Materialforschung mit Positronen an der Strahlungsquelle ELBE

Materials Research w/ Positrons at the Radiation Source ELBE

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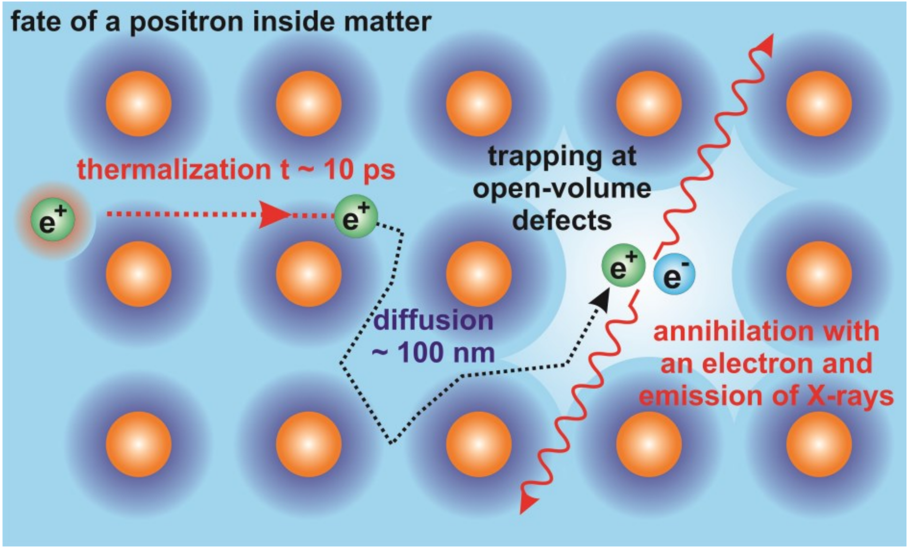
HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

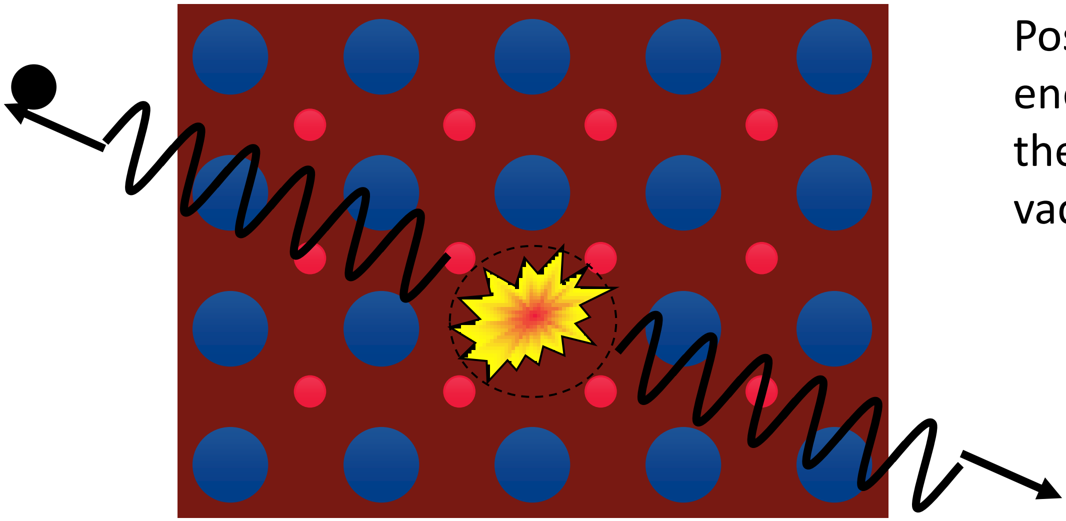
Outline



Courtesy: R. Krause-Rehberg / M. Butterling

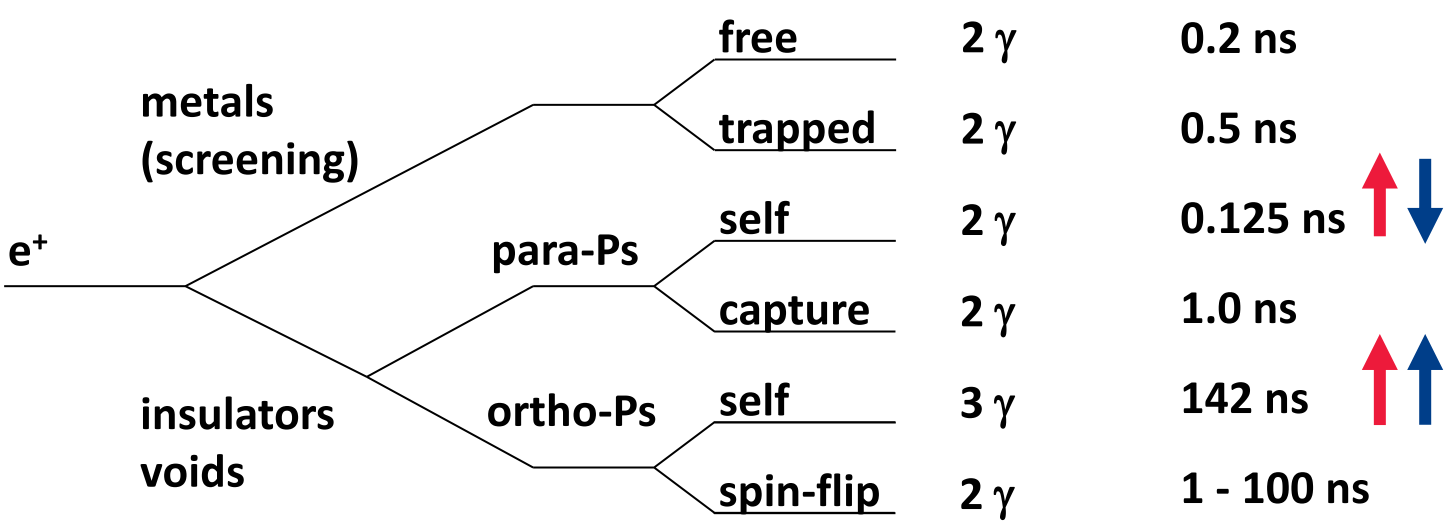
- Why using anti-matter for materials research?
- How to obtain decent amounts of positrons?
- Applying pulsed beams: positron annihilation lifetime spectroscopy for bulk materials, fluids, gases, and thin films
  - GiPS – the Gamma-induced Positron Source
  - MePS – the Monoenergetic Positron Source

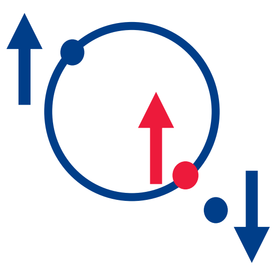
Fate of positrons in matter



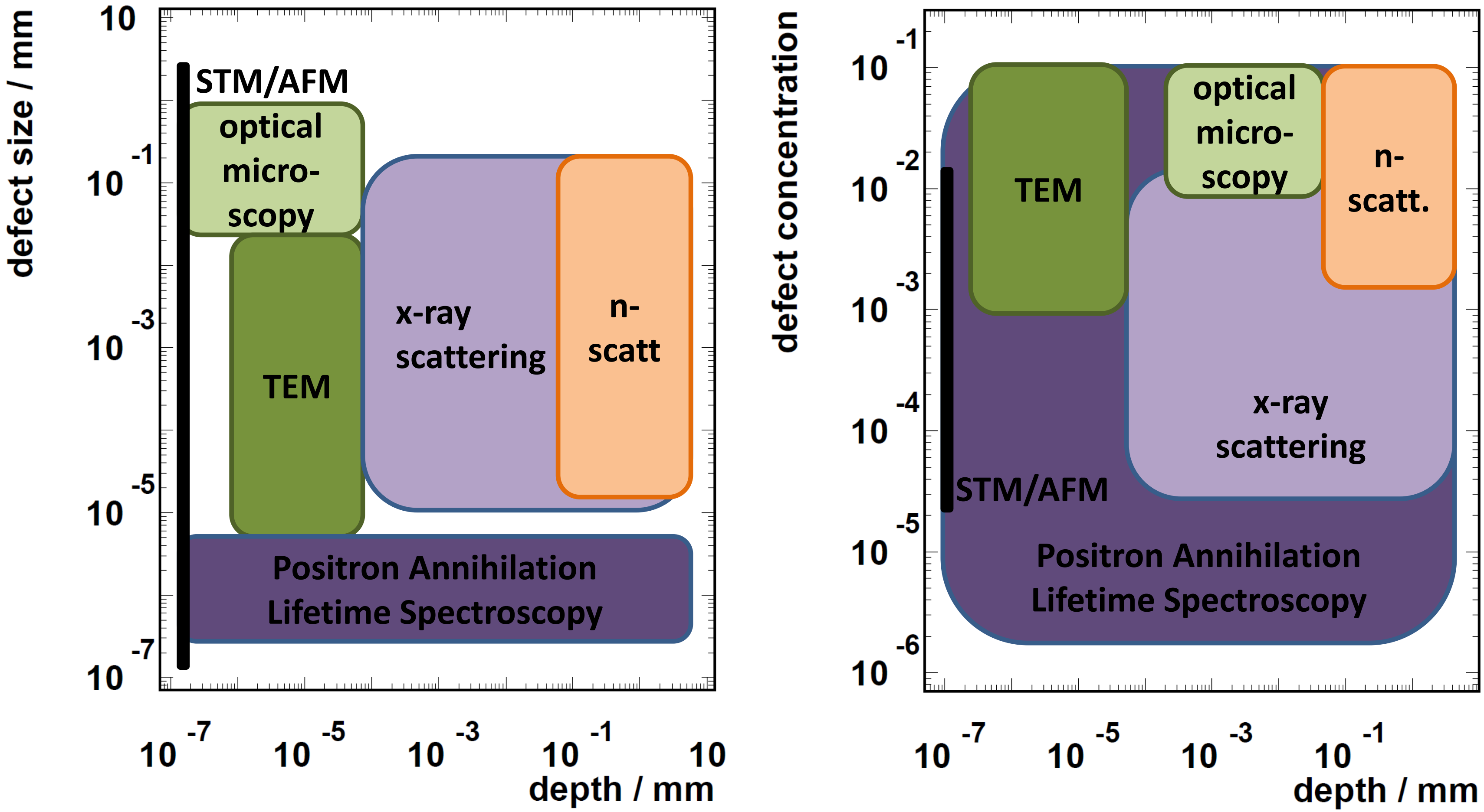
Positrons slow down to thermal energies in 3-10 ps. After diffusing inside the matter positrons are trapped in vacancies or defects.

Kinetics results in trapping rates about 10^5 times larger than annihilation rates: **defect concentrations down to 10^{-7}** are accessible.



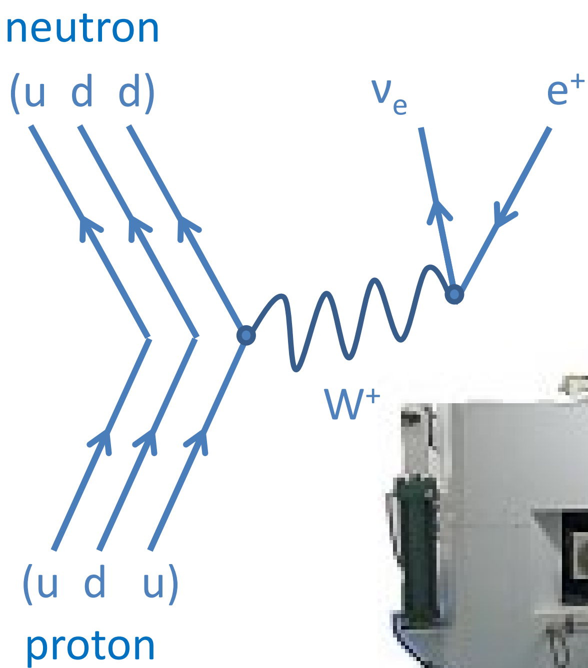


Sensitivity of Positron Annihilation Lifetime Spectroscopy

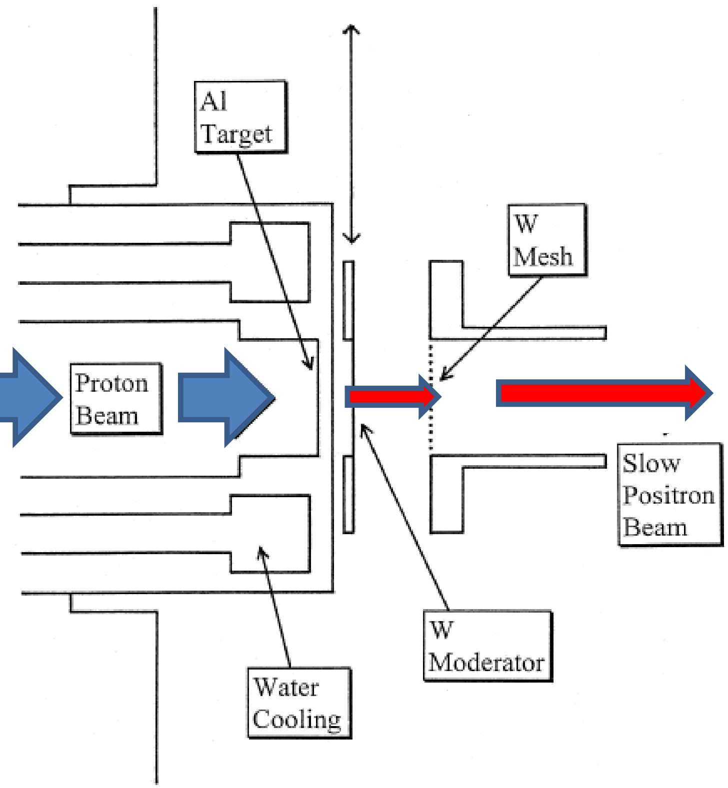


Isotopes, reactors, accelerators

Production of positrons in weak interactions (mediated by W's)



$^{27}Al(p,n)^{27}Si(\beta^{+}\nu_{e}, 4.2\ s)\ ^{27}Al$



Sumitomi Heavy Industries Cyclotron
18 MeV protons, 50 μA beam current

Isotopes, reactors, accelerators

Production of positrons through electromagnetic interactions (photons)

Use intense source of photons for pair production

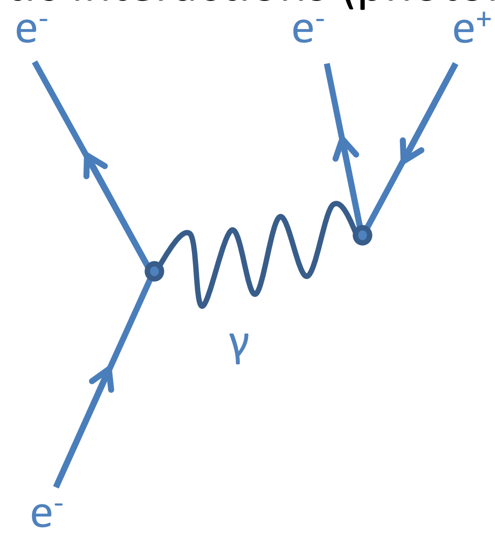
→ Capture-neutron gamma-rays from reactor

$^{113}Cd(n,\gamma)^{114}Cd$

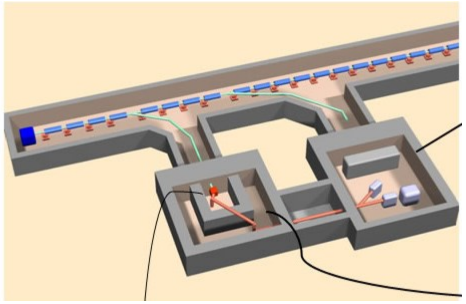
FRMII Munich

KUR Kyoto

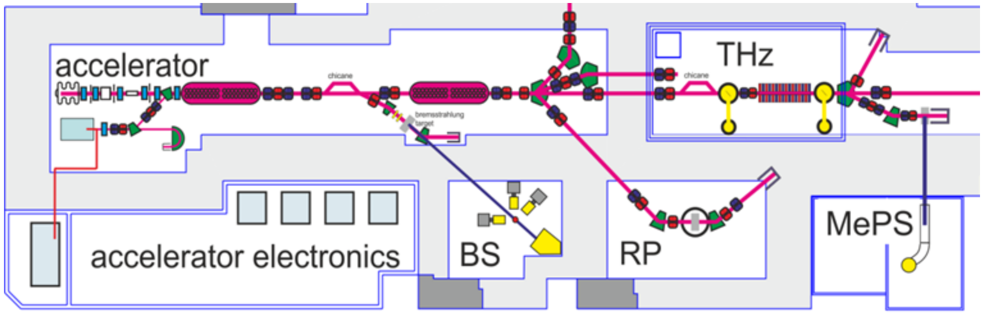
TU Delft



→ Bremsstrahlung from electron accelerators or lasers (Changsha/Wuhan, Osaka/Hyogo, ELI-NP Buccuresti)

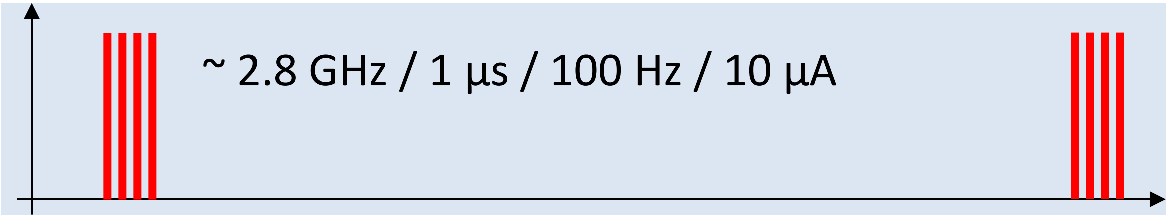


AIST, Tsukuba, Japan

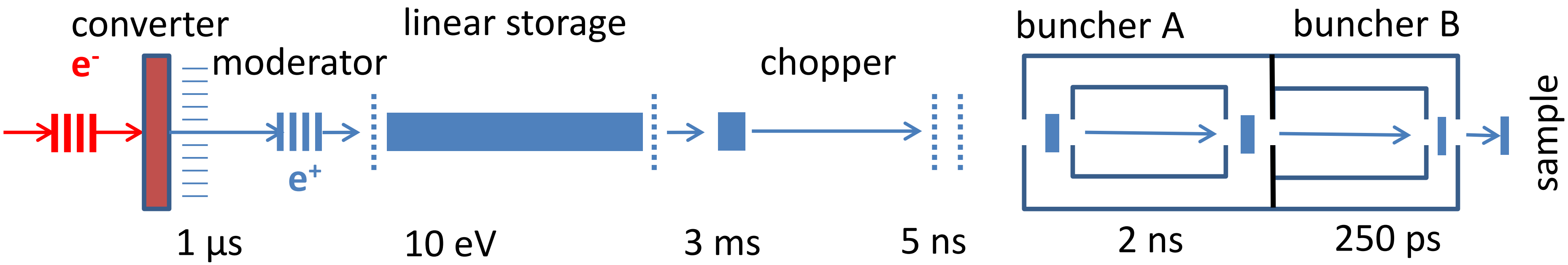


ELBE, Dresden

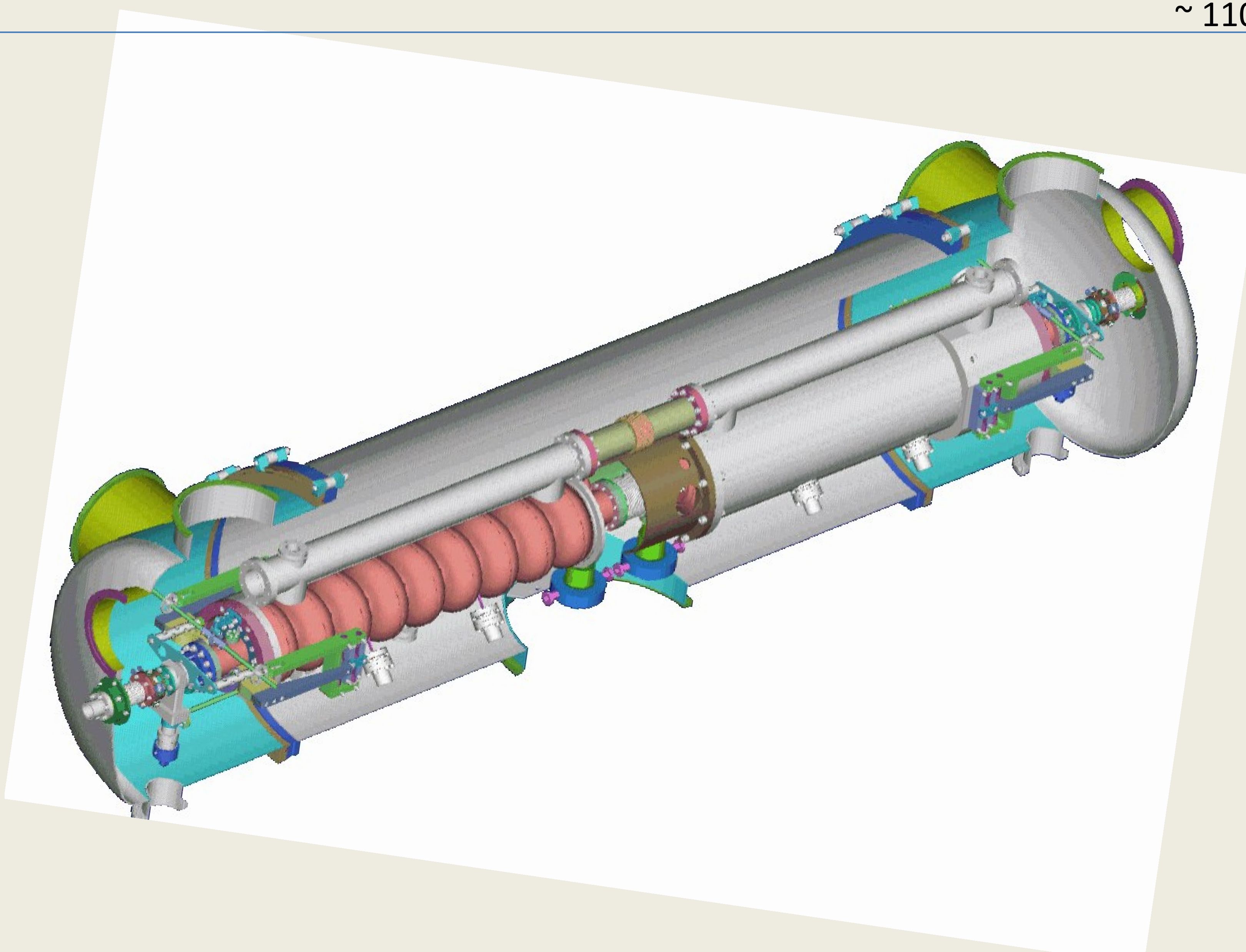
Positrons from accelerators



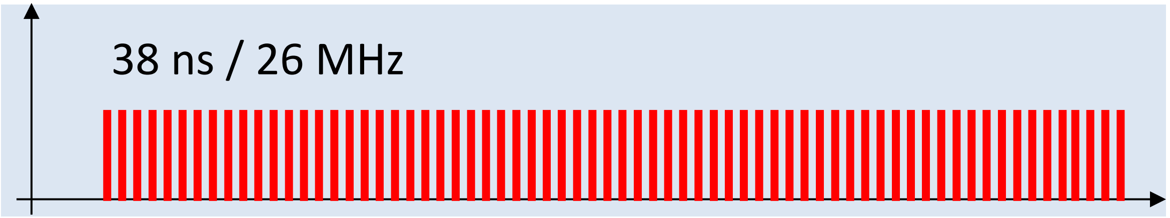
NC-LINAC in bunched mode



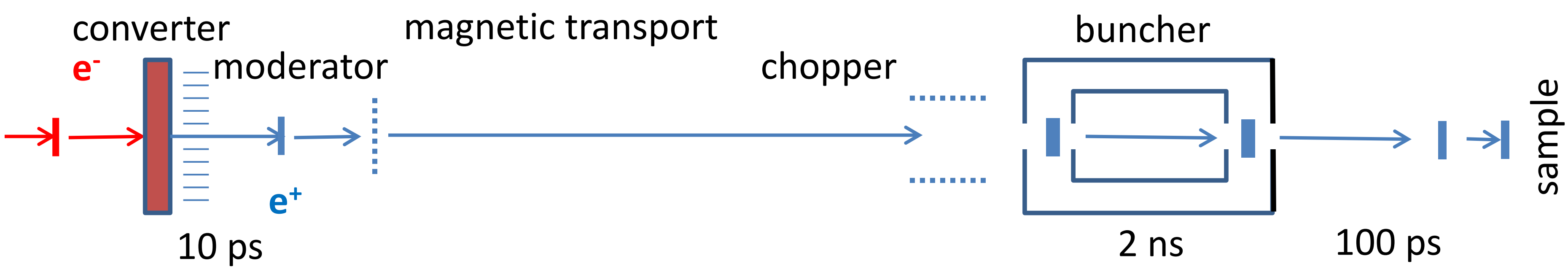
~ 110 m

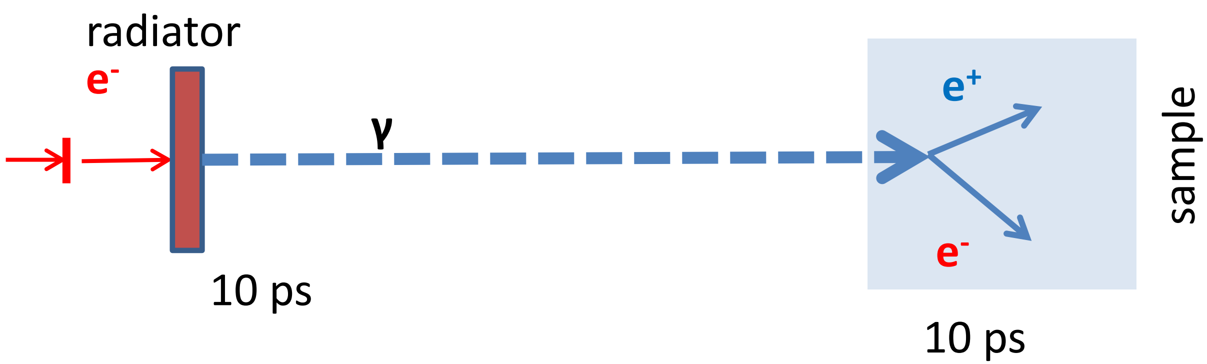


What about bulk materials, fluids, gases …?



SC-LINAC in CW mode





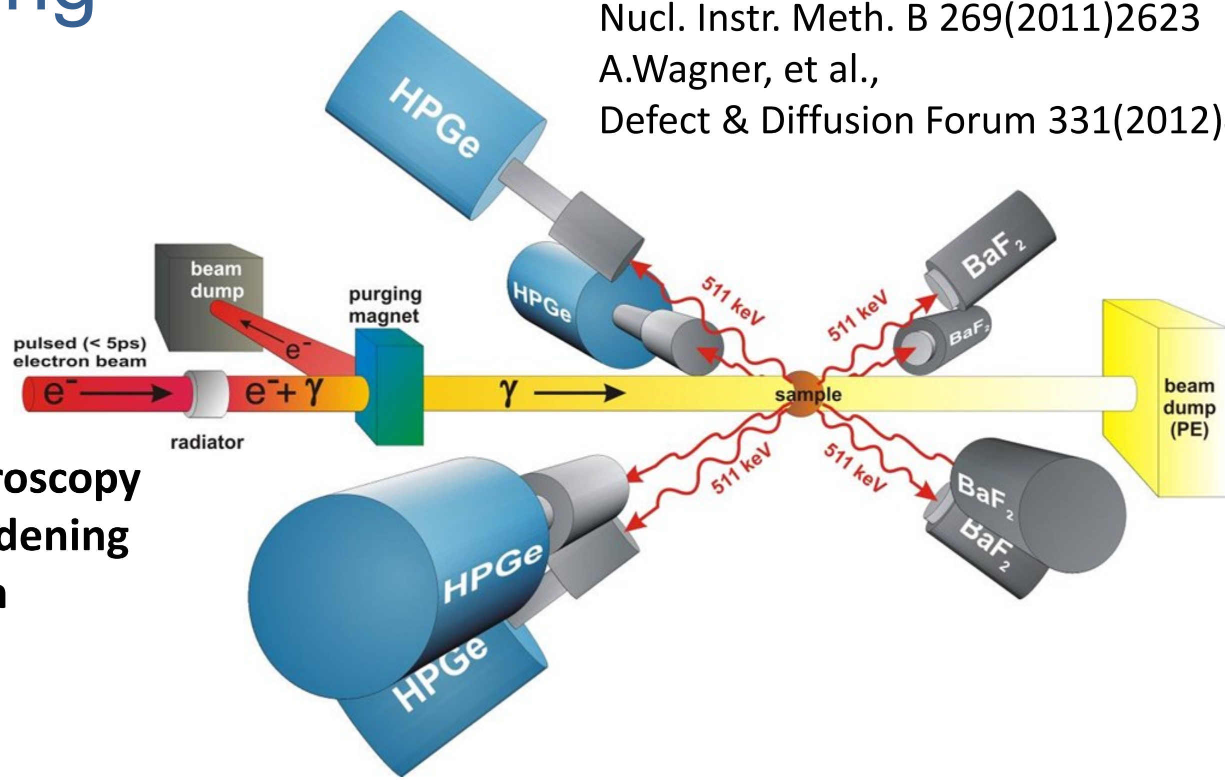
GiPS

The **G**amma-**i**nduced **P**ositron annihilation **S**pectroscopy

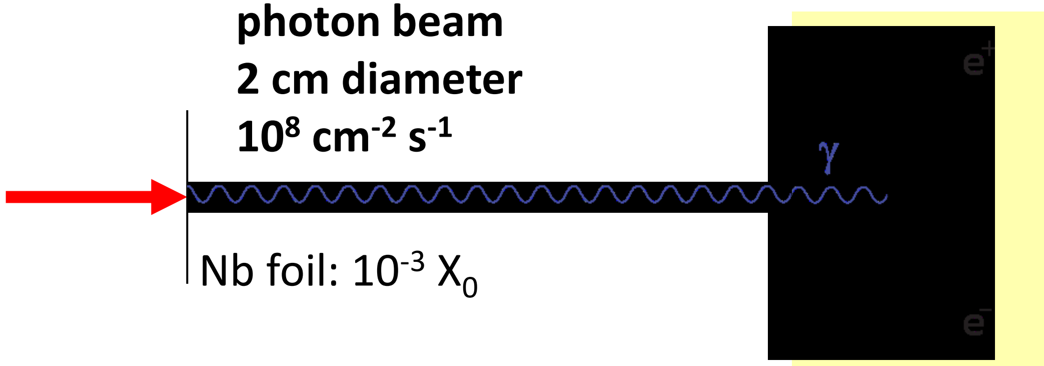
Positron production using electron-bremsstrahlung

M. Butterling, et al.,
Nucl. Instr. Meth. B 269(2011)2623
A.Wagner, et al.,
Defect & Diffusion Forum 331(2012)41

$$E_e = 16\,\mathrm{MeV}$$
$$I_e = 900\,\mu\mathrm{A}$$
$$f = 26\,\mathrm{MHz}$$
$$\sigma_t < 10\,\mathrm{ps}$$



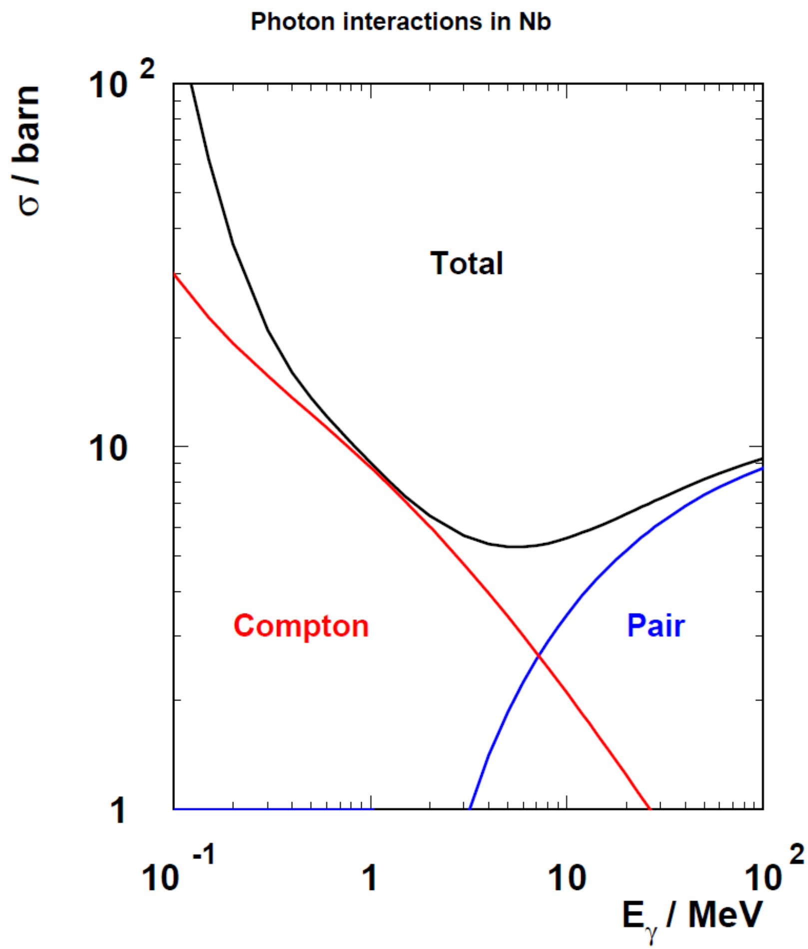
Annihilation Lifetime Spectroscopy
(Coincidence) Doppler Broadening
Age-momentum Correlation

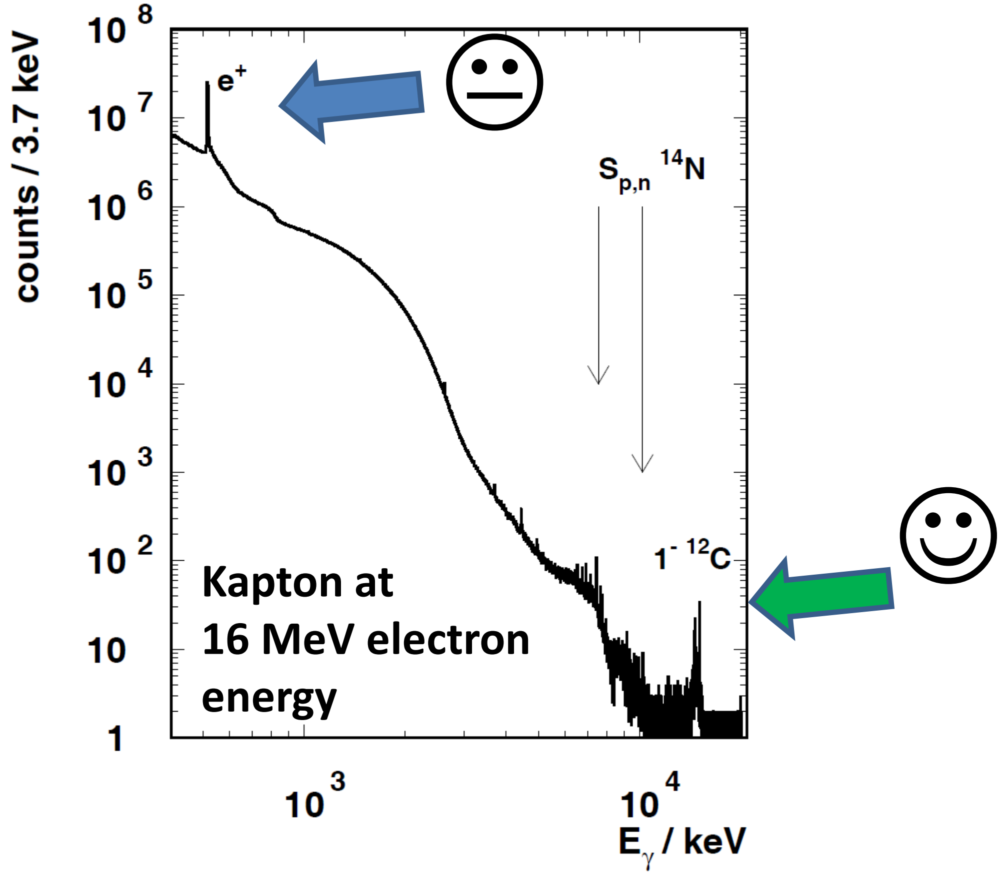


studies performed so far:

- animal tissue
- metals and alloys
- (neutron-activated) reactor materials
- water, glycerol from 10°C to 100°C

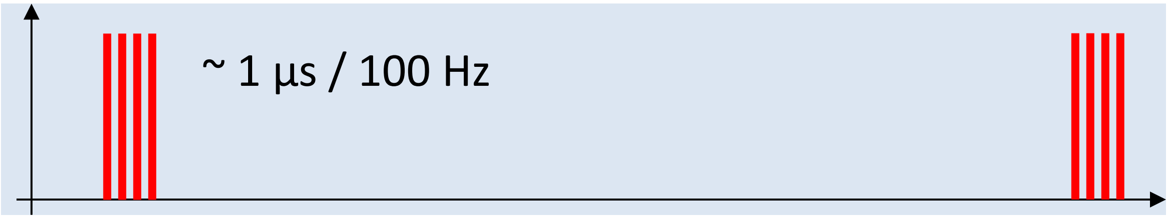
Positrons: backgnd for nuclear physics exp'ts



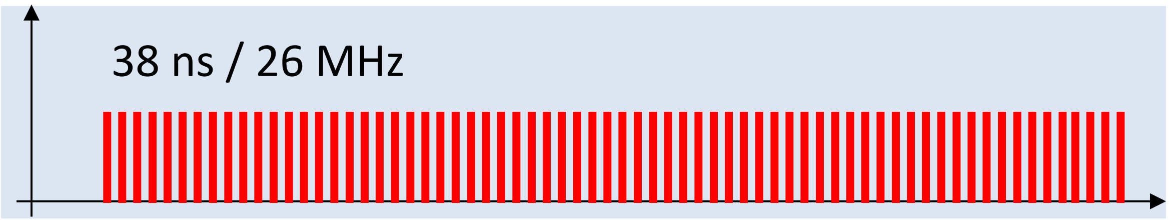


Hard bremsstrahlung produces a huge amount of positrons via pair production inside the target material. High-energy photons act as a **volume source of positrons throughout the entire volume**.

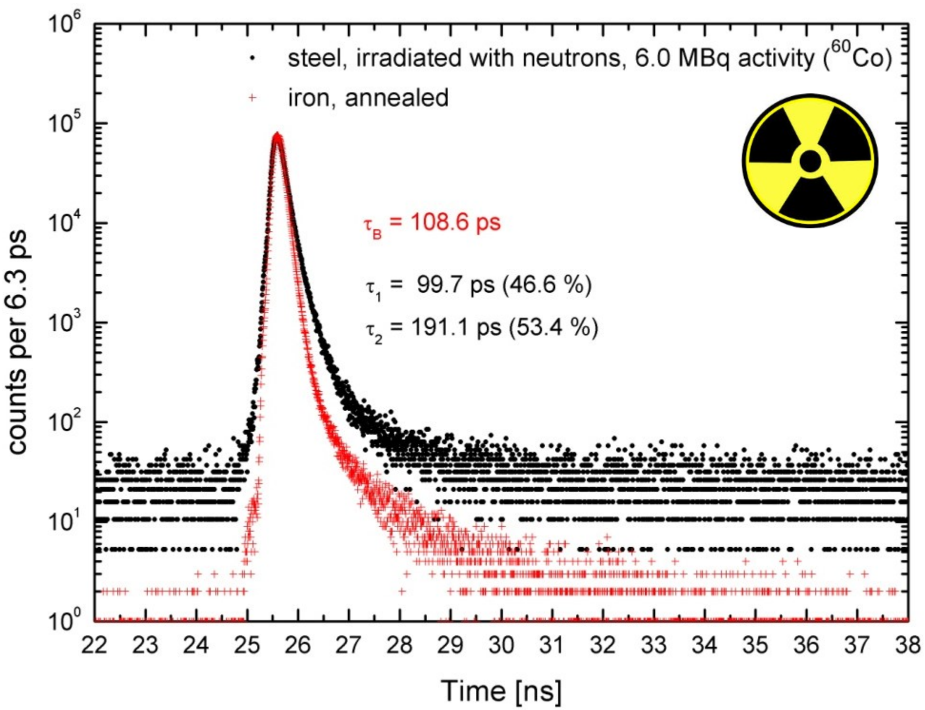
Gamma-induced Positron Spectroscopy



conventional LINAC mode
pulsed RF, highest energy
typically pile-up problems
F.A. Selim, D.P. Wells, J.F. Harmon, et al.
Nucl. Instr. Meth. A 495 (2002) 154



SC-LINAC in CW mode
highest average power –
high yield and low pile-up



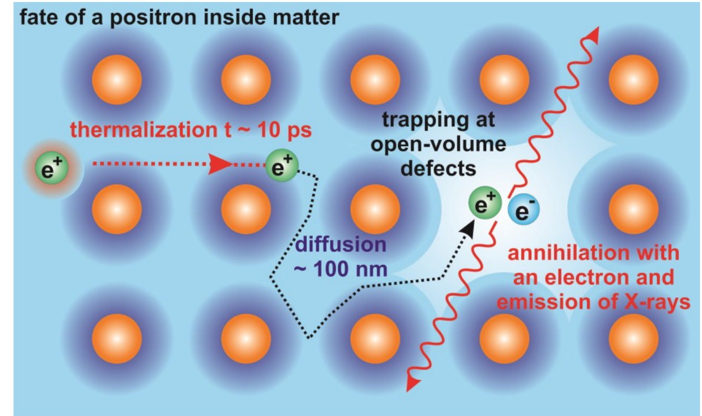
High resolution lifetime spectrum with signal to noise ratios of better than 10^5:1 using gamma-gamma coincidence techniques for background reduction. Lifetime spectra are free from artefacts.

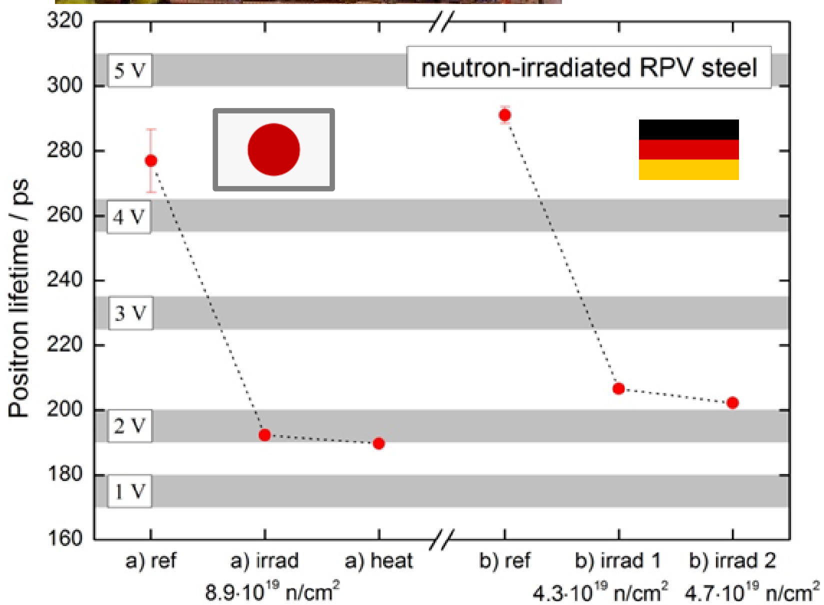
→ Long lifetimes reveal atomic defects caused by neutron-induced damage.
→ Can (and how) defects be removed by thermal annealing?

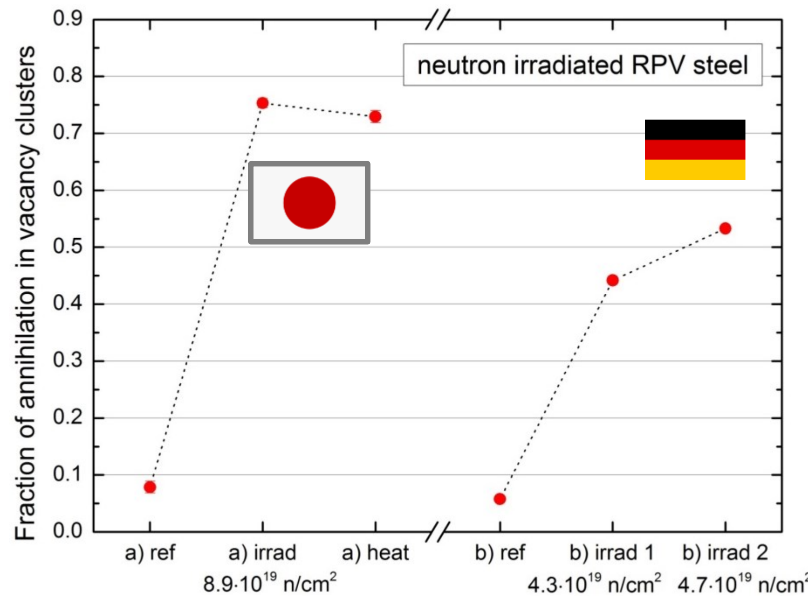
Physics with GiPS: RPV steel

Reactor vessel steel becomes brittle due to neutron-induced defects like open-volume defects. The atomic defects act as seeds for cracks.

Collaboration with Reactor Safety Division.







→ Preferential formation of double vacancies

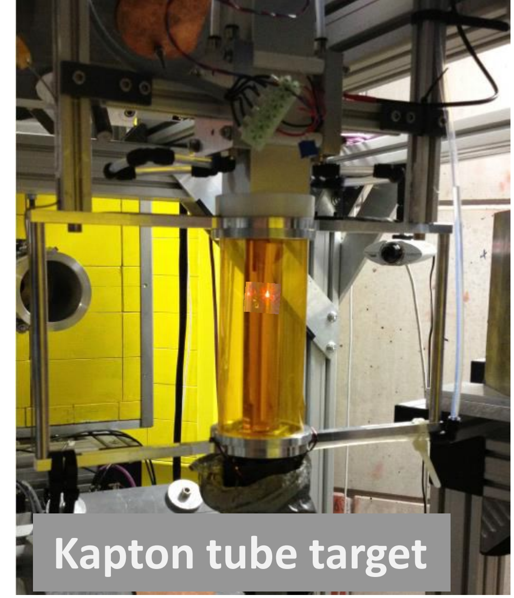
→ Thermal annealing (290°C) not sufficient to remove defects!

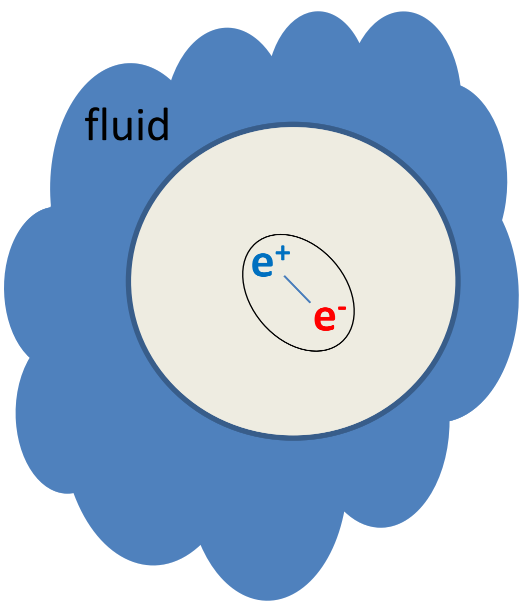
Physics with GiPS: Fluids

Conventional lifetime measurements:
→ dissolve ^{22}Na and dispose it afterwards

Positrons from bremsstrahlung
→ homogeneously distributed, sharp time stamp

Target is temperature-stabilized, continuously circulated, degassed, dry-nitrogen flushed.



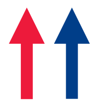


Positron Physics
Ortho-Positronium (o-Ps) in a fluid forms a bubble given by its zero-point energy and the surface tension.

We know estimate the change of the o-Ps pick-off annihilation lifetime with temperature in a bubble created by the o-Ps itself….

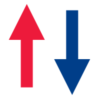
R.A. Ferell, *Phys. Rev.*, 108,167, 1957
S.J. Tao, *J. Chem. Phys.*, 56,5499, 1972
M. Eldrup *et al., Chem. Phys.*, 63,51, 1981

o-Ps



142 ns

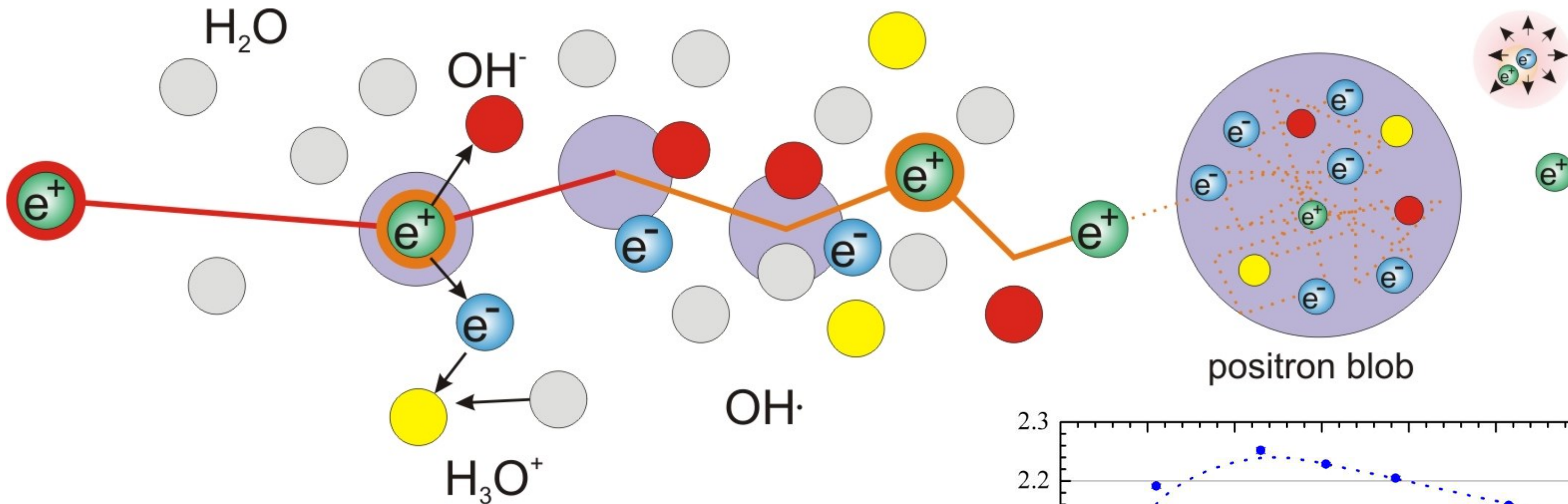
p-Ps



125 ps

Physics with GiPS: Positron(-ium) Chemistry

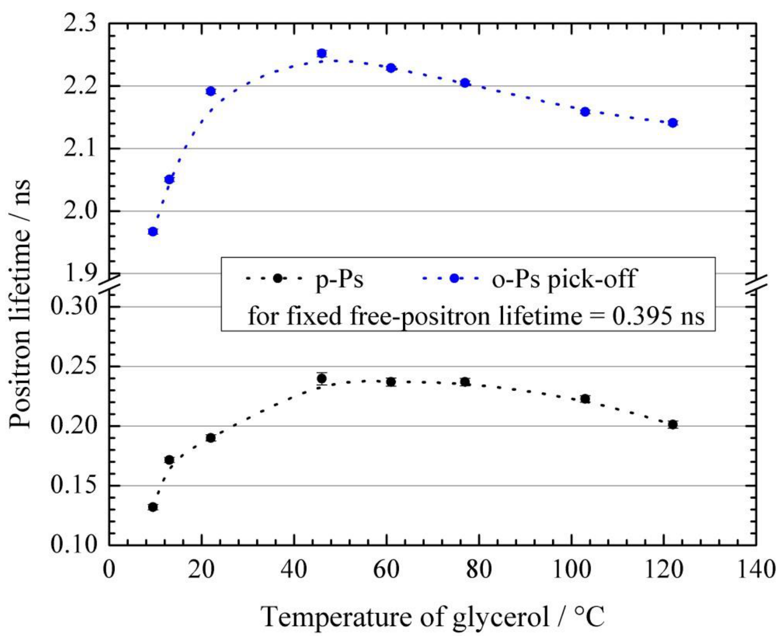
Experiments with water are **in variance** with a simple bubble-type model.
Extension: chemical reactions between radiolysis products of the slowing-down of the positron → Ps chemistry.



→ Radicals are positron scavengers which reduce annihilation lifetimes.

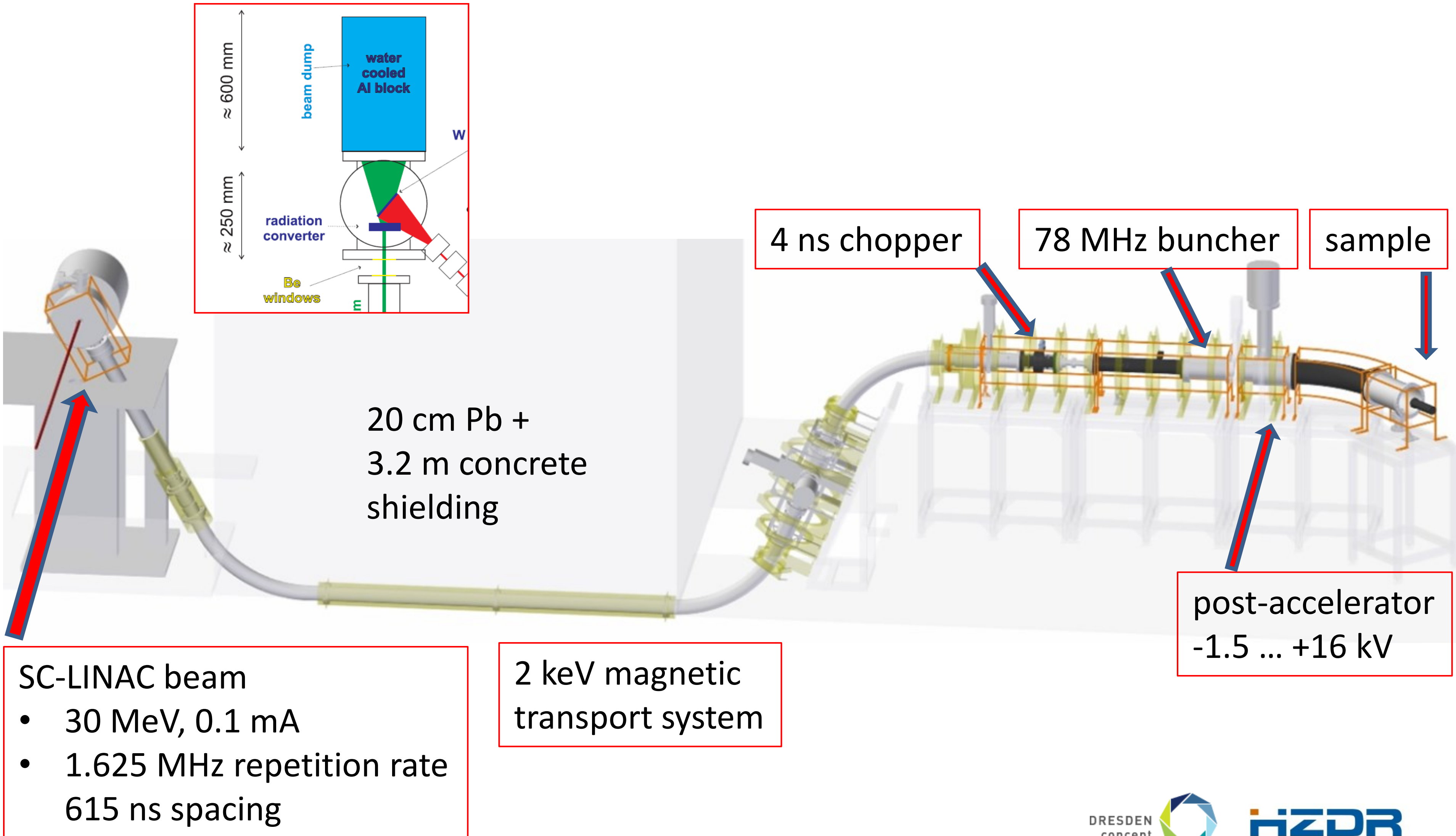
→ Extended bubble model including chemistry [S.V. Stepanov et al., Mat. Sci. Forum 607] and energetics of hydrated e^+_{aq} and e^-_{aq} (what are the relaxation times of un-/polar media?)

→ Chemistry of radiolysis directly accessible since the probe creates the ionization itself

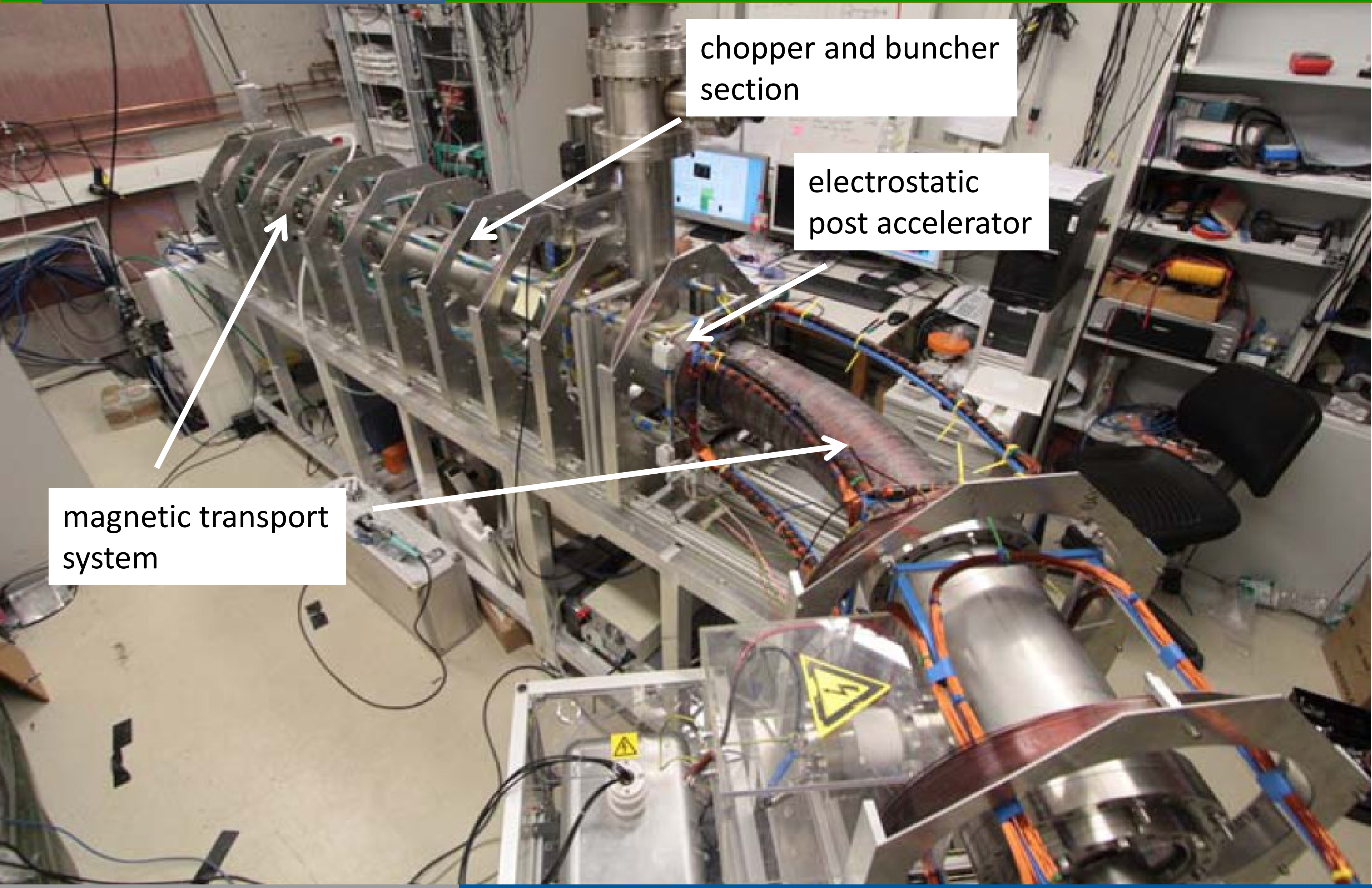


The Mono-energetic Positron Source MePS

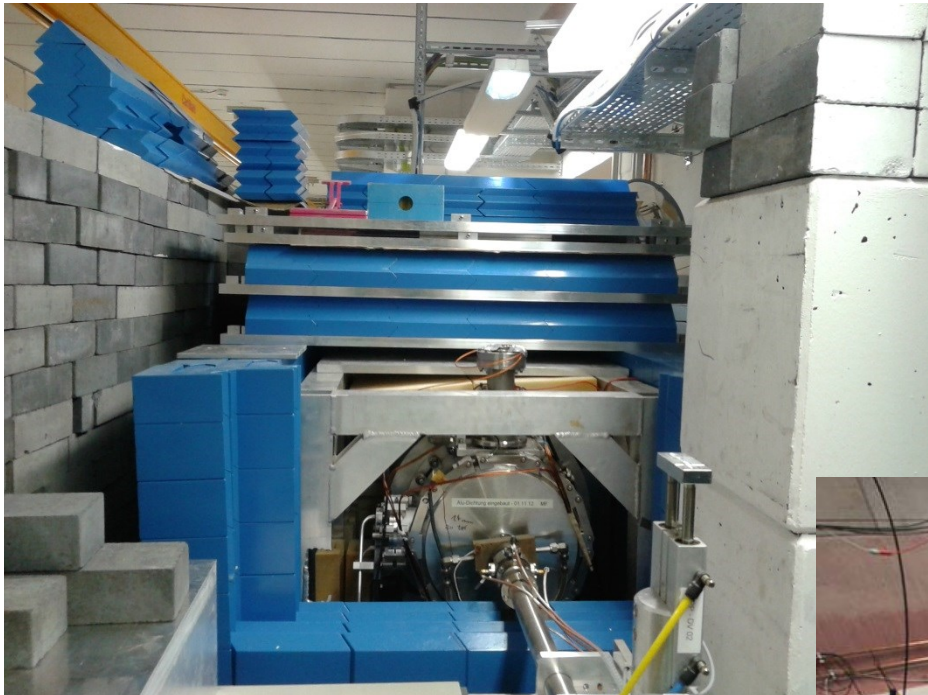
In order to perform depth-resolved annihilation lifetime and Doppler-broadening spectroscopy of **thin films**, Univ. Halle and HZDR have set-up the MePS source.



MePS setup

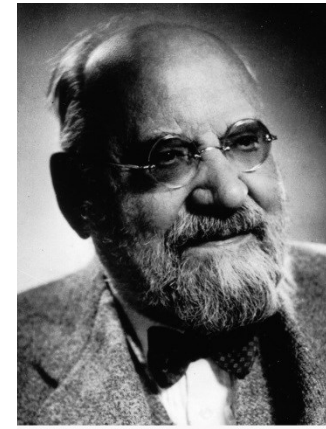

chopper and buncher section
electrostatic post accelerator
magnetic transport system

The Mono-energetic Positron Source MePS

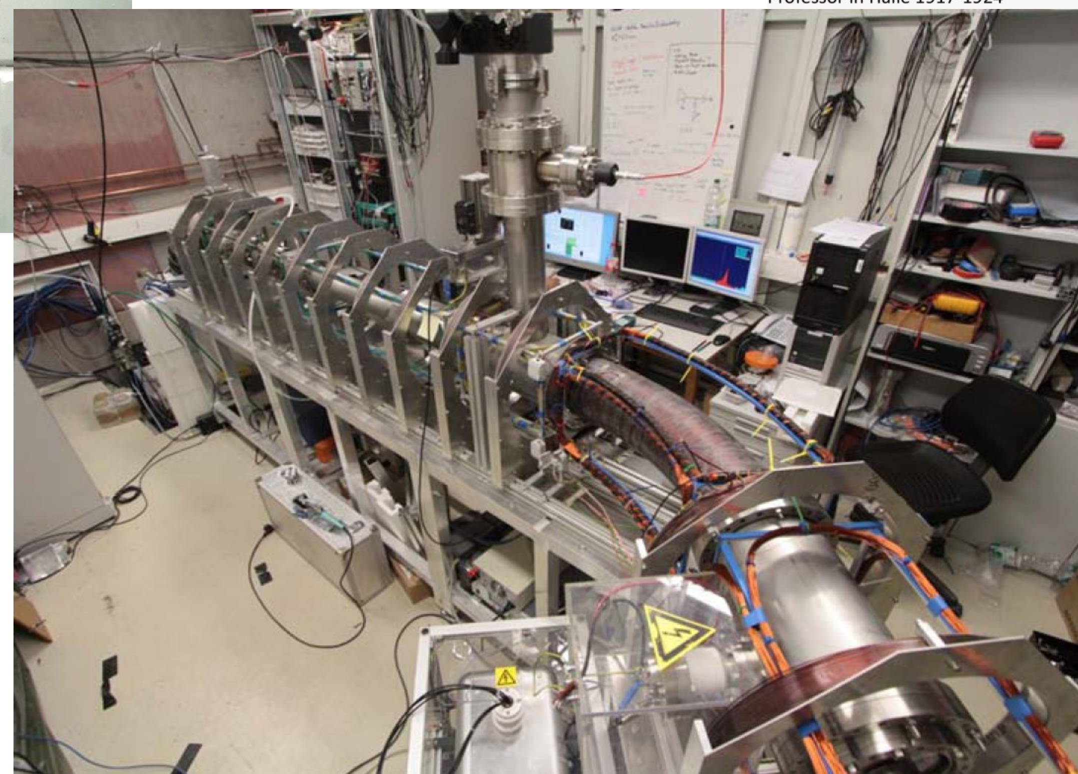


Radiation shielding around the target amounts to about:
1 Hyle of lead
1 Hyle of concrete

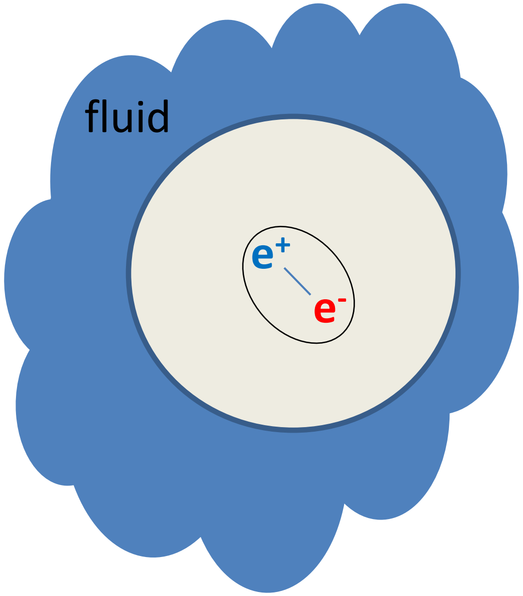
1 Hyle = 1 VAs^3/cm^2 = 10 t

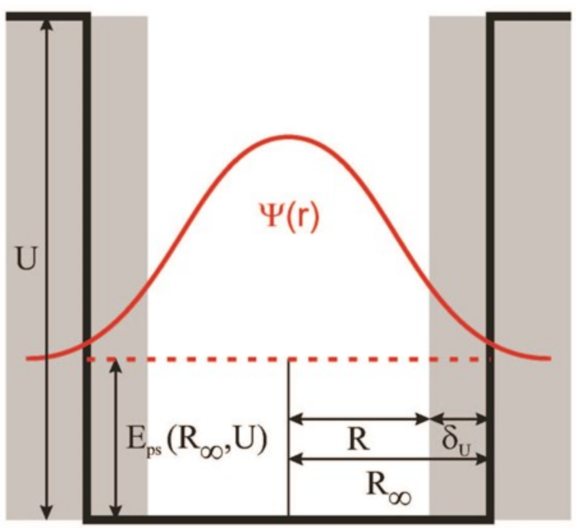


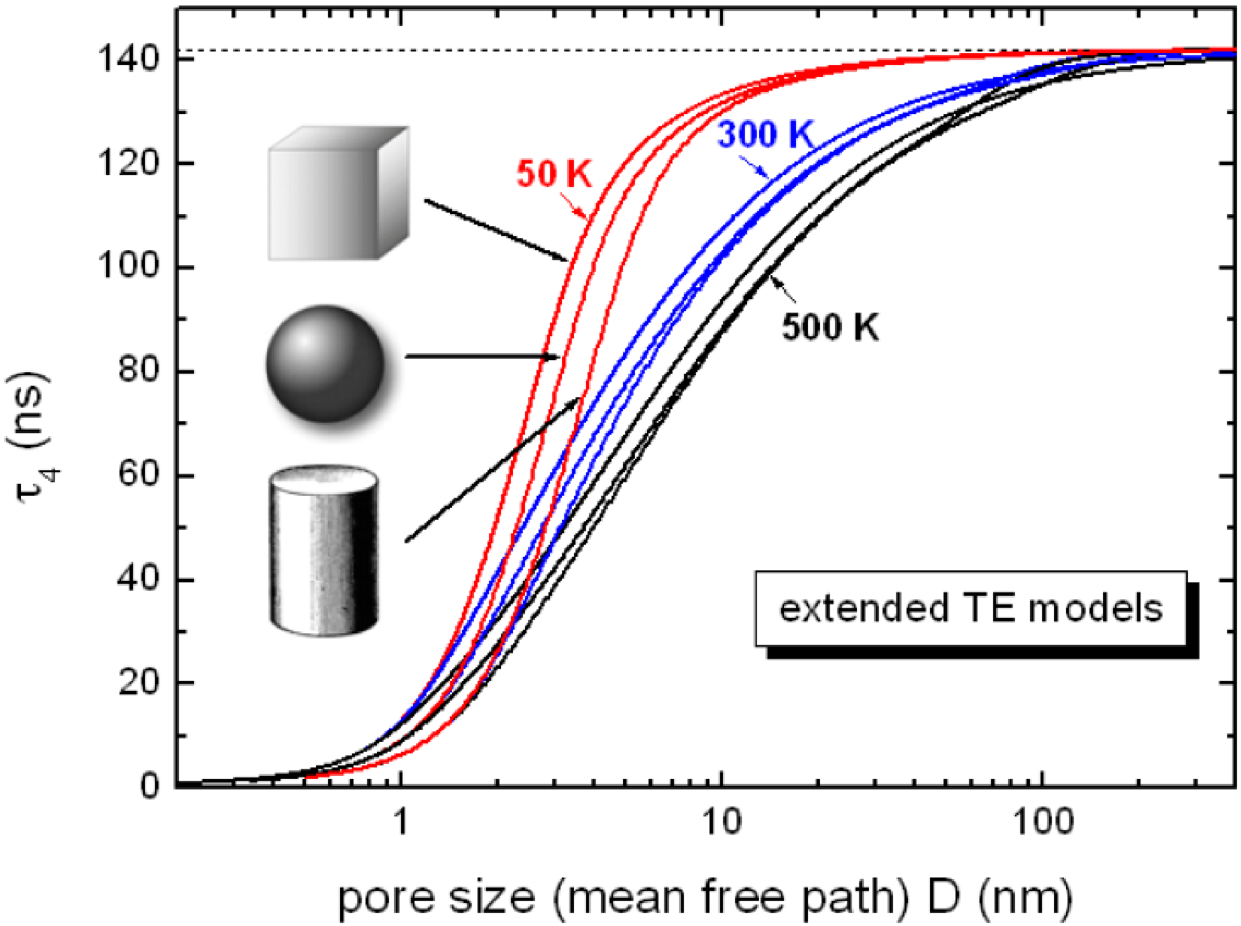
Gustav Mie (29.09.1868 - 13.02.1957)
Professor in Halle 1917-1924



Pore size and o-Ps lifetimes



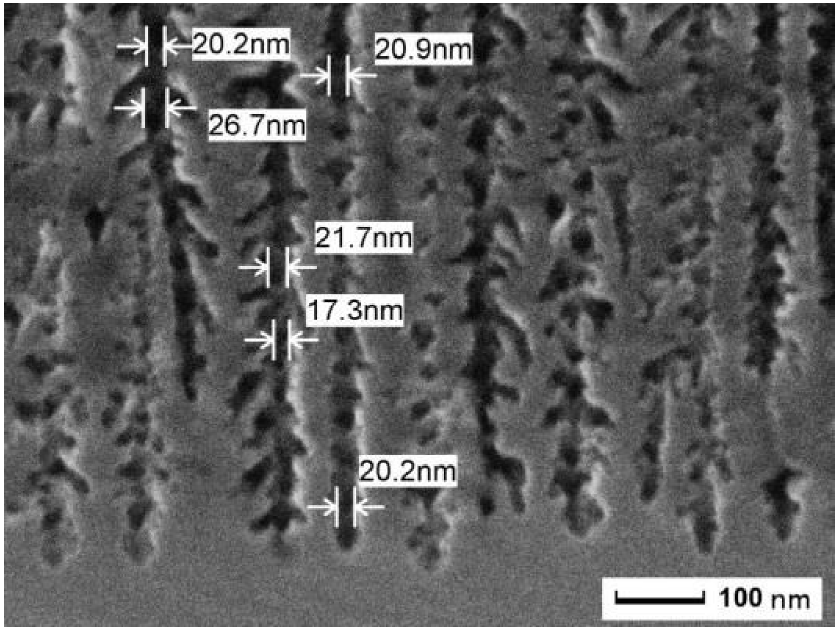




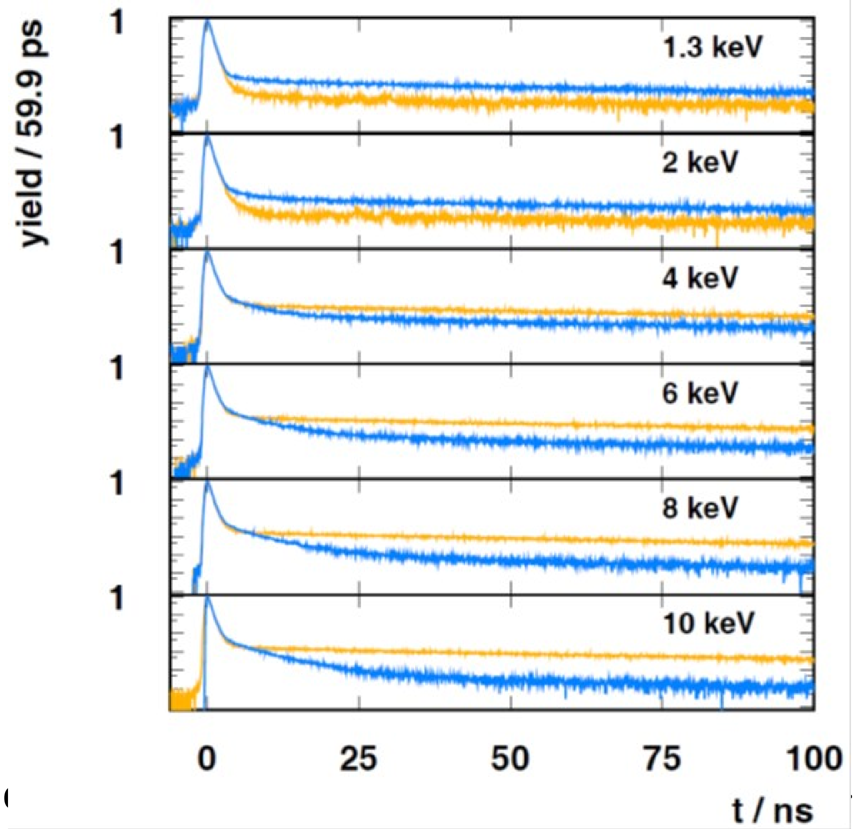
Diss. S. Thränert, MLU 2008

Experiments at MePS: nano-channeled Si

Nano-channeled silicon produced by etching for Ps storage and release.



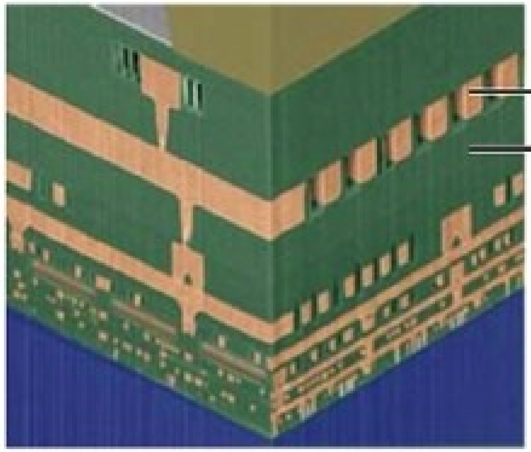
Courtesy: R. Brusa, Univ. Trento

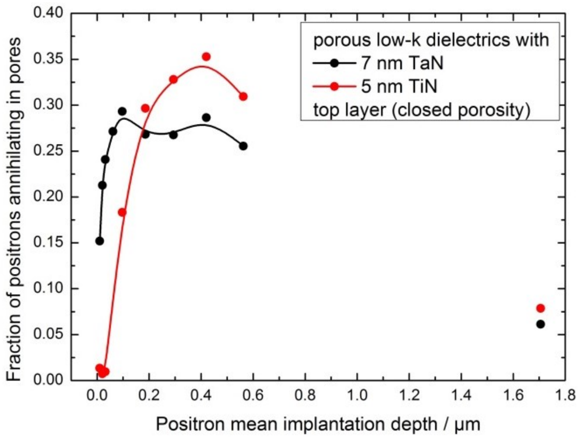


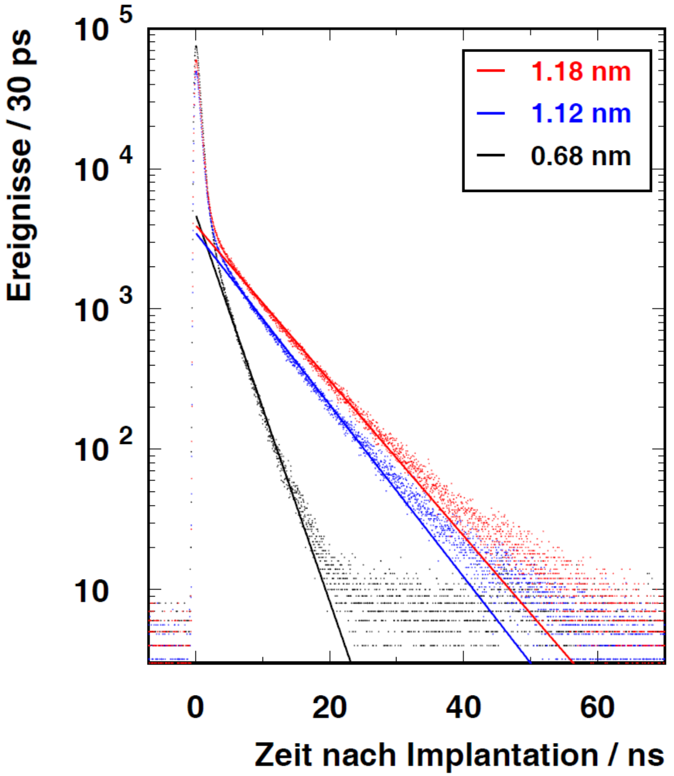
Tune the nano-channel size to optimize the influence of thermalization times (the smaller-the-better) and lowest Ps temperature (the bigger-the-better). Improve Ps output by capping with various materials for Ps reflection. -> Measure Ps lifetimes and yield depending on channel size and capping.

Experiments at MePS: low-k dieelectrics

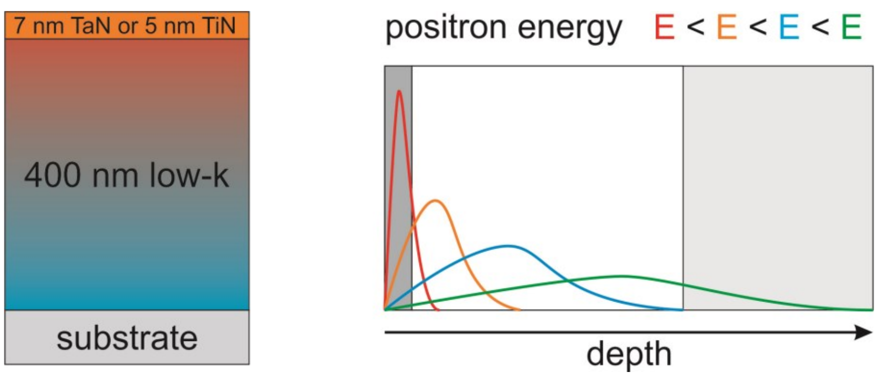
Reduction of RC time constants change switching speed of CMOS devices.





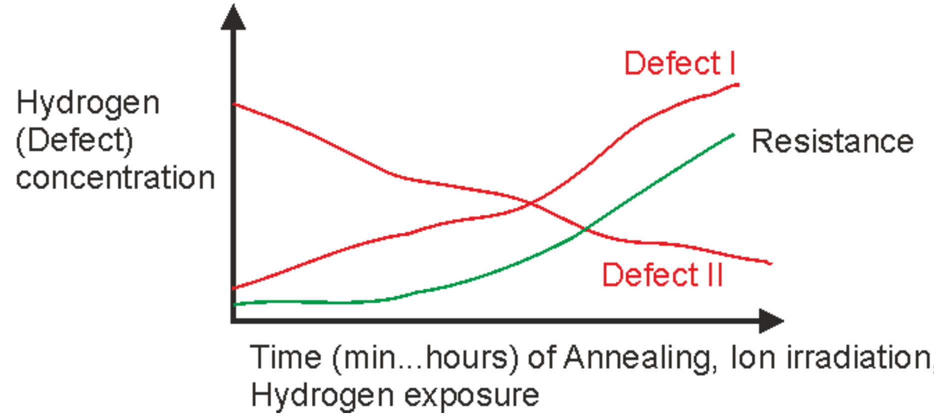


CMOS device

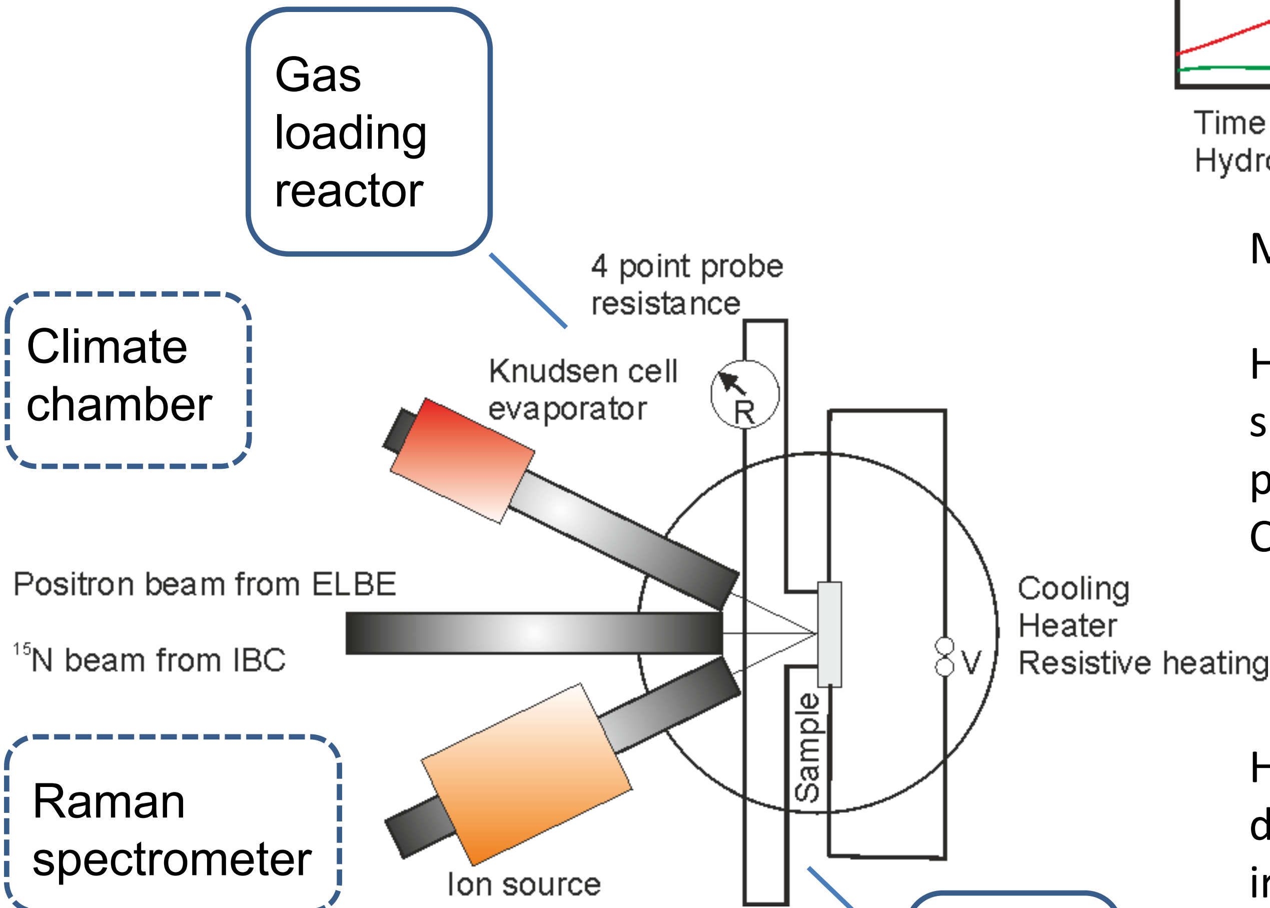


M. Jungmann, et al.,
Journal of Physics: Conference Series 443(2013) 12088
K.B. Yeap, et al.,
Journal of Materials Research 28(2013)1262

Future work: In-situ



Apparatus for In-situ Defect Analysis



XPS analysis unit

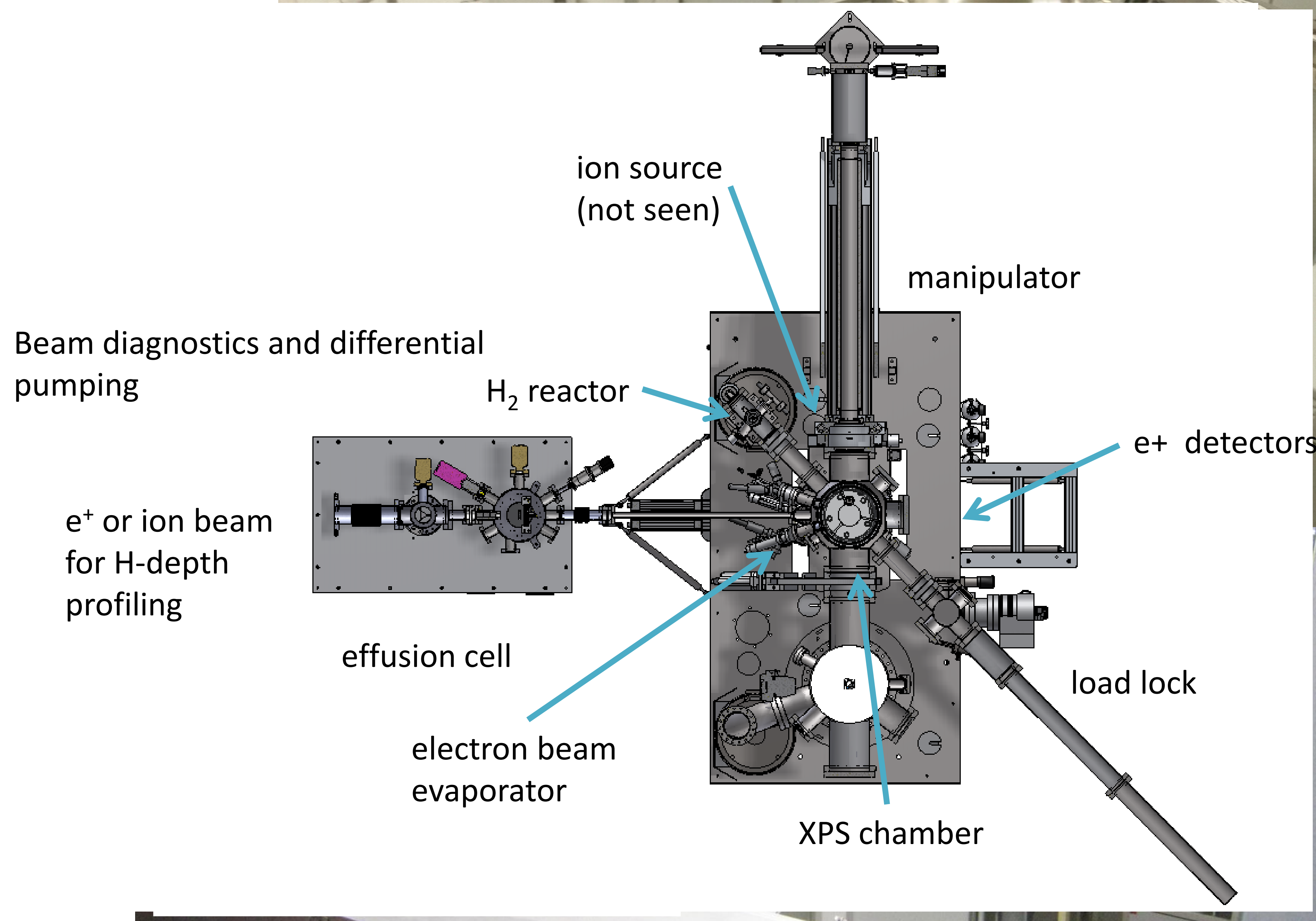
Motivation

Hydrogen diffusion:
speed of loading/deloading process, e.g. Hao et al, J. Phys. Chem. Lett. 1 (2010) 2968

Hydrogen storage capacity:
decoration of defects in e-irradiated Nb, e.g. J. Cizek et al., Phys. Rev. B 79 (2009) 054108

Talk on Tuesday by P. Hruska (H-loading)
Wednesday by M. John (sputtering)

Future w



ion source
(not seen)
manipulator
Beam diagnostics and differential
pumping
H_2 reactor
e+ detectors
e⁺ or ion beam
for H-depth
profiling
effusion cell
load lock
electron beam
evaporator
XPS chamber

The team

Helmholtz-Zentrum Dresden-Rossendorf

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A.G.Attalah, N. Hinsche,
J. Haeberle, A. Pohl, A. Krille,
B. Wehrlich, H. Benkwitz, L. Büttner,
S. Bölling, G. Jakob

and many collaborators

S.V. Stepanov, D.S.Zvezhinskiy (ITEP, MEPhI)	H_2O
C. Hugenschmidt, M. Reiner (TU Munich)	MnSi
F. Selim (U Bowling Green)	ZnO
M. Kraatz, E. Zschech (Fraunhofer IKTS)	low-k
A. Uedono (Univ. Tsukuba)	low-k
R. Brusa, L. Ravelli (Univ. Trento)	nano-Si

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Martin-Luther-Universität Halle-Wittenberg

Warum Experimentalphysiker manchmal mit Hobby-Exzentrikern verwechselt werden, die in Heizungskellern Eisenbahnanlagen nachbauen, ist bislang unerforscht...