OPERATION OF A CW HIGH POWER RFQ TEST CAVITY: THE CRNL "SPARKER"

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Summary

A 270 MHz RFQ structure with 365 mm long unmodulated vanes and a 2.5 mm minimum vane-to-vane gap was used to study cw operation at surface fields in excess of 30 MV/m. The brazed OFHC solid copper structure is flood cooled and couples rf power by a drive loop at the centre of one quadrant. Surface electric fields equivalent to twice the Kilpatrick limit were obtained at 39 kW power. The structure was rapidly conditioned with alternating periods of pulsed and cw operation to levels above 45 kW. Bremsstrahlung end point energies were used as a measure of peak vane-to-vane voltage. Several interesting observations have been made. Glowing pinpoints of light were seen near the vane tips, some extinguishing with time, others appearing - but their number and intensity increasing with rf power. Microdischarges were seen, consisting of very small localized flashes of light between the vane tips, usually accompanied by a complete collapse and re-establishment of the structure rf field over a 20 μs interval. The frequency of field collapses varied with power but was independent of gas pressure and species up to $4 * 10^{-3}$ Pa. As structure power was increased above the conditioned level, a rapid succession of microdischarges would occur, increasing the reflected power beyond the fast trip level.

Introduction

The RFQ "sparker"[1] experiment was designed to determine practical voltage limits and to learn about sparking phenomena in the four-vane RFQ geometry. The long term program at CRNL to develop accelerator breeder technology[2] includes development of a high current cw proton RFQ, and the design was found to be so strongly influenced by the choice of maximum practical vane voltage that it was considered necessary to build a test cavity.

Böhne et al.[3] did a similar study of rf conditioning and sparking limits at 12% duty factor for the UNILAC high gradient single gap cavities prior to freezing their design. They showed that the sparking rate was very dependent upon conditioning methods, choice of metal type and operating history. A practical upper limit of 20 MV/m was suggested for the 108 MHz single gap devices in "clean vacuum systems".

This suggested that operation of a cw 108 MHz RFQ system might be feasible at up to 1.7 times the Kilpatrick limit[4], although the large difference in voltage gap dimensions could influence the comparison.

Tuning, Field Distributions and Installation

Construction and tuning of the "sparker" have been reported previously[1], and are only summarized here. It is a brazed OFHC copper structure with unmodulated RFQ vane geometry, operating at 270 MHz with a single coupling loop drive. The pertinent geometry (including dimensions) of the sparker assembly and of the vane tips is shown in Fig. 1.

Final quadrant magnetic field balancing was done with small transverse movement of the vane tips, equalizing vane-to-vane voltages to within ± 3% (measured using metal beads in the quadrants). Eight small magnetic field sampling loops were then installed and calibrated in the quadrant corners beyond the vanes (Fig. 1) to monitor quadrant fields. The vane gaps are not identical, but for a gap equal to the average of the two smaller gaps, the 1 x Kilpatrick (1 Kp) value for the surface electric field (16.6 MV/m) is achieved at a vane-to-vane voltage of 38.6 kV.

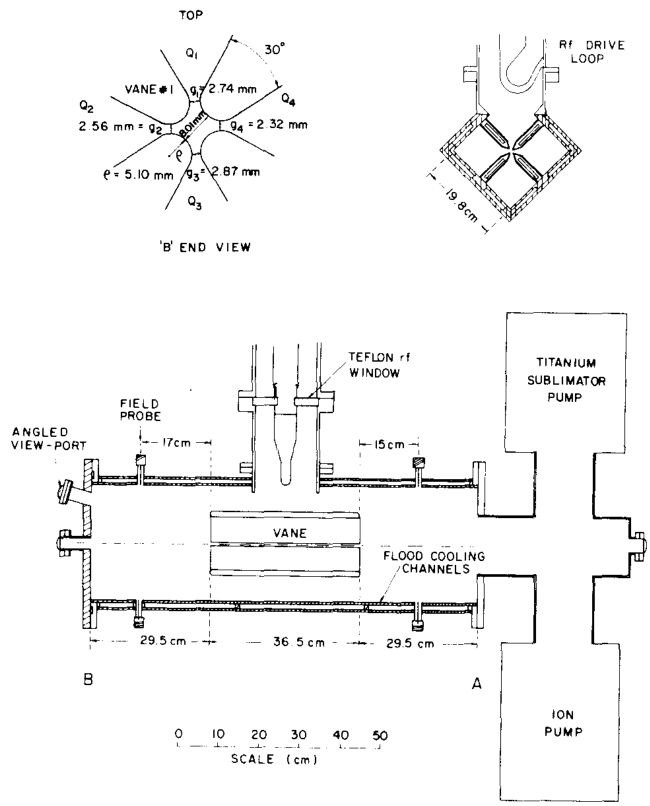

Fig. 1 Schematic of the sparker, including dimensions of the vane-tip region.

The sparker assembly was placed in a lead lined enclosure and final Q and coupling measurements done in-situ. A base pressure of $1.3 * 10^{-5}$ Pa ($1 * 10^{-7}$ Torr) was obtained after a bakeout to 90°C. The measured properties of the sparker are listed in Table 1.

Table 1

Measured Properties

Frequency (Quad. Mode)	= 266.711 MHz (22°C, no water flow)
	= 266.532 MHz (17°C inlet water temperature)
Frequency (Dipole # 1)	= 270.517 (22°C)
Frequency (Dipole # 2)	= 264.8 (22°C)
Mode Voltage Reflection Coefficients:	
Quadrupole:	0.08 overcoupled (VSWR = 1.17)
Dipole # 1:	0.30 overcoupled
Dipole # 2:	>0.98 undercoupled
Unloaded Q	= 9700 ± 40 (22°C uniform structure temperature)

Conditioning - Pulsed and CW Operating Limits

Initial rf conditioning and breakdown measurements were done with a 40 kW cw tetrode based rf system and subsequent operation at higher power was with a 400 kW cw triode system. Conditioning was achieved alternating pulsed and cw operation, the pulsed peak power usually exceeding the cw power level by 20%. During the first hour, the vacuum excursions went to ≈ $4.6 * 10^{-3}$ Pa, but subsequent operation was always less than $1.3 * 10^{-4}$ Pa.

The initial conditioning sequence was as follows: two hours pulsed up to 1.5 Kp (pulse length, $\tau \approx 0.15$ ms, prf = 10 pps), three hours cw up to 1.3 Kp, six hours pulsed to 2.0 Kp, five hours cw up to 2.0 Kp. This method of alternating pulsed and cw operation was found very effective, for after 15 hours of conditioning, the system was operating stably at 2.0 Kp cw. Over the following a few months, operating levels of 77 kW (2.9 Kp) pulsed ($\tau \approx 0.25$ ms) and 50 kW (2.3 Kp) cw were achieved.

Characteristics of the "Conditioned" Cavity

Light Emission

Observation of the vane tip region through a quartz window using a TV camera revealed numerous small pinpoints of light distributed randomly over a region close to the tips. There was a wide variation in the light intensity of the individual points, but all intensities increased with rf power level. Over a period of a few hours of cw operation at a constant power level, some of the brightest of these pinpoints were seen to extinguish, others appeared elsewhere, but many remained for days in the same location. After a few months of operation, the vanes were washed and cleaned with acetone, trichlorethene and ethanol and reconditioned. The number of glowing points was reduced by an order of magnitude.

The time dependence of the light emitted from a group of these pinpoints during pulsed operation was measured using a low gain photo-multiplier tube. At 35 kW peak power the risetime (10% to 90%) of the light intensity was estimated at 1.3 ± 0.3 ms, independent of pulse length and duty factor. After this slow rise, the intensity then remained constant during the rf pulse and decayed with ≈ 0.8 ms time constant after shut off of the rf. (The 10 to 90% fill time for rf power in the tank is approximately 8 μs.) The dependence of the average light intensity on the power level is shown in Fig. 2, with arbitrary normalization.

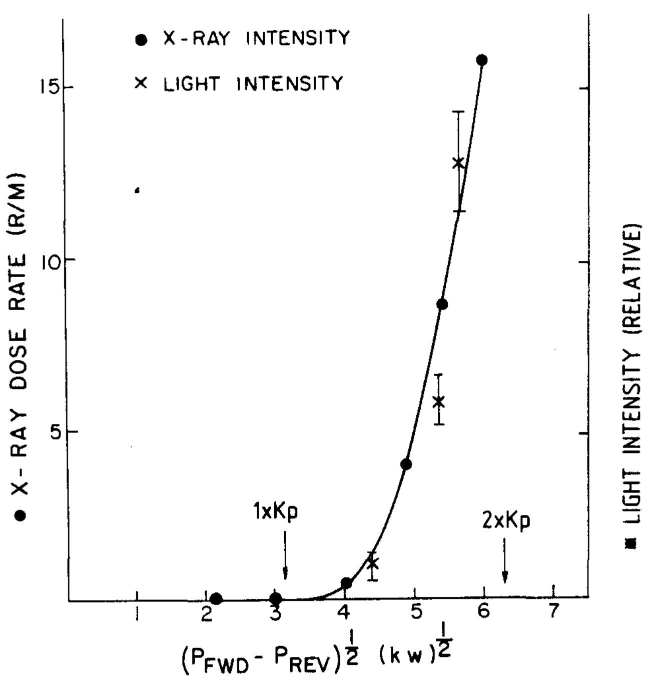

Fig. 2 Graph of the x-ray intensity and light intensity (measured immediately outside a quartz viewport) as a function of the square root of tank power (which is proportional to the vane voltage).

During any specific period of pulsed operation, breakdown occurred when a certain peak light output intensity was exceeded. This meant that the maximum peak power attainable was almost independent of pulse length for pulses longer than the risetime of the light (≈ 1.3 ms). However for successively shorter pulses, higher rf levels were required to reach the critical light intensity at which breakdown occurred. The time constant associated with the rise of the light output suggests some form of heating mechanism.

An Ebert spectrometer was used to analyze the light produced during cw operation. The spectrum consisted mainly of continuum blackbody radiation ($T \approx 1200$ K), skewed slightly towards shorter wavelengths. Only two distinct broad lines were seen (692.9 nm and 694.4 nm, widths of 1 nm) and they could not be identified with the atomic spectrum of any element. The measured absolute light intensity, temperature and estimated number of glow points yield a size of 1 to 10 microns diameter for the individual points. Possible mechanisms for the pinpoints of light are (1) heating of small whiskers, grains of material or regions of surface impurities by enhanced electron emission currents or (2) heating of small regions of impurities or grains of material by surface or displacement currents.

X-ray Emission

Along with light generated at the pinpoints, x-rays were observed through the quartz windows. The x-rays were generated by electrons which were accelerated across the vane-to-vane gap; the transit time is so short that the peak electron energy reflects the instantaneous vane-to-vane voltage. The x-ray intensity at the quartz window (Fig. 2) was measured during cw operation with a calibrated Baldwin-Farmer 0.6 cc ion chamber (Fig. 2). Clearly the radiation intensity is a very non-linear function of power, with an apparent threshold near the Kilpatrick limit (≈ 16.6 MV/m). The similar dependence of the average light intensity on power (Fig. 2) suggests they may be related phenomena, although the previously mentioned cleaning of the vanes and reduction in absolute light intensity had very little effect on the x-ray intensity. The time dependence of the x-ray intensity was measured during pulsed operation - the risetime was ≈ 1.2 ms, the fall time was less than 150 μs.

An intrinsic germanium x-ray spectrometer was used to measure the x-ray spectrum endpoint energy and thus the peak vane-to-vane voltage as a function of tank power (Fig. 3). The measured endpoint energies were approximately 10% lower than the theoretical predictions. A series of endpoint measurement calibration runs were done using a 40-100 kV monoenergetic electron beam stopped by a copper target. The endpoint energy was determined as a function of the shape of the distribution near the tip. These measurements also produced a rough estimate of the average electron current flowing between the vanes in the sparker. A 70 keV dc electron beam of ≈ 20 μA produced the same number of x-ray counts per solid angle as the cw "sparker" operating at 70 kV peak vane-to-vane voltage.

Microdischarges - A Criteria for Conditioning?

Microdischarges in the sparker were seen as small discrete flashes of light between two vane tips accompanied by a momentary increase in reverse power. During low power cw conditioning (< 1 Kp), a rapid series of microdischarges would apparently move along the vane tips and then build into an overall glow causing a reverse power trip. After conditioning to 2 Kp, the occurrence of these multiple microdischarges effectively ceased at lower power levels. However, single discrete flashes were still observed, and usually found to be accompanied by a complete collapse of the rf fields (90% to 10% as seen on the field

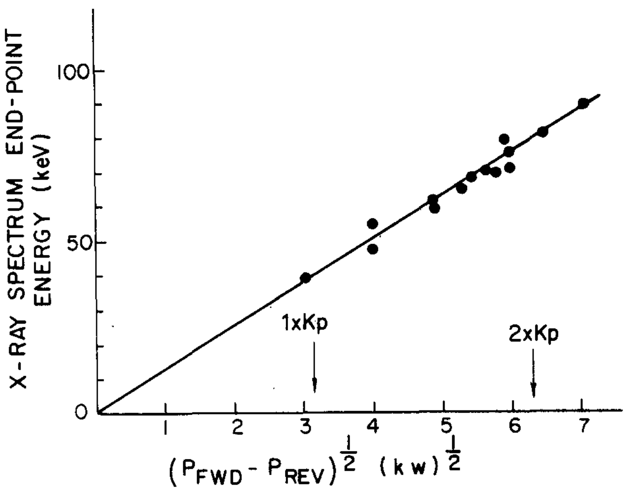

Fig. 3 Measured x-ray spectrum end point energy as a function of the power into the tank.

probes) over a period of 2 μs (≈ 500 rf cycles), after which the tank fields were completely re-established with an 8 μs fill time.

Separate runs were done introducing individually hydrogen, nitrogen, argon or air into the sparker at pressures up to 4.6 * 10^{-3} Pa. The microdischarge rate increased for an initial 5 minute period, and then returned to its initial value at low pressure. A subsequent set of high pressure runs were done at 45 kW cw (≈ 2.3 Kp) by shutting off the ion pump and bleeding in a selected gas over the next five to ten minutes. Hydrogen, argon and nitrogen each had approximately the same upper pressure limit (9 ± 2 * 10^{-3} Pa) at which cumulative microdischarges caused rf shutdown. As the pressure increased, the x-ray level increased (≈ 20%) for hydrogen and argon and decreased (≈ 25%) for nitrogen. The changed x-ray intensity persisted for some time after subsequent pumpdown.

The effect of an ion beam on the microdischarge rate was tested by passing a few hundred microamps dc of 750 keV protons through the sparker, initially as a narrowly collimated beam and then as a spray intercepting the vane tips. No effect was seen, visually with the TV camera, in the microdischarge count rate, in the x-ray intensity or in the rf characteristics.

In an operating accelerator, the beam would be lost during microdischarges, and the rf control system possibly disrupted. Thus the rate of occurrence of these microdischarges is an important operating parameter. A pulse counter was used to detect them over a series of long (4 to 6 hour) cw runs: at 25 kW (≈ 1.65 Kp) the rate was 4 per hour; at 35 kW (≈ 1.93 Kp) the rate was 25 per hour. The system vacuum during these runs was ≈ 4.6 * 10^{-5} Pa.

Conclusions

1. Solid copper OFHC vanes can be conditioned to at least 2.3 Kp, cw, using a suitable pulse and cw conditioning sequence, assuming only ordinary care in surface preparation.

2. It is possible to achieve levels of 3 Kp for short pulse operation, the increase over cw operation possibly being related to the risetime of the x-ray and light intensities in the cavity.

3. The number of emitting pinpoints seen in the cavity during cw and long pulse operation is not directly correlated with the ultimate conditioned voltage.

4. Microdischarges between the vane tips are accompanied by a collapse (over many cycles) and subsequent re-establishment of the tank fields. Sustained discharges do not appear to occur at high power levels, but rather a rapid sequence of microdischarges occurs which eventually produces high average reverse power.

5. The microdischarge rate is not significantly influenced by gas pressures up to 9 * 10^{-3} Pa of hydrogen, nitrogen or argon.

6. The microdischarge rate is not influenced by the presence of a dc high energy proton beam, even when directed at grazing incidence onto the vane tips.

The "sparker" experiment has satisfied its immediate objectives of providing design limits for a high current cw proton RFQ. Although no clear understanding of the voltage limiting phenomena was obtained, it is clear that surface shape and chemistry are important.

References

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