STATUS OF THE RARE ISOTOPE REACCELERATOR FACILITY REA*

D. Leitner[1,2], D. Alt[2], T. M.Baumann[2], C. Benatti[2], K. Cooper[2], B. Durickovich[1], K. Kittimanapun[2], S. Krause[2], A. Lapierre[2], L. Ling-Ying[2], F. Montes[2], D. Morrissey[2], S. Nash[2], R. Rencsok[2], A. J. Rodriguez[1], C. Sumithrarachchi[2], S. Schwarz[2], M. Steiner[2], M. Syphers[2], S. Williams[2], W. Wittmer[1], X. Wu[1]

[1]Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824 USA

[2]NSCL, Michigan State University, East Lansing, MI 48824, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) is currently in the preliminary design phase at Michigan State University (MSU) [1]. FRIB consists of a driver linac for the acceleration of heavy ion beams, followed by a fragmentation target station and a ReAccelerating facility (ReA). While FRIB is expected to start commissioning in 2018, the first stage of ReA called ReA3 is already under commissioning [2, 3]. ReA was connected to the Coupled Cyclotron Facility at MSU in 2012 and has delivered its first radioactive ion beam to the experimental hall in 2013. An overview of the facility will be discussed. In addition, this paper focuses on the technical progress and first commissioning results with radioactive ion beams.

INTRODUCTION

Nuclear science research requires reaccelerated radioactive isotope ion beams in a range of kinetic energies from thermal energies to near 20 MeV/nucleon. Isotope Separation On-line (ISOL) and Projectile Fragmentation (PF) are the two most common methods used to produce high quality radioactive ions beams (RIBs) for the various nuclear science experiments. In the ISOL technique the RIBs are produced in a thick target from which they have to diffuse out before they can be ionized and used as radioactive beams. While this technique offers unmatched yields for a number of isotopes, chemically reactive isotope are more difficult and slow to extract.

Projectile fragmentation on the other hand can be used for a broad range of interesting nuclei, since the reaction products recoil out of the target in forward direction, which makes the production method chemically indifferent. In order to separate the desired isotope from the bulk of the other reaction products, in-flight fragmentation facilities are often combined with a high acceptance fragment separator [4]. This combination offers a versatile method to develop a wide range of isotopes in a short time. As an example, in the 10 years of operation of Coupled Cyclotron Facility at Michigan State University more than 1000 rare isotope beams have been produced and more than 870 have been delivered to users for experiments [5]. The energy however of those radioactive beams are close to the primary driver beam energy (80-150MeV/nucleon) which can be too high for some nuclear physics experiments.

The physics reach can be further enriched if such a facility is combined with a gas stopper and a re-accelerator. Then in addition to the fast RIBs of 50 to a few 100MeV/u, high quality beams can be provided from the lowest energies of a few 10s of keV/nucleon (for trapping and spectroscopy experiments) to an energy range between a few 100 keV/nucleon and 20

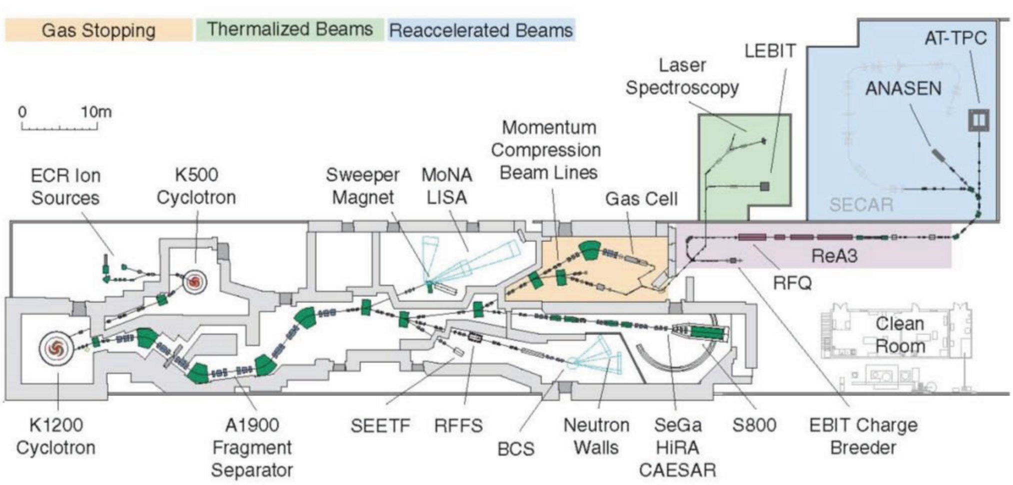

Figure 1: Facility layout of the National Superconducting Cyclotron Laboratory with the Coupled Cyclotron Facility and the newly commissioned gas stopping area and reaccelerated radioactive ion beam capabilities[5].

MeV/nucleon. The recently commissioned re-accelerator facility ReA is the first rare isotope post accelerator coupled to a projectile fragmentation facility. An overview of the Coupled Cyclotron Facility and the ReAccelerator Facility is shown in Figure 1 and a detail layout of ReA is shown in Figure 2.

FACILITY OVERVIEW AND STATUS

The first stage of the re-accelerator facility ReA3 consists of a rare isotope beam stopping area, a transport section, a charge breeder, a compact SC-linac and a beam distribution system. In the stopping area, the rare isotopes are thermalized by using a combination of solid degraders with a linear gas cell [6]. After extraction, a low energy beam line [7] transports the 1+ or 2+ ions or molecules to the trapping areas and laser spectroscopy experiments, or to an Electron Beam Ion Trap (EBIT) [8, 9] for charge breeding and subsequent acceleration. The linac consists of a second off-line stable ion beam injector, a multi harmonic buncher, a room temperature RFQ, a buncher cryomodule (CM) and two low beta cryomodules with a total of fifteen superconducting cavities [2]. The last of the three cryomodules, designed for a beta equal to 0.085, is currently being assembled and is expected to be installed in July of 2014, after which phase 1 (ReA3) will be completed.

ReA3 is nominally capable of accelerating ions with a charge-to-mass ratio Q/A=0.25 from 300 keV/u to 3 MeV/u and for Q/A=0.5 from 300 keV/u to 6 MeV/u. In its final configuration ReA will consist of three buncher cryomodules, one β_o=0.041 and four β_o=0.085 accelerating CMs with a total of 41 superconducting quarter wave cavities (funding proposal submitted). In this configuration, ReA will nominally provide heavy ion beams from 0.3 MeV/u to 12 MeV/u for the heaviest ions and energies from 0.3 MeV/u up to 20 MeV/u for light ions. Figure 3 shows the nominal energy range of the facility in the first phase, and the high energy upgrades with the three additional beta=0.085 cryomodules. The first of the three high energy cryomodules is currently under design (see section below) and is expected to be completed in 2015.

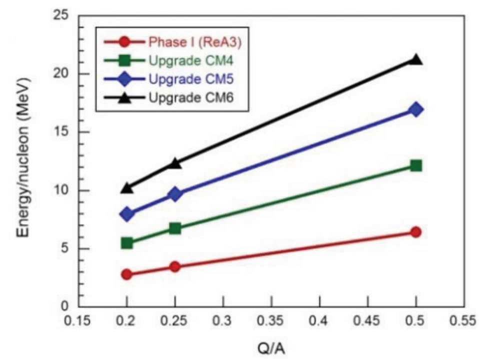

Figure 3: Energy range of the ReAccelerator facility [4].

The current facility was commissioned using stable beams between 2011-2012 [2, 3]. The linear gas stopper and low energy beam transport lines were commissioned with rare isotopes and stable beams in 2013[7]. The first of the three transport lines into the low energy beam hall was commissioned in summer of 2013 [3] and the first radioactive ion beam was delivered to users in August of 2013 (see below). The remaining two beam lines are under construction and are expected to be completed by December of 2013.

PILOT BEAM DEVELOPMENT

One of the challenges of radioactive post accelerators is the wide dynamic range that the beam diagnostics need to cover [10, 11]. Due to the low rate of the injected radioactive ions (10-10^6 pps), the front end and the linac must be phased and pre-tuned using stable (pilot) beams (10^9pps or more). Therefore in preparation for the radioactive ion beam commissioning experiment, stable pilot beams from the off-line injector ion source (H_2 and He)

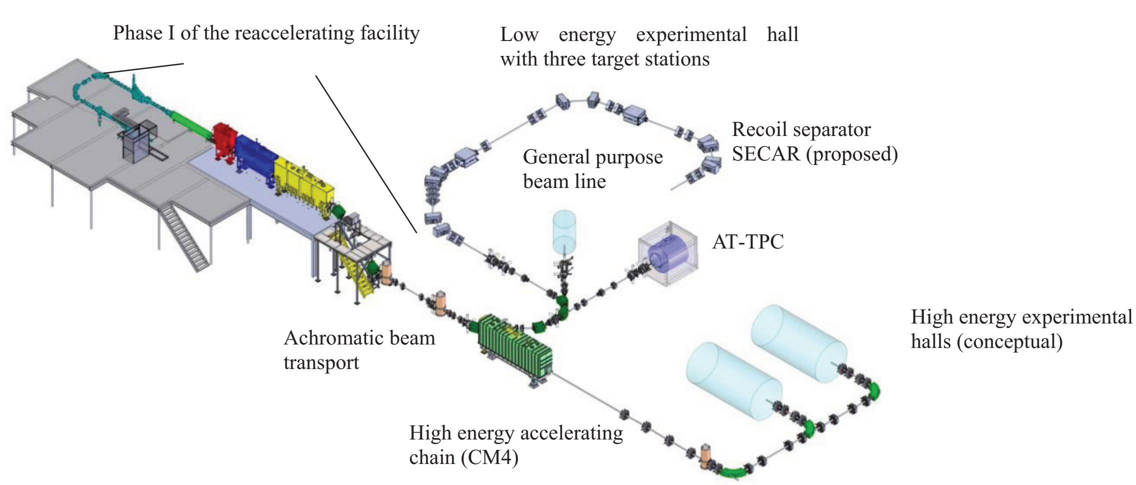

Figure 2: Layout of the ReAccelerator facility and the transport lines into the low energy experimental hall. In addition, the first cryomodule of the high energy section of the linac is shown.

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and heavy ion beams pilot beam from the EBIT were established. In order to scale from one A/Q to the next the injection voltage into the RFQ must be well matched to ensure efficient acceleration. For this purpose the energy acceptance of the RFQ was measured by varying the injection energy of the EBIT beam. Figure 4 shows the results of the calibration. An absolute energy acceptance of ±250V FWHM or ±0.75% relative was measured. This value is slightly lower than the simulated RFQ energy acceptance of ±2% for a 1.4nsec (±20 degree) long beam bunch [12] which will be further investigated.

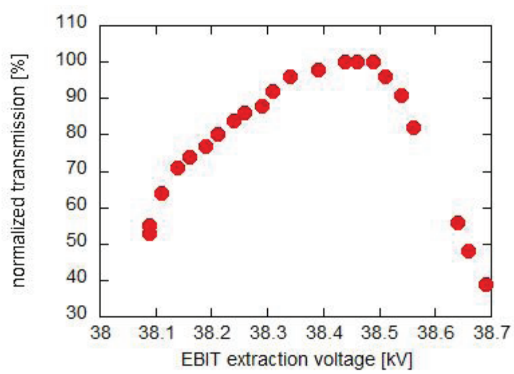

Figure 4: RFQ energy acceptance in dependence of the EBIT extraction voltage for a $^{16}O^{5+}$ beam.

In addition, the full acceleration scheme for radioactive ions was tested by injecting 1+ ^{85,87}Rb ions from the gas stopping area into the EBIT, charge breeding the rubidium ions to high charge states and subsequently accelerating $^{85}Rb^{27+}$ as well as $^{87}Rb^{28+}$with the linac. Figure 5 shows the superposition of four spectra measured with a scattering-gold foil silicon detector mounted at 30 degrees [10]. The first peak is recorded when the detector is retracted from the beam line and depicts the energy spectra of ^{241}Am α-calibration source (5.486 MeV). The second, third and fourth peaks are recorded as the beam line, the RFQ injection voltage, and RFQ vane voltage were scaled from the $^{16}O^{5+}$ pilot beam settings to the $^{40}Ar^{13+}$ beam (third peak) and finally to the $^{87}Rb^{28+}$beam (fourth peak). As the maximum A/Q scaling was only 4%, the linac settings were kept unchanged for this test. For the radioactive ion beam online experiment the linac was scaled using fixed velocity beam energy profiles in order to achieve the desired beam parameters and energy on target.

RADIOACTIVE ION BEAM COMMISSIONING

^{37}K Beam Production

To produce ^{37}K ($T_{1/2}$=1.23s), a primary beam of ^{40}Ca was extracted from the Coupled Cyclotron Facility at an energy of 140 MeV/nucleon, fragmented in a thin beryllium target, and separated in the A1900 fragment separator[5]. The ^{37}K was then transported to the beam stopping area, which consists of a high energy beam momentum compression beamline, a degrader and wedge

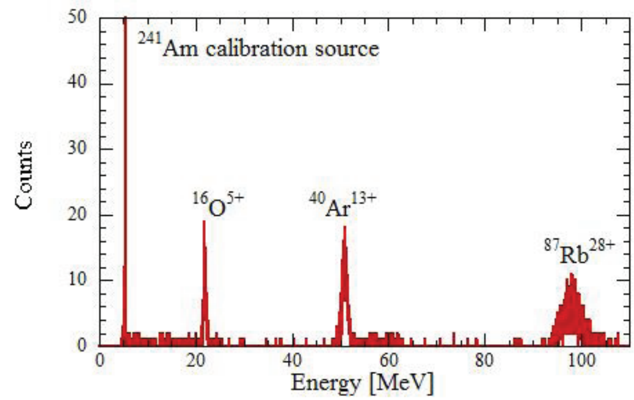

Figure 5: Energy spectra obtained using the scattering-foil silicon detector for three heavy ion tunes.

section, and a 1.2 m long linear gas cell operated at about 100Torr [6].

After the fragments are slowed down to less than one eV in the helium gas of the gas cell, they are extracted as singly or doubly charged ions and singly or doubly charged molecular ions, mass-analyzed and transported to the EBIT charge breeder.

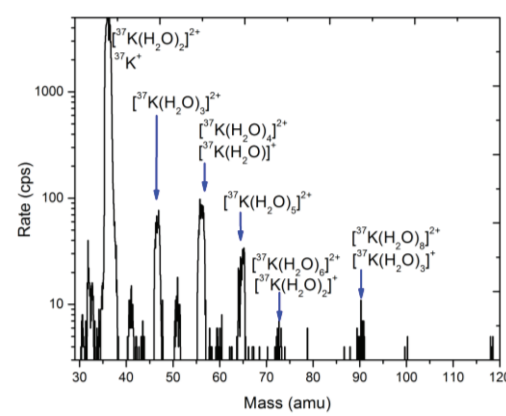

Figure 6: Scan of the extracted beam from the gas cell after the analyzing magnet in the low energy beam line.

As an example, Figure 6 [11] shows the mass (activity) scan of the beam extracted from the gas cell using a β-decay counter/Faraday cup assembly after the analyzing magnet in the low energy RIB injection line [11]. For potassium, the low energy beam consists mostly of ^{37}K ions (≈ 94%) and a few small peaks of weakly bound molecular 1+ and 2+ ions which are formed with one to a few water ligands from residual contaminates in the gas cell. In the preliminary commissioning tests this summer, ion beams with intensities of up to 10^5 particles per second have been thermalized and total extraction efficiencies of up to 14% have been achieved. Further increases of the efficiency are expected once the vacuum is improved in the cell. After mass analysis, the RIBs are injected into the EBIT charge breeder and charge bred to $^{37}K^{17+}$.

Post-Acceleration

An important design choice for the ReA accelerator was the selection of an EBIT as charge breeder. With the expected rates of radioactive ions from the reaccelerator of 10 to 10^6 ions per second, minimizing the stable ion beam contamination from residual gas ions is an important factor. The ReA EBIT has a cryogenic ion trapping structure [9] to minimize the beam contamination from residual ions. As expected, the intensity levels for beam other than the typical residual gas ions such as nitrogen, helium, and oxygen are very low. As an example, Figure 7a shows the charge state spectrum of background ions from the EBIT where the positions of various ^{37}K charge states are indicated. Due to the energy required by the experiment of 2.4 MeV/nucleon, charge state of 15+ and higher were needed for the linac. Figure 7b shows a high resolution Q/A scan of the 16+ to 19+ region.

In addition to possible beam contaminations the charge breeding efficiency was considered as well when $^{37}K^{17+}$ (helium like ion) was selected as the best choice for the experiment. During off-line charge breeding tests, an efficiency of 4 to 5% into K^{17+} using stable potassium 1+ ions was achieved [9]. A similar efficiency was measured with radioactive ions with a repetition rate of 6Hz (≈167 ms charge breeding time). The efficiency was slightly lower (≈2%) when the repetition rate was increased to 20 Hz due to the shorter breeding time.

After the beam was extracted from the EBIT and mass analyzed, it was subsequently accelerated with the RFQ and the superconducting linac to an energy of 2.4 MeV/u using the first two cryomodules during the 80 hours of beam delivery. In order to achieve the required energy for the experiment several cavities were operated at twice the original specified gradients and all of them well beyond specification. Overall the cavity amplitudes were set at 170% of the nominal values and ran stable without any issues throughout the experiment. The overall transport efficiency from the EBIT through the linac was about 60% during the experiments (close to the maximum expected transmission through the MHB and the RFQ of about 70%). The linac and injection lines were pre-tuned using a $^{16}O^{7+}$ beam, and then scaled to $^{15}N^{7+}$ while maintaining a fixed velocity tune in the linac. Finally during the $^{37}K^{17+}$ delivery the linac and the injection line were scaled for the remaining 1.5%. Only minor corrections were necessary after scaling to deliver the beam to the experimental station [3]. Several decay counters along the beam line were installed to monitor the activity during the tuning process and optimize the transmission. Beam impurities were analyzed using in-beam silicon detectors and the ionization chamber mounted in the experimental station. In addition to the $^{37}K^{17+}$ ions, about 1000 ions/sec $^{13}C^{6+}$ and about 100 ions/ sec of $^{37}Cl^{17+}$ were identified as impurities in the accelerated beam.

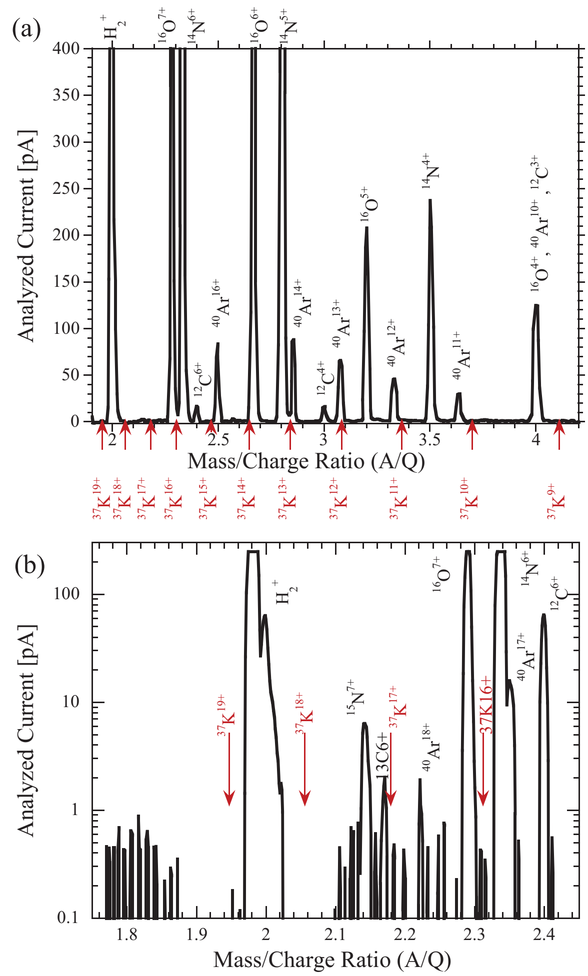

Figure 7: (a) Charge state distribution of the residual ion beam from the EBIT where the position of various $^{37}K^{n+}$ ions are indicated. (b) High resolution, high sensitivity A/Q scan, charge states for $^{37}K^{16+\ -\ 19+}$ ions are indicated.

Figure 8 shows two dimensional PID (particle identification) plots of the energy in the first segment (partial beam energy loss, delta-E) versus total energy (total beam energy loss) in all segments of the ionization chamber, in arbitrary units. This figure is provided courtesy of the ANASEN collaboration. The top panel shows the particle identification without injection of the ^{37}K into the EBIT, and the bottom panel with injection. The separation of mass 13 from 37 is evident, and it was for this reason that $^{37}K^{17+}$ was chosen for transport to the experiment. The small background rate of ^{37}Cl was relatively low and separated from the ^{37}K.

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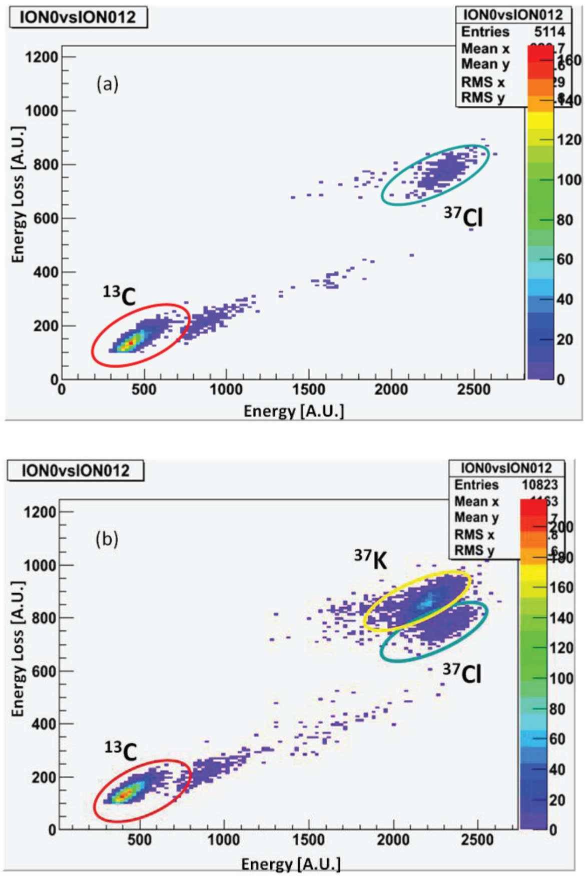

Figure 8: Particle identification (PID) obtained with the ANASEN ionization chamber. (a) PID without injection radioactive ^{37}K into the EBIT (b) PID when radioactive ^{37}K is injected into the EBIT.

FUTURE DEVELOPMENTS

The third cryomodule with a design β=0.085 is currently in its final assembly stage. It consists of eight quarter - wave SRF cavities and three superconducting solenoids for focusing. Once it is installed in the beam line it will add nominally 8.4 MV acceleration voltage to the accelerating chain. Eleven cavities have been successfully tested, all of which achieved a performance well above the nominal required accelerator gradient and Q-value (see figure 9) [2, 13]. A detailed description of the cavity design and its development can be found elsewhere [13]. Figure 9 shows the final acceptance test of the eight cavities mounted in the cryomodule.

In parallel the first cryomodule of the high energy accelerator chain is under development. It will consist of additional eight cavities and three solenoids, providing a nominal total accelerating voltage of 14.24 MV. Additionally one cold beam position monitor will be mounted after each solenoid. Contrary to the top-down cryomodule design of the first three cryomodules, where the coldmass is mounted on a strongback and supported from the top flange of the cryomodule, the new cryomodule is based on a modular bottom-supported design, which is optimized for mass-production and efficient precision assembly [14]. This cryomodule serves also as prototype cryomodule for the eleven FRIB β=0.085 cryomodules of linac section 1 [1].

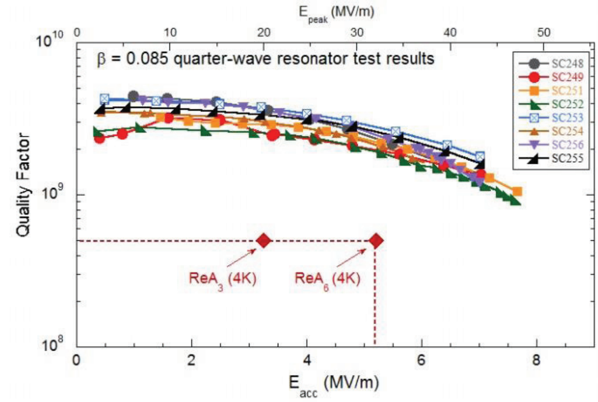

Figure 9: Q_0 vs. E_{acc} ($V_a/\beta\lambda$) curves measured during vertical acceptance tests of the β=0.085 ReA3 cavities at a temperature of 4.2 K.

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