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

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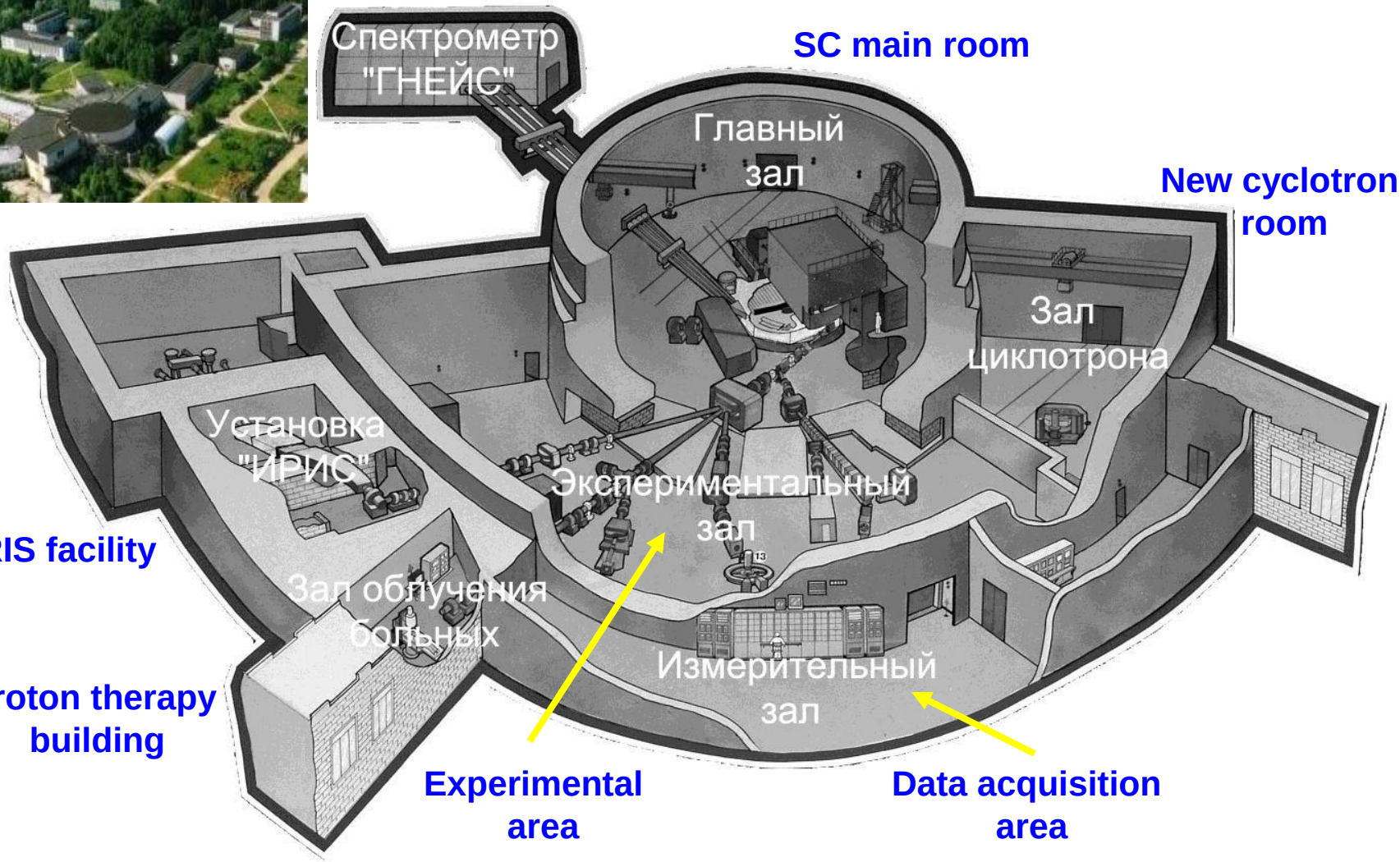
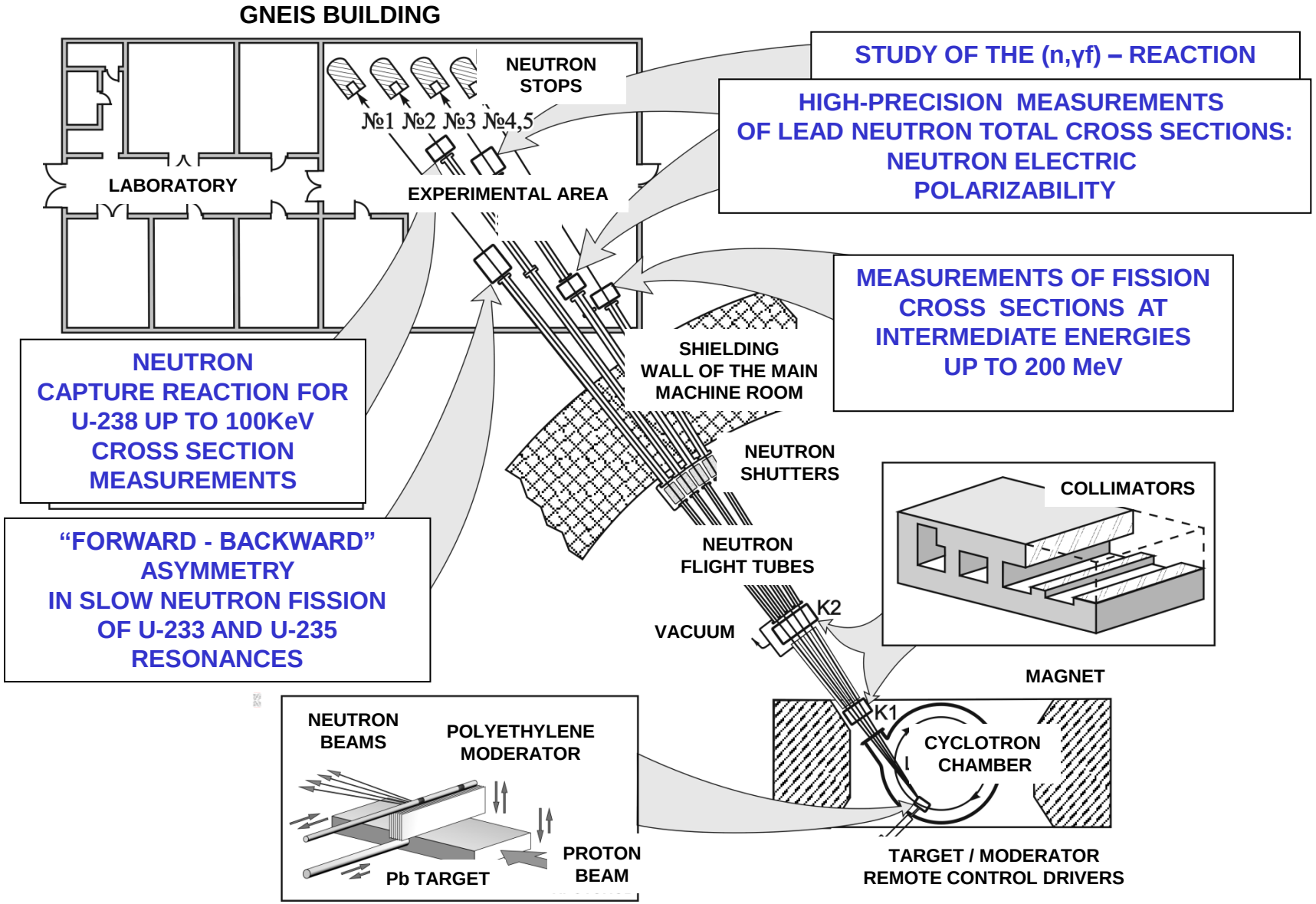
1 GeV proton synchrocyclotron of the PNPI
(in operation since 1970)



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)	$1/E^{\alpha}$, α=0.65-0.82
Type of neutron spectrum Beam #5 (En > 0.1 MeV)	“spallation”

GNEIS NEUTRON TOF-SPECTROMETER (since 1975)



COMPARISON OF THE GNEIS FACILITY WITH OTHER NEUTRON SOURCES

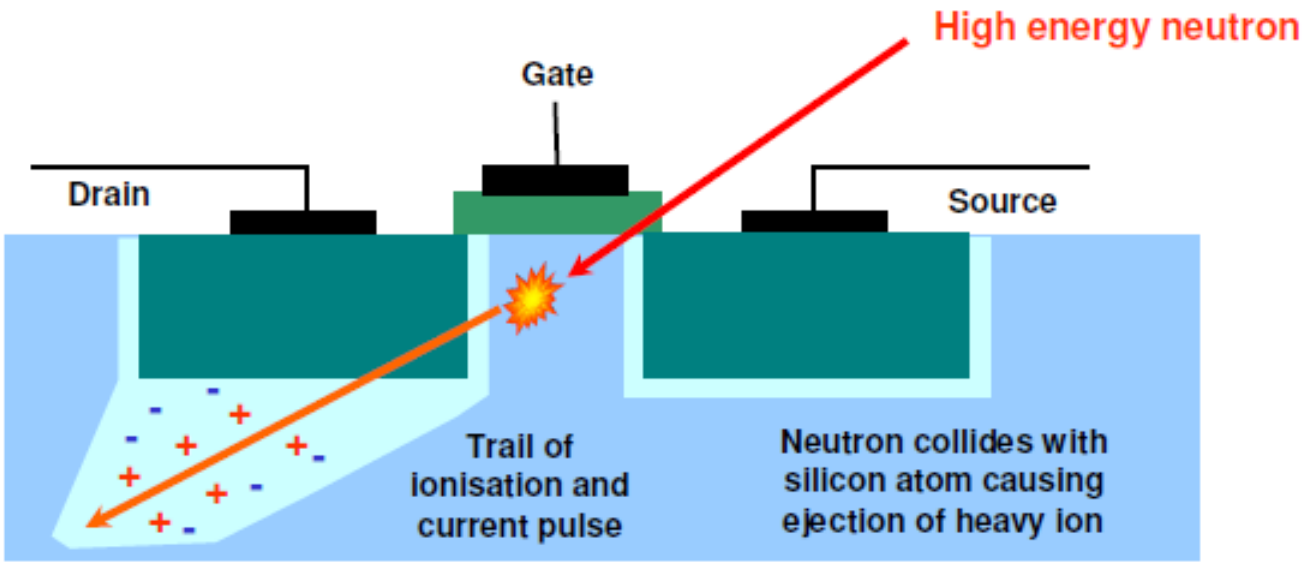
Neutron source (Laboratory)	$<I_n>$, 10^{15} n/s	Δt, ns	Q, 10^{30} n/s³
ORELA (ORNL, USA)	0.13	30	0.14
GELINA (IRMM, Belgium)	0.05	1	50
LANSCE (LANL, USA)	10	125	0.64
CERN PS n_TOF (CERN, Switzerland)	0.4	10	4
LUE-40+IBR-30 (JINR, shutdown)	0.5	1600	0.0002
IREN (JINR, project)	1.0	400	0.0062
GNEIS (PNPI, Gatchina) neutron beam N5	0.3	10	3

$<I_n>$ - average intensity of neutrons emitted in 4π solid angle

Δt - neutron pulse width

$Q = (<I_n>/\Delta t)^2$ - "quality" coefficient of the neutron source

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

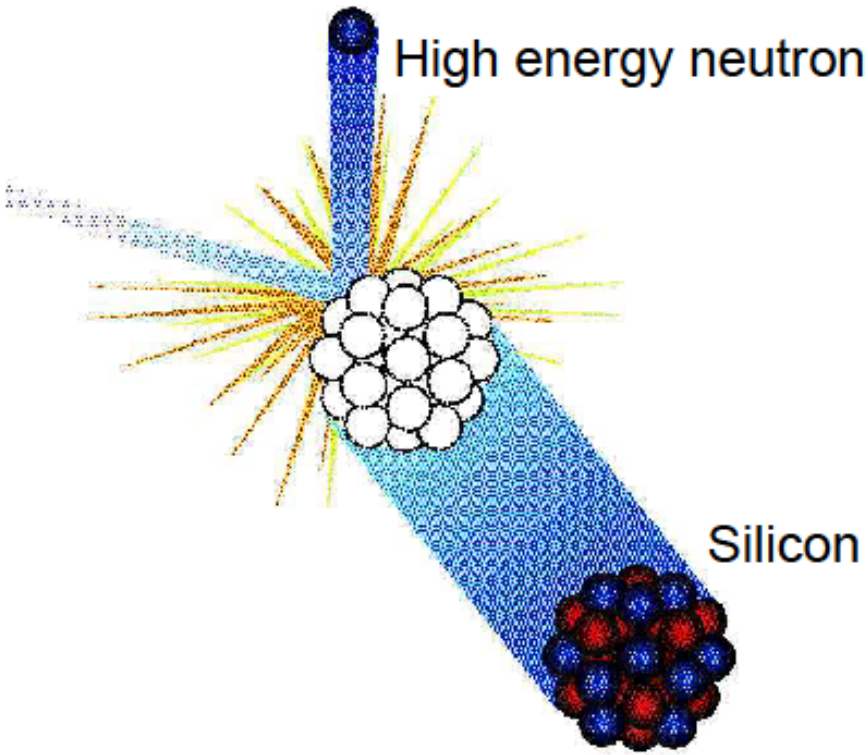


What are Single Event Effects and why are they important?

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

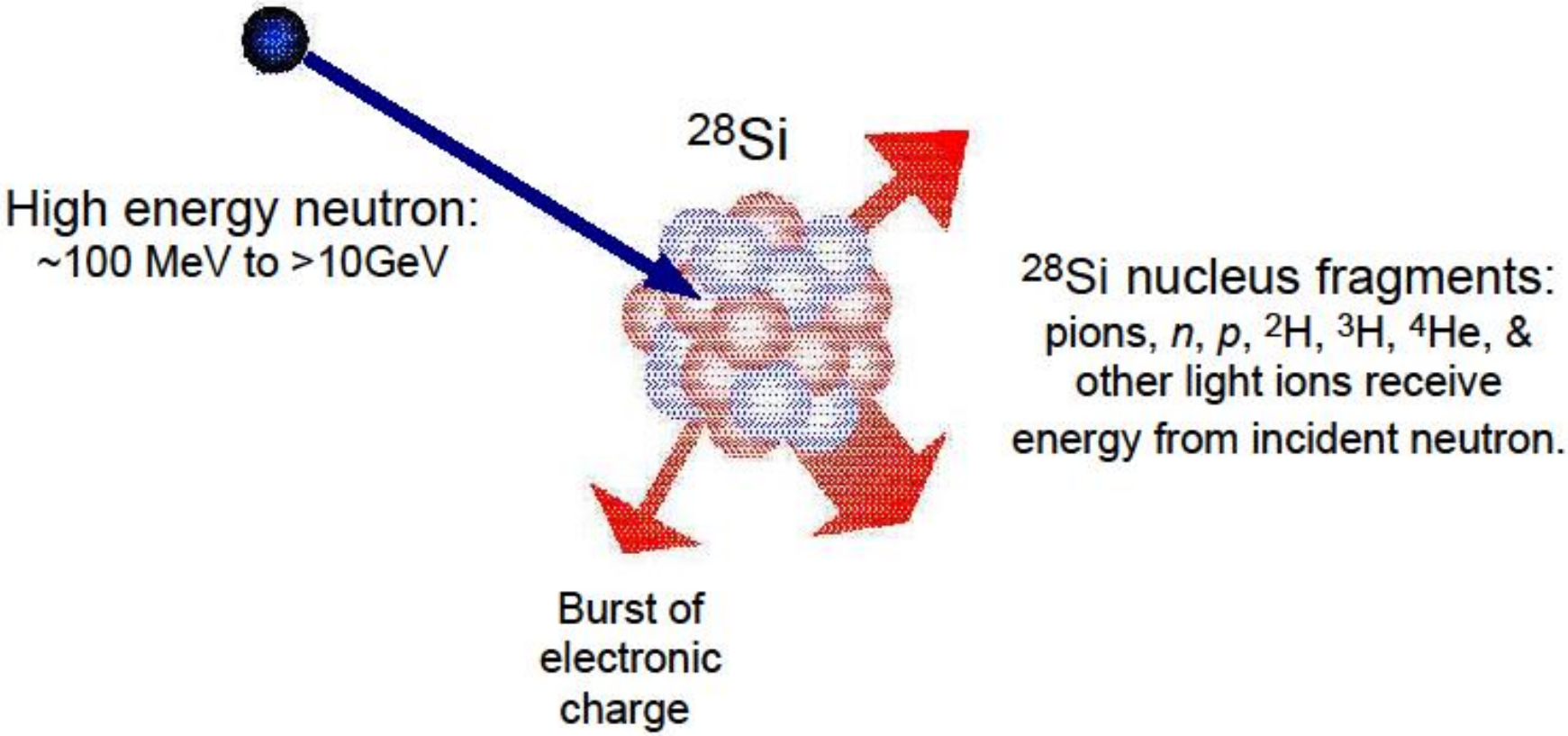


Energy and momentum from cosmic caused neutron can be transferred to a silicon or other IC nucleus.

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



R. Baumann, Texas Instruments [1]

ACCELERATED NEUTRON TESTING OF SEE

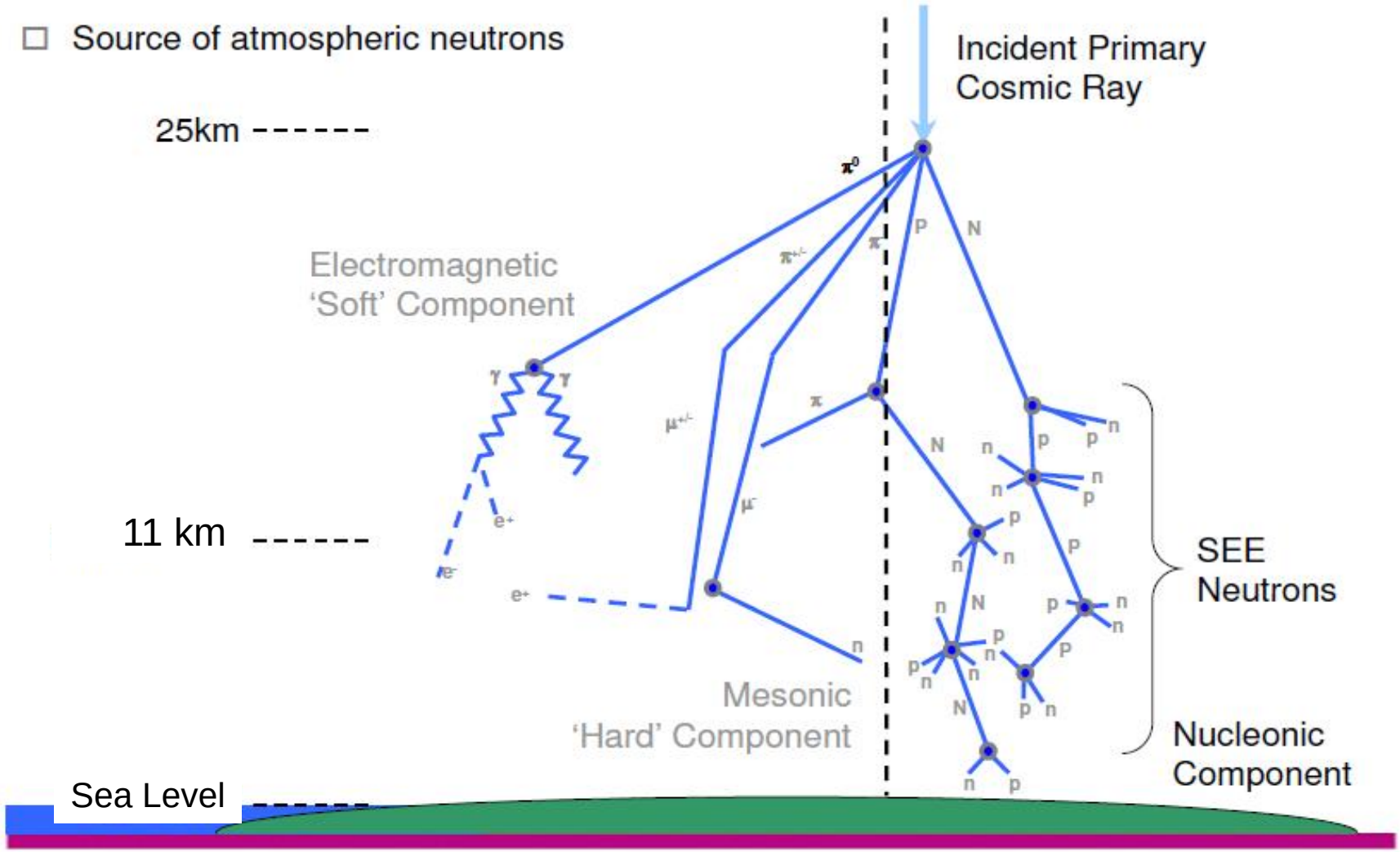
- Whole system or component testing of representative equipment to establish the risks and reliabilities

- 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

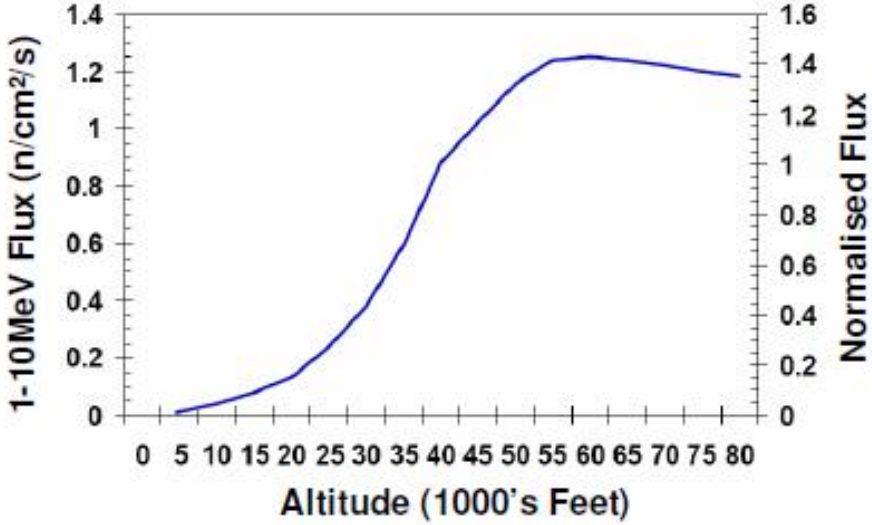
NEUTRON COMPONENT OF COSMIC RAYS

- Source of atmospheric neutrons



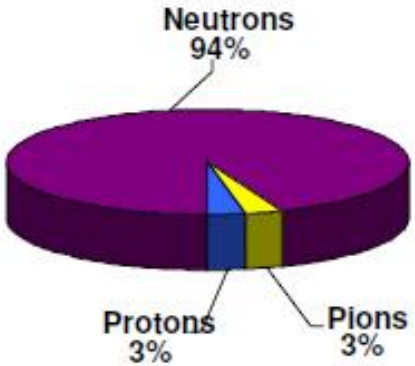
NEUTRON COMPONENT OF COSMIC RAYS

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

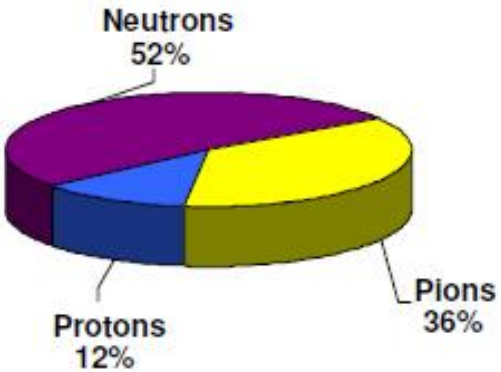


Source: Boeing Radiation Effects Lab

1000 Feet = 304.8 m



Sea Level

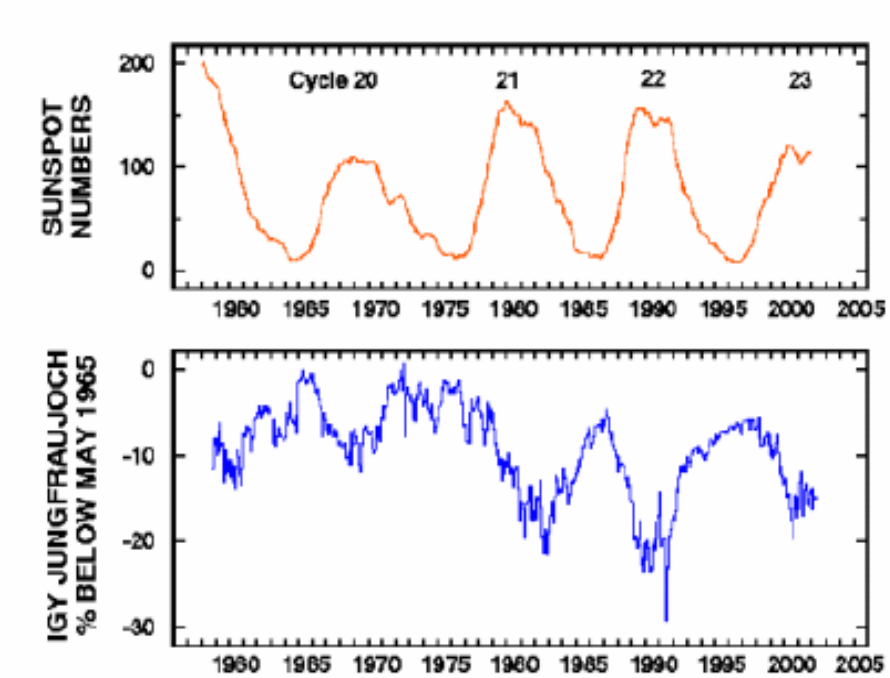


32,000 Feet

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

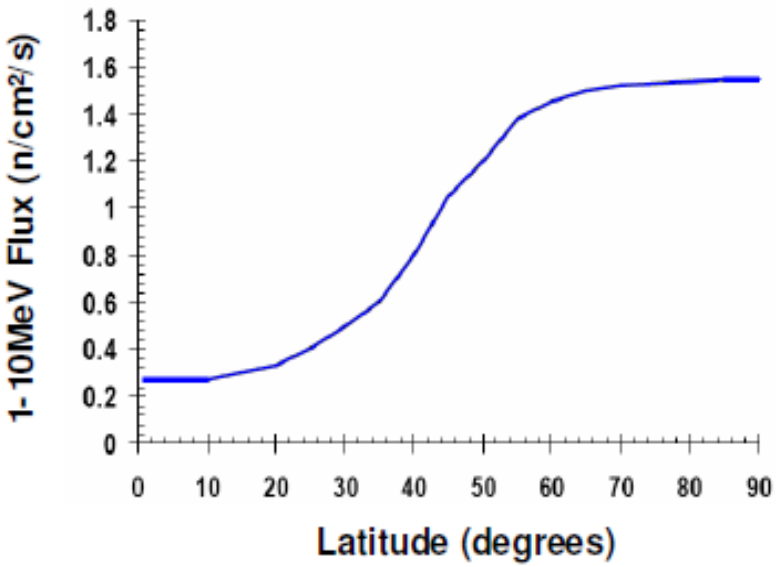
NEUTRON COMPONENT OF COSMIC RAYS

- Intensity with Latitude and Time



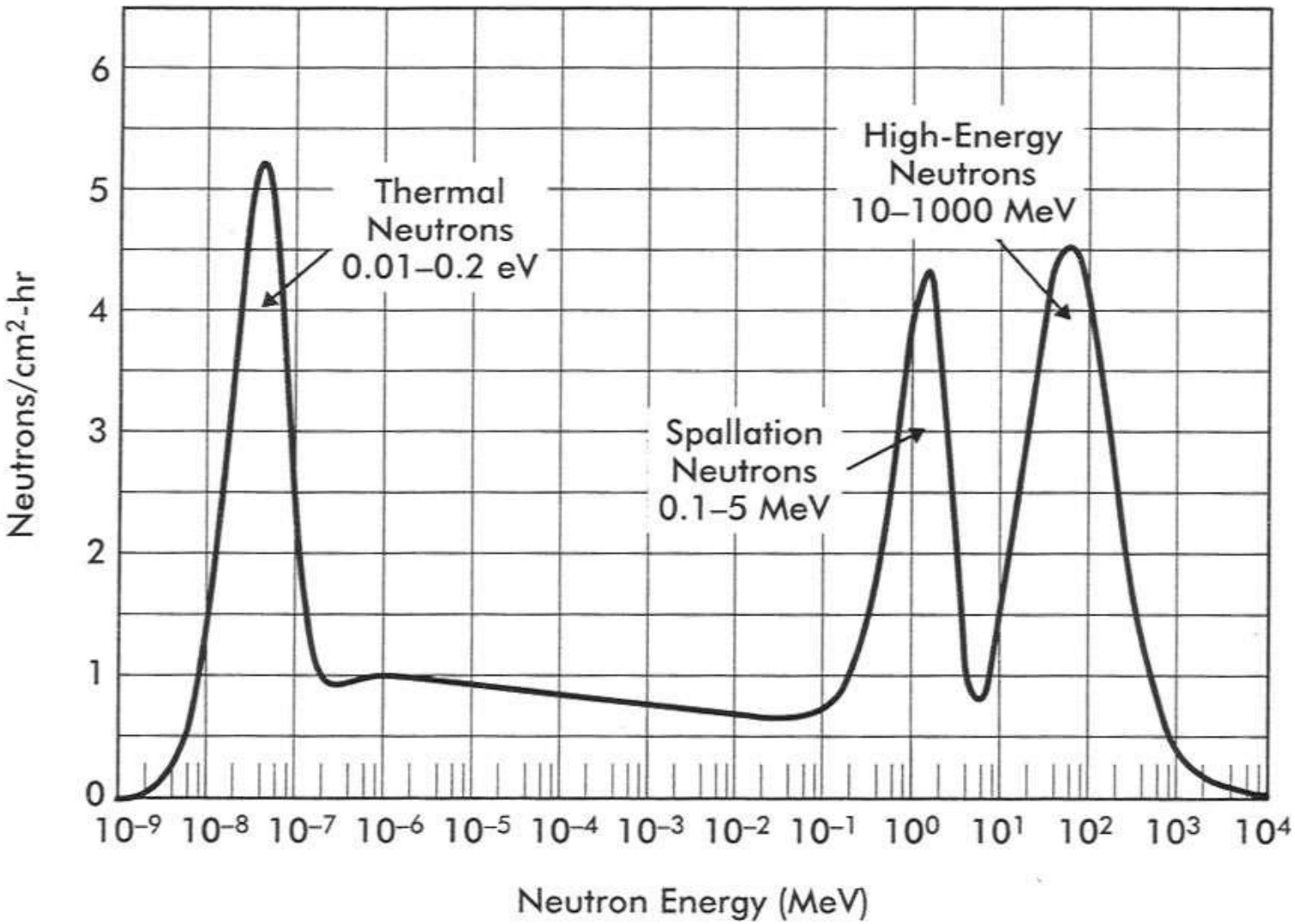
Source: Jungfraujoch neutron monitor data were kindly provided by the Cosmic Ray Group, Physikalisches Institut, University of Bern, Switzerland

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

JEDEC

EIA Electronic Industries Alliance

JESD89A (2006)
STANDARD TERRESTRIAL NEUTRON SPECTRUME

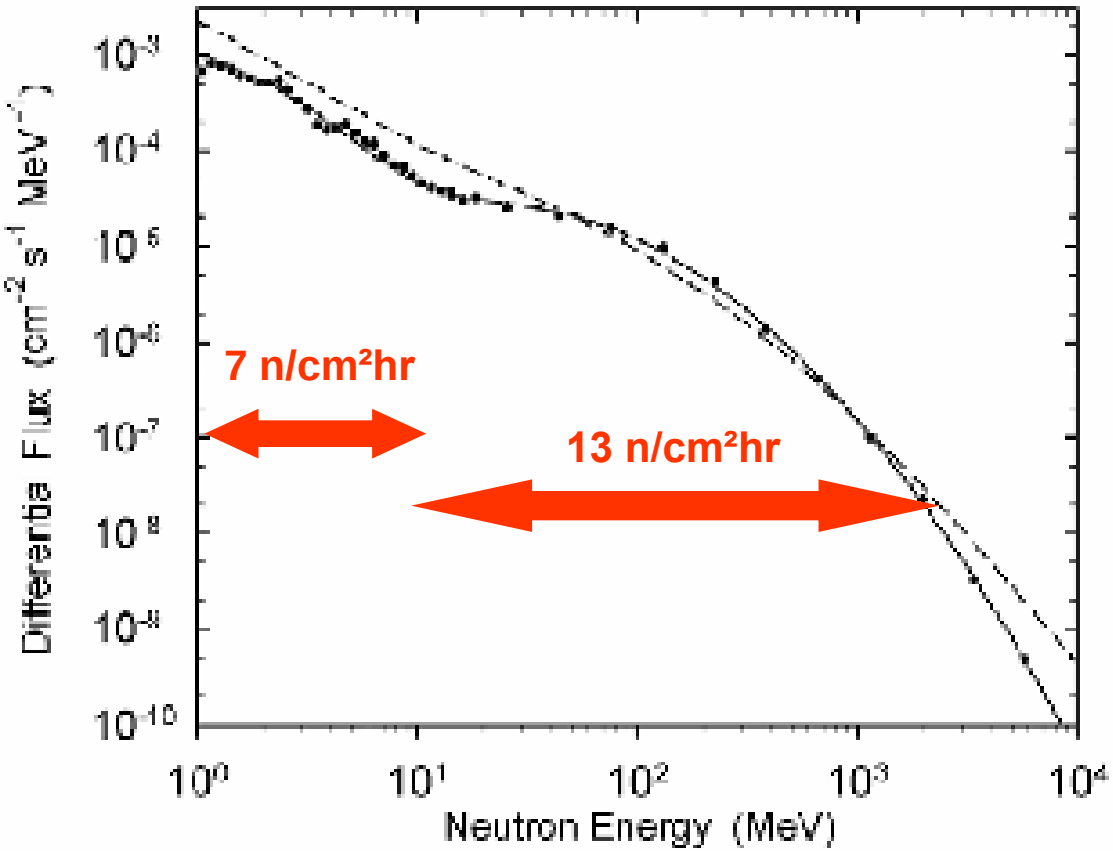
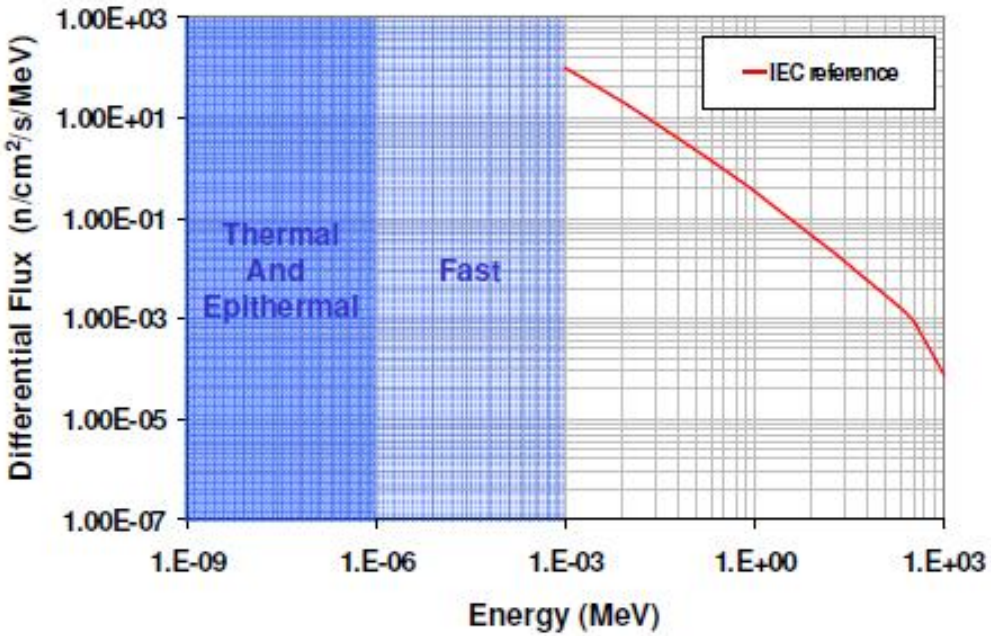


Figure A.2.1 — The differential flux of cosmic-ray-induced neutrons as a function neutron energy under reference conditions (sea level, New York City, mid-level so activity, outdoors). The data points are the reference spectrum, the solid curve is analytic fit to the reference spectrum, and the dashed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

INTERNATIONAL STANDARD (by IEC)

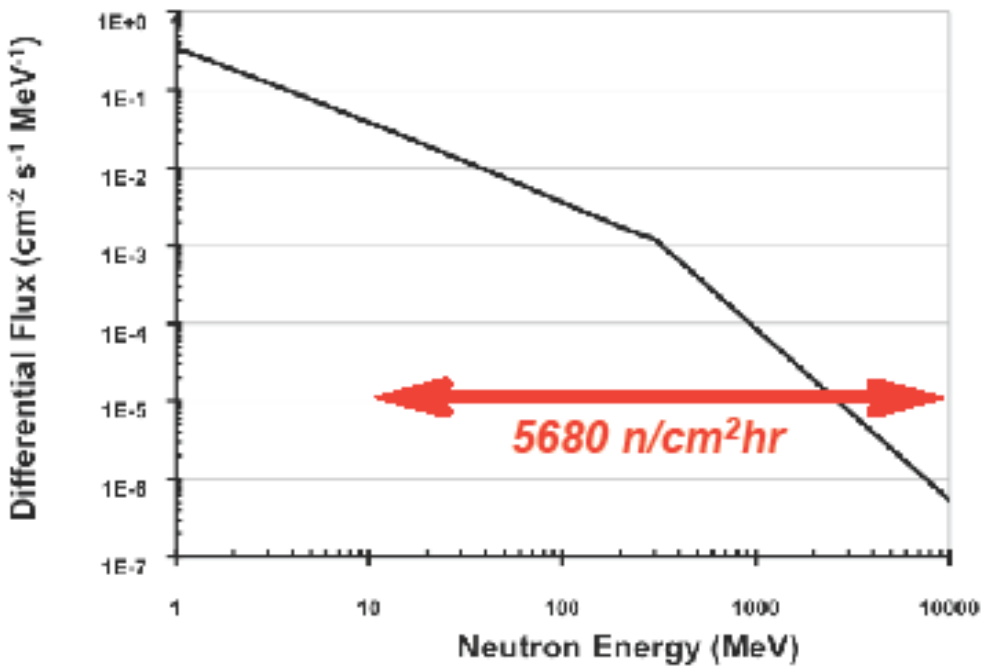
- Atmospheric Neutron Spectrum for SEE Testing
  - SEE effects above ~1MeV
  - Flux profile is IEC standard
    - International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes international standards for all electrical, electronic and related technologies.



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

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

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

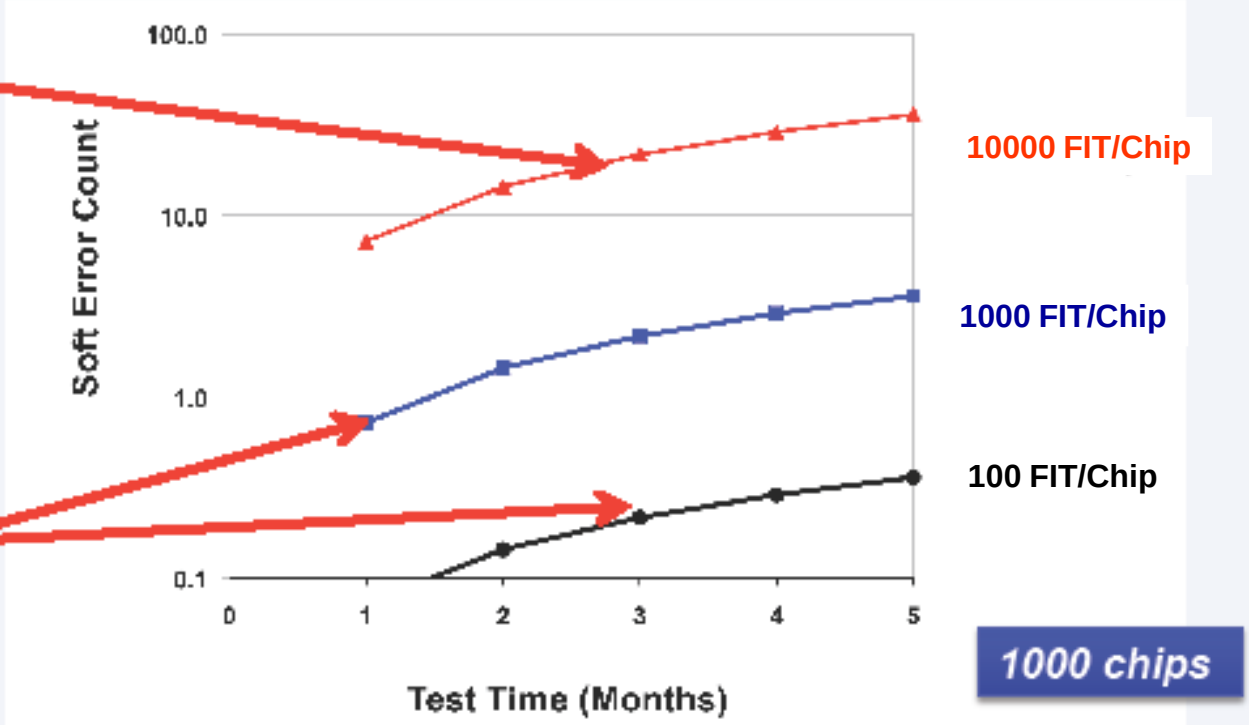
WHY ACCELERATED NEUTRON TESTING IS NEEDED?

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



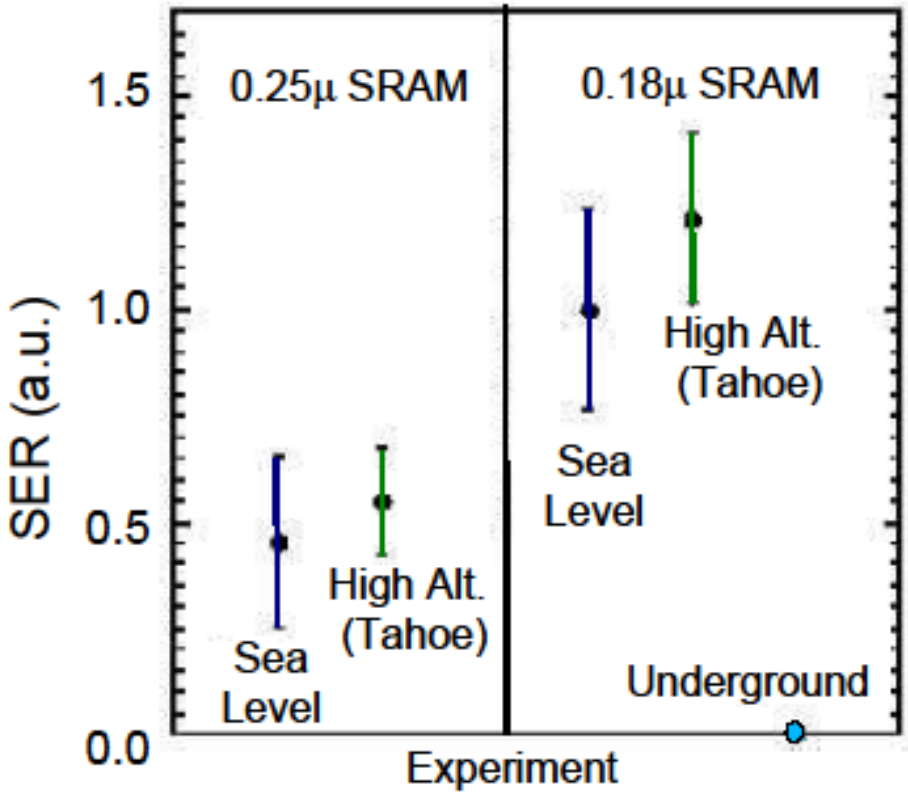
FIT: Failure In Time; 1 FIT is one error in 10^9 device-hours.

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.

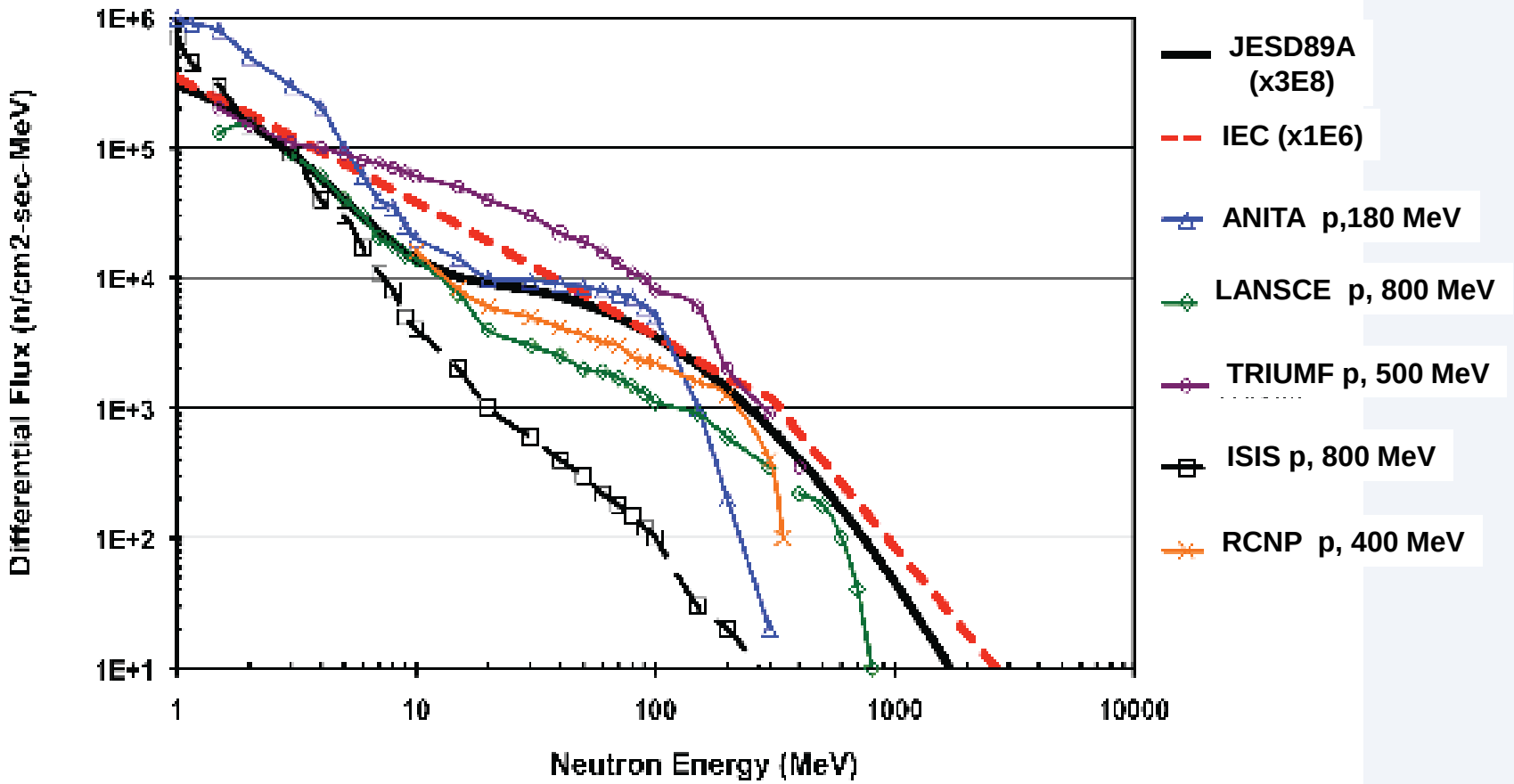


H. Kobayashi, et. al., Sony [5].

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, England
  - Neutron Irradiation Facility
- Research Center for Nuclear Physics at Osaka University (RCNP), Japan
- Petersburg Nuclear Physics Institute
  GNEIS Neutron TOF Facility

NEUTRON SPECTRA OF TESTING FACILITIES



Replication of higher energy (>100MeV) spectra depends upon the facility

RUSSIA

Test Facilities at JINR (Dubna) and PNPI (Gatchina) managed by Branch of Joint Stock Company "United Rocket and Space Corporation" - Institute of Space Device Engineering (ROSCOSMOS)

Technical features of Test Facilities expected in 2013 – 2015

	IS VE	IS VE NI	IS OE SVE
Conditions	Forvacuum	Forvacuum	Atmosphere
Ions	O, C, Ne, Ar, Fe, Kr, Xe	O, C, Ne, Ar, Fe, Kr, Xe, (Os)Bi	Xe, Kr, Au
Range in Si, mm	0,3 ÷ 2,0	0,2 ÷ 2,0	≥ 50
Energy, MeV/nucleon	20 ÷ 40	20 ÷ 40	500 ÷ 2000
Flux, particles/cm^2 x s	$10 \div 10^5$	$10 \div 10^5$	$\geq 10^3$
Irradiation area, mm	Ø > 50	Ø > 50	Ø ≥ 50
Uniformity, %	≤ 10	≤ 10	± 10

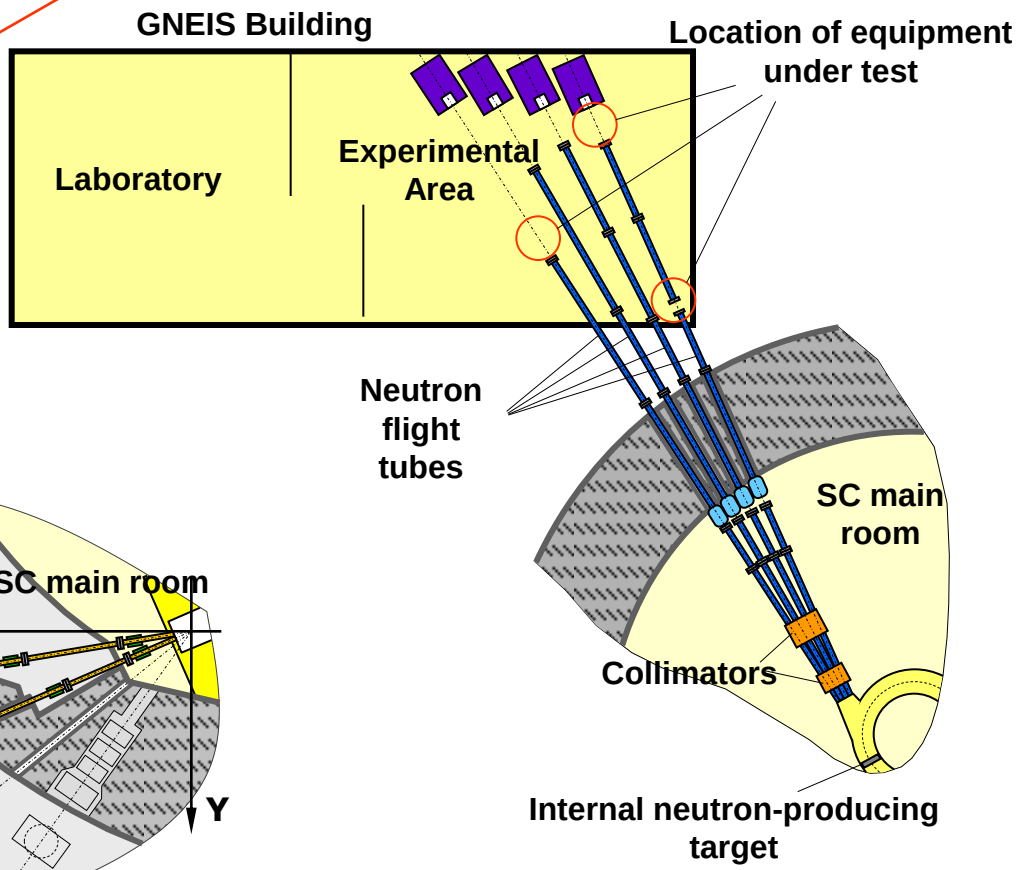
JINR

	IS SC-1000	IS C-80	IS SC-1000
Conditions	Atmosphere	Atmosphere	Atmosphere
Particles	Protons	Protons	Neutrons
Energy, MeV	200 ÷ 1000	40 ÷ 80	1 ÷ 1000
Flux, particles/cm^2 x s	$10^5 \div 10^8$	$10^5 \div 10^8$	2×10^5
Irradiation area, mm	Ø ≥ 25	Ø ≥ 25	Ø ≥ 50
Uniformity, %	≤ 10	≤ 10	≤ 10

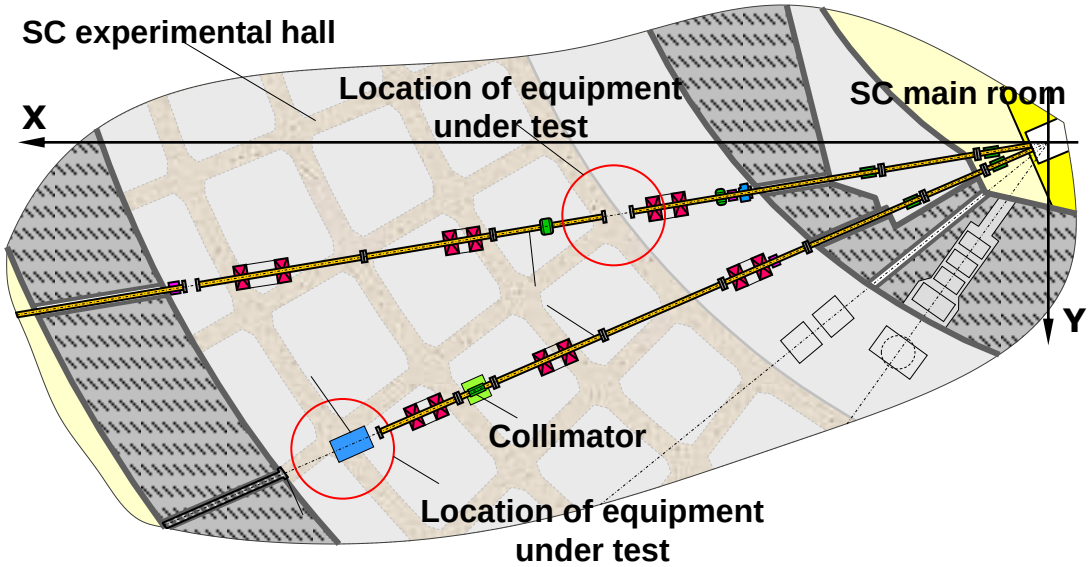
PNPI

TESTING OF ELECTRONIC EQUIPMENT AT THE PNPI PROTON AND NEUTRON BEAMS

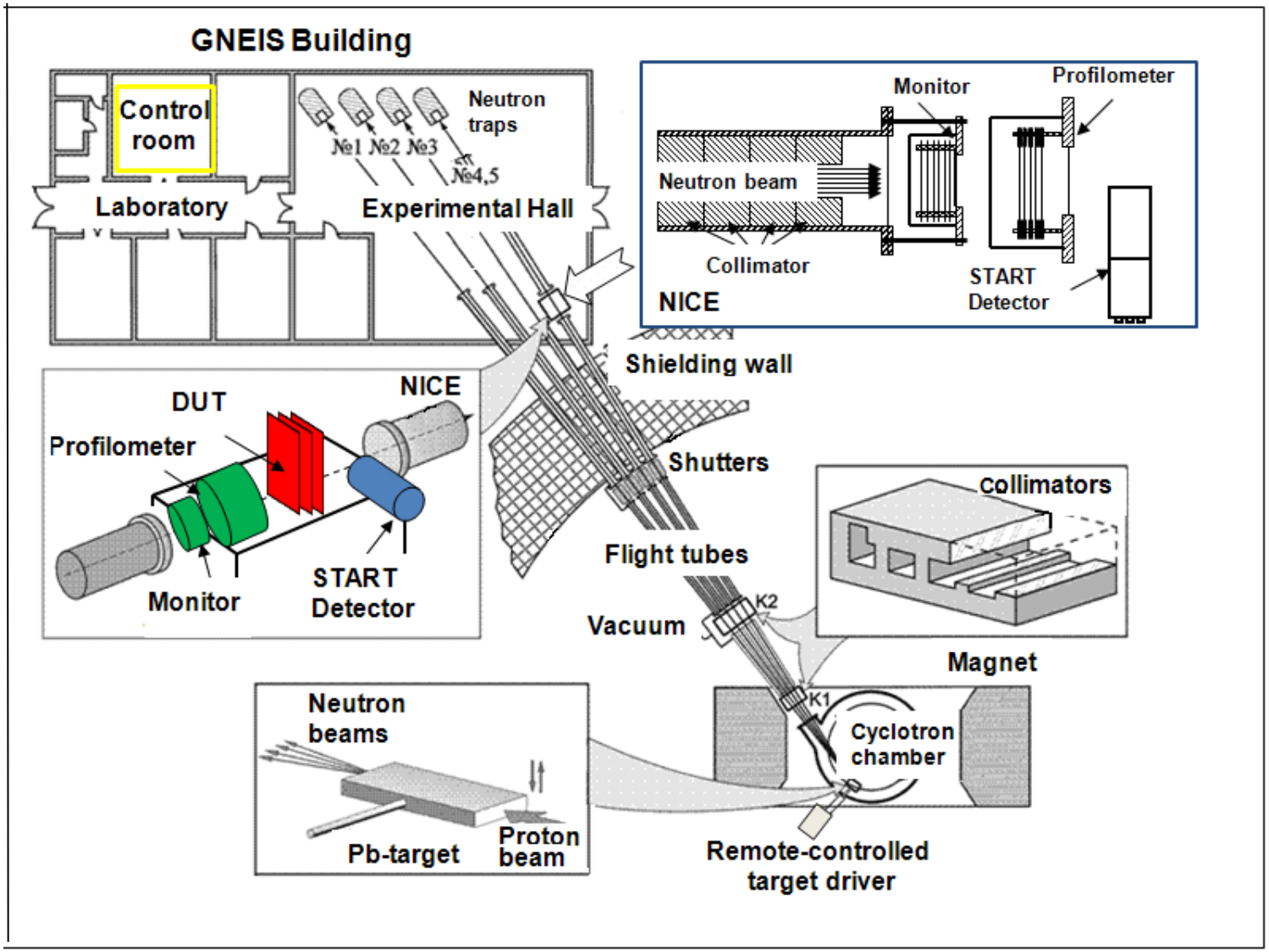
Neutron testing site



Proton testing site



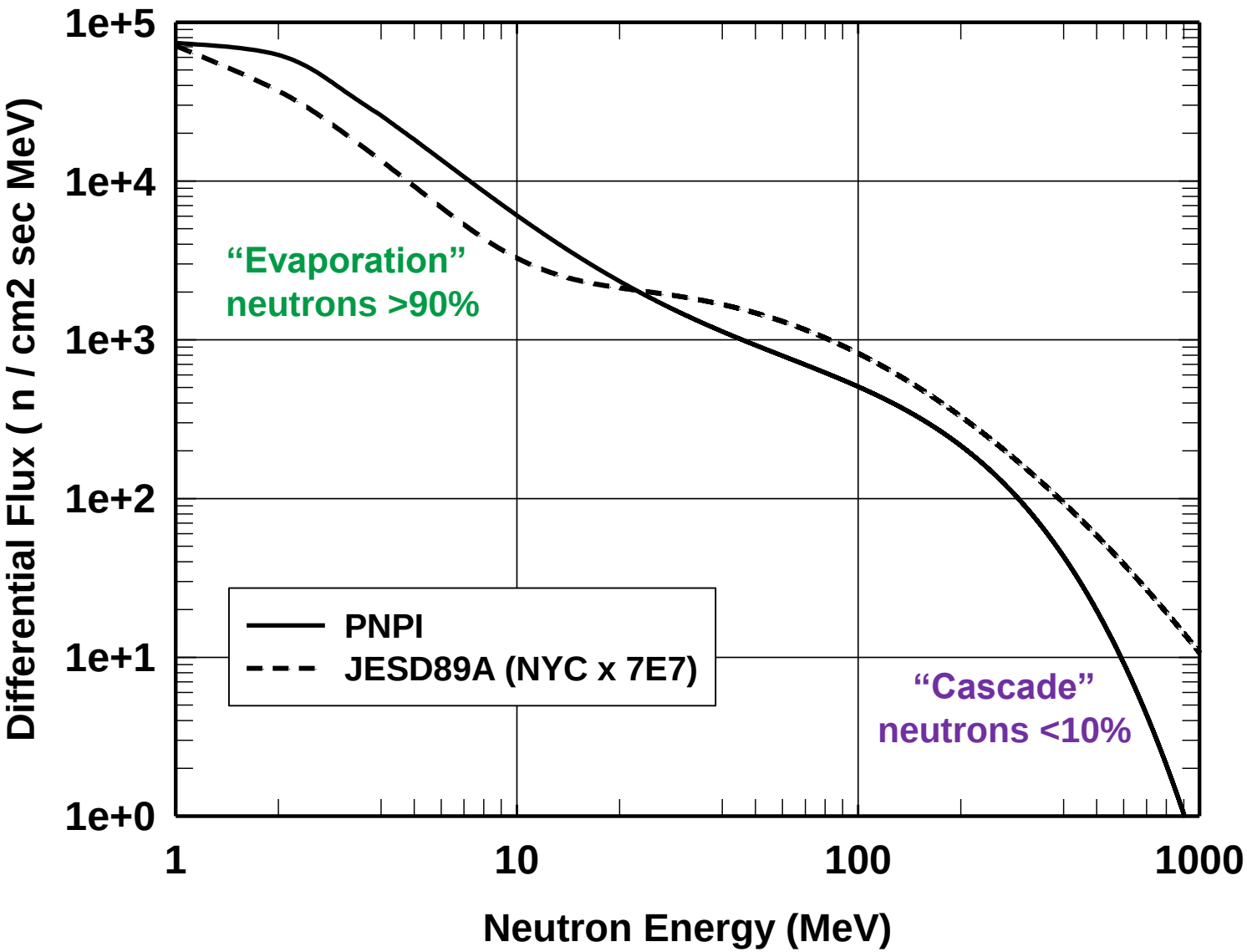
General View of the GNEIS and NICE Test Facility



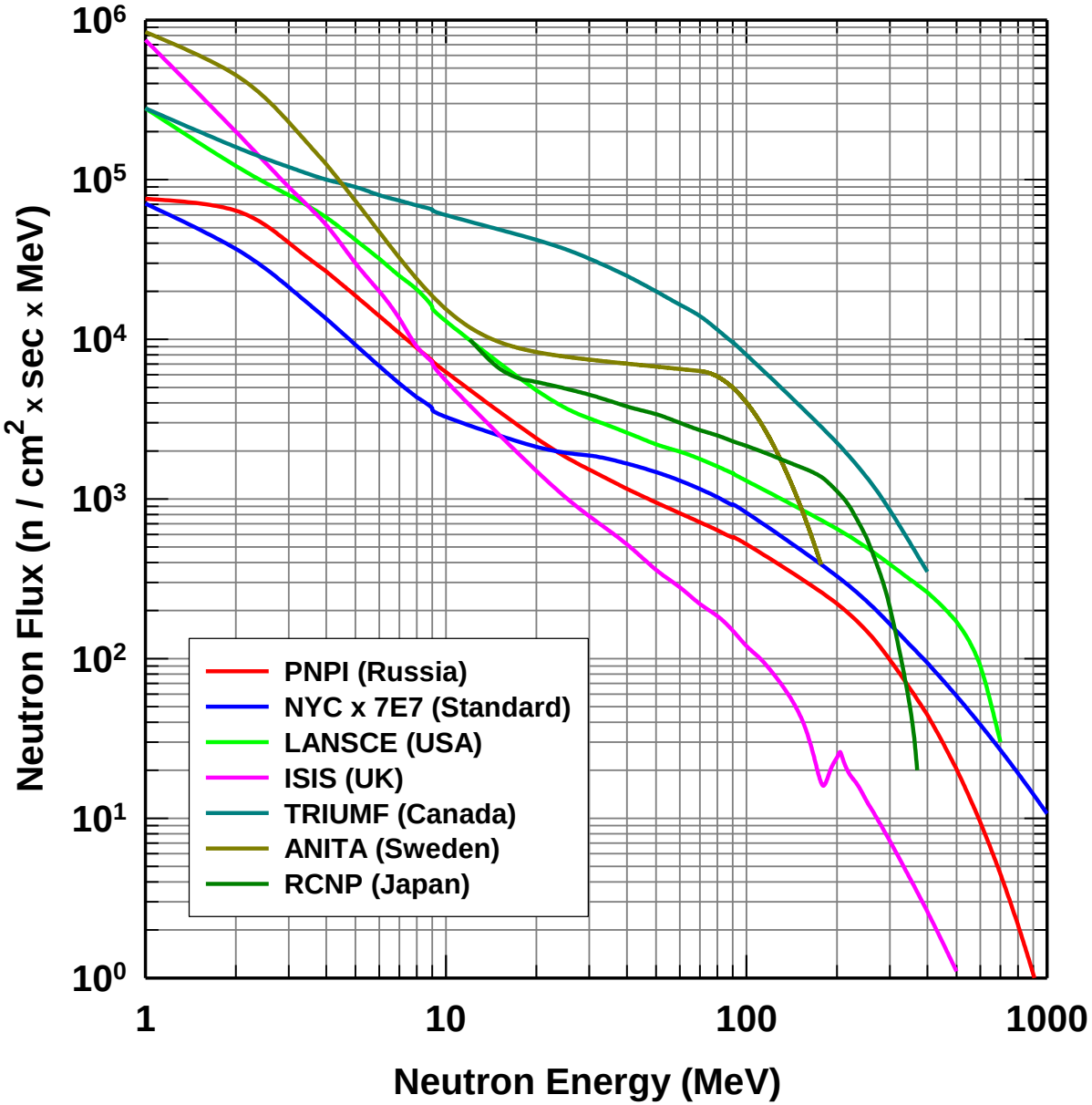
Neutron Irradiation of Chips and Electronics = NICE (home nickname!)

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 $\phi(E)$ is the differential neutron flux and $\sigma(E)$ is the energy dependent soft error cross sections defined as

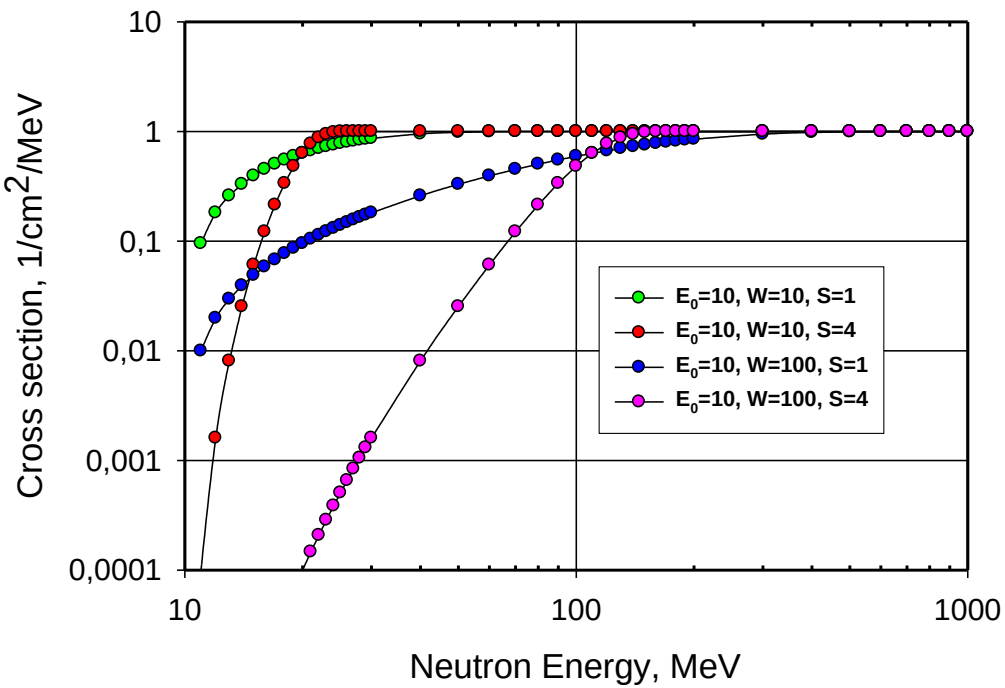
$$\sigma(E) = \frac{Number\ of\ Soft\ Error\ Events}{\phi(E)T}$$

and T is time

Theoretical Weibull Approximation of Cross-section

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

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



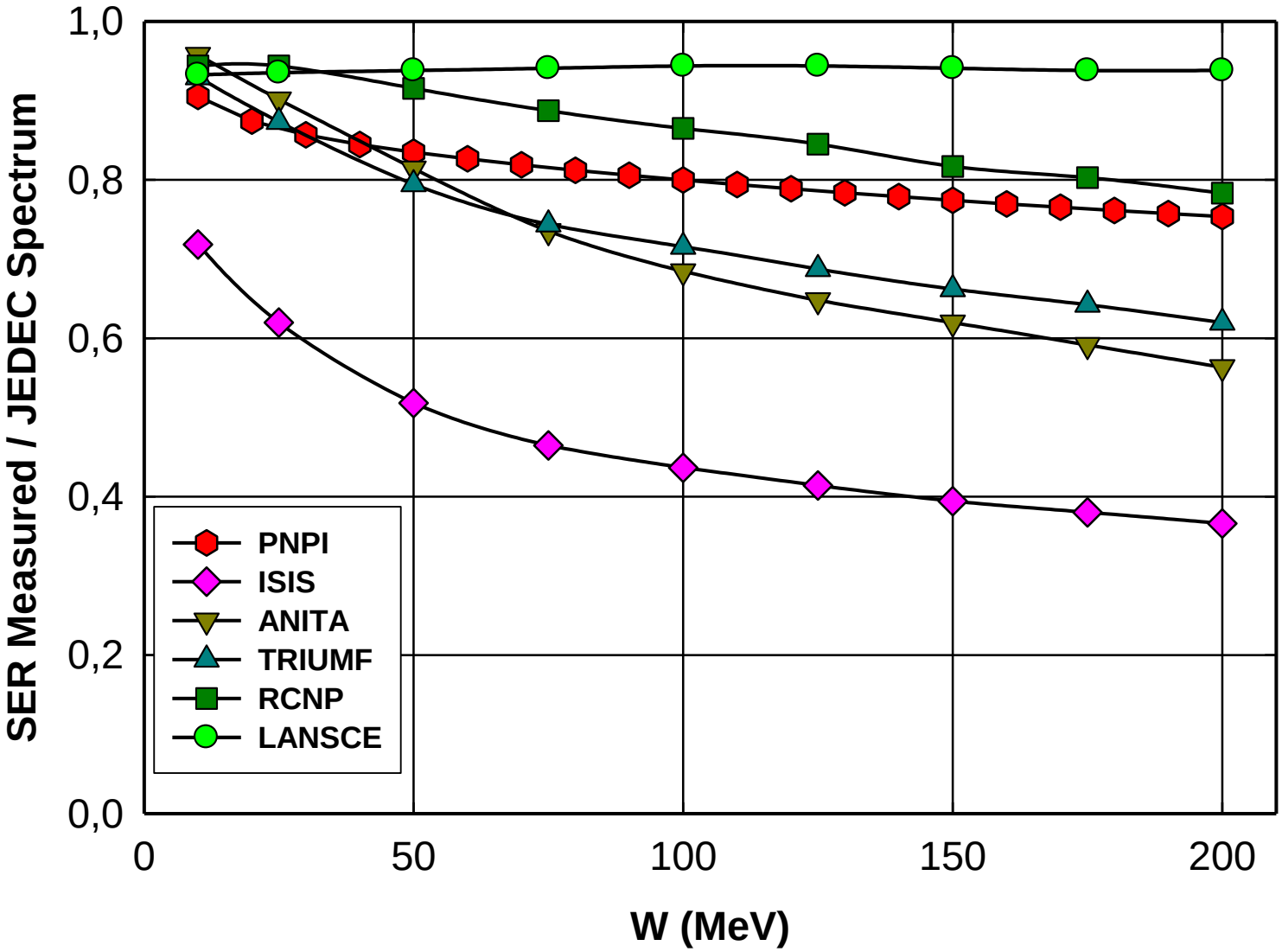
Error Ratio – Due to Mismatch of Beam Facility and Real Neutron Spectra

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

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

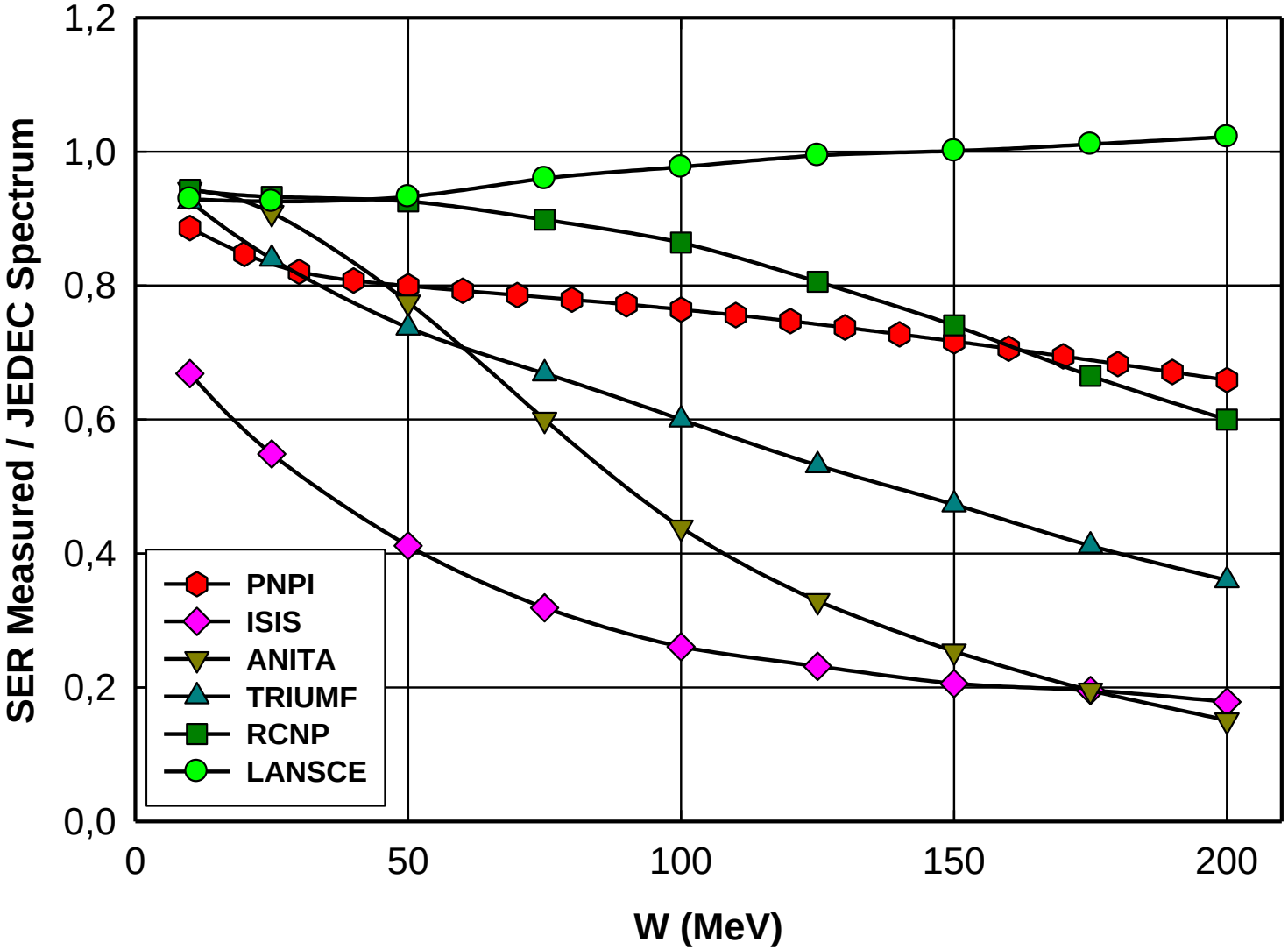
Error in SER estimate as a function of W

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



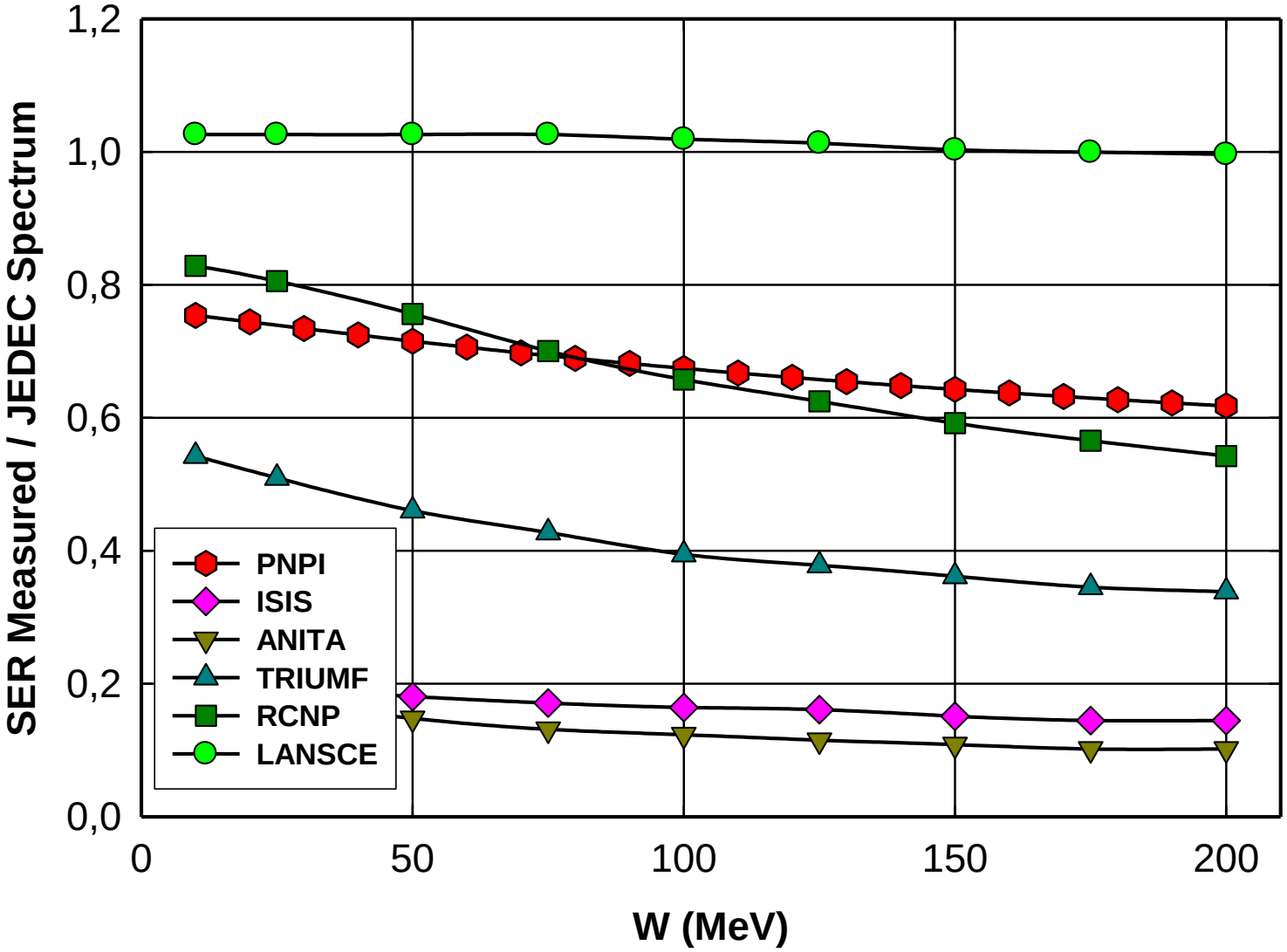
Error in SER estimate as a function of W

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



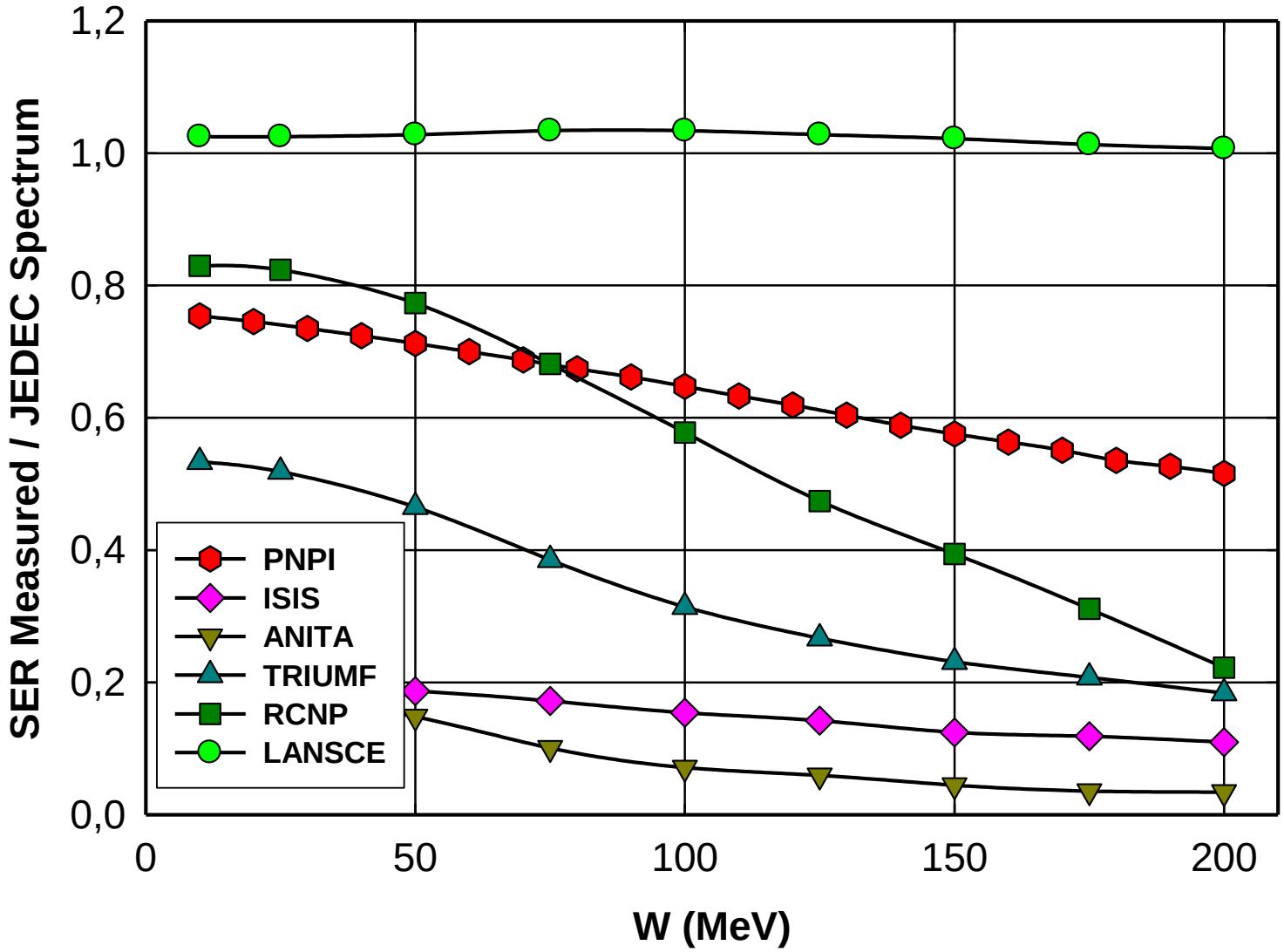
Error in SER estimate as a function of W

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

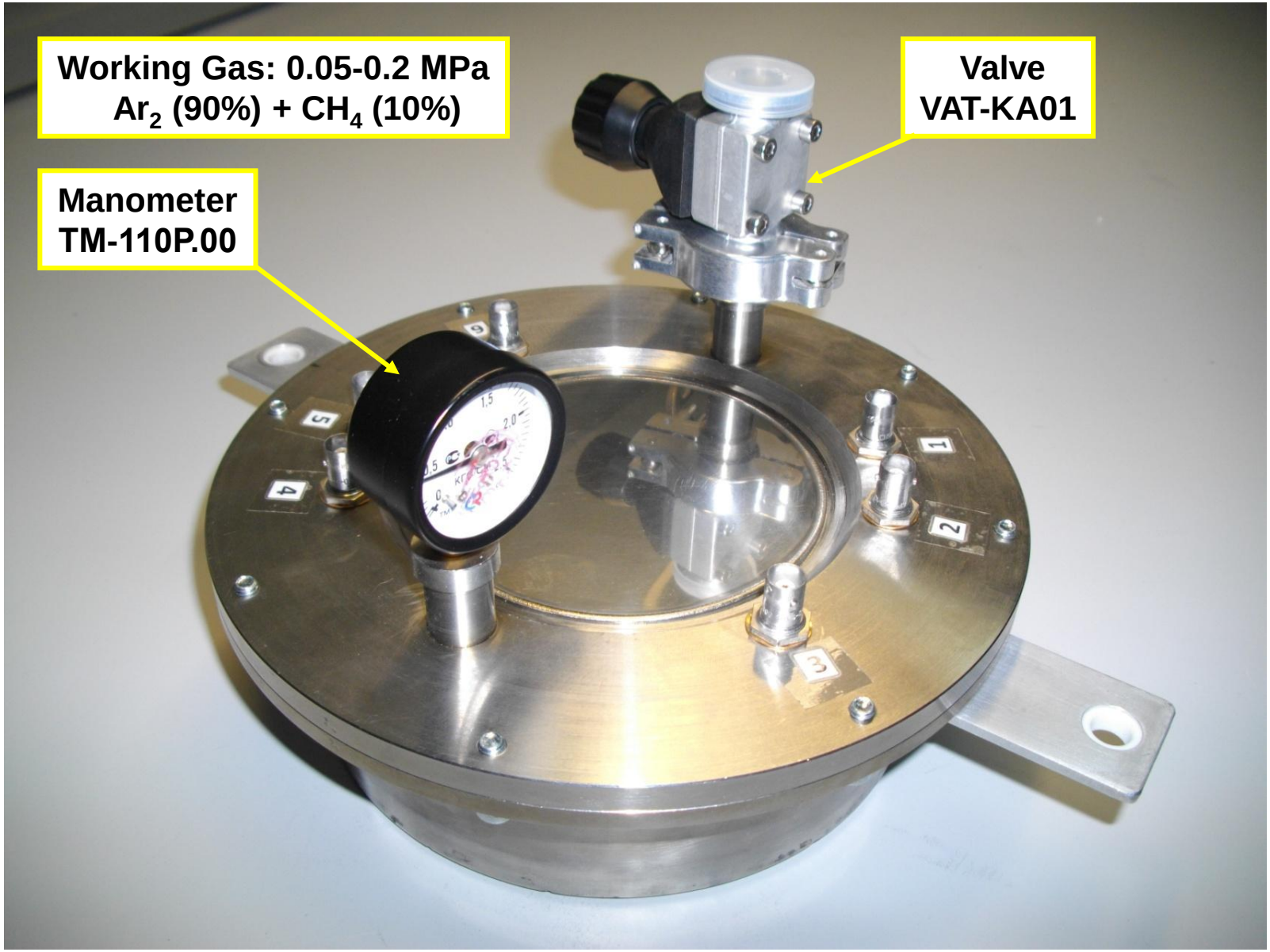
Monitor: Fission Ionization Chamber (FIC)

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

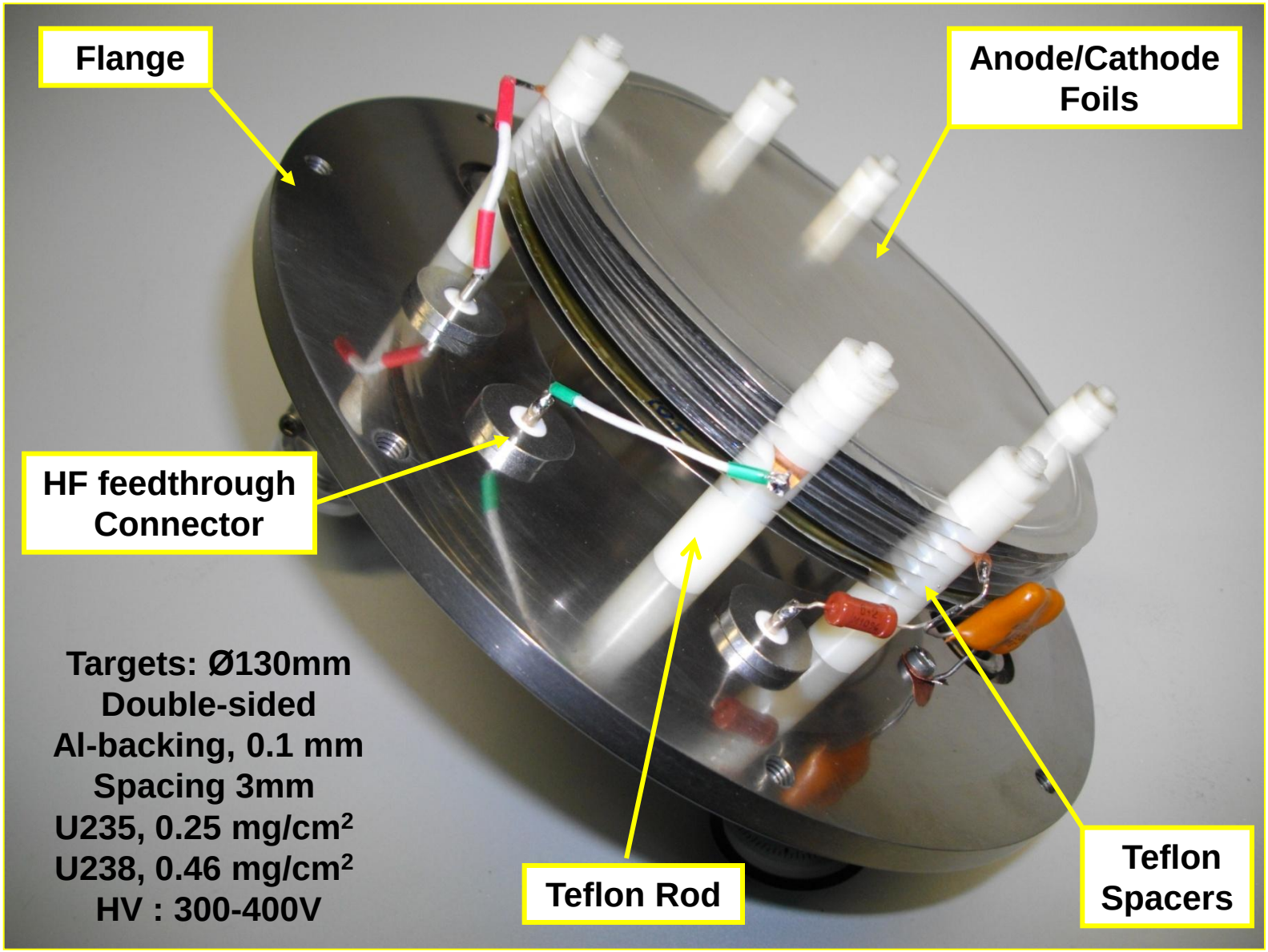
Frofilometer: Multiwire Proportional Counter (MWPC)

- 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

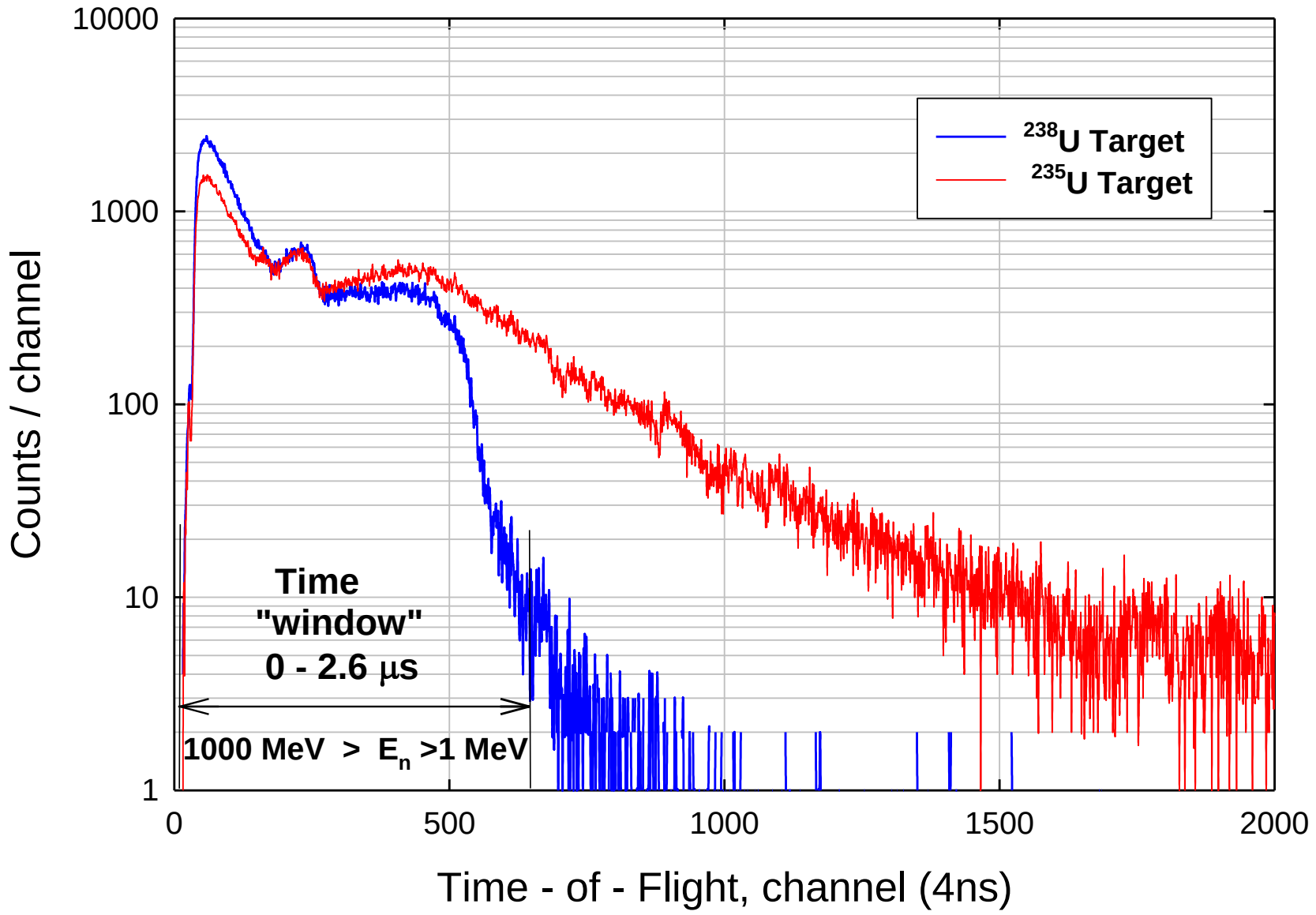
Neutron Beam Monitor - Fission Ionization Chamber (FIC) with U-235 and U-238 targets



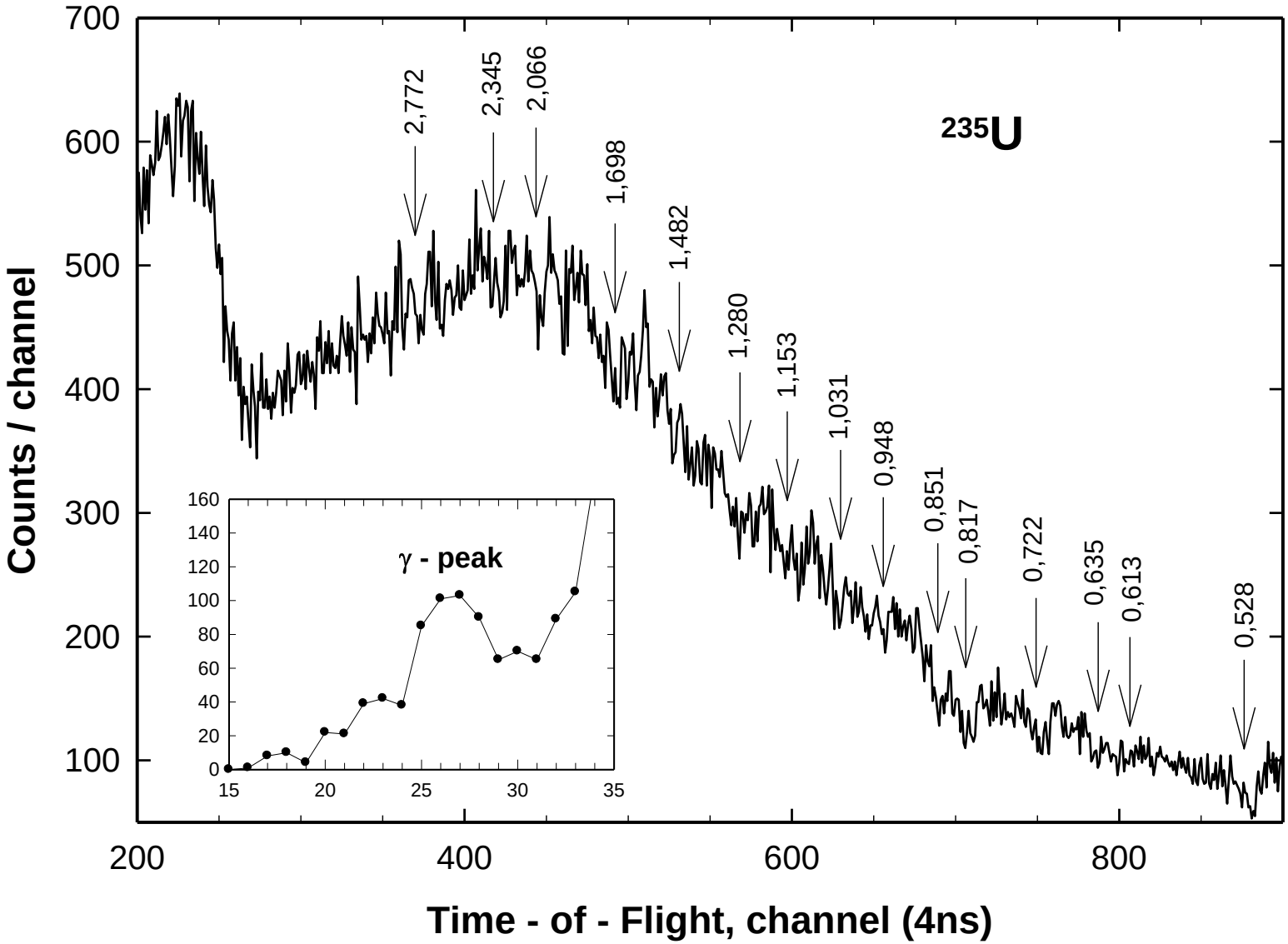
Internal structure of the Neutron Beam Monitor - FIC with U-235 and U-238 targets



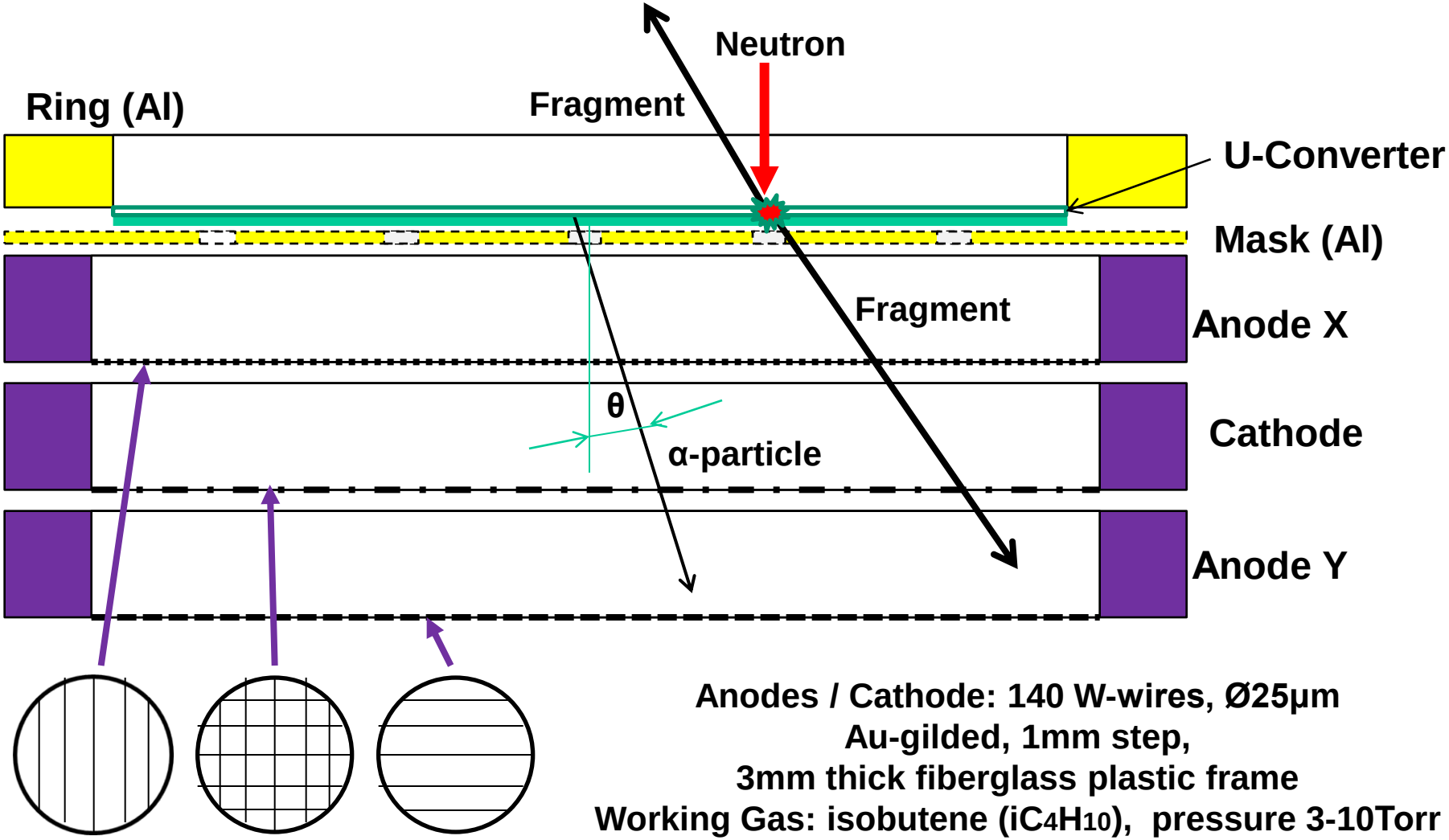
TOF – Spectra Measured with FIC (Neutron Beam Monitor)



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

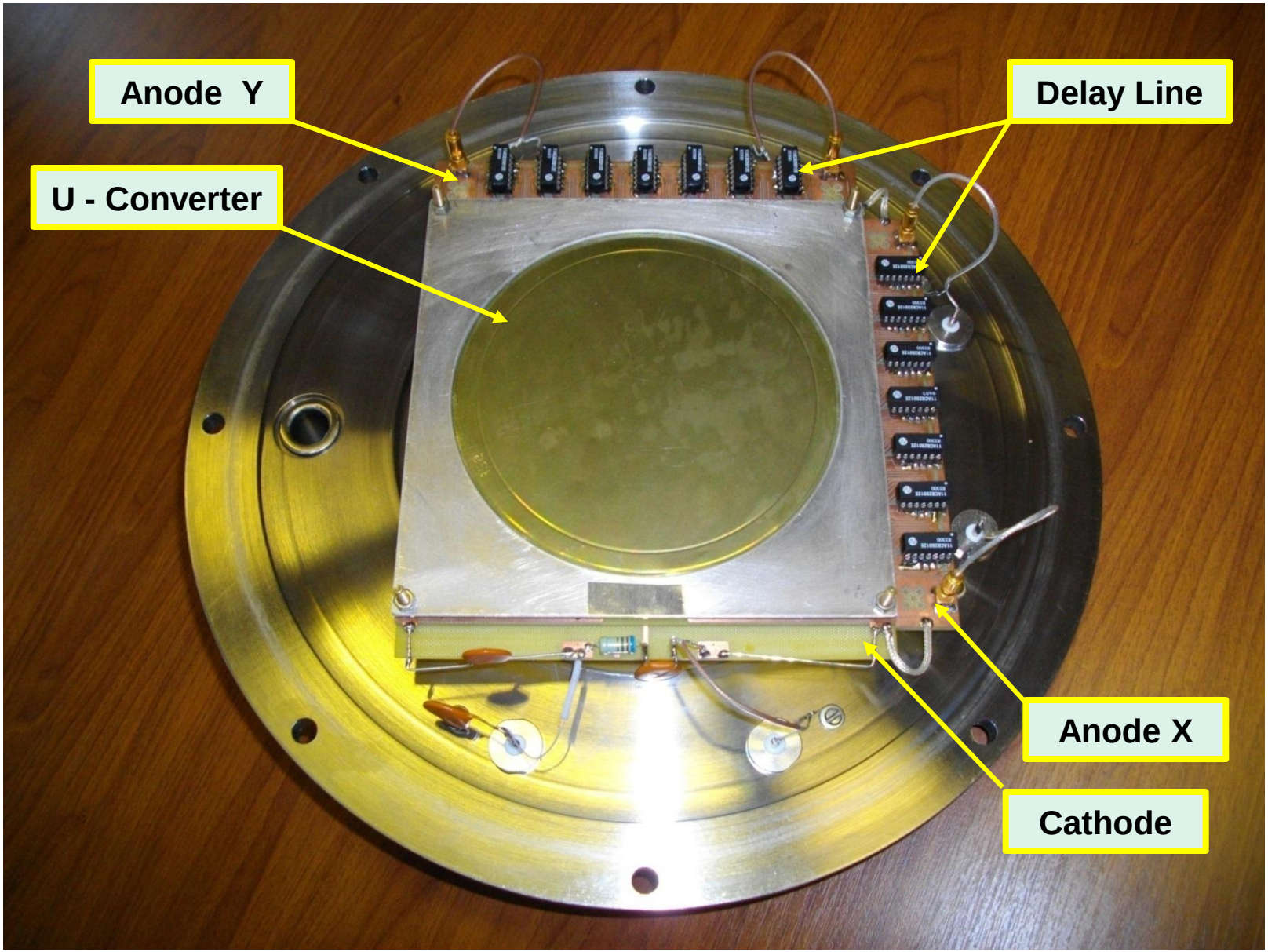


MWPC – Neutron Beam Profilometer
(2D-type MultiWire Proportional Counter)

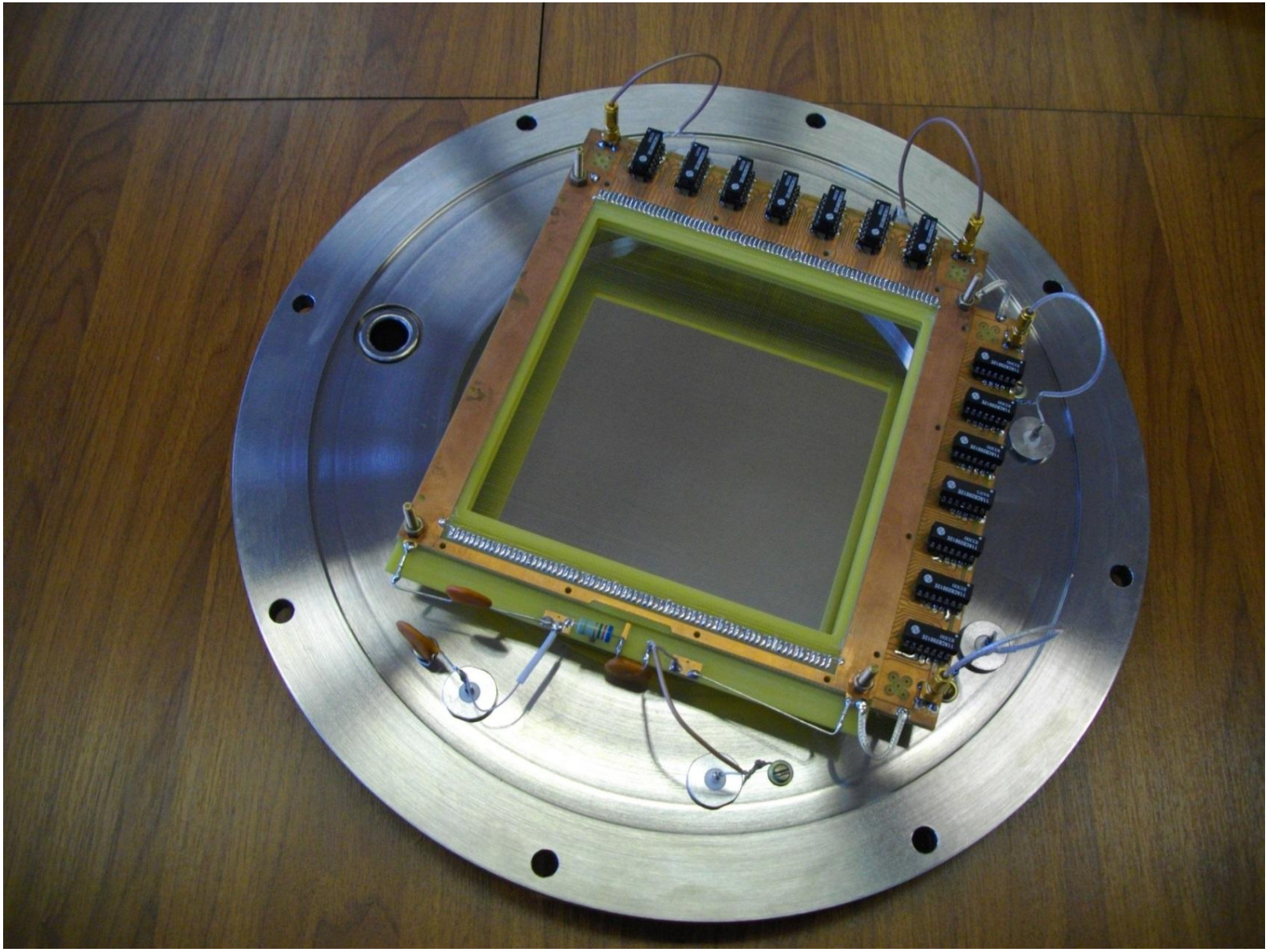


Anodes / Cathode: 140 W-wires, Ø25μm
Au-gilded, 1mm step,
3mm thick fiberglass plastic frame
Working Gas: isobutene (iC_4H_{10}), pressure 3-10Torr

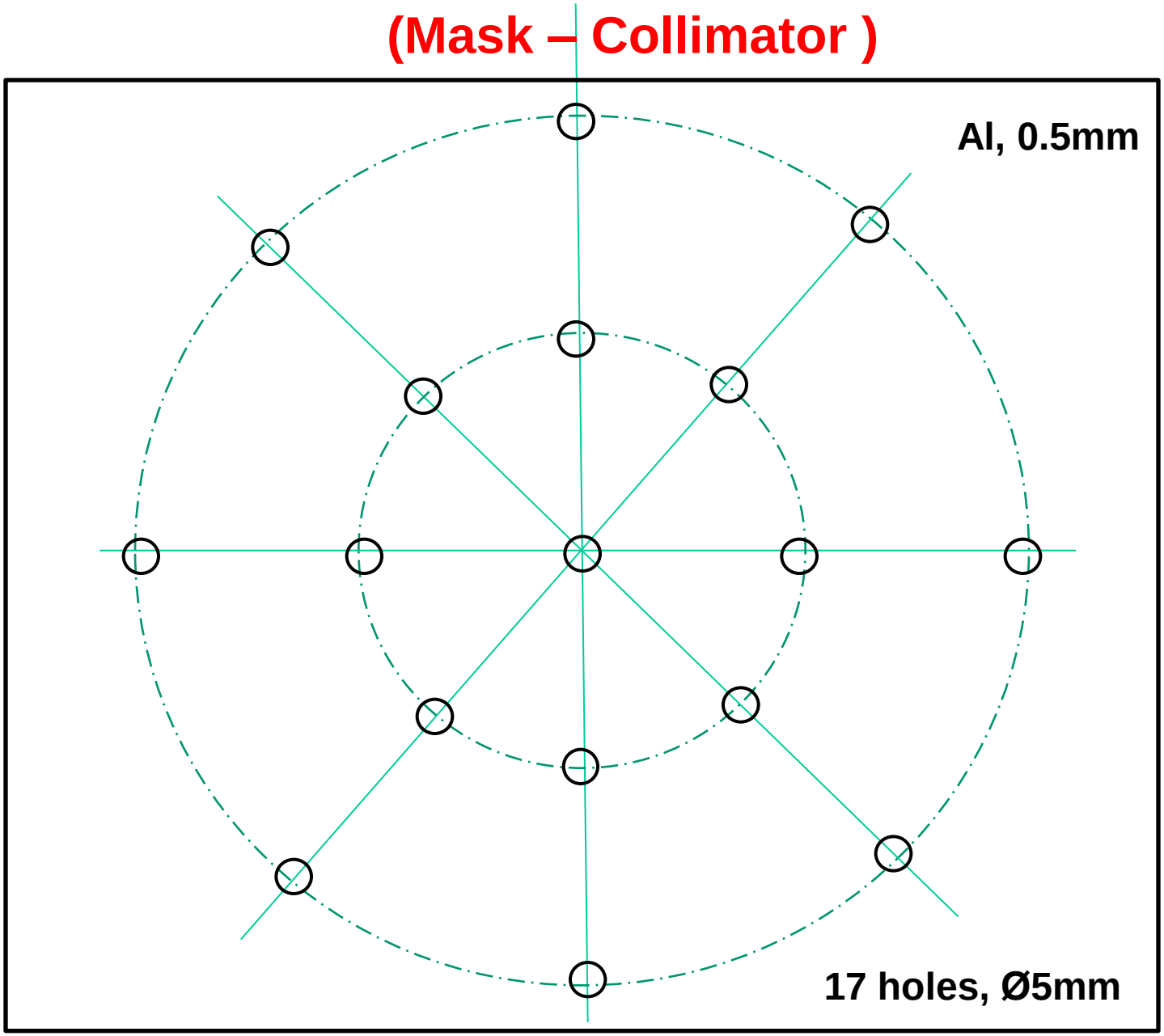
MWPC – Neutron Beam Profilometer



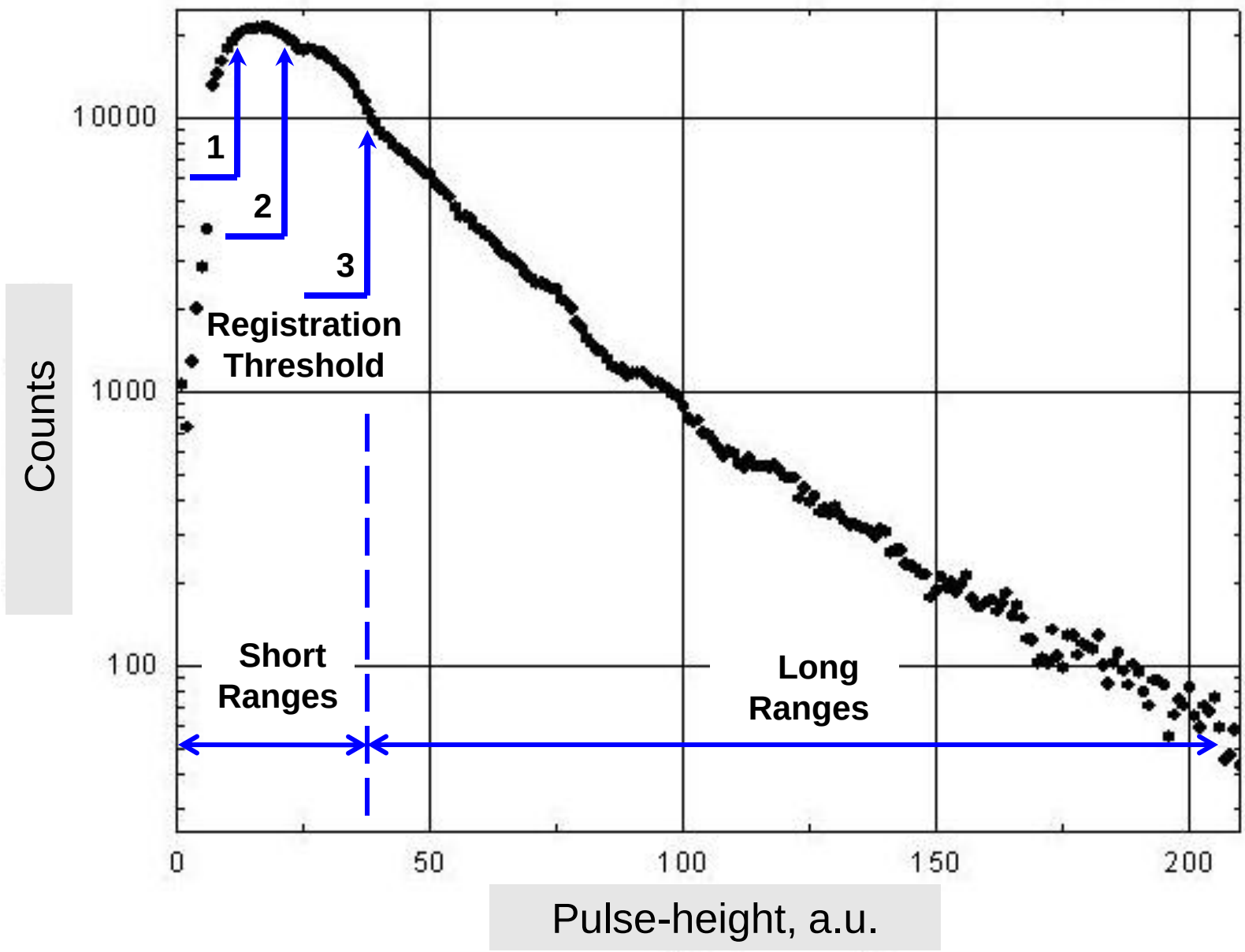
MWPC – Neutron Beam Profilometer



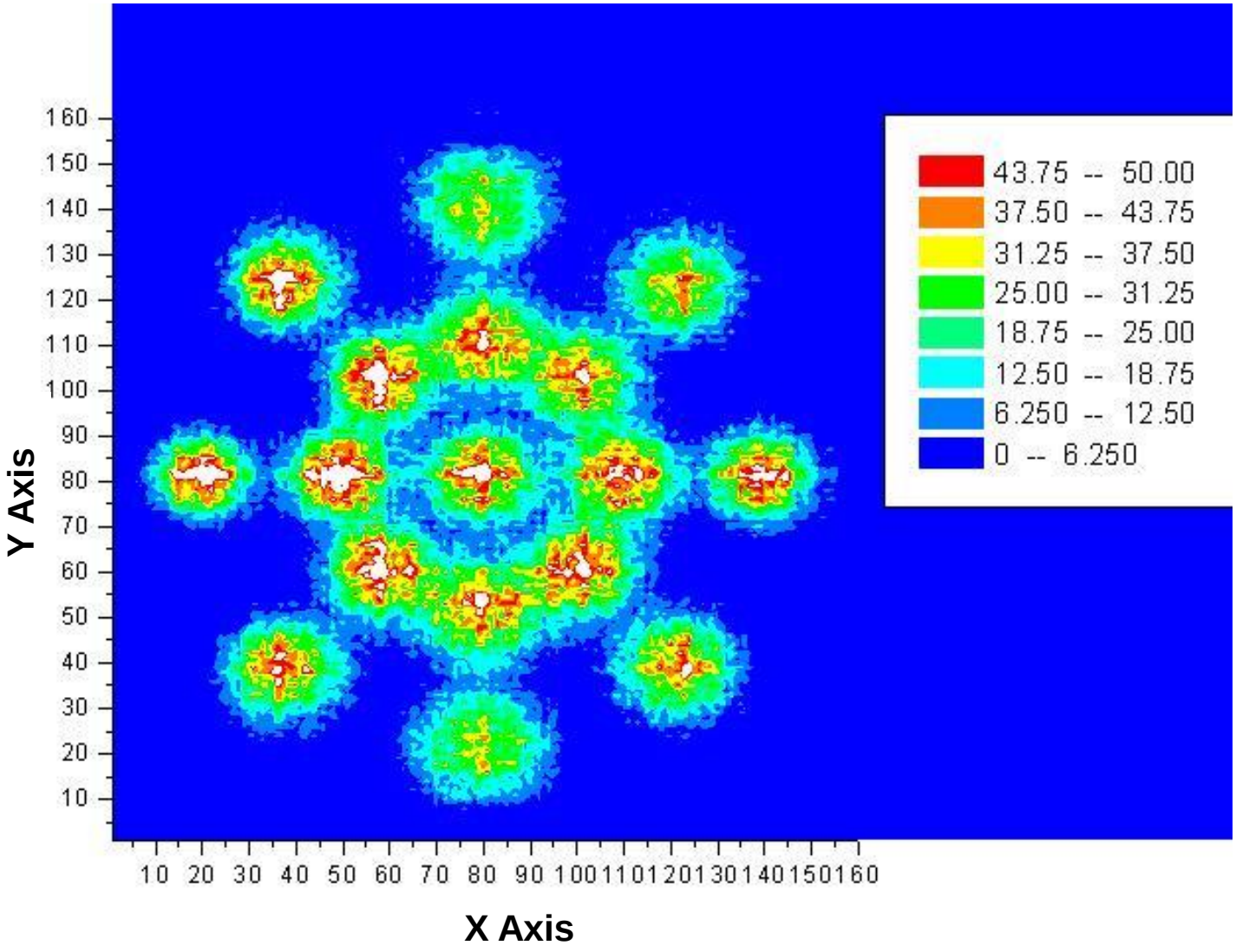
MWPC – Neutron Beam Profilometer
(Mask – Collimator)



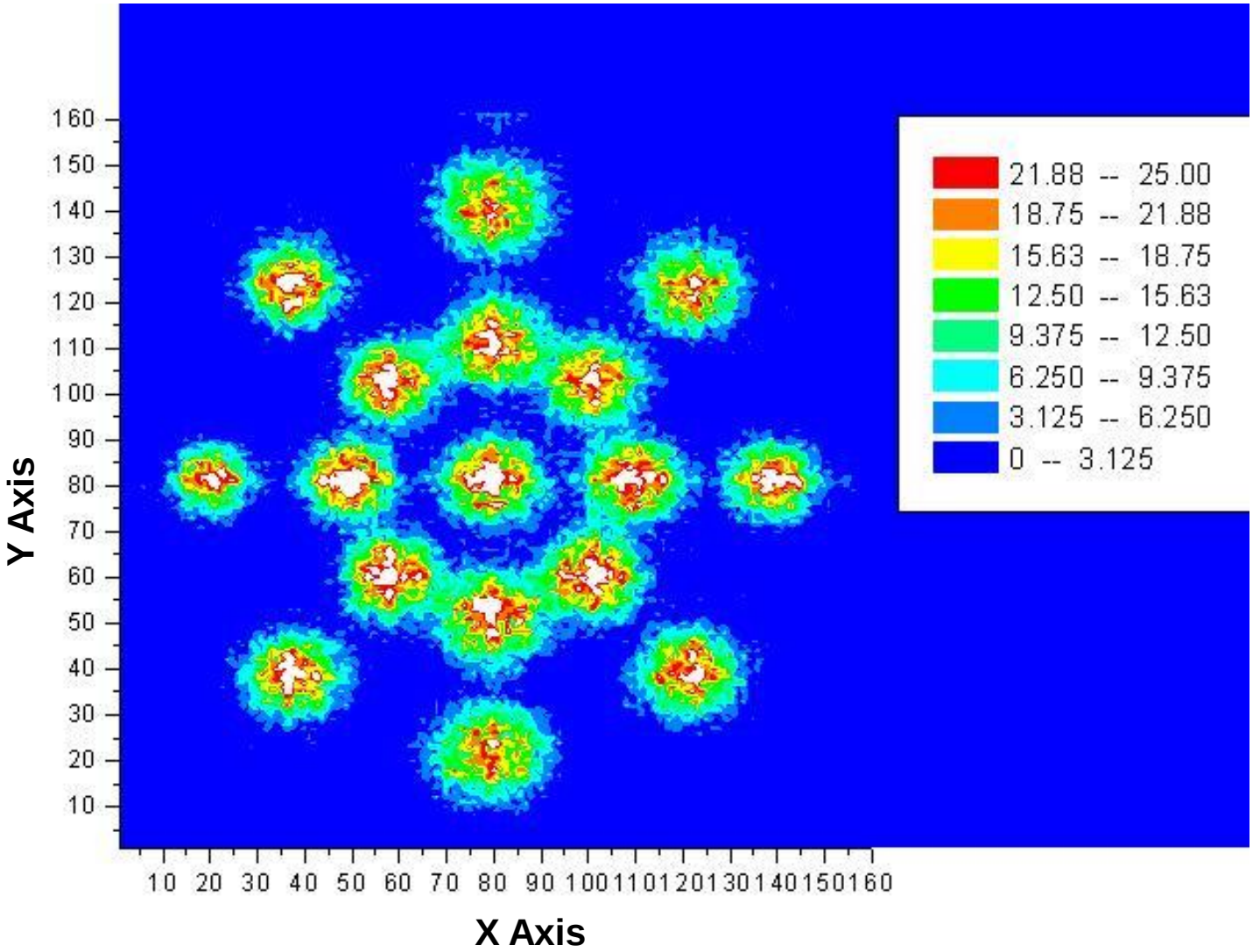
Cathode Pulse-Height Spectrum (α-particles)



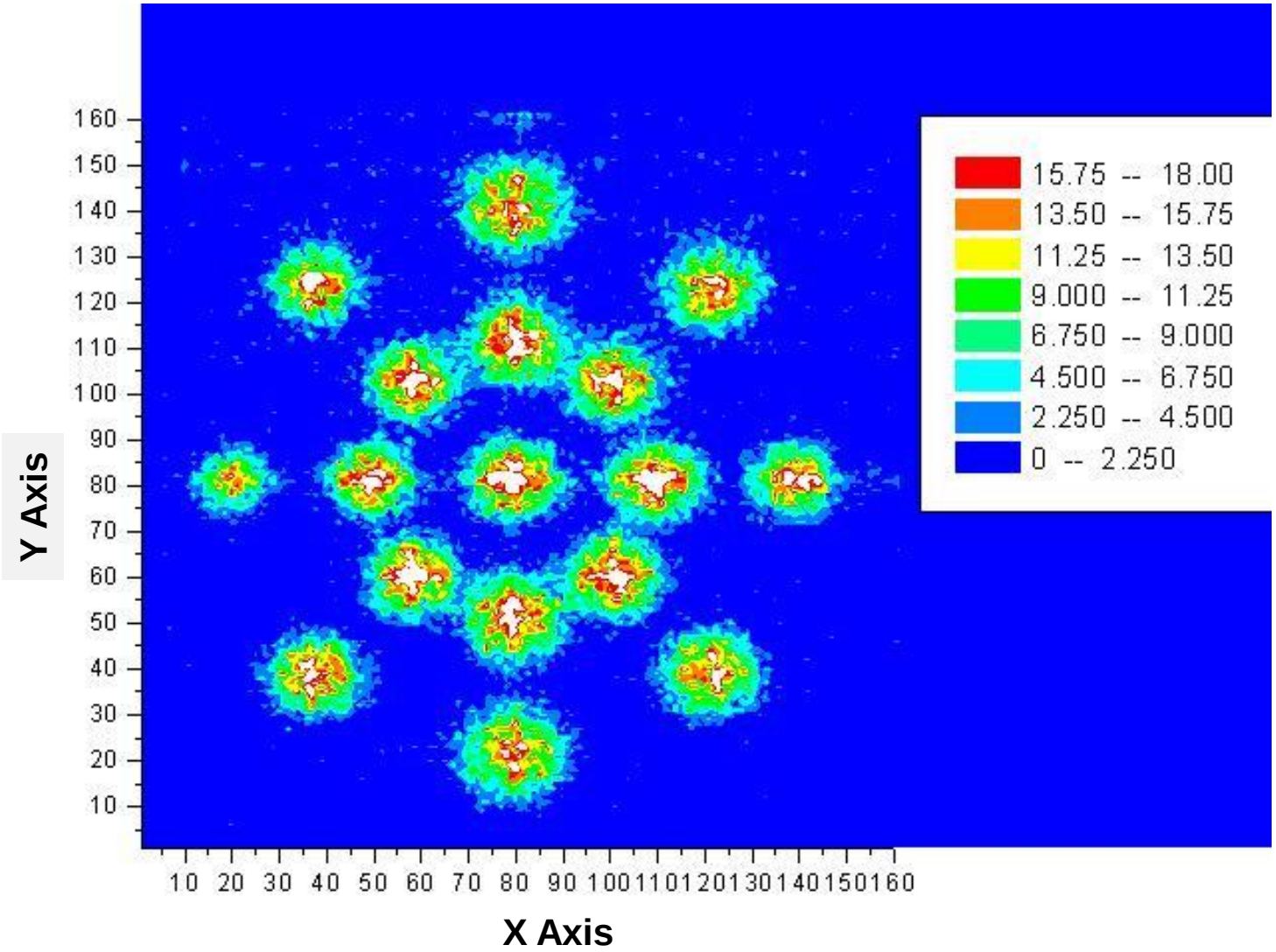
Anode 2D Pulse-Height Spectrum of α-particles (In Coincidence with Cathode Pulses, Reg. Threshold #3)



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

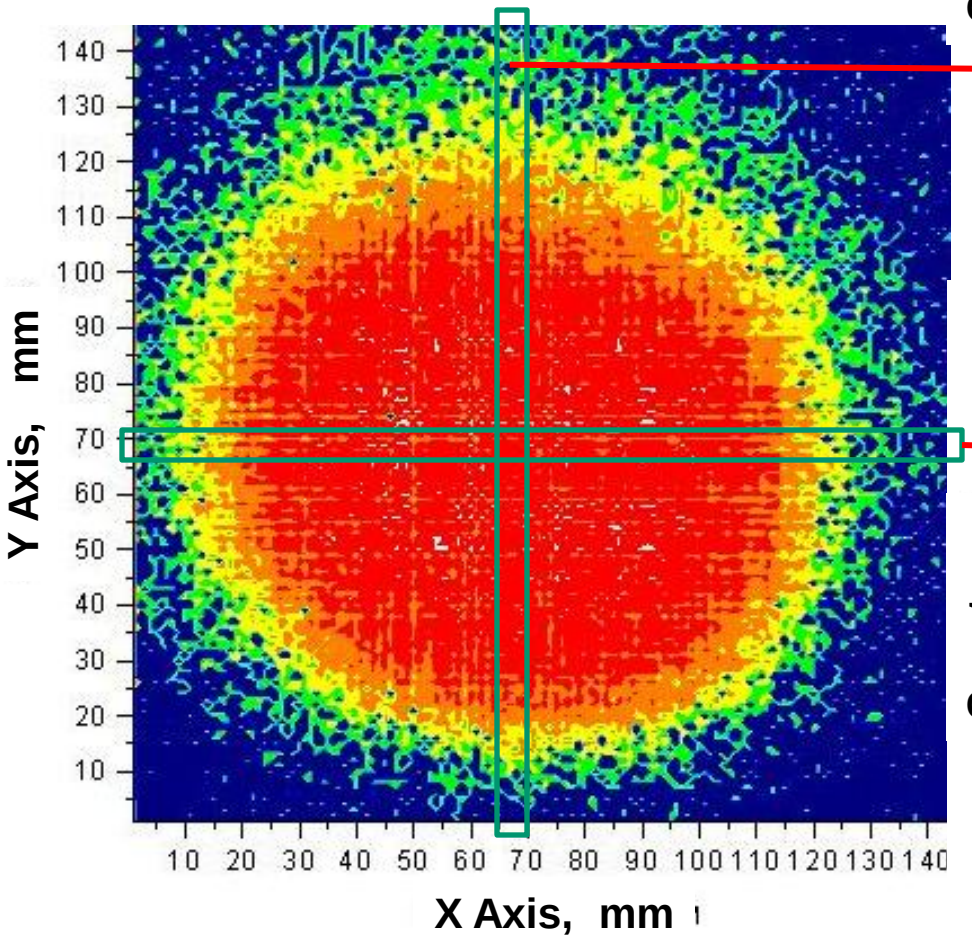


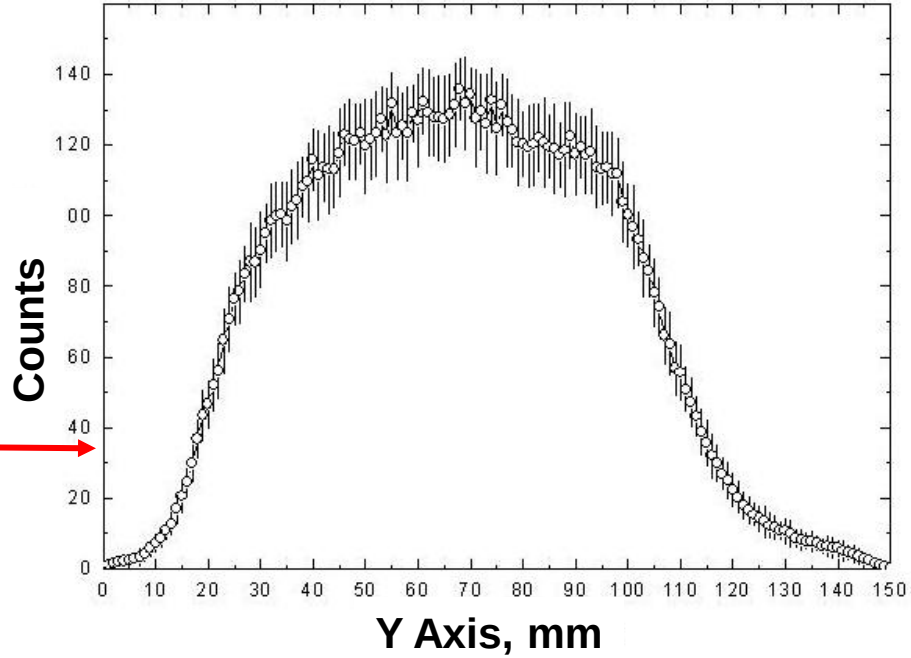
Anode 2D Pulse-Height Spectrum of α-particles (In Coincidence with Cathode Pulses, Reg. Threshold #1)

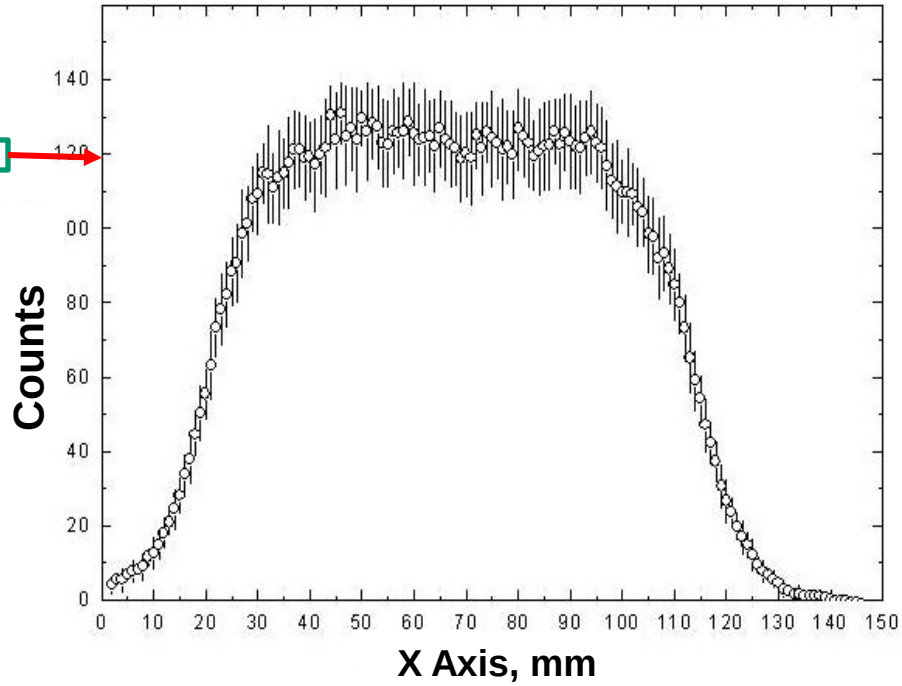


NEUTRON BEAM PROFILE

Collimator Ø96mm

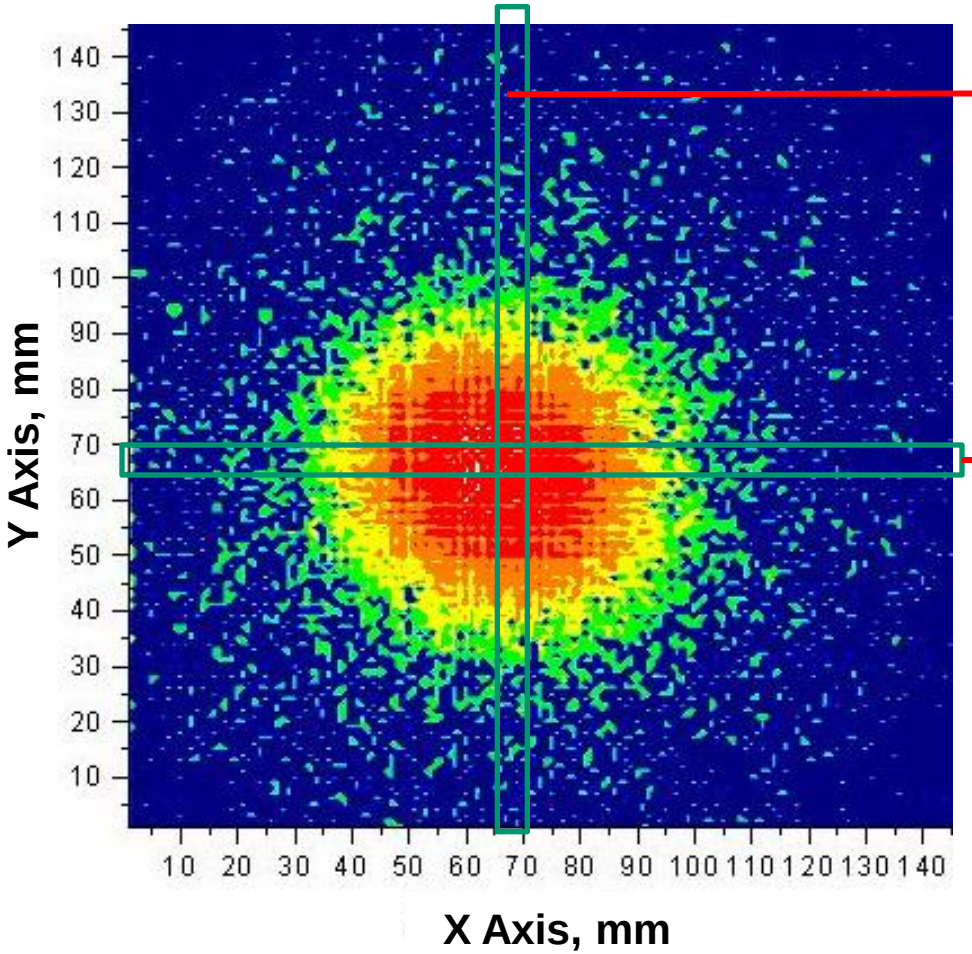


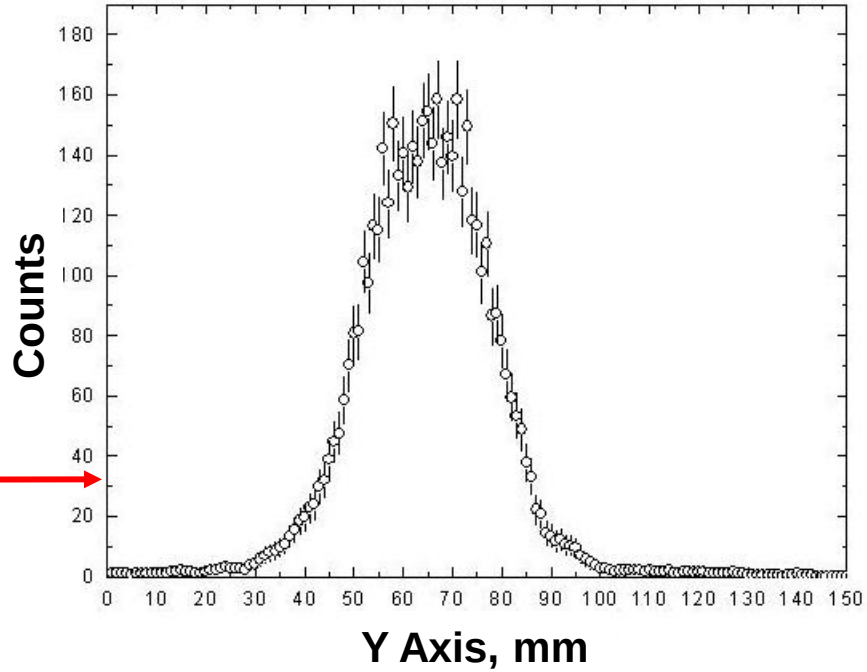


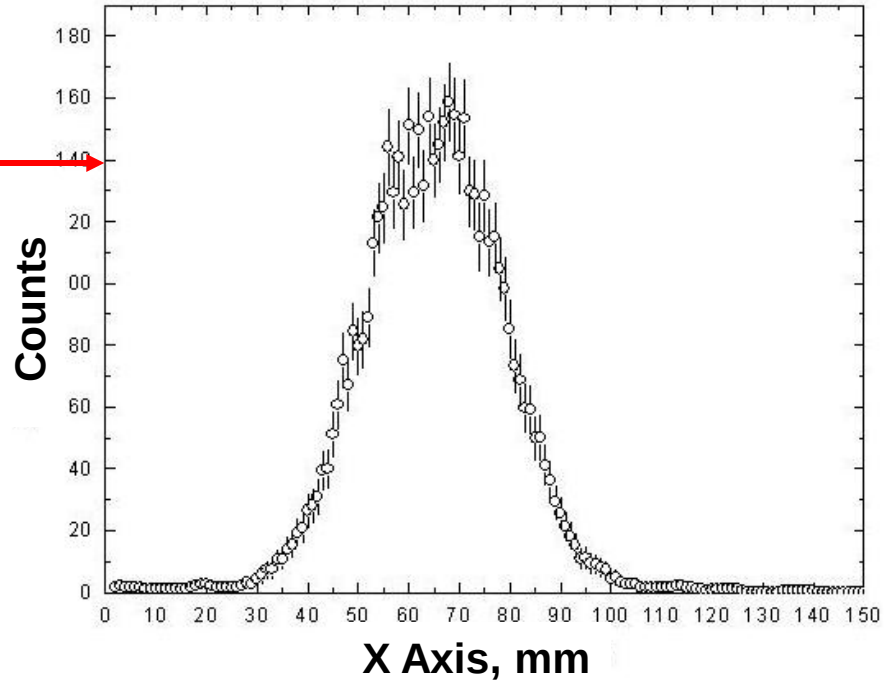


NEUTRON BEAM PROFILE

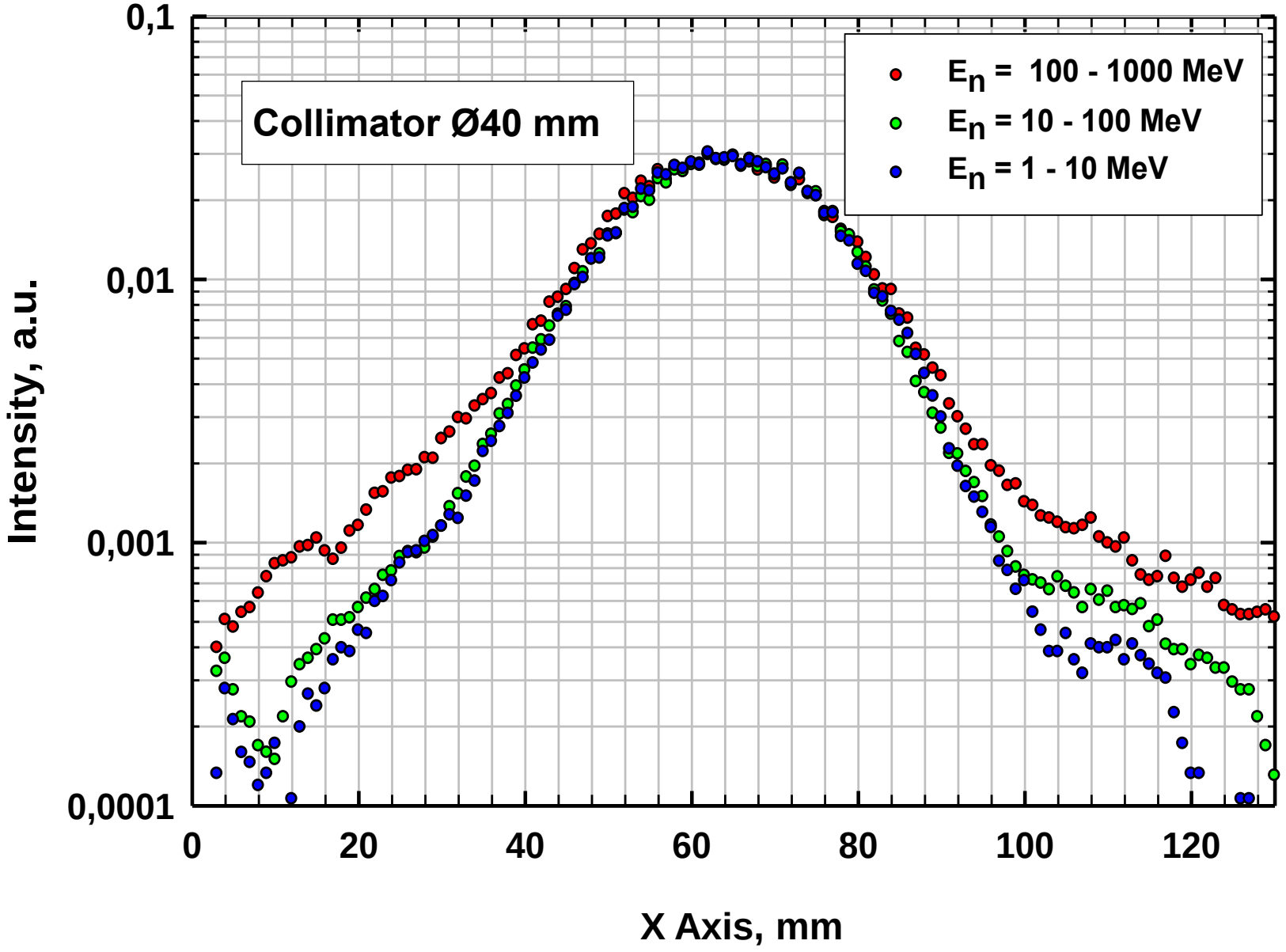
Collimator Ø40mm







Neutron Beam Profile vs Neutron Energy



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:

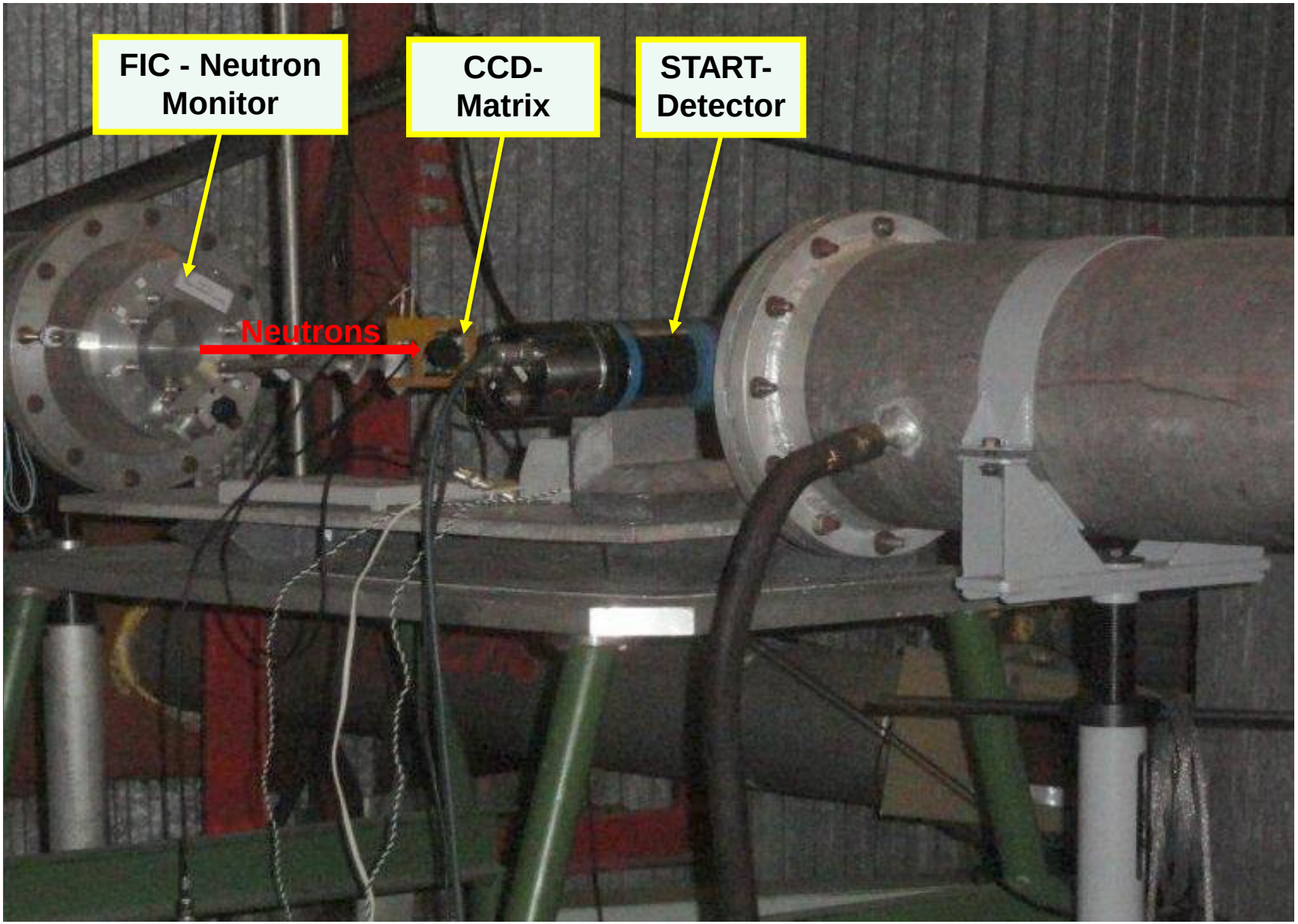
- overall degradation
- appearance of isolated pixels, the so-called "spikes";
- "spikes" look as isolated white spots , which lead to the image distortion and subsequent equipment failure;
- example: failure of the navigation system during the process of spaceship docking.

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

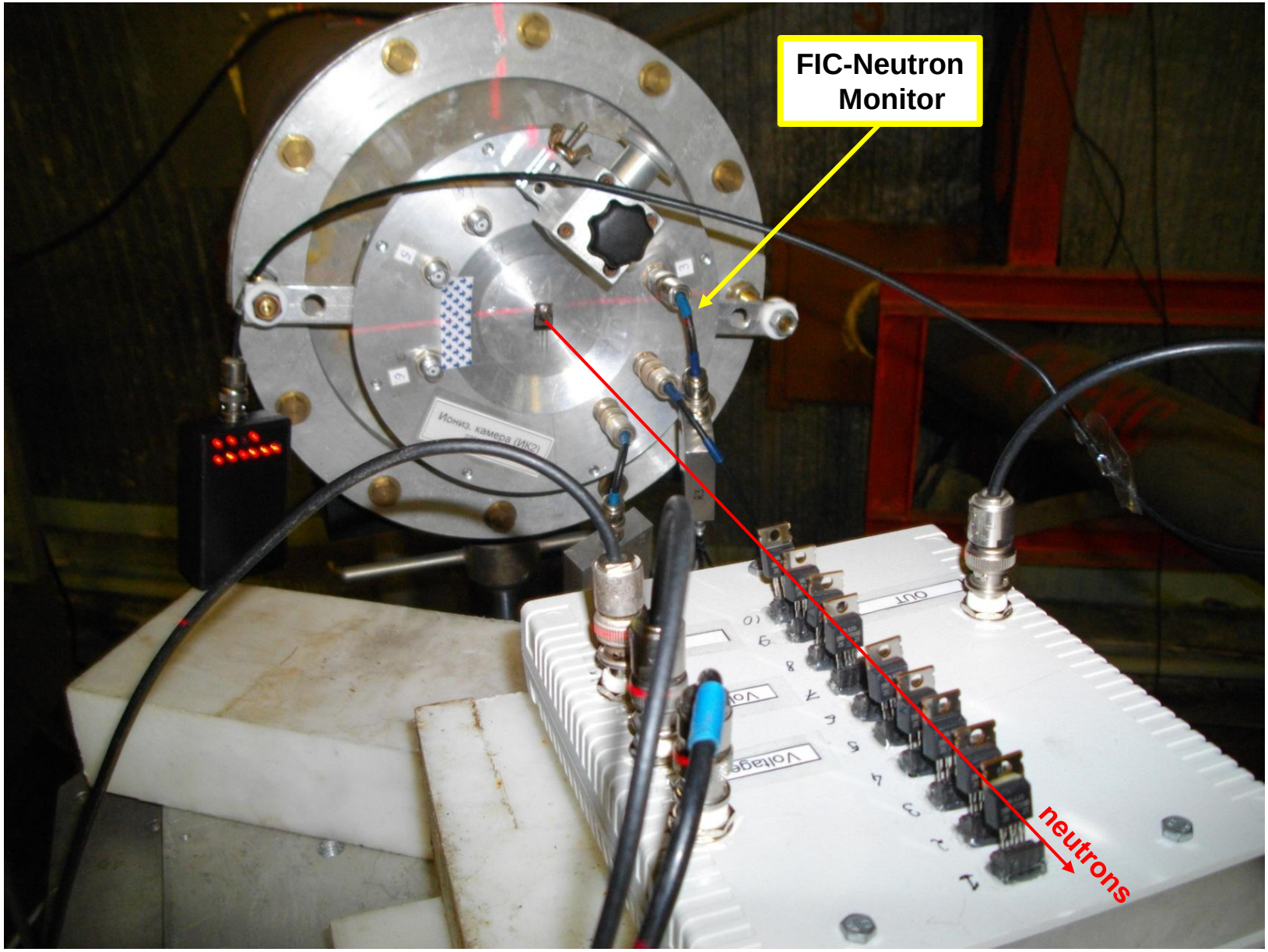
This is first experiment at the GNEIS (2010)

devoted to the neutron radiation resistance test of electronics.

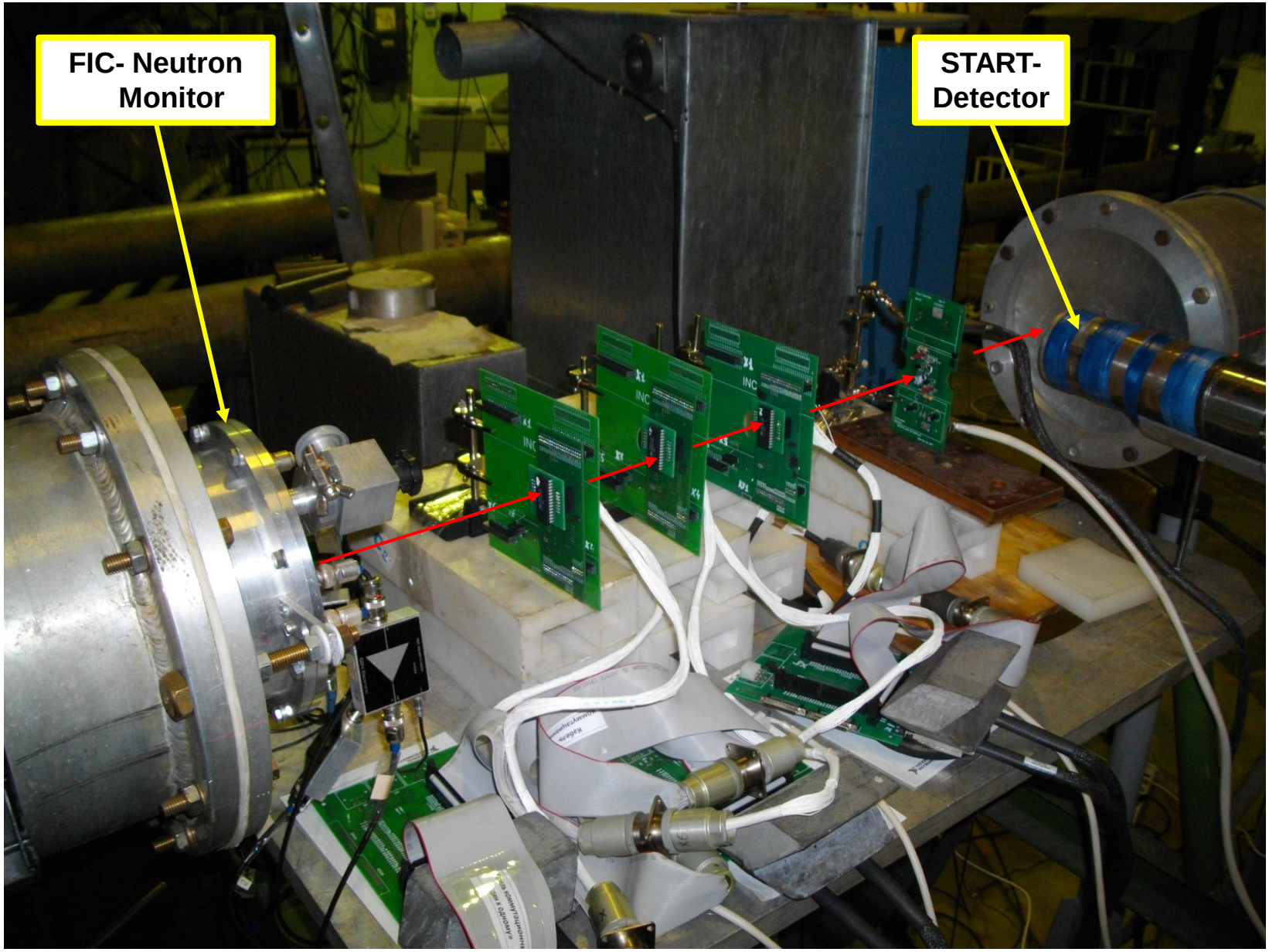
Neutron Irradiation of CCD-Matrix (2010)



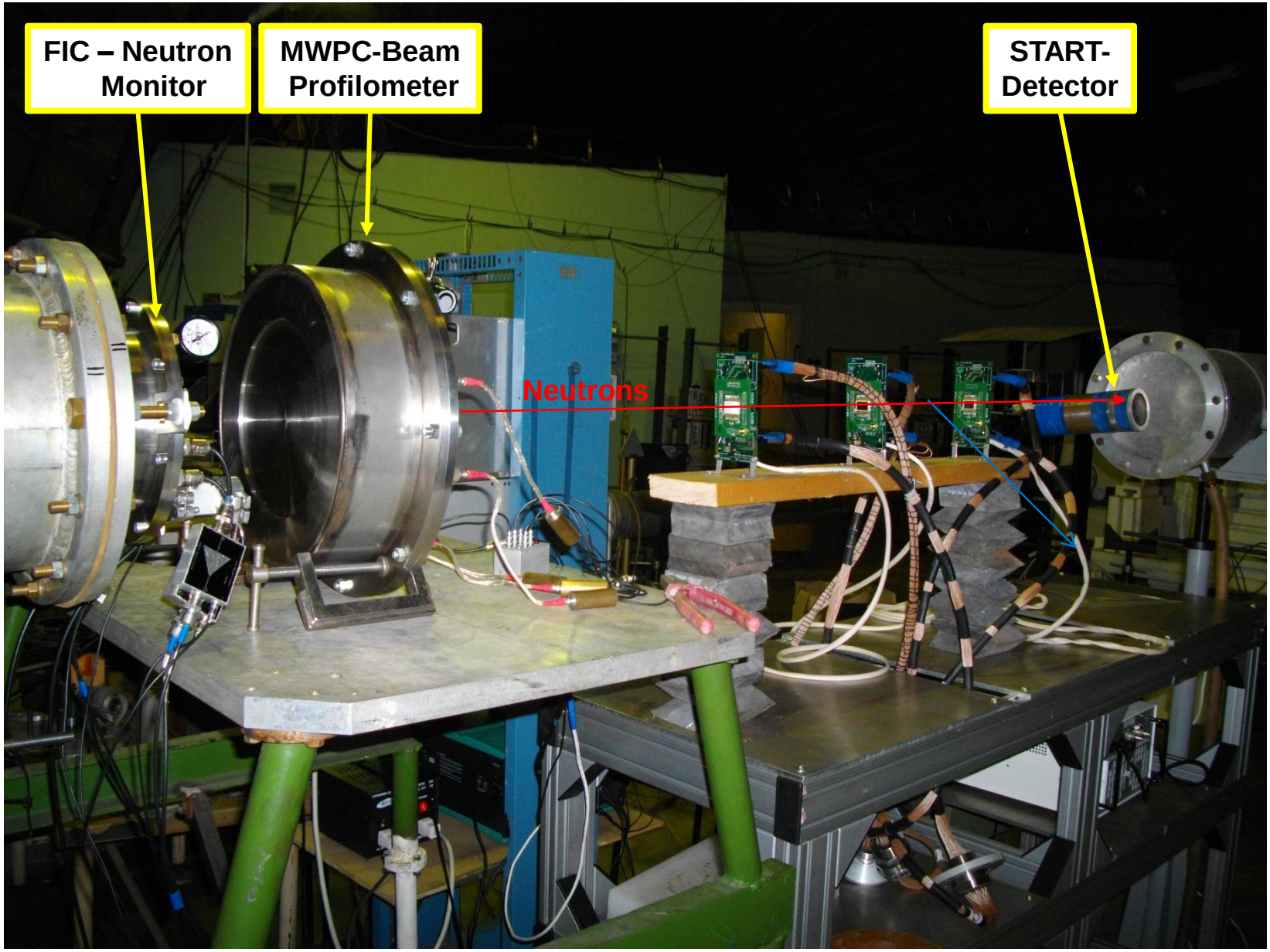
Neutron Irradiation of MOS - Transistors (2012)



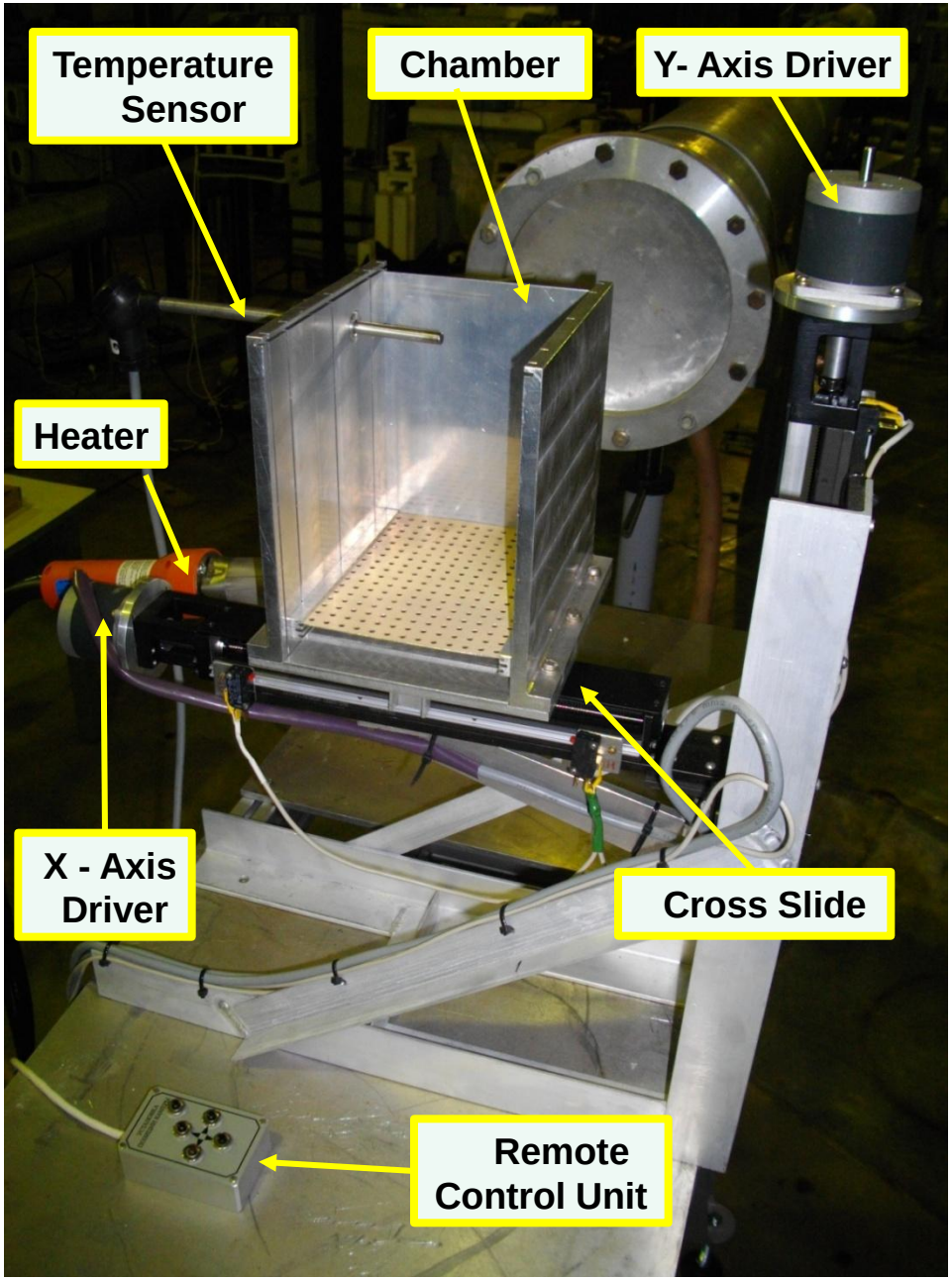
Neutron Irradiation of SRAM - Chips (2013)



Neutron Irradiation of SRAM - Chips (2014)



System for DUT (Device Under Test) Positioning and Heating



DUT enclosed in the Heating Chamber can be:

- **heated, temperature range 20^0C – 130^0C**

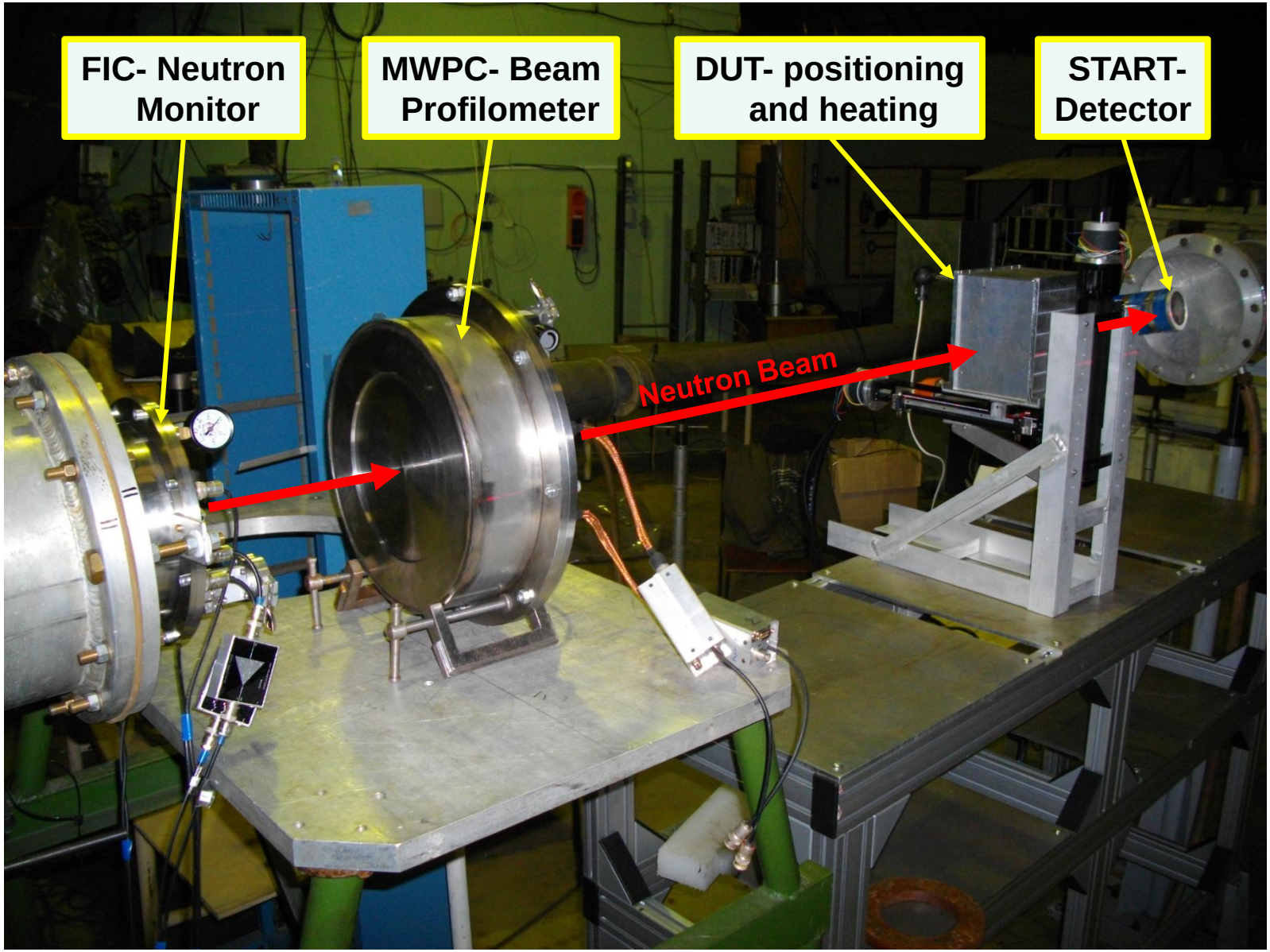
- **max. heating / cooling time 300 sec (closed chamber) 600 sec (upper cover removed)**

- **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)



CONCLUSION

1) at the neutron TOF-facility GNEIS based on the 1 GeV proton synchrocyclotron of the PNPI, it is developed a neutron resistance test facility with atmospheric – like neutron spectrum in energy range 1 – 1000 MeV and integral neutron flux $5 \cdot 10^5$ n/cm^2·s (at 36m);

2) our facility enables to carry out accelerated neutron resistance tests of electronic equipment; 1 hour of neutron irradiation at the GNEIS is equal to 125 000 hours of natural neutron irradiation at the altitude of 10-12 km and $5 \cdot 10^7$ hours (5700 years) at the sea level;

3) during 2010-2014, the neutron irradiation tests of various electronic devices at the PNPI have been done simultaneously with the proton irradiation tests;

4) in 2014, the neutron resistance testing of the electronic devices used in avionic and space equipment at the atmospheric – like neutron spectrum is included in a national system of standards.


Welcome to NICE House GNEIS in Gatchina!