FECRAL: First Fourth generation ECR ion source with Advanced design in Lanzhou

FECRAL - a 45 GHz fourth generation ECR ion source and its technical challenge

H.W. Zhao, L. T. Sun, W. Wu, J. W. Guo, Y. Yang, W. Lu, B.M. Wu, X.Z. Zhang, L. Zhu, Y.Q. Chen

Institute of Modern Physics (IMP) ,Chinese Academy of Sciences Lanzhou, China

G. Sabbi, M. Juchno, R. Hafalia, D.Xie

Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

Aug.28-Sept.1, 2016, ECRIS2016

Outline

1.HIAF and FECRAL brief introduction

2. FECRAL preliminary design

3. Technical Challenges

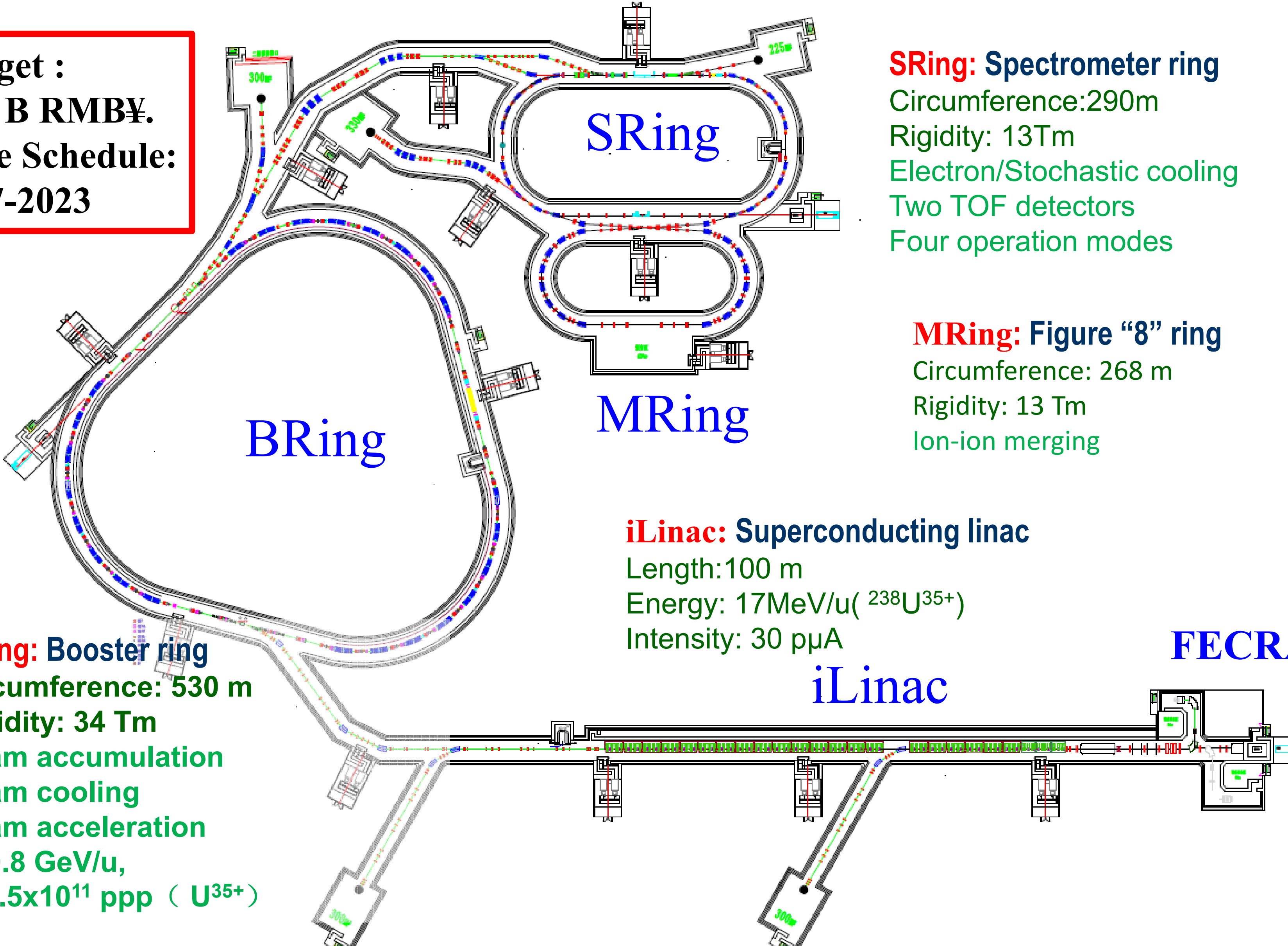
4.Summary

HIAF: **H**igh **I**ntensity heavy ion **A**ccelerator **F**acility

FECRAL: First **F**ourth generation **ECR** ion source with **A**dvanced design in **L**anzhou

HIAF Layout ----Phase I

Budget :
1.53 B RMB¥.
Time Schedule:
2017-2023



SRing: Spectrometer ring
Circumference:290m
Rigidity: 13Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

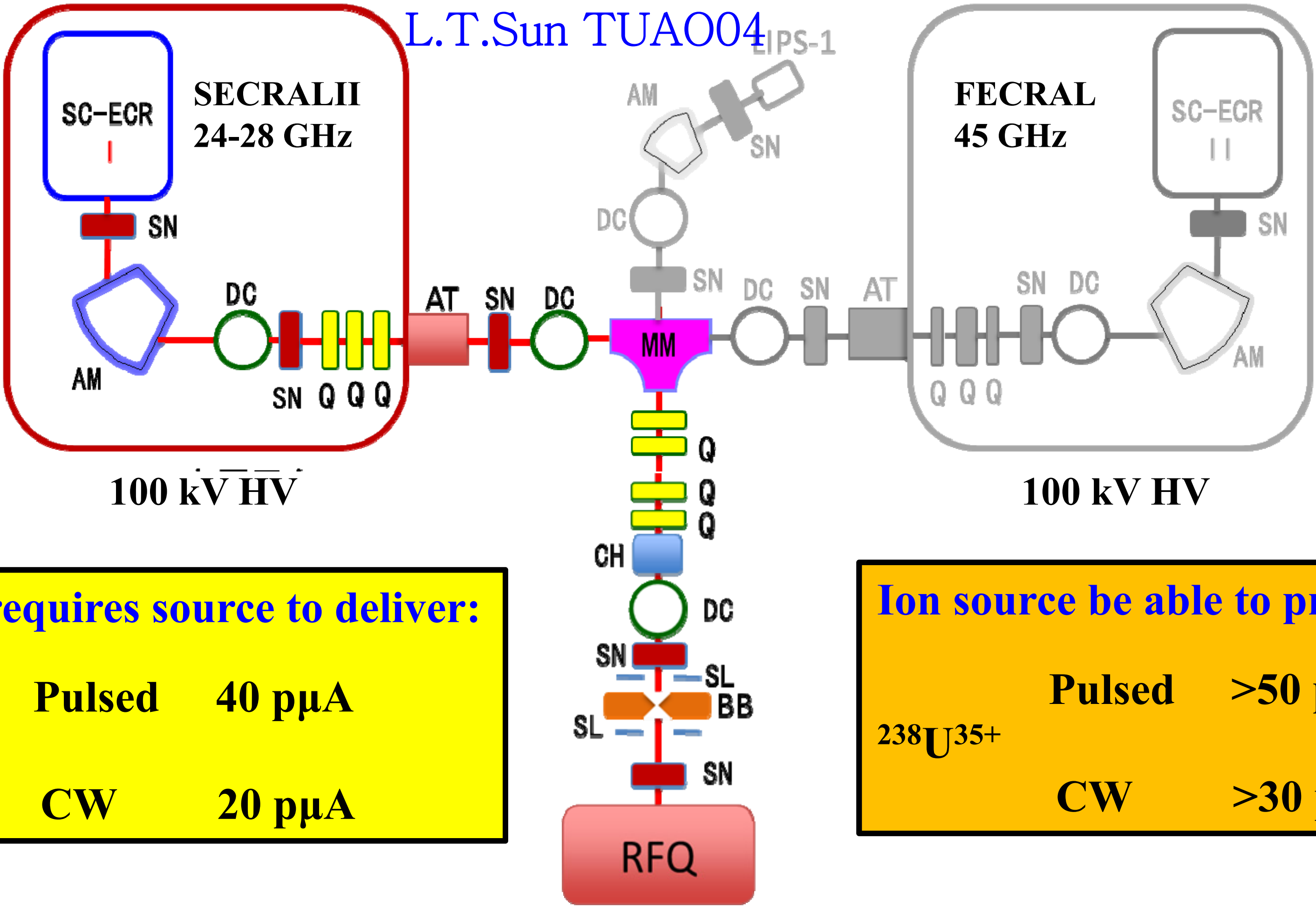
MRing: Figure "8" ring
Circumference: 268 m
Rigidity: 13 Tm
Ion-ion merging

iLinac: Superconducting linac
Length:100 m
Energy: 17MeV/u($^{238}U^{35+}$)
Intensity: 30 pμA

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration
E=0.8 GeV/u,
I= $1.5x10^{11}$ ppp（ U^{35+}）

HIAF ion sources and intensity requirement

HIAF ion source layout and LEBT



HIAF requires source to deliver:

$^{238}U^{35+}$	Pulsed	40 pμA
	CW	20 pμA

Ion source be able to produce:

$^{238}U^{35+}$	Pulsed	>50 pμA
	CW	>30 pμA

LBNL VENUS : CW $^{238}U^{35+}$: 10-12 pμA

Challenging !!

FECRAL key parameters and goal

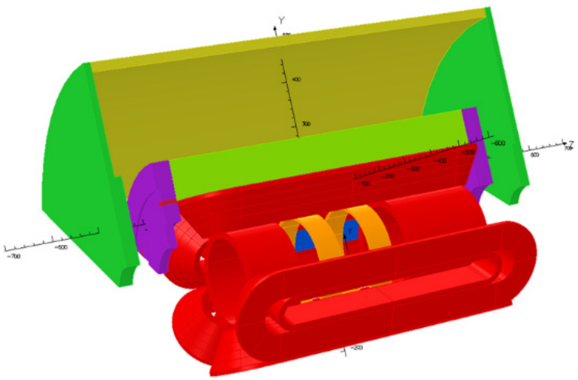
FECRAL key parameters

Parameters	Unit	FECRAL
Frequency	GHz	45
B_{ECR}	T	1.6
B_{inj}	T	>6.4
B_{extr}	T	3.2
B_r	T	>3.2
Mirror to mirror	mm	500
chamber ID	mm	150
Warm bore ID	mm	170
Extra. voltage	kV	50

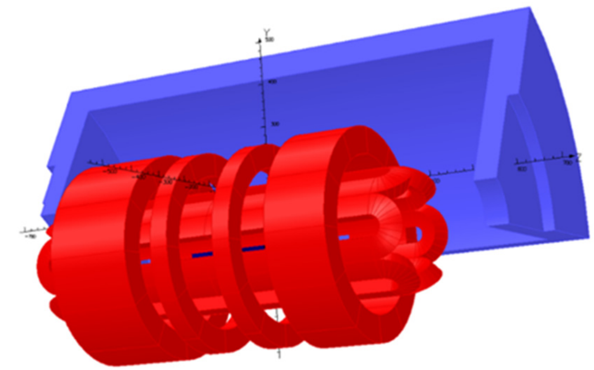
FECRAL expected beams and intensities

$^{129}Xe^{30+}$	>1000 μA
$^{129}Xe^{45+}$	50-100 μA
$^{209}Bi^{31+}$	>1000 μA
$^{209}Bi^{55+}$	30-100 μA
$^{238}U^{35+}$	>1000 μA
$^{238}U^{41+}$	200-400 μA
$^{238}U^{56+}$	30-100 μA

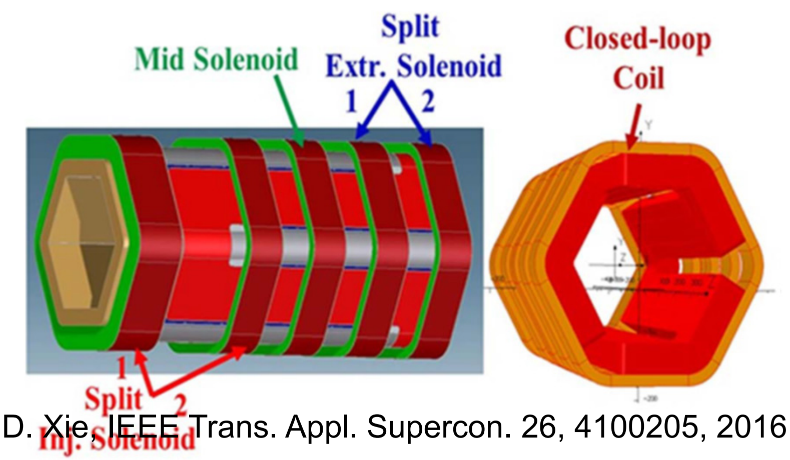
Options of FECRAL SC magnet



- Sol-In-Sext structure: SECRAL
- Maximum stress and loading factor too high

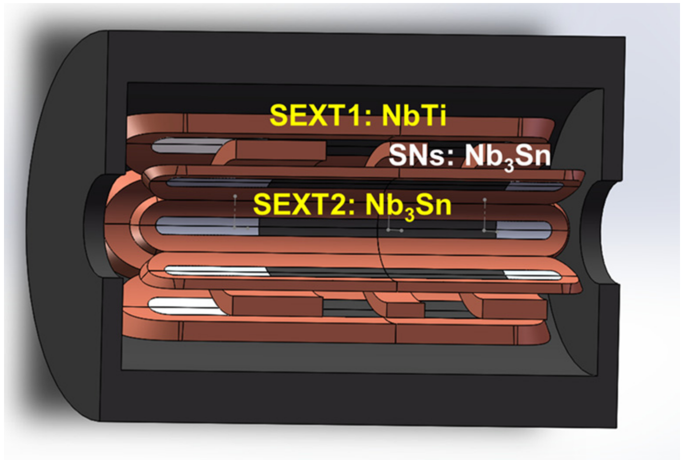


- Sext-In-Sol structure: conventional,…
- Stress acceptable. Engineering experience



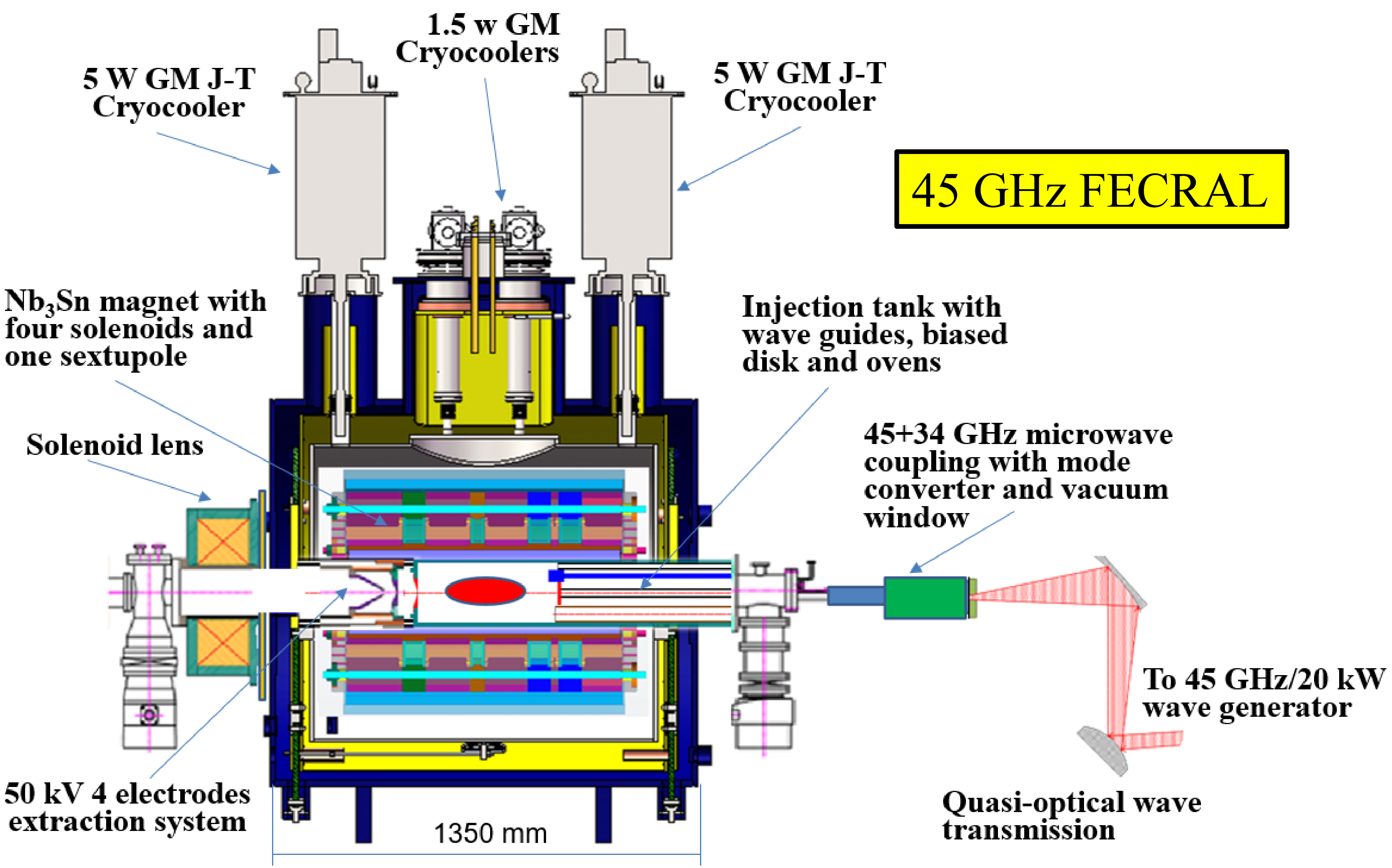
D. Xie, IEEE Trans. Appl. Supercon. 26, 4100205, 2016.

- MARS-D magnet proposed by D.Xie
- Engineering complicated and R&D needed

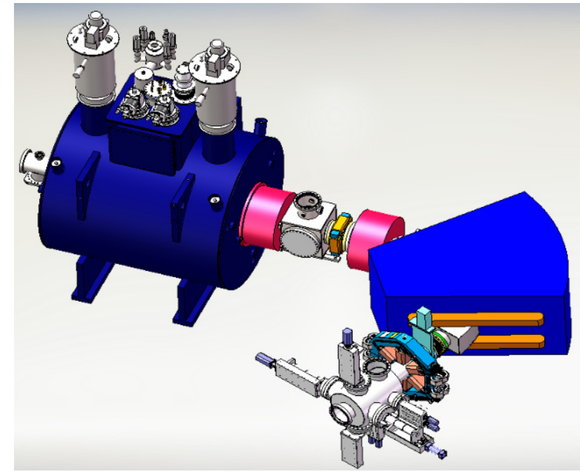


- Hybrid structure with two sextupole
- Engineering complicated and risky

FECRAL preliminary design



FECRAL beam transport and analyzing



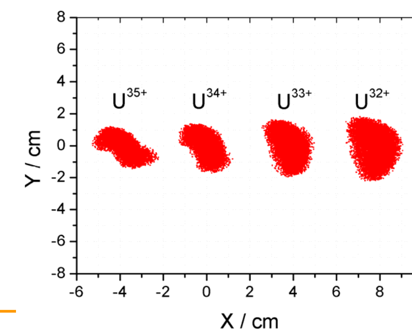
TWO SOLENOIDS and 110° bending magnet:

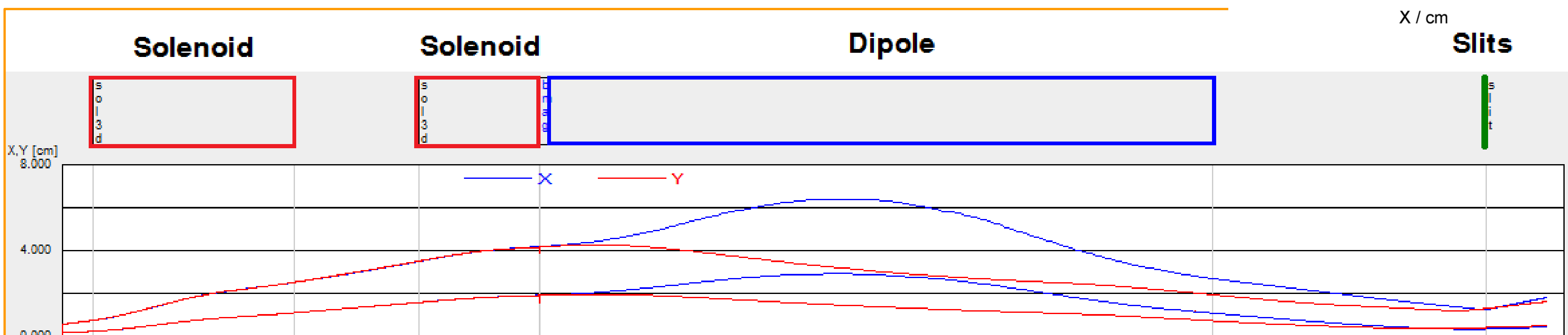
- ✓ Match for a wide range of ion beam species with different intensities.
- ✓ Improve the ion seperation by reducing the beam size at the focal plane for intense heavy ion beams.
- ✓ Higher Q/A resolution.
- ✓ Creat a right beam rotation angle

Y.Yang,WECO03

- Transverse coupling decorrelation.
- Correct phase space orientation for sextupole compensation

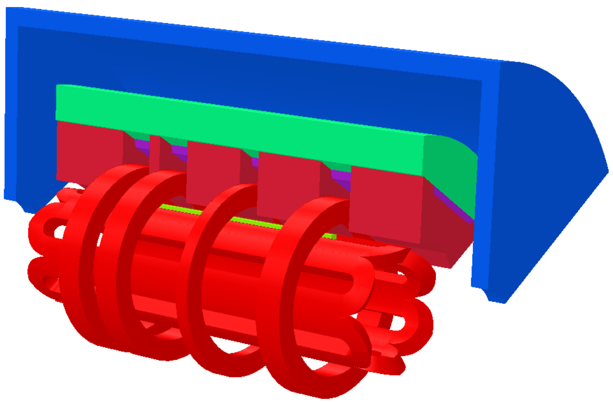
I_0: 15 emA;
I_{U35+}: 2 emA
HV: 50 kV;
SCC: 70%

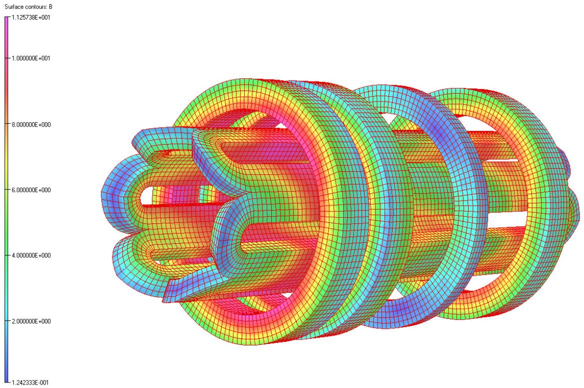




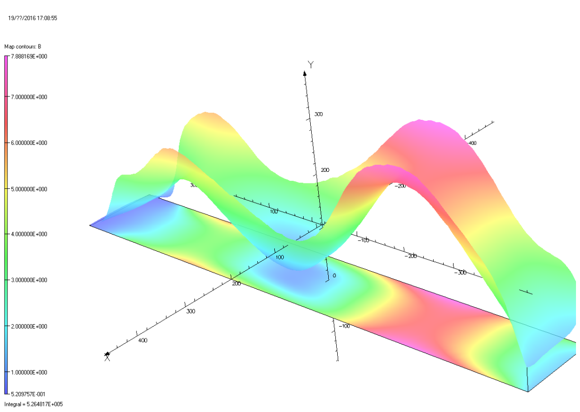
Magnet preliminary design—field distribution

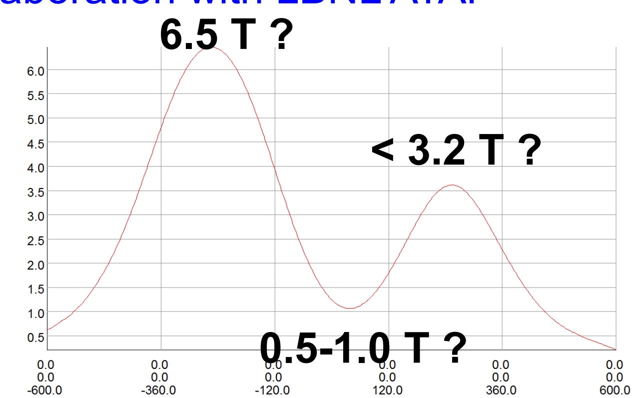
- Sextupole and solenoids: single wire winding
- OST Nb_3Sn M-Grade Round wire: wire diameter 1.3 mm, isolated 1.43 mm
- Maximum peak fields on the sextupole coil and the injection coil: ~ 11 T
- Loading factor at operating designed currents: Sextuple: 76%, Inj-Sol: 75%.
- Maximum stress on the coil: < 160 MPa



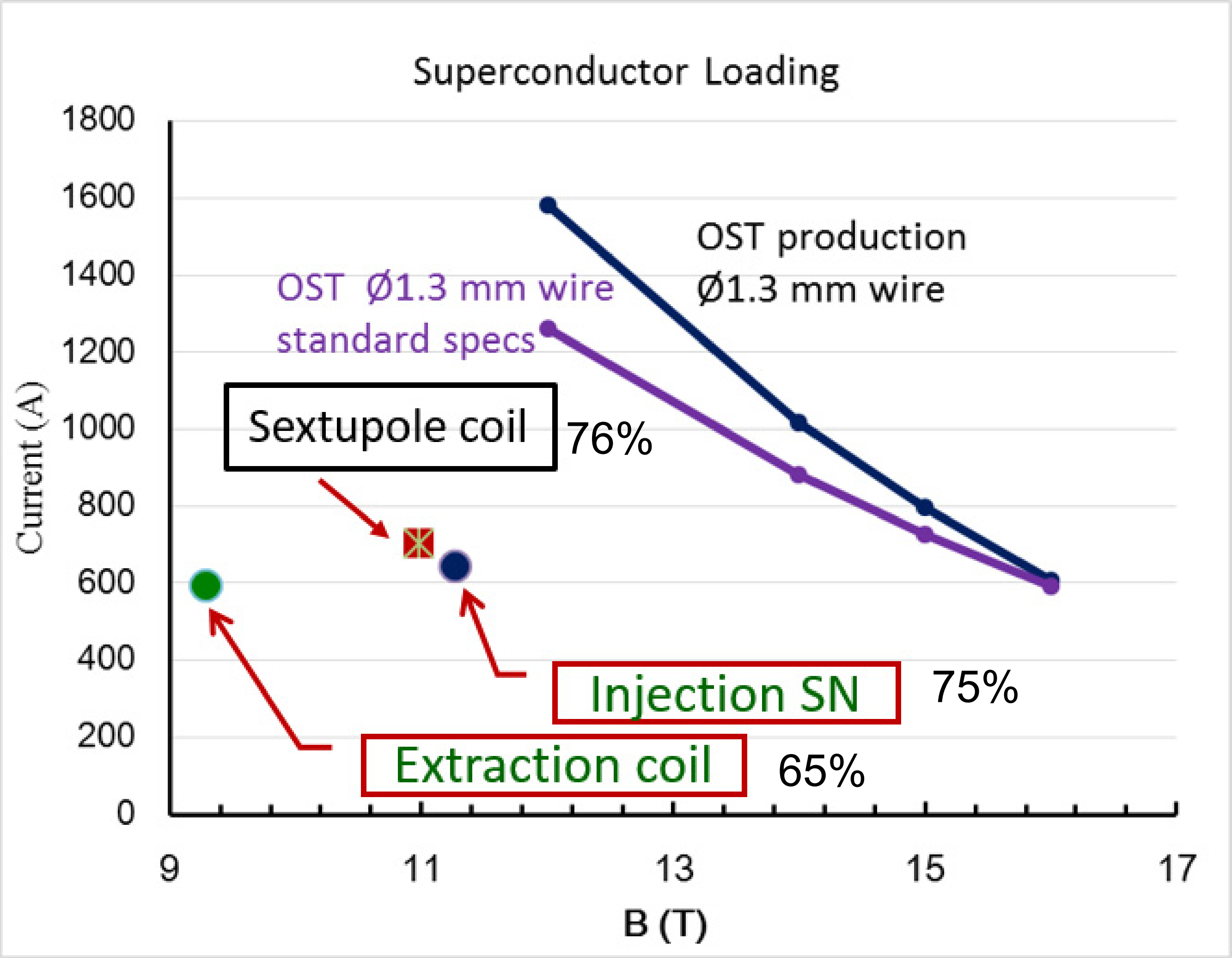


Nb_3Sn magnet design by collaboration with LBNL ATAP



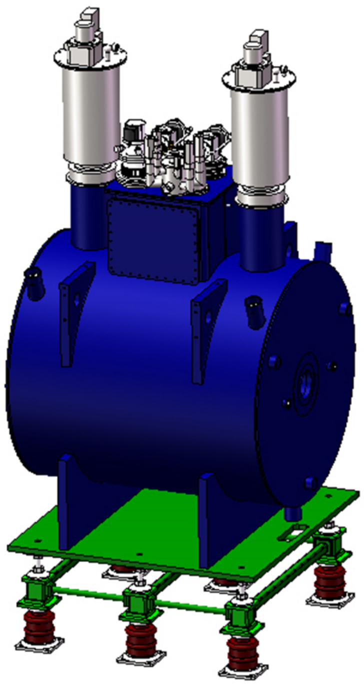


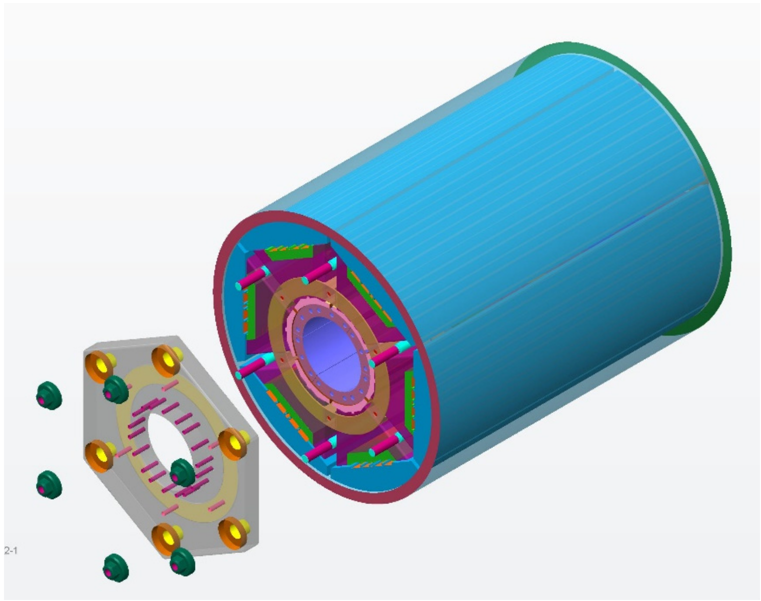
Magnet preliminary operation conditions

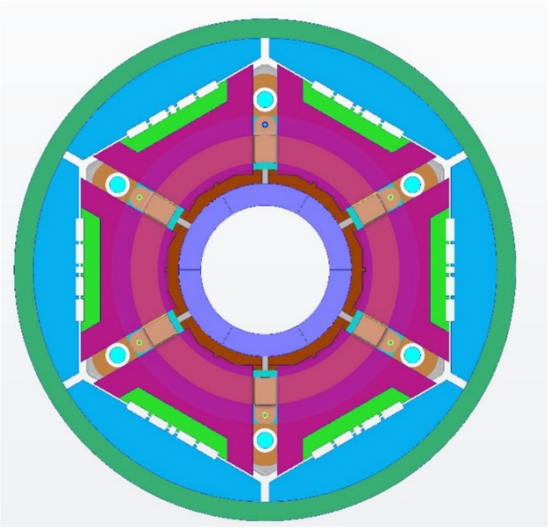


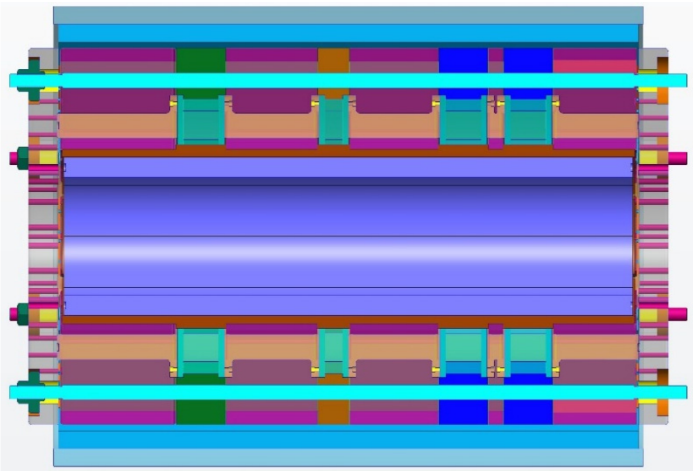
Magnet preliminary design—mechanical structure

Nb_3Sn magnet design by collaboration with ATAP/LBNL





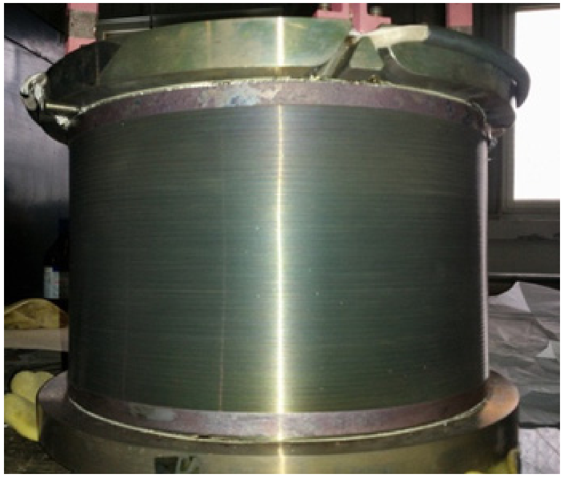




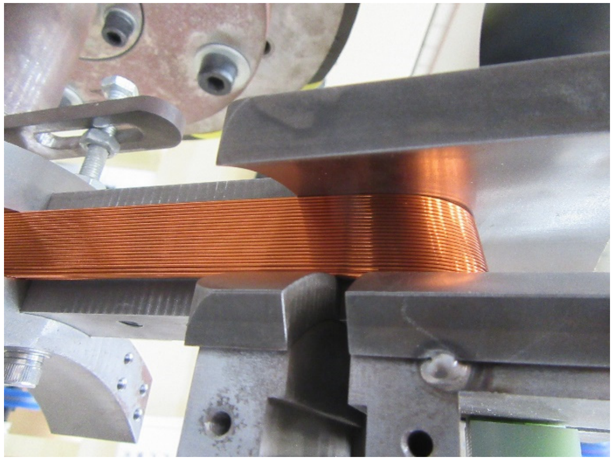
- Mechanical support and clamping are provided by an Aluminum shell， iron yoke, iron pads and stainless steel collars.
- Assembly pre-load by pressurized bladders and interference keys technologies.
- Pre-loading increases during cool-down due to contraction of the shell, the yoke and the pads.

Nb_3Sn Magnet prototyping coils

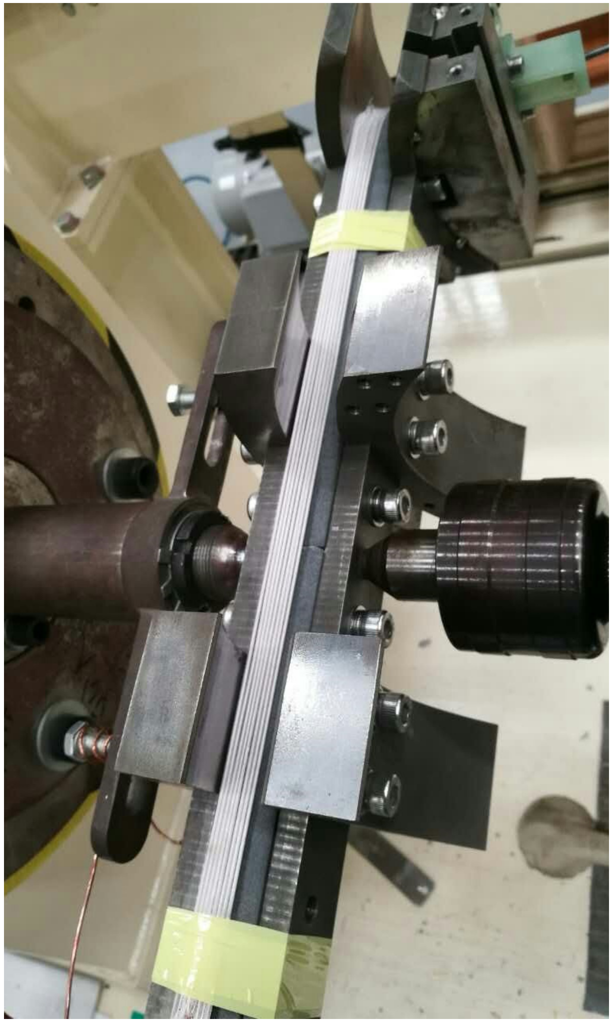
FECRAL magnet will be fabricated by a Chinese company.



Nb_3Sn solenoid coil



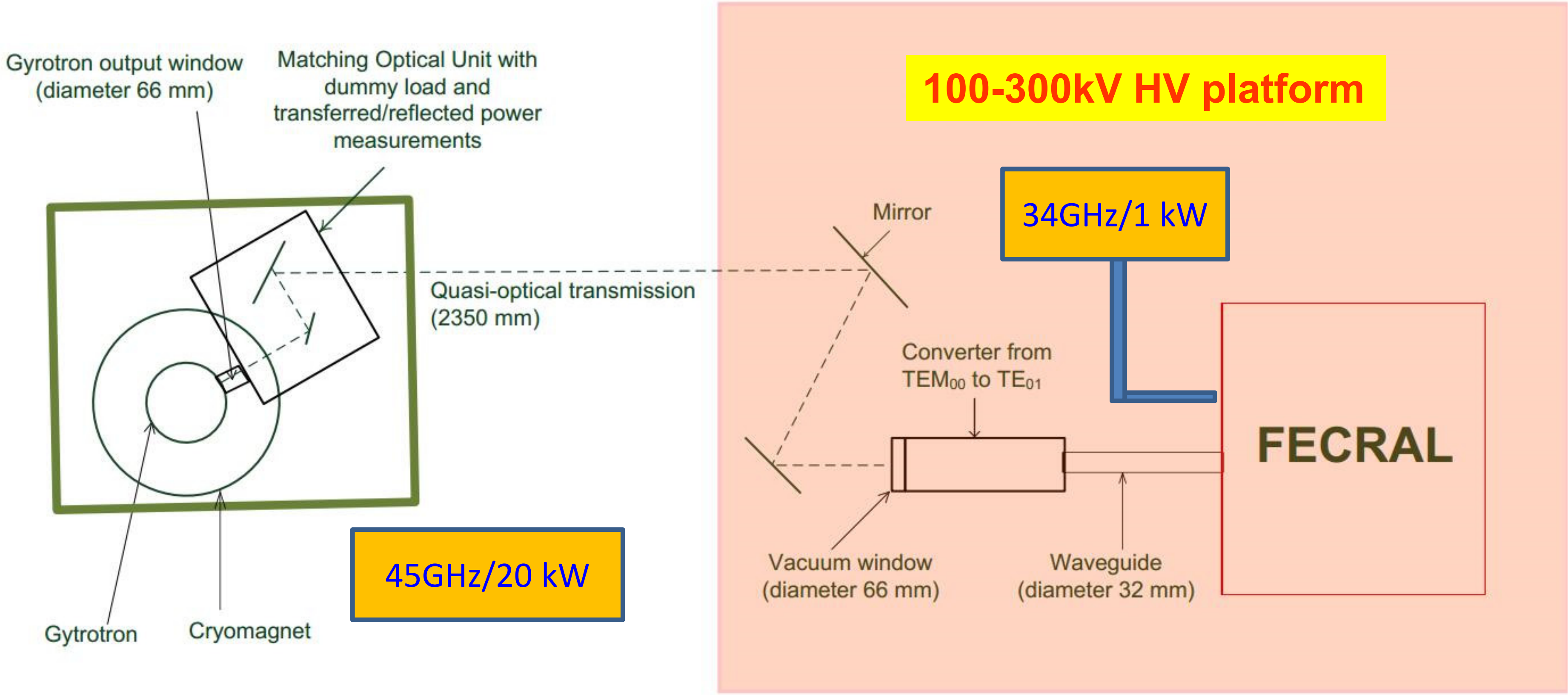
Cu Sextupole coil winding for practice



Nb_3Sn Sextupole coil winding

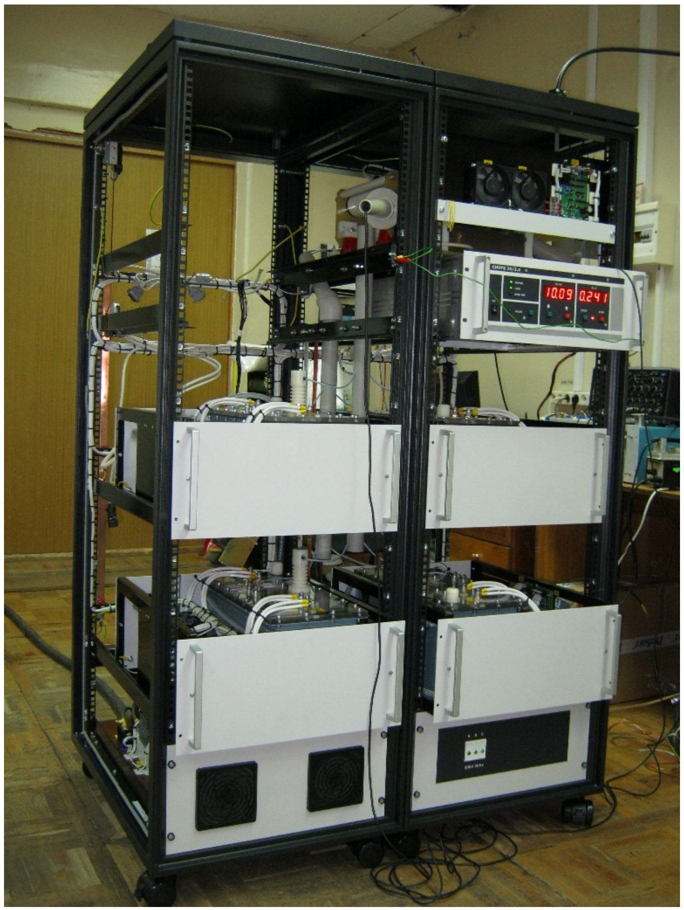
45 GHz/20 kW microwave coupling

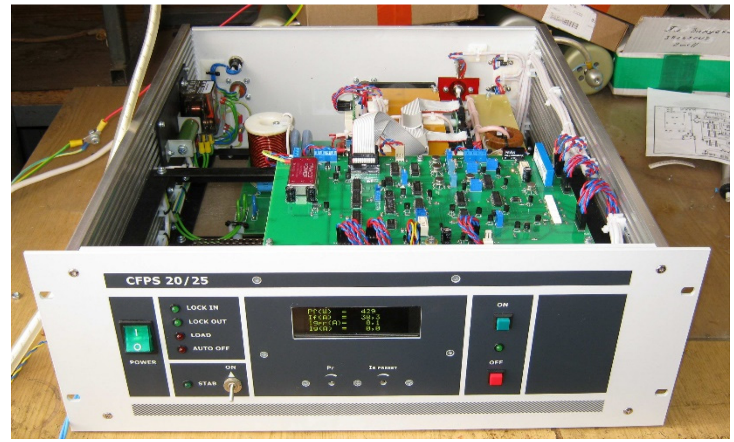
- Gyrotron Output Mode: Quasi-optical
- Quasi-optical transmission for 100-300 kV isolation
- Rf coupling: TE_{01} with φ32mm circular waveguide

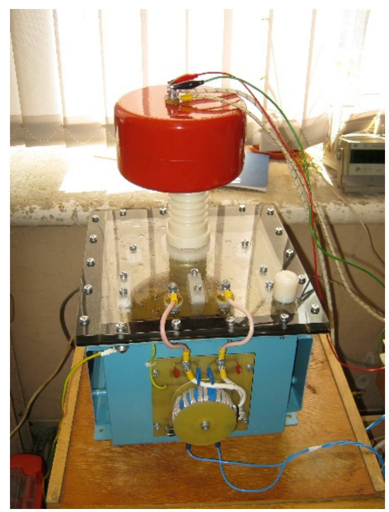


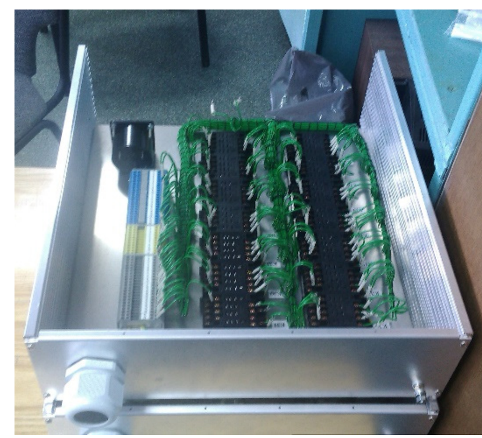
45 GHz/20 kW microwave generator

45 GHz/20 kW microwave generator is being manufactured by GYCOM, Russia.









Outline

1.HIAF and FECRAL brief introduction

2. FECRAL preliminary design

3. Technical Challenges

4. Summary

40-60 GHz scaling law

Challenge No.1

- **3^{rd} Gen. ECRISs have been validated and demonstrated a perspective and excellent performance in terms of scaling law by significant gains on *I* and *Q*.**

- **Nevertheless, big potential for 3^{rd} ECRISs to further boost the performance.**
  - ✧ **RF coupling**
  - ✧ **beam extraction**
  - ✧ **….**

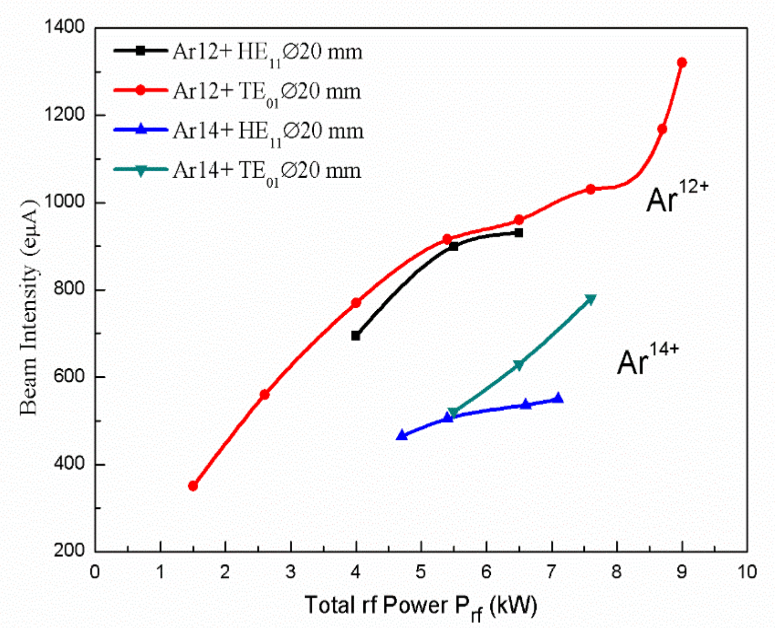
- **ω_{rf}, B, P_{rf}, which one is more critical and dominant?**

■ **Claude Lyneis proposed the 4^{th} Gen. ECRIS in terms of scaling law in 2006.**

■ $I \propto \omega^2$ for 40-60 GHz ??

■ ***B_{rad} = 2.0 B_{ecr} , B_{inj} = 4.0 B_{ecr}, B_{min} = 0.5-0.7 B_{ecr}, B_{ext} = 2.0B_{ecr} ? ?***

■ **Can 45 GHz FECRAL be able to operate at B_{inj}=6.5 T, B_{min}=0.5-0.6 T, B_{extr}=3.2 T, B_{rad}=3.2 T**

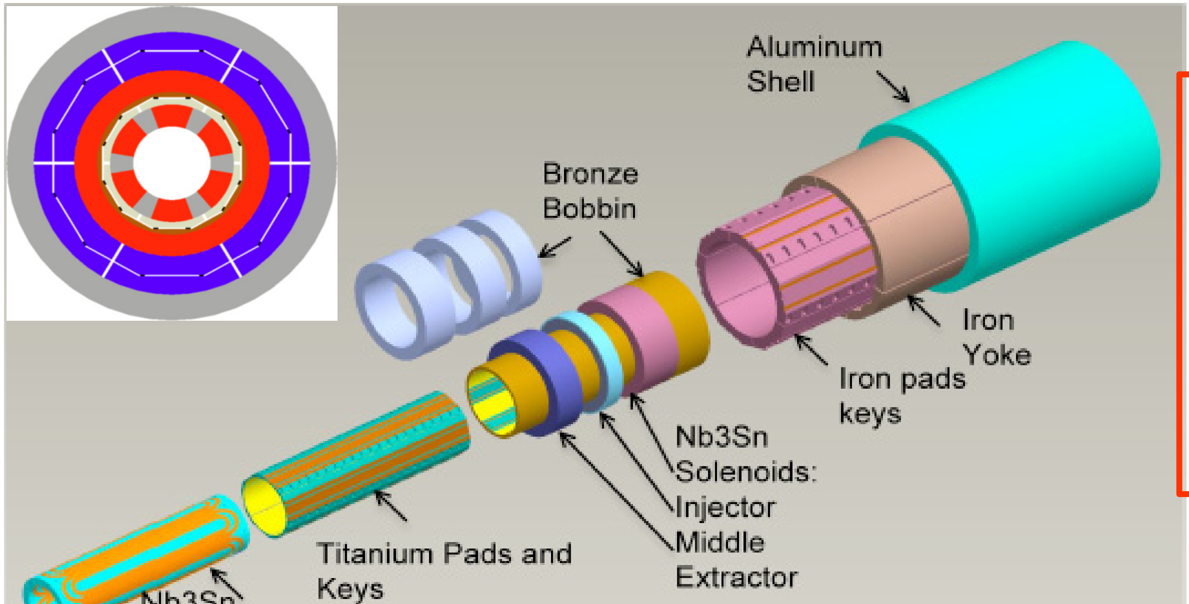


Nb_3Sn magnet for 4th Gen. ECRIS

Challenge No.2

- **56 GHz ECRIS proposed by LBNL 2006.**
- **Keystone Rutherford cable. A lot experiences from accelerator magnets. Less energizing V/m for the cable. Fast energy release during quench.**

- **High currents for the magnet (8-10 kA), no such HTC leads available, and big size for the magnet power supply.**
- **Need independent refrigerator or LHe directly from cryogenic plant.**
- **Difficult to handle at the HV platform**



C.Lyneis, RSI,79, 02A321 2008

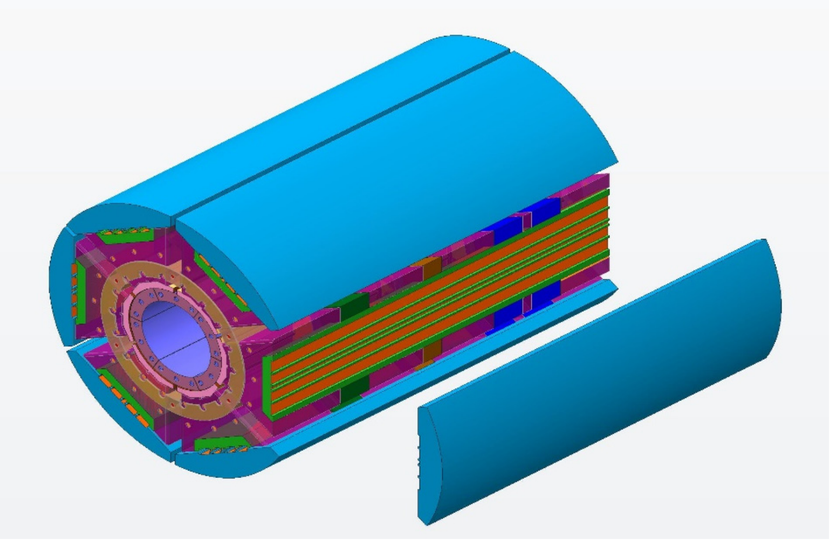
Magnet challenge

- **High peak fields: > 10 T**
- **High stress: >150 Mpa**
- **Nb_3Sn solenoids and Sext.**
- **Engineering challenging and little experience.**

Nb_3Sn magnet for 4th Gen. ECRIS

- 45 GHz FECRAL Nb_3Sn magnet with single wire winding;
  - Low current for the magnet coils, HTC leads available; GM cryocoolers cooling magnet. Small size for the magnet power supply. Suitable for the HV platform.

  - Less manufacturing experience for high field Nb_3Sn magnet with single wire winding.
  - Quite long length wire requested and high charging V/m for the wire.
  - Optimization to reduce peak fields and stress on the conductor.
  - Difficult to handle quench protection and safety issue.
  - Complicated mechanical-clamping and pre-stress structure.



Cold-mass of FECRAL Nb_3Sn magnet

45 GHz/20 kW transmission and coupling

Challenge No.3

- Only IAP/Nizhny Novgorod ever tested successfully 37GHz and 75GHz coupling for ECRIS with quasi-optical transmission, but not for highly charged ECRIS.
- **24-28 GHz microwave coupling to 3rd Gen ECRIS not well understood;**
- How to design an optimum and efficient quasi-optical transmission and coupling system for a 45 GHz highly charged ECR plasma?

3rd -4th Gen ECRIS need urgently experts who know microwave engineering and plasma heating. Collaboration with fusion people?

High 4.2 K dynamic heat load

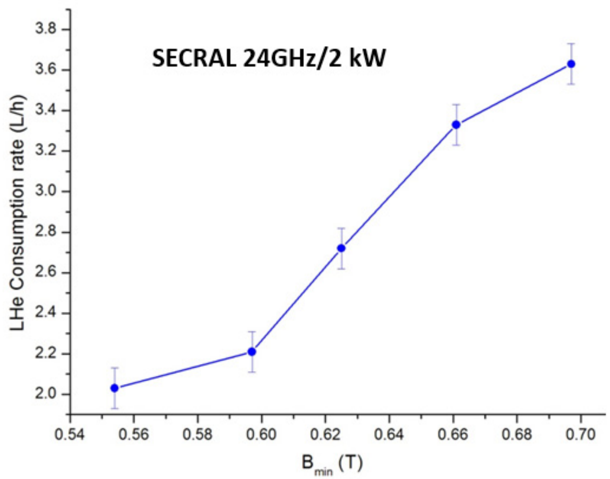
Challenge No.4

- **High flux x-ray heating to the magnet due to strong Bremsstrahlung**
- **Rough estimation from SECRAL operating at 24 GHz 7-9 kW**

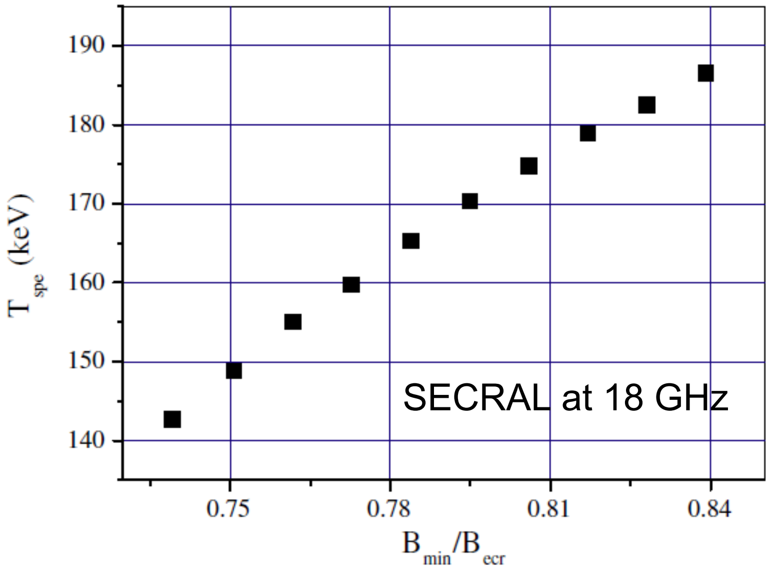
7-9 kW rf power → 1-4W heat load for 24GHz.

- **How about the heat load for 45 GHz 10-20 kW ECR heating ?**

- **How to get a compromise between good performance and low heat loading?**



LHe consumption vs B_{min}



H.Y.Zhao, Plasma Sources Sci. Technol. 18 (2009) 025021

Intense and highly charged U beam production

Challenge No.5

- **Uranium will be one of the most important and challenging beams for projects like HIAF, FRIB, FARE…**
- **Oven operational temperature > 2000℃, long-term operation challenging.**
- **LBNL VENUS achieved the best results for U beams with oven technology**

J. Benitez@ICIS2011

$^{238}U^{33+}$	450eμA
$^{238}U^{34+}$	400eμA
$^{238}U^{50+}$	13eμA

- **Some new technologies should be developed for U beam production, such as, by using laser and electron beam to evaporate U metal, which is under development at IMP.**

High intensity beam extraction and transport

Challenge No.6

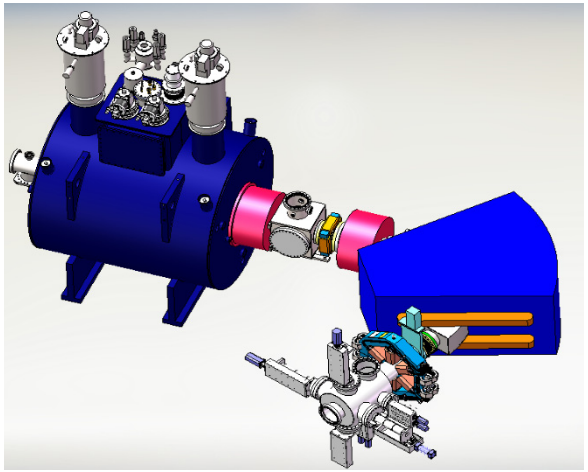
- **SECRAL**: $^{209}Bi^{30+}$ and $^{209}Bi^{31+}$ beam tests at 5kW@25 kV, total beam current ~13 emA. Total transmission efficiency to the Faraday-cup < 50%!

- **VENUS**: $^{238}U^{33+}$ and $^{238}Bi^{34+}$ beam tests at 8 kW @22 kV, total beam current >9 emA. Total transmission efficiency to the Faraday-cup only 55%! (G. Machicoane ECRIS12)

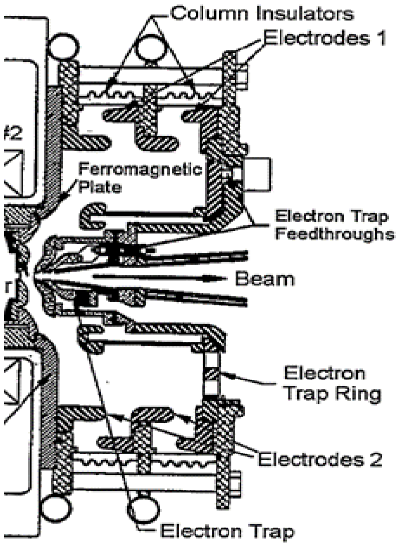
■ **Reason for such low transmission efficiency:**

Space charge and LEBT design??

■ **What is the optimum beam extraction and transport for FECRAL ??**



FECRAL and its beam transport



50 kV extraction ?
3-4 extrac. Electrodes ?

Similar to

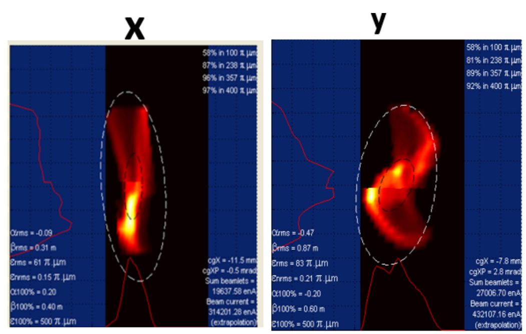
Beam quality and long-term stability

Challenge No.7

- **FRIB requests ion source: $^{238}U^{33+}$ to $^{238}U^{34+}$: CW, 13 pμA**
  HIAF requests ion source: $^{238}U^{35+}$: CW, 20 pμA; pulsed, 40 pμA
  ECRIS must be operated at RF power > 6 kW !
- **Challenge: beam quality and long-term stability !!**
- **No any ECRIS has demonstrated long-term operation at power > 6 kW !!**

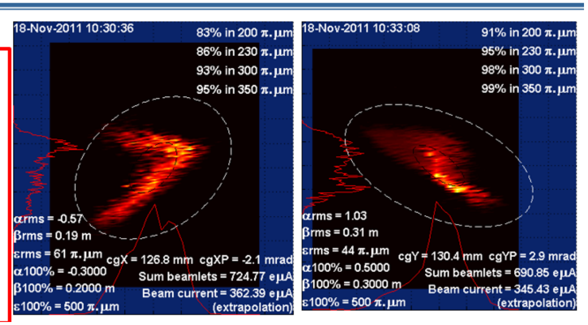
SECRAL

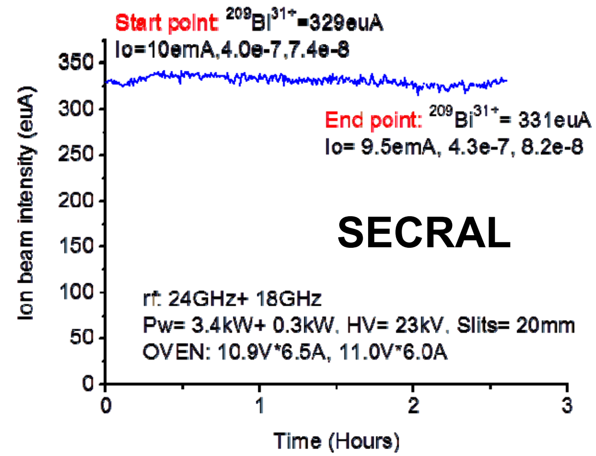
24+18 GHz P= 3.5+0.3 kW
HV= 23 kV I_o= 10 emA,
Bi^{31+}= 330 eμA
Beam: 90%-95%
$\varepsilon_x \approx$ 200-350 ε_y= 350-450 πμm rad

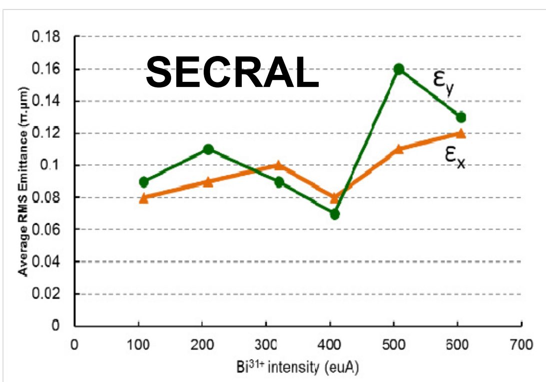


VENUS

28+18 GHz P= 6+1.8 kW
HV= 22 kV I_{extr}= 7.5 emA,
U^{33+}= 365 eμA
Beam: 90%-95%
ε_x= 200-350 ε_y= 200- 230 πμm rad
©G. Machicoane ECRIS2012







Summary

- 4^{th} Gen. ECRIS, 45 GHz FECRAL is under technical design and is going to be built for HIAF project to deliver 40 pμA pulsed and 20 pμA $^{238}U^{35+}$.

- To build a successful 4^{th} Gen. ECRIS FECRAL , the project team will focus on a few technical challenges, such as, high field Nb_3Sn magnet, 45 GHz wave optical transmission and coupling, high flux x-ray heating, high intensity beam extraction and transport, beam quality and long-term stability.

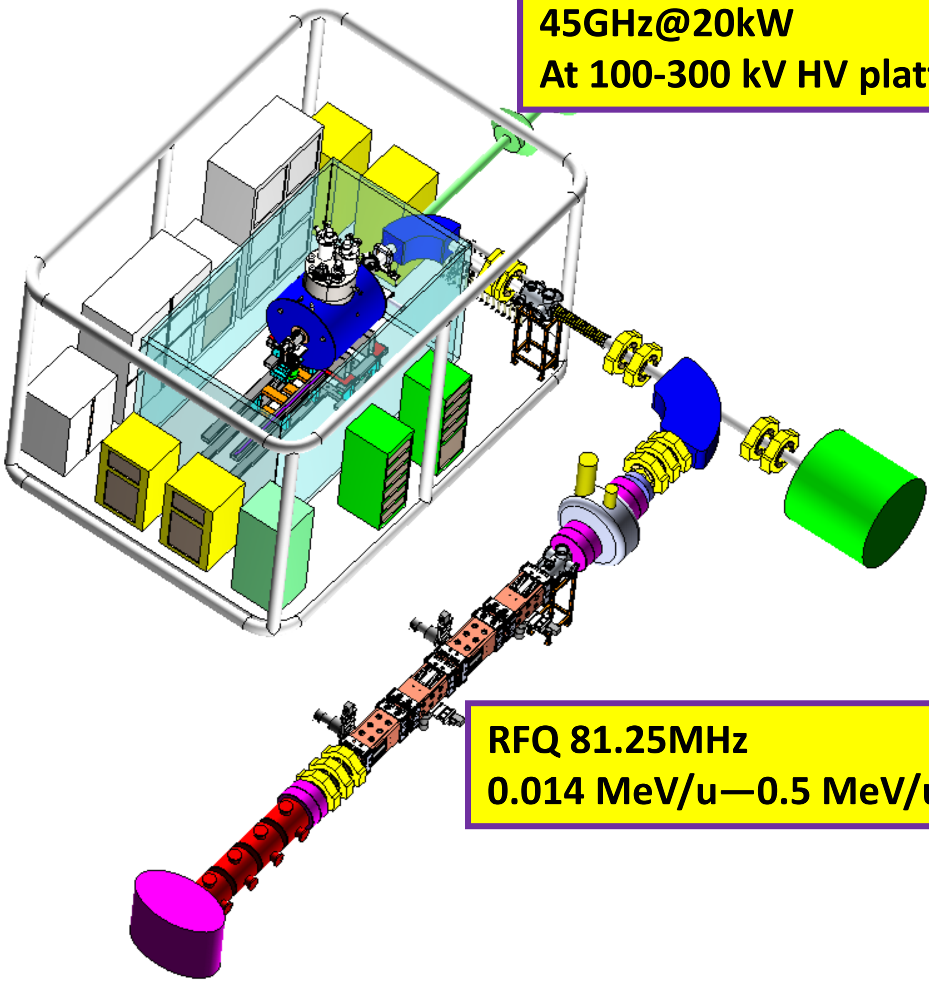
Thank you very much for your attention !

We expect to collaborate with the groups who are interested in the 4th Gen. ECRIS.

IMP is recruiting two postdocs for FECRAL source development.
Please contact me or Liangting Sun if your are interested in.

HIAF front-end R&D----LEAF project

LEAF : Low-Energy intense-highly-charged ion Accelerator Facility



Prototype of HIAF Frontend

- **Approved by NSFC. 2015-2019**
- **Acceptance test by the end of 2019 with promised performance.**

LEAF Science

- Irradiation material
- Highly charged atomic physics
- Low energy Nuclear astrophysics

FECRAL goal for LEAF

$^{129}Xe^{45+}$	30-100 μA
$^{209}Bi^{55+}$	30-100 μA
$^{238}U^{41+}$	200-400 μA
$^{238}U^{56+}$	30-100 μA