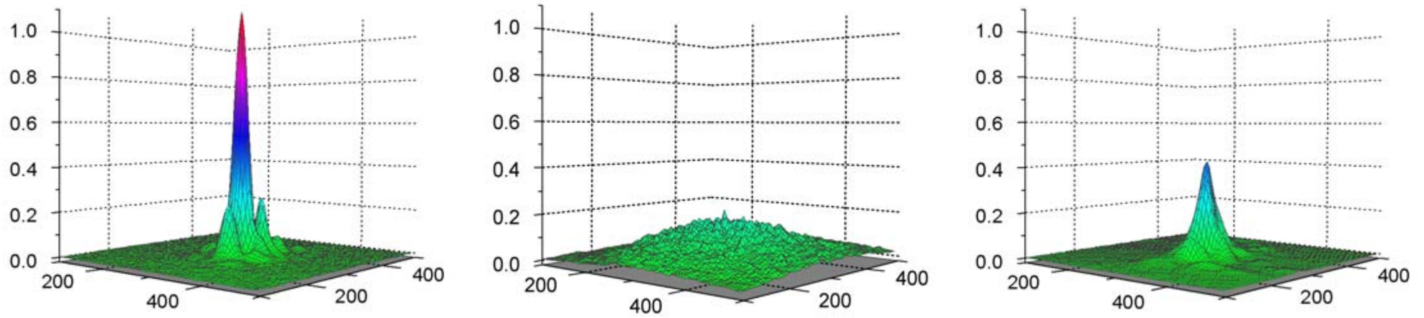
Discharge-Ablated Capillary Waveguides for Driving Short-Wavelength Lasers

Final Report for GR/M88969



(a) (b) (c)

Guiding of high-intensity laser pulses in a hydrogen-filled capillary discharge waveguide. Transverse intensity profiles in units of 10^{17} W cm^{-2} are shown for: (a) the entrance to the waveguide; and for the exit of the 30 mm long waveguide, (b) prior to the discharge pulse (data multiplied by 100), and (c) 730 ns after the onset of the discharge current. In all plots the transverse spatial scales are in µm.

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1 Introduction

The main aim of this research programme was to investigate novel types of waveguide able to overcome the strong defocusing that limits the gain length achievable in longitudinally-pumped short-wavelength lasers. Four main objectives of the research programme were identified:

1. To increase the understanding of discharge-ablated capillary waveguides
2. To improve the operation of these novel guides so as to channel pulses of higher intensity over greatly increased lengths.
3. To develop the first gas-filled versions of this type of waveguide.
4. To demonstrate the value of this technique by using it to achieve, for the first time, saturated pulse energy extraction in a table-top short-wavelength laser operating below 50 nm.

The research programme was highly successful, and objectives (1), (2) and (3) were met in full. Indeed the waveguides developed during the programme significantly exceeded the target performances identified in the proposal. It is unfortunate that we were unable to perform the experiments to demonstrate short-wavelength lasers driven in the guiding channel of the waveguide owing to problems experienced with the Astra laser at the CLF, as discussed in Section 4. As such objective (4) was not met, although our simulations indicate that our waveguide is well suited to driving short-wavelength lasers.

The research undertaken during the programme has aroused significant interest worldwide. The Principal Investigator (PI) has given invited seminars on this work at Berkeley, and AWE, Aldermaston and has been invited to give talks in 2002 at the annual meeting of the Dutch Physical Society, and the Plasma Physics and Controlled Fusion Meeting of the European Physical Society. To date the work has resulted in 4 publications in refereed journals, with 4 further papers being prepared. The results of this work have been presented at 4 international conferences.

Before describing the research in detail, we would like to acknowledge the crucial contributions made by Dr David Spence, who held a CASE studentship funded by EPSRC and the Rutherford Appleton Laboratory, and Mr Arthur Butler, who holds an EPSRC studentship.

2 Background and original context of research

Ever since the first demonstration of lasing at x-ray wavelengths in 1985, considerable effort worldwide has been devoted towards developing compact x-ray lasers better suited to the typical university or industrial research laboratory. These efforts have lead to the use of shorter (picosecond or femtosecond) pump laser pulses.

High-power femtosecond lasers based upon Ti:sapphire are very attractive for driving x-ray lasers since relatively compact (commercially-available) systems are able to output pulses with several terawatts of peak power at a repetition rate of several pulses per second. Terawatt, femtosecond lasers may be used to drive x-ray lasers using the process of optical field ionization (OFI), which occurs at peak laser intensities of order 10^{16} W cm^{-2}, and higher, when the electric field of the electromagnetic radiation is greater than that which binds valence electrons within atoms. The rate of OFI exhibits a threshold behaviour with the intensity of the laser radiation, and consequently the ion stage produced may be controlled by adjusting the intensity of the driving laser. The kinetic energy acquired by the ionized electrons depends upon the polarization of the laser field: circularly polarized radiation results in electrons with high kinetic energies; linear polarization leads to relatively cold electrons[1].

A wide variety of schemes for pumping x-ray lasers with femtosecond and picosecond laser pulses has been developed. A number of these, particularly those using femtosecond pulses, employ longitudinal pumping. In this case the driving laser propagates along the gain length of the short-wavelength laser, and hence diffraction of the driving laser beam restricts the gain length to the order of the Rayleigh range $Z_R = \pi W^2 / \lambda$, where W and λ are the waist size and wavelength of the driving laser. In order to reach the pump intensity required to generate the lasant ions by OFI, the waist size should typically be of order 30 μm, and hence $Z_R \approx 3.5$ mm, for $\lambda \approx 800$ nm. In practice the gain length generated is often further limited by refraction of the driving laser beam by transverse gradients in the electron density of the gain medium.

In order to overcome the limitations imposed by diffraction and refraction it is necessary to develop techniques for guiding the driving laser pulse at peak intensities of 10^{16} W cm^{-2} and greater. As we noted in our original proposal, the propagation of intense laser pulses through plasmas is also important in other fields such as high-harmonic generation and laser-plasma accelerators, with required driving intensities of order 10^{15} W cm^{-2} and 10^{18} W cm^{-2} respectively.

2.1 Guiding techniques available at the time of the proposal

The refractive index experienced by a laser pulse propagating through a plasma may be written as $\eta = \sqrt{1 - N_e e^2 / \gamma m_e \varepsilon_0 \omega^2}$, where N_e is the electron density, ω the angular frequency of the laser radiation, and γ describes the relativistic increase in electron mass resulting from the quiver motion of the plasma electrons in the laser field. In order to achieve channelling of the laser pulse, the plasma must either be encased in a hollow waveguide, or the refractive index must be peaked on axis by a favourable radial variation of γ and/or tailoring of the transverse electron density profile.

At the time of the original proposal a number of techniques for guiding intense laser pulses had been investigated. Optical guiding by grazing-incidence reflection at the walls of an evacuated capillary had been reported by Jackel *et al.*[2]. They measured a transmission of ~ 25% through 30 mm long capillaries for 1 J, 0.9 ps laser pulses. However, a major concern with this technique is the lifetime of the capillary which is only 1 - 3 laser shots. Furthermore, at the time of the proposal guiding with plasma-filled capillaries had not been demonstrated.

At intensities of order 10^{18} W cm^{-2} relativistic self-channelling arises from a favourable transverse variation of γ, as well as from the expulsion of electrons from the axial region by the ponderomotive force. Prior to the present proposal relativistic channelling had been observed experimentally[3, 4] over lengths of several millimetres. However, short laser pulses are not guided by this mechanism, and long pulses can develop significant longitudinal modulation[5]. These difficulties, together with the strong power dependence of the guiding mechanism, are likely to make it difficult to apply this technique to applications such as driving short-wavelength lasers.

A number of plasma waveguides had been investigated prior to submission of the present proposal. In an ideal plasma waveguide the radial electron density profile is parabolic, *i.e.* of the form $N_e(r) = N_e(0) + \Delta N_e \left(r / r_{ch}\right)^2$, where $N_e(r)$ is the electron density at radius r from the axis, and ΔN_e is the increase in electron density at $r = r_{ch}$. In the absence of further ionization of the plasma channel, and ignoring relativistic and ponderomotive effects, a lowest order Gaussian beam will propagate through the channel with a constant spot size W, provided that $W = W_M$ where $W_M = \left(r_{ch}^2 / \pi r_e \Delta N_e\right)^{1/4}$, in which r_e is the classical electron radius.

Several techniques for forming a plasma waveguide had been investigated at the time of the present proposal. Durfee and Milchberg[6] had studied a plasma waveguide formed after the hydrodynamic expansion of a cylindrical plasma created by focusing ~ 100 ps laser pulses with an axicon lens. They demonstrated guiding over 22 mm with input intensities of up to 5×10^{15} W cm^{-2}. Volfbeyn and Leemans[7] extended this approach to guide pulses at input intensities of up to 10^{17} W cm^{-2} over lengths of ~ 1 mm. However, a difficulty in applying this technique to short-wavelength lasers driven by OFI is that the plasma channel formed is already highly ionized and heated. Consequently, the control over the plasma conditions afforded by OFI are lost, and the gain of any laser transition will be greatly reduced by significant Doppler broadening.

2.2 The discharge-ablated capillary waveguide

In 1996 Ehrlich *et al.* demonstrated channelling in a plasma waveguide formed by discharge ablation of an initially-evacuated capillary[8]. Those workers described guiding of laser pulses with a peak input intensity of 10^{16} W cm^{-2} through 10 mm long polypropylene (PP) capillaries, with a pulse energy transmission of 75%.

Prior to the present research proposal we were able to confirm[9] those promising results using 0.5 J, 2.5 ps pulses from the Nd:Glass laser at Imperial College, London, for an input laser intensity of 1×10^{16} W cm^{-2}. Furthermore, we also undertook the first interferometric measurements of the electron density profile of the plasma formed by the discharge ablation of the capillary wall[10]. That work showed clearly that the plasma developed a parabolic profile. For example, 340 ns after the onset of the discharge current the plasma profile was found to be parabolic with $N_e(r)[10^{18}\ \text{cm}^{-3}] = 4.0 + 1.8\left(r[\mu\text{m}]/175\right)^2$, corresponding to a matched spot size $W_M = 37\,\mu$m.

2.3 Key questions to be answered by the research programme

In the proposal we identified the discharge-ablated capillary waveguide as the most promising and practicable scheme for guiding intense driving laser pulses in novel, short-wavelength OFI lasers. In particular the technique was simple; it could be extended straightforwardly to longer lengths; the temperature of the plasma channel was not too high; and the lifetime of the capillary was reasonable, although at only a few hundred shots it needed to be improved for real applications.

However, there remained much to be investigated:

- The mechanism responsible for forming the guiding plasma channel was not understood. Potential mechanisms were: (a) radial flow of plasma from the ablating capillary wall towards the axis; (b) conduction of heat to the capillary wall.
- The behaviour of the propagating laser pulse within the plasma channel was not known.
- It was desirable to be able to guide pulses over longer lengths, and to increase the lifetime of the capillary.
- For applications, particularly in driving novel short-wavelength lasers, it would be necessary to be able to control the ion species present in the plasma channel by introducing gas into the discharge, or by varying the capillary material.

Our research proposal was designed to investigate these issues, and also to demonstrate the potential of this approach by undertaking experiments to demonstrate gain in OFI lasers driven within the guiding channel of a waveguide. The main objectives given in Section 1 were identified.

3 Key results and advances

In outline, the key advances made during the research programme are:

- The invention of a new type of waveguide for high-intensity laser pulses: *the gas-filled capillary discharge waveguide*.
- The peak intensity of the guided pulses has been increased by an order of magnitude to 1×10^{17} W cm^{-2}.
- The length over which guiding has been demonstrated has been increased by a factor of 5 to 50 mm, with realistic prospects of increasing the waveguide length to greater than 100 mm.
- The lifetime of the waveguide has been increased by some 3 orders of magnitude to more than 10^5 shots.
- Operation with a wide variety of ions doped into the plasma channel is now possible.
- The mechanisms responsible for forming the plasma channel are well understood.
- A code has been developed for simulating the propagation of intense laser pulses through plasma channels.

- Simulations indicate that our waveguide can increase the gain length of OFI lasers by more than an order of magnitude.

3.1 Electron density profile measurements of discharge-ablated capillaries

The radial electron density profile was measured interferometrically for a range of discharge-ablated (initially-evacuated) capillaries and for a wide range of discharge conditions. Both PP and silica capillaries were investigated with inner diameters in the range 220 μm - 420 μm. To help interpret the large amount of data recorded, a quality parameter *Q* equal to the ratio of the curvature of the channel to the axial electron density was devised, such that channels with high values of *Q* would have smaller matched spot sizes and would be less susceptible to ionization-induced defocusing.

Whilst the axial electron density was found to increase steadily during the discharge pulse, the quality factor *Q* remained approximately constant. No systematic dependence of *Q* was found on the peak discharge current, the duration of the current pulse, or the material from which the capillary was made. The observed independence of *Q* on the material of the capillary strongly suggested that the formation of the plasma channel was largely due to thermal processes rather than radial plasma flow (see Section 3.4).

However, *Q* was found to vary strongly with the radius *a* of the capillary: $Q \propto a^{-1.65}$. It is interesting to note that the quasi steady-state model for gas-filled capillary discharges discussed in Section 3.4 predicts $Q \propto a^{-2}$. This reasonably good agreement strongly suggests that for discharge-ablated (initially-evacuated) capillaries, the properties of the plasma channel are largely determined by thermal conduction of heat to the capillary wall, and are relatively insensitive to the details of the wall ablation.

3.2 Development of a propagation code

We developed a propagation code in order to understand in detail the propagation of intense laser pulses through the plasma channel[11]. The code solved implicitly the paraxial wave equation in cylindrical co-ordinates for a plasma undergoing optical field ionization, thereby accounting for refractive de-focusing arising from further ionization of the plasma by the propagating pulse.

The code was used to model the guiding experiments with a discharge-ablated PP capillary performed at Imperial College prior to the research programme[9]. Simulations of the evolution of the pulse energy transmission and the transverse spatial profiles in the exit plane of the capillary showed excellent agreement with the experimental data. Having established this, the simulations were used to investigate the propagation of the laser pulse within the capillary. Calculations of the laser fluence passing each grid point showed that the laser pulse was strongly de-focused by further ionization of the plasma channel after propagating less than 2 mm into the waveguide[11]. The strongly de-focused beam had a peak intensity more than an order of magnitude smaller than that at the entrance to the capillary, and so did not further ionize the plasma channel. As such, the waveguide was able to re-focus the propagating pulse, thereby avoiding losses at the capillary walls, and producing a second focus close to the exit plane of the capillary. Thus, for certain delays *t* the production of a small laser spot in the exit plane of the capillary, coupled with high pulse energy transmission, gave the illusion of guiding, although in reality for most of the length of the capillary the peak axial intensity of the propagating pulse was low.

We concluded that it was likely that similar problems would have occurred in earlier experiments by other research groups with discharge-ablated capillary waveguides. Furthermore, discharge-ablated capillaries were always likely to suffer from ionization-induced de-focusing in this way since the plasma formed from the wall material was only partially-ionized.

Quasi-matched guiding

The simulations referred to above lead us directly to the concept of *quasi-matched guiding* in a partially-ionized plasma waveguide[11]. In this regime the plasma channel is further ionized by the propagating laser pulse to a highly stable ion stage to form a raised, but still parabolic, electron density profile. Provided that the additional ionization occurs on the leading edge of the laser pulse, and out to a radius several times the spot size, the bulk of the propagating pulse can be guided by the modified electron density profile. Simulations confirmed that discharge-ablated PP capillaries would guide better at intensities of order 5×10^{17} W cm^{-2} by operating in the quasi-matched regime, further improvements being possible by using plasma channels formed from boron or pure hydrogen[11].

Simulations of OFI laser systems

The propagation code was employed to investigate the propagation of a driving laser pulse through doped plasma channels suitable for driving OFI lasers in Xe^{8+}, Kr^{8+}, and Ar^{8+}. For example, for H_2-filled waveguides doped with 5 mbar of Xe our simulations show that the doping does not perturb the waveguide significantly, and that the lasant ion stage can be generated over lengths of > 80 mm compared to only ~ 5 mm in the absence of the waveguide. Since Ar^{8+} is so stable against further ionization, the Ar^{8+} laser could also be driven using pure argon gas fills by operating in the quasi-matched regime. Simulations with the propagation code indicate that the lasant ion stage could be generated over a length in excess of 25 mm even at the relatively high pressure of 33 mbar.

3.3 Development of the gas-filled capillary discharge waveguide

The electron density measurements described in Section 3.1 had indicated strongly that the plasma channel was formed by thermal processes rather than by plasma flow. It was realized, therefore, that a discharge in a capillary pre-filled with gas should also form a plasma waveguide. This would have several advantages: independent control of the plasma density; control over the atomic number of the plasma ions by changing the gas; and, since the capillary wall would no longer be the source of the plasma, the capillary could be formed from a refractory material so as to avoid ablation and increase its lifetime.

It was clear that it would be highly desirable to produce a plasma channel in a capillary pre-filled with hydrogen since hydrogen could be fully ionized by the discharge fairly easily. Furthermore, even if the hydrogen were only partially ionized by the discharge, the plasma channel would operate extremely efficiently in the quasi-matched regime since hydrogen is fully ionized by OFI for laser intensities as low as approximately 10^{14} W cm^{-2}.

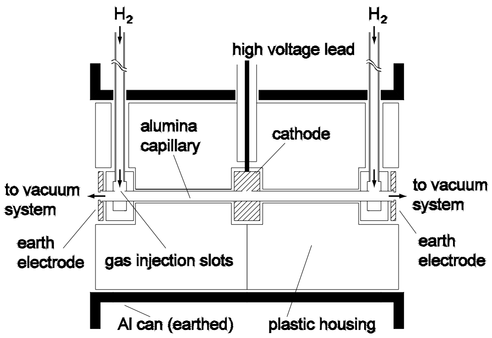


Figure 1. Schematic diagram of the gas-filled capillary discharge waveguide.

The development of the gas-filled capillary discharge waveguide involved several important changes to the design of discharge-ablated capillary waveguides. Our latest design is shown schematically in Figure 1. The capillaries are commercially available alumina capillaries with an inner diameter of ~ 300 μm. Gas is flowed into the capillary through slots machined by a copper-vapour laser. The high-voltage electrode is placed at the centre of the capillary, further slots enabling the discharge current to flow from the electrode to the plasma. An earth electrode is positioned coaxially at each end of the capillary. The capillary and electrodes are mounted in a Perspex housing, the housing itself being mounted in a cylindrical, earthed aluminium can.

Measurements of the electron density profiles for hydrogen-filled capillaries showed that the electron density profile created by the discharge was indeed parabolic[12]. For example, for a 300 μm diameter capillary it was found that 60 ns after the onset of the discharge current the electron density was fitted by $N_e(r)[10^{18}\ \mathrm{cm}^{-3}] = 2.72 + 1.29\left(r[\mu\mathrm{m}]/150\right)^2$, corresponding to a matched spot size of $W_M = 37.5\,\mu\mathrm{m}$. By comparing the electron density profile with the known initial H_2 pressure the average ionization was found to be $Z^*_{initial} = 0.99^{+0.01}_{-0.12}$.

3.4 MHD simulations

In collaboration with Prof. Sergei Bulanov and colleagues at the General Physics Institute of The Russian Academy of Sciences, we performed magnetohydrodynamic (MHD) simulations of our hydrogen-filled capillary discharge waveguide[13]. The MHD simulations are in very good agreement with the measured[12] electron density profiles. The simulations show that the plasma is essentially fully ionized for $t > 55$ ns, and that ablation of the capillary wall is negligible.

The MHD simulations gave great insight into the mechanisms responsible for forming the plasma channel. Both the pinch effect and radial flow were found to be negligible. It was found that for $t > 80$ ns the plasma is in a quasi steady-state equilibrium in which Ohmic heating of the plasma balances thermal conduction of heat to the capillary wall by the plasma electrons. Since the plasma pressure is constant across the radius of the capillary, thermal conduction ensures that on axis the plasma is hotter, and hence of lower density.

It has been possible to develop a simple analytical model of the discharge during the quasi steady-state phase, and this has been shown to be in very good agreement with the full MHD simulations. The simple model is particularly useful in that it provides an expression for the scaling of the matched spot size of the plasma channel: $W_M \propto \left(a^2 / N_{0i}\right)^{1/4}$, where a is the capillary radius, and N_{i0} the initial density of hydrogen atoms. This scaling relation will be particularly important for future development of gas-filled capillary discharge waveguides.

3.5 Guiding experiments

As explained in Section 4, two experiments to demonstrate guiding of high-intensity laser pulses were undertaken at the Astra laser facility at the CLF.

In the second of these experiments 160 mJ, 73 fs pulses from Astra were focused to a spot size of approximately 30 μm at the entrance to the waveguide, corresponding to a peak input intensity of 1×10^{17} W cm^{-2}. The pulse energy transmission, transverse spatial profile, and spectrum of the transmitted pulses were measured as a function of time during the discharge for both 30 mm and 50 mm long capillaries, and at a wide range of hydrogen pressures[14]. Figure 2 shows the measured pulse energy transmission as a function of the time of injection t of the laser pulses relative to the onset of the discharge current for the 30 mm long capillaries. Once the discharge was established the transmission rose rapidly to approximately 93% and 85% for the 30 mm and 50 mm long capillaries respectively. This very high transmission corresponds to the lowest coupling and propagation losses yet reported for any waveguide able to guide pulses with a peak intensity greater than 10^{16} W cm^{-2}.

Figure 3 shows the measured transverse intensity profiles of the laser pulses at the entrance plane of the capillary, and at the exit of the capillary prior to and after the onset of the discharge current. For $t < 0$ strong ionization-induced defocusing in the neutral H_2 causes the transmitted beam to fill the entire diameter of the capillary, with a small energy transmission of < 10%. As the discharge develops the energy transmission of the pulses increases and the transmitted beam is constrained to the axial region. For example in Figure 3(c) the transmitted pulse has an energy transmission of 85%, a spot size of 41 μm, and an axial intensity of 36% of that of the input pulse. We emphasize that the reduction in axial intensity observed in Figure 3(c) is almost entirely caused by the increase in spot size of the transmitted beam owing to a small mismatch between the input spot size of the laser and the matched spot size of the plasma channel.

Since the plasma channel is essentially fully ionized by the discharge, ionization-induced defocusing should be eliminated, and hence the spot size of the propagating pulse should remain close to that of the input pulse throughout the length of the waveguide, with only small variations arising from possible mismatching to the channel. Furthermore, temporal or spectral distortion of the pulse will also be minimized. An initial analysis of our measurements of the spectra of the transmitted pulses shows that they have similar spectral shape and widths to that of the input pulses.

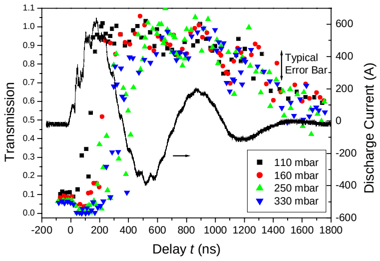
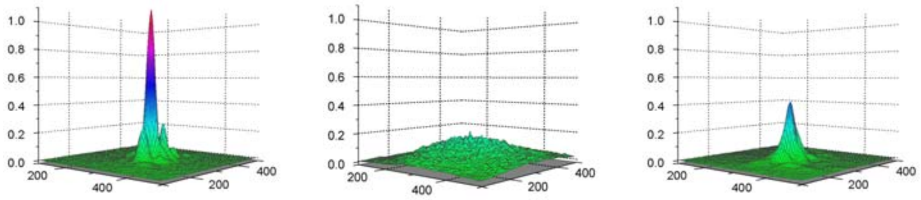


Figure 2. Measured transmission as a function of delay t for a 30 mm long capillary at different initial hydrogen pressures. Also shown is the temporal profile of the discharge current.



(a) (b) (c)

Figure 3. Measured transverse intensity profiles in units of 10^{17} W cm^{-2} at: (a) the entrance to the capillary; and at the exit of the 30 mm long capillary (b) prior to the discharge pulse (data multiplied by 100), and (c) t = 730 ns. In all plots the transverse spatial scales are in μm.

3.6 Summary

The key advance made by this research has been the invention of a new type of waveguide: the gas-filled capillary discharge waveguide which has become recognized as a very promising technique for guiding high-intensity laser pulses for applications such as driving novel x-ray lasers, high-harmonic generation, and electron acceleration. The waveguide has several important advantages over alternative techniques:

- The plasma channel is essentially fully ionized, eliminating ionization-induced defocusing and minimizing temporal or spatial distortion of the guided laser pulse.
- The guiding channel is stable and long-lived (> 100 ns) making injection of laser pulses straightforward.
- The waveguide can be extended to long lengths (> 100 mm) using multi-stage, or alternative discharge designs.
- The device is simple: no auxiliary laser systems or complex high-voltage circuitry are required.
- The lifetime of the capillary is long (> 10^5 shots) which will be of great practical importance in applications.

4 Project plan

With one exception, the project progressed smoothly according to the original Project Plan. The sole difficulty arose following our first set of guiding experiments performed with the Astra laser at the CLF. Those experiments appeared to be very successful, with an energy transmission of approximately 90% being achieved for 20 mm long capillaries. However, several months after their completion we were informed by the CLF that there may have been unwanted temporal structure on the pulses output from Astra. In particular it had been discovered that under certain conditions the output pulses were not single pulses with a duration of ~100 fs, but a train of approximately 8 pulses each of ~ 100 fs duration, separated in time by some 100 ps. This multi-pulse structure would not have been detectable using the single-shot autocorrelator available to us.

The uncertainty in the temporal structure of the laser pulses meant that one of the key parameters of any guiding experiment - the input intensity of the laser pulses - was uncertain by a factor of ten. The possibility of multiple output pulses made our results much harder to interpret, although we were able to publish our results in terms of the laser fluence[15].

We decided that it was of primary importance to repeat the guiding experiments during our second, and final, period of access to Astra. This period of access was to be have been used to seek evidence of gain in short-wavelength lasers driven in the guiding channel of the waveguide (original objective 4). The objectives of the experiments performed during the second periods of access were therefore revised to:

4(a) Demonstrate guiding for peak input laser intensities of order 10^{17} W cm^{-2}. Measure the energy transmission, spatial profile, and spectrum of the transmitted laser pulses as a function of time during the discharge.

4 (b) Set-up a longitudinal flat-field spectrometer and, if time, seek evidence for lasing using H_2 gas fills doped with lasant gases such as Xe, Kr, and Ar.

The first of these revised objectives was met successfully. However, it proved not to be possible to squeeze two five-week experiments into a single slot of 5 weeks. We did set-up the spectrometer, and were able to take spectra on a total of approximately 5 days, although no short-wavelength lasing was observed. We do not believe this to constitute evidence of a flaw in the proposed scheme, merely that there was not sufficient time to investigate a sufficiently wide range of experimental parameters.

5 Research impact

The results achieved during the research programme have caused a great deal of interest worldwide, and has lead to new collaborations being formed with a number of internationally-renowned research groups.

The driving force behind the development of the waveguide was the prospect of driving short-wavelength lasers within the guiding channel. This remains an important goal, and to this end we have established a collaboration with the group of Prof. Peter Nickles of the Max Born Institute, Berlin. We expect, during 2002, to undertake collaborative experiments with Prof. Nickles's group to demonstrate lasing in the guiding channel. We are also discussing the possibility of working with Dr Brigitte Cros of the University of Paris XI on OFI lasers driven in the guiding channel of our waveguide.

Our work has aroused considerable interest amongst those groups investigating laser-driven plasma accelerators. The length and plasma density for which we have already demonstrated guiding are well-suited to this application, offering the prospect of acceleration of electrons to energies of order 1 GeV in lengths of only a few tens of millimetres. The electron bunches are expected to contain $\sim 10^{10}$ electrons in pulses of only a few femtoseconds duration, and would be a unique source for femtosecond time-resolved electron diffraction experiments, as well for pulse radiolysis studies, and isotope generation. Furthermore, the electron bunches would be ideal for driving compact free electron lasers (FELs) capable of generating coherent, femtosecond, radiation tunable from the water window to the infrared.

The exciting prospect of developing compact, short-pulse sources of electrons and coherent photons, synchronized to femtosecond accuracy, has lead to the formation of a UK-wide collaboration of research groups and the submission of a four-year programme of research to the Basic Technology Research Programme. The major goals of that programme will be: (a) demonstration of controlled acceleration of electrons to the GeV level with low energy spread; (b) the first demonstration of an FEL driven by electron bunches from a laser-based accelerator. This work is also the focus of a new (as yet un-funded) collaboration of groups throughout Europe.

We have formed a close collaboration with the group of Dr Dino Jaroszynski of the University of Strathclyde, and his group are now using gas-filled capillary waveguides in their experiments. As described in Section 3.4, during the present programme we have also formed a fruitful collaboration with Prof. Sergei Bulanov of the Russian Academy of Sciences.

6 Further research

The research undertaken during the present programme has opened up several promising research fronts. We plan to undertake future research into applications such as short-wavelength lasers, high-harmonic generation, and electron acceleration.

A large number of short-wavelength laser systems could be driven within the guiding channel of the waveguide, greatly increasing the single-pass gain, enabling saturated energy extraction, and improving the divergence of the output radiation. As discussed in Section 3.2 simulations for some possible systems indicate that collisionally-pumped OFI lasers could be driven using gas fills doped with the lasant gas. Furthermore, it may be possible to drive recombination lasers in which the dense pool of relatively cold (~ 7 eV) electrons from the discharge-ionized hydrogen recombine with ions formed by OFI of dopant gases. Very much along these lines, recent calculations by Grout *et al.* show that the gain of the OFI-driven recombination laser at 23.2 nm in Ar^{7+} can be increased from 10 cm^{-1} to 350 cm^{-1} by the addition of a buffer gas of H_2.

The use of waveguides to enhance the efficiency with which high harmonics are generated by phase-matching has become well established[16]. Since our waveguide is able to operate at very much higher intensities than those which have been used to study HHG to date, it may be possible to generate very much higher harmonics than has hitherto been possible by generating harmonics in ions, rather than in neutral atoms. We would also like to investigate the prospects for using tapered or periodically-structured waveguide channels for enhanced phase-matching.

Finally, as noted above, we plan to develop the gas-filled capillary discharge waveguide for electron acceleration as part of the collaborative proposal submitted to the Basic Technology Research Programme. If it is funded, our contribution to that programme would be: (a) tailoring the properties of the waveguide to the requirements of electron acceleration; (b) the development of channels with longitudinally-increasing density, which would improve phase-matching between the electron bunch and the laser-driven plasma wave, thereby enabling acceleration to higher electron energies[17]; (c) the development and investigation of periodic waveguides, and their application to the development of novel FEL-like plasma structures.

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15. D. J. Spence, A. Butler, and S. M. Hooker, J. Phys. B: At., Mol. Opt. Phys. **34**, 4103 (2001).
16. C. G. Durfee, A. R. Rundquist, S. Backus, et al., Phys. Rev. Lett. **83**, 2187 (1999).
17. P. Sprangle, B. Hafizi, J. R. Penano, et al., Phys. Rev. E **63**, 056405 (2001).

Appendix - Publications arising from the research programme

1 Papers in refereed journals

1. D. J. Spence and S. M. Hooker, "Simulations of the propagation of high-intensity laser pulses in discharge-ablated capillary waveguides," *J. Phys. B: Atomic and Molecular Physics* **17** 1565-1570 (2000).

2. D. J. Spence and S. M. Hooker, "Investigation of a hydrogen plasma waveguide" *Phys. Rev. E* **63** 015401(R) (2001).

3. D. J. Spence, A. Butler, and S. M. Hooker, "First demonstration of guiding of high-intensity laser pulses in a hydrogen-filled capillary discharge waveguide," *J. Phys. B: Atomic and Molecular Physics* **34** 4103-4112 (2001).

4. N. A. Bobrova, A. A. Esaulov, J. -I. Sakai, P. V. Sasorov, D. J. Spence, A. Butler, S. M. Hooker, and S. V. Bulanov, "Simulations of a hydrogen-filled capillary discharge waveguide," *Phys. Rev. E, accepted for publication* (2001).

2 Journal papers in preparation

5. A. Butler, D. J. Spence, and S. M. Hooker, "Guiding of high-intensity laser pulses in a hydrogen-filled capillary discharge waveguide," *to be submitted to Phys. Rev. Lett.*

6. A. Butler, D. J. Spence, and S. M. Hooker, "The hydrogen-filled capillary discharge waveguide for high-intensity laser pulses," *to be submitted to Phys. Rev. E.*

7. S. V. Bulanov and S. M. Hooker, "Capillary plasma discharges for x-ray lasers and for guiding intense laser pulses," *an invited review article for Rev. Plasm. Phys.*

8. D. J. Spence, A. Butler, and S. M. Hooker, "Applications of the gas-filled capillary discharge waveguide," *to be submitted to J. Phys. B: Atomic and Molecular Physics.*

3 Papers presented at conferences

9. D. J. Spence and S. M. Hooker, "Simulations of the propagation of high-intensity laser pulses in discharge-ablated capillary waveguides," In *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, Washington DC) 2000.

10. D. J. Spence and S. M. Hooker, "H-filled slow capillary-discharge waveguides," *Ultraintense Laser Interactions and Applications - 2*, Pisa, Italy, September 29 - October 3 (2000).

11. D. J. Spence, A. Butler, and S. M. Hooker, "Guiding of high-intensity laser pulses in a hydrogen-filled capillary discharge waveguide," Conference on 2nd Generation and Plasma Accelerators, Giens, France, 24 - 29 June (2001).

12. D. J. Spence, A. Butler, and S. M. Hooker, "Investigation of a novel hydrogen plasma waveguide for high-intensity laser pulses," In *Trends in Optics and Photonics (TOPS) Vol. 65, Applications of High-Field and Short Wavelength Sources IX*, OSA Technical Digest, Postconference Edition, pp. TuE21, OSA Technical Digest (Optical Society of America, Washington DC) 2001.

4 Other reports

13. D. J. Spence, A. Butler, and S. M. Hooker, "First demonstration of guiding of high-intensity laser pulses in a hydrogen-filled capillary discharge waveguide," *Annual Report 2000/2001*, Central Laser Facility, Rutherford Appleton Laboratory (Central Laboratory of the Research Councils), pp. 67-69, 2001.