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CONTROL OF CAFe BEAM ENERGY USING LINEAR ACCELERATOR SIMULATION SOFTWARE AVAS AND BEAM LINE CALIBRATION TECHNOLOGY*

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Abstract

A new accelerator simulation code named Advanced Virtual Accelerator Software (AVAS) was developed by the Institute of Modern Physics, Chinese Academy of Science. Although the code is proposed to simulate the particle transport in the linac of the China Initiative Accelerator Driven System (CiADS), it can be also used for common linacs. We have constructed a framework for the accelerator simulation program AVAS based on the structure, function, parameters, errors, and operational logic of real accelerators. The mapping relationship between the operating parameters and simulation parameters of the Chinese ADS Front-end Demo Linac (CAFe) superconducting section was successfully established through AVAS. In the testing experiment, AVAS successfully set the operating parameters of the CAFe superconducting section, and the deviation between the energy setting value and the actual measurement value was about 0.5%.

INTRODUCTION

AVAS [1] is a linear accelerator simulation code developed for the requirements of the CiADS [2]. The code is based on particle-in-cell (PIC) algorithm [3] and implemented in the C++ language. All accelerator elements as well as algorithms are packaged into an executable program, which can be run after installation on the windows operating system. On the one hand, AVAS has developed the S-PICNIC [4] algorithm by improving the standard PICNIC [5] algorithm, which significantly reduces the computational effort to solve for space charge effects. On the other hand, AVAS achieves efficient parallelism. The above work has resulted in a significant reduction in the AVAS multi-particle simulation time, which is a significant advantage in large-scale multi-particle simulations.

The operating parameters of the accelerator are different from those used in the accelerator simulation program. In order to obtain the operating parameters of the accelerator directly from the numerical simulations, it is necessary to establish a correspondence between the operating parameters of the accelerator and the numerical simulation parameters. In this paper, AVAS program is introduced first, and then how to establish the corresponding relationship between accelerator operating parameters and AVAS simulation parameters is explained. Finally, it is tested on CAFe [6] superconducting section.

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MATERIALS AND METHODS

The CAFe is the pre-validation device for CiADS and is structured as shown in Fig. 1. In CAFe, the beam is mainly accelerated in the RF superconducting cavity and the energy of the exiting beam is determined by the parameters of the RF superconducting section. In this paper, we use AVAS to map the superconducting section of CAFe to achieve a process that gives the accelerator operating parameters directly through simulations and changes the beam energy.

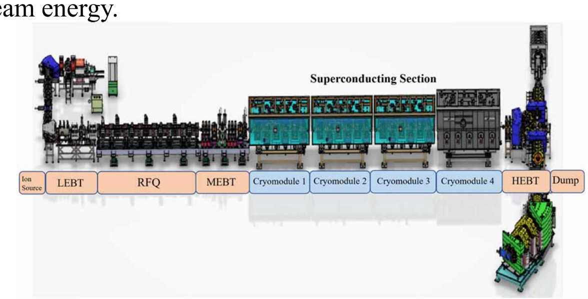

Figure 1: CAFe structure schematic.

The superconducting section of CAFe contains four cryomodules (Cryomodules 1-4), the exact composition of which is shown in Fig. 2. The first three cryomodules contain six solenoids and six RF cavities each, and the last cryomodule contains five solenoids and five RF cavities. The operating parameters of the solenoids are the current of the solenoid magnets and the operating parameters of the RF cavities contain the RF field amplitude and the RF field phase. Therefore, the superconducting section of CAFe has a total of 69 operating parameters. If these 69 operating parameters can be given directly by simulation when the beam energy needs to be changed, stable beam transmission can be achieved quickly.

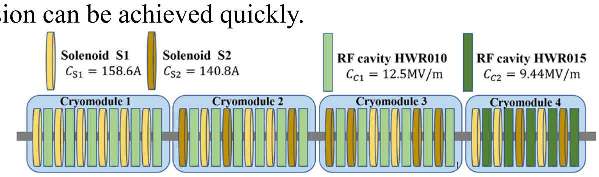

Figure 2: Cryomodule composition diagram.

These three types of parameters contain two types of mapping relationships, one for magnitude, including solenoid current and RF field amplitude, both of which are linearly related to the magnitude of the electromagnetic field (EMF) in the corresponding element, which is controlled in AVAS by adjusting the magnification of the reference electromagnetic field. Therefore, it is necessary to determine the proportionality constants between the reference EMF and the real EMF per unit current (or per unit RF field

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amplitude) in the simulation program in order to obtain the values of current and RF field amplitude in the accelerator. The equation is as follows:

$$I_s = C_s K \tag{1}$$

$$E_{pk} = C_c K \tag{2}$$

where C is the amplification of the reference EMF in the simulation program, I_s is the solenoid current value and E_{pk} is the RF field amplitude. Another type of mapping relationship is the mapping of phases, which is the key part of establishing the mapping. The electric field in an RF cavity is:

$$E = E_0 \cos(\varphi_0 + \omega t) \tag{3}$$

The mapping of phases is the determination of the phase difference $\Delta\varphi$ between φ_0 (denoted as φ_v) in the simulation program and φ_0 (denoted as φ_{RF}) in the RF cavity. The equation for mapping the phase of the numerical simulation to the phase of the real accelerator is

$$\varphi_{RF} = \varphi_v + \Delta\varphi + n \times 360 \tag{4}$$

AVAS determines the phase of the RF cavity by scan-phase. Eq. (5) is the way the RF cavity electric field is calculated in AVAS

$$E = E_0 \cos\left(\phi_0 + \omega(t - t_0)\right) \tag{5}$$

The relationship between Eq. (5) and Eq. (4) is shown in Eq. (6):

$$\varphi_v = \phi_0 - \omega t_0 \tag{6}$$

In addition, the electric field in the RF cavity can be calculated in AVAS using Eq. (7). This allows AVAS to skip the scan-phase process and simulate using the real phase of accelerator operation, giving simulation results that are closer to the real accelerator.

$$E = E_0 \cos(\varphi_v + \omega t) \tag{7}$$

In summary, the design of AVAS ensures a bi-directional mapping between the numerically simulated phase and the real accelerator phase.

RESULTS AND DISCUSSION

The goal of the experiment was to increase the energy of the beam (Composed of $^{40}Ar^{12+}$) to 186.6 MeV by adjusting the operating parameters of the CAFe superconducting section. Firstly, simulate the beam propagation in the CAFe superconducting segment using AVAS. The simulated parameters in AVAS were repeatedly adjusted so that the beam was accelerated to 186.6 MeV in the program. subsequently, the operating parameters of the CAFe superconducting section were obtained based on the mapping of the simulated parameters to the real accelerator operating parameters (Eq. (1-2), (4)).

The CAFe superconducting section contains two solenoids, denoted S1 (C_{s1} = 158.6) and S2 (C_{s2} = 140.8), and two RF cavities, denoted HWR010 (C_{c1} = 12.5)and HWR015 (C_{c2} = 9.44), and the phases of each cavity are independent, as shown in Fig. 2. All parameters in the experiment, including the 27 mapped parameters, 69 simulated parameters and the 69 operational parameters calculated from the simulated and mapped parameters are shown in Table 1 and Table 2, the unit of E_{pk} in the table is MV/m.

Table 1 includes the field amplification factor K of the solenoid in the simulation and the solenoid current I_s(A) calculated through Eq. (1). Table 2 includes the field amplification factor K and phase φ_v used in the simulations, and the operating parameters of the accelerator, including the RF field amplitude E_{pk} and phase φ_{RF}, can be calculated using Eq. (2) and Eq. (4). The last three RF cavities in CM4 are switched off.

The beam energy was measured by a TOF (Time Of Flight) located at the end of the CAFe linear section. The distance between the two oscilloscopes in the experiment is $L = 0.6132\text{m}$, and the measured beam time of flight $\Delta t = 20.453ns$, according to Eq. (8), the energy of the beam can be calculated as 187.5MeV.

$$E_k = \left(\frac{1}{\sqrt{1-(\frac{L}{\Delta t \cdot c})^2}}\right) E_0 \tag{8}$$

where c is the speed of light and E_0 is the rest energy of the $^{40}Ar^{12+}$, which is 37218.6 MeV.

In summary, AVAS provided parameters suitable for accelerator operation through simulations. In the actual test, the energy of the beam was 187.5 MeV, with a relative error of 0.48% from the simulated energy (186.6MeV). Subsequently, only minor adjustments to the RF field amplitude or phase of the last RF cavity are required to achieve the required beam energy, avoiding re-scan-phase, simplifying the beam energy switching process in real accelerators, and quickly achieving stable beam transmission.

Table 1: Mapping of Solenoid Currents to Simulation Parameters in CAFe

CM1 Solenoid						
	S1	S1	S1	S1	S1	S1
K	0.8	0.78	0.81	0.88	0.75	0.98
I_s(A)	126.9	123.7	128.5	139.6	119.0	155.4
CM2 Solenoid						
	S2	S1	S2	S1	S1	S2
K	0.87	0.95	0.47	1.05	0.9	0.9
I_s(A)	122.5	150.7	66.0	166.5	142.7	126.7
CM3 Solenoid						
	S2	S2	S1	S1	S2	S2
K	0.9	0.84	0.87	0.95	0.82	0.92
I_s(A)	126.7	118.3	138.0	150.7	115.5	129.5
CM4 Solenoid						
	S1	S1	S2	S1	S2	-
K	1.0	0.99	0.98	0.95	0.78	-
I_s(A)	159.0	157.0	138.0	150.7	109.8	-

Table 2: Mapping of CAFe RF Cavity Operating Parameters to Simulation Parameters

CM1 Cavity						
	1-1	1-2	1-3	1-4	1-5	1-6
K	1.28	1.2	1.8	1.6	1.5	1.9
E_{pk}(MV/m)	16	15	22.5	20	18.8	23.8
$\Delta\varphi(deg)$	116	148	44	83	107	-36
$\varphi_v(deg)$	-171	-140	100	42	45	93
$\varphi_{RF}(deg)$	-55	8	144	124	152	56
CM2 Cavity						
	2-1	2-2	2-3	2-4	2-5	2-6
K	2	1.86	2	2.2	2.4	2
E_{pk}(MV/m)	25	23.2	25	27.5	30.0	25.0
$\Delta\varphi(deg)$	-146	-139	103	171	-77	-76
$\varphi_v(deg)$	147	7.2	-45	-30	17	137
$\varphi_{RF}(deg)$	0.8	-132	59	141	-60	61
CM3 Cavity						
	3-1	3-2	3-3	3-4	3-5	3-6
K	2.1	2	2.3	2.24	1.76	2
E_{pk}(MV/m)	26.2	25	28.7	28	22.0	25
$\Delta\varphi(deg)$	-143	-117	-50	-96	-15	41
$\varphi_v(deg)$	-174	98	46	46	86	107
$\varphi_{RF}(deg)$	42	-19	-4	-50	71	148
CM4 Cavity						
	4-1	4-2	4-3	4-4	4-5	-
K	2.90	1.22	0	0	0	-
E_{pk}(MV/m)	27.4	11.5	0	0	0	-
$\Delta\varphi(deg)$	145	149	-37	-74	-	-
$\varphi_v(deg)$	111	10	-	-	-	-
$\varphi_{RF}(deg)$	-104	159	-	-	-	-

CONCLUSION

This paper describes the process of mapping the operating parameters of the CAFe superconducting section to the AVAS simulation parameters. After the mapping is completed, control of the CAFe beam energy is achieved. In the future, further information will be used, such as information from sensors in accelerators and historical data, to establish more mapping relationships between numerical simulations and real accelerators, in order to achieve complete reconstruction of real accelerators in computers.

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