Positron-Annihilation Lifetime Spectroscopy using Electron Bremsstrahlung

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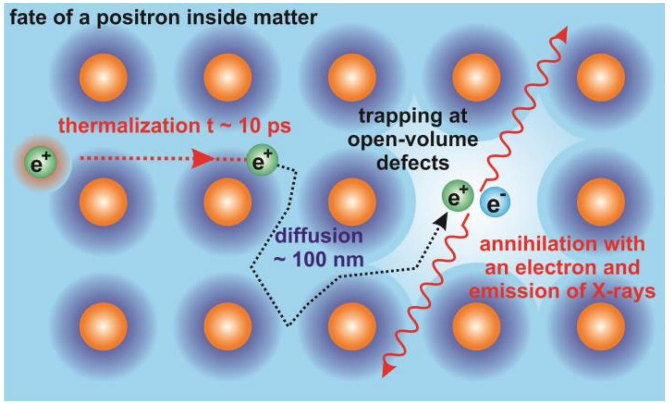
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Outline



Courtesy: R. Krause-Rehberg / M. Butterling

- Motivation

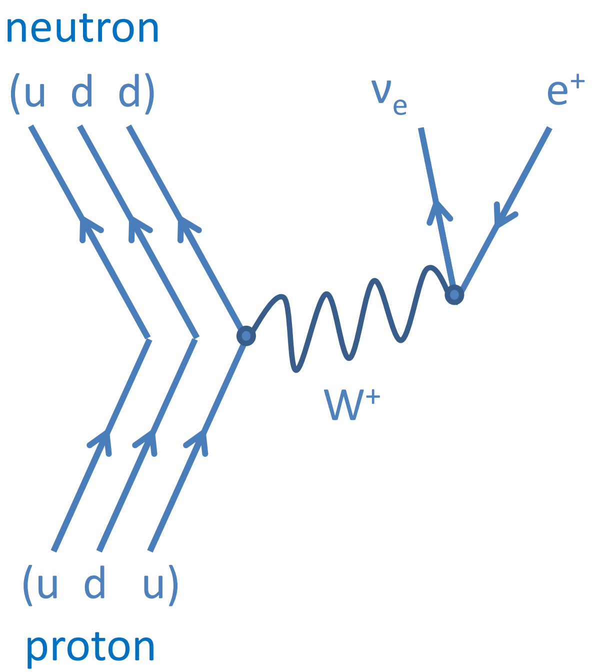
- Accelerator-based positron production and annihilation studies at a superconducting electron LINAC: What marks the difference to reactors and radio-isotope sources?

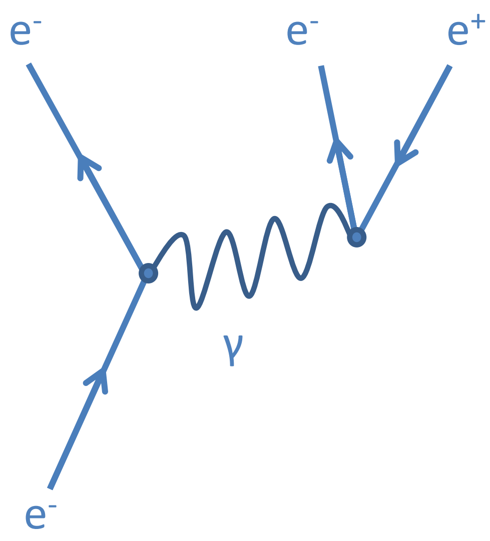
- Applying pulsed beams: positron annihilation lifetime spectroscopy at thin films, bulk materials, and fluids

- Development of a pixelated detection system for position-sensitive positron annihilation lifetime measurements and experiments with structured targets and tomographic image reconstruction

Isotopes, reactors, accelerators

Production of positrons in weak (W^+) or electromagnetic interactions (γ)

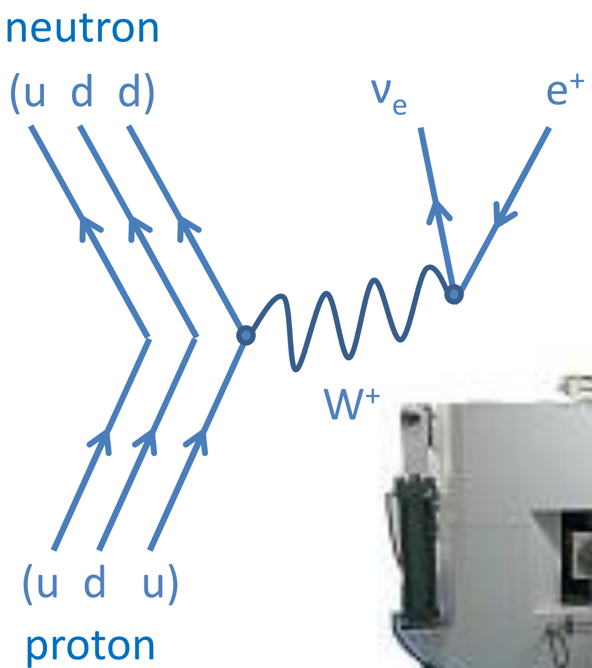




Free proton decay is forbidden by energy conservation
→ we need the proton inside a nucleus where it undergoes β^+-decay

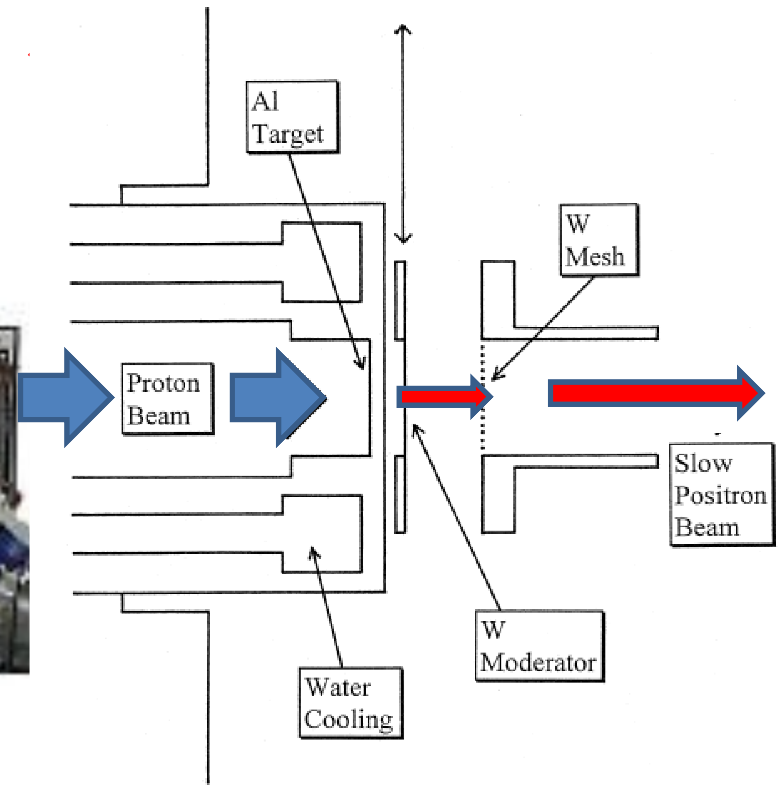
Isotopes, reactors, accelerators

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

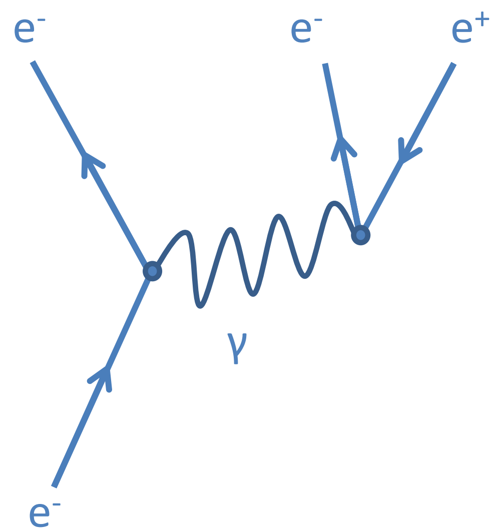
Production of positrons through electromagnetic interactions (photons)

Use intense source of photons for pair production

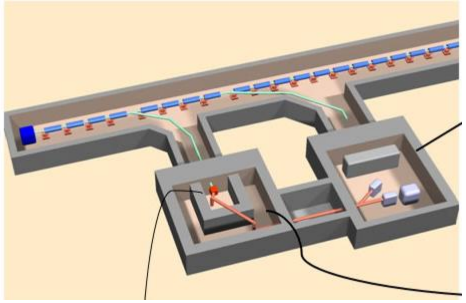
→ Capture-neutron gamma-rays from reactor

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

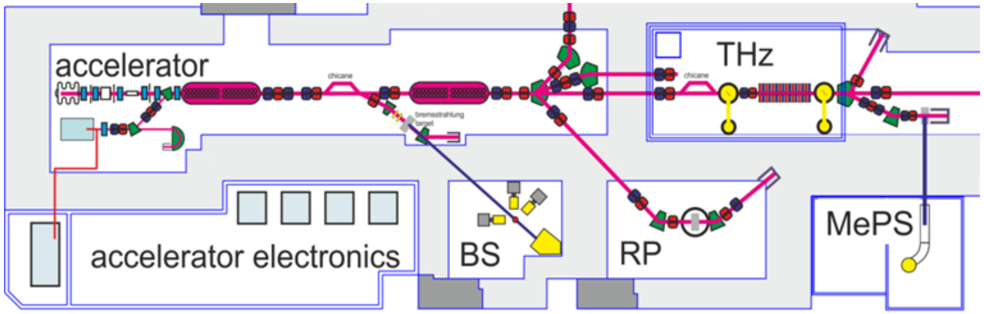
FRMII Munich



→ Bremsstrahlung from electron accelerators



AIST, Tsukuba, Japan



ELBE, Dresden

Positrons from accelerators

Accelerators can produce intense and pulsed slow positron beams.
LINear ACcelerators are favored due to their high beam power and time structure.

A) normal conducting LINAC (AIST)

$E \sim 50$ MeV
$I_{peak} \sim 100$ mA
$t_{bunch} \sim 1$ µs
$f_{rep} \sim 100$ Hz

beam power 500 W

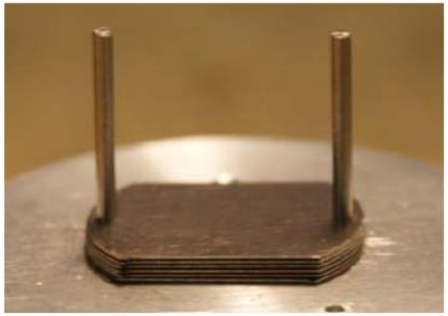
B) superconducting LINAC (HZDR)

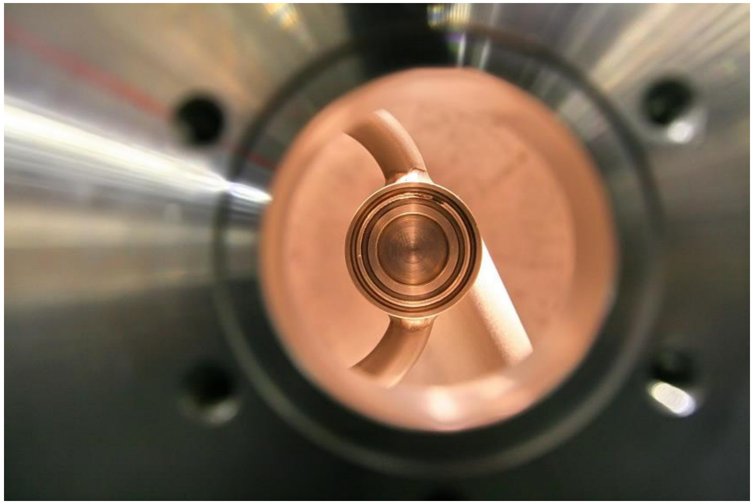
$E \sim 50$ MeV
$I_{average} \sim 1$ mA
$f_{rep} \sim 10$ MHz

beam power 50 kW

sophisticated converter designs and heavy shielding needed

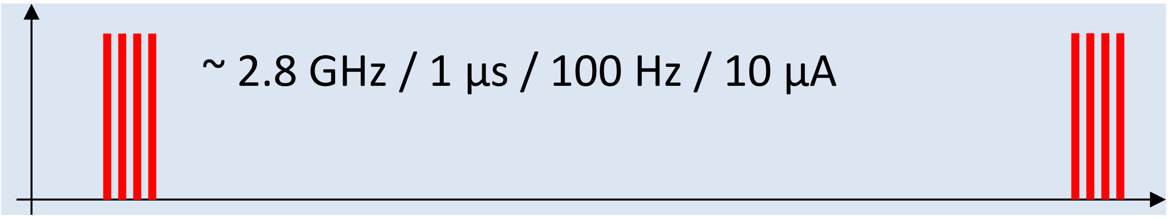
stack of 50
100 µm thick W foils



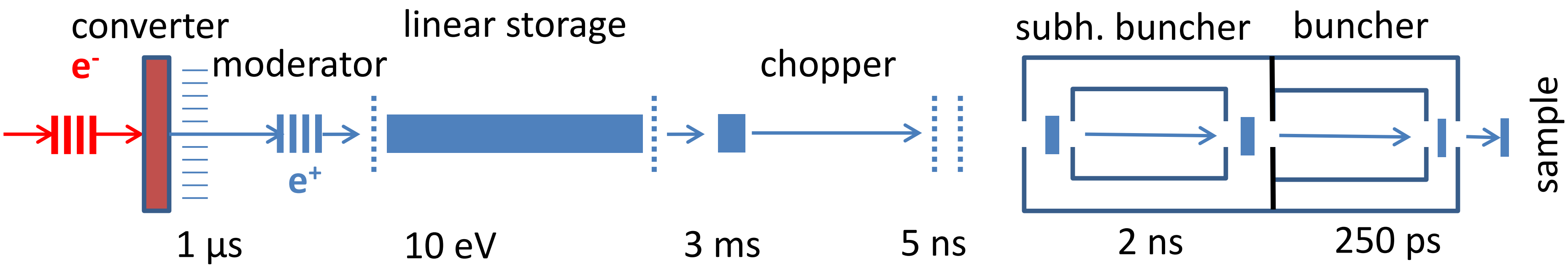


EPOS water-cooled converter

Positrons from accelerators



NC-LINAC in bunched mode



SC-LINAC in CW mode

EPOS facility

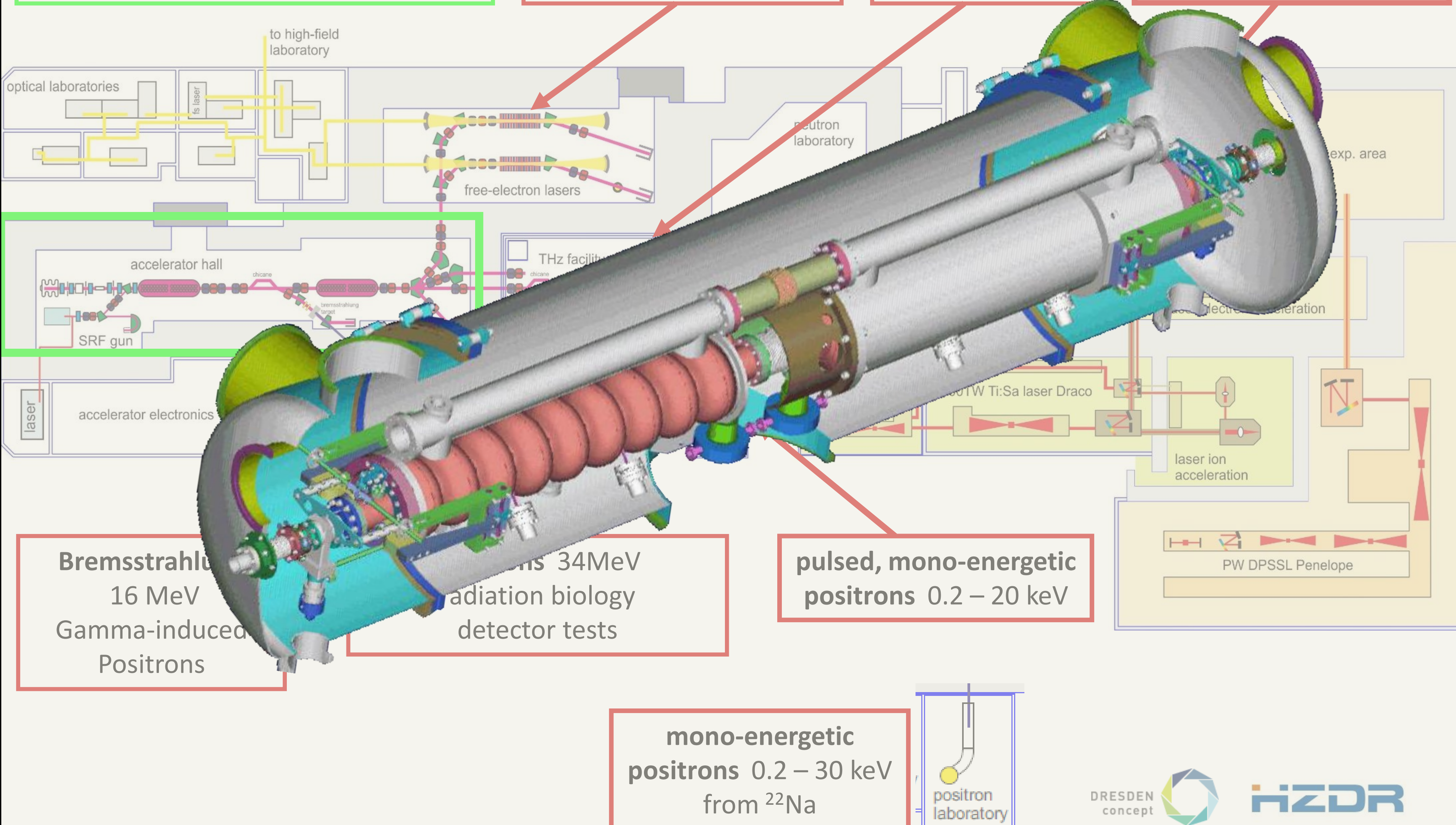
Positrons from accelerators

1.6 mA, 40 MeV (64 kW)
CW electron accelerator

coherent IR-radiation
3 – 230 μm

THz radiation
100 μm – 3 mm

neutron time of flight
E_n 0 – 10 MeV



Bremsstrahl
16 MeV
Gamma-induced
Positrons

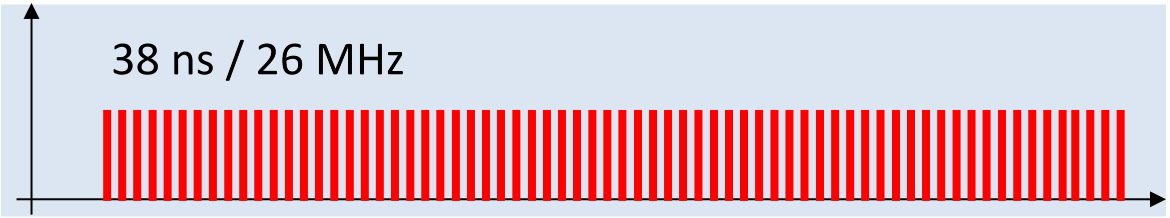
ns 34MeV
adiation biology
detector tests

pulsed, mono-energetic
positrons 0.2 – 20 keV

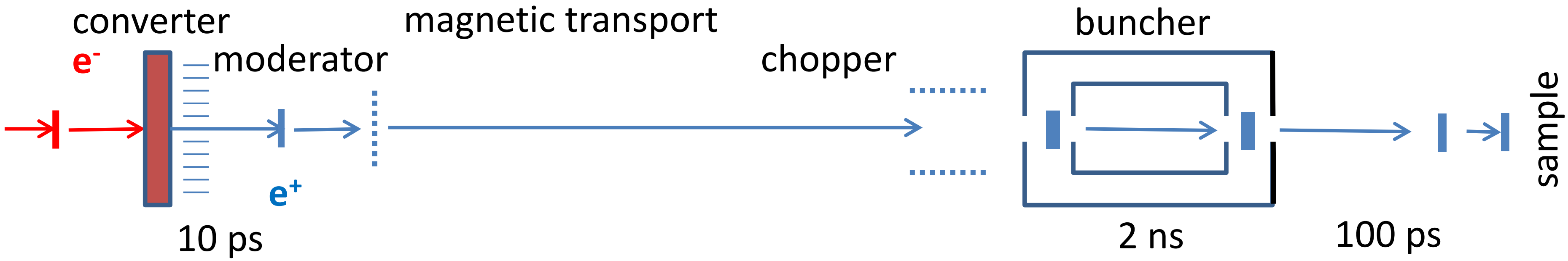
mono-energetic
positrons 0.2 – 30 keV
from ^{22}Na

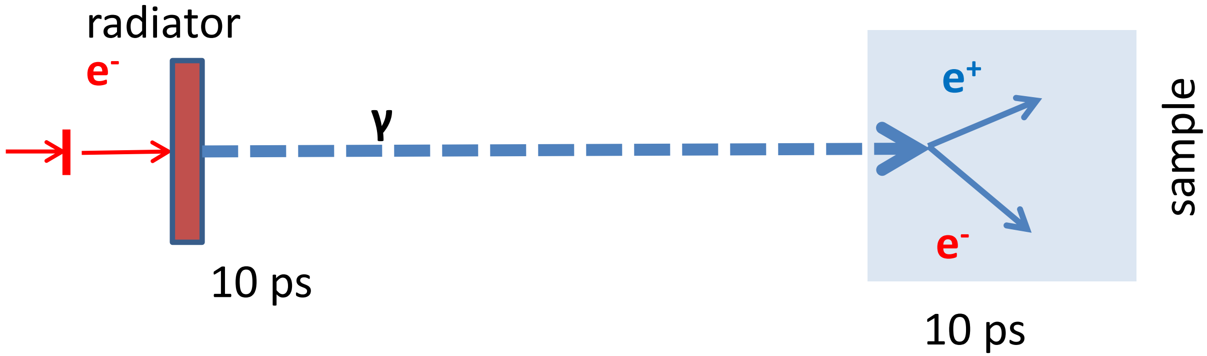
DRESDEN concept
HZDR

What about bulk materials, fluids, gases …?



SC-LINAC in CW mode





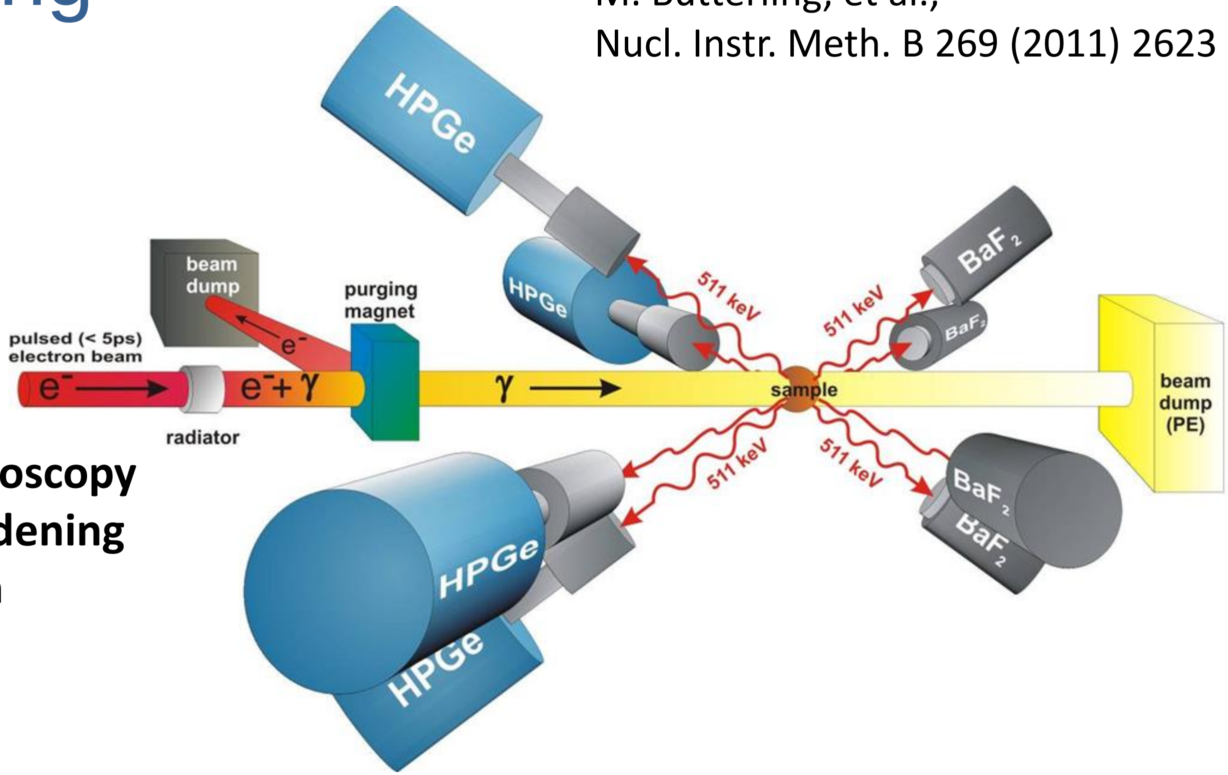
GiPS

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

Positron production using electron-bremsstrahlung

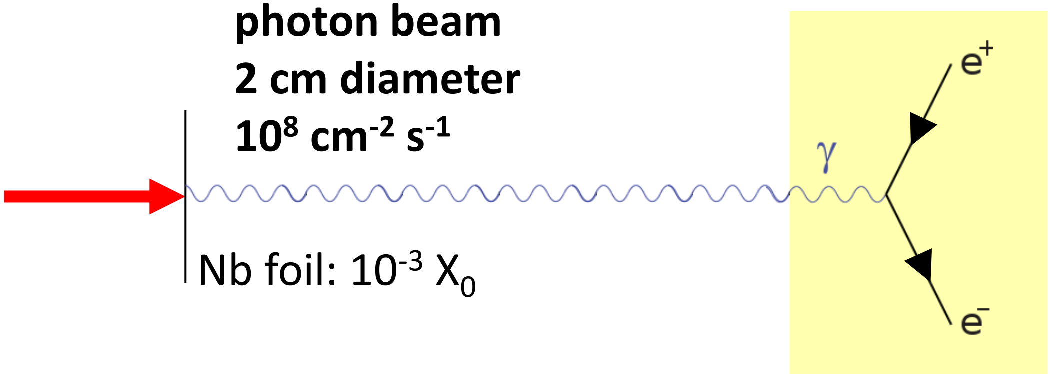
M. Butterling, et al.,
Nucl. Instr. Meth. B 269 (2011) 2623

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



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

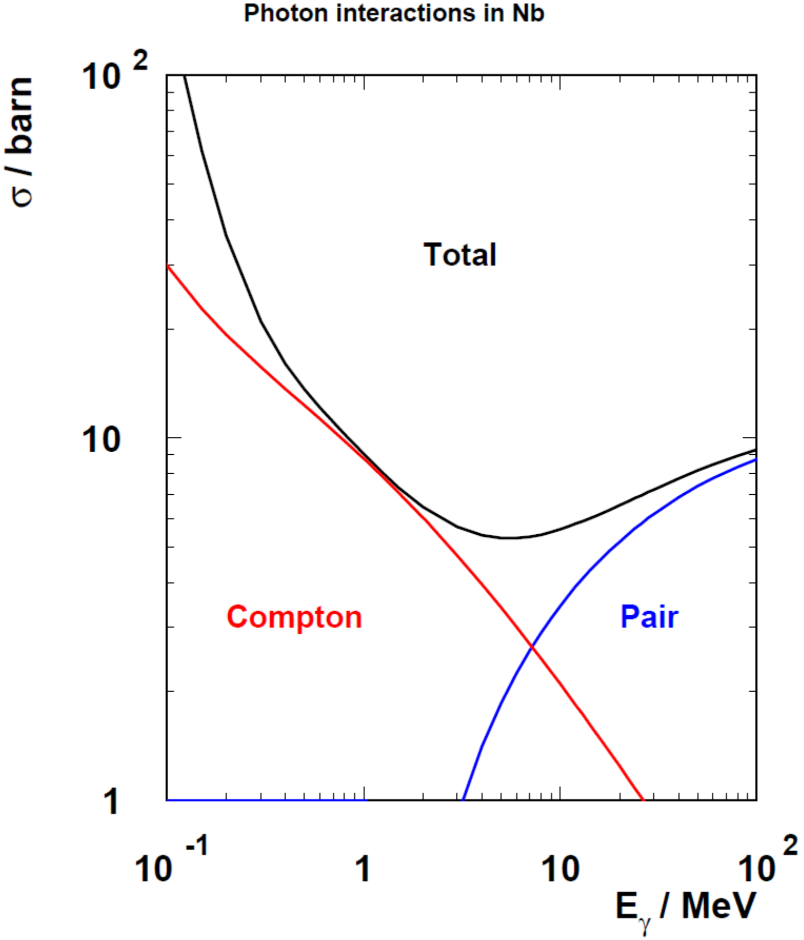
photon beam
2 cm diameter
10^8 cm^{-2} s^{-1}

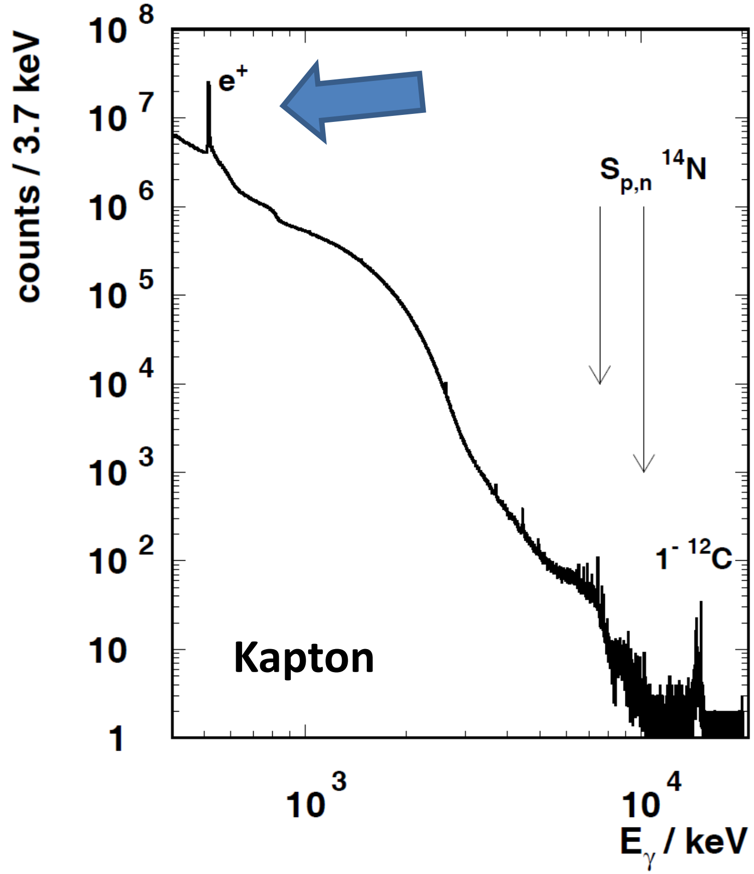


Nb foil: 10^{-3} X_0

studies done so far:
- water, glycerol from 10°C to 100°C
- animal tissue
- metals and alloys
- **neutron-activated reactor materials**

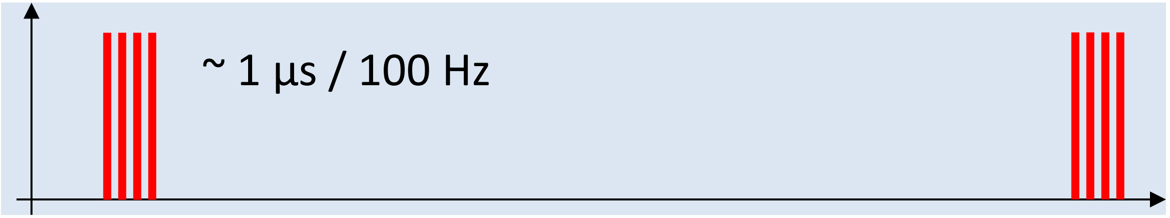
Positrons: backgnd for nuclear physics exp'ts



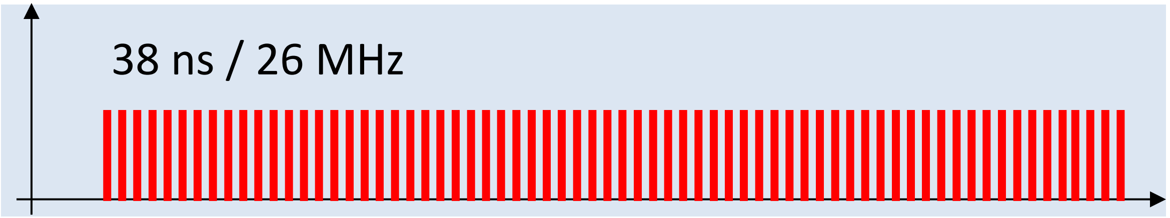


Hard bremsstrahlung produces a huge amount of positrons via pair production inside the target material. High-energy photons act as a **volume source of positrons throughout the entire volume**.

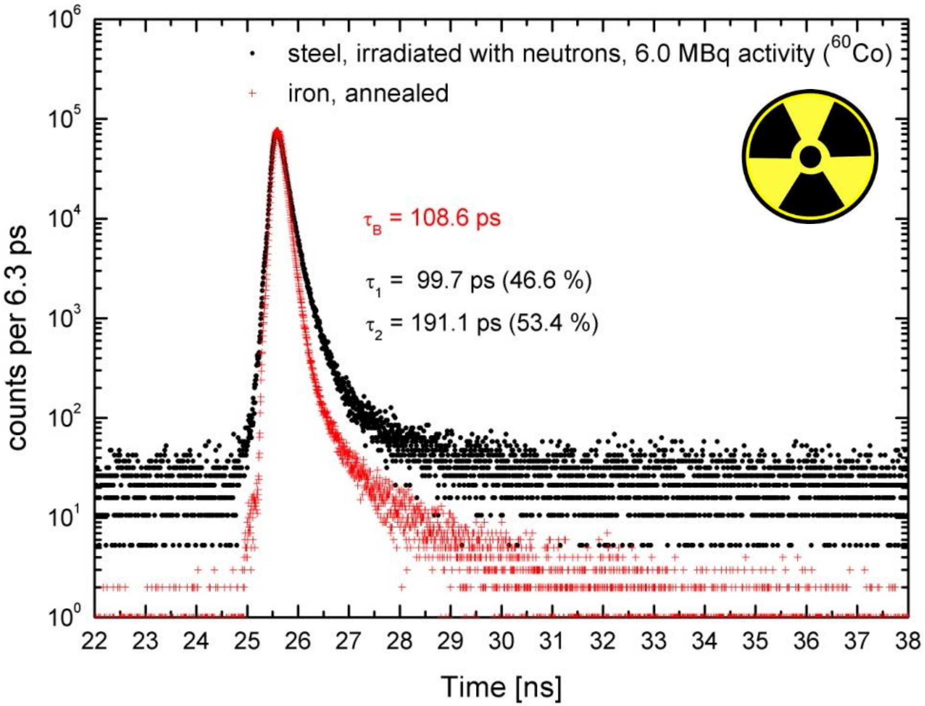
Gamma-induced Positron Spectroscopy



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

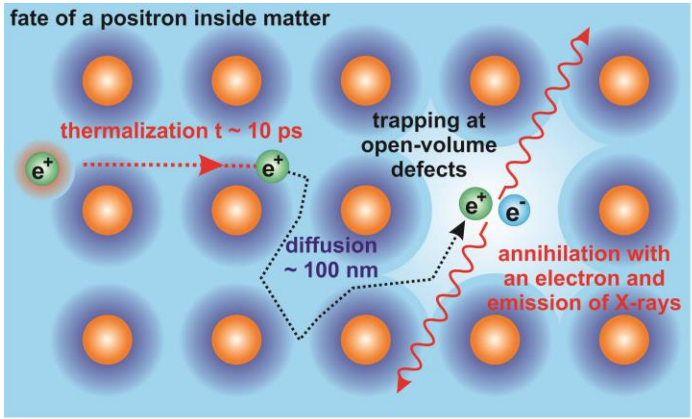


High resolution lifetime spectrum with signal to noise ratios of better than 10^5:1 using gamma-gamma coincidence techniques for background reduction. Lifetime spectra are free from artefacts.

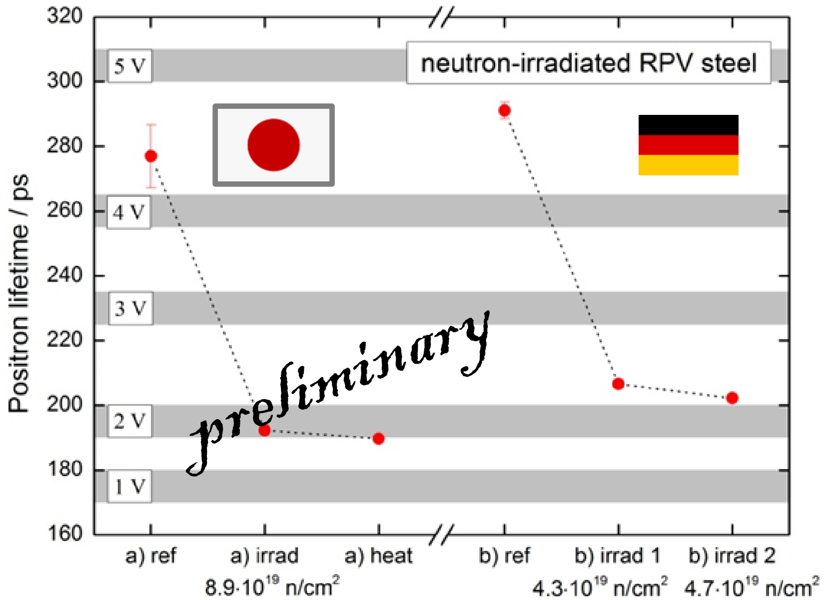
→ Long lifetimes reveal atomic defects caused by neutron-induced damage.
→ Can (and how) defects be removed by thermal annealing?

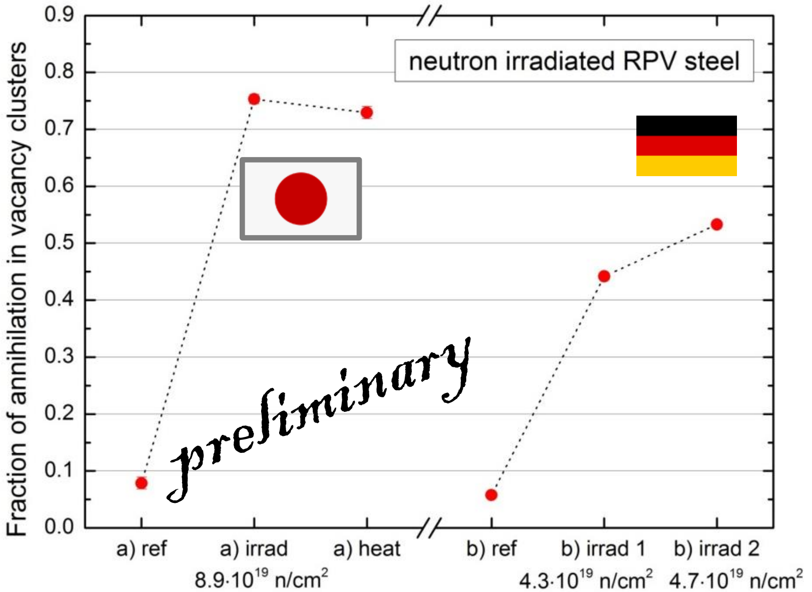
Physics with GiPS: RPV steel

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.



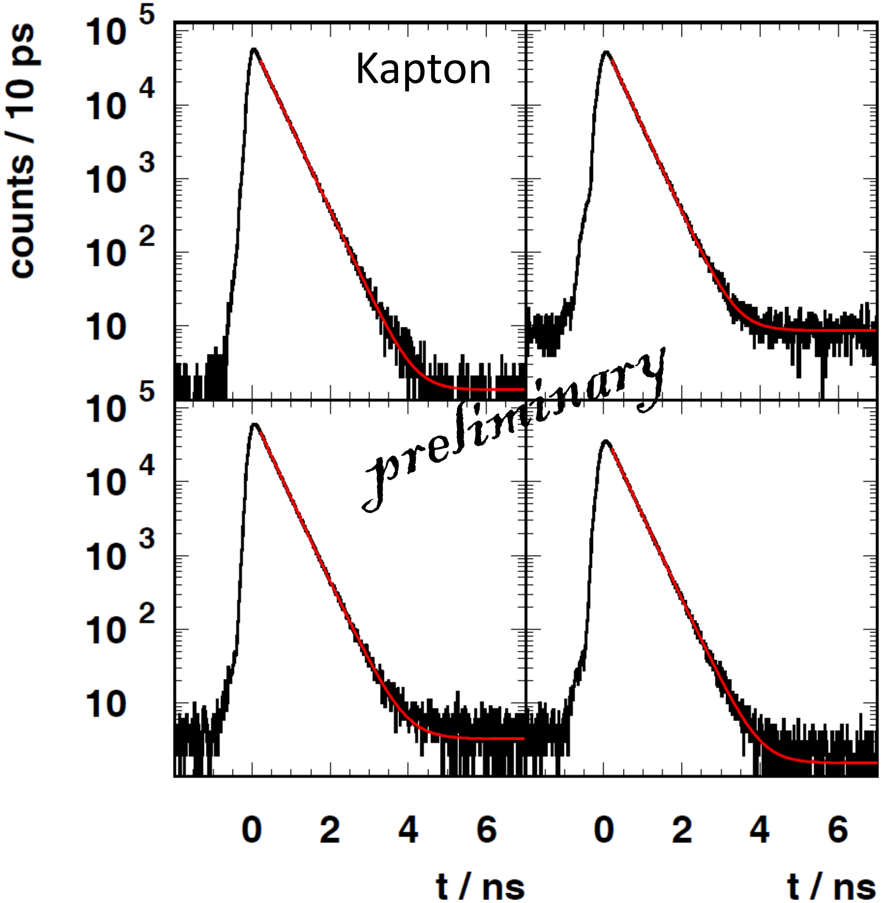


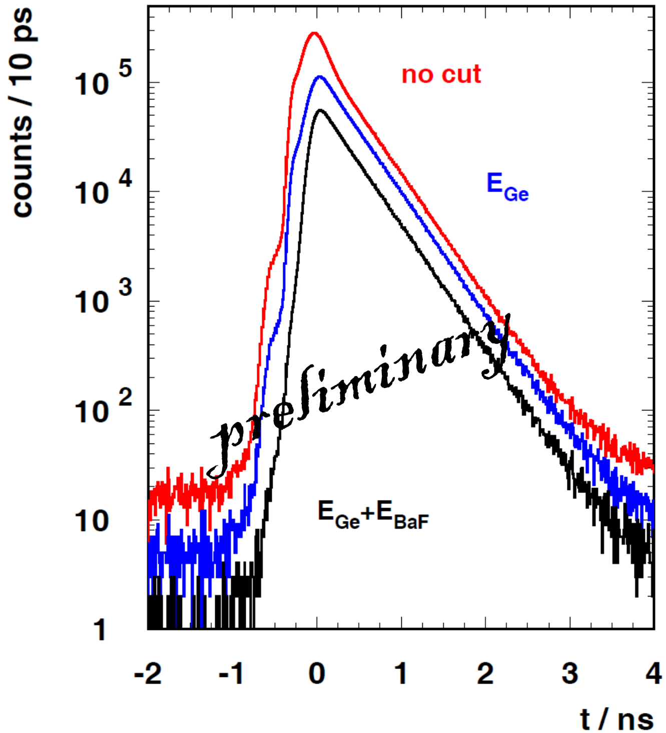
→ Preferential formation of double vacancies

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

Physics with GiPS: Kapton

Annihilation lifetime in Kapton has been under debate for quite some time. Here, we try to get a measurement without source correction.





applied cuts on Germanium and BaF_2 detector energy signal reduce background from interactions outside the sample

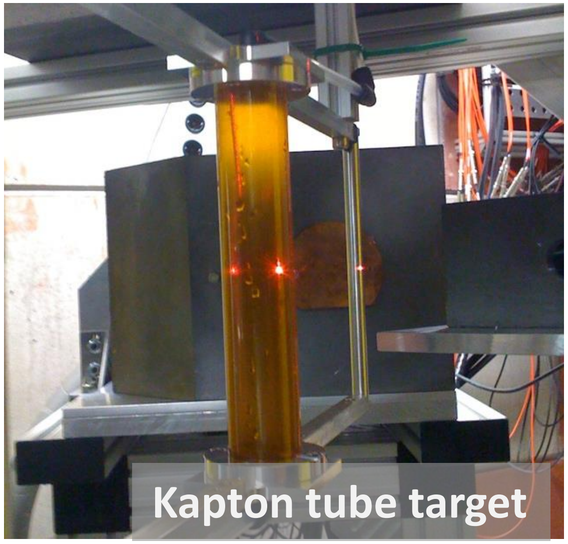
→ consistent single positron lifetime of **(381 ± 1) ps**
two components show larger χ^2

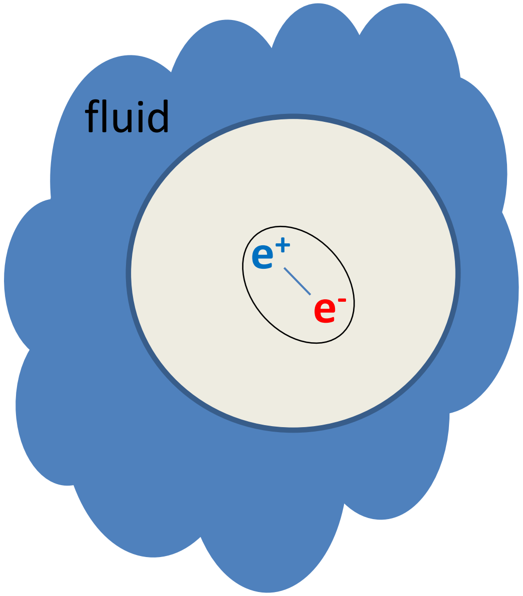
Physics with GiPS: Fluids

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….

o-Ps

142 ns

p-Ps

125 ps

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

Physics with GiPS: Fluids

$$-\frac{\hbar^2}{2m_{Ps}}\Delta\Psi + U(r)\Psi = E\Psi$$

stationary Schrödinger eqn.

$$\Psi = R(r)\cdot\Theta(\vartheta)\cdot\Phi(\varphi)$$

$$R(r) = R_0\, j_l(kr)$$

Ansatz: spherical Bessel fct.

$$j_0(kr) = \frac{\sin kr}{kr}$$

1st non-trivial solution

$$E_0 = \frac{h^2}{8m_{Ps}r_0^2} = \frac{\pi^2\hbar^2}{4m_e r_0^2}$$

zero-point energy

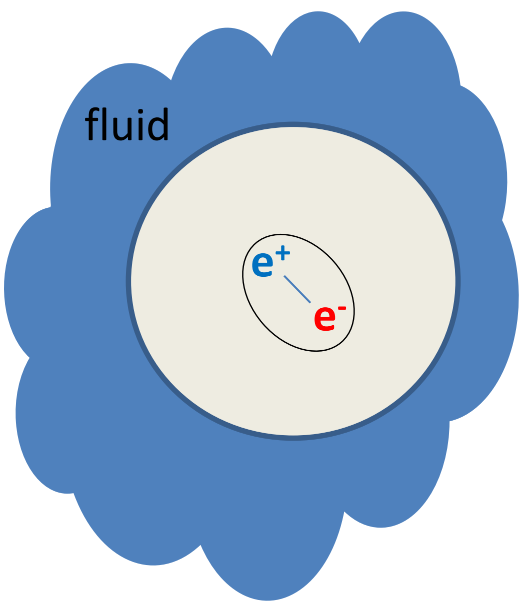
$$E_{surf} = 4\pi r_0^2\sigma$$

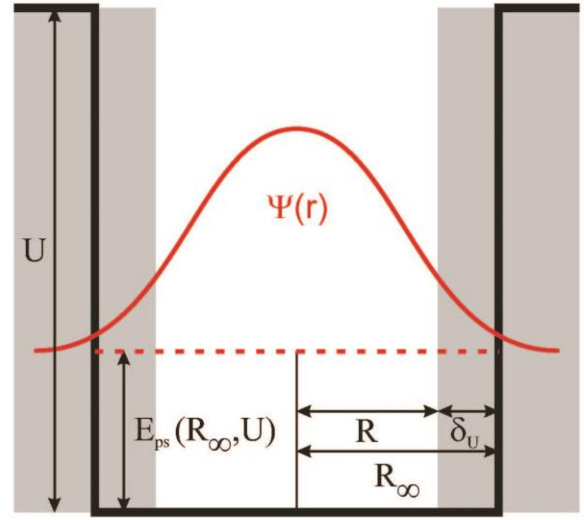
$$\frac{\partial}{\partial r_0}\left(E_0 + E_{surf}\right) = 0$$

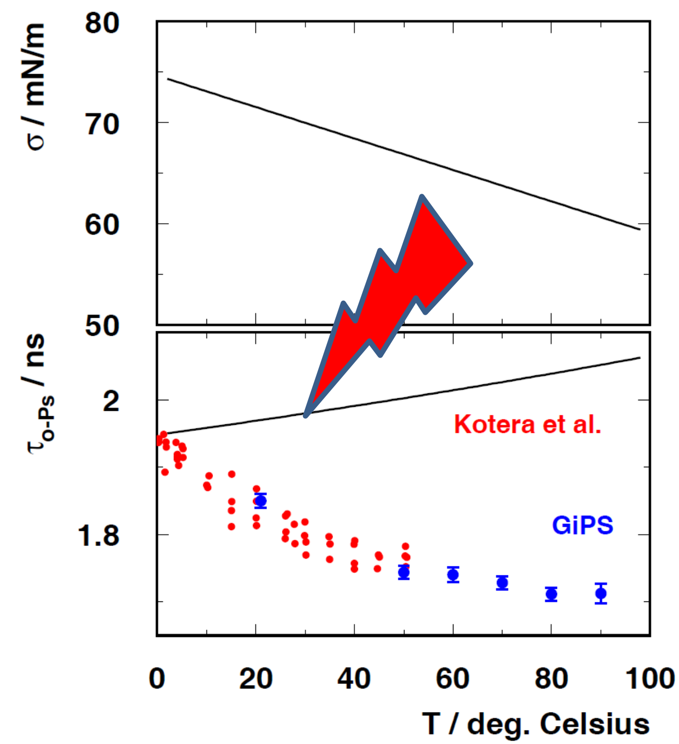
$$-\frac{\pi^2\hbar^2}{2m_e r_0^3} + 8\pi r_0\sigma = 0$$

$$r_0 = \sqrt[4]{\frac{\pi\hbar^2}{16 m_e\sigma}} = 4.3\ \text{Å}$$

$$a_0 = \frac{4\pi\varepsilon_0\hbar^2}{m_\mu e^2} = \frac{\hbar c}{\alpha\, m_\mu c^2} = 1.06\ \text{Å}$$

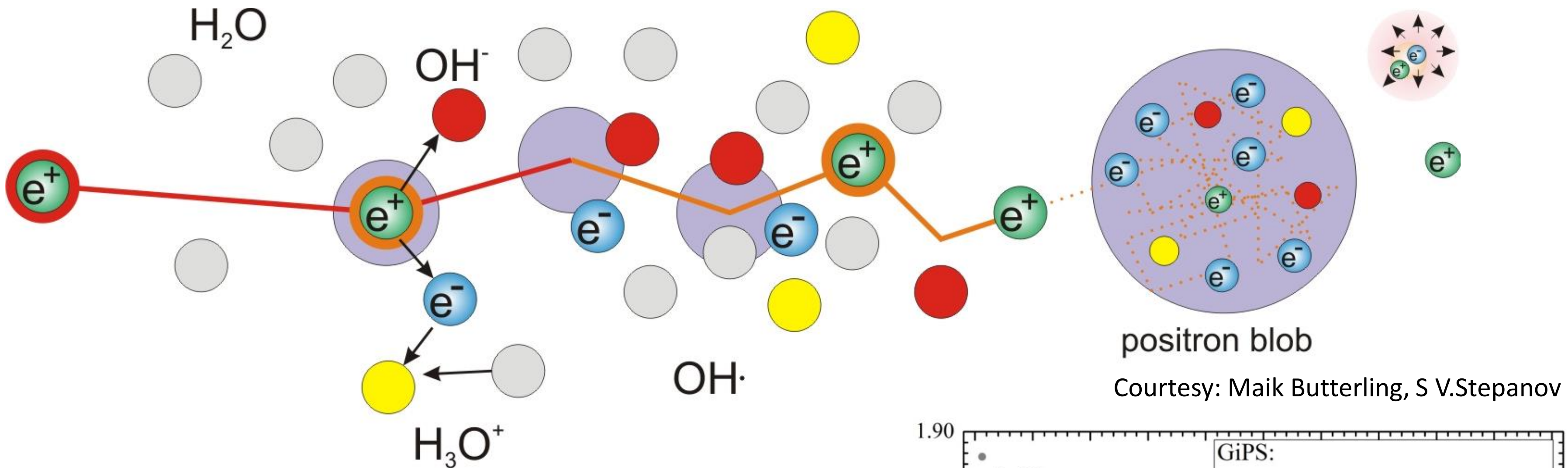






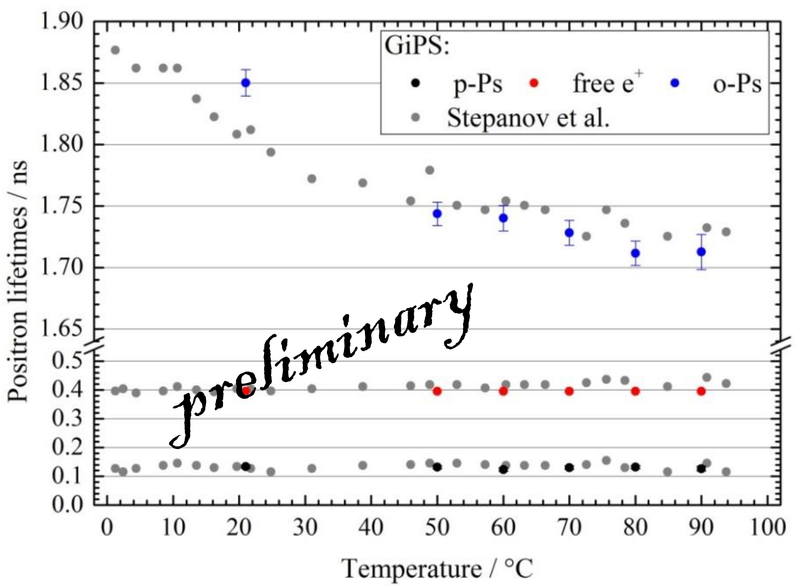
Physics with GiPS: Positron Chemistry

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.



Courtesy: Maik Butterling, S V.Stepanov

- → Radicals are positron scavengers which reduce annihilation lifetimes.
- → Extended bubble model including chemistry [S.V. Stepanov et al., Mat. Sci. Forum 607] describes data well.
- → Relevance for PET diagnostics since 2γ / 3γ ratio is affected.
- → Chemistry of radiolysis directly accessible since the probe creates the ionization itself



Towards imaging of defects

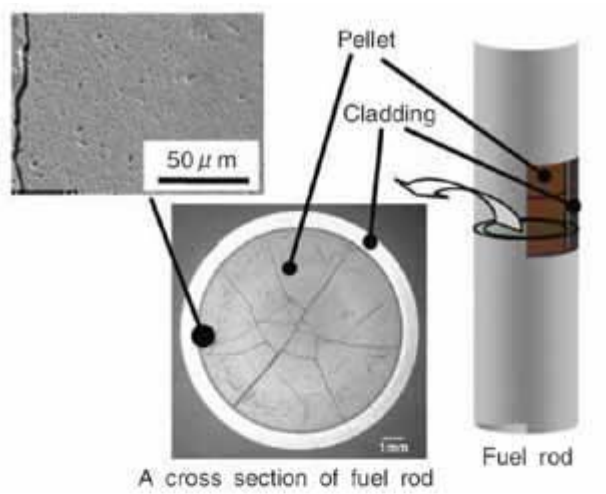
Material failures impose a significant threat to the integrity and the safety of technical systems. A thorough understanding of the microscopic origin and the development of defects requires advanced methods.

Motivation

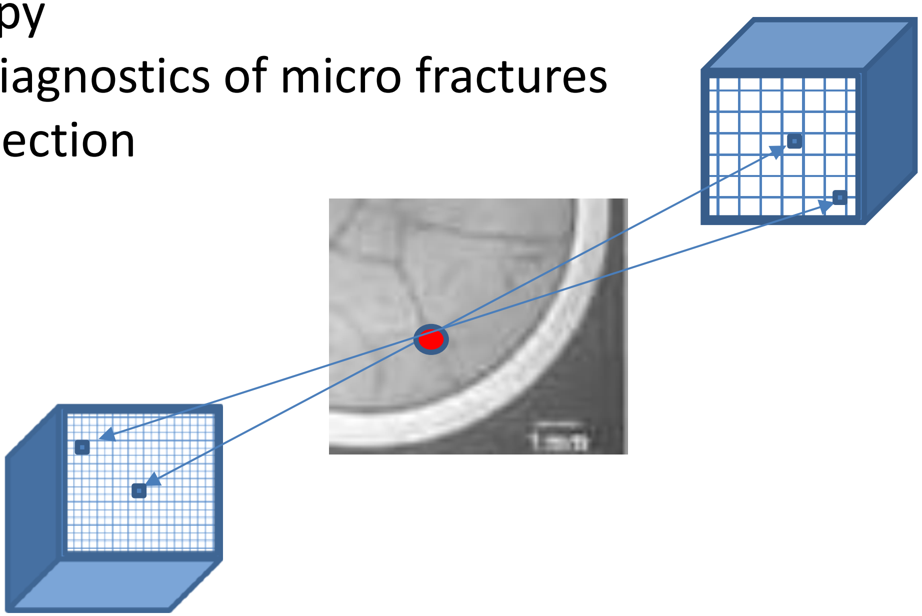
Establish a **non-destructive** and **non-intrusive** method which allows for **spatially resolved** positron-lifetime spectroscopy. Reconstruct PET-like images plus positron annihilation lifetime.

Possible Applications (list not complete):

- Porosimetry
- Medicine — in-beam positron lifetime spectroscopy during hard x-ray tumor therapy
- Engineering — pre-failure diagnostics of micro fractures; fuel rod inspection

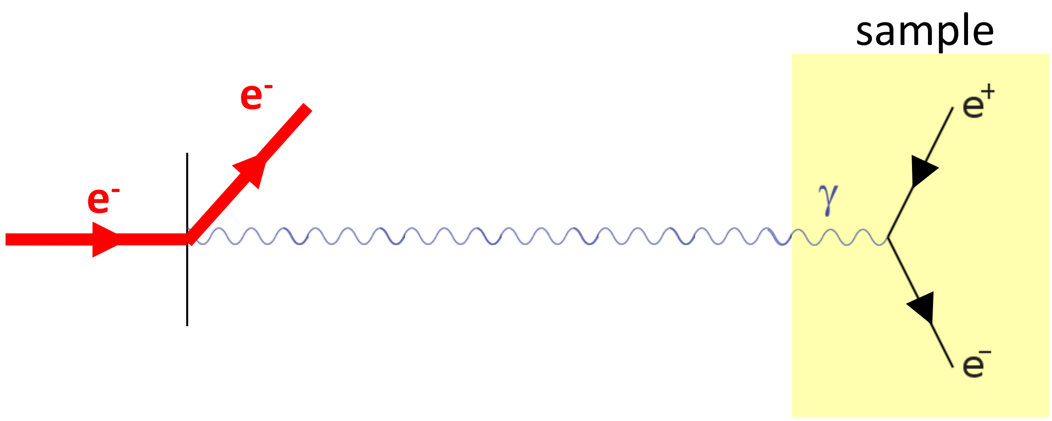


APS Physics & Society Newsletter 2011. R. Hargraves, R. Moir

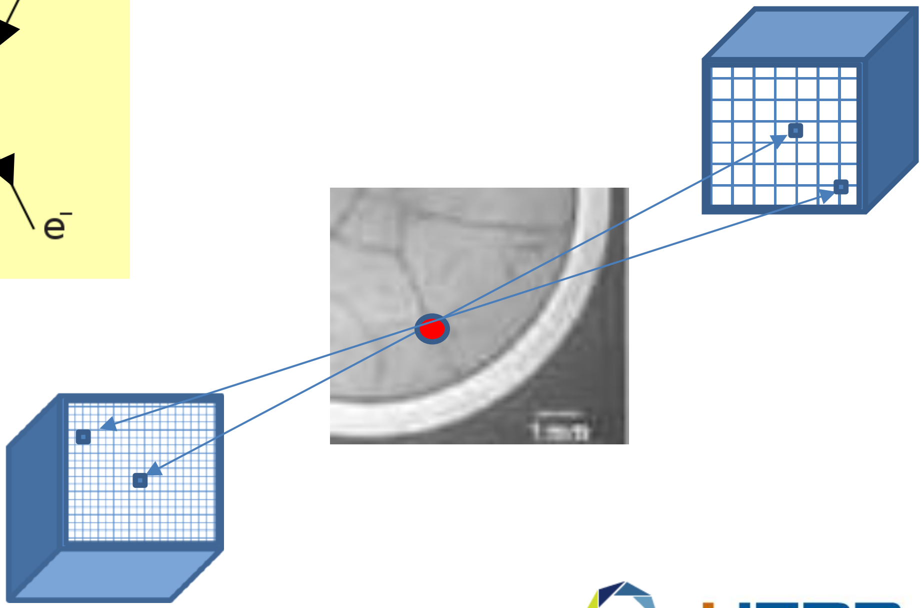


Prerequisites

• Intense source of positrons with deep penetration (cm)	≈15 MeV X-rays
• Accurate time-stamping of positron creation (<10 ps)	CW LINAC
• Position-sensitive positron detectors (mm)	Siemens LSO PET
• Time-resolution for lifetime spectroscopy (~100 ps)	in-house (physics)
• Efficient data acquisition	in-house (physics)
• 3-D image reconstruction	in-house (medicine)

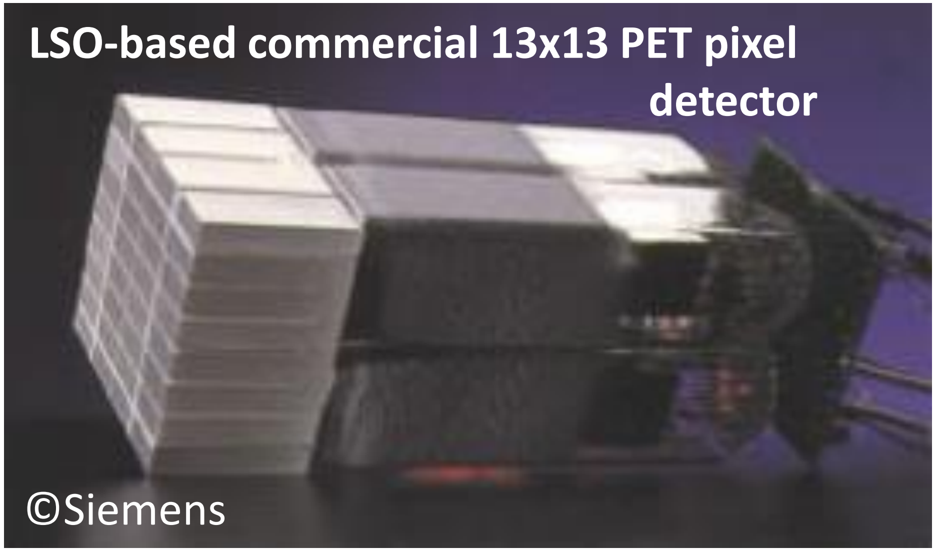


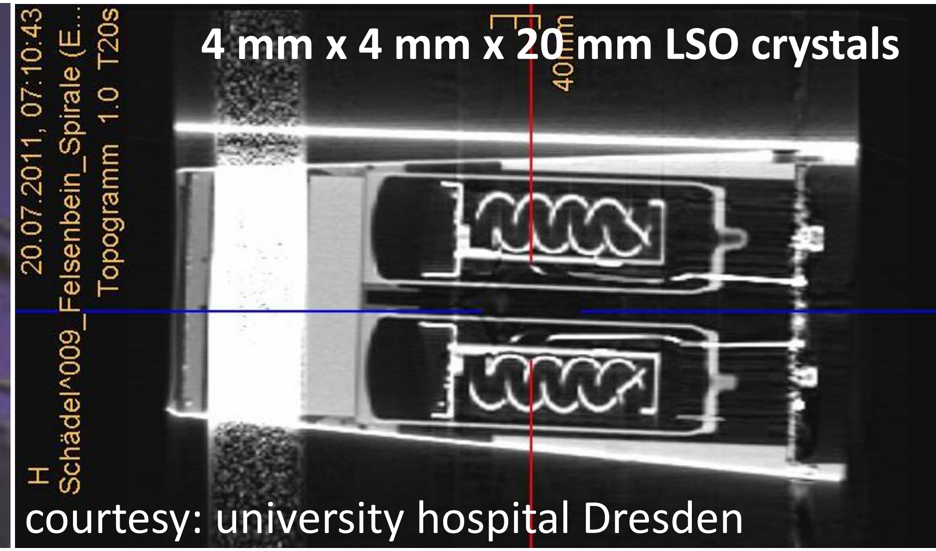
Gamma-**i**nduced **P**ositron **S**pectroscopy



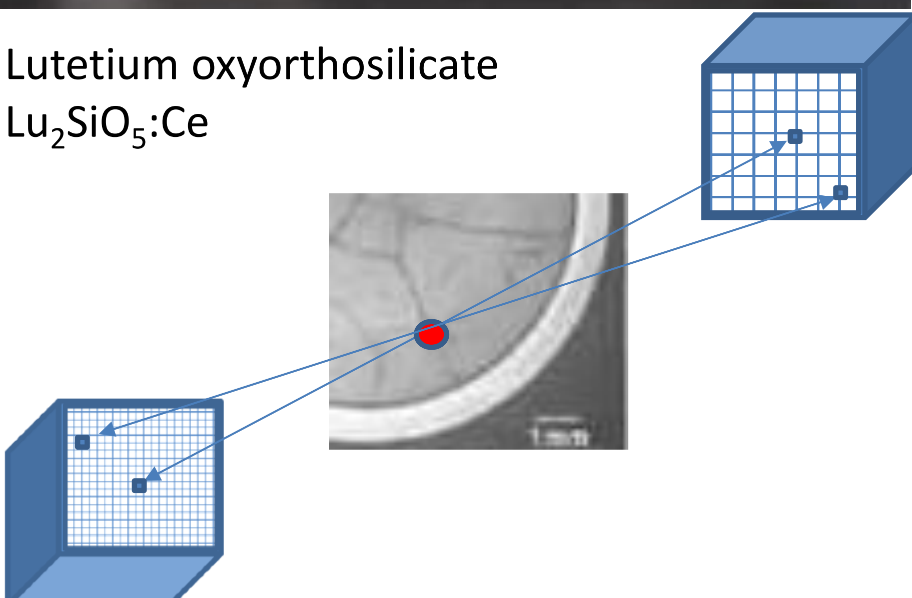
Towards 2/3-D positron lifetime tomography

- Two position-sensitive photon detectors with 169 elements each



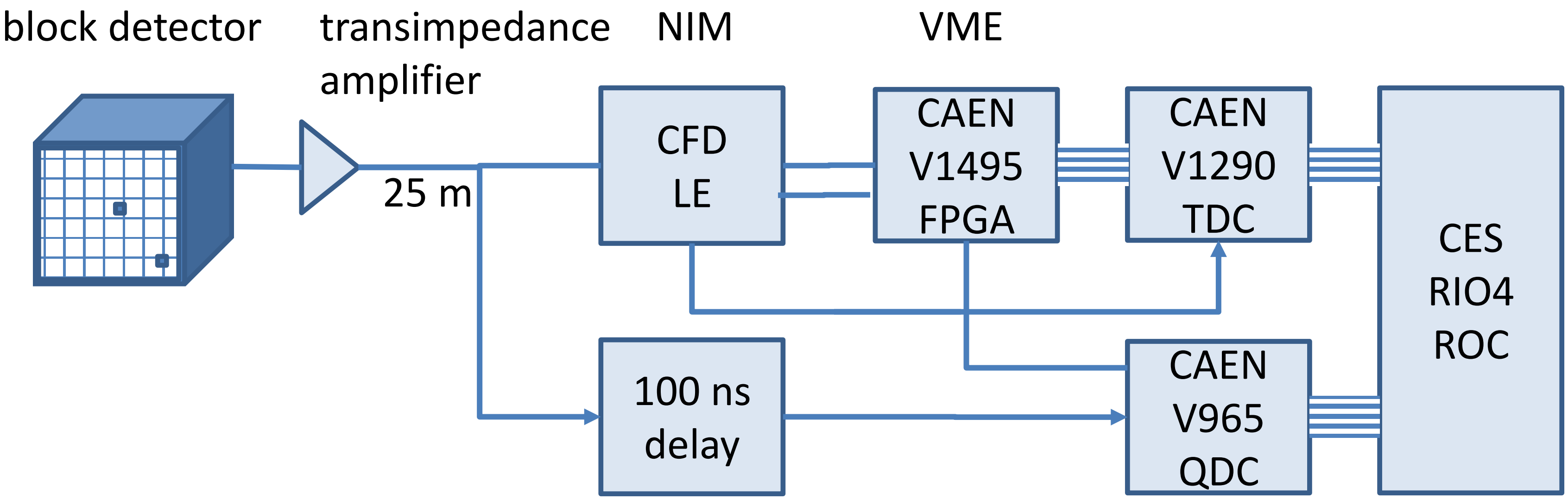


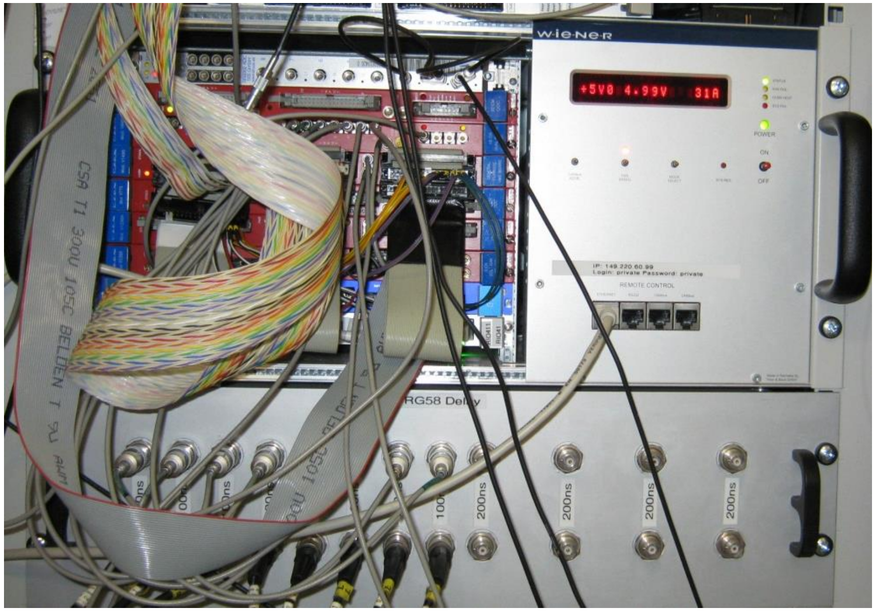
Lutetium oxyorthosilicate
Lu_2SiO_5:Ce



- Each crystal array read out using 4 PMT
- Summed PMT signal -> gamma energy
- Correlation of individual PMT signals -> position
- Positron annihilation time given by sum over all 8 PMT involved

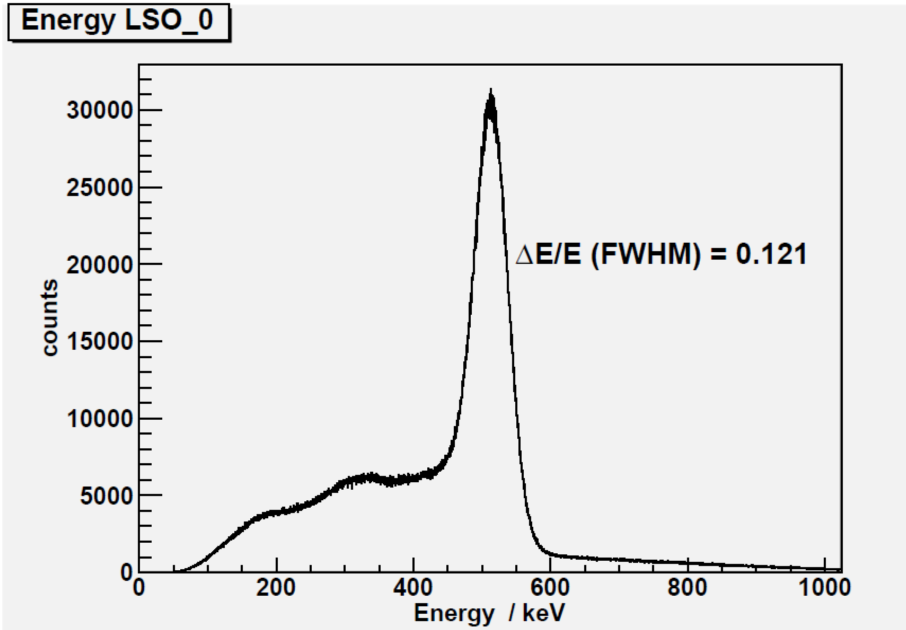
Electronics (VME)

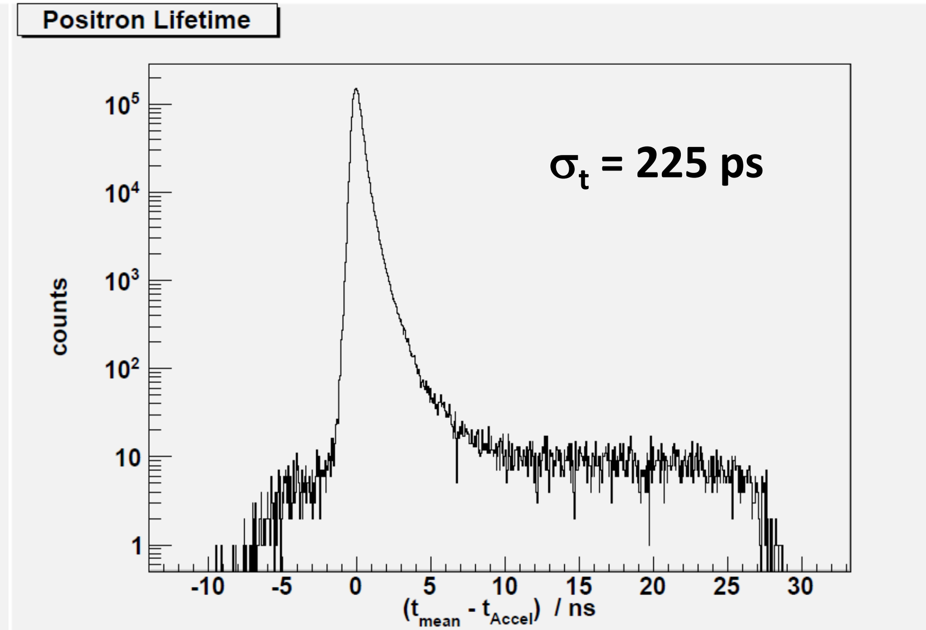


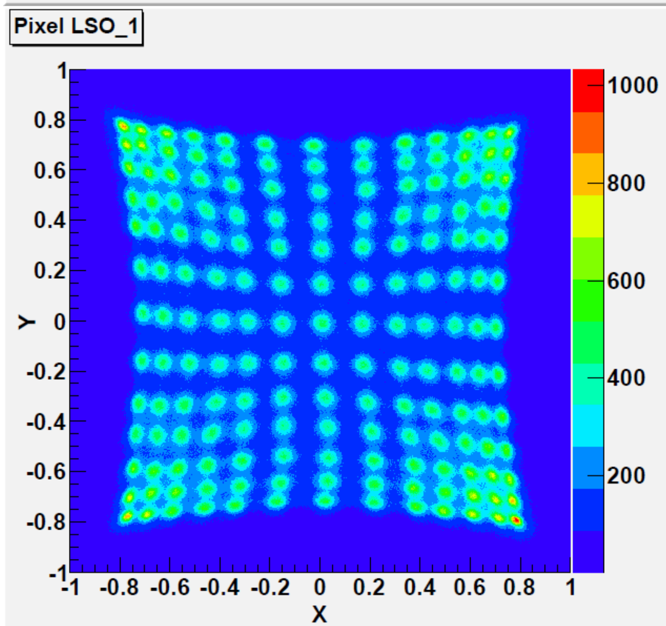


Multi-hit and multi-event buffered readout in VME block mode and readout with 10 µs dead time for 36 channels (QDC & TDC) per event.
Throughput is about 10 MB/s sustained.
Data acquisition and analysis framework using Multiple-Branch System MBS by Helmholtz-Center for Heavy Ion Research (GSI).

Calibrations







$$E = E_1 + E_2 + E_3 + E_4$$

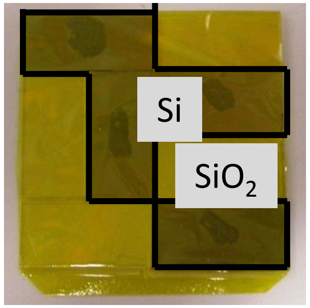
$$t = \frac{1}{4}(t_1 + t_2 + t_3 + t_4) - t_{accel}$$

$$x = \frac{(E_1+E_2)-(E_3+E_4)}{E_1+E_2+E_3+E_4}; \quad y = \frac{(E_1+E_3)-(E_2+E_4)}{E_1+E_2+E_3+E_4}$$

Calibration done using 7 cm x 7 cm aqueous ^{18}F source w/ 200 MBq ($T_{½}$ ≈ 2 h) produced in-house.

DRESDEN concept HZDR

Sample cases

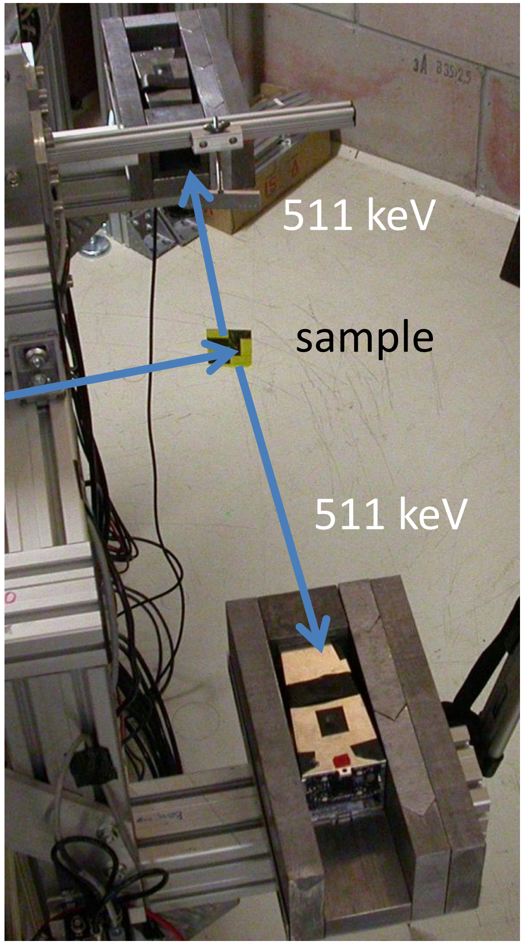


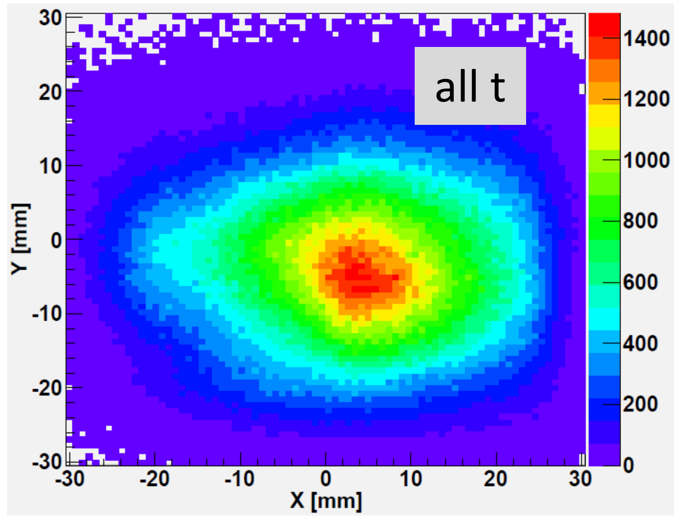
Proof of principle, first test
Simple 2D target
→ proof of principle
→ simple back-projection method

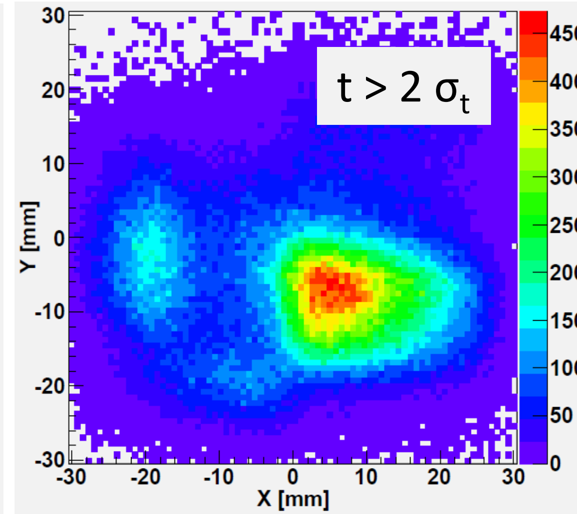
3D target
→ Reconstruction of data as a function of life time

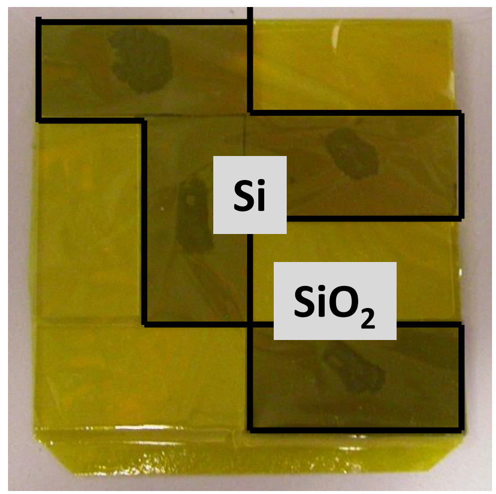
Real world sample (cutout from 91.4 T magnet coil)
→ What we can learn from our method

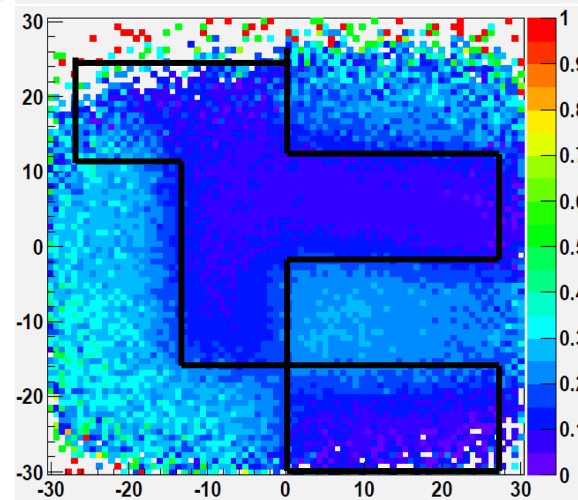
Setup and results: 2D image reconstruction







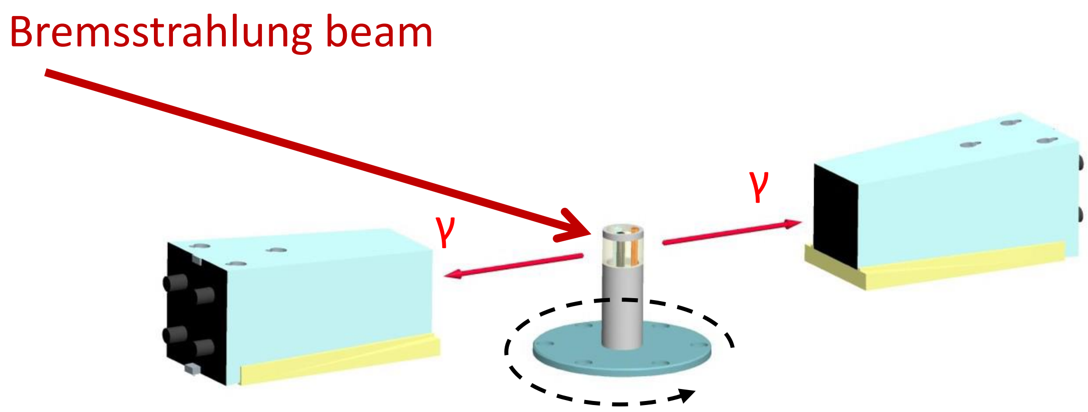




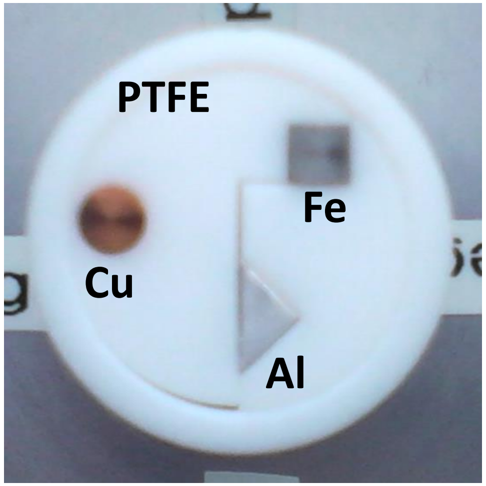
Sample selected to give balanced positron yield.

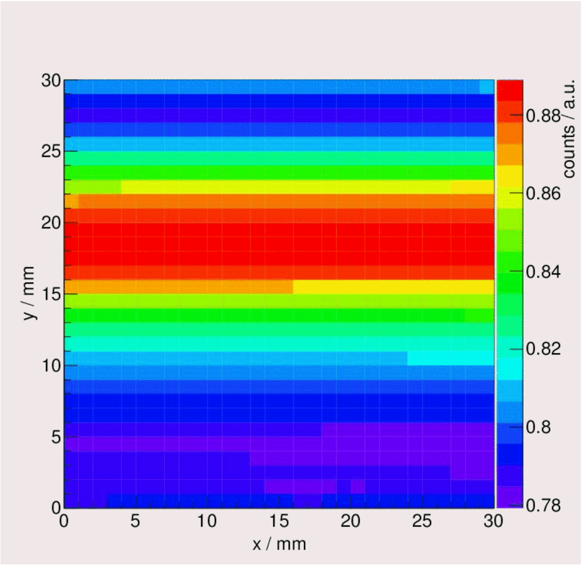
Lifetime-gated 2D reconstructed image by back-projection.

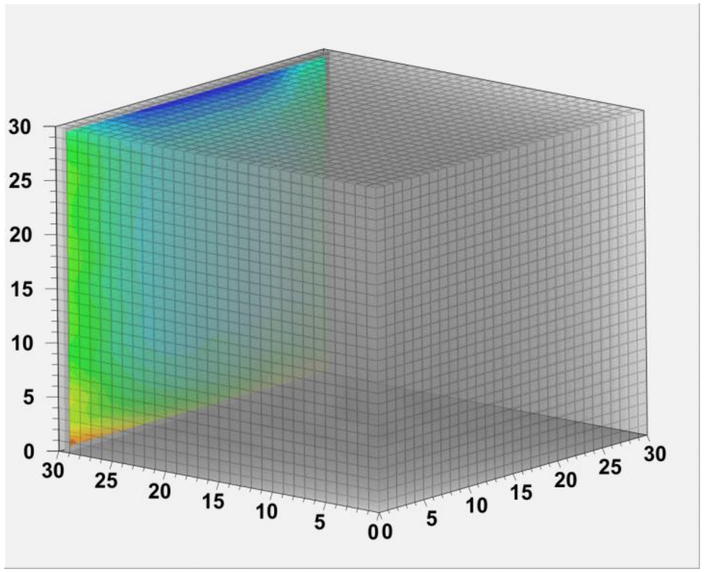
3D reconstruction



3D tomography applied for the **first time** using bulk volume positron production. Target is rotated in 2 deg. steps and the image is reconstructed using a cubical $(30\ mm)^3$ voxel space and back-projection algorithm.







Maximum Likelihood Expectation Maximization

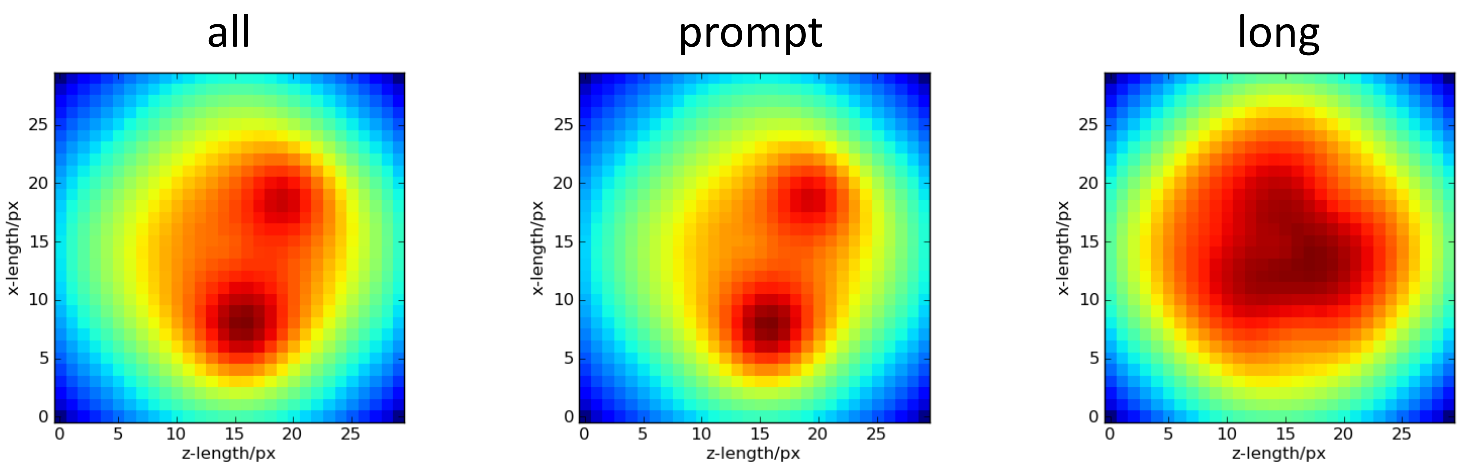
Iterative method for image reconstruction based on a algorithm developed in PET [L.A. Shepp, Y. Vardi, IEEE-MI 2 (1982) 113].

Solves the inversion problem numerically where one has a **system matrix** M, an a-priori unknown **source distribution** s and a **measured distribution** r.

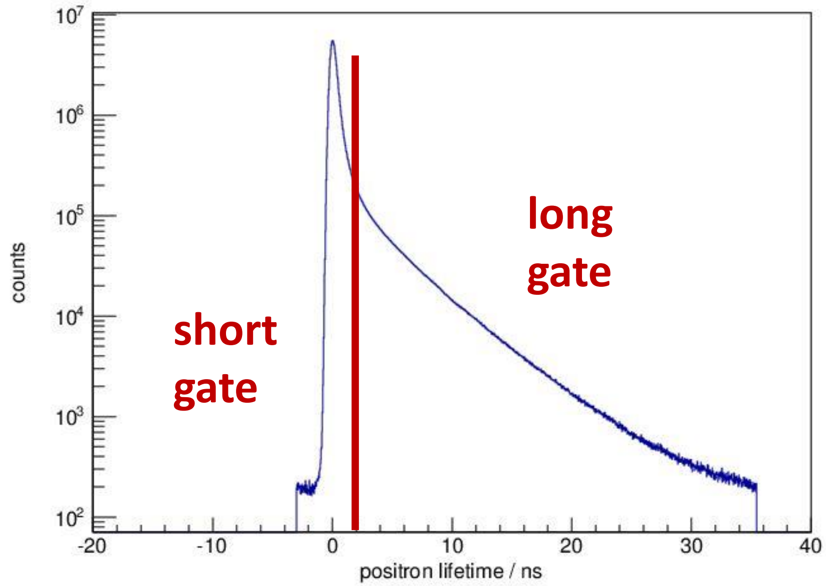
$$\hat{M} \cdot s = r$$

The system matrix has a size of $13^2 \times 13^2 \times 180 \times 30^3 = 138 \times 10^9$.

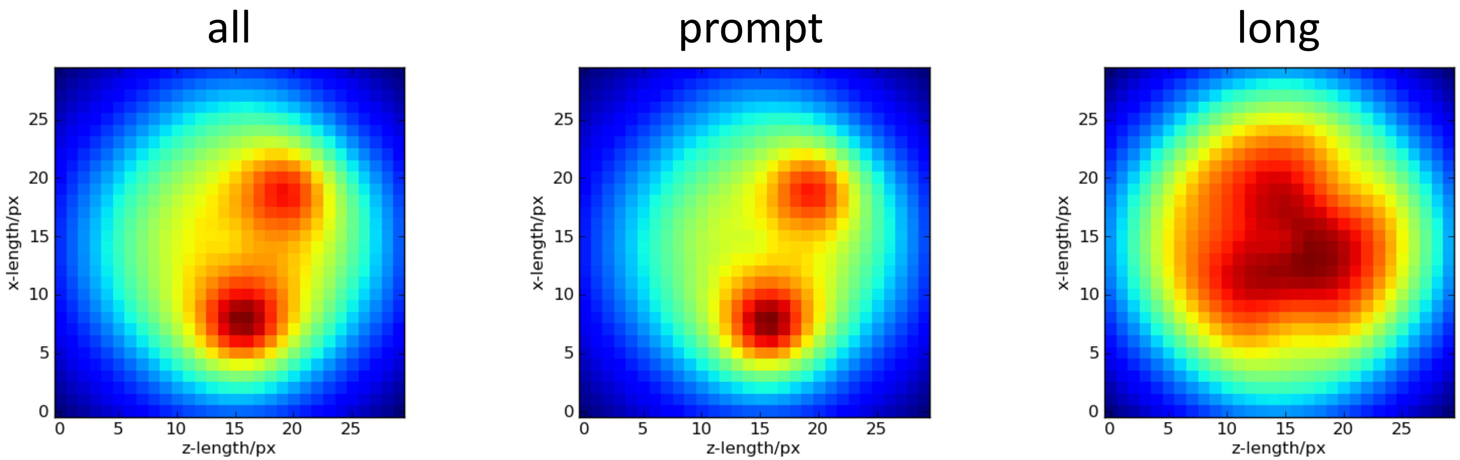
step 1



MLEM

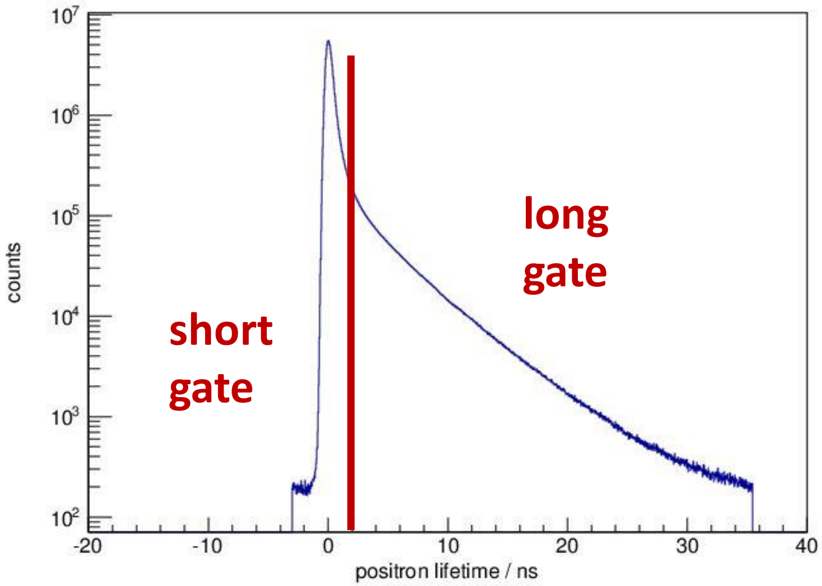


step 2

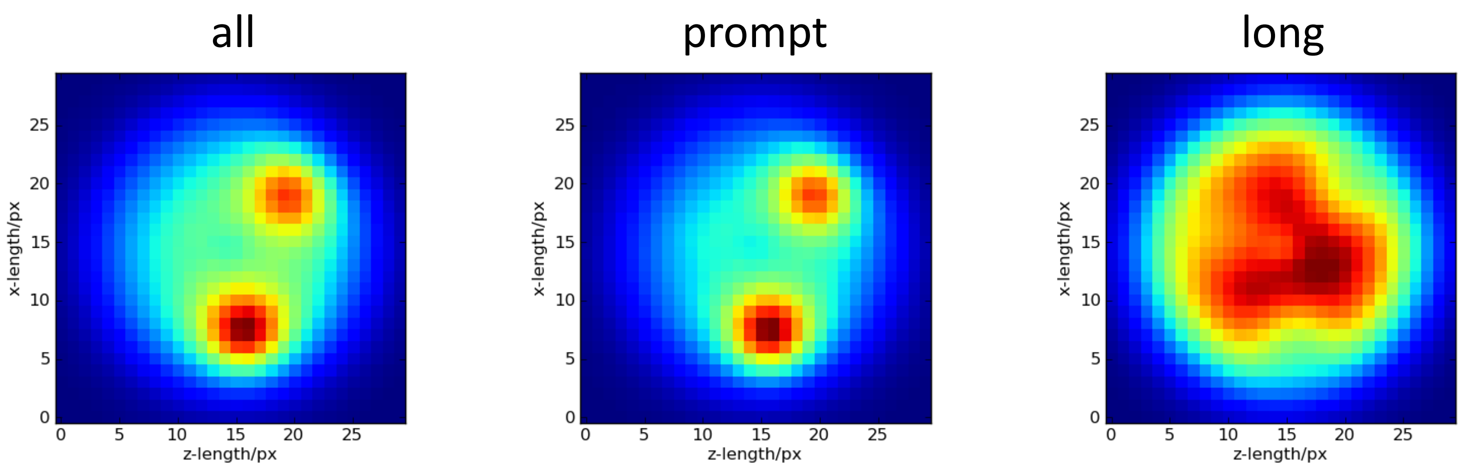


2nd Iteration

MLEM

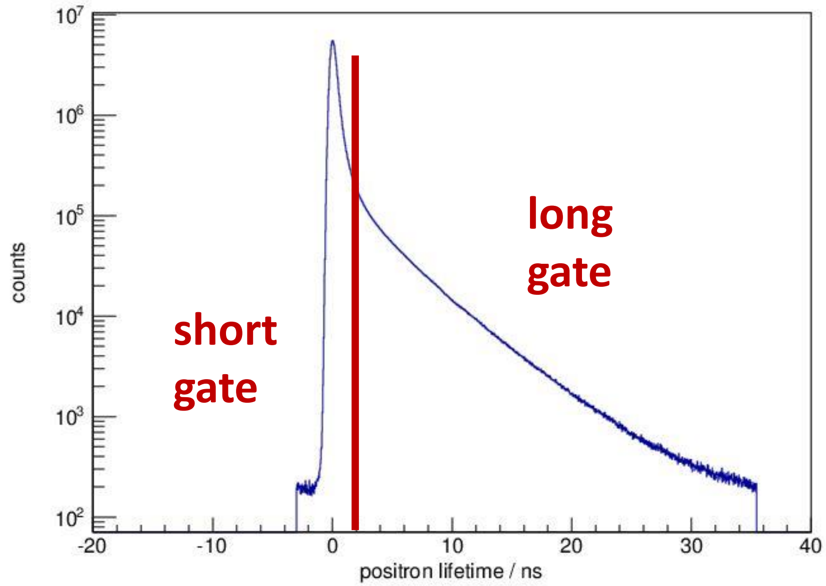


step 5

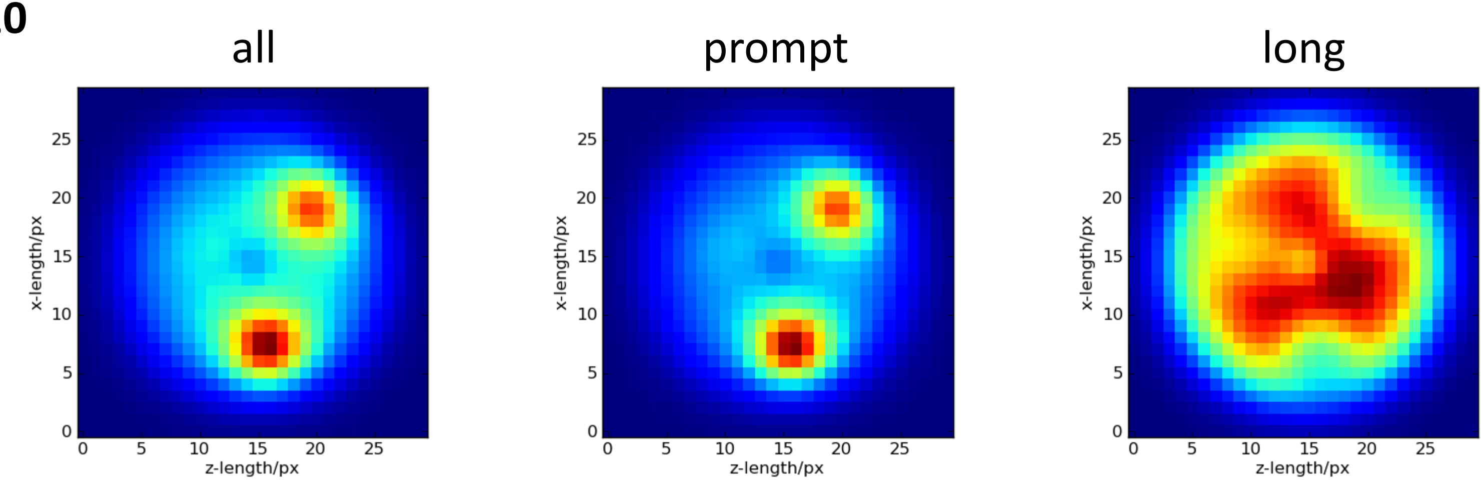


5th Iteration

MLEM

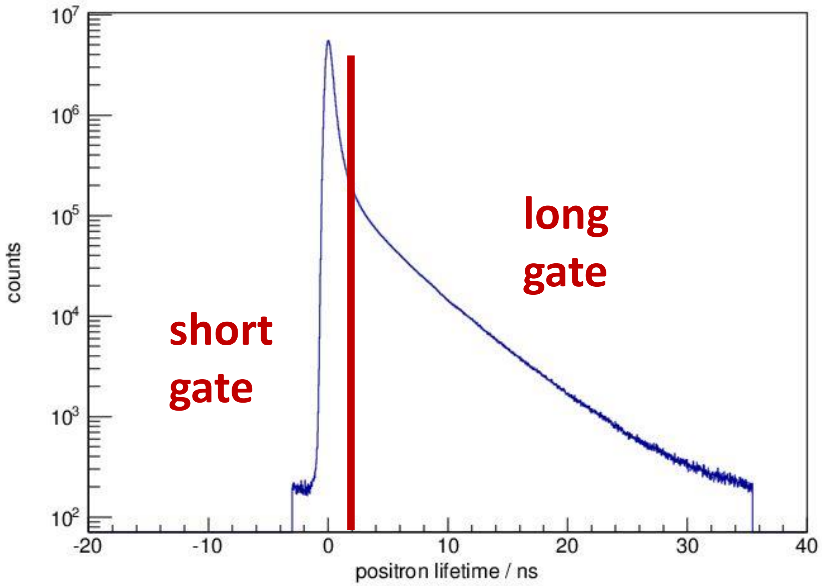


step 10

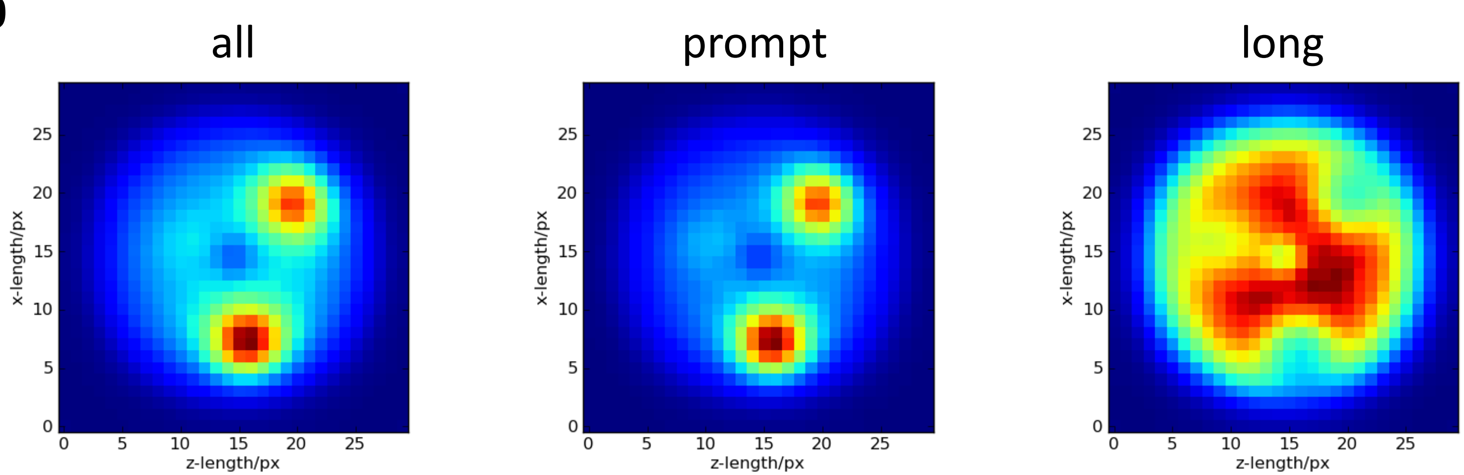


10th Iteration

MLEM



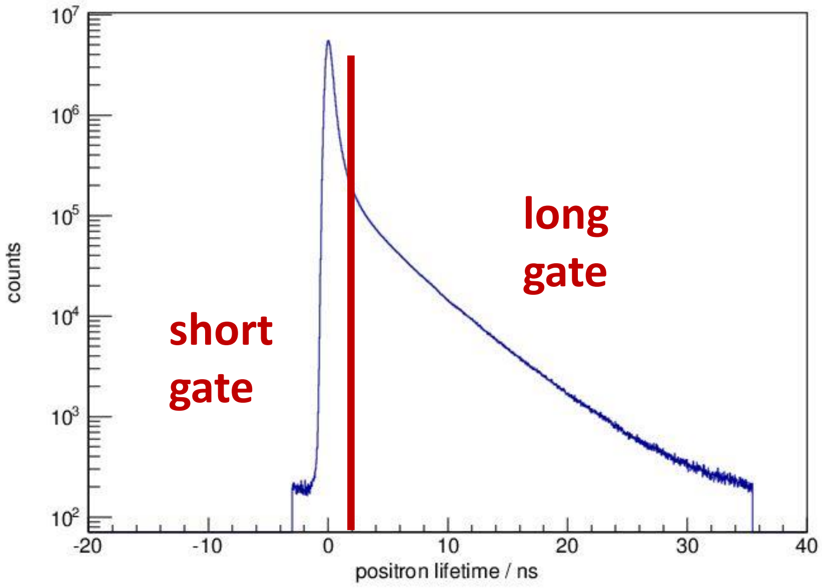
step 20

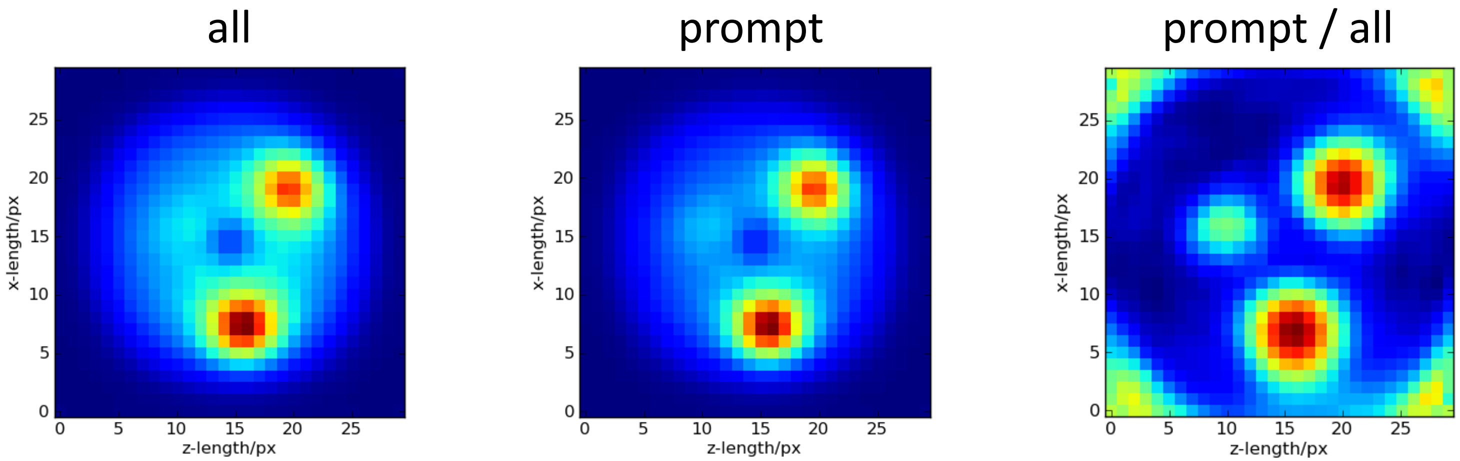


20th Iteration

MLEM


Aluminium
Steel
Copper

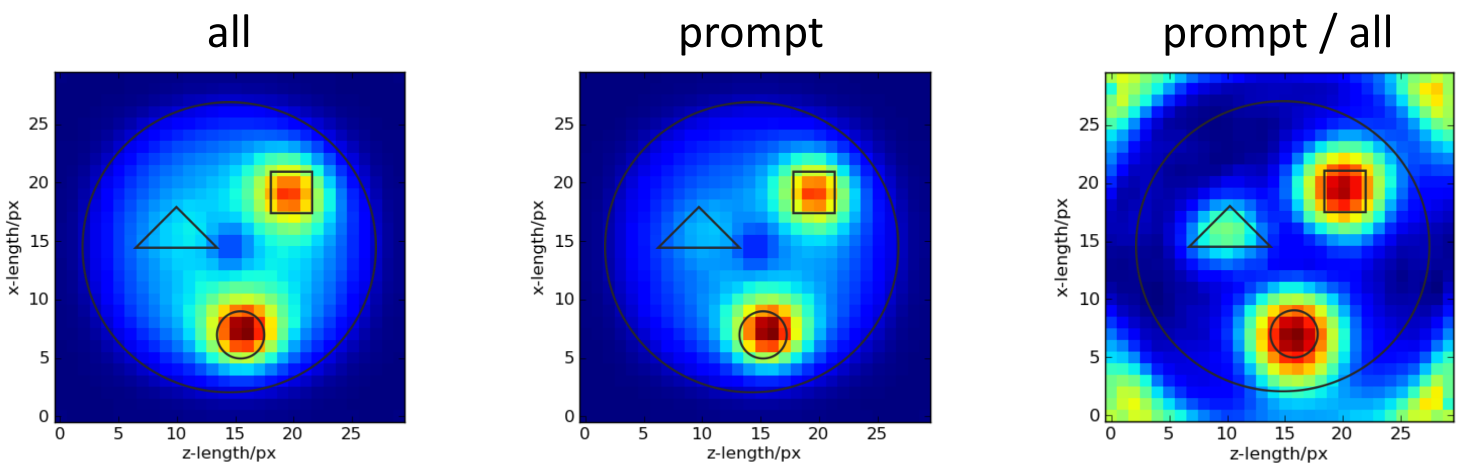

counts
positron lifetime / ns
short gate
long gate


all
prompt
prompt / all
x-length/px
z-length/px

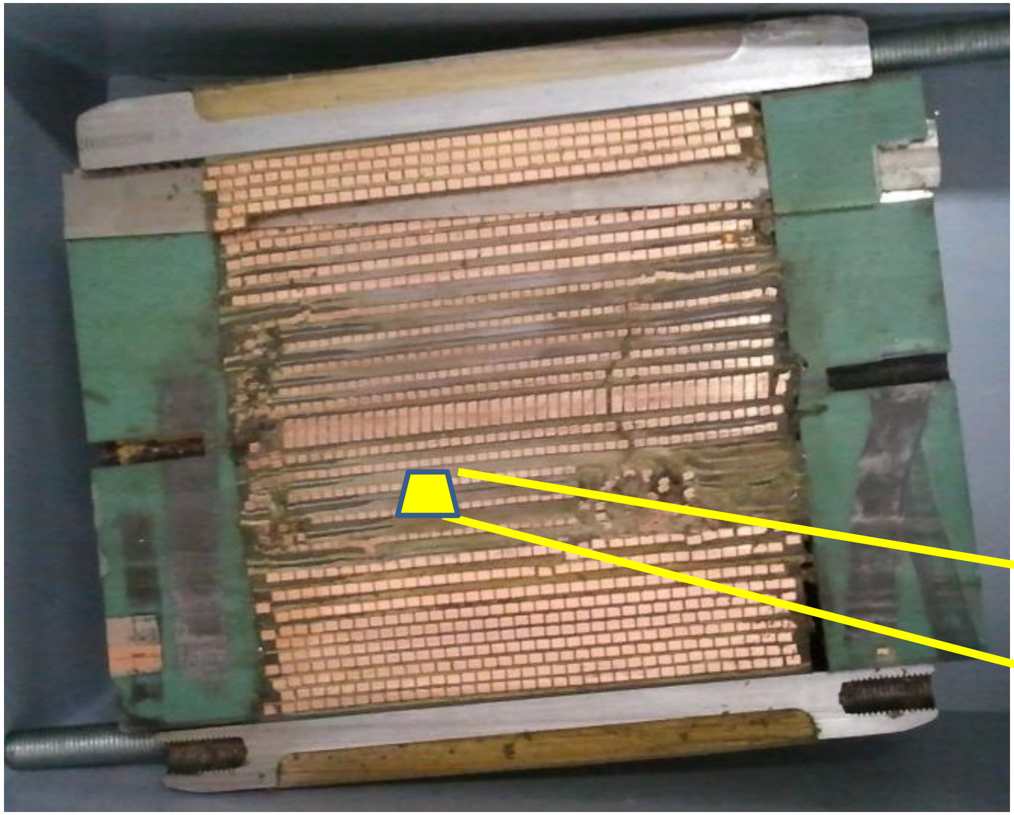
MLEM

Gating on positron lifetimes with 225 ps timing resolution.

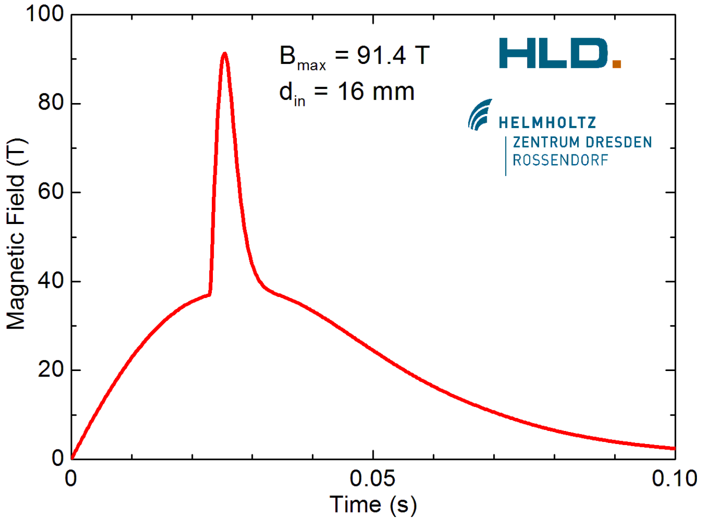
Now the Al is clearly discriminated against the surrounding Teflon.



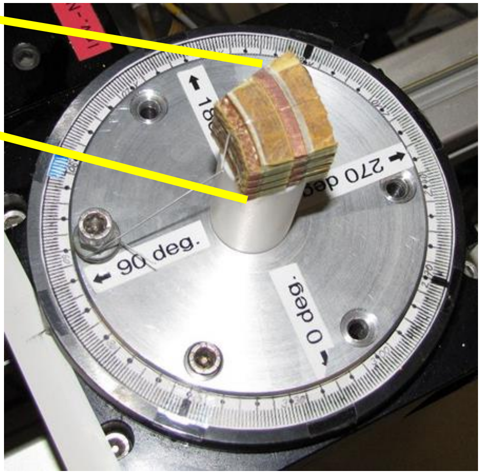
Lifetime-sensitive analysis
B-field coil



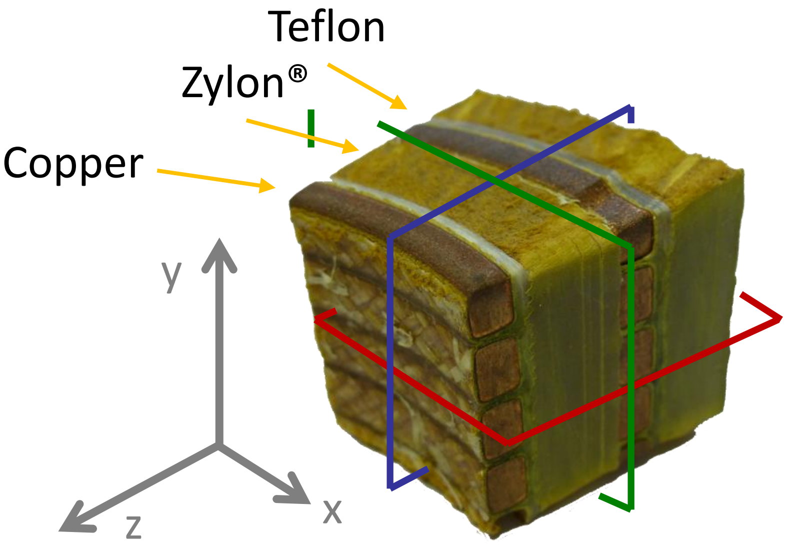
Cut through the record coil which reached 91.4 T peak field. Coil is fed by the world's largest capacitor bank w/ 50 MJ stored energy.

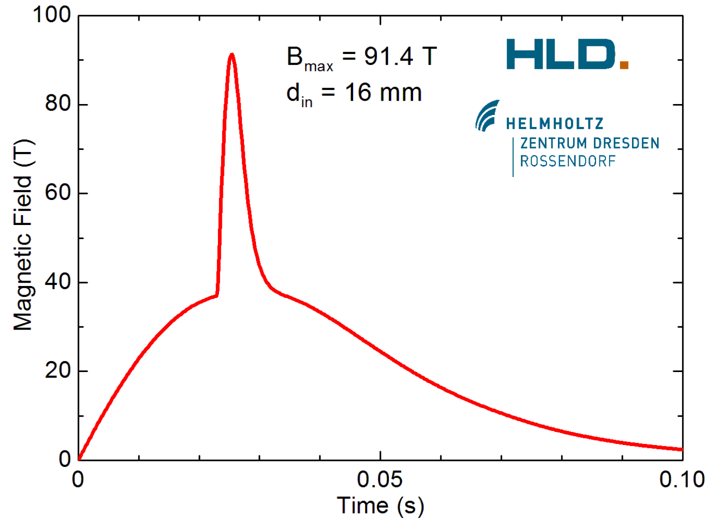


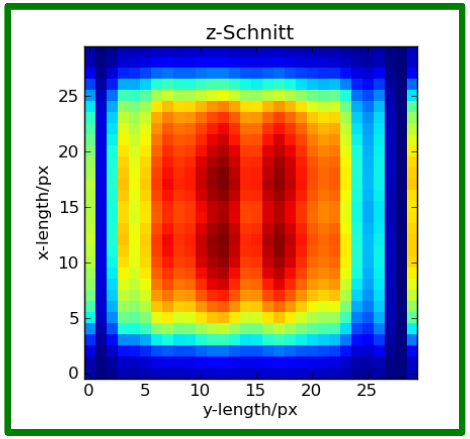
Courtesy: Jochen Wosnitza

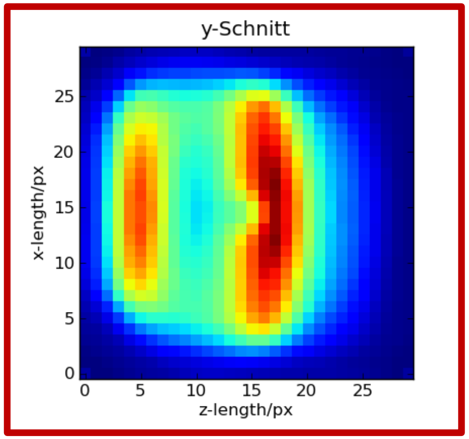


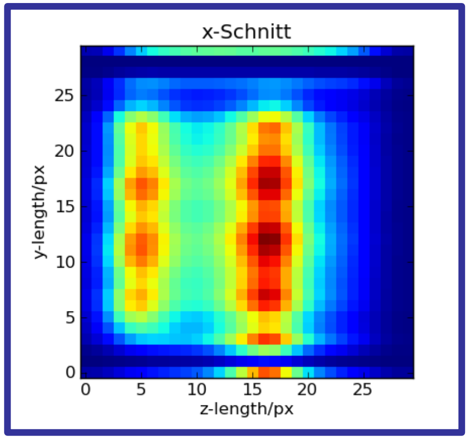
Tomography: B-field coil





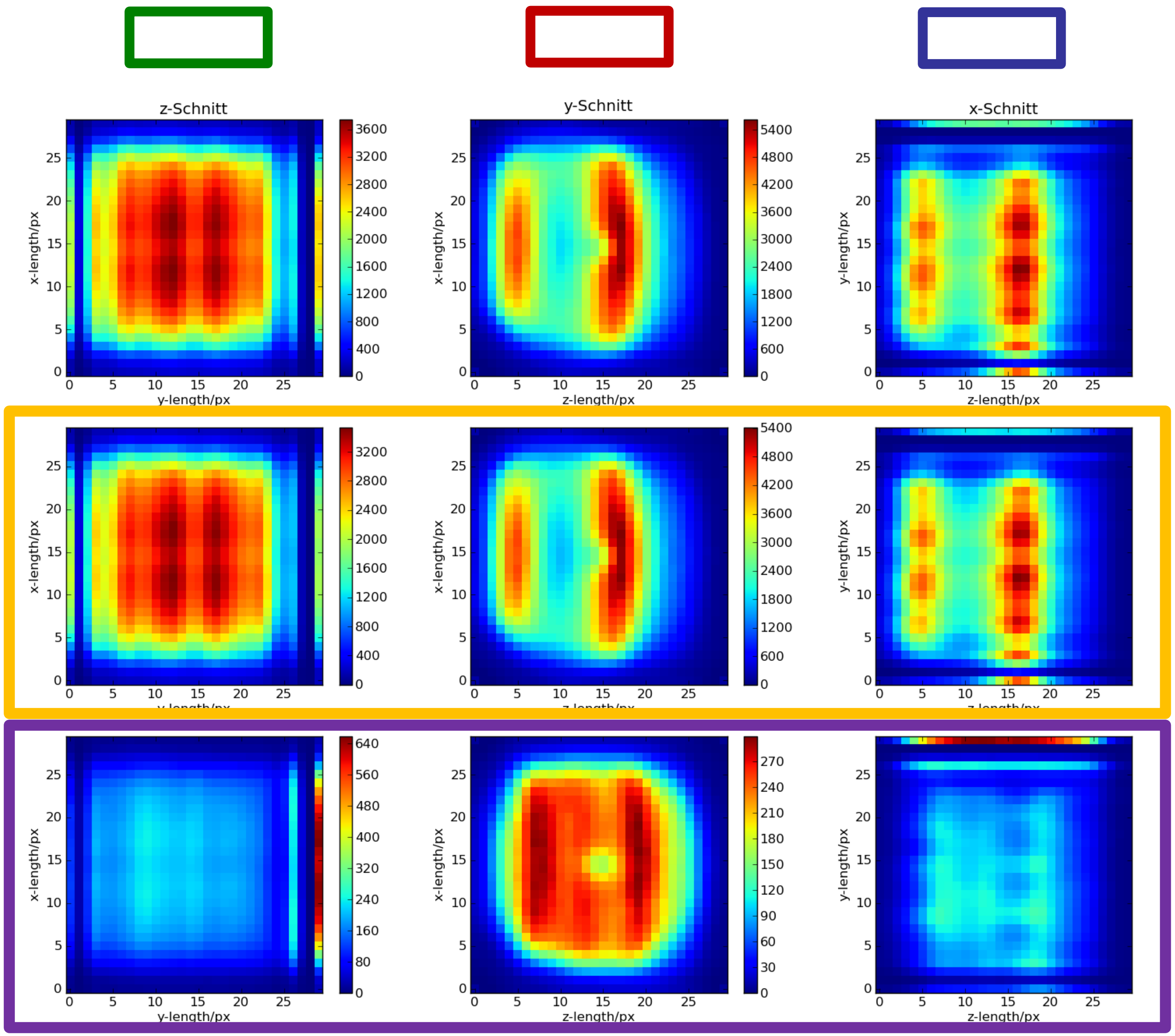


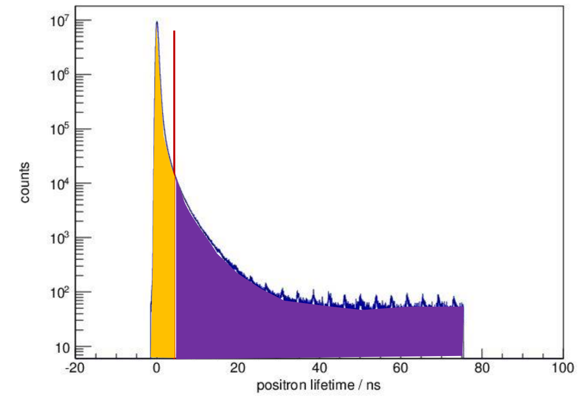


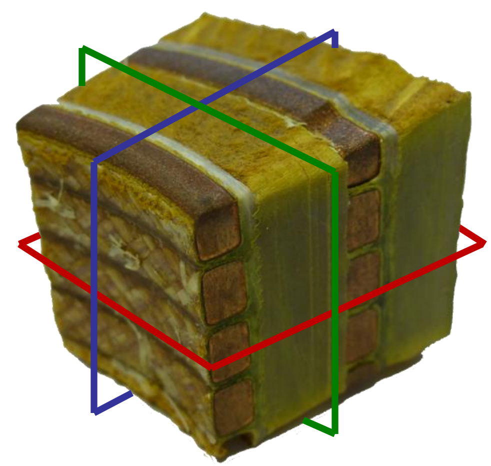


48 h measurement time, 316 GB, 1.6 G events
324 M filtered coincidences

Lifetime-sensitive analysis: B-field coil



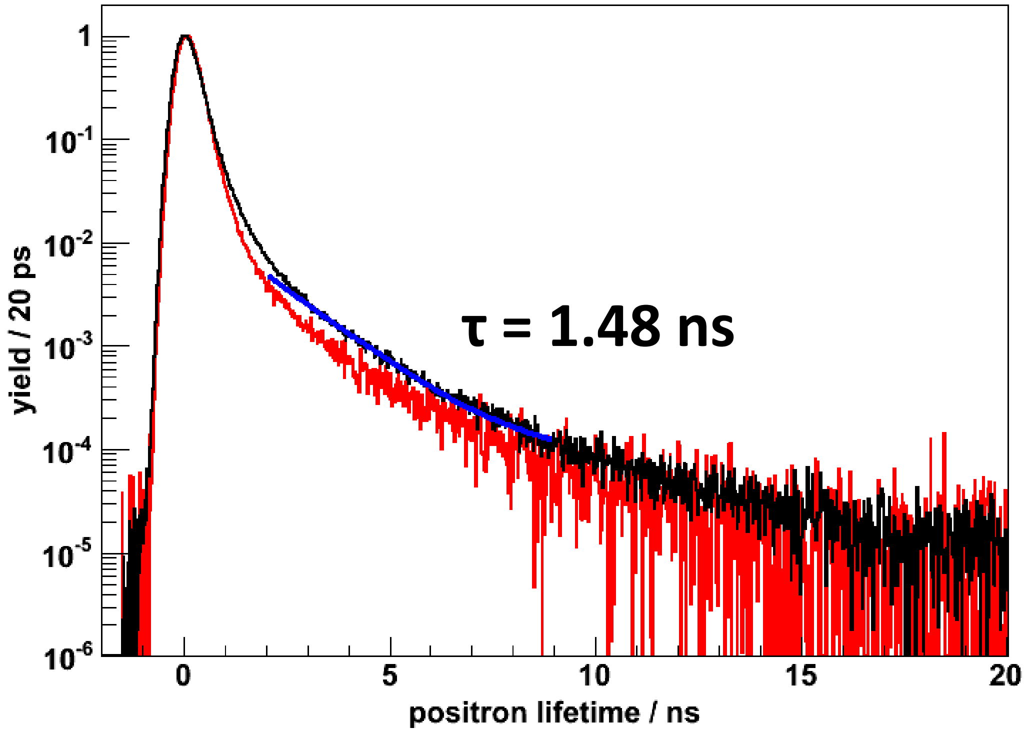


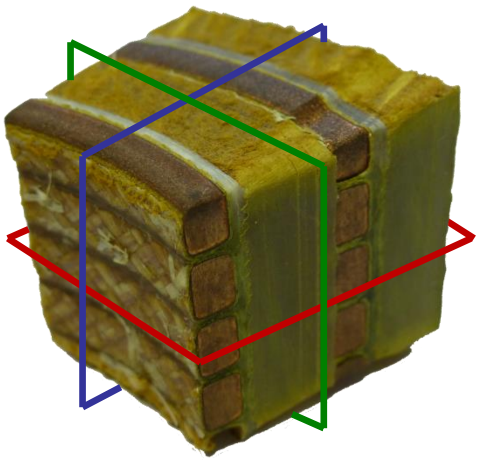


DRESDEN concept

HZDR

Lifetime-sensitive analysis: B-field coil

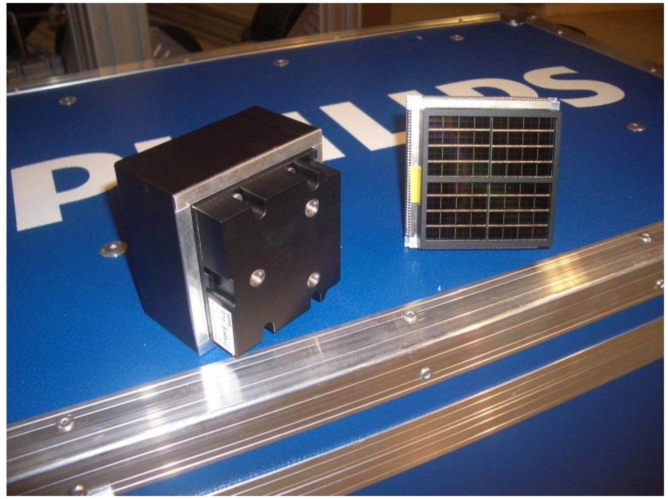


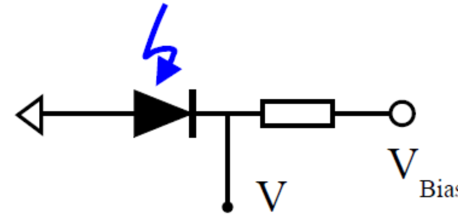


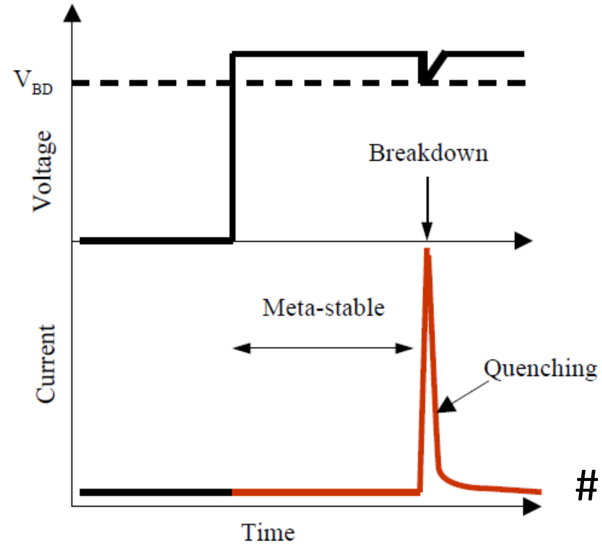
Now, we select specific voxels and determine the annihilation lifetimes for spatially separated regions. Since the voxel is identified as an ensemble over all possible lines-of-response between two detector crystals, the lifetime distribution is a convolution as well. Some real physics questions needed …

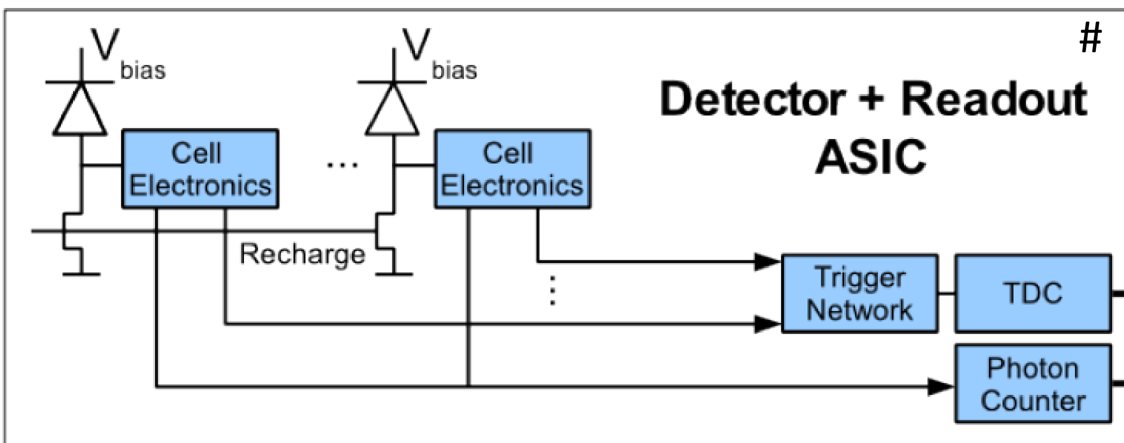
Extensions

Digital Silicon Photomultiplier (dSiPM) Module
DPC3200-22-44
(819200 pixel each)









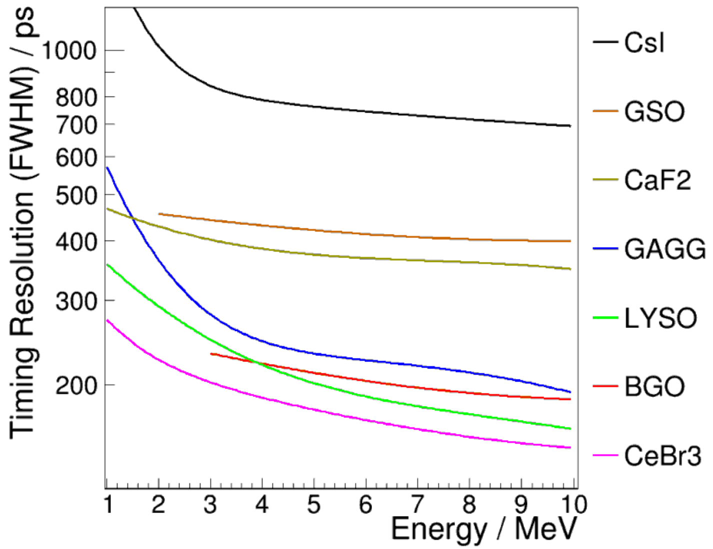
Digitally counting the number and the time of arrival of scintillation photons (here LYSO)

#Courtesy: Philips Digital Photon Counting

Extensions

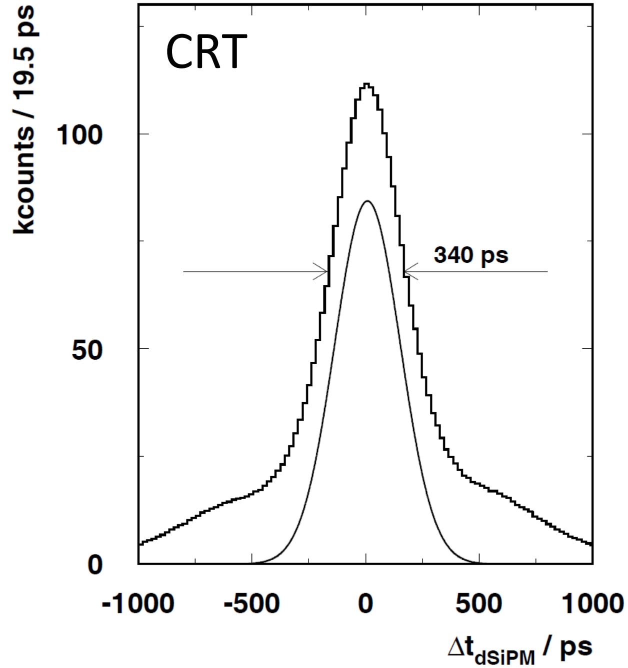
digital Silicon Photomultiplier (dSiPM)

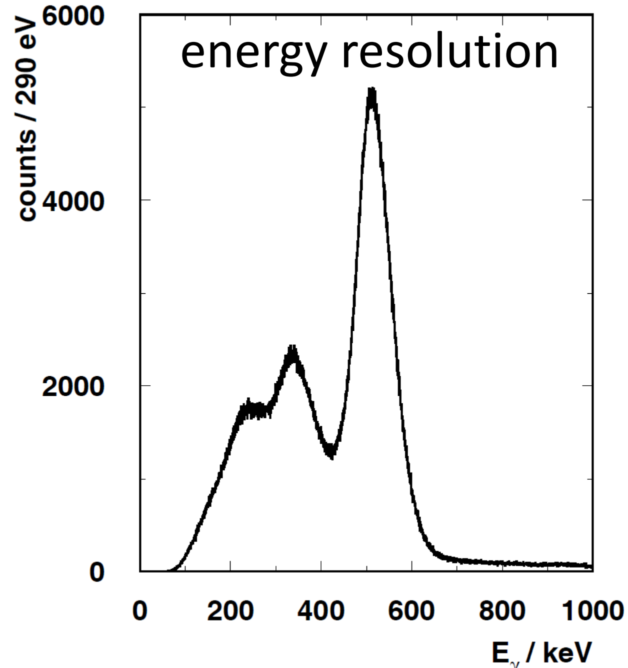
Employ the scaled accelerator radio frequency (13 MHz) via a phase-locked loop (PLL) as dSiPM system clock.
-> Intrinsic synchronization for optimal timing resolution.
-> 170 ps FWHM seem possible



Scintillation materials

Collaborative effort within gamma-ray imaging group at particle-therapy center Oncoray.
(Courtesy: J. Petzoldt, K. Römer, G. Pausch, et al.)

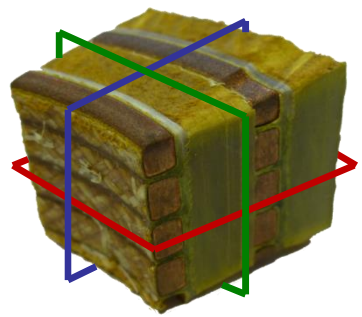


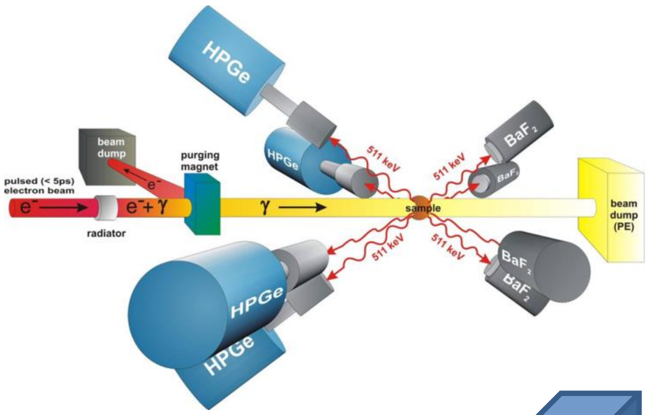


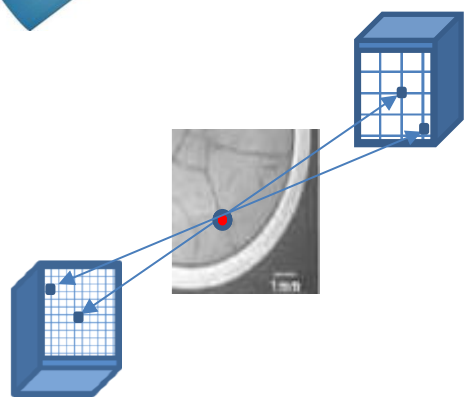
Summary

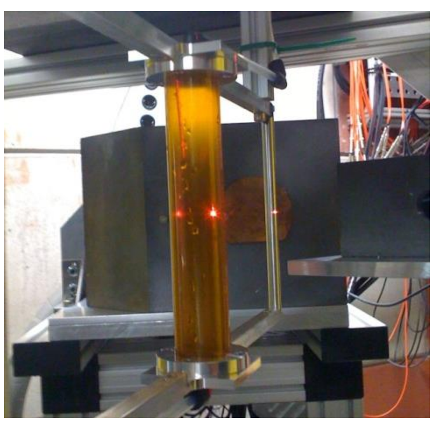
Summary:

- Accelerator-driven positron production
- Annihilation lifetime spectroscopy for fluids, reactor materials…
- First results for 3D tomography









The team

Apply for beam time: deadlines 1st weeks in May and November

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Maik Butterling

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Fine Fiedler

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P. Fobe

and all the collaborators

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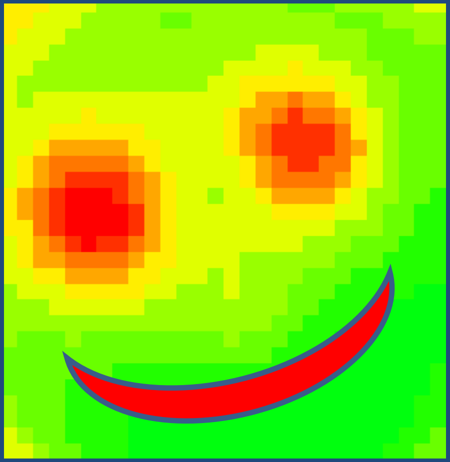
S.V. Stepanov, D.S.Zvezhinskiy (ITEP, MEPhI)



Thank you for attention