Center of Accelerators
and Nuclear Analytical Methods
(CANAM)

LABORATORY OF CYCLOTRON

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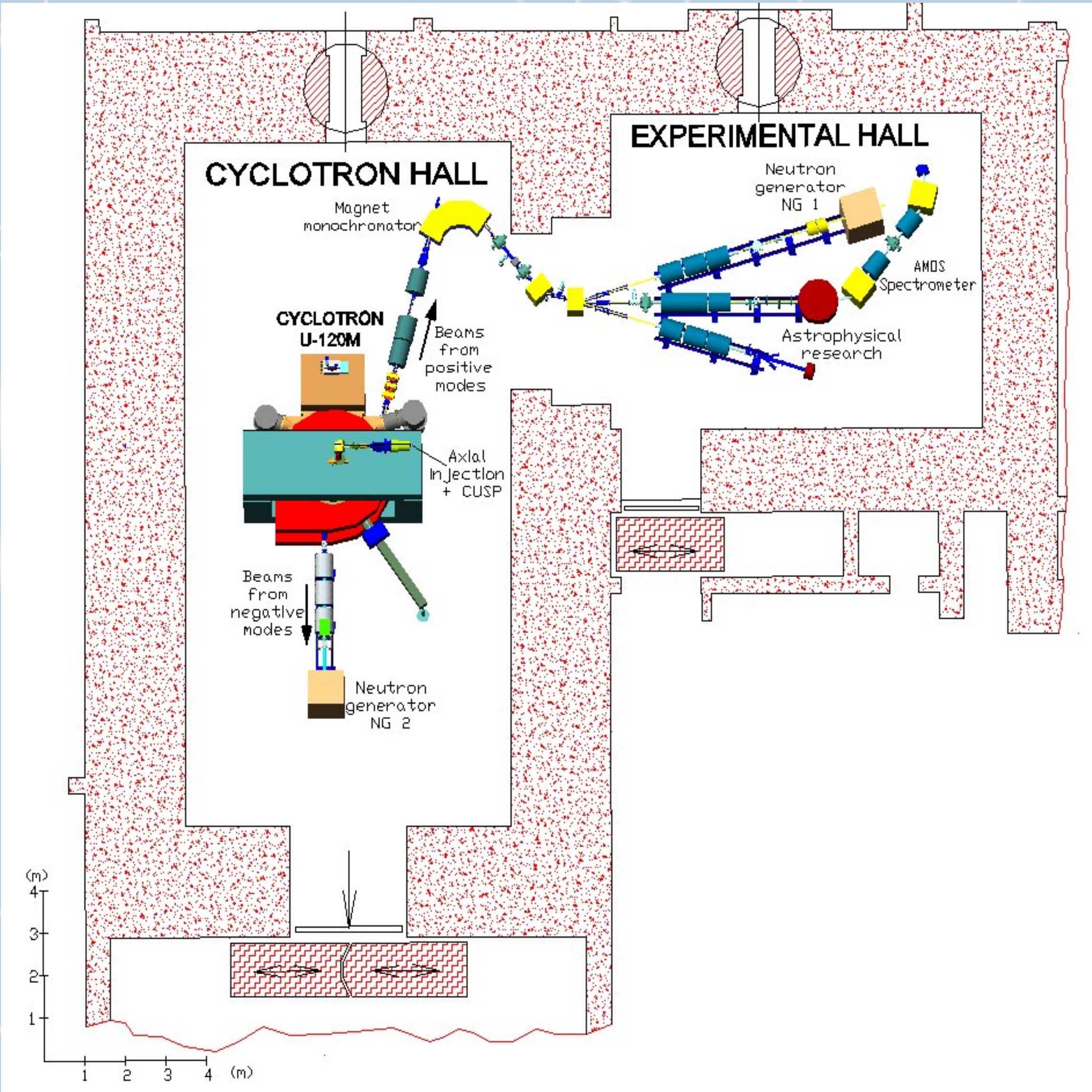
Pavel Krist, technical staff

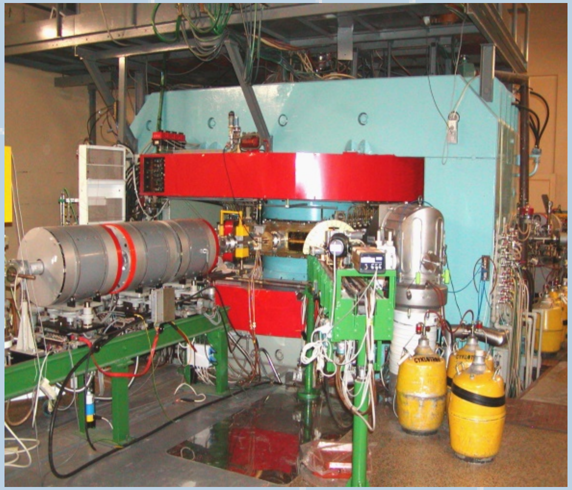
Isochronous cyclotron U-120M

Experimental layout



Beam parameters

ions	beam location	energy (MeV)	max. current (μA)
p	int. beam	2–37	> 200
p	ext. beam	6–25	5
H^-/p	ext. beam	6–37	50–30
d	int. beam	2–20	> 80
d	ext. beam	12–20	5
D^-/d	ext. beam	11–20	35–20
$^3He^{2+}$	int. beam	3–55	20
$^3He^{2+}$	ext. beam	18–52	2
$^4He^{2+}$ (α)	int. beam	4–40	40
$^4He^{2+}$ (α)	ext. beam	24–38	5



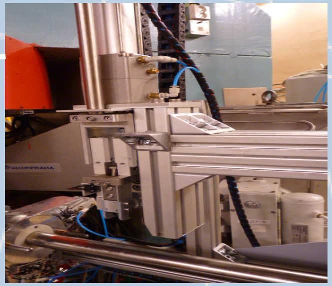
UPGRADE OF THE INFRASTRUCTURE (2013 – 2015)

❑ new internal integral probe with revolving target system

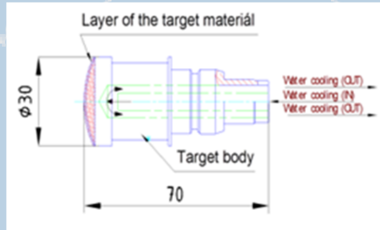
- replacement of the old internal integral probe for beam diagnostic measurements
- precise vertical and horizontal position adjustment (+/- 10mm with acc. +/- 0,1mm)
- revolving targets - irradiation with the high internal beam currents (beam power dissipation~ 1,5 kW) esp. for $^{3}He^{+2}$, $^{4}He^{+2}$
- pneumatic arm for automatic taking off the irradated target into a shielded container
- new electric and pneumatic drivers, new control

Target station construction

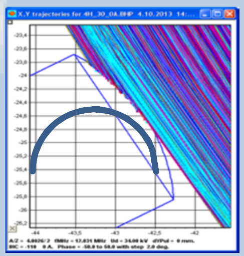
Pneumatic arm

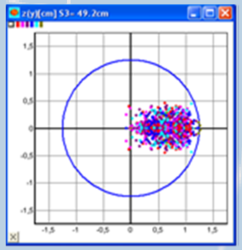


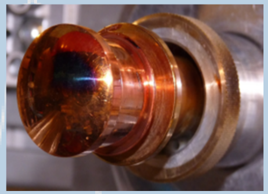
Assembly drawing of the revolving target

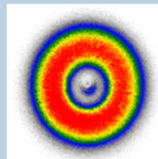


α particle beam (30 MeV) distribution on a spherical cup





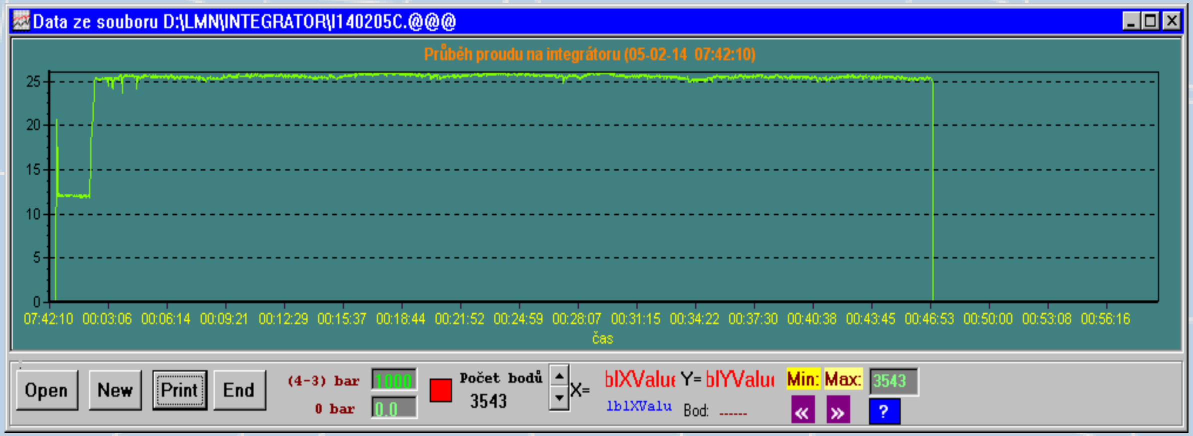




Radiogram of the revolving target

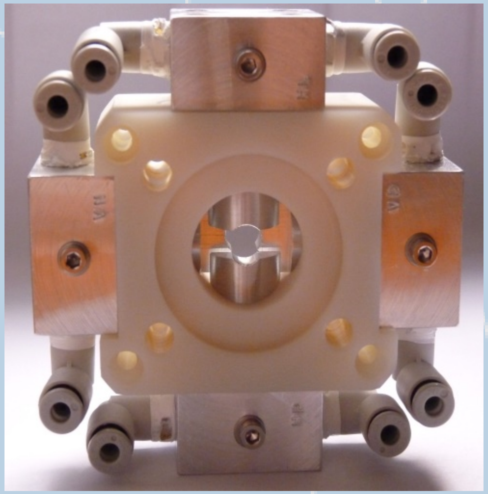
❑ Beam diagnostics - new beam current integrator

- accurate monitoring of the beam current and charge of the beam (key parameters esp. for measurement of excitation functions)
- range of the beam current measurements : 10nA up to 170µA
- record of the beam current trends, PC controled



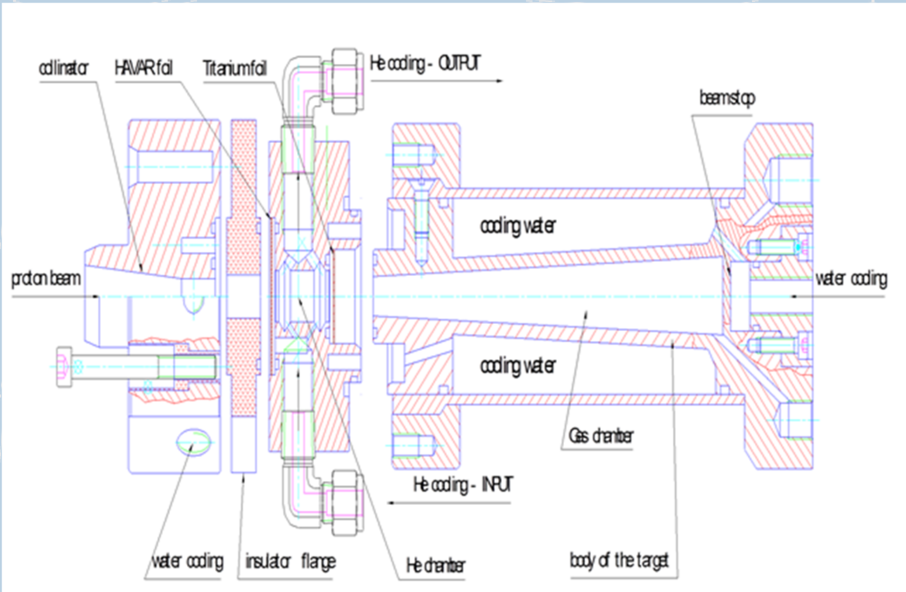
❑ beam diagnostics - universal water cooled 4-segment collimator

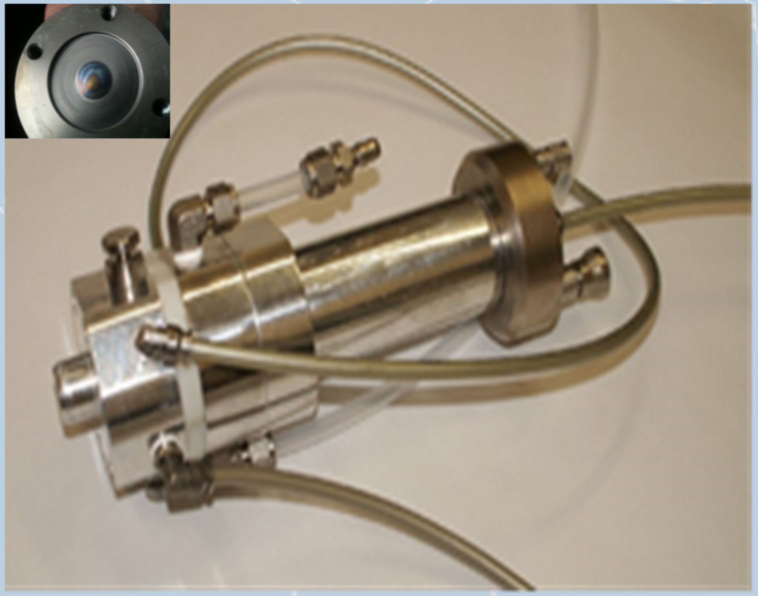
- monitoring of the beam position
- improoved beam tuning
- correction of the beam position during irradiation
- improoved reproducibility of the radionulide production yield



❑ new gas target system for ^{83}Rb production

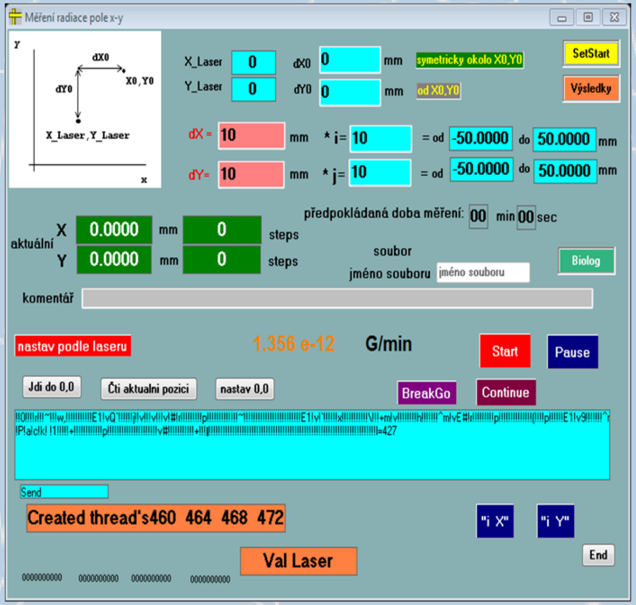
- short-lived isomer ^{83m}Kr ($T_{½}$ = 1.83 h) formed by decay of ^{83}Rb ($T_{½}$ = 86.2 d) is an ideal calibration source in low-energy experiments i.e. KATRIN or XENON
- water cooled aluminium (alloy EN 6082) mechanical interface for easy connection of the target to the beam line
- holder of He-cooled foils (vacuum separation foil – Havar 0.025 mm, target window – Ti 0.1 mm)
- aluminium (alloy EN 6082) water cooled target body with 150mm long cone-shaped target chamber of the volume 27.1 ml
- nickel-coated internal surface of the chamber
- regular ^{83}Rb production, six-hour irradiation with 15 µA proton beam resulted repeatedly in ca 300 MBq of ^{83}Rb (EOB)

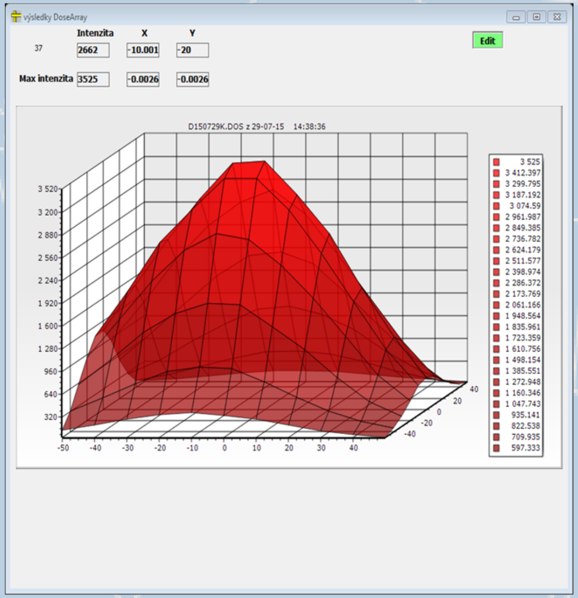


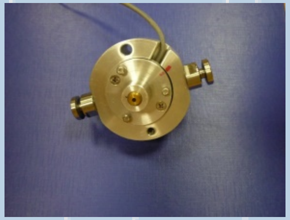


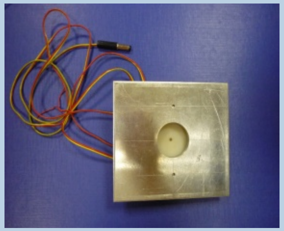
❑ X–Y axis movable system for a beam profile determination

- scanned area: horizontal X-axis (-140mm, +200mm), vertical Y-axis (-370mm, +200mm), two stepping motors, maximum load: ~ 0,7 kg
- minimal horizontal and vertical step: 0,002646 mm, Vx velocity: 7,8mm/s, Vy velocity: 3,12mm/s
- inbuilt laser + photodiod for system setting
- neutron and gamma shielding of electronics
- ionization chamber UNIDOS for beam profile scanning
- PC controlled



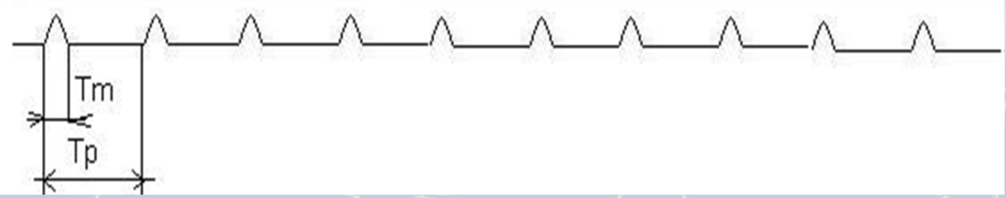


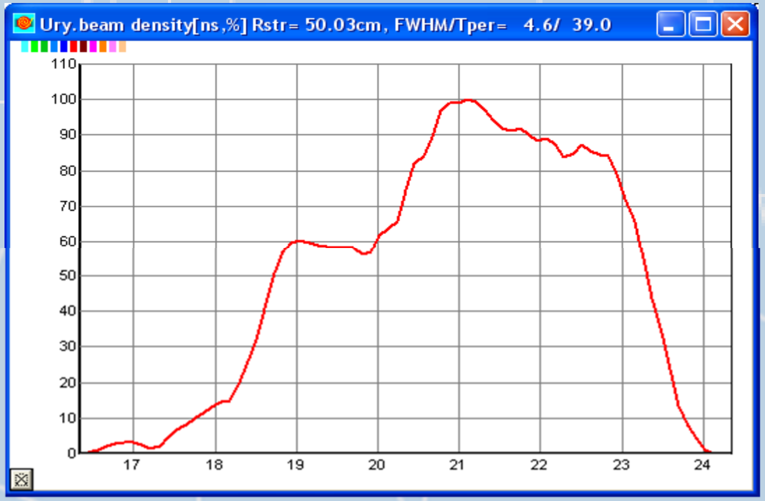




PHYSICAL DESIGN OF THE INTERNAL BEAM CHOPPING SYSTEM ON THE CYCLOTRON U-120M FOR NEUTRON TOF MEASUREMENT

Time structure of the beam:





Ep ~ 36MeV - extracted proton beam energy

fo = 25.672 MHz - RF frequency

Tp = 38.95ns - bunches repetition period

Tm - width of beam bunches:
fwhm ~ 4.6 ns
at 10% of maximum ~ 6 ns

Tm/Tp ratio ~ 1 : 6.5

Requirement:

Tm/Tp ratio ~ 1 : 100

Principle of multi-orbital beam extraction

- the internal deflection system – Karlsruhe Isochronous cyclotron *)

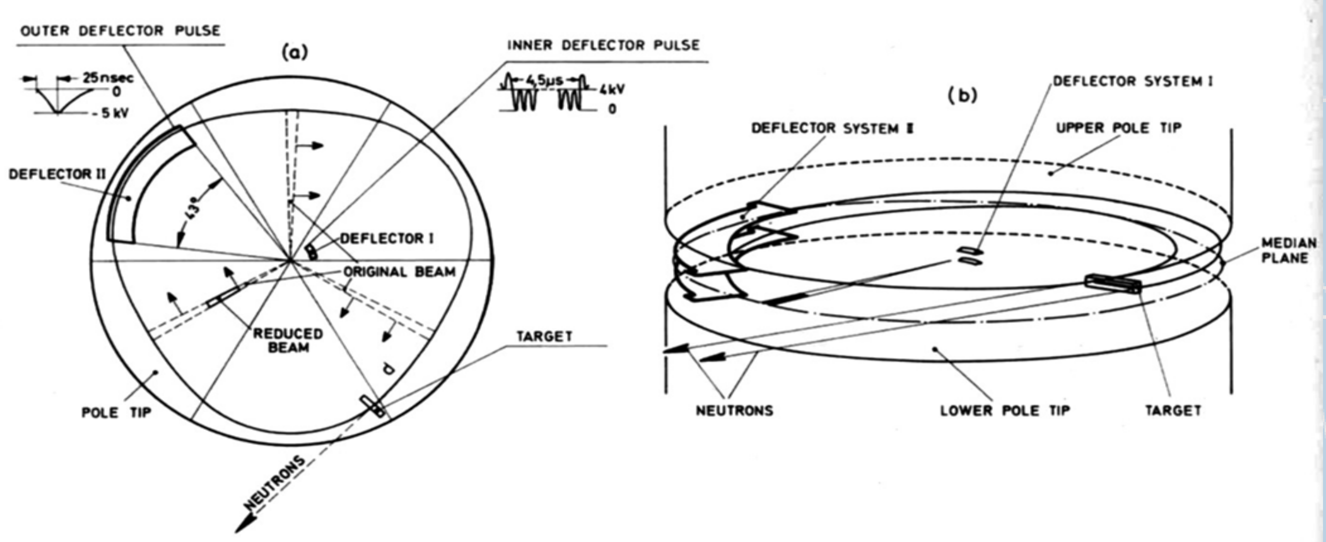


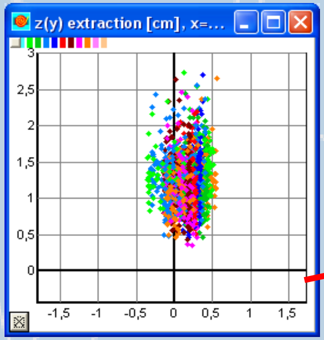
FIG. 1. Scheme of the bunching deflection system. (a) Top view. (b) Schematic drawing.

- vertical deflection of beam orbits at the interval of radii elevated by a high voltage pulse to the internal target
- number of orbits is determined by the geometry and dimensions of the deflector II
- the neutron production target positioned above the median accelerating plane

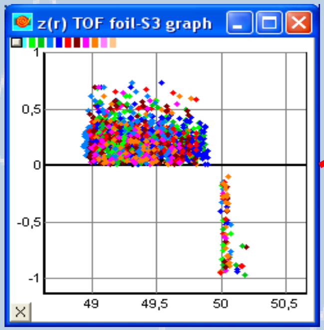
*) The Review of Scientific Instruments, Volume 39, No 9, 1279-1288 (1968)

Layout of multi-orbital beam extraction at U-120M

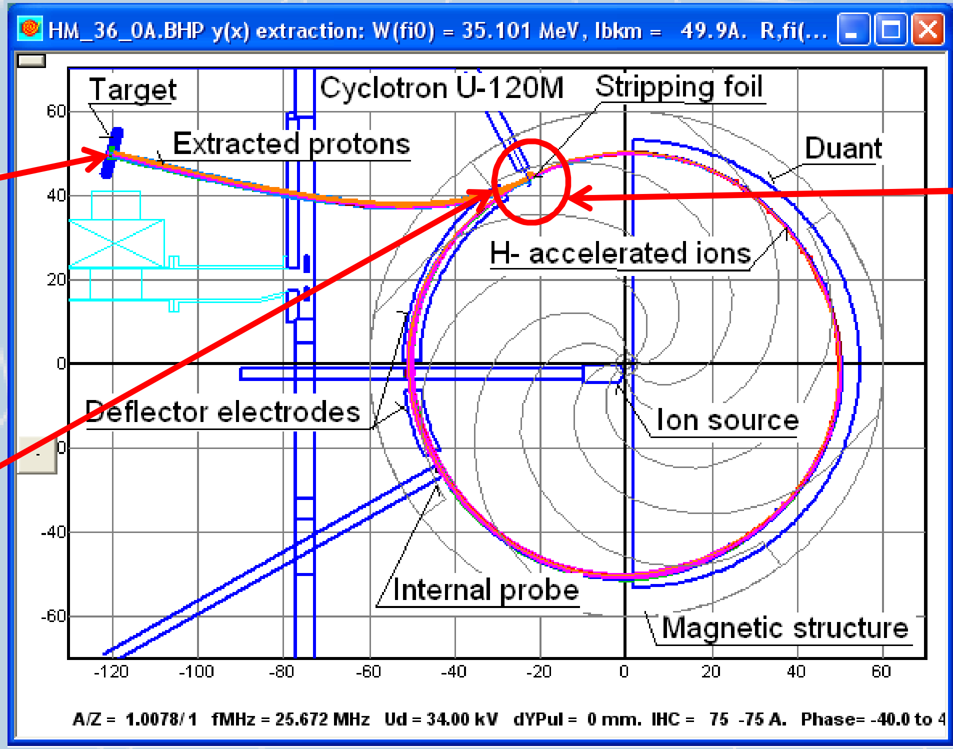
- acceleration of H^- ions
- deflection of the beam orbits in the deflector region (~ 10mm) by means of the deflection electrodes supplied with the HV pulse
- extraction of the proton pulse by the carbon stripping foil ($H^- \longrightarrow p$)
- neutron production target positioned outside of the vacuum chamber

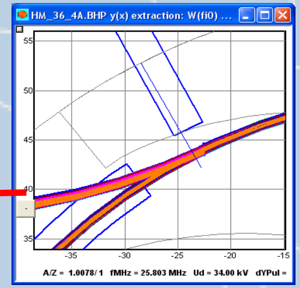


Extracted ions



Deflected ions on the stripper



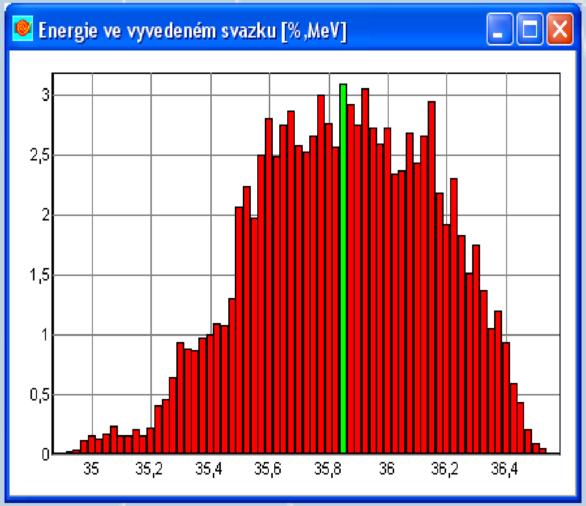


Advantages:

- higher extracted proton beam energy ~ 36 MeV
- multi-orbital accelerated ion beam extraction i.e. increase of the number of extracted ions
- reasonable requirements for the pulse power supply:
  voltage ~10kV, rising resp. falling time ~ 12ns
- up to 100% extraction efficiency (minimum heat load)
- minimal production of parazitic neutrons between extracted beam bunches

Disadvantages:

- extracted bunch width ~ 6 nsec
- extracted beam energy spread ~ 2 %



REVIEW OF MAJOR RESEARCH TOPICS ON THE U-120M

Accelerated beams were provided for the following research and applications:

- Measurements of S-factors for reactions important in nuclear astrophysics by indirect methods (particularly with worldwide rarely accessible beam of $^{3}He^{2+}$) and study of reaction mechanisms.
- Nuclear reaction data measurements (excitation functions and thick target yields of deuteron-induced reactions on ^{93}Nb, Fe isotopes, ^{89}Zr, ^{27}Al, ^{nat}Ti)
- Production of novel medical cyclotron radionuclides (^{61}Cu, ^{64}Cu, ^{99m}Tc, ^{124}I, ^{52}Mn, ^{197}Hg) and calibration sources and tracers (^{56}Co, ^{83}Rb, ^{90}Nb).
- Material modifications with accelerated ion beams (i.e. production of fluorescent nanodiamonds).
- Irradiations of biological samples.
- Electronic device and component (integrated circuits, memories etc.) testing, i.e. radiation hardness measurement under specific irradiation conditions
- In connection with target stations developed at the FNG, the cyclotron is a unique and powerful source of highly intense fast neutron beams.

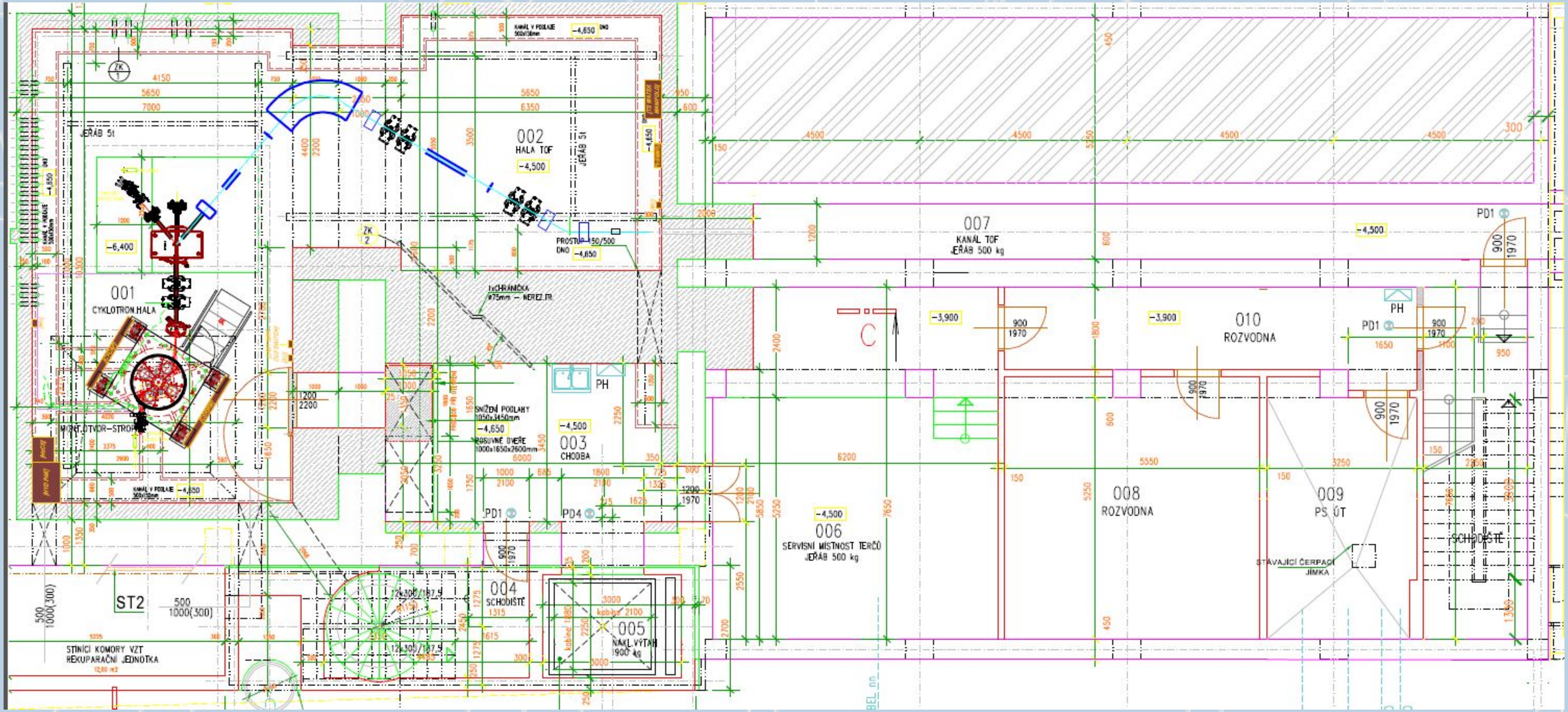
PROJECT OF THE NEW CYCLOTRON TR 24 (2013–2015)

- Selected employees of the LC actively participated in the preparation and implementation of the project – role of the general contractor.

- All required documentation and data necessary for tenders and reconstruction of the building, for installation of the new cyclotron were elaborated, e.g.:

- the contract with cycloron supplier Advanced Cyclotron System Inc. (ACSI), Canada
- design of a heavy concrete shielding of the cyclotron vault including hall for neutron Time Of Flight (TOF) and shielding doors to the cyclotron vault
- demolition work, construction of a new building from steel skeleton
- project of new building disposition, electrical scheme project, lighting design, project of HVAC and cooling of all technological subsystems
- shipment, transfer and installation of the cyclotron to the vault
- supervision of all subcontractors work during the project implementation
- elaboration and successfull approval of all required documentation for the State Office for Nuclear Safety.

TR 24 LAYOUT



001
CYKLOTRON HALA
002
HALA TOF
003
CHODBA
004
SCHODIŠTĚ
005
NAKL.VÝTAH
1900 kg
006
SERVISNÍ MÍSTNOST TERČŮ
JEŘÁB 500 kg
007
KANÁL TOF
JEŘÁB 500 kg
008
ROZVODNA
009
PS ÚT
010
ROZVODNA
ST2
STÍNÍCÍ KOMORY VZT
REKUPARAČNÍ JEDNOTKA
SCHODIŠTĚ
STÁVAJÍCÍ ČERPACÍ
JÍMKA

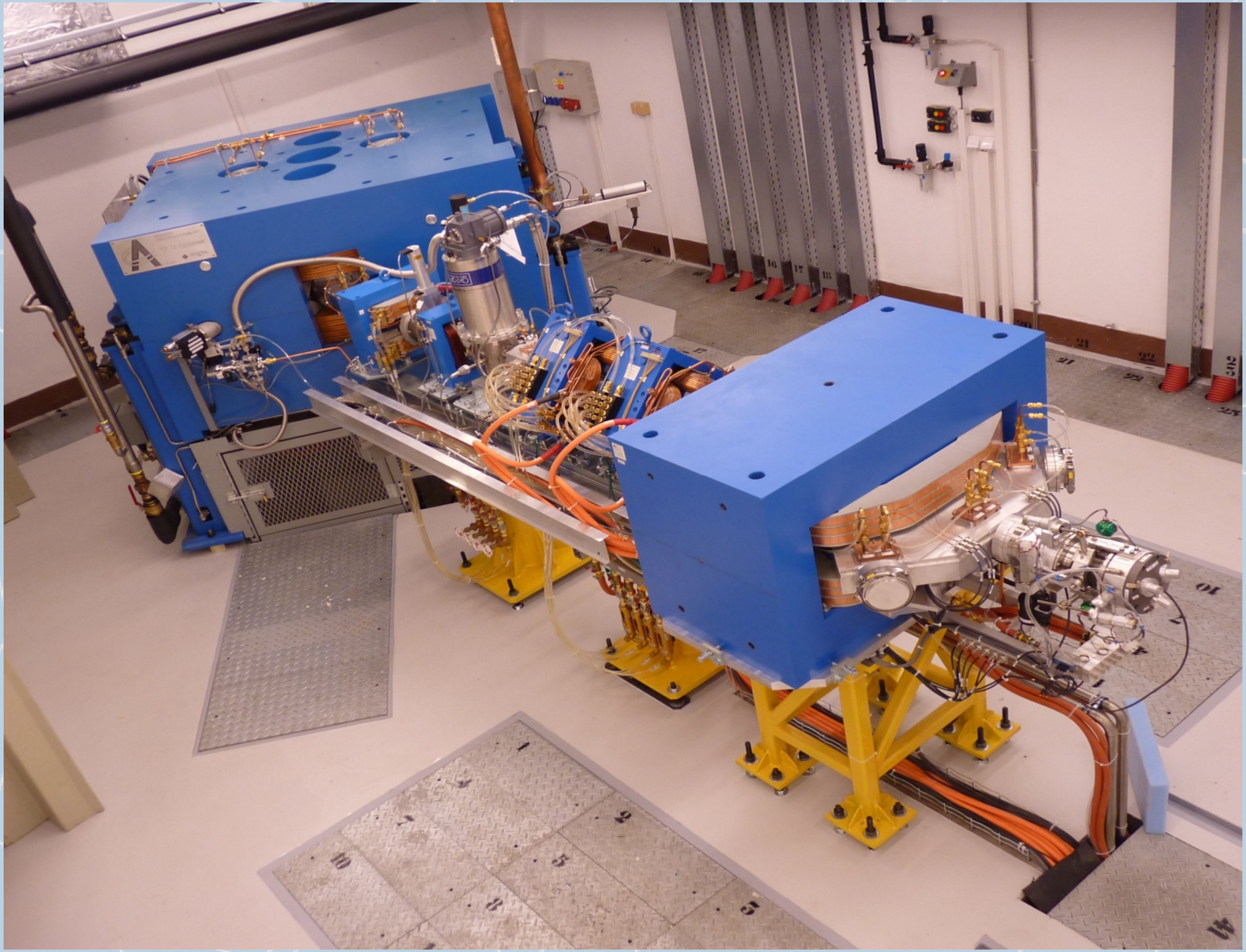
CONSTRUCTION OF THE SITE

TR 24 INSTALLATION
September 2014

BASIC PARAMETERS OF THE TR 24 CYCLOTRON

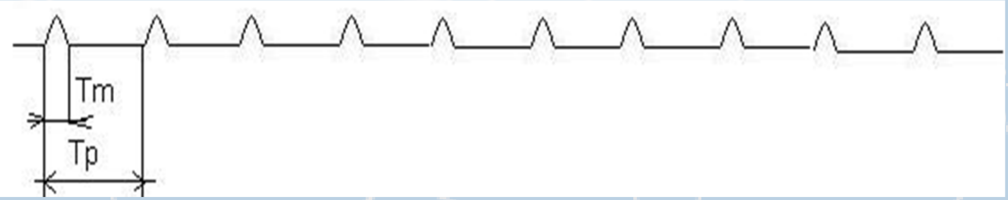
TR 24 – Advanced Cyclotron System Inc. (Canada)	
Proton energy range	18–24 MeV
Max. proton beam current	300 μA
Acceleration frequency	85 MHz
Acceleration voltage	50 kV
H^{-} Ion source	Multi-CUSP
Simultaneous beams	2
Weight	25 t
Dimensions	1.8×1.8×2.5 m
Power	180 kW
Middle magnetic field	1.4 T

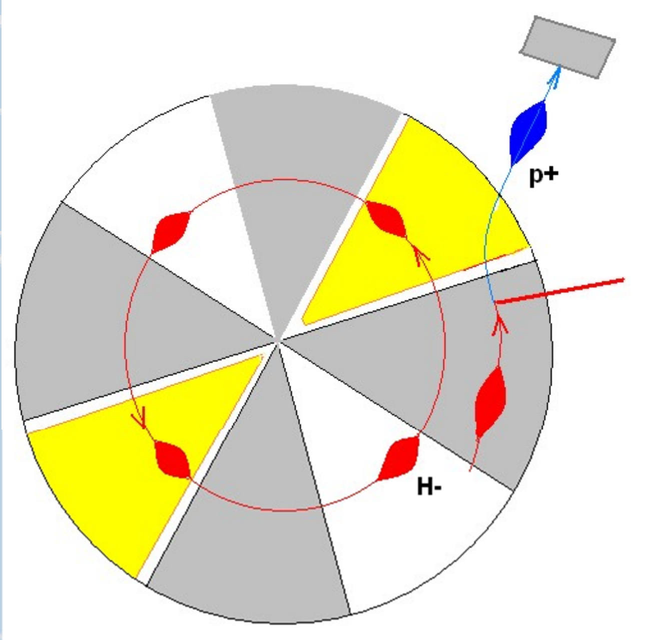
TR 24 COMMISSIONING – October 2015



PHYSICAL DESIGN OF THE BEAM CHOPPING SYSTEM ON THE CYCLOTRON TR 24 FOR NEUTRON TOF MEASUREMENT

Time structure of the beam:





E_p = 24 MeV - extracted proton beam energy

f_{dees} = 84.75 MHz – 4. harmonic
f_{revol} = 21.19 MHz

Tp = 11.8 ns - bunches repetition period

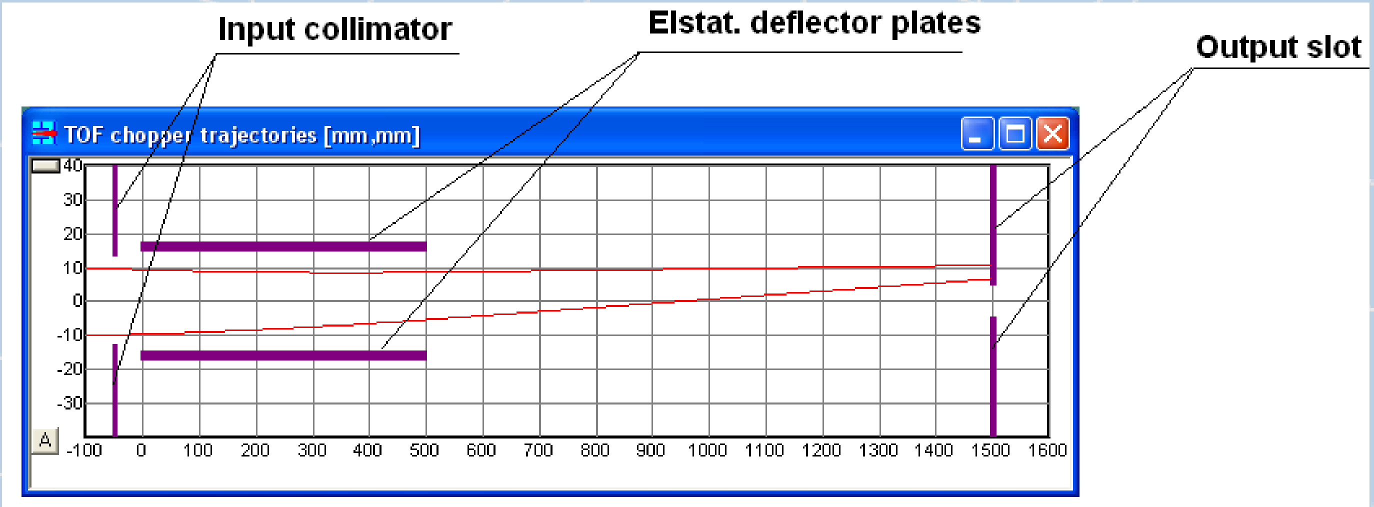
Tm - width of beam bunches:
fwhm ~ 2.3 ns

Tm/Tp ratio ~ 1 : 5.13

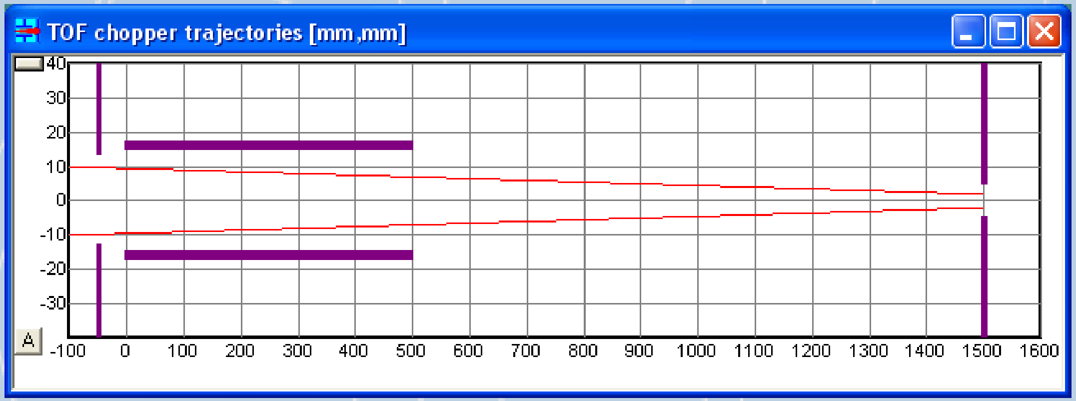
Requirement:

Tm/Tp ratio ~ 1 : 100

Chopping of the extracted beam using the electrostatic deflector

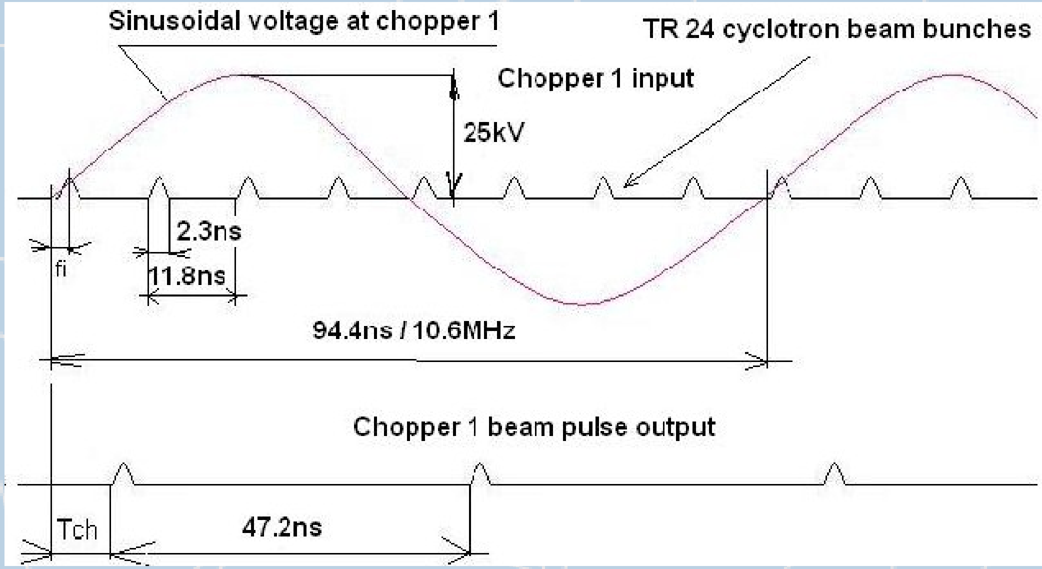


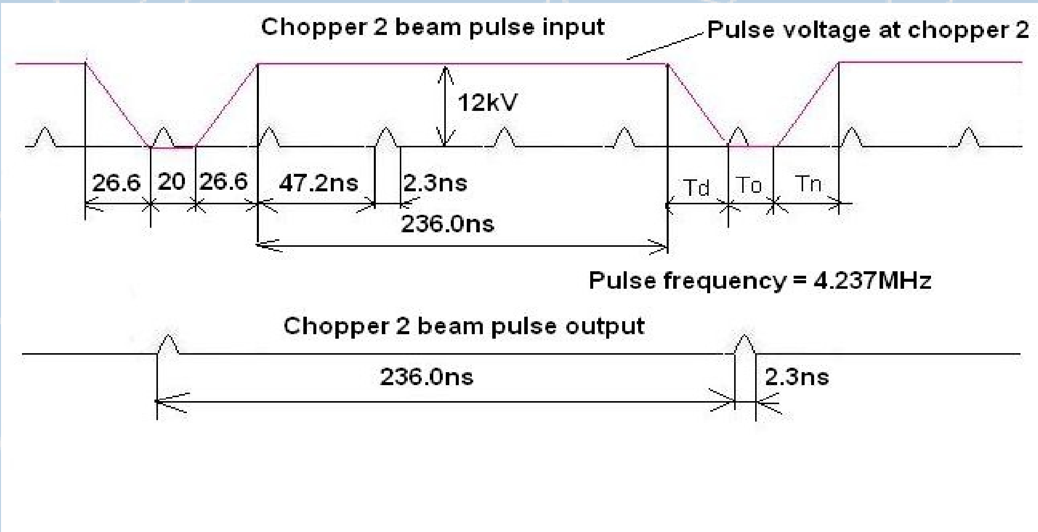
Proton trajectories deflected by the electric field



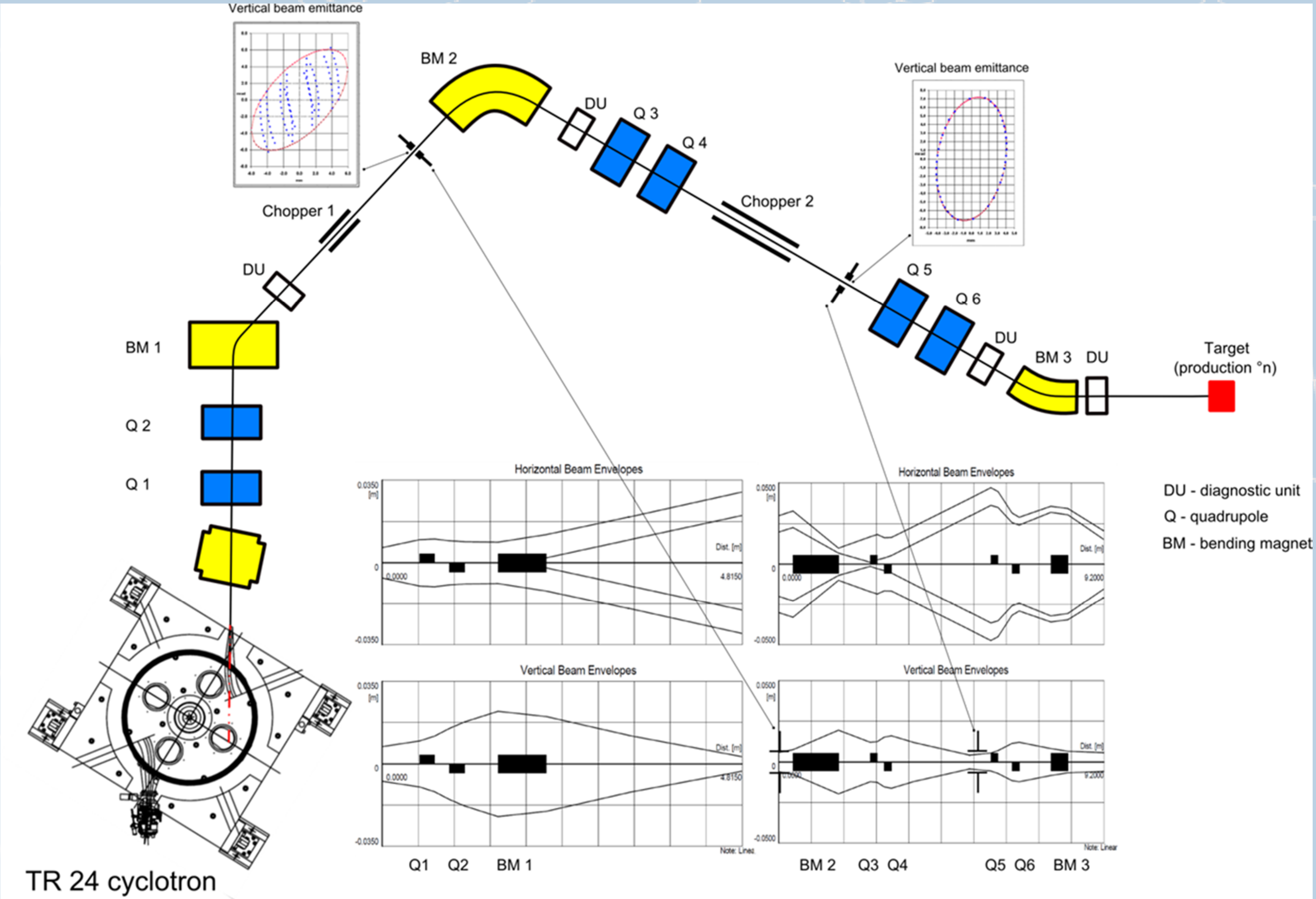
Proton trajectories at zero voltage of the electric field

Principle of selected beam bunch separation at TR 24





TOF system on the TR 24



Advantages:

- output bunch width 2.3 ns (bunch period 236 ns)
- high beam current intensities at the cyclotron TR 24 up to 300 uA

Disadvantages:

- two stage system: high power consuming system, high-voltage high-frequency sinusoidal (25kV) and nanosecond pulse (12kV) power supplies are necessary
- high beam power losses at chopper output slits
- high parazitic neutron generation between selected bunches
- low beam transmission efficiency ~ 3%

RESEARCH PROGRAM

- Experiments and research projects associated with the generation of high fluxes of fast neutrons:
  - measurements of observable cross sections induced by fast neutron irradiations
  - nuclear data for new fusion-fission and advanced fission systems

- Production of novel medical radionuclides and new ways of production of established radionuclides, including casual production of tracers and calibration sources, e.g.
  - longer-lived radionuclides e.g. ^{44}Ti, ^{67}Cu, ^{89}Zr and ^{68}Ge
  - feasibility study of implementing direct production of ^{99m}Tc via (p,2n) reaction as an viable alternative to reactor-produced generator ^{99}Mo/^{99m}Tc.

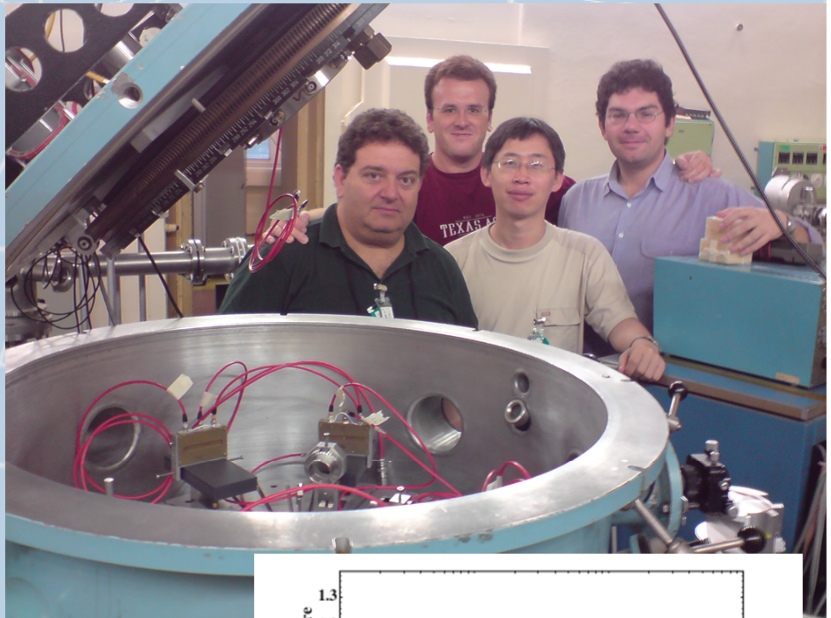
FUTURE UPGRADE OF THE TR 24 INFRASTRUCTURE

- The design and implementation of a new ion beam line with external chopping system that allows to change and program the time structure of the extracted beam for TOF measurements.
- In cooperation with FNG group development high-power neutron targets.
- Development or purchase the high-power targets for production of novel research radionuclides and generators.

Indirect methods in nuclear astrophysics in U120M

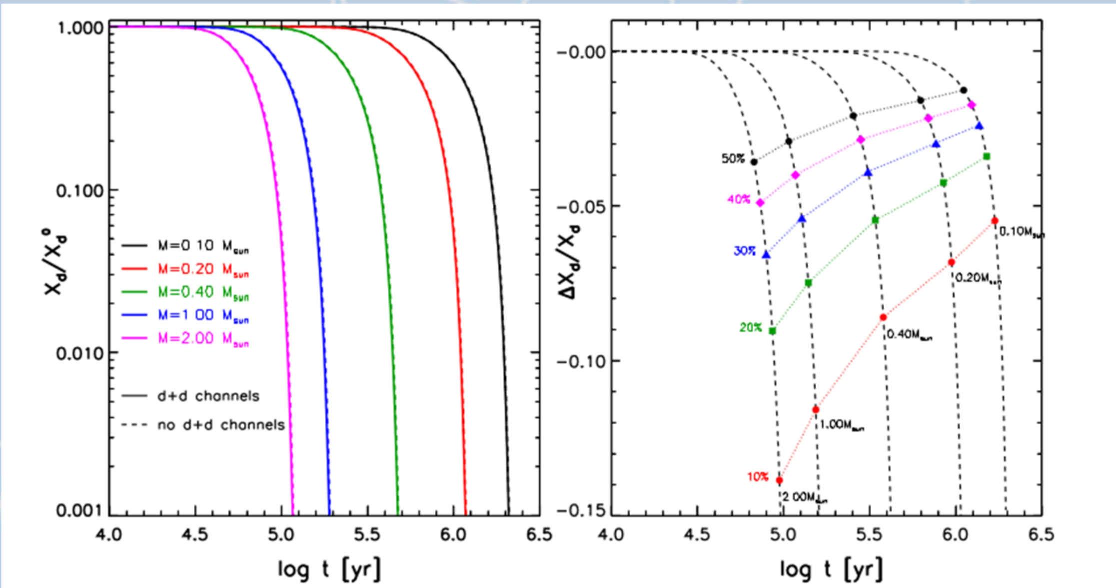
CANAM proposal no. 99

IR: Jaromír Mrázek



New determination of the 2H(d,p)3H and 2H(d,n) 3He reaction rates at astrophysical energies:

- Trojan Horse Method – indirect method was used with 3He as a “Trojan horse”
- Collaboration with group of prof. Spitaleri – CATANIA, INFN LNS
- Fusion reactions d(d,p)t and d(d,n)3He from 1.5 MeV down to 2 keV
- Reaction rates change by up to 15% in SBBN region and up to 20% in temperatures relevant to PMS stars
- Impact on production of Lithium in SBBN (~10%)
- Unscreened data allow to understand the models for plasma screening
- deuterium abundace models in PMS star cores tested for impact of the newly measured channels



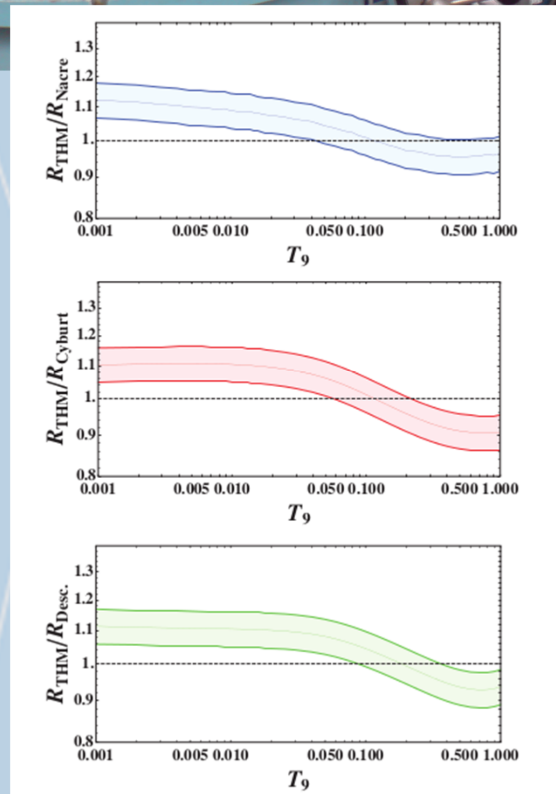
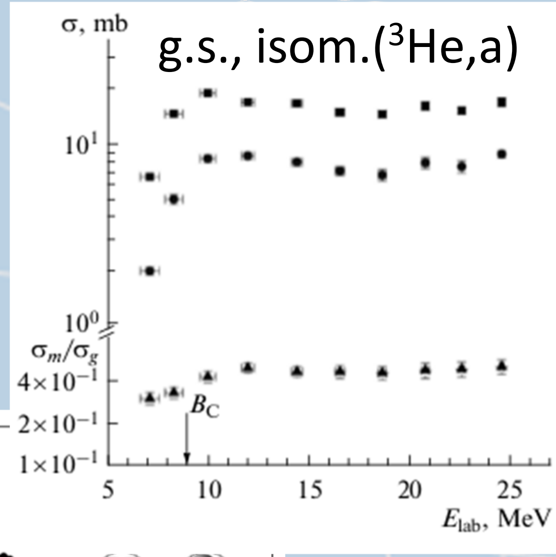


Figure 22. Rate ratios for the $^2H(d,n)^3He$: blue line = THM-NACRE

Journal of Physics: Conference Series 337 (2012) 012017, The Astrophysical Journal 785 (2014)

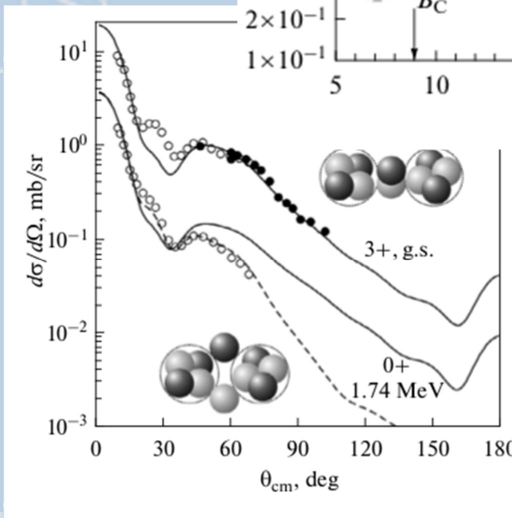
Reactions mechanisms near Coulomb barrier and in cluster transfer

CANAM proposal no. 58, 168



Reaction mechanisms close to Coulomb barrier :

- 45Sc+3He reactions measured – reaction x-section peaking at energies close to Coulomb barrier when formation of **alpha particle**
- 3He + 194Pt (80%) and 197Au reactions studied – similar first observations, similar findings
- Complementary measurements deuterons (Rez) and 6He (in Dubna) show differences at Coulomb barrier energies – Z dependencett

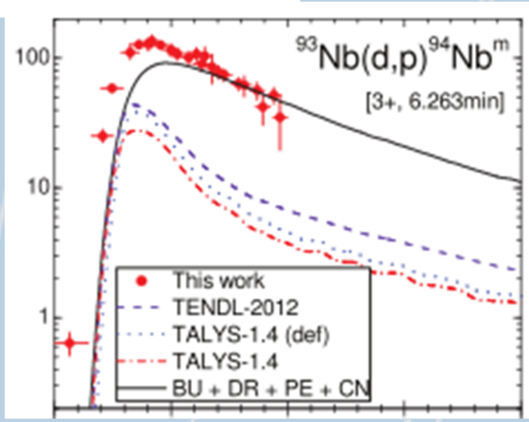


Isobar analog states in 10B and 10Be studied:

- OP parameters trends points to more compact configurations of 10Be (2 alpha)
- Isobar analog states in 10B and 10Be suggest different cluster structures
- Cluster (triton/3He) transfer from 9Be was observed suggesting its cluster structure

Study of deuteron activation of 93Nb and Fe isotopes :

- Deuteron activation of materials in future accelerators and targets
- Complete description of excitation function – direct r., breakup, PE, CN
- Comparison to TALYS and TENDL-2012 libraries



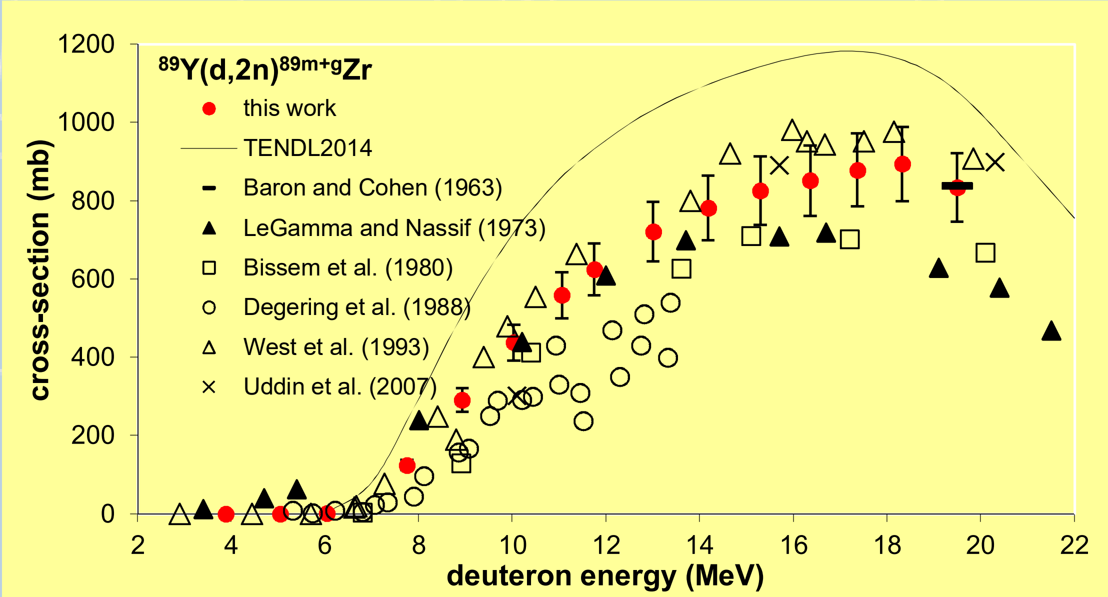
Physics of Particles and Nuclei Letters, 2014, Vol. 11, No. 2, pp. 114
Physics of Particles and Nuclei Letters, 2013, Vol. 10, No. 5, pp. 410
Phys.Rev.C 88, 014612 (2013), Phys.Rev. C 89, 044613 (2014),
Phys. of Part. and Nuc.Lett, 2015, Vol. 12, No. 5, pp. 703

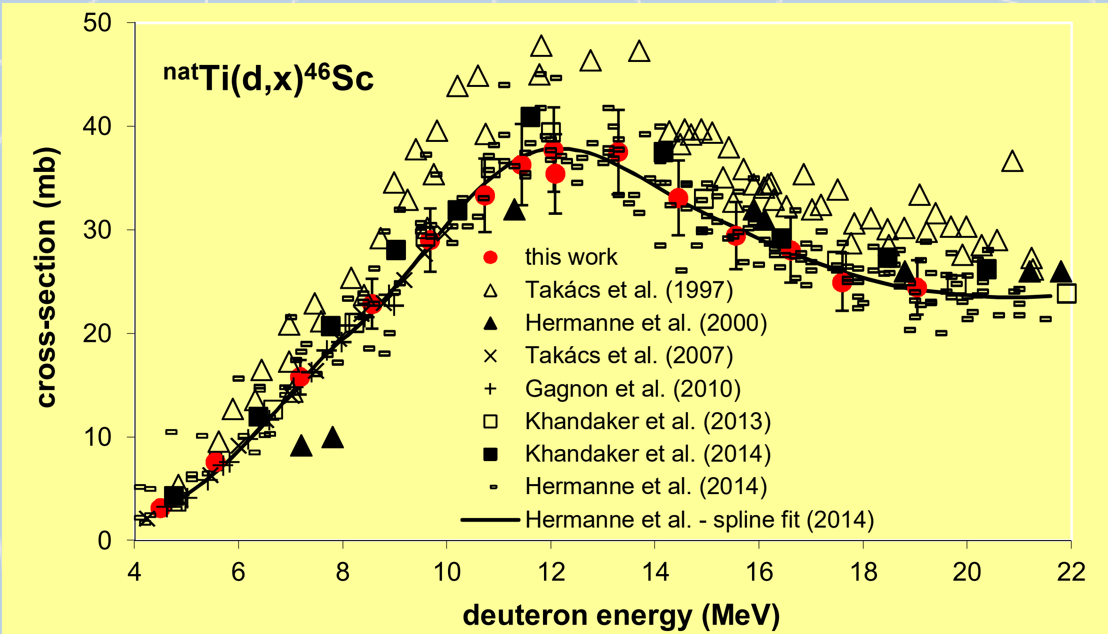
Excitation functions of Deuteron-induced reactions on ^{89}Y in the energy range 3–20 MeV

CANAM proposal no. 64

O. Lebeda, J. Štursa, J. Ráliš

The aim was the systematic re-measurement of the cross-sections for formation of all measurable radionuclides in deuteron-induced reactions on ^{89}Y up to 20 MeV. Besides that, we also compared ^{27}Al and ^{nat}Ti monitors and came to a conclusion that recommended cross-sections for ^{24}Na are probably systematically shifted. The results are relevant for production of ^{89}Zr, a novel positron emitter for PET, and the data allowed to deduce both the yield and achievable radionuclidic purity.
We also confirmed fitted data for a recently recommended new monitoring reaction ^{nat}Ti(d,x)^{46}Sc.





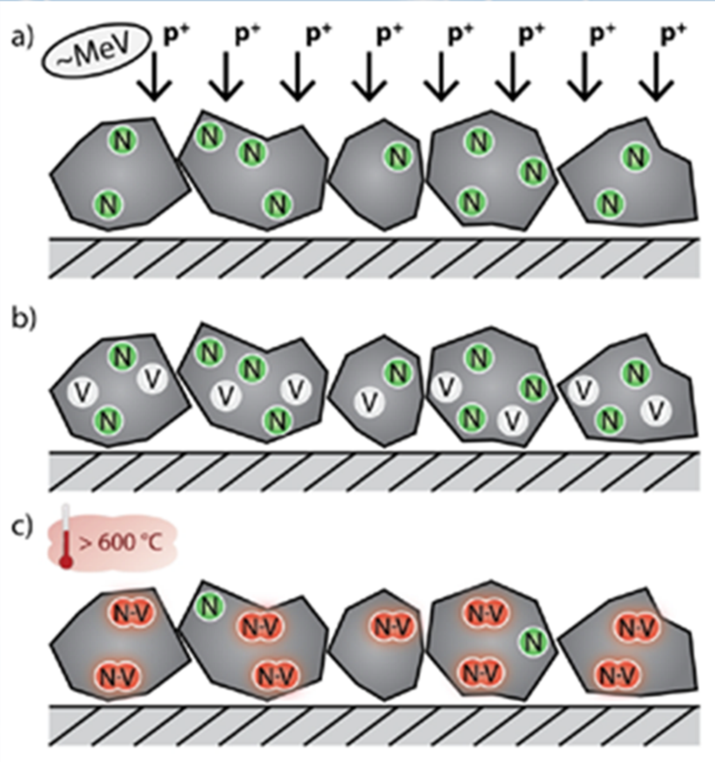
O. Lebeda et al.: Nucl. Inst. Methods Phys. Res. B 360, pp. 118–128, 2015.

Preparation of fluorescent nanodiamonds (FNDs)

CANAM proposal no. 152

Nanodiamond: biocompatible carbon nanomaterial (Ib HPHT), powder or aqueous solution, variable size ranging from ~ 5 to 100 nm

Creation of NV centers:

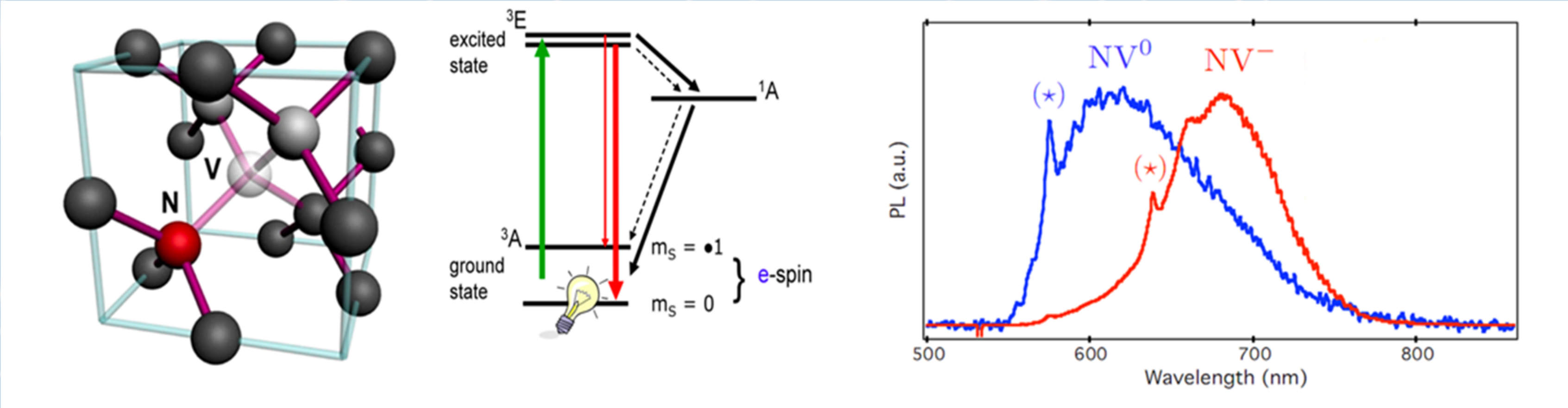


irradiation with accelerated ions (H^+, D^+, a), energies 6–30 MeV (depending on used particle, type of target)

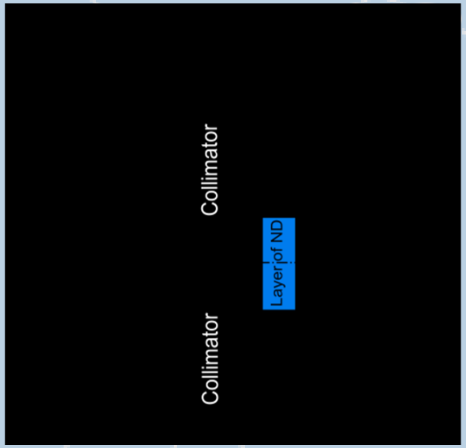
vacancies created by irradiation

formation of NV centers by high temperature annealing ~ 900 °C

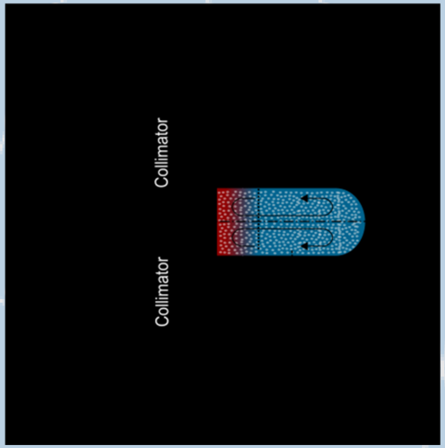
Photoluminiscence centers NV^0, NV^-

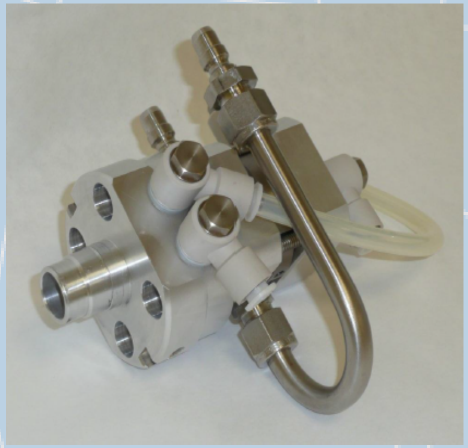


Proton irradiation of a compressed solid ND pellet



Proton irradiation of 5% ND aqueous solution





Bioimaging, biolabeling, substitution of quantum dots, single particle tracking, nanoscale magnetic field sensing etc.

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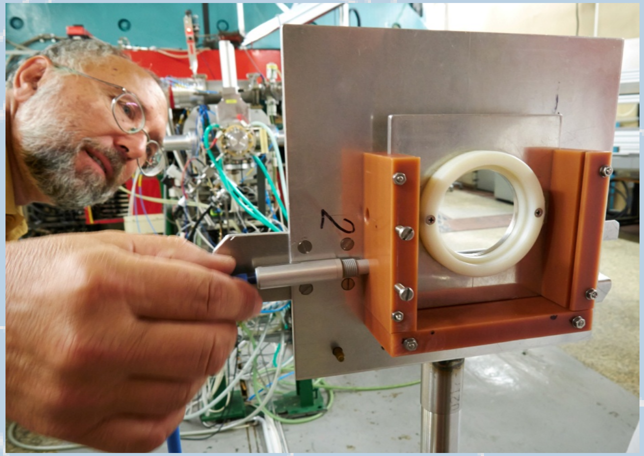
BIOLOGICAL EFFECTS OF IONIZING RADIATION

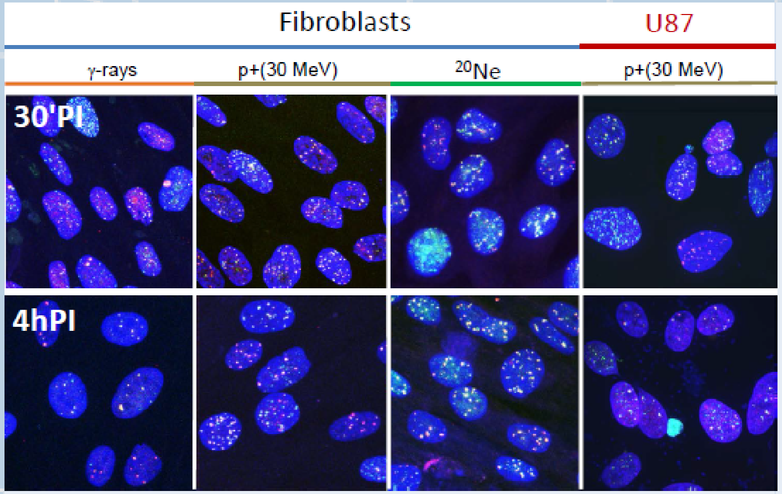
CANAM proposal no. 129

Marie Davídková et al.



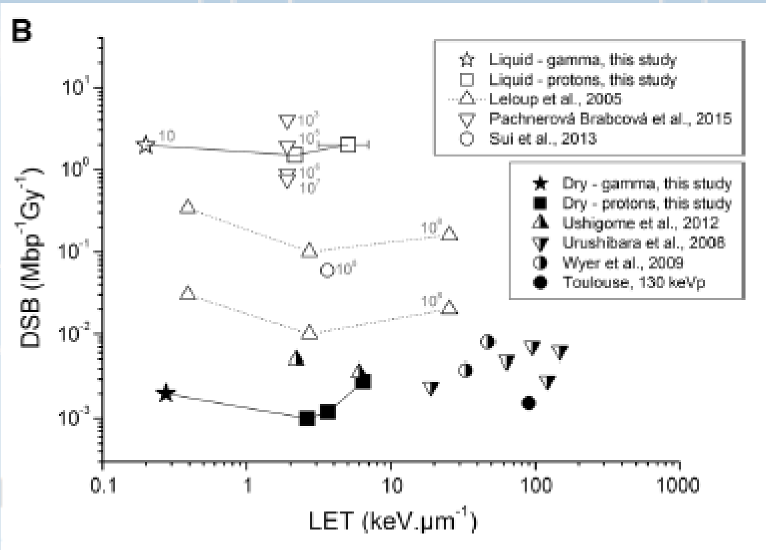
Radiation damage at molecular level:
Direct and indirect damage to DNA (DNA plasmids irradiated in dry layers or water solutions - SSB, DSB, oxidized bases, complex damages)

- Radiation damage to lipids
- Activity changes of restriction enzymes (EndoIII, PvuII))



Cell radiobiology:

Response of cell cultures to radiation (normal human skin fibroblasts, U87 glioblastoma, stem cells): survival, apoptosis, DNA damage repair, micronuclei formation, oxidative stress



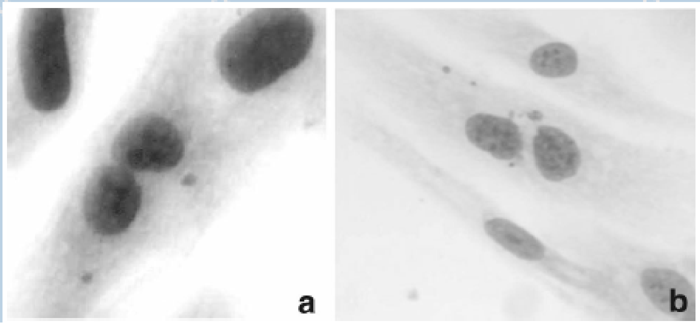
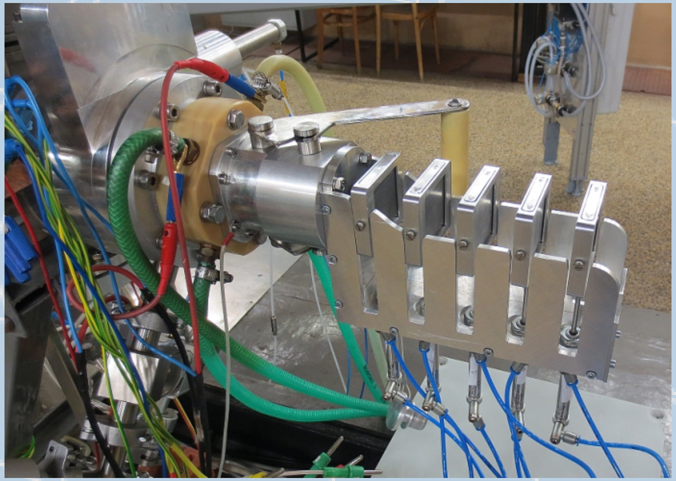


Fig. 1 Examples of micronuclei formation in human neonatal fibroblasts at first division after irradiation by 3 Gy using a Co-60 gamma rays, b scanning pristine 30-MeV proton beam

Cyclotron and URHIC groups within framework of CANAM

CANAM proposal no. 60



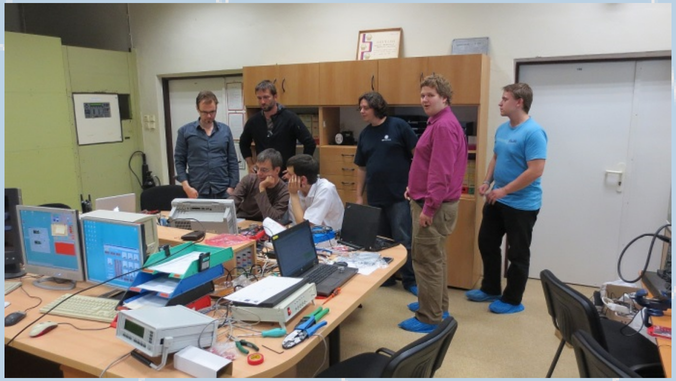
Radiation hardness of components placed in vicinity of intensive CERN LHC beams = crucial aspect for the design of detectors.

Common effort to improve the infrastructure for irradiations:

- 2 micrometric movable systems with beam profile determination.
- PC controlled pneumatic energy degrader/beam stopper.

Dosimetry techniques includes:

- Ionization chamber with PTW UNIDOS system.
- Silicon hybrid TimePix detector.
- Scintillator PMT counter.
- Activation foils with subsequent gamma analysis (HPGe & Si(Li))



Some of the activities:

- Search for commercial grade radiation hard FPGA for ALICE Inner Tracker System (ITS) upgrade
- Selection of radiation hard fast signal cables for ITS
- Single Upset Event cross section measurements for different SRAM types in 180 nm technology
- Electronics for recently installed ALICE TPC readout upgrade

Results presented in regular meetings of different working groups in CERN, international conferences and entered Technical Design Report.

Center of Accelerators
and Nuclear Analytical Methods
(CANAM)

Thank you for your attention.

Presented by Jan Štursa
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