MULTI-MW K-BAND 7TH HARMONIC MULTIPLIER FOR HIGH-GRADIENT ACCELERATOR R&D*

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Abstract

A preliminary design and current status are presented for a two-cavity 7th harmonic multiplier, intended as a high-power RF source for use in experiments aimed at developing high-gradient structures for a future collider. The harmonic multiplier is to produce power in K-band using as its RF driver an XK-5 S-band klystron (2.856 GHz). The multiplier is to be built with a TE_{111} rotating mode input cavity and interchangeable output cavities, a principal example being a TE_{711} rotating mode cavity running at 20 GHz. The design that is described uses a 250 kV, 20 A injected laminar electron beam. With 8.5 MW of S-band drive power, 4.4 MW of 20-GHz output power is predicted. The design uses a gun, magnetic coils, and beam collector from an existing waveguide 7th harmonic multiplier. The gun has been re-conditioned and the desired operating parameters have been achieved.

INTRODUCTION

High-power, high-frequency pulsed RF sources above X-band are needed for investigating frequency scaling of RF breakdown, and for high power accelerating structure tests in the context of high gradient accelerator R & D, [1]. A simple and inexpensive high-power frequency multiplier using an XK-5 2.856 GHz klystron feeding the drive cavity has been developed for these purposes.

Based generally on CARA [2, 3], the frequency multiplier design has been significantly refined to obtain improved beam optics and better symmetry of the accelerating fields in the drive cavity. An innovative 20 GHz output power extraction system based on use of azimuthally distributed slots [4] has been simulated and developed for the frequency multiplier. Moreover, an electron gun for the frequency multiplier has been resurrected and undergone successful conditioning so as to meet the required parameters. General improvements in simulation and design and results of the gun commissioning are presented and discussed in this report.

BEAM OPTICS IMPROVEMENTS AT THE FREQUENCY MULTIPLIER

The beam optics of the frequency multiplier has been simulated to improve the beam trajectories and to achieve the high transverse beam compression ratio necessary for operation. Simulations predict for the Pierce gun with a post-accelerating gap at a cathode voltage of –250 kV that a transverse beam compression ratio of 400:1 and a perveance of ~ 10^{-6} A/$V^{3/2}$ can be anticipated [2].

The gun and the focusing system are to provide a beam with energy of 250 keV and pulse current of 20 A focused nearly to the Brillouin diameter in the magnetic system of the harmonic multiplier. The computed beam diameter in the drive cavity is 2.5 mm. The simulated longitudinal profile of magnetic field for such transverse beam compression and corresponding layout of the magnetic system are shown in Figures 1(a) and 1(b). The magnetic system is designed to use existing coils and to fit existing installations, including the oil-filled gun tank, an in-line vacuum valve after the first coil, input WR284 waveguide locations, etc.

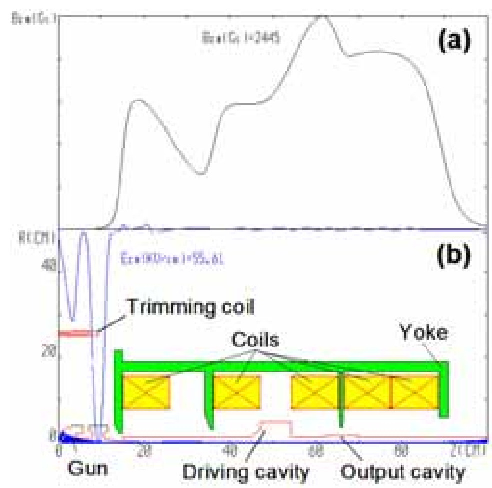

Figure 1: (a) longitudinal profile of the required magnetic field; (b) gun accelerating field profile (blue), and layout of the magnetic system. Beam trajectories and device outline are also shown at bottom of figure.

RF SYSTEM ADVANCED SIMULATION AND DESIGN

The RF system design of the frequency multiplier was significantly improved to achieve symmetric distribution of the fields in the drive and output cavities [4].

In drive cavity field it was done by use of protrusions located on the cylindrical cavity surface opposite the waveguide ports as shown in Figure 2. For cyclotron acceleration in the drive cavity, a rotating dipole TE_{111} mode at a frequency of 2.856 GHz is used. The rotating field is excited by two waveguides shifted by 90º. The calculated loaded drive cavity *Q*-factor is 210, and the maximum surface electric field strength is ≈ 66 kV/cm at input RF power level of ~ 8.5 MW.

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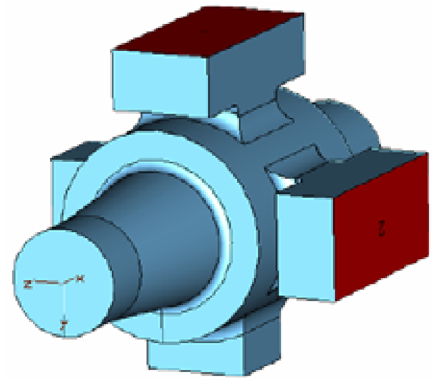

Figure 2: Picture of the drive cavity with two ports, shown in red. Protrusions from the opposite sides were optimized to compensate field asymmetry.

The output TE_{711} mode cavity is tuned to 19.992 GHz, which is 7^{th} harmonic of the drive frequency. The TE_{711} rotating mode is excited by the rotating accelerated beam. The output cavity loaded Q-factor is ≈ 900 and the maximum surface electric field 179 kV/cm at an output power of ~ 4.4 MW.

Dynamics of electrons subject to cyclotron acceleration in the drive cavity and excitation of the output cavity are shown in Figure 3.

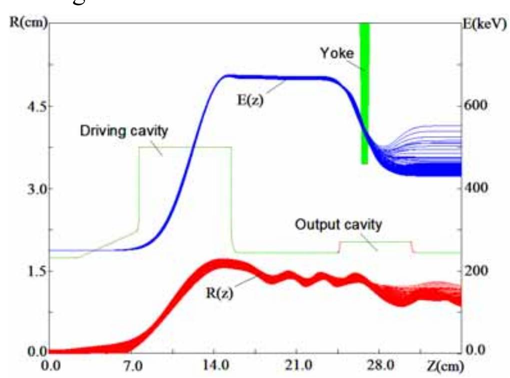

Figure 3: Beam particle energies (blue, right scale), radial excursions (red, left scale) in the drive cavity tuned to 2.856 GHz in the TE_{111} mode, and in the output cavity tuned to 19.992 GHz in the TE_{711} mode. Cavity outlines are shown in green. Drive power is 8.5 MW.

In Figure 3 it is seen that the drive cavity increases energy of the electron beam from 250 keV to 670 keV due to cyclotron acceleration, thereby increasing the beam power from 5 MW to ~ 13.4 MW. The cyclotron acceleration mechanism is seen to have an efficiency of over 98%, based on 8.4 MW beam energy increase with 8.5 MW of applied drive power.

The TE_{711} mode rotating field energy can be effectively transferred into the output waveguide system with azimuthally distributed slots in a travelling wave, if the wave phase velocity in the waveguide and the azimuthal location of coupling slots are matched to the azimuthal mode index in cavity.

The amplitude of a rotating TE_{711} mode in the output cavity can be written as:

$$A(\varphi) = A_0 \cdot e^{i(\omega t - N_{CAV}\cdot\varphi)},$$

where N_{cav} is the cavity azimuthal index, and φ - the angle coordinate. Each coupling slot will excite the waveguide with the amplitude $A_{WG}=\alpha{\cdot}A(\varphi_i)$, where , α *is* coupling, $\varphi_i = 2\pi i/N_s$, and N_s - the number of slots.

In the waveguide two waves are excited: a direct wave having amplitude D (running in the same direction as the rotating mode in the cavity) and a reverse wave having amplitude R (opposite directions). The amplitudes of these modes can be written:

$$D(N_{WG}) = \alpha \cdot A_0 \cdot e^{i(\omega t - N_{WG}\cdot\varphi)} \cdot \sum_{m=1}^{N_S} e^{-i(N_{CAV}-N_{WG})\cdot 2\pi \frac{m}{N_S}}.$$

$$R(N_{WG}) = \alpha \cdot A_0 \cdot e^{i(\omega t + N_{WG}\cdot\varphi)} \cdot \sum_{m=1}^{N_S} e^{-i(N_{CAV}+N_{WG})\cdot 2\pi \frac{m}{N_S}}.$$

Here, N_{WG} is the output cavity surrounding waveguide azimuthal index.

Simulations give, for $N_S = 28$ and $N_{WG} = 7$, $D = 26$ and $R = 0$, as shown in Figure 4.

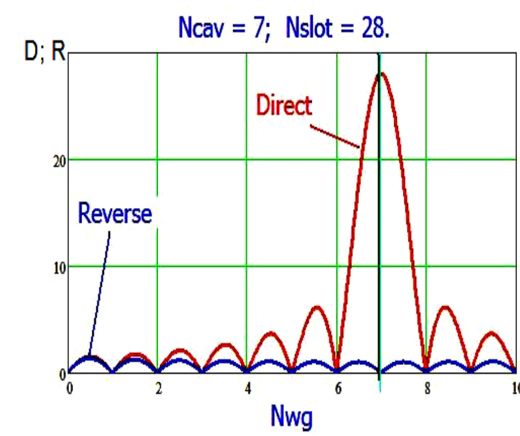

Figure 4: The direct and reverse wave amplitudes at the azimuthally distributed slot coupling.

Simulated distribution of the electric field in the output cavity and in the coupled output waveguide system is shown in Figure 5. Cavity was excited from one of the waveguide port. Picture shows good quality of the traveling wave in cavity.

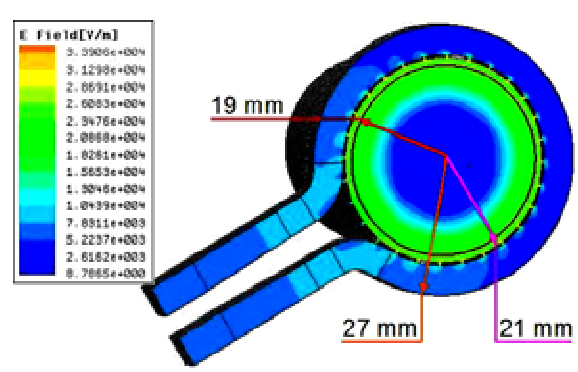

Figure 5: Distribution of the complex magnitude of the electric field in median plane section of the output cavity and coupled output waveguide.

The advanced simulation that was carried out for the distribution of output cavity electric field amplitude for the proposed azimuthally distributed slot coupling system showed a quite flat response, with a deviation less than 3%, as seen in Figure 6. The expected output power of the 20 GHz frequency multiplier is 4.4 MW.

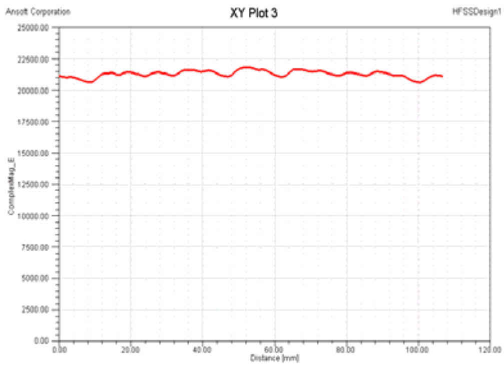

Figure 6: Distribution of the complex magnitude of the electric field in the output cavity on arc of radius 17 mm.

A general layout of the output cavity and the output waveguide of the frequency multiplier disposed inside the solenoid coil are shown on the right in Figure 7. The pole piece is shown on the left has the pair of cuts for waveguides and the two additional compensation pairs of cuts separated by 120° in azimuth that provides no dipole and quadruple perturbation of the magnetic field at the beam cyclotron radius in the output cavity. The sextupole perturbation on the beam orbit is ~10^{-3} of the main magnetic field and, thus, the sextupole perturbation does not affect the beam dynamics.

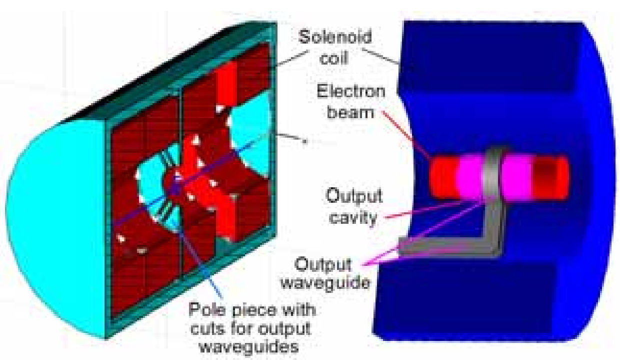

Figure 7: Left: part of the magnet yoke with cuts for output waveguides. Right: general layout of the output cavity and the output waveguide of the high-power frequency multiplier.

CURRENT STATUS

The high-accuracy advanced simulation for the beam dynamics and the RF system, including the high performance drive and output cavities and the performance output coupling system, have been completed. Design of the magnetic system is likewise completed. Mechanical design of the sub-systems is in progress.

The high compression, long-neglected electron gun has been conditioned through overheating of the dispenser cathode. The conditioning in high vacuum with a filament power exceeding the nominal value by ≈30 % during about 40 days recovered the electron gun after it had been inadvertently stored at atmospheric pressure for years (Figure 8).

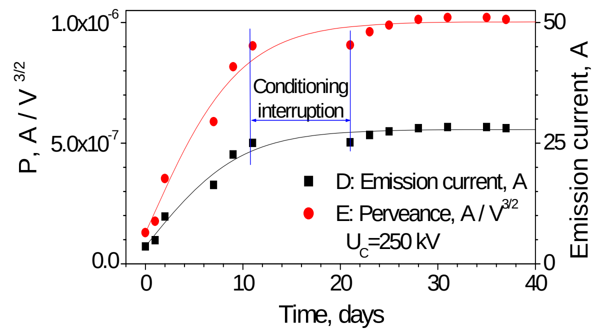

Figure 8: History of the cathode recovering. Conditioning interruption was caused by technological reasons.

Values of the cathode emission current I_C and the gun perveance P measured with the available high voltage CARA pulse modulator at operation with nominal filament power after the conditioning vs. the cathode pulse voltage U_C and respective intermediate anode voltage U_I are shown in Table 1 and correspond to data obtained in simulations. Measured beam transmission through the magnetic system was better than 96%.

Table 1

U_C, kV	200	250	300
U_I, kV	73.3	91.7	110
I_C, A	20	28	36
P, A / $V^{3/2}$	1.01×10^{-6}	1.01×10^{-6}	0.99×10^{-6}

SUMMARY

A simple, high-power, two-cavity frequency multiplier employing cyclotron acceleration in a single-cavity CARA, using a high compression two gap electron gun, and improved magnetic and RF systems is under development. It is expected that this source will provide RF power of over 4 MW with good phase stability at 20 GHz. This source should find immediate application in high gradient accelerator R&D.

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