Progress on the commissioning of Radioactive Isotope Beam Factory at RIKEN Nishina Center

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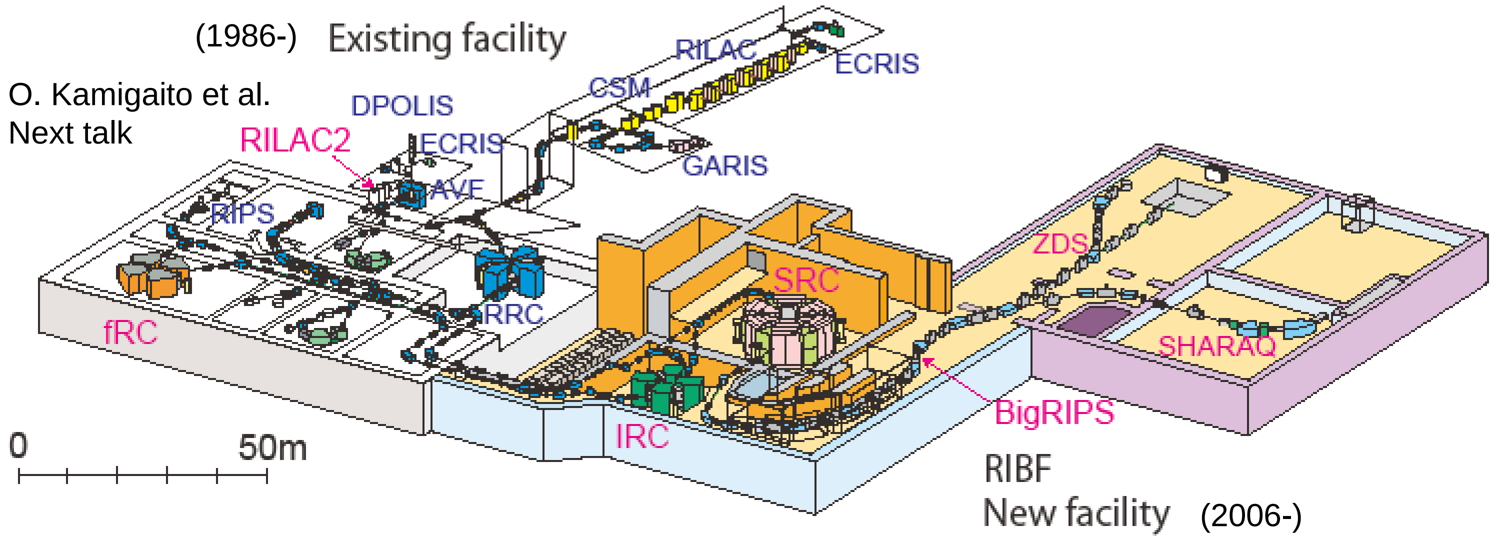
RI Beam Factory (RIBF) at RIKEN Nishina Center

Aims : To produce the world's most intense RI beams

To make systematic studies on unstable nuclei far from stability



RILAC : RIken heavy-ion LinAC
CSM : Charge-State Multiplier
RRC : Riken Ring Cyclotron
fRC : fixed-frequency Ring Cyclotron
IRC : Intermediate-stage Ring Cyclotron
SRC : Superconducting Ring Cyclotron

E = 440MeV/u (light ion)
E = 400MeV/u (heavy ion)
E = 345MeV/u (very heavy ion, uranium)
Design goal I = 1pμA (6 x 10^{12} #/s)

Ring cyclotrons

fRC

IRC

SRC

	RRC	fRC	IRC	SRC
K-number (MeV)	540	570	980	2600
Sector magnets	4	4	4	6
Velocity gain	4.0	2.1	1.5	1.5
Trim coils (/sector)	26	10	20	4(SC) 22(NC)
RF resonators	2	2+FT	2+FT	4+FT
Frequency range	18-38	54.75	18-38	18-38

SC = superconducting
NC = normal conducting
FT = flat-top resonator

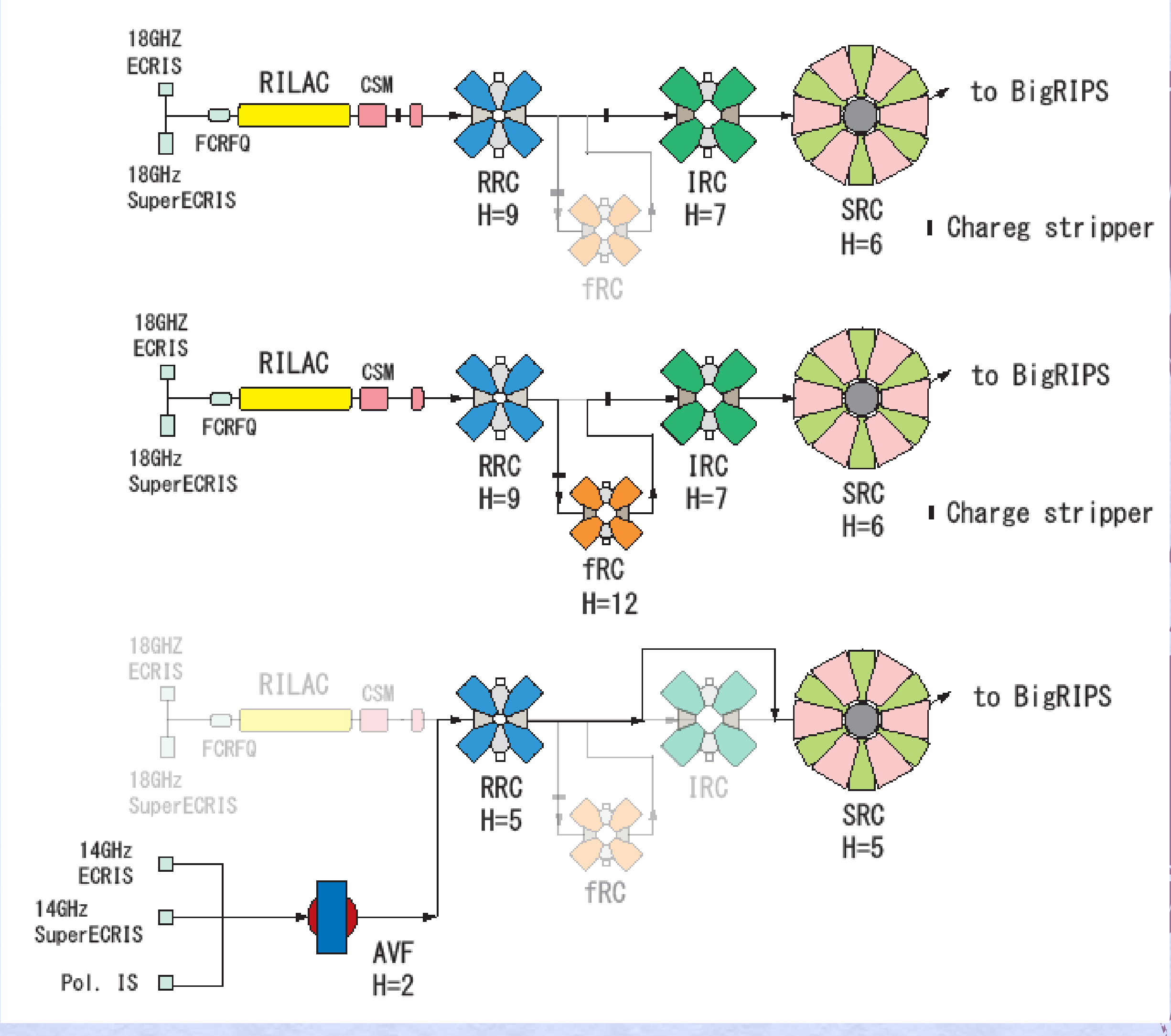
RF SYSTEM: N. Sakamoto et al., TU10.

Acceleration mode of RIBF

Variable-energy mode :
^{27}Al, ^{48}Ca, ^{86}Kr
up to 400 MeV/u @SRC

Fixed-energy mode :
^{238}U
345 MeV/u @SRC

Light ion mode :
Pol. d, ^{14}N
250-440 MeV/u @SRC

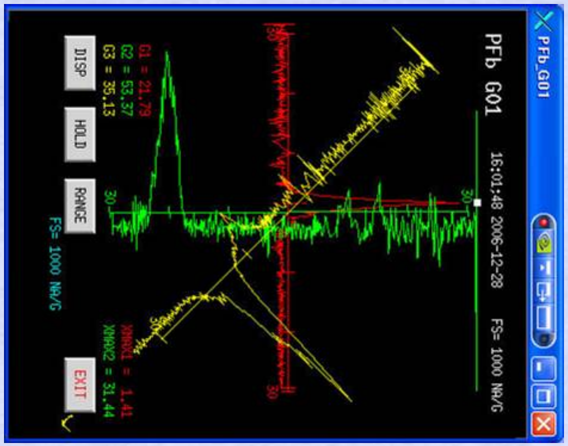


Milestones

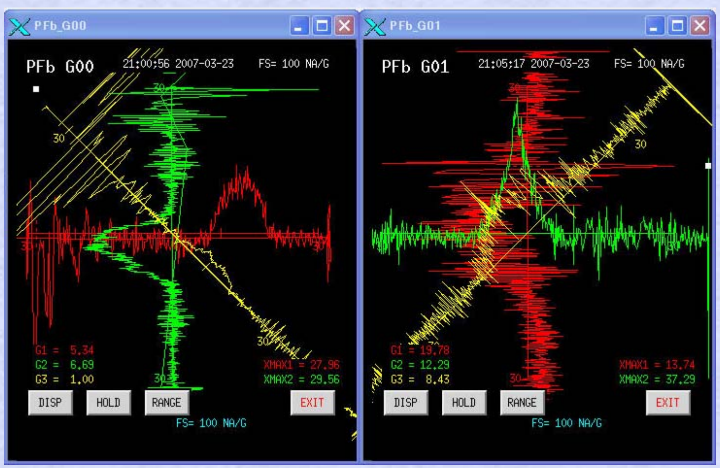
Date	Preparation of SRC hardware	Date	Beam commissioning of RIBF
2005/9/19	1st Cool-down started	2006/9/29	First beam extracted from fRC ($^{238}U^{73+}$ 50MeV/u)
2005/10/13 1:00	All main coils transited to superconducting state	2006/11/25	First beam extracted from IRC ($^{84}Kr^{31+}$ 114MeV/u)
2005/11/7	Excitation test (Imain = 5000 A, Itrim = 3000 A)	2006/12/17	Beam injection to SRC
2005/11/8	Trouble due to a helium leak	2006/12/28 16:00	First beam extracted from SRC ($^{27}Al^{10+}$ 345MeV/u)
2006/4/15	Full excitation again	2007/3/15	First RI beam production at BigRIPS
2006/4/17-2006/6/14	Magnetic field mapping	2007/03/23	First 345MeV/u $^{238}U^{86+}$ beam extracted from SRC
2006/6/14	Fast shutdown test from full excitation	2007/05-6	New isotope search (^{125}Pd and ^{126}Pd was discovered)
2006/6/24	Arrival of RF resonators	2007/11	$^{86}Kr^{34+}$ 345MeV/u 32pnA from SRC
-2006/10	RF, beam diagnostics, vacuum pumping system were installed	2008/11	Intensity of uranium beam multiplied up to 0.4pnA
2006/10/18	Vacuum for the beam < 10 $^{-5}$ Pa	2008/12	High intensity 345MeV/u ^{48}Ca beam (170pnA)
2006/11/13	RF conditioning started.	2008/12	New isotope search (~20 candidates)
2007/12-2008/9	Trouble of helium cryogenic system	2009/3-5	250MeV/u ^{14}N and Pol d beam acceleration

First beam extraction of SRC

2006/12/28 16:00 $^{27}Al^{10+}$ 345MeV/u



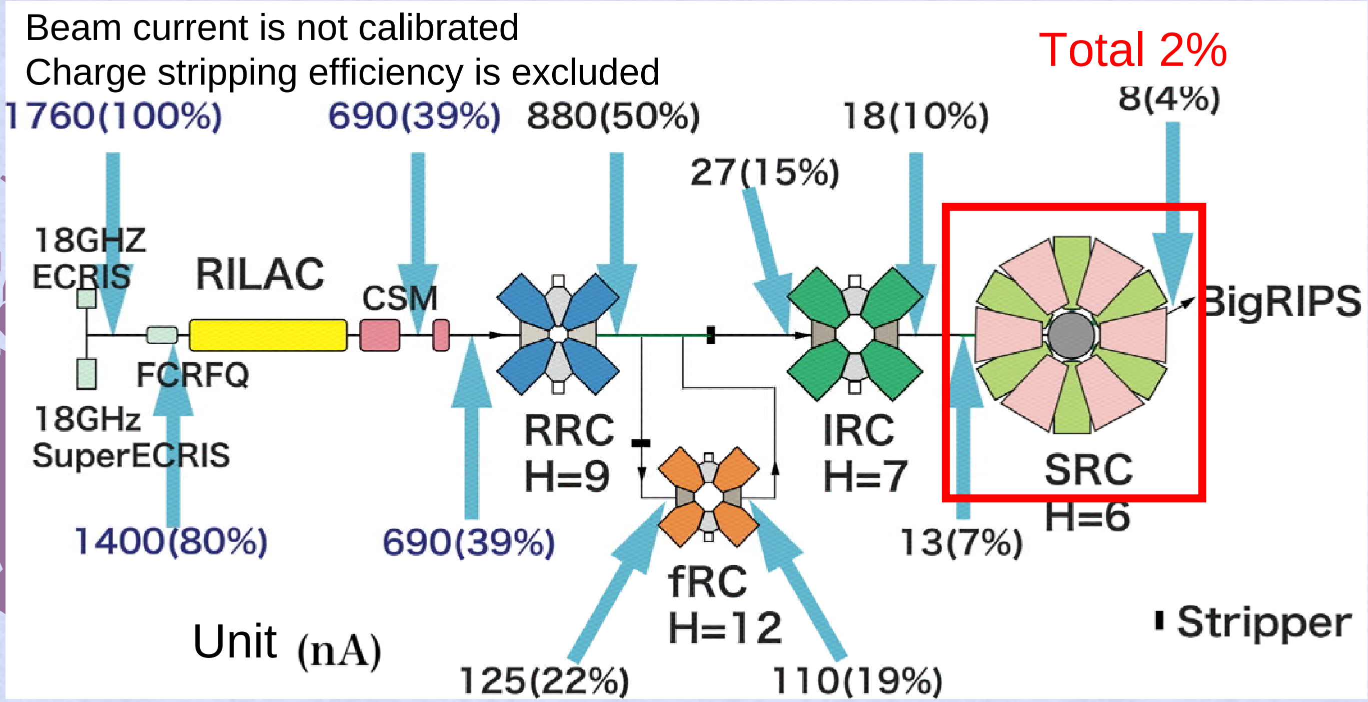
2007/3/23 21:00 $^{238}U^{86+}$ 345MeV/u



2007/5/8~6/3
First experiment at RIBF

New isotope search
(^{125}Pd and ^{126}Pd were discovered)

Transmission efficiency of ^{238}U beam at 2007/6



Extraction efficiency
fRC : 88%
IRC : 67%
SRC : ~40%

N. Fukunishi et al., Proc. of PASJ4-LAM32, WO01.

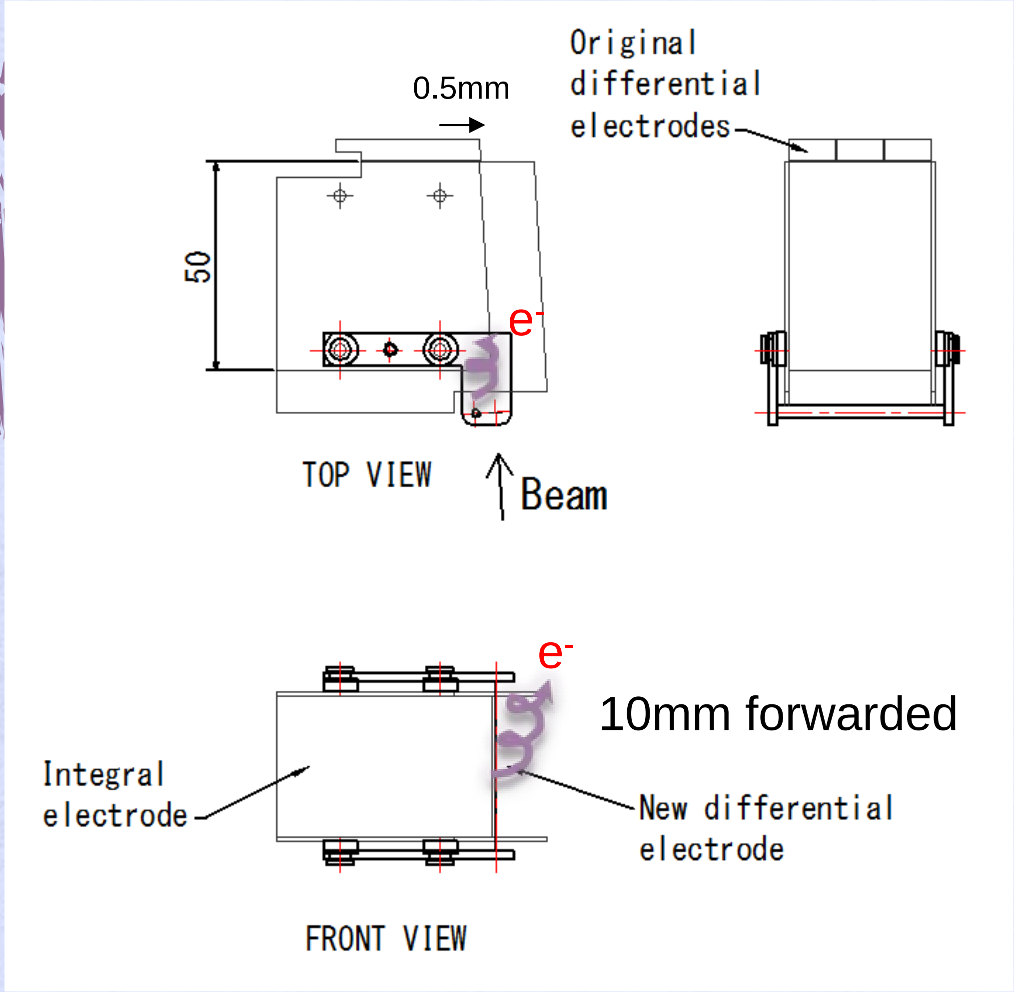
- Insufficient beam tuning
→Inappropriate beam diagnostics
(Huge number of secondary electrons)
→Instability of rf in RILAC
- Poor uniformity and lifetime of strippers

- Modification of beam diagnostics
- Renewal of low-level circuit
- Development of stripper
→foil, rotating, gas…

Example : modification of SRC-MDP

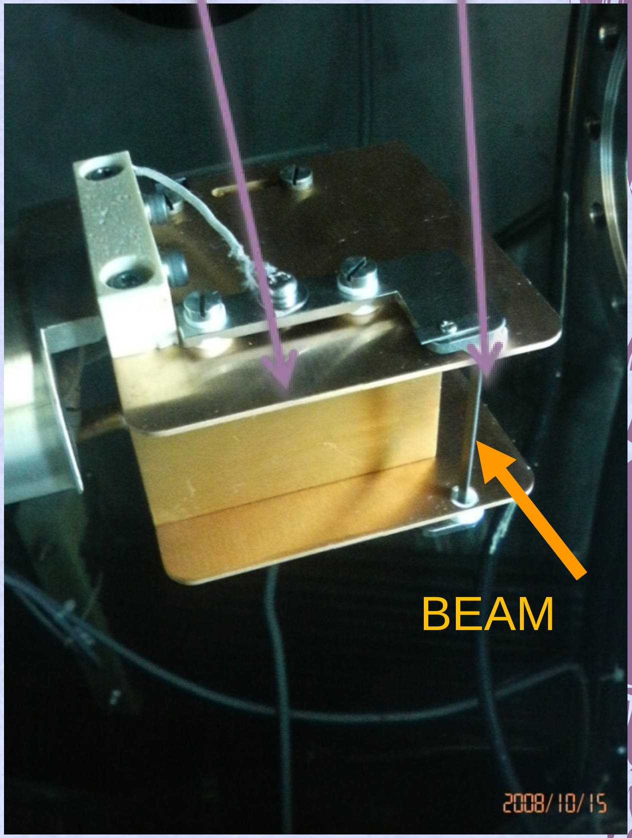
Huge number of secondary electron

Take account of radial beam pattern

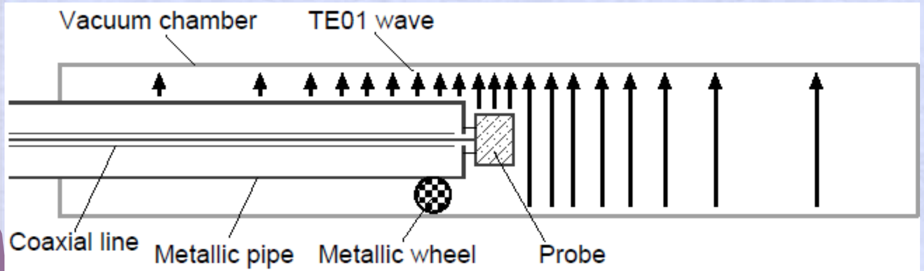


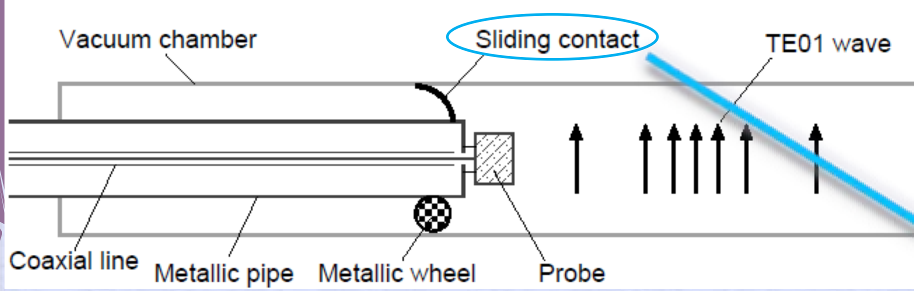
Large fence for secondary-electron

New differential electrode W 0.3mm×3mm

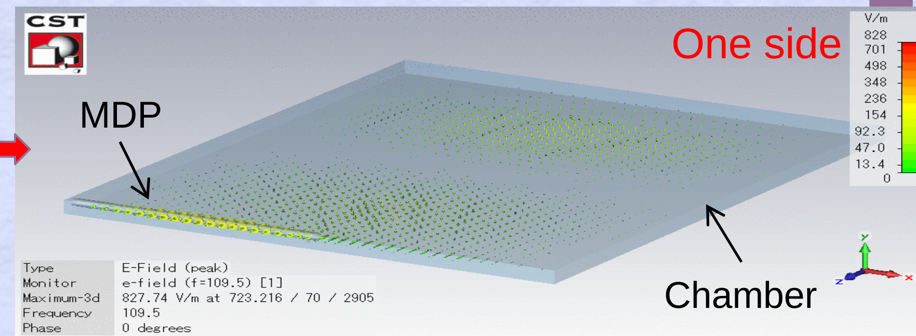


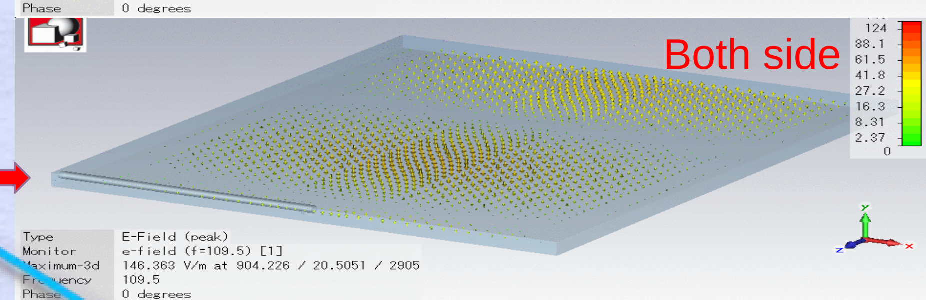
Measures to reduce noise





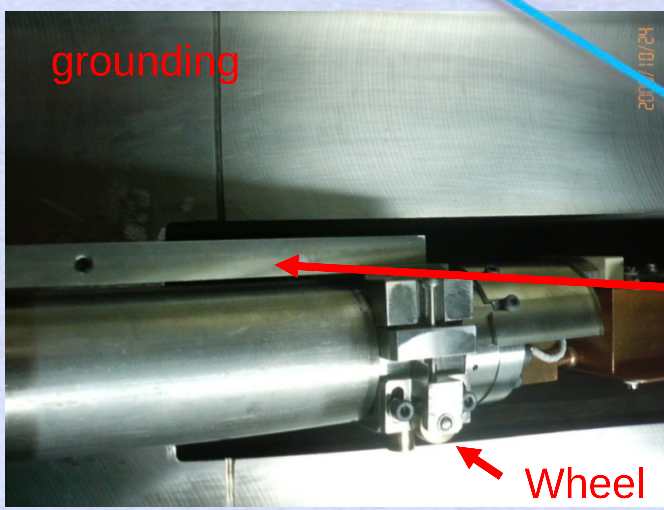
E field (TE01 mode) W=2500mm, H=90mm, F_c=60MHz



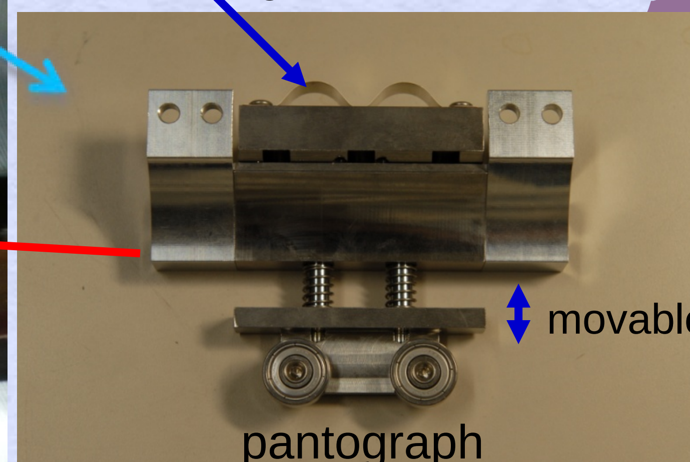


One side grounding
→ both side

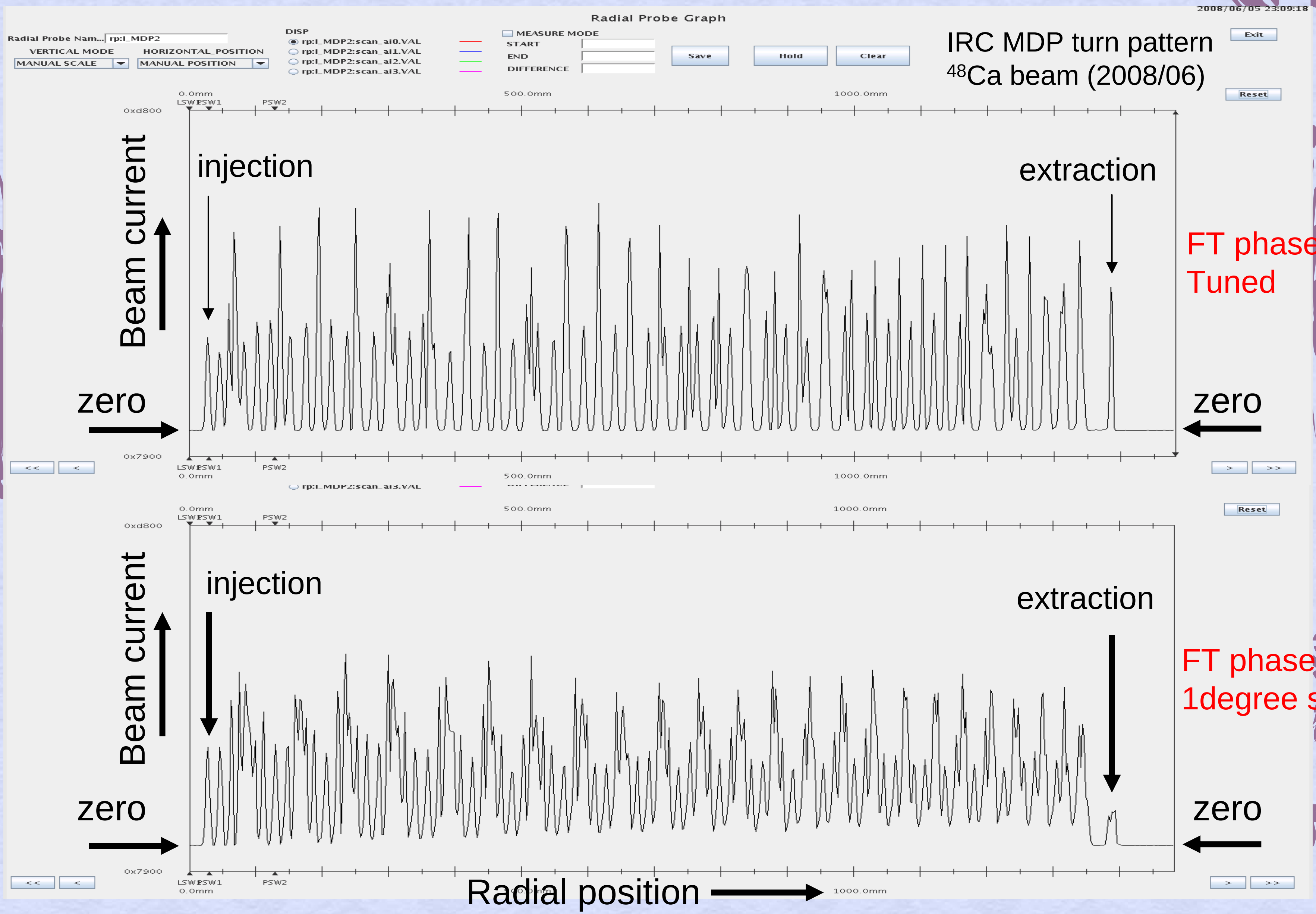
Precise adjustment of shorting-plate in FT resonator



Contact finger

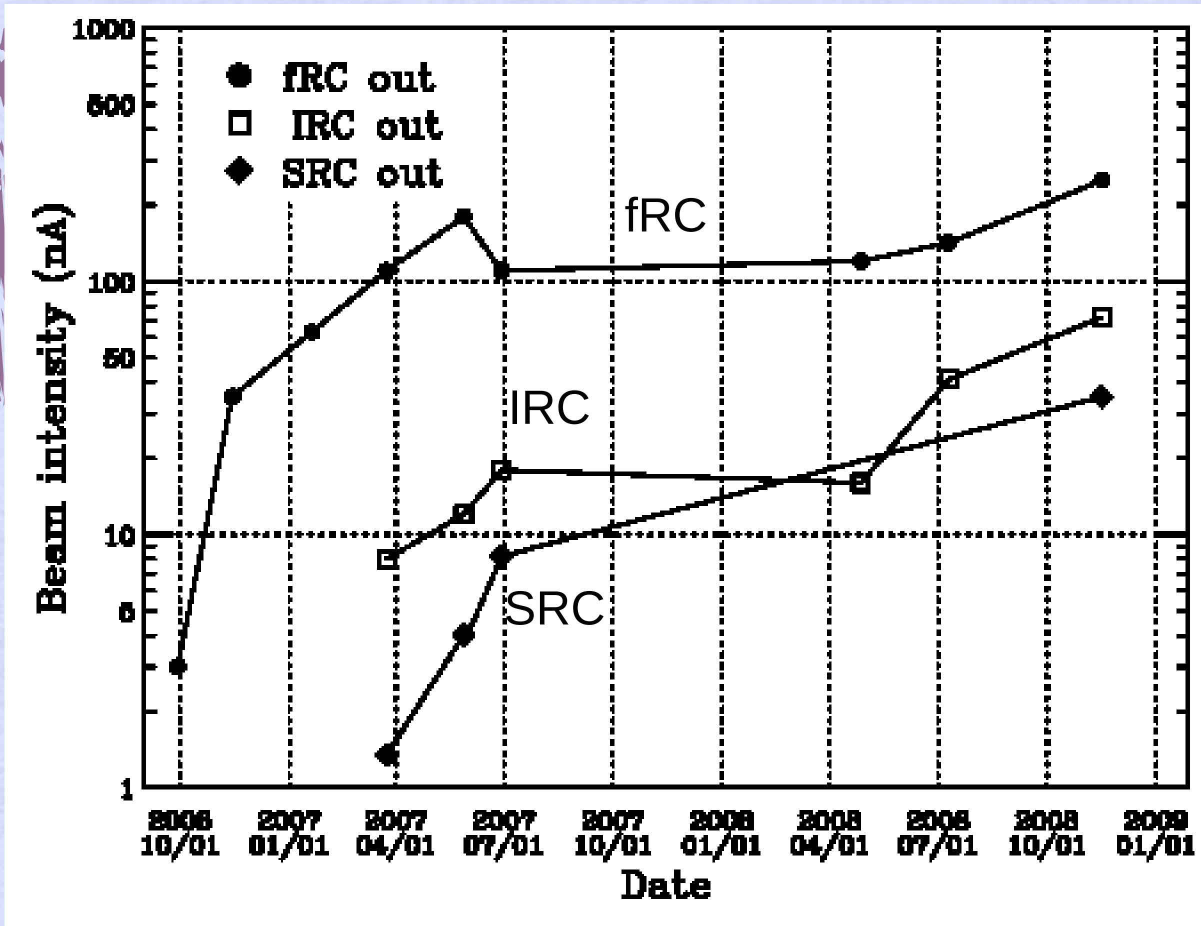


Necessity on precise adjustment of flat-top resonator



Intensity evolution of uranium beam

Transmission efficiency of uranium beam has been improved after the modification of beam diagnostic devices.



Extraction efficiency
2007/6 2008/11
fRC : 88%→>90%
IRC : 67%→86%
SRC : 40%→66%

Beam intensity
2007/6 2008/11
4nA 35nA
(0.4pnA)

~10 times higher

Influence of high intensity ^{48}Ca beam

$^{48}Ca^{20+}$ 345MeV/u : 170pnA (2008/12)

Transmission efficiency

SRC extraction: 82%

Total : 35%

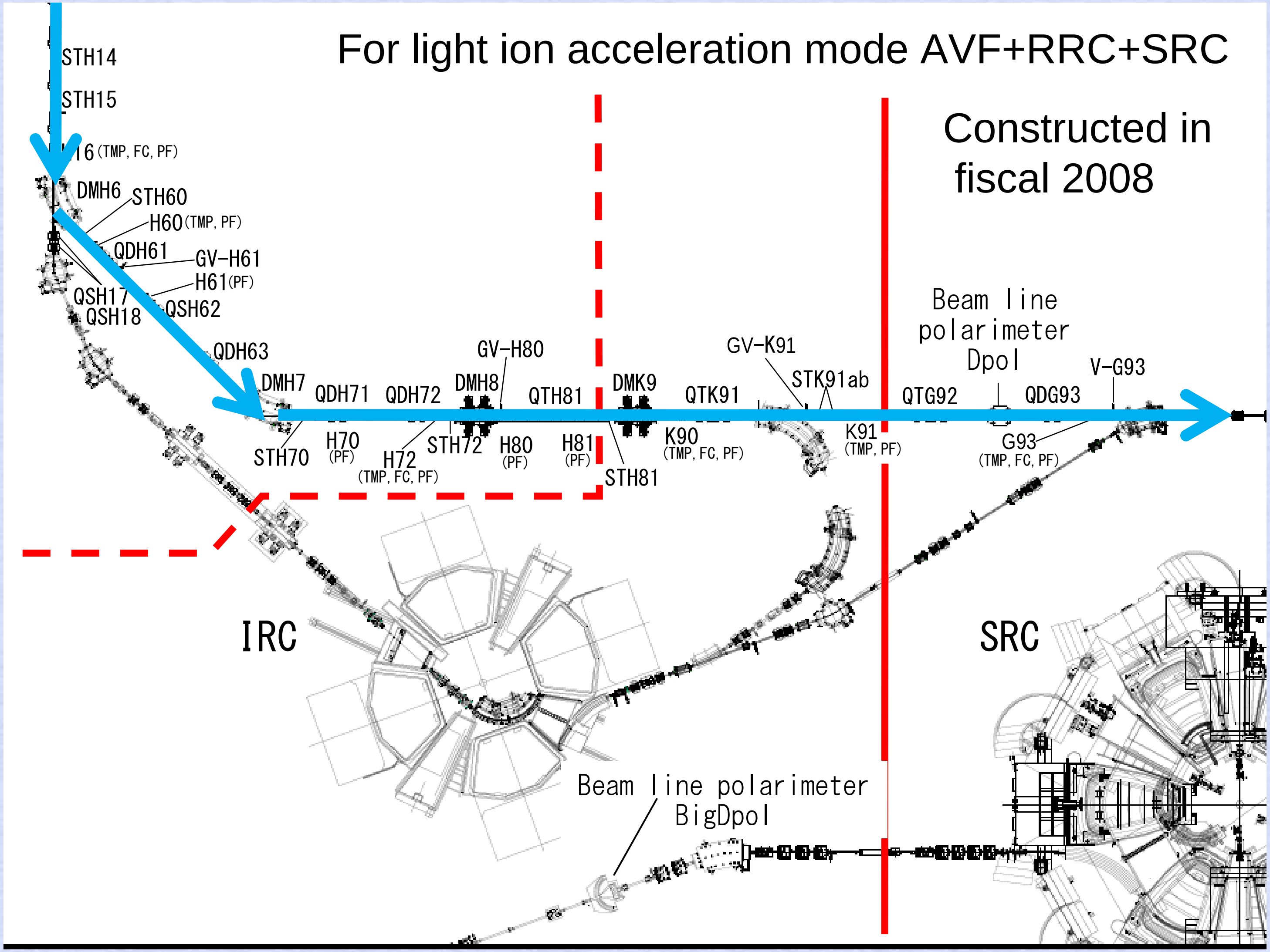
^{48}Ca+Be secondary beam production

	BigRIPS	RIPS
^{22}C	10cps	0.006cps
^{30}Ne	300cps	0.2cps
^{31}Ne	10cps	20(4days)
^{32}Ne	5cps	-
^{42}Si	15cps	-

^{31}Ne beam production

		RIPS 1997	BigRIPS 2008	BigRIPS/RIPS ratio
Yield [cps]		0.0005	10	20,000
Primary beam intnsity[pnA]		2	100	50
Target[g/cm^2]		0.3	2.8	10
Acceptance	θ_x [%]	60	90	1.5
	θ_y [%]	60	97	1.6
	Δp [%]	30	60	2
σ (^{48}Ca→^{31}Ne) [arb]		1	8	8

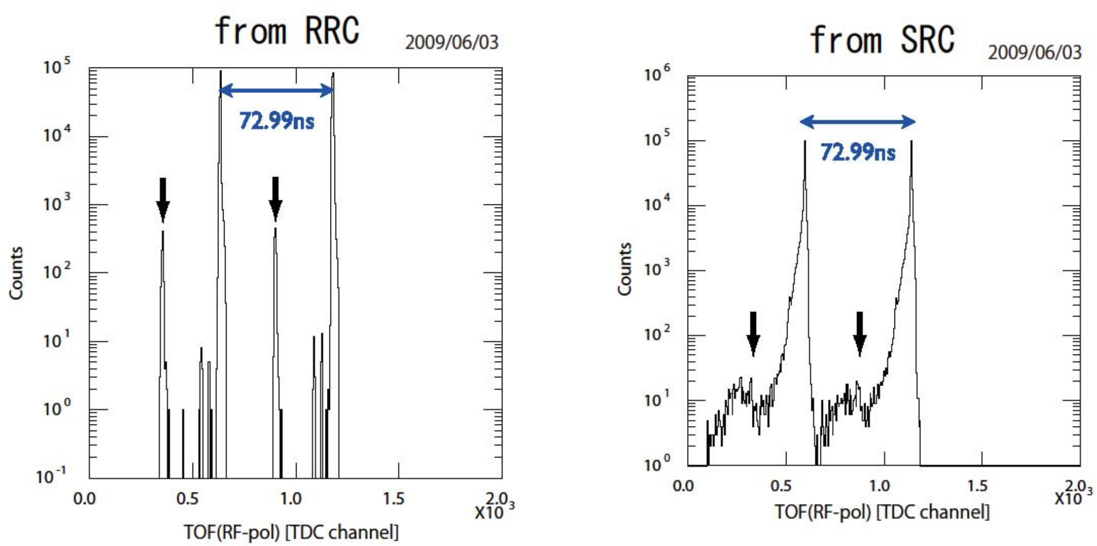
IRC-bypass beam line



Light ion beam acceleration

2009/2 : acceleration test of ^{14}N 250MeV/u
2009/3 : commissioning of SHARAQ spectrometer by ^{14}N beam
2009/4 : experiment using 250MeV/u polarized deuteron beam
(single turn extraction was required)
2009/5 : BigRIPS and SHARAQ test experiment using ^{14}N beam

250MeV/u polarized deuteron beam



Good single turn extraction of SRC (less than 0.01%)

Outlooks

What we should perform to increase beam intensity much

- Charge stripper (uniformity, lifetime …)
  → difficult but significant problem…..
- To improve stability
  → renewal of low-level circuit for RILAC
  → modification of reference-signal distribution
  → magnet, supply… temperature?
- Construction of new superconducting ECRIS
- Construction of new injector linac RILAC2
- Radioactivation, maintenance, interlock…..

HTS SQUID beam current monitor: T. Watanabe et al. WE5.

Summary

- **World's first superconducting ring cyclotron SRC was successfully commissioned and works good**
- **Transmission efficiency was improved after modifying beam diagnostic devices**
- **170pnA ^{48}Ca and 0.4pnA ^{238}U are now available**

- **Charge stripper has significant problems (uniformity and lifetime)**
- **Low-level circuit of RILAC will be renewal**

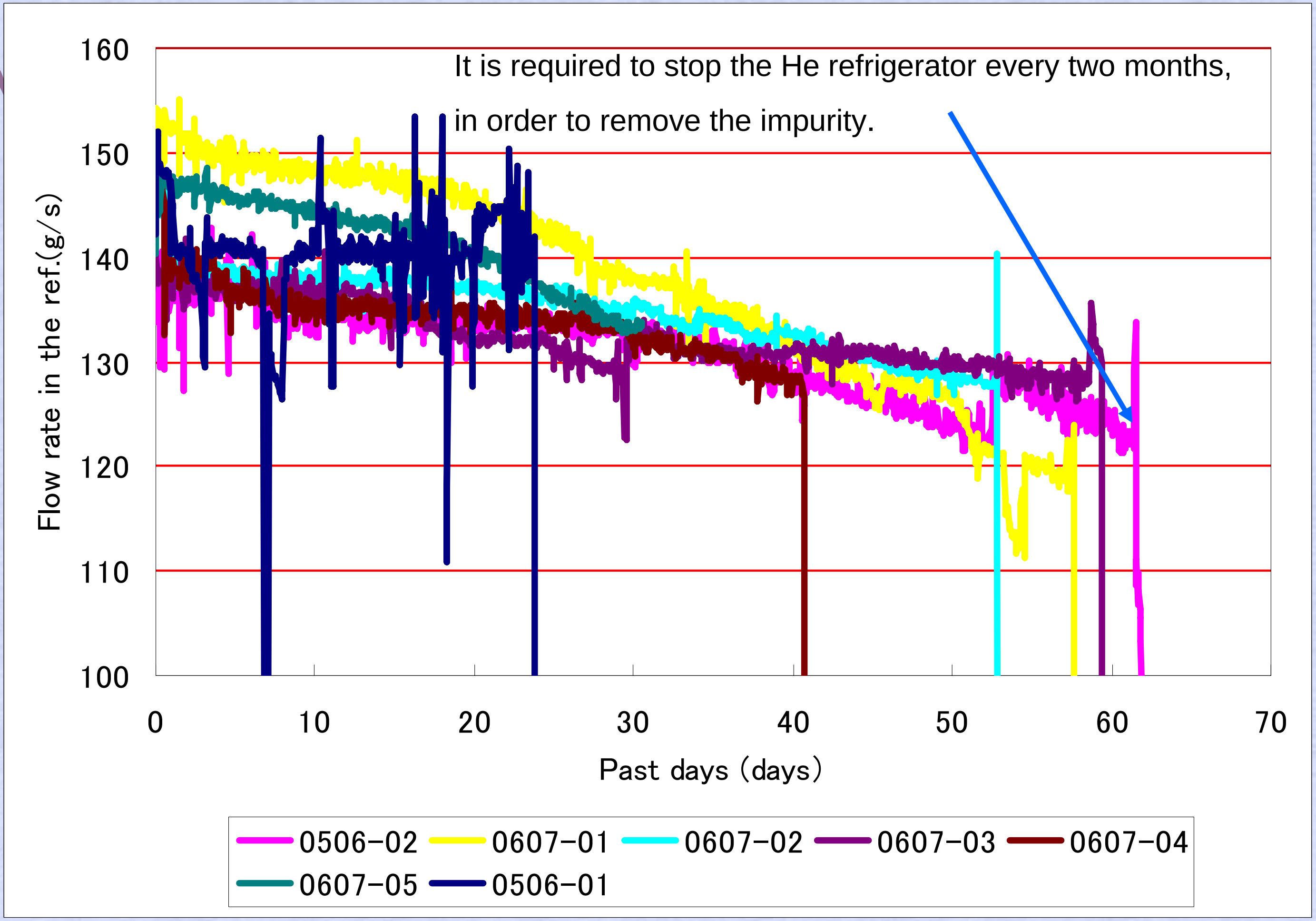
- **Test of new superconducting ECR ion source has started**
- **New injector linac is now in progress.**

Morgue

Degradation of cooling power of He refrigerator

- Increase of temperature of 80K stage adsorber.
- Decrease of inlet pressure at the 1st turbine.

→ Accumulation of some impurity somewhere around the 1st turbine.



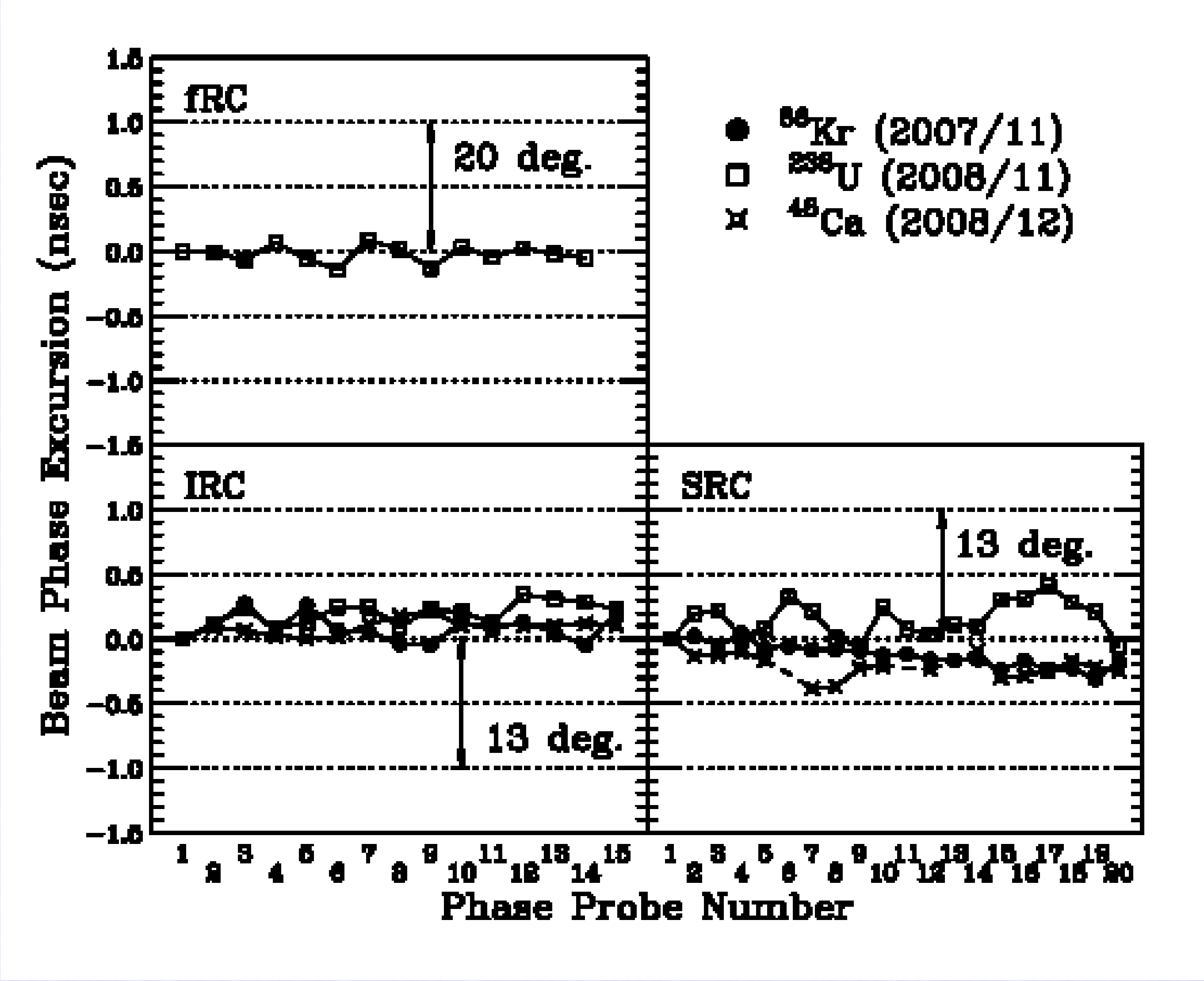
What is the impurity?

→Compressor oil !!

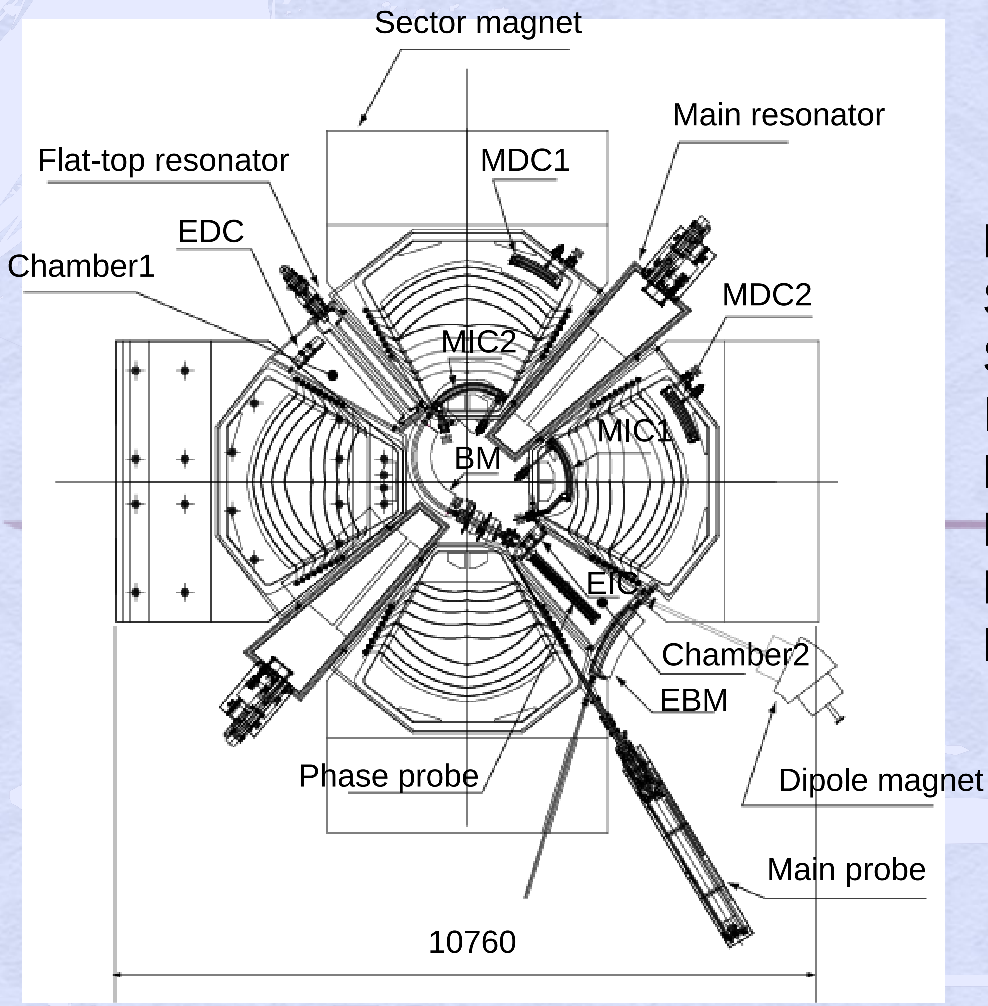
Now washing away the refrigerator.

Extension of the 3.5th and 5th oil separator.

Isochronous quality of new cyclotrons



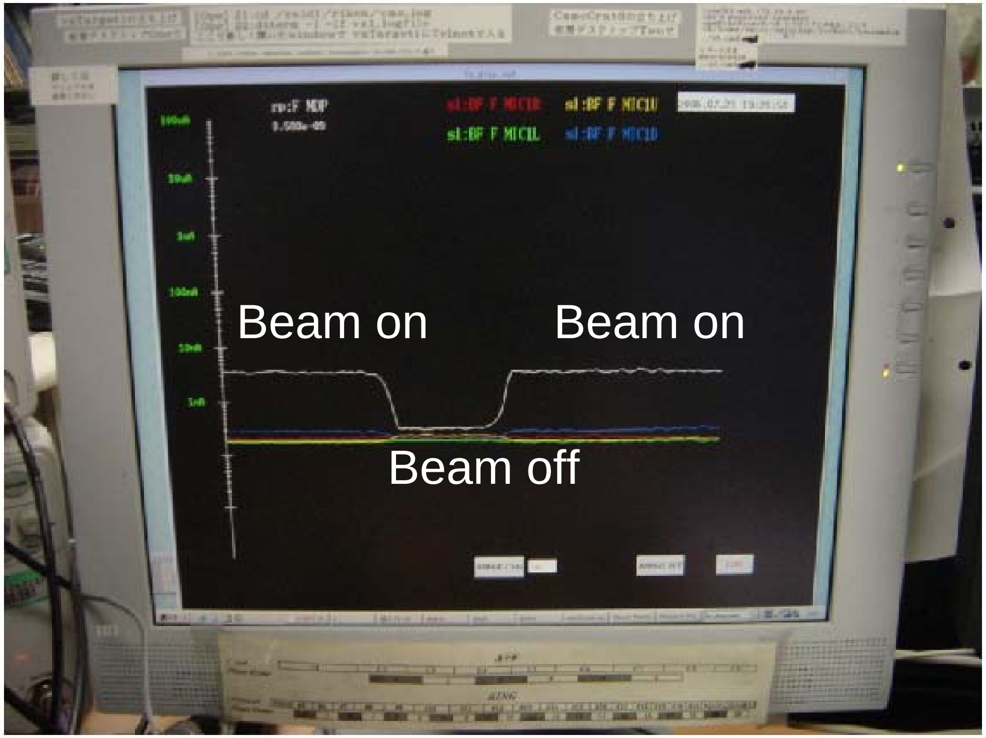
fRC (fixed-frequency Ring Cyclotron)



K-value	570 MeV
Sector	4
Sector angle	58 deg.
Injection radius	1.55 m
Extraction radius	3.30 m
Resonator	2 + 1 (FT)
RF frequency	54.75 MHz
Harmonics	12

July 21st, 2006 fRC

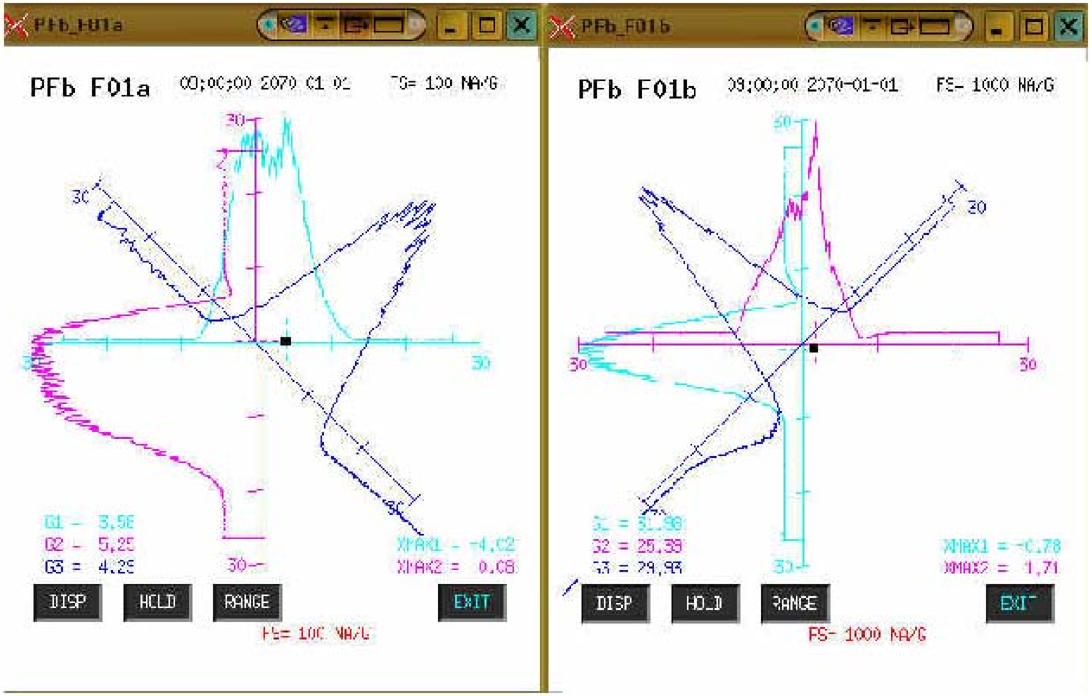
Beam was accelerated up to the energy of design goal.



Measuring the beam intensity at final orbit of fRC.

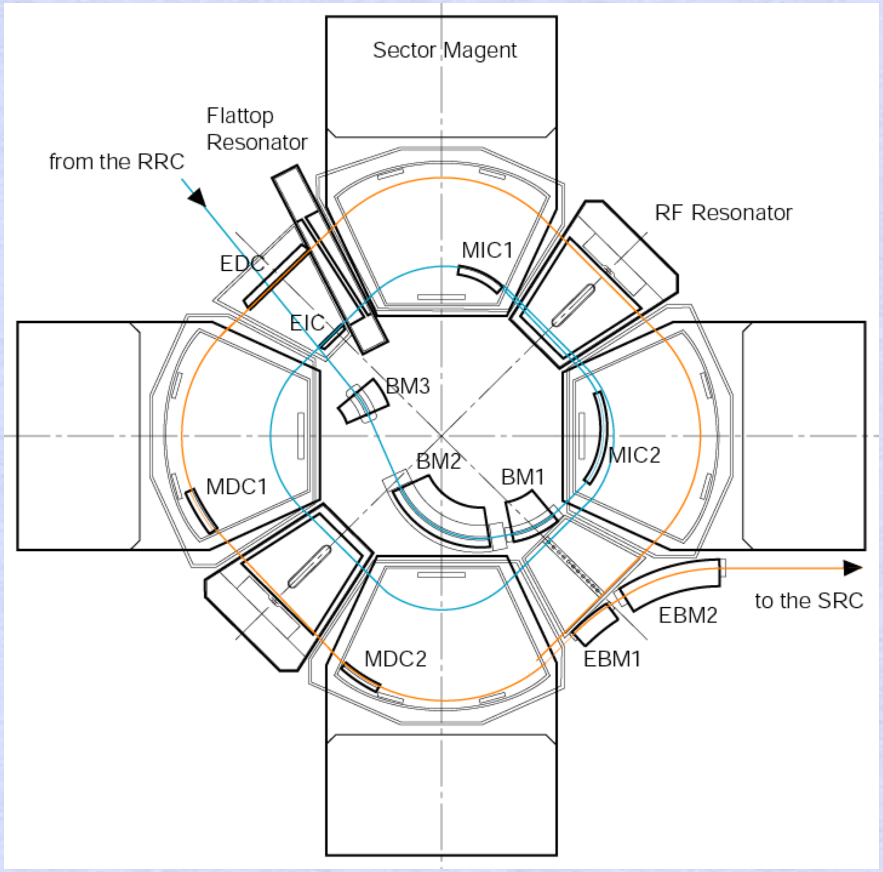
September 29th, 2006

First beam extraction of $^{238}U^{73+}$ 50 MeV/n from fRC.



Beam profile at the downstream of fRC.

IRC (Intermediate-stage Ring Cyclotron)

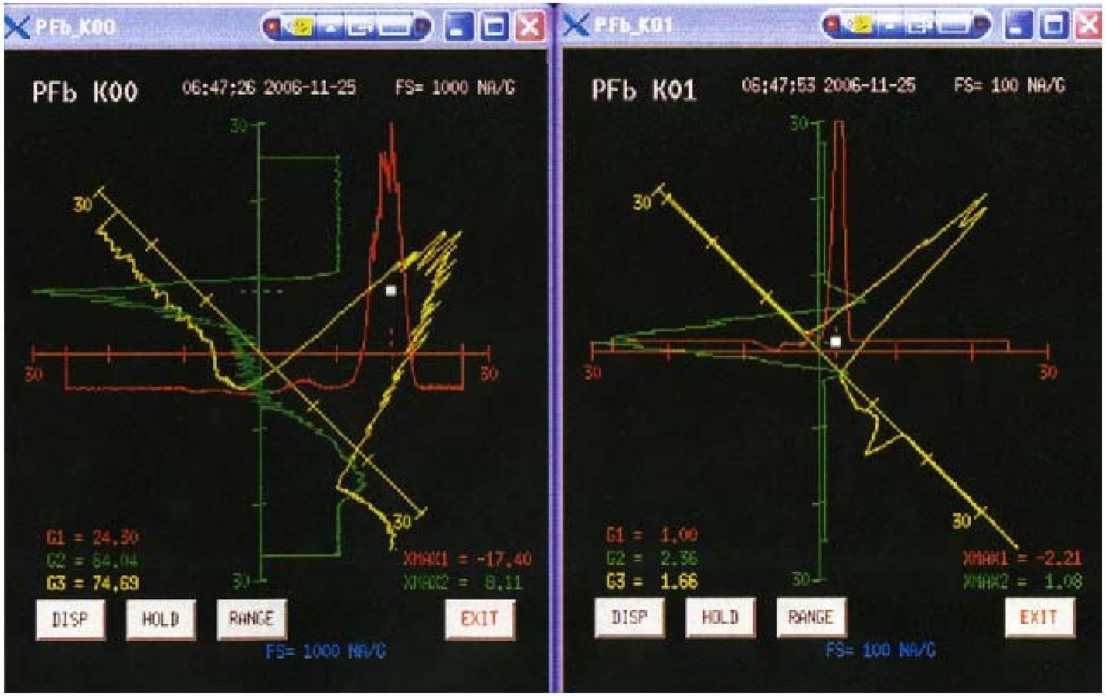


K-value	980 MeV
Sector	4
Sector angle	53 deg.
Injection radius	2.77 m
Extraction radius	4.15 m
Resonator	2 + 1 (FT)
RF frequency	18—38 MHz
Harmonics	7

November 25th ,2006 2:20

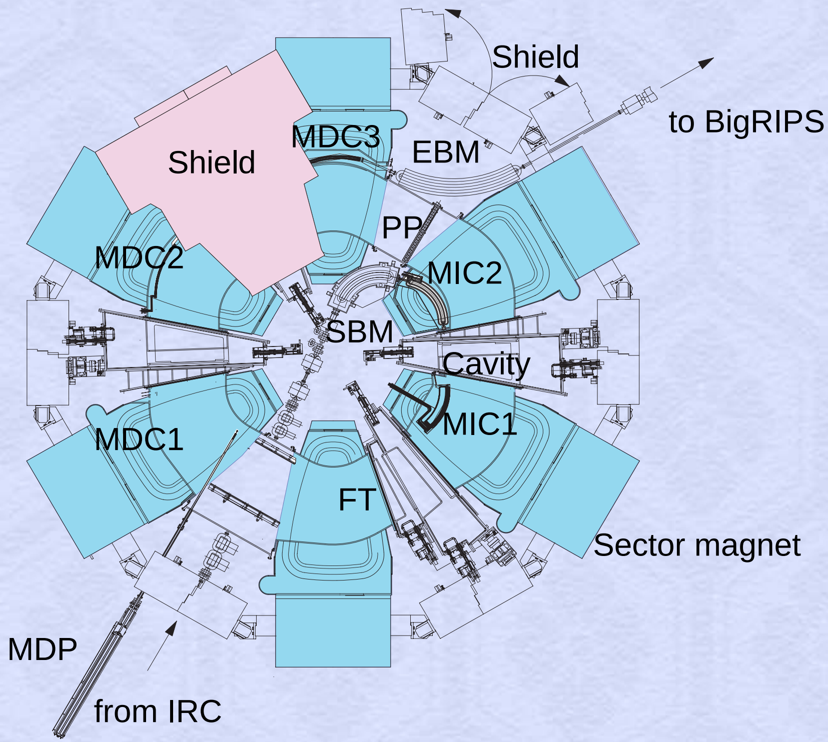
First beam extraction of $^{84}Kr^{31+}$ 114 MeV/n from IRC.

Only 110 minutes from injection to extraction.



Beam profile at the downstream of IRC.
(Four hours after the beam extraction.)

SRC (Super-conducting Ring Cyclotron)



K-value	2600 MeV
Sector	6
Sector angle	25 deg
Injection radius	3.56 m
Extraction radius	5.36 m
Resonator	4 + 1 (FT)
RF frequency	18—38 MHz
Harmonics	6 (5)

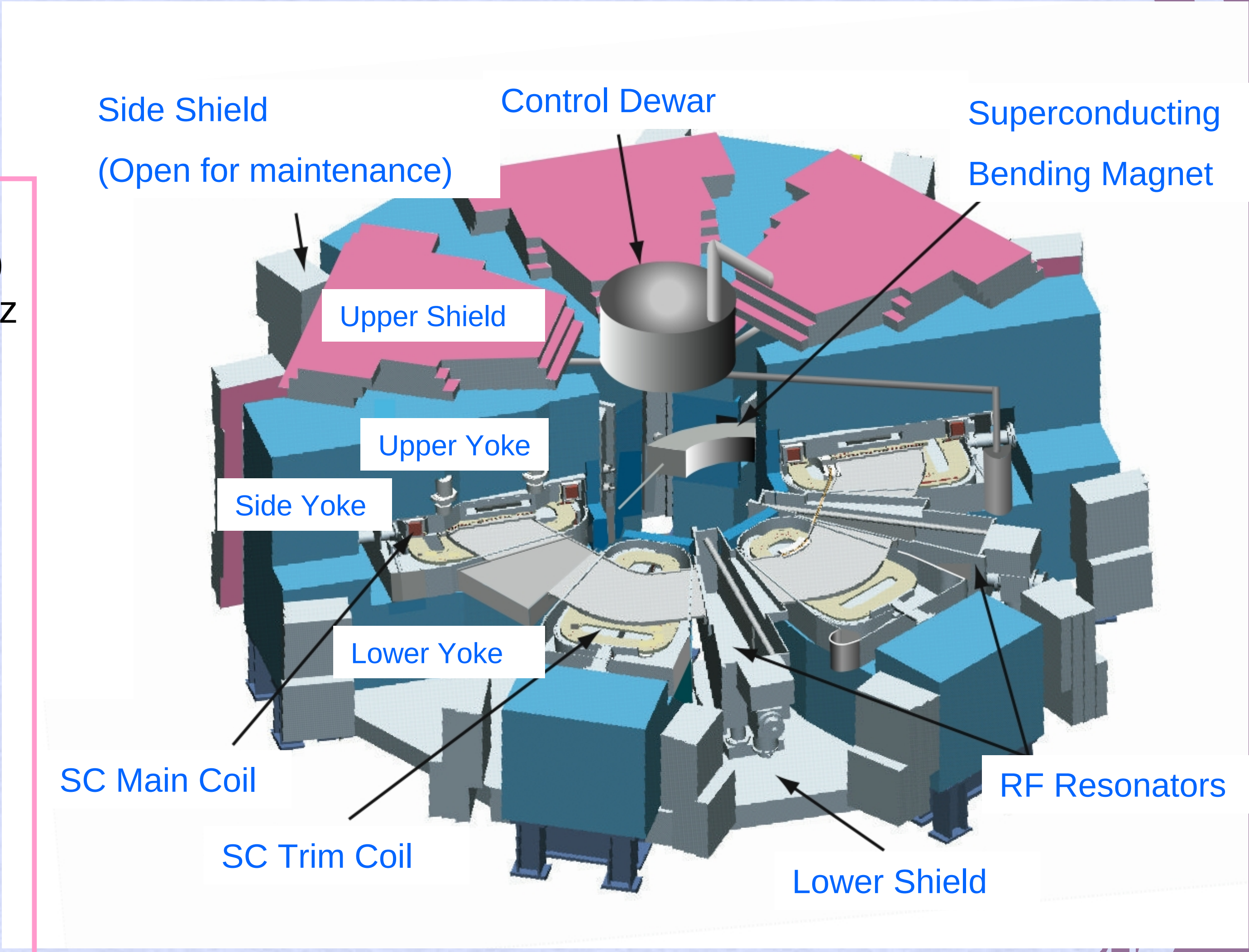
SRC

Superconducting Ring Cyclotron (SRC)

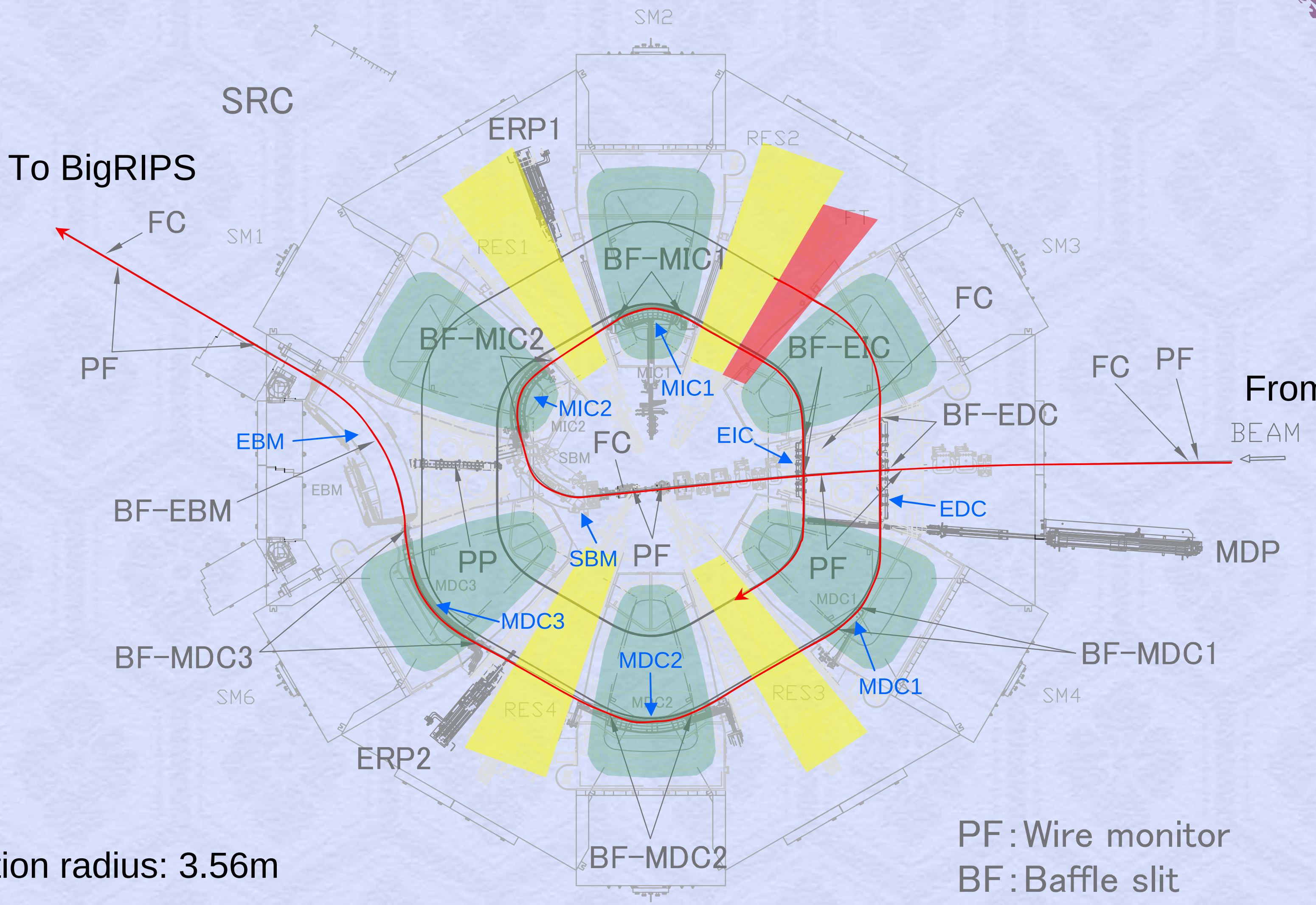
K = 2,600 MeV
Max. field: 3.8T (235 MJ)
RF frequency: 18-42 MHz
Harmonic Number: 6
Diameter: 19 m
Height: 8 m
Weight: 8,300 tons

Sector magnets: 6
Sector angle: 25 deg.
RF resonators: 4
Flat-top resonator: 1
Injection elements.
Extraction elements.
Beam diagnostics.

Self Magnetic Shield
Self Radiation Shield



Injection/extraction devices and diagnostics of SRC

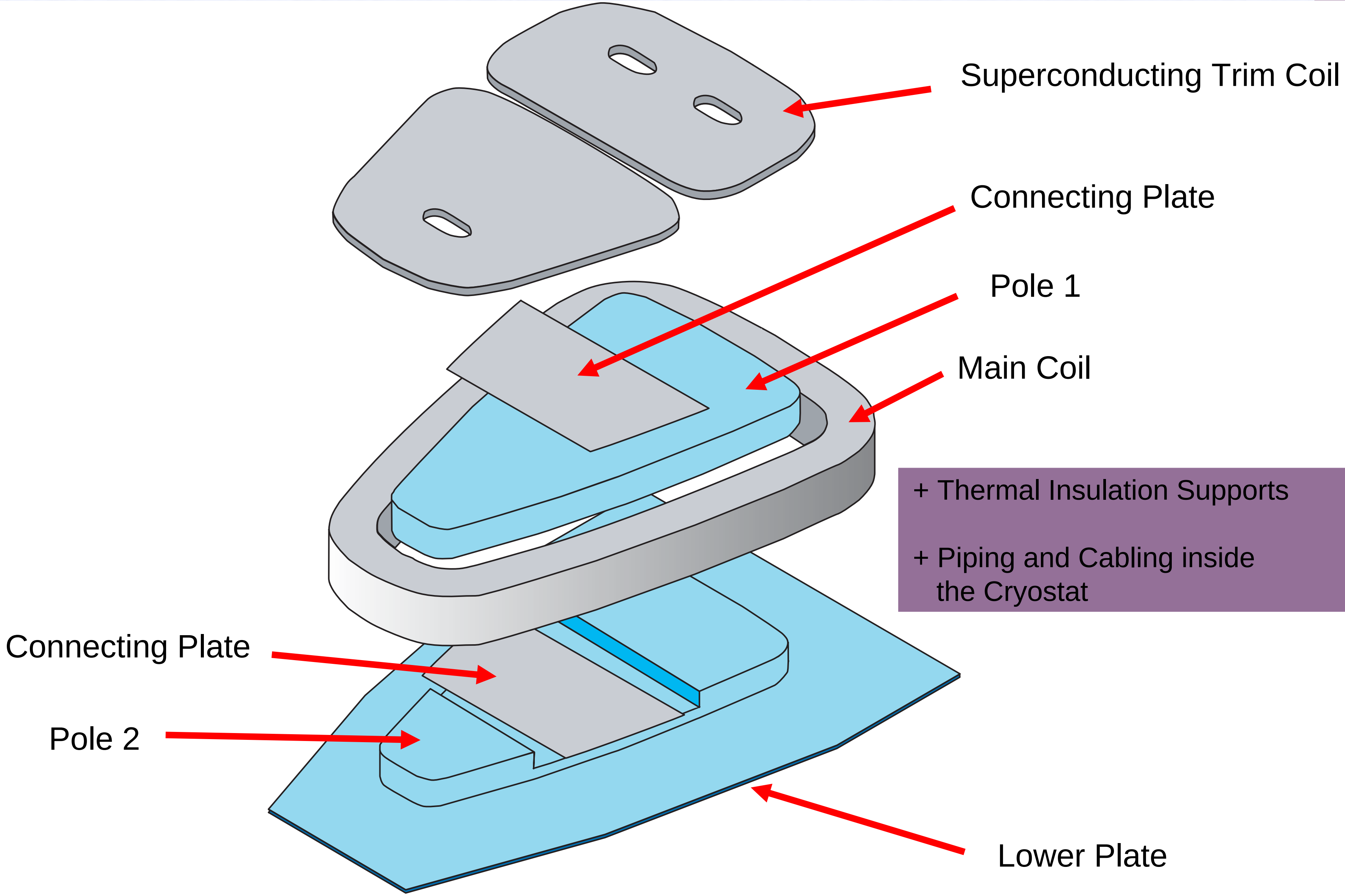


Injection radius: 3.56m

Extraction radius: 5.36m

PF: Wire monitor
BF: Baffle slit
FC: Faraday cup
PP: Phase probe

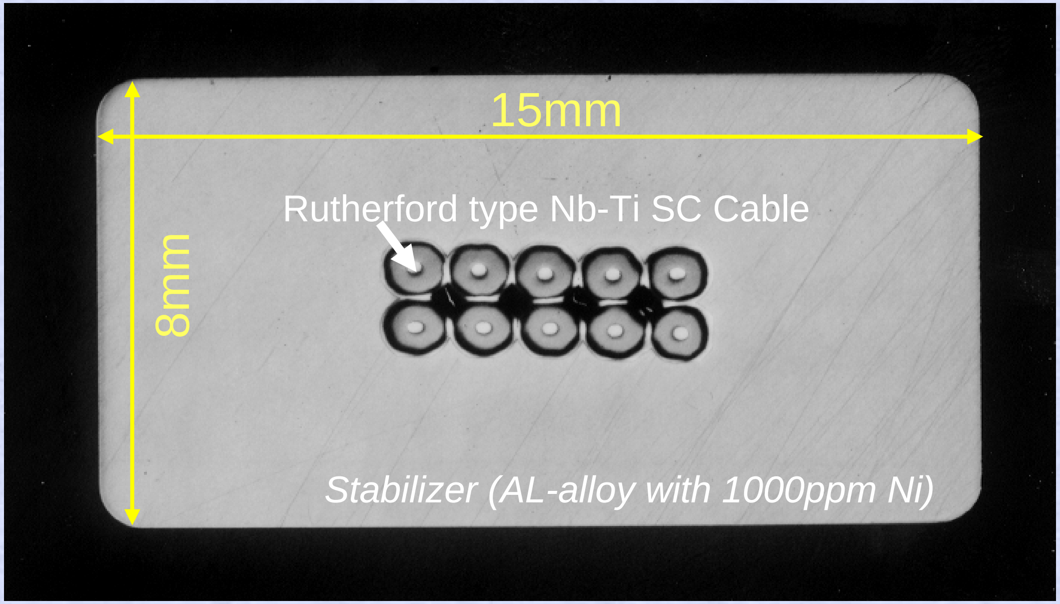
Cold mass assembly

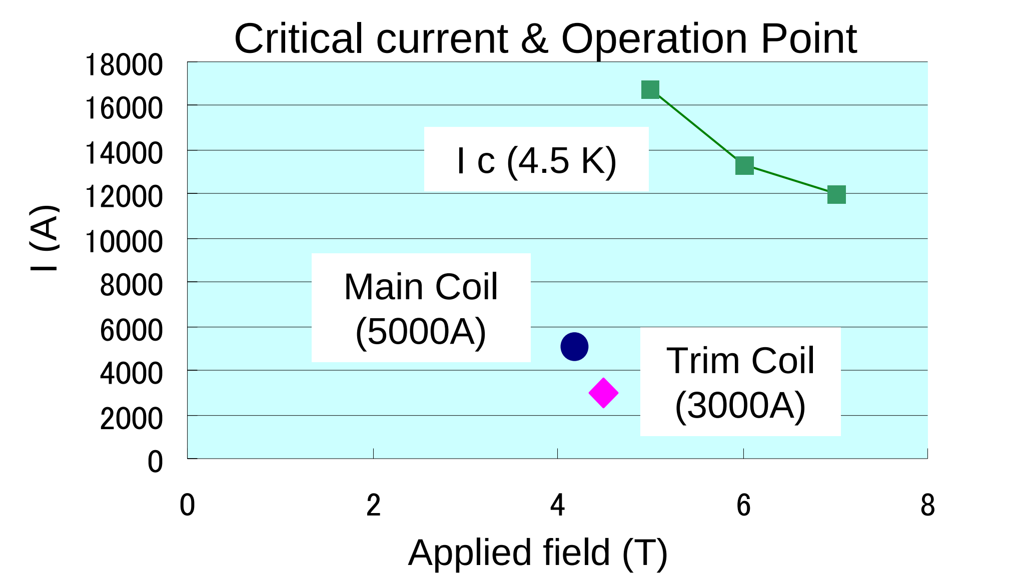


+ Thermal Insulation Supports

+ Piping and Cabling inside the Cryostat

Superconductor





Yield Strength > 56.2 MPa

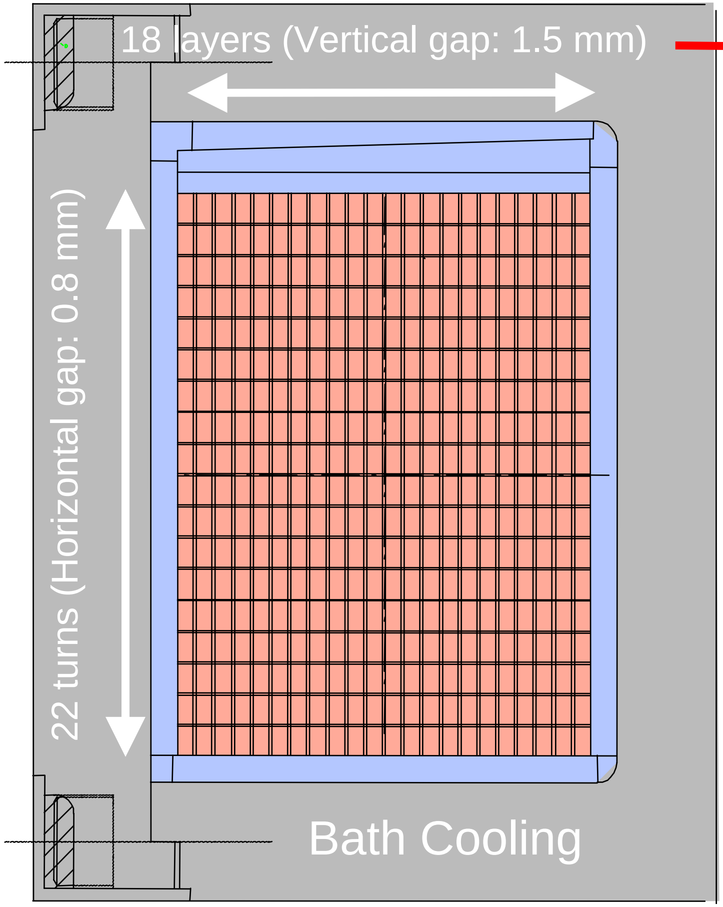
(cf. 40 MPa for pure Al)

Residual Resistivity Ratio of Al > 803

Structure of the main coil block

Circumference ~10m Imax = 5000 A

Solenoid winding with 396 turns → 4 MAT/sector

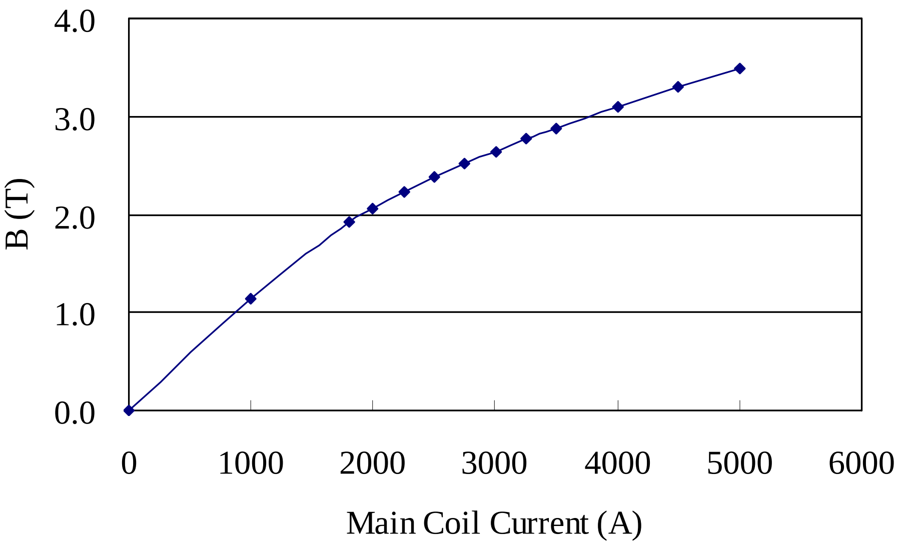


→ Vertical Cooling Channels (50 %)

Maddock Stabilization current: 6300 A

> Operational Cuurent: 5000 A

Excitation curve (R = 5.4m)



Super conducting coil of SRC

Four sets of coils

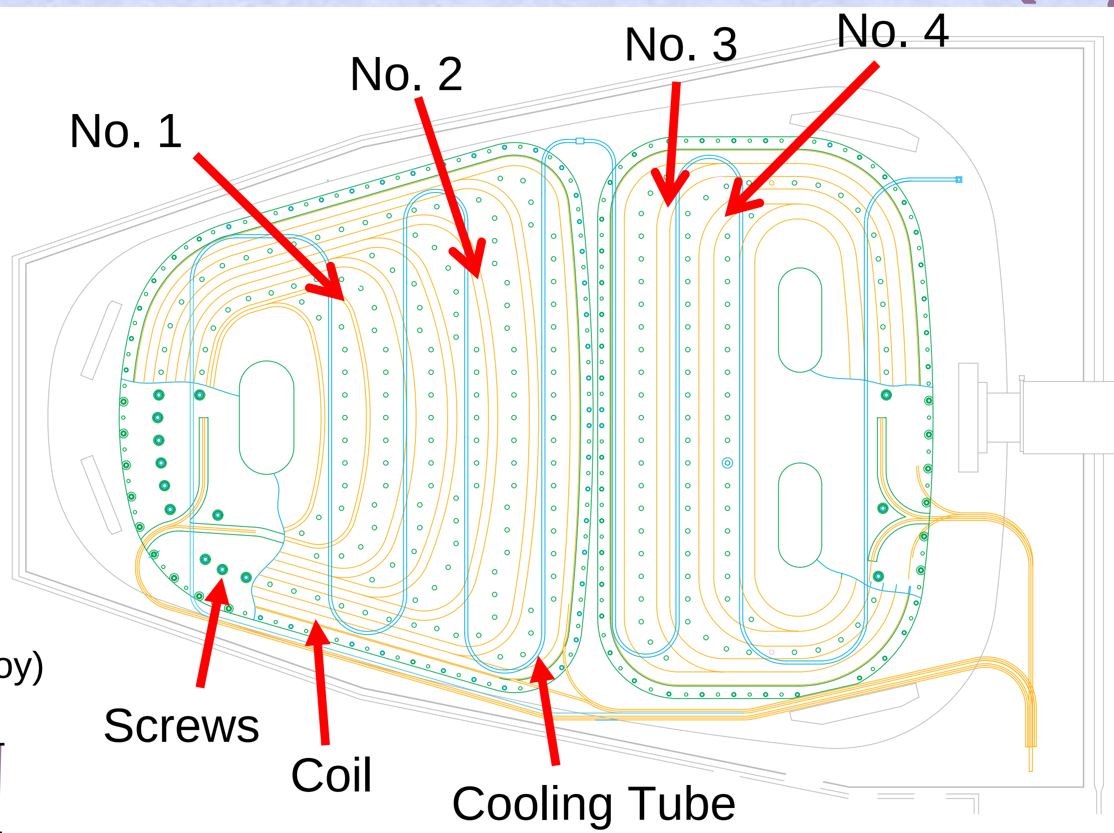
I max = 3000 A

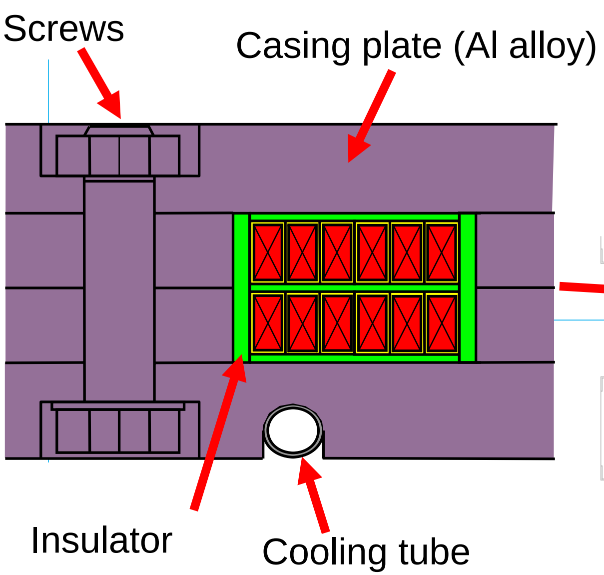
Double pancake winding

Indirect cooling

by forced 2 phase helium

Temp. margin ~2.1K





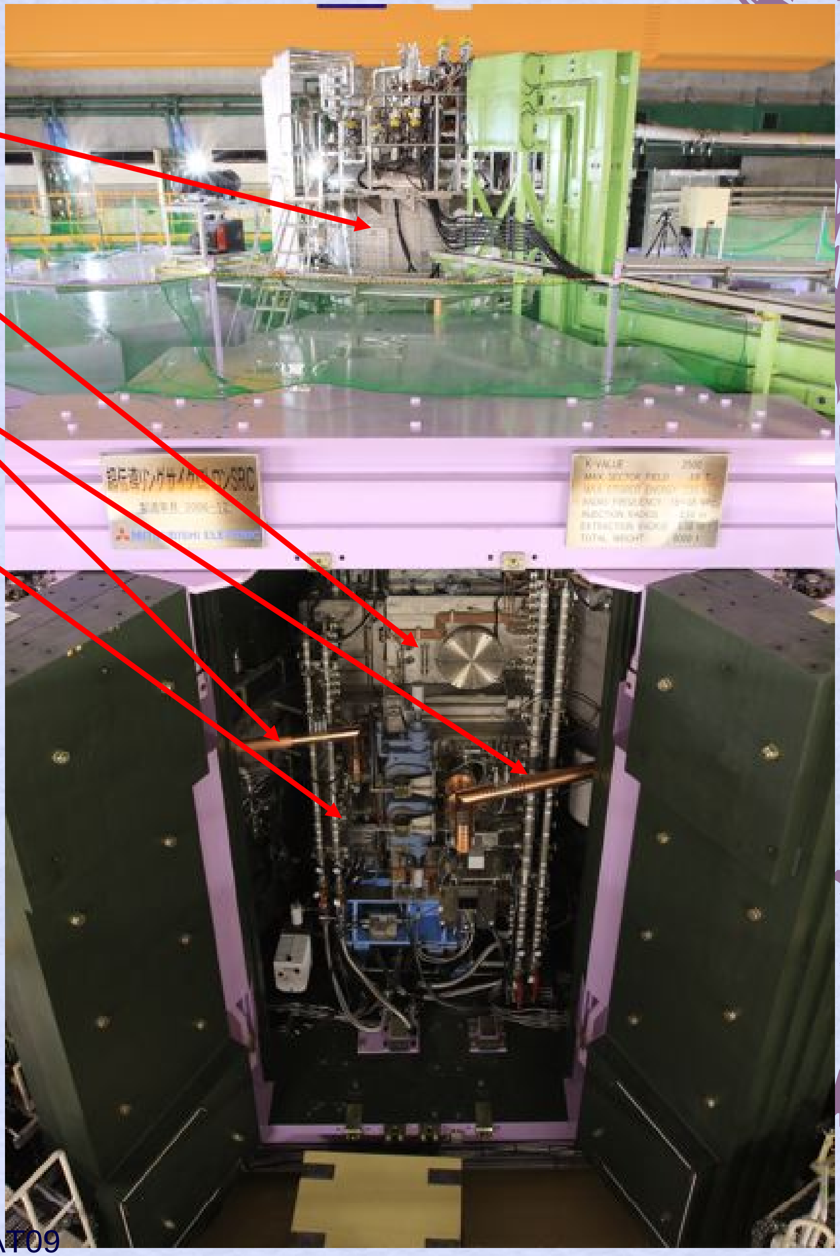
RF resonators

Control Dewar

Acceleration Resonator

Coaxial Transmission Lines

Flat-top Resonator

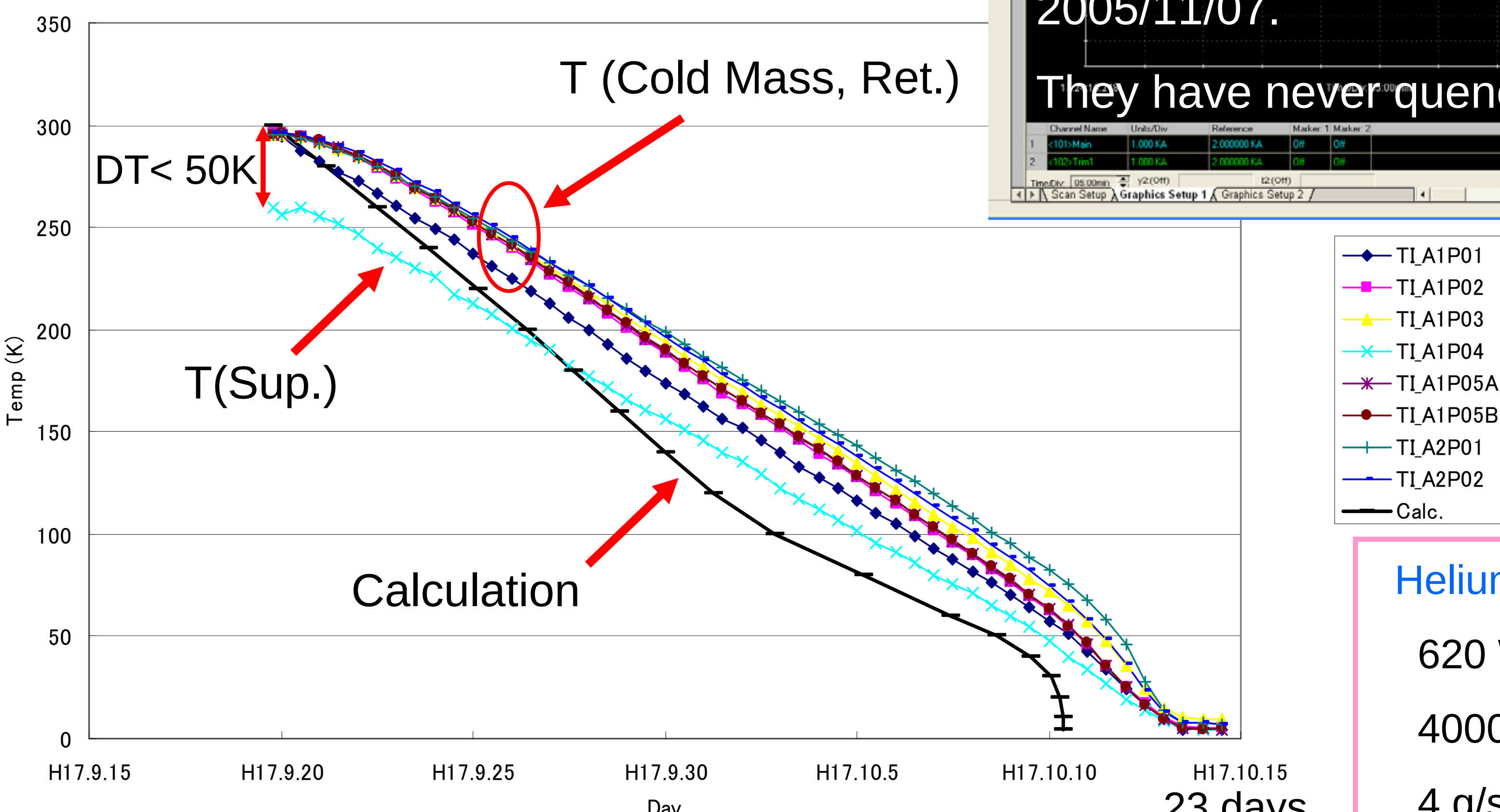


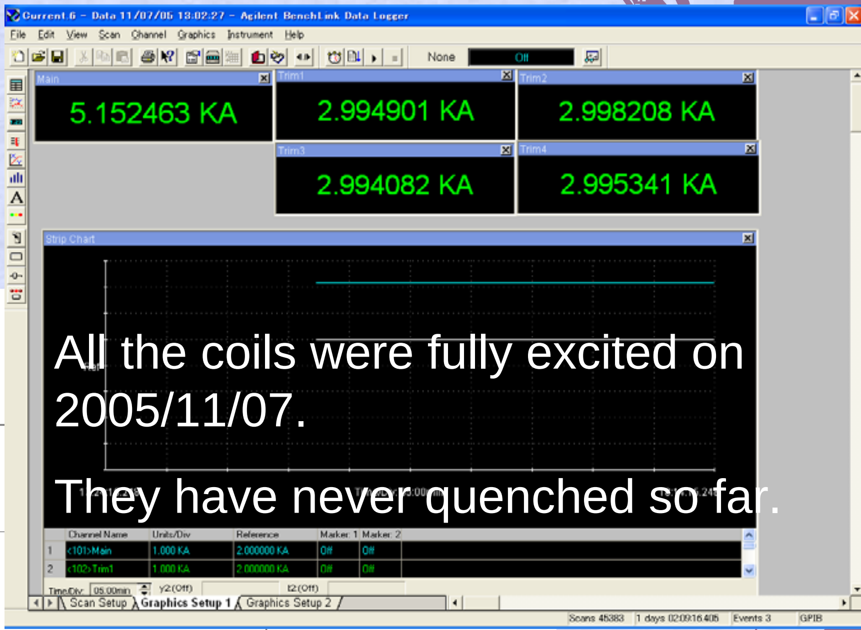
Acceleration Resonators: 4
Gap: Single
Freq.: 18—42MHz
Max. Voltage: 600kV
Power Amp.: 150kW

Flat-top Resonator: 1
Gap: Single
Freq.: 72—126MHz
Max. Voltage: 350kV
Power Amp.: 60kW

The first cool-down and excitation of SRC

Cold Mass :142 tons





All the coils were fully excited on 2005/11/07.

They have never quenched so far.

Helium refrigerator

620 W at 4.5 K

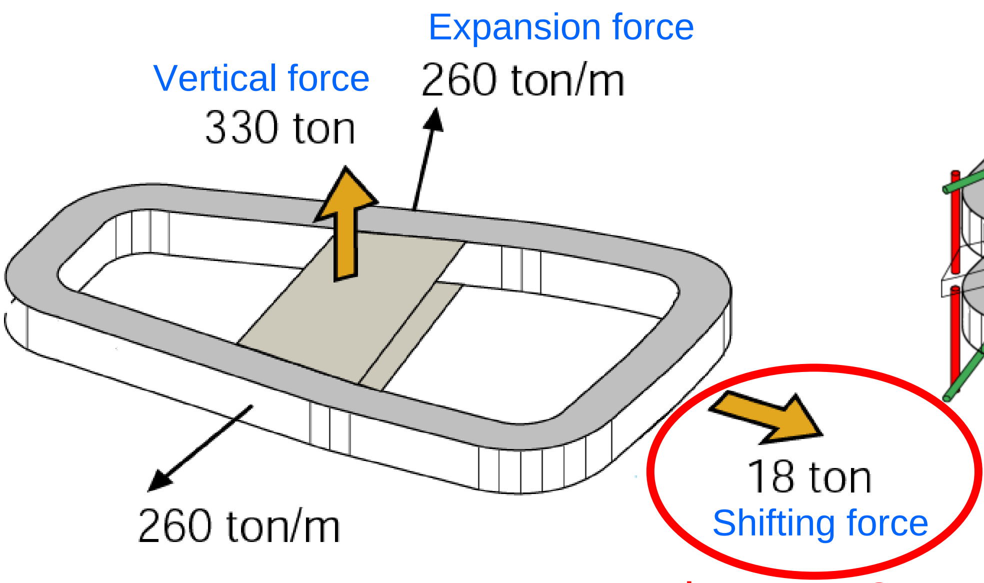
4000 W at 70 K

4 g/s gas helium

Magnetic forces in excitation of SRC

Huge magnetic forces on the coils

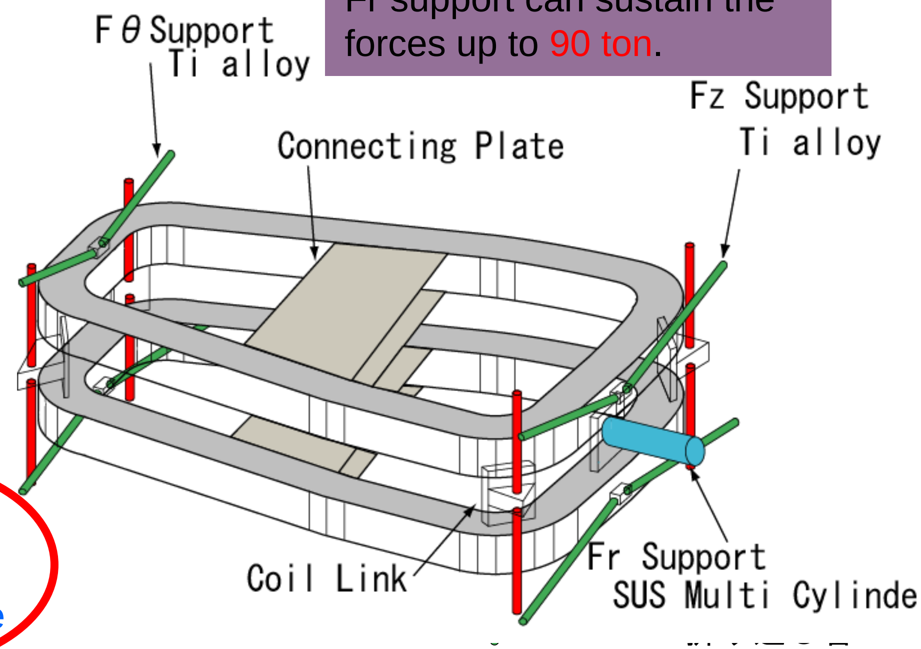
Forces on the upper coil (TOSCA calculation)



Big Errors?

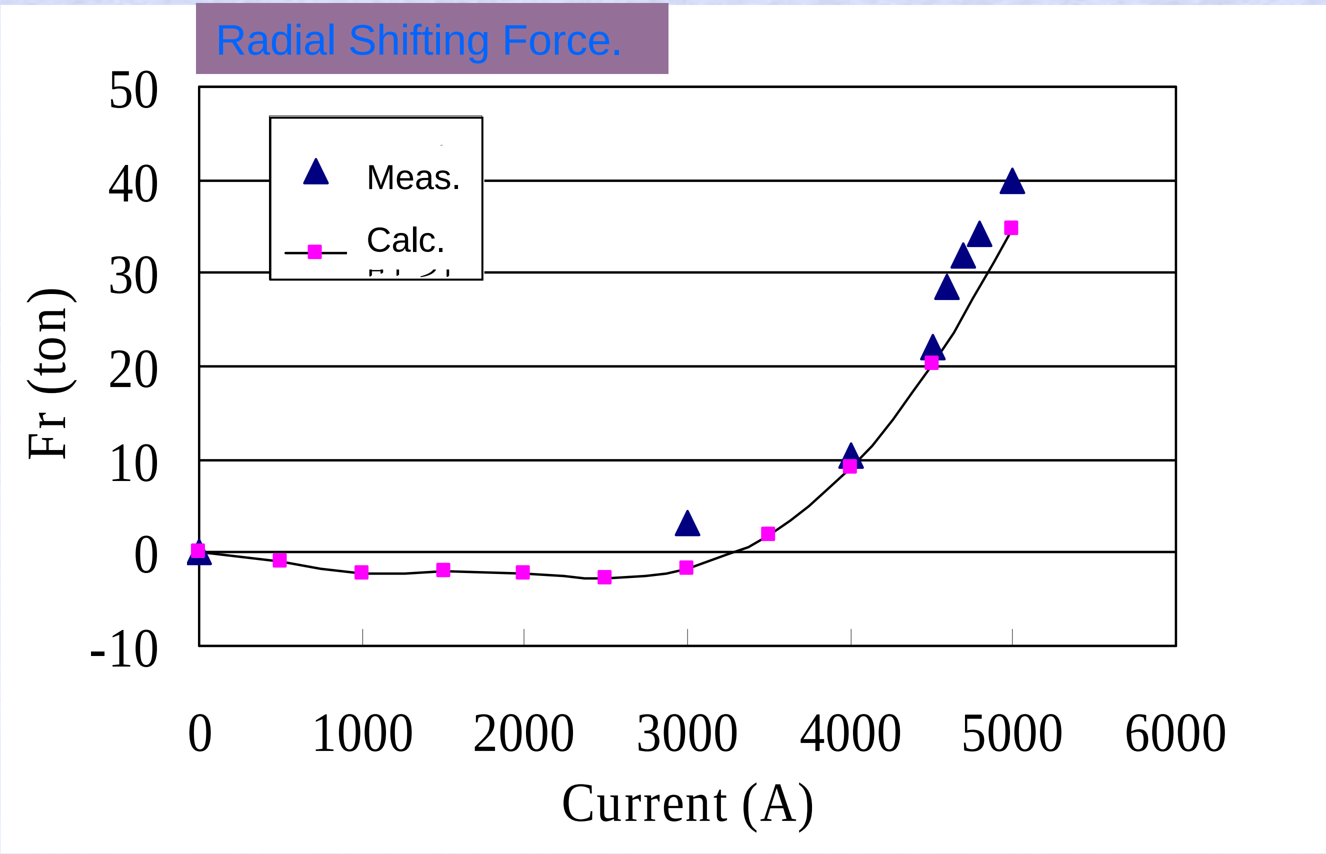
Mechanical supports for the cold mass

Fr support can sustain the forces up to 90 ton.



In the excitations, we continuously measured the forces using the strain gauges attached to all the supports in the excitations, checking whether our calculations are correct or not.

Magnetic forces in excitation of SRC

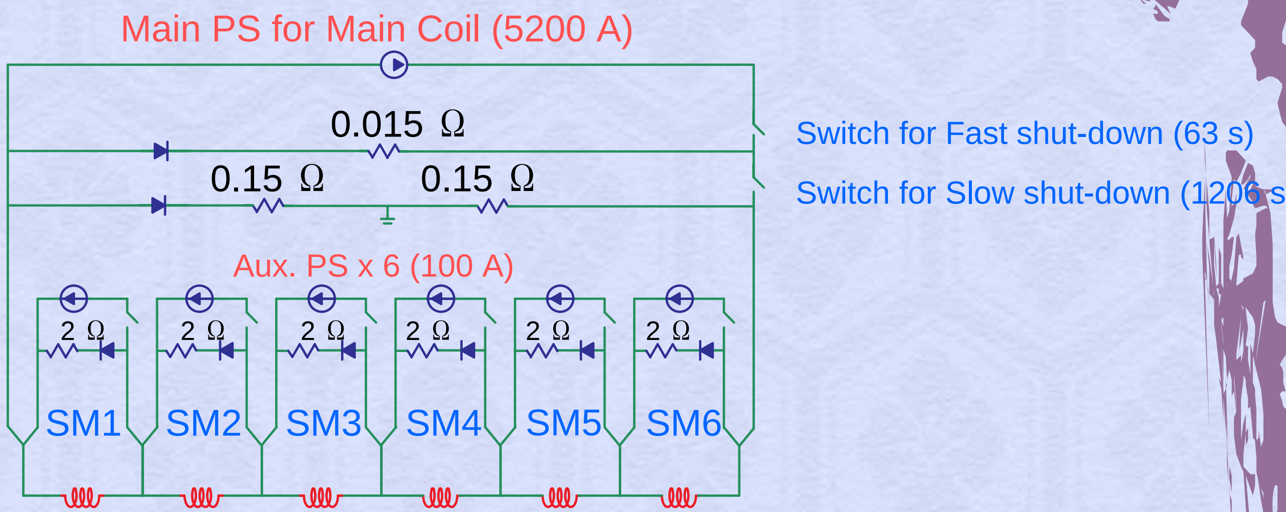


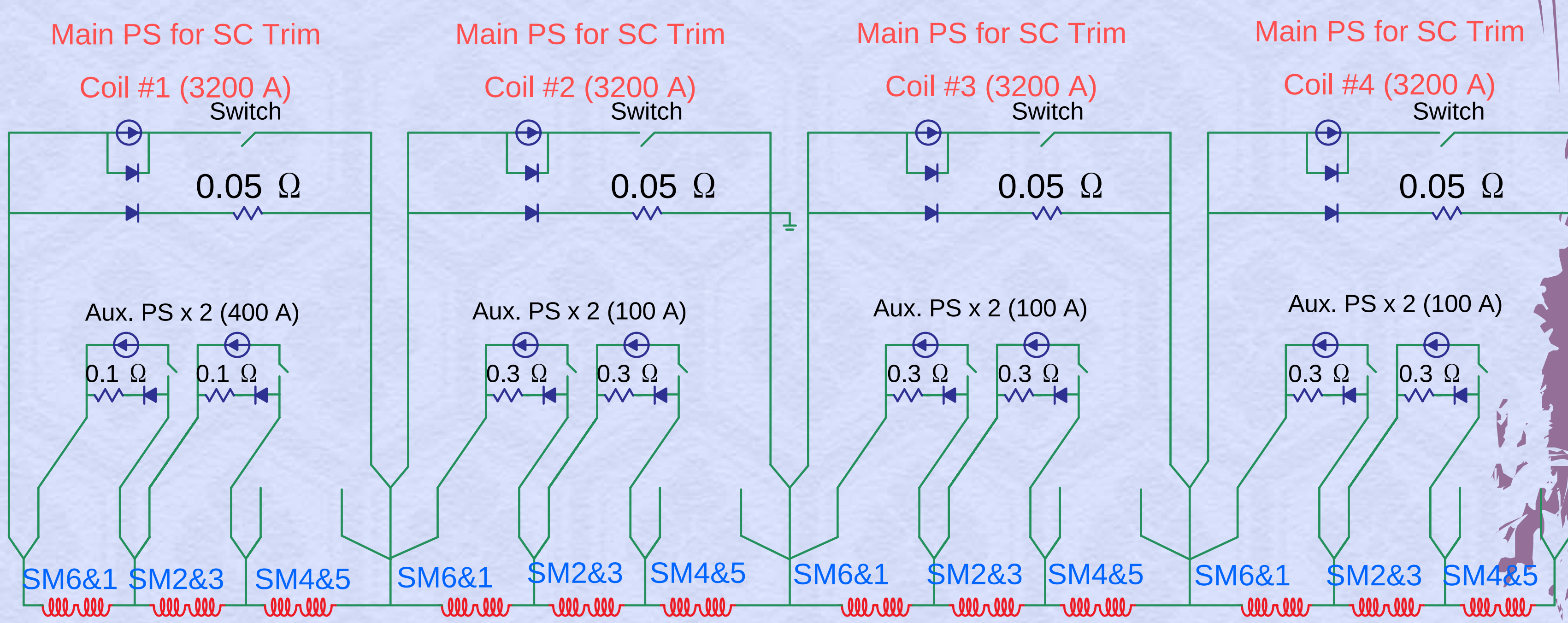
The measurement clarified that the forces were smaller than the designed limit and enough to keep displacements of the coils small in excitations.

Power supplies and coil protection of SRC

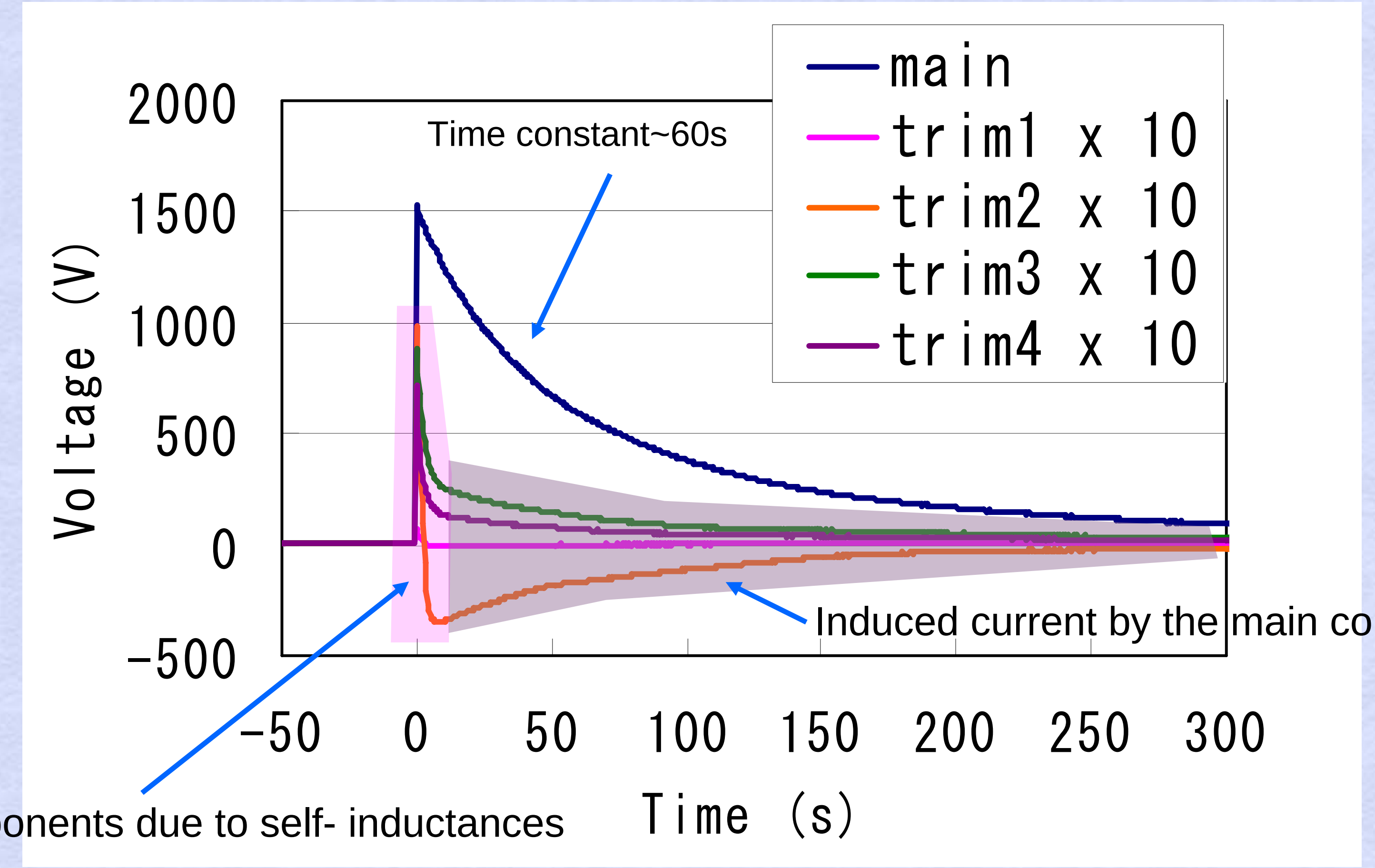
Quench characteristic

Current decay:	63 sec
Temp. rise:	140 K
Volt. induction:	1.5 kV/2





Coil voltages in fast shut-down test from full excitation of SRC

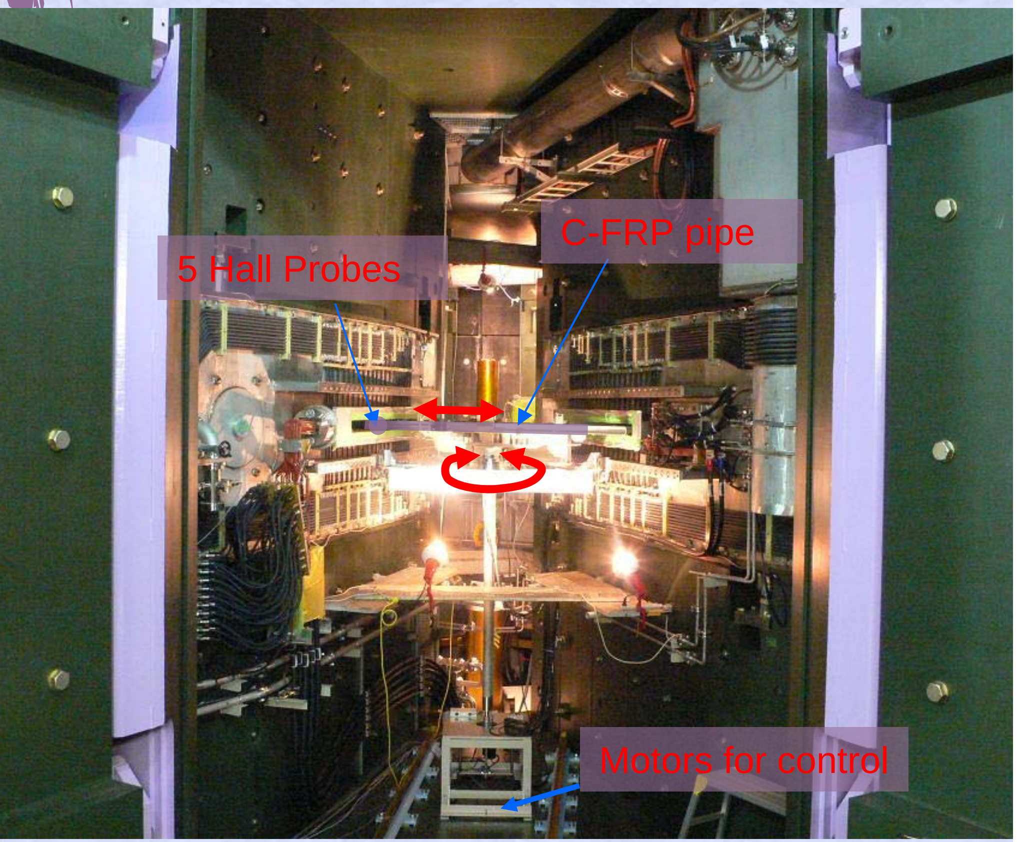


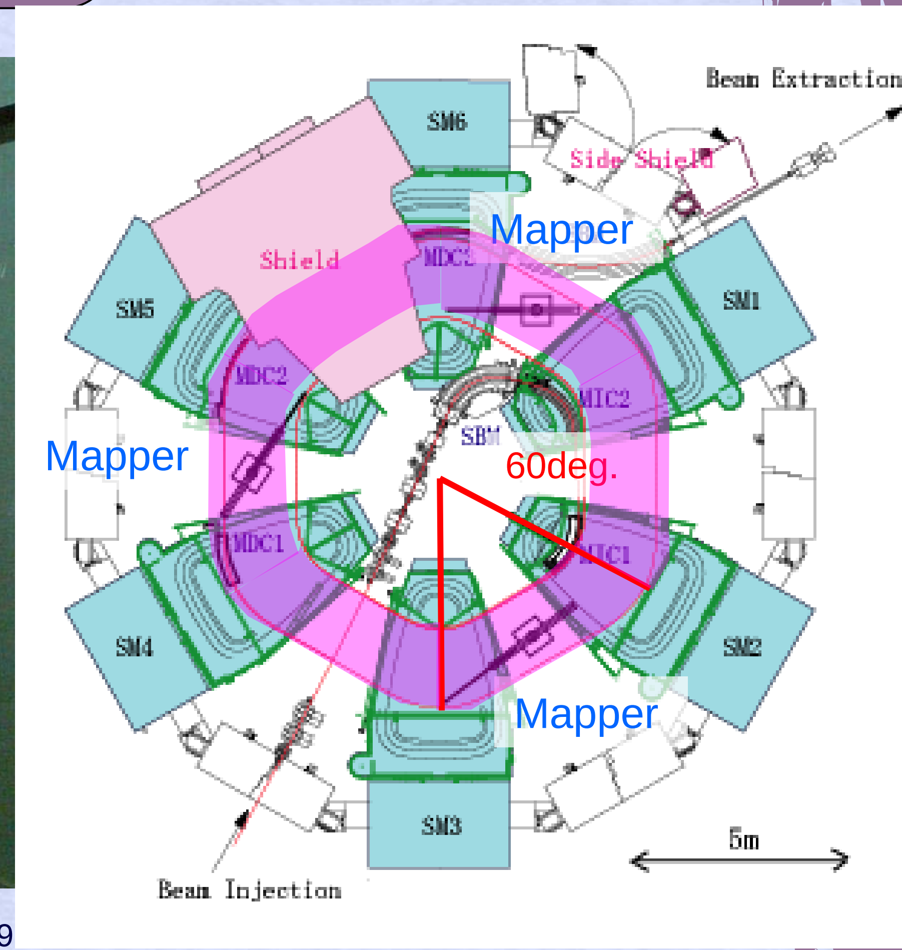
The main coils and S.C. Trim coils are strongly coupled together due to their relative positions.

All the coils were safely shut down even in emergency.

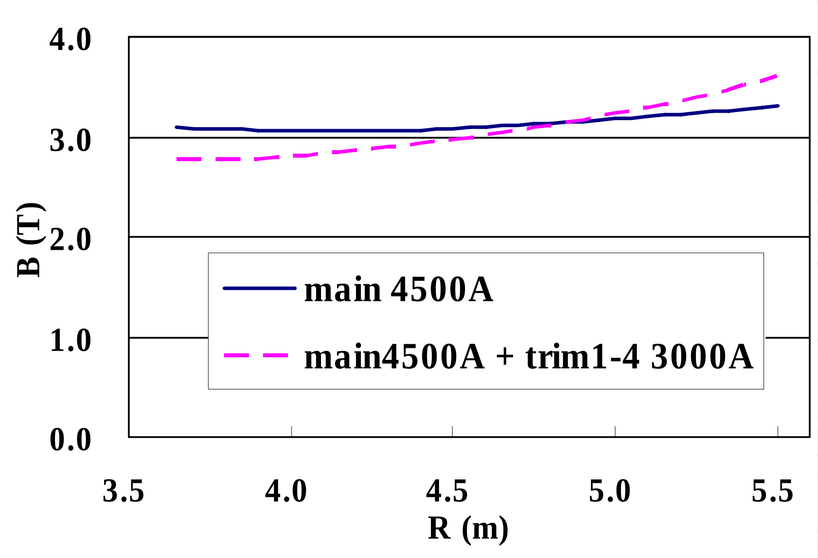
Field mapping over the acceleration region of SRC

Field Mapper:	3 (60 deg./each)
Hall Probe:	5
Control:	2 axis (Rot./Trans.)
Mesh:	about 50mm
Meas. Time:	about 3h30m/60deg.





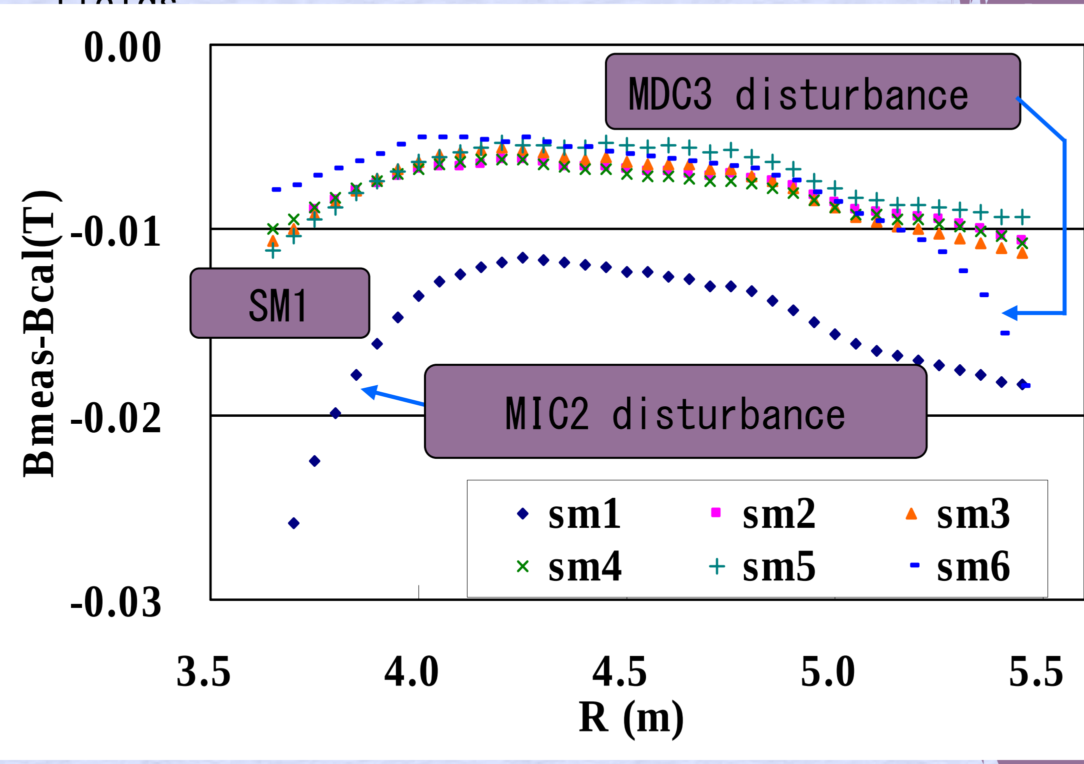
Measured field profiles along the sector-center axis of SRC



Main Coil: Bending power during the acceleration

Trim Coil: Isochronous field

Difference between measured and calculated fields



○ Good agreement (0.16%~0.35%)
○ Small field dispersion among the sectors

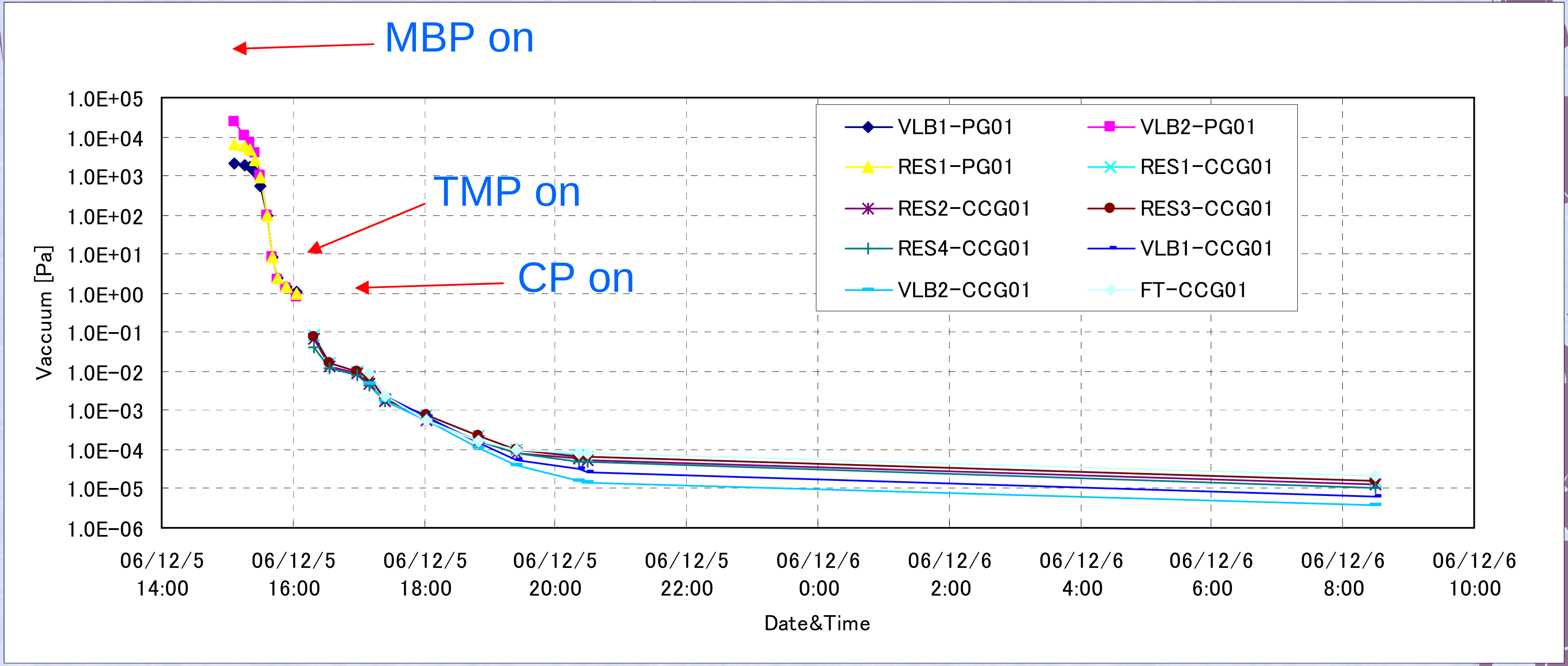
Field Disturbances
・SM1 has a slightly different shape.
・Disturbance from MIC2 and MDC3

Small enough to be adjusted by the correction coils in the magnetic channels and aux. power supplies of the main and trim coils.

Evacuation of SRC beam chamber

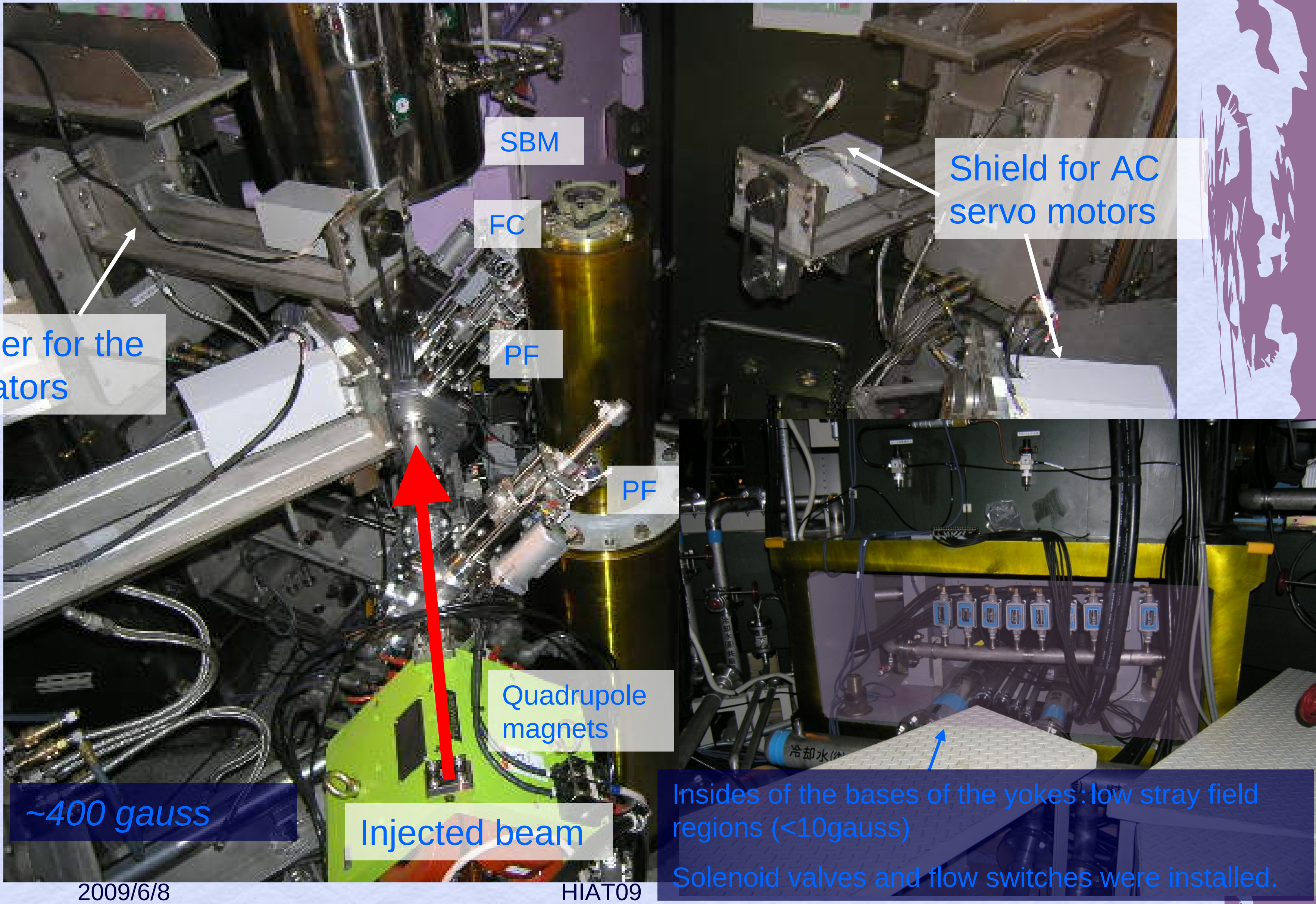
Evacuation started in September.

Cryopumps were started on ’06/10/18.



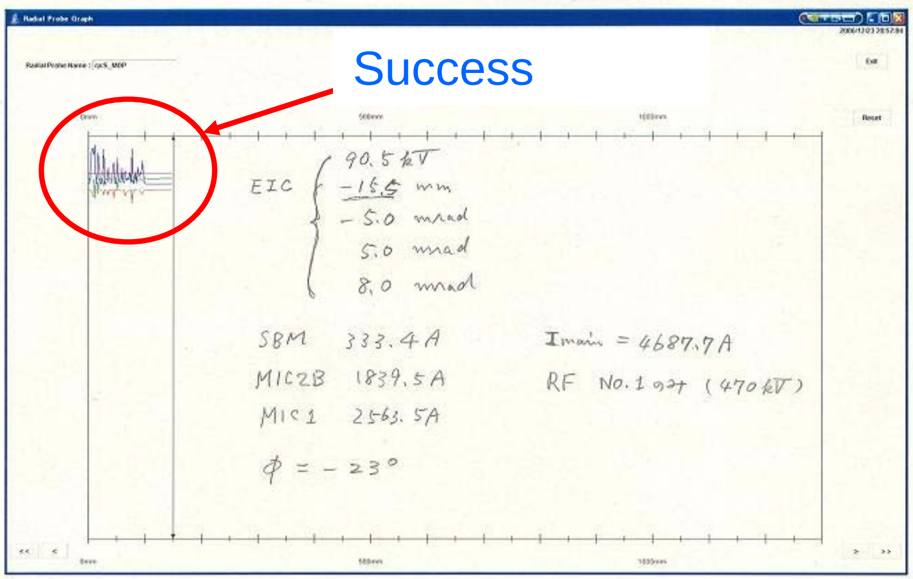
Vacuum pressures in normal operation : 2~3 x 10 $^{-6}$ Pa

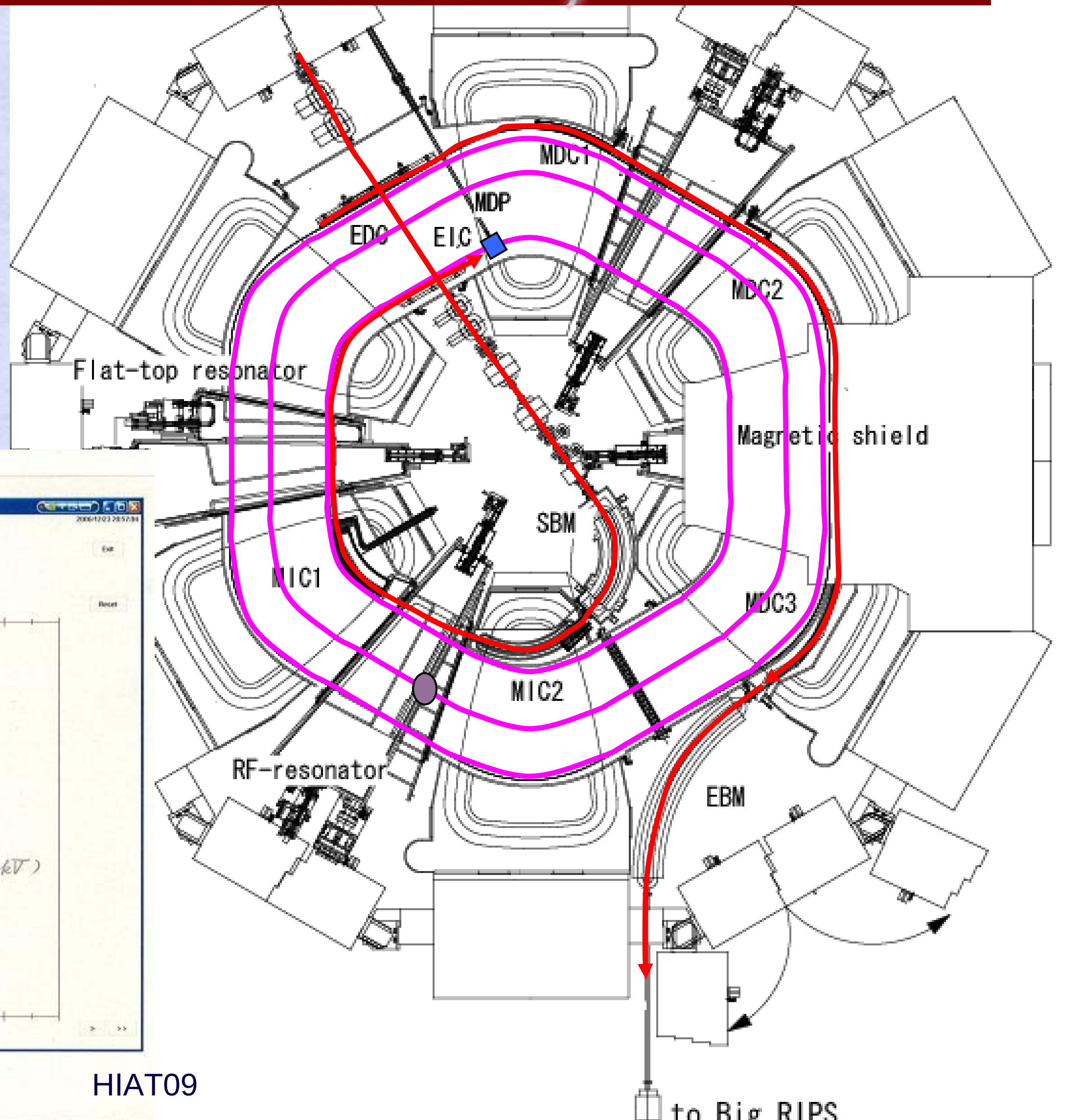
Local magnetic shields (ex. The parts in the central region)



SRC Beam commissioning ($^{27}Al^{10+}$ 345AMeV)

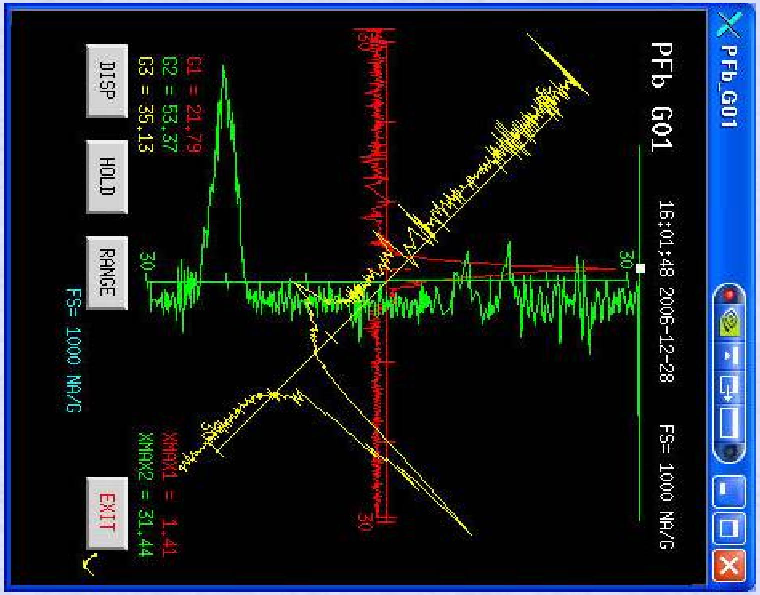
- 12/17 18:20 Beam Injection started.
- 12/21 16:00 Acceleration Tuning started. (currents of Imain, Itrim, Injection orbits and phase of RF)
- 12/23 21:00 Acceleration up to 10cm from r_{inj}.
- 12/24 02:00 Acceleration up to 100cm from r_{inj}.
- 12/25 23:45 Something @100cm from r_{inj}.





December 28th, 2006 16:00

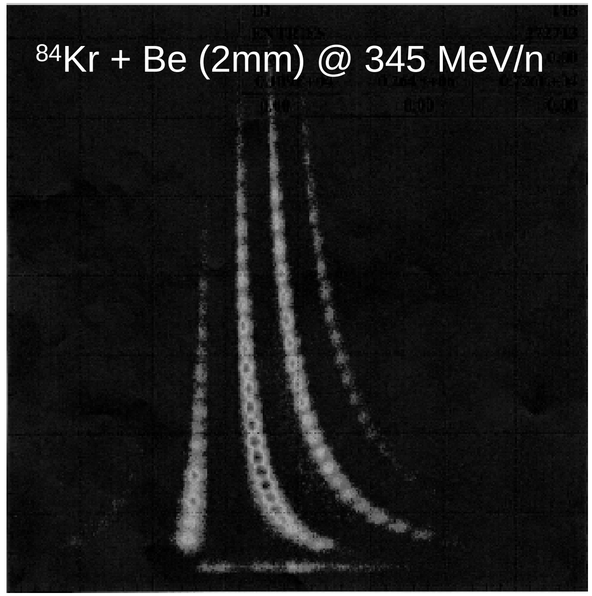
First beam extraction of $^{27}Al^{10+}$ 345 MeV/n from SRC.



Beam profile at the downstream of SRC.

March 15th, 2007
First RI beam production at BigRIPS.
(^{86}Kr 345 MeV/n)

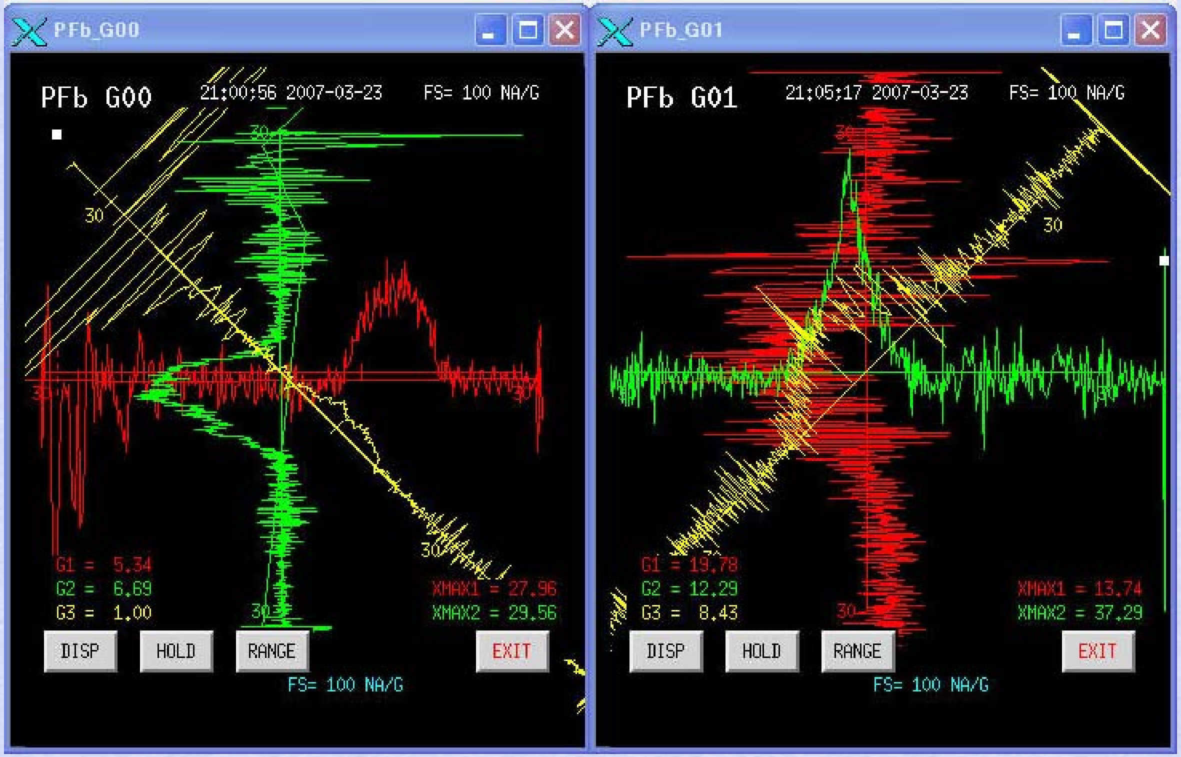
ΔE



TOF (F3—F7)

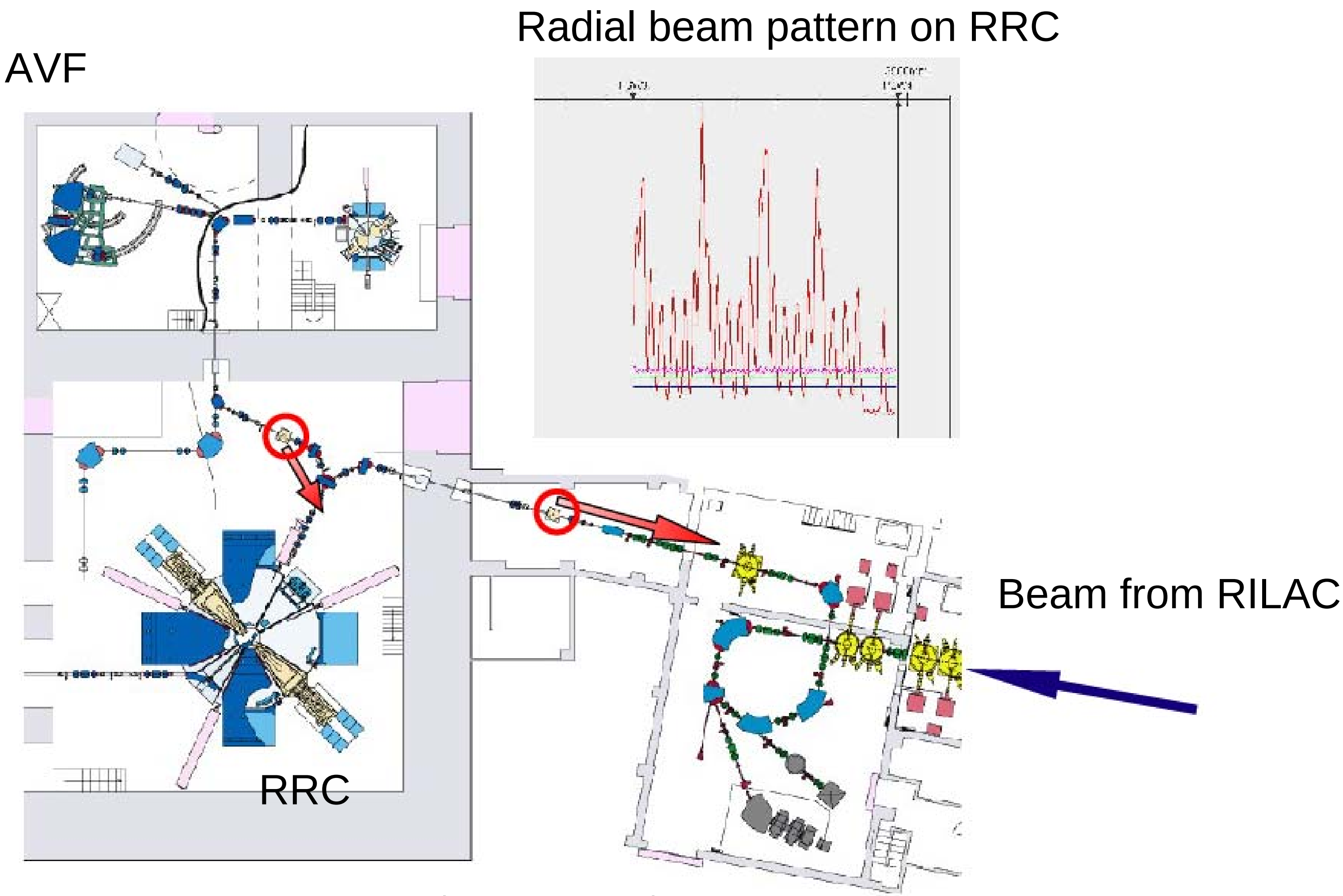
March 15th, 2007
Facility inspection
March 22nd, 2007
Passed

March 23rd, 2007 21:00
First beam extraction of $^{238}U^{86+}$ 345 MeV/n from SRC.



Full operation of RIBF.

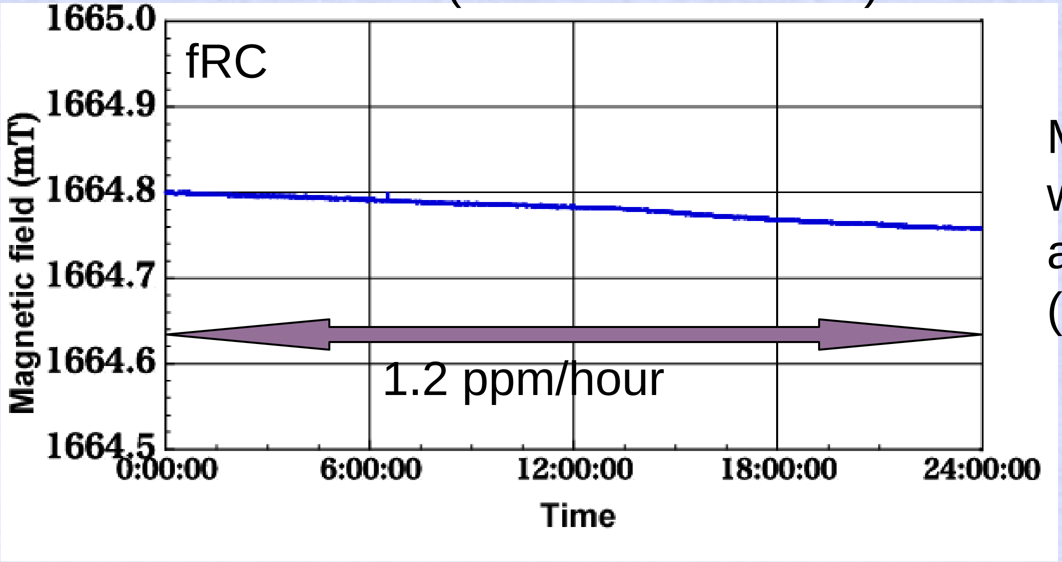
For the first experiment at RIBF using uranium beam, re-buncher system was reconstructed (April 2007).



New isotope search (May 8th – June 3rd, 2007) → Discovery of ^{125}Pd.

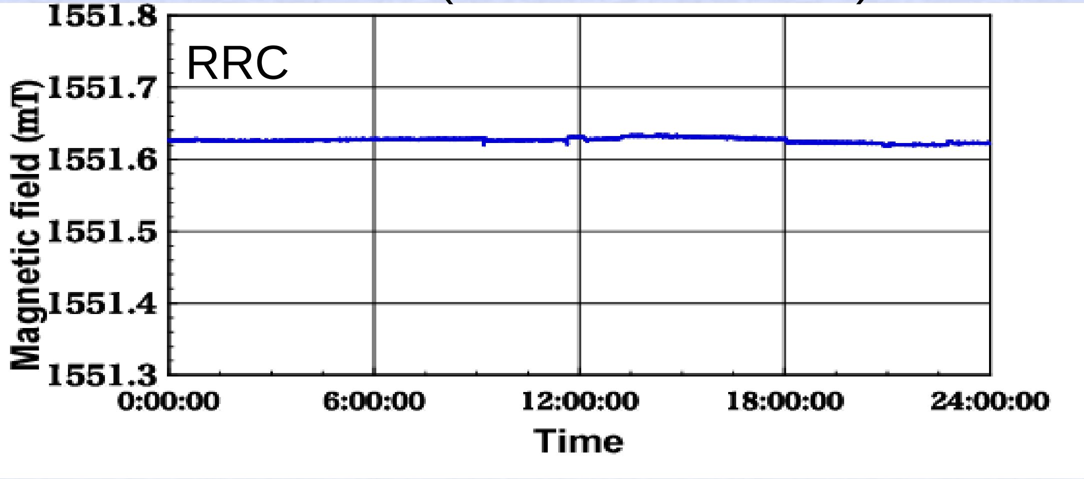
Stability of magnetic filed on fRC

07/06/26 (Power on 07/06/19)

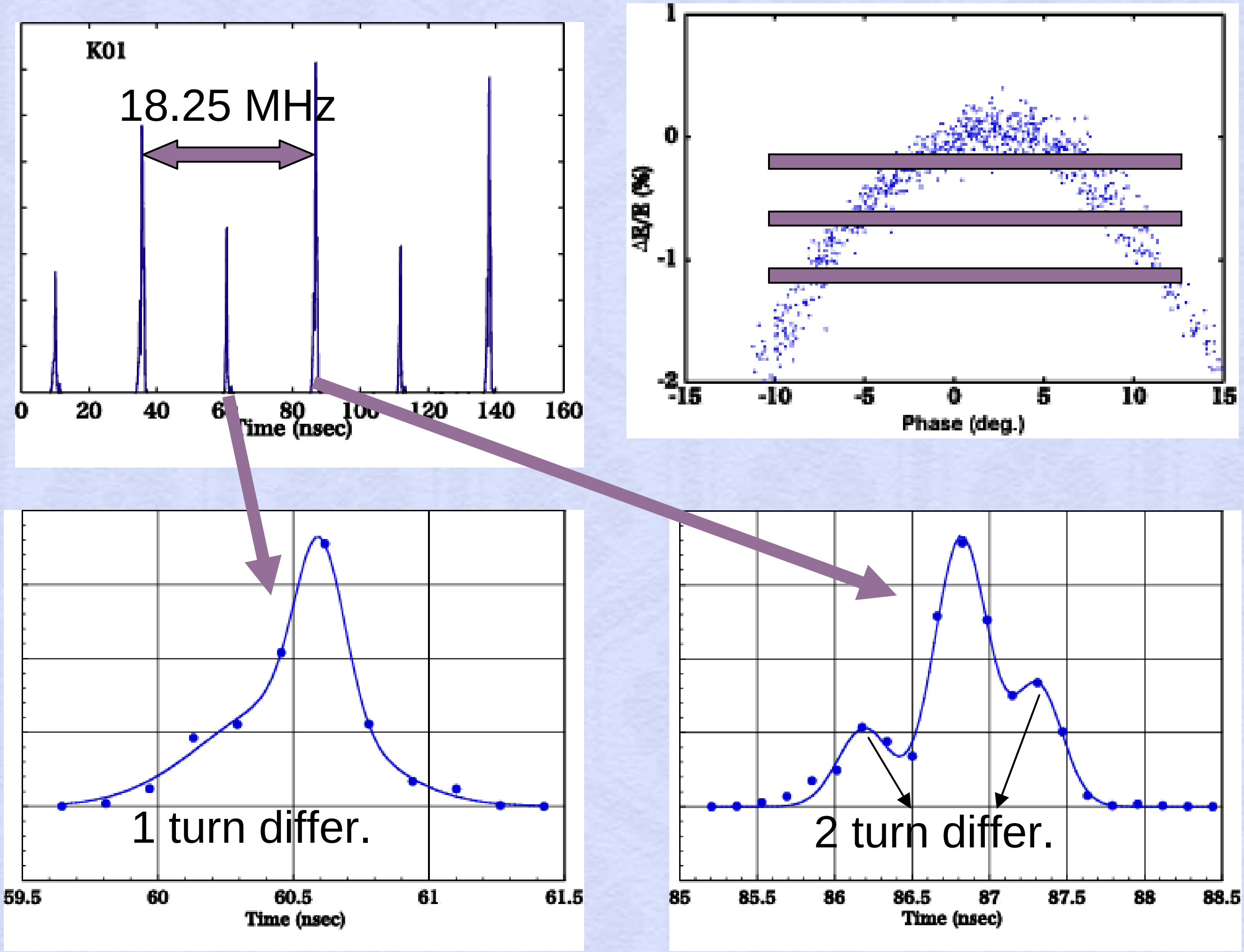


Magnetic field
was adjusted
at the previous night
(+0.8 gauss)

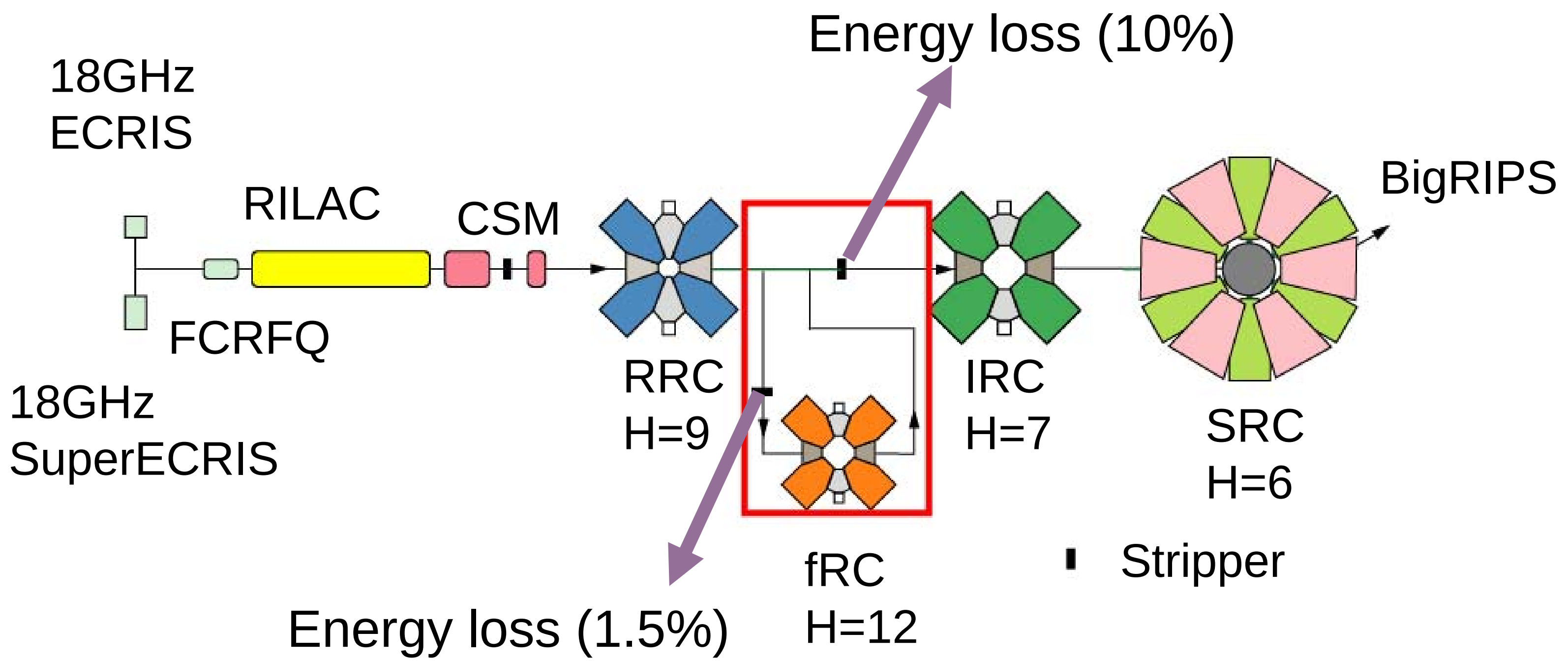
07/05/14 (Power on 07/05/09)



Longitudinal profile for IRC beam



Section that causes beam-quarity down.

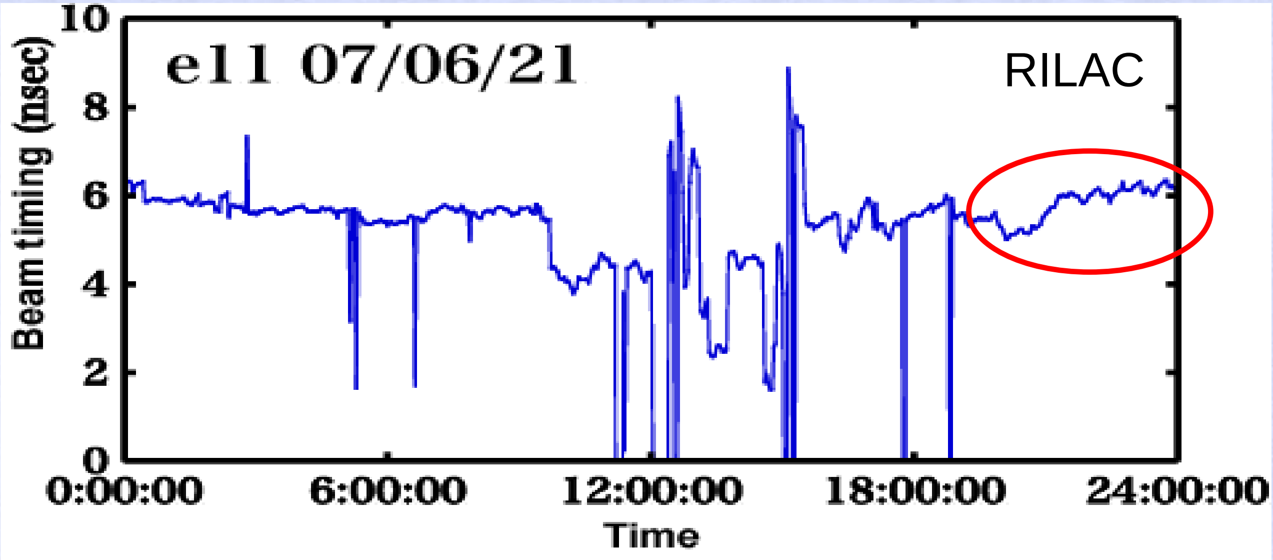


Matters should be investigated and improved.

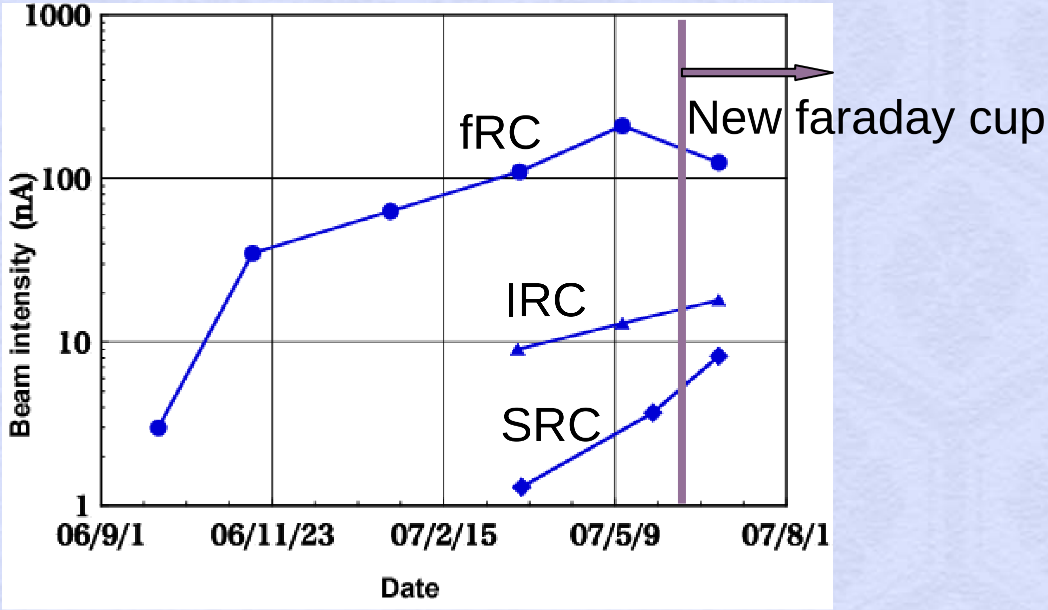
Vacuum between ion source and RILAC.
Advance of beam diagnostics.
- Faraday cup
- Radial probe
- Plastic scintillator for TOF measurement.

Make full use of flat-top resonator.
Im.provement of long-range stability

Beam phase measured by LIA.



History of uranium beam intensity during beam commissioning.



Improvement

Feb. 2007 → Jun. 2007

Beam intensity from ion source : 2 times

Transmission efficiency of RILAC : 2 times

Feb. 2006 → Jun. 2007

Transmission efficiency of RRC : 2.4 times

Summary

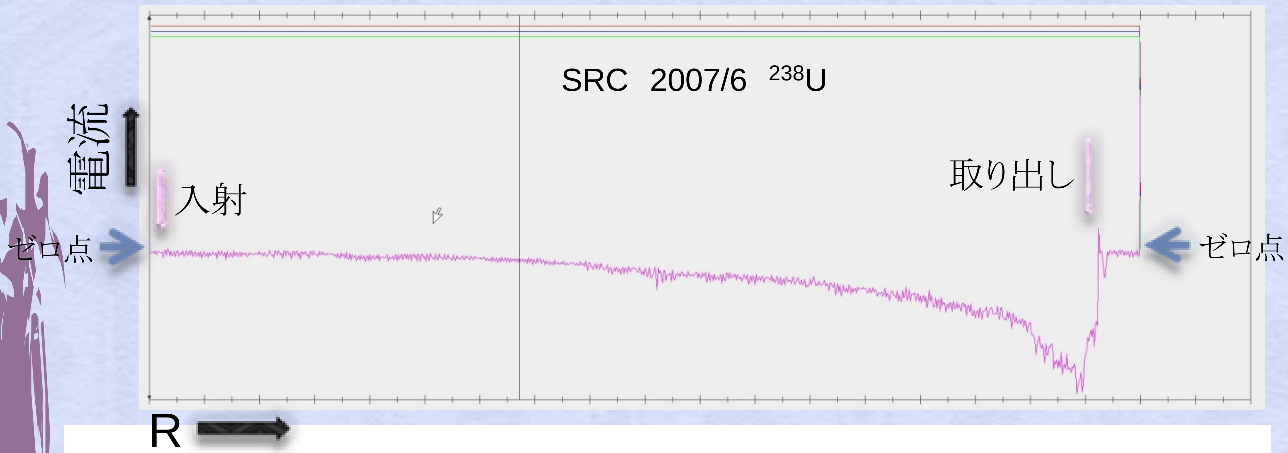
Beam commissioning was successfully achieved.

Transmission efficiency is insufficient.
→ many improvement is required.

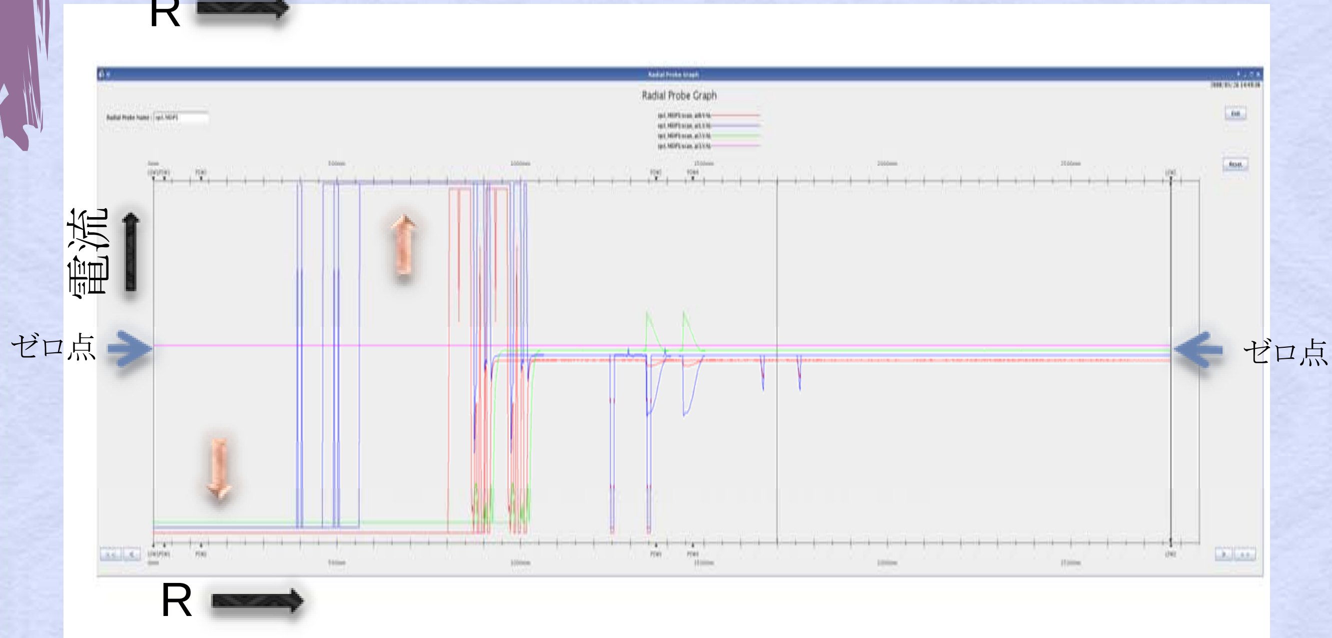
↓

Transmission efficiency → Up to 90% for fRC, IRC, and SRC.
High power uranium beam → New ion source.

Problem of SRC-MDP

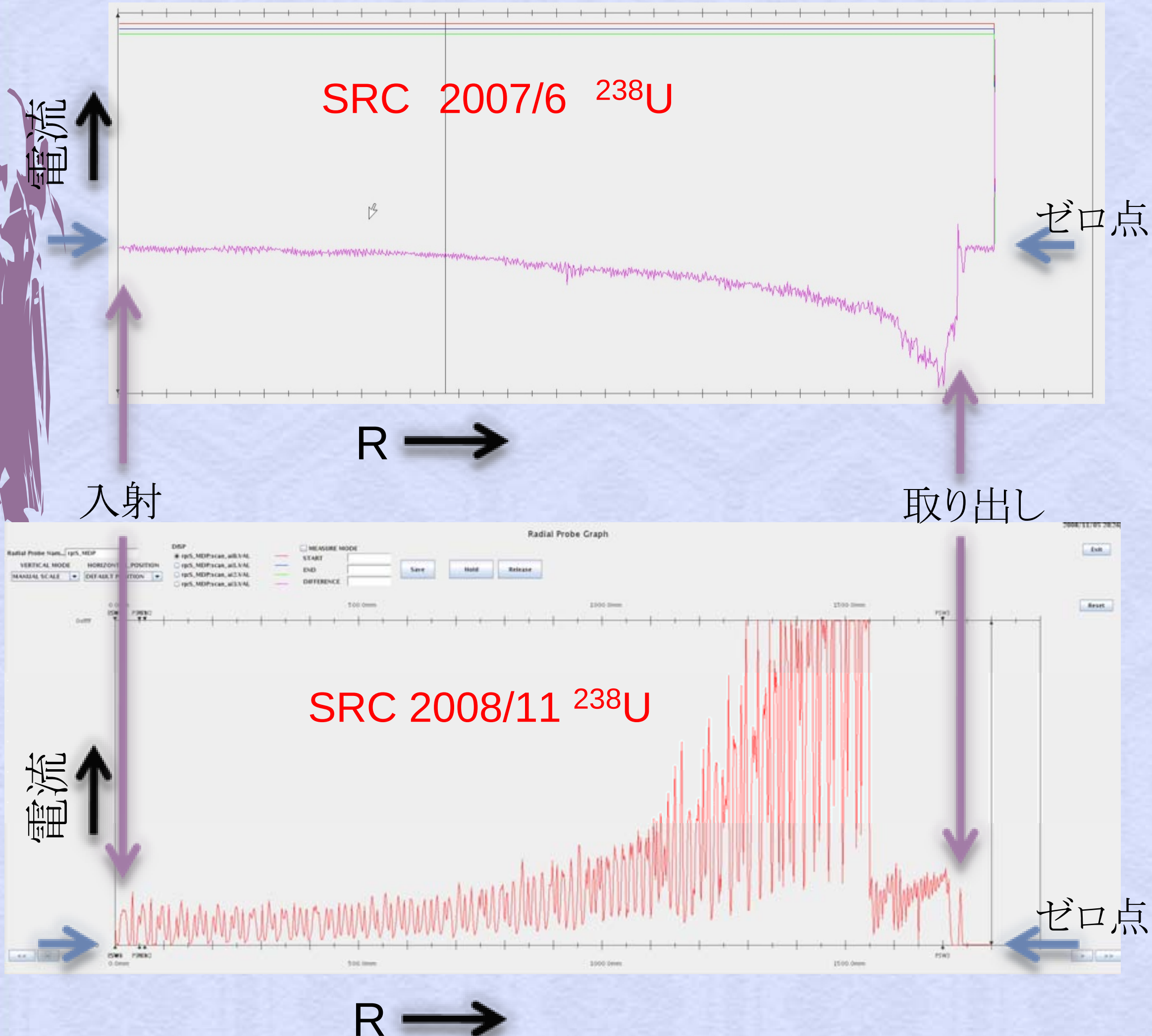


パターンがつぶれる
外周側で負の値になる
⇧
微分電極に二次電子
低磁場領域



ノイズがのる
値が振り切れる
⇧
FT空洞の漏れ電磁波
プローブがアンテナ

Effect of FC, MDP modification



周回パターン読める
取り出し電流値精度向上

SRC微調整可能

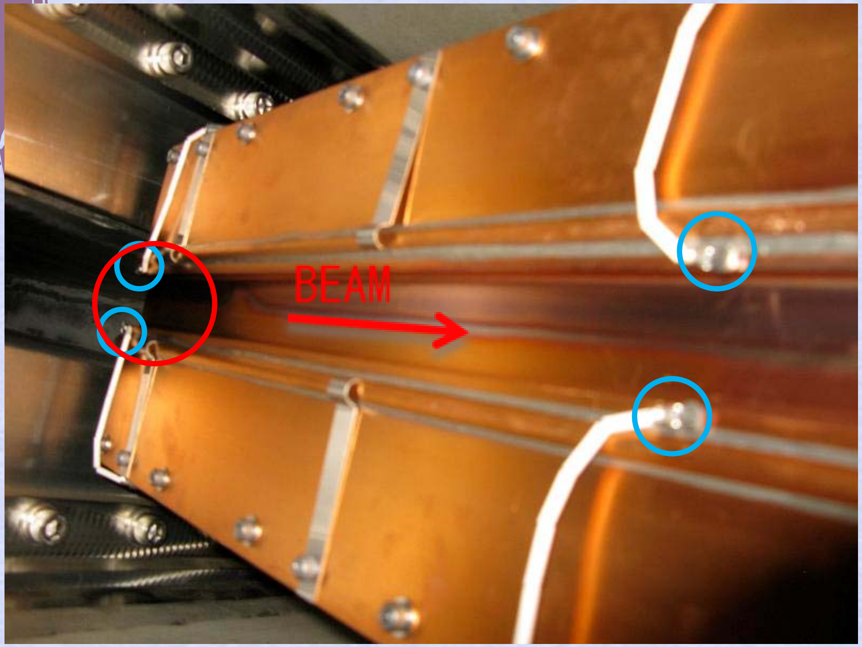
⇩

SRCビーム通過効率向上
^{238}U 345MeV/u
2007/6 : <40% (<5nA)
↓　～10倍
2008/11: 60% (40nA)

FTと同時使用できず
→^{48}Caへ向けて改良

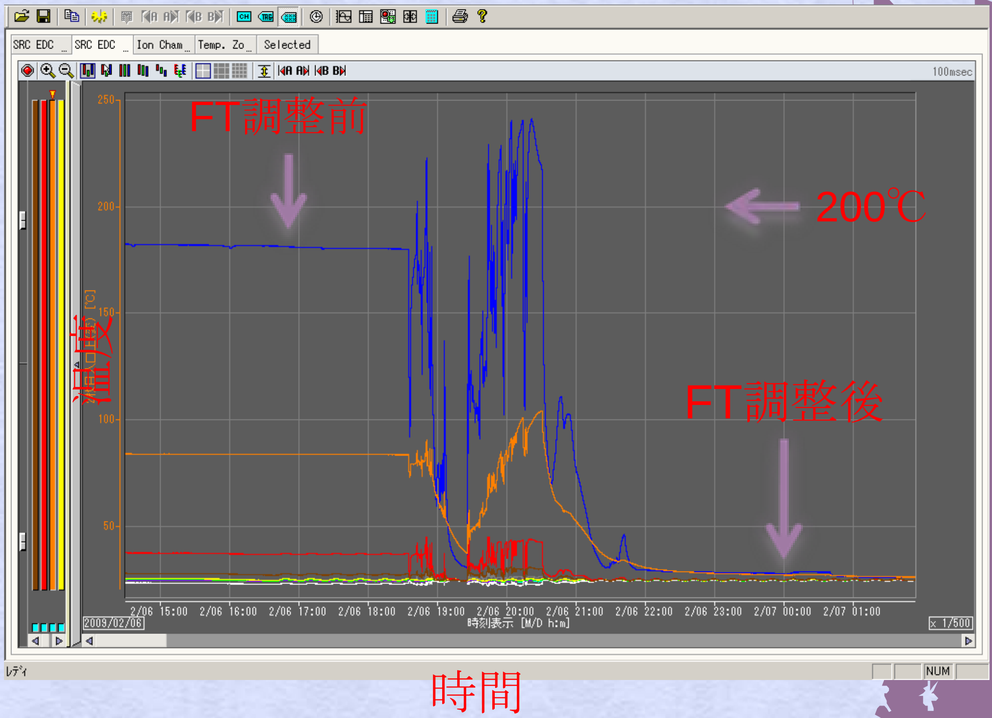
Heat protection of SRC-EDC

大強度ビーム加速
^{48}Ca 345MeV/u 200pnA = 3.3kW
EDC許容 : < 500W
・EDC保護
・温度上昇が減るように調整
(SRC-EIC, IRC-EDC にも適用予定)



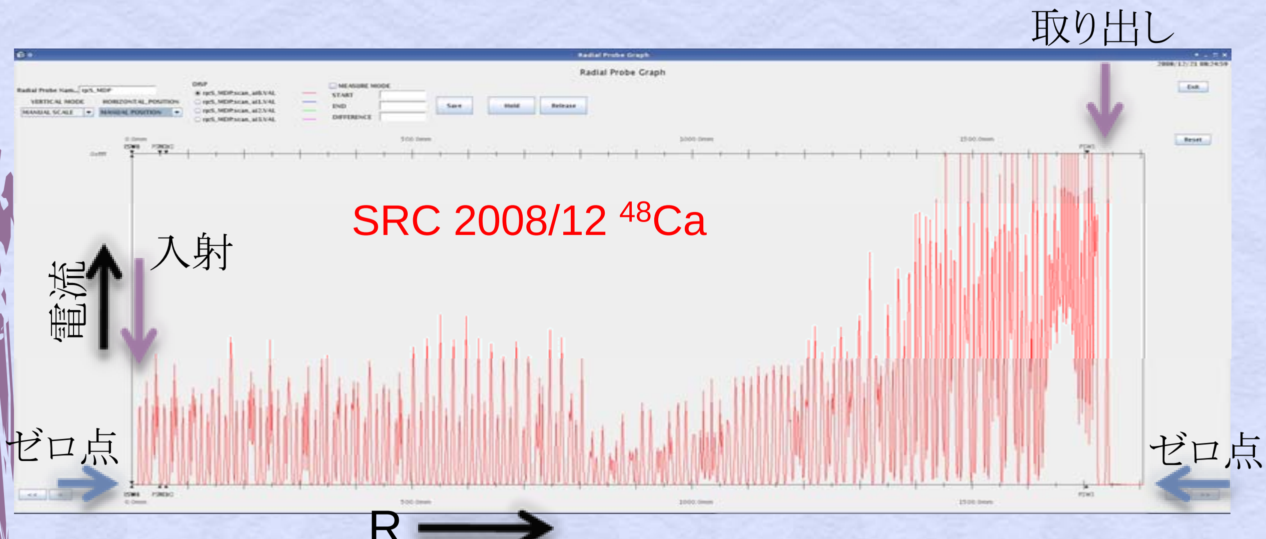
EDCセプタム(2009/01/29)

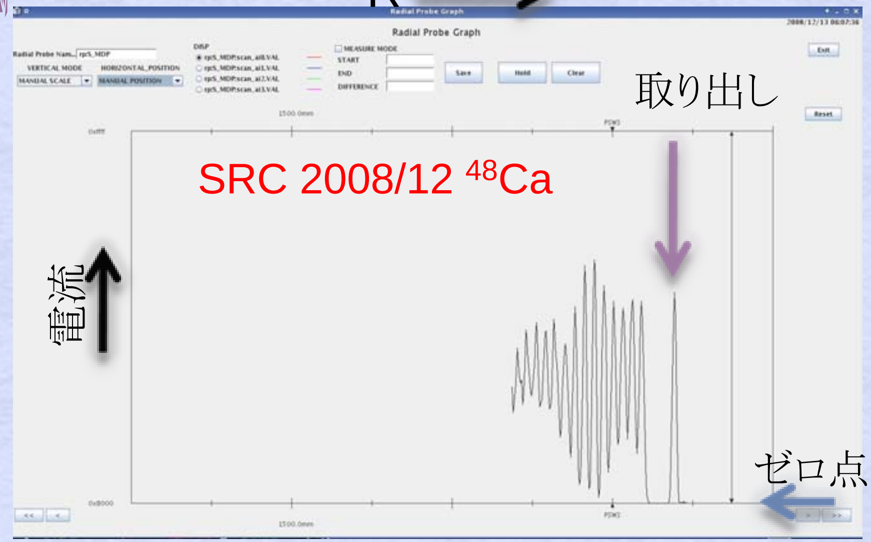
FT粗同調板調整時のEDC温度変化



FT漏れ電磁波の減少

High intensity ^{48}Ca beam





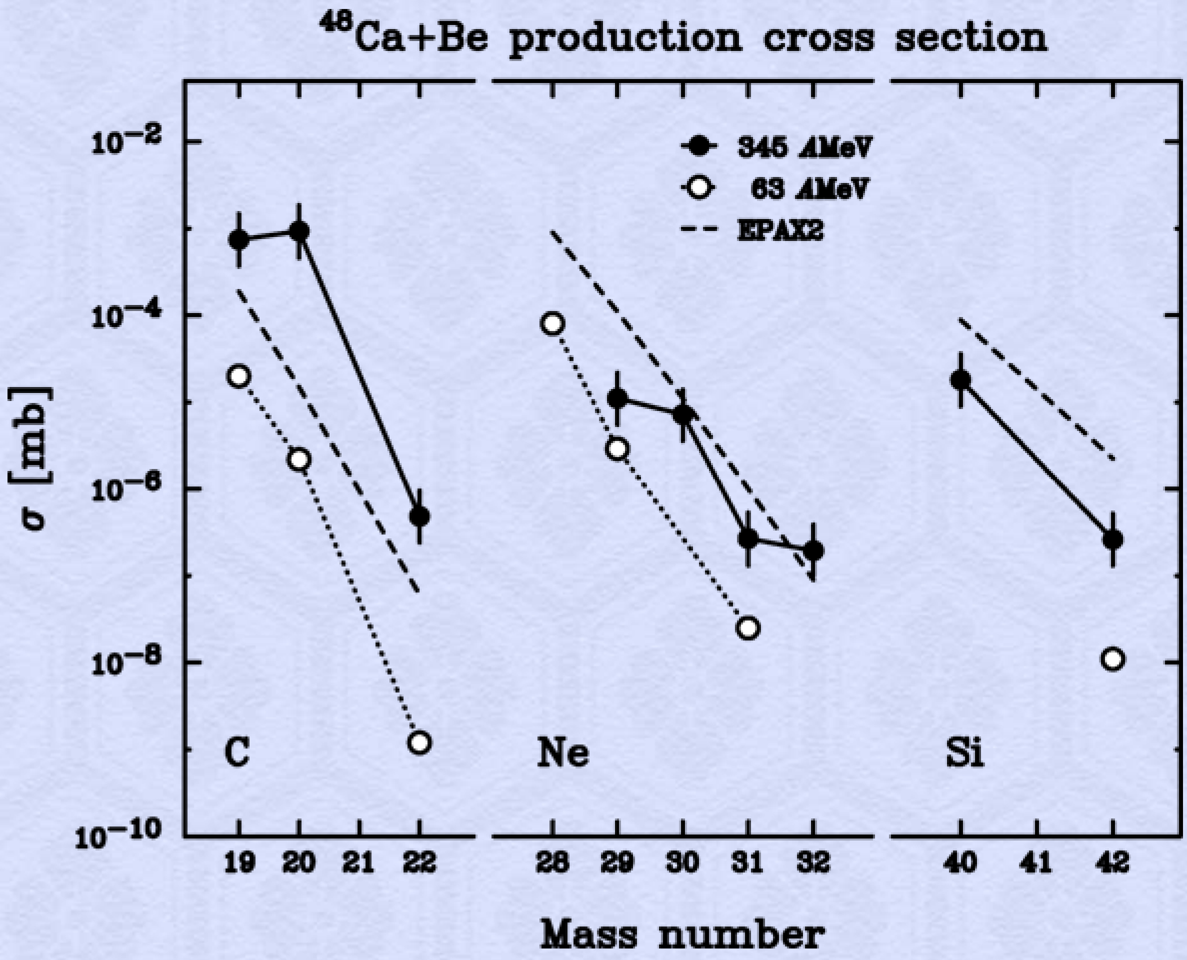
FTオンでも全域読める

RF(FT)微調整可能

通過効率向上

^{48}Ca 345MeV/u 2008/12
SRC取り出し効率: ～85%
ビーム強度: 4000nA 最強!!

Energy dependent cross sections of projectile fragmentation



DayOne Experiments

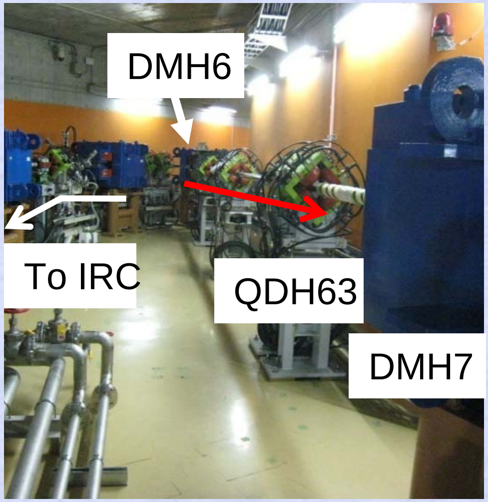
- Reaction Cross Section (Ohtsubo et al.)
  ~3 days
  $^{29-32}Ne$
  $^{30-34}Na$

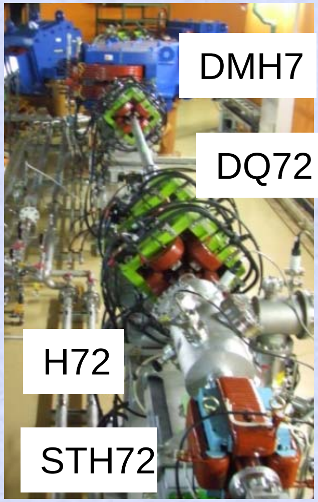
- Coulomb Breakup (Nakamura et al.)
  ~2.5 days
  ^{31}Ne
  $^{19,22}C$

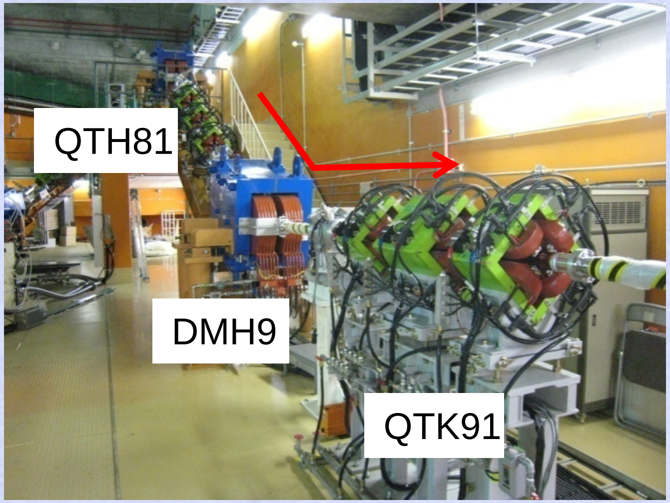
- γ Spectroscopy (Scheit et al.)
  ~0.5days
  ^{32}Ne

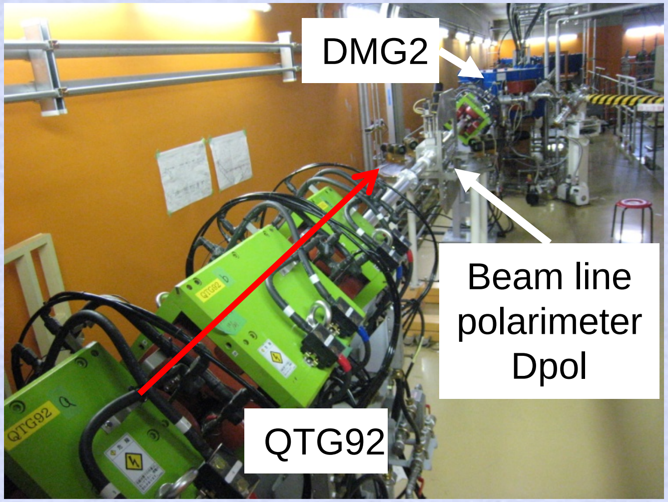
- γ Spectroscopy (Takeuchi et al.) → Canceled
  ^{42}Si

IRC-bypass beam line

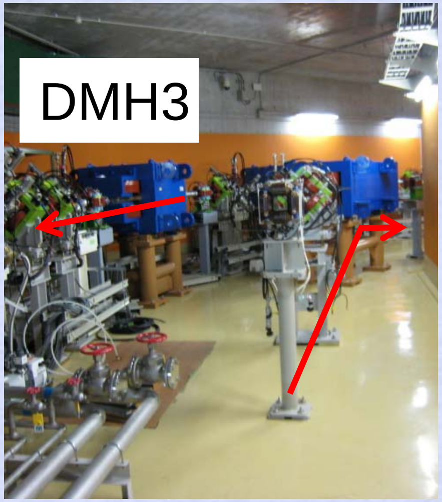




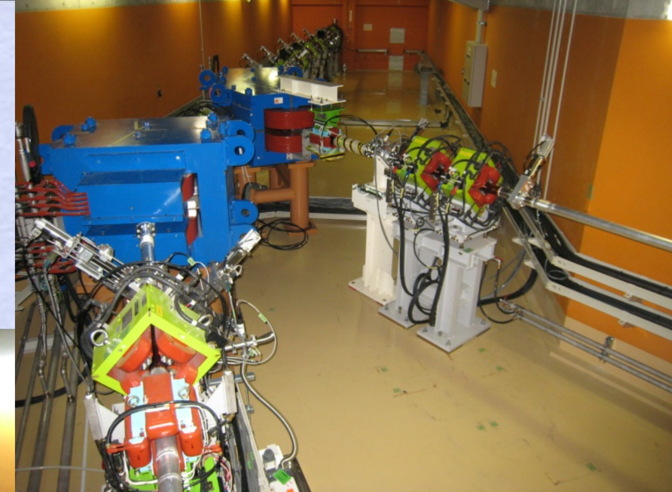


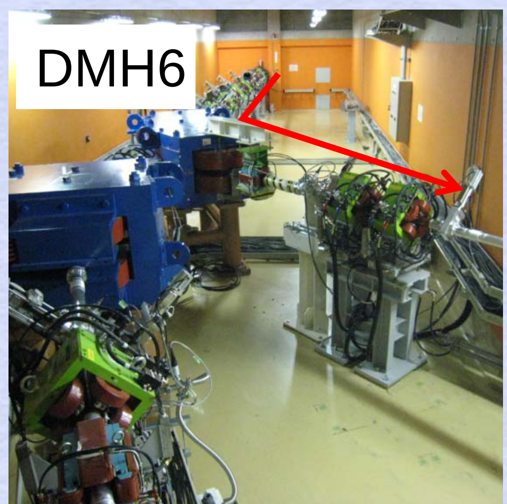


IRC-bypass beam line



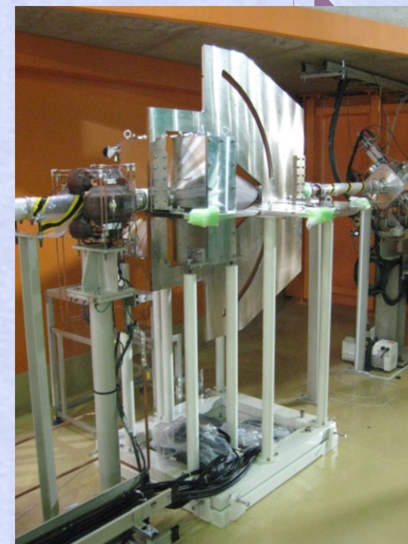


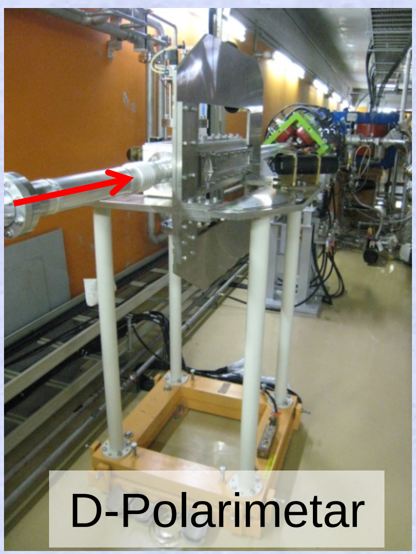


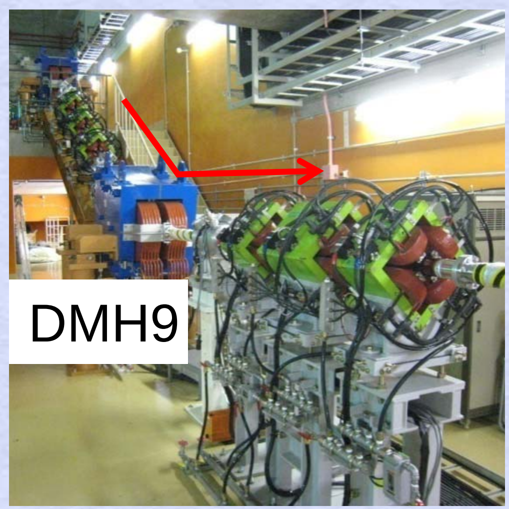


DMH6

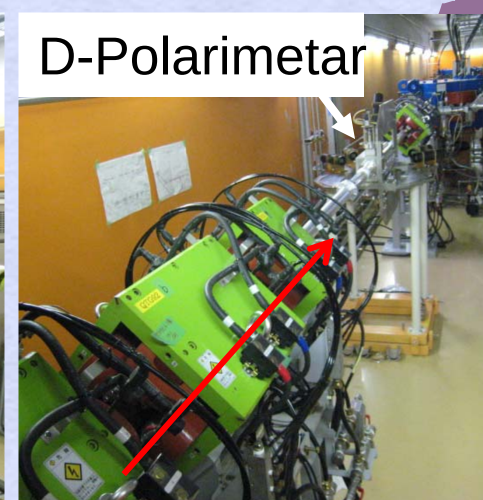
DMH7

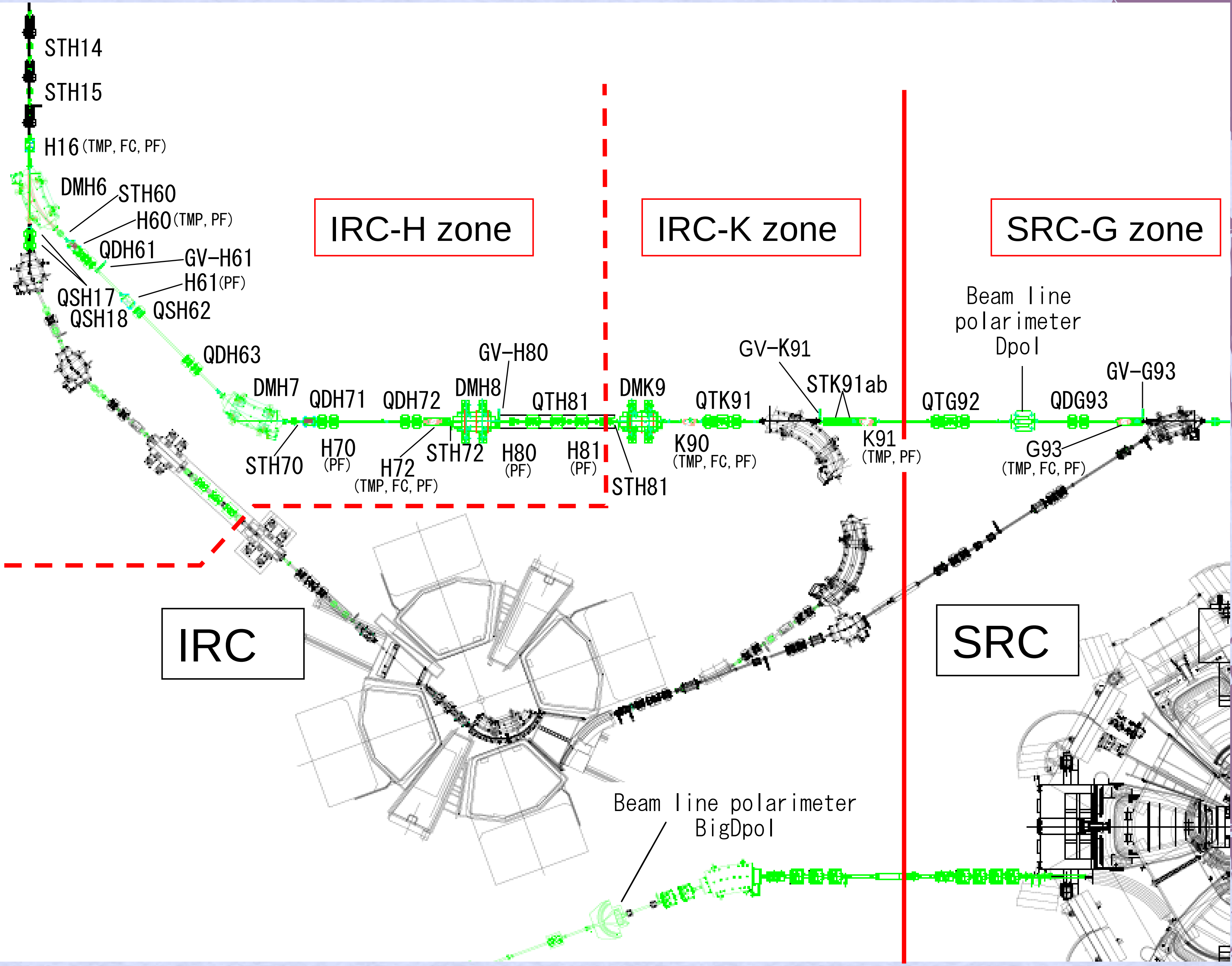
IRC-bypass beam line

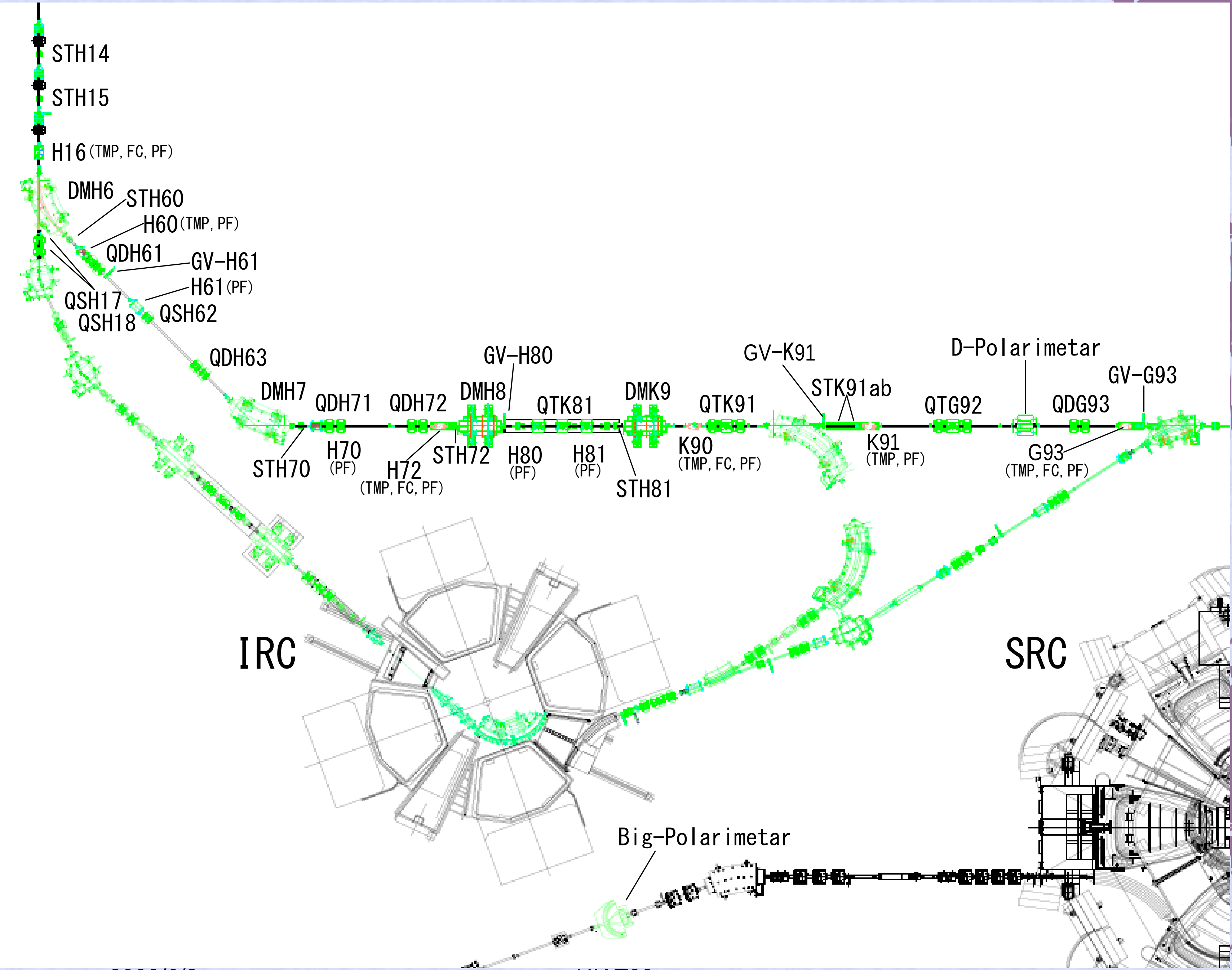









STH14
STH15
H16(TMP, FC, PF)
DMH6
STH60
H60(TMP, PF)
QDH61
GV-H61
H61(PF)
QSH17
QSH18
QSH62
QDH63
DMH7
QDH71
QDH72
DMH8
GV-H80
QTH81
STH70
H70 (PF)
H72 (TMP, FC, PF)
STH72
H80 (PF)
H81 (PF)
STH81
IRC-H zone
IRC-K zone
SRC-G zone
DMK9
QTK91
GV-K91
STK91ab
K90 (TMP, FC, PF)
K91 (TMP, PF)
Beam line polarimeter Dpol
QTG92
QDG93
GV-G93
G93 (TMP, FC, PF)
IRC
SRC
Beam line polarimeter BigDpol


STH14
STH15
H16 (TMP, FC, PF)
DMH6
STH60
H60 (TMP, PF)
QDH61
GV-H61
H61 (PF)
QSH17
QSH18
QSH62
QDH63
DMH7
QDH71
QDH72
DMH8
GV-H80
QTK81
DMK9
QTK91
GV-K91
STK91ab
D-Polarimetar
QTG92
QDG93
GV-G93
STH70
H70 (PF)
H72 (TMP, FC, PF)
STH72
H80 (PF)
H81 (PF)
STH81
K90 (TMP, FC, PF)
K91 (TMP, PF)
G93 (TMP, FC, PF)
IRC
SRC
Big-Polarimetar