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RF SYSTEM FOR THE INDIANA UNIVERSITY CYCLOTRON FACILITY COOLER PROJECT

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# Summary

The IUCF will take 200 MeV Particle beams from the cyclotron and lower their emittance via electron cooling. A further use for the Cooler is to increase the energy of the particles; it is proposed to accelerate protons to 500 MeV. The RF system for the Cooler must provide the voltage for acceleration, and also maintain the bunch structure to enable 'time of flight' experiments. The main RF system contains a cavity salvaged from the PPA which has been revised to operate from 6 to 20 MHz. as a bias tuned structure and also from 1.7 to 5 MHz. A UHF cavity tunable from 440 to 460 HMz. provides 40 Kv. for tight bunching.

This paper describes these cavities and the low level system which synchronizes the RF with the Cooler magnetic field. Provision is made for fast coherent digital phase control.

# Introduction

The purpose of the Cooler is to examine low cross section reactions at and above the cyclotron output energy. With a RF resolution of 1 Hz., experiments using cooled beams are enabled to 10 KV. resolution.<sup>1</sup>

## The RF Buncher/Accelerator Cavity Resonator

We have acquired one of several dual gap, ferrite tuned cavity resonators, originally constructed for the Princeton-Pennsylvania Accelerator, for the Indiana University Cooler Project. To cover the 2-32 MHz tuning range required then, two different ferrite tuned resonators were employed; one for 2-6 MHz and the other for 6-32 Mhz. The 6-32 MHz. circuit consists of 4 quarter-wave ferrite loaded tank circuits connected as two separate half-wave cavities, the two then connected in parallel so that the electric vectors at both gaps are series aiding. The parallel RF connection also provides a series D.C. connection for biasing the ferrite in all four quarter-wave tank circuits. Initial tests, using signal generator level RF and a stand-by 2000 Amp. D.C. power supply for ferrite bias showed that a 4500 Amp. power supply would be necessary to operate over a 6-20 MHz frequency range. At 4th harmonic, protons may be accelerated from 100 to 500 MeV between 6 and 10.5 MHz, or, at 7th harmonic the acceleration range extends from 30 to 500 MeV between 6 and 18.4 MHz. A push-pull RF power amplifier was designed to use 4CW2000A Eimac power tetrodes, and a transistor driver amplifier module was purchased from ENI.

A block diagram of the RF system, Fig. 1, was developed while the driver and final amplifier subassemblies were completed and bench tested. Also, at this time, many components of low level electronics were prototyped and bench tested. Next, the amplifiers, power supplies, and some low level modules were assembled as a test station, and connected to the cavity for initial tests, still using the stand-by power supply, from 6-15 MHz. The Push-Pull 4CW2000A Final Amplifier was mounted directly on one of the two half-wave resonator sections of the dual Cavity. The initial tests were generally satisfactory; some debugging and calibration of the maximum available output voltage resulted.

By this time, the output voltage requirements had been upgraded upward so that, at some energies, the maximum available gap voltage appeared marginal. At a saturated power level, the optimum load resistance for 4CW2000A is approximately 1700 ohms/plate; the early low level tests had located this resistance at 7.2 MHz. where for,

Pout ≈ 3.5 Kw. (two tubes)

Vout = 
$$\sqrt{(7000 \times 3400)}$$
 = 4880 volts/gap

= 9760 volts/turn

The full power tests also revealed a lower Q than for the low level tests degrading,

Vout ≈ 7000 volts/turn.

Even though Q increases somewhat with increasing frequency, the inductively tuned, resonator circulating current varies directly with frequency. At 20 MHz., plate to plate  $\rm R_L$  had decreased to 790 ohms. Since the 4CW2000A tetrodes are current sources,

at 20. MHz, Vout 
$$\approx 1.5 \times 790 = 1185$$
 volts/gap

= 2370 volts/turn

Adding a small inductance in series with the resonator, to improve the load impedance match was tested first with the SPICE computer program, Fig. 2. which shows that a series L=1.0 uHy optimizes the impedance match at 20 MHz. However, this inductance resonates with the output capacitance of the tube at  $F \approx 30$ MHz., significantly enhancing the 2nd harmonic distortion at 15 MHz. Reducing the series L to 0.6 uHy inductance moves the 2nd harmonic to 41 MHz. (out of band) and,

## Vout = 4000 volts/turn.

The SPICE computer program was also used to develop an approximate equivalent circuit for the Cavity, Fig. 3, and to verify the response of the many wave filters designed for the System. To develop more than 4000 volts per turn at higher frequencies, the 4CW2000A Amplifier could be duplicated, and mounted on the 'other side' of the dual cavity structure. To find out whether doubling the RF power would increase the output voltage approximately 1.4 times, one of the two parallel connected cavity sections was disconnected. All of the amplifier power, delivered to one half-wave cavity, produced the expected voltage gain.

The 6-20 MHz. tuning range accomodates harmonic numbers, h>4. Adding capacitance, optionally, to the four quarter-wave resonators, enables approximately 3.333:1 tuning ranges at lower frequencies. This feature is implemented; four 3000 pf vacuum capacitors switched in shunt with the resonators enable a tuning range from 1.7-5.7 MHz. These capacitors are switched in or out of circuit by Jennings vacuum switches to shorten bandswitching delays and to extend the life of the vacuum variable capacitors. The capacitors are variable to optimize output voltage against frequency range because capacitively loaded tuning also requires additionsl RF power for a given output voltage. The bandswitching feature is provided to accomodate harmonic numbers, h<3.

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#### Low Level RF

In the case of running very low intensity polarized beams ( $I/\beta < 4 \mu A$ ), beam position feedback control of RF frequency is difficult so the signal source needs to run on an open loop basis. One of the approaches explored is a synthesized frequency source.

#### Direct Digital Synthesis

Direct digital synthesizers can switch frequencies at a very high speed (~1 $\mu$ S). Many types can also sweep over a wide frequency range (e.g. from 0.1 Hz to 30 MHz) with phase and amplitude continuity. Prototype modeling, however, found that modulations due to phase and amplitude quantization need to be considered carefully.

DDS works on a digital sampling principle in which the sine value corresponding to a designated phase angle is picked from a ROM table and then converted to analog voltage by a fast DAC. If the phase increment between samples is  $\Delta\phi$  and the time interval of sampling is  $\Delta t$ , then the frequency is  $\Delta\phi/\Delta t$ . Since the precision of the sine value is limited by the number of bits the digital circuit can handle, there are various non-harmonically related spurious spectrums due to truncating.<sup>2</sup>

The number of discrete sine values stored in the ROM covering  $2\pi$  radians in many models is 512. To increase this number, the resolution or word length of the ROM has to increase also, which is not easy at high sampling speed. For a synthesizer with 9 bits of ROM, samples are computed at  $2\pi/512$  intervals. Phase accumulation is achieved by adding the phase increment information (which also determines the frequency) repeatedly into a phase accumulation register. In order to obtain frequency steps smaller than  $\Delta \omega = (2\pi/512)$  f, where f is the sampling clock frequency, the adder and the phase accumulation register is made much longer than the ROM. This is equivalent to ignoring the bits beyond number 9 of the sine value corresponding to an angle. A negative systematic phase error is thus introduced. This phase error grows in time but when it reaches  $2\pi/512\,,$  a carry from the lower phase accumulator bits enters the ROM, adding an additional phase increment of  $2\pi/512$ . This accumulation of systematic phase error and compensation results in a PM whose rate can be very low, generating closely spaced sidebands around the carrier (Fig. 4). Generally if a direct table look-up DDS has m bits of ROM and n bits of accumulator register, the slowest PM frequency due to this effect is f/2n-m, where f is the sampling clock frequency. The maximum amplitude of the sidebands are bounded by phase error allowed. In the models we tested they are about -48dB with respect to the carrier. If we set the top 9 bits of phase accumulator only and reset the rest of bits to zero, all phase accumulation data are directly addressed to the ROM table so the corresponding frequencies do not have this effect. The close-in sidebands due to other errors are noticibly smaller (Fig. 5).

There are concerns, therefore, that the repeated RF angular modulation may in time excite synchrotron oscillation whose amplitude is large enough that  $\Delta p/p$  of the beam exceeds the momentum acceptance of the machine. Quantitative calculation of this effect is underway.\*

#### Other Frequency Sources

Among other synthesier technologies, "Fractional-N" PLL technique uses a single loop structure and can vary frequencies with phase and amplitude continuity over a wide range. Although "Fractional-N" involves phase error accumulation and compensation, too, the error is limited to the digital circuit and compensated before reaching the PLL VCO.<sup>3</sup> The non-harmonically related spuriouses can thus be lower, over 70 dB.<sup>4</sup> While its switching speed is too slow to allow sweeping of complicated patterns, it should perform well for our CW operation.

# The UHF Buncher Cavity

A cylindrical cavity resonator, Q approximately 10000, has been designed for higher frequency bunching in The Cooler; more specifically to preserve the main injector cyclotron bucket size during stacking. This cavity would operate nominally at 450 MHz. and 40000 volts. While this may turn out to have been somewhat premature, a 1500 watts PEP Cavity Amplifier for Final and a 300 watts Cavity Amplifier for the Driver were purchased from Eimac. Both Amplifiers are grounded-grid configured with common frequency from 430 to 470 MHz. The 80db UHF Power train also includes a 25 watts broadband transistor amplifier The frequency source for this Buncher would be integer harmonics of the Cooler RF range (typically Cyclotron RF/2). Since the maximum frequency of the Cooler is specified at 20 MHz., the integer harmonics will be separated by up to 20 MHz. The design specification for UHF tuning range is 440-460 MHz., and for 5-20 MHz of the Cooler RF range, the harmonic numbers, n, of interest are,

#### 23≤ n ≤88.

Initially, the Cavity design avoided ceramic windows because 40000 volts at 450 MHz. in ceramic yields too little shunt impedance. If a ceramic window can be positioned where there is little or no electric field then the possibility of separating a tuning section in air from the acceleration region in vacuum seems likely. The design eventually focused on a half-wave cylindrical resonator with a tuning and acceleration region separated as required by a cylindrical ceramic window. The ceramic chosen for this window is a salvaged vacuum insulator from an Eimac 4CW100KE power tetrode; not the best of all possible shapes, but it is available. Elaborate modelling of this Cavity design, using the SUPERFISH computer program and data from Eimac for their 4CW100000E insulator, suggests less than 900 watts total for 40000 volts. A quarter-section TEKPLOT view of this design is shown in Fig. 6. Approximately 0.6 of the output voltage, and 0.4 of the power develop across the ceramic window; a more efficient design could be developed around a customized ceramic window. The cavity is tunable, also according to SUPERFISH, from 433-461 MHz. by a cylindrical tuner which alters the maximum radial dimension of the tuning region by moving axially through one of the radial side walls over most of the axial width dimension. Instrument specialties spring finger contacts complete the circuit to and from the sliding tuner. A design sketch is shown in Fig. 7.

\*Much of the information on RF effect on beam dynamics was generated from discussions with T. Ellison, engineer of beam diagnositics of IUCF.

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Fig. 1











Fig. 6 A 1/2 section Superfish Model of the UHF Puncher Resonator