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# ICRF system efficiency

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The efficiency of heating and current drive systems is one of the key parameters for a successful operation of fusion demonstration power plants like DEMO. In an earlier review article, overall efficiencies of H & CD systems were estimated at 20 – 30 % [1]. In this paper we present a detailed breakdown of the overall efficiency for ICRF (ion cyclotron range of frequencies) based, where possible on experimental data: 1) the *technical efficiencies* (RF generator, transmission lines, losses in antenna); 2) the *interface efficiency* (hardware/plasma), and 3) *heating efficiency* (absorption in plasma). This leads currently to an *overall efficiency for heating* in the range 40% to 55%. Future improvements can lead to an overall efficiency of up to 75 %.

Keywords: heating, current drive, ICRF, ICRH, efficiency

## Introduction

The efficiency of the heating and current drive systems is a key parameter for the successful operation of a fusion power plant. In an often cited paper about research and development issues for DEMO an overall efficiency for ICRF of 30 % was mentioned [1]. An overall efficiency of typically 60 % has to be reached for running a fusion power plant. We present data of currently archived efficiencies of the ICRF system of the ASDEX Upgrade (AUG) tokamak and show that further developments can lead to future improvements.

## 1. Efficiencies for heating

Energy conversion efficiency is the ratio of the used output energy and the input energy. In our case it is the ratio of the power absorbed in the plasma and the electrical input power. We have split this up in 3 components: 1) the technical efficiencies 2) the interface efficiency 3) heating efficiency. We will for each component discuss the achieved and the achievable numbers.

### 1.1. Technical efficiency

This number itself includes the efficiencies of producing the RF energy (power supplies and RF generator), the losses in the transmission lines and the antennas.

#### 1.1.1.Power supplies

The efficiency of today's power supplies is high when they are used close to their maximum ratings. Thyristor (SCR) controlled high voltage supplies reach efficiencies up to **95%** [2]. The number in bold will be summarized in table 3). Newer power supply topologies like the pulse step modulator (PSM) reach up to **97%** [3]. The efficiency of PSM power supplies can benefit from new wide band gap semiconductors that allow a significant reduction of the number of modulator stages needed.

#### 1.1.2. RF generation efficiency

Amplifiers that are currently used by ICRF systems are built in a traditional way: one or two semiconductor stages with power levels of 100 W up to several kW followed by two or three vacuum tubes stages (triodes or tetrodes) reaching a output power of up to 2 MW [4, 5, 6]. These amplifiers are operated in the so called Class-B mode, allowing a maximum efficiency of 78.5 % [7]. As the operation of the amplifier need subsystems like power supplies for the filaments and grids of the electron tubes, pumps and ventilators for cooling etc., this energy consumption has to be included when calculating the efficiency. To calculate the technical efficiency of the ASDEX Upgrade ICRF system we also included the ICRF subsystems such as the air supply for the transmission lines, the vacuum system for feed troughs TLs and the control and data acquisition which, for the 2 MW generators of AUG, consume about 56 kW per RF generator. The efficiency of the AUG RF generator #1 operated at 30 MHz with an output power of up to 1 MW during a 2 T H-mode discharge of ASDEX Upgrade is shown in Fig.1. During the second half of the discharge the plasma-antenna distance was changed several times. Although a 3-dB hybrid was used to decouple the changes of the antenna impedance from the RF generator, the small residual load changes at the generator cause a variation of the RF generator efficiency, between 65% and **75%**, which is about the maximum achievable with Class-B amplifiers. To operate the RF generator with maximum efficiency an adapted anode voltage as discussed in [8] is vital. Higher efficiencies of up to 80 % can be reached by operating this kind of amplifier in Class-C mode [9]. It requires a redesign of internal power supplies and the driver stage. The lifetime of the tetrodes is however likely to decrease in this operation mode because of the higher power dissipation at the grids. Today's semiconductor RF power amplifiers are reaching an output power of tens of kW and are widely used for broadcast applications [10] as they are more reliable and show much lower maintenance costs, even though the efficiency in some broadcast application does not exceed those of tube amplifiers.

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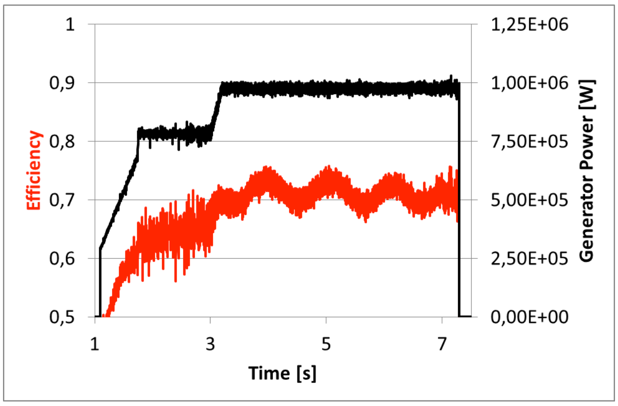


Fig.1 The efficiency (red) and output power (black) of the ICRF generator #1 during shot 32141, incl all. subsystems.

In the last few years a few high power amplifiers have been designed for particle accelerators, one of the earliest reaching up to 190 kW at 352 MHz, used at the SOLEIL synchrotron [11]. Supervision circuits allow easy failure detection and the modular design allows short repair times. Due to the further development of the LDMOS devices the number of LDMOS transistors has been reduced from 724 to 256, as the output power of each transistor was increased from 350 to 650 W [12]. A new design approach is to replace printed circuit board and λ/4 couplers used to combine the power of individual amplifiers with a cavity resonator, which led to lower losses and to a more compact design [13]. Currently a 2 x 2 MW rf amplifier at 200 MHz using 5120 LDMOS-FETs is under development [14]. The currently ongoing development of wide band gap semiconductors like GaN and SiC HEMT, with characteristics that outperform the currently used Si LDMOS, would even allow moving from the linear class B amplifier topology with an efficiency of 70 % to the switch mode class E amplifier topology which can reach an efficiency of **88 %** [15].

### 1.1.3. Matched transmission line and waveguides

ICRF systems typically use coaxial transmission lines with impedances between 25 Ω and 50 Ω to transfer power to the antenna. A minimum of attenuation can be achieved using a coaxial transmission line with 77 Ω. While the losses of the inner conductor are about the same as on a 50 Ω transmission line, the smaller diameter of the inner conductor leads to a much higher temperature, therefore a 50 Ω transmission lines are used as a good compromise. Fig. 2 shows the attenuation and cw power handling limits for 50 Ω coaxial transmission lines with Cu inner and Al outer conductor for 120 °C inner conductor temperature and 40°C ambient temperature. The losses on the inner conductor and the weak thermal conductivity of air are the limiting factor for continuous operation. Successful tests with actively cooled conductors have been made [16], reaching 6 MW at 49.6 MHz, which is equivalent to the resistive losses at 4.25 MW and 74 MHz, but accessing the inner conductor for cooling remains complicated. Table 2 shows an overview of different TL sizes and the minimum number of TLs that would be needed for a 50 MW ICRF system for DEMO.

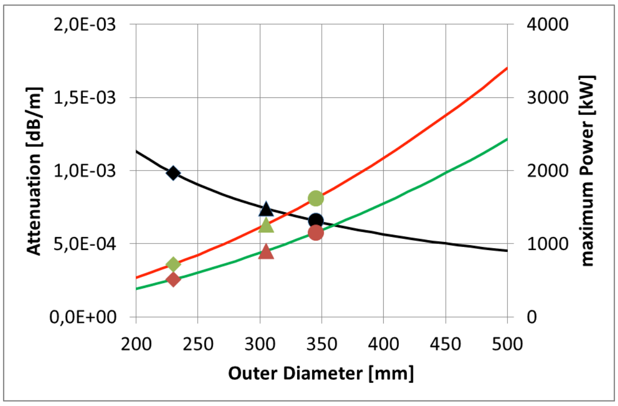


Fig.2 Shows the attenuation (black) and cw power handling capability of a matched 50 Ω coaxial transmission line with Cu inner and Al outer conductor at 74 MHz as function of diameter of the outer conductor. The red curve is the maximum allowable power for 120 °C at the inner conductor and 40 °C ambient temperature of an unpressurized coaxial line, the green curve is valid for 3 bar air pressure.

Table 2: power limits and losses for different TLs at 74 MHz

| TL type | outer diam. [mm] | max. power [kW] | # TLs for 50 MW | losses / m @ 50 MW |
|---|---|---|---|---|
| RL100-230 | 230 | 719 | 70 | 12.5 kW |
| 12" | 305 | 1264 | 40 | 9.39 kW |
| RL 150-345 | 345 | 1618 | 31 | 8.31 kW |
| 12" cooled | 305 | 4251 | 12 | 9.39 kW |

The typical length of the matched TLs for an ICRF system is about 100 m, and with the values of Table 2, the losses are between 1.6 and 2.5 %. In the unmatched section of the transmission line standing waves are present, which increases the losses depending the reflection factor ϱ. The total losses can be reduced by a careful selection of the impedance of the transmission line with respect to the impedance of the antenna. A λ/4-transformer directly connected to the antenna loops greatly helps to minimize the losses in the unmatched section. High radiation levels of the ITER and DEMO can cause an increase of the dielectric losses of ceramic insulators used to center the inner conductors. This problem can be solved by using conducting λ/4 long supports of the inner conductors; a relative bandwidth of +/- 5 % of the center frequency can be easily achieved with supports that are spaced n*λ/4 apart. This setup also allows easy access for gaseous or liquid coolant to the inner conductor. Efficiencies for the transmission lines are thus of the order of 97.5 to **98.4%** at a VSWR = 1.
The design of ICRF systems at ITER and DEMO are very demanding as it requires the transmission of several tens of megawatt to the antennas. This can be done by using multiple coaxial transmission lines in parallel where the overall losses are determined by the losses of the design of the coaxial transmission line. As the problem of cooling the inner conductor remains, a solution like a rectangular waveguide where the power is dissipated at easy accessible surfaces could be an option. The largest standard waveguide size available is WR2300, which allows operation between 320 and 490

MHz. Waveguides might be not a solution for ITER where the ICRF operates at 40 – 55 MHz, but should DEMO operate between 66 and 74 MHz [17], a waveguide measuring 3000 mm by 500 mm results in a more compact design than several parallel coaxial TLs and is cheaper and easier to install. The transmission losses of such a wave guide at 74 MHz are one fourth compared to 50 Ω TLs with a 345 mm outer conductor. Such a waveguide can be directly attached to an amplifier with a cavity combiner. Waveguide efficiencies could thus be up to **99%**.

#### 1.1.4. Antennas and (short) unmatched section

Recent ICRF antennas use a relatively small number of antenna loops to couple RF-power to the plasma, with an average power density of about 2 $MW/m^2$ and a coupling resistance of the order of a few Ohm per antenna loop. The losses of the antenna can be estimated by comparing the vacuum impedance of the antenna with the impedance during plasma operation, typical ratios are around 0.1 which means that 10 % of the power is lost in the antenna (eff. **95%**). For DEMO new approaches use 360° distributed antennas fully integrated in the blanket [18, 19, 20]. The local power density of this distributed antenna is lower than on current designs. Since the coupling resistance is close to the characteristic impedance of the transmission line, the power losses and the maximum voltage in the unmatched antenna feeding lines are reduced due to a low VSWR. The low VSWR of such an antenna demands only a simple matching system like a λ/4 transformer or no matching system at all. Conservatively we take the same efficiency (**95%**).

## 1.2 Interface efficiency

We define interface efficiency as the power that reaches the confined plasma divided by the power that leaves the antenna. This thus takes into account power losses in the scrape-off layer. In present-day machines, good absorption in the (confined) plasma of the power leaving the antenna in a single transit is not always guaranteed. However, since the tokamak vessel acts as a Faraday cage from which RF power cannot escape, all power launched from the antennas needs to be absorbed. Crudely speaking the power density $P_d$ absorbed locally in a plasma is the product of the electric field **E** amplitude squared and a plasma dependent factor $C_p$ involving density, temperature, etc.: $P_d=C_p|\mathbf{E}|^2$. When the plasma absorptivity is low, $C_p$ is small and the electric fields need to be large to ensure that the above equality is satisfied for a given amount of power launched. Since the RF waves are evanescent (and thus their amplitude varying exponentially) in the low density edge, their $|\mathbf{E}|$ is largest close to the launchers and the risk for parasitic absorption is highest there. Optimizing the core plasma heating scheme thus is the best way to limit wave induced plasma wall interaction. How good the core (being here defined as the region where the plasma is confined) plasma heating scheme is, can be quantified with the single transit absorption. The single transit absorption is a calculated value: the ratio of power absorbed in two passes, from the antenna through the plasma, and back from the inner side of the plasma on the HFS to the antenna (since this can be asymmetric due to cut-off and mode conversion layers). This calculated value of the "single transit" absorption takes into account absorption in the confined plasma on ions and electrons. One can make an estimate of the losses in the edge, by assuming that a fraction of the power, not absorbed in each pass is lost in the edge. For AUG we find experimentally, that scenarios with a calculated single transit absorption larger than 15%, do not lead to operational problems and 70% of the power is absorbed in the plasma. This leads to a calculated loss per double pass in the (outer) edge of 6.5 %. The total loss in the edge is then 30% and the interface efficiency thus **70%**. In large size machines, the heating efficiency is commonly good unless evanescence layers prevent the launched waves to reach the core plasma (see e.g. [21]): In ITER, wave absorption during a single transit of the RF wave over the plasma will be in excess of 80% with the appropriate choice of frequency. Taking the same values of loss per pass (6.5%) also in larger machines (which is likely an overestimate, because of the smaller extend of the SOL to the main plasma), and using the calculated single transit absorption is 80%, we find for the total losses in the edge less than 5 %. The corresponding interface efficiency is thus **95 %**. Strictly speaking, the efficiency cannot be computed in this way: although the tokamak acts as a (metal) Faraday cage forcing the power launched from the antenna necessarily to be absorbed inside the vessel, parasitic absorption in the edge is more important when the core absorption is weak than when it is strong. Likewise, waves re-incident on the antenna modify the current pattern on the antenna as well as the phase and amplitude of the vacuum waves in between the generator and the antenna. Hence the fate of the power in one subregion influences the behavior in other subregions. Nevertheless the attempt to isolate the various subregions to get a first estimate of the role played by the different regions, clearly leads to an underestimate of the efficiency in the large machines.

## 1.3. Heating efficiency

The heating efficiency is defined as ratio of the power that is useful to heat the plasma to the power that reaches the confined plasma. In the case of ICRF, this efficiency takes for example into account that, for certain scenarios, one could heat in the confinement region ions to very high energy that are lost before they could transfer their energy to bulk ions and electrons. For present day machines, because of the scenario used (minority heating) and the relative small value of the confining plasma current and machine size, this can indeed be a concern, though a minor one. In ITER and DEMO-like machines, the proper path to ignition resides in starting from a sufficiently low density plasma to initiate the heating and to gradually crank up the energy both via density and temperature increase. Once the plasma ignites it will contain high energy D-T fusion-born $\alpha$ particles. The heating scheme needs to avoid unconfined ions and be resistant against non-desired wave-induced further acceleration of the $\alpha$'s. The adopted solution is to rely on an RF heating scheme that sidesteps this problem altogether from the start: second harmonic T heating, possibly with $^3He$ minority. Since the machines are designed to confine the very energetic alpha-particles, losses related to the heating of non-confined energetic particles is not an issue. Heating efficiency in those cases can confidently be set to 100%.

## 2. Current drive efficiencies

Modeling suggests that ignited plasmas should *not* require auxiliary heating at all and can solely be heated through the slowing down of the $\alpha$ population. After the ramp-up phase of the discharge, the RF heating system could then be exploited for another purpose: current drive. The current drive efficiency is a number that calculates the driven current per power absorbed in the confined plasma. To get the relevant number for the power balance of a reactor, one also needs to take into account the efficiencies from the plug to the power in the plasma. To first order, one can take for this latter values the number obtained in the heating section. The local current drive efficiency $J/P_d$ of an RF heating scheme is usually estimated relying on an approximate expression proposed by Ehst [22]. Here J is the current density driven by a power density $P_d$ passed on from the waves to the electrons. Integrating over the obtained current density profile provides the total current that can be driven for a given input power. Ehst's expression accounts for the fact that trapped particles do not contribute to the current, at least not in the zero orbit width limit. As a consequence, driving a current close to the plasma core is more efficient than driving a current off-axis, and driving a current on the high field side is more efficient than driving it on the low field side. Somewhat misleadingly, Ehst's expression also predicts a high current drive efficiency when the parallel wave phase velocity $\omega/k_{//}$ (where $\omega$ is the driver frequency and $k_{//}$ the parallel wave number) is large w.r.t. the electron thermal velocity $v_{th,e}$ ($w=\omega/[k_{//}\ v_{th,e}] >>1$). However, in such case the current drive efficiency is large because the absorbed power is small, not because the driven current is significant. Which merely points to the need for good electron absorption as a prerequisite for driving current. In practice, w ideally is close to but slightly higher than 1 (at 1, the electron damping is optimal). Accounting for that condition and for profiles deemed realistic for DEMO, current drive efficiencies of the order of 30-40kA per MW launched have been found for equatorial launch and up to 60kA/MW for near-top launch [23]. Only if the antenna spectrum can be adapted when the plasma temperature varies one can hope to maintain optimal efficiency during a discharge. Similarly low current drive efficiency numbers are obtained for other heating systems (see e.g. [24]), indicating that novel ideas are required if one aims at *steady state* fusion machines becoming economically viable.…

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## Summary table

Table 3: reached and expected total ICRF heating efficiency

| | efficiency at AUG | Possible for DEMO |
|---|---|---|
| power supply | 0.95 | 0.97 |
| RF generator | 0.75 | 0.88 |
| transmission line | 0.98 | 0.99 |
| Antenna | 0.95 | 0.95 |
| sum. technical efficiency | 0.66 | 0.80 |
| interface efficiency | 0.70 | 0.95 |
| plasma heating efficienc | 1 | 1 |
| total heating efficiency (power in plasma/plug power) | **0.46** | **0.76** |
| current drive efficiency (current/absorbed power) | not tested | 0.06 A/W absorbed |
| current drive efficiency (current / plug power) | not tested | 0.046 A/W absorbed |

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