CYCLOTRONS 2007, Giardini Naxos, Messina, Italy

Progress and perspective for high frequency, high performance superconducting ECR Ion Sources

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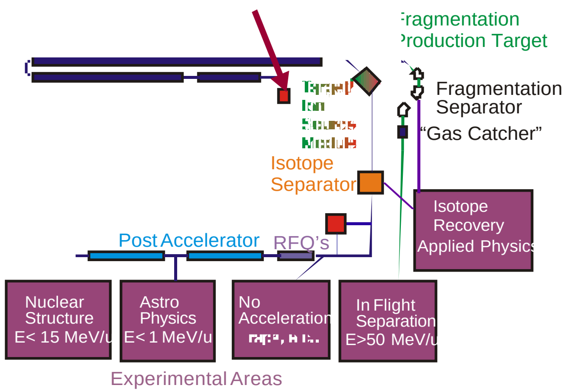
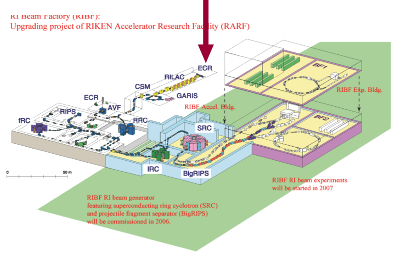
- Introduction
- 3rd Generation ECR ions source / VENUS project
- Key parameters for the performance of an ECR
- Recent results from VENUS
- Perspectives on 4th generation ECR ion sources

The requirements of next generation heavy ion facilities made the development of 3rd Generation sources (and maybe 4th Generation) ECR ion sources necessary

VENUS,
270 eμA U^{33+} and 270 eμA U^{34+}

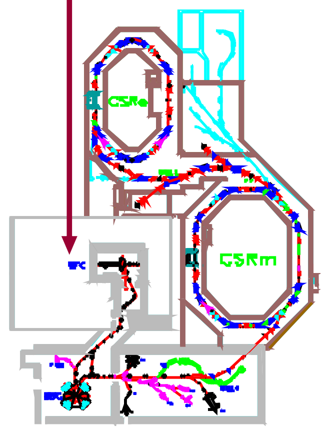


SC-ECRIS,
RIKEN, Japan



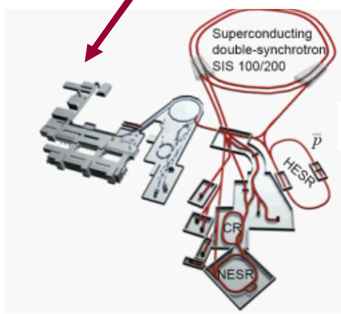
525 eμA U^{35+}

SECRAL,
Lanzhou, China
H. Zhao

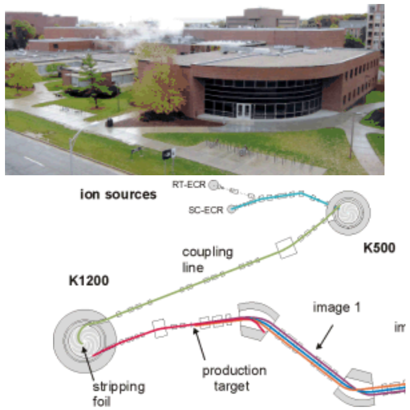


50-100 eμA U^{41+}

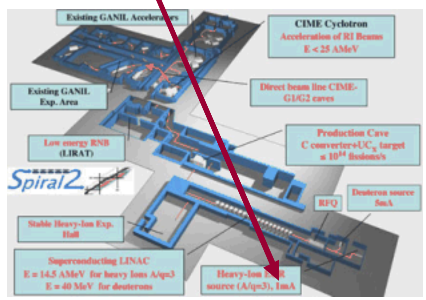
MS ECRIS
GSI, Germany



SuSI
NSCL,USA

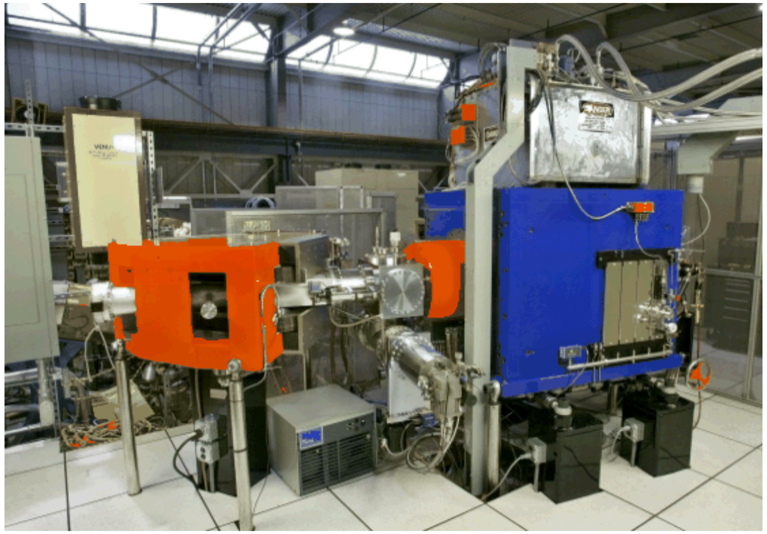


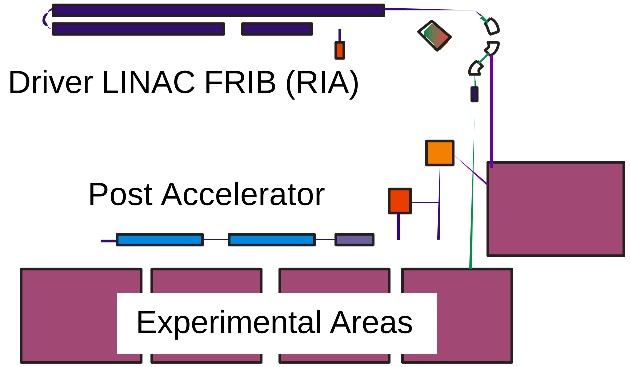
SPIRAL 2,
GANIL, France



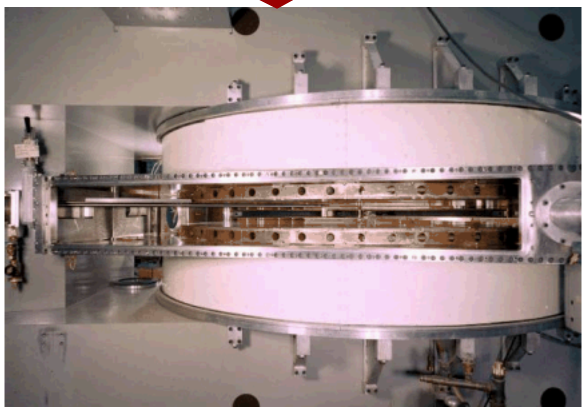
1mA Ar^{12+}

VENUS has a dual mission: Major upgrade for the 88-Inch Cyclotron and prototype for next generation heavy ion facilities

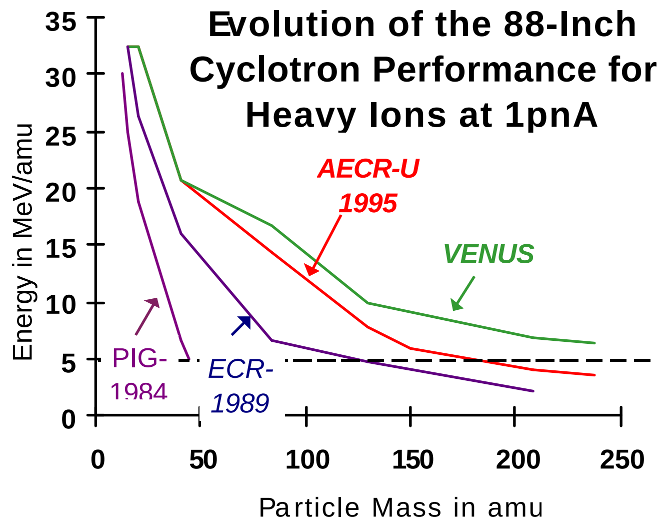




Provide (very) high intensity high-charge state beams for the next generation heavy ion accelerators q/A .14



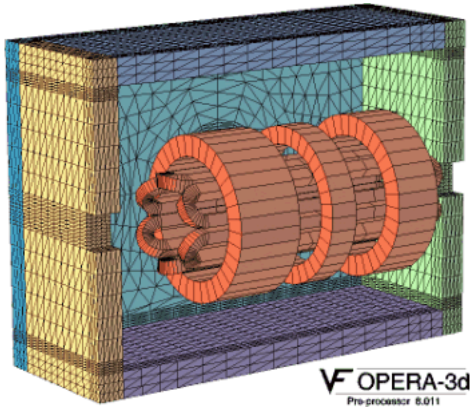
Produce intense (very) high-charge-state heavy ion-beams for the 88-Inch Cyclotron q/A .2 to .5



VENUS is the first and currently only high field SC ECR ion source optimized for and operated at 28 GHz

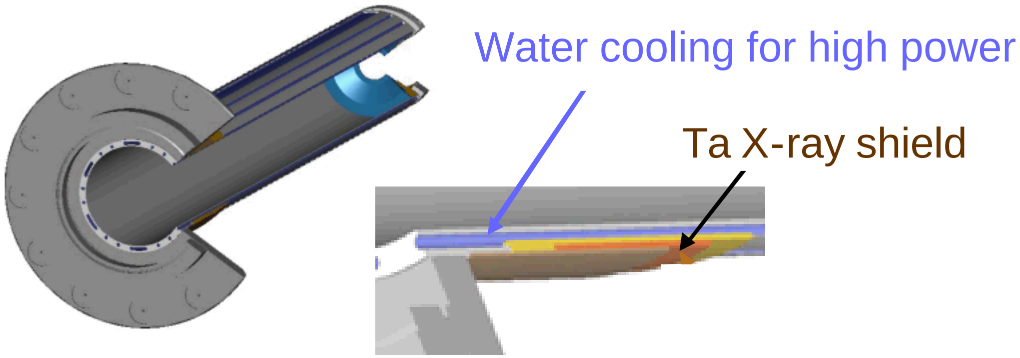
Design solutions developed in VENUS have been incorporated in the design of other 3rd generation ECR ion sources

Superconducting magnets state of the art cryostat

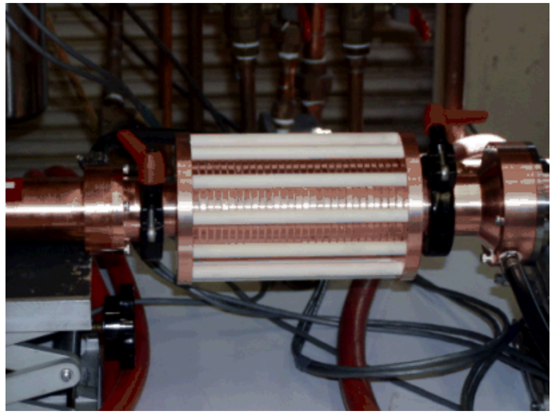


Beam transport with high transmission dipole magnet

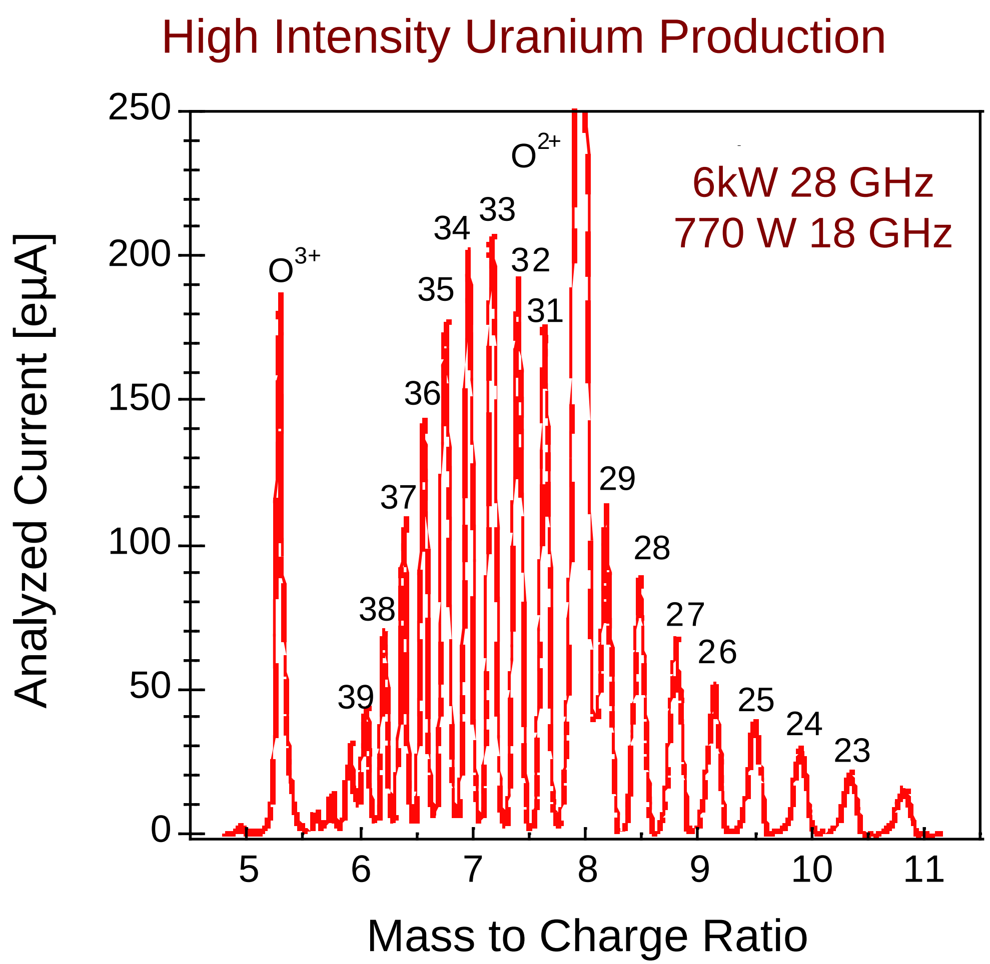
Aluminum plasma chamber for high power operation with incorporated x-ray shield



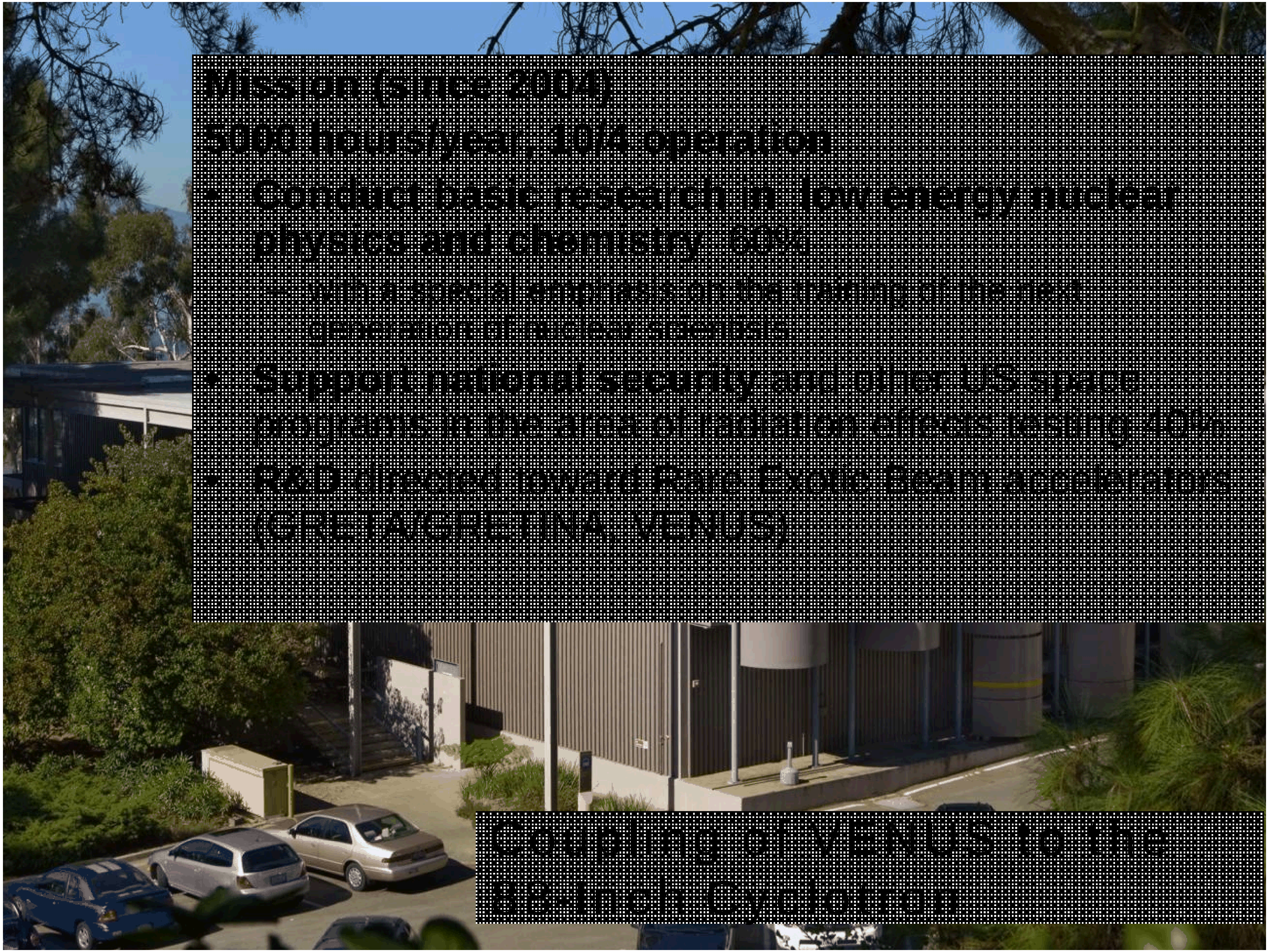
28 GHz microwave technology



The demonstrated source performance show that the next generation accelerator performance requirements are possible



	VENUS 28GHz or 28+18 GHz	SECRAL (18 GHz) e• A
O^{6+}	2860 e• A	2300 e• A
O^{7+}	850 e• A	810 e• A
O^{8+}	~ 400 e• A	
Ar^{12+}	860 e• A	510 e• A
Ar^{17+}	36 e• A	8.5 e• A
Xe^{35+}	28 e• A	12 e• A
Xe^{42+}	.5 e• A	
U^{34+}	200 e• A	
U^{47+}	5 e• A	



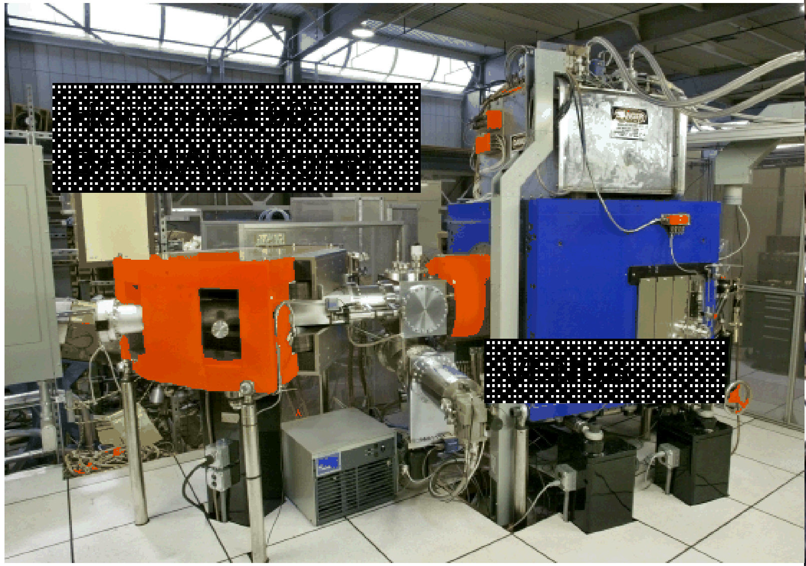
Mission (since 2004)

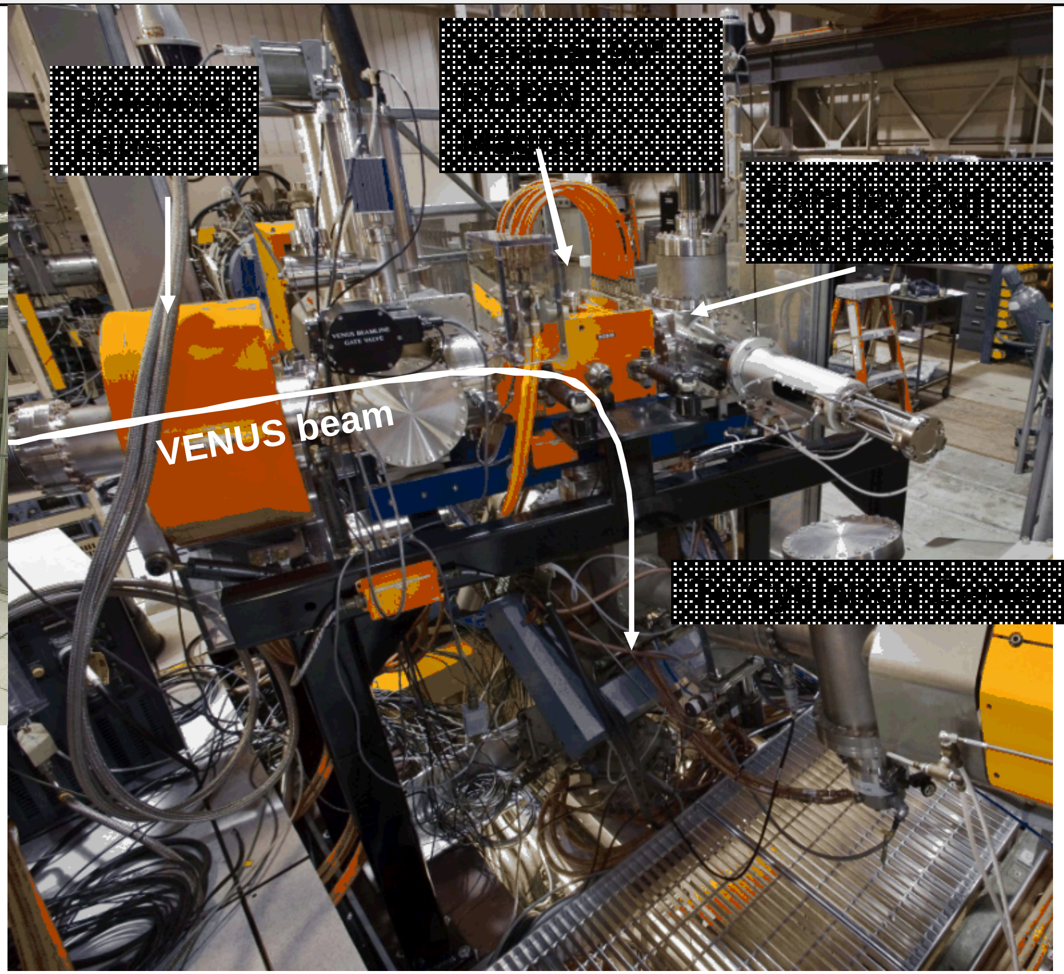
5000 hours/year, 10/4 operation

- **Conduct basic research in low energy nuclear physics and chemistry** 60%
  - with a special emphasis on the training of the next generation of nuclear scientists
- **Support national security** and other US space programs in the area of radiation effects testing 40%
- **R&D** directed toward Rare Exotic Beam accelerators (GRETA/GRETINA, VENUS)

Coupling of VENUS to the 88-Inch Cyclotron

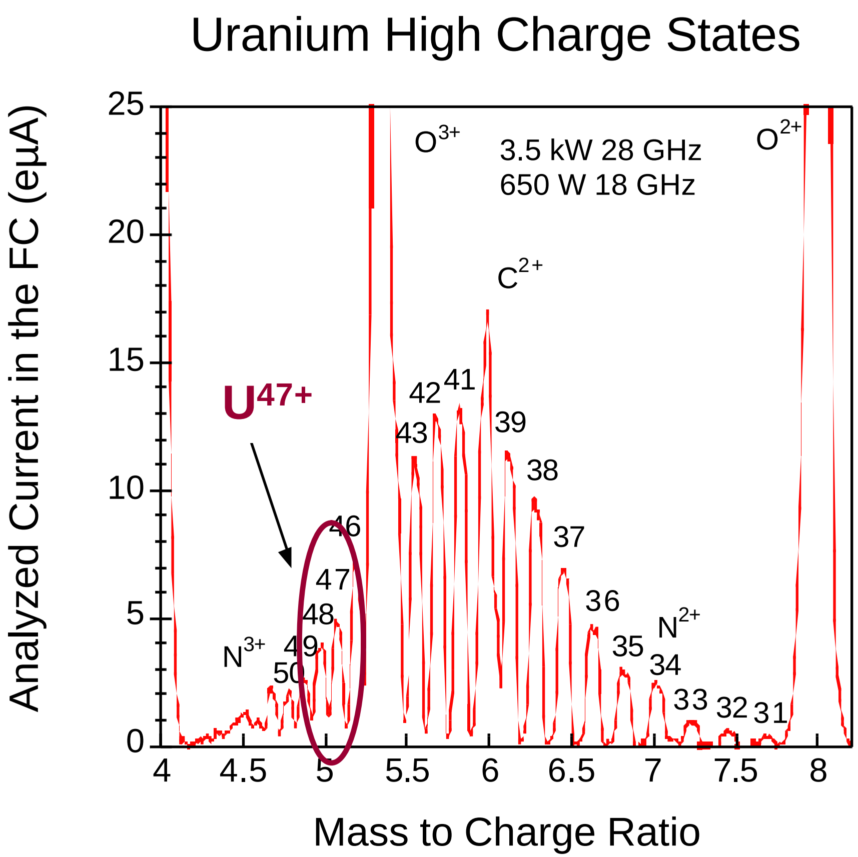
Beam line connection into the axial injection line





First Beam from VENUS extracted from the Cyclotron September 2006, Ar^{9+} at 200 MeV

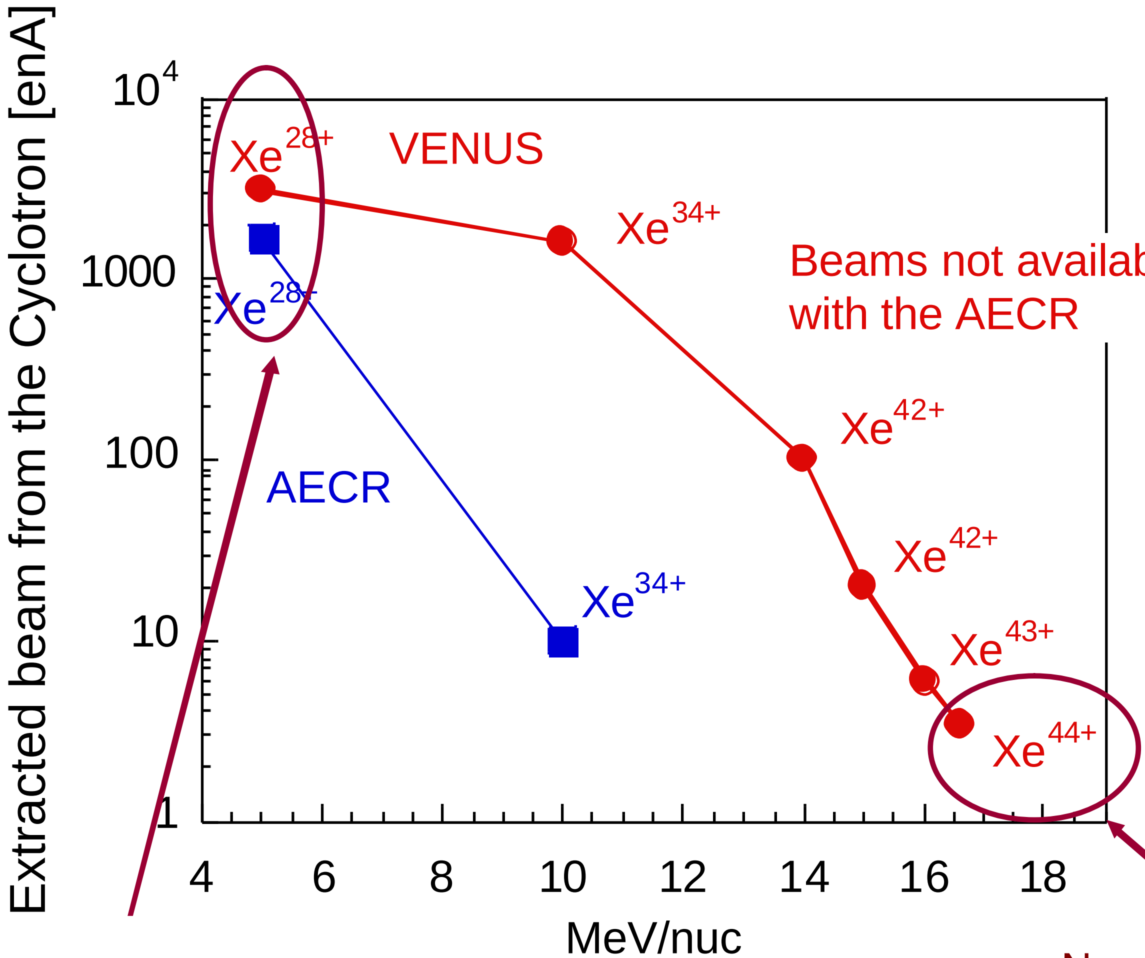
Beam developments with heavy ion beams show the potential of VENUS to boost the energy and intensity out of the 88-Inch Cyclotron



- 11x more beam extracted than with the AECR, uranium intensities make nuclear structure experiments feasible
- 160 x more Xe beam intensity was extracted at 10MeV/nuc
- 80 x more Kr beam intensity was extracted at 10 MeV/nuc

First commissioning experiments for high charge state heavy ions have been promising

Xenon beam developments show big gains for high charge state ion beams, but smaller or no gains at lower charge states



88-Inch Cyclotron
K=140

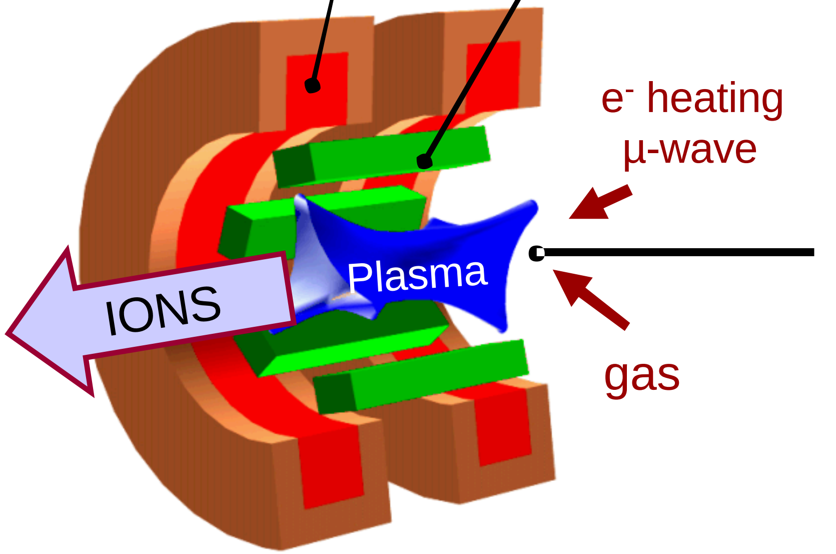
Beam intensity is space charge limited in the injection line, and by the buncher gradient
upgrade of the cyclotron center region and injection line will be necessary.

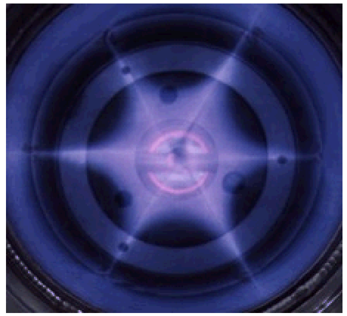
Neon like Xe has been extracted, pointing to plasma densities ~$10^{12}/cm^3$
($n_e \tau_i \sim 2 \cdot 10^{11}$ sec/cm^3)

Plasma is resonantly heated with microwaves

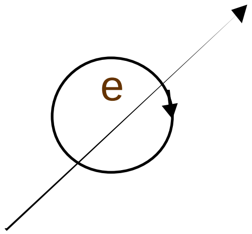
$$w_e = \frac{e \bullet B}{m} = w_{rf}$$

Solenoids and Sextupole form a minimum-B field confinement structure





Magnetic flux line



$$q \cdot v \cdot B = m \cdot w^2 \cdot r$$

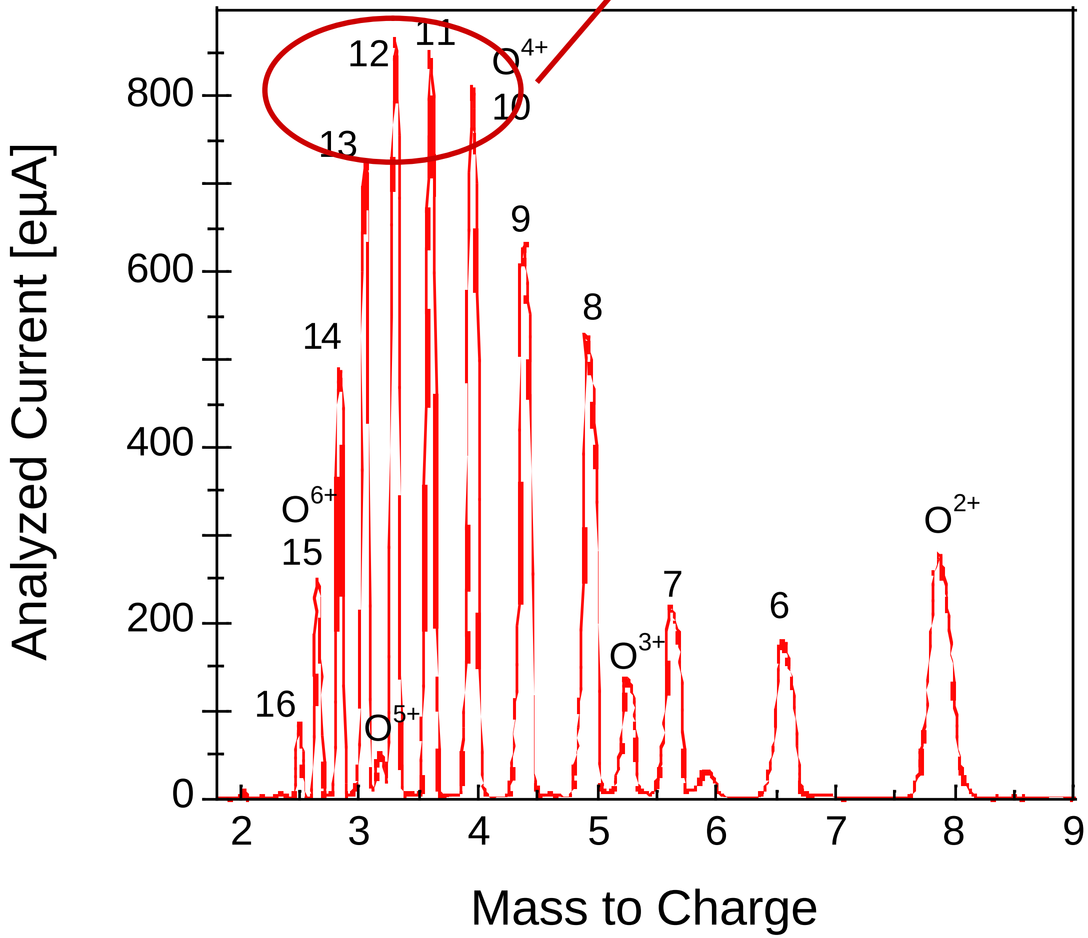
$$r = \frac{m \cdot v}{q \cdot B}$$

f=28 GHz, B= 1T

r_{Lamor}=0.01…1 mm

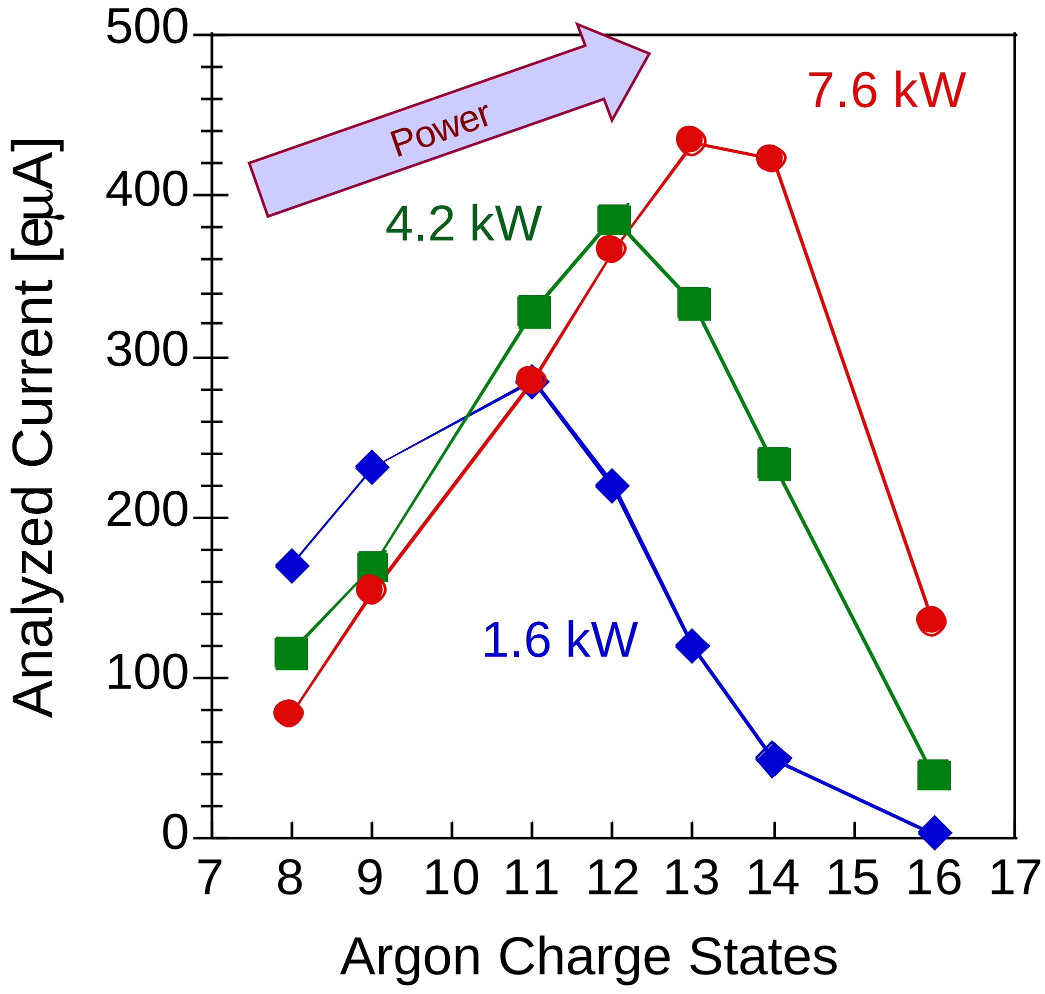
Key parameters	
Ion confinement times t_i	**~ms**
Plasma densities n_e	**10^9 - 10^{12} /cm³**
Electron temperature T_e	eV to MeV
Charge exchange/ neutral gas density σ_{ex}	$q^{1.17} \times I_p^{-2.76} \times 10^{-12} cm^2$

Motivation: 1mA Ar^{12+} for the SPIRAL II Project



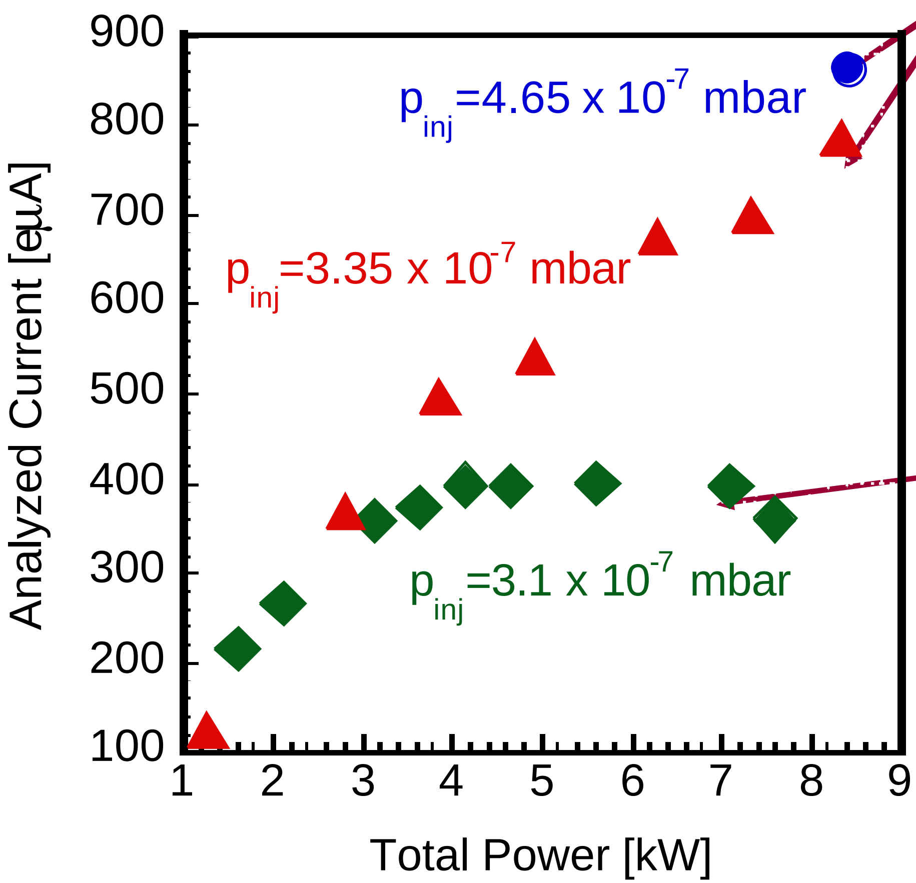
Ar	VENUS (28GHz) e• A
12^+	860
14^+	514
16^+	270
17^+	36
18^+	1

Product of $n_e \bullet t_i$ increases with power



The argon CSD shifts from lower charge states to higher charge state for constant gas flow and same confinement fields as the power coupled to the plasma increases.

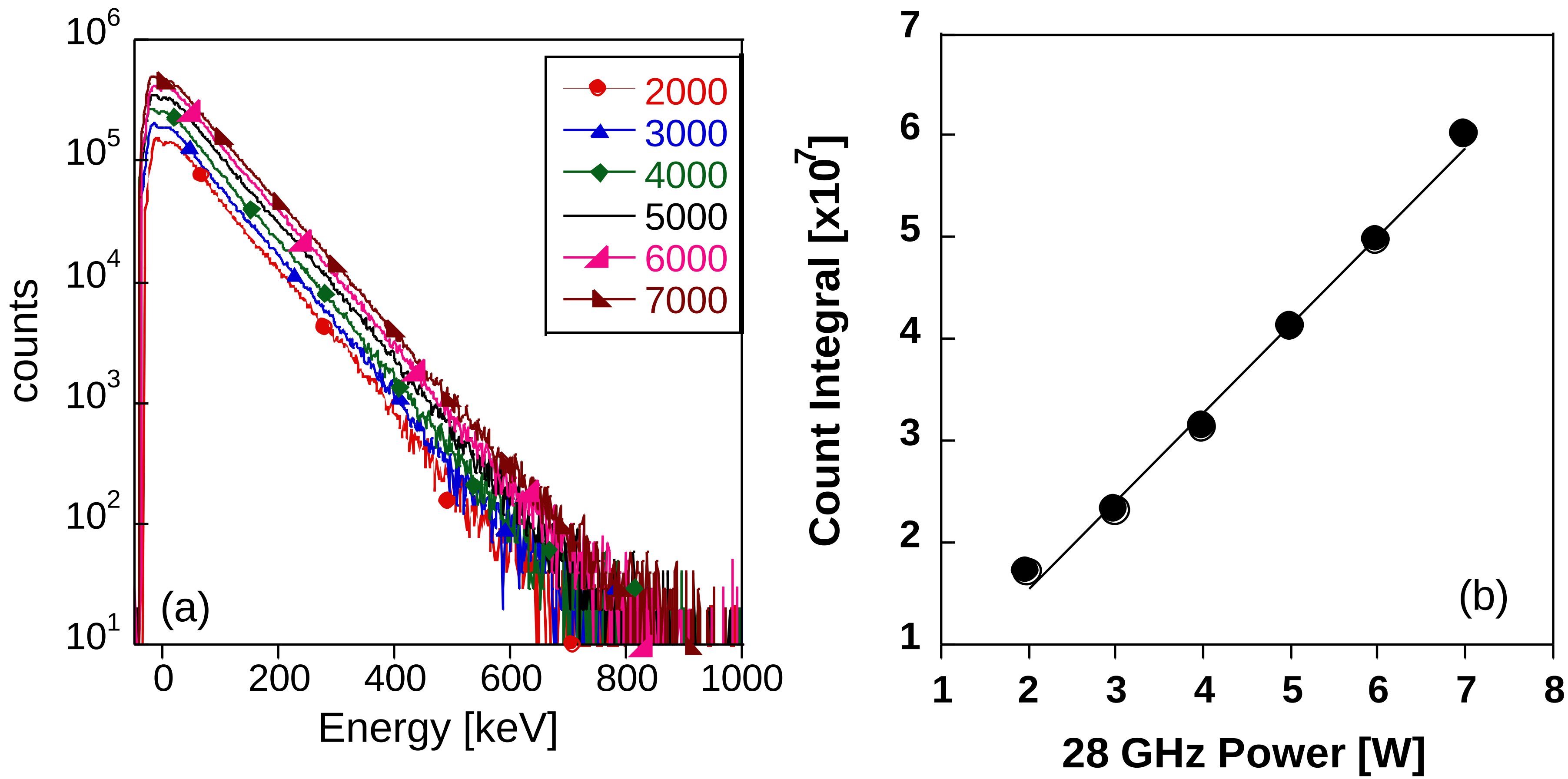
Product of $n_e \cdot t_i$ increases with power



To keep the CSD peaked on Ar^{12+} more gas needs to be added to the plasma

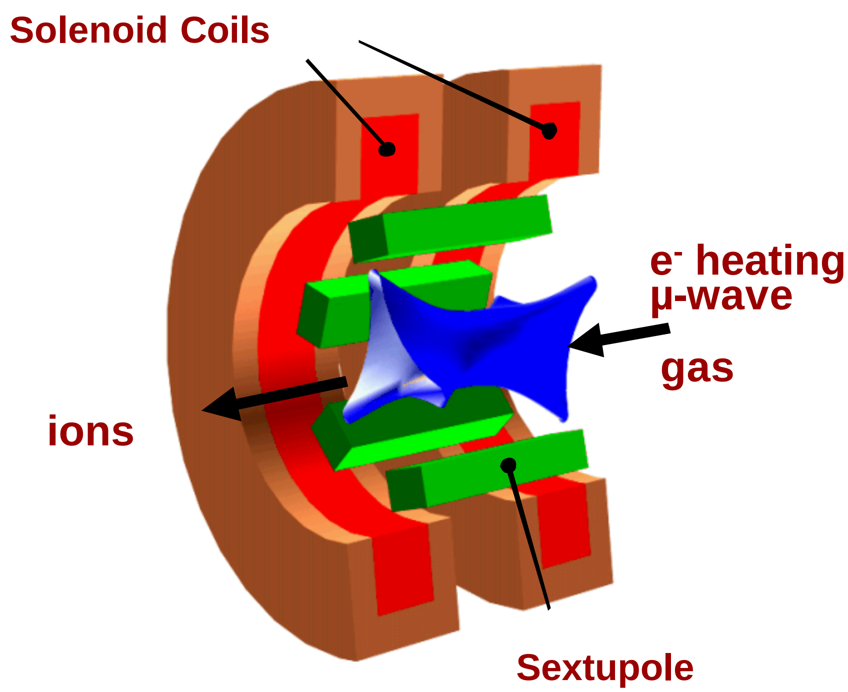
CSD is shifted to higher charge states

Axial bremstrahlung measurements indicate an increase in plasma density with power



The energy spectra of electrons does not change with power
Electron temperature remains constant

Next Generation ECR Ion Sources
Higher magnetic fields and higher frequencies



Minimum-B field Confinement

$$W_e = \frac{e \bullet B}{m} = W_{rf}$$

$n_e \propto \bullet_{rf}^2$

$\tau_{ion} \propto B_{max}/B_{min}$

$I \propto \bullet_{rf}^2/M$

$I \propto n_{ion} / \tau_{ion}$

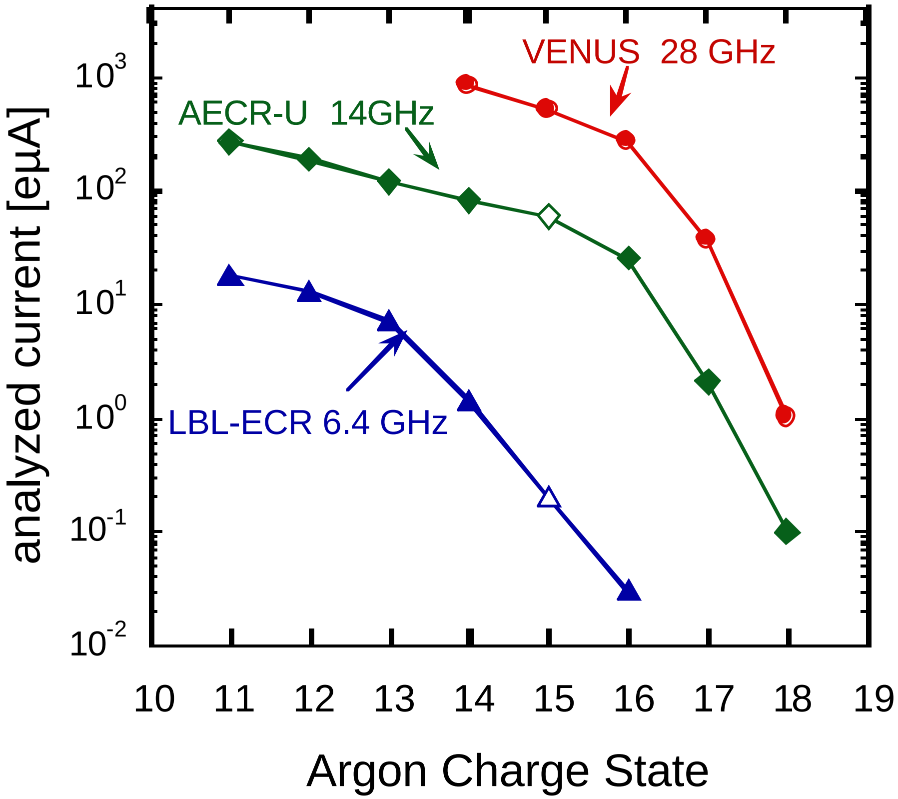
28 GHz B_{ECR}= 1 Tesla

56 GHz B_{ECR}= 2 Tesla

To achieve optimum confinement fields superconducting magnets are necessary

Next Generation ECR Ion Sources
Higher magnetic fields and higher frequencies

Argon beam intensities for the LBNL ECR, AECR and VENUS



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28 GHz B_{ECR}= 1 Tesla

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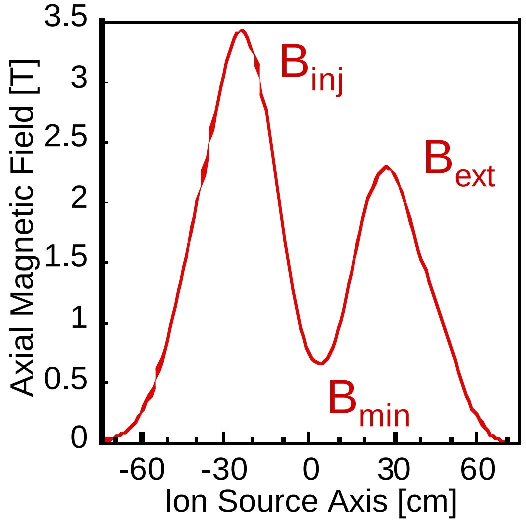
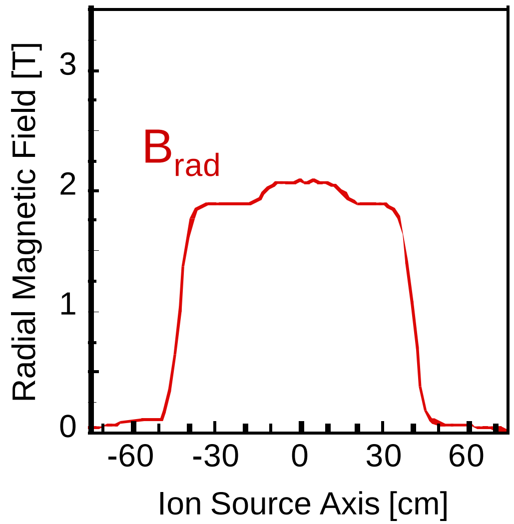
To achieve optimum confinement fields superconducting magnets are necessary

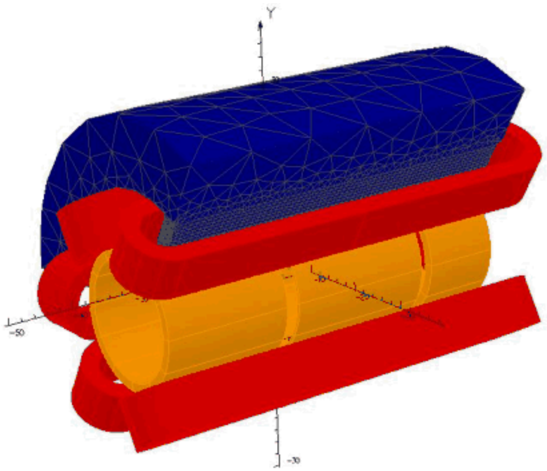
ECR Design ‘Standard Model’

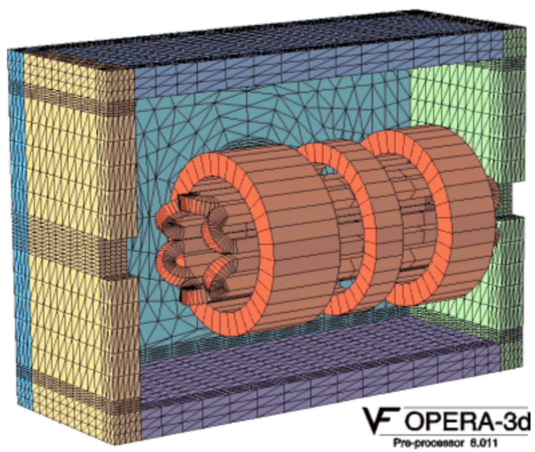
		56 GHz
B_{inj}	~ 4 • B_{ecr}	8T
B_{min}	~ 0.8 B_{ecr}	1-1.6 T
B_{ext}	~ B_{rad}	4T
B_{rad}	• 2 B_{ecr}	4T

28 GHz VENUS Tune



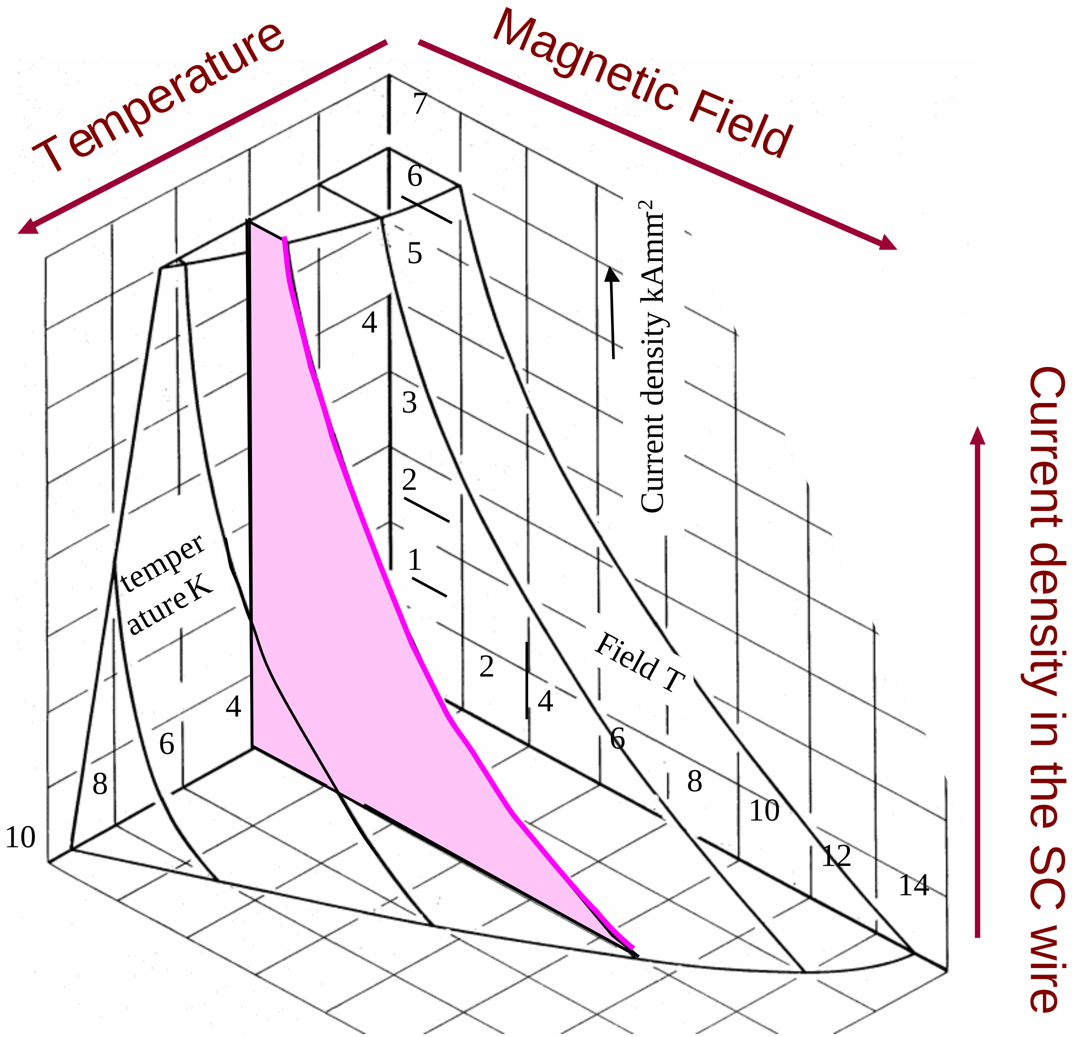






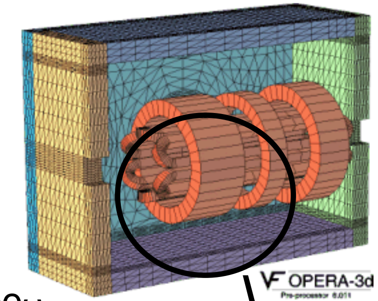
Main challenge for are the forces between the sextupole and solenoid magnet coils and the maximum field on the superconductor

Critical line and magnet load lines

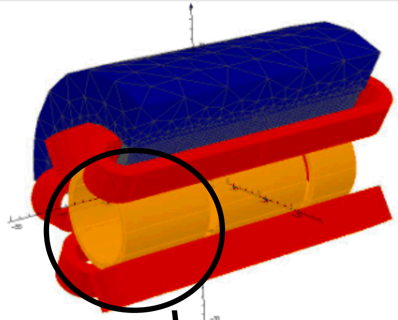


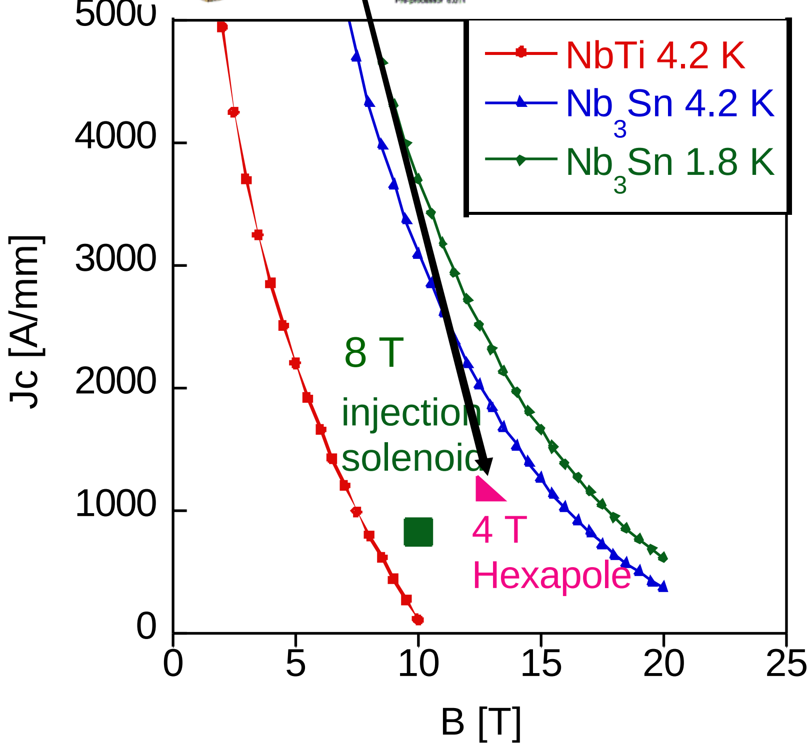
Martin Wilson, Superconducting Magnets,
Oxford University Press

Preliminary Analyses of a 56 GHz source

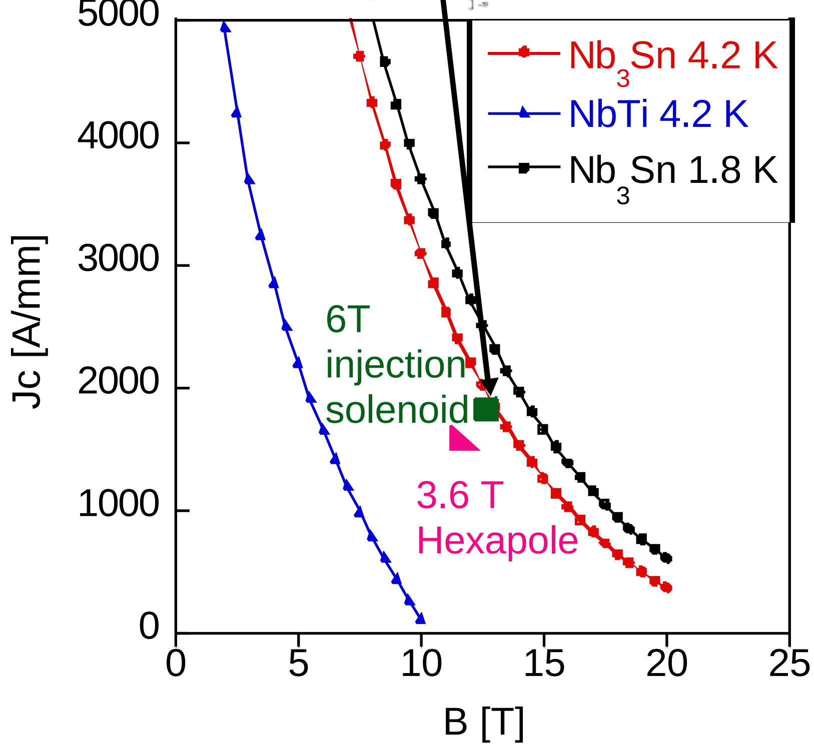


In both cases the clamping will be very challenging, since the forces increase a factor of 4





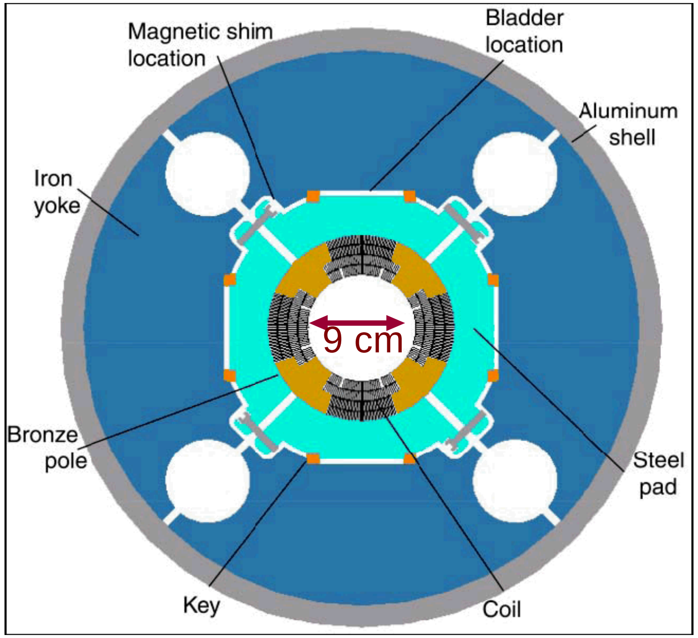
Critical component in the traditional design is the maximum field at the sextupole coil.

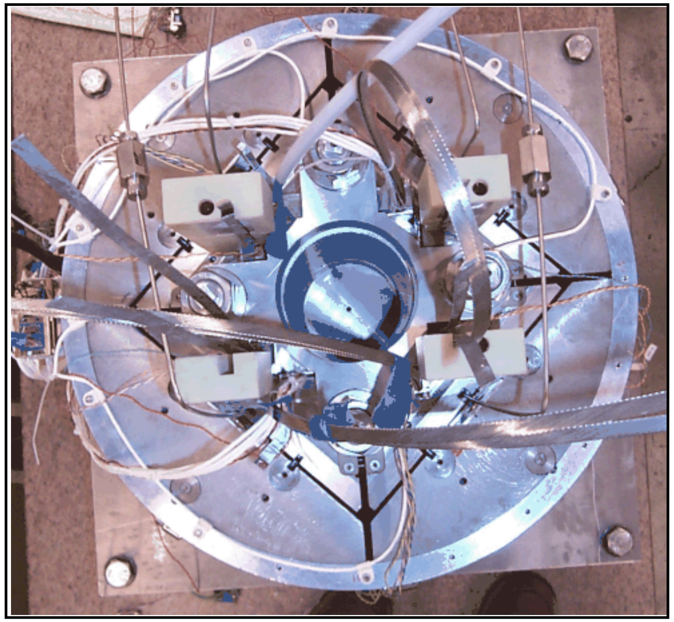


Critical component in the inverted design is the maximum field at the injection solenoid coil

Status of high field Nb_3Sn Magnets

G. Sabbi et al., “Nb_3Sn quadrupole magnets for the LHC IR”, ASC 2002, Houston (TX), August 2002.



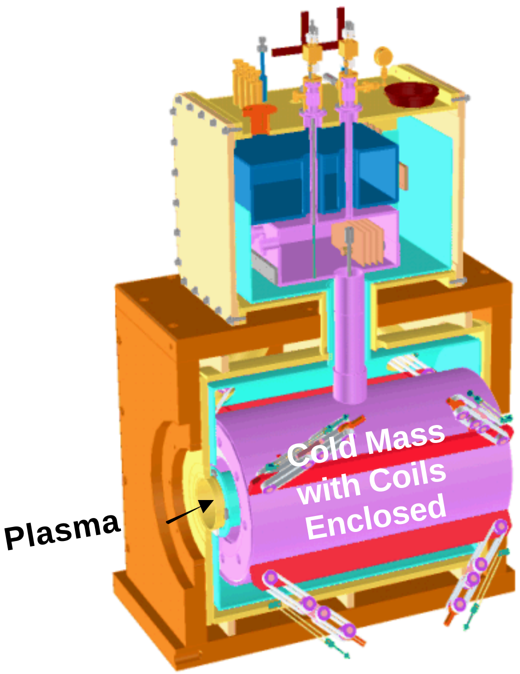


	Peak field	
Solenoid	22 T	Commercial
Dipole	13 T	National Labs, including LBNL
Quadrupole	10 T tested 11 T under development	National Labs, including LBNL

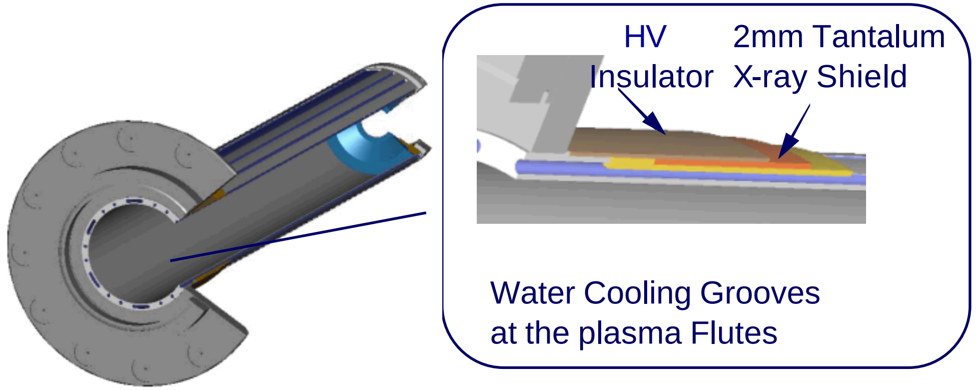
Perspectives on 4^{th} Generation Sources

Other Challenges

A major challenge for high field SC ECR ion sources is the heat load from bremsstrahlung absorbed in the cryostat



Technical Solution
VENUS Aluminum Plasma Chamber with 2mm Ta x-ray shield



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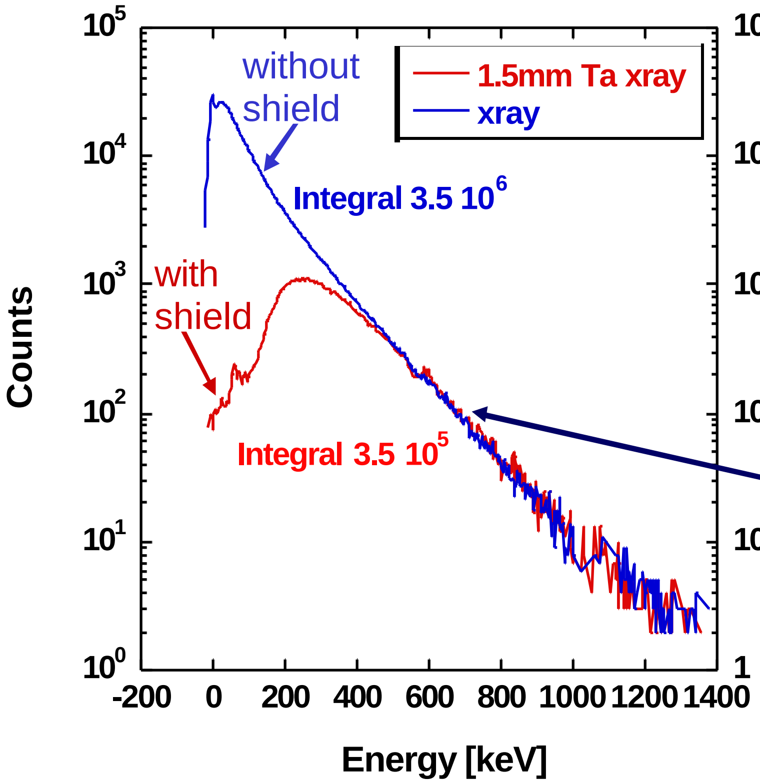
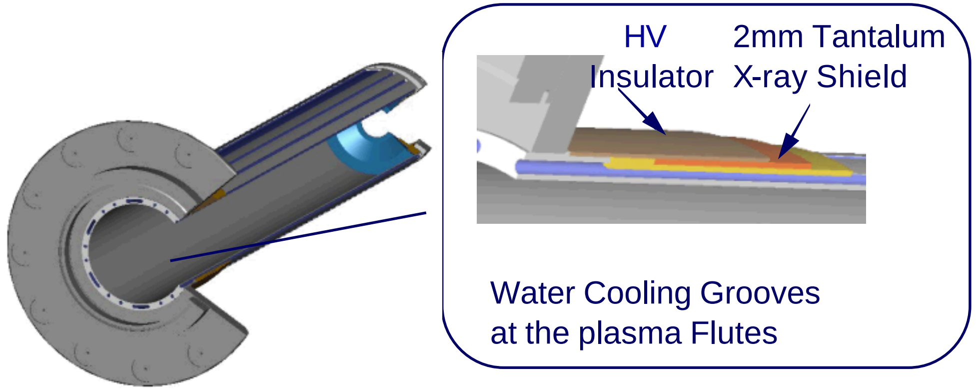
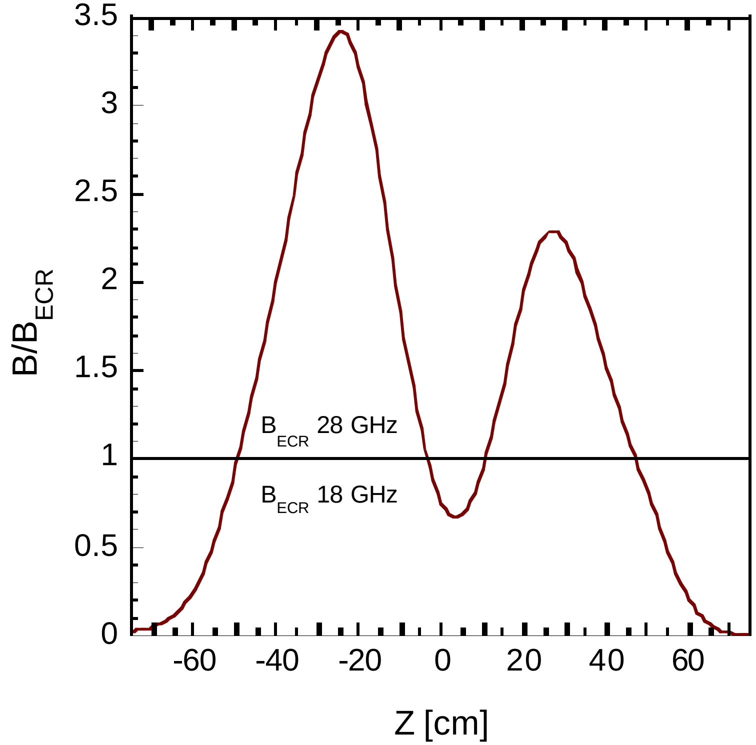
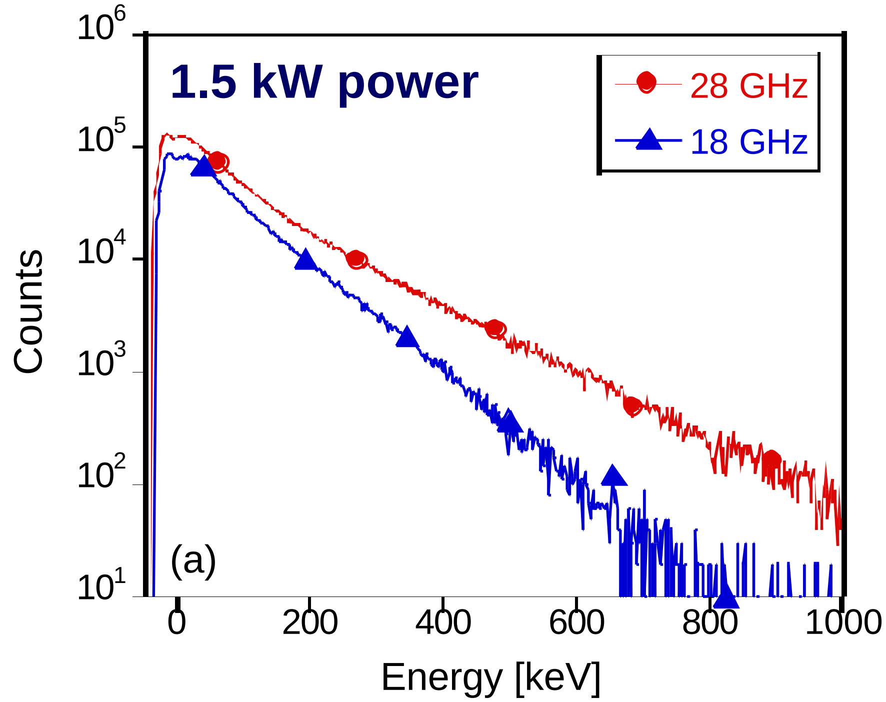




1.5 - 2 mm Ta shielding effectively attenuates the low energy bremsstrahlung, but becomes transparent for x-rays above 400keV

Using scaled magnetic fields for 18 and 28 GHz (same ECR zone size), 28 GHz heating results in x-ray flux and energies

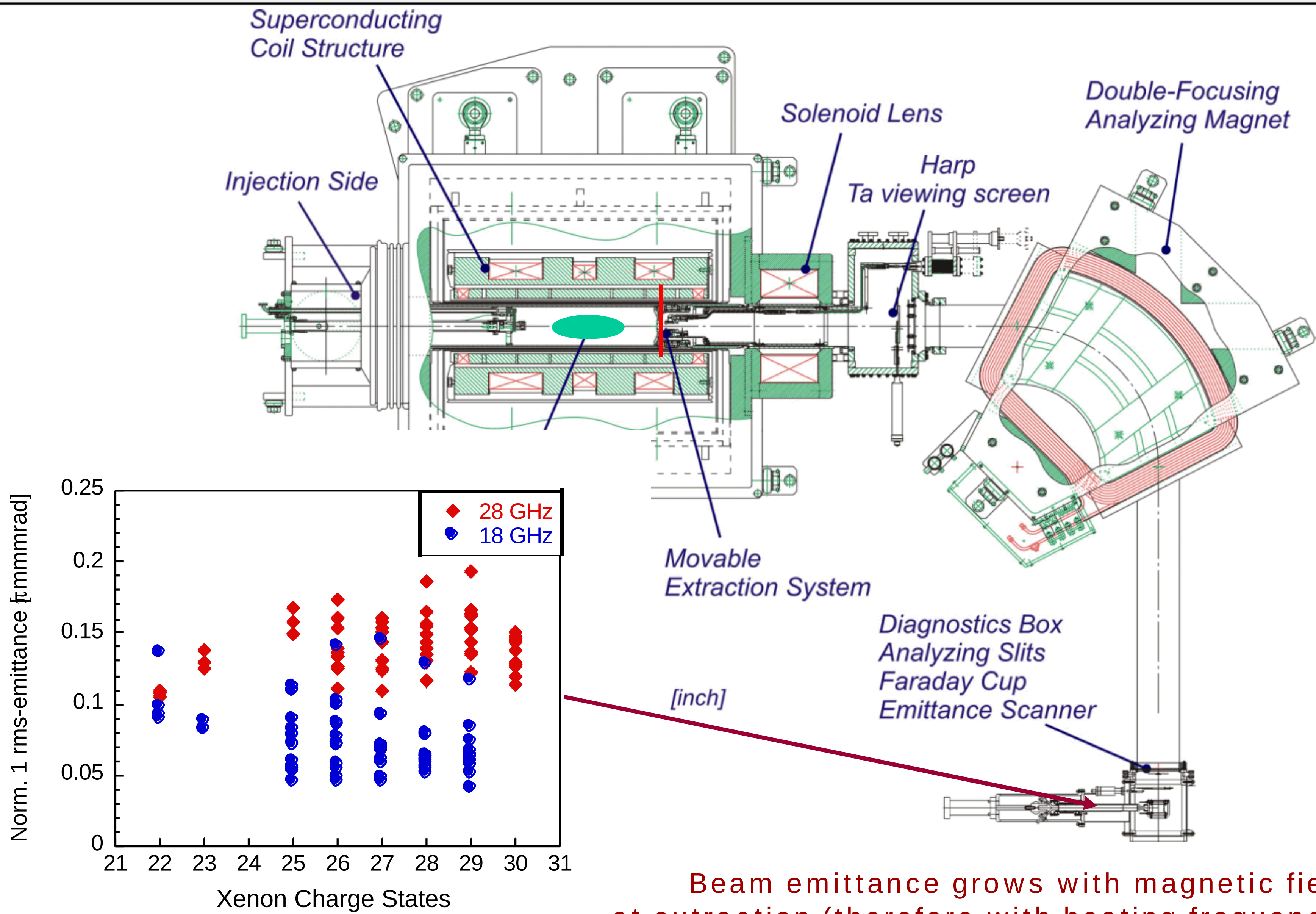




The scaling of the electron energy temperature with frequency has important consequences for 4th generation superconducting ECR ion source with frequencies of 37GHz, 56GHz.

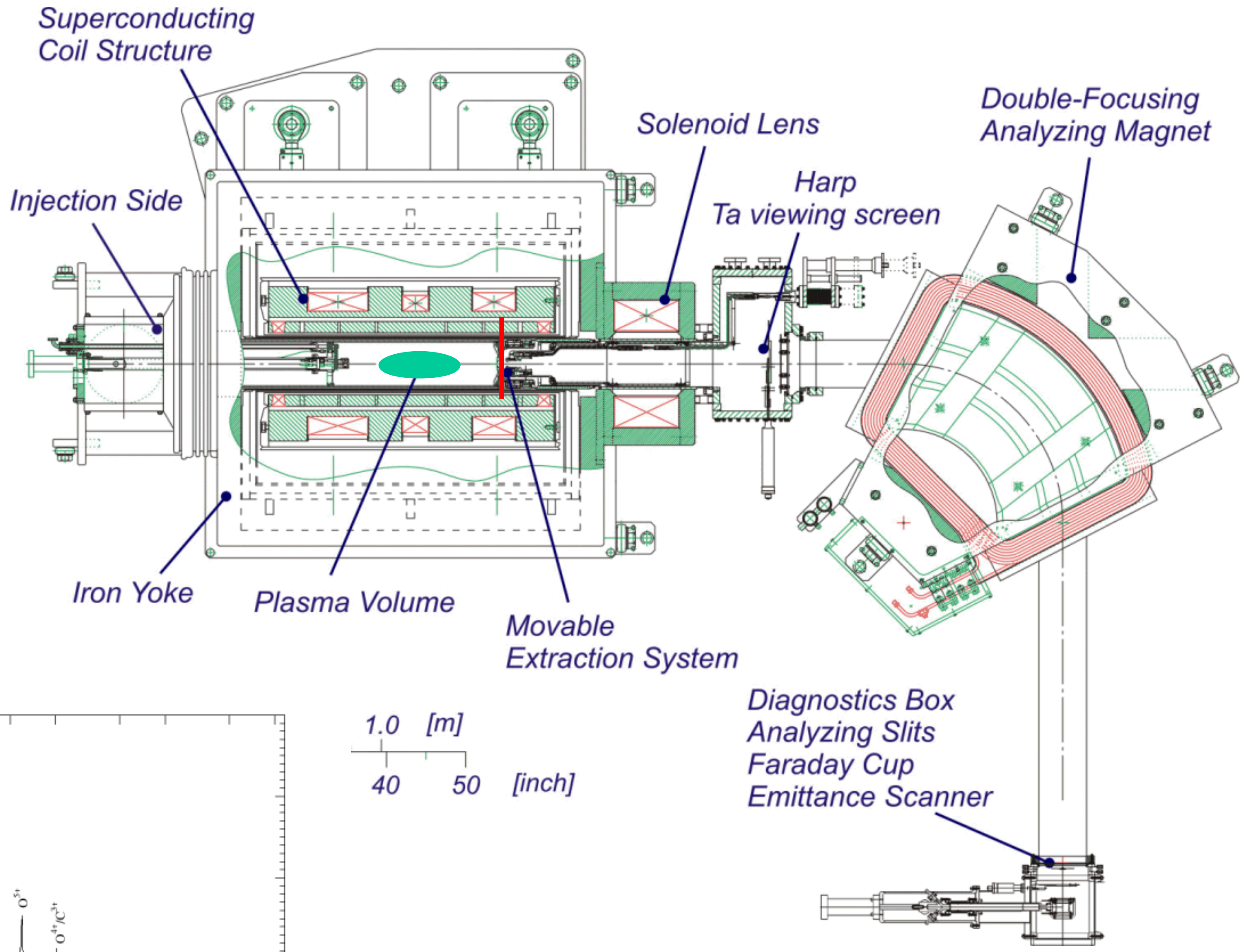
Several (10s of) watts of cooling power must be reserved for the cryostat.

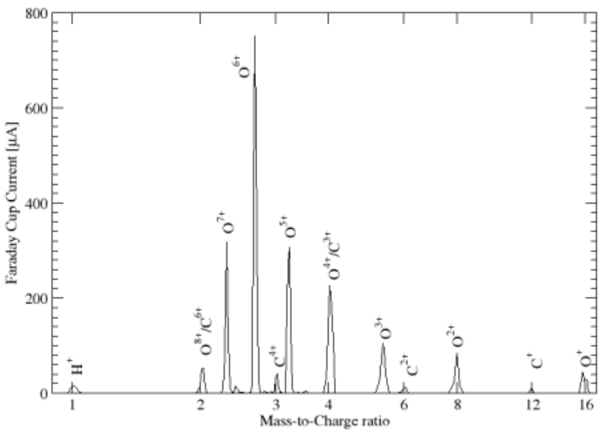
Beam transport is a challenge for high field SC ECR ion sources



Beam emittance grows with magnetic field
at extraction (therefore with heating frequency)

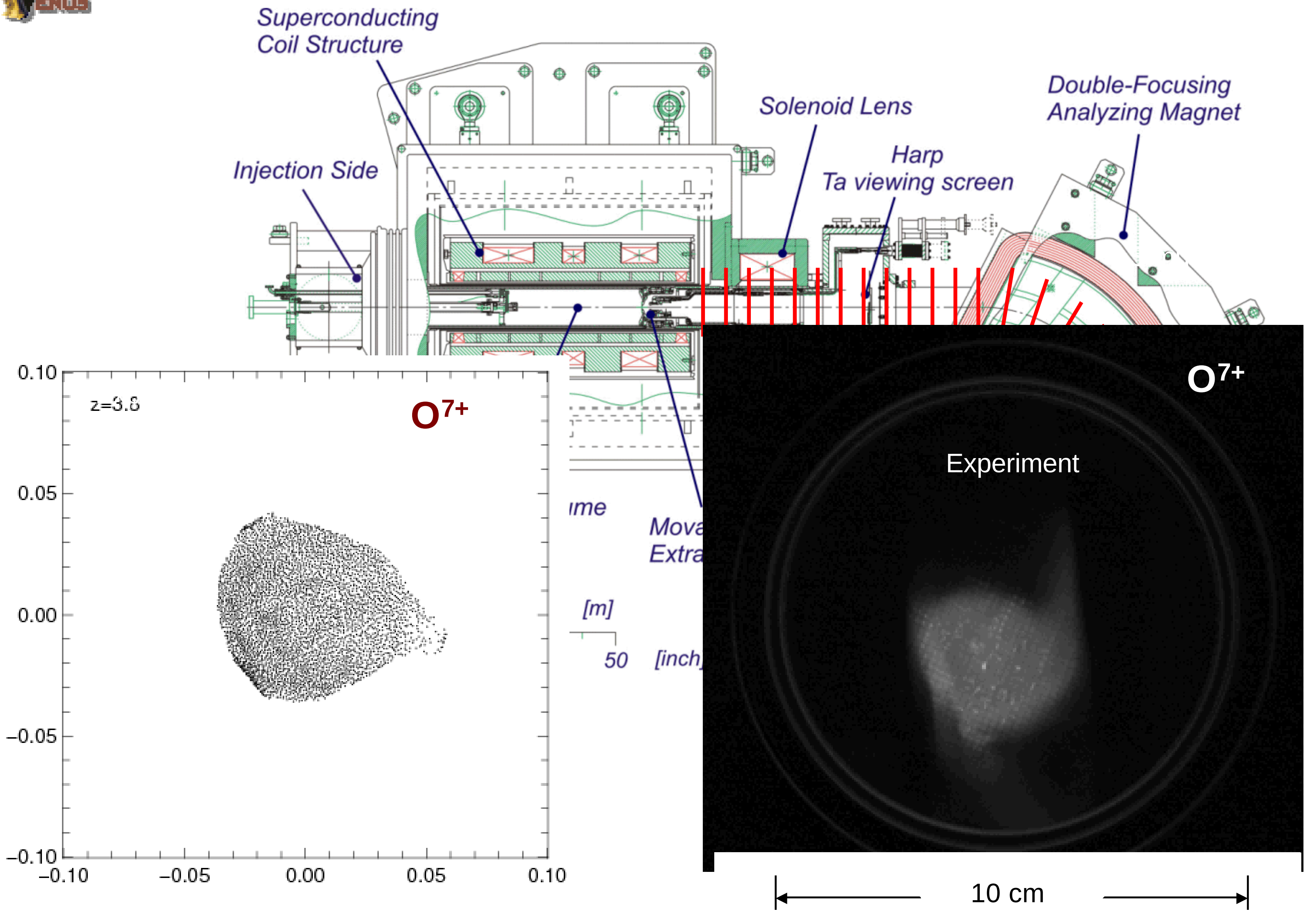
Beam transport is a challenge for high field SC ECR ion sources





D.S.Todd et al., LBNL RSI submitted

Simulation of oxygen beam extraction and transport



Summary

- 3^{rd} Generation sources fulfill their intensity promises
- The performances are still increasing with power, but mA of high charge state ions have been demonstrated

  For example with VENUS

  – 2860 eµA of O^{6+}

  – 860 eµA of Ar^{12+}, 270 eµA of Ar^{16+}, 1 eµA of Ar^{18+}

  – 200 eµA of U^{34+}

However intensity needs and performance gains for next generation heavy ion accelerator might justify 4^{th} generation ECR ion sources (>28 GHz)

- New magnetic materials (Nb_3Sn) will be needed to fabricate a 56 GHz ECR magnet structure
  – Further advances in technology will be necessary
  – Prototyping will be essential
- X-ray heating will be a major challenges for 4^{th} generation ECR ion sources
  – Measurements of the axial bremsstrahlung on the VENUS ECR ion source show that the electron temperature and x-ray flux increase with increasing frequencies
- Beam transport
  – Emittance grows with magnetic field, but not as strong as expected
  – Understanding of the beam formation at the ECR extraction will be key to optimize the beam transport for high field ECR ion sources

Operational Experience with 28 GHz since 2004

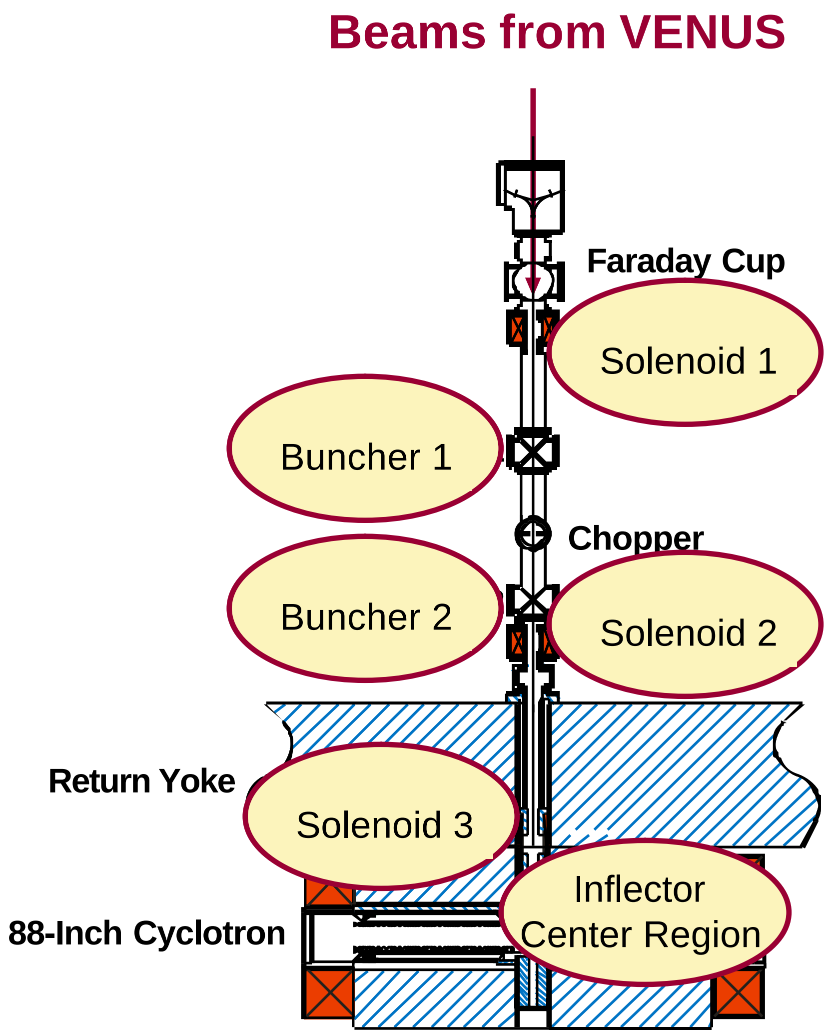
- Superconducting Magnets
  - Robust and reliable magnet system
  - Magnets can be independently energized
  - No conditioning after warm up required
  - Magnetic fields can be explored over a wide range

- Conventional design has been optimized for operational reliability and ease of maintenance
  - Source has been designed as an UHV device all metal seals (including 28 GHz components)
    - fast recovery after source maintenance
  - Plasma chamber (Al+Ta), which allows for high power operation

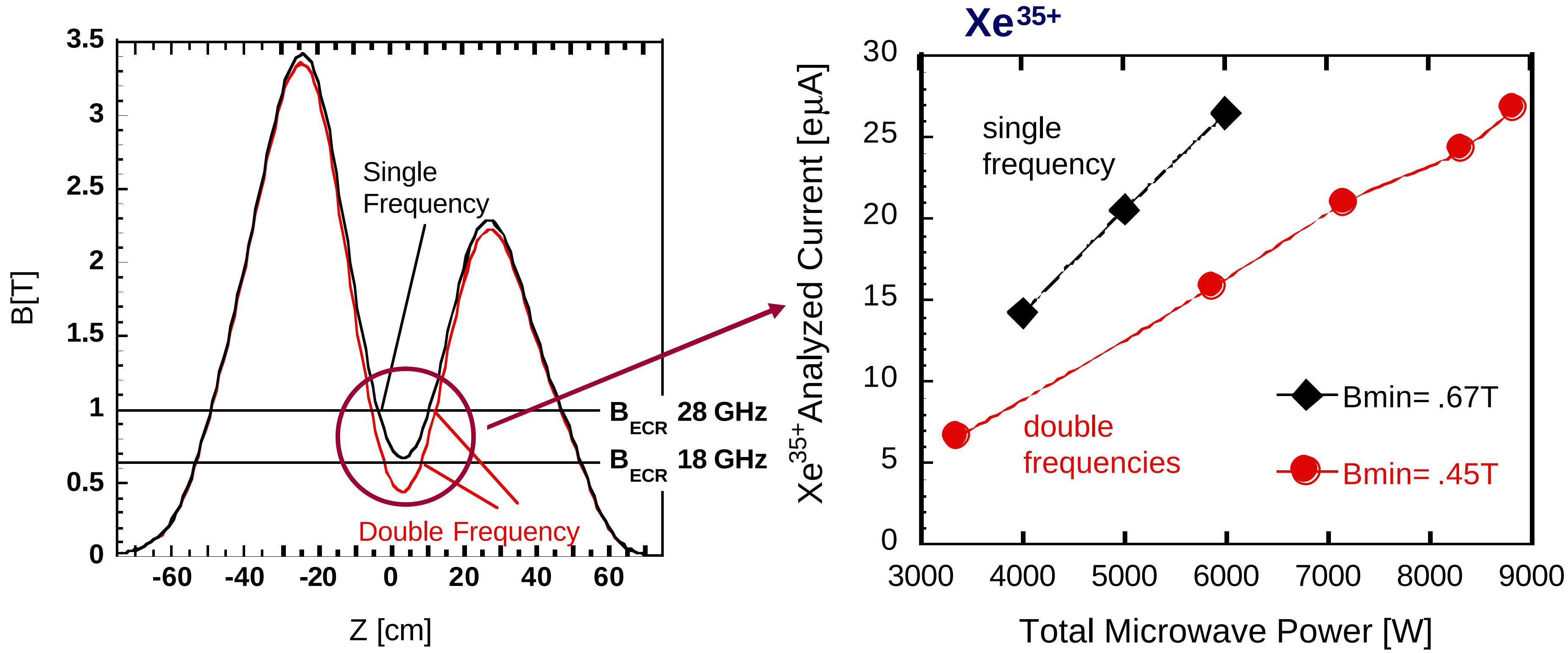
- Performance is still increasing with power, the maximum total power coupled into VENUS so far has been 9 kW (1kW/liter), 12 kW available

To take full advantage of the high current available from VENUS an upgrade of the cyclotron injection and center region is necessary

- High intensity of the VENUS beams have reached the space charge limit of the current cyclotron injection beam line (~100eμA)
- Transmission of the cyclotron injection line increases with injection voltage
- Current beam line components do not have sufficient focusing strength for injection energies above 15 kV
- Center region of the cyclotron will require upgrade for high intensity operation



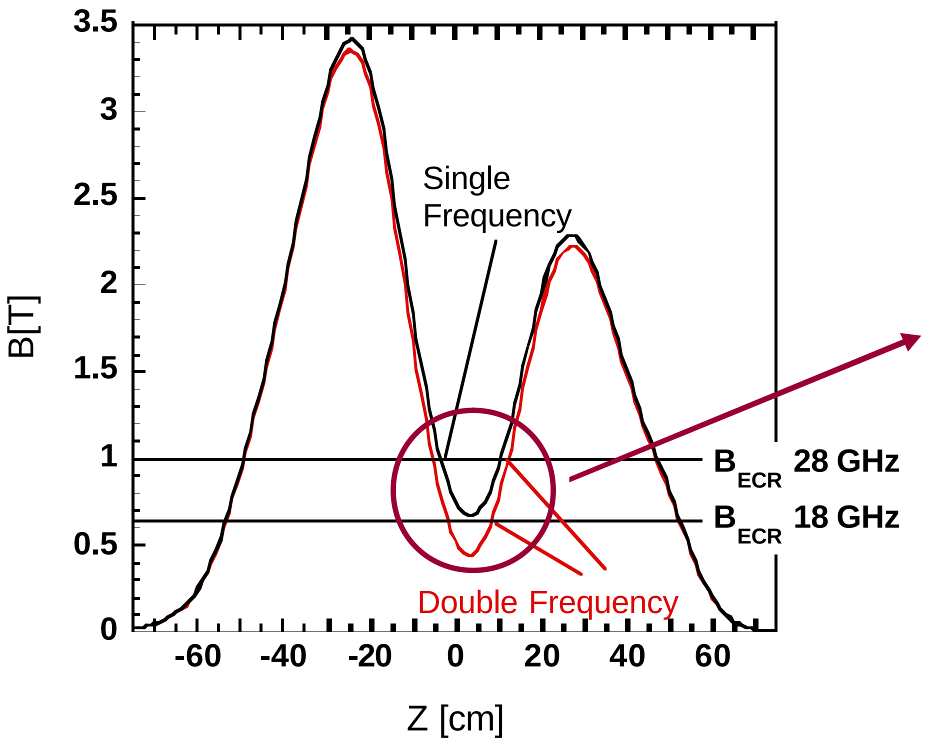
Double frequency heating (steep + gentle) and single frequency heating (gentle gradient) can achieve similar performance at different power levels

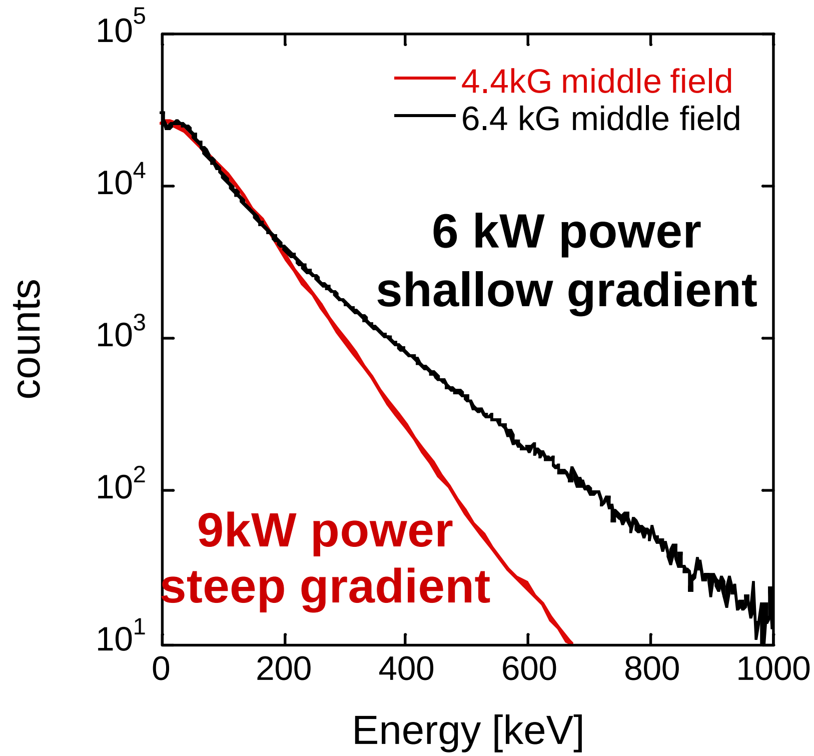


See also PA56, PA32

Similar performance if the count rate for low energy x-rays is similar

Double frequency heating (steep + gentle) and single frequency heating (gentle gradient) can achieve similar performance at different power levels



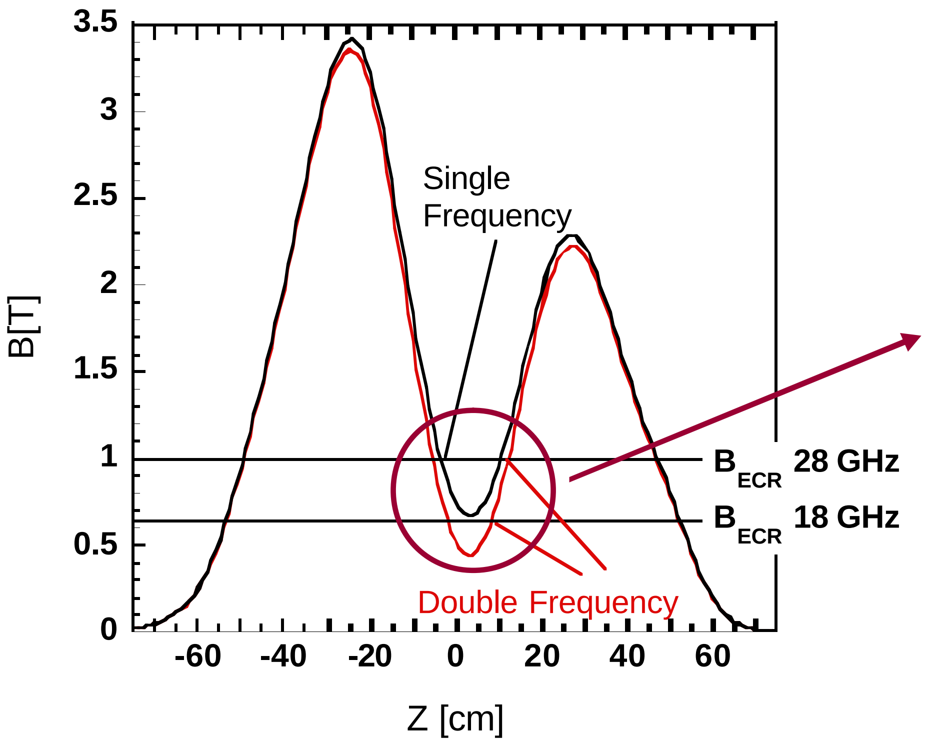


To achieve the similar performance in the two configurations the electron density below 200keV needs to be similar

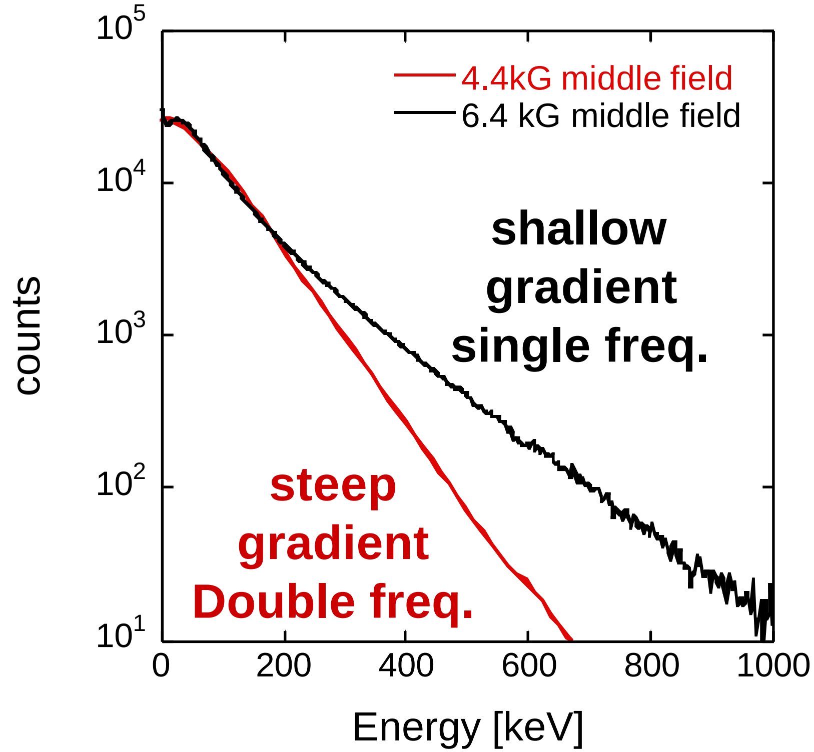
See also PA56, PA32

The gradient of the magnetic field at the resonance zone strongly influences the heating efficiency and hot electron tail

Magnetic field configuration for optimized single and double frequency heating.



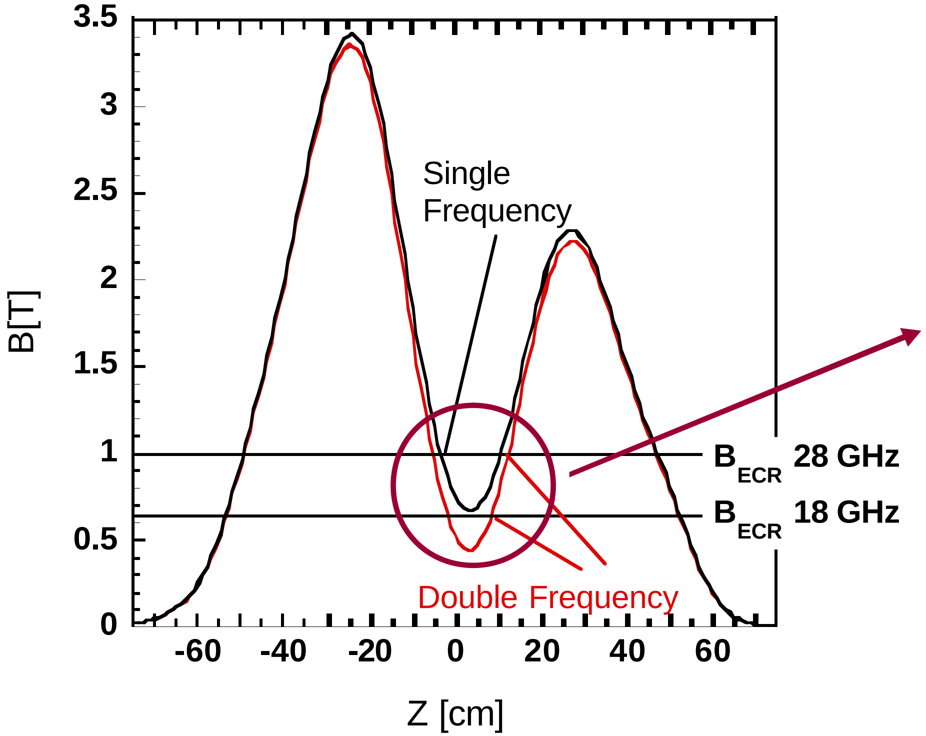
Axial Bremstrahlung spectra from VENUS for the two field configuration

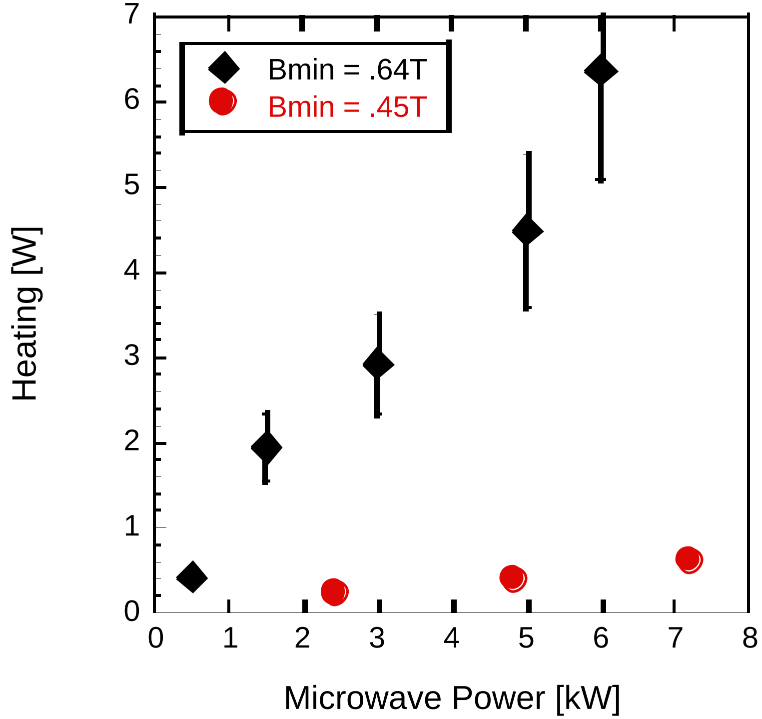


The bremsstrahlung spectrum with a shallow magnetic field gradient at the resonance contains much higher x-ray energies.

The gradient of the magnetic field at the resonance zone strongly influences the heating efficiency and hot electron tail

Consequently, the gradient of the magnetic field at the resonance zone strongly affects the heat load into the cryostat





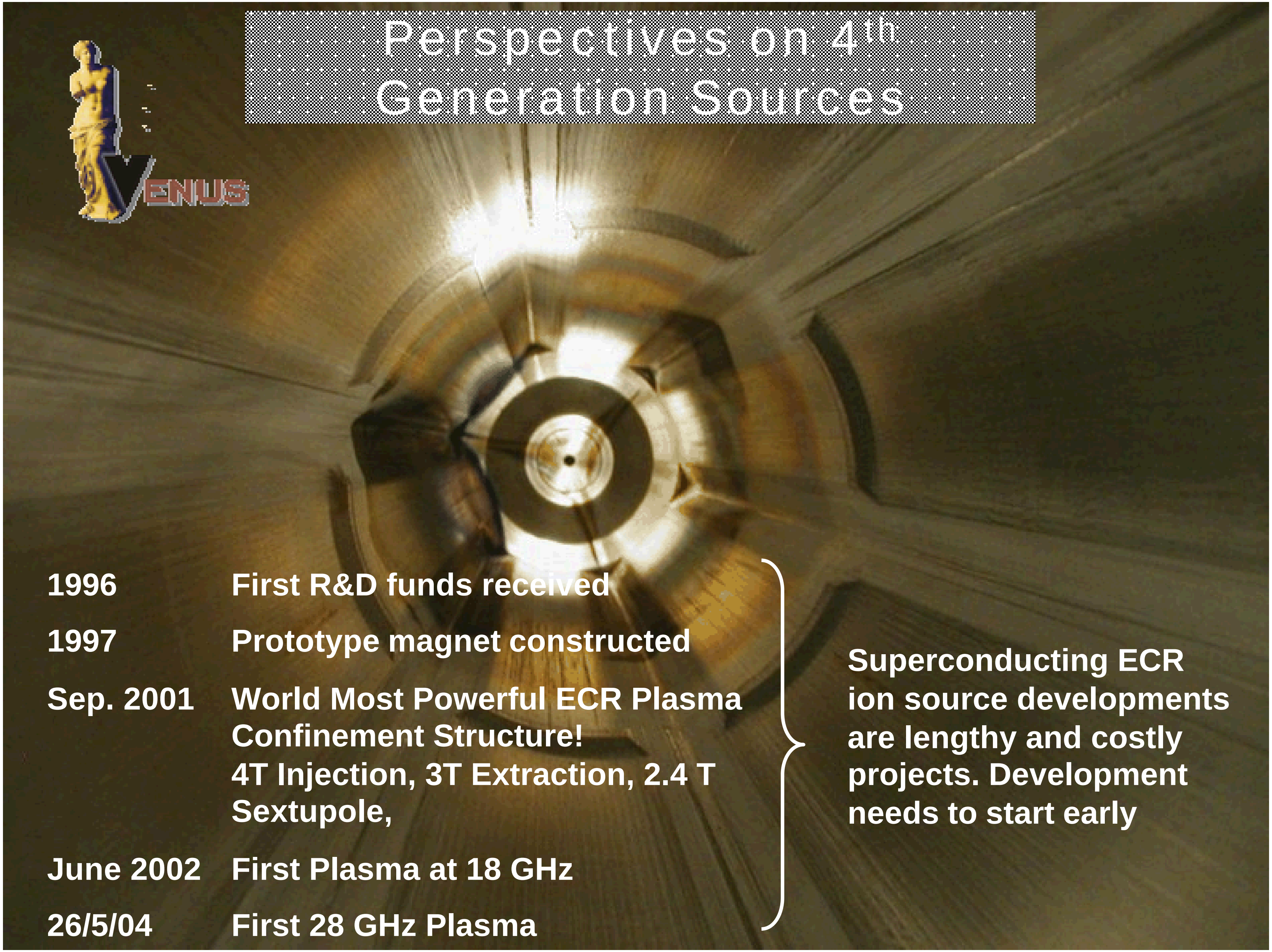
Progress and perspective for high frequency, high performance superconducting ECR Ion Sources

Daniela Leitner

M.L. Galloway, T.J. Loew, C.M. Lyneis, D.S. Todd

- Introduction
- 3rd Generation ECR ions source / VENUS project
- Key parameters for the performance of an ECR
- Recent results from VENUS
- Perspectives on 4th generation ECR ion sources

Perspectives on 4th Generation Sources

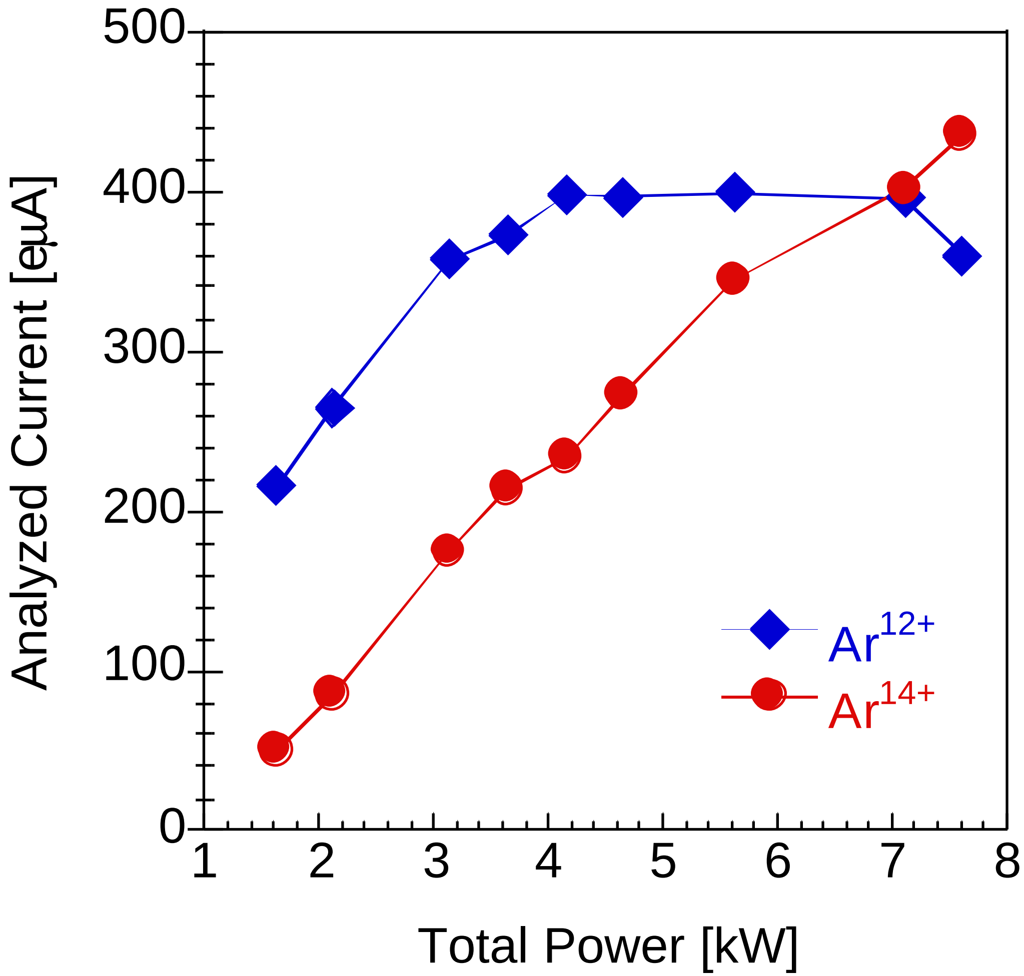


1996	First R&D funds received
1997	Prototype magnet constructed
Sep. 2001	World Most Powerful ECR Plasma Confinement Structure! 4T Injection, 3T Extraction, 2.4 T Sextupole,
June 2002	First Plasma at 18 GHz
26/5/04	First 28 GHz Plasma

Superconducting ECR ion source developments are lengthy and costly projects. Development needs to start early

Product of $n_e \cdot t_i$ increases with power

- Dependence of Ar^{12+} and Ar^{14+} on power



- constant gas flow rates
- constant confinement field

The ionization rate for Ar^{12+} into higher charge states increases with power

To keep the CSD peaked on 12+ more gas has to be added