Commissioning the Front End Test Stand High Performance H^- Ion Source at RAL

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Abstract. The RAL Front End Test Stand (FETS) is being constructed to demonstrate a chopped H- beam of up to 60 mA at 3 MeV with 50 p.p.s. and sufficiently high beam quality for future high-power proton accelerators (HPPA). High power proton accelerators with beam powers in the several megawatt range have many applications including drivers for spallation neutron sources, neutrino factories, waste transmuters and tritium production facilities. The aim of the FETS project is to demonstrate that chopped low energy beams of high quality can be produced and is intended to allow generic experiments exploring a variety of operational conditions. This paper details the first stage of construction- the installation and commissioning of the ion source. Initial performance figures are reported.

Keywords: Negative H^- Ion Sources, Test Stand
PACS: 29.25.Ni, 52.59.-f

INTRODUCTION

High power proton particle accelerators in the MW range have many applications including drivers for spallation neutron sources, neutrino factories, transmuters (for transmuting long-lived nuclear waste products) and energy amplifiers. In order to contribute to the development of HPPAs, to prepare the way for an ISIS upgrade and to contribute to the UK design effort on neutrino factories, a Front End Test Stand (FETS) is being constructed at the Rutherford Appleton Laboratory (RAL) in the UK. The aim of the FETS is to demonstrate the production of a 60 mA, 2 ms, 50 p.p.s. chopped H^- beam at 3 MeV with sufficient beam quality.

FETS consists of a high power ion source, a 3 solenoid magnetic LEBT, a 324 MHz, 3 MeV, 4-vane RFQ, a fast electrostatic chopper and a comprehensive suite of diagnostics.

ION SOURCE OVERVIEW

The basic design of the ISIS H^- source has previously been described in detail[1]. The source is of the Penning type[2], comprising a molybdenum anode and cathode between which a 55 A low pressure hydrogen discharge is produced. A transverse magnetic Penning field is applied across the discharge. Hydrogen and Caesium vapour are fed asymmetrically into the discharge via holes in the anode. The anode and cathode are housed in a stainless steel source body.

The beam is extracted through an aperture plate (plasma electrode) using an extraction electrode. On the ISIS operational source the aperture is a 0.6 mm by 10 mm slit and the extraction electrode is of an open ended jaw design, with a jaw spacing of 2.1 mm and a separation from the aperture plate of 2.3 mm. A +17 kV extraction voltage is used operationally. For the FETS high performance source a +25 kV extraction voltage is used, the aperture widened and the extract electrode terminated.

The source is pulsed at 50 Hz, the operational source runs with a 250 µs pulse length. The FETS source is modified to run with a 1.8 ms pulse length by improving the cooling system[3].

After extraction the beam is bent through a 90° sector magnet mounted in a refrigerated coldbox (Figure 1). The sector magnet has two main purposes; to analyze out the electrons extracted with the H- ions, and to allow the coldbox to trap Caesium vapour escaping from the source.

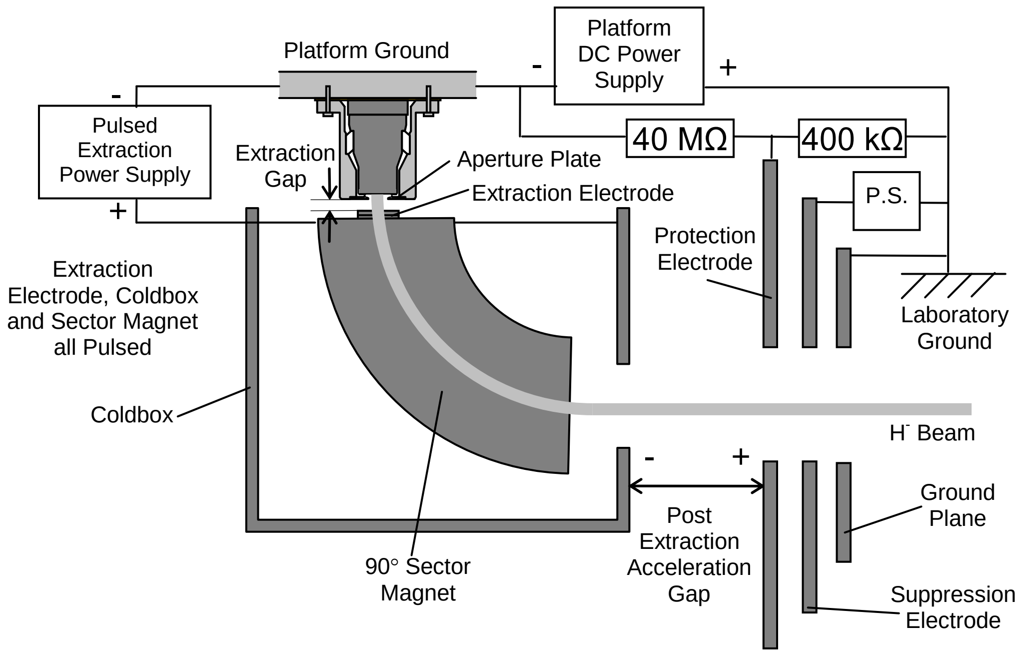


FIGURE 1. Schematic of the FETS ion source extraction and post acceleration system.

The H^- beam emerges through a hole in the coldbox and is further accelerated by a post extraction acceleration gap. On the ISIS operational source this is an 18 kV post acceleration voltage giving a total beam energy of 35 keV. For FETS this is a 40 kV voltage giving a total beam energy of 65 keV.

FIGURE 2. The FETS ion source.

SECTOR MAGNET MODIFICATIONS

A detailed study of beam transport[1,4] in the sector magnet has shown the poles used in the ISIS operational source can be modified to improve beam transport. The angle of the sector magnet pole faces can provide weak dipole focusing. The field gradient index, n of the sector magnet can be calculated as follows:

$$n = -\frac{R_e}{B_e}\left(\frac{dB}{dR}\right) \tag{1}$$

Where, R_e is the radius the centre of the beam follows as it goes through the sector magnet and B_e is the magnetic flux density at that radius. When n > 1 the beam is defocused vertically (radially), when n < 1 the beam is focused vertically (radially).

Historically the field gradient index in the ISIS sector magnet was always quoted as being n = 1. Recent detailed finite element modeling[4] has shown that the field gradient index of the operational source actually closer to n = 1.4. By integrating the field around different radii the overall field gradient index can be calculated including the fringe field effects at the entrance and exit of the dipole. Figure 3 shows how n varies across the magnet aperture, the top of the plot is the inside radius and the bottom of the plot the outside radius of the sector magnet. Figure 3(a) shows field gradient index variation for the ISIS operational source; n varies from 1.25 to 2.25 across the magnet aperture. This explains why previous studies[1] have shown severe defocusing in the vertical plane. Figure 3 also gives an indication of what proportion of the magnet aperture is good field region. For the sector dipole magnet, the good field region is the area where the value of n is within a certain range. In Figure 3(a) when particles near the top and bottom edges of the good field region they see higher field gradient indexes and are therefore defocused out of the beam.

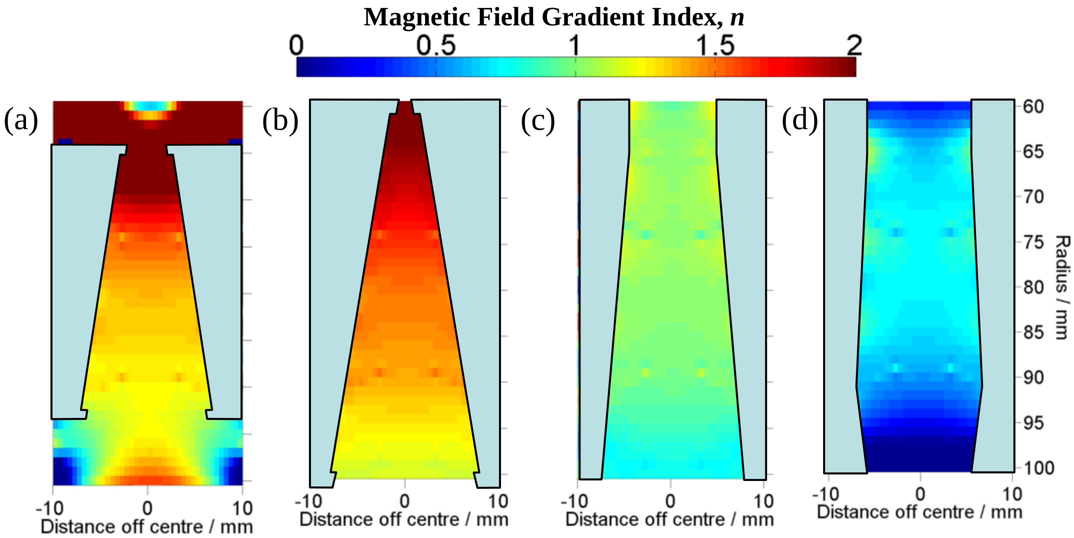


FIGURE 3. Contour plots of *n* for (a) the standard ISIS pole pieces; (b) ISIS pole pieces with wider radial extent; (c) n = 1 poles; (d) n = 0.75 poles with enlarged shims at the outer radius.

Figure 3(b) shows how n varies across the aperture for wider poles. Increasing the radial width of the poles increases the size of the good field region which means that particles that would have previously been lost are now transported through the dipole.

By changing the angle of the poles the field gradient index can be altered, Figure 4(c) shows the variation in n for an n = 1 average index. To provide focusing in the vertical (radial) direction a set of poles was also designed to give an n = 0.8 average field gradient index.

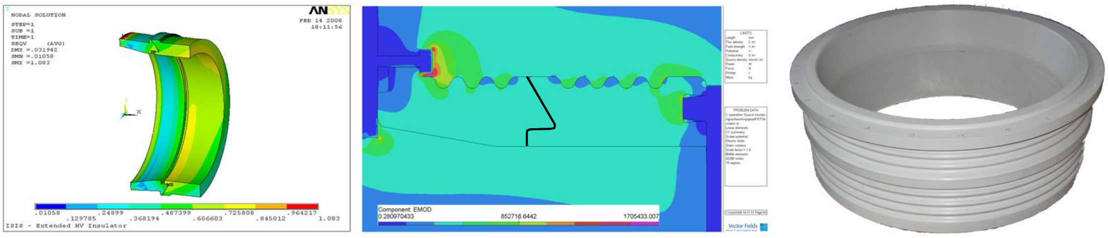
All three of these designs have been manufactured and tested[4], some results are shown in the final section of this paper.

POST EXTRACTION ACCELERATION

As mentioned in the overview, after being transported though the sector magnet the beam is then further accelerated by a high voltage gap. The focussing properties of this gap have been investigated in previous studies[5] and a field gradient of 9 kVm^{-1} found to provide the smallest emittance growth, some results are shown in the final section of this paper.

Ion Source 70 kV Insulator

To implement the post extraction accelerating voltage the ion source is mounted on a flange which is supported by an insulator. On ISIS this insulator must hold off 35 kV. For FETS it must hold off 70 kV: to do this its length must be doubled. The insulator must support the full 150 kg load of the ion source. The insulator is manufactured out of Noryl-GFN3 (a machinable, fibre-glass reinforced plastic). This material is used because of its high strength. Unfortunately Noryl-GFN3 is only manufactured in slabs of a certain thickness and so the longer insulator had to be constructed from two adhered sections.



(a) Mechanical Model (b) Electrostatic Model (c) Completed Insulator

FIGURE 4: The 70 kV insulator.

Mechanical and electrical finite element modelling is used to confirm the design of the new 70 kV insulator.

Post Extraction Acceleration Electrode Assembly

The 70 kV insulator is mounted on the post extraction acceleration electrode assembly shown in Figure 5. This assembly has several purposes: It is a spacer to separate the insulator from the ion source vessel discussed in the next section. It supports the electrode to protect the extraction power supply from main platform supply in the event of a flashover (circuit is shown in Figure 1).

It supports the suppression electrode to prevent ions travelling back across the post acceleration gap. It supports the beam current toriod and ground electrode. It also employs mu-metal sheets to magnetically shield the diagnostics from the sector magnet's stray field. The post acceleration gap is variable between 4 and 10 mm.

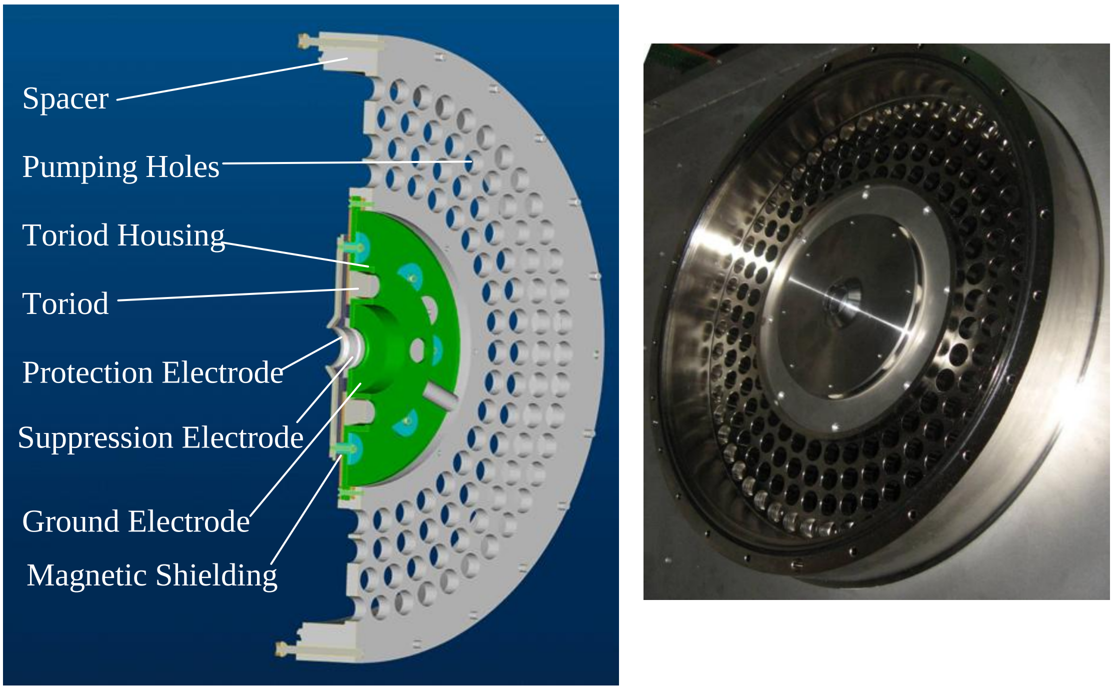


FIGURE 5: The post extraction acceleration electrode assembly.

Ion Source Vessel

The post extraction acceleration electrode assembly mounts on the ion source vessel shown in Figures 6 and 7.

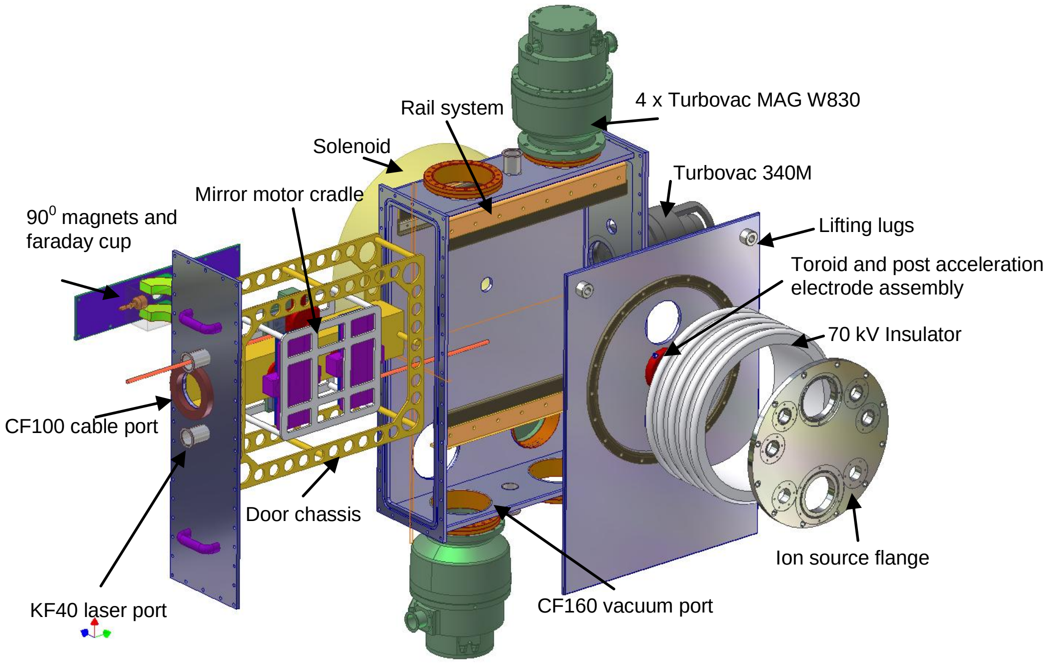


FIGURE 6: Exploded view of the beam profile measurement system inside the ion source vessel.

The vessel supports 4 turbo molecular pumps and pressure measurement heads. Several ports are included for electrical feedthroughs for connection to the post acceleration electrode assembly.

FIGURE 7: Ion source vessel in situ.

Diagnostics

The ion source vessel contains a laser wire beam profile measurement system[6], based on the photo-detachment of the outer electron of the H^- ions with a laser. The detached electrons are detected in the faraday cup arrangement shown in Figure 8. The laser wire system allows the transverse beam density distribution to be determined at full beam power without affecting the beam. This is achieved by stepping the laser beam through the ion beam at a variety of different angles to collect many different projections and then combining these using either the Algebraic Reconstruction Technique[6] or the Maximum Entropy algorithm[7].

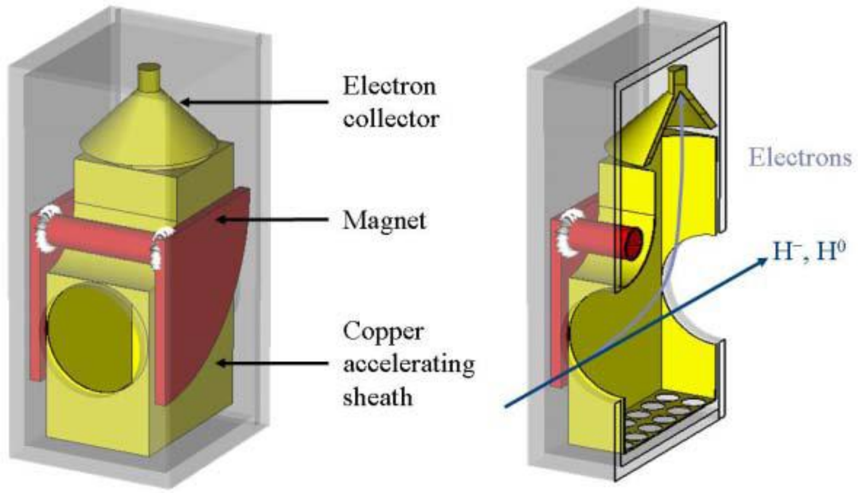


FIGURE 8: The electron collection system for the laser wire profile measurement system.

A temporary diagnostics vessel containing a pair of X and Y slit-slit emittance scanners and a scintillator profile measurement system is installed after the ion source vessel to allow commissioning of the laser wire system. The temporary diagnostic chamber will be moved along the beam line as it is constructed.

ANCILLARY EQUIPMENT

High Voltage Platform and Cage

A 70 kV a high voltage platform is required to support the ancillary equipment required to operate the ion source. This must be surrounded by an interlocked high voltage cage for personnel protection (Figure 9). The platform is supported using commercially available post insulators and has a handrail to allow safe working.

FIGURE 9: The high voltage cage and platform and the 70 kV DC power supply.

An in-house built 70 kV DC power supply is used to energise the platform and a 1 μF capacitor is used to minimise droop during the beam pulse. Platform voltage is monitored using a voltage divider and an automatic dumping system is used to earth the platform.

Two oil-filled 70 kV isolating transformers are used to provide single and three phase power to the ancillary equipment on the platform.

Other Equipment

The ion source requires numerous ancillary equipment to operate. This is all mounted in four racks on the high voltage platform. The layout of these racks is shown in Figure 10.

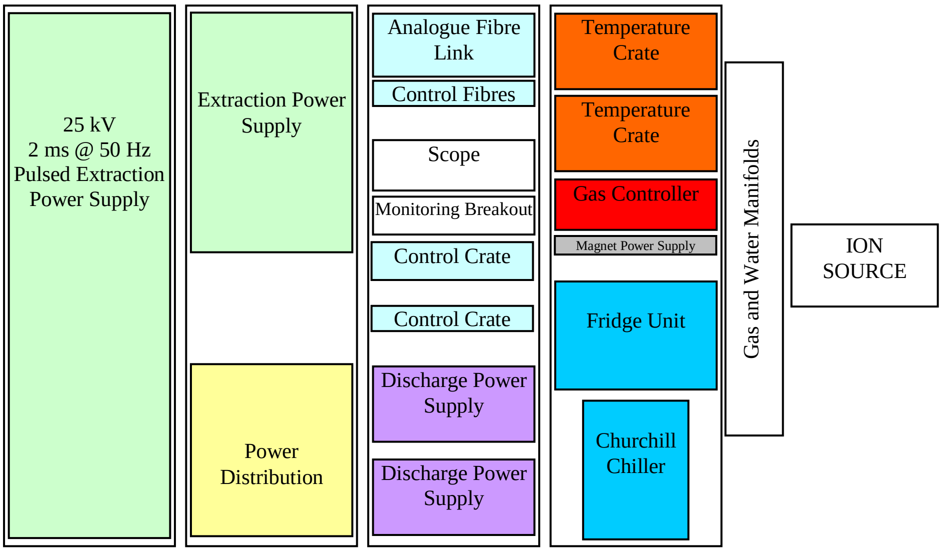


FIGURE 10: The layout ancillary equipment racks for FETS.

A new 25 kV (10% d.f. at 50 Hz) extraction voltage power supply has been developed, based on the standard ISIS design but using a larger TRITON 8960 tetrode tube. Danfysik DC and pulsed power supplies are used to power the source plasma discharge. New temperature controller crates have been built including extra temperature channels for additional monitoring. The rest of the equipment (H_2 controller, fridge unit, water chiller, monitoring and control) are standard ISIS items. Manifolds are used to distribute the cooling water, compressed air and hydrogen.

INITIAL PERFORMANCE

At the time of writing the installation is nearly complete. Alignment of the rail systems and completion of the upgraded pulsed extraction power supply are the main outstanding items. First beam should be produced in autumn 2008. It is possible to predict performance based on results[3] obtained from the Ion Source Development Rig (ISDR) at ISIS.

Extracted pulse lengths have been limited to 500 μs at 50 p.p.s. by the available pulsed extraction power supplies, however discharge lengths of up to 1.8 ms at 50 p.p.s. have been demonstrated. Extraction voltages have also been limited to 20 kV, but even at this voltage beam currents of 76 mA have been achieved when using the 0.8 mm wide aperture plate. Figures 11 and 12 show emittance and profile measurements taken 615 mm downstream from the ground plane of the post extraction acceleration gap for a 17 kV extraction voltage and a 2 mm, 18 kV post extraction acceleration gap. The beam current in both cases is 55 mA.

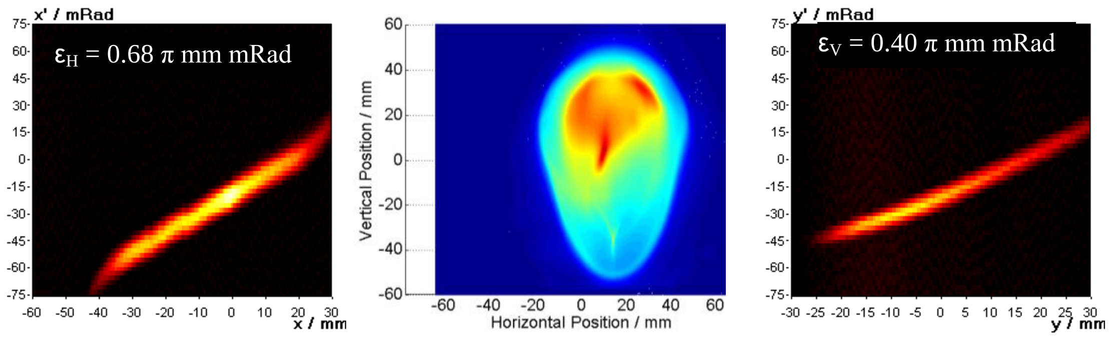


FIGURE 11. Beam emittance and profile from widened ISIS pole pieces with 17kV extraction voltage.

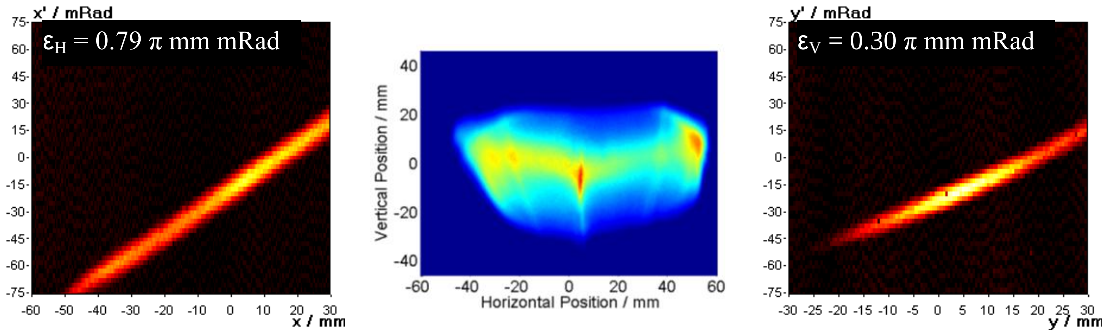


FIGURE 12. Beam emittance and profile from n = 1.0 pole pieces with 17kV extraction voltage.

DISCUSSION AND CONCLUSIONS

The installation is almost complete and although no beam has yet been measured on FETS, extensive testing on the ISDR indicate that the predicted performance will be close to the 60 mA, 2 ms, 50 p.p.s. design values. The only significant unknown is the amount of droop in beam current during the beam pulse, this can only be measured when the upgraded extraction power supply is completed.

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