Generation of Short-Duration, High-Power heavy ion beams in BRing at HIAF

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Abstract

Maximizing beam energy deposition requires capturing the entire ion population within a single short-duration bunch to achieve peak power. Using the typical beam 238 U 35+ in the Booster Ring (BRing) at the High Intensity Heavy-Ion Accelerator Facility (HIAF) as an example, we systematically analyze the manipulation processes. Initially, four bunches generated by the RF system at harmonic number = 4 are combined into a single bunch via two distinct strategies: (i) direct adiabatic debunching followed by rebunching at = 1, and (ii) sequential 4:2:1 bunch merging. The resulting single bunch undergoes longitudinal phase space rotation for compression. By quantitatively comparing final bunch length and peak power, we identify the optimal merging scheme and provide the corresponding RF voltage profile. Furthermore, space charge effects on beam parameters are evaluated due to the high beam intensity.

Full Text

Preamble

Generation of Short-Duration, High-Power Heavy Ion Beams in BRing at HIAF

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ABSTRACT

Maximizing beam energy deposition requires capturing the entire ion population within a single short-duration bunch to achieve peak power. Using the typical 238U35+ beam in the Booster Ring (BRing) at the High Intensity Heavy-Ion Accelerator Facility (HIAF) as an example, we systematically analyze the manipulation processes. Initially, four bunches generated by the RF system at harmonic number h = 4 are combined into a single bunch via two distinct strategies: (i) direct adiabatic debunching followed by rebunching at h = 1, and (ii) sequential 4:2:1 bunch merging. The resulting single bunch undergoes longitudinal phase space rotation for compression. By quantitatively comparing final bunch length and peak power, we identify the optimal merging scheme and provide the corresponding RF voltage profile. Furthermore, space charge effects on beam parameters are evaluated due to the high beam intensity.

Keywords: Heavy ion beams; Bunch compression; HIAF; BRing; Space charge effects; High energy density physics.

1. Introduction

High energy density physics (HEDP) investigates matter under extreme conditions, primarily achieved through intense heavy ion beams. This rapidly advancing field addresses critical applications in astrophysics, fusion research, and national security, driving prioritization at leading global accelerator facilities. The Super-FRS (Super FRagment Separator) at the Facility for Antiproton and Ion Research (FAIR) serves as a primary platform for HEDP studies. In China, the Institute of Modern Physics (IMP) of the Chinese Academy of Sciences is developing a more advanced facility, the High Intensity Heavy-Ion Accelerator Facility (HIAF), to advance HEDP research.

The facility integrates key components such as a Superconducting Electron-Cyclotron-Resonance ion source (SECR), superconducting linear accelerator (iLinac), high-intensity synchrotron Booster Ring (BRing), versatile high-precision synchrometer Spectrometer Ring (SRing), and superconducting radioactive fragment separator (HFRS) connecting both rings. Designed as an integrated accelerator complex, HIAF delivers intense primary and radioactive ion beams to support multidisciplinary research in nuclear physics, atomic physics, plasma physics, and HEDP. Key parameters of the BRing are detailed in Table 1 .

As the core component of the HIAF facility, the BRing is specifically engineered to generate heavy-ion beams with record-breaking intensity and power density, primarily targeting HEDM generation. The final bunch duration of heavy ion beam at the target plays a decisive role in determining the energy deposition efficiency, where shorter bunch durations exponentially enhance the achievable energy density through inertial confinement effects. The BRing delivers 238U35+ with 3.0$\times$10^{10} particles per pulse, with energy increased from 17 MeV/u to a peak energy of 830 MeV/u, corresponding to a magnetic rigidity of 34 T·m. During beam capture and acceleration, the RF system operates with harmonic number h = 4 across a frequency sweep from 0.324 MHz to 1.789 MHz, creating four distinct ion bunches within the ring. Figure 1 [Figure 1: see original paper] illustrates the resulting phase space distribution at extraction energy, where the abscissa represents the longitudinal position and the ordinate indicates the normalized momentum spread.

To meet the stringent requirements for HEDP generation, two critical beam manipulation stages are implemented: (1) Bunch merging: coalescence of four discrete bunches into a single continuous distribution, and (2) Longitudinal compression: 90° phase space rotation to achieve sub-microsecond bunch durations. This sequential process enables the transformation of the accelerator's raw beam parameters into the extreme power densities required for HEDP experiments.

Two principal methodologies are conventionally utilized for merging four bunches into one: (1) adiabatic debunching with subsequent rebunching at harmonic number h = 1, and (2) sequential 4:2:1 merging, a two-step technique involving progressive bunch coalescence. Extensive numerical simulations were conducted to analyze these merging dynamics. The subsequent bunch compression process was thoroughly investigated, with particular focus on how merging parameters govern final pulse duration and beam power. Through rigorous parametric scanning of the RF system, time cost analysis, and detailed evaluation of beam parameters, an optimal merging protocol was established. Moreover, accounting for BRing's high-intensity beam operation, the coupling between beam intensity and longitudinal space charge effects was quantitatively evaluated, quantifying the impact of varying beam intensities on both the final bunch duration and beam power.

2. Theory

Non-adiabatic longitudinal compression generates compact bunches through rapid longitudinal phase space rotation. This process involves rapidly increasing the RF gap voltage amplitude from an initial pre-bunching value V_i to a final compression value V_f over a short ramping time t_r (where t_r   T_s, with T_s denoting the synchrotron period). The applied voltage induces a velocity gradient across the bunch: the bunch head experiences deceleration while the tail accelerates, thereby shortening the bunch duration during propagation. Following a 90° phase-space rotation, the final bunch duration approximates:

$$\sigma_{t,f} \approx \frac{A}{Z}\sqrt{\frac{V_i}{V_f}}\sigma_{\delta,i}$$

where A denotes the atomic mass, Z the charge state, V_i and V_f the initial and final RF voltages applied during the compression process, and σ_δ,i the initial relative momentum spread. In the linear regime, *σt,f is directly proportional to the square root of the ratio V_i/V_f, indicating that lower V_i and smaller $\sigma\delta$*,i yield shorter σ_t,f. However, excessively low values of V_i drive the compression process beyond linearity, causing phase-space filamentation. This manifests as beam tail formation around the core bunch, significantly increasing beam loss risks.

3. Debunching, Recapture, and Compression

The proposed scheme comprises three sequential stages: (1) adiabatic debunching of four discrete bunches into a coasting beam, (2) recapture at harmonic number 1, and (3) non-adiabatic longitudinal compression. As established in prior studies, adiabatic debunching requires gradual reduction of the RF cavity voltage amplitude at a rate much slower than the synchrotron frequency to minimize induced momentum spread. The debunching duration must be optimized carefully to balance requirements against operational cycle constraints. The principles and requirements for adiabatic debunching align with those for beam capture, with the time-dependent RF voltage profile expressed as:

$$V(t) = V_i \exp\left(-\frac{t}{\tau}\right) + V_f$$

where V_i = 4.52 kV and V_f = 0.10 kV denote initial and final RF cavity voltage amplitudes, respectively, and τ = 4.52 kV.

We systematically investigated the relationship between debunching time and root-mean-square longitudinal momentum spread through particle-tracking simulations using 238U35+ ions at 830 MeV/u. The RF voltage was adiabatically reduced from V_i = 4.52 kV to V_f = 0.10 kV over duration t_d, with the synchrotron period T_s = 7.5 s at 4.52 kV serving as the adiabaticity benchmark. Figure 2 [Figure 2: see original paper] (black line) quantifies root-mean-square longitudinal momentum spread versus debunching duration, showing $\sigma\delta$ *decreases from 10.29*\$×10⁻3*att*$_d$ = 10*μsto*8.64×*\$10^-3 at t_d = 180 s, corresponding to a 16% reduction. Notably, at t_d = 70 s (where t_d 9.3T_s),* $\sigma\delta$ = 8.99\$×10⁻3, *onlyslightlyhigherthantheasymptoticvalueof*8.64×\$10^-3 at t_d = 180 s. This supports selecting t_d = 70 s as the optimal parameter, balancing momentum spread minimization with machine cycle efficiency. Figures 3 [Figure 3: see original paper] and 4 [Figure 4: see original paper] contrast longitudinal phase-space distributions at t_d = 70 s and 120 s, respectively, with the latter exhibiting significantly reduced phase-space filamentation.

Following the primary debunching process (voltage reduction from 4.52 kV to 0.10 kV over 70 s), an additional post-debunching stage was implemented to further suppress momentum spread while the beam drifted for time t_{pd}. Here, the voltage was stabilized at V_f = 0.01 kV. Color-coded traces demonstrate momentum spread reduction compared to cases without post-debunching. Crucially, asymptotic behavior for $\sigma\delta$ *is observed when t*{pd} exceeds 4 s, reaching 8.31\$×\$10^-3 at t_{pd} = 10 s. Consequently, these operational parameters were selected.

After the debunching process, a recapture process transforms the debunched coasting beam into a bunched configuration for subsequent compression. The RF voltage profile V(t), as derived from Reference [12], is expressed by:

$$V(t) = V_i + (V_f - V_i)\left(1 - \exp\left(-\frac{t}{\tau}\right)\right)$$

where V_i and V_f represent the initial and final voltage amplitudes of the RF cavity, respectively. The recapture time t_r serves as a critical parameter that must be minimized to reduce the overall cycle duration. Upon completion of the beam recapture process, the voltage undergoes a rapid 10-microsecond ramp-up from 1.4 kV to a final V_f of 240 kV. This voltage jump is crucial for enabling effective bunch compression. The selection of V_i = 1.4 kV as the RF cavity voltage amplitude at the end of the recapture process is intentional, designed to create a bucket area 1.5 times greater than the emittance of the debunched coasting beam.

Systematic parameter studies have been extensively conducted to investigate bunch compression at the BRing, with particular emphasis on varying recapture times. Figure 6 [Figure 6: see original paper] demonstrates beam ion distribution in phase space for recapture time t_r = 25 s, and Figure 7 [Figure 7: see original paper] shows the distribution under t_r = 35 s. Simulation data demonstrate a clear correlation between recapture time and compressed beam parameters. As the recapture time increases from 25 s to 35 s, the bunch duration exhibits progressive elongation from 165 ns to 185 ns, as shown in Figure 8 [Figure 8: see original paper]. Concurrently, the beam power follows a distinct trajectory: initially climbing from 3.56 TW to a peak of 3.86 TW, then decreasing to 3.64 TW at maximum t_r. The system achieves optimal performance at two operational extremes—minimal bunch duration (165 ns at t_r = 25 s) and peak beam power (3.86 TW, corresponding to 177 ns bunch duration). Notably, the momentum spread maintains remarkable stability throughout this parameter range, fluctuating minimally around an average value of 2.55$×$10^-3. Simultaneously, the final operational efficiency demonstrates marked improvement, escalating from 0.86% to 0.93% across the tested recapture time spectrum. These interrelated phenomena are comprehensively illustrated in Figure 9 [Figure 9: see original paper].

4. 4:2:1 Bunch Merging and Compression

The method of generating a single bunch involves not only recapturing the coasting beam resulting from the debunching of four initial bunches but also incrementally combining multiple beam bunches. This method demonstrates particular effectiveness when handling even-numbered bunch configurations. For the BRing, we process four bunches post-acceleration through a 4:2:1 merging sequence: initially merging into two paired bunches before final combination into a single bunch. This multi-stage process, previously documented in our prior research, reveals through preliminary analysis that the initial 4:2 merging phase critically influences both the bunch duration and beam power characteristics of the compressed short bunch. Therefore, this study specifically focuses on how merging time and voltage in the 2:1 merging stage affect compression outcomes, with the ultimate goal of optimizing RF parameters for this 2:1 merging process.

Our simulation studies systematically evaluated the impact of merging time (16-30 s range, 1 s increments) under a fixed voltage (V = 1 kV) on beam loss, bunch duration, and beam power after compression. As illustrated in Figure 10 [Figure 10: see original paper], the total efficiency demonstrates a non-monotonic relationship with merging time, initially rising from 84.59% to a peak value of 95.66% at t = 23 s before decreasing to 91.42%. Beam loss mechanisms are primarily attributed to momentum spread exceeding the BRing's momentum acceptance limits, as detailed in Figure 10 showing momentum spread evolution. Bunch duration exhibits concave temporal dependence, decreasing from 154 ns to a minimum of 138 ns before increasing to 204 ns. Beam power evolution mirrors the efficiency trend, peaking at 5.65 TW when t = 23 s, as shown in Figure 11 [Figure 11: see original paper].

Beyond the merging time, the merging voltage is another critical optimization parameter in the 2:1 process. We performed systematic investigations across twelve voltage values spanning 0.4 kV to 1.5 kV with 0.1 kV increments. As shown in Figure 12 [Figure 12: see original paper], the bunch duration displays a positive correlation with merging voltage, whereas beam power follows an inverse trend relative to bunch duration. The minimum bunch duration of 122 ns is achieved at V = 0.4 kV, accompanied by a peak beam power of 5.65 TW.

Our comprehensive analysis of the 238U35+ ion beam at 830 MeV/u with 3×10^9 particles per pulse reveals significant technique-dependent variations in bunch duration and peak power, despite identical RF system configurations. The bunch merging technique demonstrates superior performance metrics compared to alternative methods: achieving a 30% reduction in bunch duration (122 ns vs. 177 ns), 46% enhancement in peak power (5.65 TW vs. 3.86 TW), and 54% reduction in total cost duration (48 s vs. 104 s). These quantitative results establish bunch merging as the optimal approach for single bunch generation.

5. Evaluation of Longitudinal Space Charge Effects on Bunch Compression

For the 238U35+ ion beam with projected intensities exceeding 3.0×10^{10}, longitudinal space charge effects may be considered as established in prior research. This collective effect may induce beam loss and quality degradation through modified particle dynamics. Analysis of longitudinal phase space evolution reveals that beam distribution is governed by the temporal profile of the RF electric field (voltage). The space charge contribution alters the effective voltage distribution according to:

$$V_{\mathrm{eff}}(t) = V_{\mathrm{RF}}(t) + V_{\mathrm{SC}}(t)$$

where V_{RF} denotes the external RF voltage and V_{SC} represents the space charge-induced component.

At the BRing design intensity of 3.0$\times10^{10} ions, theresultsindicatenegligiblespacechargeeffects:$
$amere 0.5 nsincreaseinbunchduration(from 122 nsto 122.5 ns)anda 0.16 TWpowerreduction(from 5.65 TWto 5.49$
$seeoriginalpaper].Subsequentanalysisacrosssevenintensitylevels(4.0\times10^{10} to 1.0\times10^{11} ions, in 1.0\times10^{10} increm$
ions while maintaining acceptable quality parameters.

6. Conclusion

The two-plane painting injection technique enables effective accumulation of 238U35+ ions in BRing, storing over 3.0$×$10^{10} ions per pulse from the iLinac at 17 MeV/u. Subsequent acceleration employs a fourth-harmonic alloy-core loaded high-frequency cavity. The accelerated beam then executes a 4:2:1 hierarchical merging protocol, systematically combining four bunches into one. Final longitudinal compression via non-adiabatic processing achieves optimal beam characteristics. This integrated approach yields a high-performance 238U35+ ion beam with 122.5 ns bunch duration and 5.49 TW peak power, establishing BRing as a premier facility for heavy-ion beam applications.

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References

[1] P. Spiller, K. Blasche, B. Franczak, M. Kirk, P. Hülsmann, C. Omet, S. Ratschow, J. Stadlmann, Accelerator plans at GSI for plasma physics applications, Nuclear Instruments and Methods in Physics Research Section A 544 (2005) 117-124.
[2] J.C. Yang, J.W. Xia, G.Q. Xiao, H.S. Xu, H.W. Zhao, X.H. Zhou, X.W. Ma, Y. He, L.Z. Ma, D.Q. Gao, J. Meng, Z. Xu, R.S. Mao, W. Zhang, Y.Y. Wang, L.T. Sun, Y.J. Yuan, P. Yuan, W.L. Zhan, J. Shi, W.P. Chai, D.Y. Yin, P. Li, J. Li, L.J. Mao, J.Q. Zhang, L.N. Sheng, High Intensity heavy ion Accelerator Facility (HIAF) in China, Nuclear Instruments and Methods in Physics Research Section B 317 (2013) 263-265.
[3] H.W. Zhao, L.T. Sun, J.W. Guo, W.H. Zhang, W. Lu, W. Wu, B.M. Wu, G. Sabbi, M. Juchno, A. Hafalia, E. Ravaioli, and D.Z. Xie, Superconducting ECR ion source: From 24-28 GHz SECRAL to 45 GHz fourth generation ECR, Review of Scientific Instruments 89, 052301 (2018) 052301-1-10.
[4] Z.J. Wang, Y. He, H. Jia, S.H. Liu, C. Li, X.B. Xu, B. Zhang, W. Wu, H.W. Zhao, CONCEPTUAL DESIGN OF SUPERCONDUCTING HEAVY ION LINEAR INJECTOR FOR HIAF, Proceedings of LINAC2012 (2012) 561-563.
[5] B. Wu, J.C. Yang, J.W. Xia, X.L. Yan, X.J. Hu, L.J. Mao, L.N. Sheng, J.X. Wu, D.Y. Yin, W.P. Chai, G.D. Shen, W.W. Ge, G. Wang, H. Zhao, S. Ruan, X.W. Ma, M. Wang, S. Litvinov, W.Q. Wen, X.C. Chen, R.J. Chen, M.T. Tang, W. Wu, C. Luo, T.C. Zhao, C.F. Shi, X. Fu, J. Liu, L. Liang, The design

of the Spectrometer Ring at the HIAF, Nuclear Instruments and Methods in Physics Research, A 881 (2018) 27-35.
[6] L.N. Sheng, X.H. Zhang, J.Q. Zhang, J.C. Yang, Z.Y. Sun, L.J. Mao, W. Wu, D.Y. Yin, S. Ruan, G.D. Shen, W.P. Chai, M. Wang, X.W. Ma, X.H. Zhou, J.W. Xia, H.W. Zhao, G.Q. Xiao, Ion-optical design of High energy FRagment Separator (HFRS) at HIAF, Nuclear Instruments and Methods in Physics Research Section B 469 (2020) 1-9.
[7] YE YanLin, YANG XiaoFei, LIU Yang & HAN JiaXing, Radioactive ion beam physics related to HIAF, SCIENTIA SINICA Physica, Mechanica&Astronomica, 50, 112003 (2020) 112003-1-10.
[8] ZHOU XiaoHong, ZHANG ZhiYuan, GAN ZaiGuo, XU FuRong & ZHOU ShanGui, Research program of superheavy elements and nuclides based on HIAF, SCIENTIA SINICA Physica, Mechanica&Astronomica, 50, 112002 (2020) 112002-1-19.
[9] GUO Bing, LIU WeiPing, TANG XiaoDong, LI ZhiHong & HE JianJun, Research program of nuclear astrophysics based on the HIAF, SCIENTIA SINICA Physica, Mechanica&Astronomica, 50, 112007 (2020) 112007-1-14.
[10] MA XinWen, ZHANG ShaoFeng, WEN WeiQiang, YANG Jie, ZHU XiaoLong, QIAN DongBin, YAN ShunCheng, ZHANG PengMing, GUO DaLong, WANG HanBing & HUANG ZhongKui, Atomic physics at the HIAF under extreme conditions: QED effects from strong Coulomb fields to beyond Schwinger limits, SCIENTIA SINICA Physica, Mechanica&Astronomica, 50, 112008 (2020) 112008-1-15.
[11] ZHAO YongTao, ZHANG ZiMin, CHENG Rui, HOFFMANN Dieter, MA BuBo, WANG YouNian, WANG YuYu, WANG Xing, DENG ZhiGang, REN JieRu, LIU Wei, QI Wei, QI Xin, SU YouWu, DU YingChao, LI FuLi, LI JinYu, YANG Jie, YANG JianCheng, YANG Lei, XIAO GuoQing, WU Dong, HE Bin, SONG YuanHong, ZHANG XiaoAn, ZHANG ShiZheng, ZHANG Lin, ZHANG Ya, ZHANG YanNing, CHEN BenZheng, CHEN YanHong, ZHOU Zheng, ZHOU XianMing, ZHOU WeiMin, ZHAO HongWei, ZHAO QuanTang, ZHAO ZongQing, ZHAO XiaoYing, HU ZhangHu, WAN Feng, LI JianXing, XU ZhongFeng, GAO Fei, TANG ChuanXiang, HUANG WenHui, CAO ShuChun, CAO LeiFeng, SHENG LiNa, KANG Wei, LEI Yu & ZHAN WenLong, High-energy-density physics based on HIAF, SCIENTIA SINICA Physica, Mechanica&Astronomica, 50, 112004 (2020) 112004-1-23.
[12] S. Y. LEE, Accelerator Physics. 2nd Ed. Singapore, World Scientific, 1999, pp. 242-243.
[13] D. Y. Yin, J. Liu, G. D. Shen, H. Du, J. C. Yang, L. J. Mao, F. C. Cai, and W. P. Chai, Longitudinal Beam Dynamics for the Heavy-Ion Synchrotron Booster Ring at HIAF, Laser and Particle Beams.
[14] J. Liu, J.C. Yang, J.W. Xia, D.Y. Yin, G.D. Shen, P. Li, H. Zhao, S. Ruan, B. Wu, CISP: Simulation Platform for Collective Instabilities in the BRing of HIAF project, Nuclear Instruments and Methods in Physics Research Section A 881 (2018) 36-43.
[15] B. Zipfel, H. Klingbeil, U. Laier, K.-P. Ningel and C. Thielmann, 4:2:1 Bunch Merging in SIS18, GSI SCIENTIFIC REPORT 2010.

[16] H. Hotchi, M. Kinsho, K. Hasegawa, N. Hayashi, Y. Hikichi, S. Hiroki, J. Kamiya, K. Kanazawa, M. Kawase, F. Noda, M. Nomura, N. Ogiwara, R. Saeki, P. K. Saha, A. Schnase, Y. Shobuda, T. Shimada, K. Suganuma, H. Suzuki, H. Takahashi, T. Takayanagi, O. Takeda, F. Tamura, N. Tani, T. Togashi, T. Ueno, M. Watanabe, Y. Watanabe, K. Yamamoto, M. Yamamoto, Y. Yamazaki, H. Yoshikawa, and M. Yoshimoto, Beam commissioning of the 3-GeV rapid cycling synchrotron of the Japan Proton Accelerator Research Complex, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 12 (2009) 040402-1-040402-22.
[17] G.F. Qu, W.P. Chai, J.W. Xia, J.Ch. Yang, H. Du, Zh.Sh. Li, W.W. Ge, W. H. Zheng, P. Shang, Two-plane painting injection scheme for BRing of HIAF, Nuclear Science and Techniques 28 (2017).
[18] A. V. Eliseev, I. N. Meshkov, V. A. Mikhailov, and A. O. Sidorin, Longitudinal Dynamics of 197Au32+ and 197Au79+ Ions in NICA Injection Chain, Physics of Particles and Nuclei Letter 7(7) (2010) 473-477.
[19] Oliver Boine-Frankenheim, Space charge effects in bunches for different rf wave forms, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 8, 034201 (2005).

Note: Figure translations are in progress. See original paper for figures.