Broad Band Energy Science Research Section

T. Kii, Associate Professor
F. Kin, Assistant Professor

1. Introduction

We are engaged in research aimed at new applications of energy over a wide range of spatiotemporal scales. For magnetic field energy and plasma energy, we are working on establishing powerful and precise magnetic field control methods, pioneering new local high field and strong gradient applications, optimizing fusion plasma confinement by magnetic fields, and clarifying plasma transport phenomena.

2. Generation of strong periodic magnetic field

Synchrotron radiation is produced when charged particles are accelerated. If the acceleration is periodically applied by a device that generates a periodic magnetic field, so called an undulator, intense synchrotron radiation can be obtained via interference. Therefore generation of strong and precise periodic magnetic field is quite attractive to develop high performance future synchrotron light sources. The resonant wavelength of the emitted radiation from planer undulator λ_R can be expressed using period length of the undulator λ_U, energy of the electron beam E, and the maximum transverse magnetic field strength of the undulator B_0 as following equations (1) and (2).

$$\lambda_R[\text{Å}] = \frac{\lambda_U}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \approx 13.056\frac{\lambda_U[\text{cm}]}{(E[\text{GeV}])^2}\left(1+\frac{K^2}{2}\right) \quad (1),$$

$$K = \frac{e\cdot B_0\cdot\lambda_U}{2\pi\cdot m_0 c} \approx 93.36 B_0[T]\cdot\lambda_U[m] \quad (2).$$

Here, γ is the Lorentz factor, K is the undulator parameter which determines property of radiation, e is the charge of the electron, m_0 is the mass of electron, and c is the speed of light. The unit of wavelength is Å, undulator period length is cm, electron energy is GeV, and magnetic field is Tesla respectively. According to Eq. (1), use of high energy electron beam is essential to generate short wavelength synchrotron lights. Thus, high brightness hard X-ray higher than 10 keV, which play an important role in material science, has been provided mainly at 6-8 GeV-class large synchrotron radiation facilities such as SPring-8 or high-energy linac facilities such as SACLA. In order to increase usability of the hard X-ray, new innovative technology for generation of hard X-rays in a compact and energy-saving 3 GeV-class accelerator facilities is desired. Therefore, we focused on bulk superconductors, which can handle ultra-high currents, and have been working on an innovative undulator that enable to generate hard X-ray even at the 3 GeV-class accelerator facility.

The new undulator consists of stacked bulk high critical temperature superconductor array and a 6 T superconducting solenoid magnet. In this year, we have developed a hybrid array structure consisting bulk GdBaCuO superconductor and vanadium permendur. Photograph of the new undulator prototype and the hybrid array is shown in fig. 1, and on axis undulator field measured at 10 K is shown in fig. 2. This is the world highest level of the periodic magnetic field.

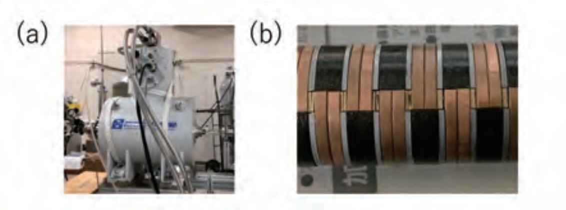

Fig. 1 (a) Photograph of the new unduloator prototype and (b) the new hybrid stacked array.

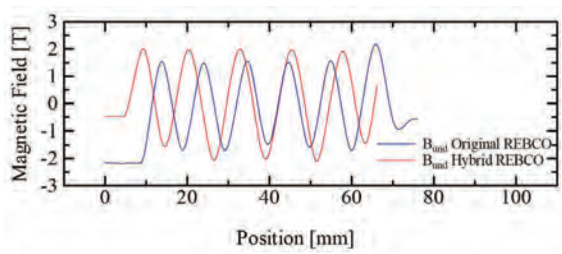

Fig. 2 Unduloator field using the hybrid array of GdBaCuO bulk super conductor and vanadium permendur (red line: Hybrid REBCO) is stronger than that of conventional GdBaCuO bulk superconductor array (blue line: Original REBCO). Fluctuation of peak field strength is slightly reduced.

3. Direct sampling ECE radiometer for investigate avalanching transport in magnetized plasmas

The magnetic confinement nuclear fusion is one of the promising energies to realize a sustainable society. Over many years, the study of plasma confinement has been the central issue of magnetic fusion research. The widely known problem is called power degradation: the degradation of energy confinement time (τ_E) against heating power (P), i.e., $\tau_E \propto P^{-0.6\pm0.1}$. Due to the power degradation, the plasma heating for achieving fusion reaction becomes inefficient. The origin of power degradation is caused by turbulence, which is present a broad range of scales. Although the variety of dynamics due to the nonlinearity of turbulence makes the system complex, the recent studies predict the significant amount of avalanching transport, which is based on the self-organized criticality [1,2]. In this year, we have work on the study of turbulence and avalanching transport in the experimental device, Heliotron J.

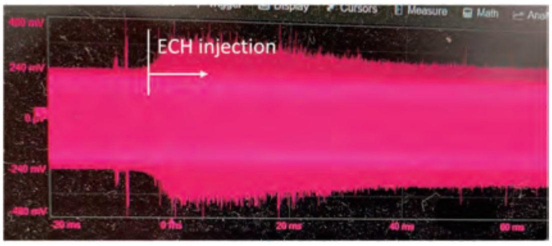

Fig. 3 A waveform of ECE obtained by the GHz sampling DSO.

The electron cyclotron emission (ECE) is one of the promising diagnostics to measure electron plasma temperature (T_e). Because avalanching transport ranges from micro to macro scale, the high spatial resolution is necessary for the measurement. In this year, we tested the direct sampling of the intermediate frequency (IF) of ECE radiometry. This technique has advantages to the previous filter-bank type of radiometer in the point that the spatio-temporal resolution and signal-to-noise ratio (SNR) can be adjusted after the data acquisition [3]. The GHz sampling digital storage oscilloscope (DSO) with a sampling rate of 80GHz, a band width of 36GHz and a record length of 2Gpts are tested for the measurement. At the front-end, the local oscillator of 56GH is used for down-converting the radio frequency (RF) waves to IF with single-side-band. Thus, the RF waves from 56GHz to 98GHz (f_{IF} = 0-36GHz) are simultaneously measured by the DSO (Fig. 3). The relation between spatio-temporal resolution and SNR, which is based on the radiometer equation, was confirmed from the measurement data. We also investigated the effect of noise from electron cyclotron heating (ECH). The correlations between ECH radiation (70GHz) and other IF channels show no-correlation, which indicates the ECE system is not directly suffered by the ECH noise.

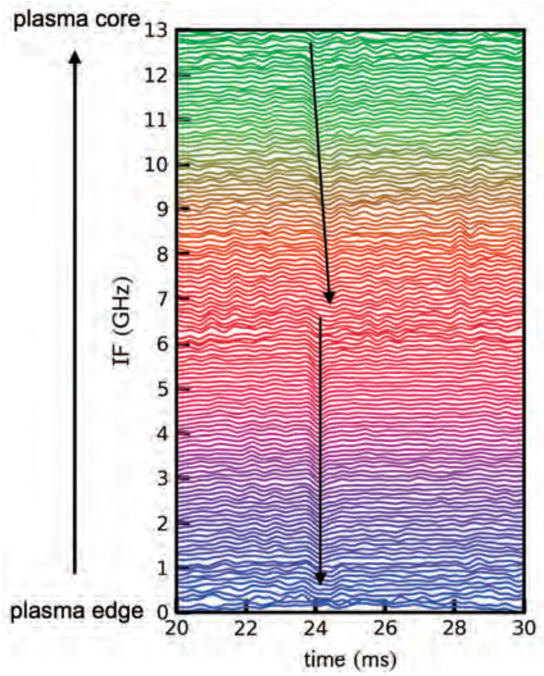

Fig. 4 Temporal evolution of direct sampling ECE radiometer observed in Heliotron J. The large-scale avalanche-like dynamics is indicated as the black arrow.

Figure 4 shows the spatio-temporal evolution of ECE fluctuations. The interval of IF frequency, which corresponds to the spatial location, is set to 0.1 GHz. This is roughly equivalent to the spatial resolution of $\Delta(r/a)$ ~ 0.008. As shown in Fig. 4, the large scale (almost half of the plasma radius) of avalanche-like events are shown with slowly propagating (~160 m/s) and rapidly propagating (almost simultaneous) features. The temporal dynamics of avalanches are found as a signature of *1/f* type of ECE spectrum. We also found the *1/f* spectrum is increased against the increases of heating power, which suggest the cause of power degradation.

Acknowledgement

These researches were partly supported by grants from JSPS KAKENHI (JP22H03870) and (20K14446).

References

[1] W. Wang et al., *Nucl. Fusion*, **60**, 066010 (2020).
[2] F. Kin et al., *Nucl. Fusion*, **63**, 016015 (2023).
[3] W. A. Bongers et al., *Rev. Sci. Instrum.*, **82**, 063508 (2011).

Financial Support

Grant-in-Aid for Scientific Research
紀井俊輝, 基盤研究(B), バルク超伝導体アンジュレータへの電子ビーム入射

金史良, 若手研究, トカマクプラズマにおける内部輸送障壁の大域的応答の解明

Publications

Y. Uozumi, T. Furuta, Y. Yamaguchi, H. Zen, T. Kii, H. Ohgaki, E. Velicheva, V. Kalinnikow, Z. Tsamalaidze, P. Evtoukhovitch, Study of crystalline scintillator response with development of single-electron beam of 2–6 MeV at KU-FEL, Journal of Nuclear Science and Technology, 2023

H. Ohgaki, K. Ali, T. Kii, H. Zen, M. Fujimoto, Y. Taira, T. Hayakawa, T. Shizuma, Generation of Flat-Laser Compton Scattering Gamma-ray Beam in UVSOR, IPAC2022 - Proceedings, THPOMS046, 2022

全炳俊, 紀井俊輝, 大垣英明, 京都大学自由電子レーザ施設の現状, Proceedings of the 19th Annual Meeting of Particle Accelerator Society of Japan, 1079-1083, 2023

紀井俊輝, 富田優, 赤坂友幸, バルク MgB2 を用いた超伝導アンジュレータ試験機の開発, Proceedings of the 19th Annual Meeting of Particle Accelerator Society of Japan, 545-547, 2023

H. Arakawa, M. Sasaki, S. Inagaki, M. Lesur, Y. Kosuga, T. Kobayashim F. Kin, T. Yamada, Y. Nagashima, A. Fujisawa, K. Itoh, Formation Process of a Solitary Vortex in a Zonal FlowDrift-Wave Dynamics, Plasma and Fusion Research, 17, 1301106, 2022

F. Kin, K. Itoh, T. Bando, K. Shinohara, N. Oyama, M. Yoshida, K. Kamiya, S. Sumida, Experimental evaluation of avalanche type of electron heat transport in magnetic confinement plasmas, Nuclear Fusion, 63, 1, 016015, 2023

Presentations

紀井俊輝, 富田優, 赤坂友幸, バルク MgB_2 アレイを用いた周期交替磁場の生成, 2022 年度第 103 回春季低温工学・超伝導学会研究発表会, タワーホール船堀, 2022.6.21

大垣英明, Khaled Ali, 紀井俊輝, 全炳俊, 早川岳人, 静間俊行, 藤本将輝, 平義孝, Generation OF Flat-Laser Compton Scattering Gamma-Ray Beam in UVSOR: Simulation Study, 日本原子力学会 2022 年秋の大会, 茨城大学日立キャンパス, 2022.9.8

全炳俊, 紀井俊輝, 大垣英明, 京都大学自由電子レーザ施設の現状, 第 19 回日本加速器学会年会, Online, 2022.10.18-19

紀井俊輝, 富田優, 赤坂友幸, バルク MgB2 を用いた超伝導アンジュレータ試験機の開発, 第 19 回日本加速器学会年会, Online, 2022.10.18-19

大垣英明, 全炳俊, 紀井俊輝, 早川岳人, 静間俊行, 平義隆, 藤本将輝, アリ カレッド, UVSOR における F-LCS ガンマ線ビーム発生に関する研究：実験, 日本原子力学会 2023 年春の年会, 東京大学駒場キャンパス, 2023.3.14

元木貴則, 三輪将也, 仙波実怜, 近藤莉帆, 下山淳一, 紀井俊輝, SDMG 法 REBCO 溶融凝固バルクの中低温捕捉磁場特性, 第 70 回応用物理学会春季学術講演会, 上智大学 四谷キャンパス＋オンライン, 2023.3.16

宍倉文夫, 全炳俊, 早川建, 小松崎良将, 早川恭史, 境武志, 野上杏子, 高橋由美子, 田中俊成 , 紀井俊輝, 大垣英明, ザリガニの複眼からコオロギの複眼へ：中赤外線反応の普遍性と反応の生物学的意義を求めて, 令和 4 年度 LEBRA ユーザーミーティング, 日本大学理工学部船橋校舎, 2023.3.22

小林進二, 永岡賢一, 稲垣滋, 長﨑百伸, 伊藤龍志, 藤田智大, 山戸瞭雅, 大垣英明, 紀井俊輝, 全炳俊, 岡田浩之, 大島慎介, 門信一郎, 南貴司, 木島滋, 水内亨, ヘリオトロン型磁場配位で観測される統計加速現象におけるエネルギー拡散過程, 日本物理学会 2023 年春季大会, Online, 2023.3.23

永島芳彦, 藤澤彰英, 山崎広太郎, 稲垣滋, 文贊鎬, 金史良, 河内裕一, 荒川弘之, 山田琢磨, 小林達哉, 糟谷直宏, 小菅佑輔, 佐々木真, 井戸毅, 発光信号トモグラフィーによる規格化電子温度・電子密度揺動推定, 日本物理学会 2022 年秋季大会, 東京工業大学, 2022.9.12-15

戸羽佑輔, 南貴司, 安原亮, 釼持尚輝, 邱德川, 松谷遼, 寺田凱, 高橋千尋, 金史良, 門信一郎, 大島慎介, 小林進二, 木島滋, 稲垣滋, 長﨑百伸, 発光信号トモグラフィーによる規格化電子温度・電子密度揺動推定, 第 39 回プラズマ・核融合学会年会, 富山国際会議場, 2022.11.22-25

近藤恭斗, 大島慎介, 桑原大介, 井下圭, 南貴司, 門 信一郎, 小林進二, 木島滋, 水内亨, 岡田浩之, 稲垣滋, 金史良, 長﨑百伸, ヘリオトロン J におけるドップラー反射計を用いた周辺磁気島領域の径電場分布計測, 第 39 回プラズマ・核融合学会年会,

富山国際会議場, 2022.11.22-25

P. Zhang, S. Ohshima, H. Zhao, S. Kobayashi, S. Kado, T. Minami, F. Kin, A. Miyashita, A. Iwata, Y. Kondo, D. Qiu, C. Wang, M. Luo, S. Konoshima, S. Inaga, H. Okada, T. Mizuuchi, K. Nagasaki, Construction and initial result of the 320 GHz interferometer system in Heliotron J, 第39 回プラズマ・核融合学会年会, 富山国際会議場, 2022.11.22-25