Center of Accelerators
and Nuclear Analytical Methods
(CANAM)

Laboratory of Cyclotron and Fast neutron Generator

NPI Nuclear Reactions Department (NRD), Neutron Section

- member of European Consortium for Nuclear Data (ECND), supported by F4E
- member of collaboration NPI - NFS (Neutrons for Scince, SPIRAL-2, Ganil)

✓ ofers own infrastructure (current and planed) to access for external users within LC&FNG CANAM

✓ utilizes a partial support of CANAM to own research program

Staff of NRD NS

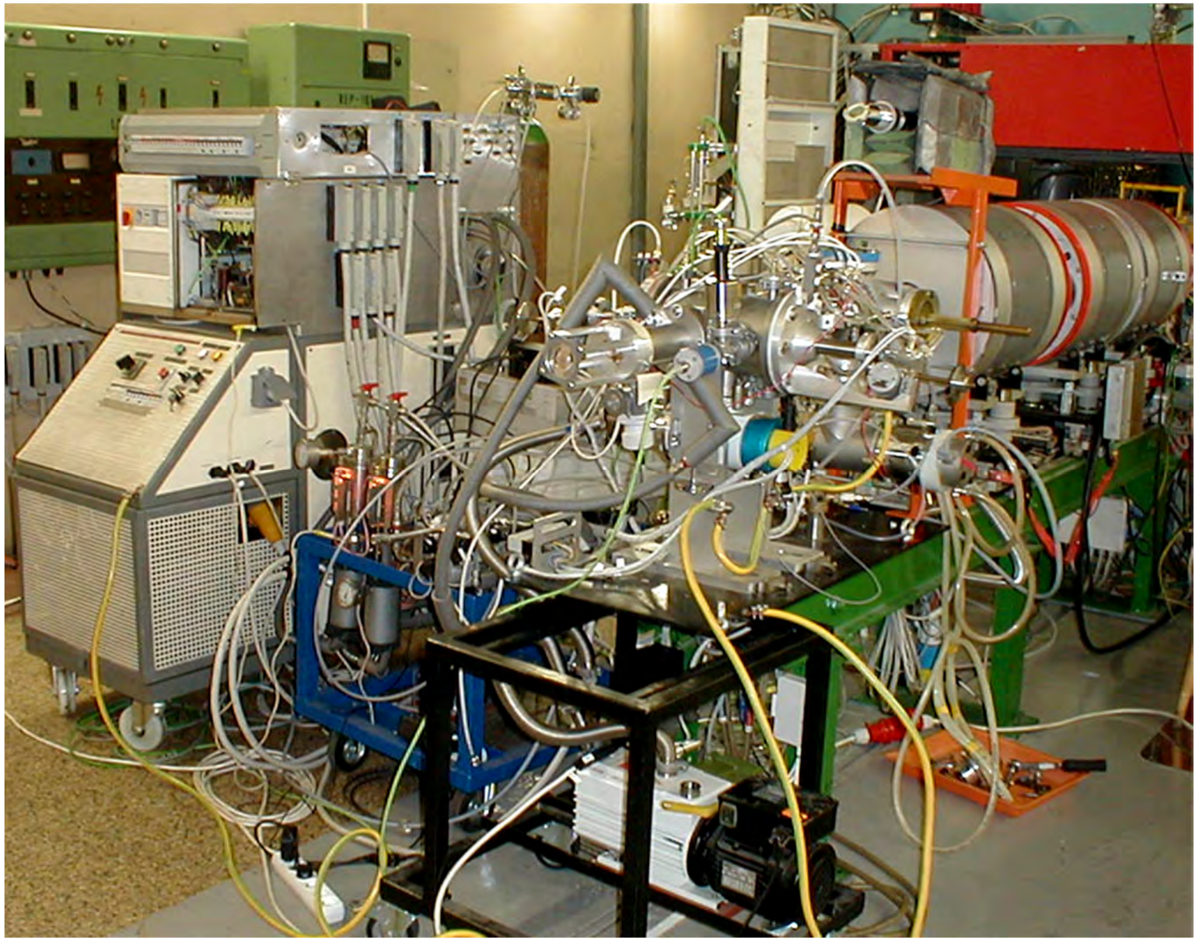
Jaromír Mrázek (head of NRD), Mitja Majerle (spokesperson of NS), Jan Novák (FNG coordinator CANAM), Milan Štefánik (instruments responsible), Eva Šimečková, Miloslav Götz, Pavel Bém, Radomír Běhal and technical staff

Content of report

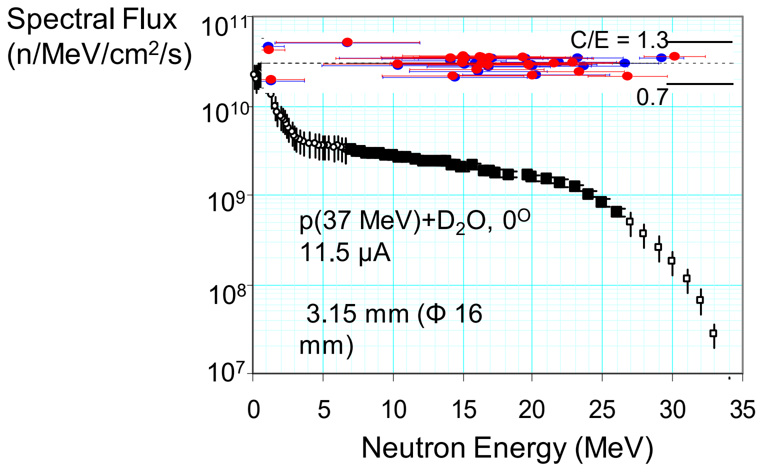
- **FNG activities 2013-15**
  - **Review and upgrade of infrastructure**
  - **Research activities of external users**
  - **Research program of NRD (under CANAM support)**

- **Planned upgrade of FNG infrastructure**
  - **Collimated neutron beam on U-120M cyclotron**
  - **High-power neutron generator on TR-24 cyclotron**
  - **TOF neutron facilities, proposal**

Review – High-power broad-spectrum neutron generator

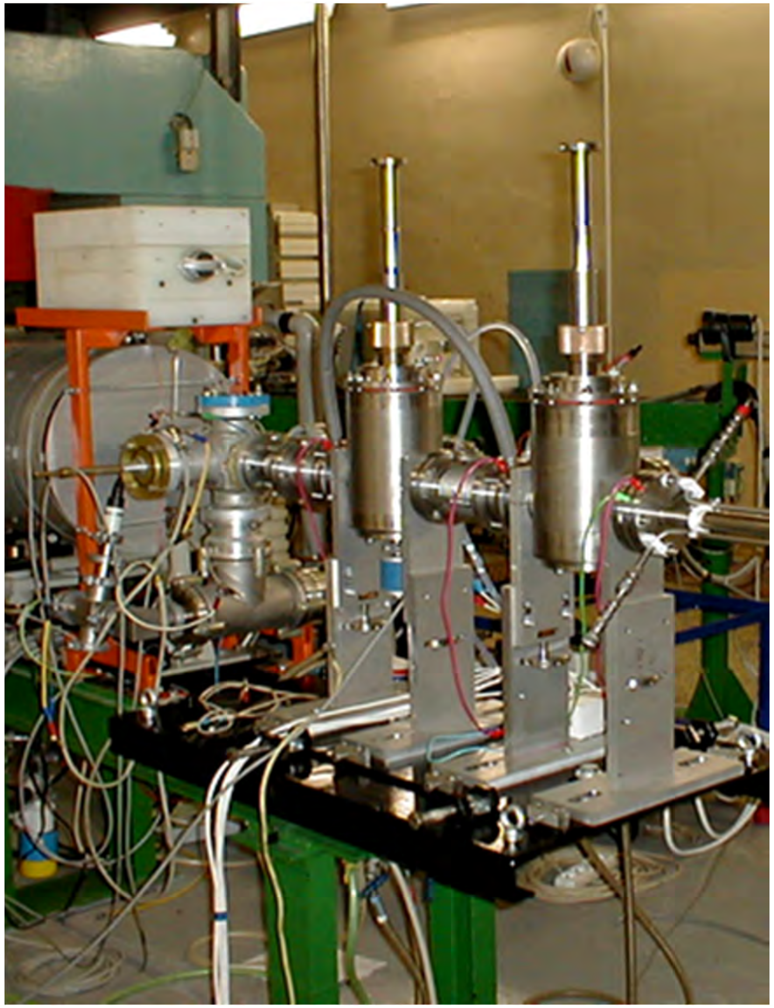


- Neutron production:
  p(37 MeV)+D_2O target
- Mean energy: 14 MeV
- Extension: up to 32 MeV
- Integral flux: up to 10^{11} /cm^2/s

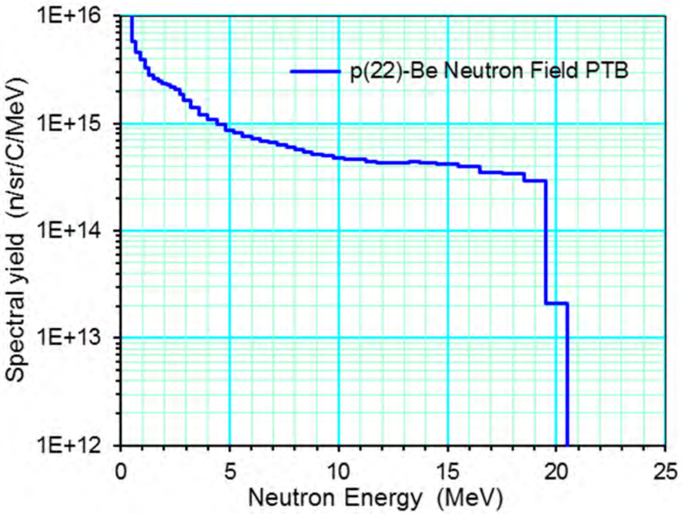


The p(37 MeV)+D_2O spectrum is obtained by activation technique and SAND-II adjustment procedure.

Review – Variable-energy broad-spectrum neutron generator



- Neutron production: p+Be, d+Be
- E_{proton}= 10 – 37 MeV
- $E_{deuteron}$= 8 – 20 MeV
- Mean energy: 4 - 12 MeV
- Integral flux: up to 10^{11} /sr/s

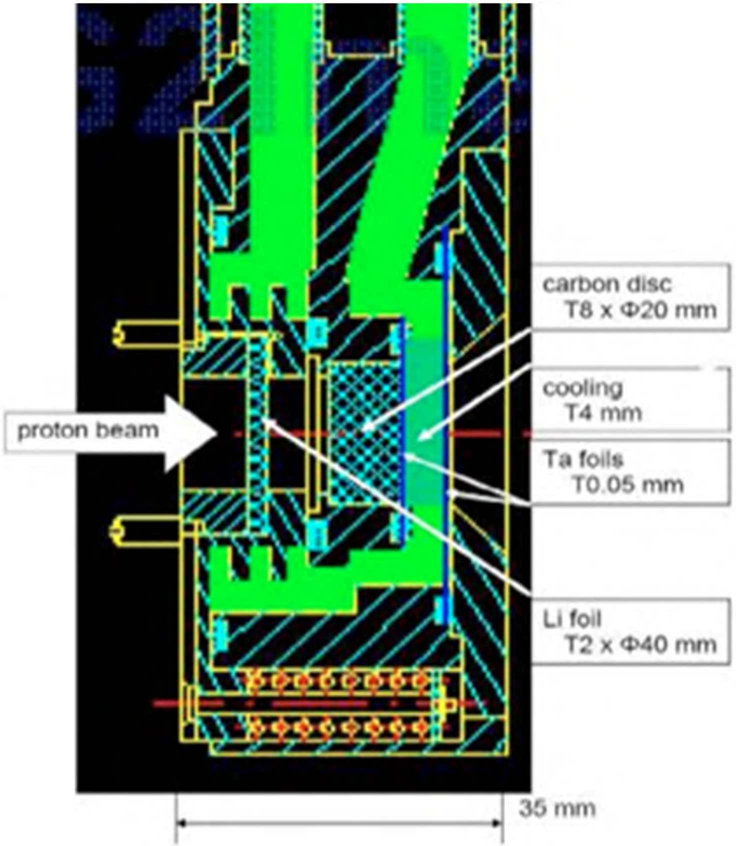


The shape of spectrum valid for p(22 MeV)+Be neutron source at NPI. The reference neutron field data from PTB Braunschweig are used.

Review – High-power and variable-energy broad-spectrum neutron generators

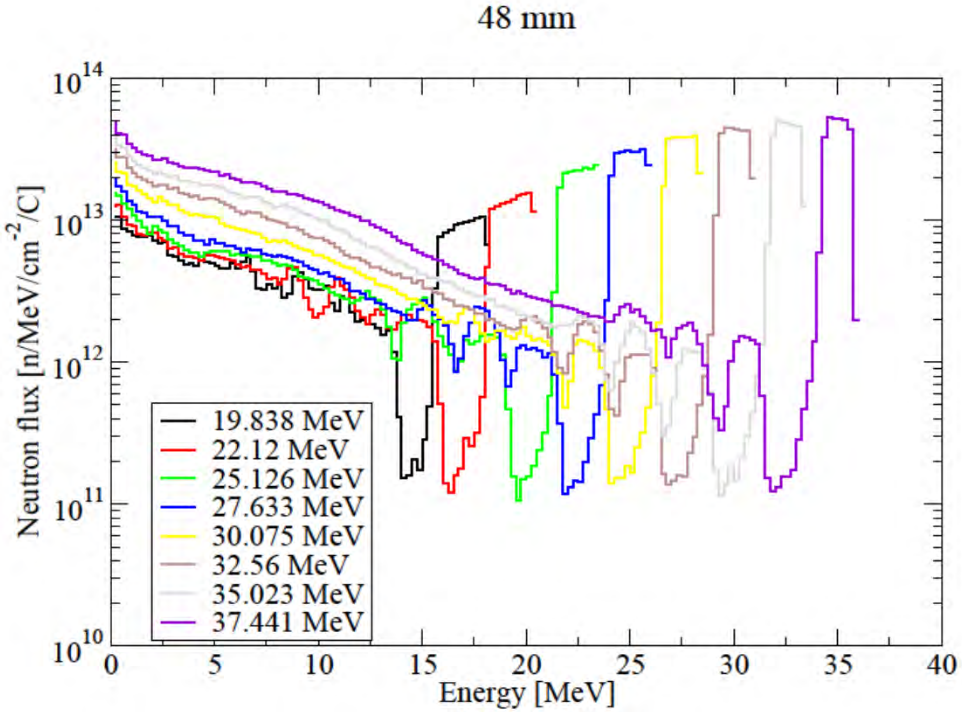
- Developed for benchmarking the neutron data relevant to the fusion and ADS technologies, and to the radiation-damage of microelectronics.
- The neutron spectrum at the position of irradiated samples is determined, by the multi-foil activation technique together with the SAND-II unfolding procedure and by the MCNPX predictions (with ENDF/B-VII).
- HPGe-detector method is used for the off-line investigation of activated samples.
- Pneumatic post system enables to transport the samples from the irradiation position of p/d-Be neutron source to the HPGe detector below 10 seconds.
- The sample holder and the relevant cabling is available to the on-line operation of irradiation procedure.

Review – Quasi-monoenergetic neutron generator



- Neutron production: p+^{7}Li
- E_{proton}= 20 – 37 MeV
- Peak energy: up to 36 MeV
- Neutron flux density in the QMN peak:
  up to 10^{9} n/cm^{2}/s

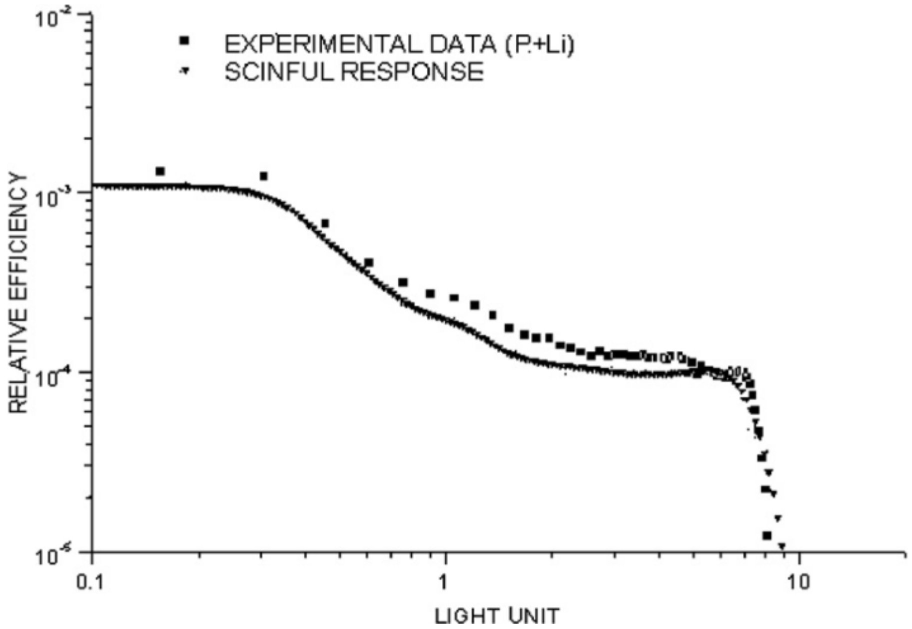
Review – Quasi-monoenergetic neutron generator



The neutron spectra calculated with MCNPX code at different proton energies at 48 mm distance of the sample from the Li target are given.

- Developed for the experimental investigation of integral activation cross-sections and for the tests/calibrations of various neutron detector systems.
- The spectral flux is simulated using the MCNPX code.
- The simulated spectra were compared to the experimental TOF-data and to an absolute measurements performed with a proton-recoil telescope technique.
- Pneumatic post system for the sample transport to the HPGe detector.
- Sample holder and relevant cabling are available to the on-line operation of irradiation procedure.

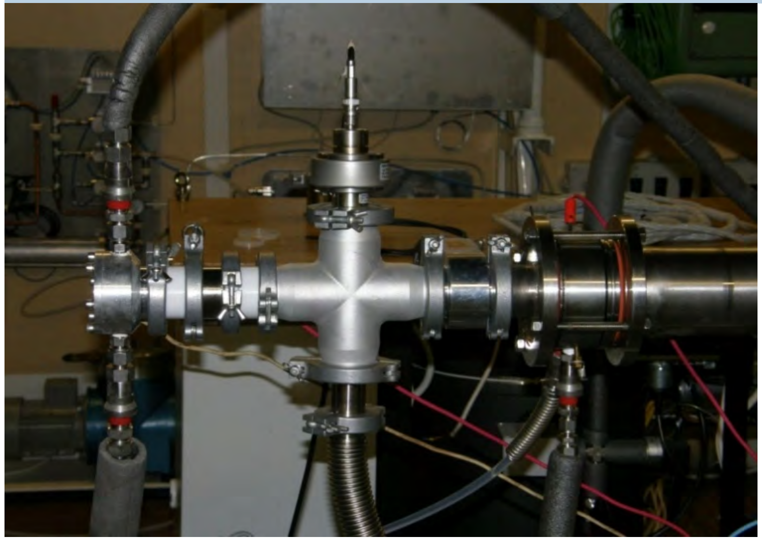
Review – Online neutron detection systems - NE 213 scintillator

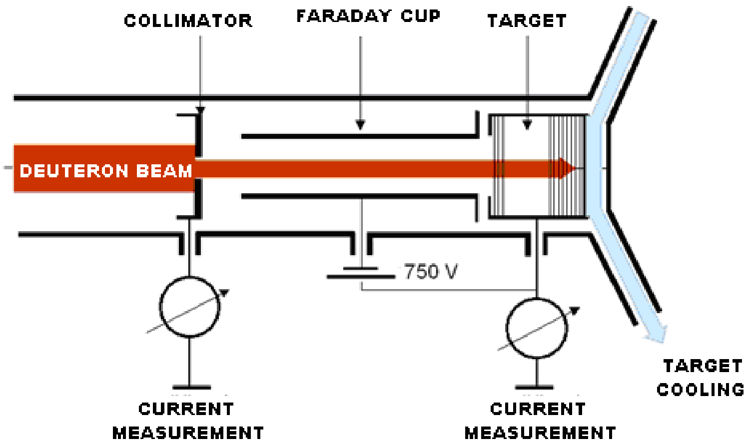


- Based on the detection of scintillation from the interaction of protons (or other charged particles) from neutron reactions.
- The light ray intensity converted to electric pulse.
- From the pulse spectrum, coming from the n-p recoil, the neutron spectrum reconstruction, based on the response function knowledge, is possible.

In the real experiment, gamma photons interact with the scintillator also.
=> Neutron – γ discrimination based on the pulse shape analysis (PSA).

Review – Nuclear data measurements with ion beams

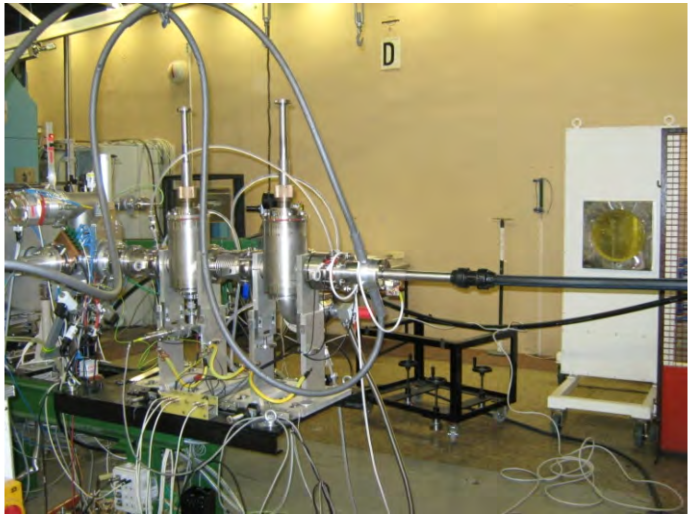




- Proton and deuteron production
- E_{proton}= 10 – 37 MeV
- $E_{deuteron}$= 8 – 20 MeV

- ❑ Developed for irradiation of different materials with protons and deuterons and investigation of activation cross-sections using the stacked-foils method.
- ❑ The irradiation chamber is equipped by Farraday-cup
- ❑ The cooling of stacked foils is possible.
- ❑ The HPGe-detector technique is used for the off-line investigation of activated samples

Upgrade of infrastructure
– Offline detection systems

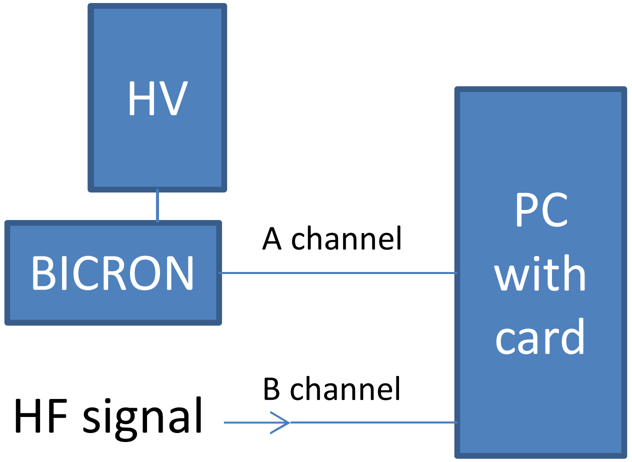


Pneumatic post system is used for fast transport of the irradiated samples to the detectors.

- HPGe detector CANBERRA GR 5021, Lynx DSA operation system
- HPGe detector ORTEC GEM50
- Research Amplifiers , HV Power supply, ADC,…
- The lead shielding of gamma-detector

Upgrade of infrastructure – Online neutron detection systems - TOF

- The U120M cyclotron frequency is 20-25MHz.
- The time window of 50 ns can therefore be used for the TOF. The beam pulse duration is 5 ns.
- 50 ns at 5 m distance from the neutron source target is enough to determine the neutron spectrum from the maximal energy of 35 MeV down to 15 MeV.

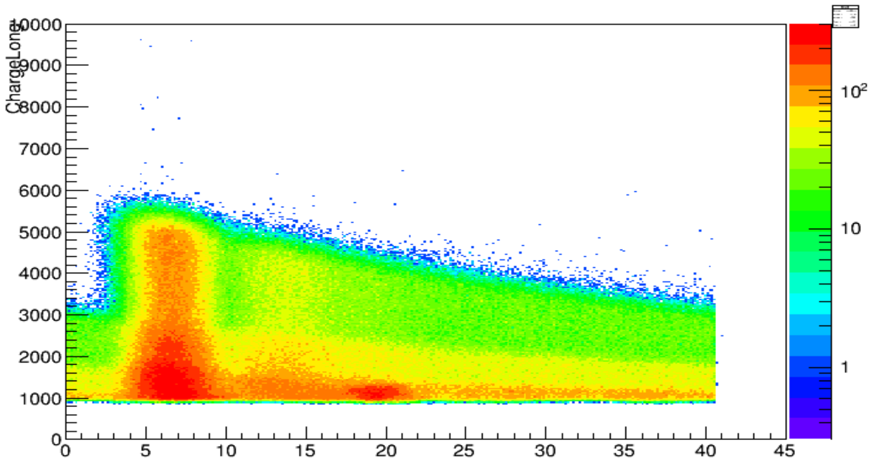


- Two channels can be sampled simultaneously with 1 GHz sampling frequency.
- Neutron – γ discrimination based on the pulse shape analysis (PSA).
- The first channel samples the NE213 assembly pulses, the second channel samples the high frequency cyclotron signal to determine the phase.
- 10 bit 1GS/s 8 input channel CAEN digitizer is used.

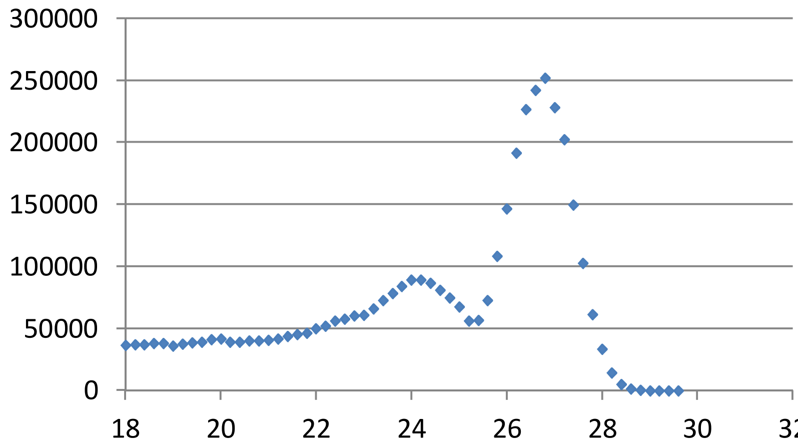
Upgrade of infrastructure – Online neutron detection systems - TOF

- Feasible for the direct neutron spectra measurement.
- The multichannel coincidence set up can give the input neutron energy as one of the reaction parameters
- From the two channel graph of the scintillator response vs. TOF, the scintillator response at given time/energy can be extracted.

Currently, the LC&FNG prepares a new TOF set up for the significantly longer base and the significantly longer time range.



Scintillator response vs. TOF at 10 m distance, thin Be target with 31,4 MeV protons.

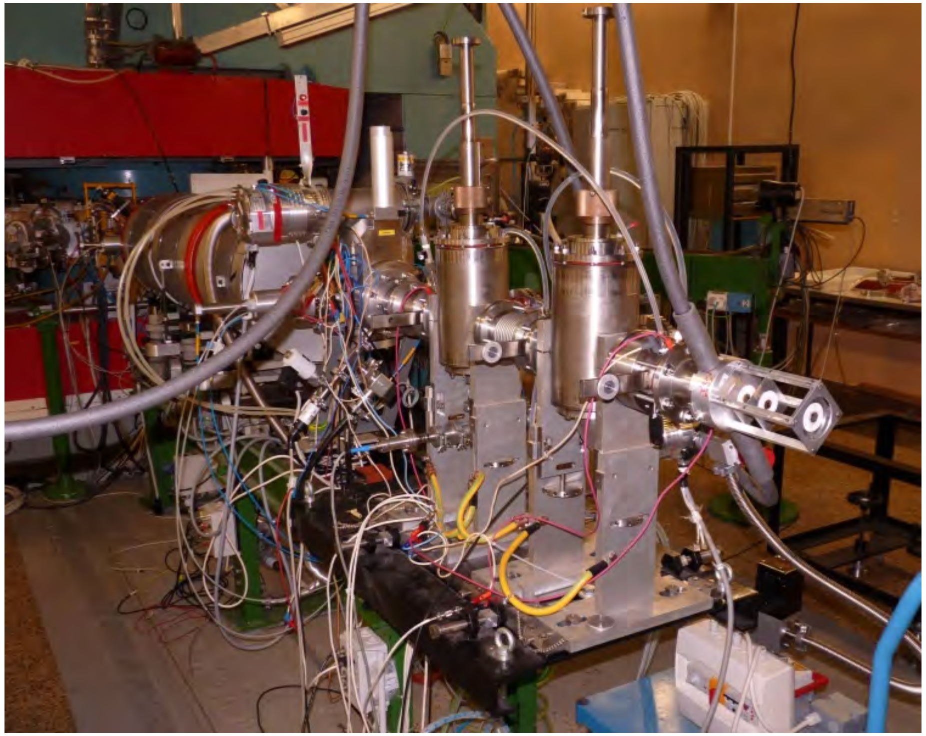


Obtained neutron spectrum, the same conditions.

Upgrade of infrastructure – p(35)-Be White Neutron Source

- Standard operation for E_p = 20 MeV
- Operation at E_p = 35 MeV since 2013

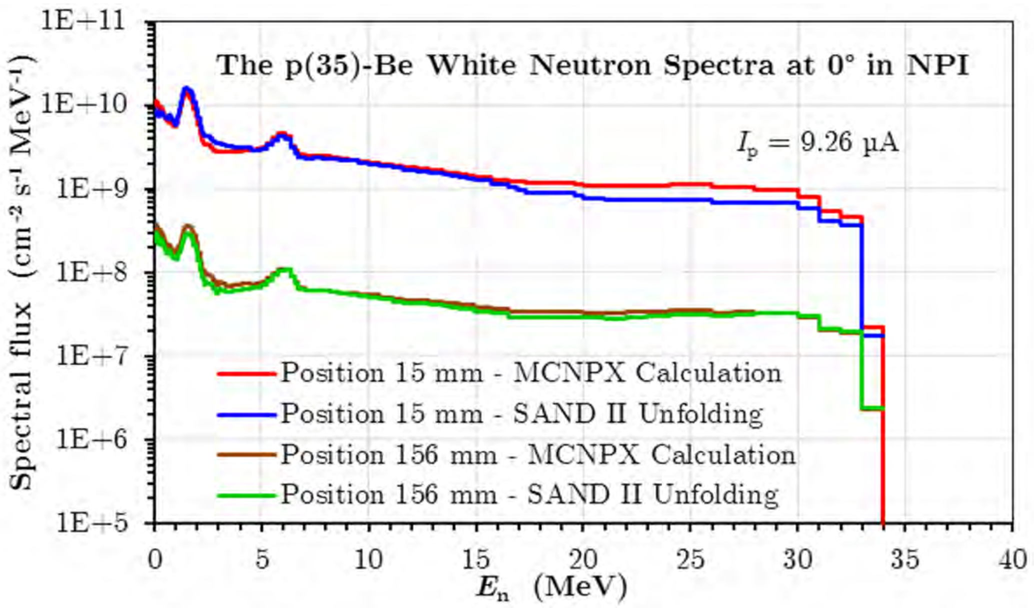
New high-power p(35)-Be white neutron source



- ❑ Source reaction
  - p + ^{9}Be, Ep = 18–35 MeV, Ip ≤ 15 μA
- ❑ Target station set-up
  - ^{9}Be target (thickness of 8 mm)
  - Alcohol coolant (5 °C)
  - Beam-power of 500 W
  - Pressure and temperature of alcohol are measured
- ❑ White neutron spectrum
  - Broad neutron spectrum up to 34 MeV
  - Spectral flux up to 10^{11} cm^{-2}s^{-1} at the irradiation position of 15 mm
- ❑ Multi-foil activation method + MCNPX calc. + SAND-II unfolding

Upgrade of infrastructure –
p(35)-Be White Neutron Source

Multi-foil activation technique
- Al, Nb, Sc, Y, MnNi, Co, In, Lu, Au, Ti, Fe, Bi
Neutron spectra reconstructed by SAND-II code



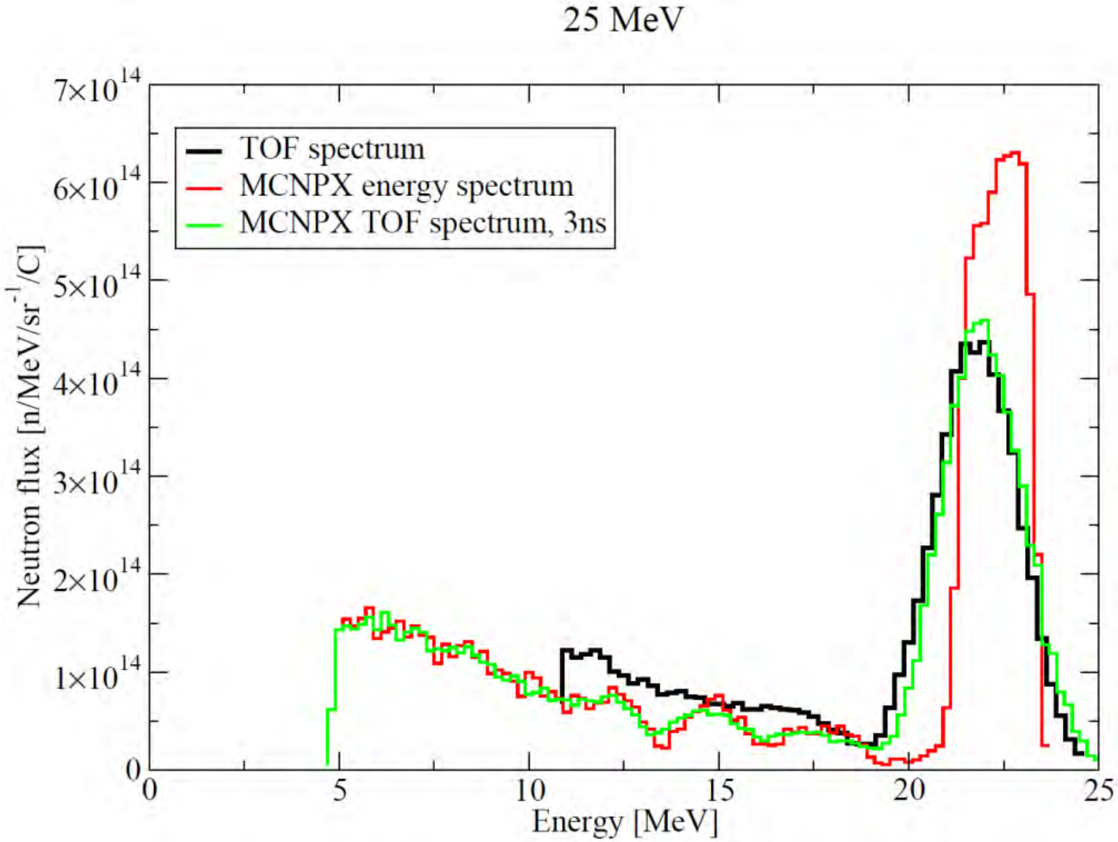
Neutron field of NG-2 generator (p-Be target station) at two positions measured by multi-foil activation technique at NPI

Utilisation of the new high-power p(35)-Be white neutron source

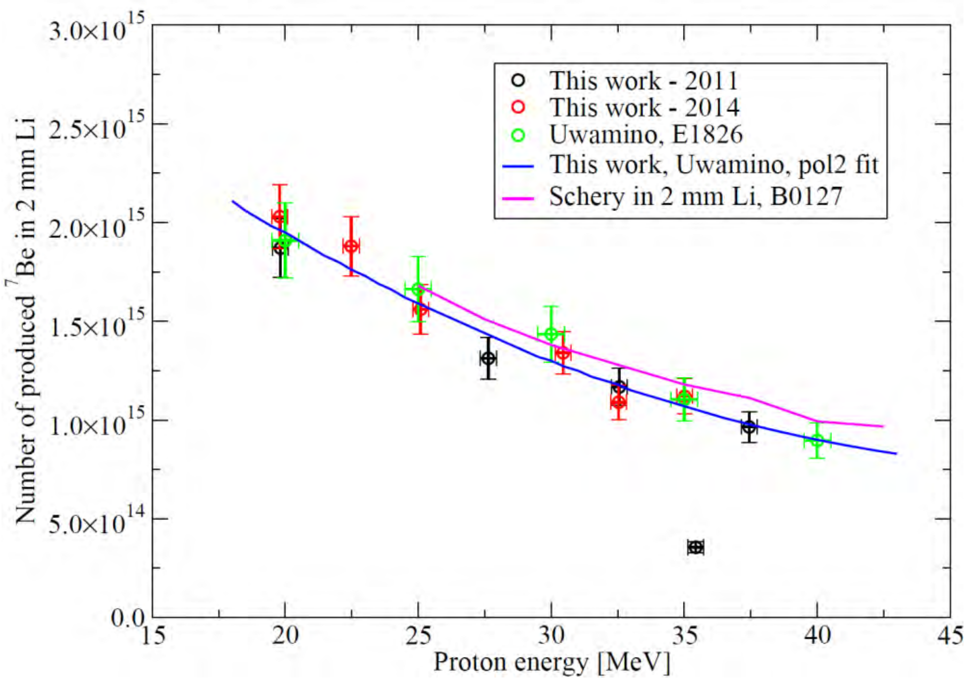
- ❑ Mean energy of approx. 14 MeV corresponding to the ITER (14 MeV d-T reaction)
- ❑ Energy range is compatible with the main energy range of the IFMIF facility (reaction of d(40)-Li with mean energy of 14 MeV)
- ❑ Replacement for p(37)-D_2O neutron source with white spectra

Upgrade of infrastructure – p-Li Neutron Source

The QM neutron spectra of the p-Li source for different proton energies between 18 and 36 MeV were measured by TOF method and compared with the MCNP energy spectra. The spectra were normalized using the measurement of the ^{7}Be production in the Li target.



Upgrade of infrastructure –
p-Li Neutron Source



- The QM neutron spectra are used to measure neutron cross sections.
- The ^{7}Li production errors were important sources of neutron spectrum systematic errors.
- The neutron spectrum improvement leads to the improvement of the measured neutron cross sections.

Due to disagreement of the total cross section between Schery and our measurement, the new measurement of produced ^{7}Be nucleus number in 2 mm Li plate is prepared.

Research activities
– Research programs realized in the white neutron fields of NG-2 neutron source

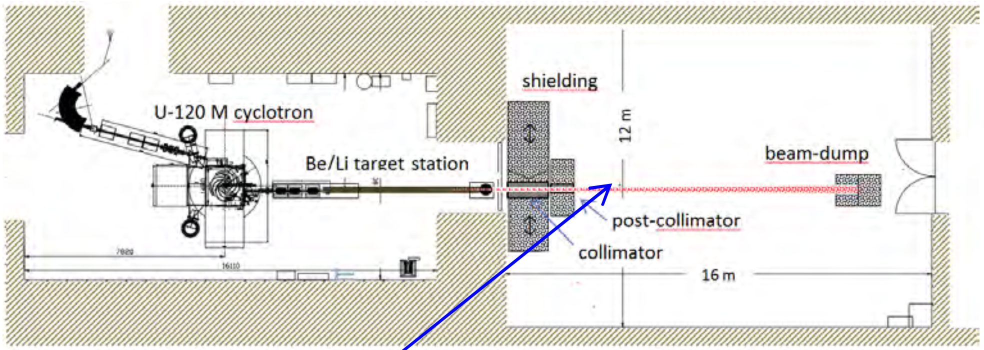
- IFMIF related reserach programs – experimental simulation of IFMIF neutron field (up to 35 MeV)
- The integral benchmarks
- Cross-section data validation – IRDFF and EAF-2010 data library
- Testing the hardness of micro-electronics against the fast neutron fields
- Irradiation of RADMONs and MEDIPIX detectors developed for CERN
- Students projects

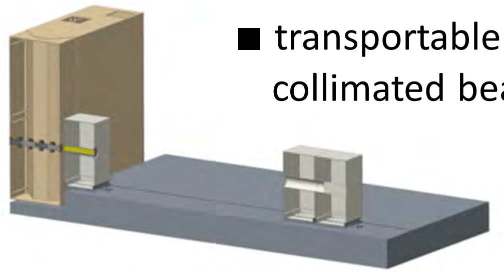
Research activities
– Research programs realized in the quasi-monoenergetic neutron fields

- ERINDA related reserach programms – response of diamond detectors and $^{12}C(n,\alpha)$ cross section over 20 MeV (IRMM)
- neutron cross sections on the Y in the QM spectrum (SWIERK)

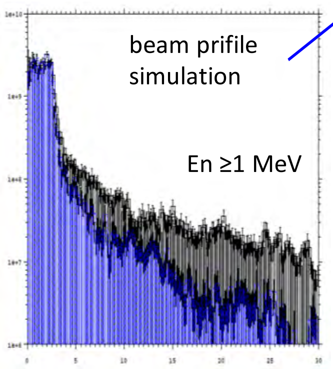
Planned upgrade of FNG – Collimated neutron beam on U-120M cyclotron (2016)

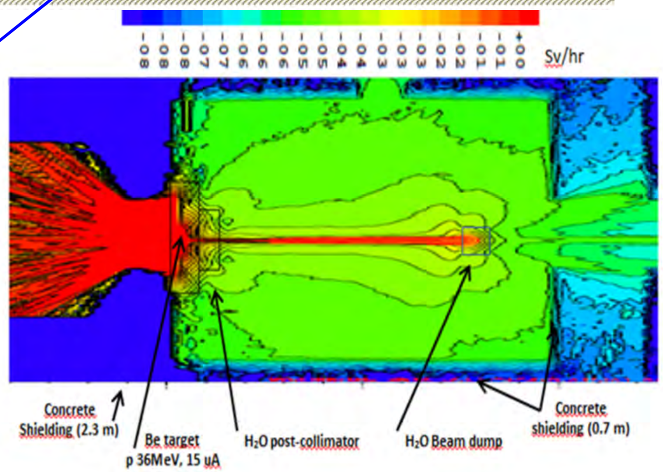
- for collimated neutron beam a flight path (15 m) to beam dump available (low backscattering background)
- high intensity flux (3 m) and suitable energy selection under natural time-structure of cyclotron beam achievable





- transportable shielding (blocks), collimated beam size: 3 cm to 25 cm (in diameter)



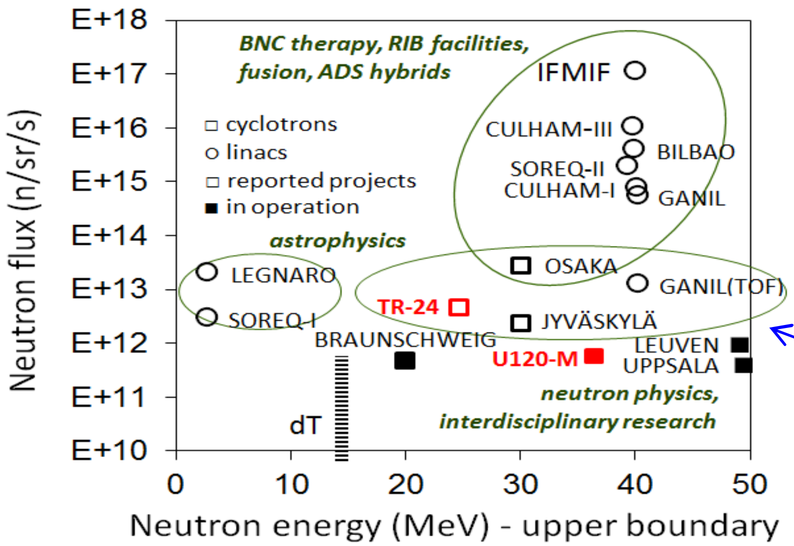


- p+Be (thick target) source reaction
  - white spectrum neutron beam up to 35 MeV, ≤ 7 10^7 neutrons/sec, local irradiation
- p+Be/Li (thin target) source reactions
  - QM neutron beam 20-35 MeV range ≤ 3 10^6 neutrons/sec, rough TOF energy selection

- double-collimator set ensure requested beam profile
- simulated neutron dose rate at adjacent quarters falls below allowed limits

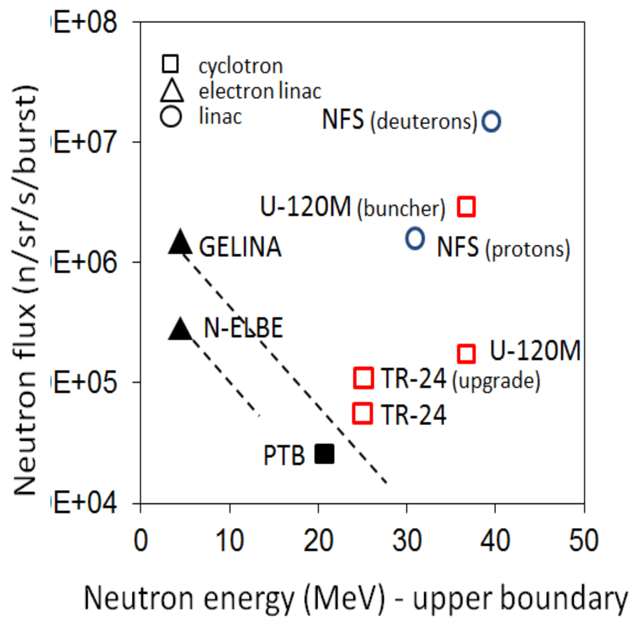
- FNG becomes competitive to neutron facilities at Uppsala and Leuven-le-Neuve
- Shielded acquisition stations will enable to measure differential CS observables - more sensitive tests of CS models and data libraries
- First-day experiment: Investigation of ms-isotopes from (n,xn) reactions, e.g. $Bi^{208(m)}$ (MYRRHA project collaboration)

Planned upgrade of FNG – **Proposed new neutron facilities based on U-120M and TR-24 cyclotrons**



- currently installed new compact cyclotron TR-24 (EBCO, CANADA) provides protons of 15-24 MeV energy and beam current of 0,3 mA (upgrade to 1mA allowed by external ion source)
- evaluated neutron flux 6x10^{12} n/s/sr (2x10^{13} in upgrade version) from **proposed p+Be TR-24 source** (En ≤ 22 MeV)
  - overcomes by an order the U-120M
  - classes the TR-24 neutron source with medium energy projects of neutron facilities for basic and interdisciplinary research

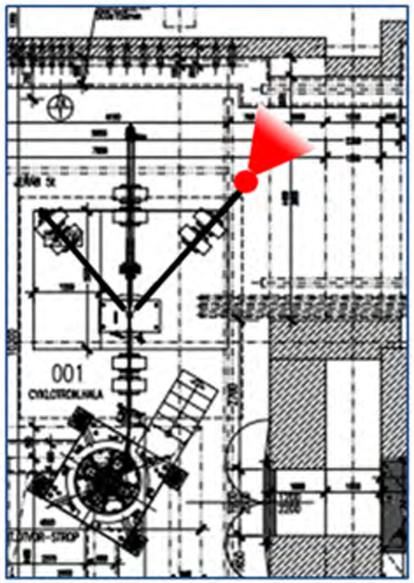
- energy measurement by TOF technique requires a specific time structure of the pulsed beam to ensure a high resolution energy measurement and to prevent overlap from previous bursts
  - evaluated neutron flux per burst of both TR-24 U-120M neutron sources exceed data of current European TOF facilities (PTB, N-ELBE and GELINA) at higher energy region
  - U-120M facility in proposed bunching-mode operation is competitive even with most up-to-now advanced project NFS



- therefore – comparative study of all options mentioned for both cyclotrons will be done for proposed upgrade of FNG infrastructure

Planned upgrade of FNG – **High-power neutron source of TR-24 cyclotron (2017)**

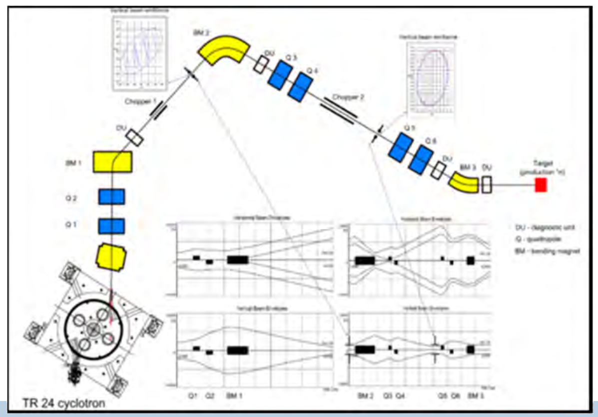
- cyclotron TR-24 and basic beam-lines to three target stations are under field test by provider (EBCO, CANADA)



- different set-ups of neutron Be converters for p+Be source reaction (rotating, conical, gliding incidence) are considered for evaluated neutron flux 6×10^{12} n/s/sr and 8 kW of dissipated power (2×10^{13} n/s/sr and 24 kW power in upgrade version)

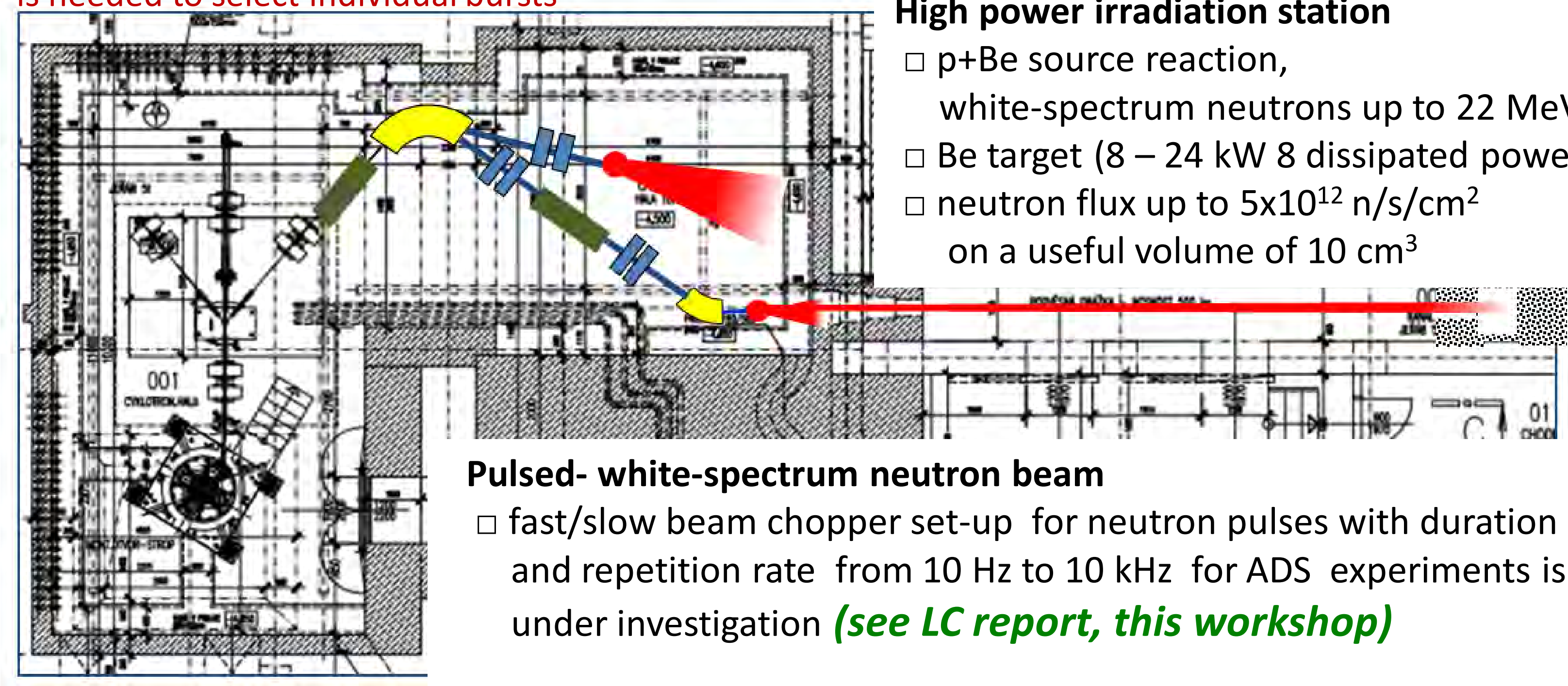
- neutron flux/spectrum of TR-24 source presents suitable tool for ITER neutronic investigations due to correspondence with neutron density in ITER diverter (10^{12} n/cm^2/s, 1–13 MeV range)
- First-day experiment: radiation tests of ITER candidate Hall sensors - investigation of transmutation processes affecting sensors performance in neutron fields with ITER relevant spectrum (proposed NPI Řež/IPP Prague collaboration under F4E support)

- extended beam-lines set-up is under study to develop the simultaneous utilization of TR-24 facility for local irradiation (collimated neutron beam) and for TOF neutron spectrometry as well
- for TOF technique a slow-fast double chopper is considered to select one unique burst from basic time structure of TR-24 proton beam (2ns width, 12 ns interval)



Planned upgrade of FNG – **Neutron TOF/beam facility of TR-24 cyclotron (2017)**

- Advantages/setbacks for TOF neutron production
  - high current 300 μA of extracted proton beam guaranteed, upgrade of current output to over 1000 μA allowed
  - location for beam transport set-up, target stations, collimator and 20 m long channel for n-TOF available
  - control of beam pulsation employing external ion source **not validated by producer** – post acceleration chopper is needed to select individual bursts



High power irradiation station

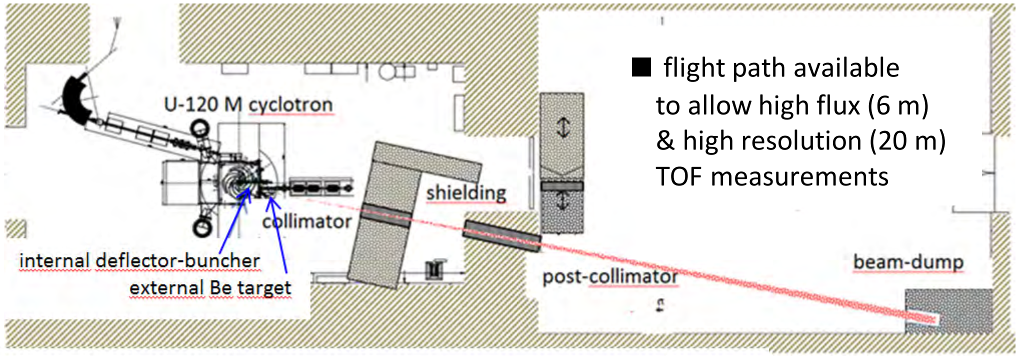
- p+Be source reaction, white-spectrum neutrons up to 22 MeV
- Be target (8 – 24 kW 8 dissipated power) under study
- neutron flux up to 5×10^{12} n/s/cm^2 on a useful volume of 10 cm^3

Pulsed- white-spectrum neutron beam

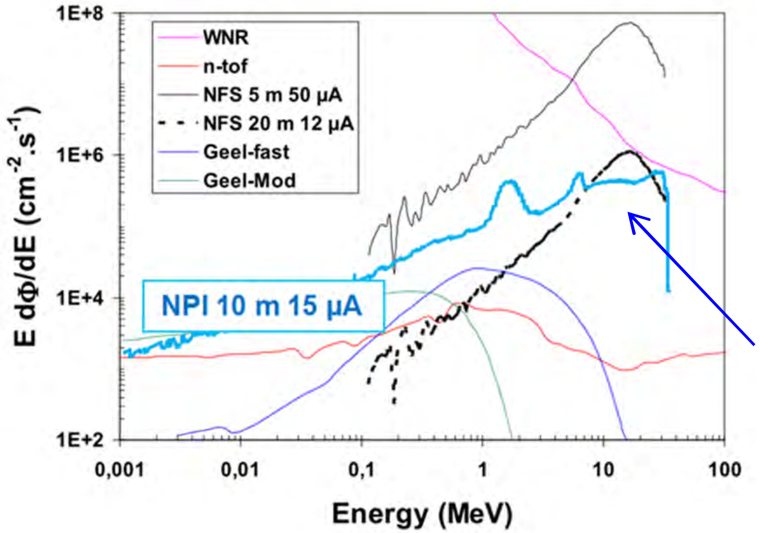
- fast/slow beam chopper set-up for neutron pulses with duration of 0.5 – 100 μs and repetition rate from 10 Hz to 10 kHz for ADS experiments is of first importance under investigation ***(see LC report, this workshop)***

- future research program of the TR-24 neutron facility will follow mainly the fusion-fission and ITER neutronics due to correspondence of TR-24 neutron spectrum to spectral neutron characteristics in these systems

Planned upgrade of FNG – **Neutron TOF facility of U-120M cyclotron (2017)**



- ■ basic idea of „deflection-bunching" TOF method (Karlsruhe cyclotron, 1980) uniquely adopted ***(see LC report, this workshop)*** to the negative-ion cyclotron U-120M:
  - □ internal deflector diverts last 10-50 orbits simultaneously above the cyclotron median plane to extracting foil
  - □ extracted protons hit external Be target in short bursts



- ■ main advantage - requested extension of repetition interval (from 30 to 1500 ns) between individual bursts (4 ns FWHM) does not lead to reduction of beam intensity
- ■ projected parameters for white spectrum neutron beam up to 35 MeV:
  - □ TOF neutron flux 7 10^6 n/s/cm^2 at 3m distance
  - □ energy resolution ≤ 4% FWHM at 15 m distance evaluated flux
- ■ exceeds more than two orders of magnitude the data of other major TOF facilities (n-ToF CERN and GELINA) in the 5-35 MeV energy region
- □ The upgrade of U-120M with deflection-bunching set-up may partly be competitive with most up-to-now advanced project NFS

- ■ TOF method will enable to measure energy-angle dependent cross section observables – sensitive experimental tests of nuclear models calculations
- ■ energy range of U-120M TOF facility well matches to database requests of IFMIF (International Fusion Material Irradiation Facility) coordinated by European Consortium for Nuclear Data (ECND) under support F4E

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Thank you for attention

Presented by Jan Novák