Reproducing beams for therapy and research with replaced power supplies of Main Dipole Magnet in HIMAC synchrotron and HEBT systems.

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Introduction

At HIMAC (Heavy Ion Medical Accelerator in Chiba), major replacement of power supplies for bending magnets were carried out in the summer, 2014. For the upper ring, a new power supply with IGBT was introduced while existing power supply with thyristor is retained and can be utilized by manual switching. For the beam transport lines after extraction from rings, all power supplies for bending (itching) magnets are replaced by new ones. To meet therapy needs it had been scheduled that supply of beam be resumed after about 1 week of retuning or adjustment period that follows the summer shutdown. We were able to resume beam as scheduled. Here we will report our key feature as well as lessons learned during the replacement returning processes.

Bending magnets power supply for the synchrotron

Output current \( I_{\text{op}} \) should follow pattern \( \text{Ip} \).
- \( I_{\text{op}} \) is controlled by feedback \( V \) (voltage pattern) and by feedback ACR.
- Error, or difference \( \Delta I = I_{\text{op}} - \text{Ip} \), is minimized by an iterative modification of \( V \), what we call “learning”.
- We first tried with \( V \) calculated from measured value of \( R \) and \( L \) of the magnets.
- \( \Delta I \) remained in ramping zone, and with “learning”, \( \Delta I \) became minimal.

### Therapeutic operation pattern (for Wobbler)

- Setting current value for BM power supply

### Therapeutic operation pattern (for scanning)

- Setting current value for BM power supply

### Synchrotron cycle is 3300msec typically

\[ V = IR + L \frac{\text{d}I}{\text{d}t} \]

### Calculating current

- Difference from target current value

- Before replace
  - FB-8: 106.300[A]
  - FT-1: 796.831[A]
- After replace
  - FB-8: 106.325[A]
  - FT-1: 796.741[A]

Difference in current output between the new P.S. and the old P.S. was detected by measurement of magnetic field. This difference is derived from current detection system and is found tolerable when we accelerate beams and check them in treatment rooms.

### Bending magnet power supply for HEBT system

#### Setting value for new P.S.

- \( B \) relation, we decide to calculate new current setting via linear approximation of \( B - I \) formula of respective old and new P.S.
- We succeeded to provide therapy beam in time. However, few beams needed further fine tuning.

#### Approximate expression

\[ B \ [\text{mT}] = 2.881 \times I_{\text{old}} \ [\text{A}] + 3.470 \]

\[ B \ [\text{mT}] = 2.884 \times I_{\text{new}} \ [\text{A}] + 3.939 \]

#### Further challenge

- In looking the transient part more carefully we find larger undershoot and oscillation at lower energy cases. It correlates with zero-volt output at ramping down.

#### Limit of linear approximation

- Obvious saturation in high field region and unexpectedly large deviation in low excitation region (see (5) for possible cause) are being studied for better solution.

### Conclusion

- Beam must be clearly characterized (eg. COD in the ring, Q scan etc. data for standard transport verification) before P.S. replace and should be compared systematically after the replacement.
- Magnetic field measurement is indispensable, simplified linear formulae can work to provide beams when field data is available.
- A Change in a transient scheme can cause extended challenge or new unexpected results like undershoot and insufficient control on forcing voltage.

#### Lessons learned

- 1. Difference between “old” and “new”.
- 2. Straight forward way: We calibrated new P.S. with the same external DCCT that also measured current output of old ones in a stabilized time zone. Thus old and new P.S. output must be identical.
- 3. When we measure magnetic field \( B \), it differs sometime a few mT. We find a different behavior of current in the critical transient zone. We attribute \( B \) difference to this \( \Delta I \) difference.
- 4. Remedy to provide therapy beam in time.
- 5. Since magnetic field for therapy falls off to linear range in \( I \) relation, we decide to calculate new current setting via linear approximation of \( B - I \) formula of respective old and new P.S. We succeeded to provide therapy beam in time. However, few beams needed further fine tuning.
- 6. Further fine tuning.
- 7. Approximate expression

\[ B \ [\text{mT}] = 2.881 \times I_{\text{old}} \ [\text{A}] + 3.470 \]

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#### The difference between the target value

- Orange : Current value for about 290MeV/u
- Blue : Current value for about 400MeV/u
- The output voltage became 0[V] as current value was ramped down drastically. (cf. blue line of (1))

### Output voltage

\[ \text{Current value} \ [\text{A}] \]

\[ \text{Time} \ [\text{sec}] \]

#### The difference from the approximated value

- Red : (Measured value) - (approximate value)