Positron annihilation studies using the superconducting electron LINAC ELBE @ HZDR

R. Krause-Rehberg, A. Wagner

- ELBE = Electron LINAC with high Brilliance and low Emittance
- MePS = Mono-energetic Positron source
- GiPS = Gamma-induced Positron Source
- User-dedicated Positron Facilities in Germany (FRM-II & ELBE)
• electron beam repetition frequency 26/2^n MHz
• pulse width 5 ps
• 34 MeV, 1.6 mA cw mode → 54 kW
ELBE facilities

1.6mA, 40MeV CW electron accelerator

coherent IR-radiation
3 – 230 μm

coh. THz radiation
100 μm – 3 mm

neutron time of flight
$E_n$ 0 – 10 MeV

ELBE electrons
10 – 34MeV

Bremsstrahlung
0 – 17 MeV
bulk sample positrons

pulsed, mono-energetic positrons
0.2 – 30 keV

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

electron laser interaction

GiPS

MePS

Thermo-ionic electron source at ELBE

- working principle of triode
- 250 kV DC voltage
- pulse length 500ps → 11cm
- energy 250 keV
- bunch charge up to 120 pC @ 13 MHz
- but cannot be larger, also not for reduced repetition time

→ $I_{beam}$ up to 1.6 mA for 13 MHz
Superconducting LINAC – Beam Generation

**thermal-ionic gun**
- 250 kV DC
- 13 MHz pulsed grid

**injection**
- two RF bunch compressors, apertures, macro pulse generator

**linac 1**
- DE $\sim$17 MeV
- @ 10 MV/m CW

**linac 2**
- DE $\sim$ 19 MeV
- @ 10 MV/m CW

**Bunch length:** 500 ps

**Time structure:**
- **beam**
  - (a) CW
  - (b) macro-pulsed

- 0...77 pC bunch train (480 Mio electrons)

- 0.1...36 ms pulse length
- 40 ms...1 s period
- 1E-4...0.9 duty cycle

- 1.5...10 ps bunches
- 4 ns...10 µs period

**Helium Liquifier LINDE**
- 200 W @ 1,8 K

Martin-Luther-Universität Halle
HZDR in house developed CW superconducting accelerators

Two 1.3 GHz 9-cell TESLA cavities inside a 1.8K helium vessel

250 keV, 1 mA, $\beta=0.74$

20 MeV $\cdot$ 1 mA = 20 kW, $\beta \approx 1$

RF power input, fed by two 10 kW klystrons
Positrons from accelerators

- Bunch length can be adjusted according to lifetimes to be measured
- SC accelerators may provide CW mode - are very useful
EPOS (ELBE Positron Source)

**MePS**
Monoenergetic Positron Spectroscopy
- monoenergetic (slow) positrons
- pulsed system
- LT, CDBS, AMOC

**Information Depth:** 0...5 μm

**CoPS**
Conventional Positron Spectroscopy
- LT, CDBS, AMOC
- using $^{22}$Na foil sources
- He-cryostat
- automated system
- digital detector system (in future)

**Information Depth:** 10...200 μm

**GiPS**
Gamma-induced Positron Spectroscopy
- Positron generation by Bremsstrahlung
- Investigation of bulky samples (up to 10 cm³)
- all relevant positron techniques (LT, CDBS, AMOC)

**Information Depth:** 0.1 mm ... 2 cm
What is the optimum electron energy for positron generation?

- positron yield is strong function of electron energy
- however: mean positron energy increases strongly

![Graph showing positron yield and mean positron energy vs. electron energy](image)

\[ Y \left[ e^+ / 10^9 e^- \right] = 3.319 \times 10^{-4} \left( E_{e^-} [\text{MeV}] \right)^{3.327} \]

- mean positron energy is about 1/5 of electron energy for \( E_{e^-} > 100 \text{ MeV} \)
- moderation efficiency drops strongly at high \( e^+ \) energy
- there must be an optimum energy
- MC simulations required including moderation
What is the optimum electron energy for positron generation?

- Relative yield of positrons as a function of the incident electron energy.
- The yield of total positrons increases virtually continuously (closed squares).
- The number of thermalized positrons appears to approach saturation at about 60 MeV both for reflected moderation (filled circles) or transmitted moderation (open circles).

SLOPOS-12 (Magnetic Island, Australia) talk of Sergey Chemerisov, Chemistry Division, Argonne National Laboratory
MePS: Monoenergetic Positron Source

Flux: $1.2 \cdot 10^6$ e$^+$/s on sample

- max 500 V/cm
- max 2.5 kV/cm

20 cm Pb + 3.2 m concrete shielding

SC-LINAC beam
- 30 MeV, 0.1 mA
- 1.625 MHz repetition rate
- 615 ns spacing

4 ns chopper
78 MHz buncher
Sample

2 keV magnetic transport system

30% HPGe detector for DBS
BaF$_2$ detector for PALS

post-accelerator
-1.5 ... +20 kV
Improvement of spectra quality

Low-k dielectric layers (500nm)
$E_e = 5$ keV

2011

Porous glass

2017

Measured by an analogue System using ORTEC modules
Porous polymer sample

Area: 25 Mio. counts in 8 min
≈ 50 000 counts/s
FWHM ≈ 196 ps
E⁺ = 8 keV
5 ps/ch
Electron beam power = 3.6 of 54 kW

Digitizer: ADQ14-DC for MTCA Form factor
Teledyne SPDevices
14 bit resolution, 2 GS/s, 1.2 GHz analogue bandwidth
1 CPU core = Maximum count rate ≈ 5×10⁴ /s
Possible count rate with hyper-threading is expected to be > 5E5 /s

Advantages of dPALS

Timing with 10⁻⁶ accuracy
Nothing to be adjusted/calibrated
Main advantage: 5 ps/ch possible even for 2 µs long spectra (for 14 bit-MCAs @ 2µs only 122 ps/ch)
AIDA-II at MePS Beamline

- AIDA = Apparatus for in-situ Defect Analysis
- Will be on top of MePS lab
- UHV system for surface analysis and treatment (ions, wide T-range, XPS, positron lifetime)
- Layer deposition
- Time schedule:
  - 2017: beam switch tested
  - April 2018: positron beam tests (resolution, intensity …)
  - End of 2018: setup finished
AIDA-II at MePS Beamline
AIDA-II at MePS Beamline

XPS analysis and PALS chamber
- Positrons are generated in the whole sample volume
- Up to 2cm diameter
- Volume of large samples are completely measured
- Useful for liquids, coarse powders, radioactive samples...
- In spite of scattered original gammas the Peak-to-BG is up to $10^{-5}$
- One has to measure AMOC spectra in 12...24 h
GiPS: Gamma-induced Positron Spectroscopy

- Positrons are generated inside the sample
- Coincident measurement → no problem with scattered gammas from sample

$E_e = 16$ MeV

$I_e = 900$ $\mu$A

$f = 26$ MHz

$\sigma_t < 10$ ps

studies performed so far:
- animal tissue
- metals and alloys
- semiconductors
- (neutron-activated) reactor materials
- water, glycerol from 10°C to 100°C

- total count rate in GiPS spectrum: $12 \times 10^6$
- Extremely clean spectra
- FWHM $\approx 160$ ps
- Peak-to-BG $> 10^5$

**Example: Water at RT**

- M. Butterling et al., Nucl. Instr. & Methods 2011, Volume 269, pp. 2623
• Neutron irradiated steel from reactor vessel steel shows $^{60}$Co activity
• Conventional lifetime takes up to 14 days in triple coincidence
• Due to HPGe coincidence at sharply 511 keV with BaF2 detector: high statistics and low background
User-dedicated intense Positron Sources in Germany

- Two intense positron sources available (positrons by pair production)
- **NEPOMUC** (NEutron induced POsitron Source MUniCh) at FRM-II
  - PLEPS (monoenergetic positron lifetime system)
  - PAES (Positron-induced Auger Electron Spectroscopy)
  - CDBS (Coincidence Doppler Broadening Spectroscopy)
  - SCM (Scanning Positron Microscope)
  - user beam line
- **EPOS** (ELBE Positron Source) at Helmholtz Center Dresden-Rossendorf
  - MePS (Mono-energetic Positron Spectroscopy)
  - GiPS (Gamma-induced Positron Spectroscopy)
  - CoPS (conventional setup using 22Na sources)

- at both sites: web-based application system for beam time
- Next date at ELBE is 9. April 2018 (contact me for help)
Conclusions

• A superconductive LINAC is an ideal positron source due to unique time structure
• Optimum electron energy is 40...60 MeV
• Electron beam repetition time can be adjusted according to positron lifetime (38 ns .... 1.3 µs)
• **MePS:**
  o 1 µs bunch length is possible without intensity losses: 5...10×10^4 cps possible now
  o Digital positron lifetime for high count rates available
• **GiPS:**
  o high-quality spectra possible for bulky, radioactive or liquid samples
  o All data measured as AMOC spectra

This presentation can be found soon as pdf-file on our Website:
http://positron.physik.uni-halle.de
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http://positron.physik.uni-halle.de
The GiPS setup includes 8 Detectors (4 Ge and 4 BaF$_2$)
Digital positron lifetime measurement

- simple setup
- timing very accurate
- each detector for start & stop (double statistics)
Screenshot of two digitized anode pulses

Time difference = 2.65471 samples = 663.67 ps