# Effect of the drift gap between the undulator sections on the operation of the Fusion-FEM

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**Abstract**

The 'Fusion FEM' is a Free Electron MASER based on an electrostatic accelerator. An electron beam of 12-A, 1.35—2 MeV is injected into a step-tapered undulator to generate 1 MW of radiation in the range 130—260 GHz. The undulator is built from two sections with different field strength (step-tapering), separated by a field-free gap. Tapering enhances the efficiency at high output power. Proof of principle has been demonstrated in short-pulse regime, without an energy recovery system. The latter is now being installed and will allow long-pulse operation. The experiments have shown that high output power can be generated and that the FEM has the tendency to lock onto a single longitudinal mode. The influence of the length of the gap between the undulator sections has been investigated and is the subject of this paper. The experimental results are reasonably well explained by simulations.

PAC's: 41.60, 41.60.C, 52.50.G, 29.17

## 1 Introduction

The main purpose of the Fusion FEM [1, 2] is to develop a high power mm-wave source suitable for electron-cyclotron applications on magnetically confined plasma's in nuclear fusion experiments. The advantage of using the FEM -principle over the alternative, the gyrotron, is the ease of tunability which is important for the above mentioned application. Furthermore, it has, within the mm-wave range, no upper frequency limit. The efficiency of a FEM itself is quite low. In order to achieve an overall efficiency of over 50% the energy in the electron beam, emerging from the undulator, has to be recovered.

In the Fusion FEM a 12 A electron beam with an energy between 1.35 and 2 MeV is steered along a straight path through a cavity to generate 1 MW quasi-continuous mm-wave power in the range 130—260 GHz. The cavity is formed by a corrugated waveguide in a step-tapered undulator. On both ends, steps in one transverse dimension of the waveguide act as mirrors which allow the electron beam to pass but confine the $HE_{11}$-mode of the mm-wave radiation. Reflection is 100% at the upstream side and adjustable at the downstream side. The stepped-waveguide mirrors have a bandwidth of around 10%. The output frequency is tuned with the beam energy. This can be done quite fast over the bandwidth of the cavity. For a larger range the cavity and the beam optics system have to be tuned as well, which, of course, will slow down the tuning process. The straight beam line has been chosen in order to facilitate almost complete beam transport.

The conversion efficiency in the undulator has to be $\geq$6.2% in order to extract 1 MW from the beam at 1.35 MeV. Note that a much higher efficiency in the undulator is not desirable either, as this would lead to an energy spread too high for energy recovery in a decelerator and a depressed collector [3]. The feedback ratio, $R$, should be relatively low to keep the RF-field inside the cavity within breakdown limits. The design value is $R = 1/3$. This implies that the single pass gain $G$ (power ratio), in saturation $G_{sat} = 3$, and the linear gain, $G_{lin} >> 3$ so that the closed loop gain $G_{cl} = GR >> 1$ to start-up from noise into saturation in a reasonable short time. Experiments show that the start-up time is 2 $\mu$s [1, 2]

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The cathode of the gun and the collector-housing are at ground level while the cavity is at high-voltage level. The main energy is delivered by the power supplies of the depressed collector and the beam loss current by the 2 MV high-voltage supply. The output resistance of the 2 MV supply causes beam energy to drop when the beam is lost. The maximum allowable loss is 20 mA.

## 2 The undulator

The KIAE-4 undulator [4] satisfies the contradictory requirements of high gain and high efficiency. It has been designed explicitly for the Fusion-FEM. It is step-tapered by using two sections. The first section has 20 full-strength periods with a peak field of 0.20 T and the second section 14 periods with a peak field of 0.16 T. All periods are of length $L_u = 4\,\text{cm}$. The length of the zero-field drift gap between the sections, $L_g$, can be varied. In the second (weaker) section the longitudinal velocity of the electrons is larger and therefore the resonance frequency higher. At high power level the average deceleration of the beam in the first section is such that also the second section comes into resonance and acts as an amplifier. To illustrate the effect of

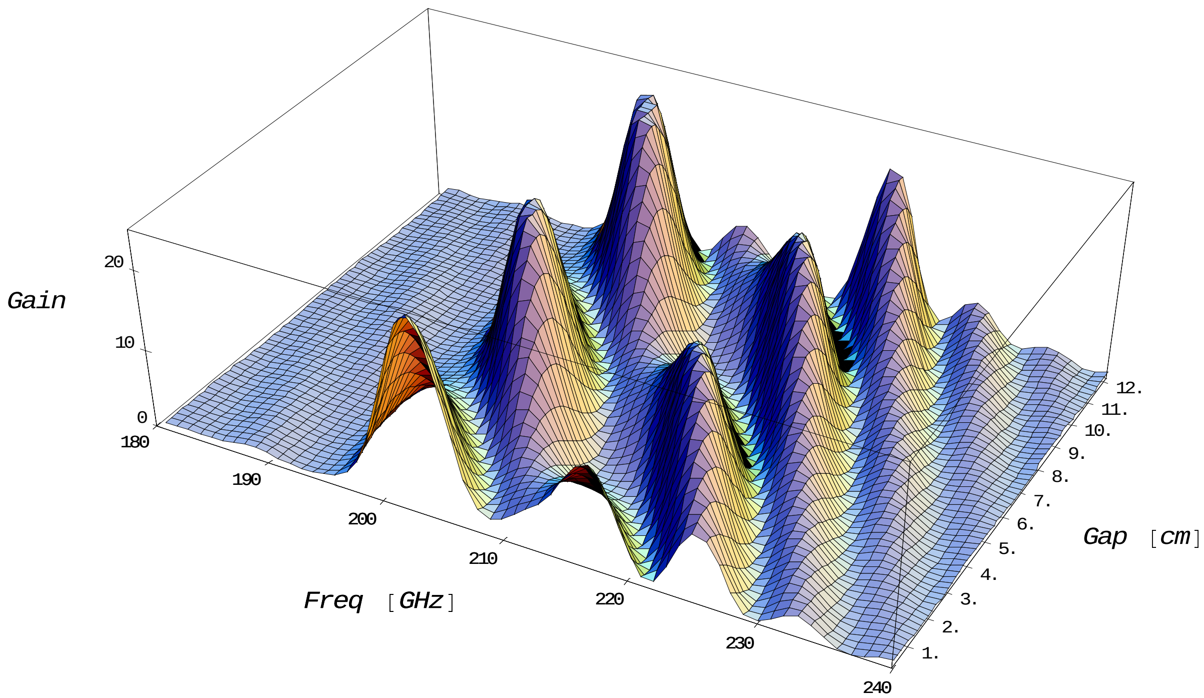


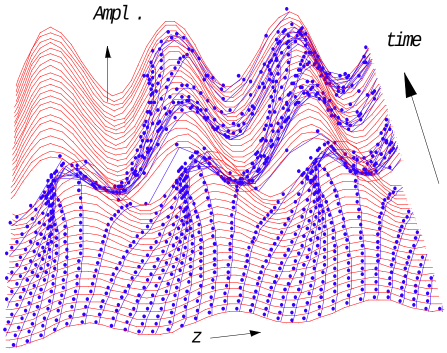

Figure 1: *'Madey hills'*, Single-pass linear gain versus frequency and gap length in the step-tapered undulator of the Fusion-FEM as calculated by particle tracking with the code GPT.

the length of the gap, we calculated $G_{lin}$ as a function of the frequency and $L_g$ for an ideal electron beam of 1.75 MeV and without space charge. The result is shown in fig. 1. The left front peak, as we will see later, will dominate the start-up behavior of the FEM . These computational results are obtained by particle tracking with GPT [5] in the combined field of the undulator and the mm-wave radiation with the inclusion of particle-wave interaction [6]. The results are in accordance with those obtained analytically [7]. The advantage of the GPT-method is that all beam parameters and the matching periods of the undularor are automatically taken into account.

$G_{lin}$ has a maximum when the electrons travel over half a period of the ponderomotive wave during their trip through the first section, change phase in the gap and travel over one and a half period of the ponderomotive wave in the second (weaker) section. In other words, when the condition for maximum gain is fulfilled in the first section and the velocity in the second section corresponds to the second, much lower, peak in the Madey curve. The beam entering the second undulator section can be considered to consist of a continuous part and a bunched part. The gain contribution from the bunched part is sensible to $L_g$. The single pass gain at saturation $G_{sat}$, not shown here, has a much flatter profile. At the design value of maximum power level the deceleration is such that the electrons remain on the right slope of the ponderomotive wave in both sections of the undulator.

The movement of the electrons on the ponderomotive wave for the points of maximum gain for low and for high power level is illustrated in fig. 2. For the linear case, on top, we see bunches develop on the positive slopes and move towards the crests at the end of the first undulator section. In the second section the electrons travel over approximately $3\pi$. The gap represents a backward shift in the ponderomotive wave equal to $k_u L_g$, where $k_u = 2\pi/\lambda_u$ is the undulator wavenumber. This sudden shift is clearly seen. The higher longitudinal velocity in the gap, corresponding to an extra phase shift of $11\pi L_g$, looks like a forward jump.

At saturation, (lower plot) the bunches are already optimal halfway the first section and are visibly decelerated while the wave increases in amplitude. In the second section the bunches, or what remains of them, in general remain on the positive slopes of the ponderomotive wave.



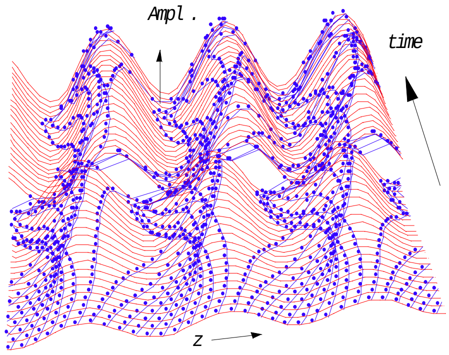




Figure 2: Movement of electrons on the ponderomotive wave at $f$ = 202 GHz, $P_{in}$ = 40 KW, $L_g$ = 9.7 cm (at left) and at $f$ = 198 GHz, $P_{in}$ = 500 KW, $L_g$ = 7.5 cm (at right). The code used is GPT. Both cases correspond to a gain maximum.

# 3 Experimental Results

The experiments without the energy recovery system and during which the length of the gap between the undulator sections has been varied are carried out with a fixed setting of the stepped waveguide mirrors and a beam current of 7 A. At each setting of the gap length the initial beam energy was adjusted for maximum output power. The output power is measured in three ways: by a fast broadband detector, calorimetrically, and by observation of the temperature profile of an absorbing sheet. The first method gives the spatially integrated power as a function of time, the last method gives the time integrated power as a function of position, i.e. the mm-wave beam profile. The calorimetry is used for calibration. The 'mm-wave spectrum' is the IF-frequency from a mixer. During a 'shot' the beam energy drops, by lack of recovery, over 1 keV/$\mu$s/A, which corresponds to $\approx$ 0.2 GHz/$\mu$s/A. This means that the output power will rise and fall as the gain profile corresponding to the beam energy sweeps trough the gain profile of the cavity. Fig. 3 shows the measured peak output power as a function of $L_g$. The main feature of this result is a peak at 5.5 cm and a dip at 3.5 cm. To explain the experimental results we calculated the closed-loop gain, i.e. the product of the calculated single pass gain and the measured reflection of the mirrors and, for good comparison with experiment, included all relevant beam parameters and the effect of the space charge. Fig. 4 shows the result in the form of contour plots of $G_{cl}$ in the $f$-$L_g$-plane with the linear case at left and the saturated case at rigth. For the linear case $G_{cl}$ peaks around $L_g = 6$ cm. Oscillation is possible within the contour $G_{cl} = 1$, which is at 3.5 cm $< L_g <$ 7.5 cm. Both facts are consistent with the measurements. The contour for $G_{cl} = 1$ at saturation predicts a larger range for high output power than measured. We expect this to be due to the short pulse character of the measurements.

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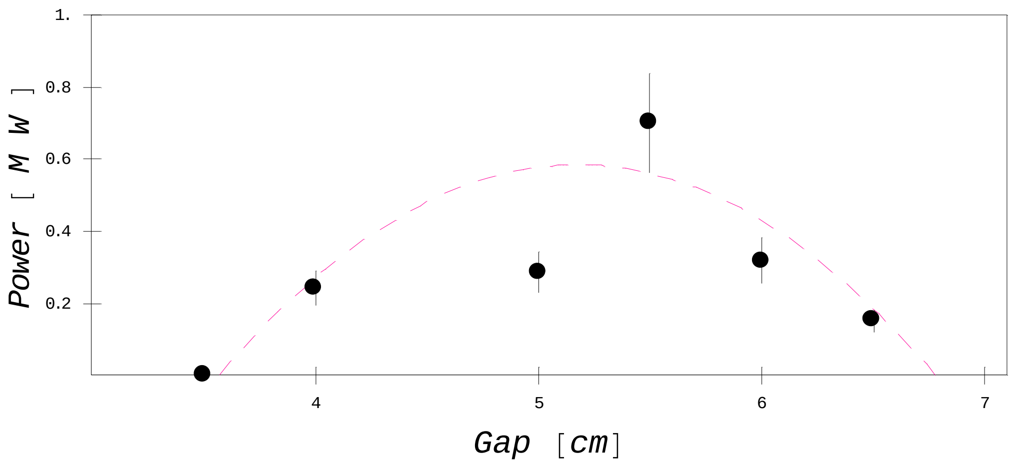


Figure 3: Measured peak output power of the Fusion-FEM as a function of the length of the intersection gap. The measurements have been carried out with a 7A, 1.75 MeV electron beam and the FEM cavity tuned at 200 GHz.

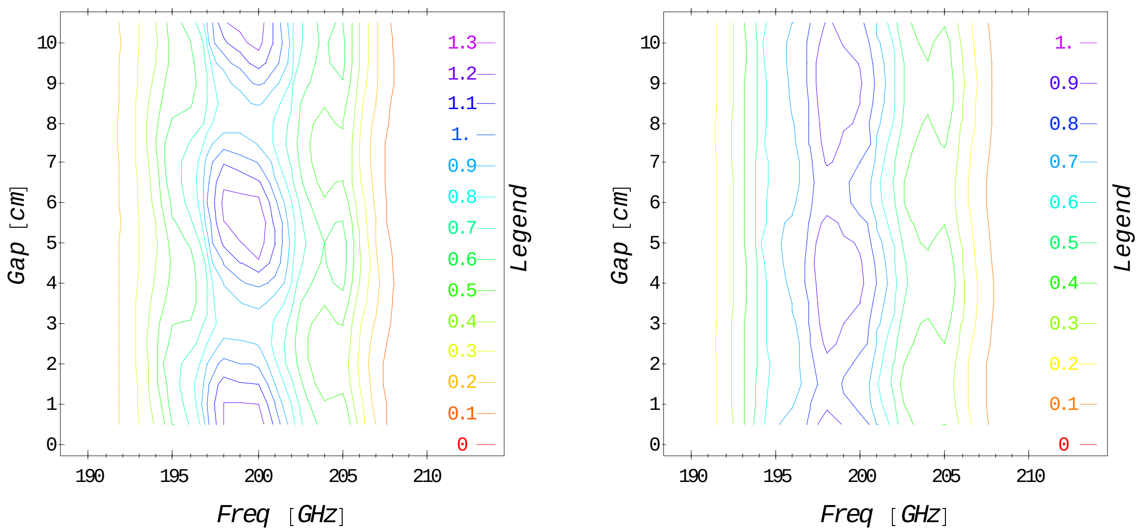


Figure 4: *Closed loop* Gain contours in the frequency-gap-plane calculated for the actual beam with space charge for low power, shown at left, and for high power, at right.


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