The prospects of ICRF generators at ASDEX Upgrade

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Abstract. The ICRF system at ASDEX Upgrade (AUG) currently uses five RF generators with a total nominal output power of 10 MW. The contract for delivering the initial 4 generators was signed in 1987 and operation started in 1992. In 2018, we added a fifth generator, one that had been put into operation in 1983 for the AUG predecessor, the ASDEX tokamak and later also used for the Wendelstein 7-AS advanced stellarator. While this is a testimony to the longevity of the generators in this frequency range - a legacy of their extended development as radio transmitters - it does rely on spare parts remaining available, in particular tetrodes. Since the initial operation starting in 1983 and 1992, the original tetrodes for the pre-driver stage (Siemens RS 1054) and final stage (ABB CQK 650-2) became unavailable. The pre-driver tetrode can be either replaced by a widely used triode or by a semiconductor amplifier. As a replacement for the ABB final stage tetrode, we successfully tested an EIMAC 4CM2.500KG tetrode in the ASDEX/W7-AS generator mentioned above. Recently however, it was announced that the EIMAC tetrode might no longer be available. Consequently only a single electron tube manufacturer remains, able to produce a tetrode of the type needed for the final stage. Security of supply and lack of competitive pricing could become a cause of concern. We investigate to what extend it is already possible now to replace tube based ICRF generators with semiconductor based RF amplifiers and what future developments can be expected.

INTRODUCTION

The ICRF system at the ASDEX Upgrade tokamak is in operation since 1992. The system originally consists of four RF generators, a complex transmission and matching system and four ICRF-antennas in the vessel. A maximum power of 7.2 MW was achieved; up to 5.5 MW were applied for experiments regularly with four two strap ICRF – antennas [1]. Two of these antennas have been replaced with two three strap antennas; these antennas have shown that ICRF can be operated in a tokamak with a fully metal first wall [2].

The available power was increased by integrating an even older generator that has been refurbished to allow the operation with CPI 4CM2.500KG final stage tetrode [3,4].

THE HIGH POWER TETRODE, A DYING SPECIES

The IPP has ordered first two high power generators for ICRF in 1983 for the ASDEX tokamak [5]. The maximum output power was 1.5 MW per generator; the installation of new coolers for the final stage tetrodes and other minor changes increased the output power to 2 MW in 1989. After the shutdown of ASDEX the generators were in operation till 2001 for the Wendelstein 7-AS advanced stellarator. Four ICRF generators for the ASDEX Upgrade tokamak were commissioned in 1990, in April 1992 the ICRF system was the first additional heating system that delivered power to ASDEX Upgrade. All these generators share the same design principle: they are multistage amplifiers: the first stage is broadband high gain solid state amplifier (SSA) with 100 W output power followed by three tetrode stages in series with 4 kW, 100 kW and 2 MW output power correspondingly. As the demand for high power tetrodes is declining since many years two tetrode types are no longer available. The supply of the final stage tetrode ABB CQK 650-2 ended in 1998, in 2012 the production the pre-driver tetrode Siemens RS 1054SK was terminated. To allow further operation of the rf-generators we rely on the rebuilding of the final stage tetrodes. Rebuilding is a process where the cathode and grids of the tetrode are replaced by new ones, as these parts show aging after typically 10,000 hour of operation. As the electron tube must be opened at the screen grid – anode ceramic and vacuum tight resealed, the process does not always turn out successfully. Also the number of rebuilding procedures is limited. The replacement of the pre driver stage tetrode was done by a total redesign of this stage to a commonly available triode (CPI YU-191B) in grounded grid configuration.

Electron tubes have been around for now 110 years, only a few niches are still occupied by them, e.g. micro wave generation and amplification, generation of x-rays and high RF power. With the development of actively cooled tridodes and tetrodes around 1920 the design of high power amplifiers for broadcast purposes became available. Electron tubes dominated this field for the next 80 years. The development of high power tetrodes peaked around 1985 [3], with tubes that can deliver power up to 2.5 MW. Due to advancements in solid state devices and

the decline of amplitude modulated broadcasts in the LW, MW and SW-bands since around 2000 the demand for high power electron tubes almost totally vanished. As a result of the low demand for high power electron tubes the manufacturers do no longer offer them, e.g. in 2010 we modified one of our old ASDEX generators to accept the CPI 4CM2.500KG final stage tetrode [3, 4] which became unavailable in 2017. Currently only one supplier offers a tetrode with up to 2 MW RF power in the ICRF frequency range, to integrate this tetrode in our generators the tube socket and grid power supplies need to be adapted. As the ITER ICRF amplifiers will use vacuum tubes, either tetrodes or diacrodes, there are chances that a second vacuum tube supplier enters the market again.

SOLID STATE DEVICES

The first patent of a field-effect-transistor, which is the equivalent to a triode, dates back to 1925, but it took more than 25 years to realize the design in semiconductors. High power RF-solid-state devices became available in the 1980s, the most prominent device was the Motorola MRF150. The currently furthest developed semiconductor technology for generating rf-power in the ICRF range are LDMOS FETs (laterally diffused metal-oxide-semiconductor field-effect transistor), they offer up to 1.8 kW power per element [6].

As different technologies have advantages and disadvantages, in TABLE 1 typical parameters of high power tetrodes and high power LDMOS FETs are compared.

TABLE 1. An overview of a high power tetrode versus a high power LDMOS FET

	Tetrode ABB CQK 650-2	**LDMOS NXP MRFX1K80N**
introduced	1983	2018
availability	Canceled in 1998	15 years from product launch
typ. operating voltage	24 kV	65 V
typ. operating current	175 A	40 A
typ. Amplification	14 dB	24 dB
input capacitance	860 pF	765 pF
max. RF output power	2 MW	1.8 kW
max. power dissipation	1.25 MW	3.3 kW
dimensions	Ø 405 x 778 mm	32 x 19 x 4 mm
weight	130 kg	~ 15 g
lifetime	Up to 20,000 h	some 100,000 h

While the tetrode wins at the output power, the LDMOS device shows an almost unlimited lifetime, also the degradation of the electrical parameters with time, which is unavoidable in tetrodes, is virtually unknown to solid state devices. The need of high voltage installations for tetrodes makes the electrical installation of an amplifier complex. Together with the limited lifetime the operation of tetrode based ICRF amplifiers needs qualified personal. On the other hand, the maximum power of LDMOS FETs is low compared to tetrodes, for the typical output power of 1.5 – 2 MW for an ICRF generator at least 1000 LDMOS FETs are needed. The question is: Is an amplifier, which consists out of 1000 amplifier elements, technically feasible?

HIGH POWER SOLID STATE AMPLIFIERS

In the year 2000 it was decided to use a solid state power amplifier (SSPA) for the SOLEIL accelerator instead of an IOT (inductive output tube) or a klystron at 352 MHz. By 2004 the first 35 kW SSPA was commissioned and in 2006 the first 180 kW SSPA went into operation [7]. This 180 kW SSPA uses 724 RF-modules with an output power of 330 W, 42 of the modules are in stand-by. Each of these modules has its own power supply. A microcontroller is monitoring the forward and reflected power of and the drain current of the LDMOS FET. These data is multiplexed to a central control unit. Based on the good operational experience with the first in-house designed SSPAs contracts with the industry were made. A reworked version of this amplifier with modules that can deliver 650 W resulted in a 150 kW amplifiers which needs only 256 modules. Such amplifiers were installed at ESRF (European Synchrotron Radiation Facility) [8].

Compared the needs of ICRF at midsized tokamaks like ASDEX Upgrade, an output power of around 150 kW is about the size of a driver stage for a typical tetrode based 2 MW ICRF generator. In 2016 CERN decided to replace the tetrode based 200 MHz rf-generators of the Super Proton Synchrotron (SPS) accelerator. A new SSPA design was chosen; in this case a 2 MW amplifier is built out of 16 “towers”. One tower basically consist out of 4 19”-racks that are arranged around the central cavity combiner. Each of the tower hosts 80 rf-modules (4 x 20) and each modules contains two LDMOS FETs, summing up to 2560 LDMOS FETs per 2 MW amplifier. Based on a nominal power of 144 kW per tower, each LDMOS FET delivers 900 W power. A cavity power combiner in each tower is used to add the power of the individual modules, a special, yet not published decoupling circuit is used to allow the removal of modules during operation [9]. The CERN SPS SSPA will be fully commissioned in 2020 [10]. One main difference between rf-generators for accelerators and ICRF at fusion experiments is the needed bandwidth as the typical bandwidth of a cavity combiner is only a few percent, which is sufficient for accelerators. As long as the ICRF community needs the flexibility to heat different ion species at different magnetic fields at the fundamental or harmonic frequencies for scenario development, this amplifier design cannot be applied to ICRF generators because of its small bandwidth.

Beginning around 2000 a number of digital broadcast services (ATSC, DAB, DVB-T, etc.) were introduced. All these services are based on SSPAs. The choice of SSPA over tetrode based amplifiers was based on higher reliability, lower maintenance and overall operating cost due to the lack of replacing expensive electron tubes even if the efficiency was lower. Currently power densities of 80 kW power per 19”-rack are archived using water cooling, the maximum efficiency is 75 %. Unfortunately none of these amplifiers cover the ICRF range.

SOLID STATE AMPLIFIERS AT THE ASDEX UPGRADE ICRF SYSTEM

For test purposes the ICRF group at the IPP ordered a SSPA from a small manufacturer. The BEKO HVL-6200 can deliver up to 5 kW for 15 s long pulses in a frequency range from 20 – 62 MHz. The pulse length is limited by the losses in ferrite power combiner and is 30 s for 2 kW or 60 s for 1 kW output power. The air cooled amplifier uses four Ampleon BFL188XR LDMOS FETs and is compatible with 19”-racks measuring 483 x 520 x 222 mm. This amplifier could replace the electron tube in the pre driver stage of our ICRF generator, due to its broadband design of the amplifier; three of the 12 matching units inside the generator could be removed. The wall plug to RF power efficiency is about 60 %.

As the 5 kW SSPA fits in a 19”-rack, the question is in which way multiple SSPA modules can form high power amplifiers? Based on the dimensions up to 8 5 kW SSPAs can be mounted in 19”-rack with 2000 mm height, giving a total power of 40 kW, the same power density as in the CERN SPS SSPA. If one would like to replace the current driver stage of the ICRF generator one would use four of these 19”-racks, that could provide up to 160 kW power. This would be a significant upgrade of the currently used driver stage that can deliver up to 100 kW, which is at some frequencies is limiting the maximum output power of the ICRF generators.

When building a SSPA for ICRF one should question if the currently used output power of 2 MW per generator is the best choice. E.g. the newer 3-strap antennas need active control of both, the power ratio and the phase between the central and outer straps [2]. During commissioning of the 3-strap antennas the maximum power applied to the antenna was limited by the output power of a single rf-generator that supplied the central strap. Adding an additional rf-generator to power the central straps increased the total ICRF heating power significantly [11]. To gain more flexibility SSPAs as 1 MW units would be better, e.g. 32 racks 40 kW racks.

As mentioned above, the CERN SPS SSPA cavity combiner structure cannot be used for an ICRF generator due to the lack of bandwidth. 3 dB-hybrids have been in use for adding, splitting und decoupling purposes since many years and they provide a bandwidth of e.g. 30 – 60 MHz, enough for operation at fusion experiment [1]. The dimensions of 3 dB-hybrids are determined by the center frequency; e.g. 42.5 MHz, the geometrical middle of a 30 – 60 MHz frequency range leads to couplers that are mechanically around 2 m long, short enough to install them in a 19”-rack. For 8 SSPA modules in a rack four EIA 7/8”, two EIA 1 5/8” and one EIA 3 1/8” 3-dB hybrids are needed, each hybrid has to be equipped with a 50 Ohm termination. The output connector of a rack would be EIA 3 1/8”. The outputs of several SSPA racks can be combined by further 3-dB hybrids, e.g. 32 racks forming a 1.25 MW amplifier. A major advantage using of 3-dB hybrids in the amplifier is that a broken SSPA modules has only minor effects on the amplifier performance; also no tuning of the amplifier is needed.

OUTLOOK AND CONCLUSIONS

A 5 kW SSPA has been successfully tested and is used to provide power for a number of applications. The average efficiency of LDMOS based SSPAs in the linear class B operation mode is 50 to 65 % in broadband applications. Based on the positive results gained with the 5 kW SSPA, a development of a 10 kW SSPA was initiated.

A much higher efficiency can be archived when the amplifier is operated in switch mode operation, e.g. in class E where the efficiency can reach up to 85 %. At the moment the main limitation is the maximum voltage limit of LDMOS FETs, as the voltage during operation 3.6 times higher as the supply voltage another limitation is the bandwidth that is only 1 to 1.3 (e.g. 30 ~ 40 MHz) [12].

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