RF PARAMETERS FOR THE 12 GeV UPGRADE CRYOMODULE

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Made at the request of the 12 GeV project management, this Tech Note is divided in two parts. The first part reviews the starting assumptions and the methodology by which the parameters and requirements for the 12 GeV upgrade cryomodule were determined. In large part it draws on the May 2001 Report of the 12 GeV SRF Plan Team that included:

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The second part updates the analysis, based on measurements of microphonics in the first prototype upgrade cryomodules (FEL03 and SL21).

Part 1: BASELINE PARAMETERS

Gradient

The starting assumptions and top level requirements were:

Final Energy:	12 GeV after 5.5 passes
Maximum current:	460 μA
Voltage provided by existing cryomodules:	594 MeV/linac (6 GeV total in 5 passes)
Number of new cryomodules:	10
Accelerating length in new cryomodules:	5.6 m

Average operating voltage provided by upgrade cryomodule:

$$\frac{12000-(6000+594)}{5.5\times 10}=98.3\text{ MV}$$

Average operating gradient of upgrade cavities:

$$\frac{98.3}{5.6}=17.6\text{ MV/m}$$

The average operating gradient of 17.6 MV/m assumes that all cavities are operating. Based on existing experience a safety factor of 10% was assumed to take into account the fact that a number of cavities may be off-line. With these assumptions the average gradient of operating cavities would be 19.3 MV/m or 108 MV/cryomodule.

The voltage of 108 MV, corresponding to 19.3 MV/m in each cavity, is the voltage for which each cryomodule needs to be designed. In particular each cryomodule must be able to accommodate the power dissipation associated with such gradient.

Rf Power

In the CEBAF and 12 GeV upgrade concept, each cavity is individually powered by a single klystron, and every klystron must be able to power and control the cavities at the maximum field at which they may operate.

The design gradient of 19.3 MV/m is an average between 8 cavities in each cryomodule, and it is reasonable to expect a $\pm 10\%$ spread in the operating gradient of the 8 cavities. Thus, the rf power must be sufficient to operate cavities at a field of $1.1 \times 19.3 = 21.2$ MV/m.

The rf source needs not only to create the fields in the cavity and transfer power to the beam it must also be sufficient to operate the cavity when its resonant frequency is different from that of the beam. This frequency difference (or detuning) has two components:

- Static detuning: The difference between the **average** cavity frequency and the reference frequency. In principle, it can be controlled by tuners (mechanical and/or piezo) but not completely eliminated because of residual deadband or hysteresis and also because of the lifetime of those tuners. In practice, it means that the average cavity frequency will be allowed to wander inside a band, and the tuners will be activated only when the frequency steps outside the band. In the analysis it is assumed that the average cavity frequency is at the edge of the allowed band.
- Dynamic detuning: Time-dependent frequency variations caused by external effects (vibrations, pressure fluctuations, etc.) that occur in a time scale too short to be controlled by mechanical means.

In [1] a methodology was developed to estimate the total amount of detuning that the rf system must be able to accommodate, in order to reduce the probability of any cavity being out-of-lock below a given goal. The assumptions and requirements were:

- Probability of being out-of-lock: $< 10^{-6}$
- Static detuning window: ± 4 Hz
- Probability density of microphonics: Gaussian
- Standard deviation of microphonics: 3.5 Hz

With those assumptions, a total detuning that must be accommodated by the rf system was estimated to be ± 25 Hz, and the required rf power and optimal external Q can be determined. In Fig. 1 it is further assumed that the beam current is 460 μA, the R/Q of the cavity is 1114 Ω/m.

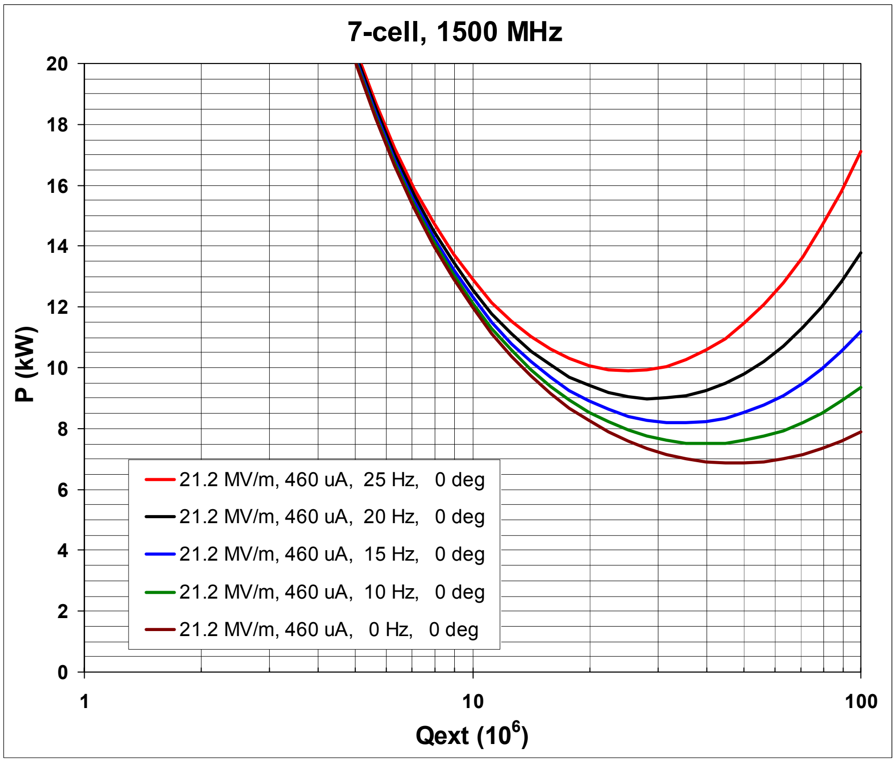

Figure 1: RF power as function of Q_{ext} for various amount of detuning at 21.2 MV/m

From Fig. 1 the optimal Q_{ext} is seen to be 2.5×10^7, at which the required rf power 9.3 kW. It can be noted that the power absorbed by the beam is 6.9 kW.

From past experience, an error of ± 1.5 dB (a total range of 2) should be assumed in achieving the target Q_{ext}.

For reasons that are not clear from the minutes of the meetings of the SRF Team, the design Q_{ext} was subsequently chosen to be 2×10^7. This does not change substantially the rf power required at the optimal Q_{ext}, but has a significant impact at $0.7 \times Q_{ext}$.

Also, from the above graph it is apparent that the amount of microphonics that can be controlled with an available amount of rf power decreases very rapidly on the low side of Q_{ext}, while it decreases very slowly on the high side. Thus it is best to err on the high side.

With the assumptions made in the report, at a Q_{ext} of 1.4×10^7, the amount of rf power that is needed is 10.1 kW. This is the amount of power that must be available to the cavity while the rf source is still operating in its linear range. To take into account the losses between the rf source and the cavity input and the difference between linear and saturated output a somewhat arbitrary increase of 1 dB is added, resulting in 12.7 kW.

If the allowable range for Q_{ext} is taken to be $1.7 – 3.4 \times 10^7$, the amount of linear power at the cavity is 9.6 kW, resulting in a 12.1 kW rf source.

Part 2: UPDATED ANALYSIS

Subsequent measurements of microphonics on the first two prototype upgrade cryomodules by Kirk Davis and Tom Powers [2] indicated that the assumption of a standard deviation of 3.5 Hz was extremely pessimistic. The measured values ranged from 0.61 to 1.27 Hz in FEL03 and 0.76 to 1.26 in SL21. Measurements on an old-style cryomodule (SL20) produced values from 2.8 to 4.1 Hz. All those cavities had the same cell geometry (FEL03 and SL21 were 7-cell, SL20 was 5-cell). The main difference, and probable reason for the increased level of microphonics, was that the cavities in SL20 had the waveguide HOM couplers which lack mechanical rigidity.

It is therefore reasonable to reduce the detuning window from ± 25 Hz to ± 15 Hz. From Fig. 1 the optimal Q_{ext} 3.2×10^7, at which the required rf power is 7.9 kW. If the allowable range for Q_{ext} is $2.2 – 4.4 \times 10^7$, then the required linear rf power at the cavity is 8.2 kW. Adding 1 dB for losses and increase to saturation yields a requirement for the rf source of 10.3 kW.

On the other hand, as shown in Fig. 2 and if the Q_0 of the cavities allows it, the baseline linear rf power at the cavity of 10.1 kW would allow control of ± 15 Hz over a Q_{ext} range of $2.4 – 5.0 \times 10^7$ at gradients of up to 25 MV/m.

Analysis of the power dissipation in the waveguide based on the model of Larry Doolittle [3] also shows a much larger power dissipation in the waveguide at a Q_{ext} of 1.4×10^7 than at any value in the range of $2.4 – 5.0 \times 10^7$.

Figure 3 shows the integral $\left\langle \int I^2 dl \right\rangle$ taken around the cross section of the wave guide as a function of the position along the waveguide at 25 MV/m for external Q's between 1.4×10^7 and 5.0×10^7. This integral is directly proportional to the local power dissipation.

Figure 4 shows the same thing at $Q_{ext}=1.4 \times 10^7$ for gradients between 21 and 25 MV/m

RECOMMENDATION:
The specification for the external Q of the upgrade cavities should be modified to: $2.4 – 5.0 \times 10^7$.

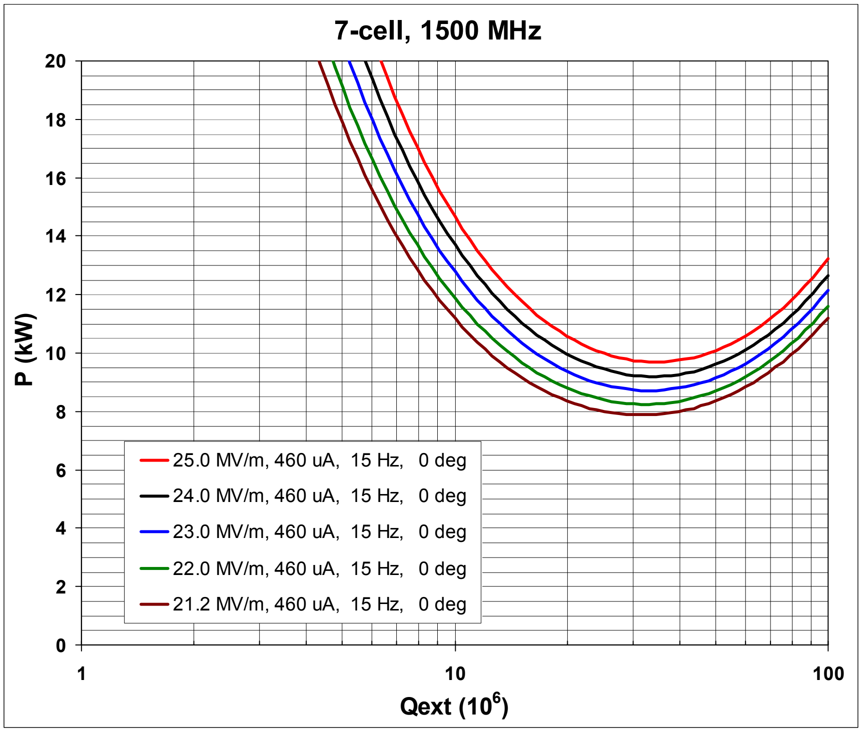

Figure 2: RF power as a function of Q_{ext} for various gradients at a detuning of ± 15 Hz

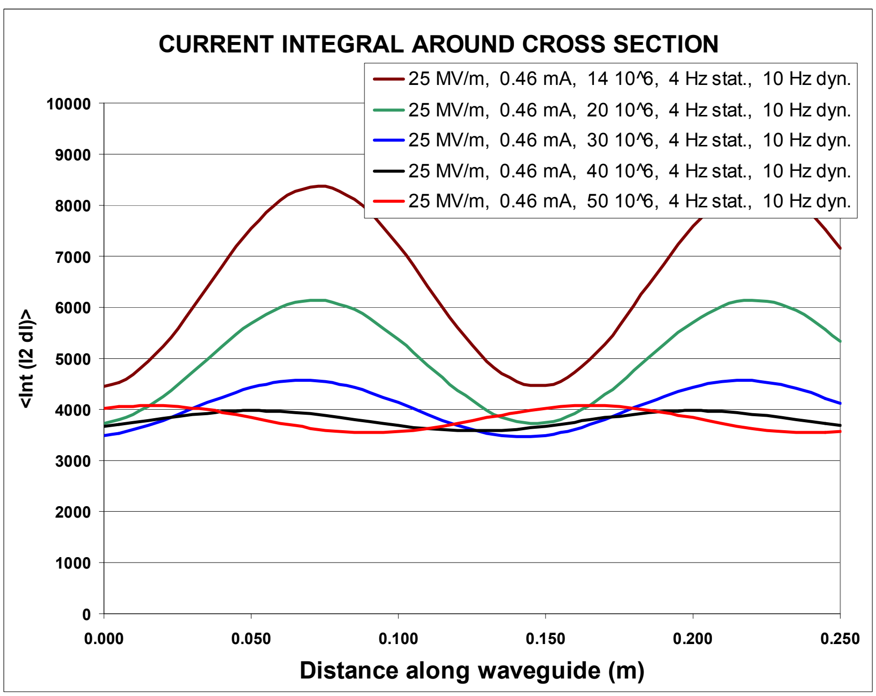

Figure 3: Current integral as a function of position along the waveguide at 25 MV/m for Qext between 1.4×10^7 and 5.0×10^7.

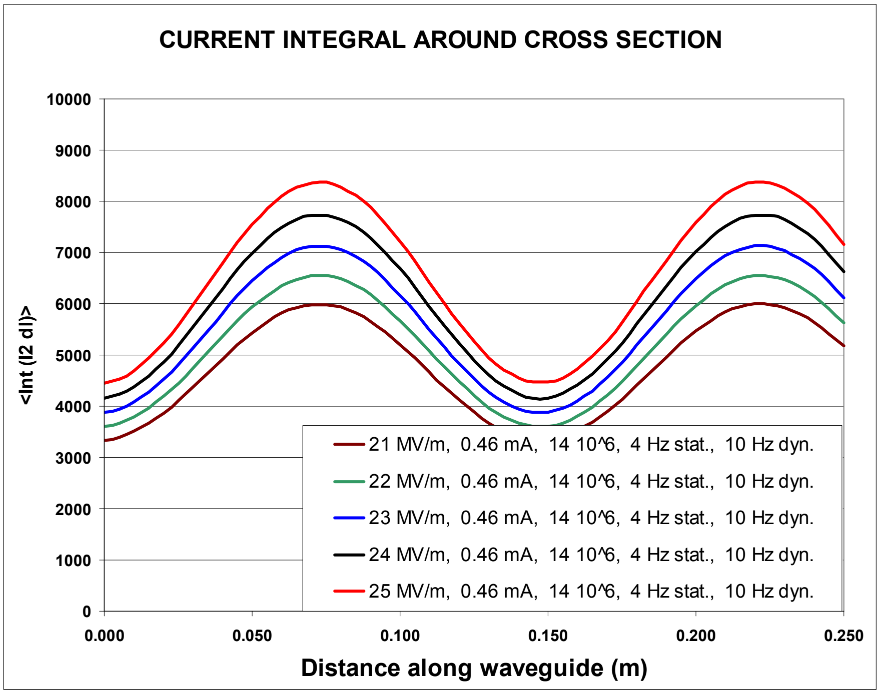

Figure 4: Current integral as a function of position along the waveguide at Qext = 1.4×10^7 for gradients between 21 MV/m and 25 MV/m.

References:

[1] J. R. Delayen, and L. H. Harwood, "Determination of Low Level RF Control Requirements for Superconducting Cavities from Microphonics Measurements", Proc. PAC 2003.

[2] Kirk Davis, Tom Powers, "Microphonics Evaluation for the CEBAF Energy Upgrade, TN-05-040.

[3] Lawrence R. Doolittle, "Waveguide Surface Currents", TN-99-012.