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Unique characteristics and performance of a mid-infrared laser source for muonic hydrogen spectroscopy and proton Zemach radius measurement: The laser of the FAMU experiment(*)

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Summary. — The FAMU experiment, aimed at improving the precision in determining the proton Zemach radius via muonic hydrogen spectroscopy, is currently in the second half of its planned data-taking campaigns. Conducted at the ISIS facility of the Rutherford Appleton Laboratory (UK), the experimental method requires an intense pulsed muon beam to generate muonic hydrogen, which is then excited using a custom-designed laser system to excite the hyperfine splitting in the muonic hydrogen 1S state. Developed by the INFN Trieste section in collaboration with University of Campania and Elettra-Sincrotrone Trieste, the laser is unique in its class, providing high energy, narrow linewidth, and precise tunability in the mid-infrared range around 6.78 μm, corresponding to an energy of 0.182 eV. The laser operates via a Difference Frequency Generation (DFG) process within a $BaGa_4Se_7$ nonlinear crystal, combining a commercial 1064 nm Nd:YAG pump with a custom-built tunable 1262 nm Cr:forsterite-based laser source. To ensure long-term stability and remote operation, a dedicated control system was developed, integrating energy, wavelength, and beam position sensors with active feedback piezoelectric actuators. Throughout four completed data taking runs, the mid-IR radiation, with linewidth of 15 pm, has featured an excellent energy stability, with pulse energies exceeding 1.5 mJ and a standard deviation of 5%, a central wavelength reproducibility of 3 pm together with a tunability step of 10 pm.

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1. – Introduction

The FAMU (Fisica Atomi MUonici) collaboration is dedicated to precisely determining the proton Zemach radius through the measurement of the 1S state hyperfine splitting (HFS) in muonic hydrogen [1].

The experiment is located within ISIS Neutron and Muon source at the Rutherford Appleton Laboratory (UK). A pulsed muon beam, produced by the facility, is stopped in a hydrogen gas target, leading to the formation of muonic hydrogen. A narrow-linewidth laser beam, finely tuned in a range around 0.182 eV (6.78 μm), is injected into a multipass optical cavity placed inside the gas target to induce the hyperfine splitting transition in the ground state thermalized muonic hydrogens. The spin flip transition, is not directly detectable, instead, the experimental method relies on monitoring the variation of the muonic transfer rate from hydrogen to a high-Z impurity, specifically oxygen, present in the target. This transfer rate is directly correlated with the kinetic energy of muonic hydrogen. When the laser excites the HFS transition, because of the subsequent de-exitation, the muonic hydrogen hydrogen acquires kinetic energy, resulting in an increased muon transfer to oxygen [2,3]. A measurable change in the muonic transfer rate, identified by observing characteristic muonic oxygen X-ray lines, signifies that the laser is tuned to the exact energy required to trigger the muonic hydrogen spin flip.

This work details the laser system specifically developed for the FAMU experiment. It produces 7.5 ns pulsed radiation at a 25 Hz repetition rate, with a peak energy of 1.7 mJ, a linewidth of 15 pm, and tunability across the 6730 to 7135 nm range. These characteristics position this laser as a unique coherent radiation source within our region of interest.

2. – FAMU Laser System

The nonlinear process chosen to generate a pulse laser source for the FAMU experiment is the Difference Frequency Generation (DFG), which is capable of providing tunable, narrow-linewidth, high-energy mid-IR light pulses. DFG requires two distinct single-mode, narrow-linewidth laser sources that must be combined before being injected into the nonlinear crystal. For this application, the 1064 nm beam was selected as the pump, and the 1262 nm beam as the signal. These are subsequently combined and monitored before being introduced into the DFG unit for the generation and monitoring of the 6.78 μm light. More detailed description of the laser can be found in [4]. A photo of the laser system with the described part highlighted can be seen in fig. 1.

The resulting 6.78 μm light is then coupled into the FAMU gas target, which incorporates a multi-pass optical cavity. The entire laser system is situated on an optical table and enclosed within a non-flammable, interlocked plastic box. This enclosure serves both safety purposes and thermal stabilization, thereby enhancing the overall stability of the laser system.

The pump source is a commercially available injection-seeded, single-longitudinal mode (SLM) Nd:YAG laser system, primarily centered at 1064.426 nm. This system has been specifically modified to satisfy the experiment's requirements regarding pulse duration. It operates as a master-oscillator power-amplifier (MOPA) Nd:YAG laser (INNOLAS SpitLight Hybrid II), seeded by a highly stable continuous-wave fiber laser at 1064.4305 nm (Rock Fiber Laser Seeder, NP Photonics). A feedback-controlled piezomotor system ensures the maintenance of single longitudinal mode operation, achieving a 0.35 pm linewidth.

The laser beam serving as the signal in the DFG process is centered at 1262 nm and offers tunability within the 1257-1267 nm range, exhibiting a linewidth of 0.23 pm. Operating in a single longitudinal mode, this laser generates pulses with a duration of 10 ns, a max energy output of up to 45 mJ, and a time jitter of ±3 ns. This 1262 nm laser beam is produced by a dedicated Cr:forsterite MOPA laser system, which integrates a Cr:forsterite crystal pumped by an internal Nd:YAG laser (LS-2138N, LOTIS TII). The emitted light is then directed into a 3-stage, 16-pass power amplifier, which is in turn pumped by another Nd:YAG laser (INNOLAS SpitLight 600) [5, 6].

To maximize the efficiency of DFG process it is necessary to have time synchronization, spatial superposition and correct polarization of the 1064 nm and 1262 nm beams at the nonlinear crystal. These are respectively obtained by tuning the pulse generator (Quantum Composer, model 9520) that triggers both laser flashlamps and Pockels cells, a set dedicated telescopes and mirrors for the alignment and two waveplate to change to match the phase-matching angle of the crystal.

The nonlinear crystal is mounted on a 6-axis kinematic stage for precise alignment and to set the correct phase-matching angle. Different nonlinear crystal were tested [7], the final chosen crystal is an $8.9 \times 10.3 \times 28.5$ mm^3 $BaGa_4Se_7$ crystal in type-I phase matching.

To prevent absorption of the IR light in the ambient air, primarily due to atmospheric water vapor, the DFG setup and the light path leading to the target are enclosed within sealed covers filled with dry air, maintaining an internal atmosphere with less than 5% relative humidity. At this stage, the generated 6.78 μm mid-IR beam, after its comprehensive characterization, is directed towards the FAMU target.

The laser system is integrated with a specially developed software, termed FAMU Laser Control (FLC). This software continuously monitors and sets the parameters of the entire laser system in real-time through an array of sensors and piezoelectric actuators. The software incorporates automatic stabilizers that actuate the piezomotors in the oscillator cavity, utilizing real-time measurements collected by the program as input, to stabilize the wavelength.

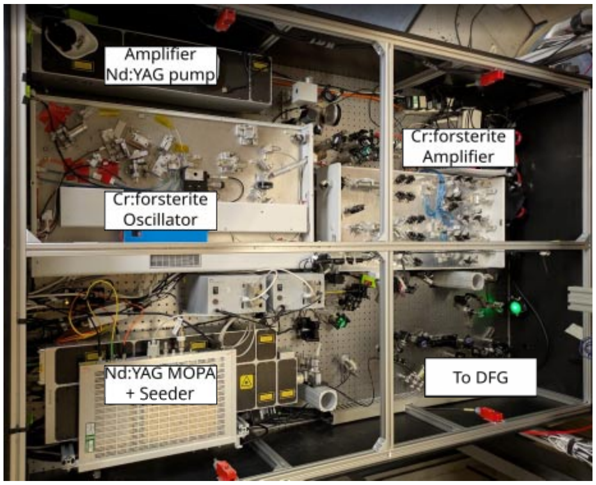


Fig. 1. – A photo of the laser setup inside its safety box. The major components are highlighted.

3. – FAMU Laser specification

The system is tunable over a broad spectral range from 6730 nm to 7135 nm, centered around the target wavelength of 6.78 μm. However, during the data acquisition campaigns, the laser was specifically operated within the narrow interval from 6788.400 nm to 6789.100 nm to match the experimental requirements.

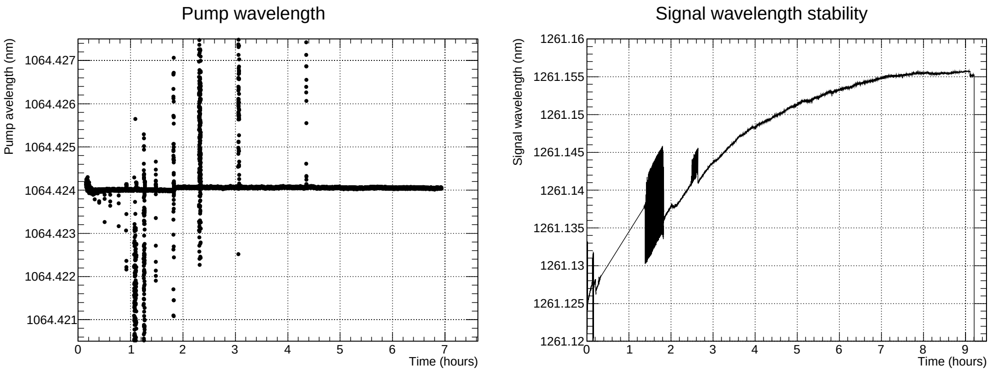
The linewidth of the mid-IR radiation at 6.78 μm was estimated to be approximately 15 pm, based on the measured linewidths of the pump (0.35 pm at 1064 nm) and signal (0.23 pm at 1262 nm) sources.

During the data taking, the pulse energy ranged from 1 mJ to 1.7 mJ, with an average value of 1.5 mJ, ensuring the minimum level of energy to observe the muonic hydrogen spin-flip transition.

Laser stability, in terms of central wavelength, linewidth and pulse energy, is crucial for the FAMU experiment. Data collection typically spans 10 consecutive days of continuous (24/7) operation, with a single wavelength measured every 23-24 hours. Throughout this period, the laser must maintain both a stable wavelength and consistent energy output. This level of long-term operational stability is, to our knowledge, unique among mid-infrared pulsed laser sources with comparable characteristics.

Thermal and mechanical effects can introduce instability into the laser system and principally on the Cr:forsterite oscillator's cavity, leading to a loss of single-mode laser emission or wavelength drift, which can negatively affect the FAMU data collection.

An example of the effect of the temperature on the laser wavelength and single-mode operation can be observed in fig. 2, which shows the pump and signal wavelength in the first hours after startup. During the operating condition, the temperature increases inside the laser box due to the working laser and we can observe on the right the temperature affecting the wavelength in the signal laser, on the left the loss of single mode on the pump laser.



Pump wavelength

Signal wavelength stability

Fig. 2. – The two plots show the wavelength behavior of the pump and signal lasers during the initial hours after startup. On the left, the pump wavelength becomes nearly stable after the second hour, with rapid vertical fluctuations occurring alongside temporary losses of single-mode operation, which gradually subside over time. On the right, the signal wavelength exhibits a pronounced drift that stabilizes after approximately 7 hours, primarily due to temperature variations in the laser during startup.

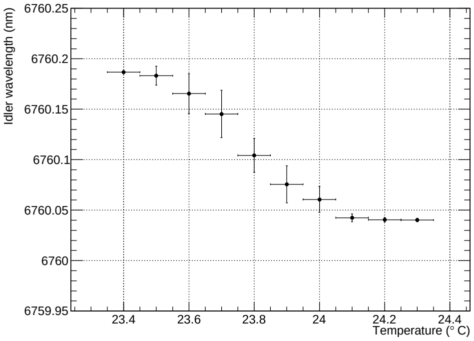


Fig. 3. – The graph displays the mean idler wavelength corresponding to each measured temperature inside the laser enclosure. No temperature correction is applied. A clear trend is observed in the curve; however, the plot is limited by the temperature resolution of the measurement system.

This thermal effect is clearly visible in fig. 3, which shows a direct correlation between temperature and wavelength: the wavelength tends to increase as the temperature decreases. Measurements were taken after the laser reached thermal equilibrium, over a total period of 11 hours. The wavelength drifted by 150 pm due to a 1 °C temperature shift and has to be compared to the wavelength step and stability achieved by the experiment which is of the order of 3 pm. This last result can be only achieved with the automatic stabilizers activated.

4. – Conclusion

A mid-IR, tunable, and narrow-bandwidth laser source, emitting around 6.78 μm, has been successfully developed for the FAMU experiment. The core objective of this experiment is to precisely determine the proton radius by measuring the hyperfine splitting of the 1S state in the muonic hydrogen atom. This laser is essential for exciting the desired transition in muonic hydrogen. Its design is based on a DFG scheme, employing a fixed light source at 1064 nm and a tunable laser operating around 1262 nm, which collectively enable the generation of infrared radiation within the spectral range of 6730-7135 nm.

The FAMU laser system effectively meets all the experiment's requirements and was used in four data taking between 2023 and 2024. To our current knowledge, it represents a unique source at this wavelength, boasting a linewidth narrower of 15 pm with a wavelength stable to the 3 pm level and an energy output of up to 1.5 mJ.

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