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ABSTRACT

The High Brightness Test Stand is a 2 MeV, ≤ 10 kA electron accelerator module. This accelerator module designed as an upgrade prototype for the Advanced Test Accelerator (ATA) combines solid state nonlinear magnetic drives with state-of-the-art induction linac technology. The facility serves a dual role as it not only provides a test bed for this new technology but is used to develop high brightness electron optics. In the following we will both further describe the accelerator as well as present some of the preliminary electron optics measurements.

INTRODUCTION

Among the extended family of particle accelerators, the induction accelerator probably carries the distinction of being the least complex. Primarily this stems from the fact that they do not involve the conversion of power into RF and the subsequent filling of a standing wave structure. It is rather simply a pulse transformer to which a single polarity pulse is applied to a series of primary windings wound around ferri-magnetic cores and the electron beam comprises the secondary.

The performance of these accelerators in the past has been limited by the modulators which supply the primary drive. The requirements for very high power levels ($\geq 10^{10}$ watts) in very short times ($\leq 10^{-8}$ s) could not be met

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reliably at high repetition rates and average power levels. A simplified comparison between the drive supplied to RF accelerators and induction linacs is provided in Fig. 1.

Recent advances in nonlinear magnetic compression technology have made available power conditioning systems with high reliability and which are remarkably well-suited to driving induction linacs. The principles of magnetic pulse compression have been amply described in many publications and it should suffice here to direct the reader to the simplified schematics in Fig. 2 which compare our ATA spark gap based modulators with the solid state MAG-I drivers used on HBTS.

A cross-sectional view of these modulators can be seen in Fig. 3, while a block diagram of the module connection to the accelerator cells is exhibited in Fig. 4.

The High Brightness Test Stand (HBTS) a new ≤ 2 MeV accelerator utilizing these modulators was constructed at LLNL in 1984. As shown schematically in Fig. 5, this down-sized accelerator employed two MAG-I's as drivers. These units each supply a 1000 J, 15 gigawatt pulse to two of the four accelerator cells, providing a test bed for electron gun optics designs operating anywhere from 0 $\rightarrow$ 2 MeV and 0 $\rightarrow$ 10 kA. The pulse energy not used to generate the electron beam is dissipated in flowing Cu SO₄ dummy loads. A cross-sectional view of this injector is presented in Fig. 6. Here HBTS is shown outfitted with a field emission pentode and a field free collimator has been affixed to the exit beam pipe for beam quality measurements.

BRIGHTNESS EXPERIMENTS

The High Brightness Test Stand was constructed in part to investigate the generation of high quality electron beams. This has become of interest due to

the ongoing Free Electron Laser research in which the Beam Research Program is involved. The goal has been to generate a 1 - 2 kA electron beam of the lowest emittance (highest brightness) possible in such a manner that is compatible with high average power operation.

The term brightness has been coined to describe the 4-space density of the electron beam and is defined here simply as

$$J_n = \frac{\pi^2}{(8\gamma)^2} \frac{d^4 I}{dV^4}$$

where I is the electron current and V_4 is the 4-space volume. V_4 , the 4-space volume being defined as

$$V_4 = \frac{\pi^2 E_r^2}{2}$$

with E_r the edge emittance given as

$$E_r = bV$$

for an ellipsoidal distribution which satisfies

$$1 - \frac{(x^2 + y^2)}{b^2} - \frac{(x'^2 + y'^2)}{v^2} = 0$$

Experimental measurement of brightness is accomplished with a field free collimator like the one shown in Fig. 7. The entry and exit slit determine the effective pipe size while steering coils located both before the entry slit and between the two slits allow sampling of different sections of the beam. To understand the operation of this collimator it is best to consider a pipe of radius R_p and length L . To first order the electrons which pass through the pipe have initial conditions which satisfy

$$(x + x'L)^2 + (y + y'L)^2 \leq R_{ps}^2$$

The 4-space volume of initial conditions satisfying this inequality is

$$V_c = \frac{\pi^2 R_p^4}{L^2}$$

A measurement of the current passing through the collimator yields the brightness as

$$J_n = \frac{IL^2}{(By)^2 R_p^4}$$

Efforts to maximize the brightness involved optimizing both the electron optics as well as the cathode. The cathode is of course of primary importance as the beam brightness will never be better than the source creates. The electron optics determine how badly the brightness will be degraded in accelerating the electrons from the cathode surface into the output beam pipe.

ELECTRON OPTICS

The actual geometries of the injector electrodes for the different configurations to be tested were determined through a combination of analytical work, computer modeling and experimental verification. The computer modeling involved the use of several computer codes: DPC (authored by J. K. Boyd), E-GUN (authored by W. Herrmannsfeldt), and EBQ (authored by A. C. Paul). Of these codes DPC proved to be the best match for our particular needs and the other codes served as backups to verify the predictions generated by DPC.

The experiments on each candidate cathode type involved testing a succession of various electron optics. The various electrode geometries were optimized for different extracted current densities.

If perfectly uniform electron emission is assumed, holding geometric aberrations constant, the brightness will increase linearly with the extracted current density. In the case of field emission cathodes the emission uniformity has been shown to improve as the extraction density is increased.

The thermal cathodes exhibit the opposite tendency and as the thermal emission limit is approached the uniformity begins to degrade rapidly. With the thermal cathodes emission non-uniformity coupled with the roughness of the emitting surface are the two factors which increase the emitted electron temperature above what one would expect based only on the surface temperature. Field emission cathodes are much more difficult to understand.

It is the belief of the authors that the operation of field emission cathodes is strongly dependent on the presence of condensed gas at the surface. Application of a high electric field stress is accompanied by true field emission causing evaporation and subsequent ionization of this material, thereby creating a plasma from whose sheath electrons can be extracted. Factors which determine the cathode limited brightness include the Debye length, the smoothness, uniformity and temperature of the plasma sheath.

EXPERIMENTAL RESULTS

In the following we will attempt to describe the results obtained from each of the various cathode candidates tested. Research around each cathode type involved several electrode geometries aimed at various extraction densities. Only the geometries which gave the best results will be described.

FIELD EMISSION CATHODES

The field emission cathode work initially involved the testing of a wide variety of cathode materials. The first efforts centered around various types of graphites and the results seemed to indicate that the brightness increased as the applied field stress; rate of application of that stress; and the surface porosity increased. To make a long story short we will skip to what appeared to be the brightest field emission source and that was felt. Felt was certainly the most porous of all our candidates. The best test results were achieved with a pentode pierce column as shown in Fig. 6.

The electrodes were machined out of titanium and conditioned to allow the maximum E-stress to be applied. The experimental brightness measurements are outlined in Fig. 8. While the DPC code predictions are supplied by Fig. 9.

It was believed that further research in this area could probably result in a brightness exceeding 10^6 , Amperes-cm⁻²·Ster⁻¹. In spite of steady improvements in this area, research was discontinued rather abruptly after it was found that none of the field emission cathodes tested would operate at duty factors much in excess of 10^{-6} . During operation above this level the cathodes would soon show signs of non-uniform emission and after several minutes would cease to emit at all. Upon returning to lower duty factors, the cathodes would generally recover to their original performance.

THERMAL CATHODES

Successive experiments all employed thermal cathodes. Candidates were restricted to oxide and dispenser cathodes as other thermal cathodes (i.e. tungsten, thoriated tungsten, etc.) with exception of LaB₆ offered insufficient emission density and the use of LaB₆ would have required extensive modifications to the accelerator as the operating temperature is quite excessive.

Oxide cathodes appeared at first to offer great promise. While usable DC emission densities are typically only a few amperes/cm², these cathodes have exhibited emission densities exceeding 100 amperes/cm² when operated at the duty factors we were interested in ($\leq 10^{-4}$). The vacuum system for HBTS was upgraded to provide a base pressure of order 10^{-8} Torr, a coating mix (#33-C-185A) was purchased from RCA, and G. Konrad (SLAC) donated two Nickel-A blanks of type used in the XK-5 klystrons. These nickel blanks, trimmed down to 7.4 cm diameter, were used at first. Successive experiments utilized

blanks fabricated here from different nickel alloys. Attempts were also made to vary such parameters as surface roughness. A sketch of the electrode geometry which was finally arrived at as well as some sample data is presented in Fig. 10. Measurements of the brightness were conducted over a range of extraction densities running as high as 35 amperes/cm². The data shown in Fig. 11 was collected at an extraction density of 20 amperes/cm².

The fabrication of oxide cathodes is somewhat of a black art and not fully understood by the authors. Consequently it is not obvious that the disappointing brightness measurements could not be improved upon through some act of magic worked by some old craftsman in a back room somewhere. We did feel like we gave it our best shot, but do plan some additional experiments in the future. The code prediction supplied by Fig. 12 indicates that the brightness is most certainly cathode dominated, and it is worth noting that the surfaces of the oxide cathodes tested were not very smooth. The coating used forms a grainy surface of small spherulities. This surface roughness is sure to degrade the brightness somewhat although it is not known whether or not this was the dominant factor.

The cathodes which have provided the most satisfactory results are the dispenser cathodes. The first experiments here with this type of cathode employed a 3.5" diameter 311 scandate currently under production at Spectra-Mat for use in the SLAC 50 MW klystron.

The dispenser cathodes possess a polished metal surface from which emission densities exceeding 40 amperes/cm² can be obtained. A sketch of the electron optics as well as some of the preliminary data is supplied in Fig. 13. The experimental measurements of brightness versus current shown in Fig. 15 gave good agreement with DPC predictions given in Fig. 14. The

differences are most probably due to an accumulation of alignment errors, spacing tolerances, as well as cathode related effects. In order to achieve the best brightness measurements as wide a margin as possible was established between the extracted current density and the thermal emission limit. Unfortunately this entailed operating the cathode at temperatures which greatly reduced its life. In fact the operating temperature of 1300°C resulted in a lifetime of only 40 hrs. Efforts are currently underway to fabricate a new cathode design which will have a renewable surface and be indirectly heated by electron bombardment. This should minimize the fiscal impact of this issue.

CONCLUSION

It indeed appears possible to generate multi-kiloampere electron beams with brightnesses exceeding 10^6 amperes·cm⁻²·Ster⁻¹. HBTS has proven to be a flexible test bed which has enabled us to test many different cathodes and electrode configuration under various conditions. To date dispenser cathodes appear by far to give the most satisfactory performance and it is hoped that further research into such areas as controlled Porosity Dispensers will yield even better results.

Figure 5 Simplified schematic of the High Brightness Test Stand HBTs.

Figure 6 Cross-sectional view of the HBTs accelerator module; HBTs accelerator output waveform, all pulses 20 ns/div.

Figure 7 Cross-section of Field Free Collimator

HBTS

HIGH BRIGHTNESS TEST STAND
BRIGHTNESS MEASUREMENTS

BRIGHTNESS VS. CURRENT (AMP)

CATHODE TYPE: PENTODE PIERCE COLUMN
GUN DESIGN: 4 CM. DIAM. FELT FIELD EMISSION
EXTRACTION DENSITY: 160 AMPS./CM²
THERMAL LIMIT: NA
OPERATING TEMPERATURE: NA

Figure 8

HBTS

HIGH BRIGHTNESS TEST STAND
DPC BRIGHTNESS PREDICTIONS

BRIGHTNESS VS. CURRENT (AMP)

GUN DESIGN: PENTODE PIERCE COLUMN
CATHODE: 4 CM. DIAM. FELT FIELD EMISSION

Figure 9

HBTS

HIGH BRIGHTNESS TEST STAND
PRELIMINARY RESULTS: OXIDE CATHODE EXPERIMENT
CATHODE TYPE: SLAC XK-5 KLYSTRON CATHODE

INJECTOR VOLTAGE
.5 MEV/d, 20 ns/d

OUTPUT CURRENT
400 AMPS/d, 20ns/d

Figure 10

HBTS

HIGH BRIGHTNESS TEST STAND
BRIGHTNESS MEASUREMENTS

BRIGHTNESS VS. CURRENT

CATHODE TYPE: 2.9" DIA. OXIDE
GUN DESIGN: 3:1 AREA CONVERGENT TRIODE
EXTRACTION DENSITY: 20 AMPS./CM²
THERMAL LIMIT: 40 AMPS/CM²
OPERATING TEMPERATURE: 1000 °C

Figure 11

BRIGHTNESS VS. CURRENT

Figure 12

HBTS

HIGH BRIGHTNESS TEST STAND

INJECTOR VOLTAGE
.5 MEV/d, 20 ns/d

OUTPUT CURRENT
500 AMPS/d, 20 ns/d

PRELIMINARY RESULTS:

3.5" DIA. DISPENSER CATHODE

66-C-88/88-119

Figure 13

HBTS

HIGH BRIGHTNESS TEST STAND

DPC BRIGHTNESS PREDICTIONS

BRIGHTNESS VERSUS CURRENT

66-C-87/88-137

Figure 14

HBTS

HIGH BRIGHTNESS TEST STAND

BRIGHTNESS MEASUREMENTS MARK II TRIODE

BRIGHTNESS VS. CURRENT (AMP)

CATHODE TYPE - 3.5" DIA. DISPENSER
GUN DESIGN - 4:1 AREA CONVERGENT TRIODE
EXTRACTION DENSITY - 18 AMPS/CM
THERMAL LIMIT - 40 AMPS/CM
OPERATING TEMPERATURE - 1300 C
CATHODE LIFETIME AT TEMPERATURE - 40 HRS.

Figure 15