THE TRIUMF ARIEL RF MODULATED THERMIONIC ELECTRON SOURCE*

F. Ames, Y. Chao, K. Fong, S. Koscielniak, N. Khan, A. Laxdal, L . Merminga, TRIUMF, Vancouver BC, Canada
C. Sinclair, Cornell University, Ithaca NY, USA
D. Storey, University of Victoria, Victoria BC, Canada

Abstract

Within the ARIEL (Advanced Rare IsotopE Laboratory)[1] at TRIUMF, a high power electron beam will be used to produce radioactive ion beams via photo-fission. The electrons are accelerated in a superconducting (SC) linear accelerator (linac) up to 50 MeV. The electron source provides electron bunches with charge up to 15.4 pC at a repetition frequency of 650 MHz. The 300 keV kinetic energy of the electrons is chosen to allow direct injection into an SC accelerator cavity. The main components of the source are a gridded dispenser cathode in a SF_6 filled vessel, and an in-air high voltage power supply. The beam is bunched by applying DC and RF fields to the grid. Unique features of the gun are its cathode/anode geometry to reduce field emission, and transmission of RF modulation via a dielectric (ceramic) waveguide through the SF6. The latter obviates the need for an HV platform inside the vessel to carry the RF generator, and results in a significantly smaller/simpler vessel. The modulation concept has first been implemented and tested on a 100 keV prototype source before it was installed on the final source. Both the prototype and the final source were able to deliver the intended average beam current and pulse charges. The transverse emittance of the 300 keV has been determined to <10 μm and the pulse length to ±12º of the RF phase.

THE TRIUMF ARIEL PROJECT

At present rare isotopes are produced at TRIUMF by bombarding solid targets with up to 100 μA protons at 500 MeV from an H^- cyclotron. Within the ARIEL project two additional target stations will be built to allow the simultaneous delivery of up to three rare isotope beams to experiments. One target station will use an additional proton beam from the cyclotron, while the other one will produce rare isotopes via photo-fission of actinide targets or (γ,n/p) reactions. Thus, it will not only increase the quantity of delivered beams to the users but also provide a complementary composition and purity of the delivered isotopes. The photo-fission will be achieved by using Bremsstrahlung from up to 50 MeV electrons hitting a converter target in front of the isotope production target. The electron beam will be produced by a superconducting linac with five 9-cell cavities operating at 2 K at a frequency of 1.3 GHz. For the final beam power at the converter target of up to 0.5 MW, the linac will operate at a continuous beam current of 10 mA. The accelerator cavities will be distributed in three cryogenic modules. The existing injector module houses one cavity, whereas the following two accelerator modules will be equipped with two cavities each. The project is staged such that two cavities will be added in 2014 and two more over the next few years.

ELECTRON SOURCE REQUIREMENTS

The electron source should allow continuous beam operation up to an average current of 10 mA. In order to match to the accelerator structures, modulation of the beam at 650 MHz, at half of the cavity frequency, has been chosen. This results in a bunch charge of up to 15.4 pC. With an additional buncher cavity in front of the injector module the requirement for the pulse length at the source is <±16º of RF phase at 650 MHz, corresponding to 137 ps. The minimum energy for injection into the accelerator has been determined by electron optics simulations to be 250 keV. In order to operate in a safe regime above this limit, and as it deemed technically not too challenging, the design operating voltage of the source has been set to 300 kV. The normalized transverse emittance should be about 5 μm. An additional requirement is the capability to change the duty factor of operation between 0.1% -100 % by superimposing a macro-pulse structure at Hz to kHz frequency. This will allow beam tuning and set up at the full bunch charge but at lower average beam power. The lifetime of the isotope production targets are expected to be up to 5 weeks. Thus, to minimize down time, the maintenance intervals for the source should exceed this time.

ELECTRON SOURCE IMPLEMENTATION

General Concept

The best way to fulfil the above requirements is with a thermionic dispenser cathode. When equipped with a grid in front of the cathode surface the beam can be modulated. The method has been developed by Bakker et al. [2] for the FELIX accelerator. It uses a superposition of DC and RF voltages at the grid. The negative dc voltage blocks the electrons from passing the grid and the source becomes conducting only during a short interval determined by the RF voltage. The grid voltage and the resulting electron current are shown schematically in figure 1. The dependence of the electron current on the grid voltage can be assumed linear with

$$\mathrm{I}(t) = g_{21}(U_g - U_c), \quad (U_g - U_c) \geq 0 \tag{1}$$

With g_{21} being the transconductance and U_c the cut-off voltage. Both parameters depend on the cathode material and geometry. This results in a charge per bunch Q of

$$Q = \frac{2g_{21}}{2\pi\nu} U_{rf} (\sin(\psi) - \psi \cos(\psi)) \qquad (2)$$

With ν the RF frequency and U_{rf} the amplitude. The pulse length can be expressed as twice the phase angle ψ with respect to the modulating frequency. It only depends on the dc voltage U_b and the rf and cut-off voltages.

$$\cos(\psi) = \frac{-U_b + U_c}{U_{rf}} \qquad (3)$$

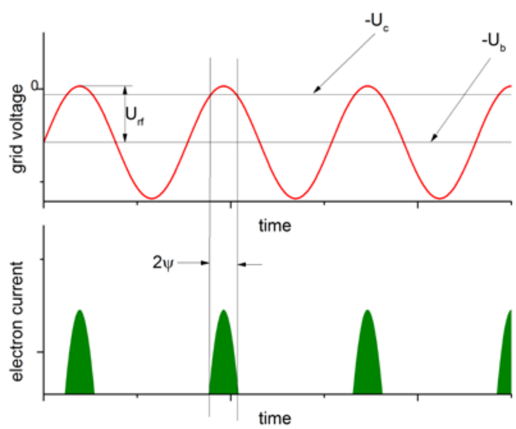

Figure 1: Time dependence of the grid voltage and the electron current.

Typical values for the cathode assembly Y-845 from CPI and an operating voltage of 300 kV are g_{21} = 22 mA/V and U_c = 10 V. For the design beam requirements of a bunch charge of 15.4 pC and a bunch length of ±16° this results in a dc grid bias voltage of -201 V and an RF amplitude of 198.5 V.

Source Design

A cross section of the source can be seen in figure 2. It consists of an Al_2O_3 ceramic insulator with conflat flanges at the cathode and anode side. The shape of the electrodes has been optimized both for the electron optics and to minimize electrical field strength on the surfaces. The design has been made in such a way, that the electrode surface of the cathode parts is kept small and the field strength on the surface is below 10 MV/m to minimize field emission. The material of the cathode side electrodes has been chosen to be titanium (grade 5) for its low electron emission probability. The anode is made of beryllium copper to ensure a good heat conductance. All surfaces are highly polished. Pumping is performed through the beam extraction tube and thirteen 6x32 mm^2 slots in the anode electrode. Directly after the anode two pairs of steerer coils around the extraction beam tube can be used for correcting the beam angle. A first solenoid is located after the anode flange. The source is located in a vessel filled with 2 bar of SF_6.

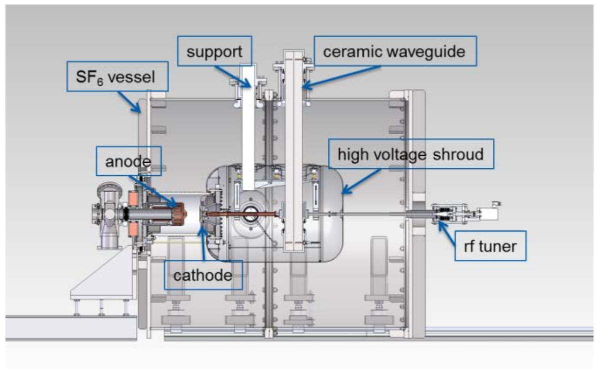

Figure 2: Cross section of the source installed in the SF_6 vessel.

A dispenser cathode assembly from CPI (Y-845) has been chosen. It has a coaxial geometry, which allows an easy matching to apply radio frequency (RF) voltages to the grid. A coaxial transmission line has is used to match the cathode impedance of about 2 kΩ to the RF amplifier. The length of this line can be adjusted for a fine tuning of the resonance frequency. In order to reach the necessary voltage an RF power of about 10 W at the grid is needed.

The basic functionality of the modulation method has been tested with a prototype, using a source body on loan from Jefferson Laboratory operating up to 100 kV in air. The RF power was transmitted via a high voltage insulating RF transformer to the grid. It became evident very soon that 100 kV was close to the limit both for isolation and transmission losses and it would not work at 300 kV. Therefore, a dielectric waveguide has been developed. It consists of an Al_2O_3 ceramic made out of two semi-circular cross-section rods with matching RF chokes on both sides to transport an electromagnetic wave through the ceramic. HFSS simulations were used to optimize the matching chokes. The minimized transmission losses throughout the waveguide at 650MHz are -3.0 dB from the simulation.

BEAM TEST RESULTS

The basic RF modulation functionality has been demonstrated first with a prototype source, which was operated up to a voltage of 100 kV. The RF power was modulated at low frequencies up to 10 kHz to apply a duty factor and macro-pulsing to the beam. This allows regulating the total beam power. The source was connected to a test beam line with the capability to completely characterize the phase space of the emitted beam. For the transverse emittance measurement both an Allison emittance scanner [3], which can operate up to a total beam power of 1 kW, and beam imaging on view screens as function of focussing solenoid settings have been used. In order to find the longitudinal emittance momentum spread and pulse length have to be measured. The beam can be deflected by 90° with a dipole magnet and imaged on a view screen to find the momentum spread. Directly after the dipole, a transverse deflecting mode cavity, synchronized with the beam modulation, bends the beam perpendicular to the plane of the magnetic bender. The deflection depends on the phase difference between the cavity field and the beam pulse. Thus, the beam width in this direction as viewed on the screen allows a determination of the pulse length.

After the diagnostics systems were commissioned with the 100 kV prototype source the final source has been set up. The system has been conditioned to 320 kV and beam extracted at 300 kV. In a first measurement the DC characteristics of the cathode assembly were measured. The transconductance was determined to be g_{21} = 23 mA/V and the cutoff voltage U_c = -12 V. After this, RF modulated beam was send to a Faraday cup to verify again the modulation and duty factor capabilities, as was already established with the prototype. The system allowed operation up to a grid bias voltage of -400 V at the maximum current of 10 mA within the peak of the macro-pulsing, well above the requirement for the bunching. The emittance of the beam has been measured and an example transverse emittance measurement with the Allison emittance scanner is given in figure 3. The measurement has been performed with a peak beam current of 10 mA and a duty factor of 1%. A normalized rms emittance of $\varepsilon_{rms,norm}$ = 7.5 µm can be calculated from it. This is above the originally specified value of 5 µm, but still within the acceptance of the planned beamline and accelerator. A possible reason for this may be a non-homogeneous emission from the cathode, as can be seen when imaging the beam on one of the view screens in the beam line. If needed, the cathode can be exchanged. Figure 4 shows an example of a longitudinal emittance. This measurement has been performed at a peak current of 1.75 mA and a grid bias voltage of U_b = -160 V. With the measured transconductance this would result in a pulse length of ψ = ±10°. The result of the measurement is ±12.3°, which is a good agreement - given the uncertainty of the measurement and the approximation of a linear dependence between grid voltage and electron current. From the same measurement, an energy spread of ΔE =± 500 eV can be obtained.

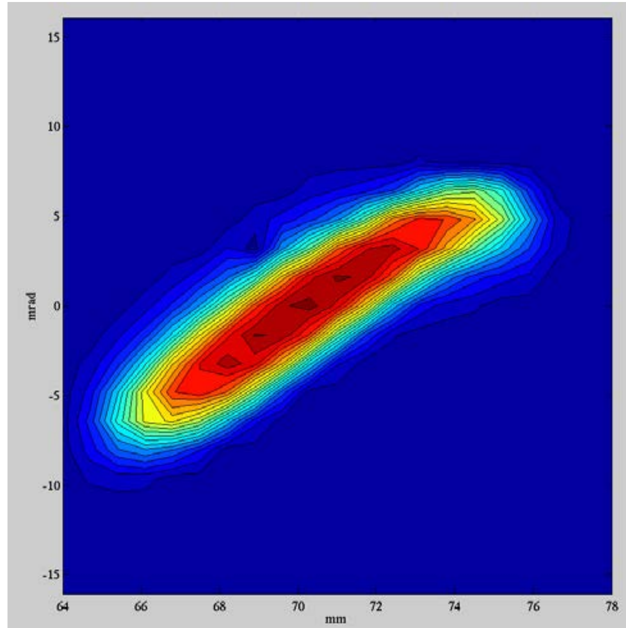

Figure 3: Transverse emittance as measured with the Allison emittance scanner for a 300 keV 10 mA beam.

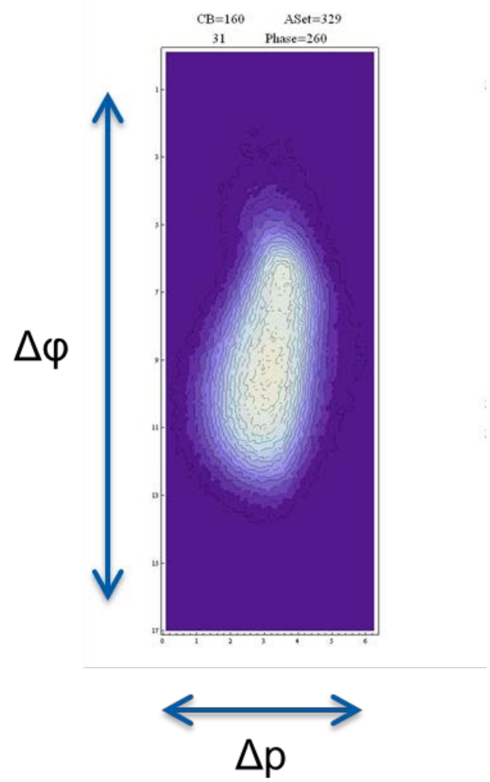

Figure 4: Longitudinal emittance as measured with a combination of a magnetic dipole and RF deflector cavity.

SUMMARY AND OUTLOOK

An electron source has been set up at TRIUMF for the electron linac of the ARIEL project. It uses a gridded thermionic dispenser cathode and delivers a beam of up to 10 mA of electrons at an energy of 300 keV. The beam is modulated at 650 MHz with a bunch length of <16°. Unique features of the source are its high average current operation, the geometry for reducing field emission and the use of a ceramic waveguide to transport RF power to the cathode grid. An initial characterization of the phase space of the beam has been performed with all parameters within the acceptance of the accelerator.

The source will now be set up in front of the accelerator and final commissioning and a complete characterization will be performed within the next few months.

ACKNOWLEDGMENT

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REFERENCES

[1] L. Merminga et al., "ARIEL: TRIUMFS's Advanced Rare IsotopE Laboratory" IPAC2011, San Sebastián, September 2011, WEOBA01, (2011) http://www.JACoW.org

[2] R.J. Bakker et al., Nucl. Instr. and Meth. A307 (1991) 543.

[3] A. Laxdal et al., "High Power Allison Scanner for Electrons", BIW2012, Newpor News, April 2012, TUCP04, (2012) http://www.JACoW.org