

# DEVELOPMENT OF A HIGH POWER FIBRE LASER FOR LASER BASED ELECTRON BEAM DIAGNOSTICS\*

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## Abstract

We present the latest results on the development of a high power fibre laser system for use in a linear collider laser-wire experiment. The laser consists of a solid state oscillator which can be synchronised to an external frequency reference, and two amplification stages in double clad doped fibre, giving 1µJ pulses in a burst mode suitable for a linear collider laser-wire system. This output is amplified in large mode area photonic crystal fibre to generate the high pulse energy necessary for Compton scattering without any deleterious nonlinear effects, whilst maintaining the high spatial mode quality and beam pointing stability of a fibre laser. These properties are essential for producing the sub-micron spot sizes required for the measurement of small particle beam sizes.

## INTRODUCTION

Meeting the challenging performance specifications of proposed future colliders will require flexible and reliable beam diagnostics. Laser-wires are beam profile measurement systems that are non-destructive, fast and can work for profiles down to the micron level [1-4]. The construction of a complete laser-wire is a complex task, and in this paper we concentrate on the high power laser required and the current progress being made on developing a fibre based laser amplifier.

### Laser requirements and proposed architecture

The parameters for a system suitable for laser-wire experiments are summarised in table 1. The requirement for high pulse energies (50 – 100µJ) at relatively high repetition rates (6.49MHz) is beyond current fibre laser technology. However, the laser will operate in a burst mode covering 1ms at 5Hz which reduces the average power requirements to within current capabilities (although such a system has not yet been demonstrated). The major advantages of using fibre lasers instead of solid state technologies are their excellent beam pointing stability and quality, efficiency, and lack of necessity for direct cooling of the fibre, due to the high surface area to volume ratio.

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Table 1: Required laser parameters

Parameter	Value
Repetition rate	6.49MHz
Pulse energy	50 - 100µJ
Pulse duration	~ 1ps
Beam quality	$M^2 < 1.1$
Wavelength	~ 500nm

The proposed architecture for the final laser is:

- i) a solid state oscillator operating at ~ 1µm locked to an external frequency reference;
- ii) chirped pulse amplification (CPA) in two stages of ytterbium (Yb) doped double clad fibre [5];
- iii) final power amplification in Yb doped photonic crystal fibre [6-8];
- iv) pulse compression using fused silica gratings and
- v) frequency conversion to ~ 500nm.

After compression and frequency conversion the green beam is transported to the laser-wire interaction point (IP).

## EXPERIMENT

To carry out preliminary investigations into fibre amplification, a test system has been set up as shown schematically in figure 1.

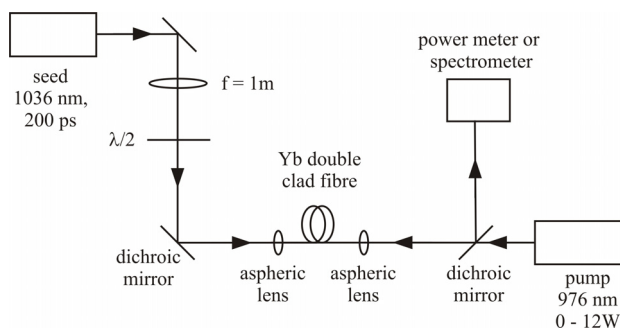


Figure 1: Experimental test system layout.

The commercial oscillator and CPA laser (Amplitude Systemes, Bordeaux) [9] is used to seed an Yb doped polarisation maintaining double clad fibre amplifier. The

fibre core diameter is  $15\mu\text{m}$ , which is slightly multimode at this wavelength, but single mode operation can be obtained with careful alignment of the input.

The pump is a continuous wave (cw) 976nm diode laser (Jenoptik) with output power up to  $\sim 12\text{W}$ , which is coupled into the inner cladding (diameter  $130\mu\text{m}$ ) of the 2.7m fibre. The seed and pump are coupled into opposite ends of the fibre using dichroic mirrors, which are transmissive at the pump wavelength of 976nm and highly reflective at 1036nm, allowing the seed to be separated from the pump at the end of the fibre and any unabsorbed pump to be safely dumped at the input end of the fibre. Coupling the seed and pump into opposite ends of the fibre allows for optimisation of the alignment for each beam separately and is also the most efficient use of the pump light. The fibre has two stress rods incorporated into the inner cladding which introduce birefringence and allow the input (linear) polarisation of the seed to be maintained along the fibre length, provided that the polarisation is correctly aligned to the fibre axis (controlled by the  $\lambda/2$  plate in the input arm). It is necessary for the amplified beam to have a stable linear polarisation for frequency conversion to shorter wavelengths.

The output power of the pump laser is controlled by the driving current, and the power and spectrum of the amplified seed are measured at the output of the fibre. For these experiments the seed input was kept at an average power of 100mW and the pump power increased to a maximum of 12W. The seed laser can be operated in two ways: by using the grating compressor, the output consists of short (0.5ps) pulses, and bypassing the compressor produces pulses of  $\sim 200\text{ps}$ . To avoid nonlinear effects in the fibre (produced by high peak powers) most of the experiments were carried out with the long pulses.

## RESULTS

The output power of the amplifier as the pump is increased is shown in figure 2.

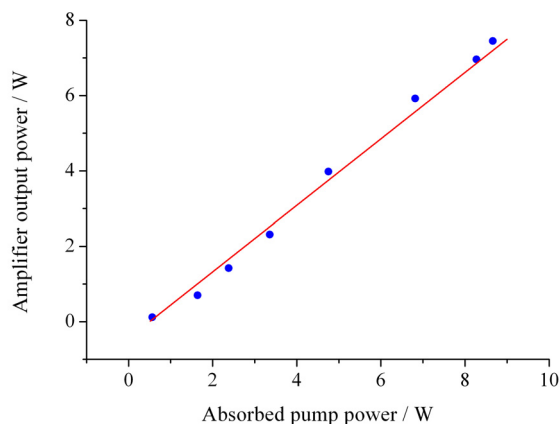


Figure 2: Output power of fibre amplifier.

The output is clearly pump limited, showing no sign of rolloff at high powers. The slope efficiency found from the linear fit is 88%. In a further experiment, the total output of the amplifier was increased to 9.4W by seeding it with 3W of seed power, and by using higher pump powers ( $\sim 400\text{W}$ ) this can be significantly increased again.

The spectra at the highest powers show no signs of nonlinear effects, as can be seen in figure 3. This shows the spectrum of the seed laser before the amplifier and the spectrum of the output at high power (7.5W). The spectra are nearly identical, showing no signs of self-phase modulation (SPM) or stimulated Raman scattering (SRS) [10].

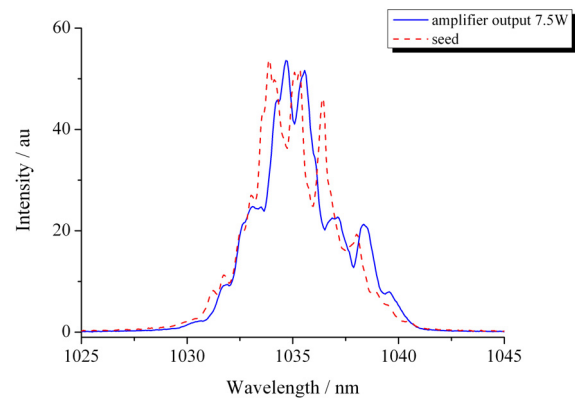


Figure 3: Spectra of the seed and amplifier output.

To demonstrate what the effect of nonlinearity in the amplifier would have on the output, figure 4 shows spectra of the short and long seed pulses amplified to a power of 6.9W. The amplified short pulse clearly shows significant spectral broadening, whereas the amplified long pulse spectrum is identical to that of the seed input.

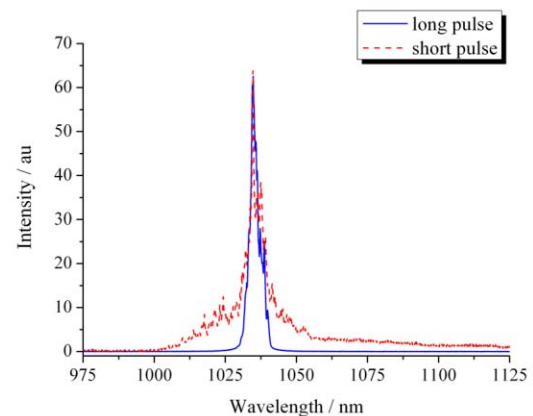


Figure 4: Spectra of long and short seed pulses amplified to 6.9W.

It is clear from this figure that it is necessary to use the uncompressed seed pulses, perhaps even lengthened further, to be able to amplify to the required pulse energy without spectral distortion. Avoiding spectral broadening

in the amplifier is important for the laser-wire project, as the lens used to focus the beam to the IP has a restricted bandwidth ( $< 2\text{nm}$ ) and exceeding this severely degrades its performance. The current output from the seed laser ( $4-5\text{nm}$ ) is rather wider than is required, although we aim to narrow the seed either by cutting the spectrum in the stretcher or by placing a narrow band filter before the final amplification stage. We are also investigating alternative lens and focusing mirror designs with wider spectral acceptance to avoid this problem.

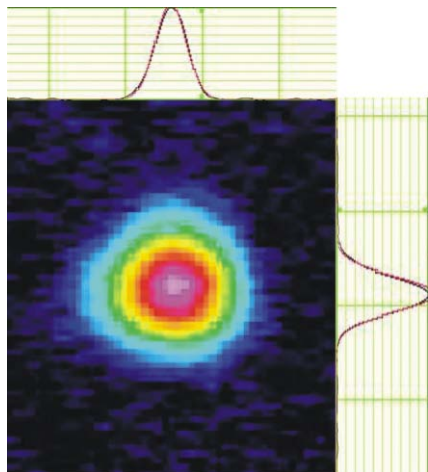


Figure 5: Beam at output of fibre, with lineouts through the peak and Gaussian fits.

Figure 5 is a CCD image of the seed beam transmitted through the fibre, showing that is a nearly perfect Gaussian intensity distribution. This data was taken without pumping the fibre, but the excellent spatial quality of the output is maintained at all levels of amplification.

### FUTURE WORK

More work is needed to fully characterise the test system, including  $M^2$  measurements of the amplified beam and measurements of its degree of polarisation and the output pulse duration. The implementation of higher power pump diodes will enable the investigation of the upper limit for amplification without nonlinearities or significant amplified spontaneous emission (ASE) for the uncompressed seed output in this particular fibre. Having determined the performance of the amplifier under quasi-cw conditions we will then run it with burst mode seeding to determine the optimum pumping conditions to amplify the pulses without introducing an unacceptable amount of ASE into the beam. This will be used to produce a specification for the doped photonic crystal fibre which will be used in the final system. The eventual aim of the project is to install this laser at an accelerator test facility and demonstrate that it meets linear collider requirements.

### CONCLUSION

We have demonstrated significant progress towards a high power fibre laser system suitable for use in a laser-wire experiment. The test system currently produces an average power of  $9.4\text{W}$  at a repetition rate of  $6.49\text{MHz}$  with excellent beam quality and no spectral distortion. Achieving this average power under burst mode conditions would easily fulfil the design criteria of  $100\mu\text{J/pulse}$  and this is the focus of continuing work on the project.

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