DEVELOPMENT OF POWERFUL FEMS OF X, KA AND W BANDS FOR PHYSICAL AND INDUSTRIAL APPLICATIONS*

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Abstract

The possibility to develop powerful FEMs capable for physical and industrial applications is being studied at Tel-Aviv University, IAP RAS, JINR and The University of Liverpool within the framework of the INTAS collaboration project. Present paper summarizes the progress in three successful FEM experiments: (1) Electrostatic-accelerator driven 70-130 GHz Tandem-FEM with kW-level pulse power (Tel-Aviv University); (2) Linac-driven 30-GHz FEM with pulse RF power of ~ 20 MW (JINR + IAP RAS); (3) Sub-relativistic e-beam industrial FEM tunable over X-band with output power up 1 kW (The University of Liverpool).

INTRODUCTION

Free electron masers (FEMs) are among the main sources of powerful microwave pulses from X to W-bands. Interest to such sources is caused by the large number of potential physical and industrial applications, requiring a wide variety of the radiation parameters. For example a new generation of the accelerators (SLAC, CERN etc.) requires sources of ~100 MW pulse power at 30-38 GHz with a narrow spectrum. Material processing stations require kW-level average power. Spectroscopic and imaging experiments as well as biological experiments, require lower power but fine control and tuning of the radiation spectrum.

Presently there are no ready industrial RF sources with parameters necessary for the applications mentioned above. Investigations carrying out in collaboration between aforementioned Institutes are aimed to partially fill up the gap with FEMs from X to W bands for different applications including testing components of high gradient accelerators and material processing. Present paper is devoted to the progress in the development of FEMs and their applications.

70-130 GHz TANDEM FEM

The Israeli FEM [1] resonator was re-designed in order to reduce the overall round-trip losses and achieve control on the radiation output-coupling. In its new configuration, the resonator consists of overmoded corrugated rectangular waveguide and two radiation mode splitters, separating the high-energy e-beam from the laser radiation. The electron input splitter is based on Talbot effect in an overmoded rectangular waveguide. The radiation out-coupling is done in the output splitter. It is based on novel design and it combines Talbot effect between two parallel plates with free space propagation, and focusing by two curved cylindrical mirrors in a confocal imaging scheme. The waveguide and the splitters were tested experimentally, showing improved performance in comparison with the former resonator. The measured unloaded Q-factor of the new version is increased by a factor of ~ 3, attaining up to Q = 25 000. Accordingly, the round-trip losses are ~ 23%. Rotating grids control the radiation out-coupling allowing wide variation for maximization of the radiation output power and extraction efficiency.

Additional R&D work was aimed on increasing FEM power by boosting the electron beam energy after the radiation build-up. A fine control of the electron beam energy during the radiation pulse is designed to compensate the small energy degradation during the pulse. Also, a controlled ramp (up or down) in the electron energy during the pulse will be applicable as well. We compared the theoretical estimations of the output power in the presence of electron energy change during the pulse, to the obtained experimental results. Two models, showing good agreement between them and with the existing data, were compared: low-gain analytical model based on the pendulum equation, and rigorous 3D FEM interaction model solved numerically. Another expected result of the design is to further extend the pulse duration with stable conditions and to obtain improved coherency.

30 GHz JINR-IAP FEM

The FEM-oscillator has been developed in Ka-band during last few years in a collaboration between JINR (Dubna) and IAP RAS (Nizhny Novgorod) [2]. These experiments aim to develop a pulsed power microwave source for testing behaviour of materials in high-Q structures under the influence of RF-pulses. Information about the life-time of different metals in strong RF-fields would be beneficial, in particular, when designing high-gradient accelerating structures for future linear colliders [3]. Such application requires a high power RF-source with a narrow frequency bandwidth. In addition, the

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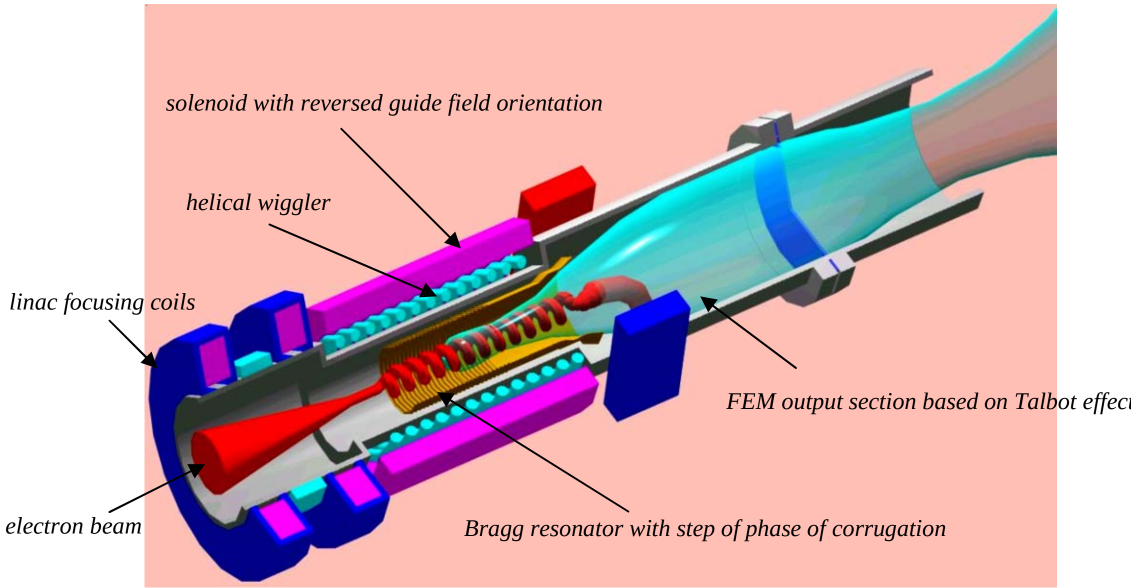

Figure 1: Schematic diagram of the JINR-IAP FEM.

radiation frequency should be exactly matched to the operating frequency of the accelerating structure, and therefore precise frequency tuning is essential for such a generator.

A schematic diagram of the JINR-IAP FEM experiments is shown in Fig.1. The induction linac LIU-3000 (JINR), which generates a 0.8 MeV / 200 A / 250 ns electron beam with a repetition rate of 1 Hz, drives the FEM-oscillator. Transverse velocity in the magnetically guided beam is pumped in a helical wiggler of 6 cm period. The main advantages of developed FEM is the use of a reversed guide field, which provides high-quality beam formation in the tapered wiggler section with a low sensitivity to the initial beam spread, alongside with Bragg resonator having a step of phase of corrugation, which possesses high electrodynamical mode selection. As a result, stabile single-mode operation with high electron efficiency was achieved in the FEM. At the present stage, the FEM generates 20 MW / 200 ns pulses at 30 GHz with the spectrum width of 6 - 10 MHz (Fig.2).

Precise tuning of the oscillation frequency of the FEM was performed by inserting short sections of smooth waveguide between the two Bragg structures. If the phase shift between the Bragg structures is varied from 0 to 2π the frequency of the fundamental eigenmode moves from the lower to the higher edge of the Bragg zone. It is important to note that only one high-Q eigenmode exists inside the Bragg zone at any value of phase shift, i.e. the high selective properties of the resonator are maintained over a sufficiently wide frequency band. For a phase shift equal to π the frequency of nearly 30 GHz was measured. In the experiments frequency tuning was achieved over a range of 6%, the spectrum width in all regimes of oscillations did not exceed 0.1% (Fig.3).

The test facility to study surface heating effects at 30 GHz, which was constructed based on the FEM source [4], is shown in Fig.4. The experimental set-up includes a two-mirror confocal transmission line and mode

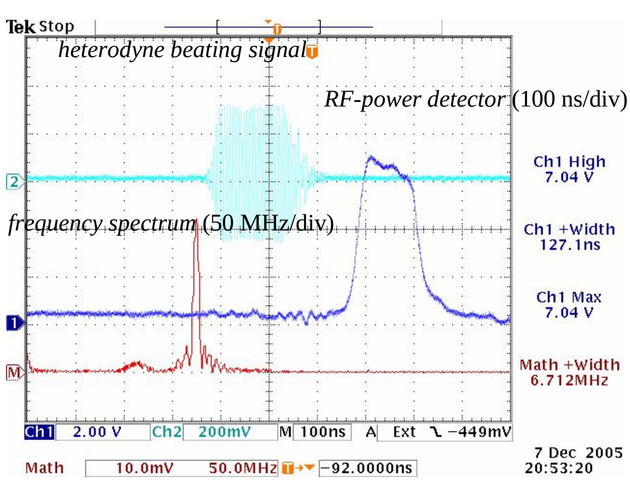

Figure 2: Typical oscilloscope traces of the RF-pulse generated by 30 GHz JINR-IAP FEM.

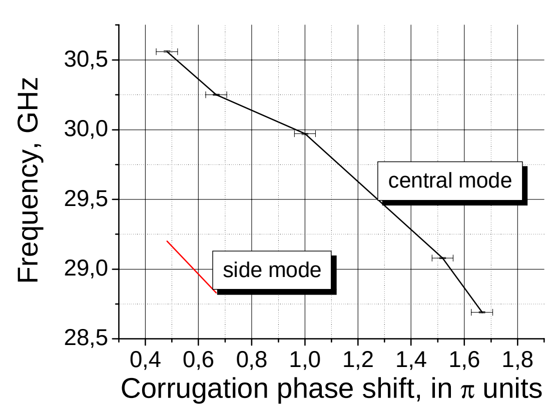

Figure 3: Measured dependence of the FEM oscillation frequency on the value of the phase shift of corrugation between the Bragg structures.

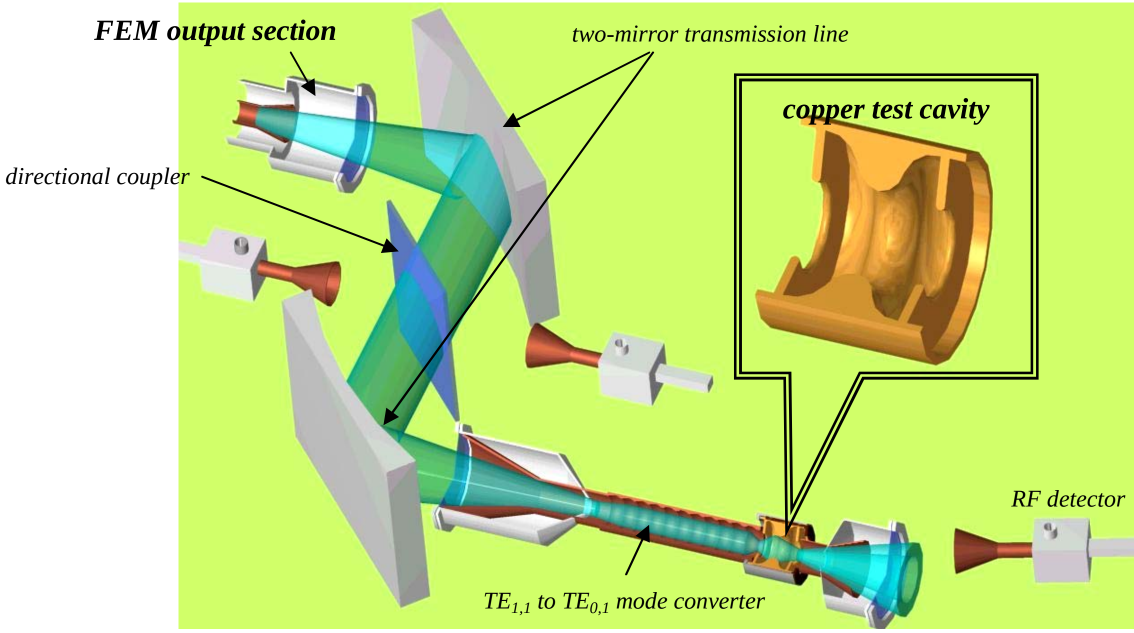

Figure 4: Schematic diagram of the test facility for studying surface heating effects based on JINR-IAP FEM.

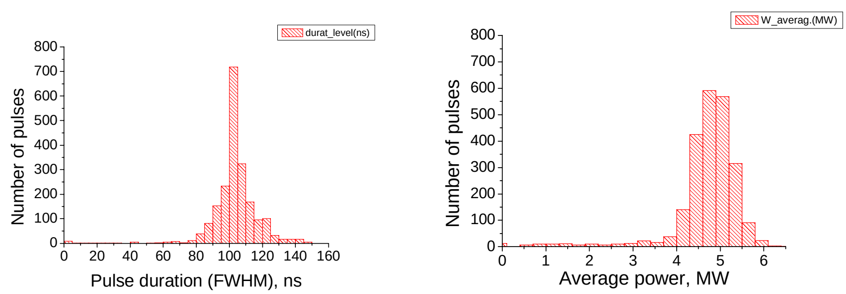

Figure 5: Statistic distributions of pulse duration and RF-power after the test cavity in the series of 10^4 pulses.

converters to transport the RF-power from the FEM to the test cavity. A special copper cavity operating with $TE_{0,1,1}$ mode and having Q-factor ~ 1500 was designed to model temperature regime in a high-Q accelerating structure of the CLIC project. The profile of the cavity surface was optimized to enhance the RF magnetic field in a certain zone and provide needed temperature rise during each RF-pulse. The resonant frequency of the cavities is also mechanically tuned to coincide with the frequency of the FEM source. A directional coupler is included to control both the incident and reflected powers. After a certain number of pulses the Q-factor of the cavity would be monitored using a network analyzer to detect early signs of surface damage. “Cold” tests of all components of the experimental set up were carried out and demonstrated good agreement with designed parameters.

Simulations carried out demonstrate principal ability of the FEM to be used for the aforementioned application. Results of the first experiments also proved possibility of the FEM to operate at the high-Q load. When frequency of the test-cavity was tuned to the FEM generation frequency it was observed that during the RF-pulse the reflected signal decreased and the test-cavity became transparent. As a result, accumulation of the RF-power in the load was achieved. At the present stage the effect of the copper surface degradation at 30 GHz was studied in the statistics of 10^5 pulses (Fig.5) at the temperature rise of 50 °C during each RF-pulse. The test cavity providing temperature rise at the certain zone up to 150 °C was designed and the experiments with the statistics of 10^6 pulses, which are important for design of CLIC collider components (CERN), are in progress currently.

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