Energy deposition of protons in silicon sensors at MedAustron

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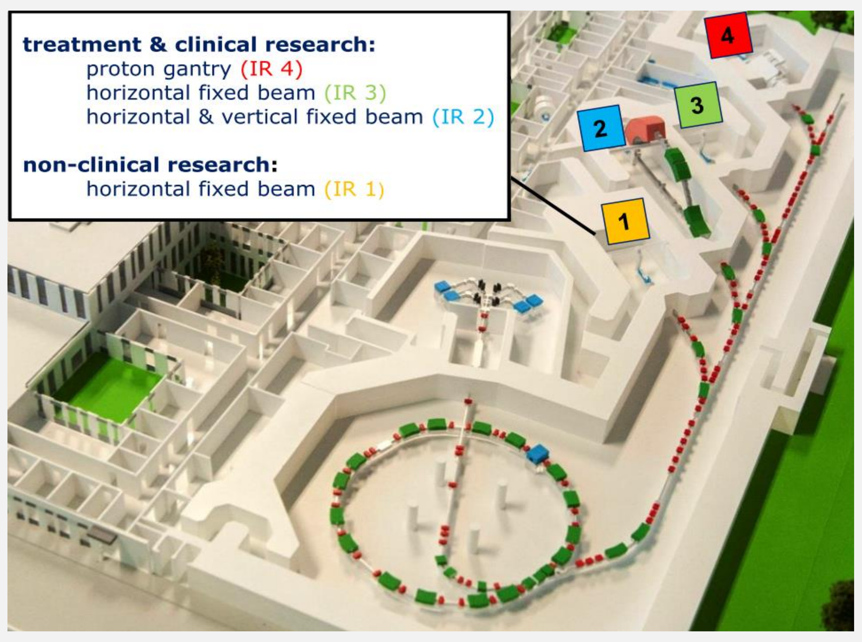
Introduction and objective



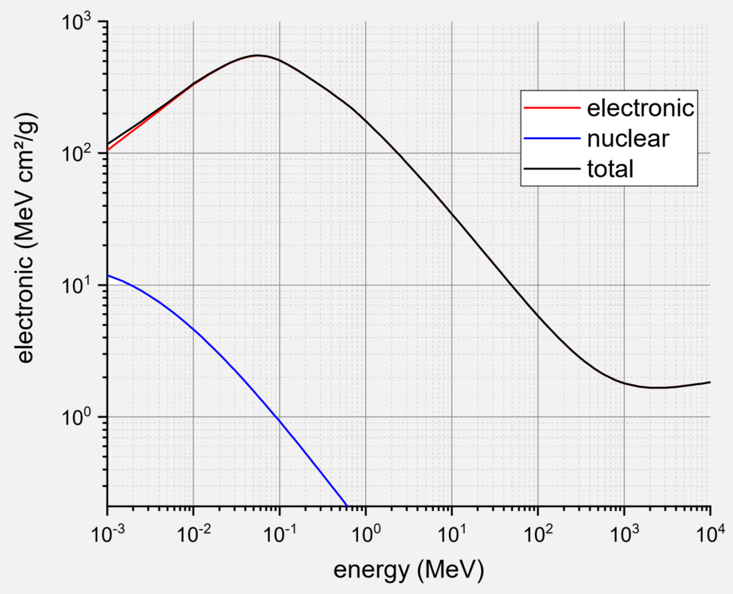
Layout of MedAustron with its four irradiation lines

MedAustron is a proton and heavy ion synchrotron used for hadron therapy, medical, biological and high energy physics experiments. Its circumference is 78 m with 16 dipole and 24 quadrupole magnets. Currently ion beam energies of 252 MeV are in operation. In the coming months of 2019, higher beam energies of up to 800 MeV should be achieved. MedAustron is equipped with four irradiation lines (IR), three of them are for clinical purpose (IR 2-4). The remaining one (IR1) is reserved for non-clinical research purposes, like in our case for performance tests on strip sensor protoypes.

The first testbeam was the first ever for silicon sensors at MedAustron. It aimed to verify the applicability of a so-called "ALiBaVa"-Setup[1] by conducting energy deposition measurements with silicon strip at different proton energies. The resulting energy deposition should follow the Bethe-Bloch equation:

$$-\frac{dE}{dx}\Big|_{coll} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\underbrace{\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2}}_{\text{semi-relativistic}}\ \underbrace{-\beta^2}_{\text{relativistic correction}}\ \underbrace{-\frac{\delta(\beta\gamma)}{2}}_{\text{density correction}}\right]$$

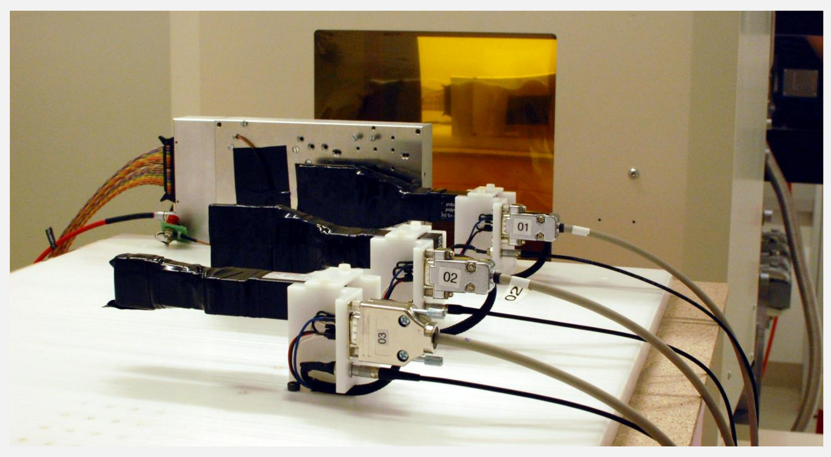
According to this equation, the distribution of the deposited energy has a minimum, the "minimal ionizing particle" (MIP), which is at ~2.45 GeV for protons in silicon.



Stopping power of protons in silicon according to the Bethe-Bloch equation

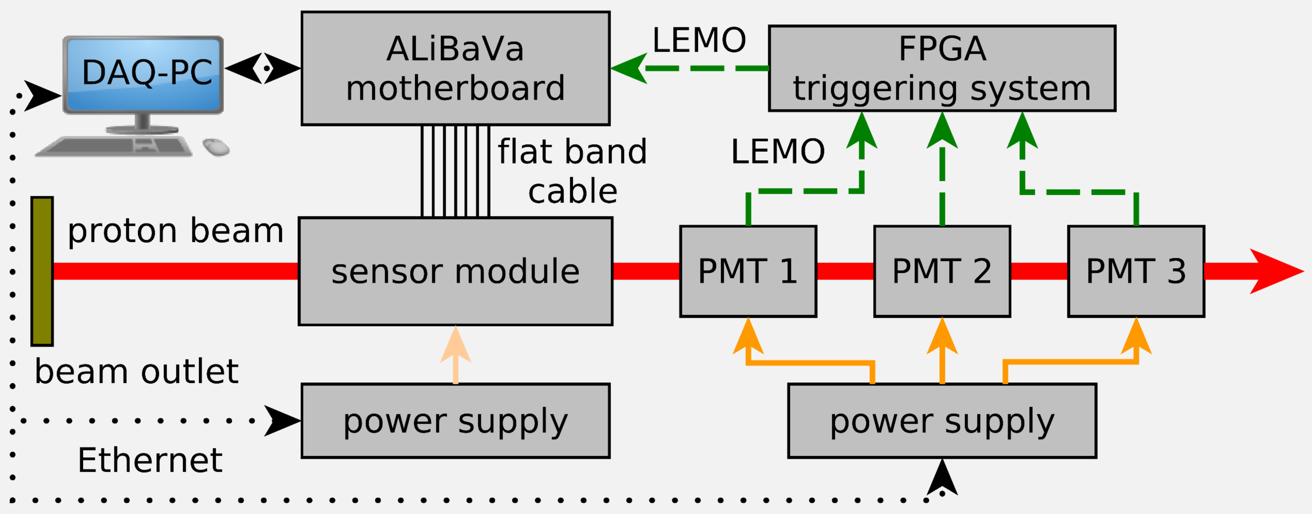
Second testbeam (TB 2)

During data analysis after testbeam 1, it became clear that particle rates of 10^8/s or higher lead to pile-up effects and high occupancy, which negatively affected energy and spatial resolution. These effects also lead to exaggerated energy depositions. To encounter this problem, the MedAustron staff made several changes to the synchrotron based on predefined recommendations [3][4].



Scintillators after DUT, TB 2

To improve energy resolution at lower energies, we altered the setup by placing all scintillators after the sensor (DUT, device under test) and decreasing distance to the beam outlet window.
For trigger control, we developed a triggering and coincidence system using a commercial, general purpose FPGA board.

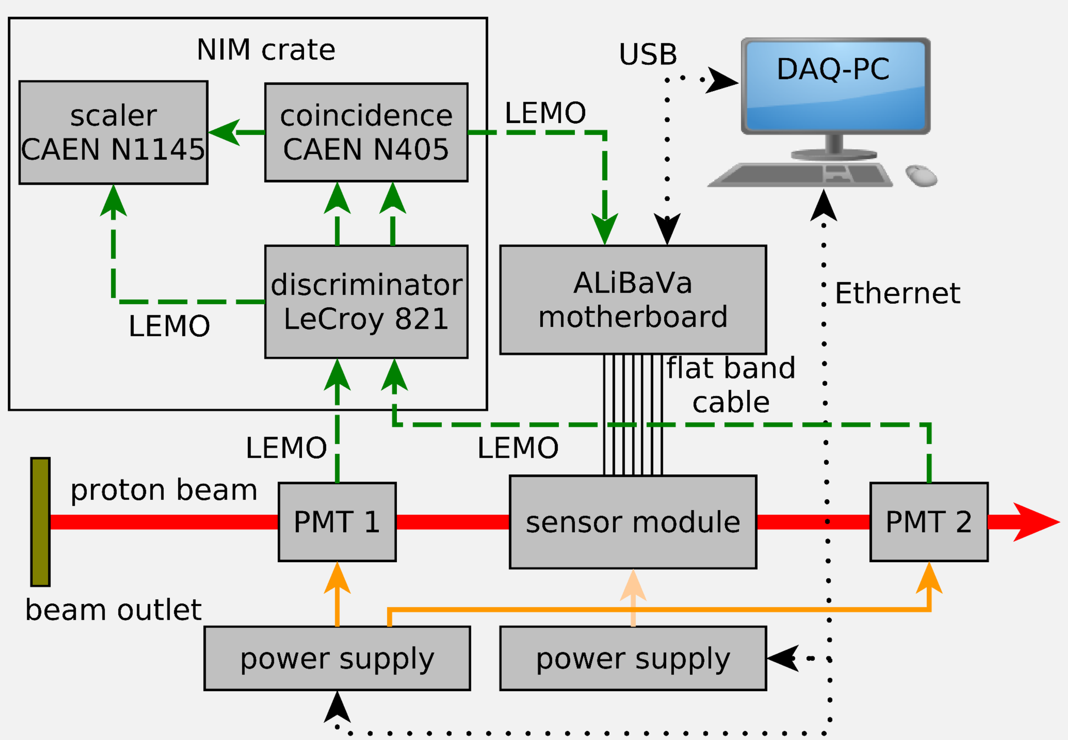


DAQ, triggering and power supply at testbeam 2

After this testbeam we observed less pileup and occupancy, so determination of energy deposition was less error-prone.

First testbeam (TB 1)

For the first testbeam, we decided to utilize a "classic" trigger setup with one scintillator in front and one after the strip sensor (DUT, device under test). The trigger signals were directly fed to NIM-modules, readout and data acquisition was done by the ALiBaVa[1] system and an external trigger control system was implemented.
Data transfer was achieved by connecting the ALiBaVa motherboard to a DAQ-PC via USB. This PC was remotely controlled via SSH and VNC. The DAQ-PC also operated the SMUs for power supply of the photomultipliers and the DUT. This allowed online monitoring of the data via the ALiBaVa-GUI, including trigger efficiency, histograms of the analog signal height and hitmaps.
Monitoring the LED indicators of the SMUs and NIM modules happened via webcams, provided by MedAustron. Beam alignment was done manually by using a provided laser coordinate projection system, which allowed us to aim at the sensor without major corrections.

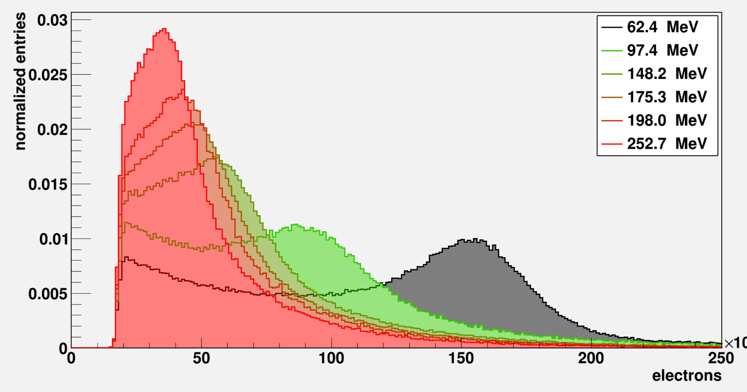


DAQ, triggering and power supply at testbeam 1

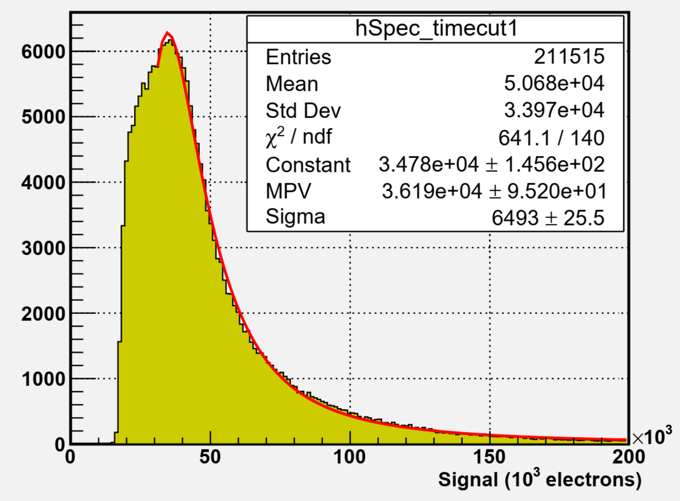
Effective particle rates were between 10^8/s and 10^{10}/s. Through this high particle rates, testbeam data suffered from pile-up effects and occupancy, which resulted in overestimated energy deposition.

Results

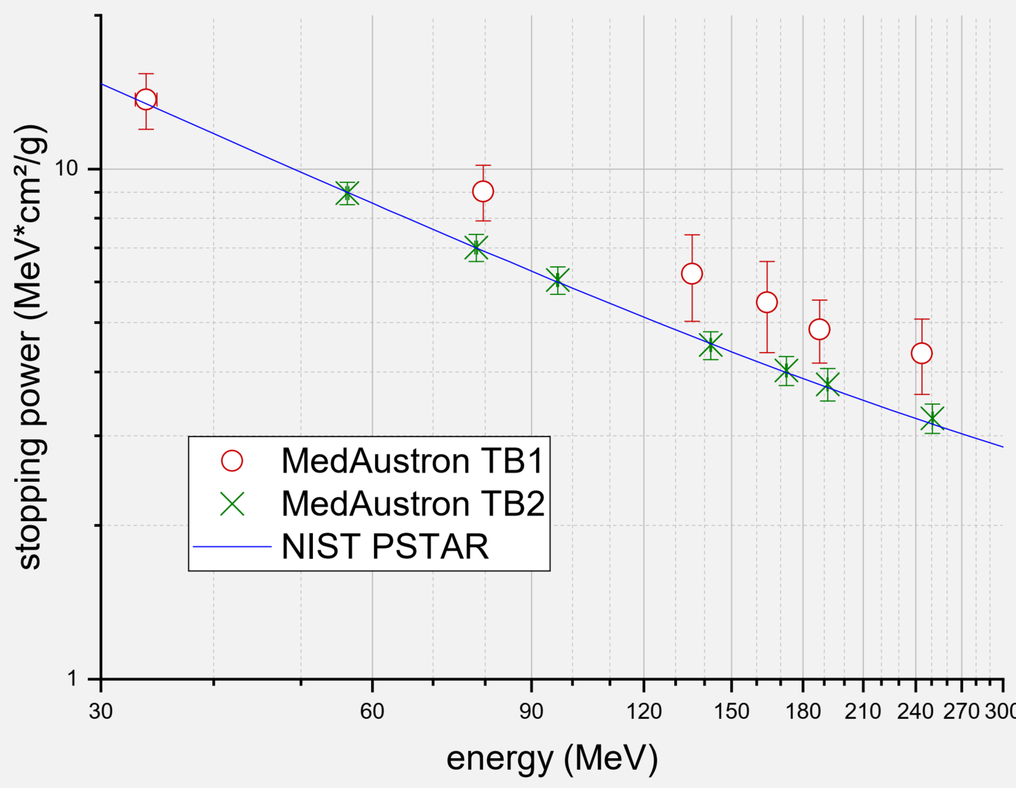
Determination of energy deposition was achieved by fitting a Landau profile to the histogram of the signal pulses. The mean of the profile represents the mean energy deposition.
After the first testbeam, results of the analysis showed that high particle rates, which lead to pile-up effects and high occupancy. Both testbeams exhibit high noise levels at small signal ranges, whereas this problem did not show up at the preparatory tests at HEPHY. We assume that this noise was caused by extrinsic factors, like focusing magnets, vacuum pumps and other control devices of the beam outlet. Modeling this noise behavior via an exponential function and subtracting it from the signal failed, so it was difficult to distinguish between noise and signal.



Overlay of all energy deposition histograms of TB 1



Fit of a Landau profile to the energy deposition histogram of the strip sensor at testbeam 1. The proton energy is 252.7 MeV.



Stopping power of both testbeams, compared to reference data[5]. The shift is caused by absorption through air and polyvinyl toluene.

Simulation of energy loss

It became clear that energy loss of protons through air and plastic at the used energy ranges (62 to 252 MeV) should not be neglected. Due to the scintillator thickness of 1 cm, it was expected to lose approximately 10 MeV at the lowest energy of 62 MeV. The stopping power of air is three magnitudes lower, but the penetrated material thickness was two magnitudes higher (60 cm). To encounter this issue, the setup of the second testbeam was changed.
To quantify energy losses, the simulation tool SRIM ("Stopping and Range of Ions in Matter"[2]) was used. Material budget was modeled as consecutive, homogeneous layers. Because polyvinyl toluene (scintillator) and polyvinyl chloride (tape) have similar and non-negligible stopping powers, the light shielding tape was also taken into account.
The results were used to make an energy correction for determined stopping powers.

Conclusion

For achieving better energy resolution in future testbeams, well-defined particle rate control by MedAustron is essential. If there is a demand for low-energy testbeams, it is essential to analyze the non-linear gain behavior in the upper range of the ALiBaVa's capability of measuring deposited energies up to 10 MIPs. Based on that, one may eventually extend the analysis software algorithm. Further procedures should cover protection against electromagnetic interference. Finding an appropriate model to characterize electronic noise contribution to improve signal-to-noise ratio would be advantageous.
At MedAustron, short night shifts of only six hours of beam time made troubleshooting difficult. For the next testbeams, it is recommended to conduct two or more consecutive shifts at weekends to expand active beam time, generating more data runs and improving time efficiency.

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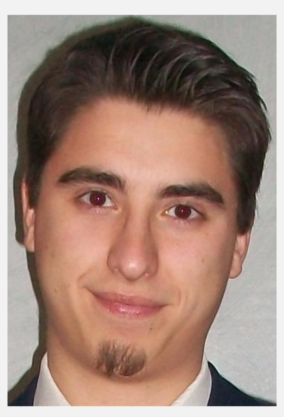

References

[1] Alibava user's manual. https://www.alibavasystems.com/, accessed in January 2019
[2] J. F. Ziegler, M. D. Ziegler, and J. P. Biersack. SRIM - The stopping and range of ions in matter (2010). *Nuclear Instruments and Methods in Physics Research B*, 268:1818–1823, June 2010.
[3] L. (TERA) Badano and S. (CERN) Rossi. Characteristics of a betatron core for extraction in a proton-ion medical synchrotron. *THPS048*, January 2006
[4] Jan Borburgh and Thomas Kramer. Design of electrostatic septa and fast deflector for medaustron. THPS048, January 2011.
[5] NIST PSTAR. Physical measurements laboratory, 2017.