Inter University Accelerator Centre, New Delhi
(An Autonomous Institution under the University Grants Commission)
Primarily for research purposes in Basic Science

# 3D simulation studies and optimization of magnetic holes of HTS-ECRIS for improving the extraction efficiency and intensities of highly charged ions

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www.iuac.res.in;www.iuac.ernet.in

19th International Workshop on ECR Ion Sources, Grenoble,2010

# Outline

- IUAC, New Delhi:

PELLETRON (Tandem Van de Graaf)

SC-LINAC(based on superconducting quarter wave resonators)

LEIBF (Nanogan ECR ion source based low energy ion beam facility)

HCI (High Current Injector to LINAC)

HTS-ECRIS PKDELIS + RFQ + DTL

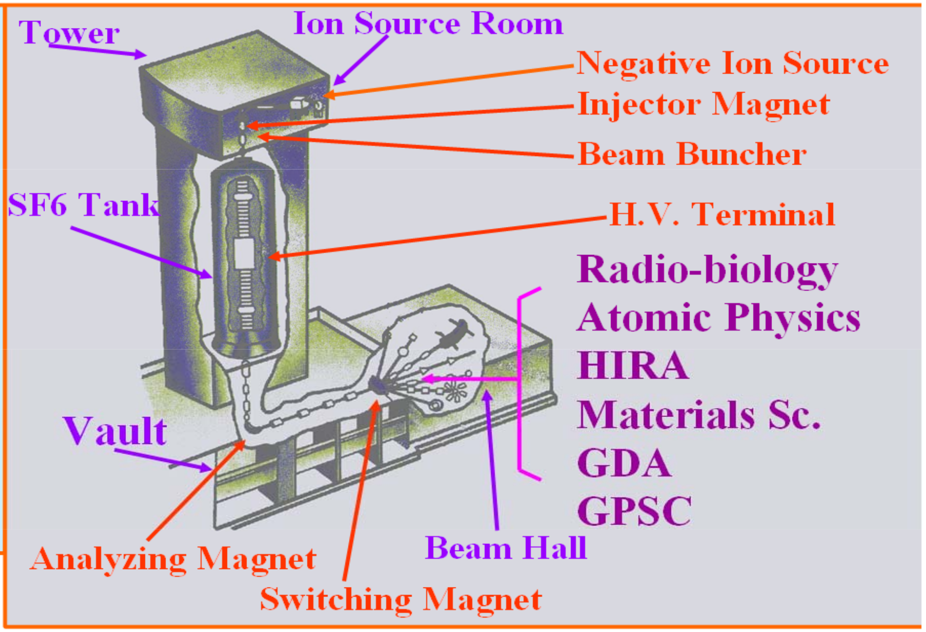
- Critical parameters for intense beams of highly charged ions
- 3D simulations using RADIA and experimental results
- Summary and Conclusions

# 15UD Pelletron Accelerator at IUAC

Tank height: 26.5 m
Diameter: 5.5 m
Pressure: 86 PSI
$SF_6$ gas

Ions accelerated:
H to Au beams

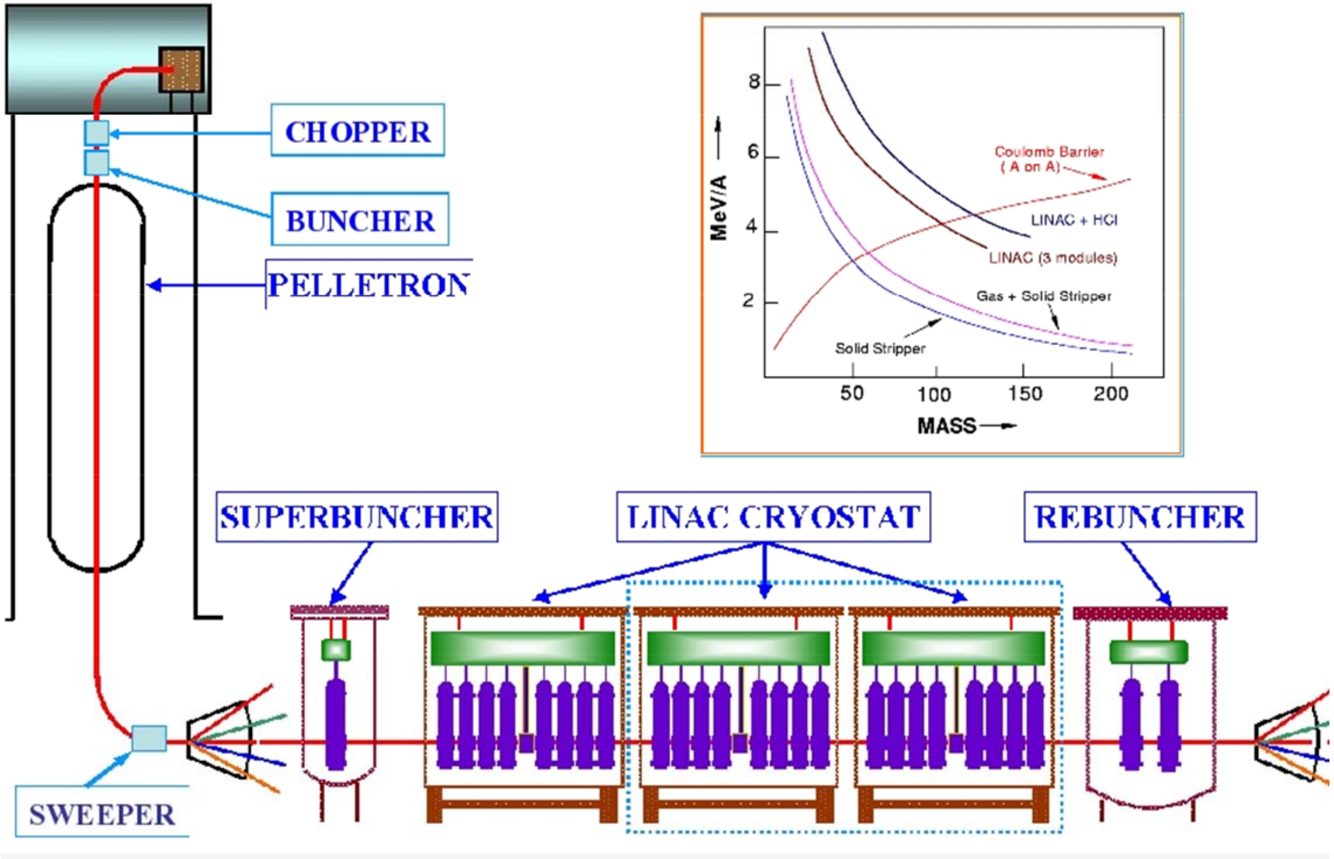
Currents: ~ 1 -50 pnA
Energy : 30 – 270 MeV



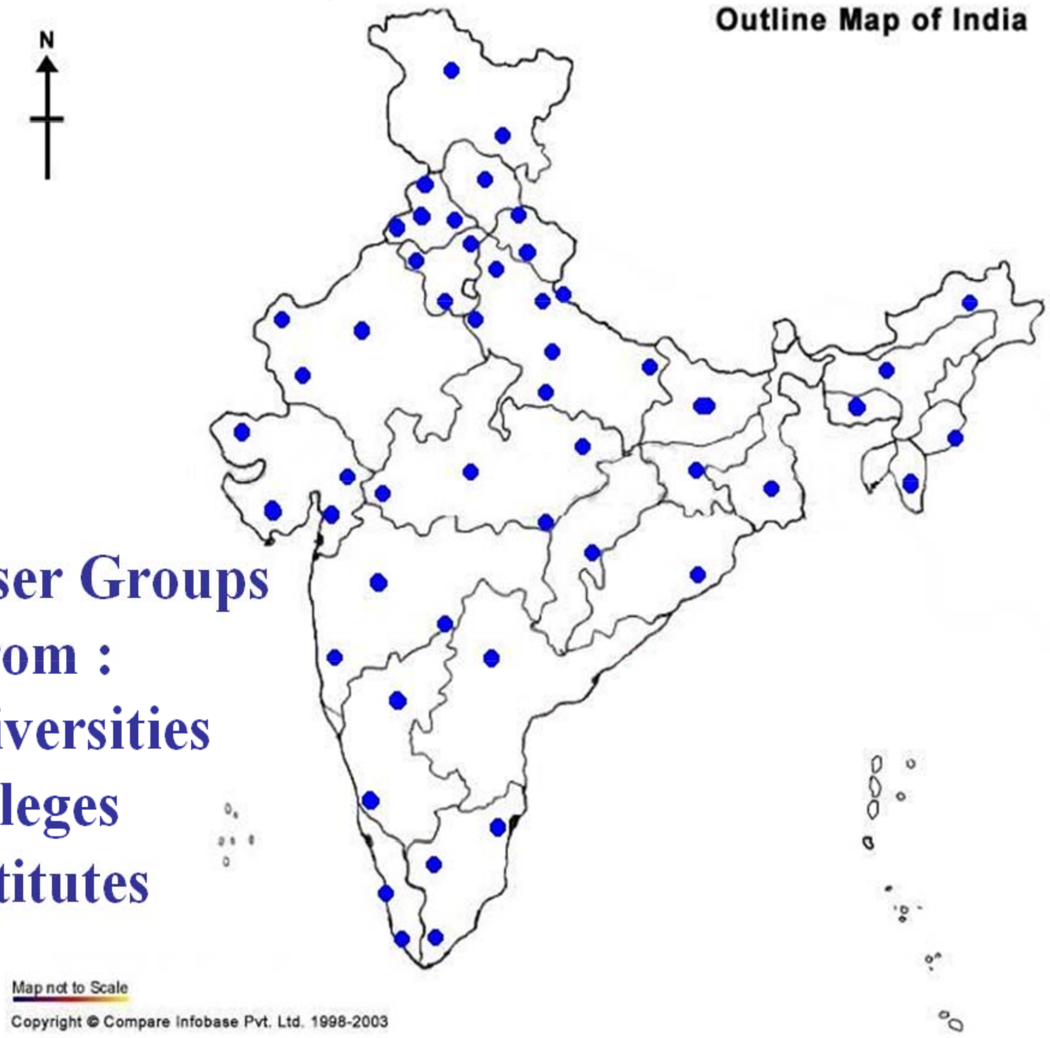

Special Features: 1. Off-set QP in Terminal
2. Earthquake Protection
3. Compressed Geometry Tubes

www.iuac.res.in;www.iuac.ernet.in

# Layout of 15 UD Pelletron + SC-LINAC



# User Community of IUAC



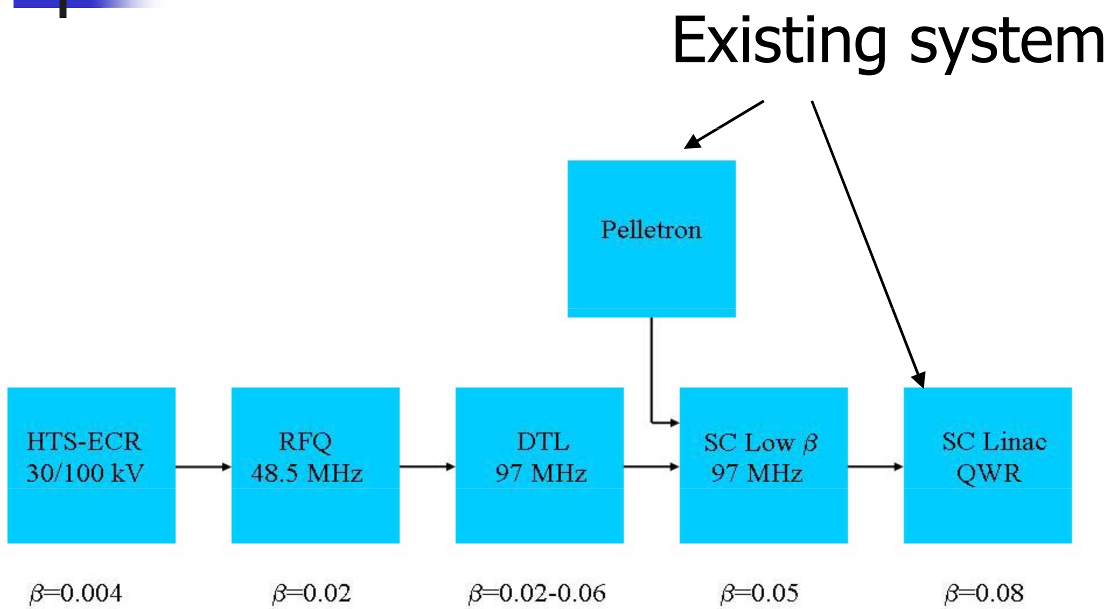

**> 300 User Groups from :**

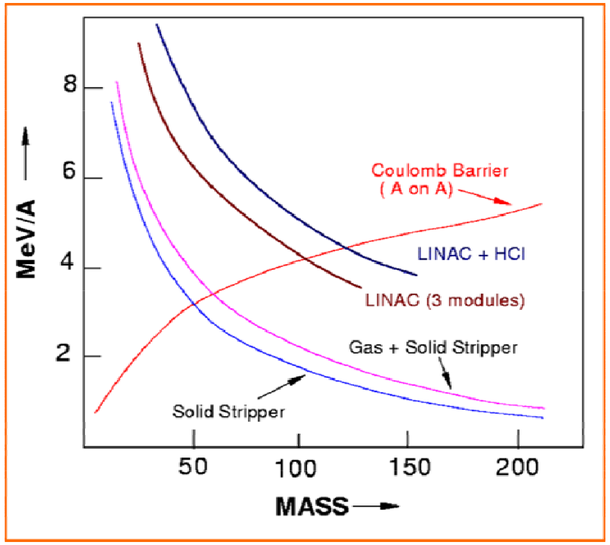
**76 Universities**

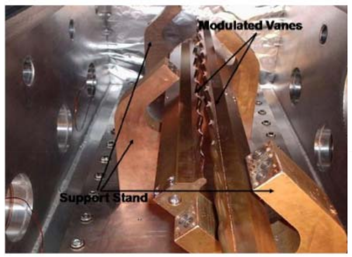
**44 Colleges**

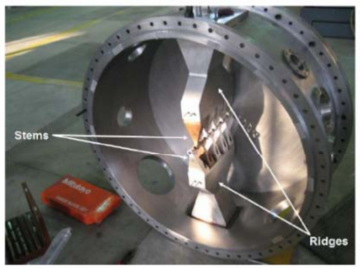
**45 Institutes**

# Schematic of High Current Injector (HCI) w.r.t to Pelletron + LINAC

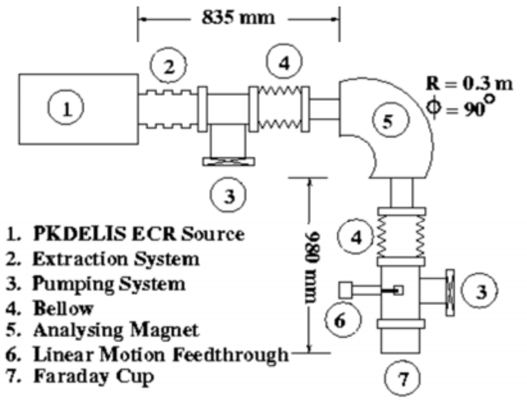


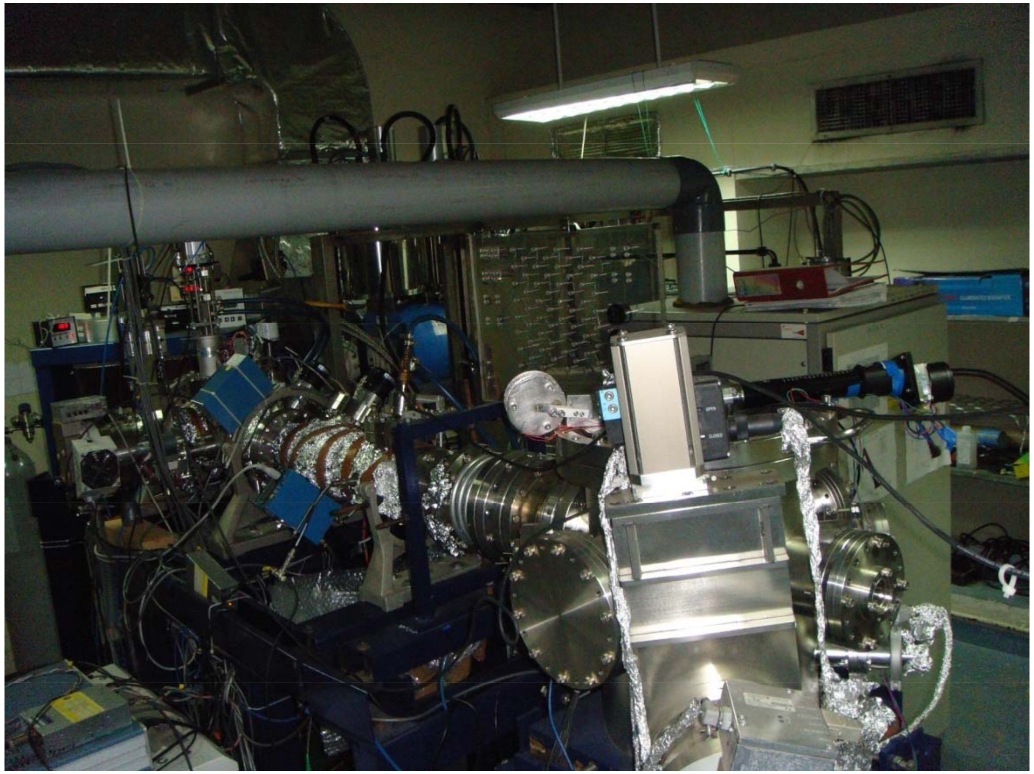



# HTS - ECR Ion Source, PKDELIS & Low Energy Beam Transport (temporary location)



R.McMahon et al., IEEE Transactions on Applied Superconductivity, Vol.14, No.2, June 2004
C.Bieth et al, Nucl. Instr. Meth. B 235 (2005) 498
D.Kanjilal et al., Rev.Sci.Instrum.,77 (2006) 03A317

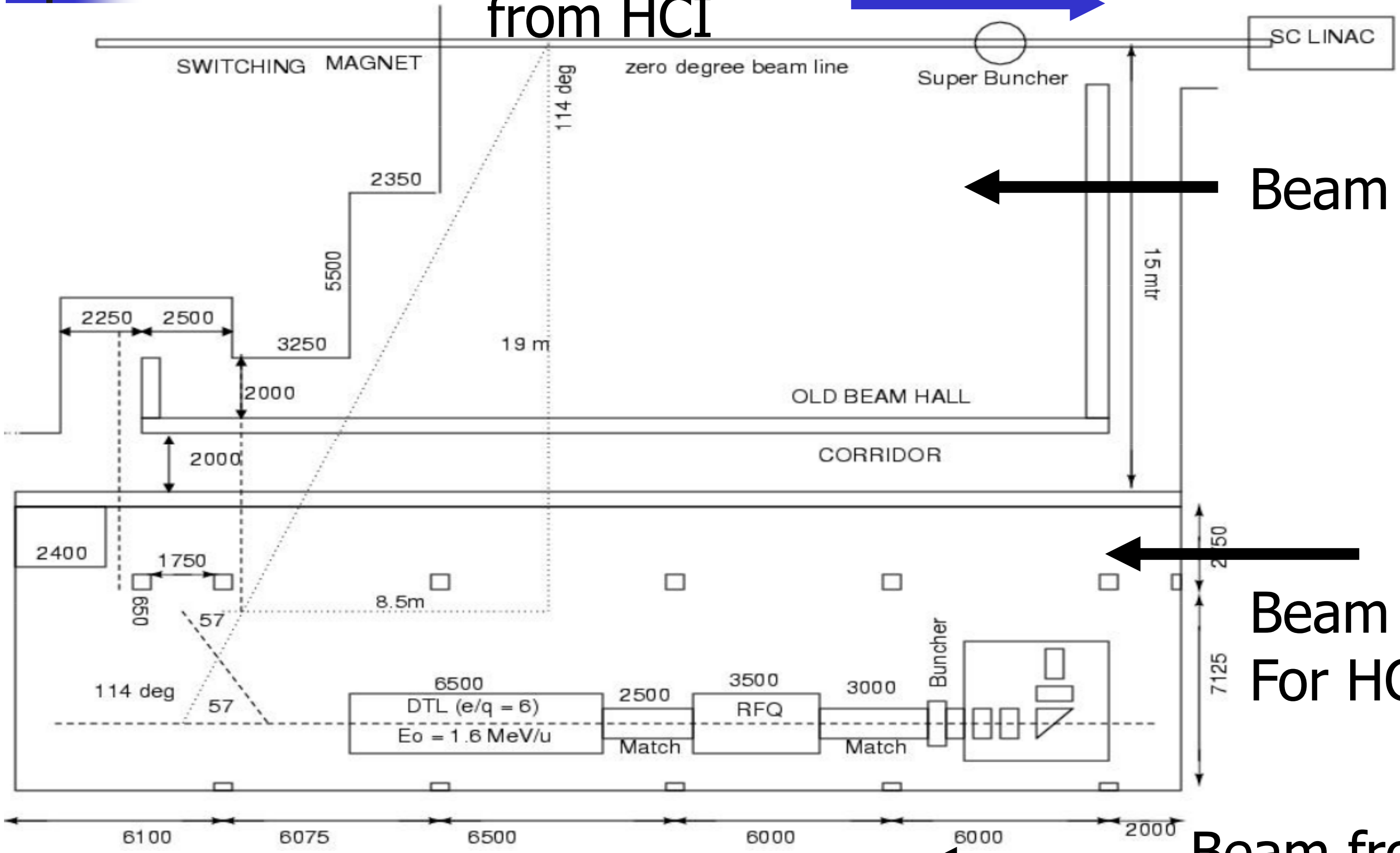
# HTS-ECRIS PKDELIS

| | |
|---|---|
| Operating frequency | 14.5, 18 GHz |
| Max, Injection field | 1.8 T |
| Max. Extraction field | 1.5 T |
| Operating temperature | 23 K |
| Radial field at chamber wall | 1.3 T @ 35 mm |
| Max.RF power | 1.7 kW |

- Transverse to co-axial injection
- Multi-electrode extraction system

# Layout of High Current Injector (HCI)to prepare for injection to SC-LINAC

Boosted energy from HCI

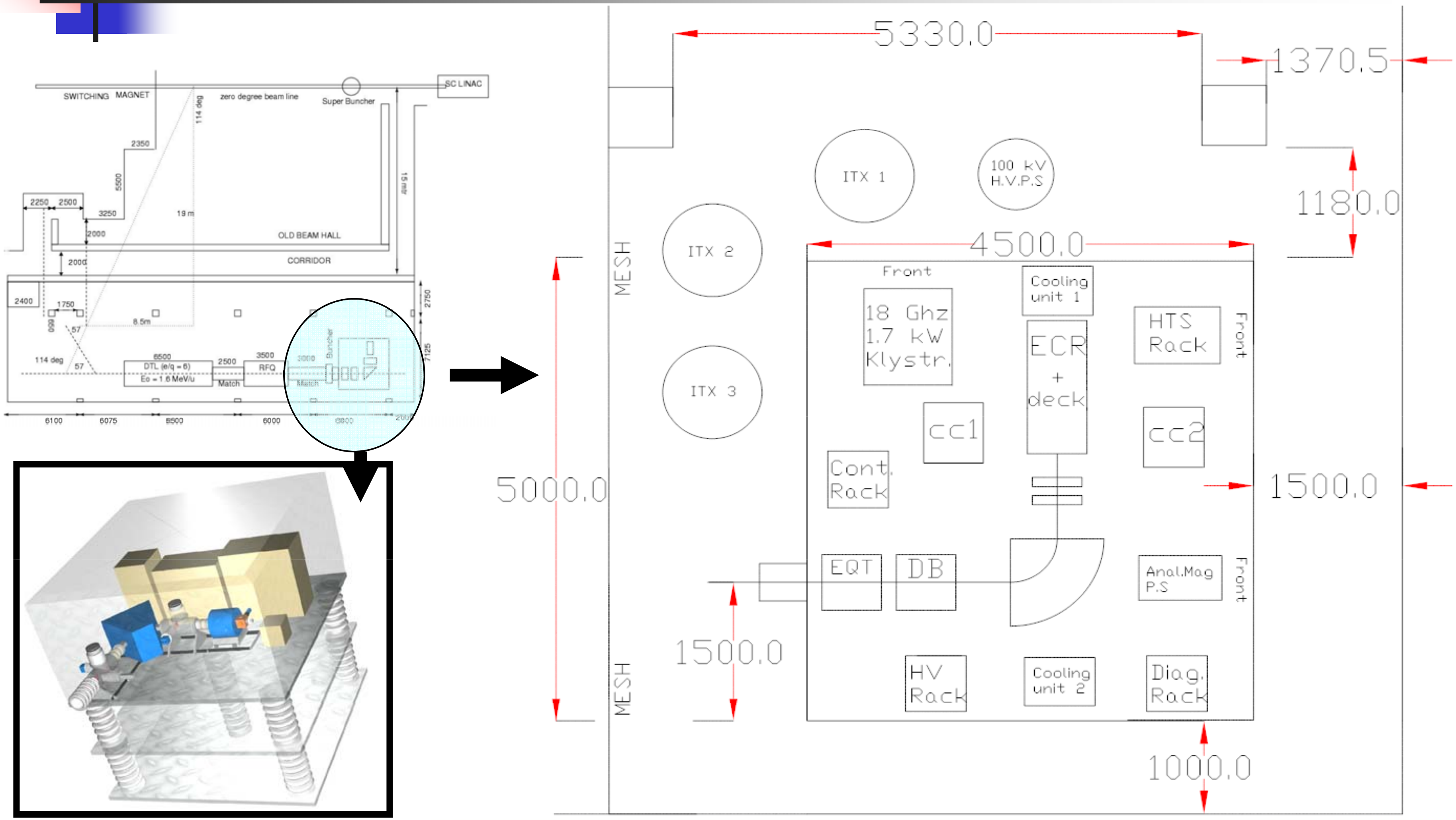



Beam Hall I

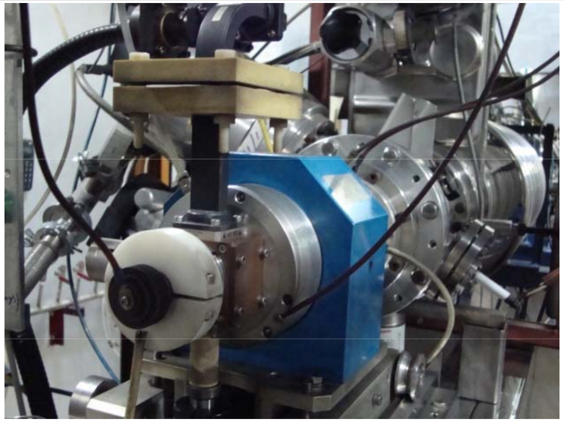
Beam Hall III For HCI

Beam from HCI

# 400 kV Platform Layout



# Low Energy Ion Beam Facility (E/q = 300 keV)



NANOGAN ECR Source

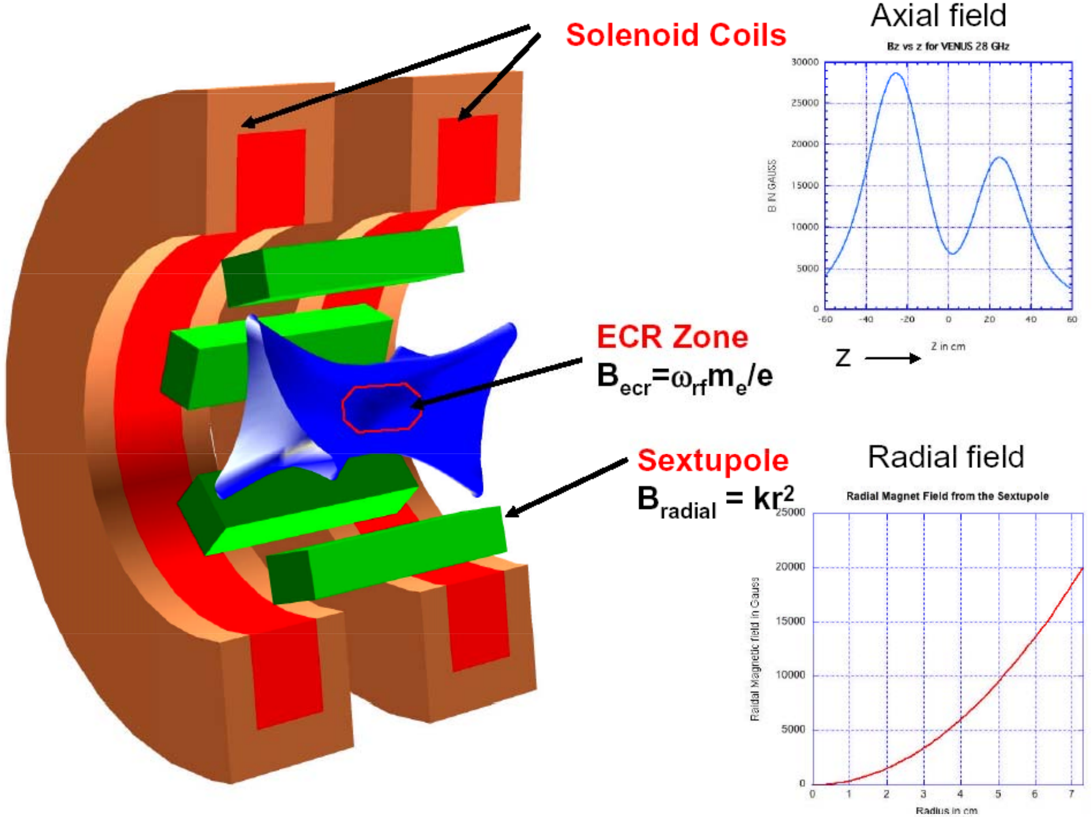
$15^{o}$ beamline

Polarised on 300 kV Platform

$90^{o}$ beamline

G.Rodrigues et al, Proc. $15^{th}$ Int.Workshop on ECR Ion Sources, Jyvaskyla, Finland, 2002

# Minimum-B field Confinement




Courtesy of Claude Lyneis, ECRIS 2008

# Critical parameters to produce intense beams of highly charged ions

- Ion confinement time
- Electron density
- Electron temperature

- Main ionization process is electron impact ionization, electron energy should be high to ionize (Electron temperature $T_e$)
- Step by step ionization process is most probable, necessary to keep the ions for longer time to reach the desired charge state (Ion confinement time, $\tau_c$)
- To produce intense beam, it is important to obtain high density (electron density, $n_e$)

Beam intensity

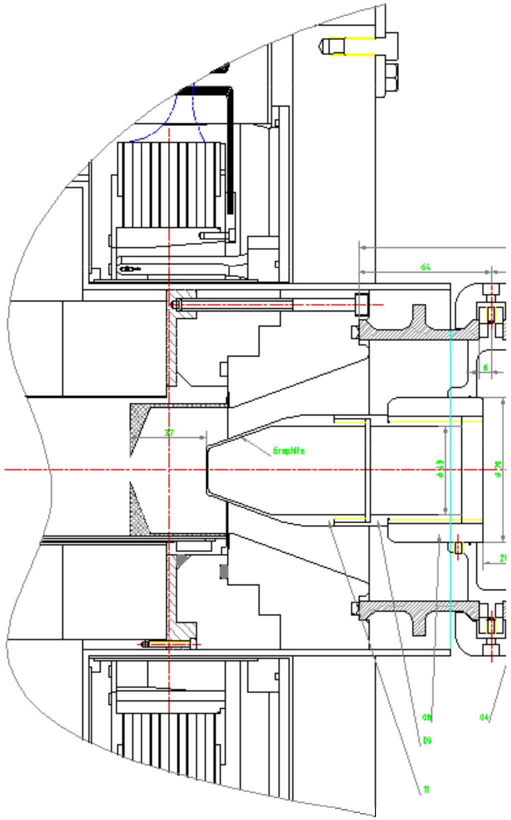
$I_q = (n_q qV/\tau_c)f_{ext}$ ; $f_{ext}$ : Efficiency of beam extraction at the extraction hole of the source

Here, $f_{ext}$, is the most important factor determining the intensities

To maximise the beam intensity,

a)Minimise $\tau_c$ and the same time keeping $n_e\tau_c$ = constant

b)Maximise $f_{ext}$ by changing several key parameters of ECRIS



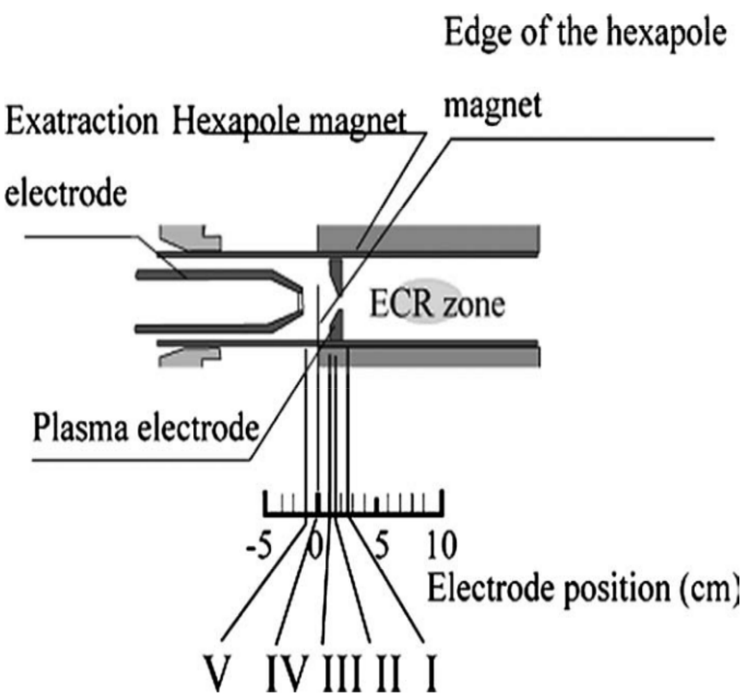
**Optimising the position of the plasma electrode**

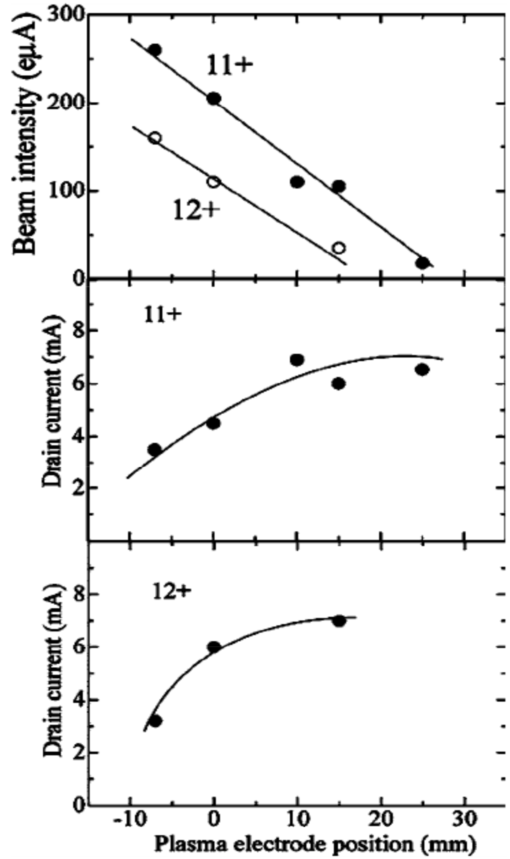
a)Moving furhter away from ECR zone gives higher beam intensities of highly charged ions

b)Moving  closer to the ECR zone gives higher beam intensities for the lower and medium charged ions

c)RIKEN and JYFL ECR ion sources have shown the experimental results

d)Clearly it shows there is an optimum position for each of the low, medium and high charge states



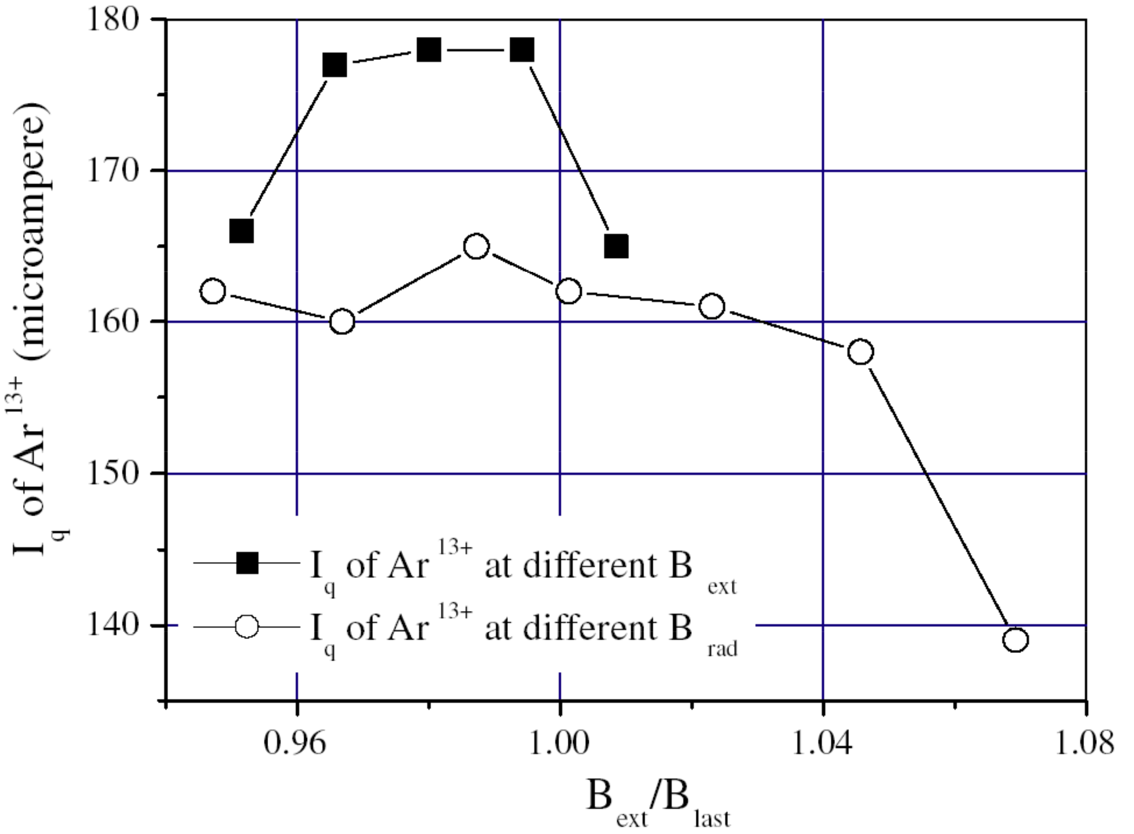

Y.Higurashi et al, Rev.Sci.Instrum 77, 03A329 (2006)
P.Suominen et al., Rev.Sci.Instrum. Vol 75,No.5 (2004)1517

- OK ! to move the plasma electrode further away from ECR zone towards the exit of the hexapole to improve the beam intensities of highly charged ions.
- But, the radial field of the hexapole decreases or the length of the hexapole is not sufficient
- There arises a situation when $B_{ext} >= B_{rad}$
- $B^2_{last}$[#] $= B^2_{min} + B^2_{rad}$

- This still does not mean that highly charged ions cannot be extracted
- That situation of extracting intense beams of highly charged ions would improve dramatically if $B_{ext} < B_{rad}$

[#] D.Hitz, Advances in Imaging and Electron Physics, vol. 144

# Example




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

# Improvements of beam intensities, etc..

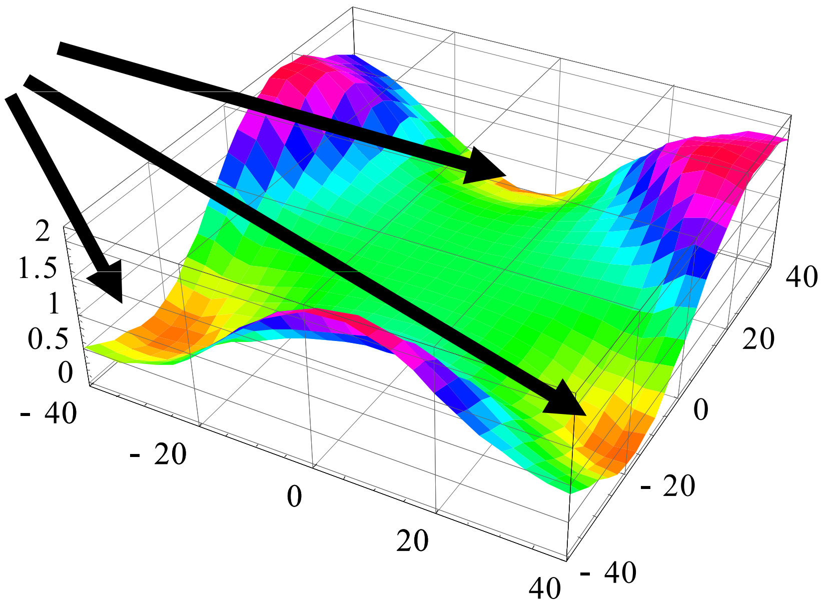
- X.Q.Xie and C.M.Lyneis, Proc.13th Int.Workshop on ECR Ion Sources,1997,pg.16
- Elimination of off-axis magnetic holes in ECR Ion Sources
- Shows it’s importance and key point

# What are magnetic holes ?

- In any plasma confinement device, there are always weak and strong field regions depending on the nature of the magnetic configurations
- Plasma confinement is usually achieved by using mirror magnetic fields
- However, in the case of an ECRIS, the superposition of radial and axial fields especially at the ends of the hexapole produces three weak regions where the plasma can escape rather than being extracted as beam. These are called “magnetic holes”

# How does a magnetic hole look ?

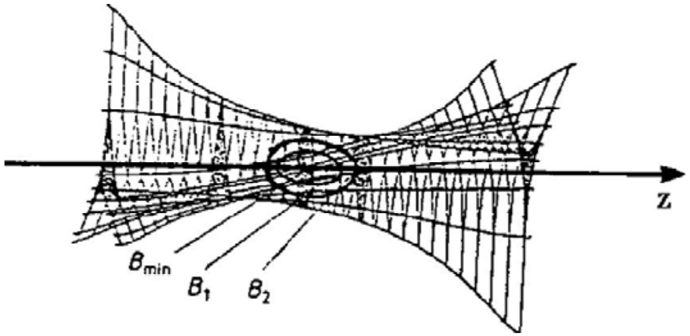
Three weaker field regions which are off-axes (close to the chamber surface) when compared to the field at the extraction electrode where the field is higher,the plasma can escape than being extracted

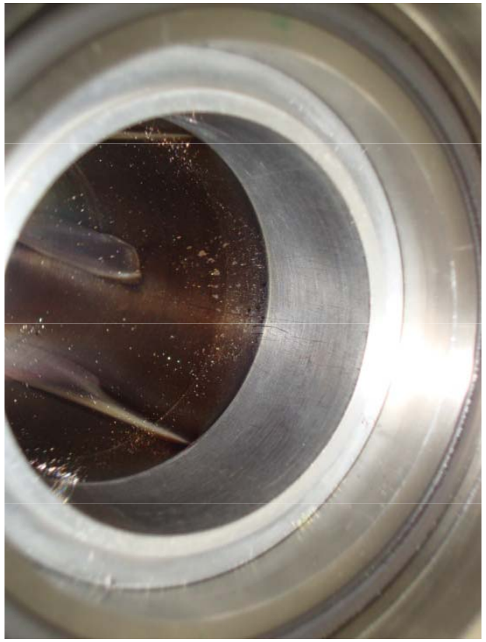


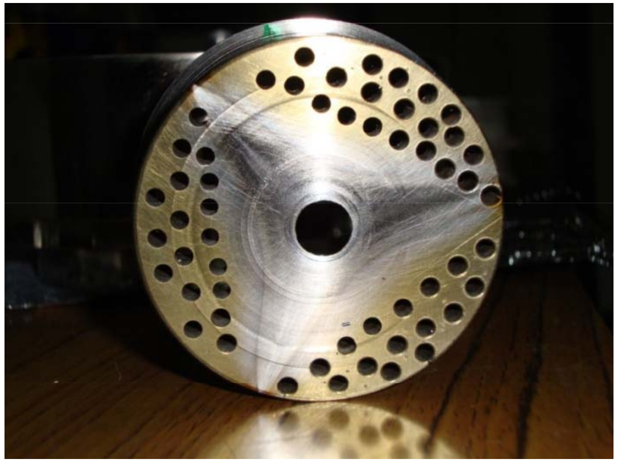

1. $B_{ext}$ >= $B_{last}$
2. $B_{ext}$ < $B_{last}$

$B_{ext}$ – field at extraction
$B_{last}$ –last closed ECR surface within the plasma chamber

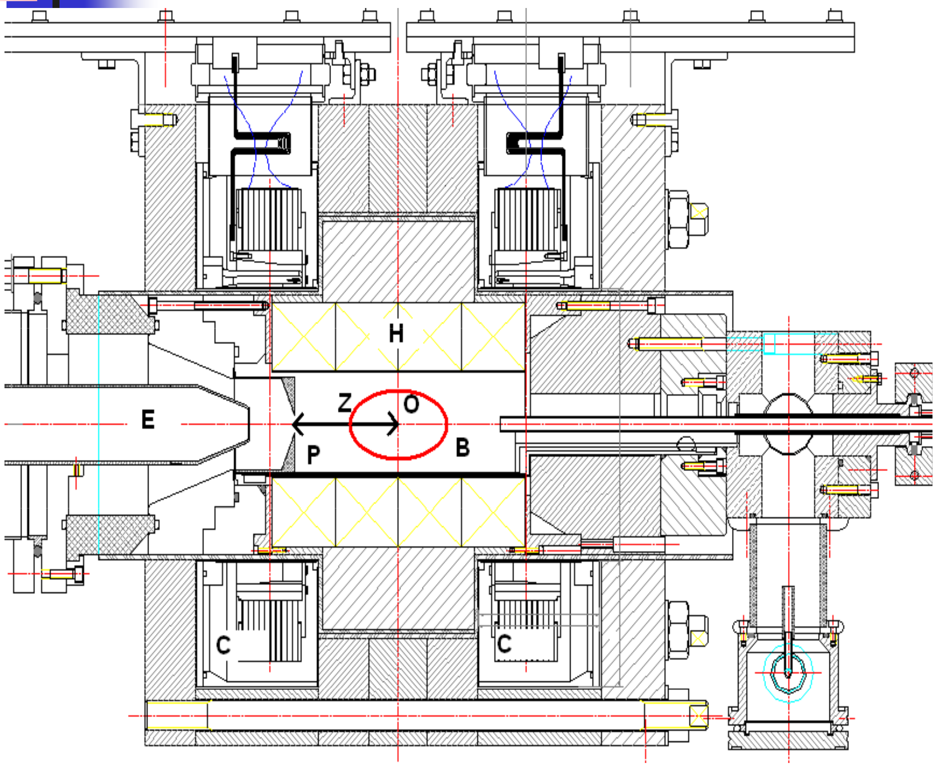
# ECRIS Plasma shape and impact on wall, electrodes

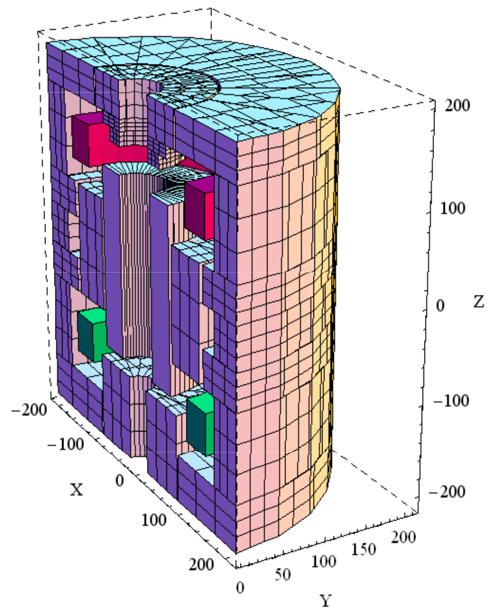


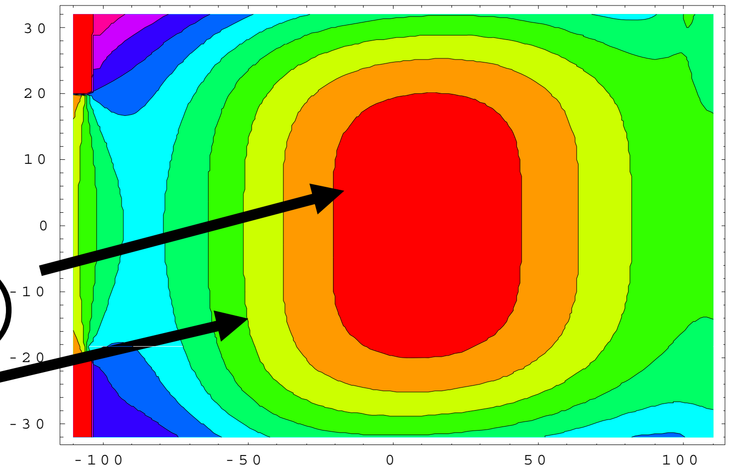





# HTS-ECRIS Magnetic structure



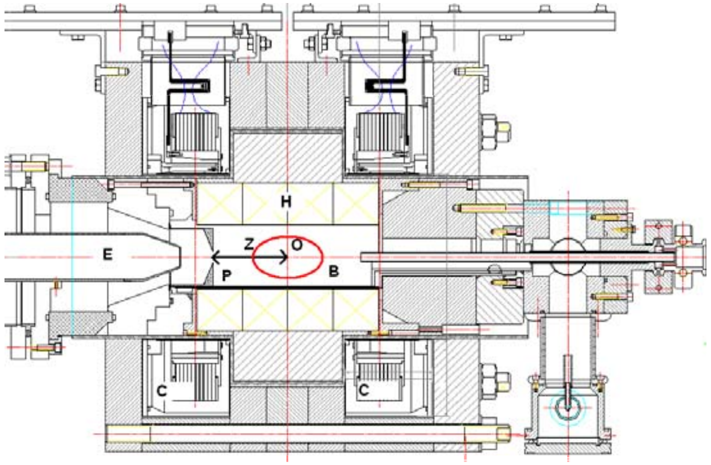



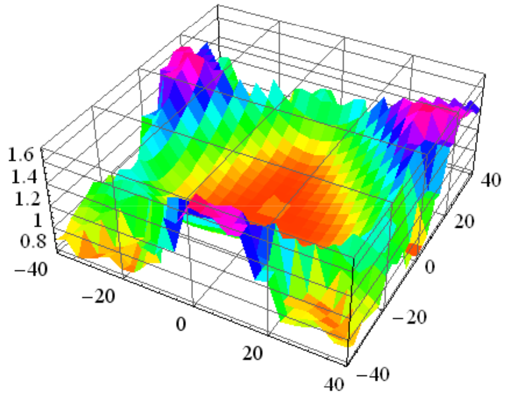

$B_{ecr}$ (0.6428 T)

$B_{last} = 2B_{ecr}$

http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/Radia

# Plasma electrode position, z=82.5 mm,$B_{rad}$=12.5kG,$B_{ext}$ =8 kG

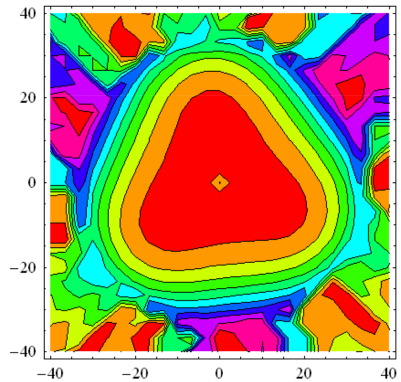


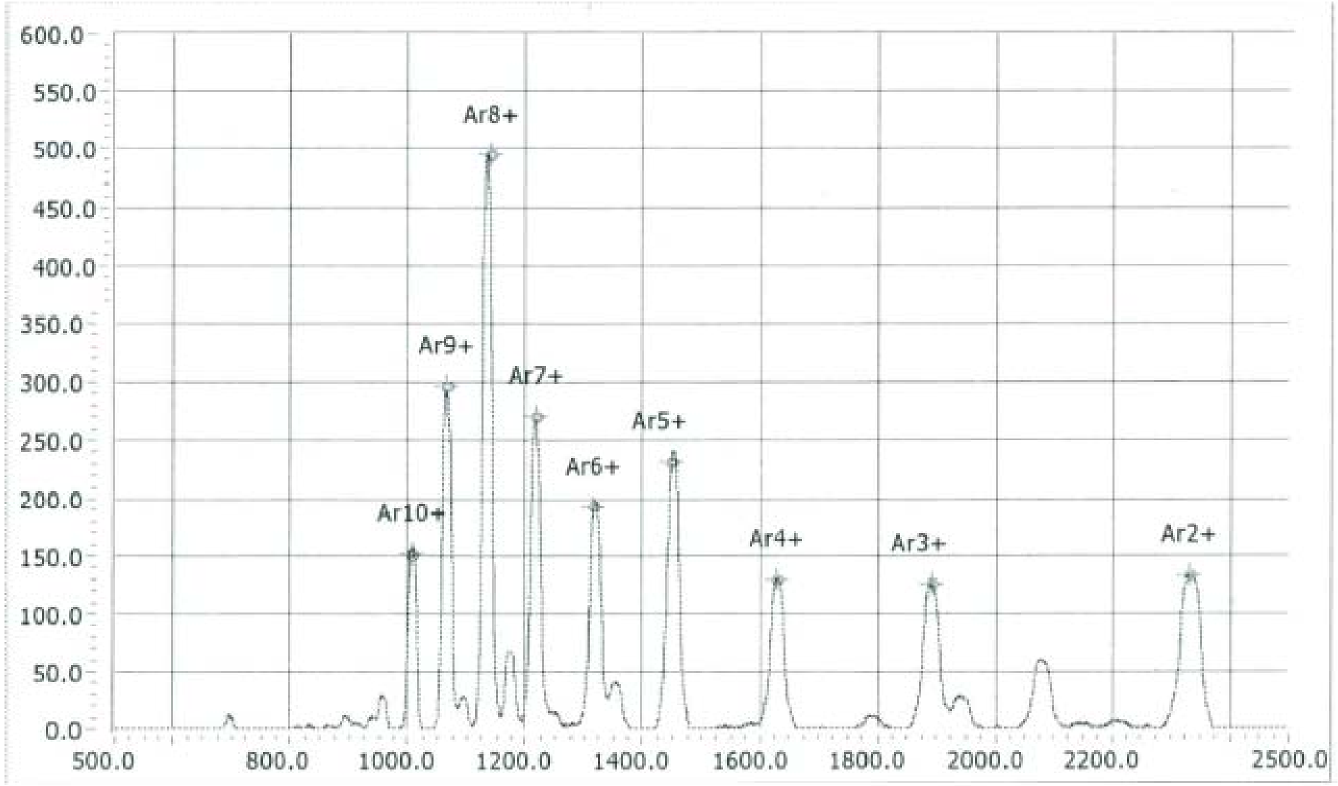

Not the best position to extract intense beams of highly charged ions

Medium and low charged ions is OK

No magnetic holes exist in this case



# Optimization on $Ar^{8+}$ (using gas mixing, 14.5 Ghz, 500 W)

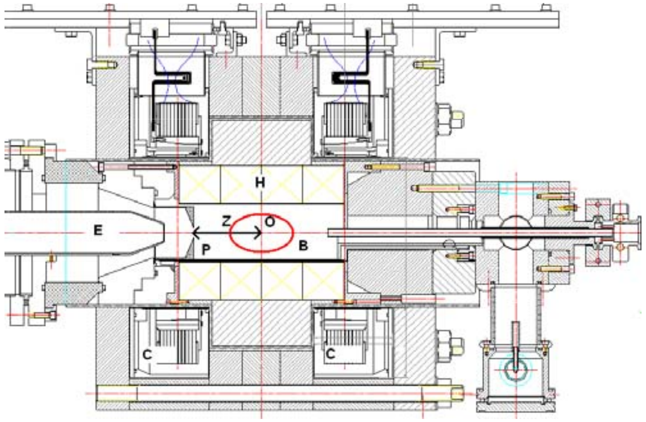


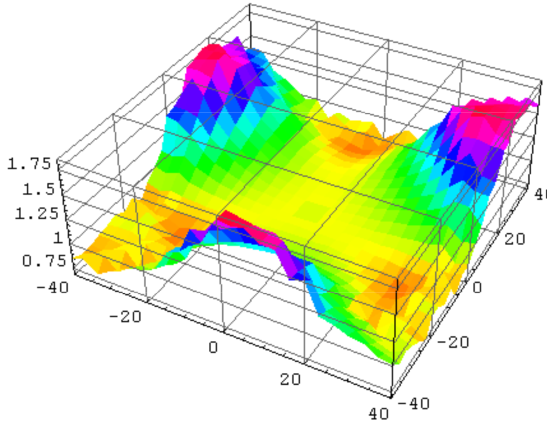

Maximum extracted beam of Ar8+ = 720 μA !!!

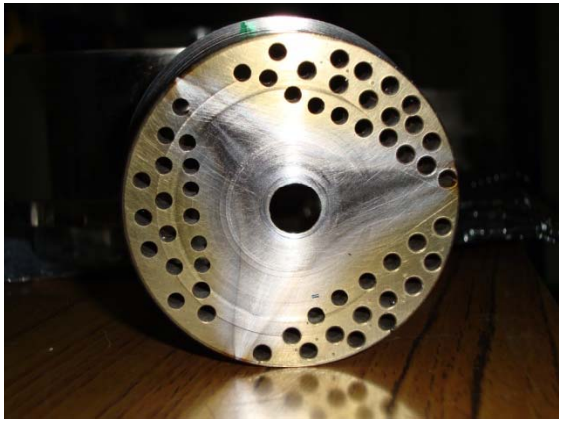
D.Kanjilal et al., Rev.Sci.Instrum.,77 (2006) 03A317

- Tried to explore moving the plasma electrode away from the ECR zone
- From z=82.5 to 98 mm (total length of hexapole = 200 mm)
- At this position, Brad=0.9 T, Bext=0.94 T
- Clearly, the loss favour is more to the wall.....

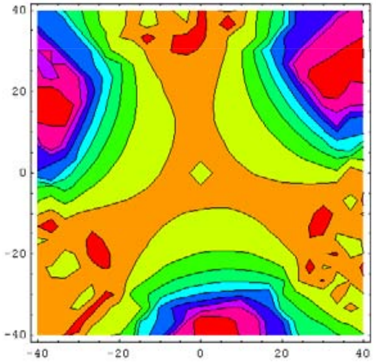
# Plasma electrode position, z=98 mm, $B_{rad}$=9.0 kG,$B_{ext}$=9.4 kG



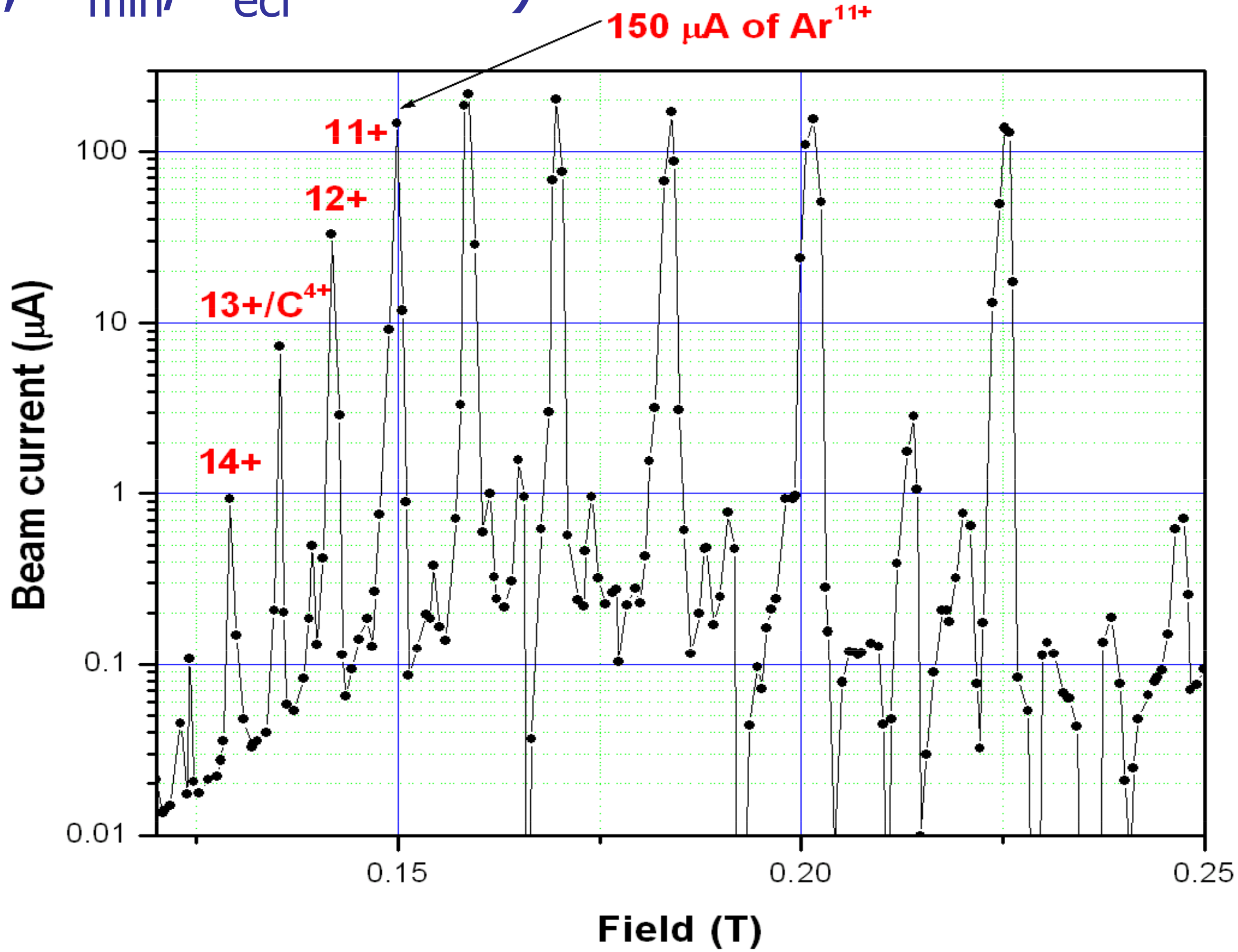



Existence of magnetic holes



# Optimization on $Ar^{11+}$ (no gas mixing,400 W, 18 Ghz, $B_{min}/B_{ecr}$ =0.65)



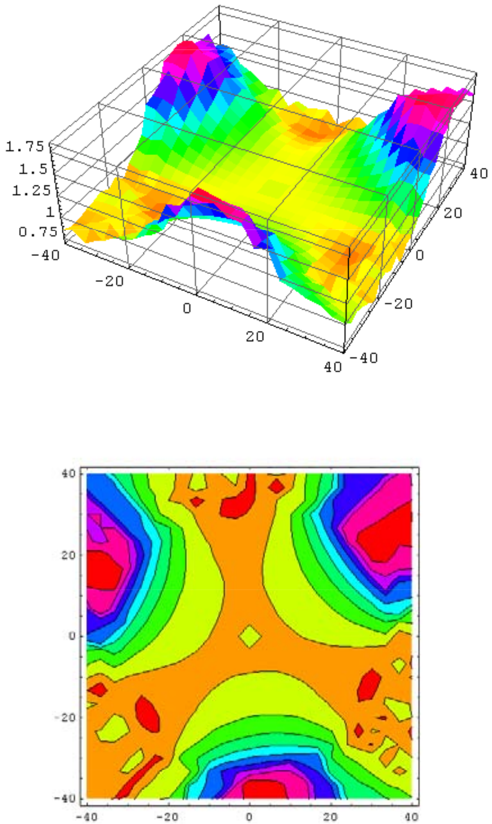

Optimum position for extracting highly charged ions, but .......

G.Rodrigues et al., Rev.Sci.Instrum. Vol 81,02A323 (2010)

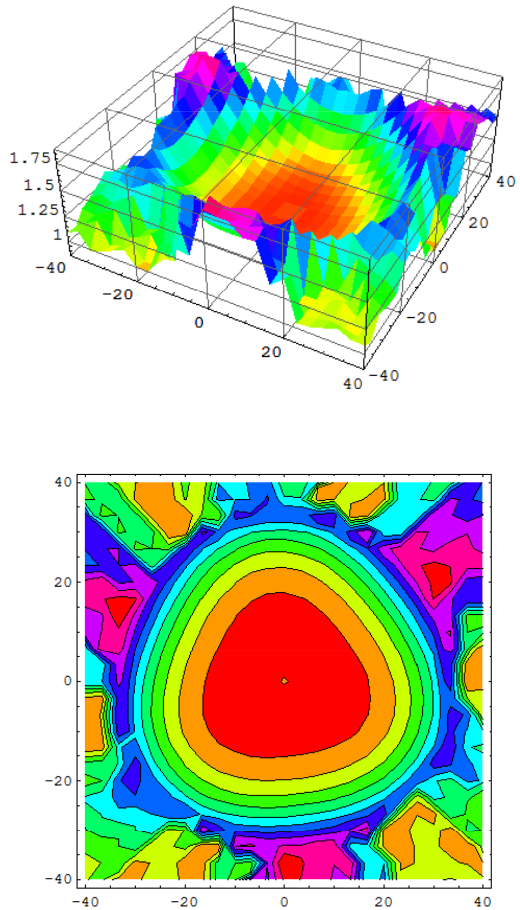
## How to optimise the magnetic holes to further improve the intensities of highly charged ions ?

- Solution is to extend the effective length of the hexapole by various means
- Increase it's physical length
- Add iron such that the effective length increases
- More economic to tune the field using iron

## Hexapole length increased by 25 mm
## Plasma electrode position, z=98 mm, $B_{rad}$ =12.5 kG, $B_{ext}$ = 9.4 kG



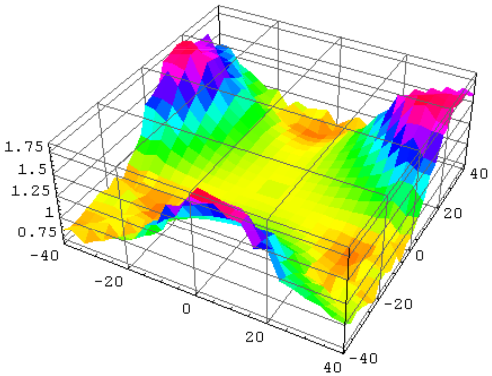

Before (with magnetic holes)

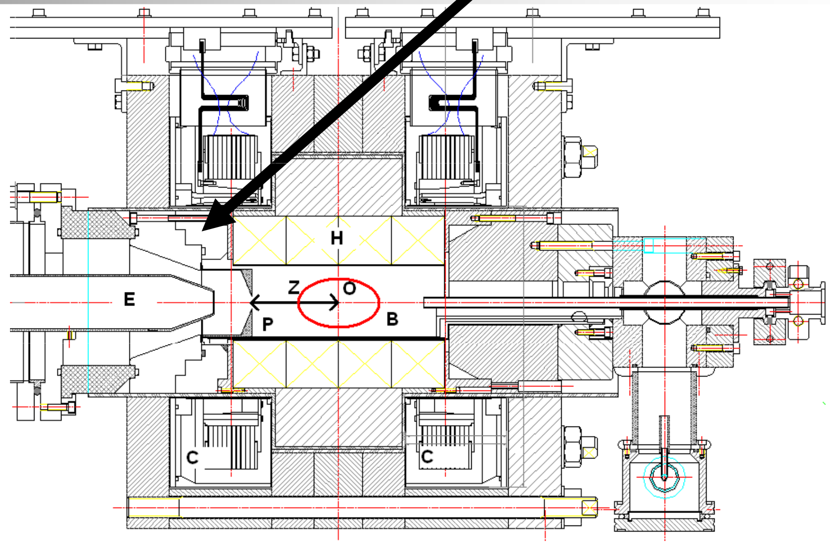


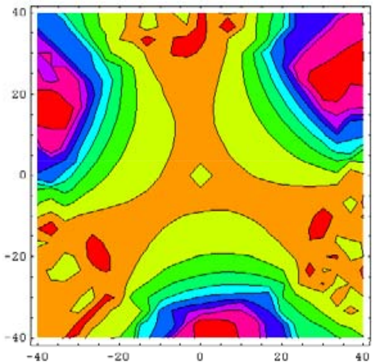

After (no magnetic holes)

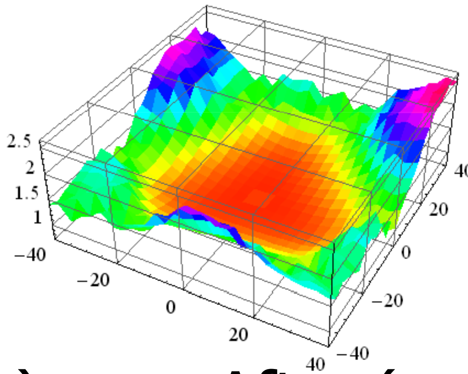
Hexapole effective length increased by adding iron

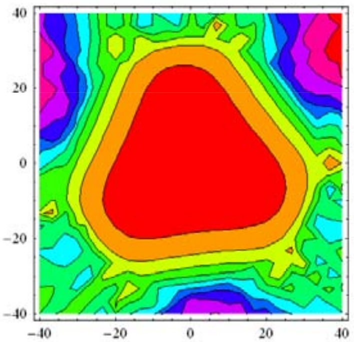
plasma electrode position,z=98 mm, $B_{rad}$ =12.5 kG, $B_{ext}$ = 9.4 kG




Before (with magnetic holes)

After (no magnetic holes)

# Summary and Conclusions

- The technique shows definite improvements in the field for the magnetic holes
- Efficiency is expected to scale 'three-fold'
- Intense beams for the highly charged ions
- Localized heating of the plasma chamber can be reduced, with better vacuum conditions
- Lifetime of synthetic high voltage insulators for the plasma chamber can be increased
- For fully sc sources, the heat load to the cryostats and localized heating in the sc coils (quenches) can be reduced

# Thank You

# For Your Kind Attention