Design for a One-Gigawatt, Annular-Beam Klystron

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Abstract

A one-gigawatt, annular beam klystron (ABK) is being developed by Los Alamos National Laboratory in collaboration with the Stanford Linear Accelerator Center (SLAC). The pulse length is 1 µs, the pulse repetition frequency is 5 Hz, and the operating frequency is 1.3 GHz. The beam voltage and current are 800 kV and 4 kA. Since the electron beam parameters are considerably beyond the state-of the-art, an aggressive cathode and electron gun design is required. The magnetron injection gun (MIG) configuration was chosen over the standard Pierce geometry that is typically used in klystrons. The tube design, design issues, and status are presented.

1 BACKGROUND

For many decades accelerators and radar systems have used high power klystrons to provide the RF energy for their operation. The klystrons for these applications use electron beams with a solid cross-section. The beams are typically produced by thermionic electron guns using a Pierce geometry. As the need increases for higher peak power, the voltage and current of the beam must increase. Since raising the beam voltage above 800 kV is expensive and impractical, one must instead raise the beam current. For a klystron with 1 GW output and a nominal efficiency of about 30%, the required beam current is 4 kA. Not only is this beam current well beyond what has been previously used in klystrons, but beam potential energy considerations dictate that an annular beam, rather than a solid beam must be used.

The beam injection energy is partitioned into two parts: the kinetic energy and the potential energy due to the space charge fields. In a conventional klystron the current is low enough that the beam potential energy can be ignored. However, in an intense beam klystron the beam potential energy can be a significant part of the injection energy unless one adopts an annular configuration with the beam flowing near the drift tube wall. Since a klystron produces RF energy by slowing the electron bunches in the output cavity gap (turning the kinetic energy into electromagnetic energy), any potential energy residing in the beam is lost because potential energy is not converted to RF. Moreover there is a minimum beam energy allowable in the output gap that is dictated by the space charge limiting current [1]. This minimum energy is

$$\gamma_{\min}^{\frac{2}{3}} = \left[\frac{I_{peak}}{8.5\,\text{kA}} \log \frac{r_w}{r_b} \right]^{\frac{2}{3}} + 1$$

where r_w and r_b are the wall radius and the beam radius. The maximum power that can be extracted from the beam based on his minimum beam γ is

$$P_{max} = \frac{1}{2} I_1 (511\text{kV}) (\gamma_{\text{inj}} - \gamma_{\min})$$

To put the design challenge into perspective, Table 1 shows the state of the art in klystron technology. The highest power tube to-date is the DESY tube at 200 MW with a 700 A solid beam built by SLAC. To our knowledge, the only klystron ever constructed with an annular beam from a thermionic cathode was a 10 MW experimental tube built by Varian in 1961. A klystron with an annular beam produced from an explosive field emission cathode was built by Los Alamos in the early 1990's and produced almost 500 MW in single shot pulses that exhibited significant RF pulse shortening.

Source	Beam Voltage (kV)	Beam Current (A)	Beam Power (GW)	Output Power (MW)	Pulse Length (µs)	Output Energy (J)	Pulse Rate (Hz)	Year
ABK (LANL-design)	800	4,000 thermionic, annular beam	3.2	1000	1	1,000	5	---
DESY Klystron (SLAC)	535	700 thermionic, solid beam	0.375	200	3	600	60	1998
MIG Klystron (Varian)	100	220 thermionic annular beam	0.022	10	1		---	1961
RKA (LANL)	700	5,000 EFE, annular beam	3.5	500	0.5 (half power points)	160	Single Pulse	1993

EFE = explosive field emission

Table1. Comparison of state-of-the-art klystrons

2 ELECTRON GUN DESIGN

One of the more challenging aspects of the ABK tube design is the electron gun. It must produce a stable, high current, annular electron beam with reasonable lifetime and reliability. For good RF power extraction efficiency, a klystron operating in the high current regime must use an annular beam to avoid the electron kinetic energy loss caused by potential depression due to the high space charge. Achieving a stable electron beam with minimal scalloping is critical because the beam must flow within a few millimeters of the drift tube wall to minimize the beam potential depression.

Both Pierce and magnetron injection gun configurations were examined. A stable Pierce geometry was developed but the cathode area needed to achieve 4 kA with a 20 kA/cm^2 emission current density resulted in an overall electron gun diameter too large to fit through the 11 inch diameter magnet bore. Since the diameter of the MIG design was considerably smaller, the Pierce design was dropped in favor of the MIG approach.

The gun uses a dispenser cathode that will operate at 20 A/cm^2, near the limit of the maximum emission current density for a reasonable cathode lifetime. The MIG design is based on modeling with several codes including DEMEOS, EGUN, and ISIS. The basic gun design was done using DEMEOS to determine the optimal shape of the gun electrodes because DEMEOS runs quickly, thereby enabling rapid design iterations. ISIS is a generalized particle-in-cell code that pushes particles in the electromagnetic field in 2-1/2 dimensions. ISIS uses a large number of particles and a body-fitted coordinate system with a robust charge-conserving current algorithm and is therefore quite accurate. ISIS complements electrostatic design codes such as DEMEOS. DEMEOS' speed allows one to quickly iterate to a desired geometry. ISIS takes much longer to run, but is able to check if a given design is susceptible to a wide class of beam instabilities. ISIS also handles both temperature limited and space charge limited emission. In the case of the MIG design, ISIS computed a static solution for the space charge limited case which was very challenging for DEMEOS.

The DEMEOS final design is shown in Fig. 1. The emission surface is angled at 8 degrees to the horizontal and the beam undergoes a slight compression. The ISIS simulation of the same geometry shows a stable beam in Fig. 2. In these simulations the beam parameters are 800 kV and 4 kA giving a perveance of 5.6 µP. The drift tube radius is 4.25 cm and the beam filling factor is 0.75. The magnetic field tapers up from about 1.2 kG at the cathode pole piece to a maximum value of about 5 kG. A sectioned view of the MIG gun is shown in Fig. 3.

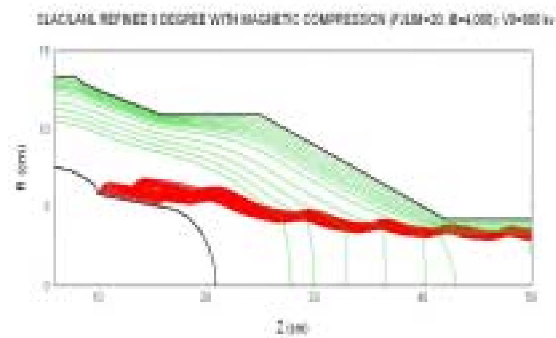

Fig. 1. Final DEMEOS MIG Design

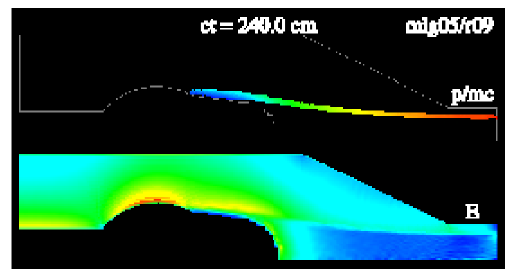

Fig. 2. ISIS Simulation of the MIG

Fig. 3. Magnetron injection gun sectioned view

3 BEAMSTICK

Because a stable, high quality electron beam is so important to the operation of the ABK, a beamstick will be assembled and tested. The beamstick is being fabricated at the SLAC klystron facility. The beamstick consists of the MIG gun, two RF cavities, and the beam collector. A cross-section of the beam stick is shown in Fig. 4. Both RF cavities have coupling loops. The loops will allow us to excite the beam at a low level and examine the degree of modulation induced on the beam. This data provides useful information on the gain we can

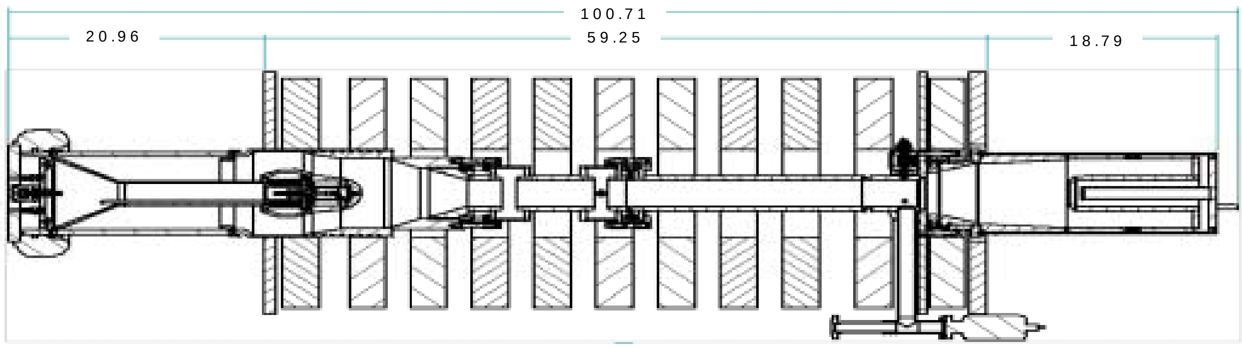

Fig. 4. Cross section of ABK beamstick with magnet coils

expect in the ABK and will aid in the design of the complete RF circuit.

The cavities will also be used as a beam diagnostic to detect beam halo. By varying the magnetic field profile we can tune the beam diameter. At the same time we can examine the field in the cavities and observe where the field becomes unstable due to beam interception and RF breakdown. This diagnostic should give us a feel for the importance of the beam halo problem and for how close we can transport the beam to the drift tube wall.

4 RF CIRCUIT

After the beamstick is tested it will be returned to SLAC for installation of the RF cavities and output circuit. RF conditioning over several million pulses and full power testing will be performed at Los Alamos on the Banshee modulator, which produces a 1 μs pulse length at 5 Hz pulse repetition frequency.

5 SUMMARY

An 800 kV, 4 kA thermionic electron gun in a MIG configuration has been designed and is now being fabricated. The gun will provide the annular beam for a one GW klystron whose RF circuit is still in the design phase.

REFERENCES

[1] B. Carlsten, et al, “Intense Space-Charge Beam Physics Relevant to Relativistic Klystron Amplifiers”, *IEEE Trans on Plasma Sci*., 22(5), p.719, 1994.

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