PROCEEDINGS OF SCIENCE

Hadron Polarization in the Electron Ion Collider*

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Electron Ion Collider (EIC) requires high polarization for both ion and electron beams. To reach 70% proton polarization, six snakes will be used for EIC hadron storage ring (HSR). Extensive simulations have been done to make sure the polarization will be preserved through HSR. The simulations show that with pre-cooled beam size, the polarization can be preserved. In addition, polarized He3 acceleration has been simulated. Polarized deuteron has also been explored. This paper will summarize the overall strategy and status of the EIC hadron polarization.

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1. Introduction

Relativistic Heavy Ion Collider (RHIC) has provided polarized proton beams over an energy range from 31 GeV to 255 GeV in the past two decades. To preserve polarization through numerous depolarizing resonances over the whole accelerator chain, harmonic orbit correction, partial [1] and full Siberian Snakes [2], and a horizontal tune jump system [3] have been used. In addition, close attention has been paid to betatron tune control, orbit control and magnet alignment. A polarization of 60% at 255 GeV has been delivered to experiments with an intensity of 1.8×10^{11} protons per bunch [4]. For the EIC, part of the RHIC rings will be used as hadron ring. The EIC requires polarized proton beams with 70% polarization and 3×10^{11} protons/bunch out of the Alternative Gradient Synchrotron (AGS). The beam brightness has to be maintained to reach the desired luminosity. Since the EIC will only use RHICs counter clockwise ring(yellow), the spin rotators and snakes from the clockwise ring (Blue) can be converted into additional Siberian Snakes for the EIC hadron ring. With a proper arrangement of six snakes in the hadron ring and additional skew quad system in the AGS [6], the polarization is expected to reach 70% at 275 GeV beam energy. In addition, polarized He-3 and deuteron have been considered as future upgrade to probe spin properties of neutron.

The polarization out of polarized source is measured as about 80-82% at 200MeV and 55-60% at RHIC store. There is about total of 30% polarization loss. From the polarization measurements at AGS extraction, it is estimated that about 15% of polarization is lost in each of AGS and RHIC. The portion of polarization loss in AGS is believed to be due to residual polarization loss from horizontal resonances [5]. With pulsed skew quads in the AGS[6], the polarization loss in the AGS from horizontal resonances is expected to be mostly eliminated.

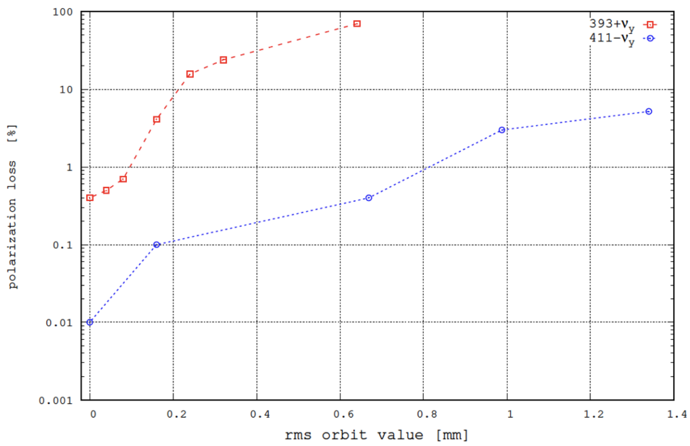

Figure 1: The polarization simulation results after crossing two intrinsic resonances in RHIC with two Siberian snakes as function of vertical rms orbit errors. Note that the vertical scale is in log scale.

There are about 10-15% polarization loss in RHIC when beam is accelerated to 255GeV. Extensive spin simulations with ZGOUBI [7] have been carried out to understand the root cause. Polarization is preserved for nominal emittance in RHIC if orbit errors are not included. However, simulations show that two snakes are not enough for polarization preservation with rms emittance of

2.5μm and vertical orbit error >0.2mm. This is due to the interference of strong intrinsic resonances and nearby imperfection resonances, or so-called overlapping resonances. As shown in Fig. 1, the polarization losses after crossing two strongest intrinsic resonances are growing with the increase of the vertical rms orbit error. The estimated vertical rms orbit error in RHIC is not smaller than 0.2mm. For a 0.2mm rms vertical orbit error, the polarization loss from the strongest resonance $393 + \nu_y$ is around 10%. It also shows that intrinsic resonances weaker than this one in general do not cause much polarization loss, unless the vertical orbit error is larger than 0.5mm. In other words, in the presence of higher than 0.2mm vertical orbit error, two Siberian snakes are not enough to preserve polarization on the ramp to 255 GeV. The reproduction of RHIC polarization loss gives us confidence of the simulation tool.

The highest resonance strength, calculated by DEPOL [8], for a particle with 10 μm normalized emittance invariant is about 0.18 below 100 GeV and about 0.45 beyond 100 GeV. As the intrinsic resonance strength is proportional to the square root of vertical emittance, the resonance strength (assuming 2.5 μm) seen in RHIC is 0.09 below 100 GeV and 0.225 beyond 100 GeV. This implies that the two snakes can preserve polarization for intrinsic resonance strength 0.09 but not for 0.225. The resonance strength threshold for 100% polarization transmission efficiency with two snakes may therefore lie somewhere between 0.09 and 0.225. In current EIC design, the vertical emittance of ion beams will be pre-cooled at the injection of HSR down to $0.5 - 1$ μm [9]. Taking the middle value of 0.75μm, the corresponding strongest resonance strength is around 0.09. This implies that two snakes may work. On the other hand, the resonance strength for He-3 is stronger and six snakes are expected to be needed. Since six snakes are needed, the simulation study was done with six snakes configuration.

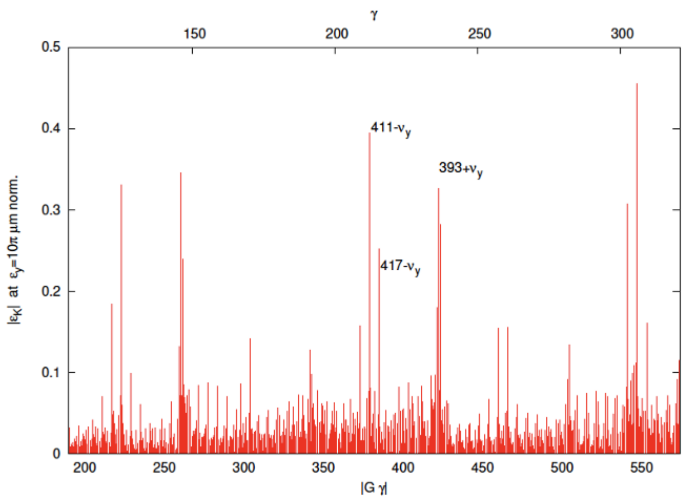

Figure 2: The resonance strength spectra for HSR lattice from DEPOL [8] for particles on 10 μm normalized emittance invariant. The systematic resonance strengths in HSR lattice are in general weaker than those in RHIC, but the non-systematic ones are stronger.

In the early version of the HSR lattice, the 3-fold symmetry of the lattice is broken. The resonance strengths of the systematic resonances, located at 393+ν_y, 411-ν_y, 231+ν_y, 255-ν_y, appear weaker in HSR(Fig. 2), compared to RHIC(Fig. 3). The opposite occurs for non-systematic

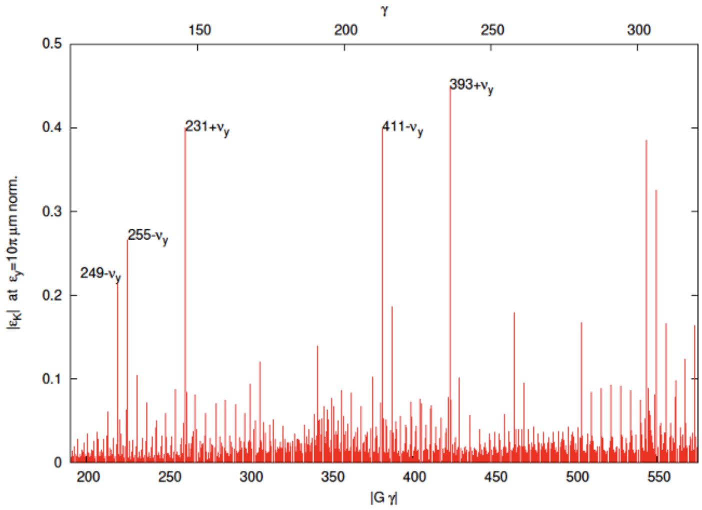

Figure 3: The resonance strength spectra for RHIC as a reference for EIC from DEPOL [8] for particles on 10 μm normalized emittance invariant.

resonances. The latter effect is an indication that the 3-periodicity of RHIC lattice is in jeopardy in its HSR evolution as shown in Fig. 2. A potential adverse configuration which results regarding resonance crossing, is the presence of wide non-systematic resonances in the direct vicinity of systematic resonances. These non-symmetrical resonances will create numerous overlapping resonance scenarios, which will make polarization preservation a challenge.

For emittance preservation and high luminosity in EIC, electron cooling at HSR injection is planned. The goal is to make the rms emittance down to 0.5-1.0 mm-mrad from 2.5 mm. The one IR HSR lattice includes six Siberian snakes, 60 deg apart, with axes at -45, +45, +135, +45, -45, +45 degrees, respectively. Lattice tunes are ν_x=28.2313, ν_y= 26.2053. Chromaticities are about 2. Ramp speed used in simulation is the nominal RHIC ramp rate $\dot{\gamma}$ = 1 (peak voltage $\hat{V}$= 68.9 kV, synchronous phase ϕ_s = 2.967 rad). Transverse densities of the bunch tracked are Gaussian with rms emittance of 2.5 μm. Momentum spread is Gaussian with rms 7×10^{-4}, truncated at 2 sigma. Simulations were done with ZGOUBI[7] for various vertical rms orbit errors for two strong intrinsic resonances at $395 + \nu_y$=421.2(Fig. 4) and $410 - \nu_y$ = 383.8(Fig. 5). 100 particles are used. The results show that six snakes preserve proton polarization with rms emittance of 2.5 mm-mrad (and small rms vertical orbit error such as 0.2mm).

With six snakes, it is expected that polarization will be preserved in HSR of EIC for 2.5μm rms emittance and ~0.2mm rms vertical orbit error.

2. He-3 Polarization in EIC and Snake Upgrade

From new EBIS source, the expected intensity is 2×10^{11} He-3 ions in 10 μs pulse and the maximum polarization is larger than 80%. Polarized He-3 source is expected to be ready in 2026. An AC dipole has been installed in the Booster to overcome intrinsic resonances. It has been tested with proton beam for its functionality [10]. Simulations show that the imperfection resonances up to $|G\gamma|$ = 10 can be corrected by existing orbit correctors (25A maximum current). AGS will

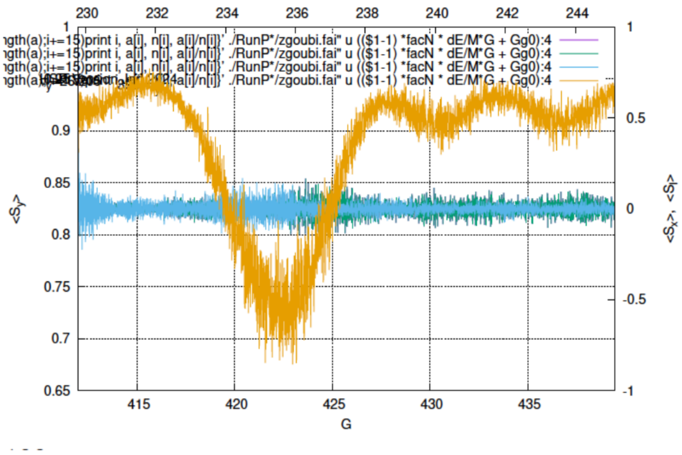

Figure 4: The simulation results of HSR lattice with six Siberian snakes for proton beam through a strong intrinsic resonance at $395 + \nu_y = 421.2$. The rms vertical orbit error is 0.65mm. The vertical polarization component is given in yellow color and left axis for scale. The horizontal and longitudinal components are given in cyan and green, while using right axis for scale. The average initial polarization is 0.945 and final polarization is 0.935 with the transmission efficiency as 0.989. Polarization is essentially preserved.

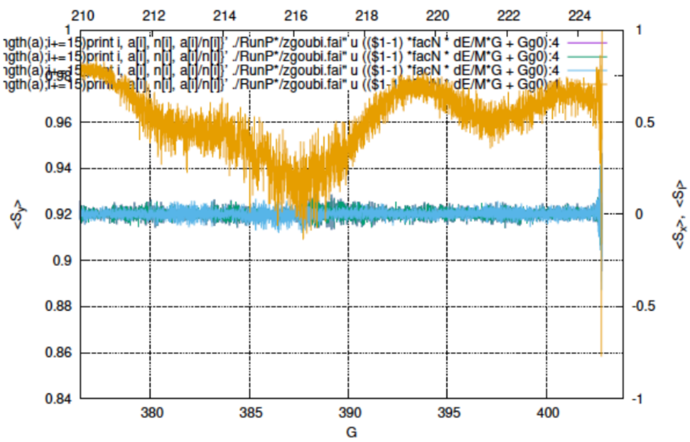

Figure 5: The simulation results of HSR lattice with six Siberian snakes for proton beam through a strong intrinsic resonance at $410 - \nu_y = 383.8$. The rms vertical orbit error is 0.18mm. The average initial polarization is 0.983 and final polarization is 0.975 with the transmission efficiency as 0.992. Polarization is essentially preserved.

run with two partial snakes, 25%+14% (due to larger |G| value, same B field gives stronger partial snake) and both betatron tunes will be put into spin tune gap(ν_x=8.95, ν_y=8.98). Tracking with 8 particles on the ellipse of $3 \times 2.5\mu$m emittance (near the edge of the beam) for 25%+14% partial snakes indicates that polarization is good before the very strong intrinsic resonance 60-ν_y as shown in Fig. 6. This extraction energy is fine for both AGS and EIC kicker strengths.

With larger |G| value, the depolarizing resonance strength in HSR is much stronger than proton case as shown in Fig. 7. Much stronger resonance strength requires more snakes. Six snakes are

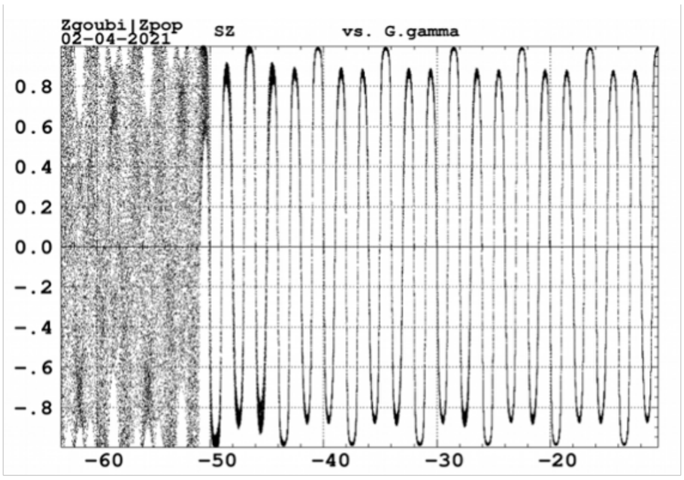

Figure 6: The simulation results of AGS with two partial Siberian snakes for He-3 beam through the whole energy range. Note that the acceleration is going from right to left due to negative G value of He-3.

planned for the HSR. In the EIC, only one hadron storage ring is needed for ion beam acceleration and storage. In this case, the spin manipulating devices from the RHIC "Blue" ring can be used in the EIC hadron storage ring. A configuration with six Siberian Snakes will be created by moving the two existing RHIC "Blue" snakes into the appropriate locations in the Hadron Storage Ring, and constructing two more snakes using the helical dipoles of the RHIC "Blue" spin rotators.

For an energy independent spin tune with multiple snakes, the simplest snake arrangement is for all snakes to be equally spaced azimuthally. The snake axis angles are $\phi = \pm 45°$ from the longitudinal axis in the local Serret-Frenet frame, ensuring, a spin tune of $\nu_{\rm spin} = 3/2$, following

$$\nu_{\rm spin} = \frac{1}{\pi}\left|\sum_{k=1}^{N_s=6}(-1)^k \phi_k\right|. \tag{1}$$

where $N_s = 6$ is the number of snakes. Due to the injection region constraint, the snake near IP6 cannot be put in the symmetric position. As such, the snake near IP12 needs to be moved. The proposed snake locations are as following with counting starting at IP12: snake1 = ϕ, snake2=$\pi/3 - \phi$, snake3 = $2\pi/3 - \phi$, snake4 =$\pi + \phi$, snake5 = $4\pi/3 - \phi$, snake6 = $5\pi/3 - \phi$, where $\phi = 0.0435$rad. In this arrangement, only snakes 1 and 4 are not in ideal locations. Ideal locations for them would be snake1 =$-\phi$, snake4 =$\pi - \phi$. Then all snakes will be separated by $\pi/3$ bending angle. Spin simulations were done for ideal snake locations and a pair of snakes with offset in RHIC lattice.

Simulations through the strongest depolarizing resonances for He-3 at 763-ν_y and 681 +ν_y in EIC lattice were done for 1000 particles with Gaussian distributions in 6D phase space as shown in Fig. 8. Realistic acceleration rate is used. The betatron tunes are $\nu_y = 26.21$ and ν_x =28.228. The rms normalized emittance for uncooled beam is $\epsilon = 2.5\mu$m in both planes and is $\epsilon = 0.5\mu$m in vertical plane for pre-cooled beam. Pre-cooling is necessary for polarization preservation even with six snakes.

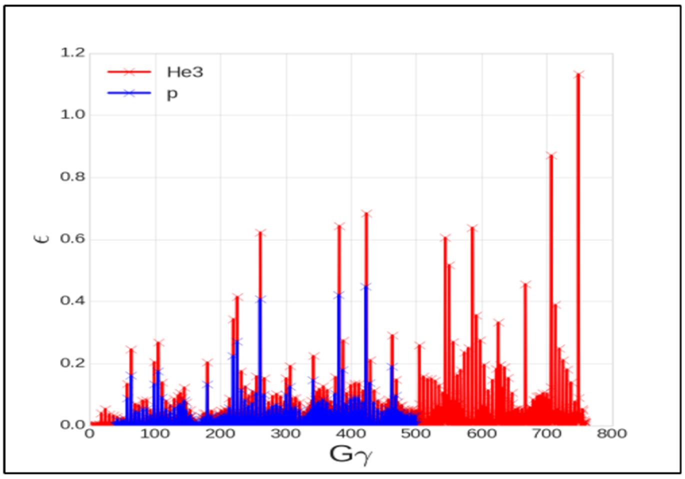

Figure 7: The resonance strength spectra for RHIC from DEPOL [8] for proton and He-3 particles on 10 μm normalized emittance invariant.

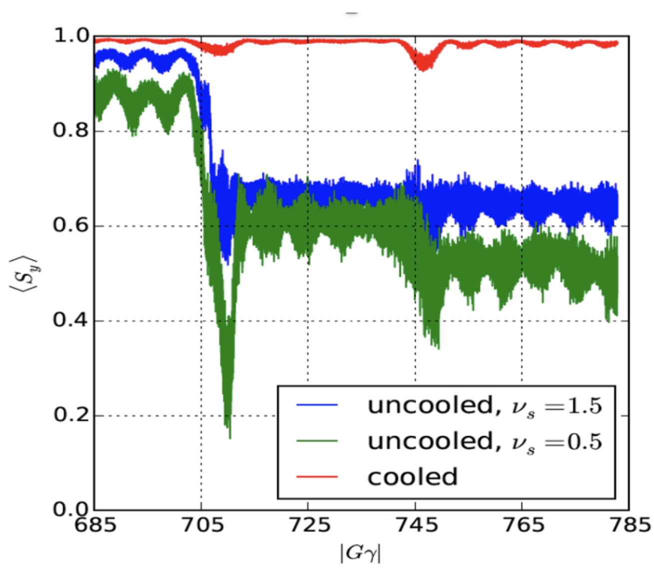

Figure 8: The simulation results of HSR ring with six Siberian snakes for He-3 beam through a strong resonance region.

3. Polarized Deuteron in HSR

Unpolarized deuteron beam has been used in RHIC during ion physics program. Present EIC physics program does not include polarized deuterons. Due to its small G value (G_d=-0.143), there are several features of polarized deuteron beam. First, a much higher magnetic field is required for spin rotation (the existing Siberian Snakes field is not feasible). However, smaller G value also means weaker resonance strengths and small number of resonances, which makes it possible to deal with individual resonances.

First of all, there will be no depolarizing resonance in the energy range of Booster and AGS.

The $G\gamma$ range of HSR is from -1.6 to -20.9. There are 19 imperfection resonances. With rms orbit error of 0.3mm, the strongest resonance strength is less than 0.0015. From the nominal ramp rate in RHIC d-Au run, the ramp rate is about $d\gamma/dt$=90/220s which corresponds to resonance crossing rate α=1.2E-7. A partial snake can be used to overcome these resonances. The required partial snake strength is 0.22%. The existing RHIC snakes are not strong enough. Adding a solenoid is a solution. 15Tm warm solenoid (0.45% partial snake) should work. As a comparison the AGS solenoidal 5% partial snake used in 1990s is 4.7Tm and 2.4m long [13]. There are 38 intrinsic resonances in the energy range. They can be overcome by a modest vertical tune jump system (0.03 unit in 50 turns). For the strongest one with $\gamma \sim$123, full spin flip can be achieved (2μm rms emittance assumed) without using tune jump system, as shown in Fig. 9.

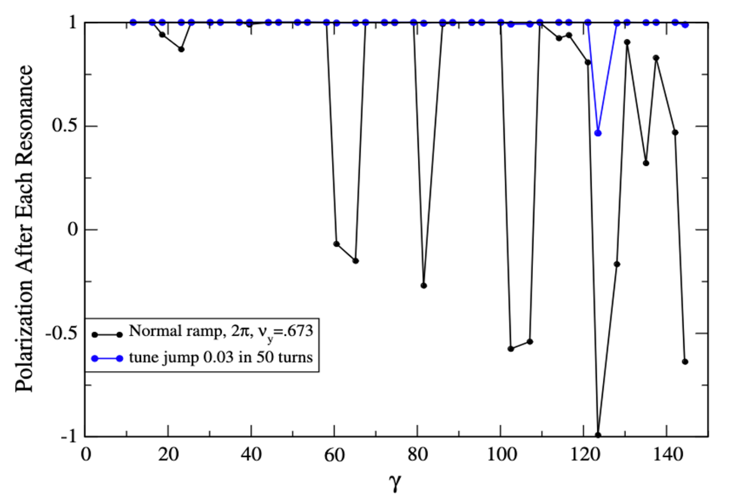

Figure 9: The polarization after each intrinsic resonance with a 2μm normalized rms emittance. Each data point represents the polarization value after crossing an intrinsic resonance. The lines between points are only drawn to guide the eye.

4. Summary

Currently, RHIC proton ring is able to deliver 60% polarization at 250 GeV for collisions with 1.8×10^{11} bunch intensity [4]. For the planned various EIC operation scenarios, AGS can deliver 67-70% polarization. Additional polarization gain would come from the newly installed pulsed skew quads system [12]. Extensive simulations have been done for protons in HSR with six snakes. Polarization can be preserved. Polarized He-3 development is expected in about two years when the source is available. Simulations show that the polarization can be preserved with six snakes for pre-cooled beam without orbit errors. With orbit errors, other optimization schemes are needed. Polarized deuteron possibility has been explored. The imperfection resonances can be overcome by a solenoid partial snake. The intrinsic resonances can be overcome with modest tune jumps.

References

[1] H. Huang, *et al.*, Phys. Rev. Lett. **99**, 154801 (2007).

[2] M. Bai, *et al.*, Phys. Rev. Lett. **96**, 174801 (2006).

[3] H. Huang, *et al.*, Phys. Rev. STAB. **17**, 081001 (2014).

[4] A. Zelenski, H. Huang, T. Roser, Proc. of PSTP 2013, 056(2013).

[5] F. Lin, *et al.*, Phys. Rev. Accel. Beams **10**, 044001 (2007).

[6] V. Schoefer, Phys. Rev. Accel. Beams **24**, 031001 (2021).

[7] F. Meot, *et al.*, Nucl. Instrum. Methods Phys. Sect. A**767**, 112(2014).

[8] E. Courant and R. Ruth, BNL report, BNL-51270(1980).

[9] S. Benson *et al.*, Low Energy Cooling for Electron Ion Collider, EIC-HDR-TN-012 (2020).

[10] K. Hock, *et al.*, Nucl. Instrum. Methods Phys. Sect. A**1059**, 168999(2024).

[11] H. Huang, *et al.*, Phys. Rev. STAB. **23**, 021001 (2020).

[12] V. Schoefer, Phys. Rev. STAB. **24**, 031001 (2021).

[13] H. Huang, *et al.*, Phys. Rev. Lett. **73**, 2982 (1994).