Status of the VENUS ECR ion source

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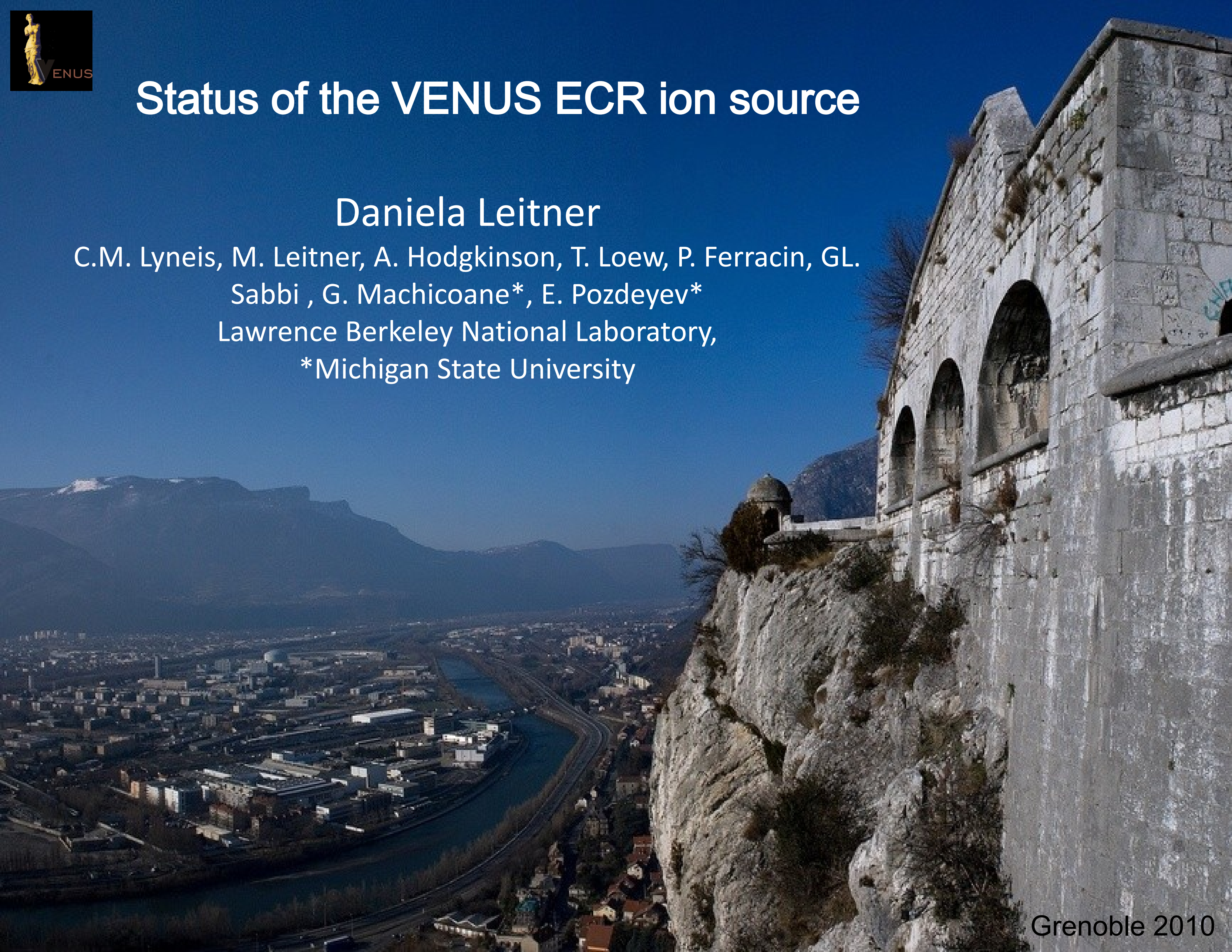

Grenoble 2010

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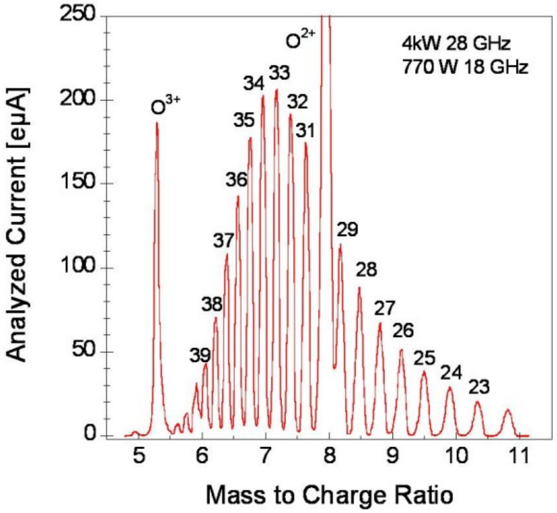
- VENUS ECR ion source
- Lead repair summary
- Re-commissioning results
- FRIB ion source design challenges
  - X-rays from the plasma
- Upgrade path for FRIB: Nb_3Sn magnet structure
- Summary

The superconducting 28 GHz ECR ion source VENUS

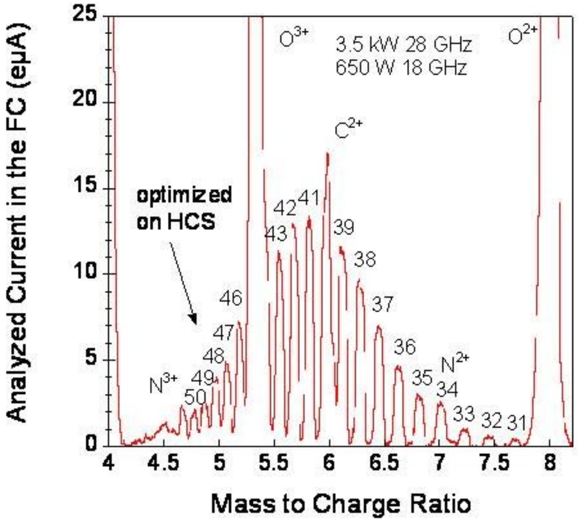
Prototype Injector for FRIB: Provide high intensity medium-charge state heavy ion beams for FRIB:

requirements	
Ion	FRIB
$^{124}\mathrm{Xe}^{18+}$	334 euA
$^{209}\mathrm{Bi}^{28,29+}$	240+240 euA
$^{238}\mathrm{U}^{33,34+}$	250+250 euA



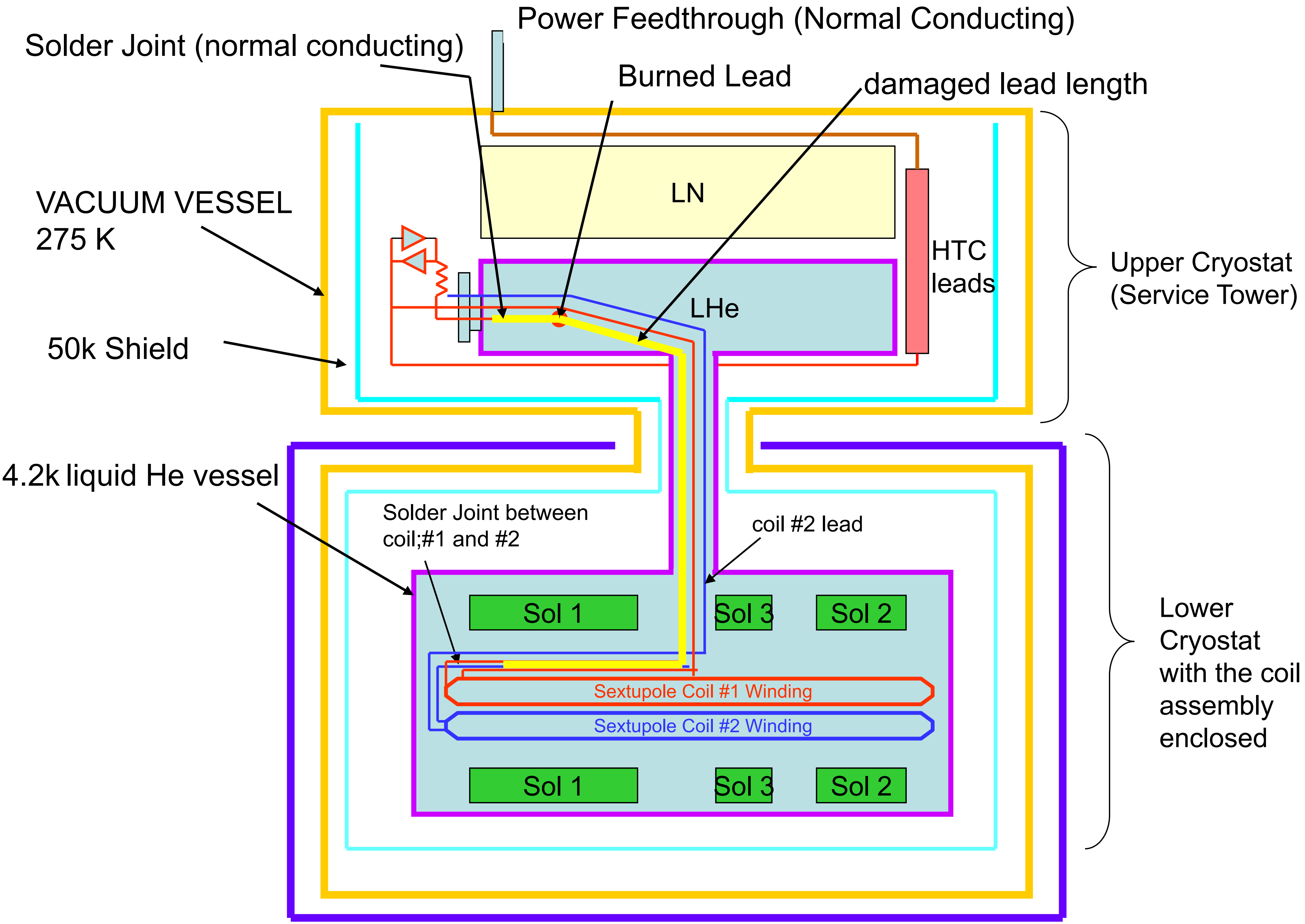
Third injector for the 88-Inch Cyclotron

requirements	
Ion	88-Inch
$^{124}\mathrm{Xe}^{35\text{-}44+}$	1-5 euA
$^{169}\mathrm{Tm}^{38\text{-}45+}$	1euA
$^{209}\mathrm{Bi}^{41\text{-}50+}$	1-5euA
$^{238}\mathrm{U}^{46\text{-}50+}$	1-5euA



Major Events of the VENUS Project	
09/97	Prototype Magnet completed
09/01	Final Magnet Tests: 4T, 3T, 2.4 T
06/02	First Plasma at 18 GHz
05/04	First 28 GHz Plasma
08/06	220 euA $U^{33+,34+}$
01/08	Quench/ Lead burn out
07/10	First plasma after repair

January 2008



Power Feedthrough (Normal Conducting)

Solder Joint (normal conducting)

Burned Lead

damaged lead length

VACUUM VESSEL
275 K

50k Shield

Upper Cryostat
(Service Tower)

4.2k liquid He vessel

Solder Joint between
coil;#1 and #2

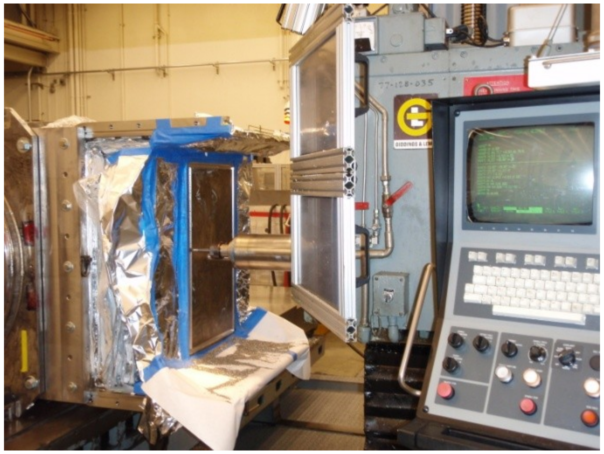
coil #2 lead

Lower
Cryostat
with the coil
assembly
enclosed

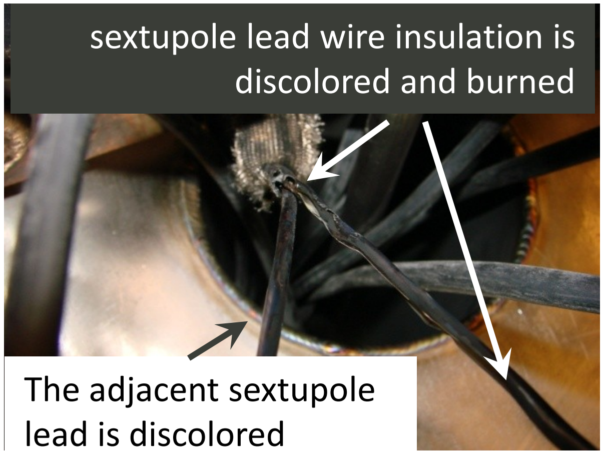
Repair Chronology 1

Preparation for repair 1/2008

Cutting the cryostat open



Inspecting the wire



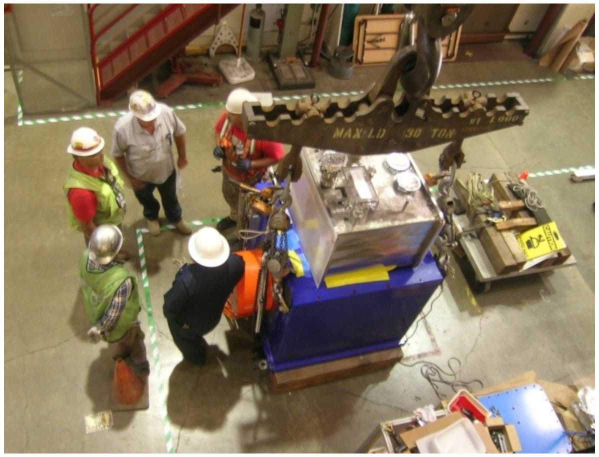
sextupole lead wire insulation is discolored and burned

The adjacent sextupole lead is discolored

Cold mass extracted 4/2008
wires tested and spliced

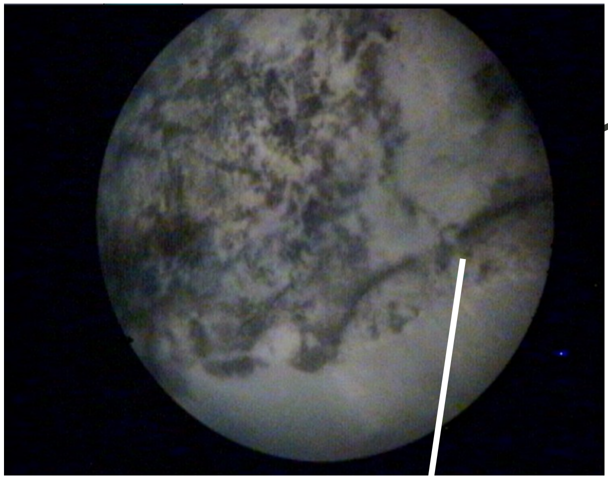
External cryostat magnet test at LBNL 9/2008 (no quenches)
4.1 T, 3.2 T, 2.1 T

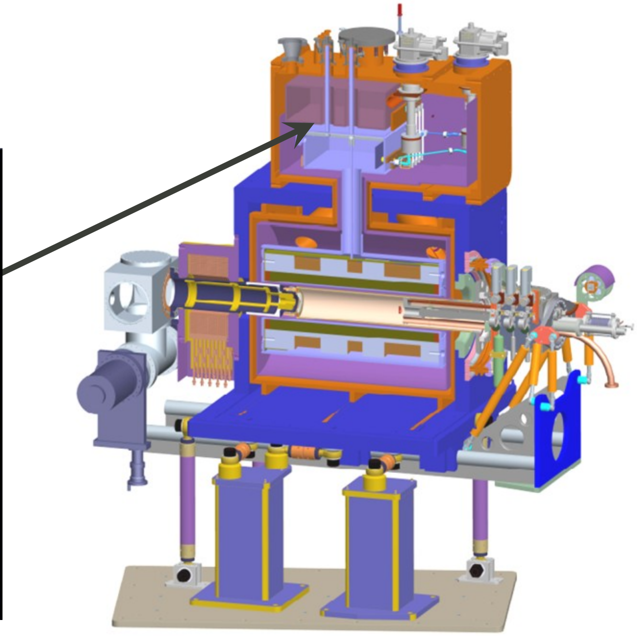
Installation at the 88-Inch Cyclotron 10/2009

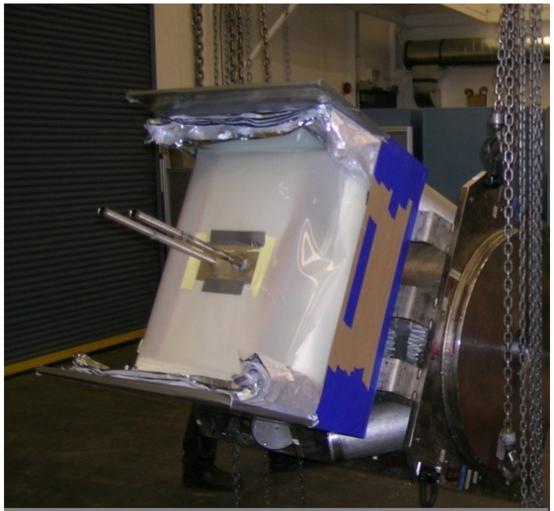


VENUS Repair 2.0

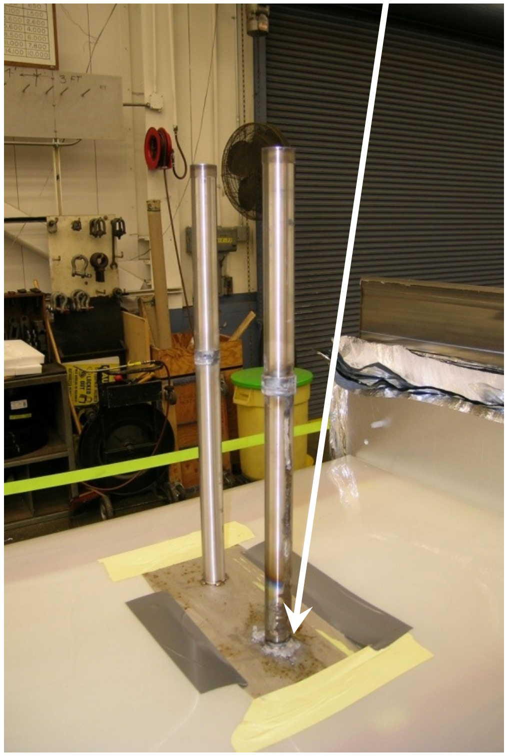
VENUS ?



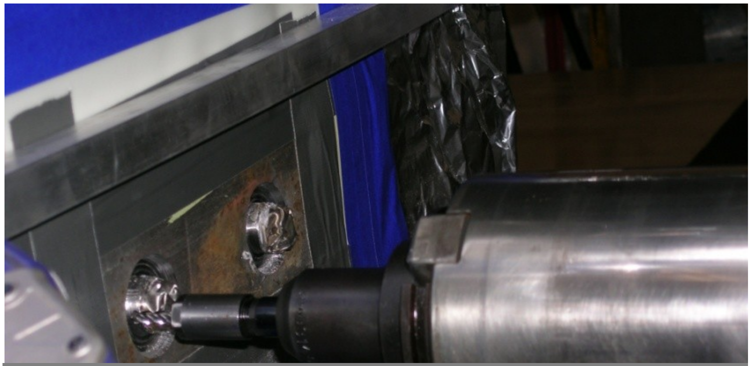




Open the cryostat 2/2010



Helium leak appeared during cool down due to material damage of the He fill tube



Replace fill tubes 2/2010
without damaging the SC wires

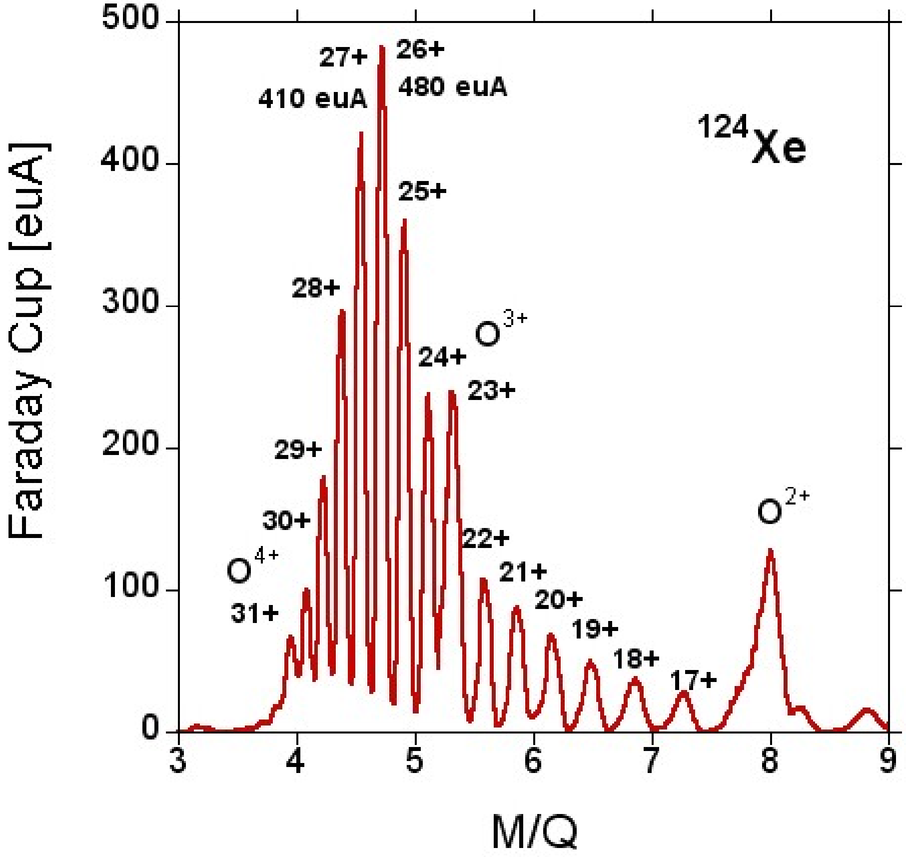
Back at the 88” 4/2010

VENUS Re-commissioning
First beam 7/21/2010

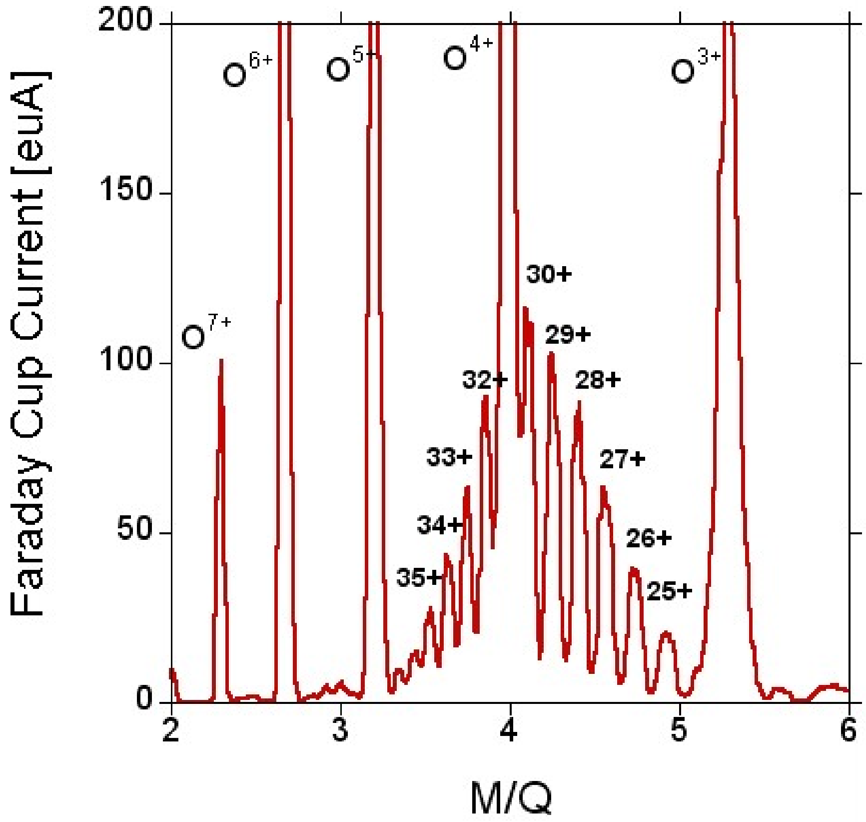
- Lessons learned: Lead quenches are to be avoided under all circumstances !
- Many improvements have been added to the cryostat and interlock system to prevent a similar accident
  - Lead cooling was improved
  - Liquid helium level interlock was improved
  - A fourth cryocooler was added to the system
- Valuable information was obtained for the FRIB injector source cryostat design and construction

^{124}Xe medium/high charge states re-commissioning

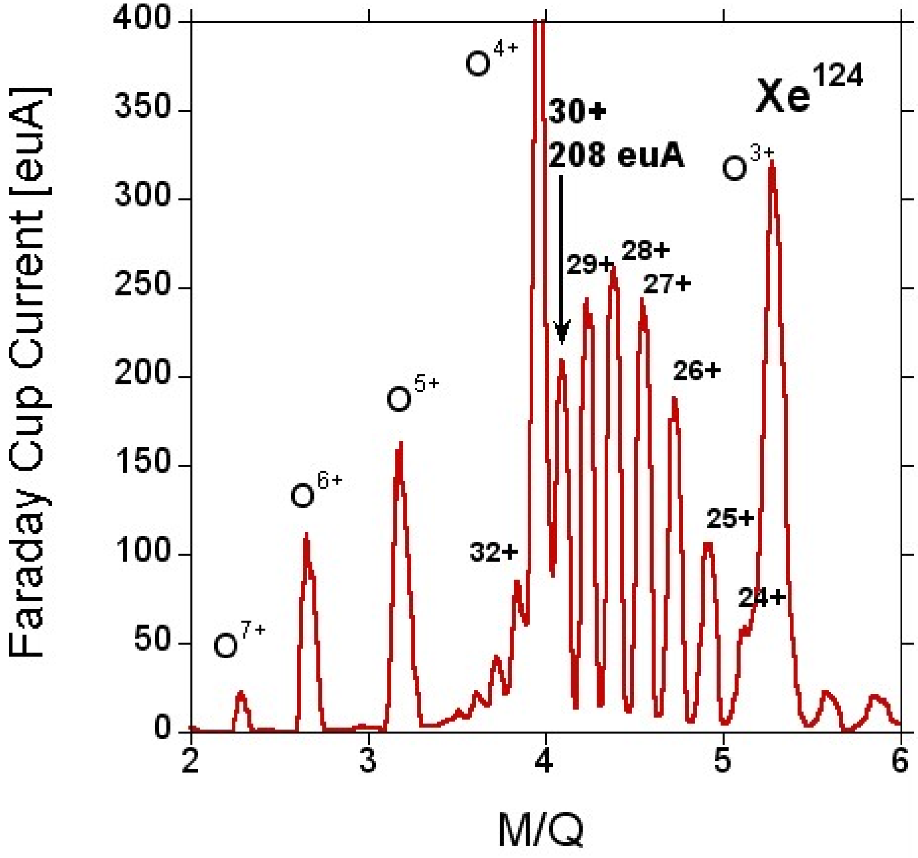
Tuning Parameters	
28 +18 Ghz	5-6 kW
Bmin	.56 T
Bmin 18 GHz	87.5%
Bmin 28 GHz	56 %
Heat load into the cryostat	1.7 W



First few tuning results during the re-commissioning



^{124}Xe medium/high charge states re-commissioning



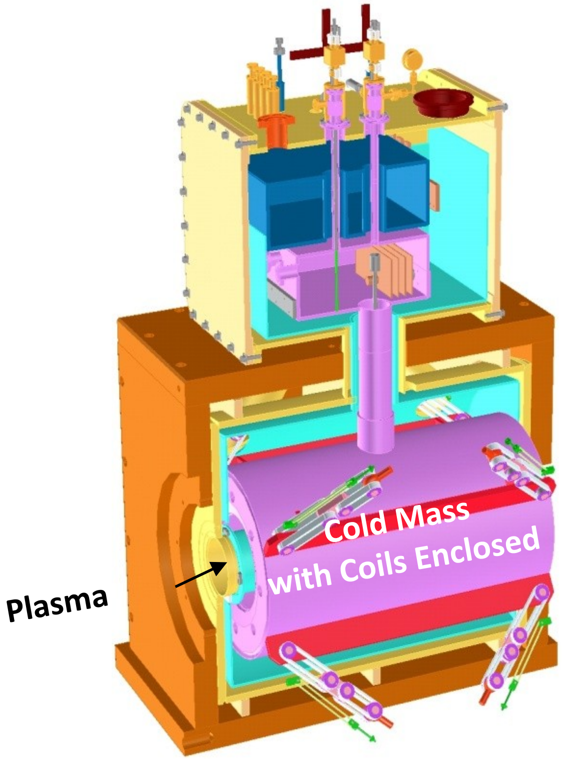
After the first few weeks of commissioning the VENUS source is slowing reaching/exceeding its previous performance level

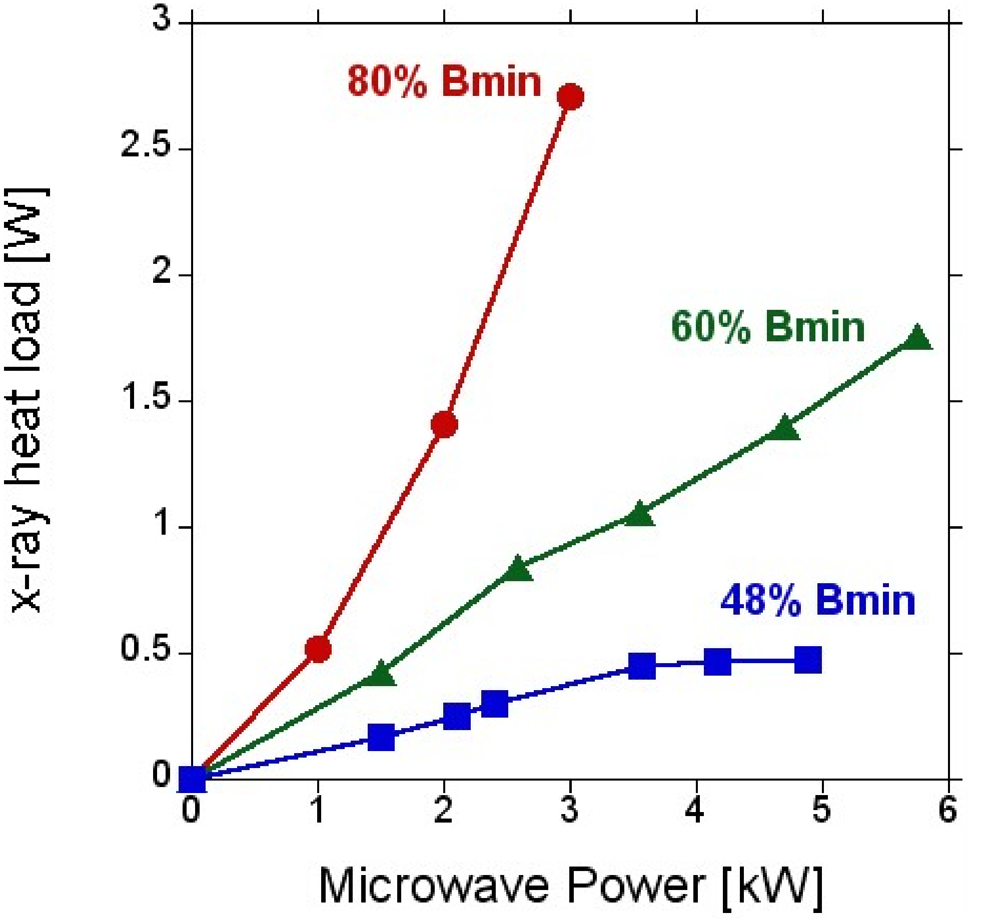
	VENUS 28+18 GHz	SECRAL (24 GHz)
Results 2006-2008		
O^{6+}	2860 eμA	2300 eμA
O^{7+}	850 eμA	810 eμA
Ar^{12+}	860 eμA	510 eμA
Ar^{16+}	270 eμA	149 eμA
Ar^{17+}	36 eμA	14 eμA
Xe^{30+}	116 eμA	152 eμA
Re -commissioning (3 weeks) 2010		
Xe^{26+}	480 eμA	480 eμA
Xe^{27+}	411 eμA	450 eμA
Xe^{30+}	211 eμA	152 eμA
Xe^{32+}	108 eμA	85 eμA (31+)
Xe^{35+}	38 eμA	45 eμA

Challenges for superconducting ECR ion sources

- Superconducting Magnet and Cryogenic Technology
- X-rays from the Plasma
- Ion Beam Transport (Tuesday)

X-rays from the plasma are a major challenge for SC ECRIS, several Watts of power can be absorbed in the cryostat

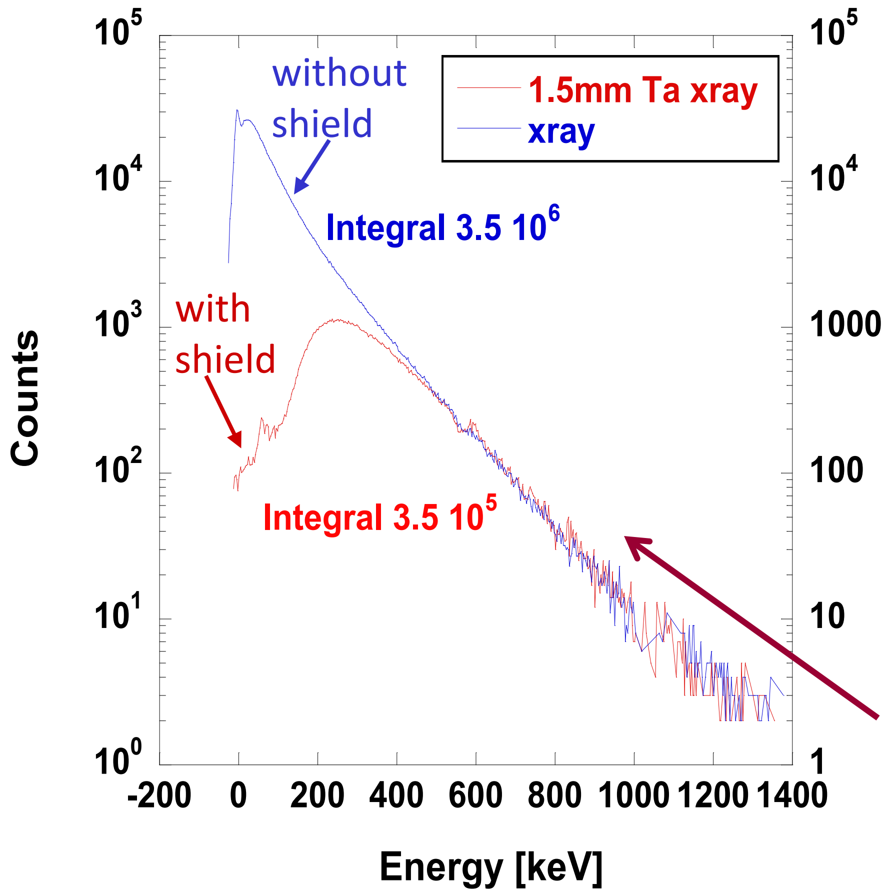




A major challenge for high field SC ECR ion sources is the heat load from bremsstrahlung absorbed in the cryostat

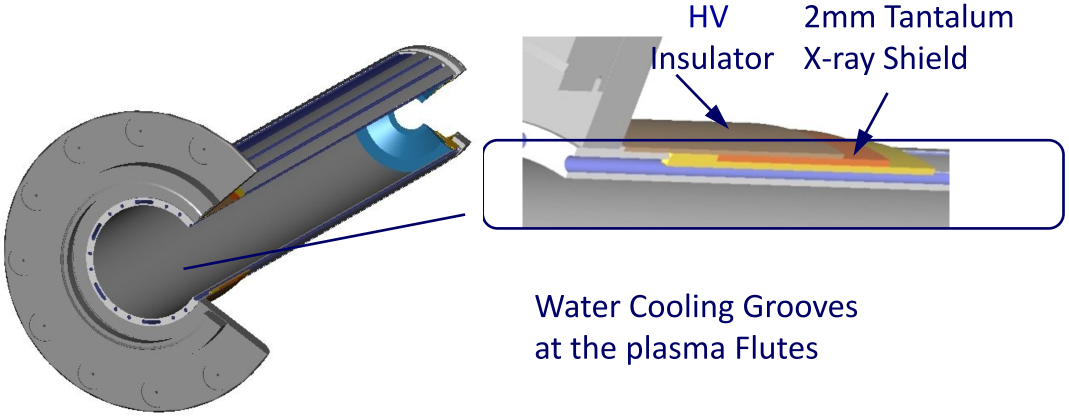
Also problematic for the HV insulation around the plasma chamber

X-rays from the plasma



Technical Solution

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

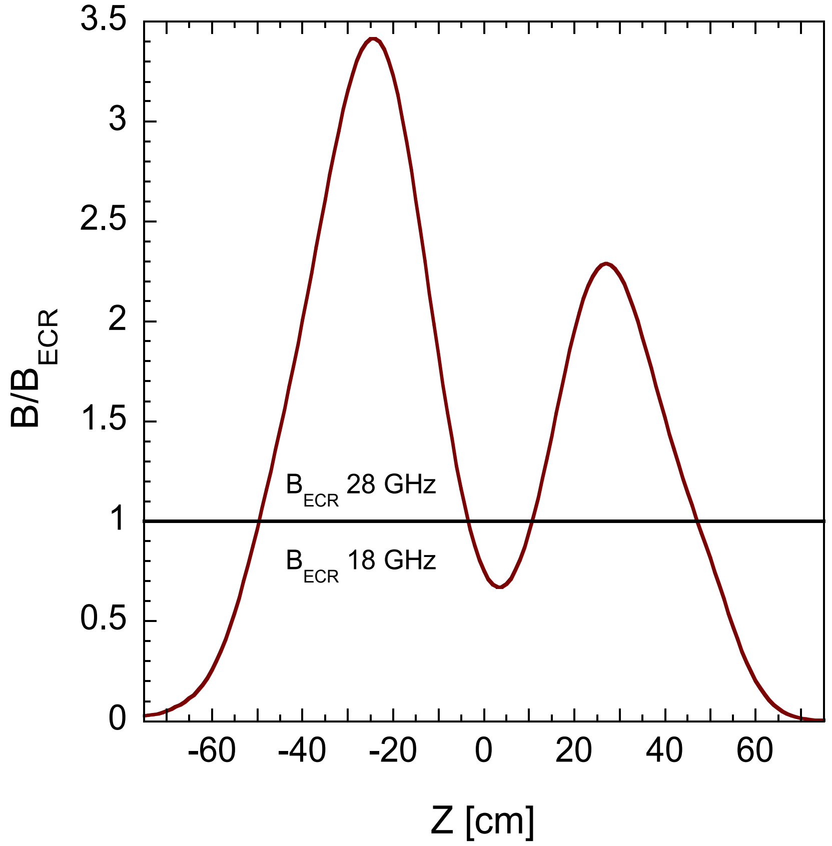


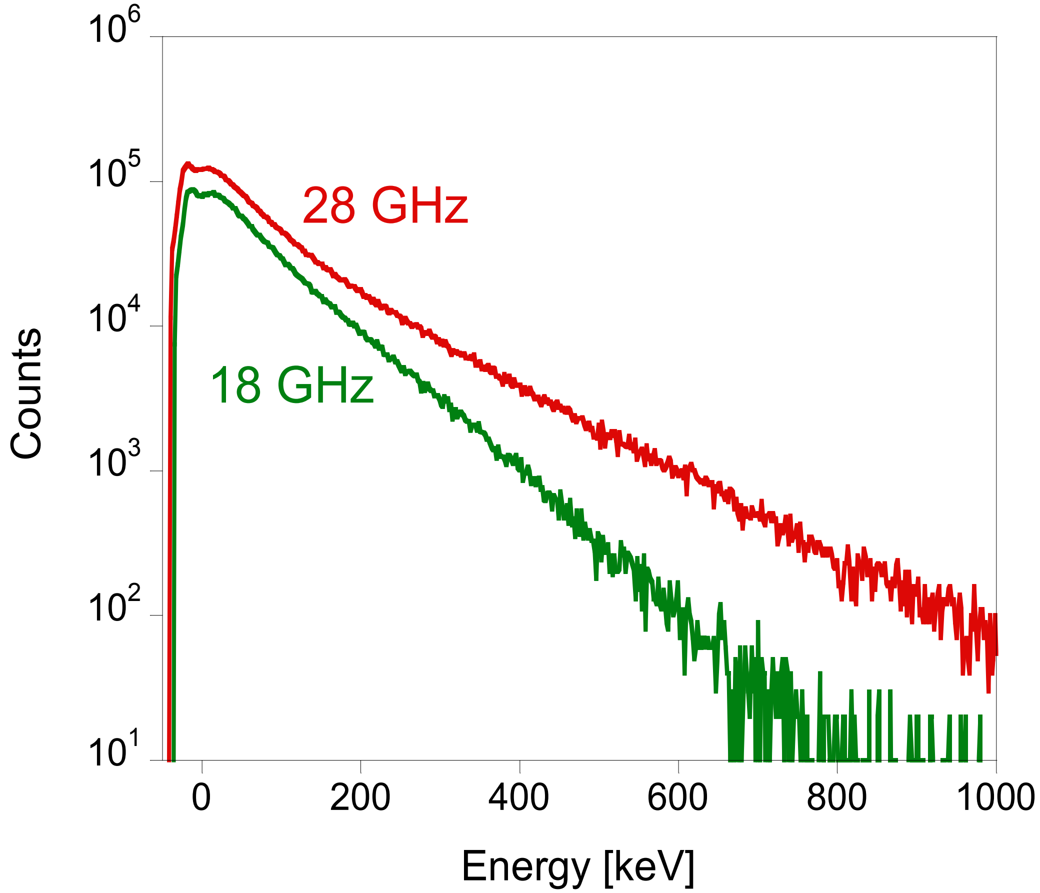
1.5 - 2 mm Ta shielding effectively attenuates the low energy bremsstrahlung, but becomes transparent for x-rays above 400keV

→ **What do we know about the x-ray energy spectrum emitted from the ECR plasma?**

The total x-ray flux and electron temperature increase strongly with increasing frequencies

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

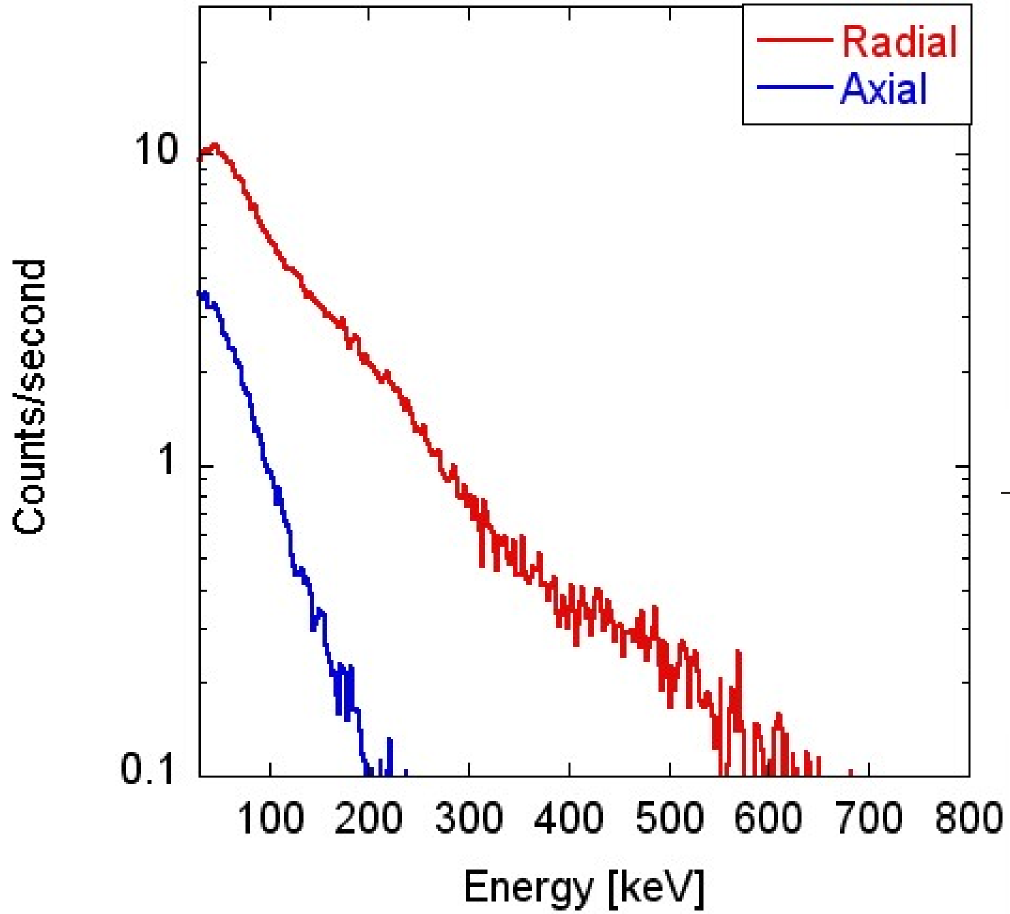




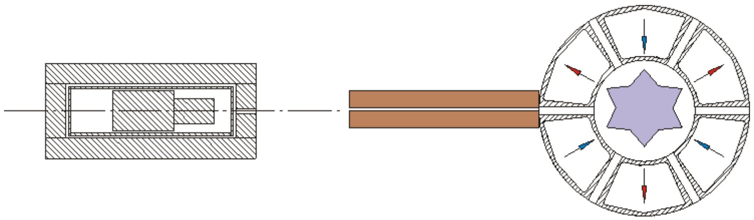
The scaling of the electron energy temperature with frequency has important consequences for 4th generation superconducting ECR ion sources (37GHz, 56GHz…)

The energy spectrum the x-rays from the plasma shows a strong anisotropy of the radial and axial x-ray spectrum

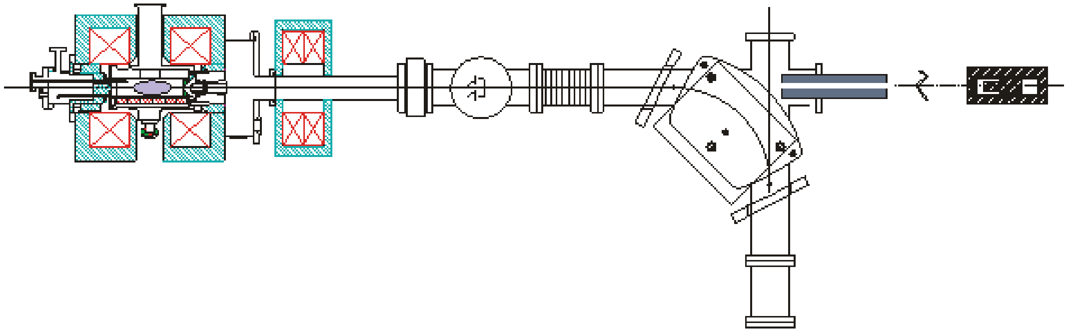
Measurements on the AECR-U type ECR ion source



Radial Set-up



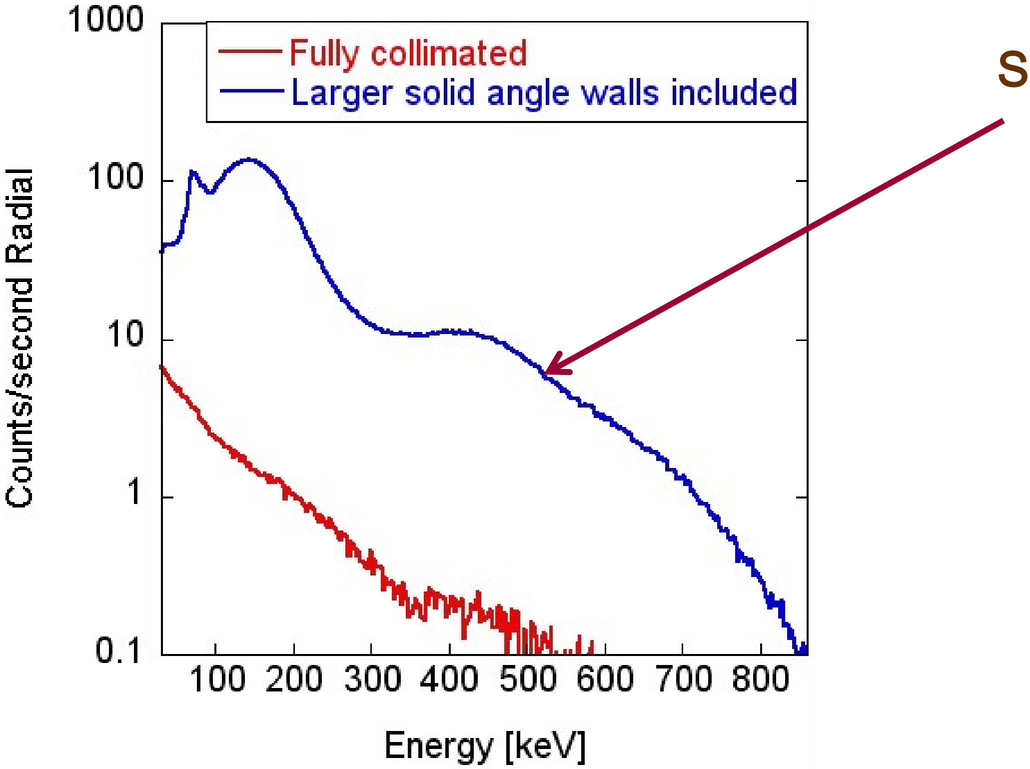
Axial Set-up



Radial x-ray energy is much higher than the axial x-ray energy
(more heat load into the cryostat)

The energy spectrum of the x-rays from the plasma wall contains much higher energies than the x-ray energy emitted from the plasma

Measurements on the AECR-U type ECR ion source



Some collimation removed

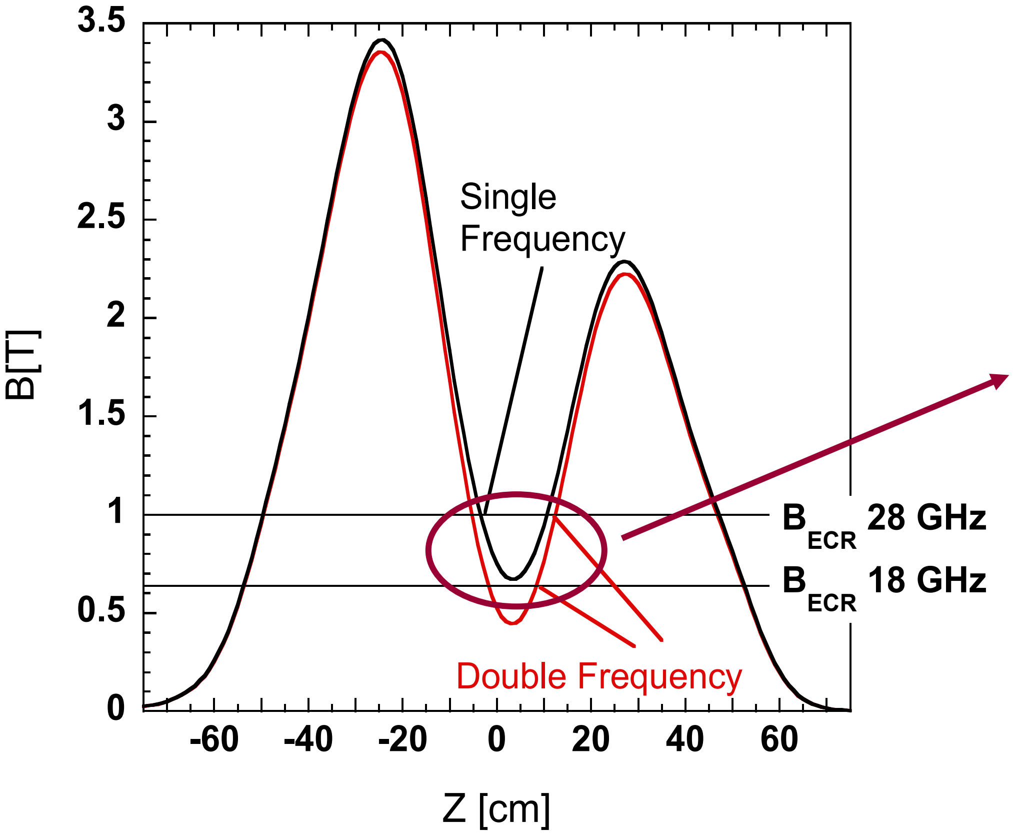
X-ray energy of particles lost to the wall is much higher than x-rays emitted from the plasma due to electron ion collisions

Collision frequency ~ $1/(T_e)^{3/2}$

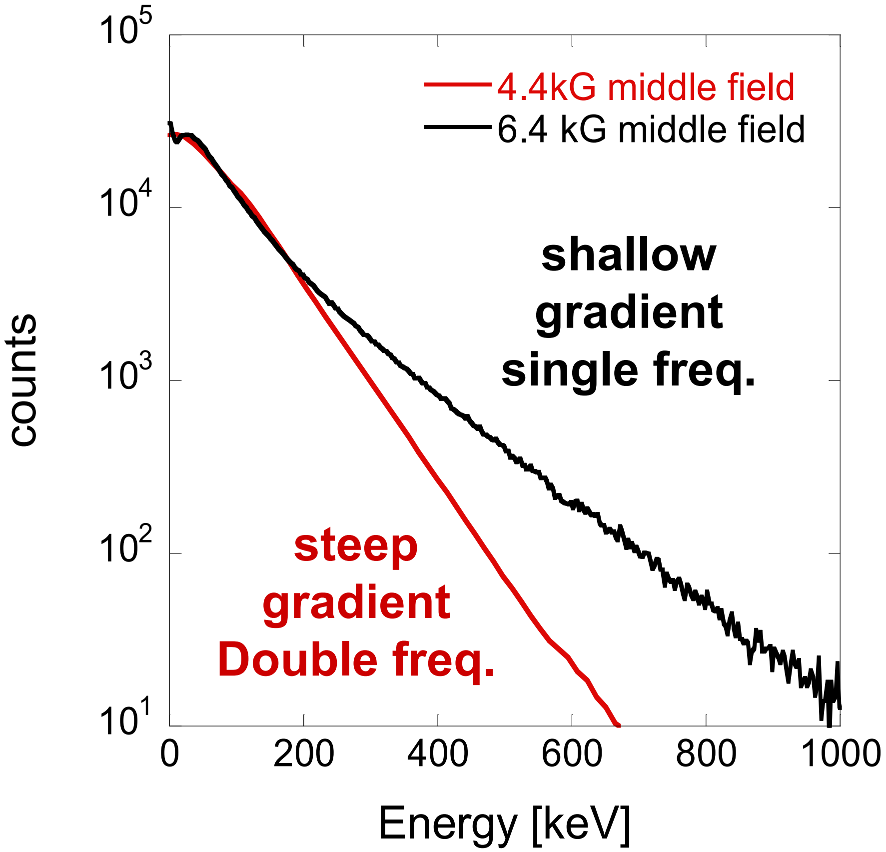
Emissivity of the solid target (plasma chamber wall) is much higher than from the thin target (plasma particles)

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.



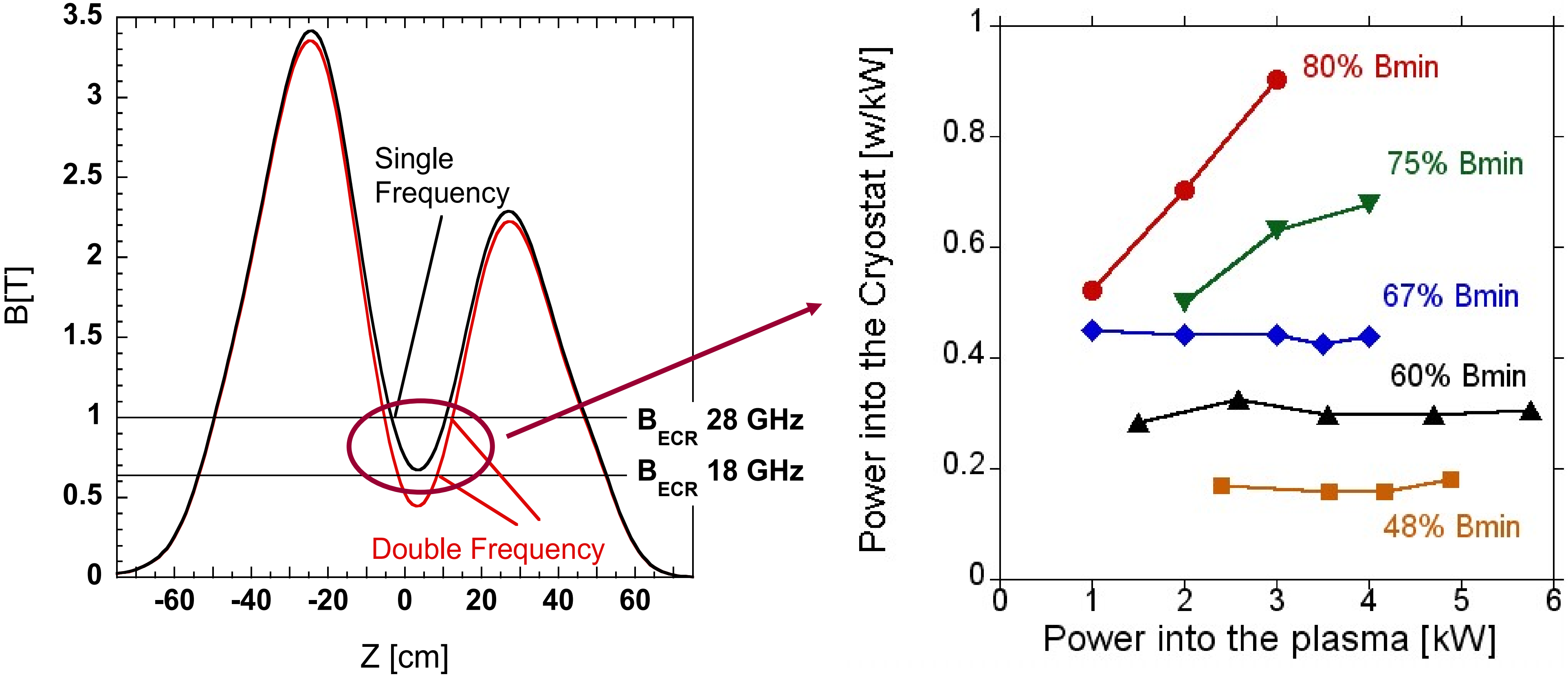
Axial Bremstrahlung spectra from VENUS for the two field configuration



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

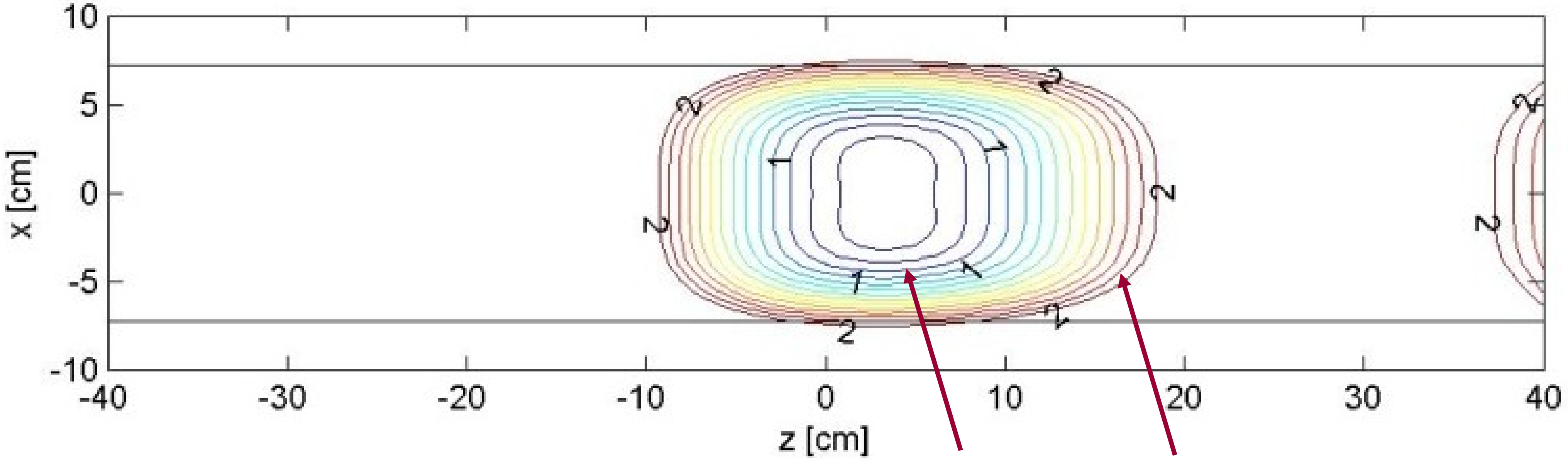
Consequently, the gradient of the magnetic field at the resonance zone strongly affects the heat load into the cryostat



Re-commisioning 2010: FRIB design data

As the demand for increased intensities of highly charged heavy ions continues to grow, the development of 4th generation ECR ion sources using Nb_3Sn is a necessity

Superconducting Magnets: ECR Design ‘Standard Model’



B_{ECR}

Last closed surface 2x B_{ECR}

28 GHz B_{ECR}= 1 Tesla

56 GHz B_{ECR}= 2 Tesla

	28 GHz	56 GHz
$B_{inj} \sim 4 \cdot B_{ecr}$	**4T**	**8T**
$B_{min} \sim 0.8\ B_{ecr}$	**.5-.8 T**	**1-1.6 T**
$B_{ext} \sim B_{rad}$	**2T**	**4T**
$B_{rad} \geq 2\ B_{ecr}$	**2T**	**4T**

Magnetic Design		**28 GHz**	**56 GHz**
Max solenoid field	on the coil	6 T	12 T
	on axis	4 T	8 T
Max sextupole field	on the coil	7 T	15 T
	on plasma wall	2.1 T	4.2 T
Superconductor		NbTi	Nb_3Sn

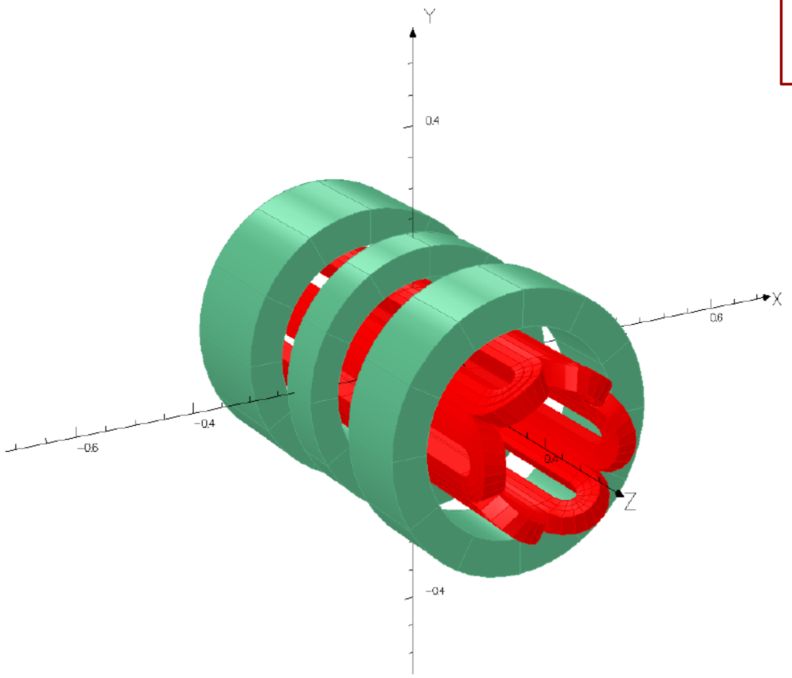
Superconducting Magnet Structure: two options

$B_{inj} = 8T$

$B_{ext} = 4T$

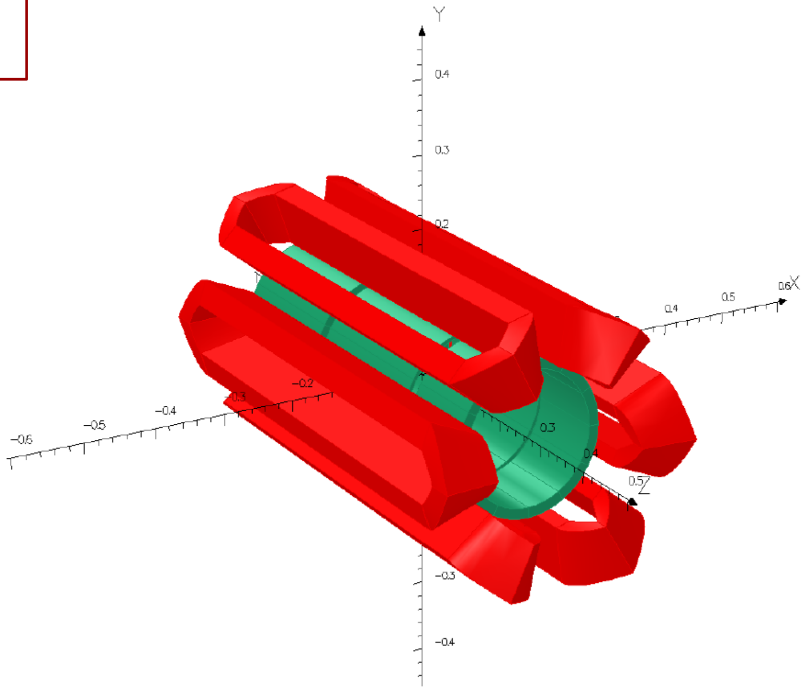
$B_{rad} = 4T$

Sextupole-in-Solenoid Geometry (VENUS)



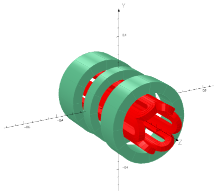
- Minimizes the peak fields in the coil
- Strong influence (forces) of the solenoid field on the sextupole ends

Solenoid-in-Sextupole Geometry (SECRAL)



- Minimizes the influence of the solenoid on the sextupole field
- Significantly higher field required for the sextupole magnet surface due to the larger radius of the coils
- Strong forces on the solenoid coils

Superconducting Magnet Structure: two options

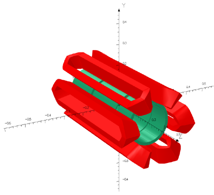


Sextupole-in-Solenoid Geometry (VENUS)

B_{inj} = 8T

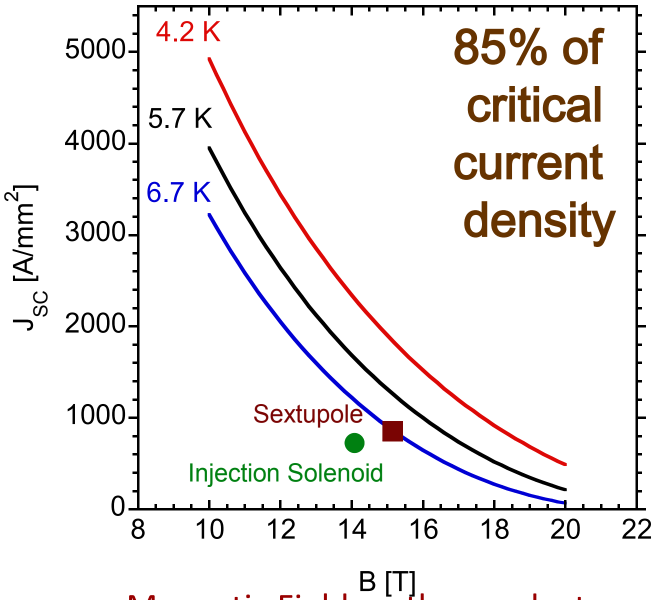
B_{ext} = 4T

B_{rad} = 4T



Solenoid-in-Sextupole Geometry (SECRAL)

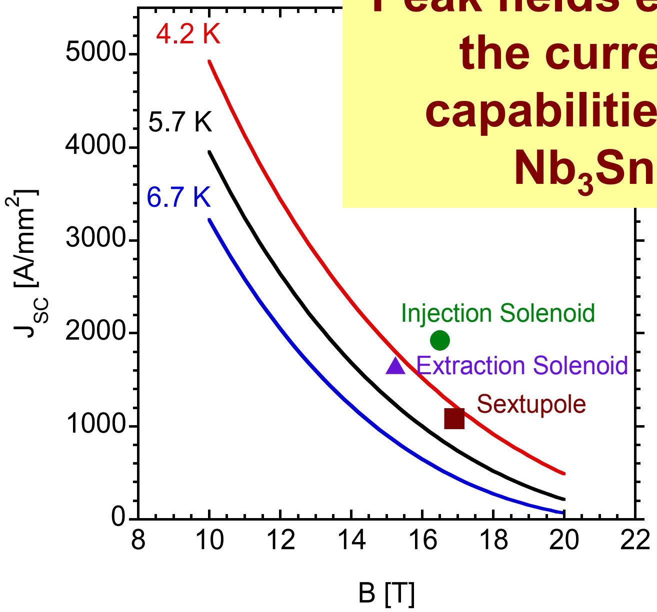
Current Density through the superconductor



85% of critical current density

Magnetic Field on the conductor

Current Density through the superconductor



Peak fields exceed the current capabilities of Nb_3Sn

Magnetic Field on the conductor

- Minimizes the peak fields in the coil
- Strong influence (forces) of the solenoid field on the sextupole ends

- Minimizes the influence of the solenoid on the sextupole field
- Significantly higher field required for the sextupole magnet surface due to the larger radius of the coils
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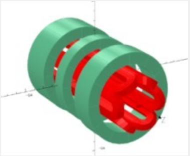
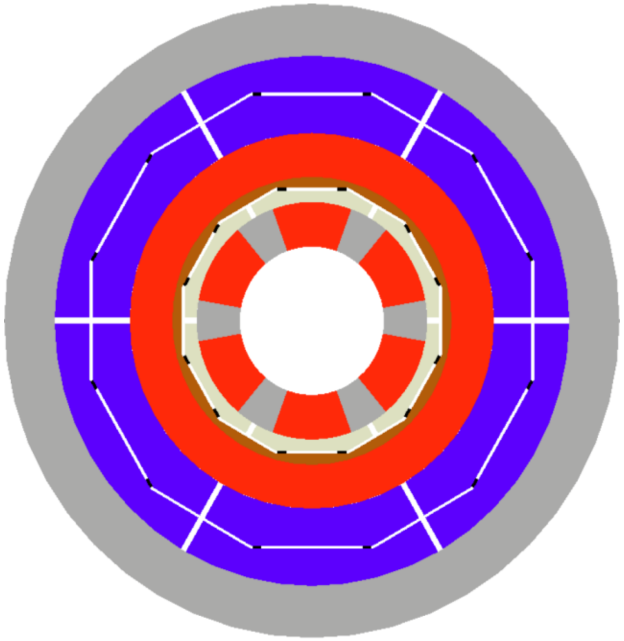
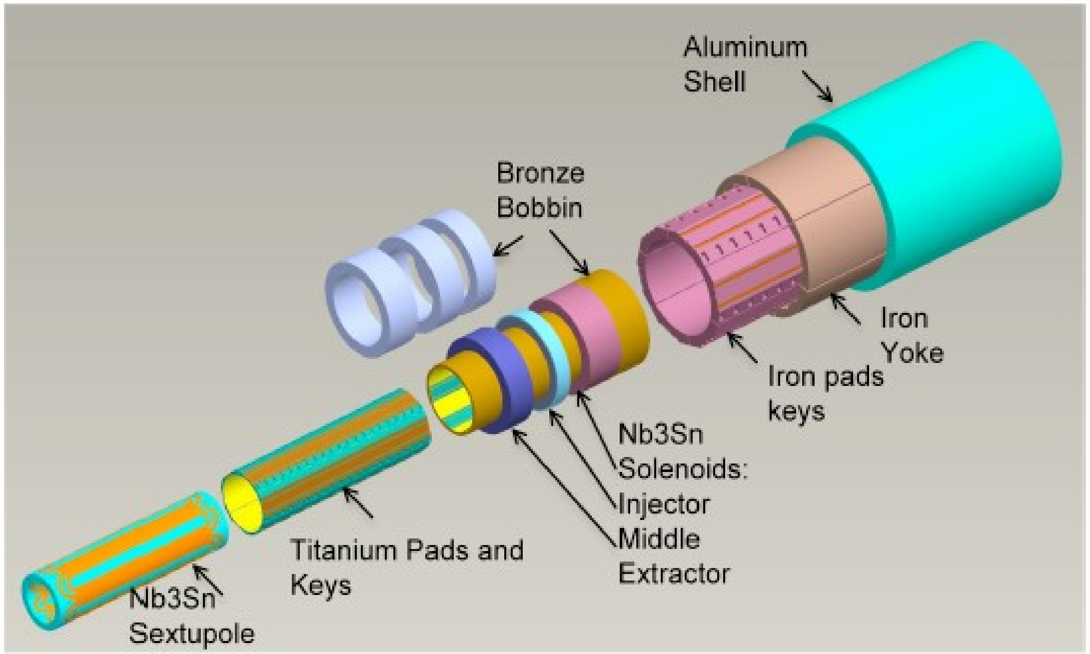


Sextupole-in-Solenoid: Clamping Structure



- A shell-based structure using bladders and keys provides a mechanism for controlled room temperature pre-stress.
- Pre-stress is then amplified by the contraction of an aluminum shell during cool-down.
- Stress values are close to the maximum acceptable values
- The method was developed at Superconducting magnet group at LBNL and successfully applied to high field magnets.

Build a prototype magnet!



Summary

- VENUS ECR ion sources is fully functional again
  - after a few weeks of re-commisioning record ion beam intensities were extracted, e.g. 211 eμA Xe^{30+}
- VENUS is the prototype source for FRIB, design changes improvements for the cryostat will be incorporated (see next talk)
- X-ray are a major issue for superconducting ECR ion sources
  - X-rays can add several Watts of heat load to the cryostat
  - The energy spectrum shows a strong anisotropy
  - The energy of the hot tail is strongly dependent on the magnetic field gradient at the resonance zone and on frequency
- Nb_3Sn Magnets are the next technology leap for ECR ion source
  - Prototyping should start now to be ready for the next generation heavy ion accelerator upgrades

X-ray summary

- X-ray are a major issue for superconducting ECR ion sources
- X-rays can add several Watts of heat load to the cryostat
- Deteriorate HV insulation
- Thin Ta liners reduce only the low energy part of the x-ray spectrum
- The energy of the hot tail is strongly dependent on the magnetic field gradient at the resonance zone
- The energy of the hot tail is strongly dependent on frequency
- The energy spectrum shows a strong anisotropy
- Measuring the low energy spectrum will give further insight on the ECR heating, confinement, and performance optimization

Summary

- VENUS ECR ion sources is fully functional again and performs well
  - after a few weeks of re-commisioning record ion beam intensities were extracted, e.g. 211 eμA Xe^{30+}
- VENUS is the prototype source for FRIB, design changes improvements for the cryostat will be incorporated (see next talk)
- X-ray are a major issue for superconducting ECR ion sources
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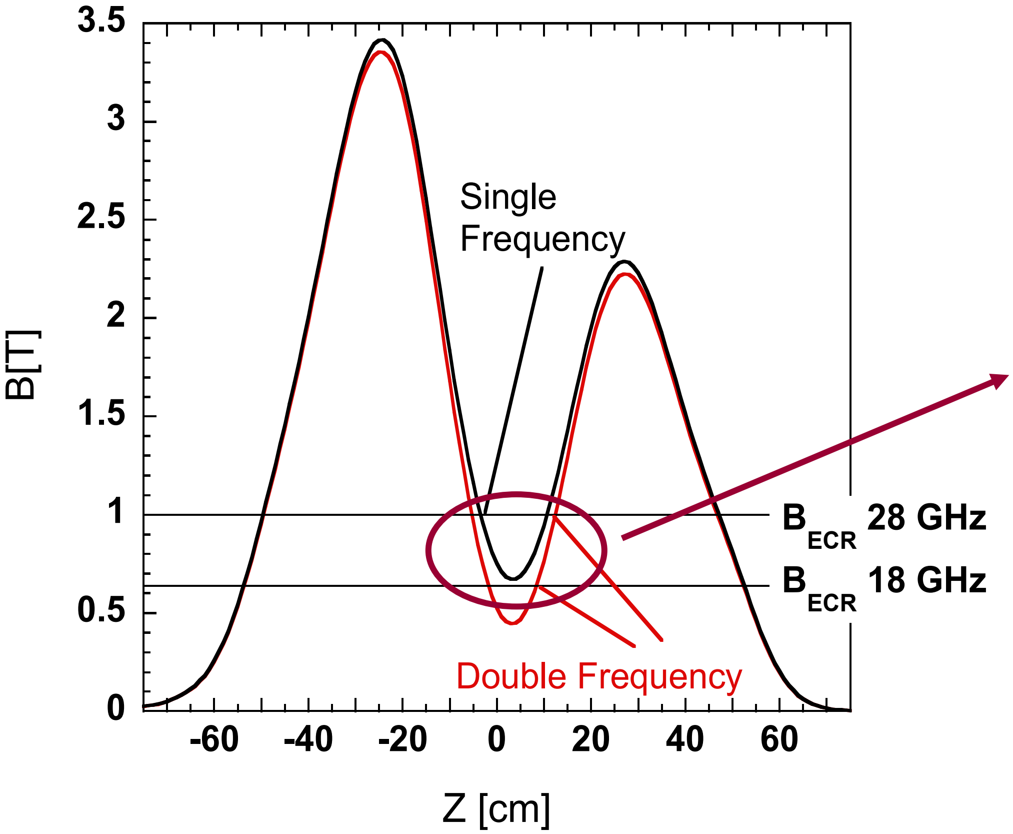
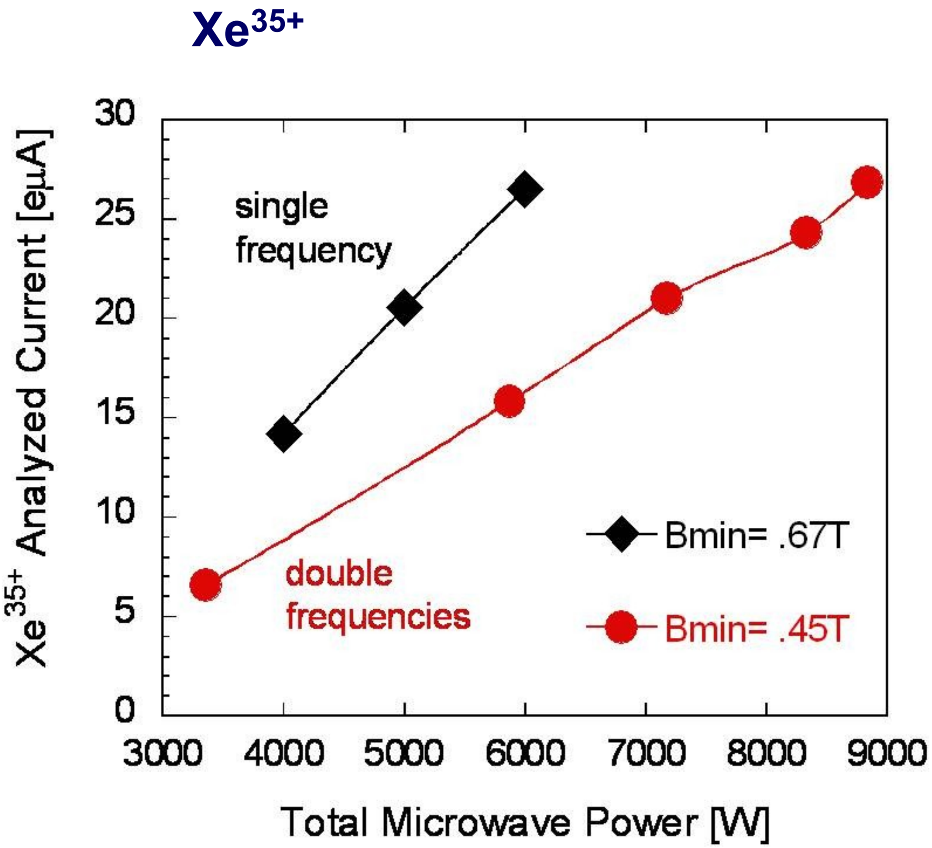
  - The energy of the hot tail is strongly dependent on the magnetic field gradient at the resonance zone and on frequency
- Nb3Sn Magnets are the next technology leap for ECR ion source
  - Prototyping should start now to be ready for the next generation heavy ion accelerator upgrades

What about performance?

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



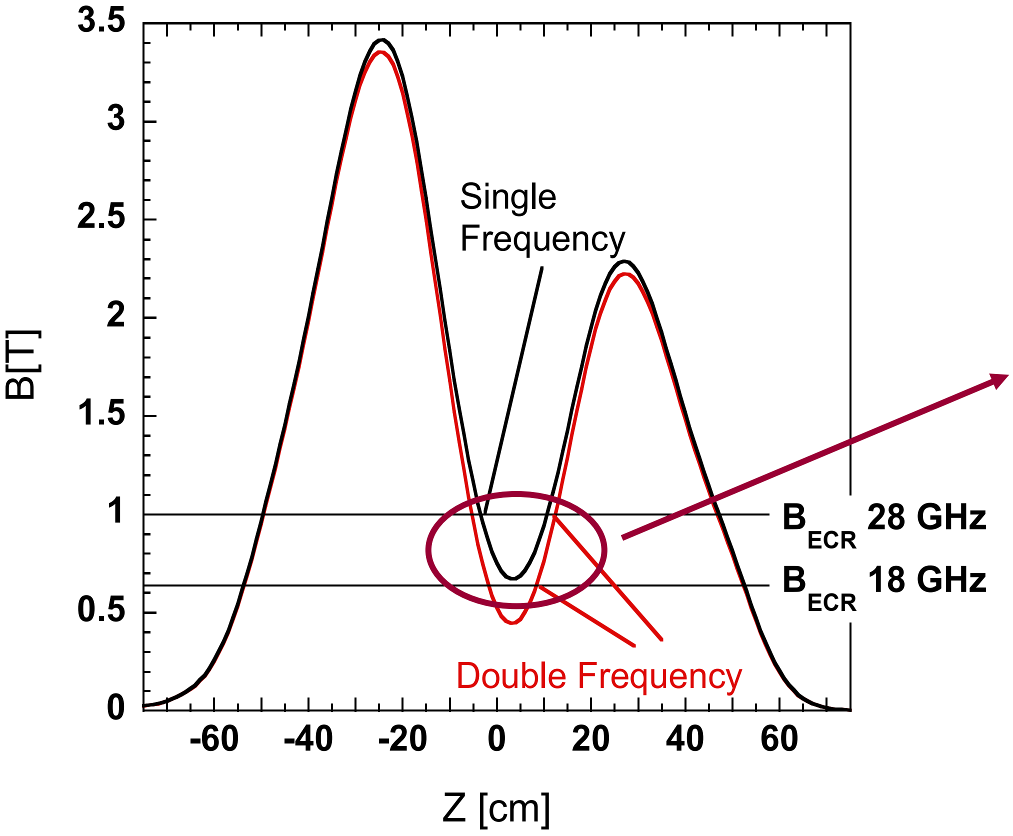


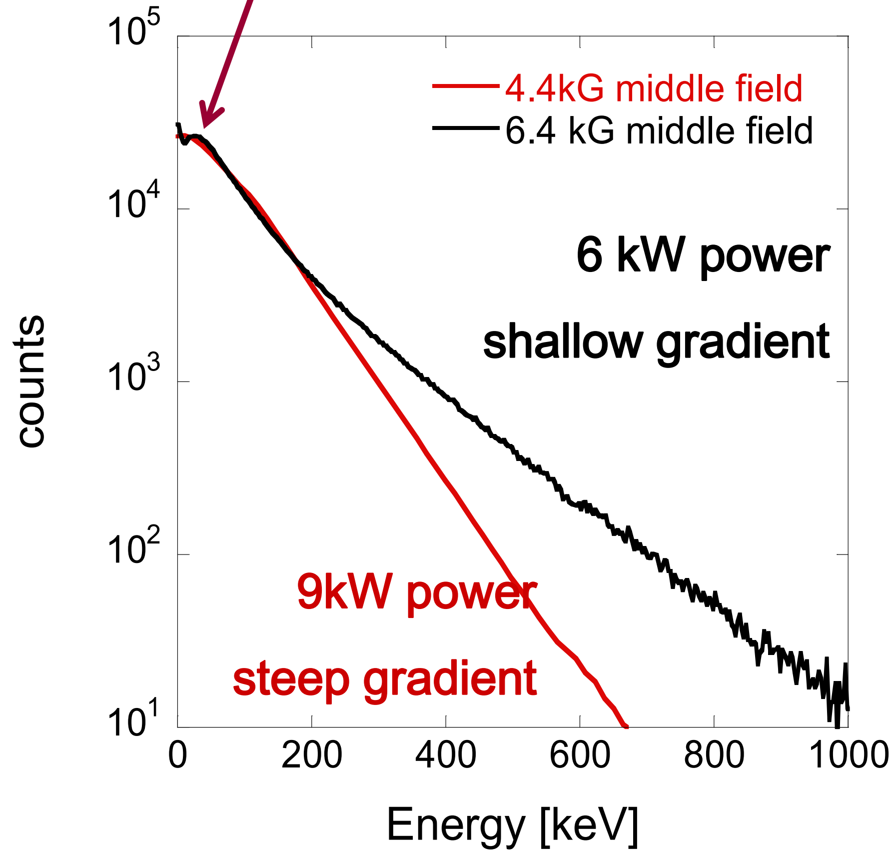
Optimum performance is achieved for gradients of about 70 to 80 %

→ Enough cryogenic cooling power is important for the FRIB source

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

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

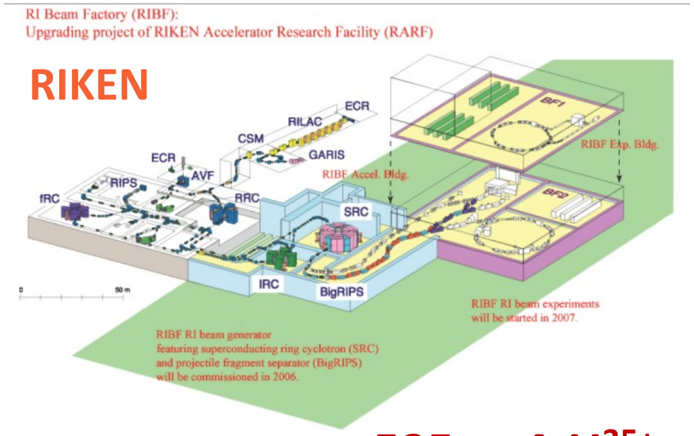




→ To understand the influence of the gradient on performance measurement of the low energy x-ray spectrum (below 50keV) is crucial (in progress at LBNL)

Development of superconducting ECR ion sources is a necessity to meet the intensity requirements of heavy ion facilities

RIKEN



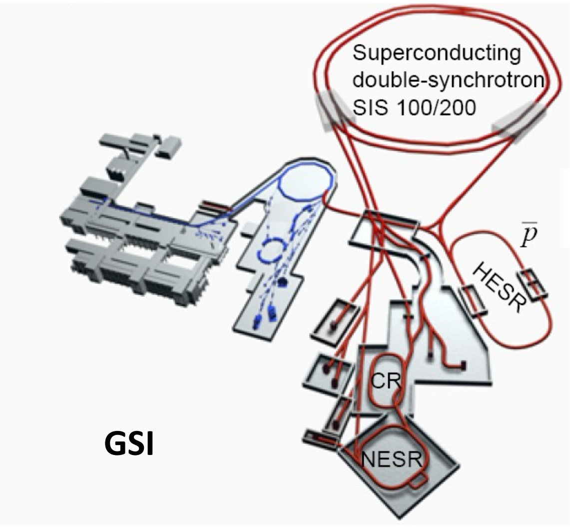
525 eμA U^{35+}

Challenges

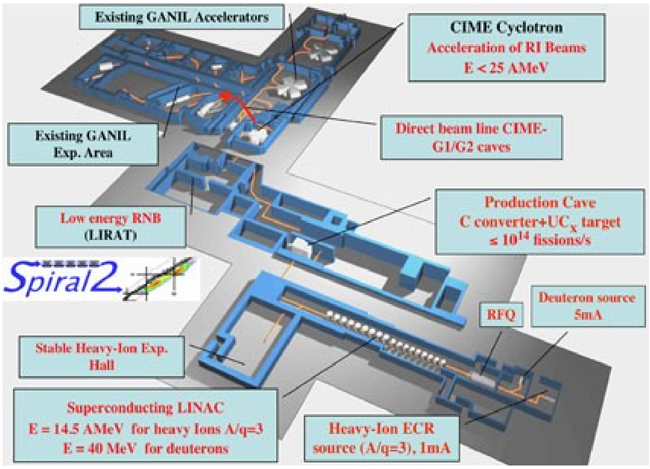
- Superconducting Magnet and Cryogenic Technology
- X-rays from the Plasma
- Ion Beam Transport (D. Winklehner TUCOAK03)

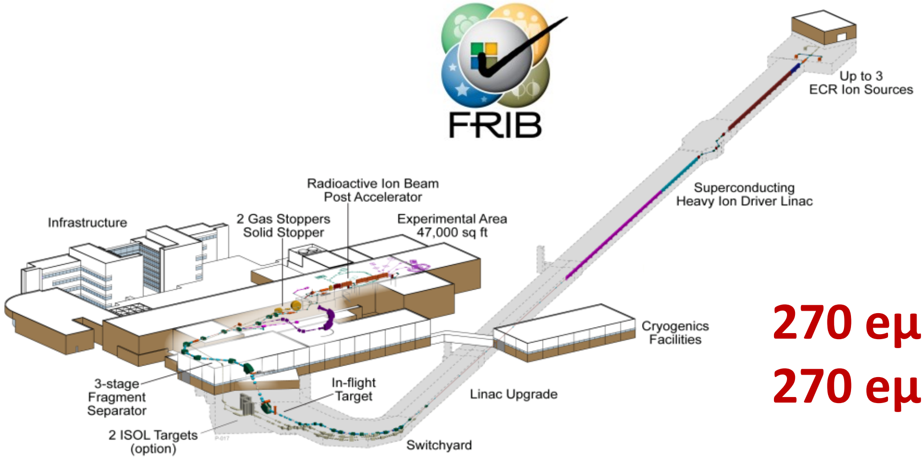
FAIR

Facility for Ion and Antiproton Research



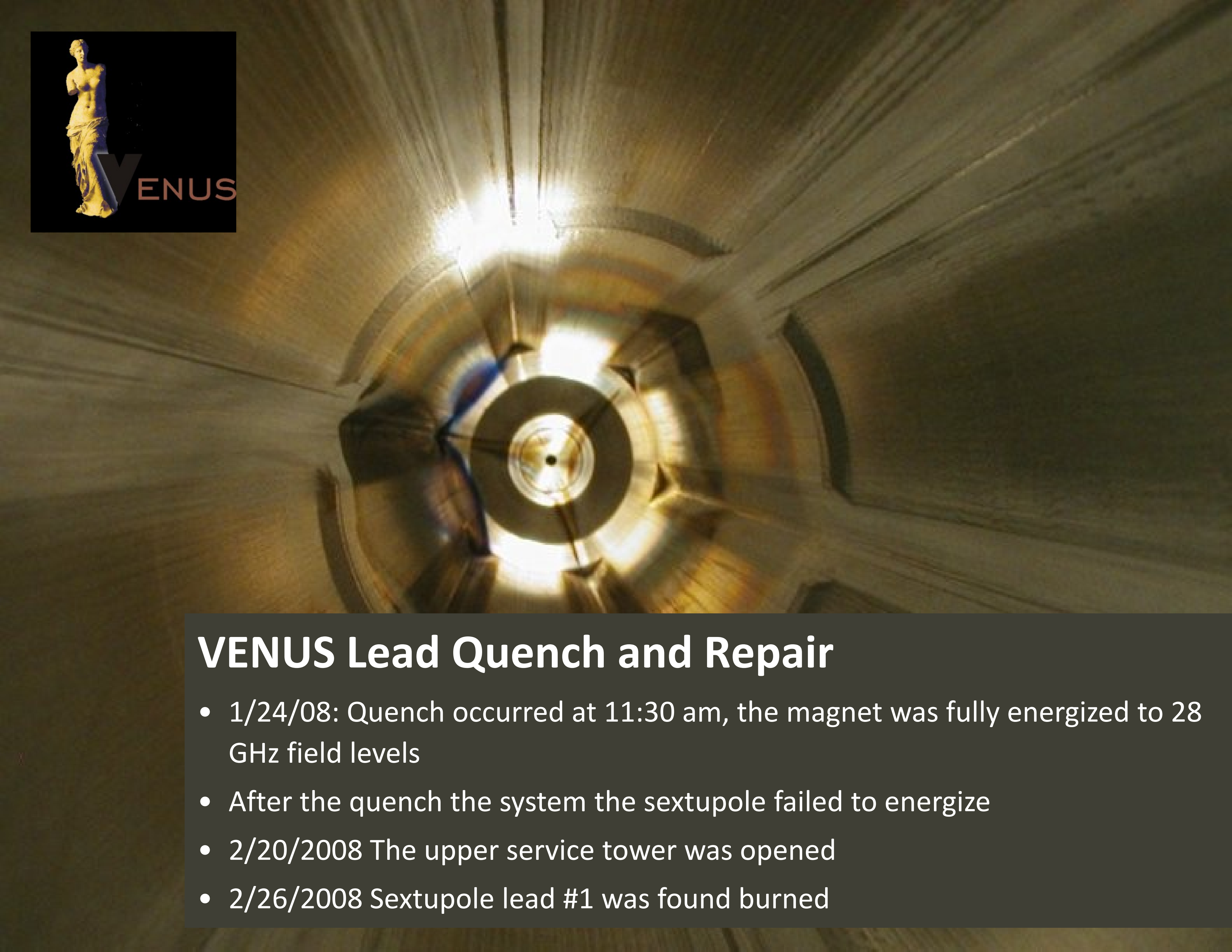
1emA Ar^{12+}





270 eμA U^{33+}

270 eμA U^{34+}



VENUS Lead Quench and Repair

- 1/24/08: Quench occurred at 11:30 am, the magnet was fully energized to 28 GHz field levels
- After the quench the system the sextupole failed to energize
- 2/20/2008 The upper service tower was opened
- 2/26/2008 Sextupole lead #1 was found burned