# CONCEPT OF THE HIGH POWER RF SYSTEMS FOR MESA*

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*Abstract*

The Mainz Energy-recovering Superconducting Accelerator (MESA) is currently designed and built at the Institut für Kernphysik (KPH) at Johannes Gutenberg-Universität Mainz. The main accelerator incorporates four superconducting cavities of the TESLA type, while the pre-accelerator MAMBO (Milliampere Booster) is a room temperature linac. The MESA high power radio frequency (RF) systems have to cover a vast power range starting at some 10 kW per cavity for the main linac modules and more 50 kW per cavity for MAMBO.

In this paper we will present the concept of a unified high power RF system for both main accelerator and pre-accelerator, based on solid state technology.

## INTRODUCTION

The MESA accelerator is a multi-turn energy recovery linac (ERL) working at low energy for particle physics experiments.

MESA will be operated in two modes: the first is the external beam (EB) mode; there the beam is dumped after being used with the external fixed target experiment P2. This experiment measures the weak mixing angle to a high precision by parity violation. The current required for P2 is 150 µA with polarised electrons at 155 MeV. Approximately 10 000 h of data taking will be necessary for P2 to reach sufficient accuracy. The second mode is energy recovery (ER). The experiment served in this mode is an internal fixed target experiment named MAGIX (MESA Gas Internal target eXperiment). It demands an unpolarised beam of 1 mA at 105 MeV. After an upgrade, 10 mA shall be provided in the MESA stage-2. Both experiments require a continuous wave (CW) beam.

The MESA lattice uses a double sided design, where the two superconducting radio frequency (SRF) modules of the main linac are placed in both long straight sections [1,2]. The design of the SRF modules follows the design of HZDR [3], but with some specific modifications [4, 5].

The injector MAMBO is a 1.3 GHz normal conducting linac in bi-periodic on-axis configuration [6–8]. The first RF-section is a graded-$\beta$ section, the following three sections have a constant $\beta$.

## RF-POWER DEMAND

To find the amount of radio frequency (RF) power that has to be installed, one has to determine the RF-budget. The RF-budget comprises beam loading and losses in the RF-section and transmission lines.

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Table 1: Figures of merit of the four MAMBO 1.3 GHz RF-sections, based on CST Microwave Studio simulations.

| No. | L | $E_{\text{eff}}$ | $\Delta T$ | $R_S$ | $P_C$ |
|---|---|---|---|---|---|
| | mm | MV/m | MeV | MΩ | kW |
| 1 | 1855.6 | 0.68 | 1.16 | 46.7 | 33.8 |
| 2 | 1914.9 | 0.65 | 1.25 | 99.3 | 15.7 |
| 3 | 1960.1 | 0.66 | 1.25 | 102.3 | 16.4 |
| 4 | 1960.1 | 0.67 | 1.25 | 102.3 | 16.7 |

Table 2: Figures of merit of the 1.3 GHz TESLA-type SRF cavities.

| L | R/Q | $Q_0$ | $Q_L$ | $\Delta T$ |
|---|---|---|---|---|
| mm | Ω | - | - | MeV |
| 1038 | 1036 | $> 5 \cdot 10^9$ | $1.4 \cdot 10^7$ | 12.5 |

The figures of merit of the injector MAMBO are listed in Tab.1. One has to keep in mind, that $R_S$ of a produced structure might be lower than simulation results by some 10 %. The maximum beam loading per section will be 12.5 kW at 10 mA. The sections will be matched to this current. The losses in the transmission line will be approximately 20 %. Therefore the MAMBO RF-sections have to be driven with 50 kW to 70 kW of RF-power, the latter needed for section 1.

Table 2 lists important numbers of the SRF cavities. Each of the modules contains two 9-cell cavities. Beam loading exists mostly in EB mode, where the modules are passed three times by the beam, resulting in 5.6 kW beam loading per cavity. Wall losses are negligible in SRF cavities, but effects such as microphonic detuning can affect the acceptance of the RF wave in the cavity. Those effects are hard to predict, since they depend strongly on the actual module and the place of installation. The cavities will be matched to $I_b$ = 150 µA. Along with an assumed detuning of $\Delta f_{\text{micro}}$ = 50 Hz and 20 % loss on the transmission line, a power amplifier (PA) should produce $P_{\text{RF}} > 10$ kW.

## SYSTEM TOPOLOGIES

There are two possible concepts of powering multiple RF-cavities:

1. one RF-section per PA, as shown in Fig. 1

2. multiple RF-sections per PA, see Fig. 2




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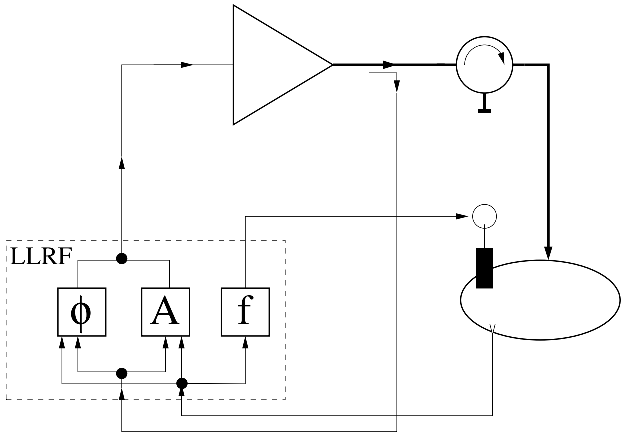


Figure 1: Schematics of one PA system driving a single RF-cavity. A, $\phi$ and f denote the set points for amplitude and phase of the accelerating field and resonance frequency of the cavity.

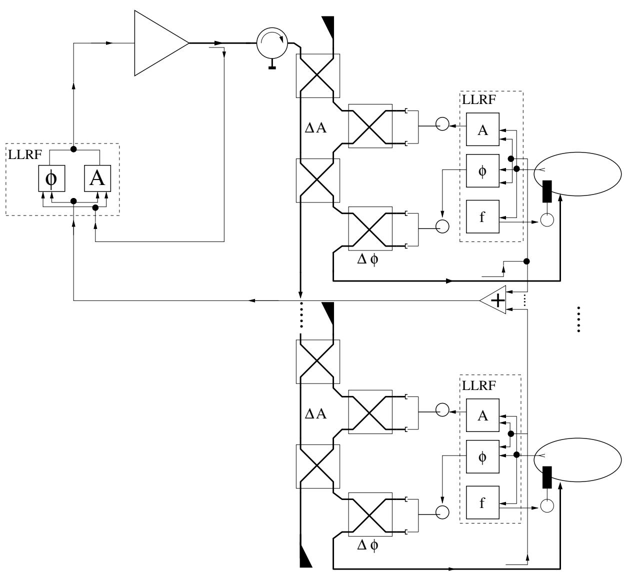


Figure 2: Schematics of one PA system driving multiple RF-cavities. Each cavity must be equipped with a wave guide amplitude shifter and a wave guide phase shifter. Again A, $\phi$ and f are the set points of amplitude, phase and frequency.

As one can see by comparing both sketches, driving multiple RF-cavities with one PA system is a very complicated and bulky set up. The RF wave is distributed between the cavities by a network of wave guide 3 dB-hybrids and motorised shorts, forming amplitude shifters and phase shifters. Regulating phases and amplitudes in the high power branch with slow mechanical actuators is a large disadvantage. The RF-amplitudes and phases in the cavities are not independent of each other, due to the characteristics of an amplitude shifter. Depending on adjustment, a considerable portion of RF-power can be dumped in the terminating load of the last amplitude shifter, which may lower the efficiency of the system.

With a single cavity set up those disadvantages are eliminated. A low level radio frequency (LLRF) system with up-to-date technology can be set up, which is capable of fast regulation (kHz vs. sub-Hz). Parameters of all cavities are independent. This topology can only be realised, if PA of sufficient power are available.

## HIGH POWER SOURCES

There are two kinds of high power sources, vacuum tubes, such as klystrons and inductive output tubes (IOT), and solid-state power amplifiers (SSPA) built of transistors.

During the last years SSPA are more and more replacing vacuum tubes, because they have some advantages compared to vacuum tubes:

SSPA are fully scalable and can be fitted to the optimum amount of power needed. As the efficiency of any PA decreases strongly, if driven only at a fraction of the maximum output power, SSPA may be more efficient than tubes. Also a SSPA operated in part load is more stable than a tube. Since MESA beam currents will be varying by some orders of magnitude, this might become an issue with tube amplifiers. The large number of transistors combined inside a SSPA leads to a higher tolerance to failure and therefore increases availability of the system. Spares of transistors are less costly by some orders of magnitude, than spares of tubes and can be stored very space-saving. Transistors are operated at low DC voltage of usually 50 V, while vacuum tubes have to be run at high voltages starting at some kV and up to some hundred kV. High voltages are hard to handle and can be hazardous, therefore demanding for safety measures. Cathodes of some klystrons have to be insulated with oil. High voltage power supplies (HVPS) may also become very bulky.

Most advantageous is the use of tubes in the power regime $\gtrapprox$ 100 kW, where their power density[1] as well as price point is still superior to SSPA. At 1.3 GHz SSPA have fully replaced vacuum tubes in the power range of up to 15 kW (CW). Currently vacuum tubes (IOT and klystron) with 30 kW, 100 kW and 300 kW (CW) are available at 1.3 GHz.

## MESA RF-SYSTEM

Since high availability of beam is a crucial point for P2 and MAGIX, the MESA RF-system has to rely completely on solid-state technology to achieve reliability via redundancy. Each main linac cavity will be powered by a dedicated 15 kW SSPA, because the advantages of an one cavity per PA set-up concerning fast regulation of RF parameters is needed to achieve the beam parameters and operational modes proposed for MESA [9].

MAMBO could be powered by tubes, since 100 kW IOT or 300 kW klystrons are available: In an one cavity per PA set-up four 100 kW IOT would be necessary to power the four cavities, but all would have to be operated in part load. In a multiple cavity per PA set-up one 300 kW klystron could

[1] one has to bear in mind, that power of tube PA usually refers to saturated power, while SSPA power usually refers to 1 dB compression.

operate all four MAMBO section. The drawbacks of both solutions have been discussed in the sections above.

The advantages of an one cavity per PA set-up in terms of regulation and feedback are needed for MAMBO, too. Especially starting the ER mode demands high flexibility of operating the injector. Both, ER and EB mode require high beam stability [10] and availability not only of the main linac but also of the injector. So we regard SSPA in combination with a modern LLRF system for MAMBO as a better solution than a tube based PA. Having only one type of PA in main linac and injector linac is also quite sensible, because it strongly reduces costs of spares inventory and simplifies maintenance.

To allow for the space restrictions in the shielded areas of the MESA halls, either of the MAMBO PA must not be larger than four 19-inch racks. Thus a newly available type of transistor with higher output power has to be used, making a prototype development necessary.

### *Current status*

In 2015 the tendering process for a 15 kW prototype SSPA was initiated. The contract was awarded to Sigma Phi Electronics beginning of 2016, delivery is expected in Summer 2017. The prototype [11] consist of eight 2 kW PA-modules, that are based on 500 W CW transistors. Power combining is done by coaxial and wave guide combiners. A drawing of the prototype is shown in Fig. 3.

The prototype SSPA will be used to test the SRF modules as well as a prototype RF section of MAMBO, both currently in production at RI research instruments.

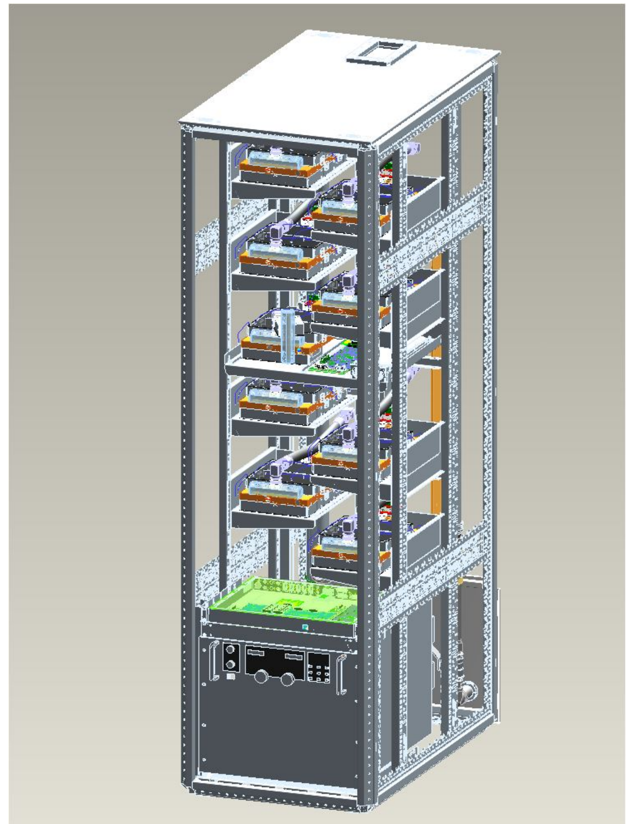

Figure 3: CAD drawing of the 15 kW prototype SSPA currently in production at Sigma Phi Electronics. (Courtesy of Sigma Phi Electronics)

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