中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

Progress of positron detection technology in IHEP and applications

Baoyi WANG
(王宝义)

Institute of High Energy Physics (IHEP),
Chinese Academy of Sciences

PPC-12@Lublin, 2017

Email: wangboy@ihep.ac.cn

Positron & IHEP

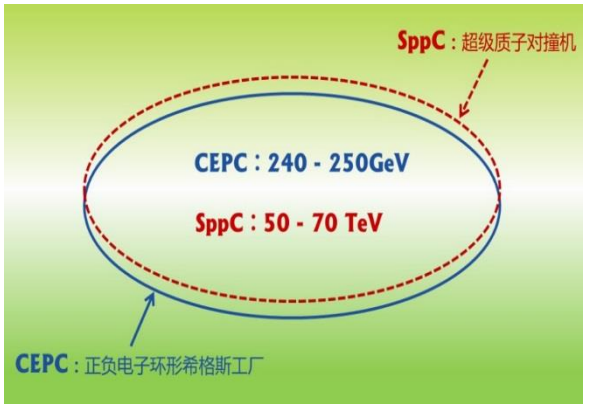
Positron discovery

Zhao Zhongyao (1902—1998)

BEPC

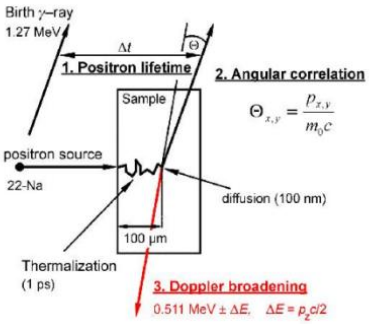
Beijing electron positron collider (1984)

CEPC

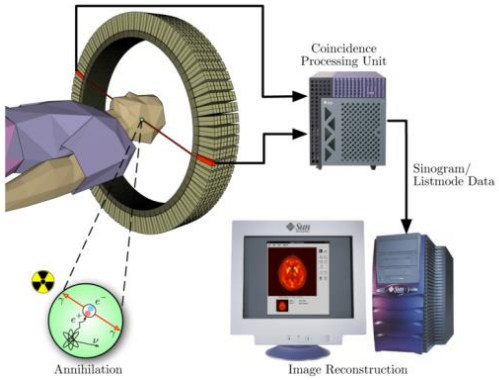


Circular Electron Positron Collider (~2022?)

IHEP

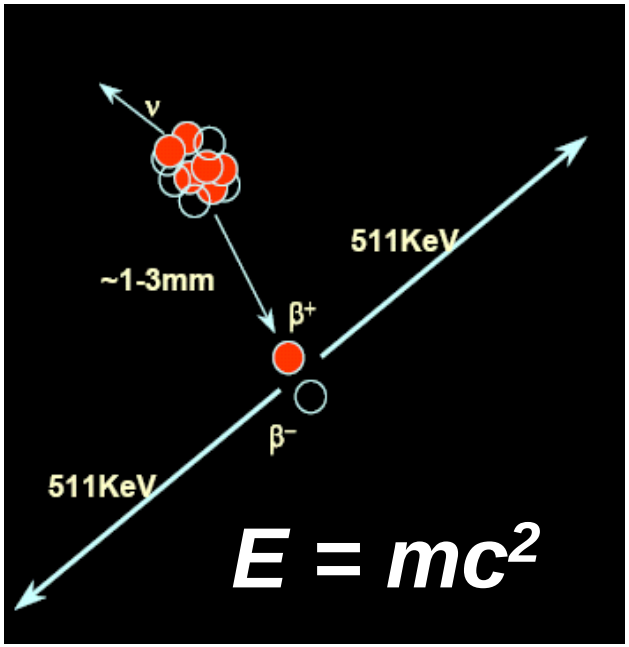


Positron Annihilation



Positron imaging

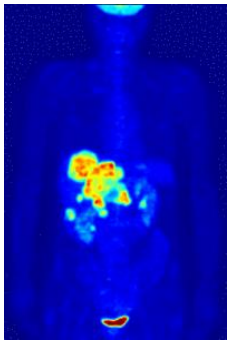
Detection of Positron Annihilation Radiation (γ rays)



To measure the properties of positron / electron at annihilation site –
e⁺ Spectroscopy

Applications：Material Science

To measure the locations of positrons at a time –
e⁺ Imaging



Applications：Medical Science

The Positron Group in IHEP

- **Measurement techniques for positron annihilation**
- **Slow positron beam**
- **Application research in material science**
- **Technology support on Gamma-ray detection for nuclear imaging**

Part I

Techniques for Positron imaging in iHEP

Positron Emission Tomography (PET)

- **Dedicated PET systems**
- **PET related technologies**

Imaging

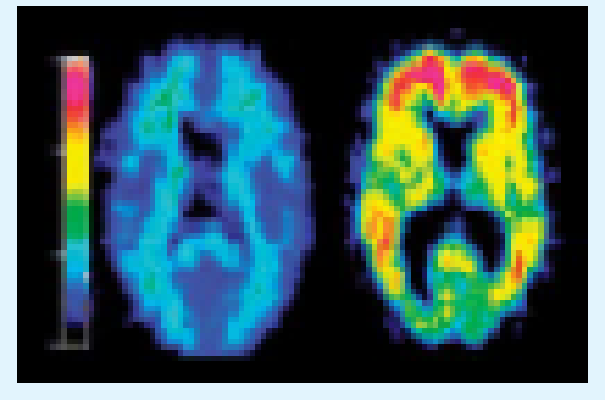
the first X-ray taken in the late 1890s by Wilhelm Roentgen of his wife Bertha's hand

Seeing is believing! A picture's worth a thousand words —and a thousand data points too.

Nothing conveys information to the human eye like a picture!

Nuclear Imaging

CT, MRI images reflecting the structural information body of (density distribution)



- nuclear imaging technology used in clinical diagnosis achieve a true sense of the word "functional" imaging
- obtain a wide range of applications. Disease early diagnosis and treatment

The image at left shows amyloid plaques in the brain of a patient with Alzheimer's disease. It was produced using positron emission tomography (PET)

PET

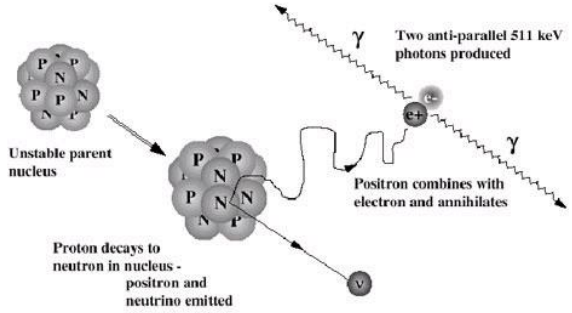


Figure 1.1. Positron emission and annihilation.

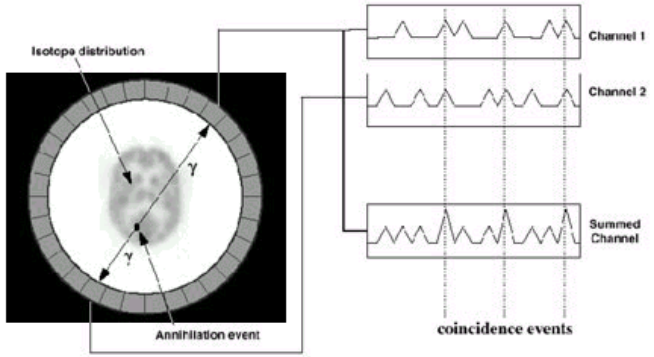
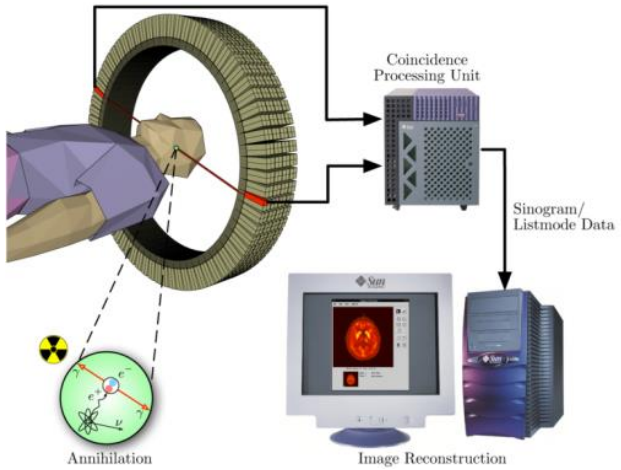
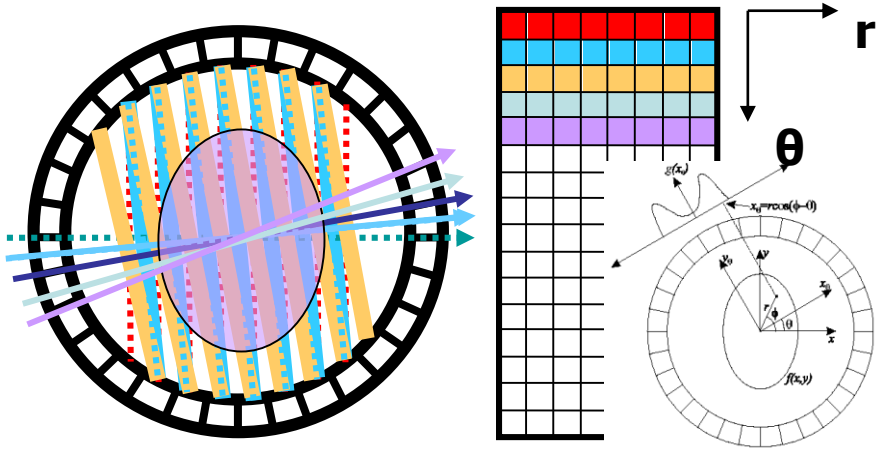


Figure 1.2. Coincidence detection in a PET camera.





Sinogram

Projections and Sinogram

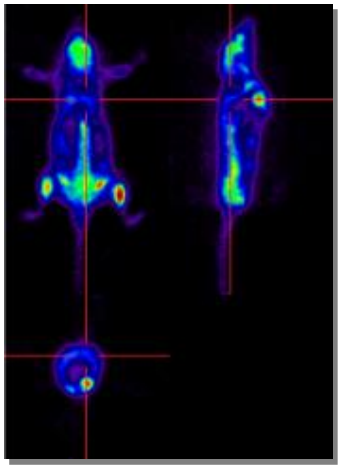
PET and related technologies @IHEP

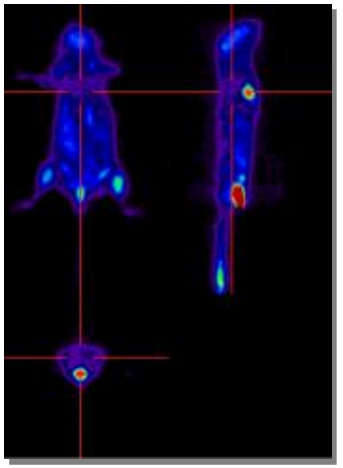
PET and PET-related imaging projects

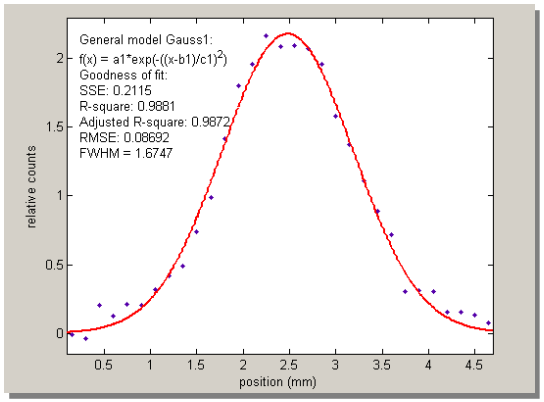
- Development of Multi-modality animal PET/SPECT/CT system
- Development of dedicated breast-PET scanner (PEM)
- Research on spatial and timing properties of new scintillators
- Research on PET Based on Time-of-Flight Technology (TOF-PET)
- Research of Scintillation Detector with High Spatial resolution and DOI ability (DOI-Detector)
- Research on PET detector working in magnetic fields

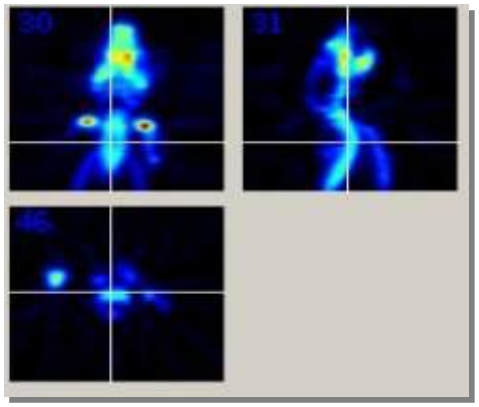
Animal PET Scanner

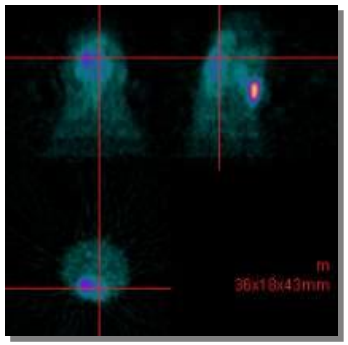
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

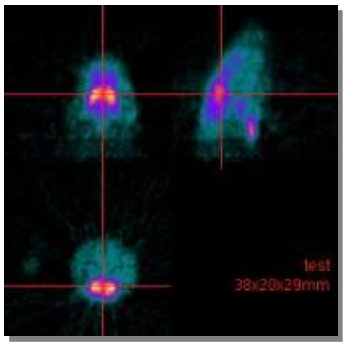


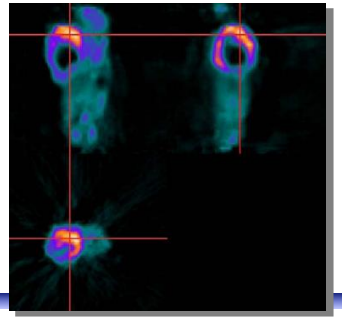




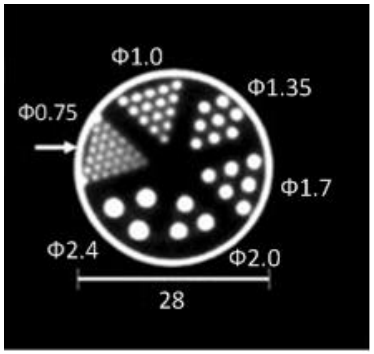


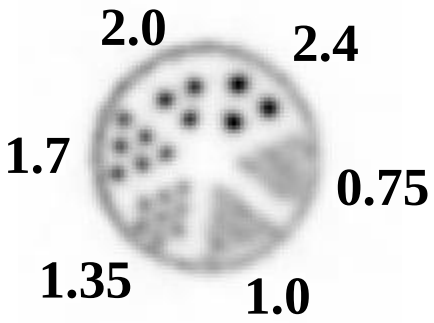






PET and related technologies @IHEP



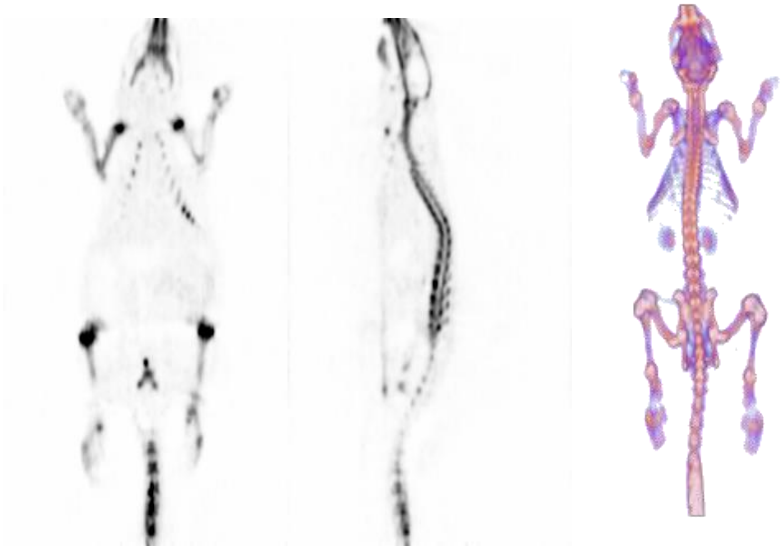


Derenzo Phantom Imaging

- Sealed phantom with FDG
- 0.5 mCi activity

Rat, 200g , 2.1 mCi of $^{18}F^-$

scanned for 20 min per bed in four bed positions



Bone imaging of a rat

Small Animal PET @ IHEP

An animal PET scanner and a PET/CT scanner were developed by IHEP for metabolic and anatomic imaging of rodents and small primates in the 2010.

Diameter of detector	**166 mm**
Diameter of Entrance	**~160 mm**
Transverse FOV	**110 mm**
Axial FOV	**64mm or 96mm**
Spatial Resolution	**< 2mm**
Sensitivity	**Better than 2.28%**
X-ray Source Max Output	**90KV, 8W**
Focal Spot Size	**5um(min)**
Diameter of CT Active Area	**60mm**
CT Resolution	**~80um**

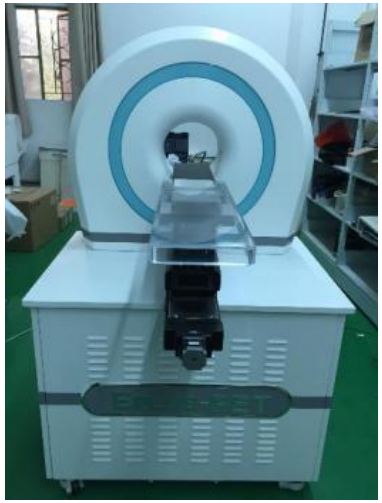
Molecular Imaging Systems@IHEP

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

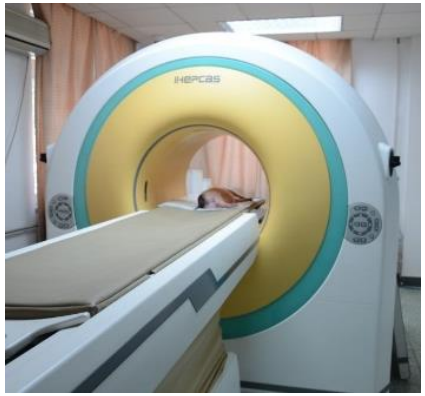
Animal PET及PET/CT

Animal Opti-PET

Animal SPECT/CT



Primate Animal PET



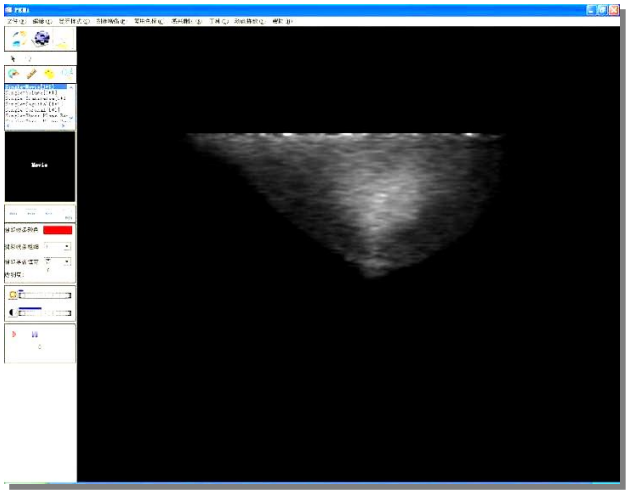
Whole-body PET

Breast PET

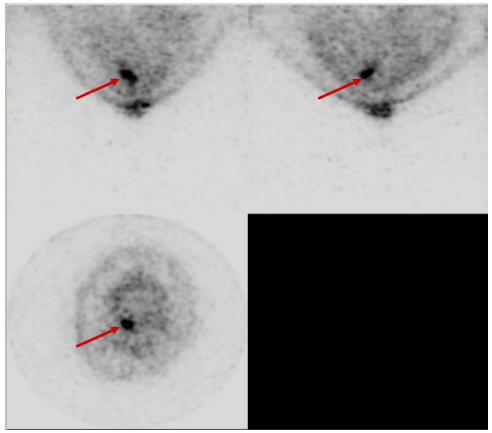
Breast SPECT

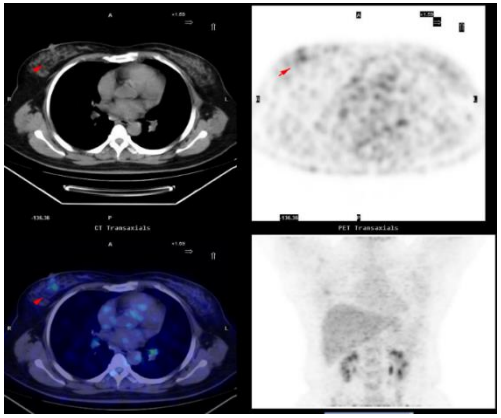
Breast CT

Breast-PET is in clinical



Breast-PET imaging





PET/CT imaging

Category-Ⅲ medical instrument, issued by CFDA to enter the market sales and clinical application (2015)

Detectors and electronics for Nuclear Imaing

Detector ring for animal PET

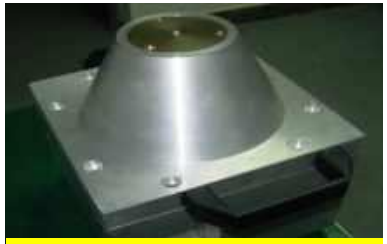
Detector ring for Breast PET

Detector for Whole-bode PET

Detector for TOP-PET

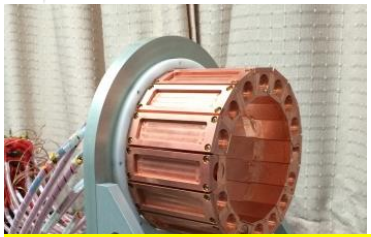
Detector ring for animal PET

Detector for SPECT, parallel pin-hole



Detector for SPECT, pin-hole

Detector for SPECT

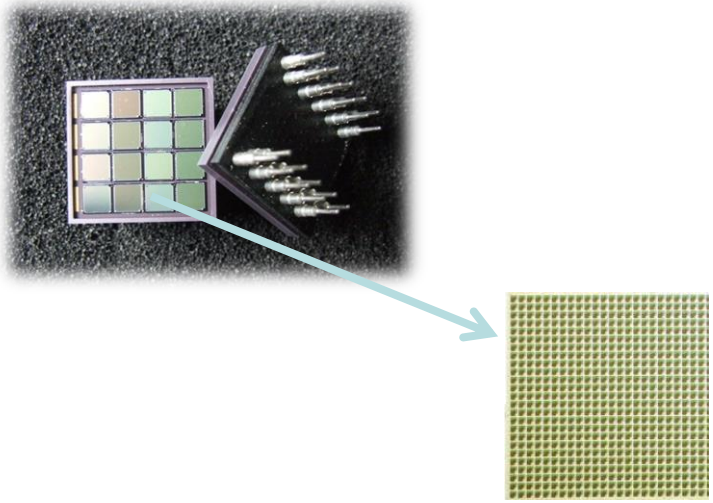


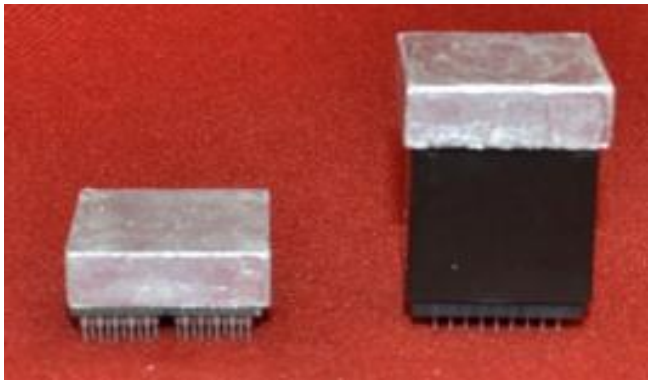
PET detector ring for MRI-PET

DAQ electronics for Nuclear Imaging

SiPM based detector for PET

- **Comparable with PMT PET detector**
  - **Energy resolution：single crystal 12%，matrix 18%-20%**
  - **Spatial resolution：FDG hot phantom 1.7mm**
  - **Coincidence timing resolution：2.6ns (or better)**
- **Other advantage**
  - **Magnetic immunity**
  - **Compact，1mm vs 40mm**
  - **Low bias，30V vs 700V**
  - **Gain uniformity，80% vs 40%**
  - **High mechanization, low cost**



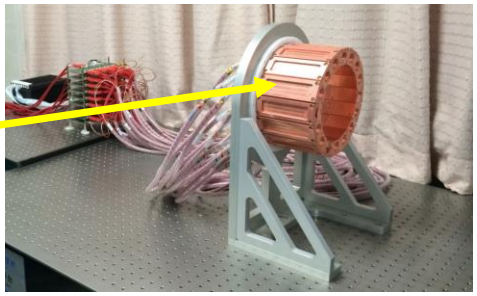


SiPM+crystals PMT+crystals

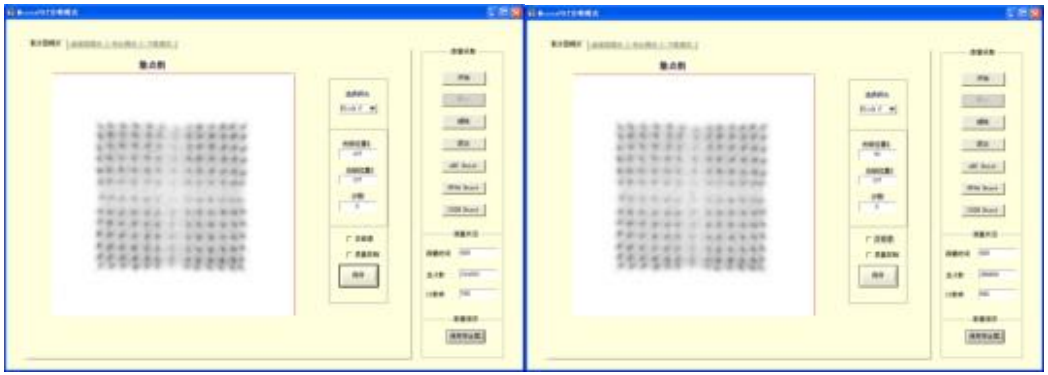
Magnetic compatibility

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

3.5×3.5×25mm³ LYSO
，14×14 matrix
SiPM: SensL ArraySM-8



- Inner diameter 151mm, external diameter 216mm
- System timing resolution 2.6ns, spatial resolution 1.5mm

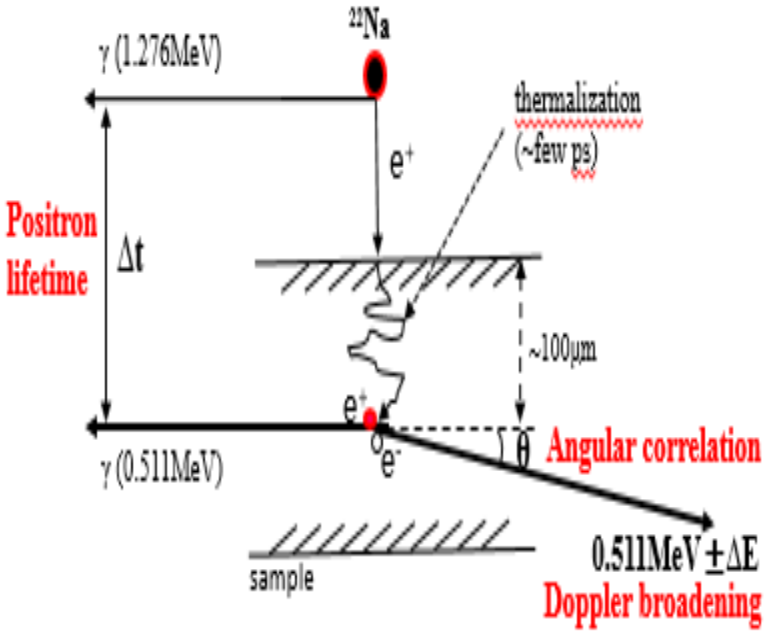


	0 T	0.3 T	0.6 T	0.9 T	1.2 T	1.5 T
Peak value	70	69	69	69	70	69
Count rate	892	889	888	892	893	892

Flood histogram, energy spectrum and count rate remain stable in 1.5T magnetic field

Positron annihilation techniques developments

- *Application on materials*
- *Methodologies*
- *Slow positron beam*

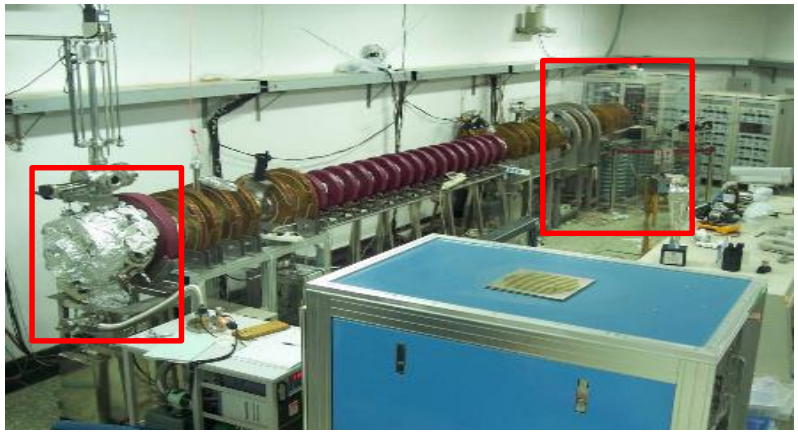


Slow Positron Beam in IHEP

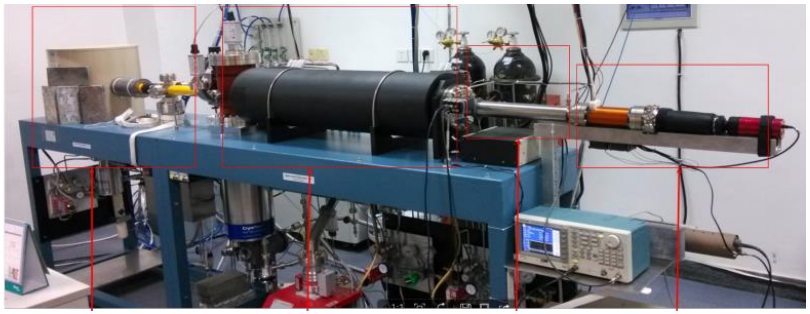
Phase I（2001~2013）

Phase II（2004~now）

Phase III（2007~now）



Phase IV（2014~now）



2013 earmarks fund from CAS

Positron Annihilation in IHEP

Ne moderator beam → **New! May, 2014. Doppler Broadening, CDB, Ps-TOF…**

Linac-based beam → **Doppler Broadening, Lifetime measurement, CDB, AMOC, Ps-TOF**

22Na- beam plugged → **Doppler Broadening, Lifetime measurement, CDB, AMOC, Ps-TOF**

Conventional positron annihilation spectroscopy

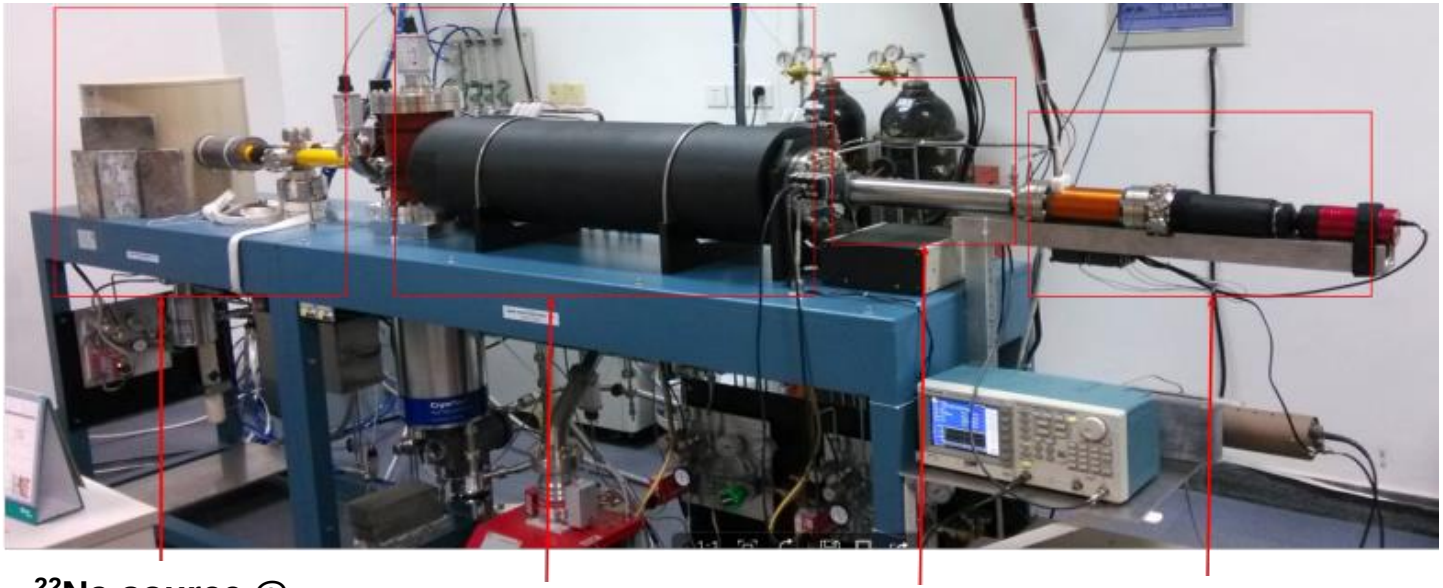
- Positron lifetime spectrometer
- High-resolution positron lifetime spectrometer
- Age-momentum correlation
- Coincidence Doppler Broadening

→ **Basic measurement**

→ **High performance**

→ **Multi-parameter measurement**

Control panel

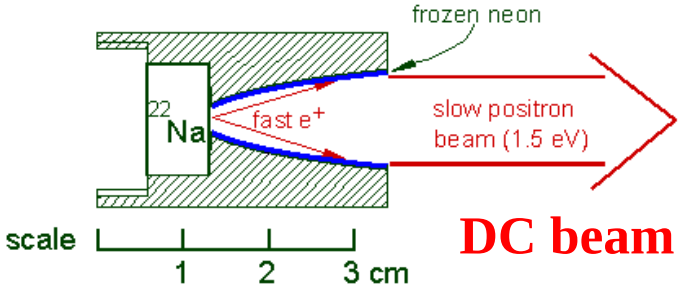


^{22}Na source @
Ne moderator
RGM-1

APBS

Buncher
Time measurement

Screen
Monitor

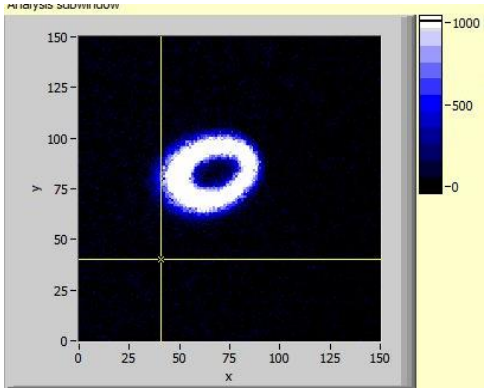


DC beam

- Frozen Ne Moderator
- Temperature: ~ 6.8 K
- Moderating Efficiency: ~1%
- Decay: <4%/day
- 22-Na source, 50 mCi

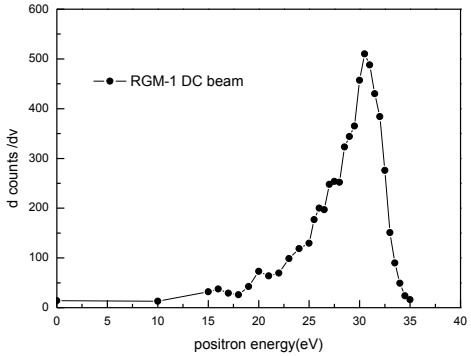
Beam characteristics

DC positron beam



Spot: 4.35x5.12 mm

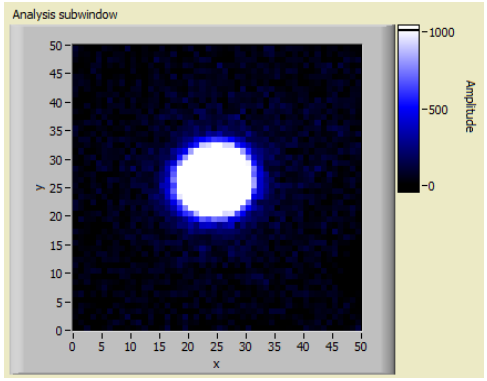
Void area: ~1.3 mm



Energy: ~ 30 ±3.0 eV

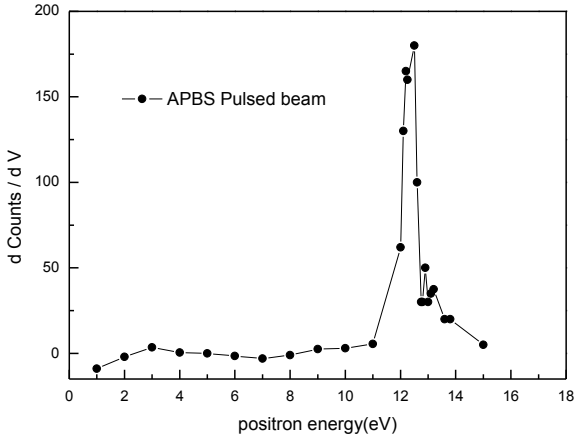
Intensity: 2.0×10^6 e+/s

Pulsed beam



1.2 mm (X); 1.2 mm (Y)

Diameter: ~1.2 mm



Ne Potential: 12 V

Energy: ~ 12 ±0.5 eV

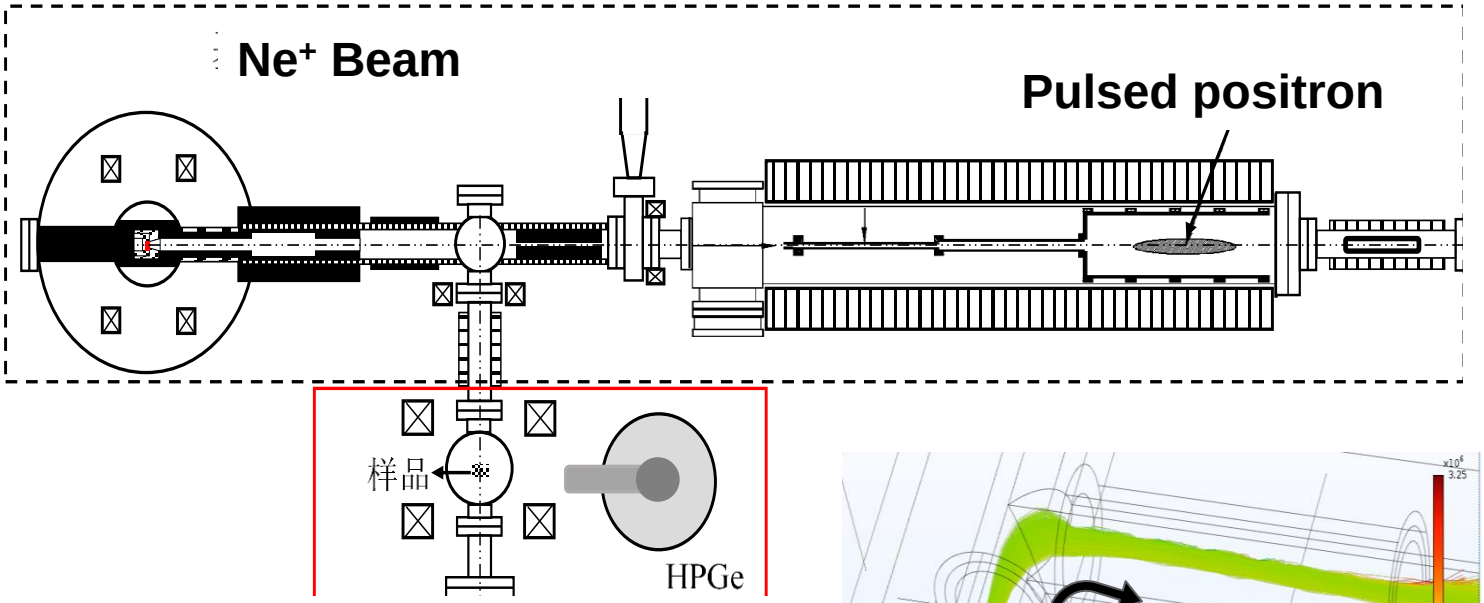
Intensity: 1.06×10^6 e+/s

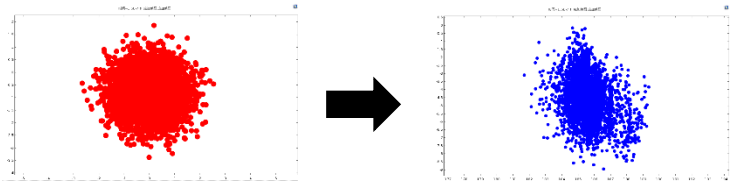
Frequency: 1~500 Hz

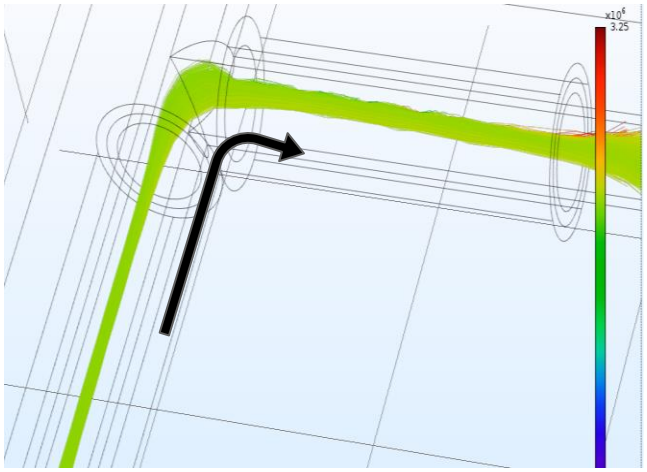
Width: 20~500 ns

(1) Beam development @ (*DB, CDB*)

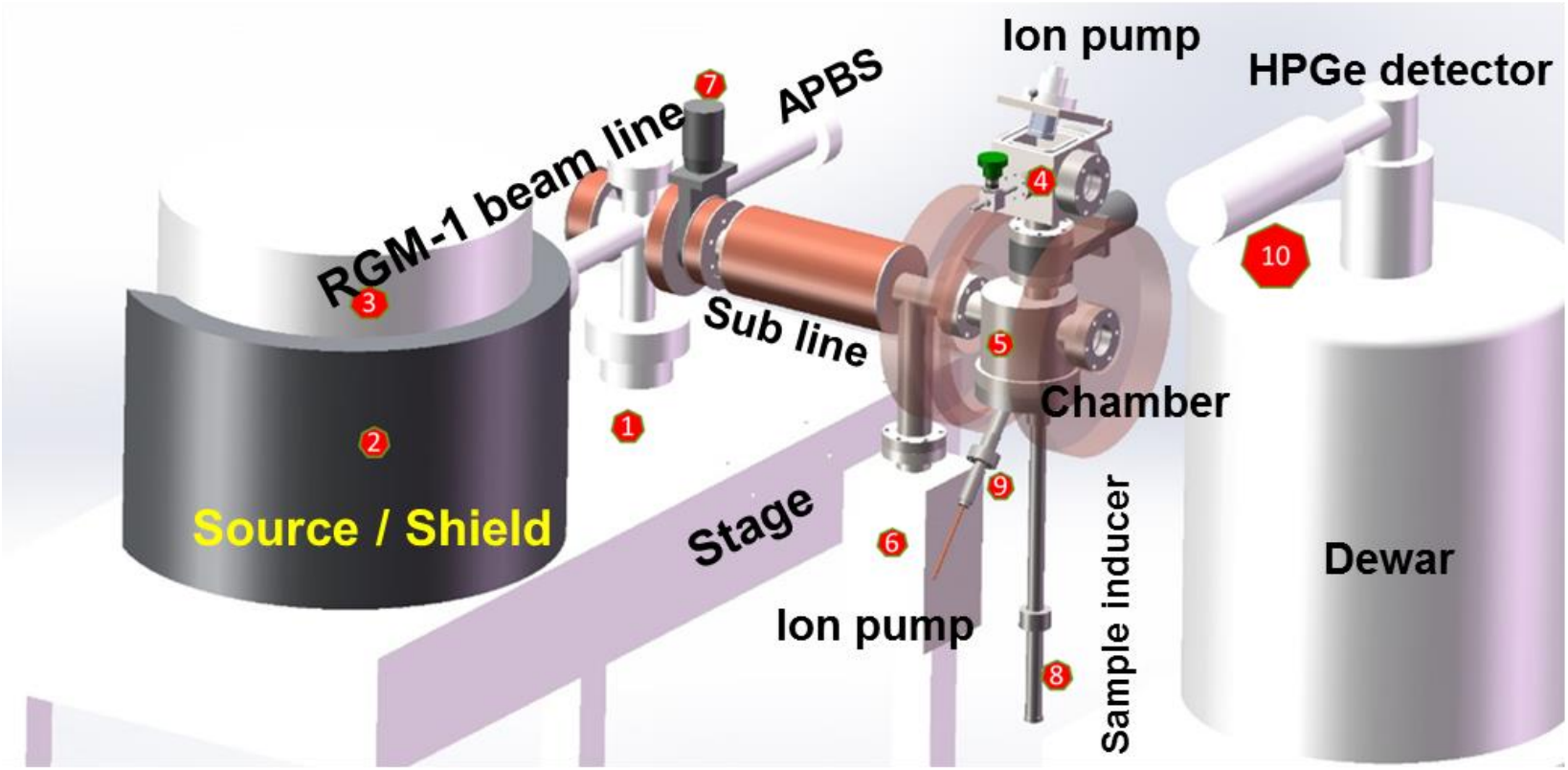
DC beam splitting





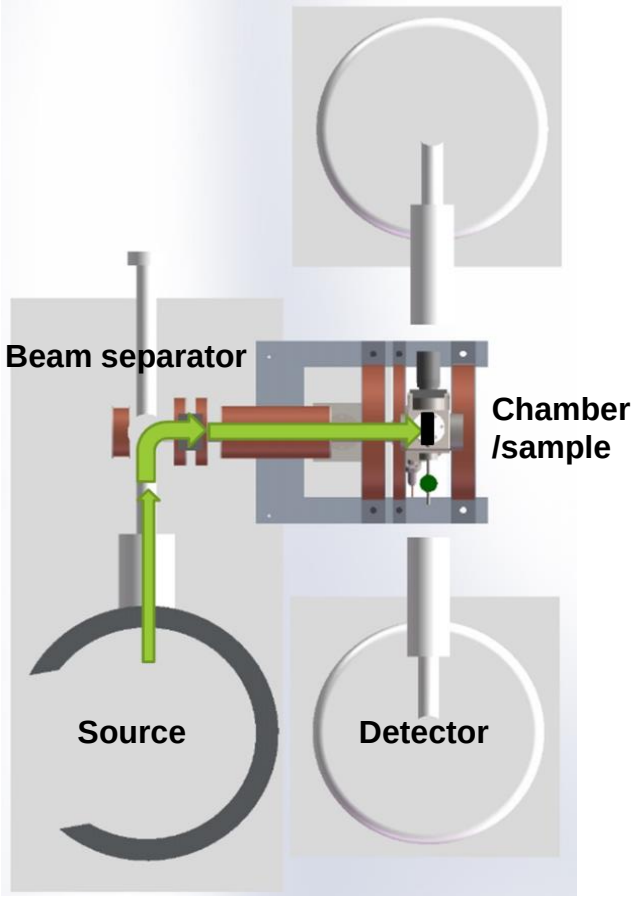


Sub beam line @chamber



Overall design scheme

DC beam characteristic



① For a big spot

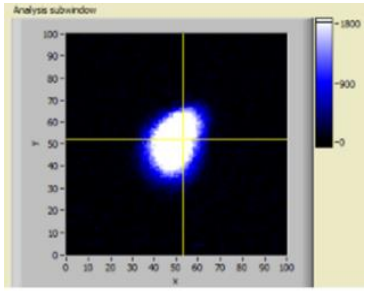
Intensity: 2×10^{6} e^{+}/s

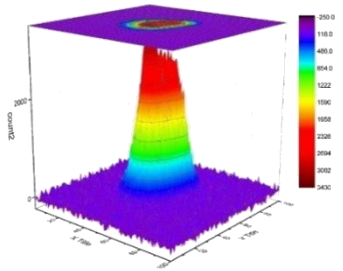
Diameter: 5.5mm

② For a small beam spot

Intensity: 7.5×10^{5} e^{+}/s

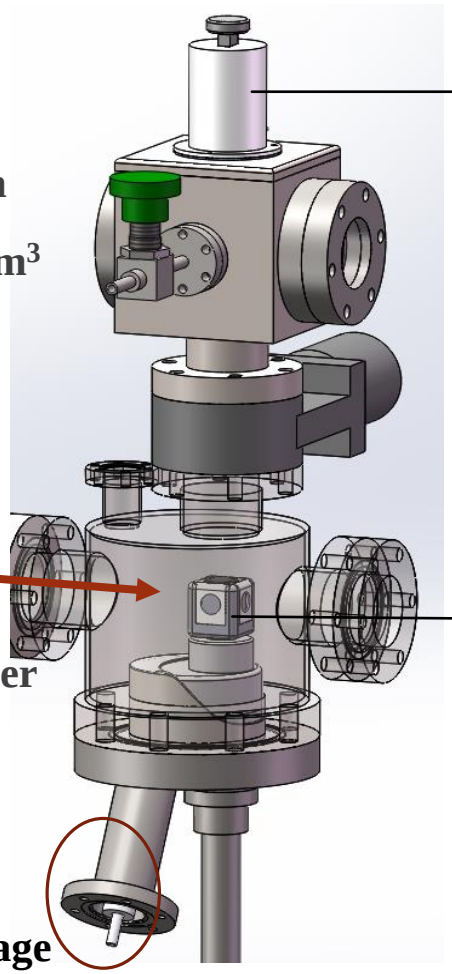
Diameter: 3mm





Chamber design

Mini size + Multi-sample import + Simple operation



Pre-vacuum

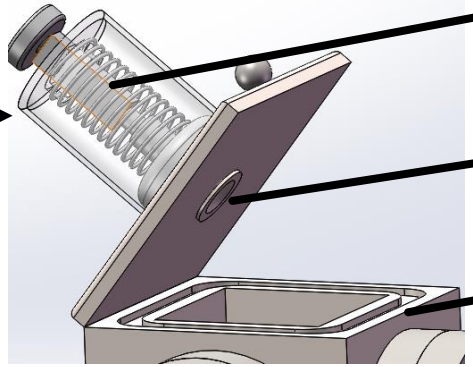
80*80*80mm^3

e^+

Sample Chamber

Φ100*100mm^3

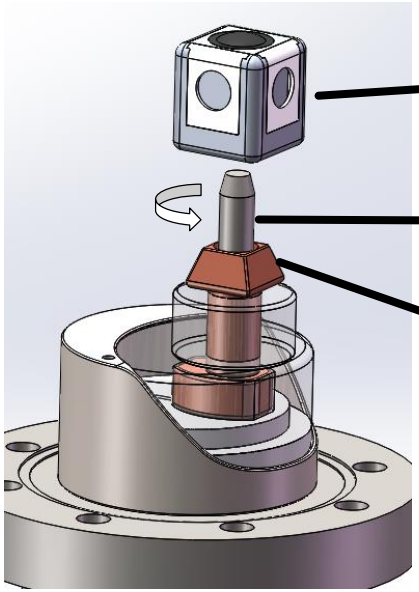
Negative high voltage



Stretching magnet: adsorb sample holder

Sample holder collimation

Fluorine aprons slot

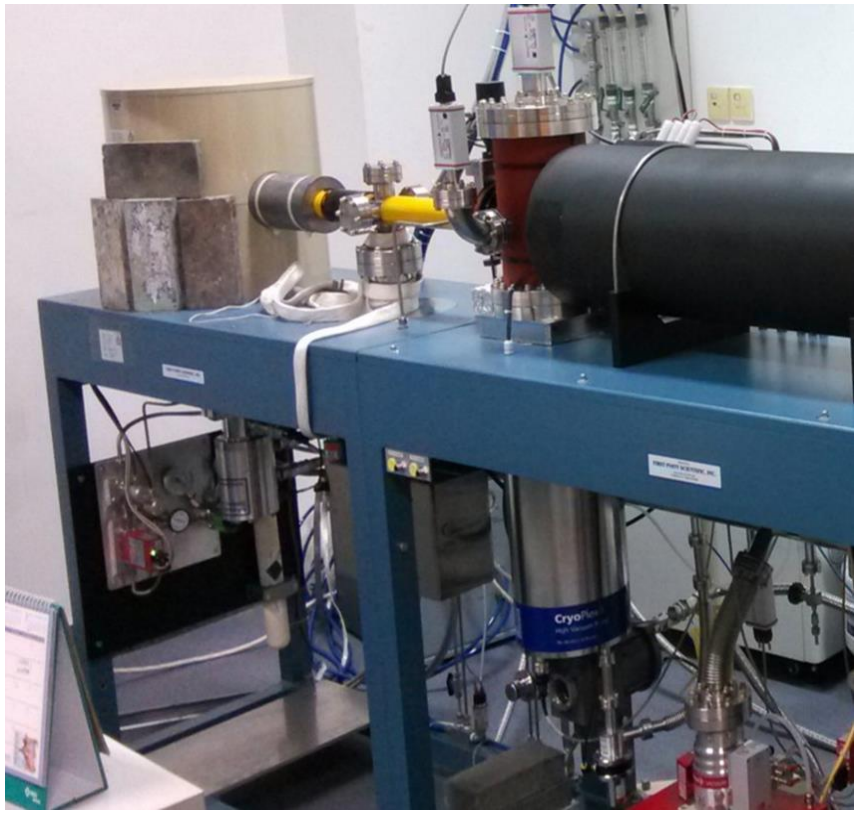


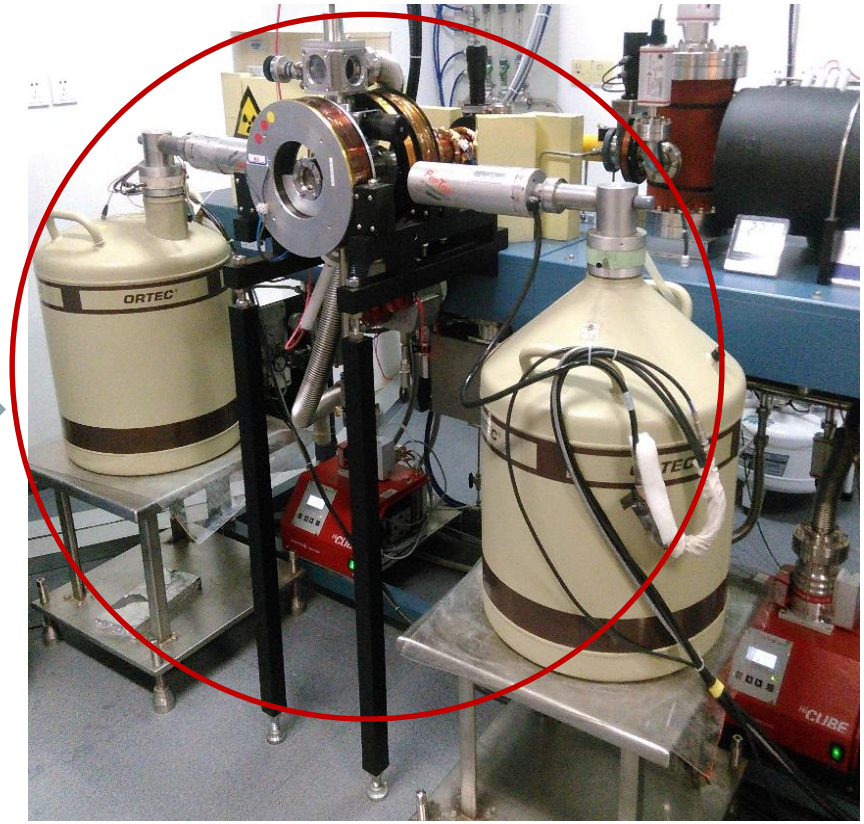
Four sides holder

Rotatable stretching rod

Holder support

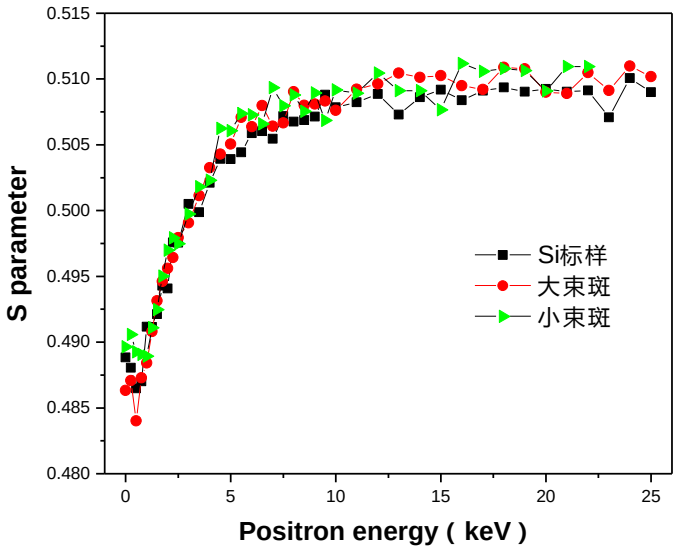
DBES/CDB measuring system



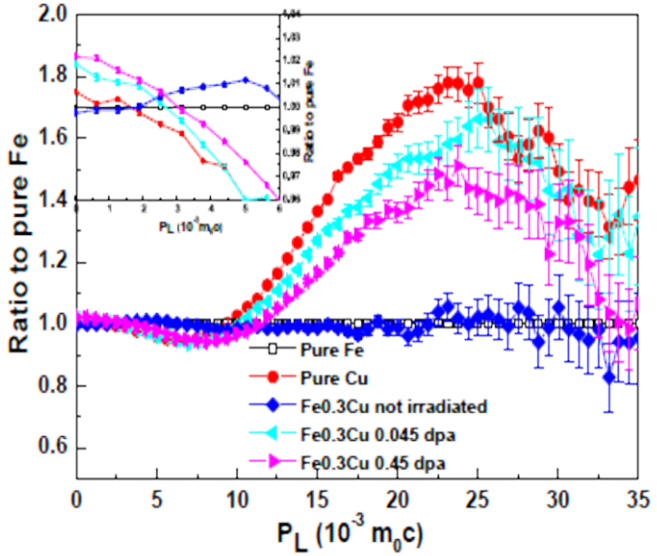


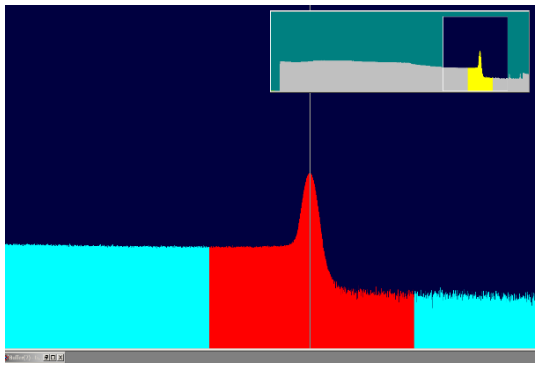
DBES/CDB results

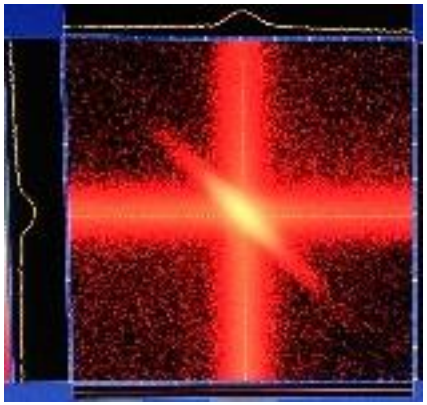
DBS: S parameter of Si sample



CDB: ratio spectrum of Fe/Cu alloy

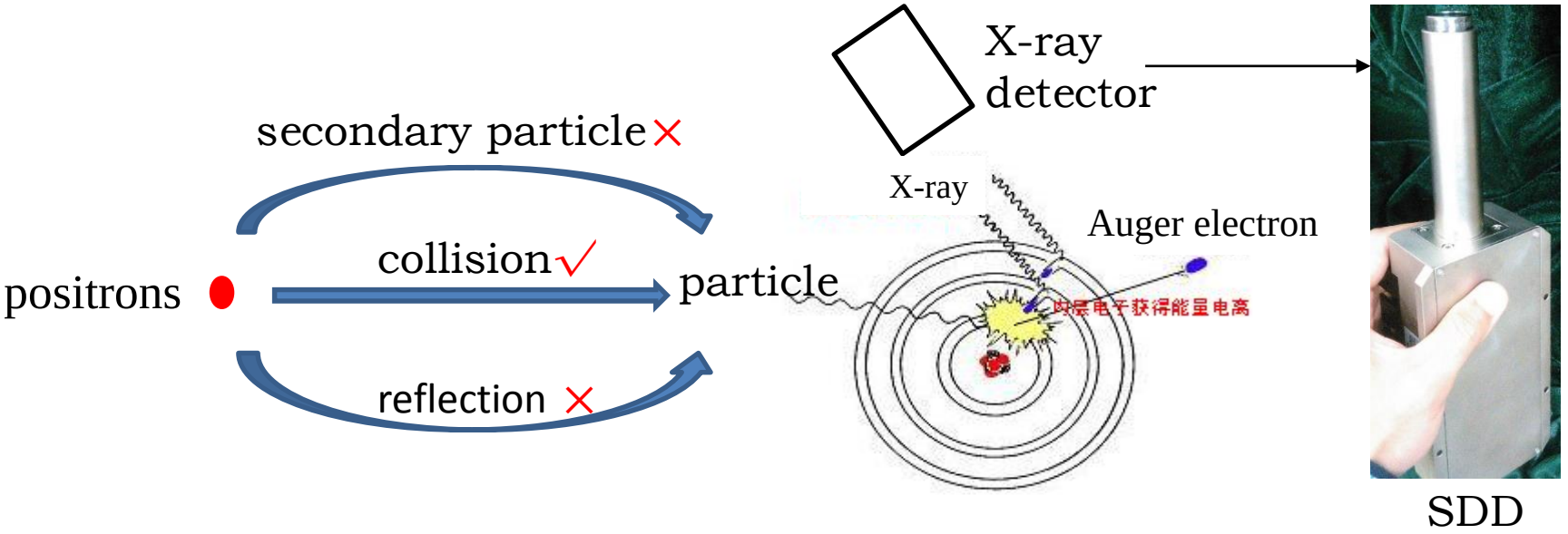






(2) DC Beam @ (e^+ ionization cross section)

- **atomic inner-shell ionization**
- **low-enery positron (<10keV)**



$$\sigma(E)=\frac{4\pi A(1-K(E))}{N_A t N_{e^+}\varepsilon(E_{ph})\Omega}N(E)$$

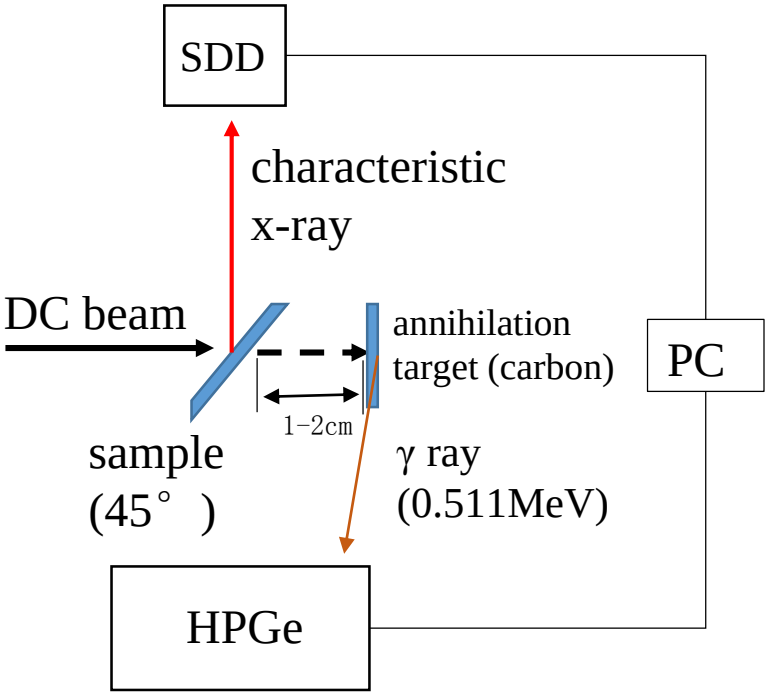
N(E) : Net count of characteristic x-ray

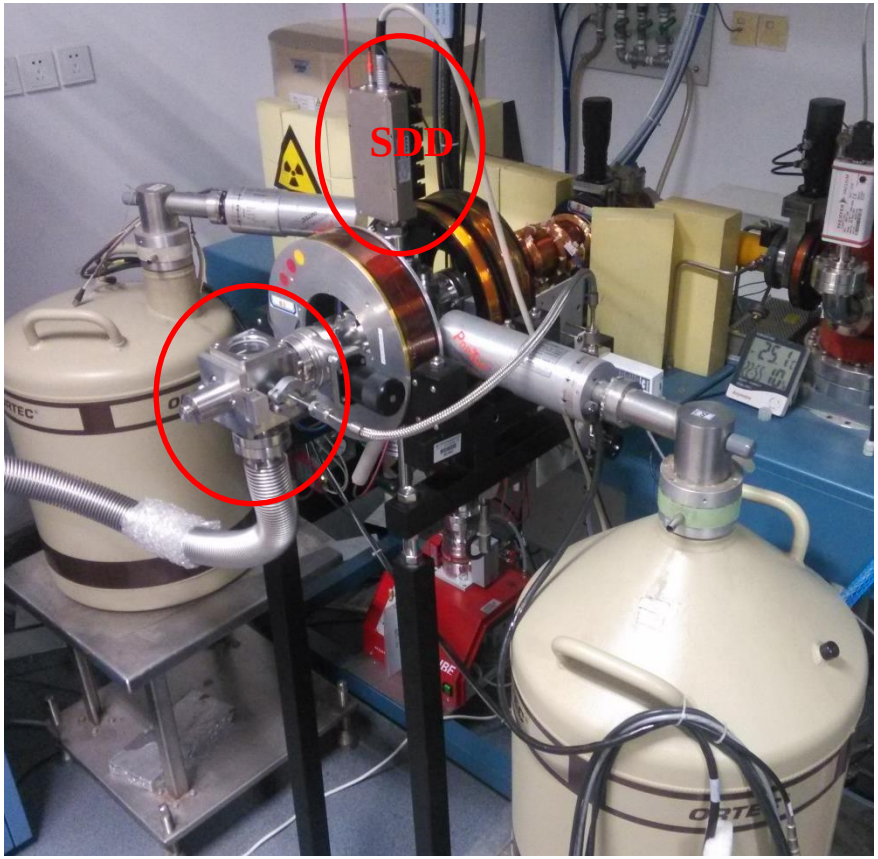
N_{e+} : The number of incident positrons

$\varepsilon(E_{ph})$: Detector (SDD) efficiency

Measure of ionization cross sections

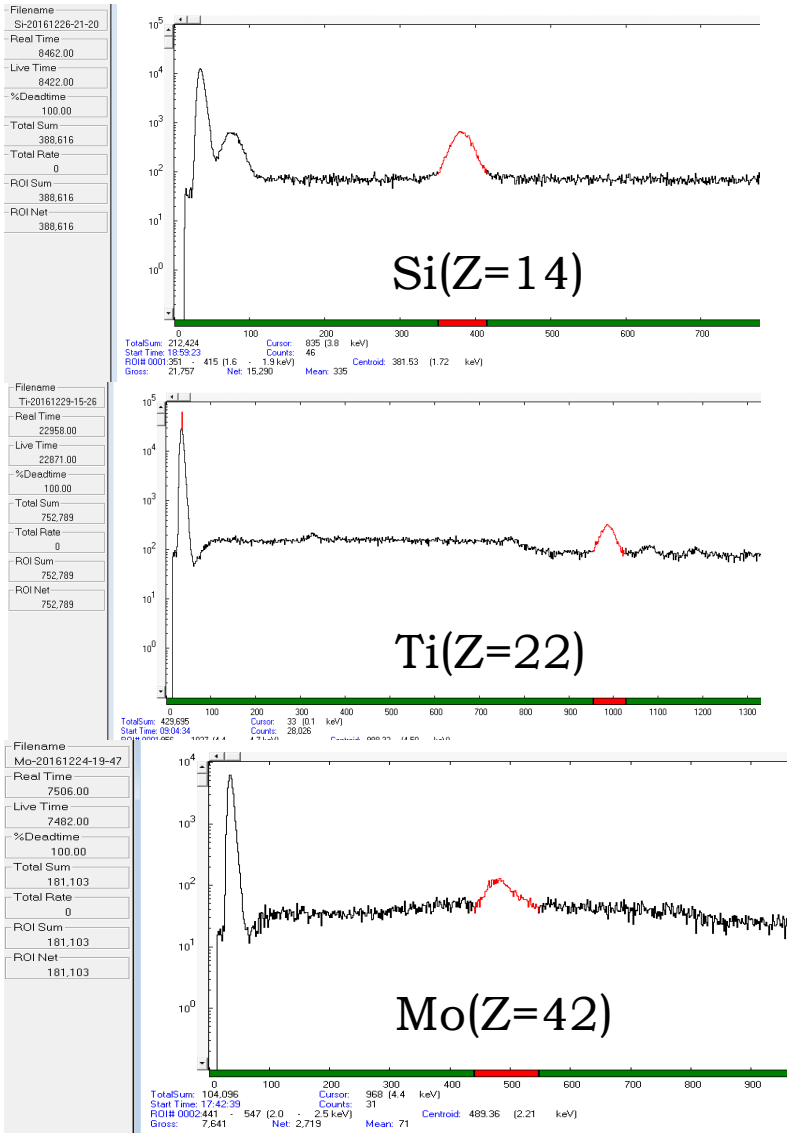
Mechanism and methods



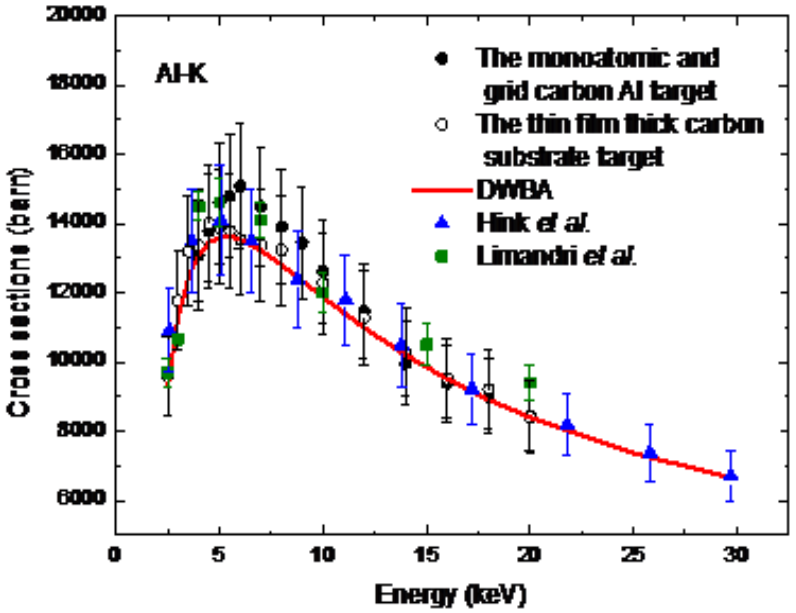


- ✓ **Improved detection efficiency**
- ✓ **DC beam stability**
- ✓ **Thin film sample**

Measure of ionization cross sections



Comparison of results between experiment and simulation

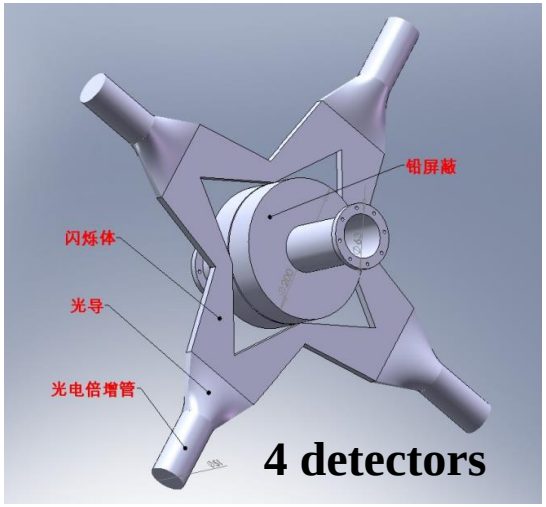


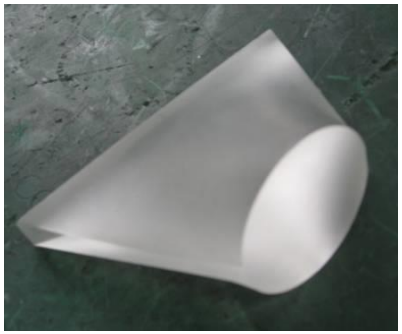
Reliable data is provided for theoretical research

Supported by NSFC NO.11275071

(3) Pulsed beam @Ps-TOF system

PALS and Ps-TOF





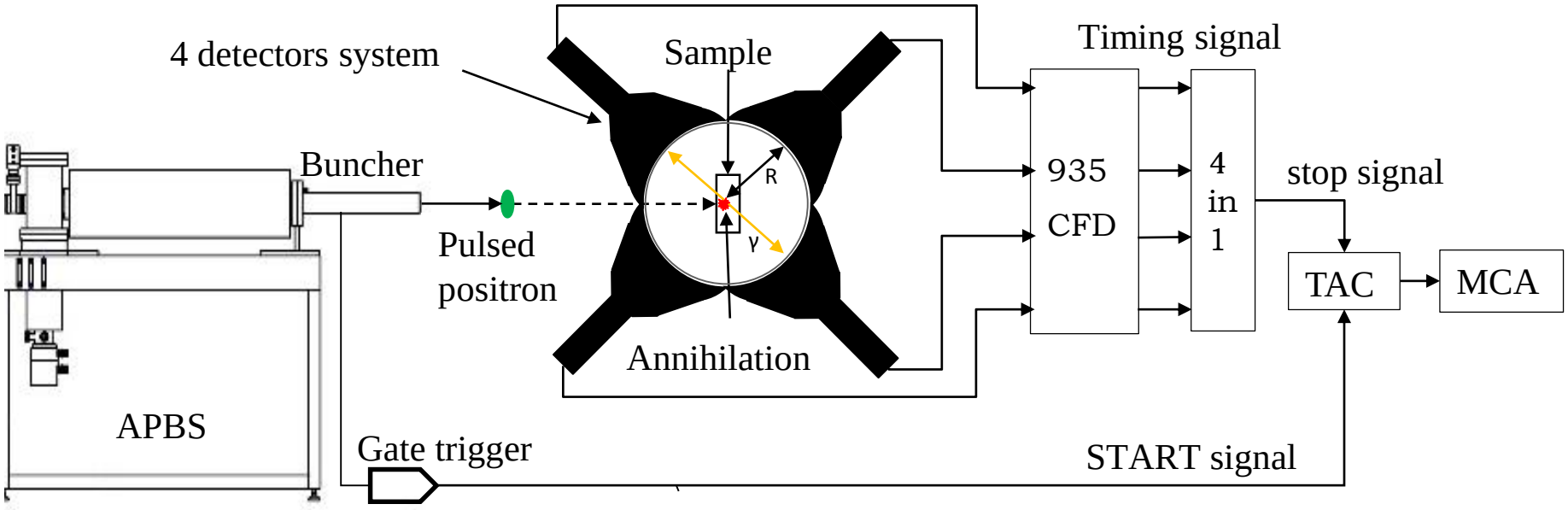
Application:

Ps: porous silicon & polymers

Ps^-: Ps^- beam and application

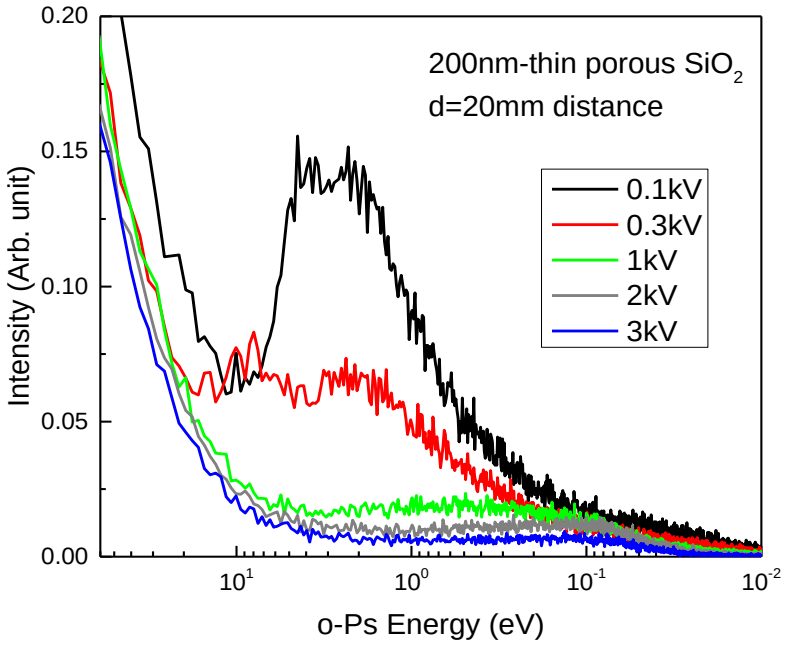
Ps-TOF system

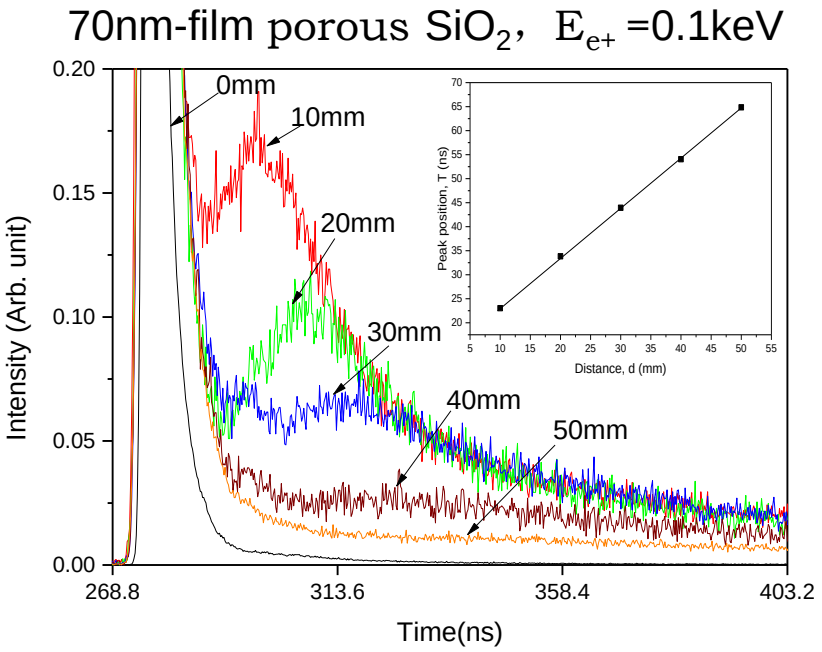
Electronic diagram



With the 4 detectors measurement system, $d>0$ is set, and the energy threshold is selected for eliminating undesired signal

Ps-TOF results in porous SiO_2



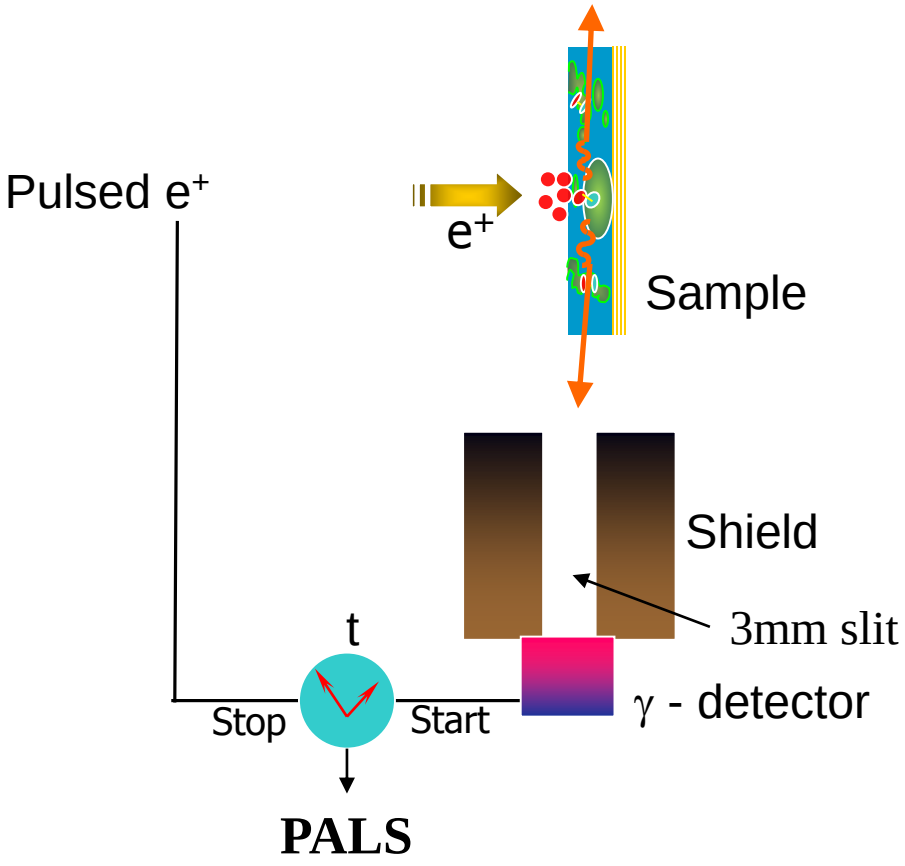


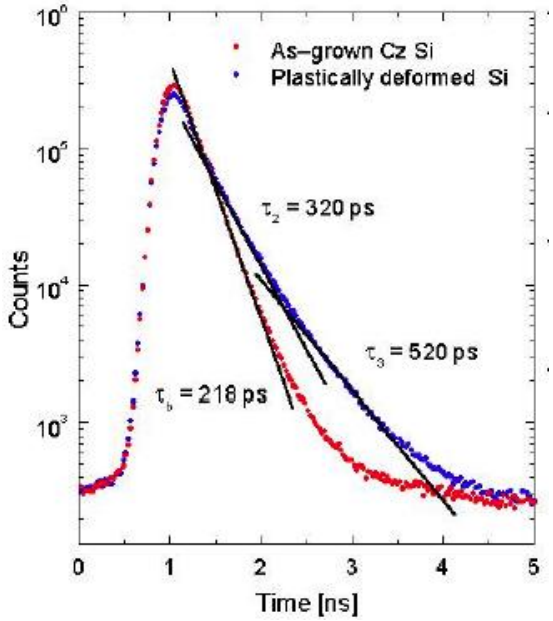
1. The higher the positron energy, the smaller the Ps-TOF peak
2. The higher the positron energy, the lower the energy of the Ps

Energy of o-Ps flight out doesn't change in a fixed positron energy

$$T = \frac{d}{v} = \frac{d}{\sqrt{\frac{2E_{o-Ps}}{M}}} = \frac{d}{\sqrt{\frac{E_{o-Ps}}{m_{e+}}}}$$

(4)Pulsed beam @PALS

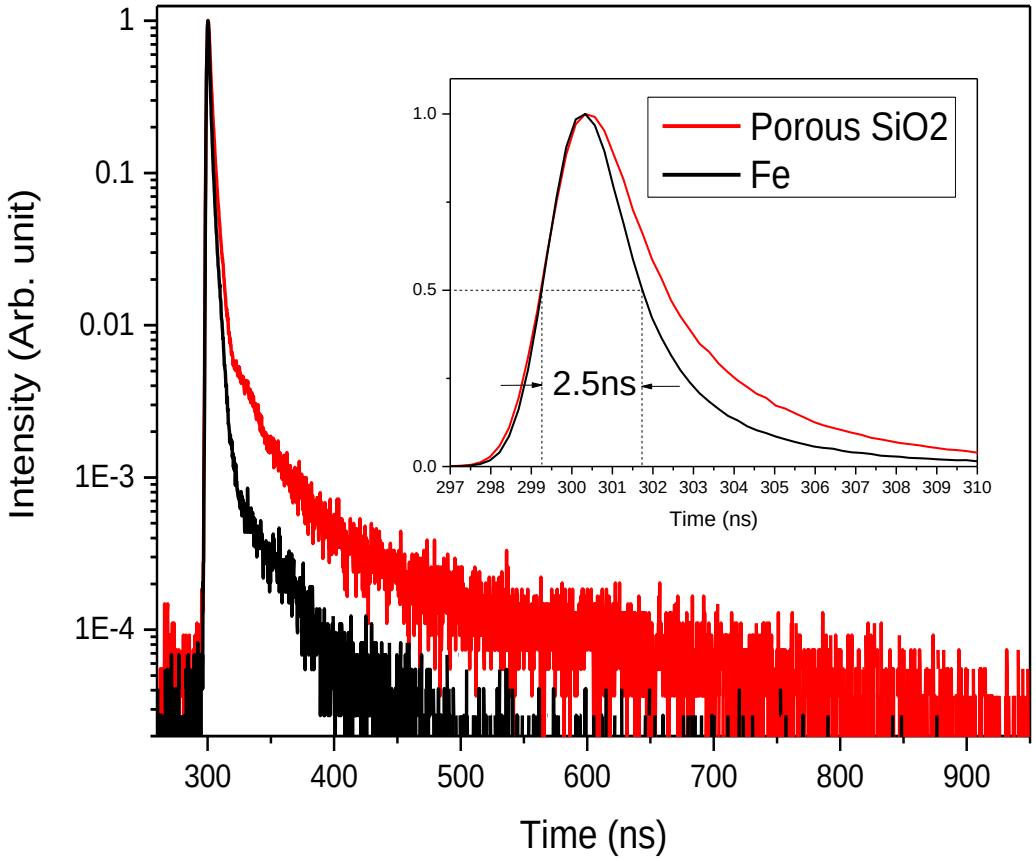




$$N(t) = \sum_{i=1}^{k+1} \frac{I_i}{\tau_i} \exp\left(-\frac{t}{\tau_i}\right)$$

d = 0 ⟹ **PALS**

PALS for a long lifetime measurement



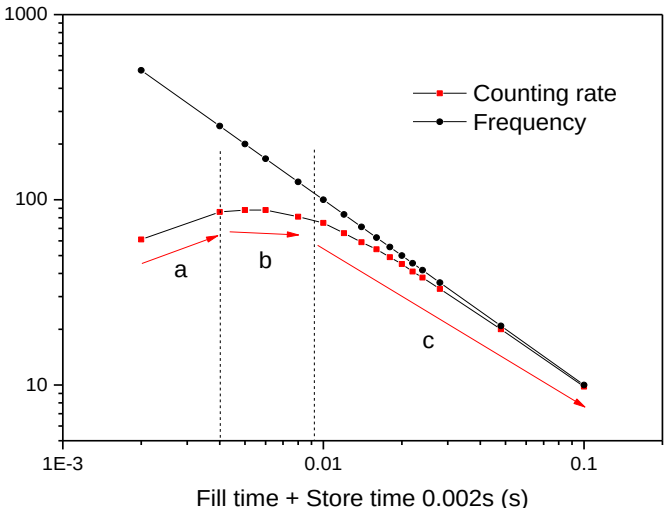
- **Distinguish between long life and short life**
- **The resolution is limited by the width of the pulse (~2ns)**
- **The counting rate is limited by the pulse repetition rate**

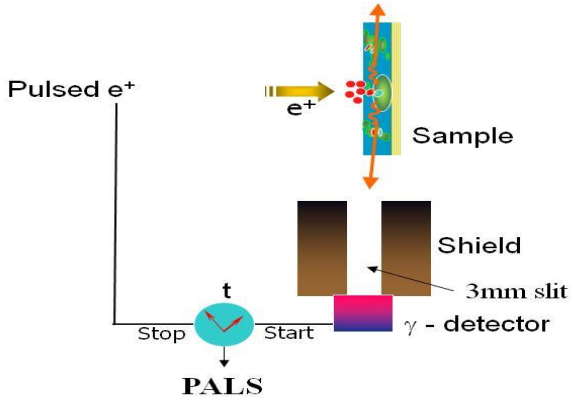
Beam intensity&count rate

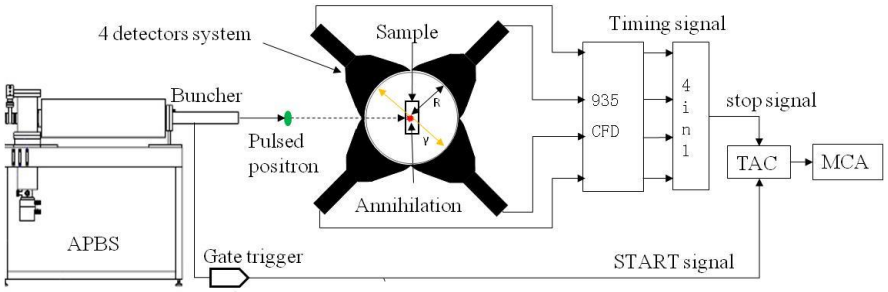
1. Frequency=1 / (Fill time + Store time + Dump time) ≤500Hz

Fill time≥1ms，Store time≥0.75ms，Dump time ≥0.25ms

2. Fill time → pulsed beam intensity







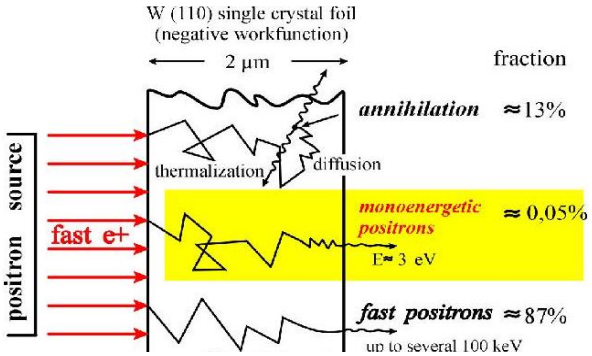
The pulsed beam intensity should be set ensure that no more than one output signal for a pulse

Part 3 positron burst

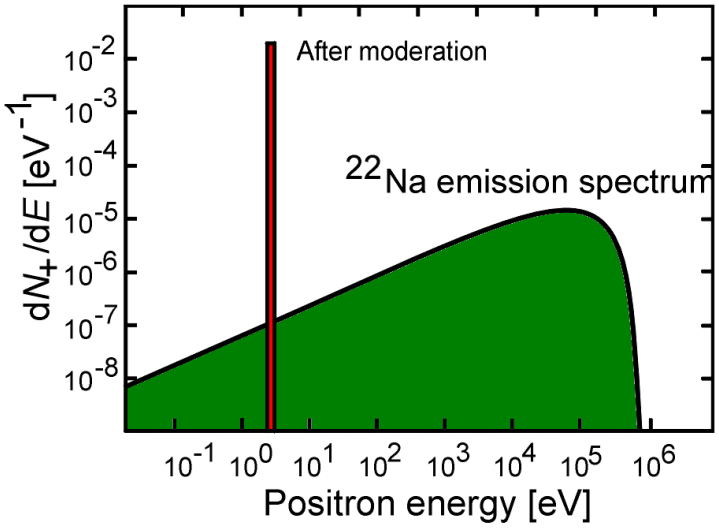
Measurement of positron annihilation lifetime for positron burst by multi-detector array

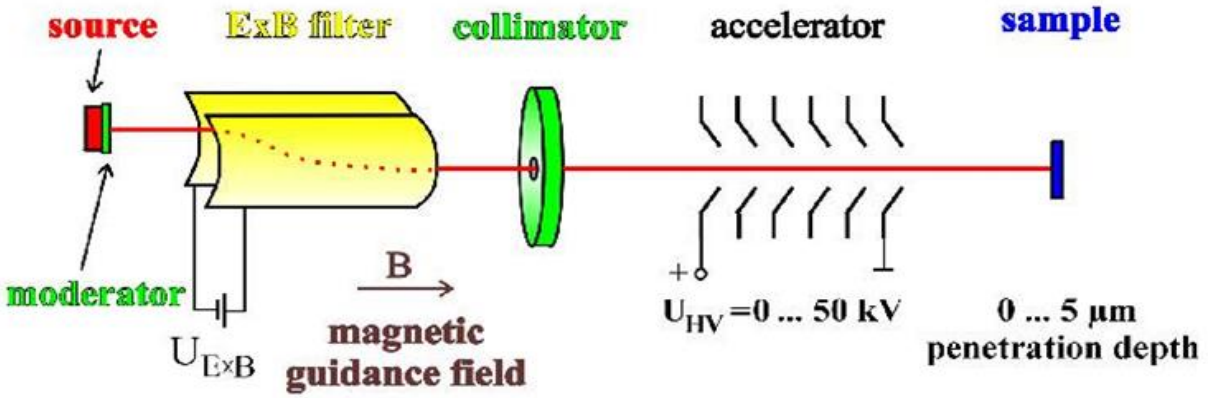
Slow positron beam technology

Moderation

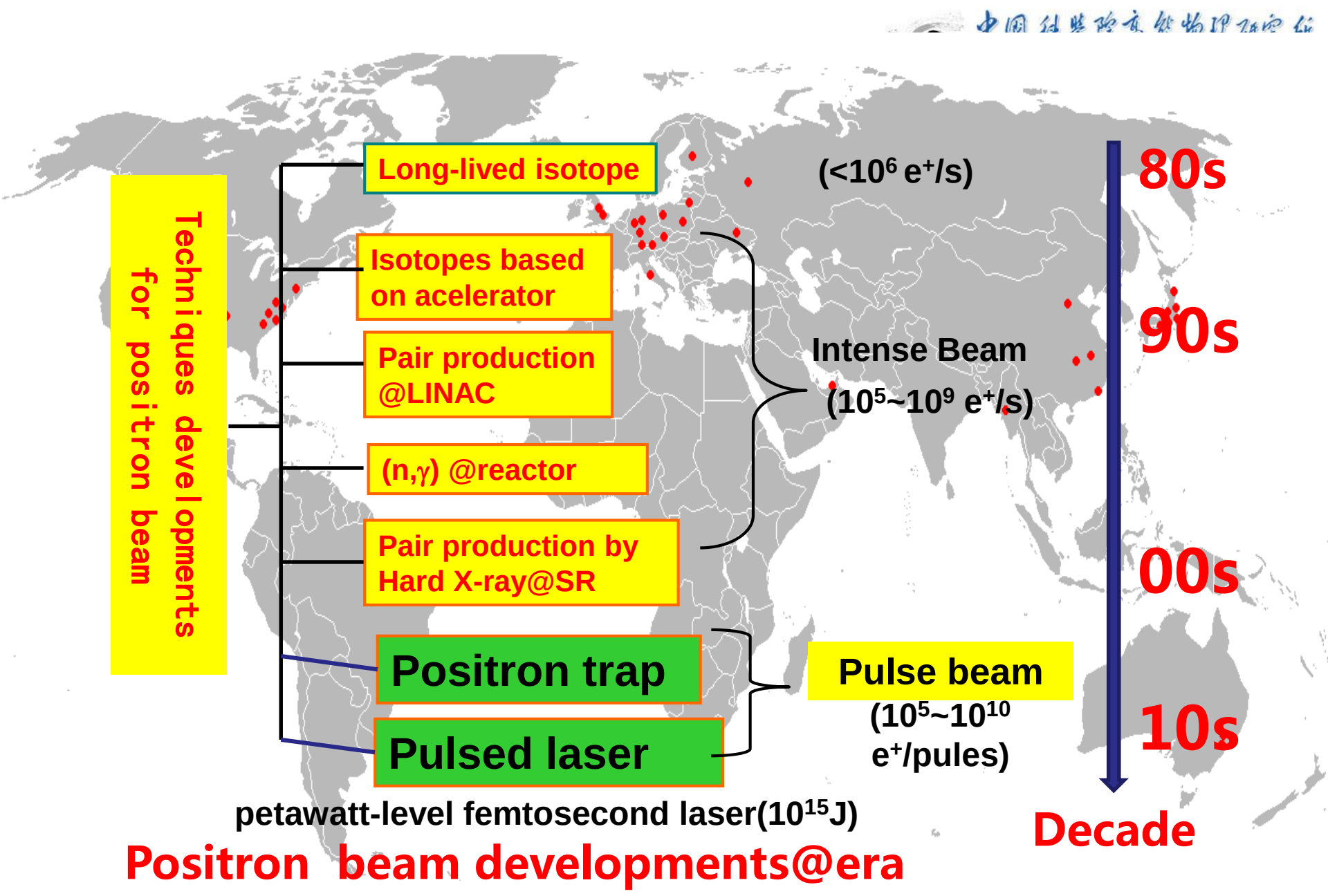


Efficiency~10^{-4}





Beam Intensity : ~$10^5 e^+/s$



Positron beam developments@era

Positron beams in world (4 in China)

Brightness

The “brightness” of the slow positron beam **PERHAPS** be the direction of the future development of positron beam

Space focus **Time focus**

microbeam + **burst**

Positron beam “BRIGHTNESS”

$\sim 10^{19}$ $e^+/s.mm^2$

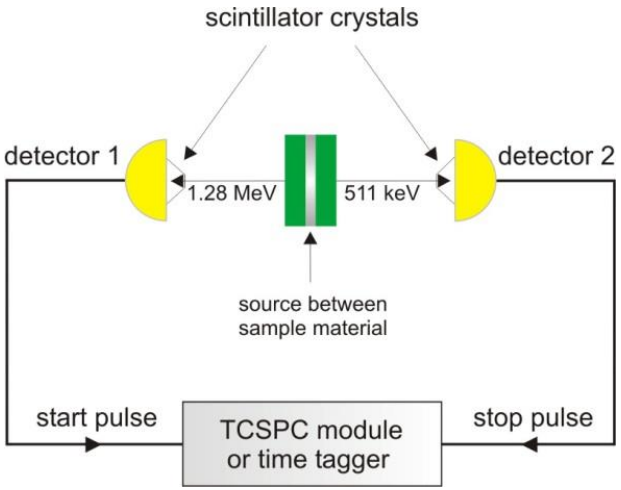
$1A = 1.6 \times 10^{19}$ e^-/s

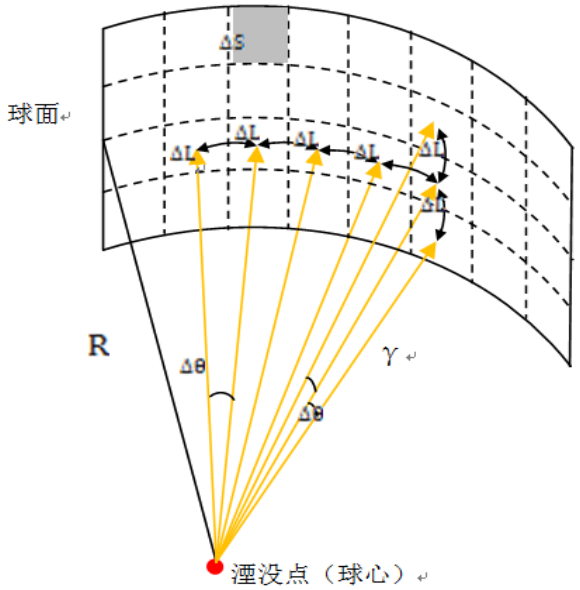
So far, there is no WAY to measure the time distribution for a large number of positron annihilation in one pulse or positron burst.

↓

Measurement of positron annihilation lifetime for positron burst by multi-detector array

Main ideas

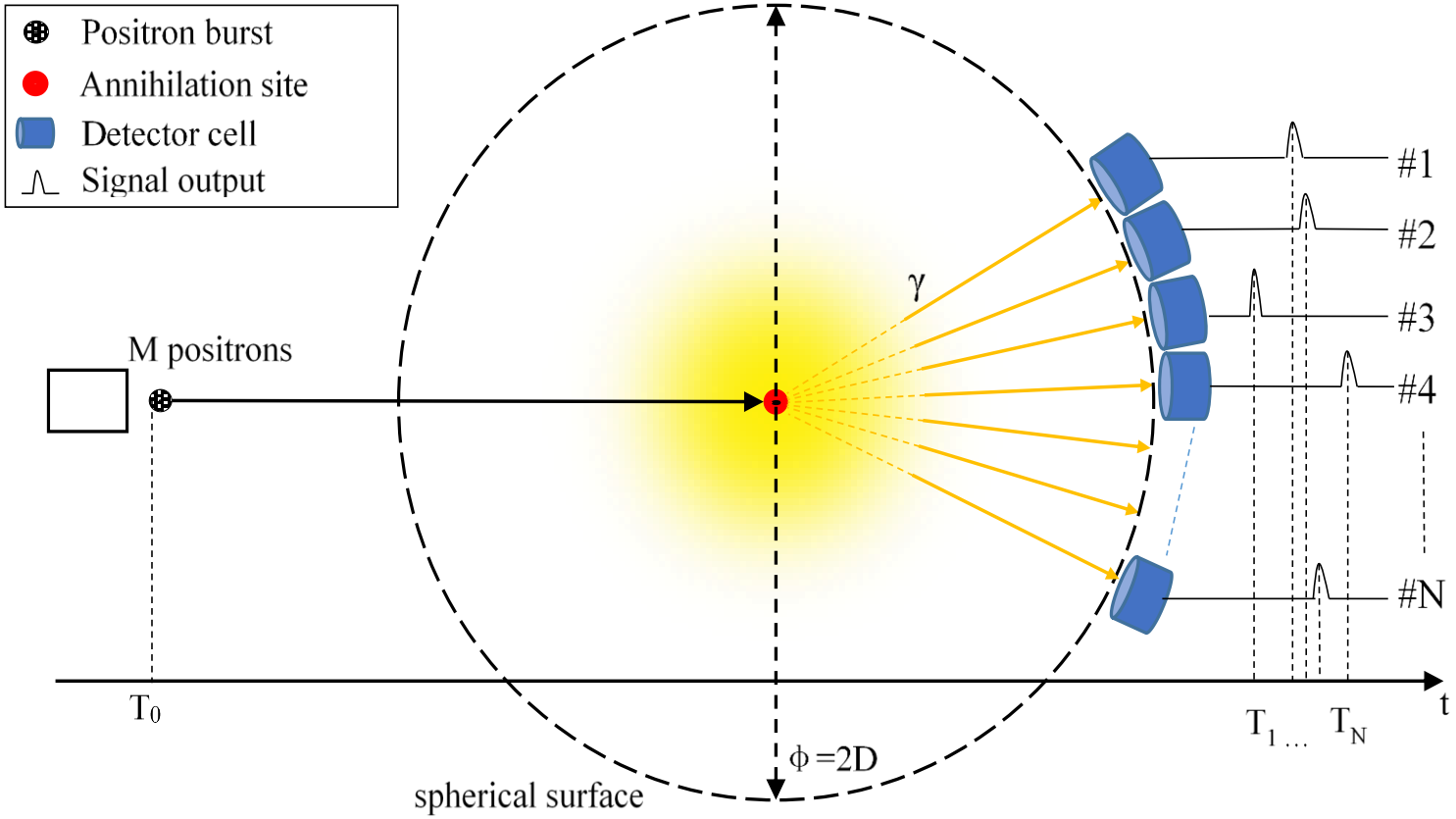




- Time spread ⇒ space distribution

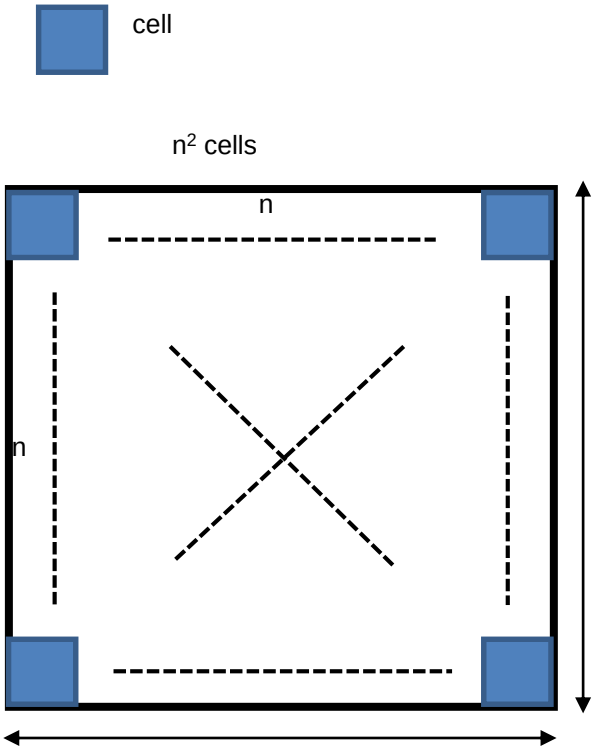
Random distribution of the annihilation gamma photons in 4π space

Principle of multi-detector method

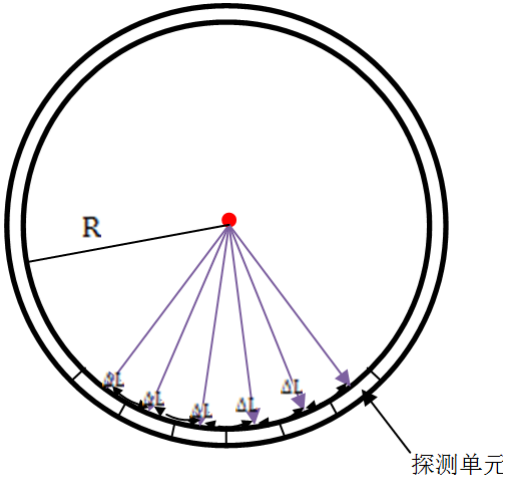


The schematic diagram of the multi-detector method for measuring a burst of M positrons annihilation lifetime with N detector cells.

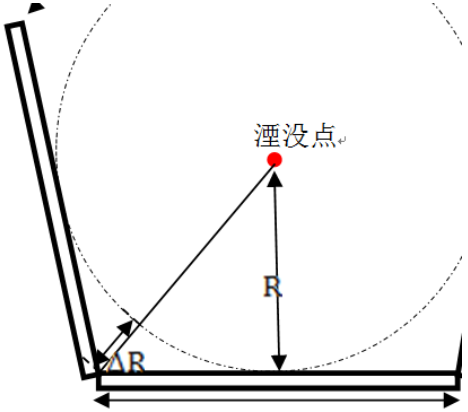
Detector array configuration



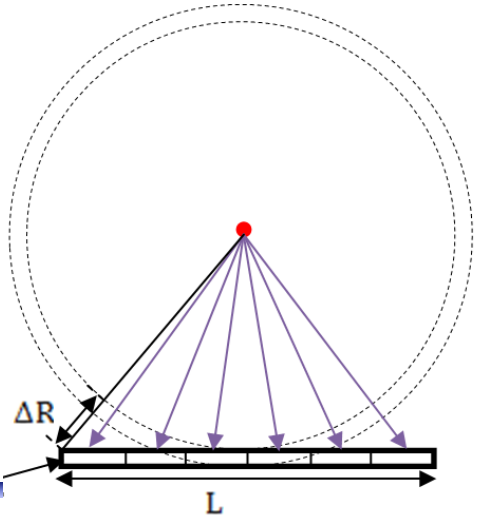
Detector array



Circle structure



“L” structure



Flat structure

Main factors

- The number/time spread of positrons in one burst
- The number/time resolution of each detector cells
- The efficiency of detector cell for 0.511 MeV γ
- The timing accuracy of electronics
- The spatial configuration of detector cells

Detection efficiency of a detection array(Probability Theory)

$$K = [1 - (1 - \eta)^n]^N$$

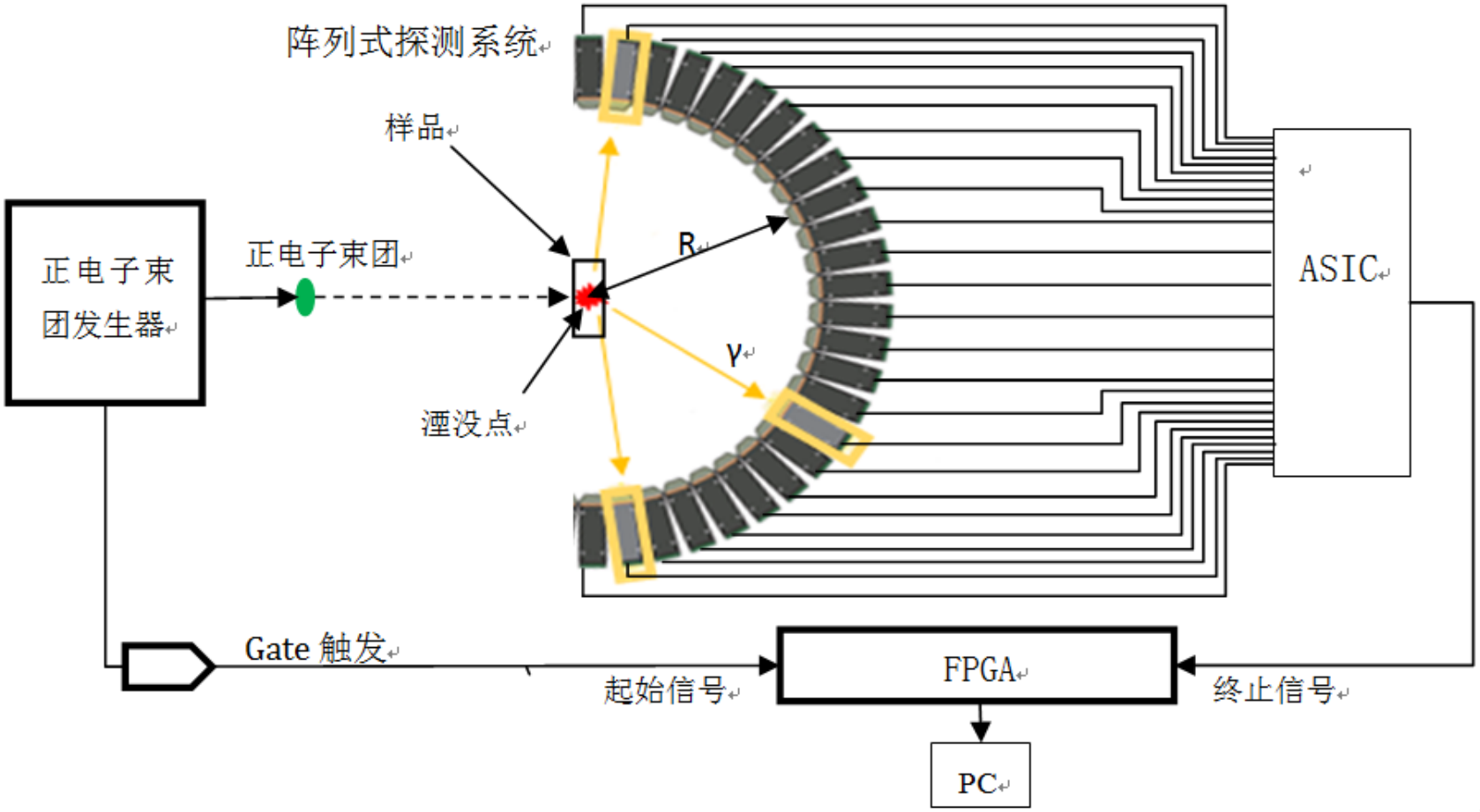
N, the number of cell in a detector array
n, the number of photons that reach the detector cells surface
η, detection efficiency for the annihilated gamma of a cell

Time resolution

$$\tau^2 = \tau_T{}^2 + \tau_P{}^2 + \tau_R{}^2 + \tau_S{}^2$$

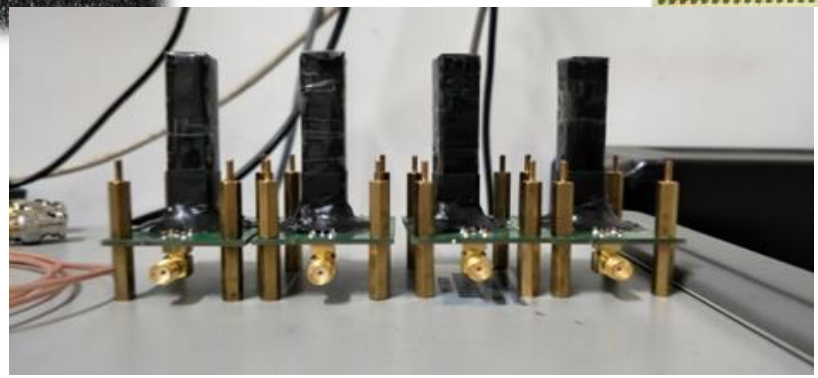
τ_T is the time width of a positron burst,
τ_P is the propagation time difference of the gamma photon,
τ_R is the time resolution of the detector cell (the resolution ability of the cells to timing signals),
τ_S is the time resolution of the detection array (time shaking as different cells detecting the same signal).

System composition



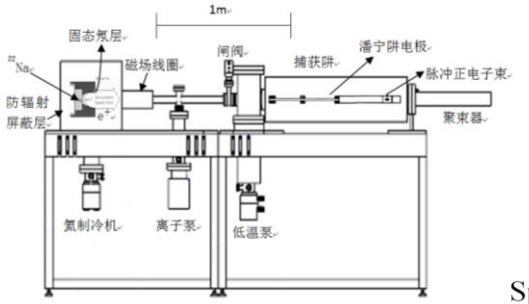
Detector design

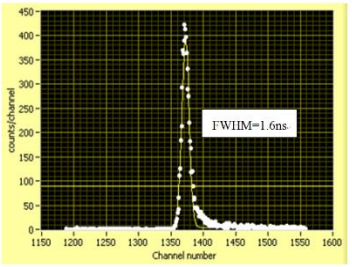
- Geiger-Mode APD array (Silicon photomultiplier, SiPM)
- Compact, low bias, high gain, immune to magnetic field, fast timing

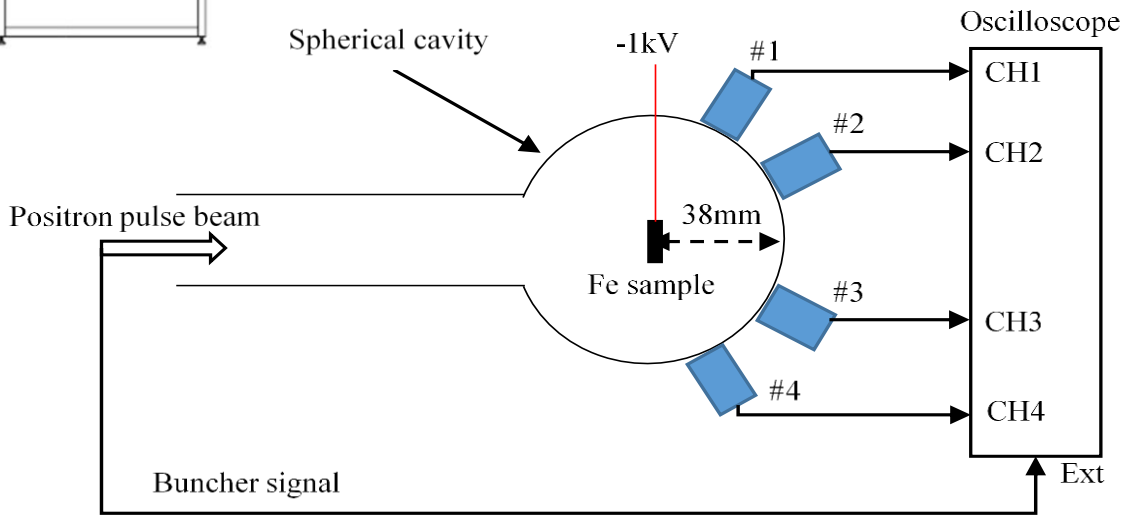


In our primal experimental setup, four detector cells equipped with plastic scintillator of 10×10×50 mm optically coupled to a SiPM with effective photosensitive area of 3×3 mm

Positron beam (trap)

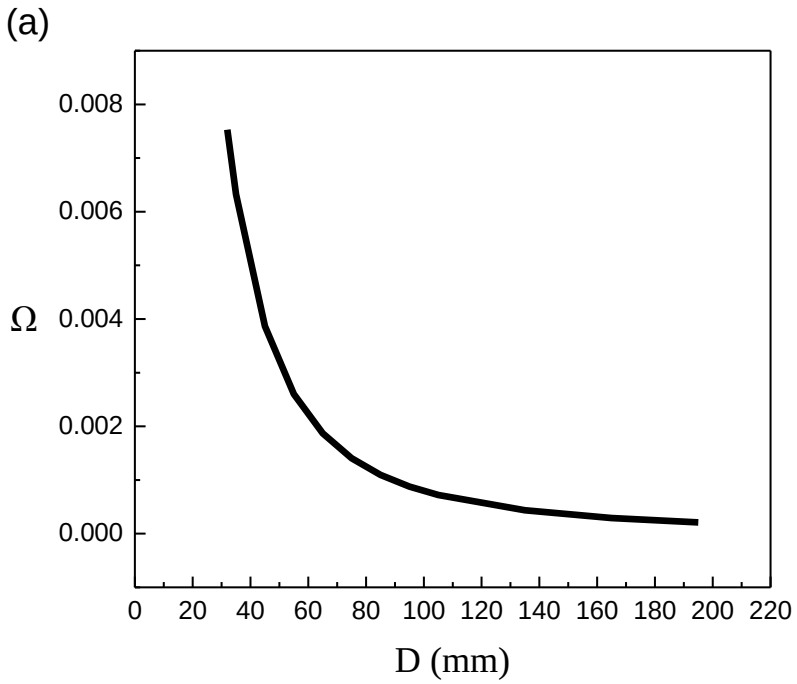


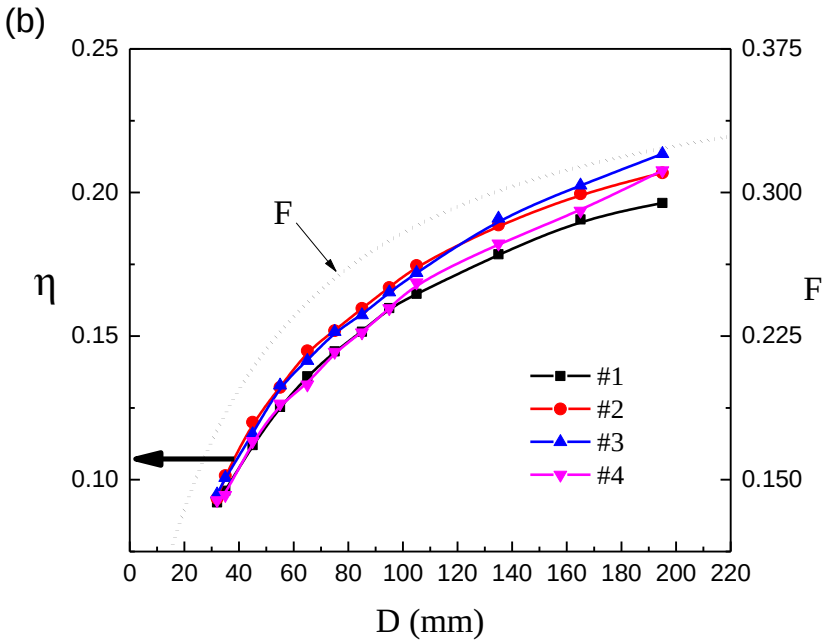




Positron burst annihilation lifetime is measured using four SiPM detectors. The positron pulse in each case contains at most one hundred thousand positrons with a time width of ~2 ns FWHM and were implanted into an annealed pure Fe sample at ~1.0 keV.

Parametres measurements

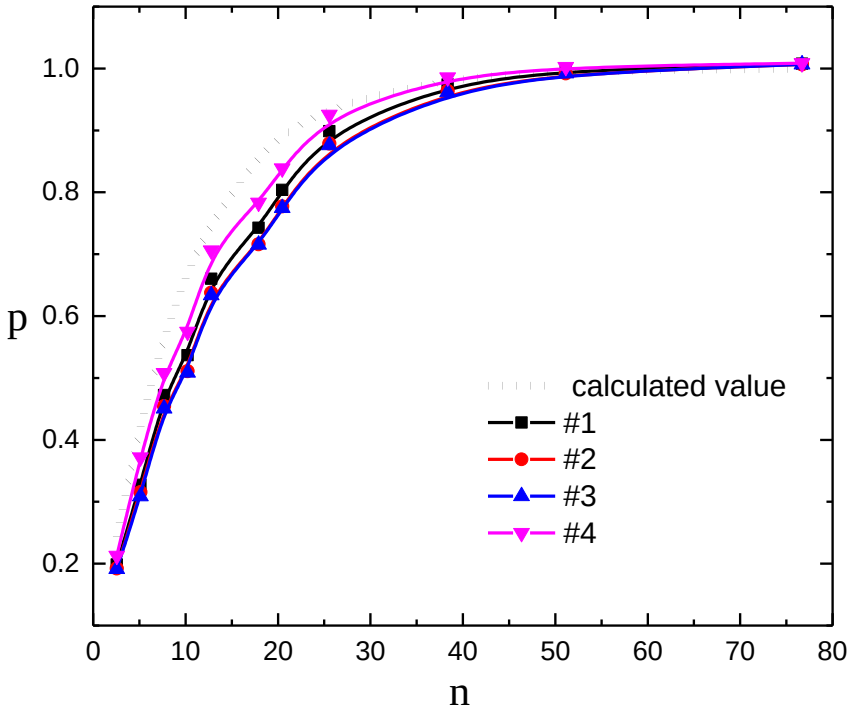




(a) The solid angle factor Ω calculated and (b) the experimental values of η as a function of the distances D.

Ω is the ratio of geometrical solid angle of a detector cell
η is the detection efficiency for the annihilated gamma of a cell.

Parameters measurement

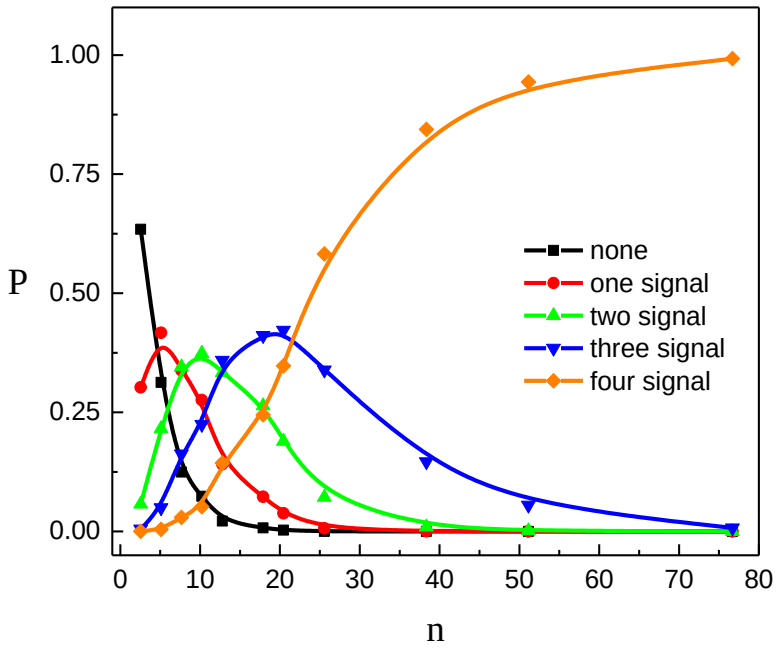


The detector cell efficiency p as a function of the average number of incident photons, wherein the dotted line is the calculated value by equation. The solid lines are the measured results.

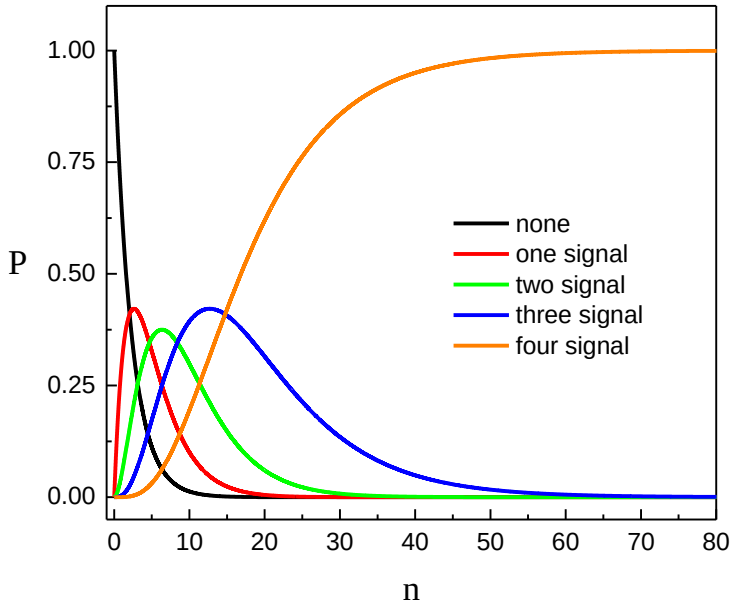
$$p = 1 - (1 - \eta)^n$$

Parameters measurement

(a)



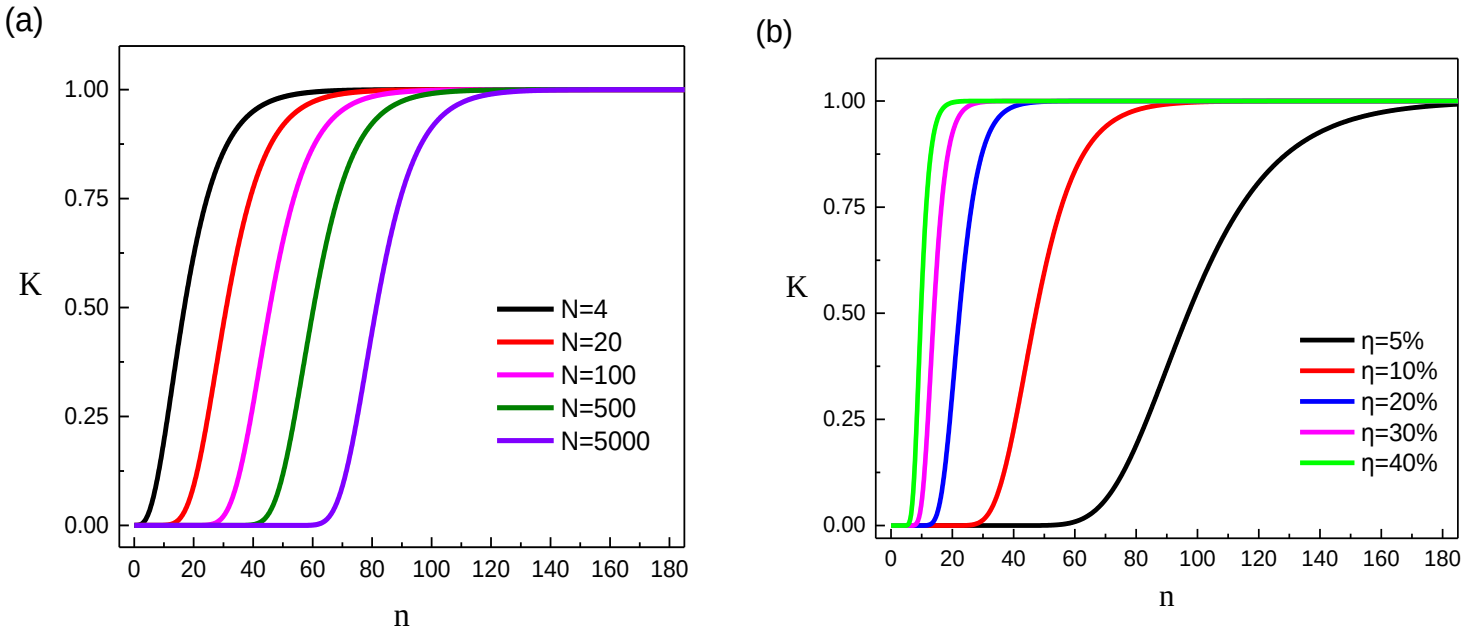
(b)



(a)The experimental values and (b) the calculated values of the detection array efficiency P as a function of the average number of incident photons n.

"None" means that all the detectors have no signals output, while "one signal" represents that only one detector has a signal output, and other color lines in the same manner.

Parameters measurement



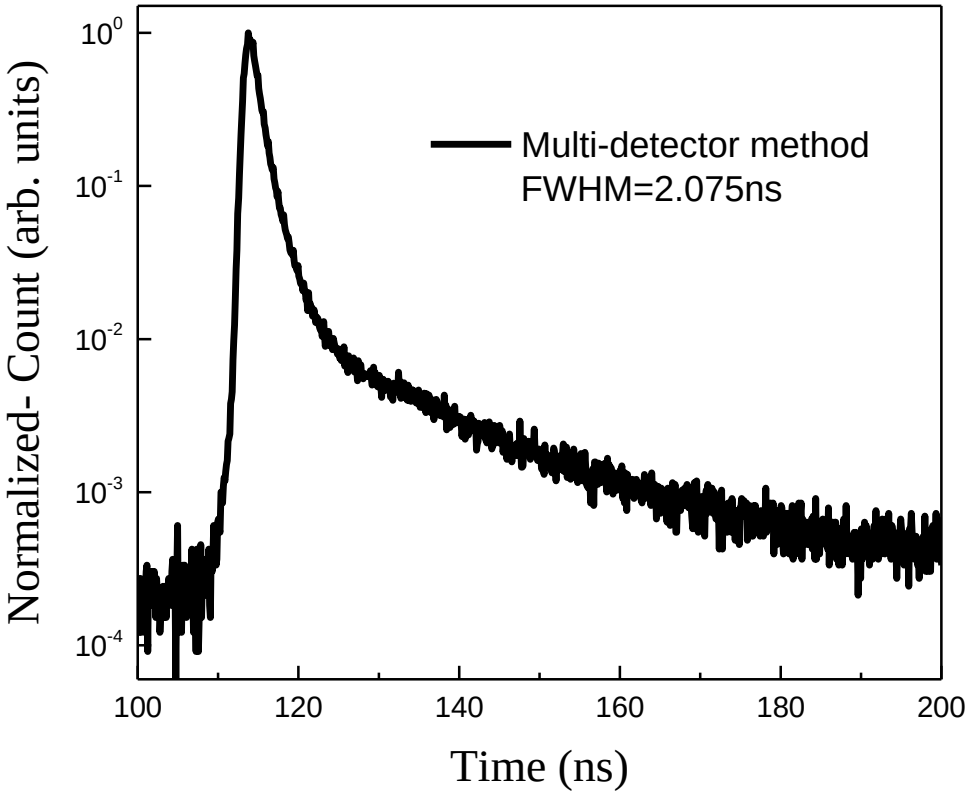
$$K = [1 - (1 - \eta)^n]^N$$

The probability K of all the cells having signals output as a function of three basic variables n, η and N.

(a) The variation of the probability K with different N and n when all the detector cells η equal to 10.3%.

(b) The K changing curve with different η and n fixing one hundred detector cells.

PALS result for positron burst in Iron sample

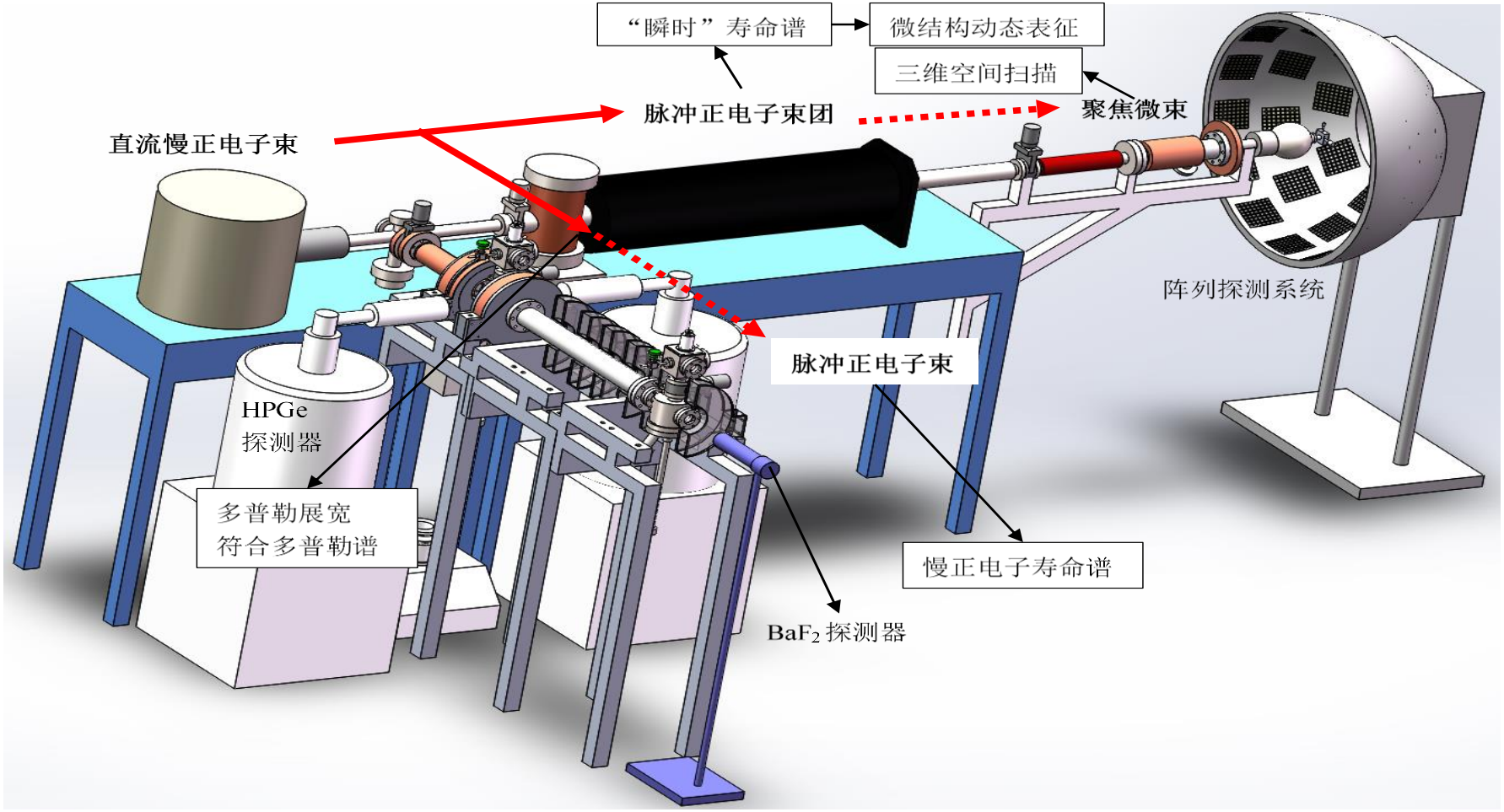


Positron burst annihilation lifetime spectroscopy of annealed Fe measured by four SiPM detectors array.

$$\tau^2 = \tau_T^2 + \tau_P^2 + \tau_R^2 + \tau_S^2$$

Lifetime system for positron burst in future

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

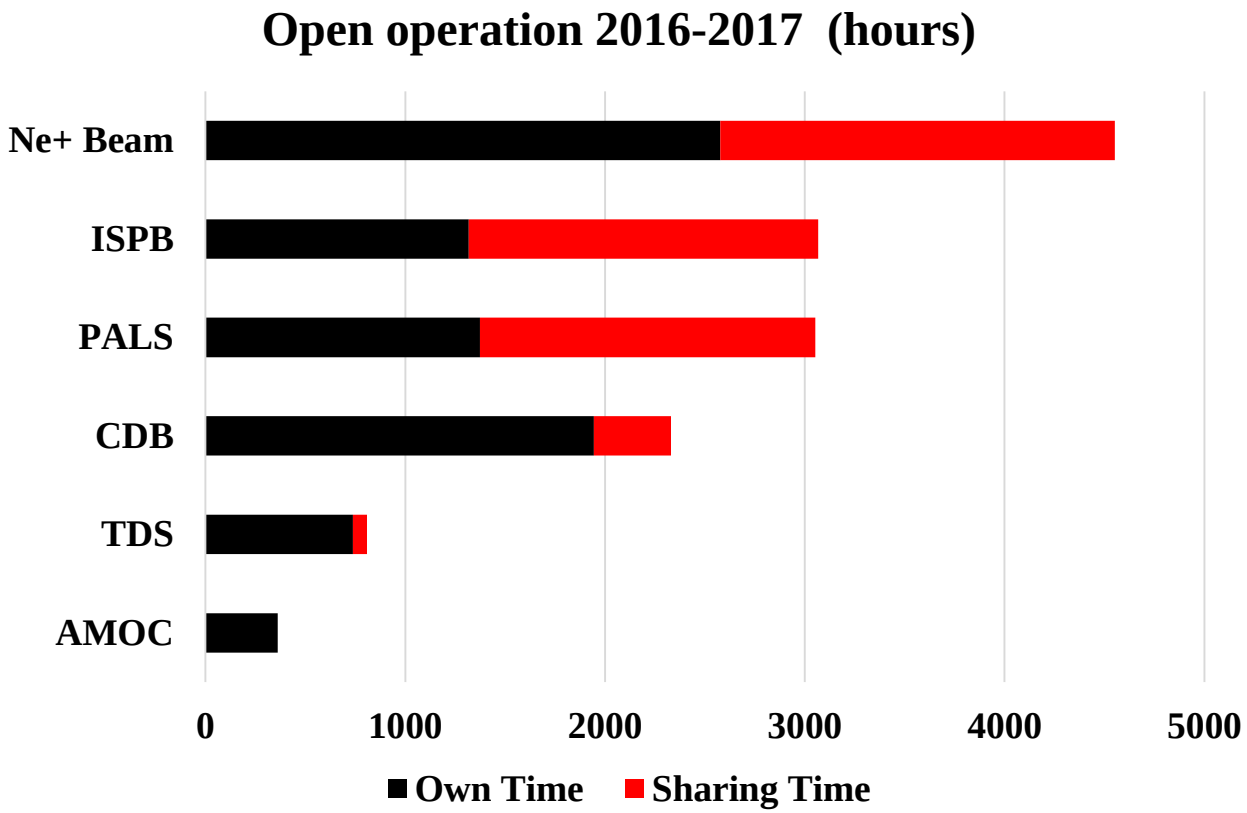


Application investigations autonomously

- Fe-Cu alloys （fund Project）
- Irradiation effect of structural materials （Project）
- Polymer materials （Project and cooperative research）
- Nanomaterial （cooperative research）
- Permeable membranes （cooperative research）

Research platform to users

Ne^+ Beam + Intense Slow Positron Beam + PALS + CDB + AMOC + TDS



Member of the Large Instrument Area of Material and Nanoscience in Beijing

Statistics for the open operation of slow positron beam

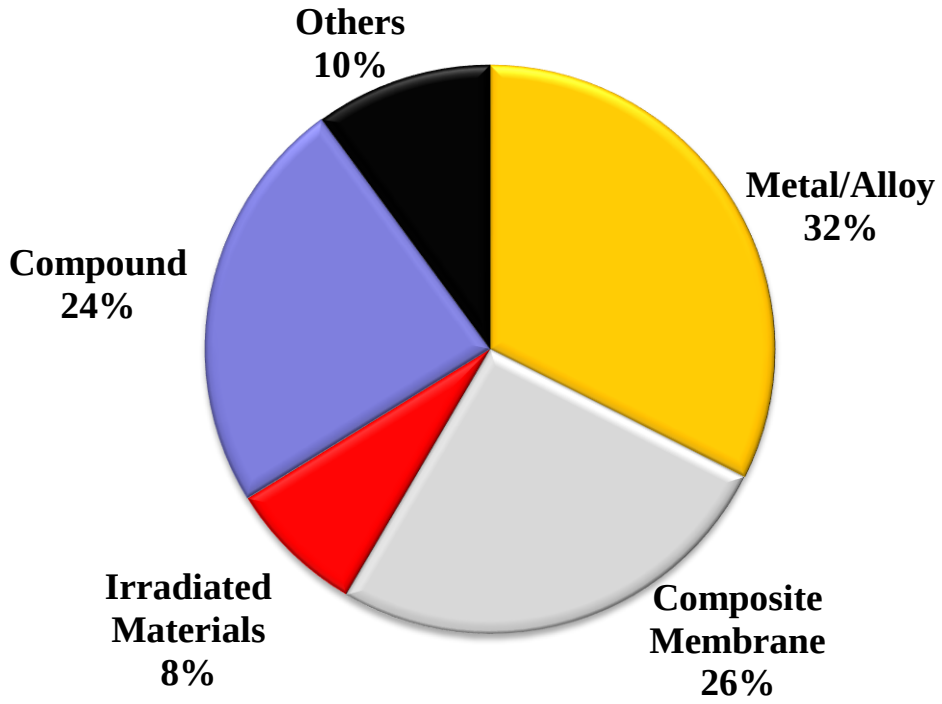
Intense Slow Positron Beam

+

Ne^+ Beam

- 22 institutes
- 38 batches
- 206 samples

Sample Category 2016-2017

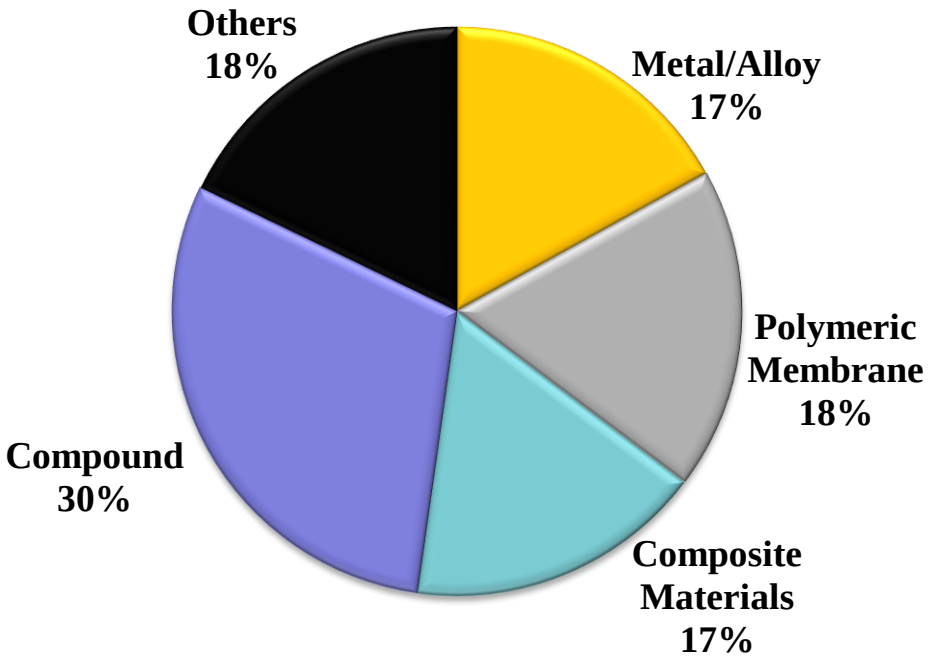


Statistics for the open operation of Conventional spectroscopy

PALS / DBES
+
CDB / AMOC

- 23 institutes
- 49 batches
- 285 samples

Sample Category 2016-2017



Application research

Deuterium occupation of vacancy-type defects in argon-damaged tungsten exposed to high flux and low energy deuterium plasma

Nucl. Fusion **56** (2016) 036010 X.-L. Zhu *et al*

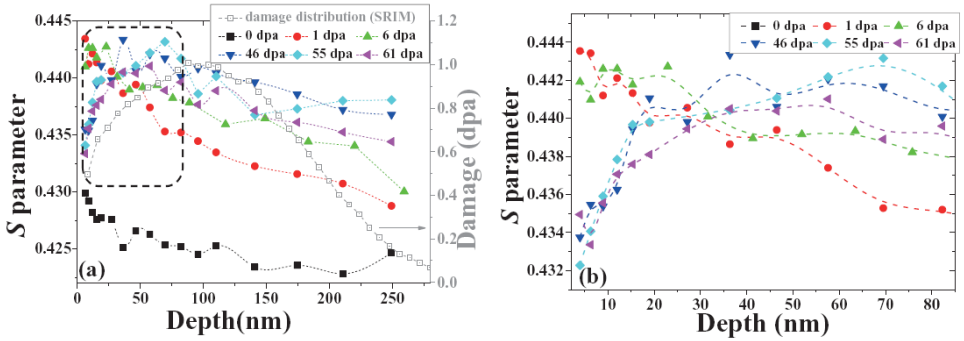
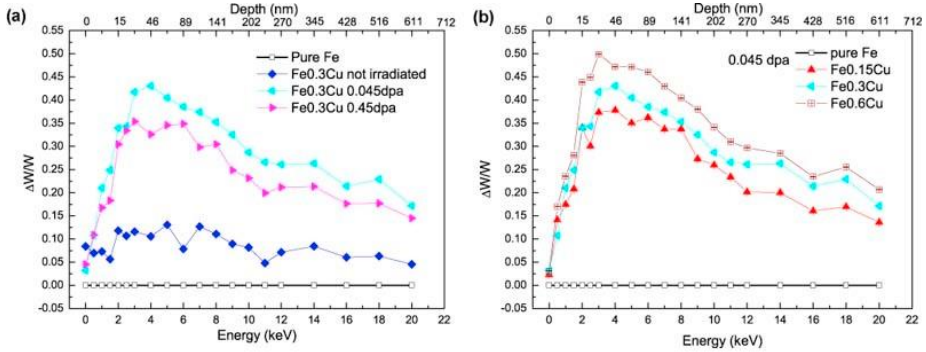
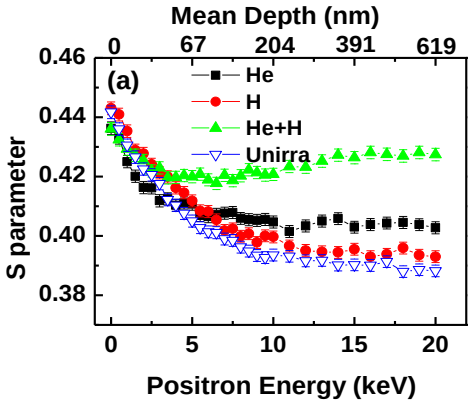


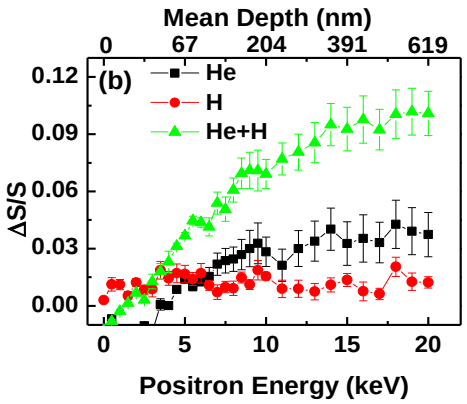
Figure 3. The *S* parameter versus depth (dash line spline fitting) in the tungsten samples. 0 dpa is the pristine tungsten sample without argon irradiation. The depth (nm) in the *X*-axis is calculated from the positron energy, *E* (keV), by the equation depth = (40/19.35)*$E^{1.6}$. The depth distribution of the damage in 1 dpa sample is shown in (*a*) for reference and the pane in (*a*) is enlarged in (*b*).

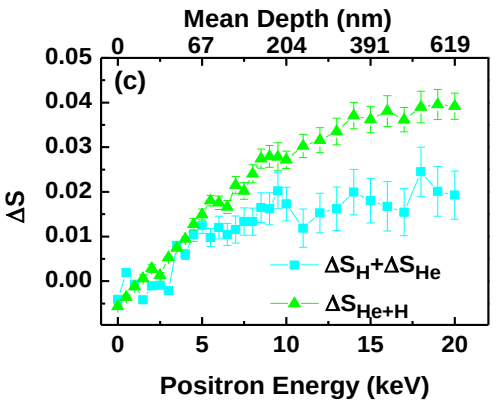
The effect of the irradiation dose, the irradiation depth and the Cu content on the Cu coverage fraction of the defects has been investigated by PAS



Application research





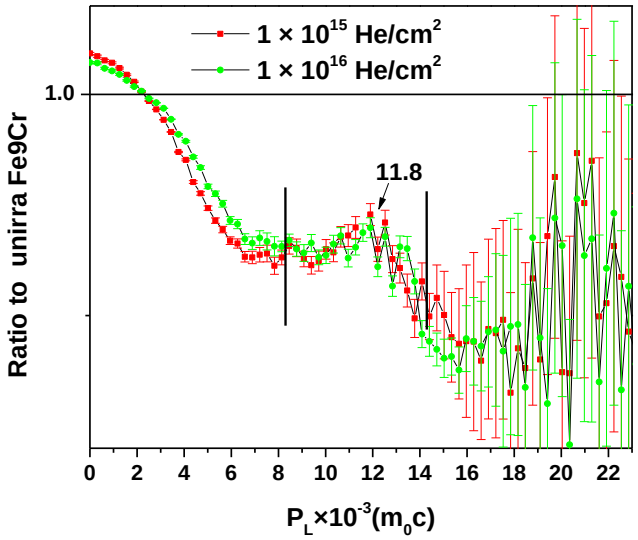


PHILOSOPHICAL MAGAZINE, 2016
http://dx.doi.org/10.1080/14786435.2015.1131901
Taylor & Francis
Taylor & Francis Group

Helium/hydrogen synergistic effect in reduced activation ferritic/martensitic steel investigated by slow positron beam

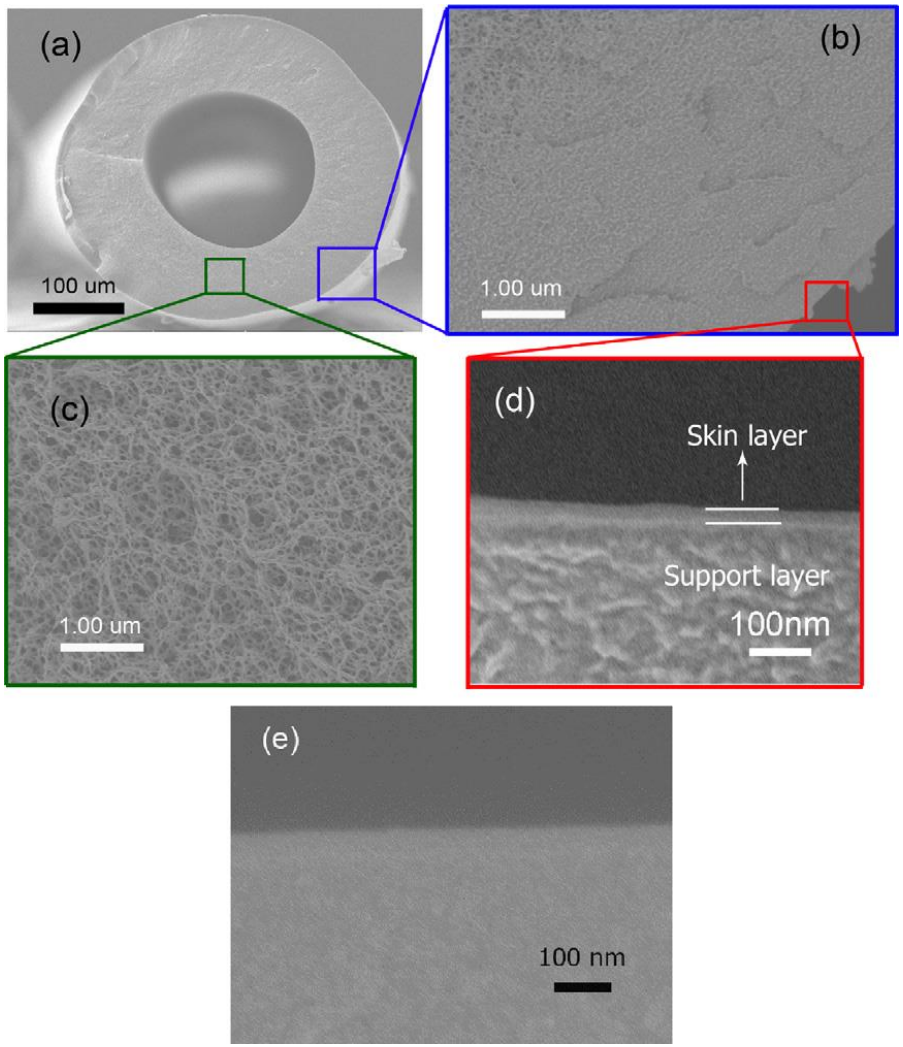
Te Zhu[a,b], Shuoxue Jin[a], Liping Guo[c], Yuanchao Hu[a], Eryang Lu[a], Jianping Wu[b], Baoyi Wang[a], Long Wei[a] and Xingzhong Cao[a]

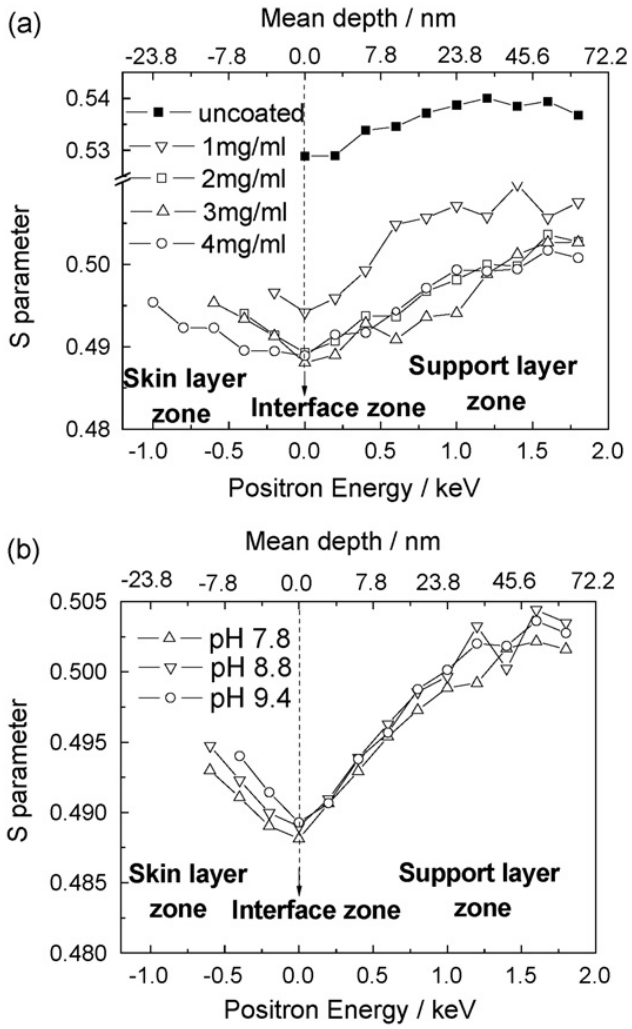
[a]Multidiscipline Research Center, Institute of High Energy Physics, CAS, Beijing, China; [b]College of Nuclear Technology and Automation Engineering, Chengdu University of Technology, Chengdu, China; [c]School of Physics and Technology, Wuhan University, Wuhan, China



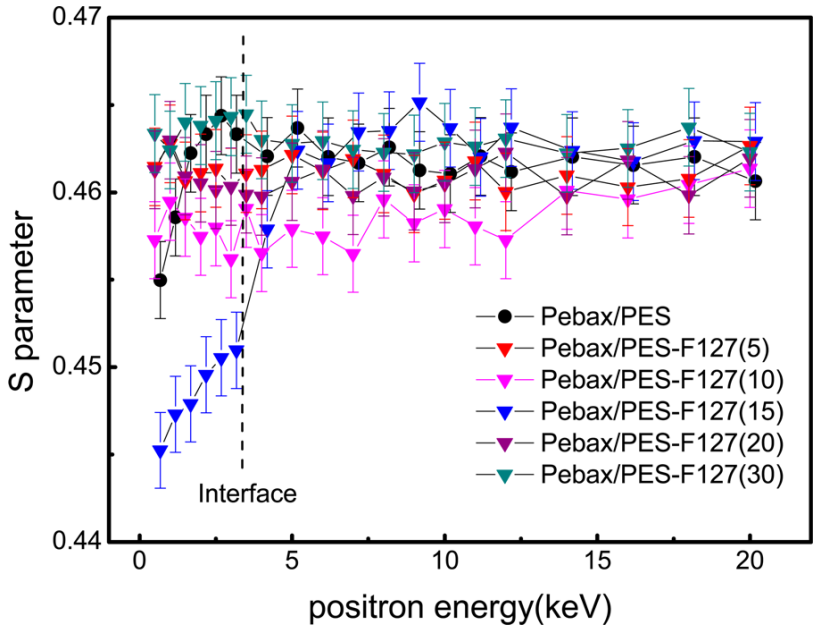
Effect of helium on electron density surroundings in positron annihilation site

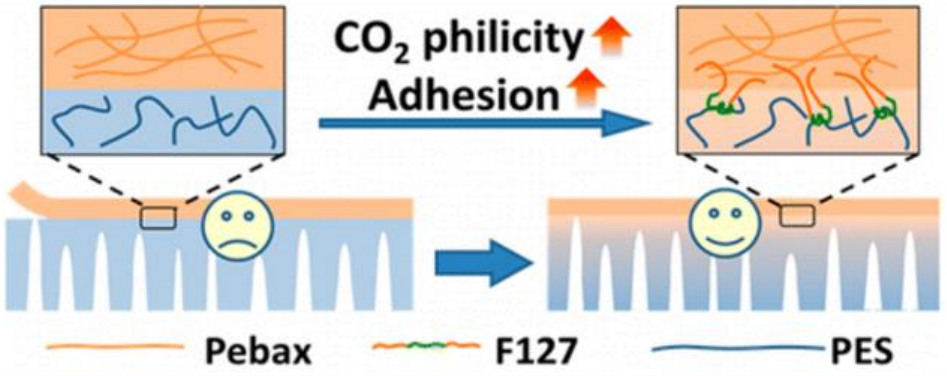
Application research



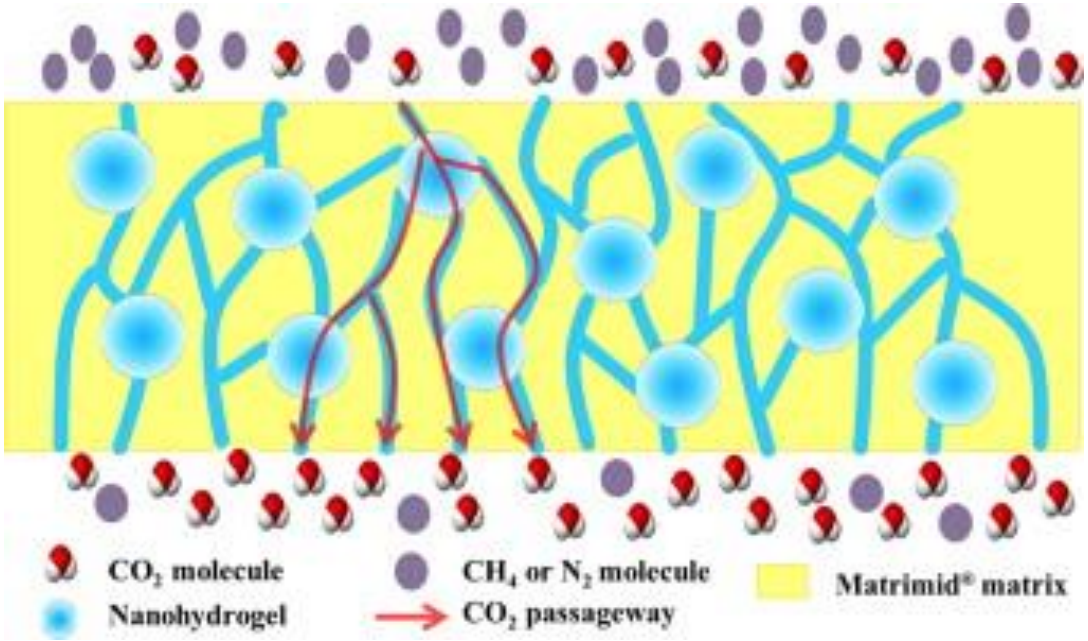


Application research





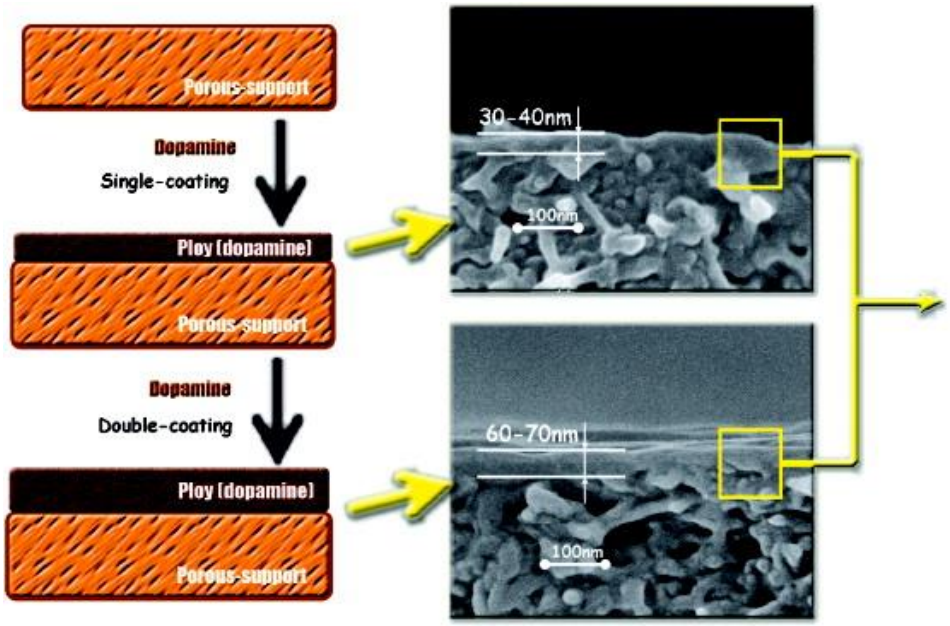
Application research

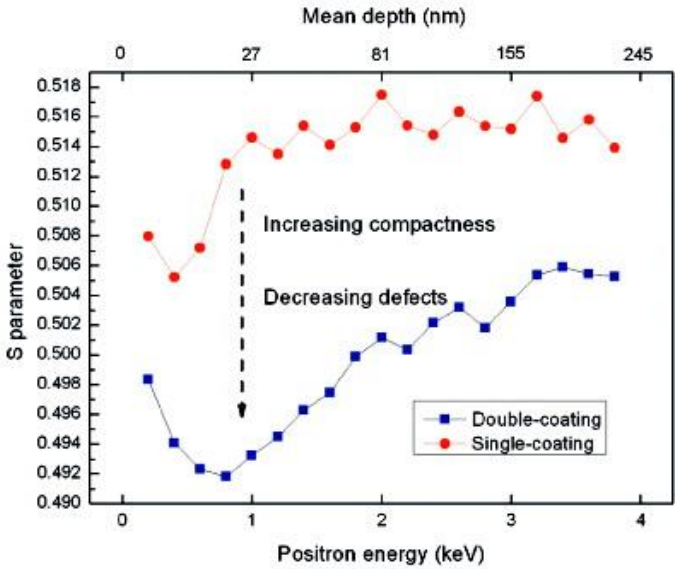


Free volume parameters of pure Matrimid® membrane and Matrimid®/NHs composite membranes.

Membrane	I_3 (%)	τ_3 (ns)	I_4 (%)	τ_4 (ns)	r_3 (nm)	r_4 (nm)	F_3	F_4	F_v
Matrimid®	8.30	0.678	3.78	2.852	0.099	0.353	0.035	0.696	0.731
Matrimid®/NHs-5	9.90	0.648	4.45	2.726	0.091	0.344	0.031	0.759	0.790
Matrimid®/NHs-10	10.10	0.662	4.86	2.691	0.095	0.341	0.036	0.807	0.843
Matrimid®/NHs-15	17.00	0.548	5.48	2.557	0.054	0.331	0.011	0.832	0.843
Matrimid®/NHs-20	6.53	0.818	5.54	2.686	0.132	0.341	0.063	0.920	0.983

Application research





New and typical user results

In May 2017, the international TOP journal Advanced Materials published online (IF: 17.9) new progress on the new hydrogen nanomaterial 1T-MoSe2 by Prof. Bo Song from Harbin industrial university.

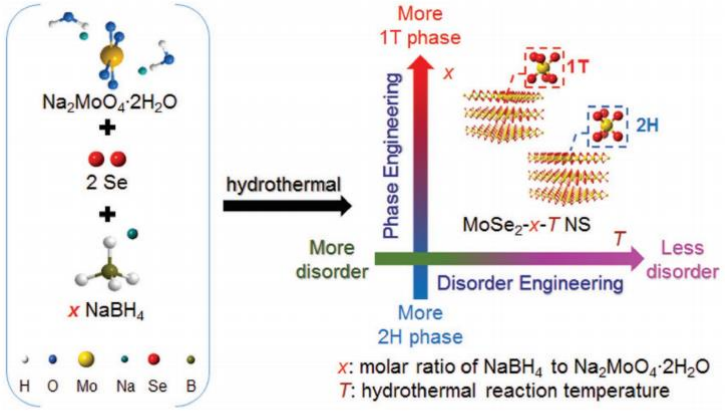


Figure 1. Schematic illustration of the phase- and disorder-controlled synthesis of $MoSe_2$ NSs through a hydrothermal technique by tuning the amount of $NaBH_4$ reductant relative to that of $Na_2MoO_4{\cdot}2H_2O$ (x) and the hydrothermal reaction temperature (T).

Table 1. Summary of the phase content, electrocatalytic performance parameters, and positron lifetime parameters for various $MoSe_2$ samples.

Samples	Phase Content		η (vs RHE) for $j = -10$ mA cm^{-2} [mV]	Tafel slope [mV dec^{-1}]	C_{dl} [mF cm^{-2}]	R_{ct} [Ω]	Positron lifetime parameters			
	2H	1T					τ_1 [ps]	I_1 [%]	τ_2 [ps]	I_2 [%]
$MoSe_2$-1-180	100	0	355	146	0.4	147	182 ± 6	48 ± 3	328 ± 8	50 ± 3
$MoSe_2$-4-140	91	9	211	72	1.25	58	176 ± 7	45 ± 3	323 ± 7	53 ± 3
$MoSe_2$-4-160	57	43	197	54	14.7	36	179 ± 3	49 ± 2	331 ± 6	48 ± 2
$MoSe_2$-4-180	45	55	152	52	27.8	16	183 ± 5	51 ± 2	347 ± 6	46 ± 2
$MoSe_2$-4-200	52	48	163	55	25.2	23	183 ± 4	54 ± 2	343 ± 6	43 ± 2

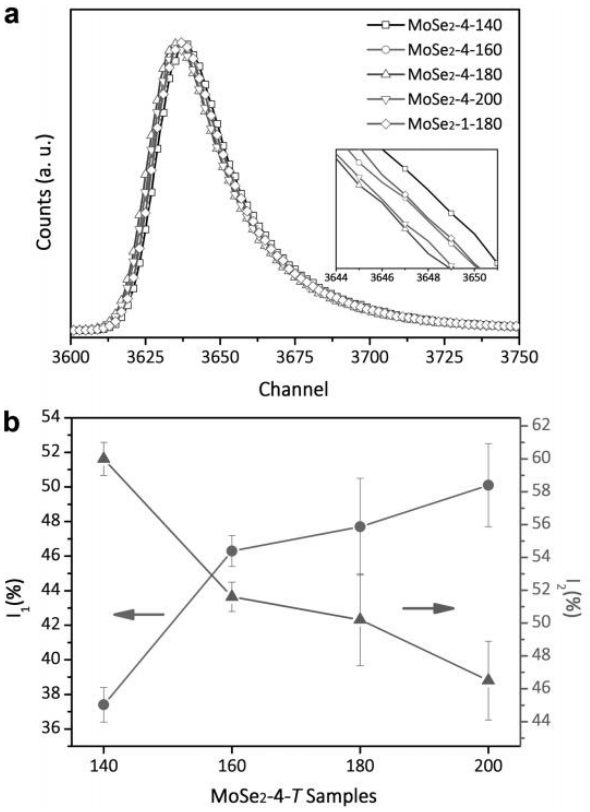
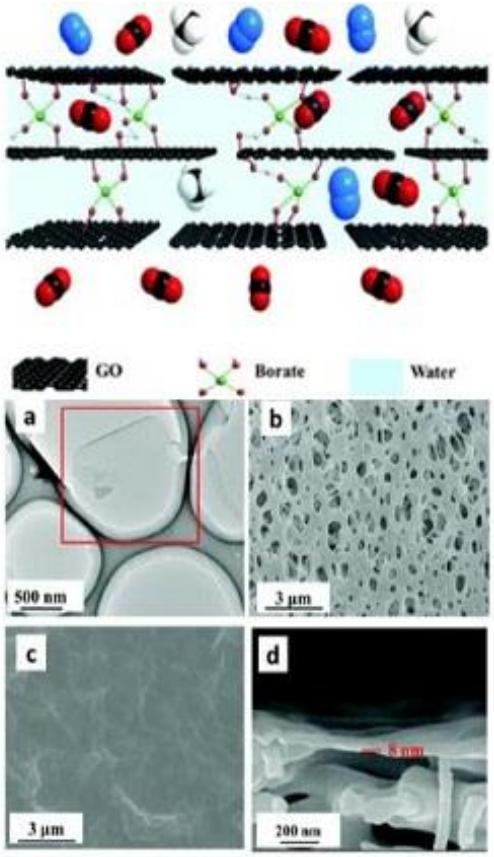


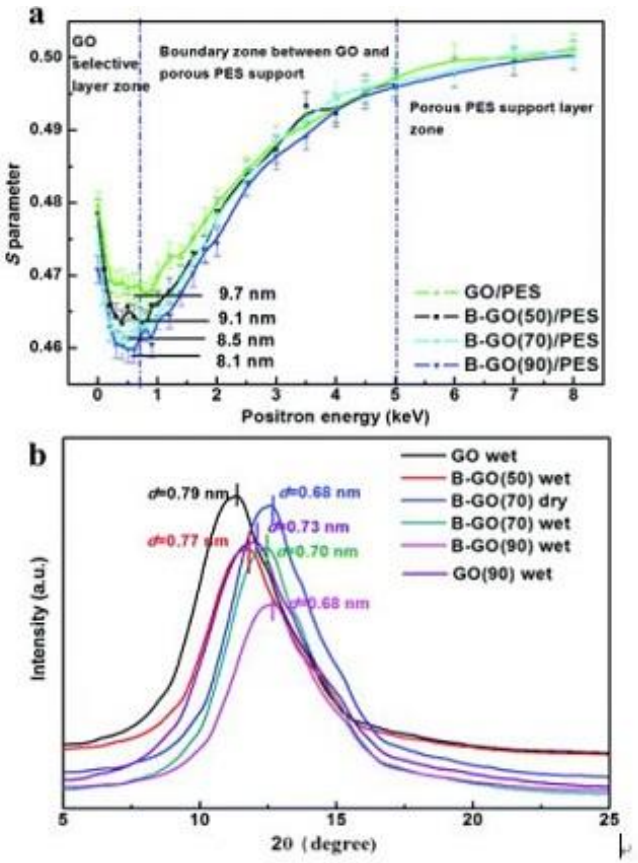
Figure 4. a) Positron lifetime spectra of the $MoSe_2$-1-180 and the series of $MoSe_2$-4-T samples. b) I_1 and I_2 as a function of the reaction temperature for the $MoSe_2$-4-T samples with ratio of $NaBH_4$ to $Na_2MoO_4{\cdot}2H_2O$ is 4:1.

© 2017 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

New and typical user results

A paper entitled A highly permeable graphene oxide membrane with fast and selective transport nanochannels for efficient carbon capture from Zhongyi Jiang's group of Tianjin University was recently published in Energy & Environmental Science (IF25.427), a top journal of the Royal Society of Chemistry.





Summary

1) Some New types of detectors especially using SiPM for nuclear imaging is studied & used in dedicated PET system with good performance (PET&MRI)
2) Some measuring systems are working based on the Ne^{+}-positron beam.
3) A new method of PALS for positron burst (pulse) was proposed & primally studied, a detector & electronical system for positron burst were designed with 2048*2048 cells.
4) Some application examples were concluded

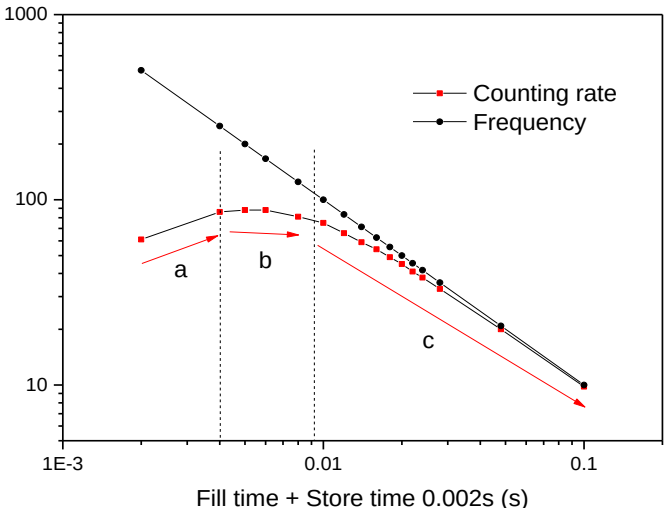
Thanks for your attention!

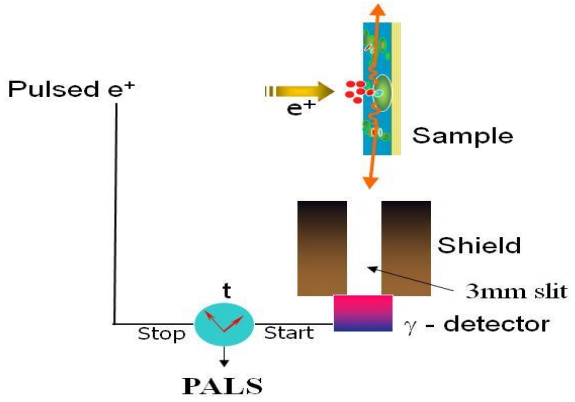
Beam intensity&count rate

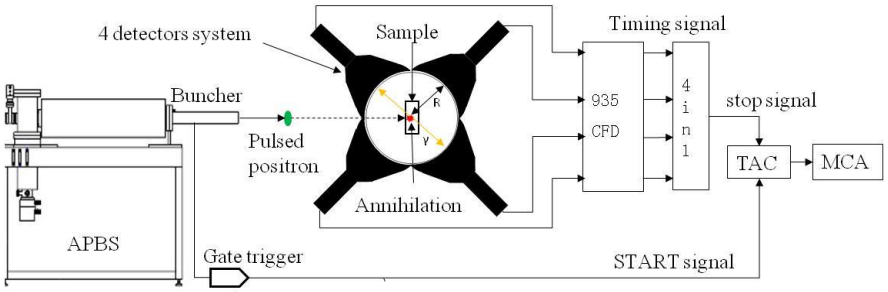
1. Frequency=1 / (Fill time + Store time + Dump time) ≤500Hz

Fill time≥1ms，Store time≥0.75ms，Dump time ≥0.25ms

2. Fill time → pulsed beam intensity







The pulsed beam intensity should be set ensure that no more than one output signal for a pulse