Multi-turn injection using air core coils at Kyushu University

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Introduction

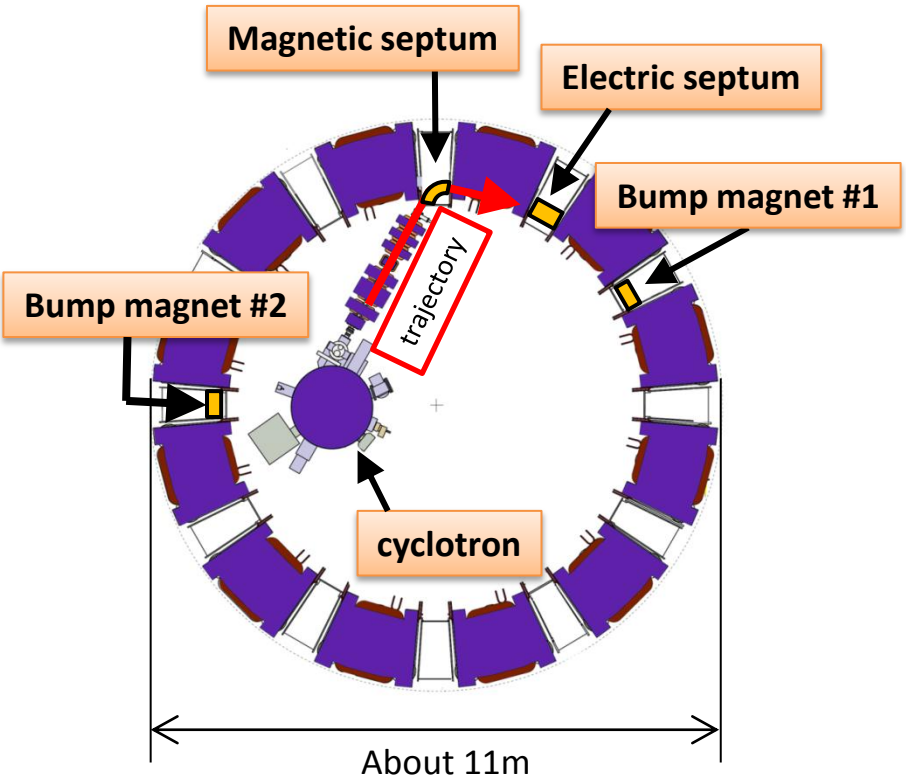
At Kyushu University, we plan to promote various research by using FFAG accelerator.

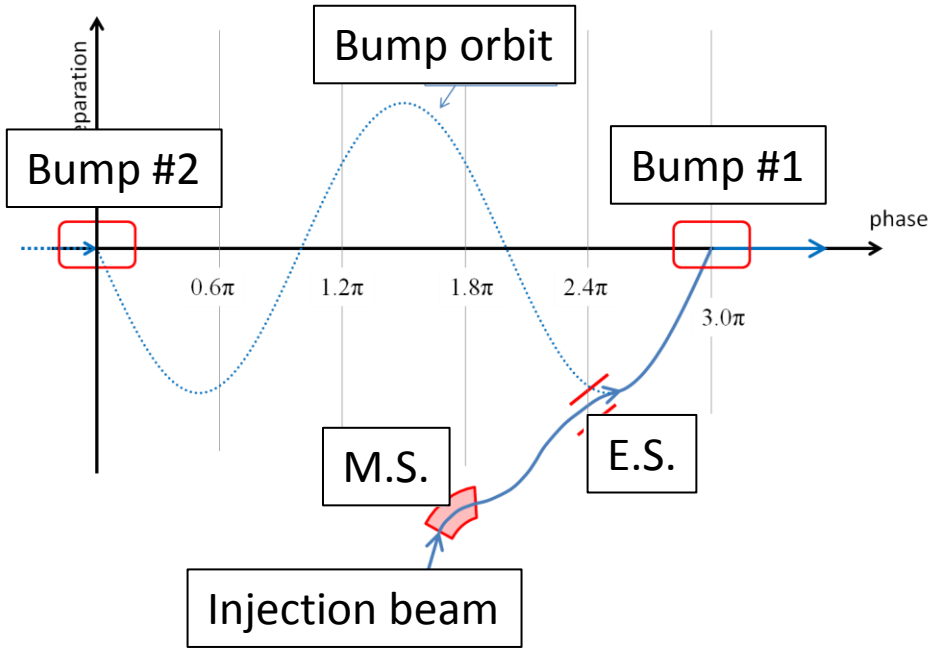
In the first stage, positive ion beam of 1 nA is required.

Multi-turn injection has been adopted as an injection scheme to increase the beam intensity.

Bump magnets have been developed, and research on multi-turn injection has been carried out using the 150 MeV FFAG.

Beam injection system of the 150 MeV FFAG

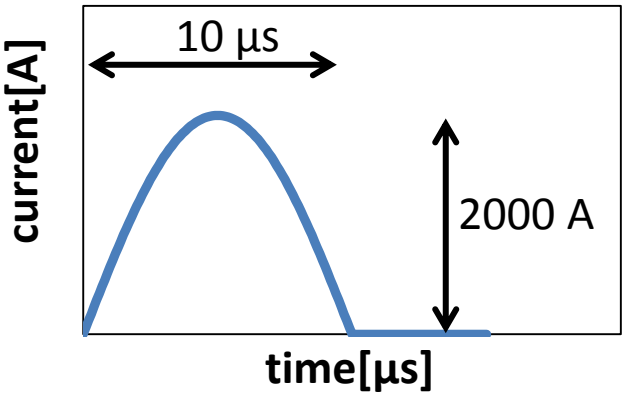




※Phase advance per 5 cell is about 3.0 π

Specification of power source for bump magnets

Wave shape	half sine
maximum current	2000 A
Pulse width	10 μs
Repetition rate	100 Hz
load inductance	＜6.5 μH



Requirements to the magnet

- If magnetic materials are installed at the straight section,
  the closed orbit should be distorted owing to magnetic flux leakage.

In order to prevent closed orbit distortion,

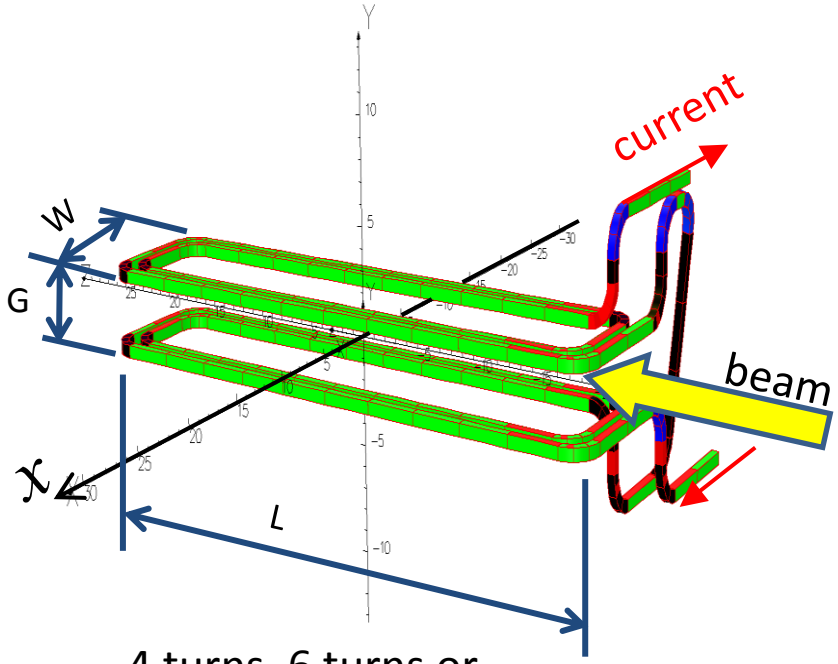
air core coils are to be employed for the bump magnets.

- Good field regions of a magnetic field on radial direction are to be more than 30 mm.
- Inductances should be less than 6.0 μH.
- Lengths on longitudinal direction are to be less than 440 mm.

The bump magnets which satisfy the above have been designed

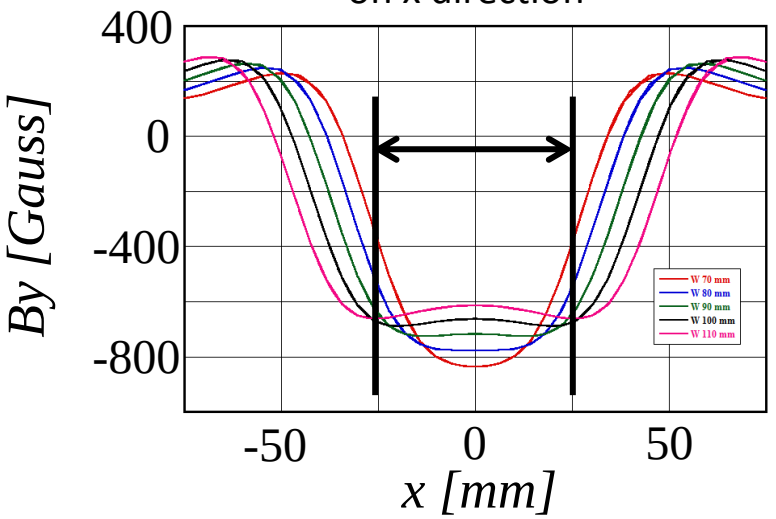
Design of the air core coils

magnetic field analysis with Opera 3d



4 turns, 6 turns or…

Magnetic field distribution
on x direction



→good field region was calculated on each condition

decision

- 4 turn coil
- L = 440 mm
- W = 100 mm
- G = 30 mm

Good field region 30 mm

inductance 5.7 μH

Simulation of beam injection

Simulation method

The equation of motion was numerically solved using the fourth order Runge-Kutta method, and the trajectory of the beam was calculated.

Initial condition

The emittance of the injection beam was determined from the aperture of the vacuum chamber and injection devices.
The distribution of spatial charge density was uniform.

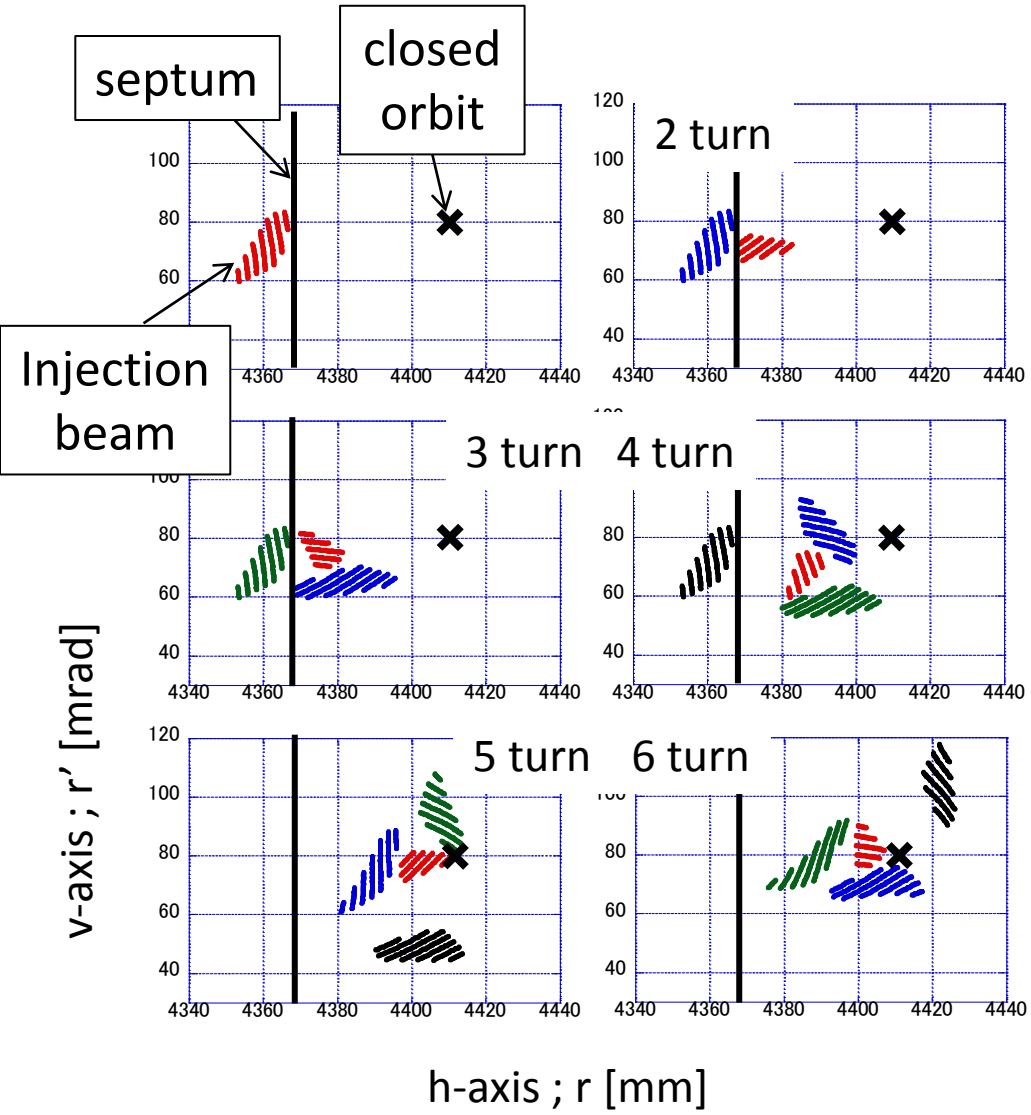
Parameters for the simulation

the position and the field strength of the septum, and the timing of beam injection

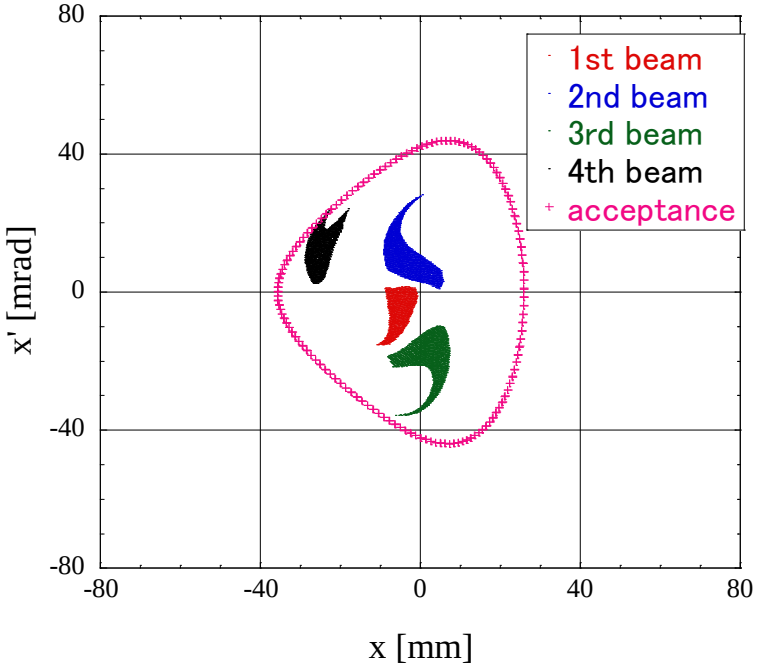
these parameters were optimized.

Simulation results

Beam distribution on the phase space
from first to sixth turn

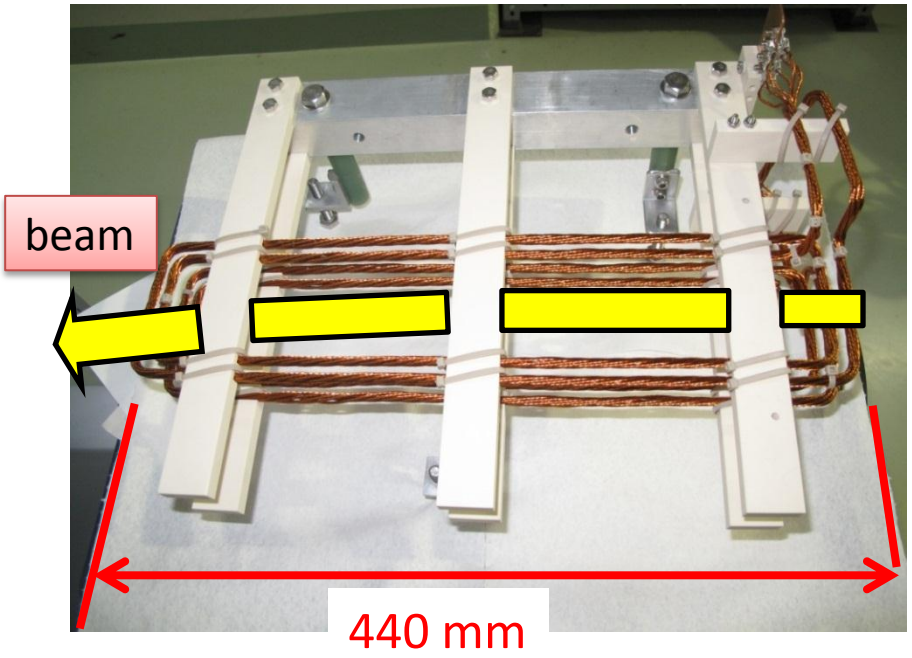


Beam distribution after injections

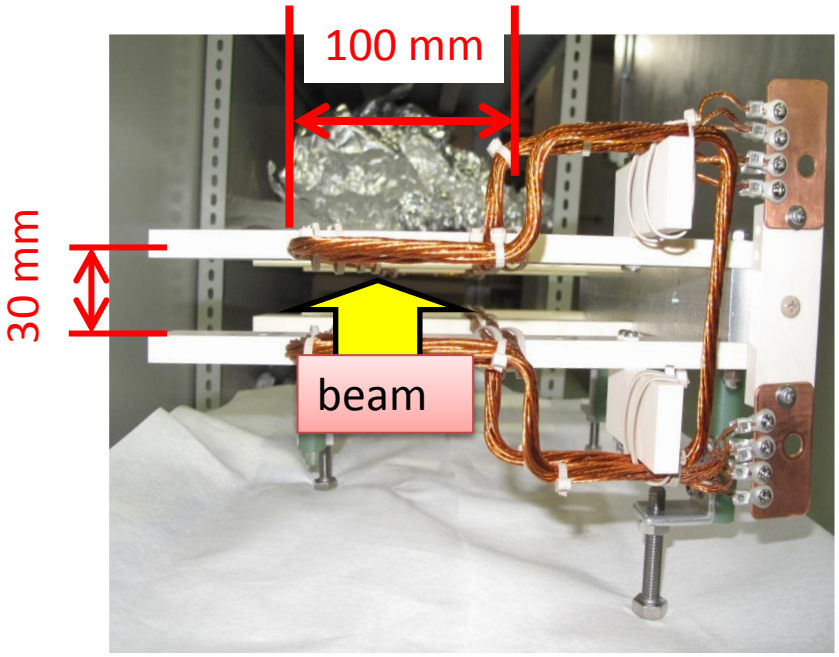


The intensity of circulating beam is 3.3 times as large as the injection beam.

Developed bump magnet



Top view



Side view

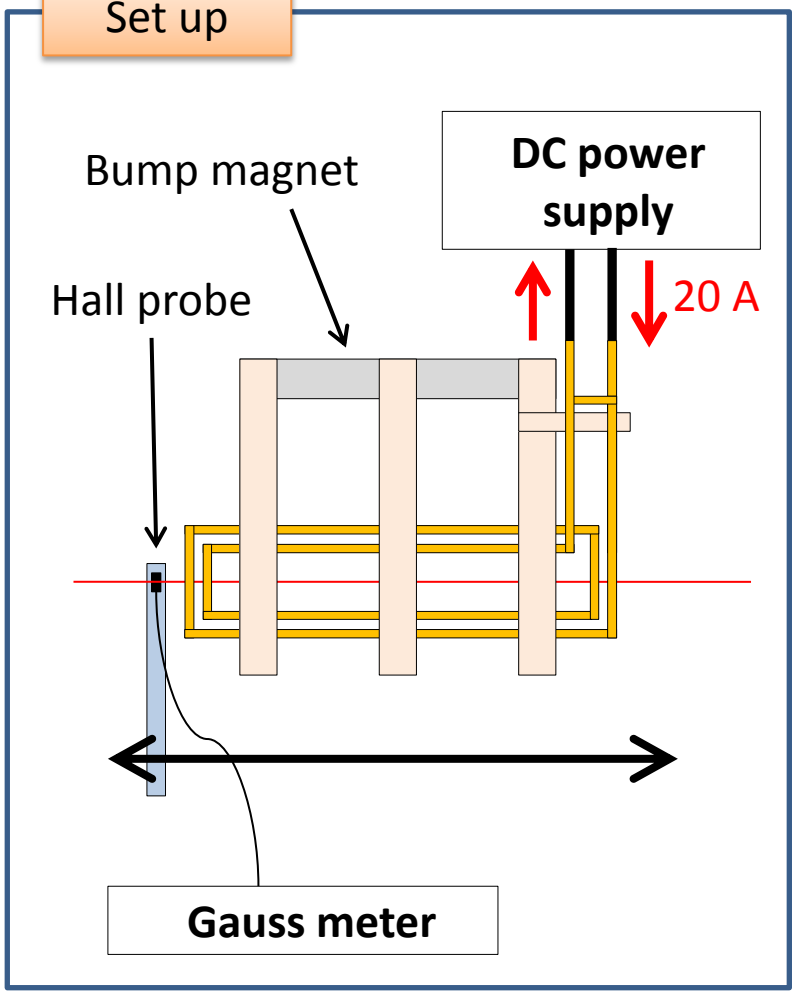
- measured values of the inductance

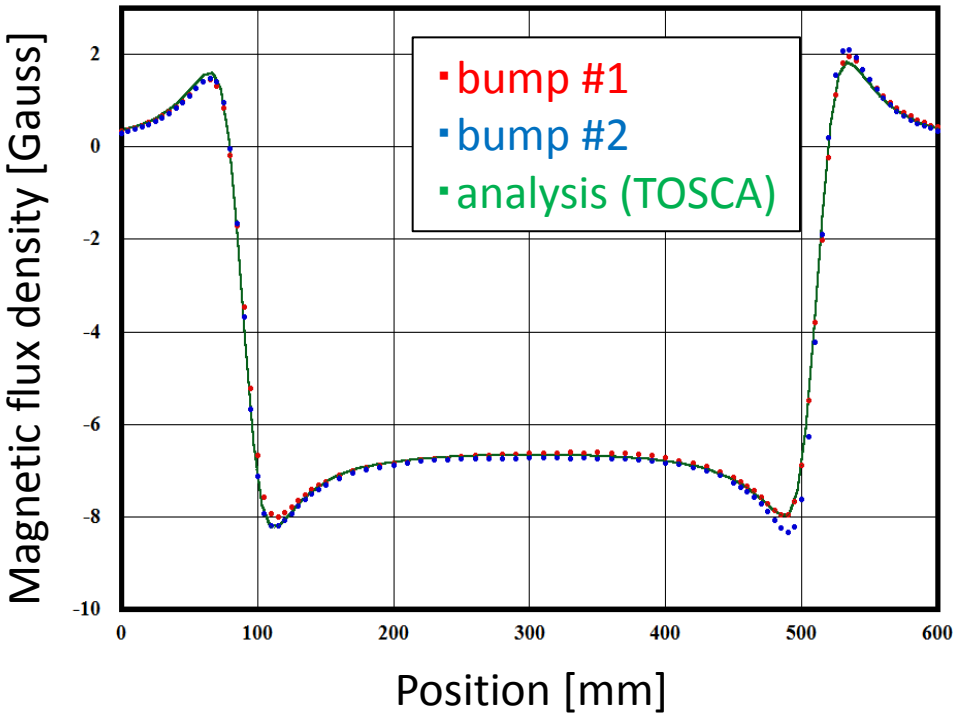
magnet #1	5.65 μH
magnet #2	5.66 μH

→ Requirement on inductance was satisfied.

Measurement of magnetic field distribution

Set up





Magnetic field distributions of measurements and calculated result

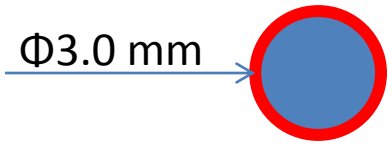
in good agreement with the calculated result

conductor of the air core coil

If a coil consists of a copper wire・・・ The temperature ; ～240℃.

Concentration of pulsed current in the surface region of the wire by skin effect is considered to cause severe heat generation.

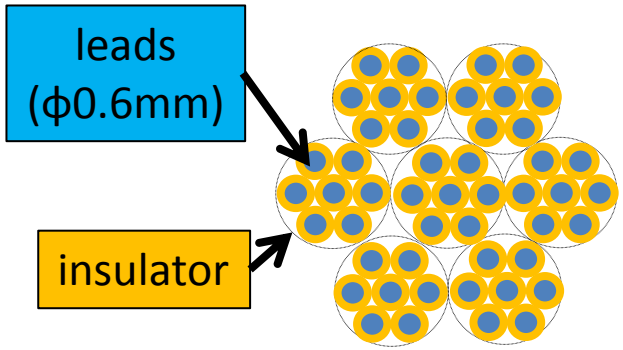
skin depth is 0.3 mm.



cross section of a copper wire

In order to suppress heat generation

➡ a cable made of insulated wires, a Litz wire, was adopted.



cross section of Litz wire

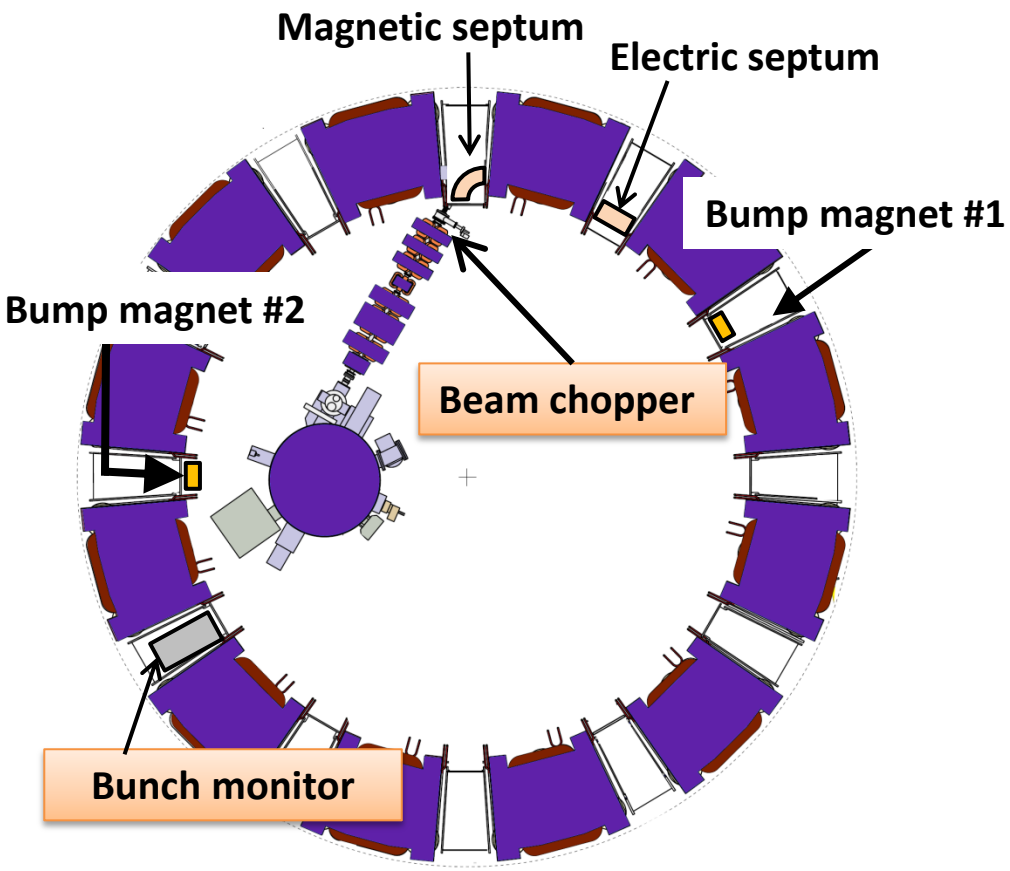
Lead resistance	7 mΩ
Joule heat	14 W
Mean temperature	75℃

It became possible to drastically lower the temperature of coil.

Experiment on beam injection

The experiment on multi-turn injection was performed to increase beam intensity.

Experimental setup



The injected beam was chopped using the beam chopper installed at the end of the beam transport line.

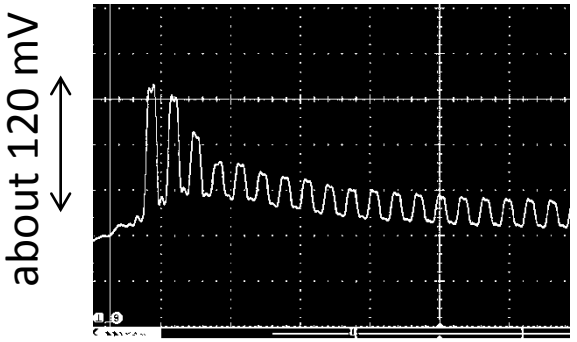
・bunch monitor

Electrostatic pickup monitor
(non destructive)
The 46dB amplifier was connected.

Results of single pulse injection

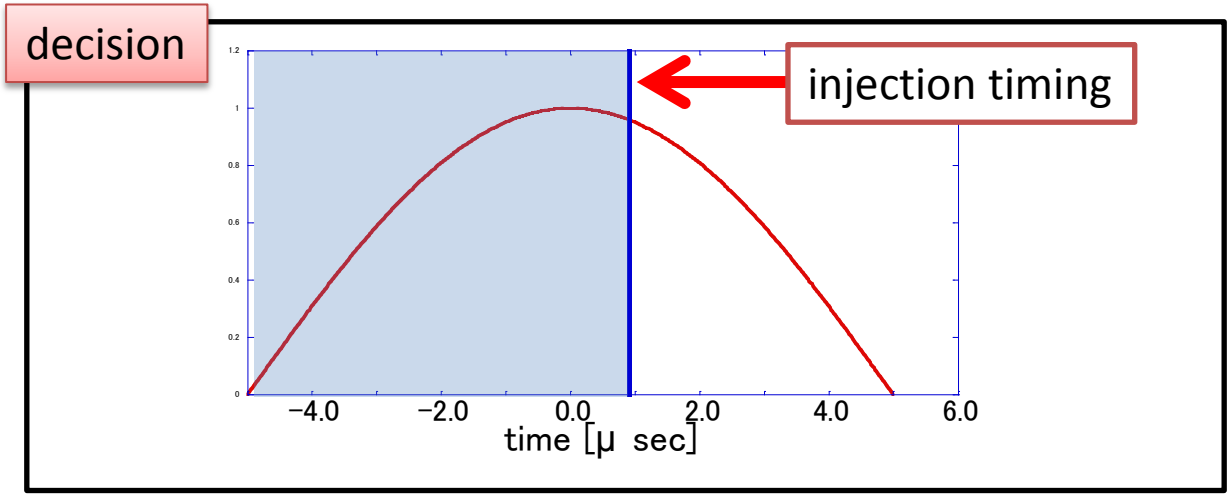
The purpose

determination of the injection timing for multi-turn injection



output signal of bunch monitor

The signal of the circulating beam at each injection timing was measured.

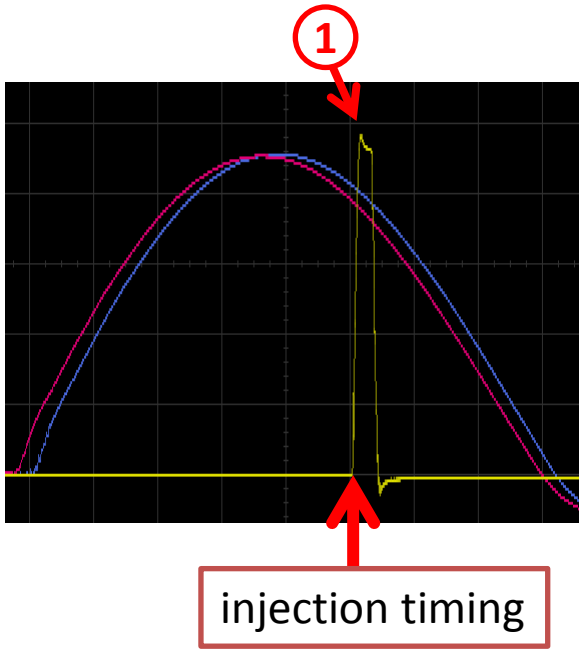


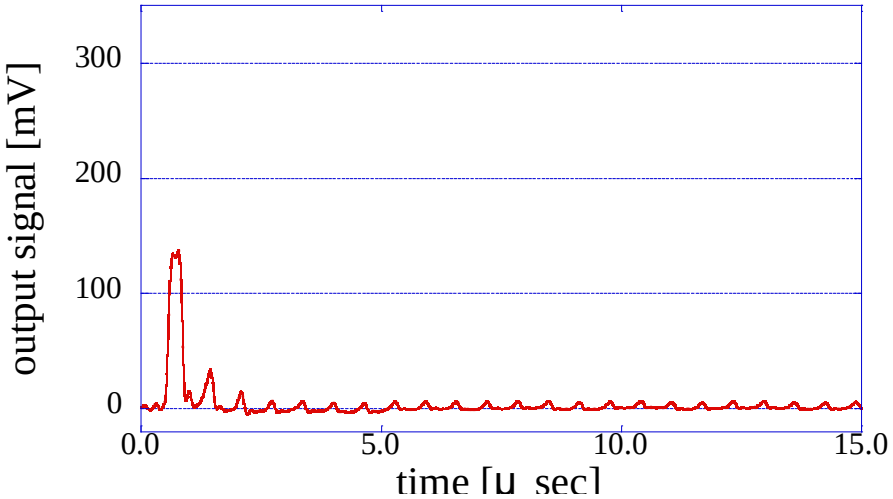
Results of multi-turn injection

The purpose demonstration of the increase of the beam intensity with multi-turn injection

One pulse injection

The signal of bunch monitor was measured when one pulse was injected.





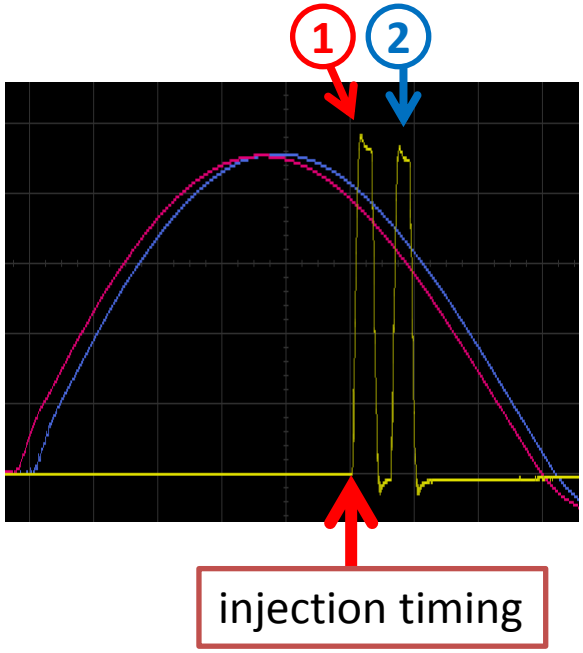
The output signal of bunch monitor

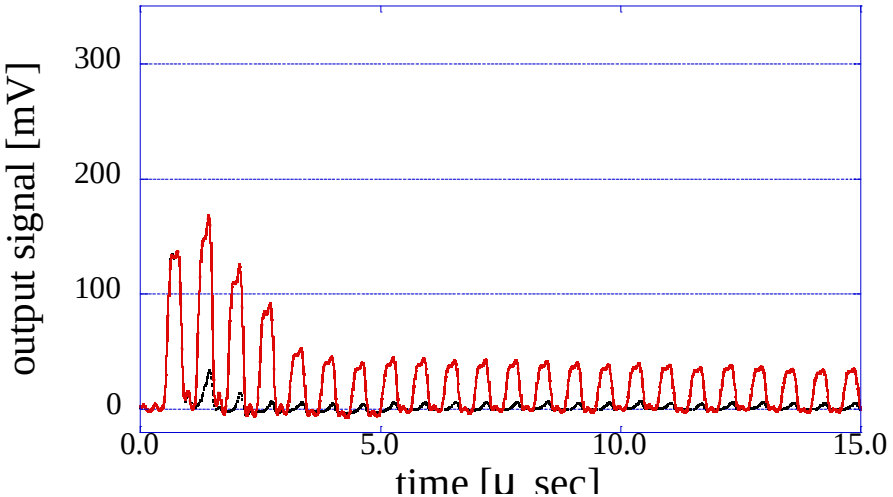
Result of multi-turn injection

The purpose demonstration of the increase of the beam intensity with multi-turn injection

Two pulses injection

The signal of bunch monitor was measured when two pulses were injected.





The output signal of bunch monitor

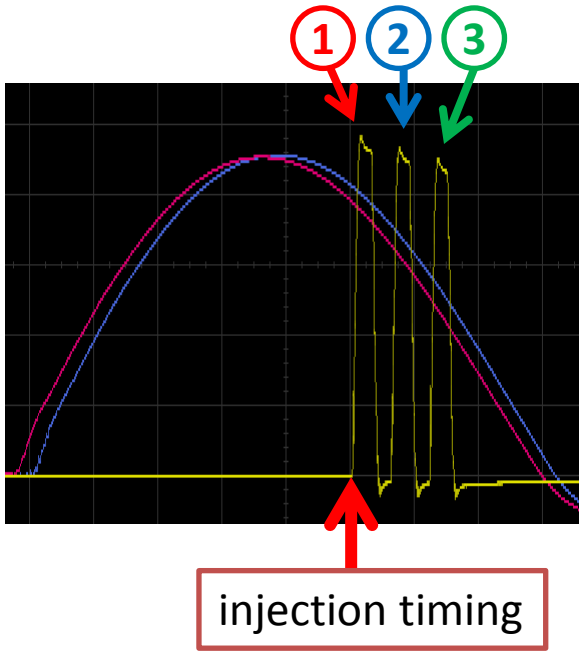
※The repetition frequency of the beam chopper was equal to the revolution frequency(1.565MHz).

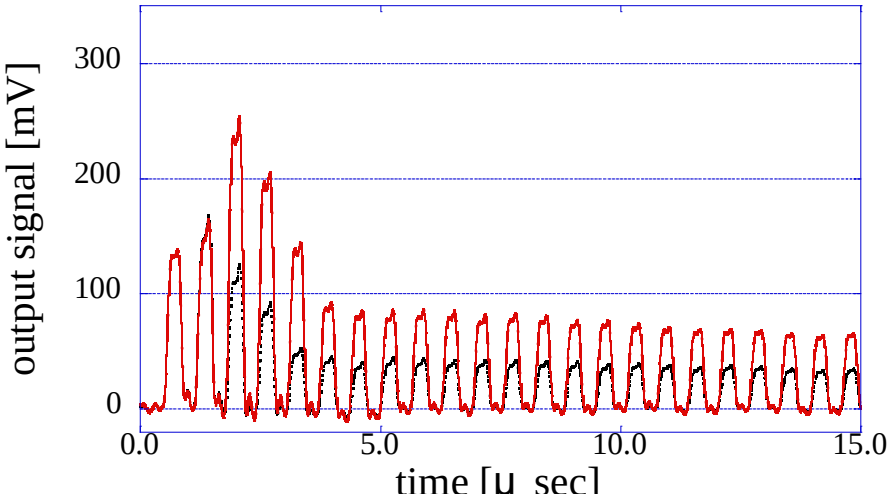
Result of multi-turn injection

The purpose demonstration of the increase of the beam intensity with multi-turn injection

Three pulses injection

The signal of bunch monitor was measured when three pulses were injected.





The output signal of bunch monitor

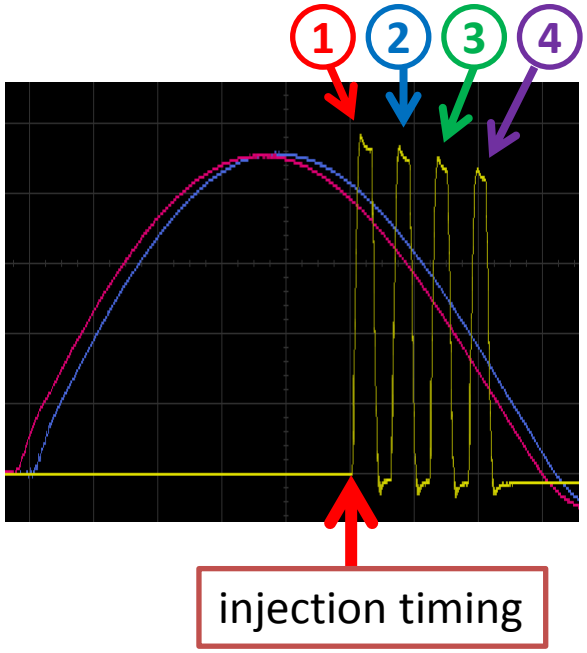
※The repetition frequency of the beam chopper was equal to the revolution frequency(1.565MHz).

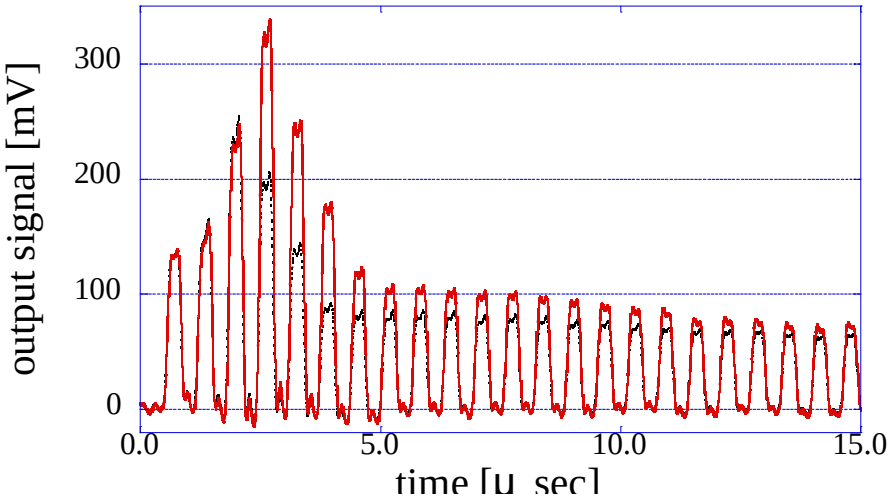
Result of multi-turn injection

The purpose demonstration of the increase of the beam intensity with multi-turn injection

Four pulses injection

The signal of bunch monitor was measured when four pulses were injected.





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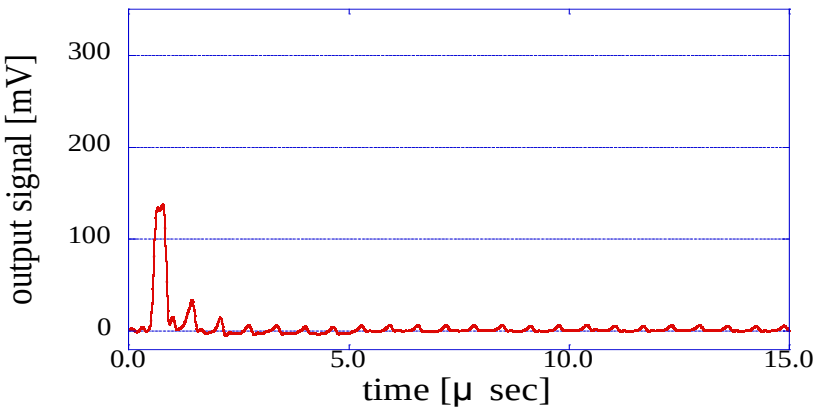
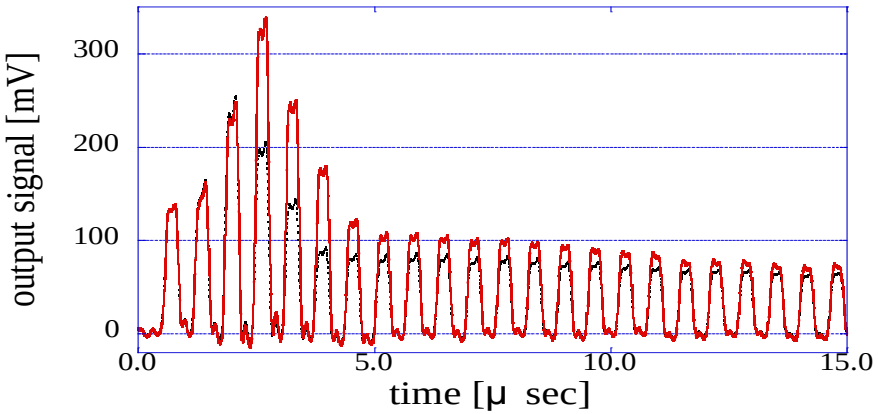
Results of multi-turn injection

One pulse injection



Four pulses injection



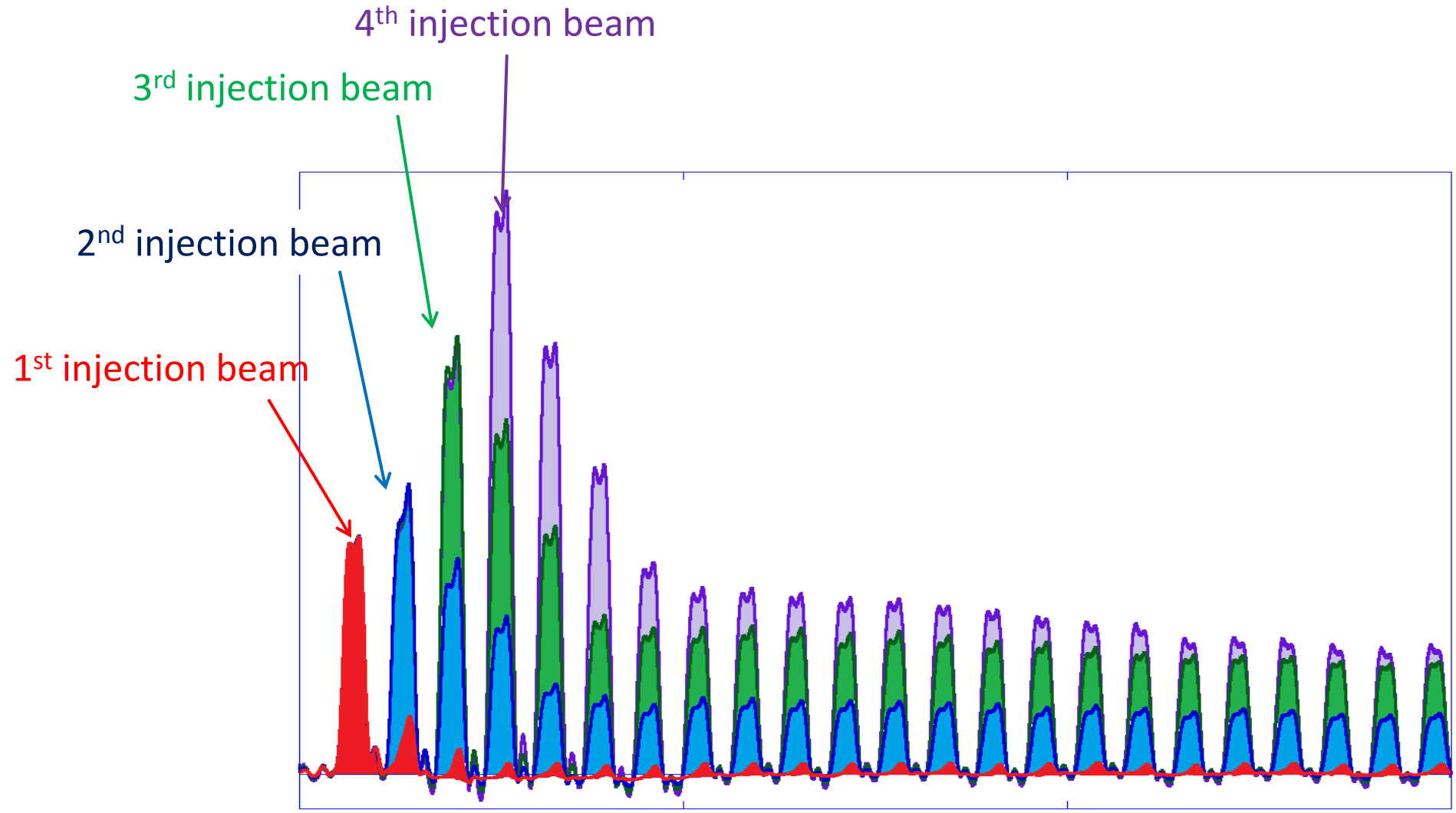
The increase of beam intensity was demonstrated with multi-turn injection.

4 pulses injection is possible.

The intensity of the circulating beam is estimated to be 0.9 nA at 100Hz.

⟶ A target value almost be reached.

Results of multi-turn injection



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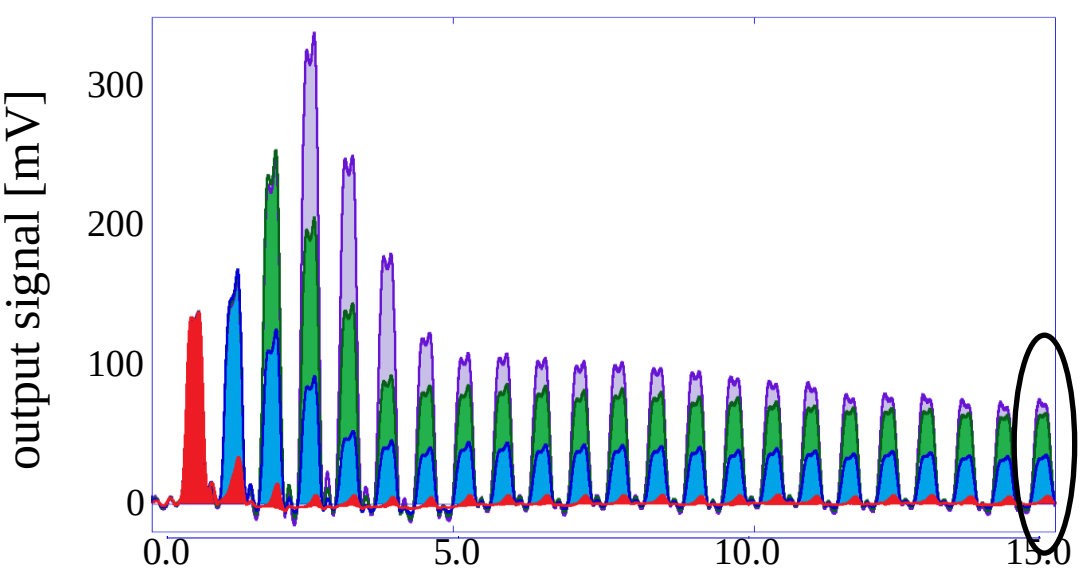
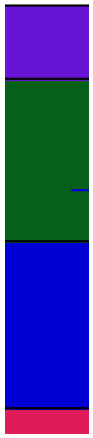


The output signal of bunch monitor



percentages

4th 17%

3rd 38%

2nd 38%

1st 7%

Optimization of injection parameters improve beam injection efficiency.

summary

The bump magnet has been developed.

- The litz wire was used in the coil
- measured magnetic field is in good agreement with the calculation.

The increase of beam intensity with multi-turn injection was demonstrated.

- 4 pulses injection is possible.

future

Optimization of the injection parameters is required for more efficient injection.

(adjustment of the beam transport line, the position and electric field of septum, the waveform of the bump magnets, etc.)