MULTIPACTING RELATED PROCESSES AND RF BREAKDOWN PROTECTION BY USING BIAS PULSING AT THE NEVIS SYNCHROCYCLOTRON *

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ABSTRACT

Instantaneous DC conduction currents of biased electrodes during multipacting were measured and multipacting related processes are discussed. It is shown that by pulsing the dee bias instead of keeping it steady, several important advantages may be gained with respect to RF amplitude buildup and discharge prevention and quenching. The breakdown protection system using bias pulsing in operation at the Nevis Synchrocyclotron is presented.

1. Introduction

Theoretical and experimental investigations[1)2)3)], along with testing and cyclotron operation[4)5)6)], have brought up several methods for avoiding or alleviating multipacting effects. Not all of them are readily applicable for synchrocyclotrons. Breaking through multipacting with fast rising RF only is nearly impossible. Keeping the frequency RF gap product out of the 70 to 10,000 MHz cm range, either by design or by extensive electrical baffling[3)] is either incompatible with the extension and disposition of synchrocyclotron resonating structures, or onerous. Baffling is practical only as a locally limited correction.[7)] There are generally other constraints which determine dee gaps. Figure 1 shows the shape and dee-to-ground gap distributions for the Nevis machine resulting from these and additional constraints for accommodating sector focusing irons.

It would seem that for synchrocyclotrons, the most convenient method for alleviating multipacting effects is electrode biasing. Most synchrocyclotrons have designs which provide bias to the electrode structure in vacuum in straightforward ways. (There is no solid grounding of the dee when there are no fixed RF voltage nodal lines.)

Bias alters the stability conditions of multipacting, changes its character but can introduce some side effects.

2. Multipacting and Electrical Currents in Biased Gaps

2.1. Excitation of Bilateral and Unilateral Multipacting

Bilateral multipacting is the best known form of multipacting: Under certain conditions of RF voltage, frequency and electrode separation, a resonant electron multiplication appears as a result of phase correlated successive impacts and secondary

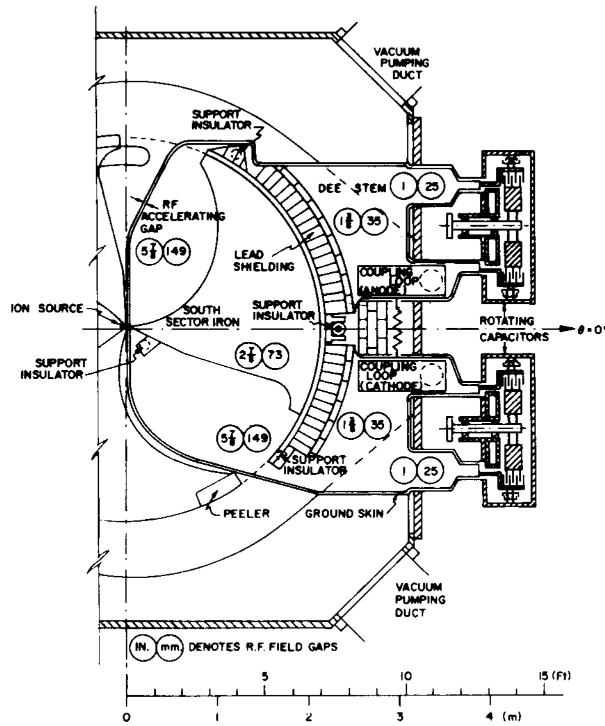

Fig. 1 Dee structure and gap distribution

emission on the two opposing electrode surfaces. If φ_{12} and φ_{21} are the flight angles of electrons in the two directions of motion, then

$$\varphi_{12} + \varphi_{21} = 2\pi \quad . \tag{1}$$

With no bias, we must have $\varphi_{12} = \varphi_{21} = \pi$; i.e., the flight time is half at the RF period for the first order multipacting (and odd multiples of T/2 for higher orders). Unilateral or one electrode multipacting may appear only in biased gaps: Electrons emitted at appropriate phase angles of the RF voltage can be decelerated by the bias field and return to the originating surface without reaching the opposite electrode. The resonance condition may be written in the same form (1), if subscript #2 refers to the return point. In the case of multipacting with bias, electrons impact the negatively biased electrode with smaller kinetic energy than the grounded electrode. For ordinary bias and synchrocyclotron gaps more secondary electrons are produced at the surface of the grounded electrode than at the dee surface. This is especially obvious if one considers the unilateral mode.

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2.2. Carrier Generation and Convection Currents

DC currents in biased multipacting gaps may appear as a result of electron "spattering" and residual gas ionization. Electrons emitted at phases and with initial velocities not matching multipacting resonance conditions become available current carriers "leaking off" after one or more RF cycles. Most of them are secondary electrons generated either by the multipacting process itself or by ion bombardment.

Ions can be produced by electrons hitting residual gas molecules or molecules absorbed on electrode surfaces. Carrier generation and the corresponding convection current may constitute an indication for the multipacting intensity and loading and can be used even for building efficient electron guns.[8] Space charge may also develop. Figure 2 shows instantaneous currents measured in the bias circuit of the Nevis Synchrocyclotron for a steady 2 kV negative bias and 28 MHz RF pulses of 500 μsec. The nonuniform gap structure (Fig. 1) and voltage distribution (~ $\lambda/2$ resonance) makes the overall process rather complex, but one can see that an increase in the dee maximum voltage (in our case, from 15 to 24 kV) results in a strong decrease in the "DC" current. At turn-on and turn-off, we have sharp current increases indicating passage through important multipacting zones at lower RF voltages. The transition time through these zones is longer at turn-off and the corresponding peaks are higher than those at turn-on; the carrier generation process has more time to build up there.

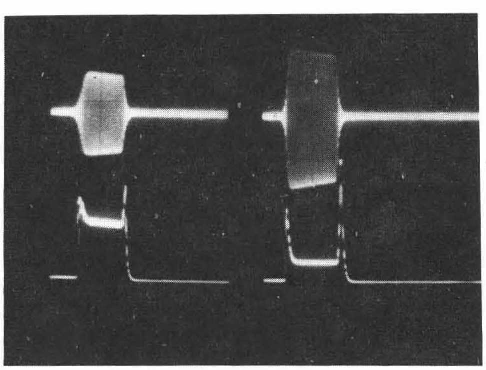

Fig. 2 Correlation between RF voltage (upper trace) and instantaneous convection current (lower trace)

In complex resonators, several RF voltage zones with intense multipacting are possible and the situation becomes even more complicated when the RF frequency is swept. Instantaneous bias current measurement has proven to be a very useful diagnostic method.

2.3. Discharges and the RF Rectification

Except for very small gaps (as those in the rotating capacitors in synchrocyclotrons) multipacting is usually the dominant breakdown mechanism for pressures in the mPa range (1 mPa = 7.5 x 10^{-6} torr). Intense multipacting precedes violent discharges, during and after which other discharge mechanisms take over. Gap resistance may drop to short circuit values and intense outgassing takes place creating local plasmoids, while the pressure in the vacuum tank goes up. Discharges have shown a tendency to accumulate in "showers" especially in case of surface contamination. This leads to electrical currents in the bias circuit which are much larger than in the case of multipacting. Discharges were detected - when a steady bias was used - on this basis: The voltage drop after a limiting resistor produced pulses which after a corresponding amplitude discrimination were counted. The discharge rate and the average bias current were found to behave similarly. In continuous operation, they both decrease in time, but the spark rate goes down faster. If during operation the RF voltage was turned lower such that the average bias current was increased, the spark rate went up noticeably.

When discharge showers were detected by our sensing circuits, the modulator and the bias were turned off temporarily. The recovery time from shower conditions seemed to be shorter when bias was removed. The importance of this observation was fully realized when a bias pulser was later installed. Secondary electron emission following ion collection in the bias field may help keep the discharge alive for a certain time in locally poor vacuum.

Another phenomenon was observed when discharges were frequent: At times, the dee negative voltage went up to values several times larger than the steady bias supply voltage causing breakdowns in the associated circuitry. Evidence indicated that this was not due to parasitic oscillations or transients. By taking appropriate measures and using independent DC probes on the dee, we were able to record relatively long lasting (several hundred μsec) negative (only) voltage levels up to 15 kV, representing thus an appreciable fraction of the RF voltage and suggesting RF rectification within the dee system. Conditions for RF rectification can appear when an asymmetry is created in the available current carriers around electrodes. In biased multipacting gaps, the energy of electrons hitting opposite electrode surfaces is not symmetrically distributed and this may result in asymmetric secondary electron yield.

During discharges, important numbers of ions are produced, and after being accelerated in the bias field, they yield on the electrode surface secondaries which are not phase correlated with the multipacting process. In addition, the RF voltage may drop during discharges enough to bring the gap into unilateral multipacting. Under such conditions electron space charge formation may locally transform the ground skin into an emitting cathode.

Once started, the rectification process would be self-sustaining for a while, the system being pushed more and more into unilateral multipacting. The building up of important negative voltage superposed with the RF leads to additional sparking, especially dangerous for rotating capacitors.

3. Pulsed Bias and Breakdown Protection

3.1. Dee Pulsing

The RF turn-on sequence is initiated at the beginning of every accelerating cycle by pulses produced by a master clock which operates in conjunction with the rotating capacitor position sensors. The plate voltage of the power oscillator is applied first, but the RF oscillations do not build up until the dee is charged by the bias pulse. This pulse brings the dee voltage to about -3 kV in a very short time using a hydrogen thyratron pulser. The bias is not needed to reduce multipacting after the RF oscillations reach a sufficiently large amplitude. After the application of the bias pulse, the dee is discharged through a resistor. In absence of intense multipacting or breakdown, the discharge curve is smooth. The remaining dee bias is practically fully discharged at the end of the accelerating cycle by the intense multipacting which takes place when the RF is turned off or prior to that if breakdown occurs. The bias voltage remains then essentially zero until a new pulse is applied. This arrangement prevents ion bombardment which, a 3 kV voltage drop could produce important secondary yield.[9] This decreases the chances of highly asymmetric or unilateral multipacting. An advantage of bias pulsing is an important reduction of the jitter of the RF pulse leading edge, making it independent of modulator risetime.

Bias pulsing has been used also at the Berkeley 184-in. Synchrocyclotron[10] but in a different sequence (bias pulse first) with the purpose of increasing the proton beam intensity.

3.2 System Protection

The shape of the residual dee bias decay throughout the accelerating cycle is used for detecting discharge conditions. After analog processing - differentiation and integration, the corresponding signal is transformed into a pulse which is positive for intense multipacting and breakdown and negative for RF rectification. A system of adjustable amplitude discriminators sends logical pulses to a modulator control circuit. These pulses turn off the modulator for adjustable intervals of time and can be recorded separately or in correlation with other logic pulses. The combination of dee bias and modulator suppression as described above provides reliable preventive breakdown protection.

The rotating capacitors have independent breakdown protection. The rotating capacitor gaps are very small (Fig. 3) and breakdown there is not directly related to multipacting. A low negative tracer bias voltage is applied to the rotor which in our case is DC insulated. A spark in the rotor-to-ground gap ($\sim$ 0.3 mm) produce a positive pulse, while a spark between rotor and stator blades produces a negative pulse (the stators are in our case a continuation of the dee resonator and have the dee bias which is larger than the rotor tracer voltage for angles of engagement where sparks between blades may occur). These pulses are handled in a way similar to the one used for pulses originating in the dee bias system. All logic pulses which turn off the modulator for breakdown protection, together with clock pulses originated in conjunction with vacuum and RF tube drive load transducers have been recorded and cross correlated by a centralizing monitor. A color coded LED display indicates real time occurrences.

3.3 Comparative Results

One of the first advantages gained by pulsed bias operation was a quicker quenching of discharge showers. In such a situation and with steady bias, it was necessary to turn off the modulator to let the system recover for about 5 sec. Using pulsed bias, it was possible to reduce the modulator blanking time to 0.7 sec. Collected operational data show a parallel evolution for dee discharges and RF rectification occurrence. Rotor-to-ground sparks appear often - about 70% - in coincidence with dee discharges, while sparks between rotor and stator blades are strongly correlated with dee RF rectification. Sparks between blades are always accompanied by rotor-to-ground sparks. The independent rotating capacitor spark protection proved to be (notwithstanding the correlation with dee conditions) very efficient in preventing gap surface damage (prior to its installation we experienced severe surface damage in rotor-to-ground gaps).

Figure 4 shows comparative monitor sample data collected after an accidental oil contamination followed by an extended exposure to air. For the same value of

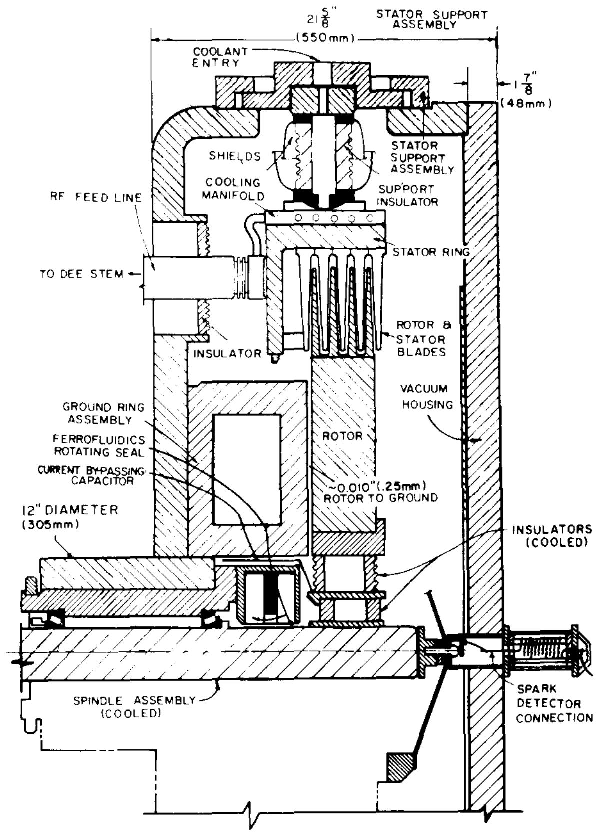

Fig. 3 Rotating capacitor with spark tracer

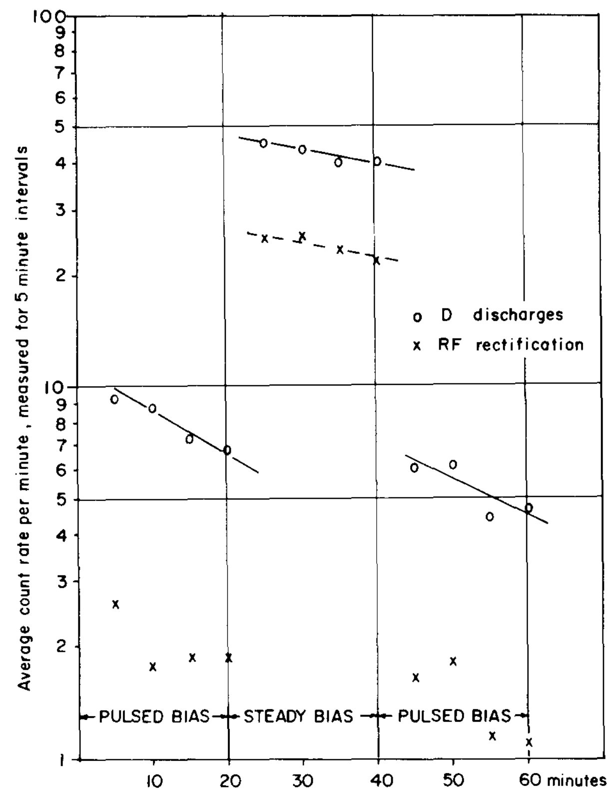

Fig. 4 Discharge and RF rectification occurrence rates during conditioning

the supply voltage, the system was switched back and forth from pulsed to steady bias for time intervals of 20 minutes. The RF voltage was the same (24 kV) and a 0.4 sec blanking time was used in both situations. The difference in discharge rates is even more dramatic if discharge counts are compared to the number of completed acceleration cycles. A considerable advantage is gained in "conditioning" time, due in part to this situation.

As a last remark, the relative rate of RF rectification occurrences with respect to the discharge rate is much smaller for pulsed conditions proving that pulsed bias operation really helps prevent rectification.

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DISCUSSION

Y. JONGEN: You have not mentioned the vacuum in the RF gaps. Can you comment about this?

F.G. TINTA: As indicated in the paper, the vacuum is in the mPa range (1 mPa = 1.5 × 10^{-6} mm Hg). Multipacking depends not only on the pressure, but also on the whole history of the surfaces inside the cyclotron, namely the surface contamination. In our cyclotron we have a lot of extra surface added by the floating ion inside the "Dees" and that made our problem especially tough. The pulsed bias is a very handy solution for decontaminating and protecting the resonating structure in vacuum.

E.G. MICHAELIS: How critical is the decay time of the bias pulse in the effectiveness of suppressing multipacking discharges?

F.G. TINTA: This is not critical. The residual bias is used for discharge protection. In the future we plan to use a different system, namely a short pause bringing the "Dee" up to 3 kV and then keeping a low steady bias used as a tracer for detecting discharges and other conditions.

M. ZACH: What are the effects of electrode material and surface treatment on multipacking?

F.G. TINTA: I did not have the opportunity to make a test rig and to obtain more quantitative data. Our experience showed that oil contamination is the worst and it seems that carbon coating helps -- how much I cannot tell you exactly.

T. KUO: Is the pulsing of the "Dee" bias synchronized with the synchro-cyclotron frequency? What is the frequency of this pulse?

F.G. TINTA: Indirectly, yes. This process is repeated three hundred times per second.

J.R. RICHARDSON: I wish to make a historical remark that you may find amusing. At the end of 1945 we were commissioning the first model of a synchro-cyclotron which simulated the acceleration of 200 MeV deutrons by a radial decrease of magnetic field of 10%. We were familiar with multifactoring and had insulated the rotating condenser. We obtained a beam at full radius almost immediately but then we remembered that we had forgotten to attach a "Dee" bias supply. However, when we did attach the supply, the beam disappeared. We had discovered accidentally an optimum self-bias for the new system.