NSCL

Design, Construction and First Commissioning results of SuSI

Peter Zavodszky

National Superconducting Cyclotron Laboratory

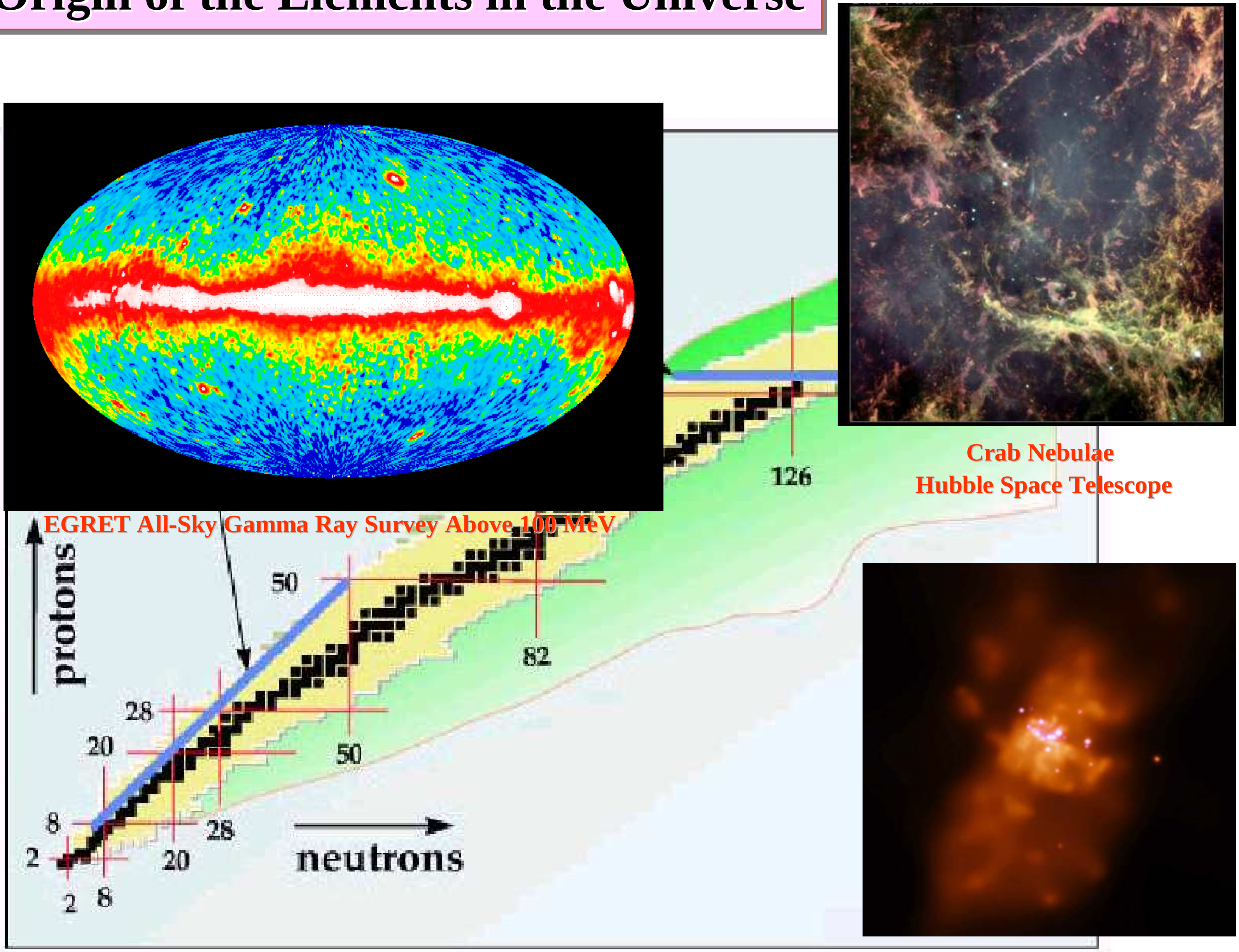
Michigan State University

East Lansing, MI 48824, USA

PAC 2007 Albuquerque, NM

June 29, 2007

The Origin of the Elements in the Universe



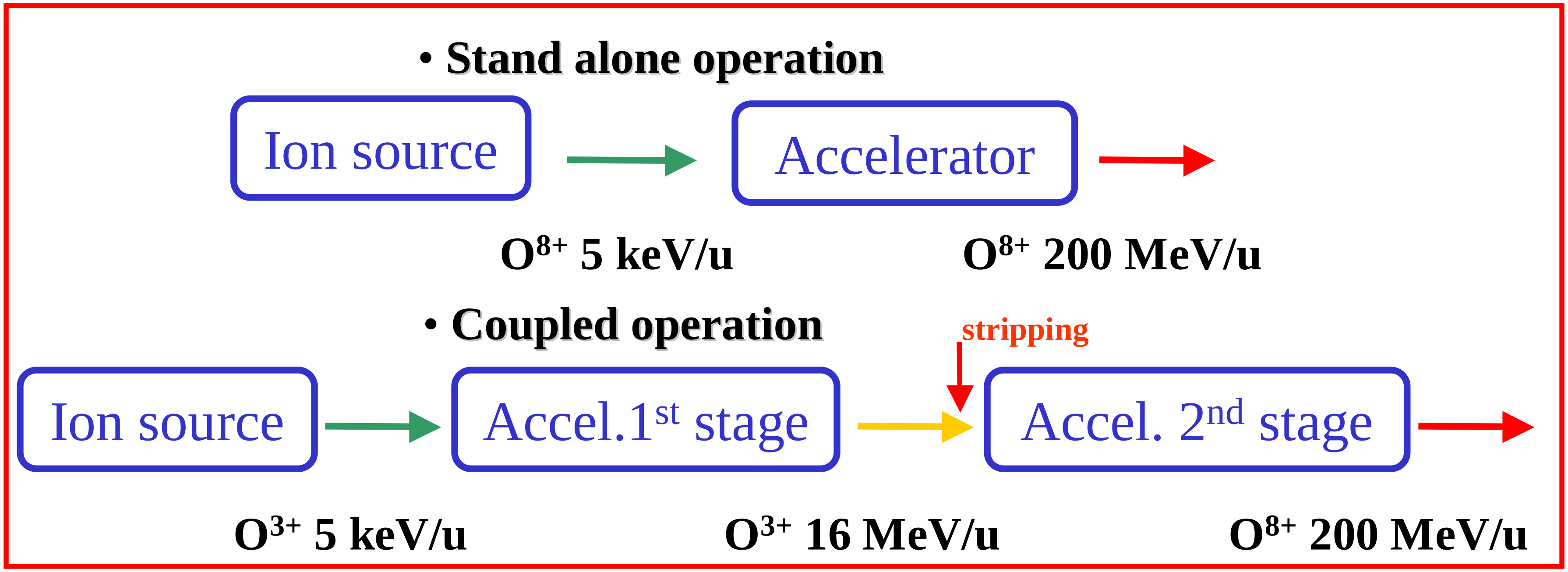
EGRET All-Sky Gamma Ray Survey Above 100 MeV

Crab Nebulae
Hubble Space Telescope

M82 Starburst Galaxy
Chandra X-Ray Observatory

Motivation for production of highly charged ions

- intense highly charged ions are used in many accelerator applications
- dc beams for RIA/ISL, RIKEN RIB, etc.
- pulsed beams for injection in synchrotrons such as RHIC, LHC, FAIR, hadron therapy
- higher M/Q from an ion source makes the accelerator more compact and less costly
- there is generally a tradeoff between intensity and charge state from an ion source



- **Stand alone operation**

Ion source → Accelerator →

O^{8+} 5 keV/u **O^{8+} 200 MeV/u**

- **Coupled operation**

Ion source → Accel.1st stage → Accel. 2nd stage →

stripping

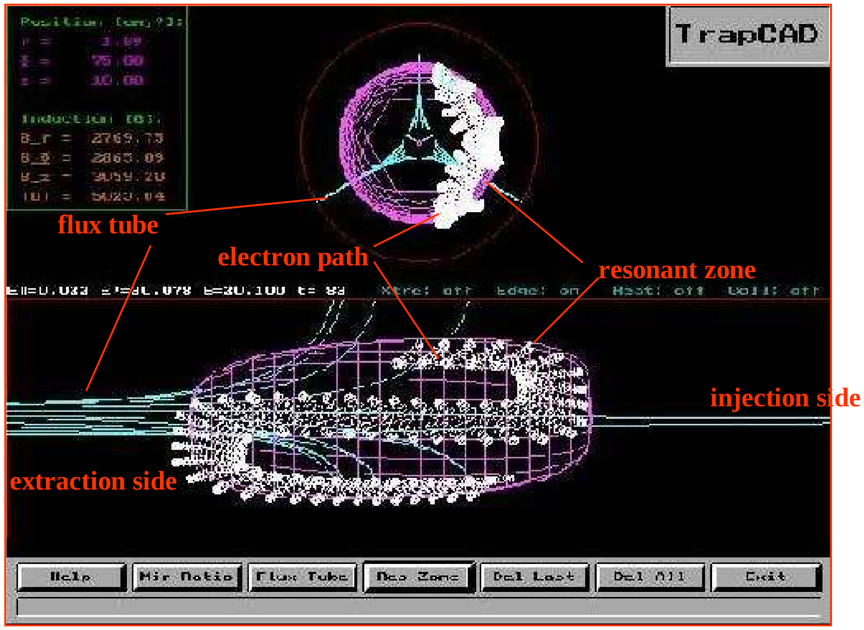
O^{3+} 5 keV/u **O^{3+} 16 MeV/u** **O^{8+} 200 MeV/u**

ECRIS Basics

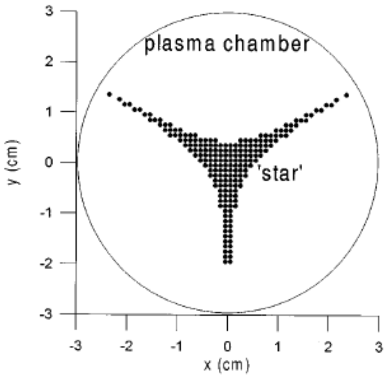
- **the energy of the electrons should be higher than the ionization potential of the desired charge state**
- **the ions should be trapped for a time sufficient to reach the desired charge state since step-by-step ionization is the dominant process**
- **a minimum-B magnetic mirror configuration confines the particles**
- **electrons are heated by interaction with rf waves at the cyclotron frequency:**

$$\omega_{ce} = \frac{e|B|_{ecr}}{m_e} = \omega_{rf}$$

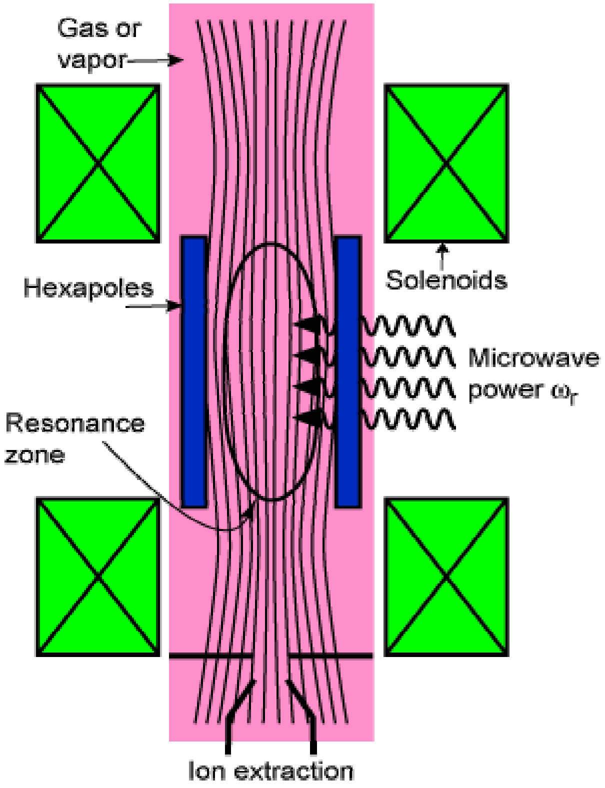
- **the created ions are extracted and accelerated with electrostatic fields**



A typical screen output for TrapCAD, a tool to design and study magnetic traps of ECRIS



Key parameters of an ECRIS



Minimum-B field Confinement

- **Magnetic field configuration:**

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

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

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

- **Microwave frequency:**

$$\omega_e = qB_{ECR}/m = \omega_{rf}$$

$$I \propto \omega_{rf}^2 M^{-1} \tau^{-1}$$

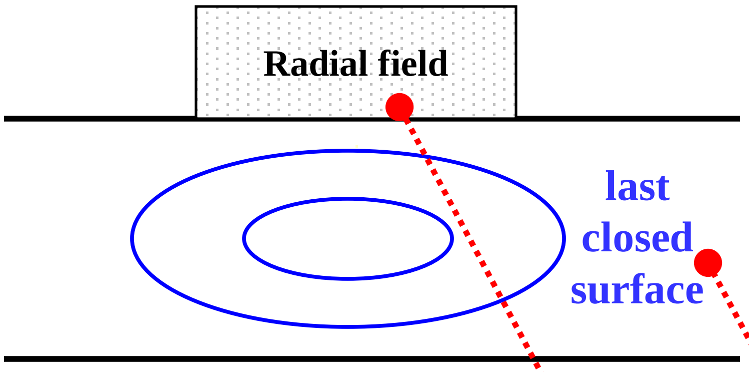
- **Extraction voltage:**

$$I \propto U_{ext}^{3/2}$$

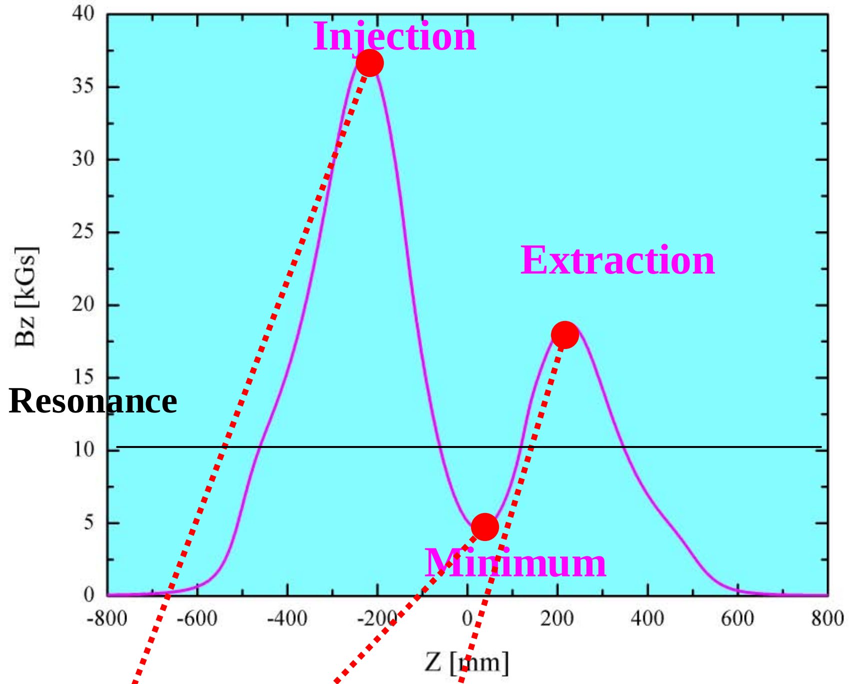
- Plasma chamber geometry (length, diameter) and wall material
- Extraction system (gap, voltage, plasma electrode position)
- Biased disc (voltage, position)

Magnetic confinement

ECRIS = magnetic structure with B minimum



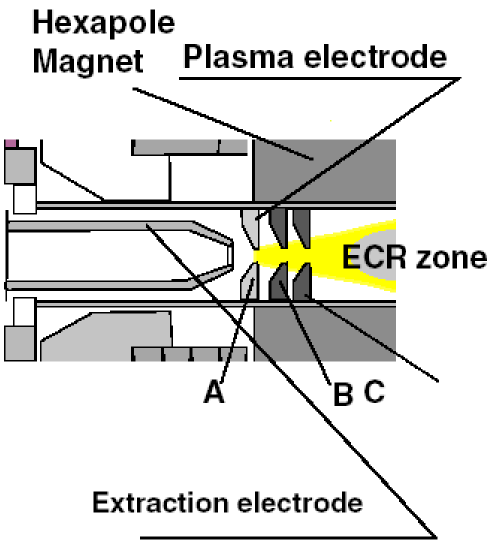
$B^2_{last} = B^2_{min} + B^2_{rad}$



Confinement : 5 parameters

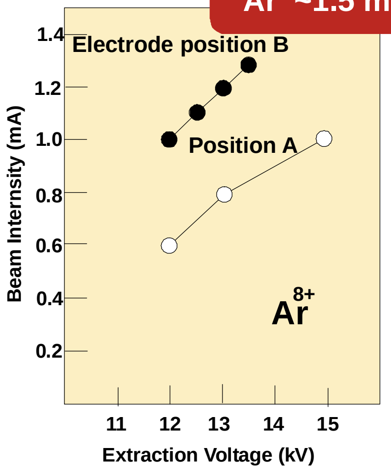
$B_{inj} \approx 4\ B_{ECR}$ $B_{ext} < B_{rad} \approx 2\ B_{ECR}$ $B_{min} \approx 0.8\ B_{ECR}$

Plasma electrode location and biased disc effect

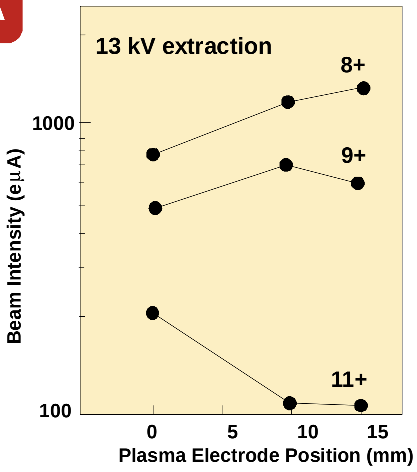


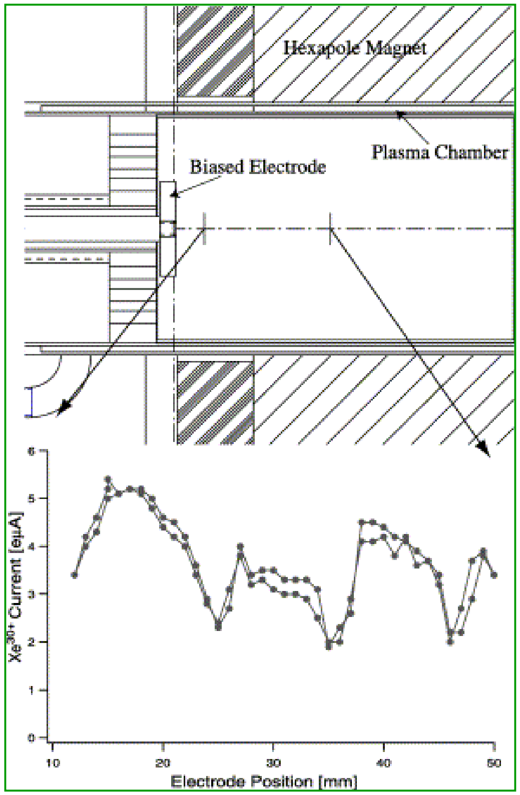
Extraction voltage

Ar^{8+} ~1.5 mA



Electrode Position



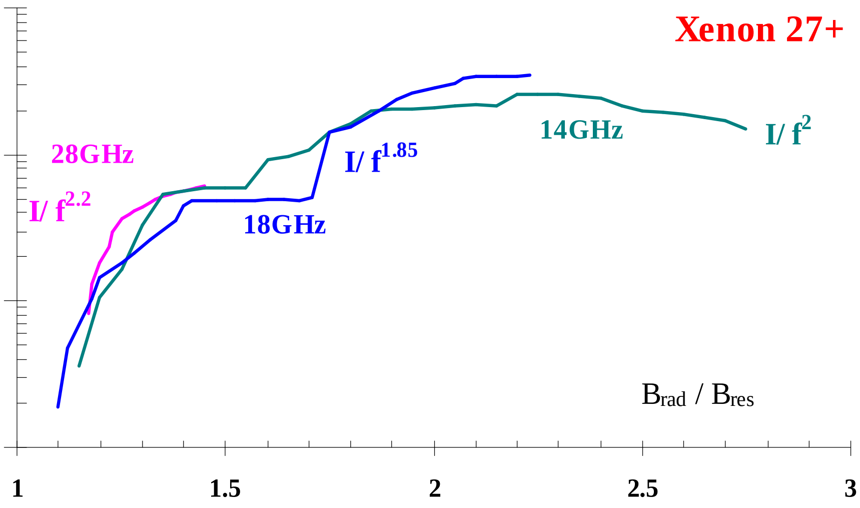


- The beam intensity is strongly dependent on the position of the bias disc
- Desirable to have an adjustable length of the plasma chamber to be able to change the matching conditions between the plasma and the microwaves

B-min ECRIS dynasty

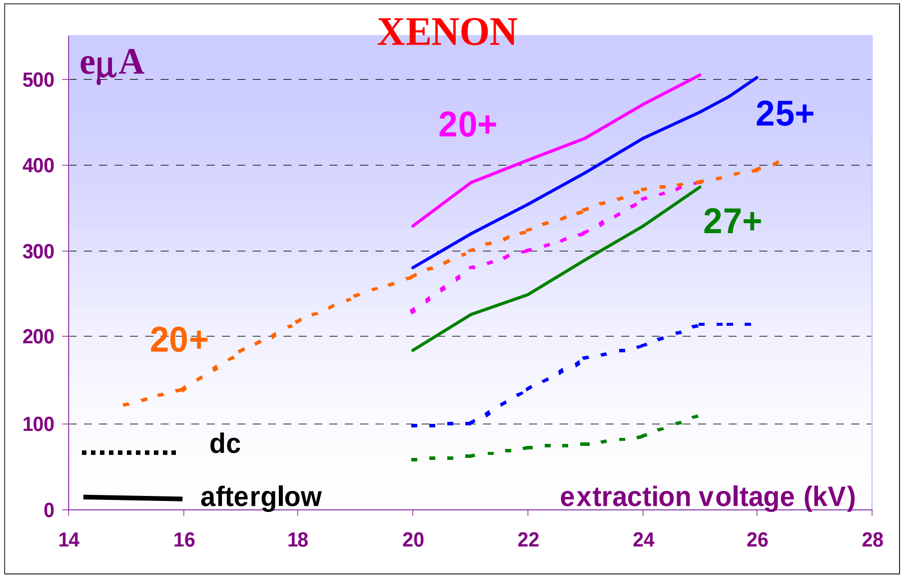
1st generation	’80s	f=6 ÷10 GHz	SUPERMAFIOS, MINIMAFIOS, ECREVIS, CAPRICE,etc.	P<1 kW	I_{tot}<mA	Q≈6÷12 for Argon
2nd generation	’90s	f=14÷18 GHz	ECR4, Hypernanogan, AECR, SC-ECRIS 18 GHz RIKEN	P≈1÷2 kW	I_{tot}≈1÷5 mA	Q≈8÷16 for Argon
	1998	f=14+18 GHz	SERSE	P≈2 kW dc or pulsed	I_{tot}≈1÷5 mA	Q≈12÷18 for Argon
2.5 generation	2000	f=28 GHz	SERSE	P≈4÷7 kW dc or pulsed	I_{tot}≈5÷15 mA	Q≈12÷18 for Argon
	2002	f=28 GHz	PHOENIX	P≈4÷7 kW Pulsed	I_{tot}≈10÷20 mA	Q≈12÷18 for Argon
3rd generation	2004	f ≥28 GHz	VENUS, SECRAL, SuSI, MS-ECRIS, SC-ECRIS in RIKEN	P ≥ 10 kW dc or pulsed	I_{tot}≈10÷50 mA	Q≈14÷18 for Argon
4th generation	2010?	f =60-90 GHz	?	P ≈ 50 ÷100 kW dc or pulsed	I_{tot}≈50÷100 mA	Q≈14÷18 for Argon

SERSE at INFN-LNS Catania, Italy

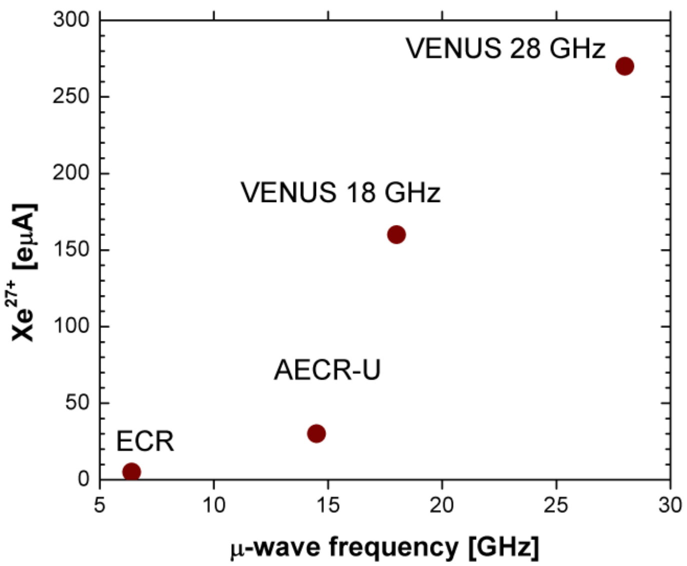

Test of scaling laws at ***14 – 18 – 28 GHz***

First 28 GHz operation (2000)
Designed for 18 GHz
B_{rad}=1.45 T

Results of 28 GHz tests
- I ~ f^2 , verified at 14, 18 and 28 GHz
- P≥ 3 kW
- Optimum B_{rad} at 28 GHz > 1.45 T



The LBNL ECR ion source group leads the way to the next generation sources with VENUS

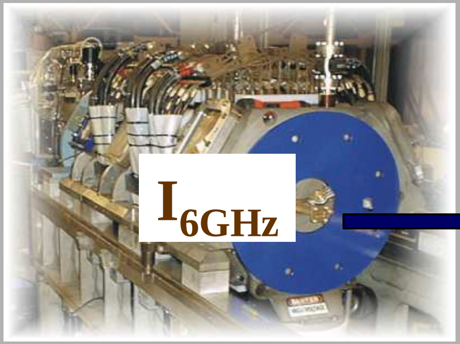


Challenges

- Superconducting Magnet
- 28 GHz microwave heating
- X-rays from the Plasma
- Ion Beam Transport

ECR (1983)

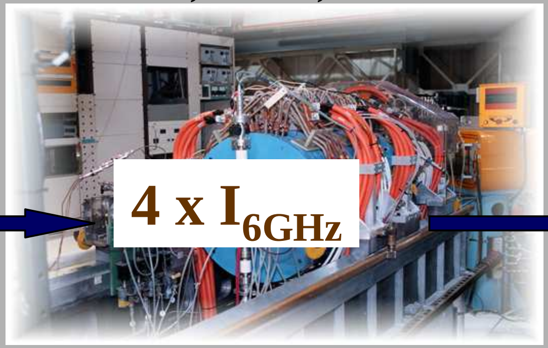
0.4 T, 0.6 kW, 6.4 GHz



I_{6GHz}

AECR-U (1996)

1.7 T, 2.6 kW, 10 + 14 GHz



$4 \times I_{6GHz}$

VENUS (2001)

4.0 T, 14 kW, 18 + 28 GHz

$16\ I_{6Ghz}$

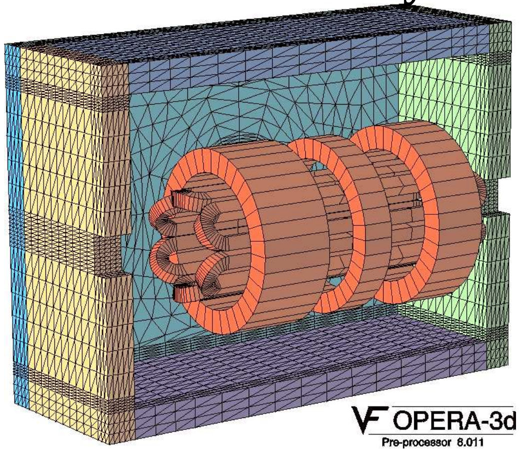
Normal conducting

⇨

Super conducting

VENUS is the first ECRIS to address these challenges

Superconducting Magnets
State of the art cryostat



New Plasma Chamber

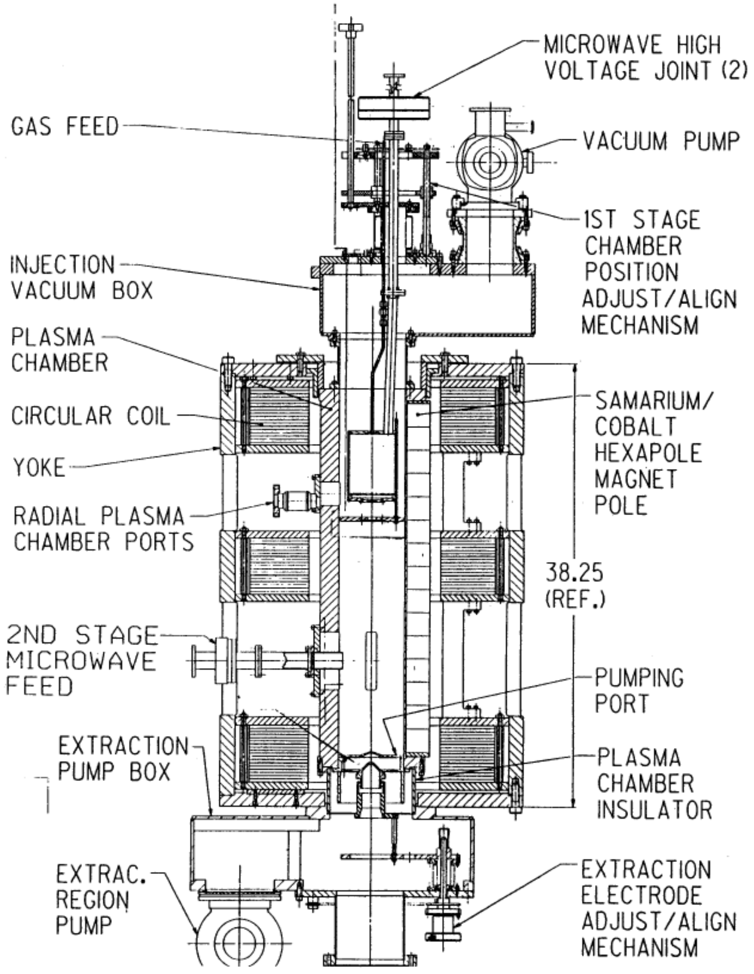
Ta X-ray shielding

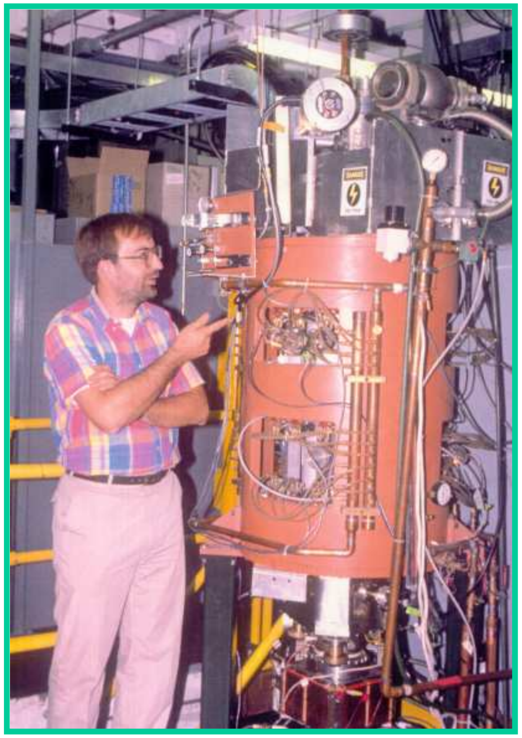
- Because of its unique position VENUS was selected as prototype injector source for the next generation heavy ion facilities in the US
- 28 GHz operation since 2004

Beam Transport

28 GHz microwave plasma heating

ECR Ion Sources at NSCL/MSU I.





RT-ECR (1985)

First ECRIS using iron return yoke

ECR Ion Sources at NSCL/MSU II.

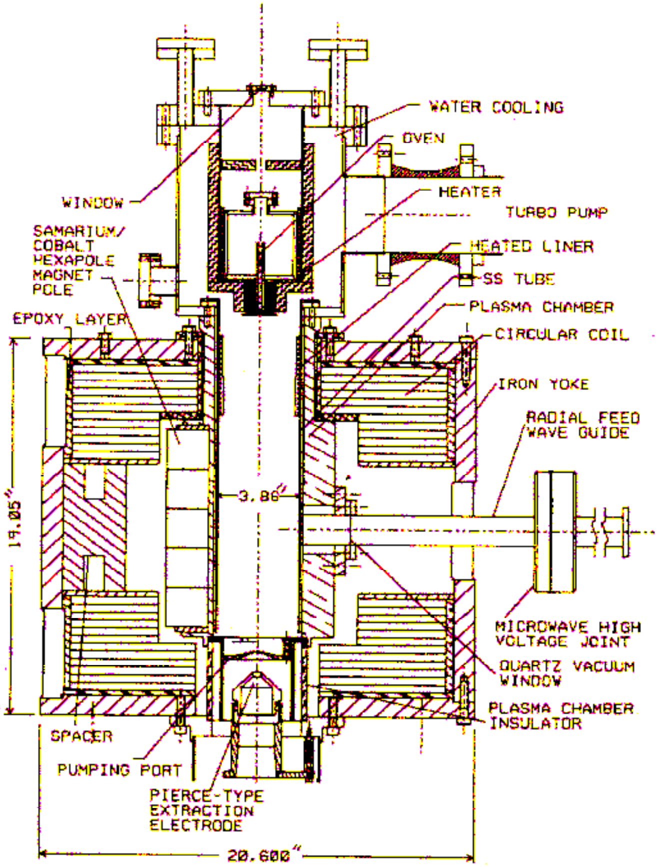
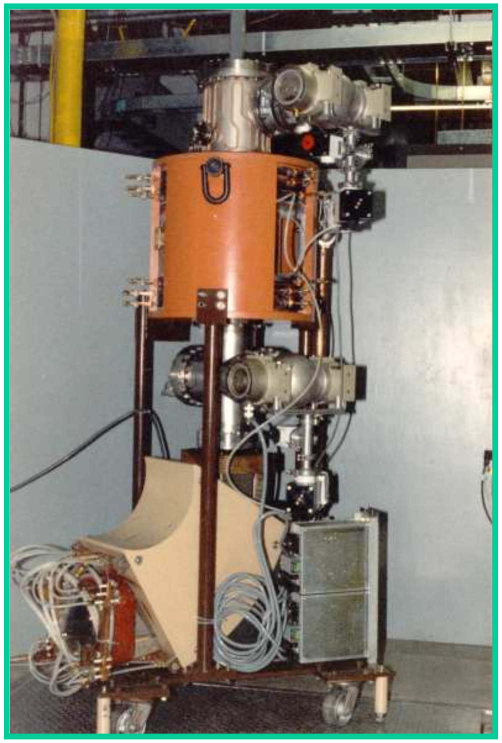


Fig. 1: The new CP-ECR, first operated in March 1987. is shown.



CP-ECR (1987)

The first ECRIS with an integral large volume oven and heated liner

ECR Ion Sources at NSCL/MSU III.

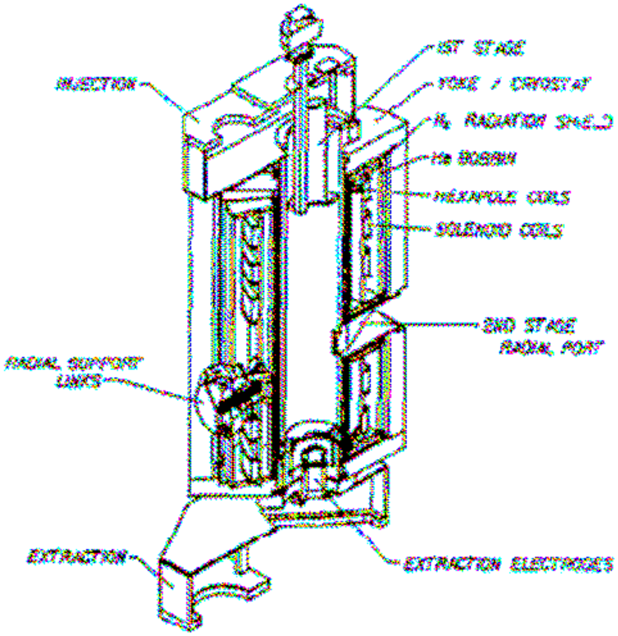


FIG. 1. The SCECR is shown in schematic form.

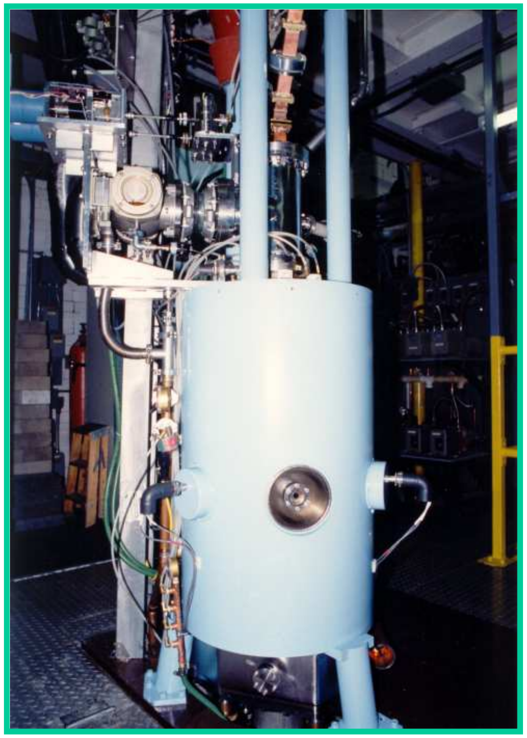
First Vertical SC ECR

Designed for 6.4 and 14.5 GHz

High B-mode demonstration at 6.4 GHz

Sextupole field too low for 14.5 GHz

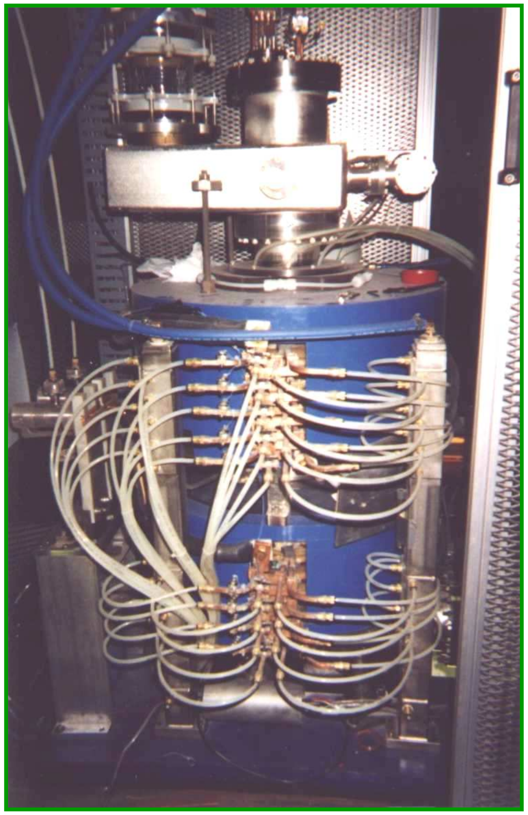
(Quenching)



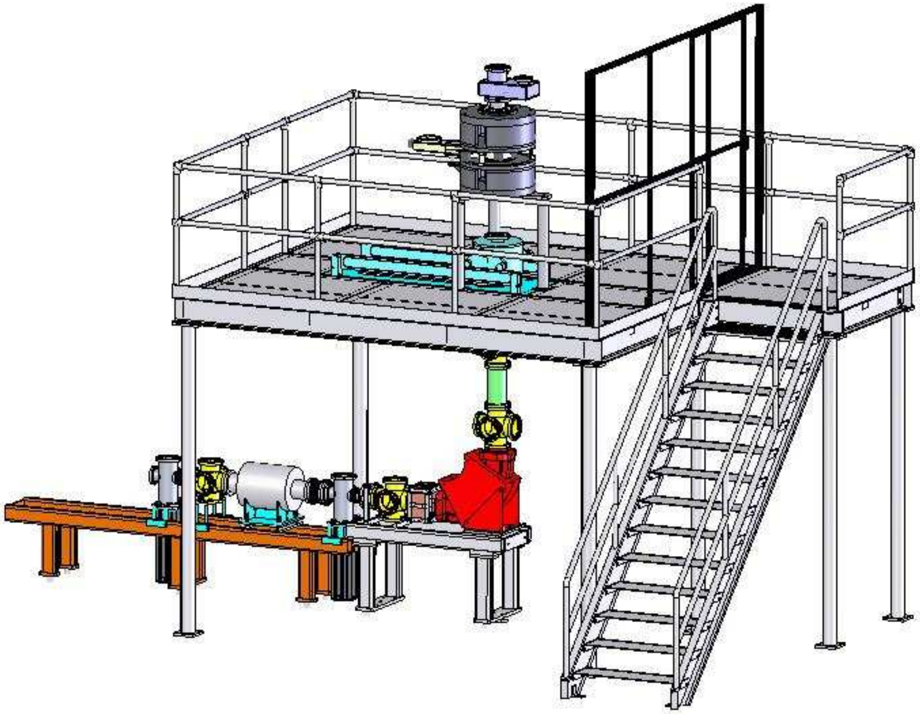
SC-ECR (1993)

The first dynamically tunable SC ECRIS using the High-B mode

ECR Ion Sources at NSCL/MSU IV.



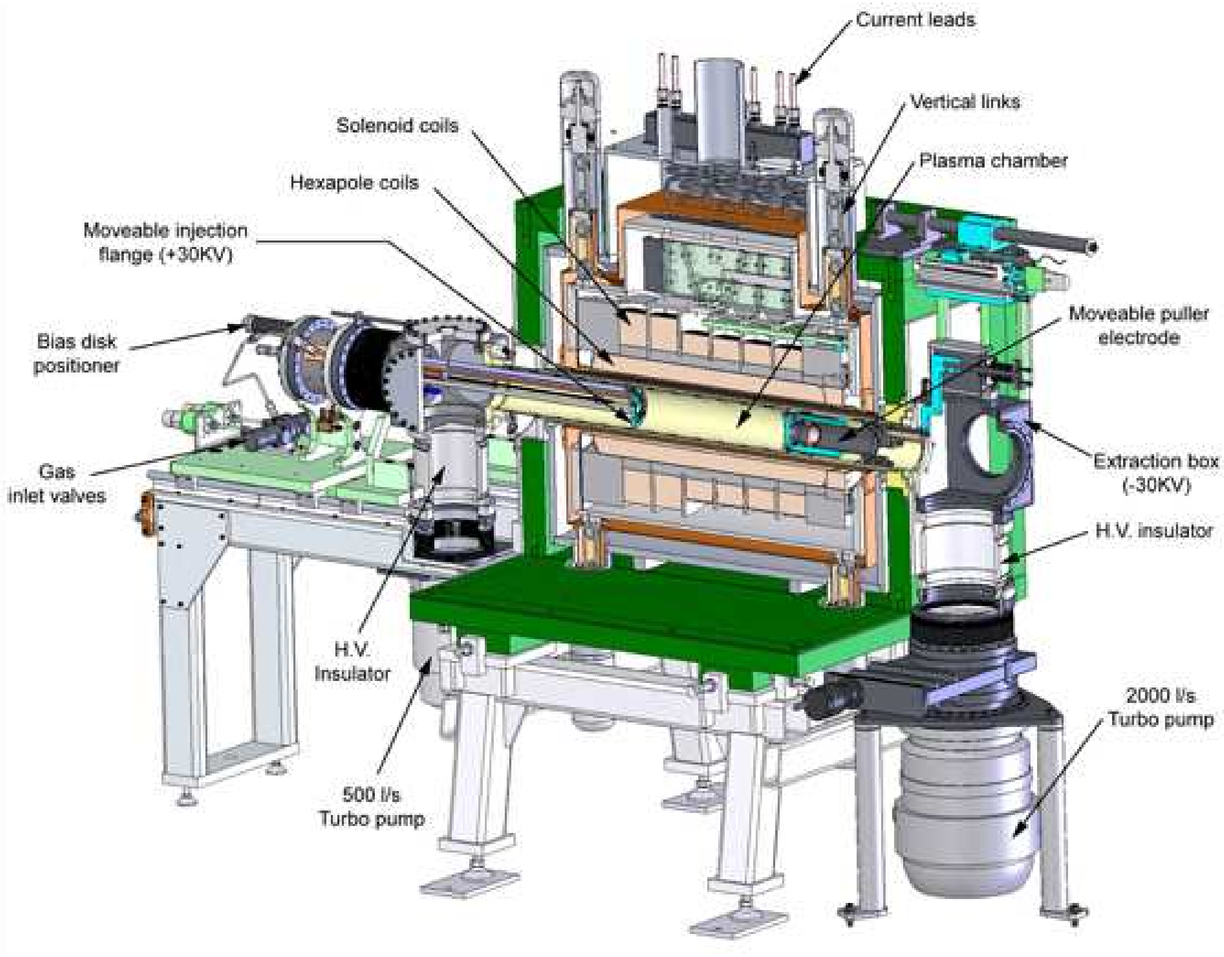
ARTEMIS-A (1999)
– modified version of AECR-U from LBL



ARTEMIS-B (2005)
off-line test bench for ion source development

ECR Ion Sources at NSCL/MSU V.

SuSI – Superconducting Source for Ions (2007)



- **maximum magnetic fields:**

Original Design:
- 2.6 T, 1.5 T axial field
- 1.5 T radial field

Tested (February 2006):
- 3.6 T, 2.2 T axial field
- 2 T radial field

- **plasma chamber diameter:** 101.6 mm (aluminum)
- **superconducting wire:**
  - 2x1 mm NbTi
  - Cu/SC ratio 3.00
- **operating frequency:**

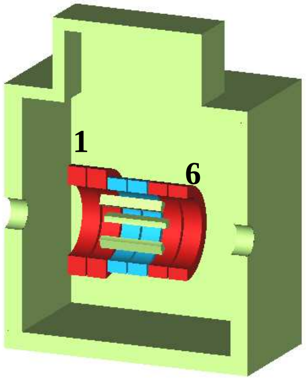
Phase I: 18 + 14.5 GHz

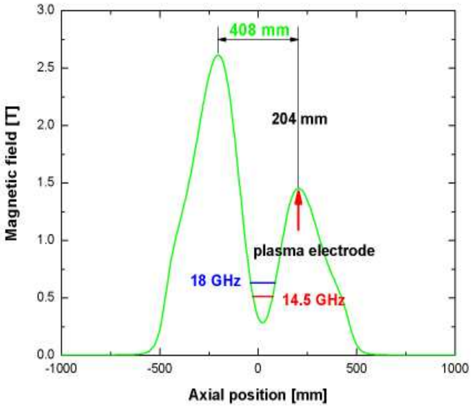
Phase II: 24-28 GHz

- **maximum extraction voltage:** 60 kV (ion source at +30 kV, beamline at –30 kV)
- **tunable plasma chamber length**
- **tunable bias disc position**

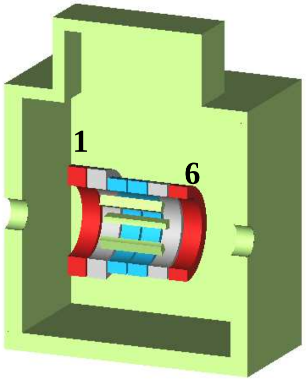
The Flexible Axial Magnetic Field Concept

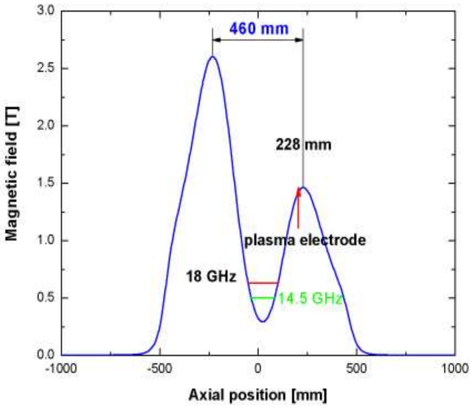
$J_1=J_2=61\ A/mm^2$
$J_3= J_4=-60\ A/mm^2$
$J_5=J_6=74\ A/mm^2$



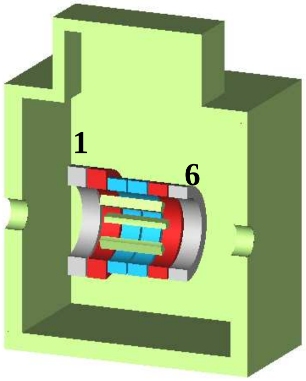


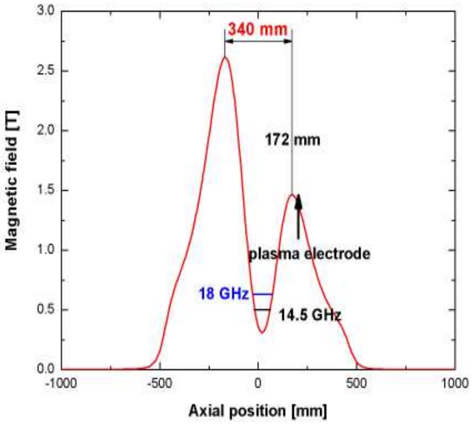
$J_1=120\ A/mm^2$
$J_2=J_5=0$
$J_3=J_4= -27\ A/mm^2$
$J_6=96A/mm^2$





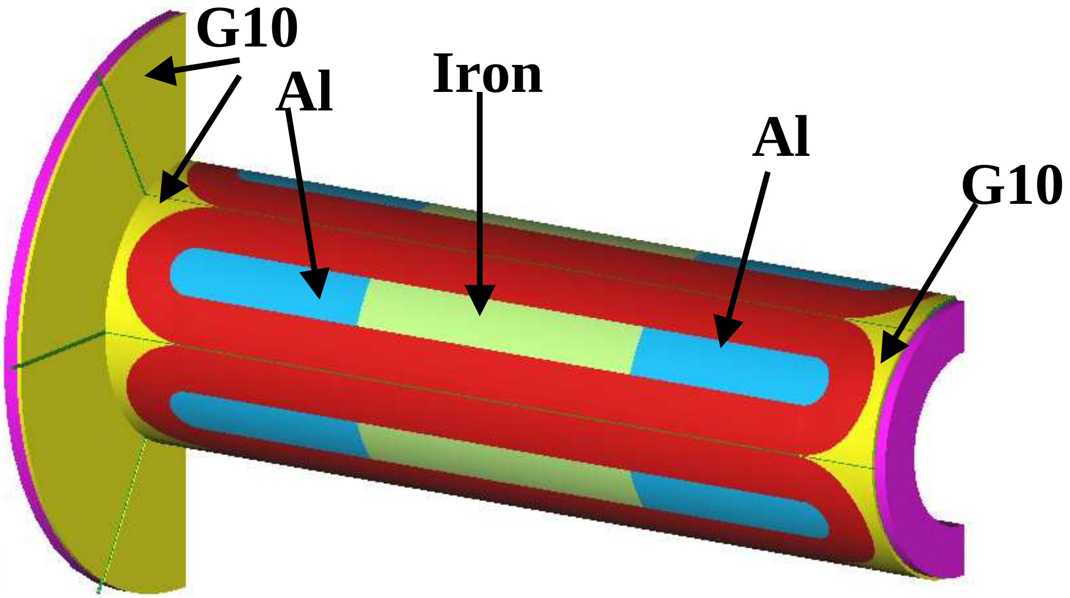
$J_1= J_6=0\ A/mm^2$
$J_2=170\ A/mm^2$
$J_3=J_4= -100\ A/mm^2$
$J_6=150A/mm^2$

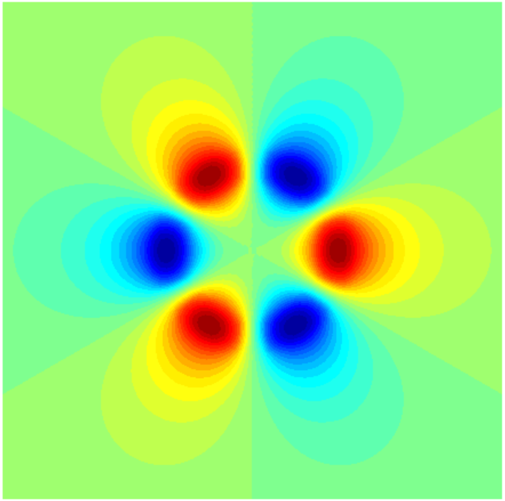


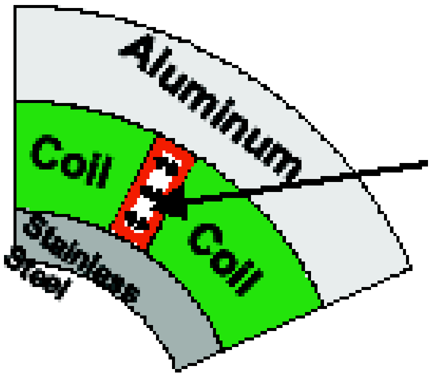


- **the relative distance between the resonant zone and plasma electrode can be varied**
- **the distance between the two magnetic maxima can be varied**
- **the “depth” of the magnetic minimum can be varied**
- **the position of the magnetic profile can be shifted**

SC hexapole coils

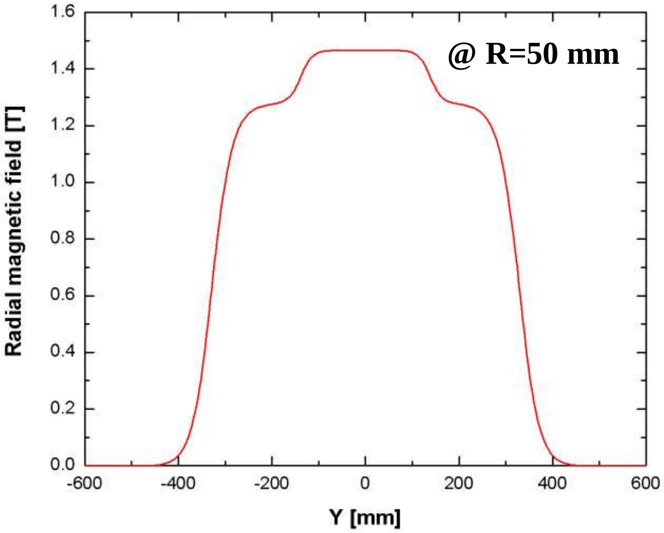




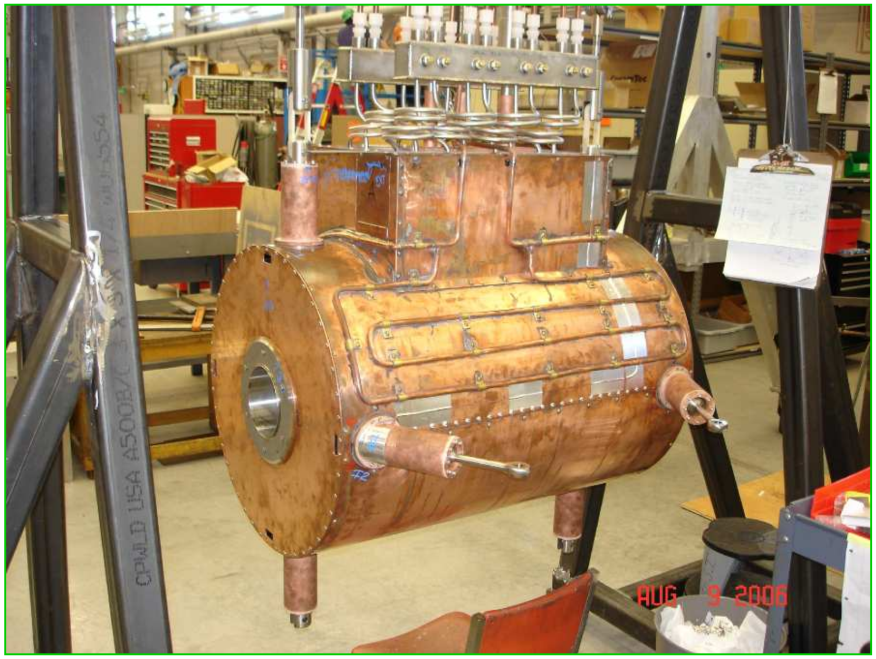


High pressure liquid metal bladder to prevent movement

Similar technology as used in VENUS construction



SuSI Magnet Construction I.



The assembly of the SuSI magnet liquid nitrogen thermal shield.

The SuSI magnet cryostat before the super insulation is applied to the front and back end of the liquid nitrogen thermal shield.

SuSI Magnet Construction II.

The SuSI magnet yoke with the injection and extraction hardware and plasma chamber with electrical isolation ready for tests.

- Magnet tested in a vertical test dewar Febr. 2006.
- LHe vessel completed, leak checked .
- LN_2 shield completed.
- Vertical and horizontal support links installed.
- Cryostat was finished in Sept. 2006.
- Vacuum vessel installation was completed in Dec. 2006.

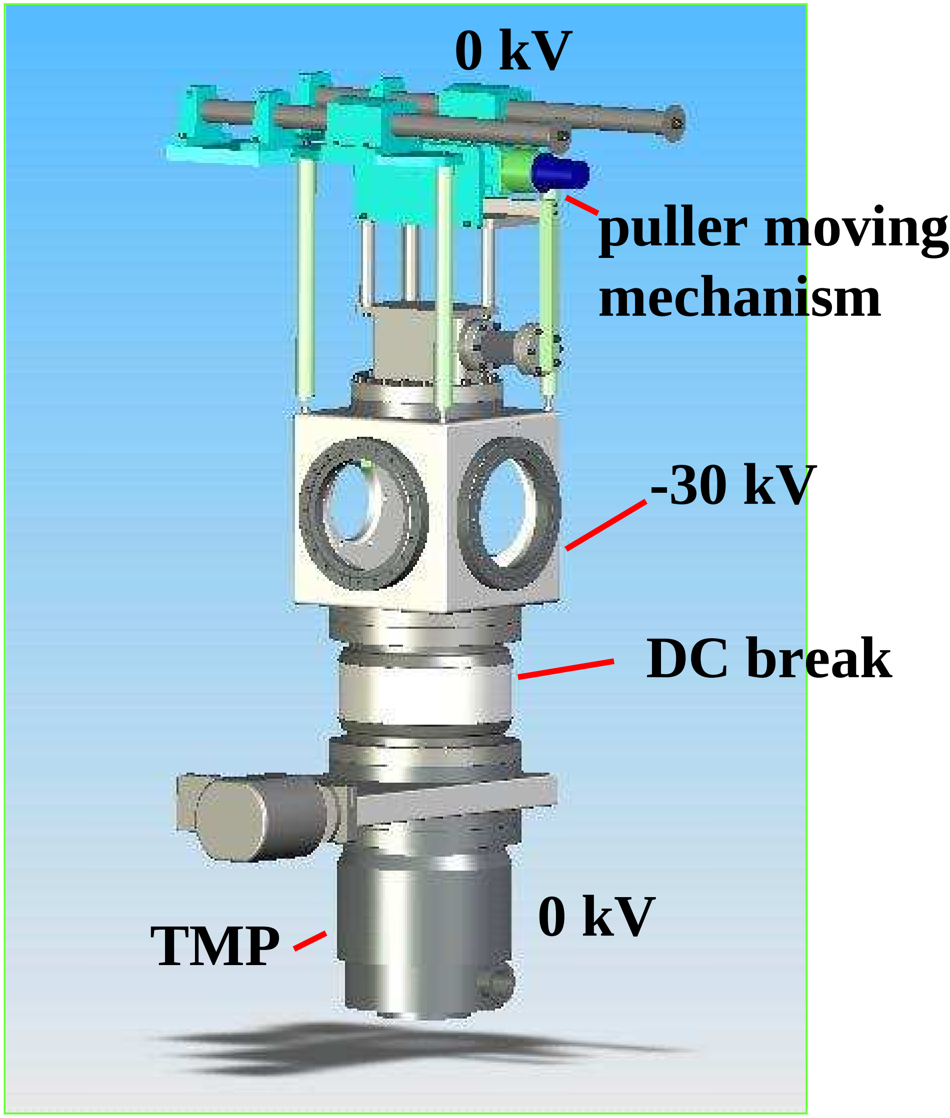
SuSI commissioning started in January 2007

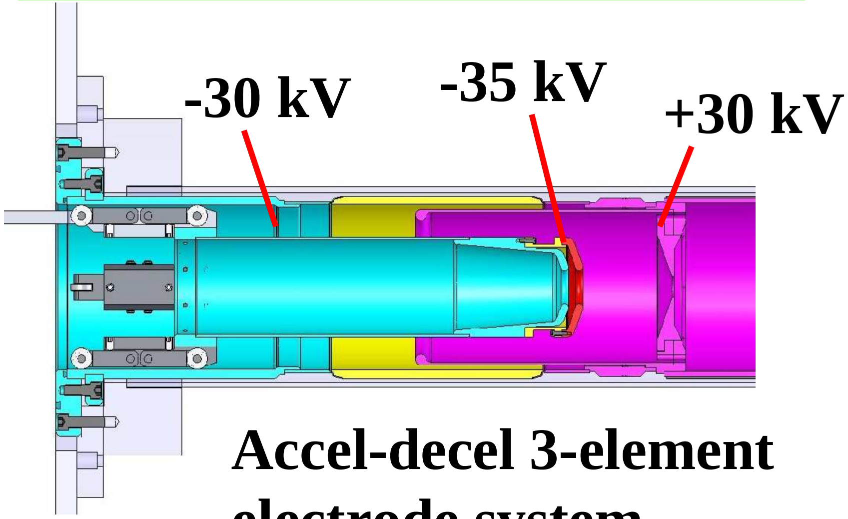
SuSI Injection Side and Plasma Chamber

Movable injection hardware with two microwave waveguides

- Testing at high voltage the plasma chamber with the electric isolation around
- also visible the spare plasma chamber with electric insulator removed

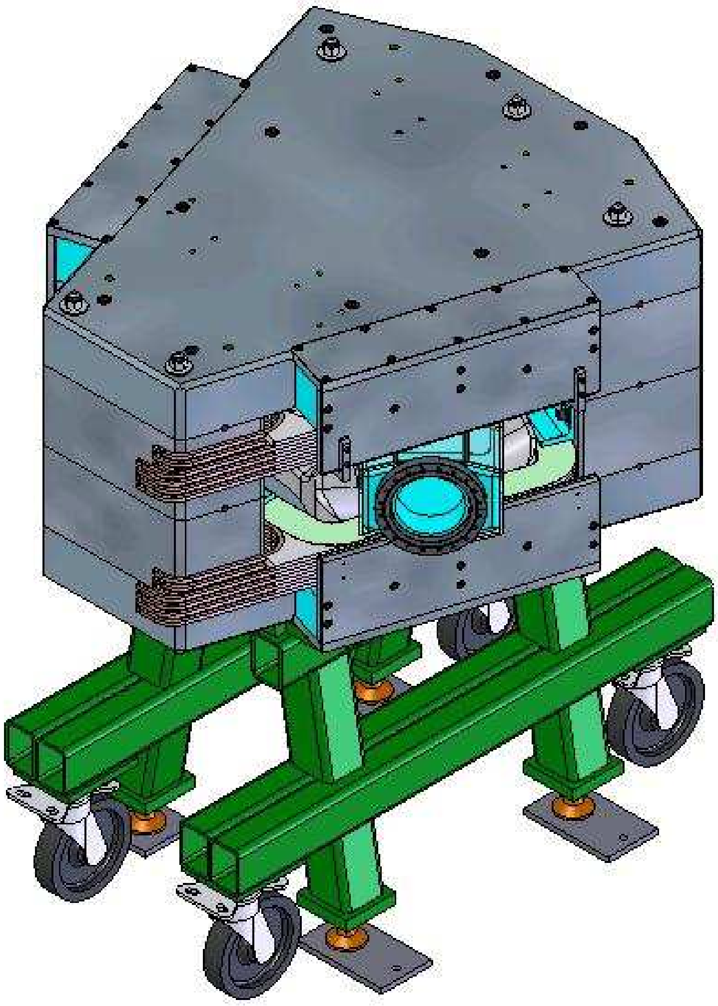
SuSI Extraction Side

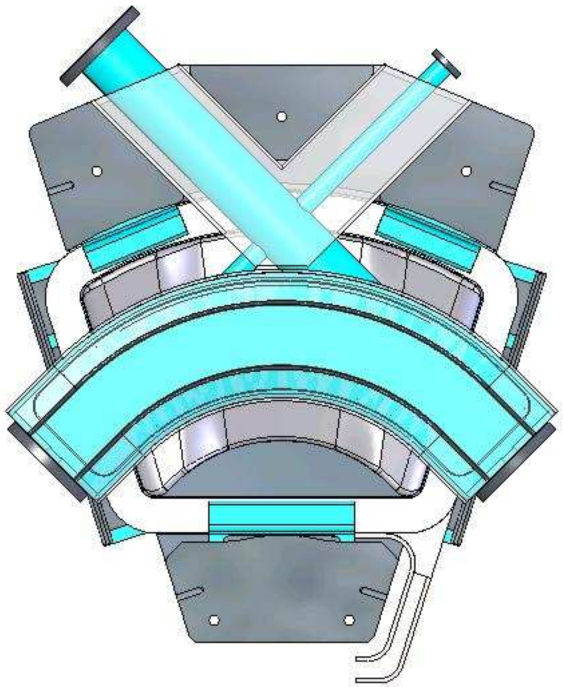




Accel-decel 3-element electrode system

90º Analyzing Magnet I.

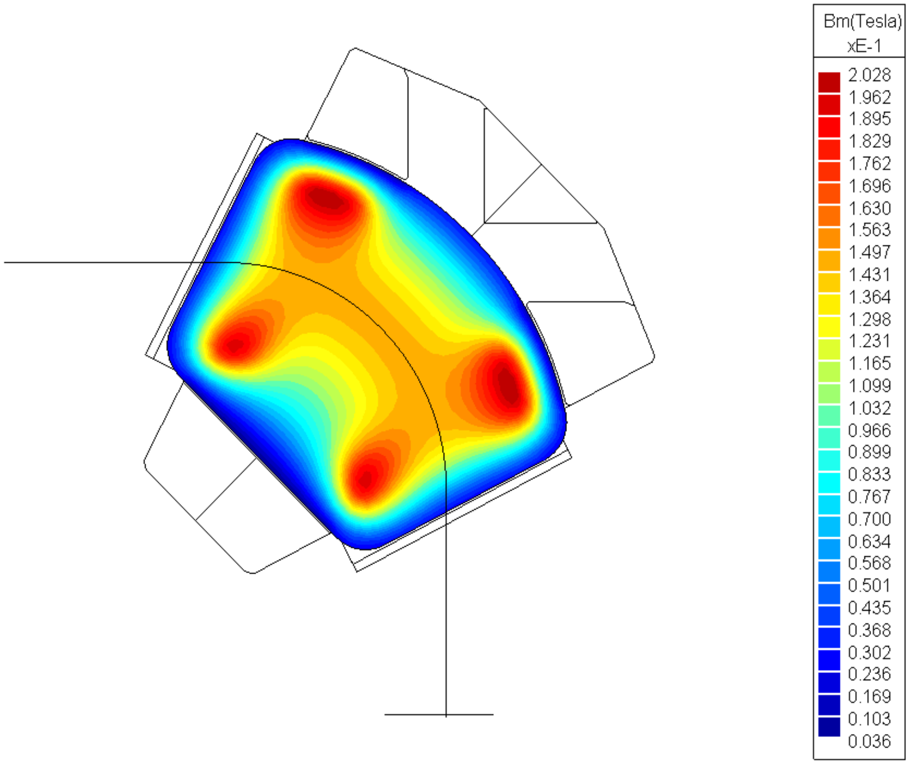




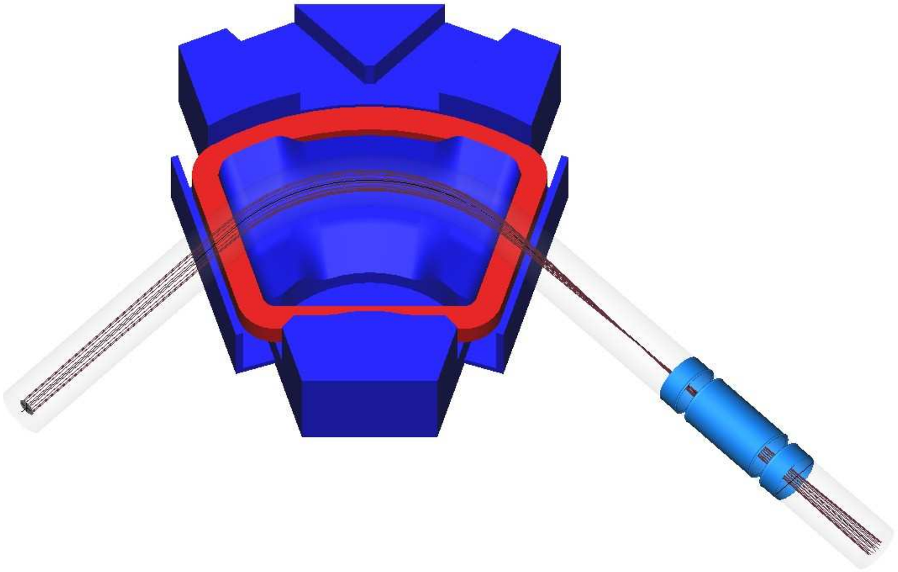
- vacuum chamber is electrically isolated from the rest of the magnet

Based on the LBL VENUS analyzing magnet design (M. Leitner)

90° Analyzing Magnet II.



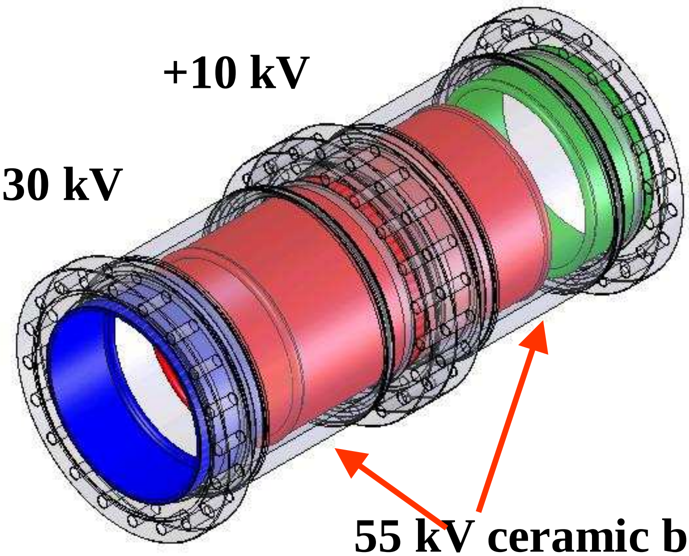
Midplane magnetic field contours



$^{48}Ca^{8+}$ beam through the analyzing magnet and the decelerator Einzel lens

- **initial beam energy: 60 kV*8=480 keV**
- **final beam energy: 30 kV*8=240 keV**

Beamline Elements



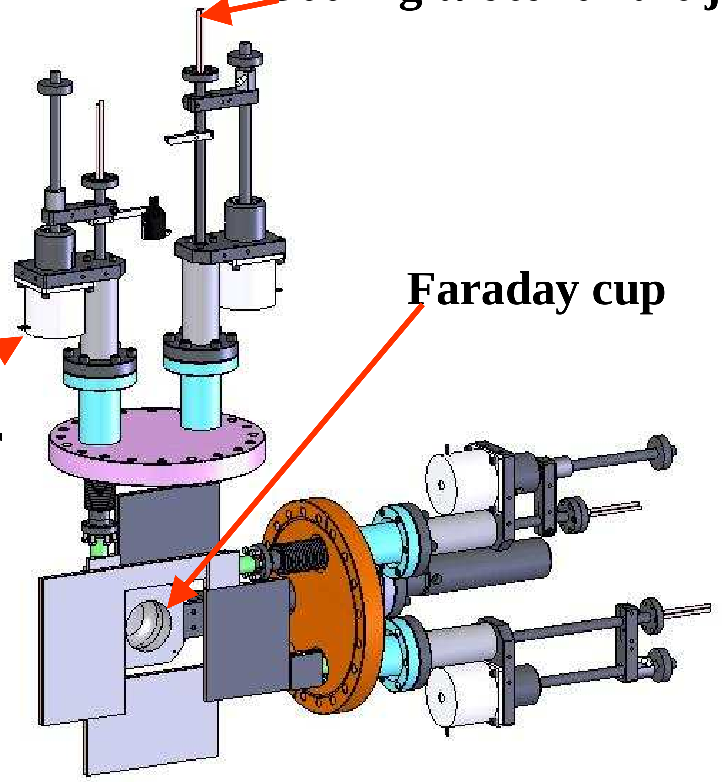
0 kV

+10 kV

-30 kV

55 kV ceramic breaker

Decelerator Einzel lens



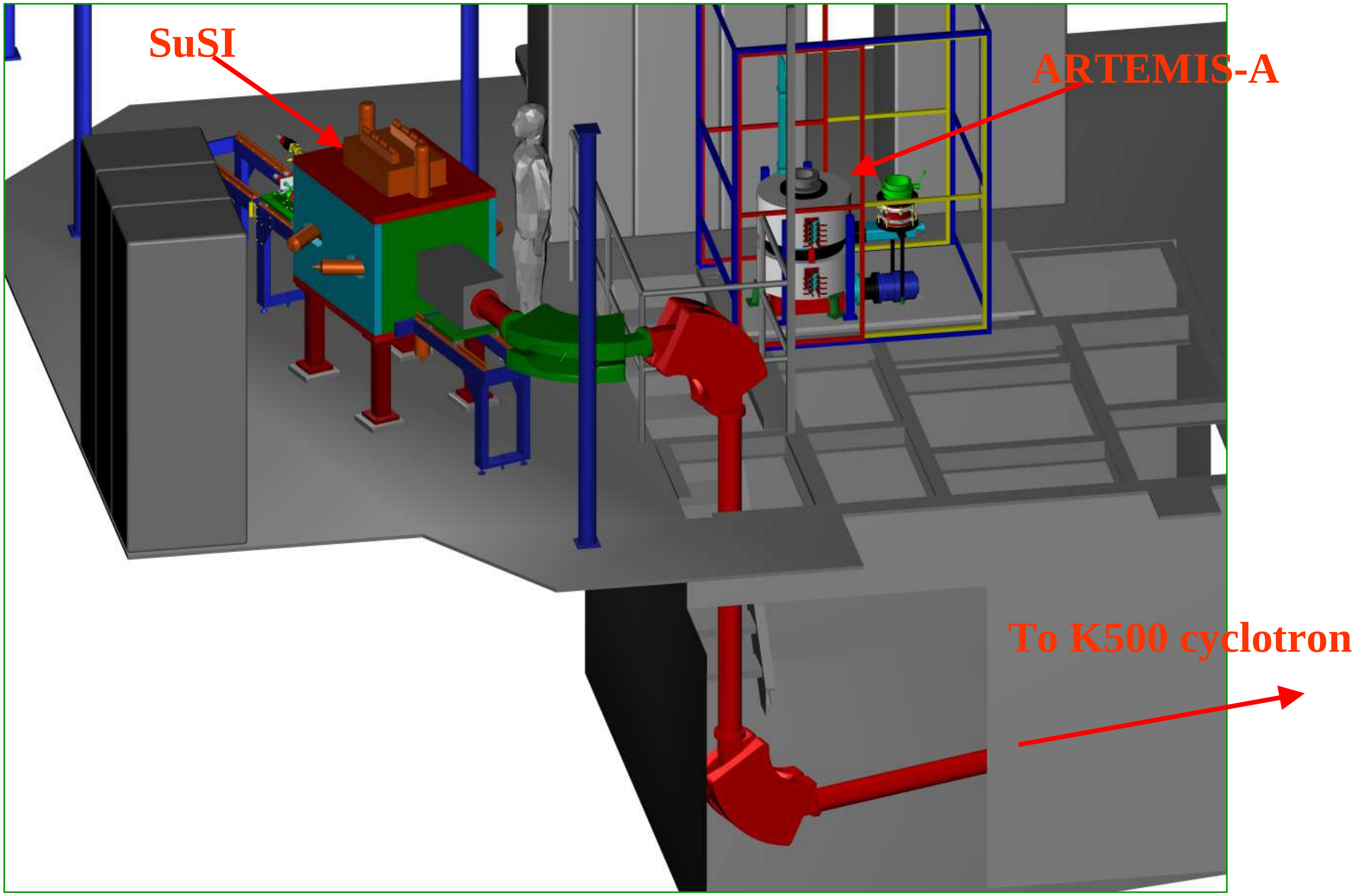
Cooling tubes for the jaw

Faraday cup

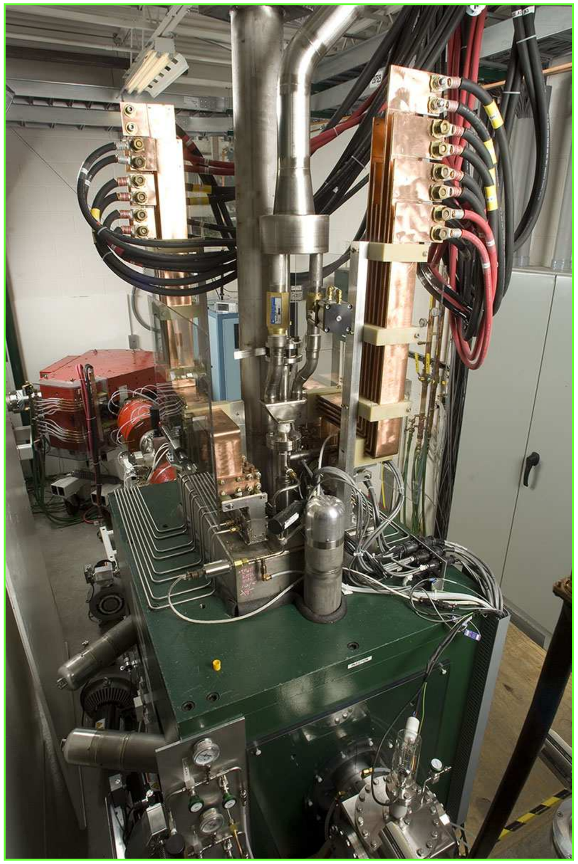
Stepper motor

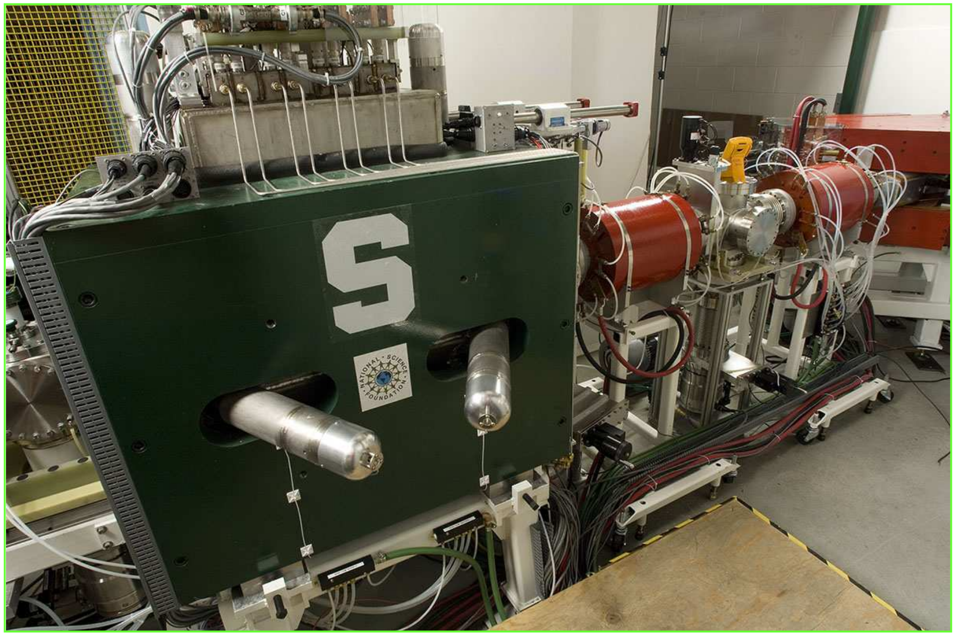
4-jaw slit system (max. opening: 90x90 mm) with Faraday cup (mounted in a 6-way cross, 8” CF)

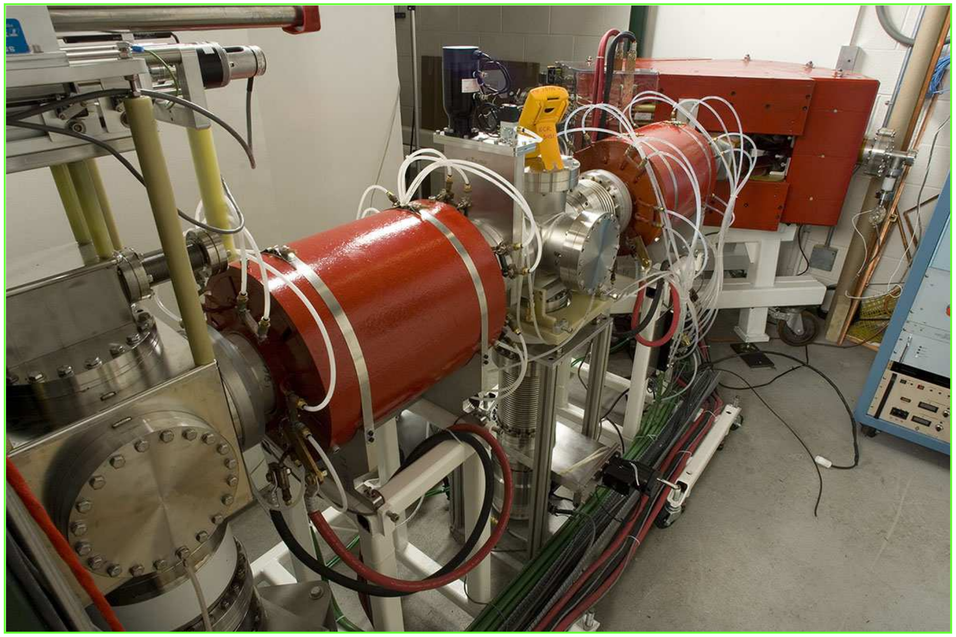
The Floor Layout for SuSI in the Production Area



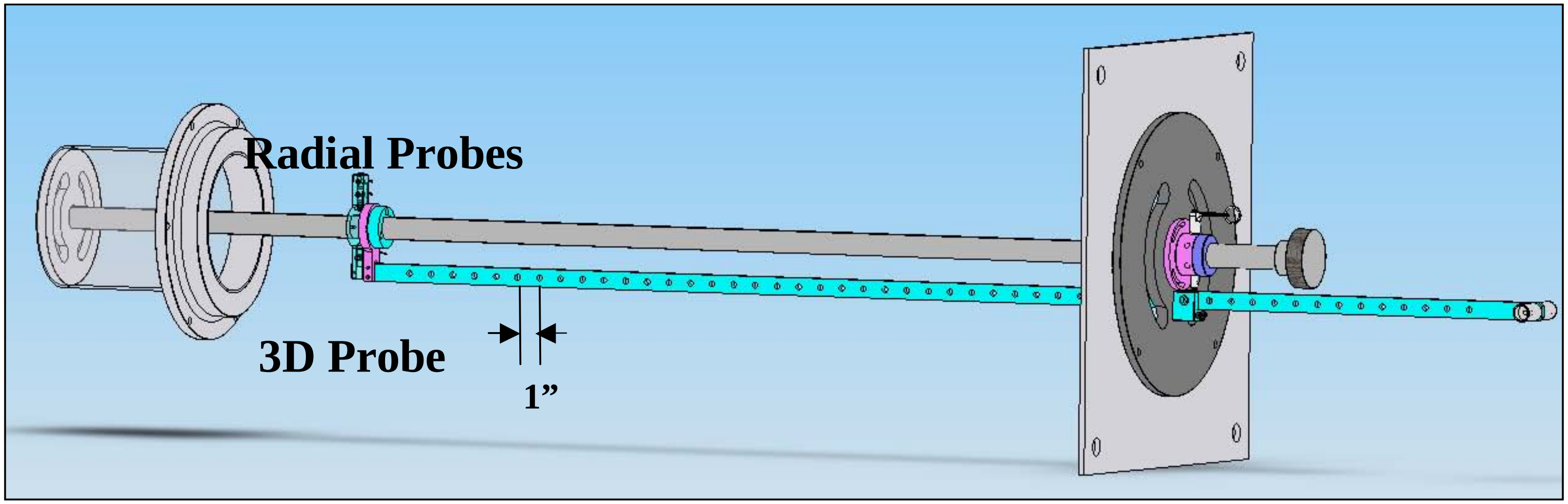
SuSI photos

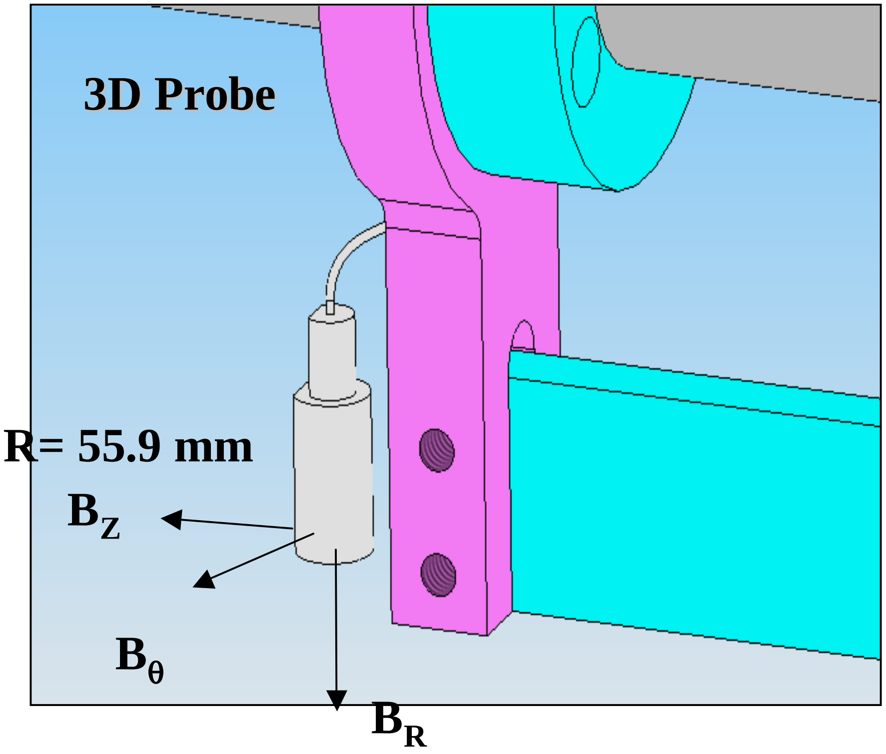


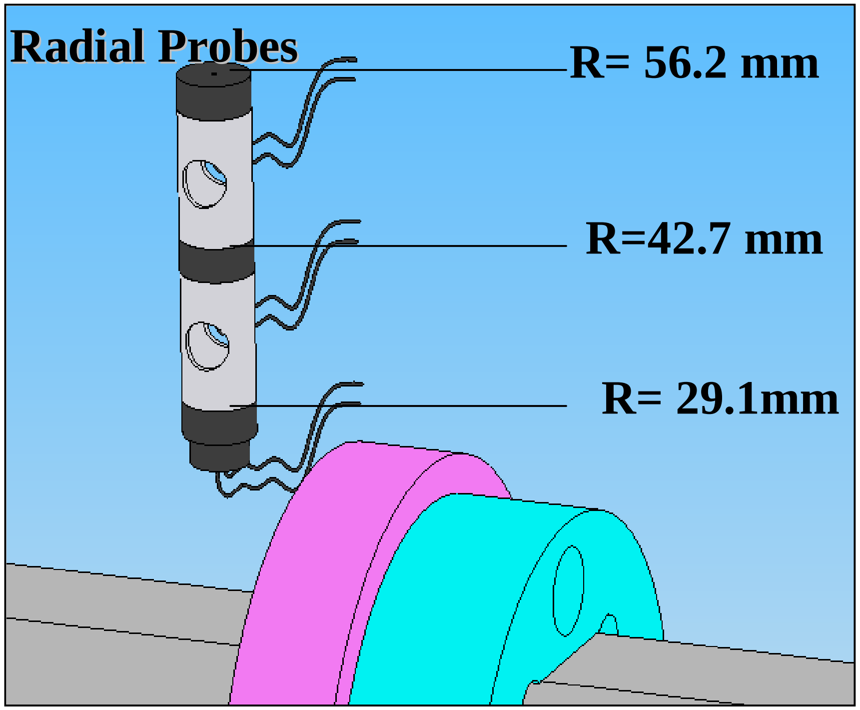




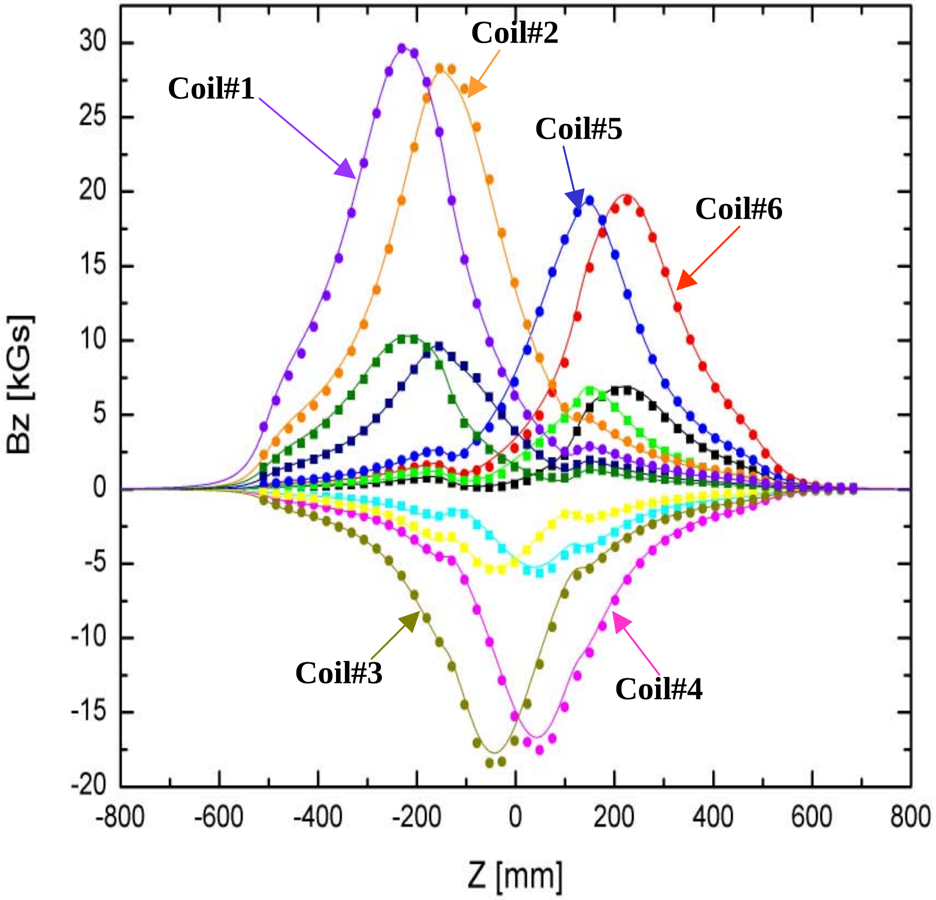
Mapping the magnet I.







Mapping the magnet II. (solenoids)



Magnetic field maps of the individual solenoid

Lines – calculated values with AMPERE

Dots – measured values

Each coil was mapped at 100 and 300 Amp

Magnetic field maps of all solenoids

Lines – calculated values with AMPERE

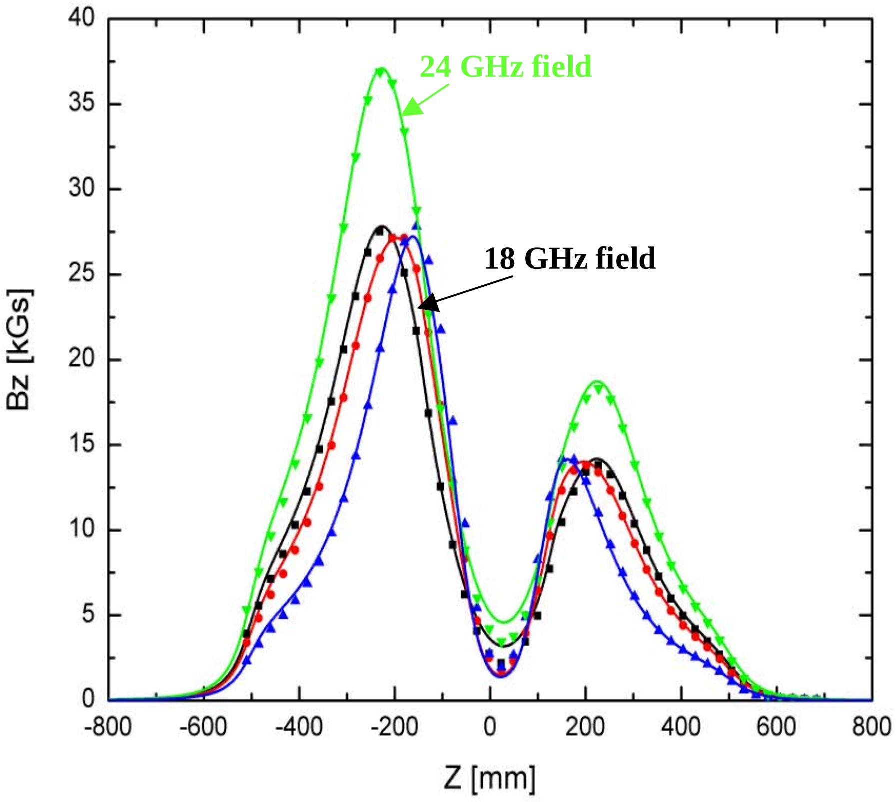
Dots – measured values

Black: 290, 0, -50, -50, 0, 210 Amp

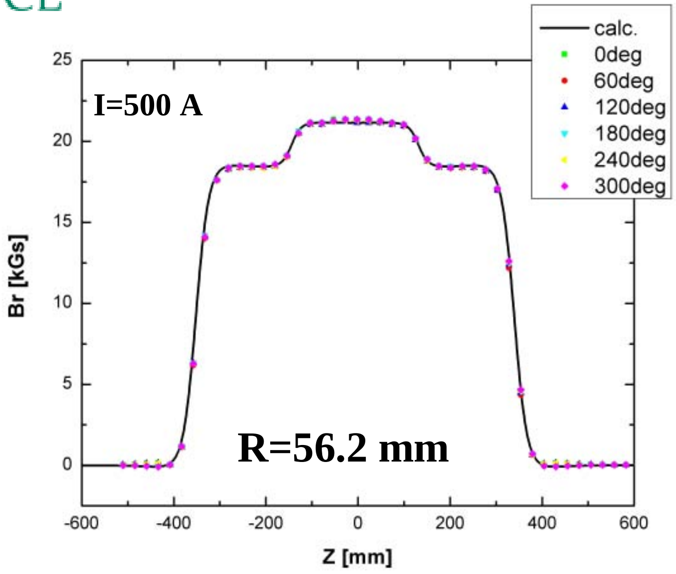
Red: 175, 175, -130, -130, 135, 135 Amp

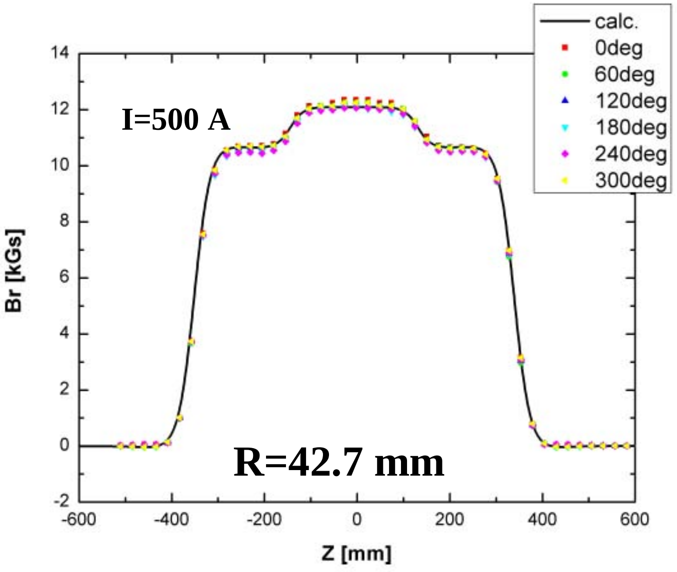
Blue: 0, 390, -220, -220, 320, 0 Amp

Green: 390, 0, -66, -66, 0, 280 Amp

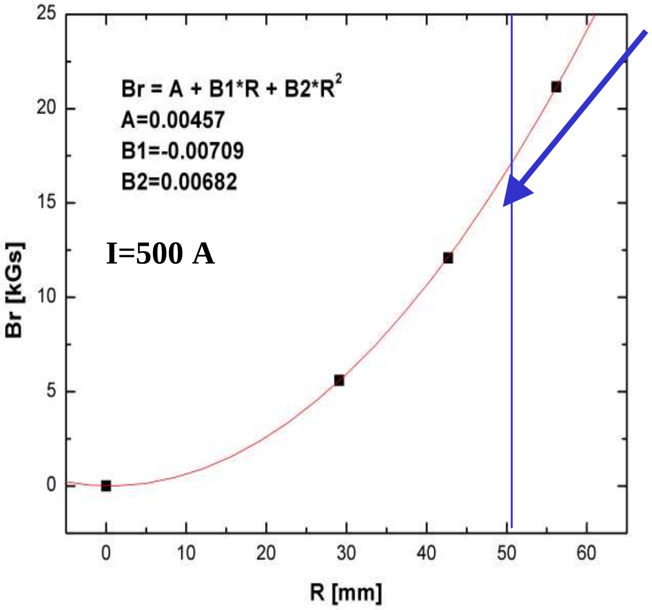


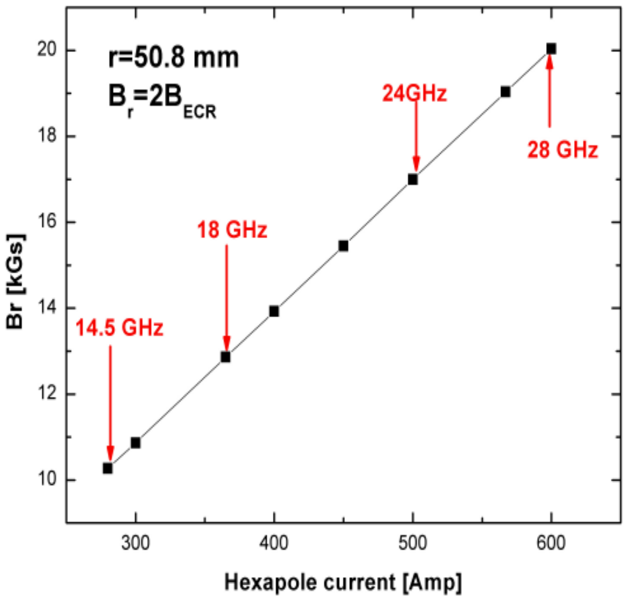
Mapping the magnet III. (hexapole)



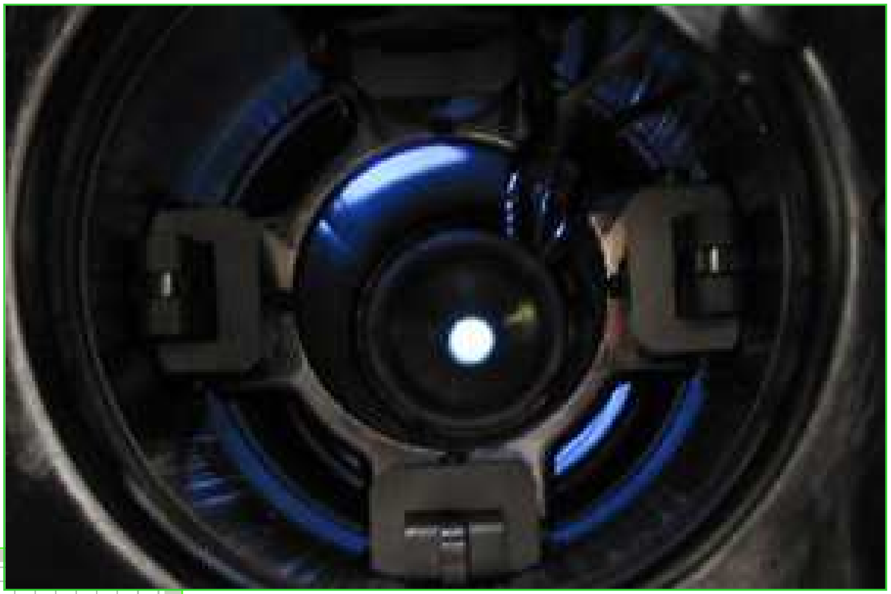


Plasma chamber wall

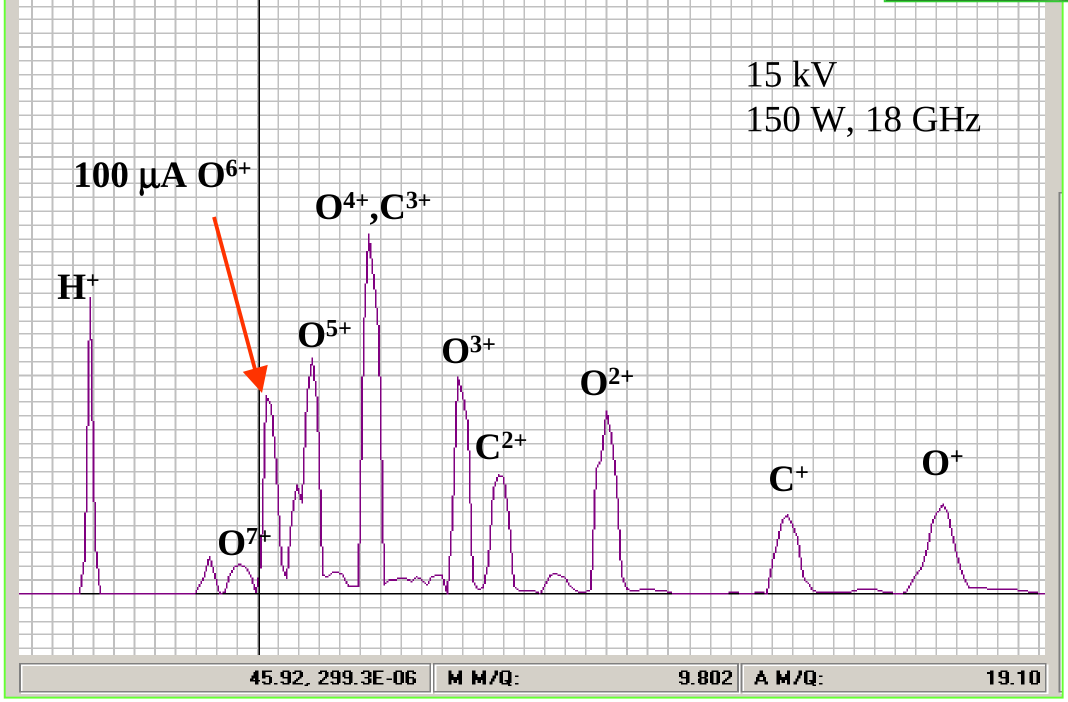




SuSI First plasma ignited on March 29, 2007



SuSI First charge state distribution obtained on June 8, 2007



45.92, 299.3E-06 | M M/Q: 9.802 | A M/Q: 19.10

NSCL People Involved in ECRIS Design and R&D

Ion Source Physicists:

Dallas Cole
Guillaume Machicoane
Larry Tobos
Peter Zavodszky

Accelerator Physicists:

Marc Doleans
Felix Marti
Peter Miller
Jeff Stetson
Mathias Steiner
Xiaoyu Wu
Qiang Zhao

Mechanical Engineers:

Ben Arend
Jim Moskalik
Jack Ottarson

Electronic and RF Engineers:

Kelly Davidson
Bill Nurnberger
John Vincent

SC magnet technology:

Jon DeKamp
Scott Hitchcock
Al Zeller

Acknowledgment

Many thanks for the generous help with material for some of the slides:

- **S. Biri** – ATOMKI, Debrecen, Hungary
- **S. Gammino** – INFN-LNS, Catania, Italy
- **D. Hitz** – CEA, Genoble, France
- **D. Leitner, C. Lyneis** – LBNL, Berkeley, CA, USA

T. Nakagawa – RIKEN, Tokyo, Japan