Reply to “Comment on ‘Uniformization of the transverse beam profile by means of nonlinear focusing method’”

Yosuke Yuri, Nobumasa Miyawaki, Tomihiro Kamiya, Watalu Yokota, and Kazuo Arakawa

Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency, 1233 Watanuki-machi, Takasaki, Gunma 370-1292, Japan

Mitsuhiro Fukuda

Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

(Received 12 February 2008; published 20 March 2008)

In order to clarify the difference of outcomes between our recent work [Y. Yuri *et al.*, Phys. Rev. ST Accel. Beams **10**, 104001 (2007)] and the work done by Los Alamos National Laboratory in the 1990s outlined in the Comment [R. E. Shafer, Phys. Rev. ST Accel. Beams **11**, 039001 (2008)], we briefly summarize the former progress of the research and development on beam uniformization by means of the nonlinear focusing method, and insist on the newness of our recent publication in this Reply.

DOI: [10.1103/PhysRevSTAB.11.039002](https://doi.org/10.1103/PhysRevSTAB.11.039002)

PACS numbers: 41.75.-i, 41.85.Ew, 29.27.Eg

In Ref. [1], we have theoretically studied uniformization of the transverse beam profile by means of the *nonlinear focusing method*. The developed formulas predict both the strength of the different nonlinear magnetic fields required for beam uniformization and the resultant width of the uniform region. The idea of beam uniformization was originally proposed by Meads Jr. in 1983 [2]. Kashy and Sherrill numerically demonstrated the formation of uniform distribution using an octupole field, considering specific parameters of a beam line [3]. Moreover, they verified that the odd-order multipole fields such as octupole and dodecapole ones are needed for uniformization of a beam with a Gaussian profile [4]. More practical studies were done extensively in the 1990s. Blind numerically studied the method for size tuning and the effect of beam jitter at a large-area target [5]. Batygin analytically calculated the nonlinear force required for production of a uniform beam in a simple beam line composed of a multipole lens and a drift space [6]. Meot and Aniel derived the octupole and dodecapole strength considering realistic beam optics [7].

Experimental approaches started also in the 1990s. The first experiment of uniform beam formation using octupole magnets was successfully carried out at Brookhaven National Laboratory [8]. The size of the uniform region was only several centimeters square and its uniformity was 7.5%. At Los Alamos National Laboratory (LANL), the beam expander system for expansion of the uniform irradiation area to 17 cm by 170 cm was designed and tested [5,9], and a special nonlinear magnet which can produce several different odd-order fields at a time was fabricated [10]. A series of the LANL work is summarized in Ref. [11]. At National Institute of Radiological Sciences, the adaptability of the nonlinear focusing method for charged-particle therapy was explored [12]. The uniformity of 4% seemed to be less suitable for this purpose. In recent years, the beam uniformization technique by means

of this nonlinear focusing method has been widely receiving attention as an alternative uniform irradiation method [13–18]. In many cases, it is employed for production of a secondary beam such as a neutron at a target, which needs severe control of the irradiation field. This method is studied also for tail reduction of nanobeams colliding in the final focusing system [19,20].

In our recent work [1], we made a step forward in the previous theoretical studies on uniformization using odd-order fields [4,6,7]. In order to realize the effect of the nonlinear magnetic fields on the beam profile, we expressed the distribution at a target using the initial distribution and well-known Twiss parameters that define the beam optics between the two positions, and then derived the strengths of all the odd-order fields required for uniformization of a beam with a Gaussian distribution. The resultant width of the uniform region was also analytically derived. Additionally, we investigated the effect of the even-order multipole fields on beam uniformization in detail, and, for the first time, demonstrated the feasibility of uniformization of a Gaussian beam using the even-order fields instead of the odd-order ones, and even an asymmetric beam, e.g., a misaligned beam, by making a combination of the even and odd-order fields, especially with the sextupole and octupole ones.

We have completed the installation of sextupole and octupole magnets for uniform beam formation at the azimuthally varying field cyclotron facility [21] of Japan Atomic Energy Agency. Recently, we have successfully formed a uniform beam in the commissioning. This experimental result will be reported elsewhere.

-
- [1] Y. Yuri, N. Miyawaki, T. Kamiya, W. Yokota, K. Arakawa, and M. Fukuda, Phys. Rev. ST Accel. Beams **10**, 104001 (2007).

- [2] P. F. Meads, Jr., IEEE Trans. Nucl. Sci. **30**, 2838 (1983).
- [3] E. Kashy and B. Sherrill, Nucl. Instrum. Methods Phys. Res., Sect. B **26**, 610 (1987).
- [4] B. Sherrill, J. Bailey, E. Kashy, and C. Leakeas, Nucl. Instrum. Methods Phys. Res., Sect. B **40/41**, 1004 (1989).
- [5] B. Blind, Nucl. Instrum. Methods Phys. Res., Sect. B **56/57**, 1099 (1991).
- [6] Y. K. Batygin, Nucl. Instrum. Methods Phys. Res., Sect. B **79**, 770 (1993).
- [7] F. Meot and T. Aniel, Nucl. Instrum. Methods Phys. Res., Sect. A **379**, 196 (1996).
- [8] N. Tsoupas, R. Lankshear, C. L. Snead, Jr., T. E. Ward, M. Zucker, and H. A. Enge, in Proceedings of the 1991 IEEE Particle Accelerator Conference, San Francisco, USA, 1991, p. 1695, <http://www.jacow.org/>.
- [9] R. E. Shafer, B. Blind, E. R. Gray, J. D. Gilpatrick, D. Barlow, and G. P. Lawrence, in Proceedings of 1997 Particle Accelerator Conference, Vancouver, British Columbia, Canada, 1997, p. 83, <http://www.jacow.org/>.
- [10] D. Barlow, R. Shafer, R. Martinez, P. Walstrom, S. Kahn, A. Jain, and P. Wanderer, in Proceedings of 1997 Particle Accelerator Conference, Vancouver, British Columbia, Canada, 1997, p. 3309, <http://www.jacow.org/>.
- [11] R. E. Shafer, Phys. Rev. ST Accel. Beams **11**, 039001 (2008).
- [12] E. Urakabe, Y. Fujita, K. Hiramoto, M. Inoue, Y. Iwashita, M. Kanazawa, A. Morita, M. Nishi, T. Norimine, A. Noda, K. Noda, H. Ogawa, T. Shirai, M. Torikoshi, M. Umezawa, and S. Yamada, Jpn. J. Appl. Phys. **38**, 6145 (1999).
- [13] S. Richter and W. Barth, in Proceedings of the 8th European Particle Accelerator Conference, Paris, France, 2002, p. 1181, <http://www.jacow.org/>.
- [14] IFMIF International Team, IFMIF Comprehensive Design Report, 2004.
- [15] J. Y. Tang, H. H. Li, S. Z. An, and R. Maier, Nucl. Instrum. Methods Phys. Res., Sect. A **532**, 538 (2004).
- [16] C. Ronsivalle, C. Cianfarani, G. Messina, G. L. Orlandi, L. Picardi, E. Cisbani, and S. Frullani, in Proceedings of the 10th European Particle Accelerator Conference, Edinburgh, Scotland, 2006, p. 2316, <http://www.jacow.org/>.
- [17] N. Tsoupas, L. Ahrens, S. Bellavia, R. Bonati, K. A. Brown, I-Hung Chiang, C. J. Gardner, D. Gassner, S. Jao, W. W. Mackay, I. Marneris, W. Meng, D. Phillips, P. Pile, R. Prigl, A. Rusek, L. Snodstrup, and K. Zeno, Phys. Rev. ST Accel. Beams **10**, 024701 (2007).
- [18] A. Bogdanov, V. Anferov, M. Ball, D. V. Baxter, V. P. Derenchuk, A. V. Klyachko, T. Rinckel, and K. Solberg, in Proceedings of 2007 Particle Accelerator Conference, Albuquerque, USA, 2007, p. 1748, <http://www.jacow.org/>.
- [19] R. Tomás, H. Braun, D. Schulte, and F. Zimmermann, in Proceedings of the 10th European Particle Accelerator Conference, Edinburgh, Scotland, 2006, p. 792, <http://www.jacow.org/>.
- [20] B. Parker, M. Anerella, J. Escallier, P. He, A. Jain, A. Marone, Y. Nosochkov, and A. Seryi, in Proceedings of 2007 Particle Accelerator Conference, Albuquerque, USA, 2007, p. 3196, <http://www.jacow.org/>.
- [21] K. Arakawa, Y. Nakamura, W. Yokota, M. Fukuda, T. Nara, T. Agematsu, S. Okumura, I. Ishibori, T. Karasawa, R. Tanaka, A. Shimizu, T. Tachikawa, Y. Hayashi, K. Ishii, and T. Satoh, in Proceedings of the 13th International Conference on Cyclotrons and their Applications, Vancouver, Canada, 1992 (World Scientific, Singapore, 1992), p. 119.