DESIGN AND SIMULATION OF A CUSP GUN FOR GYRO-AMPLIFIER APPLICATION IN HIGH FREQUENCY RF ACCELERATORS

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Abstract

Gyro-amplifiers have potential as the high frequency RF drivers for particle accelerators. They require relativistic electron beams with low velocity spread and with a high fraction of the electron energy associated with the cyclotron motion. For harmonic operation and mode control an axis-encircling beam is desirable. The passage of an electron beam through a non-adiabatic magnetic field reversal (cusp) converts part of the electron beam's axial velocity into axis-encircling transverse velocity. A cusp-based electron beam forming system, yielding a 10MW, 150kV, 70A axis-encircling beam will be presented. This cusp gun is being designed as the electron beam source for a microwave gyro-amplifier that is relevant for high frequency accelerator applications. The latest results from numerical simulations and experiments are presented and compared.

OPERATING PRINCIPLES

The gyro-TWA utilises a moderately relativistic electron beam to interact with a fast waveguide mode near the grazing intersection of the frequency versus wavenumber plot (figure 1), where the resonance line is tangent to the electromagnetic mode. As the phase velocities of the two modes are nearly matched and the group velocity of the waveguide mode is nearly equal to the axial velocity of the electron beam, the device exhibits both high gain and efficiency.

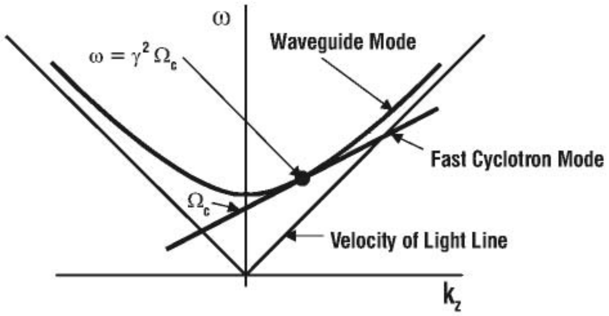

Figure 1: Dispersion Diagram for a Gyro-TWA

The axial bunching mechanism in a gyro-TWA is too weak to be of any significance and so, to benefit from autoresonance, the cut-off frequency is reduced relative to the cyclotron frequency. The lack of any resonant structures in a gyro-TWA also gives it a much larger bandwidth than a gyroklystron.

The most attractive operating regime for a gyro-TWA is that of grazing incidence of the beam and wave dispersion characteristics when the axial electron velocity is close to the group velocity of the wave. Consequently, many early gyro-TWA's employed weakly relativistic electron beams and operated at frequencies near cut-off, limiting their frequency band and making them susceptible to gyrotron oscillation (figure 1).

Gyro-TWA's driven by relativistic electron beams were able to achieve a much broader frequency band, however, numerous studies have identified velocity spread as a major limitation to both amplifier efficiency and bandwidth when operating far from cut-off, due to Doppler broadening.

In order to overcome the problem of velocity spread, consider the effect of a periodic spiral perturbation to the wall of a cylindrical waveguide (figure 2), the geometry of which is chosen such that two modes are resonantly coupled (figure 3), one close to cut-off (A) and one propagating (B). In breaking the rotational symmetry of the cylindrical waveguide, the spiral perturbation couples the left-handed and right-handed components of the waves asymmetrically, creating chirality in the eigenwave dispersion characteristics of the waveguide at frequencies close to Bragg resonance. The first partial wave resonantly interacts with the electrons, whilst the addition of the second wave results in an eigenwave with non-zero group velocity near $\beta_z = 0$, which would not be possible in a regular, cylindrically symmetric waveguide. This structure is commonly referred to as a helical waveguide and will resonantly couple pairs of waves whose axial wavenumbers and azimuthal orders differ by k_B and m_B respectively.

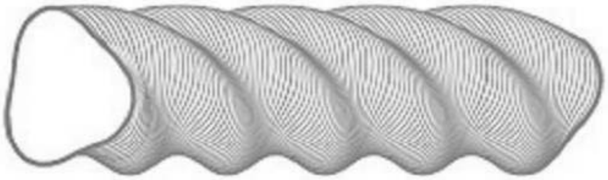

Figure 2: Helical Waveguide

Changing the geometrical parameters of the corrugation allows control of the eigenwave group velocity, which may be adjusted to the axial velocity of the electron beam to create a broad frequency band around the point where the longitudinal wavenumber is equal to zero (figure 3).

The use of helical waveguides allows the utilisation of highly attractive regimes of gyro-TWT operation.

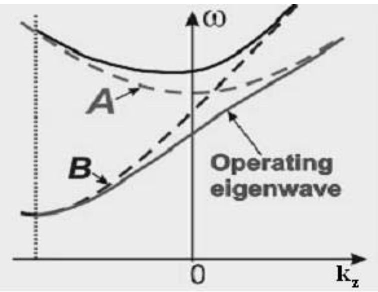

Figure 3: Coupled Modes in a Helical Waveguide

$$k_A << \omega / c, k_B \sim \omega / c \qquad (1)$$

$$\overline{m} = m_A + m_B, \overline{k} \approx k_B \qquad (2)$$

A gyro-TWA with a thin, axis-encircling electron beam also benefits from enhanced selective properties when compared with those using a magnetron injection gun (MIG), in which the electron orbits are not centred on axis. When a particle exactly orbits the axis of the waveguide, the field of the azimuthally travelling $TE_{n,p}$ mode in its orbit is a single gyrating multipole (2n-pole, where n is the azimuthal mode index of the wave), rather than the set of field multipoles found in a normal gyrotron. This single multipole (with gyrational frequency ω/n, where ω is the mode frequency) interacts resonantly with electrons orbiting at the cyclotron frequency ω_c at only one cyclotron harmonic.

In the past, axis-encircling beams have been achieved using a “Pierce-like” gun emitting a pencil beam that was then “kicked” with an asymmetric magnetic field. This “kicker” magnet requires cooling and represents an additional complication to the device. In order to eliminate the need for this “kicker”, a cusp gun has been investigated. A cusp gun produces an axis-encircling beam by passing an annular beam through a magnetic cusp, introducing an azimuthal rotation.

The magnetic cusp is produced using two solenoids wound in opposite sense. The main cavity coil produces the field required for interaction whilst a smaller secondary coil, which is positioned just behind the cathode surface, produces a reverse field.

SIMULATIONS

The complex nature and extreme sensitivity of cusp gun design creates the need for extensive simulation. To this end, several computer codes were used and their results compared - namely MAGIC, SCALA (from the OPERA 3D suite) and SURETraj (an electron trajectory code developed in-house).

MAGIC is a very powerful finite difference code able to model not only electron trajectories, but also their interaction with RF fields. The additional processing requirements of such a detailed model does, of course, lead to increased computational time.

SCALA is the component of the OPERA 3D suite (a finite element code) designed to model electron emission and trajectories (figure 4) and is capable of modelling numerous emission models.

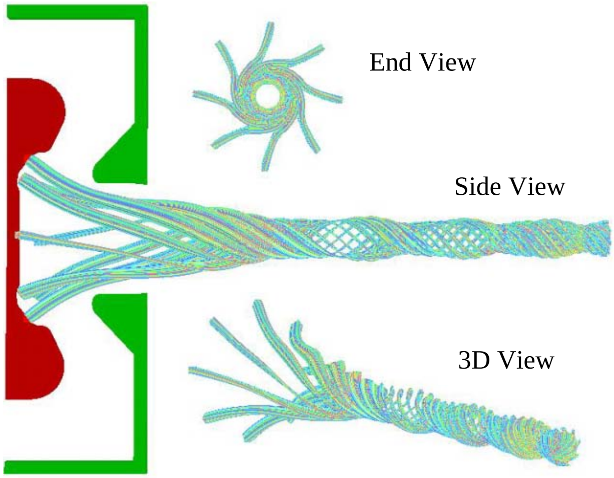

Figure 4: Electron Trajectories as Modelled in SCALA

SURETraj is a finite difference code developed at the University of Strathclyde and written in Matlab. It is capable of modelling both thermionic and cold field emission diodes.

SIMULATION RESULTS

Simulations were carried out in all three codes for the proposed cusp geometry intended for use in the gyro-TWA with the potential difference between anode and cathode set at 150kV and with a desired beam current of ~70A.

Beam Alpha

Beam alpha is the ratio of the azimuthal velocity to the axial velocity of the electrons. This is a crucially important parameter in gyro-devices as it determines what percentage of the beam energy may be transferred to the RF signal and its magnitude is determined by the change in magnetic field seen by the electrons. Hence, alpha may be tuned by adjusting the current through the reverse field coil and, hence, varying the magnetic field at the cathode surface. The results from simulating this relationship are shown in figure 5 (the cusp gun has been designed to operate with an alpha of 1.2).

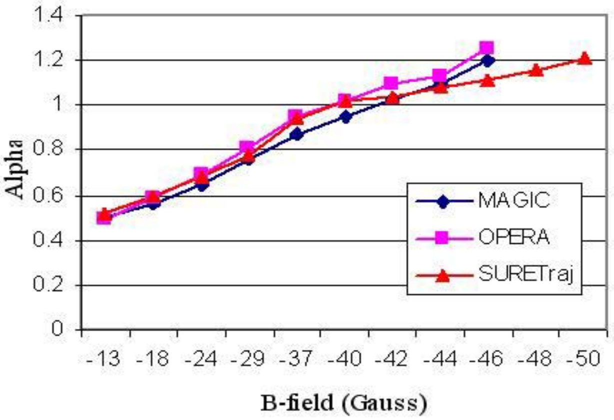

Figure 5: The Variation of Alpha with the B-Field at the Cathode Surface

Excellent agreement can be seen between SCALA and SURETraj, whilst MAGIC predicts a higher beam alpha (as much as 25%) for a given magnetic field at the cathode surface. Additionally, the spread in beam alpha was found to be less than 5%.

Beam Transport

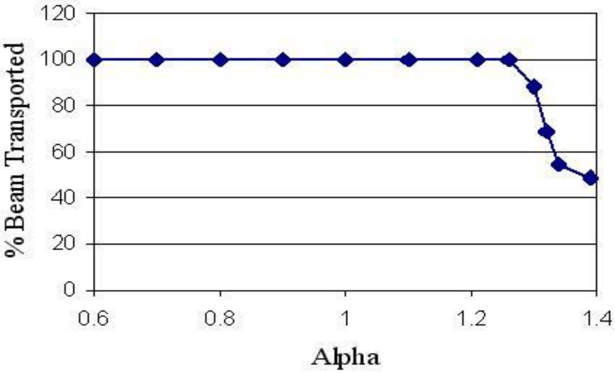

Figure 6: Loss of Beam Current at High Alpha

For high efficiency, it is vital that a very large percentage of the beam drawn from the cathode is successfully transported to the interaction region. As the beam current is increased, space charge effects make it increasingly difficult to focus the beam sufficiently to avoid interception of some electrons by the beam tube. Increasing alpha again causes greater beam interception (figure 6). Simulations in all three codes predict 100% beam transport at the desired operating beam alpha of 1.2.

INITIAL EXPERIMENTS

In order to more rigorously test the accuracy of the models, some initial experiments have been carried out using cold field emission from a velvet cathode. Using a Faraday cup, a beam current of ~37A was observed (figure 7), which is in close agreement with simulations for the case of cold field emission. Images of the beam are to be obtained using a scintillating plate and digital camera in order to verify that it is indeed axis-encircling and to estimate the value of beam alpha.

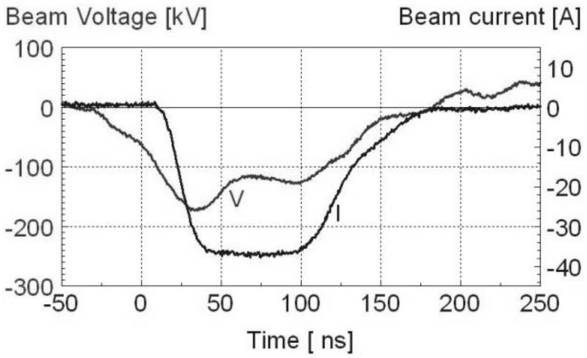

Figure 7: Beam Voltage and Beam Current Traces for Cold Field Emission Cusp Gun

CONCLUSION

All three codes predict that a 70A beam may be successfully passed from the electron gun to the interaction region with 100% beam transport at the desired operating beam alpha. Additionally, there is excellent agreement between SURETraj and SCALA with regards to the variation of beam alpha with the magnetic field at the cathode surface. Initial cold cathode experiments have shown some encouragement, particularly with regard to the predicted beam current.

FUTURE WORK

Cold field emission experiments remain in progress and, based on these and the highly promising predictions of all three codes, a thermionic cusp gun is already under construction. Further modelling aimed at introducing a grid to the cusp gun to allow switching of the beam is now at an advanced stage.

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