Optimization of FAST Electron Gun Beam Parameters Using *ASTRA*

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The RF photocathode electron gun in the FAST linac is identical to the gun developed at the Photo Injector Test Facility at DESY in Zeuthen, Germany (PITZ). However, the phase scans from FAST did not match those from PITZ. In order to explore a Schottky-like effect that could be behind this discrepency, I wrote a C program utilizing *ASTRA*, and found a set of parameters that accurately describes the behavior of the accelerator and provides insight into the behavior of the gun.

I. INTRODUCTION

The FAST (Fermilab Accelerator Science and Technology) Facility includes a superconducting RF linear accelerator that is currently being used to accelerate electrons.

The linac accommodates high energy beamlines, a high energy beam dump, and an experimental area for advanced accelerator R&D (AARD).

It also provides venues downstream and along test beamlines for research and future experiments like the Integrable Optics Test Accelerator (IOTA) [1].

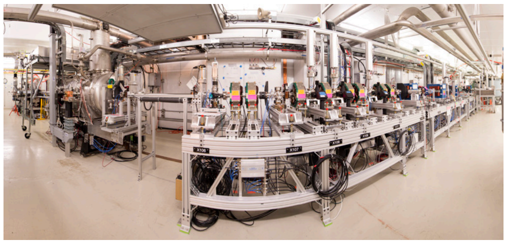

Figure 1: Image of Cyro Module and beam line, FAST Cave Configuration. Photocathode electron gun and toroid monitor to the left, beam travels to the right.

A. Photoinjector Gun

The RF photocathode electron gun in the FAST linac is identical to the gun developed at the Photo Injector Test Facility at DESY in Zeuthen, Germany (PITZ), and is a normal-conducting 1.5 cell 1.3 GHz gun.

This gun is driven by a 5 MW klystron and uses solenoid magnets to focus the beam. Each magnet has a peak field of 0.28 T at 500 A, and are normally set so the field at the photocathode is 0 in order to minimize beam emittance [1].

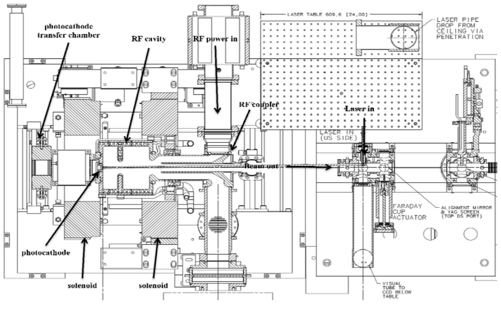

Figure 2: Cross section of gun, solenoids, transfer chamber, and downstream instrumentation [1]. Toroid monitor placed before the Faraday Cup to measure beam intensity/charge.

The electron gun is routinely operated at peak gradients of 40-45 MV/m, with an output beam energy of approximately 5 MeV. (It should be noted that this is significantly more powerful than the guns utilized at DESY for PITZ) Additionally, a temperature feedback system regulates cooling water temperature to better than ±0.02 °C for beam and phase stability.

B. Photocathode Laser

The photocathode is a 10 mm diameter polished molybdenum disk coated with Cs_2Te with 5 mm diameter photosensitive area. It is illuminated by 263 mm wavelength laser light directed onto the photocathode downstream of the RF coupler [1].

Several photocathodes have already been prepared and their quantum efficiency measured to be ~10% when new [1].

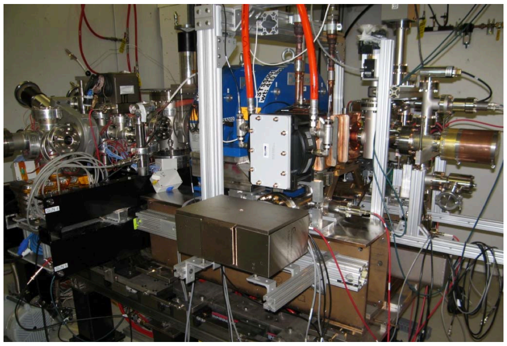

Figure 3: Photograph of the gun installation in the FAST enclosure on August 2012. Photocathode preparation chamber is to the left, and beam exits to the right. RF waveguide connection is towards the viewer (white blank-off). Solenoids are blue [1].

II. PHASE SCAN

Faraday Cups and integrating current transformers (ICT) had been used at PITZ to measure the electron beam charge. However, Faraday Cups often have issues with heat load at high energies, and can create secondary emissions that interfere with the readings. Whereas ICTs require sufficiently short and isolated bunches in order to accurately measure charge along the beam. Due to the high energy nature of the electron accelerator at FAST, our readings were taken with toroid monitors.

A. Measurement

To measure beam intensity, a toroid monitor was utilized to conduct a phase scan (accelerated charge measured as a function of launch phase).

In order to optimize gun operation, the RF phase of the gun was varied with respect to the laser across various phase scans (See Figure 4).

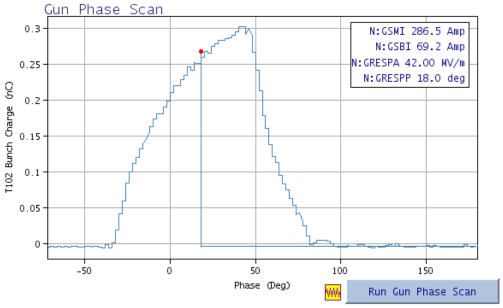

Figure 4: Measured phase scan from the electron gun in FAST. Data taken from a toroid monitor placed 1.186 m downstream from the gun. Plateau in charge is characterized by a significantly steeper slope than was observed at PITZ, which may be caused by a secondary emission of electrons.

B. Discrepancy

However, the phase scans from FAST did not match those from PITZ despite the identical nature of the guns. This is an issue, since there is no explanation for why the phase scans from FAST would be so different.

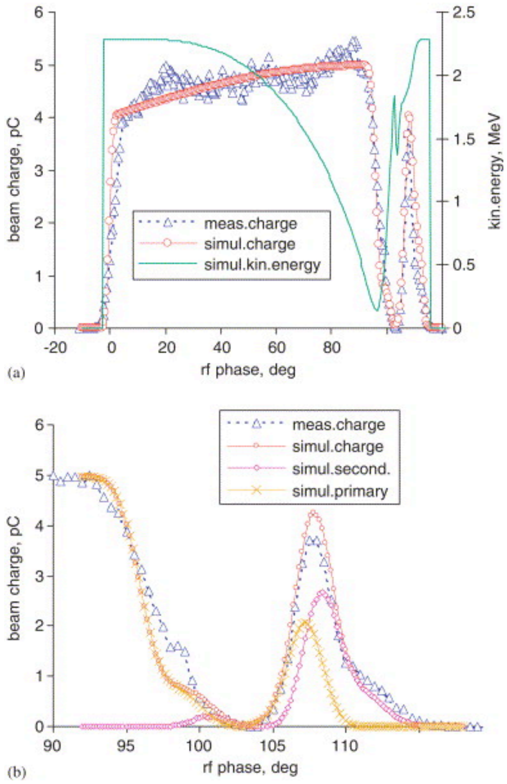

Figure 5: (a) Measured and simulated phase scan (beam charge vs. RF phase). (b) Detailed phase scan for RF phase range ~100–115° [2].

One possible explanation for the discrepancy in the recorded data is a Schottky-like effect manifesting itself in the Cs_2Te photocathode.

The Schottky effect describes the lowering of the work function or the potential barrier of a metal by an external electric field, which leads to an increased electron emission from the metal. This phenomenon may explain the unexpected results observed in the phase scan above. The charge of a bunch is determined at the time of emission as:

$$Q = Q_0 + SRT_{Q_{Schottky}} \cdot \sqrt{E} + Q_{Schottky} \cdot E$$

where E is the combined longitudinal electric field in the centre of the cathode. The charge Q_0, is the charge of the macro particles as defined in the input distribution (rescaled to fit Q_{bunch}) [3].

C. Schottky Effect

The Schottky Effect describes the lowering of the work function or potential barrier of a metal by an external electric field. This leads to an increased electron emission from the metal and could explain the unexpected phase scan at FAST.

The charge of a bunch at t_0 is determined as:

$$Q = Q_0 + SRT_{Q_{Schottky}} \cdot \sqrt{E} + Q_{Schottky} \cdot E$$

where E is the combined longitudinal electric field in the centre of the cathode and Q_0 is the charge of the macro particles as defined in the input distribution (rescaled to fit Q_{bunch}).

IV. PROGRAM

A. Simulation

ASTRA (A Space Charge Tracking Algorithm) is a software package written in Fortran 90 by Klaus

Floettmann (DESY). It simulates datasets of an accelerator beam's properties through a Monte-Carlo approximation of charges. However, *ASTRA* lacks certain tools and software, such as parameter modification, parameter optimization, and curve-fitting. Adiitionally, *ASTRA* is difficult to automate since it is packaged as an executable, and none of its source code has been made public.

In order to more efficiently and easily simulate the FAST linac, I wrote a program that allowed for the manipulation of parameters, execution of simulations, and plotting of data. This program was written in C so as to be easier to execute in the linux servers at FAST, and utilized the Fortran executable that came in the ASTRA software package.

B. Optimization

To identify the proper parameters to simulate the FAST linac, the program implemented a chi-square test for variance or standard deviation:

$$\chi^2 = \sum \frac{(f(x) - S_{sim} \cdot f_{sim}(x, \vec{a}))^2}{\sigma_f{}^2} + \frac{(S - S_{sim})^2}{\sigma_S{}^2}$$

$$\chi^2 = (f(x) - S \cdot f_{sim}(x, \vec{a}))^2$$

$$\chi = f(x) - S \cdot f_{sim}(x, \vec{a})$$

χ^2 was simplified to a delta value (χ) by taking the value of $\sigma^{\ 2}$ → 1. S was taken to be a scaling factor that occurred inherently when comparing results between software simulation and hardware readings. *f(x)* is the phase scan function that was measured experimentally through a toroid monitor. And $f_{sim}(x,\ a)$ is the simulated phase scan function outputted by the program.

Using regression analysis and the chi-square test, a set of parameters was found that accurately describes the behavior of the accelerator, and hints towards a potential hardware scaling factor. (This is due to the fact that a significant scaling factor of 0.305 was required to match the readings to the simulated results.) The program also began to shed some light on the impact of secondary emission, though arriving at a conclusion warrants more investigation in the future.

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>
#include <time.h>
#include <libgen.h>

#define LINE_CHAR 236 //236
#define LINE_BUFSIZE 2+LINE_CHAR

int interface();
int param();
int astra();
int delta();
void plot(double* xData, double* yData1, double* yData2, int dataSize);
FILE* execute(char *bash, char line[LINE_BUFSIZE]);
void writefile(FILE* pipe, FILE* out);
void appendfile(char line[LINE_BUFSIZE], FILE* out);
char* inputstring(char *s);

double lumberphase[12] = {-34, -22, -10, 2, 14, 26, 38, 50, 62, 74, 86, 98};
double lumbercharge[12] = {-0.001064046, 0.099856578, 0.158018127, 0.205068439, 0.235183701, 0.266601682, 0.282234013, 0.265988648, 0.131121278, 0.058323566, 0.002844042, -0.0006889};
double simulation[12];
char globalfile[500];

int main()
{
        //char line[LINE_BUFSIZE];
        //execute("clear", line);

        system("clear");

        //printf("\n----------------------------------------------------------------------\n\n");

        printf("\n");

        //printf("CLOCKS_PER_SEC = %i\n", CLOCKS_PER_SEC);

        interface();

        return EXIT_SUCCESS;
}
```

Figure 6: The optimization program, first written in Python, was translated to C in order to more efficiently process the large amounts of raw data that ASTRA outputs per simulation. Now, it acts as an environment in which bash script and analysis can be run side-by-side.

IV. RESULTS

In order to identify parameter values that would accurately simulate our recorded readings, the following variables were changed in ASTRA: H_max, H_min, SRT_Q_Schottky, Q_Schottky, SE_d0, SE_Epm, and SE_fs.

The last three, SE_d0, SE_Epm, and SE_fs had significantly larger values than expected, which suggests that the gun in the FAST linac was generating significantly greater secondary emissions than the gun at PITZ, due to its higher average operating power. Other parameters such as the scaling factor and Schottky variables provided insight into the behavior of the gun and additional emission events as well.

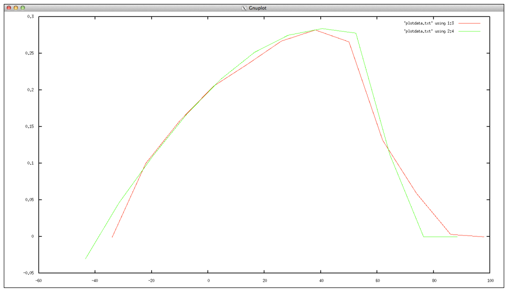

Figure 7: Through the tuning of gun geometry, charge, and Schottky parameters, a relatively accurate approximation of our recorded data was achieved. This helps us to understand the true impact of secondary emission.

However, further work is required to better simulate the secondary peak in charge observed in the phase scans at FAST and PITZ, taking into account the change in magnitude (which is currently hypothesized to be a result of the higher energies at FAST as well).

V. FUTURE WORK

In addition to discrepancies observed in the longitudinal phase scan, there have also been unexplained artifacts recorded in transverse charge measurements of the beam.

The program above, as well as the parameters it found, will continue to predict future experimental readings and diagnose issues such as this. As FAST strives for higher intensities and more bunches, this work will set the stage for future optimization.

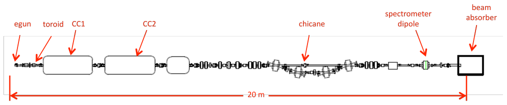

Figure 8: Upstream floor plan of the FAST photoinjector and 3 SRF cryomodules in the original building footprint. The beamline is 1.2 m above the floor, the floor is 6.1 m below grade, and the building length is 74 m [1].

VI. REFERENCES

1. Mike Church, et al. 2012. *Design of the Advanced Superconducting Test Accelerator.*

2. K. Abrahamyan, et al. 2006. *Experimental characterization and numerical simulations of the electron source at PITZ.* Nuclear Instruments and Methods in Physics Research, Volume 558, Issue 1.

3. J. Li, et al. 2012. *Emission Study of Photocathode RF Gun at PITZ.* Proceedings of ICAP2012.

4. E. Harms, 2014. *ASTA Update.* Fermilab APT Seminar.