Opportunities of Basic and Applied Research at MEDAUSTRON

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Abstract. MEDAUSTRON is a planned centre for hadron therapy and diagnosis in Austria. The central unit of this center is a synchrotron which will deliver beams of protons up to 800 MeV/c and carbon ions up to 400 MeV/c per nucleon. Although the accelerator is primarily dedicated to clinical application, its use for non-clinical research is foreseen for nights, weekends and holidays. Here, the outcome of a recent study on the potential of the facility for basic and applied research in physics and technology is pesented. Especially, the proton beam at intermediate energies is of interest with regard to the setup of a proton scattering facility for basic research as well as for the test of detectors for nuclear and particle physics. The facility offers also opportunities to implement selected applications, e.g. in material research and in dosimetry. In addition, we briefly remark on the importance of MEDAUSTRON for education and training of young researchers in Austria.

1. Introduction

MEDAUSTRON is a planned synchroton based accelerator facility for cancer treatment in Austria with proton and carbon beams which should be operational in 2013. It will be the only accelerator facility in Austria of that class, providing ion beams in the range of several hundred MeV per nucleon. Therefore it is envisaged to also use it for non-clinical research in the fields of medical radiation physics, radiation biology as well as experimental and applied physics. The potential of MEDAUSTRON for physics research and applications has been recently studied [1]. The outcome of this study is briefly summarized in this contribution.
MEDAUSTRON is a medical facility and therefore the accelerator design is correspondingly optimised. For tumor treatment the accelerator must deliver a carbon beam with energies up to 400 MeV per nucleon and a proton beam up to 250 MeV/c both of moderate intensity. In order to increase the capabilities of MEDAUSTRON for physics research especially the proton beam energy must be increased. This implies modifications of the accelerator and leads to additional costs which should kept minimal. A reasonable compromise between the needs of of potential physics experiments and the required modifications of the accelerator complex is choice of the maximum proton beam energy at 800 MeV. This value is still sufficiently below the transition energy of the accelerator (924 MeV) and has mainly impact on the synchrotron radio frequency system and the shielding of the accelerator and beam lines. In particular the shielding has to be increased to cope with the higher beam energy. The baseline beam parameters of the MEDAUSTRON synchrotron are given in Tab. 1.

	protons		carbon ions	
beam energy	MeV	60-800	MeV/u	120-400
beam intensity	protons per pulse	$< 1 \times 10^{10}$	ions per pulse	$< 4 \times 10^{8}$
extraction duration	s	0.1-10	s	0.1-10
repetition rate	Hz	1	Hz	1

TAB. 1. Baseline beam parameters of the MEDAUSTRON synchrotron

2. Detector Development

In nuclear and particle physics several new accelerator projects and associated experiments are planned or in study. The most important ones are the experiments at the planned International Linear Collider (ILC), the experiments at an upgraded Large Hadron Collider, the approved experiments at the new FAIR complex in Darmstadt and the proposed Super B factory in Japan or Europe. In most of these projects Austrian institutes are involved or consider to participate. In all these projects extensive detector developments and subsequent beam tests of prototypes will be required. It is well known that in the coming decade there will be a lack of test beams worldwide [2]. In this respect it is of interest to consider the capabilites of MEDAUSTRON whether it can be used for such beam tests.
A criterion to judge potential applications of a beam for detector tests can be obtained from considerations of the interaction experienced from the particle in the detector material. The theory describing the energy loss of fast particles in matter was originally developed by Bethe-Bloch and shows a strong energy dependence. In FIG. 1. we show the energy loss (*dE/dx* normalised to the matter density) as a function of the particle velocity ($\beta\gamma$ or equally *p/Mc*) for different materials (graph taken from [3]). The velocity dependence of *dE/dx* is similar for different materials and shows a minimum for the so-called minimal ionising particle. A particle having this energy deposes the minimal amount of energy and hence will produce a minimal signal in the detector (worst case). The energy of interest for particle detectors under consideration here is the energy range around the minimum up to very high energies. To judge the potential for detector tests we consider *dE/dx* for aluminium which is quite similar to silicon a material widely used for particle detectors. We considered the interaction of protons of three energies, i.e. 250, 800 and 1180 MeV corresponding to the energies required for medical applications, the actual energy and the maximal reachable energy in this synchrotron configuration. Compared to the minimal ionising particles the energy loss is increased by 100%, 12% and 6%, respectively. A larger energy loss corresponds usually to an increase in signal and may saturate the channels in modern highly integrated electronics. From this consideration it follows that the maximum proton energy

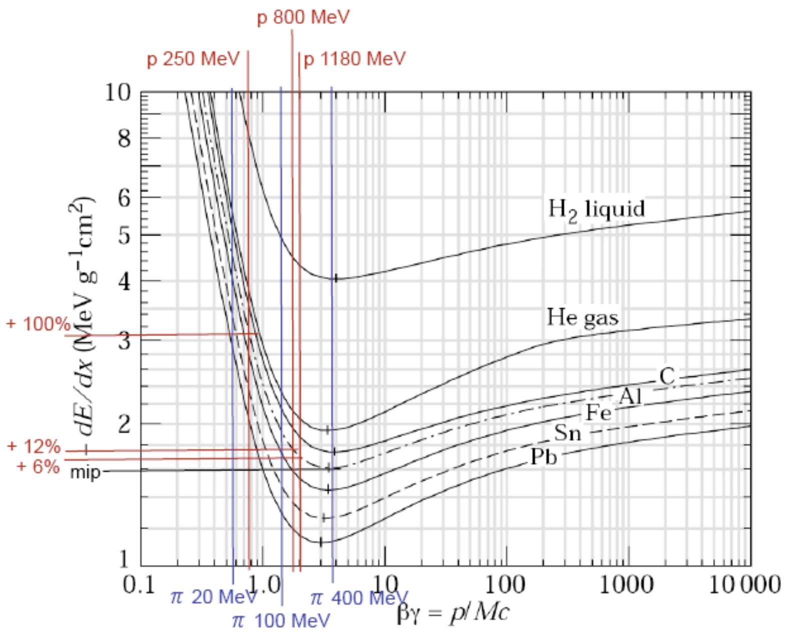

FIG. 1. Energy loss of particles in matter [3].

of 800 MeV, delivered by the MEDAUSTRON synchrotron, is well suited for detector tests and will give signals in the range generated by high-energy particles.
From the large field of different detector types we have investigated the suitability of the MEDAUSTRON beam for tracking detectors, calorimeters, time-of-flight detectors as well as for irradiation studies and rate tests:

- *Tracking detectors:* For detector tests the beam energy is of minor importance as long as the generated signals do not saturate the electronic channels. Due to multiple scattering and depending on the geometrical layout the position resolution will depend on energy. The requirement on particle rates are also moderate. Thus the proton beam delivered by the MEDAUSTRON synchrotron is well suited for such tests independent of the detector technology. Especially, Austrian groups are involved in the developments of semiconductor strip or pixel detectors, gaseous detectors and scintillating fibres which will be used in future accelerators.
- *Calorimeters:* For the test of calorimeters the variation of the beam energy is of interest. The foreseen proton beam energy can be varied between 60 and 800 MeV and is therefore of interest for applications in nuclear physics for the development of calorimeters based on semiconductors or scintillating materials. However, the energy range of the proton beam is too low and do not provide reliable tests for calorimeters in high-energy physics.
- *Time-of-flight detectors:* In future FAIR experiments like PANDA or CBM, identification of forwardly emitted particles will be performed by the time-of-flight technique. In order to achieve better time resolution and to cope with variable fringe magnetic fields the use of silicon photomultipliers is proposed. In these detectors the radiation hardness may become critical. Estimates show that radiation hardness and ageing tests are feasible at MEDAUSTRON.

For the development of future detectors irradiation studies will be of interest. The applicability of a proton beam for irradiation studies depends on the integrated flux achievable within a reasonable time. With the design parameters (TAB. 1.) and ingnoring geometric losses and inefficiences a fluence of 3.6×10^{13} protons per hour can be achieved. A realistic and practical irradiation test of detectors is feasible if the integrated flux of the test beam allows to achieve the target fluence in matter within several hours up to a day of running. Hence the intensity of the MEDAUSTRON beam is sufficient for irradiation studies up to about 10^{14} particle per square centimeter. In particular for the development of vertex and tracking detectors for the ILC, the MedAustron beam is well suited for tests. A few examples from the large number of proposed new vertex detector technologies are given in [4,5].
Another group of tests concerns rate studies which check the performance of detectors and the connected electronics at high particle rates. Especially, one tests the sensors with respect to charge up or saturation as well as the capability of the read-out and data acquisition electronics to process signals with or without dead time. The MEDAUSTRON beam can provide 10^{10} protons per pulse within a time window of 100 ms if fast extraction is used. Such a rate is sufficient to test detectors at present and future high luminosity experiments.
In summary the proton beam delivered from the MEDAUSTRON synchrotron is optimal for the test of tracking detectors independent of the technology as well as for rate tests of detector systems. While its use for calorimeter and irradiation tests is limited due to the given design parameters. In general the MEDAUSTRON beam will not only be used as a stand alone test beam, but also serves to optimally prepare test campaigns at heavily booked test beams at

large scale facilities thus significantly enhancing the efficiency of such test campaigns. In addition it provides an excellent training of students.

3. Proton Scattering Facility

The energy range foreseen for the MEDAUSTRON accelerator covers the whole transition range from low-energy nuclear structure research to high-energy nuclear physics.There are several interesting questions of nuclear research associated with this energy range, for which no beam time can be allocated at dedicated nuclear physics machines. At present only the RCP separated sector cyclotron in Osaka works in this field. Although the beam intensity is low, MEDAUSTRON offers the valuable opportunity to establish a proton scattering facility (PSF) with a complementary physics programme. Thus one would have a worldwide unique facility for nuclear research at medium and high proton energies.

3.1. Research Topics

The physics related to such a proton scattering facility comprise the determination of nuclear radii, relativistiv optical potentials, reactions cross sections of interest for nuclear data and in principle also studies of proton-proton scattering. In the following we briefly sketch the key aspects of these topics without entering into the details of the scientific aspects.
Nuclear Radii: The size of a nucleus is best expressed in terms of the nuclear radius, which can be obtained either from state-of-the-art microscopic mean-field calculations or from experiment via the analysis of cross sections. Especially one is interested in the difference between the proton and the neutron radius in order to confirm the indications of the presence of a neutron skin in heavy nuclei. The charge distribution (proton distribution) is well known from electron-nucleus scattering, X-ray spectroscopy of muonic atoms and isotope shift measurements [6]. The total nucleon distribution and thus the neutron radii can only be obtained via hadronic probes. Our knowledge of the neutron radius, extracted from proton scattering experiments [7], (^{3}He,t) charge exchange reactions [8], and antiproton atom X-ray spectroscopy [9], is worse. Recently Kohoma et al. [10,11] proposed a simple method to determine nuclear matter radii by observing Fraunhofer diffraction of protons with energies larger than 800 MeV off heavy nuclei, which act due to the high absorption like black disks. According to Babinet's theorem the diffraction of a black sphere is equivalent to Fraunhofer diffraction on a hole of the same shape. The scattering amplitude of the Fraunhofer diffraction of a proton with momentum p in the c.m. frame on a nucleus with radius a can be given in closed form. The c.m. angle of the first side maximum Θ_M of the Fraunhofer diffraction pattern which coincides with that of the elastic scattering and allows the determination of the black sphere rms radius r_{BS},

$$r_{BS} = 3.9780 \, / \, 2p \sin(\Theta_M/2) \, . \qquad (1)$$

Kohoma et al. [10] showed that r_{BS} determined from the angle of the first diffraction maximum agrees well with the value of the matter radius. This is shown in FIG. 2 for stable Ni isotopes, where Eq. (1) was used to extract r_{BS} from experimental proton elastic scattering data [12-15]. However, there are still large uncertainties in the order of 0.07 fm which we sould like to improve in a dedicated project. For an improvement of the accuracy of r_{BS} and thus of the rms matter radius it is essential to focus on the measurements of the first diffraction maximum in elastic scattering. This implies improved determination of the scattering angle and the proton energy. In addition it is useful to measure the isotope dependence keeping the energy unchanged. A concerted action is foreseen at the experiment plan to improve our knowledge of the rms radii of heavy nuclei.

Relativistic Optical Potentials: The differential elastic scattering cross section can also be used to extract effective nucleon-nucleus interactions. These so-called optical potentials are basic ingredients for most reaction calculations. Especially, at incident proton energies of about 200 MeV the proton-nucleus optical potential changes its shape. Although the phenomenon is understood in principle, a systematic study of elastic proton-nucleus scattering in the energy range between 60 and 800 MeV would allow to set up global optical potentials with descriptive power not available at present.

Reaction Cross Sections Relevant for Nuclear Data: Precise cross sections of nucleon induced reactions in the energy range of several MeV to a few GeV are of great importance for fundamental research, i.e. for a better understanding of the reaction mechanism and the features of nuclear matter. Moreover they are needed for cosmochemistry and cosmophysics, in order to interpret the production of cosmogenic nuclides in meteorites by primary particles. The data are likewise important for applications, in particular for nuclear technology and its advances as well as for radioprotection. In particular there is a longstanding demand for a detailed knowledge of gas-producing reactions, e.g. (p,α)-, (p,^{3}He)-reactions, in order to estimate the hazards of embrittlement of structure materials.

In the intermediate- to high-energy regime it is impossible to measure all cross sections of interest. Hence, in this energy regime reliable nuclear models are required, which are based on a set of well selected key reaction data. A facility such as MEDAUSTRON offers the opportunity to provide such key reaction data for improvement of the modelling over a wide energy range. An experimental programme on charged particle production (p,$n_i c_i$), gamma production (p,γ) and neutron production (p,xn) reaction cross sections is proposed for MEDAUSTRON. This programme will inevitably demand for individual detector developments in order to cope with the high energy particles, thus leading to scientific and technological innovation. The main limitation of the facility is the low proton current of 1 nA. However, there are only few competing accelerators in this energy regime.

Proton-Proton Scattering: In principle MEDAUSTRON offers also the opportunity to study the nucleon-nucleon interaction via proton-proton scattering. In particular experiments on proton-proton bremsstrahlung and pion production may provide invaluable information on the off-shell behaviour of the nucleon-nucleon interaction. Although the delivered flux is comparable with other dedicated machines, the lack of a polarisation option (polarized beam and target) does not allow competing proton-proton experiments at the moment. The availability of a

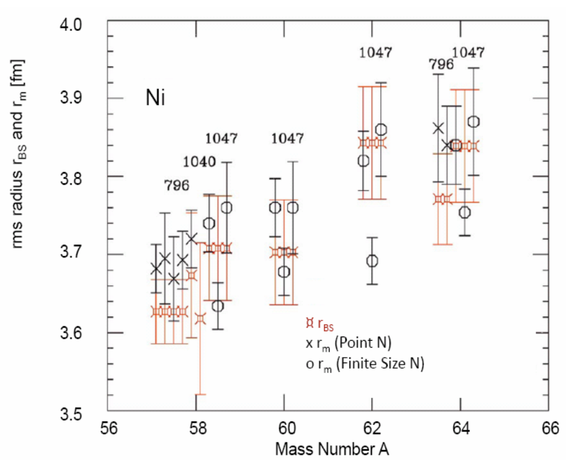

FIG. 2. The values of r_{BS} radii for Ni isotopes (red crosses) in comparison with rms radii for point nucleon (x) and finite size nucleon (o) including the errors.

polarized target would enhance the capability of the facility. Nevertehless the required instrumental efforts are significant and are not justified for a facility such as MEDAUSTRON.

3.2 Instrumental aspects

The nuclear physics experiments discussed above are well suited to be performed at MEDAUSTRON. These experiments require an absolute determination of the proton energy of better than a few MeV with an energy spread of less than few 100 keV. The absolute determination of the energy is possible with an accuracy of 10^{-4} by the Schottky noise Fourier Frequency measuring technique combined with a precise length measurement of the synchrotrons path. The energy spread should allow separation of the elastic channel from the inelastic ones which also requires resolution in the order of 10^{-4}. This requirement can be reached in a slow extraction mode of a proton synchrotron. Another important aspect is the improvement of the angle determination to less than 1.6 mrad (<0.01°). This accuracy can be achieved with a position resolution of the detectors of 1mm at at distance about 1 m from the target and emmittance of the beam in the order 1 π mm mrad.

An important parameter is the luminosity in the context of the proton scattering facility is the reachable luminosity of the beam. Assuming an intensity of 10^9 protons per second and a target with A=100 and a thickness of 100 mg/cm the luminosity is about 6×10^{29} $cm^{-2}s^{-1}$ which is sufficient to measure differential cross sections of 100 mb/sr with a rate of $60 s^{-1}$ $mrad^{-1}$. In principle this is no problem with position sensitive large area gas detectors. For a solid target with A~100, thickness 1µm and σ~100 mb typical measurement times of about 200 s will suffice to reach a statistical accuracy of about 0.1%.

The real challenge is the required detector energy resolution of a few 100 keV at an energy of ~800 MeV to separate inelastic scattering from elastically scattered protons. This is particularly important for the measurment of non-closed shell nuclei. In order to achieve the energy resolution a magnetic momentum analysis is considered. A first estimate of the properties of this system yields for a proton momentum of 1.5 GeV/c (800 MeV protons) a magnetic stiffness of $B\rho = 5$ Tm or a radius of curvature $\rho = 3.3$ m in a uniform magnetic field of 1.5 T. Assuming that the proton track outside the magnetic field can be determined with ~100 µm by layers of thin gas detectors, such as GEMs, a modest path length of about 2.5 m in the magnetic field would suffice to reach a resolution of 10^{-4}. In principle these nuclear physics experiments require charged-particle, neutron and gamma detection. Apart from the use of standard detectors new developments of individual detectors suited for the energy and fluence of the particles as well as specific instrumental conditions will be most probably necessary. However, these developments will be facilitated by the ideal conditions for detector tests at MEDAUSTRON.

4. Applied Physics

The energy range of the proton beam allows several interesting technological application in material sciences and dosimetry. In the general study on the physics opportunities at MEDAUSTRON a series of appealing and possible technological applications are considered, i.e. high enery proton computerised tomography (HepCT), study of radiation damage in high-temperature superconductors, solid-state nano-dosimetry, simulation of cosmic ray components, and a single-hit micro-probe . Here we restrict ourselves to two proposed activities, i.e. high enery proton computerised tomography (HepCT) and solid-state nano-dosimetry.

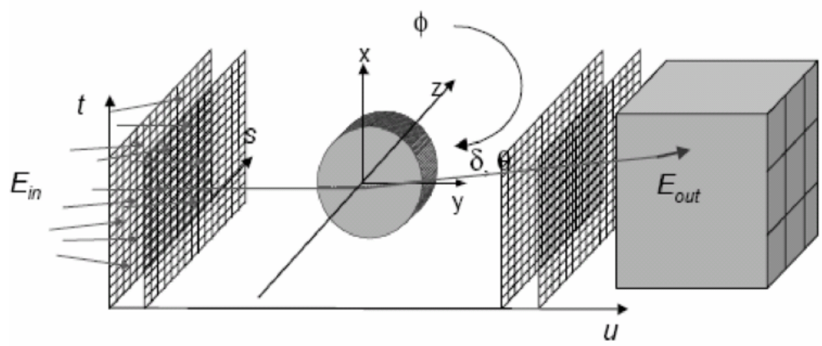

FIG. 3. Schematic layout of the proton computerised tomography station. Protons with known energy E_{in} are recorded one by one in the detector system as they transverse the object at different angles ϕ.

Proton Computerised Tomography: Proton computed tomography (pCT) aims at imaging the electron density distribution via the tomographic measurements of the energy loss in an object. The idea was successfully realised long time ago [16], but only recently there are increased efforts to enhance the quality of proton therapy by pCT imaging. The concept of pCT is shown in FIG. 3. The object is transversed by a broad, necessarily not parallel proton beam with a small energy spread and the energies of the transmitted protons are determined by a position sensitive calorimeter. The energy loss of each ray reflects the integrated electron density along each path. Thus pCT yields after inverse Radon transformation the electron distribution in the object. Usually protons of 200-250 MeV are used for pCT. At MedAustron the high energy beam gives the unique opportunity of High-energy Proton Computerised Tomography (HepCT) for high-resolution imaging of technical objects with considerable thickness. Because of the minimum energy loss and the low small angular scattering in the material the resolution is improved and the option of using HepCT for the treatment in an ion therapy centre could offer big advantages in more accurate positioning and control of the dose distribution.

Solid-State Nanodosimetry: The patterns of energy deposition in solid-thermo-luminescent (TL) crystals and biological tissues contain conceptual parallels. It is well established that the occurrence of radiobiological endpoints such as DNA strand breaks increases with ionisation density in a similar way than substantial features of the TL glow curve [17]. The availability of high-energy particle accelerators cannot only be expected to provide insight into the pathways of bystander signals transduction between neighbouring cells, but to assist the devlopment of models to describe the information of molecular structure acting as luminiscence centres after heavy-ion bombardment.

5. Summary

We have outlined a research and applied physics programme, which was worked out in a recent study [1] for the planned MEDAUSTRON centre for cancer therapy. Although the medical requirements define the baseline beam parameters and scheduling, moderate modifications of the accelerator allow its use for interesting physics experiments. The establishment of a proton scattering facility at MEDAUSTRON and specific applied physics experiments as e.g. the High energy proton Computerised Tomography (HepCT) are very appealing. In addition the proton beam is excellently suited as a test beam for the development of detectors. The MEDAUSTRON centre will be the only accelerator facility in Austria of that class and its use for non-clinical physics research will be of particular importance for the local research communities as a homebase. Apart from its research oriented purpose MEDAUSTRON will also be an almost ideal facility to train, to teach and to educate young scientists with state-of-the-art methods and technologies not only in physics, but also in electronics and electrical engineering, computer sciences, mechanical engineering and mechatronics.

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