Design and manufacture of the RF power supply and RF transmission line for SANAEM project Prometheus

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Abstract: A 1–5 MeV proton beamline is being built by the Turkish Atomic Energy Authority in collaboration with a number of graduate students from different universities. The primary goal of the project, is to acquire the design ability and manufacturing capability of all the components locally. SPP will be an accelerator and beam diagnostics test facility and it will also serve the detector development community with its low beam current. This paper discusses the design and construction of the RF power supply and the RF transmission line components such as its waveguide converters and its circulator. Additionally low and high power RF test results are presented to compare the performances of the locally produced components to the commercially available ones.

Keywords: Accelerator Subsystems and Technologies; Modeling of microwave systems; Passive components for microwaves; Waveguides

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1 Introduction

The SANAEM Project Prometheus (SPP) at the Turkish Atomic Energy Authority (TAEK)'s Sarayköy Nuclear Research and Training Center (SANAEM), aims to gain the necessary knowledge and experience to construct a proton beamline needed for future necessities [1]. A Proof of Principle (PoP) accelerator with modest requirements of achieving at least 1 MeV proton energy, with a peak beam current of few tens of µA's is under development. This PoP project has also the challenging goal of having the design and construction of the entire setup using local resources ranging from its ion source to the final diagnostic station, including its RF power supply and the RF power transmission line which are the foci of this paper. There are also two secondary goals for this project: 1) To train the next generation accelerator physicists and RF engineers on the job; 2) To encourage and develop skills of the local industry in the accelerator component construction. The ion source is a pulsed 1 kW 13.56 MHz RF driven inductively coupled plasma chamber where 20 kV potential is used to extract 10 ms $H^+$ ions with a repetition frequency of 1 Hz [2]. The low energy proton beam’s current, profile and emittance are measured using a compact measurement station at the solenoid based LEBT line, which was previously described elsewhere [3]. A "4-vane" Radio Frequency Quadrupole (RFQ) operating at 352.21 MHz is used as the low beta accelerating cavity [4, 5]. This operating frequency ($f$) was selected to be compatible with similar machines in Europe and therefore to benefit from the already available RF power supply market. The design requirements of the accelerating cavity is given in Table 1. Other parameters such as the inter-vane...
voltage (V), input energy ($E_{in}$), output energy ($E_{out}$), beam current acceptance ($I$), power dissipation at maximum Q factor ($P_d$) and the vane length ($L$) were chosen to be adequate for a first time machine. To compensate for any possible reduction in Q factor of the manufactured cavity, a safety margin is considered and the power requirement of the RFQ is estimated as 120 kW. The accelerating cavity will be followed by a beam diagnostics section and finally by a beam dump.

| Parameter | Value |
|-----------|-------|
| $E_{in}$ (MeV) | 0.02 |
| $E_{out}$ (MeV) | 1.3 |
| $f$ (MHz) | 352.21 |
| $V$ (kV) | 60 |
| $I$ (mA) | <15 |
| $P_d$ (kW) | 65.5 |
| $L$ (m) | 1.2 |

2 Overview of the RF system

The overview of the RF power transmission line for the SPP project is depicted in figure 1. The racks shown in lower left part of the figure represent the RF power supply unit (PSU). The RF power supply is required to be pulsed at a maximum duty factor of 3% and to have a peak output power of 120 kW at 352.21 MHz. The master oscillator’s frequency precision is required to be at least 1 kHz in order to fine-tune the accelerator cavity (at this level, no LLRF system is used to follow the frequency of the cavity). A precision of 10 kW in power is considered to be enough to set the proper voltage level in the RFQ. The acceptable beam transmission limit of the RFQ cavity is set to be 70% for the project. The cavity’s inter-vane voltage should not fall below 56 kV compared to the design value of 60 kV to ensure such a transmission rate. Since 4 kV potential difference would correspond to about 16 kW difference from the PSU, its stability requirement can be written as ±8 kW. Additionally, remote control capability and fast-interlocks, in the case of any failures, are other requirements for the RF PSU system.

Consequently, the PSU was designed to match these requirements; the result being a two step amplifier, having both solid state and vacuum tube components. The output form factor of the PSU follows the RF amplifier cavity’s output in 3 1/8” rigid coaxial line format. A coaxial to rectangular waveguide converter has been designed to start using a half height (HH) WR2300 rectangular waveguide leading to a HH custom designed circulator to protect the power supply. The RF dump is also a custom made component, installed after a 90 degree E-bend at the third port of the circulator. The 6 meter transmission line starts at the second port of the circulator and is immediately converted to full height (FH) WR2300 using a custom designed and built adapter unit. The FH line’s last components are an H-bend followed by a flexible rectangular waveguide and finally a rectangular
to coaxial waveguide converter to couple the power to the accelerating cavity by using a magnetic loop. The rest of this manuscript is devoted to the design, building and testing of these components.

Figure 1. The overview of the SPP RF transmission line.

3 SPP RF power supply

The SPP power supply is required to operate at 352.21 MHz as a narrow bandwidth device, and to deliver about 120 kW peak power in pulsed mode at a maximum duty factor of 3%. It is designed by the project members and manufactured by a local RF company [6]. It is envisaged as a two staged amplifier, as shown in figure 2. The first stage was implemented with a solid state amplifier and the second stage with a vacuum tube amplifier. The whole system was planned to allow both remote operation over IP network and local control and monitoring over the touch screen panel on the control rack.

Figure 2. The two stage hybrid PSU design for SPP. Note that the solid state stage is only water cooled whereas the second stage with tetrode tube requires both water and forced air cooling.

The first amplification stage uses the BLF-578XR high power transistors [7] to achieve a combined output of 6 kW in continuous and over 8 kW in pulsed modes. Each solid state amplifier
(SSA) circuit provides 1.1 kW per amplifier board in pulsed mode for pulses shorter than 500 ms. The output of stage one is, thus, obtained by combining the outputs of eight such boards using home built combiner modules (figure 3).

![Figure 3. Block diagram of the combiner module.](image)

The low power RF input of the splitter/SSA/combiner component is provided by a low noise PLL (phase-locked loop) controlled oscillator and amplified with a 1 W pre-amplifier. The driver amplifier’s output power is controlled with a PLC (programmable logic controller) based gain controller to adjust the input power of the SSA modules. All error signals are evaluated with the PLC and triggering the fast-interrupts to protect the RF system, if needed. The low power 3 dB coupler splits the output of the driver amplifier into two and channels these into two identical splitter/SSA/combiner boards. On these boards, a microstrip Wilkinson 1/4 splitter was designed with a teflon substrate and a 35 µm silver plated copper strip to further split the received signal and channel it into 4 identical SSA modules. Each SSA module amplifies the RF signal up 1.1 kW with the water cooled high power transistor modules. The output signals of the transistor modules are combined with a microstrip Wilkinson 1/4 combiner for both boards. Finally, the combined output of both boards are coupled up with a high power 3 dB coupler to provide 8 kW RF signal.

The assembled combiner and a number of amplifier cards can be seen in figure 4. The power and the rise time test results of the combined pulse from the SSA combiner are shown in figure 5 and figure 6, respectively. The PSU provided about 42 ns of rise-time for an RF pulse of about 200 µs, fast enough for filling the SPP RFQ cavity. The power tests of the SSA pulse are performed with −70 dB attenuated signal and a 7.1 kW pulse power was reached in these tests.
Figure 4. SPP PSU solid state amplifier combiner.

Figure 5. Power test results of the pulse.
The second amplification stage uses a tetrode amplifier, both water and air cooled, to achieve the final peak power of 120 kW. The selected tetrode tube is the TH595 [8] which provides up to 200 kW peak power in short pulse operation mode, for frequencies up to 450 MHz. Figure 7 contains a view of the tetrode amplifier, the amplification cavity and the forced air cooling system during assembly. For the SPP setup, the tetrode gate voltages are adjusted as $G1 = -200$ V and $G2 = 900$ V, the filament voltage as 7.3 V, whereas the anode voltage is set to 13.5 kV. The completed RF PSU including all the controls, power supplies and cooling as installed in the laboratory consists of five racks. The DC power supply, control unit and the first amplification stage are as shown in figure 8 during operation.

Figure 7. SPP PSU Tetrode amplifier rack during assembly in the lab. Left section contains the RF amplifier cavity which would later house the tetrode amplifier and on the right side one can see the air intake for forced air cooling of the tetrode.
Figure 8. SPP PSU in use. The left rack has the DC power supply, the central rack has the controller and the master signal generator, and the right rack has the power supplies for the tetrode gates, the first amplification stage and the output to the Tetrode amplifier rack.

4 SPP RF transmission line

As a PoP project, SPP transmission line contains a large variety of the available components, where 3 1/8" rigid coaxial lines, a waveguide circulator, full height and half height rectangular waveguides (WR2300), a flexible rectangular waveguide and their converters and adapters can be cited as examples (figure 9). The selected rigid coaxial line has 50 Ω impedance and can carry a peak power of 440 kW, up to a maximum frequency of 855 MHz [9]. The WR2300 series rectangular waveguides operate at a lower maximum frequency, up to 450 MHz and these can carry a maximum power of about 700 MW.

![Block diagram of the SPP RF transmission line.](image)

Figure 9. Block diagram of the SPP RF transmission line.

In the whole transmission line only one component, a flexible rectangular waveguide from Mega [10], was purchased to ease alignment of the coaxial coupler to the RFQ. All the other RF
components were first designed using Computer Simulation Technology (CST) Microwave Studio’s (MWS) Frequency Domain Solver [12] for the operating frequency of 352.21 MHz and produced locally by the manufacturers in Middle East Industry and Trade Center (OSTIM) in Ankara. With the relatively modest power requirements, the SPP RF transmission line operates in normal air and doesn’t have any special isolation gas requirements. The maximum power capability requirement of the components is pulsed 120 kW with 0.01% duty factor and 1 Hz repetition frequency. Upon delivery, reflection ($S_{11}$) and transmission ($S_{21}$) characteristics of the components were measured at the operating frequency using low power output from a vector network analyzer (VNA) [13]. Lastly, the high power tests were performed with the RF PSU and the whole RF transmission line.

### 4.1 RF dump, bends and HH to FH transition

The half height RF dump is made from a triangularly ending waveguide loaded with silicon carbide. Its length is about 50 cm and it can be air cooled for high power operations. The two E-bends are to be used with the circulator setup, whereas the H-bend is for the section of the transmission line just before the RFQ. Therefore the bends are designed as HH and FH modules as shown in figure 10. These components are optimized to perform below $-85$ dB for $S_{11}$ (with PEC assumption) and produced as seen in figure 11 and figure 16, respectively.

![Figure 10](image1.png)  
**Figure 10.** Full height H-bend (left) and half height E-bend (right) designs for SPP.

![Figure 11](image2.png)  
**Figure 11.** Half height E-bend attached to RF dump.

Figure 11 contains the manufactured and assembled HH E-bend attached to the RF dump to tune the coaxial-rectangular waveguide converters just before integration to the RF transmission line (figure 13). As the RF transmission line contains both FH and HH sections, a transition
module was necessary. The design of the HH to FH transition was performed by using CST MWS while optimizing the total length, the transmission efficiency and the producibility (figure 12). Considering these factors, the $S_{11}$ of the HH to FH transition is optimized to $-61$ dB, similarly with PEC assumption.

![Image of HH to FH transition design and finished product]

Figure 12. Left: HH to FH transition design. Right: the finished product.

### 4.2 Measurements with coaxial-rectangular waveguide converters, reducers and other parts

The $S_{11}$ measurements were performed using the VNA, which provided a low power RF signal to the HH coaxial to rectangular (TEM to TE) waveguide converter with a home-built 3 1/8” to N type reducer. The 50 cm converter was attached to a 50 cm HH WR2300 waveguide, the 90 degree E-bend and finally to the RF dump as seen in figure 13. The low power pulse of the VNA, eventually absorbed by the RF dump, was used to tune the converters. Before the production phase, the $S_{11}$ parameters of the reducer and the TEM to TE waveguide converter are optimized to $-69$ dB and $-62$ dB, respectively, with the above mentioned simulation setup. The maximum CW power capability of the TEM to TE waveguide converter was found as 400 kW without any cooling. Figure 14 contains the $S_{11}$ measurement results for the previously described setup. After tuning the TEM to TE waveguide converter, at the operating frequency of 352.21 MHz, the attained $S_{11}$ value was $-60$ dB.

As previously discussed, the RF transmission line also requires a FH rectangular to coaxial (TE to TEM) waveguide converter. For the TE to TEM waveguide converter the $S_{11}$ parameter was optimized to $-63$ dB with computer simulations. The CW power handling capacity of the TE to TEM waveguide converter was calculated as 275 kW without any cooling. After the production of the TE to TEM waveguide converter the second measurement employs the same setup, except the HH TEM to TE waveguide converter was replaced by the mentioned HH to FH adapter and the FH TE to TEM waveguide converter. The $S_{11}$ for this case read as $-59$ dB after tuning, which can be found in the same figure, second screenshot. The HH TEM to TE and FH TE to TEM waveguide converters were designed as narrow-band devices due to the RFQ cavity’s requirements. For a comparison, an RF-lambda [11] product RFWA2300 has 1.3 VSWR in a bandwidth of 370 MHz and our converters have bandwidths of 4 MHz. By means of this narrow-bandwidth, designed converters have a sharper $S_{11}$ and are less lossy at the operating frequency of the cavity.

Insertion loss measurement setup is given in figure 15. Basically a low power pulse is emitted by the VNA which is converted to TE mode and propagated from left to right through HH waveguide,
Figure 13. The $S_{11}$ measurement setup for HH TEM to TE converter.

Figure 14. Top: $S_{11}$ for TEM to TE conversion. Bottom: $S_{11}$ for TE to TEM conversion. Both measurements are made by using a low power RF signal from the VNA.
HH to FH adapter and finally FH TE to TEM waveguide converter, all being previously discussed. The pulse arriving to the right side is received by the same VNA which can calculate the $S_{21}$ parameter. Its untuned measured value for the operating frequency of 352.21 MHz is $-0.17$ dB.

![Image](image1.png)

**Figure 15.** The $S21$ measurement setup of the converters.

Following the low power tests, the most of the waveguide components of the RF transmission line were assembled as in figure 16. To measure the $S21$ parameter of the whole transmission line, the same procedure was followed. For the SPP operating frequency, $S21$ of the entire line was measured as $-0.1$ dB, corresponding to about 2% power loss at the whole chain, including both of the reducers which are the main source of the power loss in the low power tests (figure 16).

![Image](image2.png)

**Figure 16.** Top: the $S21$ measurement setup of the transmission line. A low power RF pulse from the VNA goes from left to right and finally back the VNA. Bottom: the $S21$ results of the RF transmission line.

The reducers were also tested with the VNA pulse and an insertion loss of $-0.04$ dB was recorded (figure 17).
4.3 Waveguide circulator

A circulator is a non-reciprocal passive RF transformer, used to deliver the RF power to a target device, e.g. an accelerator cavity, while protecting the RF power supply with an RF load in the event of an impedance mismatch between the supply and the load. An H-plane waveguide junction circulator, to be operated at the frequency of 352.21 MHz, has been designed using CST MWS [12] for the SPP project. This RF device is intended to deliver the RF power generated by the RF power supply unit, with minimal loss, while protecting the power supply against any power reflections. The maximum power handling requirement for the project is about 120 kW which will be supplied from port-1. The circulator is designed to transfer this power to port-2, as seen in figure 18.

That port is connected to the RF transmission line, delivering RF power to the RFQ by the means of waveguides and rigid coaxial cables, discussed previously. The air cooled RF dump that was discussed in the previous section 4.1 is connected to port-3 to absorb any reflections from port-2.
The designed circulator consists of two aluminum disks and two disks of ferrites which are attached inside the HH WR2300 waveguide. Following CST MWS simulations, the ferrite material is determined as NG-1600 from the catalogue of Magnetics Group [14]. NG-1600 has a saturation magnetization $\mathbf{4\pi M_s}$ at 1600 Gauss, its maximum line width is 10 Oersted, and its dielectric constant is 14.6 while the loss tangent is below $2 \times 10^{-4}$, where all values are given by the supplier at 9.4 GHz. The Curie temperature is given as 220°C which was considered in the thermal simulations. The necessary setup to keep the ferrites at room temperature during the operation was made available via water cooling. However due to low RF duty factor (0.01%), so far no such need has arisen.

The relation between the saturation magnetic field of the ferrite $\mathbf{M_s}$ and applied field $\mathbf{H}$ both having time dependence of $\omega$ can be formulated as below:

$$
\begin{bmatrix}
M_x \\
M_y \\
M_z
\end{bmatrix} =
\begin{bmatrix}
X_{xx} & X_{xy} & 0 \\
X_{yx} & X_{yy} & 0 \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
H_x \\
H_y \\
H_z
\end{bmatrix},
$$

(4.1)

where elements of $X$ correspond to;

$$
X_{xx} = \frac{\omega_m \omega_0}{(\omega_m^2 - \omega^2)} = X_{yy},
$$

(4.2)

$$
X_{xy} = \frac{j \omega_0 \omega_m}{(\omega_m^2 - \omega^2)} = -X_{yx}.
$$

(4.3)

Thus, magnetic field becomes:

$$
\mathbf{\vec{B}} = \mu_0 \left[
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix} +
\begin{bmatrix}
X_{xx} & X_{xy} & 0 \\
X_{yx} & X_{yy} & 0 \\
0 & 0 & 0
\end{bmatrix}\right] \mathbf{\vec{H}} = [\mu] \mathbf{\vec{H}},
$$

(4.4)

where the Larmor and magnetization frequencies are respectively:

$$
\omega_0 = \mu_0 \gamma H_0,
$$

(4.5)

$$
\omega_m = \mu_0 \gamma M_s,
$$

(4.6)

where, $\mu_0$ is vacuum permeability and $\gamma$ is the gyromagnetic ratio. The permeability of the ferrite $\mu$ has been discussed in detail by Wu and Du [15]. Comparing these two frequencies, it can be seen that this circulator is working above the resonant frequency. An advantage of this operation regime is to have lower field losses as pointed out by Bosma [16]. The fields inside the circulator are so-called the acceleration mode which is $\mathbf{TM_{10}}$ (or in European notation $\mathbf{E_{10}}$) and the view of the magnetic field can be seen from figure 19, while the electric field is already presented in figure 18.

The performance of the designed circulator, obtained after lengthy optimization studies, can be seen in figure 20. At the SPP operating frequency of 352.21 MHz the return loss ($S_{11}$), insertion loss ($S_{21}$) and the isolation loss ($S_{31}$) are computed as $-55$ dB, $-0.26$ dB and $-30$ dB, respectively. VSWR is calculated to be about 1.005:1. The power handling capacity of the circulator is about 30 kW CW without needing any water cooling. As can be seen in figure 20 the bandwidth of the designed circulator is 12 MHz for a maximum VSWR of 1.2. For a comparison, an RF-lambda product RFWC2300A having 1.2 VSWR in a bandwidth of 17 MHz, has $-0.3$ dB maximum
insertion loss and −20 dB minimum isolation loss. Therefore the performance of this locally designed and manufactured circulator is comparable (−0.26 dB vs −0.3 dB and −30 dB vs −20 dB) to an industrial one.

Finally, the biasing magnetic field of the circulator is supplied by a locally designed and built dipole electromagnet to fine tune of the ferrites. The dipole is able to produce an external magnetic field of 2.3 kG to the ferrites without any cooling requirements.

4.3.1 Assembly, installation and tests

Most of the circulator components have been bought or produced locally, except the two ferrite disks purchased from TSI ceramics [14]. The non-magnetic components were constructed from 6061 series aluminum and attached to a support frame made from 2 cm thick iron layers that also served as a return yoke for the magnetic field. For field tunability, the biasing magnets were made solely from two solenoids forming a dipole. The coils of the dipole are designed to carry a current of about 17 A each. The total weight of the circulator including the coils and yokes is about 1 Ton. The 3D drawing of the whole circulator setup is given in figure 21.
The individual components were assembled in the laboratory by the team members and installed in the RF transmission line as seen in figure 22. The biasing field estimated in CST as 1910 G has been optimized as 1880 G after the installation using a VNA.

After all the components were assembled, the full transmission line (with circulator) was fed with low power RF signals to measure the S-parameters. The insertion loss for the full line is measured as $-0.34\,\text{dB}$ which is corresponds to 7.5% power loss (figure 23). Simulated electric field distribution of the whole RF transmission line is shown in figure 24.
Figure 22. 352.21 MHz waveguide circulator as it is installed in the RF transmission line. Note that the connection to the RF PSU (port-1 one left side) was made with a 3 1/8" rigid coaxial line. The electromagnet, PSU and the gauss-meter are right below the circulator.

Figure 23. The insertion loss measurement of the whole RF transmission line.

Figure 24. The electric field pattern of the full RF transmission line.
5 High power measurements

The high power tests of the RF system were performed within three phases. First, at the SSA output, second at the tetrode output, and third at the end of the RF transmission line. The performance of the RF PSU was measured with a $-60\,\text{dB}$ RF load and an oscilloscope (figure 25). All high power measurements were done with calibrated coaxial cables and attenuators. First, high power tests were performed at the SSA output with the previously mentioned setup. A 5.8 kW RF power was measured with a pulse length of 100 $\mu\text{s}$. Second, the same setup was used to calculate the tetrode’s amplification gain through feeding the RF tube with SSA power. A 15.9 kW output RF power was measured with an input power of 780.3 W. Therefore the gain of the tetrode tube was calculated as 13.1 dB. With this gain the tetrode is able to produce a 118.9 kW RF power with 5.8 kW RF input power. Unfortunately tetrode’s output RF power at this power level could not measured due to the restriction of maximum power capability of the existing RF load. After the gain measurements, the tetrode output was connected to the RF transmission line. As the third phase, the high power tests were performed at the end of the RF transmission line. An SSA power of 2.4 kW was fed to the tetrode and the amplified power was measured at the end of the RF transmission line as 47.4 kW. Regarding a power loss of 7.5% for the whole transmission line, the output power of the tetrode was calculated as 50.9 kW and the gain as 13.3 dB. Accordingly with this gain the RF PSU is enough to provide the required RF power to the RFQ cavity with a safety factor of 1.8 in case of reduction in the quality factor (Q) of the cavity.

![Figure 25. High power test setup at the end of the RF transmission line.](image)

6 RF interlock system

The RF system is protected by predefined interlock conditions (figure 26). On the power supply side, the temperature of the SSA is continuously monitored, as well as the availability of the
water cooling. For the tetrode amplifier, both water and air cooling requirements are imposed for activating the second stage. Tube’s anode, G1 and G2 voltages and currents are monitored and in case of unwanted level change the fast-interlocks (100 ns) protect the system. Additionally, the PSU finite state machine requires the “ON” signal from the independent measurement of the water flow rate (should be higher than 15 l/m) and from the circulator biasing electromagnets. In case of any failure, the PSU initiates an automated shutdown procedure. The cooling water pressure and temperature are also continuously displayed and saved to a file. The reflected RF power is continuously monitored with a directional coupler just before the RFQ to provide a fast shutdown signal to the RF PSU in case of a value above a user defined threshold.

![Diagram](image)

**Figure 26.** Fast-interlock diagram of the RF system.

### 7 Conclusions and prospects

The RF power supply and the RF transmission line for the SPP proton beamline are designed, built and installed as a combined effort between the SPP team and local manufacturers. The measurement results (power and S-parameters, etc.) on the RF transmission line correspond well to the design expectations.

The educational and training outcomes are immense since the accelerator physicists and engineers were able to design, to help the manufacturers to produce their design, and finally to compare the finished product to the concept they had initially. Moreover, the manufacturers understand the expectations concerning the level of precision and details for accelerator component production. And finally the fact that, in Turkey, there is now a set of physicists, engineers and manufacturers who can speak the same language, work on a complex product from its design to its delivery could be a big regional asset.

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