Spectroscopy of Muonic Hydrogen with a Compact FEL

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Abstract

A preliminary project for a Far Infrared Free Electron Laser to be used in a spectroscopic experiment is presented. The goal of the experiment is to measure the energy difference between levels in muonic hydrogen atoms, in order to evaluate the QED correction due to the vacuum polarization with a precision better then 10^{-4}.

1. INTRODUCTION

The aim of this experiment is to test the Quantum Electrodynamical (QED) correction to the binding energy in muonic atoms [1]. In such systems the main contribution to the QED correction is the vacuum polarization. Nowadays tests of this QED correction have reached a precision of order 10^{-3}. With this experiment it will be possible to improve the accuracy to a precision of 10^{-4} by measuring the 3P-3D resonance in muonic hydrogen (μp). The levels of μp are shown schematically in Fig.1, without the sublevels of fine and hyperfine splitting.

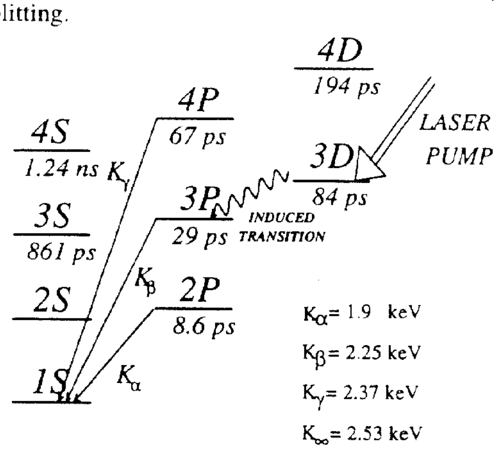

Fig. 1: Muonic hydrogen energy levels and lifetimes. Interesting transitions are shown.

When a muon is captured by a proton, it cascades down to the ground level emitting x-rays. Irradiating the system, a $3D^5_{3/2} - 3P^7_{5/2}$ transition (ΔE=5.33 meV, λ=232 µm) can be stimulated resulting in a change in the ratio between the K_α and K_β x-ray lines. The resonance will be determined by measuring the ratio K_β/K_α as a function of the laser wavelength.

An alternative transition to be studied is the $4P^7_{5/2} - 4D^5_{3/2}$, corresponding to an energy difference ΔE=2.325 meV (λ=532 µm). For this transition the laser power required is lower, but the lenght of the optical pulse must be double with respect to the 3P-3D transition.

Negative pions are injected radially into an anticyclotron device, where they decay in flight. Low energy muons are trapped by the magnetic field of the anticyclotron and slowed down. The muons are finally axially extracted at energies of 10-50 keV. A collimator of 1 cm aperture and a muon detector further select the muons and generate a muon signal, used to trigger the FIR laser. After a time which is long enough to build up the laser pulse (~ 1.5 µs), the muon reaches the target cavity, where it stops in the hydrogen gas (20 mbar). Mirrors inside the cavity enhance the laser intensity. The x-ray K-lines of the μp system (Fig. 1) are detected by CCD devices surrounding the cavity.

2. THE FREE ELECTRON LASER

The short muon life time and the high accuracy required in measuring the energy difference between μp levels impose a number of severe requirements on the FIR radiation source needed for this experiment. The tunability and pulse duration requirements rule out the possibility of using a conventional laser source, leaving as only possible solution the choice of a Free Electron Laser. The FEL source should satisfy several strong requirements that can be summarized as follows:

a) The FEL has to be triggerable within a time less then 1.5 µs after the muon detection, in order to excite the μp system during its formation.

b) Tunable operation within a range of $\pm 1\%$ at the two wavelengths 232 µm (3P-3D) and 532 µm (4P-4D) is necessary.

c) A linewidth of about $5 \cdot 10^{-3}$ is required, with a corresponding pulse duration $\delta t \sim 100$ ps (for a Fourier transform limited pulse).

The actual design is based on the choice of a RF linac in the S-band (3GHz) as electron beam source (see tab.1). Using this accelerator, together with a harmonic

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prebuncher, electron pulses of 3.7 ps (fwhm) duration can be generated within less than 1μs from an external trigger.

Table 1: Linac parameters

Electron Energy (MeV)	5.5
Peak Electron Current I (A)	40
Emittances (π mm-mrad)	16
Energy spread (r.m.s.)	0.3%

The apparatus will be compact and with moderate shielding requirements, since the electron energy set at 5.5 MeV is below the neutron production threshold. The high e-beam current obtained with the prebuncher allows lasing with a short period small number of periods undulator. A linear hybrid permanent magnet (NdFeB) undulator with a variable gap, allowing a fine wavelength tuning will be used. A waveguide resonator is recommended in this spectral region to avoid diffraction problems. Moreover varying the waveguide gap it is possible to tune the emission frequency from 232 mm to 532 mm. Most of the technical solution adopted for this FEL are tested in the FEL facility operating in Frascati [2]. A layout of the device is shown in fig.2.

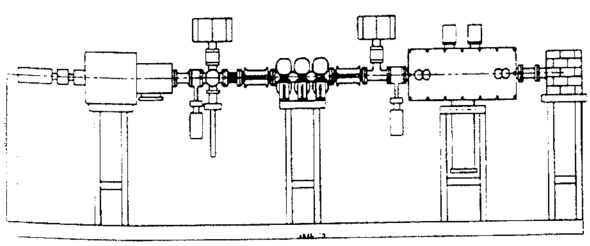

Fig. 2: General Layout.

The set of experimental parameters shown in Table 2 has been chosen in order to satisfy several different requirements on the output radiation, as wavelength, bandwidth, power and pulse duration, as well as tunability around the two wavelengths 532 mm and 232 mm.

Table 2: Undulator/waveguide parameters

Resonance wavelength (μm)	532	232
Undulator Period λ_u (cm)	2.5	2.5
Number of Periods N	16	16
Undulator Parameter K	1.412-1.425	1.180-1.232
Waveguide hor. gap a (cm)	3	3
Waveguide vert. gap b (cm)	0.188	0.4
Waveguide length L (cm)	50	50

3. FEL DYNAMICS

The behaviour of a FEL operating with the above set of parameters has been tested in the small signal regime to calculate the signal rise time and the coherence development. A multimode Hamiltonian model [4] has been used to test the FEL dynamics in a waveguide, operating with very short electron pulses. In fig.3 it is shown the average output power as a function of time. With 10% of losses the net gain per pass is g≈65% and the laser reaches saturation within 150 ns

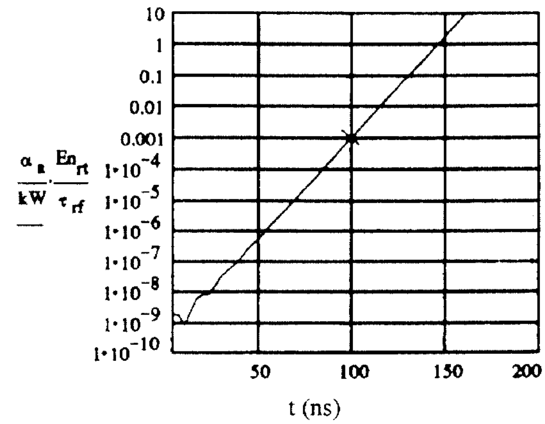

Fig. 3 Output power vs. time with 10% losses

In fig.4 it is shown a contour plot of the intensity vs frequency and round trip number. For the first round trips the spontaneous emission gives rise to fluctuatios that disappears when the steady state is reached.

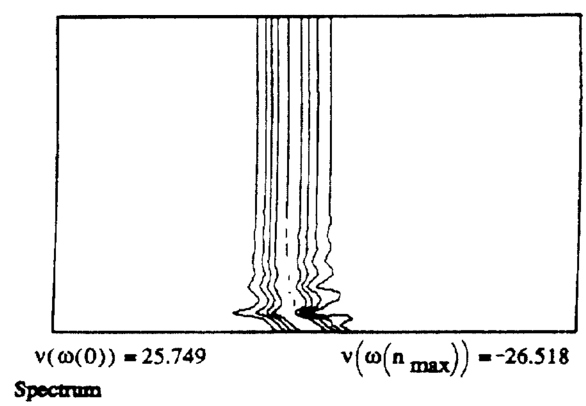

Fig. 4 Contour plot of the intensity vs frequency and round trip number for the first round trips.

In these conditions the pulse duration is only 7ps (fwhm), i.e. it is far away from the requirements. The lengthening of the pulse may be essentially obtained in two ways:

1. Detuning the optical cavity from the optimum value.

2. Introducing an ethalon intracavity to limit the number of lasing modes.

Unfortunately both those solution have the drawback of strongly reducing the FEL gain. The simulations have shown that the effects on the gain due to the intracavity ethalon and to the cavity detuning, in the small signal regime, are essentially the same and that the introduction of a longitudinal filling factor accounting for the superposition of the electron pulse and the laser pulse, suitably reproduces this gain depression. The validity of these considerations is however limited to the small signal regime. It is evident that saturation affects both the pulse shape and its mode contents. A more detailed analysis including saturation effects will be the subject of future investigations.

4 REFERENCES

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