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# EXPERIMENTALLY VERIFIED REDUCTION OF LOCAL REFLECTION OF TRAVELING-WAVE ACCELERATING STRUCTURE BY OUTPUT COUPLER UNDERCOUPLING

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*Abstract*

Hefei Advanced Light Facility (HALF) injector comprises 40 S-band 3-meter traveling wave accelerating structures, capable of delivering electrons of full energy 2.2 GeV into the storage ring. To mitigate the emission degradation caused by dipole and quadrupole fields in the coupler cavity, the coupler design incorporates a racetrack and a short-circuit waveguide to eliminate this impact. This article presents an introduction to design of the traveling wave structure. As an alternative to the pull-bead method, use an undercoupling output coupler pre-test method. We performed tuning and preliminary measurements on accelerating structure, resulting in meeting the single-cell phase deviation and accumulated phase deviation requirements of the project objectives while maintaining good measurement consistency.


## INTRODUCTION

Hefei Advanced Light Facility is the fourth generation of vacuum ultraviolet diffraction limited storage ring light source[1]. Its injector includes a pre-injector and a main accelerating section, which respectively increase the particle beam energy to 120 MeV and 2.2 GeV. The full-energy electron beam at the injector outlet is injected into the 480 m storage ring to achieve 85 pm rad. Compared with the third-generation light source, it reaches the diffraction limit in both horizontal and vertical directions[2,3].

There are 40 three-meter equal gradient accelerating structures that make up the linear accelerator. For every 3-meter equal gradient accelerating structure, the average acceleration gradient is about 20 MV/m. The injector system operates at a microwave frequency of 2856 MHz.

Some coupler designs have been compared to reduce the multipole components[4-7]. Even though quasi-symmetric single-feed racetrack couplers have weaker dipole component suppression than dual-feed racetrack-shaped couplers, quasi-symmetric single-feed racetrack couplers are still preferred because of their straightforward design and the possibility of HALF upgrade requirements being met.

Kyhl's method and Kroll's method are often used in the design to optimize the matching between the coupler and regular cells[8-10]. This article demonstrates the viability of this method through experiments by combining the Kroll's and Kyhl's methods and using undercoupling as the foundation for output coupler testing.

Parameters of accelerating structure in HALF injector have already introduced in previous articles[11]. This paper primarily presents the undercoupling-based coupler design and testing process. The constructed and tuned full-scale accelerating structure's RF properties were measured, and the tuning outcomes in actual conditions were displayed.

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## COUPLER DESIGN

### *Multipole Components*

The coupler cavity uses two circles with offset centers to form a structure similar to a racetrack. At the same time, a short-circuit waveguide of length *SC* is connected with the same coupling slot width below the coupler cavity to form a quasi-symmetrical structure. In short, the coupler design adopts a racetrack and a short-circuit waveguide structure to eliminate the dipole and quadrupole components caused by the input and output couplers[7,8].

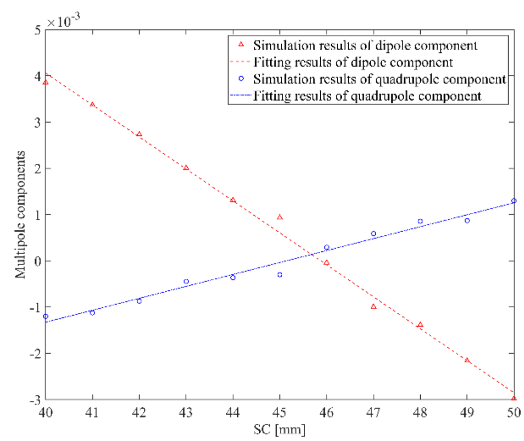


Figure 1: The effect of *SC* variation on multipole components when Rt and other dimensions fixed.

Taking the optimization process of the input coupler multipole components as an example, as shown in Fig. 1. After selecting the appropriate coupling slot width *w* and coupling cavity radius *Rc*, the quadrupole component of the coupler is mainly affected by the cavity wall offset *Rt* and the dipole component is mainly affected by the short-circuit waveguide length *SC*. When changing the length of *SC* to find a point where the dipole component is zero, it will also have an impact on the quadrupole component. Since the impact is negligible, it is reasonable to assume that the two parameters' adjustments are independent of one another. So at least two rounds of iteration are needed to obtain a better solution.

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### Local Reflection

For Kyhl's method, coupling coefficient $\beta$ and frequency deviation $\Delta f$ can be expressed as

$$\Delta f = \sqrt{f_1 f_2}\sqrt{\frac{f_2\,tan(\frac{\varphi_2}{2}) - f_1\,tan(\frac{\varphi_1}{2})}{f_1\,tan(\frac{\varphi_2}{2}) - f_2\,tan(\frac{\varphi_1}{2})}} - \frac{(f_{\pi/2} + f_{\theta_0})}{2}$$

$$\beta = \frac{(f_1^2 - f_2^2)\,tan(\frac{\varphi_1}{2})\,tan(\frac{\varphi_2}{2})}{(f_1\,tan(\frac{\varphi_2}{2}) - f_2\,tan(\frac{\varphi_1}{2}))(f_{\pi/2} - f_{\theta_0})\,tan\,\theta_0}$$

Where $f_1, f_2$ is any two frequencies, $\varphi_1$,$\varphi_2$ is the phase shift corresponding to two frequencies, $f_{\pi/2}$ is the $\pi/2$ mode frequency, $f_{\theta_0}$ is the operating mode frequency, $\theta_0$ is the operating mode.

For the design of input coupler with input energy effect, Kyhl's method is suitable. But when an output coupler with a constant-gradient accelerating structure is developed using Kyhl's method, the power input direction is different from the real scenario, therefore the matching result is not optimal. For now, the output coupler design must follow Kroll's method. The calculation formula of the local reflection coefficient $R$ is

$$R = \frac{([2\sin(\psi) - j\Delta(z)]/[2\mathrm{Sin}(\psi) + j\Delta(z)])}{\exp(2j\varphi)}$$

Where $\Delta(z) = [E_c(z+P) - E_c(z-P)]/E_c(z)$ ,$E_c(z)$ is the vector field at the position z can be obtained directly from CST[12]. $\psi = \mathrm{acos}\,(\Sigma(z)/2)$ is the phase advance per-cell, $\Sigma(z) = [E_c(z+P) + E_c(z-P)]/E_c(z)$. When $|R|$=0, the local reflection of the output coupler is 0 and design is completed at this time.

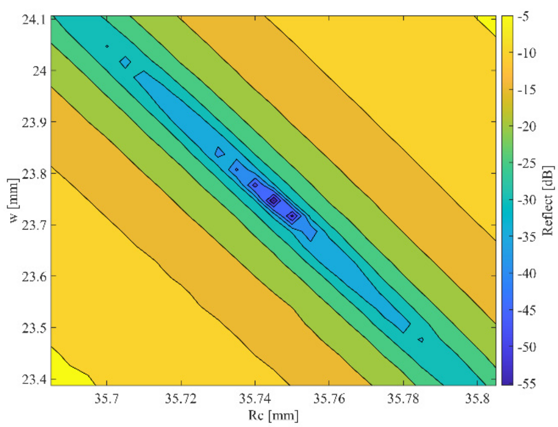


Figure 2: The local reflection coefficient changes with two dimensions.

The change of the local reflection coefficient $|R|$ of the output coupler with the coupling slot width $w$ and the coupling cavity radius $Rc$ is shown in Fig. 2. The minimum value is located at $w$ is 23.747 mm and $Rc$ is 35.745 mm. At this time, the local reflection coefficient $|R|$ is -55 dB. The coupling cavity radius $Rc$ can be adjusted within a certain range. When $w$ is fixed, the minimum $|R|$ that can be achieved by adjusting $Rc$ is determined. Choosing the minimum value of $w$ can ensure the best tolerance for machining errors.

The coupler processing effect in terms of microwaves can be first determined by pre-testing before welding, and if the inaccuracy is significant, it can be reprocessed. The measurement of the local reflection coefficient $R$ uses the bead-pull method, which requires accurate positioning of the center of the cavity, which is inconvenient for HALF projects. The different dimensions in Fig. 2 are simulated according to Kyhl's method, $\beta$ and $\Delta f$ are used as the basis for judging the current local reflection coefficient |R|. Figure 3 shows that when the coupling coefficient of the output coupler is guaranteed to be 0.947 and the frequency deviation is 0.011 MHz, it can be considered that the local reflection coefficient reaches the design value. After the deviation of the pre-test results meets the requirements, the entire structure (regular cells and coupler) will be welded. The accelerating structure can be utilized and microwave performance can be enhanced under undercoupling conditions, as shown in Fig. 3, even when output coupler design is done using Kyhl's method.

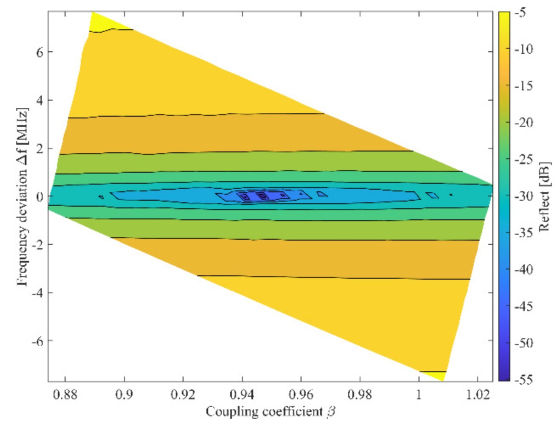


Figure 3: The local reflection coefficient changes with coupling coefficient $\beta$ and frequency deviation $\Delta f$.

## RF MEASUREMENT

Three full-scale accelerating structures have been fabricated and tuned at the National Synchrotron Radiation Laboratory. The output coupler of accelerating structure #1 was built using Kyhl's method, while accelerating structures #2 and #3 were designed using Kroll's method. However, during the actual test process, the three accelerating structures all used the Kyhl's method to determine the output coupler matching state based on coupling coefficient $\beta$ and frequency deviation $\Delta f$.

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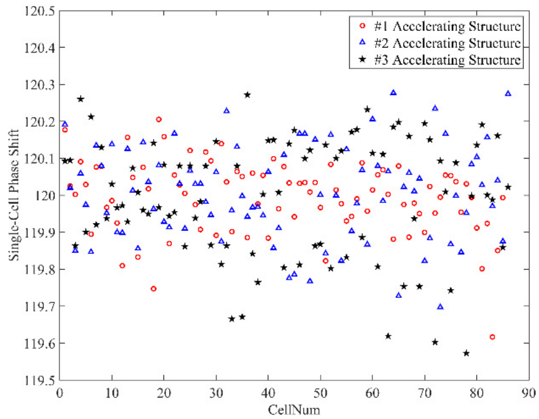


Figure 4: Single-cell phase shift of three full-scale accelerating structures.

Nodal-shift method is used to tune HALF regular cells, which needs to ensure the matching of the input coupler. First, Kyhl's method is used to calculate $\beta$ and $\Delta f$ of the input coupler. The subsequent cavity chain can be tuned when the coupling coefficient is 1 and the frequency deviation is adjusted to be close to 0 MHz. Nodal-shift method is mainly based on a single-cell phase shift, which is equal to half of the reflection coefficient $S_{11}$ phase difference between two neighboring cells. The forward wave phase also happens to be the phase that really acts on the particles. After tuning the accelerating structure, single-cell phase shift, measured cell by cell and shown in Fig. 4, were within 120±0.5 degree.

The matching of the output coupler does not affect the single-cell phase shift measured by this method because of the short-circuit surface. But it will affect the standing wave ratio of the full-scale accelerating structure. Figure 5 is the measured standing wave ratio of the #3 acceleration structure, which shows that it is feasible to use the calculated undercoupling coupling coefficient as the basis for output coupler matching.

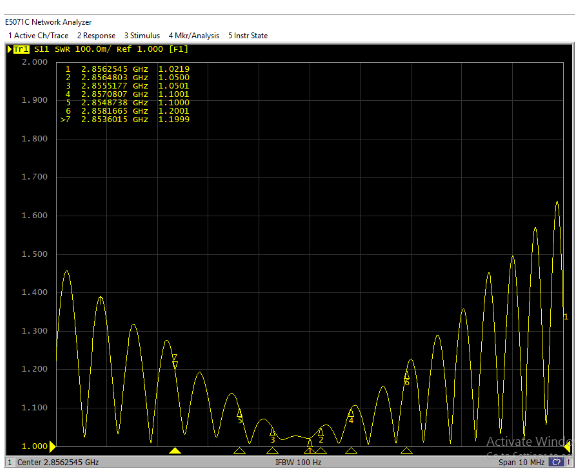


Figure 5: Standing wave ratio of the #3 accelerating structure.

## CONCLUSION

Three full-scale accelerating structure for HALF was fabricated and tuned in the past one year. We have verified in the actual accelerating structure that it is feasible to use the undercoupled coupling coefficient calculated by Kyhl's method as the basis for output coupler matching. The test results meet the design requirements, and the production and testing of the next accelerating structures will be completed according to the design of #2 and #3.

## REFERENCES

[1] Z. Sun., *et al.*, "Construction of Hefei advanced light facility begins", *The Innovation*, September 19, 2023. doi:10.1016/j.xinn.2023.100514

[2] Z. Bai., *et al.*, "A Modified Hybrid 6BA Lattice for the HALF Storage Ring" , 2021. doi:10.18429/JACoW-IPAC2021-MOPAB112

[3] M. Eriksson., *et al.*, "Diffraction-limited storage rings - a window to the science of tomorrow", *Journal of synchrotron radiation* 21 Pt 5 (2014): 837-42. doi:10.1107/S1600577514019286

[4] Z. Li *et al.*, "Coupler Design for the LCLS Injector S-Band Structures", *in Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper TPPT031, pp. 2176-2178. doi: 10.1109/PAC.2005.1591048.

[5] C. Suzuki, N. Akasaka, and T. Shintake, "Input Coupler Design for C-Band Accelerating Structure", *in Proc. PAC'97*, Vancouver, Canada, May 1997, paper 3W008, pp. 536-538. doi:10.1109/PAC.2005.1591048

[6] H. Heo *et al.*, "Development of an S-band accelerating structure with quasi-symmetric single-feed racetrack couplers", *J. Korean Phys. Soc.*, vol. 66, no. 6, pp. 905~914, March 2015. doi:10.1063/1.4827080

[7] M. D. Forno *et al.*, "Theoretical and experimental analysis of a linear accelerator endowed with single feed coupler with movable short-circuit", *Rev. Sci. Instrum*, no. 84, p. 114701, Nov. 2013. doi:10.1063/1.4827080

[8] N. Kroll *et al.*, "Applications of Time Domain Simulation to Coupler Design for Periodic Structures", *arXiv: Accelerator Physics (2000)*. doi:10.2172/765007

[9] E. Westbrook, "Microwave Impedance Matching of Feed Waveguides to the Disk Loaded Accelerator Structure Operating in the 2pi/3 Mode", 1963.

[10] S. Zheng, "Quantitative Analysis of Coupler Tuning", *High Energh Physics and Nuclear Physics,* 2001.

[11] F. Wu, J. Pang, S. Zhang, and Y. Wei, "Development of an S-band accelerating structure for Hefei Advanced Light Source facility", *in Proc. IPAC'23*, Venice, Italy, May 2023, pp. 2980-2982. doi:10.18429/JACoW-IPAC2023-WEPA135

[12] C. S. SUITE, "Cst studio suite 2020," (2020).