STATUS OF THE HIGH-INTENSITY ION SOURCE PROGRAM AT FLNR

A. EFREMOV

OUTLINE

- Test ion source
- Conceptual design of the 28 GHz ECR ion source

Test ion source

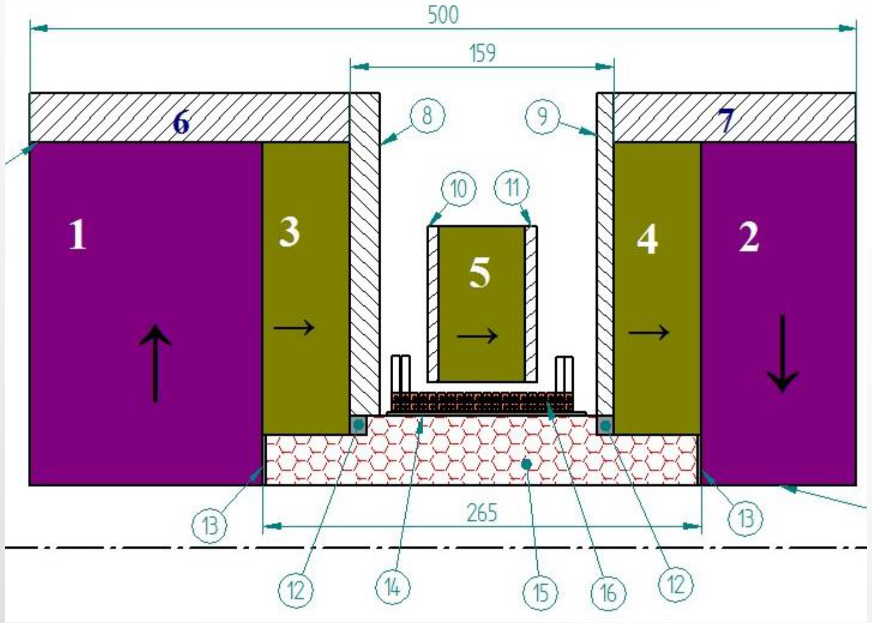
Main requirements:

- Low power consumption, reasonable price ▸ All permanent magnet ion source
- Microwave frequency – 14 GHz
- Charge states: : A/Z =4 ▸ He^{1+}; and A/Z =7 ▸ N^{2+}
- Beam intensities: up to 1 mA

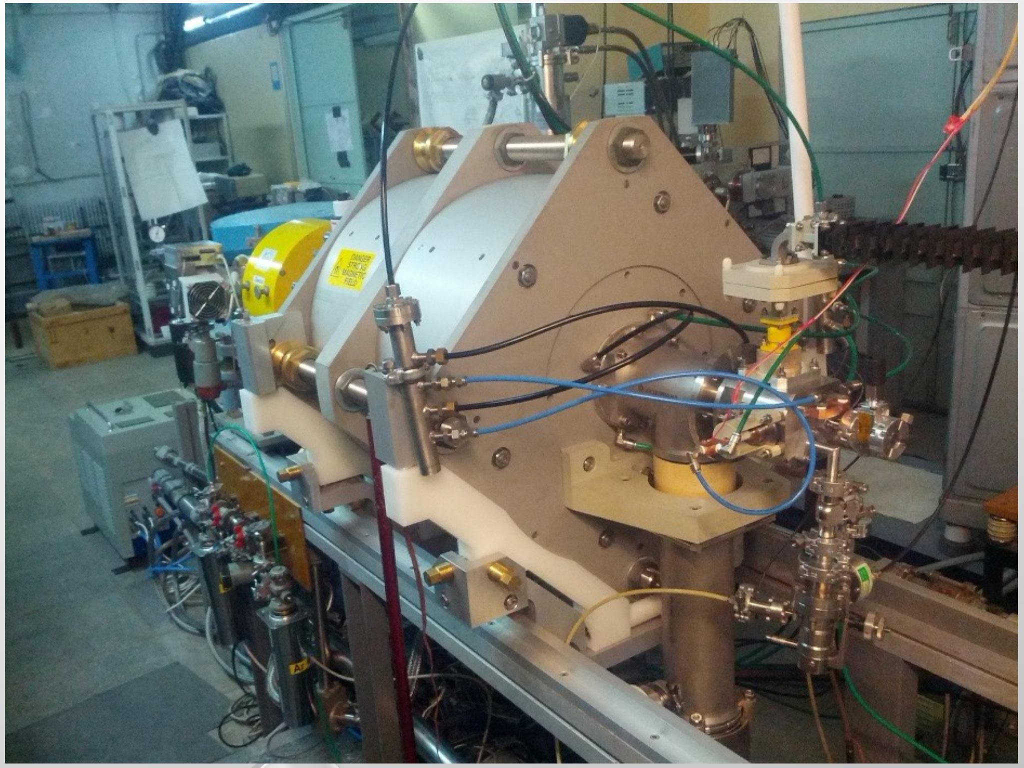
Test ion source

DECRIS-PM

PM weight ≈ 550 kg

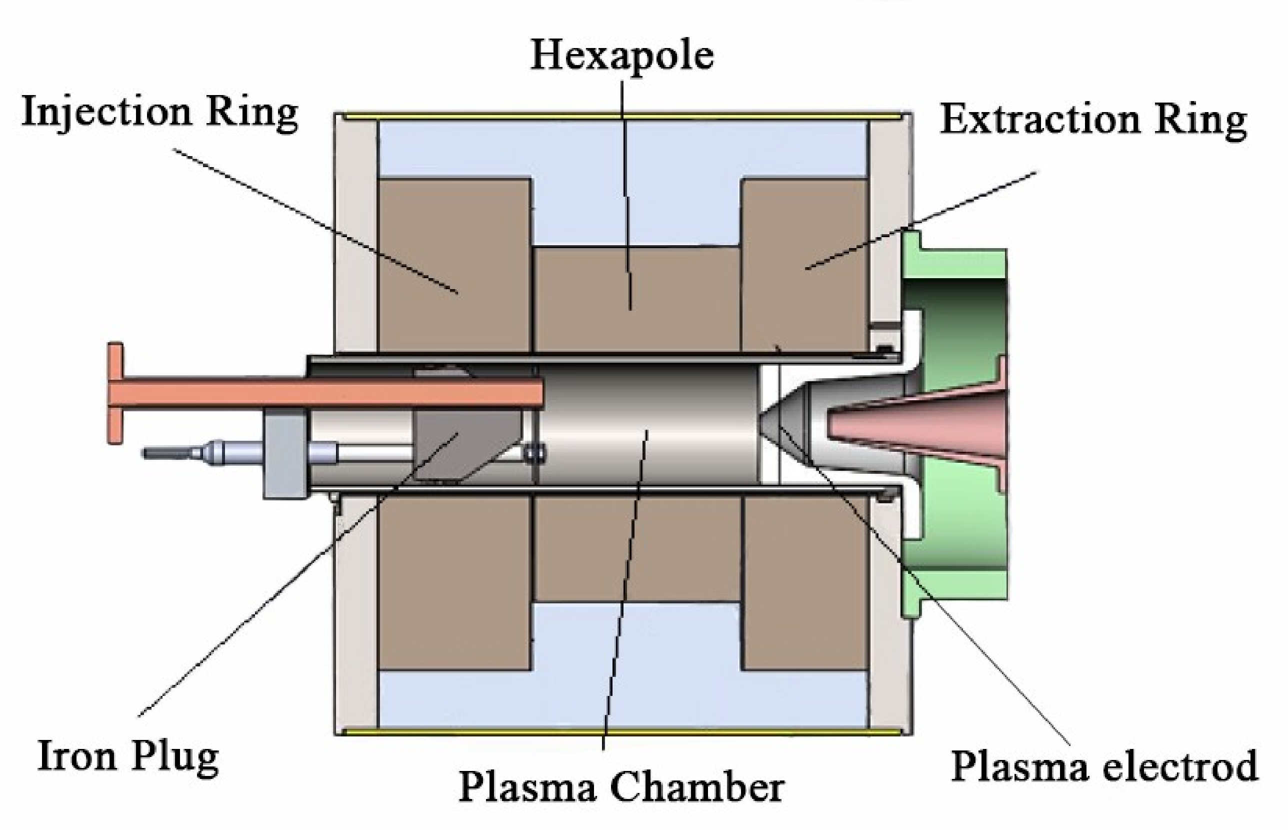


Magnetic structure of DERIS-PM.
1÷5 – PM rings; 6, 7 – soft iron rings;
8÷11 – soft iron plates,
12÷14 - auxiliary elements,
15 - hexapole, 16 – coil.



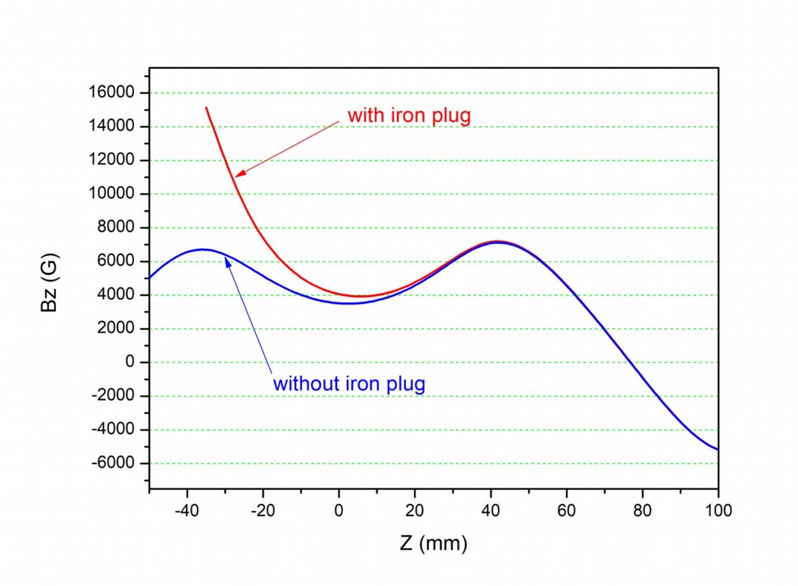
Test ion source

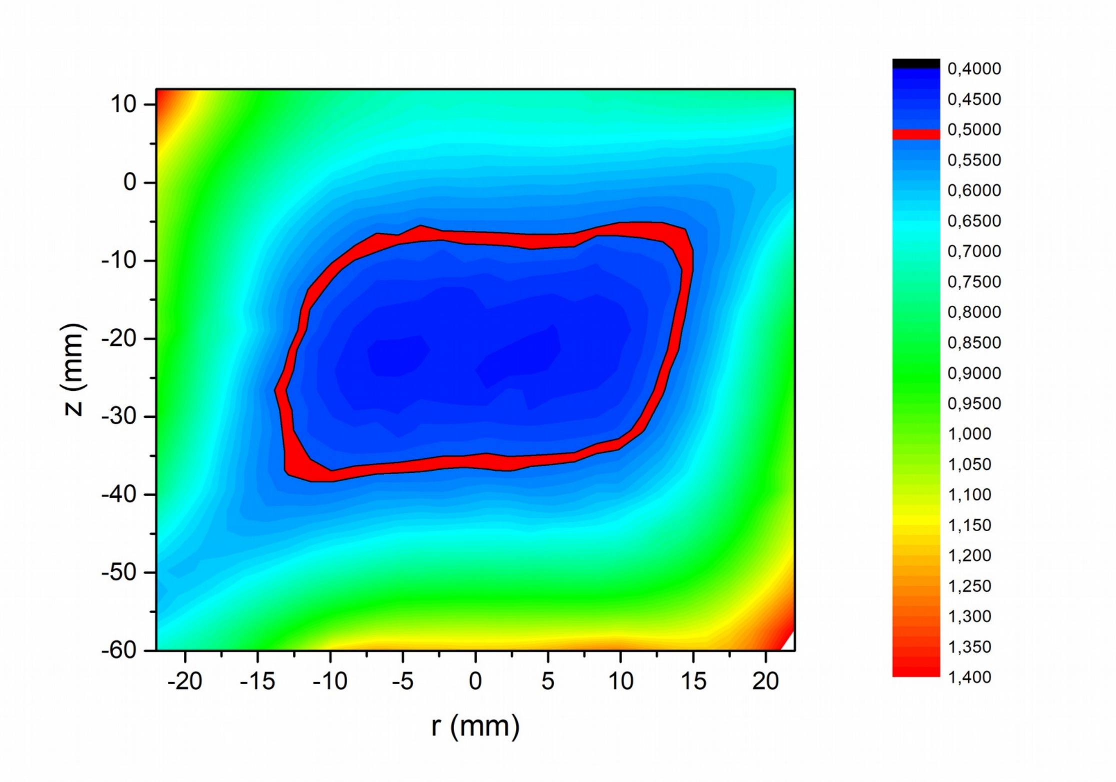
SCHEMATIC VIEW



Test ion source

MAGNETIC SYSTEM





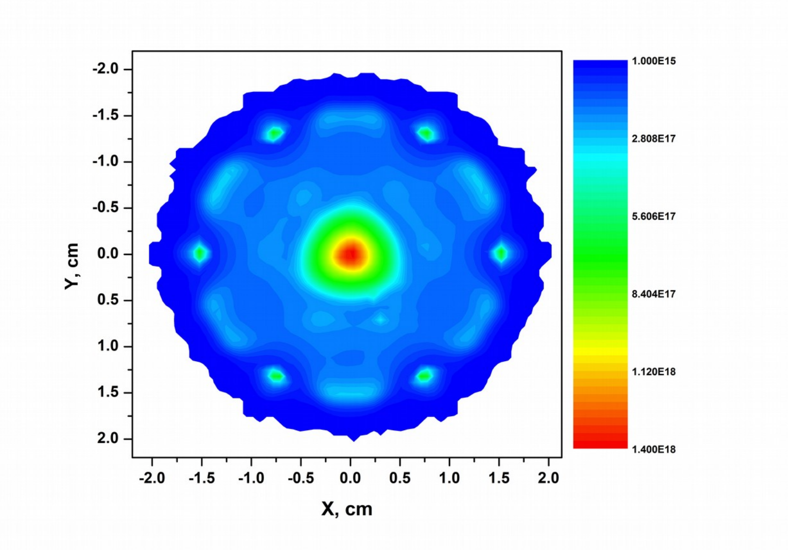
MODELING

SIMULATIONS OF THE PLASMA DYNAMICS WERE DONE FOR THE MICROWAVE FREQUENCY OF 14.5 GHZ AND THE MICROWAVE AMPLITUDE OF 100 V/CM

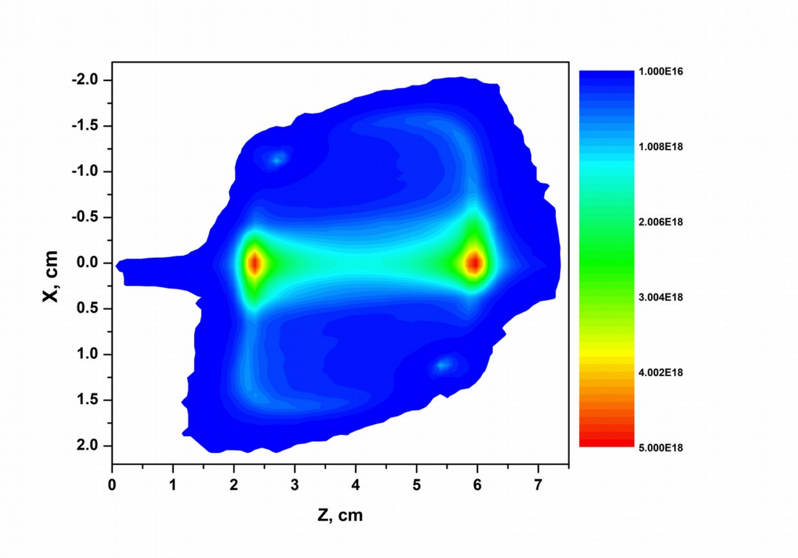
REFERENCES (CODE DESCRIPTION):

- [1] V. MIRONOV, S. BOGOMOLOV, A. BONDARCHENKO, A. EFREMOV, AND V. LOGINOV, “NUMERICAL MODEL OF ELECTRON CYCLOTRON RESONANCE ION SOURCE”, *PHYS. REV. ST ACCEL. BEAMS*, VOL. 18, P. 123401, 2015, DOI:10.1103/PHYSREVSTAB.18.123401
- [2] V. MIRONOV, S. BOGOMOLOV, A. BONDARCHENKO, A. EFREMOV, AND V. LOGINOV, “NUMERICAL SIMULATIONS OF GAS MIXING EFFECT IN ELECTRON CYCLOTRON RESONANCE ION SOURCES”, *PHYS. REV. ACCEL. BEAMS,* VOL. 20, P.013402, 2017, DOI:10.1103/PHYSREVACCELBEAMS.20.013402
- [3] V. MIRONOV, S. BOGOMOLOV, A. BONDARCHENKO, A. EFREMOV AND V. LOGINOV, “SOME ASPECTS OF ELECTRON DYNAMICS IN ELECTRON CYCLOTRON RESONANCE ION SOURCES”, *PLASMA SOURCES SCIENCE AND TECHNOLOGY*, VOL. 26, P. 075002, 2017, DOI:10.1088/1361-6595/AA7296

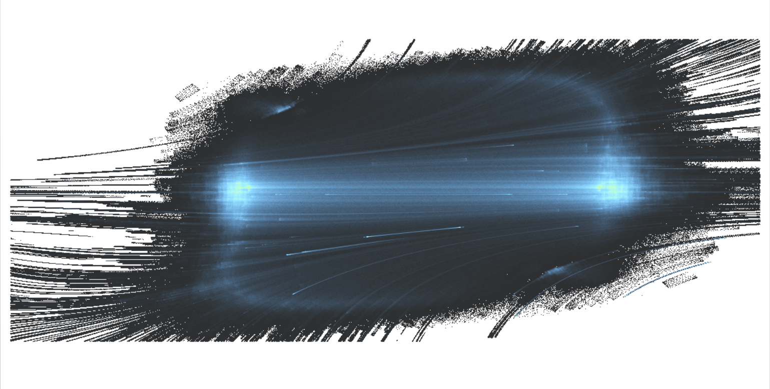
MODELING



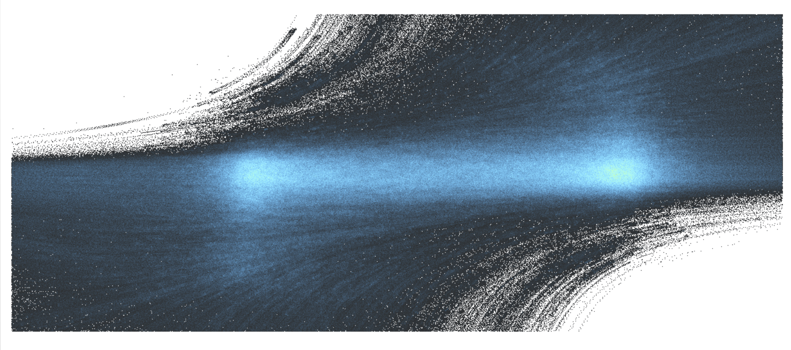
Transversal profile of the electron density



Longitudinal profile of the electron density

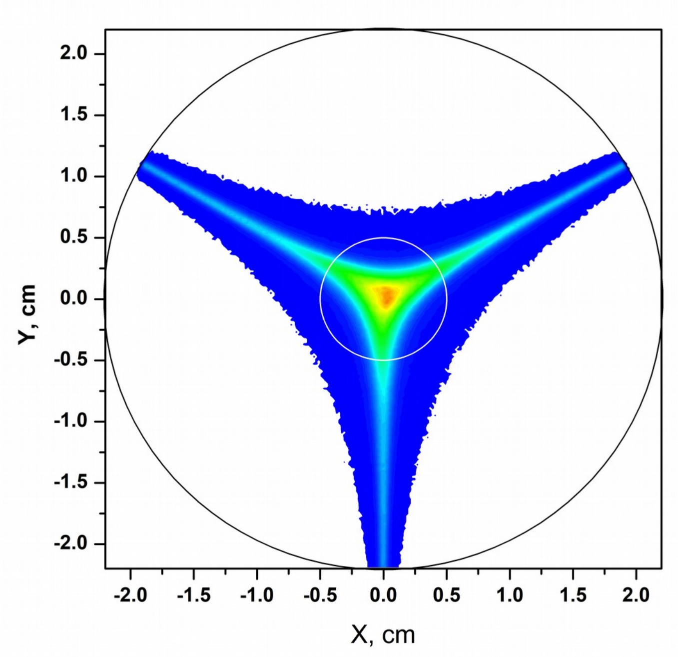


Longitudinal slice of electron trajectories

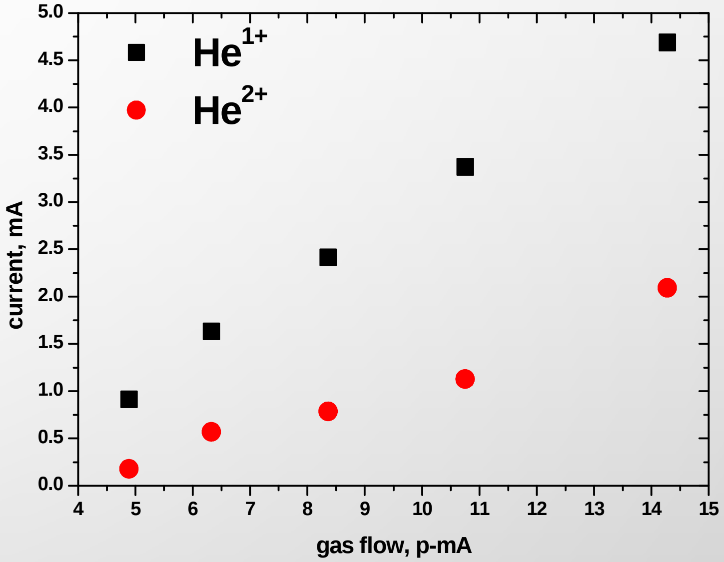


Longitudinal profile of the He1+ ion density

MODELING



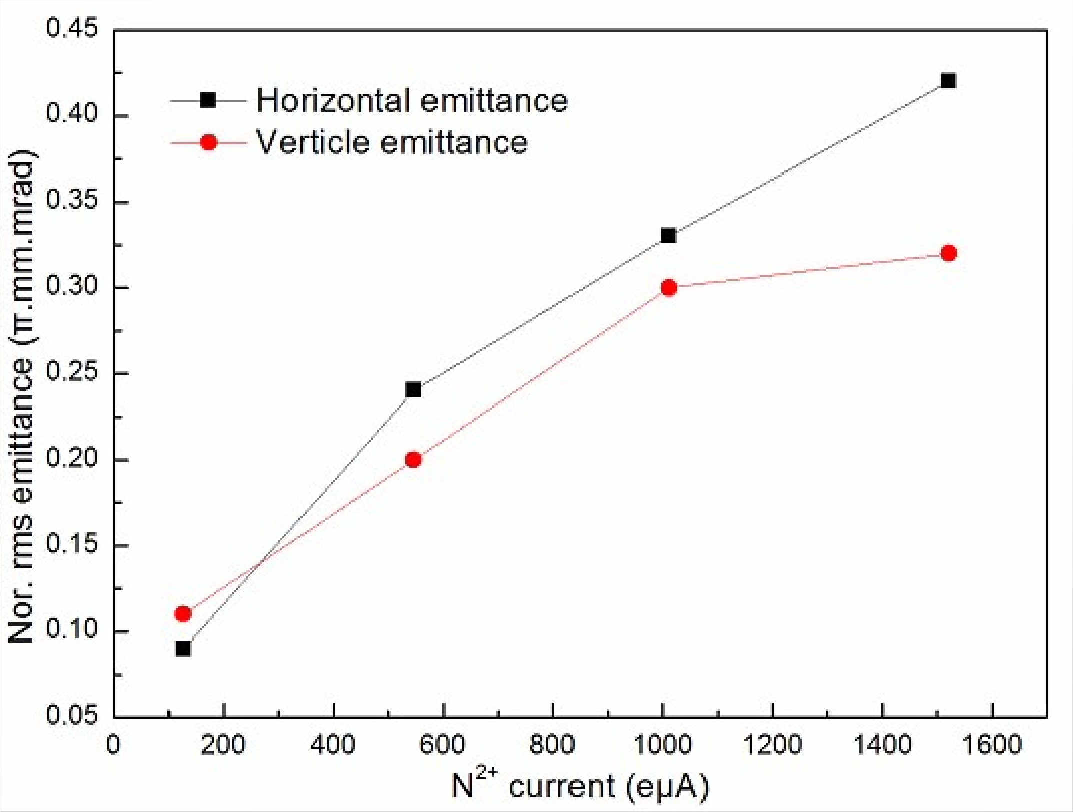
Ions at the extraction electrode



Dependence of the extracted helium ion currents on the gas flow into the source

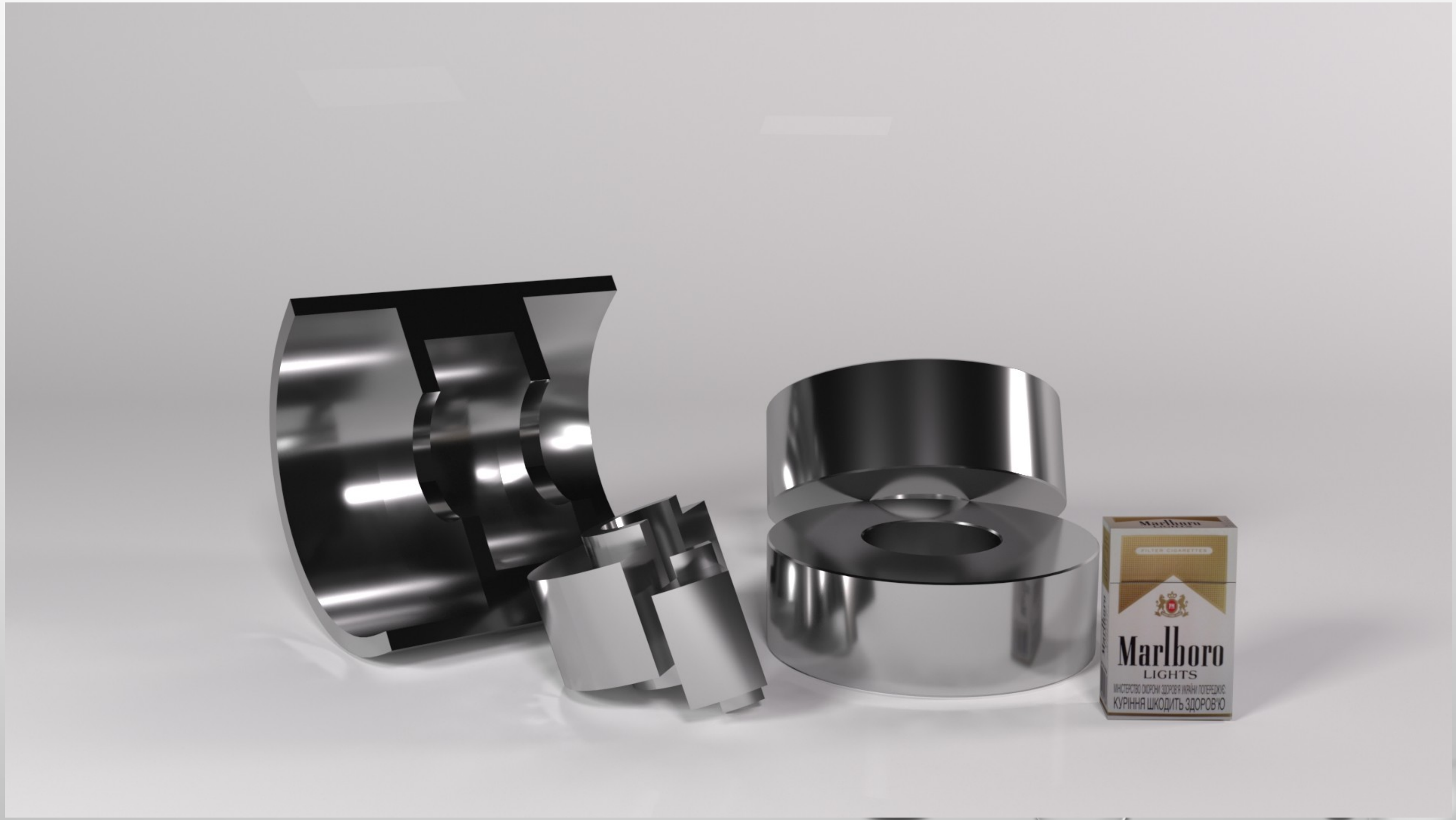
Emittances for the extracted helium ions are defined by the magnetic momentum term and are **0.12 and 0.18 π·mm·mrad for 1+ and 2+** charge states respectively. At that, no space-charge and extraction aberrations’ effects are taken into account, which can be severe.

Emittance (measured)



N2+ beam emittance versus beam intensity.

MAGNETIC SYSTEM



MAIN PARAMETERS:

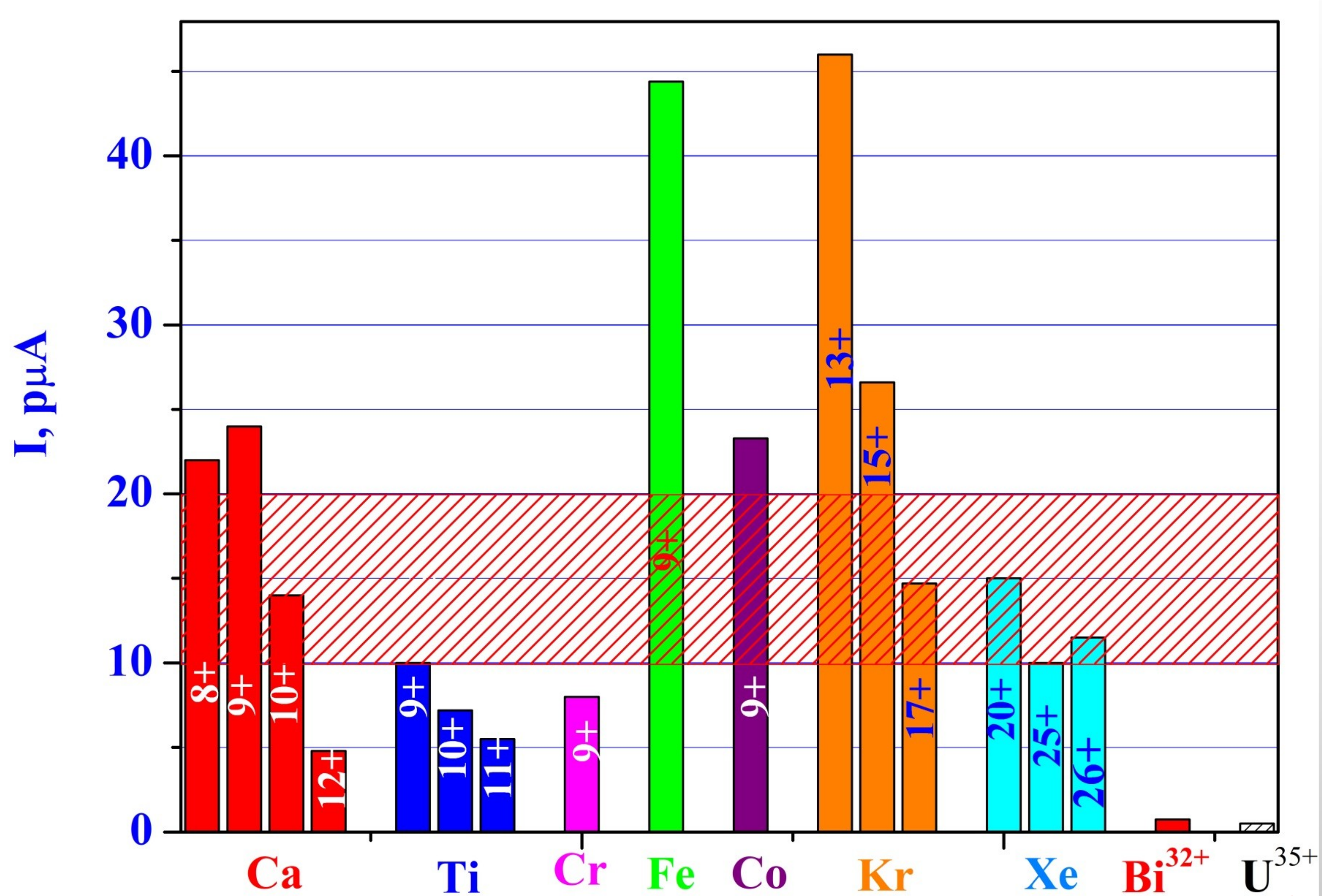
- **Microwave frequency – 14 GHz**
- **B injection – 1.4 T**
- **B extraction – 0.7 T**
- **B min ~ 0.4 T**
- **B radial ~ 0.9 T**
- **Max. microwave power – 500 W**
- **Max. extr. voltage - 30 kV**
- **Plasma chamber ø – 44 mm**
- **Water cooling ≤ 5 bars**
- **dimensions: ~ Ø200 × 200 mm**
- **Permanent magnets weight ~ 20 kg**
- **Total weight ~ 50 kg**
- **Norm. rms emittance ~ 0.3 π mm mrad**

Source lifetime ≥ 3000 h
(the sputtering of the ion optics)

28 GHZ ECR ION SOURCE

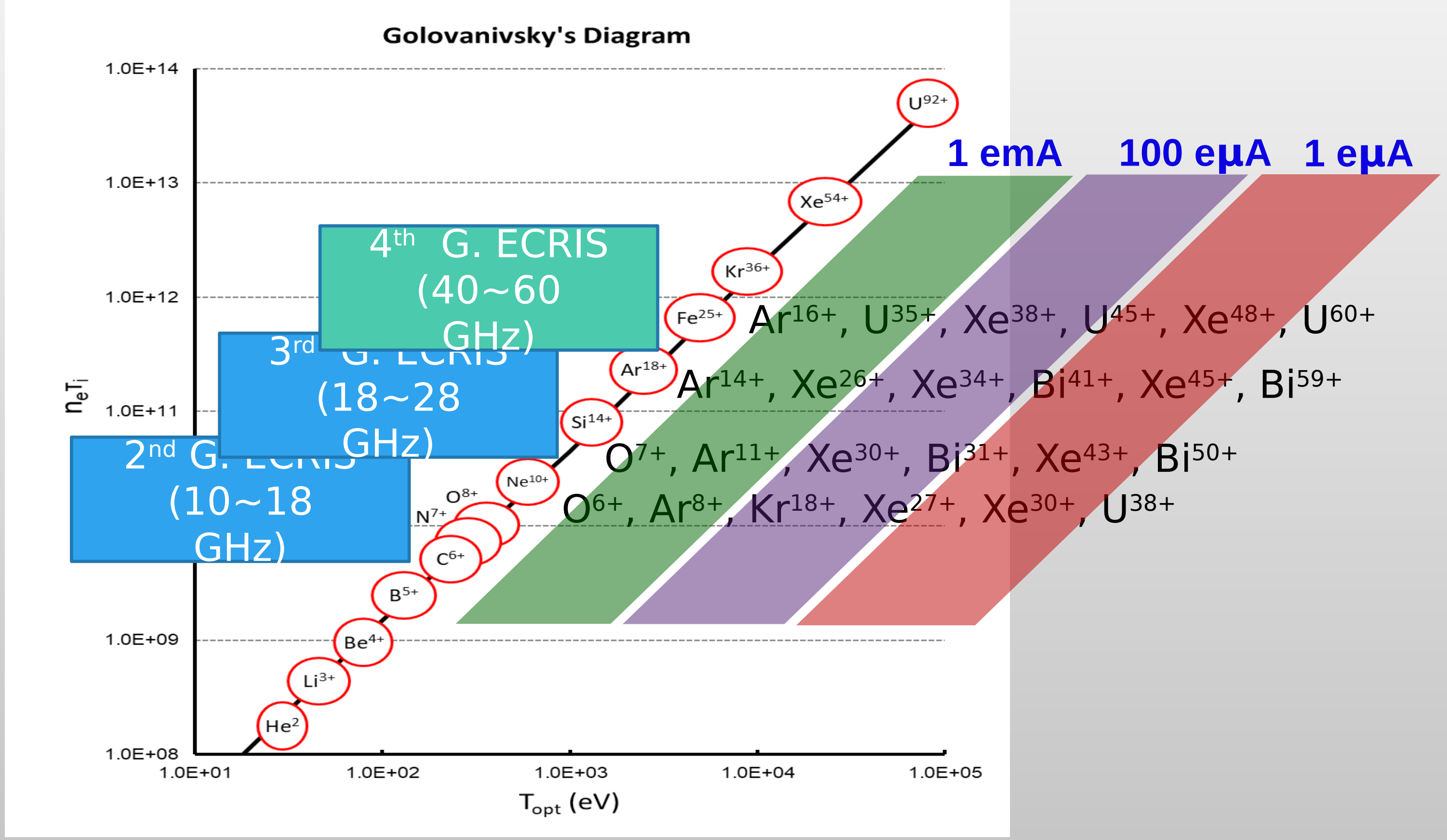
- Ions from carbon to uranium
- A/Z = 4 ÷ 7
- Beam intensity 10 – 30 pμA

Intensities from 14 & 18 GHz ion sources



18 GHz

Future Developments



4th G. ECRIS (40~60 GHz)

3rd G. ECRIS (18~28 GHz)

2nd G. ECRIS (10~18 GHz)

1 emA **100 eμA** **1 eμA**

Ar^{16+}, U^{35+}, Xe^{38+}, U^{45+}, Xe^{48+}, U^{60+}

Ar^{14+}, Xe^{26+}, Xe^{34+}, Bi^{41+}, Xe^{45+}, Bi^{59+}

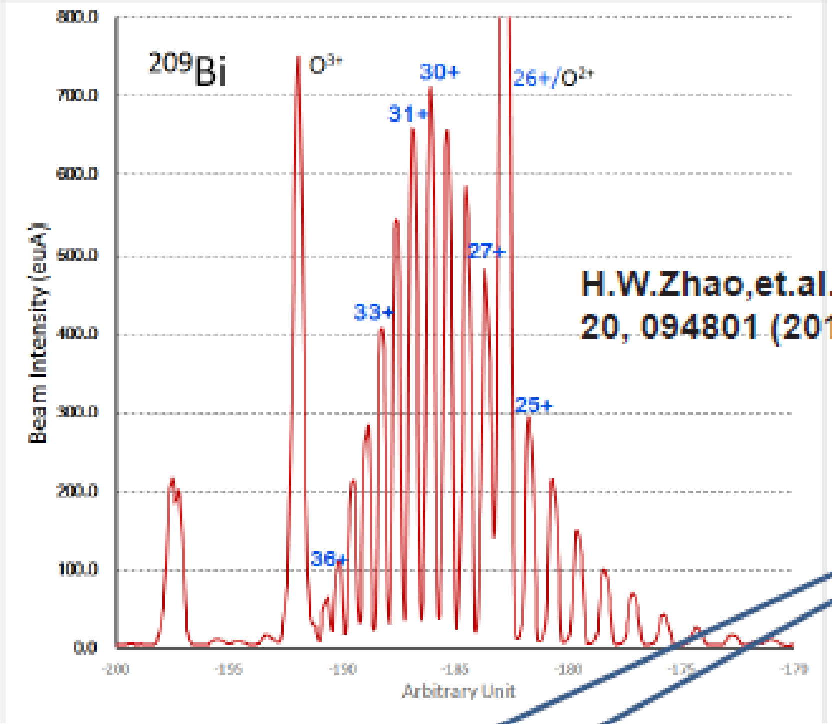
O^{7+}, Ar^{11+}, Xe^{30+}, Bi^{31+}, Xe^{43+}, Bi^{50+}

O^{6+}, Ar^{8+}, Kr^{18+}, Xe^{27+}, Xe^{30+}, U^{38+}

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



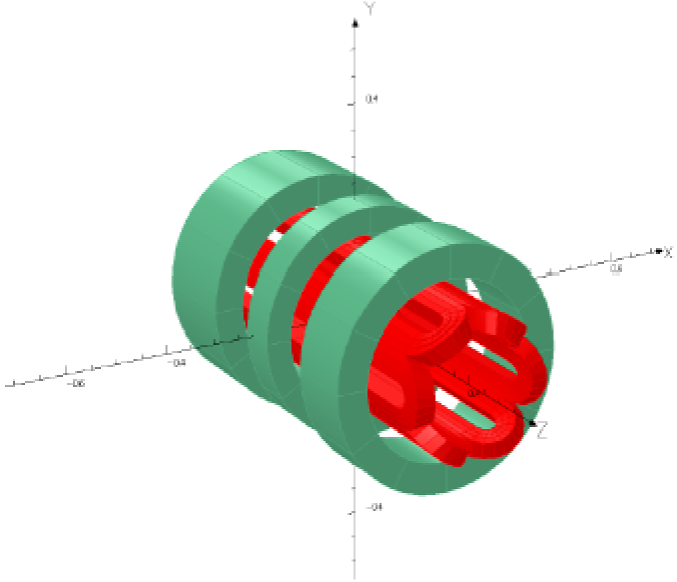
H.W.Zhao,et.al. PRAB, 20, 094801 (2017)

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

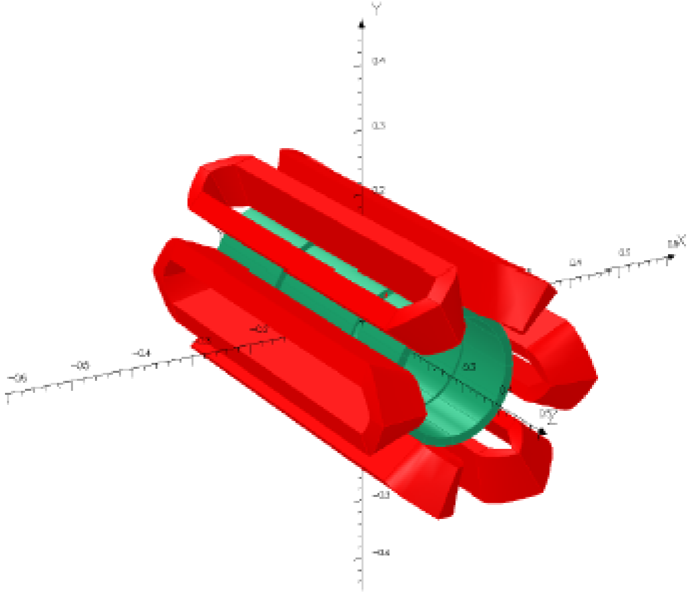
Superconducting Magnet Structure: two options

Sextupole-in-Solenoid Geometry (VENUS)



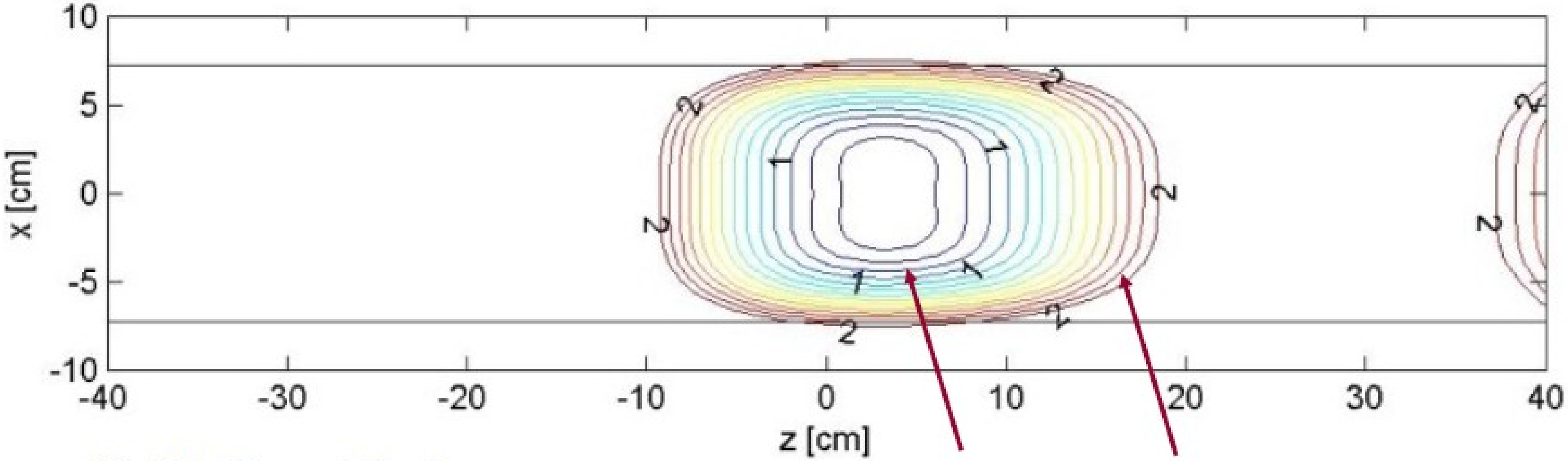
- Minimizes the peak fields in the coil
- Strong influence (forces) of the solenoid field on the sextupole ends

Solenoid-in-Sextupole Geometry (SECRAL)



- Minimizes the influence of the solenoid on the sextupole field
- Significantly higher field required for the sextupole magnet surface due to the larger radius of the coils
- Strong forces on the solenoid coils

Superconducting Magnets: ECR Design 'Standard Model'



B_{ECR}

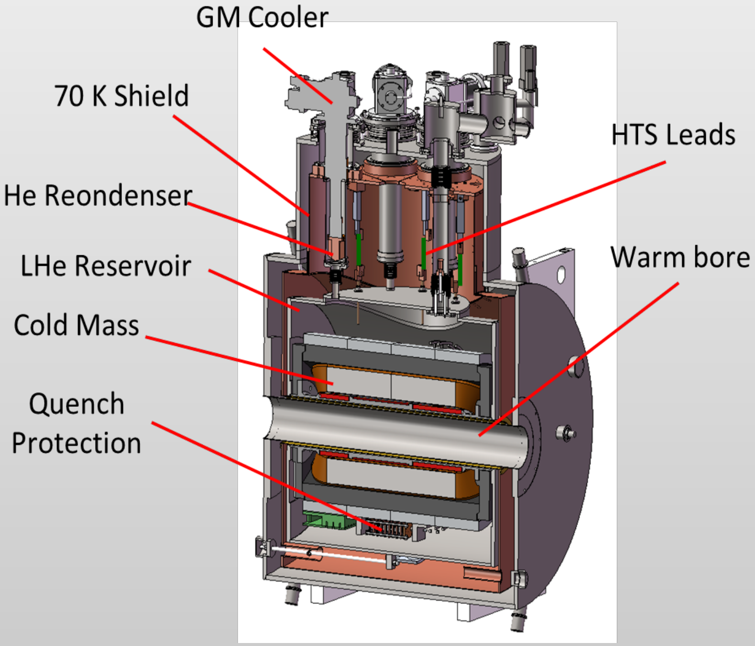
Last closed surface 2x B_{ECR}

28 GHz B_{ECR}= 1 Tesla

56 GHz B_{ECR}= 2 Tesla

	28 GHz	56 GHz
B_{inj} ~ $4 \cdot B_{ecr}$	**4T**	**8T**
B_{min} ~ $0.8\ B_{ecr}$	**.5-.8 T**	**1-1.6 T**
B_{ext} ~ B_{rad}	**2T**	**4T**
$B_{rad} \geq 2\ B_{ecr}$	**2T**	**4T**

Magnetic Design		**28 GHz**	**56 GHz**
Max solenoid field	on the coil	6 T	12 T
	on axis	4 T	8 T
Max sextupole field	on the coil	7 T	15 T
	on plasma wall	2.1 T	4.2 T
Superconductor		NbTi	Nb_3Sn



Operation Parameters

Parameters	SECRAL-II	SECRAL
ω_{rf} (GHz)	18-28	18-24
Axial Field Peaks (T)	3.7 (Inj.), 2.2 (Ext.)	3.7 (Inj.), 2.2 (Ext.)
Mirror Length (mm)	420	420
No. of Axial SNs	3	3
B_r at Chamber Inner Wall (T)	2.0	1.7/ 1.83
Coldmass Length (mm)	~810	~810
SC-material	NbTi	NbTi
Magnet Cooling	LHe bathing	LHe bathing
Warm bore ID (mm)	142 .0	140.0
Chamber ID (mm)	125.0	116.0/120.5
Dynamic cooling power (W)	~6	0

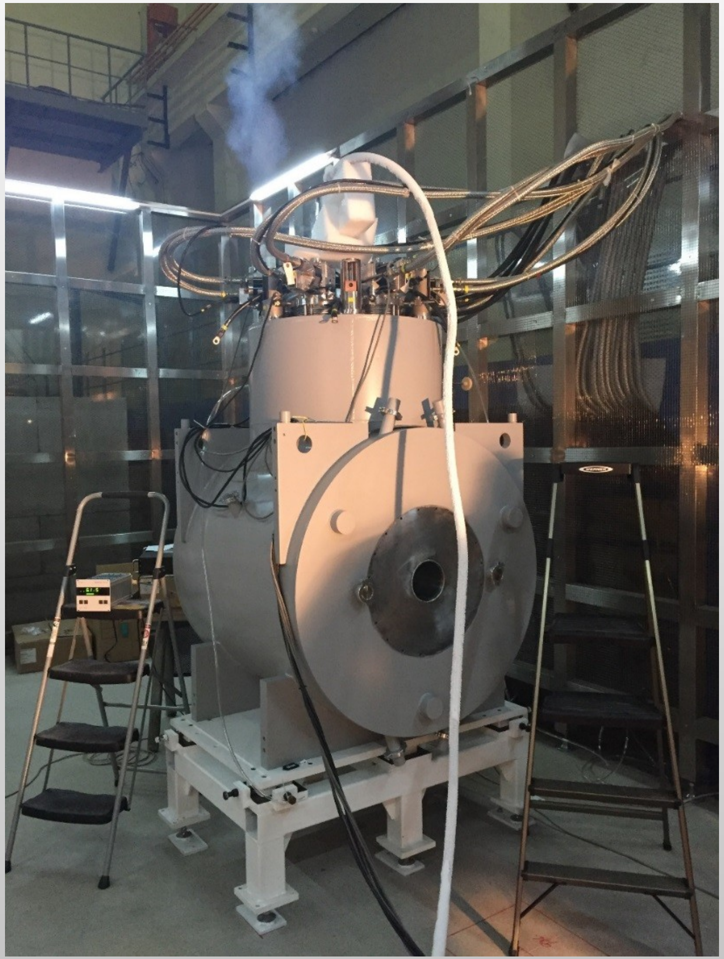
The 3rd generation ECRIS development demonstrates :

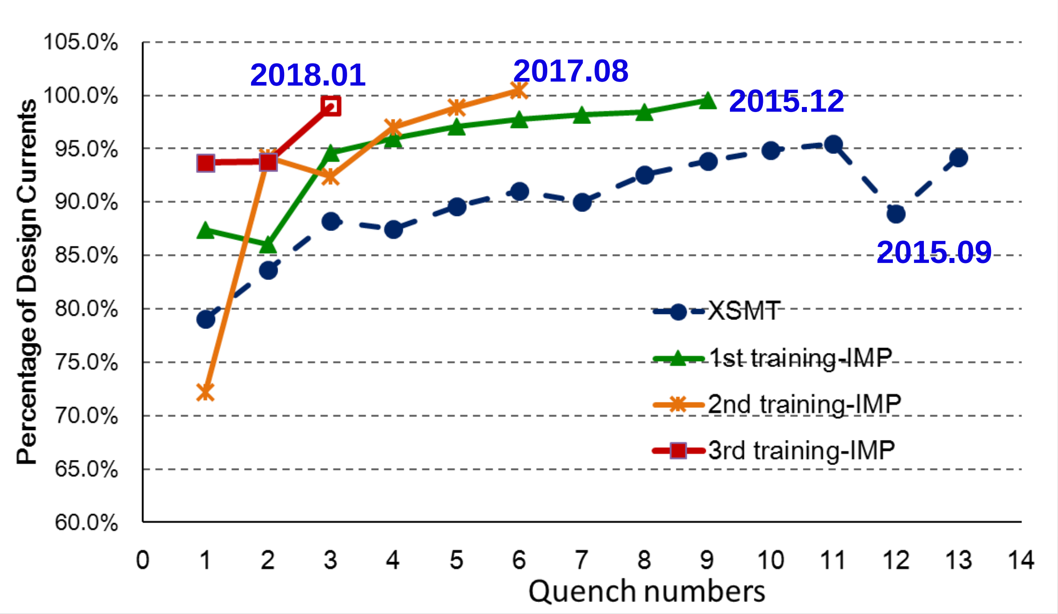
- **Big technical challenge**
- **High cost (5-10 M$)**
- **Very long time for R&D (10 years from R&D to High performance)**
- **Big risk (Could fail completely)**
- **But amazing performance and exciting results**

Time schedule for 3rd of ECR sources

SECRAL	**VENUS**
09.2000 – project approved	1997 – project started
2005 ÷ 2006 – commissioning at 18 GHz	2002 – first plasma at 18 GHz
08.2009 – first beam test at 24 GHz	2004 – first 28 GHz operation
2014 ÷ 2015 - 0.7 emA Bi^{30+}	

Developments: SECRAL-II Source





Magnet Training Story:

- **Lower and Lower risk of Training Quench after warm-up course**
- **Can reach >100% design currents**
- **No quench happens during beam commissioning**

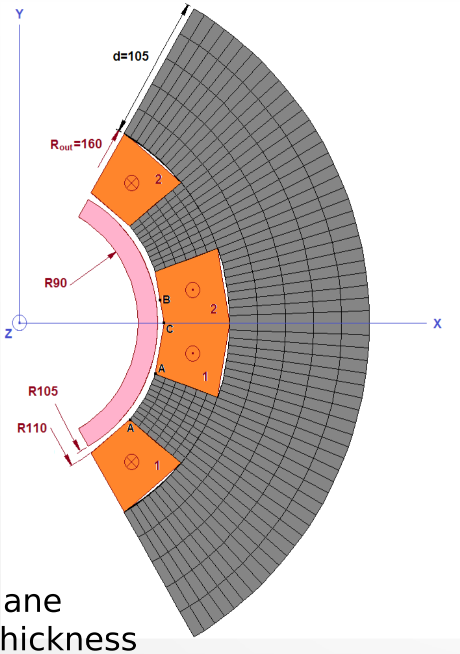
Collaboration with
Scientific Research Institute of Electrophysical Equipment
“NIIEFA”, Sankt-Peterburg

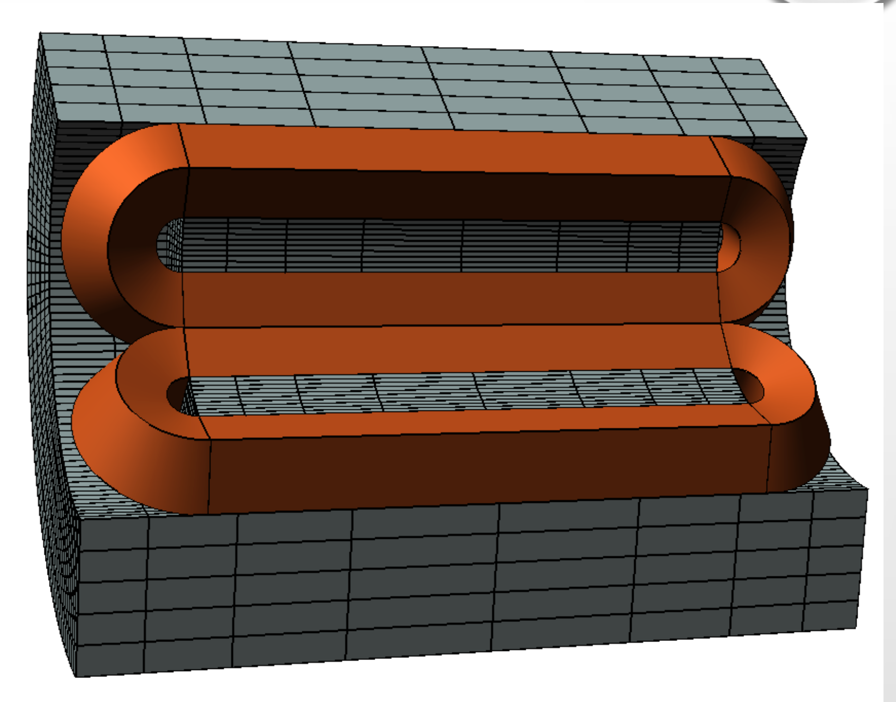
B_{inj} = 4 T
B_{extr} = 2 ÷ 2,5 T
B_{min} = 0,5 ÷ 0,8 T
B_{rad} = 2,02 T (r = 62 mm)
Warm bore ∅ = 142 мм
Distance between two peaks on the axis L = 420 мм

R&D

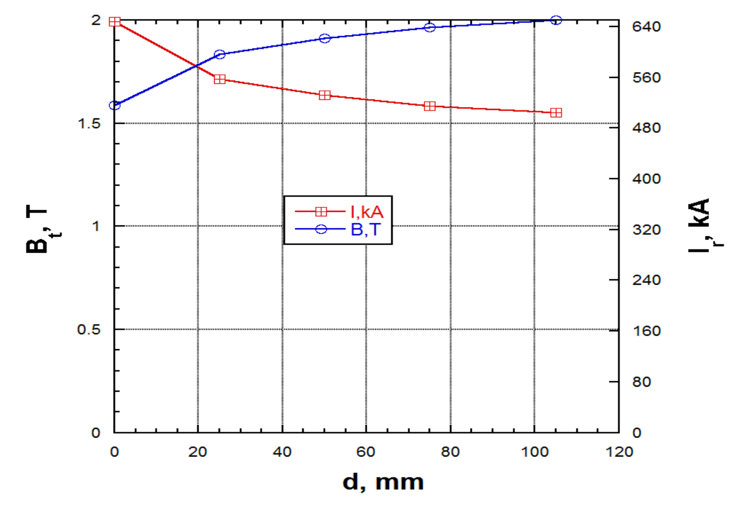
Calculation of the required magnetic field in a given geometry.
The choice of conductor and rated current.
Calculation of mechanical forces and deformations (allowable level of deformations ????).
Comparison of two options (hexapole inside or outside). The choice of option for implementation.
Development of a support system for cold masses and current leads (mass of more than 1 ton).
Calculation of heat influx.
The design of the cryostat.
Magnetic system assembly technology.

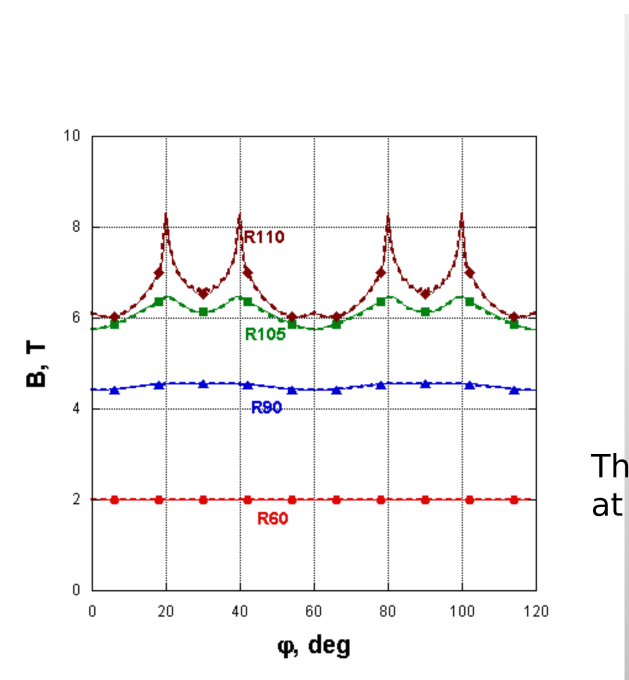
All work should be carried out in parallel
because any design change requires recalculation of the entire system!





The average transverse field in the central plane
at a radius of R = 60 mm depending on the thickness
of the magnetic screen d (round markers) and the current
required to create a 2 T field at a radius of R = 60 mm
(square markers) .





The field in the central plane
at radii R = 60, 90, 105 and 110 mm.

Preliminary conclusion:

1. The use of magnetic steel (external magnetic circuit and poles) can significantly reduce the coil currents (up to 25%).
2. To reduce the field level in the coils, both circular (longitudinal field) and racetrack (transverse field) coils should be located as close as possible to the working area. The circular coils should have the smallest possible radial thickness.
3. Both NbTi and Nb_3Sn can be used as a superconductor material for racetrack coils. But due to the com
   geometric shape of the racetrack coils, NbTi is preferred.

THANK YOU FOR YOUR ATTENTION !