FIRST ACCELERATION WITH SUPERCONDUCTING RF CAVITIES AT ISAC-II

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Abstract

We have demonstrated the first acceleration of ions with superconducting rf at TRIUMF/ISAC. Alpha particles from a radioactive source are accelerated from 2.8 MeV through the ISAC-II medium beta cryomodule to a maximum energy of 9.4 MeV. The four 106 MHz quarter wave cavities ($\beta_o = 7\%$) are set to the ISAC-II specified gradient of 6 MV/m ($L_{\rm eff} = 18$ cm, E_p=30 MV/m and $V_{\rm eff}$=1.08 MV) with a cavity power of about 7 W per cavity. The final particle energy spectra is measured with a silicon detector. The experimental set-up including details of the source and diagnostic boxes and the detector electronics are described. Beam simulations of the unbunched, uncollimated beam indicate a unique spectral fingerprint that can be used to unambiguously determine each cavity voltage.

INTRODUCTION

The ISAC radioactive beam facility at TRIUMF [1] is being upgraded with the addition of a superconducting heavy ion linac to further accelerate the exotic ions. The first phase will see the installation of twenty quarter wave bulk niobium cavities housed in five cryomodules[2]. Two cryomodules, SCB1 and SCB2, contain four cavities each with $\beta_o = 5.8\%$, while three cryomodules, SCB3, SCB4 and SCB5 contain four cavities each of $\beta_o = 7\%$. All cryomodules contain one superconducting solenoid (Fig. 1. The five cryomodules make up the medium beta section of the full linac with a further three modules of high beta ($\beta_o = 10.4\%$) expected to be added in 2008.

The ISAC-II medium beta cavity design goal is to operate up to 6 MV/m across an 18 cm effective length with $P_{cav} \leq 7$ W. The gradient corresponds to an acceleration voltage of 1.1 MV, a challenging peak surface field of $E_p = 30$ MV/m and a stored energy of $U_o = 3.2$ J and is a significant increase over other operating heavy ion facilities. To achieve stable phase and amplitude control the cavity natural bandwidth of $\pm$0.1 Hz is broadened by overcoupling to accomodate detuning by microphonic noise and helium pressure fluctuation. The chosen tuning bandwidth of $\pm$20 Hz demands a cw forward power of $\sim$200 W and peak power capability of $\sim$400 W to be delivered to the coupling loop. The 9 T solenoids are equiped with bucking coils to reduce the fringe field in the adjacent cavities.

A first unit has been assembled at TRIUMF and three cold tests have been completed to fully characterize the support structure, alignment, cryogenic parameters and rf performance[3]. The cold tests establish the integrity of the cryomodule and rf ancillaries but do not qualify the unit as an accelerator. An off-line acceleration test with alpha particles from a radioactive source has several key motivations: to establish the integrity of the cryomodule as an accelerator months before an on-line beam test is possible, to measure directly the total voltage of the cryomodule, and to gain first experience with the proposed ISAC-II accelerator control system and GUI interface.

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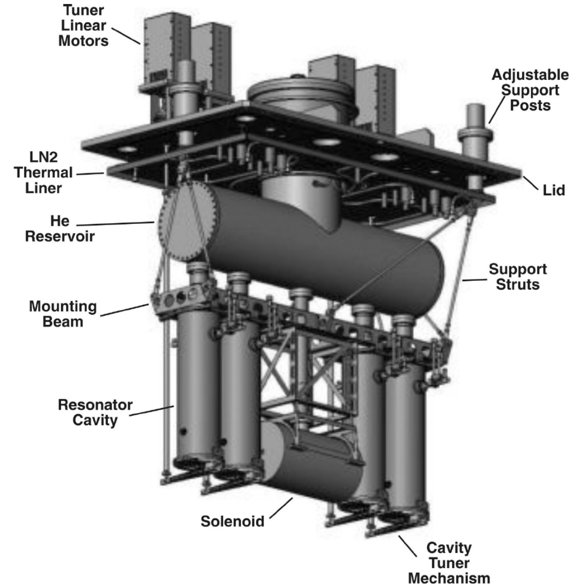

Figure 1: The ISAC-II medium beta cryomodule.

TEST SETUP

The cryomodule tests are done in the test pit of the ISAC-II clean room. The source is installed in the beam aperture of the upstream diagnostic box and the silicon detector is mounted in a diagnostic box positioned at the exit of the cryomodule downstream of the isolation valve as shown in Fig. 2.

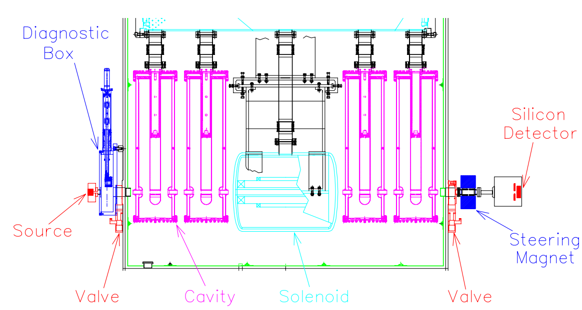

Figure 2: The test set-up for the alpha particle acceleration. The particles are accelerated from left to right.

Source

A ^{244}Cm alpha source, borrowed for the experiment, emits alpha particles with energies 5.76 MeV (24%) and 5.81 MeV (76%) with a half life of 18 years and an activity of 10^7 Bq. It is covered by a 5 μm foil of Ti to contain the radioactive material. Due to safety concerns over foil rupture and possible migration of the alpha emitters the source remains at atmosphere. A source holder (Fig. 3) is equipped with an 8μm Kapton window over a 2 mm aperture that serves as a vacuum window. Another 2 mm aperture lies downstream to further collimate the alpha beam and limit the molecular conductance in case of window failure. A foil micro-mesh (60% transmission) is installed in the downstream 2 mm aperture to catch foil fragments in the case of window rupture. The collimators reduce the flux to $\sim$40 particles/sec. The source holder has a vacuum flange on the downstream end that mates with the upstream diagnostic box of the cryomodule. The Ti and Kapton foils degrade the energy spectrum of the alphas to 2.85 MeV with a standard deviation of 200 keV.

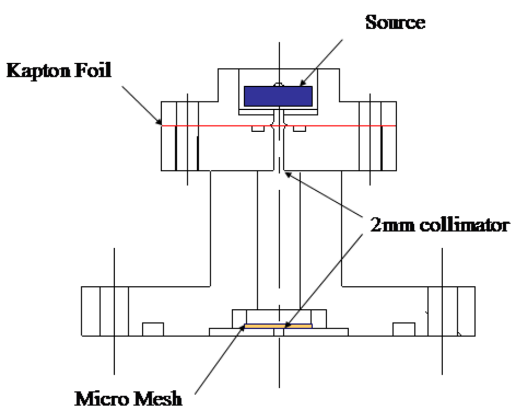

Figure 3: The source and holder.

Detector Box

A diagnostic box is placed 40 cm downstream of the cryomodule and is connected to the vacuum space by a 5 cm diameter vacuum pipe that can be isolated by a VAT valve connected to the module. A steering magnet is placed between the cryomodule and the diagnostic box to clear any electrons accelerated by the cavities. An Ortec TB-022-150-150 totally depleted silicon surface barrier detector is supported on the back plate of the box. The detector has a resolution of $\sim$ 22 keV, an active area of 150 mm^2 and a depletion depth of 150μm. The detector is biased at +80 V. A vane with hole sizes of 4.3, 6.9, 10.0 and 12.9 mm can be manually rotated in front of the detector to form an adjustable collimator. The collimator vane is electrically isolated from ground and wired to permit a measure of the electon current. The detector box is outfitted with its own vacuum system.

The detector is calibrated by moving a second alpha source close to the detector. The source consists of a mixture of ^{239}Pu, ^{241}Am and ^{244}Cm with a total activity of $\sim$103 Bq. The mixture provides three calibration peaks at 5.155, 5.486 and 5.805 MeV. Given the sharpness of the peaks and the linearity of the MCA, the calibration can be extrapolated over the energy range of 0 to 10 MeV to yield an absolute accuracy of $\pm$3%.

Electronics

The detector signal is passed through a floating ground coaxial feedthrough to a Canberra 2003BT preamp and then to an Ortec 471 amplifier. Both amplifiers are placed close to the detector box in the cryomodule pit. The amplified signal is brought to the test room on 110 feet of double shielded RG-214 cable and measured with a Norland IT-5300 multi-channel analyzer (MCA). The data acquired on the MCA is readout over a serial connection using a notebook computer running a LabVIEW program under Windows.

SIMULATIONS

An accelerating gradient of 6 MV/m corresponds to a peak voltage gain of 1.08 MV for an effective length of 18 cm. The alpha particle average initial energy of 2.85 MeV/u ($\beta = 3.9\%$) is low with respect to the design geometry of the cavity. The expected transit time factors, energy gain/cavity and expected final energy are given in Table 1.

Table 1: Expected energy gain for 2.85 MeV alpha particles accelerated through four ISAC-II cavities at 6 MV/m.

Cavity	$E_{\rm in}$	T/T_0	ΔE (MeV)	$E_{\rm out}$
1	2.85	0.46	0.99	3.84
2	3.84	0.75	1.62	5.46
3	5.46	0.92	1.99	7.45
4	7.45	0.99	2.14	9.59

Multi-particle simulations are done with the linac code LANA. The source collimator geometry is modelled to generate a realistic initial transverse phase space. The transverse beam parameters after collimation are $\alpha_{x,y} = -1.0$, $\beta_{x,y} = 0.0055$ mm/mrad and $\beta\epsilon_{x,y} = 0.45\pi$mm-mrad. Realistic three-dimensional fields generated by HFSS are used to represent the cavities and the solenoid is modeled with the standard linear matrix. Previous modeling studies have shown that the solenoid matrix represents a ray traced solution to close approximation.

ACCELERATION

The acceleration test is included as part of the third cold test of the prototype cryomodule. The first two tests provided initial data on the cold mass alignment, the cryogenic performance and rf system integrity[3]. A telescope on the cryomodule beam center line is used to provide alignment of the source holder and diagnostic.

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Test Results

The collimation reduces the intensity to $\sim$ 40pps while the accelerator acceptance reduces this further to $\sim$ 4pps. Since the beam is unbunched the actual count distribution for the higher energy particles of interest is very weak. The cavities are turned on sequentially starting at the upstream end. Each cavity is first set to the correct voltage. The solenoid is set to the optimal value found from the simulations. With the exception of cavity 1 the cavity phase is scanned in 30° phase increments to find the optimum phase. Each phase set point takes 5-10 minutes before a reasonable spectra is obtained. Once the correct phase is determined the spectra for the optimized settings are taken for twenty minutes.

The spectrum for the cavities off as well as the four spectra as the cavities are turned on sequentially are plotted in Fig. 4. Maximum particle energies for the four cases are 4.2, 5.8, 7.4 and 9.4 MeV. The results for the first two cavities are higher than the calculated single particle values in Table 1 due to the large energy spread in the initial beam. The maximum final energy depends on the phasing of the cavities and the relationship of the cavity phases to the initial energy of the beam. During the test cavity phases are chosen to optimize the energy of a statistical significant number of particles. These particles would come from some energy band located between the mean initial energy and the highest intitial energy.

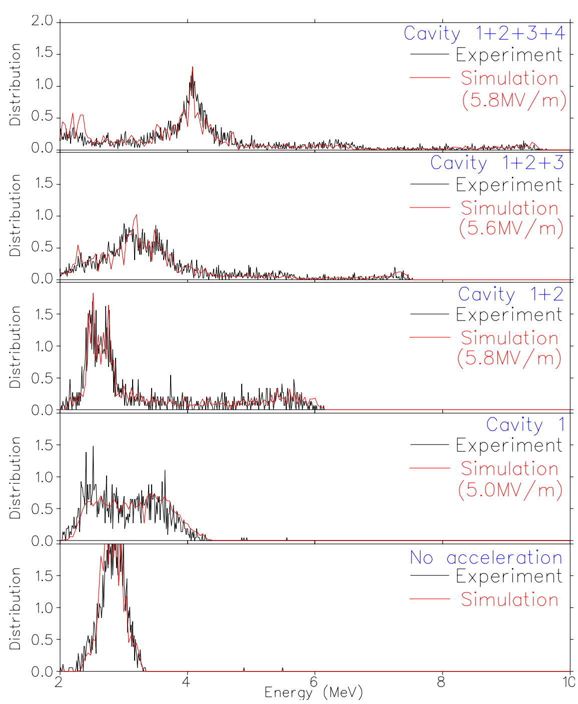

Figure 4: Experimental spectra (black) and simulation result (red) for no acceleration, and for each case with cavities from 1 to 4 on sequentially at the nominal voltage of 6 MV/m.

A true analysis of the cavity voltage can only be done with a simulation. Due to the poor quality of the injected beam most of the ions are only partially accelerated. The spectra for the unbunched, uncollimated beam provides however a spectral fingerprint. As the voltage and phase of the cavities in simulation are varied the distribution of the most energetic ions as well as that of the lower energy peaks shift and an unambiguous fit of cavity voltage is possible. The best fit simulations are superimposed on the test data in Fig. 4. The corresponding cavity voltages for these cases are 5, 5.8, 5.6, and 5.8 MV/m for cavities 1 through 4 respectively. The average cavity gradient of 5.6 MV/m, is within 6% of the design goal of 6 MV/m for each cavity.

A demonstration of this fitting method is given in Fig. 5 for the final energy spectrum with all four cavities on. The top plot gives the experimental spectrum and the best fit correspondng to the optimal voltage and phase. The four simulation results recorded below correspond to cases where the voltage and phase of cavity four are varied from the optimal values. We estimate that the cavity voltage can be determined to $\pm$5% accuracy with this method.

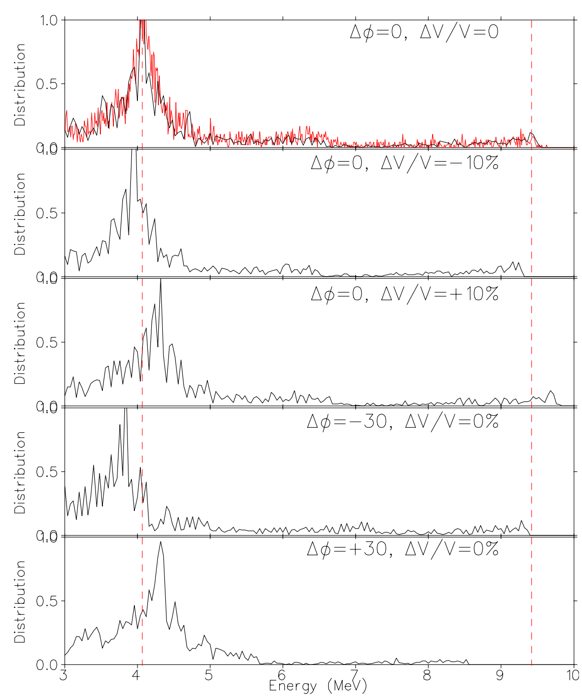

Figure 5: Experimental spectra (red) for all cavities on and five simulation results (black) showing the variation in the simulated spectrum as phase and voltage are varied from optimal values.

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