Experimental facilities: MePS at ELBE

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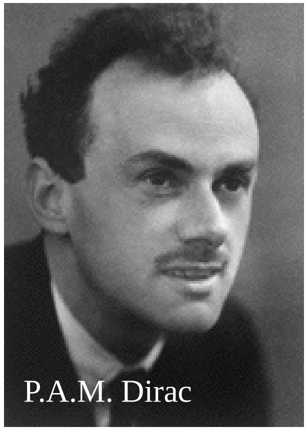
- Historical remarks
- Defect detection by positrons
- Overview: The EPOS-System at FZD
- Mono-energetic Positron Beam (MePS)

19. October 2010

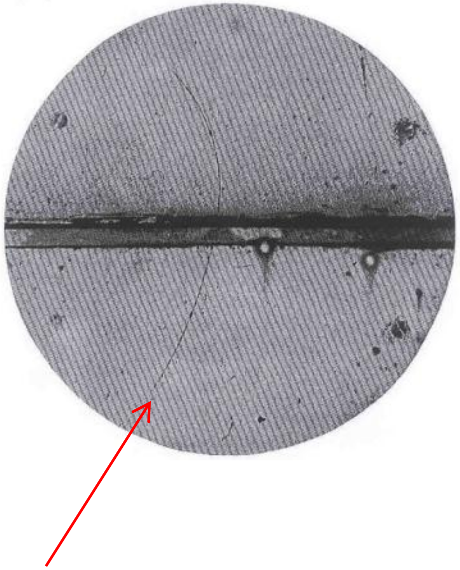
Discovery of the Positron

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



C.D. Anderson

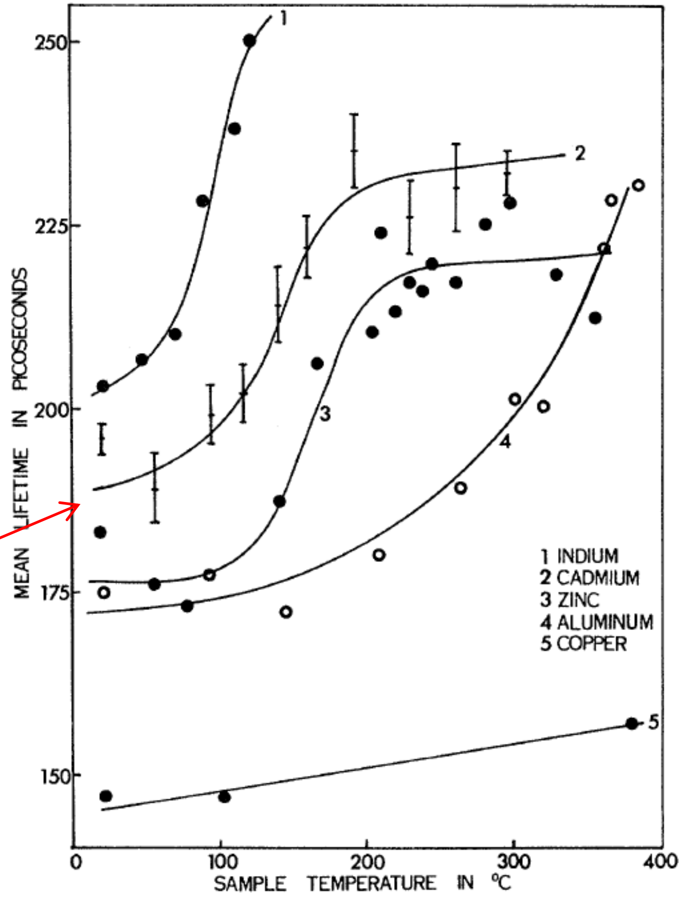
- Positronium as bound state of e^- and e^+ - lightest atom - was predicted (1934) and discovered (1951)
- Annihilation in matter was studied beginning in the 40th
- Positrons can be obtained by
  - pair production from gamma radiation (E_γ > 1022 keV)
  - β^+ decay from isotopes (mostly ^{22}Na)



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

Positrons are sensitive for Crystal Lattice Defects

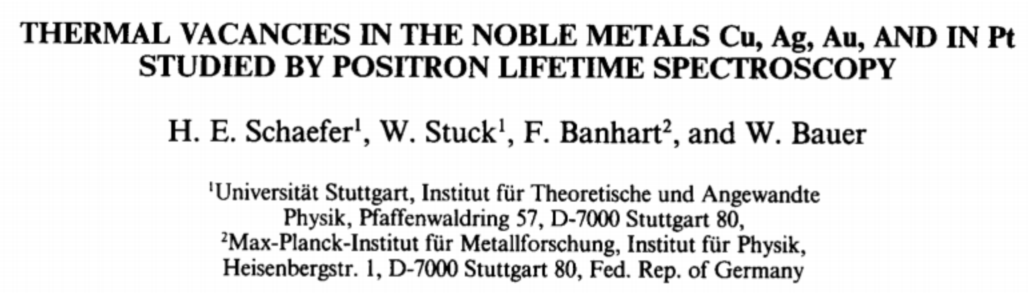
- 1950…1960: different experimental techniques were developed
- Positron lifetime spectroscopy and Doppler broadening spectroscopy
- end of 60s: lifetime is sensitive to lattice imperfections
  - Brandt et al. (1968): **vacancies in ionic crystals**
  - Dekhtyar et al. (1969): **plastically deformed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



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

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

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

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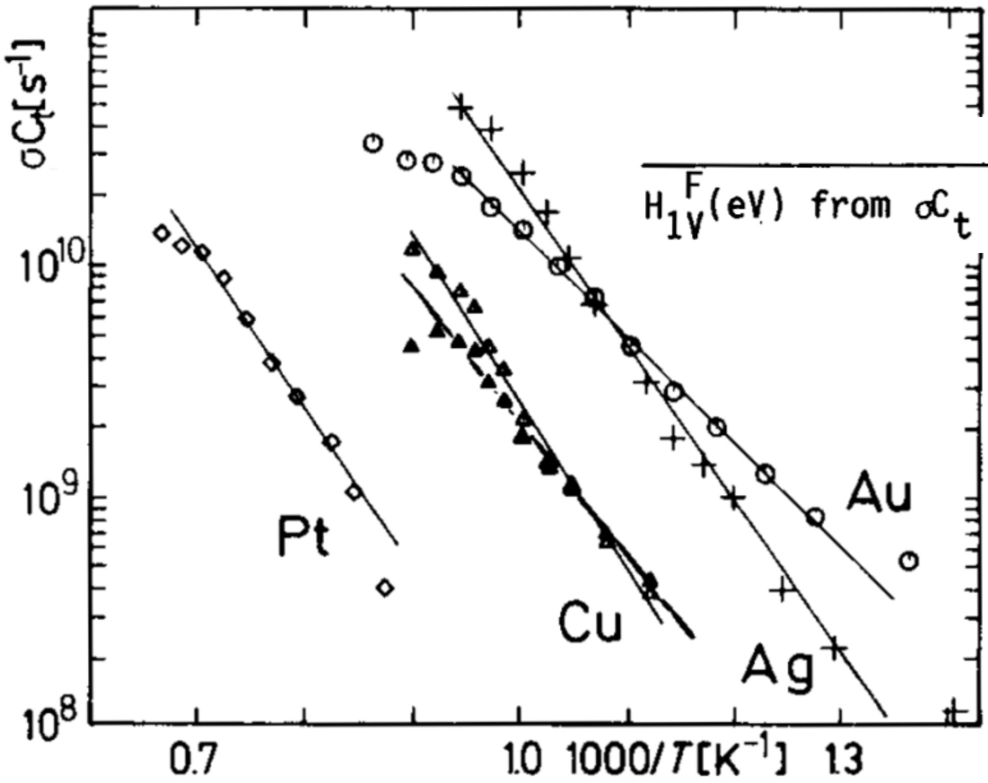
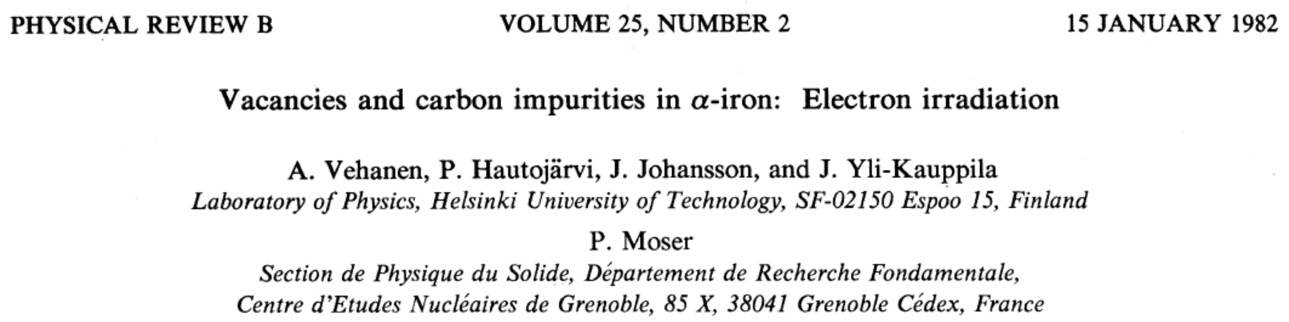
Physik, Pfaffenwaldring 57, D-7000 Stuttgart 80,
[2]Max-Planck-Institut für Metallforschung, Institut für Physik,
Heisenbergstr. 1, D-7000 Stuttgart 80, Fed. Rep. of Germany



	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

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P. Moser
Section de Physique du Solide, Département de Recherche Fondamentale,
Centre d'Etudes Nucléaires de Grenoble, 85 X, 38041 Grenoble Cédex, France

Positron lifetime spectra

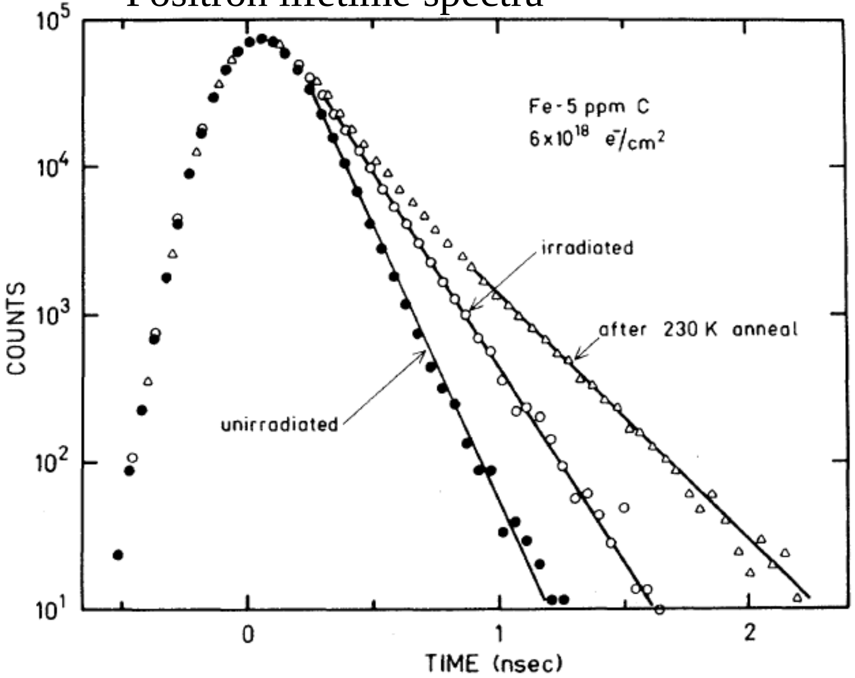
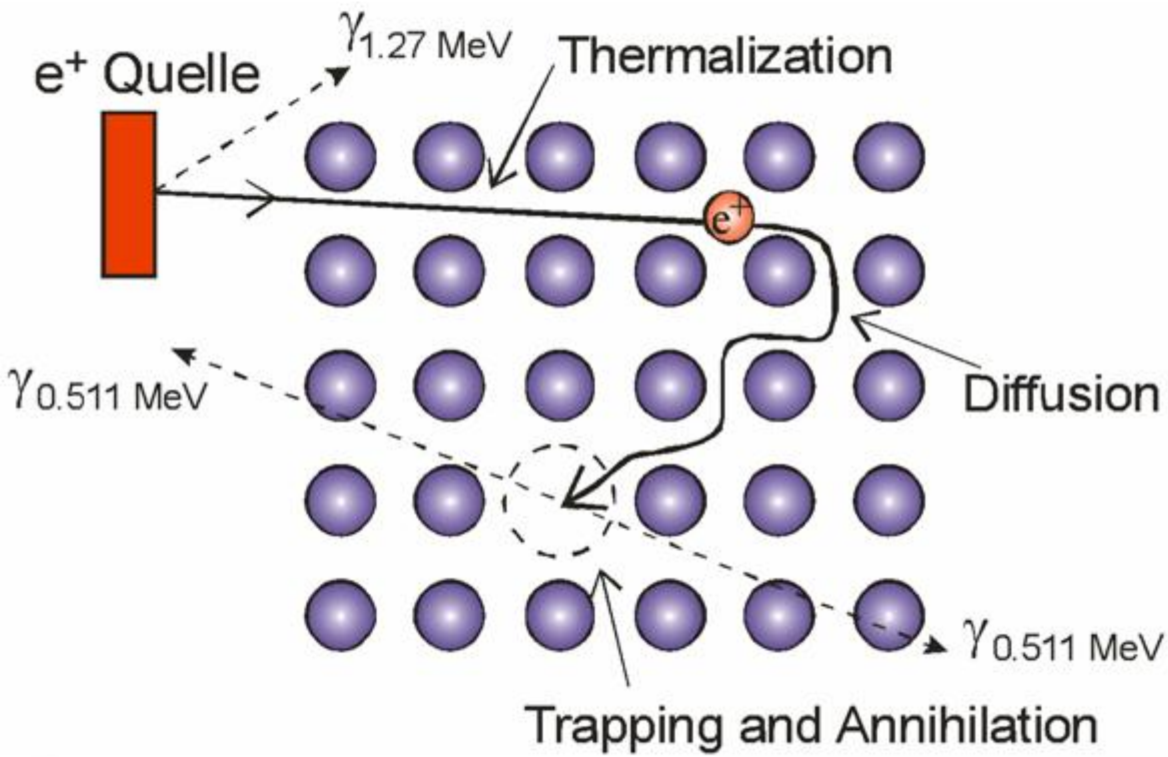


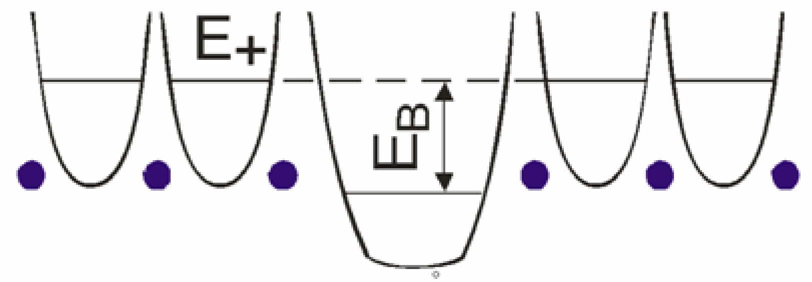
FIG. 1. Positron-lifetime spectra after source-background subtraction in electron-irradiated (6×10^{18} e^-/cm^2) high-purity iron at various stages of isochronal annealing. The dramatic occurrence of a long-lifetime component after 230 K annealing is clearly visible.

- 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

Defect Sensitivity

atomic open-volume defects

- vacancies ($\rho_v > 10^{-7}$)
- vacancy clusters (n=1…50)
- dislocations (> 10^8 cm^{-2})
- grain boundaries (only ultra-fine grained materials)
- surface

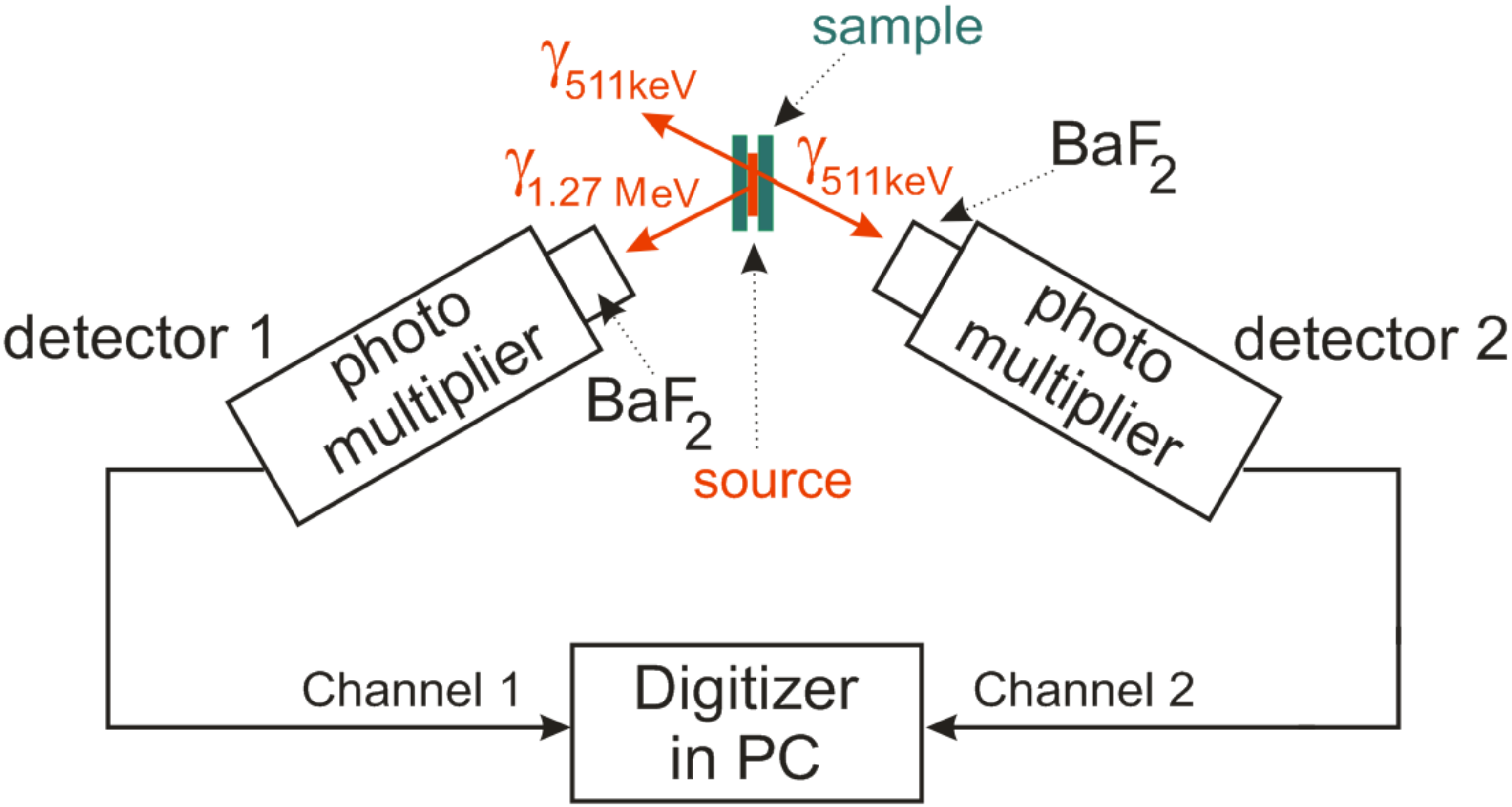
non-open volume defects

- coherent precipitates (e.g. GPZ in Al-Zn)
- negatively charged acceptors in semiconductors (“shallow traps”)

large open volume 1…50 nm (Positronium formation)

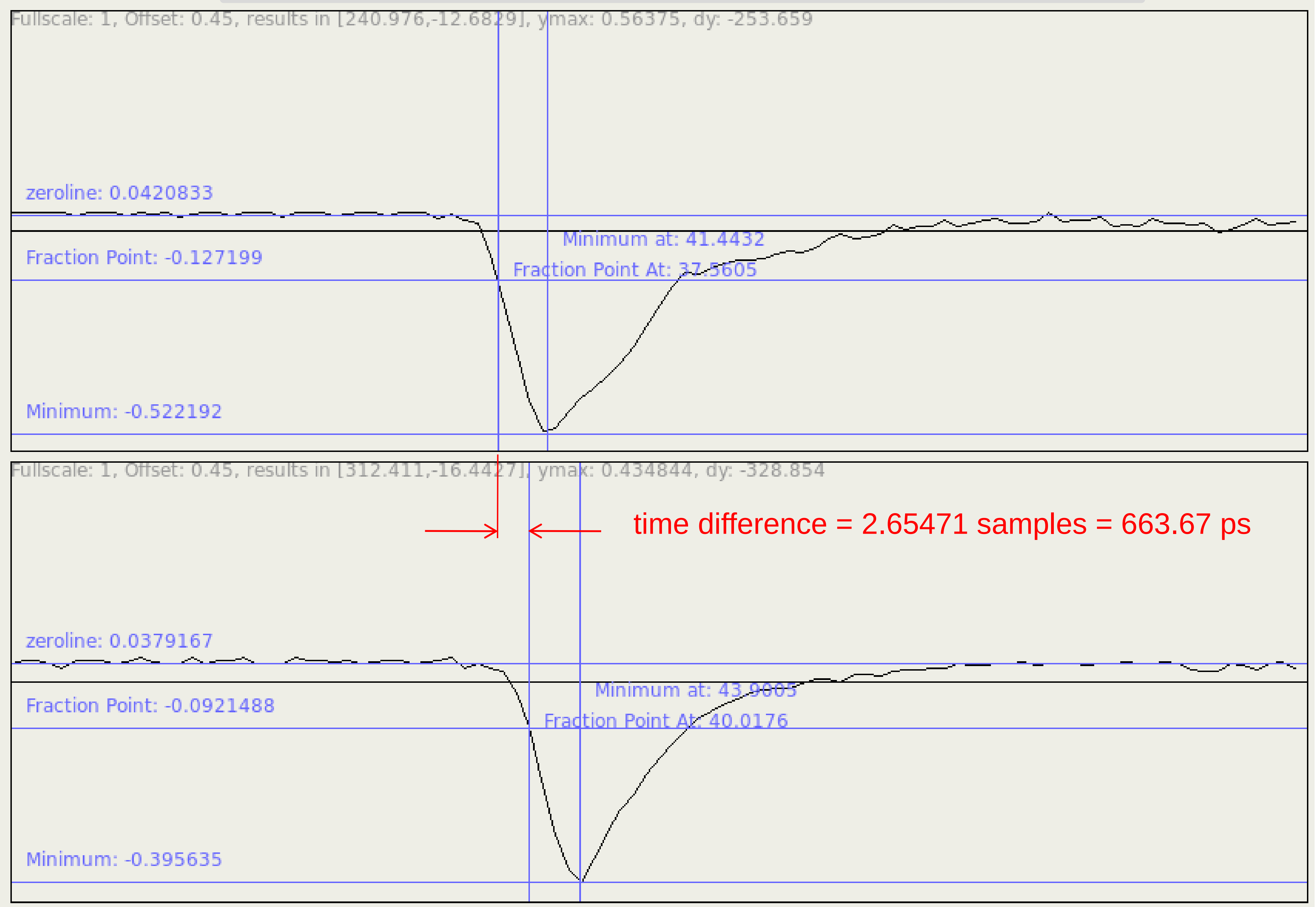
- open volume between molecular chains in polymers (> 100 Å^3)
- mesoporous dielectrica (1 nm < d_{pore} < 50 nm)

Digital lifetime measurement



- very simple setup
- timing very accurate
- pulse-shape discrimination (suppress “bad pulses”)
- each detector for start & stop (double statistics)

screenshot of two digitized anode pulses



Fullscale: 1, Offset: 0.45, results in [240.976,-12.6829], ymax: 0.56375, dy: -253.659

zeroline: 0.0420833

Fraction Point: -0.127199

Minimum: -0.522192

Minimum at: 41.4432

Fraction Point At: 37.5605

Fullscale: 1, Offset: 0.45, results in [312.411,-16.4427], ymax: 0.434844, dy: -328.854

zeroline: 0.0379167

Fraction Point: -0.0921488

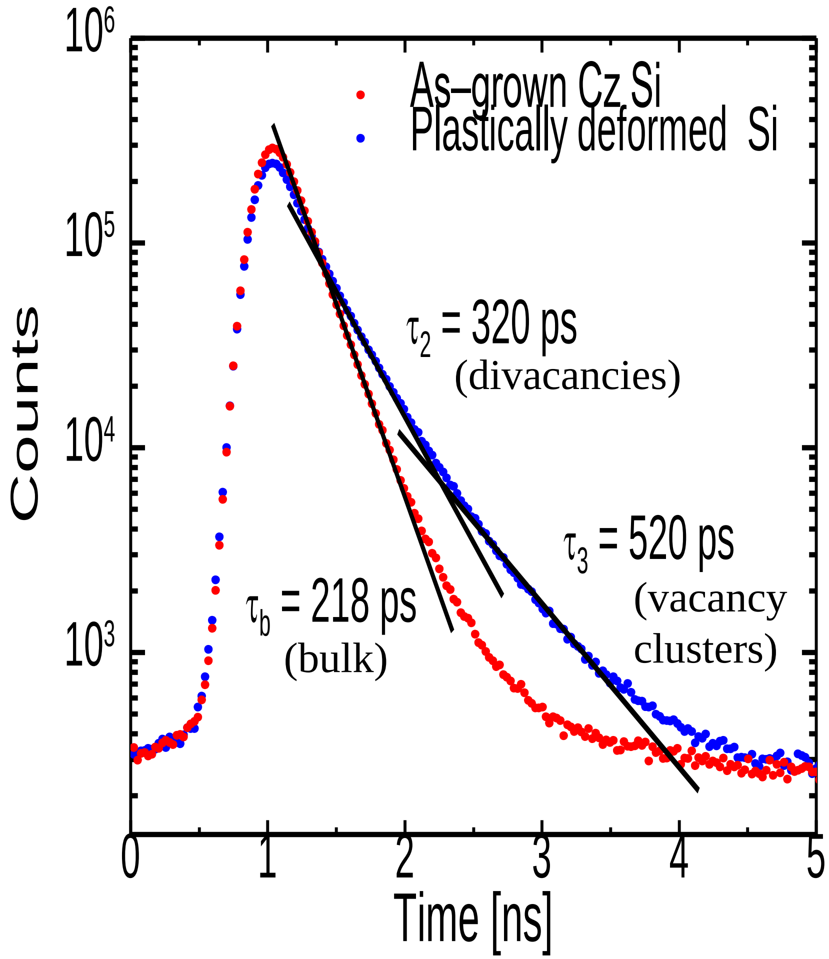
Minimum: -0.395635

Minimum at: 43.9005

Fraction Point At: 40.0176

time difference = 2.65471 samples = 663.67 ps

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:

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

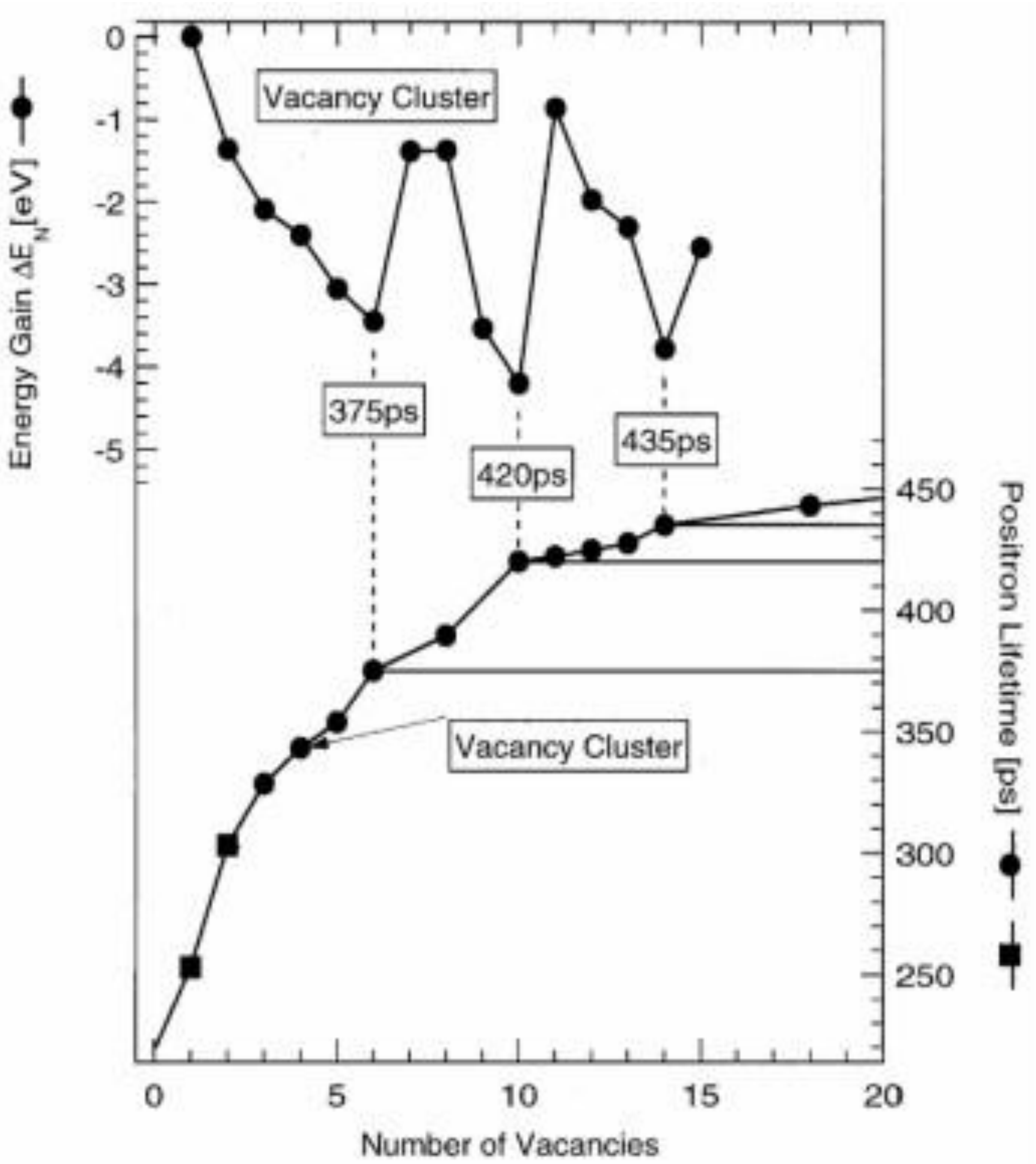
trapping coefficient

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

trapping rate

defect concentration

Theoretical calculation of vacancy clusters in Si

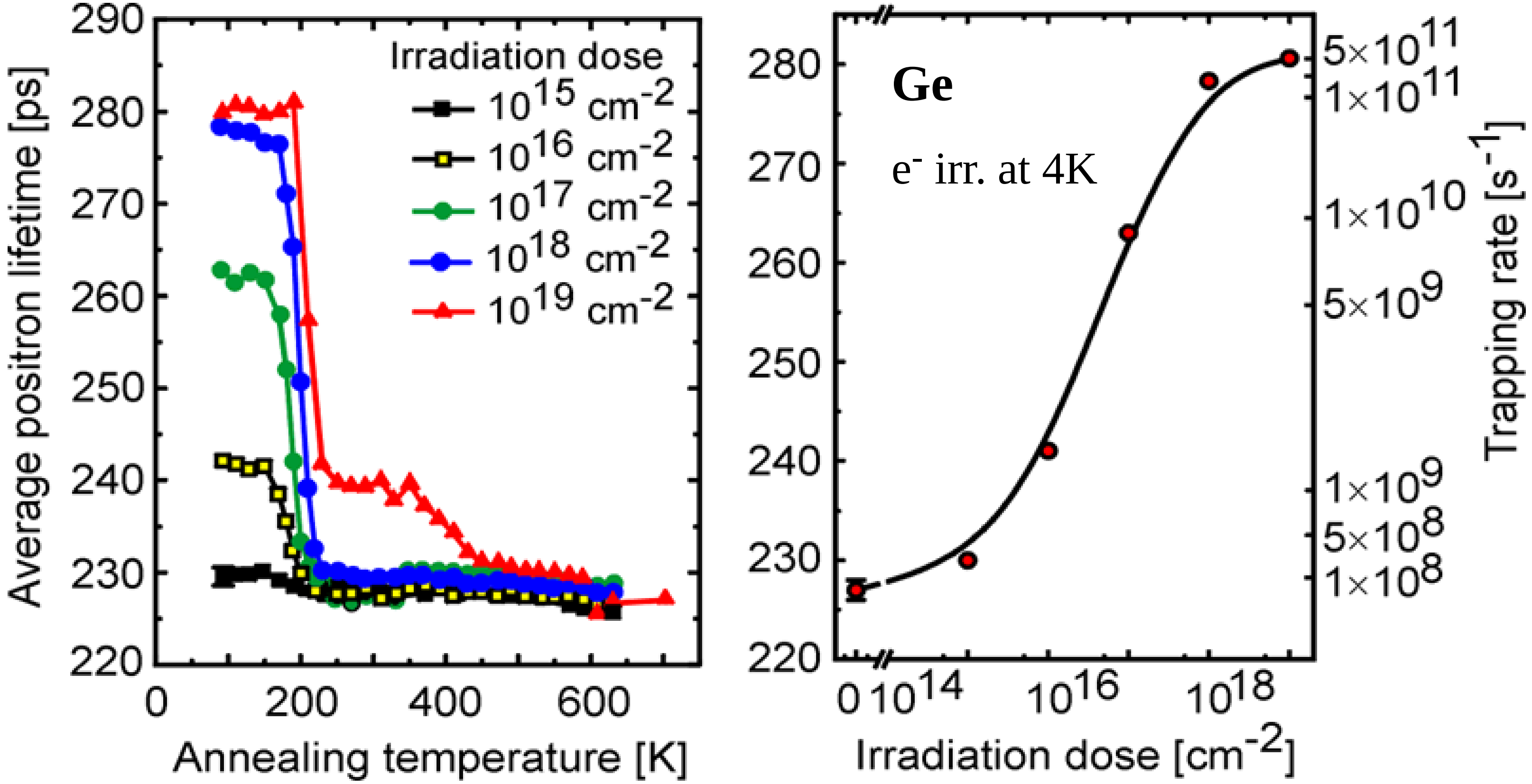


- there are cluster configurations with a large energy gain
- „Magic Numbers“ with 6, 10 und 14 vacancies
- positron lifetime increases distinctly with cluster size
- for n > 10 saturation effect, i.e. size cannot be determined

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

Defects in electron-irradiated Ge

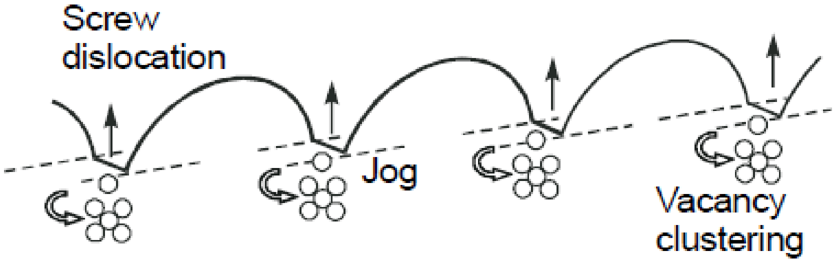
- Electron irradiation (2 MeV @ 4K) induces Frenkel pairs (vacancy - interstitial pairs)
- steep annealing stage at 200 K
- at high irradiation dose: divacancies are formed (thermally more stable)

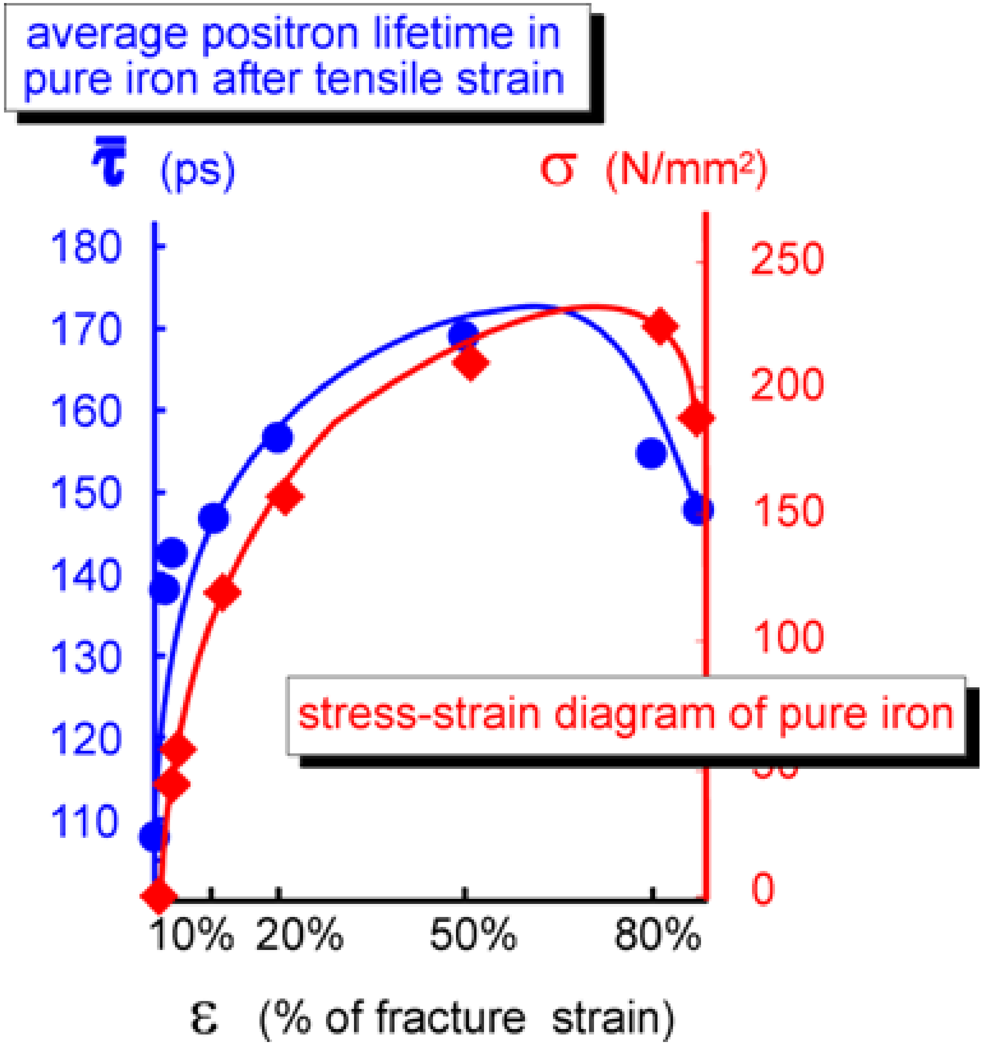


(Polity et al., 1997)

Defects in Iron after tensile Strength in Stress-Strain Experiment

- extensive study of defects in mechanically damaged iron and steel
- sensitive: detection of defects already in the elastic Hooke's range
- Vacancy cluster and dislocations are detectable in both cases
- small vacancy clusters are generated by jog dragging process



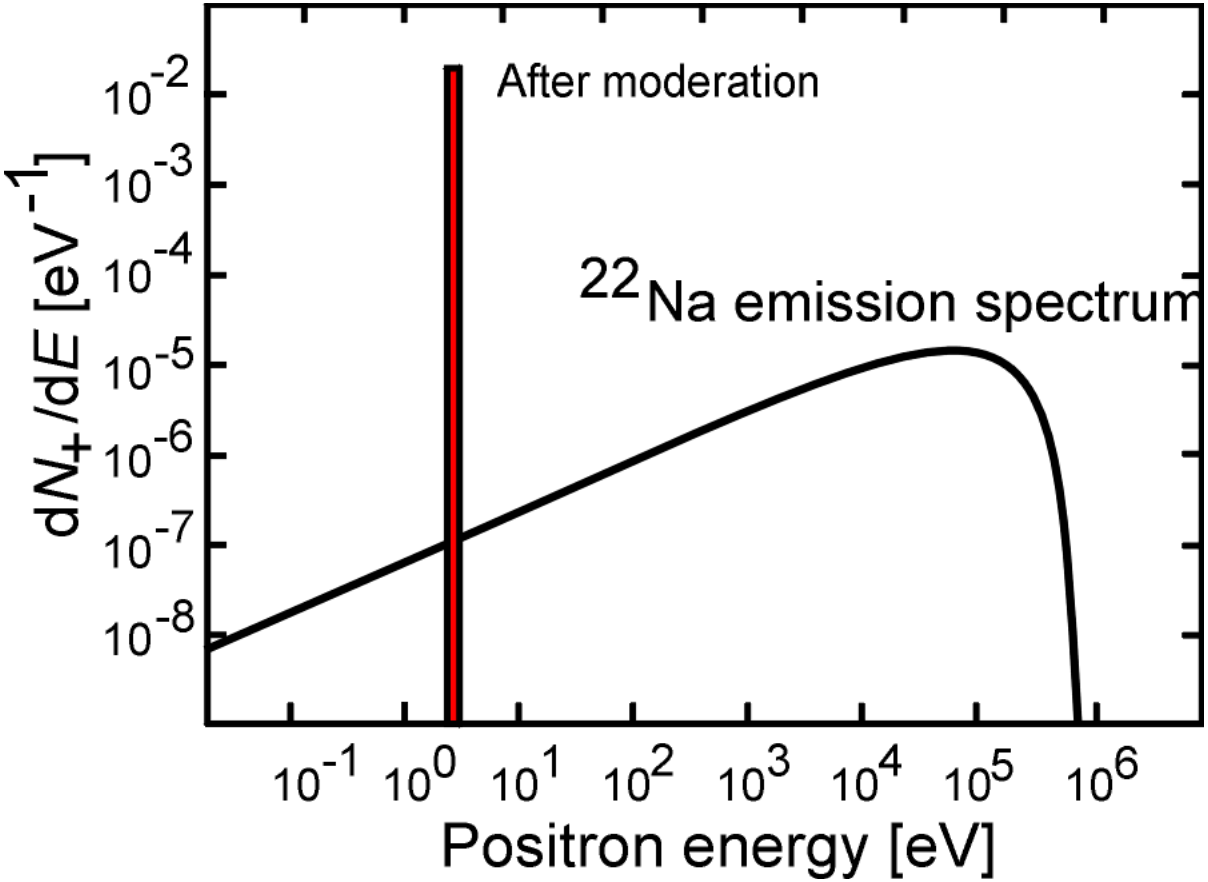

average positron lifetime in pure iron after tensile strain

stress-strain diagram of pure iron

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

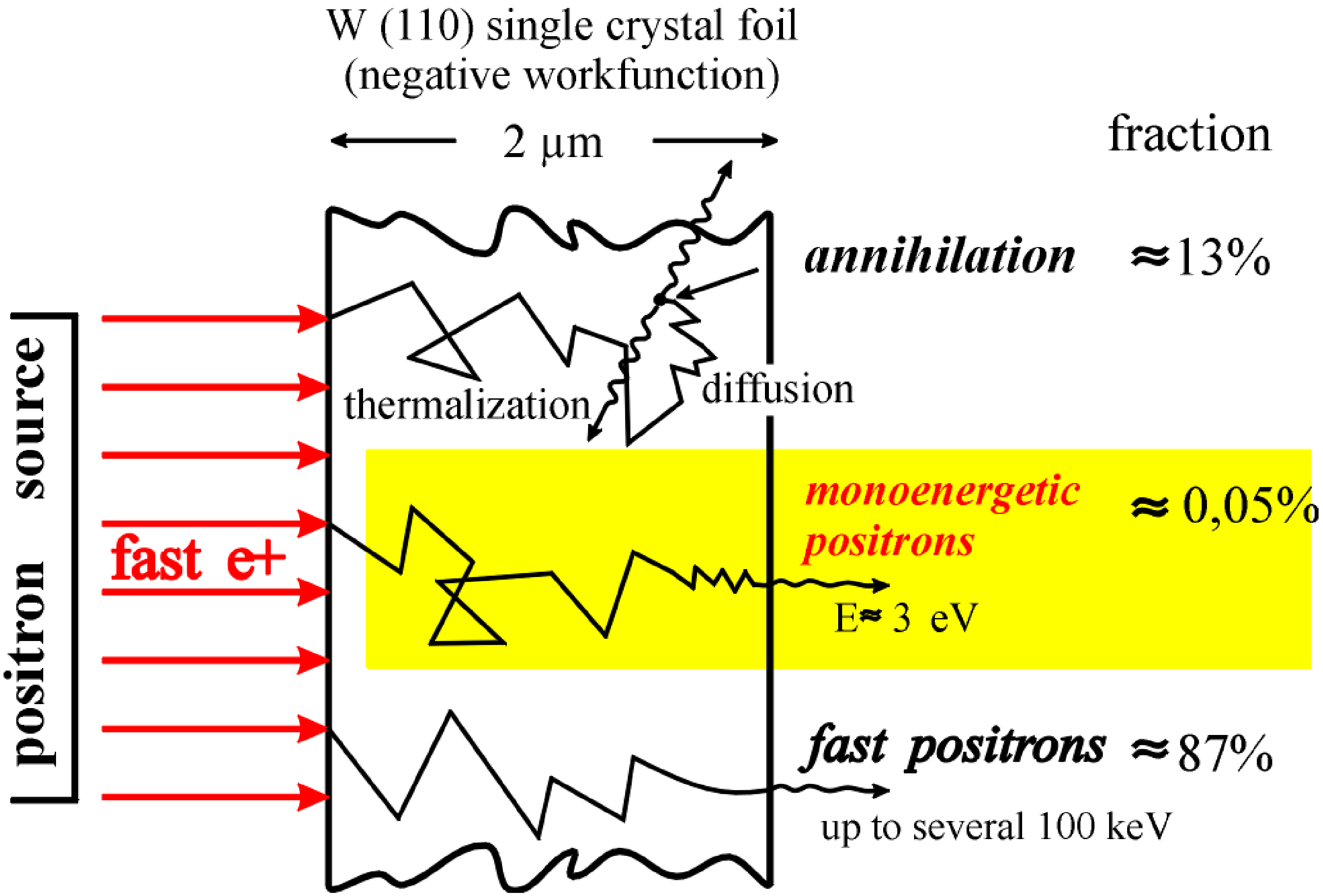
Moderation of Positrons

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



- 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



W (110) single crystal foil
(negative workfunction)

2 µm

fraction

positron source

fast e+

thermalization

diffusion

annihilation ≈13%

monoenergetic positrons ≈ 0,05%

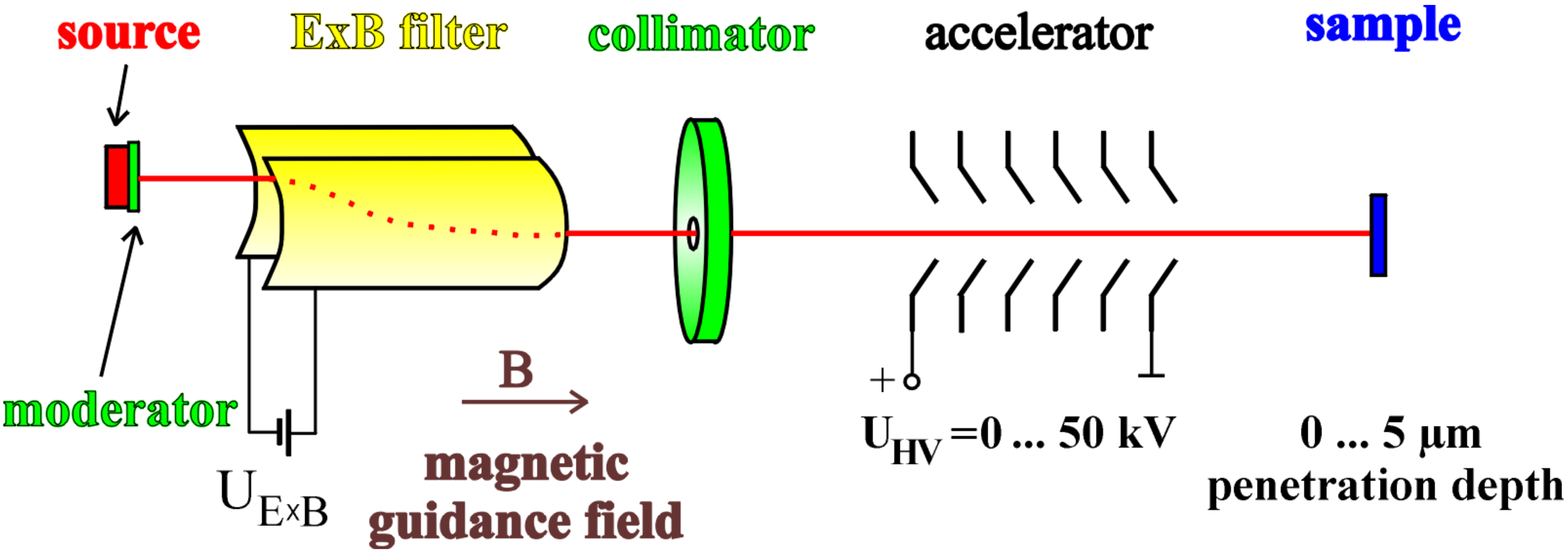
E≈ 3 eV

fast positrons ≈87%

up to several 100 keV

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

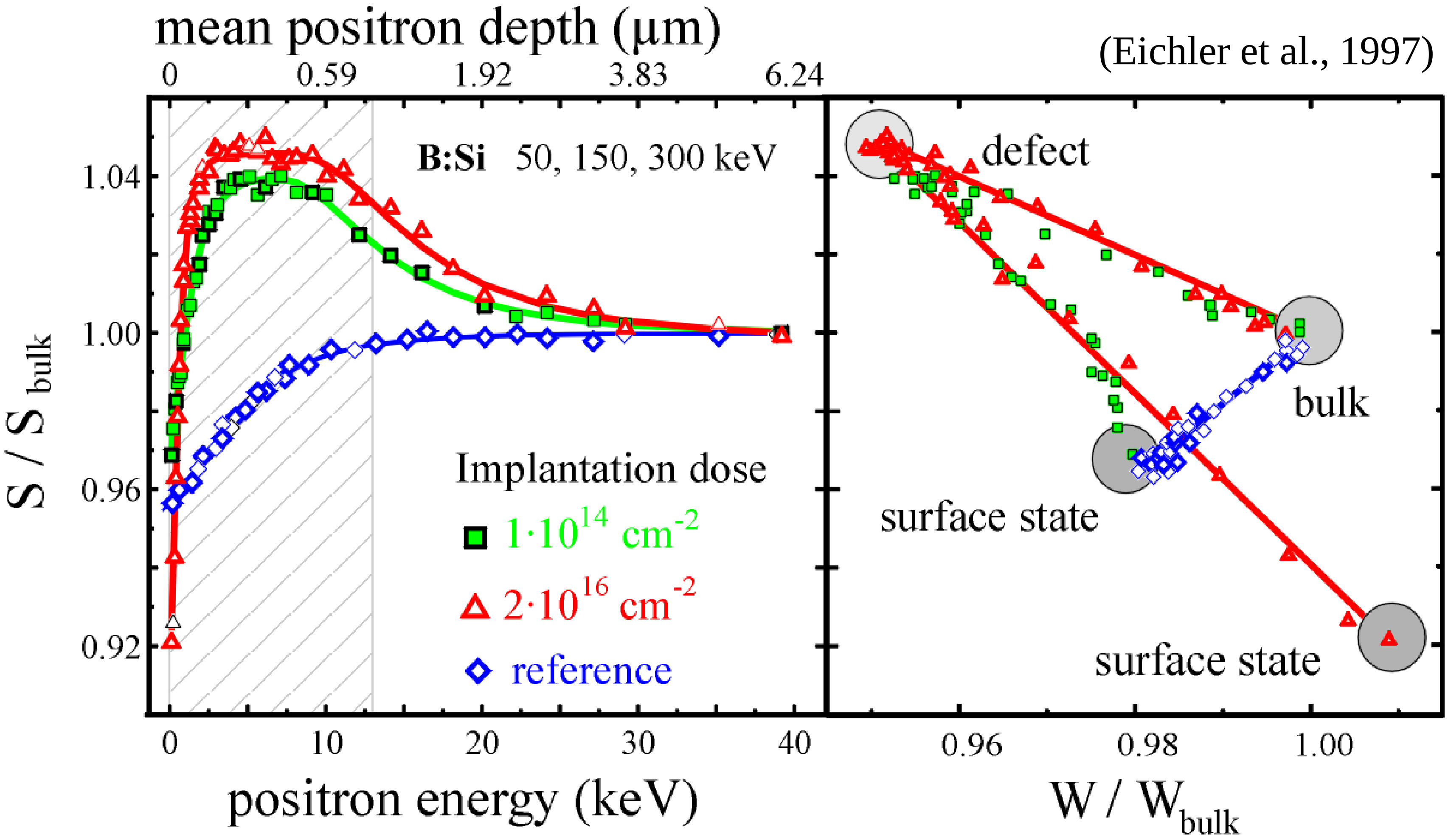
The Positron Beam System at Halle University



- positron lifetime measurement not any more possible
- way out: continuous beam must be chopped and bunched
- only two systems at intense sources available: FRM-II and Tsukuba

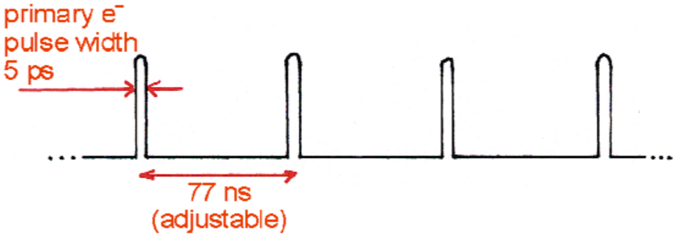
Defects in Si induced by Ion Implantation

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



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



Concept of EPOS (ELBE Positron Source)

MePS

Mono**e**nergetic **P**ositron **S**pectroscopy

- Cave 111b / Lab 111d
- monoenergetic (slow) positrons
- pulsed system
- LT, CDBS, AMOC
- Still under construction

Information Depth:
0…5 µm

CoPS

Conventional **P**ositron **S**pectroscopy

- LT, CDBS, AMOC
- using ^{22}Na foil sources
- He-cryostat
- automated system
- digital detector system

Information Depth:
10…200 µm

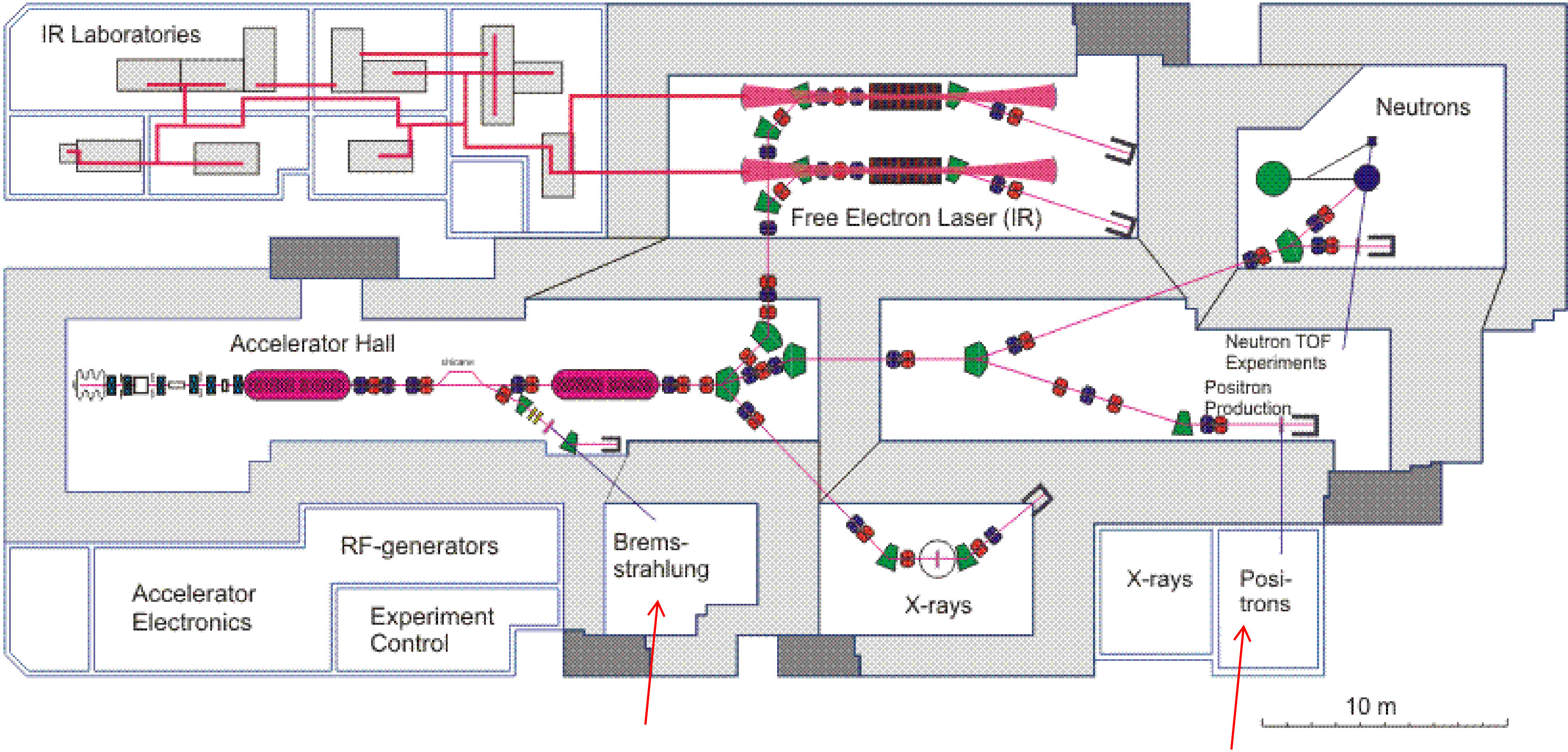
GiPS

Gamma-**i**nduced **P**ositron **S**pectroscopy

- Cave 109 (nuclear physics)
- Positron generation by Bremsstrahlung
- Information in complete bulky sample (up to 100 cm^3)
- all relevant positron techniques (LT, CDBS, AMOC)

Information Depth:
0.1 mm …5 cm

Ground plan of the ELBE hall

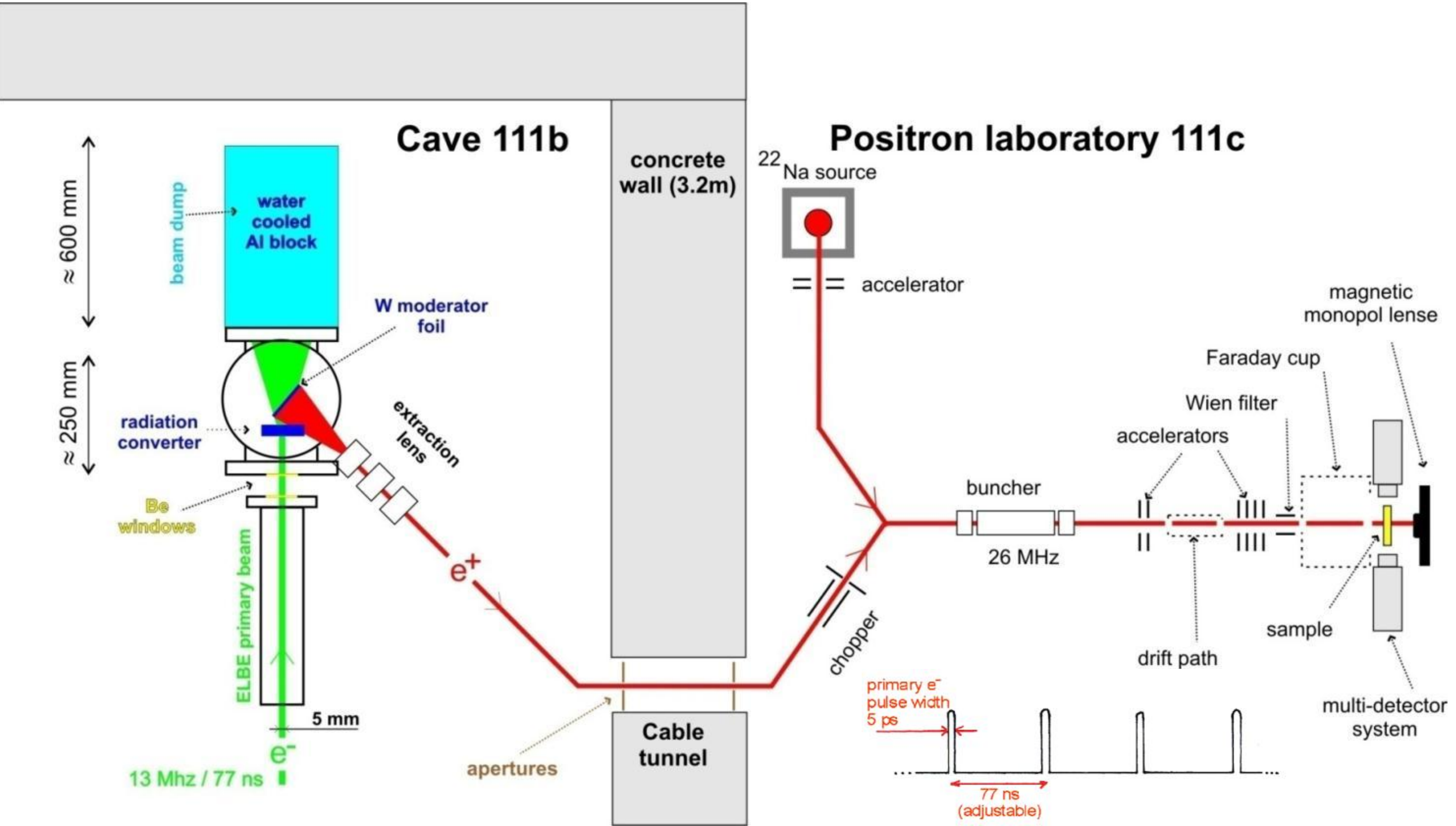


GiPS

MePS

Progress of Mono-energetic Positron Beam

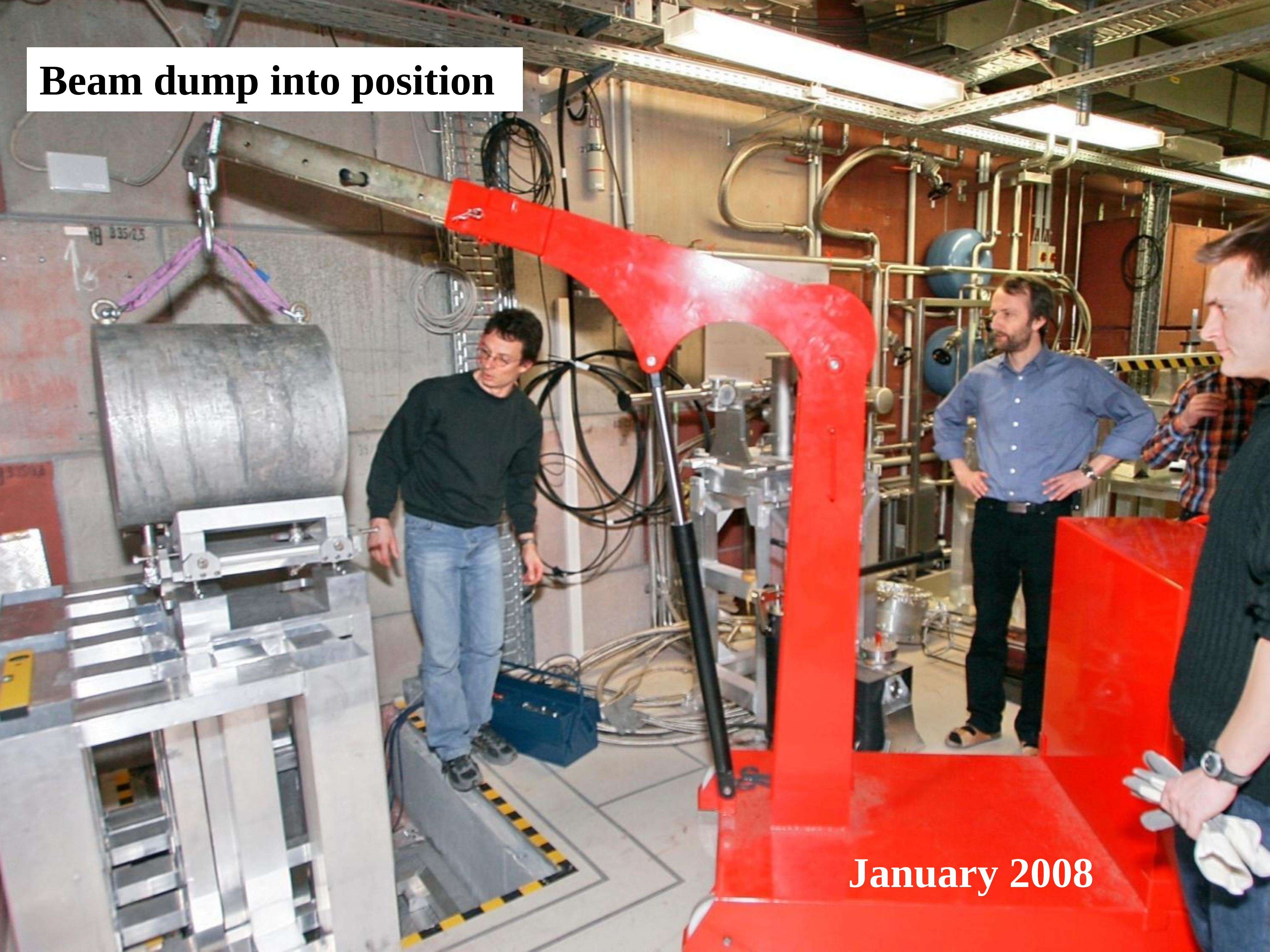
- 40 MeV, 1 mA, 26 MHz repetition time in cw mode; lifetime, CDBS and AMOC with slow e+
- Retain original time structure for simplicity and best time resolution



November 2007

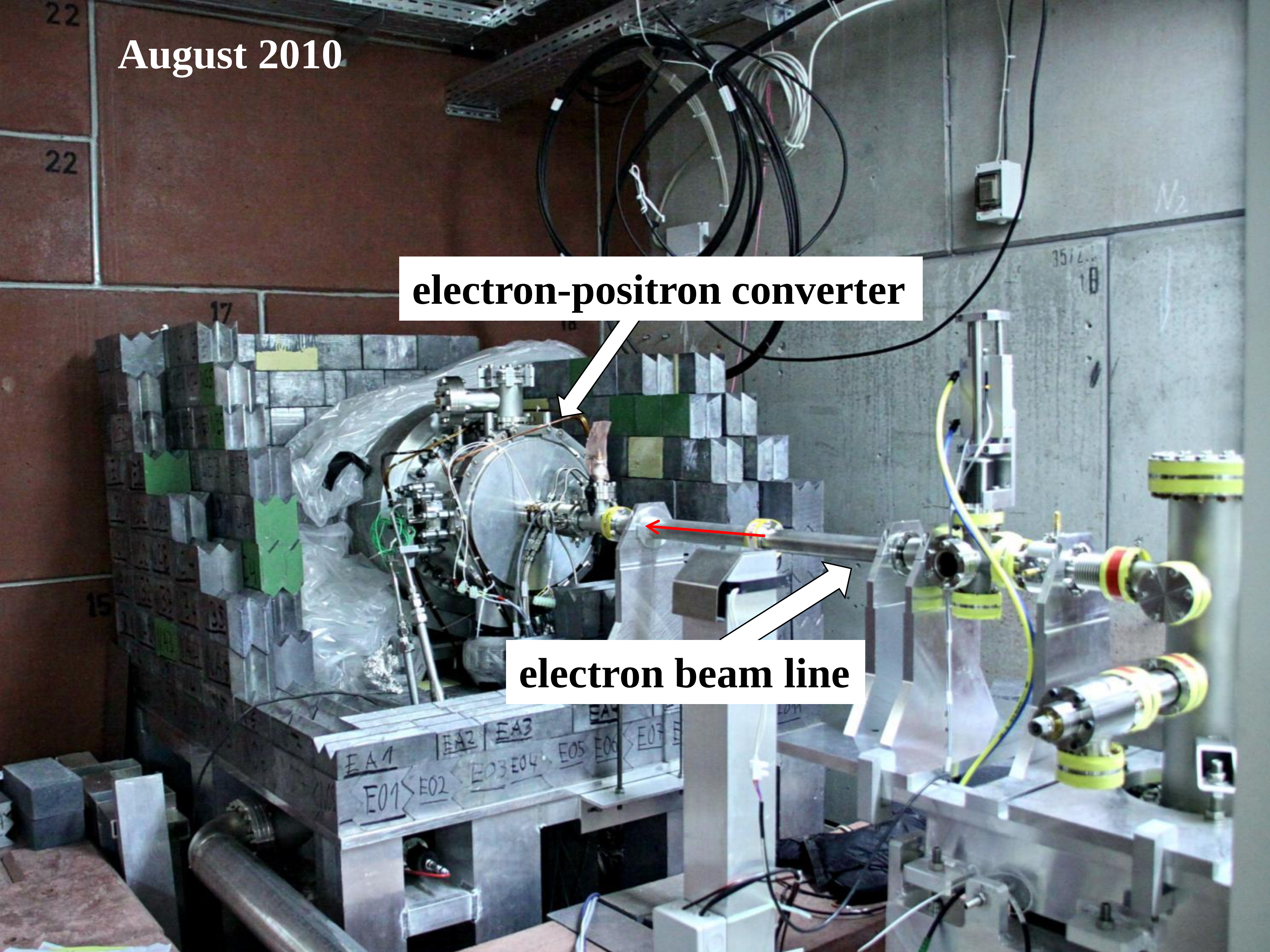
Start of Mounting

Beam dump into position



January 2008

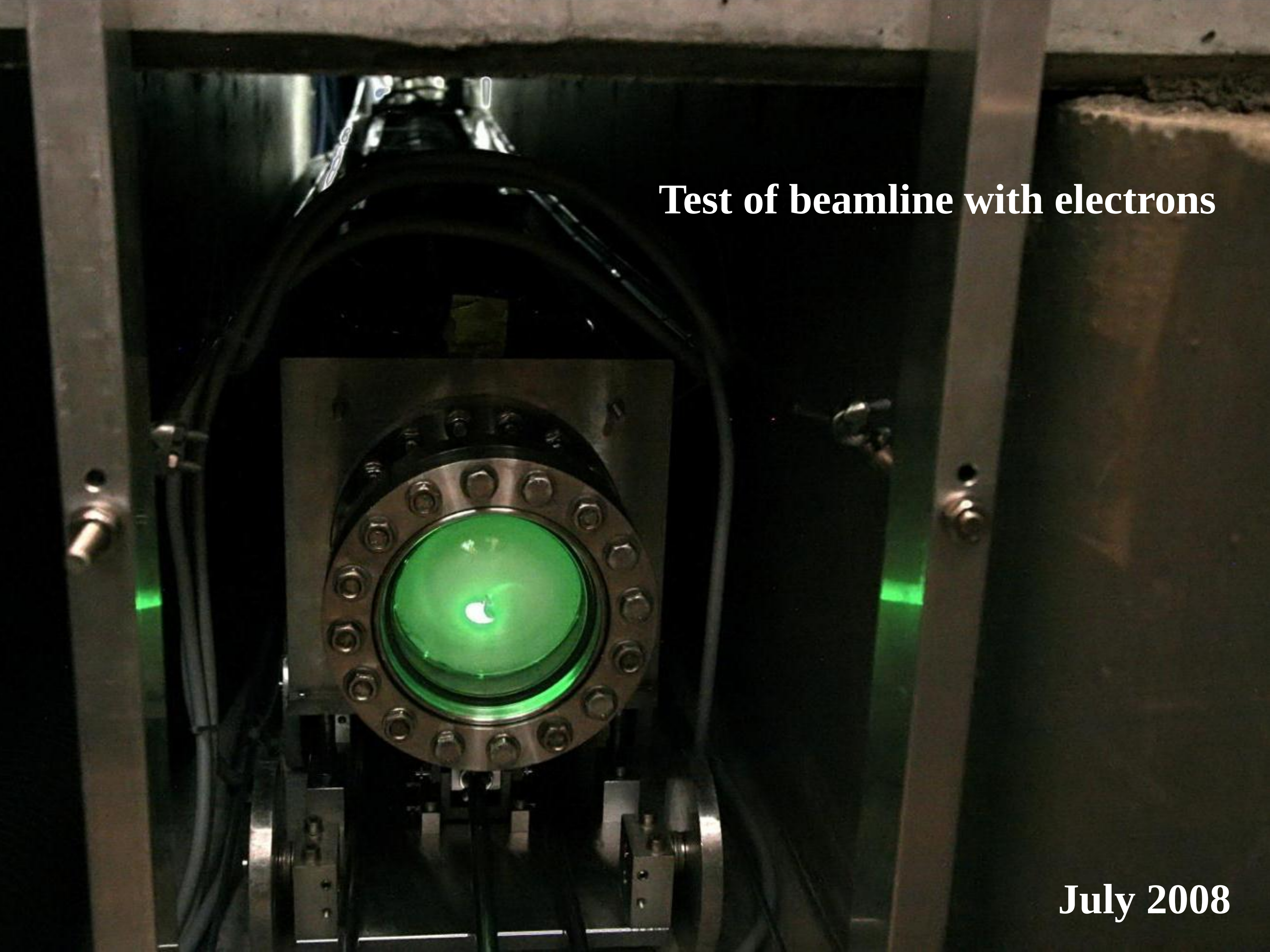
January 2009



August 2010

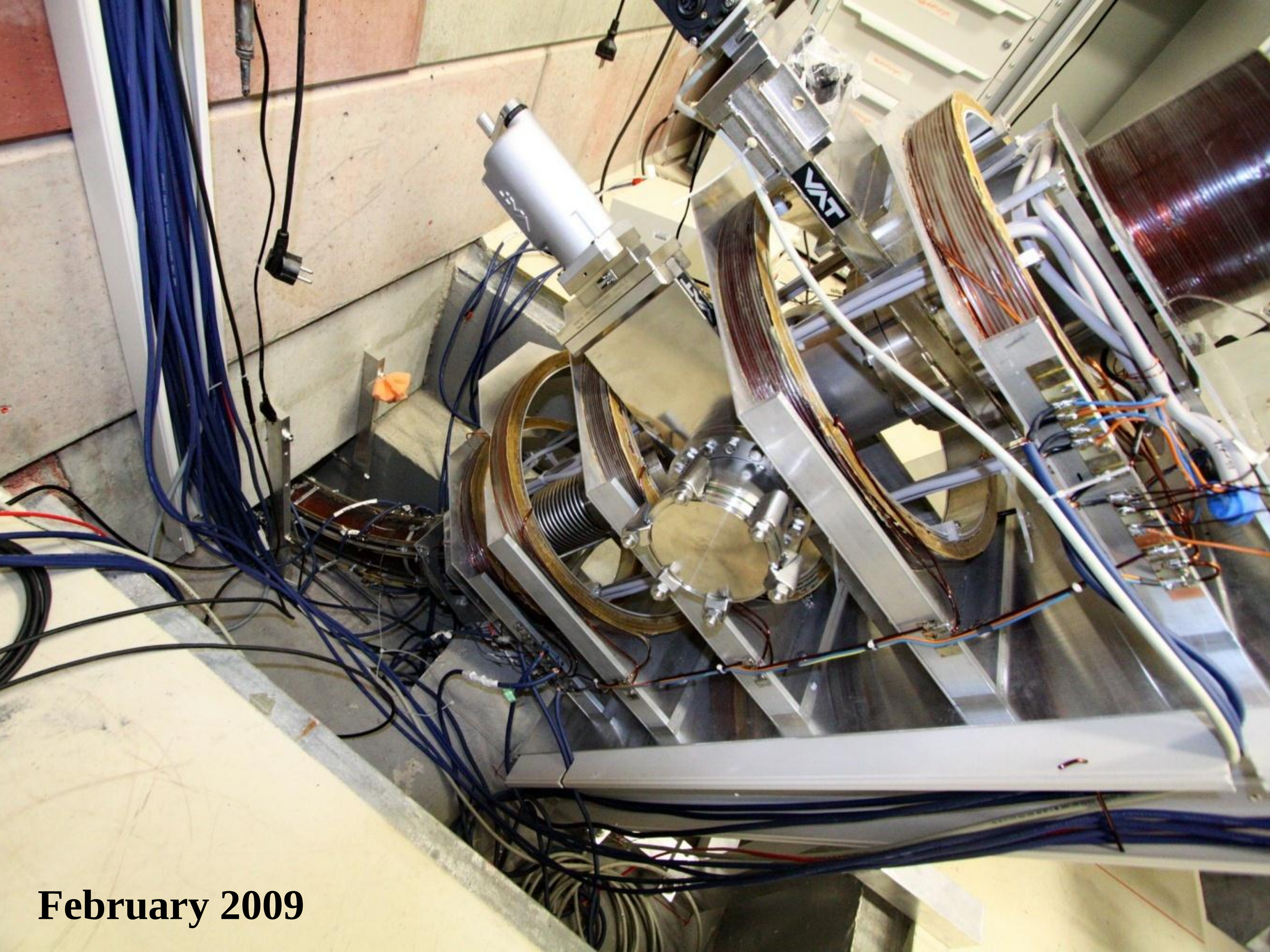
electron-positron converter

electron beam line

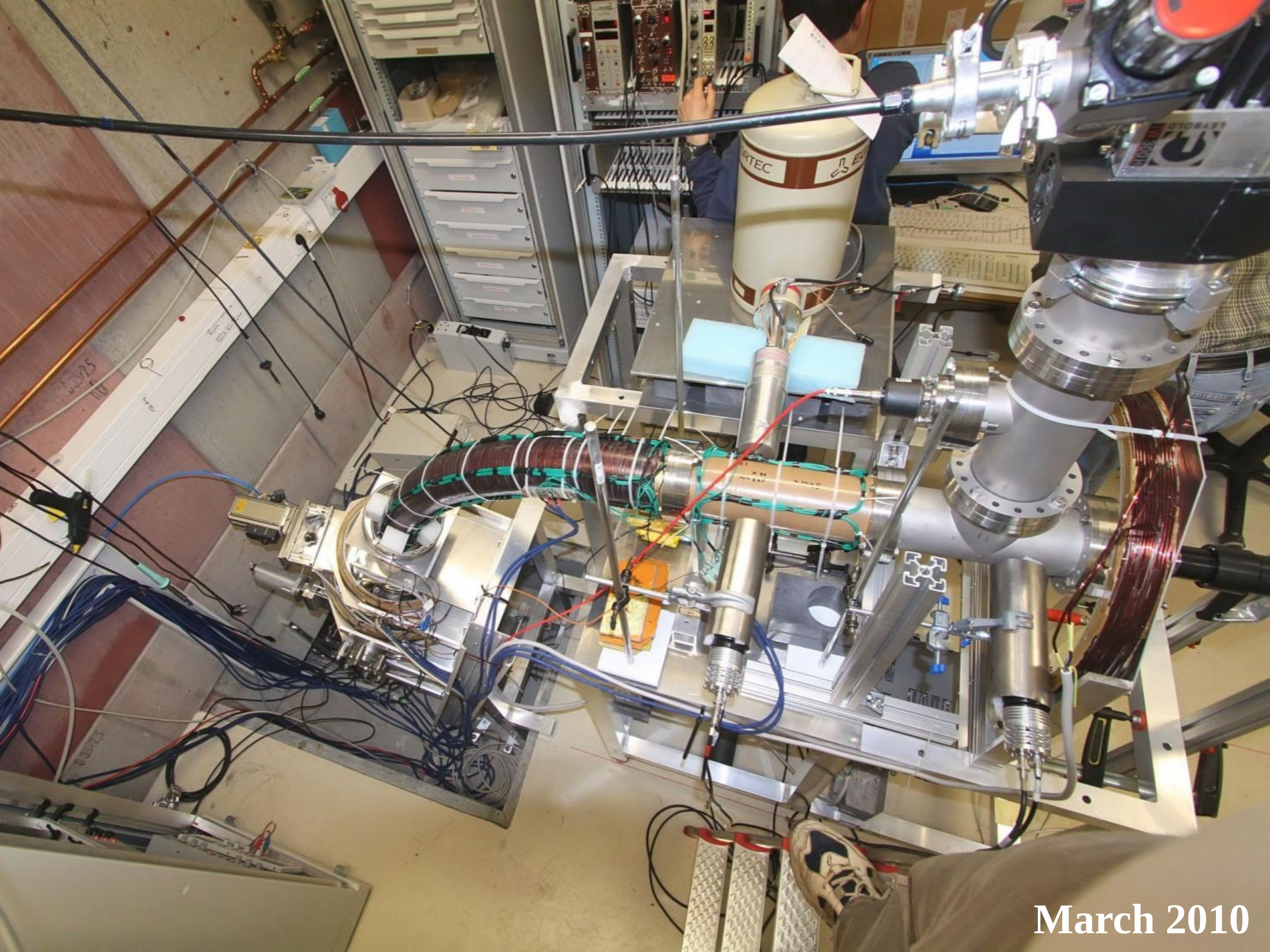


Test of beamline with electrons

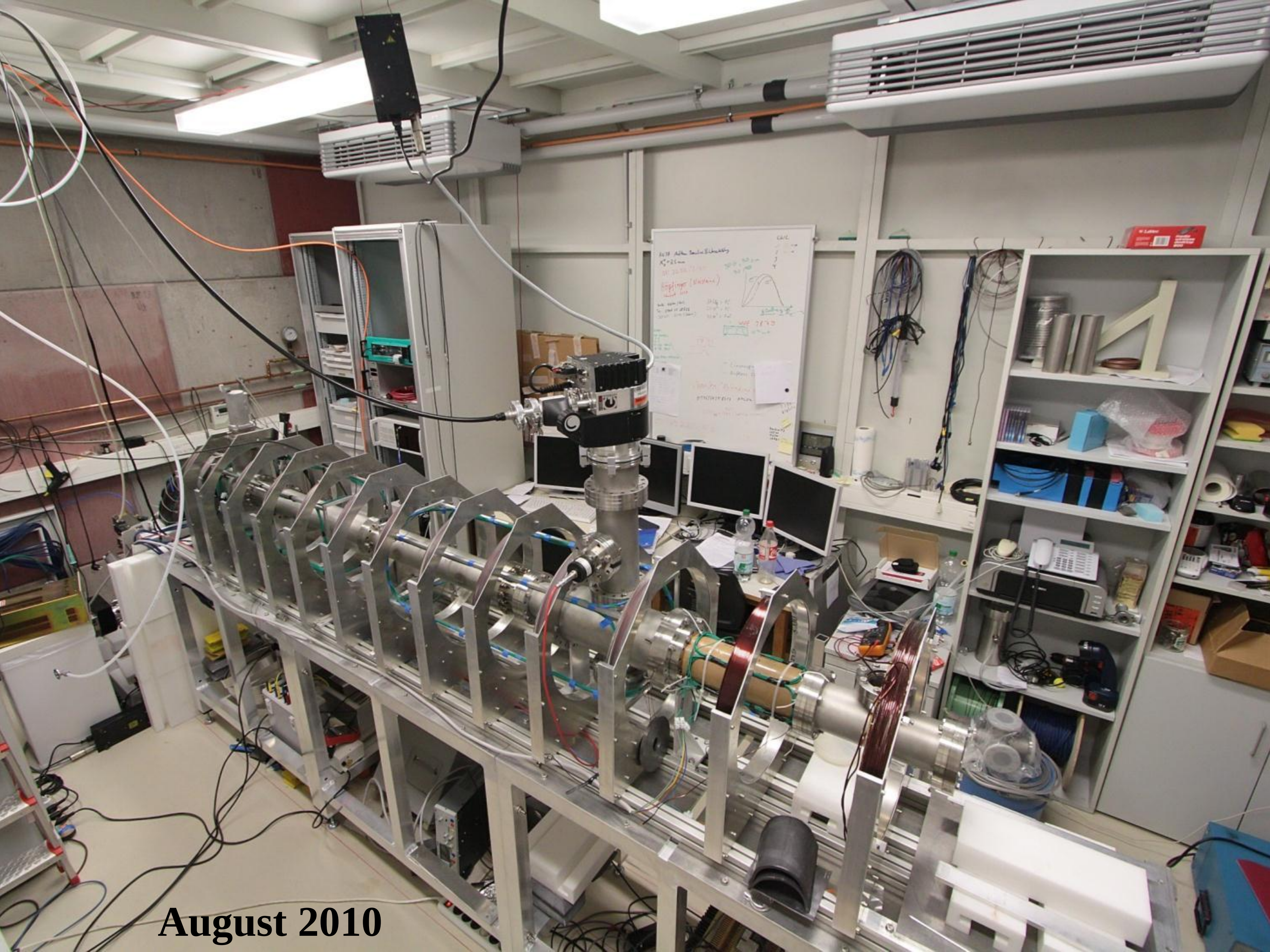
July 2008



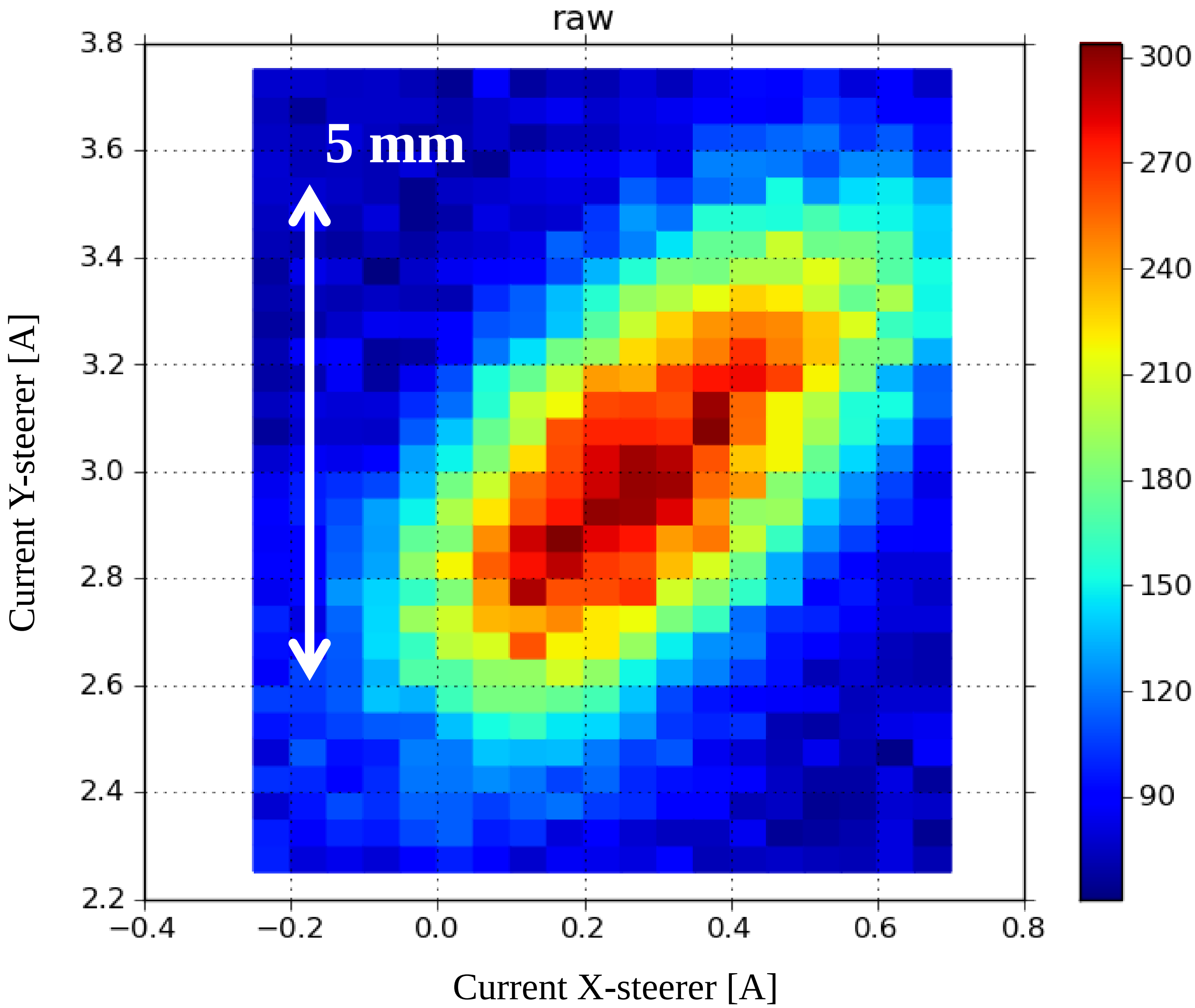
February 2009



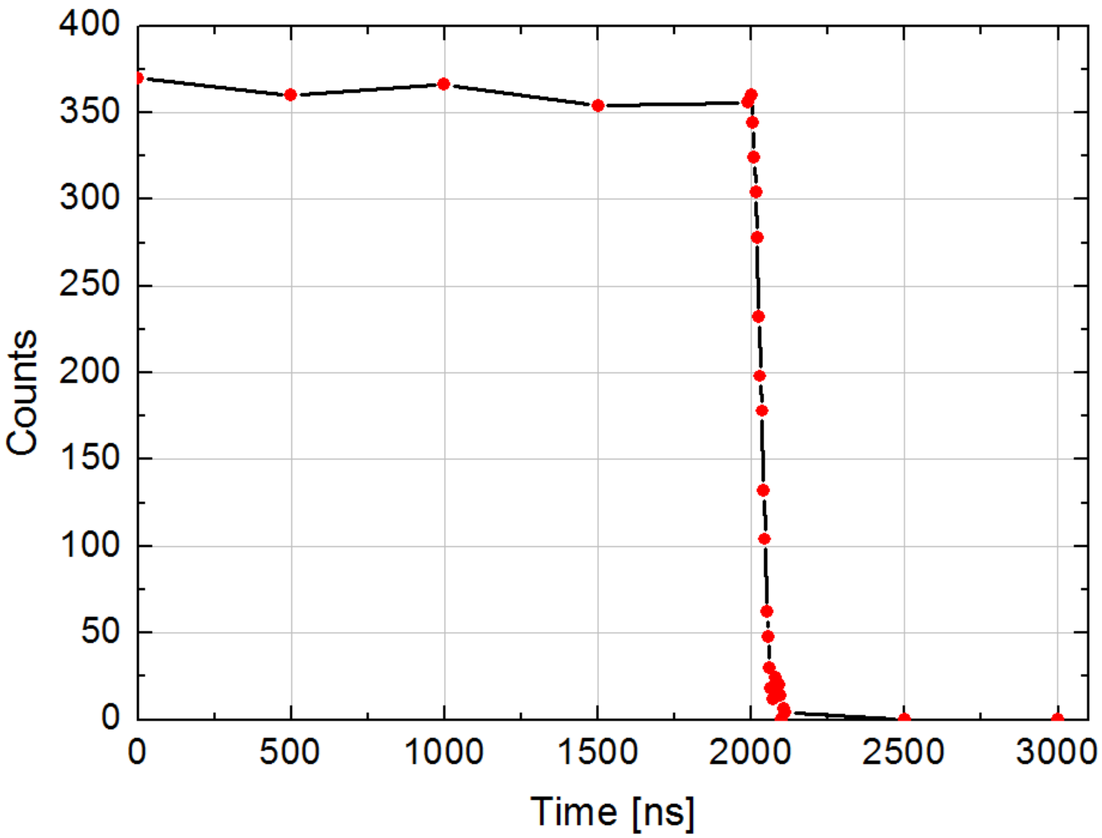
March 2010



August 2010

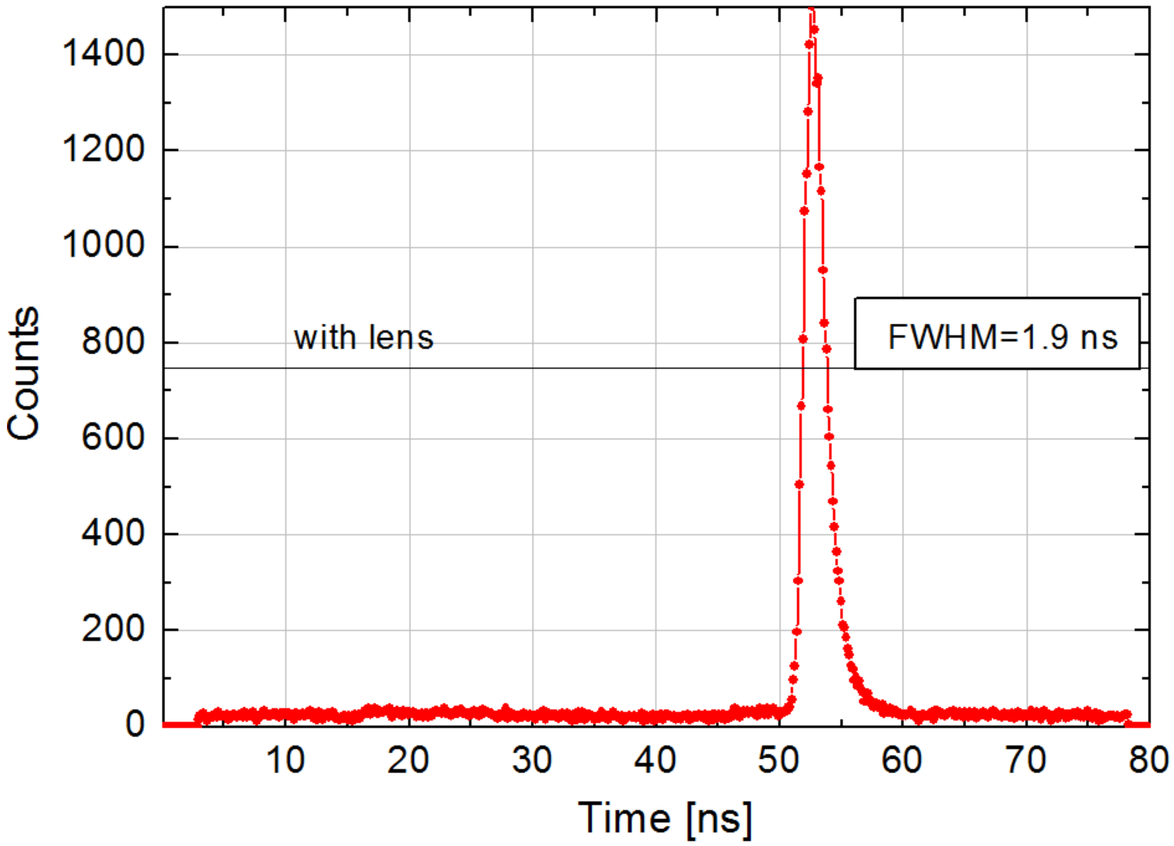

raw
5 mm
Current Y-steerer [A]
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
Current X-steerer [A]
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
300
270
240
210
180
150
120
90

Measurement of Energy Distribution by retarding Grid



- electrostatic lens in action
- 2 apertures of 5mm were mounted in a distance of half a gyration length (63 mm)

GiPS: Gamma-induced Positron Spectroscopy



- using the double aperture: time structure very useful and according to former simulation
- still missing: Chopper signal - must be 2 ns / >500V / 13 MHz repetition frequency
- time width of < 50 ps expected with chopper and buncher

Positron Annihilation Spectroscopy: Applications

Variety of applications in all fields of materials science:

- bulk defects in semiconductors, ceramics and metals
- defect-depth profiles due to surface modifications (ion implantation; tribology)
- epitaxial layers (growth defects, misfit defects at interface, …)
- soft matter physics (open volume; interdiffusion; …)
- porosimetry 1…50 nm (e.g. low-k materials - highly porous dielectric layers)
- fast kinetics (e.g. precipitation processes in Al alloys; defect annealing; diffusion; …)
- radiation resistance (e.g. space materials)
- many more …