Further upgrades of the ASDEX Upgrade ICRF system

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Abstract. The original plans were to operate the tokamak ASDEX Upgrade (AUG) for ten years. The flexibility of the experiment lead to the fact, that AUG is now operating for over three decades. As the Ion Cyclotron range of Frequencies (ICRF) heating was AUG's first auxiliary heating system, which went into operation in 1992, regular upgrades of different ICRF components are mandatory for different reasons. For example, due to a lack of supply, it became necessary to replace the pre-driver stage tetrode by a widely available triode in the ICRF generators. This change reduced the frequency range of the rf generators from 30 – 120 MHz to 30 – 60 MHz, still covering the experiment requirements. A long-time limitation was the behaviour of the high voltage supply of the driver stage of the rf generator. A new power converter was extensively tested on a test bed with promising results. Further upgrades include a redesign of the antenna vacuum pumping system to replace the maintenance intense cold heads. A redesign of the antenna vacuum feed through has also been made to increase the voltage standoff. For the implementation of a new rf generator in the near future, which will extend the frequency range from 30 MHz down to 24 MHz, changes in the antenna matching systems were made on two of the four ICRF antennas by adding a third stub tuner. For the integration of this rf generator into the AUG ICRF network, additional coaxial switches, which were recycled from a shortwave broadcasting station, are integrated in the ICRF system.

1 Introduction

The ICRF system at the ASDEX Upgrade (AUG) tokamak is in operation since 1992. The system originally consisted of four high-power rf-generators, a complex transmission and matching system and four ICRF-antennas in the vessel. A fifth rf generator from the abandoned experiment W-7 AS has been added a few years ago; a sixth rf generator will be added soon, see section 6. As the ASDEX Upgrade is expected to operate at least until 2035, we need to keep the ICRF system operational for more than ten years, while essential parts of the rf generators are no longer available. At the same time, the tasks the ICRF system should perform are getting more complex.

2 Replacing the pre-driver tetrode

As the supply of tetrodes is getting more and more problematic and many types are no longer manufactured, changes in the high-power AUG ICRF rf generators are necessary. We have already adapted an alternative final stage tetrode in one of our old ICRF rf generators [1, 2]. Unfortunately, the manufacturer of this tetrode has delisted this tetrode type, but there are chances that it can become available again [3]. The four final stage tetrodes in the ICRF rf generators have been all rebuild and are now in operation for up to 24 years. While we do have a replacement for the final stage tubes, it became clear that the delisting of the pre-driver tetrode (Siemens, then Thales RS1054 SK) in 2012 is a potential problem for operating the rf generators. Tests of a 5 kW output power solid-state amplifier (BEKO HVL-6200) on a test bench were successful, and the

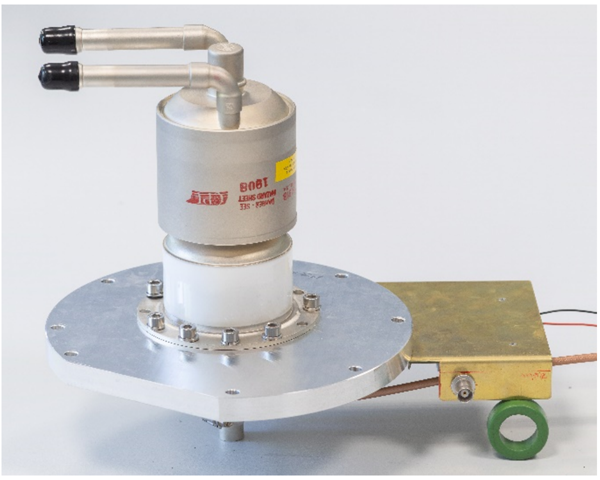

Fig. 1. The Eimac YU-191 triode attached to the mounting flange, which replaces the delisted tetrode and the tube socket. The part on the right houses switchable low-Q band pass filters for the main operating frequencies (30 and 36.5 MHz).

solid-state amplifier (SSA) was used for providing rf power for different laboratory setups. However, the price and the complex integration of such an amplifier, which would replace both the old 100 W ENI solid-state stage and the first tetrode stage, were not in favour of its use in the high-power AUG ICRF rf generators. Asking tube manufacturers for an alternative tube, which is

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widely used for industrial applications, to secure the supply of tubes, led to the conclusion that triodes are best suited. After studying datasheets of different triodes, we decided to use an Eimac YU-191 B triode shown in Fig. 1, because the data sheet reports that the input impedance in the grounded grid configuration is close to 50 Ohm. Output power and anode voltage are also within the required range.

The slightly lower amplification of the triode is compensated by purchasing new SSAs capable to deliver up to 125 W instead of 100 W. Replacement of these SSAs was needed in any case, because the old SSAs were no longer serviceable due to the lack of replacement parts.

In the grounded grid configuration, a triode does not need neutralisation and does not need a grid power supply. However, chokes on the filament supply connections needed to be implemented that can handle the filament current of 51.5 A. For the implementation in the first ICRF rf generator, we used axial suppression ferrites which were readily available. The relative initial permeability of these ferrites is about 20 (TCI Ceramics M3-1063). The choke consists out of 10 ferrites in series where the conductors (two times 4 x 1.7 mm enamelled copper wires) for the filament are fed through; the ferrite beads are housed in a cooper tube, which capacitively shorts remaining rf fields. Measurements with a vector network analyser (VNA) show an attenuation better than 20 dB between 20 and 60 MHz, which provides enough isolation from rf power. The previously used tetrode needed 3 V and 140 A AC power for the filament and the triode needs 7.5 V and 51.5 A, hence a new filament transformer was implemented. This was the only change necessary in the power supplies. The control grid and the screen grid power supplies of the tetrode were made redundant. The mechanical interface is essentially an adapter plate to mount the triode in the cubicle.

In order to identify problems in the chain of the amplifier stages, we added a directional coupler between the output of the SSA and the input of the pre-driver stage.

After these modifications, the rf generator has been tested at frequencies between 30 and 55.1 MHz. According to the data sheet of the YU-191B triode, even higher frequencies should be possible, but there is currently no demand for this at the experiment. Adding switchable low-Q band pass filters at the input of the triode helped to increase the operation stability of the solid-state amplifier during high power pulses.

3 Improvements of the driver stage power supply

The dynamic behavior of the driver stage power supply has put some limitations on the ICRF system. At the beginning of a rf pulse with an output power above 600 kW the anode voltage of the driver stage can randomly drop down to 5.5 kV, resulting in a steep increase of the screen grid current of up to 2 A, which is above the limit mentioned in the data sheet of the driver stage Eimac 8959 tetrode. In order to reduce stress on the screen grid of the driver tetrode, the rectangular high power ICRF waveforms are automatically modified by a pre-programmed 90 ms long starting phase which limits generator output power to 600 kW, followed by a ramp to the requested output power. Together with the high voltage group, we investigated this issue in detail and found a solution by adding bleeder resistors parallel to the tetrode. A continuous current of ~ 100 mA keeps the control circuit of the high voltage supply permanently active. The assembly consists of eight 20 kΩ 500 W rated wire-wound resistors connected in series, mounted in the rf generator cubicle. The additional thermal load of ~ 1.8 kW is not affecting the operation of the rf generator. The associated reduction of the anode voltage drop is shown in Fig. 2.

As the high voltage supply for the driver stages are now 40 years old and no spare parts are available, the old BBC control units and the voltage controllers will be replaced one after another. The first tests with a new voltage controller, type Siemens 6RA80, have been successful on a dummy load and later on the driver stage of an old ASDEX/W7-AS ICRF rf generator. Together with a new Siemens TIA 1500 Programmable Logic Controller (PLC) the upgraded the new power supply can be directly controlled from the ICRF control room.

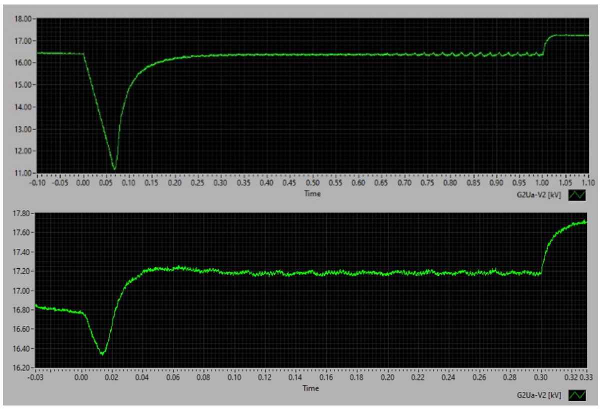

Fig. 2. The plot on top shows the anode voltage of the driver stage during a 1 MW pulse. As the voltage controller is in the idle state, the voltage drops from 16.5 kV to 11 kV. It takes about 150 ms for the anode voltage to recover. During this time, the screen grid current of the tetrode exceeds the limit. The plot below shows high voltage during a 1 MW pulse with the added bleeder resistors. As the voltage controllers is now always active, the reaction time is now only 30 ms and the voltage drop is only 1 kV instead of 5.5 kV.

4 Improvements on pumping system of the vacuum transmission lines

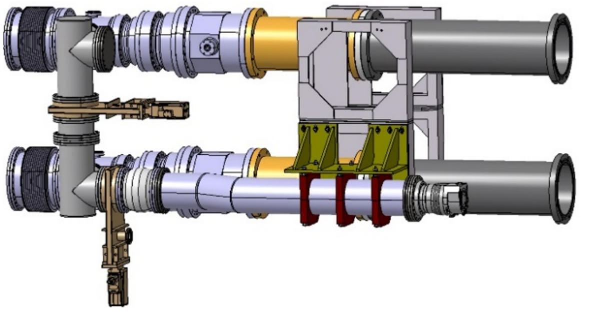

Fig. 3. A CAD drawing of the new vacuum system with the interface to the AUG ports on the left. Both vacuum transmission lines share a single turbo pump, which replaced cryopumps, thus reducing the total number of flanges.

The original vacuum system used for the ICRF Vacuum Transmission Lines (VTL) was designed in the early 1990s. Due to various technical limitations and overcomplications, the original system used cryopumps to reach pressures below 10^{-6} mbar in the vacuum transmissions lines. The drawback of the cryopumps is a huge maintenance effort needed to keep helium compressors, temperature sensors and shutters in working order. A new vacuum system for VTLs is presented in Fig. 3. The idea was to simplify the vacuum system to reduce maintenance and allow easier access for service work. New pressure gauges with network interface replaced the old pressure gauges with analog outputs. The new generation of turbo pumps allow operation close to the AUG poloidal field coils. This gave the freedom to reduce the length of the pipes between the VTLs and the turbo pump. Overall, the modified system is much more compact, consists of fewer parts, and is fully integrated in the PLC.

5 Redesign of the vacuum transmission line

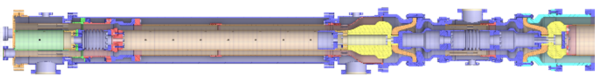

Fig. 4. The redesign of the vacuum feedthrough moves both hat-shaped ceramics out of the AUG B-ports for an easier maintenance (the antenna is connected on the left side). Both ceramics have now the same diameter. The maximum field strength was reduced by optimizing the components of the VTL.

Aside from the repair of two of the VTLs with a leakage in 2012, the other six VTLs are in operation at the experiment since 1998 without any modification. Tests prior the restart of the current AUG 2024/2025 experimental campaign showed that after this long operating time almost all VTLs have developed micro leaks. While these micro leaks do not hinder operation and the vacuum system can easily cope with them, it is clear, that the leaks can get larger with time. As the implementation of the three-strap antennas [4] asks for higher voltages, we started the process to redesign and test the VTLs [5] – see Fig. 4. The optimization showed in the simulations, that the field strength can be reduced from 2.8 kV/mm to 1.9 kV/mm in the torus vacuum section and from 2.4 kV/mm to 1.9 kV/mm in the private vacuum section. Other key points of the redesign are easier access to the ceramics, which forms the intermediate vacuum section. At the same time, different ceramic materials were evaluated [6]. We decided to use Al_20_3 ceramics for the vacuum windows, as they showed the low dielectric losses of less than 4 x 10^{-4}, a high dielectric strength of over 30 kV/mm and a acceptable thermal conductivity. After finalizing the design, the parts for one new VTL were manufactured and assembled at the test stand in 2025 and is ready for the first tests with rf power.

6 A new rf generator and it's system integration

The AUG ICRF high-power rf generators are now 35 years old, hence we decided to order an addition rf generator to compensate for the degradation of rf power due to aging of the system and possible failures which result in case of a temporary shut-off of one of the rf generators. After receiving a tender from ASIPP (Hefei, China), we started the ordering process. The rf generator is shown in Fig. 5 and basically the same type as is used at the EAST tokamak [7], but with several modifications. The frequency range covers 24 – 61 MHz; the maximum output power is up to 2 MW for 20 s pulses and up to 1.5 MW for continuous operation. Part of the tender are also the pulse step modulation (PSM) power supplies for the driver (18 kV, 20A) and the final stage (26 kV, 150A). A lot of preparations at the IPP are needed in order to allow the installation of this rf generator. The preparations range from cut-outs in the ceiling, new low voltage distribution, reworking of the water-cooling system and heat exchangers to adding coaxial switches and transmission lines. The coaxial switches obtained after the shutdown of the shortwave broadcasting facility of the *Bayerische Rundfunk* were mechanically modified to fit the Spinner RL 100-230 specifications. Although the coaxial switches were only specified for a maximum frequency of 30 MHz, their VSWR and port isolation is acceptable up to at least 70 MHz. For the high voltage supplies, the cables from the decommissioned AUG ECRH1 project will be reused. We expect the delivery of the new rf generator in 2026.

Fig. 5. The 2 MW rf generator manufactured by ASIPP. The six racks contain the power supplies for the tetrode filaments and grids, power distribution unit, control system and an 8 kW solid-state amplifier with its output filter. The tower at the left is the final amplification stage; the one on the right is the driver stage. The power supplies for these stages are not shown in the picture.

7 Extending the matching system for 24 MHz operation

The new rf generator can operate down to 24 MHz, but the two-stub tuner matching network at the two-strap antenna would be not sufficient to cover the whole frequency range for the expected antenna impedances. Adding a third stub tuner significantly increased the range of impedances which can be matched (see Fig. 6). The first problem during the integration process of the third stub tuner was the lack of exact position data of the already existing matching system. After gaining the position data and making a CAD model (Fig. 7), the scarce space due to diagnostics and manipulators together with the large dimensions of the coaxial transmission lines made it almost impossible to integrate them. At some point we asked our colleagues for modifications of their diagnostics to allow the mounting of the third stub tuner. After adding the third stub tuner, we needed to readjust the length of the transmission lines between antenna and matching system. The interface of the data acquisition system was upgraded to handle 14 stub tuners.

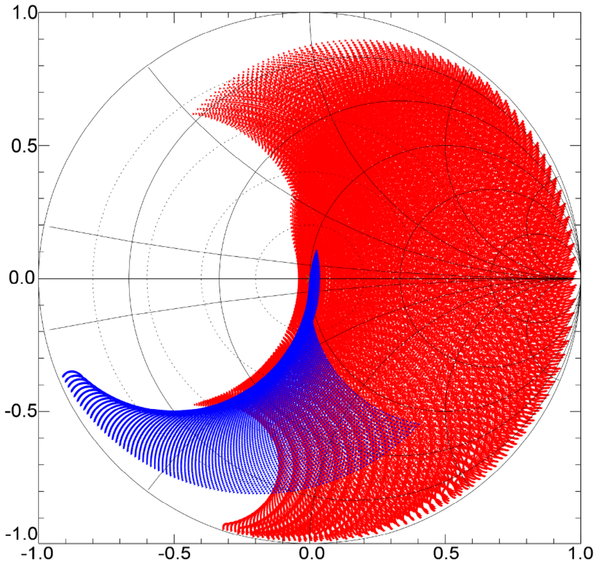

Fig. 6. The Smith-chart the blue area shows which complex impedances at the output of the matching system at 25 MHz can be transformed to 50 Ohm with the initially installed two-stub tuner matching system. The addition of a third stub tuner can increase the area of impedances which allow matching to 50 Ohm significantly, see red area.

The matching software was significantly modified to handle both the double-stub and the triple-stub systems. A matching algorithm for the triple-stub systems uses the formulation available in [8].

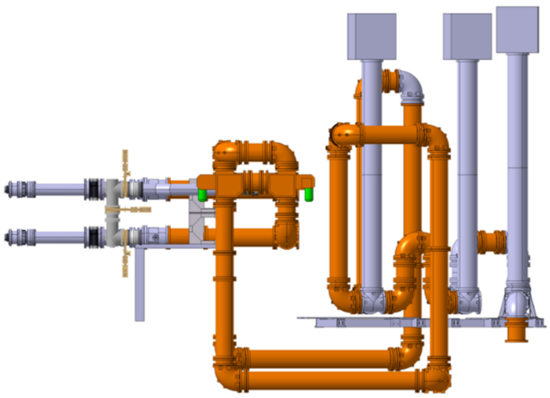

Fig. 7. A CAD drawing of the extended matching system. The actual integration of the third stub tuner (left) turned out to be complex. The stub tuner matching system is shared with both antenna feeding lines.

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