HTc-SQUID Beam Current Monitor at the RIBF

HTc: High Critical Temperature
SQUID: Superconductive Quantum Interference Device

T. Watanabe*, N. Fukunishi, M. Kase
RIKEN Nishina Center
S. Inamori, K. Kon
TEP Corporation

IBIC 2015
16 September 2015
MCEC MELBORNE

Preview

Preview

- Purpose and Importance
- How to measure?
- What Can the HTc SQUID Monitor Do?
- Improvement of Magnetic Shield
- Conclusion

Purpose and Importance of High-Tc SQUID Monitor

Purpose and Importance of High-Tc SQUID Monitor

- What do we measure?

  → The current (position) of the DC beam

- What are the advantages of measuring a beam using a SQUID?

  → (1) Nondestructively, (2) Accurately, (3) In real time

- Why do we need a SQUID monitor?

  Why 

  - For high-energy heavy-ion beams,

    If a beam is stopped by a Faraday cup,

    (1) the beam can no longer be used;

    (2) there is a danger of melting and activating of cup;

    (3) it is difficult to completely suppress secondary electrons.

- HTc SQUID monitor can address all these problems !

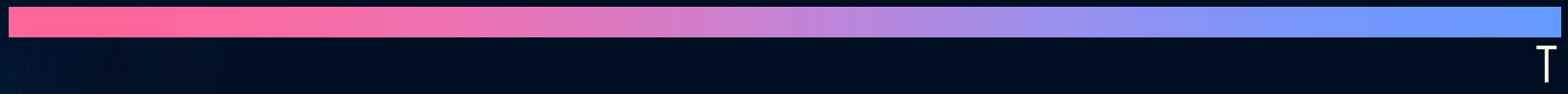
Motivation

– Why we decided to conduct present work –

Motivation

– Why we decided to conduct present work –

- Why SQUID?
  - DC Current Transformer => Sensitivity ~1μA

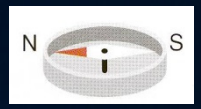


Motivation

– Why we decided to conduct present work –

- Why SQUID?
  - DC Current Transformer => Sensitivity ~1μA

Earth's magnetic field



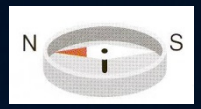
10^{-5} T

Motivation

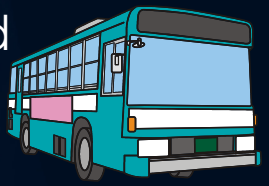
– Why we decided to conduct present work –

- Why SQUID?
  - DC Current Transformer => Sensitivity ~1μA

Earth's magnetic field



Environmental Noise



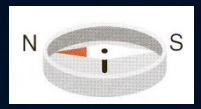
10^{-5} 10^{-6} T

Motivation

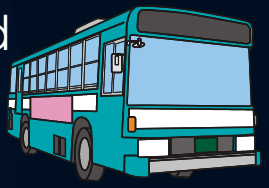
– Why we decided to conduct present work –

- Why SQUID?
  - DC Current Transformer => Sensitivity ~1μA

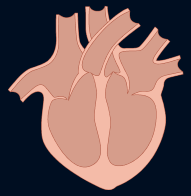
Earth's magnetic field



Environmental Noise



Heart



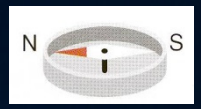
10^{-5} 10^{-6} 10^{-10} **SQUID** T

Motivation

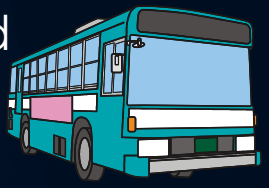
– Why we decided to conduct present work –

- Why SQUID?
  - DC Current Transformer => Sensitivity ~1μA

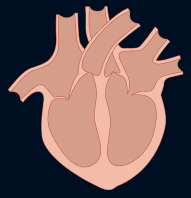
Earth's magnetic field

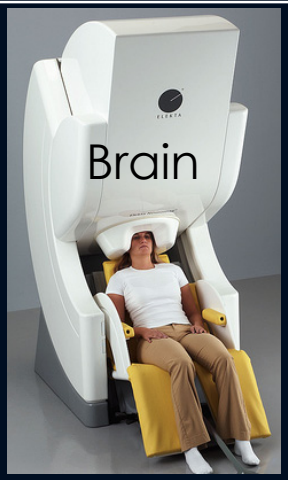


Environmental Noise



Heart





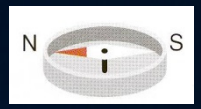
10^{-5} 10^{-6} 10^{-10} **SQUID** 10^{-13} T

Motivation

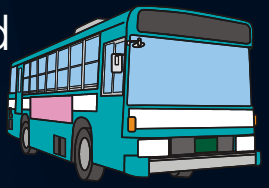
– Why we decided to conduct present work –

- Why SQUID?
  - DC Current Transformer => Sensitivity ~1μA

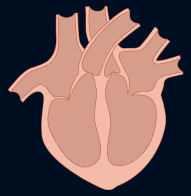
Earth's magnetic field

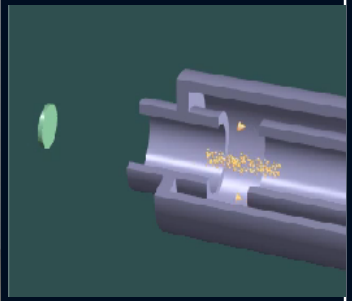


Environmental Noise



Heart





1 nA Beam @10 cm

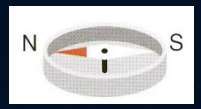
10^{-5} 10^{-6} 10^{-10} **SQUID** 10^{-13} 10^{-15} T

Motivation

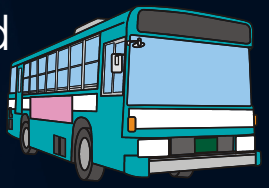
– Why we decided to conduct present work –

- Why SQUID?
  - DC Current Transformer => Sensitivity ~1μA

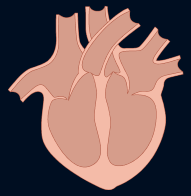
Earth's magnetic field

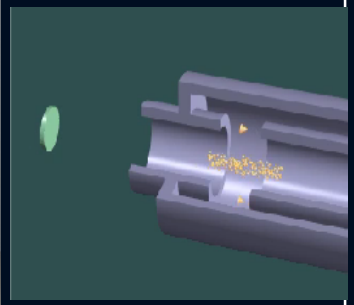


Environmental Noise



Heart





1 nA Beam @10 cm

10^{-5} 10^{-6} 10^{-10} **SQUID** 10^{-13} 10^{-15} T

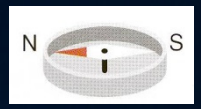
$1/10^{10}$!!

Motivation

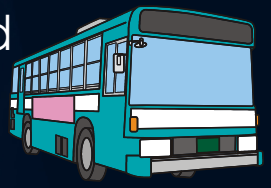
– Why we decided to conduct present work –

- Why SQUID?
  - DC Current Transformer => Sensitivity ~1μA

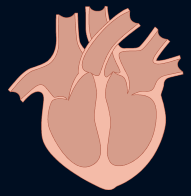
Earth's magnetic field

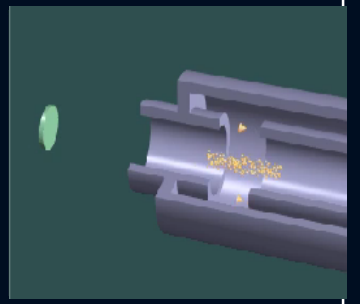


Environmental Noise



Heart





1 nA Beam @10 cm

10^{-5} 10^{-6} 10^{-10} **SQUID** 10^{-13} 10^{-15} T

$1/10^{10}$!!

0.1 μA Beam

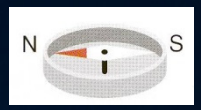
Motivation

– Why we decided to conduct present work –

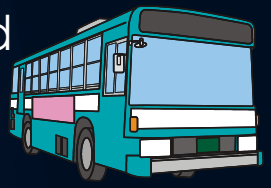
Why SQUID?

- DC Current Transformer => Sensitivity ~1μA

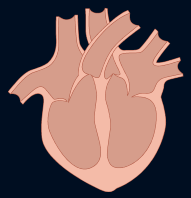
Earth's magnetic field

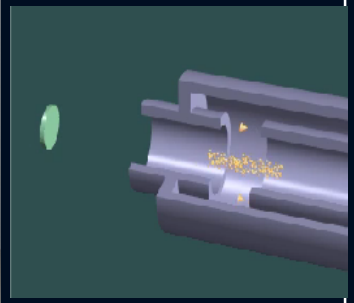


Environmental Noise



Heart





1 nA Beam @10 cm

10^{-5} 10^{-6} 10^{-10} **SQUID** 10^{-13} 10^{-15} T

$1/10^{10}$!!

0.1 μA Beam

Why High-Tc superconductor?

Superconductor

SQUID

⇒

Operation Temperature
Lq. He ⇒ Lq. N_2
4.2 K ⇒ 77.3K

⇒

Downsizing System

Reduction of running costs

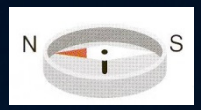
Motivation

– Why we decided to conduct present work –

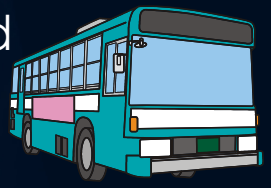
Why SQUID?

- DC Current Transformer => Sensitivity ~1μA

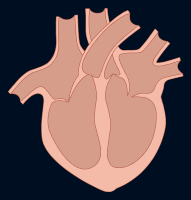
Earth's magnetic field

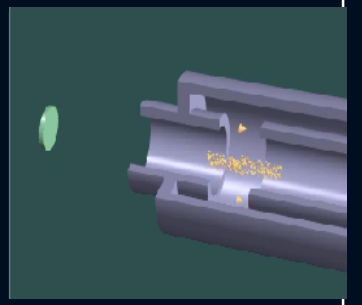


Environmental Noise



Heart





1 nA Beam @10 cm

10^{-5} 10^{-6} 10^{-10} **SQUID** 10^{-13} 10^{-15} T

$1/10^{10}$!!

0.1 μA Beam

Why High-Tc superconductor?

Superconductor

SQUID

⇒

Operation Temperature
Lq. He ⇒ Lq. N_2
4.2 K ⇒ 77.3K

⇒

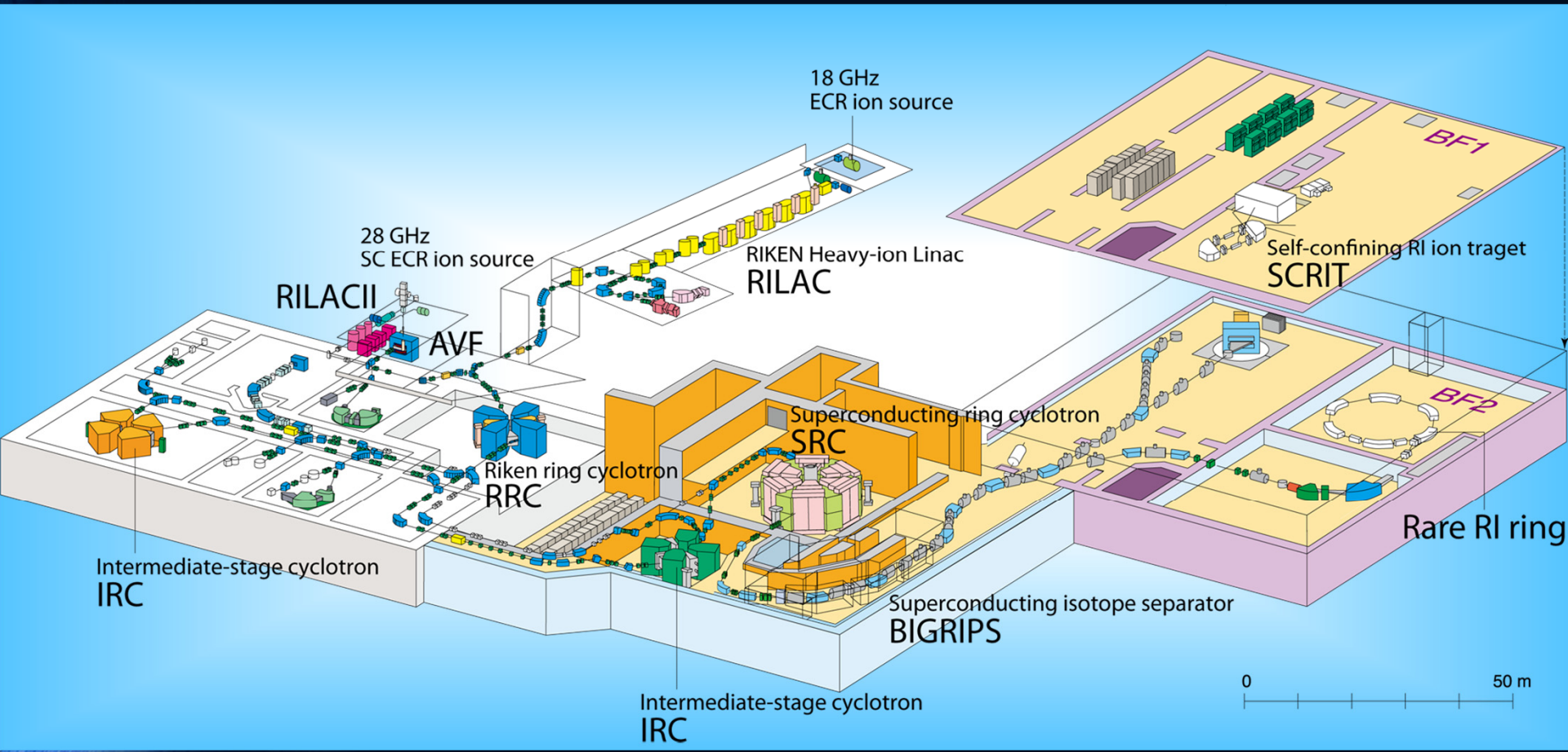
Downsizing System

Reduction of running costs

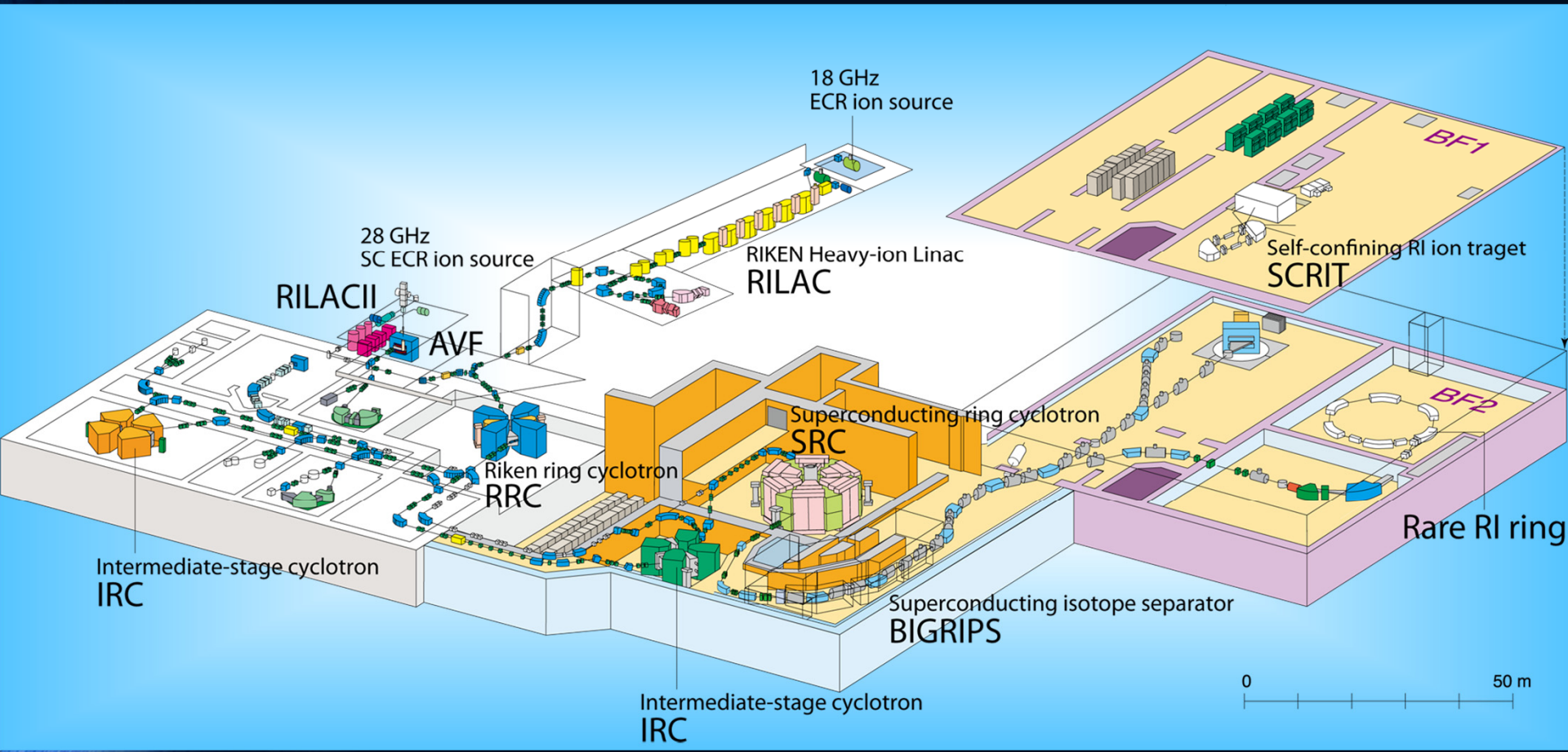
Estimation using Japanese price

	Cooking system	Unit cost	Cooling cost (1 day)	Cooling cost (1 year)
Low-Tc SQUID monitor	Lq. He	$22 /L	$220 (10 L/day)	**$80,300**
High-Tc SQUID monitor	Refrigerator	$0.1 /kWh	$4.6 (1.9 kW)	**$1,679**

Where is the SQUID Monitor?

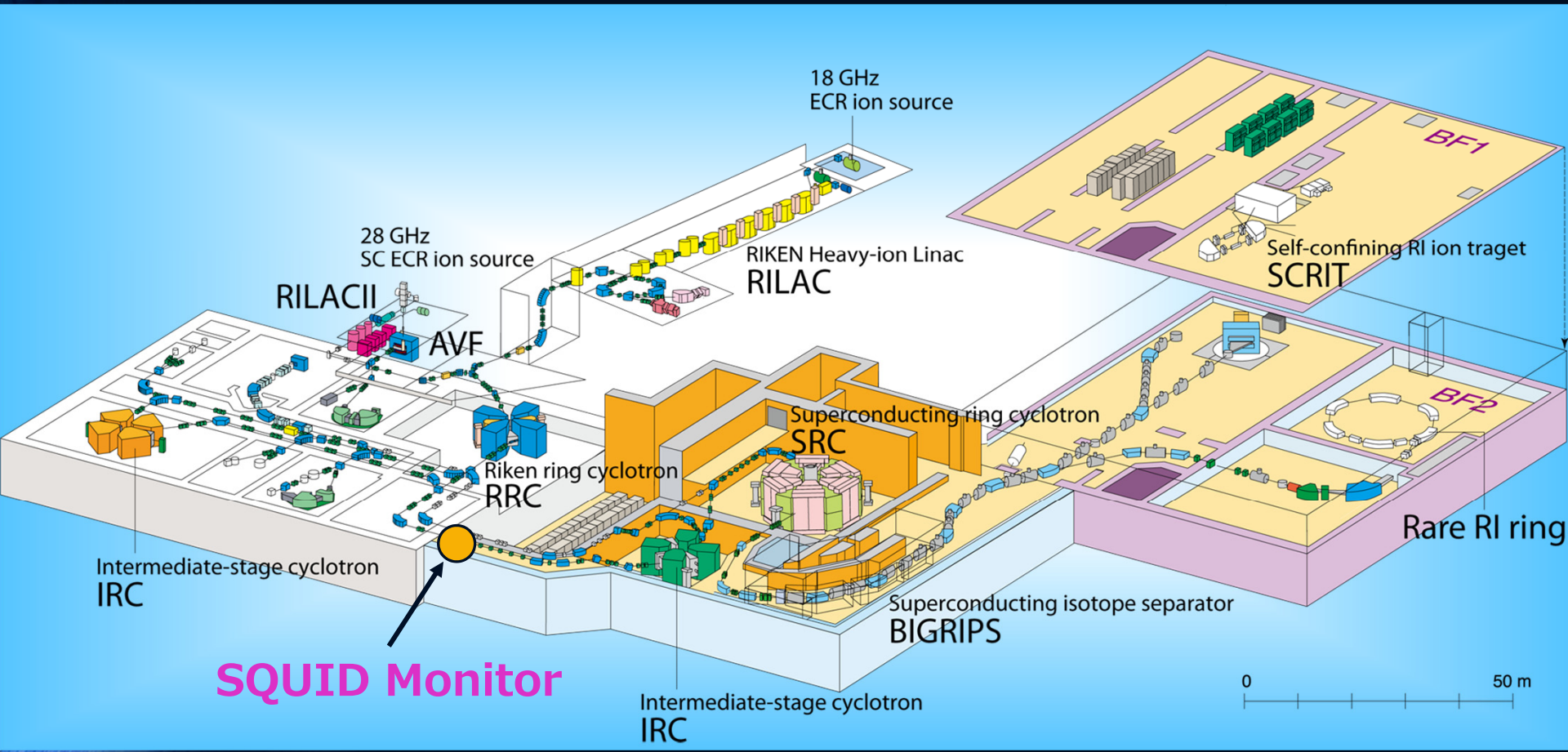


Where is the SQUID Monitor?



- ECR Ion Source Ar
- RRC A01 Ar
- IRC H11 (NOW) Ca, Zn, Kr, U

Where is the SQUID Monitor?

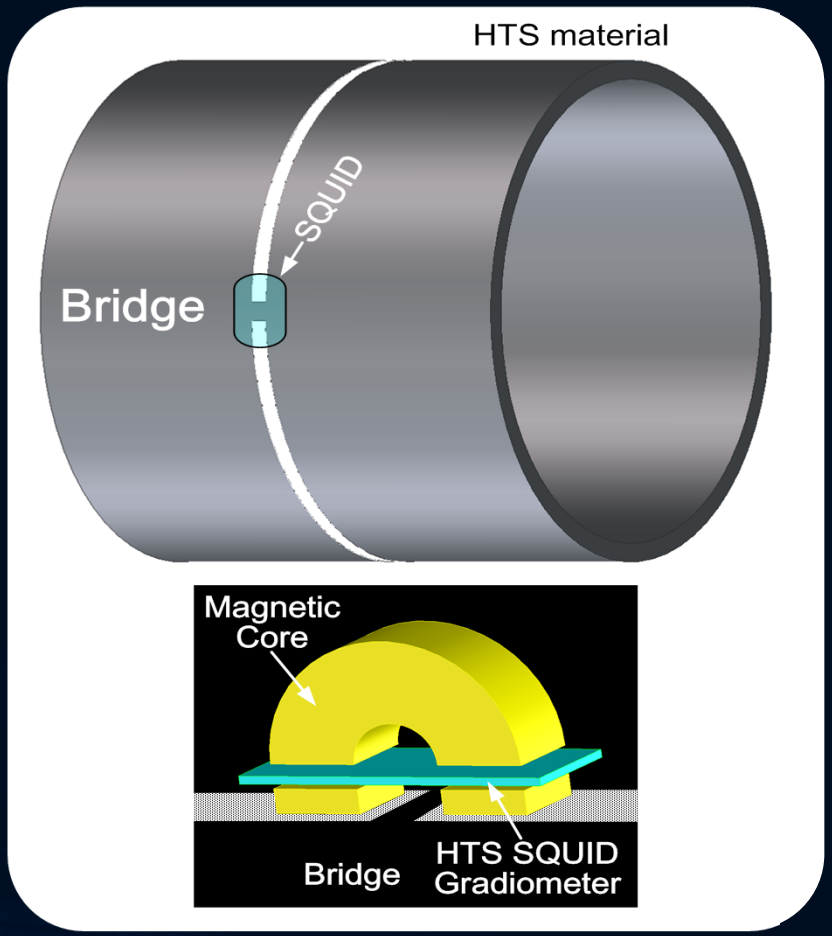


- ECR Ion Source Ar
- RRC A01 Ar
- IRC H11 (NOW) Ca, Zn, Kr, U

- Purpose and Importance
- How to measure

Principle of HTc SQUID monitor

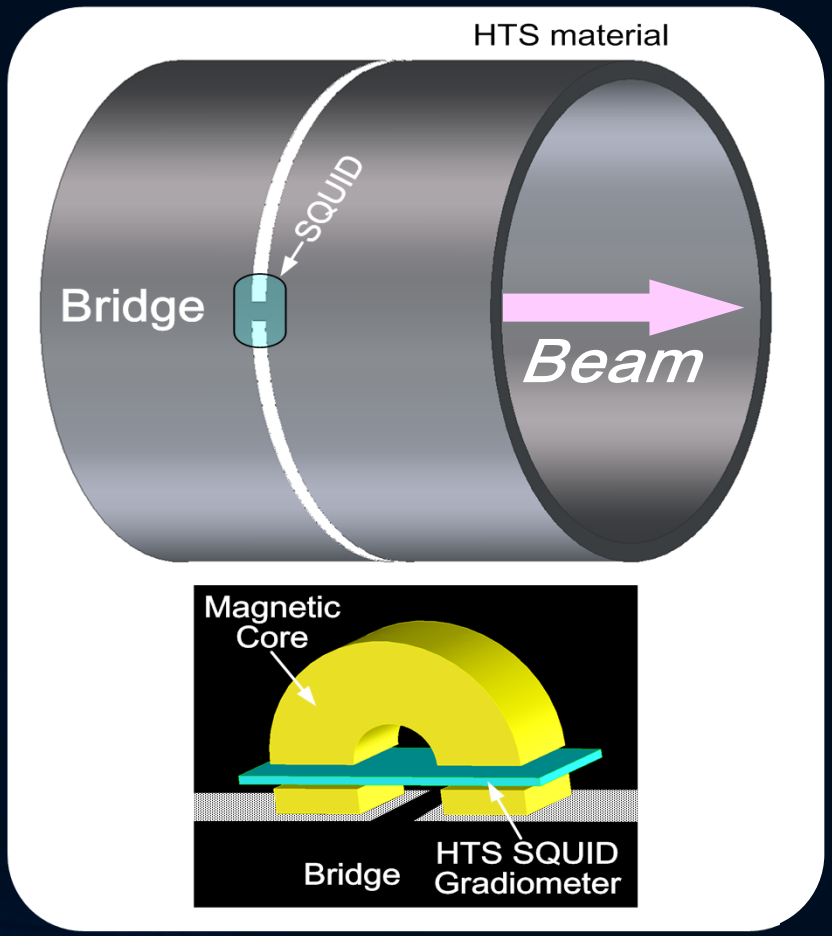
Superconductor: $Bi(Pb)_2$-Sr_2-Ca_2-Cu_3-O_x (Bi2223)
Substrate: 99.9% MgO ceramic



Principle of HTc SQUID monitor

Irradiation of beam

Superconductor: $Bi(Pb)_2$-Sr_2-Ca_2-Cu_3-O_x (Bi2223)
Substrate: 99.9% MgO ceramic



Principle of HTc SQUID monitor

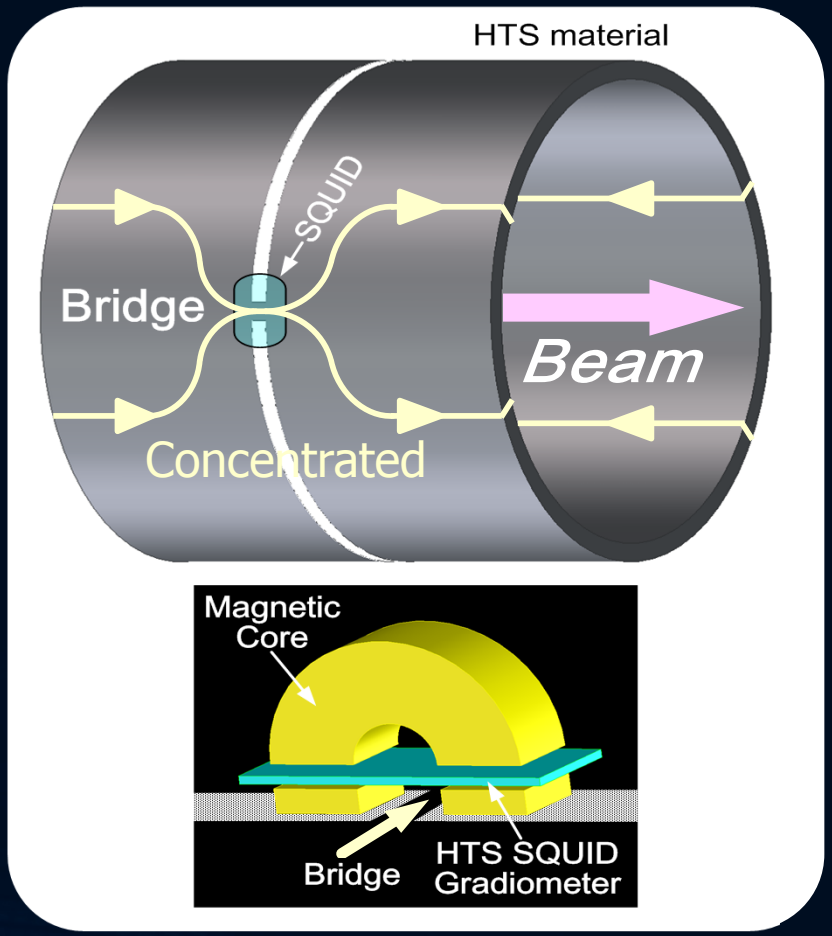
Irradiation of beam

↓

Shielding current is produced by Meissner effect

↓

Superconductor: $Bi(Pb)_2$-Sr_2-Ca_2-Cu_3-O_x (Bi2223)
Substrate: 99.9% MgO ceramic



Principle of HTc SQUID monitor

Irradiation of beam

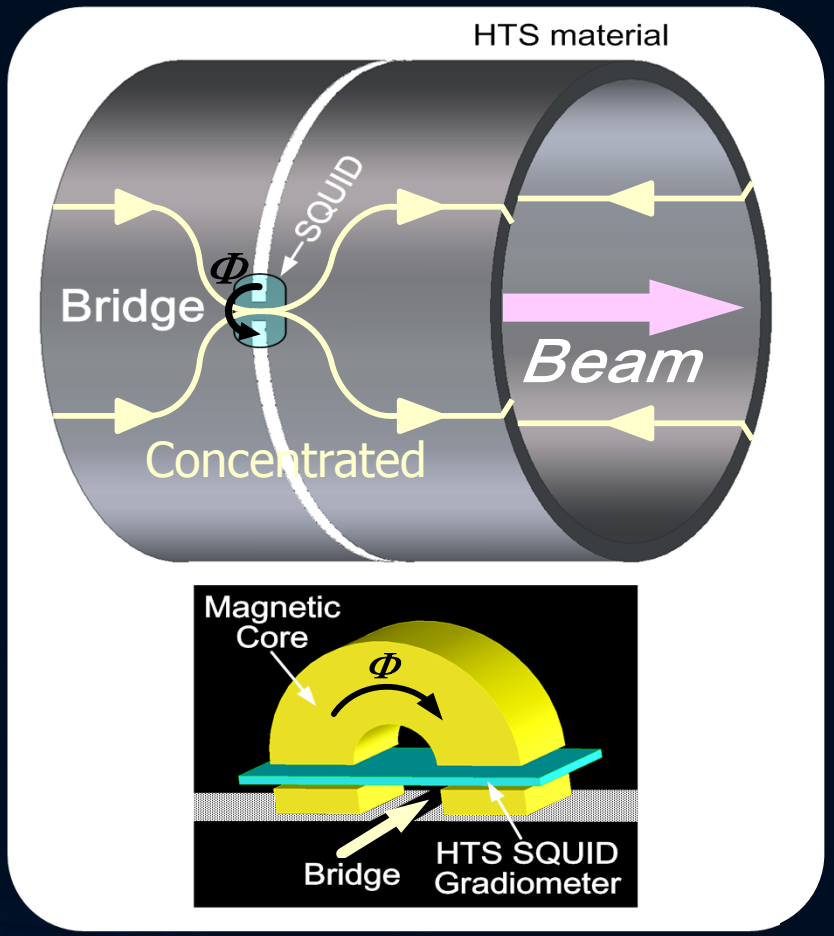
↓

Shielding current is produced by Meissner effect

↓

Designed to have a bridge circuit
Current is concentrated in bridge circuit
SQUID can detect Φ with high S/N ratio

Superconductor: $Bi(Pb)_2$-Sr_2-Ca_2-Cu_3-O_x (Bi2223)
Substrate: 99.9% MgO ceramic



Principle of HTc SQUID monitor

Irradiation of beam

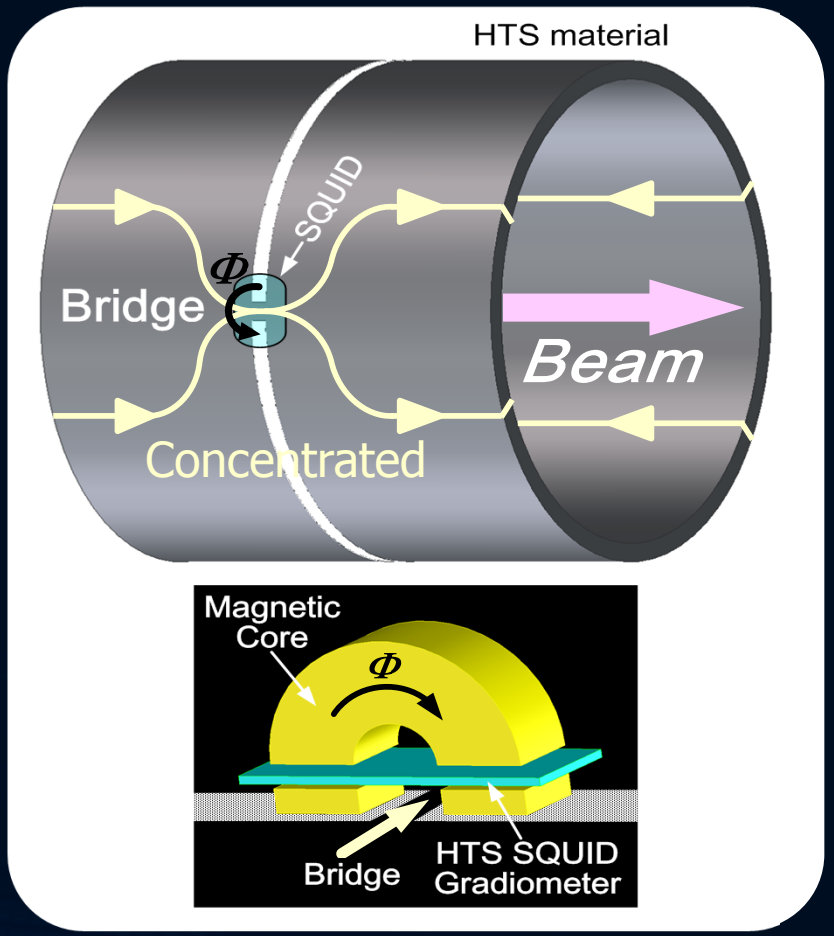
↓

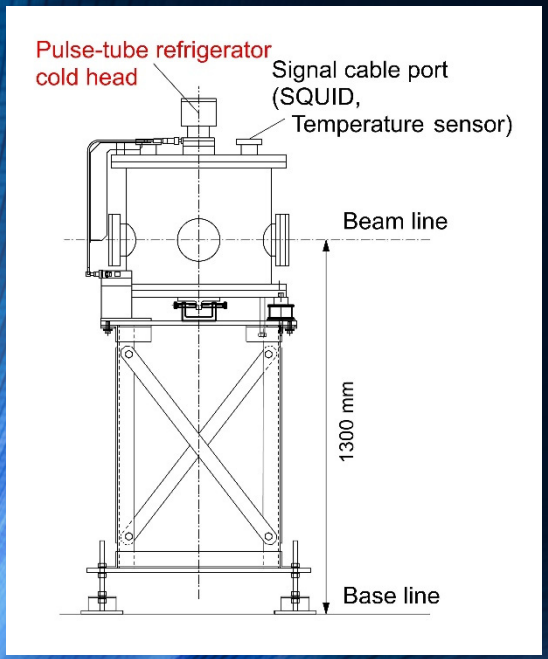
Shielding current is produced by Meissner effect

↓

Designed to have a bridge circuit
Current is concentrated in bridge circuit
SQUID can detect Φ with high S/N ratio

Superconductor: $Bi(Pb)_2$-Sr_2-Ca_2-Cu_3-O_x (Bi2223)
Substrate: 99.9% MgO ceramic





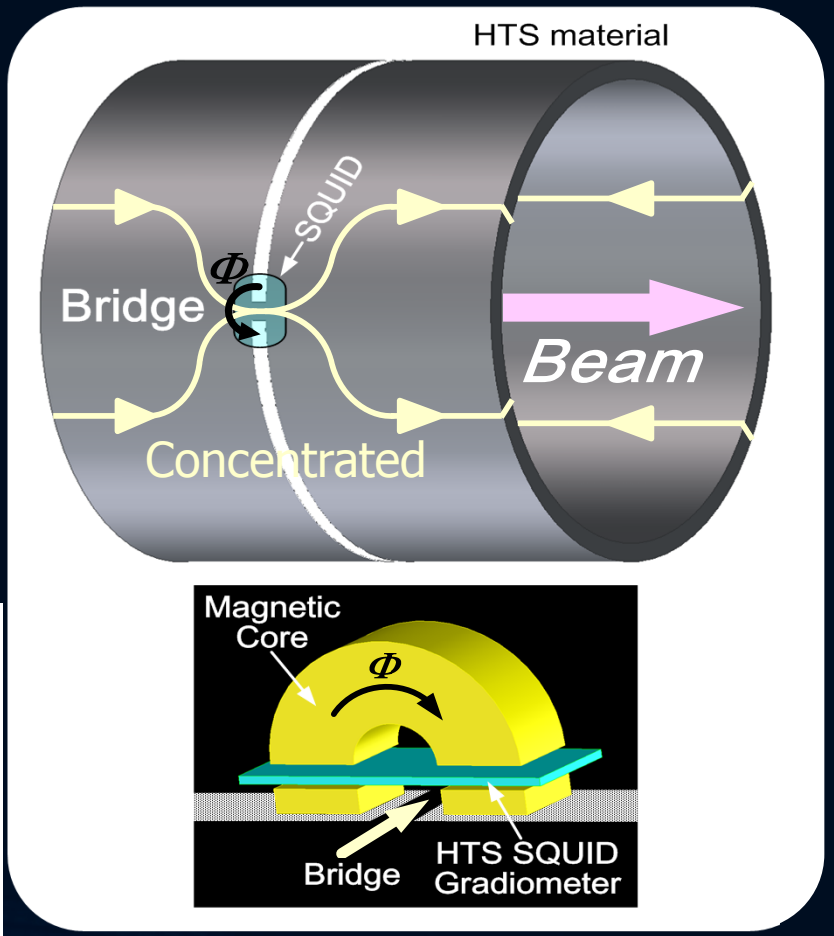
Principle of HTc SQUID monitor

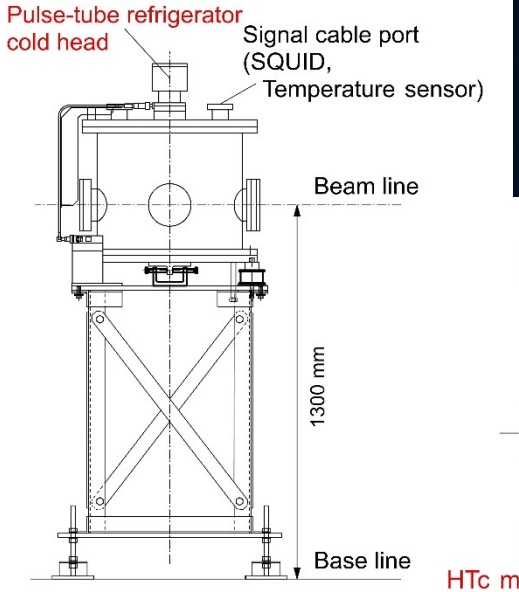
Irradiation of beam

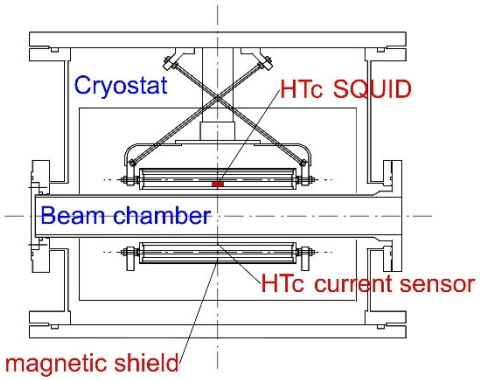
Shielding current is produced by Meissner effect

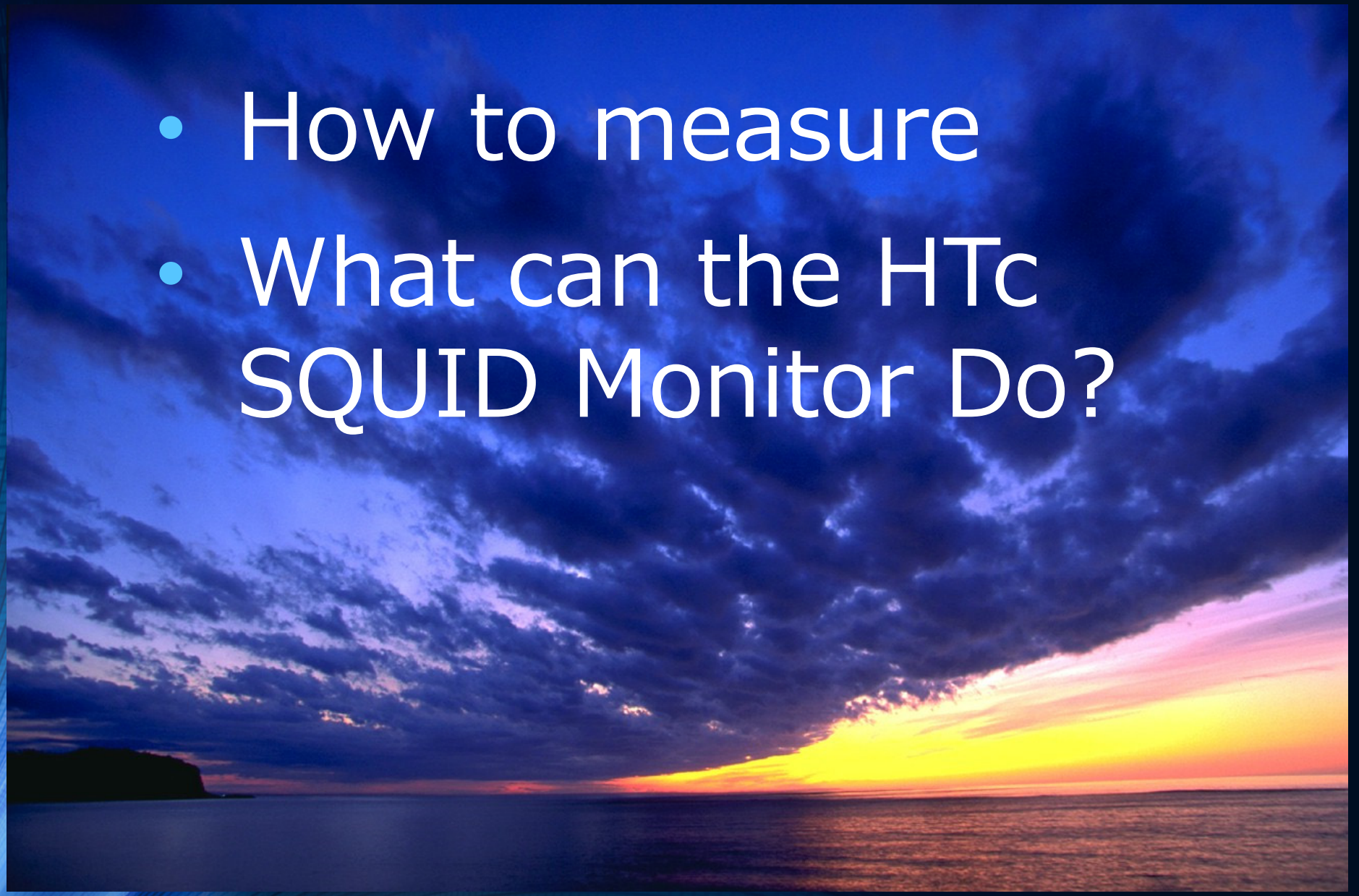
Designed to have a bridge circuit
Current is concentrated in bridge circuit
SQUID can detect Φ with high S/N ratio

Superconductor: $Bi(Pb)_2$-Sr_2-Ca_2-Cu_3-O_x (Bi2223)
Substrate: 99.9% MgO ceramic



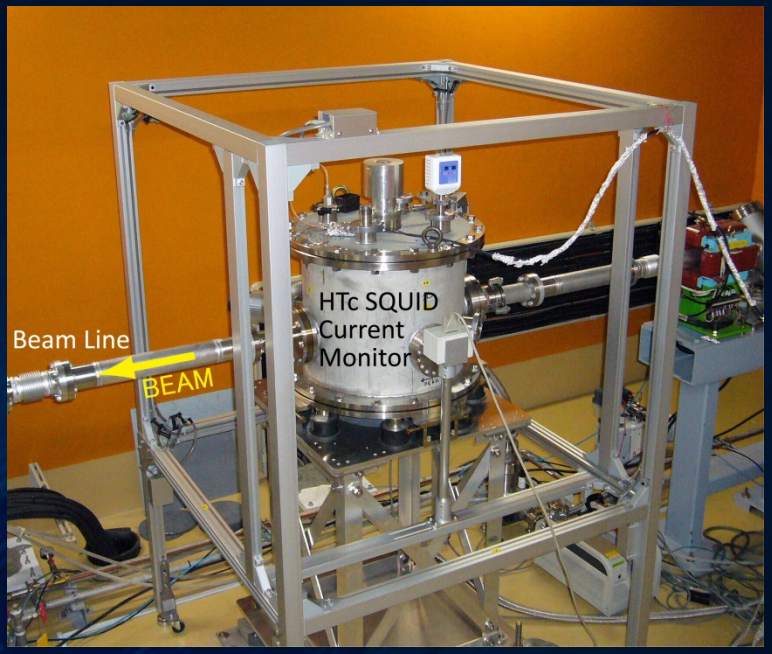





• How to measure
• What can the HTc SQUID Monitor Do?

Measurement for heavy ion beams (2014)

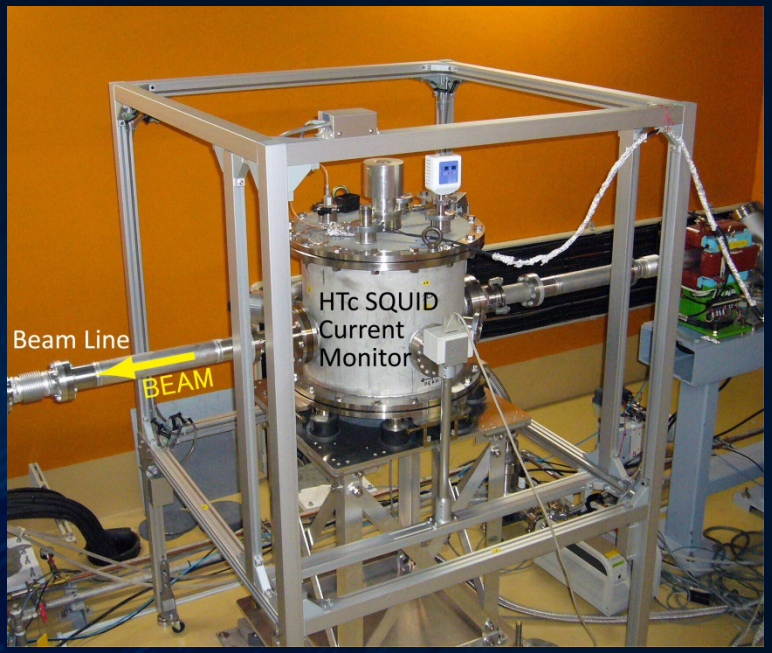
Measurement for heavy ion beams (2014)

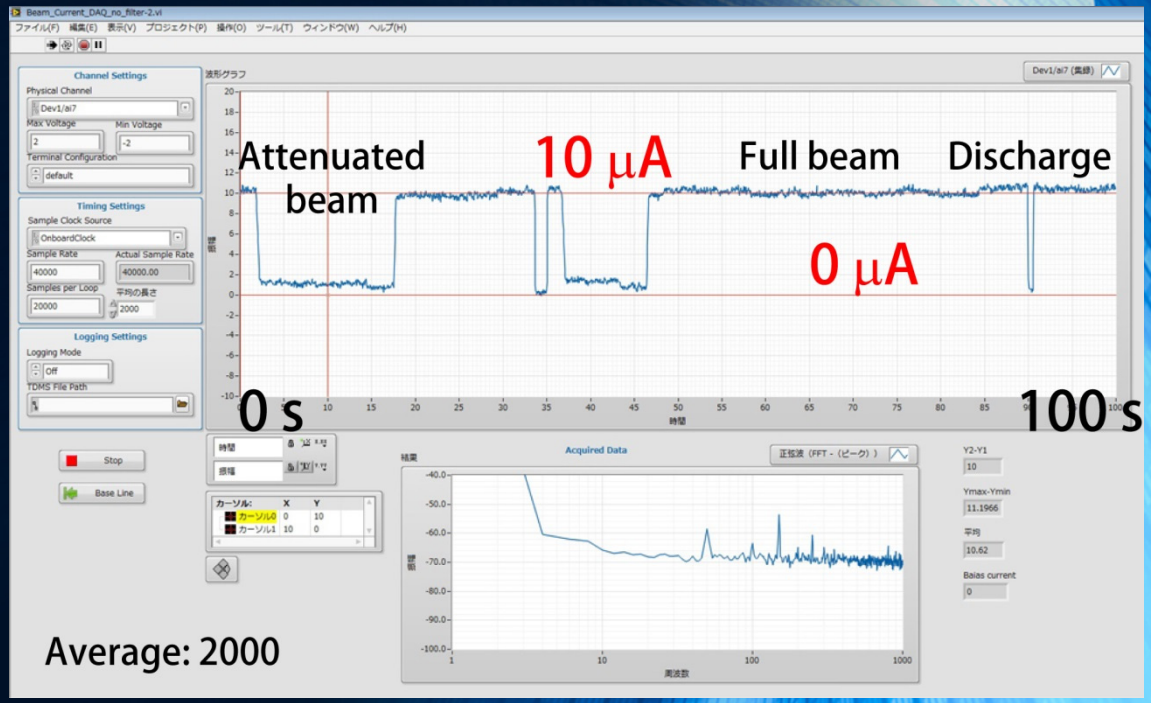


- HTc SQUID monitor installed in the IRC beam line

Measurement for heavy ion beams (2014)

Beam $^{48}Ca^{+20}$ (45.5 MeV/u)

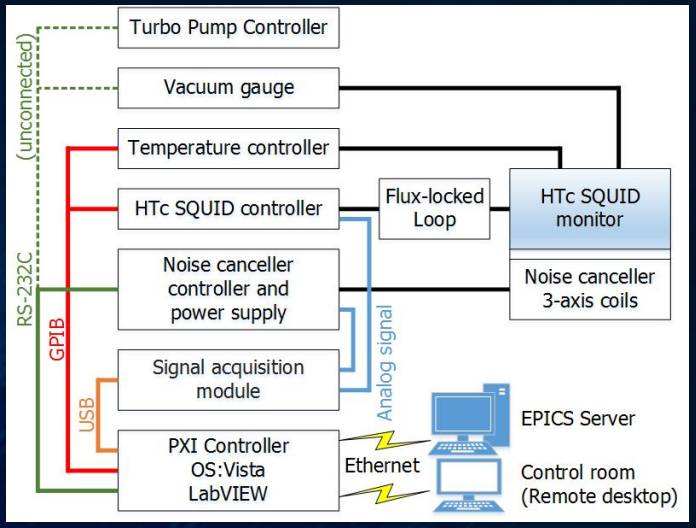




- HTc SQUID monitor installed in the IRC beam line
- 2014/12/10 19:22

Measurement for heavy ion beams (2015)

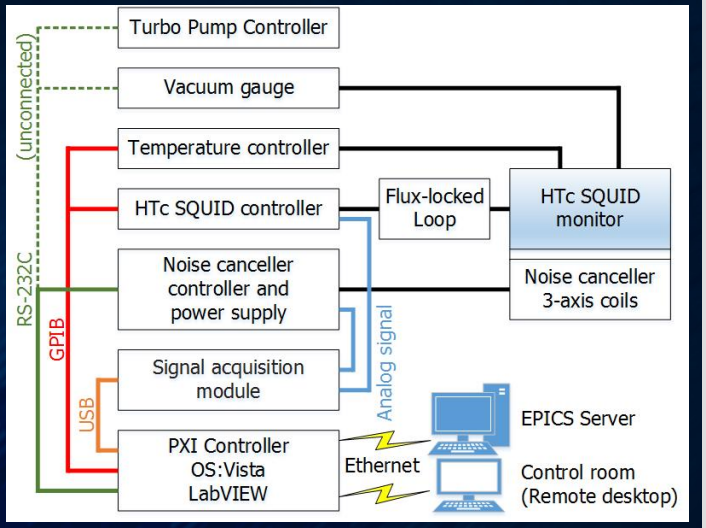
Measurement for heavy ion beams (2015)

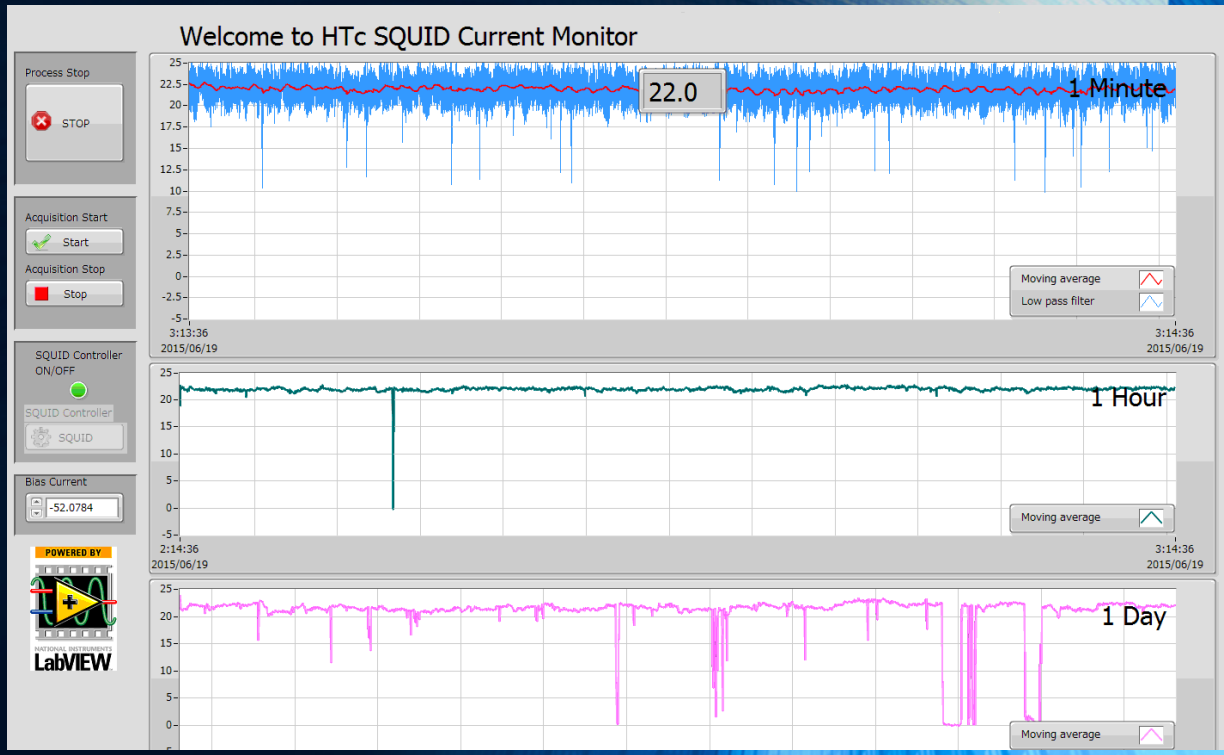


- Programed by LabVIEW

Measurement for heavy ion beams (2015)

Beam $^{78}Kr^{+60}$ (50.0 MeV/u)



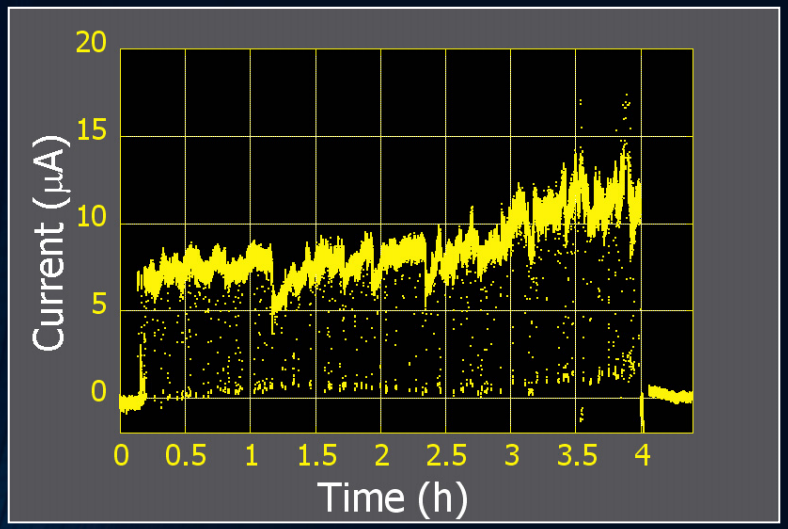


- Programed by LabVIEW
- 2015/ 6/19

FFT analysis

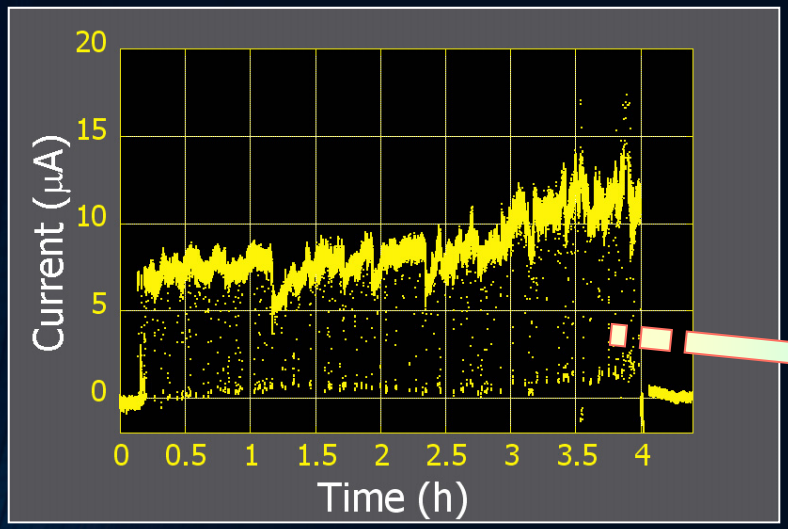
FFT analysis

Beam $^{40}Ar^{+15}$ (63 MeV/u)

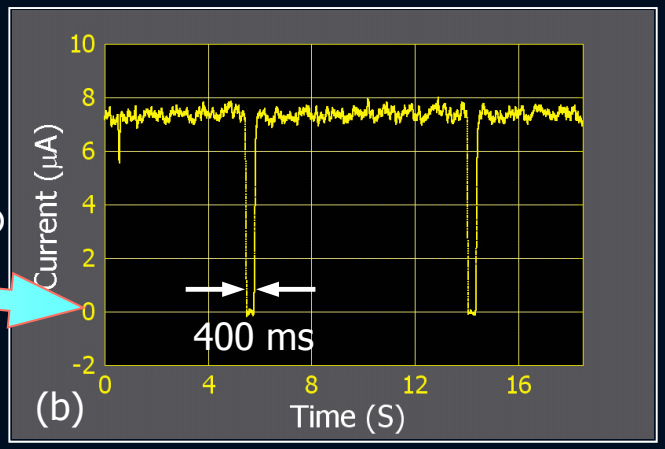


FFT analysis

Beam $^{40}Ar^{+15}$ (63 MeV/u)



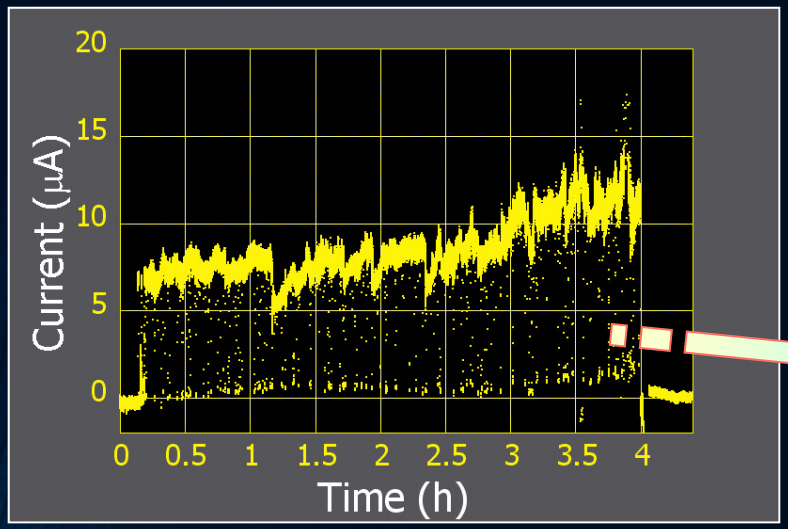
Close up



- Discharge of ECR ion source

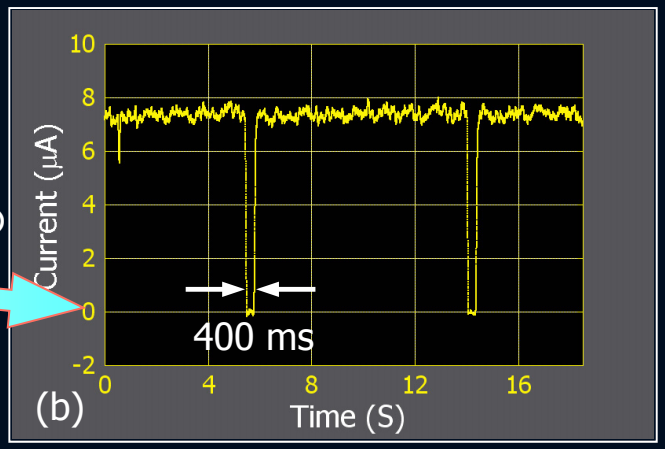
FFT analysis

Beam $^{40}Ar^{+15}$ (63 MeV/u)



- Discharge of ECR ion source

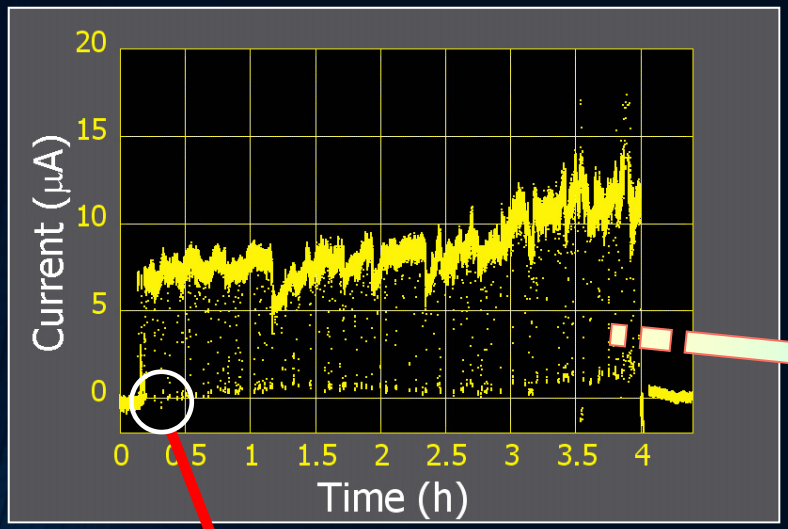
Close up



- Amplitudes of ripples in modulated beam

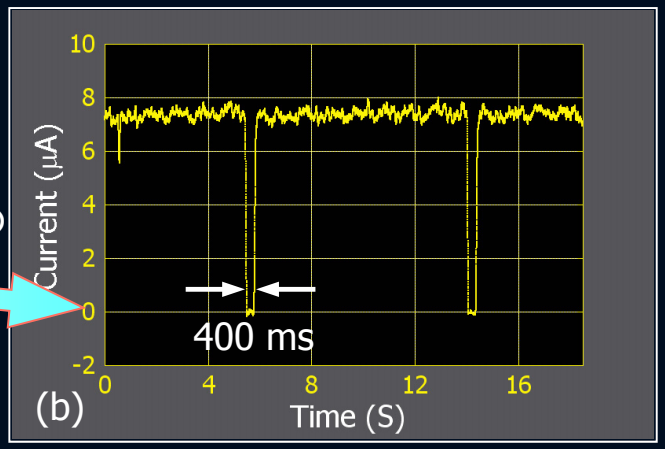
FFT analysis

Beam $^{40}Ar^{+15}$ (63 MeV/u)

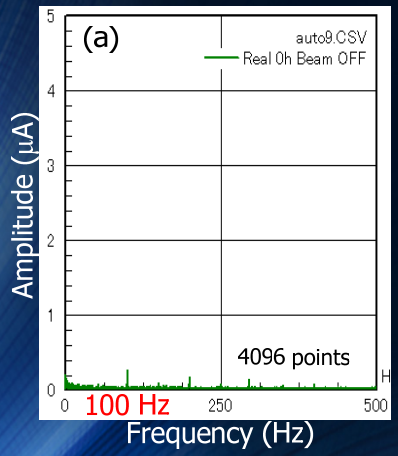


- Discharge of ECR ion source

Close up



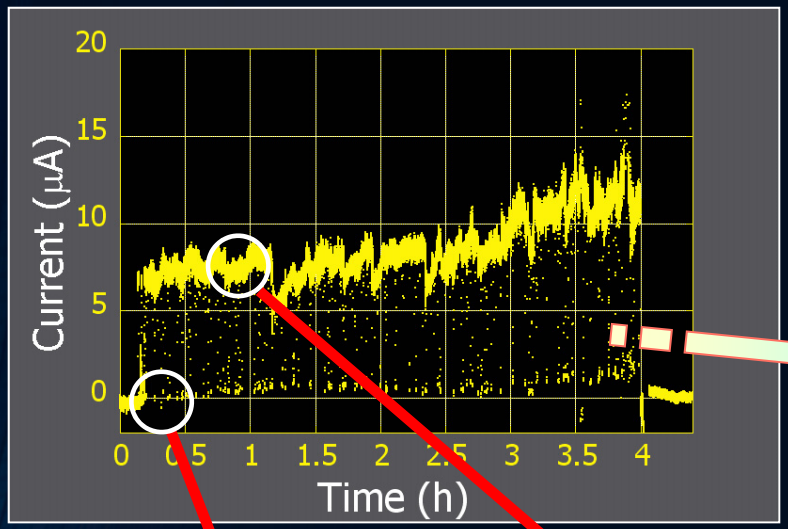
- Amplitudes of ripples in modulated beam



0 hour (beam off)

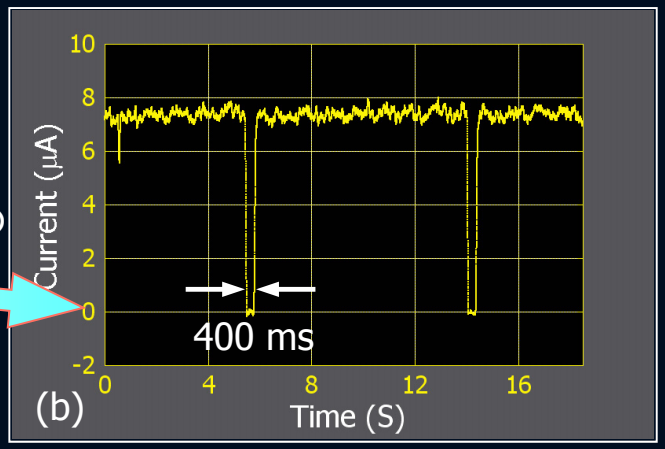
FFT analysis

Beam $^{40}Ar^{+15}$ (63 MeV/u)

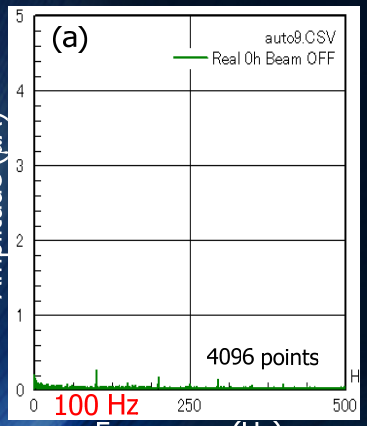


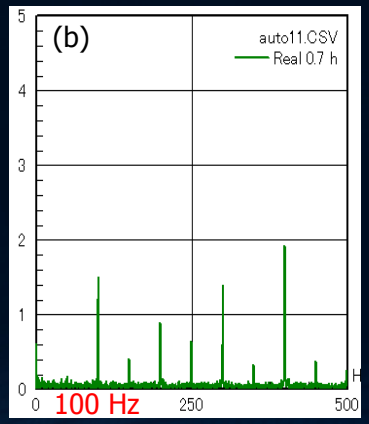
- Discharge of ECR ion source

Close up



- Amplitudes of ripples in modulated beam



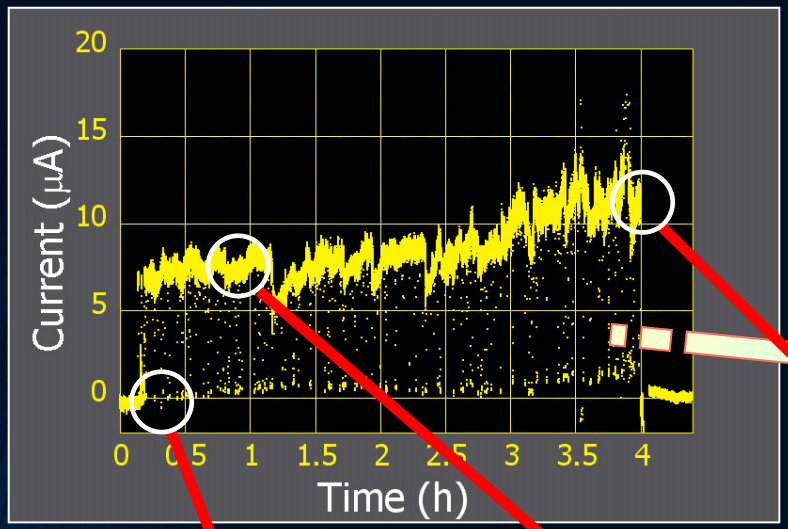


0 hour (beam off)

0.7 h

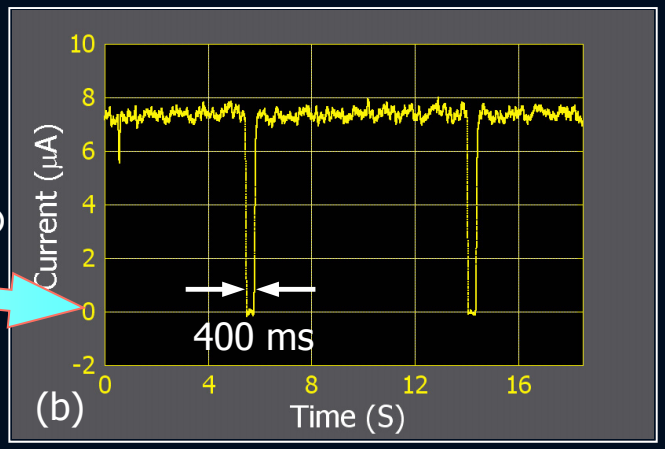
FFT analysis

Beam $^{40}Ar^{+15}$ (63 MeV/u)

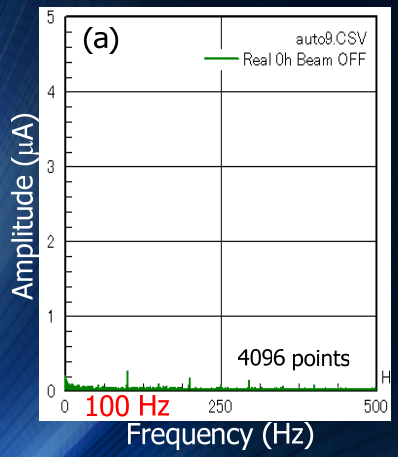


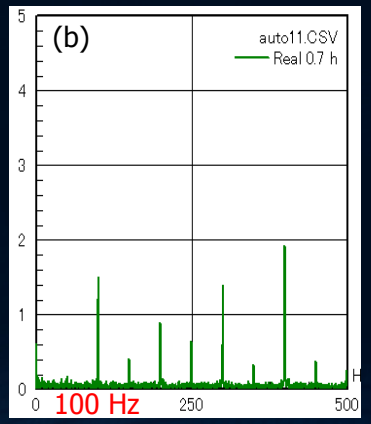
- Discharge of ECR ion source

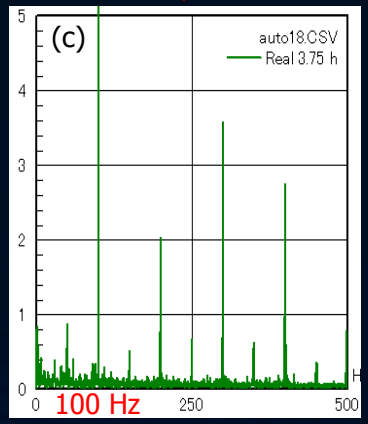
Close up



- Amplitudes of ripples in modulated beam



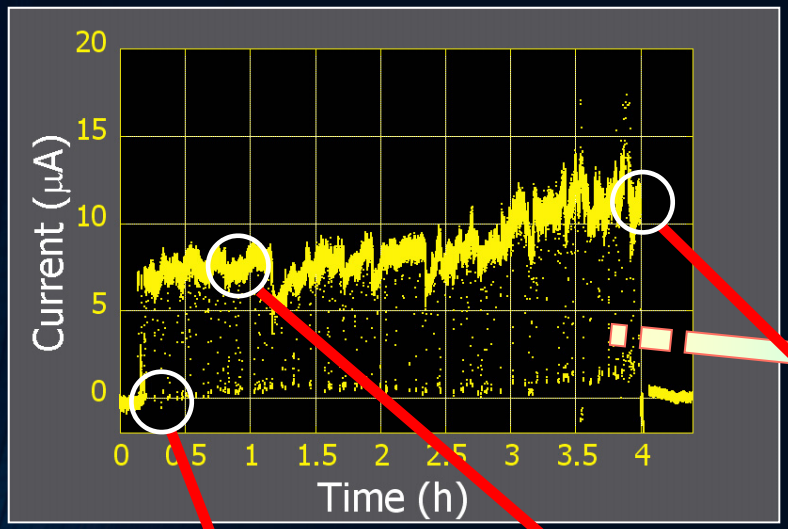




0 hour (beam off) 0.7 h 3.8 h

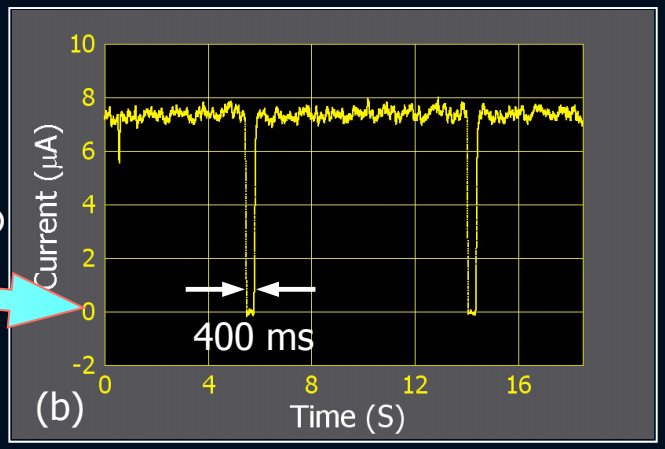
FFT analysis

Beam $^{40}Ar^{+15}$ (63 MeV/u)

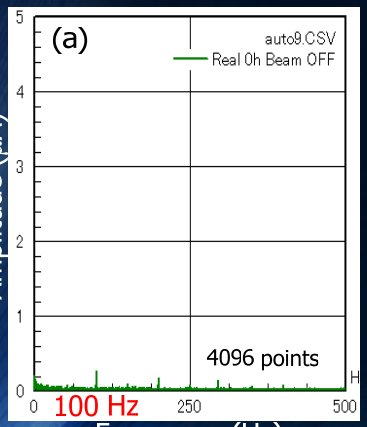


- Discharge of ECR ion source

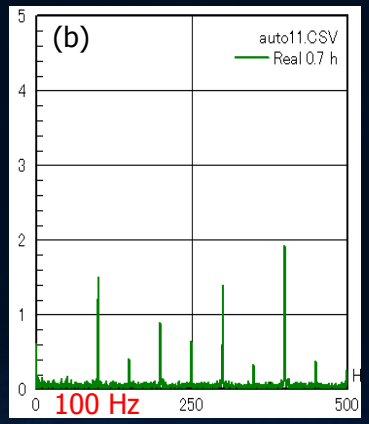
Close up



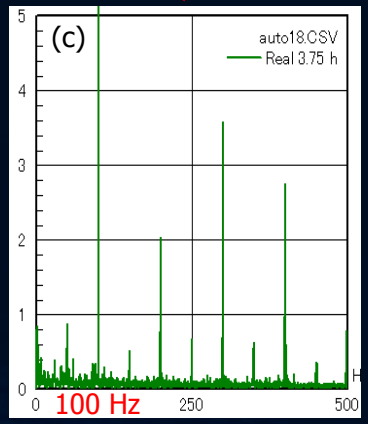
- Amplitudes of ripples in modulated beam



0 hour (beam off)



0.7 h



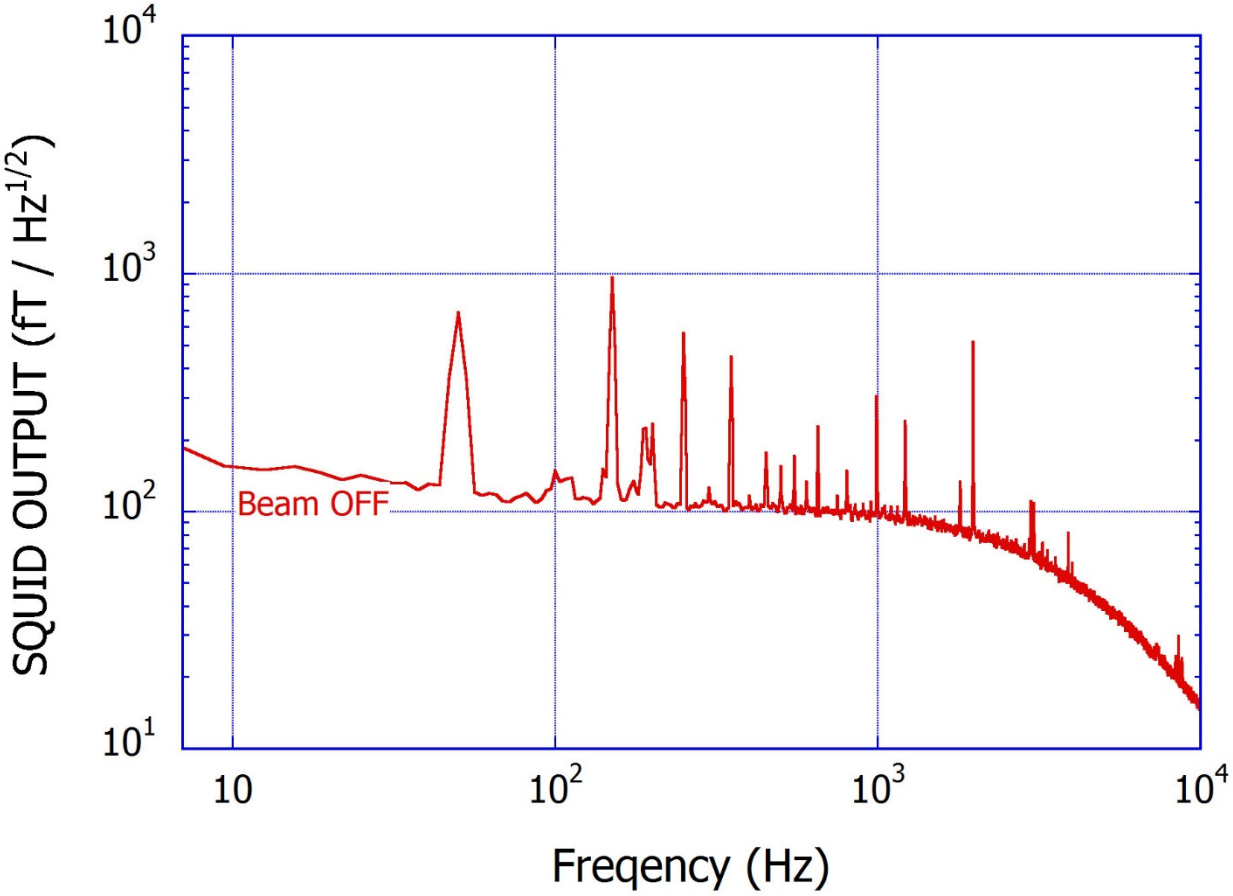
3.8 h

- Measurements and analyses
- In real time
- Without interrupting beam user's experiments

FFT analysis

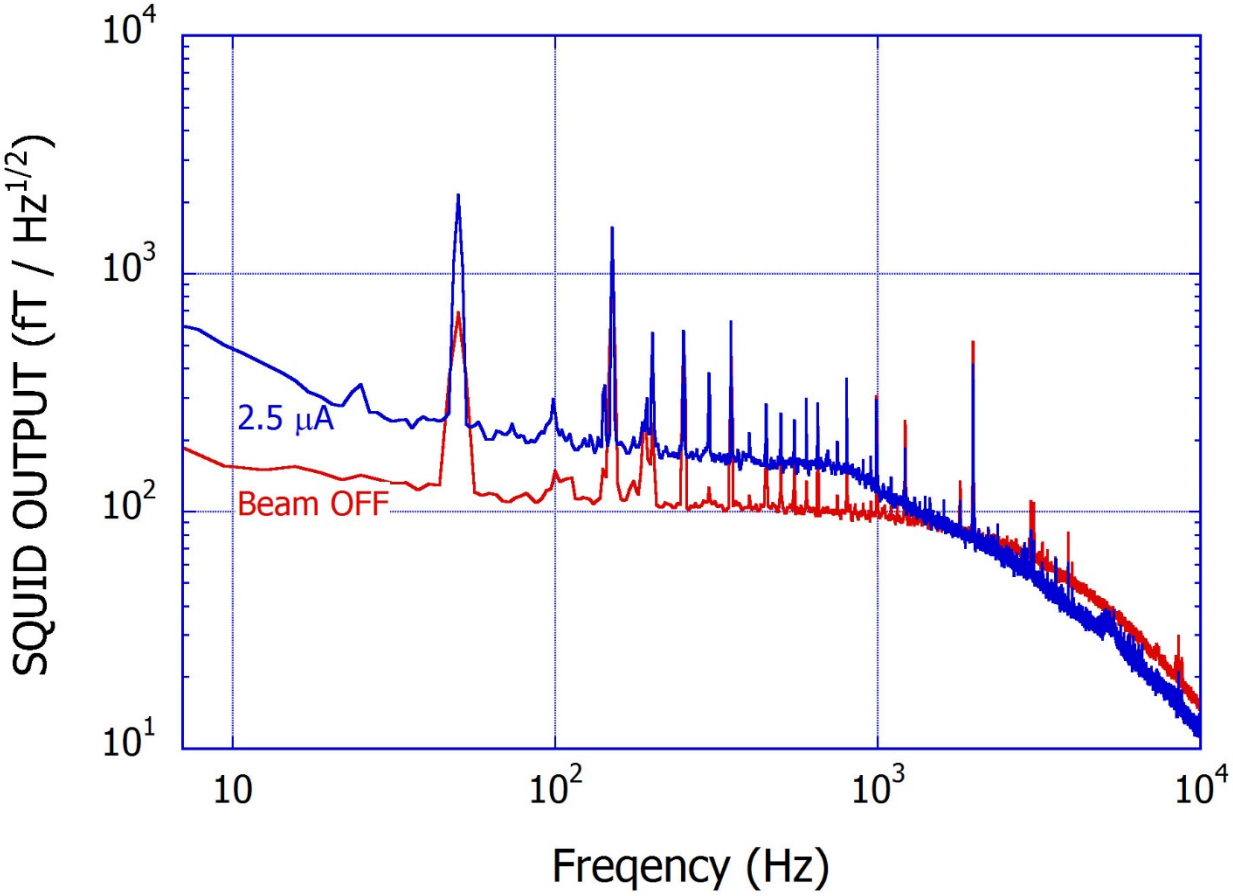
FFT analysis

Beam $^{78}Kr^{+60}$ (50.0 MeV/u)



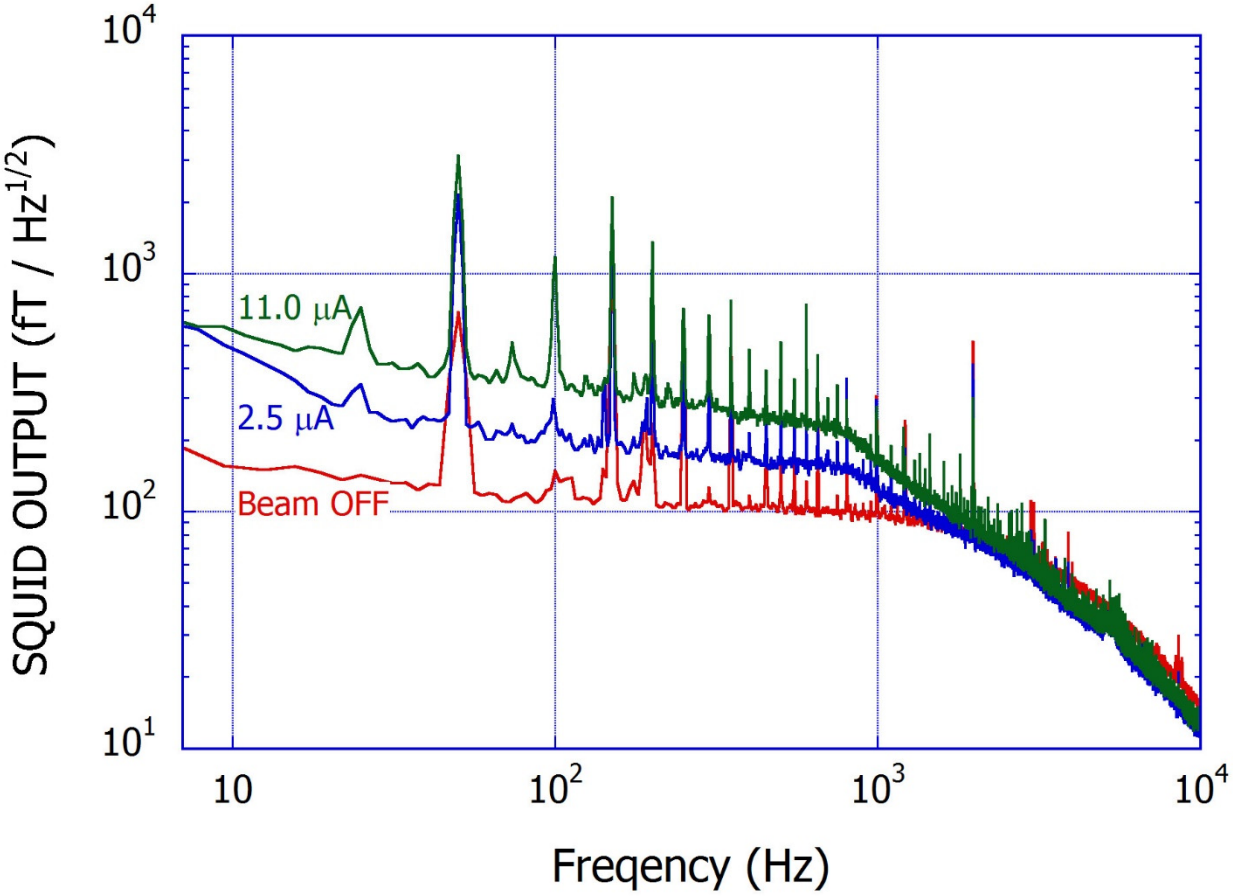
FFT analysis

Beam $^{78}Kr^{+60}$ (50.0 MeV/u)



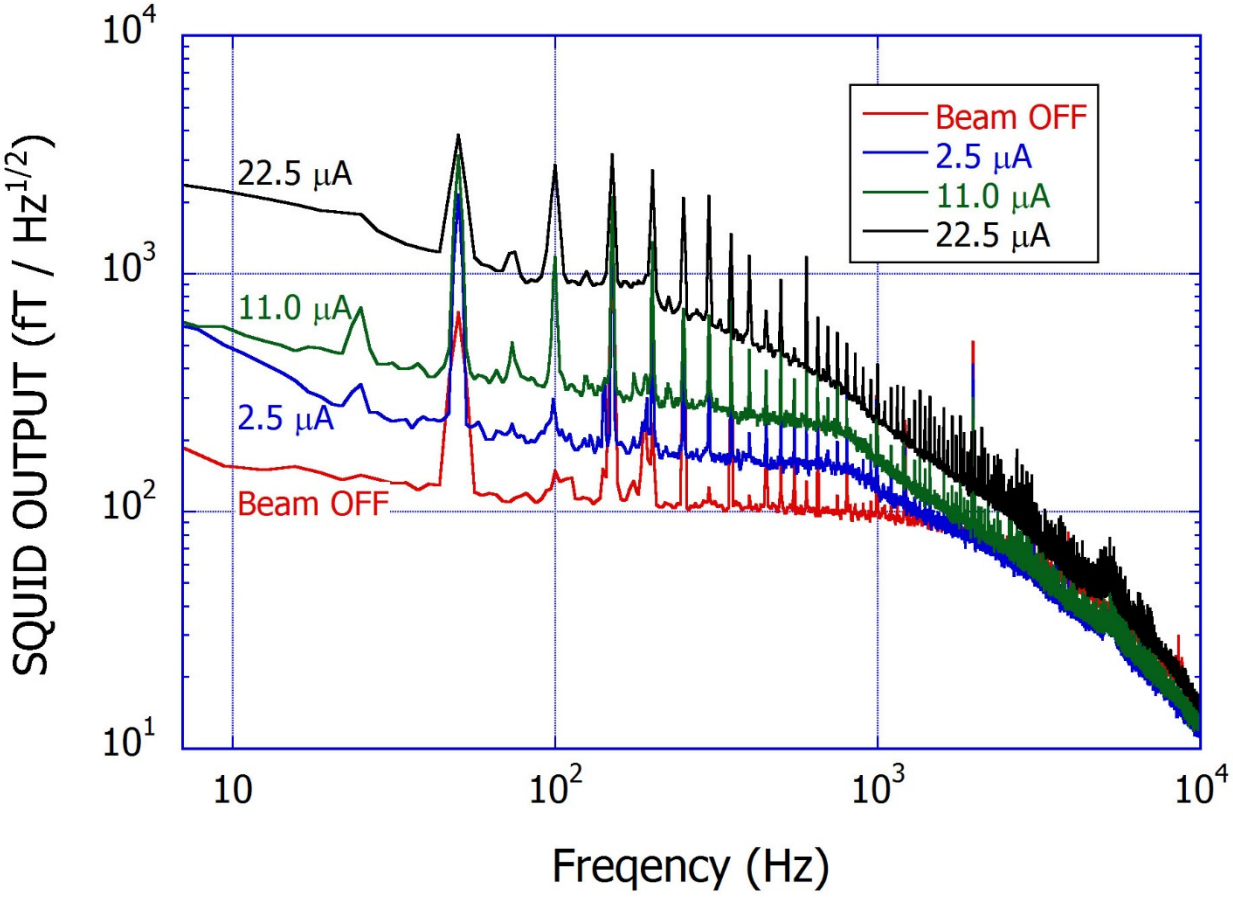
FFT analysis

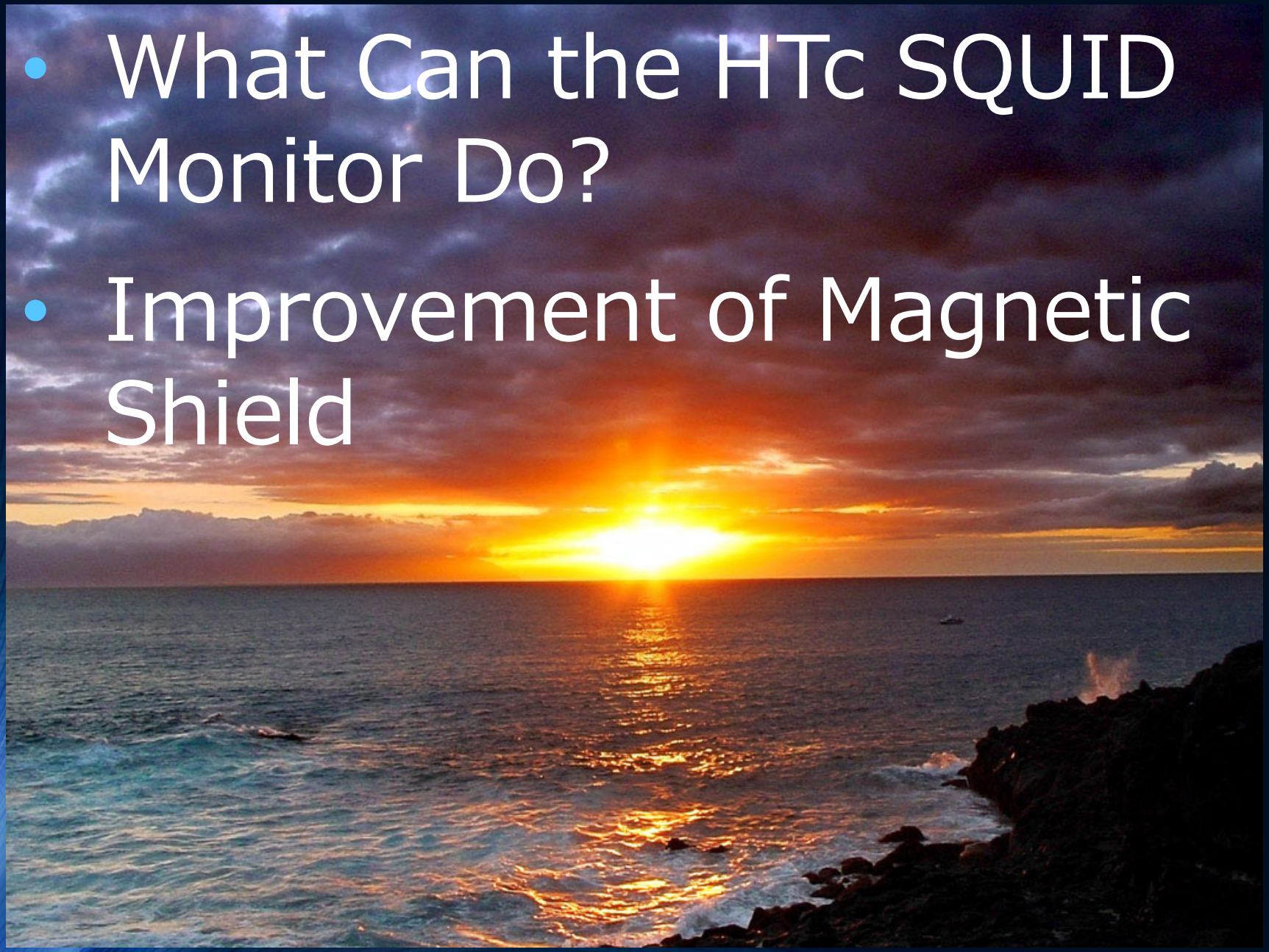
Beam $^{78}Kr^{+60}$ (50.0 MeV/u)



FFT analysis

Beam $^{78}Kr^{+60}$ (50.0 MeV/u)





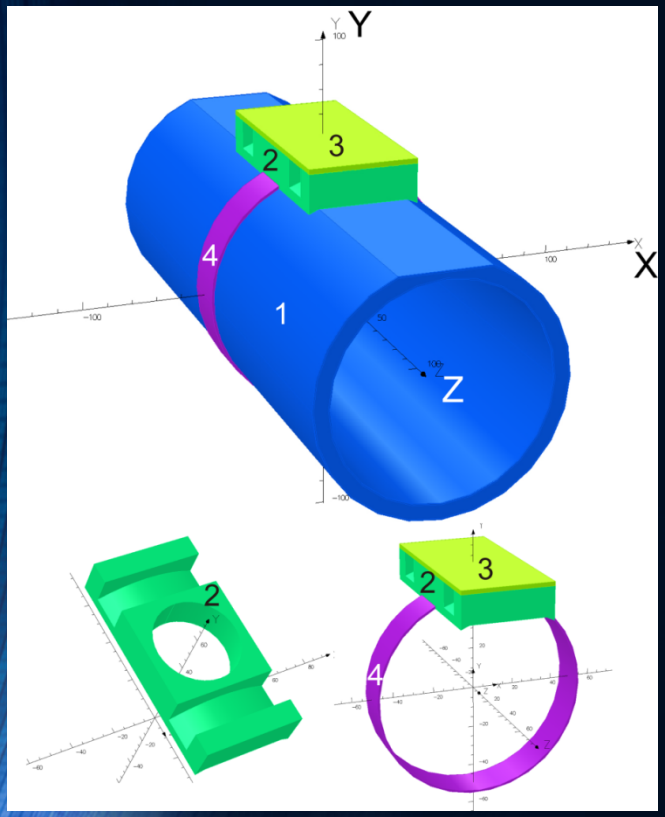
- What Can the HTc SQUID Monitor Do?
- Improvement of Magnetic Shield

Hybrid magnetic shielding system

- Calculated result by Opera-3d

Hybrid magnetic shielding system

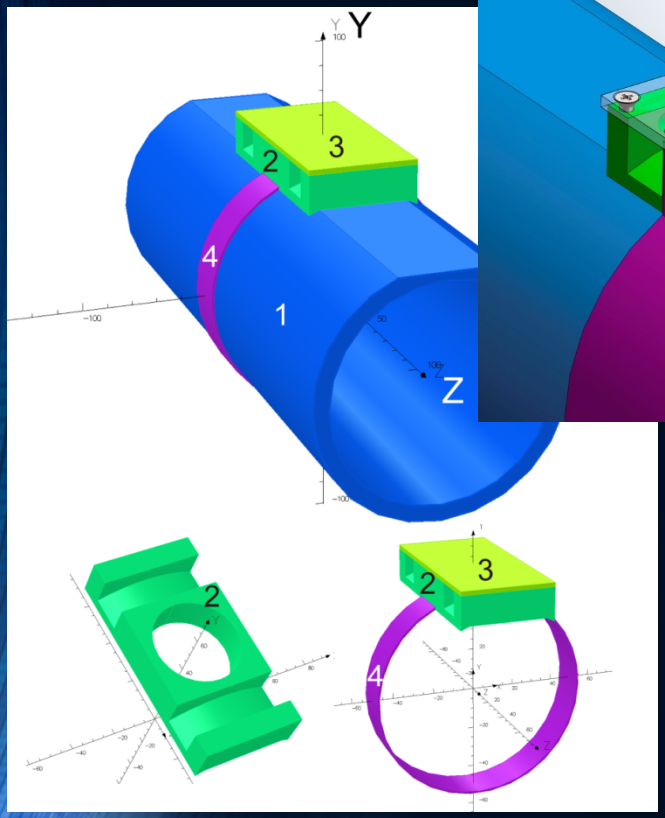
- Calculated result by Opera-3d

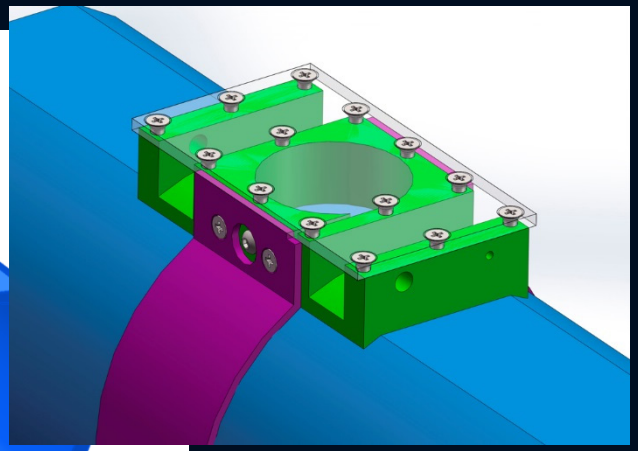


1. HTc current sensor with Ferromagnetic shielding materials, 2: frame, 3:cap and 4: band.

Hybrid magnetic shielding system

- Calculated result by Opera-3d

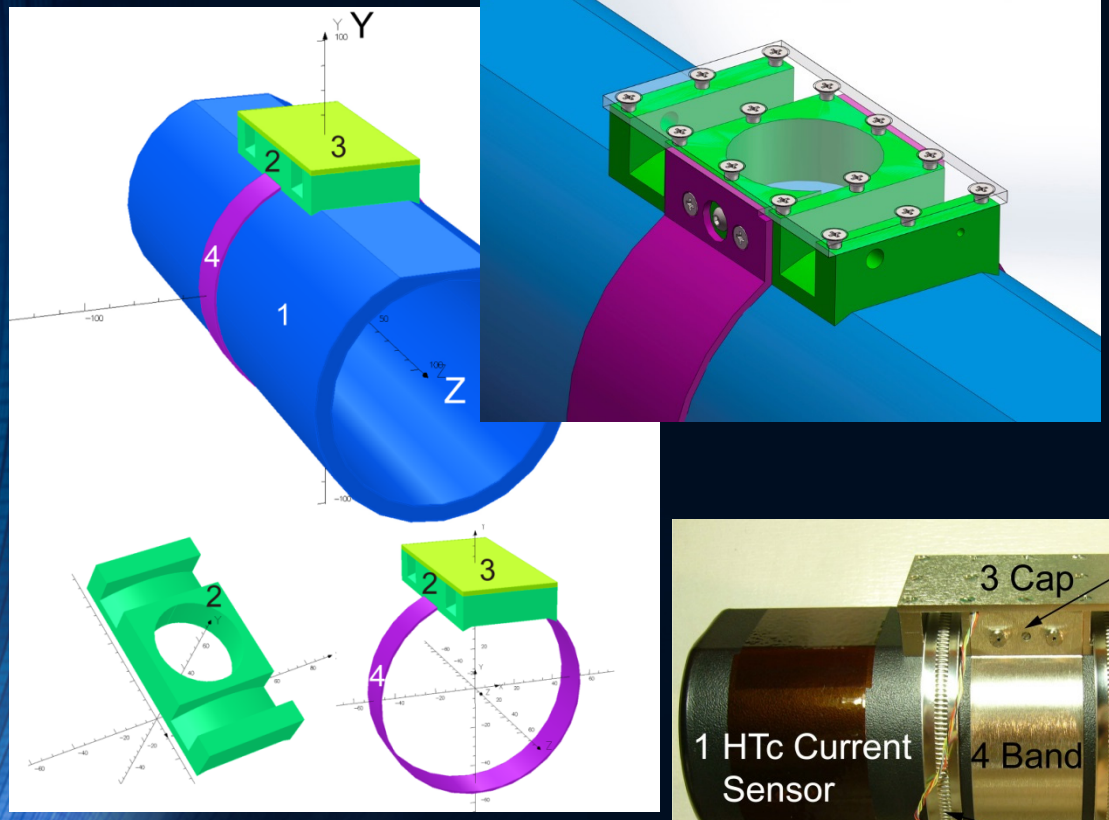


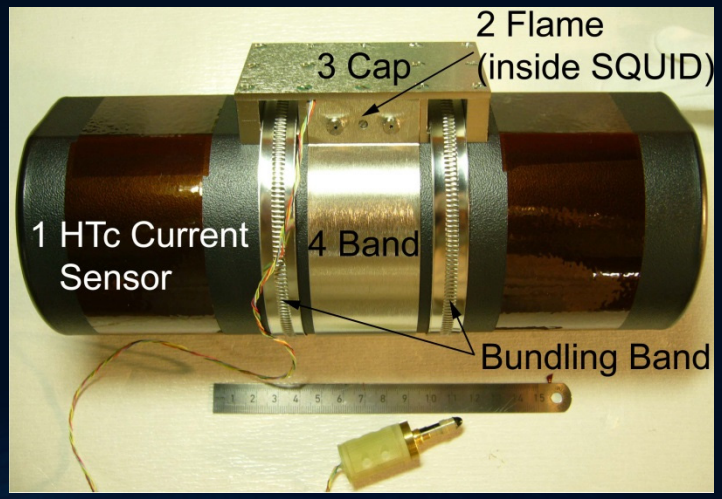


1. HTc current sensor with Ferromagnetic shielding materials, 2: frame, 3:cap and 4: band.

Hybrid magnetic shielding system

- Calculated result by Opera-3d

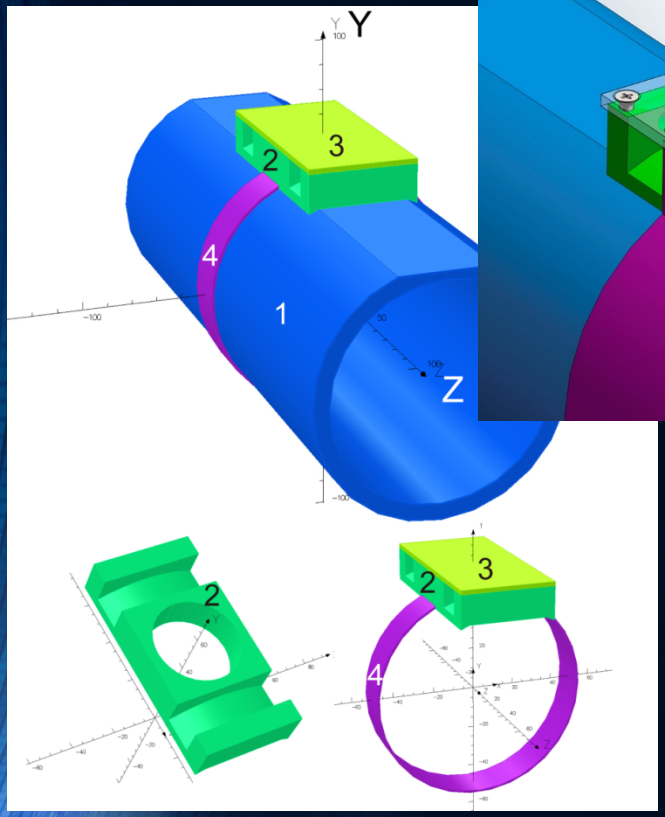


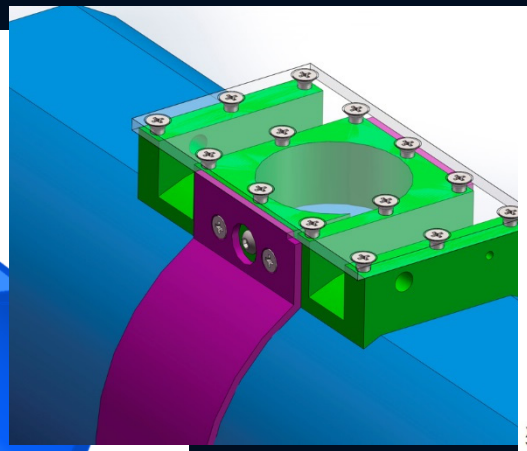


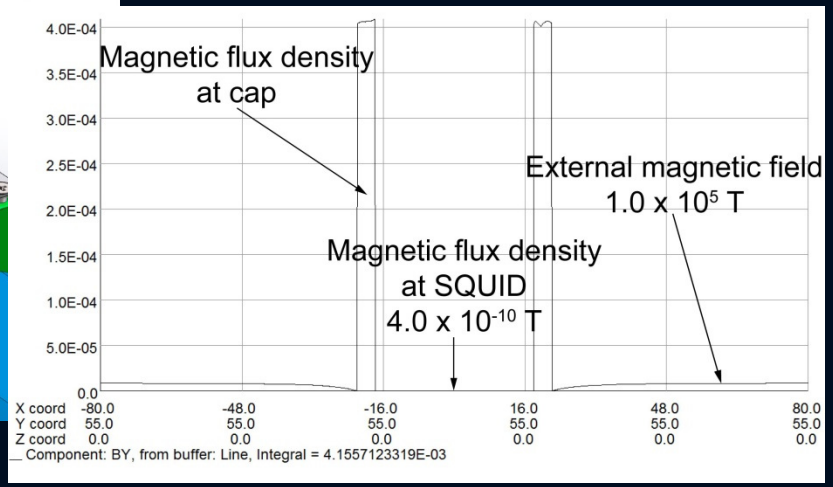
1. HTc current sensor with Ferromagnetic shielding materials,
2: frame, 3:cap and 4: band.

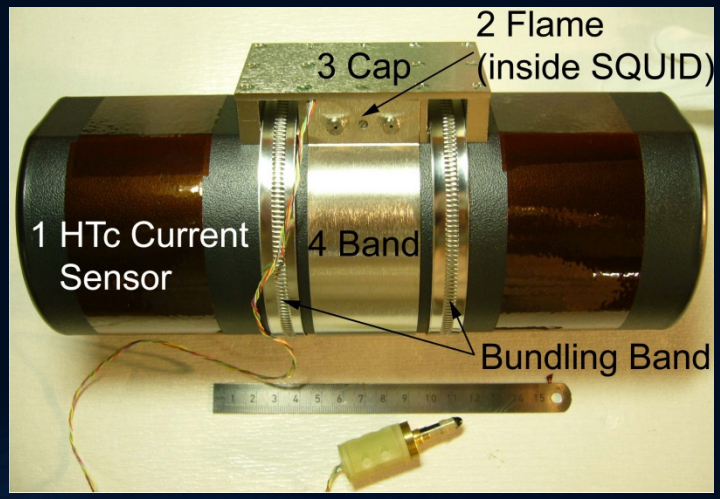
Hybrid magnetic shielding system

- Calculated result by Opera-3d





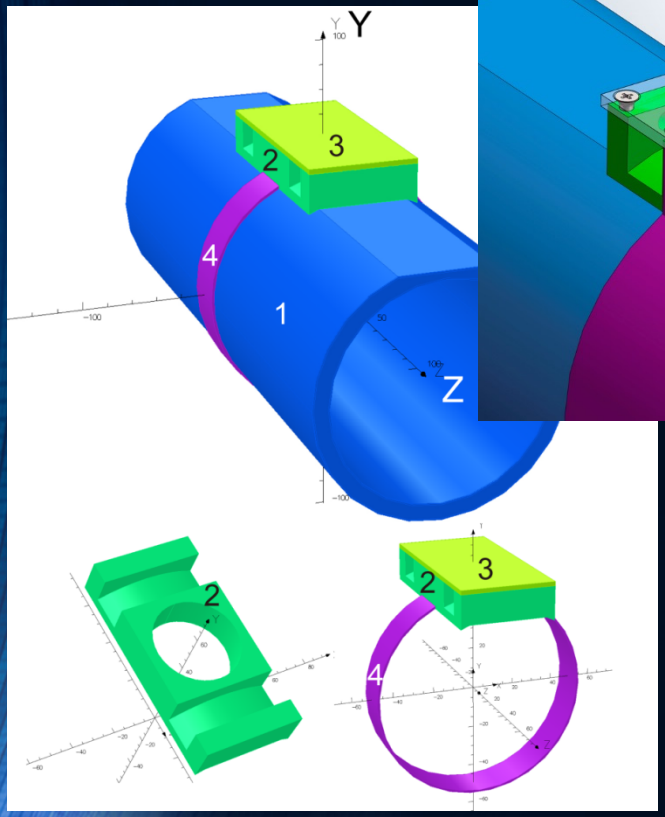


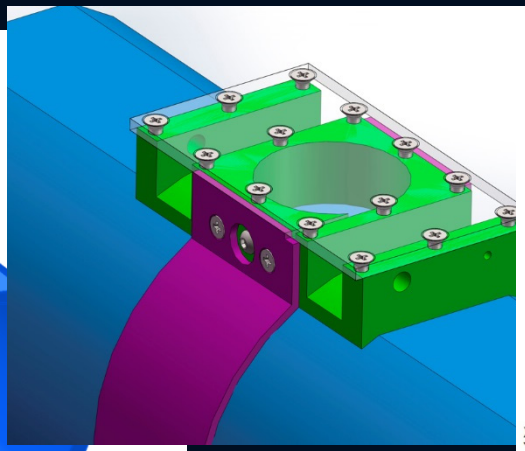


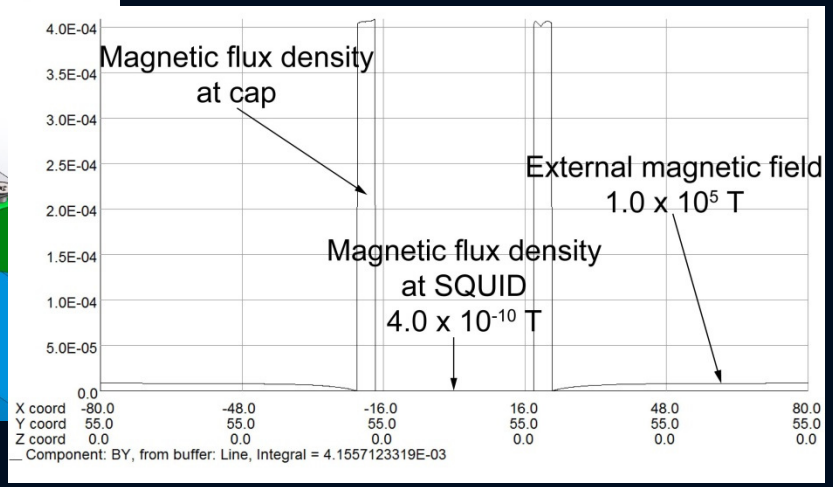
1. HTc current sensor with Ferromagnetic shielding materials,
2: frame, 3:cap and 4: band.

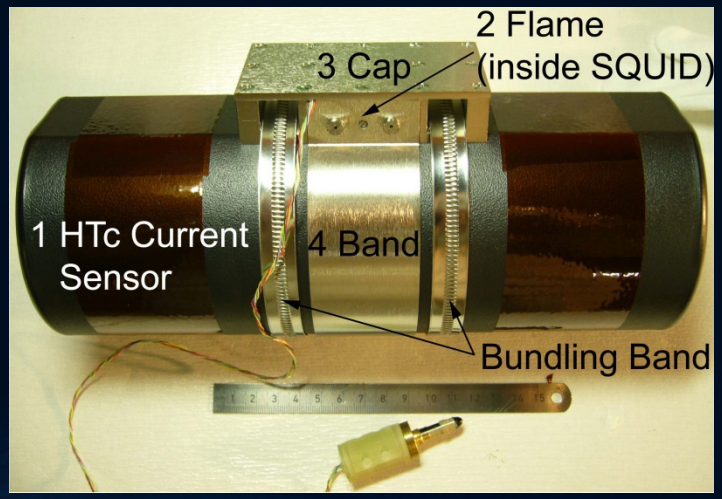
Hybrid magnetic shielding system

- Calculated result by Opera-3d







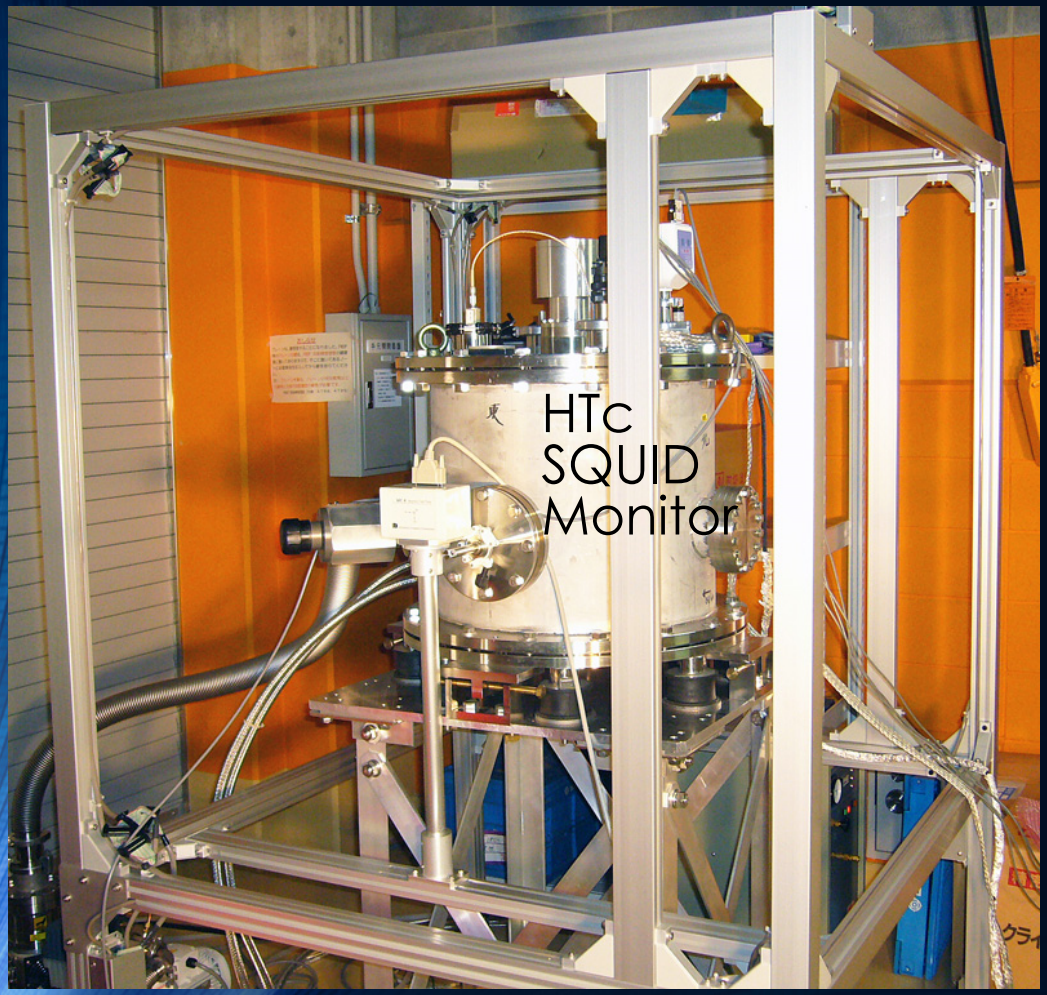


External
Magnetic Field

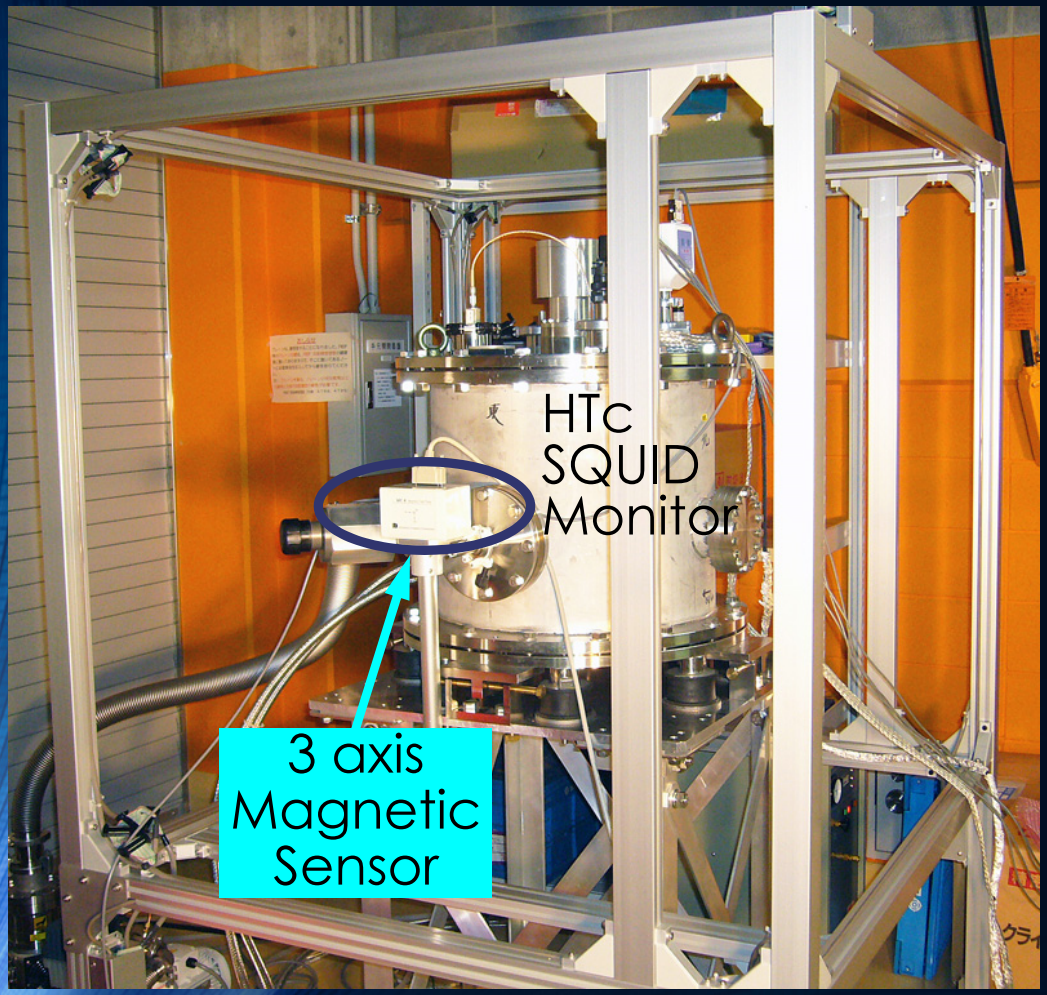
- 1.0 x 10^{-5} T
- 3(4) x 10^{-10} T

1. HTc current sensor with Ferromagnetic shielding materials,
2: frame, 3:cap and 4: band.

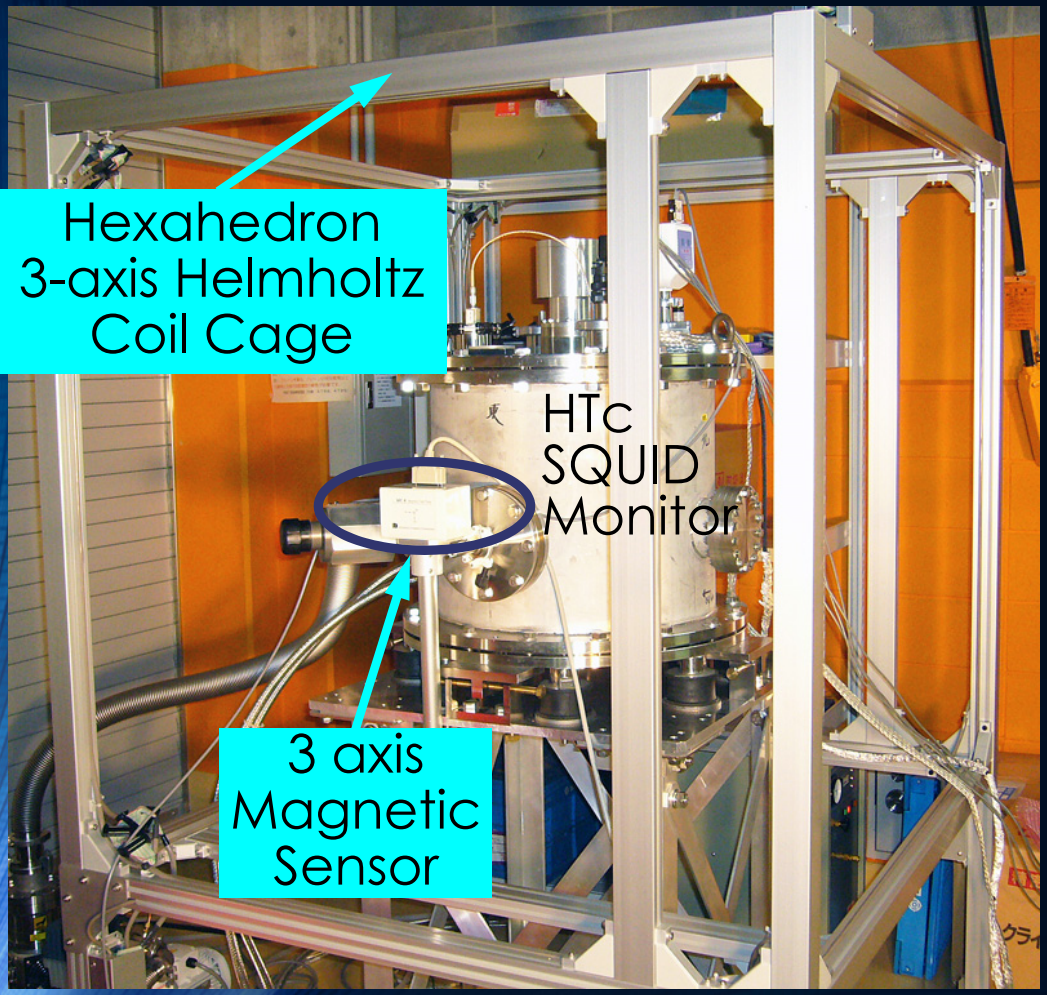
Active noise canceller system



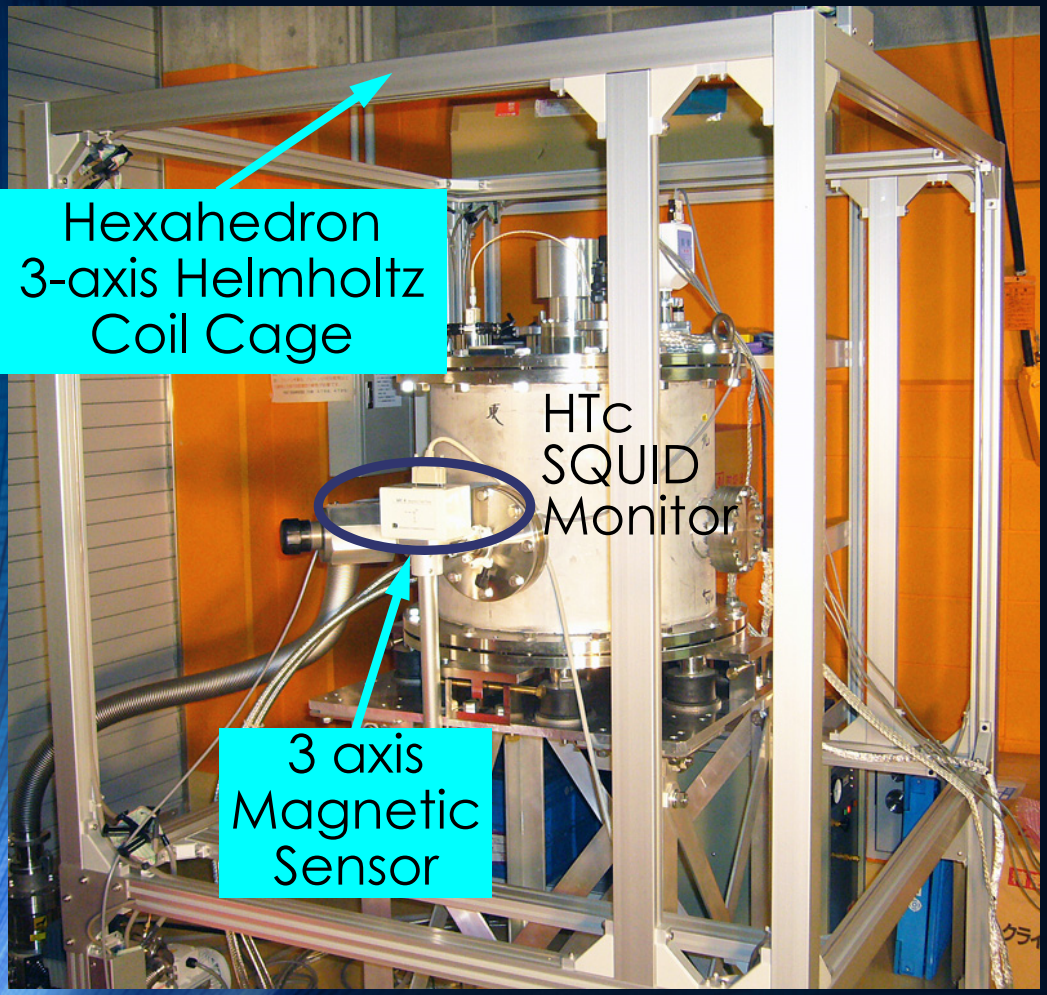
Active noise canceller system



Active noise canceller system



Active noise canceller system

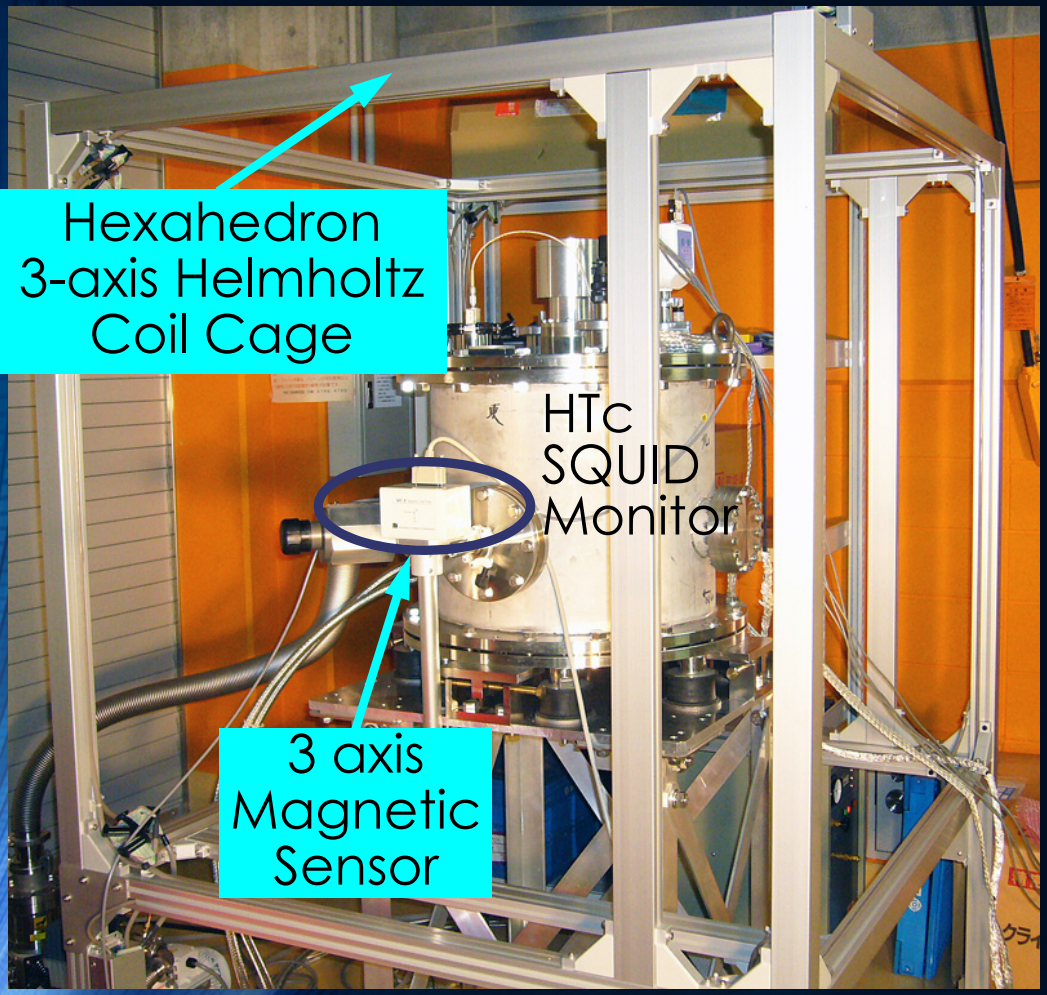


Specifications

Field attenuation	-40 dB
Max. compensation	6 μT
Bandwidth	DC(0)～1,000 Hz
AD/DA converter	16 bit
Magnetic sensor	DC : 3 axis Flux gate Magnetometer

*JEOL Ltd. http://www.jeol.co.jp/en/

Active noise canceller system

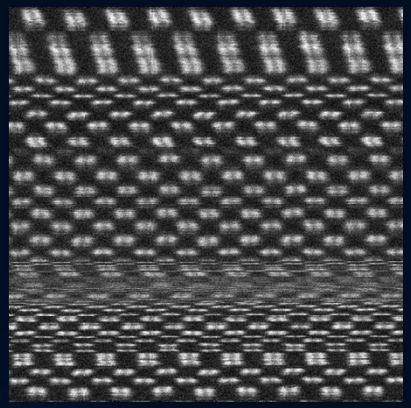


Specifications

Field attenuation	-40 dB
Max. compensation	6 μT
Bandwidth	DC(0)～1,000 Hz
AD/DA converter	16 bit
Magnetic sensor	DC : 3 axis Flux gate Magnetometer

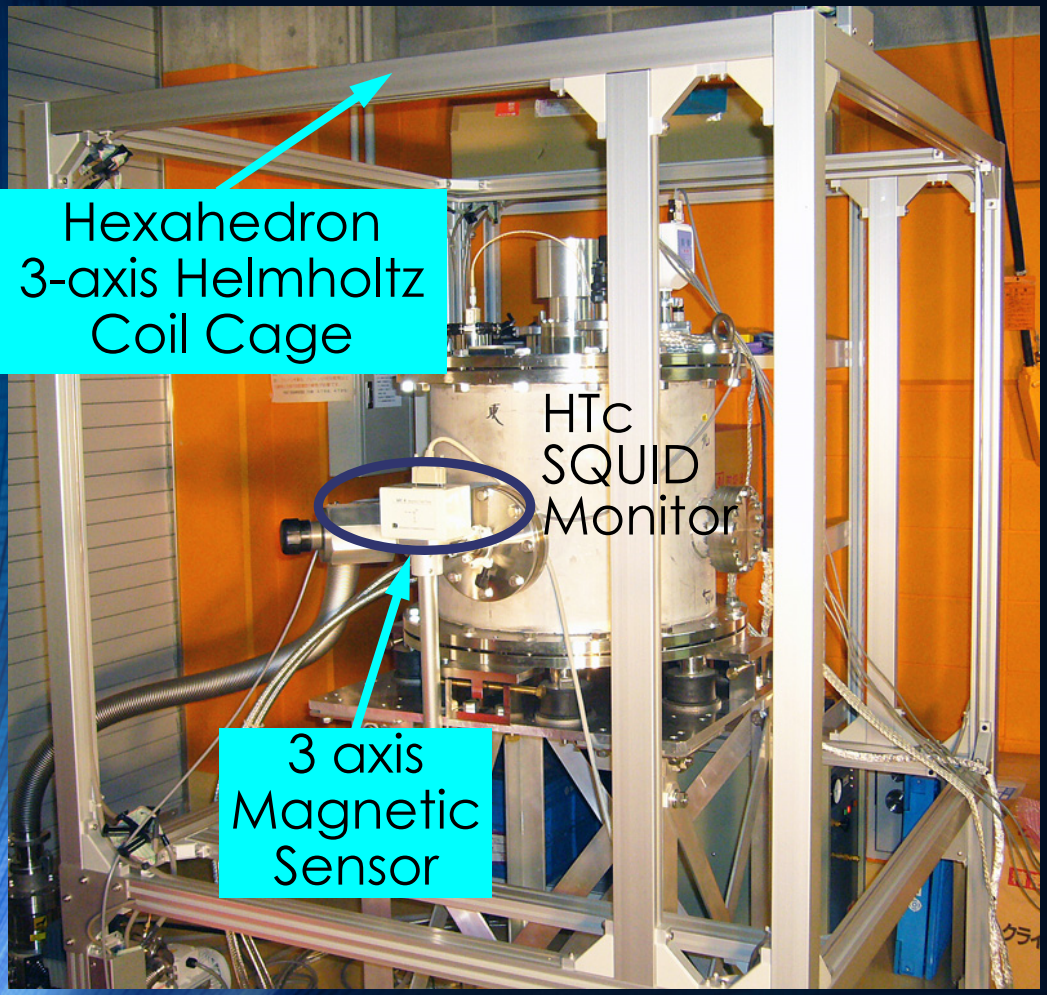
*JEOL Ltd. http://www.jeol.co.jp/en/

Surface of Si [110]



Canceller OFF

Active noise canceller system

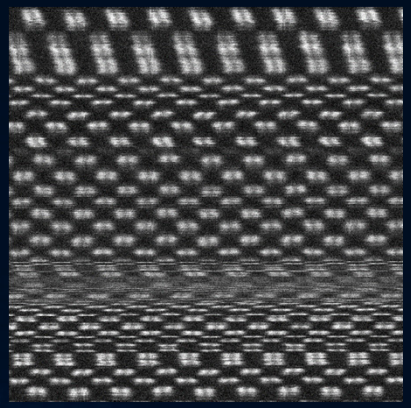


Specifications

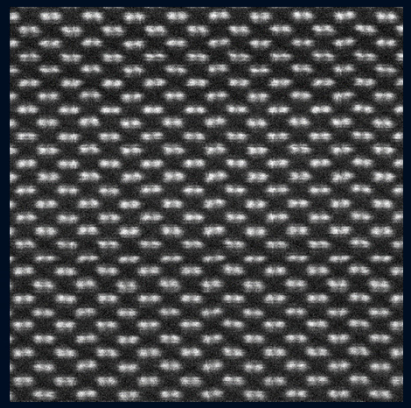
Field attenuation	-40 dB
Max. compensation	6 μT
Bandwidth	DC(0)～1,000 Hz
AD/DA converter	16 bit
Magnetic sensor	DC : 3 axis Flux gate Magnetometer

*JEOL Ltd. http://www.jeol.co.jp/en/

Surface of Si [110]



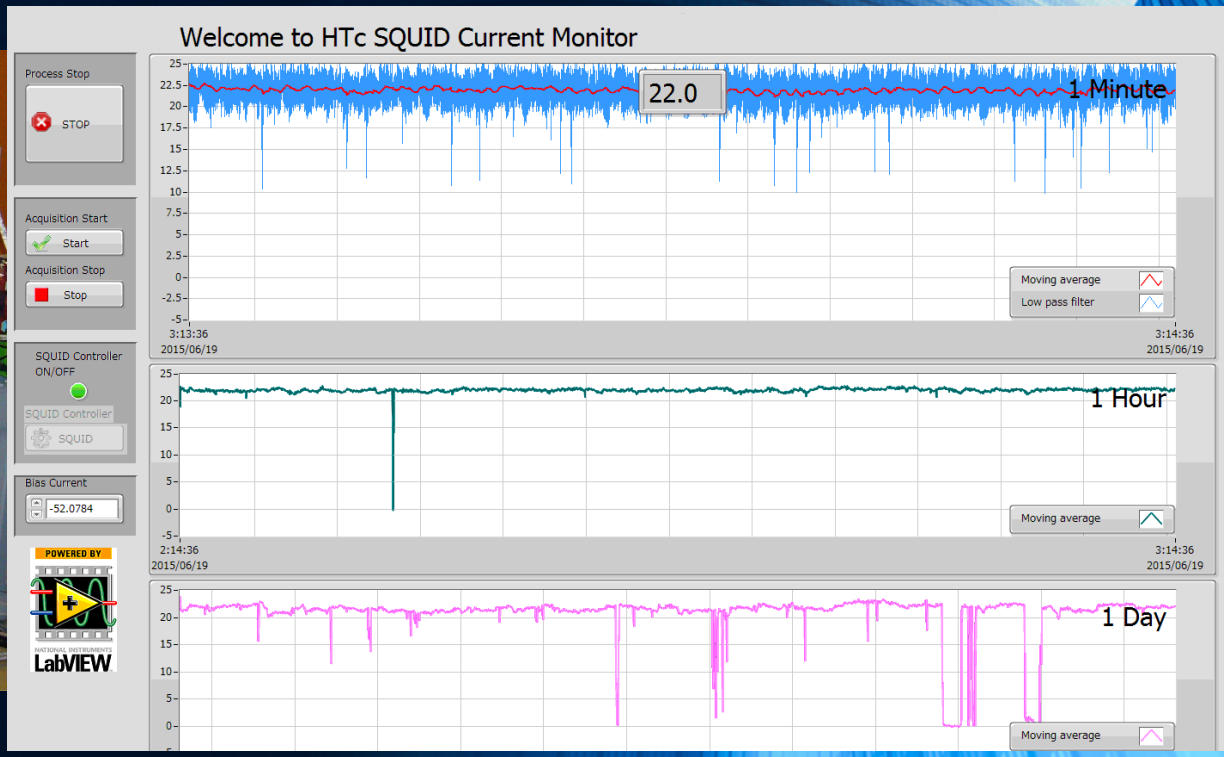
Canceller OFF



Canceller ON

Measurement for heavy ion beams

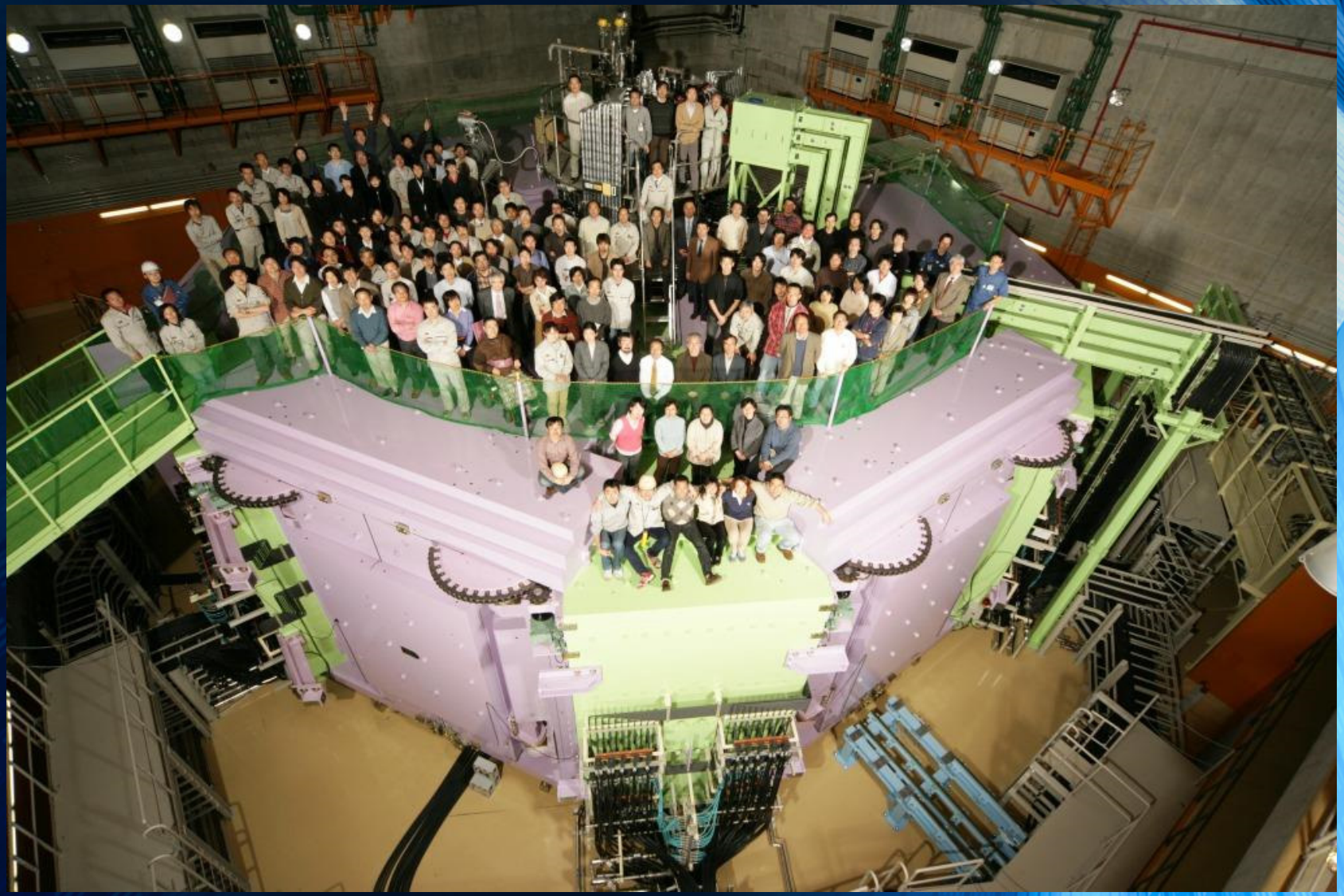
Beam $^{78}Kr^{+60}$ (50.0 MeV/u)



Conclusion

Conclusion

- To measure the DC current of heavy-ion beams non-destructively, we have developed a SQUID monitor for practical use in acceleration operation.
- We strongly reinforced the magnetic shielding system.



Thank you for your kind attention

* This work is supported by JSPS KAKENHI Grant Number 15K04749.

Tamaki Watanabe