NUMERICAL SIMULATIONS AT CEBAF USING PARMELA*

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ABSTRACT

PARMELA has been used at CEBAF for numerical modeling of the nuclear physics injector chopping system, a possible FEL laser gun injector, and the rf steering and focusing effects of the standard CEBAF SRF cavities. These applications call for the code to input field data consistently from SUPERFISH, POISSON, and MAFIA, to properly treat a focusing solenoidal lens having an actual field profile either individually or together with its adjacent rf cavity, to deal with the space charge forces, to model the longitudinal phase space matching required for bunching electrons using a phase-compressor chicane, etc. In this paper, we describe in detail these issues of general interest.

INTRODUCTION

PARMELA[1] is a versatile multi-particle computer code that can be used for studying the effects of electromagnetic fields on the dynamics of electrons. It has achieved great popularity because of its power in designing electron injectors and accelerators.

In this paper, we present our use of the code at CEBAF for numerical modeling of the nuclear physics injector chopping system, a possible FEL laser gun injector, and the rf steering and focusing effects of the standard CEBAF SRF cavities on electron beams. The emphasis will be put on how to input field data consistently from SUPERFISH, POISSON, and MAFIA, to properly treat a focusing solenoidal lens having an actual field profile either individually or together with its adjacent rf cavity, to deal with the space charge forces, to use the code effectively for longitudinal phase space matching required for bunching electrons using a phase-compressor chicane, etc.

THE CHOPPER SYSTEM

As is shown in Fig. 1, the initial part of the CEBAF nuclear physics injector consists of a 100-kV thermionic gun, a pair of apertures (A_1 and A_2) for limiting

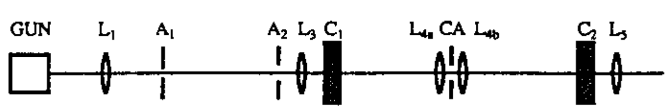

Fig. 1 Chopper system of the CEBAF nuclear physics injector

the initial emittance of the beam, and a pair of chopper cavities (C_1 and C_2) to chop a cw beam through an aperture (CA). The first lens (L_1) focuses the beam

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to a waist at the first aperture; the third lens (L_3) makes an image-to-image transform from A_1 to CA; and the lens pair L_{4a}-L_{4b} makes an image-to-image transform between the centers of C_1 and C_2. The chopper system is symmetric with respect to the chopper aperture.

Each chopper cavity is a square box operating presently at a fundamental frequency of 1500 MHz on the two modes: TM_{210} and TM_{120}. When an electron beam moves through the first cavity, it is deflected radially outward and gradually turned into a hollow beam by the two orthogonal modes. Then it is chopped at the chopper aperture. The second identical cavity is used to compensate for the radial momentum introduced by the first cavity , and completes the chopping process. See Fig. 2.

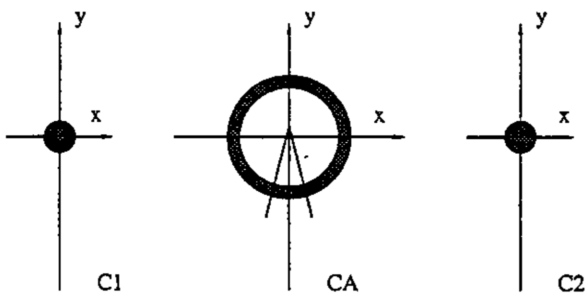

Fig. 2 Chopping process from C1 to C2

The conventional version of PARMELA assumes a hard-edge field profile for a solenoidal lens. It additionally requires that the length of the hard-edge field profile be the same as that of the rf element when the two elements overlap each other. The chopping process is treated using a zero-length transform. All these assumptions fail to apply to most of the actual cases. For example, in our case, the field profiles of all the solenoidal lenses can not be well approximated by the square ones. In addition, there exists a mutual penetration between the solenoidal field of $L_{3(5)}$ and rf field of $C_{1(2)}$. More importantly, we needed to model the energy spread performance of the chopper system, and a zero-length transform can not provide the needed information.

We modified the code to meet the requirements for our modeling. First we fitted the actual on-axis axial solenoidal field profiles using Glaser and Gaussian distributions. A paraxial approximation is applied to the transverse magnetic field components. The lens L_1 is treated as an individual one. We modified the card $CELL$ and the subroutine $CELLIMP$ to accommodate both the rf fields from $C_{1(2)}$ and the solenoidal fields from $L_{3(5)}$ in one numerical element. The rf fields in the chopper cavities are calculated using MAFIA. The approach adopted to calculate the rf fields in PARMELA from those obtained using MAFIA is the one developed by Z. Li[2] and will be introduced in a later section.

The purpose for modeling the chopper system is to clarify its energy spread performance. For each slice of the beam, an energy spread is induced when it passes through the first cavity. As the beam passes through the second cavity properly in phase, its emittance introduced by the first cavity is undone. We needed to clarify whether the energy spread is undone simultaneously with the emittance.

Numerically we found that the phase difference between the two orthogonal modes must be 90^0 in both cavities, instead of $+90^0$ in one cavity whereas -90^0 in the other. This finding is consistent with the experiment. Then we found that the relative phase difference between the two identical modes in the two cavities controls the cancellation of emittance, and the energy spread follows exactly the same process as for the emittance. See Fig. 3. The underlying mechanism is that an electron is flipped 180^0 in the transverse plane by the lens pair L_{4a}-L_{4b}, therefore it experiences an acceleration or deceleration process which is opposite to that occured in the first cavity. The details will be presented elsewhere[3]. This numerical calculation has been confirmed with the experiments carefully designed and conducted by M. Tiefenback *et al.*[4]

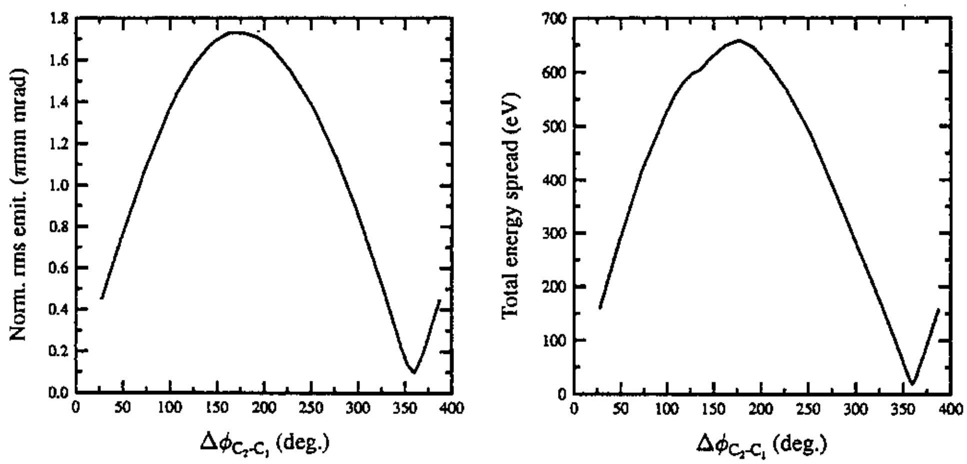

Fig. 3 Emittance and energy spread of the chopper system versus the rf phase difference between the two identical modes in the two cavities

THE FEL INJECTOR

CEBAF has been studying an IR FEL and a UV FEL utilizing the superconducting accelerator technology that has been developed at CEBAF, aimed at industrial applications and fundamental scientific research[5–8]. An FEL injector, consisting of a photocathode DC gun, a prebuncher, a cryounit containing two standard CEBAF SRF cavities, and a phase-compressor chicane, would be used as a high-brightness cw source. The specifications for the FEL injector are summarized in Table 1. $4\sigma_t$ and $4\sigma_E$ are used to represent the bunch length and

Table 1 FEL Injector Specifications

Energy	10 MeV
Charge per bunch	120 pC
Bunch length ($4\sigma_t$)	2 ps
Energy spread ($4\sigma_E$)	400 keV
Normalized rms emittance (ϵ_n)	15 mm mrad
Average beam current	900 μA
Repetition frequency	7.677 MHz

bunch energy spread. For ideal Gaussian distributions, they correspond to 95% particles.

Based on the previous calculation[8], the performance of the FEL injector has been optimized and thoroughly investigated using time-consuming but accurate integrated numerical modeling[9]. The beam dynamics is calculated using a version of PARMELA with the point-by-point method for space charge treatment[10,11]. The code POISSON was used to generate the DC electric field in the photocathode gun, and the code SUPERFISH was used to generate the 2-D RF field distributions in the prebuncher and two standard CEBAF SRF cavities in the cryounit. In each integrated simulation (~ 10 cpu-hours on an HP 9000/730 UNIX workstation), the same electrons are followed from emission at the photocathode through the gun, the prebuncher, the cryounit and the chicane. The results for the baseline design are listed in Table 2. The various distributions are shown in Fig. 4.

Table 2 Baseline Design and its Performance

<u>Gun parameters:</u>	
Voltage (V_0)	500 kV
Laser pulse length ($4\sigma_l$)	100 ps
Cathode diameter (d_0)	3 mm
Field gradient (E_0)	10 MV/m
<u>System characteristics:</u>	
Prebuncher:	two-cell scheme
Solenoidal lenses:	two rotating lenses
Quadrupoles:	one triplet
Chicane:	R_{56}=−0.085 cm/%
<u>System performance:</u>	
Bunch charge	120 pC
Bunch length ($4\sigma_t$)	0.96 ps
Energy spread ($4\sigma_E$)	290 keV
Mean energy (E_m)	9.492 MeV
Norm. rms emittance ($\epsilon_{nx}/\epsilon_{ny}$)	4.44/4.73 (mm mrad)

The conventional version of PARMELA has no input for an electrostatic element. We deal with the DC fields in the gun calculated using the code POISSON as if they were rf fields but with $\sin(\omega t)$ and $\cos(\omega t)$ excluded. We used 14 Fourier coefficients calculated using the code SUPERFISH for the rf fields in the prebuncher and the SRF cavities, which is a standard use of the code. We found that the key point for our injector simulation is to accurately match the electron bunches in the longitudinal phase space from the second SRF cavity to the chicane to achieve the shortest possible bunch length and hence the highest possible FEL optical gain.

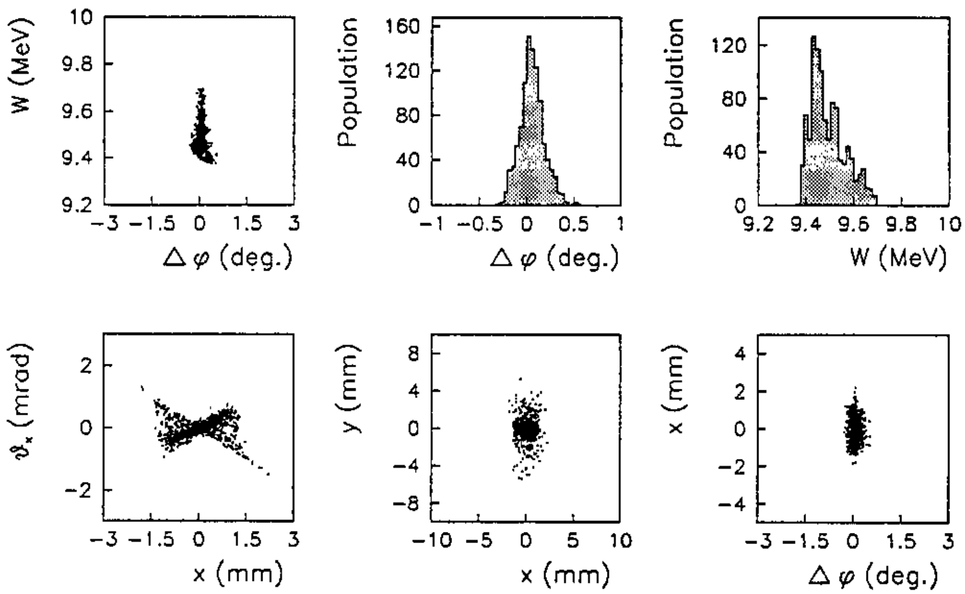

Fig. 4 Various distributions of 1000 superparticles at the exit of the chicane, showing the optimized baseline design performance listed in Table 2. *Upper left* : longitudinal phase space distribution (W – energy; $\Delta\phi$ – relative phase); *Upper middle* : phase profile; *Upper right* : energy profile; *Lower left* : horizontal trace space distribution (x – horizontal position; θ_x – horizontal divergence angle); *Lower middle* : cross-sectional distribution; *Lower right* : horizontal snap-shot.

The electrons are bunched at first for suitable injection into the cryounit using a prebuncher. Then two SRF cavities and a chicane are used for further bunching, as shown in Fig. 5. Using the σ matrix representation[12], we have

$$\sigma_{55}(1) = \sigma_{55}(0)(1 - R_{56}/f_{56})^2 + R_{56}^2\sigma_{66}(-1), \tag{1}$$

where $\sqrt{\sigma_{55}(0)}$ is the bunch length at the entrance of the chicane, $\sqrt{\sigma_{55}(1)}$ the bunch length at the exit of the chicane, $\sqrt{\sigma_{66}(-1)}$ the momentum spread at the entrance of the second SRF cavity, $R_{56} = \delta l/(\delta p/p)$ the parameter of the bunching property of the chicane, δl the path difference between electrons having an energy spread of $\delta p/p$, $f_{56} = -\sigma_{55}(0)/\sigma_{56}(0)$ the tilt of the longitudinal phase space distribution of the bunch at the exit of the second SRF cavity. It is seen that when $f_{56} \simeq R_{56}$, the final bunch length depends only on the product of the momentum spread and R_{56} of the chicane. We call the above condition the *conditioning for final bunching*, which is a term borrowed from Ref. 13. Eq. (1) has been incorporated into PARMELA so that the matching can be predicted accurately after the second SRF cavity. This has turned out to be an indispensable means for optimizing the design.

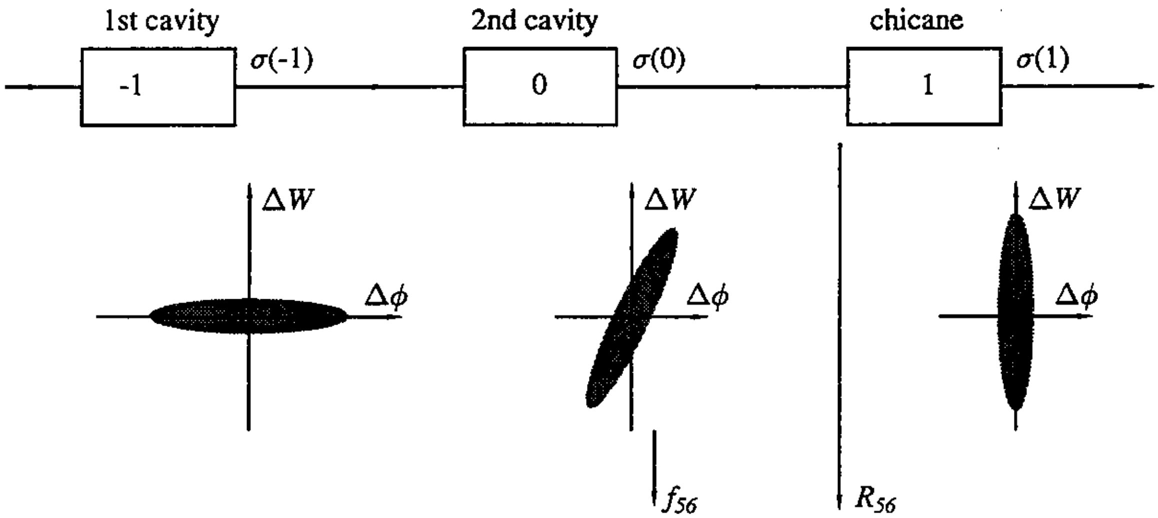

Fig. 5 Bunching process using the two SRF cavities and the chicane.

Using such a version of PARMELA equipped with Eq. (1) and the point-by-point method for space charge calculations, the following investigations have been made:

(1) the robustness of the baseline design against the laser intensity fluctuation and so the bunch charge fluctuation;

(2) the sensitivity of the baseline design on the basis of $\delta\phi = \pm 2^0$ for rf phase fluctuations and $\delta E/E = \pm 2\%$ for rf amplitude fluctuations in the prebuncher and the two rf cavities in the cryounit;

(3) the maximum operational flexibilities under various different gun operating conditions;

(4) the fluctuation of emission phases of electron bunches.

With these integrated simulations, the bunch length, energy spread, emittance, bunch-to-bunch centroid energy shift and bunch-to-bunch centroid phase shift have been fully examined. It has been demonstrated that the design will perform beyond the specifications over a quite wide range of operation conditions. In addition, some potentialities have been found for making a better compromise between the optimum performance and minimum cost. These possibilities include: (1) to employ the one-cell prebuncher scheme instead of the two-cell scheme; (2) to increase the value of the matrix element R_{56} of the chicane to allow an easier longitudinal phase space matching and thus to reduce the sensitivity in electrons bunch length and centroid phase shift. These features are under consideration for further elaborate designs.

CAVITY STEERING AND FOCUSING

The transport properties of the standard CEBAF SRF cavities have been carefully studied by Z. Li using PARMELA and MAFIA[2]. Fig. 6 shows the 5-cell cavity configuration with two couplers for 3-D rf field calculations using MAFIA.

MAFIA modeling gives the six field components for each mesh point. The six components are not defined right on that mesh point, as shown in Fig. 7. The

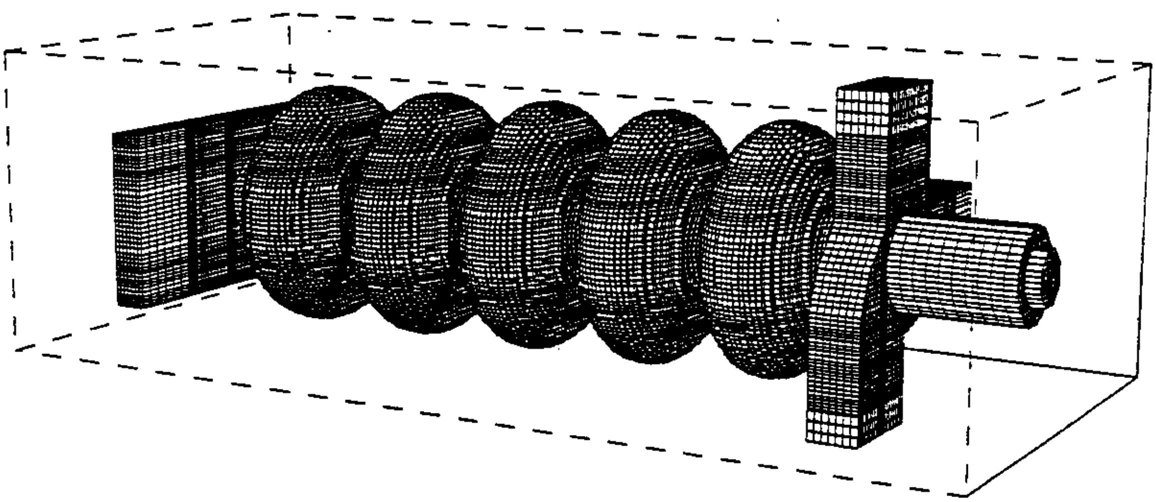

Fig. 6 The standard CEBAF SRF cavity configuration

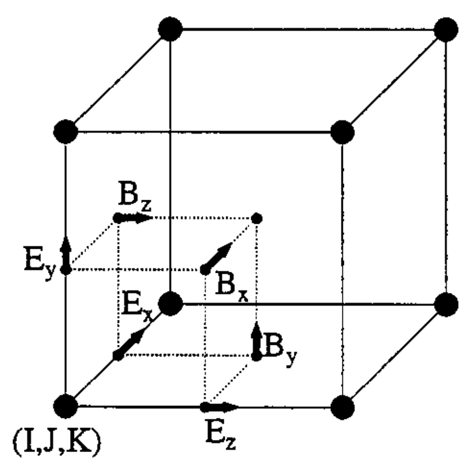

Fig. 7 Field components defined in MAFIA calculation

E_x, E_y and E_z components are defined on the grid axis with half mesh size off the grid in the x, y and z directions. The B_x, B_y and B_z components are defined at the central points of the mesh areas in the (y, z), (x, z) and (x, y) planes. Besides, the two couplers are arranged alternatively for different cavities, so the parity of a cavity must be taken into account. Z. Li has considered all these details carefully and used a 3-D interpolation subrountine *Q3DVL* from *IMSL* for calculating the 3-D rf fields in PARMELA based on the field data from MAFIA. The Fourier transform has been used to analyze the steering and focusing effects of the cavities.

SUMMARY

We have introduced our use of PARMELA at CEBAF for numerical modeling of the nuclear physics injector chopping system, a possible FEL laser gun injector, and the rf focusing and steering effects of the standard CEBAF SRF cavities on the beam. The emphasis has been put on how to modify and use the code consistently; for example, to input field data from SUPERFISH, POISSON, and MAFIA, to properly treat a focusing solenoidal lens having an actual field profile either individually or together with its adjacent rf cavity, to deal with the space charge forces, to use the code effectively for longitudinal phase space matching required for bunching electrons using a phase-compressor chicane, etc.

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REFERENCES

1. The code was originally developed by K. R. Crandall.
2. Z. Li, private communication.
3. H. Liu *et al.*, to be presented at the 1993 PAC, May, Washington, DC.
4. M. Tiefenback *et al.*, *ibid.*
5. J. Bisognano *et al.*, NIM A318, 216(1992).
6. G. R. Neil *et al.*, *ibid.*, p. 212.
7. C. K. Sinclair, *ibid.*, p. 410.
8. P. Liger *et al.*, *ibid.*, p. 290.
9. H. Liu *et al.*, to be presented at the 1993 PAC, May, Washington, DC.
10. K. T. McDonald, IEEE Trans. ED, 35, 2052 (1988).
11. H. Liu, this conference.
12. T. Raubenheimer, Workshop on Fourth Generation Light Sources, Feb., SSRL, 263(1992).
13. A. M. Sessler *et al.*, Phys. Rev. Lett. 68, 309 (1992).