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Report from RF Power Source Workshop

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Report on the RF Power Source Workshop

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Abstract

Status report on the ESS rf power source, with emphasis on the High beta Elliptical cavities. A substantial part of the content is the outcome of the rf power source workshop in Lund 2011-06-13 [1]. The main objectives of this workshop was to specify parameters concerning the rf power source for high beta elliptical cavities in order to prepare for prototype procurements. The parameter tables can be found on the ESS ad home page [2, 3]. The focus is entirely on the high beta elliptical part of the power source, due to the high power levels and the large number of units.

1 ESS RF Power Sources

1.1 Prerequisites linac parameters:

All calculations in this document is based on the ESS high level parameter table dated 15 April 2011 [4] and the Accelerator Science and Lattice parameter table 13 May 2011 [5]:

Average power: 5 MW

Beam pulse length: 2.86 ms

Beam pulse repetition rate: 14 Hz

Reliability: 95% reliability

Operation: 5200 h of operation per year including R&D and start-up.

Elliptical power coupler power to beam: 0.9 MW

The difference between the rf power calculations in this work and in a previous technical note [6] is that here a 20% safety margin for the rf power is foreseen, rather than the 10% safety margin previously used due to the uncertainty about the voltage limit of the klystron modulator for the 2.86 ms long pulses.

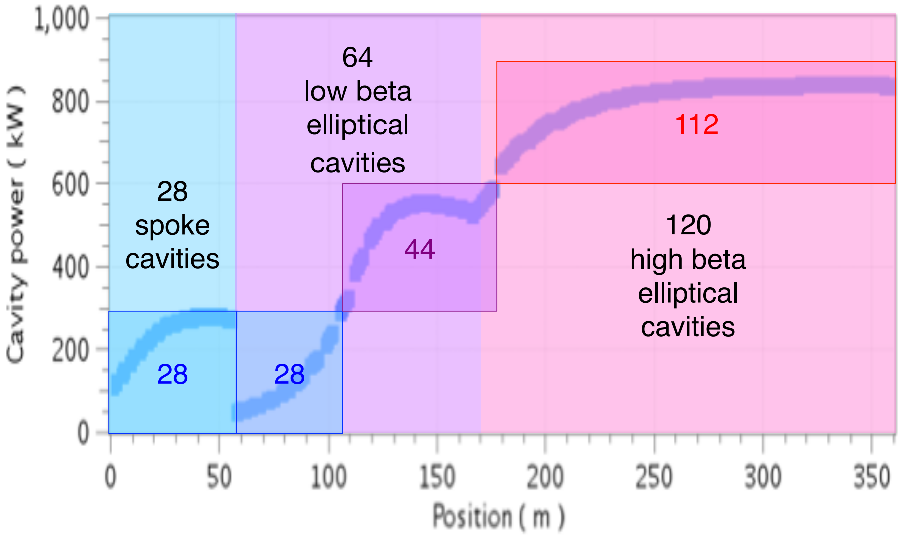


Figure 1: Power to beam of superconducting part, based on the hybrid lattice in [7]

1.2 Lattice and power to the beam

The linac consists of an RFQ, 3 DTL tanks, 28 spoke cavities, 64 low-beta ellipticals, 120 high-beta ellipticals, according to the hybrid design in [7]. The power to the beam for the superconducting part is shown in fig. 1. Five types of RF amplifiers are proposed:

Frequency MHz	Minimum Power MW	Nominal Power MW	Maximum Power MW	Number	Type
352	?	?	?	6	Klystron
352	0	0.4	0.5	28	IOT?
704	0	0.4	0.5	28	IOT?
704	0.5	0.8	1	44	Klystron
704	1	1.2	1.5	112	Klystron

The nominal and maximum peak powers of the rf amplifiers are based on scaling factors equal to 4/3 and 5/3, respectively. This is consitent with the rf calculations below for the high beta elliptical cavities. The power level for the warm part of the linac is not yet defined, however one should strive to use the same kind of modulator as for the High beta elliptical cavities.

2 RF power calcualtions

The maximum rf power delivered to the high beta elliptical cavities is 0.9 MW. 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.

2.1 Power losses in the rf distribution system

The power loss in the WR1500 wave guide is 0.053 dB per 100 feet [8]. 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 %. More investigations on losses in the distribution system are needed.

2.2 LLRF requirements

Extra rf power is required to compensate the effects of Lorentz force detuning, microphonics, synchronous phase operation, load Q variations and other perturbations (like klystron output droop and ripple, beam loading, etc.).

For the high beta elliptical cavities, the extra power for Detuning (Lorentz and microphonics) is around 1% at 100 Hz detuning but 90% at 1000 Hz. The extra power for synchronous phase operation is different from cavity to cavity during the linac, but only 1.79% at the 15 degrees that we are planning for the high beta cavities. More power would be needed as well if the load Q varies away from the optimum value. Calculation shows about 1% more power is needed for 10% variation but 14% more for 50% variation. Other perturbations like klystron output droop and beam loading also result in errors in cavity voltage. Typically, 2% more power is required to compensate per 1% error in voltage. Furthermore, if the RF system feedback loop produces an overshoot, the klystron needs to handle the voltage and power corresponding to the overshoot, which consumes much more power in principle.

We would experience very harsh difficulties if there is not enough extra power. For example, in the case of only 10% extra power for operation, we have to achieve that the cavity detuning (including both Lorentz force and microphonics induced detuning) should be strictly controlled below 100 Hz, the load Q variation could not be over 10%, and meantime the voltage error caused by other perturbations and overshoot should be strictly limited to below 3%. It needs perfect piezo tuner, perfect power input coupler, perfect modulator and everything. While 20% extra power is flexible (be able to deal with 200 Hz detuning, 20% load Q variation, and 6% voltage error by other perturbations and overshoot,for roughly estimate), though we still have to make efforts to achieve it.

However, 20% is just for normal operation. If some unexpected worse situations occur, such as cavity tuner disable, large load Q variation, and large voltage error, we have to use more extra power even up to 50%. Klystron nonlinear distortion is another factor to increase the extra power. We might not totally operate very close to saturation even after applying the linearization techniques for klystron.

For the cavity filling time, an ideal filling time is 213 μs for high beta cavities. The filling time can be shortened by applying more power, and become longer if there is less power. We also need some time for feedback stabilization. A reasonable filling time is 350 μs or more (including ideal filling time, the prolonged time due to less power, and the time for feedback stabilization). Screen shots of the forward, reflected and cavity power from SNS, shown in fig. 2, indicates that this is in agreement with the situation at SNS.

For the droop and ripple of the modulator, a requirement of less than 3% for low frequency ripple and 0.1% for higher frequency is given. That is from the limitation of the feedback proportional gain and effective bandwidth of integral gain.

2.3 Klystron and modulator

Taking into account for the 5% power loss in the distribution system and 20% 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

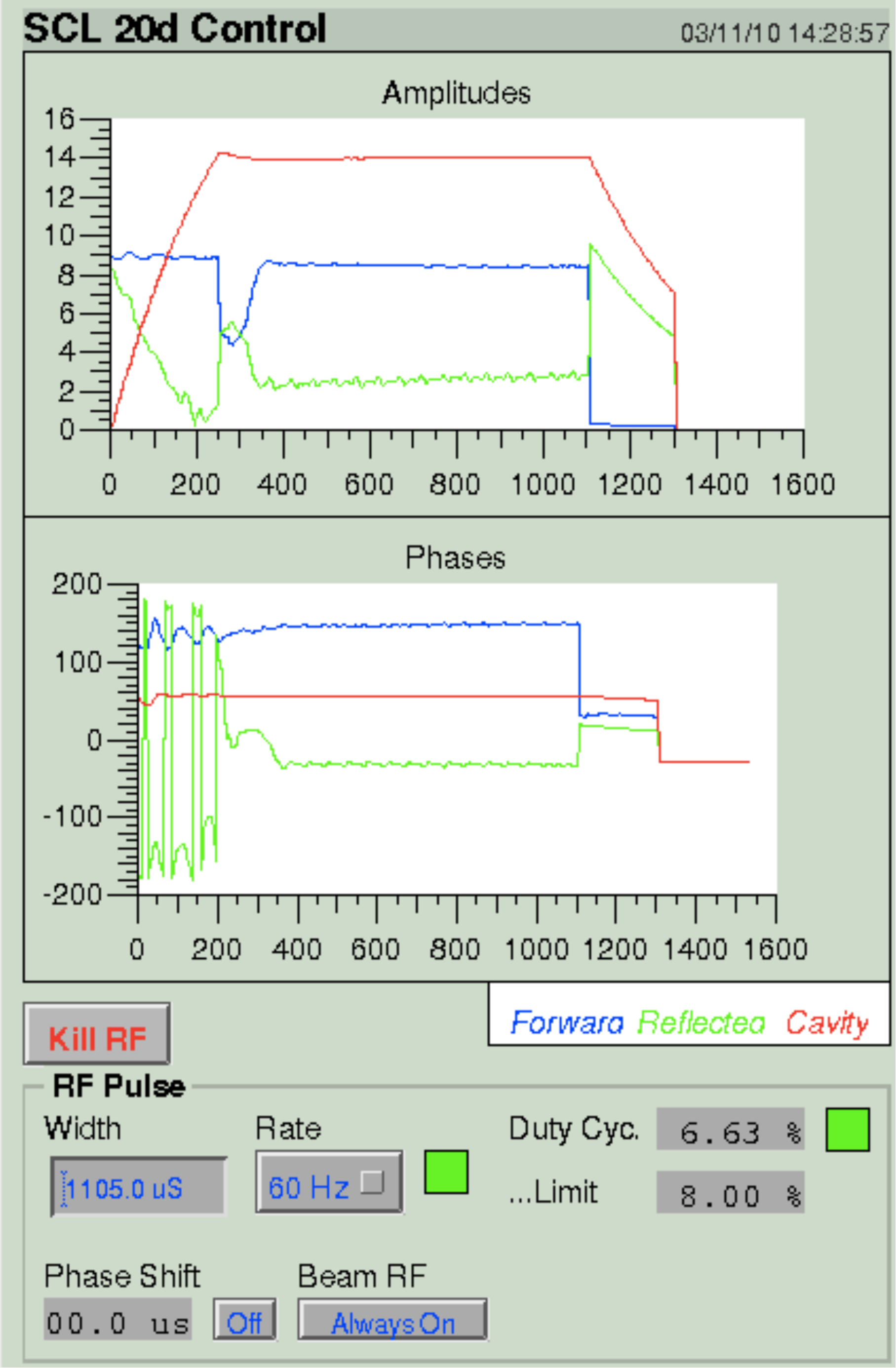
$$K = 0.55 \ \mu\text{AV}^{-3/2}$$

a 65% efficiency can be reached [9]. This is also in accordance with the formula for efficiency [10]

$$\eta = 0.78 - 0.16K$$

The nominal beam power, which has to be supplied by the modulator, is then given by

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



SCL 20d Control

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RF Pulse

Width: 1105.0 uS

Rate: 60 Hz ☐

Duty Cyc.: 6.63 %

...Limit: 8.00 %

Phase Shift: 00.0 us Off

Beam RF: Always On

Figure 2: Screen shots of the forward, reflected and cavity power for a superconducting high beta cavity (SCL22d) at SNS taken by M. Crofford. One can clearly see the fill of the cavity, start of feedback and then the beam w/ AFF on for the remainder of the pulse.

The beam perveance then gives the required nominal cathode voltage U as

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

2.4 Specified values

By dimensioning klystrons and modulators to withstand 20% extra power we can expect reliability to improve. This excess power margin will be useful in the case the cavity performance varies from cavity to cavity or if a cavity fails. In this case the voltage can be increased in other cavities to make up for the failing cavity. In additional it will be possible to adjust the rf power if the total power loss or the required LLRF margin has been underestimated. Degradation of the klystron is likely to occur over time and this needs to be compensated for by a increase the cathode voltage.

With the 20% additional power margin the specified maximum output peak power by the klystron is 1.5 MW. The klystron modulator, in its turn, needs to supply a maximum of 2.3 MW in peak power, which corresponds to a cathode voltage of 113 kV.

2.5 RF pulse duration and cooling requirements

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

Adding 400 μs to fill the cavity, according to the requirements given in section 2.2 the rf pulse duration is 3.3 ms with a rf duty factor of

$$D = 14 \text{ Hz} \cdot 3.3 \text{ ms} = 4.6\%$$

Therefore, the rf power load has to be dimensioned to absorb

$$4.6\% \cdot 1.5 \text{ MW} = 69 \text{ kW}$$

of the reflected rf power.

For a modulator with a pulse transformer the expected rise time is 200 μs, which results in a total pulse length of $\tau = 3.5$ ms. This corresponds to an rf duty cycle equal to

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

Therefore, the klystron modulator will be dimensioned for an average output power of

$$4.9\% \cdot 2.3 \text{ MW} = 113 \text{ kW}$$

which is also the maximum cooling requirement of the klystron collector.

The klystron modulator shall have a 90% power efficiency or more. The water cooling system for the klystron modulators then needs to be design for a maximum power of

$$10\% \cdot 113 \text{ kW} = 11 \text{ kW}$$

per unit. With the large number of power sources in the klystron gallery and the stringent temperature stability demands, only a small fraction, 1 kW of the excess power is allowed to be deposited in air.

2.6 Power efficiency

Taking into account 90% power efficiency for the klystron modulator the nominal power consumption can be calculated as

$$4.9\% \cdot 1.8 \text{ MW}/90\% = 100 \text{ kW}$$

In relation to the rf power delivered to the power coupler

$$4\% \cdot 0.9 \text{ MW}\% = 36 \text{ kW}$$

we can estimate the power efficiency for the high beta elliptical section to be roughly 30% if we also take into account for example the klystron solenoid, water cooling system, power supplies, etc.

Since the high beta elliptical cavities accounts for roughly 75% of the total power delivered to the beam, we can expect a total power consumption of 5 MW/0.30 = 17 MW. Then, with 5200 h per year operation the total power consumption is 87 GWh per year. This is almost a third of the total power budget for ESS, equivalent to an operation cost of roughly 5 MEUR.

3 Challenges

3.1 Technical Callenges

To our knowledge, no one has achieved 3.5 ms long pulses at these power levels and especially not for this magnitude of a klystron gallery. There is a risk that thermal stress, in terms of pulse heating, will worsen the reliability of the equipment. The probability of arcs in the klystron and rf distribution system will to some extent also increase with the pulse length. An improvement is however the overall 5% reduction in average power consumption due to the decrease in duty factor for the klystron modulators. However, this power saving might be consumed by the LLRF system, since the low frequency variations on the high voltage pulse is another concern for these long pulses. Another implication is that the size of the pulse transformer increases with $(U\tau)^2$, which corresponds to a 90% increase as the pulse length increases from 2.6 ms to 3.5 ms. On the other hand, other parts of the modulator, such as the capacitor charger power supplies, becomes smaller due to the relaxed pulse repetition rate. The only conclusion at this point is that more analysis of the implication of the longer pulses is needed.

According to C. Lingwood it is worth looking into the possibility of getting the longer pulse using a modulated anode klystron, as have been studied in reference [11]. The high power rf at JPARC is pulsed by modulating the anode voltage of the klystron. Then the klystron modulators can be replaced by large DC power supplies. This solution proved to be the most cost beneficial alternative for JPARC. According to C. Martines however, this is not an alternative for ESS because of reliability and efficiency concerns.

A more attractive solution for the rf power source would be to chose the 50/3 Hz = 16.7 Hz pulse repetition rate. This would give a beam pulse length of 2.4 ms preserving the 4 % beam duty factor. Then the high voltage pulse width is 3.0 ms, which is very close to the 2.8 ms pulse specified for the SM18 test stand prototype.

3.2 Financial and commercial challenges

The rf power source and distribution system make up for a substantial part of the total accelerator budget. There are few qualified suppliers worldwide, each with a limited production and testing capacity. Serval manufacturers are not based within the ESS member countries, which make no-cash contributions challenging.

Assuming an aggressive production, testing and installation rate of one rf power source per week, the orders must be placed in 2014 in order to deliver the first neutrons by 2019. This will require early prototyping and multiple vendors.

Several of the klystron modulator companies have their own preferred solution rather than the open solution developed at DESY and FNAL. It is therefore necessary to find a balance between on the one side the strive for an open solution with multiple sources, or on the other hand to give away as much as possible of the responsibility to the contractors.

Challenges with prototype and testing activities include the fact that parameters are not yet fixed, the SM18 test stand modulator (and klystron) are not prototypes for ESS and the short time schedule in combination with lack of high power rf experts and personnel at ESS.

Provided that the power to each of the cavities can be increased, it might be beneficial to increase the rf power in order to reduce the total number of power sources and cavities. For example, if the power delivered to each of the cavities could be increased by 30% on an average, then the production time could be shorten by roughly a year. However, splitting the power from one klystron into two cavities in the high beta elliptical section is not to recommend as concluded in [12].

Another possibility would be to use one modulator to two klystrons. The feasibility of such a solution depends on the modulator topology. The disadvantage is that in case one modulator fails, then two cavities will not be in operation. Secondly, both klystrons will be powered the same, regardless of the rf power output needed, so this will increase the power consumption. Another argument is the issues with the 3.5 ms long pulses, which are likely to worsen if the power is doubled. Again, more investigations are needed.

3.3 Reliability

The rf power sources are expensive and complex with many components. With more than 200 rf power sources and an assumed MTBF of 4 years (or 20000 h) per unit, we can expect to do maintenance every week in the klystron gallery.

With an assumed MTBF of 40000 h for a klystron implies that 20 klystrons on an average will fail each year. Not all of these will have to be refurbished, but assume that the cost for each klystron failure is 100 kEUR. Then, the operational cost for the klystrons is estimated to 2 MEUR per year.

To meet the 95% reliability demands the following is proposed:

- Chose well proven solutions only.
- Design for an overhead crane in the klystron gallery that will facilitate fast replacement of parts. The overhead crane will in addition speed up the installation in the klystron gallery.
- Design for easy access and quick replacement of modulator, pulse transformer and klystron.
- The klystrons are vertically mounted in a separate oil tanks and connected to the klystron modulator through a short (< 2 m) high voltage cable. The oil tank is taken out together with the klystron in the case the klystron needs to be replaced
- If the klystron modulator is equipped with a pulse transformer, then it should be easy to disconnect it from from the air isolated part of klystron modulator, in the case the modulator needs to be replaced.
- Insulate high voltage parts in oil.
- One rf source per cavity, so that the linac can operate also when on power source is fails.
- MTBF, MTTR and lifetime analysis of all components is necessary.

3.4 Personal Safety

Personal safety issues include large stored energy, large amount of cooling water, large quantities of oil, radiation (neutrons, x rays and electromagnetism). Lifting and transport of heavy objects is another important safety issue.

3.5 Access and Serviceability

In the present lattice design there is 1.6 m average center to center distance between the cavities in the high beta elliptical section. Thus the design of the klystron gallery is critical, and double rows of klystrons and modulators are now envisaged. Rules about working with electrical installations of this kind require 1.5 m free space behind your back when working in a cabinet.

Double rows of klystron and modulators will make it easier to optimize the layout inside the modulators, since now we can allow the modulators to become wider, up to 1.5 m with 1.7 m access in beween.

The draw back with double rows of power sources is that we probably need two klystron galleries, one on each side of the linac, as shown in 3. According to Montessinos [13] this type of power source and distribution system takes up 29 m^2 floorspace each. I.e, a 20 m width is needed in the klystron gallery only for the rf power source. With access ailes and shielding above the accelerator tunnel as shown in fig. 3, the klystron gallery is likely to be between 35 and 40 m wide, not taking into account maintenance and laboratory areas.

With 1.7 m access between the modulators we can take out klystrons between these without having to lift them over the modulators, as was suggested in the previous layout [14]. This means that the ceiling hight can be lowered.

4 Conclusions

More investigations are needed but the time is short. Prototyping is very important. The ESS project office have to be involved at an early stage. Especially the design, conventional facilities and safety teams will have to be involved to resolve issues concerning layout, access, maintenance, safety and system integration of for example cooling, oil handling, cabling etc.

References

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[2] ESS Parameter Tables. LLRF paramter table, 2011.

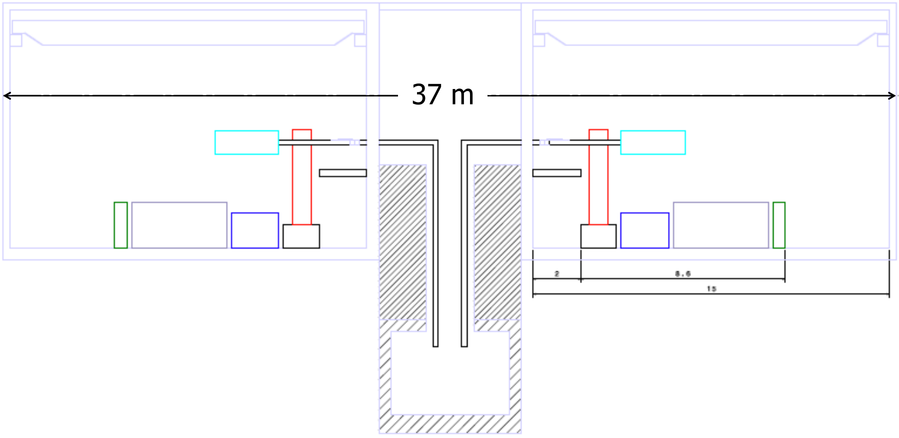

Figure 3: First draft of the cross section of the klystron gallery with double rows of power sources.

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