Beam dynamics study of RFQ for CADS with a 3D space-charge-effect *

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Abstract: The ADS (accelerator driven subcritical system) project was proposed by the Chinese Academy of Sciences. The initial proton beams delivered from an electron cyclotron resonance ion source can be effectively accelerated by 162.5 MHz 4.2 m long room temperature radio-frequency-quadrupoles (RFQ) operating in CW mode. To test the feasibility of this physical design, a new Fortran code for RFQ beam dynamics study, which is space charge dominated, was developed. This program is based on Particle-In-Cell (PIC) technique in the time domain. Using the RFQ structure designed for the CADS project, the beam dynamics behavior is performed. The well-known simulation code TRACK is used for benchmarks. The results given by these two codes show good agreements. Numerical techniques as well as the results of beam dynamics studies are presented in this paper.

Key words: accelerator, RFQ, PIC, beam dynamics, simulation, space charge, Poisson's equation

PACS: 29.17.+W, 29.20.Lq **DOI:** 10.1088/1674-1137/38/3/037005

1 Introduction

The initial acceleration of proton beam in the driver linac of the CADS project [1] will be provided by room temperature RFQ operating at the frequency of 162.5 MHz. This RFQ is purposed to work at 15 mA beam current with CW operation. The proton beam will be accelerated from 35 keV to 2.1 MeV. The basic RFQ design specifications are listed in Table 1.

The design of RFQ linac with high current beam requires careful control of particle dynamics with space charge forces. Numerous codes cover a wide range of problems connected with the simulation of beam transport and acceleration in linac and circular accelerators using 2 dimensions or 3 dimensions approach. Among others the well-developed codes are PARMILA [2], PARMTEQ [3], WARP3D [4], SIMPOSNS [5], ACCSIM [6], SAMBA [7], ORBIT [8],TRACK3D [9], and TOPKARK [10]. The code being developed at IMP is considered as a many-purpose tool for studying beam dynamics with 3D space charge effect in RFQ. The aim of this code developing work is to create a flexible software, which could be adjusted for frequently changeable problems. Basically, considering the propagating of intense charged particle beams, the PIC [11] method is used for space charge calculation.

Table 1. Initial requirement for RFQ design.

parameter	parameter values
operation frequency/MHz	162.5
duty cycle (%)	100
input particle velocity	0.00863c
output particle velocity	0.06679c
design charge-to-mass ratio	1/1
peak field at electrode surface	1.3 Kilpatrick units
resonant cavity	4 vane
normalized transverse emittance/ (πmm·mrad)	0.3
inter-vane voltage V/kV	65
average bore radius R_0/cm	0.5731
vane tip curvature R_e/cm	0.4298
vane length/cm	419.1
$m_{\max}$	2.35
number of cells	192
maximun surface field/(MV/m)	15.8
synchronous phase/(°)	−90−−22
$a_{\min}$/mm	3.2
overall beam transmission@ 0/15 mA (%)	99.7/99.5

This paper will be organized as follows. In Section 2, the original RFQ design will be presented. In Section 3,

Received 8 June 2013
∗ Supported by National Natural Science Foundation of China (11079001, 91026001) and Strategic Priority Research Program of the Chinese Academy of Sciences (XDA03030100)

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the basic model we use in our program will be discussed. In Section 4, the simulation results of this program and benchmark are listed. In Section 5, conclusions and ideas for future studies are given.

2 The RFQ desgin

RFQ working in CW mode [12–14] has been studied for several years at different labs. The RFQ of Injector Ⅱ for the CADS project was developed by collaboration with LBNL, which is expected to work in CW mode. The physical design and beam dynamics simulation are carried out by following well-consolidated techniques and using the code suite (CURLI, RFQQUICK, PARI, PARMTEQM) developed at LANL. This RFQ accelerates 35 keV H^+ beam to 2.1 MeV in a 4.2 meter long cavity, including 192 cells, resonant at 162.5 MHz. The choice of operating frequency is dictated by the desire of a compact structure and the need to inject into the following superconducting section. The optimization of the beam transport along the structure was carried out with the aim of keeping the beam loss principally below 2 MeV in order to minimize the activation in copper. Thus, taking the activation threshold energy of copper into account, the output energy of the RFQ is chosen to be 2.1 MeV.

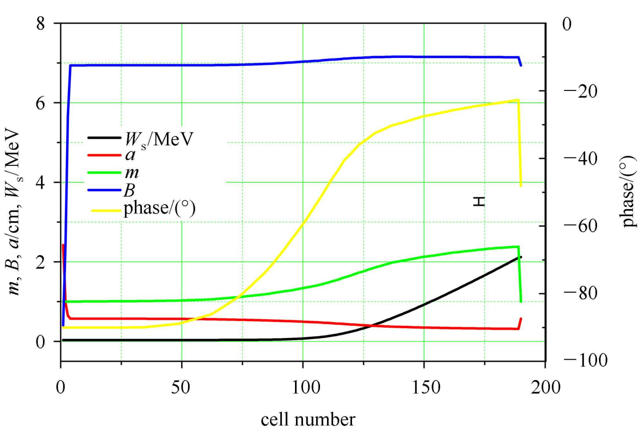

Fig. 1. (color online) Specific parameters for the RFQ of Injector Ⅱ.

The particularities of this design are the constant longitudinal voltage profile V, constant tip radius R_e and the average radius R_0. These choices allow easier and more cost effective machining of the electrode modulation. The gentle-bunch section is a critical part [15], mainly due to that the end of this section is the transverse bottleneck, which is demonstrated in our simulation in the 4th chapter. The main parameters of this section are chosen with the aim of obtaining a beam transmission more than 95%.

Because the problems caused by heat deposition are most challenging in CW operation, the inter-vane voltage of the RFQ is conservatively chosen as 65 kV. In this circumstance, the Kp factor is around 1.3, so breakdown will not be a problem in the cavity. The main design parameters of the Injector Ⅱ RFQ are shown in Fig. 1.

3 The basic model in program

From the simulation point of view, the basic equation we have to solve is shown as Eq. (1). The electric and magnetic field strength are a combination of external fields, $\boldsymbol{E}_{\rm ext}$ $\boldsymbol{B}_{\rm ext}$ and space charge fields of beam, $\boldsymbol{E}_{\rm sc}$ $\boldsymbol{B}_{\rm sc}$, seen in Eq. (2)

$$\boldsymbol{F}=qe(\boldsymbol{E}+\boldsymbol{V}\times\boldsymbol{B}), \tag{1}$$

$$\begin{aligned}\boldsymbol{E}&=\boldsymbol{E}_{\rm ext}+\boldsymbol{E}_{\rm sc},\\ \boldsymbol{B}&=\boldsymbol{B}_{\rm ext}+\boldsymbol{B}_{\rm sc}.\end{aligned} \tag{2}$$

The potential corresponding to external field $\boldsymbol{E}_{\rm ext}$ can be described in RFQ by 8-term field map [16] as shown in Eq. (3). The filed map can be rebuilt by the structure parameters given by PARMTEQm.

$$\begin{aligned}V(r,\theta,z) = \frac{V}{2}\Bigg\{&A_{01}\left(\frac{r}{r_0}\right)^2\cos2\theta+A_{03}\left(\frac{r}{r_0}\right)^6\cos6\theta\\ &+A_{10}I_0(kr)\cos kz\\ &+A_{30}I_0(3kr)\cos3kz\\ &+A_{12}I_4(kr)\cos kz\cos4\theta\\ &+A_{32}I_4(3kr)\cos3kz\cos4\theta\\ &+A_{21}I_2(2kr)\cos2kz\cos2\theta\\ &+A_{23}I_6(2kr)\cos2kz\cos6\theta\Bigg\}.\end{aligned} \tag{3}$$

The $\boldsymbol{E}_{\rm sc}$ is solved with the classic PIC method. A cuboid mesh is generated in the beam Cartesian coordinates system. The Dirichlet boundary condition for potential φ on the surface of a triangular pipe, periodic boundary condition in the longitudinal direction are adopted. Full 3D FFT is used to solve Eq. (4).

$$\nabla^2\varphi = -\rho/\varepsilon_0. \tag{4}$$

Simultaneously, the leap-frog [17] method is used to integrate Eq. (1) to push the particles to get coordinates and velocities at the next time loop, which makes the whole process self-consistent.

4 Simulation results analysis and benchmark

4.1 Beam dynamics

10 k particle with a 4D Water Bag type distribution in transverse and uniform type in longitudinal direction

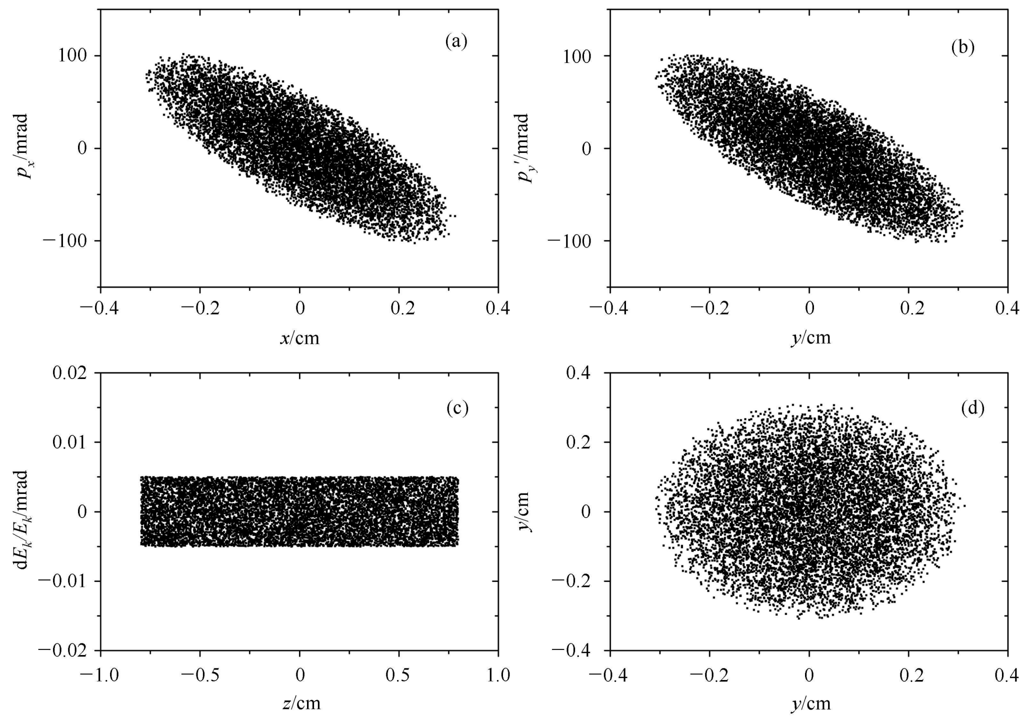

Fig. 2. Initial distribution (a) x-p_x plane; (b) y-p_y plane; (c) z-dw/w plane; (d) x-y plane.

is generated using the Monte Carlo method. The beam current is set as 15 mA. The matched distribution is shown in Fig. 2. A phase width of $\pm\pi$ with an energy spread 0.5% is considered as a continuous beam flow.

Based on the calculating results of the program developed at IMP, the RMS envelopes of transverse and longitudinal directions, the emittances of these three directions and the energy of beam evolution along the RFQ are shown in Fig. 3.

The longitudinal phase space evolutions along RFQ

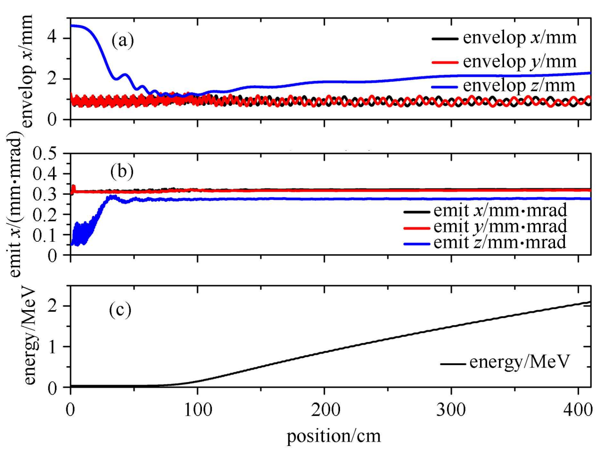

Fig. 3. (a) The beam RMS envelopes; (b) the emittance; (c) the beam energy, evolution along RFQ.

are shown in Fig. 4, separately at cell 20, 50, 80, 90, 110 and 150. The detailed evolution of the main bunch is presented in Fig. 5. During the beam evolution along this RFQ, the electrode boundary is naturally considered as the beam loss criteria in the transverse direction and no beam loss criteria in the longitudinal direction. Because of a strong nonlinear field coming from the combination of RFQ and space charge effect, the longitudinal phase space turns into filamentous and distorts a lot, as shown in Map b. Associated with the nonlinear process, the space charge force in the longitudinal direction pushes the tail particles into the neighbouring buckets, which turn one bunch into three bunches, as shown in Map c. Due to the fact that the particles in the neighbouring buckets originally come from the tails of the main bunch, so there is a big chance that some of them cannot be captured. These particles will leave far behind the main bunch, as shown in Map d and e. At last, these particles cannot be accelerated sufficiently, however, they will not get lost in RFQ, which means the total transmission is still as high as 99.99% but the effectively accelerated transmission decreases a little bit, which is 98.7%.

Figure 6 shows the transmissions with different injected beam currents. Map a is the total transmission; Map b is the effective transmission. Through the comparisons of these two maps, we find the RFQ structure between 0.5–1.0 m

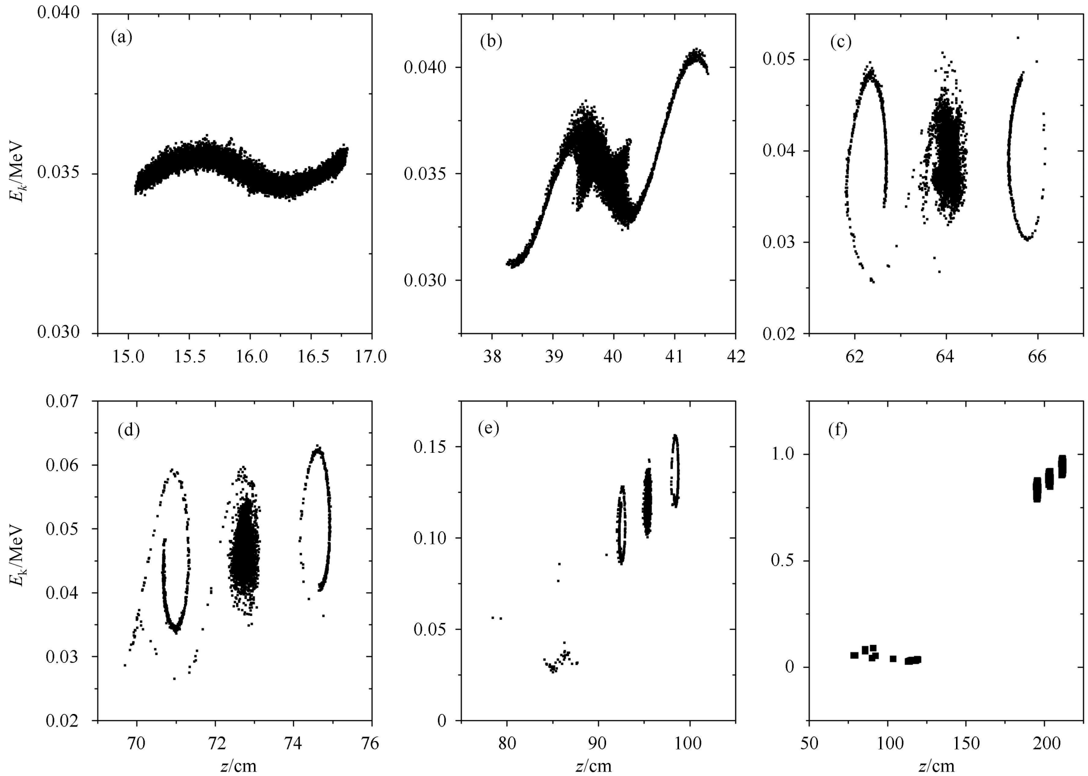

Fig. 4. The longitudinal phase space z-v_z at cell (a) 20; (b) 50; (c) 80; (d) 90; (e) 110; (f) 150.

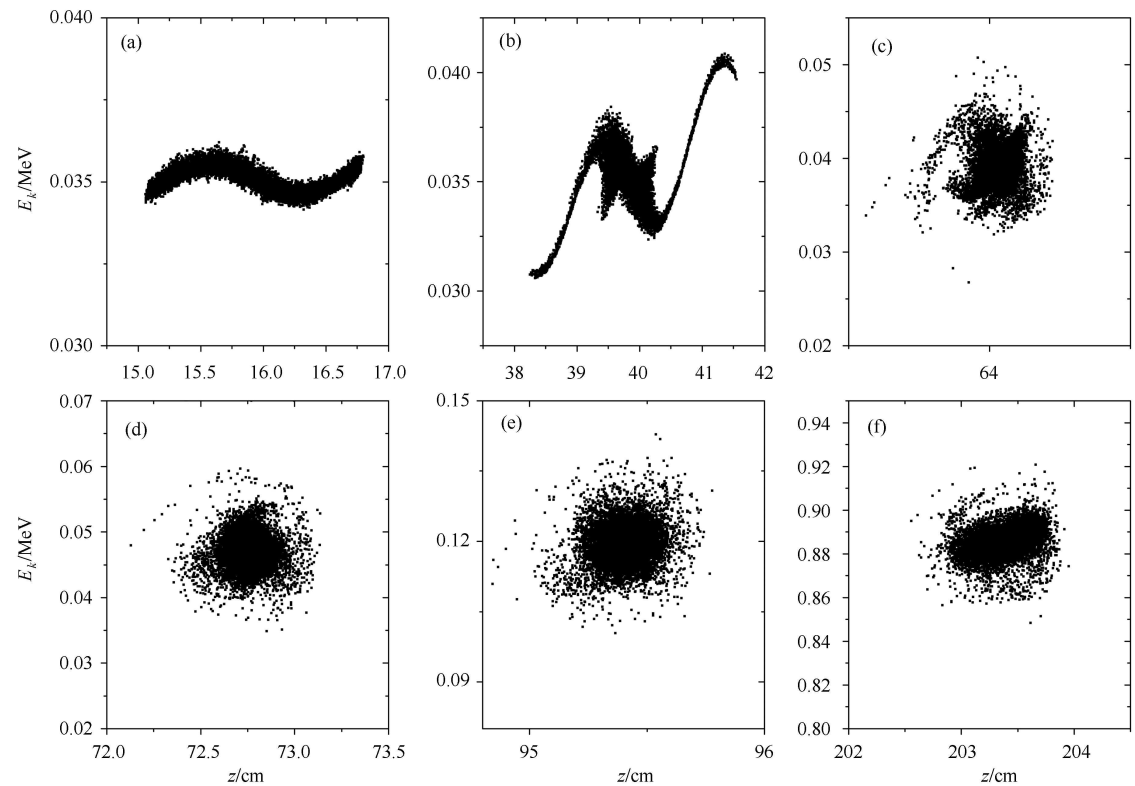

Fig. 5. The longitudinal phase space z-v_z at cell (a) 20; (b) 50; (c) 80; (d) 90; (e) 110; (f) 150.

of this RFQ affects the beam behavior a lot, which we can also distinguish from Fig. 5. This is the critical “end of gentle-bunch” section as mentioned above. The phase distribution at the last cell is shown in Fig. 7. Through this map, we can see that some halo particles emerge. These halo particles [18] with an energy of about 2.1 MeV will lead to significant problems, such as quench in the superconducting (SC) cavity, which means they should be carefully scraped out, together with the un-sufficient

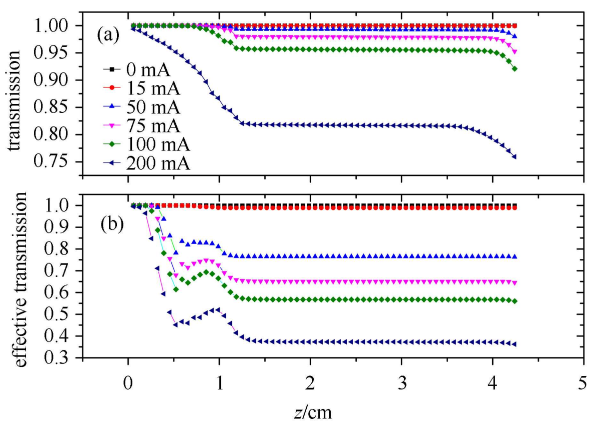

Fig. 6. (color online) (a) Total transmission; (b) Effective transmission.

Table 2. Twiss parameters at the exit of RFQ (15 mA).

parameter	value
α_x	0.021
α_y	−0.14
α_z	−0.28
β_x/(mm/mrad)	0.110
β_y/(mm/mrad)	0.212
β_z/(mm/mrad)	2.43

accelerated particles, before being injected into the SC section. The Twiss parameters at the exit of RFQ are listed in Table 2, which are quite important for the following structure design.

4.2 Benchmark

The well-known beam dynamics simulation code Track [19] is used to benchmark this program. Because different physical models and numerical methods are used in TRACK code, the results can hardly be exactly the same. This RFQ structure is established by PARMTEQ, so the the results given by PARMTEQ are also listed, as shown in Table 3. It clearly shows that there are only a few differences among them. To some degree, it demonstrates that the code we developed is reliable.

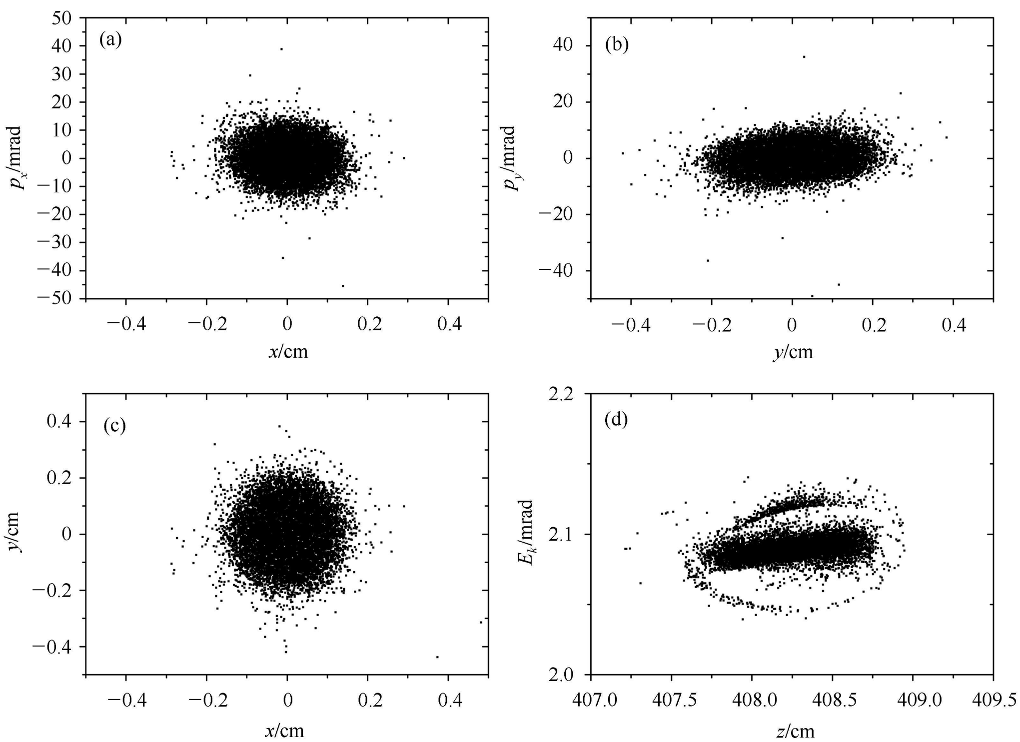

Fig. 7. The phase distribution (a) z-p_x plane; (b) y-p_y plane; (c) x-y plane; (d) z-E_k plane.

Table 3. Results given by different codes.

type	TRACK	PARMTEQ	IMP-code
transimission (%)	99.0	99.6	98.7
x RMS emit/(mm·mrad)	0.309	0.297	0.318
y RMS emit/(mm·mrad)	0.313	0.298	0.324
z RMS emit/(mm·mrad)	0.2714	0.288	0.281

5 Summary

The physical design of RFQ for the CADS project is proved robust and reliable. Using this structure, the new program developed by IMP for RFQ simulation is used to study the beam dynamics behavior. The result is crosschecked with the TRACK code and shows good agreements. In the future, more efforts will be focused on experimental areas, such as RF commissioning, beam measurement and so on.

One of the authors, Chao Li, would like to extend his sincere thanks to P. N. Ostroumov and B. Mustapha of ANL for providing the Track code, and R. A. Jameson of IAP for the helpful discussion ⋯.

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