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(Form 3)

Summary of Doctoral Thesis

Name in full Na LIU

Title Study of Phase Drift Compensation for RF Reference Distribution System at SuperKEKB Injector LINAC

My doctor thesis mainly consists of two parts: one is the radio frequency (RF) reference phase stabilization for SuperKEKB linear accelerator (LINAC), the other is the phase drift compensation between LINAC master oscillator (MO) and ring MO.

SuperKEKB is an upgrade project with 40 times higher design luminosity than the KEKB accelerator. The low-emittance and high-current beam is required. The SuperKEKB injector LINAC comprises 600 m long straight beam lines, which consist of 8 sectors (sector A-C and 1-5). The main accelerating structures are operated at 2856 MHz (S-band). The 2856 MHz reference signal, generated by the 571.2 MHz LINAC MO (LMO), is converted to the optical signal by an optical transmitter (E/O) and distributed to each sector over hundreds of meters (max. 380 m) long phase stabilized optical fiber (PSOF). The transmitted optical signal is converted to 2856 MHz RF signal by an optical receiver (O/E) at each sector and used for low level RF (LLRF) system. The propagation time delay of PSOF is 5 ps/km/°C. The PSOF is distributed in the LINAC gallery where the temperature is controlled within ±1℃ by the air conditioners and the humidity is not stabilized. The transmitted phase drift is estimated as ±2° at 2856 MHz in case of 380 m PSOF with ±1℃ temperature fluctuation. Furthermore, the transmitted phase also suffers slow drift due to the humidity fluctuation. The transmitted phase drift becomes larger. The phase regulation for the reference phase is necessary.

For SuperKEKB, the requirement of the energy spread at the end of injector LINAC is 0.07% with the rectangular beam and 4nC bunch charge. So I estimated the RF reference phase stability according to the energy spread. Taking the intra-bunch energy spread caused by wakefield, the klystron high voltage fluctuation and the low-lever RF (LLRF) control unit stability into consideration, the requirement of the RF reference phase stability is estimated as 0.2° (RMS) at 2856 MHz corresponding to 195 fs (RMS) including short-term timing jitter and long-term phase drift. The integral timing jitter of 2856 MHz RF reference phase at each sector is measured by the signal source analyzer and all the jitter was found to be less than 150 fs (RMS) from 10 Hz to 10 MHz. Thus, the long-term phase drift should be less than 0.13° (RMS) at 2856 MHz corresponding to 125 fs (RMS). Stabilization of RF reference phase for long distance transmission is very important for stable RF operation. The motivation is to propose a RF reference phase stabilization system for SuperKEKB injector LINAC to fulfill the

requirement.

To monitor the long-term phase drift, the phase monitor system is constructed in the digital field programmable gate array (FPGA) board. The 2856 MHz RF signal is down converted to the intermediate frequency (IF, 14.28 MHz) by mixing with the local oscillator (LO, 2870.28 MHz). The IF signal is sampled by 16-bit analog-to-digital converter (ADC) with the sampling rate (SR) of 114.24 MSPS. The in-phase (I) and quadrature (Q) components of IF signal are calculated in the FPGA board and the RF phase (φ) is obtained by $\varphi = \tan^{-1}(Q/I)$. More than 5° phase drift was observed for the transmitted phase, including one pair of E/O and O/E, and different lengths of PSOF. And it's also found out that the phase drift depends on the slow temperature and humidity fluctuation in LINAC gallery, where the temperature is controlled within 28±1℃ and the relative humidity fluctuation is fluctuated from 10%RH to 50%RH. To evaluate the phase drift contribution of E/O and O/E, and different lengths of PSOF, the temperature and humidity coefficients are measured by the network analyzer. The estimated phase drift is almost matched with the measurement result.

To measure and compensate the long-term phase drift, several schemes of RF reference phase stabilization system are proposed and tested in the laboratory, including the wavelength division multiplexing (WDM) technique and the optic circulator technique. 120 m PSOF is used for the performance evaluation, which is situated inside the temperature and humidity controlled chamber to change the temperature and humidity near PSOF. The same technique is adopted to detect the phase drift of long optical link. To compensate the phase drift, the mechanical variable optical delay line (VODL) and the piezo-driven fiber stretcher (PDFS) are widely used for optical length control. The VODL is driven by a stepping motor with low resolution and large optical delay range up to hundreds of millimeters. The PDFS is driven by an electrical piezo with high resolution and small optical delay range limited to several millimeters. In our case, the RF phase at 2856 MHz is very sensitive to the mechanical structure so that the VODL is used for coarse control. For precise optical length control, PDFS is adopted for the phase drift compensation. In the demonstration, we focus on the precise control.

At the beginning stage, we constructed the phase stabilization system with WDM technique. Different optical wavelengths with 1310 nm and 1550 nm are applied for the forward ($\lambda_1 = 1310\,nm$) and backward ($\lambda_2 = 1550\,nm$) signal transmission. The temperature near PSOF is changed from 20℃ to 40℃ and down to 20℃ with stable humidity 40%RH so that more than 5° phase drift is monitored. With feedback, the transmitted phase still has 0.5° (pk-pk) drift at 2856 MHz. It is found out that the transmitted phase stability depends on the temperature near PSOF. We measured the temperature coefficient of 120 m PSOF with 1310 nm and 1550 nm, the difference is 0.047°/℃. With 20℃ temperature fluctuation, the phase difference between forward phase and backward phase is 0.494° which is consistent with the measurement result. Thus, this residual phase error is caused by the large wavelength difference ($\Delta\lambda =$

$240\,nm$). Hence, the close wavelengths with 1550.02 nm and 1551.72 nm ($\Delta\lambda = 1.6\,nm$) are applied. The performance is highly improved. This technique is already used in the RF reference distribution system at KEKB ring.

With the optic circulator scheme, the same optical wavelength ($\lambda = 1550\,nm$) is firstly applied for the forward and backward signal transmission to minimize the phase error caused by the wavelength difference. The wavelength difference between forward and backward signal is less than ±0.1 nm. With the same temperature setup mentioned above, the transmitted phase can be stabilized within 60 fs to 130 fs (peak to peak) which fulfilled the requirement 125 fs (RMS). We also applied the different optical wavelengths ($\lambda_1 = 1550.02\,nm, \lambda_2 = 1551.72\,nm, \Delta\lambda = 1.6\,nm$) for the forward and backward signal transmission. With feedback, the transmitted phase can be stabilized within 130 fs (peak to peak) which also fulfilled the requirement. For all the experiments, the feedback system and RF/optic components are located inside the temperature stabilized chamber with 28±0.1℃ to minimize the system phase drift The system phase drift is also rejected by the reference tracking method.

The other main part of my PhD work is to develop the phase drift compensation between LINAC MO and ring MO (RMO). The injector LINAC delivers low emittance electron and positron beams to the damping ring (DR) and the main rings (MR). The injector LINAC, MR, and DR have their own independent MOs. They are synchronized with 10 MHz trigger generated by the main master oscillator (MMO). The DR MO and RMO are operated at 508.9 MHz and the phase drift between them is controlled within ±0.1° (pk-pk). The frequency of LMO is 571.2 MHz but the phase drift between LMO and RMO is not stabilized. Phase difference of several degrees is observed between LMO and RMO. This phase difference significantly affects the beam performance of bunch compression system (BCS) from DR to LINAC (RTL) and the beam injection to MR. The beam injection phase from LINAC to the rings should be stabilized less than ±0.1° (pk-pk) at 508.9 MHz for long-term stable beam injection. Thus, the phase drift compensation system between LMO and RMO is implemented at LINAC.

To monitor the LMO and RMO which have difference frequencies and remove the effects of temperature and humidity drift of the measurement system, the direct sampling technique is adopted for phase detection. In this method, these two different frequency signals are directly sampled by ADC using the common sampling rate. The 124.63 MHz sampling rate is carefully chosen for the phase monitor system owing to lower jitter and averaging effect. More than 8° (pk-pk) phase drift are observed between LMO and RMO. We found out that this phase drift depends on the room temperature of KEKB control room where the MR MO is located. Furthermore, the slow drift of the beam energy after the BCS cavity had strong correlation with the MO phase difference. To improve the beam performance after BCS, the phase difference between two MOs is compensated by the MO phase shifter. The MO phase difference is stabilized within 0.018° (RMS) at 571.2 MHz corresponding to 0.09° (RMS) at 2856 MHz which fulfilled the requirement 0.3° (RMS) for BCS accelerating structure. The slow drift of the beam energy after the BCS cavity is compensated. This MO phase stability also fulfilled the requirement ±0.1° (pk-pk) at 508.9 MHz for stable beam injection.

For the first part of my PhD work, a phase stabilization system with optic circulators is developed and the performance is evaluated. The phase drift is compensated by the PDFS for precise control. The transmitted phase can be stabilized within 70 to 130 fs (pk-pk) which fulfilled the requirement 125 fs (RMS). However, we found out that the transmitted phase is affected by the humidity. For higher stability, it’s better to seal the optical components with stable humidity. For the other part of my work, the LMO and RMO signals are monitored by direct sampling technique with the common sampling rate. The phase drift compensation system is developed and used in the SuperKEKB operation. The MO phase difference is stabilized within 0.018° (RMS) at 571.2 MHz which fulfilled the requirement. It is expected to make more effort to the MR beam injection.

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Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏 名　Na LIU

Title
論文題目　Study of Phase Drift Compensation for RF Reference Distribution System at SuperKEKB Injector LINAC

SuperKEKB は、KEKB に比べ 40 倍のルミノシティを目指す電子・陽電子衝突型加速器である。入射器に要求されるビームは、KEKB に対して、バンチ電荷量が 4 倍の 4 nC、且つエネルギー広がりは約半分の 0.07%となっている。このエネルギー広がりを満足するためには、入射器での RF 基準信号系の安定化が重要となり、2856 MHz の RF 周波数に対して長期位相ドリフトを 0.1 deg (rms)に抑える必要がある。また、衝突実験用の BELLE 検出器では入射ビームに伴うバックグランドも問題となっており、安定な入射と効率的な入射調整のために主リングと入射器とのマスター信号間の位相安定化も必要とされている。

Liu 氏は、入射器の RF 基準信号系の位相安定度を評価するために、全長 600 m の入射器の各セクターに分配している基準信号に対する位相ドリフトの測定を行い、数 deg (pk-pk)の変動を確認した。各コンポーネントの温度や湿度に対する依存性を測定し、湿度に対する変動も大きく寄与することを確認した。長距離伝送用光リンクの位相ドリフト補償用フィードバックシステムを検討し、テストスタンドにて性能検証を行った。その結果、0.05 deg (pk-pk)の安定度を実現し、要求性能を満足することを確認した。

更に、Liu 氏は周波数比が 55:49 の関係である入射器マスターオシレータ(LMO)と SuperKEKB リングのマスターオシレータ(RMO)間の位相安定化に関する研究もおこなった。LMO と RMO の周波数は、571.2 MHz と 508.9 MHz とで異なっているが、適切な共通サンプリング周波数を選択し、アンダーサンプリング法を用いることで、ダウンコンバートすることなく各信号を直接 ADC で取得した。これにより、ダウンコンバート系の温度ドリフト等の測定誤差を減らした位相測定を実現している。このシステムを用いて LMO/RMO 間の位相差を測定し、入射器側で RMO に追従させるように移相器を用いて LMO の位相を制御した。位相ドリフト補償前は、入射器途中の陽電子ダンピングリングのバンチ圧縮システム(BCS)から出射したビームに位相差ドリフトで生じたエネルギー変動が観測されていた。これに対して位相補償フィードバック制御により、ビームエネルギーの安定化を実現した。現在、このシステムは SuperKEKB のビーム運転において実際に使用されている。

Liu 氏は、これまで複数回国際会議等でポスター発表を行い、2017 年の日本加速器学会の年会では、ポスター賞を受賞している。また、Physical Review Accelerators and Beams(PRAB)に論文を投稿し、既に掲載されている。更にドイツの DESY にインターンシップで６週間滞在し、XFEL 施設における基準信号の位相安定化の研究に参加するなどの経験を積んできた。英語力とプレゼンテーション能力にも問題が無いことを確認し、審査会では全員一致で合格とした。