# Acceleration of Intense Heavy Ion Beams
# in
# RIBF Cascaded Cyclotrons

*On behalf of Acceleration Group*
*RIKEN Nishina Center, N. Fukunishi*

# RIKEN RI Beam Factory

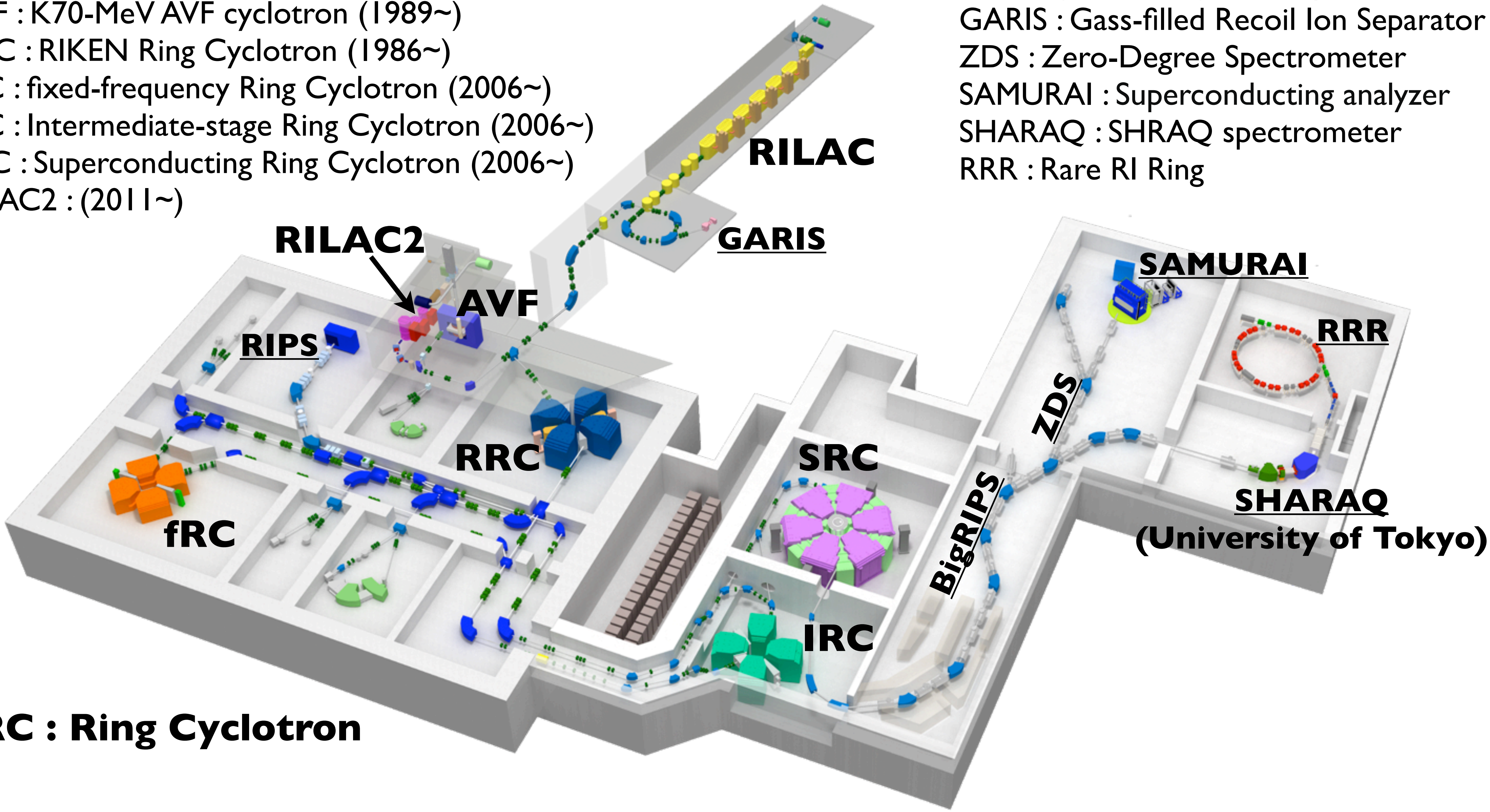
*The first of the second-generation in-flight facilities*

**Accelerators**

RILAC : RIKEN Heavy-ion linac (1981~)
AVF : K70-MeV AVF cyclotron (1989~)
RRC : RIKEN Ring Cyclotron (1986~)
fRC : fixed-frequency Ring Cyclotron (2006~)
IRC : Intermediate-stage Ring Cyclotron (2006~)
SRC : Superconducting Ring Cyclotron (2006~)
RILAC2 : (2011~)

**Research instruments**

RIPS, BigRIPS : Fragment separator
GARIS : Gass-filled Recoil Ion Separator
ZDS : Zero-Degree Spectrometer
SAMURAI : Superconducting analyzer
SHARAQ : SHRAQ spectrometer
RRR : Rare RI Ring



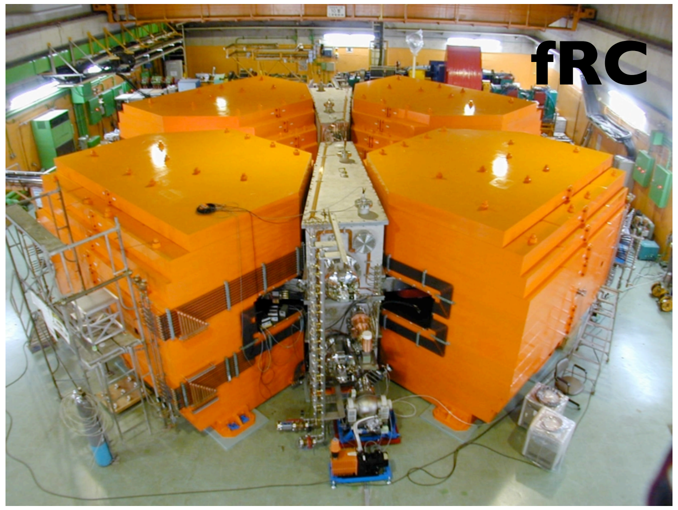
**RC : Ring Cyclotron**

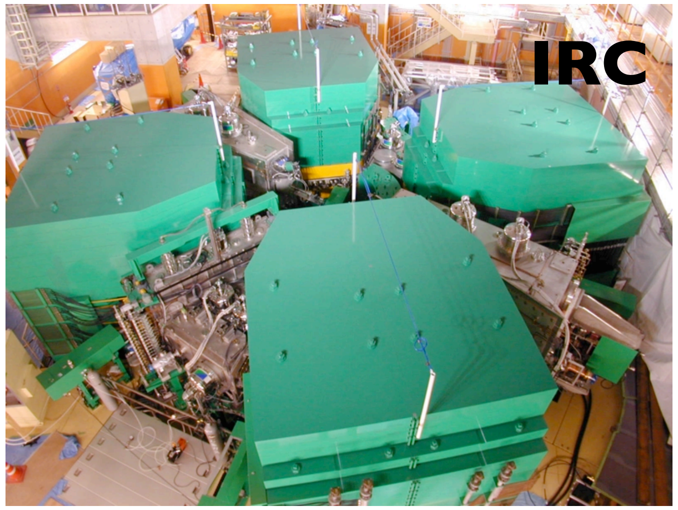
# Specifications of RIBF ring cyclotrons

| | fRC | IRC | SRC | RRC |
|---|---|---|---|---|
| K-number (MeV) | 700 | 980 | 2600 | 540 |
| $R_{inj}$ (cm) | 156 | 277 | 356 | 89 |
| $R_{ext}$ (cm) | 330 | 415 | 536 | 356 |
| Weight (tons) | 1300 | 2900 | 8300 | 2400 |
| Sector magnets | 4 | 4 | 6 | 4 |
| Number of trim coils (/ main coil) | 10 | 20 | 4 (SC)<br>22 (NC) | 26 |
| Trim coil currents (A) | 200 | 600 | 3000 (SC)<br>1200 (NC) | 600 |
| RF resonators | 2+FT | 2+FT | 4+FT | 2 |
| Frequency range (MHz) | 54.75 | 18〜38 | 18〜38 | 18〜38 |
| Acceleration voltage (MV)* | 0.8 | 1.1 | 2.0 | 0.28 |
| Turn separation (cm)* | 1.3 | 1.3 | 1.8 | 0.7 |

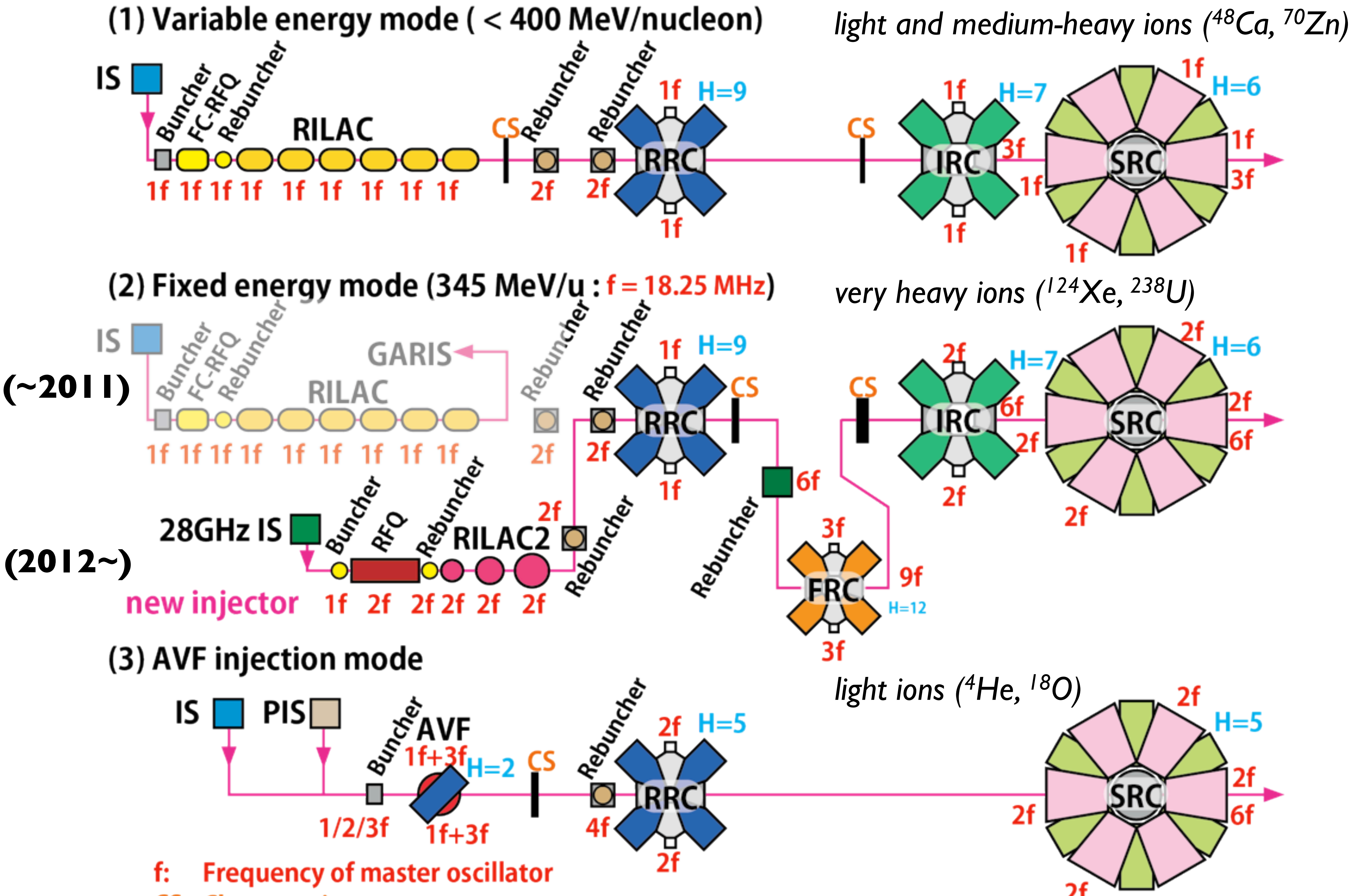
*uranium acceleration

SC : superconducting
NC : normal conducting
FT : flattop resonator





# Acceleration Modes



f: Frequency of master oscillator

CS: Charge strippers

**PIS : polarized ion source**

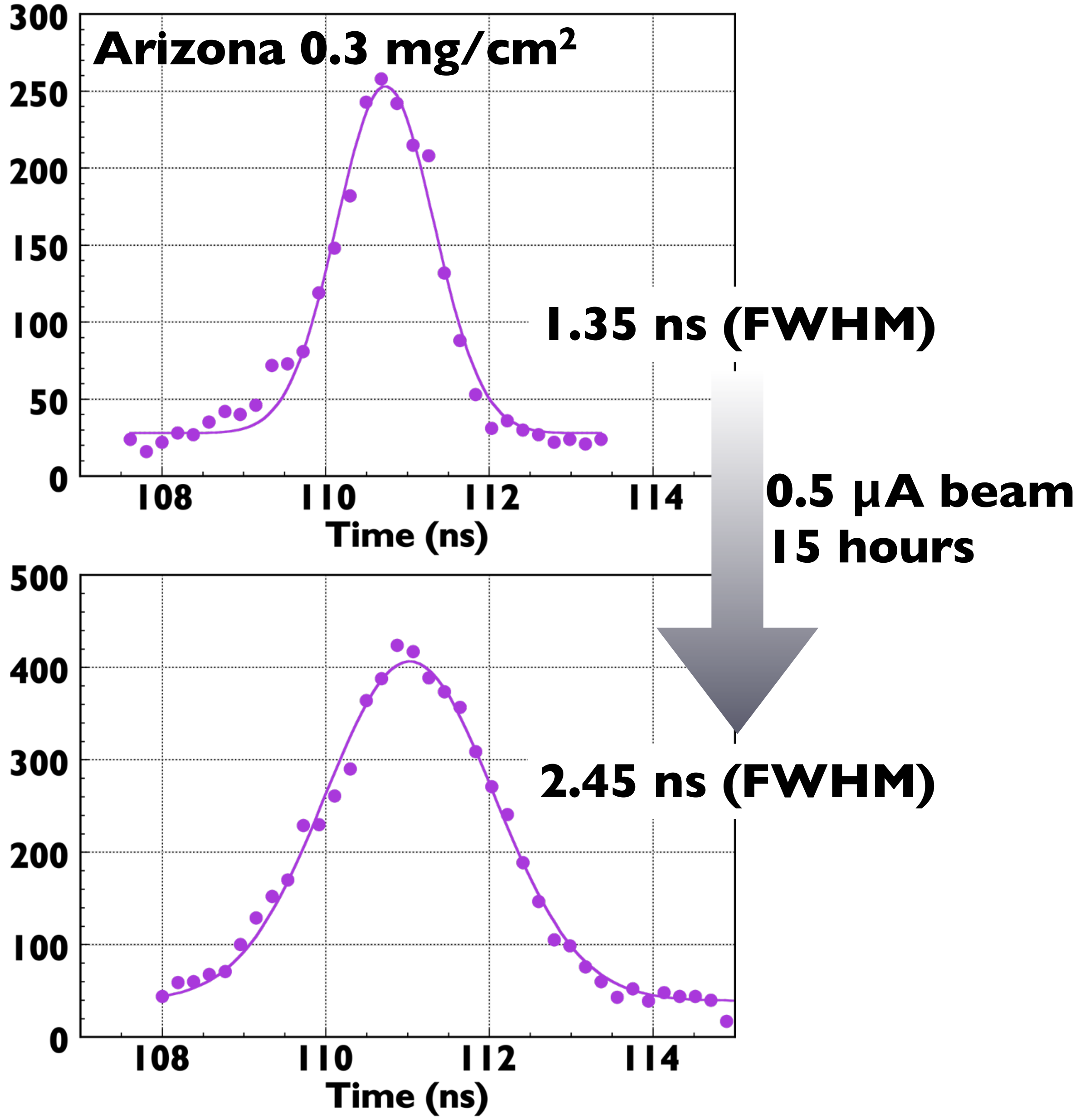
# Major Problems of RIBF until 2012

## Low beam intensity of $^{238}U$

| ion (date) | (pnA) |
|---|---|
| $^{238}U^{86+}$ (07/07/03) | 0.05 |
| $^{86}Kr^{34+}$ (07/11/04) | 33 |
| $^{238}U^{86+}$ (08/11/16) | 0.4 |
| $^{48}Ca^{20+}$ (08/12/21) | 175 |
| $^{4}He^{2+}$ (09/10/31) | 1000 |
| $^{238}U^{86+}$ (09/12/19) | 0.8 |
| $^{48}Ca^{20+}$ (10/5/31) | 230 |
| $^{18}O^{8+}$ (10/6/17) | 1000 |

*Extracts from Linac10 presentation (N. Fukunishi)*

## Too short serviceable time of charge strippers (Carbon foils)



**1.35 ns (FWHM)**

**0.5 μA beam**
**15 hours**

**2.45 ns (FWHM)**

*Longitudinal beam width measured 38 m downstream of the stripper*

# To Overcome Problems

(1)To increase the beam intensity of uranium ions, we constructed
- a 28-GHz SC-ECRIS
- a new injector RILAC2

(2)For higher-intensity uranium beams obtained by the new injector, we developed
- a helium gas stripper (first-stage stripper)
- a rotating beryllium disk stripper (second-stage stripper for uranium)
- an air stripper (second-stage stripper for xenon)
- a new beam dump to withstand a 10-kW beam loss (first-stage stripping section)

(3)Because the helium gas stripper requires acceleration of $^{238}U^{65+}$ in fRC,
- fRC was upgraded in bending power
- K-number (570 MeV → 700 MeV)

# 28-GHz Superconducting ECR Ion Source

*Y. Higurashi will report in this conference!*

**High magnetic field**

$B_{inj}$ ~ 4 T, $B_{ext}$ ~ 2 T

$B_r$ ~ 2 T, $B_{min}$ < 1 T

- *Flexible magnetic field configuration are available by using 6 solenoid coils.*
- *ECR zone, as large as possible*

**Plasma chamber**

Diameter : 15 cm

Length : 50 cm

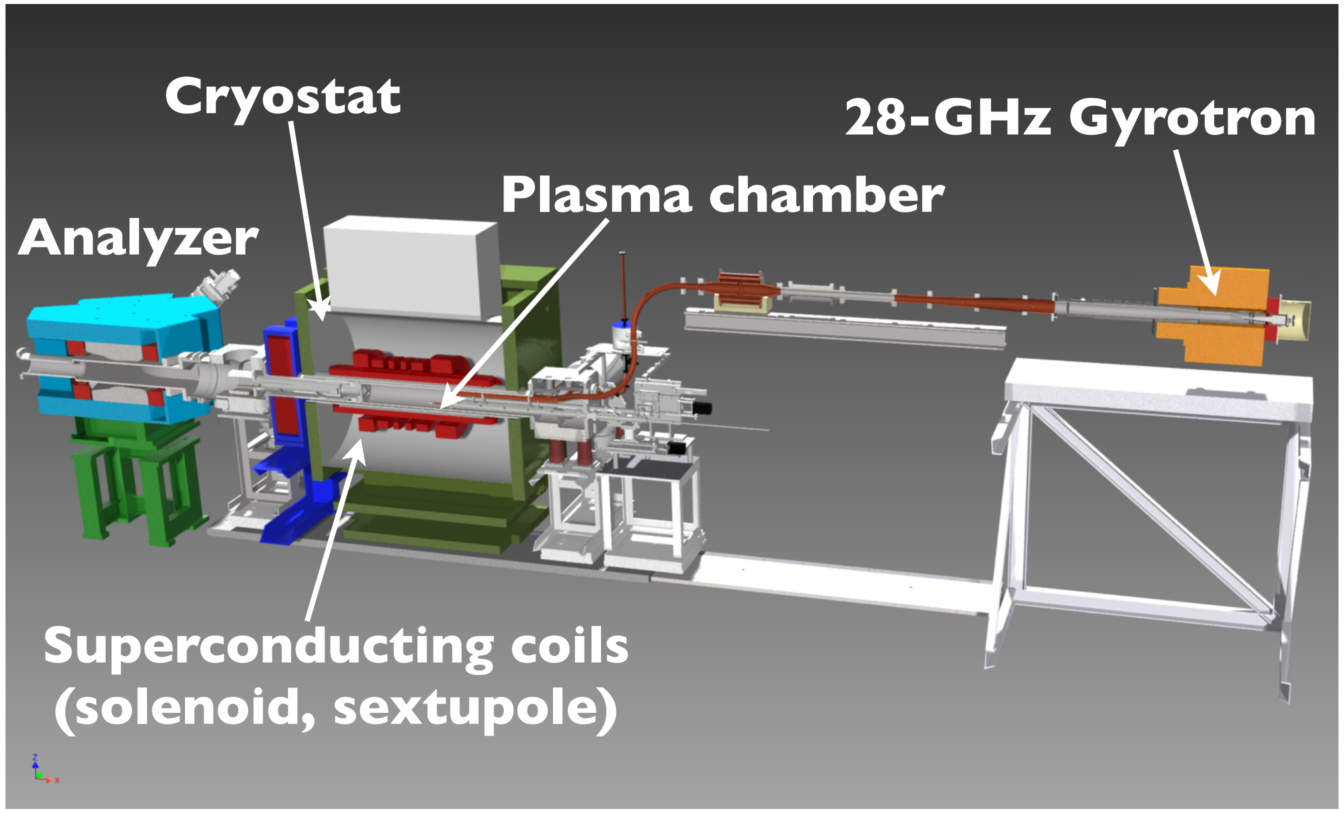
Plasma volume : ~ 1100 $cm^3$

- *large plasma volume for long confinement time*

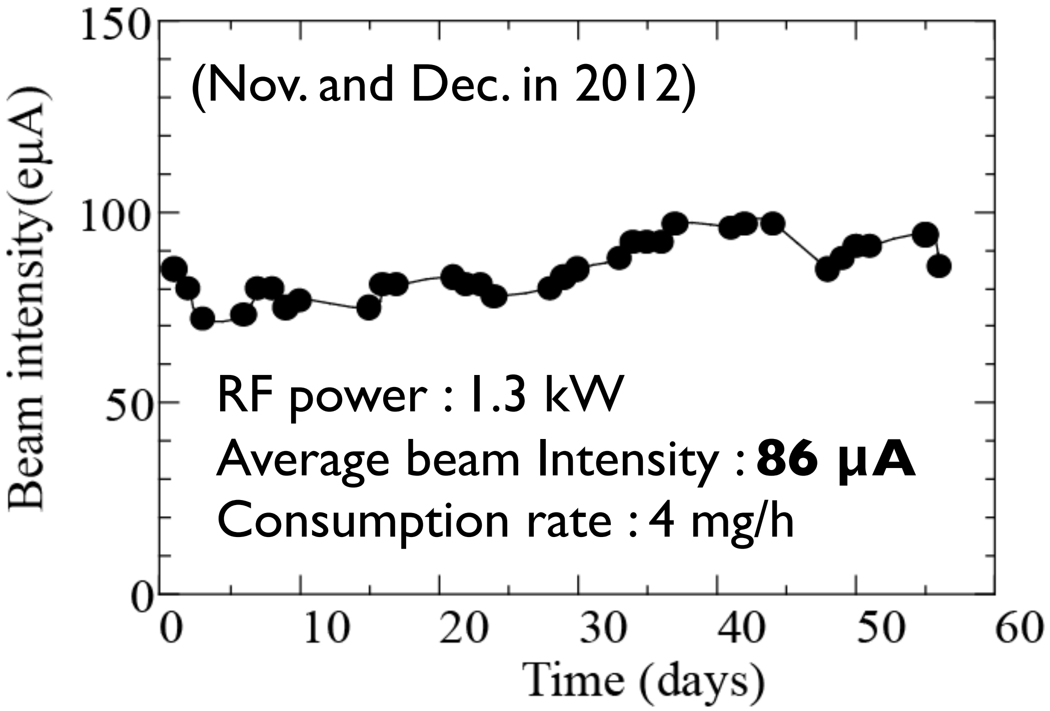
**Microwave**

frequency : 28 GHz

Power : 10 kW



**Performance in routine operation**



RF power : 1.3 kW

Average beam Intensity : **86 μA**

Consumption rate : 4 mg/h

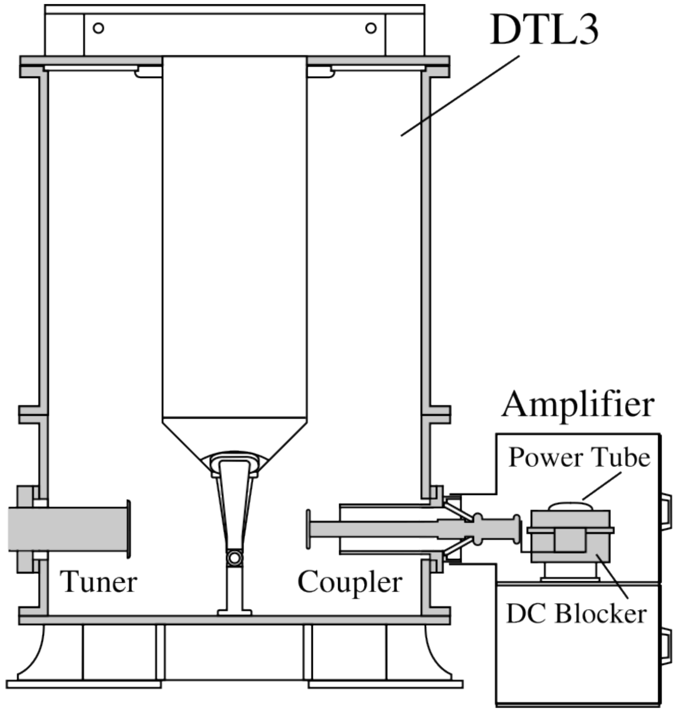
*T. Nakagawa, RIPS workshop, May 19-21, Daejeon, Korea*

# New Injector RILAC2

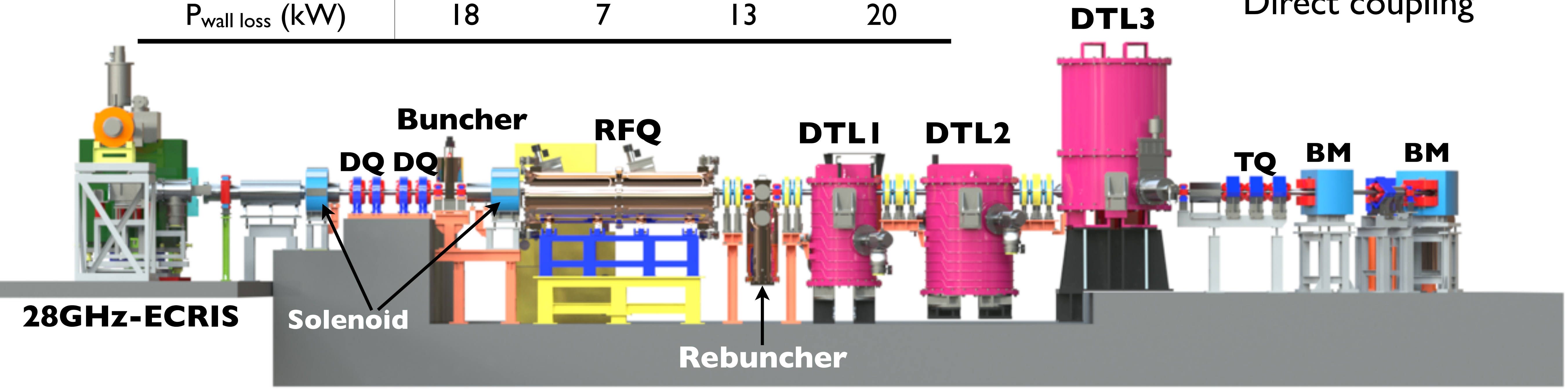
## Design parameters

| | RFQ | DTL1 | DTL2 | DTL3 |
|---|---|---|---|---|
| Frequency (MHz) | 36.5 | ← | ← | ← |
| Duty (%) | 100 | ← | ← | ← |
| m/q | 6.8 | ← | ← | ← |
| $E_{inj}$ (keV/nucleon) | 3.28 | 100 | 220 | 450 |
| $E_{ext}$ (keV/nucleon) | 100 | 220 | 450 | 670 |
| Aperture (mm) | 8 | 17.5 | ← | ← |
| Gap number | - | 10 | 10 | 8 |
| Voltage (kV) | 42 | 110 | 210 | 260 |
| $\varphi_{sync}$ (deg.) | -29.6 | -25 | -25 | -25 |
| $P_{wall\ loss}$ (kW) | 18 | 7 | 13 | 20 |

## Compact design



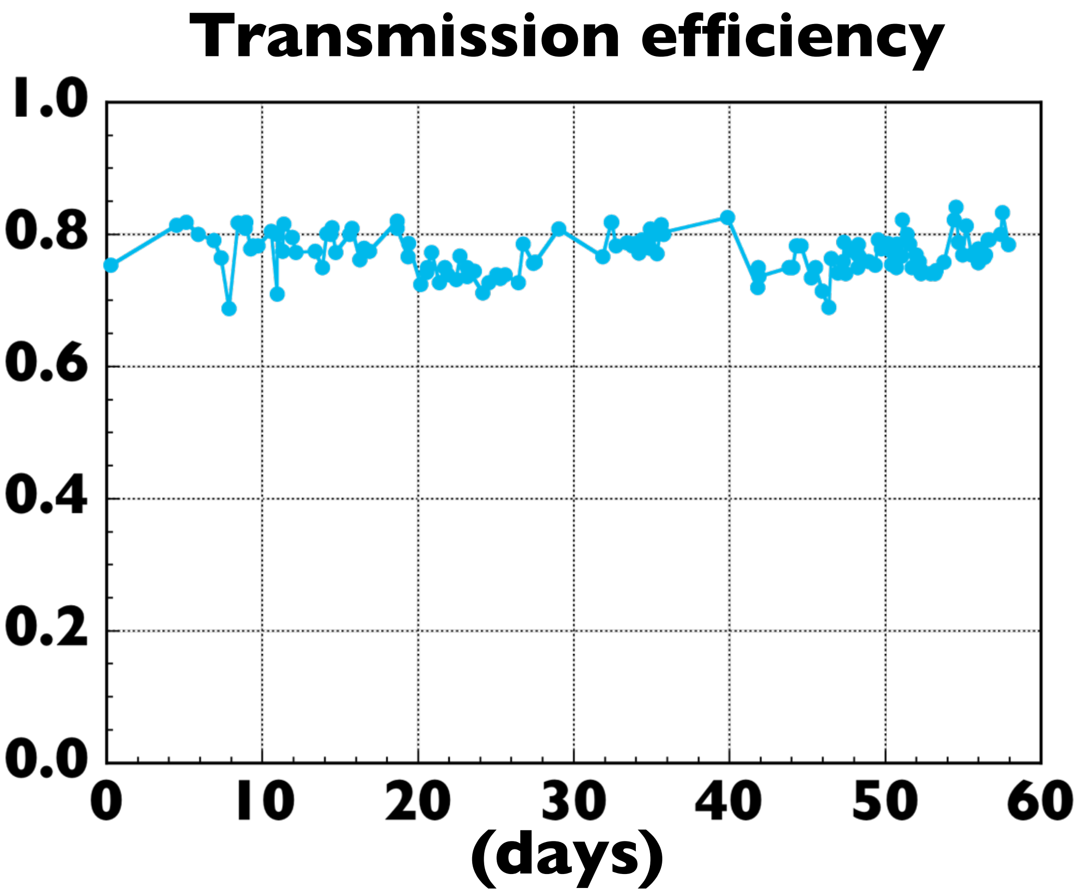
QWR structure
Direct coupling



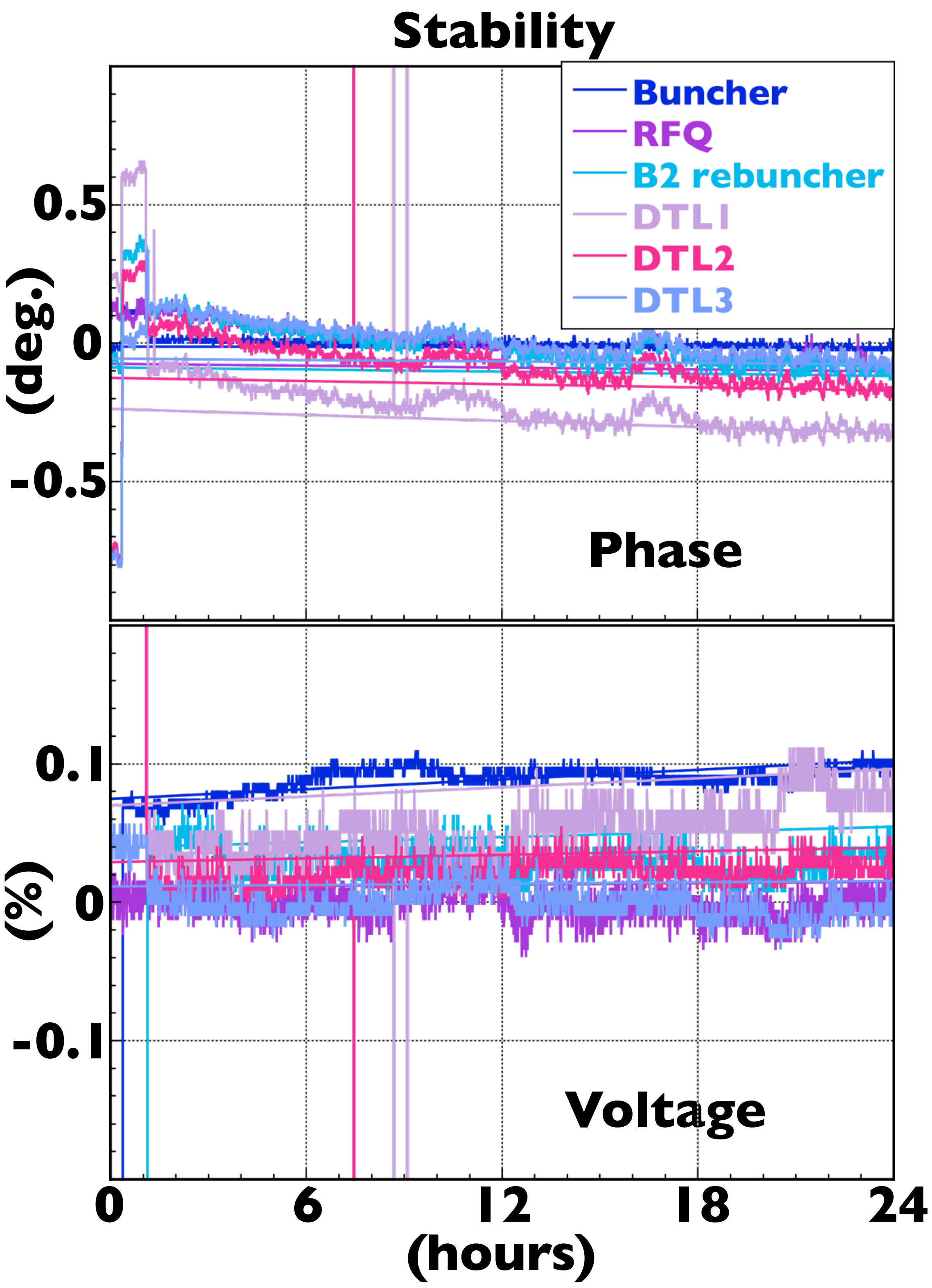
*K. Suda et al., Nucl. Instrum. Methods* ***A722*** *(2013) 55 / K.Yamada et al., IPAC12, New Orleans, Louisiana, USA (2012) TUOBA02.*

# Performance of New Injector RILAC2

- Design studies and construction
  2008 ~ 2010
- Beam commissioning
  2010 ~ 2011


Transmission efficiency

*(2011/10/09 0:00 ~)*


Stability

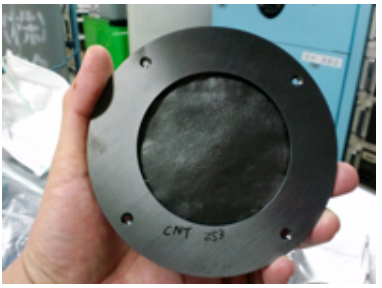
*(2011/12/04 9:00 ~ 2011/12/05 9:00)*

# Developments of Charge-state Strippers

CNT-based foil* (rotating)
3 ~ 4 days / ~10 eμA

*H. Hasebe et al., INTDS 2012
#H. Hasebe et al., RIKEN Accel. Prog. Rep. **46** (2013)

Carbon foil



***Helium Gas Stripper***

*H. Imao will report in this conference!*

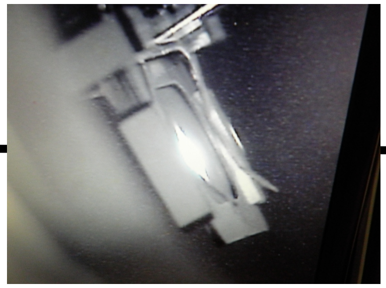
**1st stage**

**2011**

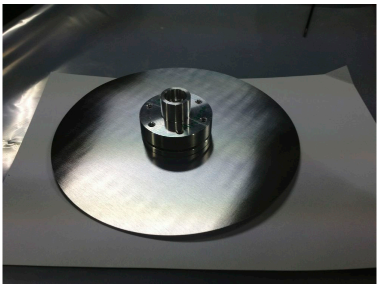
**2012**

**2013**

**2nd stage**

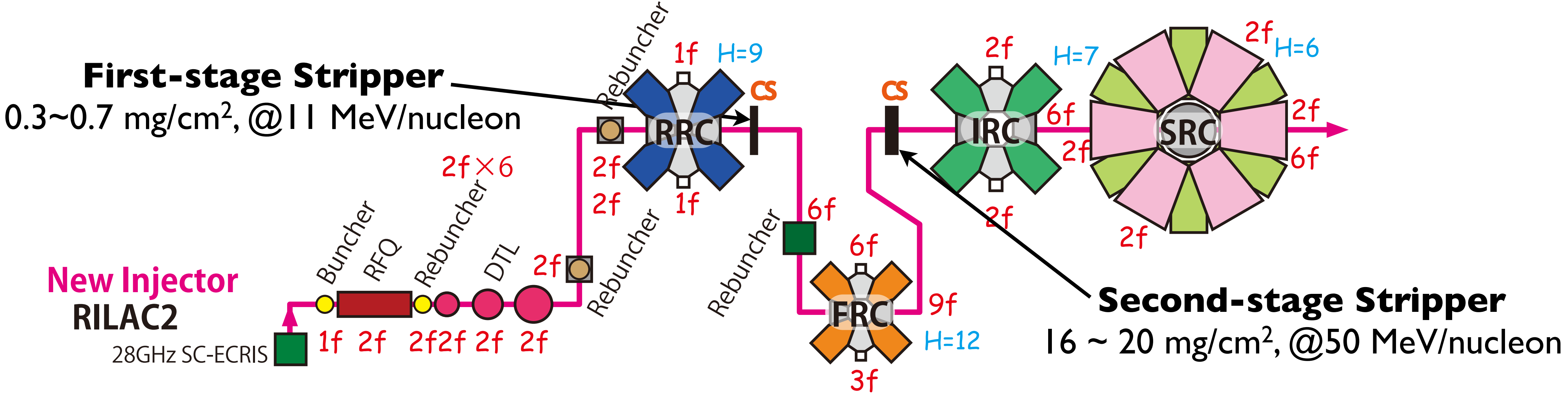


Arizona
9 hours / 2.5 eμA



Rotating beryllium disk#
> 35 days / 5 eμA
(for uranium)

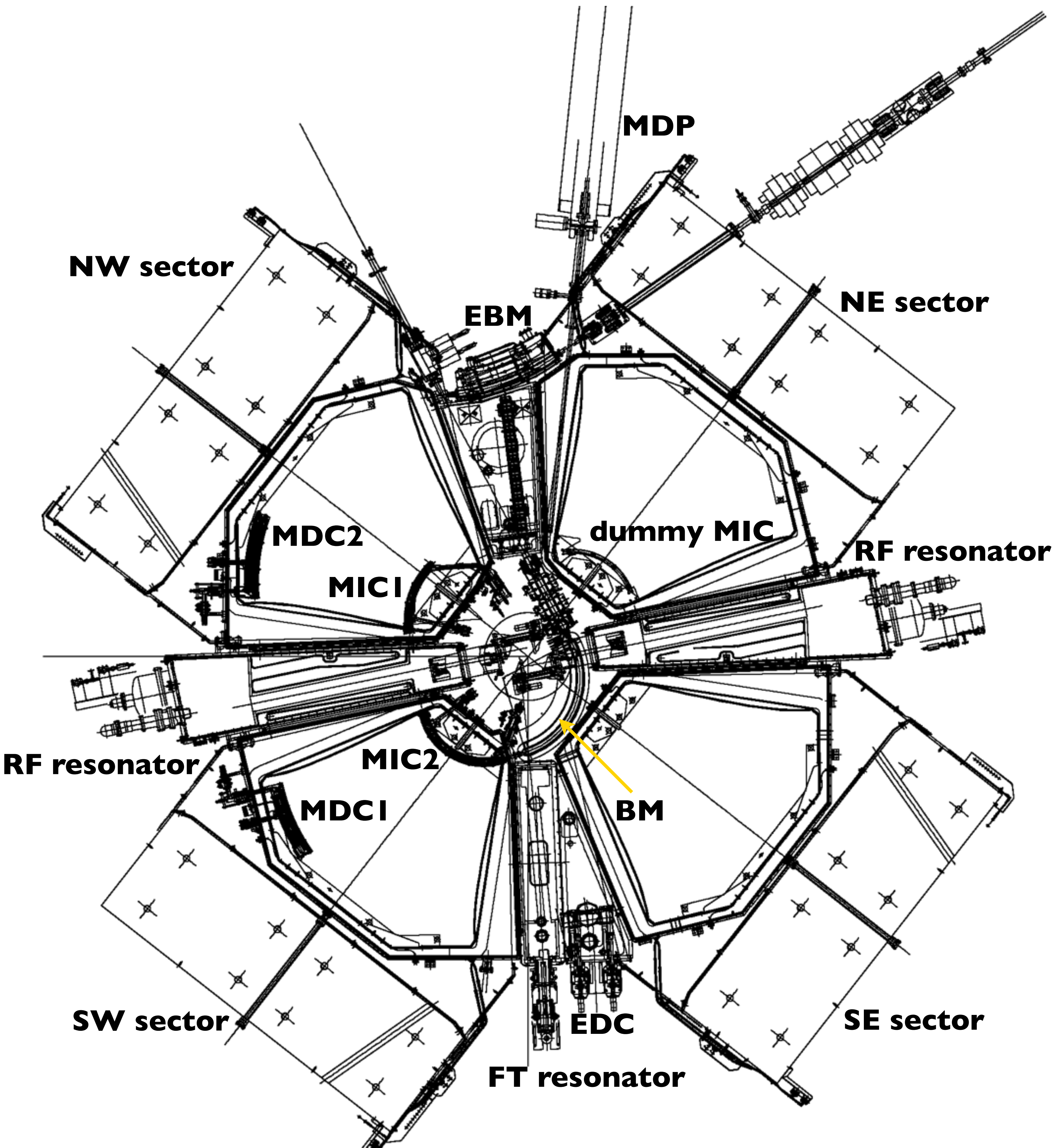
***Air Stripper***
(for xenon)



**First-stage Stripper**
0.3~0.7 mg/cm², @11 MeV/nucleon

**Second-stage Stripper**
16 ~ 20 mg/cm², @50 MeV/nucleon

# Bending Power Upgrade of fRC



**$^{238}U^{71+}$ (carbon foil )**
**➡$^{238}U^{65+}$ (helium gas)**

- *Power supplies of Sector Magnets*
  *1.69 T (588 A) → 1.85 T (830 A*)*
- *Injection Bending Magnet (BM)*
  *1.7 T → 1.9 T*
- *Magnetic Inflection Channel 2 & PS*
  *0.5 T → 0.6 T*
- *Extraction Bending Magnet (EBM)*
  *1.4 T → 1.55 T*

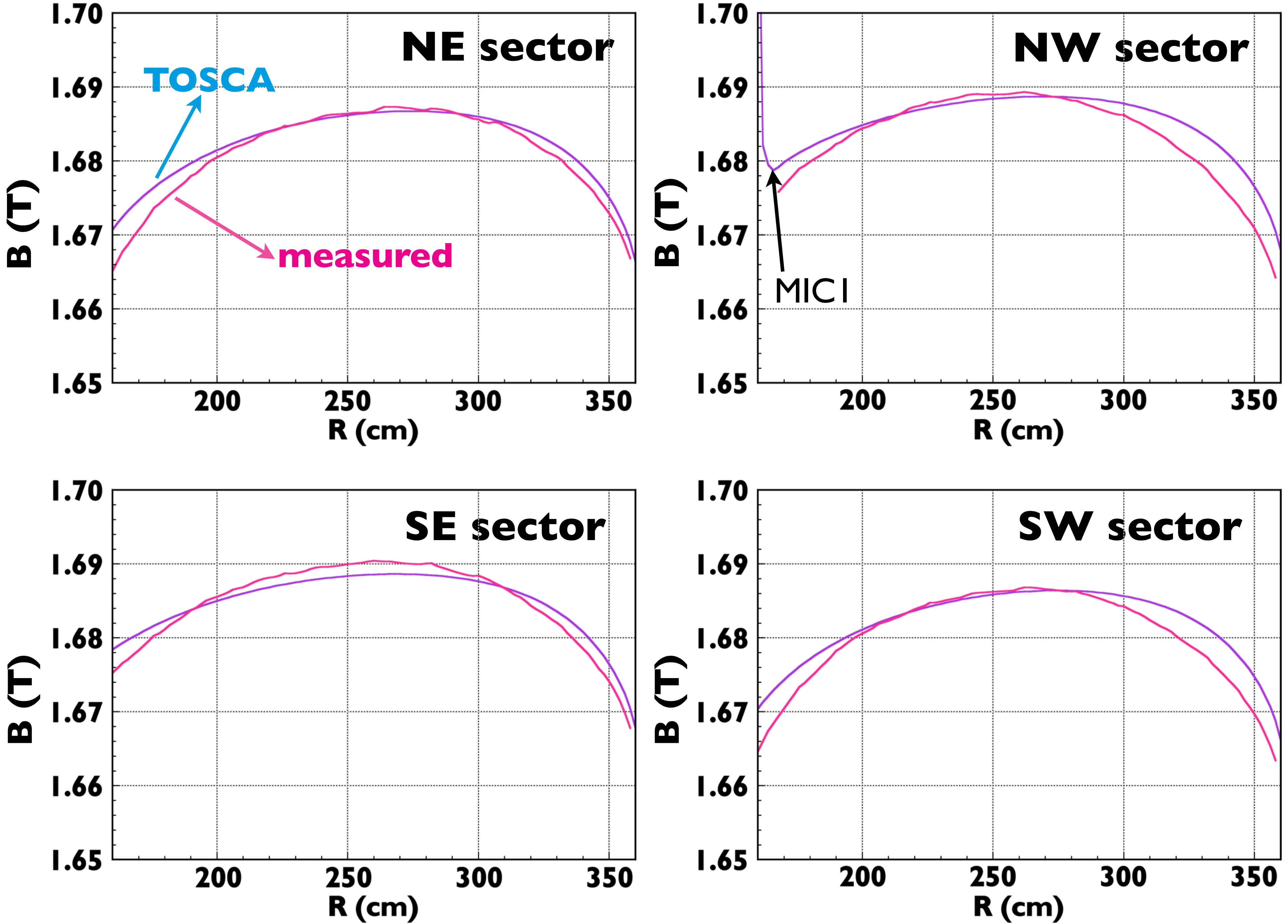
- *Steering Magnets*

**estimated by TOSCA using the default BH curve.*

*BM : Bending Magnet (injection)*
*MIC : Magnetic Inflection Channel*
*MDC : Magnetic Deflection Channel*
*EIC : Electric Inflection Channel*
*EDC : Electric Deflection Channel*
*EBM : Extraction Bending Magnet*
*MDP : Main Differential Probe*

# Prediction Capability of Magnetic-Field Calculation

$I_{\text{main coil}} = 588$ A ($^{238}\text{U}^{71+}$)

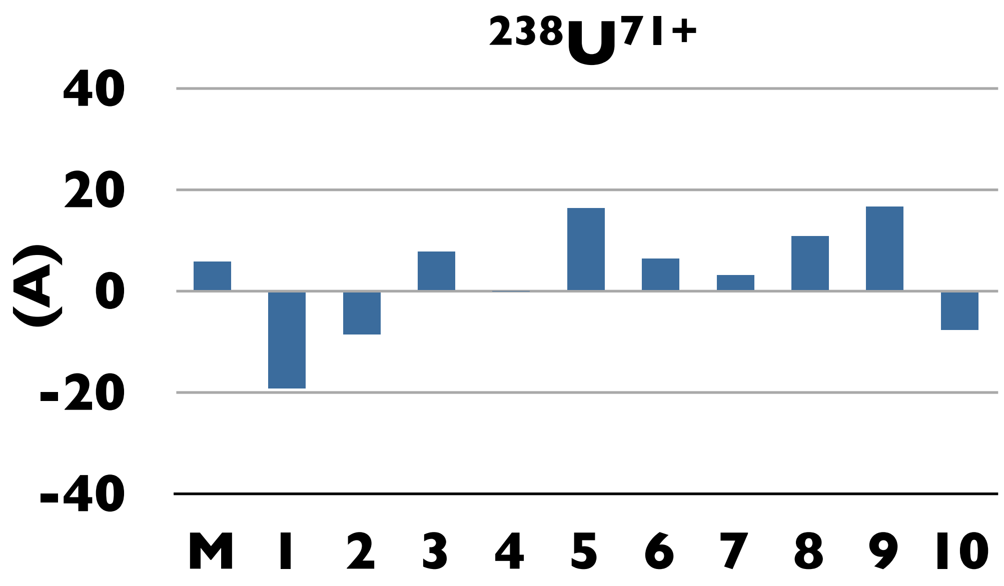


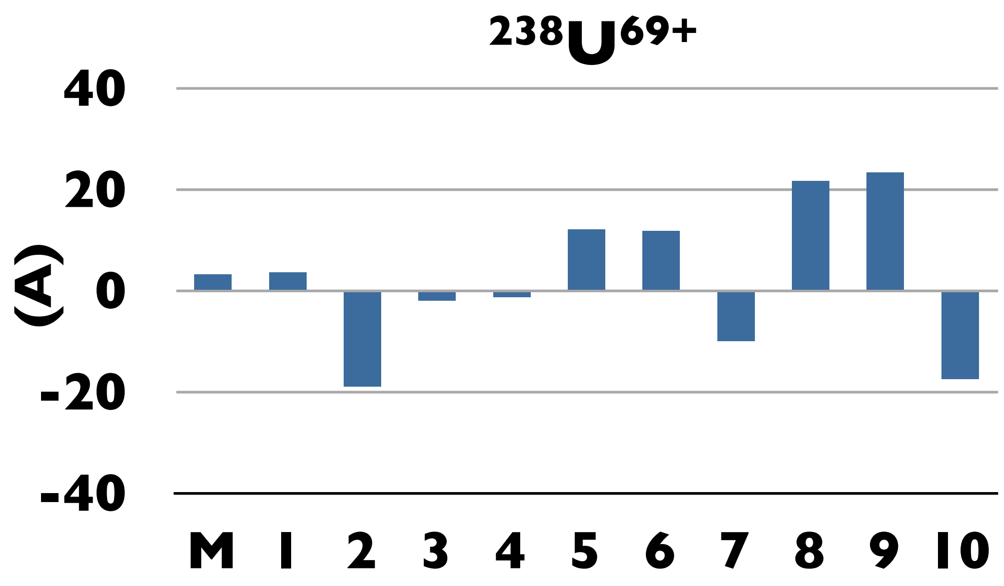
In TOSCA simulation,

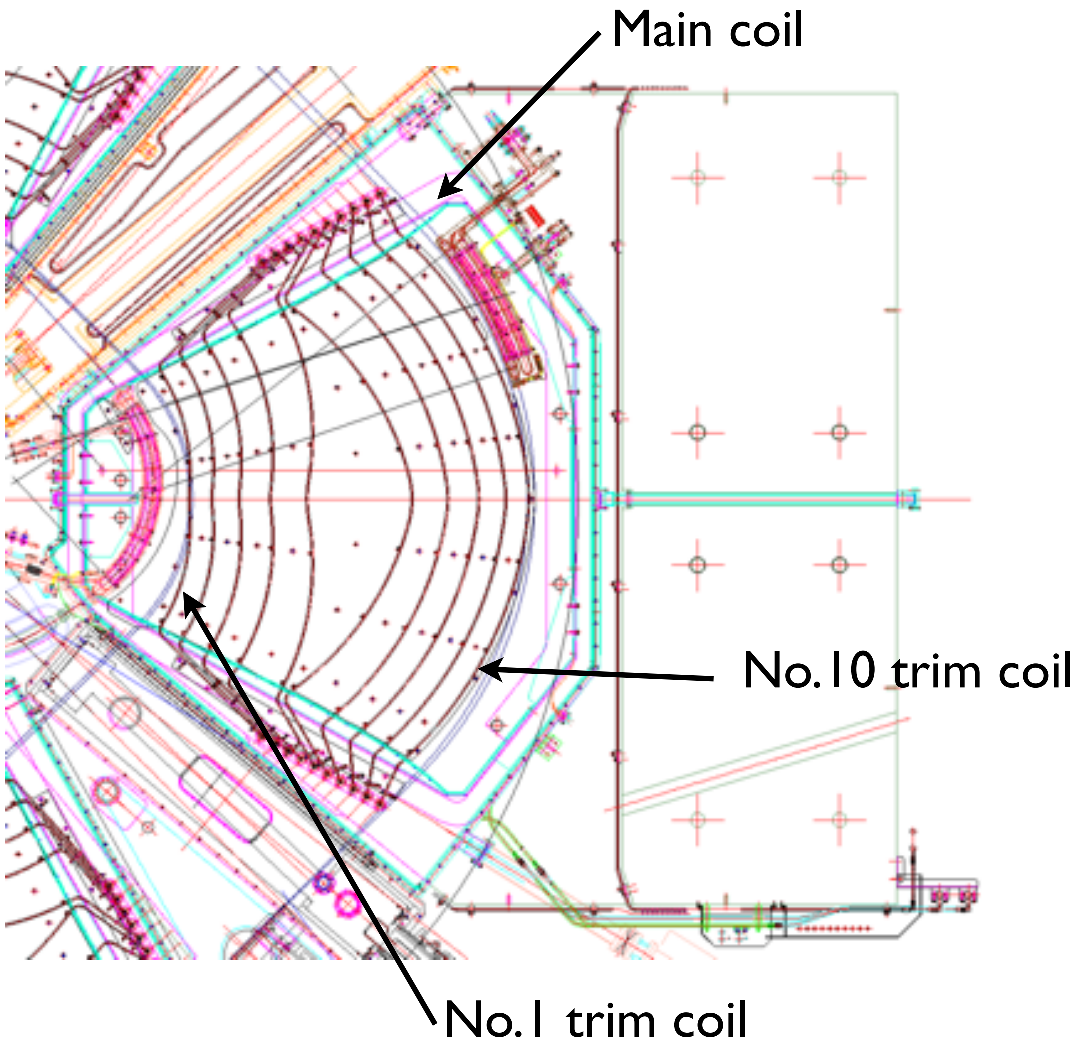
- BH curve : calibrated by measured magnetic field data obtained before fRC commissioning in 2006.
- Pole deformation (magnetic and vacuum forces) : included
- Effects of magnetic channels and bending magnets : included

# Design Tolerance

Differences between actual operating parameters and results of numerical simulation for main and trim coils.

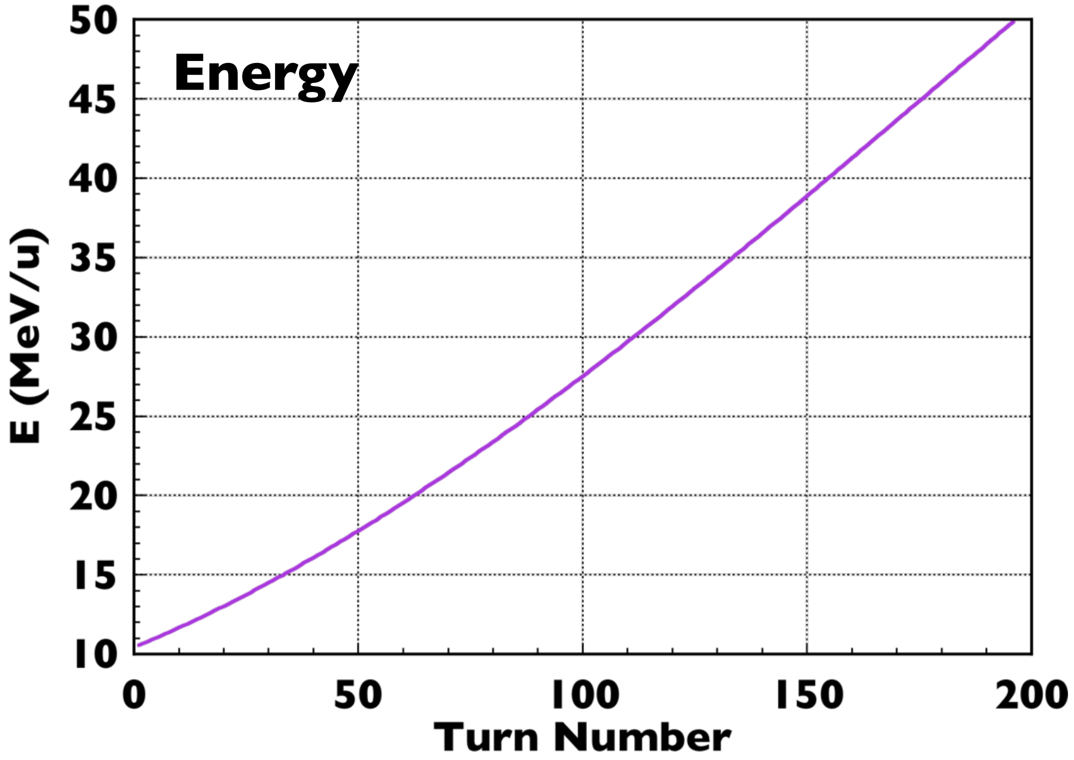


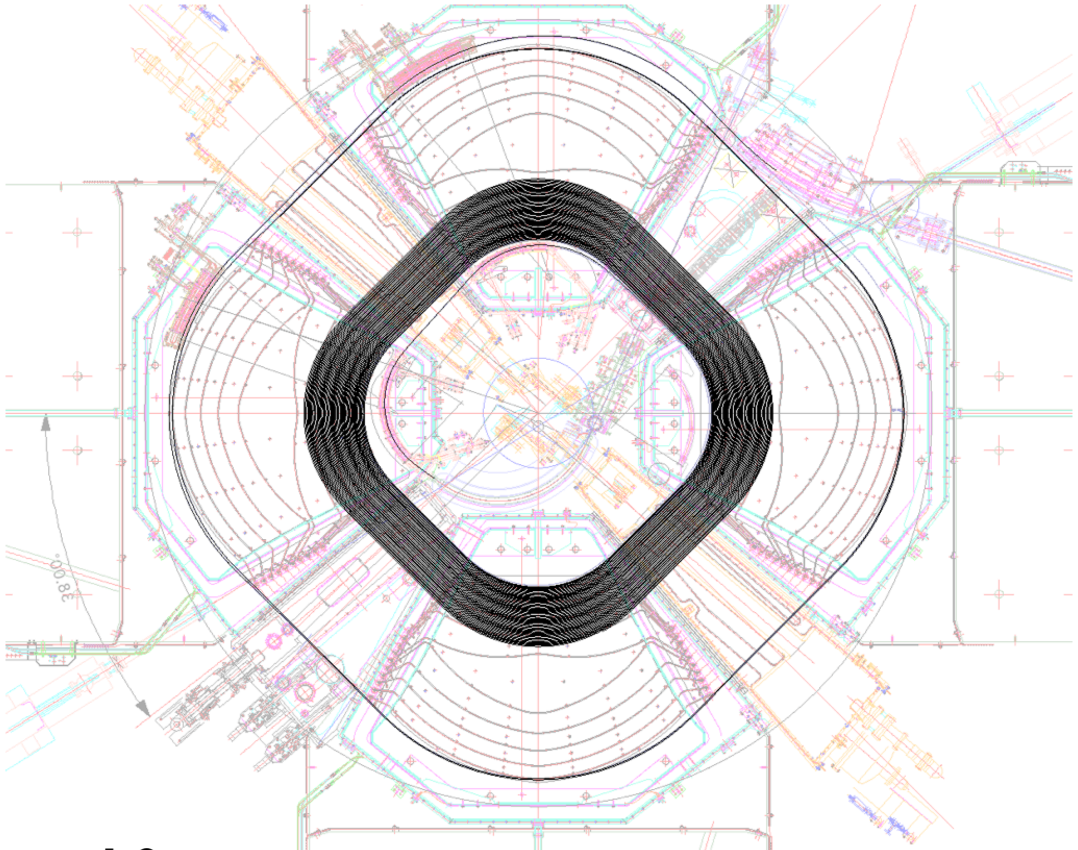


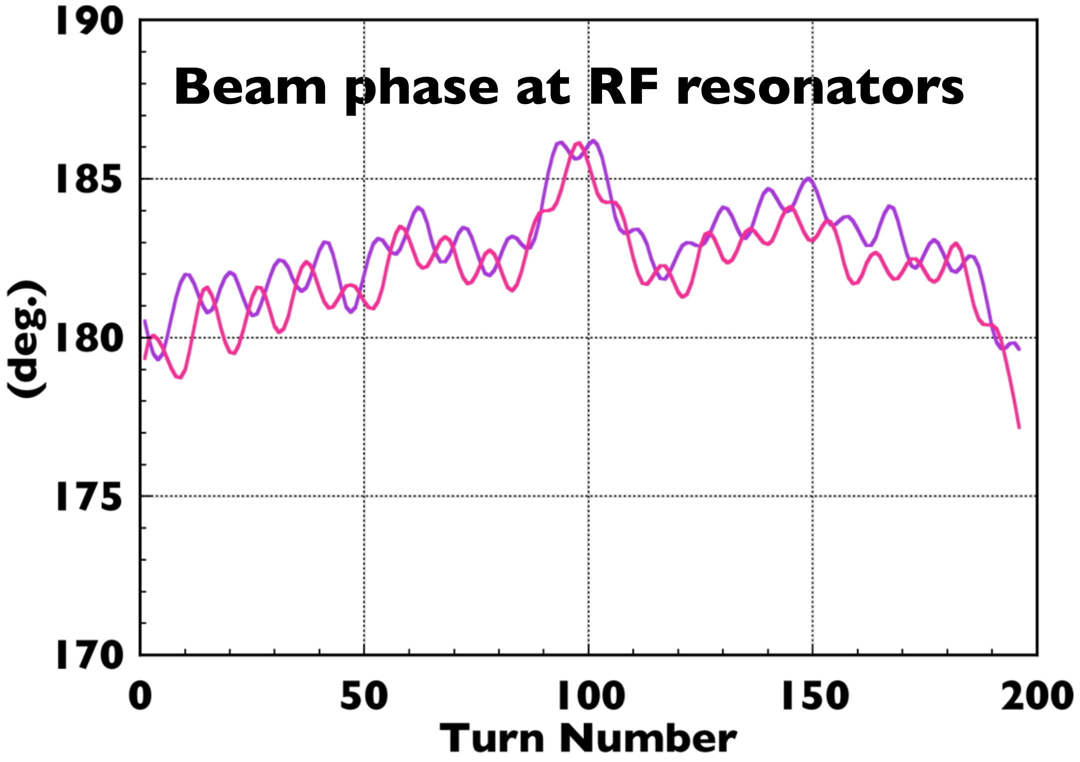


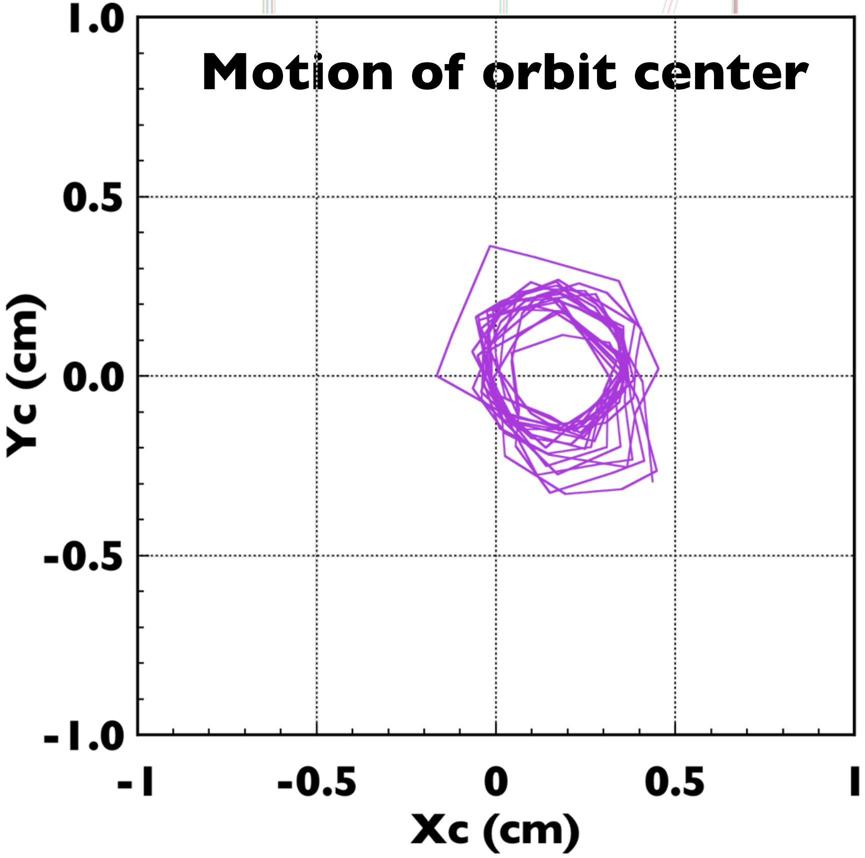
Design errors
M : Main coil → less than 5 amperes
1 ~ 10 : Trim coils → 30 A (~ 6 gauss)

# Isochronism & Orbital Motion ($^{238}U^{65+}$)









# Injection and Extraction Devices

## Specifications of upgraded devices

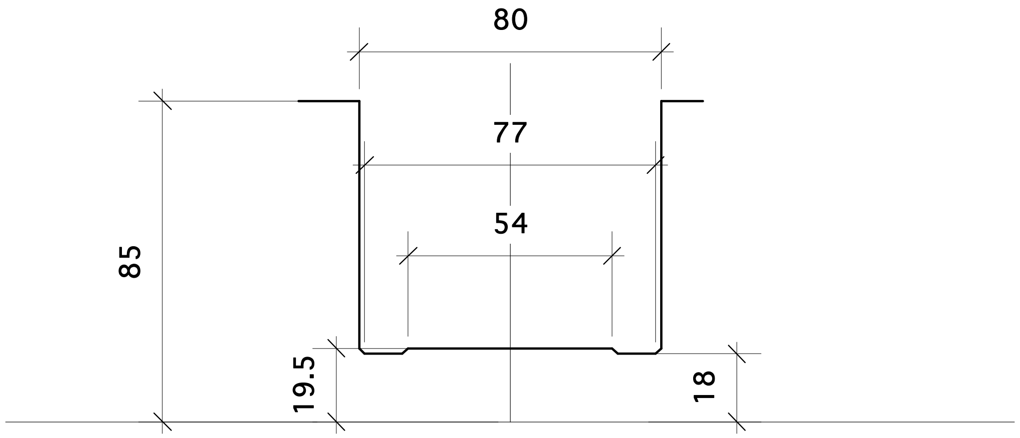
| | BM | MIC2 | ST |
|---|---|---|---|
| Curvature radius (cm) | 91 | 72 | 9 (pole length) |
| Bending angle (deg.) | 100.35 | 80 | |
| Pole gap (cm) | 40 | 25 (28) | 40 |
| Hollow conductor | □9-φ6 | □8.5-φ5<br>(□7-φ4) | □7-φ4 |
| Number of coil windings | 84 (72) | 4 | 60 |
| Number of cooking water channel | 14 (12) | 2 (1) | 6 |
| Max. magnetic field (T) | 1.95 (1.8) | 0.6 (0.5) | 1.1 |

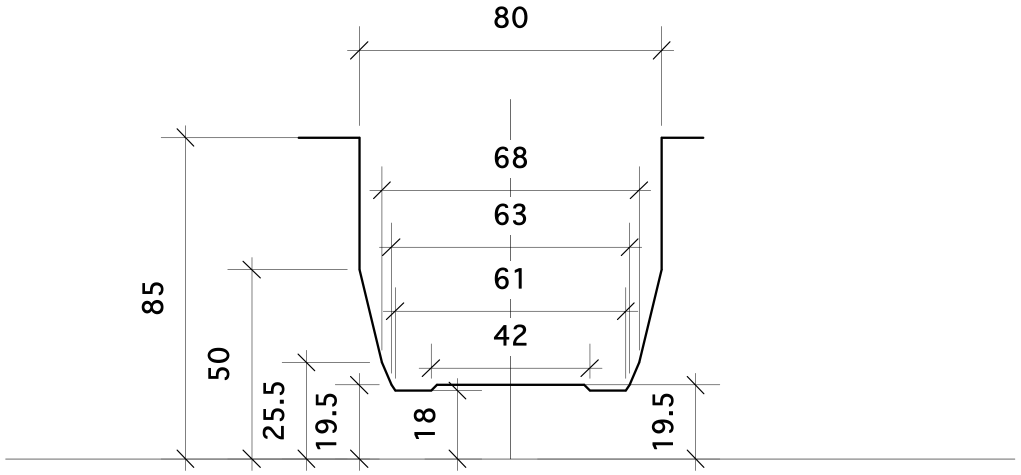
Numbers in parentheses show the old specifications.

BM : Bending Magnet used for beam injection
MIC2 : Magnetic Inflection Channel 2
ST : Steering Magnet

## Pole design of EBM

### Original design (1.4 T)

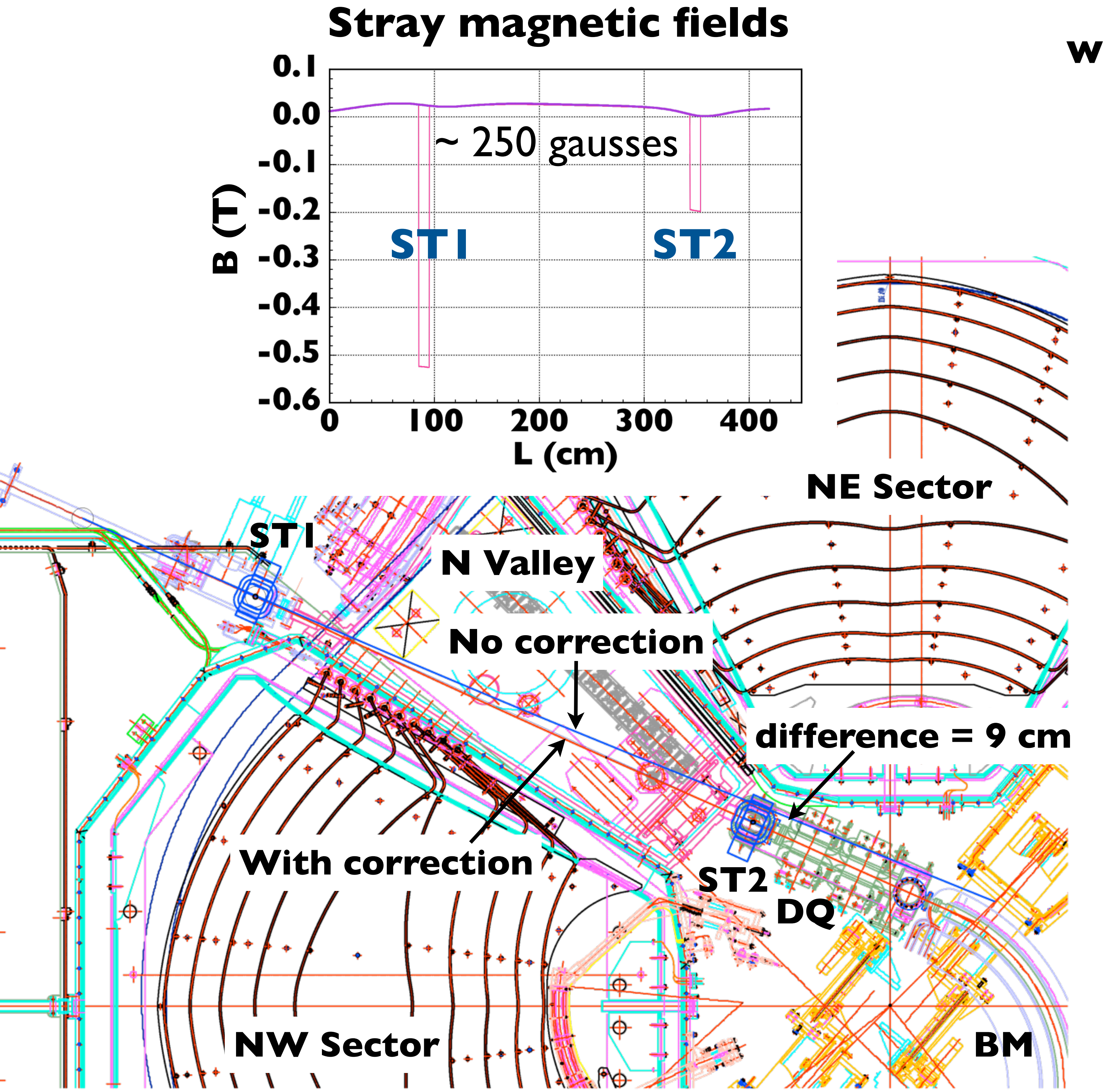




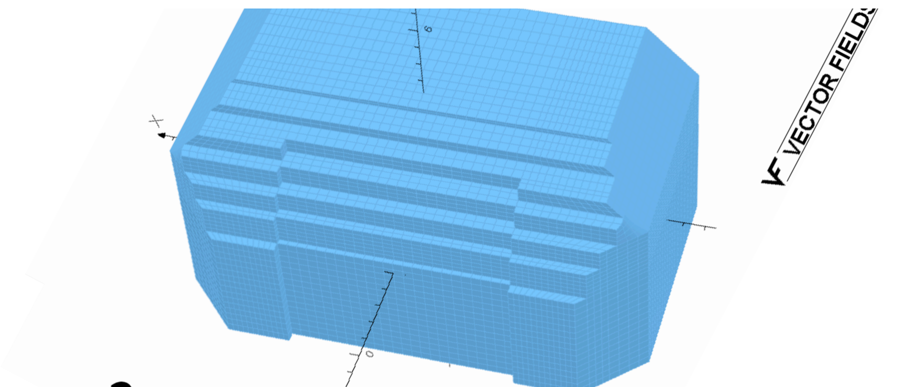
### New design (1.55 T)

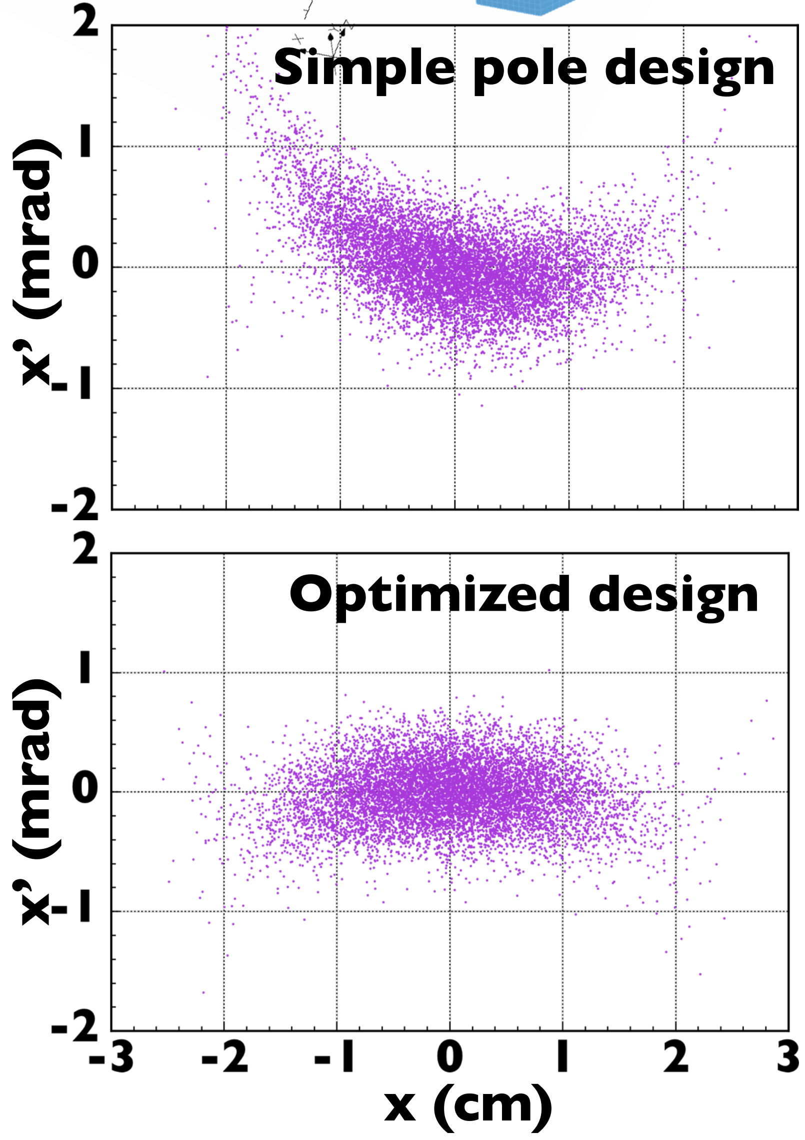
EBM : Extraction Bending Magnet

# Injection Orbit Correction



## Steering magnets (ST) with sextupole field eliminated



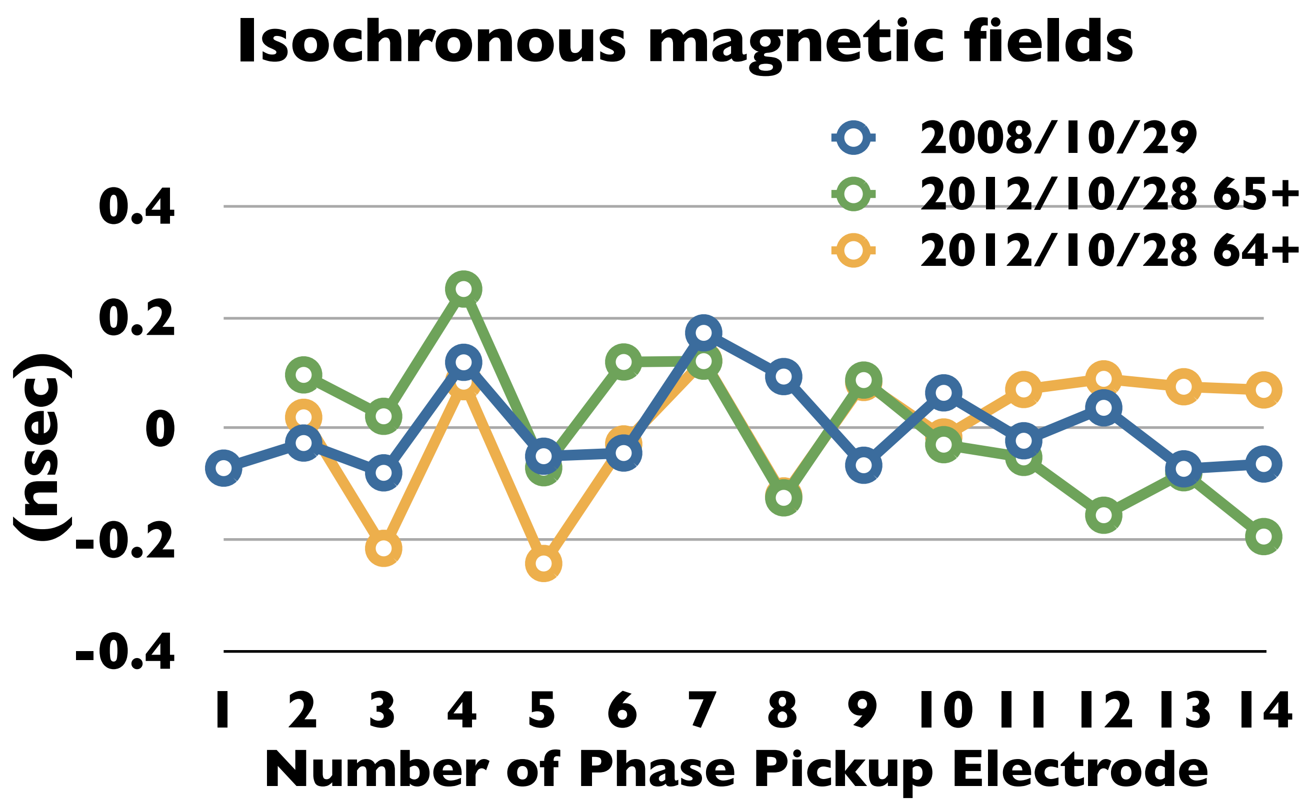


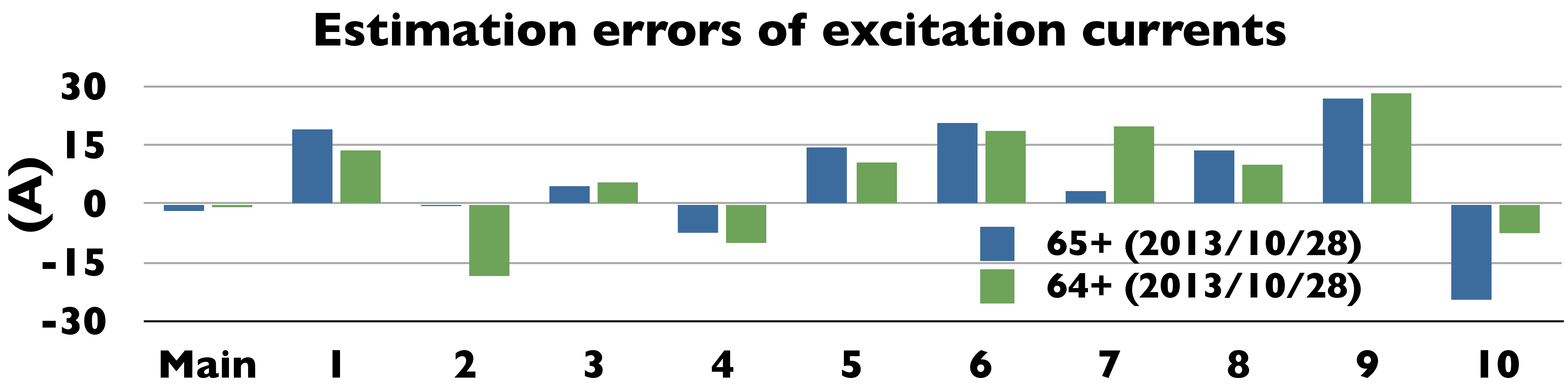
# Results of fRC Upgrade

The helium gas stripper showed

- mean charge state at equilibrium
  65+, > 1 mg/cm$^2$

- transient enhancement of charge stripping efficiency at 0.7 mg/cm$^2$
  64+ ~27%
  65+ ~21%
  owing to atomic shell effect

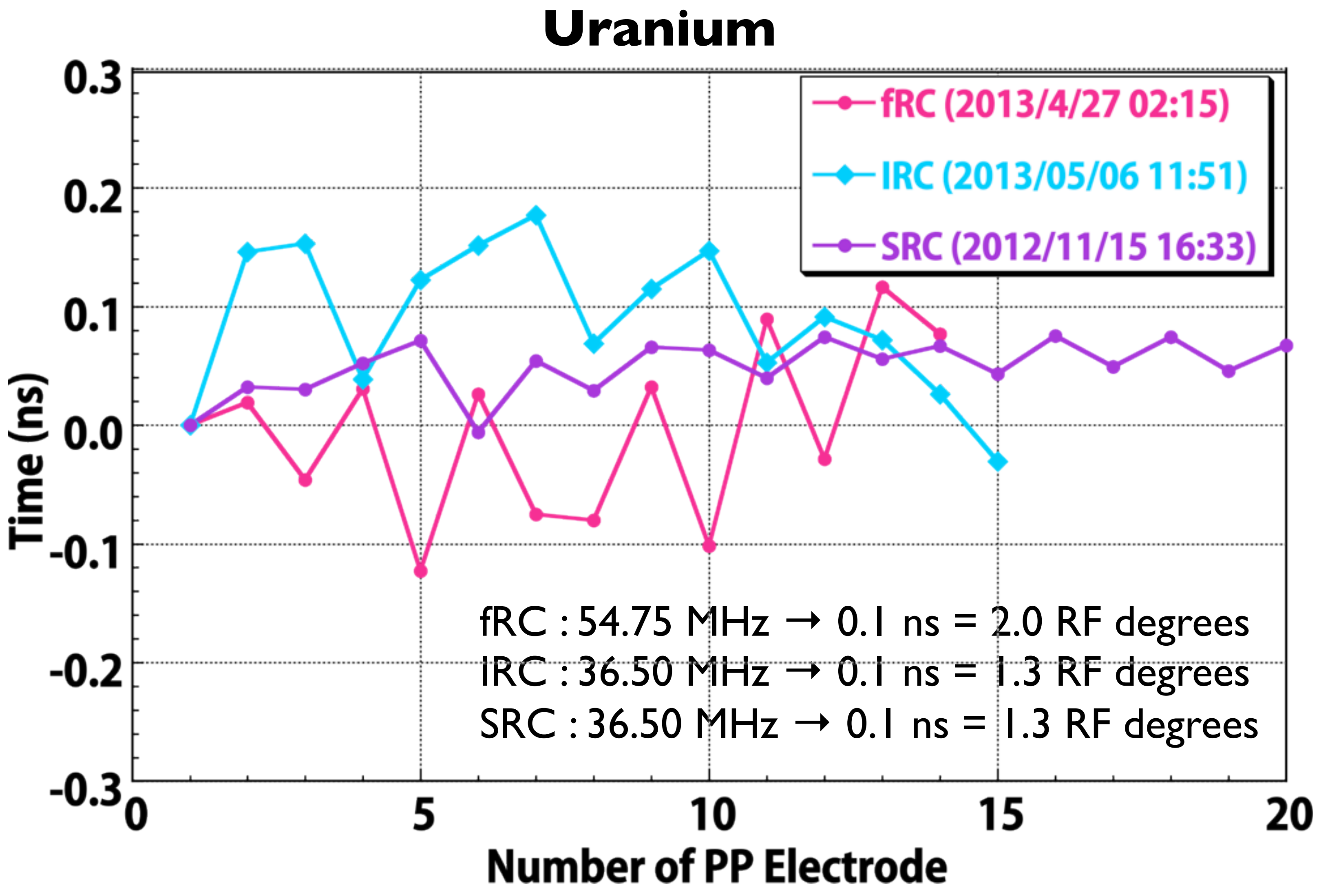




# Present Performance

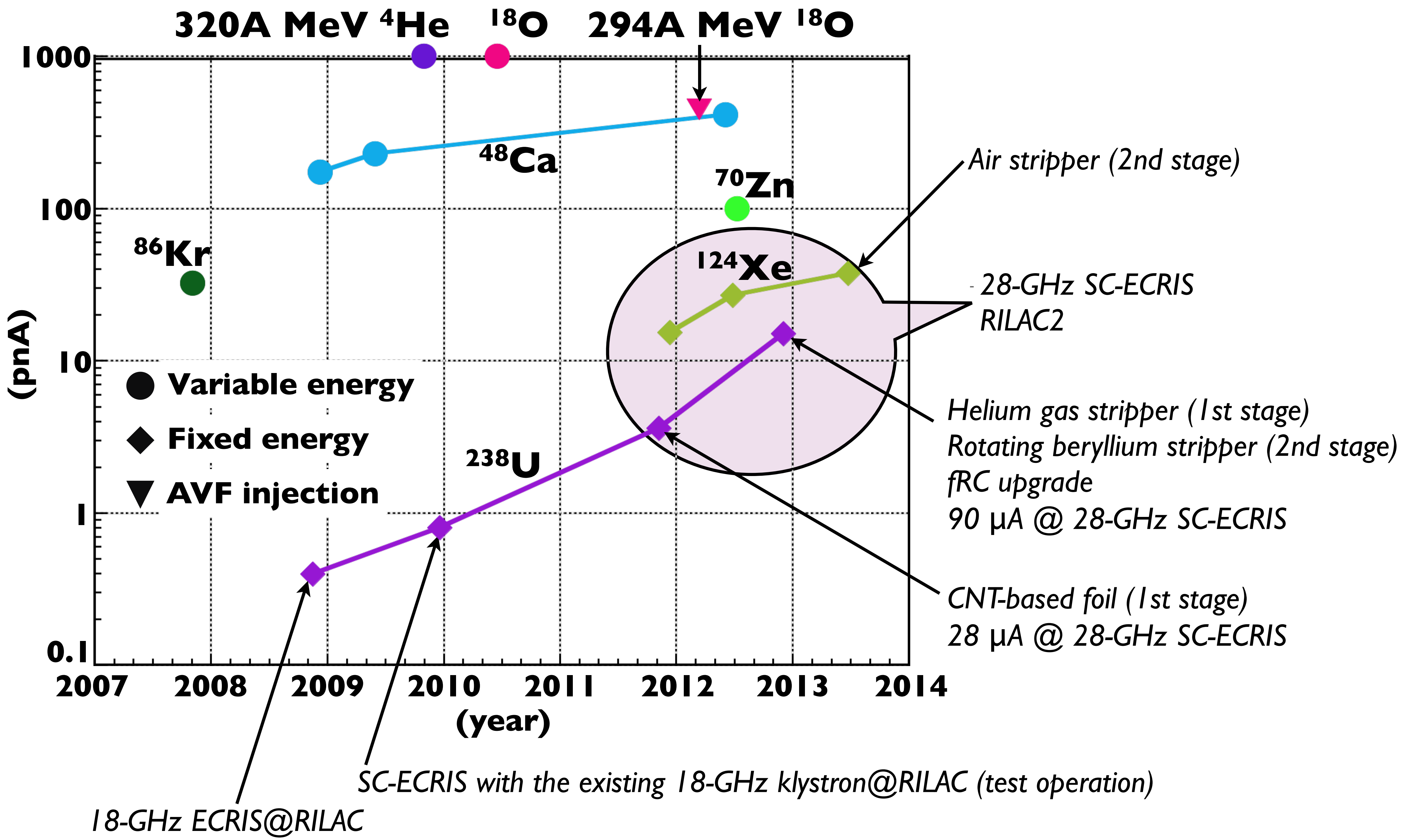
# Isochronous Magnetic Fields

**Isochronism of RRC ~ < ±0.5 ns**
RRC : 18.25 MHz → 0.1 ns = 0.65 RF degree



fRC : 54.75 MHz → 0.1 ns = 2.0 RF degrees
IRC : 36.50 MHz → 0.1 ns = 1.3 RF degrees
SRC : 36.50 MHz → 0.1 ns = 1.3 RF degrees

# History of Beam Intensity Upgrade



*Air stripper (2nd stage)*

*28-GHz SC-ECRIS*
*RILAC2*

*Helium gas stripper (1st stage)*
*Rotating beryllium stripper (2nd stage)*
*fRC upgrade*
*90 μA @ 28-GHz SC-ECRIS*

*CNT-based foil (1st stage)*
*28 μA @ 28-GHz SC-ECRIS*

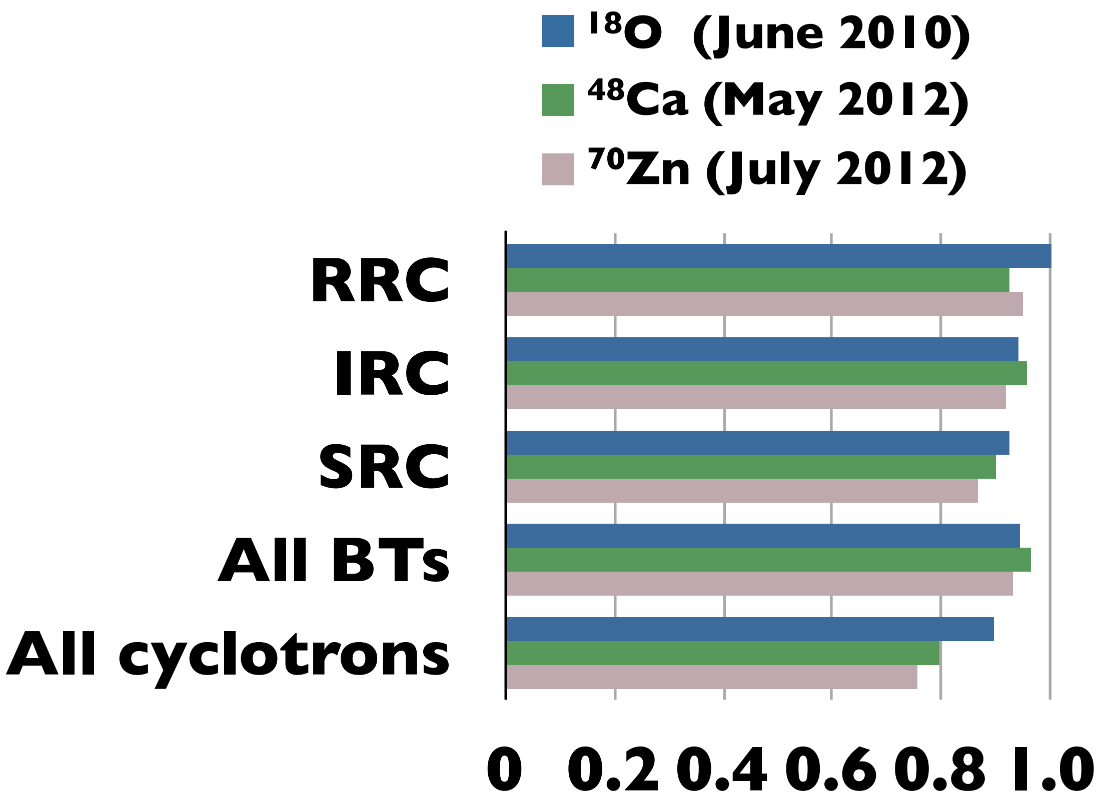
*SC-ECRIS with the existing 18-GHz klystron@RILAC (test operation)*

*18-GHz ECRIS@RILAC*

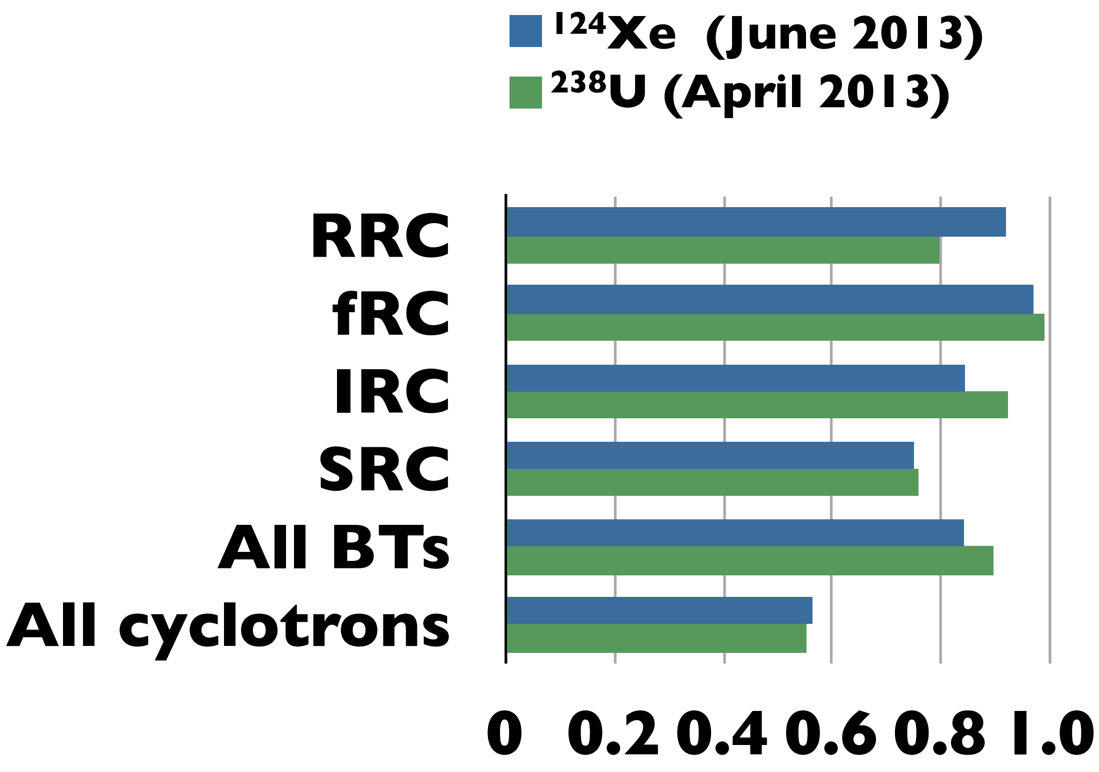
# Transmission Efficiency

*(Best performance of RIBF cyclotron cascade)*

**Variable energy mode**



**Fixed energy mode**

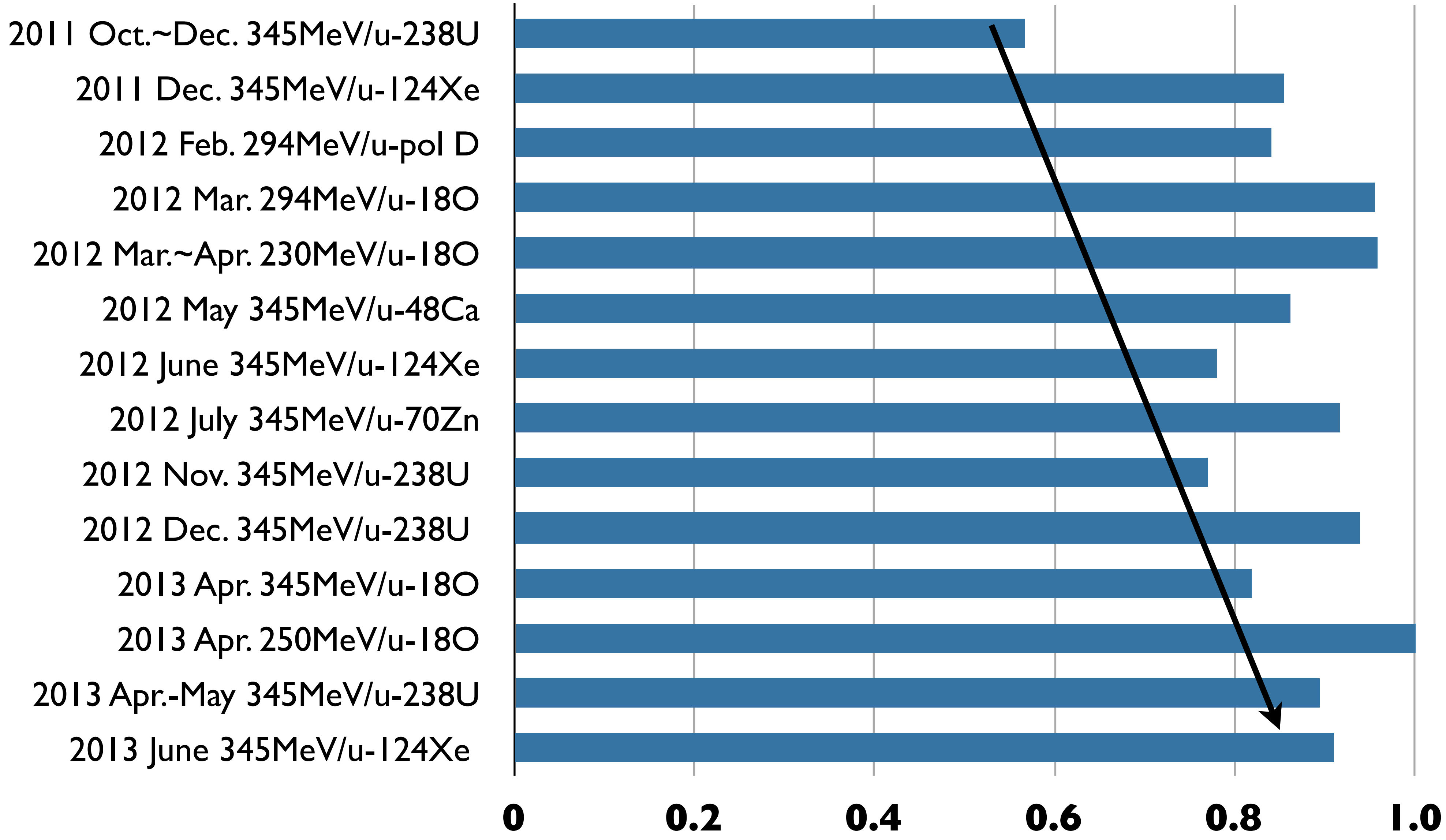


Reasons of low transmission efficiencies in the fixed energy mode are

- large energy spread due to thick charge strippers
- emittance growths in horizontal direction because the first stage charge stripper and a rebuncher between fRC and IRC are placed at dispersive points.
- others?

# Beam Availability

$$\textit{Beam availability} = \frac{\textit{actual beam service time}}{\textit{scheduled beam service time}}$$

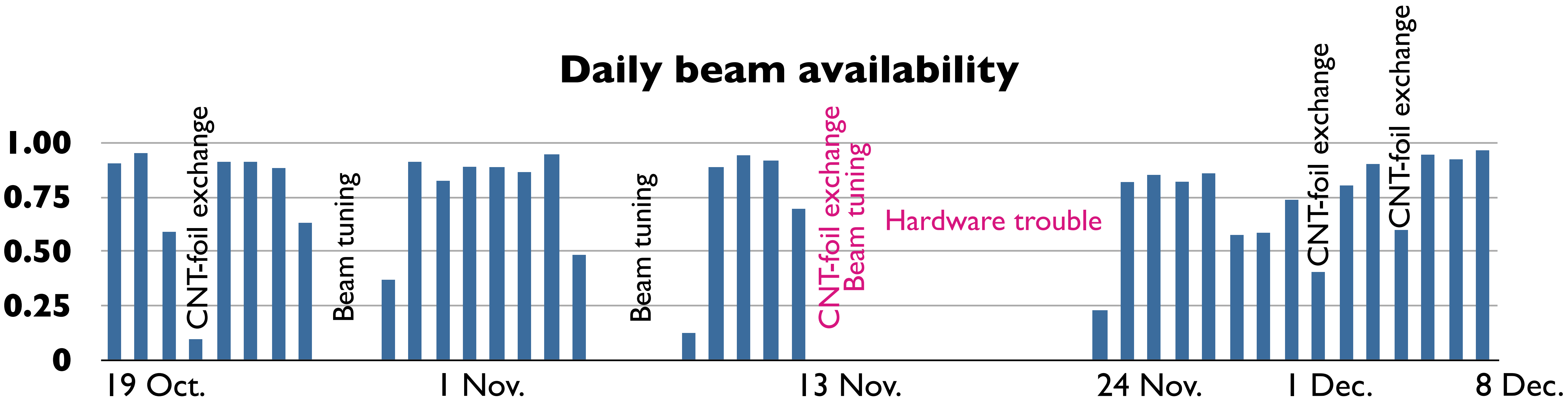


*Any unscheduled beam service interruptions are counted as the downtime!*

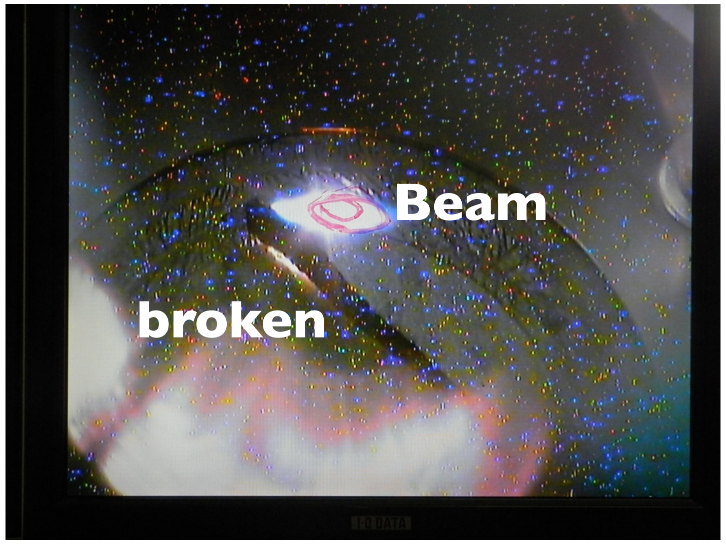
# Details of $^{238}$U Beam Service

(2011/10/19 ~ 2011/12/08)

## Daily beam availability

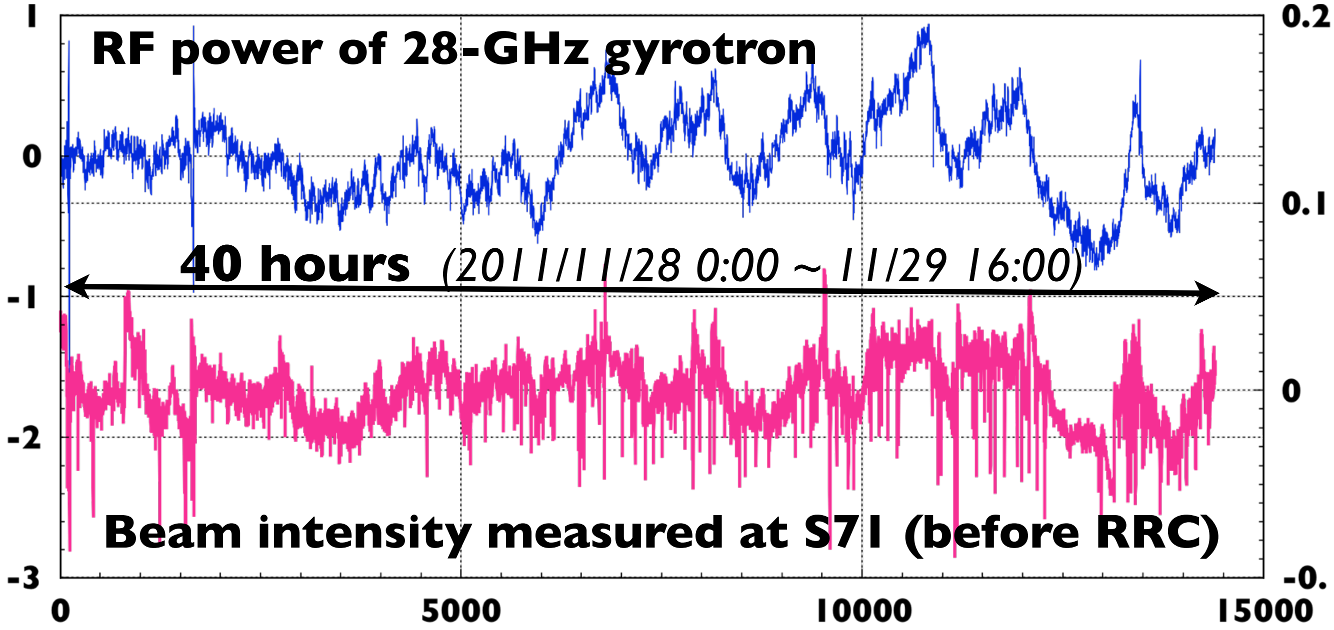


## CNT-foil



Serviceable time : 3 ~ 4 days
100 times larger than usual carbon foils

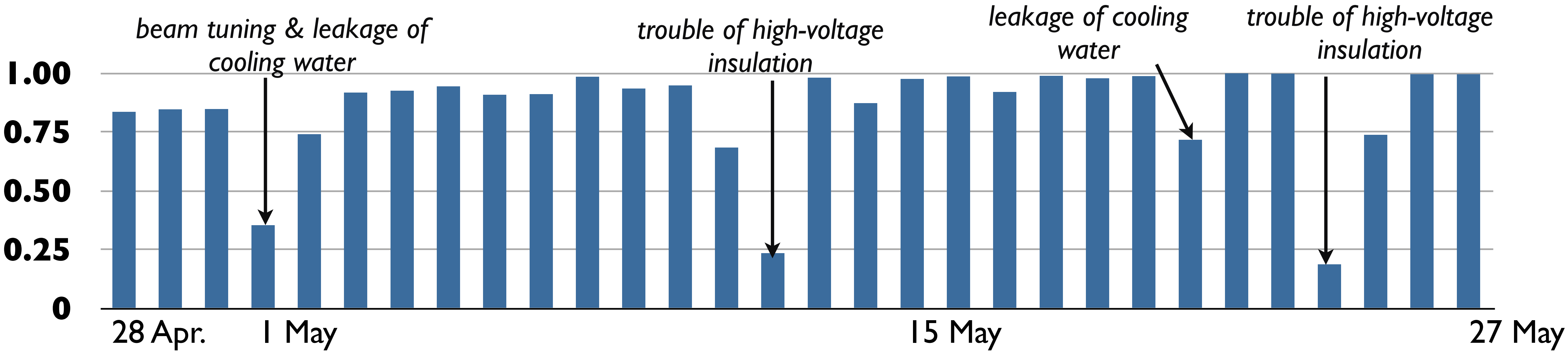
## Beam intensity fluctuation



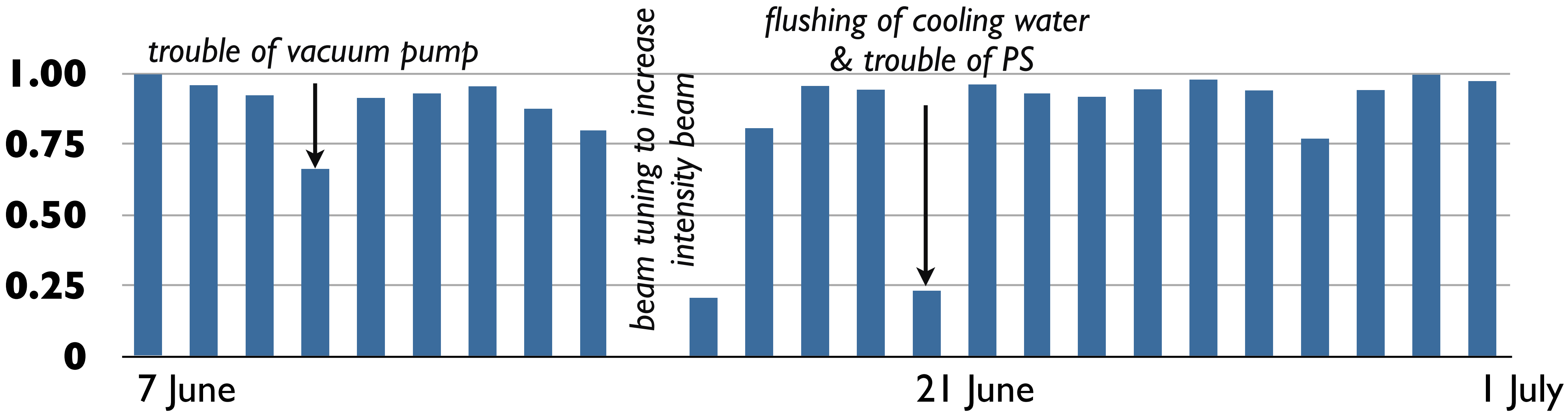
This problem was fixed by replacing the power supply of the gyrotron.

# Details of 2013 Operations

**$^{238}$U (2013/4/28 - 5/27)** ***89.5% in total***



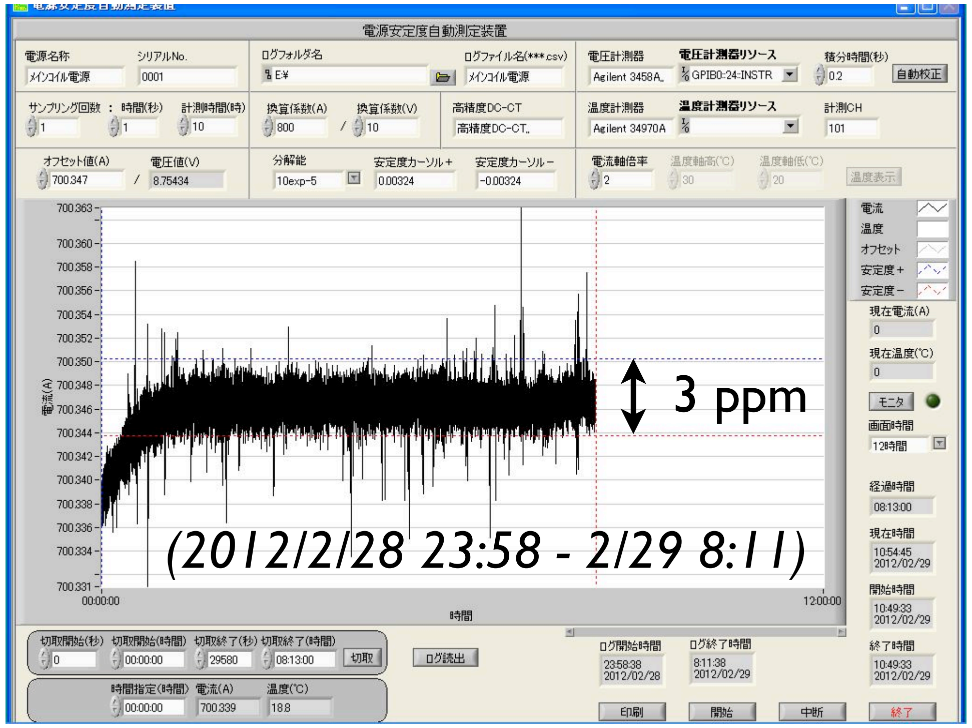
**$^{124}$Xe (2013/6/07 - 7/01)** ***91.1% in total***



*Small troubles remains but availability of 90% has been realized in the fixed energy mode!*

# Stability of Isochronous Magnetic Fields

## Stability of new fRC power supply



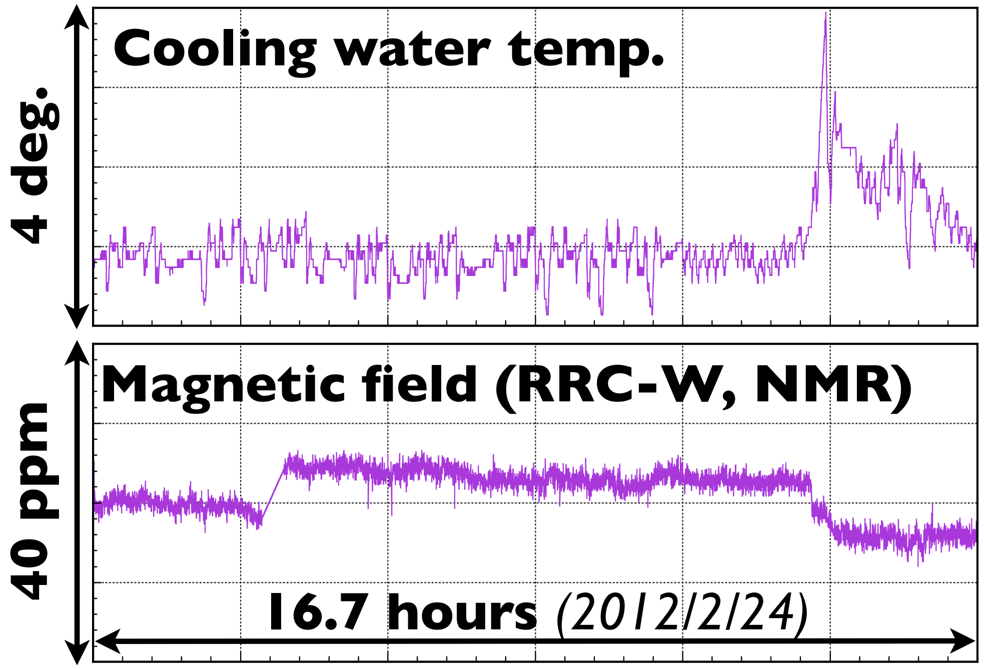
電源安定度自動測定装置

電源名称 メインコイル電源
シリアルNo. 0001
ログフォルダ名 E:¥
ログファイル名(***.csv) メインコイル電源
電圧計測器 Agilent 3458A..
電圧計測器リソース GPIB0::24::INSTR
積分時間(秒) 0.2
サンプリング回数 1
時間(秒) 1
計測時間(時) 10
換算係数(A) 800
換算係数(V) 10
高精度DC-CT 高精度DC-CT..
温度計測器 Agilent 34970A
温度計測器リソース
計測CH 101
オフセット値(A) 700.347
電圧値(V) 8.75434
分解能 10exp-5
安定度カーソル＋ 0.00324
安定度カーソル－ -0.00324
電流軸倍率 2
温度軸高(℃) 30
温度軸低(℃) 20
現在電流(A) 0
現在温度(℃) 0
画面時間 12時間
経過時間 08:13:00
現在時間 10:54:45 2012/02/29
開始時間 10:49:33 2012/02/29
終了時間 10:49:33 2012/02/29
切取開始(秒) 0
切取開始(時間) 00:00:00
切取終了(秒) 29580
切取終了(時間) 08:13:00
時間指定(時間) 00:00:00
電流(A) 700.339
温度(℃) 18.8
ログ開始時間 23:58:38 2012/02/28
ログ終了時間 8:11:38 2012/02/29

3 ppm

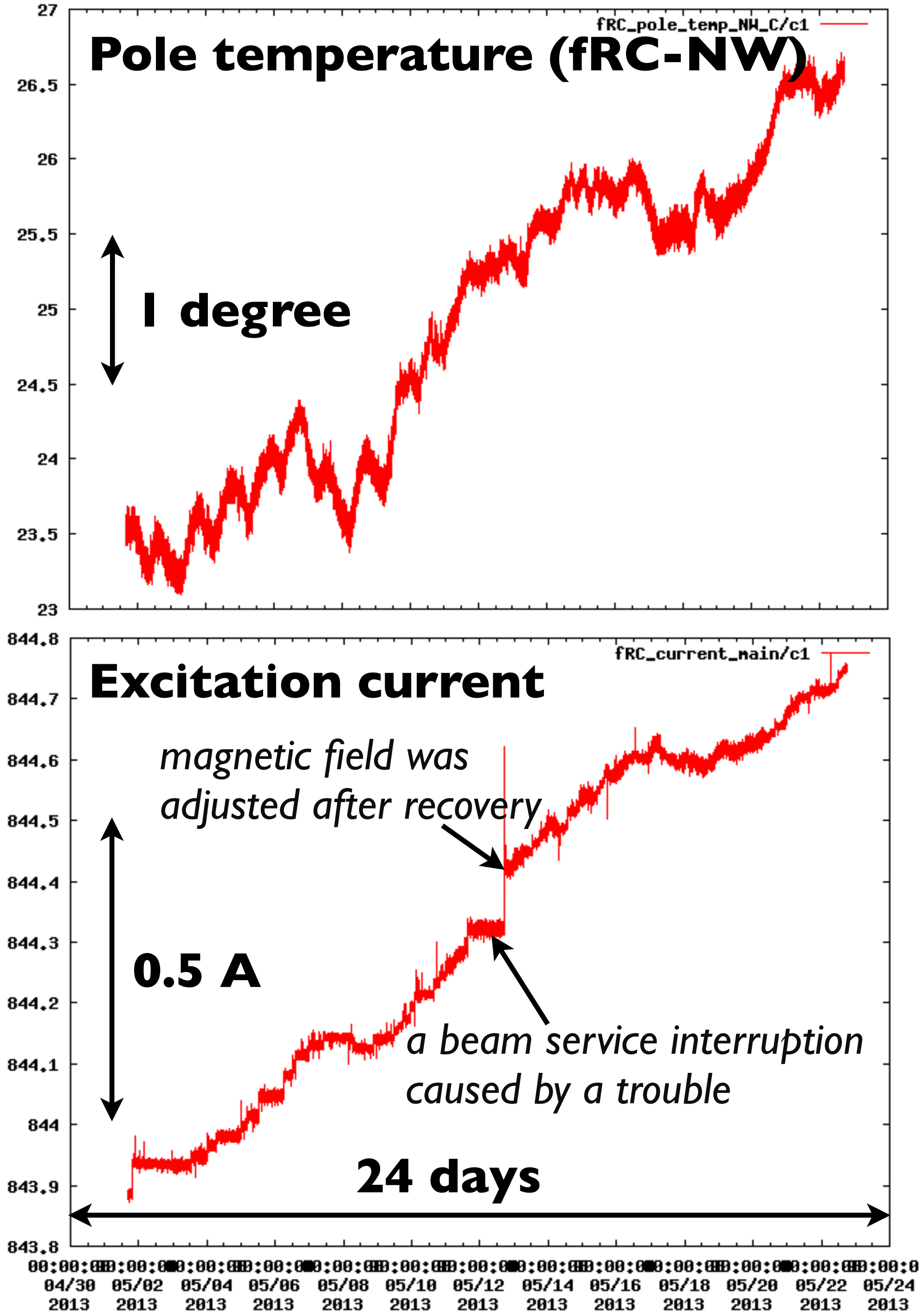
(2012/2/28 23:58 - 2/29 8:11)

## Old water-cooling control system (RRC)



**16.7 hours** (2012/2/24)

## Harmful effect of cold start



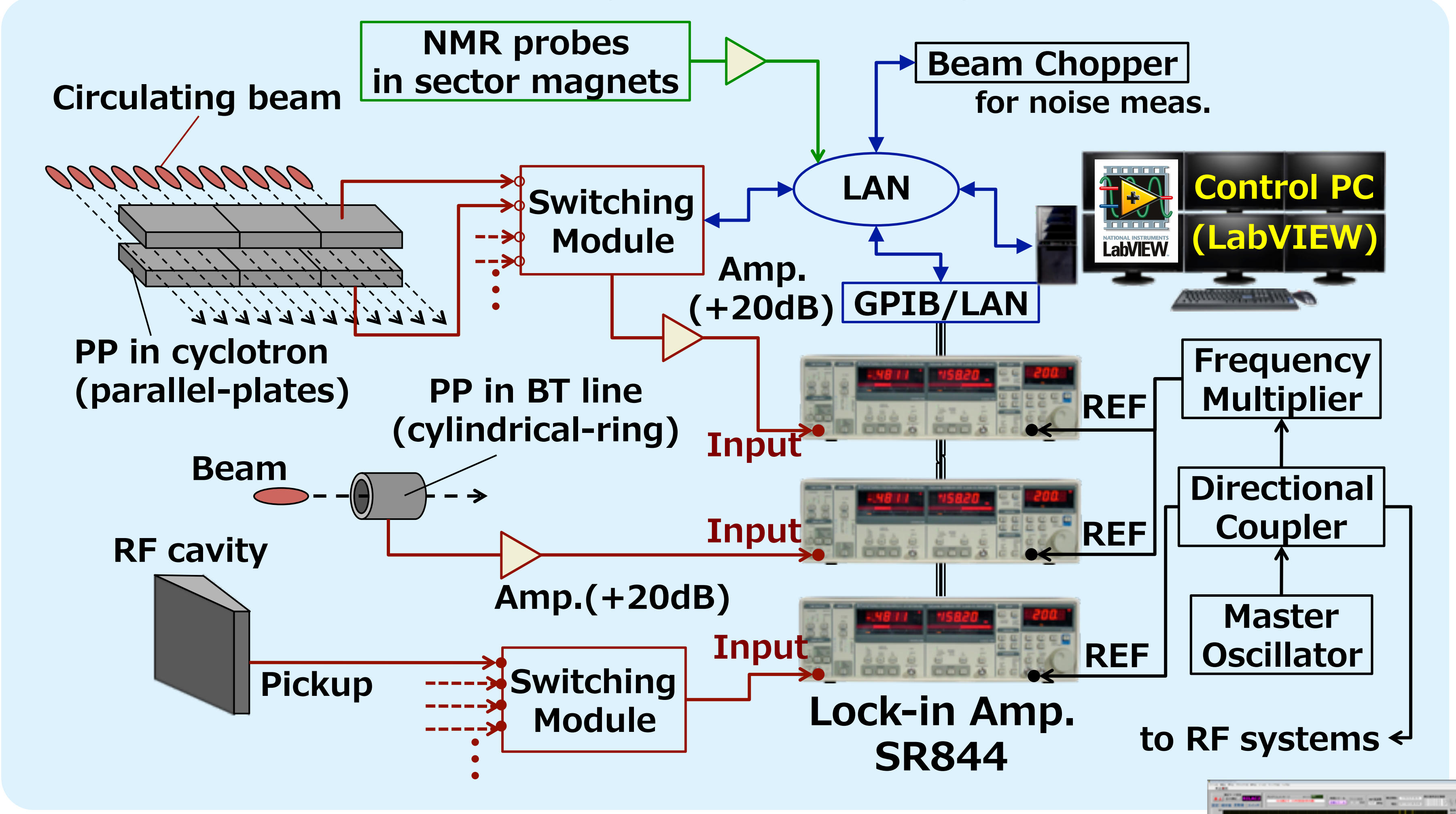
*magnetic field was adjusted after recovery*

*a beam service interruption caused by a trouble*

(2013/4/30 0:00 - 5/24 0:00)

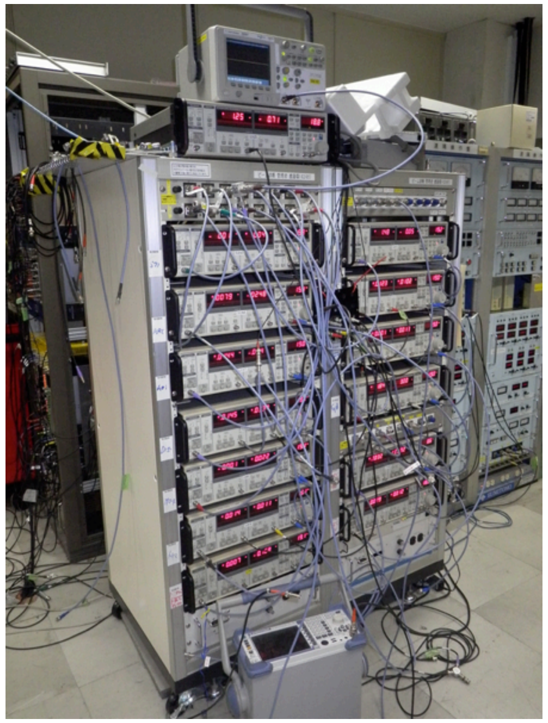
# Integrated Monitoring System

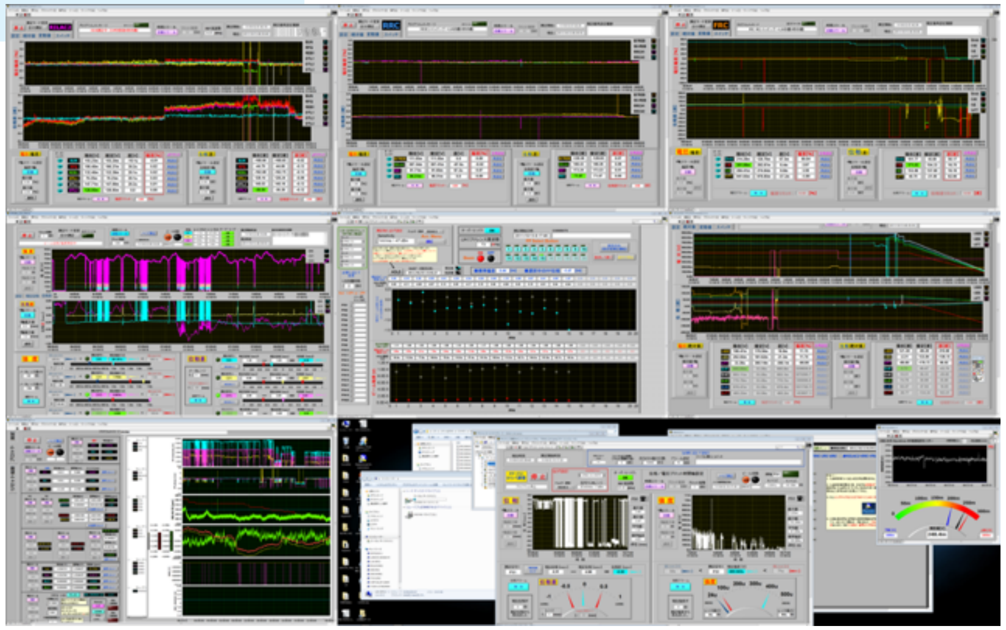
## Structure of monitoring system using lock-in amplifiers



*R. Koyama et al., Nucl. Instrum. and Meth.* ***A729*** *(2013) 788-799.*

## Lock-in amplifiers



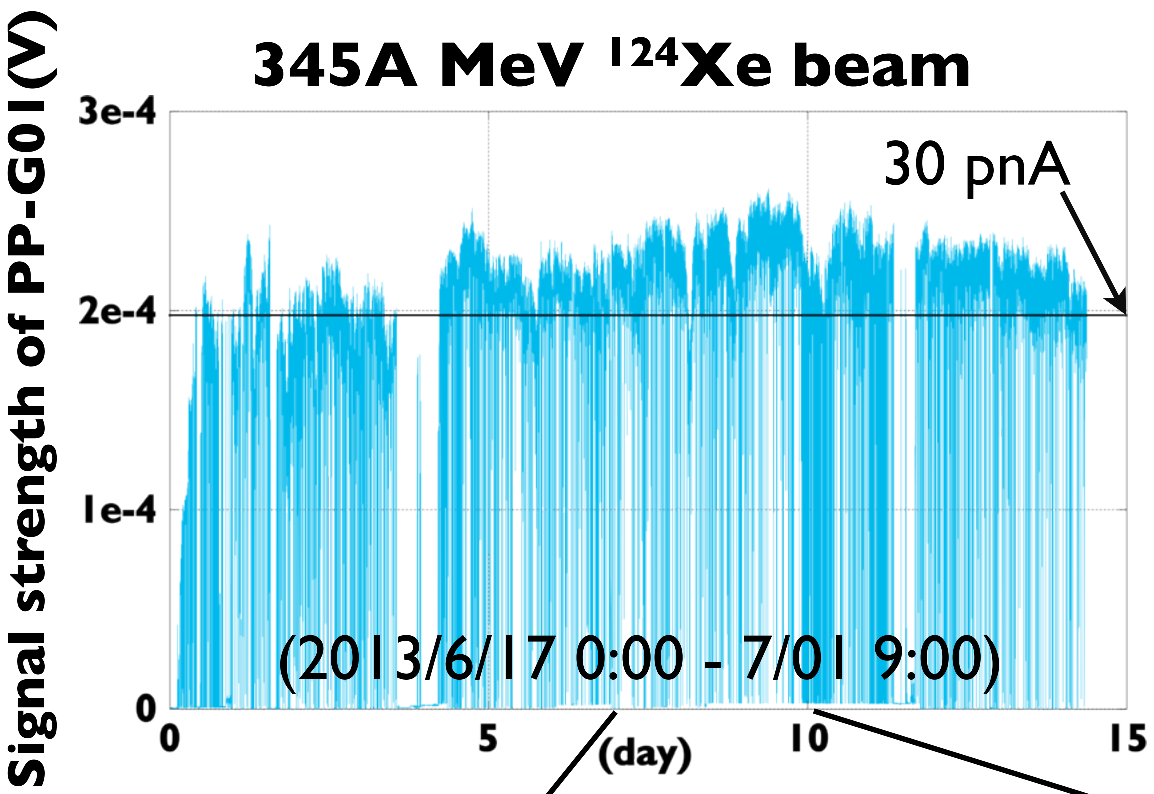


The system monitors RF resonators, magnetic fields, beam bunch signals before and after the accelerators and the strippers

Arrival times of ions at each cyclotron is maintained by the operators with assistance of the integrated monitoring system.

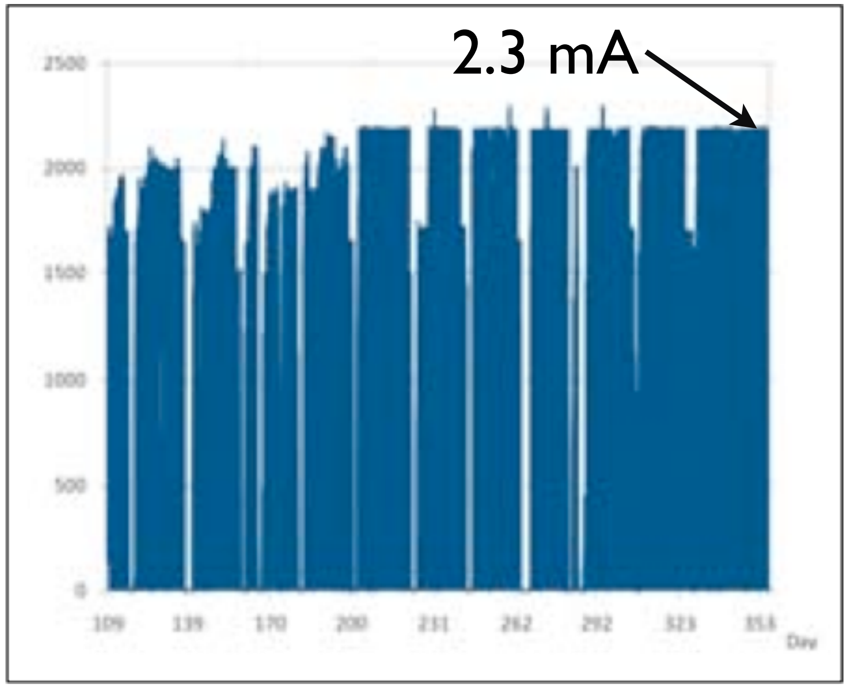
# Stability of Beam Intensity

**345A MeV $^{124}$Xe beam**

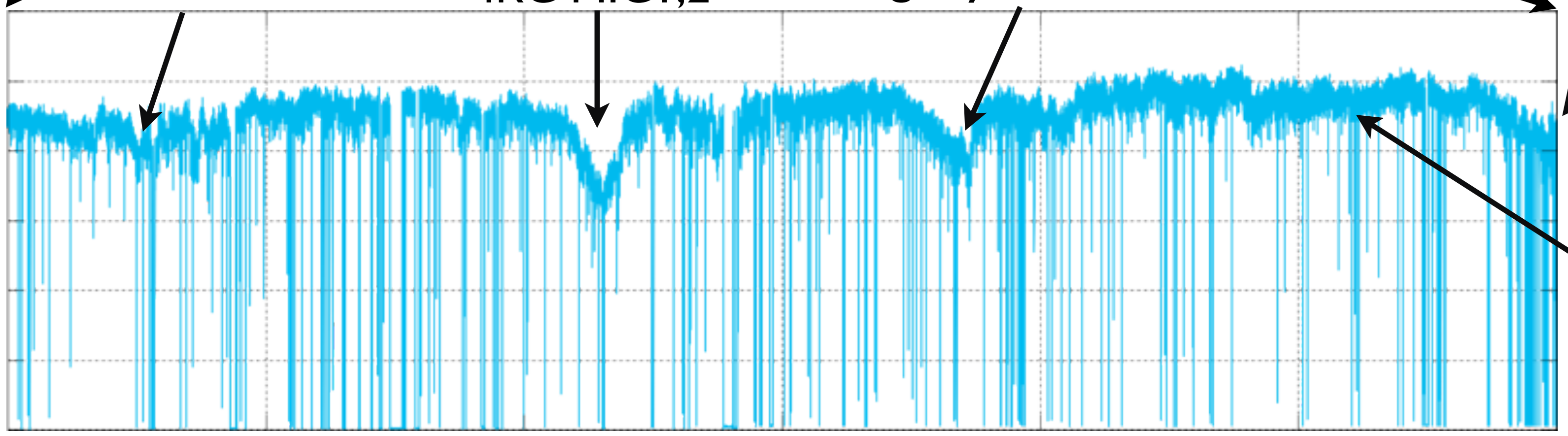


(2013/6/17 0:00 - 7/01 9:00)

**PSI**



*extract from PSI Scientific Report 2009*



Air stripper (flow rate of gas)

28-GHz SCECR (flow rate of gas) fRC MIC1,2

Many parameters slightly modified

28-GHz SCECR

Gas stripper (flow rate of gas) 28-GHz SCECR (flow rate of gas)

*Details of beam intensity fluctuation (6/24-6/26).*
*Devices tuned to recover beam intensity are shown.*

# Summary

We have successfully developed or upgraded

- 28-GHz ECRIS
- the new injector RILAC2
- helium gas stripper, air stripper and rotating beryllium disk stripper
- bending power of fRC

We have obtained 345A-MeV beams with the intensity of

- 415 pnA for $^{48}$Ca
- 38 pnA for $^{124}$Xe
- 15 pnA for $^{238}$U

after the upgrades.

Beam availability has been greatly improved (90%).

Further performance upgrades required in the near future are

- to increase the beam intensity of uranium and xenon ions by improving the transmission efficiency of the RIBF accelerator complex
- to improve the stability of the RIBF accelerator complex