RING SIMULATION AND BEAM DYNAMICS STUDIES FOR ISIS UPGRADES 0.5 TO 10 MW

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Abstract

Various upgrade routes are under study for the ISIS spallation neutron source at RAL in the UK. Recent work has concentrated on upgrading the injector, increasing injection energy from 70 to 180 MeV, and studying the challenging possibility of reaching powers up to 0.5 MW in the existing 800 MeV RCS. Studies for the longer term are exploring the possibilities of a 5 MW, 3.2 GeV RCS that could form part of a new stand-alone 10 MW next generation "ISIS II" facility. A central part of these ring studies is the use of computer simulations to guide designs, for example optimising the injection painting configuration and providing an indication of expected loss levels. Here we summarise the computer models used, indicate where benchmarking has been possible, describe optimisations and results from studies, and outline the main uncertainties. Understanding the limitations in high power RCS accelerators is an important part of determining optimal facility designs for the future.

INTRODUCTION

A range of ISIS upgrade routes is now under study, a lower beam power regime of 0.5 MW, and a higher power regime from 1 MW upwards. A key factor determining the optimal beam power for future short pulse spallation sources will be the results of ongoing target and moderator studies, which are working to optimise the brightness of neutron beams for the user.

In the lower power regime, an upgrade replacing the existing 70 MeV ISIS linac with a new 180 MeV injector is the favoured route. This could potentially boost powers to 0.5 MW and also address obsolescence issues with the present linac. This paper summarises the design of the beam dynamics for the existing ISIS RCS with the new 180 MeV injector.

For the higher power routes, a new stand alone option ("ISIS II") is the favoured route, with an initial beam power of 1 - 2 MW, capacity for multiple targets and further upgrade routes to 5 or even 10 MW. Studies are presently concentrating on a "base-line" option, consisting of an 800 MeV H^- linac and a 3.2 GeV RCS, which has been studied in some detail [1]. Such a design would have the potential for 2 – 5 MW with a single ring, and 10 MW with two stacked rings. Understanding the limitations and optimising parameters for this 3.2 GeV RCS are thus an important step in identifying the best designs. Other options, (e.g. FFAGs), will have to compare favourably with this base-line. Initial results from 1D and 3D simulations of the 2 - 5 MW, 3.2 GeV RCS are also presented below.

180 MEV INJECTION UPGRADE

The main potential benefits to the synchrotron of a new higher energy linac, chopper and energy ramping injection line are reduced transverse space charge and more flexible, optimised transverse and longitudinal injection systems.

Currently a 70 MeV, 25 mA H^- linac provides a pulse length of 200 µs for injection into the RCS. Beam is accumulated via charge exchange through a foil centred in a 4-magnet, symmetric, horizontal bump, with 45 mr deflections. Beam is painted dispersively in the horizontal plane, exploiting orbit motion due to the falling main magnet field. Vertically a sweeper magnet paints the position at the foil. About 3×10^{13} protons per pulse (ppp) are accumulated over 130 turns. Transverse acceptances are collimated at ~350 π mm mr using an adjustable collector system.

The DC accumulated beam is non-adiabatically trapped into two bunches by the ring dual harmonic RF (DHRF) system. The RF system consists of 10 ferrite tuned cavities, with peak design voltages of 168 and 96 kV/turn for the h=2 and 4 harmonics respectively. Nominal betatron tunes are (Q_x, Q_y)=(4.31, 3.83), with peak incoherent tune shifts of ~0.5. Intensity is loss limited: the main mechanisms are longitudinal trapping, transverse space charge and stability. Single turn extraction uses a fast vertical kicker and septum.

Most of the existing ring would remain unchanged for the upgrade. However, a new injection straight with higher field bump magnets and new injection beam dumps would be required. Also the ring collimation system would need modifications to intercept beam losses at higher energies. To facilitate hands on maintenance machine activation levels would be kept at existing levels.

Transverse Space Charge and Stability

Reduction of transverse space charge with increasing injection energy is expected to scale as $\beta^2\gamma^3$ allowing the existing injection intensity of 3×10^{13} ppp at 70 MeV (0.2 MW) to be raised to 8×10^{13} ppp (0.5 MW). This simple scaling law gives basic guidance, but detailed assessment and simulations with the in-house code Set [2] confirm that these intensities are the upper limit, which depend on achieving optimal bunching factors, emittances and working points. The smaller energy ramp, 180 - 800 MeV, also reduces emittance damping, which will require a small increase in the extraction system acceptance [2]. Instabilities are one of the major concerns with the most obvious problem being resistive-wall head-tail already observed on ISIS [3]. This is presently avoided by lowering Q_y. The growth rate can be expected

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to scale strongly with intensity, and lowering Q_y further will tend to increase loss associated with the half integer resonance. The development of a damping system is expected to resolve this issue [4].

Injection Scheme Specification

The new injection system assumes a linac beam current of 43 mA and a chopping duty cycle of 70% which requires 500 µs (~500 turns) to accumulate 8×10^{13} ppp. There is some freedom in selecting the timing of injection with respect to the main magnet field minimum: on the falling edge, symmetrically, or the rising edge.

The ring injection straight geometry is based on the existing design but the injection point is moved from the inside of the ring to the outside. This reduces the injection beam line complexity, and also the impact on ISIS operations, by making construction of all components (excluding the ring injection straight) independent of the existing machine. The new injection foil would be graphite of thickness 200 µg/cm^2 and have an expected stripping efficiency of >99.75% [5]. A schematic of the layout is shown in Figure 1.

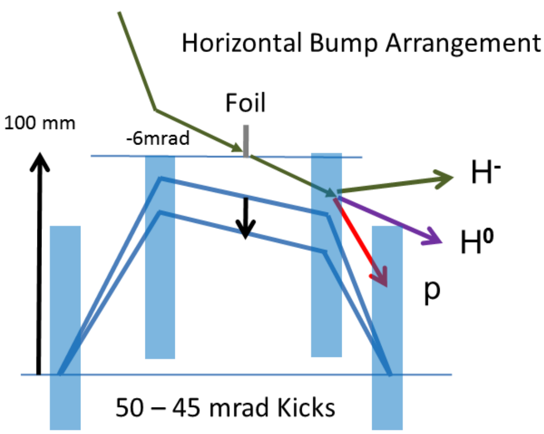

Figure 1: Schematic of injection straight.

A basic design principle has been to include as much flexibility in the beam parameters as possible, within the constraints of achieving practical hardware designs. With this in mind, transverse painting schemes allow for centroid amplitudes in the range 60 - 200 π mm mr in both planes, with free choice of correlation schemes. The beam must be accumulated and accelerated within maximum emittances of ~300 π mm mr to stay within the acceptance of the ring collimators and extraction system.

Longitudinal injection control is enhanced with the use of a chopper, with the aim to maximise the bunching factors (>0.4). The chopper requires timing modulations to track the injection line energy ramping, ±1 MeV, and varying beam revolution frequency in the synchrotron. RF requirements are limited to the peak design voltages of 168 and 96 kV/turn for the h=2 and 4 harmonics respectively. To facilitate hands on maintenance, loss levels of less than ~0.1% are required. These must be controlled, i.e. localised in the injection and collimator straights.

Transverse Painting and New Injection Straight

The injection point in the new design is on the outside of the ring, at a horizontal displacement of 100 mm and angle of 6 mr with respect to the ring central axis. Capability for centroid painting in the range 60 - 200 π mm mr in both planes is included.

The beam is painted horizontally using a combination of dispersive painting (injection energy mismatch to ring synchronous energy) and changing the local bump amplitude and angle at the foil. Dispersion at the foil is 2 m, 0.37 mr providing typical painting amplitudes 0 - ±10 mm and angles ±2 mr for a ±1 MeV variation in injection energy. The bump deflection angles are constrained to the range 45 - 50 mr providing a local displacement and angle at the foil 70±5 mm, ±10 mr respectively. The lower bound, 45 mr, conserves the position of the H^0 beam dump. The upper bound of 50 mr is considered the maximum deflection angle achievable in a magnetic design [6].

Vertical painting is achieved by varying the injection angle, 2 - 6 mr, at a constant displacement with respect to the ring central orbit of 20 mm. Beam parameters on the foil are controlled by two upstream steering magnets per plane in the transport line, which are programmed through the injected pulse. Horizontal and vertical phase space plots of the full painting amplitudes, 60 - 200 π mm mr, are shown in Figure 2. The corresponding bump magnet angular deflections for injection symmetrically about field minimum and a schematic of the real space layout are also shown.

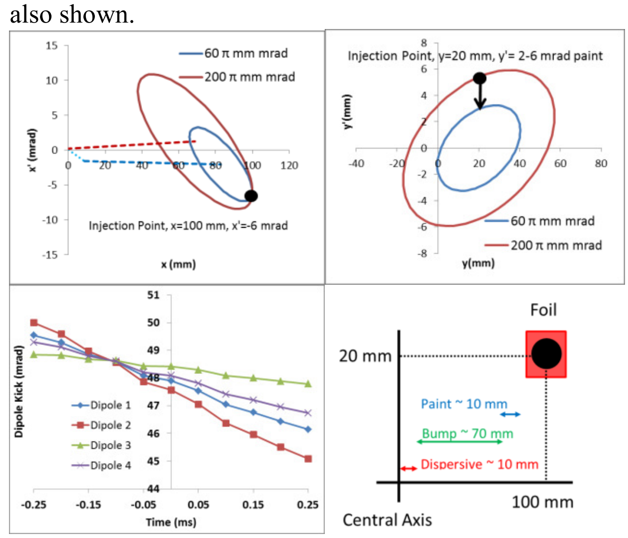

Figure 2: Transverse phase space (top), bump angular deflections over injection and real space layout (bottom).

Magnetic models of the injection straight using OPERA [7] have been used to track injection trajectories of the H$^-$, H^0 and protons to confirm beam dump positions and aperture clearances [5].

Vertical painting schemes are unconstrained for any injection timing. However, increasing or decreasing horizontal painting amplitudes for correlated, constant and anti-correlated schemes can only be achieved for

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injection symmetrically about field minimum. Therefore, symmetric injection timing is the preferred choice.

Longitudinal Painting and Acceleration

The basic viability of accelerating 8×10^{13} ppp (4×10^{13} per RF bucket) with the existing RF system has been confirmed by simulating the acceleration of an invariant Hofmann-Pedersen (HP) distribution [8, 9] taking into account space charge. If no further RF capacity is available this defines an upper limit to the painted longitudinal emittance for multi-turn injection as emittance increases during injection are inevitable. Therefore, given the chopping duty factor, an energy painting amplitude was chosen to accumulate a beam within that emittance. It is also noted that beam stability measured using the Keil-Schnell-Boussard (KSB) criterion [10] is strongly dependent on the energy spread of the beam. Within these constraints the painting amplitude as a function of time was chosen, alongside the RF phases, to paint the beam as close to a HP as possible.

The proposed painting scheme is an optimisation of previous longitudinal simulations [8], injecting symmetrically about the main magnet field minimum (-0.25 – 0.25 ms) with the injection energy sweeping non-linearly between 181.2 and 182.2 MeV. This is combined with a non-linear RF steer to paint the beam in energy from the centre of the RF bucket to 1.3 MeV off axis. The maximum injected momentum spread available from the injector design, 1.0×10^{-3} is used. RF volts are held constant at 74 and 55.5 kV per turn for h=2 and h=4 respectively through injection, and the phase between them is varied to maximise the bunching factor, and emittance by maintaining a stationary bucket. A schematic of the process is shown in Figure 3.

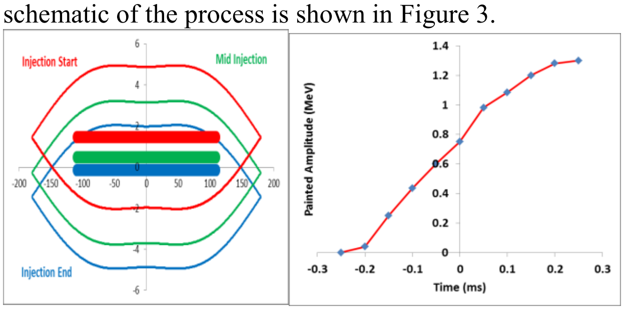

Figure 3: Longitudinal phase space painting of beam and RF bucket (left), with painting amplitudes (right).

Parameters through acceleration peak at 157.3 and 115.5 kV per turn for h=2 and h=4 respectively with the phase between the two systems varying between 9 and -64°. Second harmonic voltages are slightly above current ISIS limits to reduce losses inferred from 3D studies detailed in the next section.

The longitudinal simulation results of this injection scheme, using an in-house 1D code [8], are summarised in Figure 4. They show a well-controlled beam with bunching factors >0.4 and stability parameter [8] peaking just above 1. Options for increasing gap volts and dealing with the additional beam loading due to high intensity beams are currently under study.

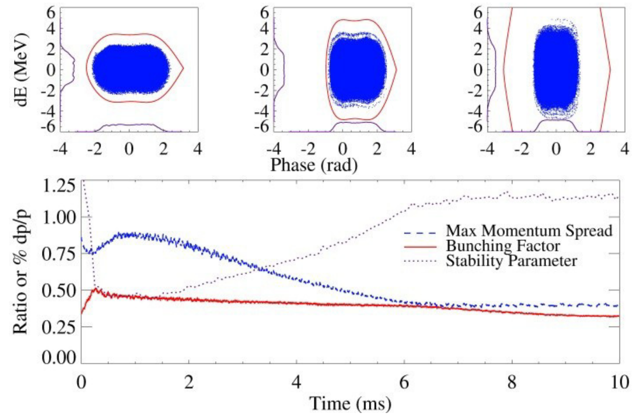

Figure 4: Phase space at the end of injection, 5 and 10 ms (top), evolution of bunching factor, stability parameter, peak dp/p for proposed injection scheme (bottom).

The ORBIT 3D Model

3D simulations of injection and acceleration use the ORBIT code [11] with modifications to allow RF bucket offsets. The ISIS ring is described using linear transfer matrices generated in MAD [12]. Injection dipoles are modelled using horizontal kicks which are dynamic during injection and then reduced to zero over 100 µs. The foil is modelled as a square, 11x11 mm, corresponding to the size of the injected beam at 3.33 sigma. Beam vacuum vessels and collimators are included. Space charge is simulated with the 3D space charge routine using a transverse grid of 128x128 and 64 longitudinal bins. Half integer driving terms are included by using quadrupole errors in the MAD model at expected levels for machine errors. Coherent instabilities are not included. A single bunch is modelled.

This simulation is based on the model benchmarked against the present ISIS machine [13] where comparisons with measurements of longitudinal profiles and beam losses showed reasonable agreement. The model has also shown good agreement with measured transverse profiles though injection [14].

Convergence tests show 5 M macro particles produce beam loss results at 0.1% levels with a deviation of 0.001%. Emittance evolutions change by 2% between 2.5 and 5 M particles. Random seed tests show deviations within these limits. Hence 5 M particles are used for final simulation results.

Injection Painting Amplitudes

The aim of the 3D painting process is to establish a stable beam distribution of 8×10^{13} ppp (4×10^{13} per bucket) within machine acceptances and minimal losses. Non-linear space charge forces lead to complicated dependencies on painted centroid emittances, tune, and bunching factors. Therefore, to identify viable working parameters a set of ORBIT scans was performed, monitoring emittance over 1000 turns for different painting conditions. For each scan centroid emittances were constant through injection. The set of scans explored the effects of varying the centroid emittances in both

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planes from 60 - 110 π mm mr. In all cases the injected beam un-normalised RMS emittance was 0.46 π mm mr.

The results, the evolution of 99% emittances for selected painting cases, are shown in igure 5. The aim was to produce the lowest emittance, stable beam on turn 1000 with minimal beam loss. Final results indicated painting amplitudes for centroid emittances of (ε_{xc}, ε_{yc})=(100, 65-75) π mm mr produced beams with 99% emittances of ($\varepsilon_{x99\%}$, $\varepsilon_{y99\%}$)=(343, 242) π mm mr. This is easily accommodated within the collimated acceptance of the ring (ε_{collx}, ε_{colly})≈(400, 322) π mm mr. The resulting distributions are shown in Figure 6.

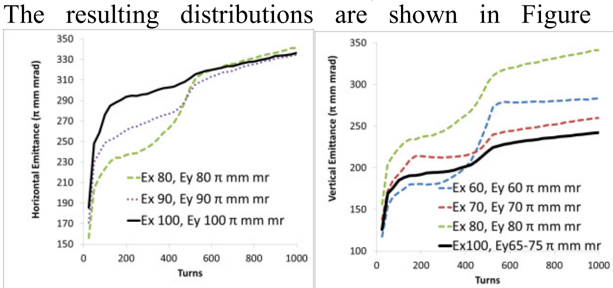

Figure 5: Emittance evolution for varying centroid painting amplitudes.

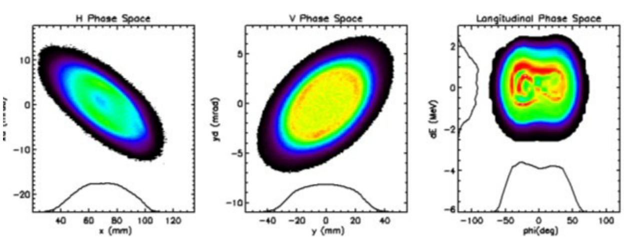

Figure 6: Phase space plots at the end of injection for optimised painting.

The foil produced 3.7 re-circulations per injected proton for the best case. Foil temperatures peak at 1657 K for 50 Hz machine operation [5] which is within safe operating temperatures.

Working Point and Envelope Errors

A main loss mechanism in the upgrade is expected to be related to half integer loss – particularly if head-tail instability forces a reduction in Q_y [15]. Therefore effects of working point and representative quadrupole driving term (DT) errors were studied with ORBIT.

Simulations were run with a nominal beam for two working points, the design (Q_x, Q_y)=(4.31, 3.83) and a raised (Q_x, Q_y)=(4.41, 3.93), and with representative quadrupole DTs on and off. Collimators were placed at 100% acceptance and normal apertures included. For each case evolution of 99% emittance and beam loss were recorded.

Evolution of emittances are shown in Figure 7 with the total loss indicated in the legend. It can be seen that adding the error term increases emittance and total loss at both working points. As expected, moving the working point up, away from resonance, reduces growth with and without driving terms but surprisingly does not reduce losses.

Whilst behaviour of emittances was as expected, beam loss levels were complicated by an additional effect due to the conformal ISIS vacuum vessels. Around most of the machine, apertures are matched to the design envelope, and working point, of the lattice: this is included in the ORBIT model. Once the tune is changed, the mis-match with the aperture effectively reduces the useful acceptance. These simulations demonstrated that, while losses were low, it was an important effect, with loss location correlating with expected ripple in the beta function. Therefore, the higher losses at the higher Q suggest the design working point may be better. This important, if subtle, effect and possible remedies will be studied further.

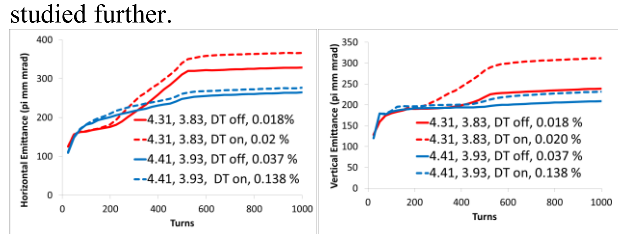

Figure 7: Emittance evolution at 99% occupancy with varying Q and harmonic envelope errors.

ORBIT Results Summary

Studies in the previous section have guided optimisations to a workable solution. An injection painting parameter set has been found based on transverse painting amplitudes in the horizontal and vertical planes of 100, 65 - 75 π mm mr respectively. This incurs 3.7 foil re-circulations equating to a maximum foil temperature of 1657 K. Longitudinally a chopper with 61% duty cycle, painted amplitude 0 - 1.3 MeV and choice of RF parameters show good control with bunching factors at the end of injection 0.51 and >0.4 for the remainder of acceleration. Simulations with 5 M macro particles suggest losses of 0.082% when collimators are inserted at 80% of the aperture.

Whilst the simulation produces a loss of <0.1%, this result will not reflect an accurate machine performance. At this stage the result suggests a plausible and workable design. Future studies to refine the design involve inclusion of non linear optics, impedances and magnet errors.

MULTI MW UPGRADE RING STUDIES

Multi MW Ring

Plans for an accelerator complex capable of producing 2 - 10 MW beams centre on the use of an 0.8 - 3.2 GeV RCS [1]. This lattice design is based on a 5 super period, 370 m circumference ring, optimised for low loss multi turn injection through a foil located in the middle of an 8° dipole operating at 30 Hz (2 MW). Transverse injection painting is dispersive in the horizontal plane and uses 4 local ring bump magnets in the vertical plane for accumulation of 1.3×10^{14} protons. The beam is chopped longitudinally, trapped and accelerated with a h=4 single harmonic RF system. Increasing the repetition rate to

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50 Hz and intensity to 2.0×10^{14}, provides an upgrade path to 5 MW. Two such rings, stacked, could then provide 10 MW.

The initial 30 Hz option has undergone some initial studies and results are given below. This design assumes a linac current of 57 mA with chopping duty factor ~50%, injecting over 800 µs (550 turns) starting 400 µs before magnetic field minimum.

1D Design and Results

Initial calculations for RF parameters are centred on the voltage required to remain synchronous with the main magnet field and overcome longitudinal space charge forces. The induced longitudinal space charge voltage will never exceed 40% of the applied RF voltage [9]. This determines an RF accelerating voltage profile.

The basic viability of accelerating 1.3×10^{14} ppp (3.25×10^{13} per bucket) with these parameters has been tested using an in-house longitudinal particle tracking code [11] including space charge and a measure of beam stability using the KSB criterion [10]. A HP distribution [9] created at main magnet field minimum accelerated stably with no filamentation or beam loss.

Preliminary longitudinal simulations (see Figure 8) have shown that the requisite intensity can be accelerated within the design specifications. RF volts are held constant at 100 kV per turn through injection and peak at 450 kV per turn mid-cycle. The injected beam energy and RF steer are used to paint the injected beam linearly from the centre of the RF bucket to 2.1 MeV off axis.

However, as also shown in Figure 8, the stability criterion is broken towards the end of the acceleration cycle (>15 ms). Further simulations and analytical calculations are required to meet this criterion, optimise longitudinal painting and hence define the RF system requirements.

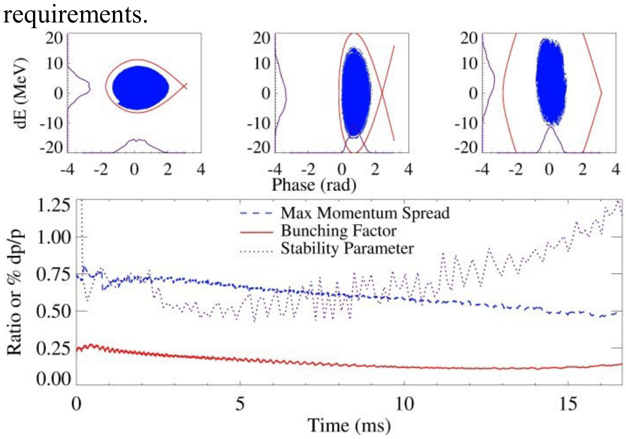

Figure 8: Phase space at the end of injection, 8.33 and 16.67 ms and evolution of bunching factor, stability parameter [8] and maximum dp/p.

3D Design and Results

The ring acceptance has been designed to accomodate a maximum unnormalised accumulated beam emittance of 135 π mm mr in each plane. Painting studies suggest anti-correlated painting with centroid emittances 60 - 40 and 50 - 70 π mm mr in the horizontal and vertical planes respectively produce reasonable beam distributions with 99% emittance of 147 and 150 π mm mr. This requires ±2.5 MeV control in injection energy and up to 32 mr deflection angles on local steering magnets. Beam distributions produced by ORBIT simulations at the end of injection are shown in Figure 9. Results look promising but many further studies are planned.

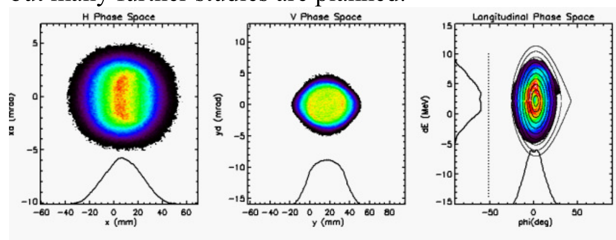

Figure 9: Phase space at the end of injection.

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