ECRIS-Upgrade at GSI

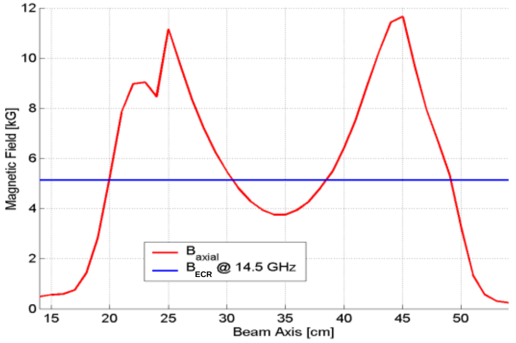
ECRIS = Electron Cyclotron Resonance Ion Source

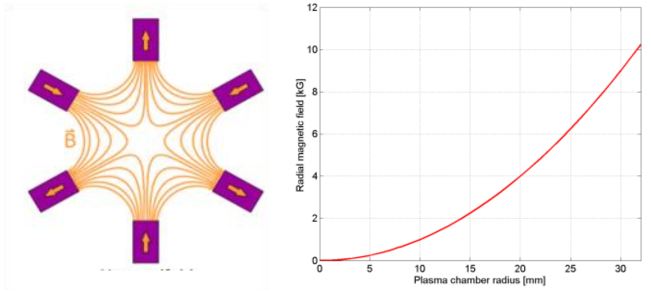
Outline

- ECRIS Working Principle and Characteristics
- ECRIS@GSI – Status quo and present performance
- Future requirements
- Upgrade strategy
- 18 GHz upgrade
- Technical concept and outlook

ECRIS Working Principle and Characteristics

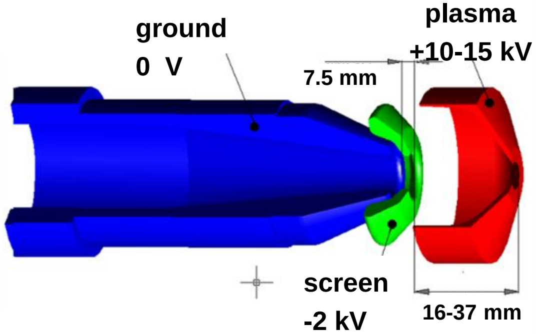
Two coils for the axial magnetic confinement system

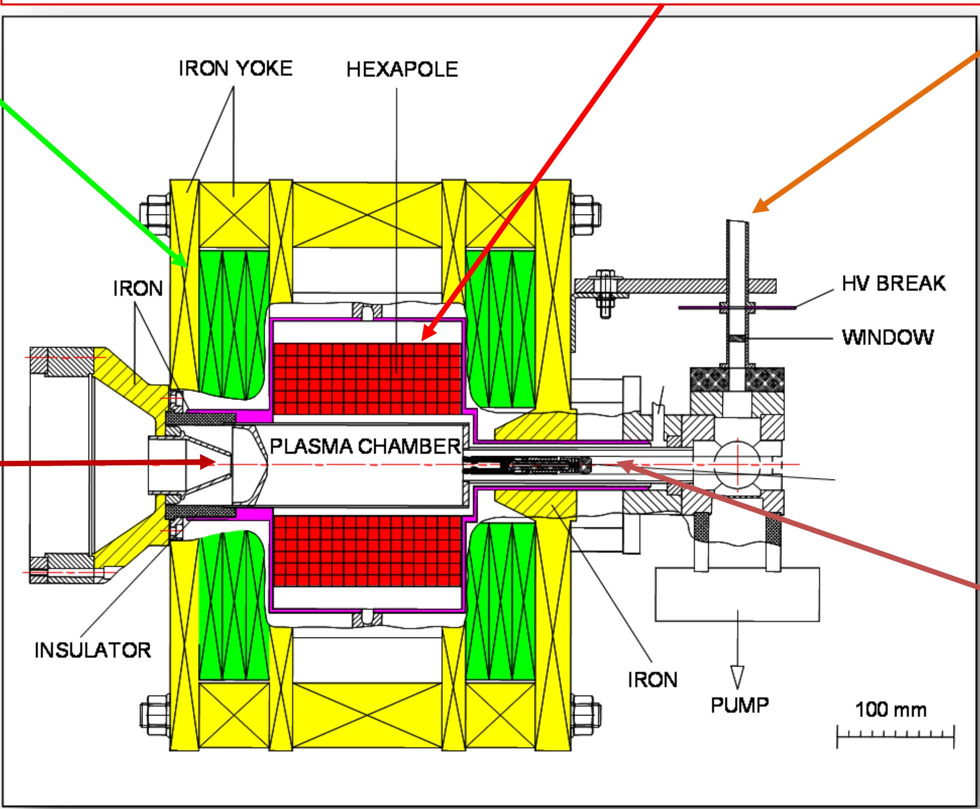




Sextupole for the radial confinement

Ion extraction





Microwave injection

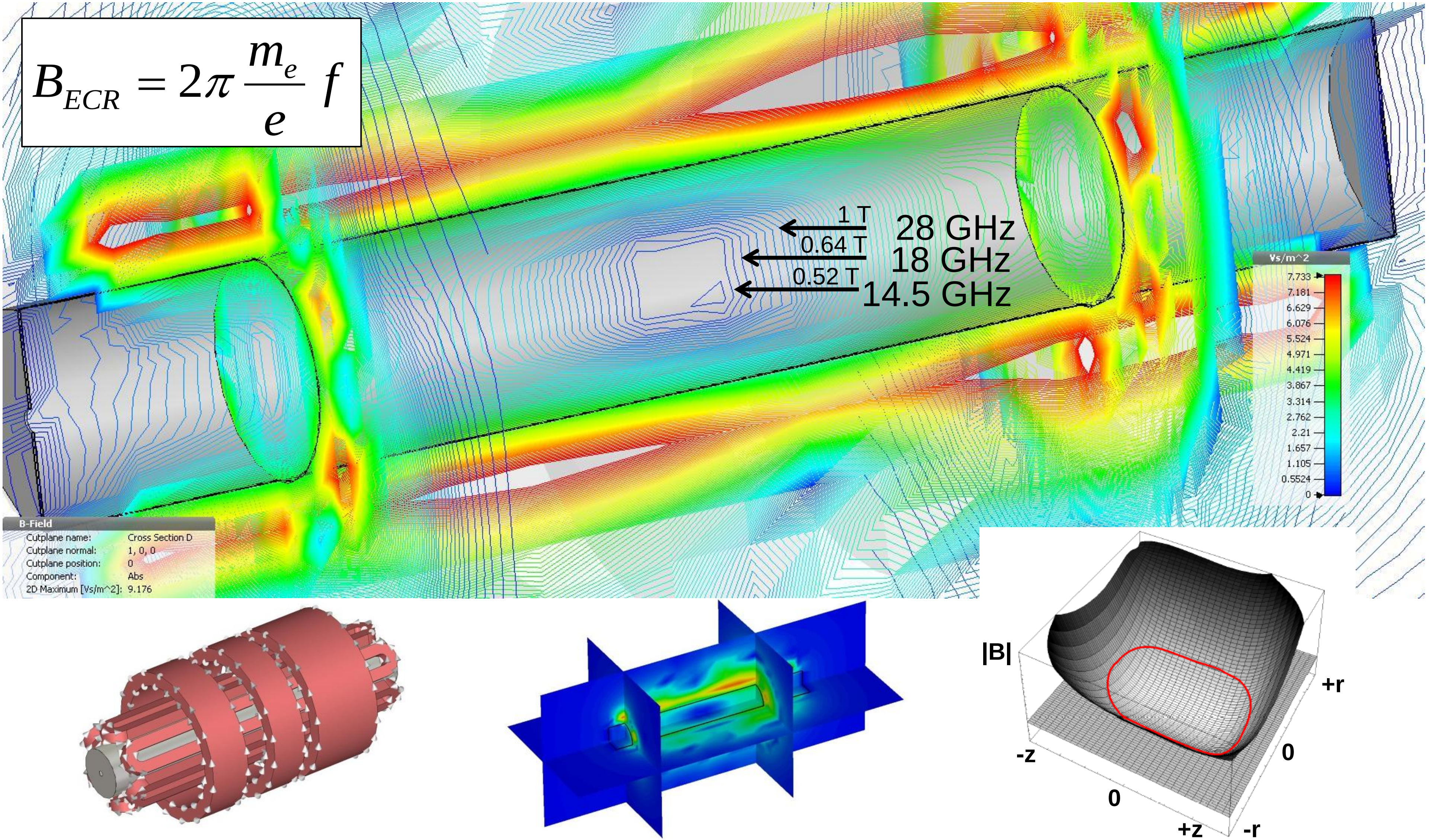
Wave energy absorption for electrons crossing the surface where ECR condition is fulfilled:

$$B_{ECR} = 2\pi \frac{m_e}{e} f$$

Gas/Vapor injection

Magnetic Confinement and ECR Surface

$$B_{ECR} = 2\pi \frac{m_e}{e} f$$



B-Field

Cutplane name: Cross Section D
Cutplane normal: 1, 0, 0
Cutplane position: 0
Component: Abs
2D Maximum [Vs/m^2]: 9.176

ECRIS's History

ECRIS Empirical Scaling Law

$$\boxed{I \propto \frac{\omega_{RF}^2}{M}}$$

High-B mode principle

$$\boxed{\frac{B_{\max}}{B_{ECR}} \geq 2}$$

ECRIS Development

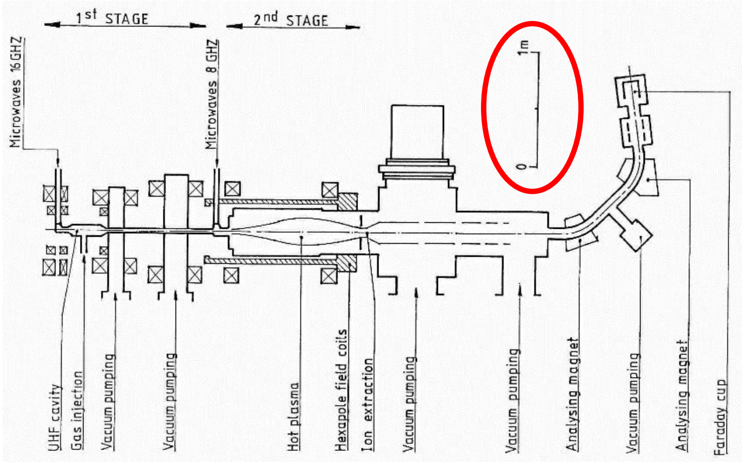
$f = 10\ GHz$ Þ B_{max} ³ $0.72\ T$

$f = 14\ GHz$ Þ B_{max} ³ $1.0\ T$

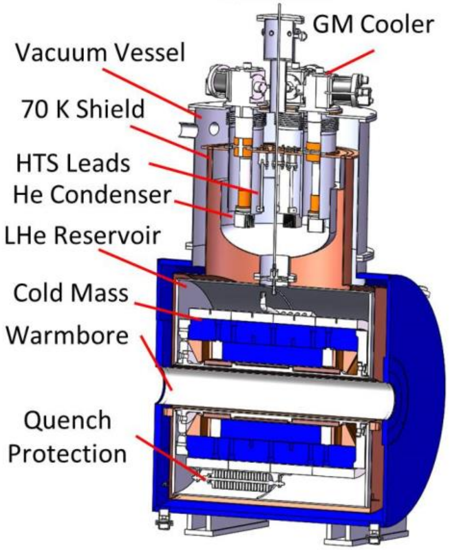
$f = 18\ GHz$ Þ B_{max} ³ $1.3\ T$

$f = 28\ GHz$ Þ B_{max} ³ $2.0\ T$

Geller's Supermafios (1975, 3 MW! 16+8 GHz)



SECRAL II
28 GHz



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ECRIS Properties

Properties and benefits:

- No filaments → reduced maintenance
- Low material consumption → long endurance and high efficiency
- Excellent long time stability
- High charge states → no postacceleration required, direct injection into post-stripper
- The very same ion source is likewise appropriate for cw-mode operation and for pulsed operation

→ ECRIS is well suited for long beam times under stable operating conditions (UNILAC and SIS)

→ Enables a parallel operation in combination with high current ion sources (HLI ⇔ HSI)

Main future requests of the experiments:

- New ion beam species to be developed from the ion sources
- Increase of ion beam intensities for most ion species

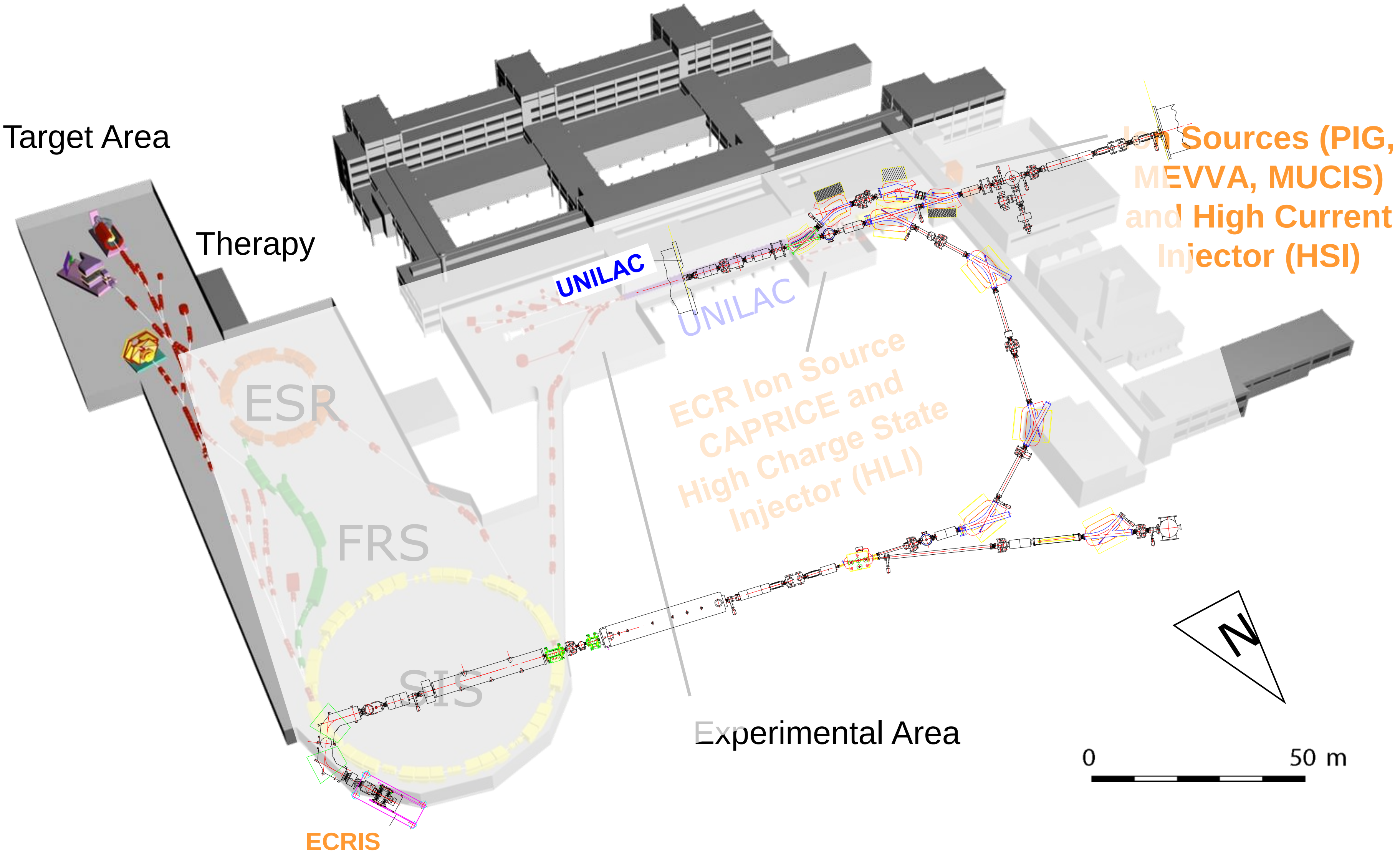
According to scaling law:

Available charge states and intensities increase with operating frequency ω_{RF}

→ Increase of microwave frequency: $\omega_{RF} = \omega_{ECR} \sim B$

→ Higher magnetic flux density necessary (superconducting magnets)

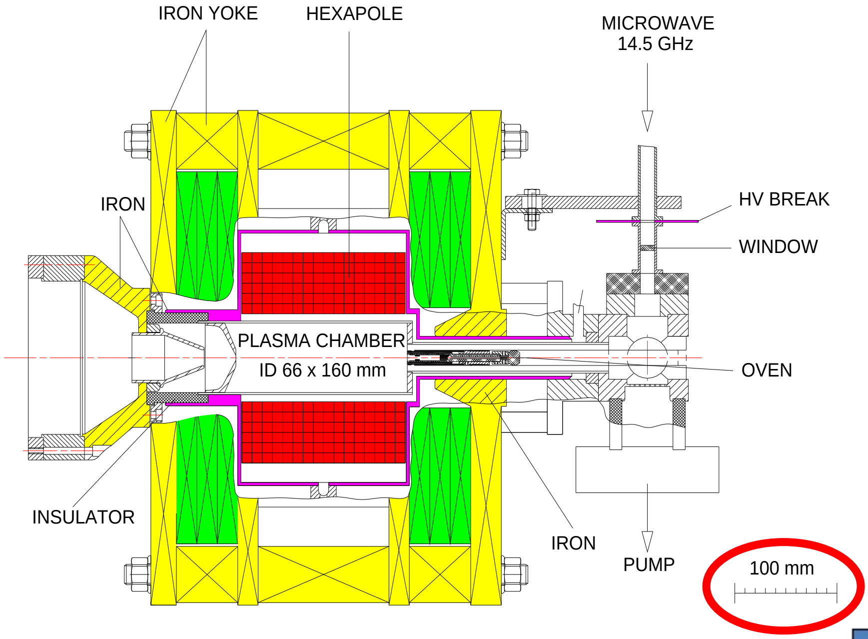
GSI Accelerator Facilities

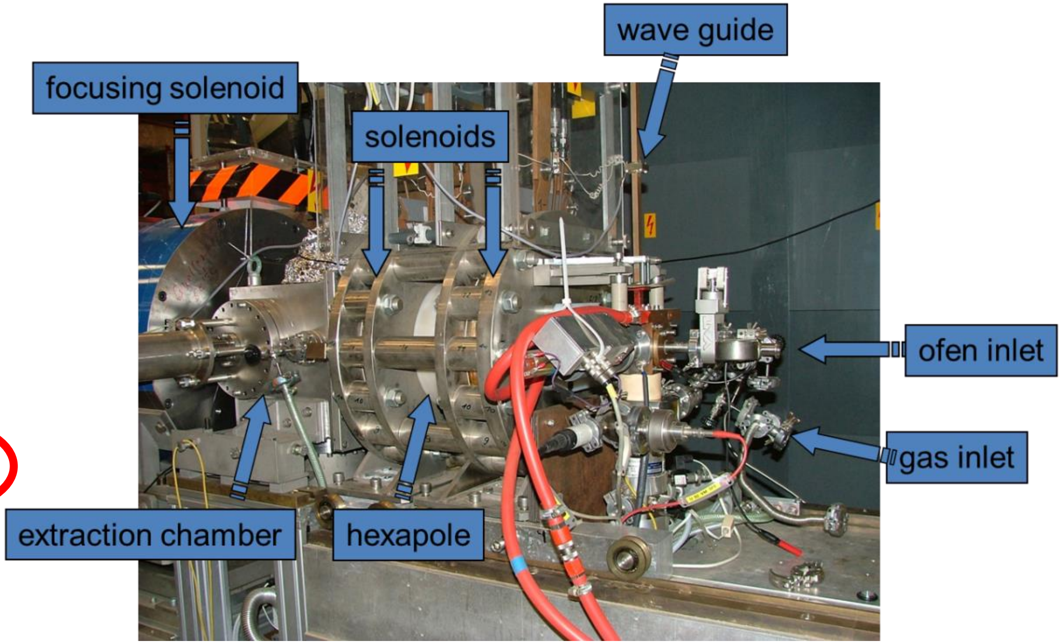


ECRIS @ GSI – Status Quo

- The CAPRICE ECR ion source (ECRIS) is in operation at the HLI since 1992.
- Total number of its operating hours for the accelerator: > 5000 hours per year.
- Despite repeated upgrades the ion source and its ancillary equipment show age related deterioration.
- Failure probability increased disproportionately in the last years.

➔ **This outdated technical standard implies the replacement by adequate modern technologies.**





Selection of Ion Species from ECRIS

Gaseous Elements and Compounds

Element	Isotope	Charge States	Main Gas	Aux Gas
H	$^{1}H_2$	1	H_2	-
C	^{12}C	2	CO_2	O_2
O	^{16}O	3	O_2	He
	^{18}O	3	O_2, *	He
Ne	^{20}Ne	4	Ne	He
	^{22}Ne	4	Ne, *	He
S	^{32}S	5	SO_2	O_2
	^{34}S	6	SO_2, *	O_2
	^{36}S	5	SO_2, *	O_2
Ar	^{36}Ar	5, 6, 7	Ar, *	O_2
	^{40}Ar	6, 7, 8	Ar	O_2
Kr	^{84}Kr	12	Kr	He
	^{86}Kr	12	Kr, *	He
Xe	^{124}Xe	15, 16	Xe, *	O_2
	^{129}Xe	18	Xe, *	O_2
	^{136}Xe	18, 19	Xe, *	O_2

Solid Elements and Compounds

Element	Isotope	Charge States	Sample Material	Aux Gas
Li	^{6}Li	1	LiF, *	He
	^{7}Li	1	LiF	He
Mg	^{24}Mg	5	Mg	He
	^{25}Mg	4	Mg, *	He
	^{26}Mg	4, 5	Mg, *	He
Si	^{28}Si	5	SiO	He
	^{30}Si	6	SiO, *	He
Ca	^{40}Ca	6, 7	Ca	He
	^{48}Ca	7, 10	Ca, *	He
Ti	^{48}Ti	7	Ti	He
	^{50}Ti	7, 8	Ti, *	He
V	^{51}V	8	V	He
Cr	^{50}Cr	8	Cr, *	He
	^{52}Cr	7	Cr	He
	^{54}Cr	8	Cr, *	He

Solid Elements and Compounds

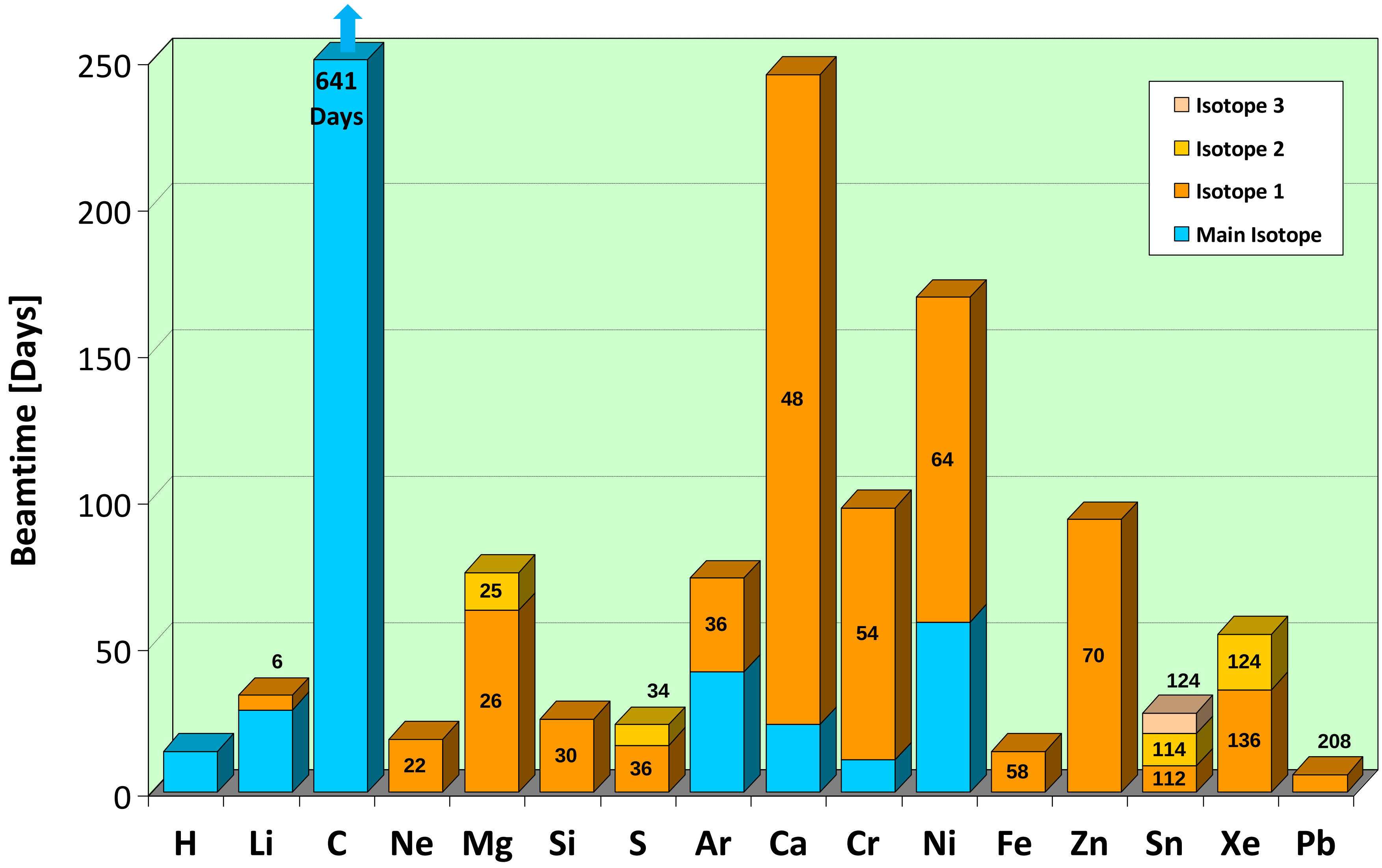
Element	Isotope	Charge States	Sample Material	Aux Gas
Fe	^{58}Fe	8, 9	Fe	He
Ni	^{58}Ni	8, 9	Ni	He
	^{62}Ni	9	Ni, *	He
	^{64}Ni	9	Ni, *	He
Zn	^{64}Zn	10, 11	ZnO	O_2
	^{68}Zn	10	ZnO, *	O_2
	^{70}Zn	10	ZnO, *	O_2
Ag	^{107}Ag	15	Ag	O_2
Sn	^{112}Sn	15, 17	Sn, *	O_2
	^{114}Sn	16, 17	Sn, *	O_2
	^{118}Sn	16	Sn, *	O_2
	^{122}Sn	17	Sn, *	O_2
	^{124}Sn	16	Sn, *	O_2
Au	^{197}Au	24	Au	O_2
Pb	^{208}Pb	27	Pb, *	O_2

*** enriched elements**

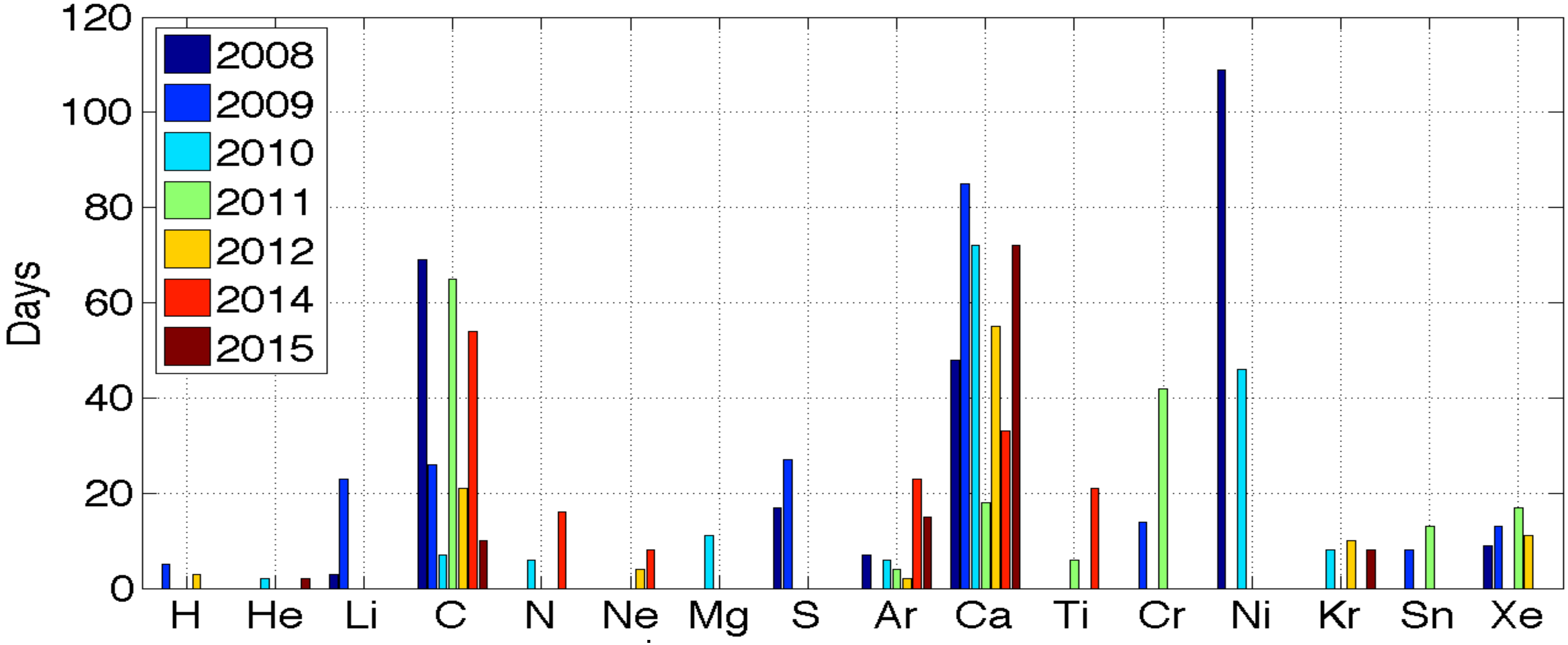
*** enriched compounds**

➔ Evaporable solids (metals) – vapor pressure of ≈10^{-2} mbar at T < 1600°C for Standard-Temperatur-Oven (STO), and at T < 2000°C for High-Temperature-Oven (HTO)

HLI Ion Beams 2002-2008



HLI Ion Beams 2008-2015



2008 High current
proton exp at SIS
$^1H_2^{1+}$

2008 RFQ commis.
2012 BIO

2008 SIS exp
2009 ESR exp

2010 Bio at SIS
2014 Phelix LASER

2012 Machine invest.

2010 SHE

2008-2009 SHE

2011-2014 SHE

2009-2011 SHE

2008-2010 SHE

2008-2010 SHE

Consumption & Efficiencies

ion species of accelerated charge state q	natural abundance (%)	isotope enrichment (%)	sample material	material consumption (µg/h)	average particle intensity (pµA)	efficiency all charge states (%/q_i...q_f)	efficiency charge state q (%)
$^{3}\mathrm{He}^{1+}$	0.00014	99.9	He				
$^{6}\mathrm{Li}^{1+}$	7.5	95	LiF	1120			
$^{22}\mathrm{Ne}^{4+}$	9.25	99.9	Ne				
$^{25}\mathrm{Mg}^{4+}$	10	99	Mg	620	38	26/2...8	5.7
$^{26}\mathrm{Mg}^{5+}$	11	99	Mg	310/170*	20	26/47*/2...9	6.4/11.5*
$^{30}\mathrm{Si}^{6+}$	3.1	99.5	SiO	1090/580*	13.3	5/10*/3...9	1.3/2.6*
$^{34}\mathrm{S}^{5+}$	4.2	80	SO_2	660	12.4	14/2...9	2.5
$^{36}\mathrm{S}^{5+}$	0.02	79	SO_2	420	12.4	23/2...8	4
$^{36}\mathrm{Ar}^{7+}$	0.34	99.5	Ar				
$^{48}\mathrm{Ca}^{7+}$	0.19	96	Ca	210	6.6	40/3...12	5.7
$^{48}\mathrm{Ca}^{10+}$	0.19	96	Ca	200	14.0	43/3...11	12.6
$^{50}\mathrm{Cr}^{7+}$	4.35	96.5	Cr	2300			
$^{54}\mathrm{Cr}^{7+}$	2.37	99	Cr	2300			
$^{58}\mathrm{Fe}^{8+}$	0.28	>90	Fe	3100/1440*			
$^{64}\mathrm{Ni}^{9+}$	0.93	93	Ni	1300	4.5	4.5/4...13	0.8
$^{70}\mathrm{Zn}^{10+}$	0.6	95	ZnO	3170	7.8	3.3/5...14	0.5
$^{112}\mathrm{Sn}^{15+}$	0.97	99	Sn	890			
$^{114}\mathrm{Sn}^{17+}$	0.65	87	Sn	1000			
$^{124}\mathrm{Sn}^{16+}$	5.8	96	Sn	1200			
$^{124}\mathrm{Xe}^{17+}$	0.1	99.9	Xe				
$^{136}\mathrm{Xe}^{18+}$	8.9	99.9	Xe	550	2.2	50/6...25	2

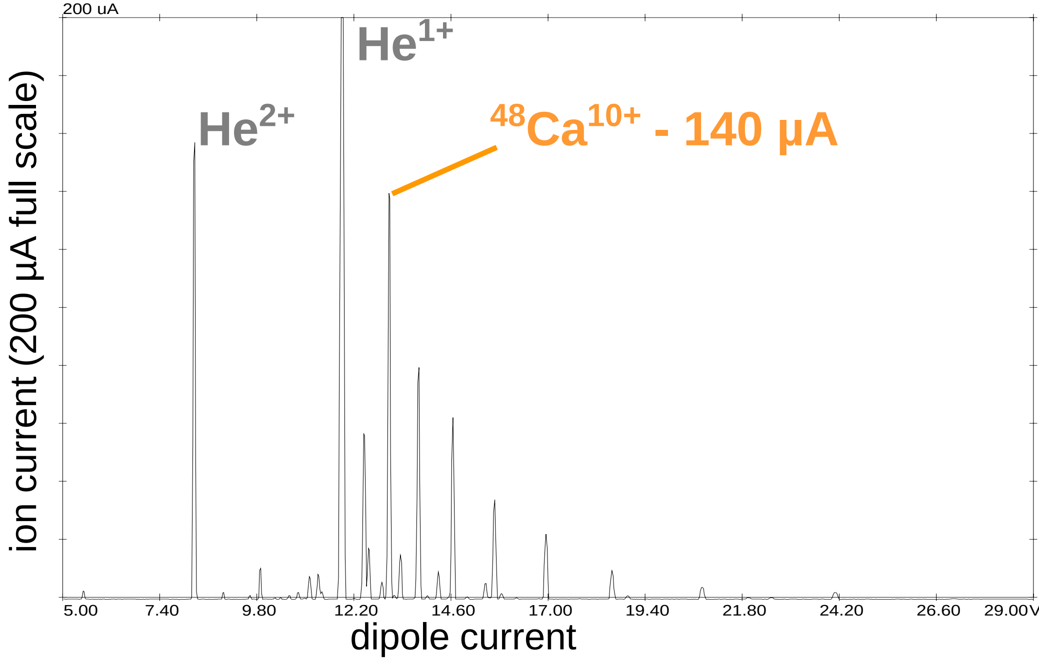
* with material recycling

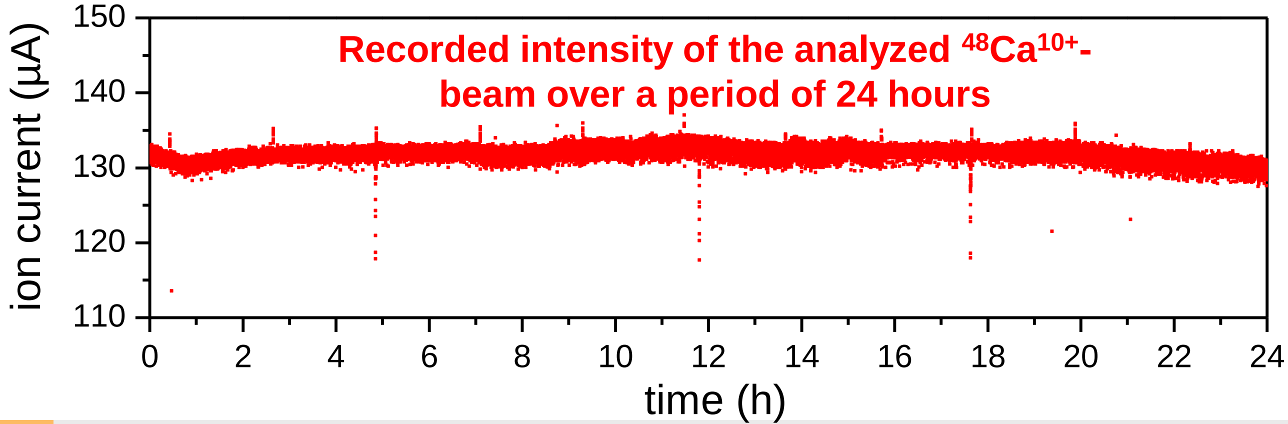
- analysed ion currents in front of the accelerator
- **no** correction for LEBT transmission

$^{48}\mathrm{Ca}^{10+}$ Beam Efficiency

- Ion charge state: $^{48}\mathrm{Ca}^{10+}$
- Average intensity: 100 ... 140 eµA
- Total run time: 1500 hours
- 3 refillings of standard oven STO
- Material consumption without recycling: 0.5 mg/h
- Material consumption with recycling: 0.2 mg/h
- Efficiency material to ion beam: > 50 %

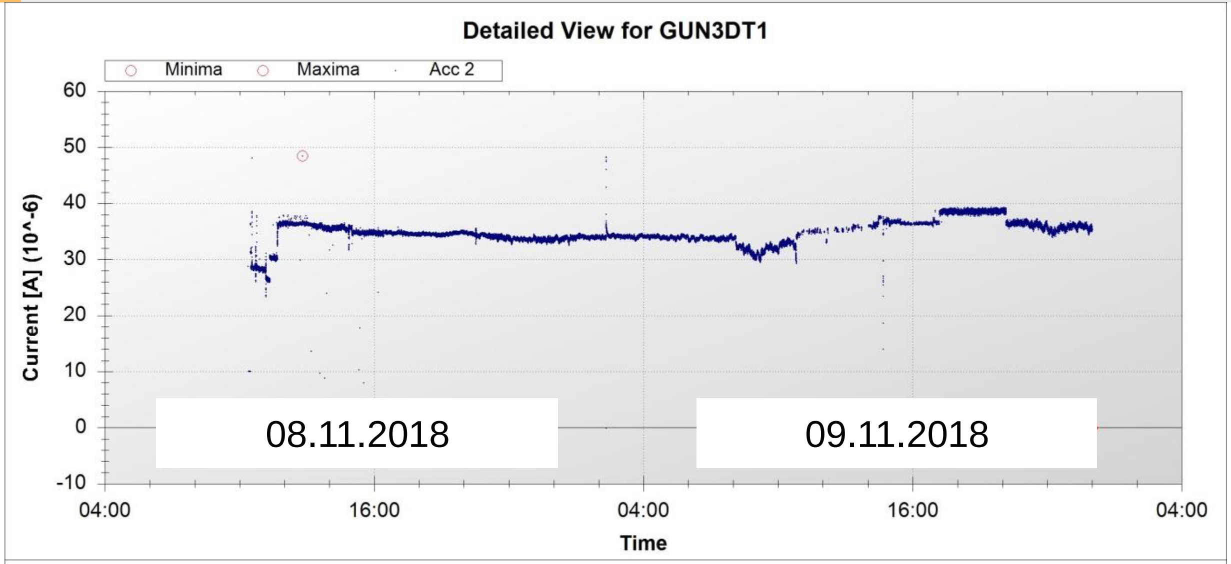
Spectrum of $^{48}\mathrm{Ca}$ + He optimized on $^{48}\mathrm{Ca}^{10+}$





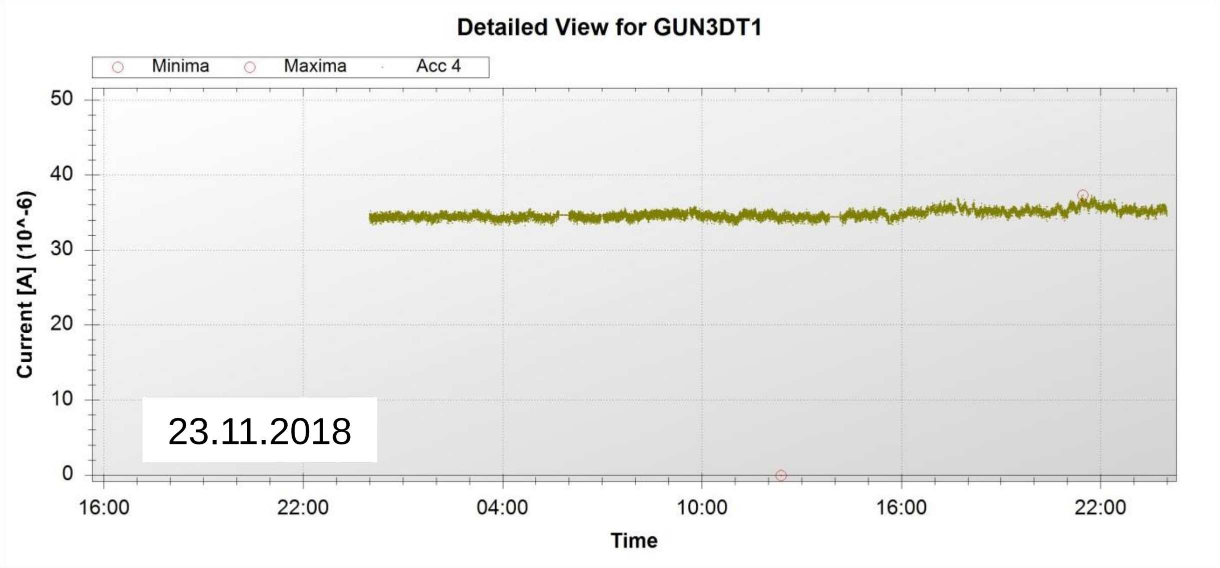
79658 pulses in 24 hours
(read out from beam transformer)

Ar Beam Stability



08.11.2018

09.11.2018



23.11.2018

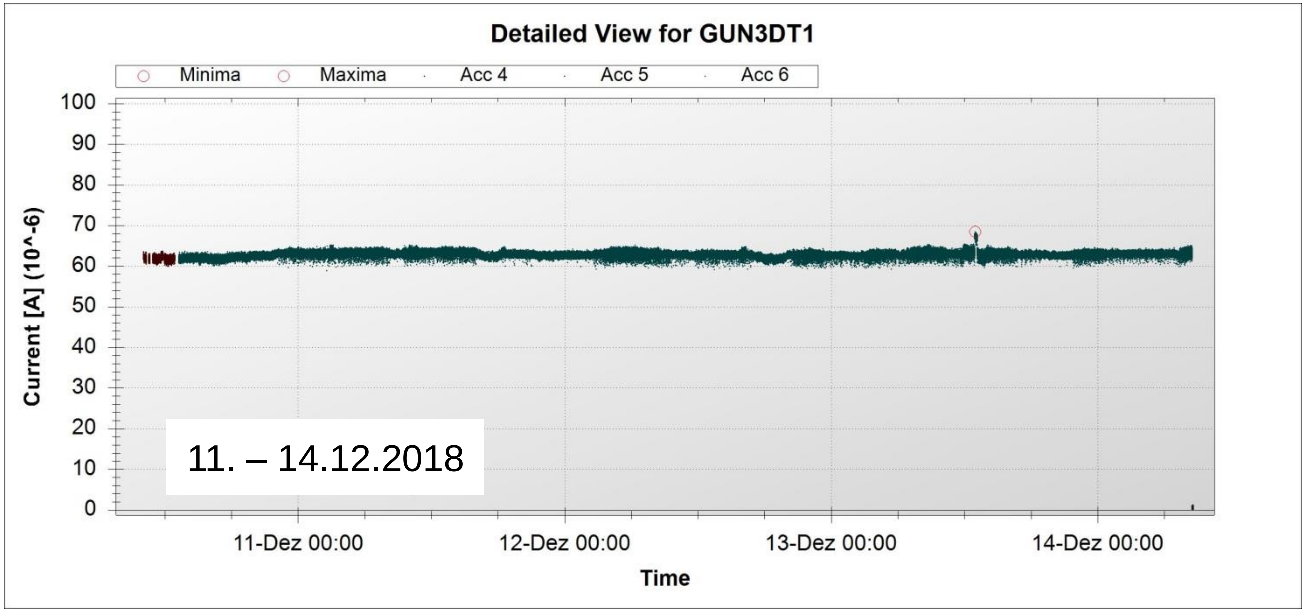
$^{40}Ar^{9+}$ run of 36 days

- without any beam interruptions
- no retuning necessary

Setting up of ECR ion source and accelerator for $^{40}Ar^{9+}$

Stable beam of $^{40}Ar^{9+}$ during the run

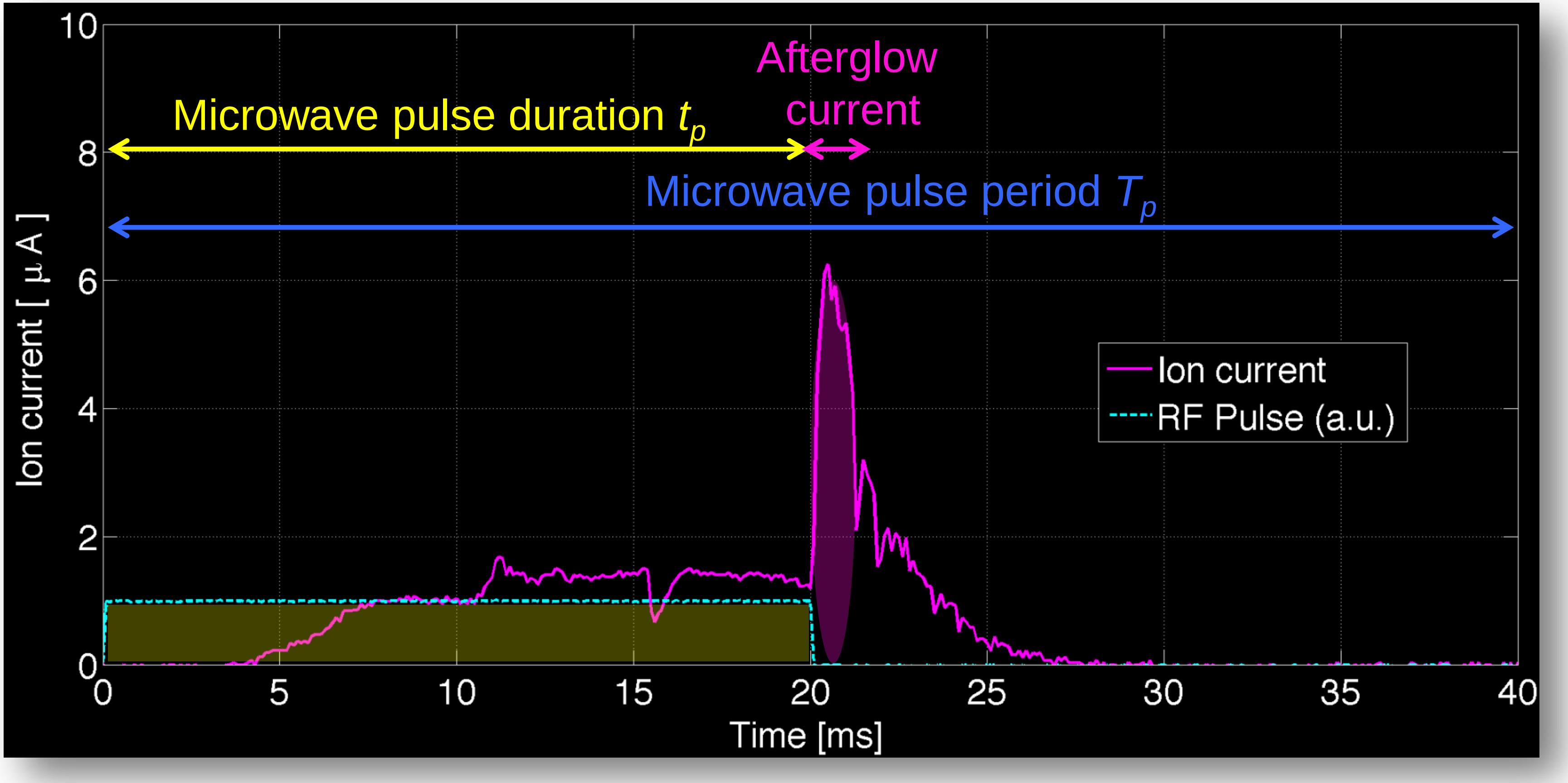
Ar Beam Stability



11. – 14.12.2018

Last period of the Engineering Run delivering stable beam of $^{40}Ar^{9+}$ to the CW-Demonstrator@HLI after intensity optimisation

Afterglow Mode



- By pulsing the microwave power, the extracted current of highly charged ions increases in burst pulses.
- The afterglow current can be optimized by tuning the pulse duration or the pulse period or the duty factor ($d=t_p/T_p$).

FAIR + LINAC Requirements

Two clients:

- Synchrotron (FAIR): Highest ion energies at low duty cycle; high pulse intensities
- LINAC: Medium energies at high duty cycle; high cw intensities

- ECRIS @GSI in cw operation or in afterglow mode
- Pulsed operation for FAIR: up to 4 pulses per second; 150 µs; asymmetric timing scheme
- Afterglow operation for FAIR: 10 pulses per second + electrostatic beam chopper
- FAIR science: great variety of ion species including rare and very rare isotopes
- LINAC science: predominantly rare and extremely rare isotopes (e.g. ^{48}Ca)

Operational requirements

- Mechanical design: as simple as possible & based on well-established techniques
- Basic requirements: easy handling & high reliability
- Easy change of main gas/auxiliary gas or of oven (lock system)
- Ion production: high ionisation efficiency of metal ion beams
- Short intervention times for change of ion species/maintenance
- Good reproducibility of ion beams
- Maintenance: Facilitation by appropriate technical construction
- Easy cleaning of the plasma chamber

Future Ion Beam Requests

- Great variety of ion beams requested for FAIR science and UNILAC science – including beams of rare isotopes
- Very economical use of enriched materials for ion beam production from rare and extremely rare (limited availability on the world market) isotopes
- Ion Beam production from ECRIS mandatory for:

He
Li (^{6}Li)
Ne (^{22}Ne)
Mg (^{25}Mg, ^{26}Mg)
Si (^{30}Si)

S (^{34}S, ^{36}S)
Ca (^{44}Ca, ^{48}Ca)
Cr (^{50}Cr, ^{54}Cr)
Fe (^{58}Fe)

Ni (^{64}Ni)
Zn (^{70}Zn)
Kr (^{78}Kr)
Sn (^{112}Sn, ^{114}Sn, ^{116}Sn, ^{122}Sn, ^{124}Sn)

- Ion Beam production from ECRIS preferable for:

C
Ar (^{36}Ar)
Bi

Ti (^{50}Ti)
Xe (^{124}Xe, ^{136}Xe)

Pb (^{204}Pb, ^{206}Pb, ^{208}Pb)
Au

Charge States

"Reasonable" charge states for injection into RFQ:

- 15 kV < U_{ex} < 30 kV (no high voltage platform)
- Fixed input velocity (specific input energy) defined by RFQ: 2.5 keV/u or 4.0 keV/u
- Particle factor: I_{el}/q (experimentalists as beam users mostly request high particle intensity)
- Choice of charge state: depending on CSD as low as reasonably possible (best compromise!)

v_{spec} ➔		2.5 keV/u	4.0 keV/u		**High Charge State Injector with CAPRICE-ECRIS 2.5 keV/u; m/q < 8.5**	
m/q ➔	2.0 - 8.5	2.0 - 8.5	2.0 - 8.5			
q/m ➔	1/8.5 - 1/2	1/8.5 - 1/2	1/8.5 - 1/2			
U_{ex} ➔		5 kV - 22 kV	8 kV - 34 kV			
Ion species	**theoretical charge state**	**reasonable charge state**	**reasonable charge state**	**particle factor**	**charge state**	**U_{ex} (kV)**
H_2	1	1	1		1	5
^{4}He	1 ... 2	1	1 ... 2	2	1	10
^{12}C	2 ... 6	2	2 ... 4	2	2	15
^{22}Ne	3 ... 10	3 ... 5	3 ... 6	2	4	13.75
^{48}Ca	6 ... 20	7 ... 11	7 ... 13	2	10	12
^{84}Kr	10 ... 36	10 ... 16	11 ... 22	2	12	17.5
^{136}Xe	16 ... 54	17 ... 23	18 ... 35	2	18	18.9
^{197}Au	24 ... 79	24 ... 32	26 ... 52	2	24	20.52
^{209}Bi	25 ... 83	26 ... 34	28 ... 55	2	27	19.35

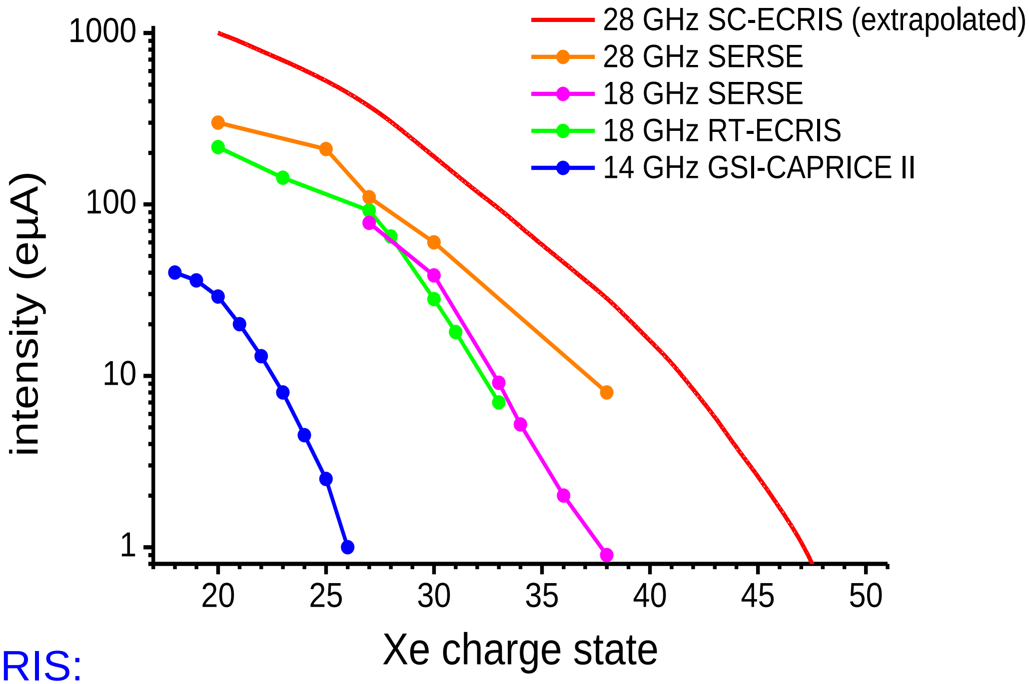
Increase of Average Intensity

- High intensity in adequate charge states
- Higher duty cycle in LINAC (requires higher charge states)

Semiempirical scaling law: $I(A^{q+}) \sim \omega_{ECR}^{2}$

➔ increase of microwave frequency: $\omega_{RF} = \omega_{ECR} \sim B$

➔ higher magnetic flux density (superconducting magnets)



Dedicated 18 GHz ECRIS + 28 GHz SC-ECRIS:

- higher electron energies (improved generation of HCI)
- higher plasma densities (enhanced extractable ion current)
- improved ion confinement (reduction of losses)
- large plasma volume (reduced plasma wall interactions)

ECRIS Performance Upgrade – Strategy

Boundary conditions:

- 14.5 GHz CAPRICE ECRIS (status quo):
  - limitation of intensities
  - limitation to ion masses only up to Xe (not available e. g.: Nd, Sm, Au, Pb, Bi, U)
- Overcome these limitations ➔ 18 GHz ECRIS + 28 GHz SC-ECRIS
- Available charge states and intensities increase with operating frequency (14 ➔ 18 ➔ 28 GHz)
  e. g. Xe^{20+} 25 µA – CAPRICE@14.5GHz ➔ 200 µA – PKISIS@18GHz = factor 8
  and Xe^{27+} 80 µA – PKISIS@18GHz ➔ 800 µA – SECRAL@28GHz = factor 10
- Applicability of 2 operating modes:
  - CW ➔ no limitation of duty cycle ➔ UNILAC/CW-LINAC
  - Pulsed ➔ SIS18 Requirements ➔ SIS/FAIR

Approach in stages:

0th stage: **Continued operation of the existing 14.5 GHz CAPRICE ECRIS**

1st stage: **Moderate upgrade at moderate cost with a conventional ECRIS (RT, Hybrid) @ 18 GHz (complementary ion source for redundancy / finally replacing 14.5 GHz CAPRICE ECRIS)**

2nd stage: **Full performance upgrade with a Superconducting-ECRIS @ 28 GHz with separate injection beam line**

18 GHz ECRIS (1st Stage)

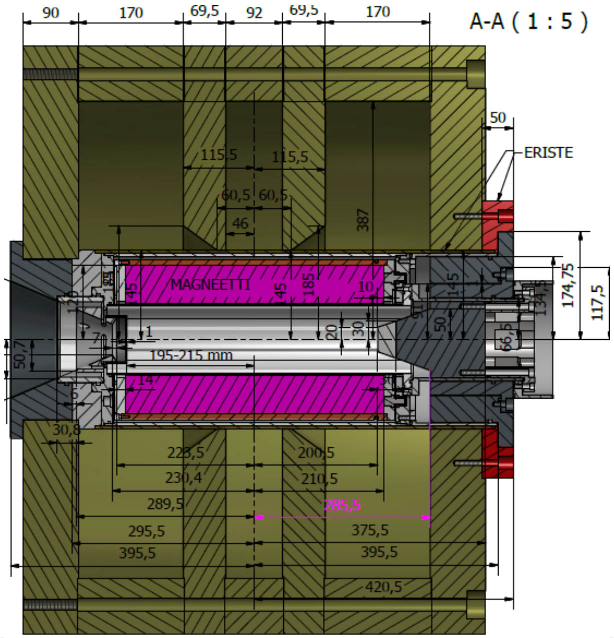
Relevant current projects and developments

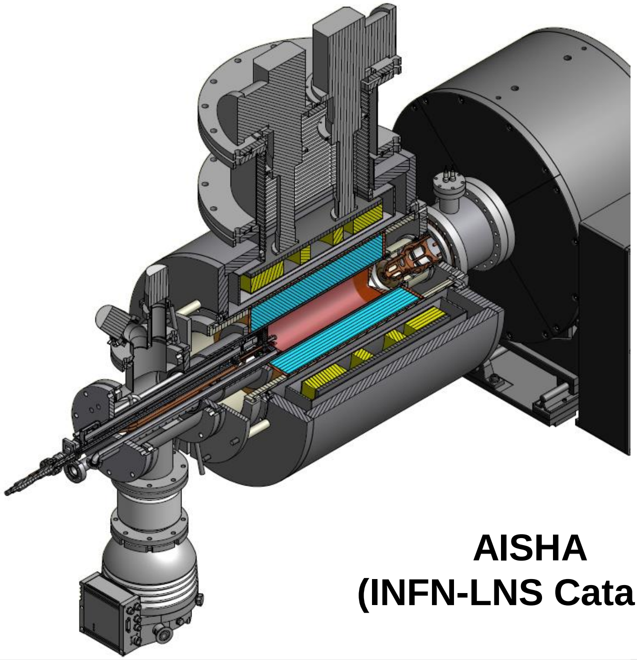
- Several promising approaches utilizing new technologies and new materials
- Easy handling; based on well-established techniques

Options:

- HIISI, University of Jyväskylä, Finland; RT: permanent magnet hexapole + RT solenoid coils
- AISHA, INFN-LNS, Catania; Hybrid: permanent magnet hexapole + SC solenoid coils
- PK-ISIS, Pantechnik S.A., Bayeux, France; Hybrid: permanent magnet hexapole + SC solenoid coils

HIISI
(University of Jyväskylä)





AISHA
(INFN-LNS Catania)

28 GHz SCECRIS (2nd Stage)

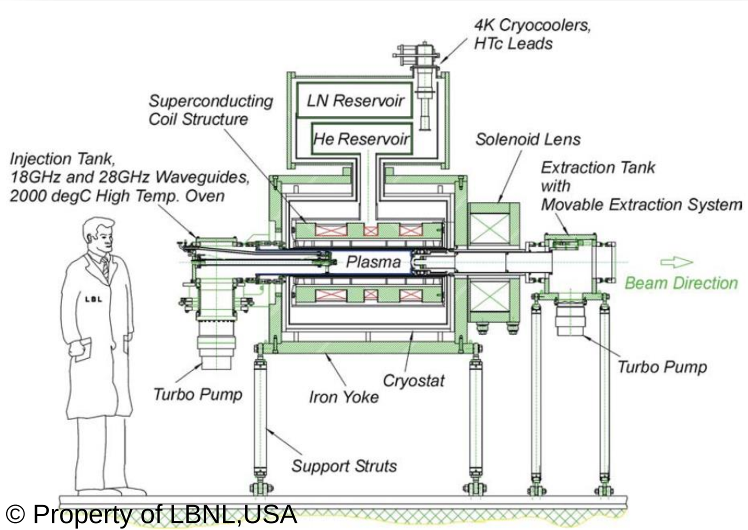
General benefits

- Considerably increased intensities of ions in medium and high charge states
- Adjustable axial and radial magnetic fields for optimum adaptation to medium and high charge states
- Established cryogenic technology

➔ Possible synergy for collaboration and a joint project GANIL – GSI (SPIRAL2 phase 1++ & FAIR@GSI)

Realised projects of the past decade

- VENUS-SCECRIS, LBNL, USA (left) ➔ upgraded version under construction for FRIB@MSU
- RIKEN-SCECRIS, RIKEN, Japan (right) ➔ second item planned @RIKEN
- SECRAL, IMP, China ➔ second item under commissioning @IMP



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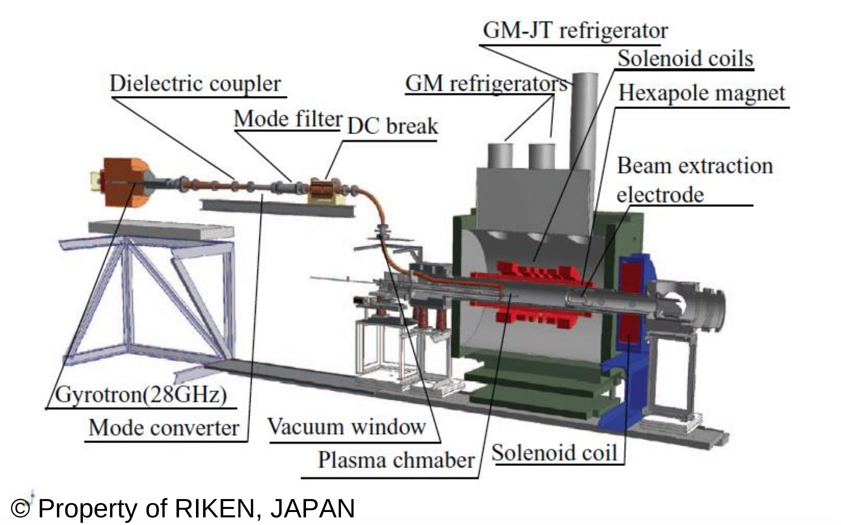

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18 GHz ECRIS Upgrade

Courtesy of Hannu Koivisto, JYFL, Finland

Objectives and approach for HIISI@Jyväskylä (JYFL)

- Increase of ion energy out of K130 cyclotron from 9 MeV to 15 MeV: 10 nA of Xe^{44+}
- Increase of ion current of medium charge states by factor >5
- 14 GHz ECRIS cannot meet the requirements
- Evaluation of existing ECRISs

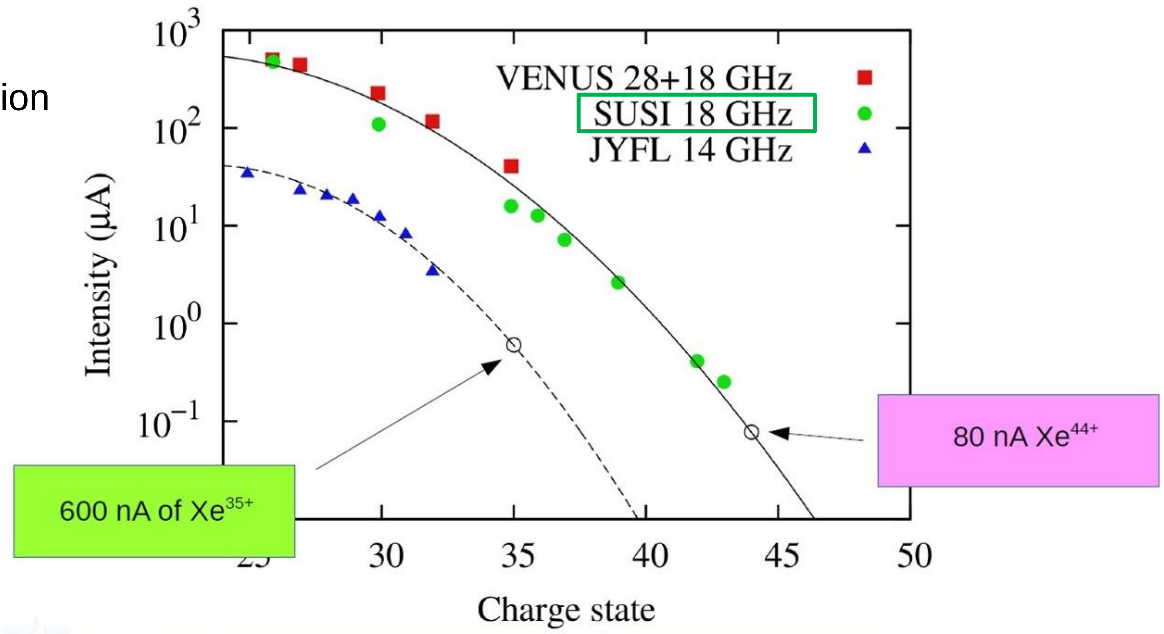
➔ SUSI (NSCL/MSU) has demonstrated adequate performance in 18 GHz operation mode

➔ Design basis for JYFL 18 GHz ECRIS

- Replace SC concept of SUSI by RT solution

SUSI = Superconducting Source for Ions

HIISI = Heavy Ion Ion Source Injector

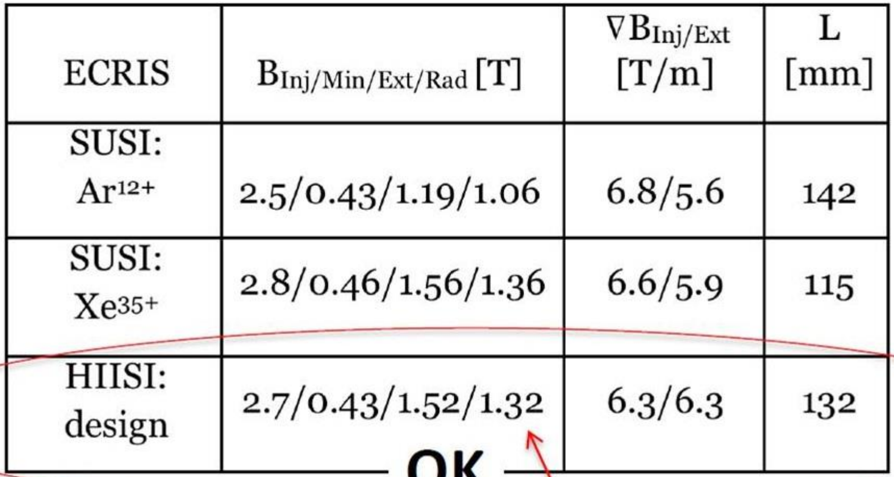


600 nA of Xe^{35+}

80 nA Xe^{44+}

Magnet System

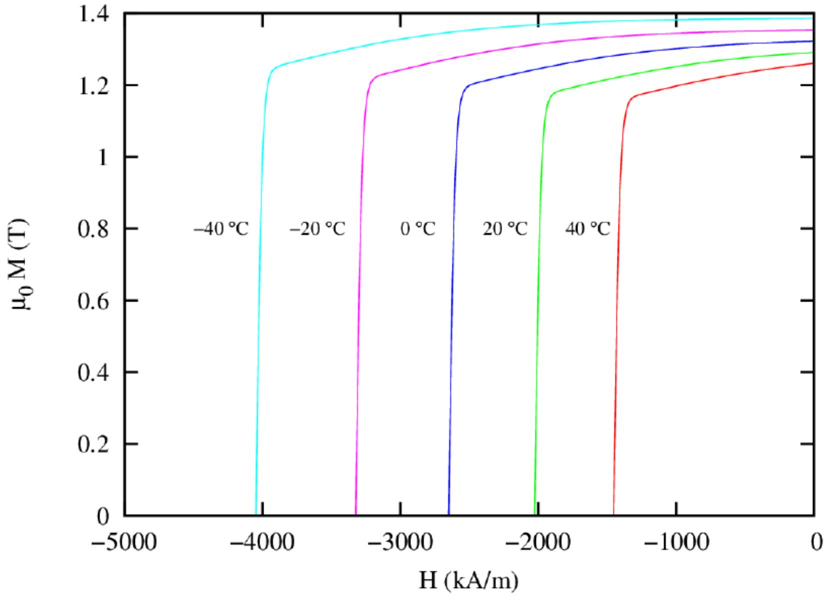
Courtesy of Hannu Koivisto, JYFL, Finland



ECRIS	$B_{Inj/Min/Ext/Rad}$ [T]	$\nabla B_{Inj/Ext}$ [T/m]	L [mm]
SUSI: Ar^{12+}	2.5/0.43/1.19/1.06	6.8/5.6	142
SUSI: Xe^{35+}	2.8/0.46/1.56/1.36	6.6/5.9	115
HIISI: design	2.7/0.43/1.52/1.32	6.3/6.3	132

OK

This value with 24 segment Halbach type
≥ 1.4 T with 36 segment Halbach configuration



Obtain B_{rad} = 1.36 T with permanent magnets is very challenging

- Refrigeration increases intrinsic coercivity → high B_r grades
- Remanence: 5% increase from +20 to -20°C
- Use of 36-sector Halbach-configuration

Permanent Magnet Properties

Courtesy of Hannu Koivisto, JYFL, Finland

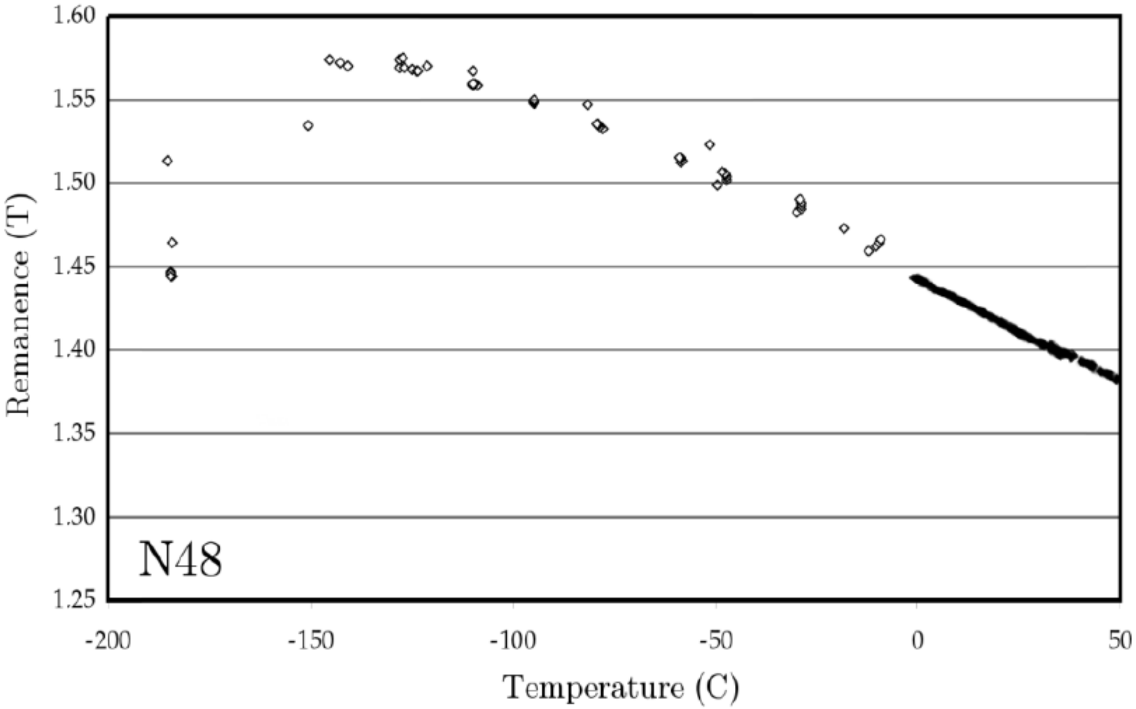
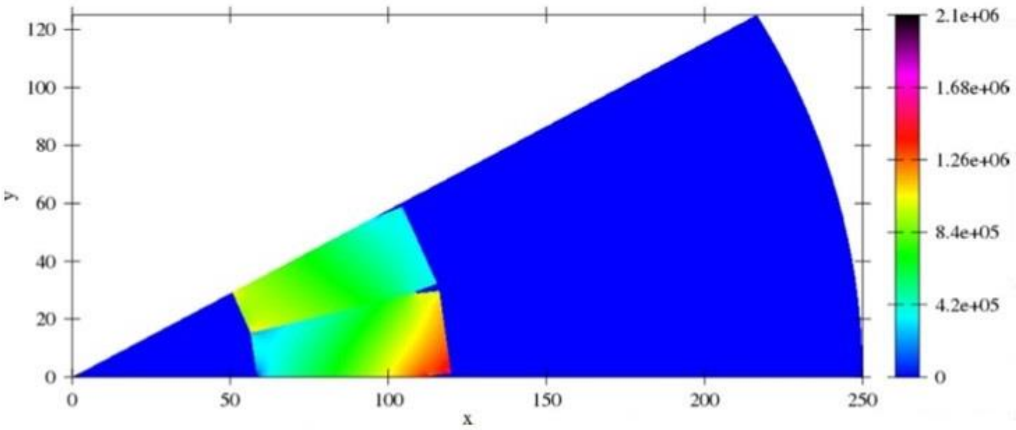
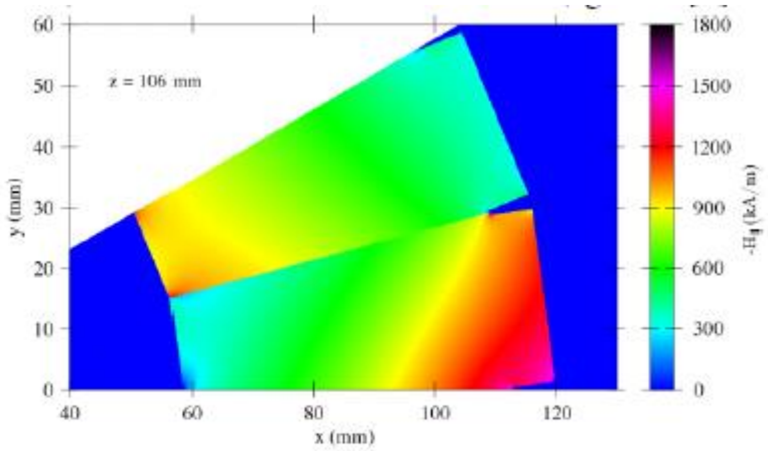


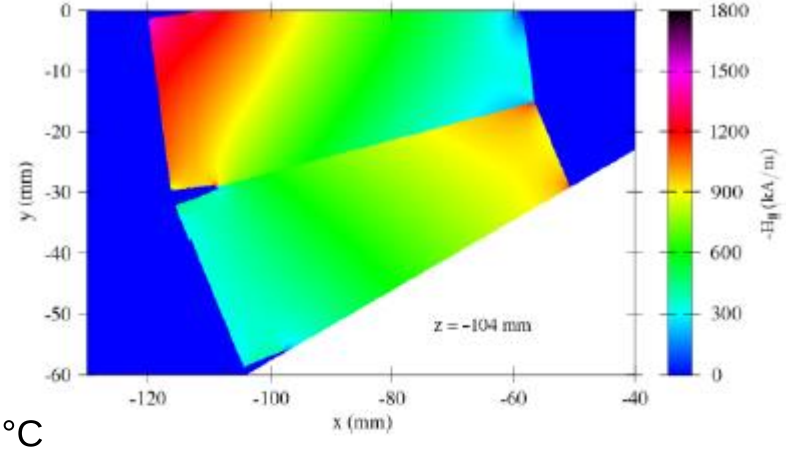
Figure 4: Remanence magnetic field B_{rem} of grade N48 permanent magnet experimentally defined as a function of temperature.

Permanent Magnet Properties

Courtesy of Hannu Koivisto, JYFL, Finland







- Demagnetisation analysis of HIISI permanent magnets at nominal axial magnetic field of solenoid system
- Colormap representation of -$H_{\|}$ (H-field component antiparallel to the magnetisation)
- Demagnetisation analysis -> magnets to be kept below 20°C

ECRIS-2014 Workshop

HIISI Innovative Solutions

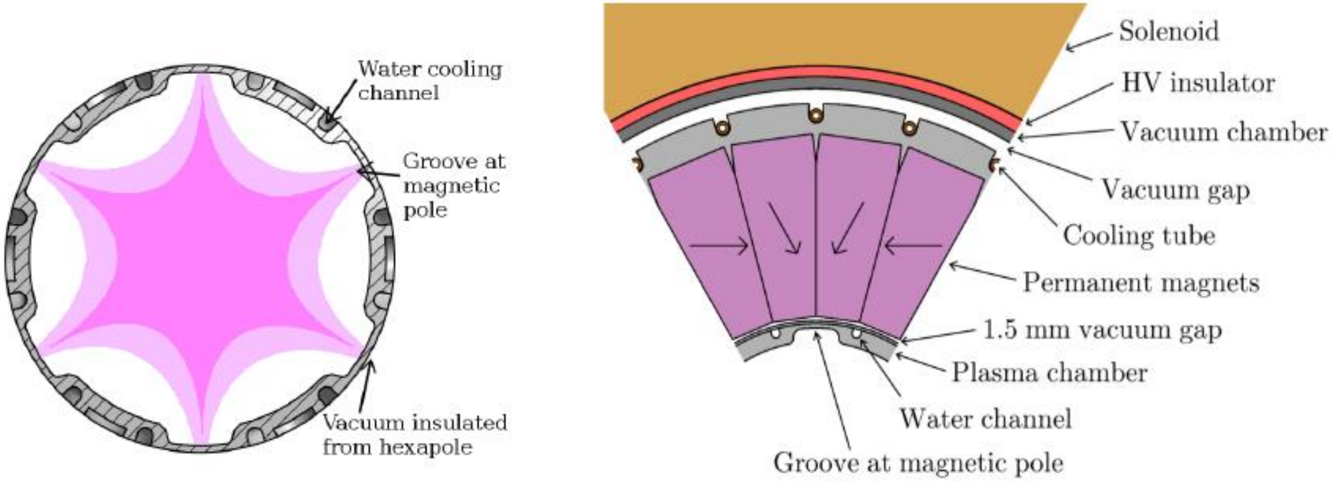
Courtesy of Hannu Koivisto, JYFL, Finland

Innovative solutions:

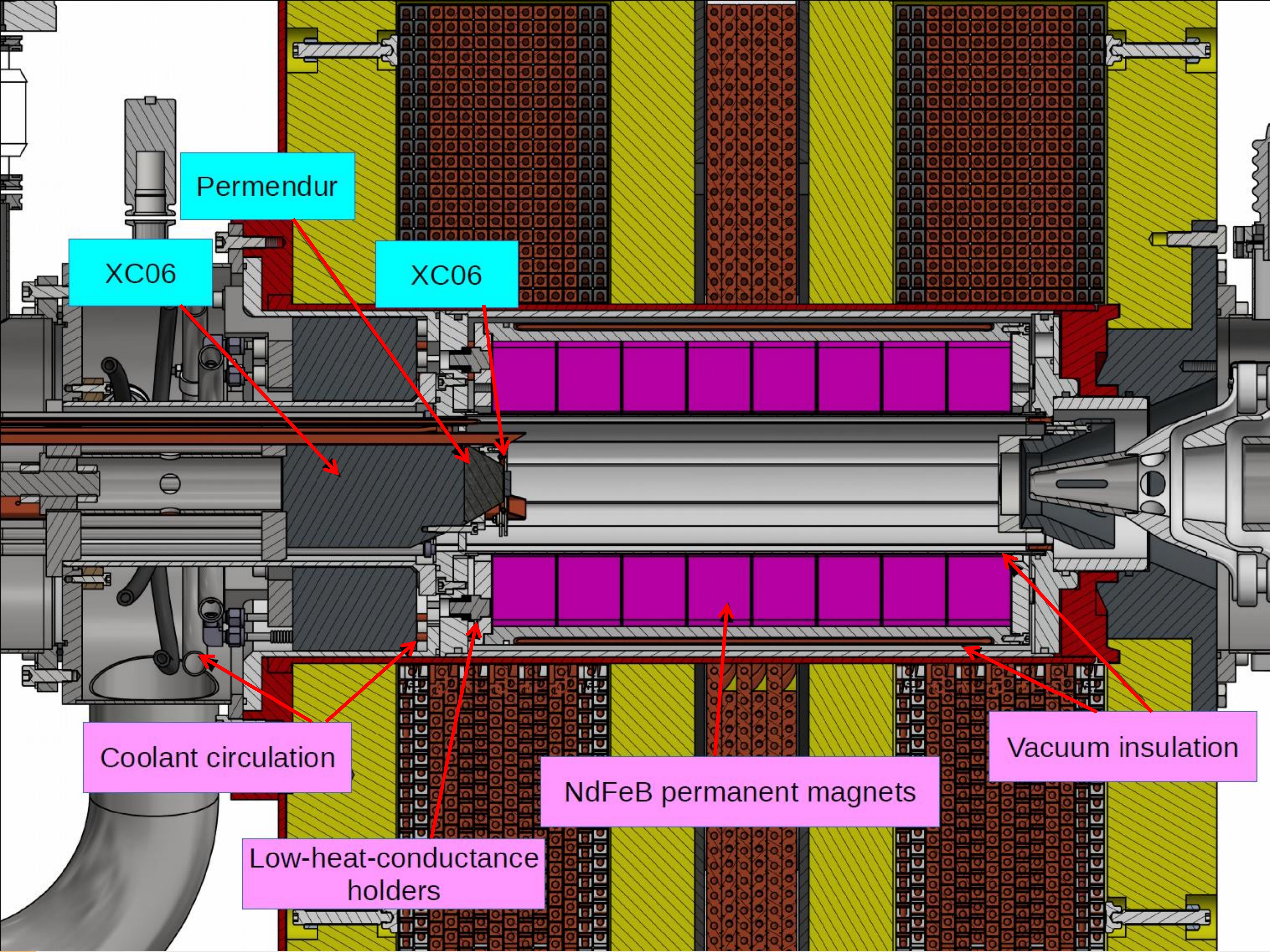
- High-permeability material in strategic places
- Refrigeration of permanent magnets for increased remanence and coercivity (-10°C)
- Grooved plasma chamber
- Solenoids (injection, extraction): 7 double pancakes with 20 radial turns, 3 similar pancakes for fine-tuning of minimum-B (total power consumption ≈ up to 200 kW)

Safety of permanent magnets: cooling

- Convective heat transfer caused by residual gas
- ➔ Full separation of plasma chamber and permanent magnet hexapole by a vacuum gap of about 1.5 mm
- Heat conduction via support structure of pumping chamber
- Heat radiation from surrounding structures



Plasma chamber structure (maximise B_{rad}, cooling of the permanent magnets)



Permendur

XC06

XC06

Coolant circulation

Vacuum insulation

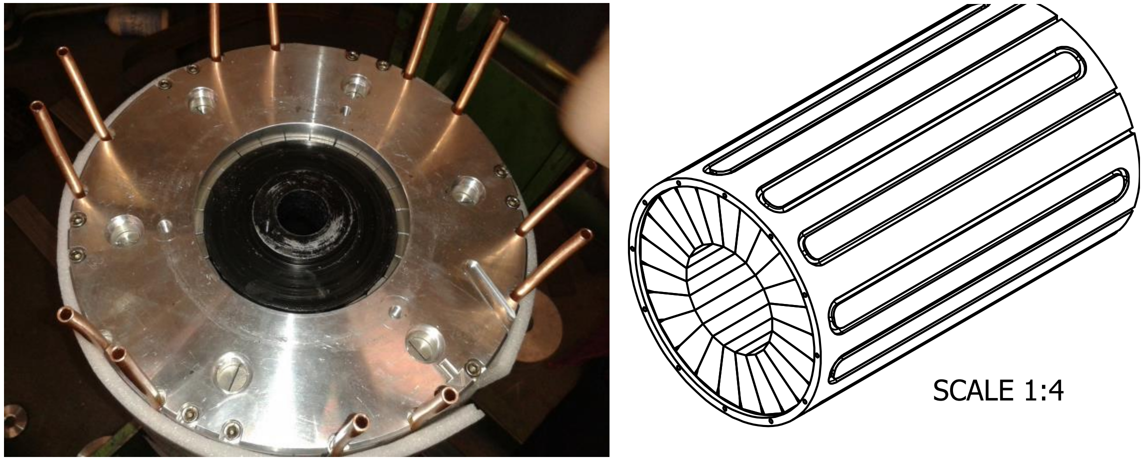
NdFeB permanent magnets

Low-heat-conductance holders

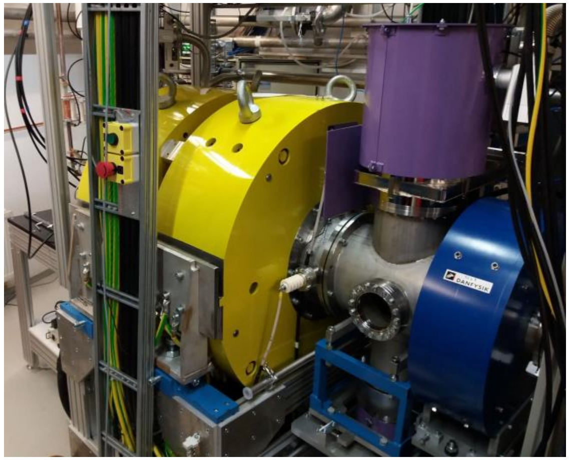
HIISI Innovative Solutions

Courtesy of Hannu Koivisto, JYFL, Finland

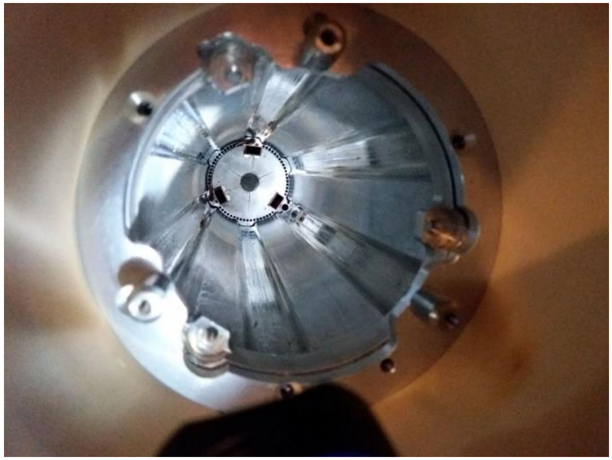
Refrigeration of permanent magnets for increased remanence and coercivity



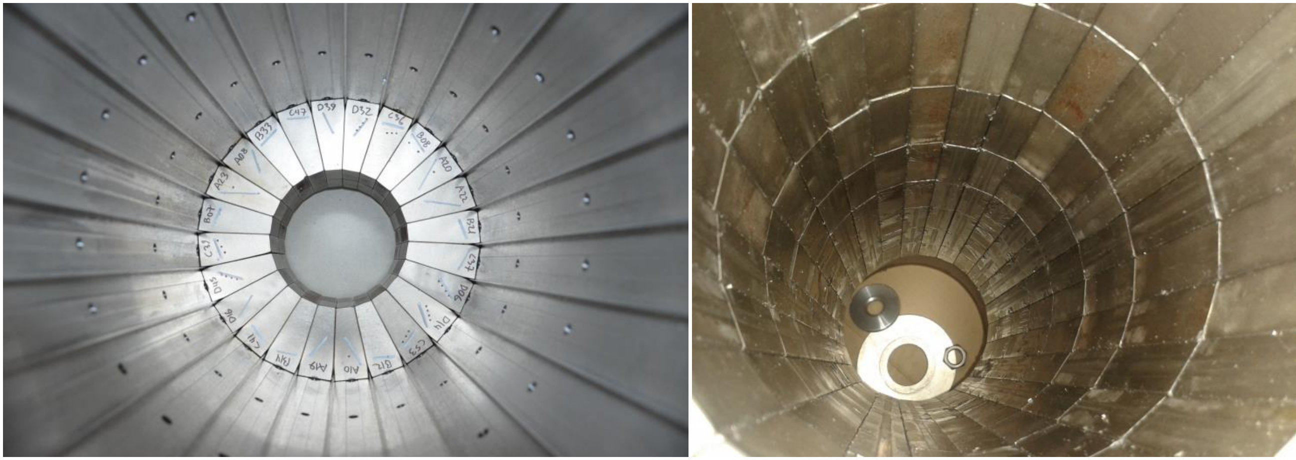
Magnetic shielding



Grooved plasma chamber (T<100°C)



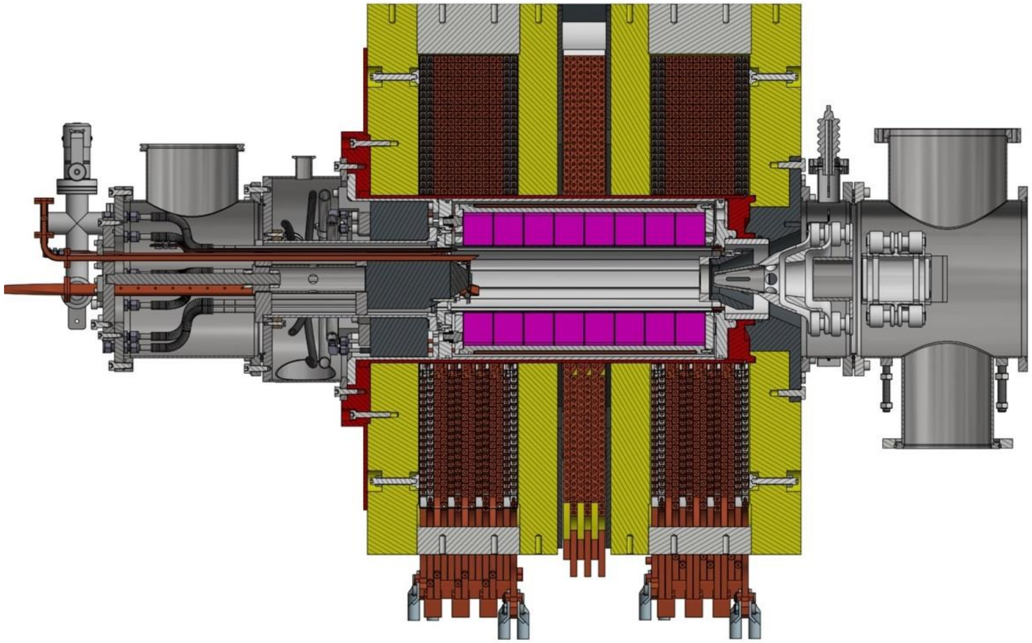
24-segment Halbach hexapole (T<20°C)



HIISI versus CAPRICE

Courtesy of Hannu Koivisto, JYFL, Finland

HIISI specifications	
Frequency	18 GHz + 14 GHz
Klystron power	2.4 kW + 2.4 kW
TWTA 8-18 GHz	P_{max}: 250 W 2 oscillators available
B_{rad} (24-segm)	1.3 T
B_{rad} (36-segm)	1.45 T
B_{inj}	2.8 T
B_{ext}	1.3 T
L (plasma)	120-150 mm
L plasma chamber	400 mm
D plasma chamber	100 mm
T hexapole	-20 --> +15˚C



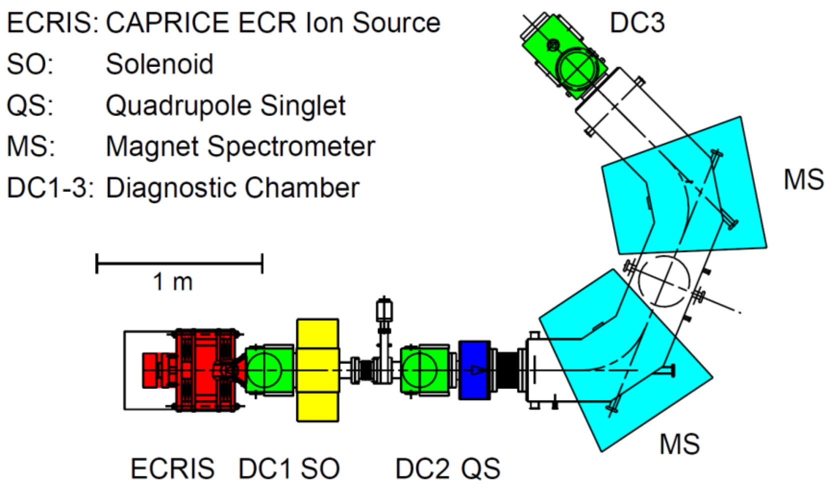
Comparison of analysed ion intensities

- HIISI results with 36 segment Halbach type hexapole (presented at ECRIS-2018 Workshop, Catania, September 2018)
- HIISI optimised for medium to high charge states
- CAPRICE optimised to medium charge states

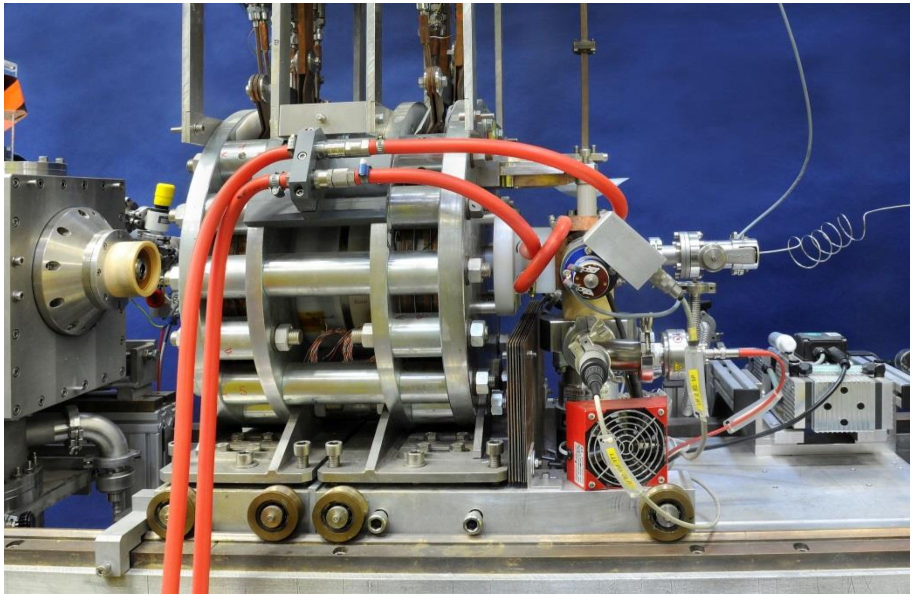
➔ Discrepancy increases with rising charge states

	Ion current (eμA)	
Argon charge state	**HIISI@JYFL**	**CAPRICE@GSI**
9	**450**	**70**
11	**680**	**30**
12	**570**	**8**
13	**330**	**2**

EIS Testbench



ECRIS: CAPRICE ECR Ion Source
SO: Solenoid
QS: Quadrupole Singlet
MS: Magnet Spectrometer
DC1-3: Diagnostic Chamber



ECR Injector Test Setup

→ Identical design as the low energy beam line of the High Charge State Injector (HLI)

Optimisation of Performance

Methods and parameters for optimisation of performance

- B-field adjustment (intermediate solenoid coil)
- µ-wave frequency tuning + double/multiple frequency heating
- Biased electrodes in the plasma chamber
- Evaporation of solid materials (oven technology)
- Afterglow mode (+ combination with µ-wave methods)
- Transfer of all best practices developed in 25 years of ECRIS operation from CAPRICE ECRIS to new 18 GHz ECRIS

Thank you for your attention!

ECRIS-Team:

Ralf Lang
Jan Mäder
Fabio Maimone
Patrick Patchakui
Klaus Tinschert

\+

with support from the
ion source staff of IOS

^{64}Ni deposit on inner side of the plasma electrode after 6 weeks of operation