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Mid-IR narrow bandwidth tuneable laser source for the FAMU experiment

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Abstract. The FAMU (Fisica degli Atomi MUonici) collaboration aims to measure the proton Zemach radius through muonic hydrogen (μp) spectroscopy. The experimental setup relies on a custom-developed pulsed mid-IR laser source that can be tuned over a specific 6780-6790 nm wavelength range needed to ignite the hyperfine transition of the µp ground state 1S (also known as spin-flip transition). The excitation is observed as a distinctive muonic X-rays emission resulting from the oxygen impurity present in the hydrogen target. The mid-IR emission is produced by Difference Frequency Generation (DFG) in a non-linear crystal, pumped with a fixed wavelength 1064 nm Nd-YAG laser and a tuneable Cr:forsterite laser centred on 1262 nm. This setup produces more than 1.2 mJ at 6780 nm with a linewidth smaller than 30 pm. The experiment requires the laser to run continuously 24/7 in a restricted/radiation-controlled area and for this reason a specifically developed control software permits to remotely act on the laser. The characterization of a series of different non-linear crystals was performed during the development of the laser, resulting in the choice of $BaGa_4Se_7$.

1 Introduction

The Fisica degli Atomi MUonici (FAMU) experiment aims to measure the proton radius with high precision exploiting the use of a unique exotic atoms spectroscopy technique [1]. The experiment is hosted inside the ISIS Neutron and Muon facility at RAL (UK).

1.1 FAMU method

The muons produced by the accelerator are injected in the cryogenic gas target formed by mixture of hydrogen and a small percentage of oxygen contaminant. Here muons are stopped and form muonic hydrogens (μp) that, once thermalized, are illuminated by a laser to excite the spin flip in the 1S state. The expected spin flip transition energy is around 0.1828 meV, which in terms of the wavelength is 6789 nm. Shortly, μps de-excite leaving considerable energy to the muons, which increase their hydrogen to oxygen transition rate. If the correct wavelength is chosen, the variation in the transition rate is measured as a variation of the muonic X-rays rate produced by oxygens [2].

2 FAMU laser system

To meet the experiment's specifications, the laser needs to be pulsed and synchronized with the muons' arrival at the target. It must also be tuneable within the desired mid-IR range, centred at 6789 nm, with a linewidth under 30 pm. Furthermore, it should exhibit consistent stability over time, and its pulse energy should be maximized, reaching a minimum of 1 mJ.

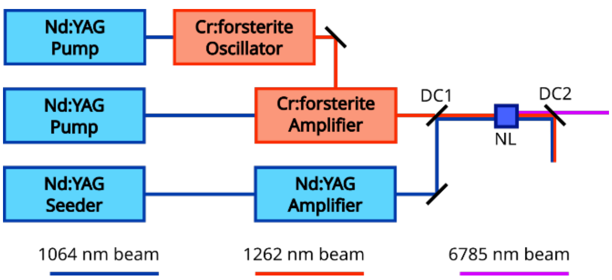

Fig. 1. Scheme of the laser setup. DC1 an DC2 indicate dichroic mirrors whereas NL indicates the non-linear crystal.

The strategy chosen for the light generation at the required wavelength is Difference Frequency Generation (DFG). In this process, two near infrared beams are combined on a non-linear optical crystal to produce a third beam. The frequency of this third beam is the difference

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between the frequency of the two input beams. 1064 nm and 1262 nm are the wavelength chosen to obtain the final laser source at 6789 nm [3]. A scheme of the reported setup is showed in **Fig. 1.**

2.1 Laser sources

The 1064 nm laser source is a commercially available Innolas Spitlight II Nd:YAG laser. It is based on a seeded MOPA with a CW laser that acts on the MOPA cavity mirror to maintain the laser in single longitudinal mode (SLM). This laser system can provide up to 140 mJ at 1064.430 nm with a linewidth of 0.35 pm.

The 1262 nm laser source was developed specifically according to the experiment requirements. The Cr:forsterite oscillator at 1262 nm light is a pumped with a Nd:YAG laser, producing up to 1 mJ of 1262 nm SLM light with a linewidth of 0.2 pm [4,5].

However, this laser system is not sufficient to provide the energy required to obtain 1 mJ at 6789 nm. Therefore the Cr:forsterite oscillator light is amplified in a 16 passage amplifier based on 3 stages, each one with a Cr:forsterite crystal pumped by another Nd:YAG laser. After the amplifier the laser beam can reach up to 45 mJ, meeting the energy requirement for the DFG process [4,5].

2.2 DFG setup

The 1064 nm and 1262 nm laser beams are synchronized, superimposed and the non-linear crystal is correctly aligned at the correct phase matching angle thus enabling the DFG process [6]. Before the injection in the non-linear crystal, the two beams are monitored to guarantee safe energy levels, and correct wavelengths and positions. A specific software controls the laser status and acts directly on the oscillator to maintain the SLM operation and to stabilise wavelength fluctuations.

3 Results

A variety of non-linear crystals has been tested in order to reach the best choice at our scope. Among them were $LiIns_2$, $LiInSe_2$, GaSe, $AgGaS_2$ and $BaGa_4Se_7$. These crystals were evaluated within a setup operating at lower energies, assessing factors such as transparency, coating quality, angle of incidence and 6789 nm energy as function of the pump beams. Each crystal possesses distinct non-linear coefficients and damage thresholds, crucial factors for selection (**Table. 1**).

Table. 1. Summary of the damage thresholds and non-linear coefficients of the tested crystals.

Crystal	Damage Threshold (MW/cm2)	Nonlinear Coefficient (pm/V)	Note
$LiInS_2$	200	d_{33}=16	[7]
$LiInSe_2$	56-66	d_{33}=11	[8]
$AgGaS_2$	25	d_{36}=13.4	[7]
GaSe	121	d_{22}=72	[9]
$BaGa_4Se_7$	557	d_{13}=20.4	[10]

$BaGa_4Se_7$ exhibited superior performance compared to others, attributed to its favourable parameters. As can be seen in **Fig. 2**, injecting 4 mJ@1064 nm and 4 mJ@1262 nm, with both beams having a 3 mm beam size, the $BaGa_4Se_7$ outperformed the others with a max energy of 40 μJ. Also, GaSe crystal demonstrated high efficiency; however, its non-coatable surface and a significant angle of incidence rendered it unsuitable.

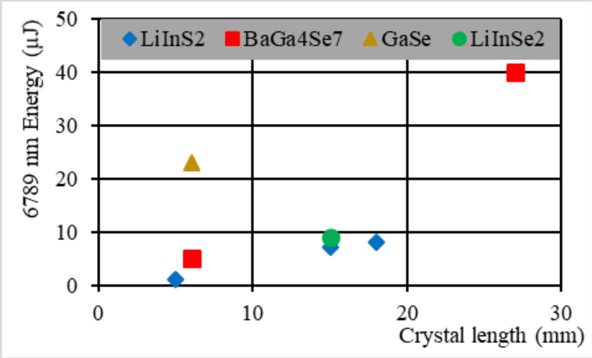

Fig. 2. The plot shows the energy produced with DFG process injecting 4 mJ@1064 nm and 4 mJ@1262.

4 Conclusion

The FAMU experiment requires a unique source of mid-IR light that is provided by the specifically developed FAMU laser system.

Different DFG crystals were tested to ensure the use of the best suitable crystal type. The chosen non-linear crystal is a $BaGa_4Se_7$.

The laser performed according to the expectation during the last two FAMU data acquisitions in 2023. The laser was able to deliver continuatively, for a maximum of 12 days 1.2 mJ of light at 6789 nm, with a stability in the order of 3 pm.

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