Recent Progress in the Superconducting RF Program at TRIUMF/ISAC

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Abstract

A heavy ion superconducting linac is being installed at TRIUMF to increase the final energy of radioactive beams from ISAC. A first stage of 20 MV consisting of five medium beta cryomodules each with four quarter wave bulk niobium cavities and a superconducting solenoid is being installed with commissioning scheduled for Dec. 2005. The cavities have been fully characterized for rf performance. Two cryomodules have been tested at cold temperatures. A high beta cavity ($\beta_0 = 0.104$) for the next phase is presently in design. A weak phase lock loop technique is used to monitor the control loop phase noise to characterize system microphonics. A recent highlight is the acceleration of heavy ions by one cryomodule as a proof of system integrity. The report will summarize all aspects of the program.

INTRODUCTION

TRIUMF is now preparing a new heavy ion superconducting linac as an extension to the ISAC facility to permit acceleration of radioactive ion beams up to energies of at least 6.5 MeV/u. The superconducting linac is composed of two-gap, bulk niobium, quarter wave rf cavities, for acceleration, and superconducting solenoids, for periodic transverse focussing, housed in several cryomodules. The linac is grouped into low, medium and high beta sections. The installation of the linac has been grouped into three stages highlighted in Fig. 1. The initial Stage 0 to be completed in 2005 includes the installation of a transfer line from the ISAC DTL (E=1.5 MeV/u) and the medium beta section to produce 20 MV of accelerating voltage for initial experiments. Stage 1, to be completed three years later, includes the installation of the three high beta modules for a further 20 MV. The ISAC-II accelerator final Stage 2 is foreseen after 2010.

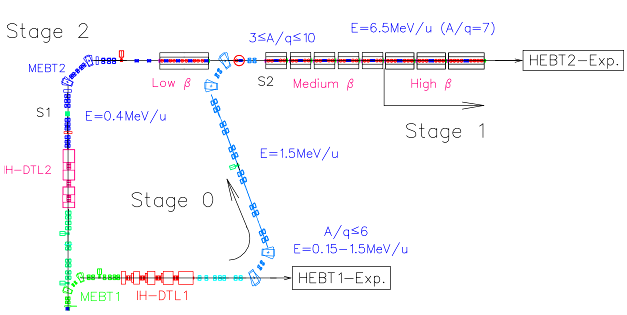

Figure 1: Stages 0, 1 and 2 for the ISAC-II upgrade.

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CAVITIES

Medium Beta Cavities

The cavities, originally developed at INFN-LNL, are two-gap bulk niobium quarter wave cavities. The first eight have a design velocity of β_o 5.7% while the remaining twelve have a design velocity of $\beta_o = 7.1\%$ (Fig. 2). The cavities were fabricated at Zanon in Italy. The initial four were chemically polished at CERN and the remaining sixteen were chemically polished at JLab. Recently two cavities received additional electro-polishing in a collaboration with Argonne[1].

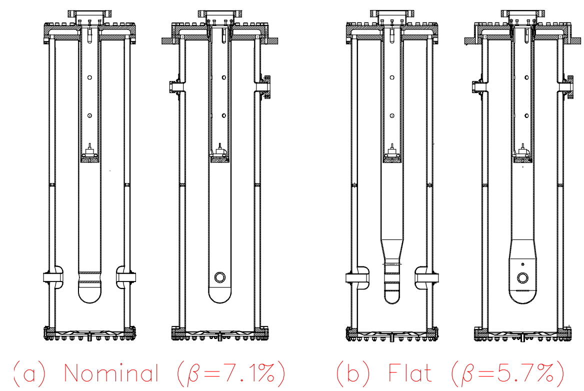

Figure 2: The two medium beta quarter wave cavities for the ISAC-II linac.

The cavities are equiped with a mechanical damper which limits microphonics to less than a few Hz rms. A demountable flange on the high field end supports the tuning plate. Rf coupling is done through a side port. To date nineteen cavities have been characterized via cold test. Typical treatment involves a 30-40 minute high pressure water rinse and twenty four hour air dry in a clean room, followed by vacuum pumping and bakeout at 95 C for 48 hours. This is followed by pre-cooling either by an addition of LN2 to the helium space or by 48 hours of radiation cooling from the LN2 cooled side shields.

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. A distribution of the initial cavity performance is shown in the top plot of Fig. 3 for the characteristic fields at 7 W cavity power. Four cavities out of the nineteen did not met specification with at least one cavity being very poor. Recent studies have shown that the cavities can have Q-disease that makes them susceptible to slow cooldowns[1]. All initial tests involved a pre-cool with LN2. A small flow of LN2 was delivered to the inner conductor volume and maintained until the outer metal sensors indicated $\sim$ 170K. Radiation and thermalization would bring the cavity to 160K before helium transfer. A fast cool-down procedure has been adopted where the cavity is radiation cooled to $\sim$ 220K for 48 hours and then rapidly cooled with LHe down below 50K in less than one hour. The LHe flow is $\sim$ 50 ltr/hr. Several of the previously poor cavities have been retested and the latest cavity performance summary is shown in the bottom plot of Fig. 3.

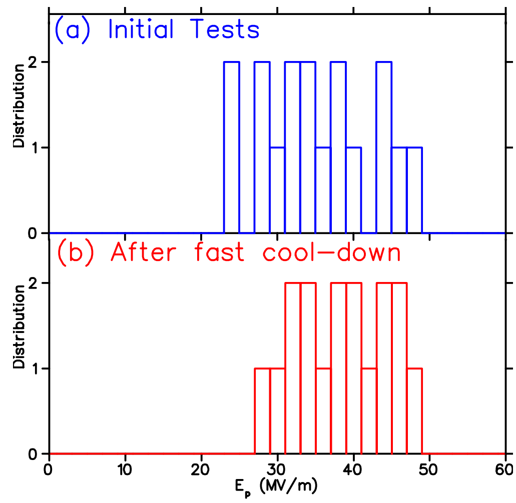

Figure 3: Histogram summarizing cavity performance for seventeen tested cavities. Shown are the numbers of cavities achieving a certain peak surface field at 7W helium load. Initial tests are shown in the top plot and recent status is shown in the bottom plot after testing poorer cavities with a fast cooldown.

Presently only one cavity does not meet specification with a hard quench limit at 3 MV/m. We are making plans to etch the cavity again to try to improve the performance.

High Beta Cavities

In the second stage of ISAC-II $\sim$ 20 MV of high β quarter wave cavities will be installed. Twenty high beta cavities are divided into two modules of six cavities and one module of eight cavities. Each of the medium and high beta cryomodules are equiped with one solenoid each. The high beta cavity will have the same transverse dimensions as the medium beta cavity but with a higher frequency to increase the design velocity. The cavity is presently in the prototyping stage with production to begin in 2006.

The rf parameters of the three ISAC-II cavities are given in Table 1.

RF SYSTEMS

RF Controls: The RF Control system [2] for the superconducting cavities is a hybrid analogue/digital system. Each system consists of a self-excited feedback loop with

Table 1: Parameters of ISAC-II cavities.

Parameter	*HB*	*MB (flat)*	*MB (round)*
f (MHz)	141.4	106.1	106.1
β_o	0.104	0.064	0.072
TTF$_o$	0.089	0.087	0.090
bore (mm)	20	20	20
gap (mm)	45	40	40
drift tube (mm)	60	40	60
L_{eff} (mm)	180	180	180
Height (mm)	577	755	750
Δy (mm)	1.3	0.56	0.75
f_{mech} (Hz)	150	80	80
E_a (MV/m)	6	6	6
V (MV)@6MV/m	1.08	1.08	1.08
E_p/E_a	4.7	5.6	4.6
B_p/E_a(mT/MV/m)	10.3	10.3	10.1
U/E_a^2(J/(MV/m)^2)	0.073	0.1	0.092
$R_sQ_0(\Omega)$	24.8	20.1	19.1
$R_{sh}/Q(\Omega$	499	486	519

phase-locked loops for phase and frequency stabilization. Amplitude and phase regulations, as well as tuning control, are performed using digital signal processors. The rf bandwidth is broadened by overcoupling.

A measurement of the phase noise is a sensitive tool to produce valuable information regarding the environment within the RF system. Fig. 4 shows the equipment setup for measuring phase noise. The white boxes are components that are already present in a self-excited regulation system, so the only extra equipment needed are a low phase noise frequency synthesizer and an FFT analyzer. In order to keep the phase detector from wrapping around due to long term phase drift, the feedback loop gain G_θ is set to the minimum required for the phase detector to remain operating in its linear region.

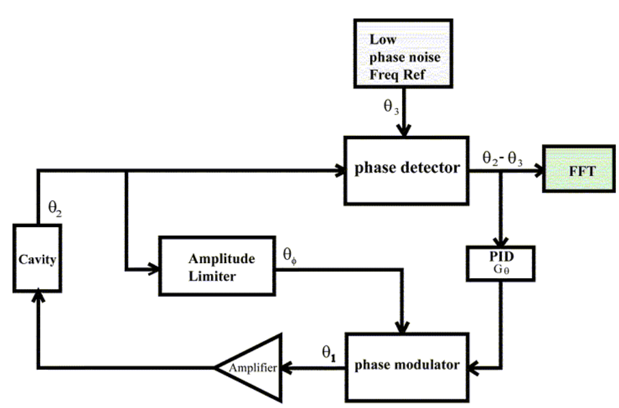

Figure 4: Schematic of phase noise circuit.

Fig. 5 shows the phase noise spectra of Cavity 2 under different feedback conditions. The different spectra show the suppression of phase noise below the regulation bandwidth when the phase loop is closed. The spectra also show the characteristics of various noises in the RF system. The broad band centered at around 4 Hz is due to cavitation boiling of liquid helium. A sharp peak at 15 Hz is the mechanical resonance of the push-rod of the tuner. Some broad band noise is evident at 50 Hz due to the cooling fans in the power amplifiers, and the noise centered around 75 Hz is the fundamental vibration mode of the center resonator.

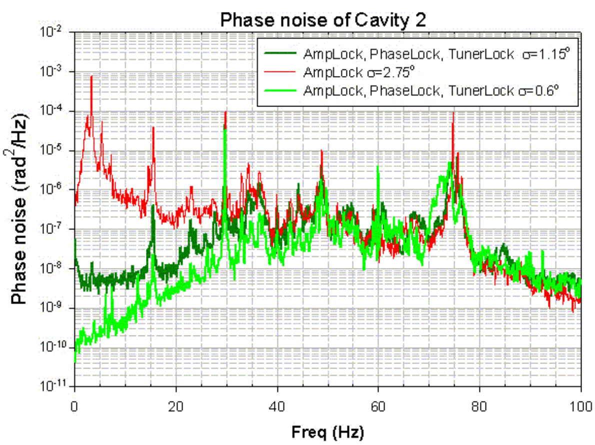

Figure 5: Phase noise spectra for cavity 2 in SCB3 during recent cold test.

LN2 Cooled Coupling Loop: Initial cavity studies at TRIUMF were done with a coupling loop designed at INFN-Legnaro suitable for operation with lower gradients and lower forward power. Tests at higher power indicate an unacceptably large amount of power is deposited at 4°K. A new coupler has been developed[3] that reduces the helium load to less than 0.5 W at the design gradient of 6 MV/m and $P_f = 200$ W. The coupler has a stainless steel body for thermal isolation and a copper outer conductor and rf feed line cooled with LN2. Cooling of the inner conductor is achieved by adopting a thermally conducting Aluminum Nitride dielectric localized in the coupling loop. Thermal radiation from the uncooled rf drive cable is intercepted by an LN2 cooled copper tube.

Mechanical Tuner: A high resolution mechanical tuner[4] has been developed. The tuning plate is actuated by a vertically mounted permanent magnet linear servo motor, at the top of the cryostat, using a 'zero backlash' lever and push rod configuration (Fig. 6) through a bellows feedthrough. The system resolution at the tuner plate center is $\sim 0.055\mu$m (0.3 Hz). The tuning plate is radially slotted and formed with an 'oil can' undulation to increase the flexibility. The demonstrated dynamic and coarse range of the tuner are ± 4 kHz and 33 kHz respectively. The demonstrated mechanical response bandwidth is 30 Hz. Amplitude and phase regulation can be maintained for eigenfrequency changes of up to 60 Hz/sec.

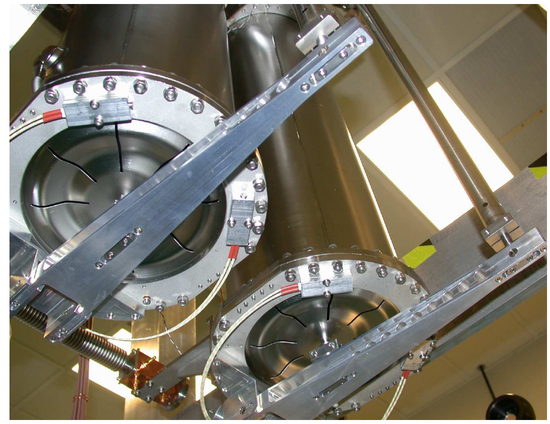

Figure 6: Photo of tuning plate and tuning lever mechanism.

MEDIUM BETA CRYOMODULE

The vacuum tank consists of a stainless steel rectangular box and lid. All services and feedthroughs are located on the lid. The entire cold mass is surrounded by a forced flow, liquid nitrogen cooled, thermal shield. The shield consists of several Cu panels riveted together to form a box with Cu tubing soldered to the panels to form a serial LN2 circuit that also cools the coupling loops. A μ-metal magnetic shield, consisting of 1 mm Conetic panels is attached to the inside of the vacuum tank outside the LN2 shield. A single LN2 panel and μ-metal shield suspended from the lid make up the top thermal and magnetic enclosure respectively. The μ metal is designed to suppress the ambient field by a factor of twenty. Cavities and solenoids are suspended from a common support frame itself suspended from the tank lid (Fig. 7). Each cryomodule has a single vacuum system for thermo-isolation and beam acceleration. This demands extreme cleanliness of internal components and precludes the use of volatile lubricants and flux, as well as particulate generators, to avoid superconducting surface contamination. Assembly is done in the new ISAC-II clean room. The cavities must be aligned to within 0.4 mm and the solenoid to 0.2 mm. A wire position monitor (WPM)[5] system has been developed to monitor the position of the cold mass during thermal cycling.

CRYOMODULE TESTING

The cryomodule assembly and commissioning tests are conducted in the clean laboratory area in the new ISAC-II building. Single cavity cold tests in a small cryostat confirmed the initial cavity parameters. An EPICS based control interface is used to interact remotely with the cryomodule systems during the test. Two cryomodules SCB3 ($\beta = 0.071$) and SCB1 ($\beta = 0.057$) have been assembled and tested to date.

Alignment-SCB3 The position of the cold mass as monitored by the WPM at three cold LN2 temperatures is repeatable to within $\pm 50\mu$m vertically and $\pm 100\mu$m horizontally. Due to the different materials involved the solenoid

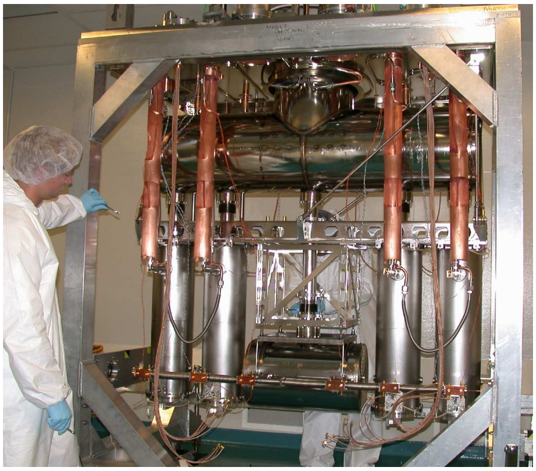

Figure 7: Cryomodule top assembly in the assembly frame prior to the cold test.

experiences more vertical contraction, with 4.4 mm at LN2 and 5 mm at LHe temperatures while the cavities contract 3.3 mm at LN2 and 3.8 mm at LHe temperatures. For beam dynamics reasons we require the cavity beamport centerline to be 0.75 mm below the beam centerline as defined by the solenoid. Cold tests I and II results show that final alignment is achieved by aligning the cavities while warm to (0,0,0,0) horizontally and (+0.28,+0.38,+0.38,+0.28) vertically with the solenoid at $(x, y) = (0, 0)$. Optical targets are then placed in the upstream and downstream solenoid bore for cold test III. The beam axis is defined by optical targets on the beam aperture of the tank. Adjusters located on the lid are used to align the solenoid targets to the beam axis targets after cooling the cold mass.

Cryogenics The helium transfer line fits to a manifold in the helium space that delivers helium in parallel to a series of 3 mm tubes that are routed to the bottom of each of the cold mass elements. This system works well to efficiently cool the cryomodule. At a total flow of 75 ltr/hr the cavities cool together at a rate of $100°$K/hr while the solenoid cools at a rate of $20°$K/hr due to its larger mass. The measured static load for SCB3 and SCB1 is 13 W each and compares well to estimates during the design phase. The LN2 flow required to keep the side shield less than $100°$K is $\sim 5\ell$/hr matching design estimates.

RF Tests The cavities are first baked at ∼90°C for 48 hours. LN2 is then fed through the side-shields and the cold mass is cooled by radiation for at least 48 hours to bring the average temperature to about 200K before helium transfer. The cavity Q_0 values are similar to those measured in the single cavity cryostat indicating that the μ-metal reduces the remnant magnetic field to a sufficient level. On two of the cold tests we have had problems with one or more cavities having an open connection on the rf feed. These open connections close after warming. The hypothesis is that the thermal contraction on cooldown is responsible for the open circuit. For simplicity we run the LN2 as a single series circuit with the side shield cooled at the same time as the coupling loops. This means that after the bakeout is complete the coupling loops can go through a large temperature excursion as the side shields are cooled. Our analysis shows that the problems with the rf feed lines have developed when the coupling loops were brought quickly (1-2 hours) from 360K to 80K. The procedure now is to regulate the LN2 flow to slow the cooldown rate.The rf cable design is also being reviewed.

In a standard cryomodule rf test all cavities are powered and locked to the ISAC-II specification; $E_a = 6$ MV/m, $E_p = 30$ MV/m, $f = 106.08$ MHz, β=200, $P_f = 200$ W. This checks not only the cavity but also the coupling loops, tuners, amplifiers and rf controls. In the most recent test cryomodule SCB3 was moved to the accelerator vault and tested in situ with the helium refrigerator in closed loop and final cabling from the final dedicated control units and supplies. Due to the rf feed problem mentioned above only three of the four cavities was operational. However the three cavity systems were powered and locked in ISAC-II specifications for a successful 24 hour test.

Solenoid and Remnant Field

Each cryomodule is equiped with a 9 T solenoid. The solenoids are equiped with bucking coils to reduce the fringe field in the vicinity of the adjacent cavities to less than 40 mT[6]. The solenoid ran up to 9 T without quenching the adjacent cavities. When the solenoid is ramped up to 9 T and then ramped to zero there is still significant frozen flux in the solenoid. If the cavities are warmed above transition and then cooled this frozen flux significantly reduces the performance of the cavities. If the solenoid is taken through a de-gaussing cycle before being turned off the fringe field from the frozen flux is reduced. The frozen flux can be quenched by warming up the solenoid above transition. Operating the solenoid can magnetize the mu-metal. In order to reduce the impact on performance the solenoid should be de-gaussed by cycling the current through zero, reversing polarity and raising the current to half the initial value and repeating until the current is less than 1% of the initial value.

Acceleration Tests

The first acceleration of ions with superconducting rf at TRIUMF/ISAC was in Nov. 2004 [7] with alpha particles from a radioactive source. The source was positioned just upstream of the cryomodule and the 5.8 MeV alphas were introduced through a thin Kapton window. The window degraded the initial energy to 2.8 MeV. The particles were accelerated through the ISAC-II medium beta cryomodule and the final energy was measured with a silicon detector in a downstream diagnostic box. The maximum energy of 9.4 MeV is within 6% of the expected energy for the four cavities operating at the ISAC-II specified gradient of 6 MV/m (E_p=30 MV/m).

In the most recent test cryomodule SCB3 was moved to the accelerator vault (Fig. 8) and tested in situ with the helium refrigerator in closed loop. The test allowed us to operate the cavities in the vault environment and with the final cabling, control systems and power supplies. The configuration was identical to the planned installation with the exception that temporary transfer lines were used for this test. As mentioned only three cavities of four were operational due to a rf cable problem.

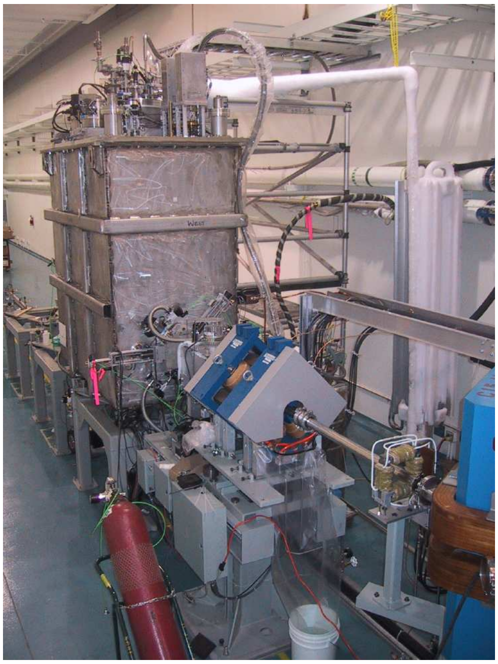

Figure 8: SCB3 in the vault during the beam test.

The tuner on-line performance was measured by altering the cavity frequency by forced variations of the helium pressure. The pressure variation was initiated by changing the speed of the main compressor. Three cavities were on and locked and remained locked during the excursion which corresponded to the equivalent of 300 Hz eigenfrequency swing. Fig. 9 shows the helium pressure and associated tuner position throughout the pressure excursion.

A 26Mg6+ beam at 1.5 MeV/u was delivered from ISAC through the S-bend transport system and tuned through the cryomodule. The superconducting solenoid was set to the theoretical field strength. A beam profile monitor and Faraday cup in the downstream diagnostic box were used to optimize the beam and a silicon detector was used to measure the final energy. The three operating cavities were turned on and phased sequentially. The final spectra of the unaccelerated beam plus the spectra after each cavity is turned on is shown Fig. 10. Assuming a synchronous phase of $\phi_s = -25°$ the three operating cavities give a total voltage gain of 3.6 MV corresponding to an average gradient of 7.4 MV/m and a peak surface field of 37 MV at 7 W per cavity.

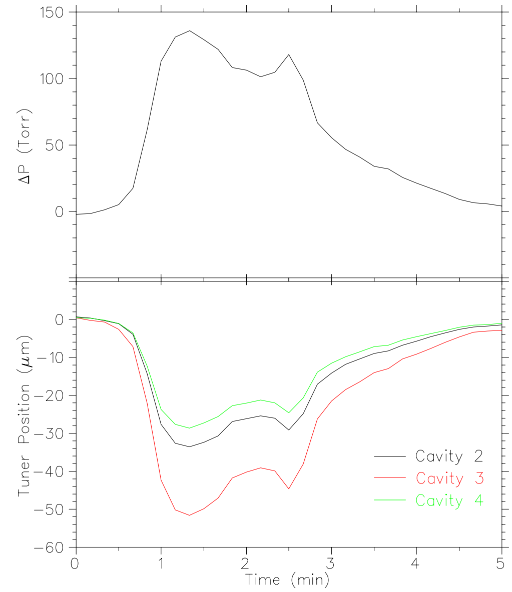

Figure 9: On-line tuner position response to a pressure excursion in the helium space due to mode switching of the refrigerator. The tuner signal from three cavities locked at 6 MV/m are displayed.

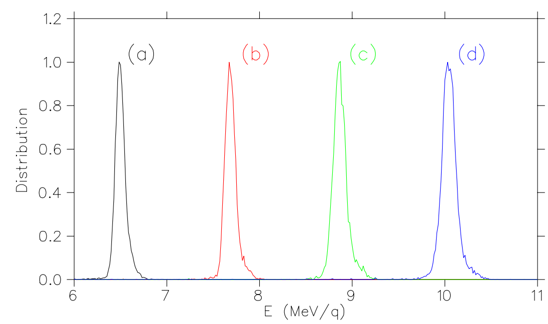

Figure 10: Energy spectra of 26Mg6+ beam. Shown are the spectra of the injected beam and the spectra after turning on and phasing three cavities sequentially.

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