Operating Experience with the RIKEN Radioactive Isotope Beam Factory

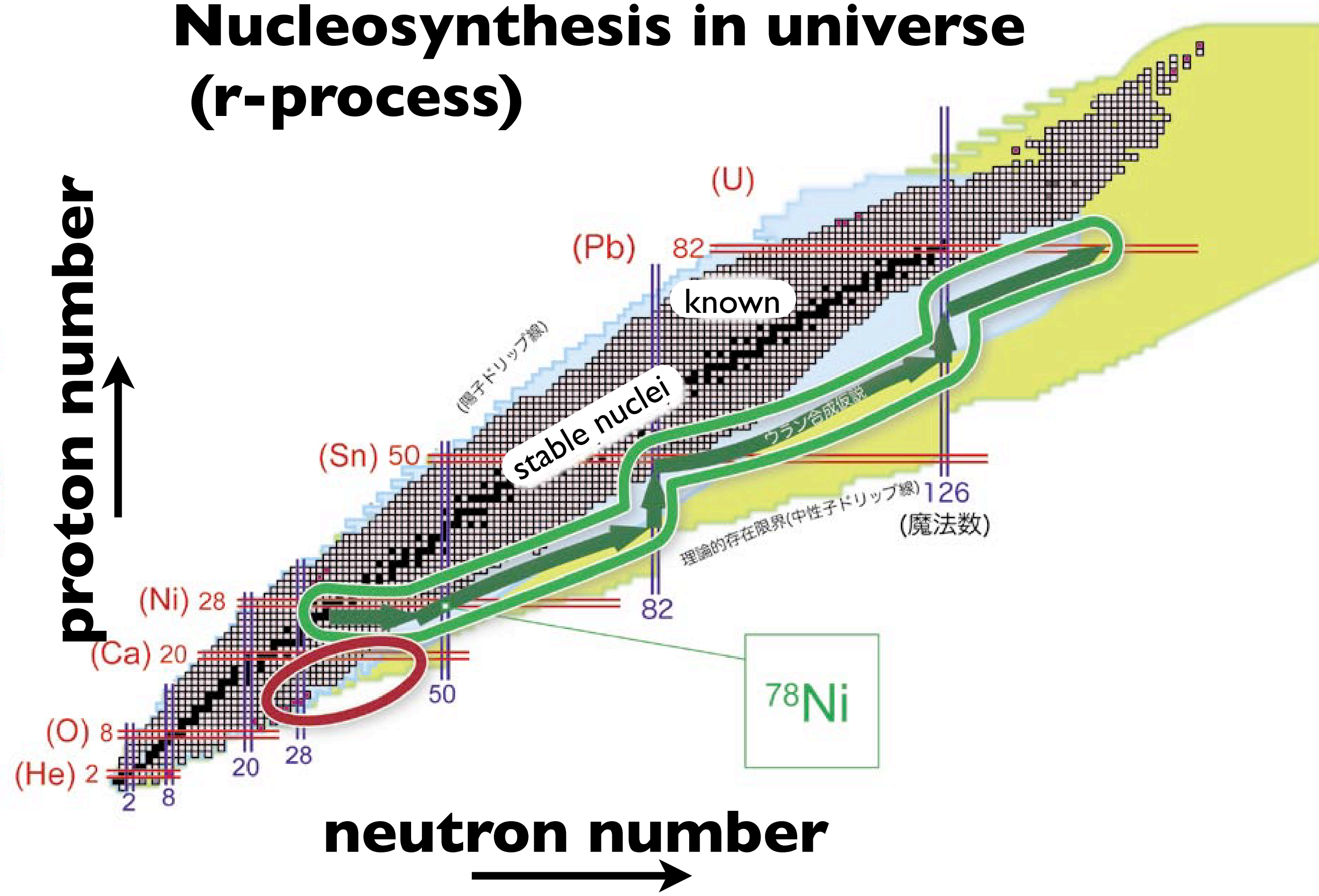
N. Fukunishi, T. Dantsuka, M. Fujimaki, A. Goto, H. Hasebe, Y. Higurashi, E. Ikezawa, T. Kageyama, O. Kamigaito, M. Kase, M. Kidera, M. Kobayashi-Komiyama, K. Kumagai, H. Kuboki, T. Maie, M. Nagase, T. Nakagawa, J. Ohnishi, H. Okuno, N. Sakamoto, Y. Sato, K. Sekiguchi, K. Suda, H. Suzuki, M. Wakasugi, H. Watanabe, T. Watanabe, Y. Watanabe, K. Yamada, Y. Yano, S. Yokouchi

Nishina Center for Accelerator-Based Science, RIKEN

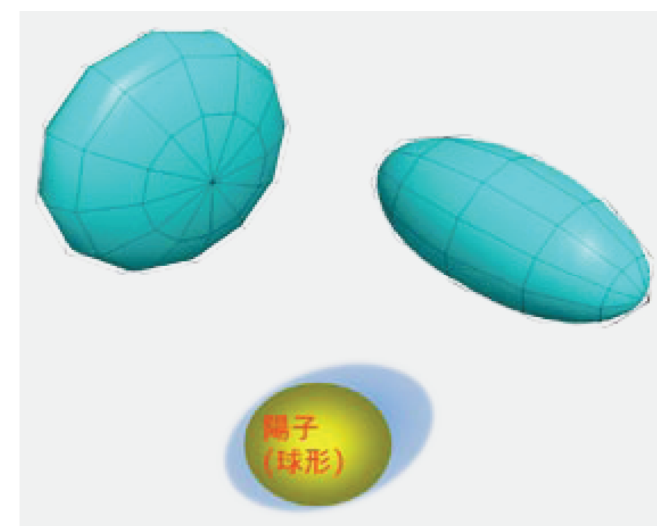
RI Beam Factory Project aims

(1) to produce the world-most-intense RI beam
(2) to make systematic studies on unstable nuclei far from stability

Nucleosynthesis in universe (r-process)

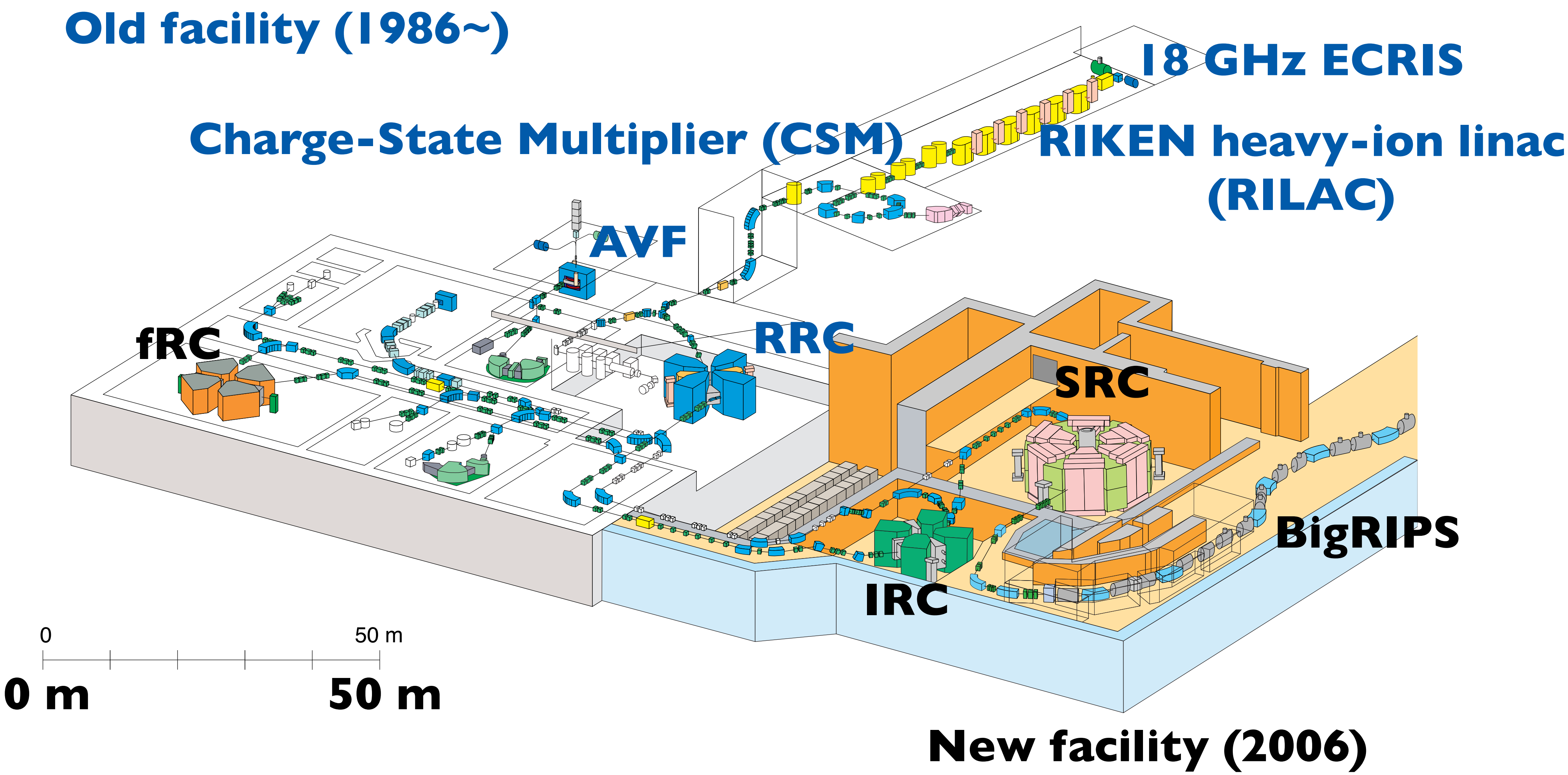


Search for unstable nuclei with novel structure



(from a pamphlet of Nishina center for Accelerator-Based Science)

Layout of RI Beam Factory



RRC = Riken Ring Cyclotron (1986~)
fRC = fixed-frequency Ring Cyclotron (2006~)
IRC = Intermediate-stage Ring Cyclotron (2006~)
SRC = Superconducting Ring Cyclotron (2006~)

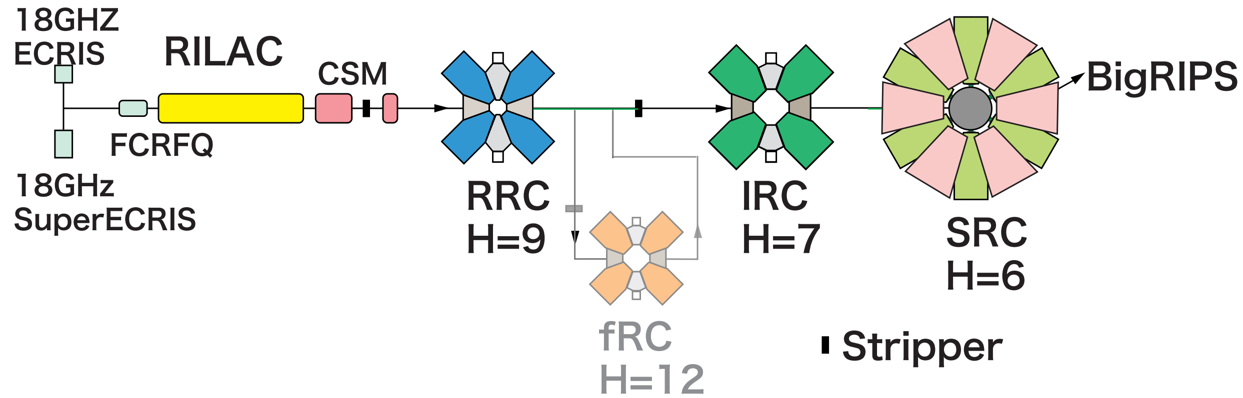
Specifications of RIBF ring cyclotrons

	fRC	IRC	SRC	RRC
K-number (MeV)	570	980	2600	540
number of sector magnets	4	4	6	4
velocity gain	2.1	1.5	1.5	4.0
number of trim coils (/ sector magnet)	10	20	4(SC) 22(NC)	26
RF resonators	2+FT	2+FT	4+FT	2
frequency range (MHz)	54.75	18～38	18～38	18～38

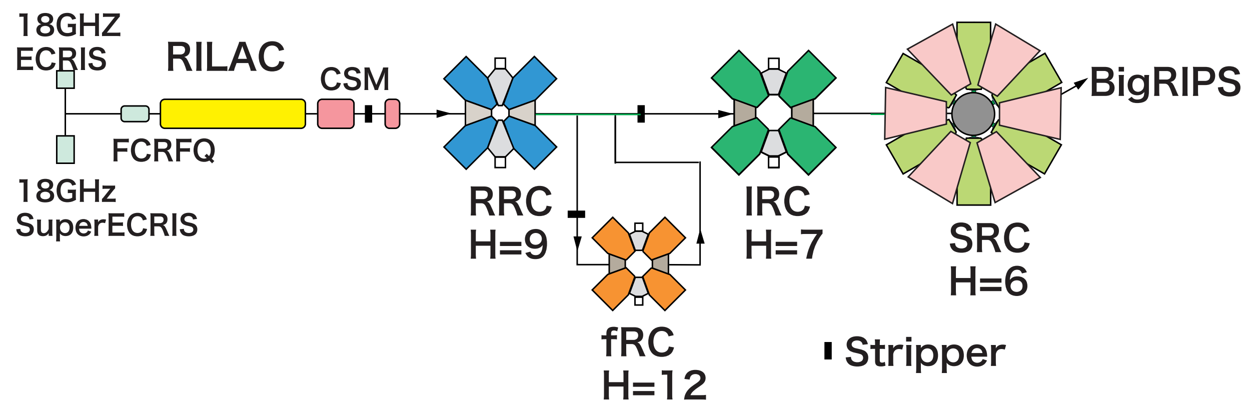
SC = superconducting
NC = normal conducting
FT = flat-top resonator

Acceleration modes in RIBF

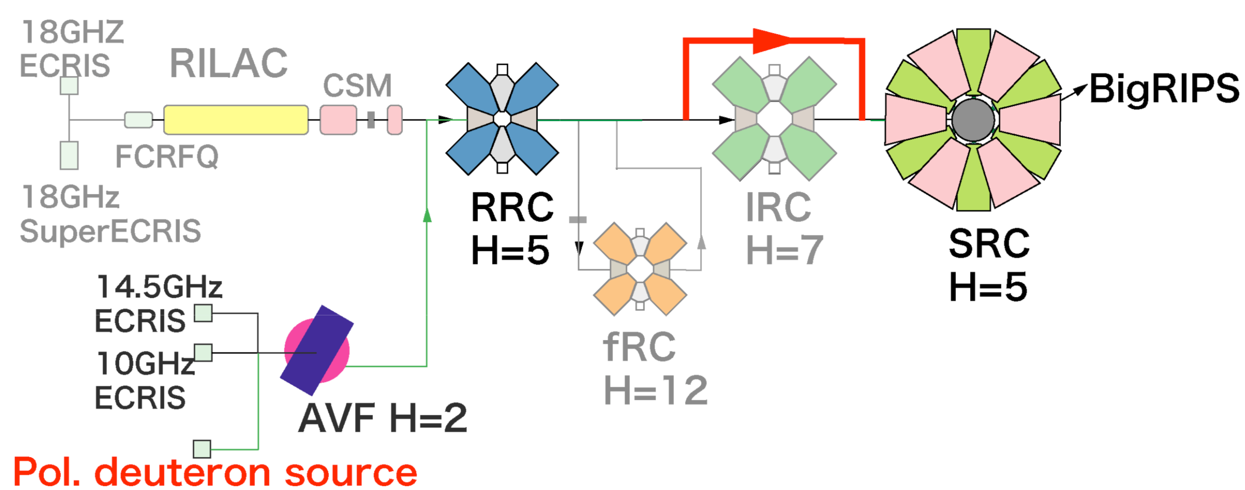
(1) Variable-energy mode
^{27}Al, ^{48}Ca, ^{86}Kr
~400 MeV/u @ SRC



(2)Fixed-energy mode
^{238}U 345 MeV/u @ SRC

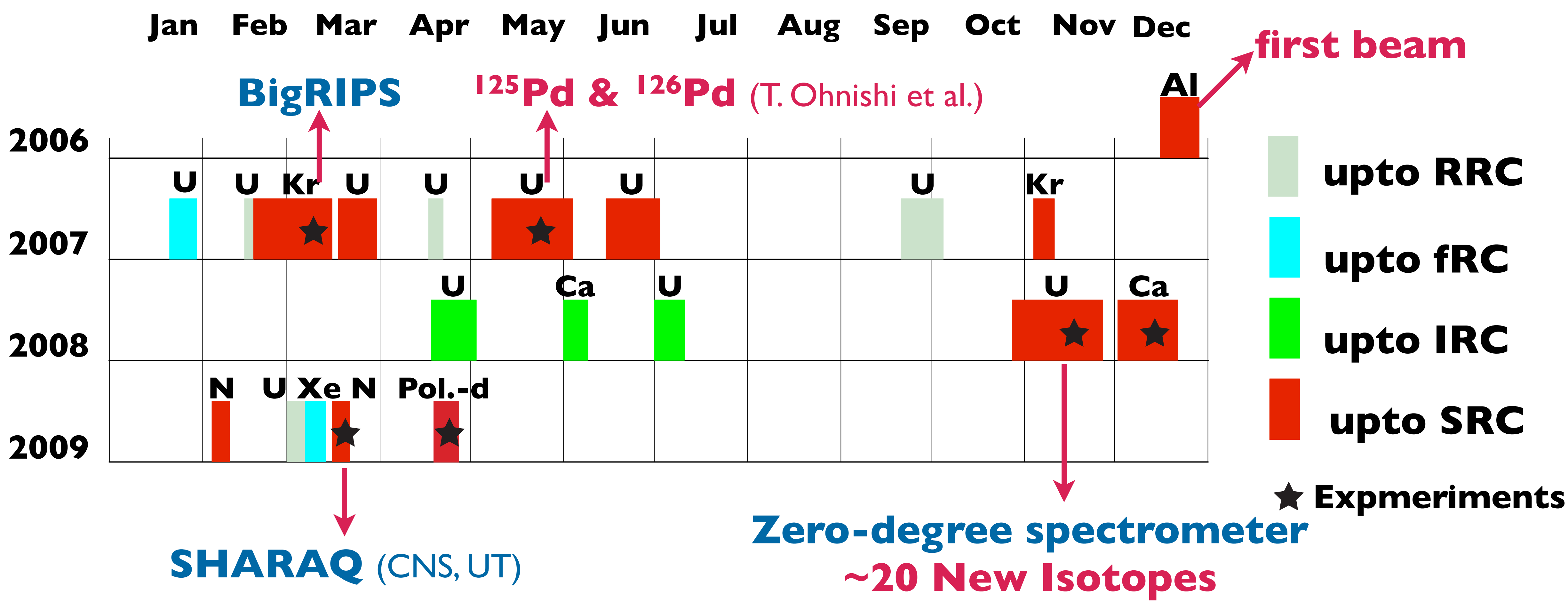


(3) AVF-injection mode
Polarized deuteron, ^{14}N
250 ~ 440 MeV/u @ SRC



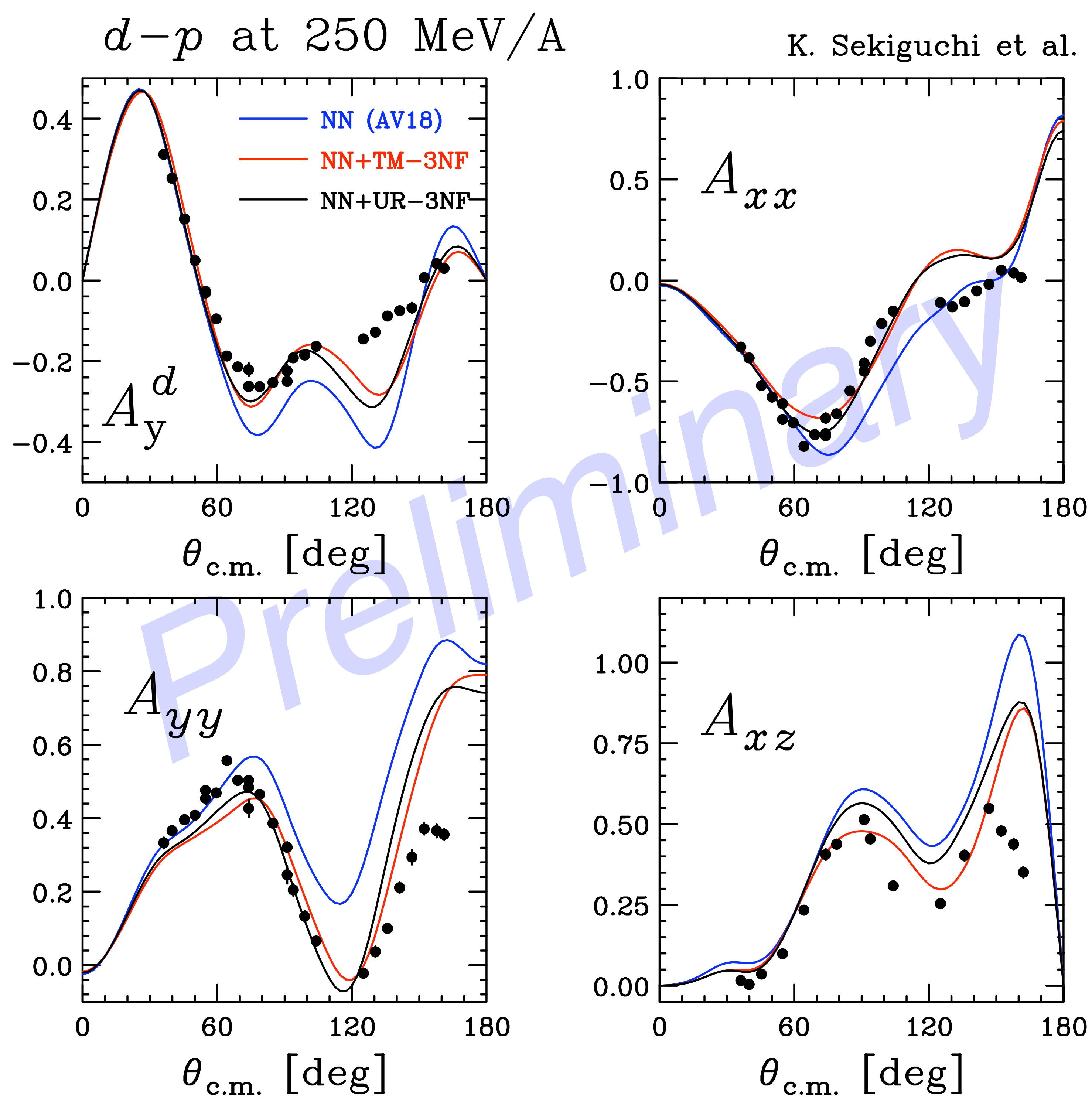
Operation history

(Does not include experiments using RRC beams.)



SHARAQ, Zero-degree spectrometer = Experimental instrumentation installed downstream the BigRIPS

Polarized deuteron beam (April, 2009)



Analyzing power measurements with single-turn extracted beams

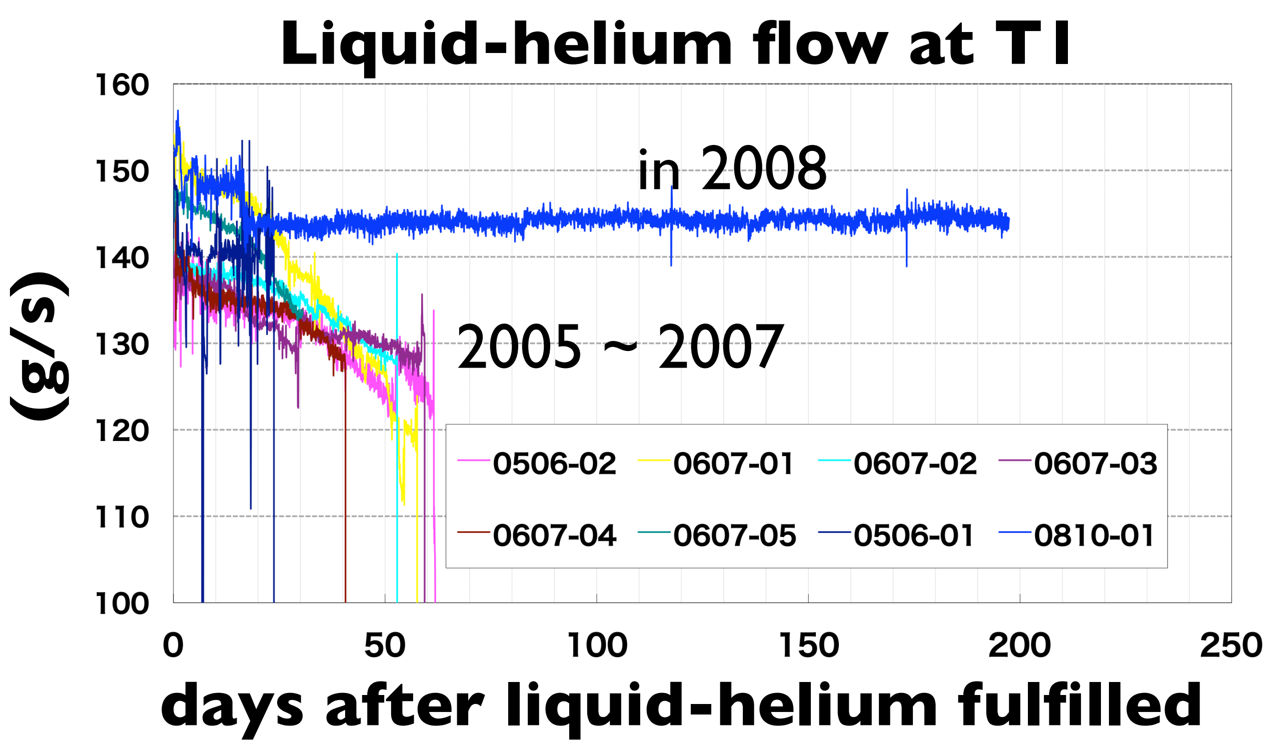
Operation statistics

Operation-time statistics (hours)

year	2008	2007
RRC operation	3961	3757
RRC experiment	1165	687
RIBF operation	2051	1845
RIBF experiment	685	414

5 months operation approved
50% used for RIBF
30% of RIBF operation used for experiments

Oil contamination in He refrigerator of SRC

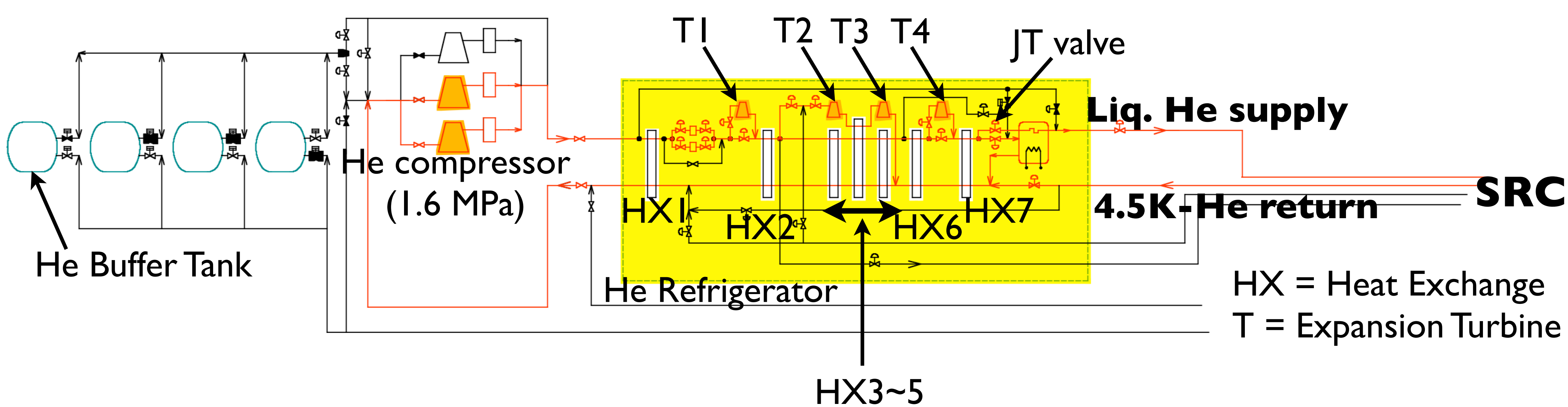


He refrigerator of SRC was contaminated with oil from He compressor. (Feb. 2008)

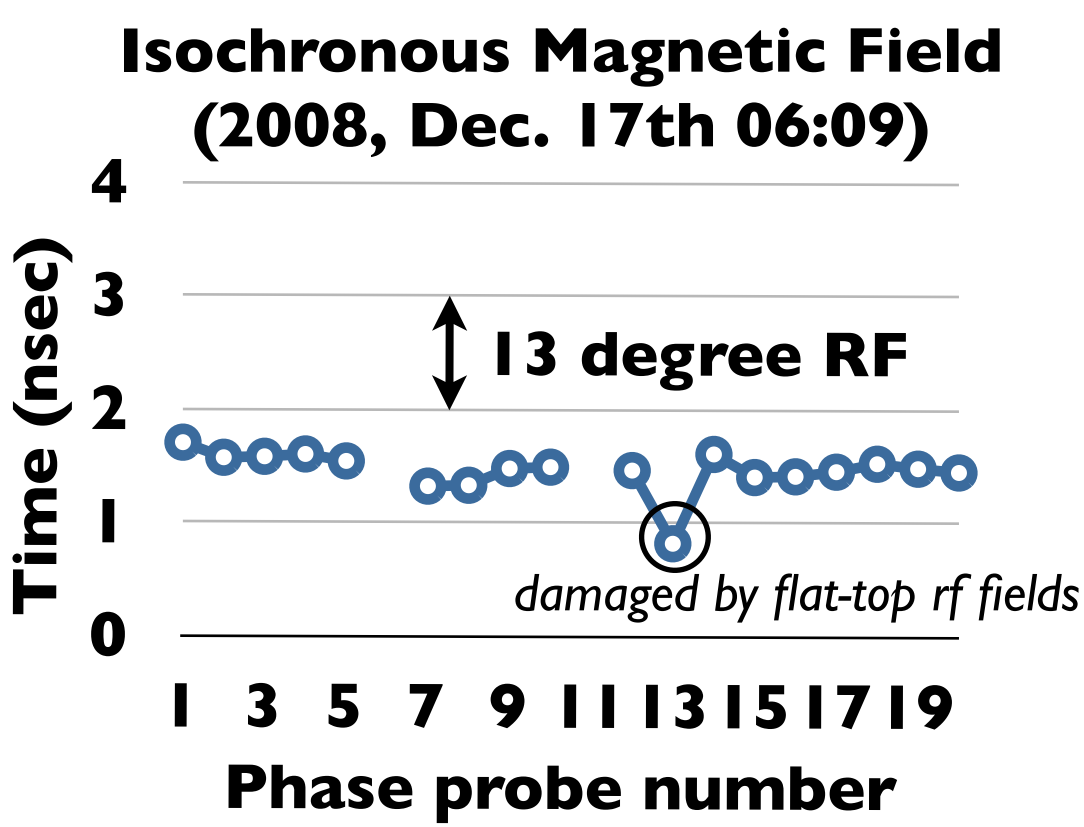
HX1~7, T1~4 etc cleaned up.

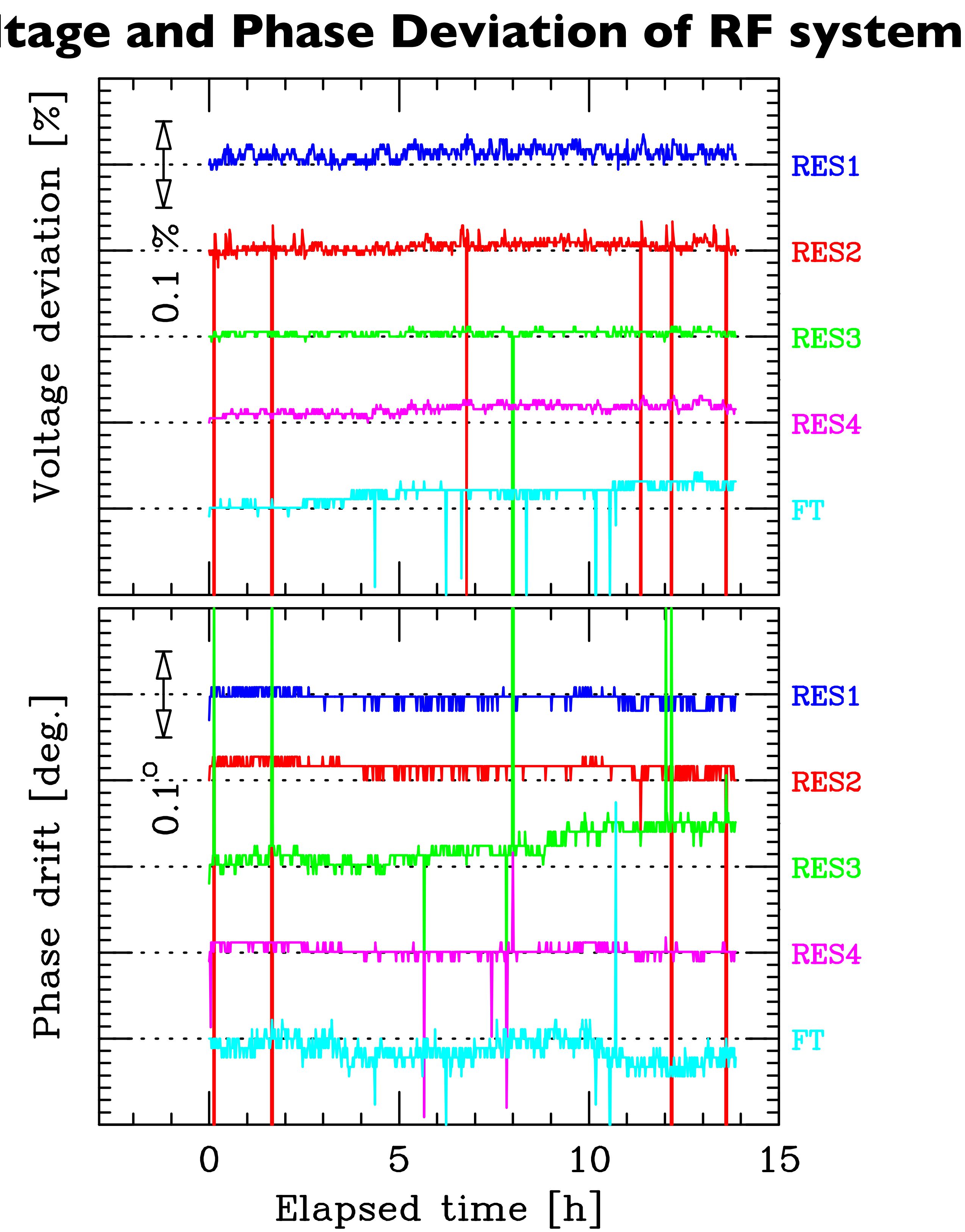
Oil separator of He compressor
4 steps → 6 steps

Cooling power 1410 W → 1378 W



SRC performance as an isochronous cyclotron





$\Delta V/V \sim 0.01\%$ $\Delta\psi \sim \pm 0.1°$ RF

Present performance of RIBF

Present status
~90% transmission efficiency in variable-energy mode
~200 pnA operation is available for light ions (^{48}Ca).

Maximum Beam Intensity

ion	(nA)
$^{238}U^{86+}$ (07/07/03)	4
$^{86}Kr^{34+}$ (07/11/04)	1100
$^{238}U^{86+}$ (08/11/16)	35
$^{48}Ca^{20+}$ (08/12/21)	3500

(yy/mm/dd)

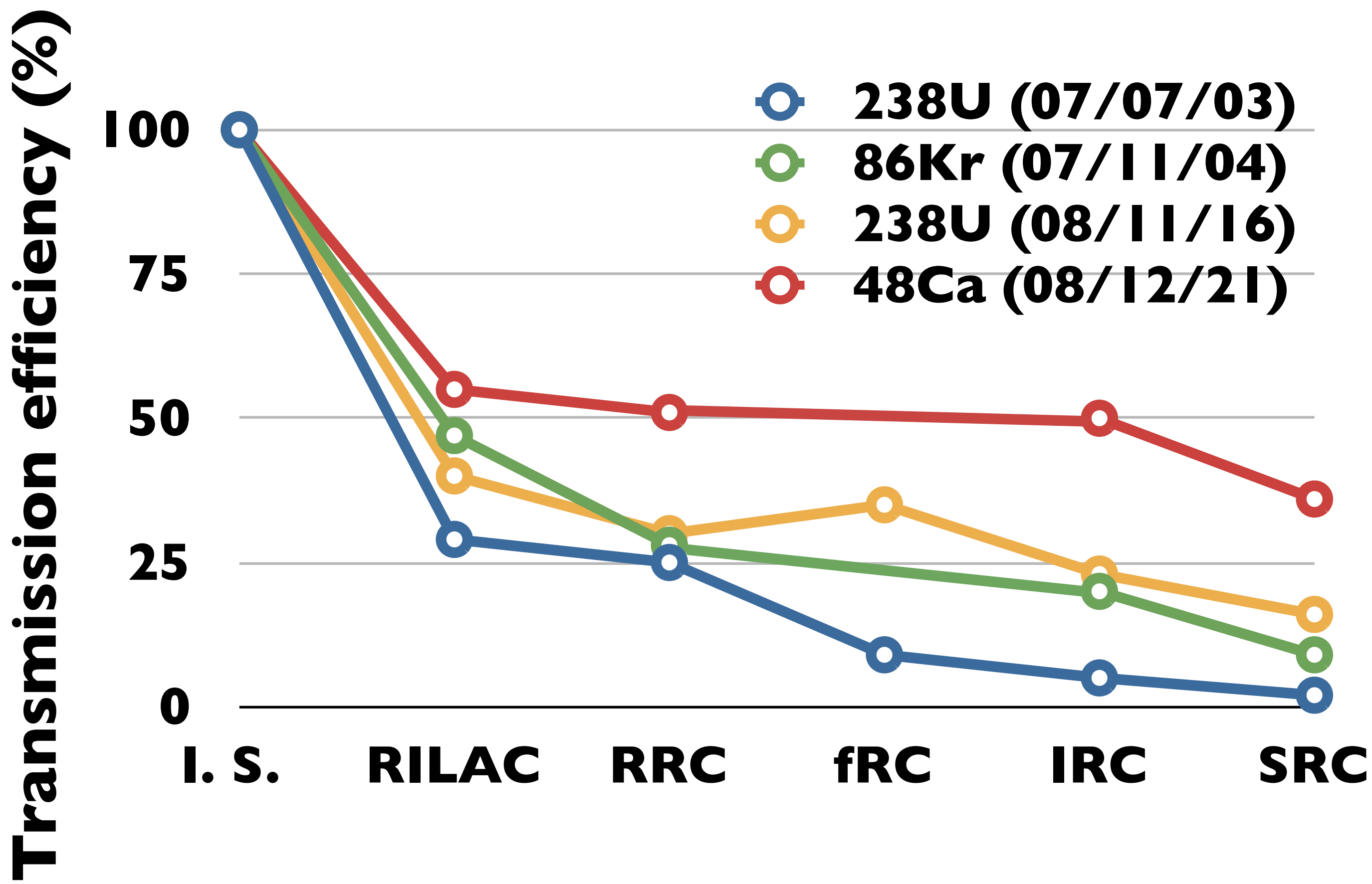
Extraction efficiency of ring cyclotrons

	^{48}Ca (08/12/21)	^{238}U (08/11/16)
RRC	95%	86%
fRC		117%*
IRC	93%	86%
SRC	82%	66%

* may include 20~30% errors

Transmission efficiency problem (^{238}U)

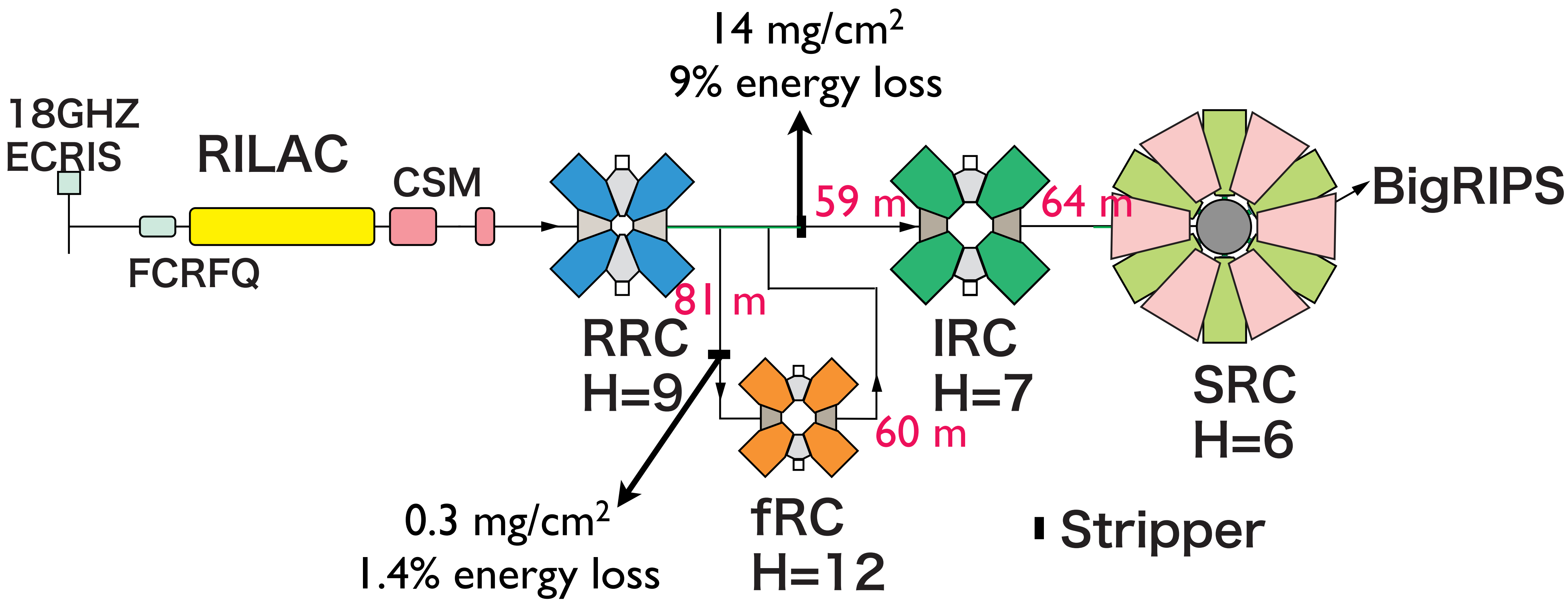
Transmission efficiency from ion source to each accelerator
(Charge stripping efficiencies are not included)



Charge stripping efficiencies
^{48}Ca : 30%
^{86}Kr : 12%
^{238}U : 4 ~ 5%

^{238}U 2% (2007) → 16% (2008)
^{86}Kr 9% (2007) → ^{48}Ca 35% (2008)

To obtain good transmission efficiency (^{238}U beam)

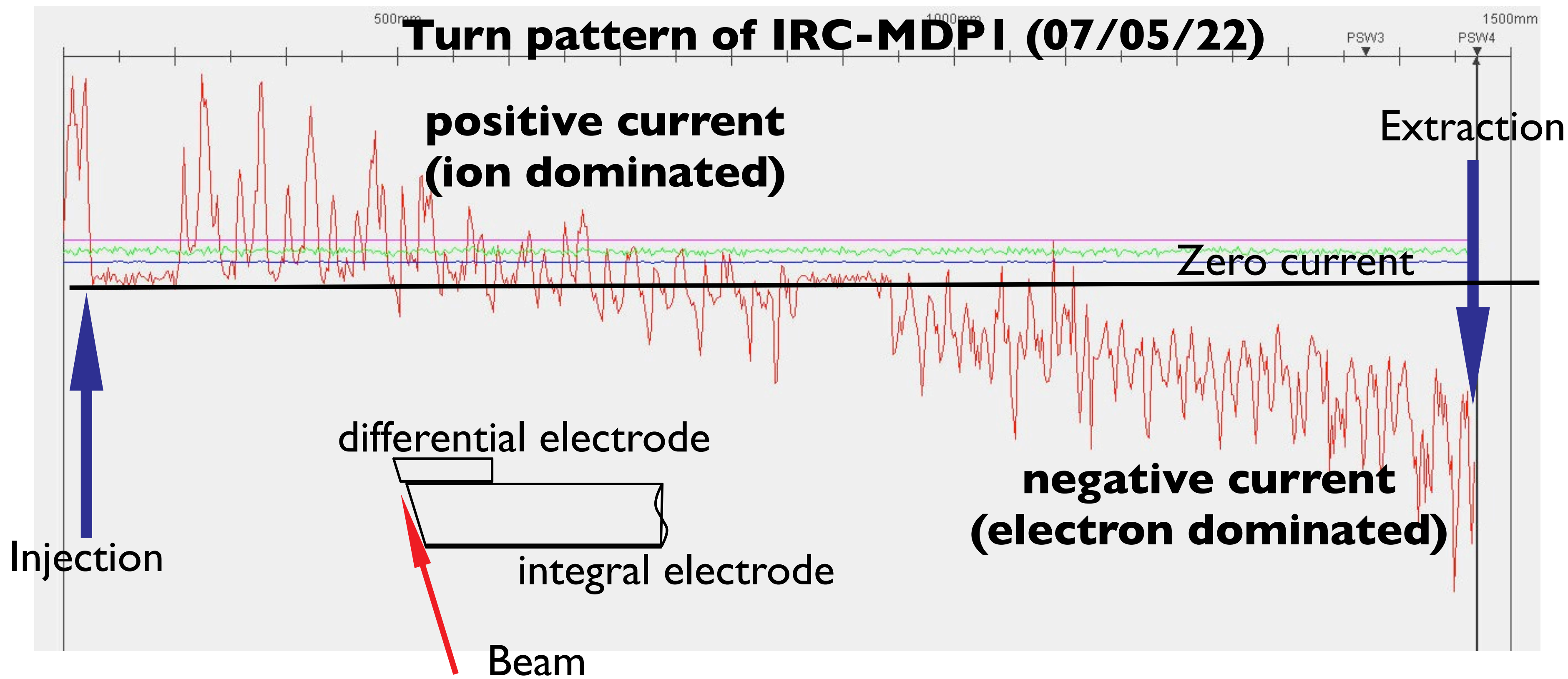


Thick carbon foil strippers
Long beam lines

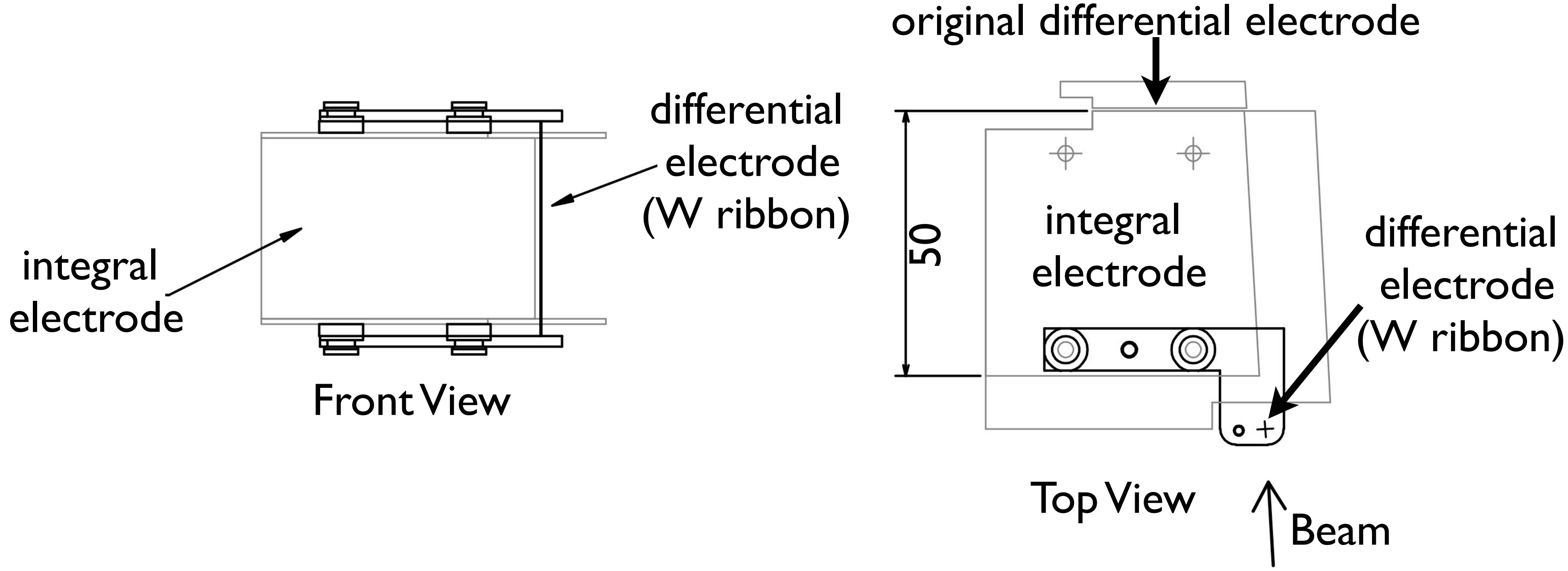
→

Good thickness uniformity
Phase adjustments of flat-top resonators
Highly-stabilized system

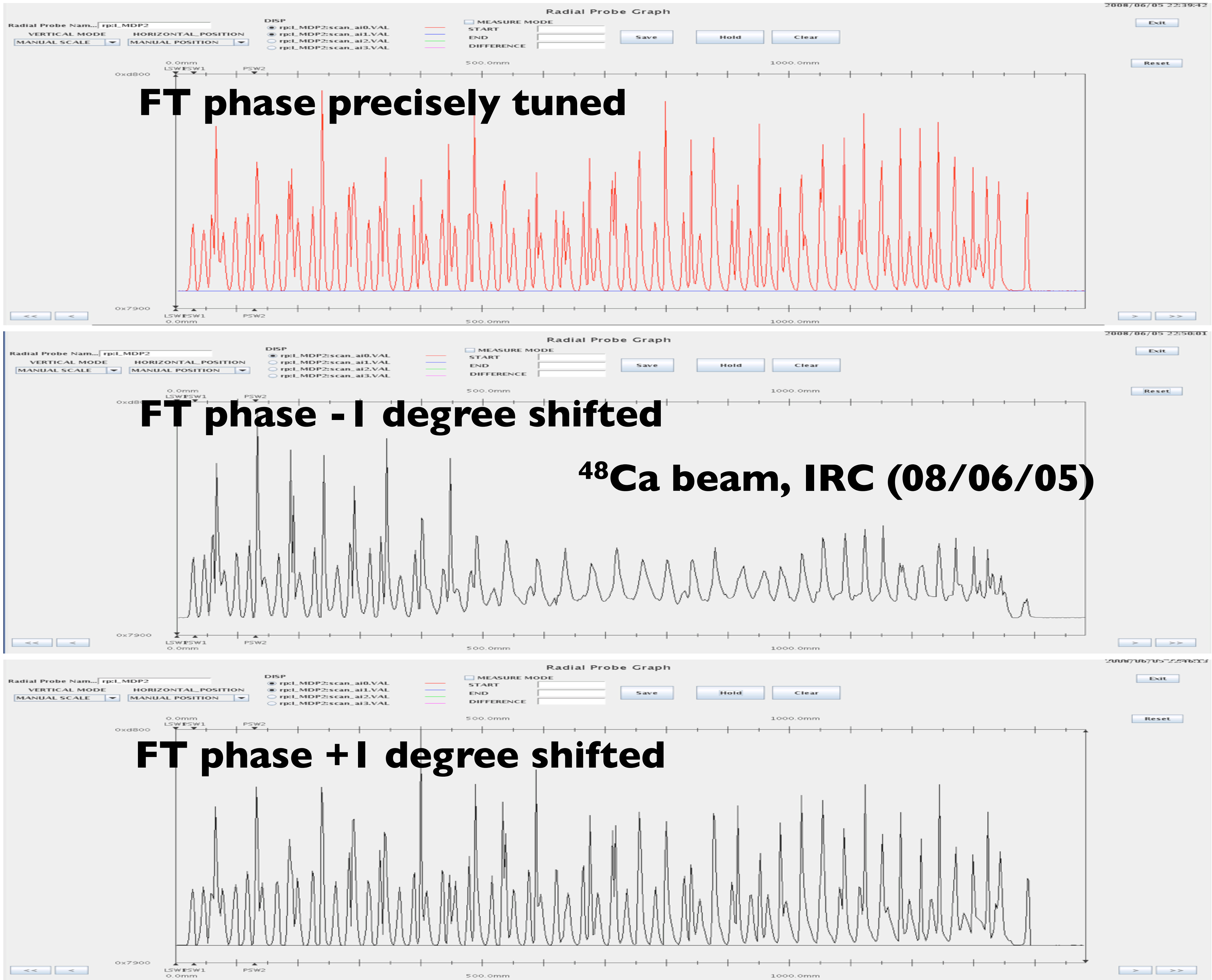
Effect of secondary electrons



Modification of SRC-MDP



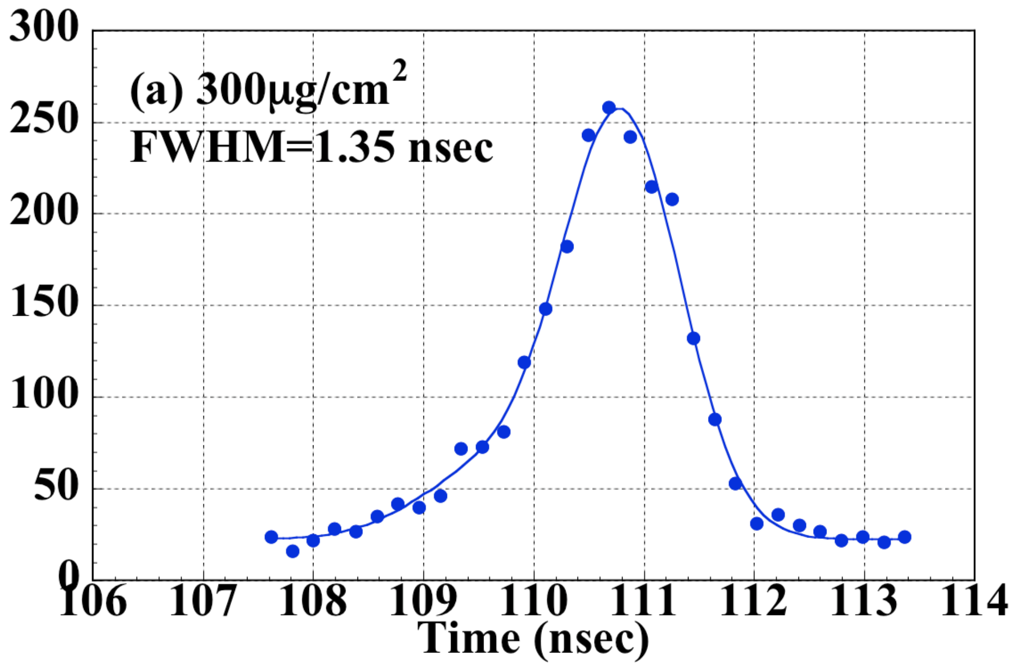
Precise phase adjustment of flattop resonators

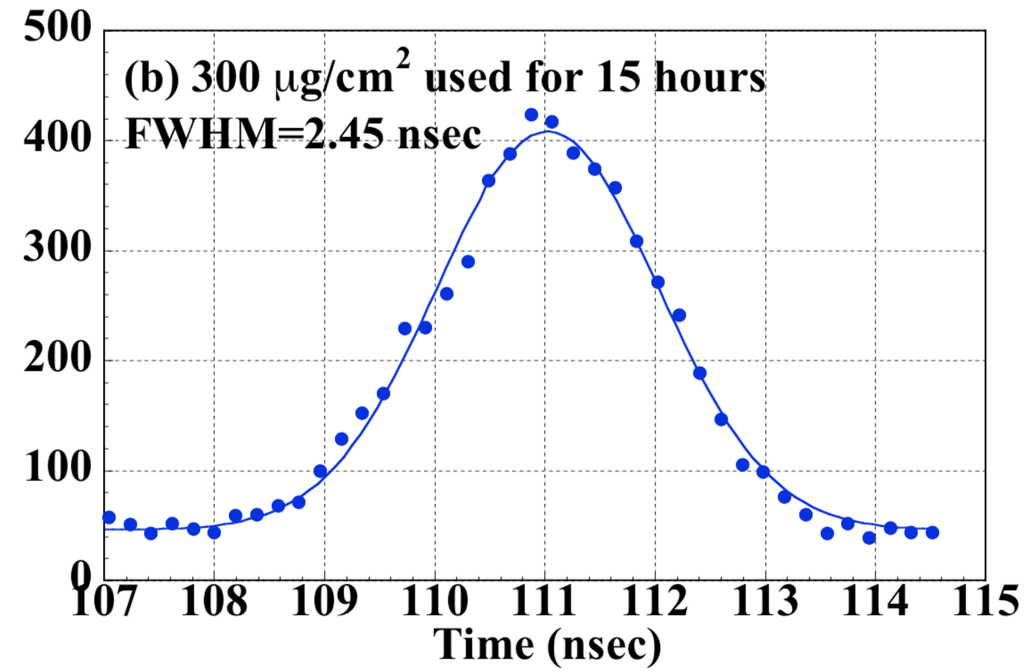


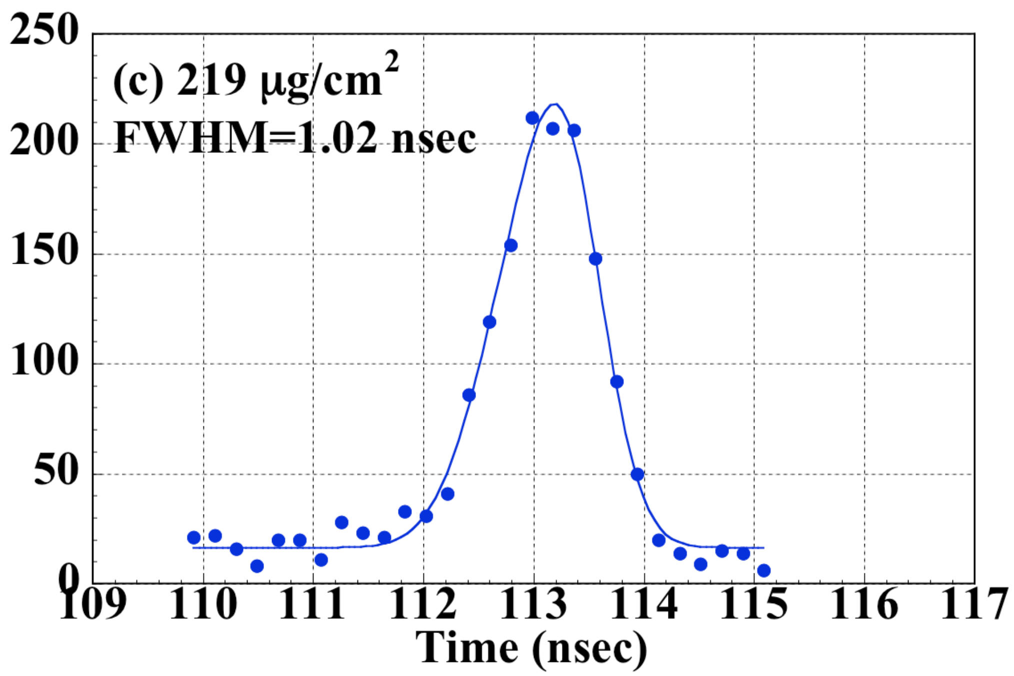
Charge stripper problem

(1) $^{238}U^{35+} \rightarrow\ ^{238}U^{71+}$ @ 10.75 MeV/nucleon (0.5 ~ 0.6 μA)

Longitudinal beam profile (@ 38 m below the stripper)







Commercial carbon foil (Arizona)

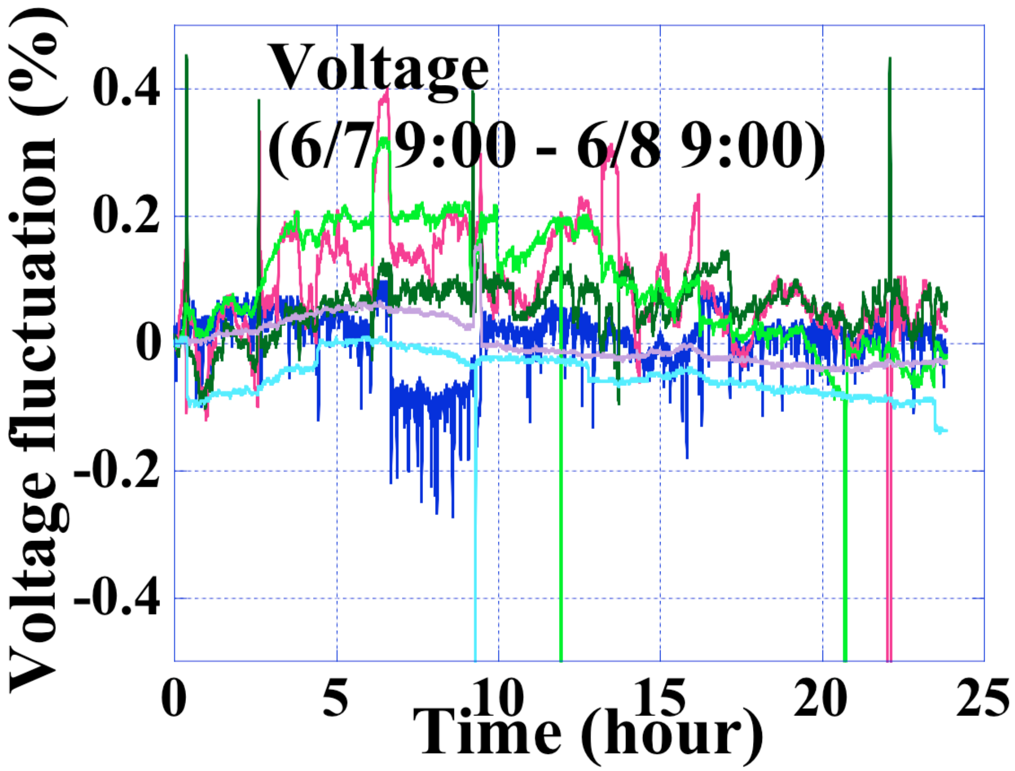
(1)Energy spread @ A01 stripper (1.4% energy loss) = ~ 0.5 %

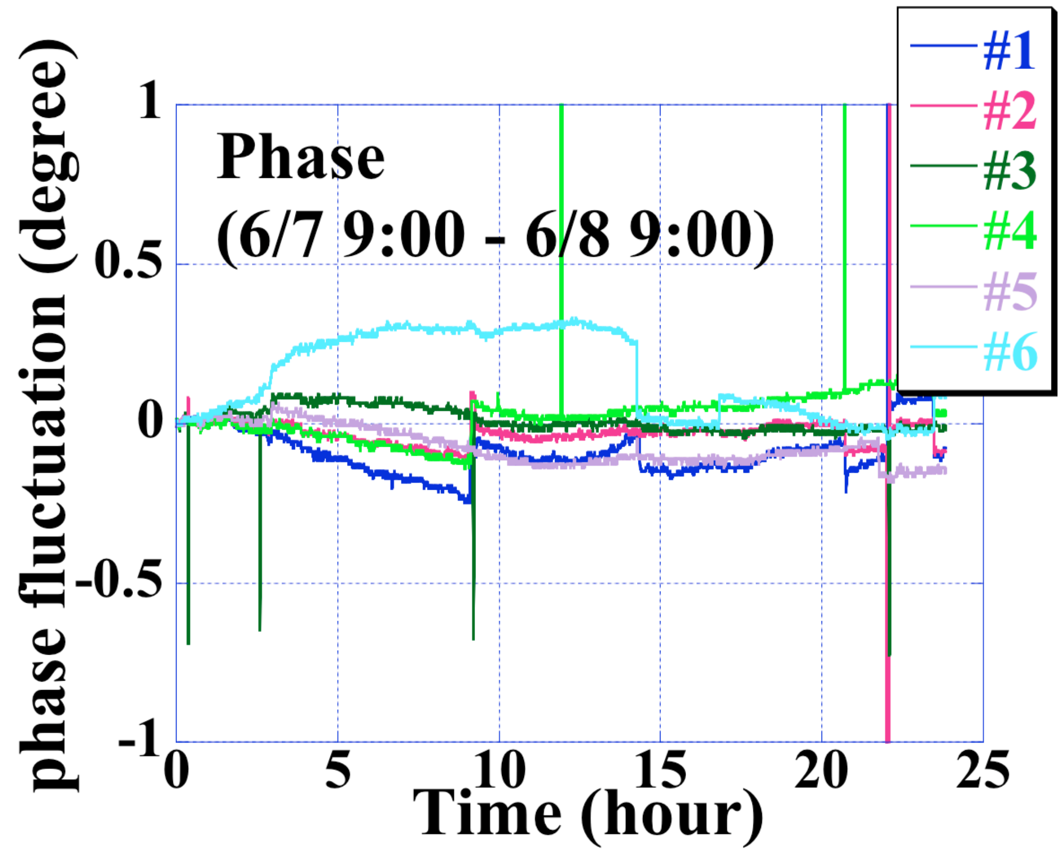
(2)Lifetime < 10 hours for 600 nA ^{238}U beam

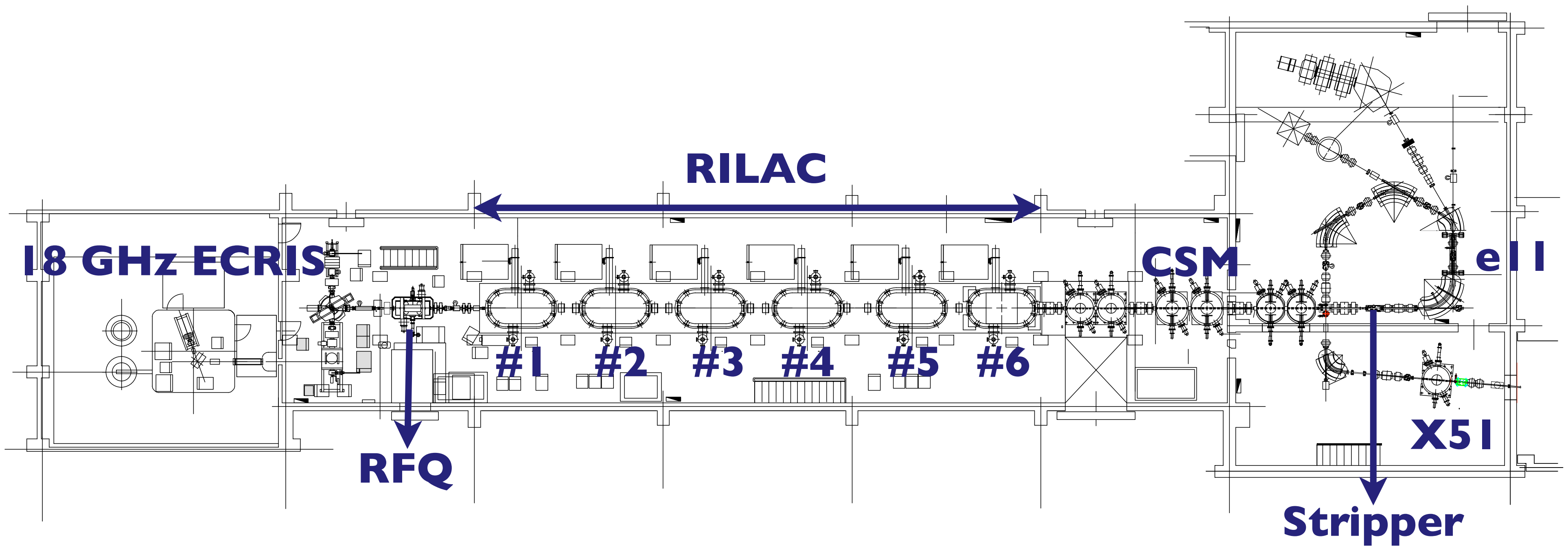
(3)multi-layer carbon, diamond-like carbon were also tested.

Stability of injector (RILAC)

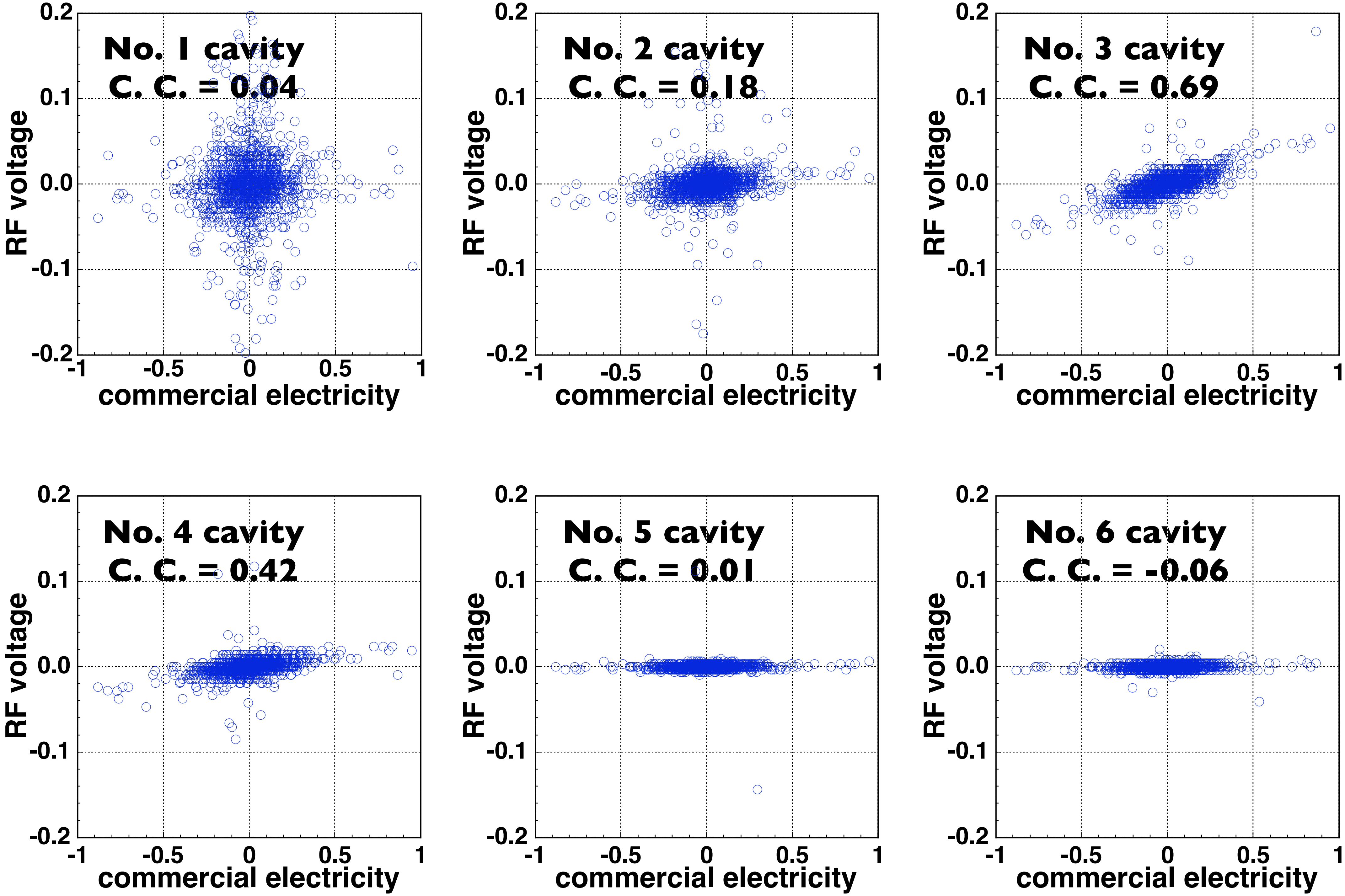
allowable limit = ±0.1 degree in phase & ±0.1% in voltage







Correlation between fluctuations of RF voltages and commercial electricity



Automatic gain controllers (AGC) were upgraded in 2002.

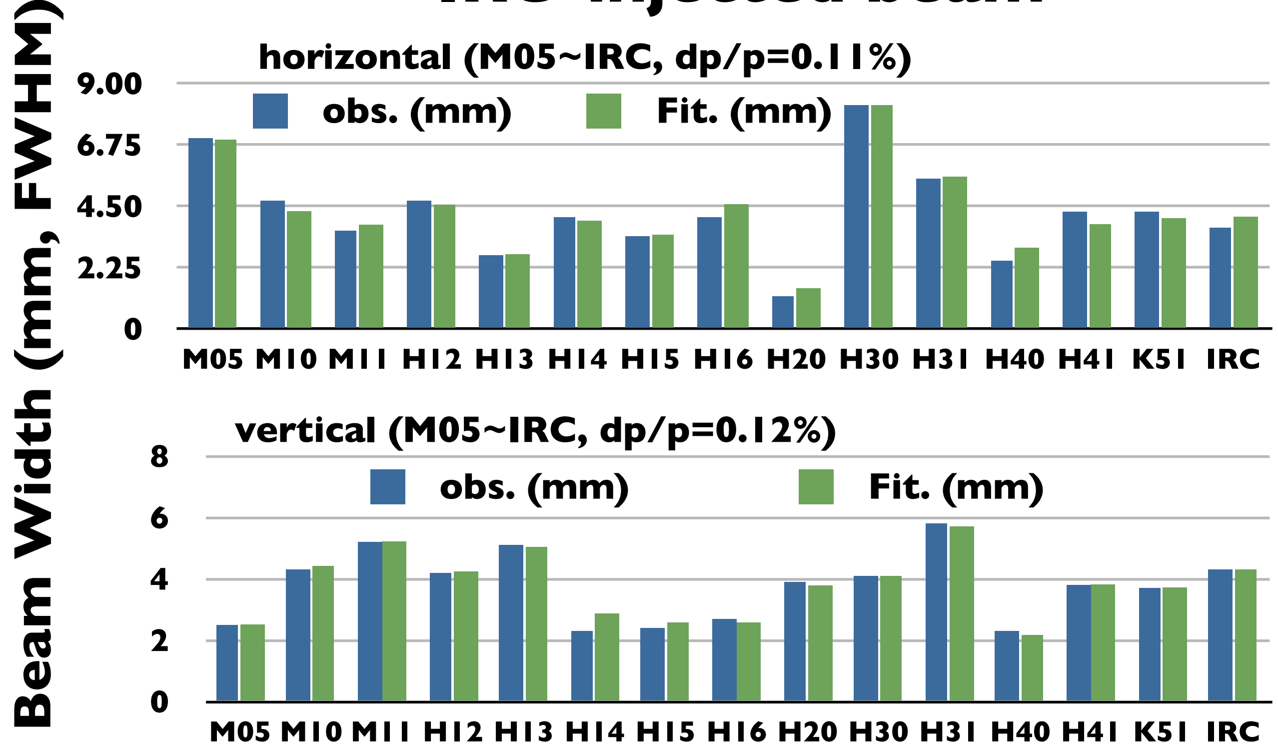
C.C. = correlation coefficient

Emittance analysis of ^{48}Ca beam (08/12/21)

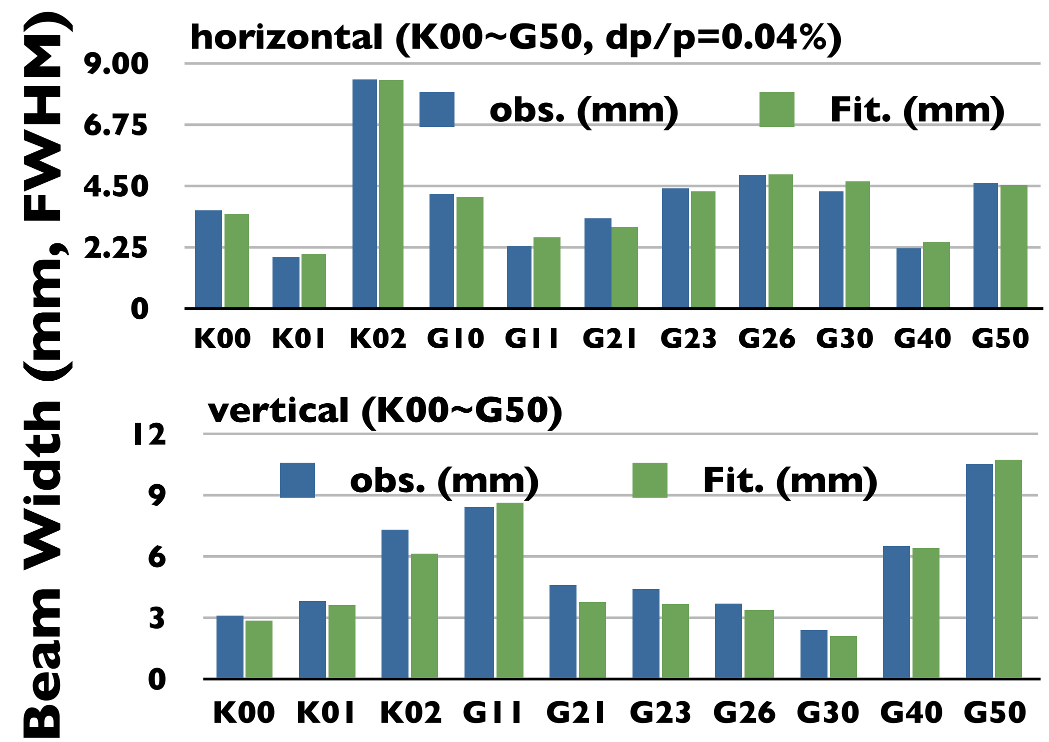
Utilizing the data of beam widths obtained by beam profile monitors, we estimated beam emittances based on the first order ion optics.

(1)Emittance (IRC-injected beam) = ***2.2 ~ 2.3*** **π** mm mrad (unnormalized, within 4σ region)
(2)Emittance (SRC-injected beam) = ***~1.7*** **π** mm mrad (unnormalized, within 4σ region)
(3)No notable emittance growth was observed.
(4)Corresponding normalized-RMS emittance is **0.19 π** mm mrad.

IRC-injected beam



SRC-injected beam



Emittance analysis for ^{238}U beam (08/11/16)

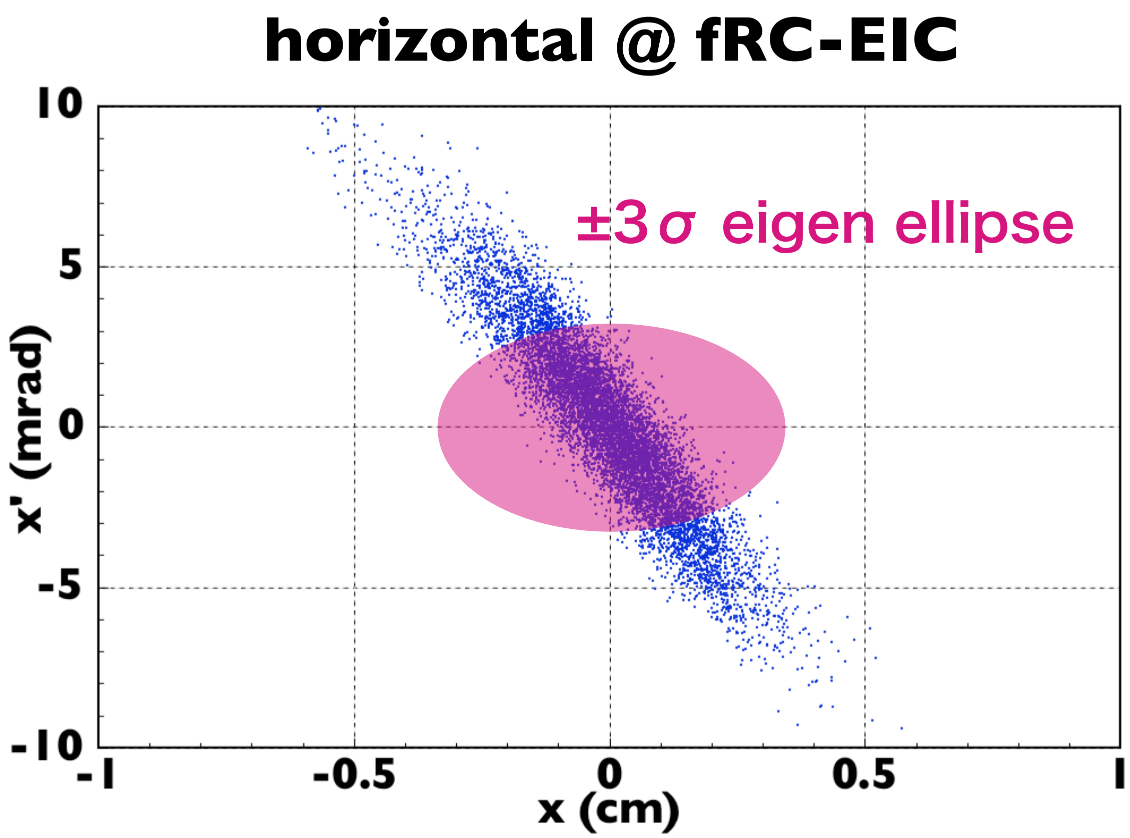
Emittance estimation based on 1st order optics
(π mm mrad, unnormalized, within 4σ region)

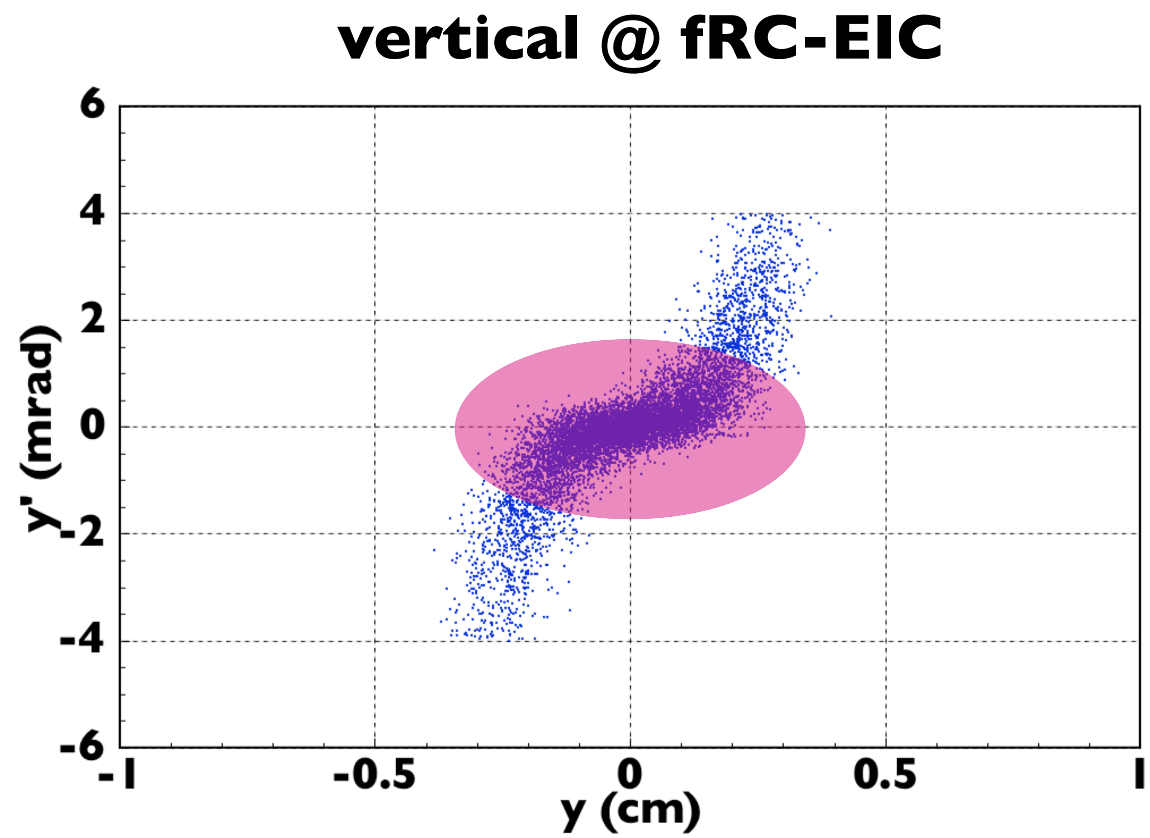
	vertical	horizontal
RRC extraction	2.6	~ 2.4
fRC extraction	1.4	5
IRC injection	2.1	5 ~ 6
SRC injection	1.4	~ 4

Vertical direction : no problem
Horizontal direction : Large emittance growth

Emittance Growth during fRC acceleration

EIC = electrostatic inflection channel



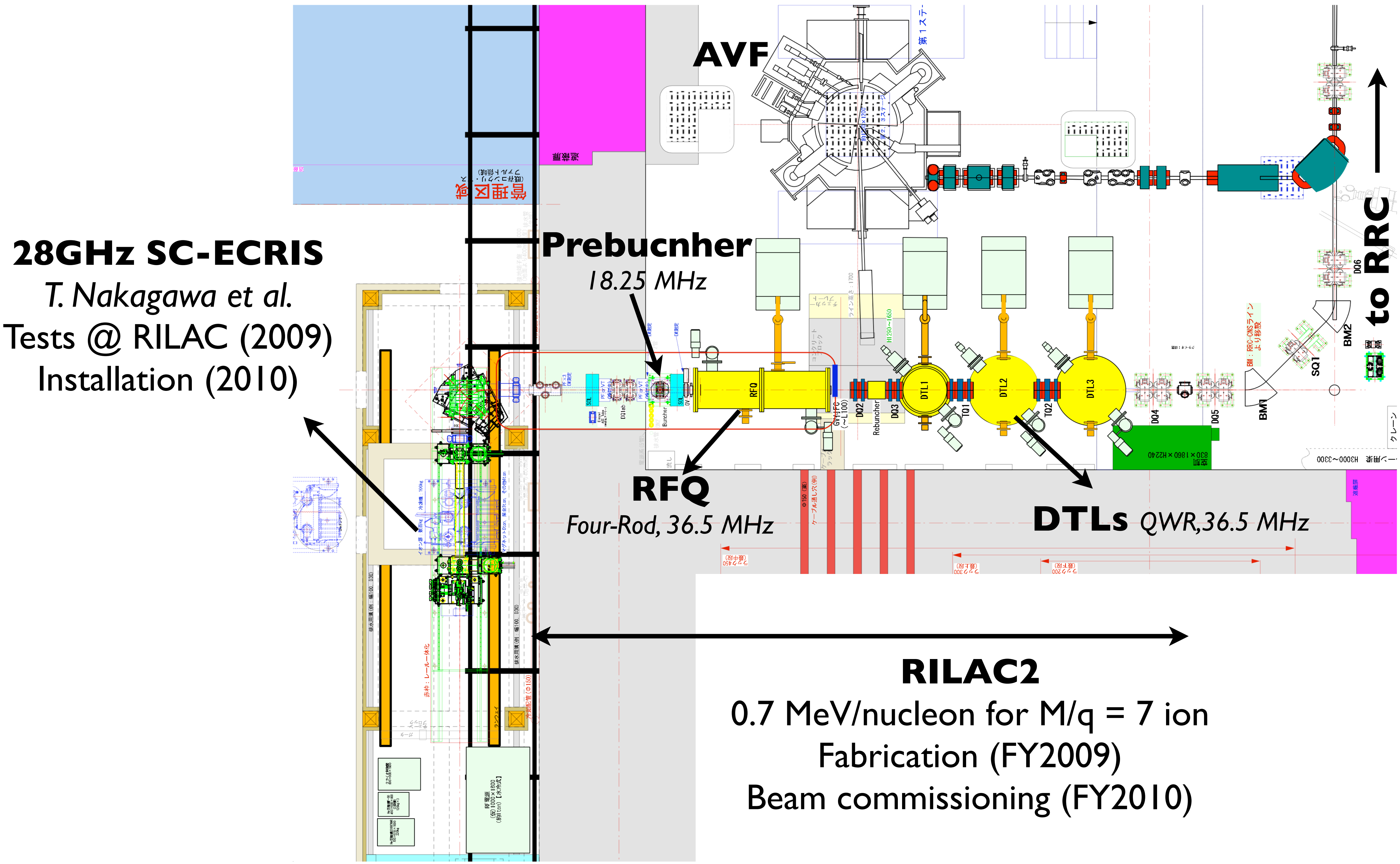


(1) Emittance growth in horizontal direction = 1.7
Horizontally over-focused
(2) Vertically, beam was strongly defocused.
Second-order aberration

Other improvements (2007~2008)

(1)Upgrade of vacuum pumps for low-energy region of the injector linac.
(2)RF contacts introduced for the radial probes to suppress leakage RF fields from flat-top resonators (TE01 mode).
(3)Interference filters were introduced to the phase probe of fRC to obtain hight S/N ratio.
(4)Beam-phase and RF-fields monitoring system using lock-in amplifiers (SR844) was developed.
(5)Beam interlock system to protect hardwares started its operation.
(6)Type-E thermocouple gauges installed to SRC-EDC to measure heat load caused by beam loss.
(7)Water-cooling thermal baffles were introduced to decrease temperature of a RF shield in front of cryopumps. (SRC)
(8)Faraday cups were modified to suppress effectively secondary electrons.
(9)High-Temperature Superconducting SQUID beam monitor started its operation.
(10)Ion-beam core monitor operating with 50 KHz has been developed.
(11)Beam line bypassing IRC was constructed and commissioned.

To obtain high-intensity uranium beam
28 GHz-ECRIS + RILAC2



RILAC2

0.7 MeV/nucleon for M/q = 7 ion

Fabrication (FY2009)

Beam commissioning (FY2010)

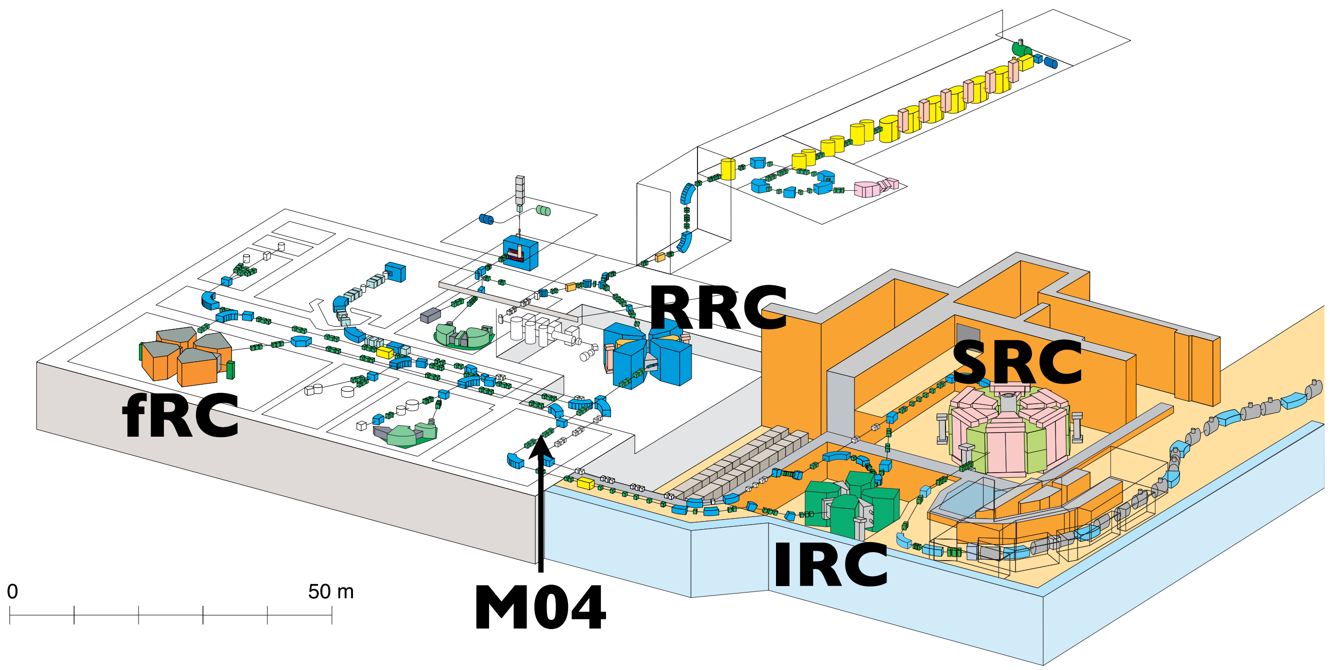
Summary

- Oil contamination problem of He refrigerator of SRC was solved.
- SRC works well as a good isochronous cyclotron.
- Transmission efficiency was improved.
- 200-pnA ^{48}Ca beam & 0.4-pnA ^{238}U beam are now available.
- A series of experiments were performed in these 6 months.

- Charge strippers used in ^{238}U acceleration are most important problem.
- Stability of RILAC should be improved.

- New superconducting ECRIS will start its operation in 2009.
- Construction of a new injector linac was started.

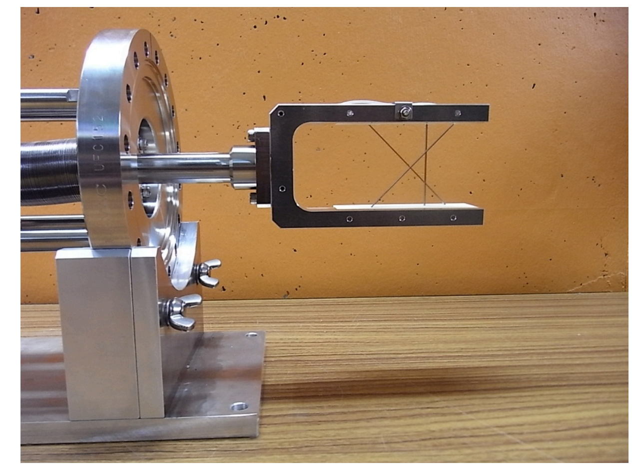
Beam monitors in beam lines



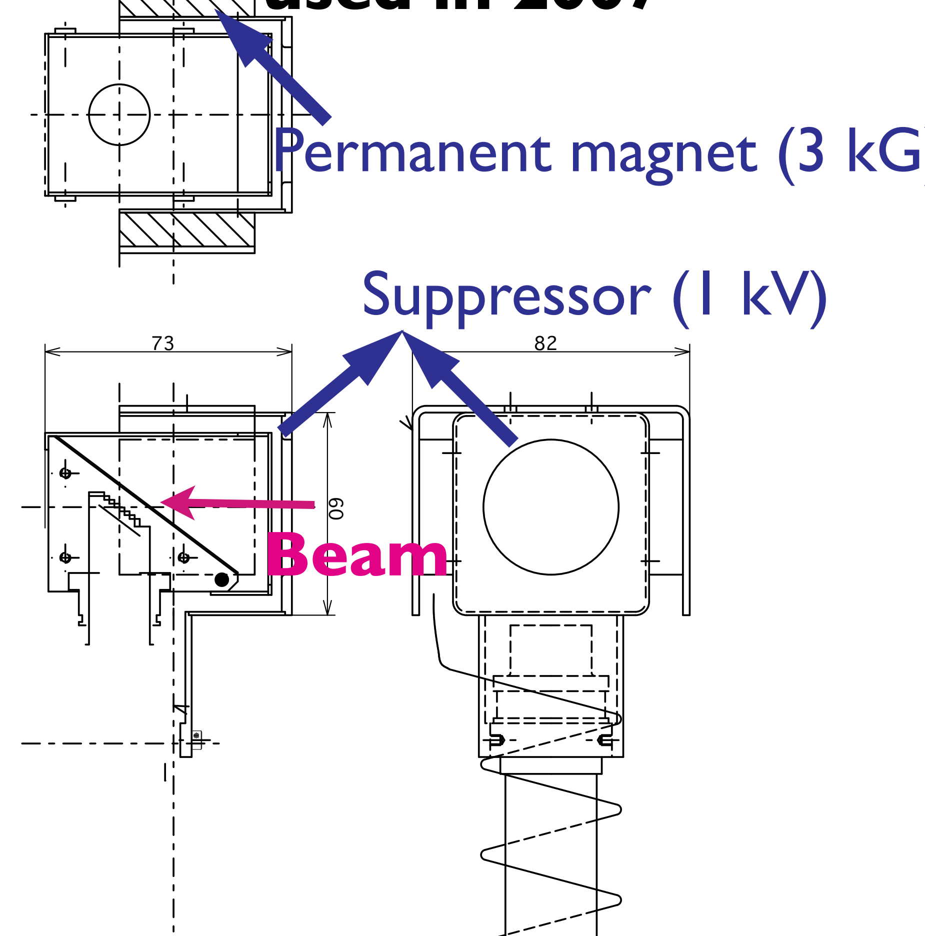
BT	length (m)	PF	FC	P.S.
RRC - fRC	78	12	9	3
fRC - M04	60	9	6	1
M04 - IRC	59	15	5	3
IRC - SRC	62	11	5	3

P.S. = plastic scintillator (longitudinal, TOF)

PF = beam profile monitor (wire-scanner type)

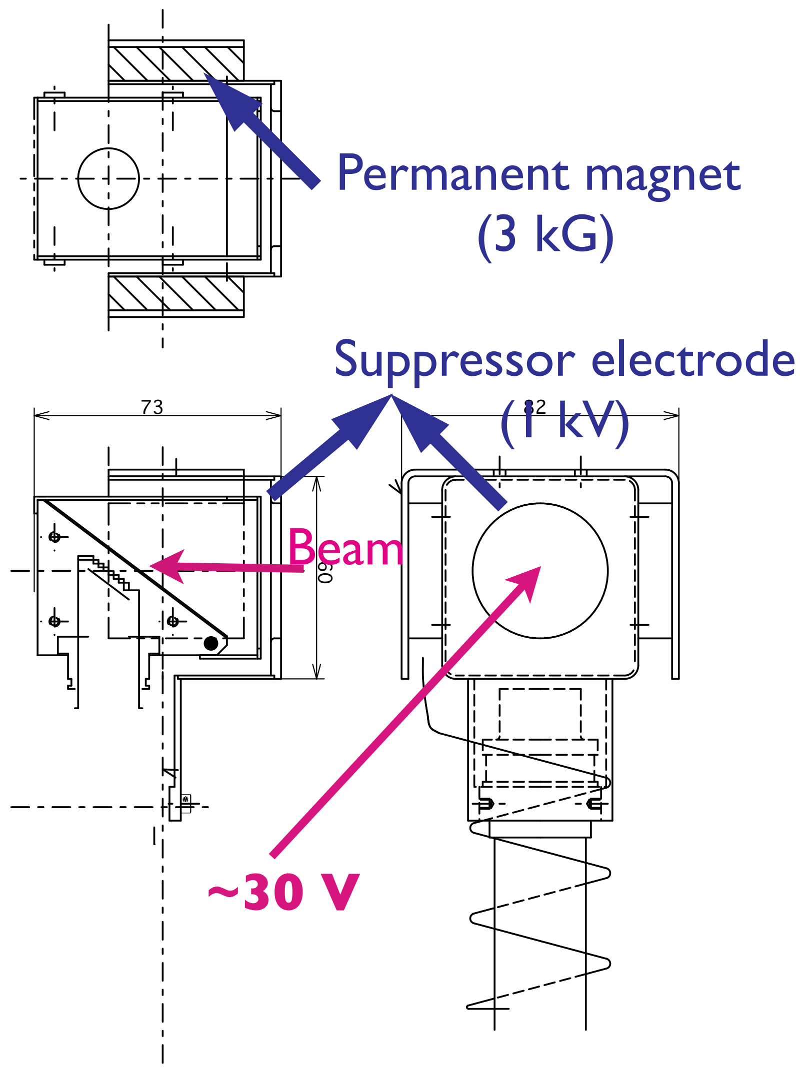


FC = Faraday cup used in 2007

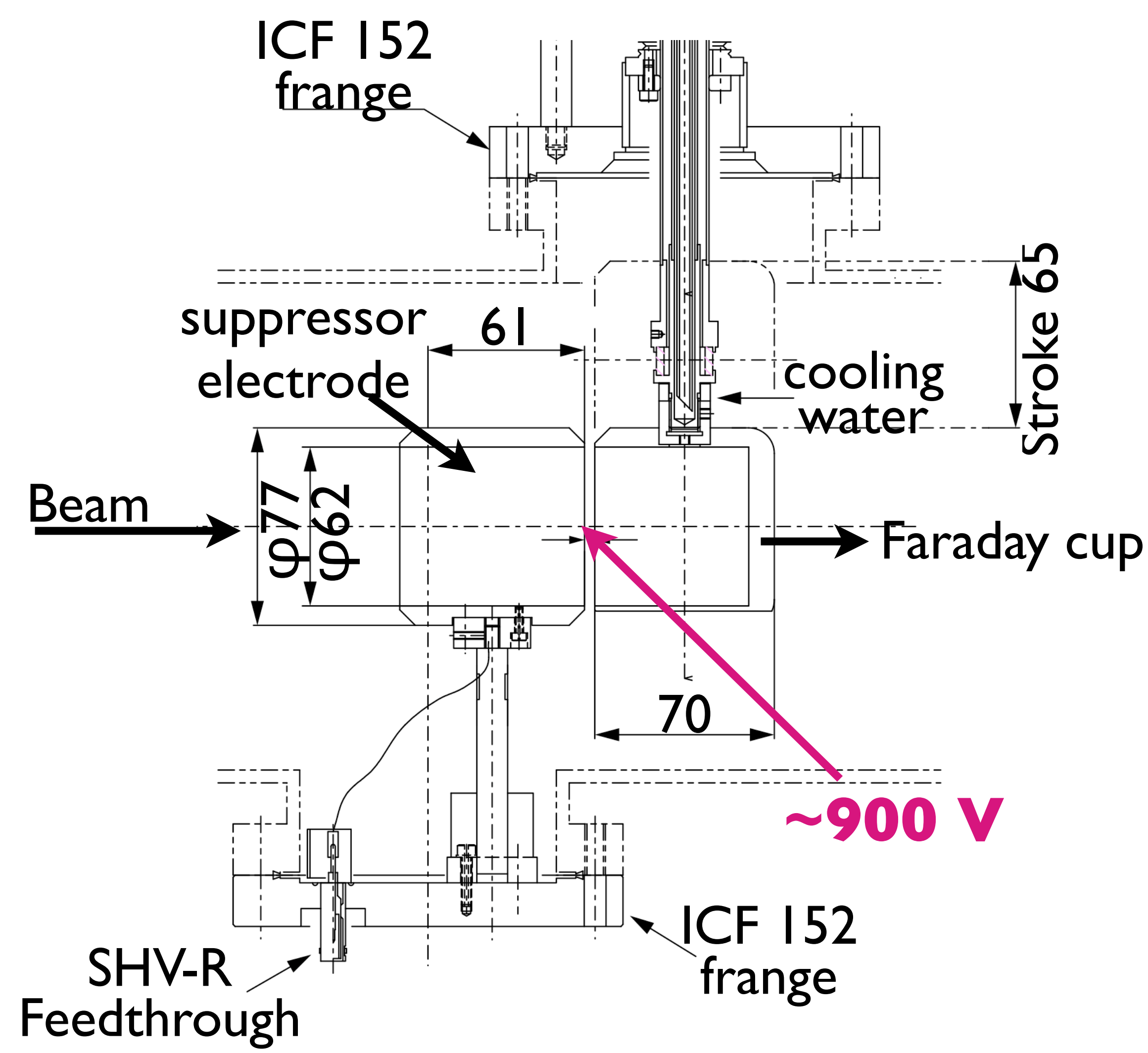


Modification of Faraday cup

Faraday cup used in 2007



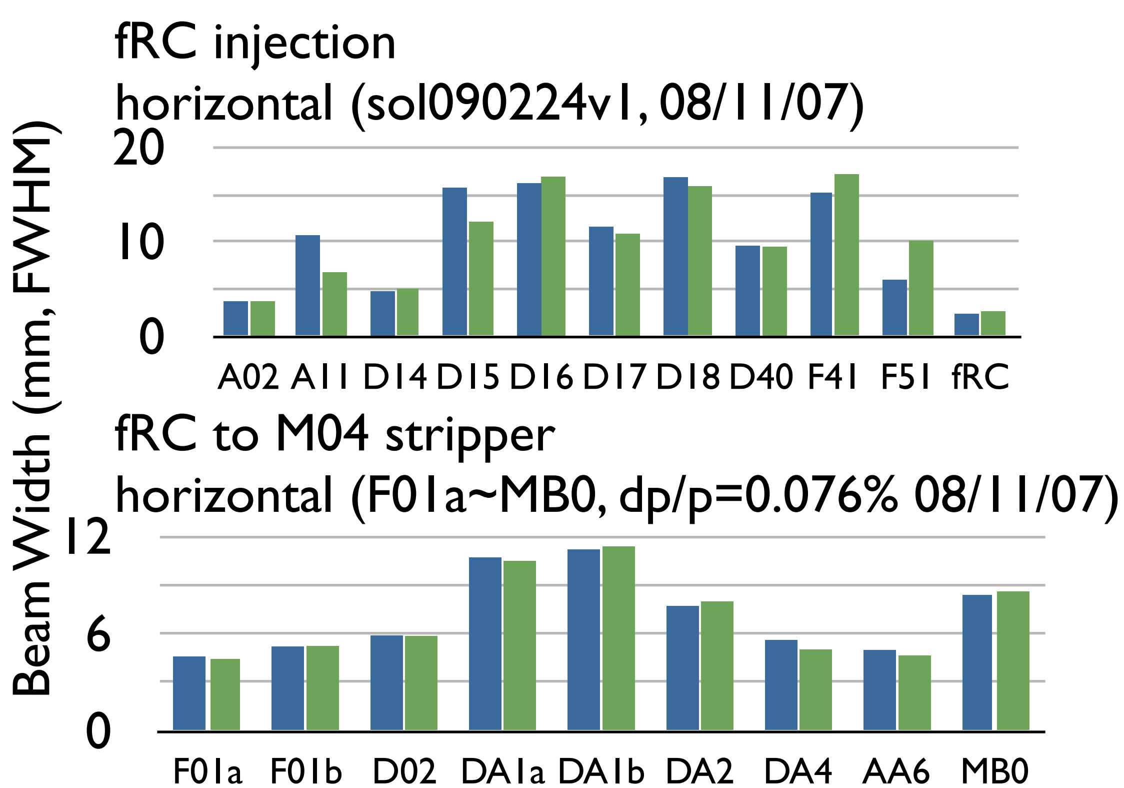
Faraday cup used in 2008

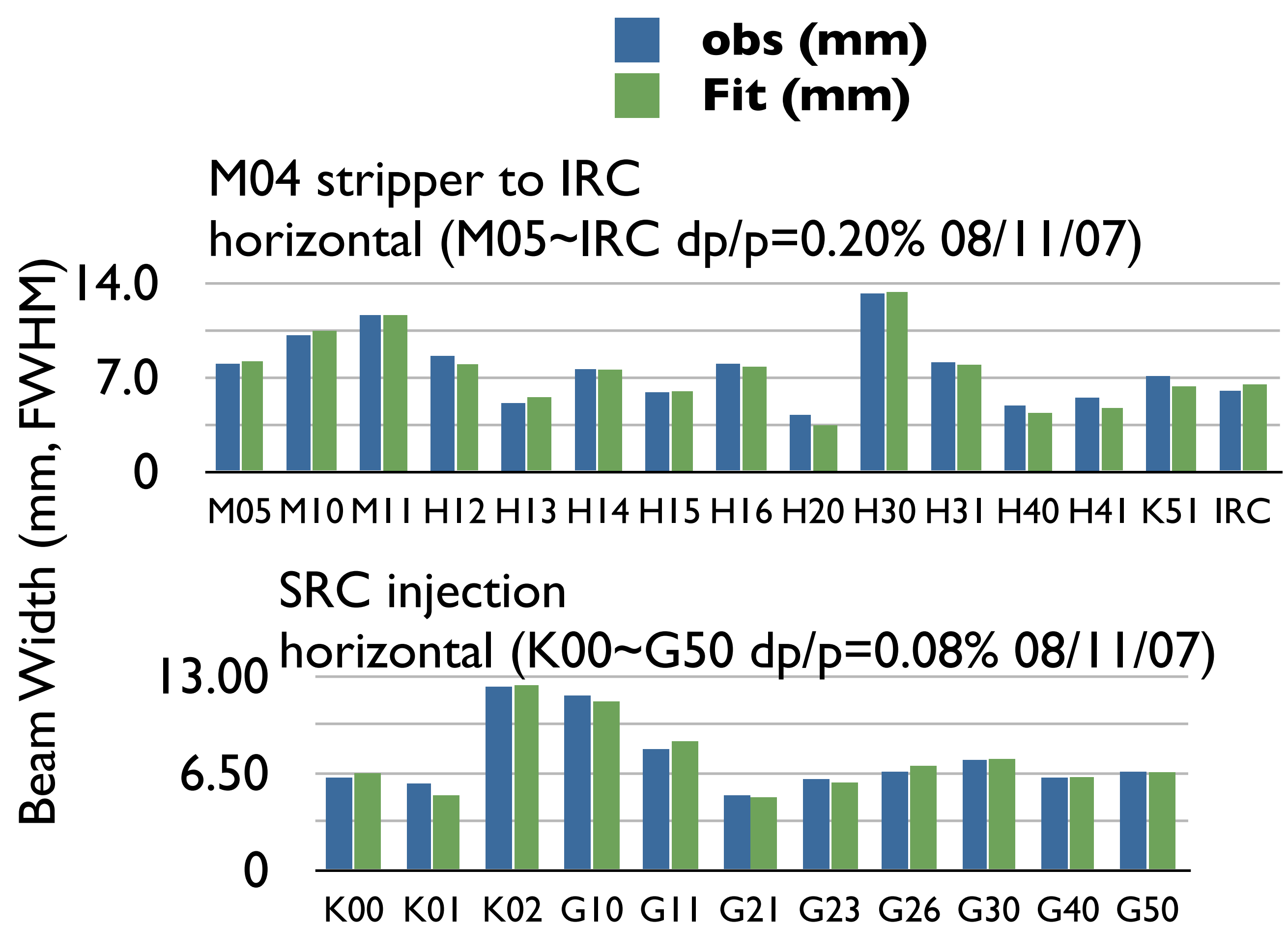


Sizable beam loss disappeared with new FCs.

Emittance analysis of ^{238}U beam (08/11/7)

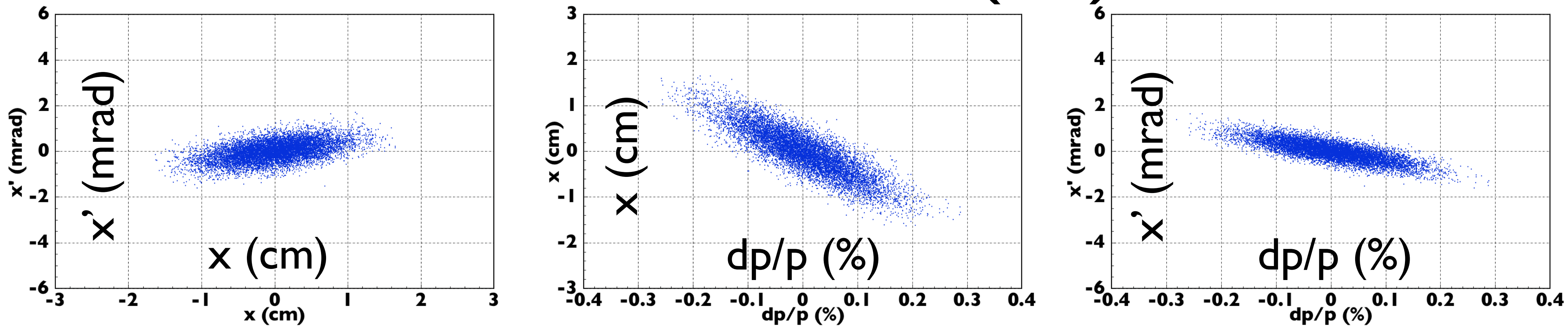
Results of beam-size fitting



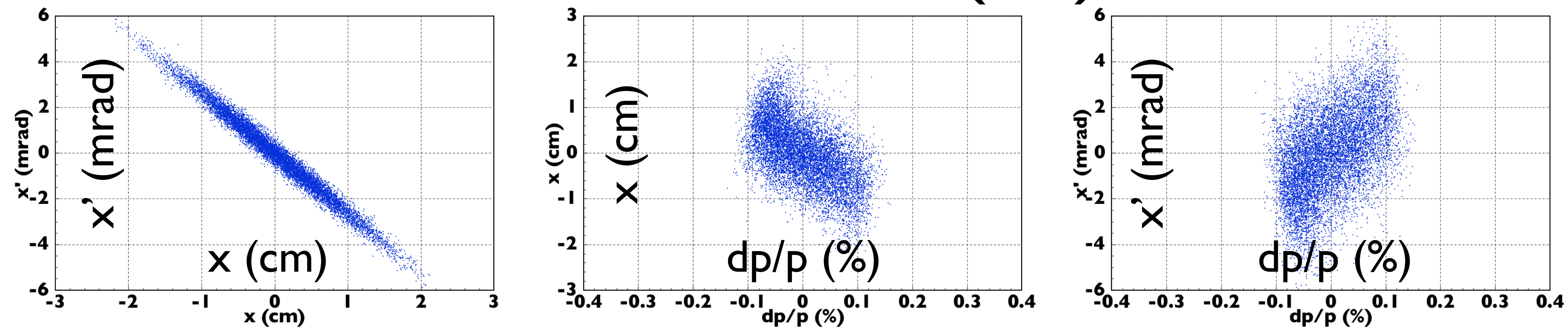


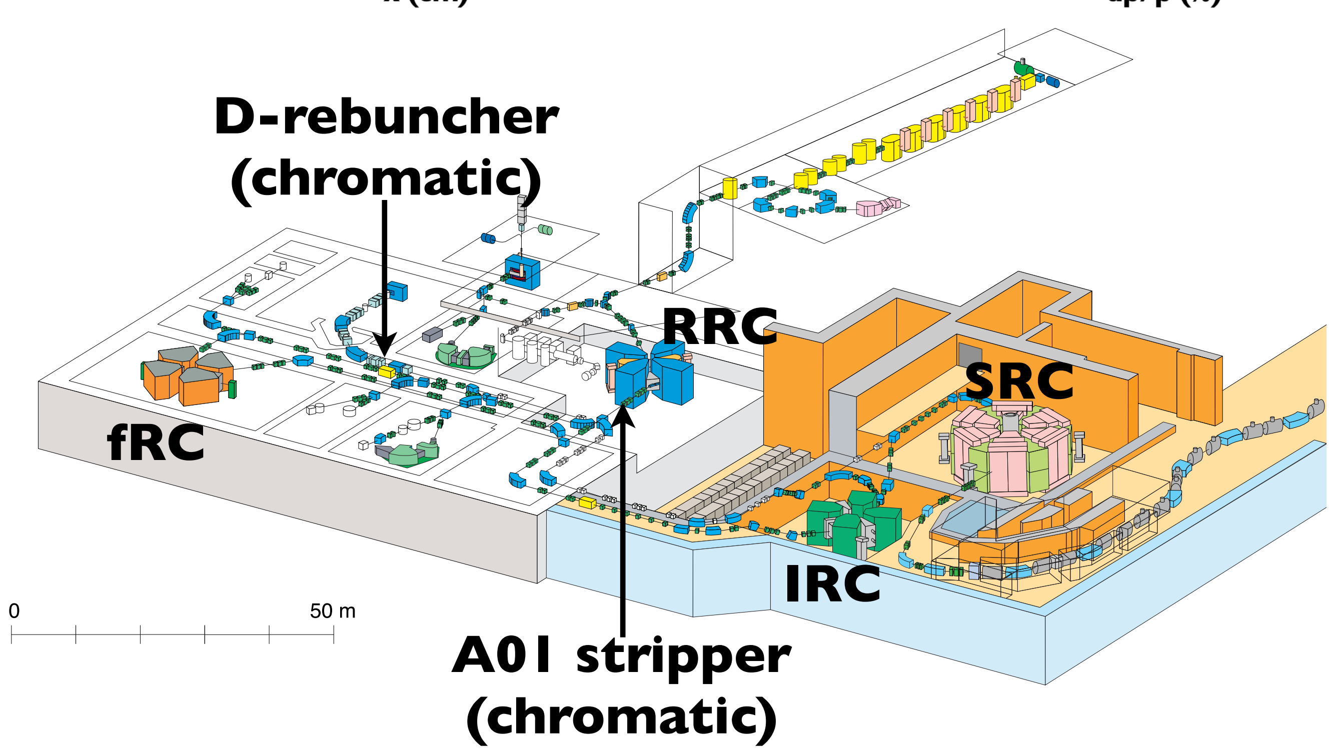
Emittance Growth @ D-rebuncher

Before D-rebuncher (D15)



After D-rebuncher (D18)

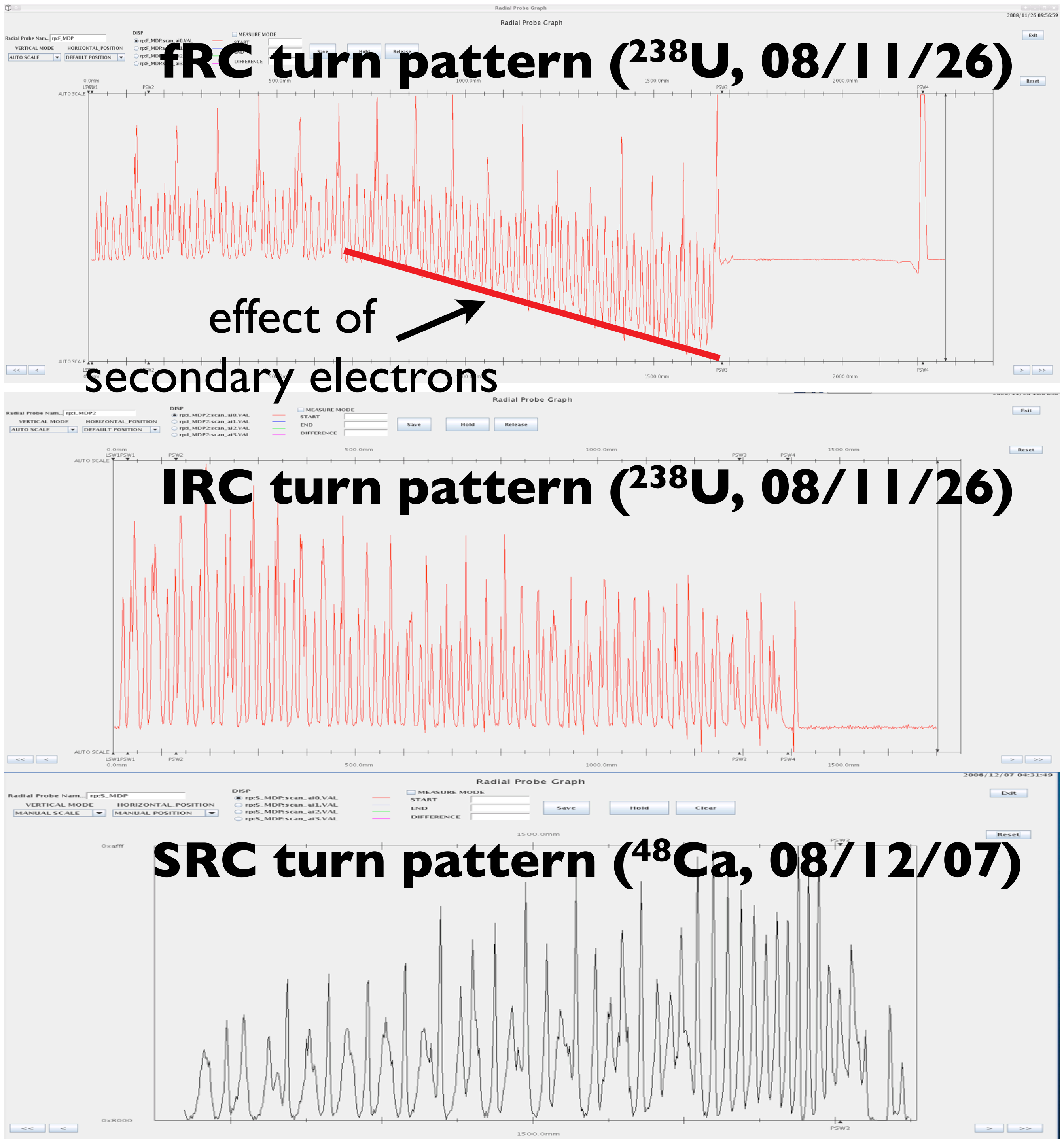




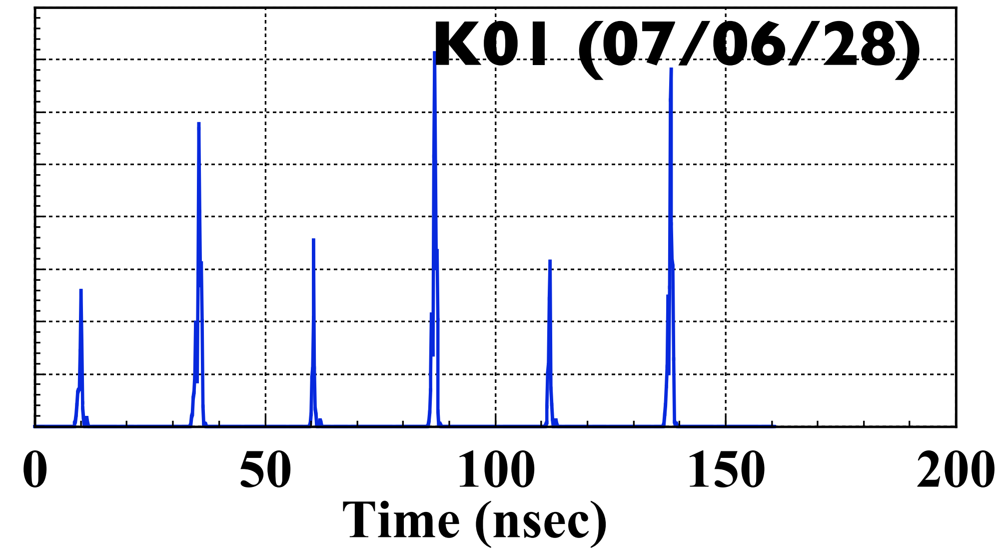
Horizontal emittance growth
@ D-rebuncher

x 1.5 (design value)
x 2.0 (observed)

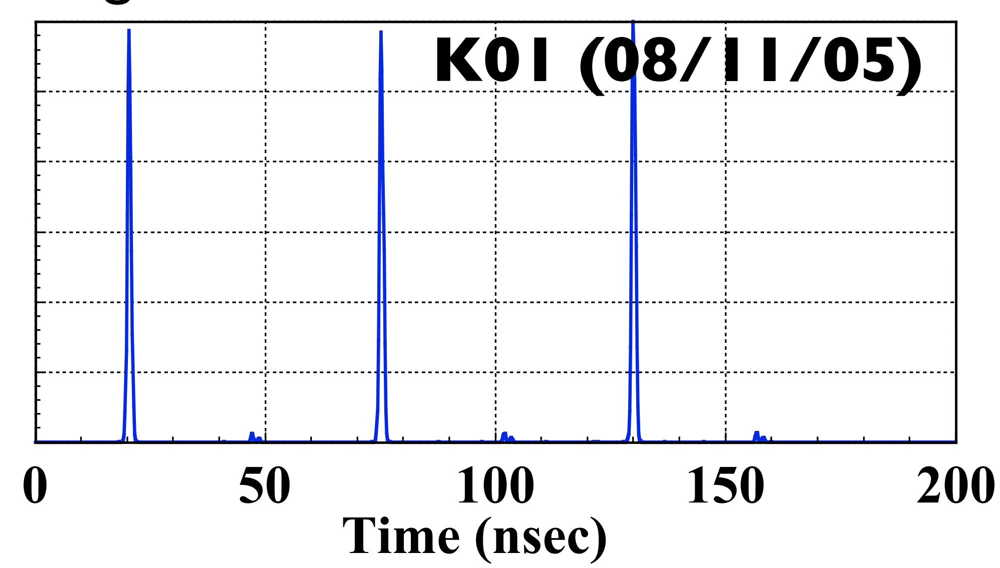
Turn Patterns



Single-turn extraction was failed



Single-turn extraction was succeeded



Reasons of low transmission efficiency especially in ^{238}U acceleration

(1) Beam monitors were not suited for uranium acceleration.
Suppression of secondary electrons was insufficient.

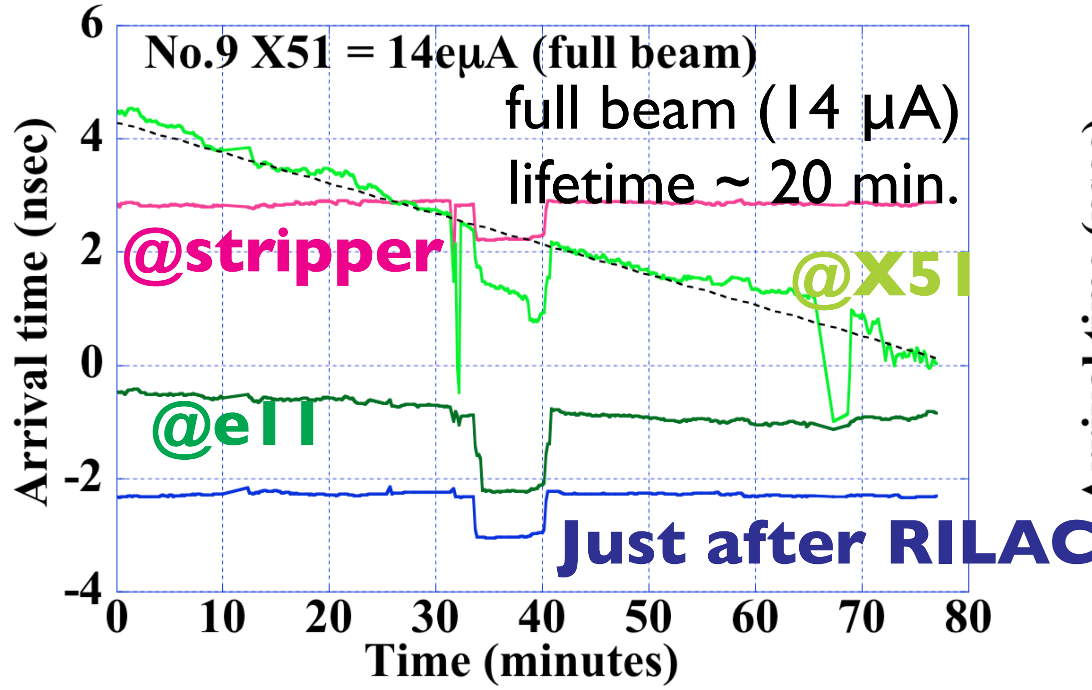
(2) Beam quality itself was bad due to the existence of thick carbon foils.
Eloss = 1.4% for ($^{238}U^{35+} \rightarrow$ $^{238}U^{71+}$) / thickness uniformity = 30%
Eloss = 9% for ($^{238}U^{71+} \rightarrow$ $^{238}U^{86+}$) / thickness uniformity = ~7%

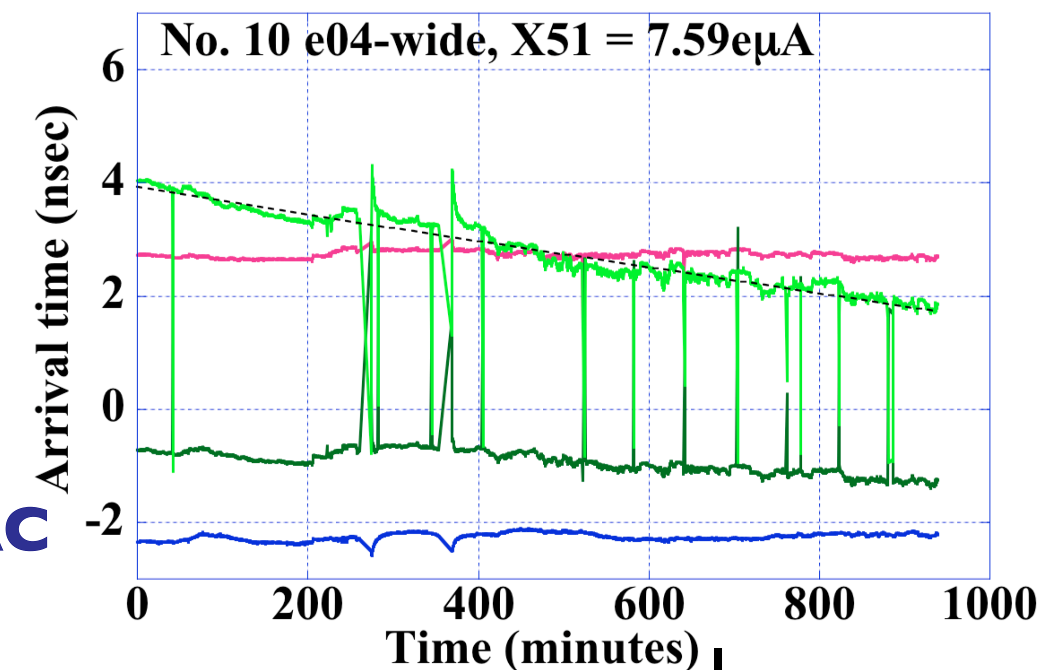
(3) Stability of the old injector linac was insufficient.

Charge stripper problem

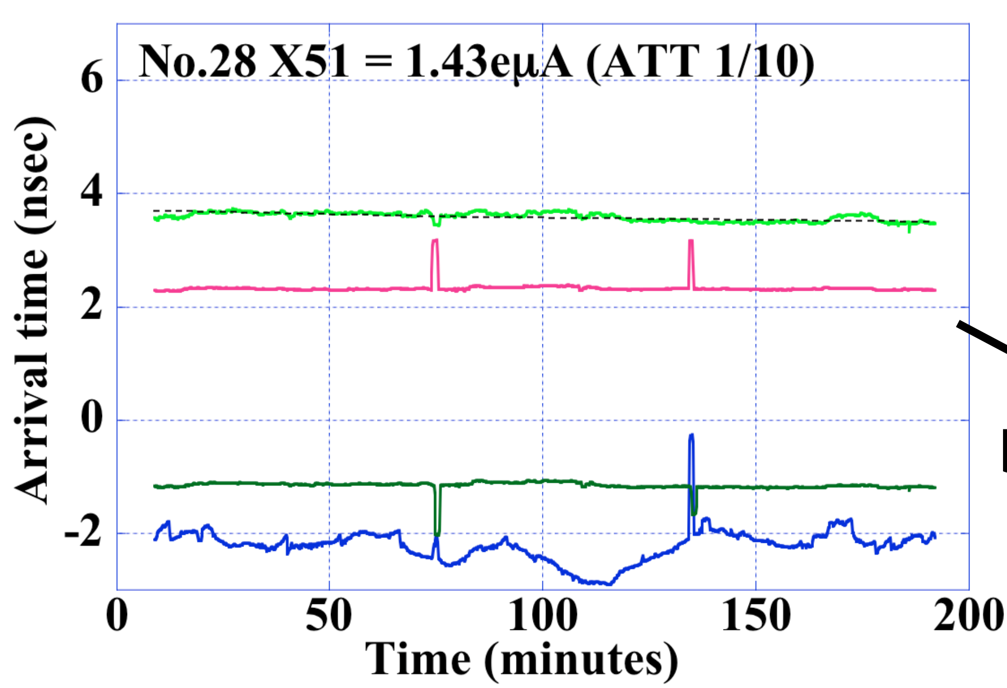
(2) $^{86}Kr^{18+}$ @ 2.3 MeV/nucleon

Beam phase monitored by the phase-pickup probe / 25 m below the stripper (X51)





full beam with enlarged beam image
lifetime ~ 80 min.

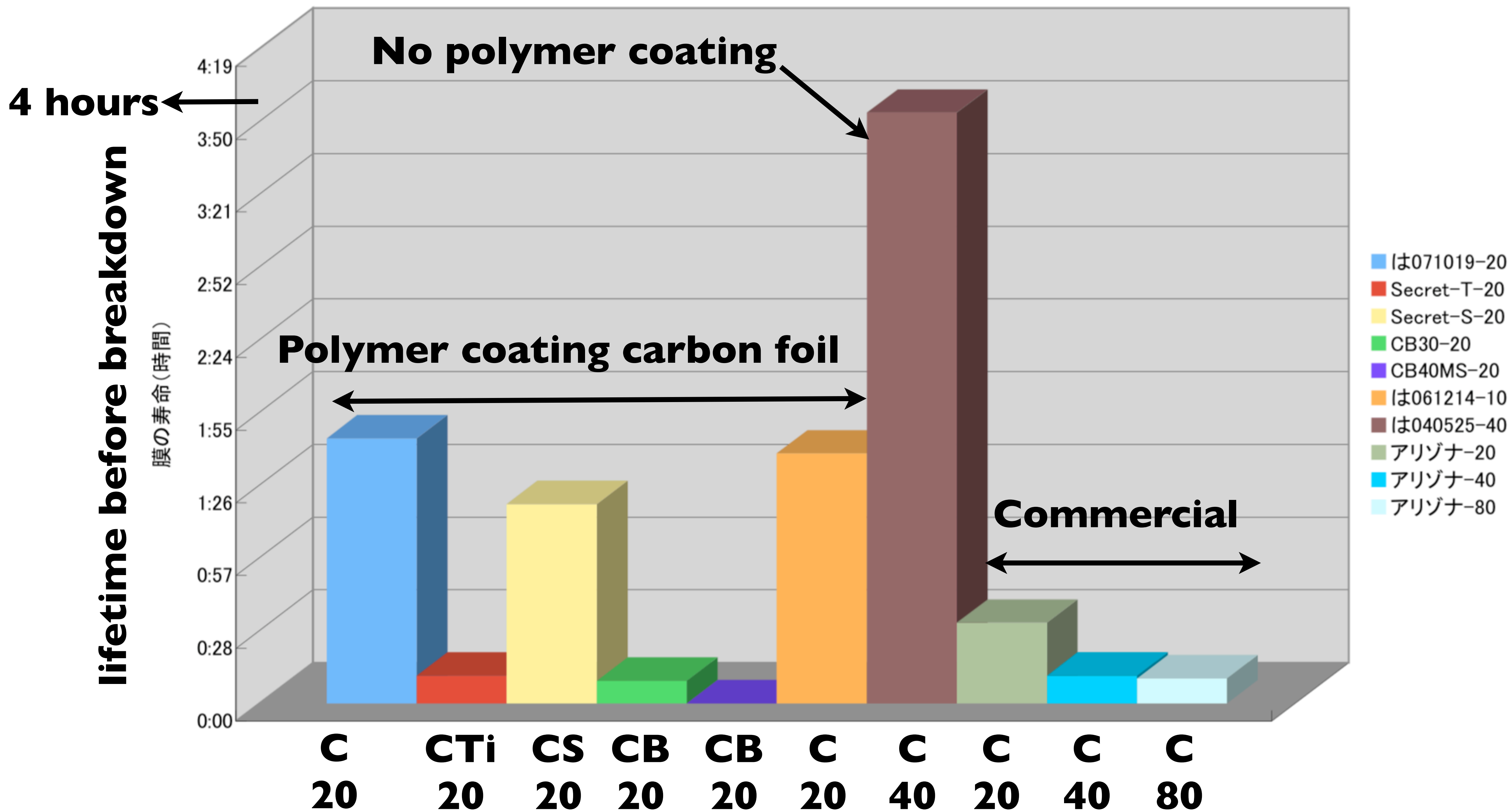


beam intensity attenuated (1.4 μA)
lifetime ~ 1000 min.

(PCC071019, 20 μg/cm^2)

Lifetime of various carbon foils

$^{86}Kr^{18+}$ @ 2.3 MeV/nucleon



Polymer = Poly(monochloro-para-xylylene), Parylene

Charge stripper status

Ion	E (MeV/u)	Intensity (μA)	Quality	Lifetime
$^{48}Ca^{10+}$	2.7	30	O.K.	O.K.
$^{48}Ca^{16+}$	45	3	O.K.	O.K.
$^{86}Kr^{18+}$	2.3	25		< 2 hours
$^{136}Xe^{20+}$	11	O.K. (gas stripper will be used)		
$^{136}Xe^{41+}$	50	Not tested		
$^{238}U^{35+}$	11	0.6	Not so good	< 15 hours
$^{238}U^{71+}$	50	0.2	Not so good	O.K.

Charge stripper problem

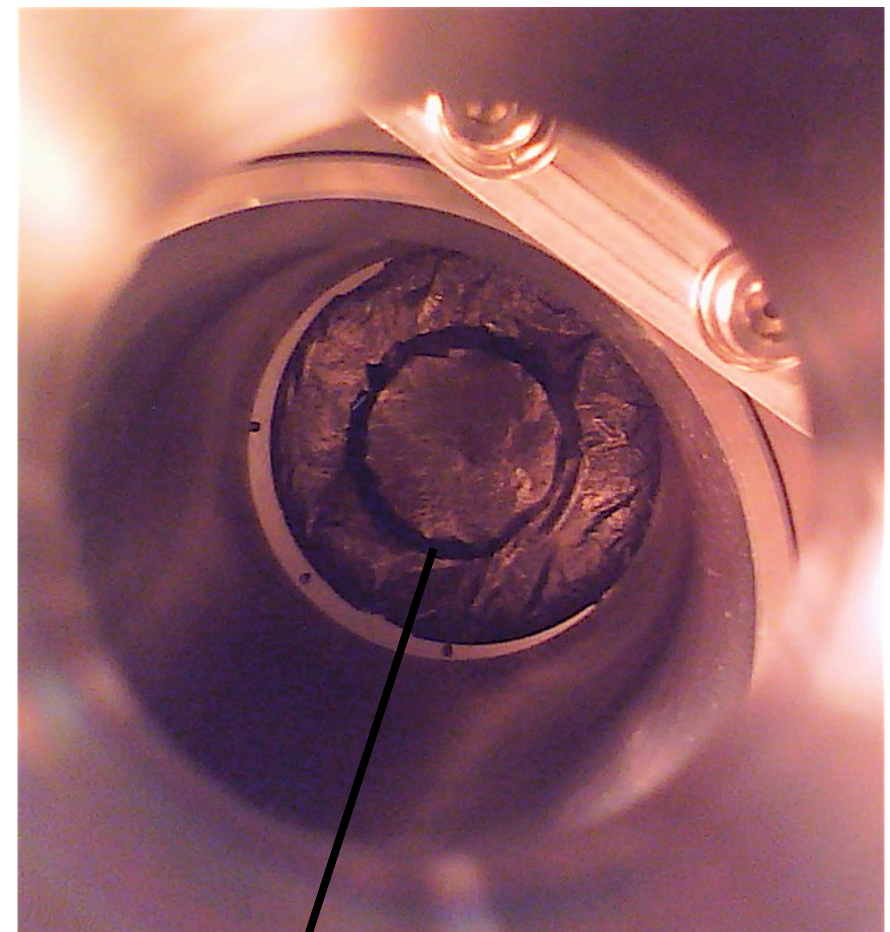
(I) ${}^{238}U^{35+} \rightarrow {}^{238}U^{71+}$ @ 10.75 MeV/nucleon (0.6 μA)

0.3 mg/cm^2 multi-layer PCC foil

very short lifetime without oven-conditioning

more than 24 hours oven (523K) for several hours

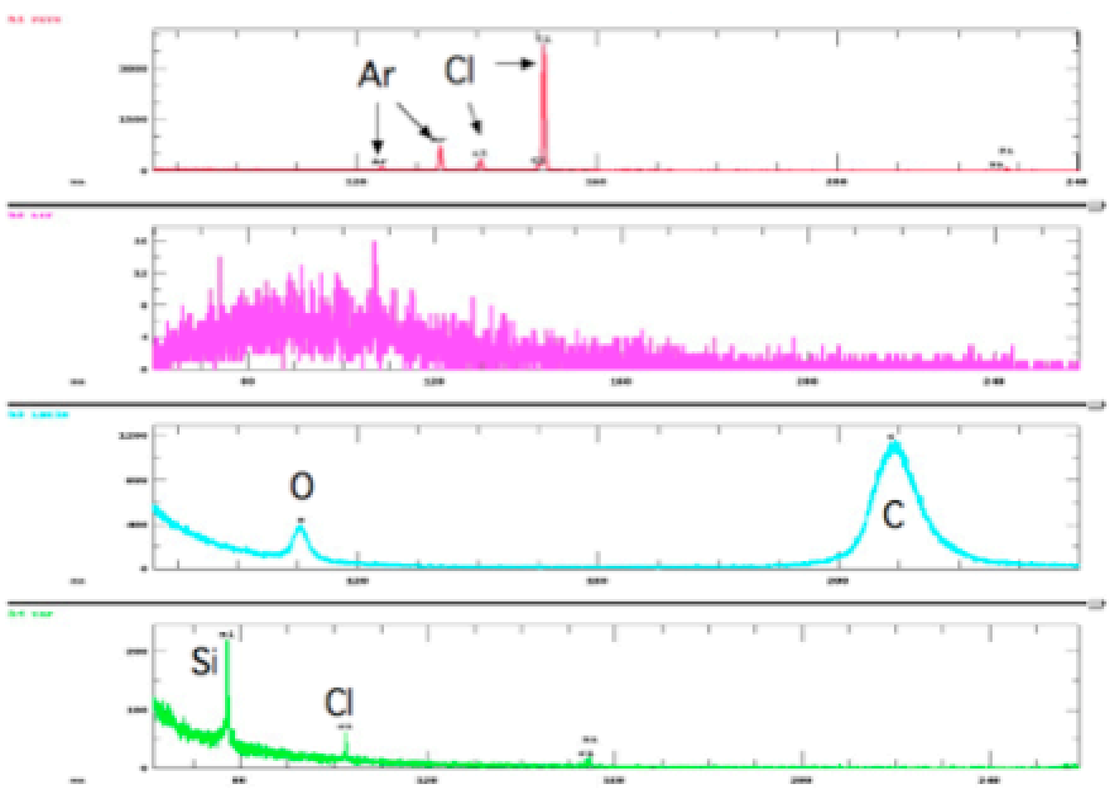
rotating carbon foil stripper
0.3 mg/cm^2 multi-layer PCC foil



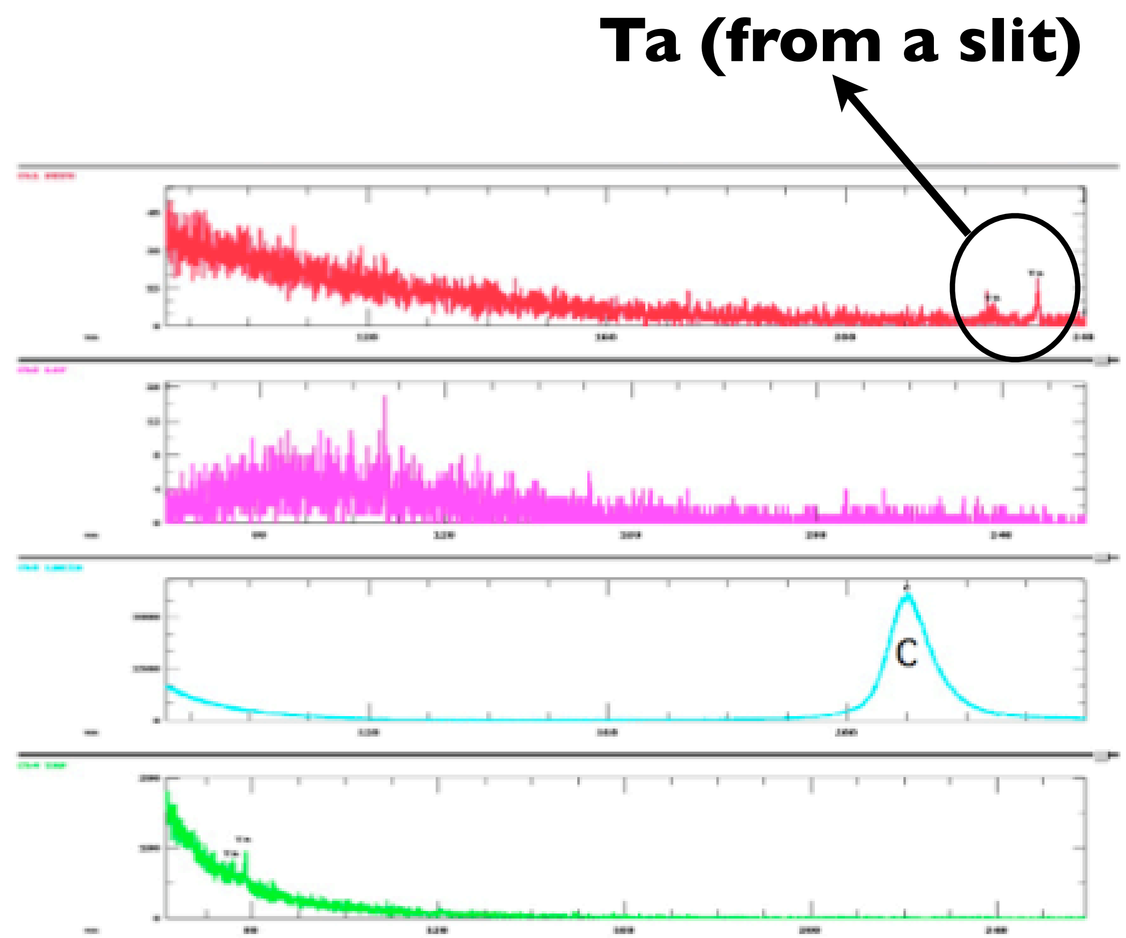
broken, within 25 minutes

Electron Probe Micro-Analysis

0.5 mg/cm^2 PCC foil



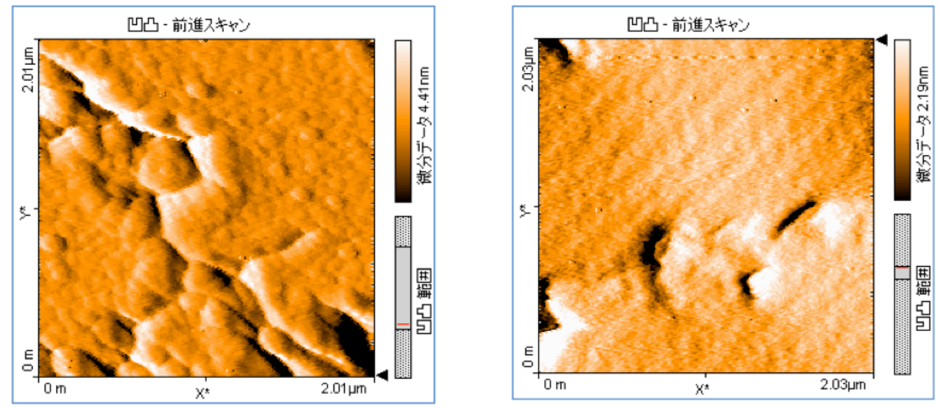
non-irradiated part



irradiated part

Atomic Force Microscope image

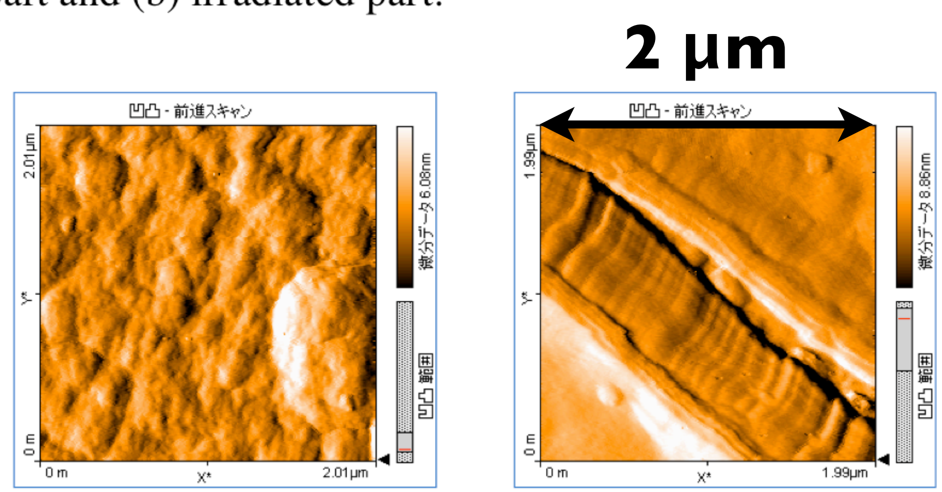
substrate side



(a) (b)

Fig. 2. AFM images of surface of the substrate side of the 300 µg/cm^2-thick multi-layer PCC-foil: (a) non-irradiated part and (b) irradiated part.

evaporating source side



(a) (b)

Fig. 3. AFM images of surface of the evaporating source side of the 300 µg/cm^2-thick multi-layer PCC-foil: (a) non-irradiated part and (b) irradiated part.

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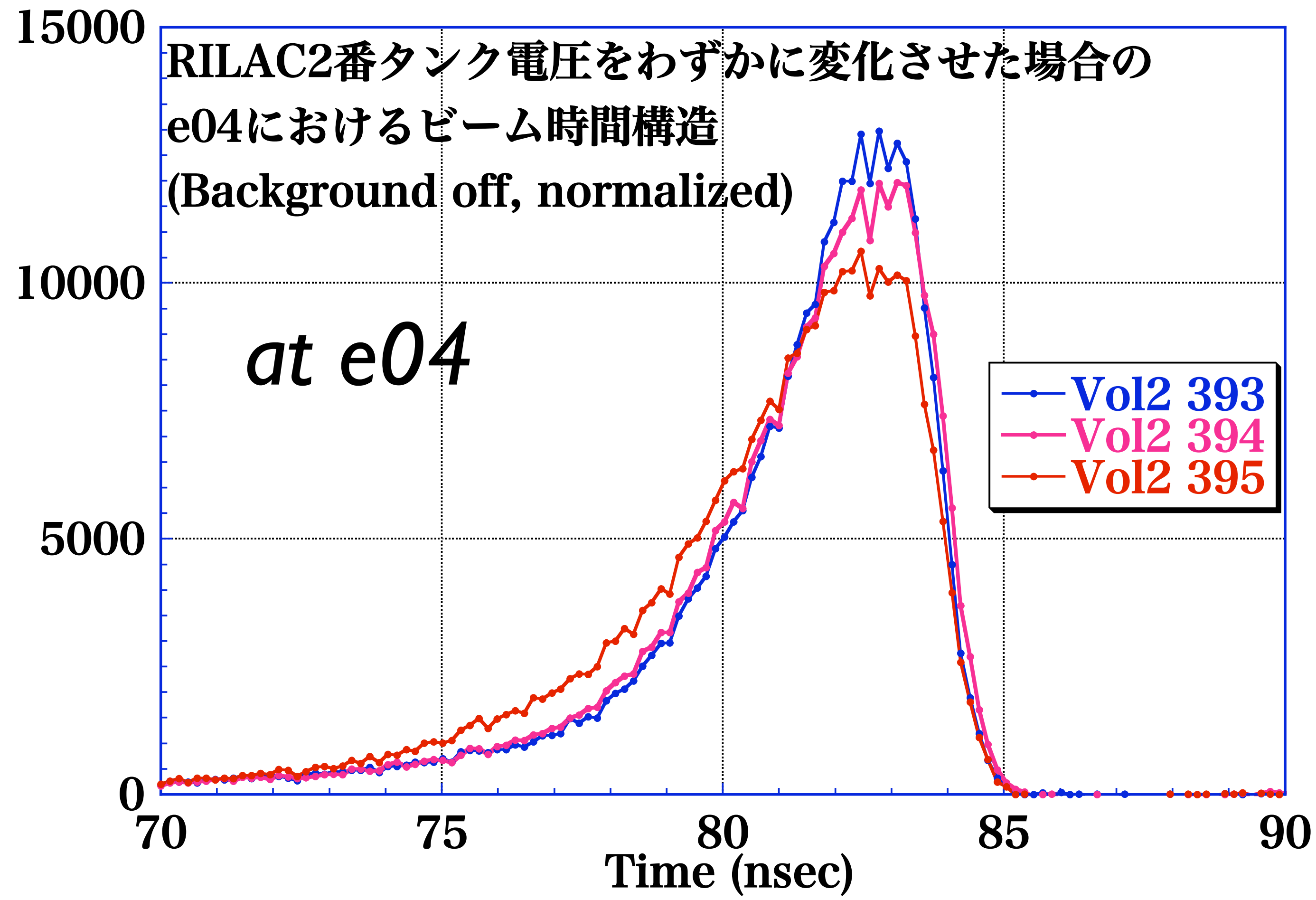
Voltage fluctuation of No.2 resonator of RILAC

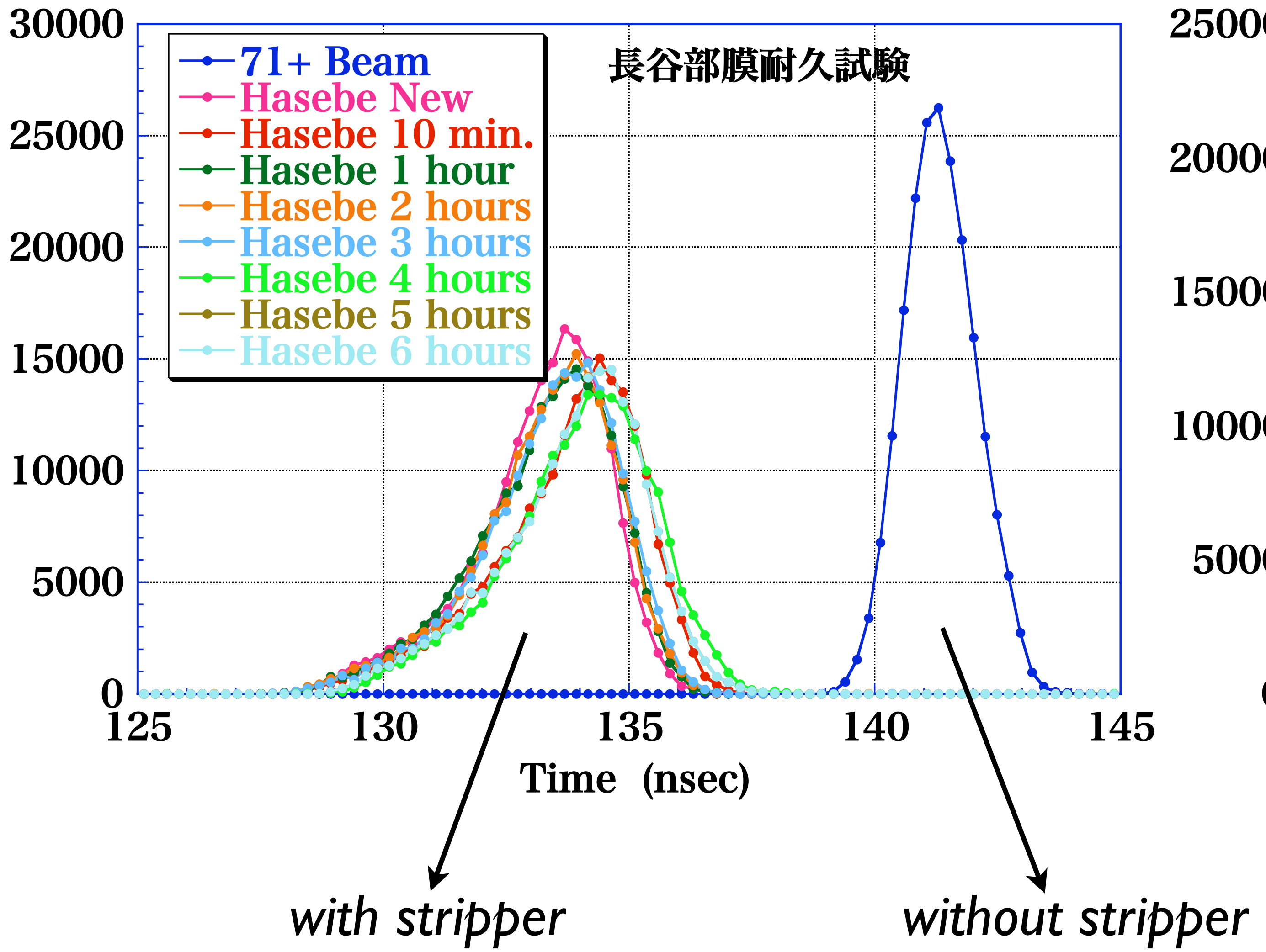
Time	V (mV,VVM)	I @ A01 (nA)
15:17:20	62.9	562
15:18:00	63.0	519
15:18:35	63.2	416
15:19:30	62.9	570

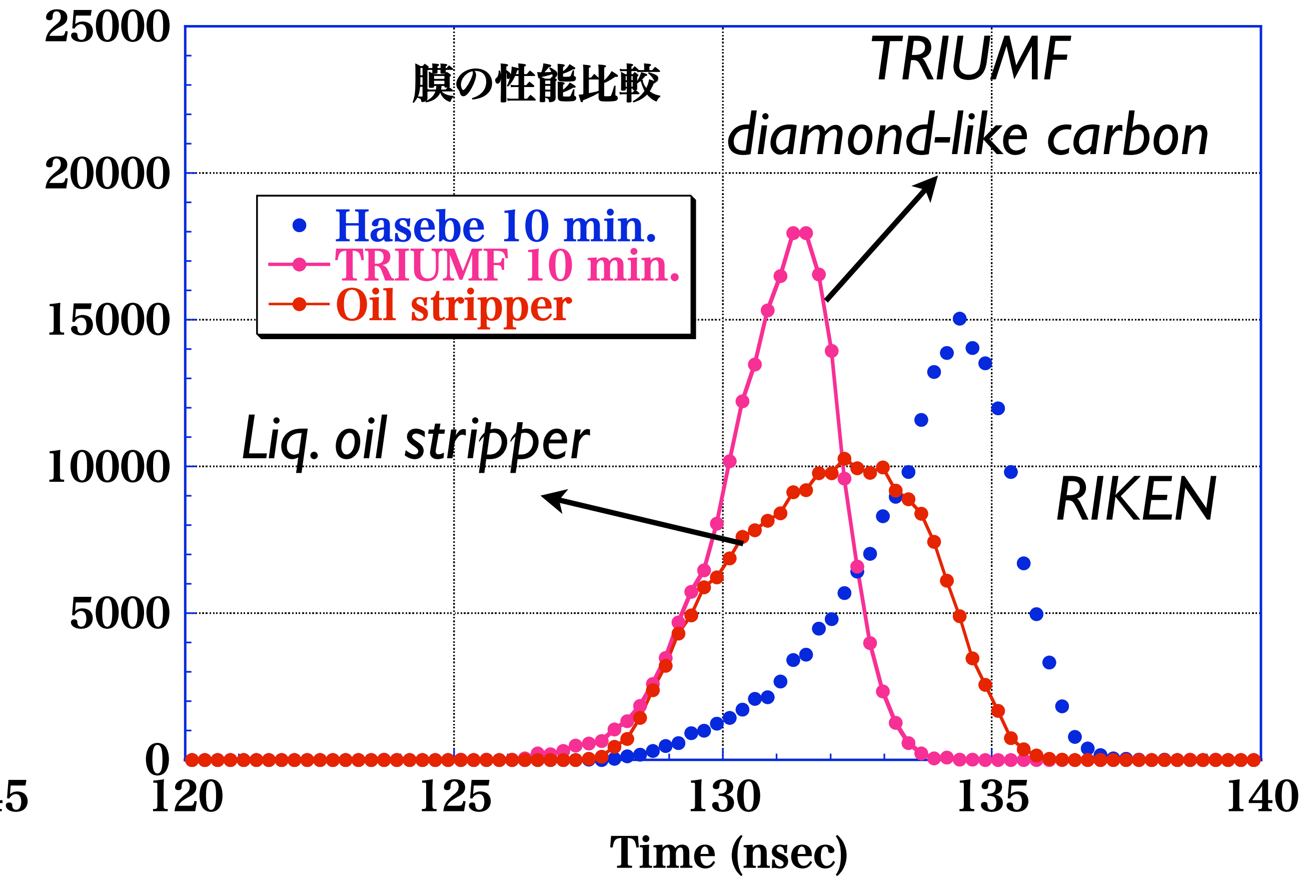
Longitudinal beam profile vs Voltage of No.2 resonator



Effects of A01 stripper

($^{238}U^{35+}$, 10.75 MeV/nucleon, 2007, Oct. 2nd)

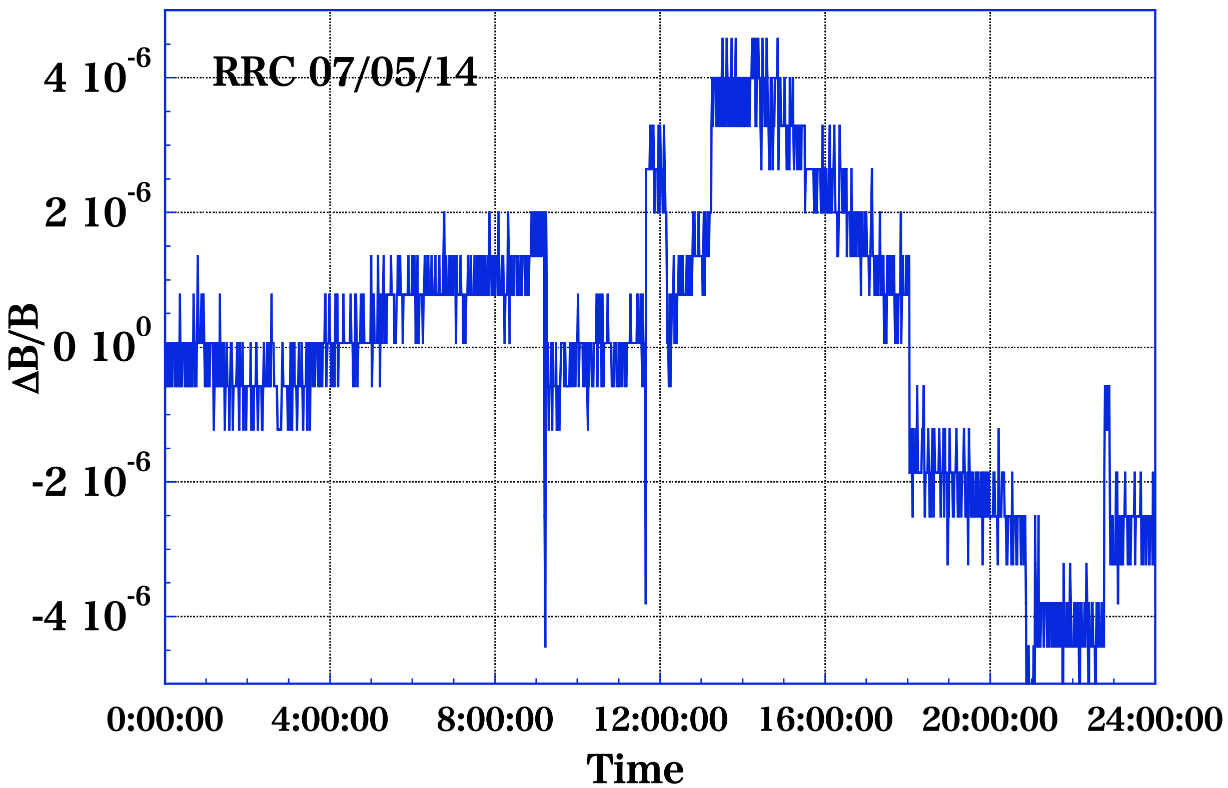




Stability of magnetic fields

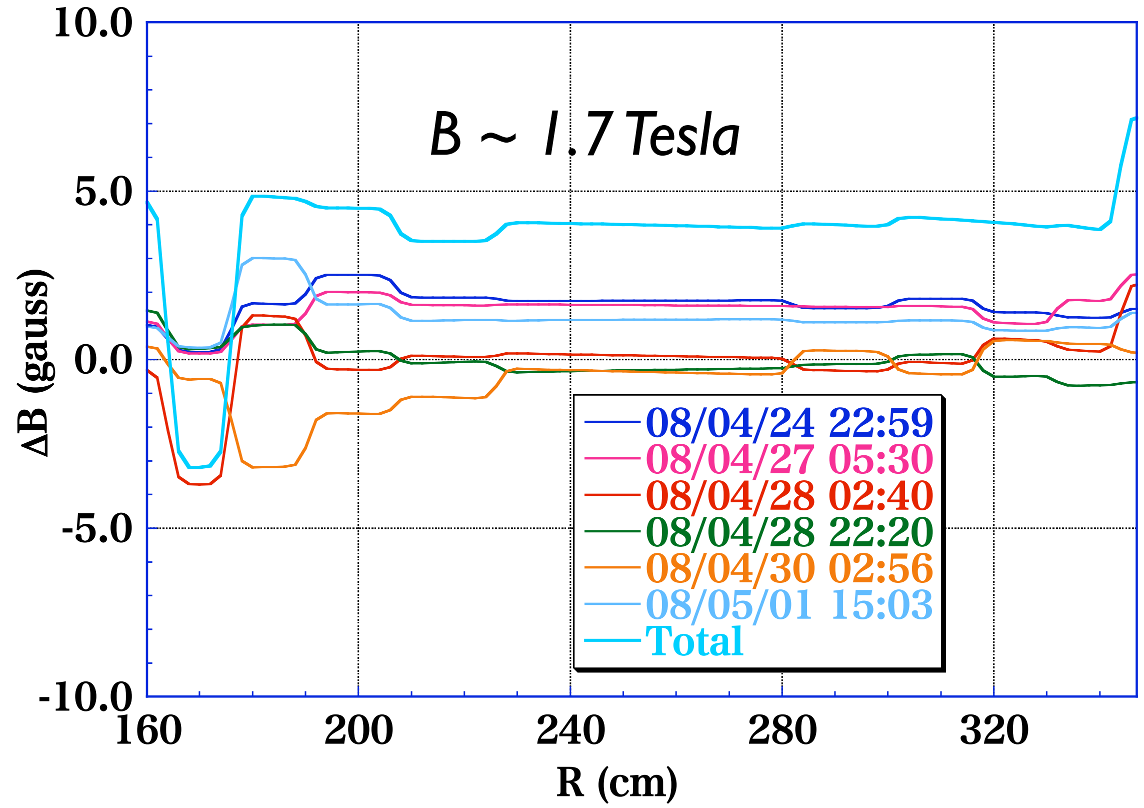
^{238}U acceleration

RRC



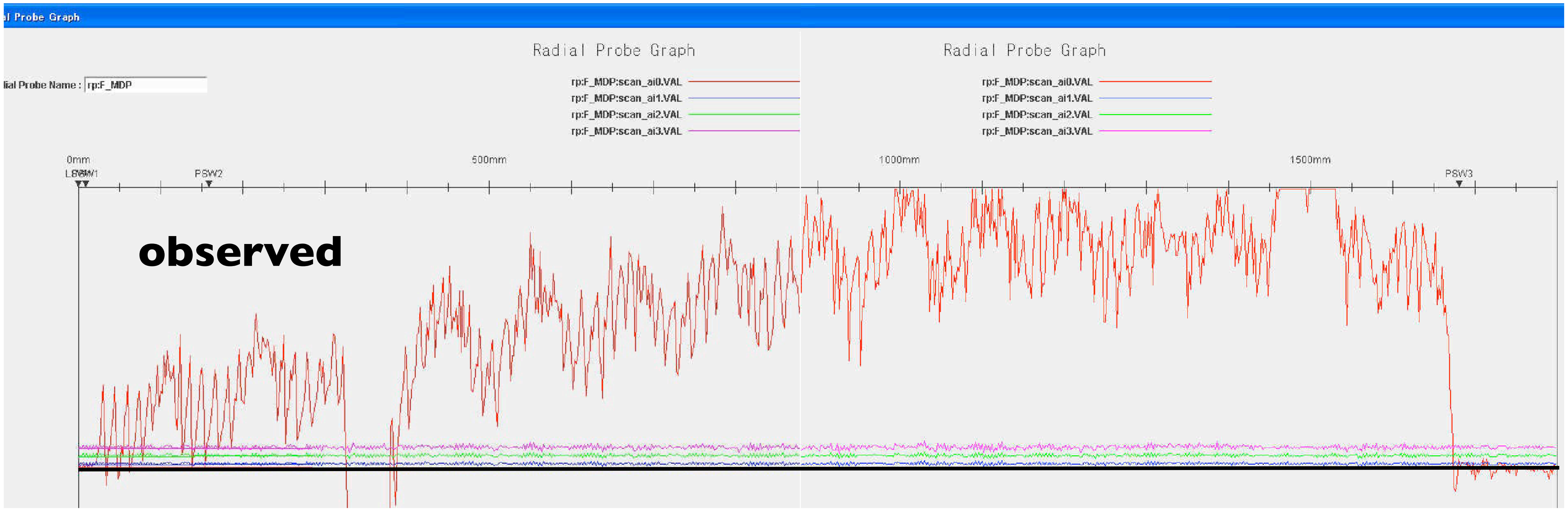
NMR measurement

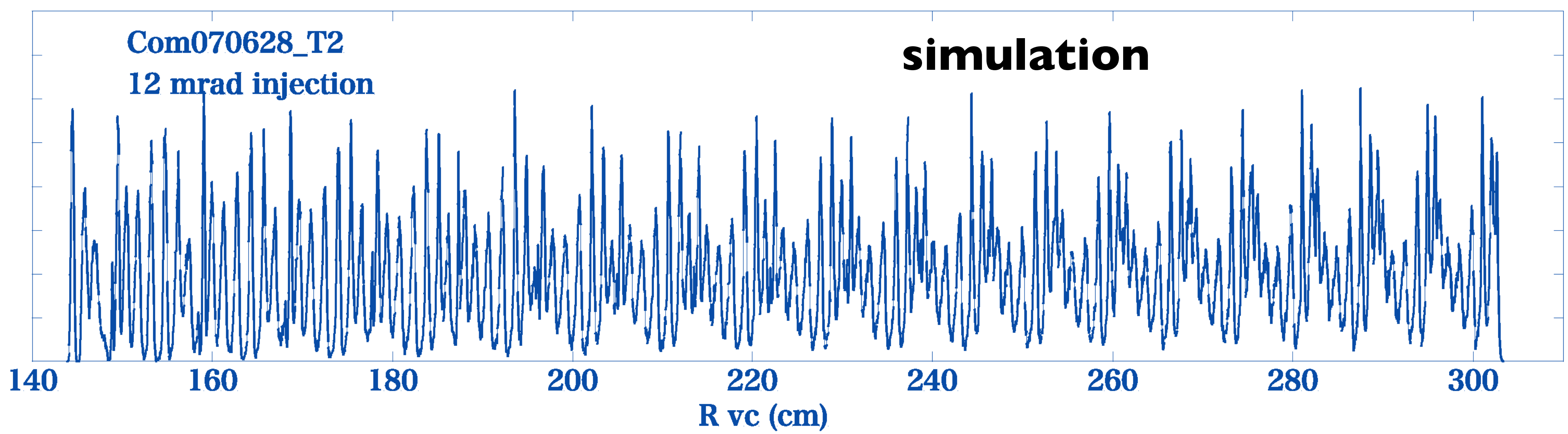
fRC



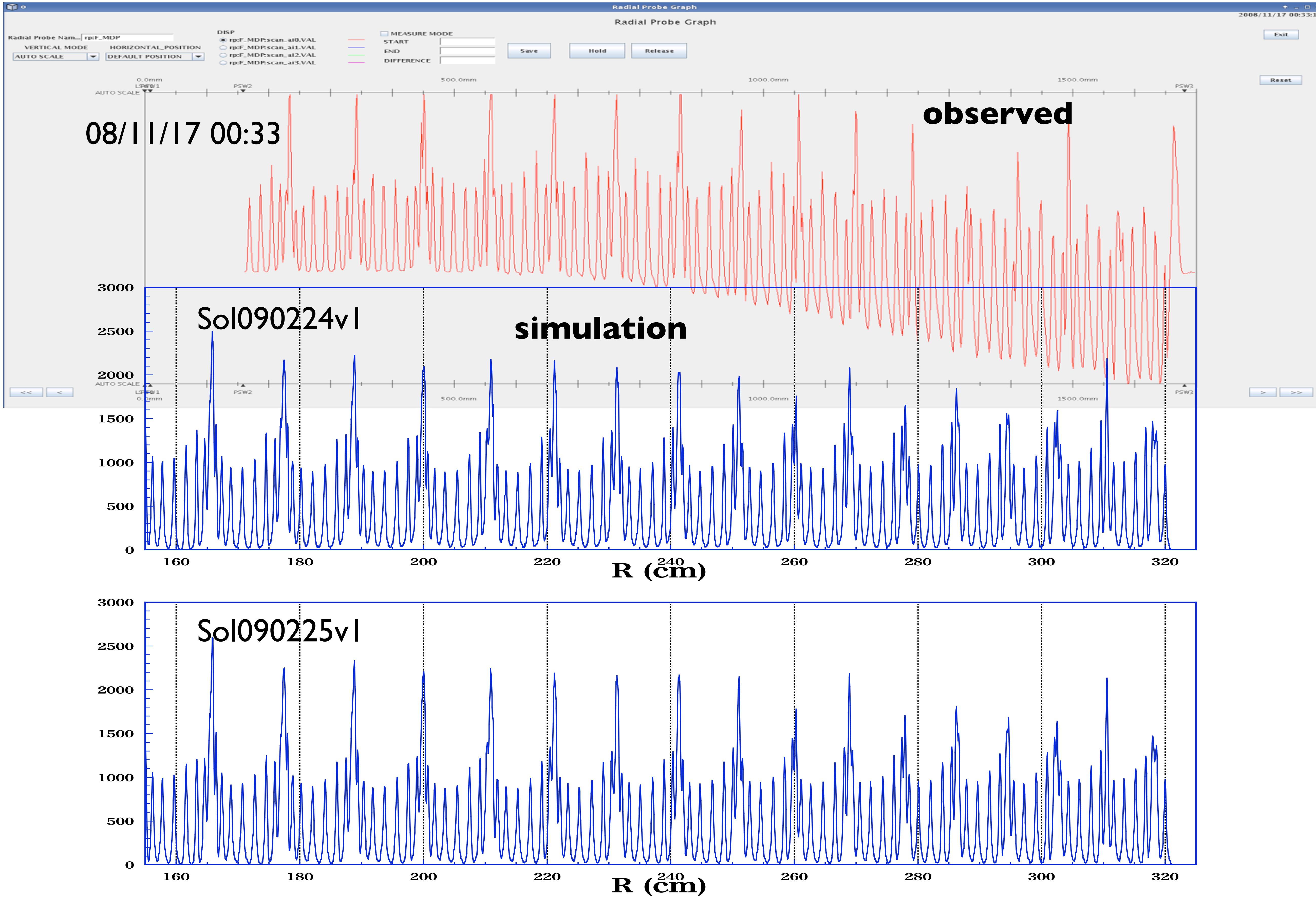
estimated by coil currents

Turn pattern obtained by old MDP



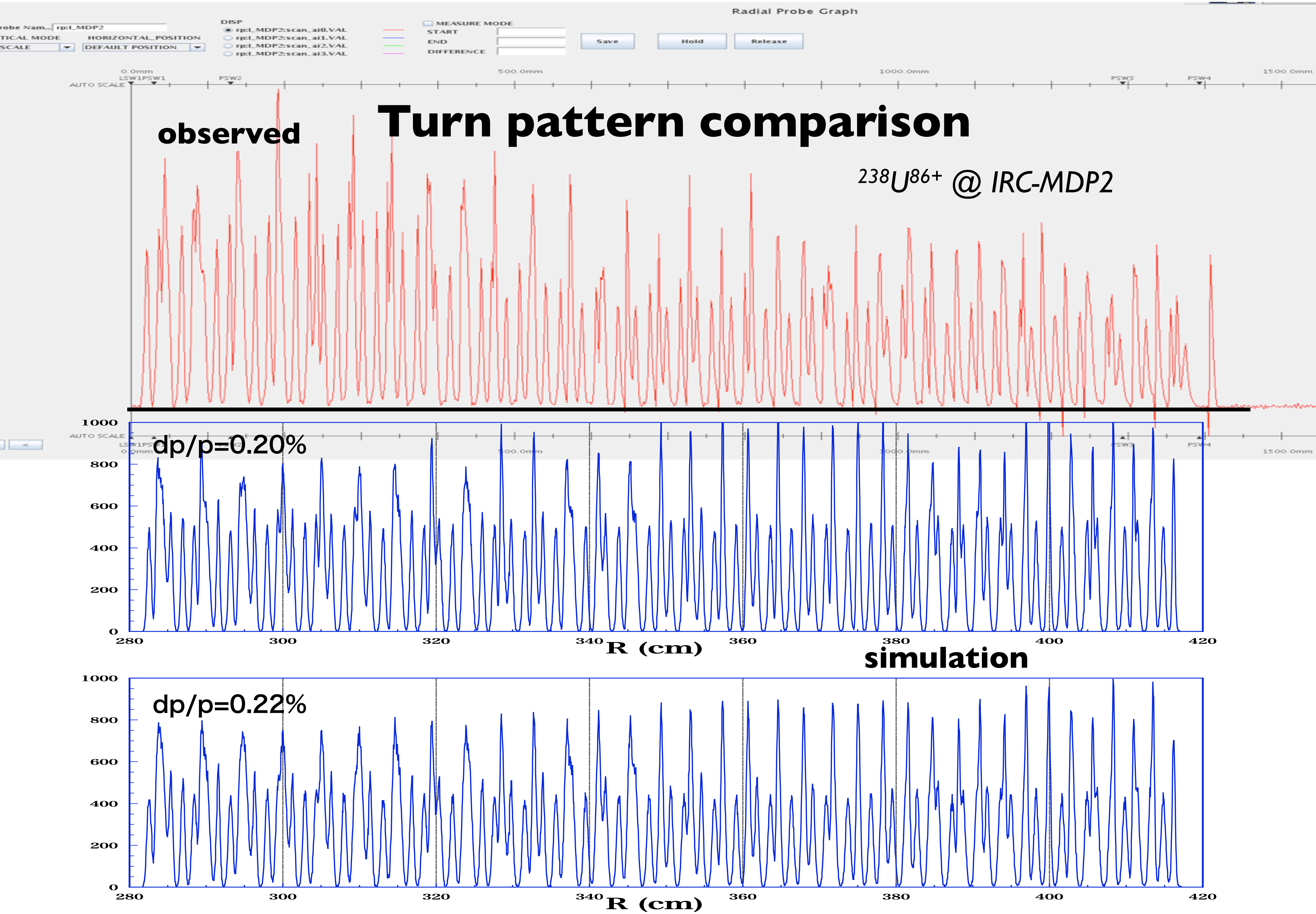


fRC Turn Pattern



Turn pattern comparison

$^{238}U^{86+}$ @ IRC-MDP2



Comparison of Beam Profile

^{48}Ca beam on IRC-injection line