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TANDETRON LABORATORY

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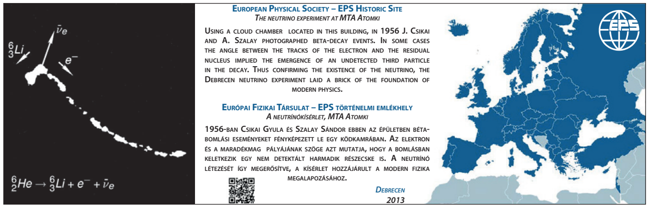
INVESTING IN YOUR FUTURE

MTA ATOMKI

MTA Atomki, the Institute for Nuclear Research is one of the 15 members of the research network operated by the Hungarian Academy of Sciences.

Researchers at MTA Atomki have never believed in borders between scientific fields; in the 65 years of the history of the Institute, the interdisciplinary approach has always been strong, and proved to be successful as well.

In the early years, as an example, the investigation of nuclear decay led to an indirect proof of the existence of the neutrino. Recently, this achievement was the basis for an award from the European Physical Society (EPS), which designated MTA Atomki as one of the Historic Sites in Europe.



More recently, a nuclear physical experiment revealed an anomaly that can be interpreted as a sign for possible existence of a bosonic particle, which, according to some theorists, may play a role in explaining the presence of dark matter in the Universe.

Today, we continue our scientific research in the same direction. Our laboratories and teams, though independent, can combine to solve problems effectively. These efforts are marked by grants, from the ERC to EUROCORES, or from RADIATE to IPERION CH, just to mention a few.

Modern science is without borders, and so is Atomki, with its hundreds of collaborations from all over the world.

Atomki researchers are among the thousands who have been hunting for the Higgs boson at CERN, and Atomki with its small-scale Accelerator Centre also hosts researchers supported by the European Transnational Access scheme.

MTA Atomki laboratories are open-access, and we are always seeking collaborators to join our efforts and/or open up new directions.

Although we have tried to cover most of the scientific fields of interest to us, science evolves rapidly. For the latest news and results from MTA Atomki, please visit:

www.atomki.mta.hu

FOREWORD

THE ACCELERATOR CENTRE

The Atomki Accelerator Centre incorporates several low-energy charged-particle accelerators, which offer the possibility of choosing ions with various charge states, energies and beam intensities.

The *Accelerator Centre* has been established as a unit separate from the traditional departmental structure of the institute.

Previously the accelerators and the staff responsible for them belonged to different departments of the institute. However, it was found that joining the accelerators in a single administrative unit would have several advantages.

Organizing and distributing beam time, for example, can be carried out in a more optimal way. The operating staff (approx. 20 engineers and technicians) can be assigned to any accelerator, depending on the work load.

Since the inauguration of the Centre, each accelerator has been operating safely, according to the schedule and without any major technical faults. In 2010 the nationwide NEKIFUT program (National Research Infrastructure Survey and Roadmap) assigned the Centre the title of Strategic Research Infrastructure.

Since in Hungary the majority of research-oriented accelerators is based in Atomki, the Accelerator Centre of the institute effectively became the national accelerator centre.

The following accelerators belong to the Centre: **VdG-5** (5 MV Van de Graaff), **VdG-1** (1 MV Van de Graaff), **ECR ion source, Tandetron, Cyclotron.**

THE ACCELERATOR CENTRE

THE TANDETRON LABORATORY

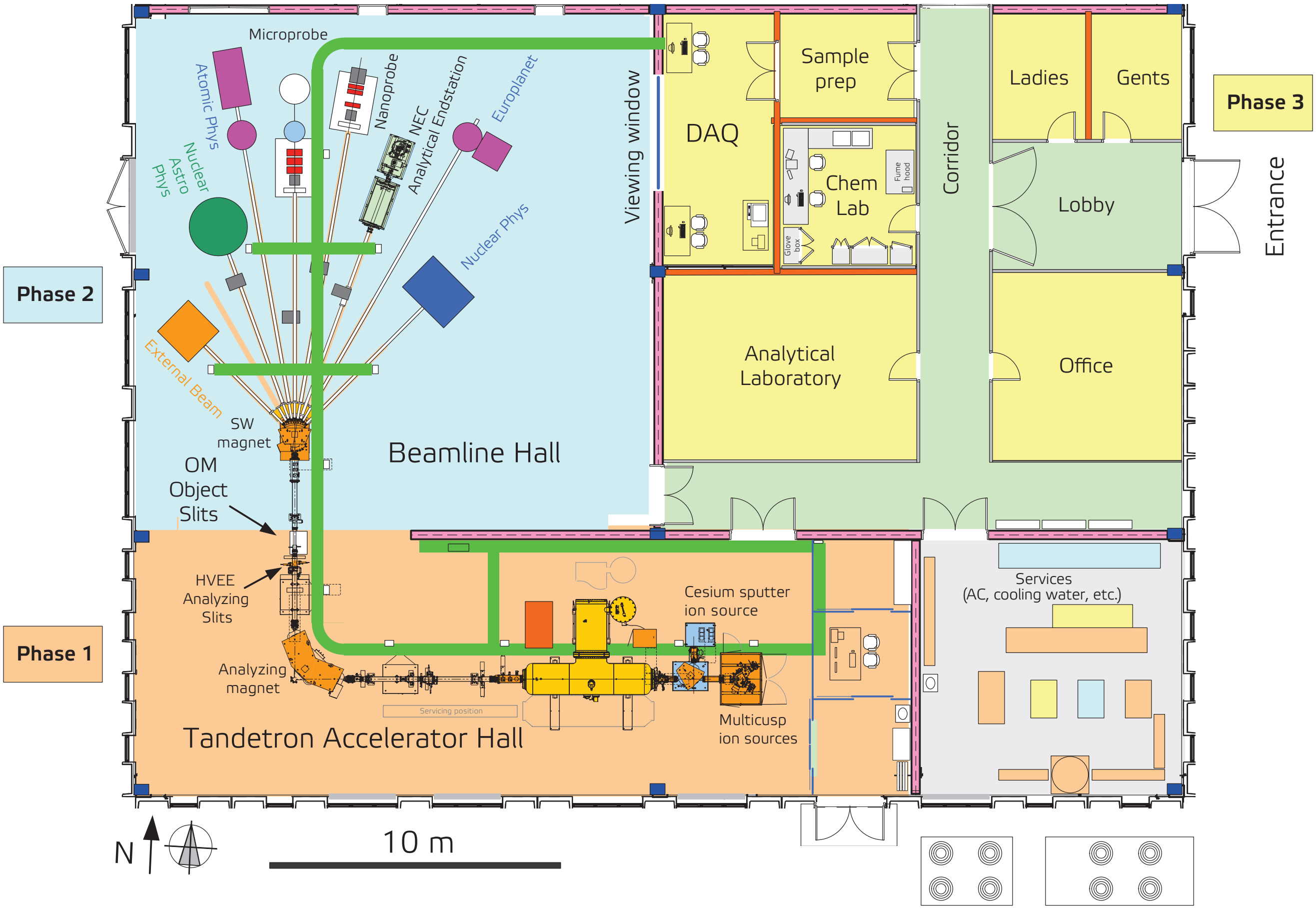
The development of the Tandetron Laboratory has been divided into three phases.

Phase 1 was financed by the Infrastructural Projects administered by the Hungarian Academy of Sciences, and has been completed in 2015. After this, the laboratory was already operational, with a limited range of ions and beam lines.

Phase 2 was completed in October 2018, by using the support of an Infrastructural GINOP grant.

The facilities of the Laboratory have been extended by several new ion sources and beam lines, giving rise to a wider variety of research activity in basic and applied research.

Phase 3 encompassing various auxiliary facilities is in the planning stage in 2019.



PHASE 1

Using support from the Infrastuctural Projects of the Hungarian Academy of Sciences, the Phase 1 of the laboratory was completed in 2015. This allowed starting certain research activities in basic and applied research.

The basic equipment of the laboratory is an accelerator manufactured by High Voltage Engineering Europa B.V. The ion source attached to the accelerator generates the ions to be applied. The acceleration is carried out in a two-step procedure, in tandem mode, giving rise to the name Tandetron™.

In the first stage of acceleration, the negatively charged ions extracted from the ion source reach the end of the first domain of acceleration. Here they cross a volume filled with Argon gas, where they lose a few of their electrons and transform into positive ions. In the second stage of acceleration the positive ions utilize the same high voltage field to accelerate further until they leave the accelerator and are directed to the selected target by magnets.

In addition to installing the accelerator, Phase 1 also included deploying a duoplasmatron ion source, which produces negative Hydrogen ions, an injector magnet and a switching magnet, which can direct the ions into nine different beam channels.

The partial reconstruction of the building that houses the accelerator was also part of Phase 1.

Here special attention was paid to keeping the strict technical standards (vibration-free environment, closed-circiut cooling system, controlled temperature and humidity) prescibed by the manufacturer.

THE TANDETRON LABORATORY

The inauguration ceremony of Phase 1 took part on 1 December 2015 in the presence of László Lovász, the President of the Hungarian Academy of Sciences.

PHASE 2

The Infrastructural GINOP grant made it possible to utilize the full capacity of the Tandetron accelerator by extending the selection of ions and by installing new beamlines and detector stations.

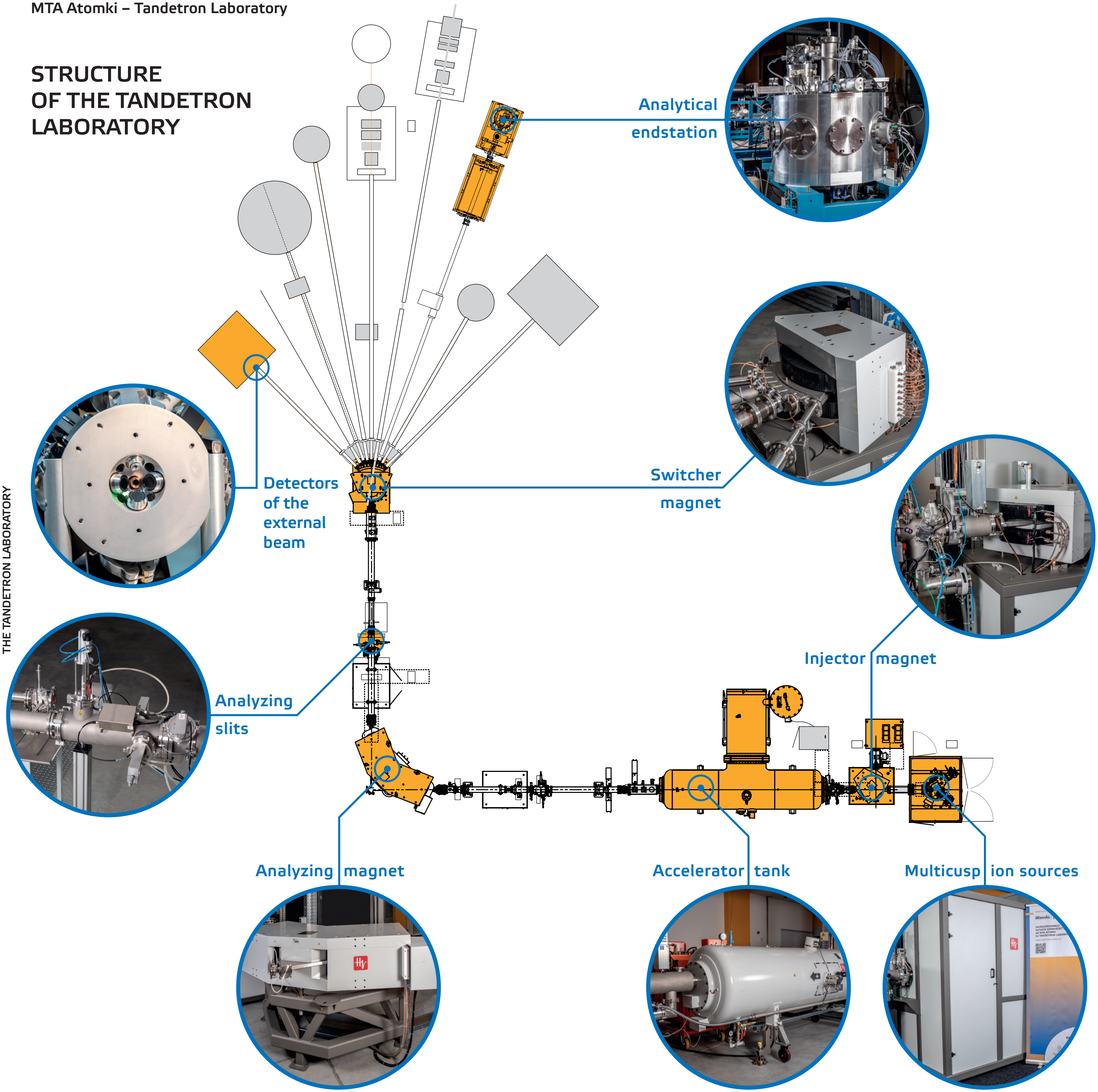
Grant No. **GINOP-2.3.3-15-2016-00005** titled *Establishing a world class research environment at the new Tandetron Laboratory of MTA Atomki,* was the first Infrastructural GINOP (Economic Development and Innovation Operational Program) project won by Atomki. Within the framework of this project the budget of 941 million HUF (approx. 3 million EUR) was spent on Phase 2 of the Tandetron Laboratory during the 36 months commencing in June 2016.

Developments included purchasing and installing equipment, as well as upgrading the building that houses the laboratory in order to secure the prescribed technological level. Three new ion sources have been installed, owing to which the selection of ions was supplemented by Helium and heavy ions (e.g. Carbon, Oxygen, Silicon, Gold). On the high-energy end a 90 degree analyzing magnet has been deployed, as the result of which even higher levels of energy stability could be reached.

The beam lines where the prospective users can install their detector systems have also been constructed. The cost of the vacuum technological equipment necessary for this (e.g. pumps, valves, etc.) were also covered by the budget of the grant. The high-quality ion beams provided by the accelerator can be used in a wide range of research projects both in basic and applied science. The former includes, e.g., atomic physics, material science and nuclear astrophysics, while the latter range from medical to atmospheric science and archaeology.

The installation of a complex analytical endstation allowed for the application of a wide range of ion beam analytical methods. With this development, as well as with the other advancements the target set out in the grant application has been reached: the Tandetron Laboratory has been equipped with world-class instruments allowing for starting the planned research projects both in basic and applied research.

STRUCTURE OF THE TANDETRON LABORATORY



THE TANDETRON LABORATORY

SPECIFICATIONS

Building

The accelerator hall and beamline hall are large enough to install the system including the necessary auxiliary equipment. Doors and corridors are available for easy passage of the system components into the rooms, even using forklift access. The building was originally built for a purpose of a workshop, its base concrete is over 40 cm thick.

This was covered with a so called floating concrete. A 12 mm thick steel fibre reinforced smooth concrete was casted on top of 1 cm thick PE foam that provides vibration isolation. Finally the surface was levelling polished with hardener cement. The floor is level within 1 mm per meter.

The halls are equipped with air conditioning with temperature and humidity control. The temperature is kept within 20 ± 4 °C, the humidity is between 35-60 % at 20 °C. There is a filtered, freeze-dried compressed air with 7 bar of pressure.

The closed loop cooling water system provides an inlet pressure of 6 bar, and outlet pressure of 1.5 bar. The water conductivity is monitored and is below 500 µS/cm.

All these are supplied from an adjacent machinery room, which is designed to serve all phases 1, 2 and 3.

BUILDING SPECIFCATIONS

2 MV Medium-Current Plus Tandetron Accelerator System

High Voltage Engineering Europa B.V.

- Low-ripple kit
- Active stripper gas pressure control

Dual source injector system for high brightness, high intensity negative Hydrogen (Model SO120) and Helium ions (Model SO130)

- Single cabinet/stage for these two ionsources
- Energy spread: approximately 10eV
- H^+ beam current: 200eμA
- He^{2+} beam current: 40eμA
- Brightness of a 2MeV H^+ beam: 8 Amp rad^{-2} m^{-2} eV^{-1}
- Dry vacuum system: turbo and scroll pumps

Negative ionsource (Model 860C) for various heavy ions

- Typical beam currents

$^{11}B^{2+}$	≥10 eμA
$^{12}C^{2+}$	≥40 eμA
$^{16}O^{2+}$	≥40 eμA
$^{28}Si^{2+}$	≥50 eμA
$^{31}P^{2+}$	≥20 eμA
$^{58}Ni^{2+}$	≥ 8 eμA
$^{63}Cu^{2+}$	≥15 eμA
$^{75}As^{2+}$	≥10 eμA
$^{197}Au^{2+}$	≥30 eμA

High energy extension

- Base vacuum level: < $5{\cdot}10^{-7}$ mbar without ionsource operation
- Dry vacuum system: turbo and scroll pumps
- 90-degree analysing magnet
  Radius 1500 mm
  Gap 40 mm
  Mass energy product 185 AMU-MeV (1.3T)
  (i.e. capable of bending heavy ions)
  Stability 10^{-5} (over 1 hour)
- SLITS feedback system for terminal voltage stabilization

Water-cooled high-power stabiliser slits (analysing slits) with feedback to the Tandetron accelerator terminal voltage driver. This improves the terminal voltage stability.

- Terminal voltage stability
  GVM ± 200 V / hr
  SLITS ± 30 V / 4 hrs

HVEE SPECIFCATIONS

Analytical Endstation

National Electrostatics Corp.

Analytical methods:

RBS: Rutherford Backscattering Spectrometry setup:
- Two ruggedized charged particle detectors fixed at 165° and 97° both of them in Cornell geometry

ERDA: Elastic Recoil Detection Analysis setup:
- Additional movable ruggedized detector in IBM geometry with support arm to allow movement of the charged particle detector from 10° to 170°
- ERD foil holder mounted on the movable detector with minimum 5 absorber foils, foil position controlled from outside of the vacuum chamber

PIXE: Particle Induced X-ray Emission setup:
- Silicon Drift Detector (SDD) 25 mm^2 active area
- Detector solid angle: over 5 msr
- Energy resolution: <130 eV at 5.9 keV (^{55}Fe) X-ray line

IBIL: Ion Beam Induced Luminescence setup:
- Fiber optic lightguide
- Vacuum feedthrough
- Detector

Beamline for channeling:
- Two sets of double slits for channeling (the distance between them is 1.5 m)
- Beam profile monitor

The Ion Beam Analysis vacuum chamber is equipped with:
- Dry vacuum system: turbo and scroll pumps
- Vacuum controller for automatic chamber venting and pumping
- Target load lock, load lock pumping

Computer controlled motorized target manipulator and goniometer:
- The goniometer has 3 translation and 2 rotation axes
- Computer controlled eucentric move (compucentric)

Sample holder for multiple samples.

Sample heating up to 500 °C
- Temperature controller
- Necessary mounting ceramic and holder
- Controlled sample cooling to allow fast sample change

Electron source to discharge insulating samples.

Data acquisition computer:
- To control all the movements in the chamber and to collect the data of all the above mentioned detectors simultaneously
- Software for automated data collection and sample advance.

SDD X-ray Detector Array

RaySpec Ltd.

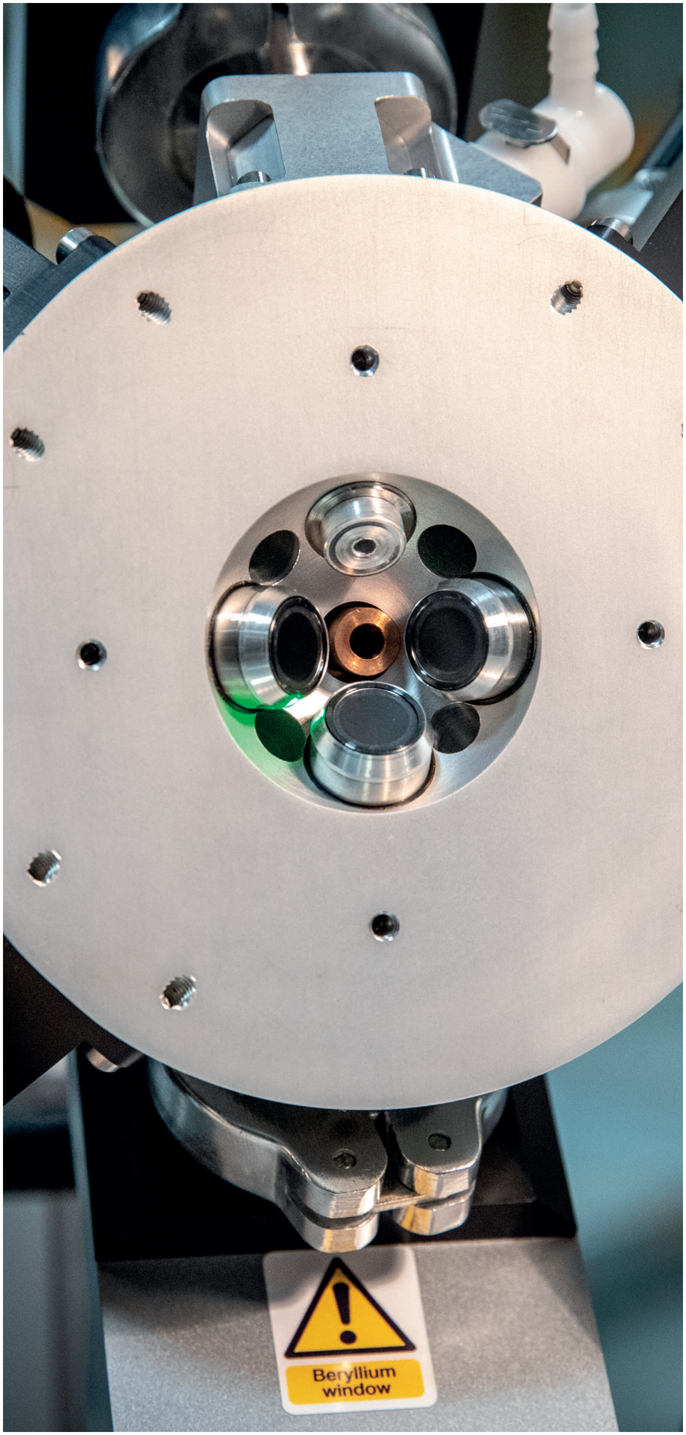
A multi-channel detection system for an external beam PIXE setup. Compact design, incorporates 4 Silicon Drift Detectors (SDD), 2 positioning lasers and 1 microscope video camera with illumination and allow the ion beam to emerge through the centre of the system. The alignment lasers are adjustable so that the two laser beams cross to identify the beam spot.

The SDD detectors:

- 3 x $50mm^2$ active area with 12.5μm Be window,
- 1 x $30mm^2$ active area with a SiN low energy window,
- The low energy detector incorporates a proton trap magnet and He flow adapter.
- Sensitive depth 0.45mm
- Resolution: <130eV @5.9keV (3kcps)
- Peak to Background ratio >10K:1

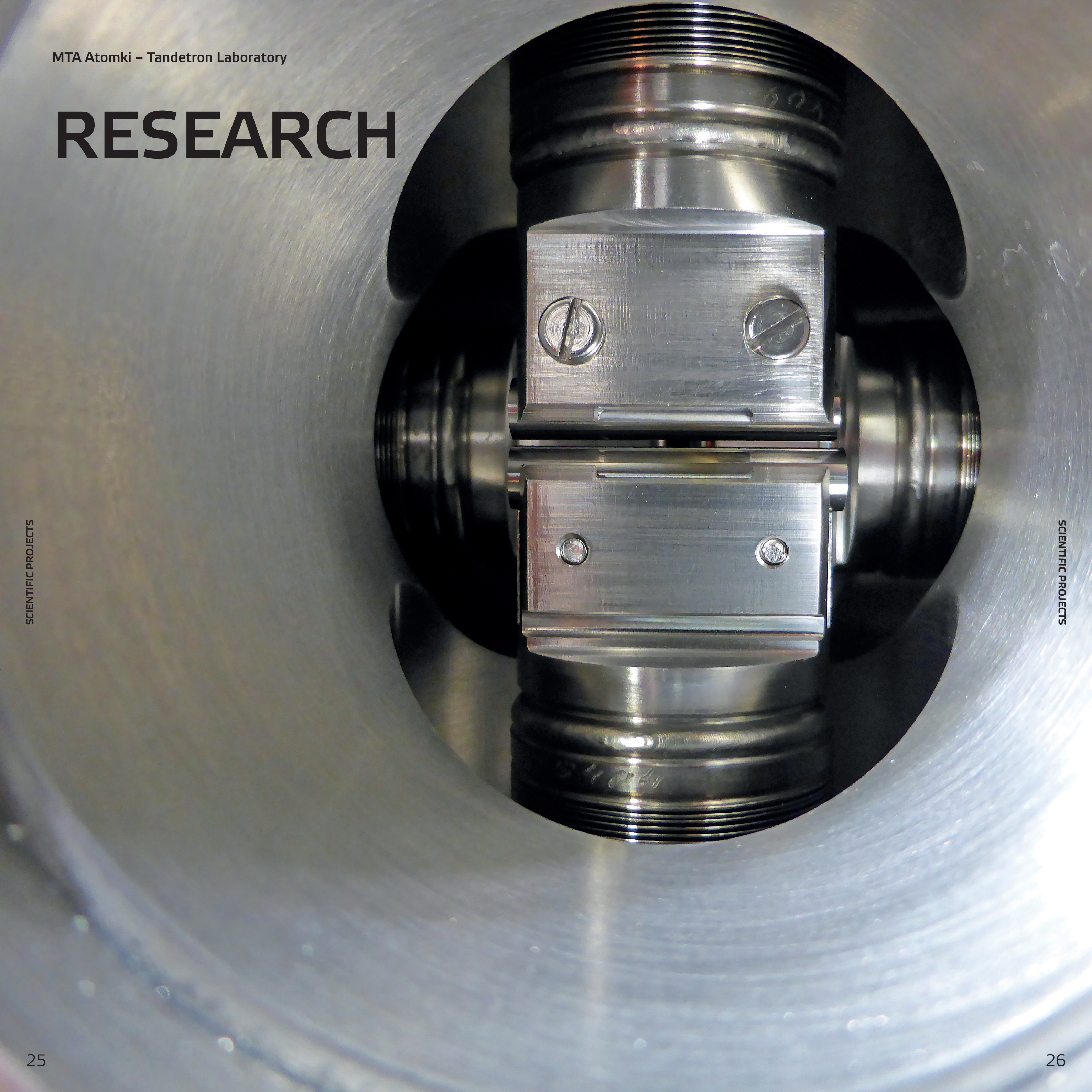
The system also includes a multi-channel digital pulse processing system:

- Control and setup software (4 channel high speed processing system)
- Gated acquisition
- Synchronised Pixel Advance
- List Mode Acquisition
- 19” PXI Crate with Crate Controller



RAYSPEC SPECIFICATIONS

RESEARCH



SCIENTIFIC PROJECTS

SCIENTIFIC PROJECTS

Continuing the traditions of Atomki, the Tandetron, as a key infrastructure of the institute will serve both basic and appiled research work. Some of the nine beam lines have already been installed by the termination of the GINOP project (June 2019), while others are to be completed later.

Accordingly, some research projects have already started, and some even reached the publication stage, wile others are in the preparatory or the planning stage.

Nuclear astrophysics is a major field in which the advantages of the Tandetron can be utilized for basic research. Nuclear processes going on in stars and supernovae typically correspond to the energy range available at the Tandetron. Instead of high energy, in this field, high beam stability and beam intensity are the key requirements; these are both provided by the Tandetron.

The Tandetron accelerator, combined with appropriate detector systems can also be applied in basic experimental studies extending beyond the range of nuclear physics. The recent discovery of an anomaly in the decay of high-lying states of the ^{8}Be nucleus in Atomki, which was interpreted as an indication for the presence of a light vector boson particle, triggered intensive research in dark matter studies. The reproduction of the original experiment with a more refined and upgraded experimetal setup is underway at the Tandetron Laboratory.

The installation of the nanoprobe at Tandetron will result in a unique instrument for applied research. With this, it will be possible to focus ion beams to a spot with dimensions below the micrometer (μm) scale, allowing for the analysis of the spatial distribution of elements in various materials. The Tandetron also facilitates the implementation of various techniques of ion beam analysis. These techniques are widely used in determining the elemental composition of samples in environmental and atmospheric research, materials science, biological and medical studies, as well as in geology and cultural heritage science.

NUCLEAR ASTROPHYSICS AT THE TANDETRON

The Tandetron facility of Atomki offers excellent conditions for carrying out experimental nuclear astrophysics research. The beams provided by the accelerator allows the cross section measurements of various key reactions of e.g. stellar hydrogen burning which was not possible in Atomki before.

In 2017 the Nuclear Physics European Collaboration Committee (NuPECC) published its latest long range plan for picturing the future directions of nuclear physics in Europe [1].

In the chapter dealing with nuclear astrophysics, the following high priority statement is made:

"We strongly recommend that dedicated nuclear astrophysics programmes at universities and small-scale facilities be supported to enable them to continue and extend their high impact science."

Indeed, owing to the special requirements of this research field, most of the results of experimental nuclear astrophysics come from small scale facilities. The Tandetron Laboratory of Atomki can be one of these small scale facilities where valuable nuclear astrophysics results are produced already now, and can be expected also in the future.

In stars, nuclear reactions take place in extremely low energies compared to the standard energy range of nuclear physics. Depending on the stellar temperature and the mass of the reacting nuclei, this energy range is typically between a few tens of keV up to a few MeV. Consequently, the study of the astrophysical relevant reactions does not require high energy accelerators. Low energy electrostatic accelerators can provide the necessary beam energies. On the other hand, the reactions have tiny cross sections which makes their study extremely difficult. The low cross sections can in part be compensated by high beam intensities.

The Tandetron accelerator fulfils both of these requirements. In the case of protons (which is perhaps the most important for nuclear astrophysics) the beam energy can be set between 200 keV and 4 MeV and intensities of several tens of μA can be reached. Moreover, the energy resolution and long term stability of the beam is excellent which are again very useful for nuclear astrophysics.

It is not surprising therefore, that one of the main motivation for launching the Tandetron project was nuclear astrophysics and the first scientific results obtained with the new infrastructure came from this research field. The first two astrophysical reactions investigated with the Tandetron were the key reactions of two cycles of stellar hydrogen burning. Some information about these measurements are shortly given below.

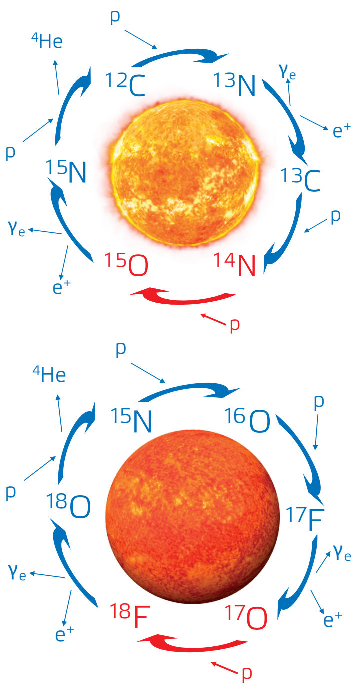


Fig. 1.
The first and the third CNO cycle of hydrogen burning. The key reactions of the cycles shown in red are the first astrophysical reactions studied at the Tandetron.

The most important energy source of stars is the hydrogen burning which means the conversion of four protons into one alpha particle. In the Sun and similar low mass stars this process goes through the reactions of pp chains. However, in more massive stars, catalytic reaction cycles play the dominant role, the most important ones being the so-called CNO cycles. The reaction flow of two such cycles can be seen in Fig. 1.

The cross section of the various CNO cycle reactions is needed for modelling the astrophysical processes. Often these cross sections are not known with the accuracy required for the high precision stellar models. Therefore, their new measurements are highly necessary and these measurements must be carried out in wide energy ranges in order to aid the extrapolations to the astrophysical energy region.

The $^{17}O(p,\gamma)^{18}F$ is an important reaction of the third CNO cycle which takes place in massive stars. The rate of this reaction is closely related to the fluorine abundance of the universe. Contradicting and scarce data were available in the literature for this reaction calling for a new investigation.

The first astrophysical experiment carried out at the Tandetron was thus the measurement of this reaction cross section in a wide energy range using the activation technique and this has led to the first publication form the new laboratory [2]. The results (which are partly shown in Fig. 2) were compared with the existing data and theoretical calculations were carried out to make the astrophysical reaction rate calculations more robust.

The key reaction of the CNO-1 cycle is the $^{14}N(p,\gamma)^{15}O$ capture reaction. This cycle is the first to be activated in stars as the temperature rises and plays an important role also in the case of the Sun through for example its influence on solar neutrino spectra. The study of this reaction is presently (in 2019) in progress representing the second nuclear astrophysics project at the Tandetron. For the cross section measurement of this reaction a novel technique is used. The amount of reactions is measured by a cyclic activation through the detection of the annihilation radiation following the β-decay of the produced ^{15}O isotope. This is shown in Fig. 3 where the activity of the irradiated target as a function of time is shown in the course of a cyclic activation. The strengths of two important resonances have already been determined and the measurement of the direct capture cross section is in progress.

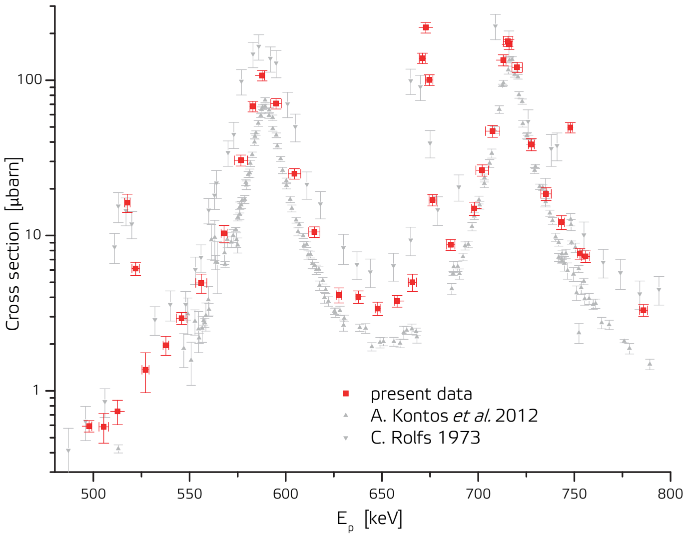


Fig. 2.
Cross section of the $^{17}O(p,\gamma)^{18}F$ reaction measured at the Tandetron accelerator and compared with available data from the literature

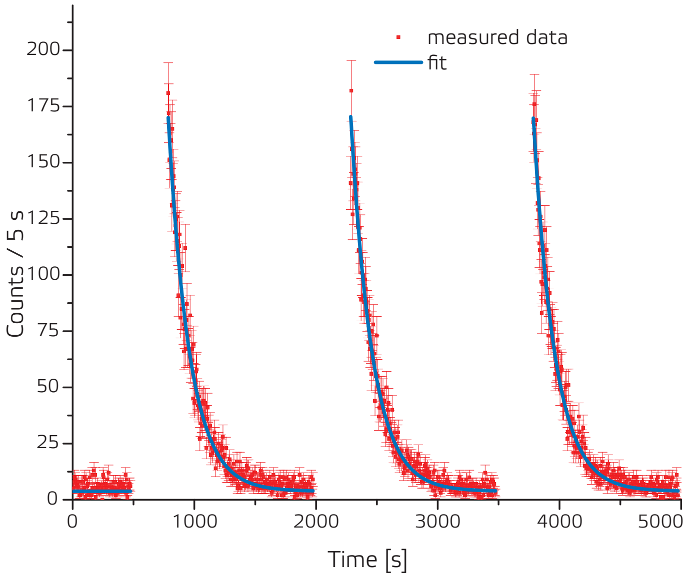


Fig. 3.
Activity of ^{15}O as a function of time recorded in a cyclic activation cross section measurement of the $^{14}N(p,\gamma)^{15}O$ reaction

Based on the experience gathered so far, the Tandetron provides excellent conditions for nuclear astrophysics experiments.

An extensive research program is therefore being developed focusing on the study of several important reactions of various processes of astrophysics.

[1] NuPECC Long Range Plan 2017,
http://www.nupecc.org/pub/lrp17/lrp2017.pdf
[2] Gy. Gyürky *et al.,* Phys. Rev. C 95, 035805 (2017)

SEARCHING FOR DARK MATTER PARTICLES AT THE TANDETRON

One of the biggest challenge in contemporary particle physics is to understand the structure of the dark matter, which amounts to about 7 times more mass than the visible matter. Our research is connected to these efforts to shed some light on the dark side of the Universe.

It has been known for a long time that light vector boson force carriers and other light hidden particles with masses up to a few tens of MeV can be searched for in rare nuclear decays.

Recently we have observed an anomaly in the internal e^+e^- decay of the 18.15 MeV state of ^{8}Be [1]. A bump appeared in the angular correlation spectra of the e^+e^- pairs. No such bump is expected from known nuclear physics processes, which predict that this transition takes place primarily through internal pair conversion with a smoothly falling distribution of e^+e^- opening angles. Furthermore, no significant excess is seen in the related isovector 17.6 MeV ^{8}Be transition [1].

The observed anomaly could be interpreted as a first hint for a 17 MeV X-boson (X17), which may connect our visible world with dark matter. The possible existence of the X17 boson and its supposed relation to the dark matter problem as well, triggered an enormous theoretical and experimental interest in the particle, hadron, nuclear and atomic physics community. According to Altmetric our article published in Physical Review Letters [1] is in the top 5% of all research.

This motivated future searches for light vector bosons and other particles in rare nuclear transitions.

DARK MATTER PARTICLES

Using a significantly modified and improved experimental setup at the Tandetron accelerator, we reinvestigated the anomaly observed in the e^+e^- angular correlation.

To populate the 17.6 and 18.15 MeV 1^+ excited states in ^{8}Be selectively, we used the ^{7}Li(p,γ)^{8}Be reaction at the E_p=441 keV and the E_p=1030 keV resonances. A proton beam with a typical current of 1.0 μA impinged on a 15 μg/cm^2 LiF (used at the E_p=441 keV resonance) and on a 300 μg/cm^2 thick Li target evaporated on 20 μg/cm^2 thick carbon foils (used at the E_p=1030 keV resonance). In contrast to our previous experiment [1], we used a thinner ^{12}C backing and we increased the number of telescopes (from 5 to 6). As a considerable improvement, we replaced the gas-filled MWPC detectors with a double-sided silicon strip detector (DSSD) array.

The e^+e^- pairs were detected by six detector telescopes placed in one plain, which is perpendicular to the beam direction. The telescopes consist of DSSD detectors and plastic scintillators. The DSSD detectors have strip widths of 3 mm. The telescopes were placed around the vacuum chamber made of a carbon fibre tube with a wall thickness of 1 mm.

The setup shown in Fig. 1 has different efficiency curve as a function of the correlation angle compared to the previously published one [1], and different sensitivity also to cosmic rays resulting practically independent experimental results.

Fig. 2 shows our experimental results (red dots with error bars) for the recent angular correlation of e^+e^- pairs together with our previous results (blue dots with error bars) measured at the proton absorption resonance at E_p= 1030 keV. There is a good agreement between the two independent sets of experimental data [4,5].

In this experiment, the previous data were reproduced within the error bars.

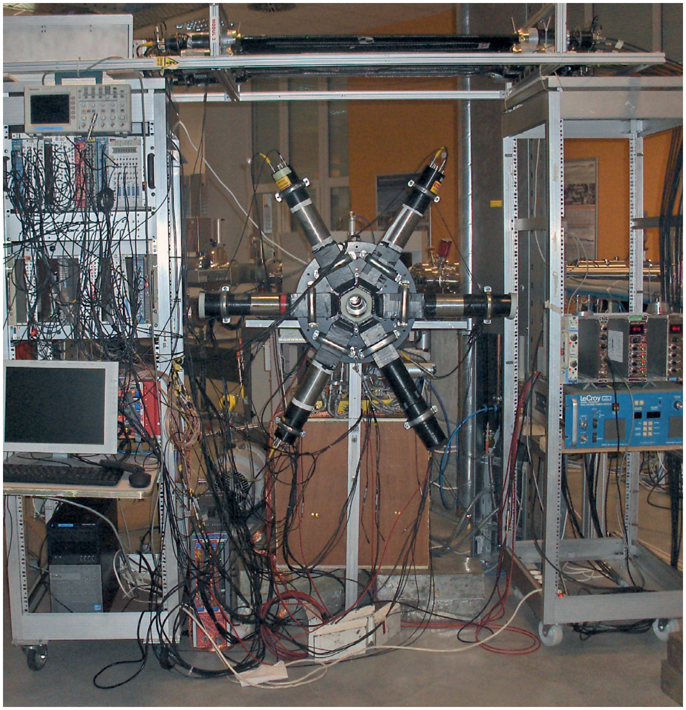


Fig. 1.
The new e^+e^- pair spectrometer with six telescopes equipped with Si DSSD's and with their electronics at the Tandetron laboratory.

DARK MATTER PARTICLES

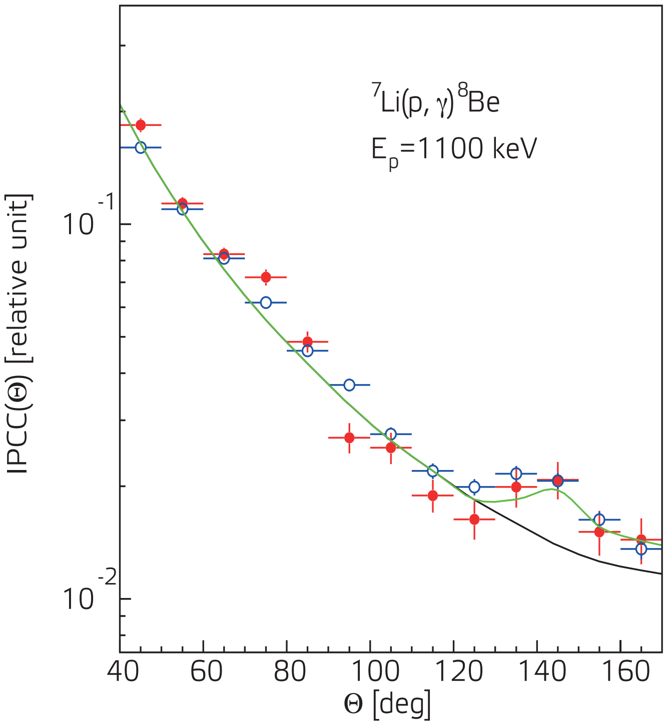


Fig. 2.
Measured angular correlations published previously in Ref. [1] (blue circles with error bars) and the present results (full red dots with error bars) of the e^+e^- pairs originated from the decay of the 18.15 MeV ground state transition in ^{8}Be. The black line represents the simulated background, while the green one is the sum of the simulated signal and background.

Our results are interpereted by Feng et al. [2] by assuming a 16.7 MeV, $J^{\pi} = 1^{+}$ vector gauge boson X, which may mediate a new force with some coupling to the standard model particles. The X boson is thus produced in the nuclear transition to the ground state, ^{8}Be* → ^{8}Be X(17), and then decays through X(17) → e^+e^- process. More recently, Ellwanger and Moretti proposed another possible explanation of the experimental results through the assumption of a light pseudoscalar particle [3]. Given the quantum numbers of the ^{8}Be* and ^{8}Be states, the X boson can indeed be a $J^{\pi} = 0^{-}$ pseudoscalar particle, if emitted with L=1 orbital momentum. According to the Landau-Yang theorem, the decay of a vector boson is forbidden by double γ emission, as opposed to that of a pseudoscalar one.

At the Tandetron Laboratory we started to study both the e^+e^- [4,5] and the γγ [6] decay of the assumed 16.7 MeV particle which may be created in the 21.1 MeV 0^{-} → 0^{+} forbidden transition in ^{4}He, in order to distinguish between the vector and the pseudoscalar boson scenario.

In order to populate the wide (Γ = 0.84 MeV) 0^{-} second excited state (E_x= 21.1 MeV) in ^{4}He, we use the ^{3}H(p,γγ)^{4}He reaction at E_p=1.00 MeV bombarding energy, which is just below the threshold of the (p,n) reaction. The γ-rays are measured by state of the art 3″x3″ $LaBr_3$ detectors shown in front in Fig. 3, while the electrons and positrons are detected by our e^+e^- pair spectrometer, which is behind the γ spectrometers.

DARK MATTER PARTICLES

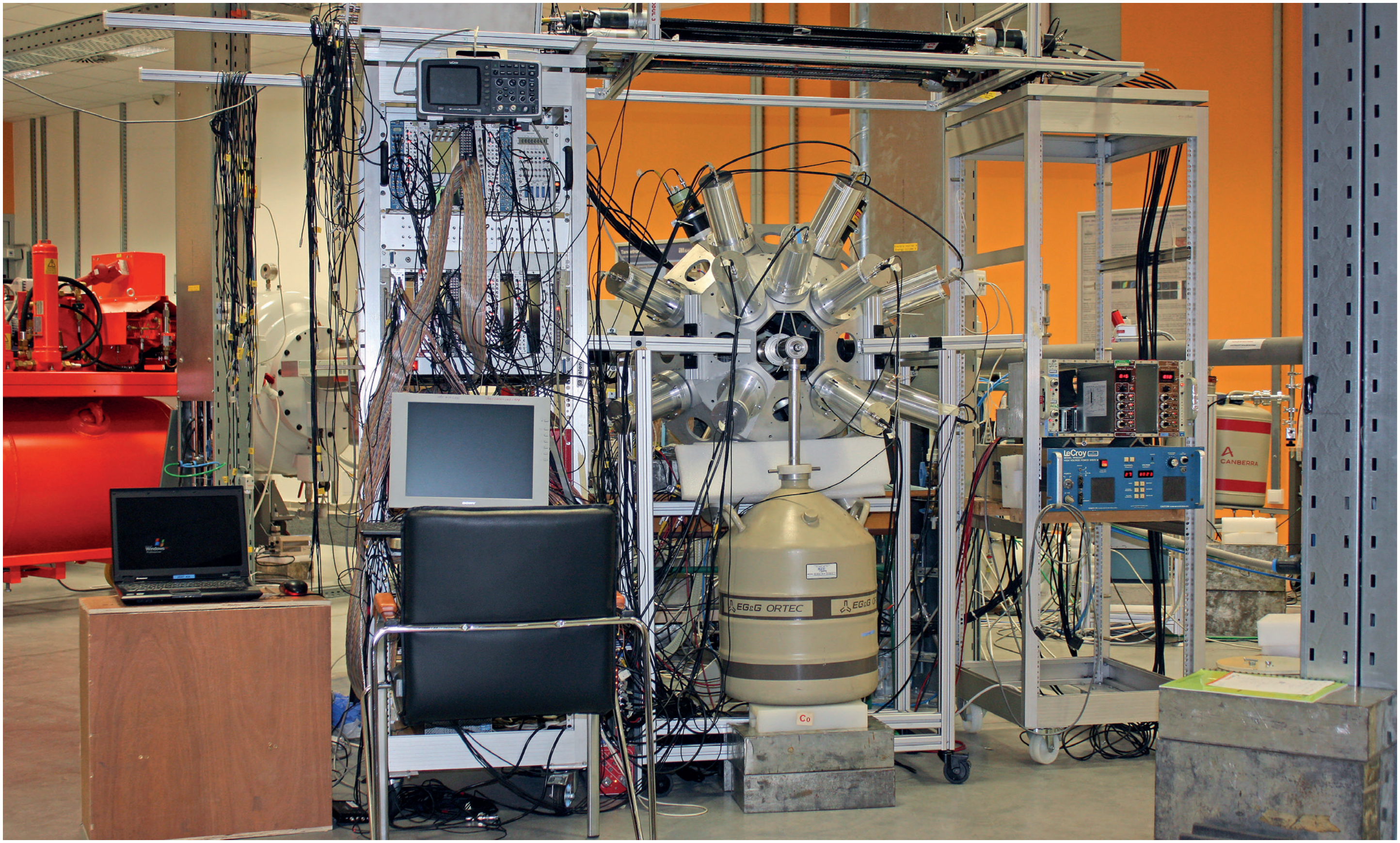


Fig. 3.
γγ and e^+e^- spectrometer together with their electronics and data acquisition system at the Tandetron laboratory. The Dewar in front is used to cool the target. At the top of the photo the active cosmic-ray shield is visible.

Preliminary results on the effect of the X(17) e^+e^- decay measured in this configuration have already been obtained.

We are planning to continue the experiment soon with better statistics, better energy resolution and a sharper cut on the symmetry energy, which will help to improve the signal/background ratio.

[1] A. J. Krasznahorkay *et al.,* Phys. Rev. Lett. 116, 042501 (2016).
[2] J.L. Feng *et al.,* Phys. Rev. Lett. 117, 071803 (2016).
[3] U. Ellwanger and S. Moretti, J. High Energ. Phys. 11, 39 (2016).
[4] A. J. Krasznahorkay *et al.,* J. Phys. 1056, 012028 (2018).
[5] A. J. Krasznahorkay *et al.,* Acta Phys. Pol. 50, 675 (2019).
[6] Á. Nagy *et al.,* (in press) Il Nuovo Cimento

DARK MATTER PARTICLES

NANOPROBE

The nanoprobe setup was initially installed on the Tandetron accelerator in Phase 1. The technical specifications outlined in the present subsection reflect the status of the nanoprobe as of May 2019.

The Tandetron machine, being state-of-the-art accelerator, provides extremely good energy stability that is of crucial importance to achieve very low chromatic aberration. The high brightness multicusp ion source is another essential condition for developing a nanoprobe facility.

The preliminary nanoprobe setup (see Fig. 1) has reached a satisfactory experimental performance of around 200 nm spot size for low current mode, and below 600 nm for high current mode.

Fig. 1.
Target chamber and quadrupole magnetic lenses of the nanoprobe.

The nuclear nanoprobe, where spot sizes below the diffraction limit of visible light can be achieved, has further niche cutting-edge application areas in nanotechnology: For example, this technology has unique advantages in cell biology, where structural and fluorescence microscopy of whole cells can be carried out at nano-resolutions, and proton beam writing, where high aspect ratio nanostructures in a wide variety of materials can be fabricated.

The major components of the beam optics were produced by Oxford Microbeams Ltd (OM). The pre-lens magnetic scan is achieved by two sets of dipoles driven by Kepco power supplies: one box in X and Y (closer to the first quadrupole lens), and the other box only in Y with half the strength and opposite polarity of the primary scan box, this way resulting in a 'dog-leg' scanning feature. The magnetic quadrupole lenses are OM-52 type with a pole gap of 9 mm. The quadrupole lenses are configured in the Oxford Spaced Triplet configuration, the supporting base allows easy reconfiguration along the beam axis. The samples can be mounted on a nanopositioning sample manipulator stage (SmarAct XYZ+R).

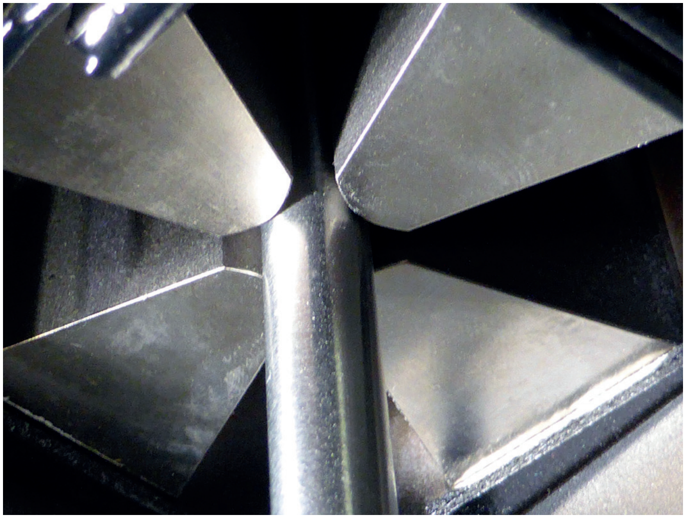


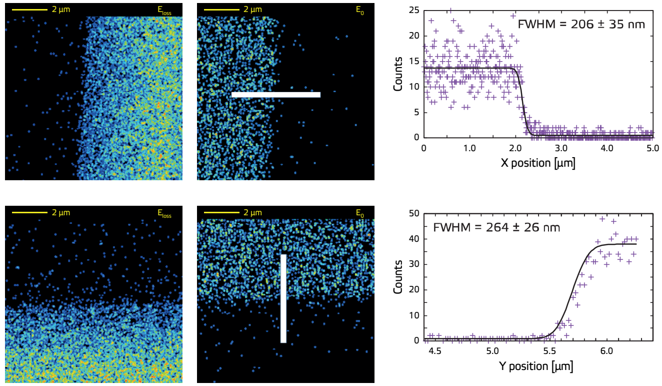
Fig. 2.
Closeup photo of a high precision quadrupole magnetic lens.

Beam spot size measurements

For 'high-current mode', where larger spot sizes are expected, off-axis STIM (Scanning Transmission Ion Microscopy) imaging of a commonly used 1000 mesh copper grid was used. Since the edge definition of the grid is not suitable for measuring spot sizes in the order of ~100 nm, which is expected in 'low-current mode', in that case a freshly broken edge of a single crystal silicon sample was used with on-axis STIM imaging. The Si sample was tilted to 7 degrees from the ideal zero incident angle, in order to make sure that we do not hit the edge along the thickness of the wafer. Thus the beam really saw an atomically sharp edge. In the STIM spectra we selected

a)

b)



c)

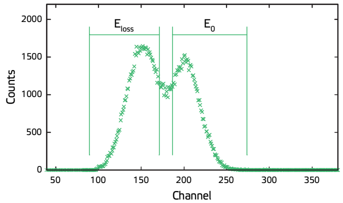


Fig. 3.
On-axis STIM images of the Si edge:
a) X-direction scan;
b) Y-direction scan. In both cases the left image is from the scattered particles (E_{loss} region), while the right image is the E_0 peak, i.e. which did not suffer scattering. This is the explanation of the inverted images. The beam spot size is determined from the E_0 image.
c) A typical STIM spectrum is shown too.

the E_0 peak corresponding the incoming beam energy, thus any scattering on the Si edge (which suffered energy loss, thus appeared in the E_{loss} region of the spectra) was not counted into the beam size measurements. The results are shown on Fig. 3.

Beam divergence measurements

For small divergences (narrow collimator settings) we only measured the X plane divergence of 0.6 mrad, while for wider collimator settings we measured both X and Y divergences, resulting in 10 mrad and 1.5 mrad, respectively (see Fig. 3). WinTRAX calculations showed similar values for the divergences. As expected, the accuracy required to position the target at the focus of the beam is most sensitive in the case of large collimator settings, and mainly in X direction. (See red symbols on the figure below. The V-shaped lines are shown only to guide the eye.)

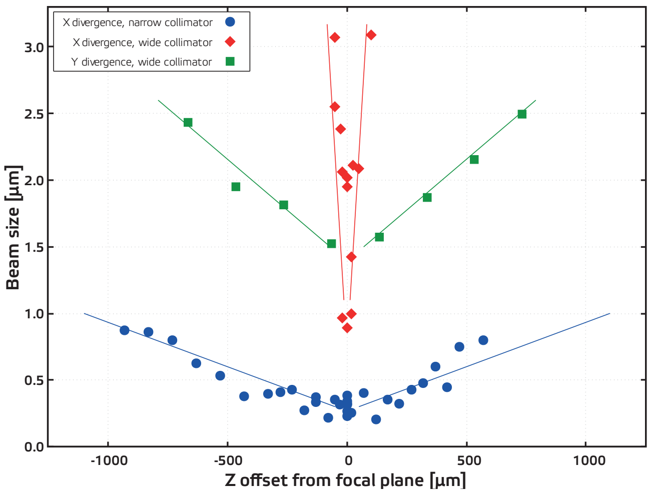


Fig. 4.
Results of the beam divergence measurements

In this case it is necessary to position the target into the beam focus with an accuracy of ≈20 μm. This can be done easily, because in the microscope we can see that ≈2 μm longitudinal movement changes the optical image focus.

WinTRAX simulations

Various calculations have been performed with the WinTRAX, which is a beam optics simulation software. First the linear behaviour of the 'dog-leg' scan was confirmed.

Furthermore, the horizontal and vertical spot sizes were calculated as a function of X and Y scan displacement. As it was expected the strongest was found in the corners of the scanned area. The vertical spot size is also affected by the X scan. The horizontal spot size is least sensitive to either scan direction. We have observed that up to 16 μm Y-offset (32 μm scan size), the vertical beam spot size remained the same. Considering a scan resolution of 512 pixels and using large scan sizes, it is clear that the distance between the neighbouring pixels is larger than the degraded beam spot size, hence the resulted image quality will not be degraded in IBA imaging. On the other hand, for proton beam writing only the small scan sizes are useful, because the feature size at the edges of larger scans would be degraded. Therefore it is anticipated that in our case stage scanning will have an advantage: very large scan sizes will be achievable without any degradation of the spot size, even if this will need a slower scan speed, settling time and frequent beam blanking. The specifications of the stage are sufficient, and OMDAQ-3 can control the stage.

Beam brightness measurements

Measurements were performed using several object and collimator aperture combinations, at 1, 2 and 3 MeV beam energies. The beam current was measured using a home-made mini Faraday-cup, with secondary electron suppression. The measured beam brightness of the Model 358 duoplasmatron ion source and 2 MV Tandetron is 0.75 Amp rad^{-2} m^{-2} eV^{-1}. The brightness specifications of the Multicusp ionsource are: guaranteed 8 Amp rad^{-2} m^{-2} eV^{-1}, expected 16 Amp rad^{-2} m^{-2} eV^{-1}, i.e. 10 times higher value is guranteed than the one achieved with duoplasmatron source. So we can expect about 5 times more current with the same slit openings and the planned 12 m object distance instead of the present 6 m.

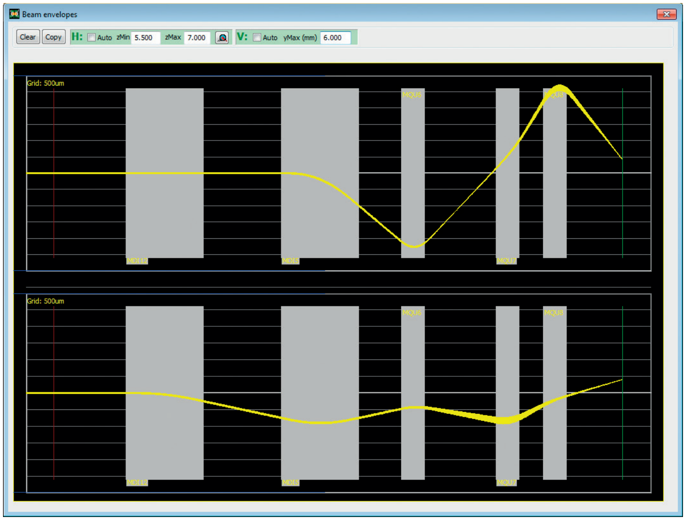


Fig. 5.
WinTRAX simulation

Conclusions

The new nanoprobe setup at MTA Atomki is completed at its temporary location, and it is performing as planned. This setup has reached a satisfactory experimental performance of around 200 nm spot size for low current mode, and below 600 nm for high current mode, using H^+ beam. Based on the required quadrupole currents for the used working distances for protons, we have also calculated that we shall be able to focus $He^{+,2+}$, $C^{2+,3+}$ and $O^{2+,3+}$ beams.

When the laboratory will be completed in its final configuration, the object distance of the nanoprobe will be about two times longer. For this longer object distance, it is important to note that the new Multicusp ion source will provide about 10–20 times higher beam brightness than the present measured value of 0.75 Amp rad^{-2} m^{-2} eV^{-1}. We can conclude that in the future, the envisaged longer object distance and corresponding higher demagnification ratios, coupled with a higher beam brightness, should result in more beam current focused into a smaller spot size. This will allow us to use smaller object aperture dimensions, thereby resulting in sub-100 nm focused spot sizes. The nanoprobe facility, similarly to the well-established microprobe facility, can be used in various application areas of Ion Beam Analysis, and Proton Beam Writing – in this case an order of magnitude better beam spot size opens up new opportunities. Such applications include, e.g. micro- and nanofluidic devices, integrated optical elements below the diffraction limit of the visible light, metamaterials, etc.

[1] I. Rajta *et al.,* Nuclear Instruments and Methods B 449, 94 (2019)

ION BEAM ANALYSIS AT THE TANDETRON

Accelerator based ion beam analytical (IBA) techniques are widely used for the structural and compositional characterization of materials.

IBA is based on the interaction of an energetic ion beam with the electrons and nuclei of the atoms in the material under investigation.

Depending on the type of interaction X-rays, gamma rays, primary scattered or secondary particles are emitted with energies characteristic to the emitting atom or nucleus. The advantages of the IBA methods are that they are fast, sensitive, multi-elemental, produce high-accuracy quantitative results, they require no or very minimal sample preparation, and very small quantities can be measured in a quasi non-destructive and non-invasive way.

Further advantage of IBA is that the analysis can be done in-air in the case of vacuum-sensitive or large samples. With the simultaneous application of complementary IBA techniques a complex analysis of a sample can be achieved in a single measurement in a very short time (typically few minutes). Ion beam analysis has a wide range of applications: environmental and atmospheric research, materials sciences, thin layer analysis, biology, medicine, geology, heritage science and many others.

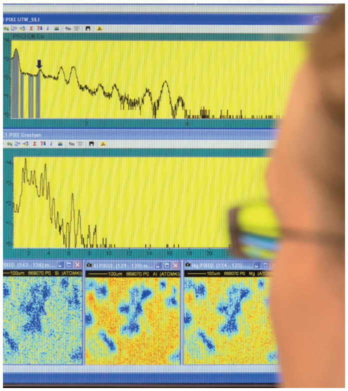
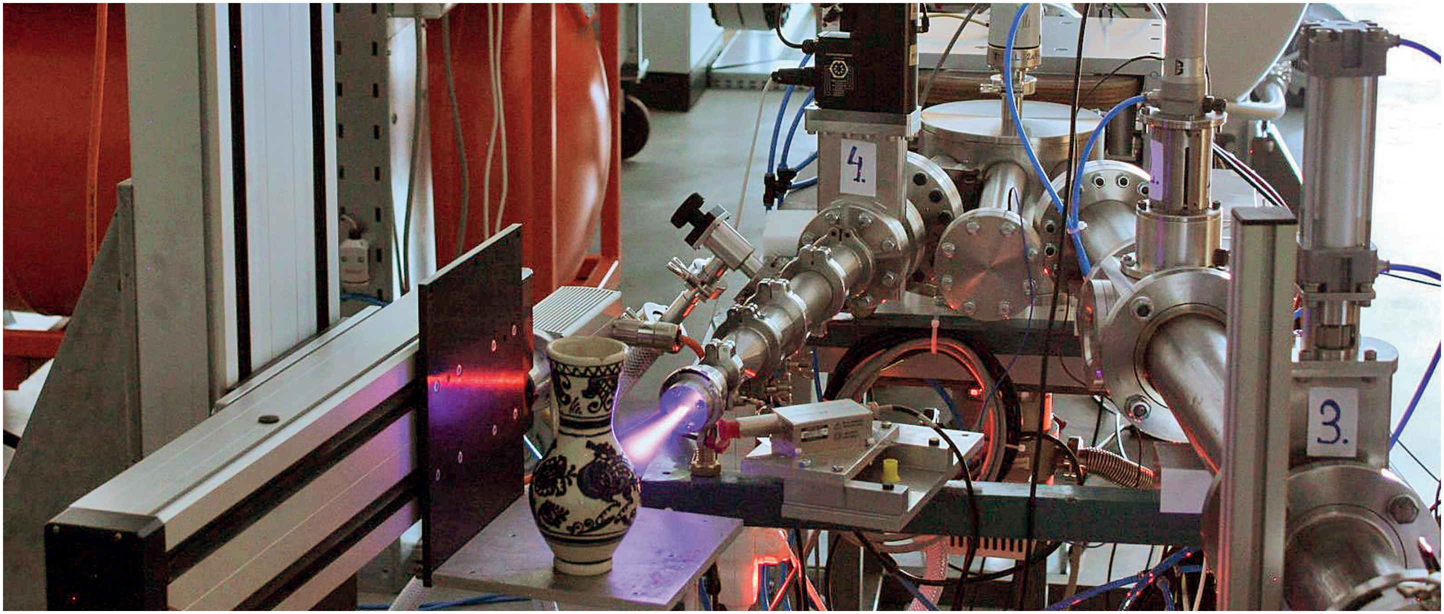


Fig. 1.
The elemental maps are constructed from the spectrum of the sample by the data acquisition software. Counts in the energy range specific to a given element are linked to the pixels on the scanned area.

ION BEAM ANALYSIS



Most common IBA methods:

PIXE (Particle Induced X-ray Emission analysis) is used to determine the elemental composition of samples in the Carbon (Boron) – Uranium range. The method is based on the measurement of characteristic X-ray radiation induced by particles (most often protons) impinging on a sample.

NRA (Nuclear Reaction Analysis) is a method for the quantitative determination and depth profiling of light elements and isotopes. NRA is based on the measurement of particles or characteristic gamma-rays induced by the ion beam in nuclear reactions. Particle induced gamma ray emission analysis (PIGE) is a special case of NRA.

RBS (Rutherford Backscattering Spectrometry) & EBS (Elastic or Nuclear Backscattering Spectrometry) is used to determine the structure and composition of materials. This method is based on the measurement of the elastically scattered primary ions from the sample.

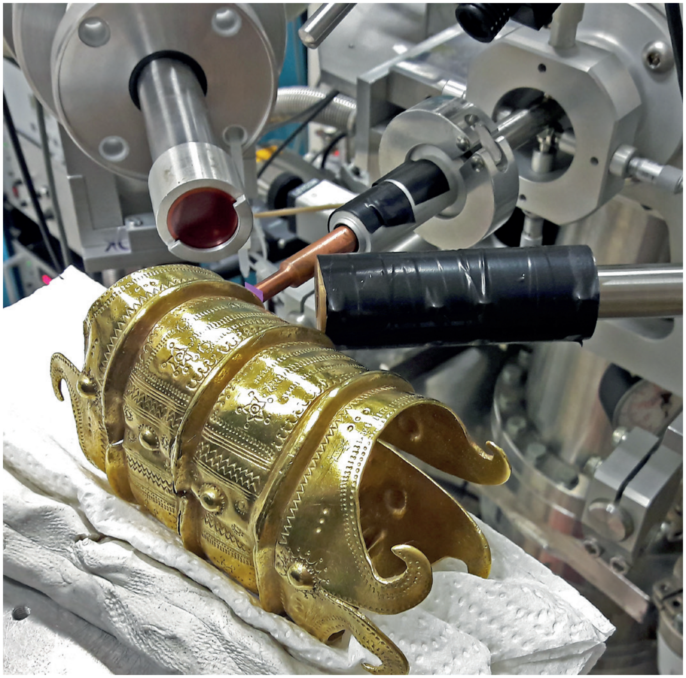
ERDA (Elastic Recoil Detection Analysis) is applied for the quantitative measurement of hydrogen. It is based on the measurement of elastically recoiled atoms by He^{+} (or heavier) ion beam.

STIM (Scanning Transmission Ion Microscopy) measures the energy loss of ions penetrating through the sample, allowing the determination of the areal density across the sample surface with high (~100 nm) lateral resolution.

ION BEAM ANALYSIS

At the Tandetron accelerator several state-of-the art measurement setups are available for the characterization of different samples in macroscopic or microscopic scale.

The new in-air millibeam system is equipped with an X-ray detector cluster, a particle detector, two sample positioning lasers and a microscope camera. The high-efficiency measurement and data acquisition setup is ideal e.g. for the analysis of atmospheric aerosol samples, when complex analysis of a large number of samples has to be done for as many elements as possible, as well as for the investigation of cultural heritage objects when it is essential to gain the analytical information under low beam intensities and short measurement times in order to avoid damage caused by the irradiating beam.



A multi-purpose analytical vacuum-chamber is installed on the Tandetron accelerator. RBS, EBS, ERDA, NRA, PIXE, ion channeling and IBIL (Ion Beam Induced Luminescence) analytical techniques can be used for the quantitative characterization of various samples.

The chamber will be applied in the following multidisciplinary research areas: materials science and applications, thin layer characterization, atmospheric aerosol research, heritage science, biomedical science, etc.

Analysis with focused ion beams

The ion beams can be focused down to micron and sub-micron sizes and scanned over the surface of the sample providing 2D and 3D information about the structure and the elemental composition of the sample.

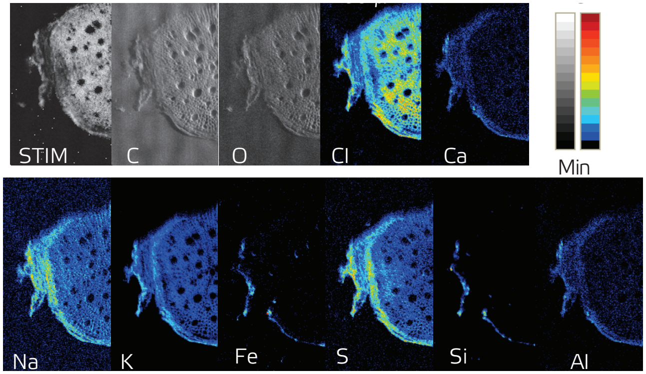


Fig. 2.
Energy loss (STIM) and micro-PIXE elemental maps of a 20 μm thick section prepared from the root of trifid bur marigold (Bidens tripartitus) recorded on the Atomki scanning nuclear microprobe

The Atomki scanning nuclear microprobe has been used extensively during its 25 years of operation in materials science, environmental sciences, biology and medical research, geology and heritage science. It has served as a basic infrastructure in numerous national and EU projects e.g. NANODERM (FP5), CHARISMA (FP7) and IPERION-CH (H2020).

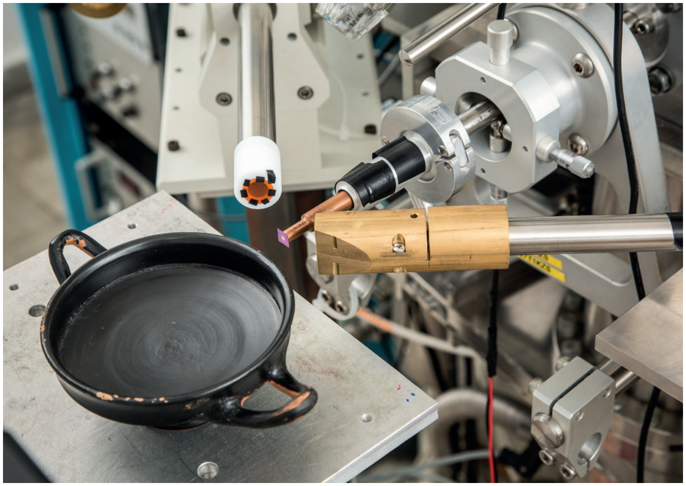


Fig. 3.
Study of a bronze-age vessel using the in-air microbeam setup at the Atomki scanning nuclear microprobe

When submicron sized structures have to be studied the new scanning nuclear nanoprobe will be applied which provides analytical information with a few hundred nm spatial resolution.

ION BEAM ANALYSIS

PROTON BEAM WRITING

Proton beam (p-beam) writing is a new direct-writing process that uses a focused beam of MeV protons to pattern resist material at micro or nanodimensions.

High aspect ratio, straight and tilted micropillars were fabricated in poly(dimethyl-siloxane) (PDMS) polymer. The polymer was applied as a negative tone resist material, in its liquid and high viscosity form. A novel microfluidic cell capture device was made, exploiting the advantages of proton beam writing to make lithographic irradiations under multiple target tilting angles and UV lithography to easily reproduce large area structures.

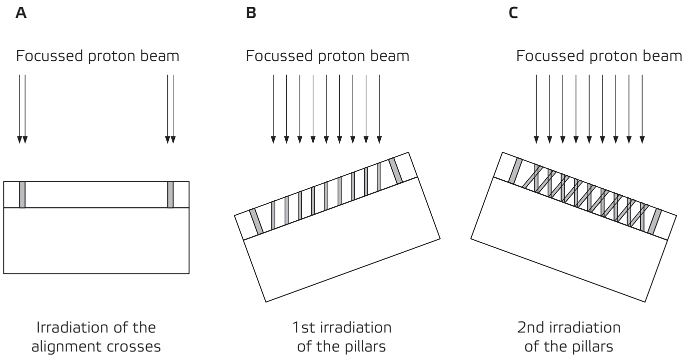


Fig. 1.
Schematic representation of the multiple angle irradiation process (side view). (A)Alignment crosses, (B) Odd rows of pillars (+20º), (C) Even rows of pillars (–20º).

The produced microfluidic device was capable to support adequate distribution of body fluids, such as blood, spinal fluid, etc., between the inlet and outlet of the sample reservoirs, offering advanced cell capture capability on the functionalized surfaces. The performance of the microdevice was evaluated by an image sequence analysis. Finally, the cell capture capability of this new generation microdevice was demonstrated by efficiently arresting cells from a HT29 cellline suspension.

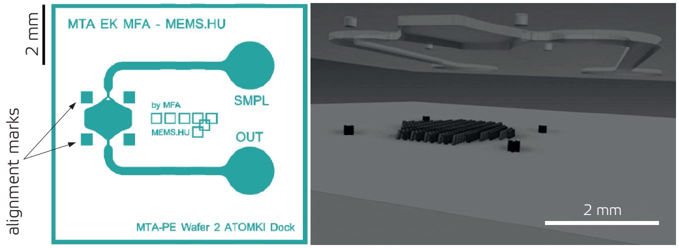


Fig. 2.
Sample transport microfluidic chip design. Left panel: Chip layout. Right panel: alignment schematics.

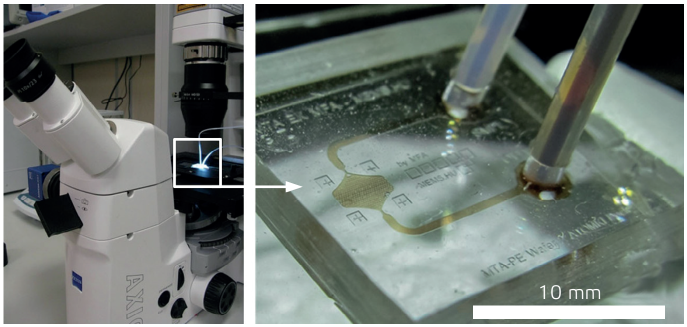


Fig. 3.
The combined capture device filled by a coloured biological test solution containing yeast cell culture

[1] R. Huszánk *et al.,* European Polymer Journal 69, 396 (2015)
[2] I. Rajta *et al.,* Electrophoresis 37, 498 (2016)
[3] G. Járvás *et al.,* Electrophoresis 39, 534 (2018)

DISSEMINATION VIA AUGMENTED REALITY

A novel method to introduce a modern particle accelerator to the general public. The project was started in Atomki with the aim of establishing a research and educational platform that would be used both by experienced nuclear scientists and interested students.

The essential idea of this innovation is allowing the visualization of the operation of objects placed within a closed volume, or in inaccessible positions.

The users can apply augmented reality to “peel” the instrument layer by layer in order to see its structure and operation. One strength of the method is that rather than being based on static pictures, it works in real time, presenting a three-dimensional image of the instrument.

The method is ideal to demonstrate the operation of the Tandetron accelerator to a wide audience, because its interconnected structural elements are hidden to the everyday observer.

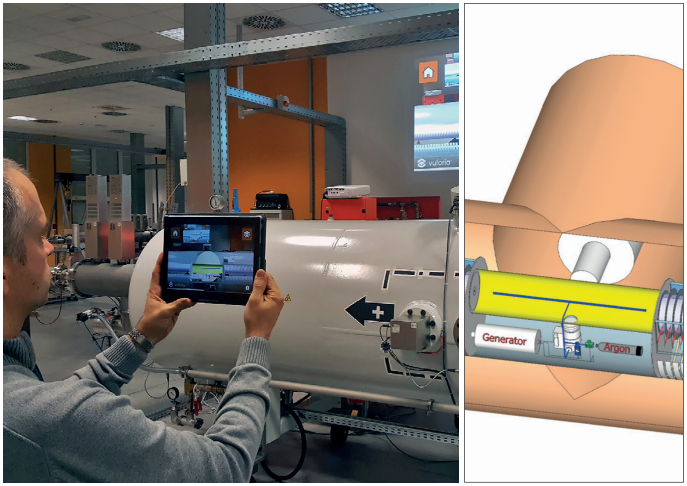


Fig. 1.
Left panel: Demonstration of the app. Right panel: 3D drawing of the inside of the accelerator. Such drawings are embedded in the developed app.

https://tandetron.atomki.hu/ar

IMPRINT

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