POSITRON ANNIHILATION SPECTROSCOPY IN MATERIAL RESEARCH (AT JINR)

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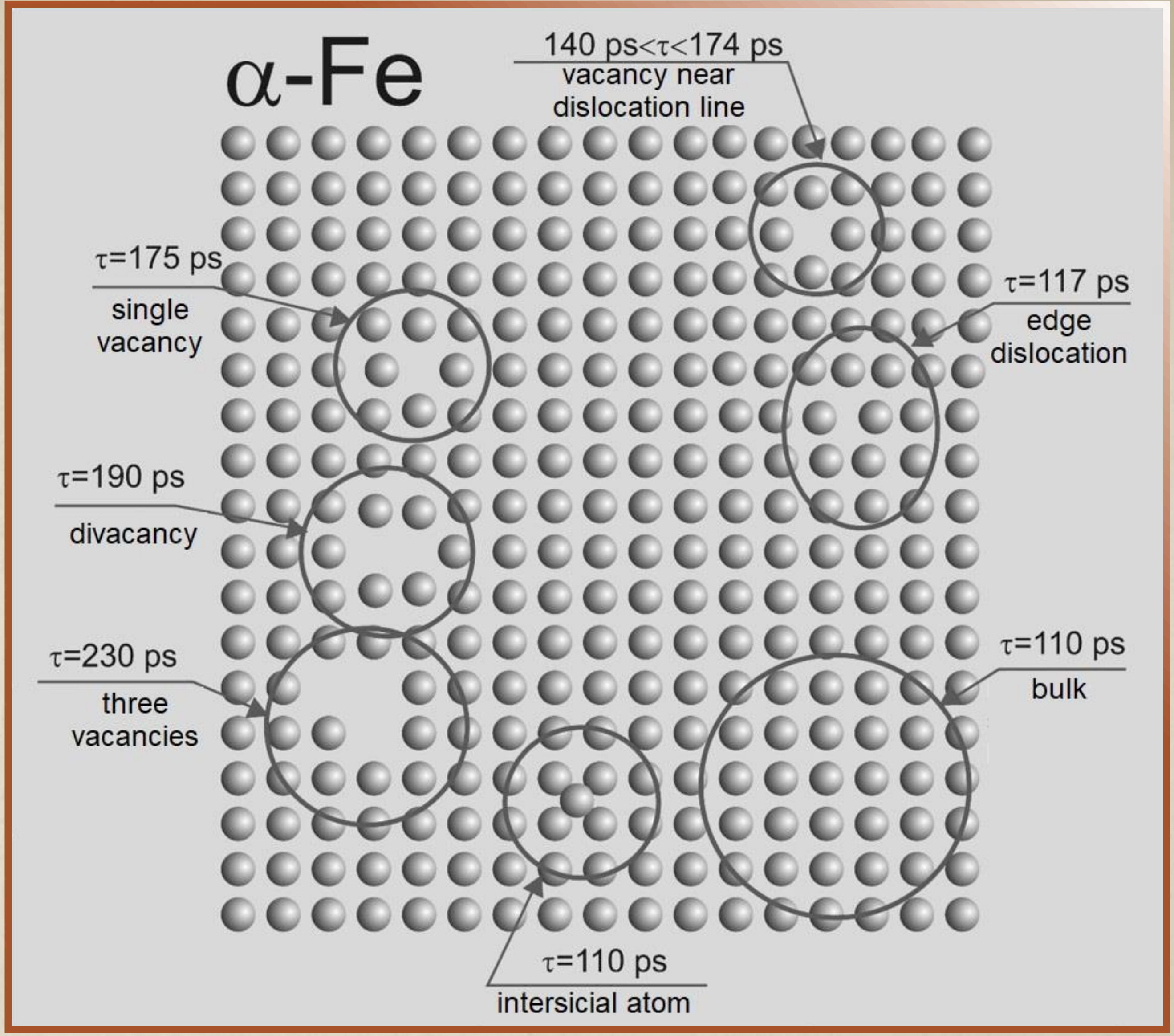
INTRODUCTION

PAS techniques:
- ❑ angular correlations of gamma quanta
- ❑ Doppler spectroscopy (DB)
- ❑ positron lifetime spectroscopy (LT)

Possibilities:
- ❑ evaluation of defect concentration
- ❑ determination of defect concentration profile
- ❑ detection of the kind and size of defects

Applications:
- ❑ solid body physics
- ❑ material and surface engineering
- ❑ metals, semiconductors, thin layers



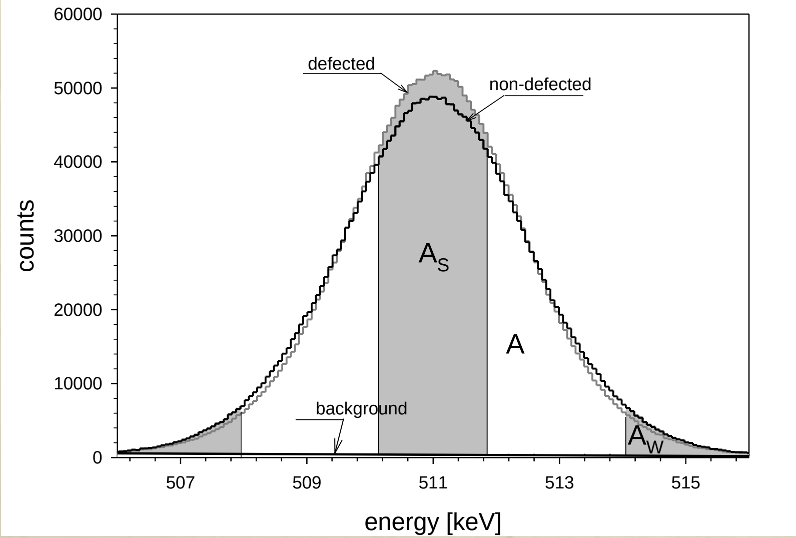
Positron lifetimes in different defects of Fe structure

EXPERIMENTAL TECHNIQUES: DB SPECTROSCOPY

The change of photon energy by relativistic Doppler effect in the laboratory system

$$E_\gamma \cong mc^2 + E_B \pm \frac{p_{||}c}{2}$$

where E_B is binding energy e^+e^- in the pair surrounding, $p_{||}$ – momentum of annihilating pair, m – electron mass, c - speed of light in the vacuum.



S parameter

- ratio of area under the central part of 511 keV line to whole area below this line

$$S = \frac{A_S}{A}$$

- defines the participation of e^+e^- pairs with low momentum
- the bigger value the bigger concentration of such defects as vacancies

W parameter

- defines the participation of pairs e^+e^- with high momentum

$$W = \frac{A_W}{A}$$

- together with S parameter gives information about kind of defects

EXPERIMENTAL TECHNIQUES: DB SPECTROSCOPY

gamma ≈ 511 keV

- HPGe detector
- preamplifier
- amplifier
- MC analyzer
- PC computer

The energy resolution of DB spectrometer is 1.2 keV at 511 keV.

EXPERIMENTAL TECHNIQUES: LT SPECTROSCOPY

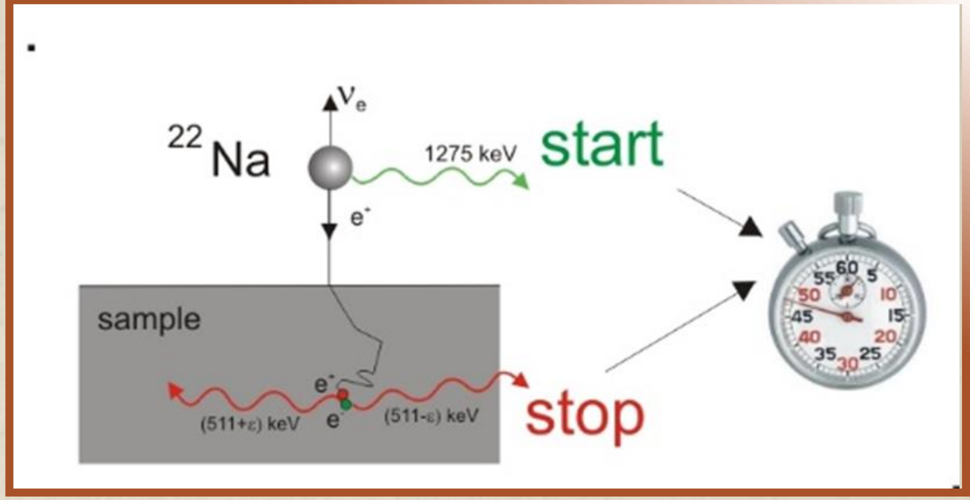
The annihilation rate λ

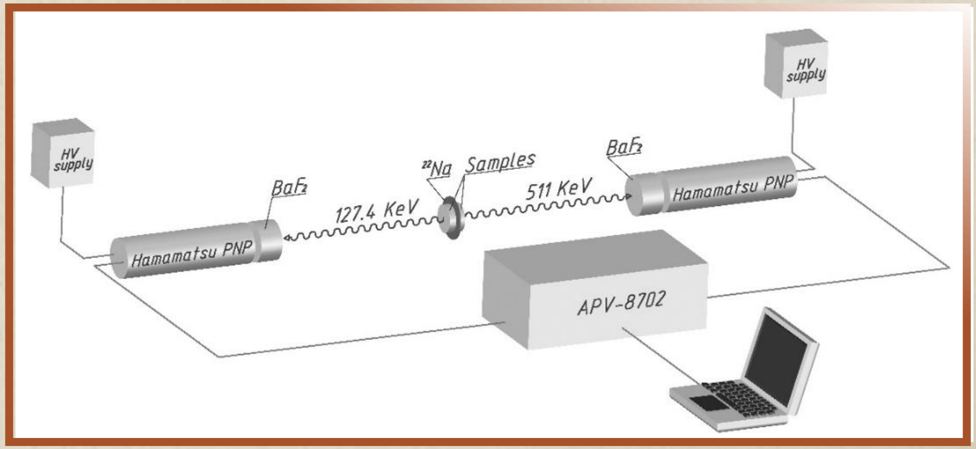
the reciprocal value of mean positron lifetime

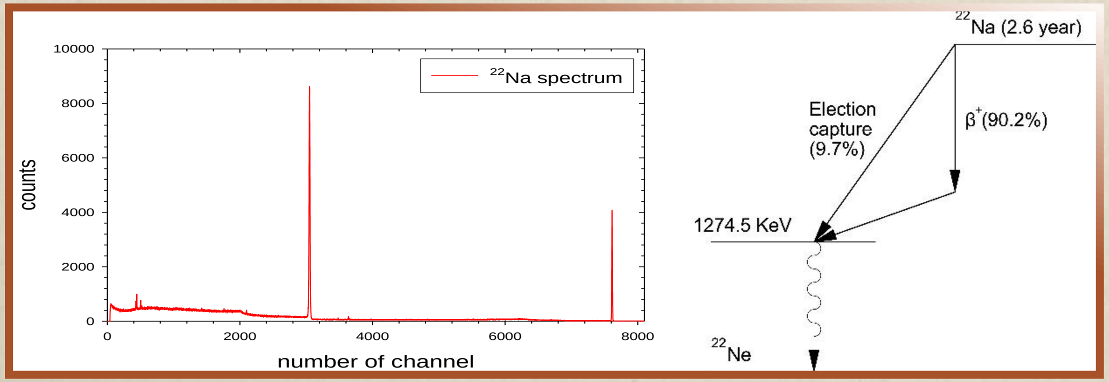
$$\lambda = \frac{1}{\tau} = \pi r_0^2 c n_e$$

r_0 – electron radius, ***c*** – speed of light

- electron density inside the defect is lower in comparison to bulk area what finds a reflect in the mean positron lifetime
- e.g. for pure Fe **τ = 110 ps** in nondefected structure while positron trapped inside vacancy lives **τ = 174 ps**

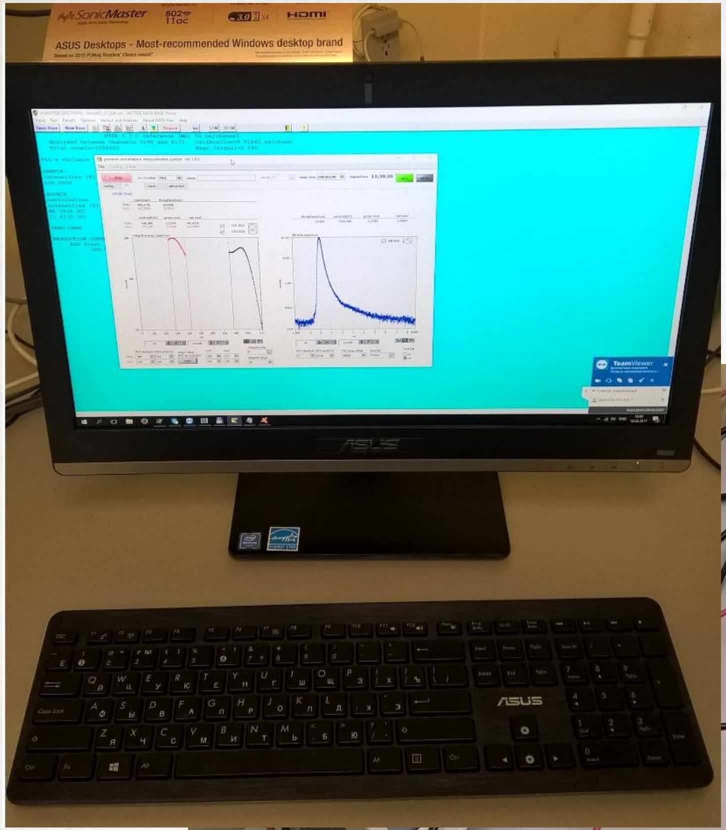


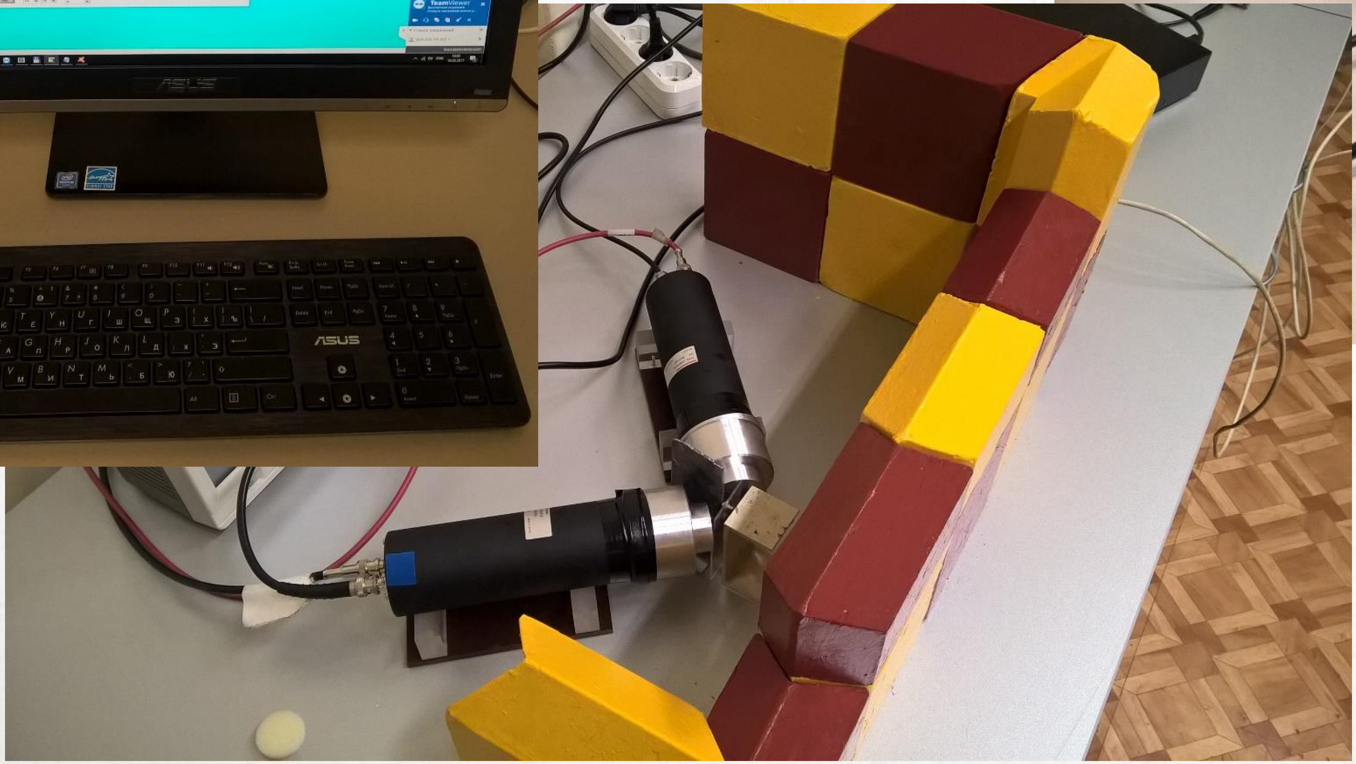


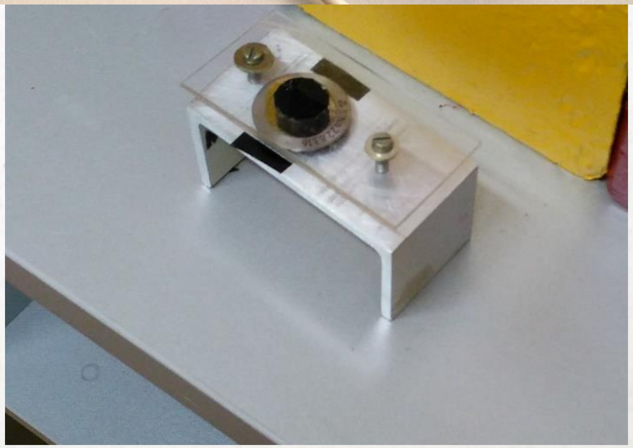


http://www.ifj.edu.pl/~mdryzek/page_a1.html

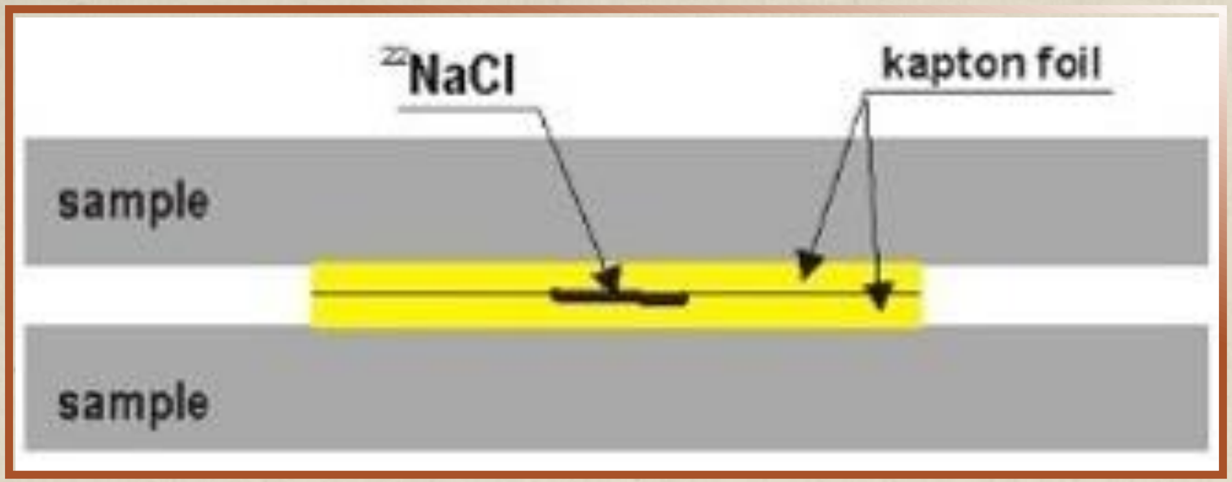
EXPERIMENTAL TECHNIQUES: LT SPECTROSCOPY







THE CONVENTIONAL PAS EXPERIMENT



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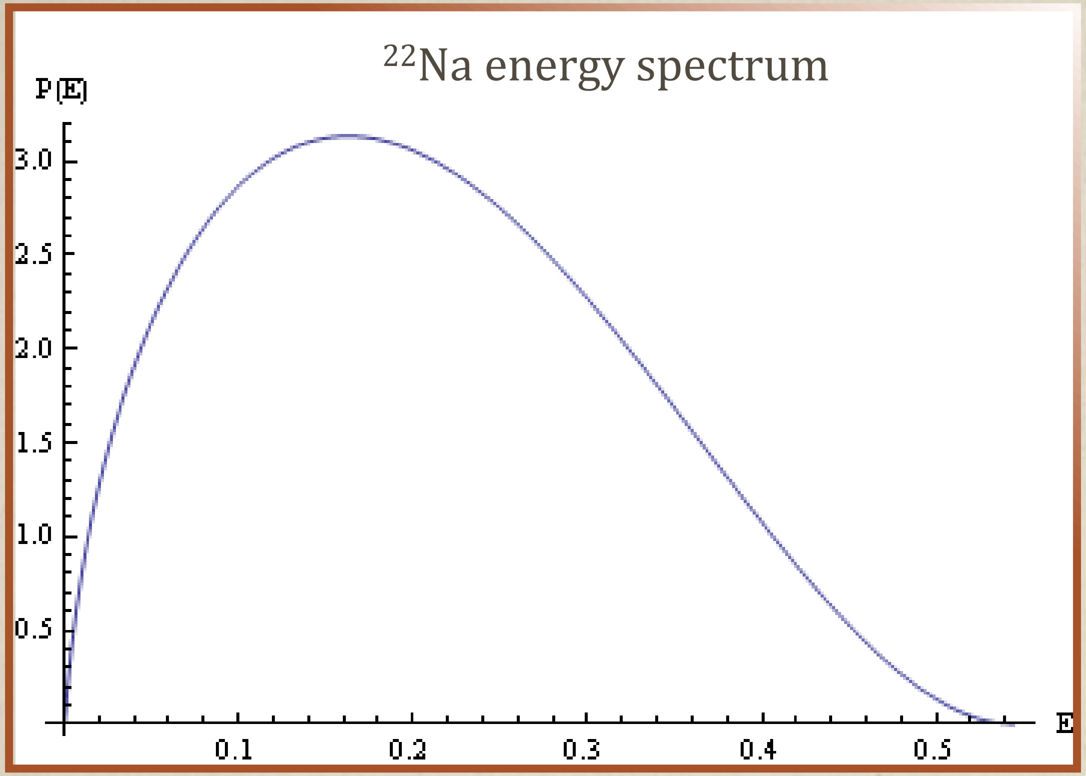
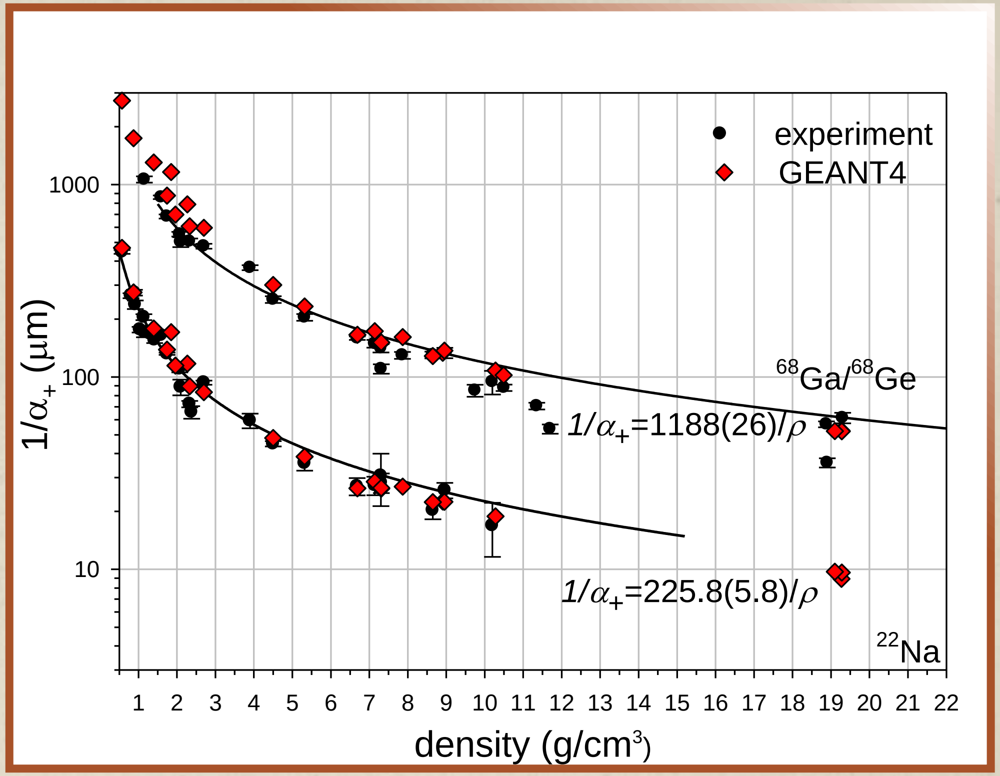
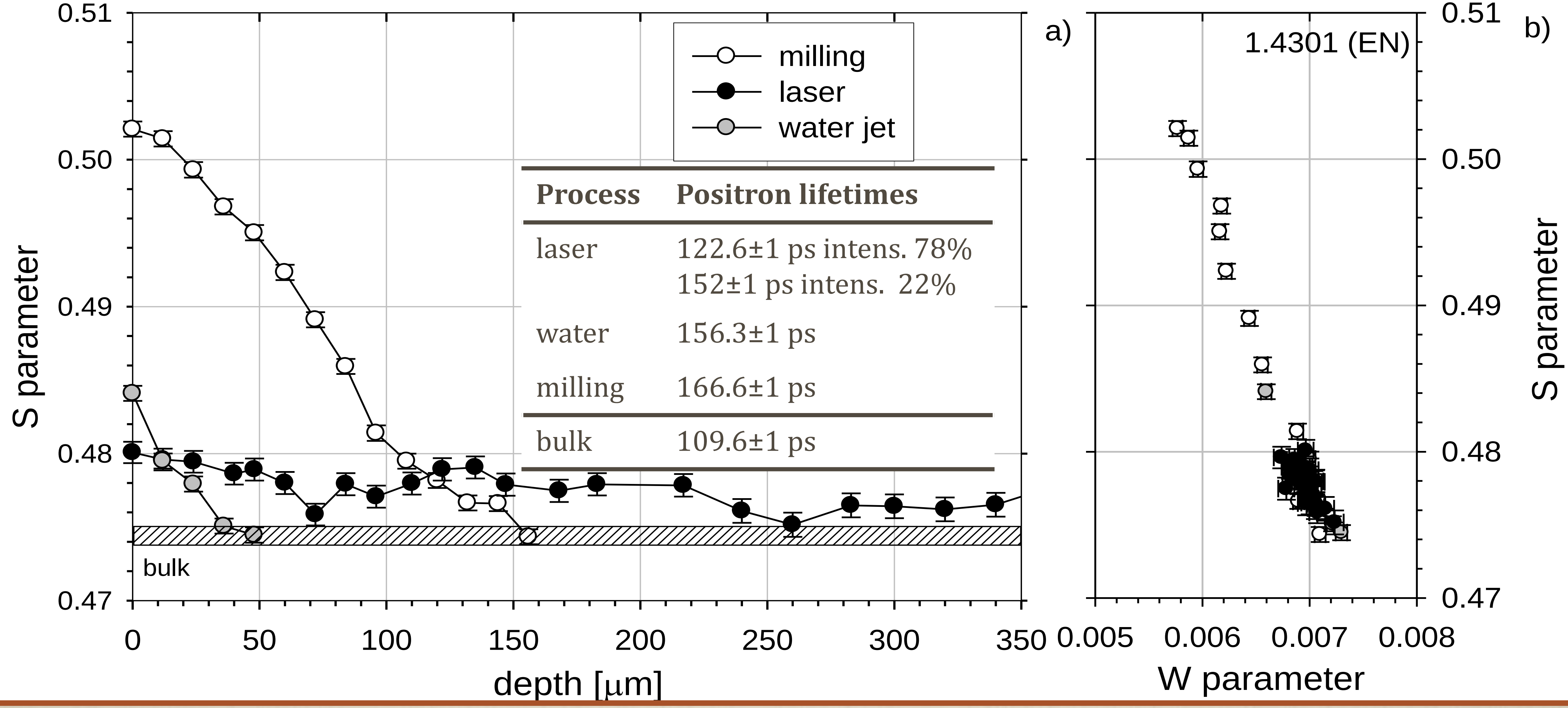




Disadvantages of experiment are a long range of positron implantation and a lack of possibility to locate positrons precisely on the given depth

P. Horodek, J. Dryzek, Nukleonika 55 (2010) 17

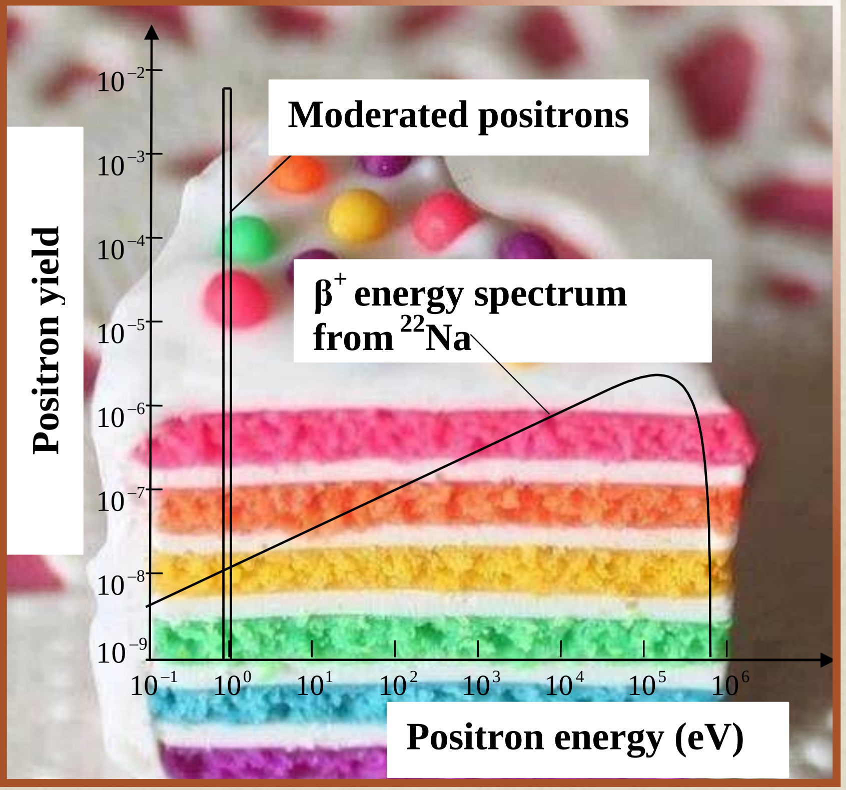
THE CONVENTIONAL PAS EXPERIMENT

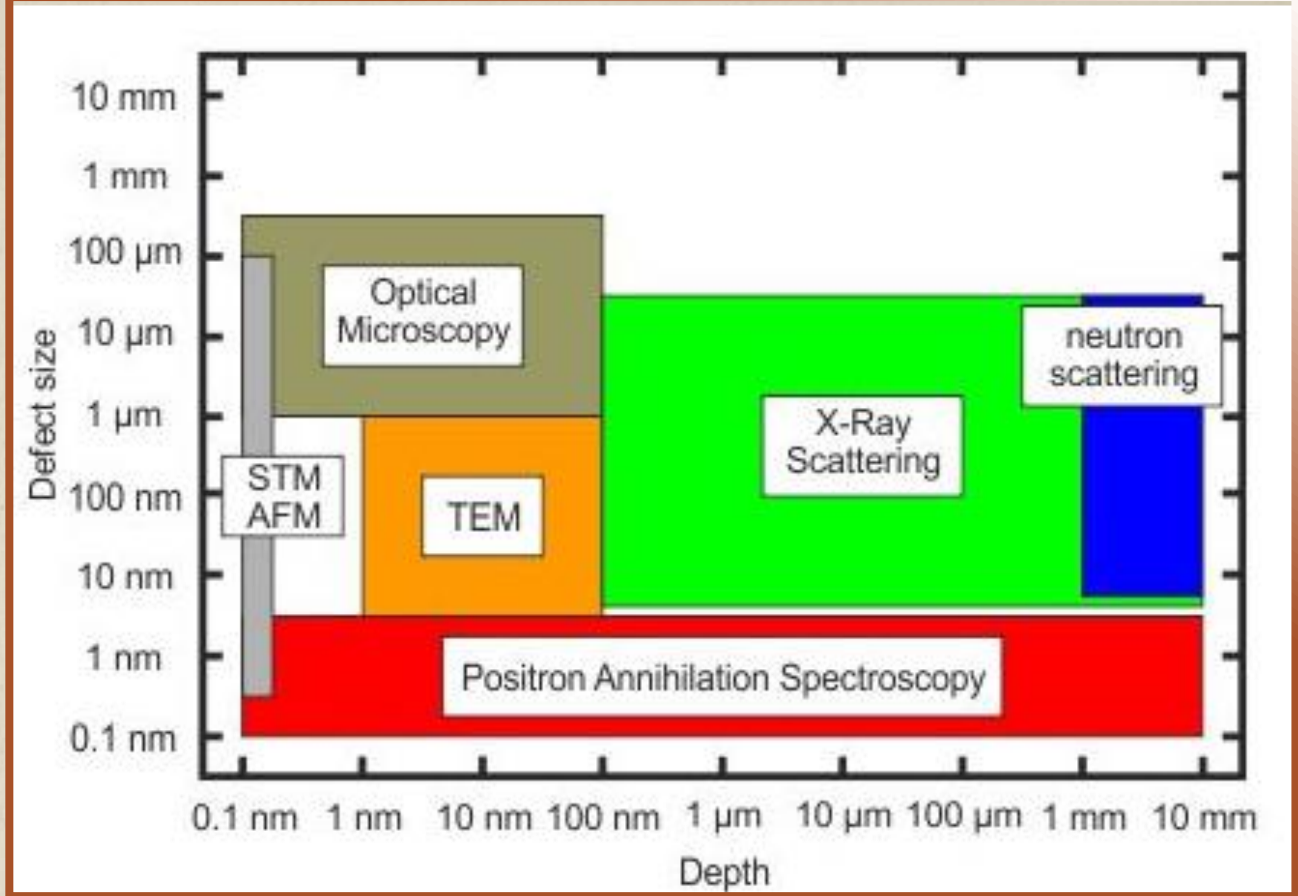


Process	Positron lifetimes
laser	122.6±1 ps intens. 78% 152±1 ps intens. 22%
water	156.3±1 ps
milling	166.6±1 ps
bulk	109.6±1 ps

P. Horodek et al., Tribol. Lett. 45 (2012) 341.

THE CONVENTIONAL PAS EXPERIMENT



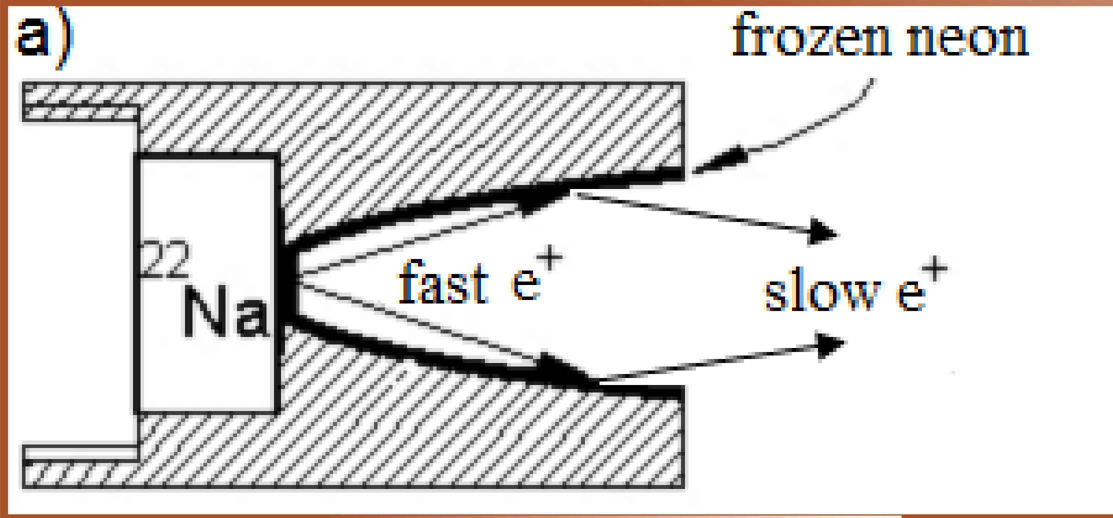


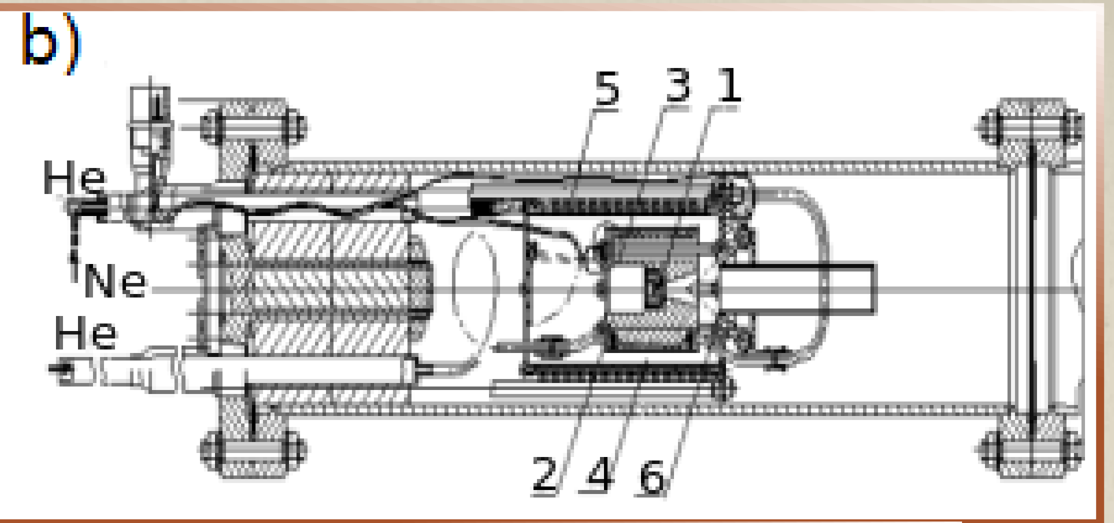
There are some areas i.e. thin layers, ion implantation, semiconductors where the application of conventional PAS experiments is strongly limited

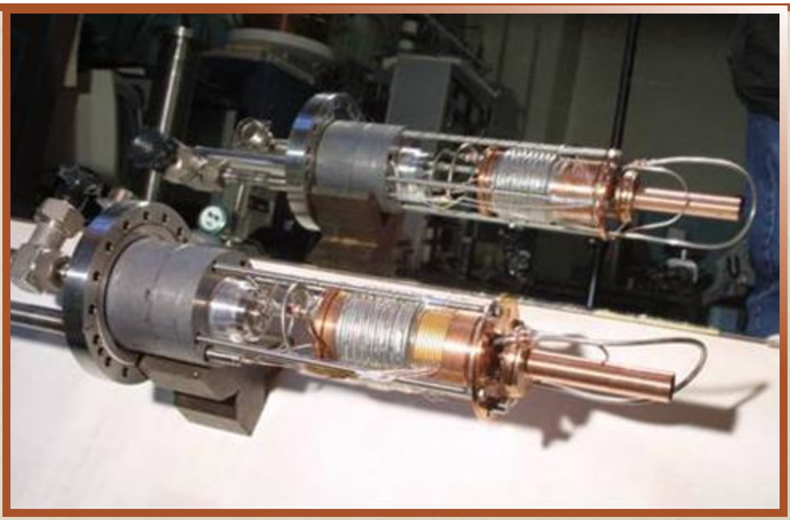
HERE EXPERIMENTS WITH SLOW POSITRONS ARE REQUIRED !!

https://www.hzdr.de/db/Cms?pNid=3581

THE VARIABLE ENERGY POSITRON BEAM







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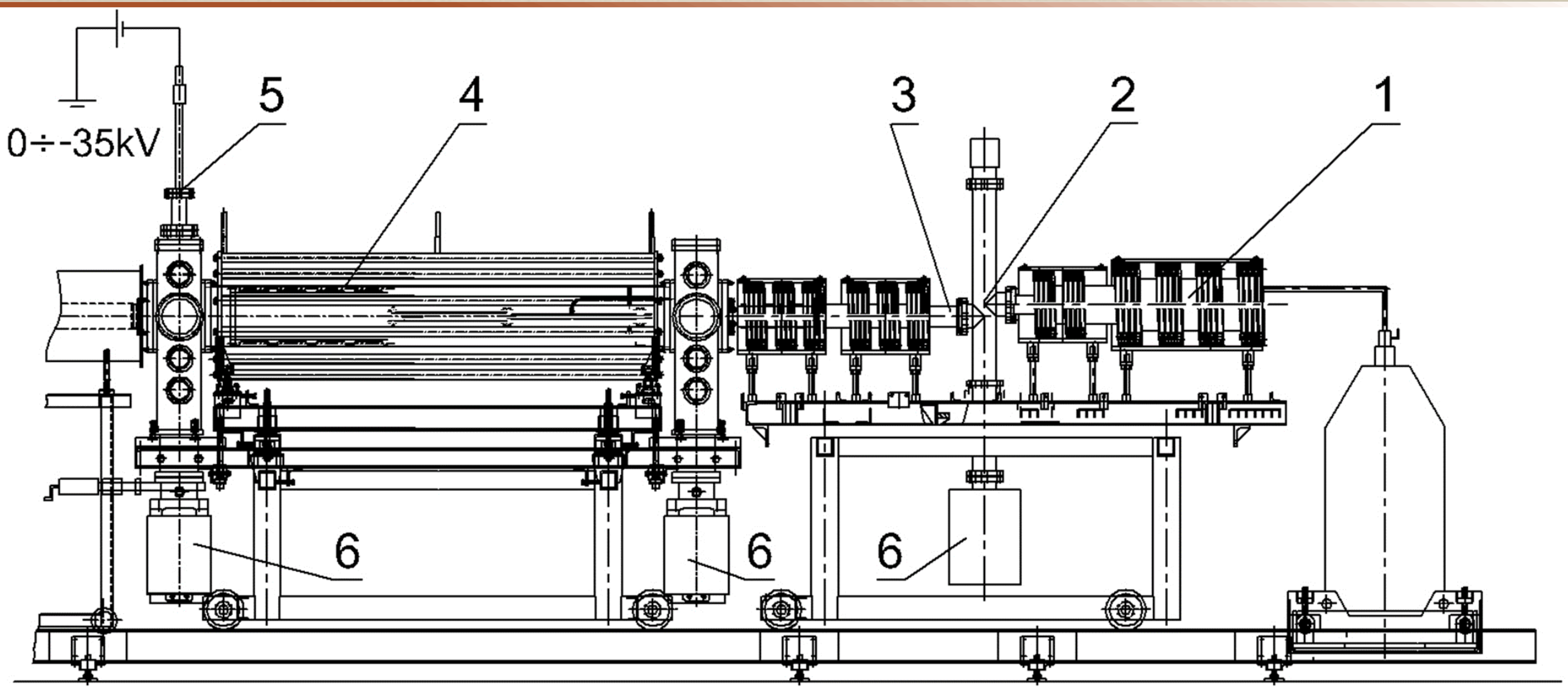

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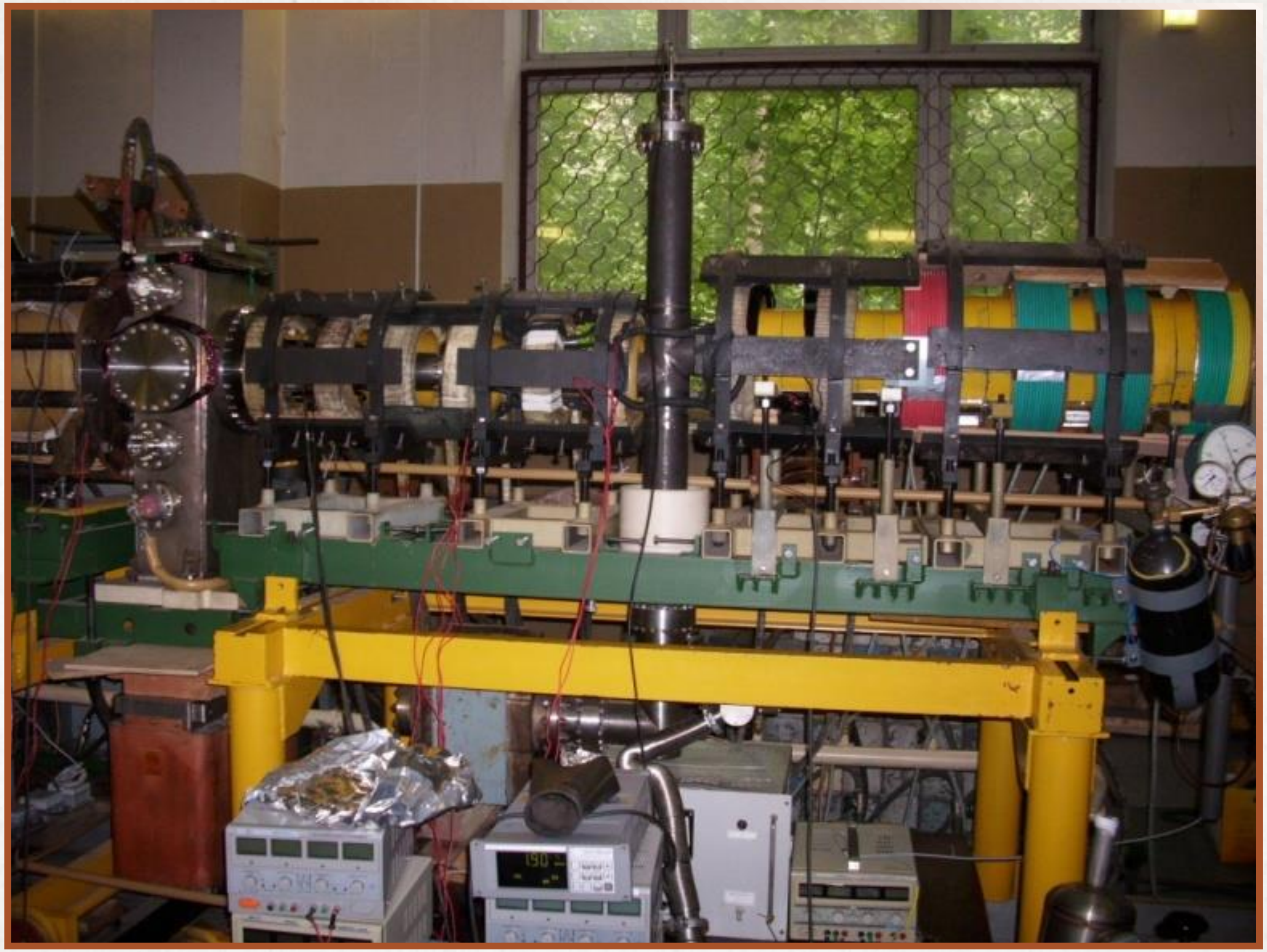

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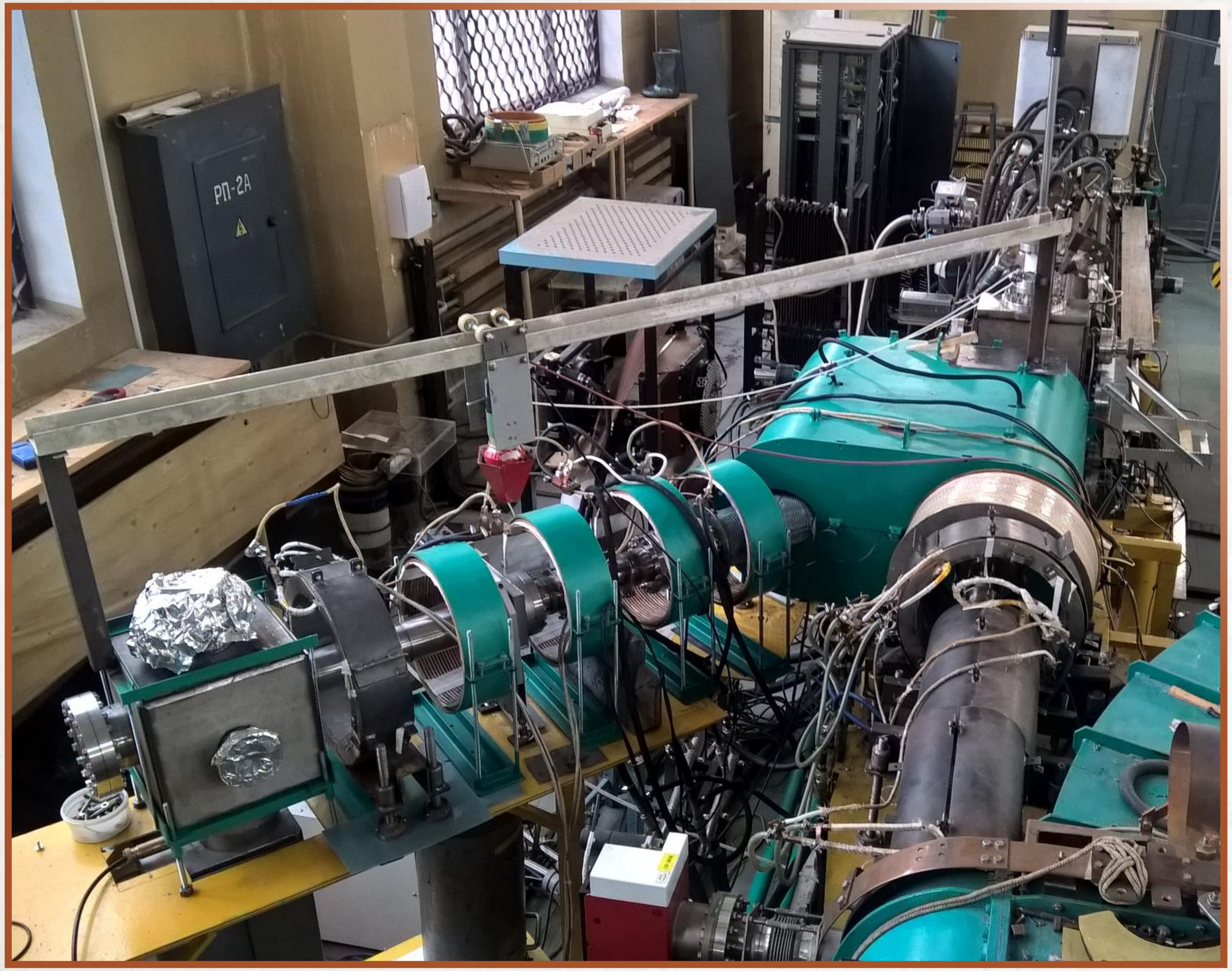

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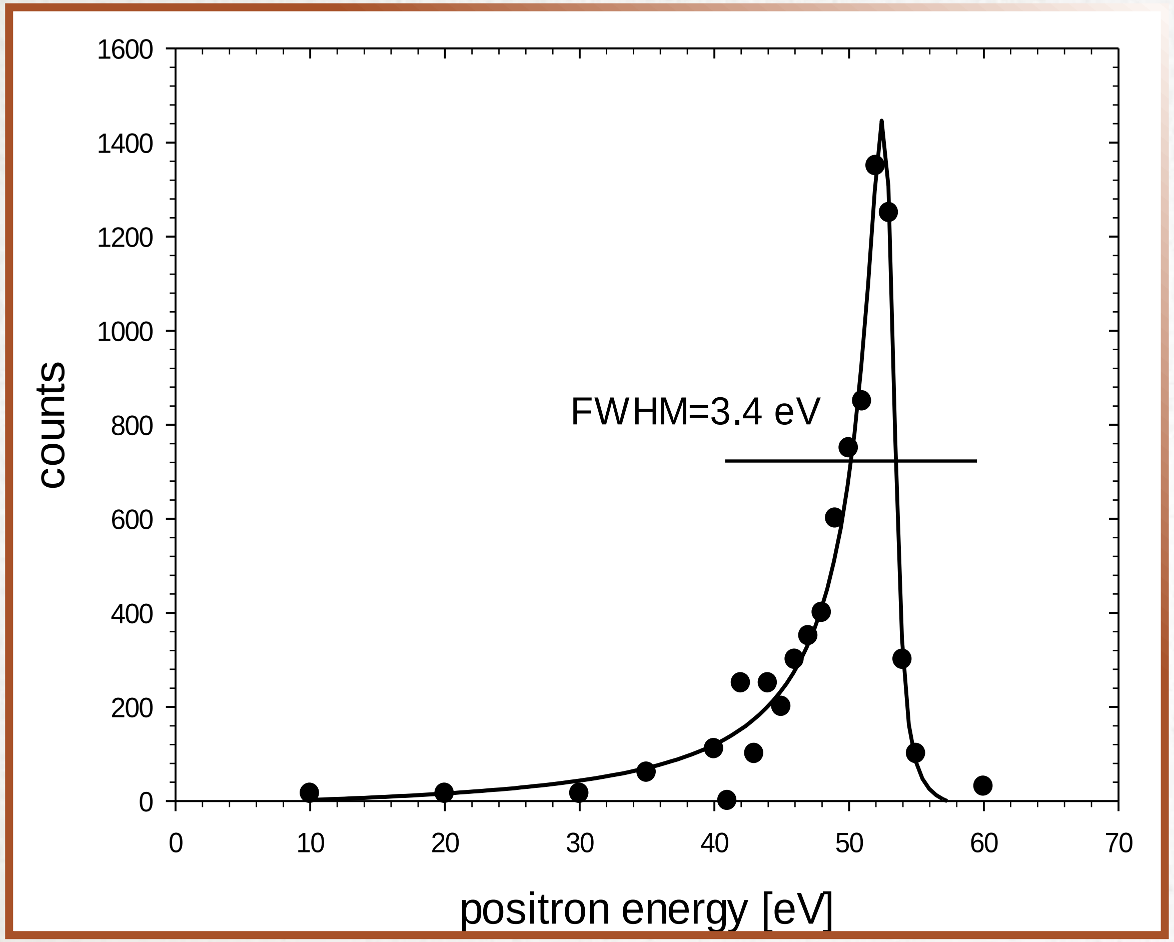
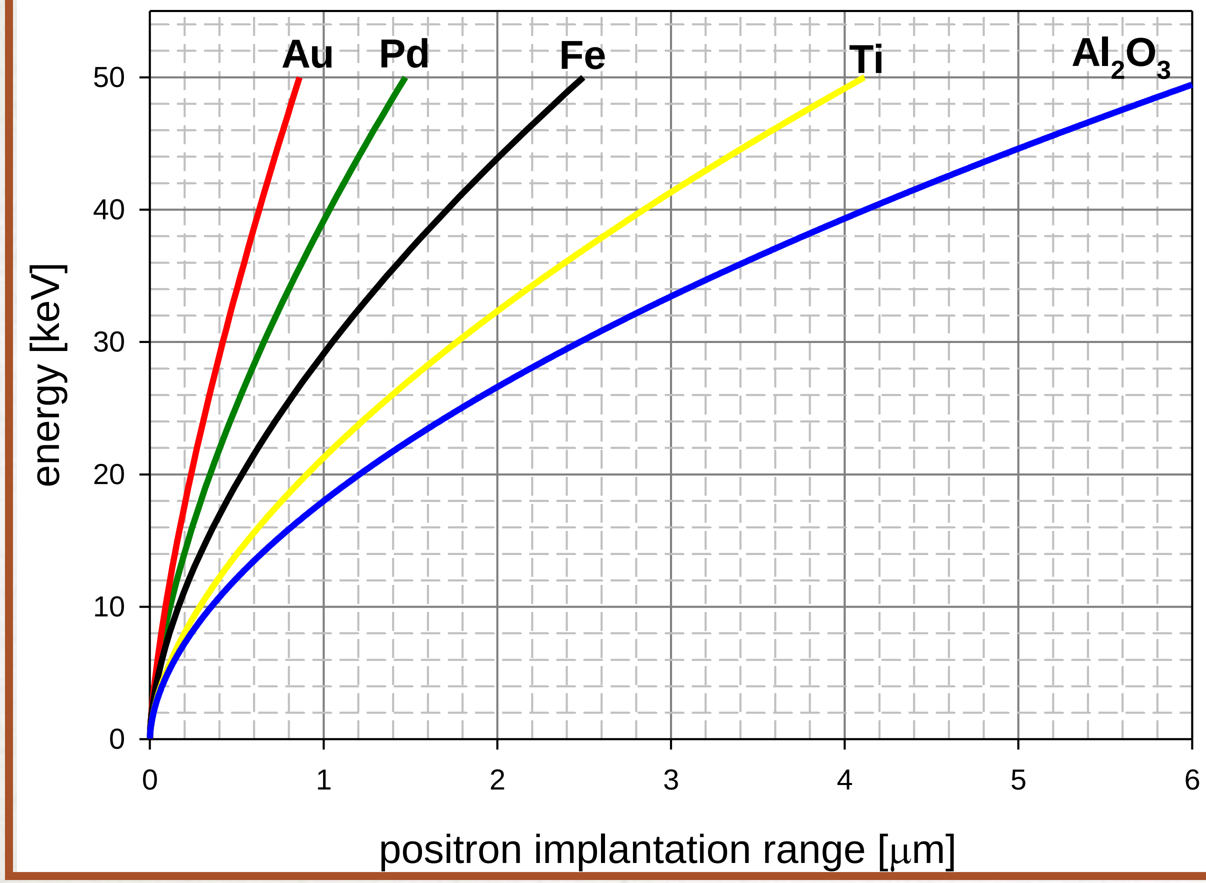
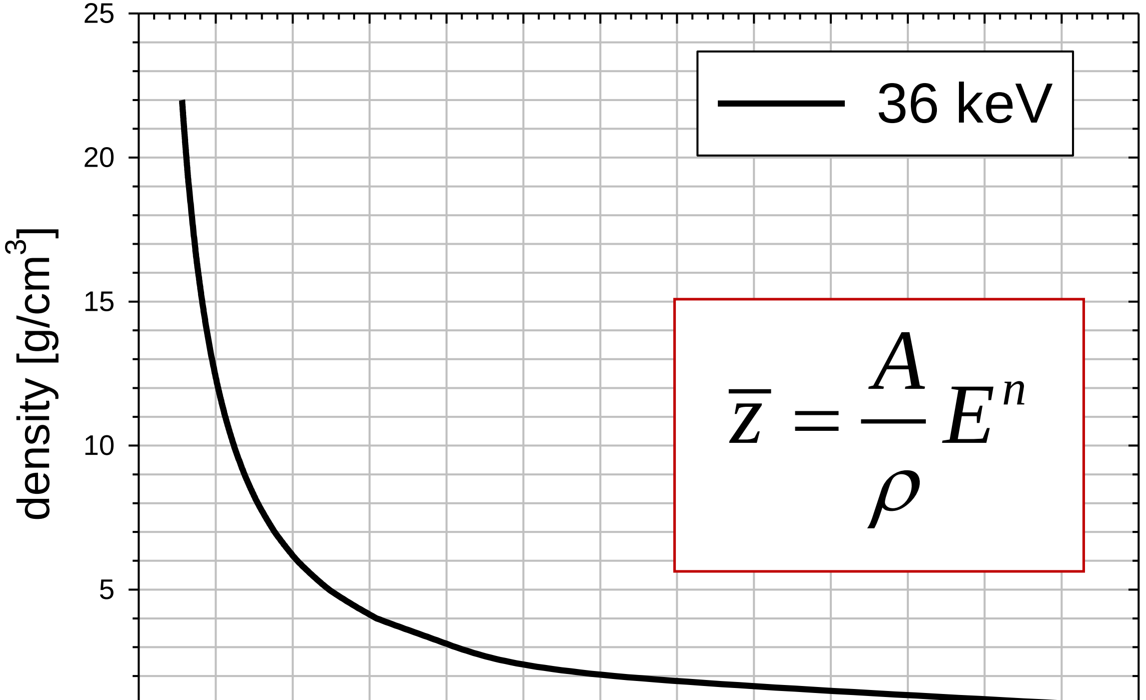


Feature	Value
activity of ^{22}Na isotope	**~30 mCi**
moderator	frozen Ne (7K)
magnetic field	100 Gs
vacuum conditions	10^{-9} Torr
intensity	**~10^6 e^+/s**
energy range	**50 eV ÷ 35 keV**
diameter of the flux	**3 mm**

THE VARIABLE ENERGY POSITRON BEAM



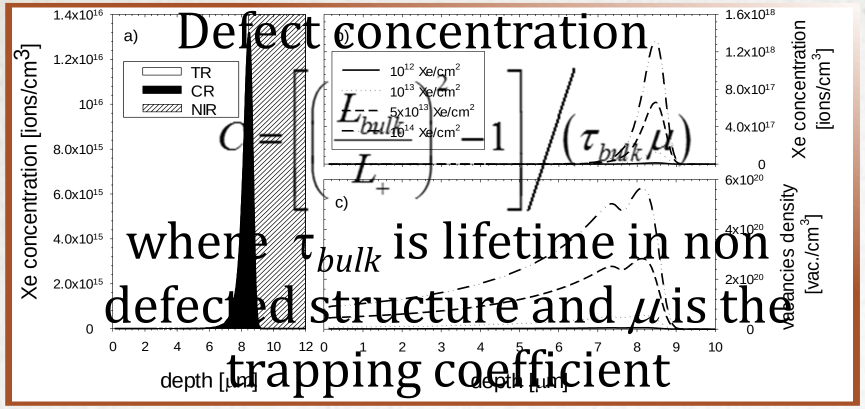


$$\bar{z} = \frac{A}{\rho} E^{n}$$

EXAMPLES OF APPLICATION

The irradiation was performed at IC-100 cyclotron at Flerov Laboratory of Nuclear Reactions at JINR in Dubna. Xe^{26+} heavy ions with energy 167 MeV or 107 MeV Kr^{17+} ions and different doses were applied. The average ion flux was 5×10^{9} cm^{-2} s^{-1}. Temperature not higher than 80 ˚C.

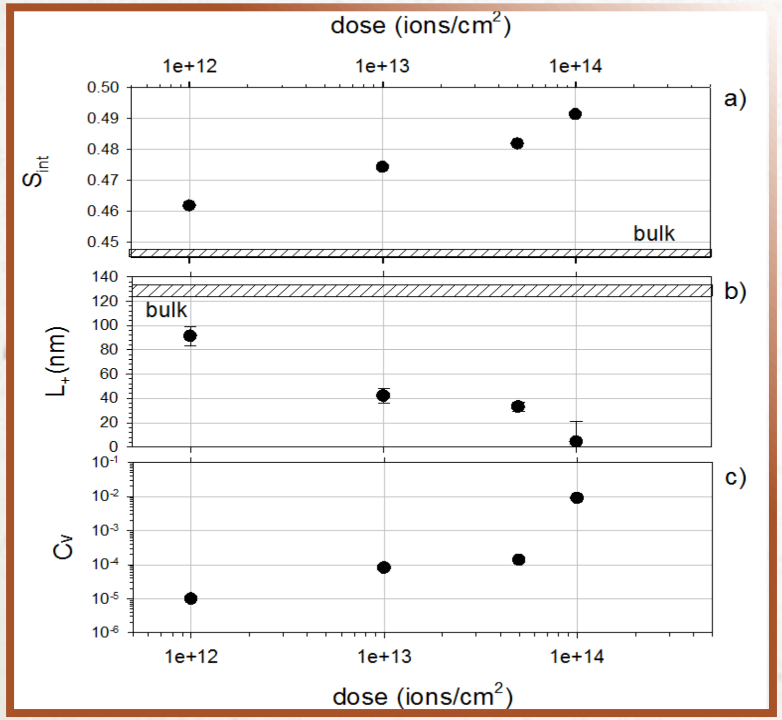
EXAMPLES OF APPLICATION: IRRADIATED FE

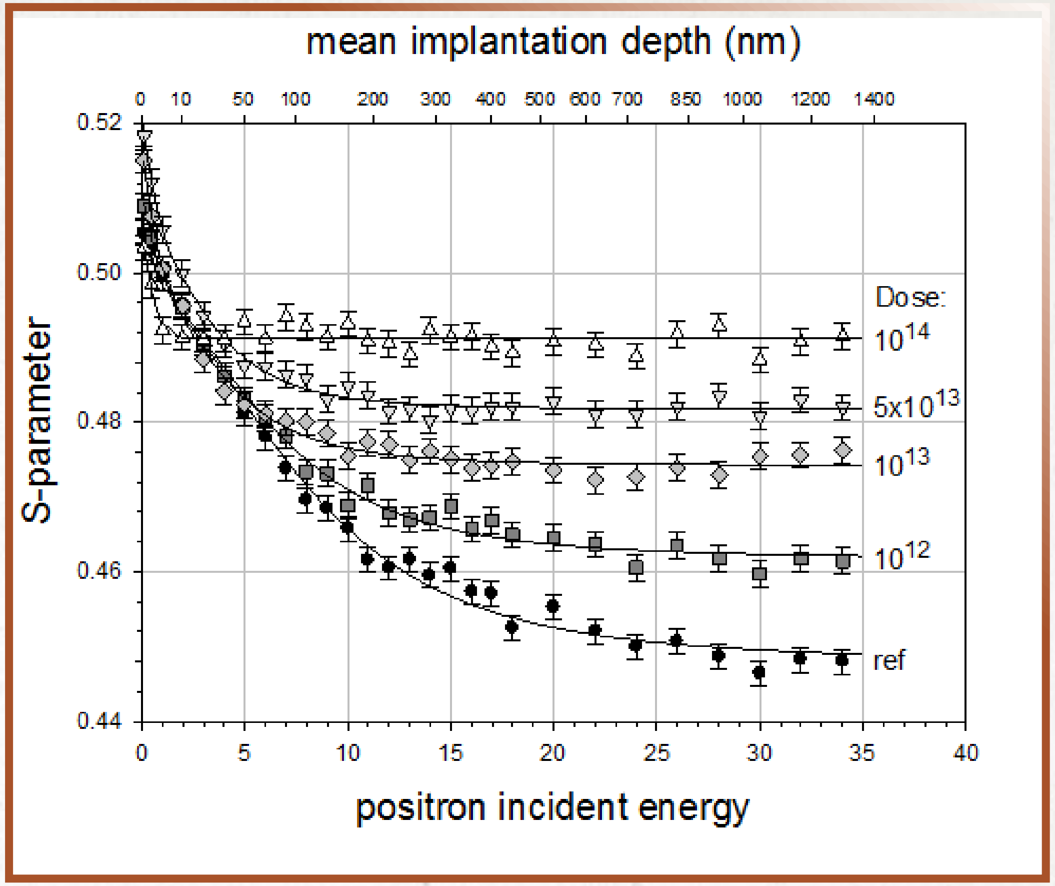


Defect concentration

$$C = \left[\left(\frac{L_{bulk}}{L_+} \right)^2 - 1 \right] \Big/ (\tau_{bulk}\,\mu)$$

where τ_{bulk} is lifetime in non defected structure and μ is the trapping coefficient



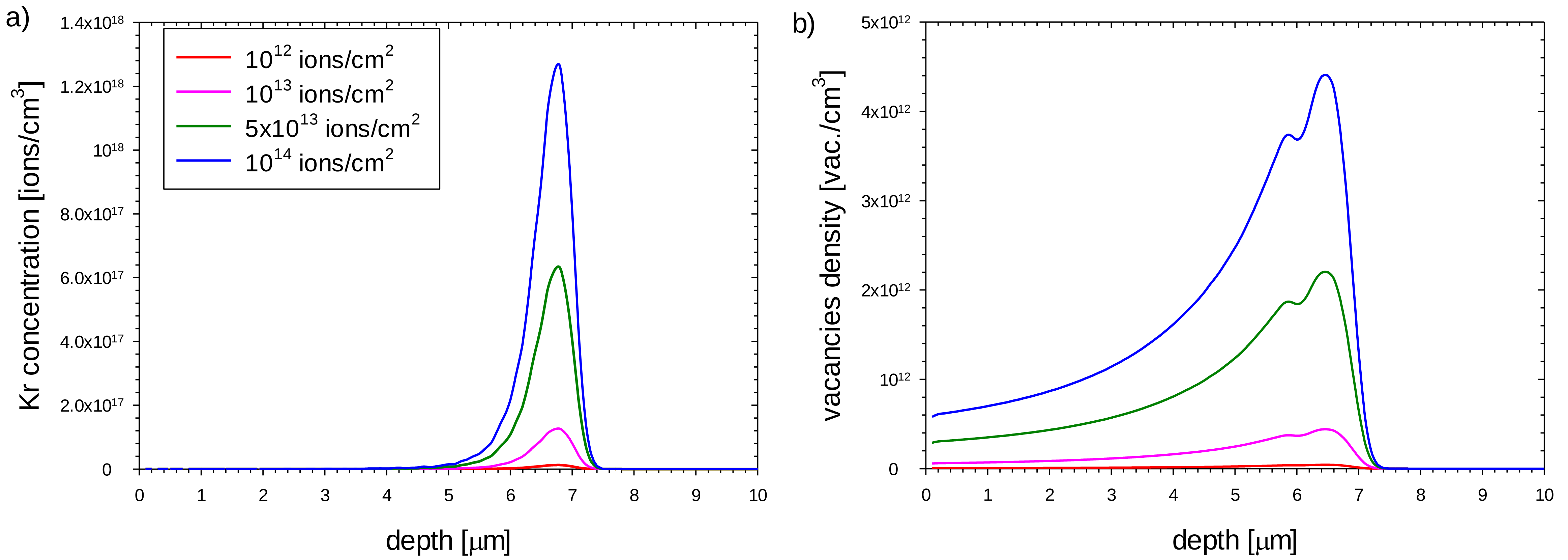


$$S(E) = S_{bulk} + (S_{surface} - S_{bulk}) \frac{\alpha}{\alpha + L_+ \lambda_{bulk}} \int_0^\infty P(x,E) \exp(-x/L_+) dx$$

where: $S_{surface}$ - S value for surface, S_{bulk}- S value for saturation, P(x,E) – implantation profile, L_+ - positron diffusion length, α- the positron absorption coefficient at the surface λ_{bulk} - the annihilation rate, x - depth

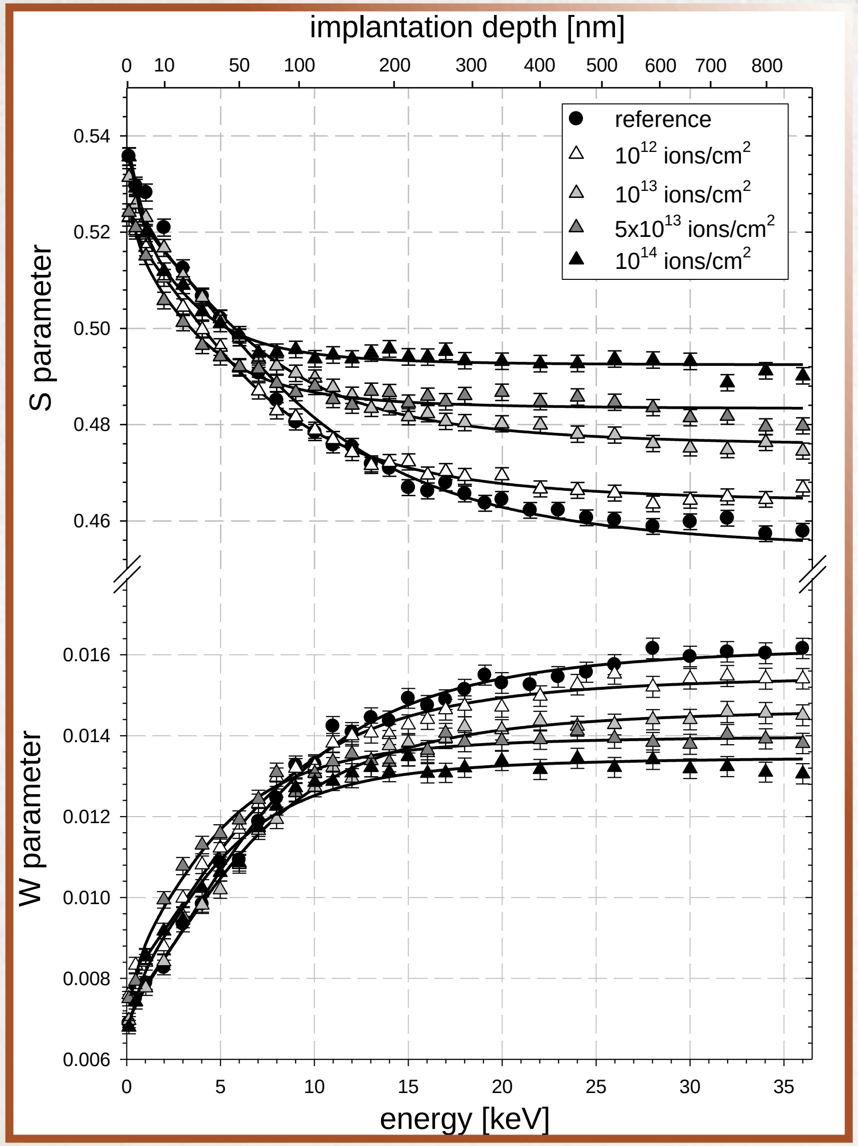
P. Horodek et al., Rad. Phys. Chem. 122 (2016) 60–65.

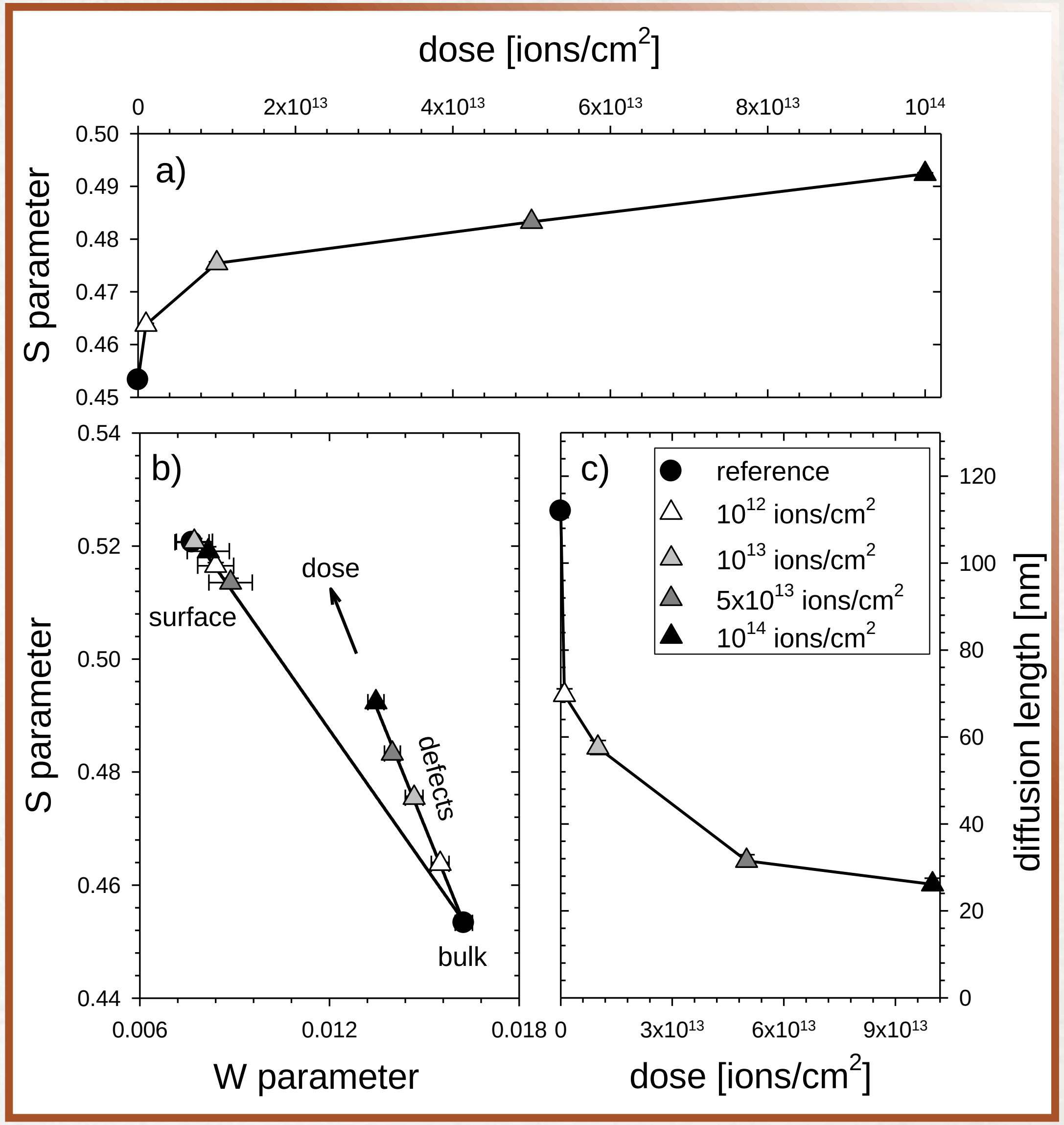
EXAMPLES OF APPLICATION: IRRADIATED PD



P. Horodek et al., Surf. Coat. Technol. 296 (2016) 65–68.

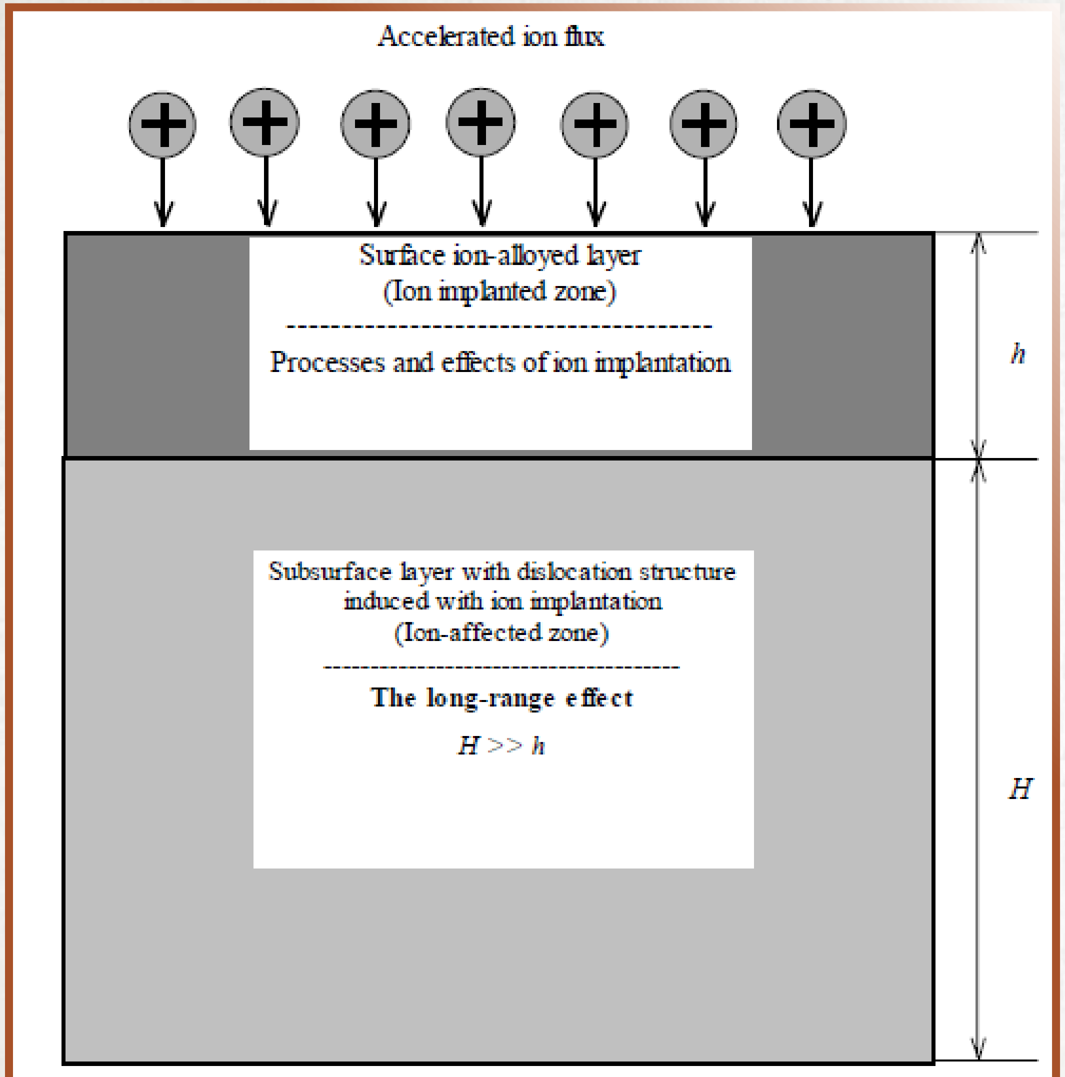
EXAMPLES OF APPLICATION: IRRADIATED PD



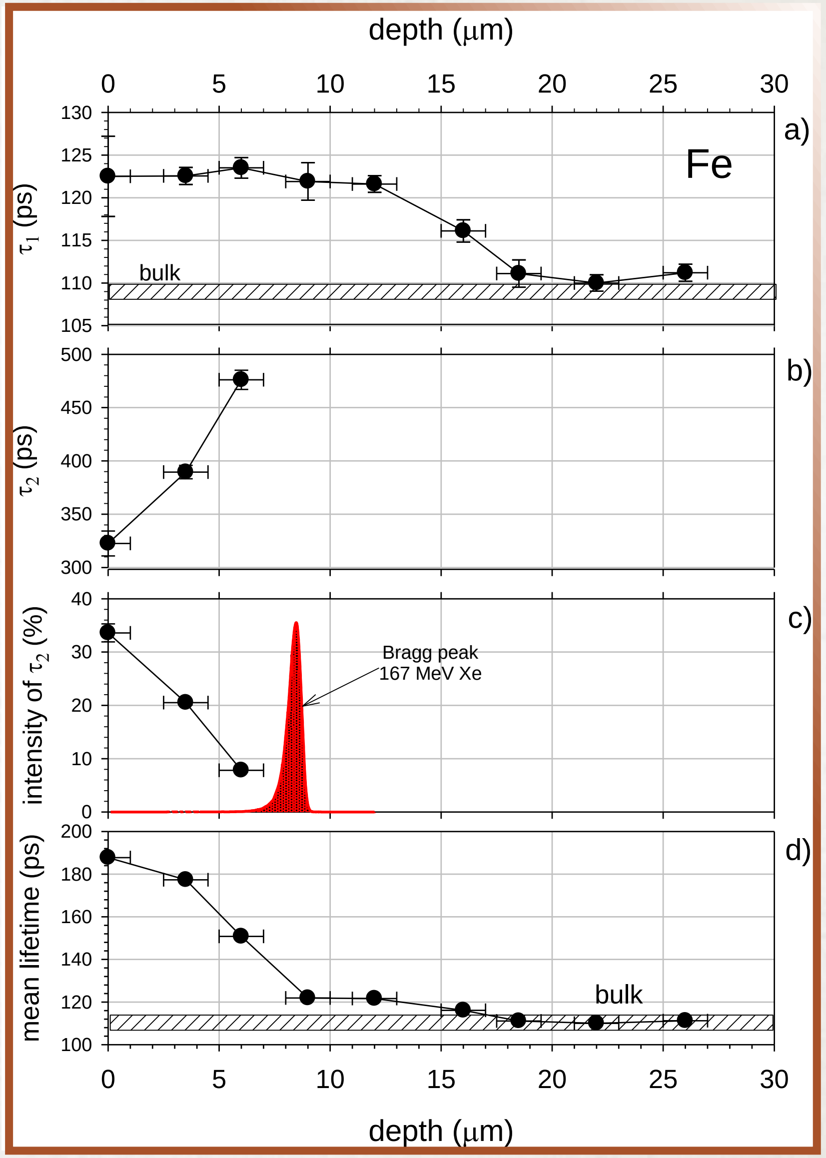


P. Horodek et al., Surf. Coat. Technol. 296 (2016) 65–68.

EXAMPLES OF APPLICATION: LONG RANGE EFFECT



The long-range effect in metal materials at ion implantation



Yu.P. Sharkeev, E.V. Kozlov, Surf. Coat. Technol. 158-159 (2002) 219.
P. Horodek, et al., Rad. Phys. Chem. 122 (2016) 60.

SUMMARY

- PAS is the sensitive method for detection the structural defects
- in dependency on used PAS technique the evaluation of defect profile, approximation of defect concentration or determination of type of defect is possible
- the modern application of PAS focuses around slow positron beam studies
- slow positron beam allows to investigate areas close to the surface of materials but it does not mean that standard techniques are relicts of past
- this method is implemented at LNP JINR