Excitation of SC Cavities

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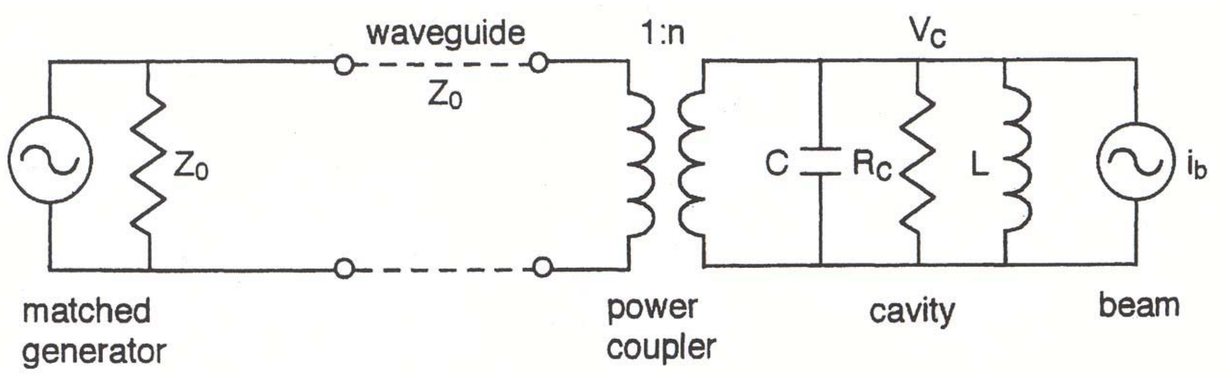
EXCITATION OF SUPERCONDUCTING CAVITIES

- EQUIVALENT CIRCUIT
- CAVITY IMPEDANCE DURING OFF RESONACE CONDITIONS – COUPLING MISMATCH, MICROPHONICS AND LORENTZ DETUNING
- UNLOADED AND LOADED Q
- PULSED OPERATION



EQUIVALENT CIRCUIT FOR CAVITY WITH BEAM LOADING

BASIC ELEMENTS OF THE EQUIVALENT CIRCUIT

- The cavity is represented as a parallel Rc, L, C circuit
- This is the shunt impedance model for which the power is equal to the square of the peak accelerating voltage divided by 2 times the shunt resistance, $V^2/2*Rc$
- The coupling loop (or E-probe or coupling aperture) is represented by a matching transformer
- The RF source is represented by a current source in parallel with the transmission line characteristic resistance, Z_0, (or it could be a voltage source in series with Z_0)
- The beam loading is represented by the current source I_b

UNLOADED CAVITY IMPEDANCE

- The unloaded quality factor, Qu, and the shunt resistance, Rc, are measured or calculated quantities
- The equivalent circuit capacitance is found from the equation for Q, Qu = w0*Rc*C, or C = Qu/(w0*Rc)
- The equivalent circuit inductance is Rc/(w0*Qu)

MATCHING CONDITIONS

- Assuming for the moment that the beam current is in phase with the accelerating voltage, the effect of the beam acts like a resistance, Rb, in parallel with Rc. The terminating resistance, R_t, is the parallel combination of Rb and Rc, (Rc*Rb)/(Rc + Rb)
- Normally, the coupling loop is set to match the power required. When matched the waveguide or transmission line sees a terminating load equal to Z_0.
- The reflection coefficient for a transmission line is given by, $k = (Z_t - Z_0)/ (Z_t + Z_0)$
- Since $Z_t = Z_0$, there are no reflections on the transmission line

RF DRIVE UNDER BEAM MATCHED CONDITION

- In a superconducting cavity, the beam power dominates the cavity excitation power, Rc>>Rb. Typically, the value of Qu is between 1 to 10 X 10^9. The loaded Q, Qe, is = (Rb/Rc)*Qu. The typical values of Qe are a few 10^6
- The effective resistance of the cavity is (Rb*Rc)/(Rb+Rc), which is ~ Rb when the beam is on since Rc>>Rb
- Therefore, when matching the cavity with beam, the coupling loop is set so that effective resistance of the cavity, Rb, is transformed to equal Z_0 on the transmission line to eliminate reflected waves.

RF DRIVE WITHOUT BEAM UNDER BEAM MATCHED CONDITIONS

- When driving the cavity with the beam off with the coupling loop set for match condition, Rb is gone from the circuit and the only resistance left is Rs. The terminating resistance on the transmission line transformed through the coupling loop is (Rc/Rb)* Z_0
- The reflection coefficient approaches unity and almost all the incoming power is reflected away from the cavity and into the circulator load.
- In the steady state case, the power transmitted into the cavity to maintain the accelerating voltage requires a klystron power that is equal to one-fourth the power required when beam is being accelerated. Almost all of which is reflected into the circulator load

EFFECT OF MISMATCHED COUPLING LOOP OR OPERATION AT A LOWER BEAM CURRENT

- Assuming that the peak beam is in phase with the peak of the RF accelerating voltage, an error in setting the coupling loop for zero reflection results in the terminating impedance that is purely resistive and larger than Z_0
- Likewise, operation at lower beam current will result in a purely resistive termination that is larger than Z_0
- Both cases result in a mismatched transmission line and in reflected power into the circulator load.
- Typical tolerances on coupling settings are up to as high as +-20% depending on how many iterations of adjustment, cool down, and measurement procedures finds acceptable.

CAVITY IMPEDANCE OFF RESONANCE

- The most common cause of being off resonance is mechanical vibrations of the cavity and support frame. The typical size of the frequency errors are 80 – 100 hertz, assuming there's not some mechanical resonance built into the mechanical structure
- The impedance of a resonant circuit when off resonance is $Ze = Z_0[1 + jQe(w/w0 – w0/w)]$, where w0 is the cavity resonant frequency
- Assuming that w = w0 + dw, and dw is small compared to w0, $Ze \sim Z_0/[1 + j*2*Qe*dw/w0]$
- For 120 Hz and a Qe of $3*10^6$ at 1300 MHz, the equivalent reactance terminating the transmission line is $Z_0[1 + j*0.554]$. This requires the klystron to operate with 8% higher output power and a 29º phase shift to hold the accelerating voltage

CAVITY FILLING TIME

- The time constant, t_c, for a resonant cavity is 2*Qe/w
- The cavity is typically filled before the beam is turned on, so the cavity is mismatched and the reflection coefficient is 1 and the power needed to hold voltage on the cavity without beam is one fourth that needed to supply beam power.
- With the maximum power delivered by the klystron during filling, the cavity would be headed for twice the voltage needed for normal operation. Therefore, Vc = 2*Vc (1 –exp(tf/ t_c)). Tf, the time to reach Vc, the filling time, is t_c*ln(1/2). For the TESLA cavities where Qe is $3*10^6$ and the operating frequency is 1300 MHz, the filling time is 510 microseconds

PULSED OPERATION

- If the cavities and beam are being pulsed, as for instance at TESLA or SNS, the cavities are filled before the beam is turned on. During the filling time the power delivered by the klystron is typically equal to the power required to match beam loading.
- When the cavities are nearly up to voltage, the beam is ramped up. Ideally, you want the full beam loading to be reached at the same time the accelerating voltage is reached. During the beam ramping period, the reflected power decreases until the matched condition is reached and all the klystron power is delivered to the beam.
- Unfortunately, the rising fields in the cavity generate a pressure on the cavity walls that changes the resonate frequency. This is known as Lorentz force detuning.

HANDLING LORENTZ FORCE DETUNING

- Typically, the cavities are set off resonance before filling, so that the frequency shift will drive the cavity unto resonance. Unfortunately, all cavities don’t behave the same, and they have microphonics causing unpredictable frequency shifts
- A piezoelectric crystal tuner has been developed and tested with some success. They have succeeded in reducing the effect, but not eliminating it.
- Cavity beam loading might not be identical. It definitely is not in something like a proton linac.
- The conclusion is that operation of several cavities off a single klystron is difficult, if not impossible, unless some type of amplitude and phase control device can de developed (like a double 3-db hybrid with fast ferrite phase shifters in between the hybrid splitters/combiners)