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

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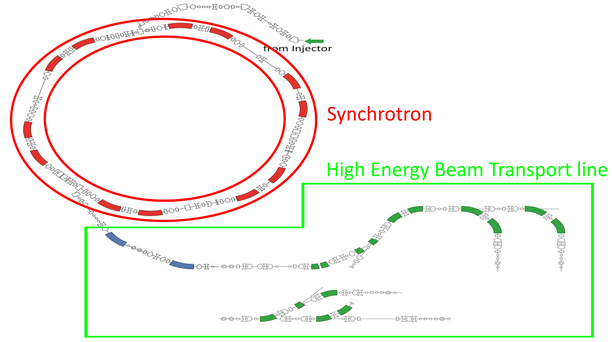


Introduction

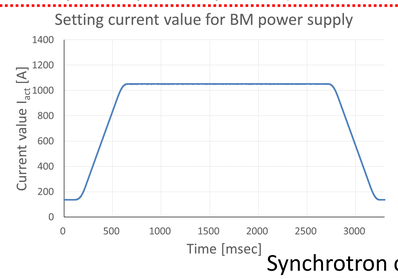
At HIMAC (Heavy Ion Medical Accelerator in Chiba), major replacement of power supplies for bending magnets were carried out in the summer, 2014. For the upper ring, a new power supply with IGBT was introduced while existing power supply with thyristor is retained and can be utilized by manual switching. For the beam transport lines after extraction from rings, all power supplies for bending (switching) 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 retuning processes.

Bending magnets power supply for the synchrotron

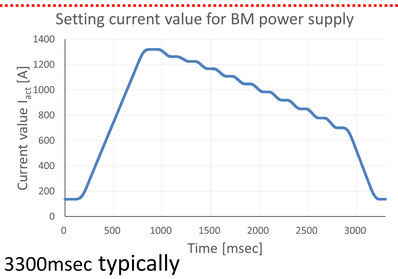
Output current I_{act} should follow pattern Ip.

- I_{act} is controlled by feed forward Vp (voltage pattern) and by feed back ACR.
- Error, or difference $\Delta I = I_{act} - Ip$, is minimized by an iterative modification of Vp, what we call “learning”.
- We first tried with Vp calculated from measured value of R and L of the magnets.
- ΔI remained in ramping zone, and with “learning”, ΔI became minimal.

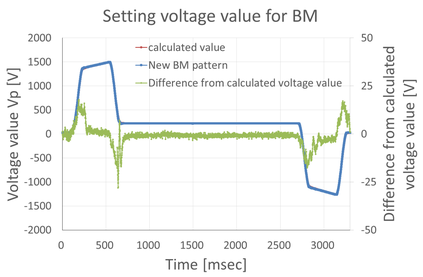
Therapeutic operation pattern (for Wobbler)

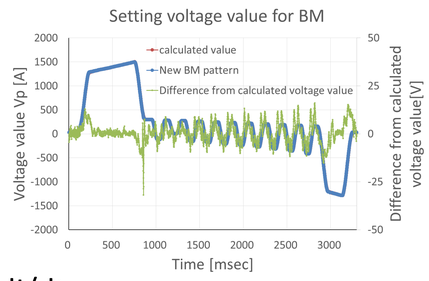


Therapeutic operation pattern (for scanning)

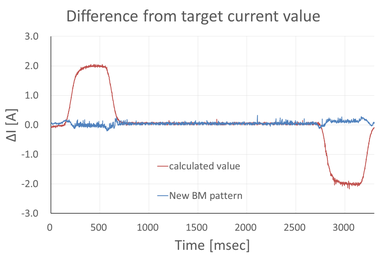


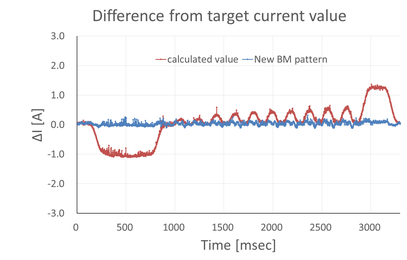
Synchrotron cycle is 3300msec typically





$$V = IR + L\,dI/dt$$





Blue : Difference from the voltage setting value after learning.
Red : Difference from the voltage setting value in the calculated value before learning.

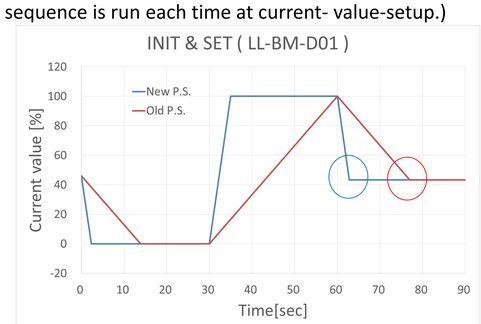
Before replace FB-B : 106.300[mT]
(for “290MeV/u”) FT-B : 796.831[mT]
After replace FB-B : 106.325[mT]
FT-B : 796.741[mT]

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 supplies for HEBT system

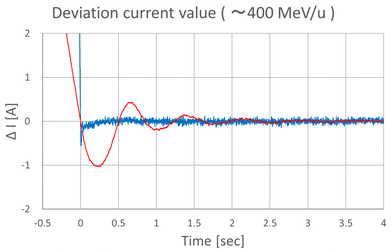
Setting value for new P.S. must be obtainable with easy and quick procedure that each operator can handle for various setup.

①Difference between “old” and “new”.
(implication was deeper than we thought ramp time of new P.S. is shortened for future operation. Initialization sequence is run each time at current- value-setup.)



②Straight 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 PS output must be identical.

③When 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 ΔI difference .



Red : Old power supply current value.
Blue : New power supply current value.

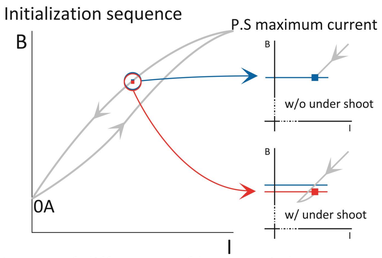


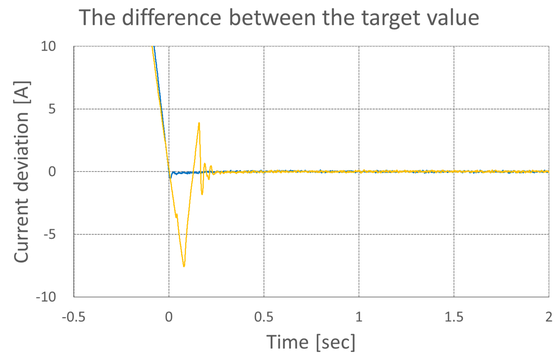
Image of difference of hysteresis loop.
Red : Old power supply , Blue : New power supply.

④Remedy to provide therapy beam in time.
Since magnetic field for therapy falls off to ‘ linear ’ range in I-B relation, we decide to calculate new current setting via linear approximation of B-I formulas of respective old and new P.S. We succeeded to provide therapy beam in time. However, few beams needed further fine tuning.

Approximate expression

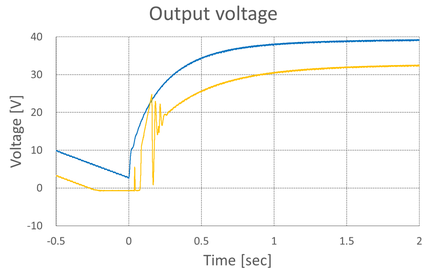
before	after
$B\,[mT] = 2.881\ I_{old}\,[A] + 3.470$	$B\,[mT] = 2.884\ I_{new}\,[A] + 3.939$

⑤Further 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.



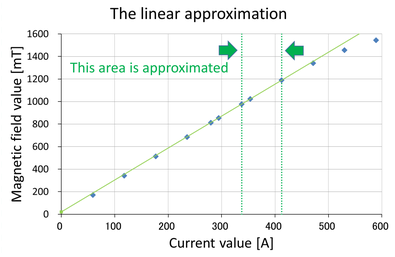
Orange : Current value for about 290[MeV/u]
Blue : Current value for about 400[MeV/u]

The output voltage became 0[V] as current value was ramped down drastically. (cf. blue line of ①)

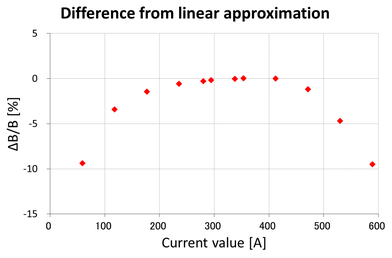


Orange : Voltage value for about 290[MeV/u], Blue : Voltage value for about 400[MeV/u]

⑥Limit 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 solation.



Blue point : Measured value of the magnetic field
Green line : Linear approximation of the linearity of a certain area.



The difference of the approximate value.
Red : (Measured value) – (approximate value).

Conclusion ～ Lessons learned～

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