A pulsed source of H$^-$ ions has been constructed with minimal cost and is currently being used for commissioning of the Indiana University Cyclotron Facility (IUCF) Cooler Injector Synchrotron[1]. A commercially available duoplasmatron, previously used with the IUCF cyclotrons, was modified for pulsed operation and has produced 25 keV H$^-$ ion beams of up to 1 mA in an emittance of less than 0.38 $\pi$-mm-mrad normalized (80%) and can operate up to 10 Hz with 50 $\mu$s to 4 ms pulse length. A simple and economical pulsed high-power MOSFET circuit is used to drive the arc and the gas valve. The beam transport line to the 7 MeV RFQ-DTL[2][3], features an Einzel lens doublet immediately upstream to match the beam from the source. The design, development and performance of the ion source and beam transport line is presented.

1 INTRODUCTION

The IUCF 'Cooler Injector Synchrotron' (CIS), a 200 MeV fast cycling synchrotron (up to 5 Hz), is being commissioned at IUCF and will be used to inject beam into the IUCF Cooler ring[3]. In order to save on cost, it was decided to commission the system using an existing DC H$^-$ duoplasmatron ion source, modify it for pulsed operation and to design and build in-house a 25 keV beam transport and diagnostics line. The RFQ was defined as having an acceptance of $\approx 1.0$ $\pi$-mm-mrad (normalized to $\beta\gamma$) with Twiss parameters of $\alpha = 0.87$, $\beta = 0.0137$ mm/mrad, and $\gamma = 128.2$ mrad/mm. Beam pulses of 300 $\mu$s duration at 1 Hz to 5 Hz repetition rates were required.

The duoplasmatron was modified to operate in a pulsed mode by increasing the diameter of the anode aperture and adding a pulsed gas valve. Pulsed power for the arc and gas valve is supplied by a simple and economical MOSFET based circuit with a fast rise time and the capability to easily adjust the pulse length and power level.

An Einzel lens doublet was designed to match the duoplasmatron beam to the acceptance of the RFQ. Ray tracing calculations were performed to test the design and subsequent emittance measurements verified the calculations. The emittance scanner is a moving slit and harp assembly that scans across the beam. Figure 1 shows the layout of the ion source and low energy beam transport line.

2 HARDWARE

2.1 Pulsed H$^-$ Ion Source

One of the first reliable techniques of producing a pulsed low-emittance milliampere beam of H$^-$ ions was by pulsing a negative hydrogen ion duoplasmatron[4]. In order to save cost and development time associated with starting up a source with technology new to IUCF, it was decided to modify one of the two negative ion duoplasmatrons previously used in DC mode.

The conventional General Ionex Duoplasmatron[6] was set up to operate in the pulsed H$^-$ mode. Little modification to the source was necessary other than the use of an extraction aperture of 1.25 mm to increase the extracted beam intensity and allow for faster gas pumping from the large source volume. Originally, the duoplasmatron was designed to run at a maximum of 2.0 A of DC arc current. Due to the low duty factor, operation of the arc with a peak current of 40 A or greater is possible. During the CIS commissioning phase, the source is operated at 5 Hz and with a peak arc current of $\geq 35$ A.

An automobile fuel injector gas pulser was first used to pulse hydrogen gas into the source. The fuel injector was very inexpensive but proved to be too variable from pulse to pulse. These valves also tended to leak slightly when closed which increased the average gas load. The fuel injector was later replaced with a General Valve Corporation 'Series 9 High Speed Solenoid Valve'[5] fitted with an optional 3 $\Omega$ solenoid. Using this valve and a MOSFET drive circuit, a gas valve repetition rate of over 100 Hz was demonstrated with pulse-to-pulse throughput variations no larger than 5% and a FWHM less than 160 $\mu$s.
ation with the small aperture and large volume of the duo-
plasmatron, pulsed gas operation could benefit the beam
intensity only up to a maximum repetition rate of 5 Hz.

2.2 Pulsed Power Circuit

A fast (few μs rise and fall time) MOSFET circuit was
developed to supply the pulsed power needed for the gas
valve drive coil and the arc current. Although the two loads
are significantly different in character, the gas valve has a
large inductance and the arc has an initially high impedance
which drops to nearly the ballast resistance after the arc
strikes. In both cases it is desirable to stabilize and control
the current and easily adjust the pulse length. Both circuits,
mounted in a 25 kVdc platform, provide excellent stability,
reliability and immunity from source spark downs.

The driver circuit for the MOSFET receives its on or off
signal from a low cost plastic fiber optic line. The driver
itself limits the maximum on time and the maximum duty
cycle to prevent damaging the power MOSFET as the peak
power for valve operation exceeds 250 W. For the maxi-
mum arc current of 50 A and 300 V the peak power of the
arc circuit is 15 kW. The arc drive circuit and the MOSFET
switch are enclosed in a Faraday shield with full protection
on the two external wire connections.

Power for driving the valve is derived from a small
75 Vdc regulated power supply. In this case, the MOSFET
switch has active current limiting at 4 A. When the drive
is removed, the inductive kickback is clamped by a 150 V
power zener.

Power for the arc circuit (Figure 2) is derived from a volt-
age doubler with 120 VAC input and an 1800 μF storage
 capacitor on the output, resulting in about 300 Vdc, unreg-
ulated. The switch is in series with a current limiting ballast
resistor and a 100 μH bifilar wound air-core inductor.

Figure 2: Circuit diagram of an inexpensive and compact
pulsed power source for the duoplasmatron arc. The peak
current and pulse length is easily adjustable.

2.3 Emittance Scanner

The emittance measuring system[7] consists of a 48 wire
harp of 0.5 mm wire spacing 113 mm downstream of a
0.5 mm slit. The system is PC controlled and moves the
slit and harp together in step sizes of 0.25 mm or 0.5 mm.
Since the beam is pulsed it is necessary to collect data for
a full scan over many beam bursts. For example, in taking
0.25 mm steps across a 3 mm wide beam a completed emit-
tance scan will contain at least 12 beam profiles, each from
a separate beam pulse. The pulse-to-pulse reproducibility
is usually excellent but there is also a provision to signal
average several beam pulses for each scanner position. The
PC moves the slit and collects and stores the data from
which ray angles as a function of position in the beam are
then calculated off line.

2.4 Beam Transport Design

The beam transport line consists of an Einzel lens whose
first ground electrode is also the extraction electrode of the
ion source. An Einzel lens matching doublet is mounted
physically onto the RFQ entrance flange, about 110 cm
downstream from the ion source. Horizontal and vertical
magnetic steering elements and a diagnostics chamber oc-
cupy the intermediate section of the beam line. The diag-
nostics chamber contains a biased Faraday cup, a BeO scin-
tillator, a single dimension 48 wire harp and has provision
for mounting the emittance scanner.

The emittance from the duoplasmatron was pre-
dicted using a charged particle optics design program,
EMP/TRAK[8]. This prediction was used as input for the
design of the matching doublet. Several Einzel lens de-
signs, including a triplet, were considered. The matching
turned out to be easy enough that it was possible to reduce
the number of lenses to two in the final design. The require-
ment of a strongly convergent beam at the entrance of the
RFQ was satisfied with voltages of 20 kV and 60 kV on the
upstream and downstream lenses respectively. The lenses
were finally designed to operate at up to 40 kV and 100 kV
if necessary. Beam properties before and after the match-
ing doublet were measured using a biased Faraday cup and
the emittance scanner.

3 SOURCE OPERATION

3.1 Source Optimization

To optimize the peak beam intensity, it was found that the
timing and width of the arc voltage and gas valve drive
pulse were effective parameters. A timing program allowed
one to vary pulse frequency, gas valve delay, gas valve du-
ration arc delay and arc duration. Pulse rate, gas valve du-
ration and arc duration were found to be the parameters
that had the greatest effect on beam intensity. Output cur-
rent was optimized at various pulse rates and combinations
of gas valve and arc duration and delay. Other paramet-
ers varied were; the position of the intermediate electrode
with respect to the extraction aperture, pinch magnet cur-
rent, and the arc current.

The highest peak beam intensities occurred at 1 Hz or
less for a gas valve drive pulse duration of 238 μs and an
arc duration of over 3.0 ms, see Figure 3 for example. This
optimal condition can produce a beam intensity of over
1.0 mA. This behavior is partly due to the ability of the
pumping system to efficiently clear out the gas in the ex-
In order to produce noise free, stable beam from pulse to pulse, it was necessary to start the arc in advance of the pressure maximum of the gas pulse. When the arc was struck in this starved mode, the source was less apt to spark and the beam flat top was free of 10 kHz to 60 kHz noise. Later runs were made with much shorter arc durations, on the order of 300 μs at 5 Hz and 10 Hz rates and 620 μA and 350 μA beam intensities respectively. Table I above includes some typical operating values after the addition of a second 500 l/s turbo molecular pump. Emittance measurements were taken with the single pump source configuration.

3.2 Emittance Measurements

The goal of the emittance measurements was to ensure that the RFQ matching lenses were capable of providing beam within the RFQ acceptance for varying source conditions. In particular, the lenses were varied through the predicted values for best matching to the acceptance. A 'best fit' ellipse was calculated for each set of data and the 80% contour used to display the emittance envelopes.

Figure 4 shows a series of three data sets, C 106 to C 108, which refer to measurements in the horizontal plane where the lenses were adjusted through the calculated matching value. The measured beam fits well within the acceptance limits. The normalized vertical emittance was measured to be 0.38 *-mm-mrad and the horizontal emittance 0.21 *-mm-mrad.

The error in these measurements is due to a quantization error that arises from the fixed linear and angular steps in the emittance data. Also, the resolution is dependent on the slit width and the distance between the slit and the harp.

Using the mathematical formalism developed by Ludwig et. al.[9], it can be calculated that these measurements over-estimate of the emittance area by about 25%. The plots are not corrected for this error.

Transmission measurements during initial operating tests of the RFQ-DTL have confirmed the expected matching[3].

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5 REFERENCES

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[5] General Valve Corp., 19 Gloria Lane, P.O. Box 1333, Fairfield, NJ 07004.
[6] Peabody Scientific, P.O. Box 2009, Peabody, Massachusetts, 01960.
[8] EMP 3.0 and TRAK 2.0, Field Precision, P.O. Box 13595, Albuquerque, NM 87192.