Joint Accelerator School - 08
RRCAT, Indore
January 14, 2008

High Temperature Superconducting ECR Ion Source (HTS-ECRIS)

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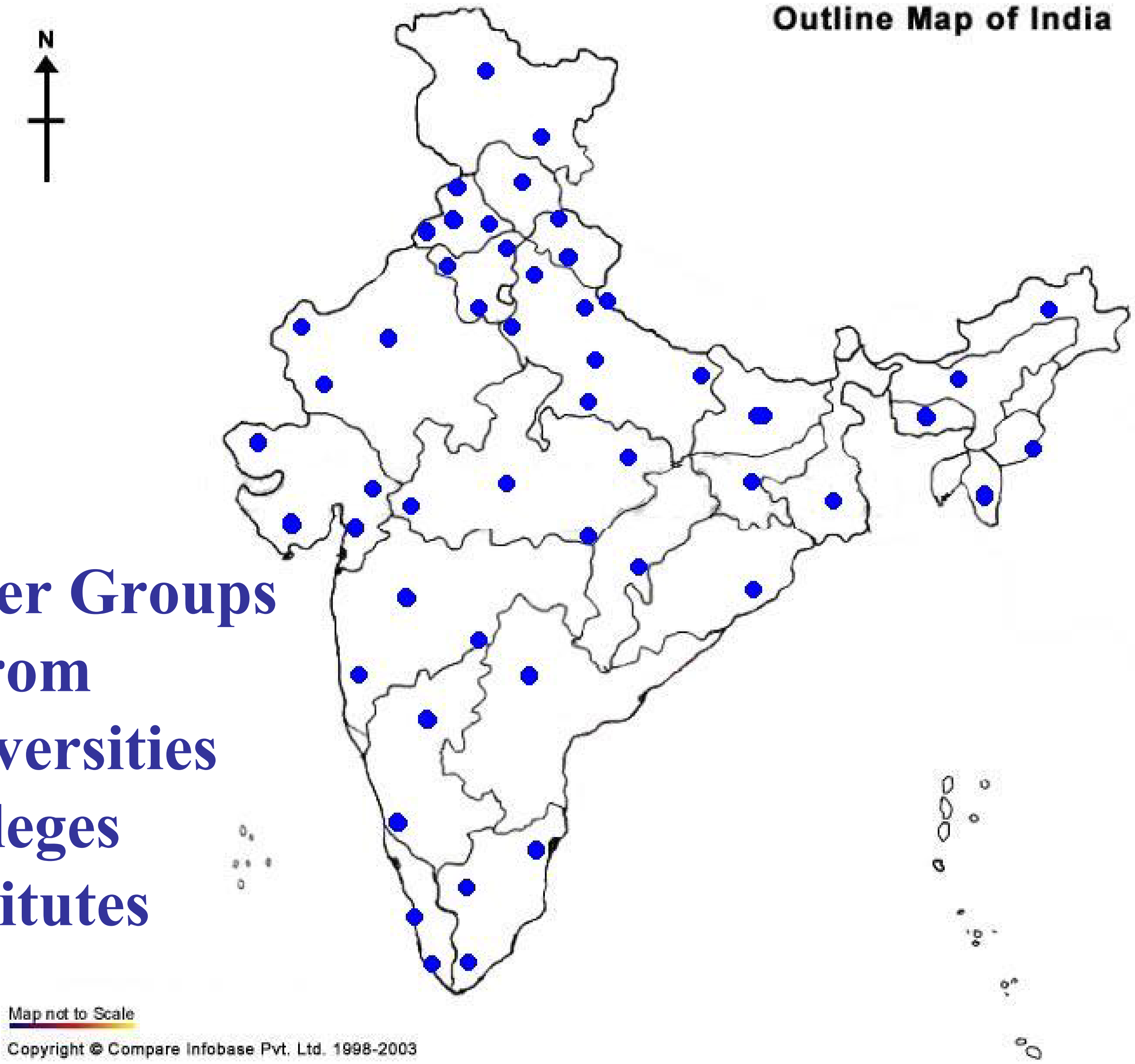
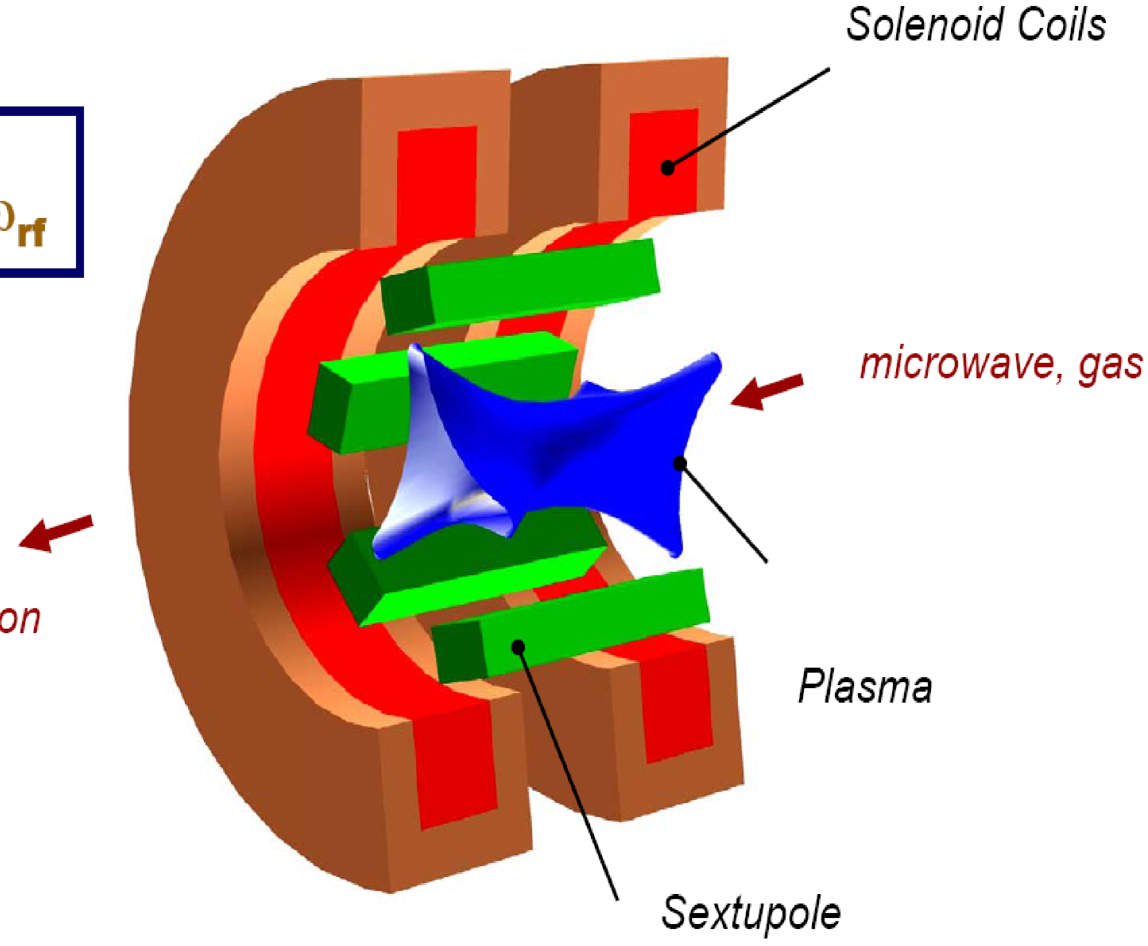
User Community of IUAC



300 User Groups
from
76 Universities
44 Colleges
45 Institutes

Principle of Electron Cyclotron Resonance Ion Source (ECRIS)

$\omega_e = eB/m = \omega_{rf}$



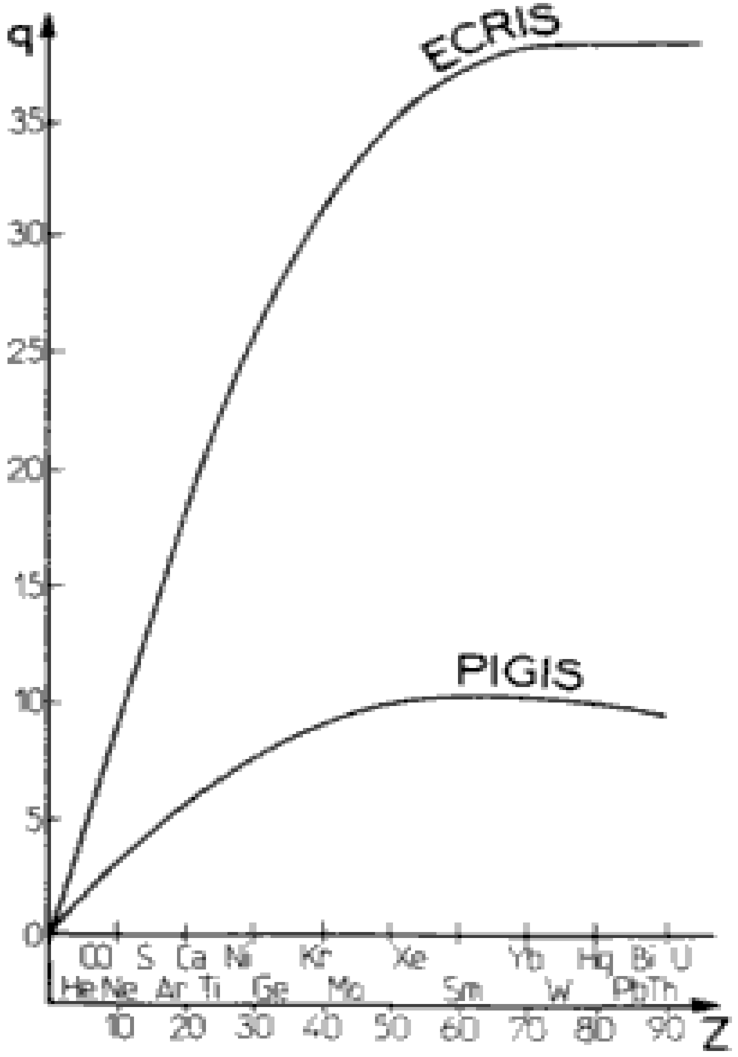
Electron cyclotron resonance:

An electron in a static and uniform magnetic field will move in a circle due to the Lorentz force. The circular motion may be superimposed with a uniform axial motion, resulting in a helix, or with a uniform motion perpendicular to the field, e.g., in the presence of an electrical field, resulting in movement along a cycloid. The angular frequency ($\omega = 2\pi f$) of this *cyclotron* motion for a given magnetic field strength *B* is given (in SI units) by

$$\omega_{ce} = \frac{eB}{m}$$

.

where *e* is the elementary charge and *m* is the mass of the electron. For the commonly used microwave frequency 2.45 GHz and the bare electron charge and mass, the resonance condition is met when *B* = 875 G = 0.0875 T.

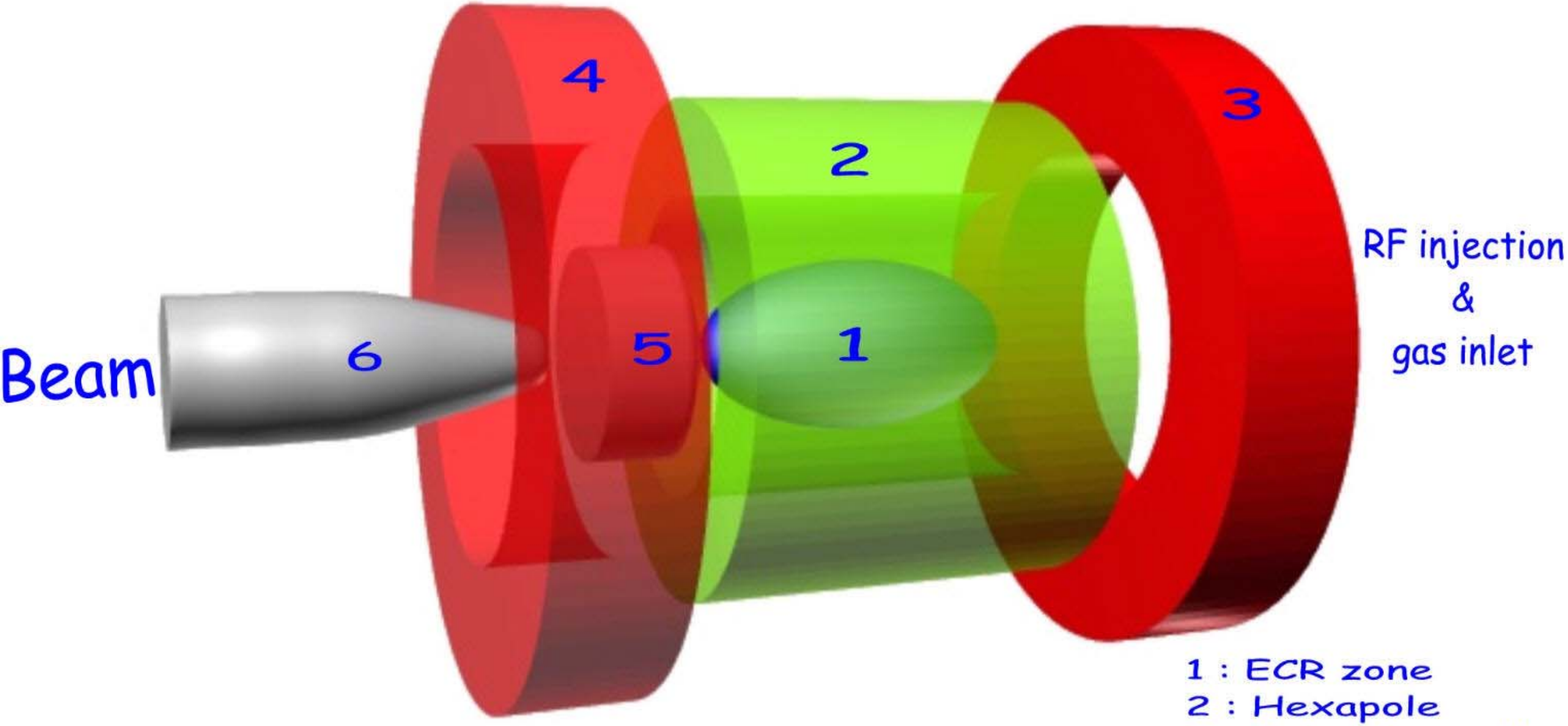


Comparison of charge states available from PIGIS and ECRIS

Ref: Electron Cyclotron Resonance Ion Sources and ECR Plasmas by R Geller

ECR ION SOURCE

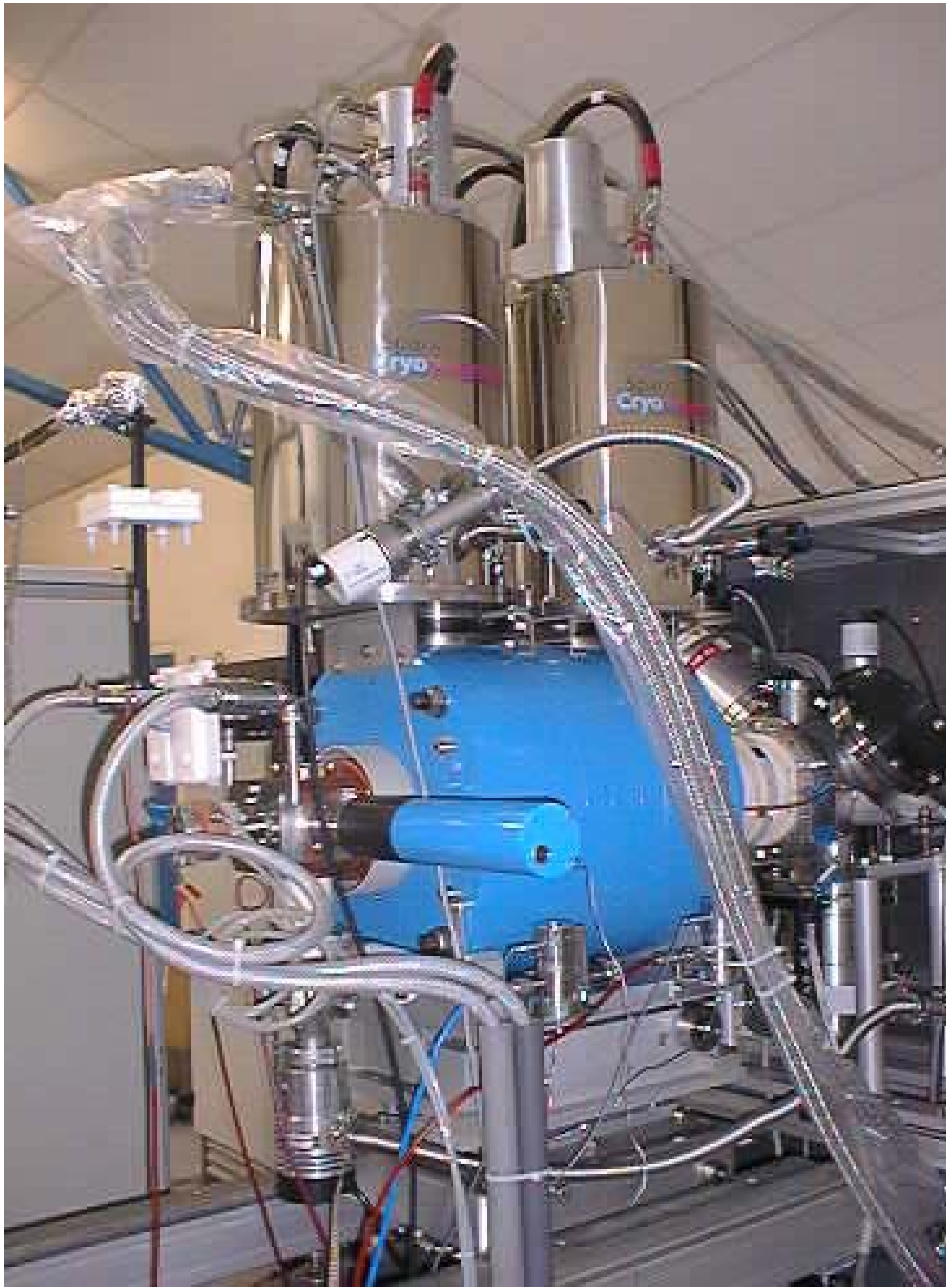
PKDELIS

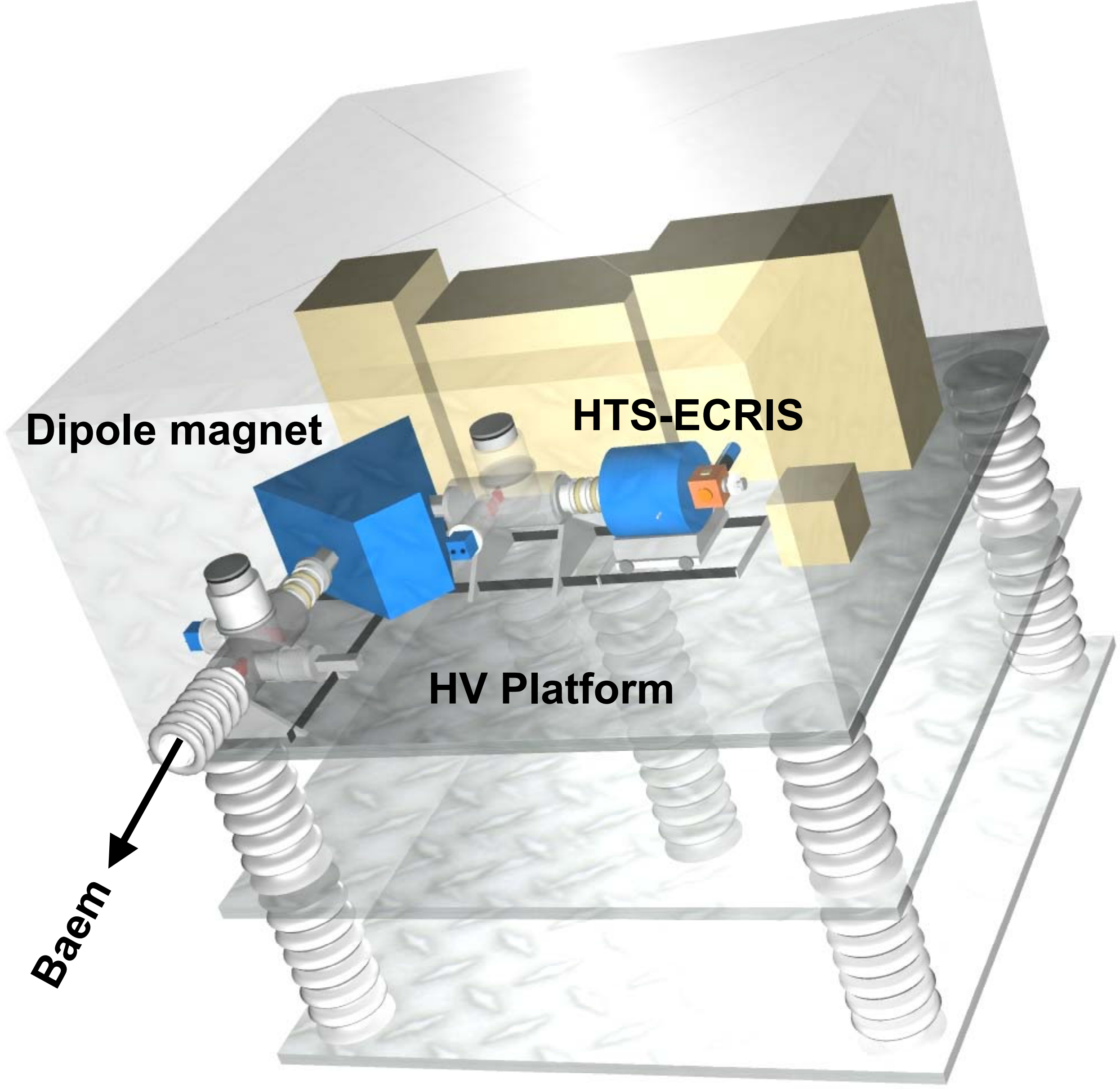


1 : ECR zone
2 : Hexapole
3 : Injection coil
4 : Extraction coil
5 : Plasma lens
6 : Puller

HTS-ECR Ion Source PKDELIS

ECR ION SOURCE PKDELIS





HTS-ECRIS on a high voltage platform

VARIOUS CHOICES FOR COOLING

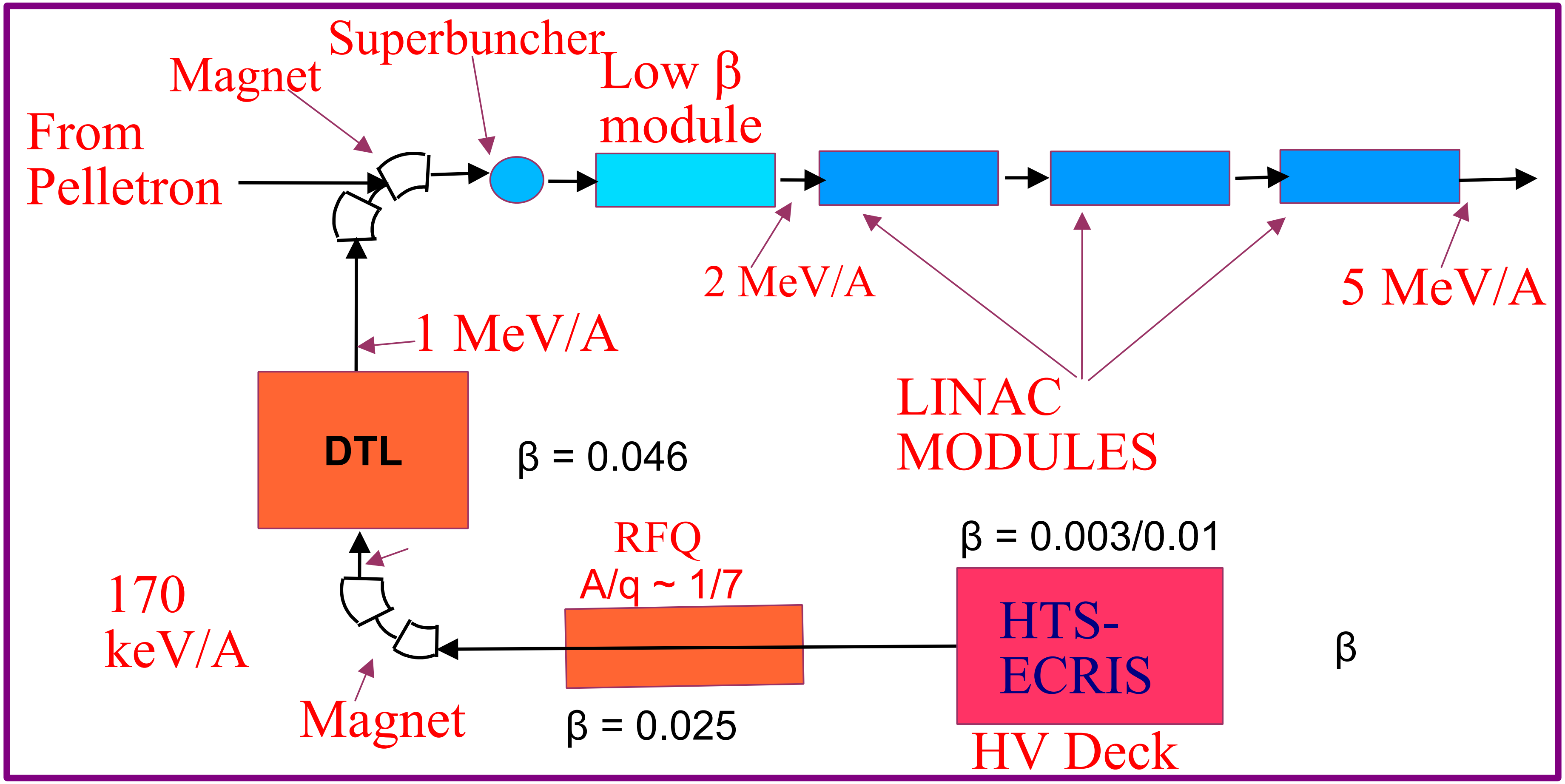
- Use liquid helium to cool the coils and let it evaporate to atmosphere.

- Recover evaporated helium gas and return this in compressed form.

- Use of gaseous helium and a refrigerator producing cooling capacity in closed cycle (GM refrigerator)

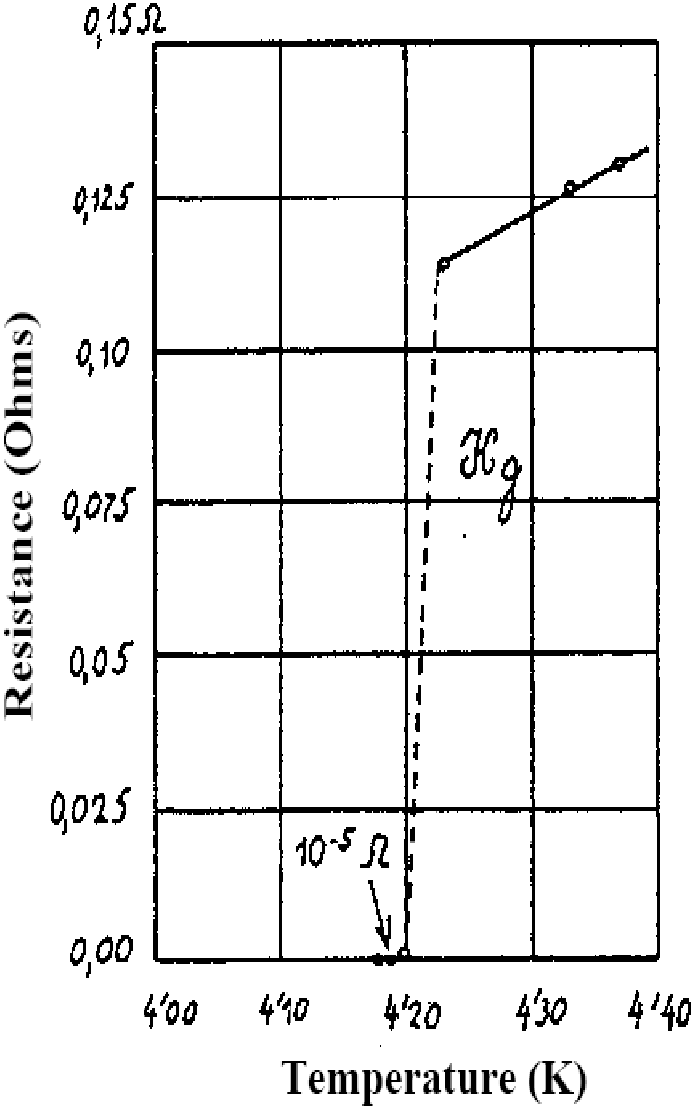
1. **Transfer of cryogenic liquids from ground potential to a high voltage platform is not advisable.**
2. **Operation of a cryogenic system on a high voltage platform is extremely complicated costly and**

HTS-ECRIS based High Current Injector for LINAC



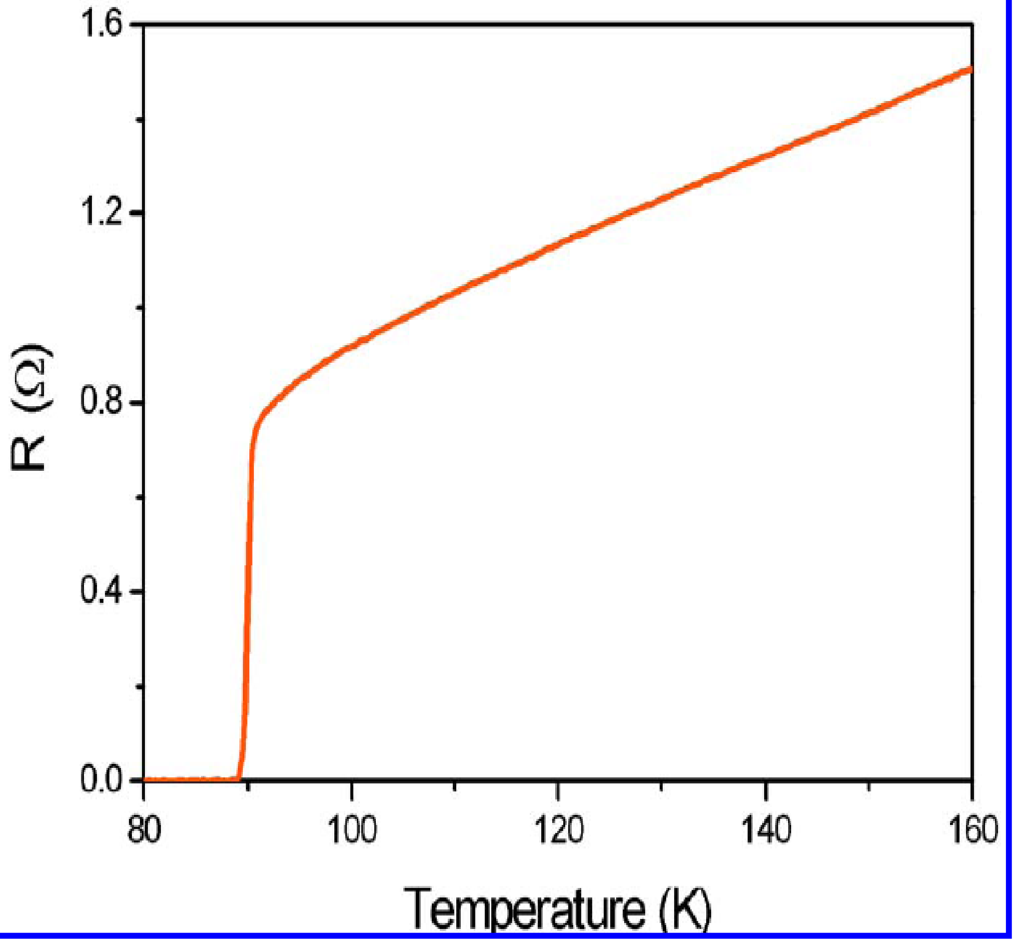
Low Temperature Superconductor Onnes (1911)

Resistance of Mercury falls suddenly below
meas. accuracy at very low (4.2) temperature



New materials (ceramics) loose their resistance
at <u>NOT</u> so low temperatures (Liquid Nitrogen)!

High Temperature Superconductors (1986)



Discovery of high-temperature superconductivity in a new class of ceramic oxides

1987: J. Georg Bednorz,
K. Alex Müller

Mark Cowan / Reuters
Alexander Zemlianichenko / AP
Stephen J. Carrera / AP

2003: Anthony Leggett, Vitaly Ginzburg and Alexei Abrikosov

VARIOUS CHOICES FOR MATERIALS

- BSCCO 2223 (T_c ~ 110 K)
- BSCCO 2212 (T_c ~ 85 K)
- YBCO (T_c ~ 90 K)

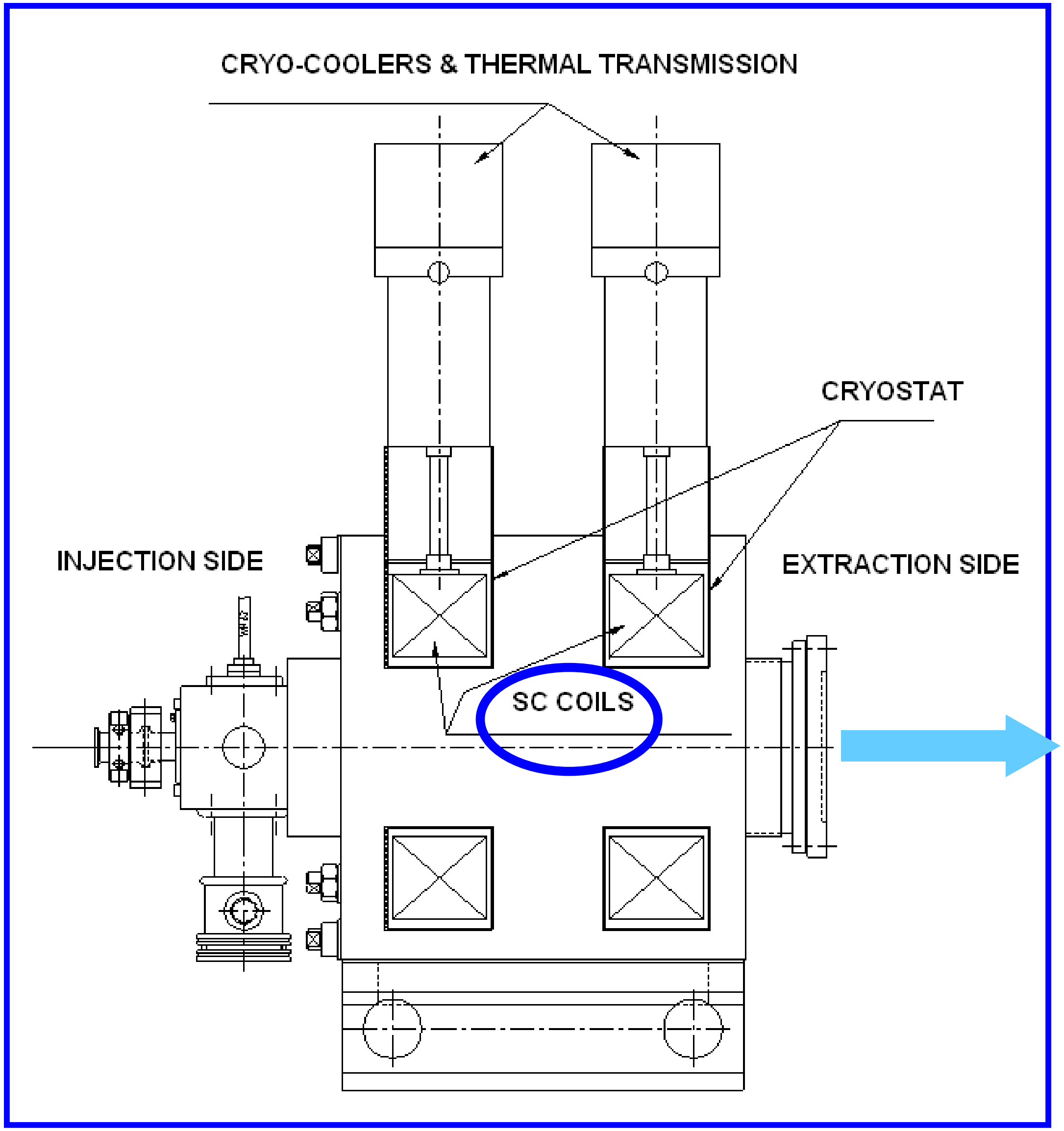
- MgB_2 is a low temperature superconductor (LTS) with critical temperature ~39 K (almost highest possible by current theories).

Of these only BSCCO2212 and BSCCO2223 (1st generation HTS) are now available in sufficient quantities to make accelerator or beam line magnets.

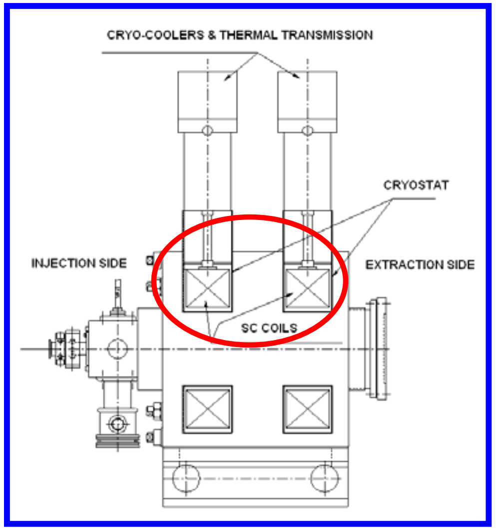
However, the future may lie with YBCO (2nd generation HTS) which, in principle, can be produced at a much lower cost (less Ag). Recent results from industry on 2nd generation HTS are encouraging.

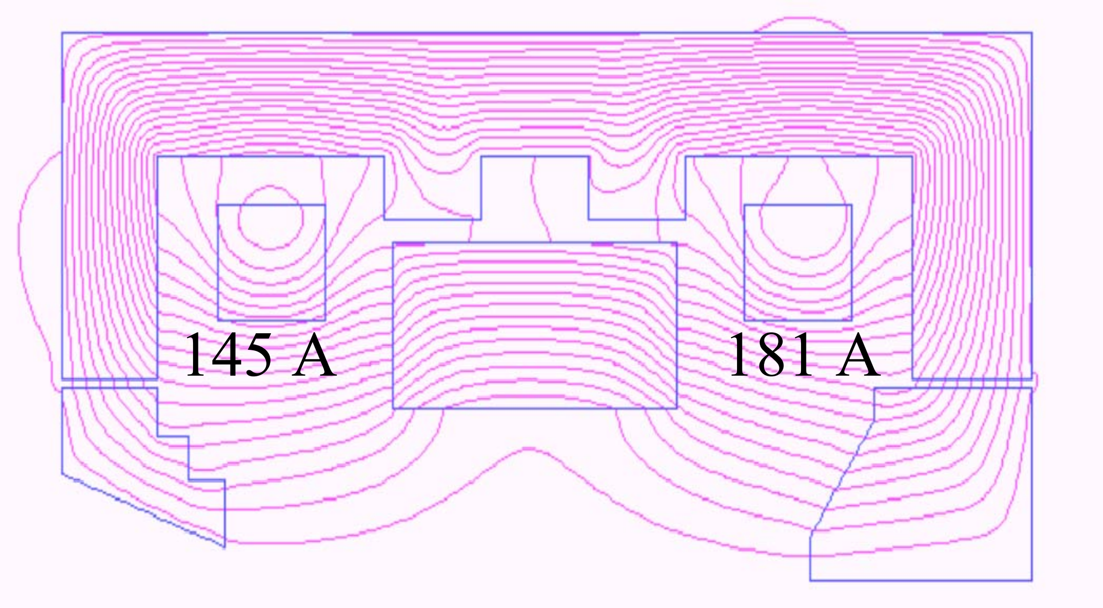
$Bi_2Sr_2Ca_2Cu_3O$ (Bi-2223)

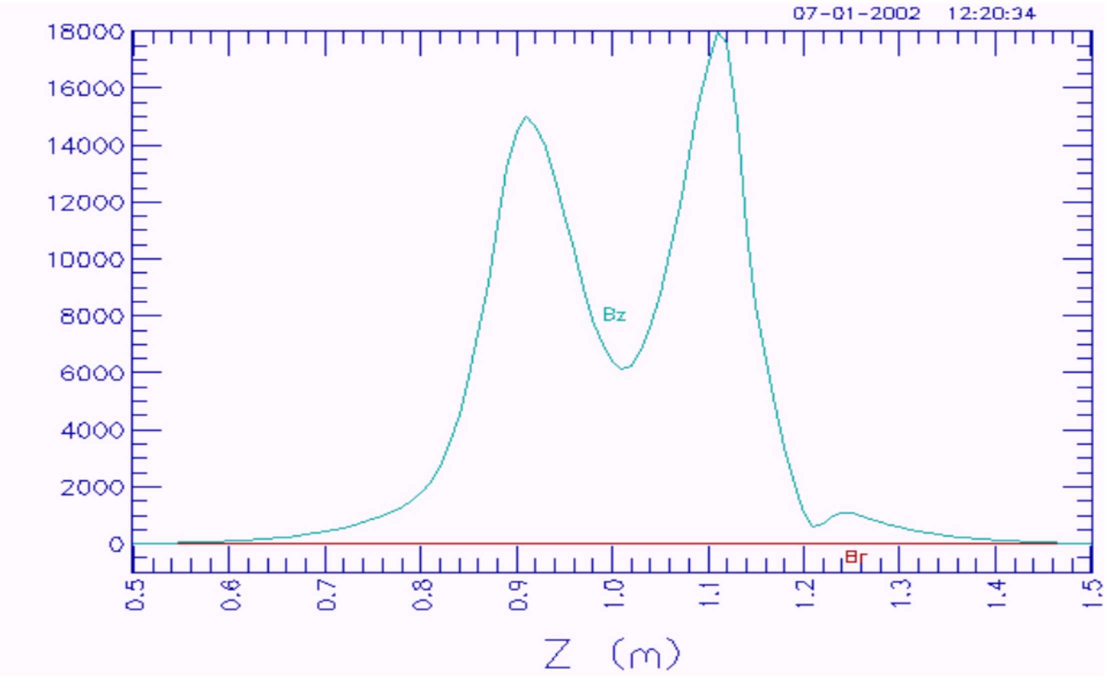
Schematic of ECR Ion Source

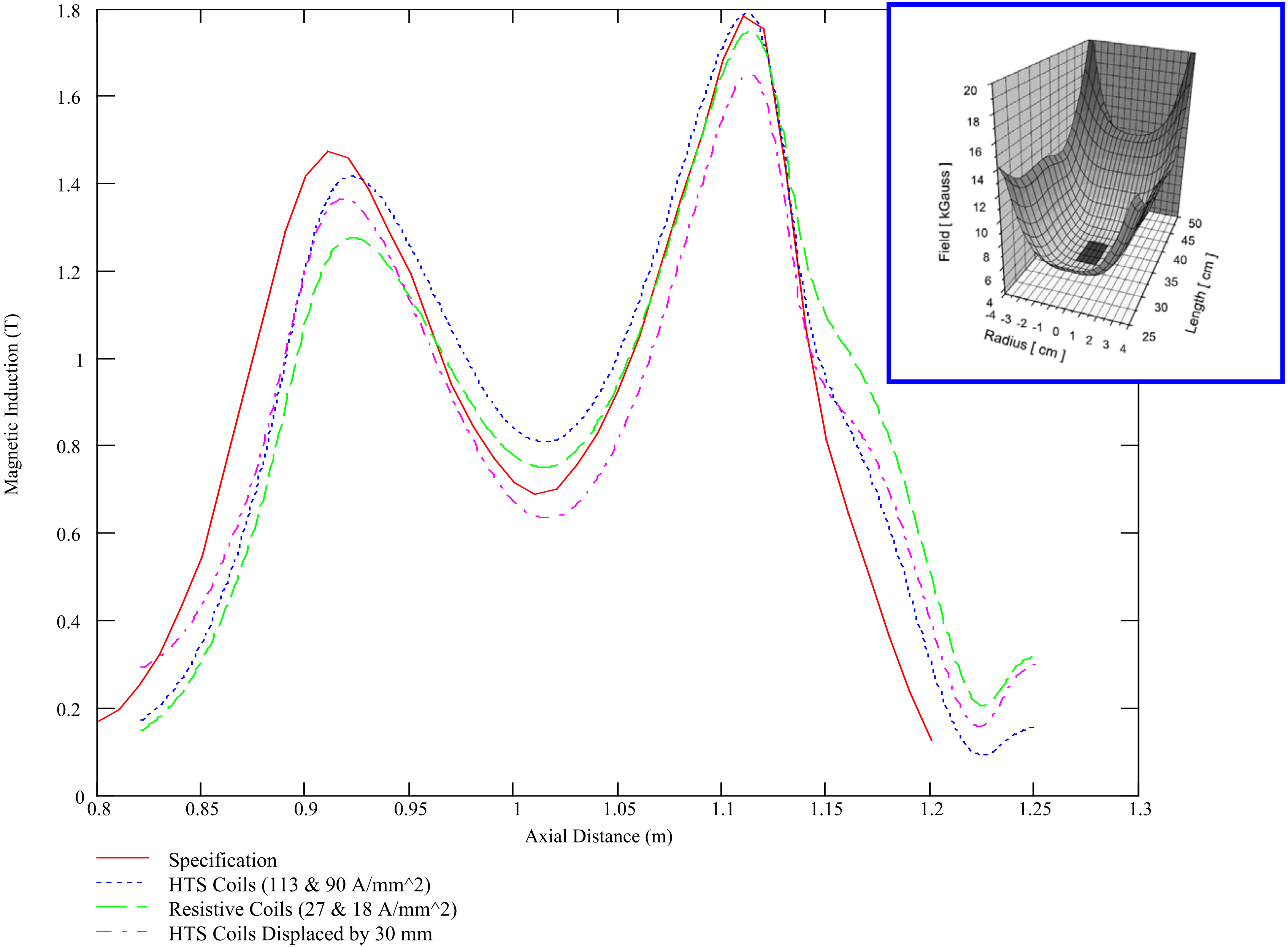


Beam direction

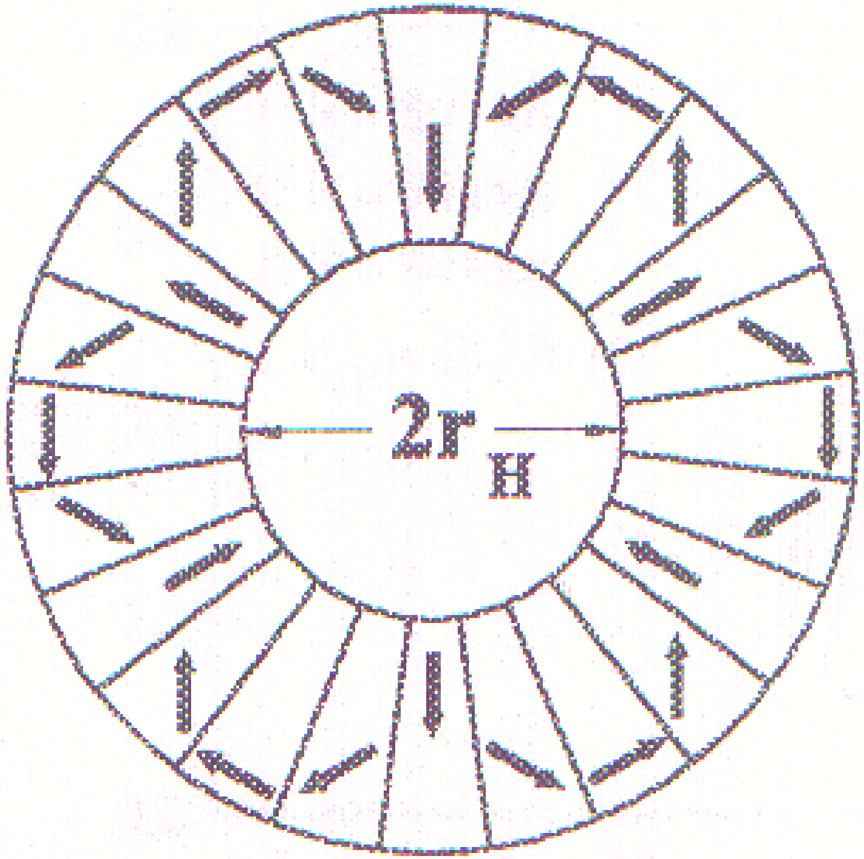

CRYO-COOLERS & THERMAL TRANSMISSION
CRYOSTAT
INJECTION SIDE
EXTRACTION SIDE
SC COILS


145 A
181 A


07-01-2002 12:20:34
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Bz
Br
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
Z (m)

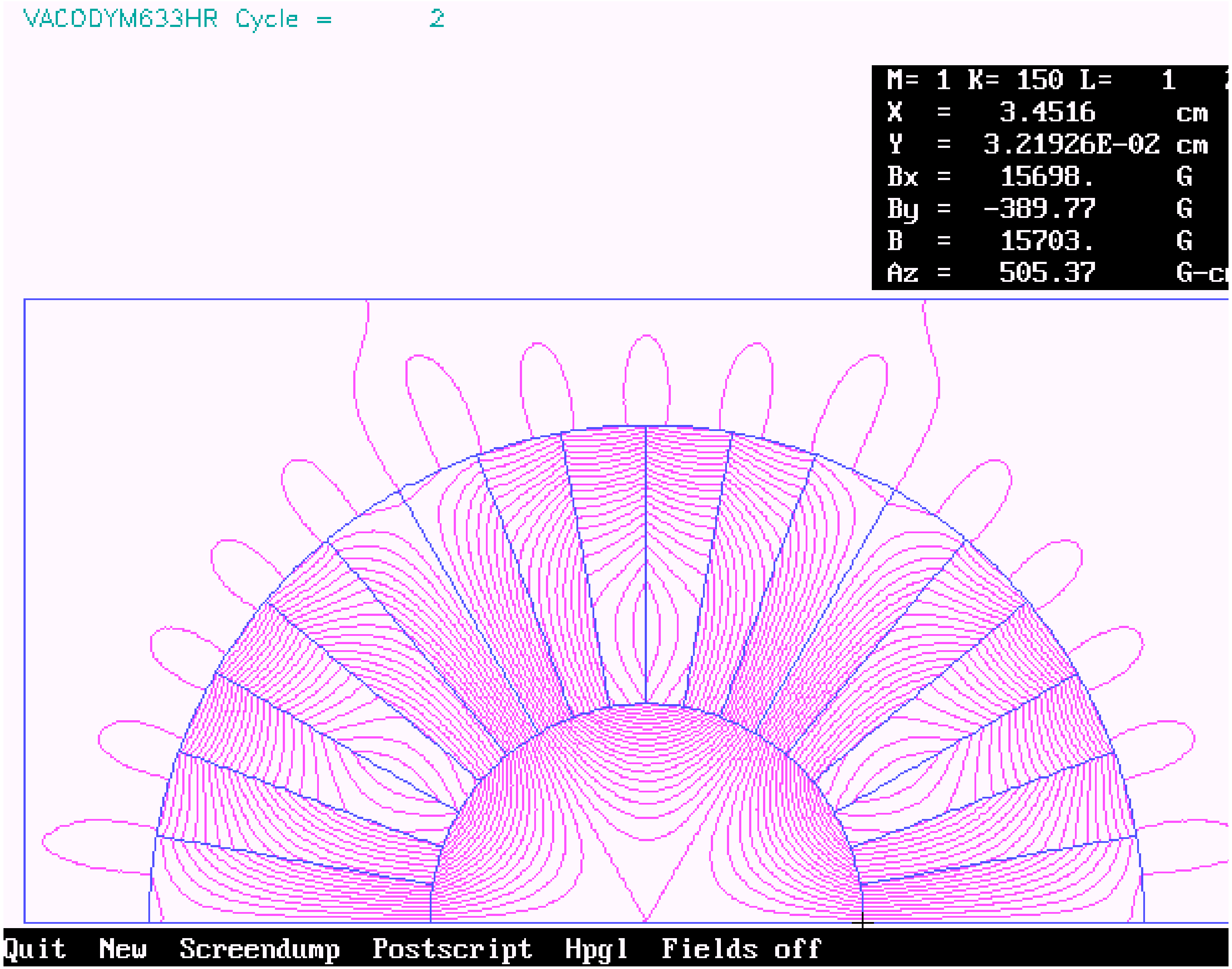


Comparison of simulated and test axial field profiles



Cross-section view of cylindrically symmetric hexapolar Halbach Structure. The arrows denote the direction of magnetisation.

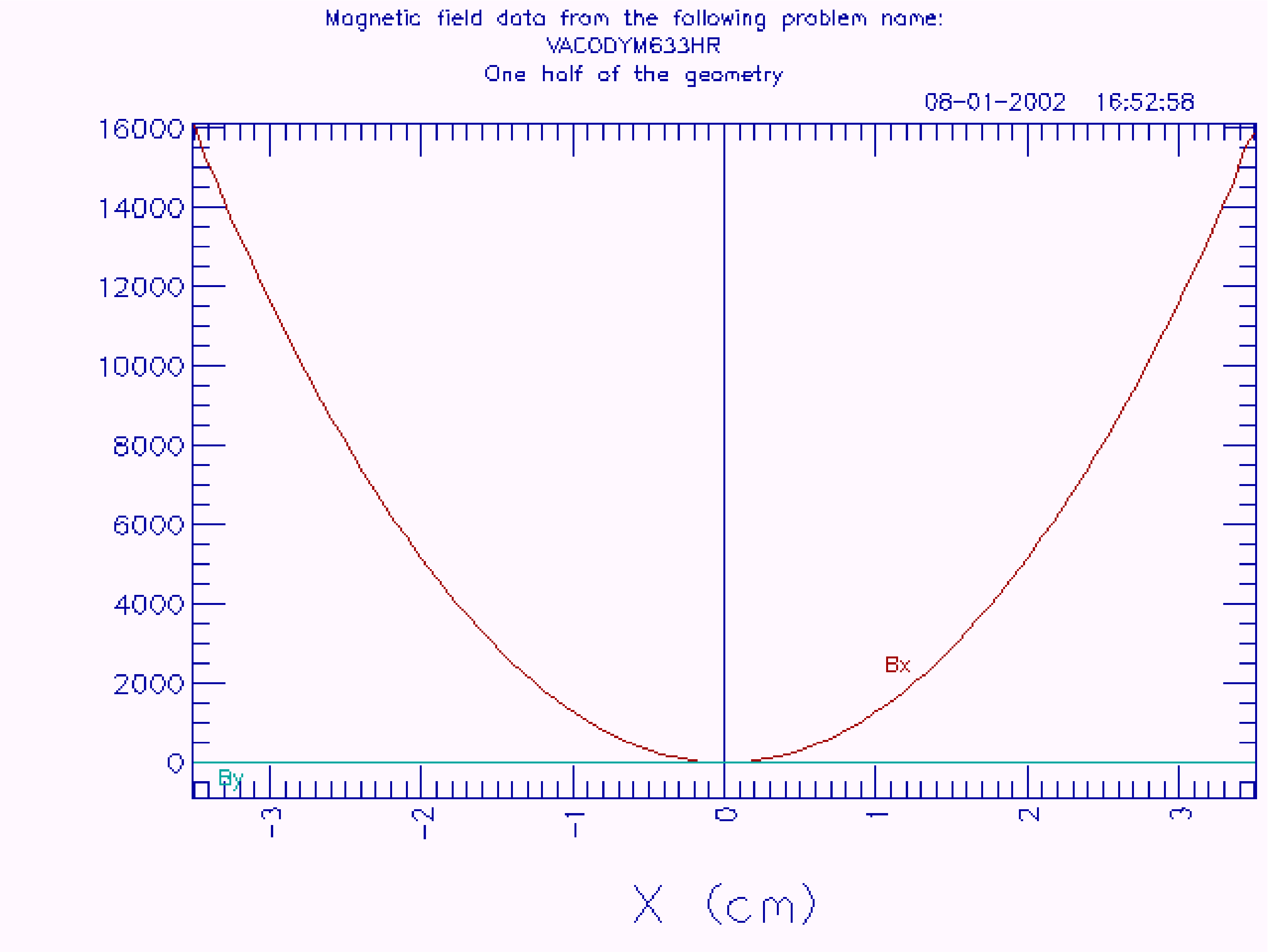
VACODYM 633HR, T_{max} = 110 °C, 36 sectors Halbach type, ID = 35 mm, OD = 80 mm



```
VACODYM633HR Cycle =       2
```

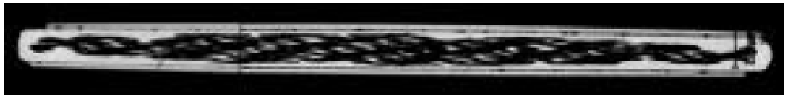
```
M= 1 K= 150 L=    1
X  =    3.4516     cm
Y  =  3.21926E-02 cm
Bx =    15698.     G
By =  -389.77      G
B  =    15703.     G
Az =    505.37     G-c
```

Radial field contours of the hexapole



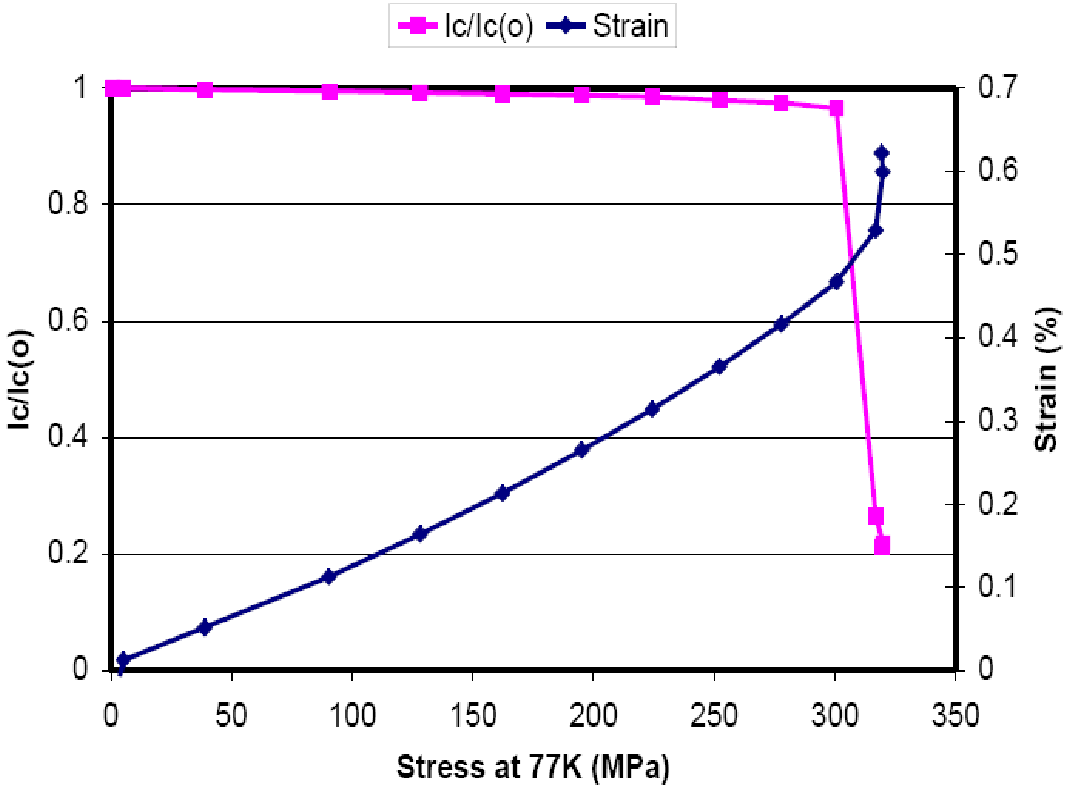
Radial field profile of the hexapole

Bi-2223 High Strength Reinforced Tape

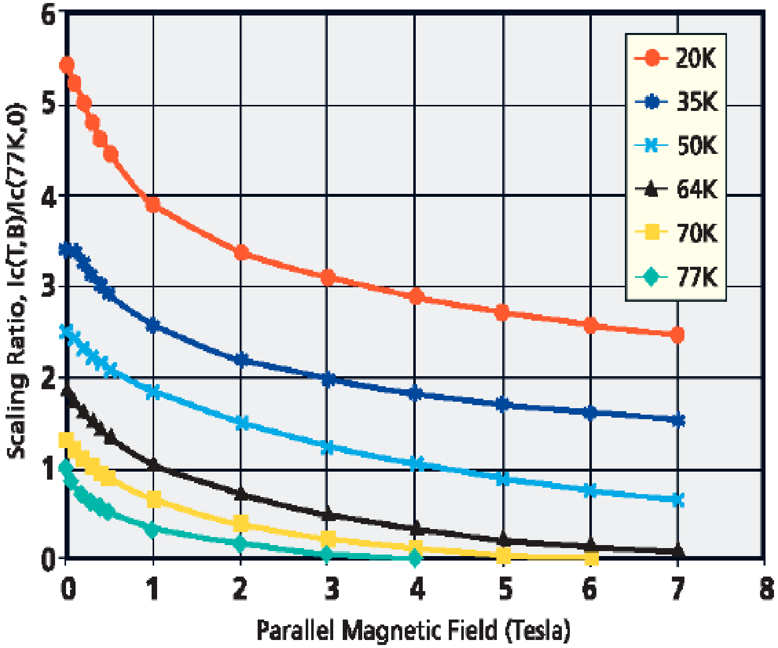


Thickness (avg): 0.31 (+/-0.02mm)
Width (avg): 4.1 (+/- 0.2mm)
Min. Critical Stress: 265 MPa
Min. Critical Strain: 0.4%
Min. Bend Dia: 70 mm

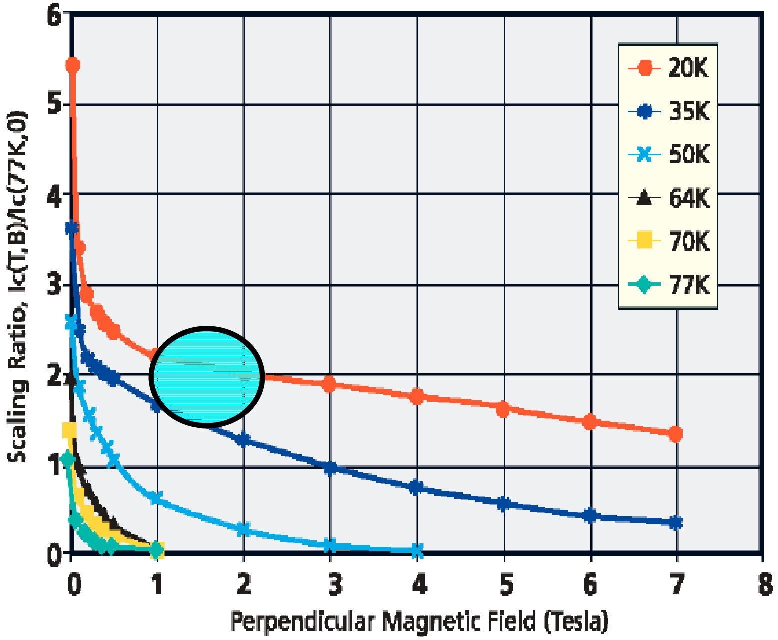
Variable Specifications:
Min. I_c: 115 A—135 A
Piece Length: 100 m —300 m



Ref: American Superconductors Inc., USA



Wire performance with magnetic field parallel to tape surface



Wire performance with magnetic field perpendicular to tape surface

American Superconductor™

REVOLUTIONIZING THE WAY THE WORLD USES ELECTRICITY™

Current carrying capacity of HTS depends on:

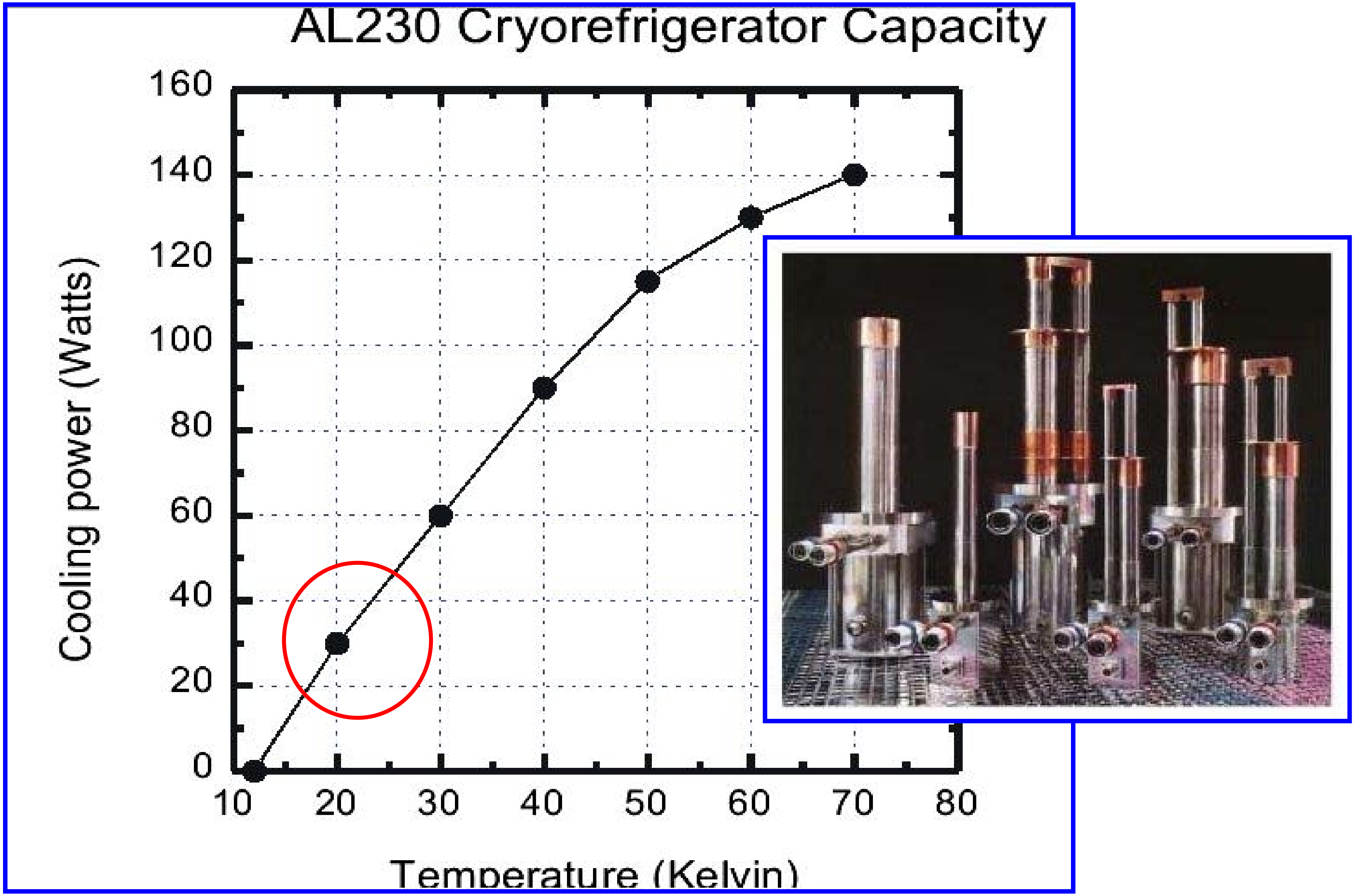
- Temperature
- Magnitude of the field

and also on the direction of the field

Maximum operating current	181 A
Maximum radial field	1.4 T
I_c @ 77 K,0B	110 A

Ref: American Superconductor Inc., USA

Gifford McMahon Cryo-Cooler



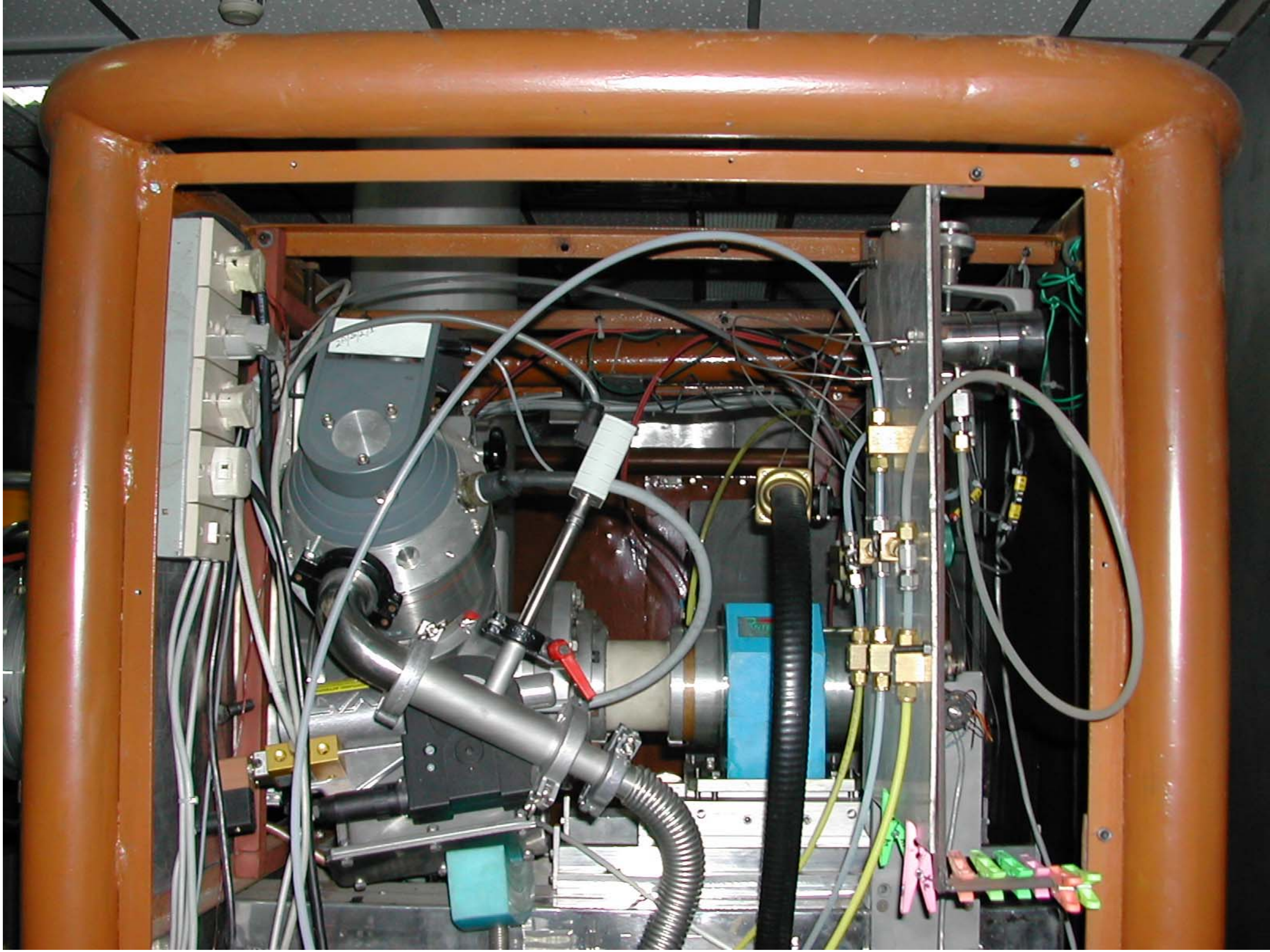
Warm current leads	16.0 W
Cold current leads	0.2 W
Radiation and internal coil heating	5.7 W
Supports	0.9 W
Contingency (20%)	4.6 W
Total	**27.4 W**

Cold head

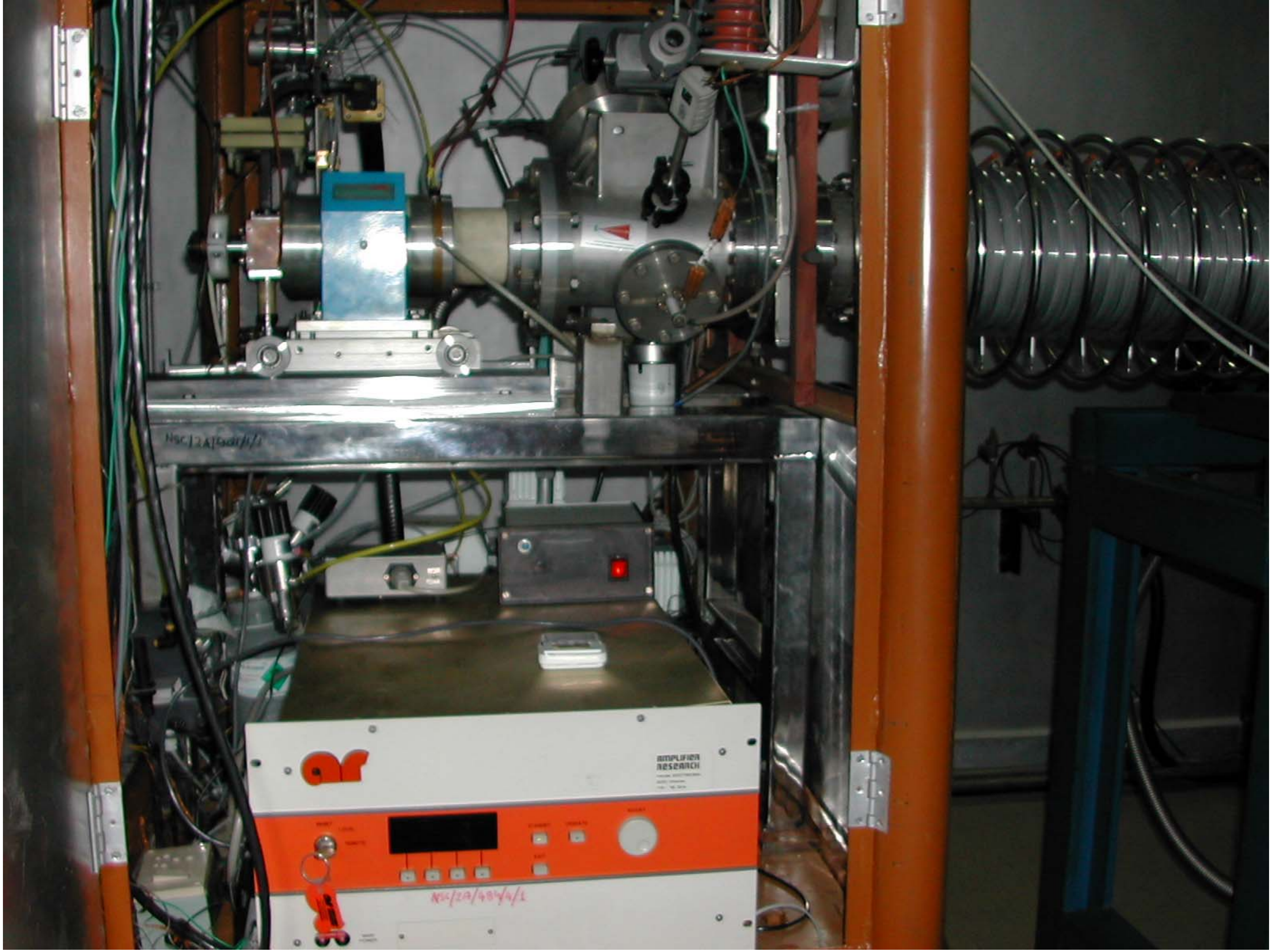
Cold finger

Coil cryostat

Testing of modulated vanes of RFQ



HV Platform with ECRIS, TP, Gas system, UHF Transmitter etc



TWT Amplifier, ECRIS on HV Deck followed by Accelerating Tube

LEIBF

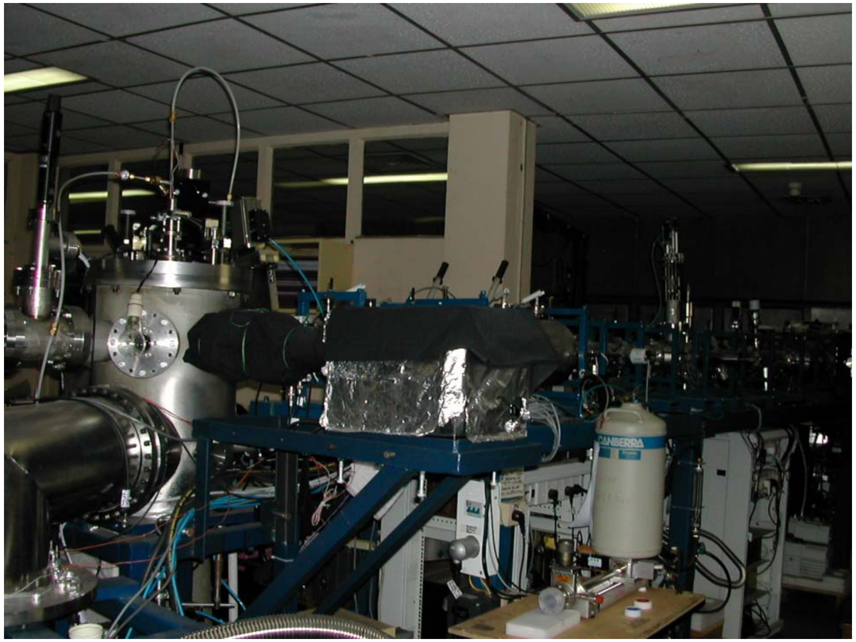
MIVOC (Metal Ions using Volatile Compounds) technique:

A new system developed for extracting metal ions using MIVOC technique.

It is used for extracting
-Fe beam using ferrocene compound $[Fe(C_5H_5)_2]$ which has a vapor pressure of 1.7×10^{-3} torr at 20^0C and
-Si beam extracted using chlorotrimethylsilane $[Si(CH_3)_3Cl]$.
Metal (As, Ge, Zn and Au) beams were developed using the micro-oven
Various atomic physics and materials science runs are are carried out using various beams.

Two operational beam lines of LEIBF

Experimental Facilities in 90 degree Beam Line



Number of Research Groups ~ 50

Ion – Micro-Droplet interaction
Experimental System in
15 degree Beam line

Rev. of Scientific Instruments 75, 5094 (2004).

Ion-solid interactions

An energetic ion transfers its energy via two processes:

Electronic (inelastic) energy loss (S_e) and Nuclear (elastic) energy loss (S_n) :

Dominant for swift heavy ion irradiation

Dominant for low energy ion implantation

$$S_e = -\left(\frac{dE}{dx}\right)_e = \frac{4\pi e^4 Z_p^2 Z_t N_t}{m_e v^2}\left[\ln\left(\frac{2m_e v^2}{I}\right) - \ln\left(1-\frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

$$S_n = -\left(\frac{dE}{dx}\right)_n = N\frac{\pi^2}{2}Z_1 Z_2 e^2 a \frac{M_1}{M_1+M_2}$$

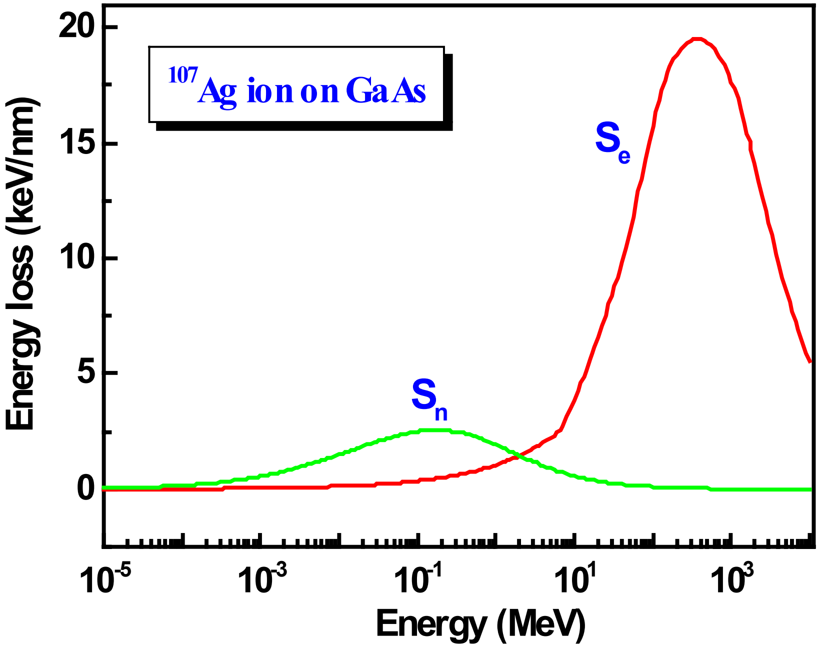
Bohr-Bethe formula

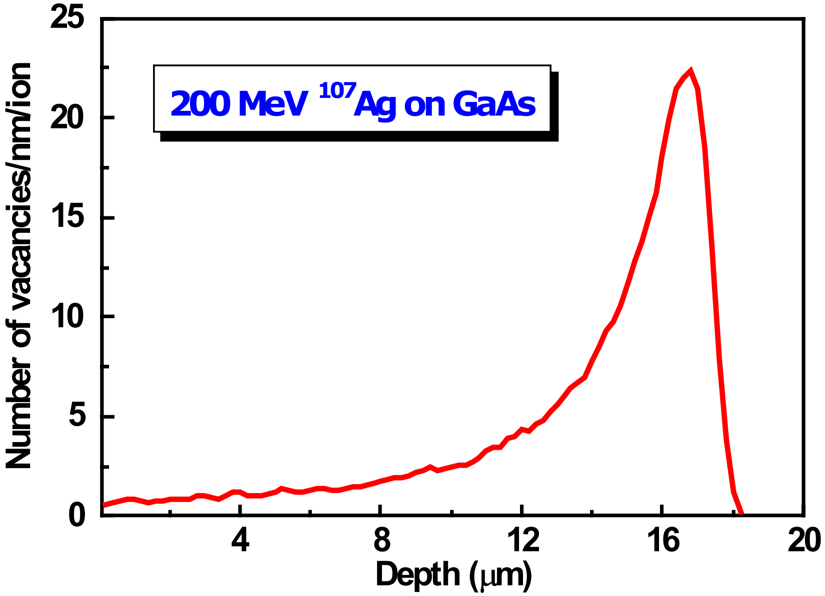
For screened Coulomb potential

Stopping and Ranges of Ions in Matter (SRIM) calculations:

The deposited energy depends on mass and energy of projectile and on mass of target

Final structure of damage depends on the type of material, temperature, ion flux etc.

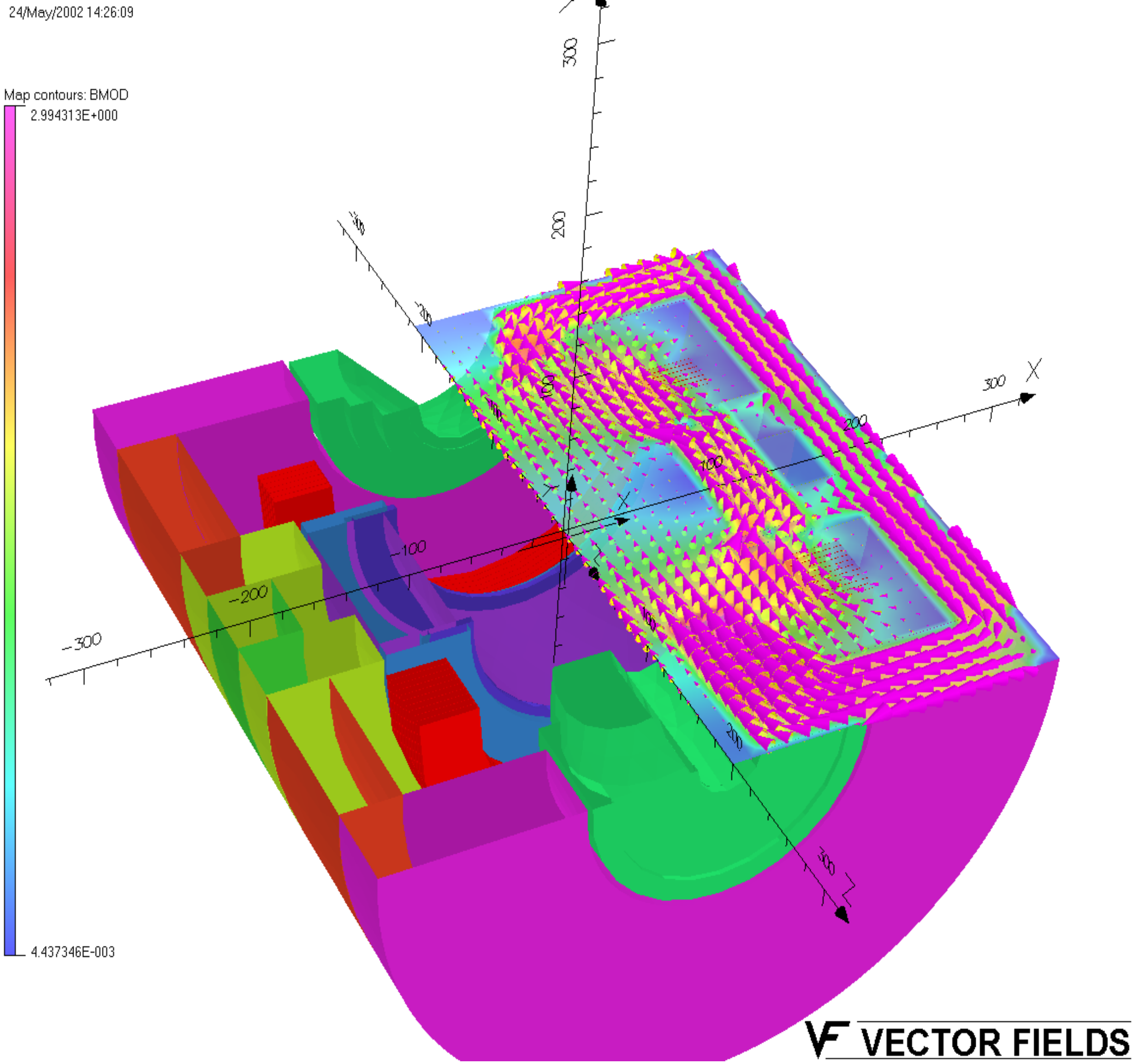




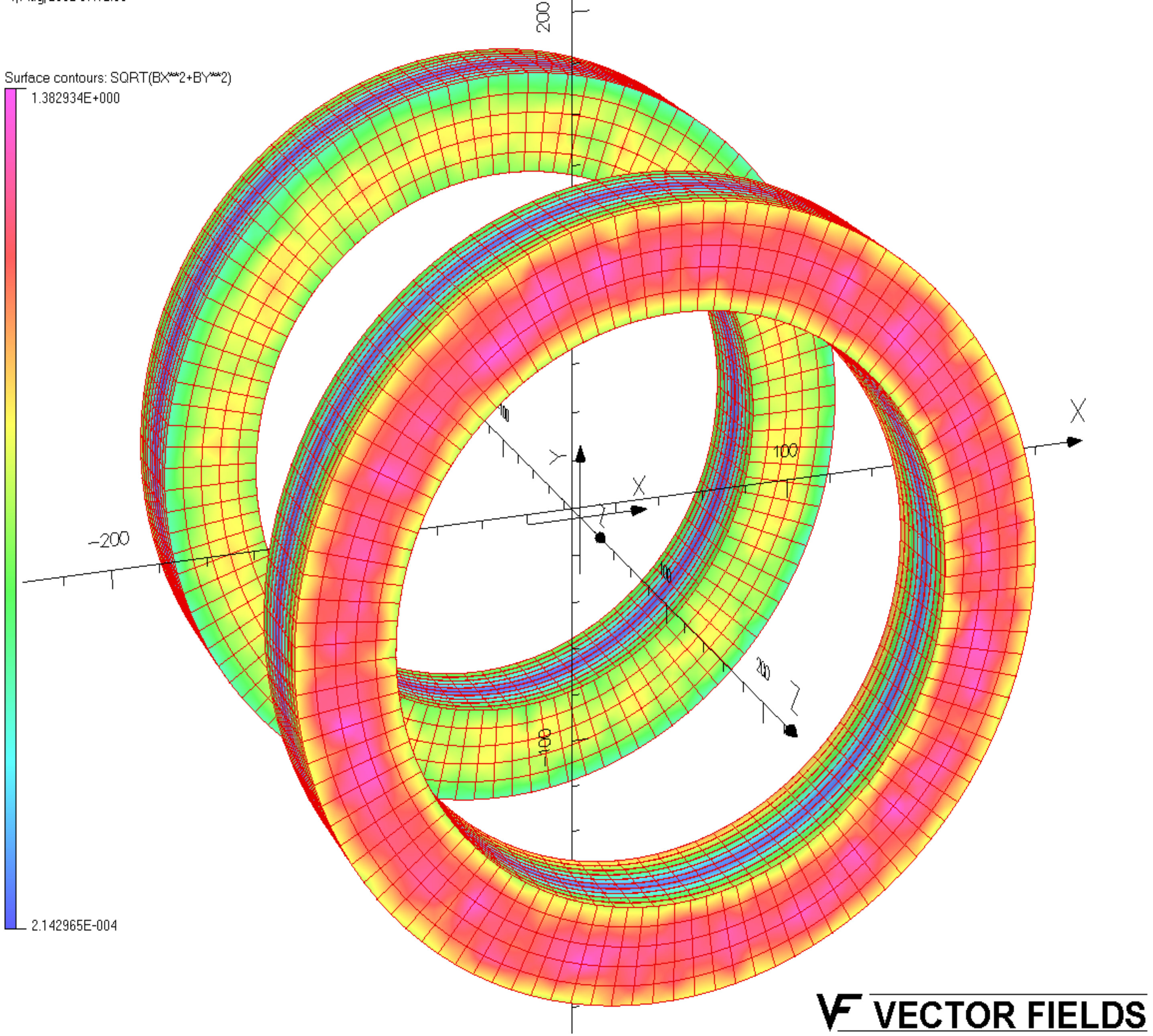
Number of displacements versus depth can be given using **Kinchen-Pease** relation:

$$n_d = \frac{0.8\nu(E,x)}{2E_d}$$

Vacancies produced by nuclear energy loss



Field vectors on the yoke cross section

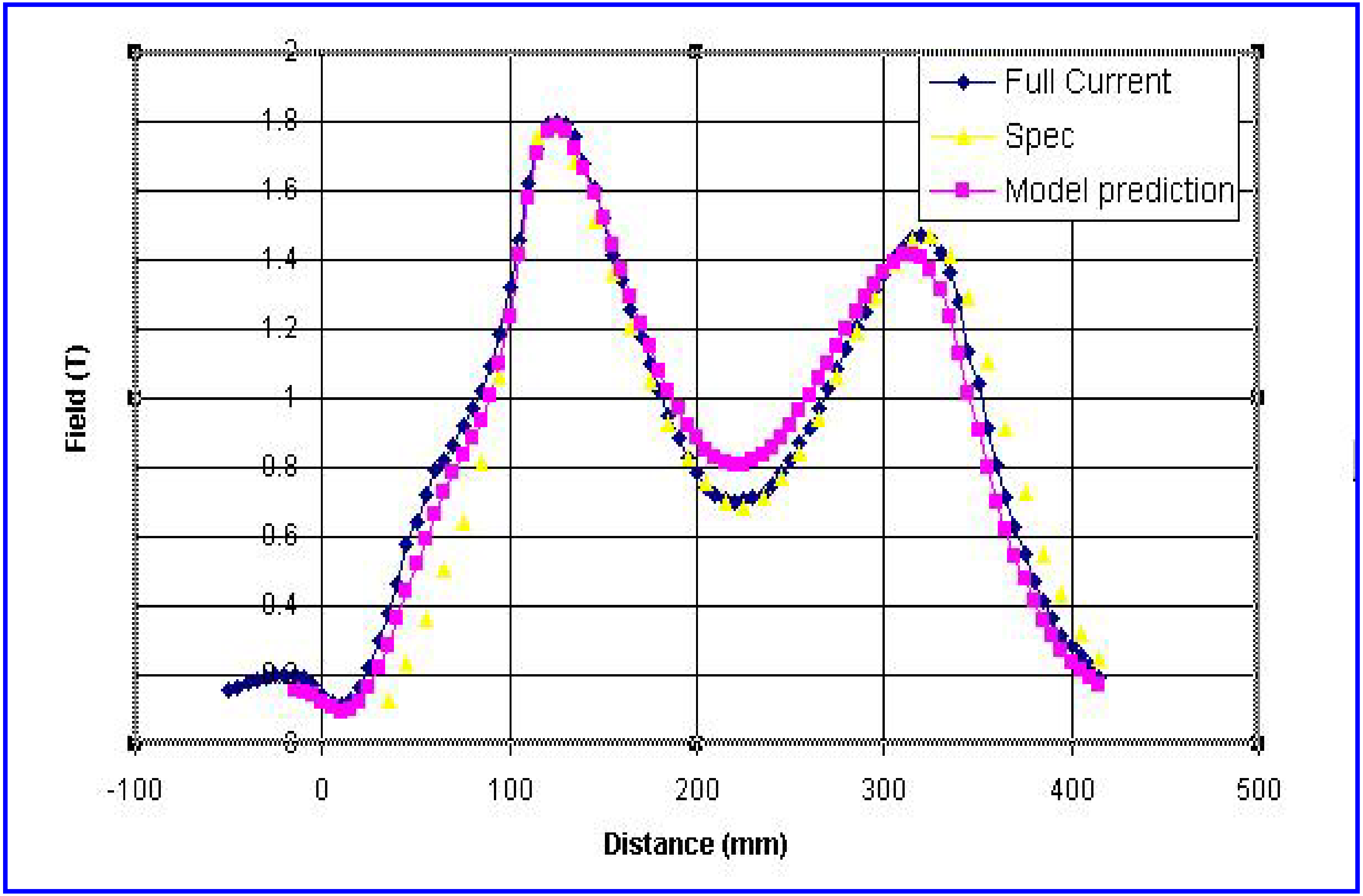


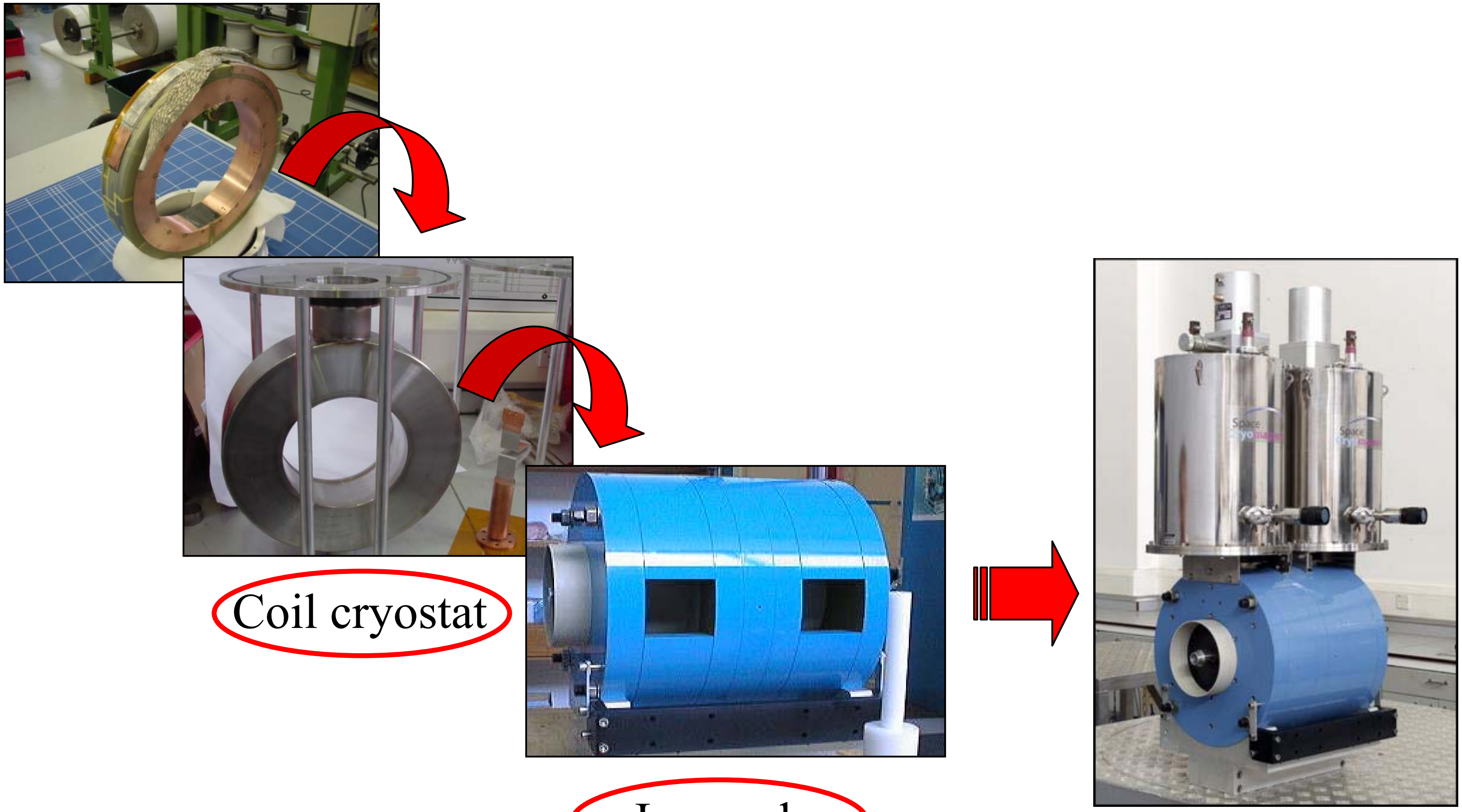
Radial magnetic field on the coil surface

Source Body with HTS coils

HTS Coil with Cryotip

Axial field measurements





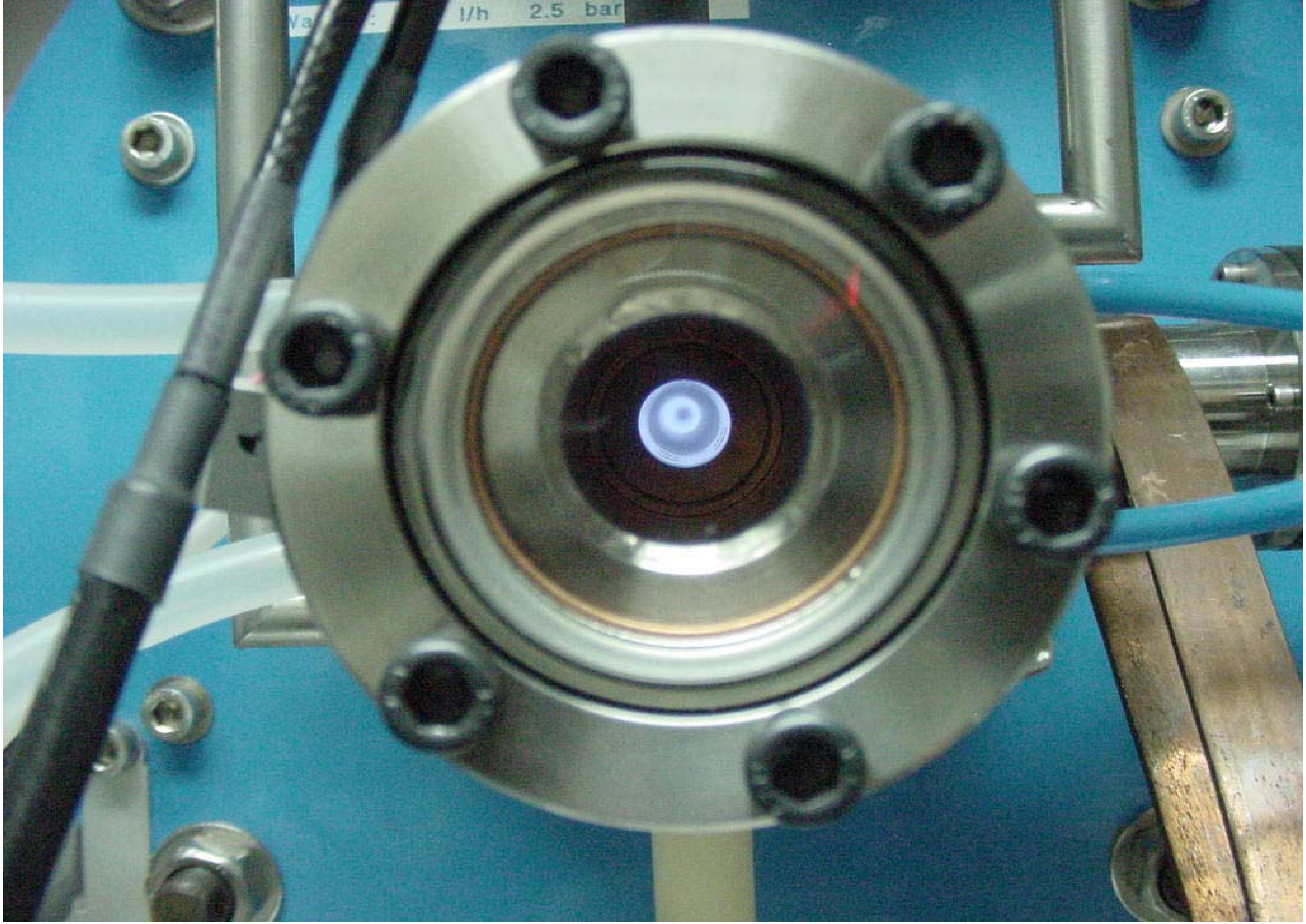
HTS coil

Coil cryostat

Iron yoke

Various Stages of Development

Closer view of the HTS-ECR source with cryoptips on top



View of Plasma generated in the ECR source

Large Acceptance analysing magnet for PKDELIS ECR source

Design goal: High acceptance, moderate mass resolution, minimum weight, air cooled

Optics code used: TRANSPORT, COSY INFINITY and GIOS

Design parameters:

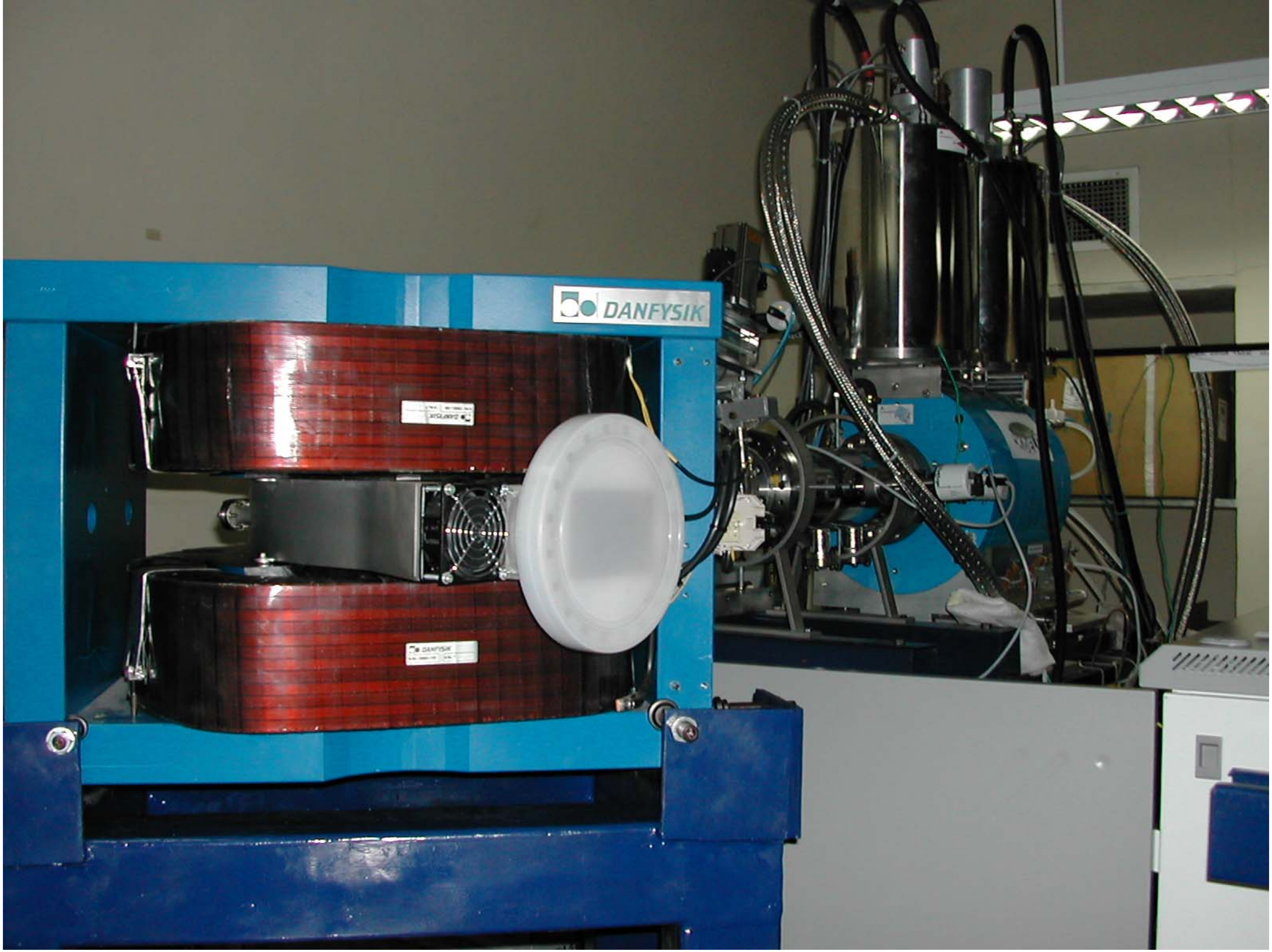
- Maximum Field (Bmax.) = 0.3 T
- Bending radius (r) = 0.3 m
- Bending Angle = 90^0
- Pole gap = 80 mm

- Entrance and exit pole shape = cylindrical
- Radius of curvature of cylinder = -0.24±0.01m
- Entrance and exit angle = $32.8^0 \pm 0.5^0$
- Pole profile
  - Entrance and exit = Rogowski
  - Side pole profile = Champhered
- Field homogeniety B(x) = $B_0(1+n_1(x/r) + n_2(x/r)^2 + n_3(x/r)^3 + \ldots)$

$$n_1 = 0,\ n_2 = -0.70 \pm 0.07,\ n_3 = +0.9 \pm 0.09$$

Test Results :

Parameters	Specifications	Model	Measured
shim angle (degree)	32.8 ± 0.5	32.0	31.7 ± 0.34
EFB radius (cm)	24.0 ± 1.0	25	25.5 ± 2.0
n1	0	0	0
n2	-0.7 ± 0.07	-0.694± 0.001	-0.67 ± 0.07
n3	0.9 ± 0.09	0.873 ± 0.004	0.81± 0.15
n4	0	-0.032 ± 0.046	-0.41± 2.49



HTS- ECRIS PKDELIS and Large Apperture Analyzing magnet at NSC

HYPERNANOGAN ➡ PKDELIS

B_{axial}= 1.3 T

B_{radial} = 1.2 T

Max required power = 200 kW

Water cooling = 6800 l/h

B_{axial}= 1.8 T

B_{radial} = 1.37 T

Max required power = 20 kW !

Water cooling 200 l/h !

Main Gas	Injection P	Beamline P	DcBias-V	HV Ext-V	Ext Elec-V	Pi 245	Date	Operator
5.43	1.2E-4	7.1E-3	242	21966	6414	488.04	30/10/	PK

Support Gas	Extraction P	UHF Tuner	DcBias-I	HV Ext-I	Ext Elec-I	Pr 245	Oven-P	Time
1.86	6.0E-7	4.64	0.70	6.95	0.88	8.31	0.00	09:56:

0

	Q+	B(G)
Ar1+	0.0	3274.8
Ar2+	675.9	2349.5
Ar3+	660.5	1902.8
Ar4+	625.5	1647.0
Ar5+	716.0	1472.9
Ar6+	654.3	1326.8
Ar7+	617.3	1230.7
Ar8+	709.9	1155.6
Ar9+	262.3	1093.0
Ar10	67.9	1026.2

17/12/2003

18:18:00

Qmin	Qmax	SAMPLE
1	10	Argon (40)

Mass 0

Symbol

Comments

INJ COIL=133A EXT COIL=74A

file path

D:\Affaires PK\DIR0\30.10.2003\605 µA Ar7+.spe

Ar Mass Analysed Spectrum

Main Gas 6.66
Injection P 2.6E-4
Beamline P 1.1E-6
DcBias-V 166
HV Ext-V 27023
Ext Elec-V 323
Pi 245 513.80
Date 27/11/
Operator PK
Support Gas 0.00
Extraction P 7.4E-7
UHF Tuner 2.77
DcBias-I 0.00
HV Ext-I 6.06
Ext Elec-I 0.01
Pr 245 12.36
Oven-P 0.00
Time 15:48:

0

	Q+	B(G)
Xe10	263.4	2058.8
Xe11	240.3	1956.5
Xe12	215.1	1871.8
Xe13	186.8	1792.7
Xe14	157.4	1726.9
Xe15	128.0	1666.5
Xe16	101.8	1611.6
Xe17	75.6	1556.7
Xe18	52.5	1514.1
Xe19	34.6	1472.9

Read File OFF
Active Cursor OFF
Measure OFF
Calibrate OFF

28/11/2003
11:10:10

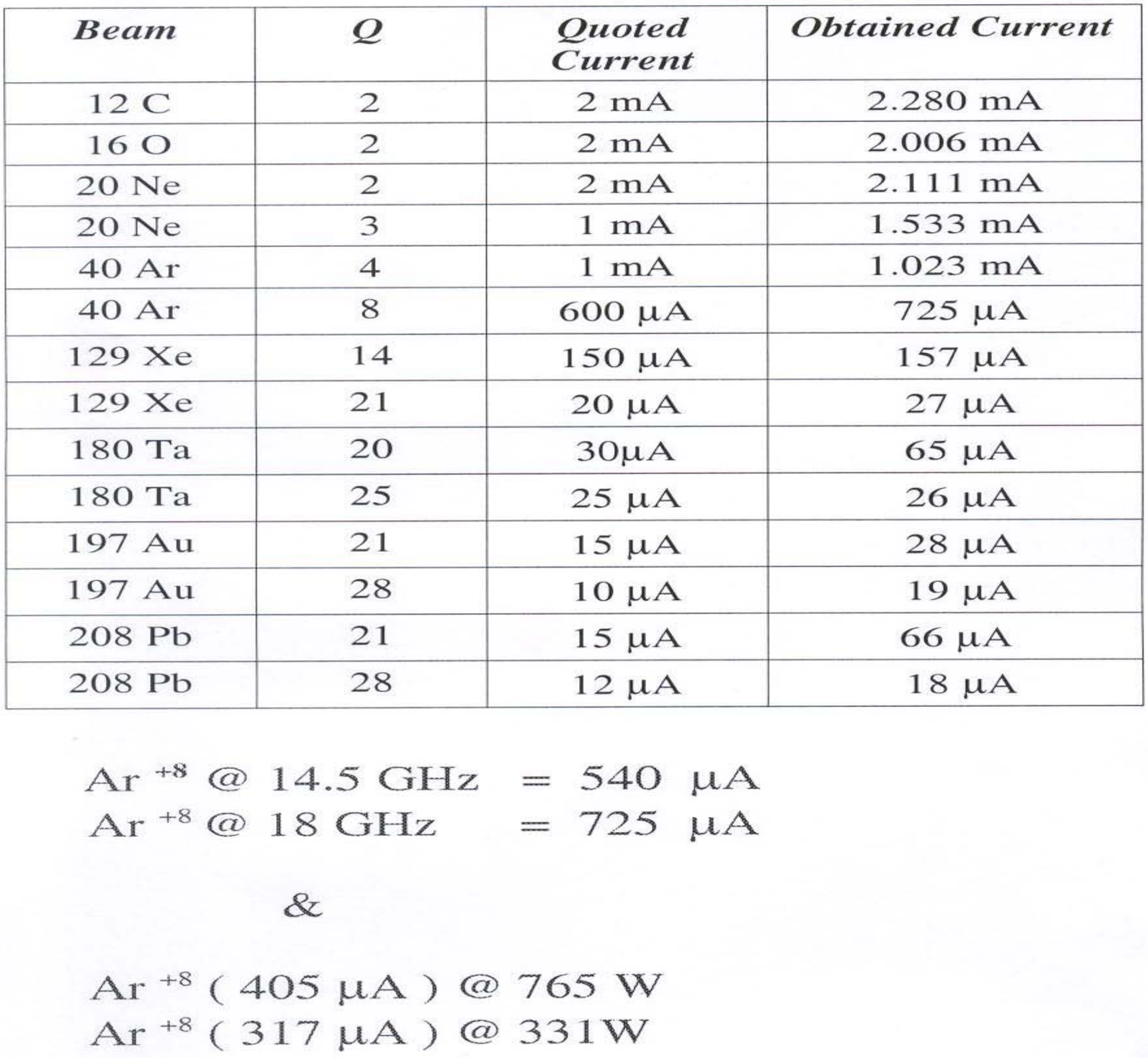
Qmin 10
Qmax 19
SAMPLE Xenon (129)

Comments
Inj Coil: Ext Coil: FockV:

file path
D:\Affaires PK\DIR0\27.11.2003 18GHz\dem 1 Xe14+ 158 µA.spe

Xe Spectrum

Analyzed beams from HTS-ECRIS PKDELIS



Beam	*Q*	*Quoted Current*	*Obtained Current*
12 C	2	2 mA	2.280 mA
16 O	2	2 mA	2.006 mA
20 Ne	2	2 mA	2.111 mA
20 Ne	3	1 mA	1.533 mA
40 Ar	4	1 mA	1.023 mA
40 Ar	8	600 μA	725 μA
129 Xe	14	150 μA	157 μA
129 Xe	21	20 μA	27 μA
180 Ta	20	30μA	65 μA
180 Ta	25	25 μA	26 μA
197 Au	21	15 μA	28 μA
197 Au	28	10 μA	19 μA
208 Pb	21	15 μA	66 μA
208 Pb	28	12 μA	18 μA

Ar^{+8} @ 14.5 GHz = 540 μA
Ar^{+8} @ 18 GHz = 725 μA

&

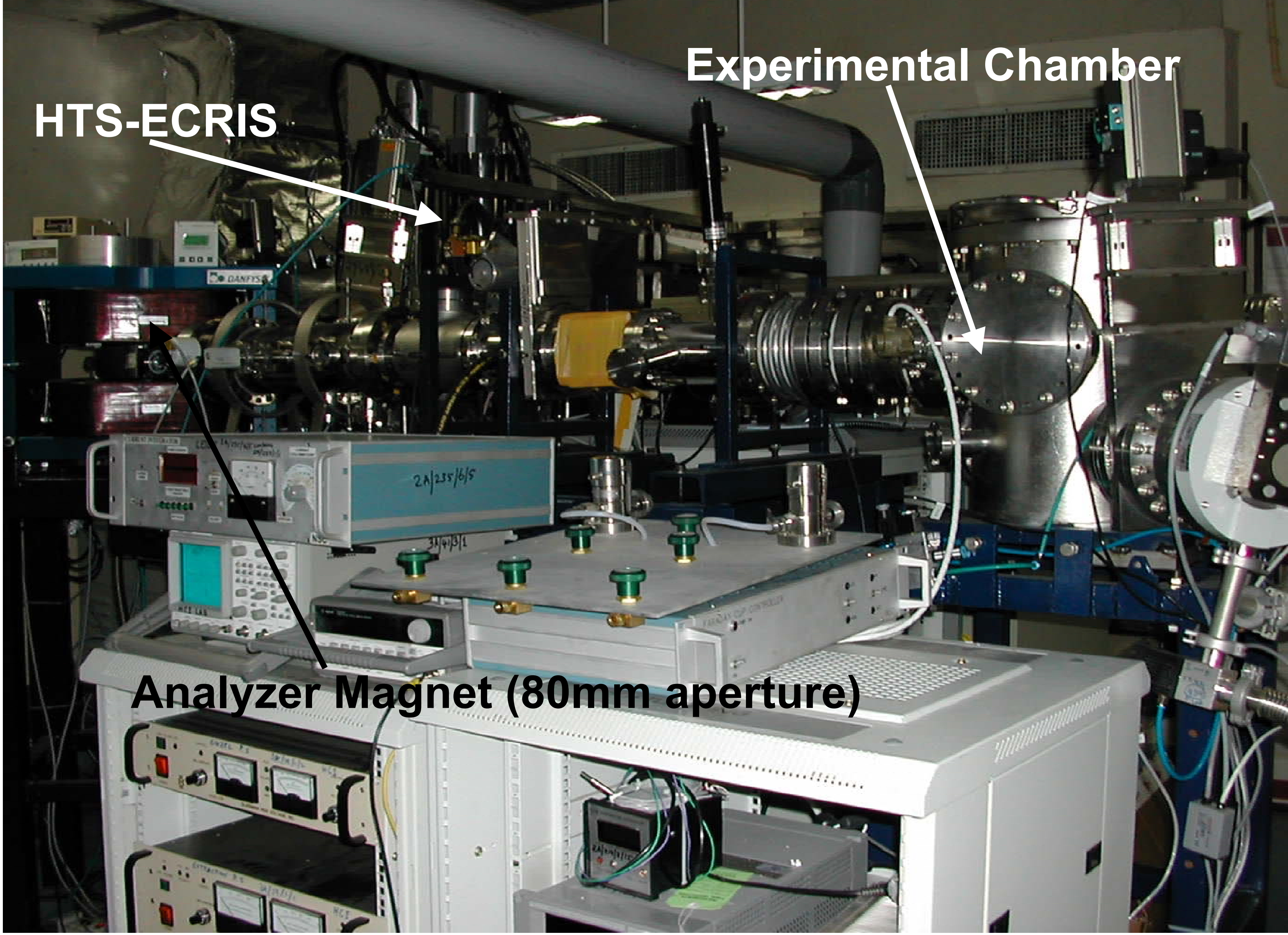
Ar^{+8} (405 μA) @ 765 W
Ar^{+8} (317 μA) @ 331W

Final Beam Test Results of PKDELIS ECR Ion Source

ION	A/Q = 6	A/Q = 7	A/Q = 8	A/Q = 9
^{12}C	Q=2+, I > 2mAe			
^{16}O			Q=2+, I≥2mAe	
^{20}Ne		Q=3+, I>1mAe		Q=2+, I≥2mA
^{40}Ar	Q=7+, I≥600μA			Q=4+, I≥1mA
^{129}Xe	Q=21+, I≥20μA			Q=14+,I≥150μA
^{180}Ta		Q=25+,26+, I≥25μA		Q=20+, I≥30μA
^{197}Au		Q=28+, I≥10μA		Q=21+, I≥15μA
^{208}Pb		Q=29+, I≥12μA		Q=21+, I≥15μA

A: Atomic Mass Unit ; Q: Ion charge state

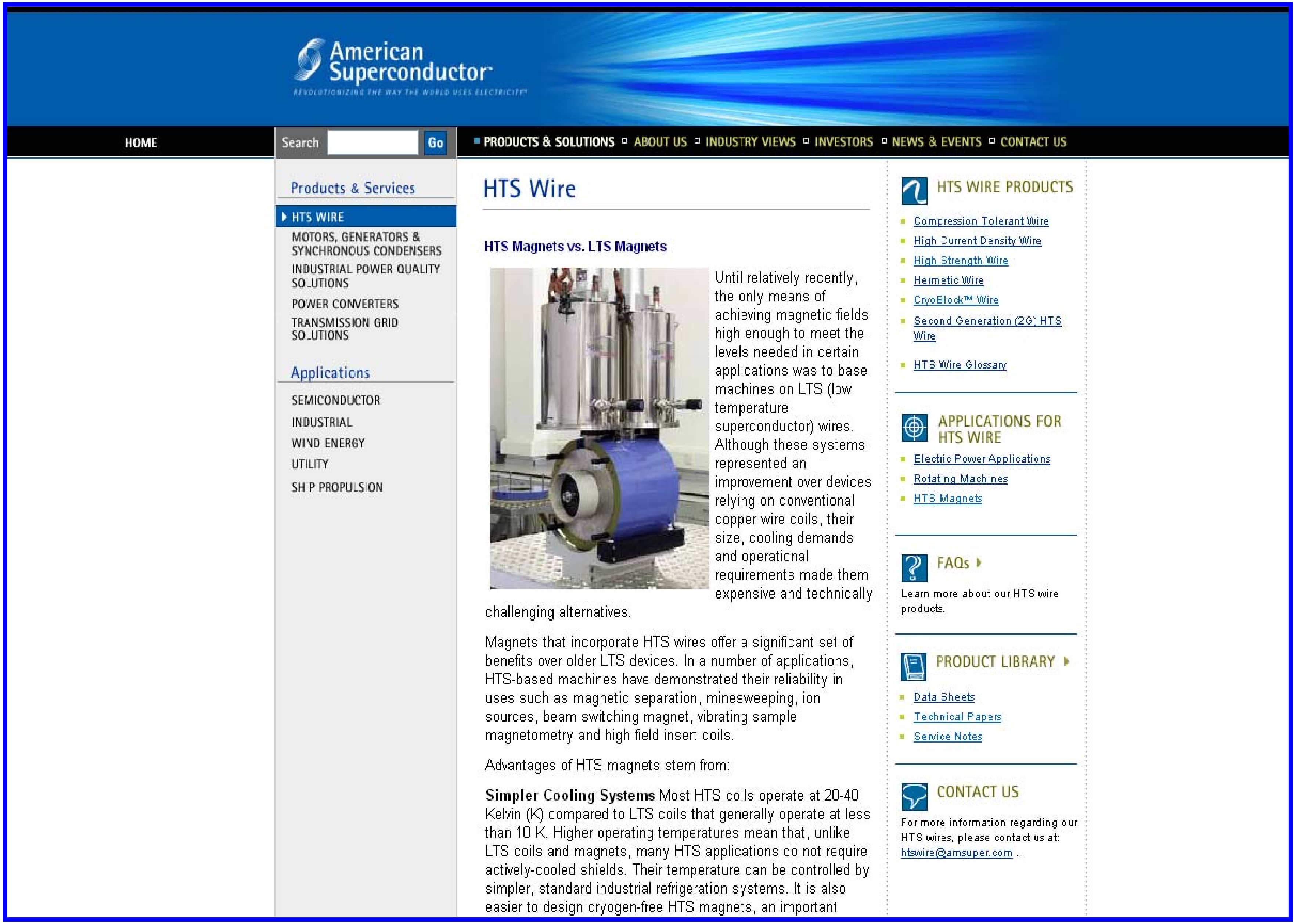
D. Kanjilal et al, Performance of First High Temperature Superconducting ECRIS, ***Rev. Sci.Instrum.,*** **(2006)**



HTS-ECRIS with Experimental Chamber (Operation >22,000 hrs)

Rev. Sci. Instr. (in press)

First HTS based ECR Ion Source in the World



HTS Wire

HTS Magnets vs. LTS Magnets

Until relatively recently, the only means of achieving magnetic fields high enough to meet the levels needed in certain applications was to base machines on LTS (low temperature superconductor) wires. Although these systems represented an improvement over devices relying on conventional copper wire coils, their size, cooling demands and operational requirements made them expensive and technically challenging alternatives.

Magnets that incorporate HTS wires offer a significant set of benefits over older LTS devices. In a number of applications, HTS-based machines have demonstrated their reliability in uses such as magnetic separation, minesweeping, ion sources, beam switching magnet, vibrating sample magnetometry and high field insert coils.

Advantages of HTS magnets stem from:

Simpler Cooling Systems Most HTS coils operate at 20-40 Kelvin (K) compared to LTS coils that generally operate at less than 10 K. Higher operating temperatures mean that, unlike LTS coils and magnets, many HTS applications do not require actively-cooled shields. Their temperature can be controlled by simpler, standard industrial refrigeration systems. It is also easier to design cryogen-free HTS magnets, an important

Learn more about our HTS wire products.

For more information regarding our HTS wires, please contact us at: htswire@amsuper.com .

Thank you

BEAMS extracted from HTS-ECRIS PKDELIS

Ion	RF power (Watts)	Beam current
$^{20}Ne^{2+}$	391	2 mA
$^{12}C2^{+}$	380	2 mA
$^{16}O^{2+}$	410	2 mA
$^{40}Ar^{8+}$	521	732 uA
$^{129}Xe^{14+}$	615	158 uA
$^{129}Xe^{21+}$	600	44 uA
$^{181}Ta^{20+}$	426	65 uA
$^{181}Ta^{25+}$	476	27 uA
$^{197}Au^{21+}$	786	38 uA
$^{197}Au^{27+}$	873	20 uA
$^{208}Pb^{21+}$	1200	99 uA
$^{208}Pb^{28+}$	776	20 uA