THE TRIUMF ARIEL RF MODULATED THERMIONIC ELECTRON SOURCE

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Abstract

Within the ARIEL (Advanced Rare IsotopE Laboratory) at TRIUMF, a high power electron beam is used to produce radioactive ion beams via photo-fission. The electron beam is accelerated in a superconducting linear accelerator (linac) up to 50 MeV. The electron source for this linac provides electron bunches with charge up to 15.4 pC at a repetition frequency of 650 MHz leading to an average current of 10 mA at a kinetic energy of 300 keV. The main components of the source are a gridded dispenser cathode (CPI –Y845) in an SF6 filled vessel and an in-air HV 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 power for the modulation via a dielectric (ceramic) waveguide through the SF6. The source has been installed and first tests with accelerated beams have been performed. The complete phase space of the beam has been characterized for different source conditions.

THE ARIEL PROJECT AT TRIUMF

Within the ARIEL project [1] two additional target stations to produce rare isotopes via the ISOL method will be built. Together with the existing ISAC facility (Isotope Separation and ACceleration) they will allow the simultaneous delivery of up to three beams to experiments. One target station will use an additional proton beam from the TRIUMF cyclotron, while the other one will produce rare isotopes via photo-fission of actinide targets or (γ,n/p) reactions. 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 operating at a frequency of 1.3 GHz. For the final beam power at the converter target of up to 0.5 MW, it will operate at a continuous beam current of 10 mA.

ELECTRON SOURCE REQUIREMENTS

The electron source should allow continuous beam operation up to an average current of 10 mA. 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 operating voltage of the source has been set to 300 kV.

The beam will be modulated at a frequency of 650 MHz. This is to match to the accelerator structures at half of the cavity frequency. At an average current of up to 10 mA it results in a bunch charge of up to 15.4 pC. With an additional room temperature 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 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. It 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

A thermionic dispenser cathode has been proven in many applications that it can operate stable and reliable over an extended period of time and doesn't require the extreme vacuum conditions of a photo cathode. Although the brightness which can be achieved with a thermionic cathode is lower, this is not a limiting factor for our application.

When equipped with a grid in front of the cathode surface the beam can be modulated at high frequency. The method has been developed by Bakker et al. [2] for the FELIX accelerator already in 1991 and more recently in 2011 it has been considered for future high intensity accelerators by P. Sprangle et al. [3]. 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.

RF Modulation of the Beam

Ideally the electron current emitted from the cathode should depend on the voltage applied to the grid following a characteristic curve of a triode. As a good approximation for the estimation of bunch charge and length a linear dependence has been assumed already in [2]. It can be written as:

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

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With g_{21} being the transconductance and U_c the cut-off voltage. Both parameters depend on the cathode material and geometry. As the actual field in between the cathode and the grid is affected by the field penetration from the anode they are also depending on the anode voltage. The charge per bunch Q can be expressed as:

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

With ν the RF frequency, U_{rf} the amplitude and ψ half of the pulse length expressed as the phase angle with respect to the modulating frequency. ψ only depends on the DC voltage U_b, the RF and cut-off voltages.

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

The grid voltage and the resulting electron current are shown schematically in Fig. 1. Typical values for the cathode assembly Y-845 from CPI and an anode 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° a DC grid bias voltage of -201 V and an RF amplitude of 198.5 V are needed.

The macro pulse structure can be achieved by modulating the RF voltage with a rectangular pulse structure.

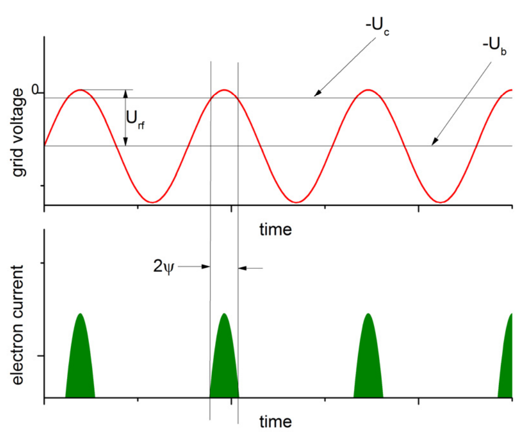

Figure 1: Time dependence of the grid voltage and the electron current.

Source Design

A cross section of the source can be seen in Fig. 2. It consists of an Al_2O_3 ceramic insulator with stainless steel 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 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 focusses the beam directly after the anode flange. The source is located in a vessel filled with 2 bar of SF_6.

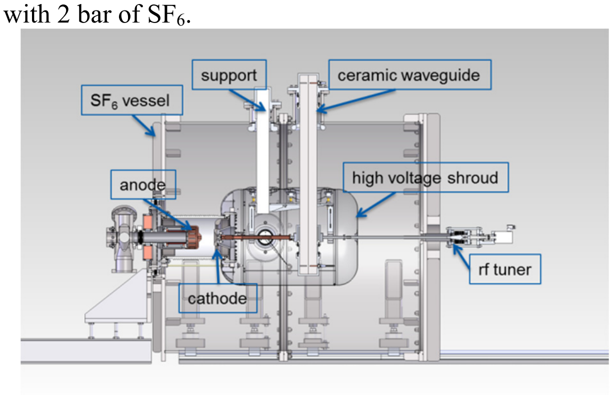

Figure 2: Cross section of the source installed in the SF_6 vessel.

With its coaxial geometry, the dispenser cathode assembly from CPI (Y-845) allows an easy matching to apply radio frequency (RF) voltages to the grid. A coaxial transmission line with sections of different sizes matches 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 some 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 with a diameter of 105 mm made out of two semi-circular cross-section rods with matching RF chokes on both sides to transport an electromagnetic wave. HFSS simulations were used to optimize the matching chokes. The minimized transmission losses throughout the waveguide at 650 MHz are -3.0 dB from the simulation and -1.6 dB from a measurement after manufacturing.

COMMISSIONING RESULTS

Diagnostic elements in the beam line following the source allow for a complete characterization of the phase space of the beam. Faraday cups measure the average current up to 300 W and the cup at the end of the diagnostics line after deflection up to 3 kW. View screens are used for beam profile measurements at low average beam power. Capacitive pick up probes are used for beam position monitoring.

After verifying basic functionality of the source components the transconductunce and cut-off voltage have been determined to g_{21} = 23.4mA/V and U_c = -8.3 V, close to the design values mentioned above.

Transverse Emittance

For the transverse emittance measurement an Allison emittance scanner [4], which can operate up to a total beam power of 1 kW has been used. Figure 3 shows an example of the transverse emittance of an electron beam with a 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 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 the view screens in the beam line.

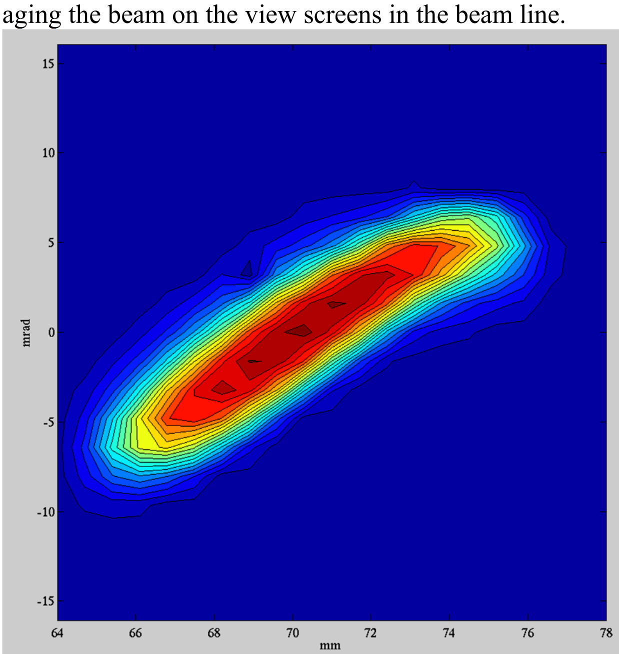

Figure 3: Transverse emittance as measured with the Allison emittance scanner for a 300 keV 10 mA beam.

Longitudinal Emittance

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. Figure 4 shows the result of such measurements for both a cathode bias voltage of 100 V and 200 V. The measured pulse length is higher than expected from equations 2 and 3 especially for low currents. In this case the assumption of the linear dependence between current and grid voltage is most likely not any longer valid. More detailed investigations also on the effects from space charge are needed. For higher beam current a higher DC voltage at the grid will be needed to satisfy the pulse length requirement. Tests up to 400 V have been performed so far.

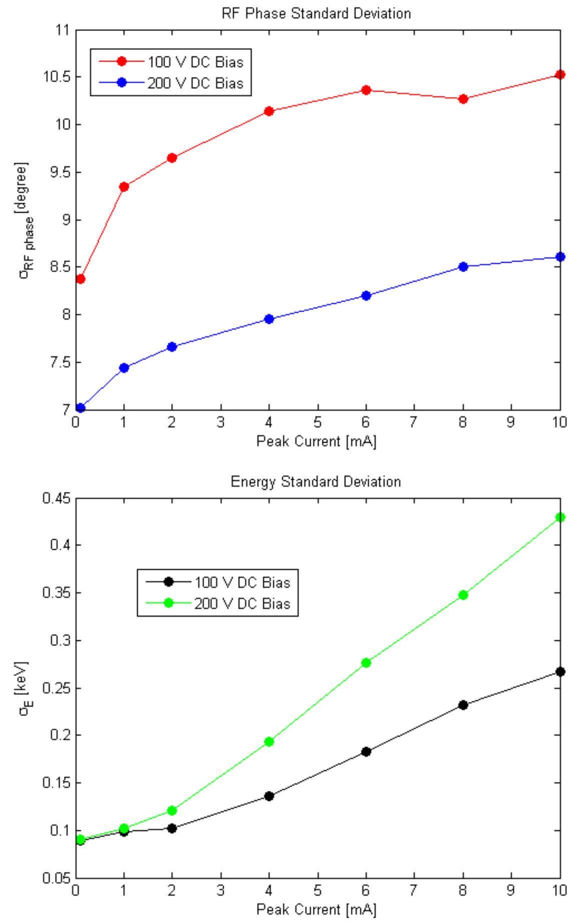

Figure 4: longitudinal emittance as function of beam current, top: pulse length, bottom: energy spread.

ACKNOWLEDGMENT

The authors would like to thank the electron source group of Matt Poelker from Jefferson Laboratory for providing the source body of the 100 kV prototype and many helpful discussions.

ARIEL is funded by the Canada Foundation for Innovation (CFI), the Provinces of AB, BC, MA, ON, QC, and TRIUMF. TRIUMF receives federal funding via a contribution agreement with the National Research Council of Canada.

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 ISBN 978-3-95450-169-4