# IMP Cyclotron Status and Development

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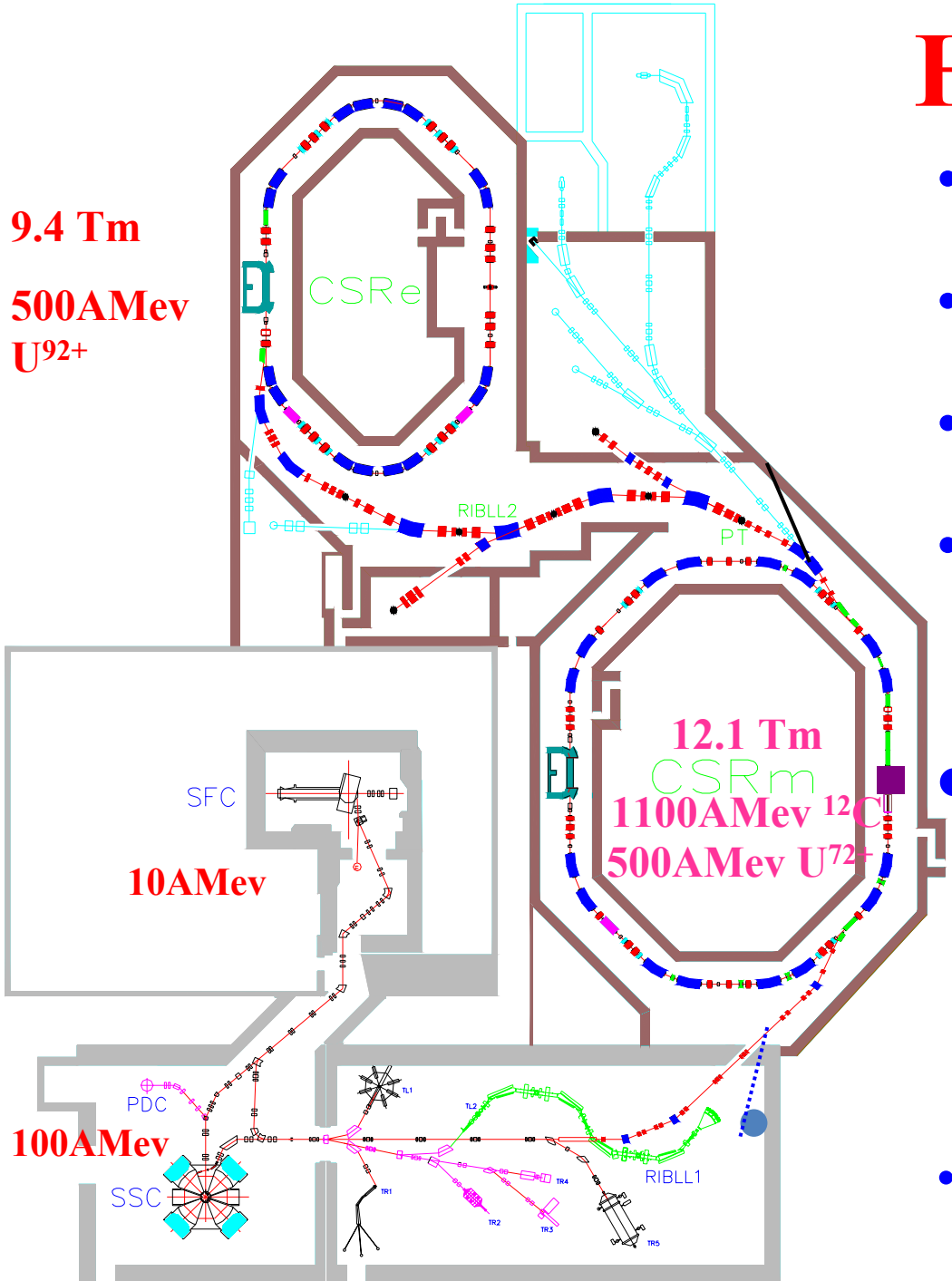
# Outline

- **HIRFL-Cyclotron Operation Status**
- **HIRFL-Cyclotron Development**
- **SECRAL Status and Development**

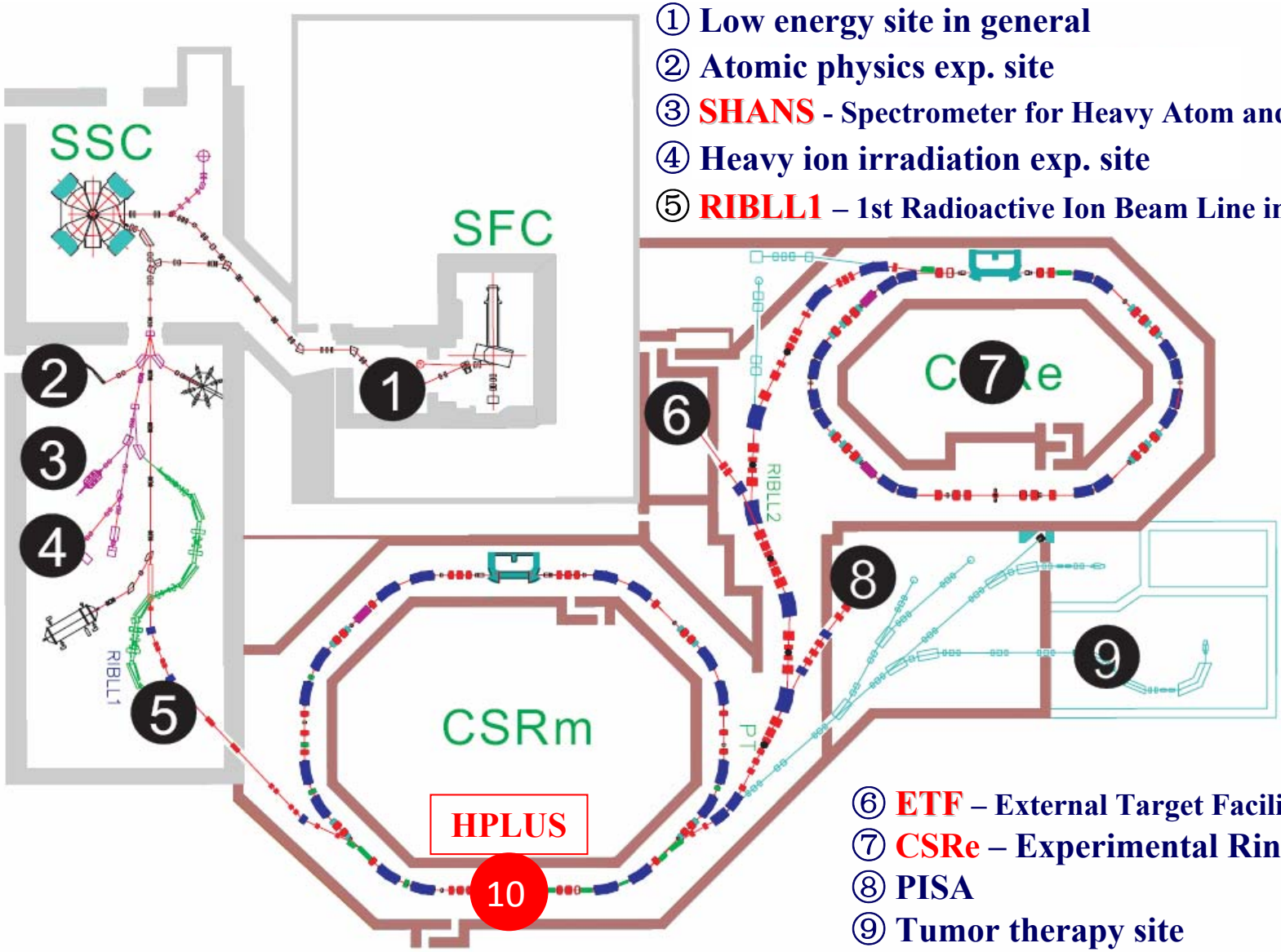
# HIRFL Layout




- **ECR Ion Source**
- **SFC K=69--10AMev**
- **SSC K=450 –100AMev**
- **CSRm: Synchrotron**
  - **Intensity: $10^{8-9}$ pps,**
  - **Circumference**: 162 m
- **CSRe: Storage ring**
  - **Accel. & Deccel.**
  - **Intensity: $10^{8-10}$ pps**
  - **Circumference**: 128 m
  - **RIB, internal target**
  - **High Resolution Spectrometer**
- **CSR budget:42 M$; 2000-2007**

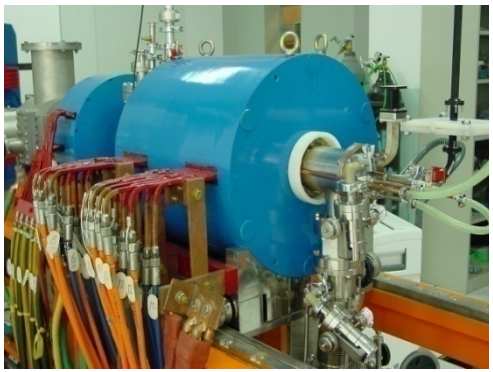
# HIRFL: Exp. Setups

① Low energy site in general
② Atomic physics exp. site
③ SHANS - Spectrometer for Heavy Atom and Nuclear Structure
④ Heavy ion irradiation exp. site
⑤ RIBLL1 – 1st Radioactive Ion Beam Line in Lanzhou




⑥ ETF – External Target Facility at CSR
⑦ CSRe – Experimental Ring
⑧ PISA
⑨ Tumor therapy site

# HIRFL Cyclotrons



ECR

SFC K=69
(1963-)

SSC k=450 (1988-)

# HIRFL Operation Status

| Year | Total operation time (hours) | Beam time on target (hours) | Percentage of beam time | Percentage of beam tuning | Percentage of equip. failure |
|---|---|---|---|---|---|
| 2007 | 7120 | 5624 | 79% | 10.0% | 11% |
| 2008 | 6956 | 4269 | 75.7% | 9.5% | 14.8% |
| 2009 | 7161 | 5578 | 77.8% | 11.6% | 10.6% |

# HIRFL Operation in 2008-2009

## HIRFL operation time distribution in Sept.2008-July 2009

| Operation time distribution | Time (hours) | Percentage |
|---|---|---|
| Total operation time | 6922 | 100% |
| Beam time | 5218 | 75.4% |
| Preparation of beams | 931 | 13.4% |
| Failure of equipments | 773 | 11.2% |

## HIRFL beam time distribution in 2008-2009

| Beam time distribution | Time (hours) | Percentage |
|---|---|---|
| Total beam time | 5218 | 100% |
| Nuclear physics, material science | 2730 | 53.2% |
| Biophysics and therapy research | 1205 | 23.1% |
| Machine study and improvement | 1283 | 23.7% |

**5218 hours beam time: 50.5% beam delivered by CSR, the others by SFC or SSC**

# Beam intensity enhancement at HIRFL-Cyclotrons

**Maximum operational beam intensities from SFC achieved in recent years and compared with those before 2004**

| SFC | C<br>6-8 Mev/u | O<br>6-8 Mev/u | Ne<br>6-8 Mev/u | Ar<br>2-3 MeV/u | Xe<br>2-3 MeV/u |
|---|---|---|---|---|---|
| Beam intensity before 2004 | 5 eμA | 5.5 eμA | 3.7 eμA | 3.2 eμA | 0.54 eμA |
| Beam intensity in recent years | 12 eμA | 13 eμA | 14 eμA | 15 eμA | 6 eμA |

**Maximum operational beam intensities from SSC achieved in recent years and compared with those before 2004**

| SSC | C<br>80 MeV/u | Ne<br>70 Mev/u | Ar<br>22－25MeV/u | Xe<br>15－20 MeV/u |
|---|---|---|---|---|
| Beam intensity before 2004 | 0.2 eμA | 0.15 eμA | 0.15 eμA | 0.01eμA |
| Beam intensity in recent years | 0.5 eμA | 0.6 eμA | 3.5 eμA | 0.7 eμA |

## Typical beams provided by SFC and SSC in recent years

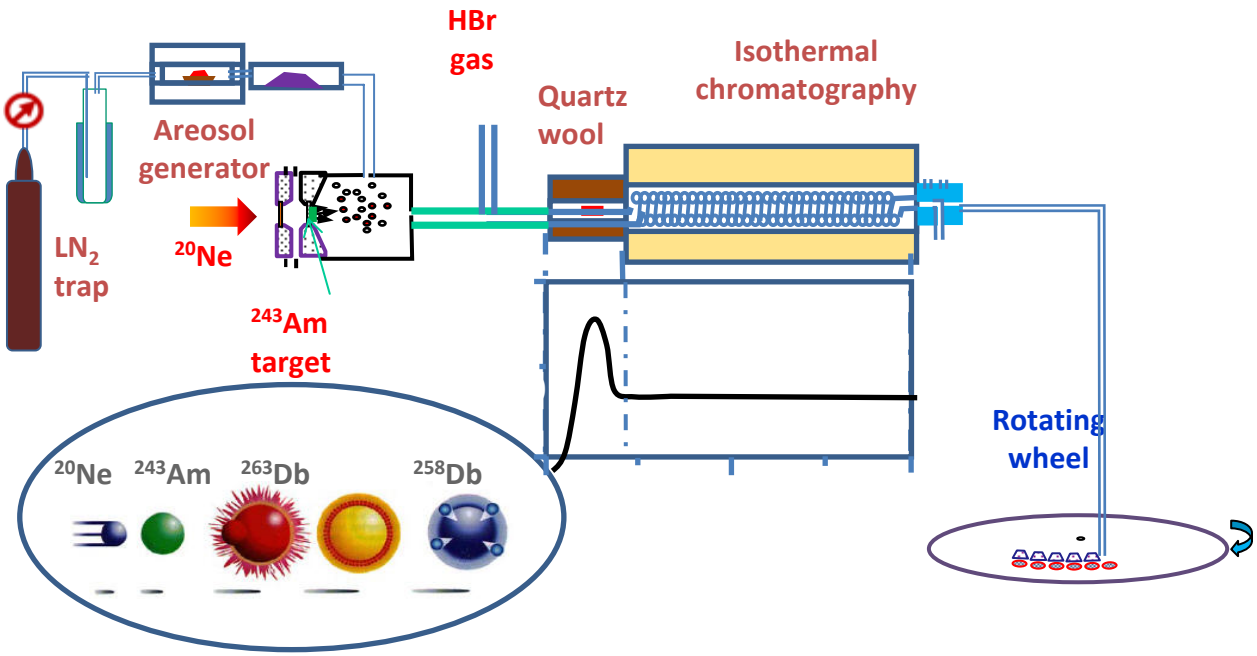
1. SSC beam intensities are still very low and need to be improved.
2. Beam long-term stability need to be improved.

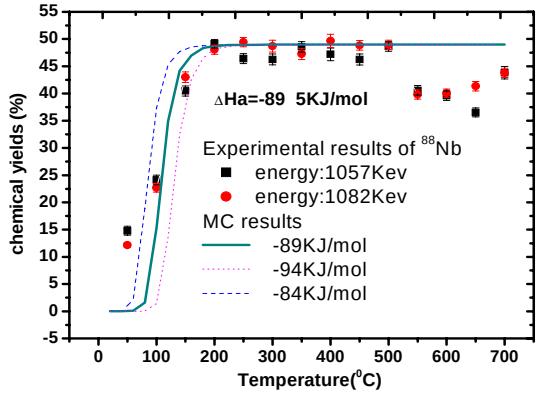
| Ion Beams | E (MeV/A) | | Beam Intensity (eμA) |
|---|---|---|---|
| | SFC | SSC | |
| $^{129}Xe^{27+}$ | 3.0 | / | 5.0-6.0 |
| $^{208}Pb^{27+}$ | 1.1 | / | 0.8-1.0 |
| $^{40}Ca^{12+}$ | 5.8 | / | 1.0 |
| $^{20}Ne^{7+}$ | 7.2 | / | 10-12 |
| $^{12}C^{4+}$ | 7.0 | / | 10-15 |
| $^{26}Mg^{8+}$ | 6.54 | / | 2.0 |
| $^{16}O^{6+}$ | 7.99 | / | 6-12 |
| $^{40}Ar^{8+}$ | 2.35 | / | 6-15 |
| $^{78}Kr^{19+}$ | 4.0 | | 7-9 |
| $^{238}U^{26+}$ | 0.81 | / | 0.33 |
| $^{12}C^{4+/6+}$ | 7.0 | 80.5 | 0.2-0.5 |
| $^{12}C^{5+/6+}$ | 8.2 | 100 | 0.2-0.3 |
| $^{32}S^{11+/16+}$ | 7.1 | 82 | 0.2-0.3 |
| $^{26}Mg^{8+/12+}$ | 6.17 | 70 | 0.3-0.4 |
| $^{40}Ar^{12+/17+}$ | 7.1 | 82 | 0.1-0.3 |
| $^{209}Bi^{31+}$ | 0.88 | 9.8 | 0.1—0.3 |
| $^{22}Ne^{7+/10+}$ | 6.17 | 70 | 0.2-0.5 |
| $^{58}Ni^{13+/22+}$ | 4.5 | 50 | 0.1-0.2 |
| $^{129}Xe^{27+}$ | 1.8 | 19.5 | 0.3-0.75 |
| $^{36}Ar^{8+}$ | 2.07 | 22 | 2.5-3.5 |

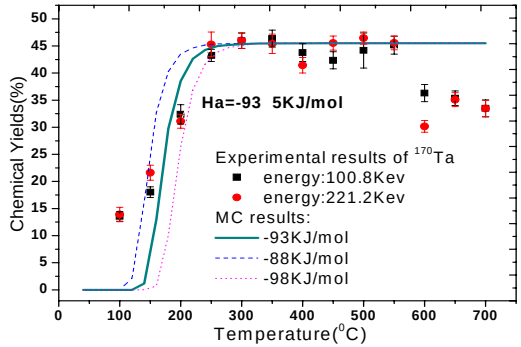
# Upgrading of HIRFL Cyclotron in the past 10 years

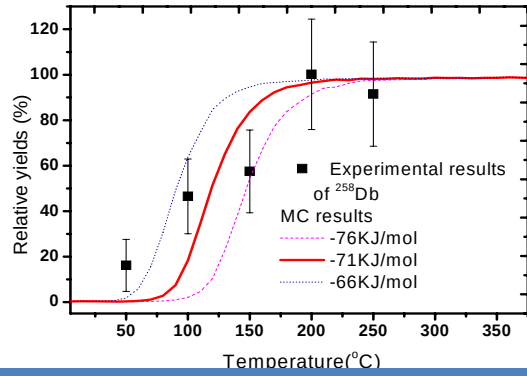
- Built a new SFC vacuum chamber
- Built two rebunchers NB1 and NB2 located between SFC and SSC
- Renovated most of old power supplies of HIRFL system
- Improve rf Dee voltage for SFC and SSC
- Upgrading SFC Axial injection beam line
- Built a new ECRIS and study beam quality from ECRIS
- Developed a new chopper for intense pulsed beam of HIRFL-CSR
- Upgrading Control and diagnostic systems
- Machine studies to improve beam intensities and stability
- …….

# Gas-phase chemistry with bromides of group 5 elements at HIRFL




**Adsorption enthalpy on quartz**

**$NbBr_5$ : -89 ± 5 kJ/mol,**

**$TaBr_5$ : -102 ±5 kJ/mol,**

**$DbBr_5$ : -71 ± 5kJ/mol**

**Volatility: $DbBr_5 > NbBr_5 > TaBr_5$**

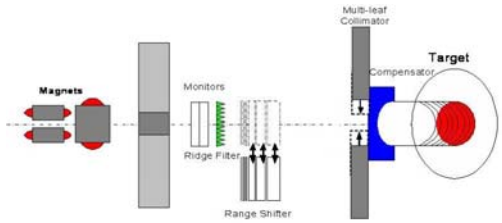
**Conclusion: experimental data consistent with relativistic self-consistent Dirac -Slater calculation, there are "relativistic effect" on the chemical properties of Db**

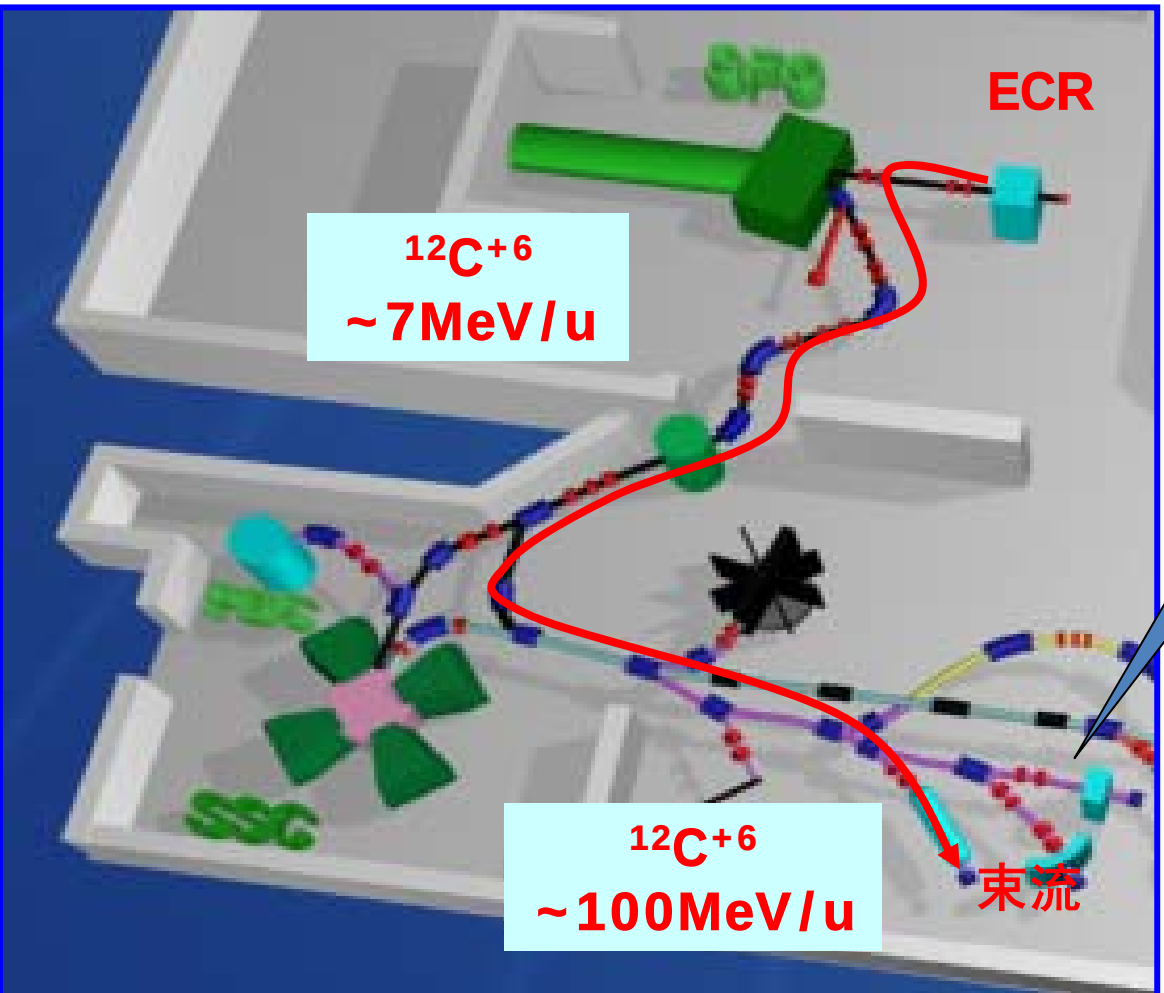
# Clinical Treatment for the shallow-seated Tumor therapy

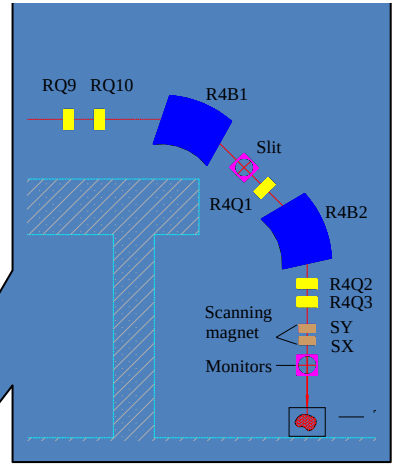
**103 patients**

➢**Double Cyclotron combination SFC+SSC**

**3D conformal irradiation method**



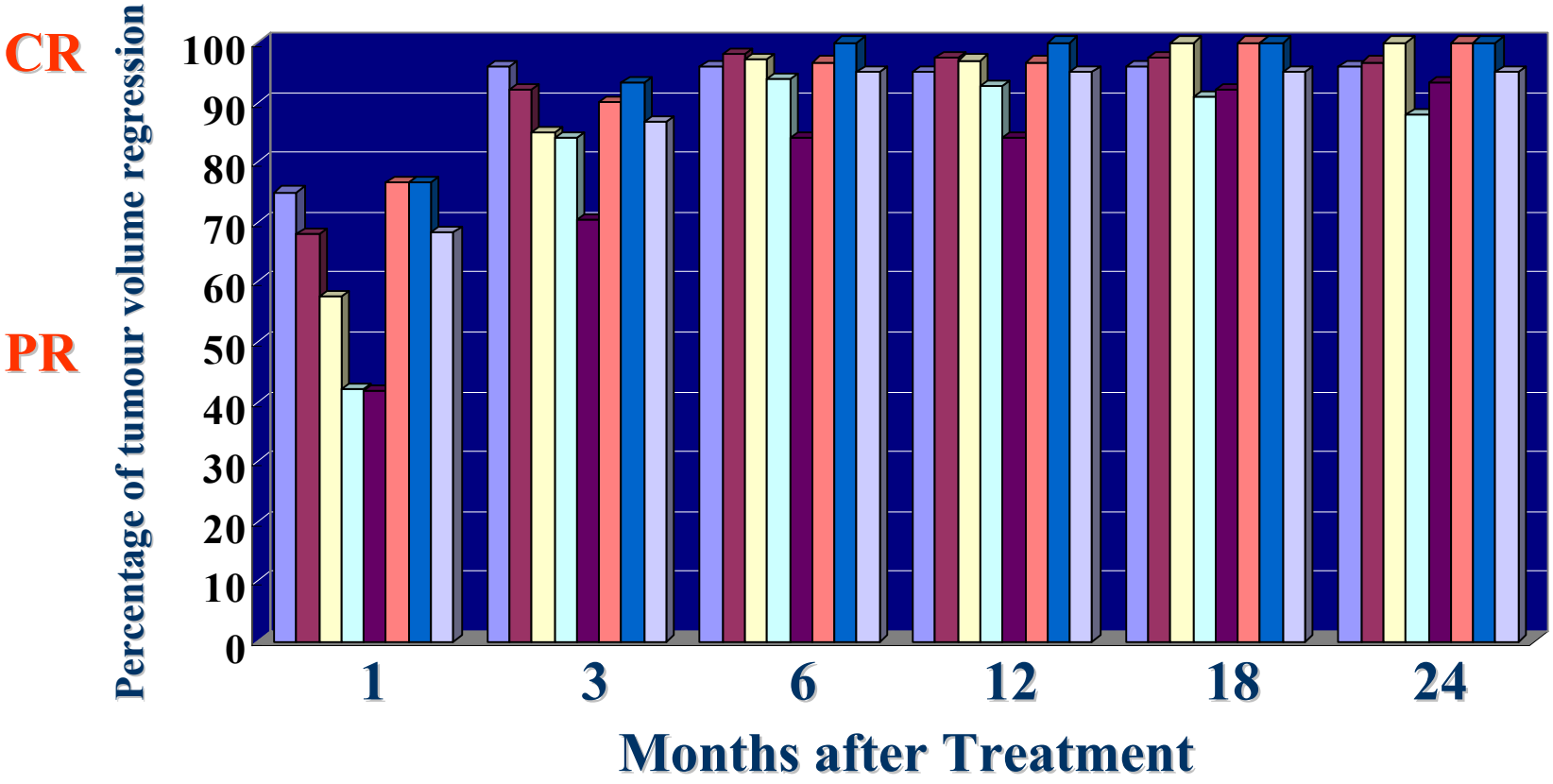




- Collaborated with local hospitals
- 103 patients treated for ~10 kinds of shallow-seated tumors (SSC)
- 8 patients for deep-seated tumors by HIRFL-CSR

| Treatment date | depth | N |
|---|---|---|
| Nov. 2006 | 1.6cm | 4 |
| Jan.2007 | 2.1 cm | 9 |
| March 2007 | 2.1 cm | 14 |
| August 2007 | 2.1 cm | 9 |
| Dec. 2007 | 2.1 cm | 15 |
| March 2008 | 2.1 cm | 15 |
| Sept. 2008 | 2.1 cm | 16 |
| March 2009 | 2.1 cm | 21 |
| April, July 2009 | 3~11 cm | 8 |

# Local Control Rates Following Treatment of 100 Patients




- Squamous cell carcinoma (42-70.4GyE/4-10fr)
- Basal cell carcinoma (54.8-61.2GyE/6-11fr)
- Malignant skin melanoma (61-75GyE/6-7fr)
- Sarcoma (51-65.7GyE/6-11fr)
- Other skin lesions (30-60GyE/6-8fr)
- Lymphoma (40-54GyE/6-9fr)
- Adenocarcinoma (40-60GyE/6-9fr)
- Metastatic lymph nodes of carcinomas (40-70GyE/6-11fr)

*Int J Mol Med*, 2008,22(suppl.) :186

# HIRFL-Cyclotron Development

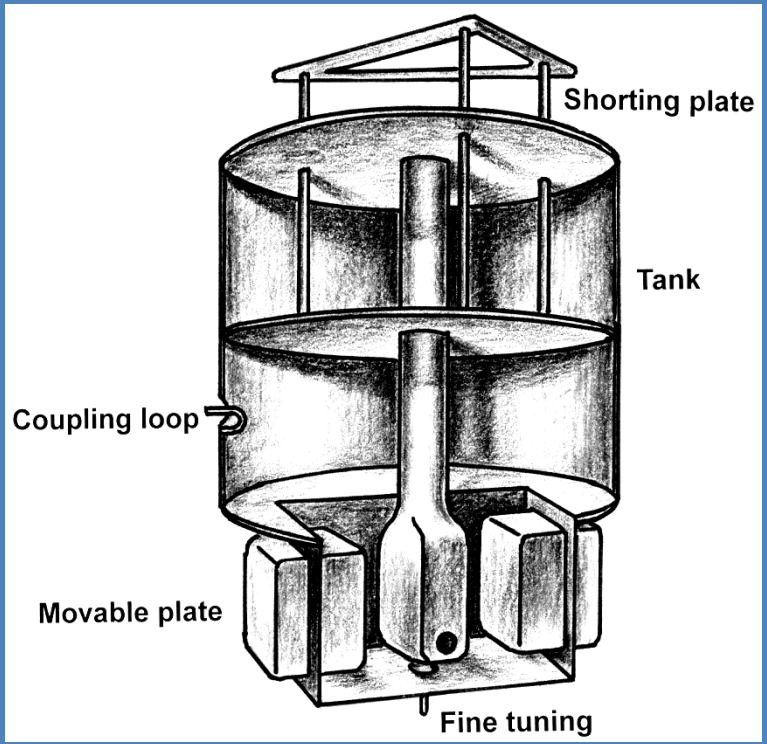
# Rebunchers NB1 and NB2

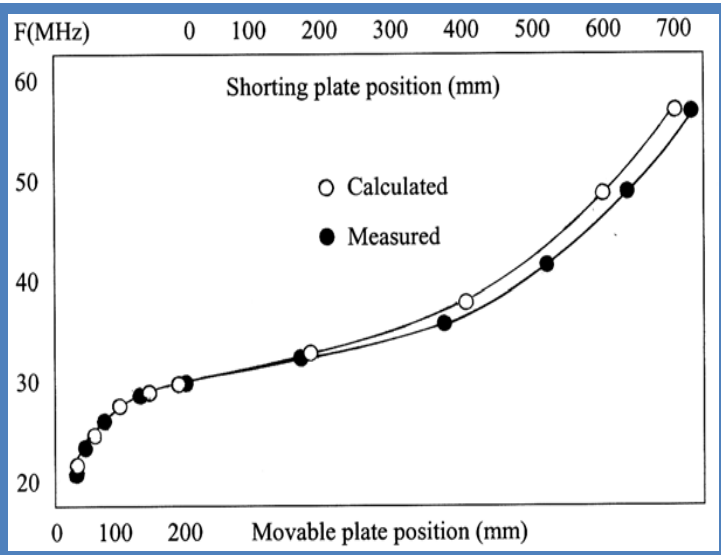
## Main parameters

| | |
|---|---|
| **Frequency** | **22～54 MHz** |
| **Peak voltage** | **150 kV** |
| **RF power** | **40 kW** |
| **Phase stability** | **±0.7** |
| **Amplitude stability** | **$1\times10^{-3}$** |
| **Frequency stability** | **$5\times10^{-6}$** |
| **Vacuu pressure** | **$1\times10^{-5}$ Pa** |

Buncher cavity structure:

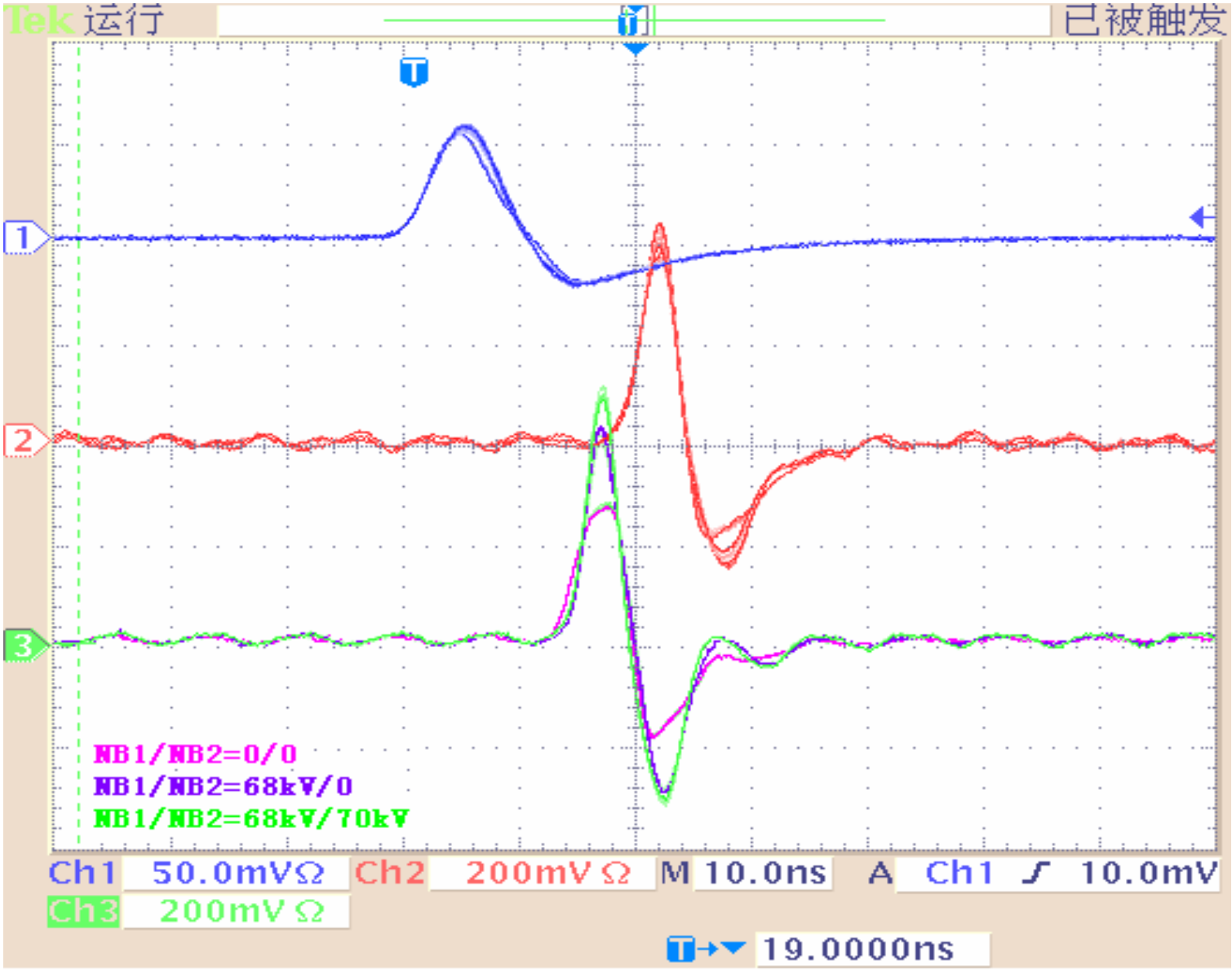
λ /4 coaxial resonator + double-gap drift tube



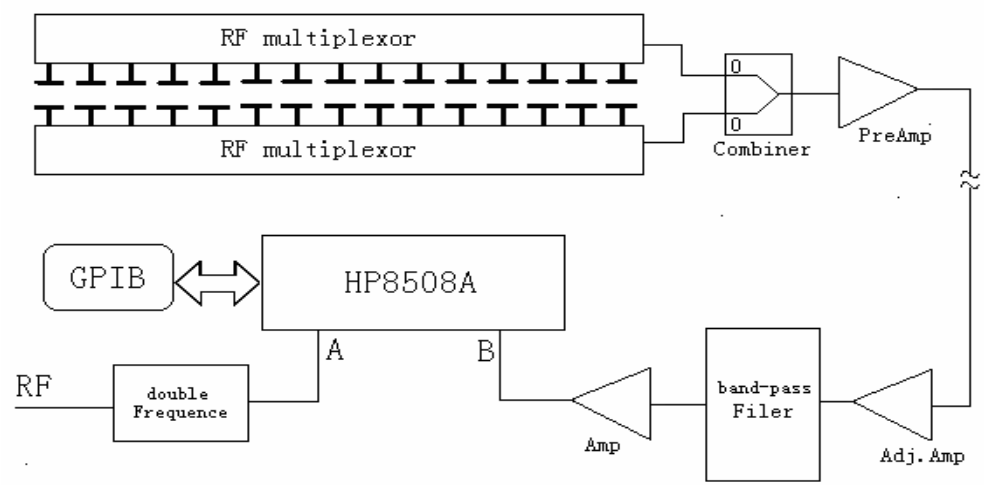



# NB1 and NB2


# NB1+NB2

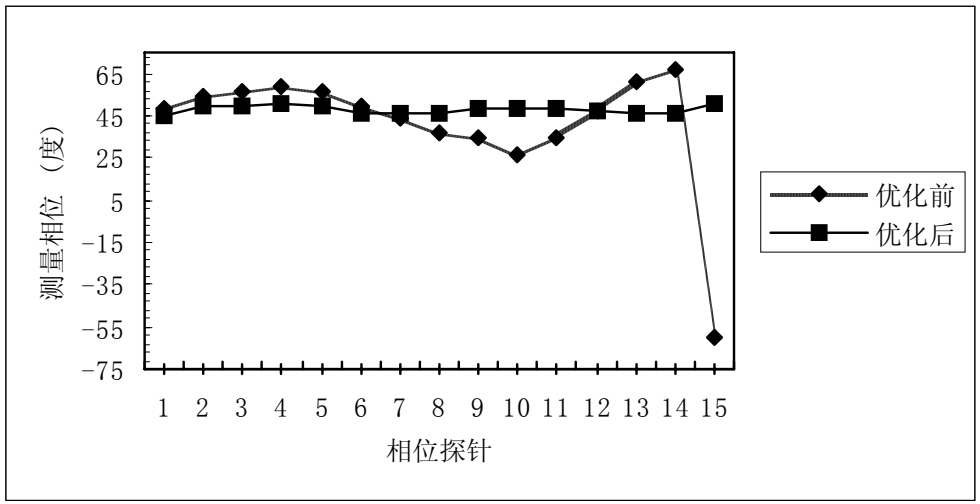

Tek 运行
已被触发
1
2
3
NB1/NB2=0/0
NB1/NB2=68kV/0
NB1/NB2=68kV/70kV
Ch1 50.0mVΩ
Ch2 200mV Ω
M 10.0ns
A Ch1 ∫ 10.0mV
Ch3 200mV Ω
19.0000ns

# Isochronous Field Optimization at SSC

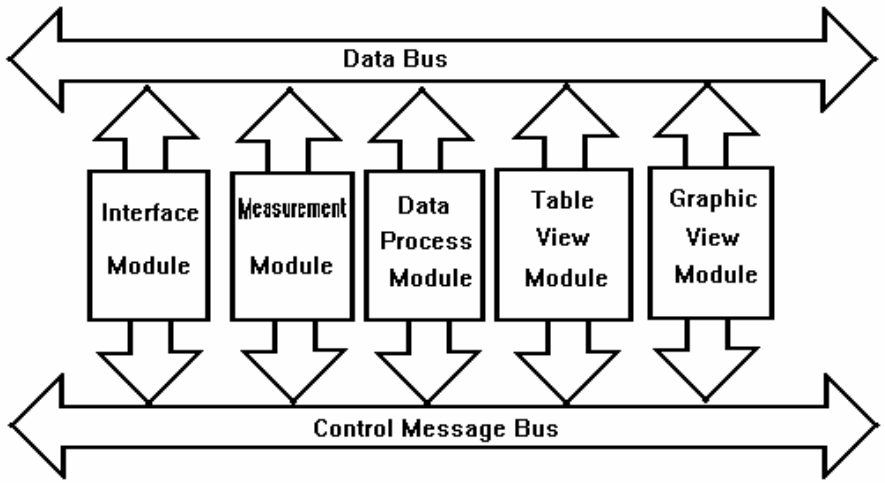



**Beam phase measurement structure**

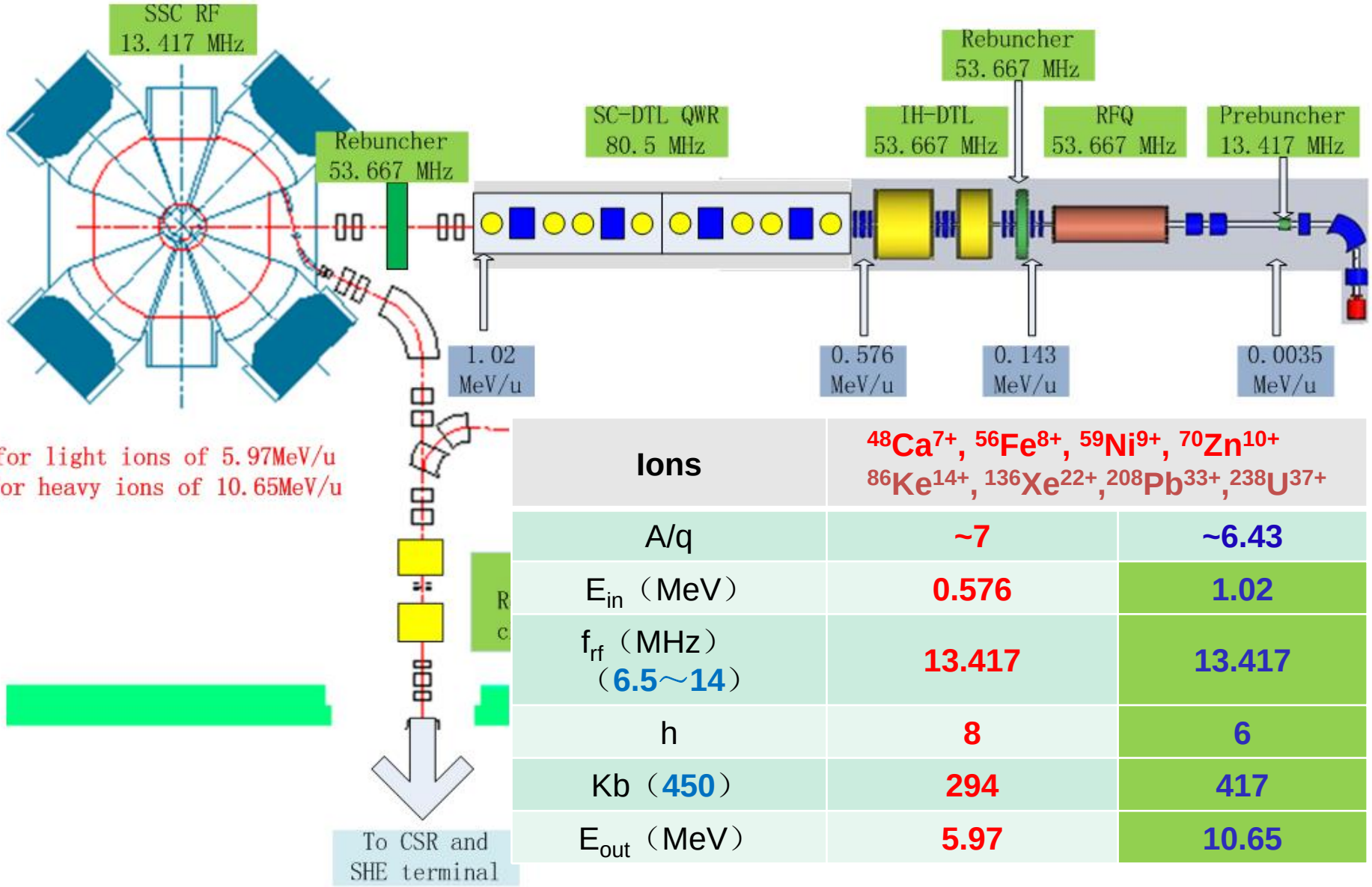
**Isochronous field optimization at SSC has been conducted successfully. And has been used in beam tuning. But it has not yet become a routine tool in operation because of control system.**




**Beam: 25 MeV/u $^{40}Ar^{15+}$**



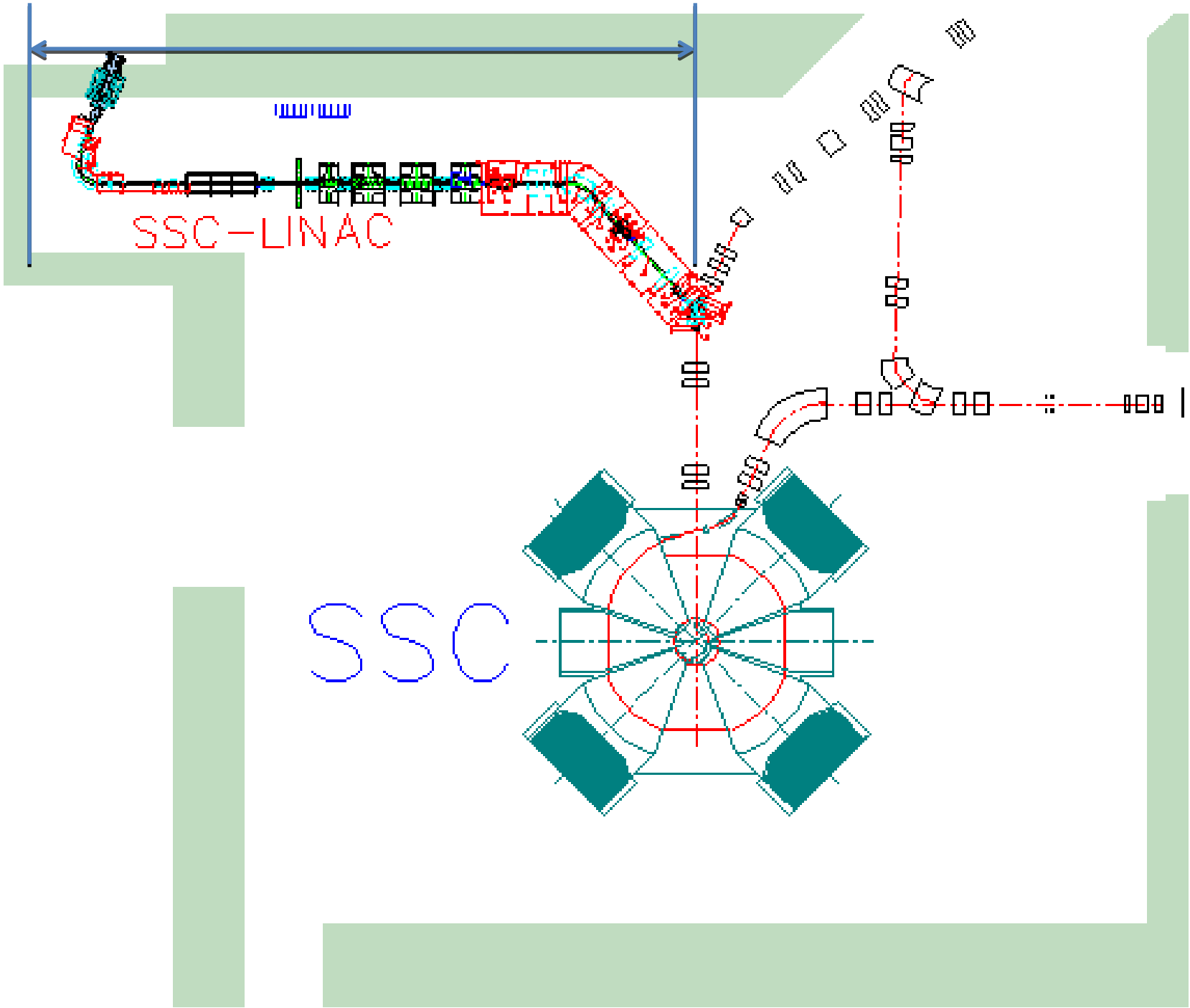
# SSC-LINAC




| Ions | $^{48}Ca^{7+}$, $^{56}Fe^{8+}$, $^{59}Ni^{9+}$, $^{70}Zn^{10+}$ $^{86}Ke^{14+}$, $^{136}Xe^{22+}$, $^{208}Pb^{33+}$, $^{238}U^{37+}$ | |
|---|---|---|
| A/q | ~7 | ~6.43 |
| $E_{in}$（MeV） | 0.576 | 1.02 |
| $f_{rf}$（MHz）（6.5～14） | 13.417 | 13.417 |
| h | 8 | 6 |
| Kb（450） | 294 | 417 |
| $E_{out}$（MeV） | 5.97 | 10.65 |

# SSC-LINAC Main Parameters

| | |
|---|---|
| SSC rf requency | 13.417 MHz |
| RFQ /DTL/QWR frequency | 53.667/80.5 MHz |
| A/Q | 7 |
| Extraction voltage of ion source | 26 kV |
| Emittance (90%nomalized) | 0.6 |
| Input Energy of RFQ | 35 KeV/u |
| Output energy 1（SHE） | 0.576 MeV/u |
| Output energy 2 (CSR injection) | 1.020 MeV/u |
| Duty factor | 100% |


SSC-LINAC
SSC

# Expected beam intensity extracted from LINAC+SSC

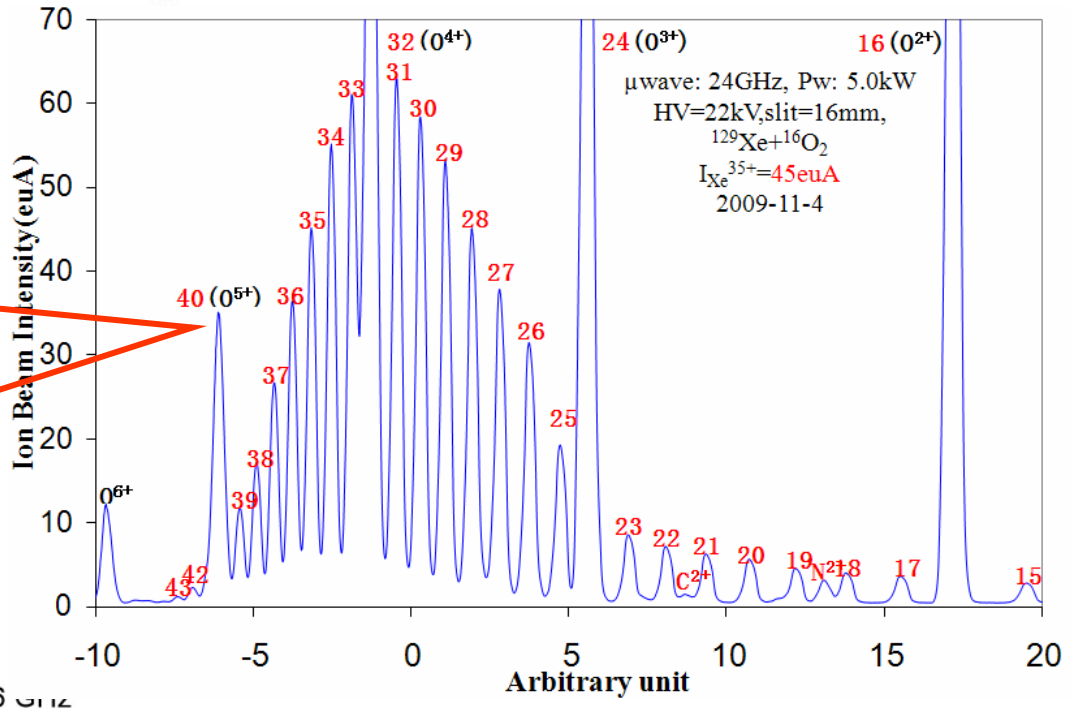
| | Energy MeV/u | ion | Intensity of ion source | Expected intensity | |
|---|---|---|---|---|---|
| | | | euA | puA | pps(E12) |
| LINAC+SSC | 5.9 | $^{48}Ca^{7+}$ | 120 | 0.8-2.0 | 5-12 |
| LINAC+SSC | 5.9 | $^{64}Ni^{10+}$ | 100 | 0.8-1.5 | 3.1-9.3 |
| LINAC+SSC | 5.9 | $^{70}Zn^{10+}$ | 100 | 0.8-1.5 | 3.1-9.3 |
| | | | euA | euA | puA |
| LINAC+SSC | 10 | $^{86}Kr^{14+}$ | 100 | 6-18 | 0.45-1.3 |
| LINAC+SSC | 10 | $^{136}Xe^{22+}$ | 160 | 9.5-28 | 0.48-1.4 |
| LINAC+SSC | 10 | $^{238}U^{37+}$ | 30 | 1.7-5.2 | 0.05-0.15 |

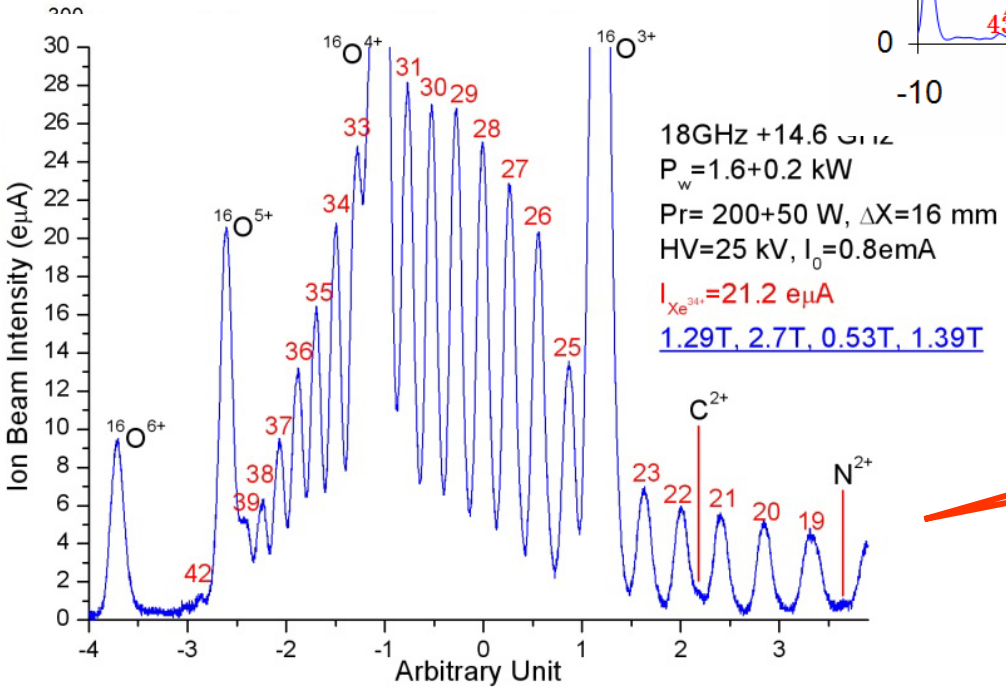
# SECRAL Status and Operation at HIRFL-Cyclotron

SECRAL with 24GHz/7kW Gyrotron System

# SECRAL 24GHz –Xe Beam

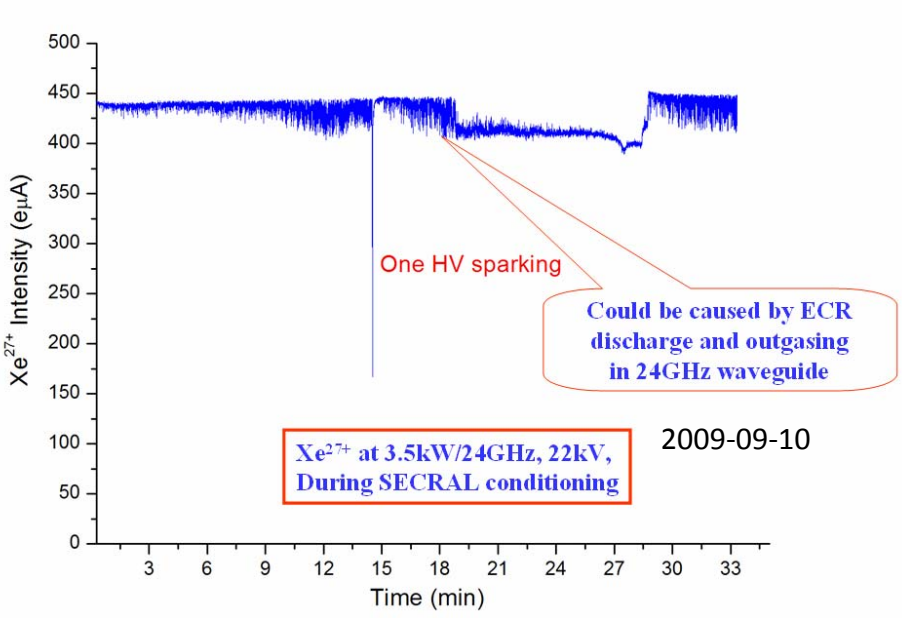
- SECRAL 24GHz, Xe HCl
- Optimize $Xe^{34+}$, $Xe^{35+}$at 3-5kW.
- With stainless steel chamber.
- Source conditioning more important and complicated.

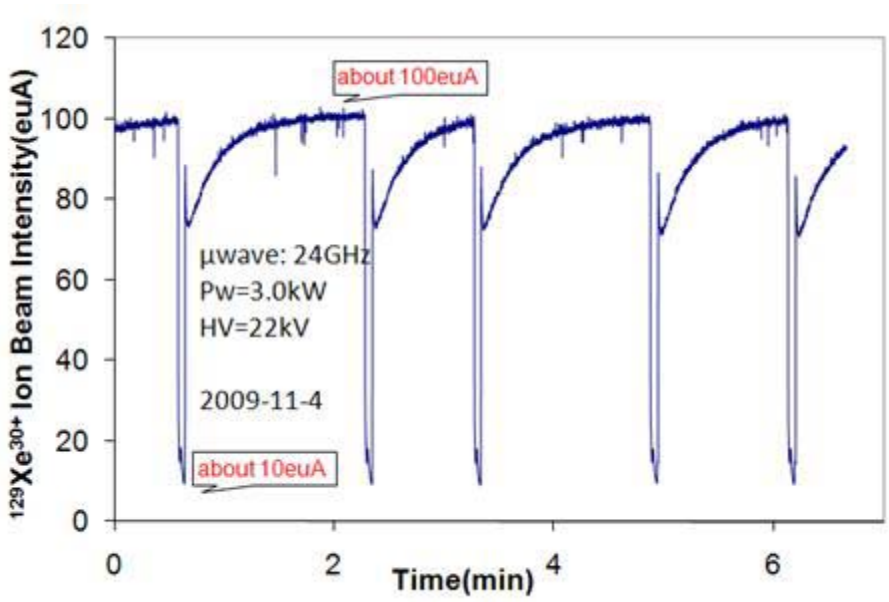


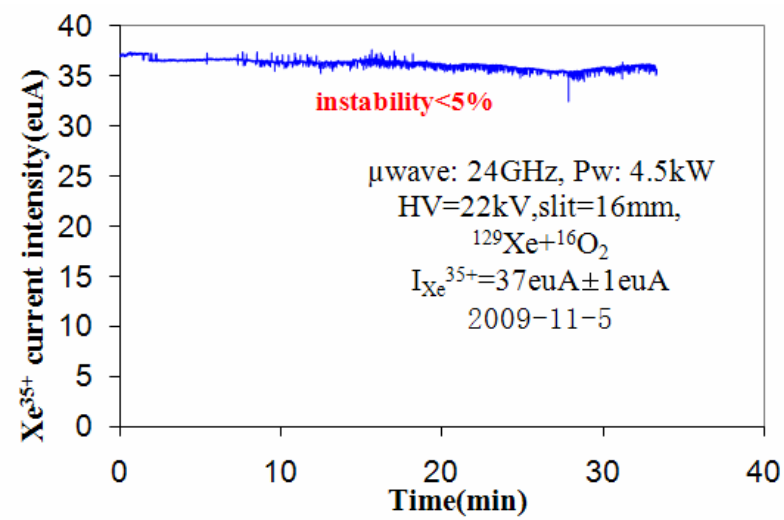




SECRAL 18+14.5GHz
Optimize $Xe^{34+}$ at 1.8 kW.
With Al chamber.

# Beam Stability at 24GHz/3-5 kW



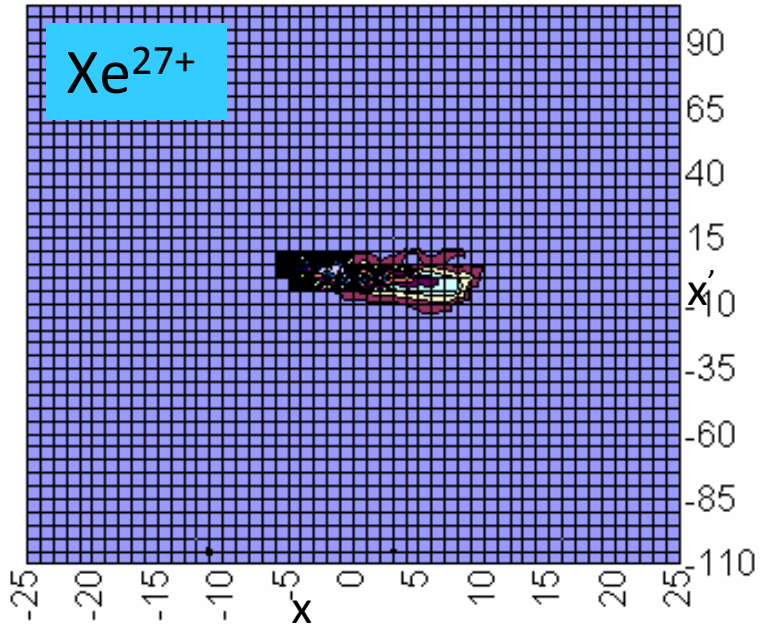



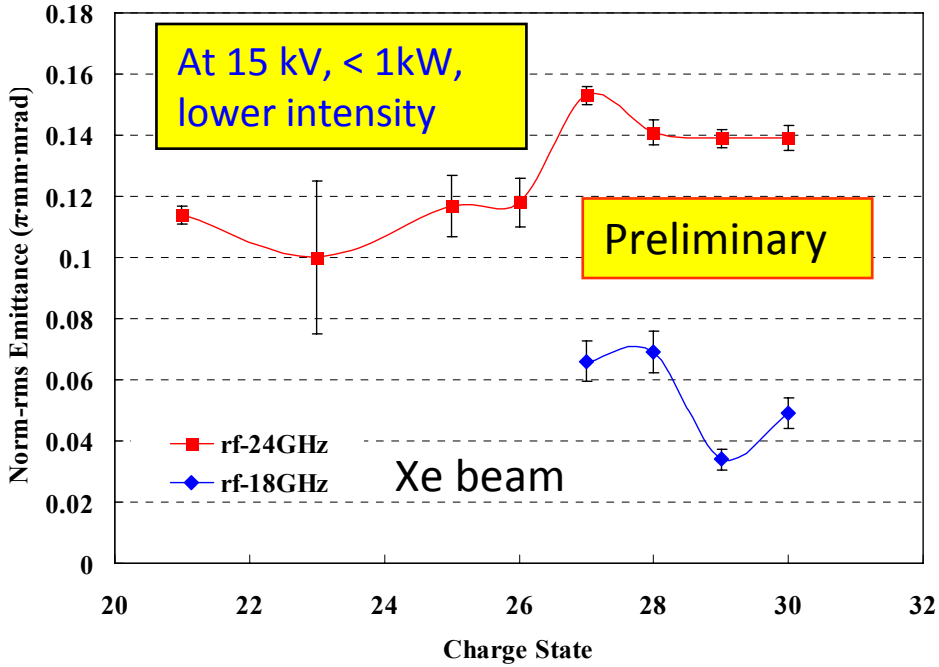

Beam long-term stability at 24GHz/3-5 KW is not as good as that at 18GHz/3kW. Reasons need to be studied.

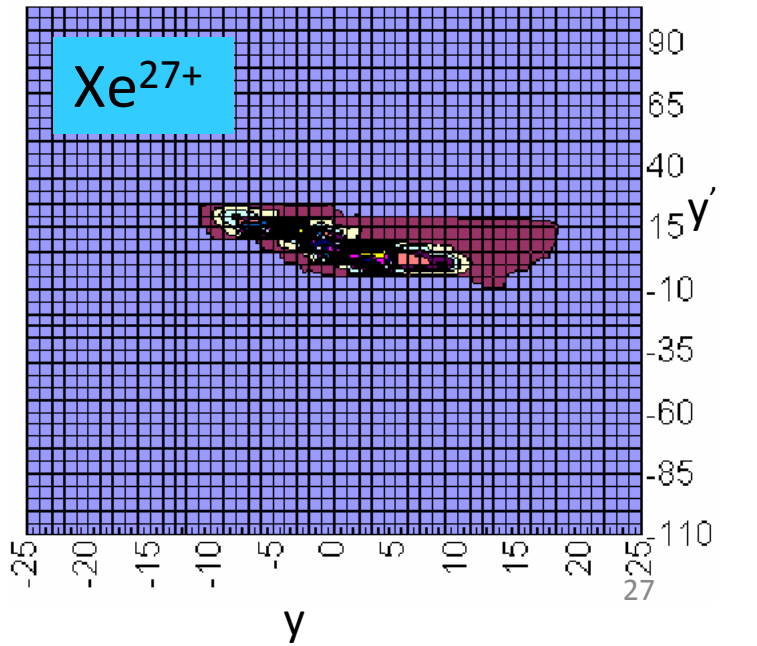
# Beam quality study at SECRAL

Use M. Stockli's code to process data

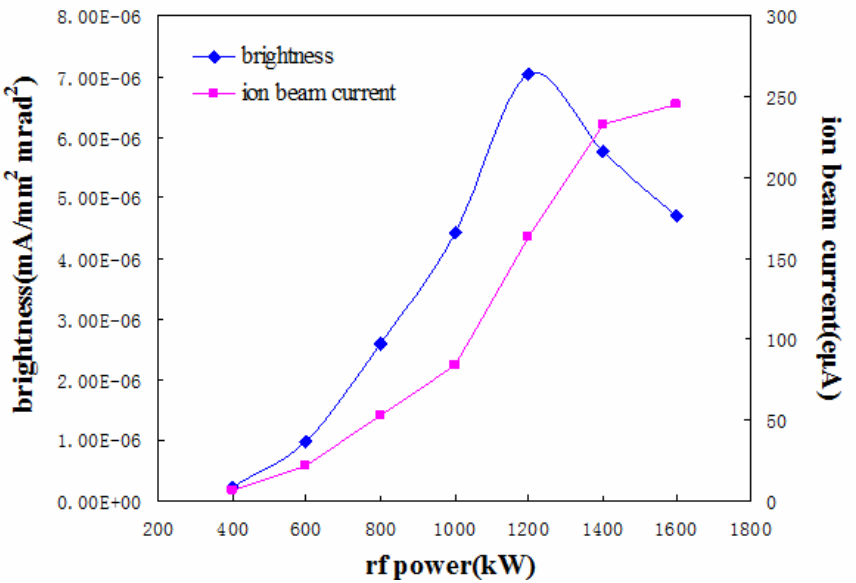
IMP Allison-type emittance scanner.
Located after the analyzing magnet

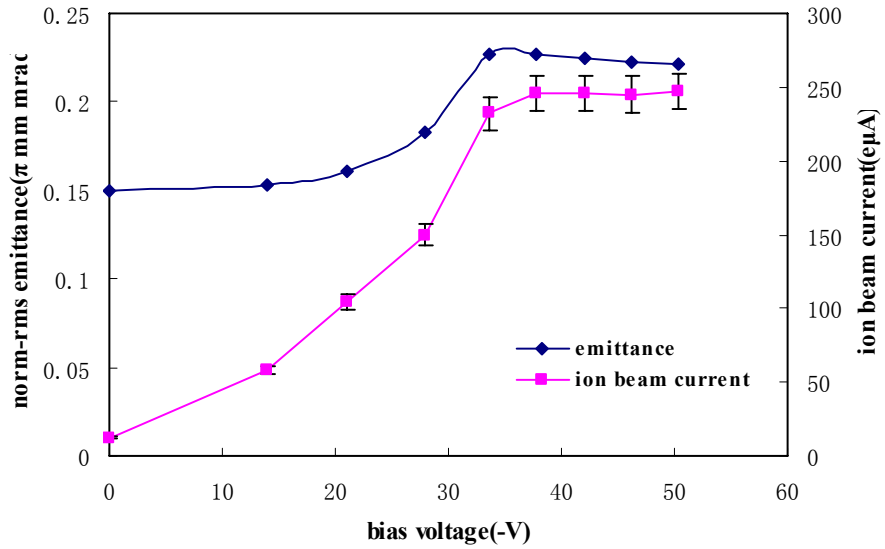


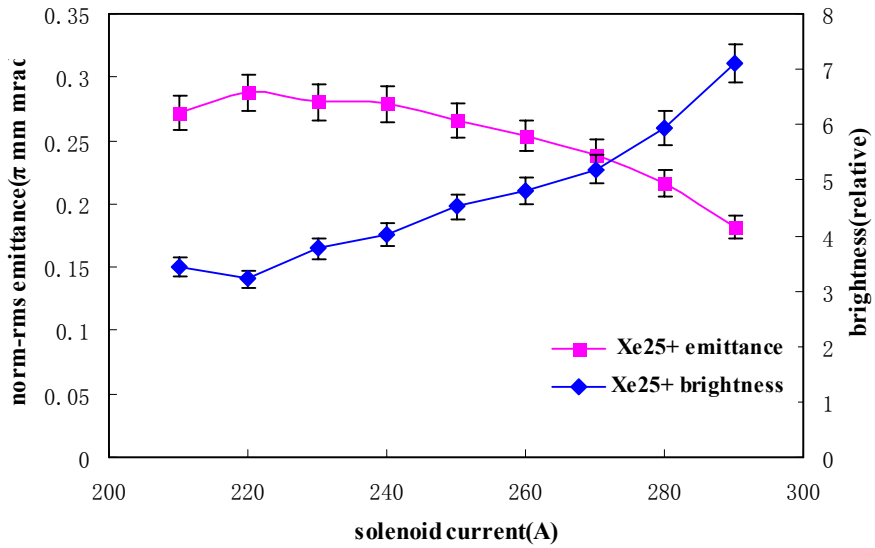



# Emittance/Brightness VS RF power, bias voltage, solenoid lens current at 18GHz

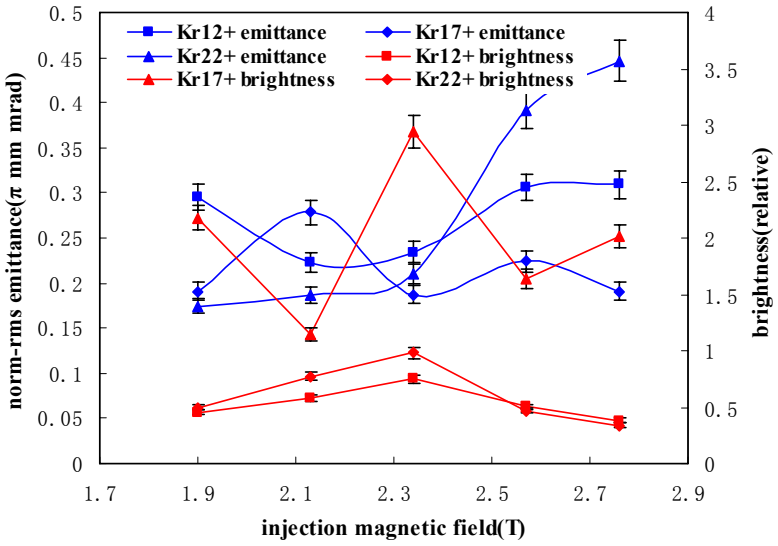


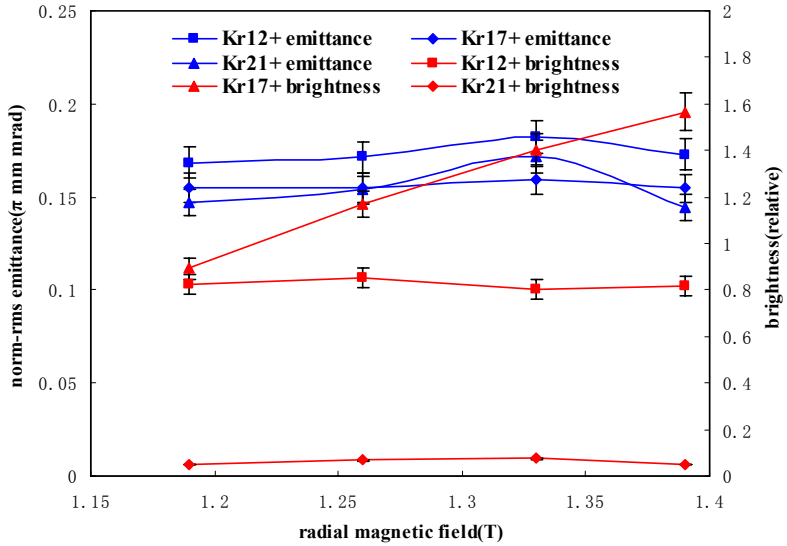



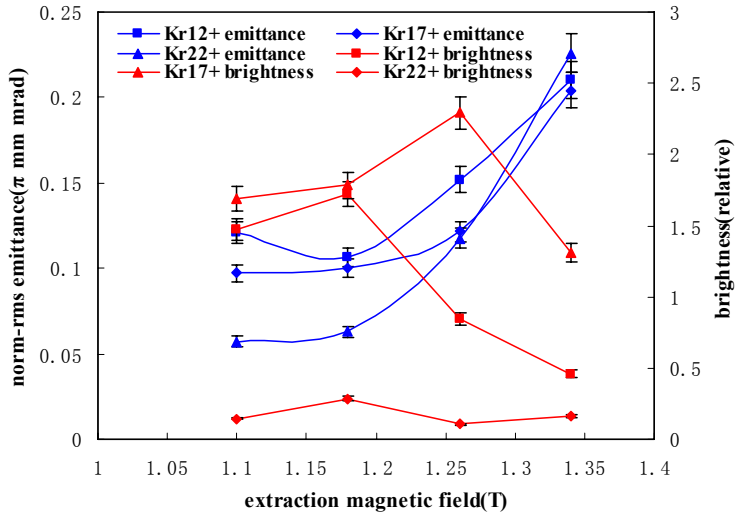




$Xe^{25+}$ optimized, rf frequency: 18GHz, HV: 22kV, drain current: 5.04emA, beam current: 245e μ A , slitX: 20mm.

# Emittance/Brightness VS magnetic fields at 18GHz



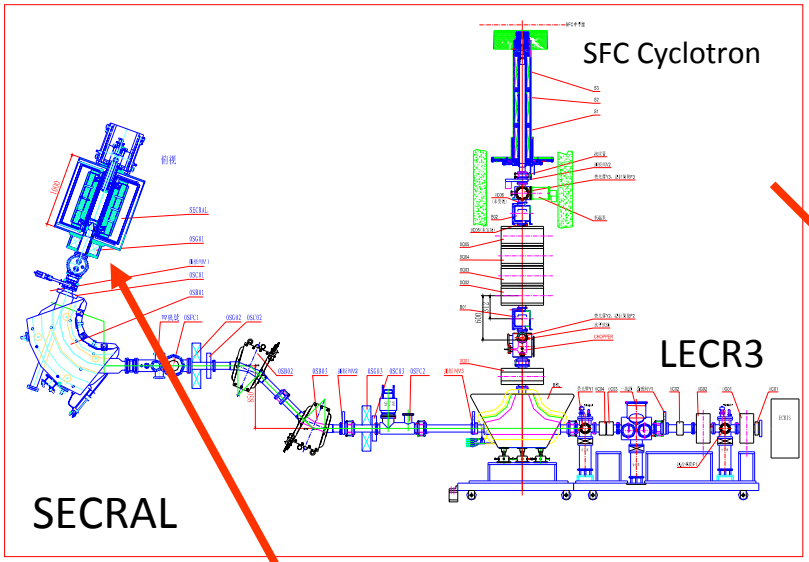



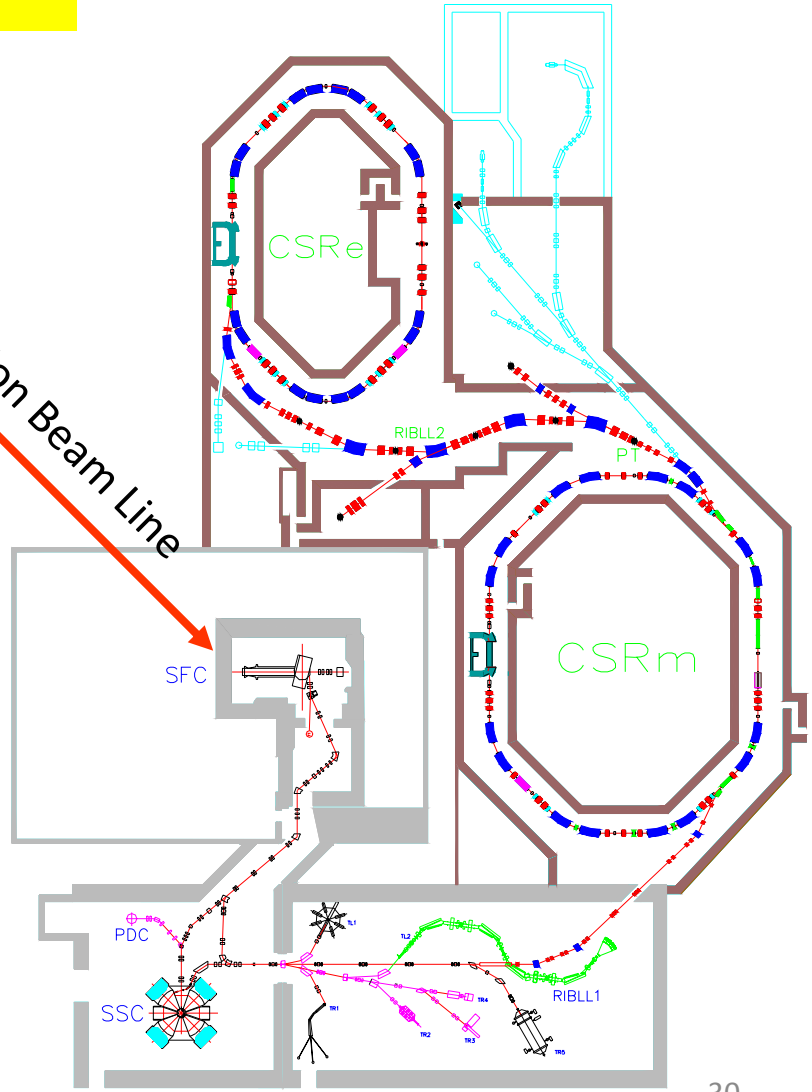

**$Kr^{17+}$ optimized, rf :18GHz, 1.5kW. HV: 15kV, beam current: 100e μ A, drain current: 3.1emA**

# SECRAL Operation for HIRFL Accelerator Since May 2007

SECRAL is dedicated only for operation of highly charged heavy ion beams.




HIRFL Accelerator Complex
At IMP lanzhou



# SECRAL Operation for HIRFL Accelerator

- Beams operated for HIRFL accelerator:
  $^{209}Bi^{31+}$, $^{129}Xe^{27+}$, $^{78}Kr^{19+}$, $^{58}Ni^{19+}$
  At 18GHz, typical rf power 1.0-2.0 kW, extraction voltage 10-22kV
  **Beam intensity during operation:**
  **100-150 eμA for Xe, Kr , 50-70 eμA for, $Bi^{31+}$, $Ni^{19+}$(9.8kV)**

- **One month continuous operation, $^{78}Kr^{19+}$ in Oct.09 and $^{209}Bi^{31+}$ in Jul. 10**

- **Total beam time from SECRAL for HIRFL: >3500 h**

- **With $^{78}Kr$ beams at CSRe, 9 new nuclides ($^{63}Ge$,$^{65}As$,$^{67}Se$…) were identified firstly in the world with $\Delta m/m=10^{-6}$**

# Beam intensity enhancement at HIRFL-Cyclotrons by SECRAL

**Maximum operational beam intensities from SFC achieved with SECRAL and compared with those with LECR2-3**

| SFC | Kr<br>2-4 MeV/u | Xe<br>2-3 MeV/u | Bi<br><1 MeV/u |
|---|---|---|---|
| Beam intensity with LECR2-3 | $Kr^{17+}$<br>2-3 eμA | $Xe^{26+}$<br>0.54 eμA | Not available |
| Beam intensity with SECRAL | $Kr^{19+}$<br>7-10 eμA | $Xe^{27+}$<br>5-6 eμA | $Bi^{31+}$<br>5-6 eμA |

**Maximum operational beam intensities from SSC achieved with SECRAL and compared with those with LECR2-3**

| SSC | Xe<br>15-20 MeV/u | Bi<br>9.8 MeV/u |
|---|---|---|
| Beam intensity with LECR2-3 | $Xe^{26+}$<br>0.01 eμA | Not available |
| Beam intensity with SECRAL | $Xe^{27+}$<br>0.6-0.7 eμA | $Bi^{31+}$<br>0.1-0.3 eμA |

# Problems of SECRAL operation for HIRFL accelerator

- Low extraction voltage (<15kV for high Q heavy ions)
- Cyclotron beam very sensitive to the plasma conditions due to variations of beam extraction, emittance and image.
- Need to refill LHe if the additional cryostat is not operated normally
- Control board of the CPI 18GHz rf generator sometimes broken if there is spark
- The long term stability of beam $^{209}Bi^{31+}$ and $^{129}Xe^{27+}$ is not as good as that of last year due to micro-leakage at the extraction insulator and one cooling tube in the injection component.

# SECRAL Status

- Now almost all record beam intensities are produced by SECRAL and VENUS
- SECRAL was tested at 24GHz and results are promising. Beam test at 24GHz has not been conducted since last November due to failure of the gyrotron power supply system .
- Beam time from SECRAL for HIRFL accelerator has been more than 3500 h at 18GHz operation. But beam quality and long-term stability at high RF power、high intensity need to be studied carefully.
- SECRAL beam test and operation at 24GHz will continue and better results should be coming up. U beam test will be conducted with a new HT oven.

A new SC-ECRIS is under design at IMP .

| | Q | SECRAL *18 GHz* *<3.2 kW* *μA* | SECRAL 24GHz *3-5kW* *μA* | VENUS *28 GHz* *5-9kW* *μA* |
|---|---|---|---|---|
| $^{16}O$ | 6+ | 2300 | | 2860 |
| | 7+ | 810 | | 850 |
| $^{40}Ar$ | 12+ | 510 | 650 | 860 |
| | 14+ | 270 | 440 | 514 |
| | 16+ | 73 | 149 | 270 |
| | 17+ | 8.5 | 14 | 36 |
| $^{129}Xe$ | 20+ | 505 | | |
| | 27+ | 306 | 455 | 411 |
| | 30+ | 101 | 152 | 211 |
| | 31+ | 68 | 85 | |
| | 34+ | 21 | 60 | 40 |
| | 35+ | 16 | 45 | 38 |
| | 38 | | 17 | 7 |
| | 42+ | 1.5 | 3 | 0.5 |
| | 43+ | 1 | | |
| $^{209}Bi$ | 28+ | 214 | | 240 |
| | 30+ | 191 | | 225 |
| | 41+ | 22 | | 15 |
| | 44+ | 15 | | 7.7 |
| | 48+ | 4.2 | | 1.4 |
| | 50+ | 1.5 | | 0.5 |

# Conclusion

- HIRFL cyclotrons have delivered more than 5000 hours beams each year and beam intensities have been enhanced a lot in the past years. However, the main cyclotron SSC typical beam intensity for high energy and heavy ion is still quite low. Further research and upgrading are underway.

- To improve beam intensity from SSC, a small linac is being constructed as an independent injector for SSC.

- SECRAL SC-ECRIS has produced many record beam intensities and has been operated at 18GHz to deliver more than 3500 hours beams for HIRFL cyclotrons. Beam emittance and long-term beam stability should be studied carefully.

Thank you for your attention!