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Nuclear Instruments and Methods in Physics Research A 407 (1998) 87–94

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

# Experimental investigation of mode build-up and mode competition process in a prebunched free-electron maser oscillator

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**Abstract**

A unique experimental set up at Tel-Aviv University (TAU) enables the study, observation and quantitative measurements of the mode competition process in a Free-Electron Maser (FEM) oscillator. The experimental results provide data on the mode build-up from noise level to steady-state saturation and on mode competition. The experimental results are recorded with the aid of a fast digital oscilloscope and are analyzed to obtain the Fourier components by use of a computer program, which we developed. The Fourier analysis shows clearly the build-up and competition of the longitudinal modes (eigenfrequencies) excited in the oscillator. We studied mode competition for two cases (1) free-running oscillator (no beam prebunching) (2) oscillator with prebunching of the e-beam. We also compared the experimental results with the results of the multi frequency simulation code MALT1D3, and found good agreement. 

## 1. Introduction

Single-mode, coherent RF radiation from a FEM oscillator was obtained after cessation of mode competition [1,2]. In the mode competition process several longitudinal (eigenfrequencies) of a FEM resonator compete with each other deriving their energy from the e-beam energy, until the mode having the highest gain wins and the other modes' growth is suppressed. However, there are several factors that may prevent the establishment of single-mode, coherent RF radiation. One factor may be insufficient time to complete the mode competition process during the e-beam pulse [1]. Another factor is interference in the mode competition process by seed radiation [3]. This latter interference can shorten the mode competition process time, in particular, if the seed radiation frequency is equal to one of the eigenfrequencies of the FEM resonator that satisfy the oscillation condition. On the other hand, the mode competition process becomes longer if the seed radiation frequency is between two eigenfrequencies of the FEM resonator that satisfy the oscillation condition [4]. The FEM at TAU has five eigenfrequencies that satisfy the oscillation condition; this enables one to interfere in the mode competition process by appropriate prebunching of the e-beam [3–6].

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0168-9002/98/$19.00 
*PII* S0168-9002(97)01374-0

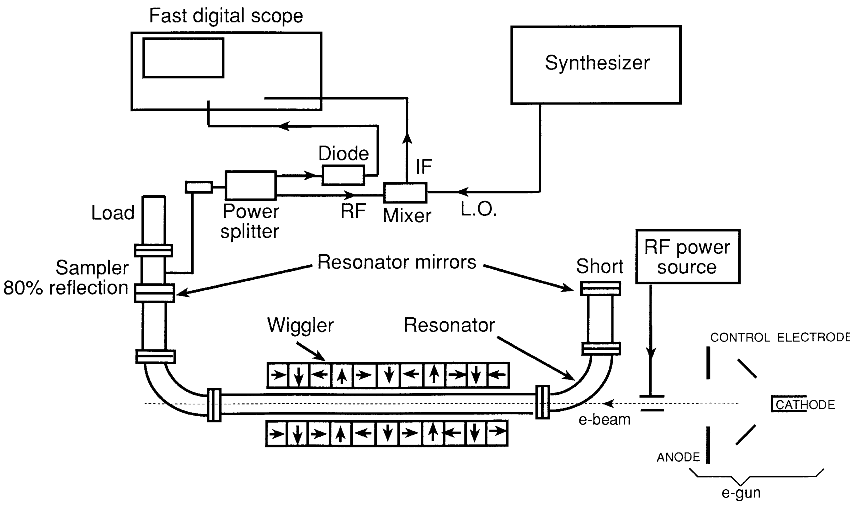


Fig. 1. Experimental set-up of the FEM oscillator.

## 2. Experimental set-up

Using an experimental set-up which includes a fast digital oscilloscope and an RF amplifier we observe and record the mode competition process from near noise level (for several eigenfrequencies) up to steady-state saturation and establishment of a single coherent mode. The experimental set-up is given in Fig. 1. We can note from Fig. 1 that the e-beam passes a prebunching region and enters the interaction region, which is a waveguide resonator located inside of a planar magnetic wiggler. A part of the radiation excited inside the resonator is out-coupled through a hole in the resonator reflector to a load. An RF sampler prior to the load provides diagnostic information in regard to power evolution with time of all modes existing in the resonator.

A power splitter divides the sampled power, feeding part of it to a diode detector and another part to a mixer. The outputs of the detector diode and the IF output of the mixer are monitored and recorded with the aid of a fast digital scope. The fast digital scope has a 500 MHz bandwidth and a sample rate of 2 Gsample/s. These parameters of the scope enable simultaneous recording of 5 longitudinal modes (which are all the modes that satisfy the oscillation condition [3]), the frequency difference between adjacent modes is about 80 MHz and the gain-greater-than-loss bandwidth is about 400 MHz. The main operation parameters of the FEM are given in Table 1.

Table 1
Parameters of the FEM

| | |
|---|---|
| *Accelator* | |
| Electron beam energy | $E_k = 70\,\mathrm{KeV}$ |
| Beam current | $I_0 = 0.5$–$1\,\mathrm{A}$ |
| *Wiggler* | |
| Magnetic induction | $B_w = 300$–$350\,\mathrm{G}$ |
| Period length | $\lambda_w = 4.44\,\mathrm{cm}$ |
| Number of periods | $N_w = 17$ |
| *Waveguide resonator* | |
| Rectangular waveguide | $2.215\,\mathrm{cm} \times 4.755\,\mathrm{cm}$ |
| Mode | $TE_{01}$ |
| Resonator length | $L_c = 130\,\mathrm{cm}$ |

## 3. Experimental results

The FEM e-beam pulse duration was adjusted to be 2.5 μs (which is normally longer than the power build-up, mode competition and mode duration [3]). The fast digital oscilloscope is set to the maximum sampling rate which is 2 GS/s and to

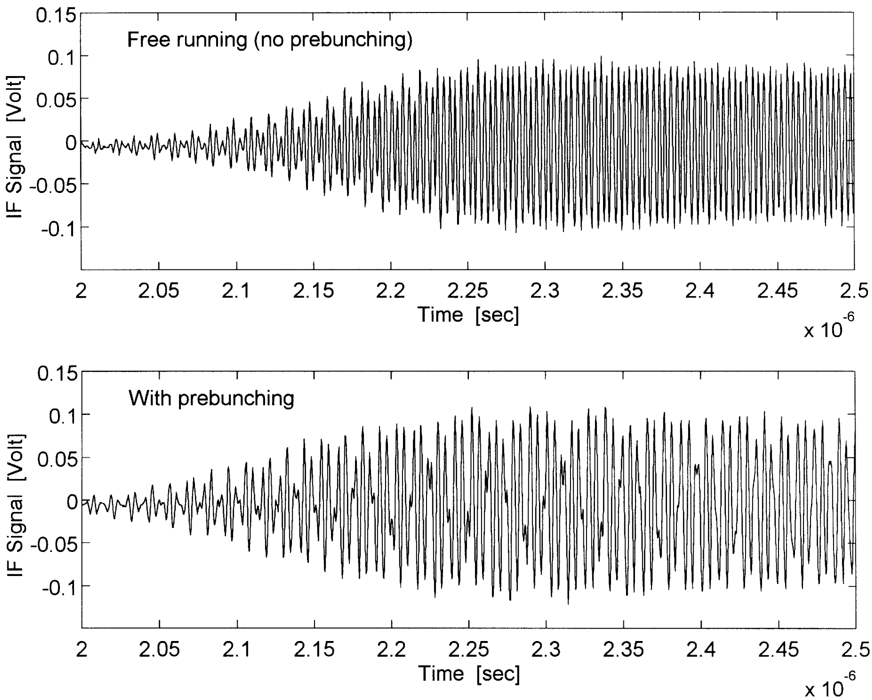


Fig. 2. Recorded experimental data for the free-running oscillator case (top) and oscillator with prebunching of the e-beam (bottom).

a bandwidth of 0.5 GHz. The scope starts recording data 2 μs before the e-beam pulse is turned on and stops recording about 1.5 μs after the e-beam pulse ends (a total recording time of 6 μs). Fig. 2 shows the recorded data of the IF signal for the first 0.5 μs of e-beam presence (between 2–2.5 μs) where the power build-up and mode competition processes occur. The recorded data is for two cases; (1) free-running oscillator (no prebunching) operation of the FEM (Fig. 1 – top) and (2) oscillator with prebunching of the e-beam at a frequency of 4.42 GHz, which is a frequency exactly between two eigenfrequencies of the waveguide resonator (Fig. 1 – bottom). A careful inspection of the graphs in Fig. 2 indicate that the mode competition process lasts longer for the second case [5]. Fig. 3 and Fig. 4 show the Fourier spectra for cases 1 and 2, respectively. These figures show the Fourier components as a function of time from $t = 0$ to $t = 6000$ ns. The data for the Fourier analysis was taken at intervals of $\Delta t = 128$ ns and for periods of 128 ns; therefore, the frequency resolution is better than 10 MHz. The dark areas in Fig. 3 and Fig. 4 indicate a Fourier component; the darker the area the stronger the Fourier component. These images show clearly that at $t = 2000$ ns (near the start of the e-beam pulse) several eigenfrequencies exist in the resonator and after $t = 2600$ ns only one strong Fourier component at 4.466 GHz prevails in the free running oscillator case. The 4.466 GHz frequency corresponds to the mode of highest gain. For the case of prebunching at a frequency of 4.42 GHz (which is exactly between two eigenfrequencies of the FEM) the eigenfrequency which wins the competition process is at 4.388 GHz, the lower adjacent eigenfrequency (see Fig. 4 and Fig. 6). Additional details of the mode competition process and of the power build-up process can be obtained from Fig. 5 and Fig. 6 which show the Fourier analysis for three sequential time interval for cases 1 and 2, respectively. Fig. 5 shows that the mode competition process is nearly at the end and that the eigenfrequency power level at 4.466 GHz is high enough to suppress the gain of the other modes in a non-linear process. Fig. 6 shows the mode competition in progress where two high gain

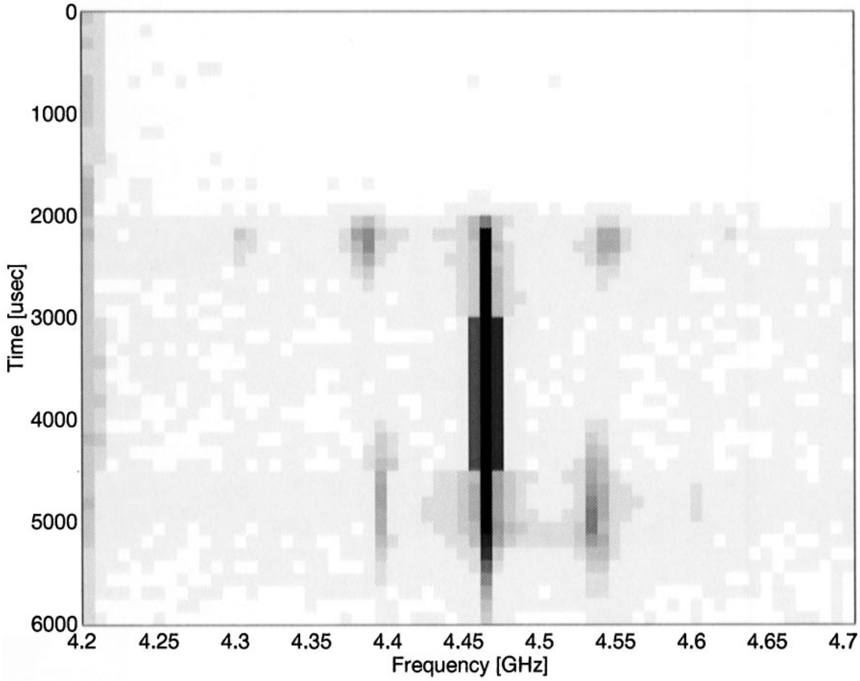


Fig. 3. Fourier components evolution in time for the free-running oscillator case (the dark areas indicate a Fourier components).

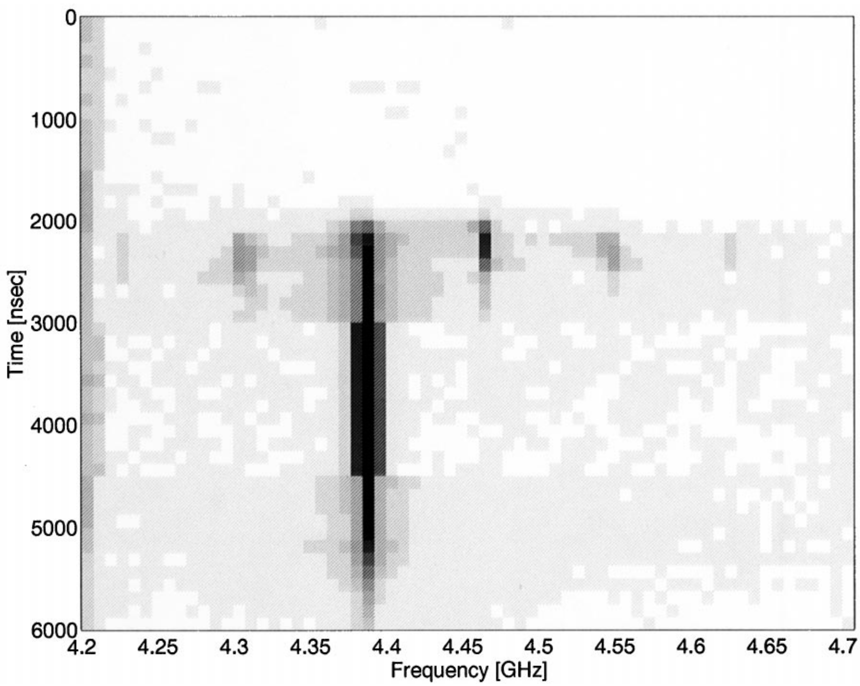


Fig. 4. Fourier components evolution in time for the e-beam prebunching case (the dark areas indicate a Fourier components).

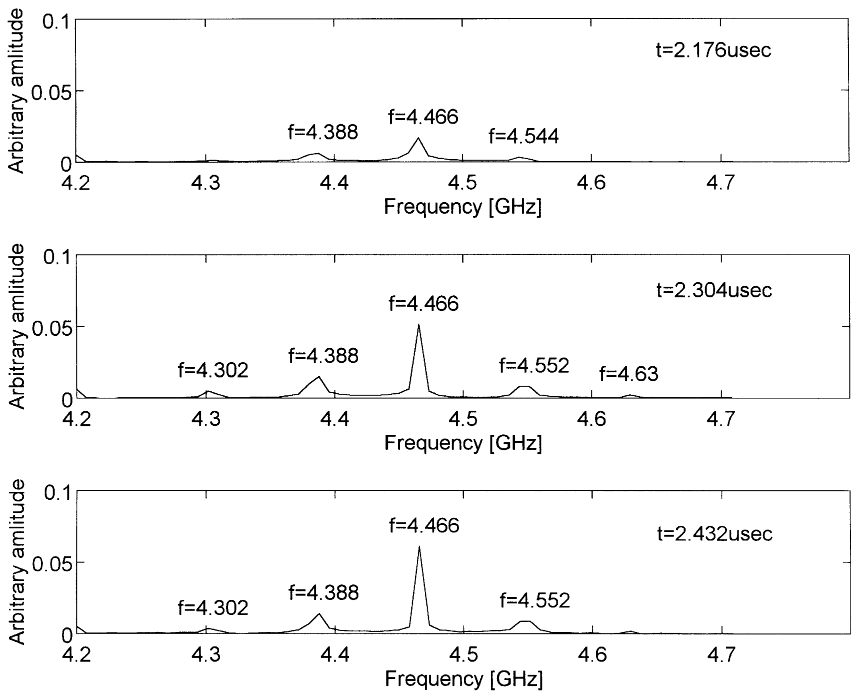


Fig. 5. Mode competition at three sequential time intervals for the free-running oscillator case.

modes compete; eventually, the eigenfrequency of 4.388 GHz wins as can be seen in Fig. 4. Now, it is clear that the mode competition and the power build-up process is longer in the second case because of prebunching of the e-beam at a frequency between two eigenfrequencies which induces equal power into the two adjacent eigenfrequencies. Fig. 7 shows an interesting phenomenon (for the free-running case) of eigenfrequency "pushing" due to the presence of the e-beam inside of the waveguide resonator. The top graph of Fig. 7 shows the eigenfrequencies during e-beam presence at the beginning of the e-beam pulse when mode competition is in progress. During e-beam presence inside the waveguide the maximum gain mode has an eigenfrequency of 4.466 GHz; it wins in the competition process and suppress all the other modes. When the e-beam pulse transit through the resonator ends no power is induced from the beam into the resonator and the power at that dominant eigenfrequency drops quickly. The quick drop in RF power of the dominant eigenfrequency gives rise to excitation of the two adjacent eigenfrequencies which the resonator supports. The modes thus excited and the dominant mode decay with time to zero. Without e-beam presence inside the resonator the eigenfrequencies are shifted (see Fig. 7 bottom) compared to the situation where the e-beam is present. The spacing between the eigenfrequencies decreases from 80 MHz when the e-beam is present (Fig. 7, top) to about 70 MHz when the e-beam is absent in the waveguide resonator (Fig. 7, bottom).

## 4. Mode competition simulation

A multimode analysis of the low gain/pass FEM was carried out in the past [1,2,7–10]. In our analysis we use a high gain/pass multimode model [1] which we feel is more appropriate for our case. Specifically, we employ the recently developed code MALT1D [11]. This code is a one-dimensional multi-longitudinal non-linear code which simulates the mode competition process taking place in FEM oscillators. Fig. 8 shows the results of simulation of temporal power evolution of the longitudinal

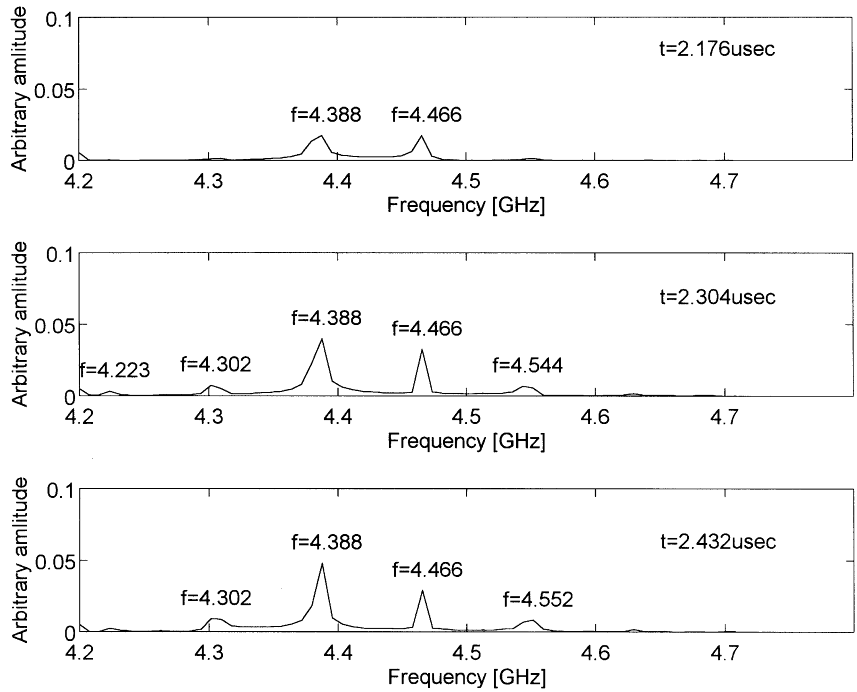


Fig. 6. Mode competition at three sequential time intervals for the prebunched e-beam case.

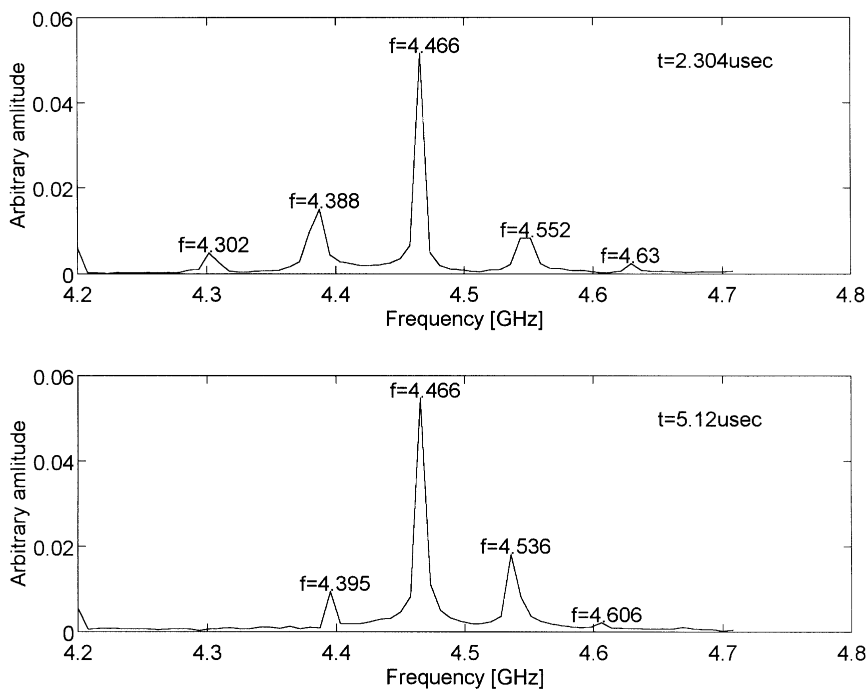


Fig. 7. Spacing between eigenfrequencies of the FEM. Top graph e-beam is transiting the resonator; bottom graph no e-beam (ringing in cavity after e-beam shut off) (only for the free-running case).

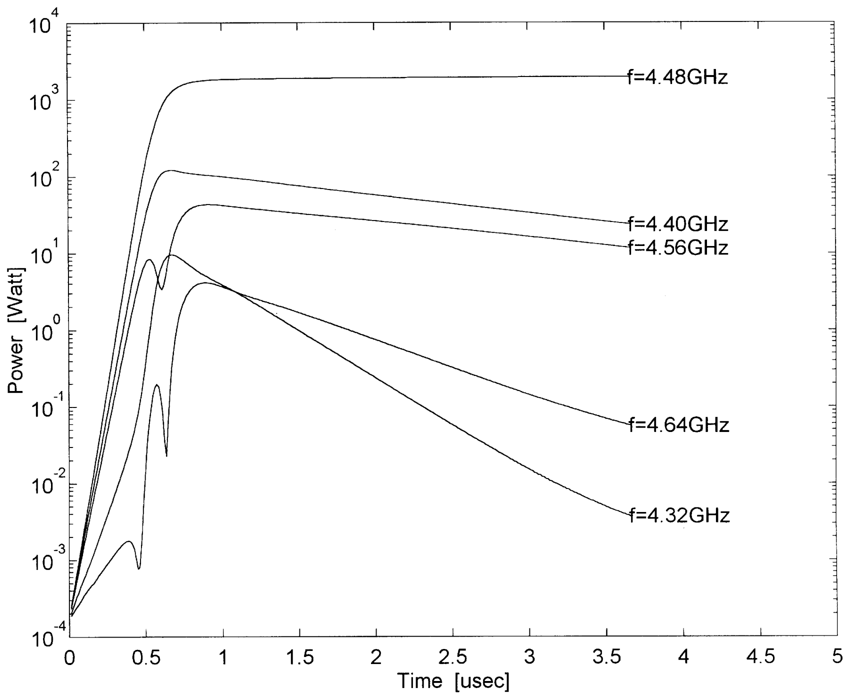


Fig. 8. MALT1D3 simulation code results for the parameters of the FEM at TAU.

modes excited in our FEM using that code. The simulation was carried out for an optimal efficiency mirror reflectivity of $\mathscr{R} = 80\%$. We can observe that steady-state operation is established in a longitudinal mode having a resonant frequency of 4.48 GHz for our FEM) near the frequency of maximum gain, while the other modes are decaying. Oscillations in several modes are excited simultaneously up to and beyond saturation of the dominant longitudinal mode of highest gain at 4.48 GHz. However, the saturated power of the two adjacent competing modes (at 4.40 and 4.56 GHz) is lower by more than an order of magnitude as compared to the dominant mode.

## 5. Conclusions

We presented first results obtained with an unique experimental set-up, that enables investigations of the mode competition and of the power build-up processes in a FEM. The analysis of the experimental results provides the time evolving Fourier components involved in the mode competition and power build-up process for the case of a free running oscillator and for a FEM with a prebunched e-beam (see Fig. 4 and Fig. 5, respectively). Furthermore, we measured the influence of e-beam presence inside of the FEM resonator on the eigenfrequencies of the resonator (see Fig. 7). The spacing between the eigenfrequencies in our FEM was reduced from 80 MHz (during e-beam transit) to 70 MHz (without beam) as can be seen in Fig. 7 top and bottom, respectively. This phenomenon is observed only in the free running case; in the case of prebunching of the e-beam the other longitudinal modes are suppressed throughout the oscillator. Good agreement was obtained between the experimental results and predictions of the simulation code MALT1D3.

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