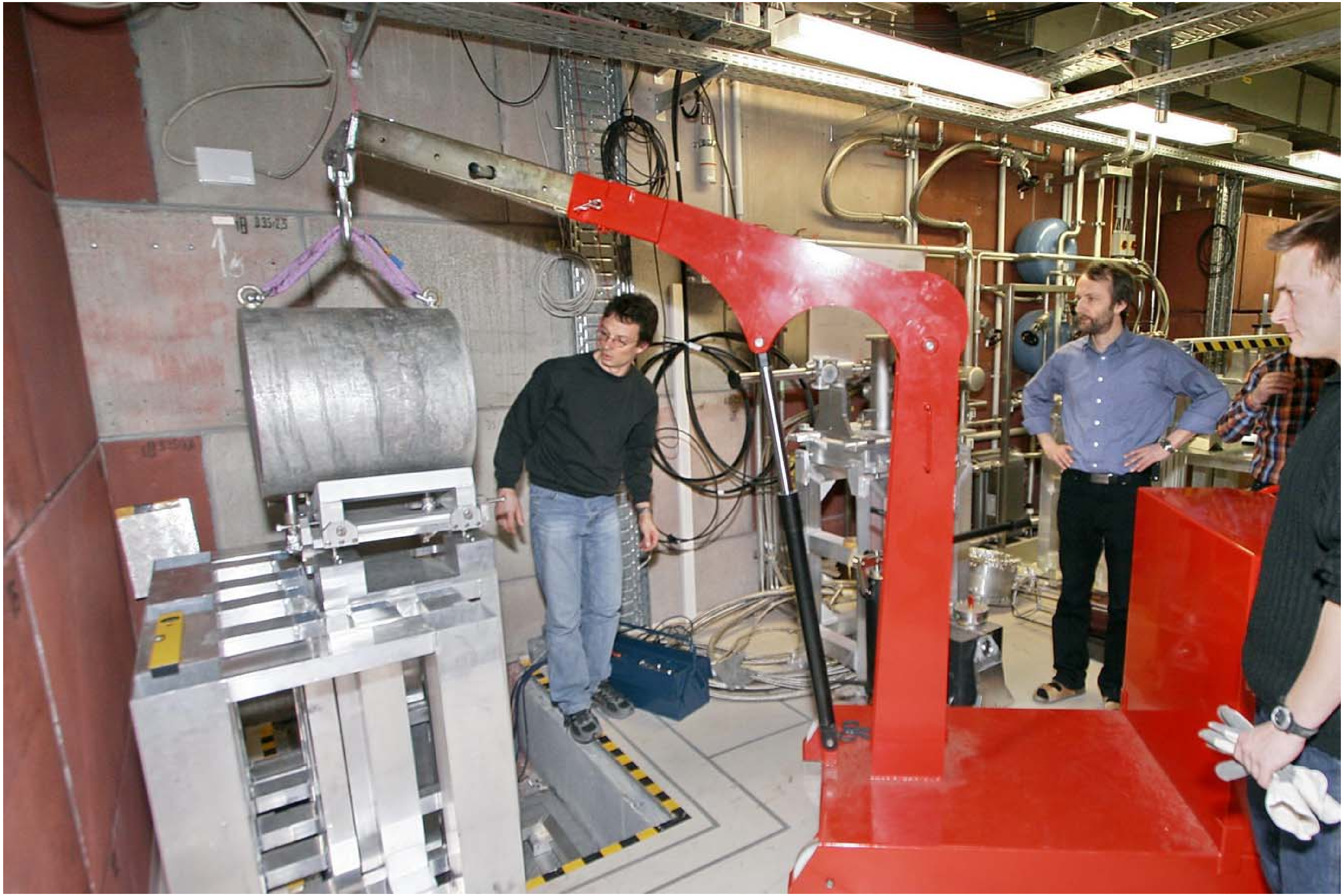
Variety of applications in all field of materials science:

- defect-depth profiles due to surface modifications and ion implantation
- tribology (mechanical damage of surfaces)
- polymer physics (pores; interdiffusion; …)
- low-k materials (thin high porous layers)
- 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 …

Beam line through cable channel under 3.2 m concrete

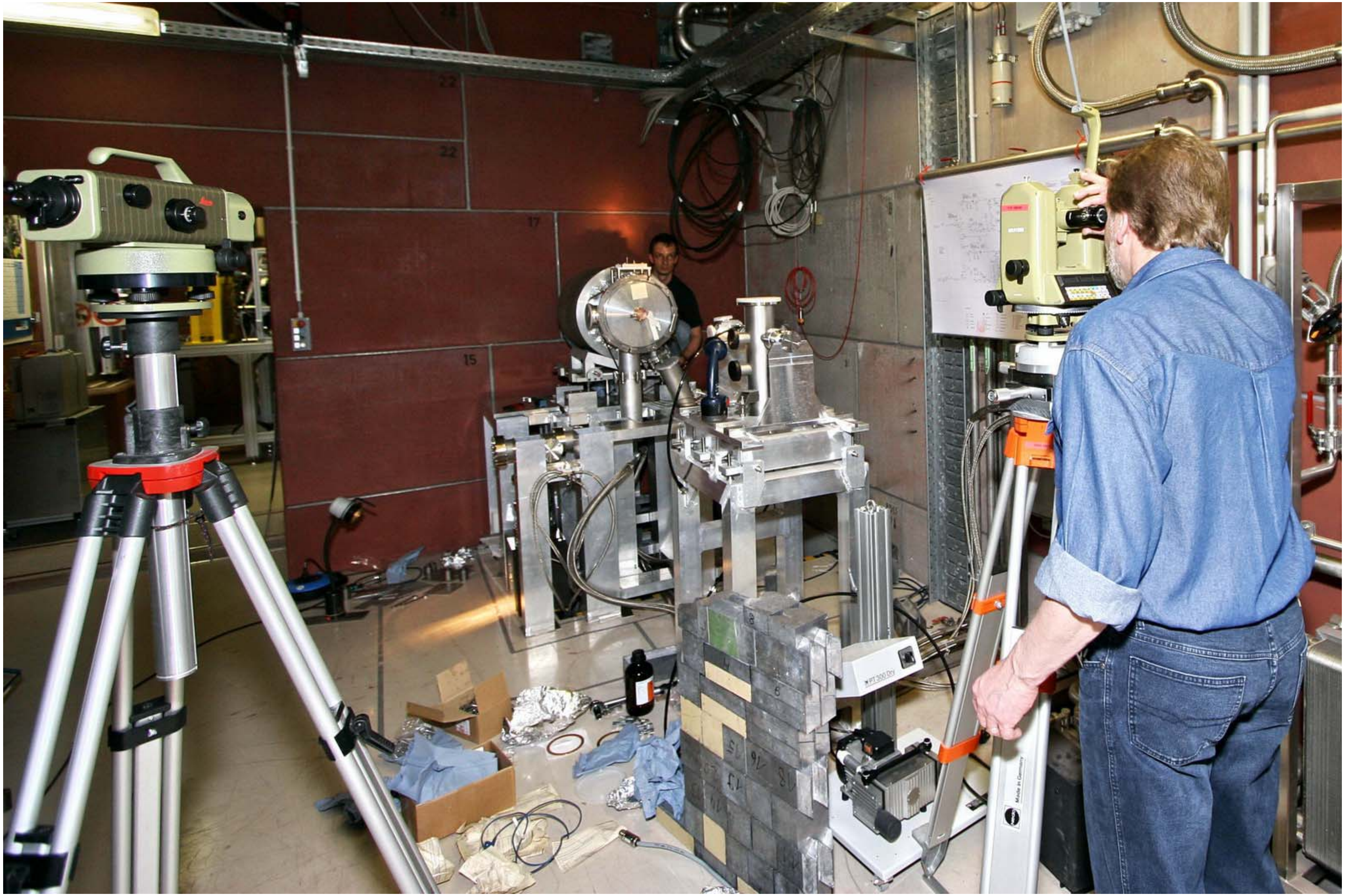


Electron beam dump is put onto the stand



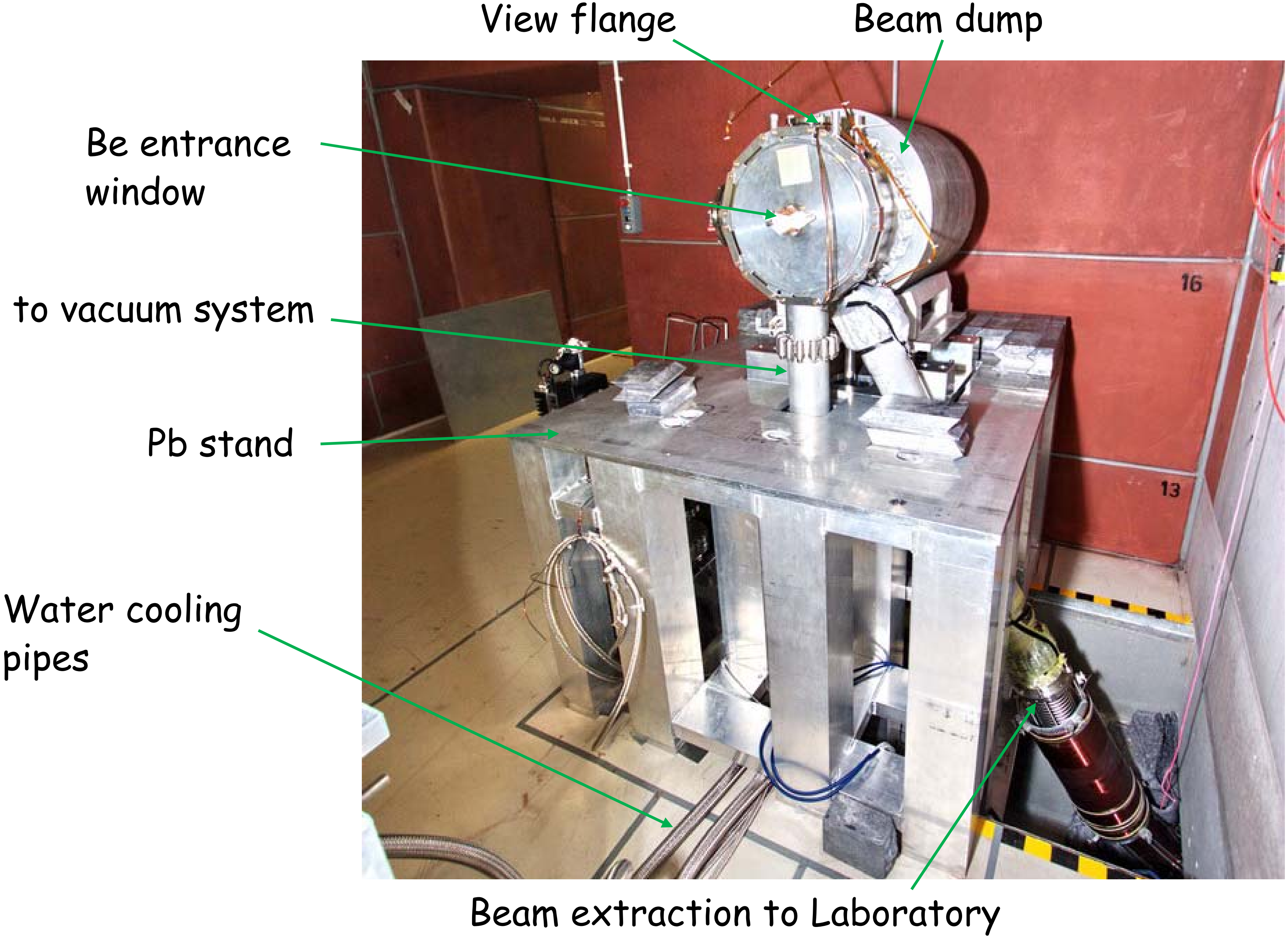
Converter chamber and vacuum system is going to be installed

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



A bow saw is used for cutting Pb bricks

First cut under progress


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

Thank you for your attention!

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