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RF Power Calculations for High Beta Elliptical Cavities

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Abstract

Supporting document to the parameter list of rf power source for the high beta elliptical cavities for ESS and prototypes. These calculations are based on the ESS high level parameter table 15 April 2011 [1] and the Accelerator Science and Lattice parameter table 13 May 2011 [2]. I.e, the beam pulse length is 2.9 ms and the power coupler peak power, to beam is 0.9 MW. The long pulses in combination with a high peak voltage is challenging for the klystron modulators. In order to avoid unnecessary safety margins that will worsen for the klystron modulators, careful analysis is needed to find out the requirements on the rf power source.

1 Peak power

1.1 Power to High beta elliptical cavities

The maximum rf power delivered to the high beta elliptical cavities is 0.9 MW [2]. It is assumed that the coupler impedance is matched to a 50 mA beam load so that no extra rf power margin needs to be added at the coupler.

1.2 Power losses in the rf distribution system

The power loss in the WR1500 wave guide is 0.053 dB per 100 feet [3]. For a 20 m long wave guide this is equivalent to

$$1 - 10^{-\frac{0.053}{10}\frac{20}{30.48}} = 0.8\%$$

power loss. To include circulators, bends, flanges and bellows, the power loss in the distribution system is estimated to be 5 %. Note that more

investigations on losses in the distribution system are needed, especially due to reflections.[1]

1.3 Margin for Low Level RF

A 20 % margin for the LLRF is expected. This corresponds to operation 1 dB below saturation, compared to 1.5 dB specified for the SPL study [5].

1.4 Klystron and modulator

Taking into account for the power loss in the distribution system and the margin for LLRF, the required nominal peak power delivered by klystron at saturation is given by

$$p_k = \frac{0.9 \text{ MW}}{0.95 \times 0.8} = 1.2 \text{ MW}$$

The klystron efficiency shall be as high as possible, without affecting lifetime and stability of the klystron. With a perveance $K = 0.548\ \mu\text{AV}^{-3/2}$ a 65% efficiency is feasible [4]. Thus the required nominal peak power delivered by the modulator is

$$p_m = \frac{1.2 \text{ MW}}{0.65} = 1.8 \text{ MW}$$

The nominal cathode voltage U is then given by

$$U = \left(\frac{p_e}{K}\right)^{2/5} = 102 \text{ kV}$$

1.5 Specified values

The specified values for the power source will include a 10% safety margin. Then the output peak power delivered by the klystron is 1.3 MW, which corresponds to a cathode voltage of 106 kV. The specified output peak power is then 2.0 MW.

2 RF Pulse duration and duty cycle

The beam pulse repetition rate at ESS is 14 Hz with a beam pulse length of 2.86 ms, which gives a beam duty cycle of 4%.

The expected filling time is 0.3 ms, however more investigations are needed to get a better precision. The cavities are equipped with piezo tuners,

[1] In the klystron specification for the SPL study [5] the parameter "Load VSWR @ any RF phase" is specified to be smaller than 1.2, so that the output power shall exceed 85% of full rated power when operated into a 1.2:1 mismatch of any phase.

which are expected to reduce the time to stabilize the LLRF. Another 0.1 ms will nevertheless be added to the rf pulse length as a safety margin.

For a modulator with a pulse transformer the expected rise time is 0.2 ms.

Thus, in total the rf pulse width τ is 3.5 ms, which corresponds to duty cycle equal to

$$D = 14 \text{ Hz} \cdot 3.5 \text{ ms} = 4.9\%$$

3 Average power and power efficiency

The modulator average output power is specified to 100 kW:

$$2.0 \text{ MW} \cdot 4.9\% = 98 \text{ kW}$$

The power efficiency of the klystron modulator is specified to 90%.

Thus, to generate an average rf power of 0.9MW*cdot*4% = 36 kW at the cavity requires 100 kW. Hence, the efficiency of the power source is nominally 36% for the high beta elliptical cavities. Since these cavities make up for more than half of the number of cavities and 75% of the power to beam, we can expect a total power consumption of 5 MW/0.36 = 14 MW. With 5200 h per year operation the total power consumption is 73 GWh/year.

4 Discussion

The size of the pulse transformer scales as $(\tau U)^2$. The present pulse transformer will therefore be a 33% larger than originally specified for the prototypes modulator with a pulse length of 2.8 ms and cathode voltage of 115 kV. The main issue is however not the size. Rather, we do know what other implications this will lead to. Therefore we are forced to be conservative when specifying the maximum voltage until this has been investigated.

However, by reducing the beam power to the coupler and the margin for LLRF and making the beam pulses longer, the power efficiency of in the klystron gallery has improved by 20%.

Another improvement of the overall efficiency would be to select a pulse modulator without a pulse transformer. Without a pulse transformer the rise time of the pulse can be almost eliminated, together with the undershoot voltage, which is expected to save another 10% in power efficiency. However, one needs to be very careful. There is only one company capable to provide a safe and well proven solution. Therefore, investigation on a larger pulse transformer is important.

For the CERN test stand there yet another issue. The 100 kW average power requirement for ESS is only half the average power needed for the SPL study. In addition, the pulse repetition rate is 14 Hz compared to the

50 Hz needed at CERN. This indicates that this klystron modulator is very different compared to the ESS modulator. The question is therefore whether the SPL modulator can be used as a prototype for ESS.

References

[1] ESS Parameter Tables High Level Parameters

[2] ESS Parameter Tables Lattice and Accelerator Science

[3] `http://www.eriinc.com/Resources/Publications/20090321006_AEN.aspx`

[4] E. L. Eisen (CPI), Statement of Work 1.5 MW Pulsed, 704.4 MHz Klystron for ESS, White paper 3/11/2010

[5] Technical Description for the Supply of 704.4 MHz, 1.5 MW, 150 kW Klystron for the SPL study