UPDATE ON RF SYSTEM STUDIES AND VCX FAST TUNER WORK FOR THE RIA DRIVER LINAC*

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Abstract

The limited cavity beam loading conditions anticipated for the Rare Isotope Accelerator (RIA) create a situation where microphonic-induced cavity detuning dominates radio frequency (RF) coupling and RF system architecture choices in the linac design process. Where most superconducting electron and proton linacs have beam-loaded bandwidths that are comparable to or greater than typical microphonic detuning bandwidths on the cavities, the beam-loaded bandwidths for many heavy-ion species in the RIA driver linac can be as much as a factor of 10 less than the projected 80–150 Hz microphonic control window for the RF structures along the driver, making RF control problematic. While simply overcoupling the coupler to the cavity can mitigate this problem to some degree, system studies indicate that for the low-β driver linac alone, this approach may cost 50% or more than an RF system employing a voltage controlled reactance (VCX) fast tuner. An update of these system cost studies, along with the status of the VCX work being done at Lawrence Livermore National Lab is presented here.

INTRODUCTION

The Rare Isotope Accelerator, as it is presently envisioned, is a heavy-ion accelerator capable of efficiently accelerating all stable or near-stable isotopes from protons to uranium. To meet the nuclear physics objectives of producing proton- and neutron-rich nuclei far from stability, the machine would be used to drive either heavy nuclei into a fast-fragmentation target or protons into an isotope separator on-line (ISOL) target. The specification of 1 puA of 400 MeV/nucleon U-238 on target is needed to obtain the largest isotope range out of the fragmentation target and is limited by the current available from an electron cyclotron resonance (ECR) source. Using protons to drive the ISOL targets bounds the light end of the ion spectrum and requires the cavities to accommodate a very large velocity range and acceleration rate. By utilizing short, low-frequency RF cavities between 57–345 MHz on independently-phased RF generators, large cavity velocity acceptances can be realized. This is achieved by using a combination of superconducting accelerating structure types that are common to the heavy ion superconducting RF (SRF) accelerator community and span quarter-wave, half-wave, and spoke, as well as elliptical, cavities [1]. The combination of light and varying beam loading (~10's–100's of uA) and very high cavity quality factor ($Q \sim 10^9$) provides an engineering challenge as how one can most efficiently couple RF power into the cavities, thereby minimizing capital and operating costs.

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RF CONTROL REQUIREMENTS

In any RF accelerator, it is desirable to optimally and efficiently couple RF energy into the beam-loaded resonator. In normal conducting accelerators, the power dissipated in the cavity walls plays a significant role in setting the loaded Q_l bandwidth of the cavity, since these losses are generally comparable to or greater than the beam power in the cavity. In superconducting accelerators, the extremely low loss and resulting high unloaded Q_0 of a cavity changes the RF control situation appreciably. The first consequence is that even modest beam current completely dominates the Q_l bandwidth of the structure. The second consequence is that the cavity is vulnerable to slight mechanical deformations that can appreciably change the resonant frequency of the cavity. Since superconducting niobium cavities are typically made of high-purity niobium sheet metal, this makes them prone to micro-scale deflections from vibrations, cryogenic pressure variations, and ponderomotive detuning.

For beams where the current is appreciable (>1 mA), setting the RF coupler for matched coupling to the beam results in a loaded cavity bandwidth of many 100's of Hertz or more. Bandwidths in this range are usually sufficient to mask the effects of microphonic detuning on a cavity. When beam loading becomes lighter (~10's to 100's of uA), the matched beam-loaded bandwidth becomes comparable to or less than the bandwidth of the microphonic excitations. This leads to significant low-level RF control problems since the cavity resonant frequency is moving around the linac set point frequency by multiples of a cavity resonant bandwidth.

To maintain stable accelerating voltage in the cavity, three basic strategies are available: 1) Beam-match couple to the cavity and attempt to adapt to the microphonic-driven detuning by rapidly driving in increased generator power when the cavity detunes in a localized microphonic excursion; 2) greatly overcouple the cavity beyond beam match with the drive coupler to increase the bandwidth; or 3) try to reduce the microphonic-driven detuning bandwidth directly. The first two approaches result in wasted RF power and larger capital costs for installed capacity, while the third requires some sort of fast tuner. The situation is shown graphically in Fig. 1 for a 345-MHz two-gap spoke resonator. The case where the cavity is overcoupled would be for a Q_x a factor of 10 below ~1.3x10^7, and for the beam-match coupled case the dashed curve would be the generator power needed to maintain cavity fields with microphonics.

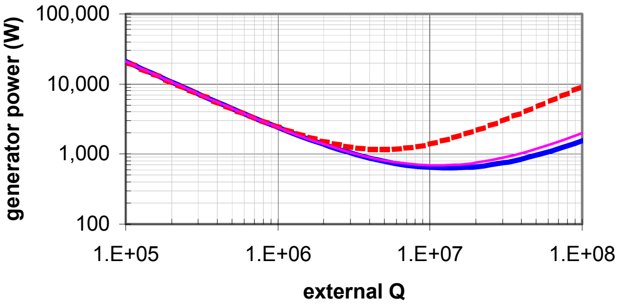

Fig. 1. Plot shows the RF generator power needed t maintain cavity fields at the desired level for a 345–MH spoke cavity with 413 uA of beam current. The uppe dashed and lower light-weight line indicate the powe needed for minus and plus 40 Hz of microphoni detuning, respectively. The heavier solid bottom curve i for beam-induced detuning as well as the fast-tune compensated microphonics case.

Microphonics

The issue of what constitutes a reasonable microphoni window is rather complicated and difficult to establisł On lightly beam-loaded heavy-ion superconducting accelerators like ATLAS, control windows for microphonics are quoted as being around 150 Hz [2]. Discussions at recent workshops [3][4][5] have indicated that while measured microphonic excursions by a given cavity may only be 5–15 Hz, having a factor of 10 on the overall control window for the system of cavities on the linac is necessary, since the actual spread of detuning across a distribution of cavities will be larger than it is for a singular cavity. This methodology of having a modest actual detuning range, multiplied by a margin factor, shall be used for the comparisons presented in this paper.

RF SYSTEM LAYOUTS AND COST BASIS

Two conceptual RF system designs were developed for comparison purposes. The first system used overcoupling to increase the bandwidth to ameliorate the effects of microphonics. The second used some form of fast tuner to significantly reduce the microphonic-induced detuning window.

In the assessment, components were chosen appropriate to the operating conditions anticipated. In the overcoupled case, transmission lines, power couplers, and circulators needed to handle infinite voltage standing wave ratio (VSWR) conditions on a continuous wave (CW) basis. This case also required larger RF amplifiers to drive the system. The fast-tuner system was similar, except the overall system power was substantially less, thereby lessening the power handling requirements on these components and decreasing the generator size. The fast-tuner assembly and impacts on the cryogenic system were also taken into account.

The conceptual designs for the respective RF systems were significantly affected by the large variation in component choices between the 500 W and 20 kW power ranges. A survey of four companies was carried out to determine component prices, which were used to establish a credible representative market price for each system. Fig. 2 shows the variations average cost in CW RF amplifiers at low power. The staircase effect suggests one would like to choose amplifier sizes to maximize cost efficiency. Fig. 3 shows how the data extends to higher power ranges using a more conventional dollar-per-Watt metric.

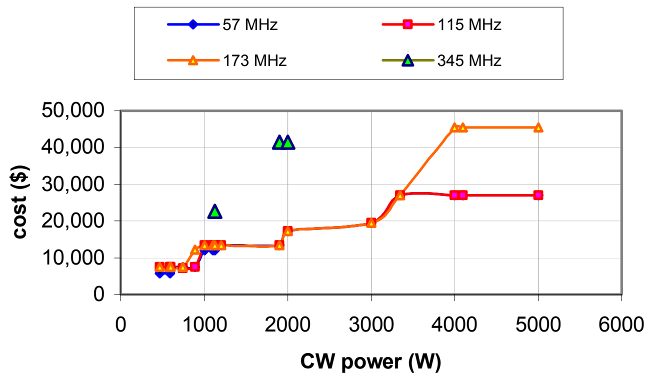

Fig. 2. Cost data for narrow-band RF amplifiers as a function of output power. The amplifiers were either Class A or AB.

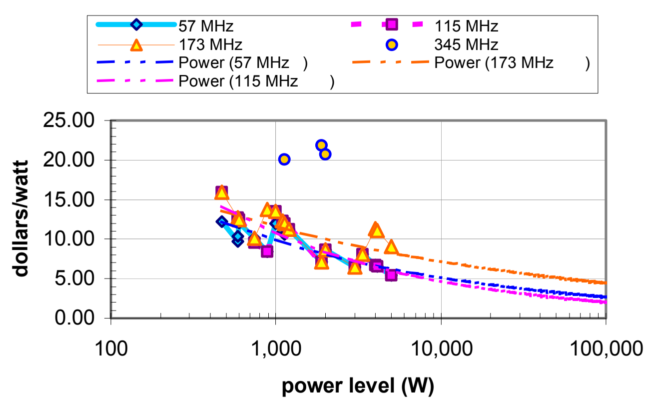

Fig 3. Cost data expressed in dollars per Watt as a function of power level. Power-function fits show how the data scales to higher power values consistent with \$3–5 /Watt.

COST COMPARISONS

Applying the cost data to the two RF architecture concepts, a cost comparison was done between fast-tuning and overcoupling-compensated microphonic cases. Table 1 shows that utilizing a form of fast tuning can reduce the installed RF power required by as much as a factor of 3 and reduce the capital cost by a factor of 1.5, potentially saving on the order of 6 million dollars.

Cavity Type	Overcoupled Case		Fast-Tuner Compensated	
low β (MHz)	installed RF power (W)	section cost (k$)	installed RF power (W)	section cost (k$)
57.5	160,000	2,155	30,000	1,160
115	225,000	2,424	45,000	1,576
172.5	520,000	7,522	104,000	3,642
345	160,000	5,508	160,000	5,098
totals:	**1,065,000**	**17,609**	**339,000**	**11,476**

Table 1. Results of a cost comparison exercise between overcoupled and fast-tuner compensated approaches for handling microphonic detuning on the low-beta section of the RIA driver linac. In the 345–MHz case, while the installed power is the same, the costs differ since the RF match is better, resulting in lower VSWR operation.

Evaluations were also made on the impacts of using fast tuning on the elliptical cavity portions of the linac, which indicate a potential reduction in installed RF power of a factor of 5.1, and a cost savings on the order of 11 million dollars could be realized. Further development would be needed to extend the present work to 805 MHz elliptical cavities.

FAST TUNING

The potential for appreciable cost savings using fast tuning on the RIA driver linac, combined with improved efficiency of the machine resulting from better coupling, is motivating work on advancing the design of the voltage controlled reactance (VCX) fast-tuner concept that was originally developed and applied on ATLAS at Argonne [6]. The original Argonne approach utilized 10 PIN-type RF-switching diodes combined with lumped inductive and capacitive elements, all immersed in liquid nitrogen, to change the reactive impedance of the cavity to effect a rapid change in the resonant frequency of the system of the cavity plus tuner. By switching the PIN diodes from full conduction to full isolation at 25 kHz, the desired precise accelerator frequency can be approximated by the vector sum of the cavity voltages corresponding to the on and off state of the tuner. To compensate the observed microphonic detuning windows on ATLAS, 15–20 kVAR (voltage-ampere reactive) of reactive power was switched.

This approach has worked for over 20 years on ATLAS at up to 97 MHz. To extend the technology to higher frequency and reactive power ranges, a different design approach is being developed and evaluated that utilizes distributed inductive and capacitive elements in a transmission-line configuration, but keeps the same proven lumped-element, high-power PIN diodes used originally. The new configuration offers the possibility of being more broadband for higher frequencies than an approach relying on lumped elements and is also potentially extendable to switching reactive power levels up to75–100 kVAR by readily adding larger numbers of PIN diodes. A drawing of the distributed element approach being investigated is shown in Fig 4.

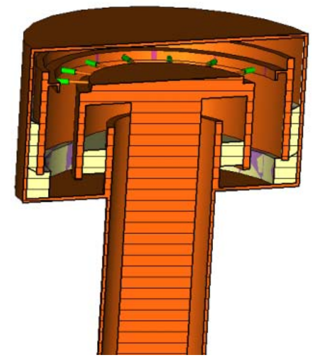

Fig 4. Drawing of a distributed element approach for a high-frequency VCX. The light components are ceramics acting as capacitors, and the PIN diodes are the circumferentially distributed cylinders. The region where the PINs are located would be filled with liquid nitrogen.

CONCLUSIONS

The light beam loading conditions envisioned on the RIA driver linac offer unique challenges and opportunities in efficiently coupling RF power into superconducting cavities. Studies have shown that appreciably less installed RF power is needed when a fast tuner is used to compensate microphonics. This benefit is motivating work on advancing the design of a higher frequency, higher power version of the original VCX tuner concept used on ATLAS.

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