June 2011

Proposal for continuation of the Front End Test Stand

A. Letchford, M. A. Clarke-Gayther, D. Faircloth, C. Gabor, S. R. Lawrie, C. Plostinar
STFC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK

J. Pozimski, S. Alsari, C. Bontoiu, A. Kurup, J. Pasternak, P. Savage, S. Jolly
Department of Physics, Imperial College, Kensington, London, SW7 2AZ, UK

J. Back
Department of Physics, University of Warwick, Coventry, CV4 7AL, UK

G. Blair, G. Boorman, A. Bosco
Department of Physics, Royal Holloway, University of London, Egham, TW20 0EX, UK

M. Lancaster
Department of Physics and Astronomy, University College London, London, WC1E 6BT

R. Edgecock
University of Huddersfield, Queensgate, Huddersfield, HD1 3DH

Executive summary

High power proton accelerators (HPPAs) are at the heart of many future large-scale scientific facilities such as a spallation-neutron source, Neutrino Factory and the Muon Collider, high energy physics at the energy or intensity frontier, accelerator driven sub-critical systems, and the transmutation of nuclear waste. Controlling beam-loss induced machine activation during injection into a circular accelerator (synchrotron or FFAG) is essential for safe operation of HPPAs and requires the beam in the injector linac to be chopped very precisely at the synchrotron revolution frequency. The Front End Test Stand (FETS) at RAL has as its primary aim to demonstrate perfect chopping of a high quality, high intensity, negative Hydrogen ion beam at an energy of 3 MeV.

Although primarily a hardware construction project, the FETS collaboration has become an efficient mechanism for sharing the wealth of real-world accelerator expertise within ISIS and the ASTeC Intense Beams Group with the wider academic community as well as benefitting from the specialisations and expertise of the university groups. The work already undertaken has contributed to the UK's continuing international reputation as a centre of excellence and has stimulated collaborations with leading international accelerator institutes such as CERN, FNAL, ESS and CNS.

FETS consists of a high-brightness Penning surface plasma negative-hydrogen-ion source, magnetic Low Energy Beam Transport (LEBT) at 65 keV to match the beam into a 3 MeV Radio Frequency Quadrupole (RFQ) operating at 324 MHz which delivers the 60mA beam to the Medium Energy Beam Transport (MEBT) where the chopping systems are situated. Comprehensive, state-of-the-art diagnostics measure the performance of the system and the beam quality. The ion source, LEBT and high power RF systems have been commissioned and the manufacture of the RFQ is underway.

With this proposal we seek the resources to complete the construction of FETS in a timely manner. This will entail:

- The installation, testing and commissioning of the RFQ;
- Accelerating the desired beam intensity and beam quality through the RFQ;
- The completion of the engineering design and the manufacture of the chopper systems;
- The installation, testing and commissioning the MEBT and chopper systems;
- The transmission of beam through the MEBT and the demonstration of precise and efficient beam chopping; and
- Evaluating the performance of the complete test stand.

In addition, we proposed to evaluate the additional benefits that will accrue from exploiting the FETS as a driver for further developments in proton accelerator systems. To achieve these goals, a total of £4.6M is requested over 3 years from April 2012.

Contents

1. Introduction

The Front End Test Stand (FETS) under construction at the Rutherford Appleton Laboratory is the UK's contribution to research into the next generation of High Power Proton Accelerators (HPPAs). HPPAs are an essential part of any future Spallation Neutron Source, Neutrino Factory, Muon Collider, Accelerator Driven Sub-critical System, Waste Transmuter etc. FETS will demonstrate a high quality, high intensity, chopped H-minus beam and is a collaboration between RAL, Imperial College and the Universtity of Warwick in the UK and the Universidad del Pais Vasco and ESS-Bilbao in Spain.

Beam chopping will be an important feature of the next generation of HPPAs. The requirement to minimise the need for remote handling of accelerator components dictates that beam loss in future machines must be kept to levels comparable to those of current facilities in order to avoid activation. With beam powers an order of magnitude or more than those currently achieved, fractional beam loss must necessarily be reduced by a similar factor. In circular machines a significant source of beam loss occurs when the continuous linac beam is trapped and bunched in the ring RF bucket. Trapping efficiency can be improved with higher harmonic RF systems but to achieve the improvements necessary for MW scale beams, the linac beam must be chopped at the ring revolution frequency. This chopped beam allows for the ring RF bucket to be precisely filled with little trapping loss. The low levels of beam between bunches can also reduce loss at extraction from the ring.

2. Front End Test Stand

Originally conceived simply as a chopper beam test, FETS has since expanded its objectives to become a generic test stand for technologies related to the front end of several proposed projects which require a high power proton driver [1]. These projects include, but are not limited to, Spallation Neutron Sources, a Neutrino Factory, Muon Collider, Accelerator Driven Sub-critical Systems and nuclear waste transmuters. A secondary objective of FETS was to encourage the study of accelerator technology by a new generation of accelerator engineers and physicists in UK universities The quality of the work being produced by the (mostly) young team working on FETS is testament to the success in this objective. FETS has also resulted in a fruitful collaboration between RAL/ISIS the ESS-Bilbao project in Spain. The exchange of ideas, experience and hardware is proving extremely beneficial to both sides

FETS consists of an H^--ion source, magnetic low energy beam transport (LEBT), 324 MHz Radio Frequency Quadrupole accelerator (RFQ), medium energy beam transport and chopper line (MEBT) and comprehensive diagnostics.

3. Proposal for Front End Test Stand continuation

3.1. Ion source and LEBT optimisation

FETS uses a modified version of the Penning type surface plasma ion source that has been developed over many years on the ISIS facility [2]. Since achieving first beam in April 2009, the ion source has been running routinely, producing currents of 50 mA or more. In order to reach the required performance specification for FETS, extensive studies have been carried out into the beam formation and extraction process [3], its transport through the 90º analysing magnet [4] and the post acceleration gap optics [5]. To facilitate these studies, improved beam diagnostics have been developed [6,7]. From a starting point of transverse emittances of >0.8 π mm mrad rms normalised, these combined efforts have achieved emittances as low as 0.3-0.35 π mm mrad [8], getting close to the FETS specification of 0.25 π mm mrad normalised rms. Although power supply limitations prevent the extraction of full 2ms beam pulses at 50Hz as required by the FETS specification, long discharge pulses have been generated and the beam parameters investigated at various points along the discharge [9].

FETS employs a 3 solenoid magnetic LEBT to transport and match the beam from the ion source into the RFQ at 65 keV [10]. The 3 solenoids are identical and designed for an on axis peak field of 0.4 T and a bore diameter of 90 mm. The solenoids were manufactured by Elytt Energy and their associated power supplies by JEMA. Both were supplied to FETS as part of our collaboration with ESS-Bilbao. Installation and commissioning of the LEBT has been completed with the first LEBT beam being achieved in spring 2010. Measurement of the solenoid magnetic field showed extremely good agreement with the design predictions. Preliminary measurements of the beam parameters at the end of the LEBT also agree well with the design specification [8,11]. Beam currents in excess of 50 mA have been transported through the LEBT with little emittance growth and just a few percent stripping losses.

During the previous three years of the FETS project considerable progress has been made on improving the performance of the H^--ion source to the point where the specification is almost met. Subtle design changes based on theory and experiment have been made at all points along the beam path from the plasma boundary to the LEBT entrance. A new extraction-electrode geometry has resulted in better confinement of the ions as they leave the plasma giving an increased current in the analysing magnet. The 90° analysing magnet filters out any electrons co-extracted with the beam and equalises the dimensions of the beam which initially has a long, thin aspect ratio due to the slit extraction geometry. To achieve this, the analysing magnet is a field gradient dipole. It was found that the field gradient and the good field region of the magnet were both sub-optimal and through extensive modelling a new magnet design has resulted in both increased beam transmission and lower emittance growth. Following the magnet the beam enters the post-acceleration region where the energy is increased from the extraction voltage of 18 kV to the final energy of 65 kV. A complete redesign of the electrostatic optics in this region has also resulted in higher current and lower emittance. In parallel with these improvements in the beam quality, power supply upgrades, improvements in the cooling efficiency and better understanding of the operating regimes has allowed the discharge pulse length to be increased to a full 2 ms at 50 Hz. In summary, since the start of the project the beam current has been doubled, the emittance reduced by a factor of three and the duty factor increased six fold.

Following on from this impressive progress there are still some areas where further improvements are necessary. At long pulse lengths a degradation of the beam current throughout the pulse has been observed. To understand this behaviour better a detailed analysis of the hydrogen delivery and caesiation processes will be undertaken. To further reduce the emittance and increase the current a higher voltage (25 kV) extraction power supply is under development. Extraction geometry changes will be investigated to achieve the optimum performance from the increased voltage. Finally the lifetime of the high performance source under 24/7 running conditions has yet to be determined. An extensive programme of extended running to determine and address lifetime issues will be necessary. A PhD student is about to begin work at the JAI at Oxford and will investigate many of these areas.

The production of H^--ion beams of high brilliance is not only required for front-line high-energy-physics applications like the LHC, Muon Collider or Neutrino Factory but also for spallation-neutron sources (ISIS) and for magnetically confined fusion reactors for neutral beam injection. On the other hand, compared with ion sources for proton beams, the available beam current as well as the achievable beam emittance produced in H^--ion sources is at least a factor of two worse. The main reasons for this behaviour are the unique plasma properties required for H^--ion production. On the one hand, a high electron temperature in the plasma is required to excite and dissociate the hydrogen molecules while on the other hand a high plasma temperature will strongly reduce the lifetime of the H^--ions produced in the plasma and reduce the current which can be extracted. Furthermore, the dipole field confining the plasma in the extraction region has a negative effect on beam extraction.

A new source will be scaled in size from the existing source (doubled in size), which will not only improve the source beam current characteristics and increase reliability but also allow suitable diagnostics to be implemented. This will allow for fundamental and detailed studies of the distribution of the ion-source plasma density and of the temperature in different regions of the ion source. These measurements are essential for the development of an understanding of the factors that limit the possible improvements of the ion source performance and lifetime. Plasma modelling simulations will be developed and benchmarked against the diagnostics measurements and will inform further improvements in the design of the source.

3.2. MEBT and Beam chopper

Fast beam chopping at low energy will be an essential feature of any future, circular-accelerator-based high power proton driver. FETS has been at the forefront of chopper R&D with the development of the proposed fast-slow chopper scheme[12,13]. This novel combination of two distinct chopper types, working in tandem, allows both very fast rise time and long flat-top pulses to be generated without losing the fidelity of the sharp pulse edges as the wave propagates through the deflector. Having previously demonstrated the feasibility of the fast pulse modulators, prototyping of the deflectors is now well under way. Two types of deflector are under investigation: a ‘planar’ type, essentially a meander line deflector and a ‘helical’ type consisting of discrete deflector plates connected by external delay lines. Unit parts of both type of deflector have been manufactured and tested to evaluate different fabrication techniques.

The beam chopper and associated beam dumps are located in the Medium Energy beam Transport (MEBT). Achieving low emittance growth under the influence of strong, non-linear space charge in a lattice which has to accommodate the long chopping elements – which inherently break the periodicity of the lattice – is challenging. The baseline FETS MEBT design [14] is 4.5 m long and contains 11 quadrupoles, 4 rebunching cavities, a fast and slow chopper deflector and two beam dumps. In particle dynamics simulations using a distribution from an RFQ simulation as input, the emittance growth is no more than 5% in the transverse plane. Beam loss for the un-chopped beam is ~1.5% while the chopping efficiency is ~99%. In addition to standard electromagnetic quarupoles (EMQs), hybrid quadrupoles are also being investigated [15]. The hybrid magnet is a combination of permanent magnet quadrupole (PMQ) and laminar EMQ (Lambertson quad.) which allows for a limited range of adjustment in a compact size. The rebunching cavities are high shunt impedance CCL type cavities [16]. Prototyping is about to begin with a cold model being manufactured as part of our work with ESS-Bilbao. The possibility also exists to test on the FETS MEBT a novel type of distributed RF cavity under development by Siemens.

The next steps will be:

- To prototype complete chopper assemblies before producing a final, fully-engineered design complete with vacuum chamber, pumps, ports etc.;
- To finalise the MEBT optics;
- To complete the design of the cavities based on the results of tests of the prototype cavities;
- To procure the quadrupoles, power supplies, RF amplifiers and vacuum system; and
- To install and commission all the equipment in the FETS before finally achieving first MEBT beam in early 2014.

3.3. *Diagnostics*

Particular attention is being paid on FETS to non-destructive diagnostics based on laser photo-detachment of electrons from the H^--ions [17]. The first laser profile measurement experiments have been completed on the beam downstream of the FETS ion source as discussed below, in addition to implementation of more conventional diagnostics systems.

3.3.1. Conventional diagnostics

A suite of diagnostics has been developed to characterise the beam in the FETS LEBT. After installation of the RFQ these same devices will be used and further developed as necessary to characterise the RFQ beam. The principle limitation is that the full beam power is almost 20 kW, which would damage most conventional ‘destructive’ devices that intercept the beam. Therefore, it will be necessary to limit the beam duty factor, and hence the power, to keep the diagnostics within their safe operating regime and also limit radiological issues.

Slit and cup emittance scanners and the associated software have been developed at ISIS over several years. Capable of making accurate scans of the transverse phase space, these devices are limited to perhaps 5% of the full FETS beam power and will become activated by the 3 MeV ions. A limitation is that they make uncorrelated measurements of the horizontal and vertical directions. To overcome this limitation a scintillator based pepper-pot device has been developed by ISIS and Imperial College which allows full 4D correlated measurements to be made. Due to scintillator damage the beam power limitation on this device is even more restrictive than the slit and cup scanners and again activation is an issue. Accurate results depend strongly on the post processing of data and the calibration technique, so additional development of the software will be undertaken.

As well as diagnostics to characterise the RFQ beam, operational diagnostics to ensure the safe and reliable operation of the MEBT will be necessary. Current transformers to measure the beam current are already available but devices to determine the beam position and profile will have to be developed. Scintillators and wire scanners are the traditional methods for measuring profiles but being interceptive they are limited in the beam power that they can tolerate and will produce radiation. The considerable experience available within ISIS will be available to help develop these devices. Beam position will be measured by strip-line or button pick-ups that also allow the RF structure of the beam to be investigated. These diagnostics will be developed drawing on the experience of the groups at RHUL and UCL.

3.3.2. Laser diagnostics

The damage to conventional devices due to the high beam power and activation by the 3 MeV beam energy make non-interceptive, non-destructive techniques very attractive. Work has already begun on developing a laser-based photo-detachment diagnostic on the beam just upstream of the LEBT. This system aims initially to measure a 1D profile by using a laser ‘wire’. Severe background problems due to residual gas ionisation so close to the ion source led to inconclusive initial results. With the procurement of a higher power laser and improvements to the detector and electronics a successful measurement of a 1D profile is anticipated soon. Considerable expertise in the design and operation of laser systems has been contributed by RHUL. With the lessons learned from this initial experiment the system will be extended to make a full 2D profile measurement which will require development of software to manipulate the vacuum mirror stages and implement tomographic reconstruction techniques. Investigations of back projection and maximum entropy methods have already begun but will need to be developed further.

Having demonstrated the ability to measure non-destructively a correlated 2D beam profile in the LEBT, the system will be commissioned at the exit of the RFQ and extended to measure 4D correlated phase space. This requires additional hardware such as a dipole magnet and beam dumps and considerably more post-processing of the data but will use similar tomographic techniques as the profile reconstruction.

3.4. RFQ commissioning

The FETS RFQ is a 324 MHz, 4-vane RFQ with a final energy of 3 MeV. The total length is 4.2 m for an interelectrode voltage of 85 kV which results in a peak surface field of approx 1.7 times the Kilpatrick field. Beam-dynamics simulations indicate a transmission of >95% for a current of 60 mA. A short cold model of a section of the RFQ, without vane modulations, was constructed to investigate the RF properties of the resonator and compare with the design theory. A novel integrated CAD, electro-magnetic and beam dynamics design method is being investigated for the FETS RFQ [18,19]. A full engineering CAD model of the modulated vane tips is imported into an electro-magnetic field solver to generate a field map through which the particles are tracked using the GPT code. The RFQ cold model has subsequently been used to develop a resonant frequency auto-tuning system [20] and will be used to confirm the operation of the low level RF control system and will allow for a test of the cooling system. Considerable effort was put onto the investigation of different methods of RFQ manufacture [21]. Particular areas of attention are the technique to be used to join the RFQ segments and the method of water cooling. Alternatives to the usual vacuum brazing technique such as laser or electron-beam welding appear to have some advantages as does a purely bolted assembly from the point of view of repairability. Alternative water-cooling methods which don’t require long, gun-drilled passages also offer some advantages. Manufacturing tests of these ideas have been undertaken and a decision was made for a bolted RFQ.

The production of detailed RFQ drawings for manufacture has been started and a first evaluation of manufacturing costs have confirmed the values previously estimated. A detailed costing will be available in August together with final drawings. A very detailed analysis of the influence of RFQ modulations on the RF frequency resulted in the incorporation of an RFQ tuning slot in sections 3 and 4 to improve field flatness.

A digital IQ RF control loop has been designed and built at the Universidad del Pais Vasco in Bilbao [22]. Based around an analogue front-end and 14 bit FPGA, the system works directly on the 324 MHz RF signal with no IF. On tests with a simple pillbox test cavity, control of pulsed RF with <±0.5% amplitude error and <±0.5º phase error has been demonstrated. The main part of the high power RF set-up is to be completed by autumn 2011 expecting arrival of the RFQ and couplers in early 2012.

For the RFQ comissioning, scheduled for the second half of 2012, a series of experiments is planned to compare the results with previous simulations. These tests will encompass the following items: RF test and tuning of field flatness, high power test of coupler and RF distribution, low level RF and tuner tests at full power;cooling tests; test of beam injection and beam transport (low duty factor) followed by an optimisation of the RFQ operational parameters at full beam power. A first beam is expected at RFQ extrction for the end of 2012 with full beam power reached in mid 2013.

3.5. Design of a CH-Linac

For the acceleration of high-current ion beams in a linear accelerator, different types of RF cavities are required to accommodate the velocity profile of the particles and to achieve a high shunt-impedance allowing for energy-effective acceleration. While at the very low energy end after extraction and electrostatic acceleration of the ions from the ion source, the structure of choice is a radio frequency quadrupole (RFQ) allowing for quasi simultaneous acceleration and transverse focusing, this structure becomes inefficient for acceleration at higher energies. Conventional drift-tube linacs (DTL's) typically used upstream of the RFQ, on the other hand, suffer from an intrinsic lower shunt-impedance and, for the high RF frequencies which are favorable in terms of efficient and compact accelerators, the performance of drift tubes suffers from the limited space available for transverse focusing magnets housed in the drift tubes. In recent years IH, CH and spoke structures have been replacing the conventional DTL's as they offer larger shunt impedance and therefore more compact and efficient accelerators.

3.6. Use of FETS and development into a proton centre

This work package will investigate the way in which the investment in the FETS infrastructure could best be put to use for the accelerator community. FETS offers, after commissioning, a unique facility producing a low-energy high-power proton beam which could be interesting for a series of experiments and applications. The aim of this work package will be to describe in detail the different options for FETS as an injector facility and nucleus for a possible Proton Beam Centre at RAL. The work package will also define the desired upgrade plan and evaluate the cost for the different options proposed. So far 5 different subjects for study have been brought forward, but it is planned to keep the work package open for other ideas and partners. The topics included so far are:

- Test of novel direct-drive cavity set-ups (solid state klystron – Siemens) on FETS;
- High-power beam test of a CH cavity linac module (as designed in work package RFQ commissioning) reusing the available RF and delivering a 5-6 MeV beam;
- High power target tests for BNCT, isotope and slow neutron production (at 5-6 MeV);
- Extension of FETS to a 20 MeV linac and injection into a low energy proton FFAG to investigate injection and acceleration of space charge dominated proton beams as required for ADSR and other applications; and
- Extension of FETS to 70 MeV (or above) using CH and SC spokes cavities as a replacement for the ISIS linac.

The ability of FETS to deliver a long beam pulse at high beam power at 50 Hz together with a fully-flexible time structure within the long pulse, offers the opportunity to deliver beam to more than one experiment for each beam pulse. Developments of the FETS could, therefore, offer a route to a long-term programme in which all the experiments listed above are served through a staged upgrade process.

4. Management

4.1. Project Organisation

The management structure for this project will consist of the following bodies:

Executive Board (EB): This will be responsible for the day-to-day running and financial management of the project. It will ensure that the project milestones are being met, monitor the expenditure and make any corrections that are necessary. The Committee will consist of the PI (Juergen Pozimski (Imperial)) and the Co-PI (Alan Letchford (STFC)) and the task managers. It will meet on a monthly basis before or after the FETS meetings.

Steering Group (SG): Although this is now a separate project, many of the activities being undertaken originate in UKNF or have close connections to the other Proton Accelerators for Science and Innovation R&D proposals. As a result, it is planned have a body, provisionally called the Steering Group, that will oversee the proposed projects. The Board will be chaired by K. Long (Imperial) and the representatives for FETS will be the PI and Co-PI. The SG will meet four times per year, twice in conjunction with the Proton Accelerators for Science and Innovation plenary meetings, and will receive reports from each project and advise on progress and the resolution of problems that may arise.

Task Management (TM): The project consists of 5 main tasks described in Section 2. Each of these is assigned a Task Manager (TM). The current list of Task Managers is shown in Table 1.1. The TM will be responsible for the day-to-day running and financial management of the task and will report on progress against milestones, deviations from the expected expenditure profile and other problems to the SC.

Project meetings: In addition to the monthly project and EB meetings already discussed, it is planned to hold general meetings of the four accelerator R&D projects being proposed twice per year, if approved, so that each project maintains a close collaboration with the others.

Table 1.1: Tasks and Task leaders

Work package	Description	Manager
1	Ion source development and beam delivery	Dan Faircloth (STFC)
2	RFQ commissioning	Juergen Pozimski (Imperial)
3	Design of a CH-Linac	Juergen Pozimski (Imperial)
4	MEBT	Replacement Jolly (Imperial)
5	Diagnostics	Christoph Gabor (STFC)
6	Future of FETS	Alan Letchford (STFC)

4.2. Cost & Financial Management Plan

The full costs for the project are shown in Annex 1. They are also summarised in Je-S. Only one ASTeC project number within the Shared Services Centre will be requested. It will be a principal responsibility of the task leader to monitor the actual expenditure against expectation. The ASTeC financial team will provide tables of the expenditure on a monthly basis. These will be sent to the PI the Co-PI and each of the task leaders and the latter will then report on this to the EB. The EB will ensure that action is taken to fix any significant deviations from the expected spend profile.

Approval will be required for all travel and hardware expenditure. Travel with a total cost of less than £1000 will need to be approved by the corresponding task manager. Travel costs above this limit must be referred to the PI by the task leaders. Hardware costs of less than £5000 can be approved by the task leader. Costs above this will need to be approved by the SC.

4.3. Project Structure

Funded staff covered by this proposal and their functions are as listed below:

ISIS

Letchford, A. (physicist, project grant) is an STFC fellow with a long-standing track record on linac design and gained extensive expertise in the running of a facility in his previous position as the leader of the ISIS linac group. He is responsible for the SFTC contribution to FETS. He will contribute to the commissioning of the RFQ and MEBT and to the management task of the project. He is leading the task on the definition of the future of FETS.

Faircloth, D. (physicist, project grant) is an internationally established ion source specialist, leading the ion source group at ISIS and has made significant contributions to the on source development and commissioning on FETS. He was initiating and contributing to the ion source development programme in the last years and his contributions have been very valuable for the improved source performance. He will contribute to the ion source R&D programme and be responsible for the beam delivery for the RFQ and MEBT commissioning. He is leading the task ion source and LEBT

Lawrie, S. (physicist, project grant) has made significant contribution to the FETS project since he joint in 2008. He successfully improved the beam emittance delivered by the ion source by means of particle trackng simulations and experiments. He also made valuable contributions to the simulations for the RFQ (matcher, field flatness and influence of RFQ modulation, cooling). He will be responsible for the ion source R&D work.

Clarke-Gather, M. (physicist, project grant) is an internationally renowned specialist in RF chopping systems and has successfully worked within FP6 on the development of the slow/fast chopper design. He will be responsible for the mechanical design of the chopper, the driver electronics and the commissioning of the chopper.

Craft support: Resource at craftsman level for support of installation and setup of FETS.

Technical support: Resource at technician level for support of construction and installation of FETS.

Engineering support: Resource at engineer level for support of design, manufacture and infrastructure.

ASTeC

Gabor, C. (physicist, project grant) is a member of the ASTeC high intensity group and responsible for the Design of the Laser wire / emittance scanner. He received his PhD at Frankfurt University on the subject of beam diagnostic using photo detachment in 2006 and is since then working on this subject at FETS. He will contribute to the overall design of the laser based beam diagnostic, contribute to the commissioning of the laser diagnostic and will be leading the diagnostics task.

Warwick

Back, J (physicist, project grant) was responsible for the particle tracking in the Low Energy Beam Transport (LEBT), which is the component of the Front End Test Stand (FETS) that transports the beam from the ion source into the Radio Frequency Quadrupole. He worked on optimising the electromagnetic design of the solenoids and contributed to the commissioning of the LEBT, the results of which were shown at the first International Particle Accelerator Conference in Japan 2010. He will be responsible for the further optimisation of the LEBT.

Imperial

Pasternak, J. (academic, project grant) is a joint lecturer at Imperial College and STFC. He is an accelerator physicist, having previously worked at CERN for the LHC project and at CNRS in Grenoble on the design of FFAG accelerators for medical applications. He is strongly involved in the development of a nsFFAG for the Neutrino Factory. His areas of expertise are charged particle optics, lattice design and beam dynamics. He will contribute to the definition of a future use of FETS as an injector into a low energy FFAG.

Pozimski, J. (adademic, project grant) is Reader at Imperial College. He is an expert on space charge related problems (space charge compensation, space charge lenses) having worked for several international accelerator projects like ESS, IFMIF and HIDIF over the last two decades. He leads

Imperial's accelerator activities on the field of hadron cancer therapy and is responsible for Imperial's contribution to FETS. His activities include particle dynamics, development of accelerator structures (RFQ's, IH/CH structures, spokes) and beam diagnostics. He will be leading the RFQ task and contributing to the ion source R&D, the work on beam diagnostics, the investigation of CH structures for a FETS upgrade and management tasks.

Kurup, A. (physicist, project grant) was contributing to the RF design of the RFQ for FETS before working as IC/FNAL fellow on the subject of high power RF cavities for the Neutrino factory. He is working on the design of the beam dumps for the MEBT and will be responsible for the commissioning of the beam dumps. In the last phase of the project he will contribute to the RDR and will be responsible for a costing of the different option for a FETS upgrade path utilizing the experience gained from leading the costing exercise for the NF RDR.

Jolly, S. replacement (physicist, project grant): S. Jolly tok responsibility for the detailed design of the RFQ. Working with the mechanical and electrical engineers as well as the beam-dynamicists, he developed the novel software suite by which the RFQ geometry was optimized. Imperial is responsible for the manufacture of the FETS RFQ. A replacement for S. Jolly is therefore essential for Imperial to discharge this responsibility. The replacement for S. Jolly will be a senior RA with experience in particle tracking and RF structures. He will be responsible for the commissioning of the RFQ and the data analysis of the beam transport experiments in the RFQ. He will further contribute to the design of the MEBT and the commissioning of the MEBT. Using the experience he will have gained, he will then take a leading role in the MEBT task.

Alsari, S. (electrical engineer, project grant) is an electrical engineer who has been working on FETS since 2008. He has contributed to bead pull measurements on the RFQ cold model, the low level RF controls and the tuner system as well as the high power RF tests of the klystron and the RF dump. He will be involved in the setup of the low and high power RF systems and controls for the RFQ as well as the MEBT. He was so far also involved in the development of detector electronics and will continue so on a moderate level.

Savage, P. (mechanical engineer, project grant) has been working on FETS from 2004 and has contributed to the largest fraction of mechanical design tasks at FETS. He was responsible for the LEBT mechanical design and is leading the design activities for the RFQ and will be responsible for manufacture and assembly of the RFQ. He will then concentrate on the mechanical design of the MEBT and in the final phase of the project contribute to the preparation of the RDR for the future of FETS

Clarke, D (mechanical technician, project grant) is a senior technician working at the workshop of the HEP group at Imperial College. While the main part of the machining and production for FETS will be outsourced to UK industry, the availability of local workshop effort at Imperial has significantly contributed to the fast prototyping of components and the production of test pieces (joining and cooling experiments etc.) for the verification of designs.

Beuselinck, R. (programmer, rolling grant) is an IT specialist in the HEP group at Imperial College supporting the extensive simulation work for FETS by taking responsibility for maintenance of the computer systems and the software packages.

Barlow, C (senior adminstrator, project grant) is responsible for the administration of the FETS project at Imperial College.

Brambilla, P. (administrator, project grant) is contributing to the administration of the FETS project at Imperial College.

Khaleeg, M. (electronic technician, project grant) is working at the electronics workshop at Imperial college and is supporting the development of electronic circuits for beam diagnostics and controls.

Kasey, V. (electronic technician, project grant) is working at the electronics workshop at Imperial college and is supporting the development of electronic circuit for the LL RF control system.

UCL

Jolly, S. (academic, project grant) worked at Imperial on FETS contributing to the design, commissioning and data analyses of the FETS pepper pot emittance scanner and was responsible for the particle tracking simulations in the RFQ. In future he will be lecturer at UCL. He will be responsible for the beam diagnostics in the MEBT and will contribute to the design and commissioning of the beam positioning monitors.

RHUL

Boorman, G. (electronics engineer, project grant) is an electronics engineer who has made contributions to the readout electronics of the FETS laser wire having gained significant laser-wire expertise at the PETRA laser-wire at DESY; he is also an expert in Labview control systems. He will be responsible for the detector system and readout electronics for the beam diagnostics with a focus on the laser wire.

Bosco, B. (physicist, project grant) is a post-doctoral RA laser specialist with experience in laser-based particle beam diagnostic. He has worked on the RHUL laser wire setup for electron beams at PETRA and got lately involved in the work for the laser-wire setup under construction at FETS. His contributions have proven very valuable for FETS and he will be responsible for the delivery of the laser beam to the experiment.

Huddersfield

Edgecock, R. (academic, project grant) R. Edgecock is leding the target studies within UKNF, he is leading the EMMA project and the EUROnu design study (FP7). He will contribute to the work on the future of FETS and takes responsibility for defining a program on slow neutron and isotope production targets as a possible FETS upgrade plan.

4.4. Schedule

The project is scheduled to last for 3 years. The plan is made under the assumption that in spring 2012 the RFQ is machined and in the assembly phase. In the first year the focus will be on the commissioning the RFQ, on beam transport experiments and the mechanical design of the MEBT. The first year should also see the start of the machining for the MEBT. In the second year the MEBT and chopper will be machine and assembled while in the last year the focus will be on MEBT and Chopper commissioning and on final beam experiments and the preparation for a proposal on the future of FETS. All of the tasks will continue for the duration of 3 years but with a varying amount of staff time allocated depending on progress. The schedule for the project has been defined in terms of milestones shown in 3.5.

4.5. Milestones and deliverables

1	**Ion source and LEBT**	
1.1	Detailed simulations of ion source plasma.	31/12/2012
1.2	Experimental determination of plasma parameters in the ion source by means of Langmuir probes, optical spectrometers and particle energy spectrometers.	30/06/2013
1.3	Design of upgraded 2X source	30/06/2013
1.4	Engineering and construction of upgraded 2X source	31/12/2013
1.5	Commissioning of ion source and evaluation of ion source performance	30/06/2014

2	**RFQ**	
2.1	RF couplers manufacture finished	30/06/2012
2.2	RFQ assembled and installed	30/06/2012
2.3	RFQ RF tests finished	30/09/2012
2.4	First beam at the RFQ exit	30/03/2013
2.5	Investigation of FETS-RFQ properties and comparison with simulations finished	31/06/2014
3	**C-H structure**	
3.1	Detailed RF simulations of 324 MHz CH structure finished	30/06/2012
3.2	Particle tracking for CH linac finished	30/06/2013
3.3	Construction of a CH cold model and RF measurements finished	31/06/2014
4	**MEBT**	
4.1	Fully engineered chopper design complete	30/09/2012
4.2	Mechanical design of MEBT finished	30/09/2012
4.3	Procurement of MEBT components	30/06/2013
4.4	Manufacture of chopper assemblies complete	30/06/2013
4.5	MEBT installation complete	31/12/2013
4.6	MEBT equipment commissioned	30/03/2014
4.7	First MEBT beam	31/06/2014
5	**Diagnostics**	
5.1	Design of MEBT diagnostic finished	30/06/2012
5.2	Installation of MEBT diagnostics complete.	31/12/2013
5.3	MEBT diagnostic operational.	30/06/2014
5.4	1D-transversal beam profile system commissioned at FETS.	30/09/2012
5.5	2D-transversal profile system and reconstruction operational at FETS.	31/09/2013
5.6	Operational emittance measurement system at FETS.	31/09/2014
6	**Future of FETS**	
6.1	Report on advanced RF sources	30/09/2012
6.2	IDR for an High Power proton beam centre at RAL.	31/06/2013
6.3	Report on CH structures for high power linac	30/12/2013
6.4	Report on FETS for slow Neutron / isotope production	31/06/2014
6.5	Report on FETS as FFAG injector	31/09/2014
6.6	RDR for a High Power proton beam centre at RAL.	31/03/2015

4.6. Risk analysis

4.6.1. Technical risk

An analysis of the main technical risks for each of the tasks is given below

WP	Description	Likelihood (0-5)	Impact (0-5)	Risk	Mitigation
1	Unable to further reduce the beam emittance from the ion source.	1	2	2	Collimation after the source at the cost of some beam current is possible.
1	Not possible to understand or control current droop in long pulses.	1	2	2	Operate at reduced beam current for long pulse lengths.
2	RF couplers cannot deal with required power.	2	2	4	Increase number of couplers with further RF power splitting.
2	Bolted design doesn't meet RF and vacuum requirements.	2	4	8	Braze RFQ and lose maintainability.
2	Unable to flatten RFQ field.	1	4	4	Operate RFQ at sub-optimal voltage.
2	Unable to tune RFQ.	1	5	5	Re-machine to correct resonant frequency.
2	Unable to achieve RFQ design voltage.	1	4	4	Operate at below design voltage with reduced efficiency.
2	Insufficient RFQ cooling	2	3	6	Operate at reduced RF duty factor.
4	Chopper deflectors do not meet impedance and bandwidth specification.	2	5	10	Re-evaluate design.
4	Chopper beam dumps cannot dissipate power.	2	3	6	Operate with reduced beam duty factor.
4	MEBT cavities cannot be tuned.	1	4	4	Re-machine cavities.
4	Beam loss above expectation.	2	3	6	Operate at reduced beam intensity.
5	Unable to detect sufficient photo-detached electrons.	2	3	6	Increase laser power, improve discrimination in electronics.
5	Reconstruction has insufficient resolution	2	2	4	Increase the number of profiles at cost of measurement time.

4.6.2. Financial risk

A large amount of hardware is required to complete FETS with an associated risk related to the cost of the equipment. In all cases the cost given are the best estimates based on experience of similar scale hardware acquisitions. Much of the equipment is similar in nature to other projects undertaken by FETS contributors or associated departments however in the nature of an R&D activity there are some uncertainties. Allowance for the cost uncertainties and a contingency for unexpected costs has been made.

4.7. De-scoping options

FETS is a well defined piece of hardware with fixed capital cost. As no part of the proposed hardware is optional the only contingency in the case of a lower level of funding than anticipated is to extend the timescale of the project to 4 or 5 years depending on the annual capital shortfall.

WPs 3 & 6 are not integral to the primary goal of FETS and require no capital. Sacrificing these tasks would lead to a saving of less than 100 k£ per year.

References

[1] A. Letchford et al, *Status of the RAL Front End Test Stand*, IPAC2010, Kyoto, May 2010

[2] D. Faircloth et al, *The Front End Test Stand High Performance H- Ion Source at RAL*, Review of Scientific Instruments, Volume 81, Issue 2, 2010

[3] S. Lawrie et al, *Plasma Meniscus and Extraction Electrode Studies of the ISIS H- Ion Source,* Review of Scientific Instruments, Volume 81, Issue 2 , 2010

[4] S.Lawrie et al, *Redesign of the Analysing Magnet in the ISIS H− Penning Ion Source*, AIP Conf. Proc. Volume 1097, pp. 253-262, 2009

[5] D. Faircloth et al, *Study of the Post Extraction Acceleration Gap in the ISIS H- Penning Ion Source*, EPAC'08, Genoa, June 2008

[6] S. Lawrie et al, *Improving the ISIS Emittance Scanner Software*, EPAC'08, Genoa, June 2008

[7] S. Jolly et al, *Data Acquisition and Error Analysis for Pepperpot Emittance Measurements*, DIPAC'09, Basel, September 2009

[8] S. Lawrie et al, *Assessing the Transmission of the H- Ion Beam on the Front End Test Stand*, IPAC2010, Kyoto, May 2010

[9] D. Faircloth et al, *Pulse Lengthening Experiments on the FETS Ion Source*, IPAC2010, Kyoto, May 2010

[10] S. Jolly et al, *LEBT Simulations and Ion Source Beam Measurements for the Front End Test Stand (FETS)*, EPAC'06, Edinburgh, June 2006

[11] J. Back et al, *Commissioning of the Low Energy Beam Transport of the Front End Test Stand*, IPAC2010, Kyoto, May 2010

[12] M. Clarke-Gayther, *The Development of a Fast Beam Chopper for Next Generation High Power Proton Drivers*, EPAC'08, Genoa, June 2008

[13] M. Clarke-Gayther, *The Development of a Fast Beam Chopper for Next Generation High Power Proton Drivers*, IPAC2010, Kyoto, May 2010

[14] C. Plostinar, *MEBT design progress for the Front End Test Stand*, IPAC2010, Kyoto, May 2010

[15] C. Plostinar et al., *A hybrid quadrupole design for the RAL Front End Test Stand (FETS)*, EPAC'08, Genoa, June 2008

[16] C. Plostinar et al, *Design progress of the re-bunching RF cavities and hybrid quadrupoles ofr the RAL Front End Test Stand (FETS)*, EPAC'06, Edinburgh, June 2006

[17] C. Gabor et al, *Diagnostic Experiments on a 3MeV H- Test Stand at Rutherford Lab*, Review of Scientific Instruments, Volume 81, Issue 2 , 2010

[18] S. Lawrie et al, *Combined Electromagnetic-Thermal-Structural Simulation of the Four-metre Radio Frequency Quadrupole to be Installed on the Front End Test Stand*, IPAC2010, Kyoto, May 2010

[19] S. Jolly et al, *Integrated Design Method and Beam Dynamics Simulations for the FETS Radio Frequency Quadrupole*, IPAC2010, Kyoto, May 2010

[20] S. Alsari et al, *A Tuning System for the FETS RFQ*, IPAC2010, Kyoto, May 2010

[21] P. Savage et al, *The Mechanical Engineering Design of the FETS RFQ*, IPAC2010, Kyoto, May 2010

[22] H. Hassanzadegan, *Design and Implementation of a Pulsed Digital LLRF System for the RAL Front End Test Stand*, IPAC2010, Kyoto, May 2010