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FINAL ~~Progress~~ Report

# MICROWAVE GENERATION FOR MAGNETIC FUSION ENERGY APPLICATIONS

Task A: Experimental and Numerical Study of Microwave Sources for ECRH Incorporating Depressed Collectors and with ITER-Relevant Parameters

Task B: Theory and Modeling of High Frequency, High Power Gyrotron Operation

For the period July 15, 1994 to July 14, 1995

Submitted by
Institute for Plasma Research
University of Maryland, College Park

# Task A: Experimental and Numerical Study of Microwave Sources for ECRH Incorporating Depressed Collectors and with ITER-Relevant Parameters

## Executive Summary

A proof-of-principle short pulse ($\sim$ 100 ns) experiment has successfully demonstrated operation of a sheet-beam FEL amplifier with output power of 250 kW at 86 GHz and with 24 dB saturated gain and $\sim$3% efficiency. Gain in the linear region was 30 dB. Measured performance parameters were in good agreement with predictions of a multi-mode, time dependent code. Also, a code has been developed to design depressed collectors which will enhance efficiency of ECRH sources (both FELs and gyrotrons). The follow-on work which is proposed is centered on the development of a high gain FEL oscillator with ITER relevant parameters ($\sim$ 2 MW output power at $\sim$ 170 GHz) and the use of this oscillator as a vehicle for benchmarking the efficacy of depressed collector in ECRH sources with ITER-relevant operating parameters. An FEL oscillator is chosen rather than an amplifier because of the lack of driver rf sources near 170 GHz. The proposed experimental study takes advantage of a state-of-the-art modulator which has recently been acquired by the University of Maryland; this modulator produces on a repetitive basis 8.5 $\mu$s pulses at voltages up to 650 kV and current up to 870 A. The proposed study will allow for evaluation of such critical issues as secondary emission of electrons in depressed collectors, tunability of FELs with ITER relevant parameters, and efficiency optimization in multi-megawatt ECRH sources.

## Synopsis of Progress and Proposed Studies

An 85 GHz, sheet e-beam, FEL amplifier has been demonstrated and studied in both the linear and nonlinear operating regimes. Peak output power of 250 kW has been achieved with an input power of 1 kW, representing a value of saturated gain of 24 dB. Linear gain was measured as 30 dB. The electron beam was a 2 cm $\times$ 1 mm, 17 A sheet of 650 keV electrons; thus saturated efficiency $\sim$3%. The wiggler magnet was untapered and consisted of 74 periods with $\ell_w = 0.96$ cm and $B_w = 3.8$ kG peak. The e.m. mode was $TE_{01}$ in rectangular waveguide with dimensions 4 cm $\times$ 3.2 mm. Both the measured value of gain and the measured value of saturated efficiency are in good agreement with the predictions of a multimode, time dependent code.

Rather than add a tapered wiggler section to the present short pulse ($\lesssim$100 ns) amplifier experiment in the expectation of increasing efficiency to $\sim$18%, it is proposed to study a high gain, FEL oscillator operating at an ITER-relevant frequency ($\sim$170 GHz) and with a longer pulse ($\sim$ 10 $\mu$s) sufficient to study such issues as oscillator mode competition. An oscillator has been chosen rather than an amplifier because of the difficulty of obtaining suitable driver sources for an amplifier operating near 170 GHz.

The experiment will incorporate a depressed collector for efficiency enhancement. Also, we will benchmark a depressed collector design code which has been developed to improve ITER-relevant ECRH sources whether they be gyrotrons or FELs. Issues such as secondary emission from the depressed collector electrode(s) will be studied with results expected to be broadly applicable.

The proposed study will take advantage of the availability at the University of Maryland of a state-of-the-art modulator capable of generating 650 kV pulses repetitively with current as high as 870 A. The pulse width (FWHM) is 12 $\mu$s with the pulse top flat to $\pm 0.5\%$ for 8.5$\mu$s.

An electron gun producing a solid electron beam of circular cross-section and matched to the modulator will be fabricated at SLAC for delivery to the University of Maryland. This SLAC gun will be modified (masked) to produce a sheet electron beam of sufficiently high quality for the FEL and energy recovery studies. FEL output power of $\gtrsim 2$ megawatts is expected. With a depressed collector overall efficiency should be $\sim$50%

## Task B: Theory and Modeling of High Frequency, High Power Gyrotron Operation

### Executive Summary

Extensive analytical and theoretical work in support of high power gyrotron development at Varian and MIT, and in support of ITER has been carried out. The following describes specific studies. The effect of beam quality on the operation of the 145 GHz gyrotrons at MIT has been characterized using experimentally measured beam velocity distribution functions. The observed performance of these devices is consistent with a 10% RMS perpendicular velocity spread. An extensive study of mode competition in the 110 GHZ experiments at Varian and MIT has been carried out. Design criteria for the suppression of parasitic modes have been given for these experiments. The issues of mode competition and beam quality in the proposed 170 GHz megawatt gyrotrons for ITER have been investigated. Designs of cavities which eliminate unwanted modes have been made, and their sensitivity to beam quality studied. The constraints of lower power density and absence of mode competition coupled with the anticipated beam quality restrict efficiency. Efficiency can be improved by increasing the power density in the wall, improving beam quality, or perhaps by using a more advanced cavity. Studies of the causes of velocity spread in MIG guns have been initiated. Further, the effect of beam cavity misalignment on mode competition has been addressed.

### Synopsis of Progress

**Effect of beam quality on operation of tapered cavity, 140 GHz gyrotrons**

Beam quality was characterized using direct experimental measurements of the velocity distribution function obtained by researchers at MIT. Experiments indicated the following: $\delta\beta_\perp/\beta_\perp \approx 15\%$ ($I = 40$ A); $\delta\beta_\perp/\beta_\perp$ is independent of $\alpha$; $\delta\beta_\perp/\beta_\perp$ increases with current. Our simulations indicate performance of 140 GHz gyrotrons is consistent with a maximum spread of $\delta\beta_\perp/\beta_\perp \approx 10\%$.

**Support and modeling of Varian 110 GHz experiments**

We have investigated the following issues: mode competition and cavity design, influence of beam quality, start-up scenario, and mode excitation in dimpled converters. Our main conclusions are as follows:

a) Of the three cavities analyzed only one was free of mode competition. (Following our suggestion, Varian used this cavity.)

b) The performance of the cavity depends strongly on the beam, $\alpha$, and measurement of this quantity would be extremely helpful in analyzing results.

c) The high-efficiency, hard-excitation regime should be accessible under the present start-up scenario.

d) Dimpled converters can be designed to be free of parasitic mode excitation.

**Modeling of 110 GHz experiments at MIT**

We have simulated the mode competition in the MIT dimpled wall converter and determined the conditions under which it should be free of parasitic mode excitation.

**Modeling of 170 GHz ITER gyrotron**

The issues of mode competition and beam quality in the proposed 170 GHz megawatt gyrotrons for ITER have been investigated. Designs of cavities which eliminate unwanted modes have been made, and their sensitivity to beam quality studied. The constraints of lower power density and absence of mode competition coupled with the anticipated beam quality restrict efficiency. Efficiency can be improved by increasing the power density in the wall, improving beam quality, or perhaps by using a more advanced cavity.

**Beam quality in MIGs**

We have initiated a study of the contribution of gyrophase mixing to the velocity spread in MIGs. A reduced model has been developed which can solve for the heating of the beam during the mixing phase. This model can be used in conjunction with simulation codes such as EGUN or ARGUS to assess beam quality.

**Modeling and design of harmonic gyrotrons**

We have completed a study of harmonic mode interaction in a high power gyrotron. The results of this study suggest that it is possible to build a third harmonic gyrotron where access to the hard excitation region of the third harmonic is assisted by the excitation of the fundamental and second harmonic.

**Effect of beam eccentricity on excitation of counter rotating modes**

The interaction of counter rotating modes in the presence of a misaligned beam has been studied. Use of this effect to couple radiation out of the cavity in two separate beams has also been investigated.

# REPORT OF INVENTIONS AND SUBCONTRACTS

*(Pursuant to "Patent Rights" Contract (Clause) (See Instructions on Reverse Side)*

*Form Approved OMB No 0704-0297 Expires Jun 30, 1992*



| 1a. NAME OF CONTRACTOR/SUBCONTRACTOR | c. CONTRACT NUMBER | 2a. NAME OF GOVERNMENT PRIME CONTRACTOR | c. CONTRACT NUMBER | 3. TYPE OF REPORT (x one) |
|---|---|---|---|---|
| University of Maryland | SAME | SAME | DEFG0587ER52147 DOE | a. INTERIM [X] b. FINAL |
| b. ADDRESS (Include ZIP Code) 4312 Knox Road College Park, MD 20742 | d. AWARD DATE (YYMMDD) SAME | b. ADDRESS (Include ZIP Code) SAME | d. AWARD DATE (YYMMDD) 930715 | 4. REPORTING PERIOD (YYMMDD) a. FROM 930715 b. TO 950714 |

## SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

| a. NAMES(S) OF INVENTOR(S) (Last, First, MI) | b. TITLE OF INVENTION(S) | c. DISCLOSURE NO. PATENT APPLICATION SERIAL NO. OR PATENT NO. | d. ELECTION OF TITLE PATENT APPLICATIONS (1) United States (a) Yes | (1) United States (b) No | (2) Foreign (a) Yes | (2) Foreign (b) No | e. CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER (1) Yes | (2) No |
|---|---|---|---|---|---|---|---|---|
| NONE | NONE | | | | | | | |

f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR / SUBCONTRACTOR

| (1) | (2) |
|---|---|
| (a) Name of Inventor (Last, First, MI) | (a) Name of Inventor (Last, First, MI) |
| (b) Name of Employer | (b) Name of Employer |
| (c) Address of Employer (Include ZIP Code) | (c) Address of Employer (Include ZIP Code) |

g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED

| (1) Title of Invention | (2) Foreign Countries of Patent Application |
|---|---|
| | |

## SECTION II - SUBCONTRACTS *(Containing a "Patent Rights" clause)*

6. SUBCONTRACTS AWARDED BY CONTRACTOR / SUBCONTRACTOR *(If "None," so state)*

| a. NAME OF SUBCONTRACTOR(S) | b. ADDRESS (Include ZIP Code) | c. SUBCONTRACT NO.(S) | d. DFAR "PATENT RIGHTS" (1) Clause Number | (2) Date (YYMMDD) | e. DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S) | f. SUBCONTRACT DATES (YYMMDD) (1) Award | (2) Estimated Completion |
|---|---|---|---|---|---|---|---|
| None | None | | | | | | |

## SECTION III - CERTIFICATION

7. CERTIFICATION OF REPORT BY CONTRACTOR / SUBCONTRACTOR *(Not required if* X *Small Business or* ☐ *Non-Profit organization)* *(X appropriate)*

a. NAME OF AUTHORIZED CONTRACTOR / SUBCONTRACTOR OFFICIAL *(Last, First, MI)*: Swann, Wayne E.

c. **I certify that the reporting party has procedures for prompt identification and timely disclosure of "Subject Inventions," that such procedures have been followed and that all "Subject Inventions" have be reported.**

b. TITLE: Executive Director, Office of Technology Liaison

d. SIGNATURE: Wayne E Swann

e. DATE SIGNED: 980803