EUROPEAN
SPALLATION
SOURCE

Accelerator Division

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Calculations on the RF Source and Distribution

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Calculations on the rf source and distribution system for the ESS elliptical cavities

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Rf parameters:

- Frequency: 704.4 MHz
- Power: 1 MW at the coupler
- Pulse length: 2 ms
- Repetition rate: 20 Hz
- Number of elliptical cavities: 96 ($\beta = 0.92$)

Transmittance in the rf distribution system: The power loss in the WR1150 wave guide, which is suggested for SPL[1], is 0.1 dB per 100 feet[2]. This is equivalent to 1.5% for a 20 m long wave guide. To include circulators, bends bellows etc the power loss in the distribution system is estimated to be below 5 %. In the case one klystron will be used to feed two cavities, additional power loss in the vector modulators needs to be taken into account. Depending on the type of vector modulator the power loss is between 6 and 20 per cent[3]. Therefore it is assumed that 10 % additional power loss needs to be compensated for in the case of power splitting. The transmittance in the rf distribution system is then given by

- 1 cavity per klystron: 95%
- 2 cavities per klystron: $0.95 \cdot 0.90 = 85.5\%$

[1] O. Brunner et.al, Phys. Rev. ST Accel. Beams 12, 070402 (2009), however this is based on SF6 pressurized wave guides

[2] http://www.eriinc.com/pubs/20090321006_AEN01w.pdf

[3] email R. Ruber

Margin for LLRF: It will be assumed that a 30% margin on the klystron peak power is needed for the low level rf system.

Klystron output peak power: Taking into account the transmission in the rf distribution system and margin for LLRF, the output peak power of the klystrons needs to be specified according as

- 1 cavity per klystron: $1\text{MW}/(0.95 \cdot 0.70) = 1.50\text{MW}$
- 2 cavities per klystron: $2\text{MW}/(0.855 \cdot 0.70) = 3.34\text{MW}$

to achieve 1 MW at the power couplers.

Klystron efficiencies: The following specification of klystron efficiencies are specified by Thales and CPI. The klystron efficiency decreased with increasing output power due to space charge.

- 1 MW output peak power: 65% (specification by CPI (Technical Proposal 10-20-06.pdf))
- 1.5 MW output peak power: 62% (estimate by CPI)
- 1.5 MW output peak power: 65% (estimate by Thales)
- 3.4 MW output peak power: 55% (estimate by Thales)
- 4 MW output peak power: 50% (estimate by CPI (Technical Proposal 10-20-06.pdf))

The experience from SNS is that the klystron efficiencies from Thales do not meet the specifications. (At Oak Ridge the Thales klystrons are successively being replaced by CPI klystrons). Therefore the following klystron efficiencies will be used for the calculations:

- 1 cavity per klystron: 1.50 MW output peak power: 62 %
- 2 cavities per klystron: 3.34 MW output peak power: 50 %

Specification of the klystron modulator: The output peak power of the klystron modulator therefore need to deliver:

- 1 cavity per klystron: $1.50\text{MW}/0.62 = 2.43\text{MW}$
- 2 cavities per klystron: $3.34\text{MW}/0.5 = 6.68\text{MW}$

Rf pulse length and duty factor: Assuming it takes 0.3 ms to fill the rf power into accelerating cavities[4] the rf pulse needs to be approximately 2.3 ms. Then, with 20 Hz repetition rate a duty factor of 4.6% is given. Assume 85 % efficiency of the modulator [5]. Then the average power requirement for each modulator is given as:

Average power requirement per modulator:

- 1 cavity per klystron: $2.43\text{MW} \cdot 0.046/0.85 = 131\text{kW}$
- 2 cavities per klystron: $6.68\text{MW} \cdot 0.046 = 362\text{kW}$

Total power consumption: With 96 elliptical cavities and (4800 + 480) h/year operation (including start up and r&d beam time) the average power consumption becomes:

- 1 cavity per klystron: $96 \cdot 131\text{kW} \cdot 5280/8766 = 12.6\text{MW}$
- 2 cavities per klystron: $68 \cdot 362\text{kW} \cdot 5280/8766 = 17.4\text{MW}$

Thus, power splitting is likely to cause an increase of the total power consumption of 4.8 MW, which is contradictory to the ESS objective of being climate neutral and reducing the estimated energy requirement from 40 MW to 32 MW[6]. The problem is that the efficiency of the klystron depends on the output power. One way to overcome this is to consider elliptical beam klystrons (This is the major reason why we started exploring the elliptical beam klystrons).

Cost estimates based on a

- zero cost for the vector modulators (which is not realistic)
- 100 000 EUR per klystron [7] (which is not realistic for the high power klystron) and 100 000 h life time of klystrons [8] (which is not realistic for the high power klystron)
- input from Jorgen Persson (energy expert at ESS) on investment in windmills, operational costs and profit from recycling surplus water

[4] The 0.3 ms filling time is based on a gradient of 15 MV/m and a current of 50 mA (email Frank Gerigk)

[5] Klas Elmquist @ Scandinova (depends on the level of droop compensation in the modulator)

[6] http://ess-scandinavia.eu/ess-and-the-environment/ess-energy-consumption

[7] Edward Eisen @ CPI

[8] Edward Eisen @ CPI

show that the compensation for the increased power consumption that the power splitting causes for the high beta elliptical cavities is not economically defensible.

The conclusion is that power splitting at high beta elliptical cavities can lead to

- Increased investment costs
- Reliability issues due to higher power in equipment and a more complex solution
- Increased time for r&d since high power klystrons and modulators will have to be developed and tested.
- Increased risk that we will have to rebuild the klystron gallery to a more safe solution...
- Need for using SF6 gas around rf windows and in circulators.
- Need for using toxic Beryllium-oxide rf windows.
- A worsen situation if we plan for 1.2 MW at the coupler.

However, power splitting is interesting for the $\beta = 0.65$ elliptical cavities, since then the power requirement is about a factor of two lower. Then we can use the same modulators and klystrons as for the high beta elliptical cavities in an efficient way.

Suggestion to reduce the power consumption Take out the tuning circuit of the klystron modulator. This system flattens out the droop of the pulse signal to make it square shaped. Compensate with the LLRF system, such that the klystron operates near saturation in the end of the pulse. This could save 2.6 MW average over a year! R&D on power distribution and LLRF is very important!