High-intensity highly charged ion beam production by superconducting ECR ion sources at IMP

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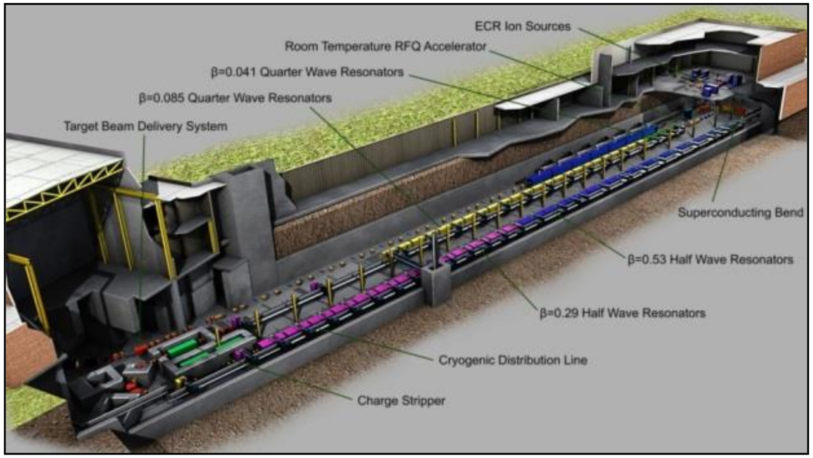
Outline

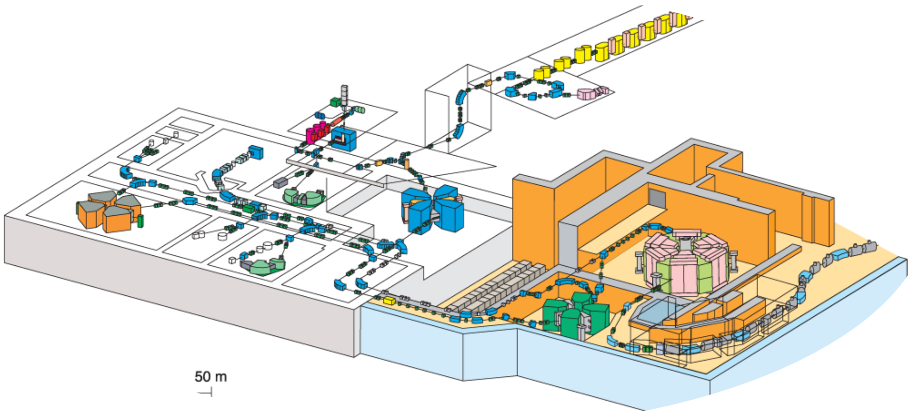
- Background and introduction
- High intensity HCI beam production by SECRAL and impact to HIRFL facility.
  3rd Gen. ECRIS
- Future development: IMP 45 GHz FECR.
  4th Gen. ECRIS
- Summary and conclusion

High power heavy ion accelerator requests intense HCI

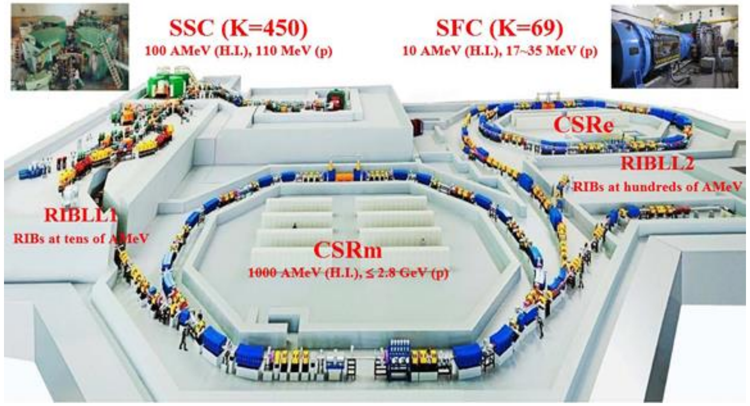
Accelerator facility for rare isotope beam production requests high intensity primary ion beams, which actually very much depends on performance of the front-end ion source



MSU FRIB U^{33+}+U^{34+} 13 pμA/ CW



RIKEN RIBF U^{35+} 500 eμA/ CW



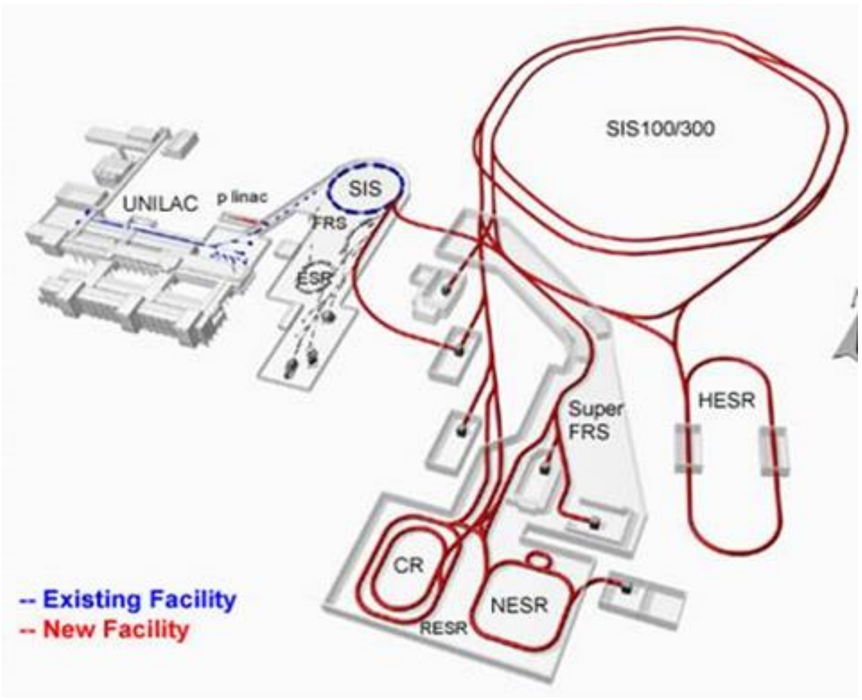
IMP HIRFL U^{41+} 100 eμA/ CW

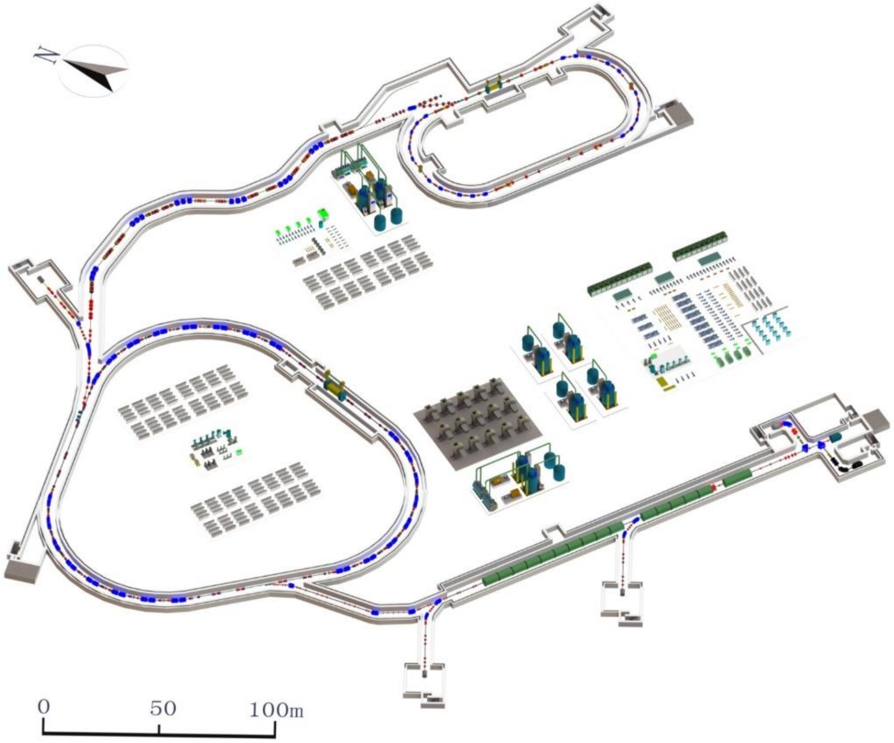
SPIRAL2 Ar^{12+} 1 emA/ CW

CW-intense highly charged ion(HCI) beams requested by RIB accelerator complex

High power RIB accelerator requests intense HCI beams

Pulsed-intense highly charged ion (HCI) beams requested by RIB accelerator complex



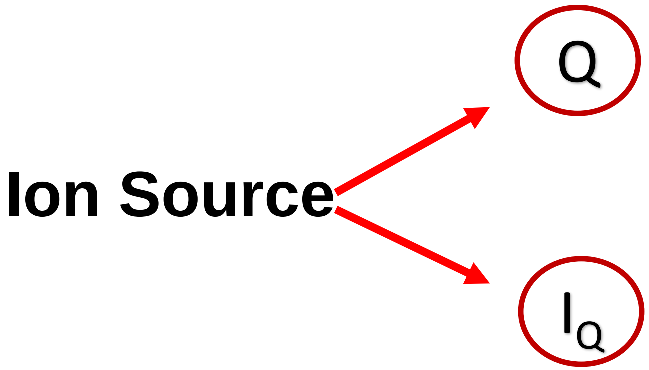


GSI @FAIR U^{28+} > 10emA pulsed

IMP HIAF U^{35+} 50 pμA pulsed

Why highly charged ion beams (1)?

Requirements of ion source for those high energy (GeV/u) high current heavy ion accelerators



$E \sim Q^2$ for cyclotrons
$E \sim Q$ for linac

Higher power
Simpler injection mode

Developing intense highly charged ion source is both performance-effective and cost-effective.

Why highly-charged ion beams (2)?

100 MeV/u SC heavy ion linac

	$^{238}U^{34+}$	$^{238}U^{46+}$	$^{238}U^{55+}$
Injection E（MeV/u）	1.3	1.3	1.3
Output E（MeV/u）	100	100	100
Design I_{max}（emA）	1.0	1.0	1.0
SC cavity			
SC cavities			
Solenoids	78	65	55
CRM Reduced		11	16
Total length（m）	288	225	197
Budget reduced		>70 M$ (MP not included)	>100 M$ (MP not included)

It is very much worthy of developing highly charged ion source aiming at very high charge state!!

Highly charged ECR ion source

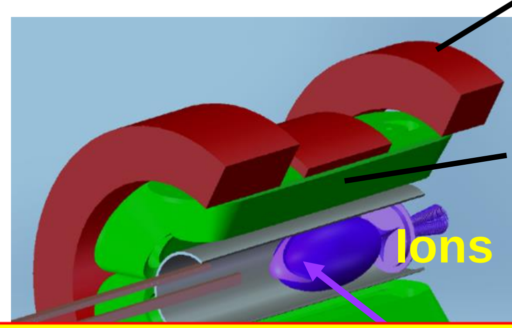
HCI ion source: EBIS;LIS;ECRIS. Only ECRIS for HCI DC and pulsed beam

ECRIS: Electron Resonance Cyclotron Ion Source

ECRIS

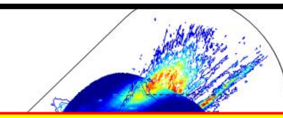
- Plasma ion source
- Plasma is produced and heated by microwave (10-28GHz)
- Plasma is confined by minimum-B magnetic field

Highly charged ECR ion source



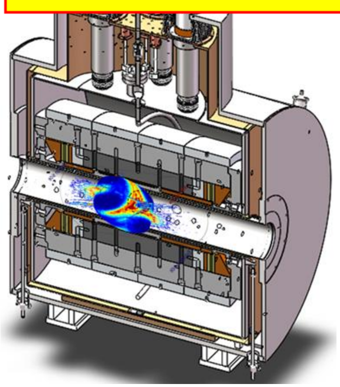
Axial mirror coils

Sextupole magnet



$$I_i^q = \frac{1}{2}\frac{n_i^q\, q\, e V_{ex}}{\tau_i^q}$$

Higher Q and higher I ⟹ Higher $n_e\tau_i$ ⟹ Higher ω_{rf} ⟹ Higher B
That is why we need to build SC-ECRIS, and also good device to study ECRIS physics.

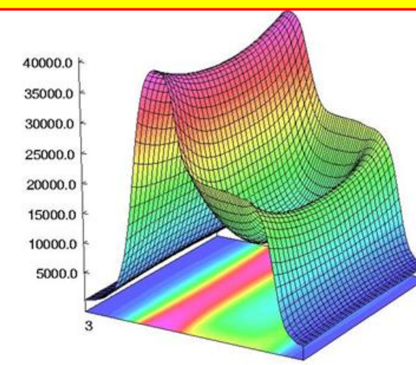


$B_{inj} \approx 4\, B_{ECR}$ $B_{ext} < B_{rad} \approx 2\, B_{ECR}$

$B_{min} \approx 0.8\, B_{rad}$

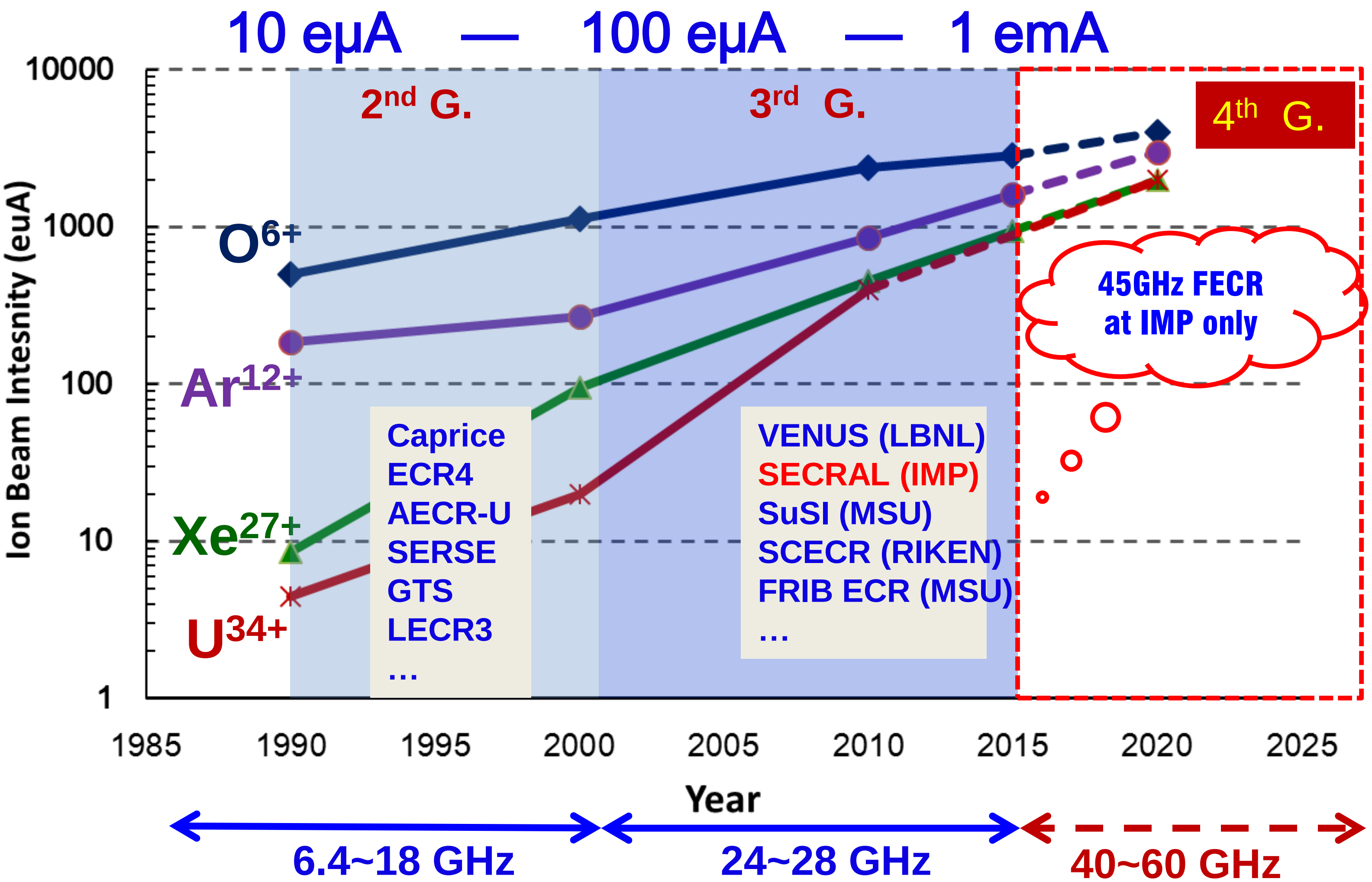
$I \propto \log B^{1.5}$

P_{rf}, f, B ⟺ n_e, T_e, τ_e, n_i, T_i, τ_i



Development of highly charged ECR ion source

Past, present and future

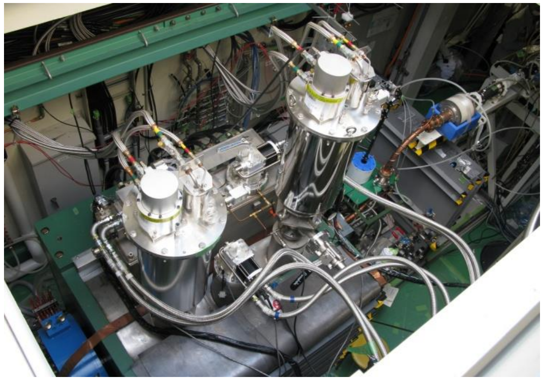


High performance superconducting ECRIS

VENUS@LBNL

SECRAL, SECRAL-II@IMP

SuSI@MSU



SCECRIS@RIKEN

Parameters	Unit	State of the Art ECRISs
ω_{rf}	GHz	24~28
P_{rf}	kW	10.0
B_{mirror}	T	3.5~4.0/2.2~2.8
B_r	T	1.8~2.0
Chamber ID	mm	Ø100~150
Mirror Length	mm	400~500
HV	kV	30

- Very high charge state
- ~ms pulse to dc beam
- High beam intensity

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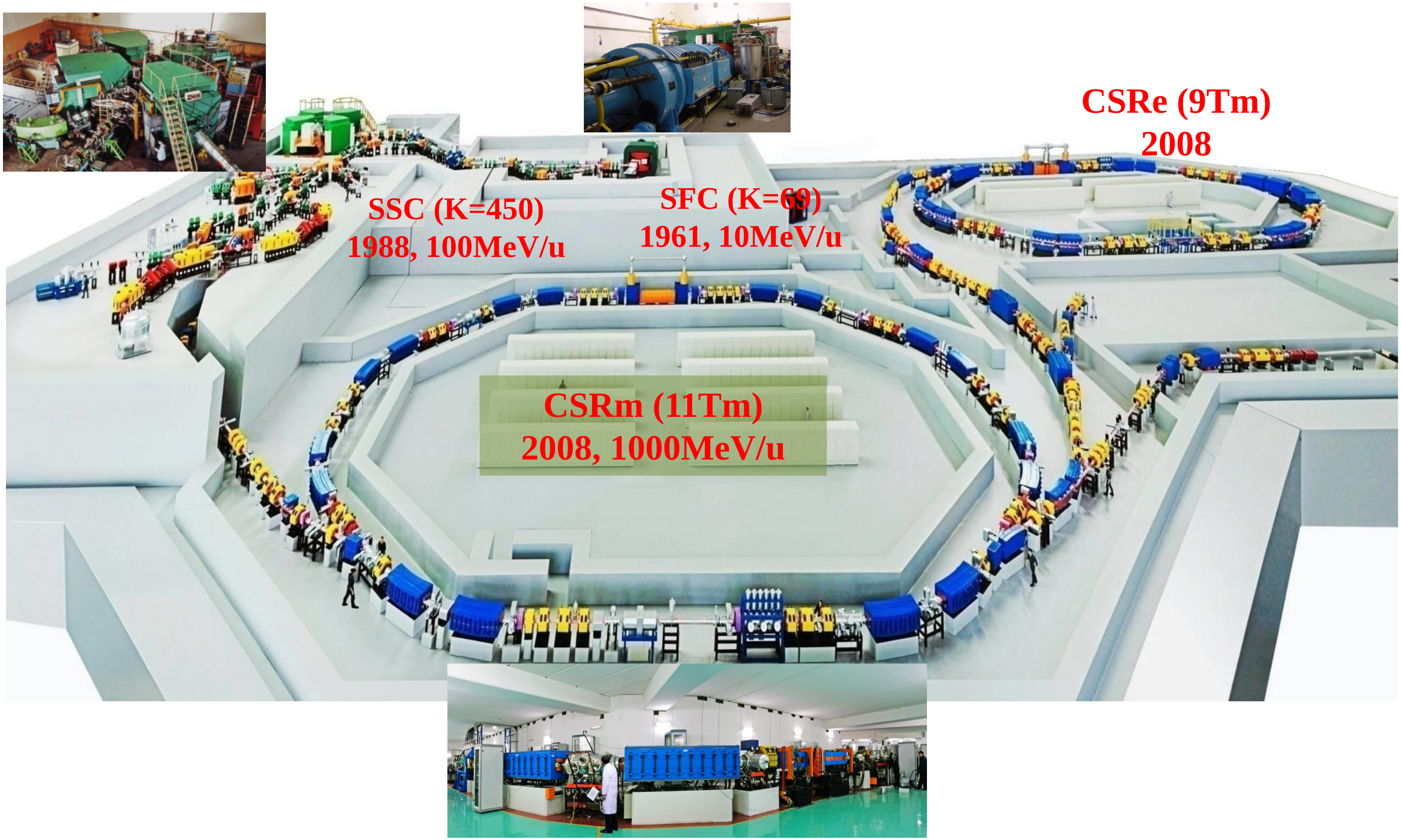
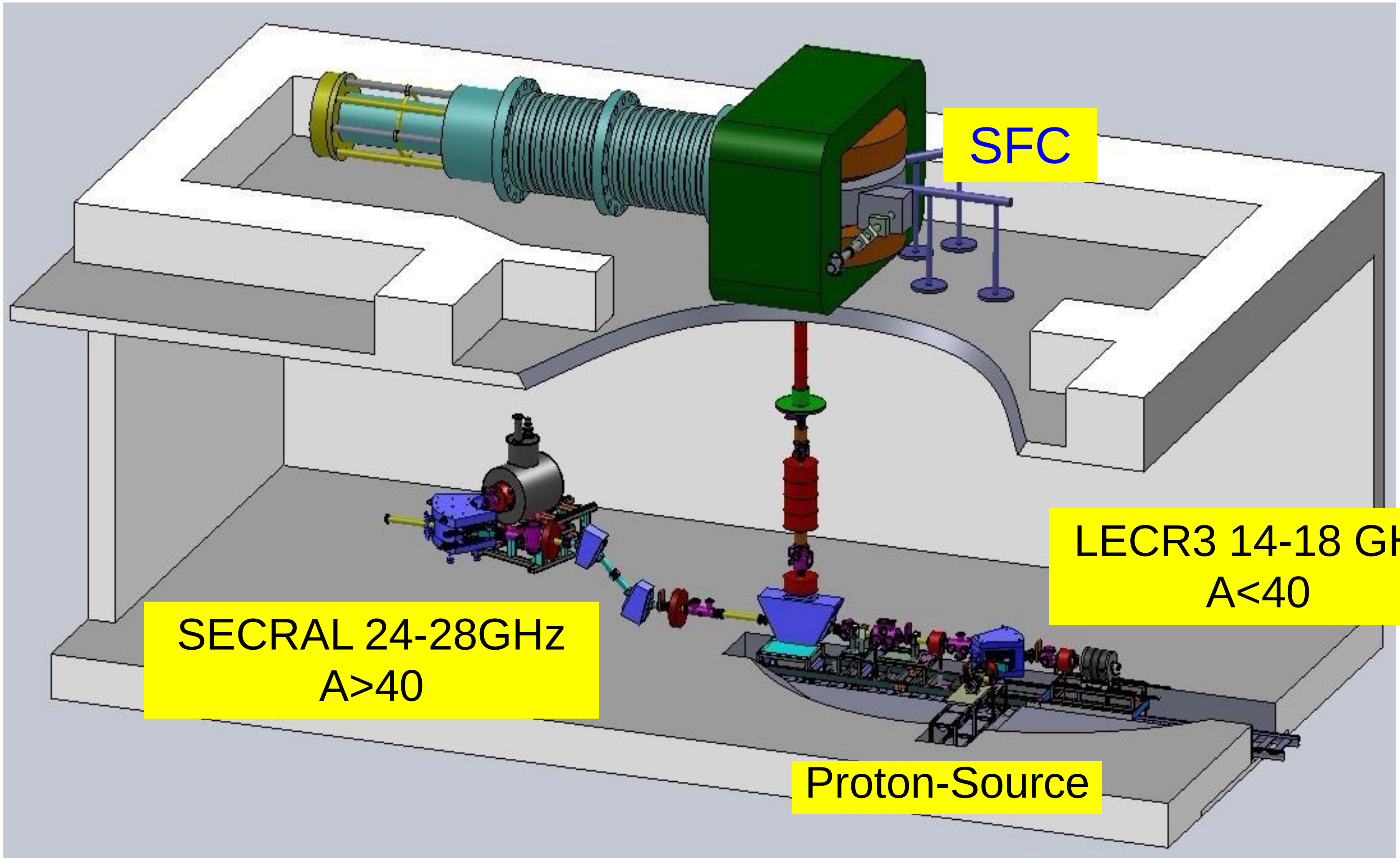
IMP existing heavy ion facility HIRFL

IMP is the biggest nuclear physics research center in China for heavy ion basic-science and nuclear technology application



Ion sources for SFC cyclotron

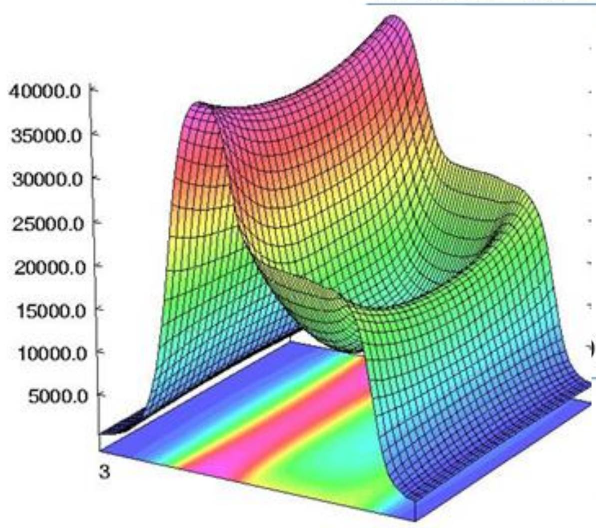


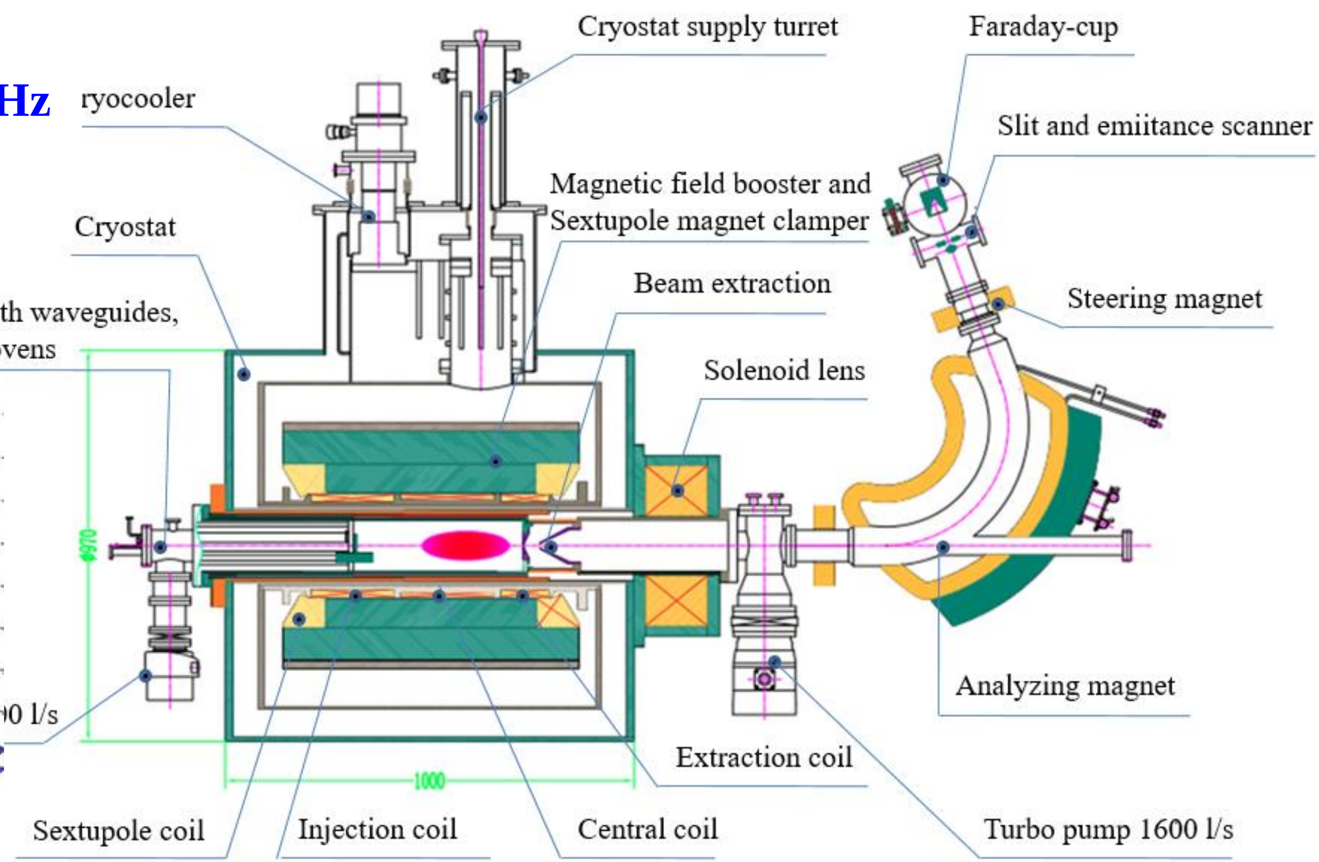
SECRAL ECR ion source

Fully NbTi superconducting magnet ECR source

SECRAL was built in 2001-2005.
Beam operation to HIRFL since 2007

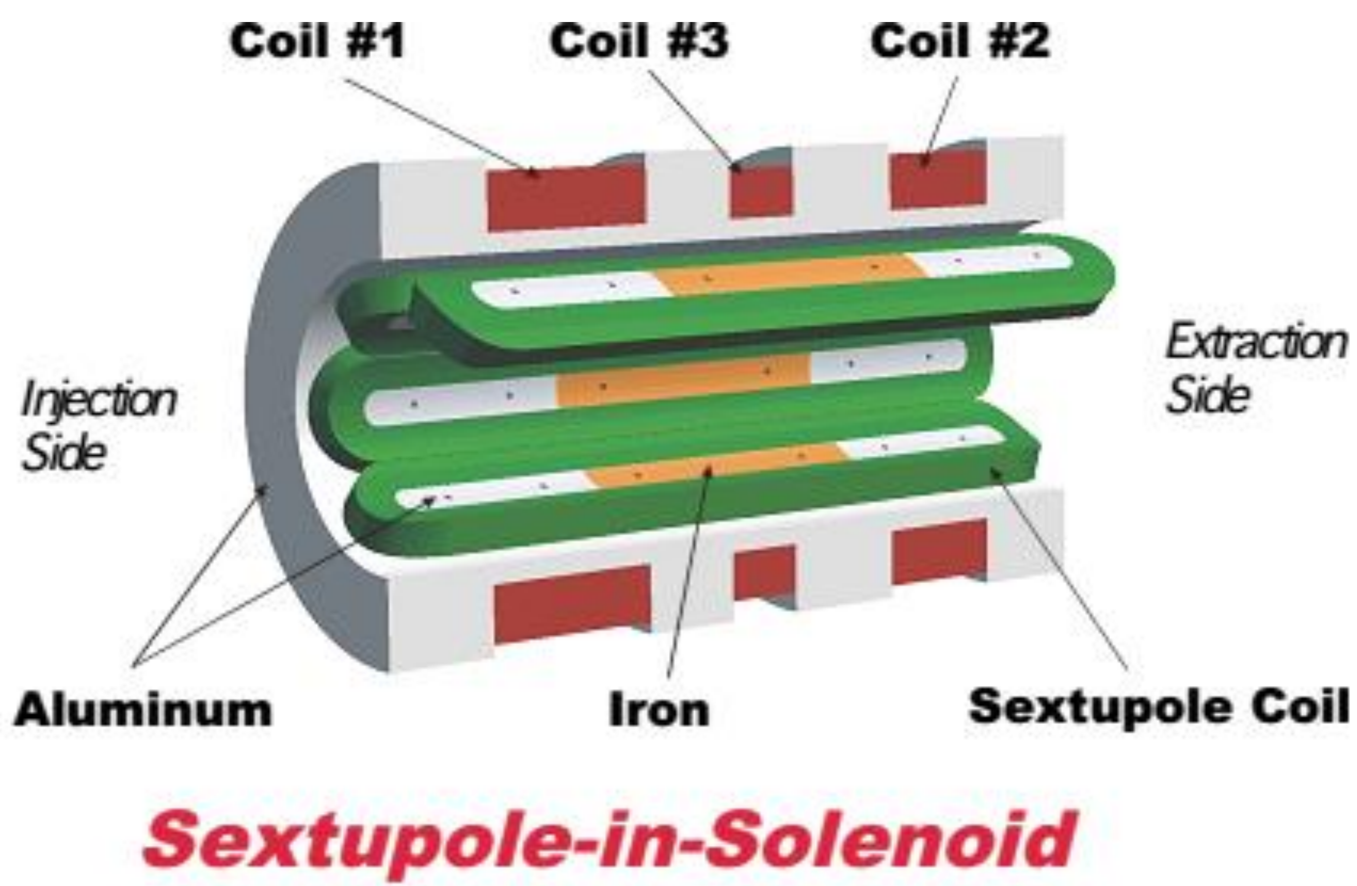
- **Axial field: 3.6, 2.2T**
- **Sextupole field: 2.0 T**
- **RF frequency: 24-28 GHz**
- **Maximum field : 8.6 T**





SERAL Layout

Conventional magnet structure of ECR ion source

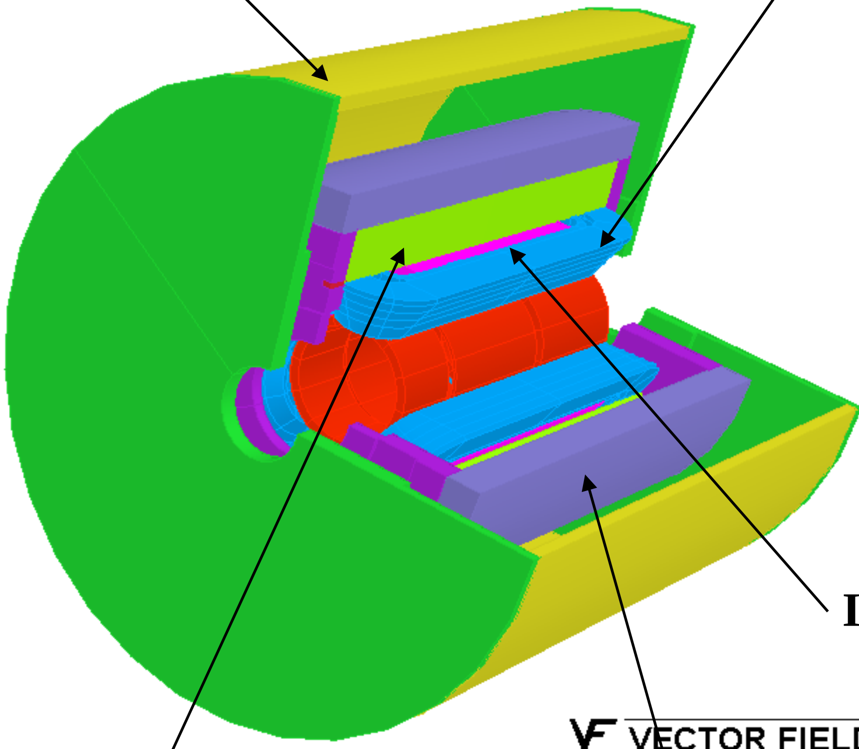


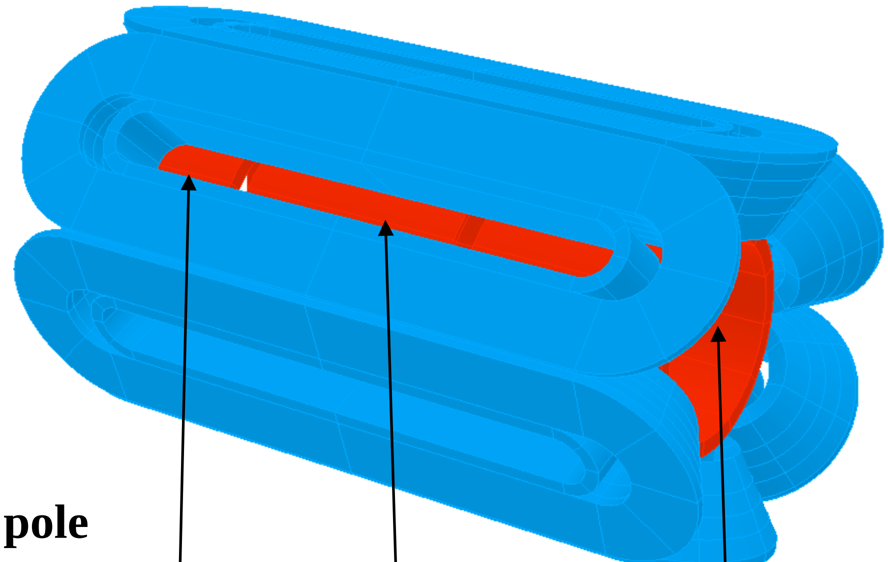
C. Lyneis@presentation ICIS2009

SERSE/LNS, VENUS/LBNL, SuSi/MSU, SC-ECR/RIKEN,….

SECRAL innovative magnet structure

SECRAL: Solenoids-in-Sextupole
Reversed to conventional structure!

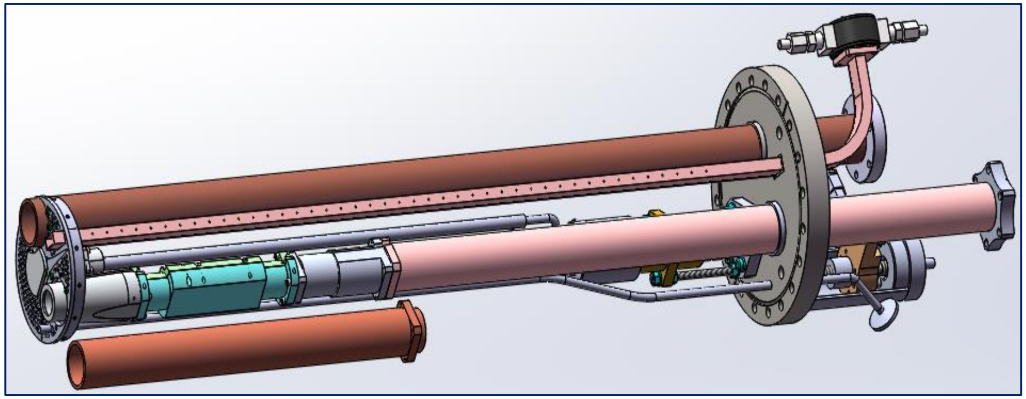




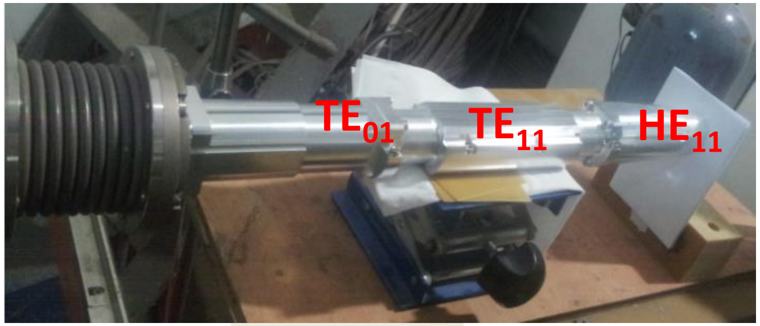
SECRAL superconducting ECR ion source

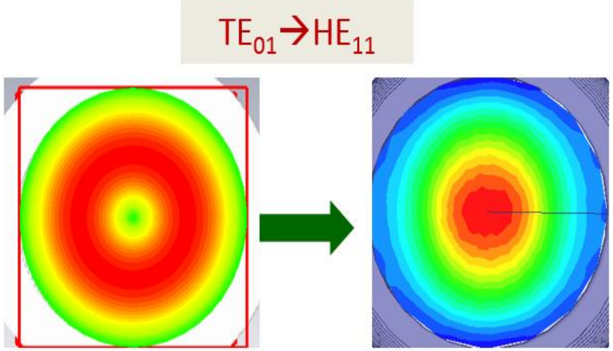
- **SECRAL first beam:2005;**
- **Beam delivery for HIRFL accelerator since 2007**
- **3000-4000 hours beam operation each year in the past 10 years.**

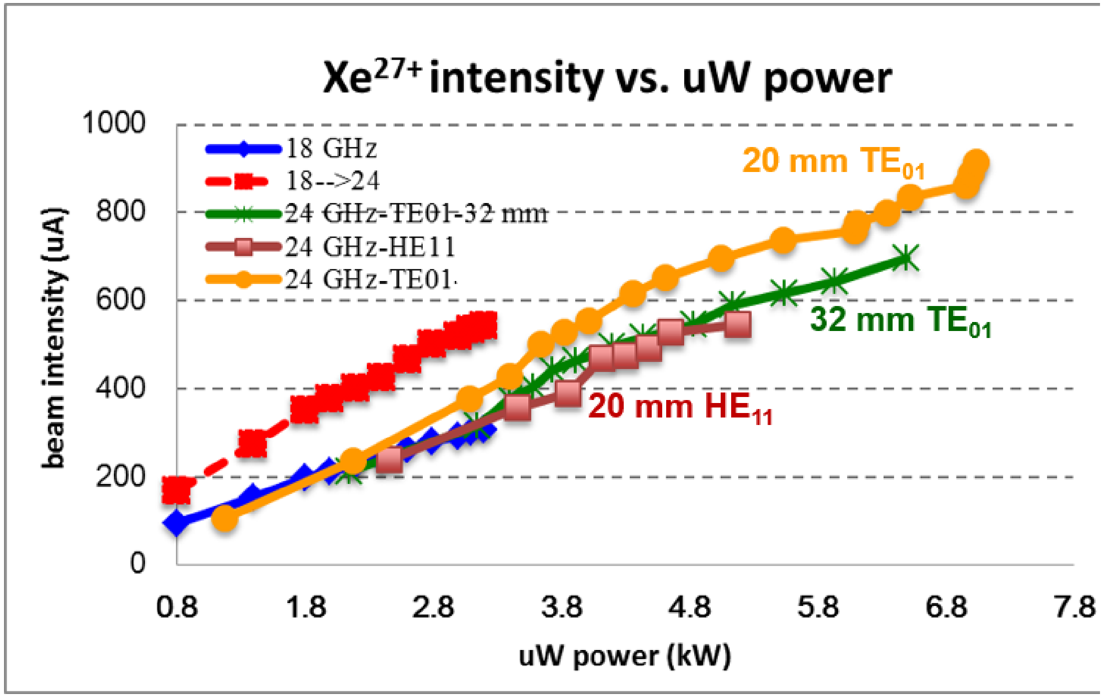
New microwave coupling system at SECRAL



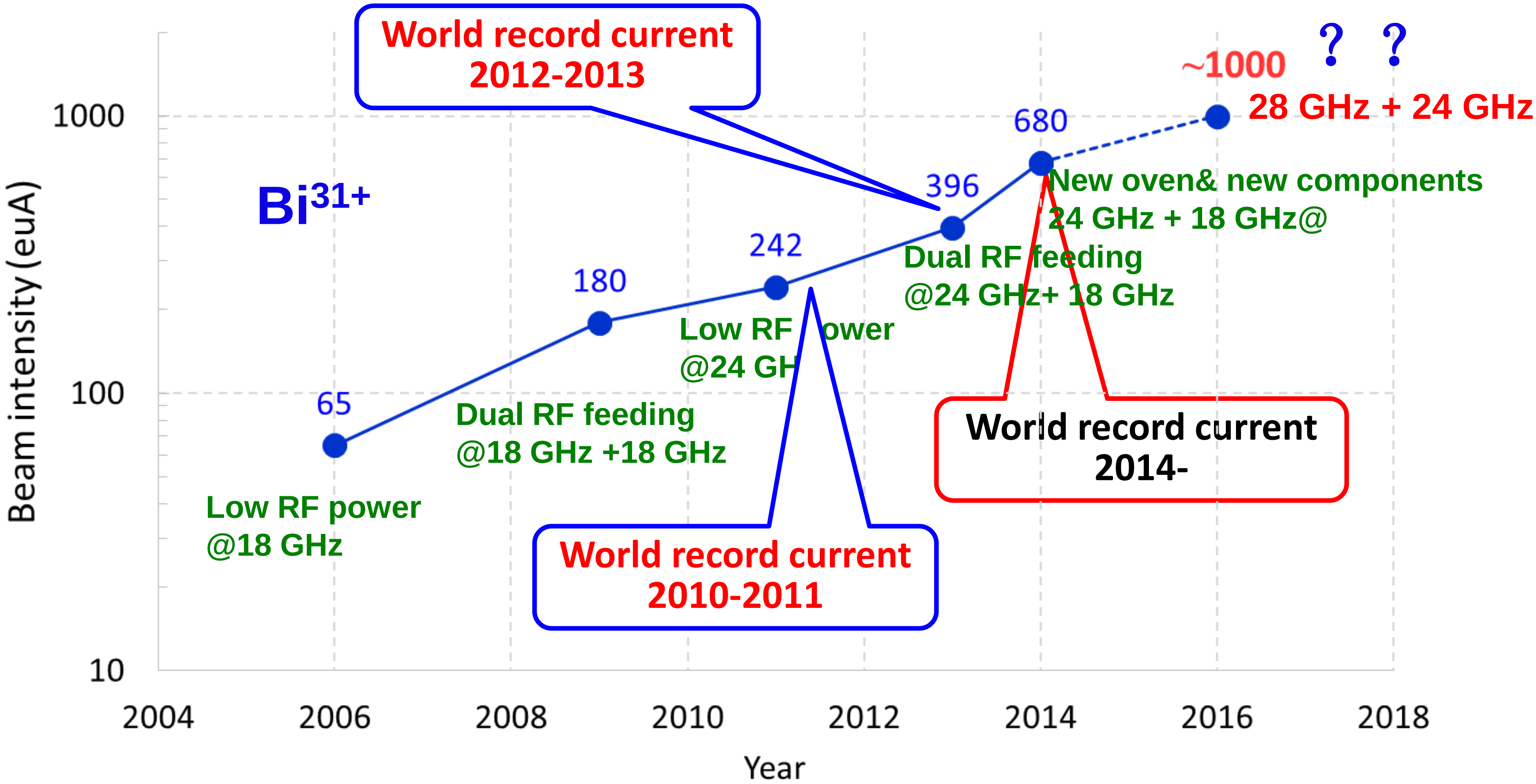
- Ø32 mm TE_{01} –traditional 28GHz
- Ø20 mm HE_{11}
- Ø20 mmTE_{01} shows the best results due to better coupling. Intensity increased by 20-50%







SECRAL beam current increasing with technologies



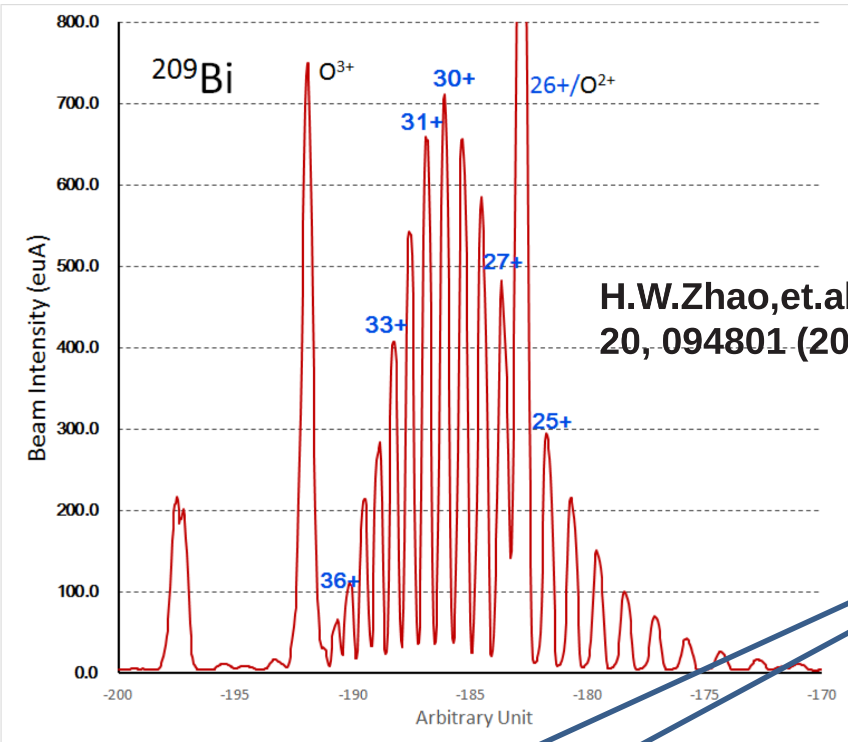
SECRAL II and Test Bench Layout

SECRAL II was built for HIRFL linac new injector

Record beam intensities produced by SECRAL and SECRAL II

SECRAL I-II beam intensities and compared to LBNL VENUS

- For the first time in ion source history, $Ar^{11\text{-}14+}$、Kr^{18+}、 Xe^{26+} > 1 emA
- Open a new era: HCI DC beams -- emA
- Important to intense-beam heavy ion linac



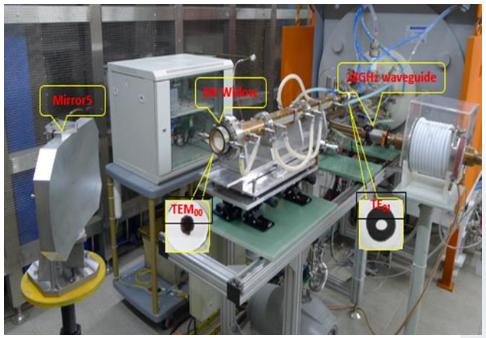
H.W.Zhao,et.al. PRAB, 20, 094801 (2017)

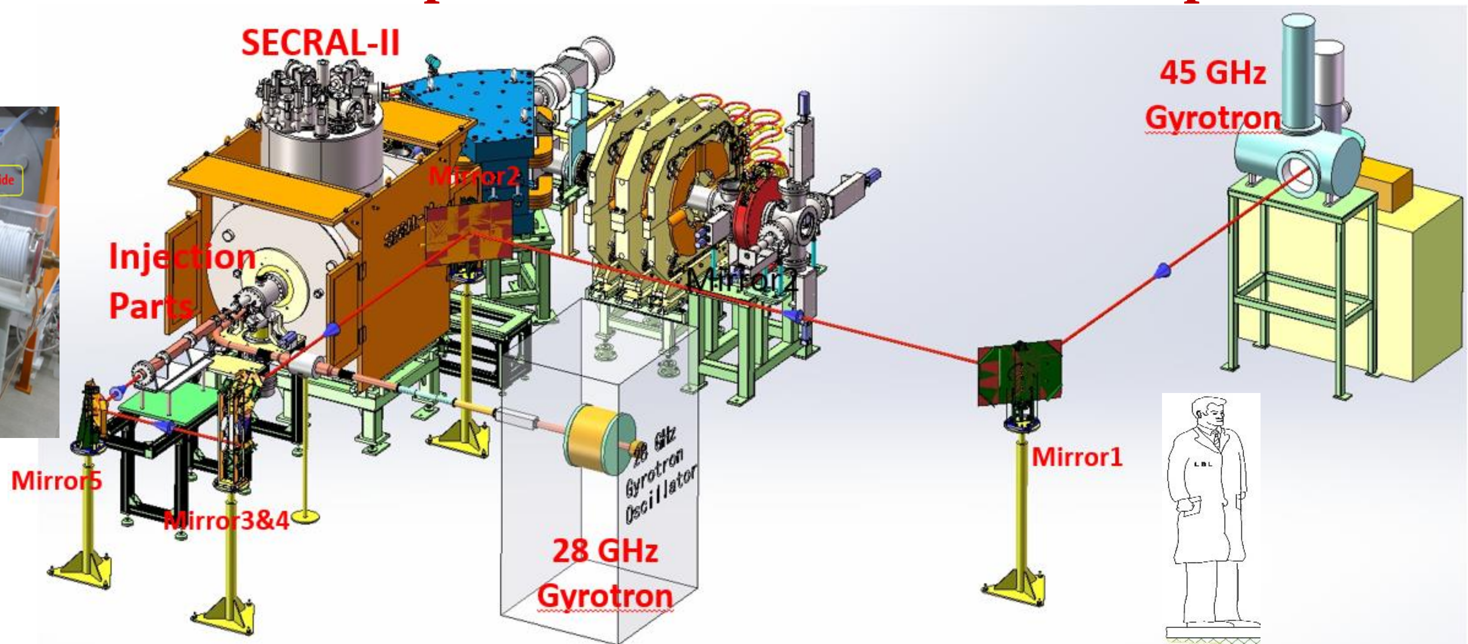
Ion Beam	SECRAL I-II (eμA)（2015-2017）	LBNL VENUS beam Intensity 2017 (eμA)
$^{16}O^{6+}$	6700	4750
$^{40}Ar^{12+}$	1420	1060
$^{40}Ar^{16+}$	620	523
$^{40}Ar^{18+}$	14	4
$^{40}Ca^{11+}$	710	400
$^{78}Kr^{18+}$	1030	770
Xe^{26+}	1100	
Xe^{30+}	320	211
Xe^{42+}	17	6
$^{209}Bi^{31+}$	680	300
$^{209}Bi^{41+}$	100	
$^{209}Bi^{50+}$	10	5
$^{238}U^{33+}$	202	440

The world record beam intensities

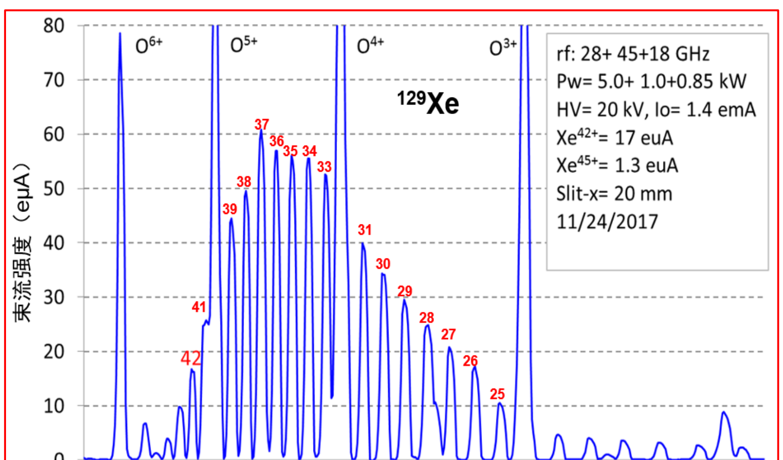
HCI beam production by 45 GHz ECR plasma at SECRAL II

World first beam test for HCI production with 45 GHz ECR plasma





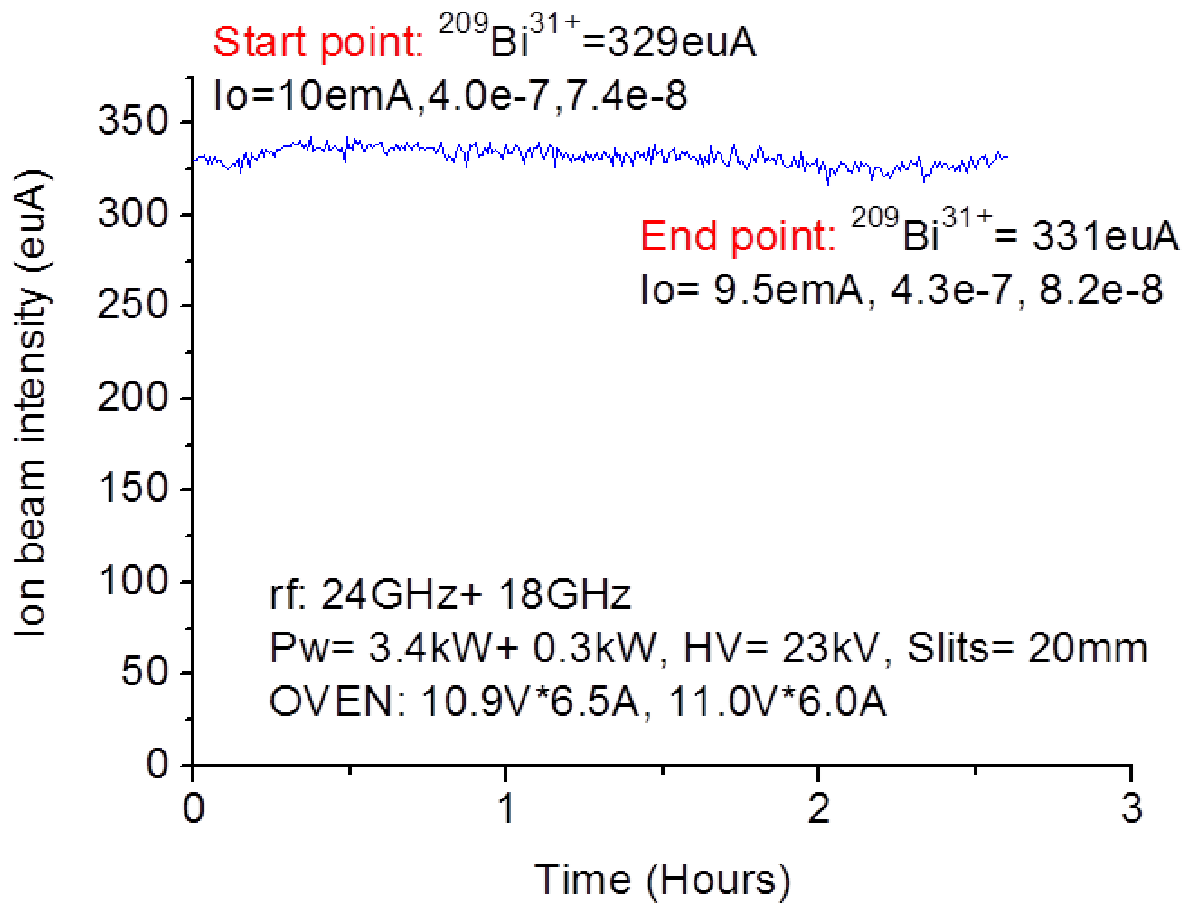
28+45+18 GHz three frequency heating



Ion	VENUS 28+18 GHz (eμA)	SECRAL 24+18 GHz (eμA)	**SECRAL-II 45+28+18 GHz (eμA)**
$^{129}Xe^{38+}$	26	22.6	**53**
Xe^{42+}	6	---	**17**
Xe^{44+}	2	1	**3.9**
Xe^{45+}	0.88	0.1	**1.3**

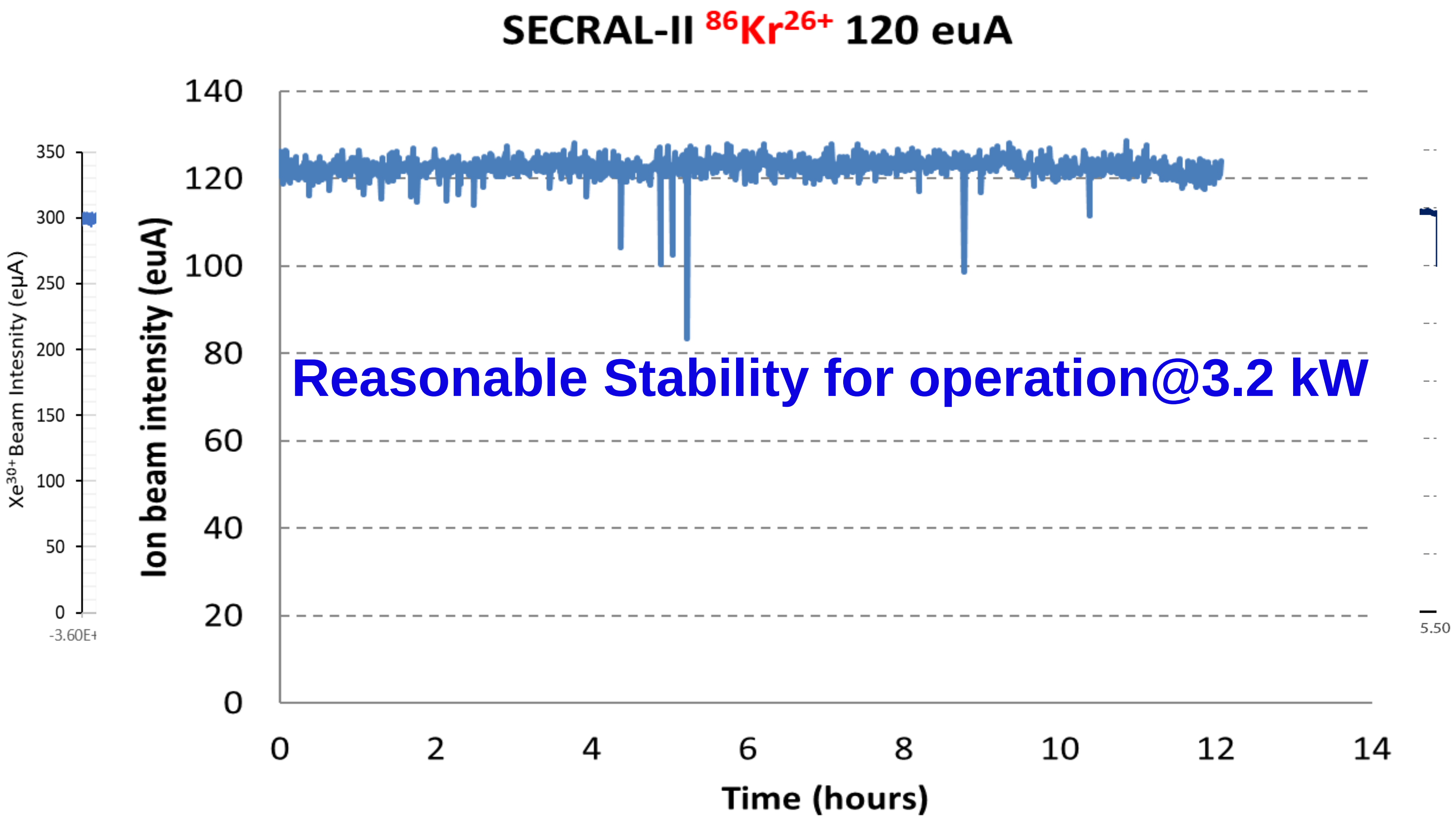
H.W. Zhao, et.al. RSI, (2018)

Intense beam stability from SECRAL



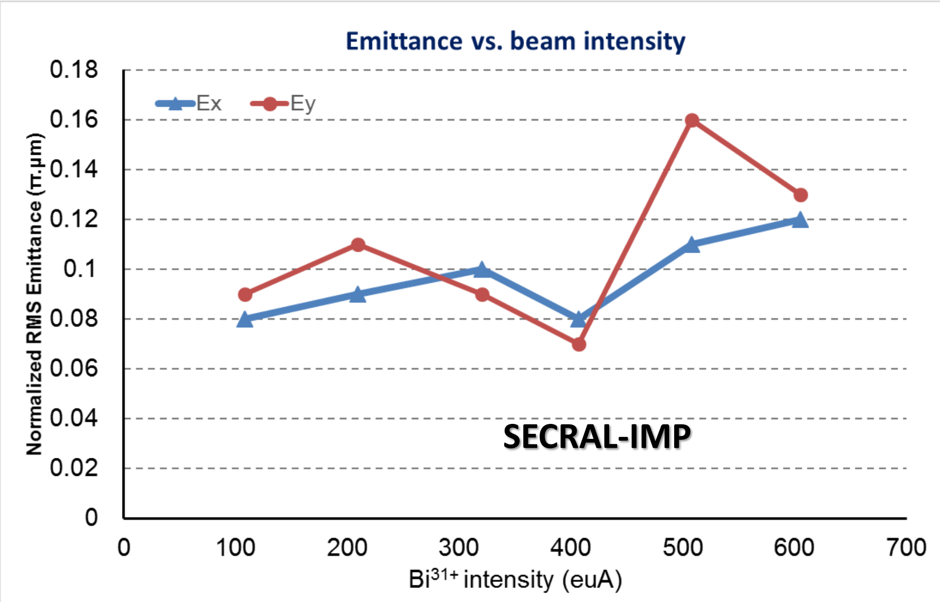
$^{209}Bi^{31+}$ 329 eμA more than 2 hours stability test operation at 3.7 kW

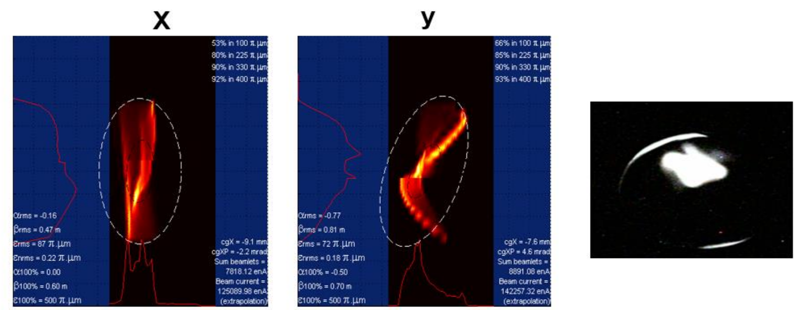
Intense beam stability from SECRAL II



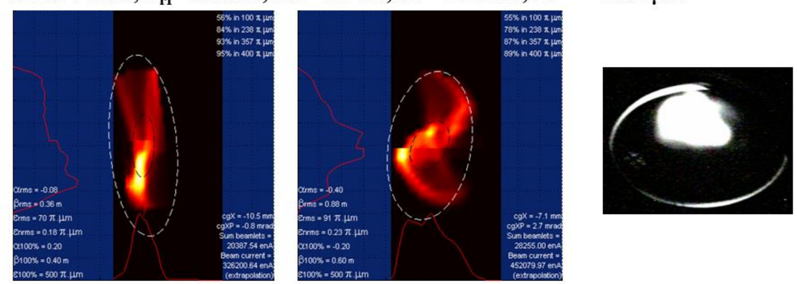
- ☐ More sparks at high RF power

SECRAL beam emittance

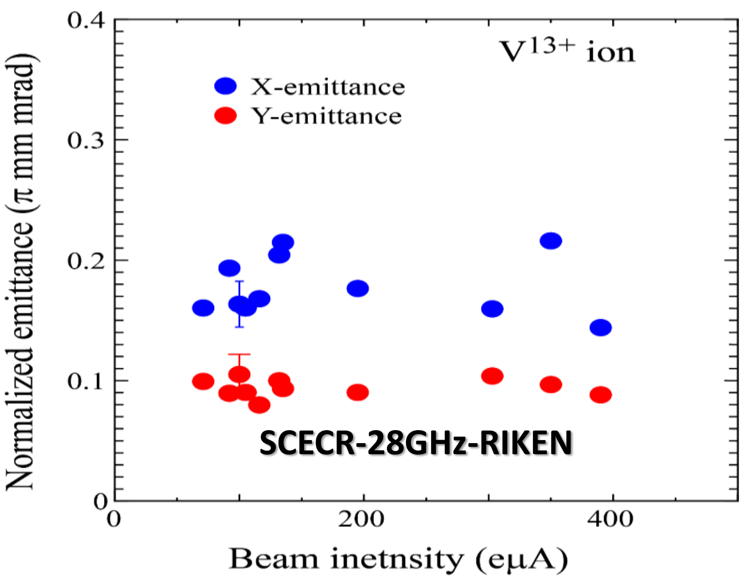




RF: 24 GHz, P_{rf}= 1.0 kW, HV= 20 kV, Io= 4.8 emA, Bi^{31+}= 115 eμA

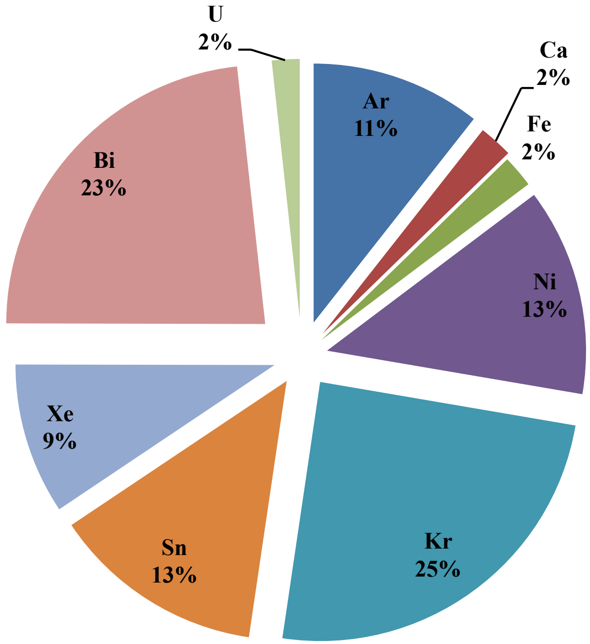


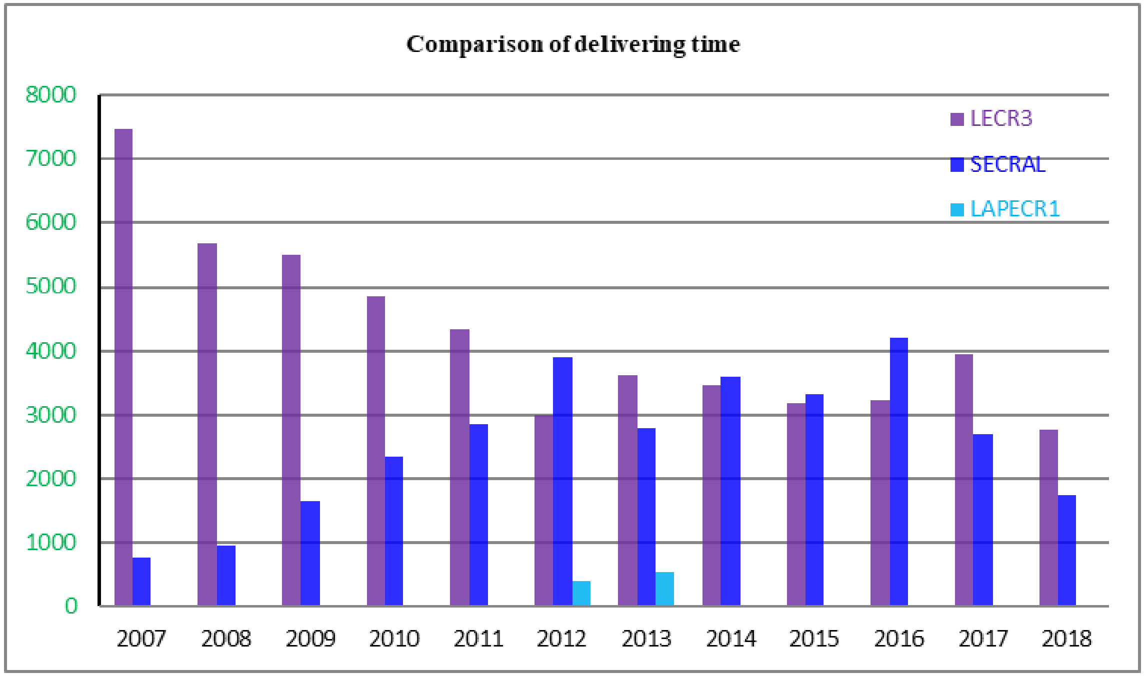
RF: 24 GHz+18 GHz, P_{rf}= 3.4 kW+ 0.3 kW, HV= 23 kV, Io= 10 emA, Bi^{31+}= 330 eμA



T. Nakagawa talk at ECRIS2018

SECRAL operation status at HIRFL

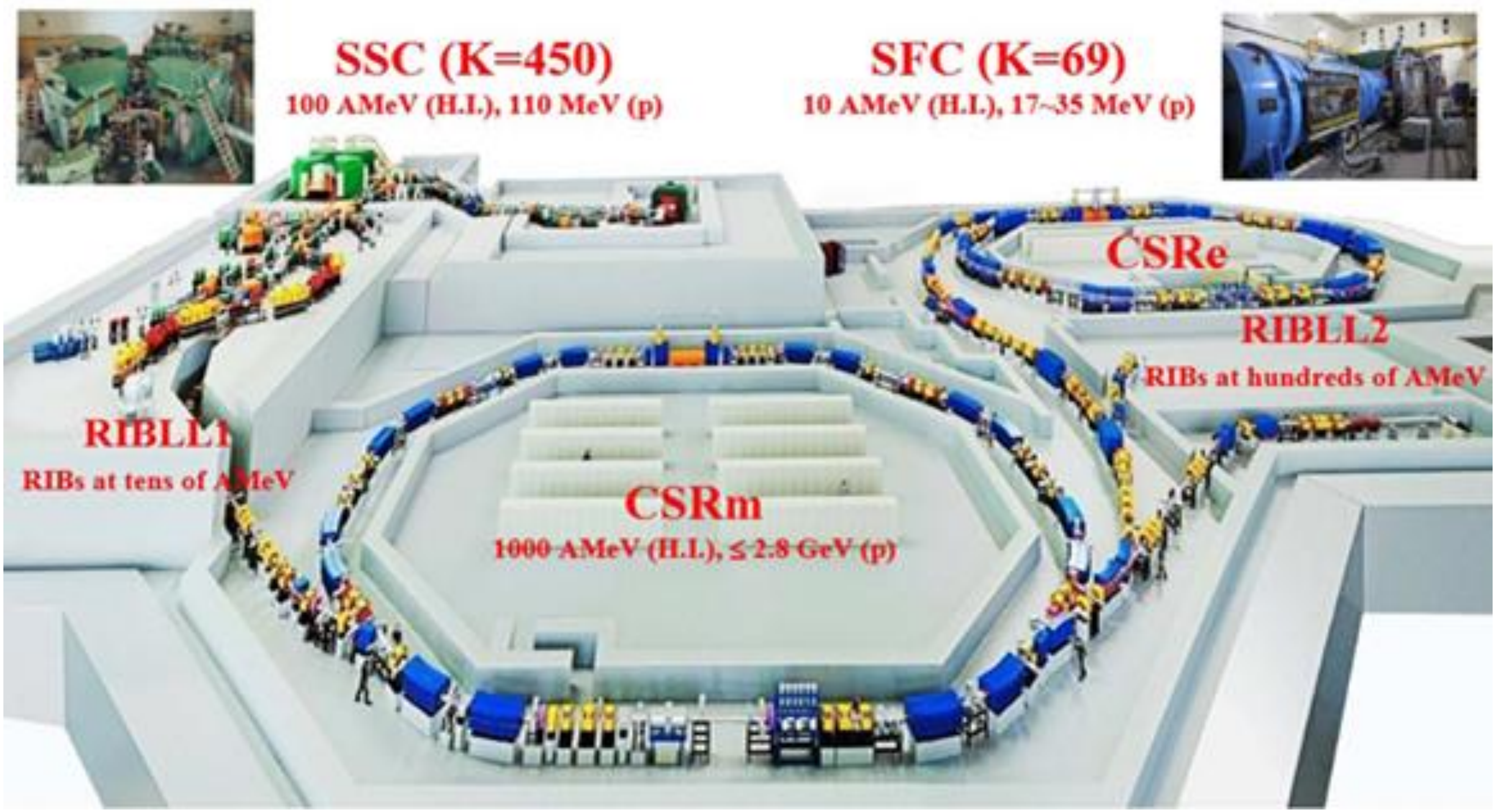




- Intense heavy ion beams
- Intense highly charged ion beams

- ~35,000 hours beam time up to June, 2018
- Demonstrate its reliability
- No any other 3rd generation SC ECRIS in the world has ever run such long-time beams

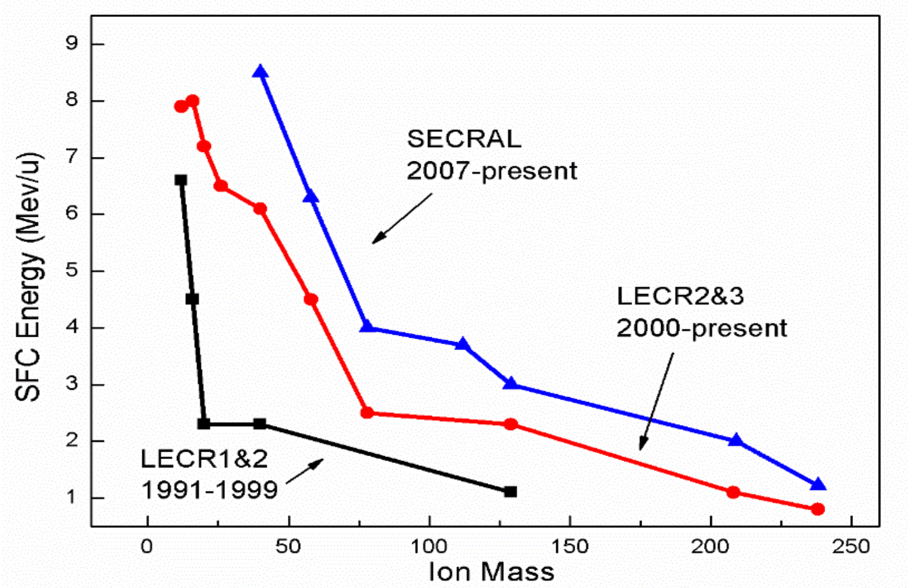
Intensity enhancement of HIRFL accelerator by SECRAL



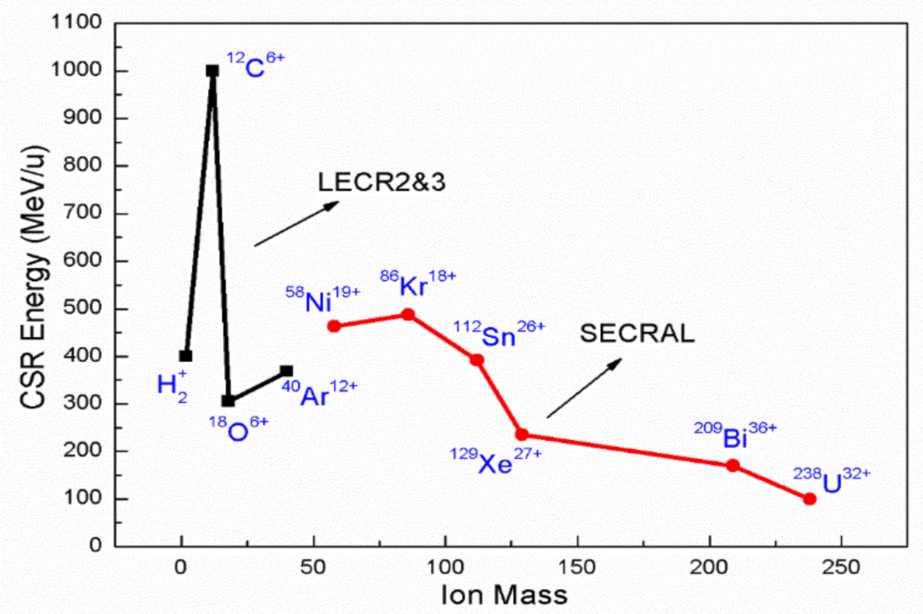
- SFC beam intensities for heavy ions such as Ni, Kr, Xe,Bi, U, increased by a factor 10
- SSC beam intensities for heavy ions such as Ni, Kr, Xe,Bi,   increased by a factor >50
- CSR is able to run those heavy ion beams such as Ni. Xe Bi, U with SFC as an injector.

SECRAL impact to HIRFL performance of beam energy

SFC



CSRm



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IMP future heavy ion facility HIAF

Bring-N: 0.8 GeV/A, 3×10^{10}ppp

HIAF: 2018-2024

Budget: 1.5+1.1 B CNY, approved

Site: Huizhou, Guangdong

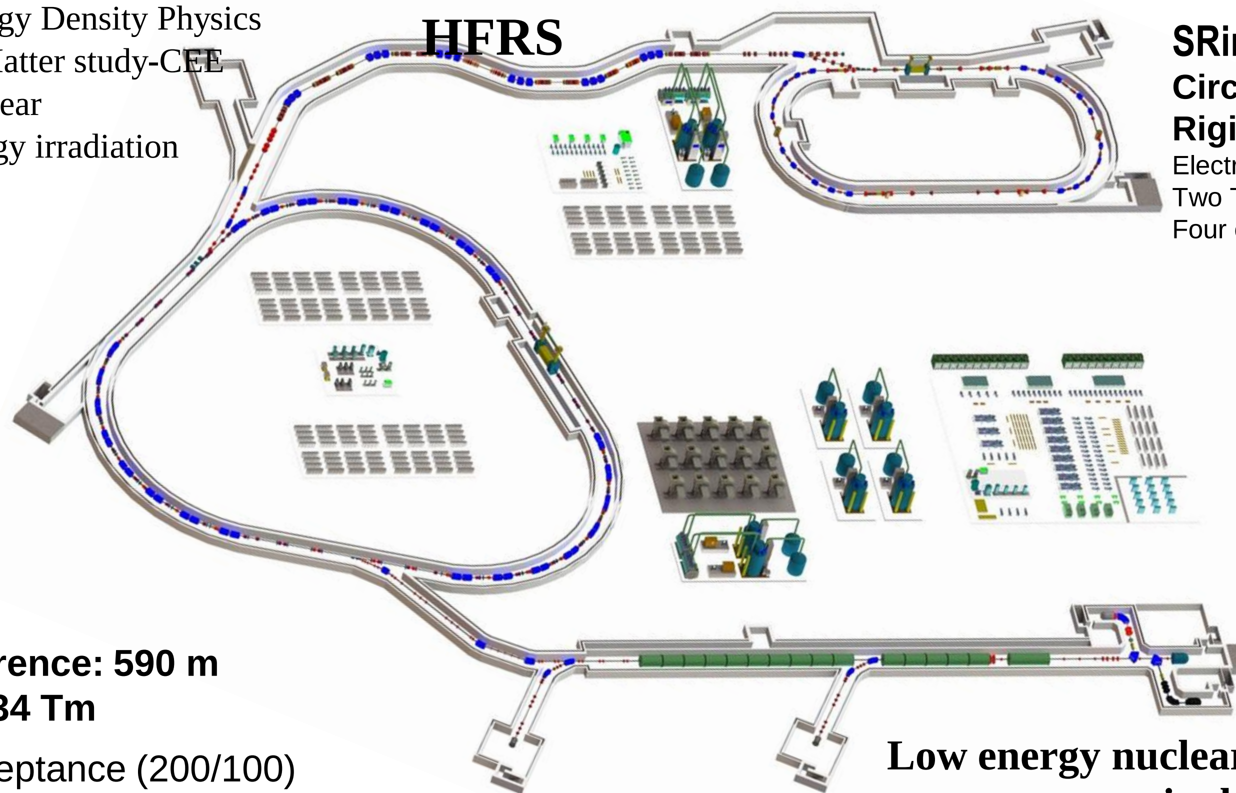
External target station

High Energy Density Physics
Nuclear Matter study-CEE
Hypernuclear
High energy irradiation

L: 180m, Bρ: 25 Tm

HFRS

SRing: Spectrometer ring
Circumference: 273m
Rigidity: 13-15 Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes



Bring-N:
Circumference: 590 m
Rigidity: 34 Tm

Large acceptance (200/100)
Two planes painting injection
Fast ramping rate（3-5-10Hz）

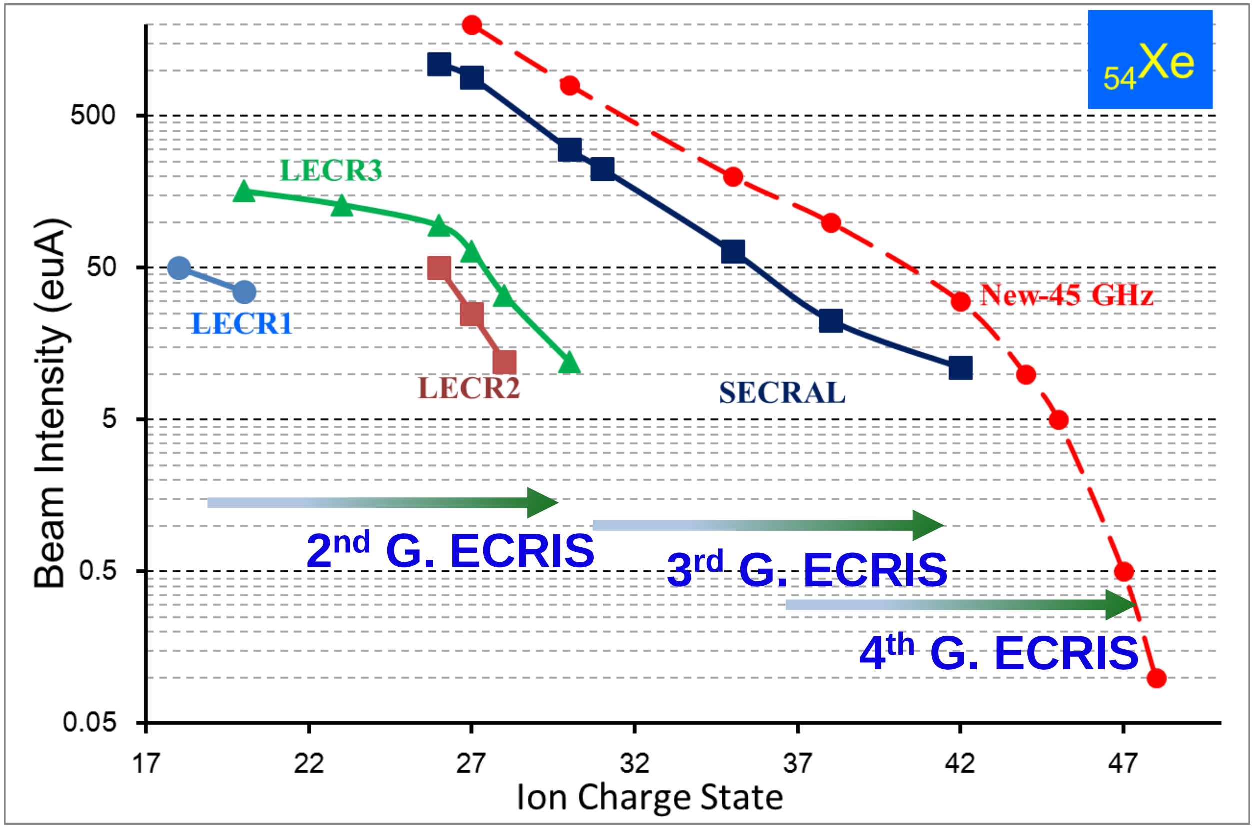
iLinac: Superconducting linac
Length:80 m
Energy: 17~22 MeV/u($U^{35+\sim46+}$)

Low energy nuclear structure terminal

SECRAL and FECR
28-45GHz,
1.0emA(U^{35+}- U^{46+})

Next Generation ECR ion source

Higher microwave frequency 40-60 GHz is the most straight forward path to achieve high beam intensity for HCI ECRIS.



IMP ECR ion source development

$I^q \ \alpha \ \omega^2_{ECR}$, $G_q \sim (28/18)^2 = 2.4$

⇩

45 GHz~ G_q=2.6

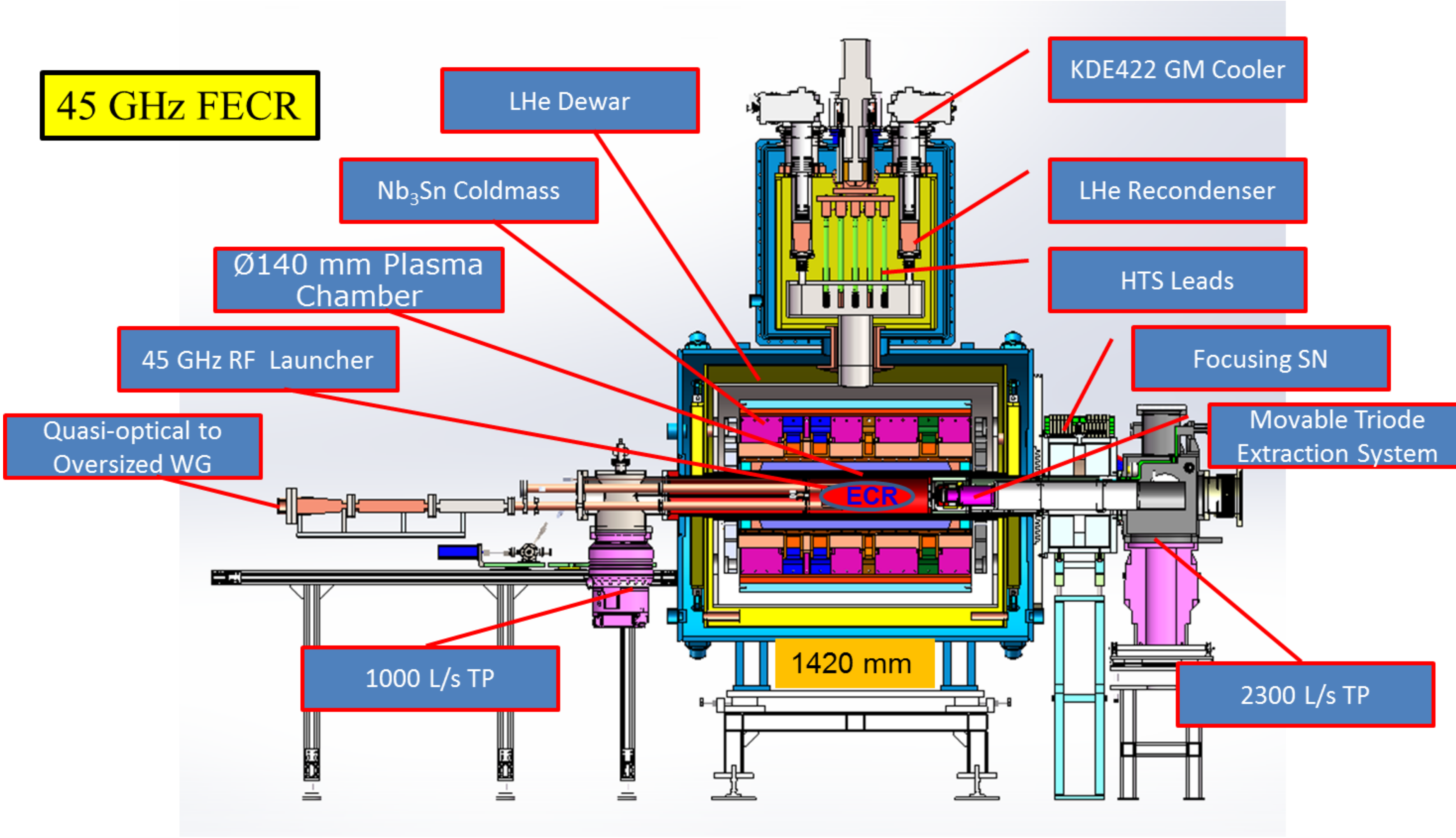
>1.0 emA U^{35+}, dc

(>2.0 emA, pulsed)

Specs.	Unit	45 GHz ECRIS
Frequency	GHz	45
Mirror Fields	T	≥6.4/3.2
B_{rad}	T	≥3.2
Mirror Length	mm	~500
Magnet coils	/	Nb_3Sn
Conductor		J_c>1500 A/mm^2@12T
Cooling Capacity@4.2 K	W	≥10.0

The world first 45 GHz ECRIS----FECR

FECR: first Fourth generation ECR ion source



FECR key parameters and goal

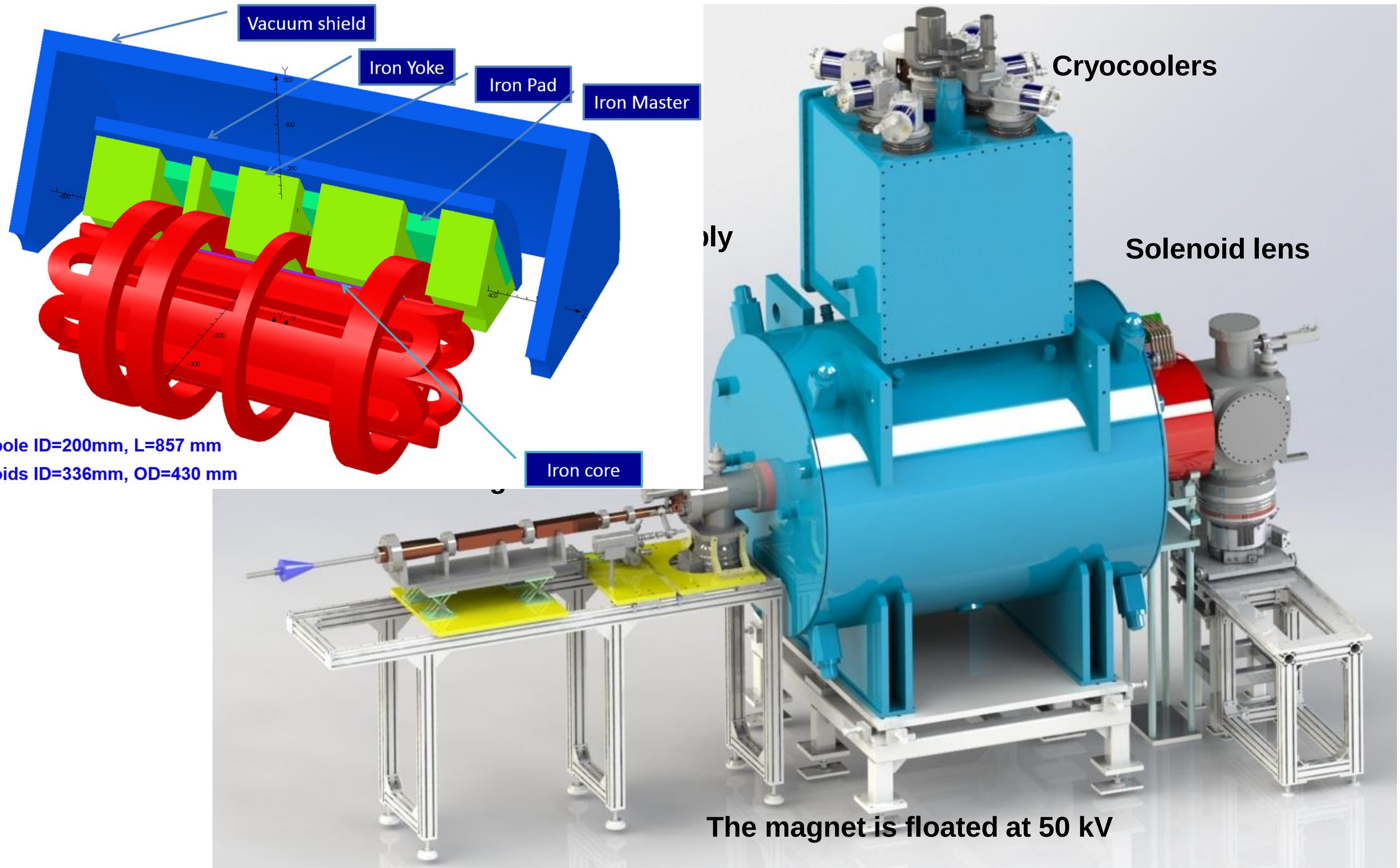
FECR key parameters

Microwave	45 GHz/20 kW
Magnet conductor	Nb_3Sn
Axial fields（T）	6.5/1.0/3.5
Sextupole field （T）	3.8@r=75 mm
Maximum field（T）	11.8 T
Maximum stress (MPa)	150
Magnet bore（mm）	>Ø160
Stored energy (MJ)	1.6
Extraction （kV)	50
Typical beam	1.0 emA U^{35+}

Beams and intensities expected from FECR

$^{129}Xe^{30+}$	>1000 μA
$^{129}Xe^{45+}$	> 50 μA
$^{209}Bi^{31+}$	>1000 μA
$^{209}Bi^{55+}$	> 50 μA
$^{238}U^{35+}$	>1000 μA
$^{238}U^{41+}$	> 200 μA
$^{238}U^{56+}$	> 30 μA

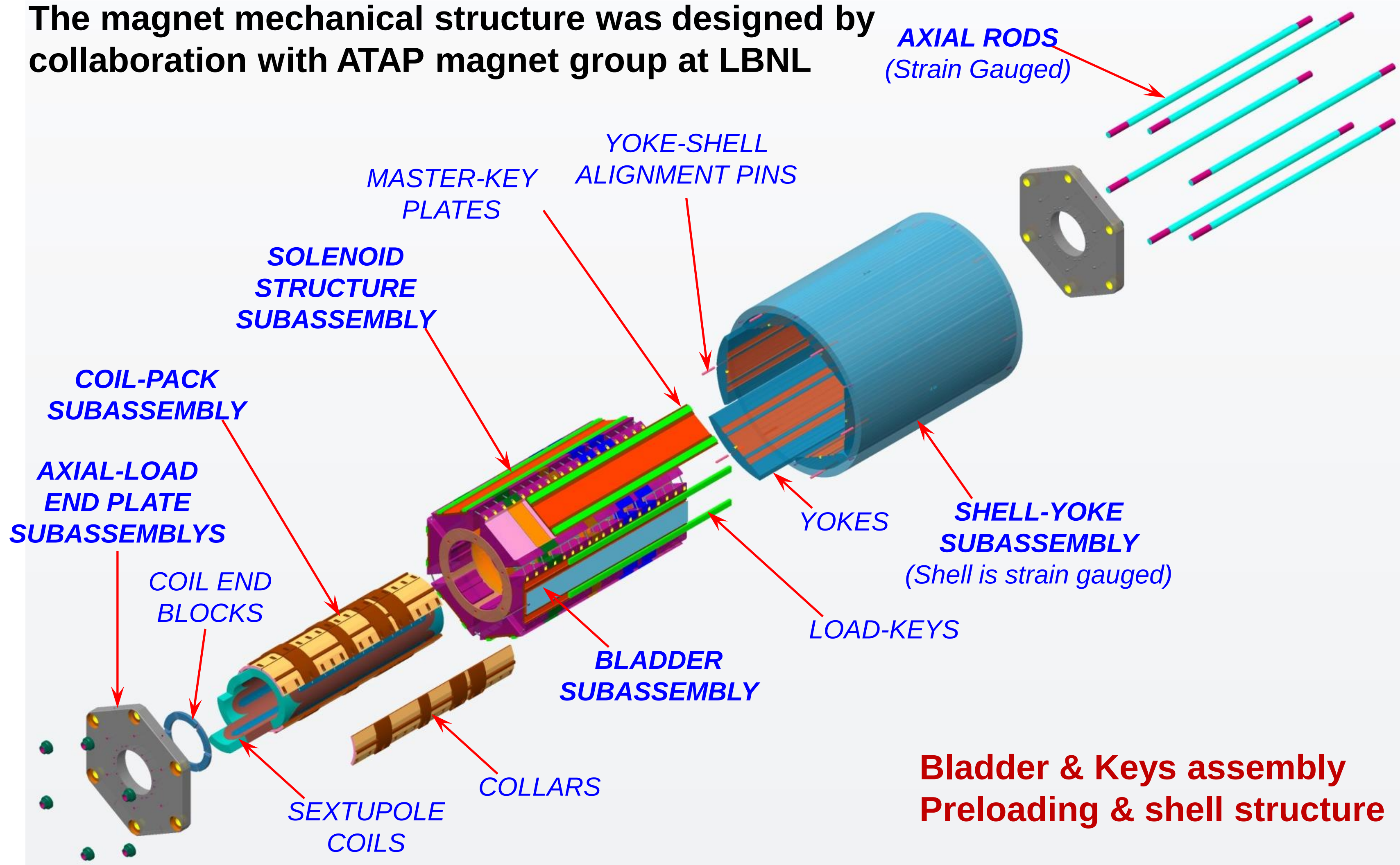
45 GHz FECR ion source



Sextupole ID=200mm, L=857 mm
Solenoids ID=336mm, OD=430 mm

FECR Nb_3Sn magnet mechanical structure

The magnet mechanical structure was designed by collaboration with ATAP magnet group at LBNL



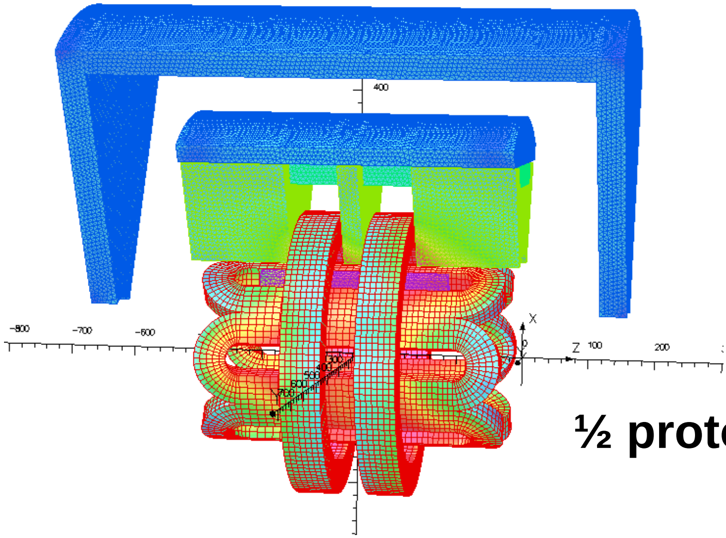
Bladder & Keys assembly
Preloading & shell structure

This Nb_3Sn magnet is being built by a Chinese company without collaboration with ATAP/LBNL. DOE did not approve such collaboration.

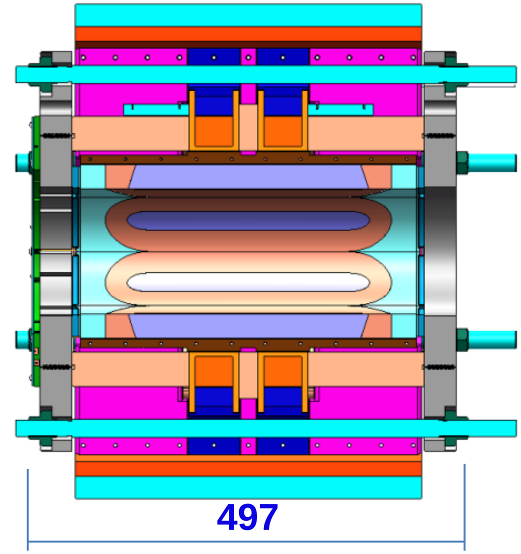
Challenges in FECR magnet development

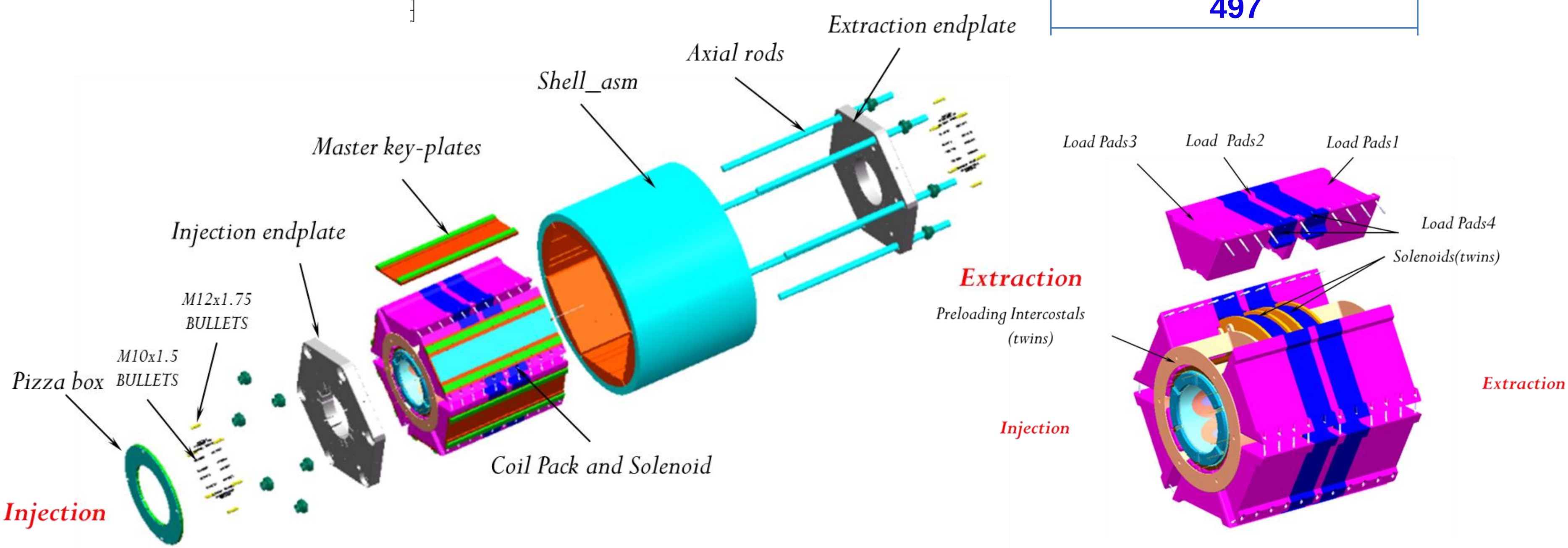
- **Coil fabrication**
  - **Nb_3Sn single wire winding (sextupole coil)**
  - **Curing with precise configuration**
  - **Large number of current leads**
  - **Insulation**
- **Integration and assembling**
  - **Precise fabrication and assembling**
  - **Tolerance control**
- **Quench protection**
  - **Quench detection and protection**
- **Dynamic heat load from 45 GHz ECR plasma**
  - **Heat load may > 2 W/kW**

Prototype of FECR Nb_3Sn magnet



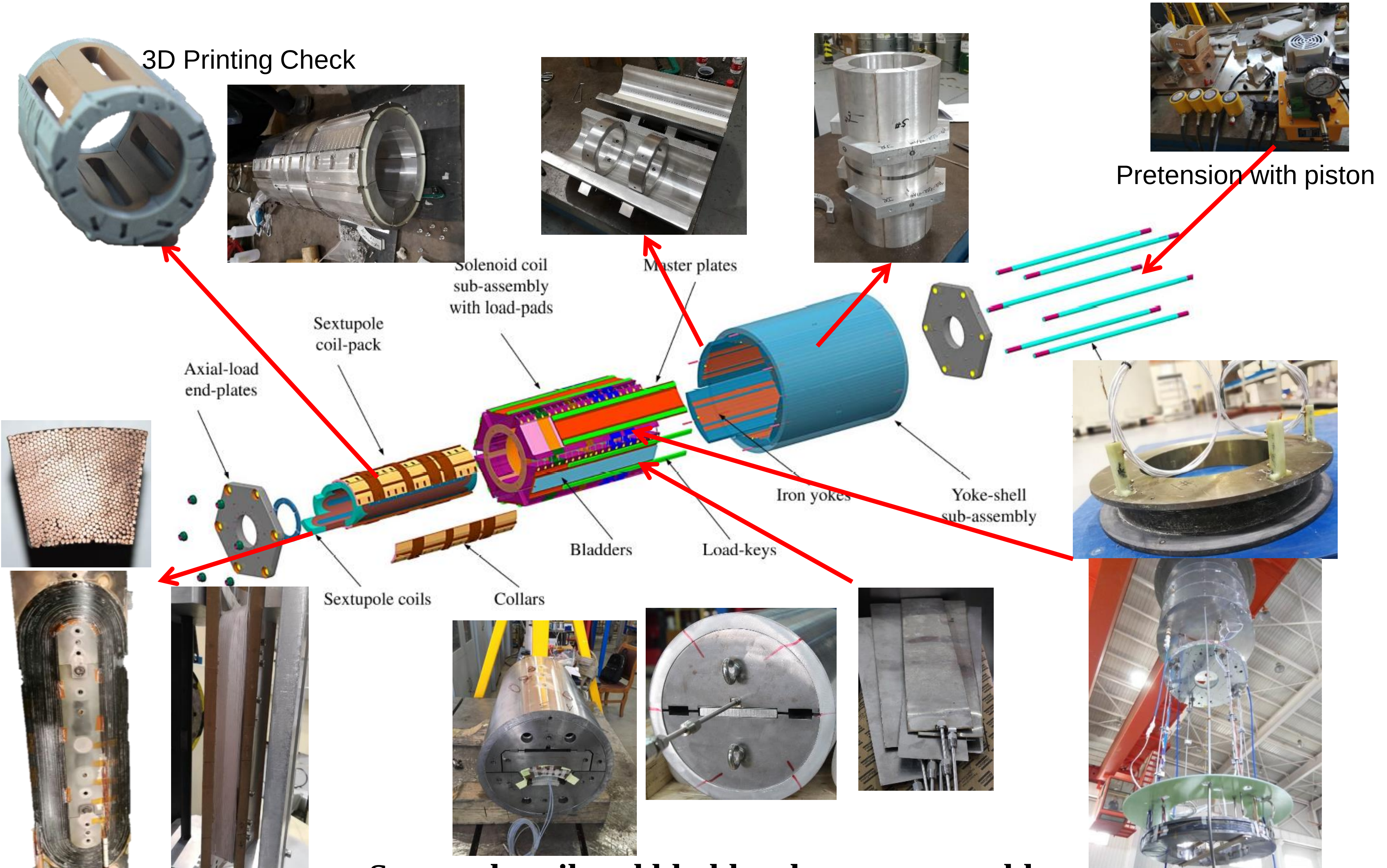
½ prototyping magnet





Prototype magnet is being fabricated by a company in China

Status of FECR Nb_3Sn magnet prototype



Prototyping Nb_3Sn sextupole coil

Sextupole coil and bladder+key test assembly

800 A no quench

Summary and conclusion

- Accelerator facility for rare isotope beam production requests high intensity primary ion beam which actually very much depends on performance of the front-end ion source.
- SC ECRIS with higher microwave frequency is the most straight forward path to achieve high beam intensity for HCI.
- SECRAL&SECRAL II, the world best performance highly charged ECR ion source,, have produced many record beam intensities, such as O^{6+} 6.7 emA ; Ar^{11-14+},Kr^{18+} Xe^{26+} > 1 emA ; Xe^{42+}. Bi^{50+}, U^{50+} > 10 eμA.
- SECRAL has delivered HCI beams for HIRFL accelerator for almost 10 years, which has demonstrated its good long-term reliability and stability, and has greatly enhanced HIRFL performance in terms of beam intensity and energy.
- SC ECRIS, such as SECRAL &SECRAL II, may provide some new research opportunities for rare isotope beam physics because of demonstrated such level of ion source performance.
- Future development of SC ECRIS is the 4^{th} generation with microwave heating frequency 40-60 GHz. IMP is developing the world first 4^{th} Gen. ECRIS—45 GHz FECR, which may get beam by July 2020.

Thanks for your attention

谢谢！

Option of FECR magnet Nb_3Sn superconductor

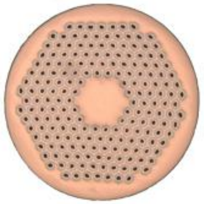
Wire √

Pros:

- No extra cabling process
- Lower power supply currents (<1000 A)
- Simpler HTS current lead solution
- HV platform feasible
- Cost efficient

Cons:

- Sextupole coil winding more difficult ×
- Quench protection issues ×
  - ~1.6 MJ stored energy
  - Higher qench voltage
- Superconducting joints
- Higher failure risk ×



OST M-Grade Nb_3Sn wire

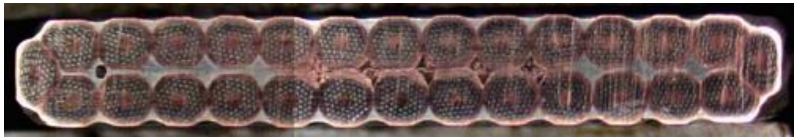
Cable

Pros:

- Successful examples of Accelerator magnets
- Good reliability
- Easier quench protection sys.

Cons:

- Not feasible for HV platform ×
  - 100~300 kV
  - 10 kA PSs on Platform
- Cryogenic solution×
- Higher cost
- Extra Cabling R&D



Rutherford Cable

FECR optimized Magnetic Design

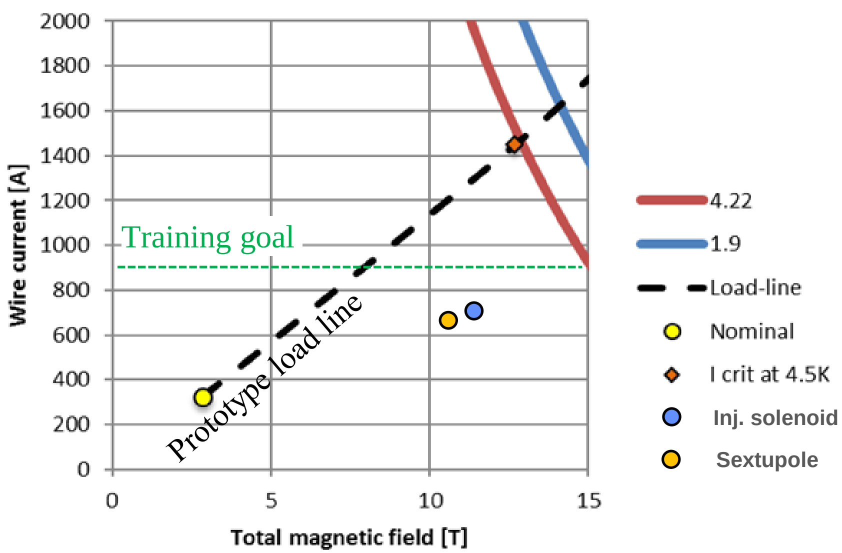
Coil and conductor operation parameters

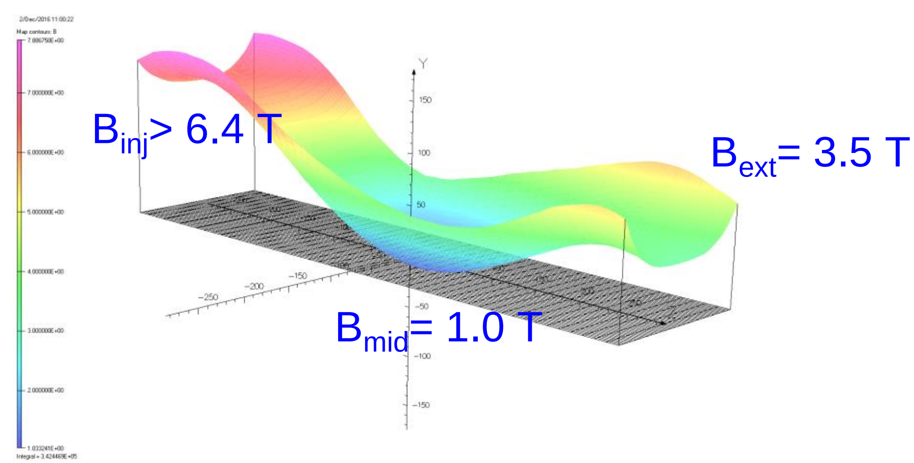
	Nominal engineering current density J_e (A/mm²)	Nominal wire current I_e (A)	Nominal peak field B_{peak-n} (T)	Load factor (%)
Sext.	**320**	**654**	**11.3**	**75.9**
Inj.	**365**	**692**	**11.8**	**78.2**
Mid.	**-200**	**380**	**5.0**	**36.5**
Ext.	**330**	**626**	**9.7**	**67.3**

Assuming packing factor of 65% (sextupole) and 70% (solenoid)

Wire: OST M-Grade Nb3Sn Ø1.43 mm with 0.13 mm S-glass included

Conductor performance, stability





Magnetic field distribution