CHARACTERIZATION OF THE NEUTRON BEAM AT THE RADIATION RESISTANCE TEST FACILITY IN GATCHINA

O.A. Shcherbakov, A.S. Vorobyev, A.M. Gagarski, L.A. Vaishnene
E.M. Ivanov
National Research Center "Kurchatov Institute"
B.P. Konstantinov Petersburg Nuclear Physics Institute, Gatchina, Russia

V.S. Anashin, L.R. Bakirov, A.E. Koziukov
Branch of Joint Stock Company "United Rocket and Space Corporation"
Institute of Space Device Engineering, Moscow, Russia

XXII International Seminar on Interaction of Neutrons with Nuclei
ISINN-23, 25-29 May 2015, Dubna

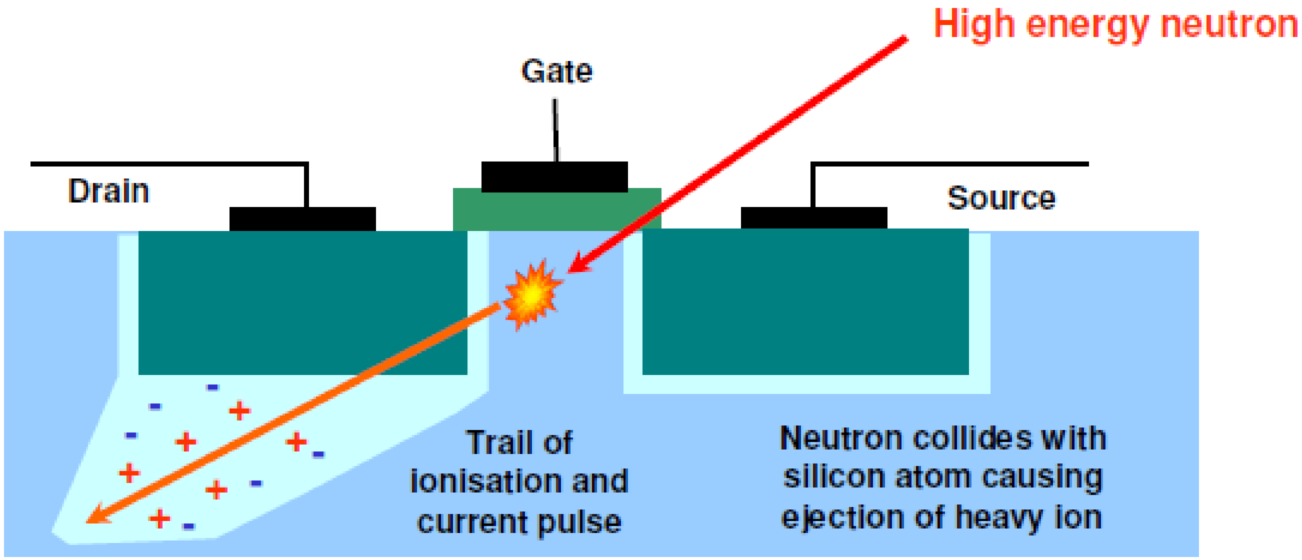
ISNP/GNEIS Facility in Gatchina for Neutron Testing with Atmospheric-Like Spectrum

O.A. Shcherbakov, A.S. Vorobyev, A.M. Gagarski, L.A. Vaishnene
E.M. Ivanov
National Research Center “Kurchatov Institute”
B.P. Konstantinov Petersburg Nuclear Physics Institute, Gatchina, Russia

V.S. Anashin, L.R. Bakirov, A.E. Koziukov
Branch of Joint Stock Company “United Rocket and Space Corporation”
Institute of Space Device Engineering, Moscow, Russia

International Conference
Radiation Effects on Components and Systems
RADECS-2015,14-18 September, Moscow

NEUTRON-INDUCED SOFT ERROR TESTING of Electronic Components Used for Terrestrial, Avionic and Space Equipment

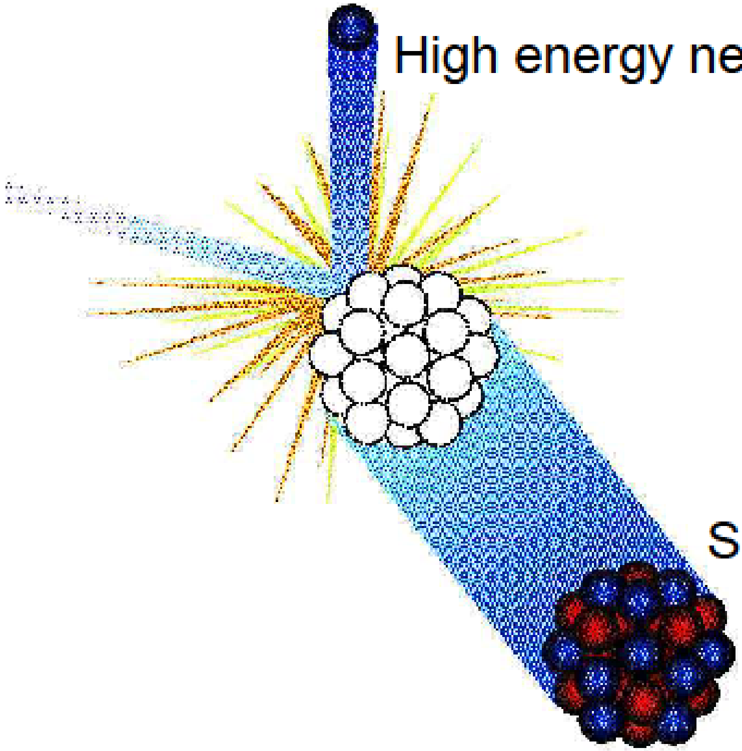


What are Single Event Effects and why are they important?

Single Event Effects are created when an energetic particle (alpha, neutron, heavy ion) generates enough charge (so-called critical charge) to upset the function of integrated circuit

Single Event Effect – SEE

ELASTIC ENERGY TRANSFER IN SILICON

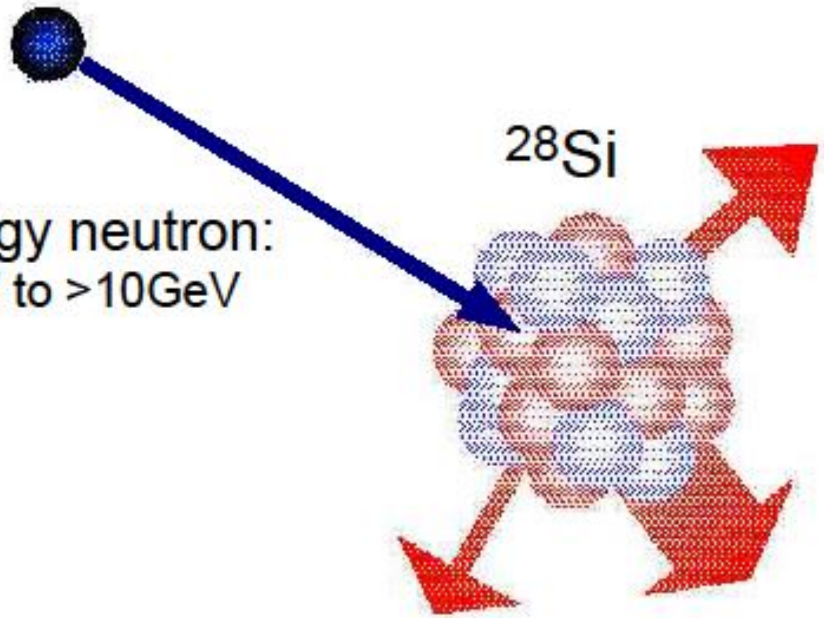


Energy and momentum from cosmic caused neutron can be transferred to a silicon or other IC nucleus.

Maximum recoil energy is 13.3-13.6% of incident neutron. For incident neutron of 100MeV => range up to 5μ (most < 2μ).

R. Baumann, Texas Instruments [1]

INELASTIC ENERGY TRANSFER IN SILICON



High energy neutron:
~100 MeV to >10GeV

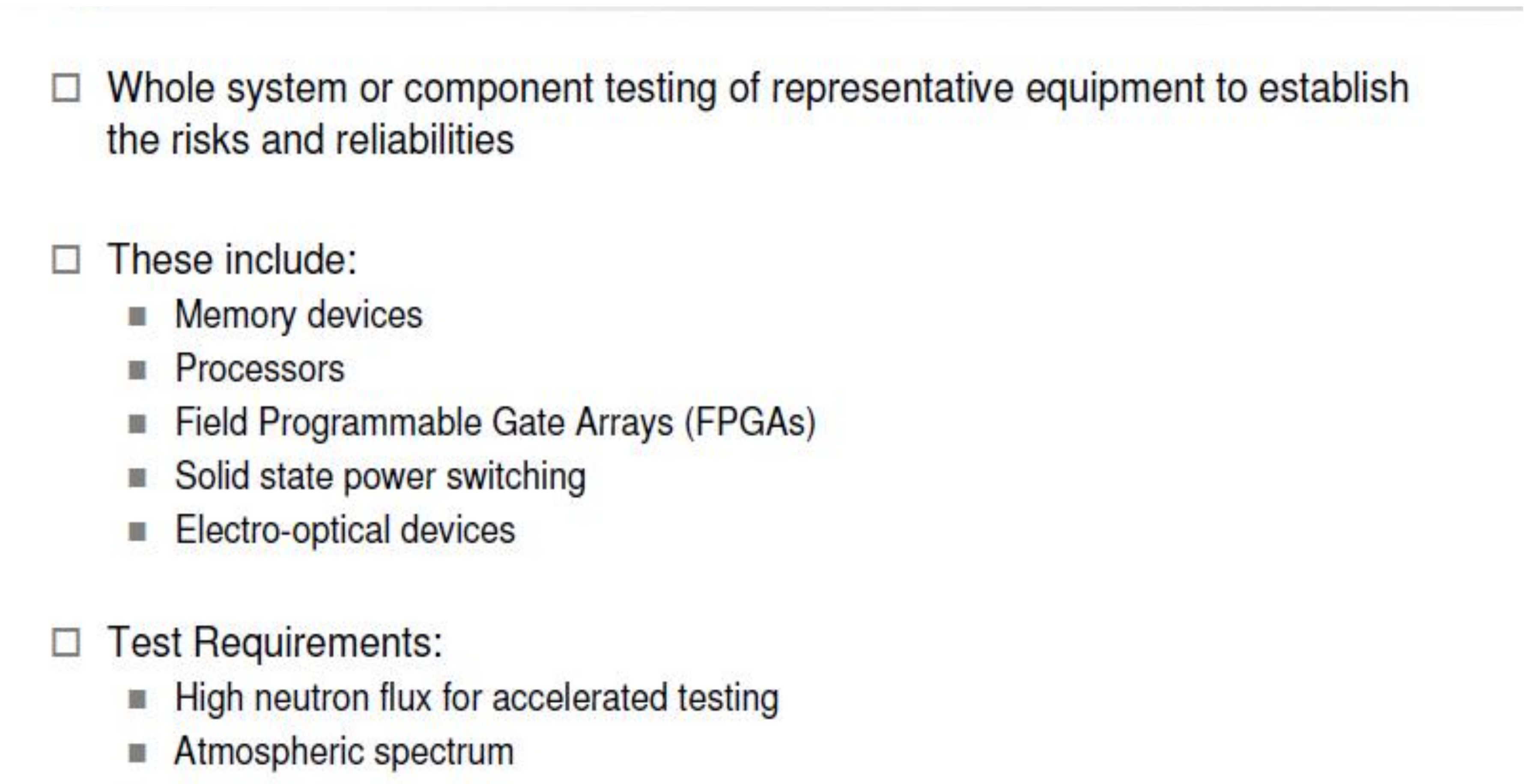
^{28}Si

^{28}Si nucleus fragments:
pions, *n*, *p*, ^{2}H, ^{3}H, ^{4}He, &
other light ions receive
energy from incident neutron.

Burst of
electronic
charge

R. Baumann, Texas Instruments [1]

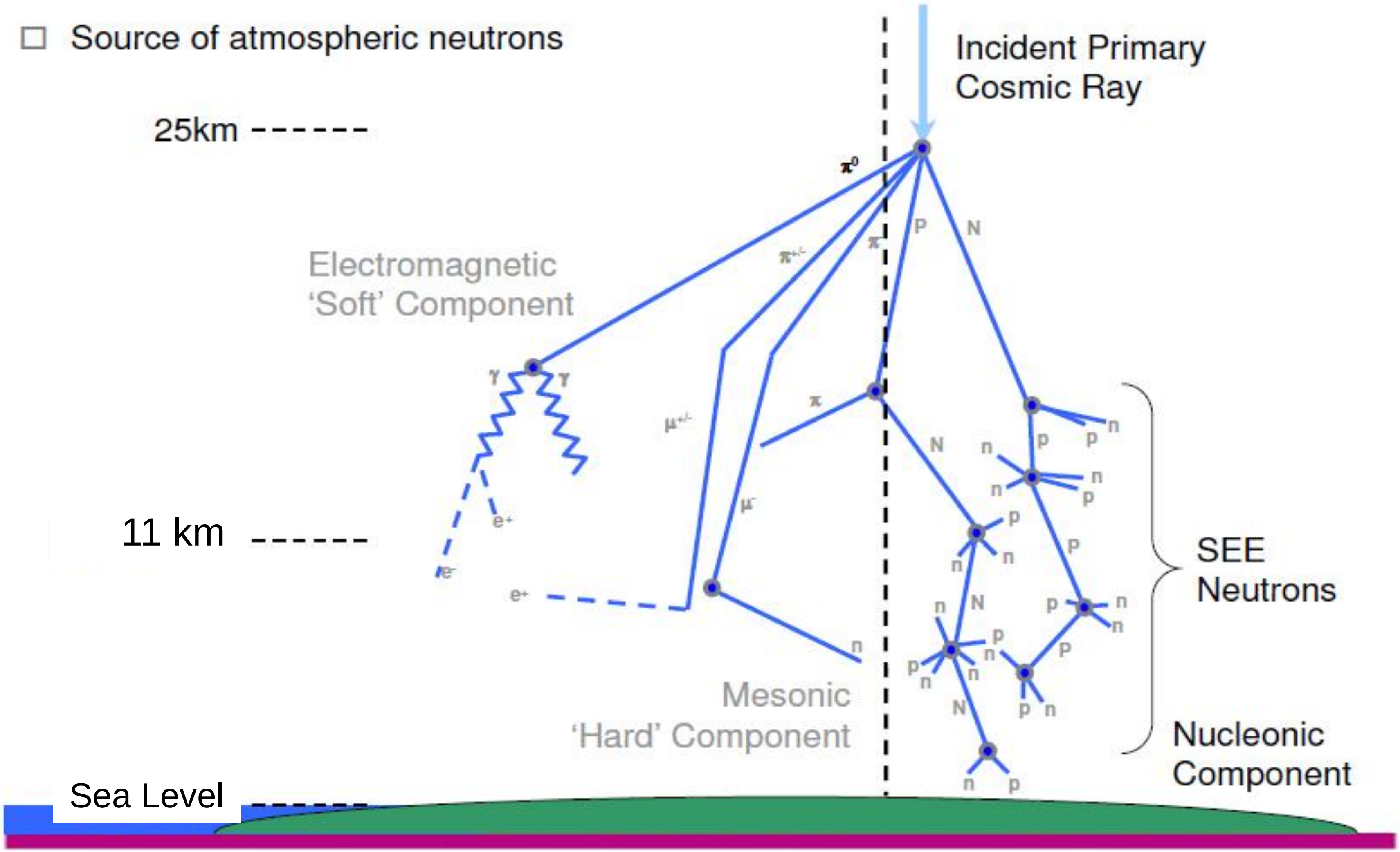
ACCELERATED NEUTRON TESTING OF SEE



- Whole system or component testing of representative equipment to establish the risks and reliabilities
- These include:
    - Memory devices
    - Processors
    - Field Programmable Gate Arrays (FPGAs)
    - Solid state power switching
    - Electro-optical devices
- Test Requirements:
    - High neutron flux for accelerated testing
    - Atmospheric spectrum

NEUTRON COMPONENT OF COSMIC RAYS

- ☐ Source of atmospheric neutrons



Incident Primary Cosmic Ray

Electromagnetic 'Soft' Component

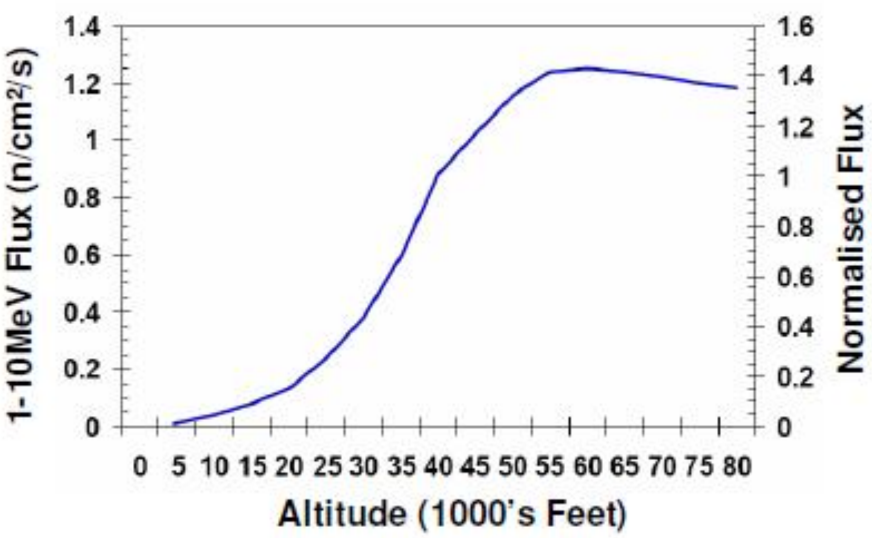
Mesonic 'Hard' Component

SEE Neutrons

Nucleonic Component

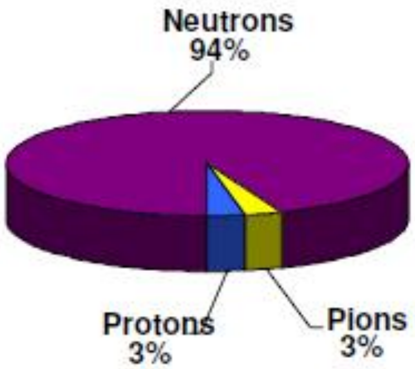
NEUTRON COMPONENT OF COSMIC RAYS

- Intensity and Composition with Altitude
  - ~ 300x Sea Level at flight altitudes

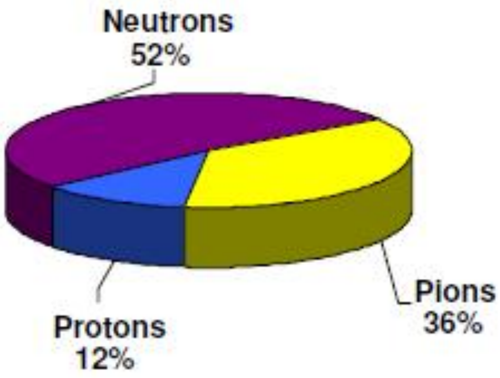


Source: Boeing Radiation Effects Lab

1000 Feet = 304.8 m



Sea Level

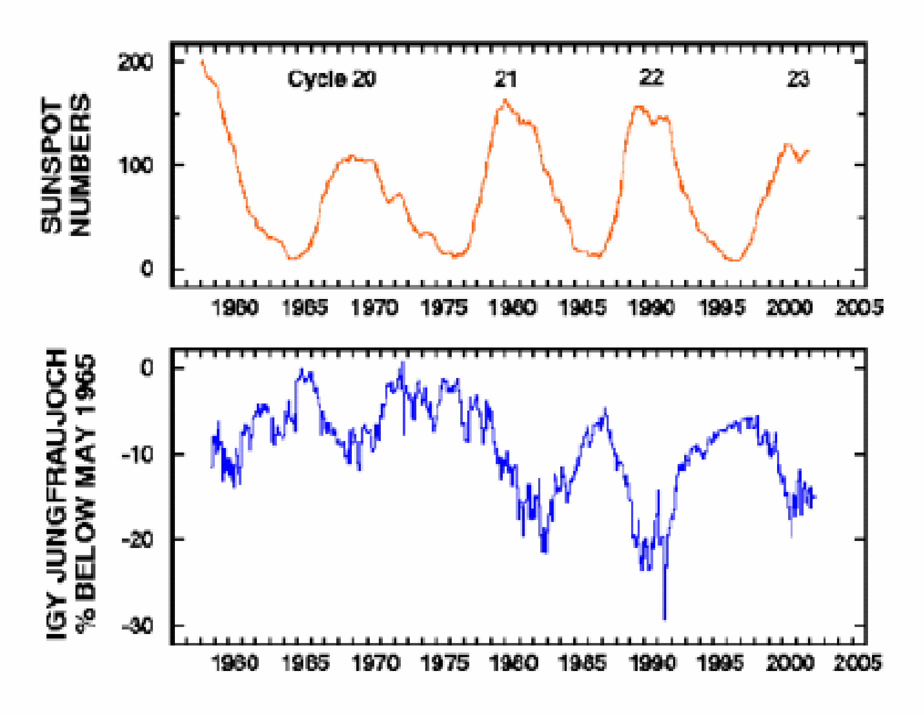


32,000 Feet

Source: JF Zilegler IBM J Res Dev 40, 19-40, (1996)

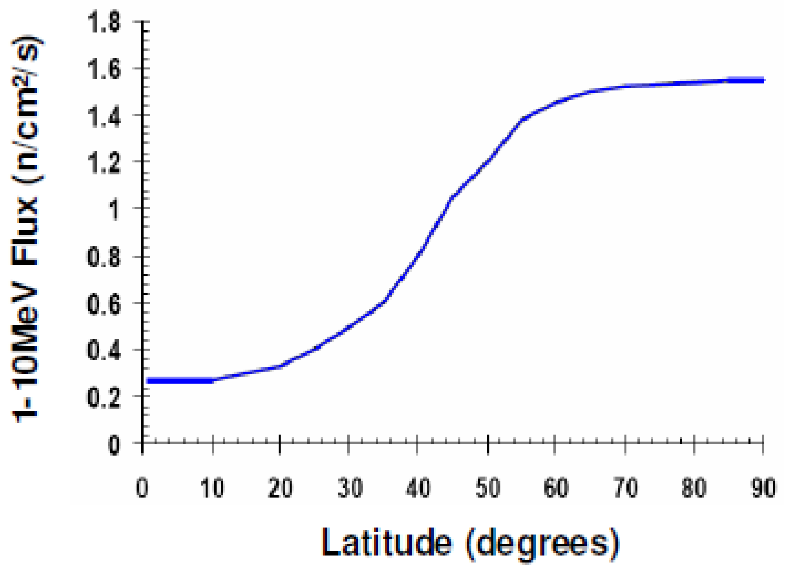
NEUTRON COMPONENT OF COSMIC RAYS

- ☐ Intensity with Latitude and Time



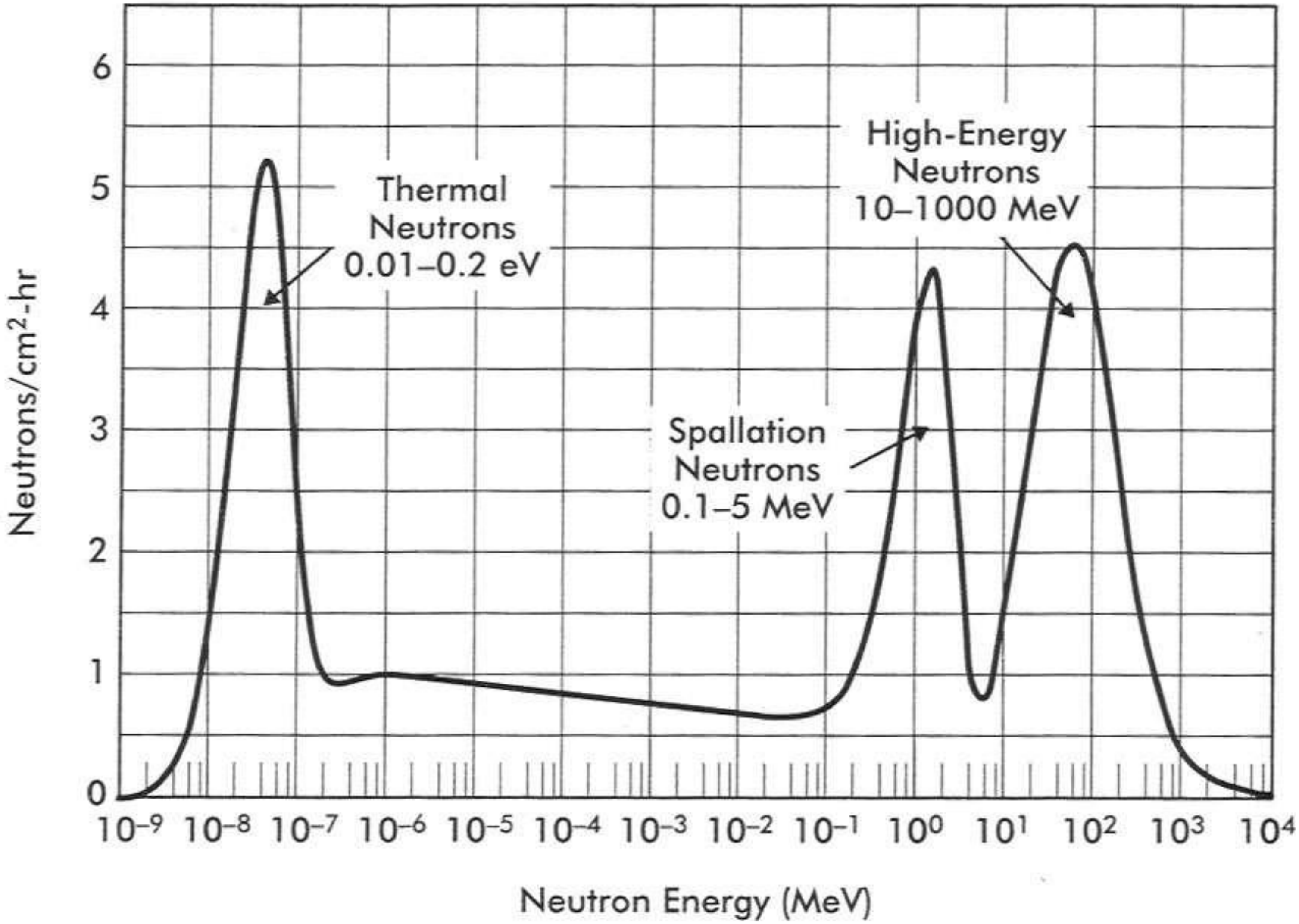
Source: Jungfraujoch neutron monitor data were kindly provided by the Cosmic Ray Group, Physikalisches Institut, University of Bern, Switzerland

Source: Boeing Radiation Effects Lab



Time of Day	<2%
Date in Year	<5%
Solar Cycle	<20%
Lat/Long	400-600%

TYPICAL SEA LEVEL NEUTRON FLUX



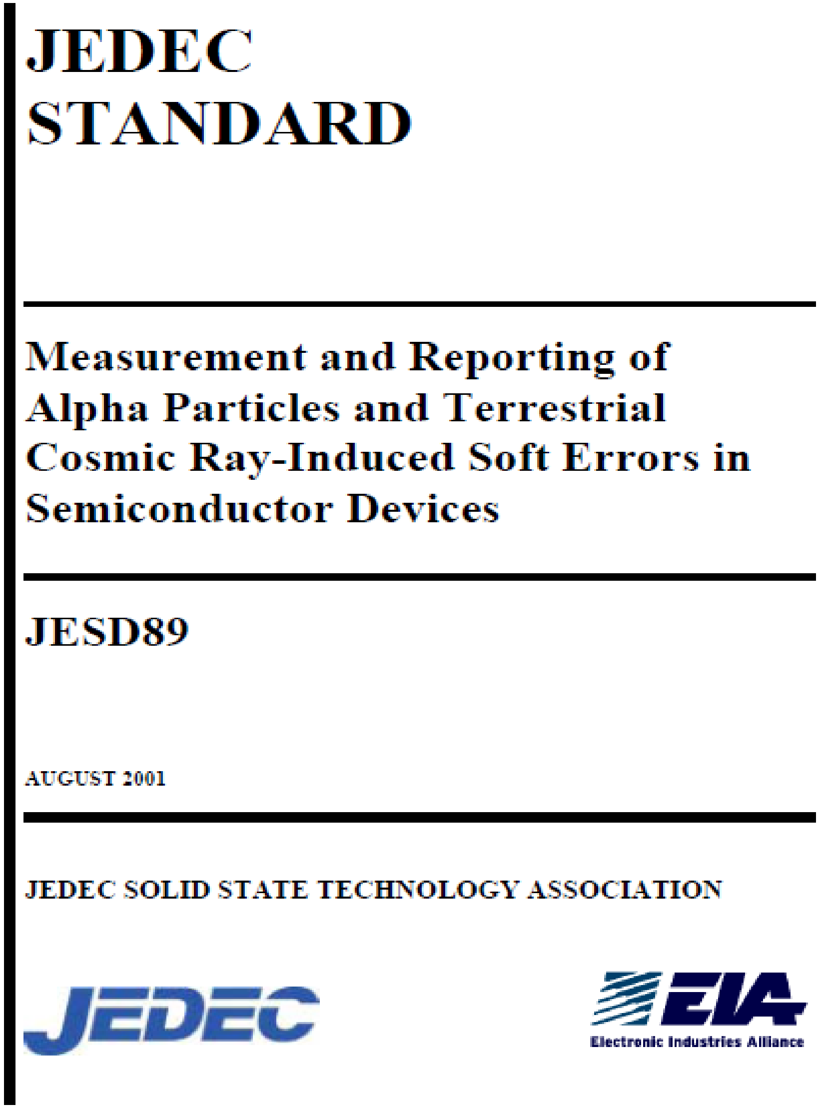
J.F. Ziegler & H. Puchner, SER-History, Trends and Challenges, Cypress. Semiconductors, 2004.

INTERNATIONAL STANDARD (by JEDEC)

Альянс предприятий электронной промышленности (Electronics Industries Alliance), до октября 1997 г. назывался Electronics Industries Association. Профессиональная организация в США, разрабатывающая электрические и функциональные стандарты с идентификатором RS (Recommended Standards). Самый известный из её стандартов - RS-232C.

В 1958 году в США Ассоциацией предприятий электронной промышленности был создан Объединённый инженерный совет по электронным устройствам (Joint Electronic Device Engineering Council - JEDEC).

В настоящее время JEDEC является мировым лидером по разработке открытых стандартов в микроэлектронной промышленности.
JEDEC насчитывает более 3000 членов, представляющих около 300 компаний.



JEDEC
STANDARD

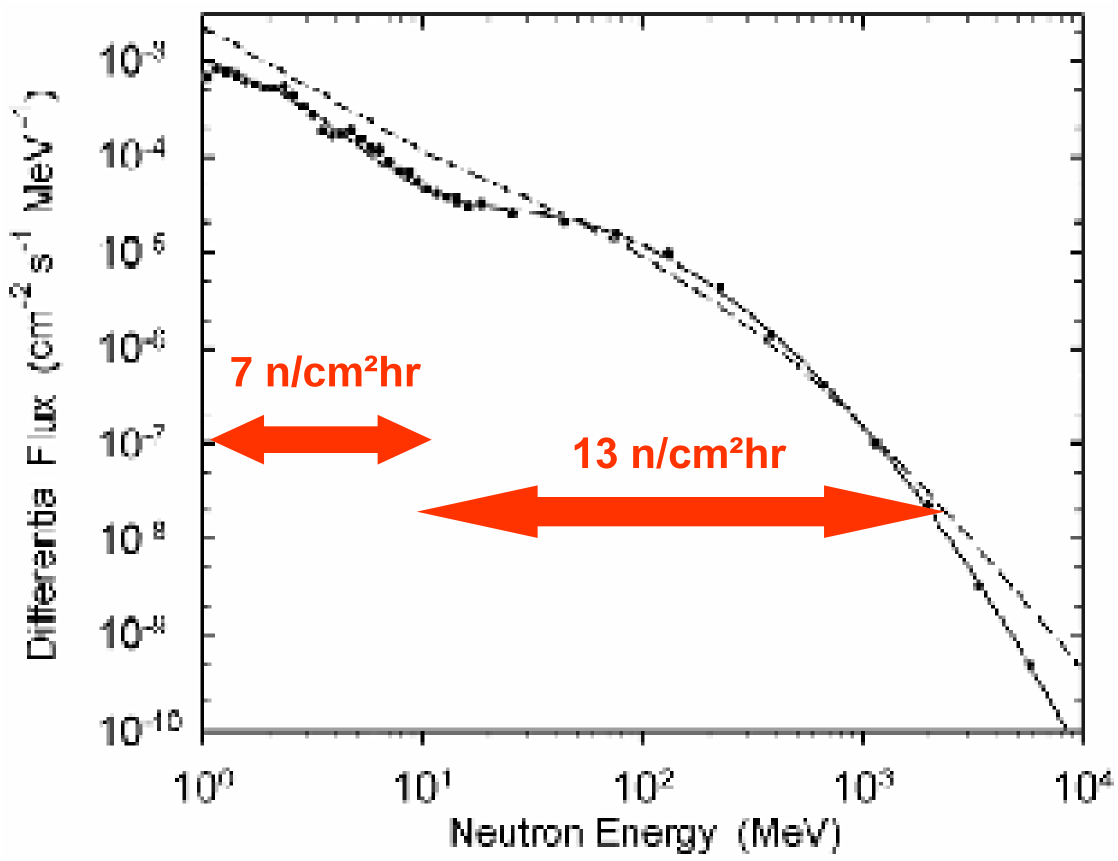
Measurement and Reporting of Alpha Particles and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices

JESD89

AUGUST 2001

JEDEC SOLID STATE TECHNOLOGY ASSOCIATION

JESD89A (2006)
STANDARD TERRESTRIAL NEUTRON SPECTRUME



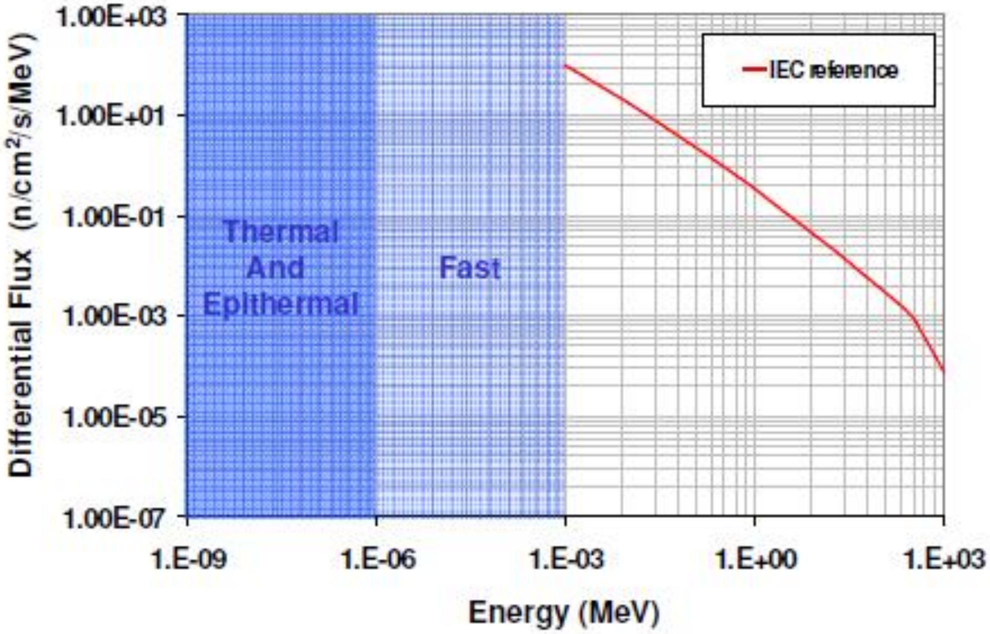
7 n/cm²hr

13 n/cm²hr

Figure A.2.1 — The differential flux of cosmic-ray-induced neutrons as a function neutron energy under reference conditions (sea level, New York City, mid-level so activity, outdoors). The data points are the reference spectrum, the solid curve is analytic fit to the reference spectrum, and the dashed curve is the model from previous version of this standard, JESD89 (2001).

INTERNATIONAL STANDARD (by IEC)

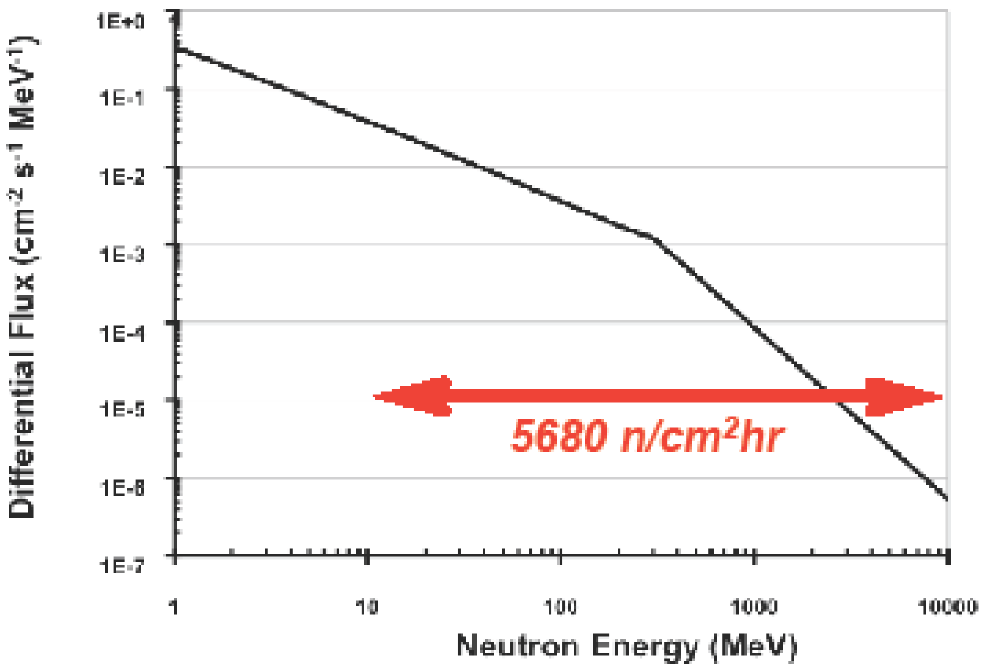
- ☐ Atmospheric Neutron Spectrum for SEE Testing
  - SEE effects above ~1MeV
  - Flux profile is IEC standard
    - ☐ International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes international standards for all electrical, electronic and related technologies.



$$\frac{dN}{dE} = 0.346E^{-0.922} \times \exp(-0.0152(LnE)^2) \quad \text{E<300 MeV}$$

$$\frac{dN}{dE} = 340E^{-2.2} \quad \text{E>300 MeV}$$

AVIONIC NEUTRON SPECTRUM AT 12 Km



- IEC Technical Specification TS 62396-1 *“Process Management for Avionics - Atmospheric Radiation Effects”*
- 400x more intense than terrestrial levels

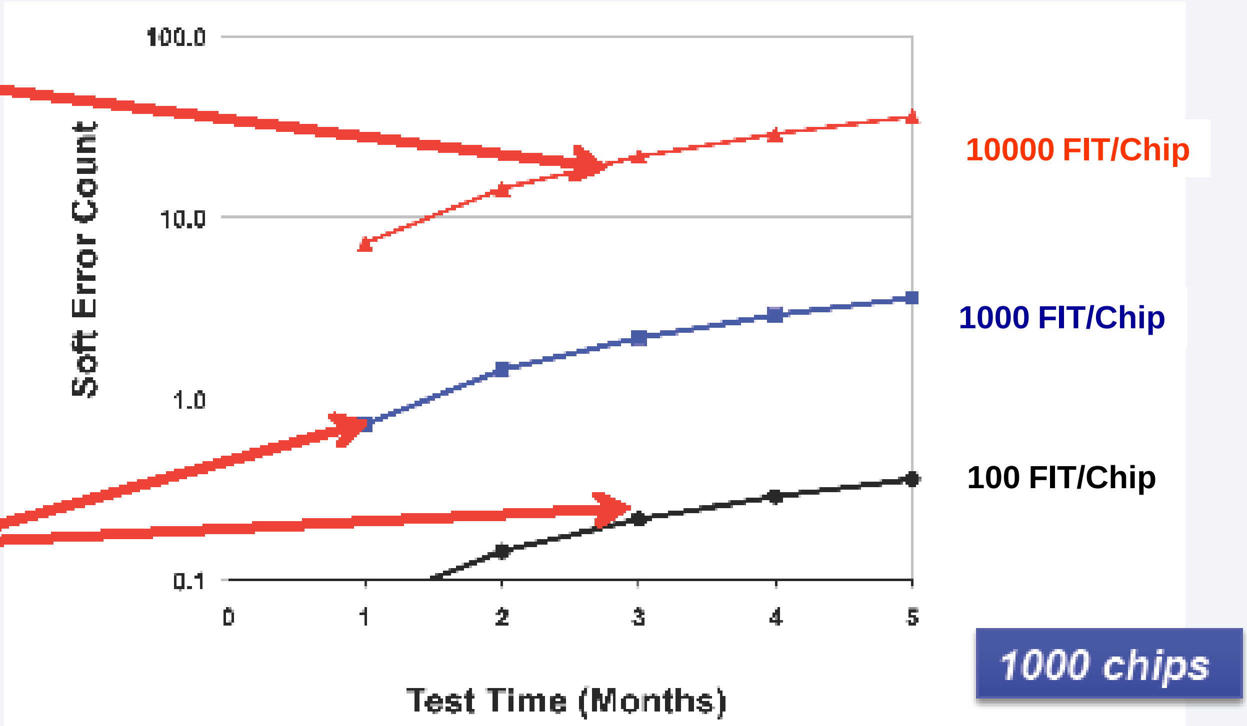
WHY ACCELERATED NEUTRON TESTING IS NEEDED?

For non-accelerated soft error testing:

Fail Count = (FIT/Chip) x (Number of Chips) x (Time-hr) x 10^{-9}

No significant error count will be observed unless soft error rate is >10,000 FIT/chip

For product with < 10,000 FIT/chip soft error rate, data is of limited statistical value



1000 chips

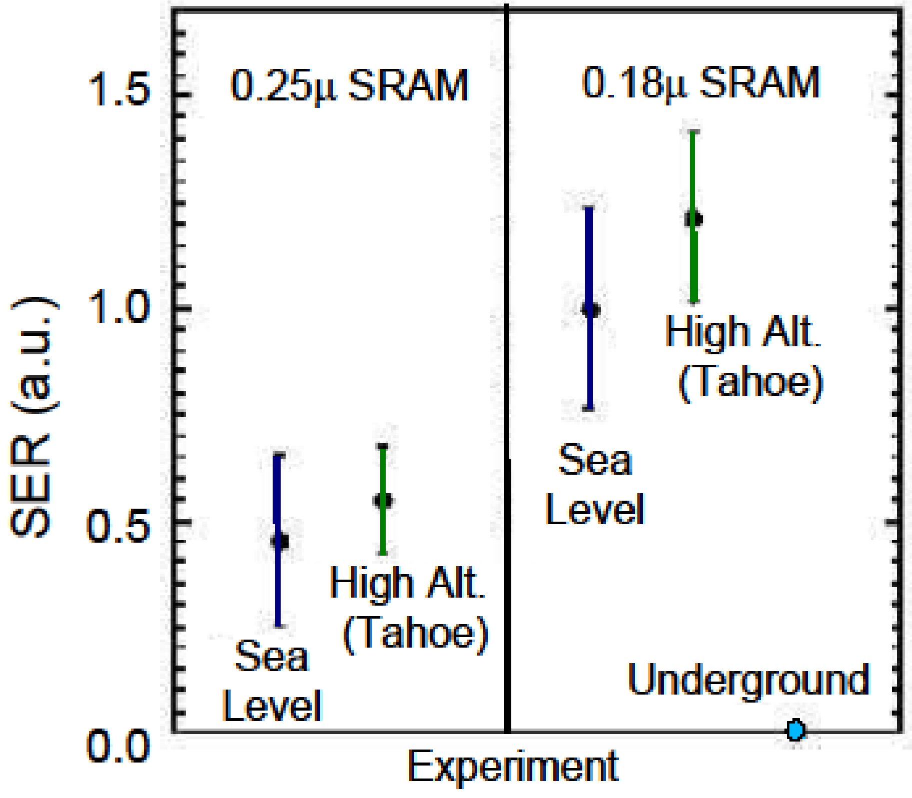
FIT: Failure In Time; 1 FIT is one error in 10^9 device-hours.

HIGH ALTITUDE SOFT ERROR TEST RESULTS

Testing at high altitude allows a 3 to 10x acceleration factor.

Neutron flux increases about 1.3x for each 1000 ft. altitude to >10,000 ft.

Testing can require months and thousands of devices under test.



H. Kobayashi, et. al., Sony [5].

FACILITIES FOR RADIATION TESTING WITH ATMOSPHERIC – LIKE NEUTRON SPECTRUM

🔵 Los Alamos National Laboratory, New Mexico, USA
  Weapons Neutron Research Facility
  ICE House ‘Irradiation of Chips and Electronics’

🔵 Tri-University Meson Facility, Vancouver, Canada
  Neutron Irradiation Facility

🔵 Uppsala University, Sweden
  Theodor Svedberg Laboratory
  ANITA Irradiation facility

🔵 Vesuvio, ISIS at the Rutherford Appleton Lab., Oxfordshire, UK
  Neutron Irradiation Facility

🔵 Research Center for Nuclear Physics at Osaka University (RCNP), Japan

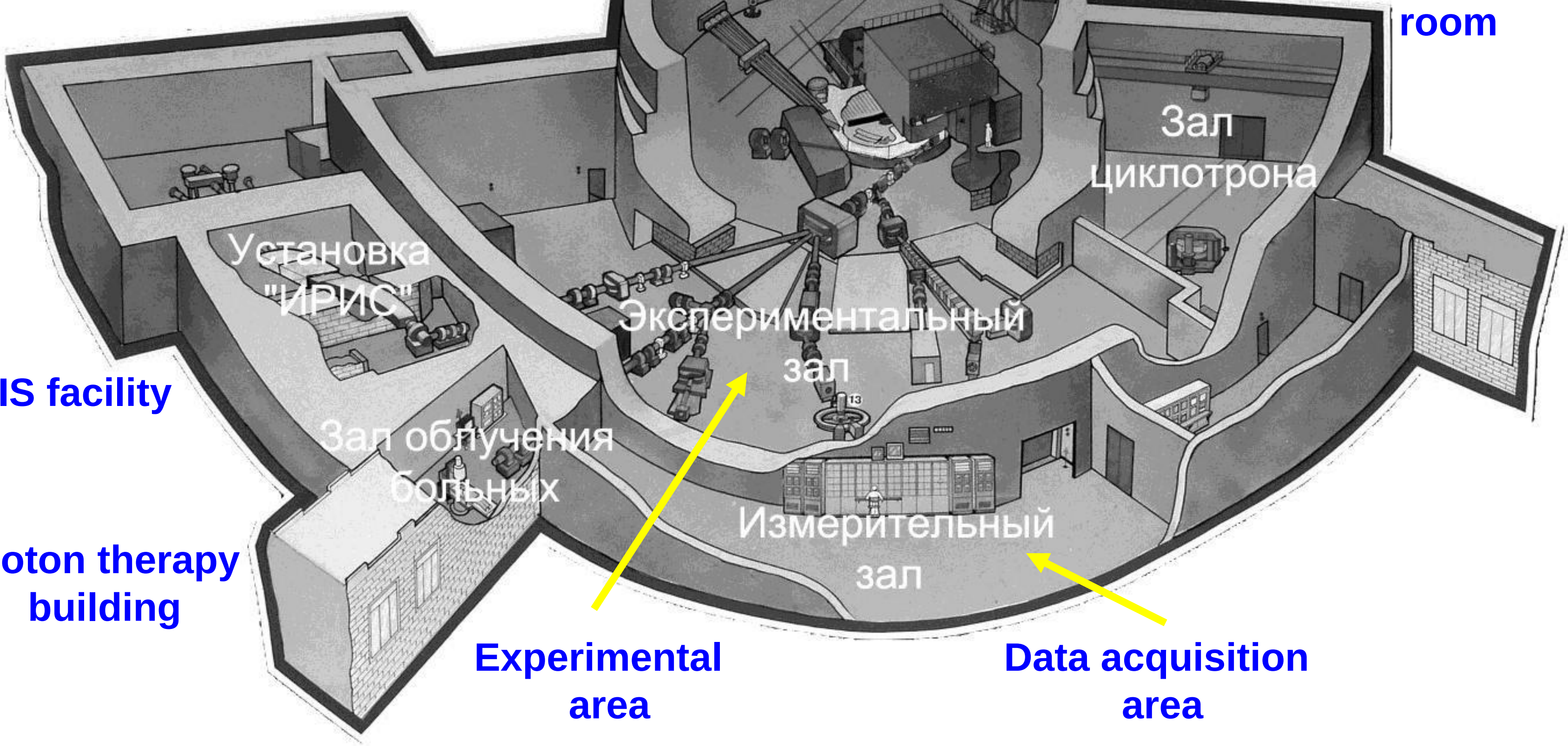
🔴 Petersburg Nuclear Physics Institute, Gatchina
  ISNP/GNEIS Neutron Irradiation Facility

ROSCOSMOS Test Facilities of the Branch of Joint Stock Company "United Rocket and Space Corporation" - Institute of Space Device Engineering (Moscow)
at
B.P. Konstantinov Petersburg Nuclear Physics Institute (Gatchina) of the National Research Center "Kurchatov Institute"

	IS SC - 1000	IS OP - 1000	IS NP - 1000
Conditions	Atmosphere	Atmosphere	Atmosphere
Particles	Protons	Protons	Neutrons
Energy, MeV	1000	200 - 1000	1 - 1000
Flux, particles/cm$^2\cdot$s	10^5 - 10^8	10^5 - 10^8	$\leq 4 \cdot 10^5$
Irradiation area, mm	Ø ≥ 25	Ø ≥ 25	Ø 50 – 100
Uniformity, %	≤ 10	≤ 10	≤ 10
Status	In operation (1998)	In operation (2015)	In operation (2010)

1 GeV proton synchrocyclotron of the PNPI

(in operation since 1970)



GNEIS building

SC main room

New cyclotron room

IRIS facility

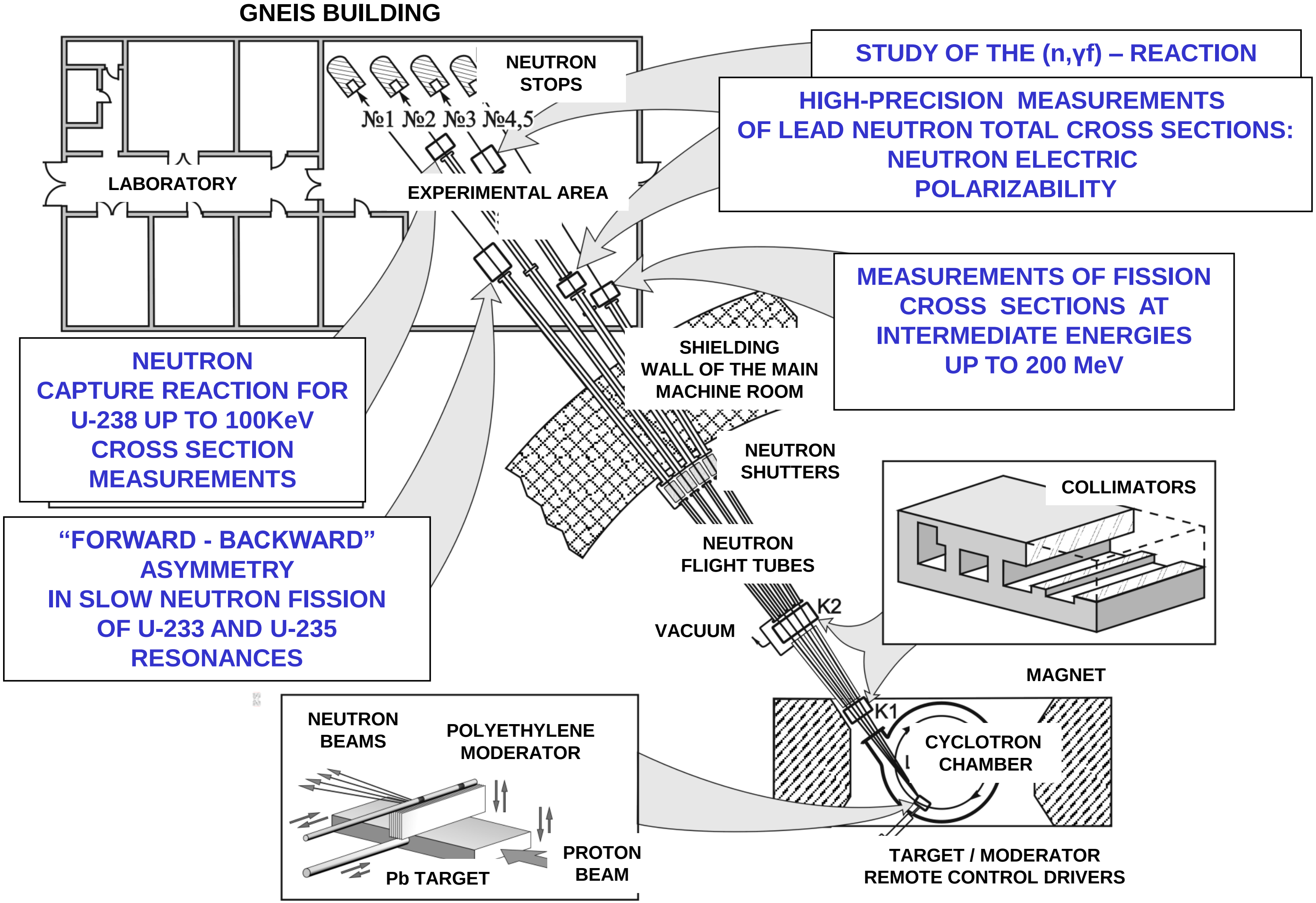
Proton therapy building

Experimental area

Data acquisition area

Synchrocyclotron SC-1000	
Proton energy	1 GeV
Internal proton beam current	$\leq 3\ \mu A$
Repetition rate	40–60 Hz
Pulsed neutron source	
Average fast neutron intensity	$\leq 3\cdot 10^{14}$ n/s
Duration of fast neutron pulse	~ 10 ns
Repetition rate	≤ 50 Hz
Neutron energy range	Thermal – 1000 MeV
Type of neutron spectrum **Beam #1-4 (En < 0.1 MeV)**	$1/E^{\alpha}$, $\alpha=0.65$-0.82
Type of neutron spectrum **Beam #5 (En > 0.1 MeV)**	“spallation”

GNEIS NEUTRON TOF-SPECTROMETER (since 1975)



STUDY OF THE (n,γf) – REACTION

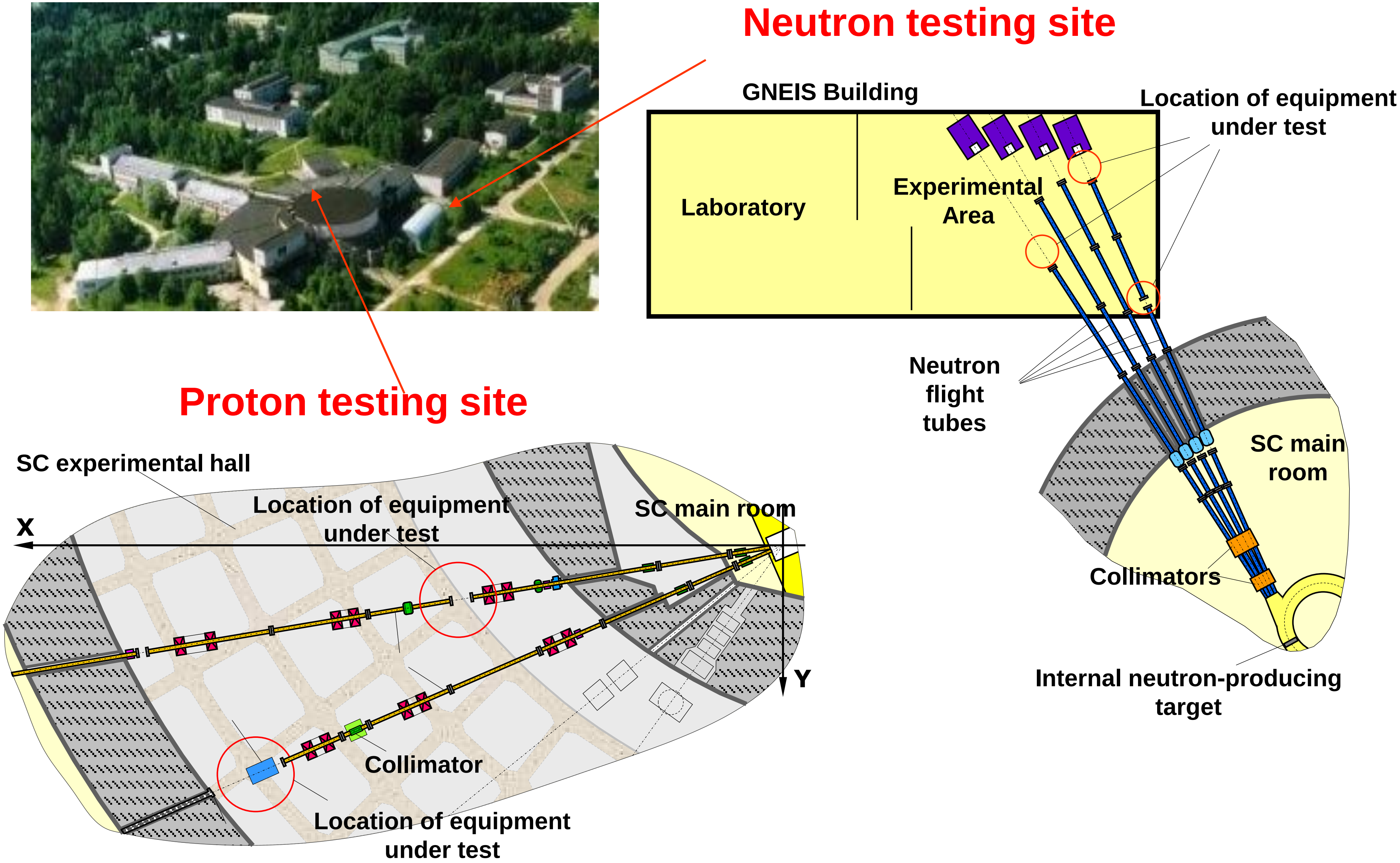
HIGH-PRECISION MEASUREMENTS OF LEAD NEUTRON TOTAL CROSS SECTIONS: NEUTRON ELECTRIC POLARIZABILITY

MEASUREMENTS OF FISSION CROSS SECTIONS AT INTERMEDIATE ENERGIES UP TO 200 MeV

NEUTRON CAPTURE REACTION FOR U-238 UP TO 100KeV CROSS SECTION MEASUREMENTS

“FORWARD - BACKWARD” ASYMMETRY IN SLOW NEUTRON FISSION OF U-233 AND U-235 RESONANCES

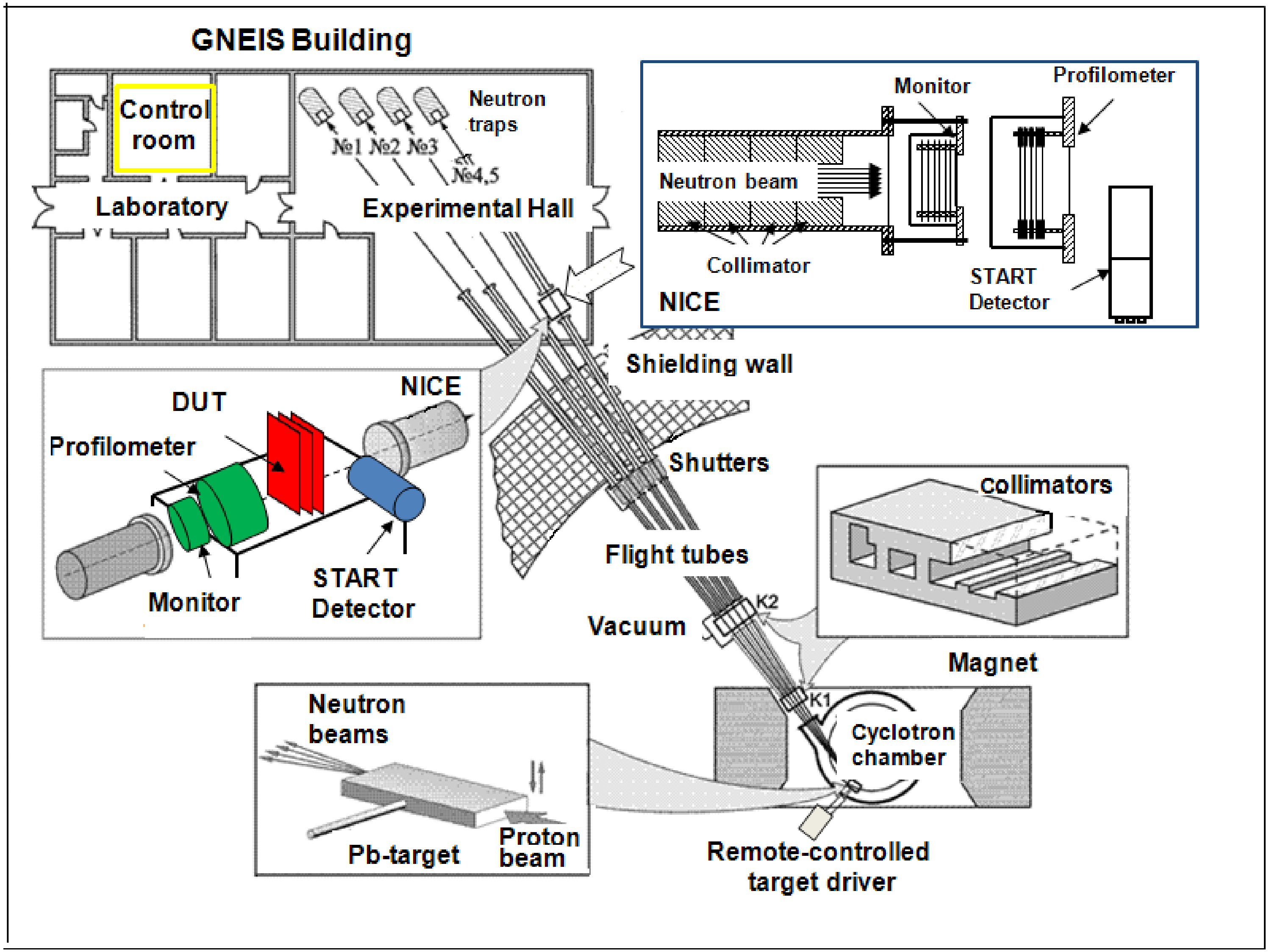
TESTING OF ELECTRONIC EQUIPMENT AT THE PNPI PROTON AND NEUTRON BEAMS



Neutron testing site

Proton testing site

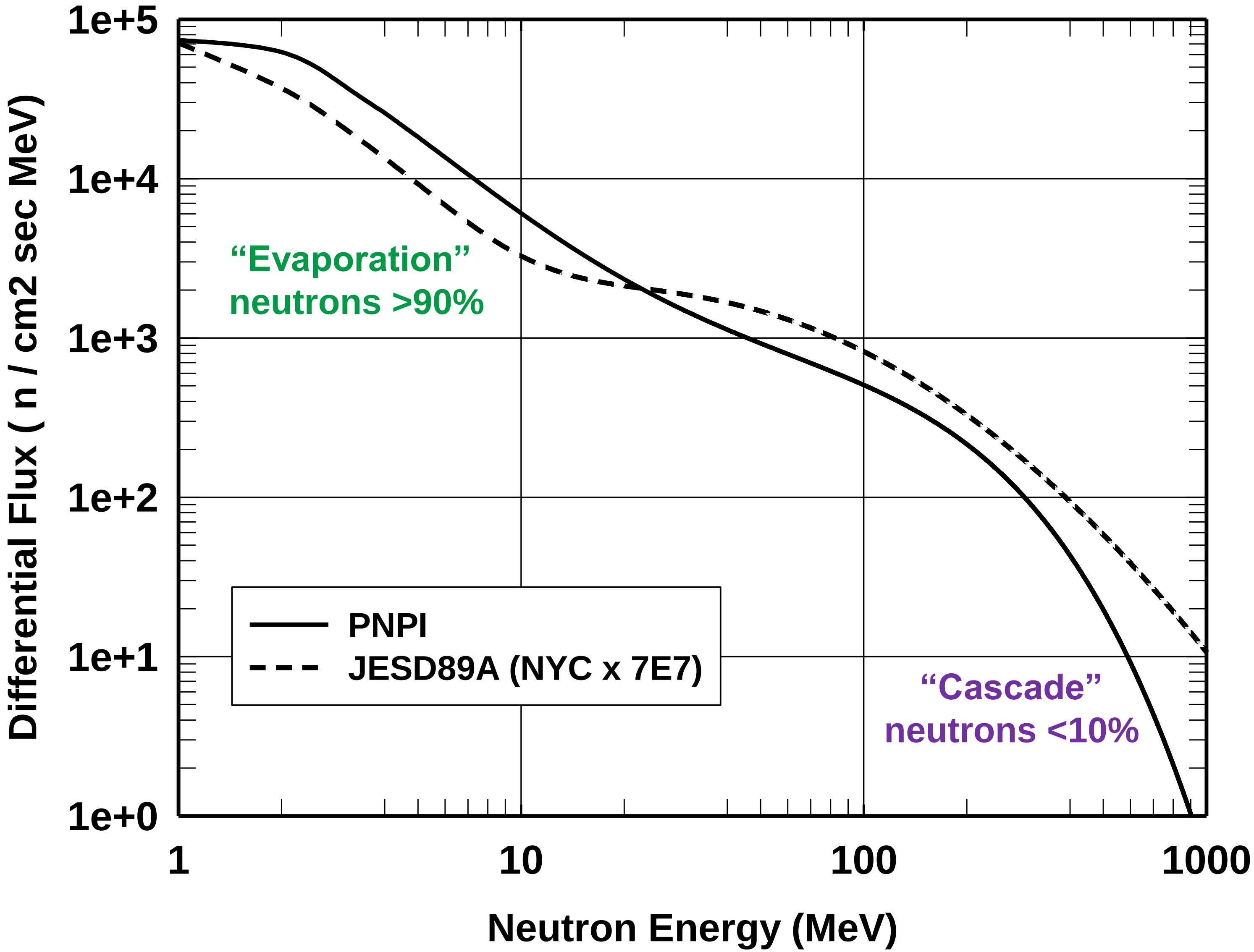
General View of the GNEIS and NICE Test Facility



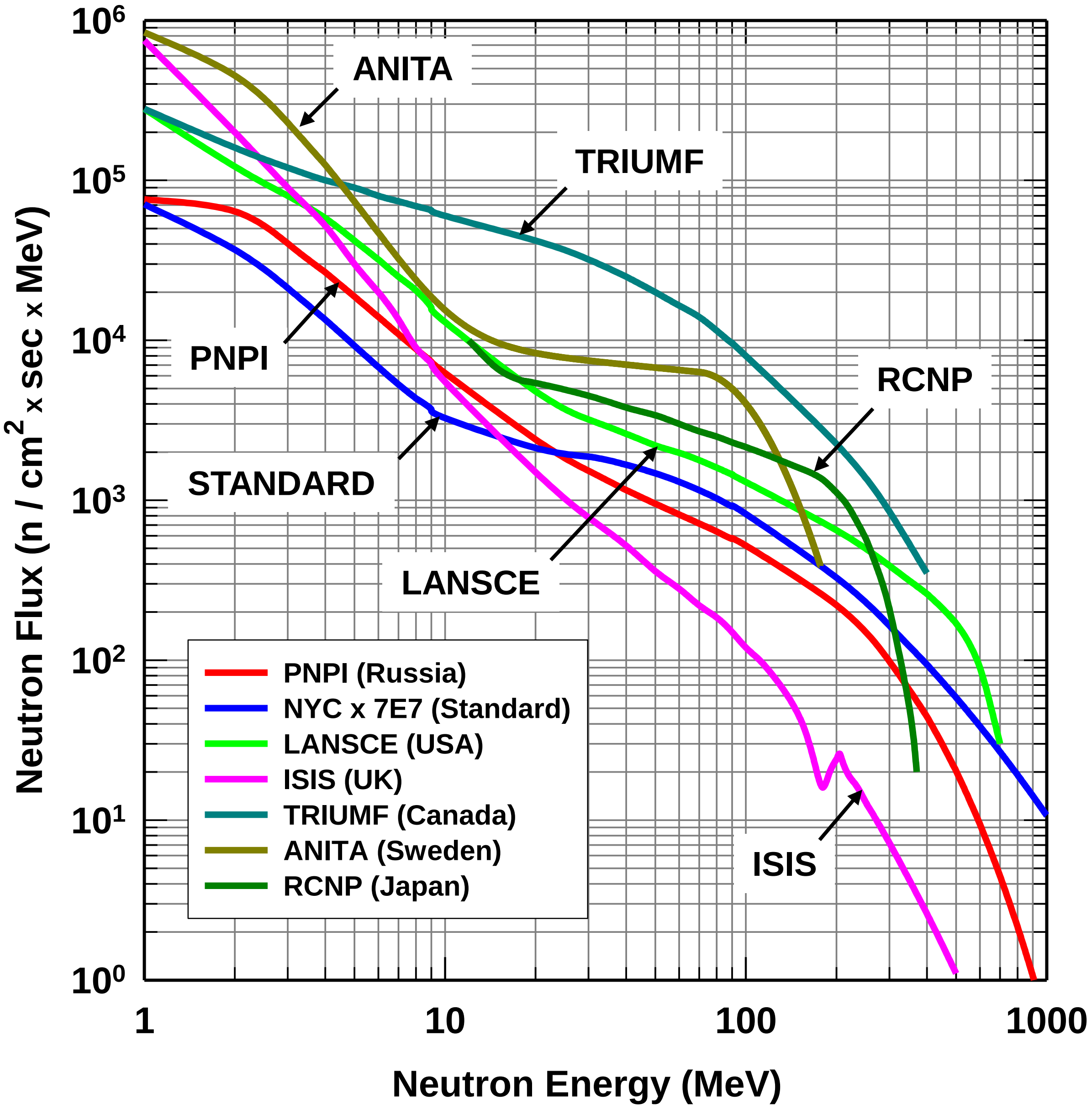
<u>N</u>eutron <u>I</u>rradiation of <u>C</u>hips and <u>E</u>lectronics = NICE (home nickname!)

IS NP – official bureaucratic name, direct English transcription of ИСНП

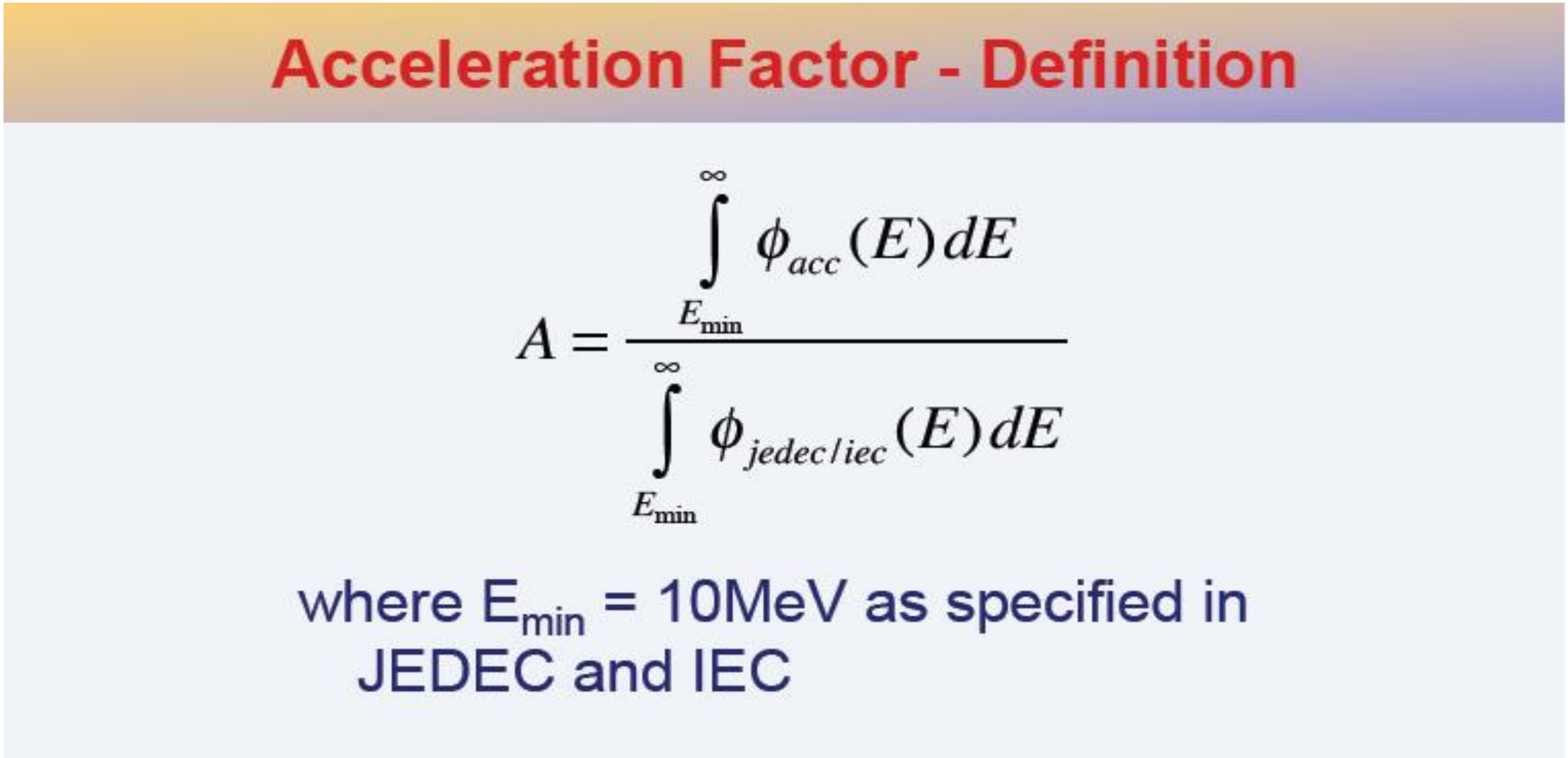
Neutron Energy Spectra of Standard and GNEIS



Comparison of Broad Spectrum Neutron Sources



How to Compare Various Broad Neutron Spectrum Test Facilities?



Acceleration Factor - Definition

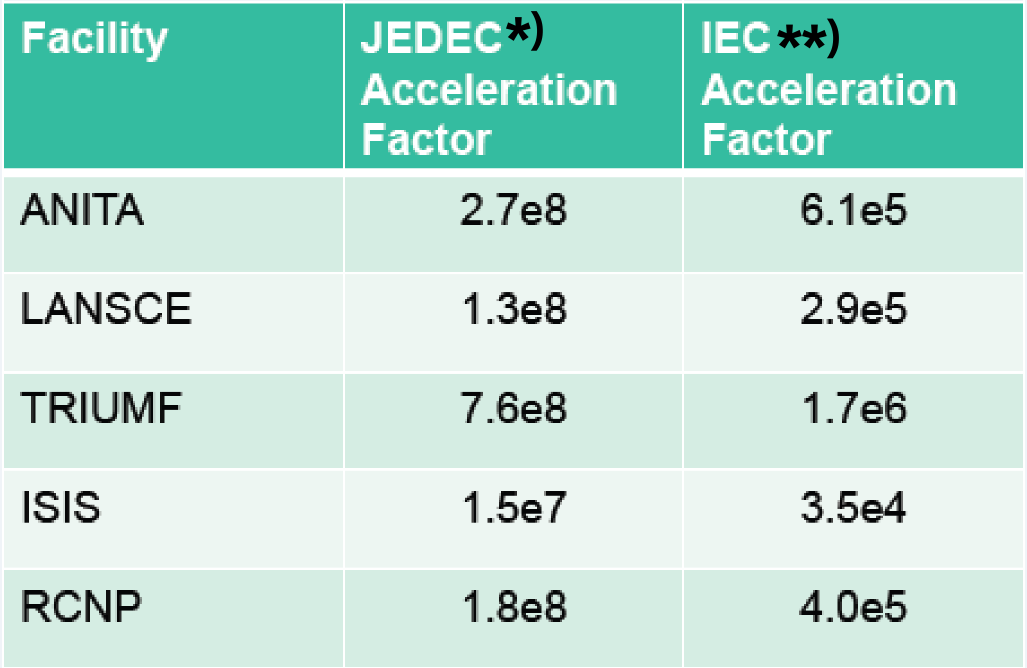
$$A = \frac{\int_{E_{\min}}^{\infty} \phi_{acc}(E)\,dE}{\int_{E_{\min}}^{\infty} \phi_{jedec/iec}(E)\,dE}$$

where E_{min} = 10MeV as specified in JEDEC and IEC

$\Phi_{acc}(E)$ - differential neutron flux from the test facility

$\Phi_{jedec/iec}(E)$ – differential terrestrial (standard) neutron flux

Acceleration Factor of Facilities



Facility	JEDEC*) Acceleration Factor	IEC**) Acceleration Factor
ANITA	2.7e8	6.1e5
LANSCE	1.3e8	2.9e5
TRIUMF	7.6e8	1.7e6
ISIS	1.5e7	3.5e4
RCNP	1.8e8	4.0e5

Acceleration Factor of NICE/PNPI Facility

PNPI	5.0e7	1.2e5

*) relative to the sea level

**) relative the altitude of 12 km

Exact acceleration factors will vary due to state of tune of the accelerator facilities

Neutron Soft Error Rate

The neutron soft error rate is

$$R = \int_{E_{\min}}^{\infty} \sigma(E)\phi(E)\,dE$$

where ϕ(E) is the differential neutron flux and σ(E) is the energy dependent soft error cross sections defined as

$$\sigma(E) = \frac{Number\ of\ Soft\ Error\ Events}{\phi(E)T}$$

and T is time

Theoretical Weibull Approximation of Cross-section

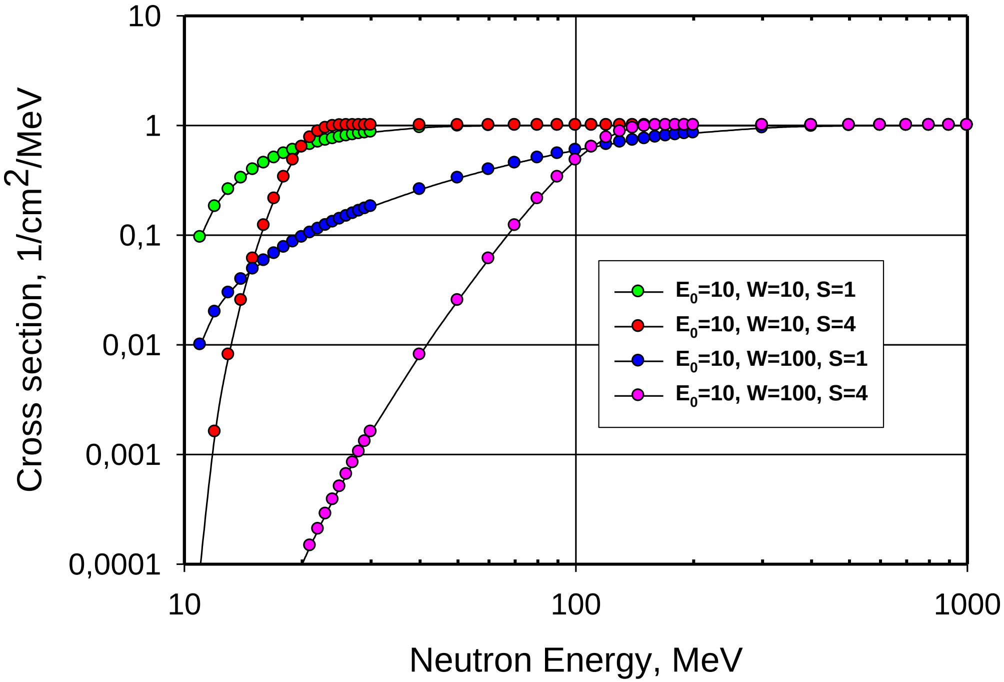
$$\sigma(E) = \sigma_L \left(1 - e^{-\left[\frac{E - E_0}{W}\right]^S}\right)$$

where σ_L - asymptotic high energy cross section

E_0 - cut-off energy (i.e. no upsets below E_0)

W - “width” parameter

S - “shape” parameter



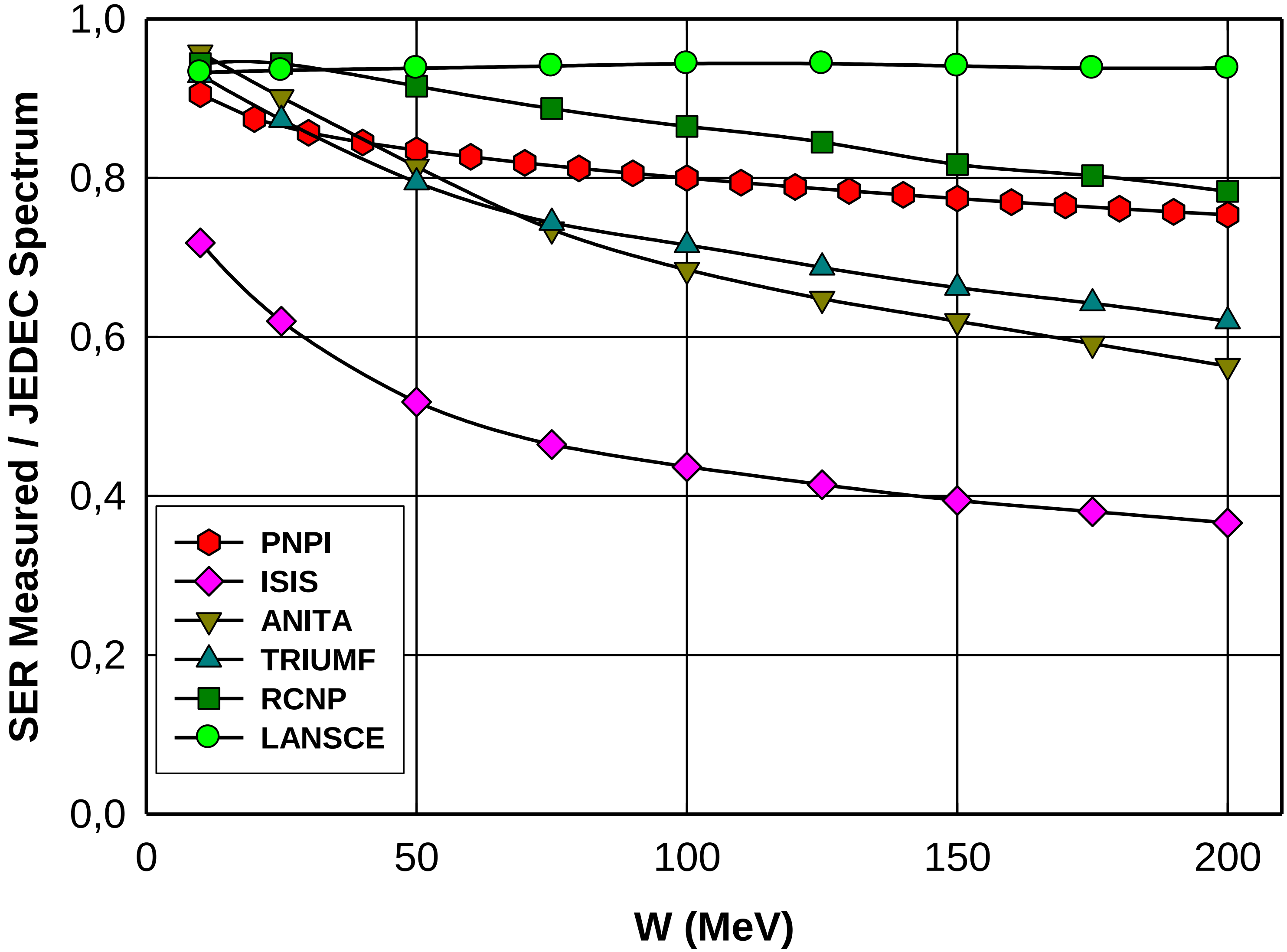
Error Ratio – Due to Mismatch of Beam Facility and Real Neutron Spectra

$$ErrorRatio = \frac{R_{measured}}{AR_{jedec/iec}} = \frac{\int_{E_{\min}}^{\infty} \sigma(E)\phi_{acc}(E)\,dE}{A\int_{E_{\min}}^{\infty} \sigma(E)\phi_{jedec/iec}(E)\,dE}$$

Error Ratio < 1	Accelerated measurement is under-predicting SER
Error Ratio = 1	Accelerated measurement is correct
Error Ratio > 1	Accelerated measurement is over predicting SER

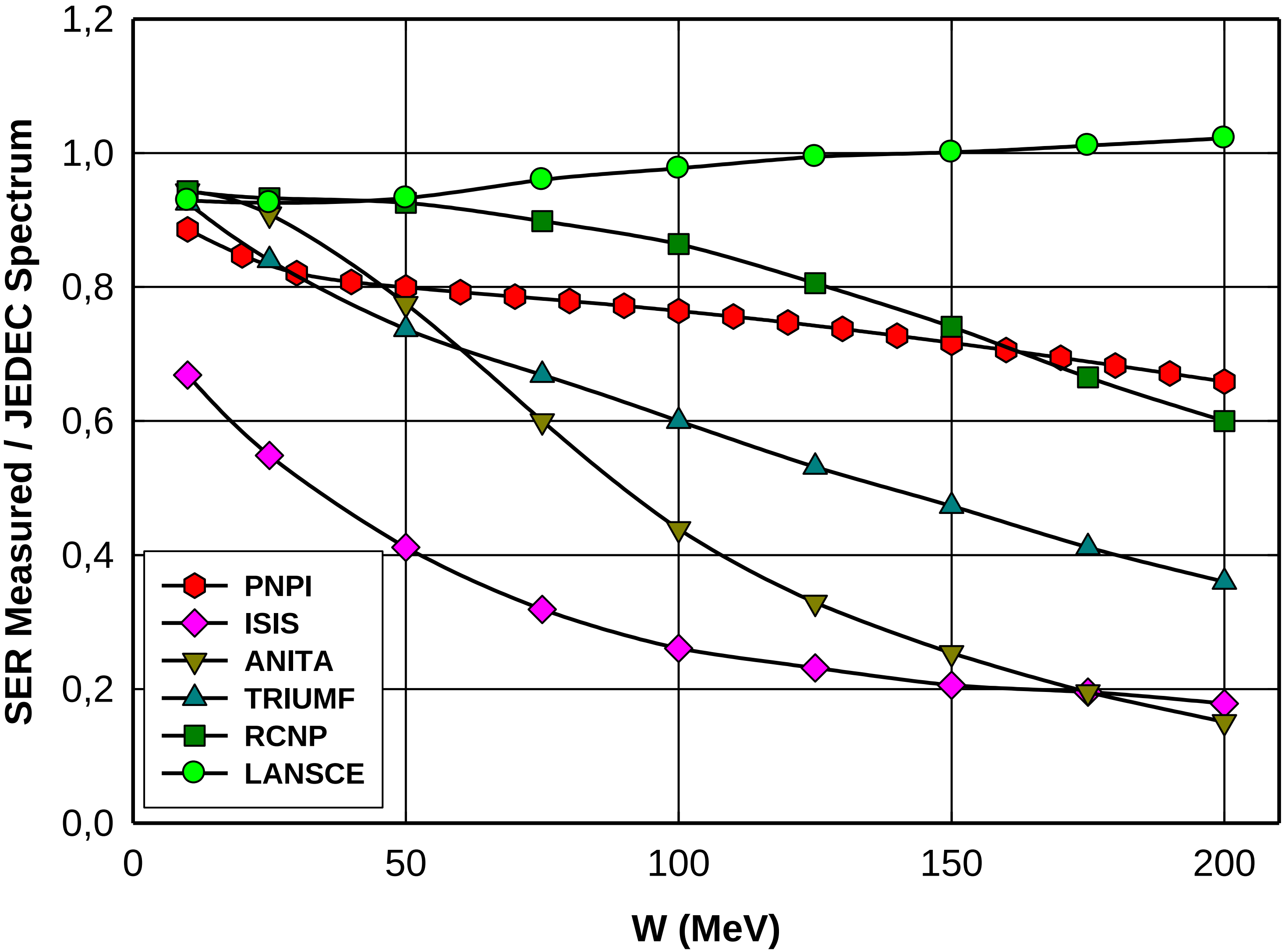
Error in SER estimate as a function of W

for E_0 = 10 MeV and S = 1 (devices with low critical charge)



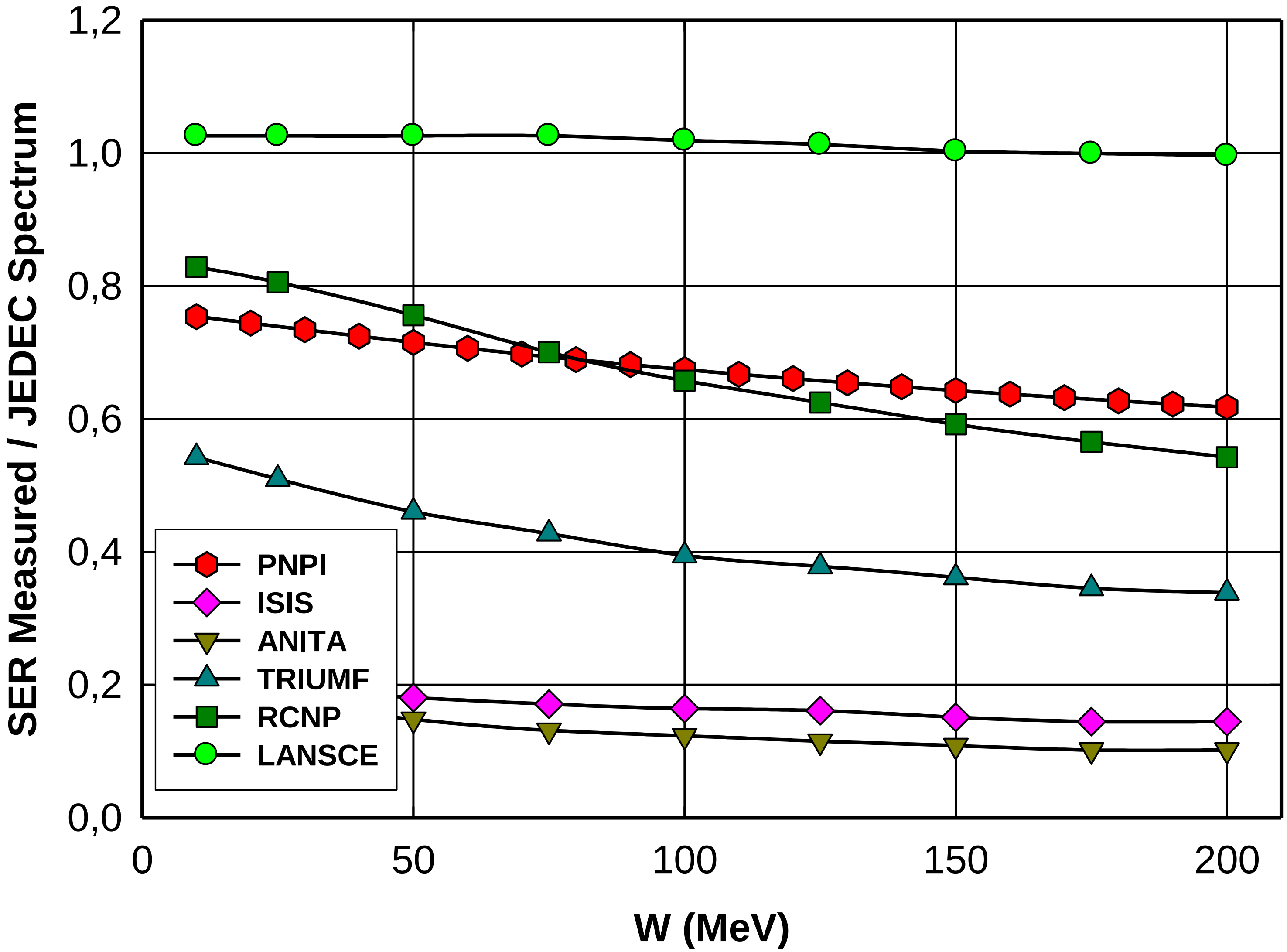
Error in SER estimate as a function of W

for E_0 = 10 MeV and S = 4 (devices with low critical charge)



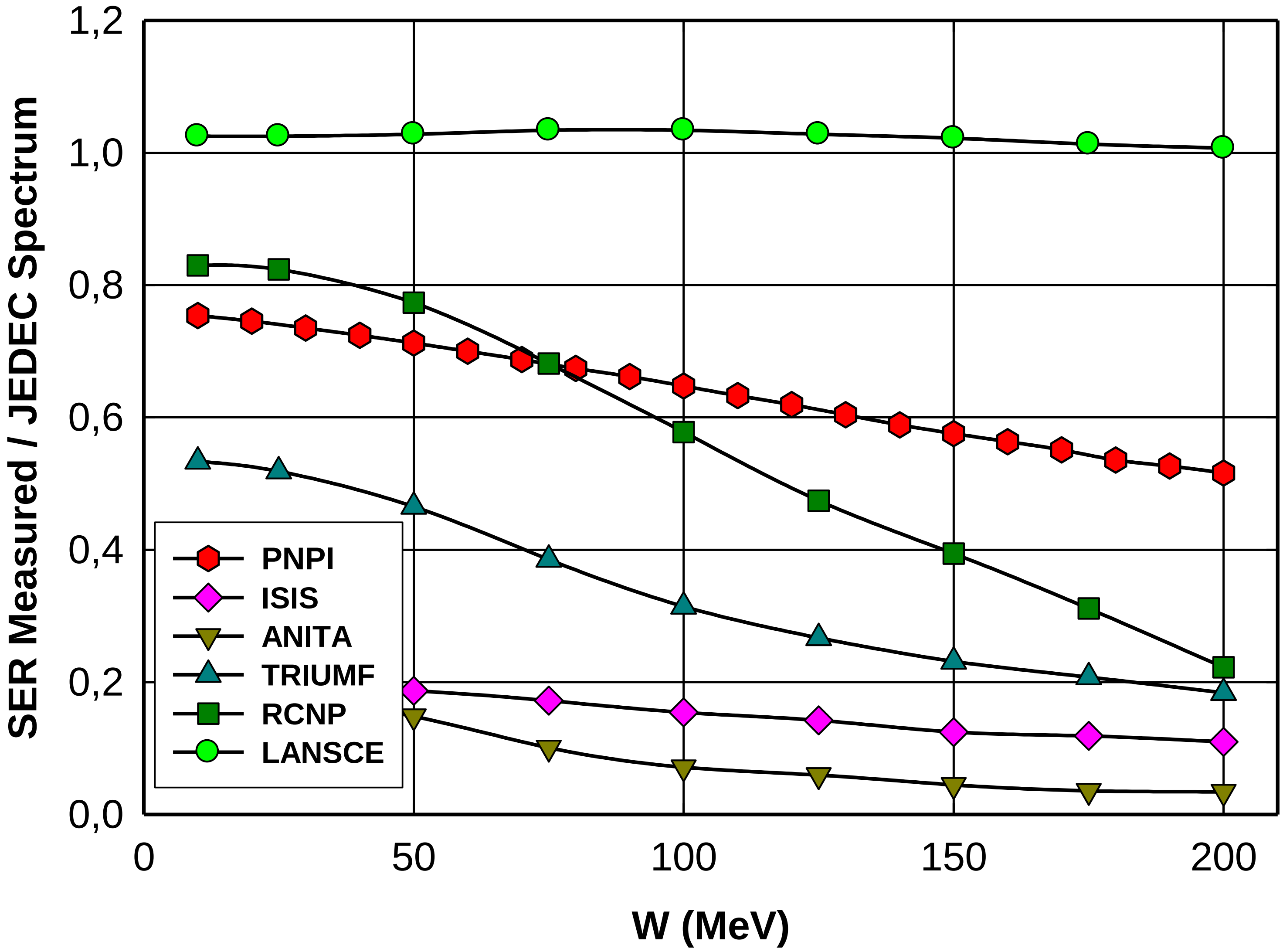
Error in SER estimate as a function of W

for E_0 = 100 MeV and S = 1 (devices with large critical charge)



Error in SER estimate as a function of W

for E_0 = 100 MeV and S = 4 (devices with large critical charge)



Devices Used at the PNPI Test facility for Characterization of the Neutron Beam

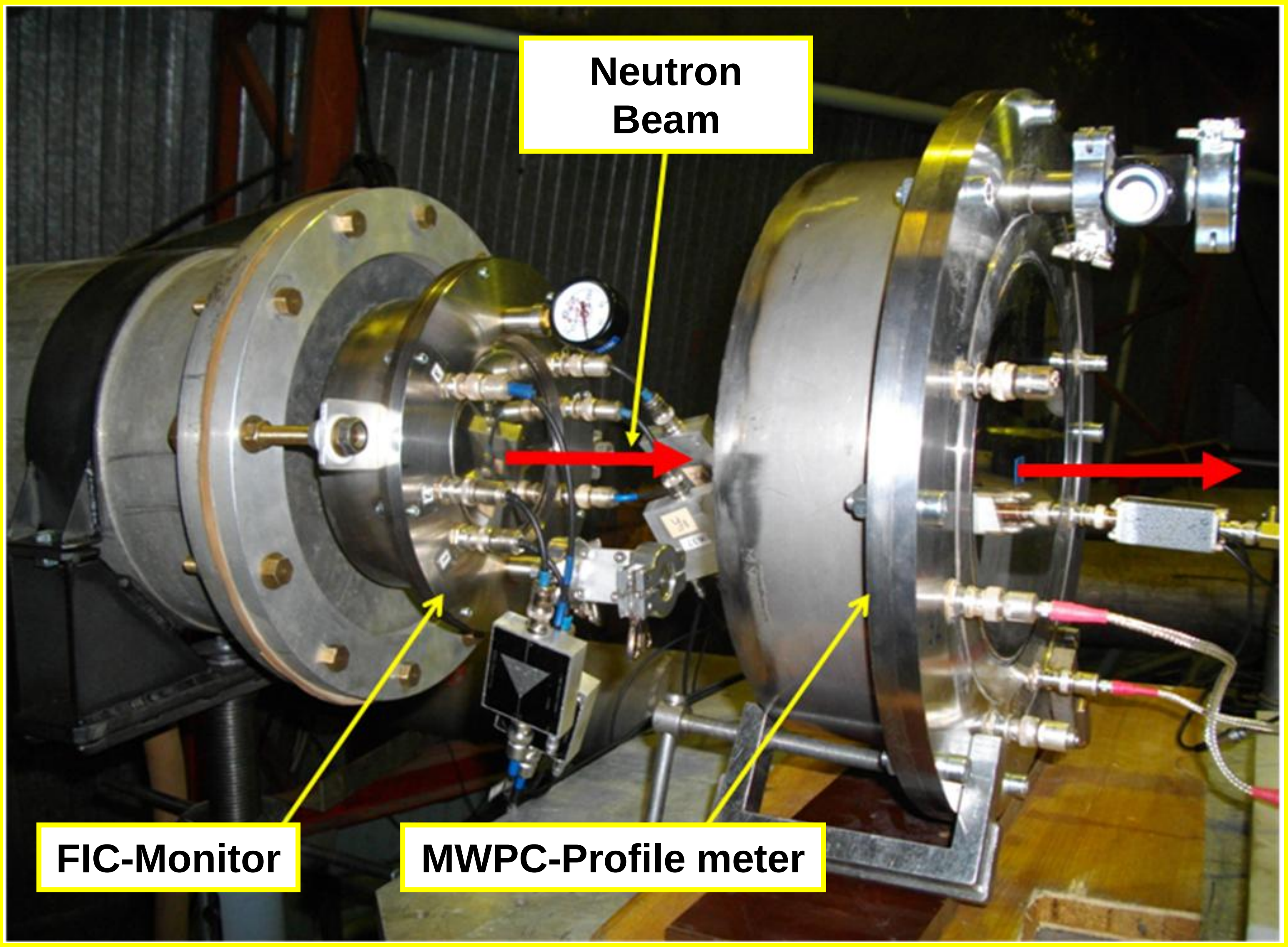
Monitor: Fission Ionization Chamber (FIC)

- differential neutron flux (energy spectrum), $\Phi(E)$, n/cm$^2\cdot$sec$\cdot$MeV
- integral neutron flux, $I = \int \Phi(E) dE$, n/cm$^2\cdot$sec
- neutron fluence, $T \cdot I$, n/cm^2

Profilometer: Multiwire Proportional Counter (MWPC)

- 2D-distribution of neutron flux, $I(X,Y)$, over beam cross section
- center of gravity of the beam cross section
- uniformity of the beam cross section
- “effective” width of the beam cross section along X,Y-axes

Devices Used at the PNPI Test facility for Characterization of the Neutron Beam

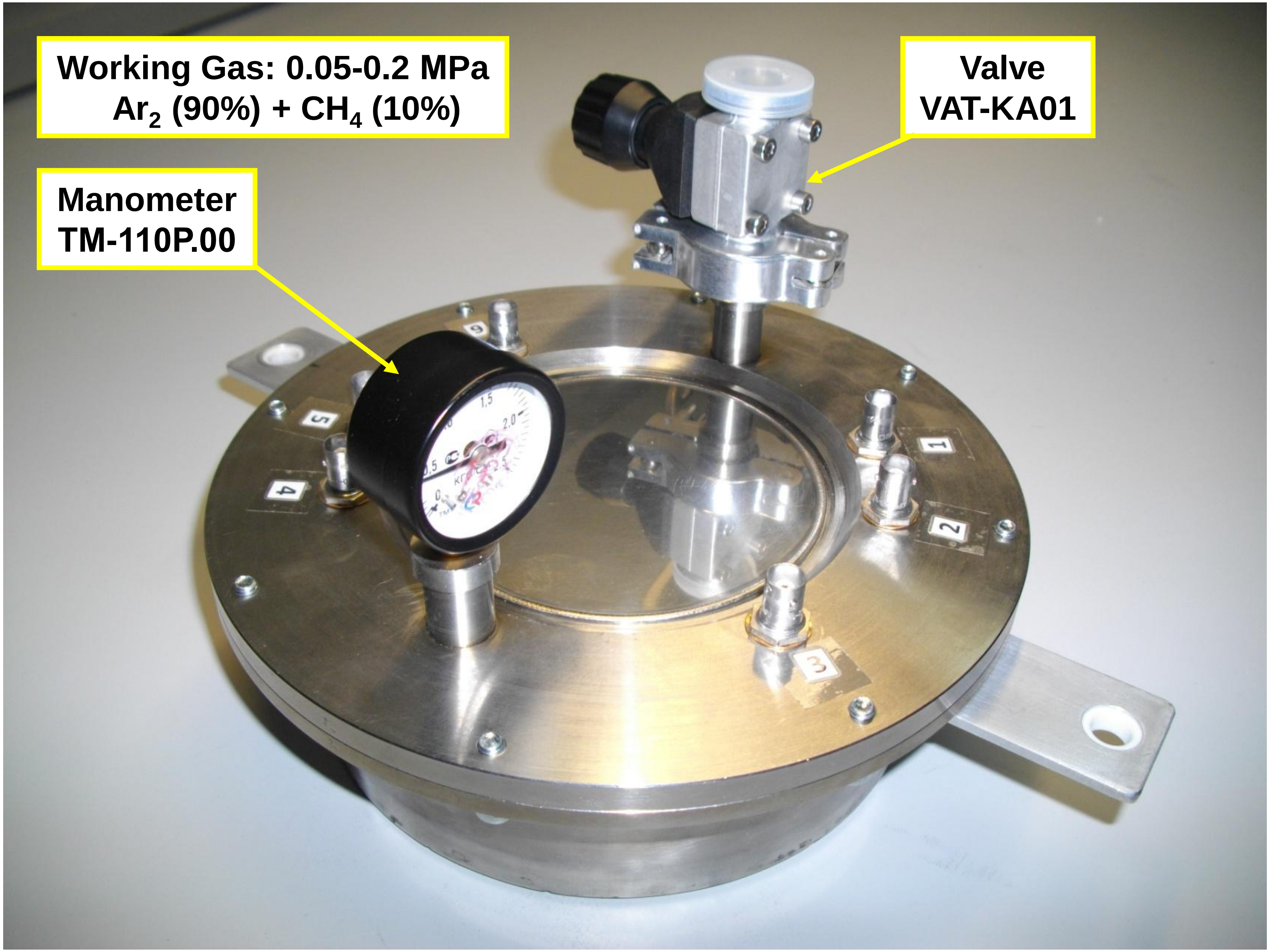


Neutron Beam

FIC-Monitor

MWPC-Profile meter

Neutron Beam Monitor - Fission Ionization Chamber (FIC) with U-235 and U-238 targets

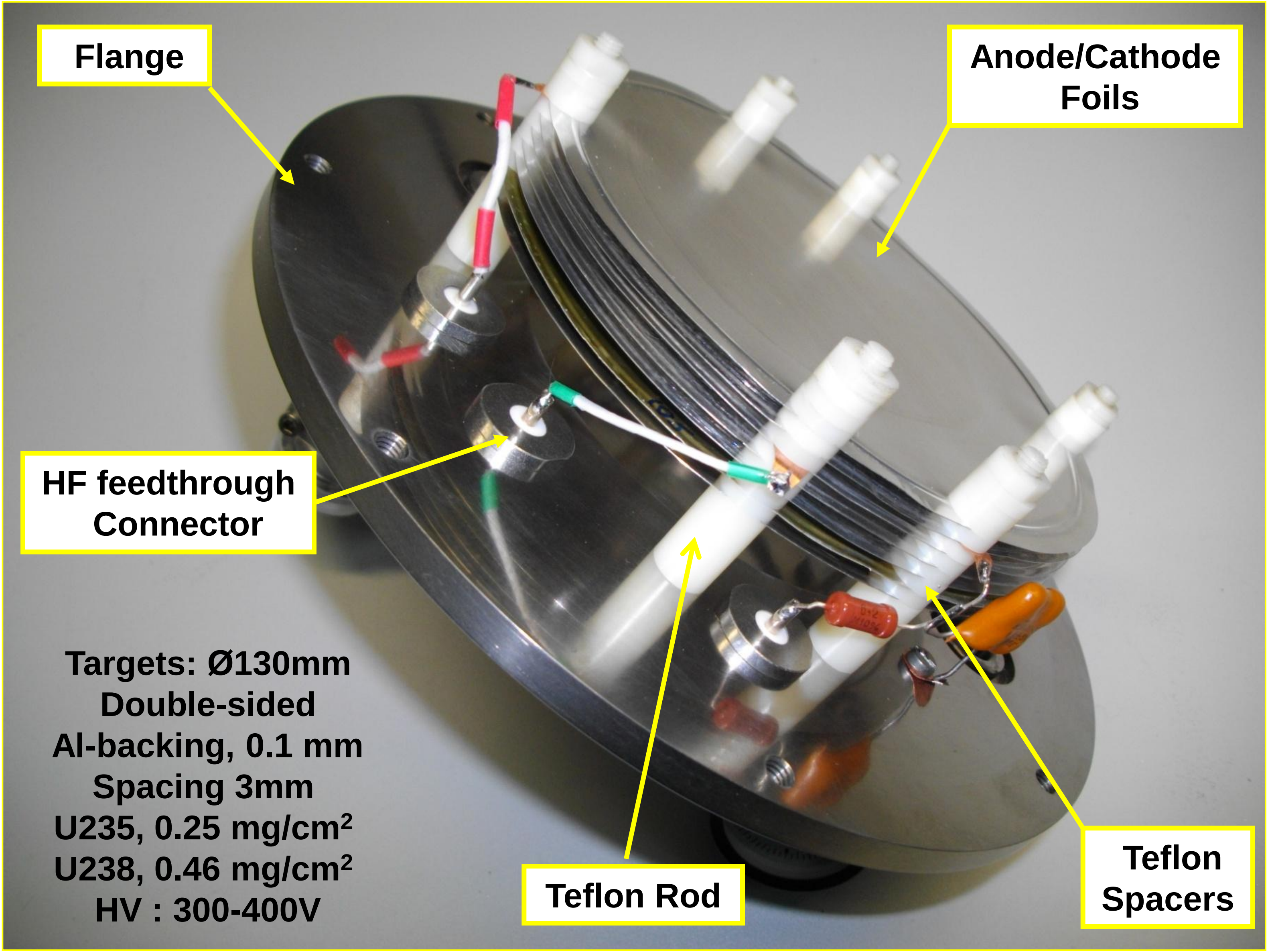


Working Gas: 0.05-0.2 MPa
Ar_2 (90%) + CH_4 (10%)

Manometer
TM-110P.00

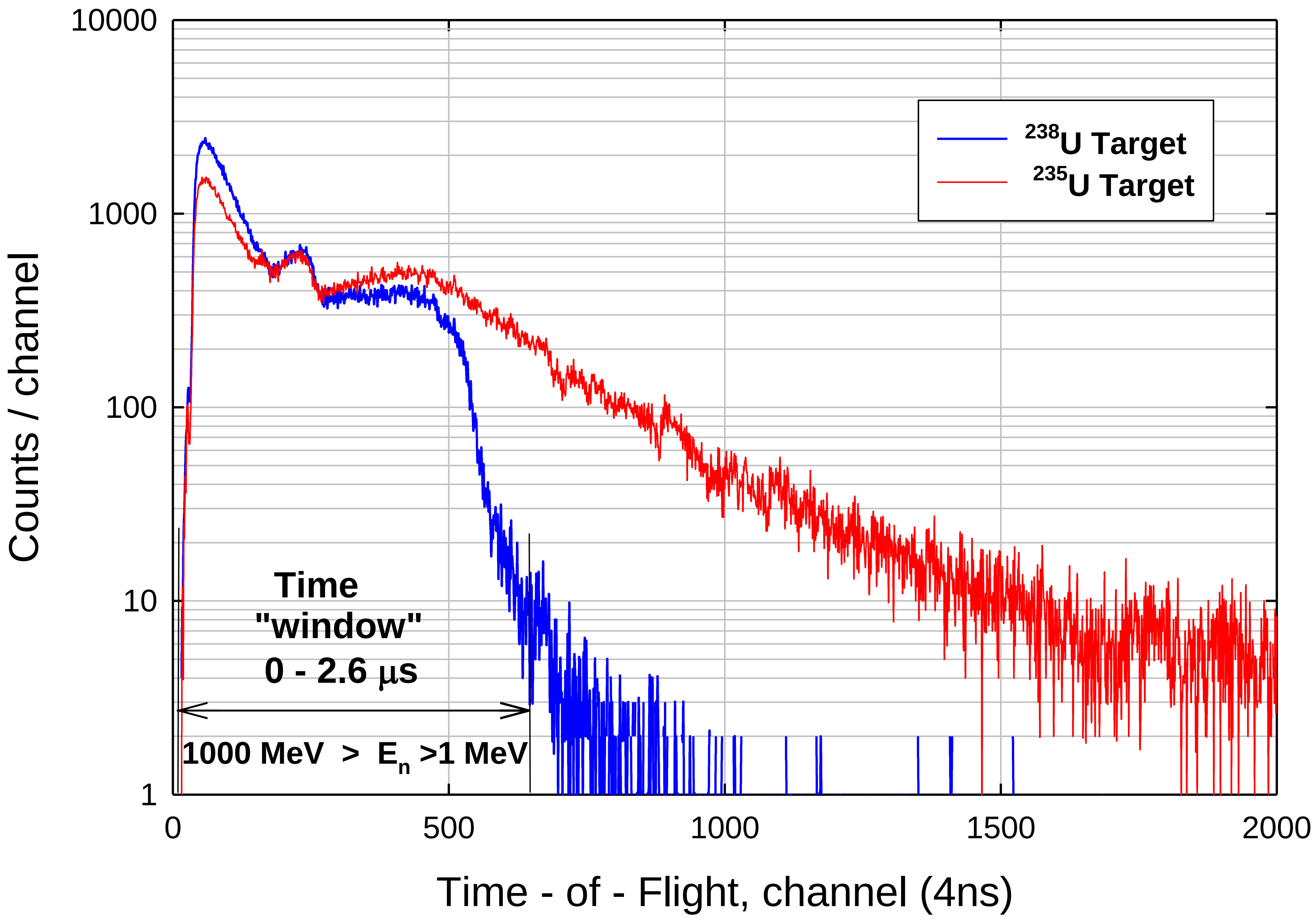
Valve
VAT-KA01

Internal structure of the Neutron Beam Monitor - FIC with U-235 and U-238 targets

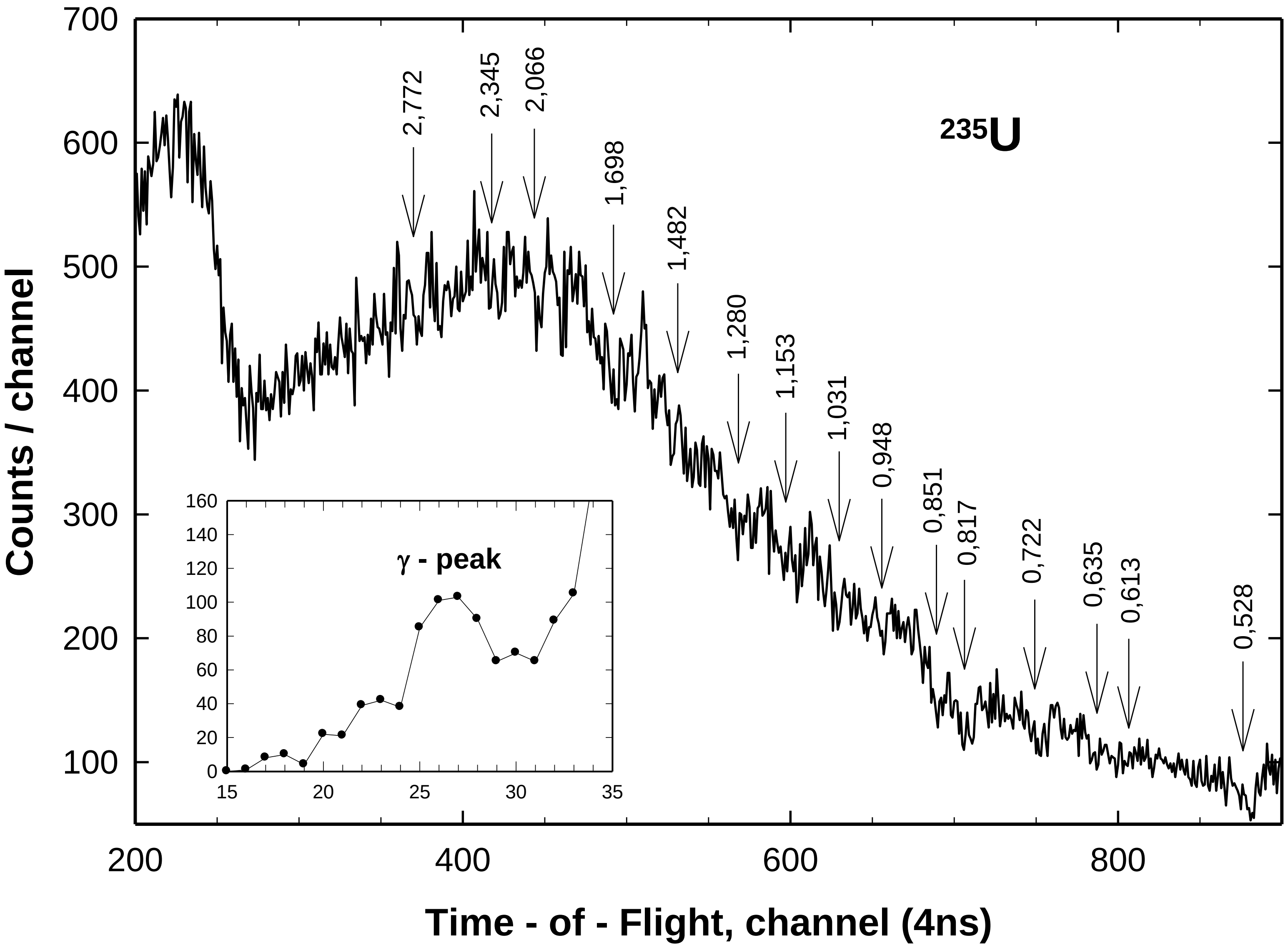


Targets: Ø130mm
Double-sided
Al-backing, 0.1 mm
Spacing 3mm
U235, 0.25 mg/cm^2
U238, 0.46 mg/cm^2
HV : 300-400V

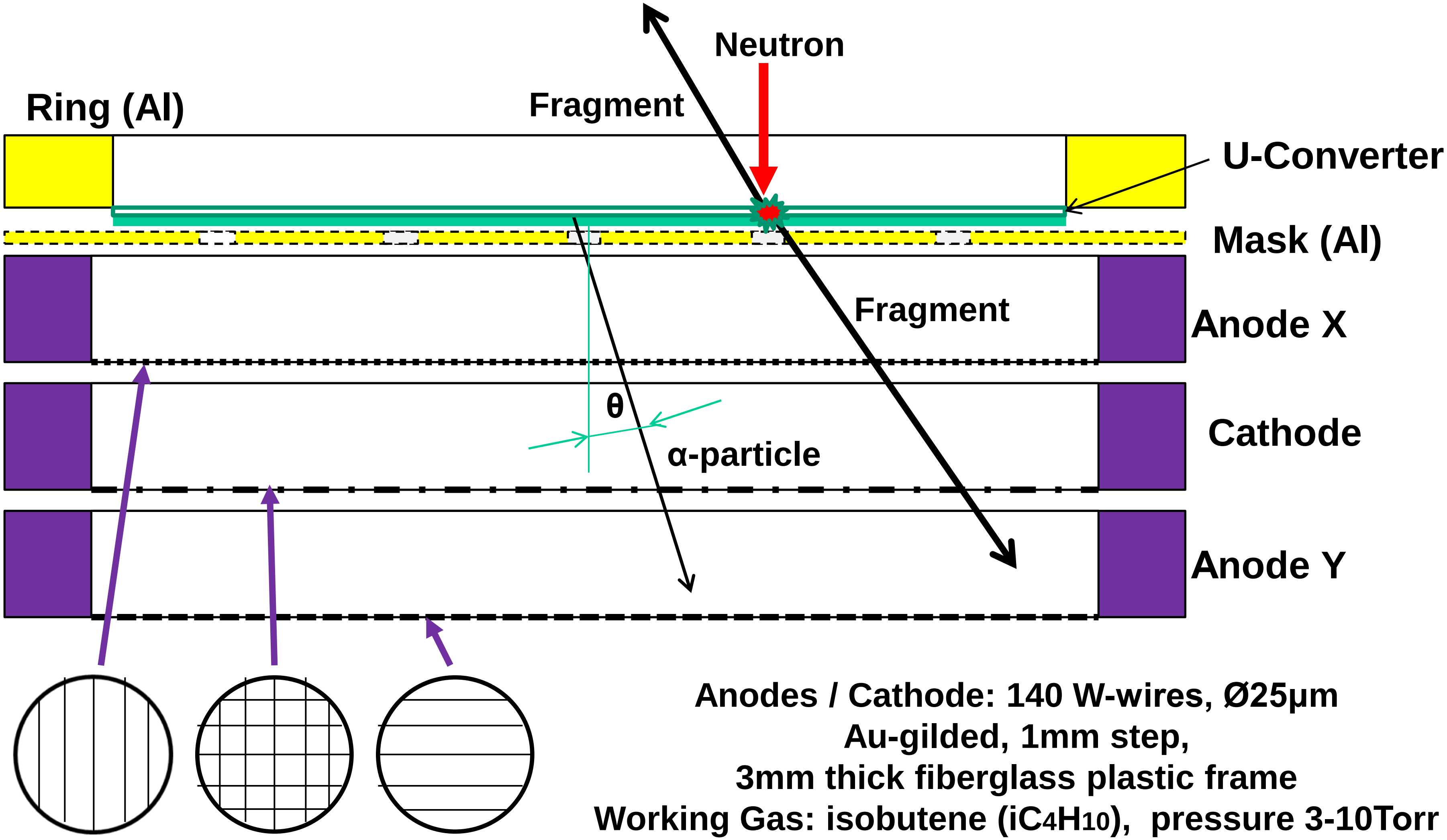
TOF – Spectra Measured with FIC (Neutron Beam Monitor)



Fine Structure of FIC-spectrum Used for TOF vs Neutron Energy Calibration

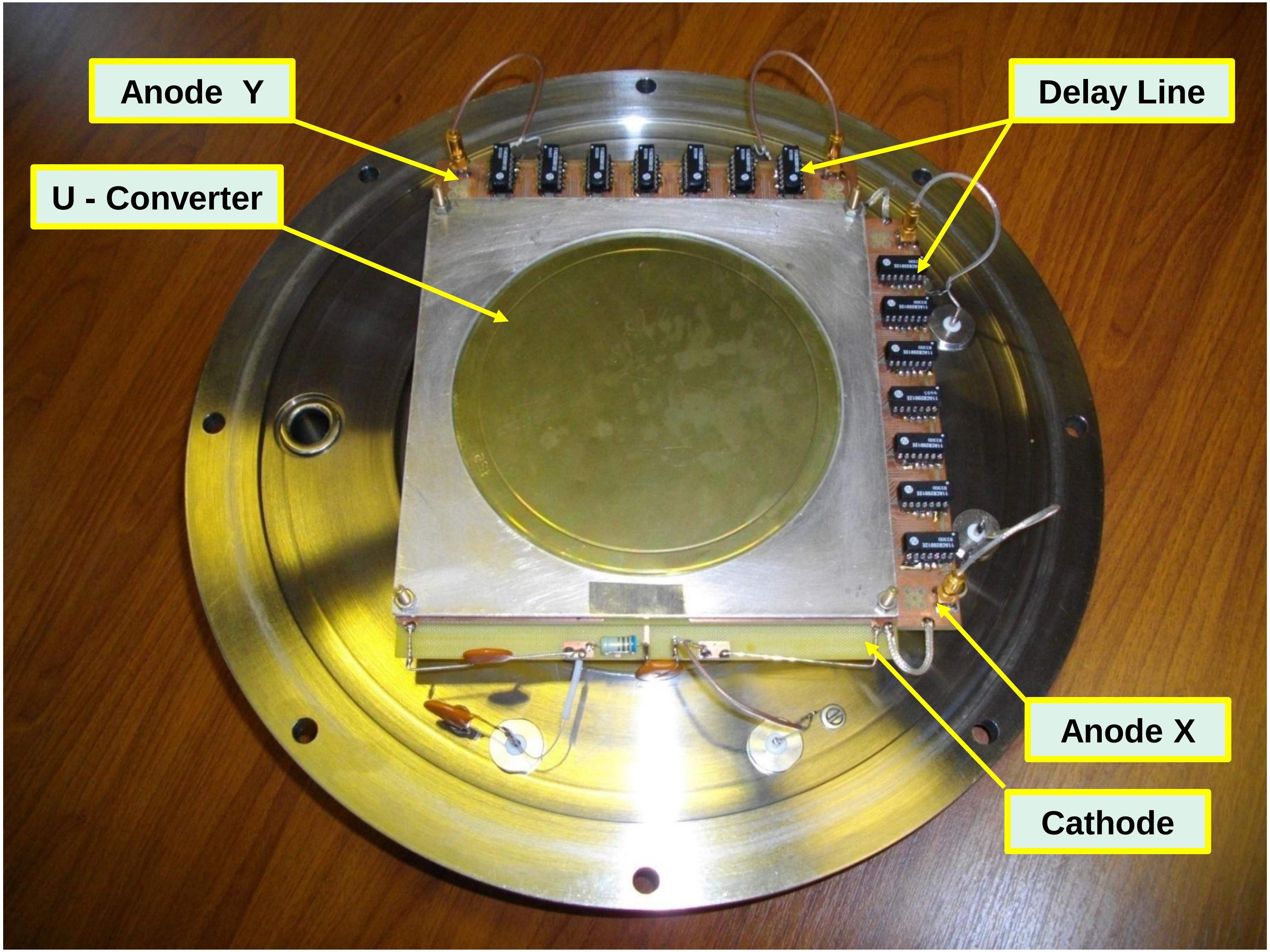


MWPC – Neutron Beam Profilometer
(2D-type MultiWire Proportional Counter)



Anodes / Cathode: 140 W-wires, Ø25μm
Au-gilded, 1mm step,
3mm thick fiberglass plastic frame
Working Gas: isobutene (iC_4H_{10}), pressure 3-10Torr

MWPC – Neutron Beam Profilometer



Anode Y

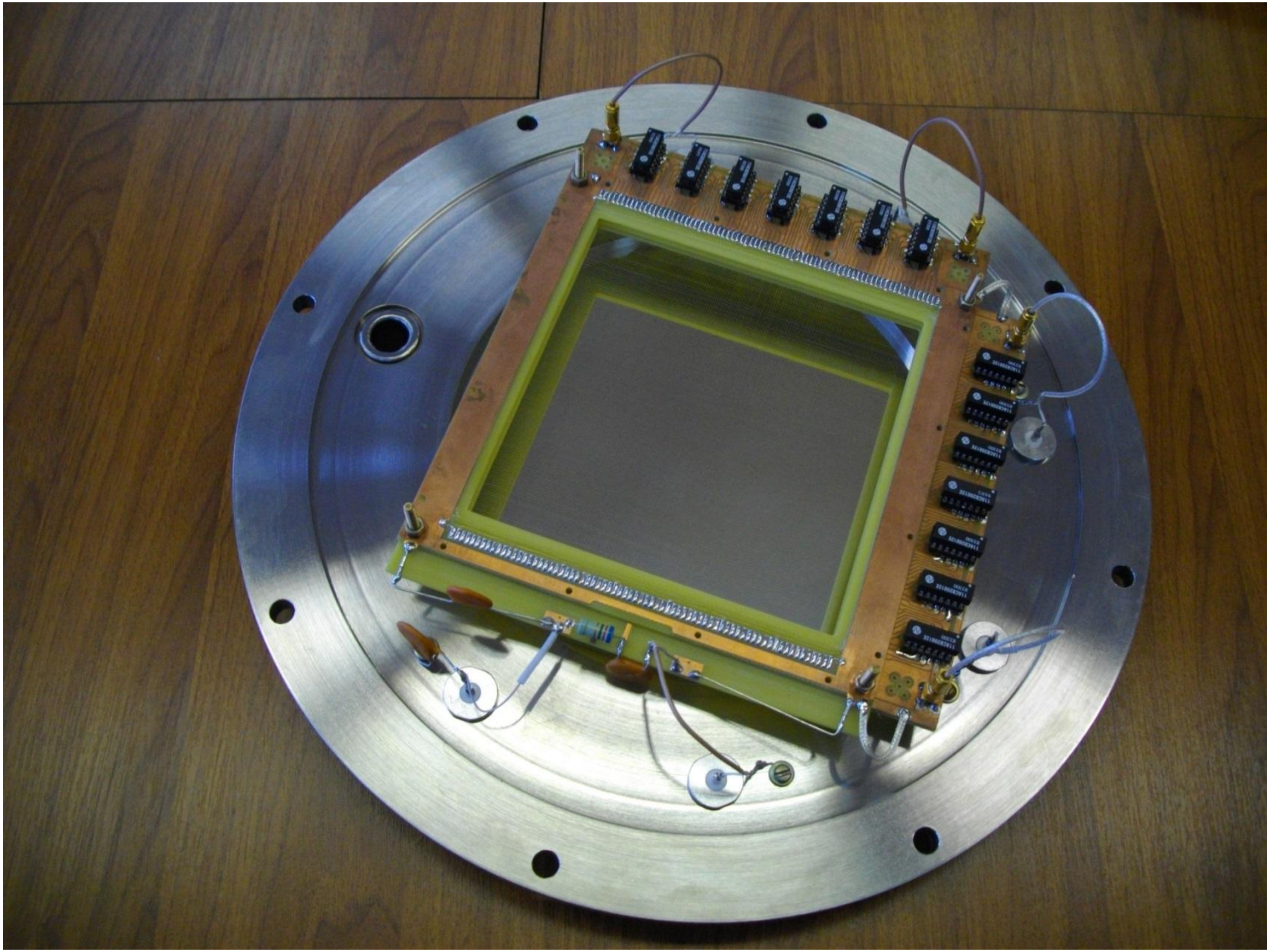
Delay Line

U - Converter

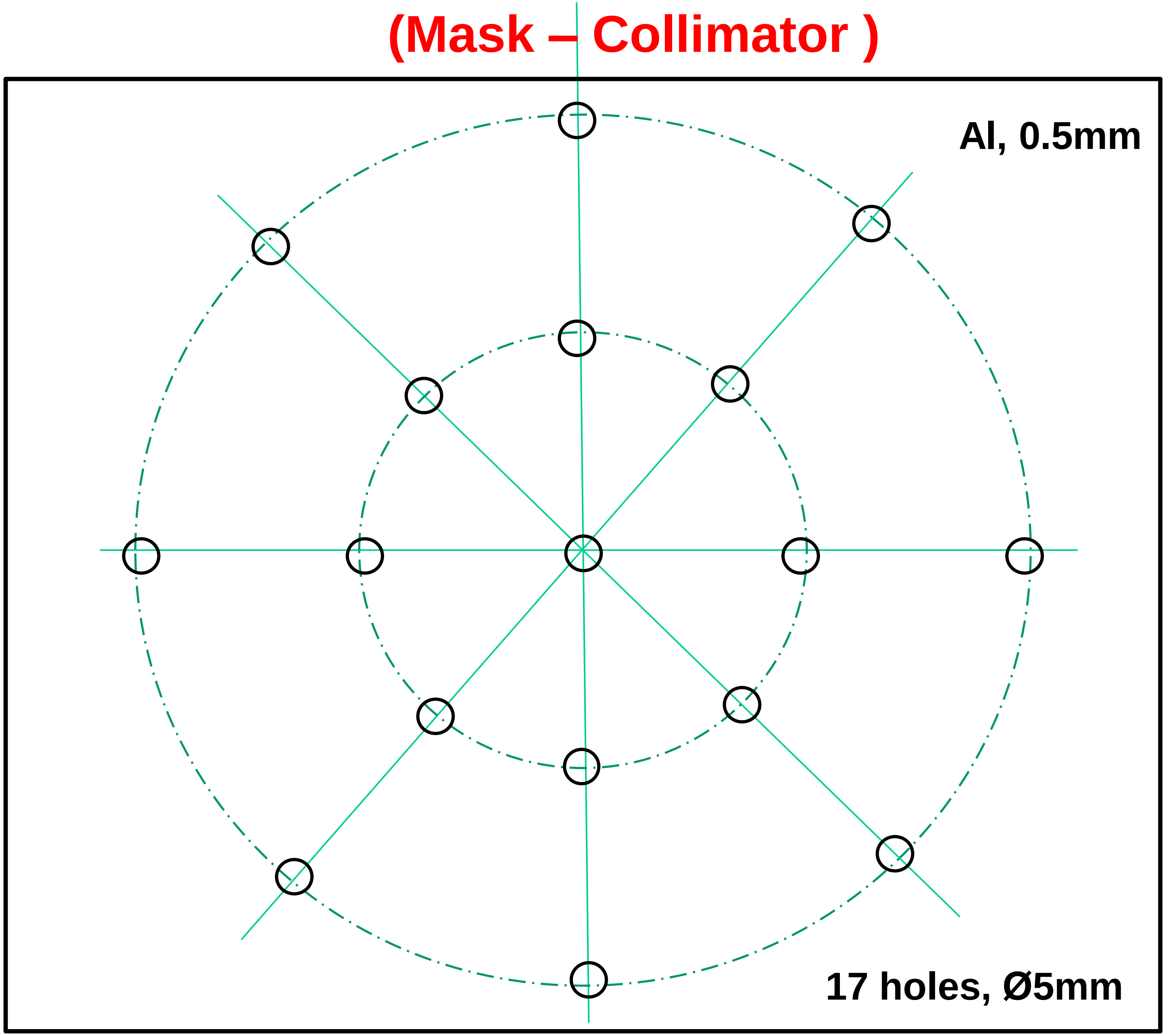
Anode X

Cathode

MWPC – Neutron Beam Profilometer



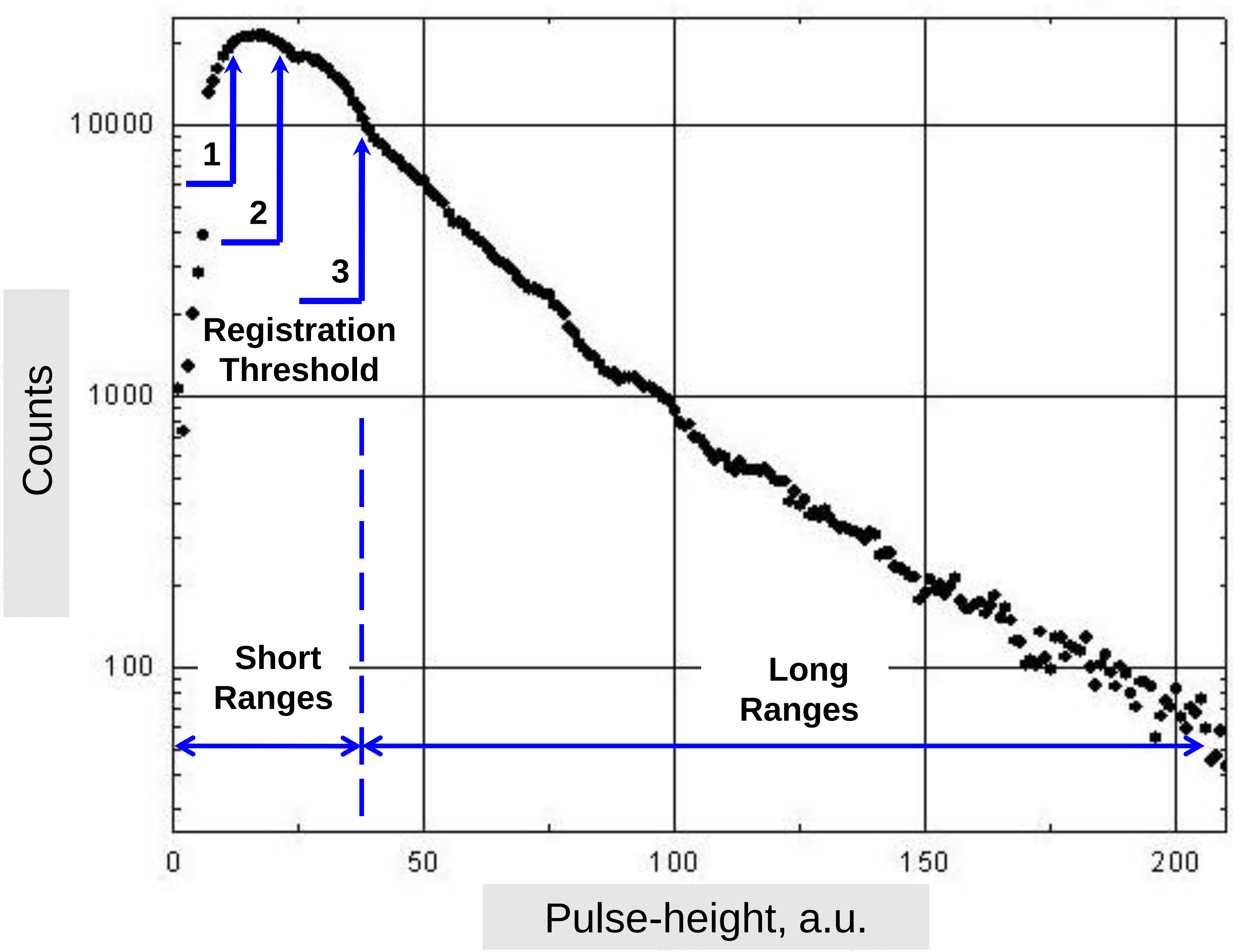
MWPC – Neutron Beam Profilometer
(Mask – Collimator)



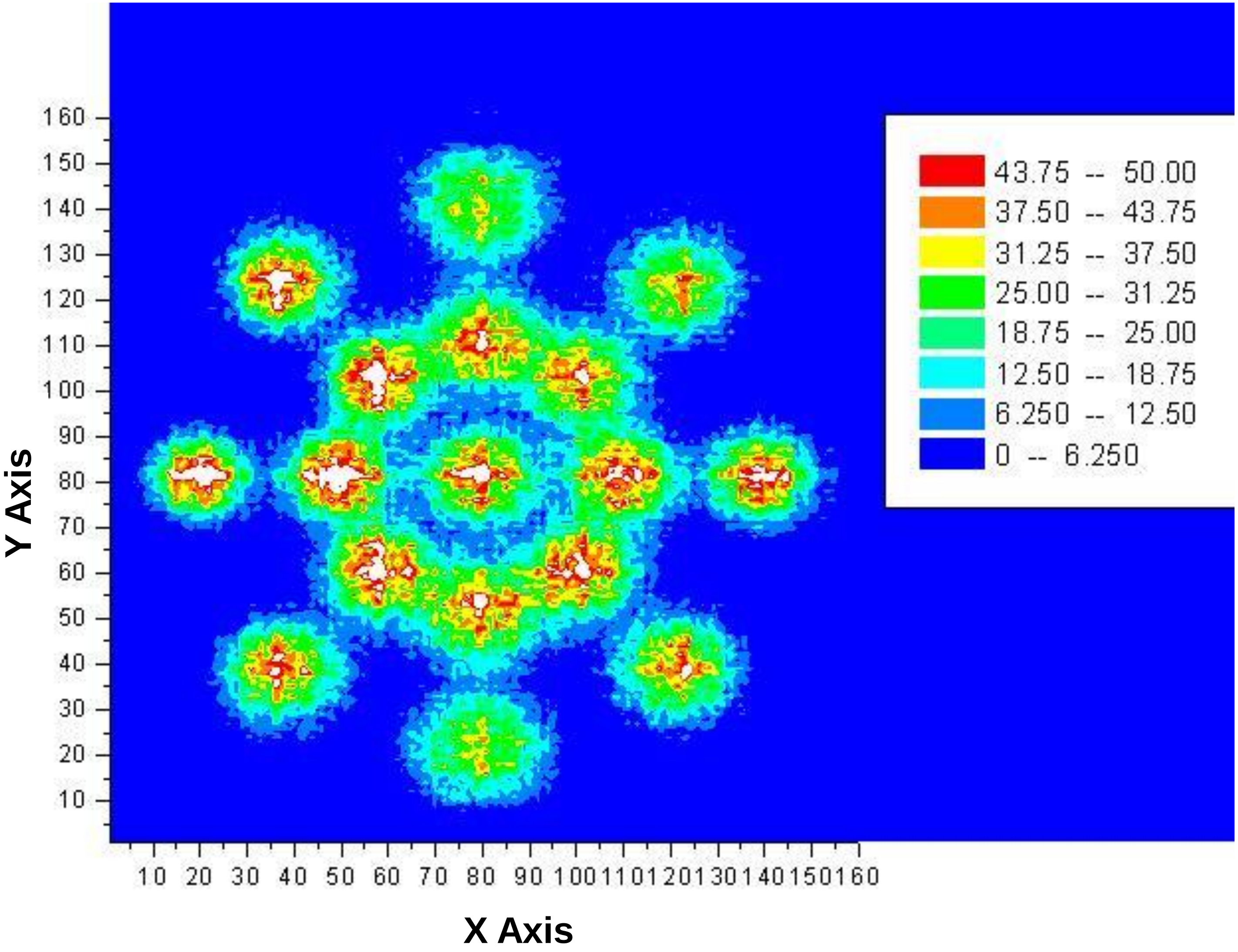
Al, 0.5mm

17 holes, Ø5mm

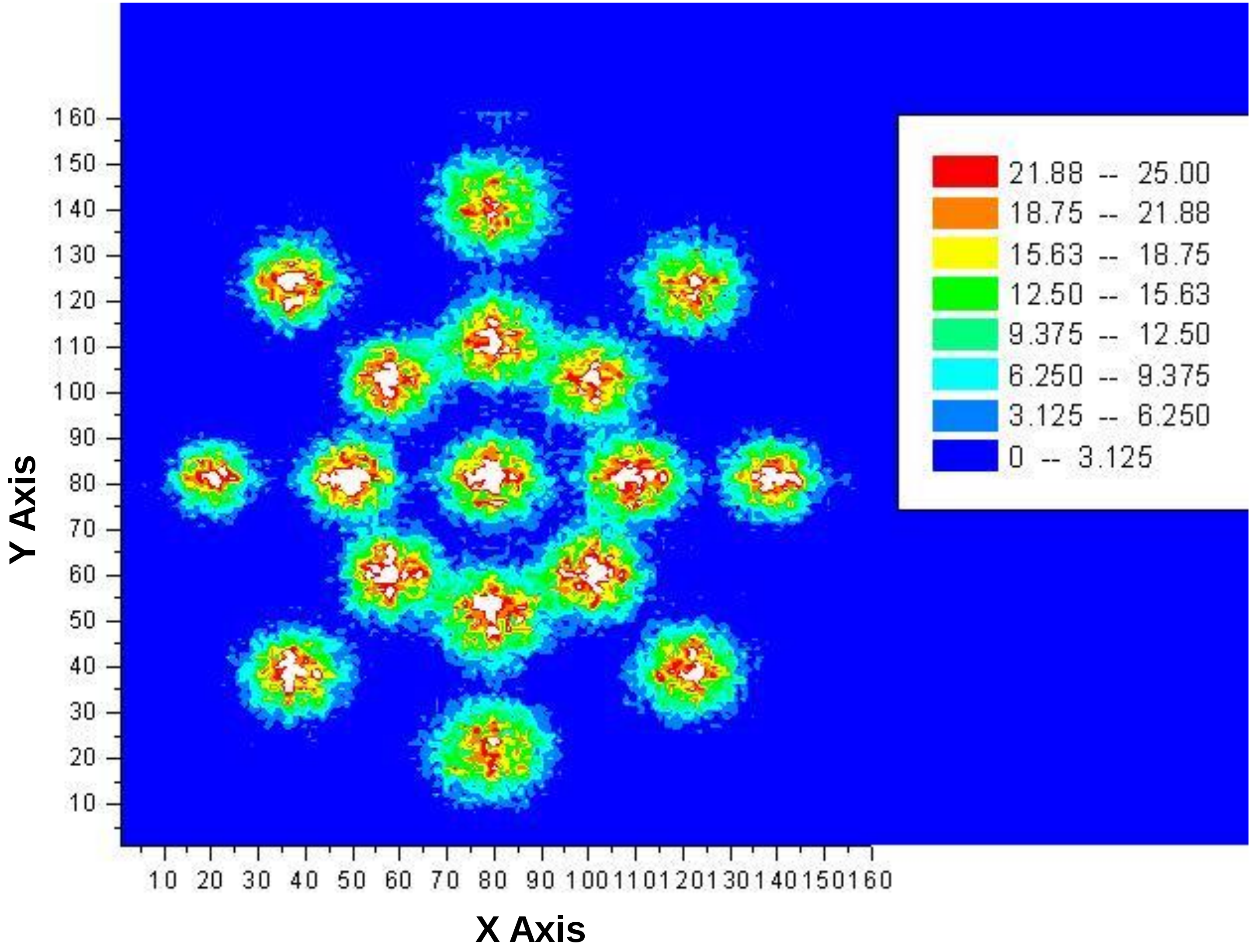
Cathode Pulse-Height Spectrum (α-particles)



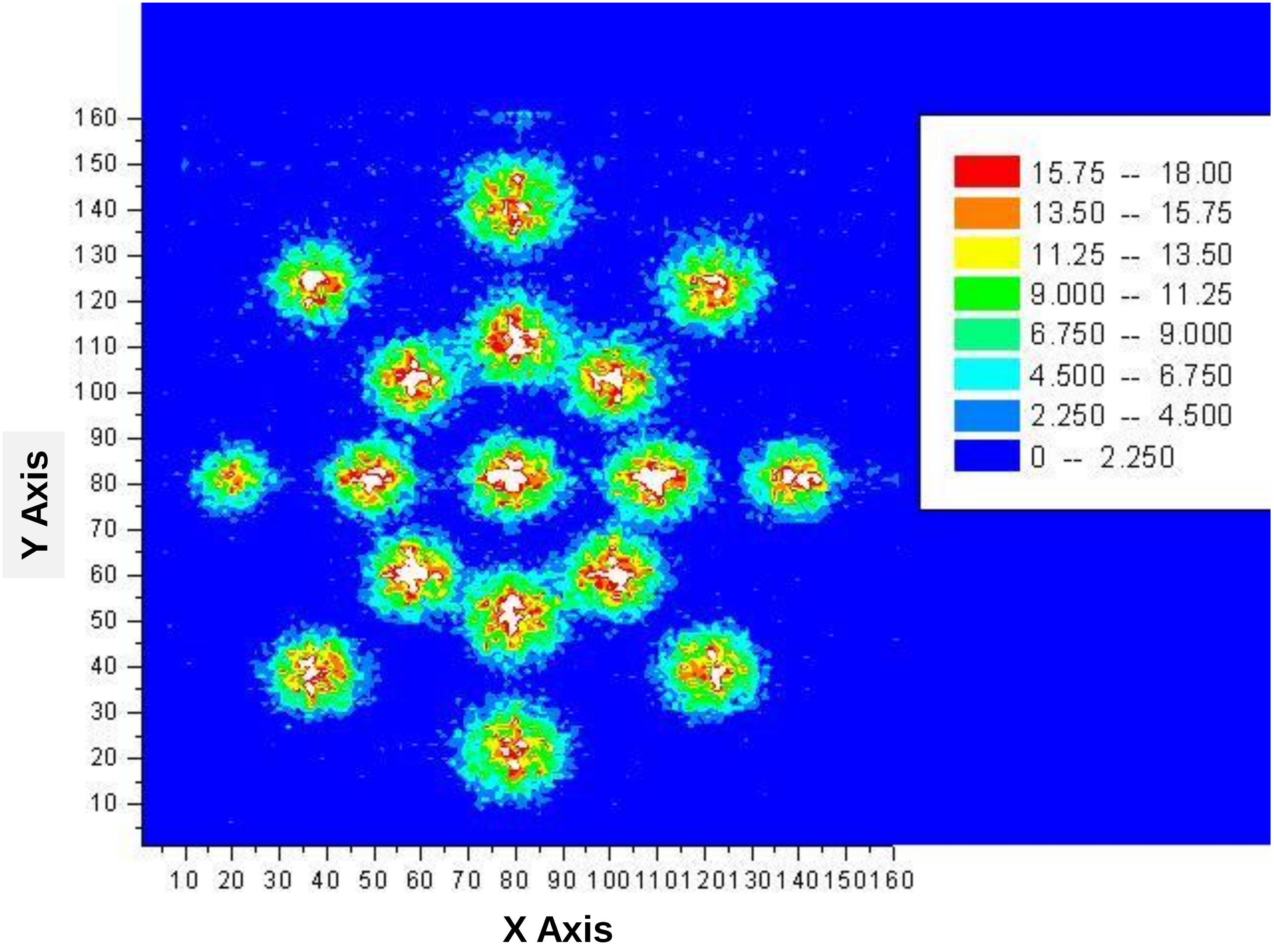
Anode 2D Pulse-Height Spectrum of α-particles (In Coincidence with Cathode Pulses, Reg. Threshold #3)



Anode 2D Pulse-Height Spectrum of α-particles (In Coincidence with Cathode Pulses, Reg. Threshold #2)

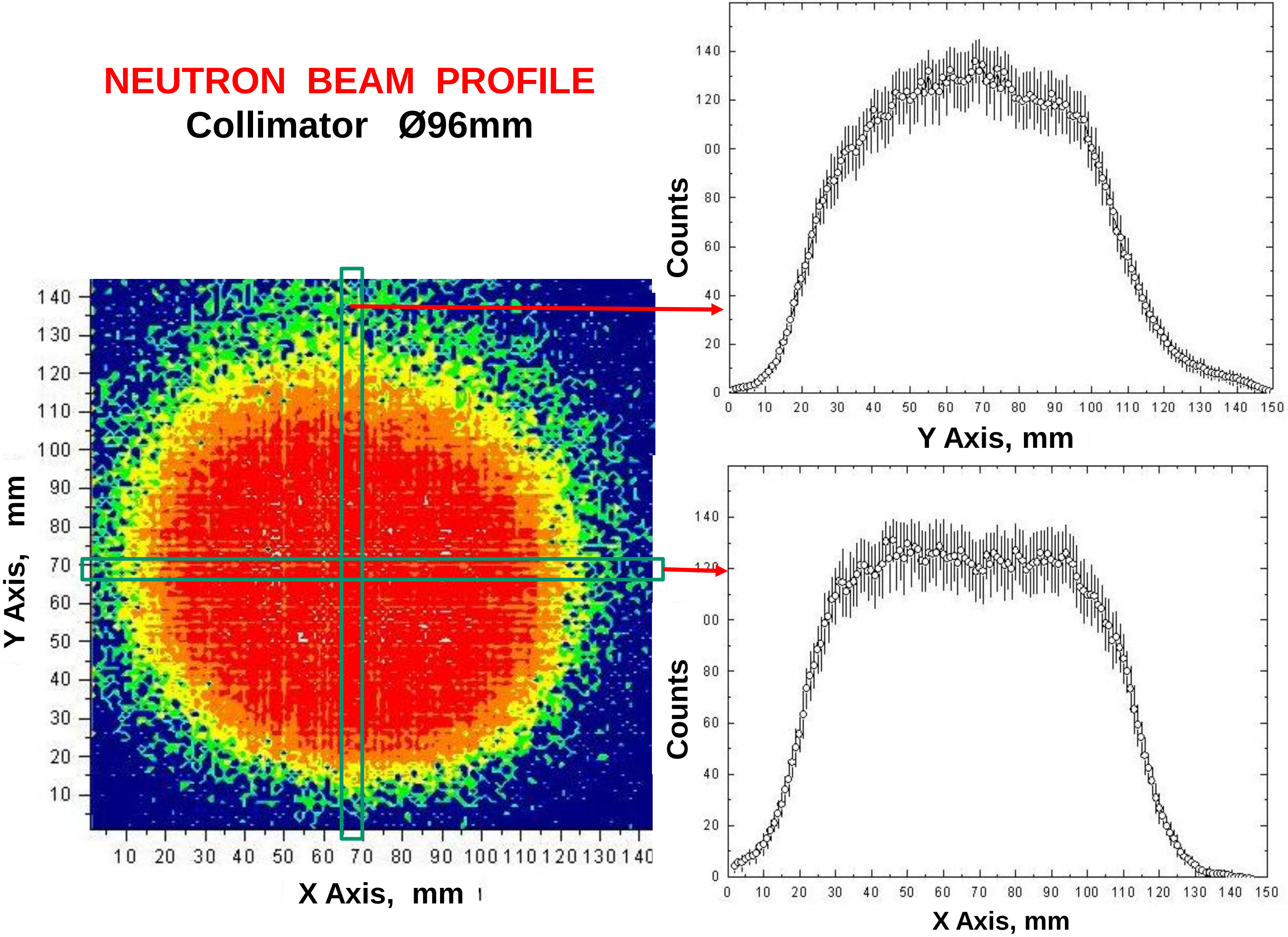


Anode 2D Pulse-Height Spectrum of α-particles
(In Coincidence with Cathode Pulses, Reg. Threshold #1)



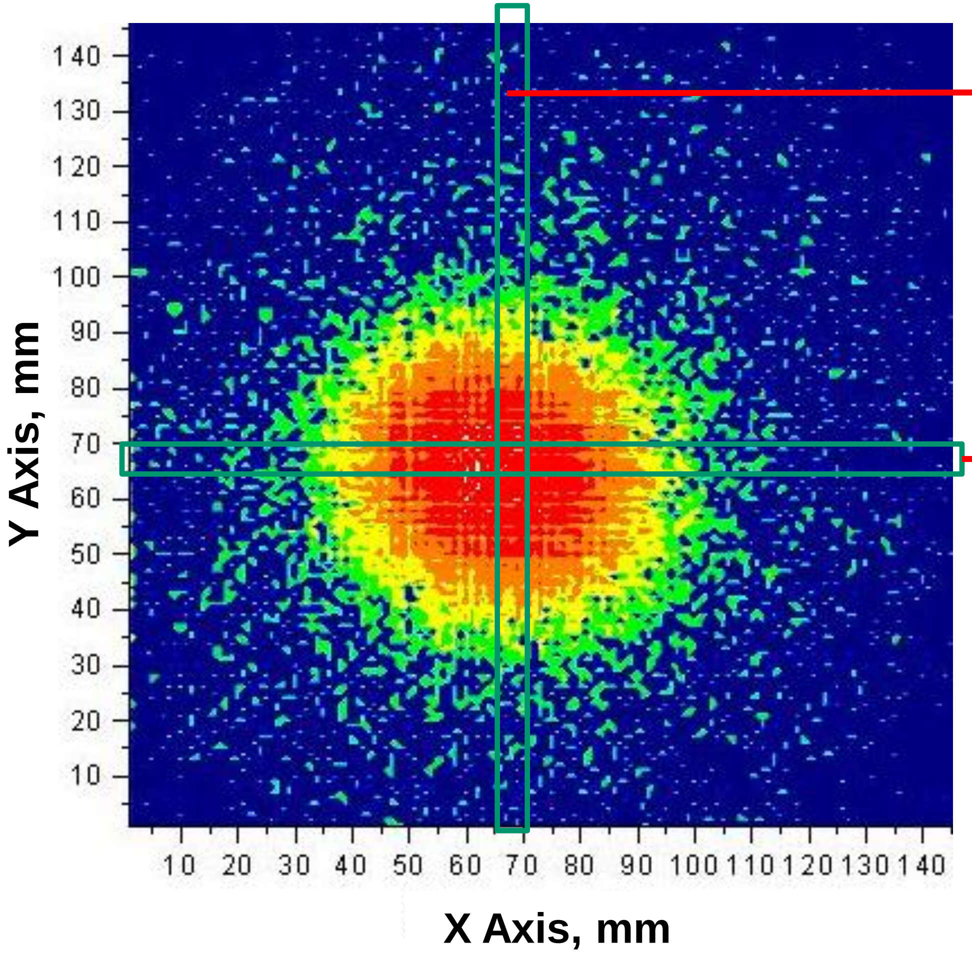
NEUTRON BEAM PROFILE

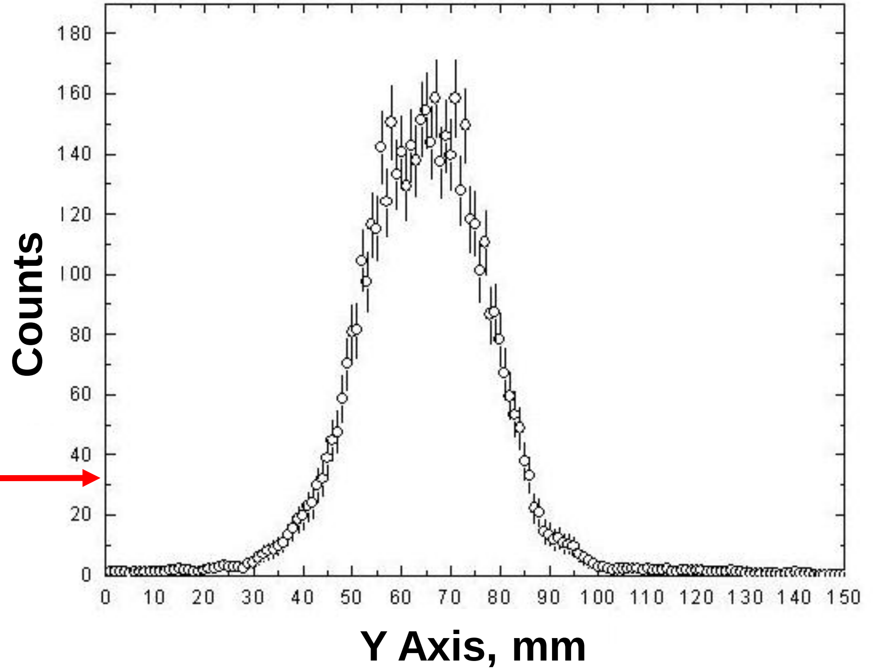
Collimator Ø96mm

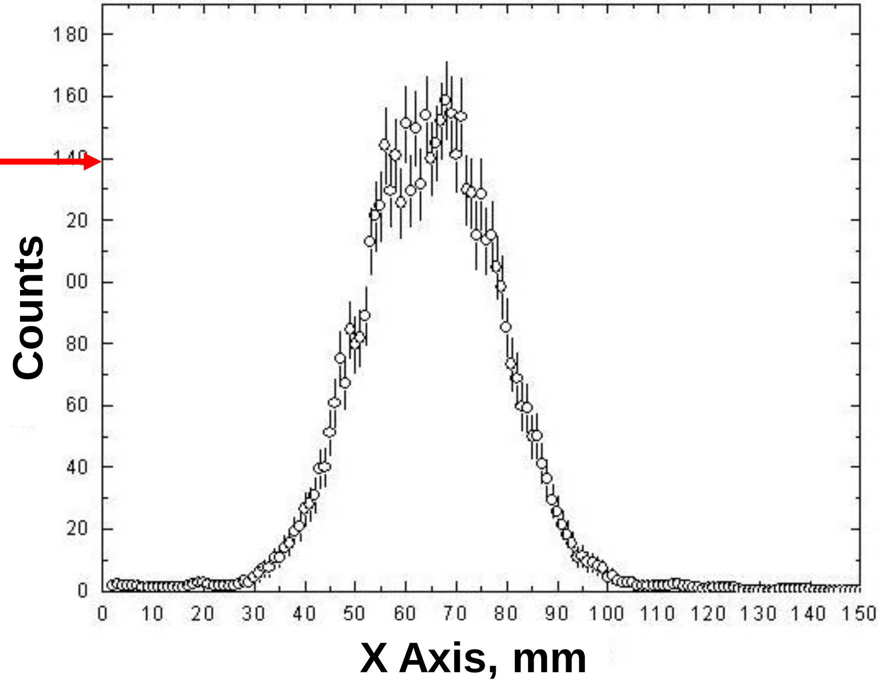


NEUTRON BEAM PROFILE

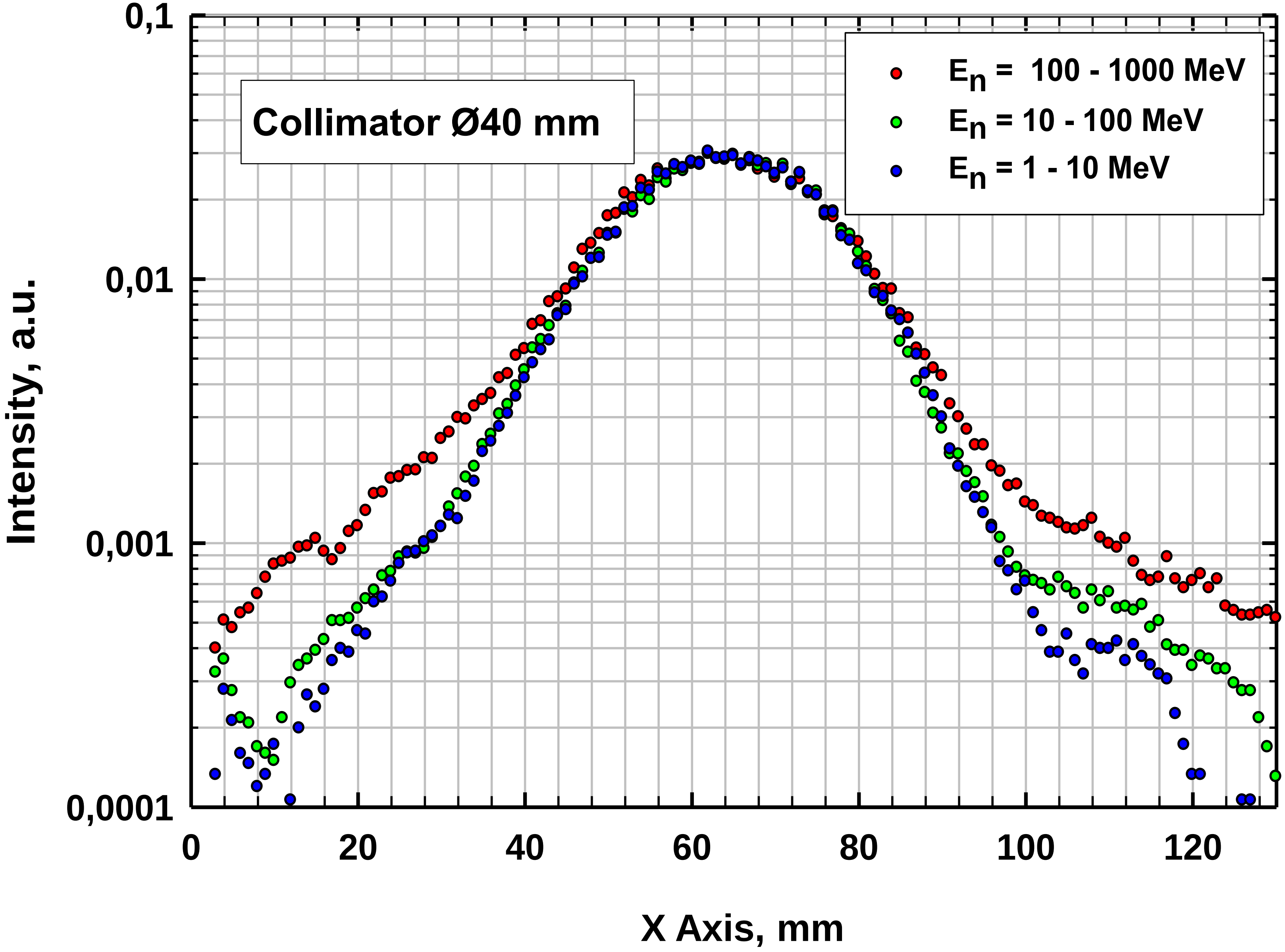
Collimator Ø40mm



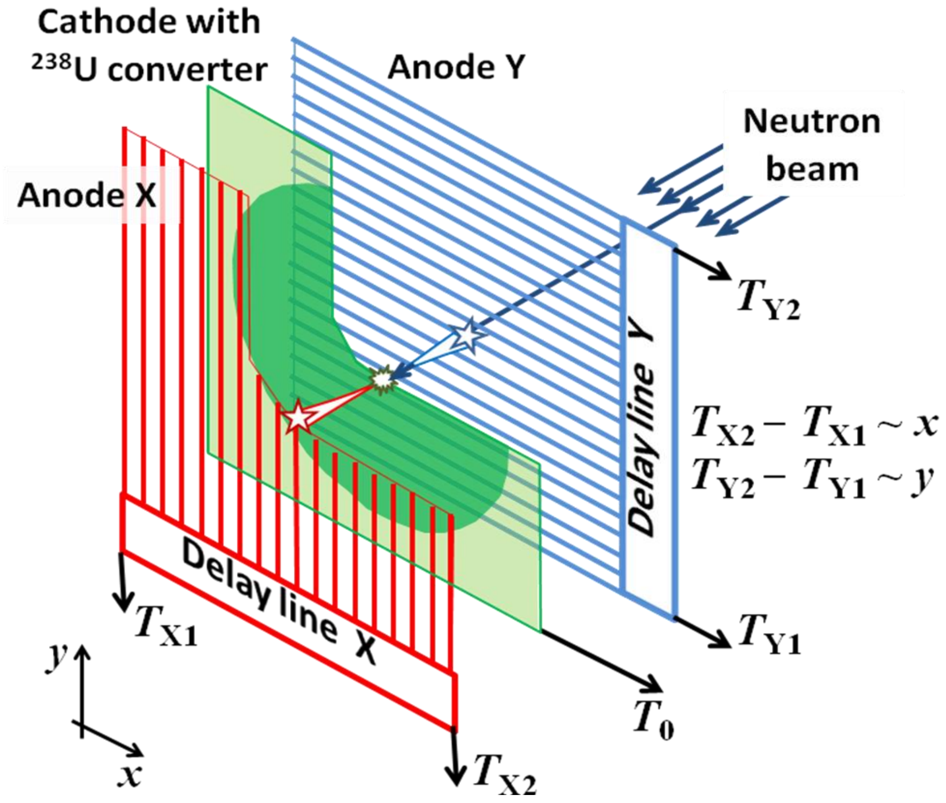




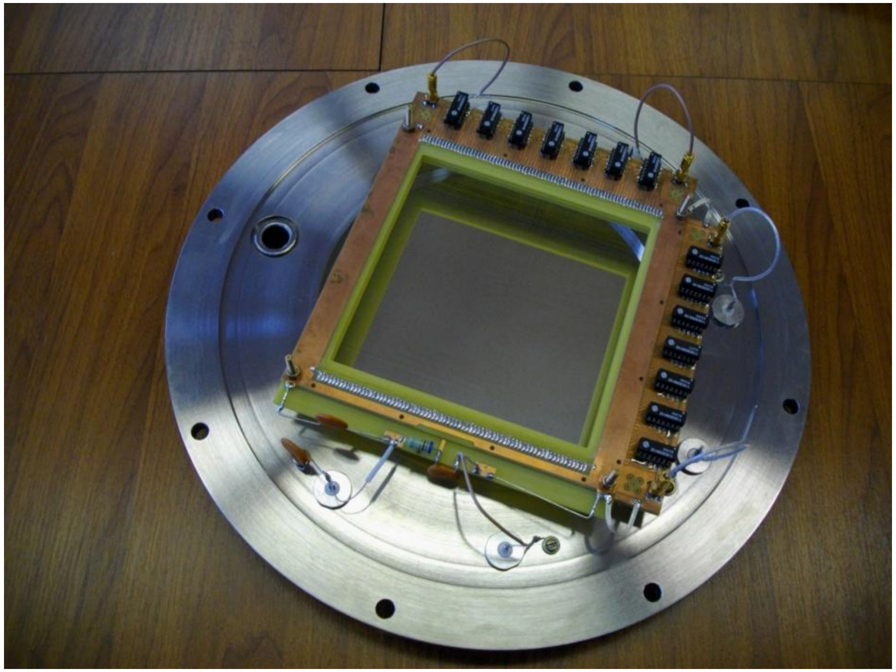
Neutron Beam Profile vs Neutron Energy



MWPC – Neutron Beam Profile Meter (position sensitive MultiWire Proportional Counter)

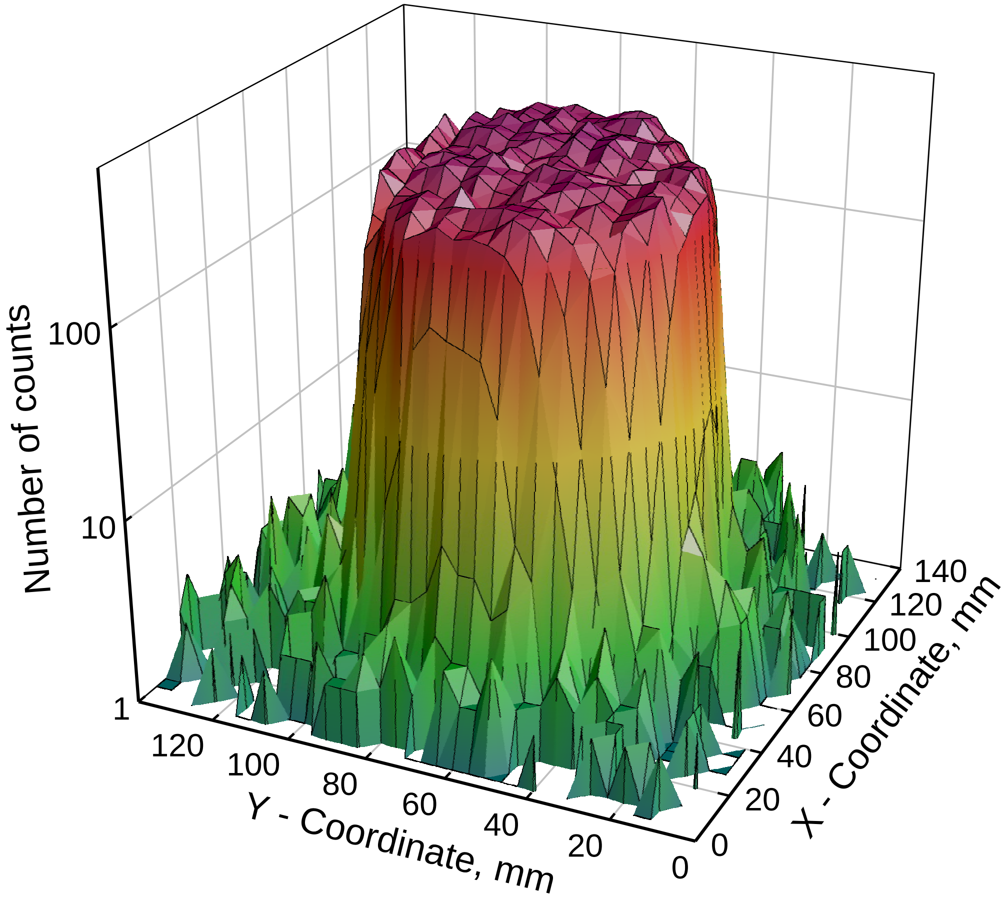


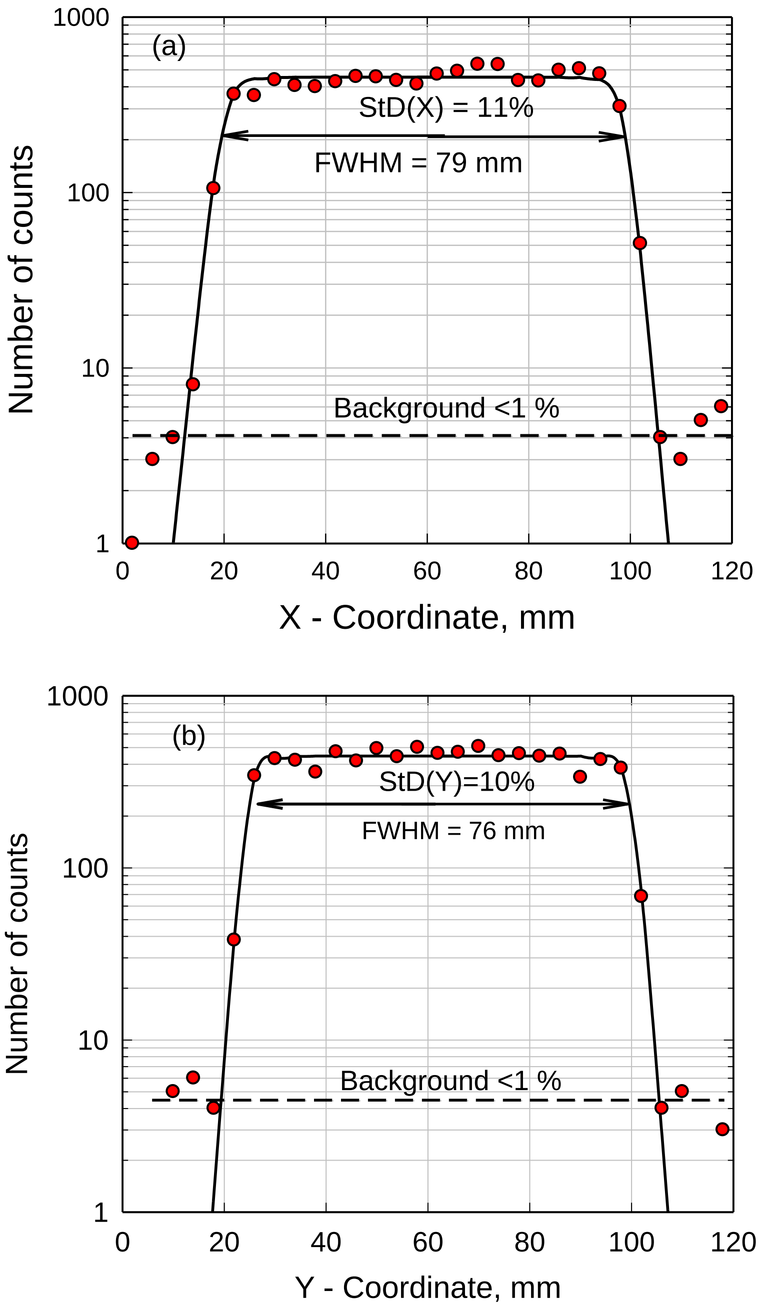
Size: 140 x 140 mm^2
Neutron detection efficiency: $3 \cdot 10^{-7}$
Spatial resolution:
2 mm < FWHM < 4 mm



Anodes: 140 gilded W-wires, Ø25μm, 1 mm step on 3mm thick fiberglass plastic frame
Cathode: 150 μg/cm^2 thick ^{238}U converter on aluminized 2 μg thick Mylar film
Working Gas: isobutene (iC_4H_{10}), 6-7 Torr
Data read-out: delay lines, 2 ns/step

3D-neutron beam profile, Horizontal (X) and Vertical (Y) beam profiles measured with <u>Ø75 mm beam collimator</u>





Comparative Study of Dark Currents in CCD – Matrix Irradiated by PROTONS and NEUTRONS

CCD (Charge-Coupled Device) - Matrix :

- image sensor Avionic and Space equipment
- commonly used in for coloured and black/white video cameras;

Irradiation of CCD-Matrix by high-energy protons and neutrons leads to:

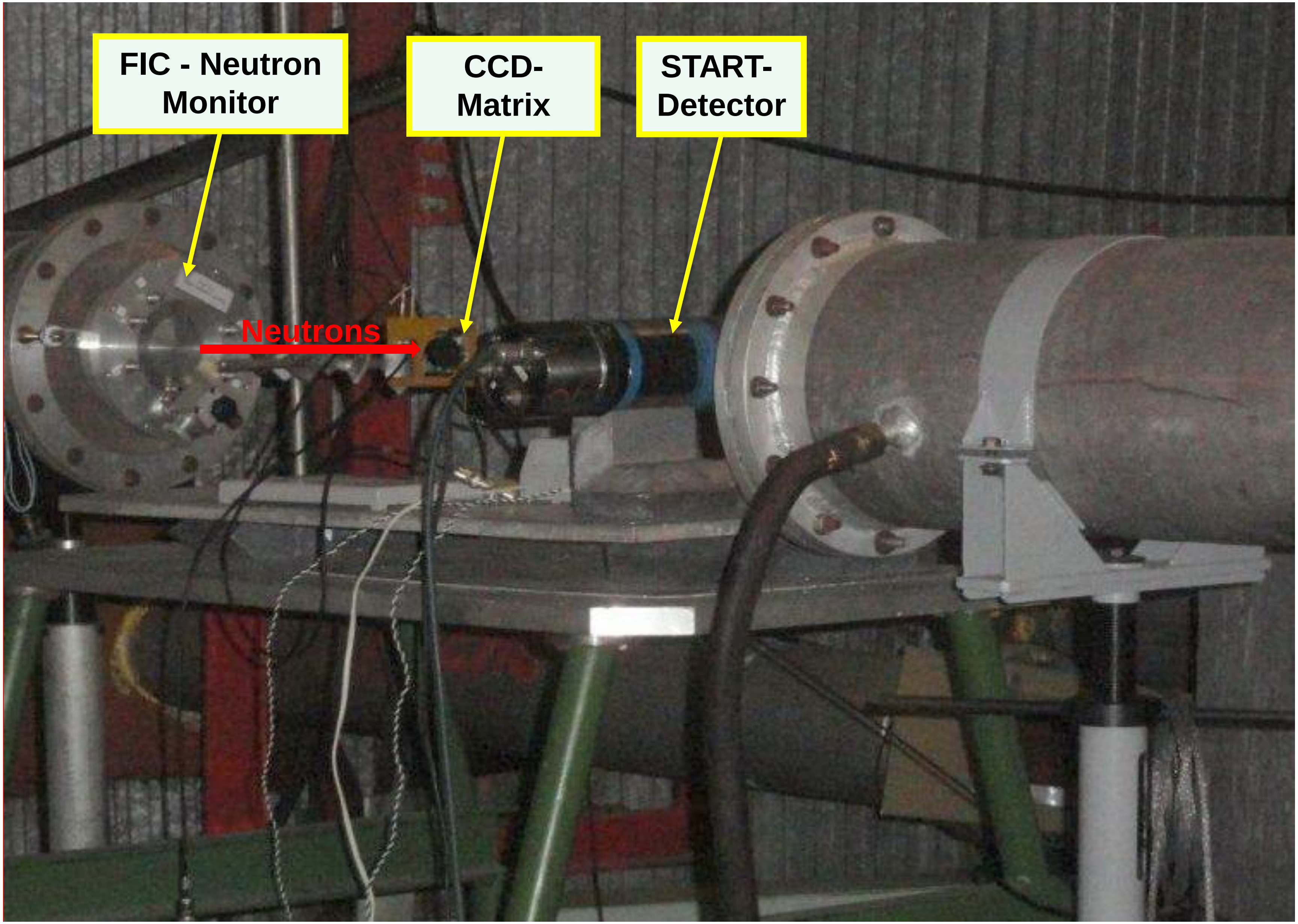
- overall degradation
- appearance of isolated pixels, the so-called "spikes";
- "spikes" look as isolated white spots , which lead to the image distortion and subsequent equipment failure;
- example: failure of the navigation system during the process of spaceship docking.

High-priority task: CCD – matrix testing with 1GeV protons and atmospheric-like neutron spectrum (1MeV – 1GeV).

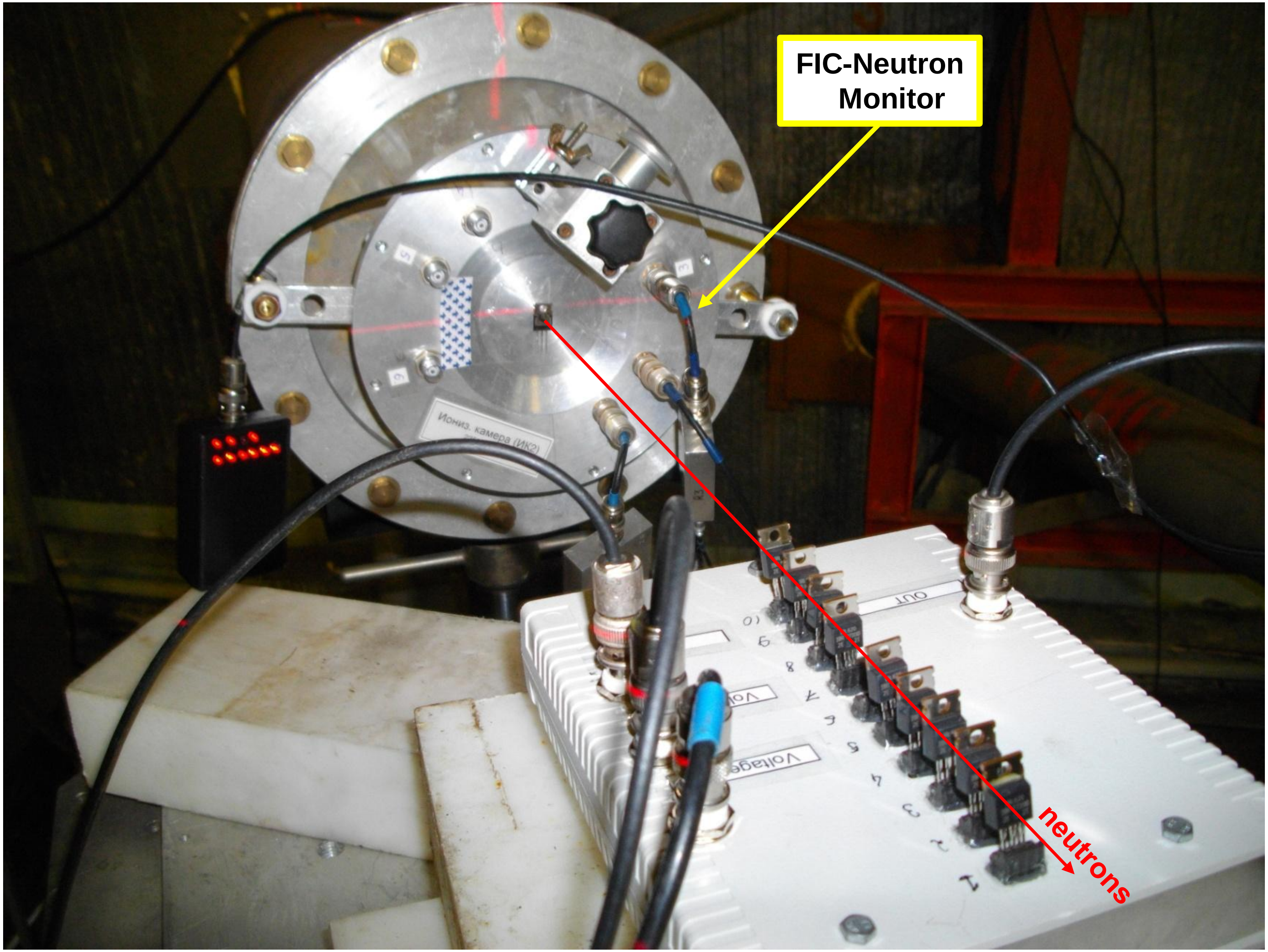
This is first experiment at the GNEIS (2010)

devoted to the neutron radiation resistance test of electronics.

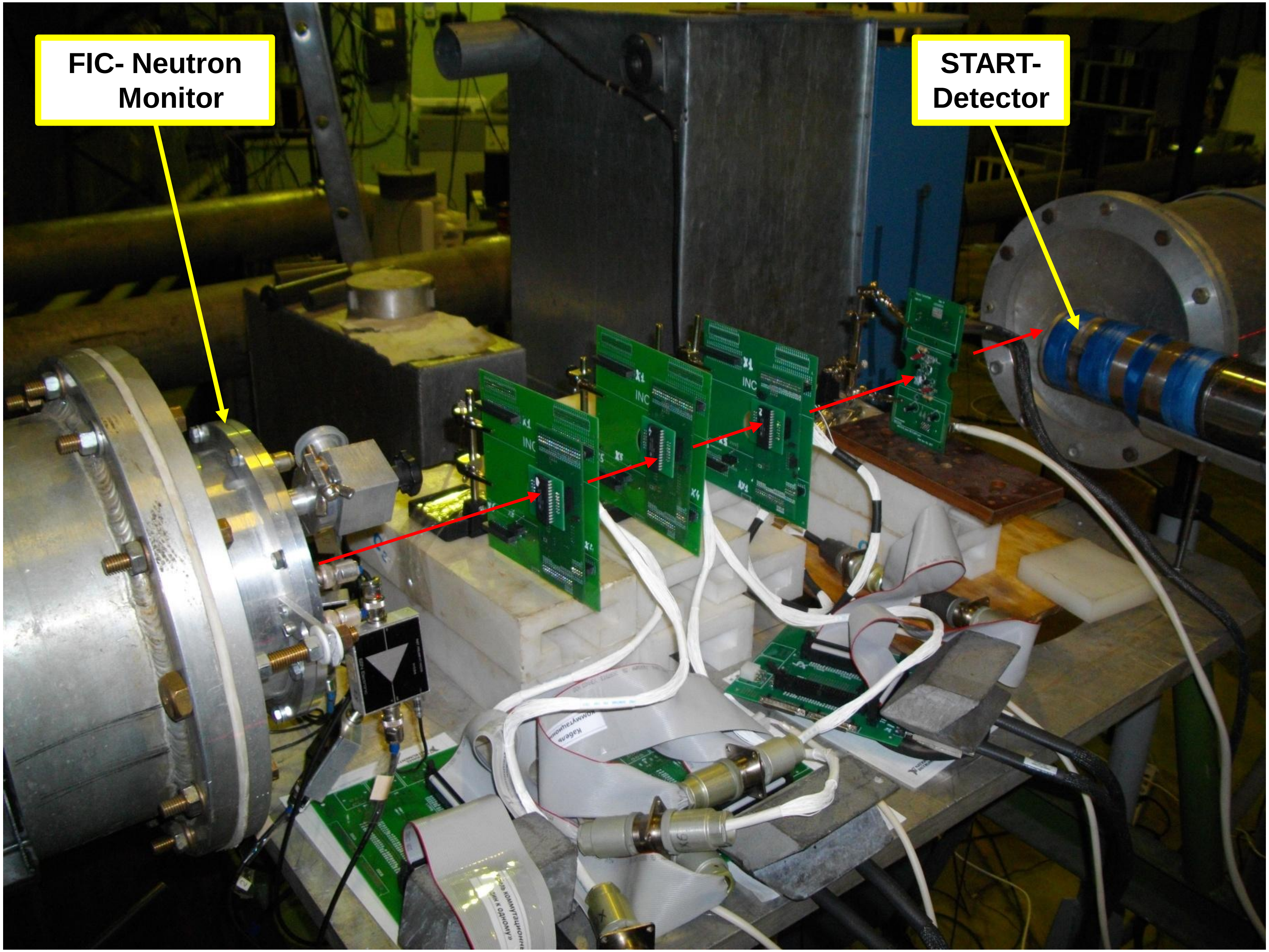
Neutron Irradiation of CCD-Matrix (2010)



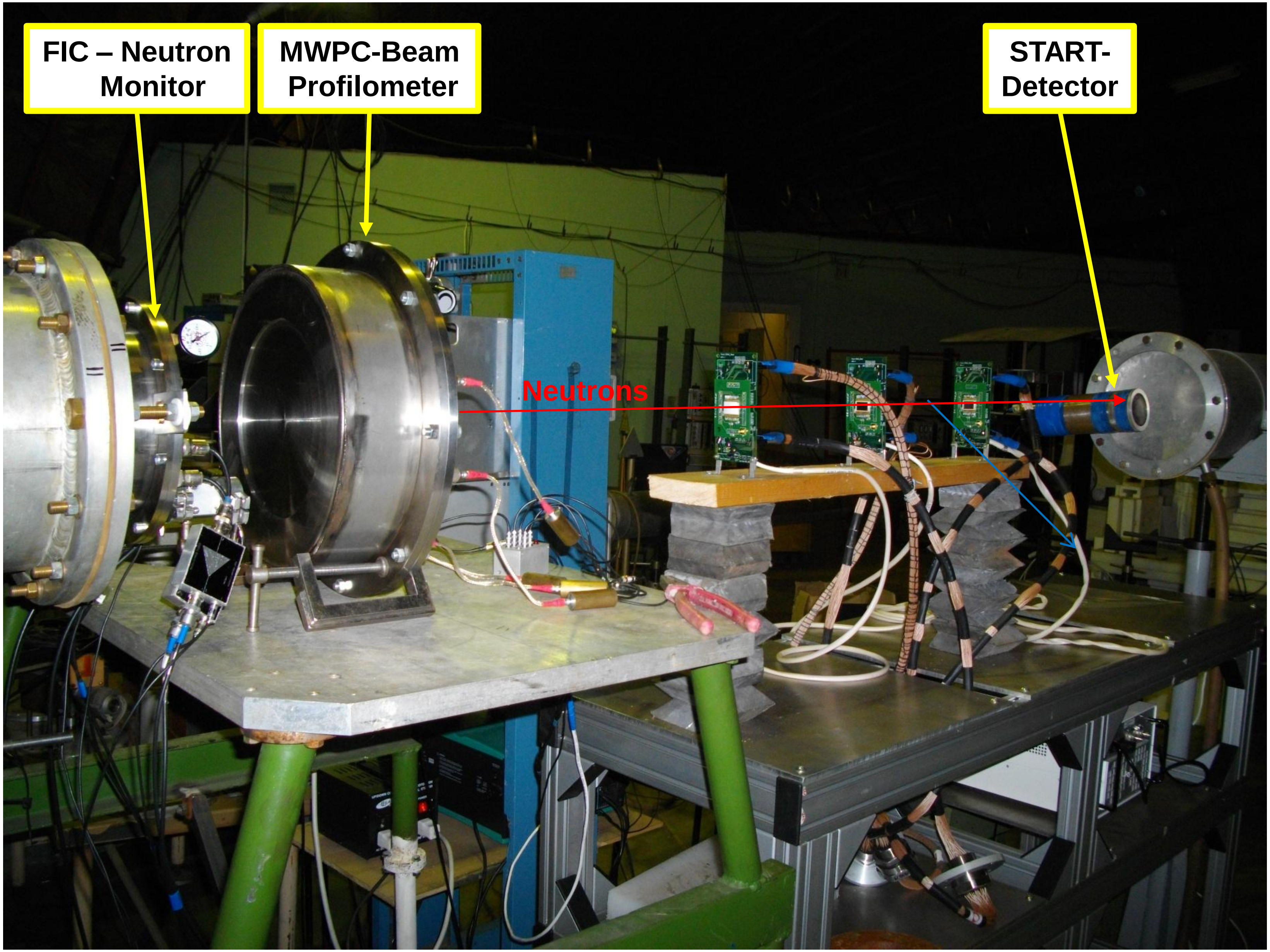
Neutron Irradiation of MOS - Transistors (2012)



Neutron Irradiation of SRAM - Chips (2013)



Neutron Irradiation of SRAM - Chips (2014)

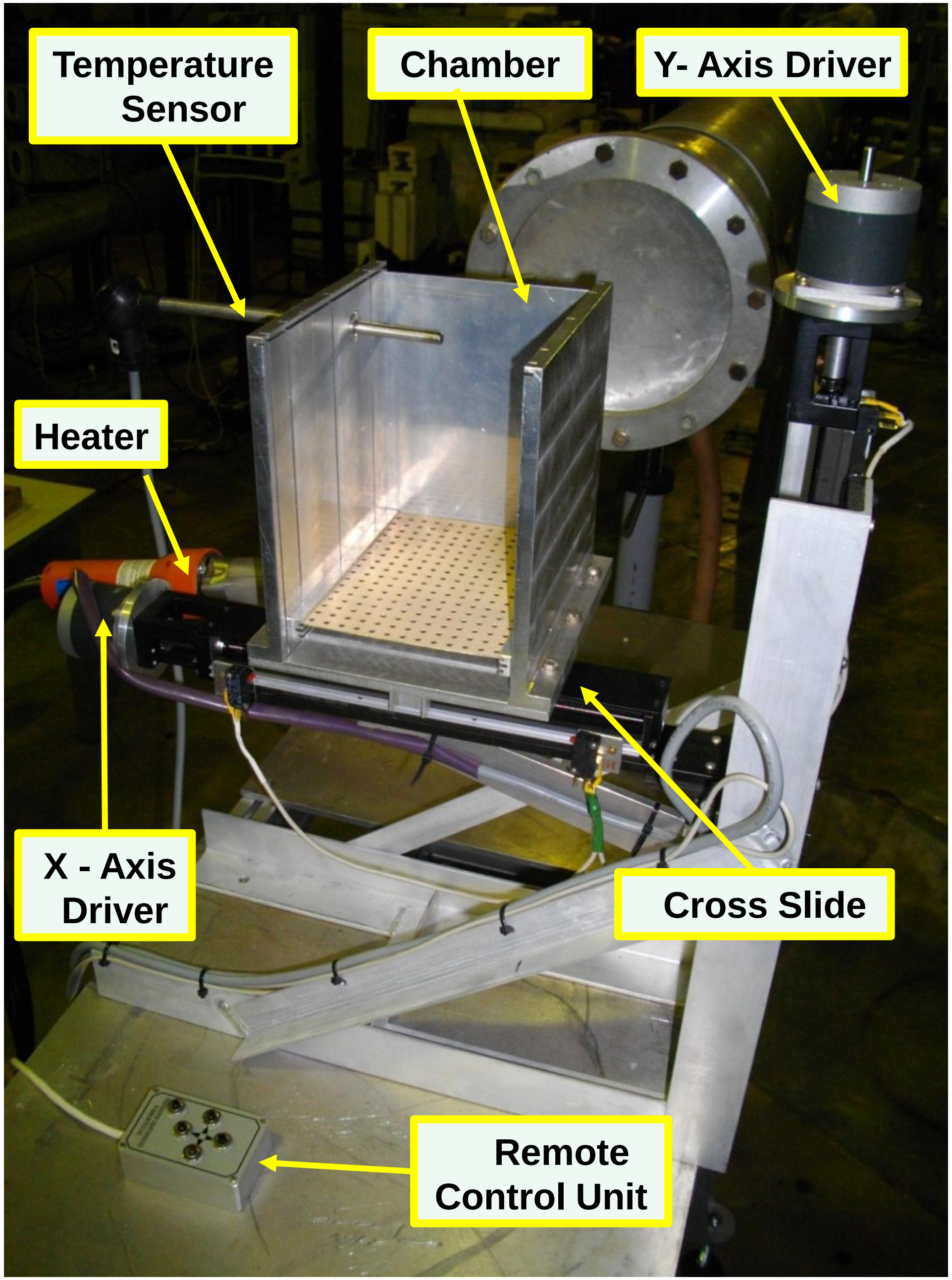


FIC – Neutron Monitor

MWPC-Beam Profilometer

START-Detector

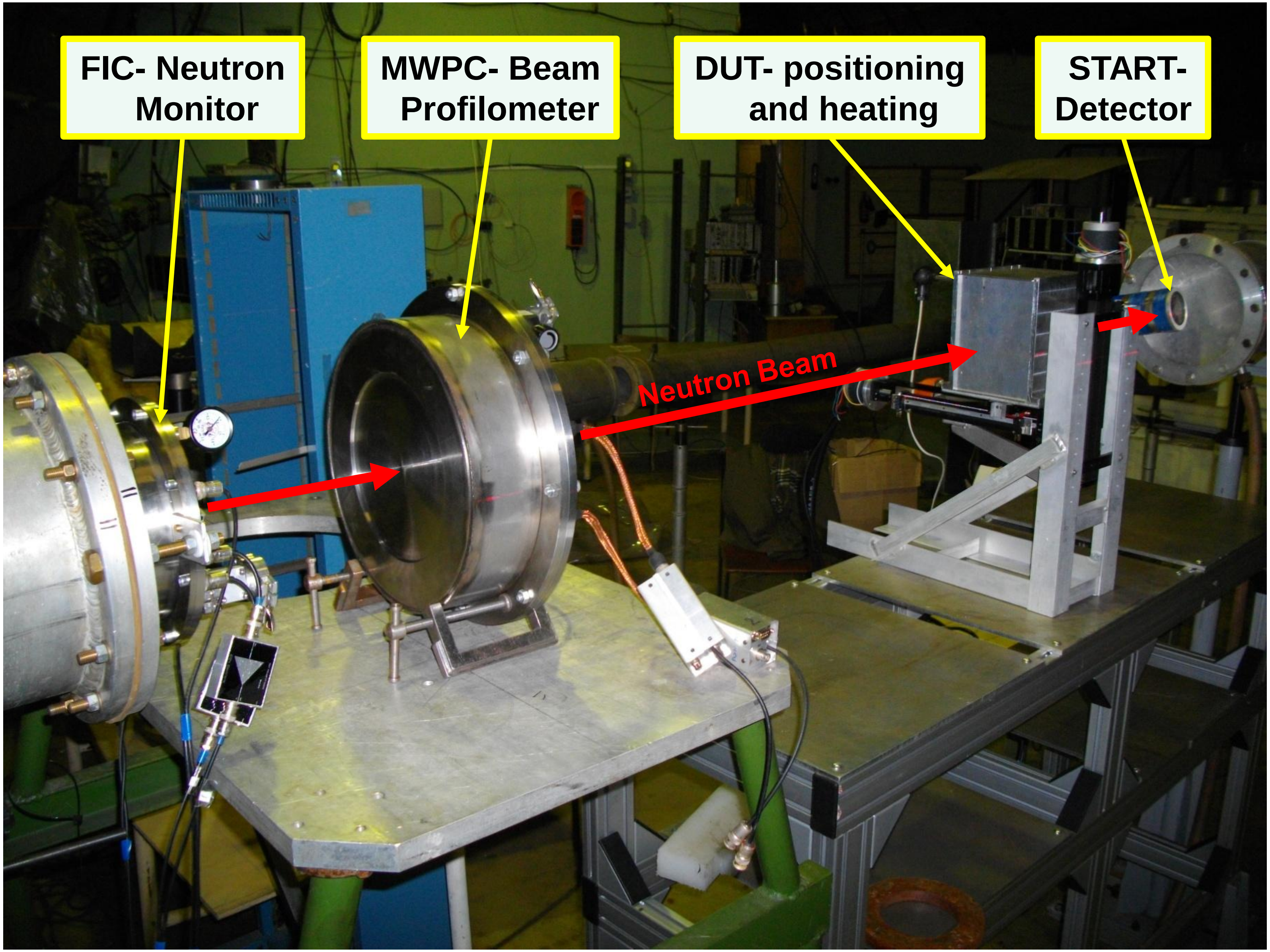
System for DUT (Device Under Test) Positioning and Heating



DUT enclosed in the Heating Chamber can be:

- **heated, temperature range 20^0C – 130^0C**
- **max. heating / cooling time 300 sec (closed chamber) 600 sec (upper cover removed)**
- **moved along X-Y axes, max. displacement range 200 mm**
- **max. DUT dimensions 150 mm x 150 mm**
- **Distant Computer control**

Neutron Testing Facility at GNEIS (2015)



FIC- Neutron Monitor

MWPC- Beam Profilometer

DUT- positioning and heating

START- Detector

Results of the SRAM tests carried out at the ISNP facility (2015)

Device type	Fluence*) (neutron / cm^2)	σ_{seu} (cm^2 / bit)
CY7C1021BN - 15ZSXE	$1.6 \cdot 10^{9}$	$9.6 \cdot 10^{-15}$
CY62256NLL - 55SNXI	$2.9 \cdot 10^{10}$	$2.2 \cdot 10^{-15}$
UT6264CPCL - 70LL	$1.4 \cdot 10^{10}$	$3.2 \cdot 10^{-14}$
CY61248ELL - 45ZSXA	$2.8 \cdot 10^{9}$	$8.5 \cdot 10^{-14}$
CY7C1049CV33 - 12ZSXA	$1.4 \cdot 10^{9}$	$6.6 \cdot 10^{-15}$
CY7C1049DV33 - 10ZSXI	$1.7 \cdot 10^{9}$	$3.0 \cdot 10^{-15}$

*)Represented data correspond to neutron fluence in the energy range 1-1000 MeV

CONCLUSION

- at the neutron TOF-facility GNEIS based on the 1 GeV proton synchrocyclotron of the PNPI, it was developed a neutron test facility with atmospheric – like neutron spectrum in energy range 1 – 1000 MeV and integral neutron flux $4 \cdot 10^5$ n/cm$^2 \cdot$s;

- our facility enables to carry out accelerated neutron tests of electronic equipment; 1 hour of neutron irradiation at the ISNP/GNEIS is equal to 110 000 hours of natural neutron irradiation at the altitude of 10-12 km and $4.6 \cdot 10^7$ hours (5250 years) at the sea level;

- during 2010-2015, the neutron irradiation tests of various electronic devices have been done at the ISNP/GNEIS simultaneously with the proton irradiation tests.

В СОЗДАНИИ НЕЙТРОННОГО ИСПЫТАТЕЛЬНОГО СТЕНДА ИСНП/ГНЕЙС
И ПРОВЕДЕНИИ ИСПЫТАНИЙ
принимали участие

- Ускорительный отдел ОПР
- Группа физики деления ядер (ГНЕЙС) ОНИ
- Отдел автоматизации экспериментов на реакторах ОНИ
- Лаборатория кристаллооптики заряженных частиц ОФВЭ
- Отдел трековых детекторов ОФВЭ
- Отдел информационных технологий и автоматизации ОПР
- Цех экспериментального и технологического оборудования
- Лаборатория радиационной физики ОПР

ОГРОМНАЯ БЛАГОДАРНОСТЬ ВСЕМ!

Welcome to NICE House GNEIS in Gatchina!

НОВЫЕ ПЕРСПЕКТИВНЫЕ УСТАНОВКИ ДЛЯ ПРОВЕДЕНИЯ ИСПЫТАНИЙ ЭКБ И СИСТЕМ НА НЕЙТРОННЫХ ПУЧКАХ С АТМОСФЕРОПОДОБНЫМ СПЕКТРОМ

ORNL (Ок-Ридж, США)

- действующий нейтронный источник SNS: протоны 1 ГэВ
- испытательный стенд HETS (High-Energy Neutron Test Station)
- ЭКБ: сечение пучка 20см х 20см, поток нейтронов 10^4 – 10^7 н/см^2/сек
- блоки ЭО: сечение пучка 1м х 2м, поток нейтронов 10^2 – 10^4 н/см^2/сек
- стоимость проекта – до 100 млн USD
- срок создания – до 5 лет

RAL (Резерфордовская Лаборатория, Чилтон, Великобритания)

- действующий нейтронный источник ISIS: протоны 800 МэВ, W/Ta мишень
- действующий испытательный стенд VESUVIO
- испытательный стенд ChipIR (Chip Irradiation)
- ЭКБ: сечение пучка 20см х 20см, поток нейтронов 10^4 – 10^7 н/см^2/сек
- блоки ЭО: сечение пучка 1м х 1м, поток нейтронов $\leq 10^7$ н/см^2/сек
- стоимость проекта –15 млн фунтов стерлингов
- установка создана, находится в процессе аттестации и лицензирования

CIP (Пекин, КНР)

- нейтронный источник CSNS: протоны 1.6 ГэВ, 25 Гц, 500 КВт, W/Ta мишень
- испытательный стенд NIS (Neutron Irradiation Spectrometer)
- ЭКБ: поток нейтронов до 2.3 x 10^6 н/см^2/сек
- начало работы – 2018