FETS progress report Dec 2013

1 Overview / Executive summary

Since the funding for FETS started in April 2012 good progress has been made in all work packages. Significant progress has been made on the infrastructure issues (shielding, RF distribution & water) connected with R8 and it is now expected that all infrastructure is ready end of 2014. The ion source has demonstrated all parameters requested individually and a demonstration of all parameters simultaneously in 2015 is expected. The initial issues of misalignment of the FETS LEBT have been identified experimentally and corrected since then. While the RFQ machining has been a serious cause of delays so far, the first section delivered so far to RAL shows very good results. Most auxiliaries for the RFQ have been manufactured and no further delay of the RFQ work packages is expected. The MEBT lattice design has been refined in the process of engineering the individual components of the lattice and is now frozen. The detailed engineering drawings for the MEBT components are ether available or in production and most of the components will be manufactured and delivered in 2014. The RF system for the RFQ was tested at low RF power and a high power test is expected early 2014. The components for RF distribution as well as the RF amplifier for the bunching cavities are on order. The components for the conventional beam diagnostics in the MEBT are ether built or engineering drawings are available. The work on the laser based particle beam diagnostic is now on track, an additional boost is expected from the collaboration with CERN.

While the overall progress on FETS was good, several items have been severely delayed due to various reasons. The first section of the RFQ was delivered with a delay of more than 18 month (details see RFQ chapter). Additionally significant building work in R8 over several months (March – August 2012) has delayed progress on the ion source development and the alignment of the LEBT. STFC was informed over the status of FETS and the origin of delays through the regular PSAG meetings. Delays in the diagnostic work package have been reduced dramatically since the management of the work package was changed and further delays are not expected. While the progress on FETS was in previous years limited by the available funding for resources / capital, the availability of engineering is now the bottle neck determining the speed of progress. In order to attempt to recover some of the project delays it is envisaged that use of RAL contract engineering will be relied upon. To date contract effort has been used to develop the shielding layout and is currently being employed to complete the MEBT support structures. The next engineering item to be progressed to manufacture via this route will be the MEBT vacuum manifold, the MEBT rebunching cavities and the MEBT chopper and chopper-beam-dump vessels.

The milestone table attached has been updated from the original milestone table submitted with the proposal in 2011. As already discussed with representatives of the SPO at the time of approval in 2011 the time schedule of FETS was very tight. It was suggested then, that FETS should apply for an extension of 1-1.5 years, when details have become clearer. In the light of the overall development of FETS over the last 18 month it is obvious that FETS will just become operational at the end of the funding period (March 2015). The collaboration agreed to prepare a proposal for a continuation of FETS for 18 month to allow for rigorous testing of the beam chopper and the laser based ion beam diagnostic. It is envisaged that staff funding will be slightly reduced and the required funding for capital/resources should not exceed ~ 50 (-100) k£ for this period.

2 Technical Progress

Ion Source and LEBT

There are four main goals for the FETS ion source and LEBT to improve compared to ISIS: 1) Fully transport a 60 mA H^- beam (35 mA on ISIS); 2) Achieve transverse beam emittance of 0.25 π mm mrad (1.0 π mm mrad on ISIS); 3) Operate at 50 Hz with 2 ms pulse lengths (0.2 ms on ISIS), and 4) Operate stably at 65 keV beam energy (35 keV on ISIS).

Significant progress was made several years ago to meet goal 2. Electrode and magnet modifications reduced the emittance to 0.35 π mm mrad, leading to a 15% improvement in transported beam which helped achieve goal 1. To bring the emittance down even further to meet the 0.25 π mm mrad goal needs a more radical change to the ion source: described later.

To achieve goal 3, a pulsed discharge power supply with uprated capabilities was built and is operating well for FETS. It can drive 2.2 ms, 50 Hz, 60 A, 70 V pulsed plasma discharges. Similarly, a new pulsed extraction power supply can deliver 2 ms long, 30 kV pulses at 50 Hz: eight times the duty factor of the ISIS extractor in a more compact rack-based footprint. The extraction power supply has been successfully commissioned at full power, but needs a small modification for reliable long-term operation. The new pulsed discharge and extraction power supplies are shown in Figure 1.

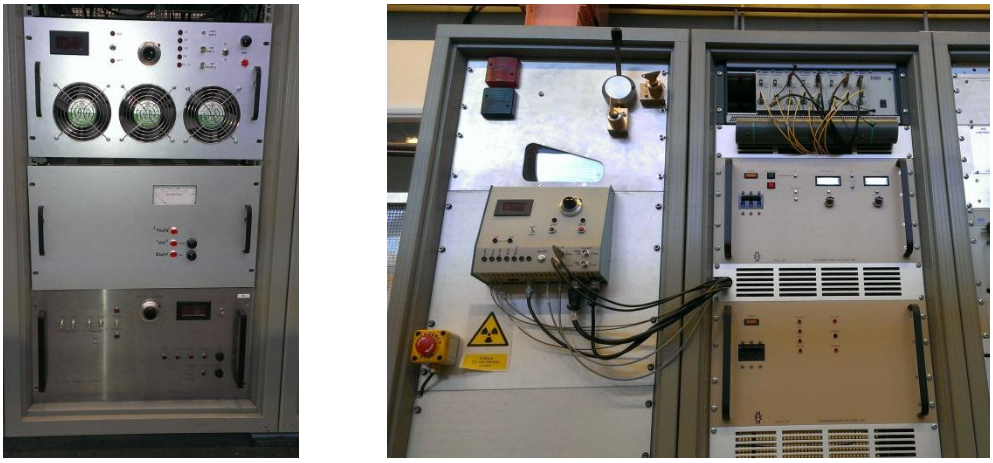

Figure 1: High power pulsed discharge (left) and extraction (right) power supplies.

The higher energy beam must still be transported round the 90° dipole magnet, which meant the magnetic circuit needed modifying to operate at a higher deflecting field. This involved increasing the size of the cold box and return yoke to avoid saturation.

To achieve goal 4, the electrodes which post-accelerate the beam to 65 keV have been modified to include a proton suppressor and easier mechanical adjustment. A high voltage insulator column has been installed which can withstand the 65 kV with minimal breakdowns.

Considerable effort has been expended improving the alignment of the ion beam to achieve goal 1. Initial results from the LEBT solenoids showed a beam of sufficient current was transported, but it was badly misaligned. A pencil-beam collimator was temporarily installed to understand the origin of misalignment, and detailed measurements and simulations were made. The alignment procedure of the ion source and insulating column was improved. The beam is now centred at the end of the LEBT and is symmetrical in phase space, as shown in Figure 2.

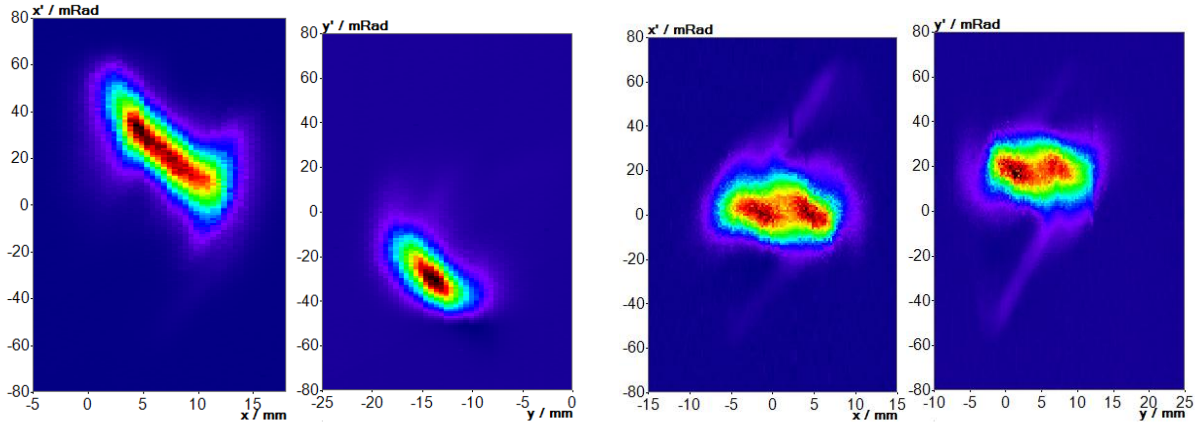

Figure 2: Horizontal and vertical phase space plots before (left pair) and after (right pair) alignment.

Other work on the LEBT has concentrated on understanding space charge compensation. Equipment has been installed to analyse the energy spread of residual gas particles which compensate the beam's space charge potential. Simulations have been performed to model the time evolution of the compensation process.

Research and Development

The modifications discussed are all to components external to the ion source. To fully achieve all four goals simultaneously, a radical redesign of the source itself is required based on a better understanding of the plasma and the extracted beam. Therefore a vacuum vessel for extraction and source plasma analyses (VESPA) is under construction. In the space of six months, a lab has been acquired, gutted from the previous use, modified to suit our needs and VESPA equipment installed. The vacuum vessel is out for manufacture and is expected early 2014. The ion source will be mounted for horizontal extraction, with the electrodes completely redesigned for loss-less and emittance-growth-free transport into the LEBT, as shown in Figure 3. Horizontal mounting will also allow for direct line-of-sight access into the plasma for spectroscopic measurements. A high resolution optical monochromator has been delivered and calibrated. Overall, the FETS ion source progress continues apace and when the VESPA is operation, the source performance should improve even more and the FETS goals will be fully met.

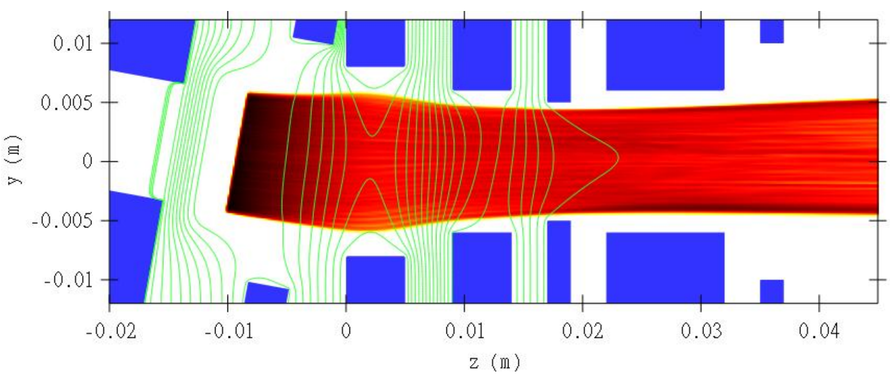

Figure 3: Particle tracking design study of the new extraction system.

RFQ

When the proposal for the FETS continuation was written early 2011, the design of the RFQ had developed to a stage that production start in summer seemed realistic and a delivery of the RFQ early 2012 seemed possible. As funding for the RFQ manufacture was available, the Proposal was written and milestones defined under the assumption that the RFQ will be delivered and paid for. Already shortly after the proposal was submitted it was foreseeable that this assumption will no longer be valid. This was communicated to the funding agency already in an early stage. Some reasons were a complicated tender process, further STFC review of the cooling design, but also pre machining preparation at the company (material storage and safety). At the start of the funding period those delays have been accumulated to more than 7 months. While the rough machining of the RFQ sections went as planned, quality issues in the final machining steps and 4 month delay in the company internal QA due to an upgrade of the metrology further significantly increase the delay of the RFQ delivery. This added up to a final delay of nearly 18 month with the first section arrived in October 2013 at RAL. The development was partly down to the fact, that neither the RFQ engineering designer nor the RFQ manufacturer have designed or built an RFQ in the past. Widely publicised failures in the production of similar structures being produced by experienced teams with larger resources than our own led to a highly cautious approach. Both designer and manufacturer were aware that a serious mistake with the RFQ could end the FETS project. First results from metrology available recently confirm the high quality that has been achieved in. The manufacturer has undoubtedly lost money in their undertaking. Additionally the originally available engineering resources have been not adequate for simultaneously an adequate supervision of the manufacturer and further component design work. Recent support from an additional engineer has proved invaluable.

Machining status

RFQ section 1 of four is complete apart from end face machining and is currently at RAL Metrology for inspection.

RFQ sections 2, 3 and 4 are at NAB Precision Engineering. Final vane machining is awaiting the conclusions from inspection. The total remaining machining operations for all twelve pieces would take approximately 4 weeks. Each vane is complete apart from vane final machining and end face final machining.

Change of machining strategy: One of the original manufacturing goals for the FETS RFQ was to perform all machining operations without the use of coolant. The main advantage was to preserve the cleanliness of the copper by not bathing it in chemical solutions over long time periods. Experience gained from machining section 1 has made us re-think this strategy. The as-delivered internal surface was very contaminated due to the end face machining operation and the surface quality was poor in places (though fortunately in the least important places). A polishing operation will therefore be developed to improve the surface quality but this will push impurities into the copper surface, somewhat cancelling out any benefit of machining without the use of liquid coolant. It has been decided therefore that for sections 2, 3 and 4 the final waveform machining operations will be performed with coolant which should produce a vastly improved surface finish. This will reduce or even remove the need for polishing altogether.

Metrology

Section 1 (see figure 4) is at RAL Metrology now and inspection has begun. The goal of inspection is to determine how well the machined RFQ structure matches the theoretically perfect 3D model and hence to indicate how well the structure will perform. The inspection plan will evolve because RAL Metrology hasn't inspected anything similar in recent memory. The lessons learned for section 1 will be employed for sections 2, 3 and 4. Early indications show that the cautious manufacturing approach has yielded high quality datums with just 3 microns flatness deviation over an area measuring 600mm x 260mm. Inspection will be complete in December 2013.

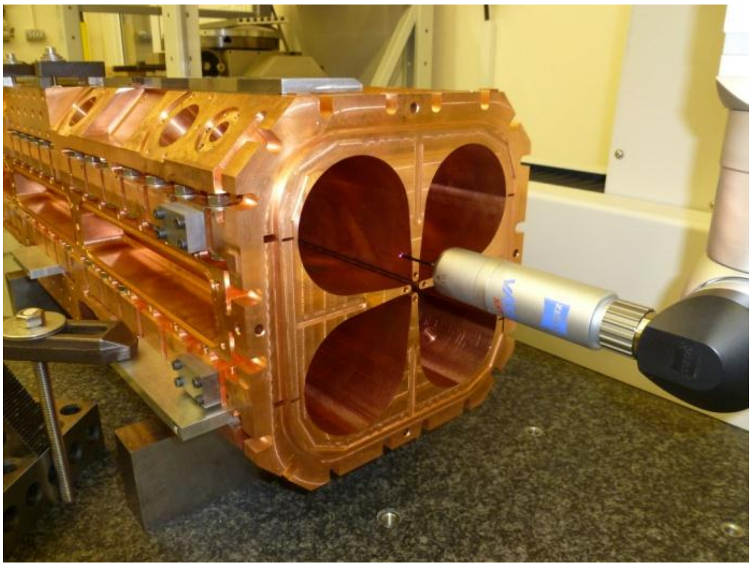

Figure 4, RFQ Section 1 being inspected at RAL Metrology.

Auxiliaries

All auxiliary items for RFQ section 1 are manufactured and ready to be fitted with the exception of the cooling baffles which are the next scheduled production items. The plan was to await proof of design before proceeding with items for RFQ sections 2, 3 and 4. However, due to time restraints some of these items have been progressed ahead of schedule to benefit from the time advantage due to mass production. Shown in figure 5 are the water cooled RFQ end flanges housing the toroid for current measurement as well.

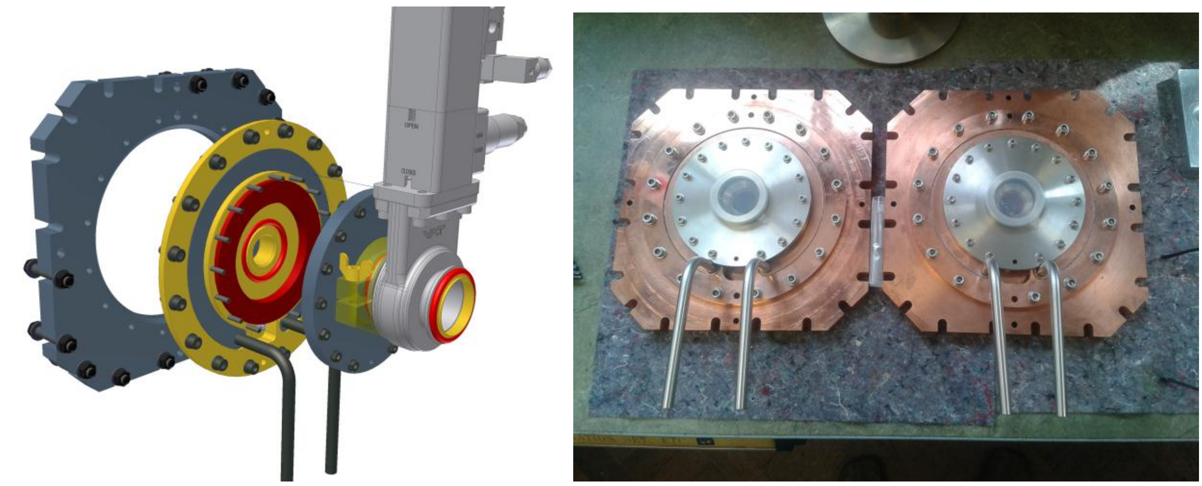

Figure 5, Exploded CAD model of RFQ end flange and photograph of built and assembled units.

Bead-pull testing, final machining and assembly

Bead-pull testing: Following on from the metrology we will perform a bead-pull test. This is expected to take place in January 2014 in RAL Metrology and will be conducted by the RF Engineer. The RFQ vanes will be adjusted for position depending on RF results. Then the tuners will be fitted and positioned to achieve a flat field electric field on (beam) axis.

Final machining: Once the bead-pull test has been completed and alignment confirmed the final end machining operation can be made. The assembled structure would be transported back to NAB for end face machining and fitting of alignment dowel blocks and then would be returned to RAL R8. The goal for the turn-around time for this operation would be 4 weeks from the item leaving RAL to returning. This is due in March 2014.

Assembly: The RFQ section now has its alignment determined by the dowel blocks and no further inspection needs to take place. The individual vanes must be dismantled one last time, polished and cleaned thoroughly. The RFQ section is then reassembled with the 3D O ring and RF seals fitted. Now the RFQ section can be fitted with all the auxiliary components. It is envisaged that bolting the vanes together will take one to two days while fitting the RFQ with the auxiliary components may take up to one week. This will take place in April 2014. The RFQ section is now ready for vacuum testing, low power testing and fitting to the FETS rails.

MEBT

While the work before 2012 concentrated on the beam dynamics design of the MEBT , the focus was then moved on to generating a fully engineered MEBT for installation in R8. For the practical realisation several difficulties with the layout had to be solved. Not only that space for auxiliaries (diagnostics, pumping, valves,...) had to be found in the very dense lattice, but the assumed field levels of up to 30 T/m in the quadrupoles have been proven to be too ambitious and could be reduced to ~20 T/m. The voltage for the bunching cavities has been reduced from 160 kV to 100 kV and the aperture of the cavities increased to from 14 to 17 mm to avoid particle losses. The MEBT was also divided into two sections according to the purpose of each section. While in the first section were beam chopper will be tested, the lattice is very dense and compact, small bore short high field quadrupoles are utilized, in the second section used for the test of the laser based beam diagnostics, longer quadrupoles with larger bore and lower fields are used to allow for a larger variation of the beam to be measured by the instrument.

Lattice

The beam chopper and associated beam dumps are located in the MEBT. Achieving a low emittance-growth under the influence of strong, non-linear space-charge forces in a lattice which has to accommodate the long chopping elements is challenging. The baseline FETS MEBT design (shown in figure 6) is 4.3 m long and contains 7 quadrupoles, 3 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, beam loss for the un-chopped beam is below 1% while the chopping efficiency is ~99.8% in both choppers. While the overall layout of the MEBT is very similar to the lattices presented in previous years significant progress has been made in terms of engineering and detailing but also in terms of performance figures. Until detailed solutions for various issues with the original lattice had been found an alternative lattice, with more space but slightly lower performance was developed in parallel. Recently with the adoption of a dual BPM system and the new cavity design the baseline lattice (shown in figure 6) was chosen to be finally built. As the lattice design was adopted in parallel to the developing engineering designs production of most parts have been started or are expected to start in 2014.

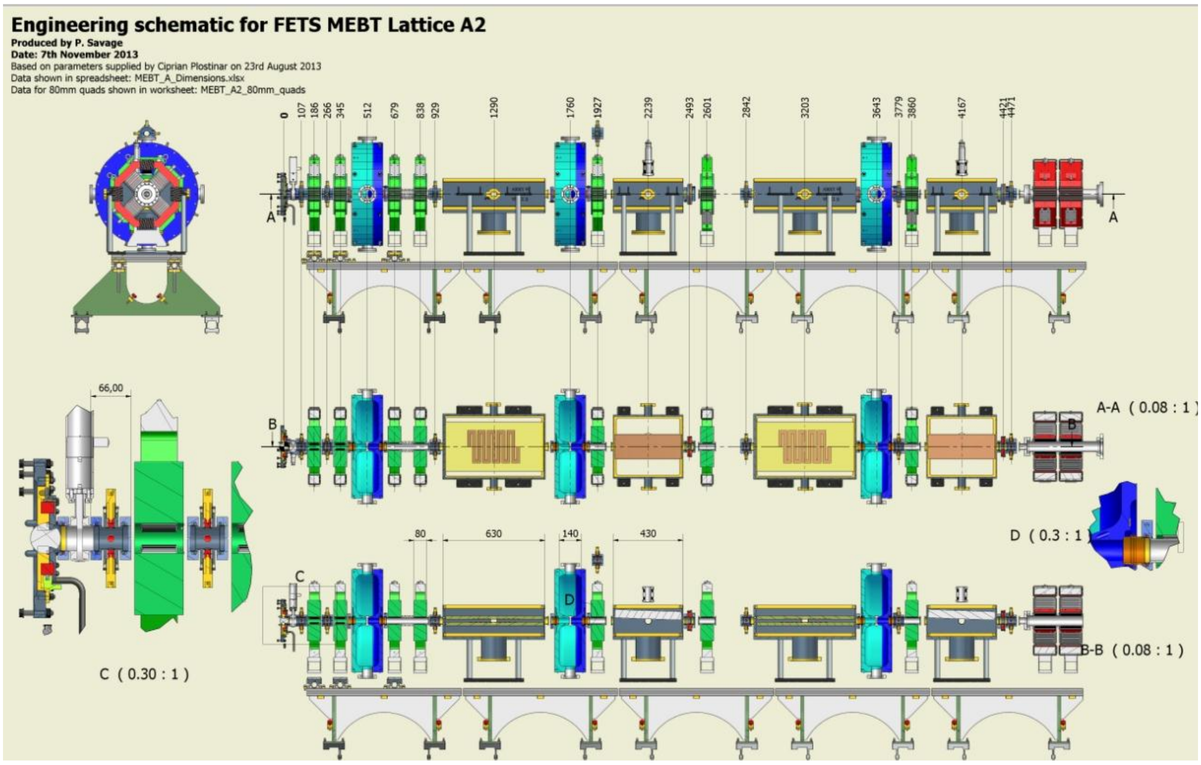

Figure 6: Baseline lattice of the FETS MEBT.

MQP

The quadrupole magnets are a major component of the FETS MEBT. While in earlier years hybrid quadrupoles have been investigated, the collaboration has decided to use conventional normal conducting D.C. magnets manufactured from steel quarter yokes and four identical water cooled coils. In addition to providing focussing, each magnet facilitates horizontal and vertical steering of the particle beam. This is achieved through the use of additional air-cooled windings on the return yokes to generate the dipole field. In consequence of the results from particle tracking studies for the laser based diagnostics following the beam choppers it was decided that two families of magnets are highly favourable. In the beam chopping section of the MEBT (~4.3 m length), 80 mm short, high field (up to 20 T/m) 'Small Bore' (38 mm beam pipe diameter) quadrupoles will be used mainly for space considerations. In the following sections housing the Laser based beam diagnostics and the primary beam dumps, long (150 mm), low field (9T/m) 'Large Bore' (60 mm diameter of beam pipe) quadrupoles are used to allow for a large phase space to be sampled by the Laser based emittance scanner and to allow reduction of beam power density for the beam dumps. Details of the magnets can be seen in figure 7.

A detailed technical specification document has been produced and forms the basis of the procurement process that has been started. The power supplies for the quadrupoles and the steering dipoles are on order and expected to arrive in 2013.

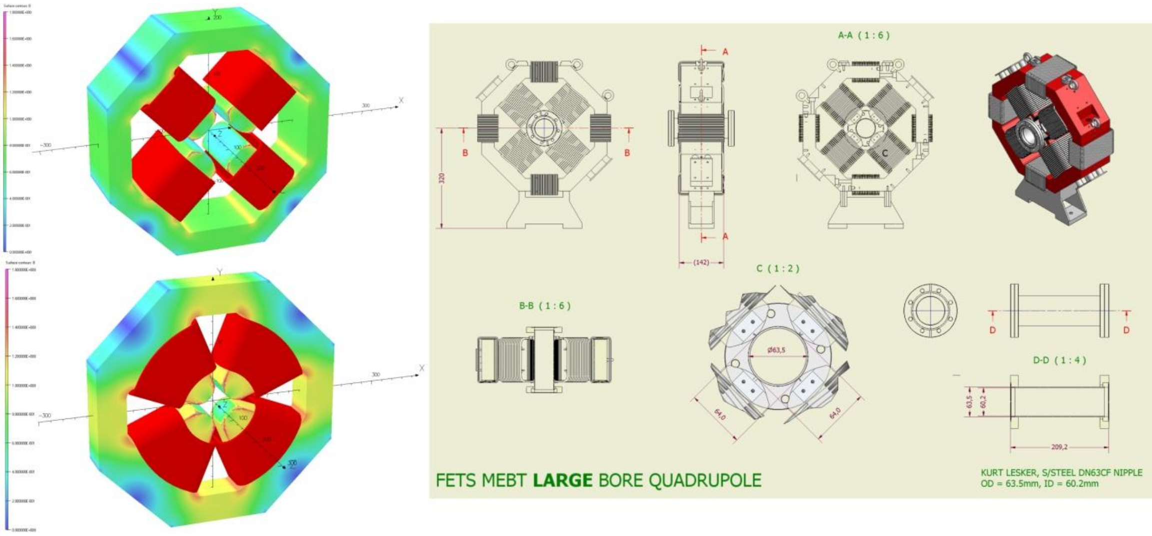

Figure 7 : Left hand side : Results of a magnetic field calculation using OPERA for the large bore (upper) and small bore (lower) quadrupoles. Right technical specification of the large bore quadrupole.

Cavities

A preliminary design for the MEBT bunching cavities was based on the LINAC4 design and developed further to suite the requirements of FETS. Several changes have been implemented following detailed investigations. The cavity voltage has been reduced from 160kV to 100kV allowing for smaller RF amplifiers and reduced cooling requirements. Simultaneously the aperture of the cavity has been increased from 14 to 17 mm. To preserve the power efficiency of the cavity this required a reduction of the nose cone angle. Furthermore the cooling scheme has been altered following the results of a detailed thermal analysis of the cavity (see figure 8). In contrary to the original plans the cavity will now no longer be manufactured from copper but instead the body will be mild steel and copper plated. In the moment a cavity with a transversal elliptical shape of the acceleration gap to prevent particle losses in this region is under investigation. Depending on the results of these investigations a final decision will be made and engineering drawings produced. Mean while a cavity plating test is in preparation to investigate the variation in copper thickness. The machining of the cavities is expected to start in June 2014 with a delivery of the cavities end 2014 expected.

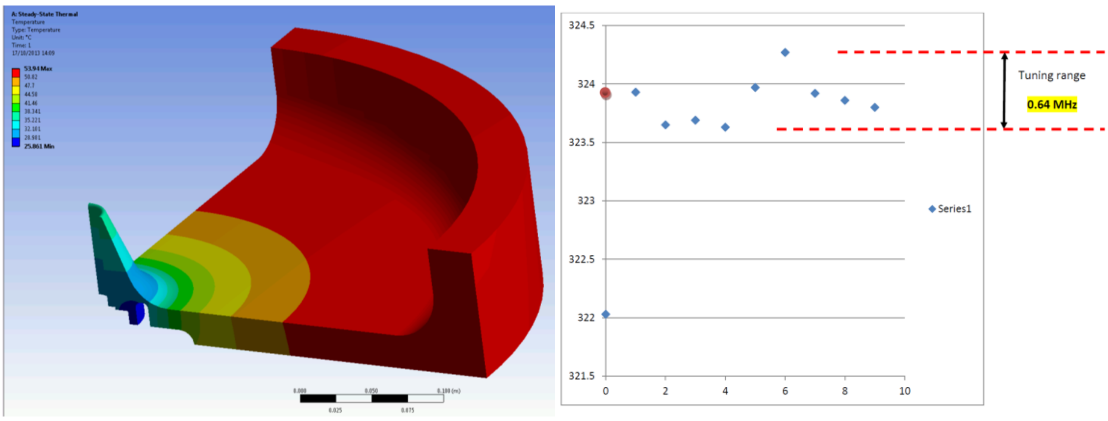

Figure 8 : FETS rebunching cavities. Left: Thermal model of a circular cooling channel. Right: Frequency variation for different cavity models including various error sources (plating thickness, vacuum load, thermal expansion).

Chopper

‘Fast’ (slow-wave electrode) structure

Models and prototypes of the RAL helical and planar strip-line slow-wave designs have demonstrated that both will probably produce full scale structures with the required transmission line characteristics, coverage factor and field uniformity. However, the designs have many high precision parts, and manufacturing costs will be high. A decision was made in 2012, to re-visit the CERN micro-strip design, with a view to improving coverage factor and field uniformity. The motivation behind this decision was the perception that a ‘micro-strip on ceramic substrate’ design may offer a better compromise between performance and cost than the existing strip-line designs. Transmission line characteristics, coverage factor, and field uniformity, were modeled in CST Microwave and EM studio, for both the original and modified CERN micro-strip designs. Simulations, completed at the end of 2012 indicated that significant improvements in coverage factor and field uniformity were possible.

However, conductor ‘feature size’ in both the original CERN, and the modified CERN micro-strip design were below, or ‘on the limit’, respectively, for the specified ‘thick film’ manufacturing process. A novel suspended micro-strip structure has been designed that eliminates the ‘feature size’ problem. Simulations in the frequency and time domains suggest that the transmission line characteristics, coverage factor, and transverse field uniformity of the new design will be superior to those of the original CERN design. In addition, the larger conductor feature size of the new design, should meet with the standard requirements of the manufacturing process.

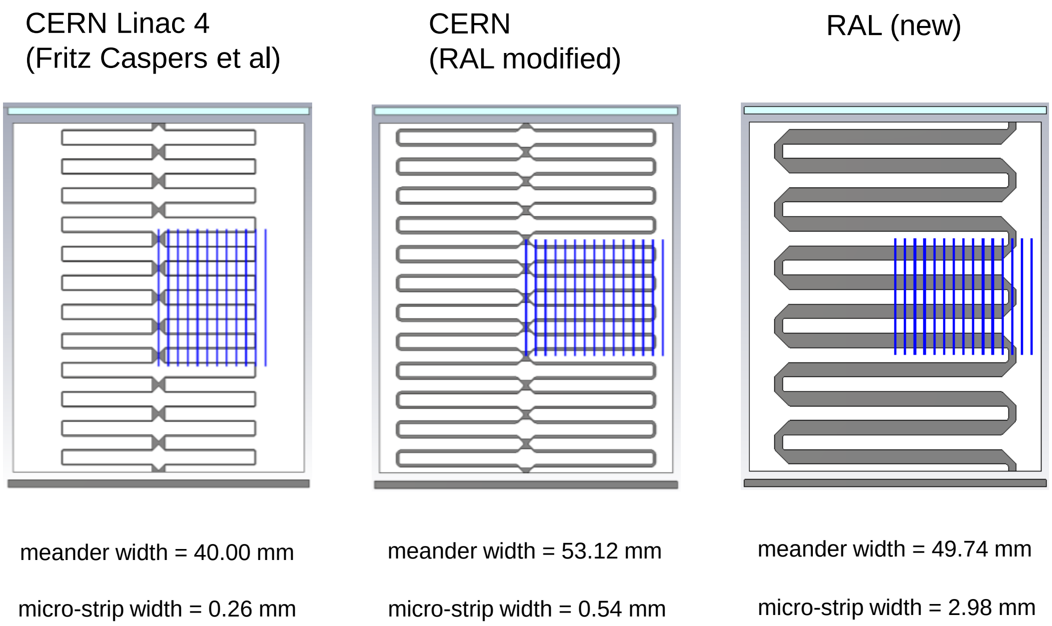

Figure 9: Comparison of different micro-strip designs (details see text).

'Slow’ (discrete electrode) structure

The shunt capacitance and series inductance of the liquid cooled electrodes are critical parameters that must be minimized in this design. The electromagnetic properties of the design are being modeled and optimized in CST EM Studio. Measurements of the capacitance and inductance of two ‘off the shelf’ liquid cooled high vacuum feedthroughs have been compared with data from the simulations.

Specialized Components

A key timing component has been purchased, following an extensive search. The Tektronix DTG5078 Data Timing Generator with three DTGM21 output modules has been selected as the master timing generator for the chopper systems. This ‘hard to find’ ex-rental instrument was sourced from ‘ORIX Rentec’ (Japan), and was competitively priced. It appears to be in excellent condition, and was supplied with a new calibration certificate, ancillary equipment, and user manuals. A comprehensive acceptance test indicated that the instrument performance was in compliance with the manufacturer’s specifications. A Heinzinger 3500V 0.6A capacitor charging power supply and a complete set of ‘push-pull’ high voltage MOSFET switches and low inductance energy storage capacitors (10 + spares) for the ‘Slow’ chopper, have been purchased.

Figure 10: Timing electronics (left) and MOSFET switches (right) for the beam choppers.

Beam dumps

The beam dumps for the beam choppers have been investigated in detail to allow for mechanical design of the dump plates. The peak power is identical for both dumps, but the average power for the fast chopper dump is only 0.667 kW, while the slow chopper dump receives 4.75 kW of beam power. Therefore the 2nd slow chopper dump sees the most demanding cooling load and hence will present the greatest engineering challenge. An investigation of suitable materials in terms of radiation production, mechanical and thermal properties was followed by studies of plate designs and cooling options. Results of these investigations are shown in figure 11. Due to the limited engineering and design resources available the finalisation of the beam dump design is delayed.

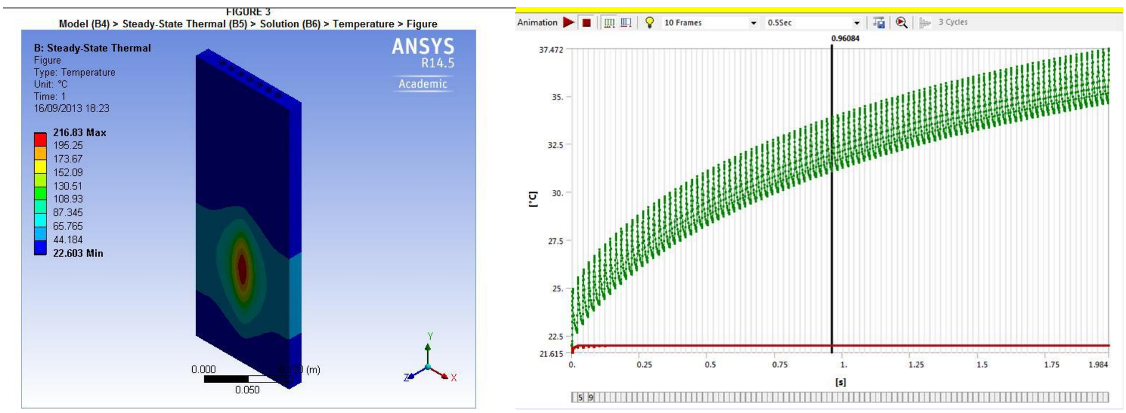

Figure 11: Left: Temperature distribution on the chopper beam dump 2, determined using ANSYS. Right: Result of an investigation of the transient temperature for the beam dump1 showing 2ms beam ON periods followed by 18ms OFF periods over a total time of 4 seconds.

Supporting framework

Each MEBT components, with its adjustable alignment system, will be mounted to rails that sit on a supporting framework. This framework also acts as the vacuum manifold support system. Figure 12 shows one such frame without its rails. These assemblies are currently being progressed through RAL contract effort.

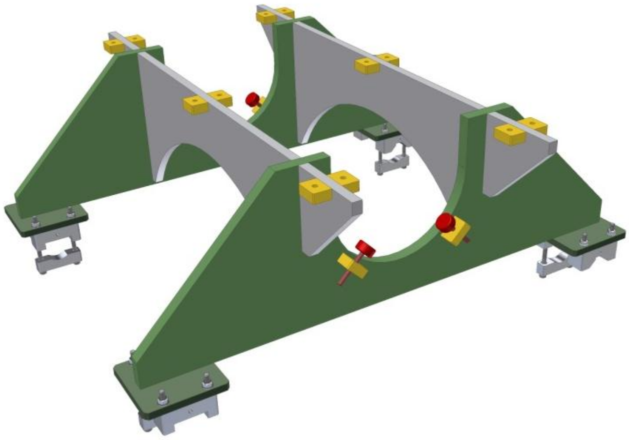

Figure 12: One MEBT support frame (of five). This is an example of an engineering component that can be delivered using contract effort.

FETS Diagnostics

Toroids

A suite of nine conventional AC current transformer toroids, eight of which have been designed, constructed and tested in-house, will be used to measure the beam current at various locations along the beam-line. The toroid immediately after the ion source is a Bergoz ACCT with a fast response. The toroids have varying response times according to the pulse parameters at its location. Two of the toroids built in-house have been tested to determine the rise-time and droop and are shown in Figs. 11 and 12. As can be seen both toroids meet the specification for rise time, but one has a droop of about 3 %/ms, possibly due to a lower than expected core permeability.

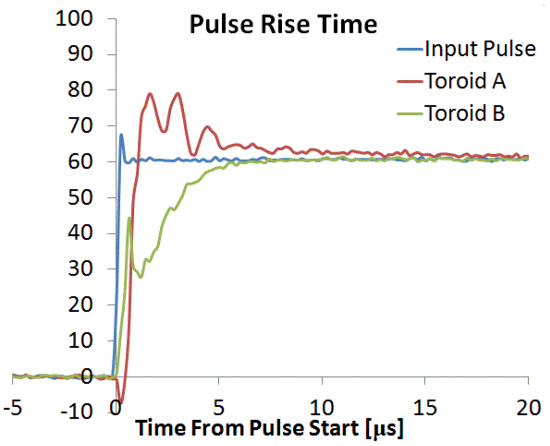

Figure 11. Experimentally determined rise time of toroids.

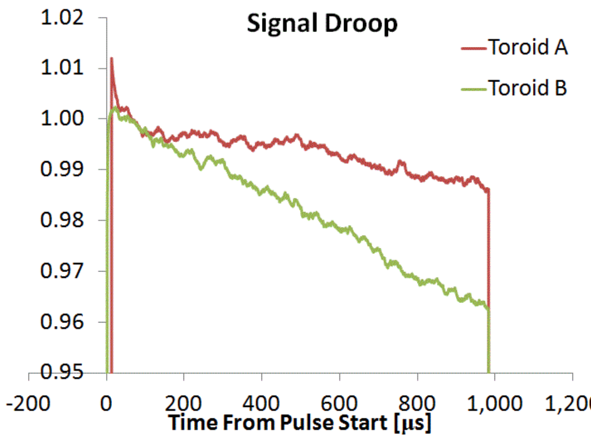

Figure 12: Experimentally determined droop of the toroid signal.

Three toroids are already installed in the LEBT and have been running for over a year with no problems. More testing of the toroids T4-T9 will take place in the lab before being installed in the beam-line in 2014. The readout electronics is available. The beam current measurements will indicate the transmission of the RFQ, fast and slow beam choppers.

Beam Position Monitors

Six BPMs are situated with the beam-line MEBT and will determine the beam position before and after the fast and slow chopper elements and also after the RFQ. Each BPM will produce a position of the beam centroid. In order to provide the most cost-effective solution for online position monitoring, several BPM designs have been investigated, including commercial button, split ring and stripline designs from NTG and existing shoebox monitors installed at ISIS. Given the limited resources for FETS developing a complete BPM system from scratch seemed not possible and it was decided to make use of existing technology and hardware wherever possible. On the other hand the available space for diagnostics was very limited. Following intense discussions a twofold approach was agreed. 2 longer (60 mm) stripline BPM (see figure 13), developed by CERN for use on the LINAC4 will be used, one immediately before Chopper 2 and one at the end of the MEBT beam line while shorter self designed button BPMs (see figure 14) will be used elsewhere. The advantages of using 2 designs include greater redundancy against failure and the option for direct comparison – providing valuable information which can be fed back to CERN. CERN have agreed to provide the necessary design drawings as well as a spare 60 mm stripline for the purposes of testing by FETS. In addition, members of FETS visited CERN at the end of October to discuss the BPM hardware and electronics and refine the BPM testing procedure. The front end electronics will be adopted boards designs from CERN. The IF signals are digitized at 40.500 MHz and processed in an FPGA to produce the position of the beam at each BPM location, with an estimated precision of better than 100 µm. The digitizing and processing of the BPM IF signals is performed by a National Instruments PXI-7954R FPGA card and NI-5752 modular 32-channel digitizer card. The FPGA code is programmed using National Instruments LabVIEW with the FPGA module. A test-rig is being constructed at RHUL to enable the characterisation of each BPM.

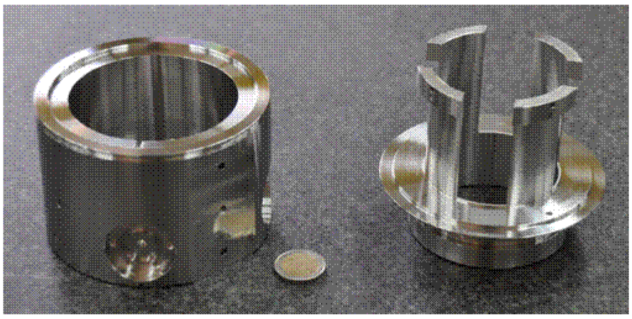

Figure 13: CERN 60 mm strip line BPM

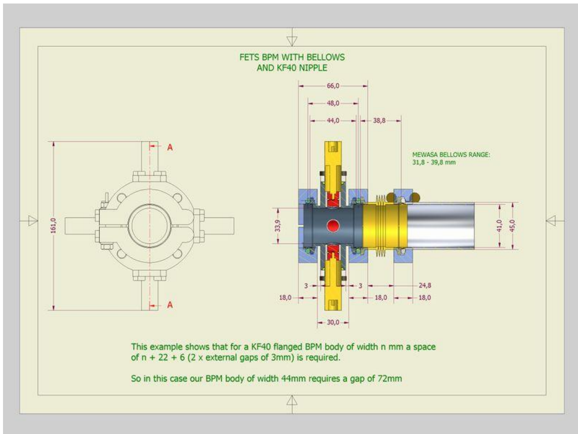

Figure 14: Model of button BPM

Laserwire Emittance Scanner

The transverse profile and emittance of the H^- beam will be measured by a laserwire scanner, which neutralizes H- ions in the narrow slice of the particle beam traversing the laser. The beamlet of neutral particles drifts downstream where the spatial profile is recorded by a suitable detector. The transverse emittance is reconstructed as the position of the laserwire is scanned. Figure 15 shows the main components of the set up under design for FETS. The interaction will take place in the field of a dipole magnet. The neutrals generated by interaction between laser and beam ions will be detected by a scintillator screen. The light density produced by the screen is then recorded by and (shielded CCD camera).

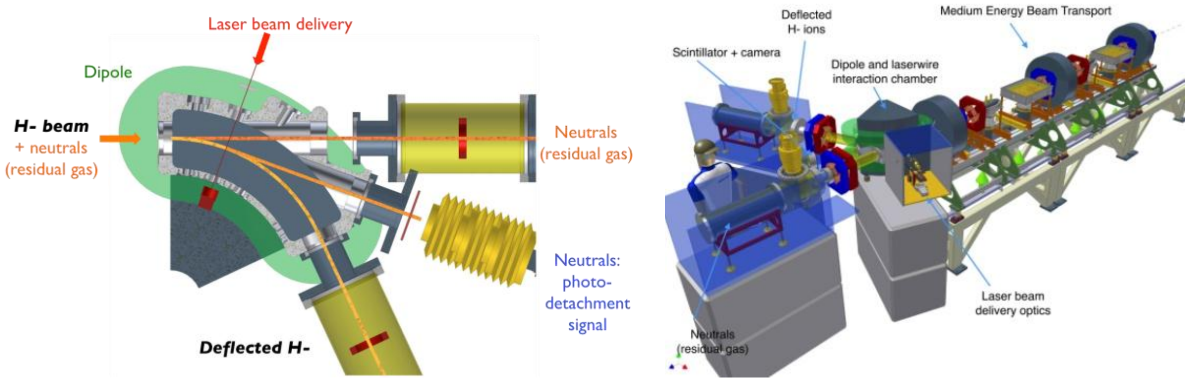

Figure 15: Overview of the laserwire emittance scanner at FETS.

During 2013, a fibre-coupled beam delivery system was developed and built to precisely control the thickness and position of the laserwire delivered to the interaction region. Good spatial beam quality (M^2<1.7) was measured after the transport fibre and the results were presented in multiple poster presentations at IPAC and IBIC. The pulsed laser was characterized and shown to produce the required <110ns pulses at 30 KHz rate and amplified with up to 28W average power. A drop of peak power with duty cycle was noted, stimulating investigations by the manufacturer. Scintillator tests were also performed at Fermilab, as detailed in the IPAC report.

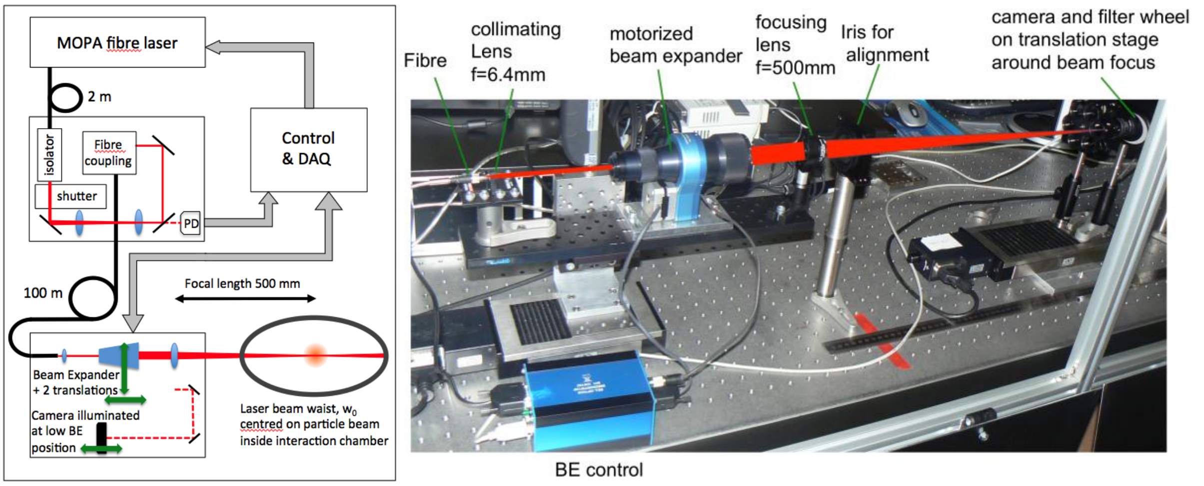

Figure 16: Layout of the laser beam delivery and test setup for beam quality measurements at RHUL.

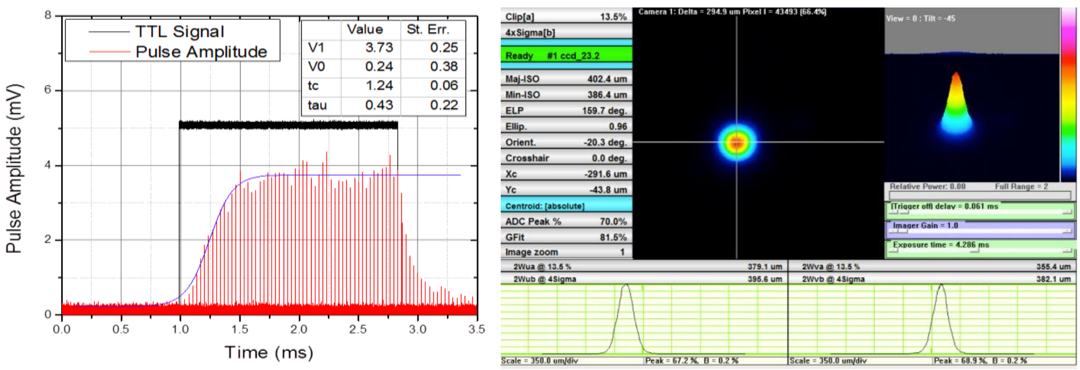

Figure 17: Amplified pulses from the FETS laser and laser profile at focus after the transport fiber.

Laser Particle Tracking

A GPT framework has been set up for extensive particle tracking simulation of beam transport through the laser diagnostics vessel. The aim is to determine for various settings of the MEBT quadrupoles the best placement and size of the 2D scintillating detector, along with the range and resolution of the instrument to allow for a final mechanical design of vaccum chamber and the purchase of the dipole magnet. Additionally the power distribution in the beam dump has been determined. A more detailed summary of the calculations is in the IBIC proceedings.

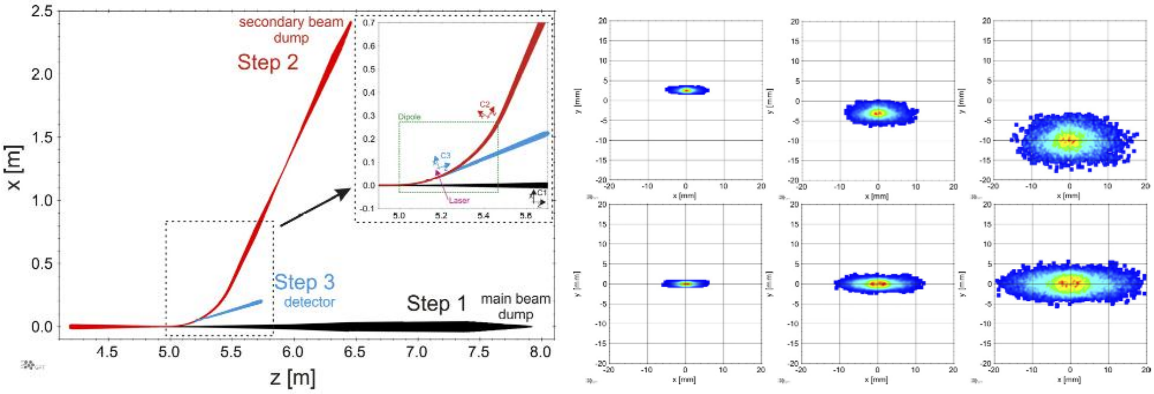

Figure 18: Particle trajectories and evolution of transverse distribution of neutrals with distance (z=0mm, 300mm and 800mm) after the laser interaction, for laser positions, y=0 and y=+3mm.

Collaboration with CERN

The new Linac4 under construction at CERN will accelerate H- ions to 160 MeV and will ultimately replace the existing 50 MeV proton linac as part of the CERN SPL. During initial commissioning, the 3 MeV front end of Linac-4 has strong synergies with the FETS project. A collaboration between FETS and CERN was formed in 2013 to jointly develop a laserwire scanner for the new injector for the LHC and to leverage CERN expertise on BPMs for FETS. This collaboration has proven very fruitful. Following visits to the UK by the head of CERN Beam Instrumentation and the Linac-4 accelerator, a Memorandum of Understanding has been agreed. A CERN doctoral student was trained at RHUL in laserwire development during the summer 2013 and FETS collaborators have provided FETS equipment and effort for the Linac4 accelerator project at CERN. In November 2013, the FETS laserwire system was delivered and installed in the Linac4 accelerator at CERN, ready for tests with the first 3 MeV beam in the coming weeks. A major benefit of the collaboration is to provide a test bed that drives the continuous FETS diagnostic development, prior to 3 MeV beam being available at FETS. We eagerly await imminent first results with this system.

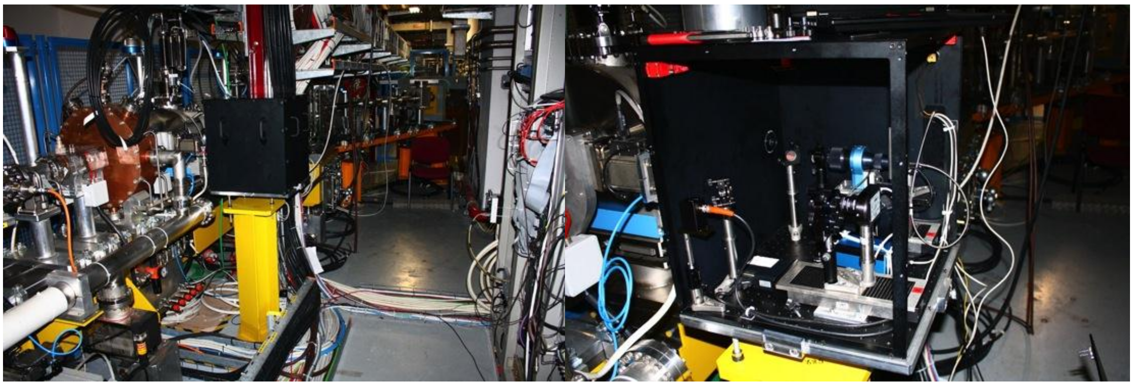

Figure 19: The FETS laserwire beam delivery system installed in Linac-4 at CERN in November 2013 (left). Right: FETS laser beam delivery system without safety covers, revealing the motorized optics that precisely control the thickness and position of the laserwire delivered to the Linac4 accelerator.

Future of FETS

Proton Accelerator Alliance

Several members of the FETS collaboration are actively involved in the preparation for a proposal for a Proton Accelerators for Science and Innovation Alliance, which is envisaged to provide a frame for proton accelerator R&D within the UK. The ability of FETS to deliver a 2 ms long beam bunch train of high beam intensity at 50 Hz, together with a fully-flexible time structure within the long pulse due to the unique chopping system, offers the opportunity to deliver beam to more than one experiment with each bunch train. With the upgrade of ISIS as a long term goal in mind, FETS could be developed into a high intensity proton accelerator to energies up to 70 MeV to deliver beam for different R&D purposes in the energy range from 3 to 70 MeV at the RAL site (see figure 20).

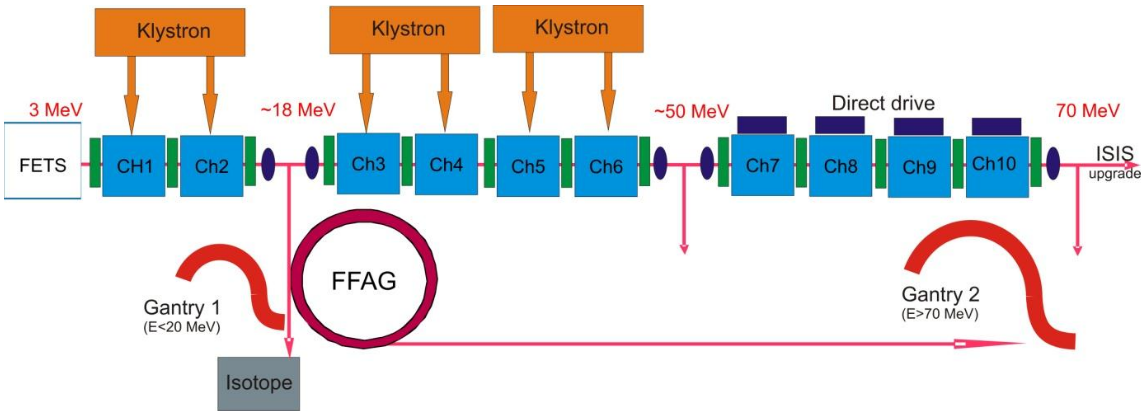

Figure 20: Layout of a future generic accelerator and high power proton beam test facility.

Siemens solid state RF driver

Proton accelerators require large amounts of radio frequency (RF) power to generate the necessary electric fields. Traditionally the sources of this RF power have been vacuum tubes such as triodes and tetrodes or klystron amplifiers. These devices all have certain drawbacks in common: they are large and expensive; they require complex high voltage power supplies; they have limited lifetimes; they can be a source of x-ray radiation. The 'holy grail' for accelerator RF engineers would be a solid state klystron but until very recently, transistors were not a viable alternative at the required power levels and frequencies for proton linacs. In the last few years this situation has begun to change with some solid state high power klystron alternatives becoming a reasonable proposition. STFC and members of the FETS team have been working closely with Siemens who are developing a solid state microwave generator for accelerator applications based on Silicon Carbide transistor technology. STFC are the technical consultants and providing expert advice from the end user perspective. First prototypes are in the early stages of manufacture. FETS will be the beta test site for when the first MW scale generators become available.

CH

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. In recent years CH and spoke structures have been replacing the conventional DTL's as they offer larger shunt impedance and therefore more compact and efficient accelerators allowing for a significant cost reduction. As the first step towards an modular design of a linac as shown in the PAA chapter, the RF properties of the first 1 m long CH section of the linac has been studied in detail. Some results of these studies are shown in figure 21.

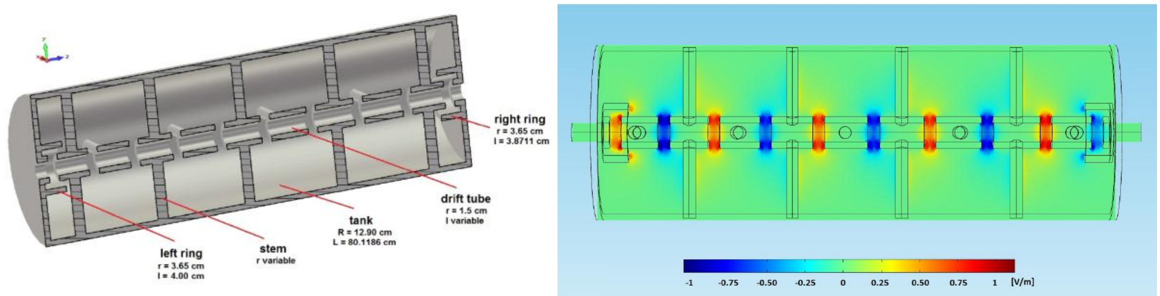

Figure 21: Model of the CH resonator (left), distribution of the electric field in the cavity (right).

The field flatness of the resonator is reasonable good with some influence of the resonator end cells still visible (figure 22 left). The right hand side plot of figure 22 shows the first results of studies of the acceptance of the solenoid lattice. These investigations will continue depending on available resources and the development of the PAA.

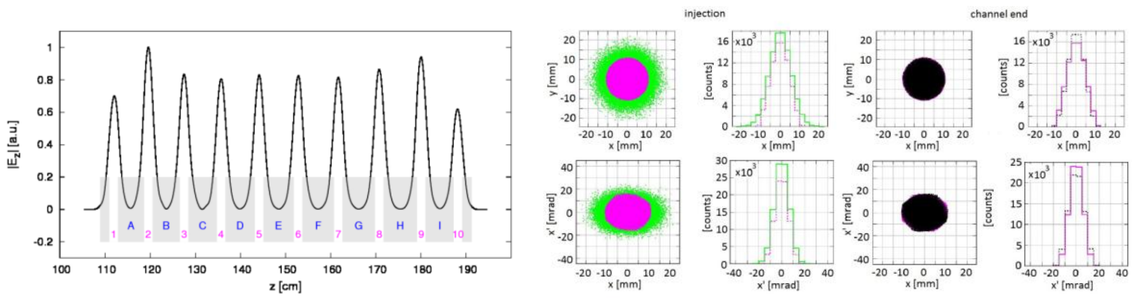

Figure 22: Field flatness of the electric field in the CH module (left plot) and determination of input acceptance (magenta) for the 10 module acceleration channel assumed.

Infrastructure

Radiation shielding

When FETS is operational there will be several potential sources of ionising radiation: bremsstrahlung x-rays from stray electrons in the ion source post acceleration gap, bremsstrahlung x-rays from field emitted electrons in the RFQ and MEBT cavities plus neutrons and gamma rays produced by beam loss and in the final beam dumps. In order to protect personnel from the radiological hazard shielding is required around the accelerator.

X-rays from the ion source have a maximum energy of 60 keV and are locally shielded to allow ion source operation in the absence of any bulk shielding. The x-rays from the RFQ and cavities will have energies no greater than 100 keV and a low intensity due to careful surface preparation and good vacuum. Self-shielding by the thick steel and copper of the cavities means that only relatively modest external shielding will be required. By far the most significant radiological sources are the beam dumps and beam loss at 3 MeV after the RFQ. In some common materials, most notably copper and steel, (p,n) reactions from the 3 MeV beam will produce neutrons and induce activity in the components. In order to reduce the neutron flux and reduce the problem of component activation, wherever possible materials with no (p,n) reaction at 3 MeV will be used in beam facing positions. With the exception of the RFQ where copper is unavoidable, aluminium has been chosen as the material for beam pipes and the beam dumps. Although the aluminium will not produce neutrons or become activated it will still produce a significant flux of high energy gammas. Worst case beam loss calculations at full beam power together with calculated fluxes from the dumps has led to a 600 mm thick bulk concrete shield design which has been approved by the RAL radiation protection advisor. Figure 23 shows the shielding layout. Concrete blocks for the walls have been procured and the roof is being designed.

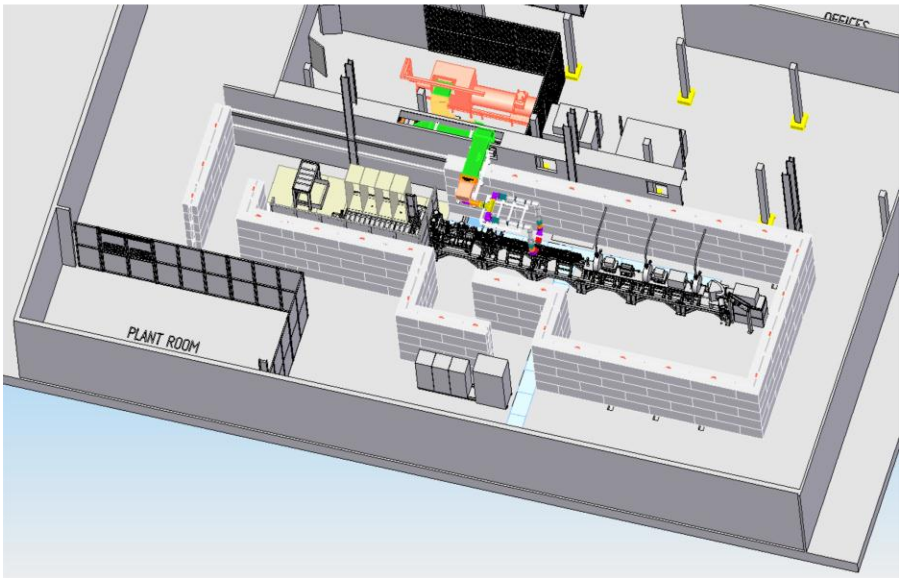

Figure 23: The concrete radiological shield around FETS. Roof not shown for clarity.

RF power distribution

Approx. 1 MW of RF power is required for the RFQ and will be generated by the 324 MHz Toshiba klystron. The RF will be transported via a circulator and through the radiation shielding by a system of WR2300 waveguide and 6 1/8” coaxial line. Due to its lower loss, waveguide will be used for as much of the distribution system as is practical.

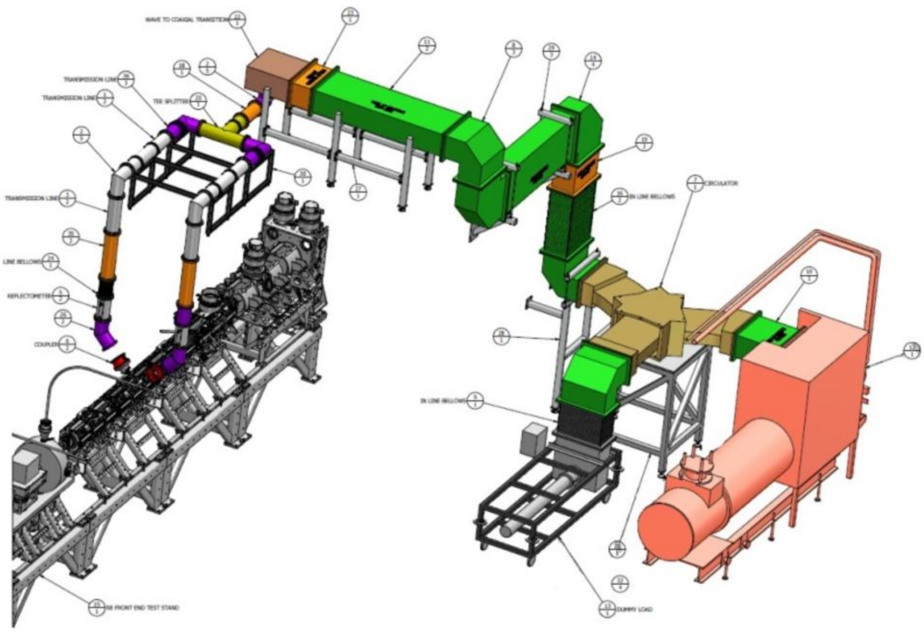

Figure 24: The RF power distribution system

The RFQ has two power couplers so the RF will be split by a matched, balanced, 6 1/8" coaxial Tee just after the transition from waveguide to coax. For ease of access and assembly the Tee will be external to the shielding with the two phase-balanced output legs passing through the shield roof. Figure 24 shows the klystron, circulator and RF power distribution system design. All the major waveguide and coaxial components have been procured. Full power tests of the klystron and RF distribution will be completed using a high power load loaned to FETS by the ESS Bilbao team.

Laser room and laser safety

The FETS photo-detachment diagnostics requires the use of a high power laser. In order to protect personnel working close to the beamline from the associated hazard and to more easily comply with relevant laser safety codes, the laser will be housed externally in a dedicated laser room with the light transported to the diagnostic instrument by optical fibre. The designs of the interlocks and safety systems for the laser room have been completed to conform to national and internal regulations and have been approved by the RAL laser safety officer.

Klystron cage

Due to its very high operating voltage of 120 kV, the klystron is a potential source of x-rays. Integral to its design is lead shielding to reduce exposure of personnel in its vicinity however in a few areas very low dose rates are still detectable. To exclude personnel from these areas and to allow for a reduced shielding thickness in a congested area to the south of the adjacent wall, an interlocked, caged area will be constructed around the klystron allowing close access only when the device is unpowered.

Stores

As increasing numbers of high value components and equipment are procured and to help with housekeeping a safe storage area has become necessary. To this end a secure, caged store has been constructed in the under-utilised north west corner of R8.

3 Publications

Journals

Jolly S et al., 2014, 'Novel integrated design framework for radio frequency quadrupoles', *Nuclear Instruments & Methods in Physics Research Section A - Accelerators Spectrometers Detectors and Associated Equipment*, Vol:735, ISSN:0168-9002, Pages:240-259

S. R. Lawrie et al., 'Development of the FETS and VESPA H– ion sources at RAL', Rev. Sci. Instrum. Vol. 85 Iss. 2, Proceedings of ICIS 2013, Chiba Japan.

C. Gabor et. al., 'Matching an H– Beam into the FETS RFQ at RAL', Rev. Sci. Instrum. Vol. 85 Iss. 2, Proceedings of ICIS 2013, Chiba Japan.

Conference proceedings

"Beam-line Diagnostics at the Front End Test Stand (FETS), Rutherford Appleton Laboratory, Oxfordshire, UK", G. Boorman et al.; http://ibic2013.org/prepress/papers/tupc26.pdf

"Overview of Laserwire Beam Profile and Emittance Measurements for High Power Proton Accelerators"; S. Gibson et al., http://ibic2013.org/prepress/papers/tupf15.pdf

"Particle Tracking for the FETS Laser Wire Emittance Scanner", J.K. Pozimski et al., http://ibic2013.org/prepress/papers/tupf05.pdf

"Description of Laser Transport and Delivery System for the FETS Laserwire Emittance Scanner" A. Bosco et al., http://ibic2013.org/prepress/papers/tupf14.pdf

"Status of the RAL **Front End Test Stand**", A. Letchford at al., http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/thpwo086.pdf

"Design of a Photo-detachment Emittance Instrument for **FETS**", C. Gabor et al., http://accelconf.web.cern.ch/AccelConf/HB2012/papers/mop254.pdf

"**FETS** RF System Design and Circulator Testing", S.M.H. Alsari et al., http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/wepfi067.pdf

"Production of the **FETS** RFQ", P Savage et al. , http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/thpwa043.pdf

"Acceptance and Transmission Simulations of the **FETS** RFQ", S. Jolly et al., http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/thpwa041.pdf

"MEBT Design for the Front End Test Stand Project at RAL", M. Aslaninejad et al., http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/thpwo090.pdf

"Investigation of Space Charge Compensation at **FETS**, J.K. Pozimski et al., http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/thpwa042.pdf

"Status Report of the **FETS** Photo Detachment Emittance Instrument at RAL", C. Gabor et al., http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/mopwa049.pdf

"A New Long Pulse High Voltage Extraction Power Supply for **FETS**", D. C. Faircloth et al., http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/mopea064.pdf

"Current Status of the RAL Front End Test Stand (**FETS**) Project", D.C. Plostinar et al., http://accelconf.web.cern.ch/AccelConf/LINAC2012/papers/thpb004.pdf

"Design of a Photo-detachment Emittance Instrument for **FETS**", C. Gabor et al., http://accelconf.web.cern.ch/AccelConf/HB2012/papers/mop254.pdf

"Investigation of Space Charge Compensation at **FETS**", J. Pozimski et al., http://accelconf.web.cern.ch/AccelConf/IPAC2012/papers/moppd037.pdf

"The Manufacture and Assembly of the **FETS** RFQ", P. Savage et al., http://accelconf.web.cern.ch/AccelConf/IPAC2012/papers/thppp053.pdf

"Thermal design of the FETS Chopper Beam Dumps", S. Mishra et al., http://jacow.web.psi.ch/conf/pac13/prepress/MOPMA05.PDF

4 Financial summary

Front End Test Stand: Finance Summary (all figures in £k)

	Approved (excluding contingency) (1)	Transfers (1a)	Actual spend in previous years 2012/13 (2) separate columns for each FY		Current financial year 2013/14: Actual spend up to most recent quarter (3)	Current financial year 2013/14: Projected spend this year (4)	Latest estimate of future requirement (5): 3rd FY 2014/15	Latest estimate of future requirement (5): 4th FY 2015/16	Latest estimate of future requirement (5): 5th FY 2016/17	Total: Actual spend (2+3) (6)	Total: Projected spend (2+4+5) (7)	Variance: Actual (6-1-1a)	Variance: Projected (7-1-1a)
Imperial College London	726,166		237,317		120,704	242,055	246,794			358,021	726,166	-368,145	0
University of Warwick	84		28		14	28	28	0	0	42	85	-42	0
University College London	45,046		15,015		7,508	15,015	15,015			7,508	30,030		
Royal Holloway University of London	131,407		21,140		21,552	42,906	43,925	22,620	0	42,692	130,591	107,971	-816
University of Hudderfield	18,759		6,253		3,127	6,253	6,253						
University Sub-Total[1]													
STFC Overheads													
STFC Effort	964		295		196	334	262			491	891	-473	-73
Equipment[1]	952		354		183	264	226			537	844	-415	-108
Travel	30		8		6	8	10			14	26	-16	-4
Working allowance													
Total (including VAT & WA)													

5 Review Progress against Milestones

	Infrastructure	expected	finished
M1	Evaluation of internal /external space	01.12.2013	
M2	Agreement with Radiation safety to shielding plan	31.12.2013	
M3	Order of remaining wall elements	31.01.2014	
M4	Order of roof elements	30.04.2014	
D1	North wall of shielding built	30.04.2014	
D2	Wall of shielding complete	30.08.2014	
D3	Shielding fully assembled	31.10.2014	
M5	Loan of RF load from Spain agreed	31.01.2014	
M6	High power circulator test with RF load complete	31.05.2014	
M7	RF distribution to shielding complete	30.07.2014	
M8	RF distribution into shielding complete	30.10.2014	
D4	RF power available in shielding	31.12.2014	
	Diagnostics	**expected**	**finished**
M8	Design of MEBT diagnostic finished	30.06.2012	30.06.2013
M9	BPM electronic processing chain finalized and tested.	30.04.2014	
M10	BPM turntable wire rig commissioned at RHUL. (Rig to be built from CERN	30.06.2014	
D5	BPM manufactured and characterized.	30.09 2014	
D6	Toroid manufactured and tested	30.06.2013	30.06.2013
M11	LINAC4 experiments finished and Laser returned to RAL	31.03.2014	
M12	Dipole magnet and vacuum chamber design finished	30.04.2014	
D7	Operational emittance measurement system at FETS.	31.03.2015	
	Ion source	**expected**	**finished**
M13	Detailed simulations of ion source plasma.	31.03.2014	
M14	Experimental determination of plasma parameters.	30.04.2014	
M15	Design of upgraded 2X source finished	30.09.2014	
M16	Engineering and construction of upgraded 2X source	31.12.2014	
D8	Commissioning of ion source and evaluation of ion source performance	30.06.2015	
	RFQ	**expected**	**finished**
M17	First section of RFQ return for final machining	01.03.2014	
M18	First section of RFQ assembled and ready for conditioning	31.04.2014	
M19	All sections assembled and ready for conditioning	31.08.2014	
D9	RFQ conditioned and ready for beam	31.10.2014	
M20	RFQ coupler design ready	30.04.2014	
D10	RFQ coupler manufacture finished	30.09.2014	
	MEBT	**expected**	**finished**
M21	MEBT lattice frozen	31.12.2013	30.11.2013
M22	Support frame design finished	31.12.2013	
M23	Vacuum manifold ready to be outsourced to manufacturer	31.01.2014	
M24	Plating test bunching cavity finished	28.02.2014	
M25	Detailing of cavity design ready for tender	31.05.2014	
D11	Cavities delivered to RAL	31.11.2014	
M26	Chopper and chopper dumps vessel detailing finished	31.03.2014	
M27	Chopper and chopper dumps vessel manufactured	31.07.2014	
D12	Fast chopper internals ready	31.12.2014	
D13	Slow chopper internals ready	31.03.2015	
M28	Chopper beam dump design finished	31.09.2014	
D14	Chopper beam dumps ready	31.12.2014	
M29	All MEBT auxiliaries manufactured	31.12.2014	
M30	MQP on order	31.03.2014	
D15	MQP delivered to RAL	31.12.2014	

6 Risk register

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.