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Abstract:

The report describes selection of RF power source and distribution scheme for spoke cavities at ESS and FREIA. The European Spallation Source (ESS) is the world's most powerful neutron source, which contain 36 superconducting spoke cavities at 352MHz and provide power of 0.5MW to the beam. The baseline for the RF system is a point-to-point generation and distribution from a single source to a single accelerating cavity .The RF system that has to generate this power and distribute it to the accelerating cavities, is a main resource driver for linear accelerators in form of investment, operation and maintenance. Therefore the technical alternatives are compared to minimize capital and running cost of the accelerator, without compromising its reliability. At 352 MHz and 350 kW RF power output, tetrode amplifiers are selected because of their advantages of being cheap, reliable, simple and efficient as compared to the other RF power amplifiers. The tetrodes, due to their low gain, need a pre-driver. The solid state amplifier technology is selected as a pre-driver due to its simplicity, reliability and efficiency. Half height aluminum WR2300 wave guides shall be used for RF distribution. This solution makes it possible to discard the circulator from the RF distribution chain, thus improving system efficiency.

1. Introduction

The European Spallation Source (ESS) is the world's most powerful neutron source. The ESS linac [1] will accelerate 50mA of protons to 2.5 GeV in 2.86 ms long pulses at a repetition rate of 14 Hz. It produces a beam with 5 MW average power and 125 MW peak power. There are 36 superconducting spoke cavities which provide power of 0.5 MW to the beam.

For the ESS proton linear accelerator, in relation to other proton accelerators, a high power level is required. The RF system, that has to generate this power and distribute it to the accelerating cavities, is a main resource driver for linear accelerators in form of investment, operation and maintenance resources such as material, electricity and manpower. Therefore the choice between different technical alternatives will affect the investment, operation and maintenance resources required for the RF system and shall not compromise its reliability.

The baseline for the RF system is a point-to-point generation and distribution of the RF power from a single source to a single accelerating cavity [1]. The RF power source converts the DC input power into RF power. It consists of a power supply, a power amplifier and a RF signal generator. The RF distribution system consists of waveguides, circulators, directional couplers etc. that transmit the RF power to the accelerating cavities.

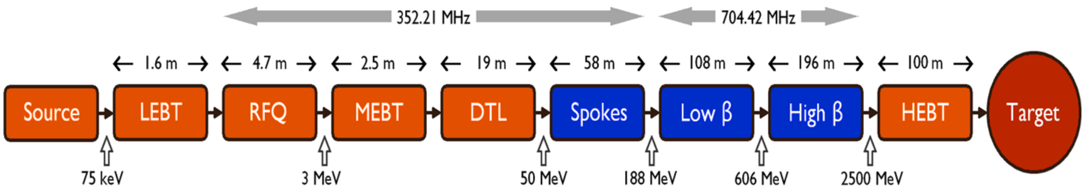

Fig.1: Schematic of ESS linac

The ESS linac uses two different frequencies, namely 352.21 MHz and 704.42 MHz. The spokes section contains 36 superconducting spoke resonators at 352 MHz[1].

The capital and running cost of an accelerator is strongly affected by the RF power amplifiers in a number of ways. The capital cost of the amplifiers (including replacement tubes) is an appreciable part of the total capital cost of the accelerator. Their efficiency determines the electric power required and, therefore, the running cost. The gain of the power amplifier determines the number of stages required in the RF amplifier chain. The size and weight of the amplifiers determines the space required and will therefore, have an influence on the size and cost of the gallery in which the accelerator is installed. Hence selection of power source is very important.

FREIA, the test facility at Uppsala University will be prototype the ESS RF power source and RF distribution system for the superconducting spoke resonators.

2. Layout

The basic layout of the RF system is shown in fig.2[2]. The RF power source consists of the LLRF signal generator and a RF power amplifier driven by a power supply. There will be only one spoke resonator per power source. The RF distribution system transmits the RF power from the RF power amplifier to the spoke resonator. The RF distribution system consists of circulator, directional couplers, wave-guide and dummy load.

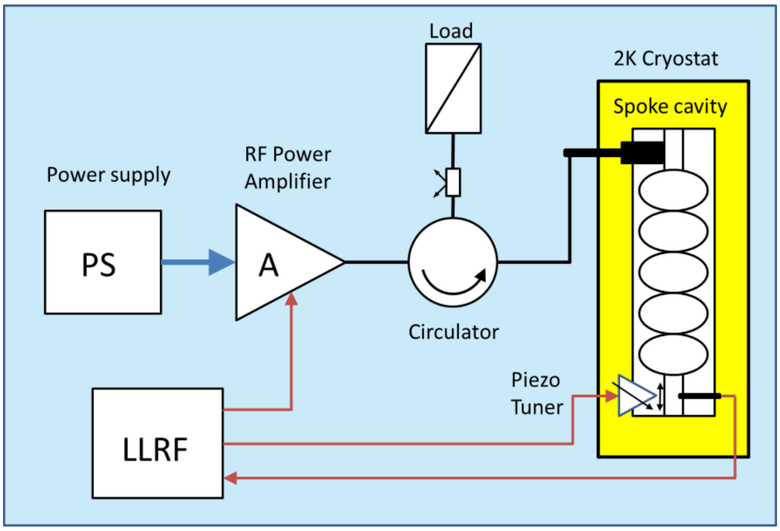

Fig.2: Basic layout of an RF system.

The maximum required RF power for a spoke resonator at 50 mA beam current is 245 kW. Considering a LLRF overhead of 25 % and a RF loss budget of 5 %, the required RF power can be fixed at 320 kW. The beam pulse width shall be 2.86 ms at the repetition rate of 14Hz. The fill time of the cavity is 600 µs and no beam power is required after the pulse. Thus the duty factor of the amplifier shall be at least 4.6 %. The system band-width should be at least 100 times larger than spoke resonator band-width for tuning and regulation delay. The loaded Q of the cavity will be in the order of 160000, which sets the cavity band-width in the order of 2 kHz. The 3 dB bandwidth of the output power referenced from the maximum saturated power shall be greater than 200 kHz.

In summary, the specifications of RF amplifier are:

Frequency = 352.21 MHz

Power = 350 kW

Band-width = 200 kHz.

Pulse width = 3.5 ms

Pulse repetition rate = 14 Hz

Selection criteria used for selection of amplifiers will be discussed in the next section.

2a: Amplifier:

Typical power sources used at 352 MHz are tetrodes, klystrons, IOTs, solid state amplifiers and diacrodes.

The technology of the tetrode is well proven and this tube benefits from robustness and reliability in operation. It requires several DC power supplies: a high voltage supply for the anode and a moderate voltage supply for the screen grid. In saturation regime, when the anode current is limited by the field-emission properties of the cathode, the tetrode is not sensitive to ripples or drops of the anode voltage therefore it imposes moderate requirements on the anode voltage supply. Thus making the system simple (no.15, table 1). The tetrode gain is relatively low, around 20 dB, and an intermediate amplification stage is required.

Table 1: Table showing comparisons of different types of amplifiers [3].

No.	Parameter	Tetrode	Klystron	IOT	Solid state amplifier
1.	Cost of driver tube (kEUR)	38	300	313 for one tube	1000
2.	Cost of other required accessories (kEUR)	150	20	20	820
3.	Number of sources producing power (350 kW)	Single tetrode	Single	2 IOT with 200 KW of each	70 modules of 5 kW each are combined
4.	Size	Size ϕ = 17 cm H = 21 cm	1 m x 1 m	1 m x 1 m	approx. 20 m^2
5.	Size of output cavity	Size ϕ = 1 m H = 1 m	-	-	-
6.	efficiency	60 -70 %	60 – 65%	70 %	65 %
7.	Gain (dB)	12 - 20	37	23	54 (ref to 1 W)
8.	Type of cooling	Water cooled	Water cooled	Water cooled	Water cooled
9.	Power supplies for driver Maximum DC voltage (kV)	DC power supply 22	Modulator 100	DC power supply 30	For each module: 50 V, 200 A
10.	Cost of power supply (kEUR)	135	600	200	Included in Cost of other accessories
11.	Need of other device for combining and their number	No	No	Hybrid coupler One	Hybrid coupler Several
12.	Need of circulator (device to handle	No	Yes	Yes	Circulator(s) is needed

	reflection)				
13.	Pre-driver	Needed Power = 20 kW	Not needed	Needed Power = 2 kW	Not needed
14.	Life time (khours)	20 - 25	40 - 50	the estimate is 60 to 70	Estimate is > 50
15.	Replacibility	Very easy (1 or 2 hours)	Difficult	Total IOT to be replaced	Can be made easy.
16.	Simplicity of system (pl. refer to the discussion)	Simple	No	Simple	Complex
17.	Delivery time	6 months	Depends on modulator	12 months	More than 18 months
18.	Cost of amplifier and power-supply system (kEUR)	325	920	850	1820
19.	Capital cost of amplifier and predriver (kEUR)	448	920	860	1820
20.	Running cost (kEUR) (pl. refer to section 4)	395	425	395	425

Klystrons are based on the velocity modulation principle whereas the gridded tubes (IOT or tetrodes) are based on the density modulation principle. Mentioned differences in the efficiency behavior are related to the fact that velocity modulated devices have the advantages of high gain and high efficiency at saturation. Density modulated devices employ RF control of the electron flow directly at the cathode surface, making them more compact than velocity modulation based devices. Moreover, because electron emission is controlled by the RF signal, the efficiency is high even in the linear regime. The difference in modulation principles results also in different values of gain. A klystron can demonstrate a gain of 37 dB or more whereas the gain of gridded tubes is below 20 dB. Due to the high gain of klystrons, a preamplifier is not needed. However a klystron is typically ten times costlier than a tetrode. Similarly, modulators which are used to power a klystron are complex and ten times costlier than the DC power supplies which are used to power tetrodes. Thus one essential advantage of gridded tubes over the klystron is simplicity of their power supply that is a high-voltage DC power supply (no. 15, table 1). The klystron gain is dependent on reflected power so it needs circulator for handling reflection. These modulators operate at fairly high voltage and need to meet requirements on the voltage and current stability that make them much more expensive than DC power supplies. From the point of view of the efficiency, cost and complexity gridded tubes are therefore in favour compared to klystrons. Due to its rugged structure, the life time of a klystron is typically 40 - 50 khours. Due to its big size and high weight (5 ton) it is rather difficult to replace a klystron.

As we mentioned, there are two candidates among gridded tubes namely the tetrode and the IOT. The IOT is a relatively new device in accelerator physics and can be considered as a klystron/tetrode hybrid. It has advantages over the klystron in terms of linearity and efficiency and over the tetrode in terms of gain and output power. The IOT is a success in the television broadcasting domain where it almost completely replaced the klystron. They are now under active development for scientific applications and being used in the Diamond Light Source, Elettra Light Source as well as the Australian National Synchrotron at 500 and 1300 MHz Despite recent progress on IOTs for accelerator driver applications, there are still no commercially available IOTs at 352 MHz with a the high level of power required for our application.

Solid state power amplifiers employ LD-MOS transistors fabricated from wide band-gap semiconductor material. Each transistor can give an output of 1000 W maximum pulsed power and 700 W CW. Generally RF modules consist of eight transistors combined with a combiner to an output power of 5 kW. To achieve higher power like 350 kW, many such modules are combined in parallel. If operated in class AB, the efficiency of solid state RF pre-amplifier is 65 %, and its gain is 54 dB. It has the highest gain among all the amplifiers. Its life time is also the highest among all the amplifiers: more than 50 khours. But at the same time its size is very large (foot area 20 m^2), very big even than a klystron and also it is the ten times costlier than tetrodes.

If we compare all the amplifiers, the tetrode is the cheapest solution: the tetrode is at least 10 times cheaper than all the other types of amplifiers. It can have a high efficiency dependent on the class of operation. In case of a class C amplifier, the efficiency can reach up to 75 %. The size of the amplifier is determined by the foot area of output cavity, around 1 m x 1 m. Its gain is 15 - 20 dB. So it needs a pre-driver with output power of 20 kW. It can be water cooled to avoid blower noise. The tetrode can work with standard DC power supplies. It requires anode power supply, filament power supply, control grid power supply and screen grid power supply. The details about the power-supply are discussed in another report [4]. As the tetrode can handle 100 % reflection, a circulator is not needed. The lifetime for the tetrode based amplifier is in the order of 17 - 20 khours. Its lifetime is shorter as compared to the other devices but it is very easy to replace the tetrode. It can be replaced in 2 - 3 hours.

Thus tetrode is the best choice as the ESS amplifiers for the superconducting spoke resonators at 352 MHz

2b: Preamplifiers

As explained in the previous section, the tetrode is the preferred choice for the amplifier type. As the gain of tetrodes is limited to around 12 dB, a preamplifier is needed. The required output power of the pre-amplifier is about 20 kW. Either triodes or solid state amplifiers can be used as preamplifiers.

The triode is again a gridded tube, which is discussed in the section 2a. It can be used for an output power of 20 kW. Due to a structural difference with the tetrode, its life time is limited to only 12 - 15 khours. Further, due to its low gain, it needs a pre-predriver which can be again a triode, with an output power of 1 kW, and in addition a solid state low power amplifier with an output power of 100 W. Each triode requires three power supplies: anode power supply, screen-grid power supply and control-grid power supply. The complexity of the system is higher, though its cost is less than the cost of alternative solutions. The dimensions of such a system are 0.61 m x 0.86 m x 1.93 m with a weight of 500 kg.

Solid state amplifiers are discussed in section 2a. The amplifier consists of four modules of 5 kW each to reach an output power of 20 kW. The power supply is a distributed power supply of 50 V and 200 A. Due to its high gain (73 dB), it doesn't need an extra pre-amplifier. If operated in class AB, its efficiency is 60 %. Its efficiency can be increased to 70 %, by operating in class C mode.

Table 2: Predriver for 350 kW tetrode (power 20 kW, freq. 352MHz).[3]

Parameters	Solid state amplifier	Triode
Cost (kEUR)	125	74.50
Power (kW)	20	20
Size	0.8 m x 1 m x 33 U	0.61 m x 0.86 m x 1.93 m
Weight (kg)	400	500
Efficiency	70 %	50 - 60 %
Gain (dB)	73	20
Power supply	50 V, 200 A (distributed power supply for each module of 5 kW)	Included, input 400 V AC, 50 Hz, 3-phase
Type of cooling	Water cooling	Air cooling
Life time (khours)	> 50	12 - 15
Number of stages	Only one	It consists of three amplifier stages. It requires pre-predriver triode(1 kW), and solid state low power amplifier (100 W)
Simplicity	Simple	Complex system. 3 amplifier stages, their power supplies, interlocks
Replacibility	Modular system, so easy	Triodes can be replaced easily in 1 -

	replacement possible. Can work even if 1 or 2 modules fail.	2 hours. Cannot work if even if 1 stage fails.
Reliability	Good	Poor
Connector for RF input	SMA	Selectable
Connector for RF output	EIA 3”1/8	EIA 3”1/8
Delivery time	6 months	6 - 8 months

If we compare solid state amplifier and triode as pre-drivers, the triode is the cheapest option. But due to the low gain of a triode, the triode based per-driver consists of in total three stages: two triodes and one solid state amplifier. There will be six power-supplies for two triodes and thus the system becomes complex. Due to the low lifetime of a triode and the number of power supplies, the chance of failure increases, thus the system reliability is lower. Therefore a solid state amplifier is the preferred solution for the preamplifier.

2c: RF Distribution:

The RF distribution consists of transmission line, circulators and loads. The transmission line at 352 MHz and 350 kW power can be either coaxial line or waveguide.

Table 3: Comparison between coaxial line and wave-guide

No.	Parameter	Coaxial line	Waveguide
1.	Standard name	6 1/8 inch	WR2300
2.	Outside dimension	6 inch	23 inch x 11.5 inch
3.	Material	Inner conductor : Copper Outer conductor : Aluminum Dielectric : Teflon / ceramic Inner conductor joint: Be Cu	Aluminum
4.	Loss in dB/m	> 0.0035	< 0.002
5.	Peak power handling capability	> Few MW	Few MW
6.	Installation	Difficult	Easy
7.	Cost	3100 euro/m + cost of ceramic + cost of inner conductor joint	1900 euro/m

It can be clearly seen from the table 3 that capital cost for RF distribution will be low if waveguides are used. Further they offer low loss and their installation is also easy. In conclusion, waveguides are selected for RF distribution.

The type of waveguide used is WR2300 in the frequency band 320 - 490 MHz with dimensions 23 inch x 11.5 inch. Their power handling capability is in the order of a few MW. The power requirement for the spoke cavities is only 350 kW, so a half height waveguide (23 inch x 5.75 inch) can be used. This reduces the waveguide size and cost. Also it will save space and handling will be easier. The waveguide material can either be copper or aluminum. As compared to aluminum, copper is more costly. Also due to a difference in weight density, the components made from copper will be 3.5 times heavier than those made using aluminum. Thus aluminum would be the preferred material for waveguides. Acceptable alloy types are 6061-T6, anticorodal 100, 6060, 6081, 4103 or equivalent. As the waveguides will be used indoor, uncoated waveguides can be used.

Initially during beam fill time and tuning, the spoke cavity will act as a short and full power will be reflected back to the RF amplifier. When a circulator is used in between the RF amplifier and cavity, the power reflected from the spoke cavity will be diverted to a load attached to the circulator and the reflected RF power will be dissipated there. As a tetrode can handle 100 % power reflection, the circulator can be avoided, thus decreasing capital cost of the system. This has one more advantage that the power dissipated in the dummy load can be avoided, thus increasing efficiency of the system.

The directional coupler used to monitor the RF power in the waveguide system shall be a dual directional coupler due to its compact size and good RF properties like insertion loss, coupling, directivity etc. It has a low insertion loss around 0.05 dB, coupling of 50 - 70 dB and directivity more than 25 dB.

A dummy load will be used to test the system of RF amplifier and distribution before a superconducting spoke cavity is attached. It can either be a water load or ferrite load with a return loss more than 25 dB. The final test of the complete system will be performed with a superconducting spoke cavity.

3: Layout of the final system.

The final system layout is shown in figure 3.

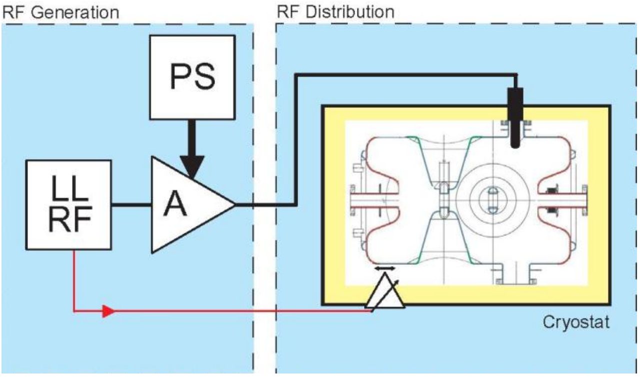

Fig. 3: Layout of the final system.

The RF power amplifier (A) is a chain of amplifiers consisting of a tetrode and a solid state amplifier. The power supply (PS) consist of anode power supply, filament power supply, control grid power supply and screen grid power supply for the tetrode plus additional DC power supplies for the solid state amplifier. The RF distribution system will not have a circulator. Initially the amplifier will be tested for full power using a matched dummy load before connecting the spoke cavity. Half height, uncoated WR2300 waveguide will be used for RF distribution. Dual directional coupler will be used for measurement of reflected power. The total system is water cooled except for the tetrode filament.

The estimated cost of the amplifier is 315 kEUR (tetrode plus solid state) and that of power supplies is 135 kEUR, leading to a total cost of the amplifier chain of 448 kEUR. The gain of the total system is 83dB with efficiency between 60 – 70 %.

4: Efficiency of spoke cavity section of ESS:

Efficiency is related to the amount of DC input power that is converted into RF power. The power which is not converted into RF power is lost as heat.

Peak power delivered by tetrode = $Ppk = 350\ kW$

With 70 % efficiency of the tetrode amplifier, the power supplied by the power supply is given by,

$$Pps = \frac{Ppk}{0.7} = 500\ kW$$

The beam pulse width shall be 2.86 ms at the repetition rate of 14 Hz. The fill time of the cavity is 600 µs and no beam power is required after the pulse. So the duty factor D of the amplifier shall be

$$D = 14\ Hz * 3.5\ ms = 4.9\ \%$$

Hence the tetrode DC power supply will give an average power of

$$Pavg = 4.9\% * 500\ kW = 24.5\ kW$$

Considering the efficiency of the cavity to be 80 %, the RF power delivered to the RF coupler in the spoke cavity is,

$Pcoupler = 4\% * 24\ 5\ kW = 9.8\ kW$

Thus the power efficiency of the spoke cavity section is roughly 40 %.

The spoke cavities account for roughly 10 % of the total power delivered to the beam. The total power consumption for the 36 spoke cavities is then expected

$Ptotal = 24.5\ kW * 36 = 882\ kW$

Then with annual operation of 5200 hours, the total power consumption for a year is $4.6\ GWh$.

At an electricity price of 0.76 SEK/kWh, roughly 0.086 EUR/kWh, the total operating cost of spoke cavity section for a year is $395\ kEUR$.

5. Reliability of RF amplifier section for ESS:

The RF amplifier consists of tetrode and solid state amplifiers. The life time of solid state amplifiers is more than 50 khours. The life time of tetrodes is in the order of 20 - 25 khours. The tetrode life time is mainly limited by the filament. By operating the filament at 10 % undercurrent its life time can be increased by more than 15 % [5].

ESS assumes continuous operation with 5200 operation hours per year with 98% availability. So a tetrode will last for 2.8 years and a solid state amplifier will last for 5.7 years. For a system of 36 tetrodes, if we expect a tetrode failure once a month, i.e. every 800 hours, the mean time between failures shall be greater than 29,000 hours. The mean time to repair or replace a tetrode shall be less than 3 hours. A 3 hour repair every 800 hours contributes to less than 0.05 % of down time.

6. FREIA test stand as prototype for ESS:

The ESS spoke cavity section consists of 36 superconducting spoke cavities mounted in 18 cryomodules with two cavities each. 36 amplifier-chains will be needed, each consisting of a tetrode amplifier with solid state amplifier as its pre-driver. The power-supplies will be DC power supplies. They can be of a modular type consisting of multiple elements, so that even if one or two modules fail, those can be replaced easily and fast while the system can continue to function properly. This increases the reliability of the system. To make the system more efficient, the tetrode as well as solid state amplifier can be operated in class C mode: RF output from the amplifier is only present when the signal generator generates a pulse. The capital and operational cost of the RF amplifier chain with DC power supplies are 448 kEUR and 395 kEUR respectively.

At Uppsala, a single amplifier chain will be developed and tested for high power as a prototype for ESS. After its satisfactory testing, the amplifier chain will be duplicated to be tested with two spoke cavity in a single cryomodule. Then it will be used to carry out acceptance test of a series of cryomodules.

6. Conclusion.

At 352 MHz and 350 kW RF power output, all the available amplifiers alternatives are compared. Tetrode amplifiers are selected because of their advantages of being cheap, reliable, simple and efficient as compared to the other RF power amplifiers. The tetrodes, due to their low gain, need a pre-driver. The solid state amplifier technology is selected as a pre-driver due to its simplicity, reliability and efficiency. Half height WR2300 wave guides made in Aluminum shall be used for RF distribution. This solution makes it possible to discard the circulator from the RF distribution chain, thus improving the system efficiency.

7. References:

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