10 MW, W-BAND RF SOURCE FOR ADVANCED ACCELERATOR RESEARCH

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Abstract

A conceptual design is presented for a W-band RF source that should be suitable for testing advanced accelerator structures and related components. The source is an 8th-gyroharmonic converter, in which 28 MW of X-band power at 11.424 GHz is used to energize and spin up an injected 500 kV, 40 beam in a TE_{111} cavity; and in which over 10 MW of W-band power at 91.392 GHz is extracted from the beam in a TE_{811} output cavity. A mode converter is employed to provide a Gaussian output beam.

1 INTRODUCTION

Efforts have been directed at design and fabrication of accelerating structures to operate at W-band (91.4 GHz) because of the expectation of achieving an acceleration gradient ~1 GeV/m, based on empirical scaling [1]. This gradient allows a 5 TeV electron/positron collider to be built within a length of 5 km, not including the final focus region. It is this dramatic reduction in size of a future multi-TeV collider that has provided much of the stimulus for the W-band work. But to test the susceptibility of accelerating structures and components at high-power to rf breakdown and fatigue, it is apparent that a high-power W-band source will be required.

No megawatt-level W-band source exists for this task. Some moderate power sources at W-band are presently available, and others are under design. Notable are the W-band gyro-klystron amplifiers developed at Naval Research Laboratory (NRL) [2] and at Institute of Applied Physics in Nizhny Novgorod, Russia [3]. These devices currently deliver peak output powers of over 100 kW and over 200 kW, respectively. Design of a W-band multi-beam klystron that embodies several 100 kW “klystrinos” is also currently underway [4]. Furthermore, a preliminary design has been published for a 7.5 MW, W-band three-cavity second-harmonic gyro-klystron [5]. No other W-band amplifier has been designed heretofore with a peak power of more than 10 MW.

2 CONCEPTUAL DESIGN

A design for an 8th-harmonic frequency multiplier is described here that is predicted to have 40% efficiency for power conversion from 11.424 GHz up to 91.392 GHz. A conceptual drawing of the heart of the device is shown in Fig. 1. Computations described below show a peak output power of 11.3 MW at W-band, for an input of 28 MW at X-band. This converter could be driven from an X-band SLAC klystron [6], or from the Omega-P/NRL 60-MW, X-band magnicon [7]. Either driver would allow one to obtain a 1-3 μsec W-band output pulse with a repetition rate determined by the available modulator. The 11.3 MW output power level is not an absolute upper limit, but is set in the present design by the beam current (40 A) from the available modulator at NRL. Features of the tube include:

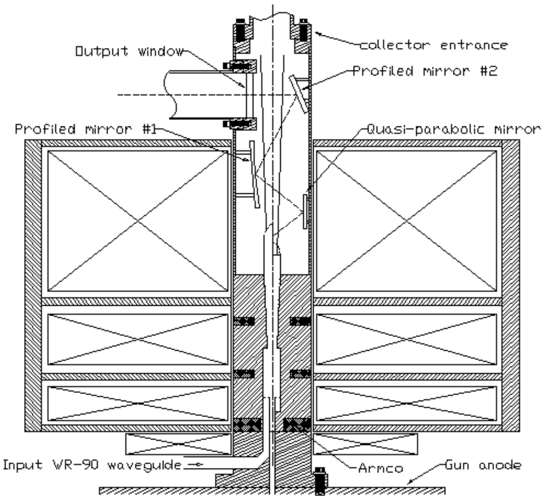

Fig. 1. Conceptual design of W-band source. Not shown are gun at bottom, and beam collector at top.

a. Two WR-90 input waveguides, with an H-plane miter-bend to feed a coupling aperture in the bottom face of the TE_{111} input drive cavity. The second input waveguide is disposed at 90° with respect to the first, and is not seen in the drawing. Opposite each input waveguide is an aperture in the cavity wall with a tuning section to symmetrize fields in the drive cavity. Each waveguide is to carry 14 MW of 11.424 GHz input power from the rf driver, a level well below the waveguide breakdown limit.

b. A four-coil room-temperature magnet structure, with three carefully tailored Armco rings that help produce the steeply contoured axial magnetic field required for achievement of high efficiency in this device. Such a steep contour may be difficult to produce with a cryomagnet of the same room-temperature inner bore diameter as this coil

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system (70 mm). The entire magnet structure can be raised up over the top of the tube without breaking vacuum, to allow bakeout and other adjustments. The lowest coil is to provide the field needed to match the beam emerging from the gun anode and pole piece as it flows through the long beam tunnel to the input cavity.

c. An input drive cavity that supports a rotating TE_{111} mode at 11.424 GHz, as fed by the two input waveguides phased in time-quadrature. Cavity radius and length are 8.10 mm and 40.9 mm. The ratio of ohmic-to-beam-loaded quality factors for this cavity is 136, indicating that the efficiency for imparting rf drive power to the beam is 99.2%. Peak surface rf electric field in this cavity at rated drive power is 250 kV/cm, far below the breakdown limit at 11.4 GHz. A short cut-off section is inserted between the drive cavity and the output cavity, with radius 4.6 mm and length 12 mm.

d. A TE_{811} mode output cavity, with radius and length 5.07 mm and 14.7 mm, ending in a gently up-tapered output waveguide. Output power is 11.3 MW at 91.392 GHz, with only 0.85 MW in spurious modes at higher harmonics. Lower harmonic spurious modes are suppressed by careful circuit design. Peak surface rf electric field in this cavity is 727 kV/cm, safely below the breakdown limit at 91.4 GHz.

e. A quasi-optical mode converter for producing a Gaussian output wave beam, consisting of a helical cut in the output waveguide, a quasi-parabolic mirror, two profiled mirrors, and an output window. In addition to producing the low-transmission-loss Gaussian beam, the mode converter separates the wave beam from the spent electron beam, which passes to the collector above. Spurious modes are not focused by the mode converter.

Further detail on each of these elements is given below.

The modulator that would be used to power the W-band tube is rated at 500 kV, 250 A, in 1.1 μsec pulses at a 10 Hz rep rate. This modulator now powers the 11.4 GHz magnicon that will furnish rf drive power for the W-band tube, so that the driver and converter will be operated in parallel on the same modulator. Since the magnicon requires 210 A to run the tube at rated output and gun voltage, only 40 A will be left over for the W-band tube.

Fig. 2 shows the optimum result found for design of this gun, using the code Super-SAM [8]. The beam is seen to be in nearly ideal laminar flow. Maximum electric field on the focus electrode is found to be 195 kV/cm, which is well below the 230-420 kV/cm fields that are sustained by SLAC X-band klystron gun focus electrodes [7]. Cathode loading of 8 A/cm^2 is well within an acceptable range for dispenser cathodes. Geometric emittance is below the irreducible thermal emittance value of 6π mm-mrad; 500:1 electrostatic compression produces a beam with a diameter of 1.1 mm, and subsequent magnetic area compression of about 5:1 in the gradually-increasing field of the input cavity gives a beam diameter computed to be about 0.5 mm. But to provide a margin of safety, simulations of converter performance shown below are for a beam with diameter of 0.8 mm, corresponding to an overall area compression of ~1000:1.

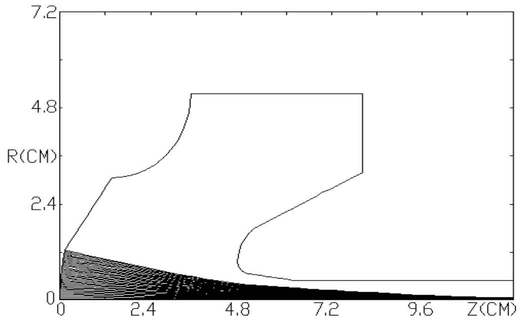

Fig. 2. Optimum conceptual design of electron gun for W-band source.

Table I lists other relevant parameters for the gun. The mechanical design for this gun will be very similar to the gun already delivered and built by Budker INP for the 34 GHz magnicon now under development by Omega-P, Inc.

Designs were optimized of three linked sub-systems of the W-band source, namely magnet, drive cavity, output cavity and mode converter. Fig. 1 shows these elements together. The highest tolerable 11.4 GHz input power level was found to be 28 MW for the available beam current of 40 A; the beam is accelerated in the drive cavity by 700 keV to produce a 1.2 MeV beam at the entrance of the output cavity. For rf drive power above 28 MW, beam energy spread increased and output power decreased. The output cavity, with radius of 5.07 mm and length of 14.7 mm, and a tapered output waveguide, has a diffraction *Q* of about 400. Suppression of harmonics below the eighth was achieved in the design shown here because the cavity radius is such that these are cutoff. To study the device in detail, a self-consistent system of equations for the electromagnetic fields and electron motions was applied, using time-tested interaction codes.

Fig. 3 shows the optimum magnetic field profile, the structure of the two-cavity/up-tapered output system, and resulting electron trajectories. The power that emerges from the cavity and passes along the following up-taper is seen in Fig. 4 to be about 11.3 MW. Some power (totaling about 0.85 MW) is radiated into other harmonics, also shown in Fig. 4. But these harmonics are not expected to be focused into a Gaussian output beam by the output converter optics that are designed for the TE_{81} mode.

To convert the $TE_{8,1}$ 91.4 GHz output mode into a nearly Gaussian wave beam that can be transported to a load with negligible loss, a quasi-optical mode converter

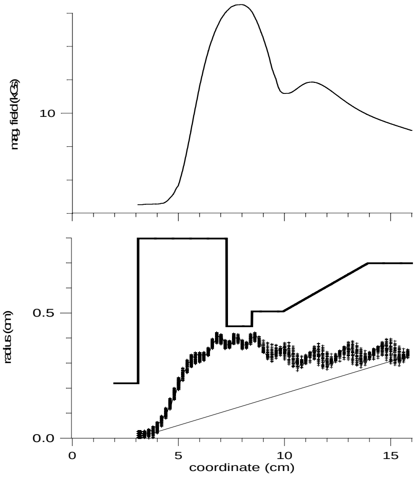

Fig. 3. RF circuit outline, and radial excursions of beam electrons (bottom); magnetic field profile (top).

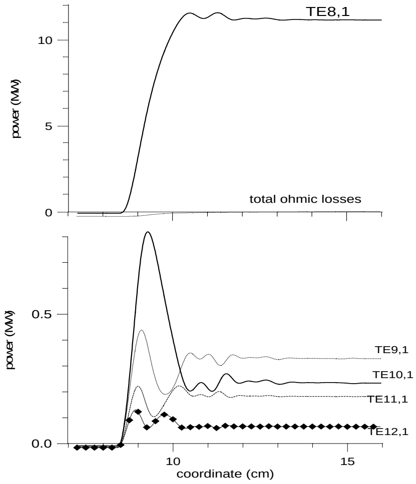

Fig. 4. W-band output and ohmic losses (top), and power in spurious modes (bottom).

has been designed. This mode converter consists of a special waveguide cut, a quasi-parabolic mirror, and two profiled turning mirrors, as shown in Fig. 5. The output structure ends with 40 mm diameter window.

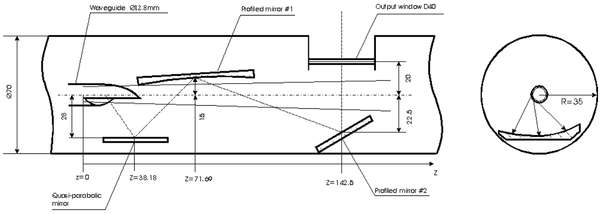

Fig. 5. Quasi-optical output mode converter.

Collector design is essentially the same as that of a collector already designed and built by Omega-P, Inc. for the 34 GHz magnicon [7].

A summary of the main parameters embodied in the 10-MW W-band source design are given in the Table below.

Table. Main parameters for proposed 10-MW, W-band source. *Modes not focused by output mode converter.

beam voltage	480 kV
beam current	40 A
gun perveance	0.12×10^{-6} A-V$^{-3/2}$
cathode diameter	25 mm
maximum cathode loading	8 A/cm^2
beam area compression	1000:1
maximum E-field in gun	195 kV/cm
rms beam thermal emittance	6π mm-mrad
rms beam geometrical emittance	0.5 π mm-mrad
11.4 GHz drive power	28 MW
91.4 GHz output power	11.3 MW
Output mode purity	η_a = 99.15%, $\eta_{a,\varphi}$ = 98.56%
Output beam radii	a_x = 8.26 mm, a_y = 7.99 mm
output power in spurious harmonics*	0.85 MW
peak magnetic field	13.1 kG
total magnet power	32.3 kW

It is estimated that, with relatively minor redesign, a 20 MW version of this W-band source could be built. The higher power version would employ a 80 A, 500 kV beam, and would require approximately 55 MW of rf drive power at 11.4 GHz.

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