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Status report and recent developments with VENUS

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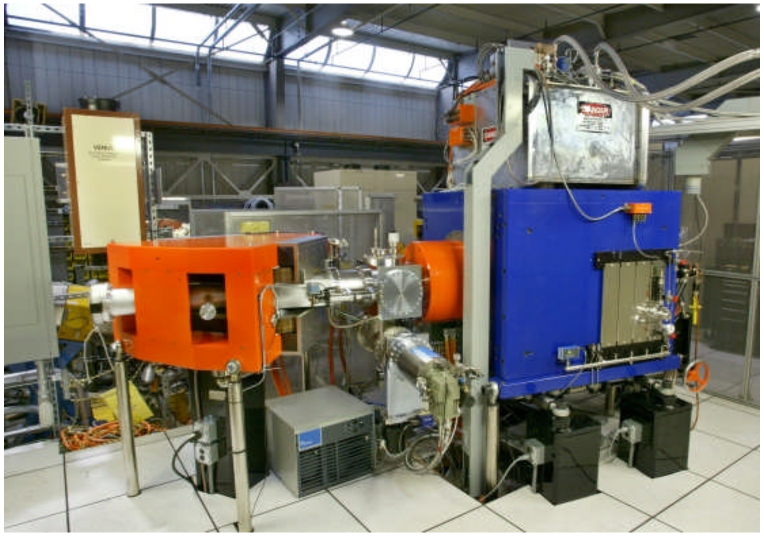
Outline

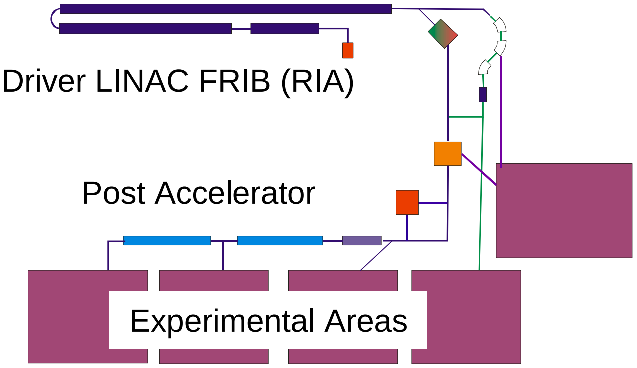
- Introduction
- Summary of the VENUS performance
- Influence of the magnetic field configuration and heating frequency on x-ray energy
- Influence of the heating frequency on the electron energy and heating efficiency

- VENUS lead quench
- Repair status of the VENUS magnet
- Discussion of the failure mode and analyses
- Conclusion

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

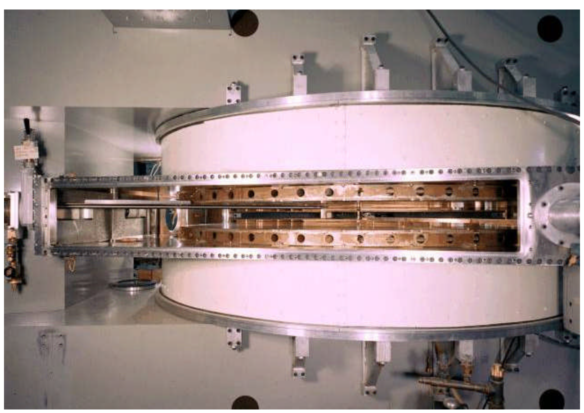


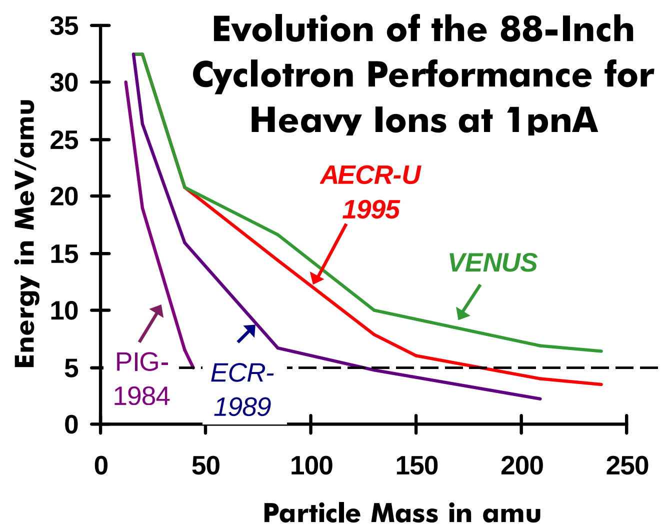
Prototype Injector



Provide (very) high intensity high-charge state beams for the next generation heavy ion accelerators M/Q~7

Injector Ion Source

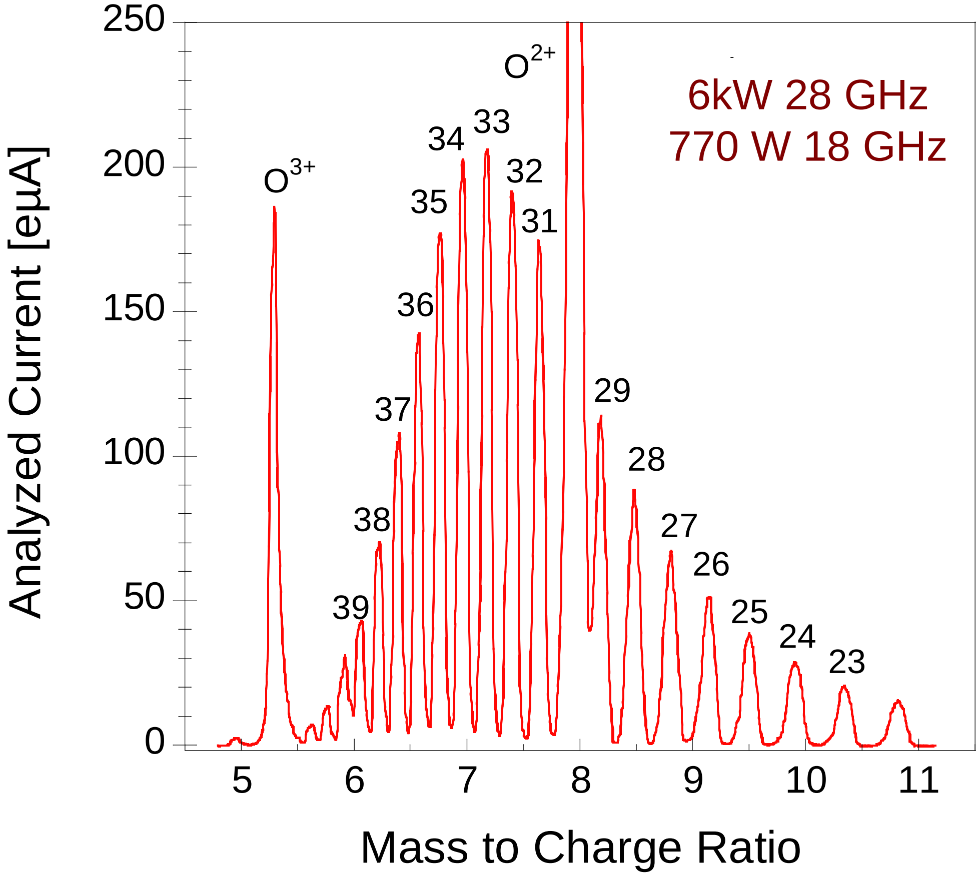




Produce intense (very) high-charge-state heavy ion-beams for the 88-Inch Cyclotron M/Q ~ 2 to 5

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

High Intensity Uranium Production



	VENUS 28GHz or 28+18 GHz	SECRAL (18 GHz) eμA
O^{6+}	2860 eμA	2300 eμA
O^{7+}	850 eμA	810 eμA
O^{8+}	~ 400 eμA	
Kr^{25+}	220 eμA	
Kr^{30+}	1 eμA	
Xe^{35+}	28 eμA	12 eμA
Xe^{42+}	.5 eμA	
U^{34+}	200 eμA	
U^{47+}	5 eμA	

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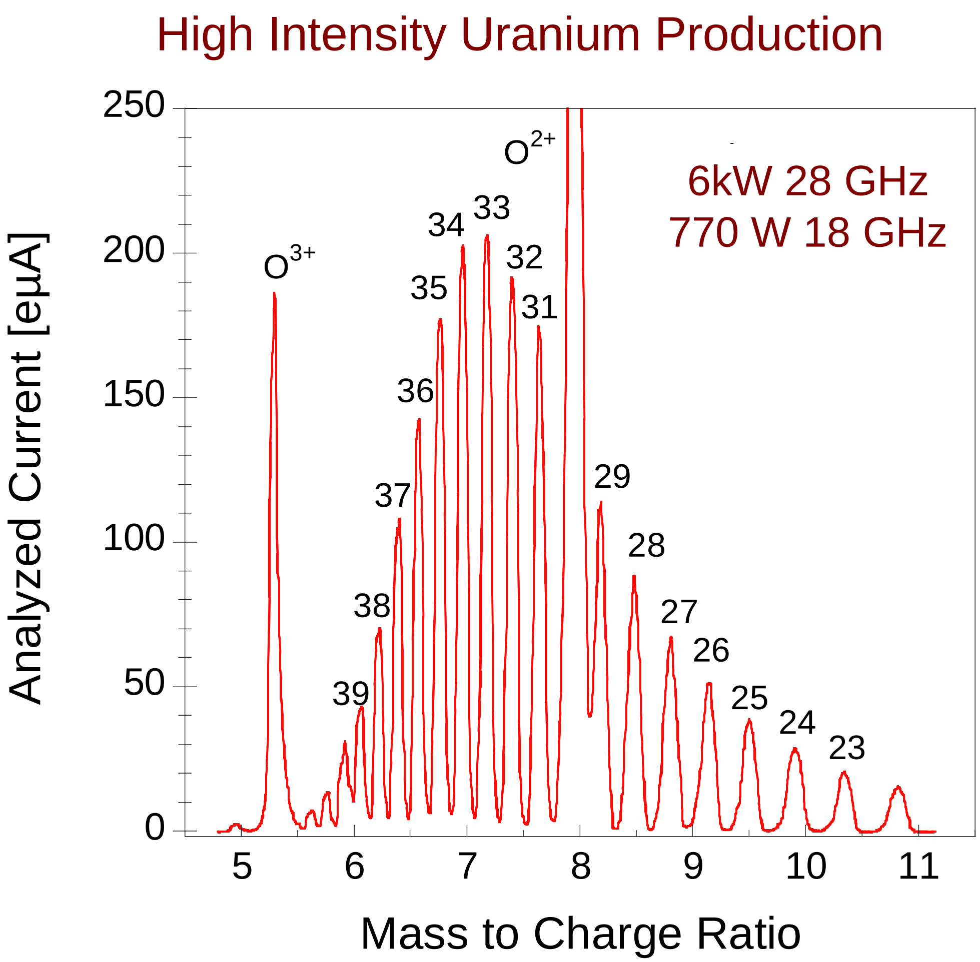

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O^{6+}	2860 eμA	2300 eμA
O^{7+}	850 eμA	810 eμA
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Ar^{12+}	860	510
Ar^{16+}	270	73
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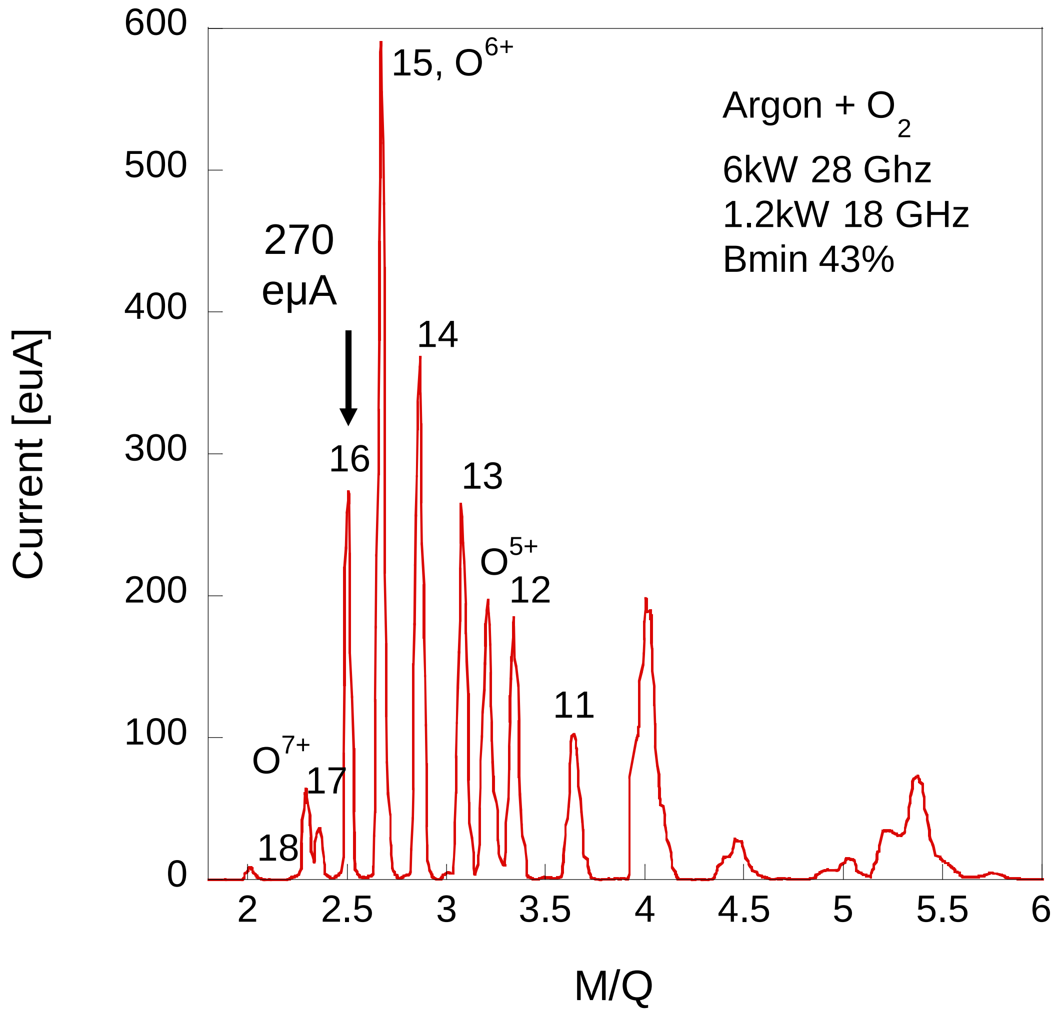


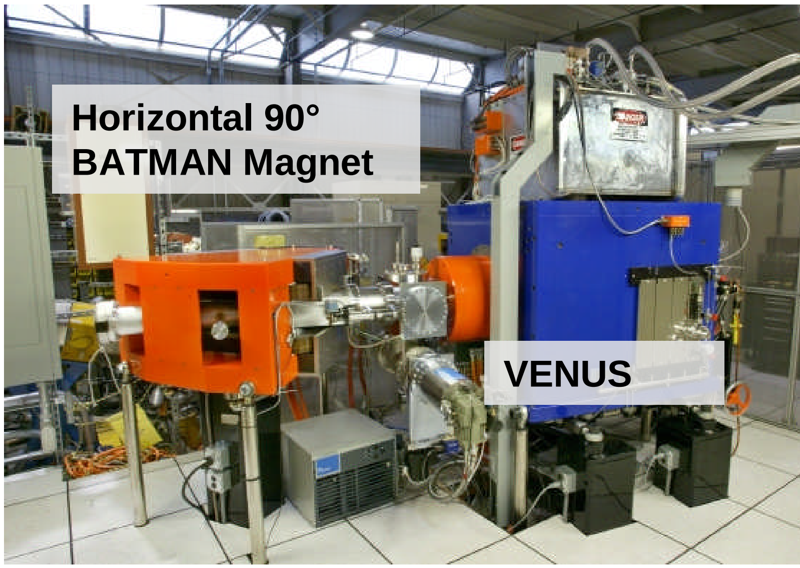
Ar	VENUS (28GHz) eμA	SECRAL (18 GHz) eμA
12^+	860	510
14^+	514	270
16^+	270	73
17^+	36	8.5
18^+	1	

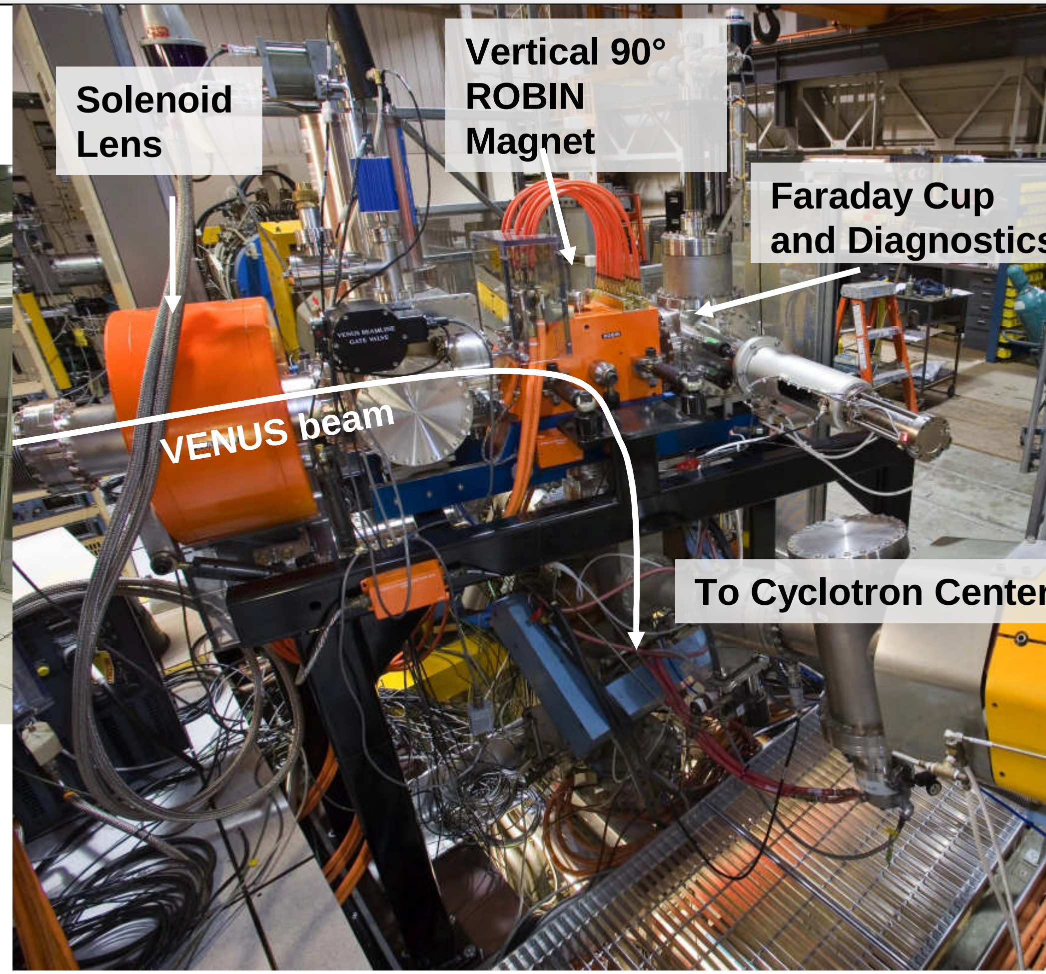
Results from VENUS and SECRAL show that frequency scaling

$$I \sim \omega^2$$

between similar sources is valid (for medium charge states)

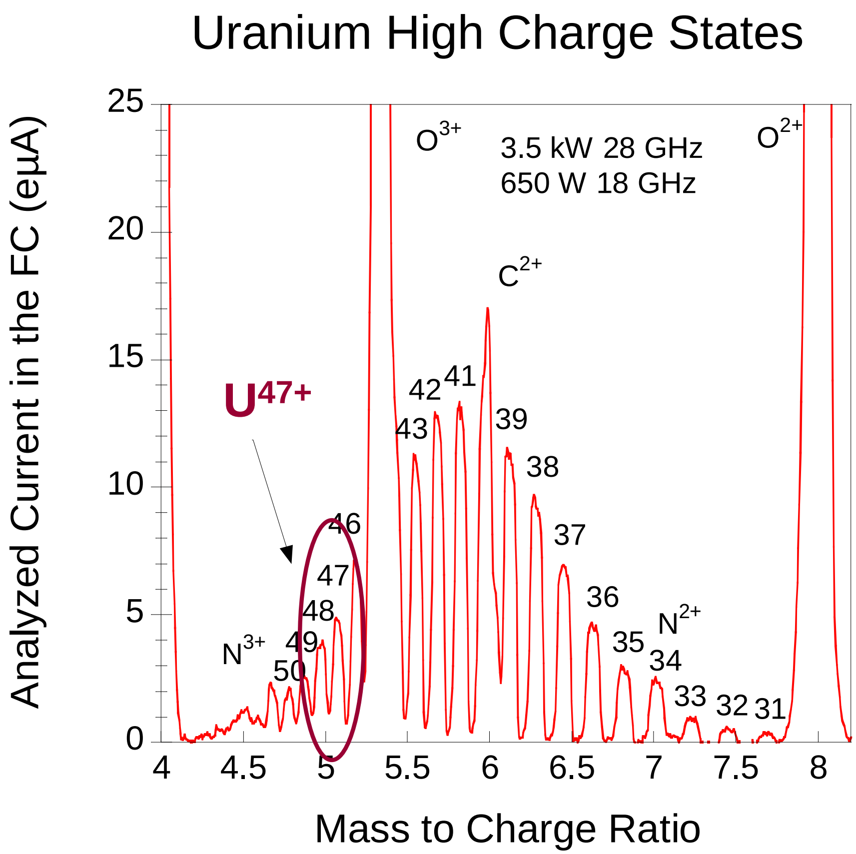
Beam line connection into the axial injection line





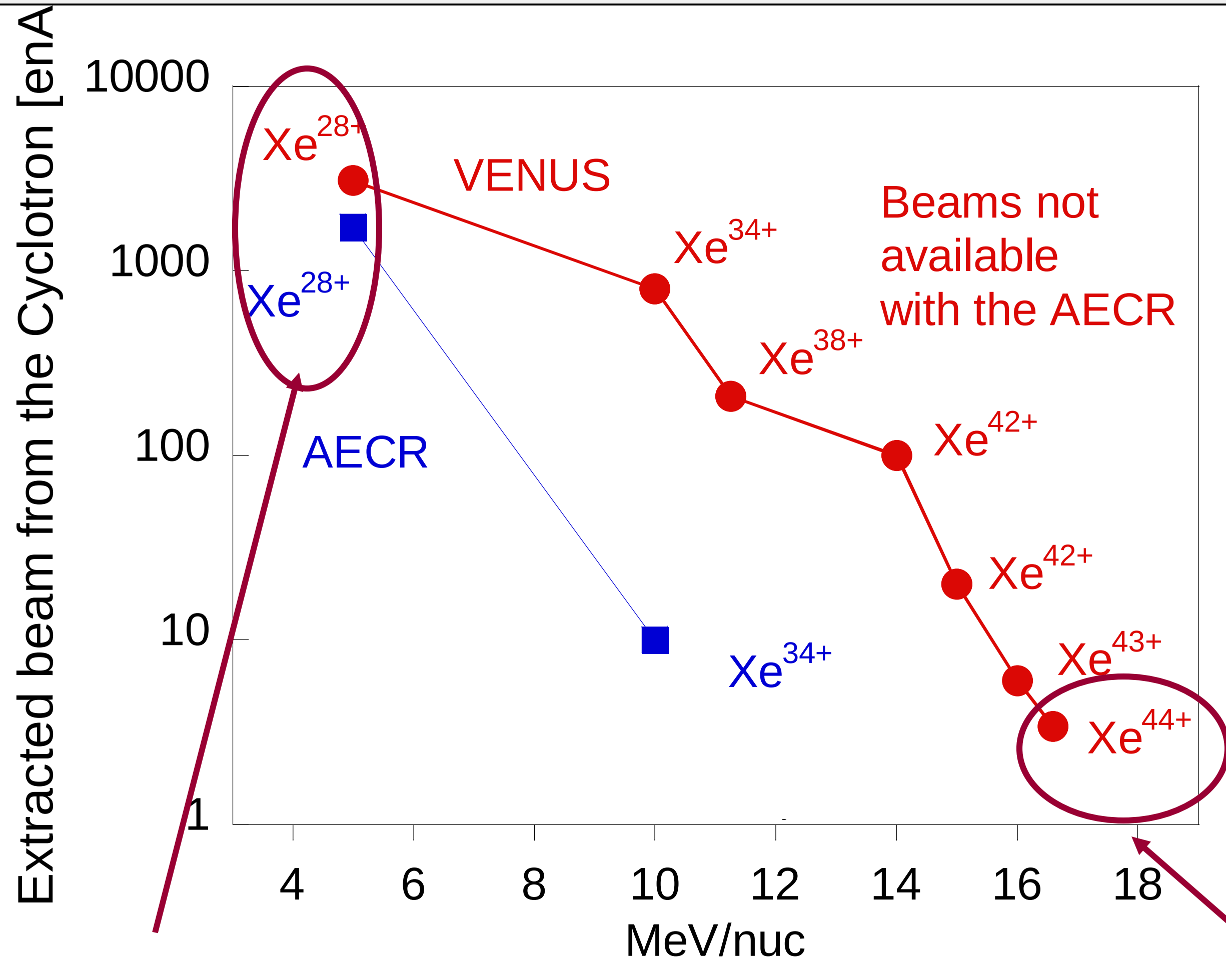
First Beam from VENUS extracted from the Cyclotron September 2006, Ar^{9+} at 200 MeV

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

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

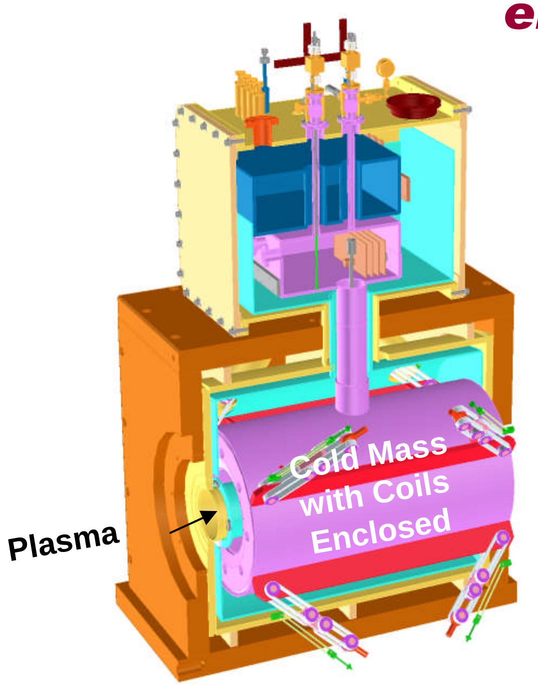


88-Inch Cyclotron
K=140

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 ~$10^{12}/cm^3$
($n_e \tau_i$ ~$2 \cdot 10^{11}$ sec/cm^3)

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



Parameters that influence the x-ray flux and energy

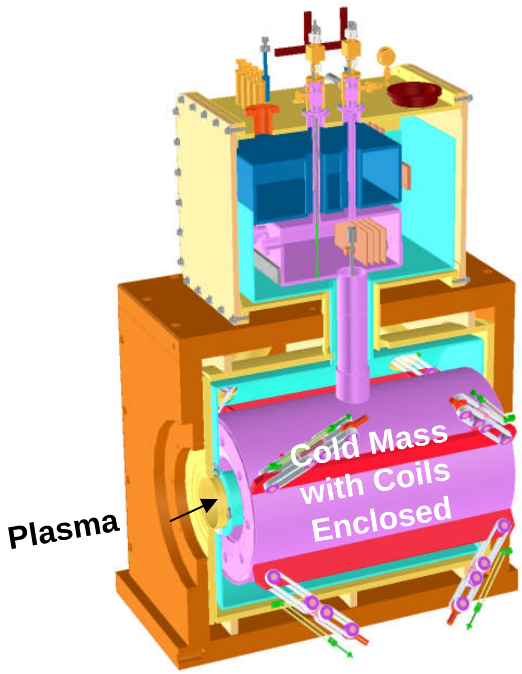
X-ray energy spectrum and flux

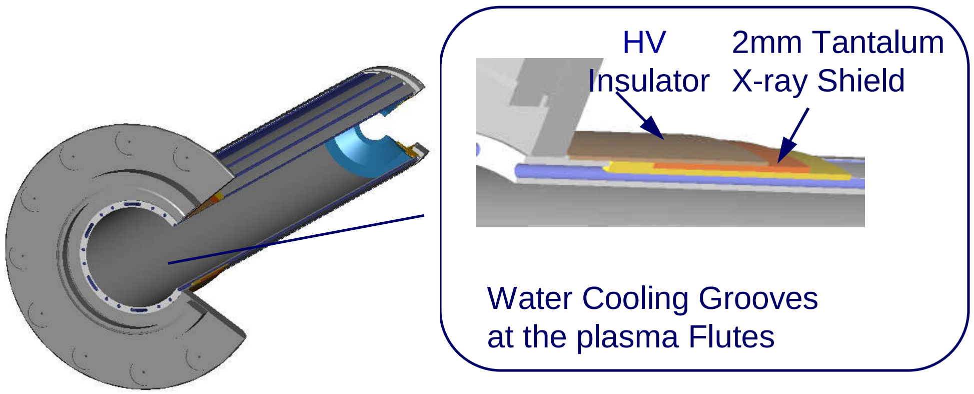
- Field gradient at the resonance zone
- Heating frequency
- Plasma instabilities
- Mirror ratio
- Power

X-rays also provide an important diagnostic's window into the ECR plasma

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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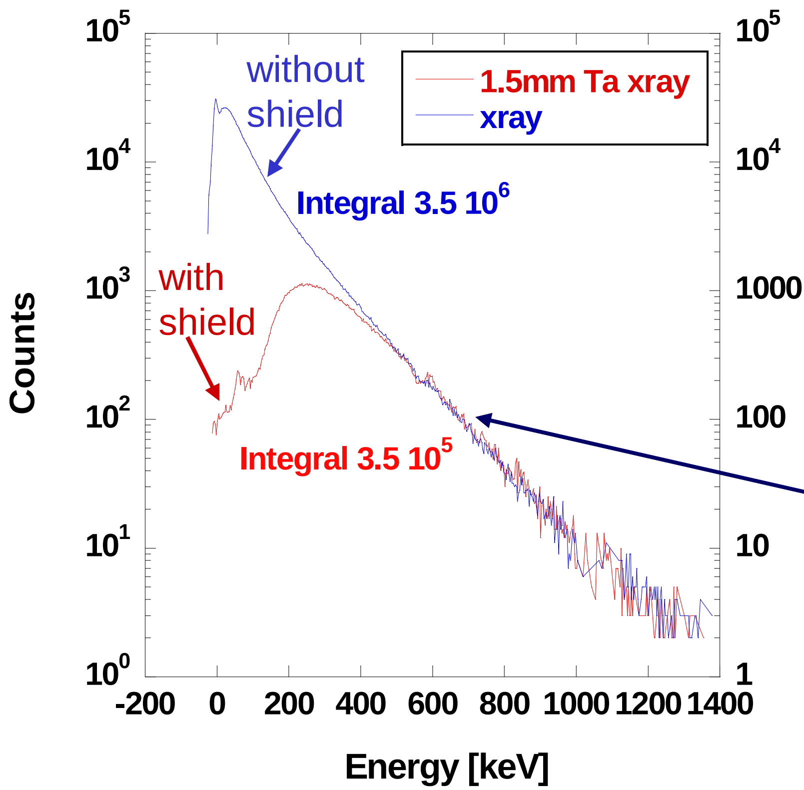
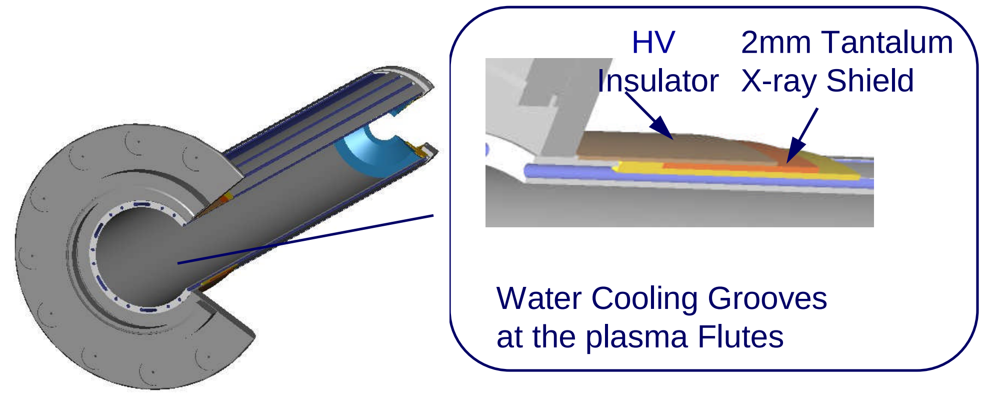
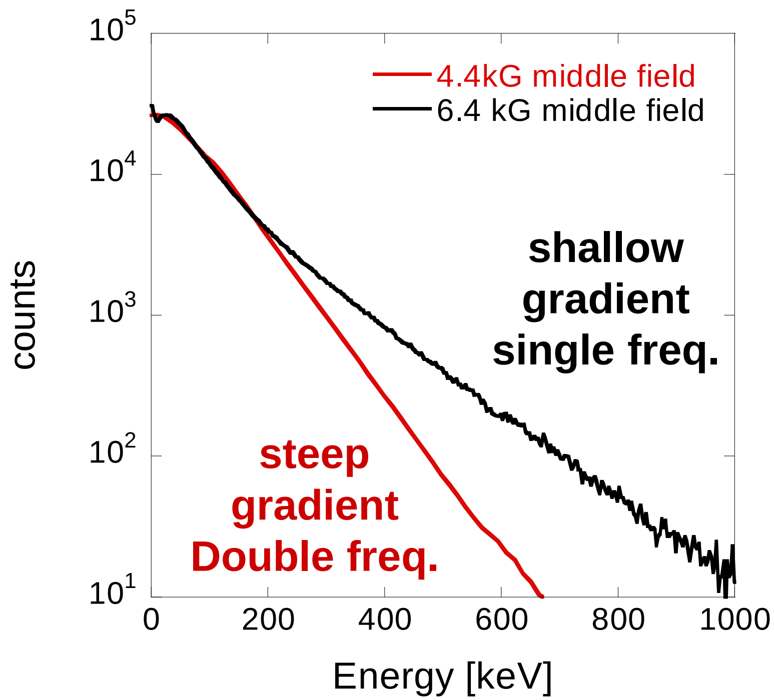


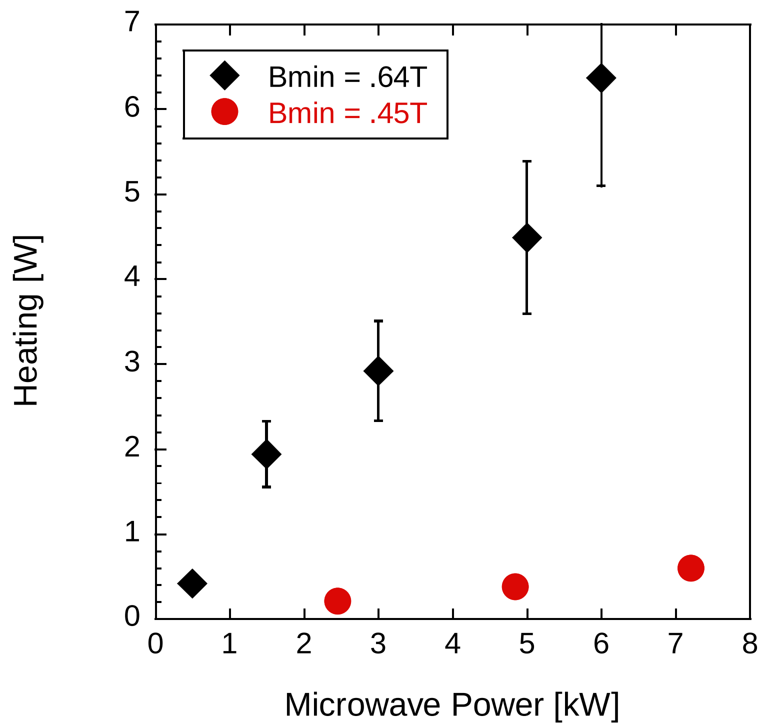


1.5 - 2 mm Ta shielding effectively attenuates the low energy bremsstrahlung, but becomes transparent for x-rays above 400keV

x-rays also provide an important diagnostic's window into the ECR plasma

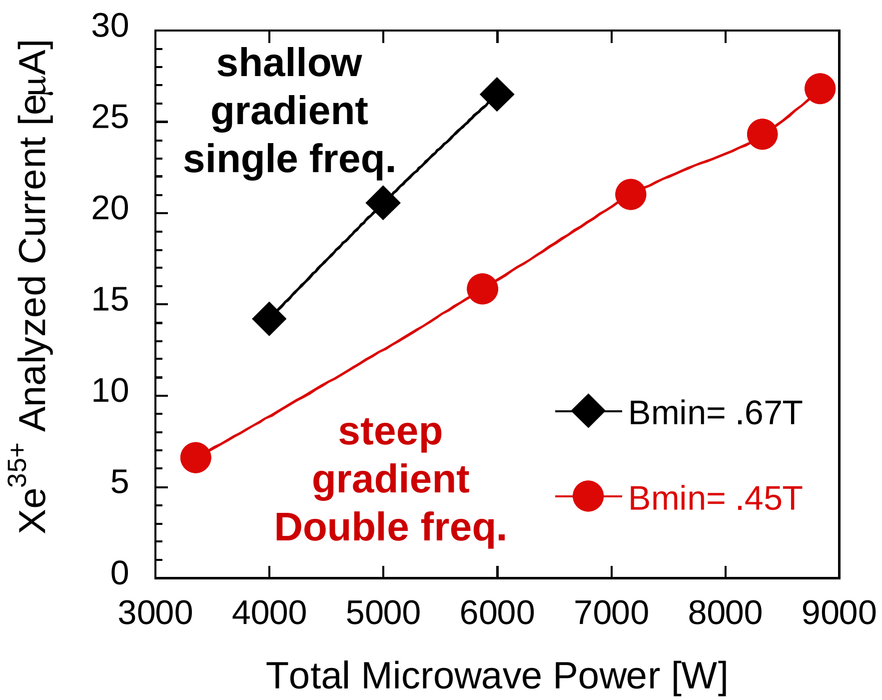
Parameter that influence the x-ray flux and spectrum

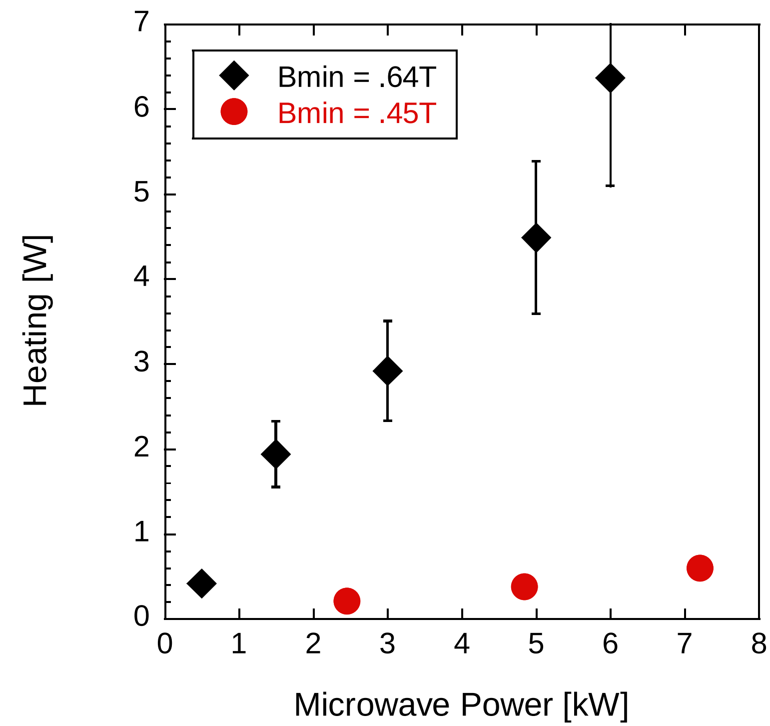




- Field gradient at the resonance zone (0.08 T and 0.13 T)

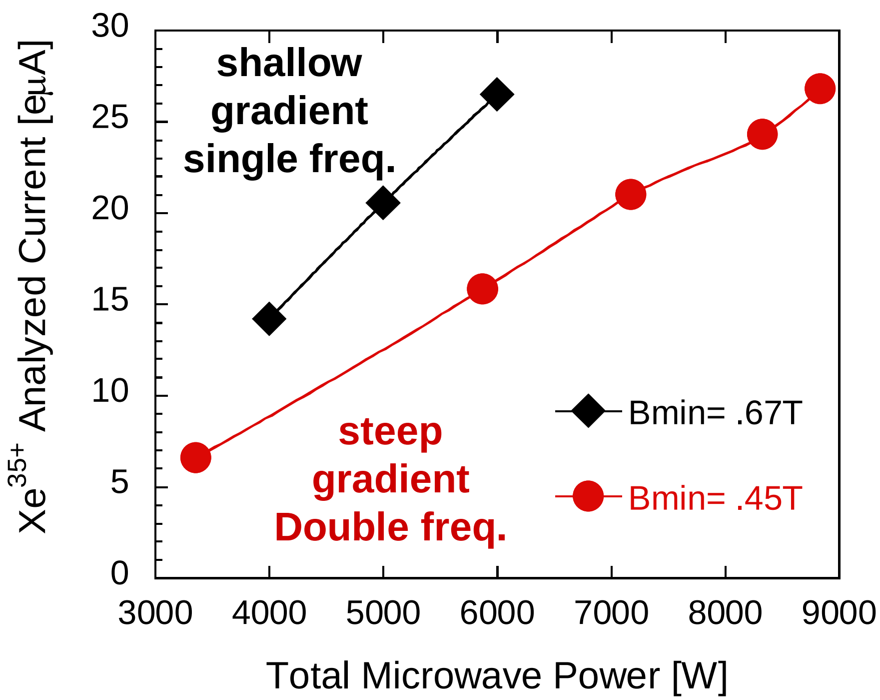
Parameter that influence the x-ray flux and spectrum

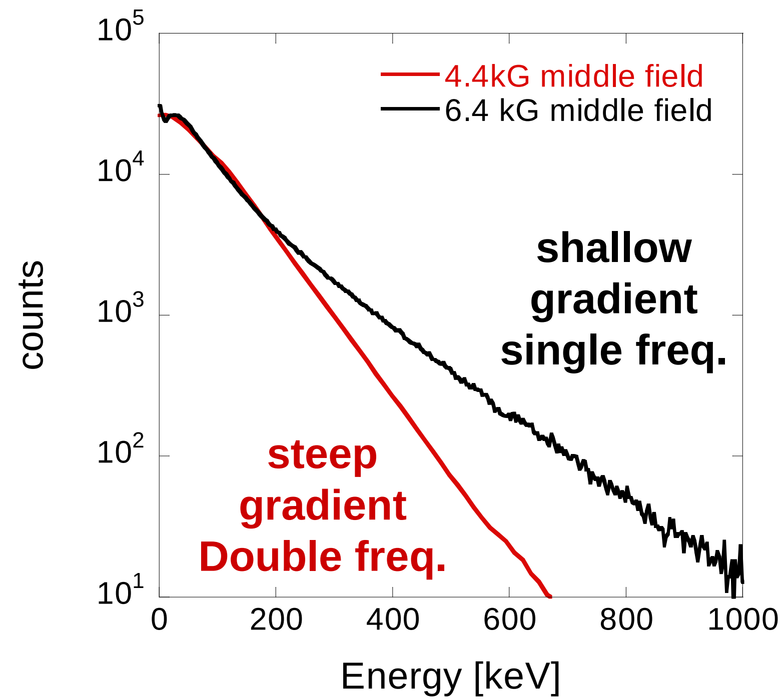




Double frequency heating (steep + gentle) and single frequency heating (gentle gradient) can achieve similar performance at different power levels

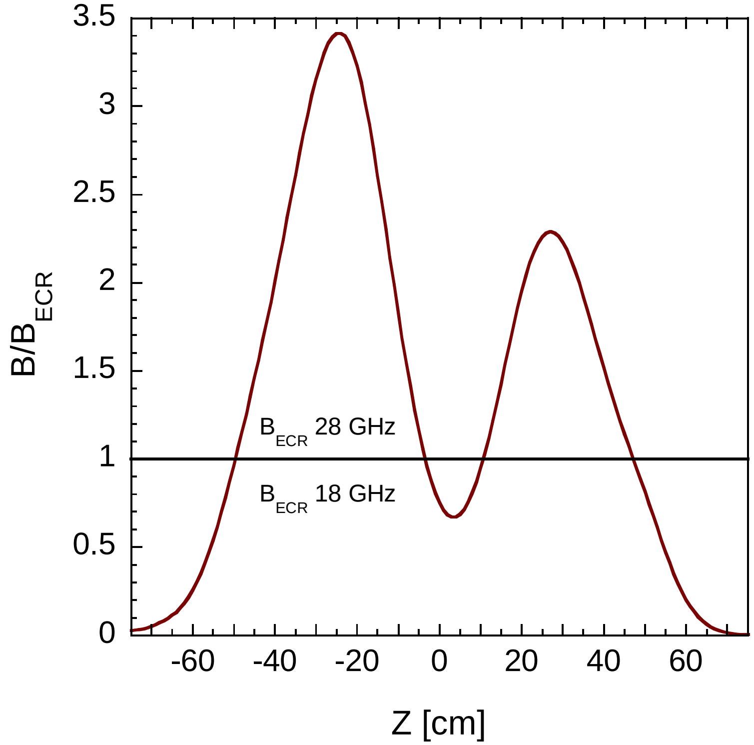
Parameter that influence the x-ray flux and spectrum

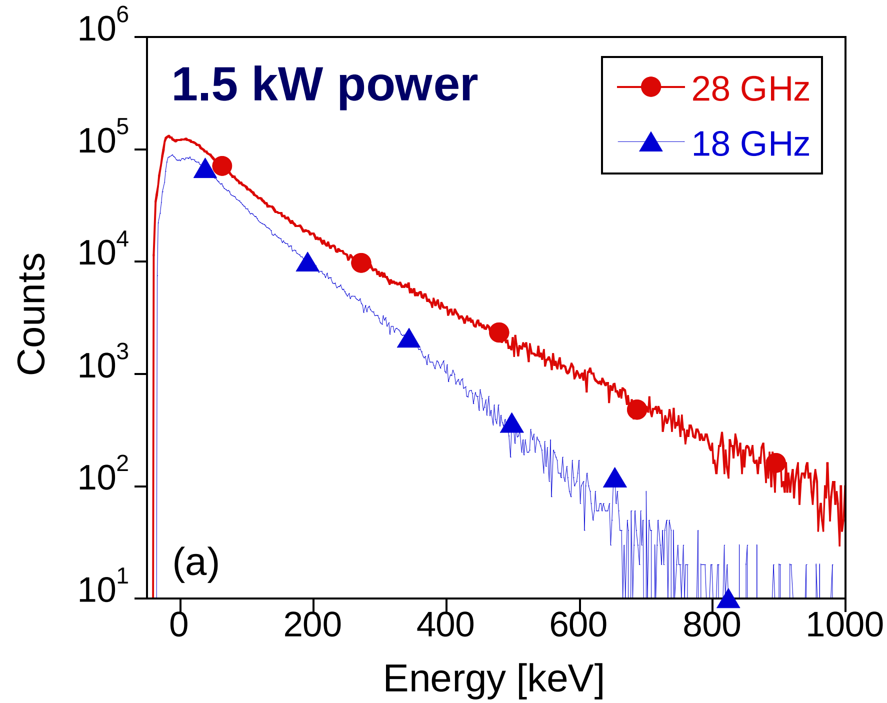




Double frequency heating (steep + gentle) and single frequency heating (gentle gradient) can achieve similar performance at different power levels

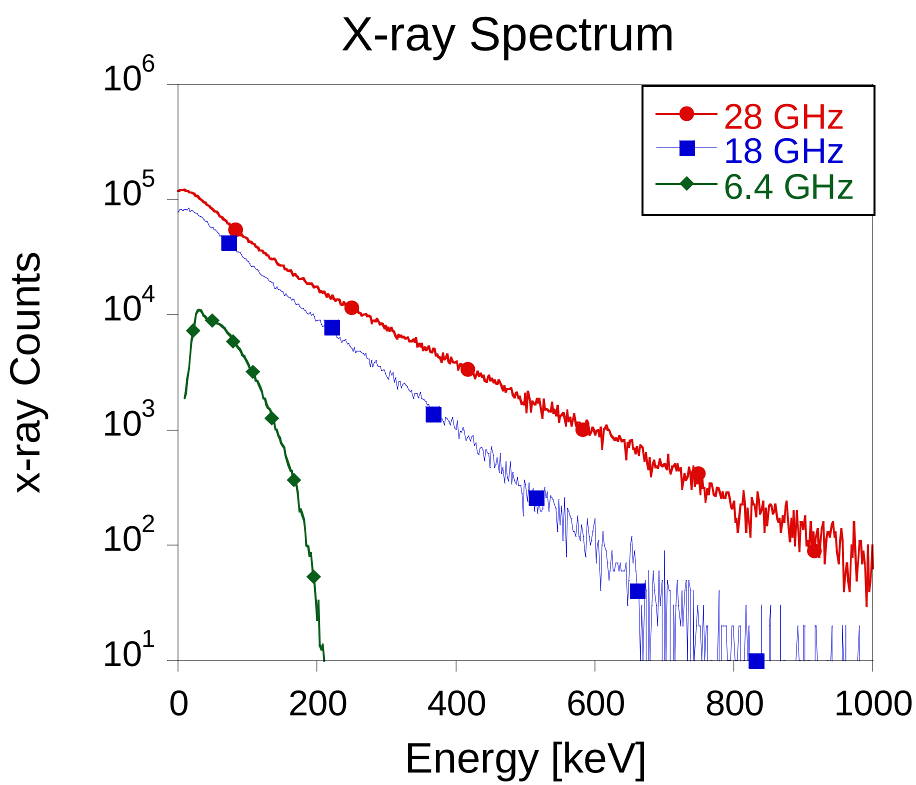
Using scaled magnetic fields for 18 and 28 GHz (same ECR zone size), 28 GHz heating results in much higher x-ray flux and energies

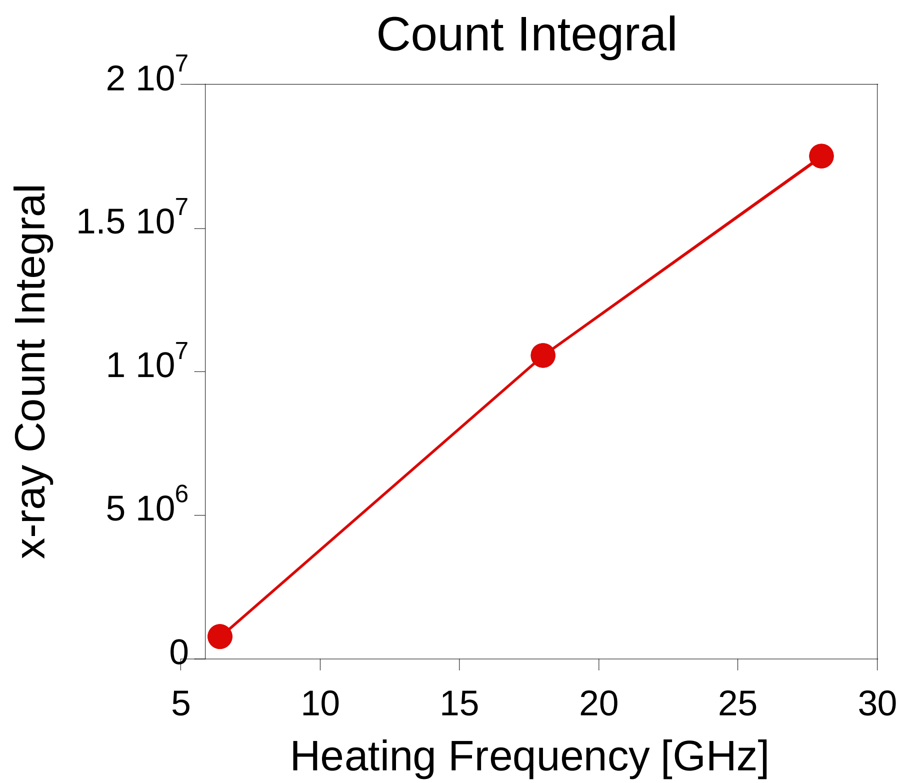




The scaling of the electron energy temperature with frequency has important consequences for 4th generation superconducting ECR ion source with frequencies of 37GHz, 56GHz.
Several (10s of) watts of cooling power must be reserved for the cryostat.

Is there a general frequency scaling law for the x-ray flux ?





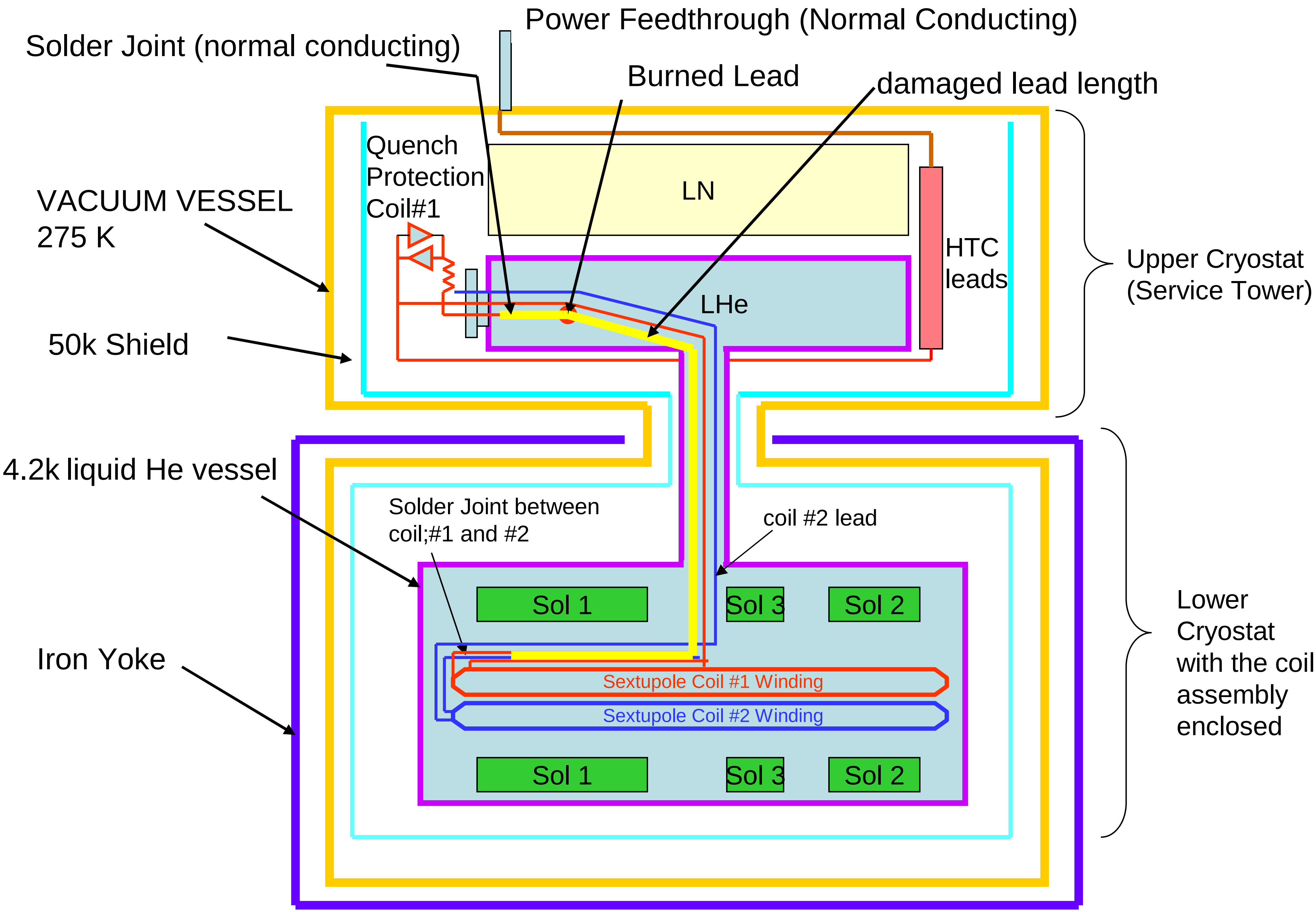
Data were taken for same power density in the ECR –zone and B_{min} ratios, but
different plasma chamber power densities and mirror ratios
(should be ideally measured using a superconducting ECR ion source such as VENUS for all frequencies)

(see Poster this afternoon)

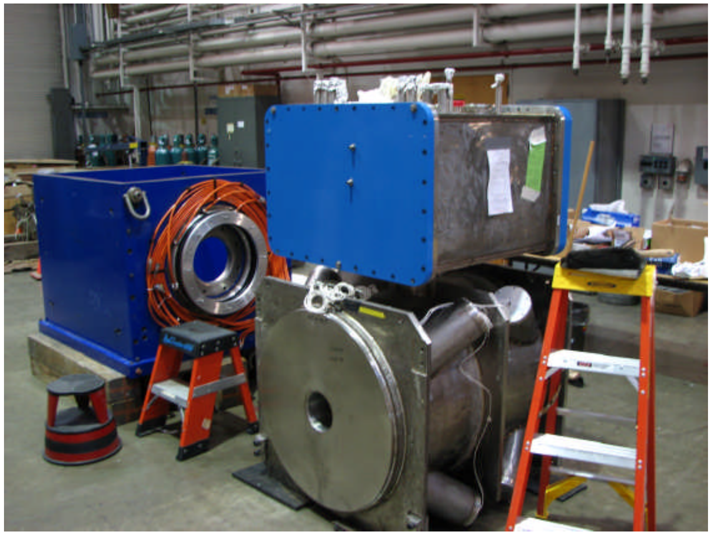
VENUS Lead Quench and Status of the Repair

- 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

Schematic of sextupole wiring for 2 of the 6 coils (not to scale)



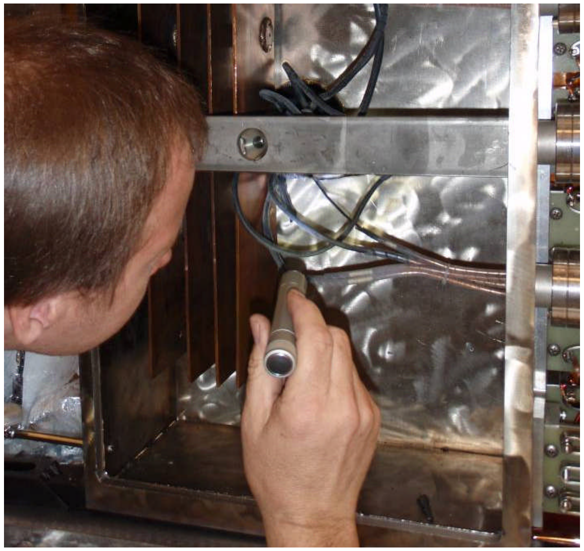
VENUS lifted out of the iron yoke at the 88-Inch Cyclotron



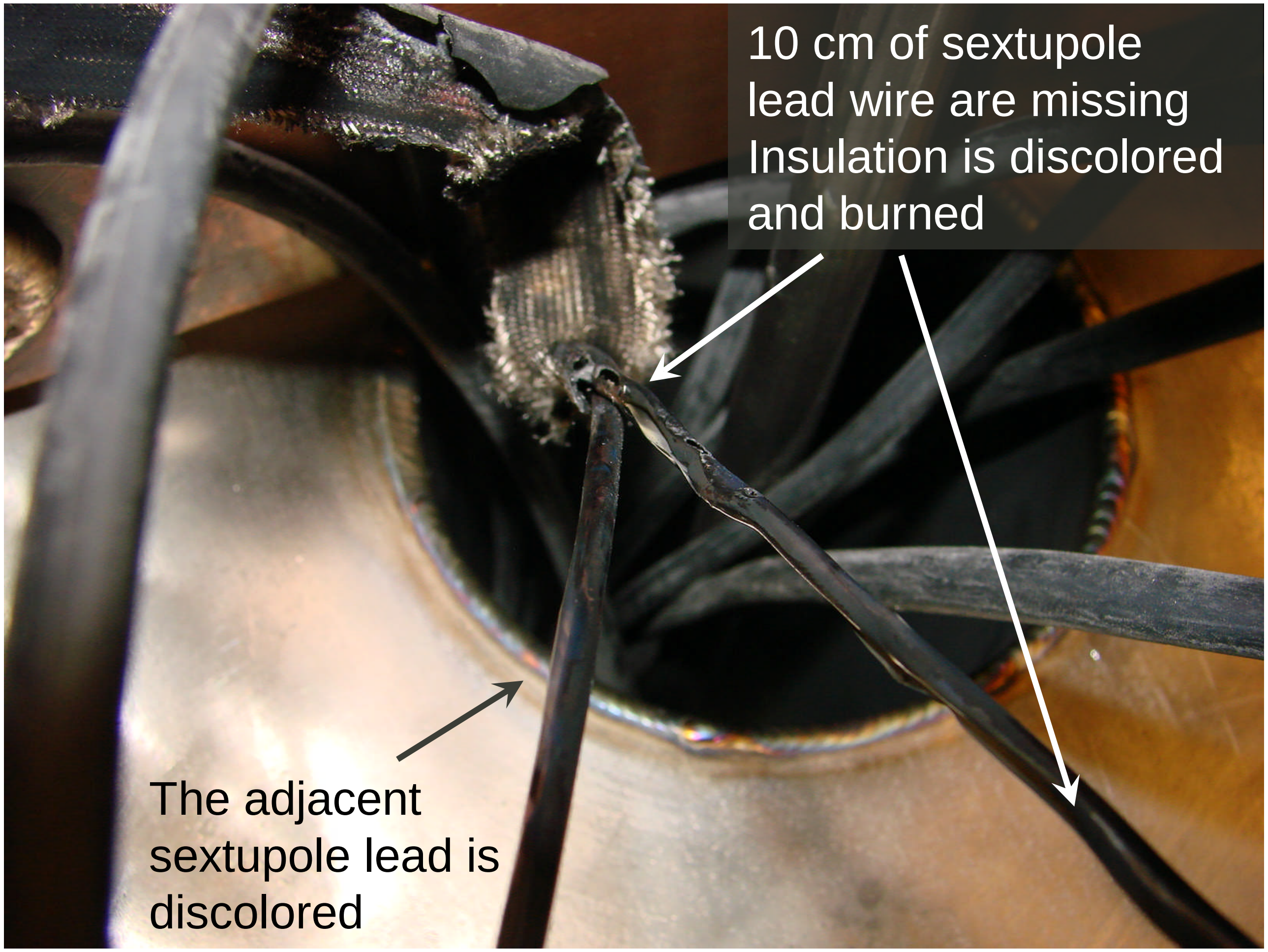
The vacuum vessel is cut open in the service tower

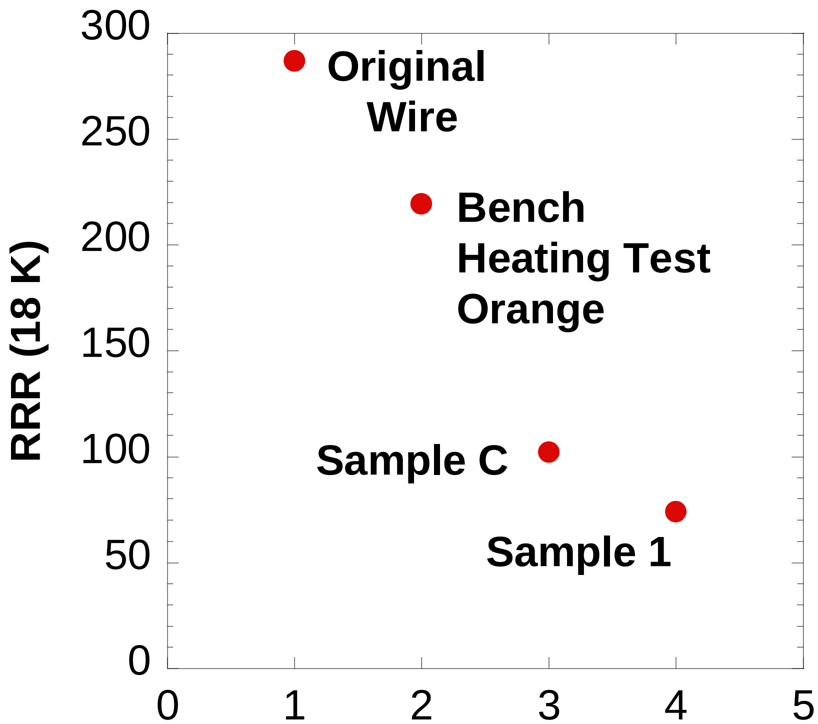
Milling the upper cryostat He vessel open

Inspecting the wires

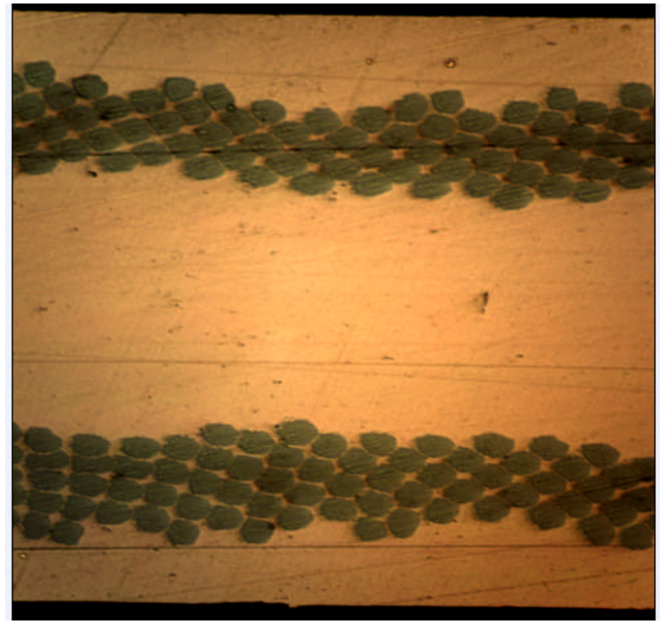


About 10 cm of the lead wire was burned and the adjacent wire insulation was discolored

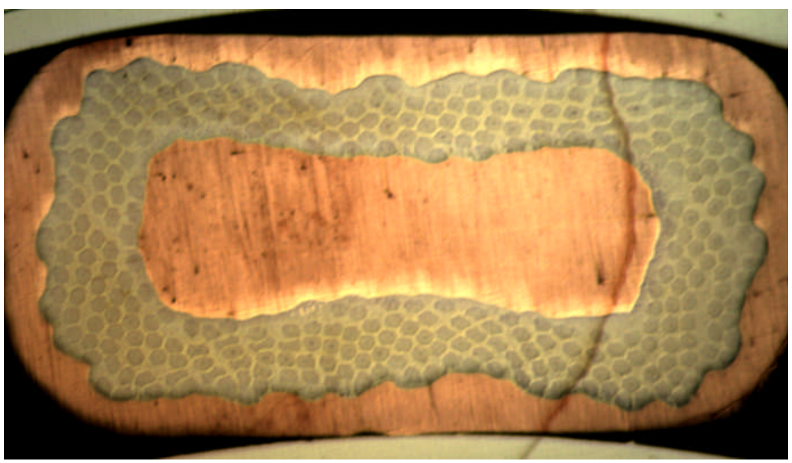




Microscope picture of the virgin NbTi wire



Microscope picture of the NbTi wire
Near the burned section



RRR – Residual Resistivity Ratio of Copper

(Resistance of wire at room temperature)/(Value at 77K or 20K)

The RRR measurement provides a means to gauge how much Cu has been contaminated by Ti due to excessive heating of the wire.

Opening of the lower cryostat and extracting the cold mass

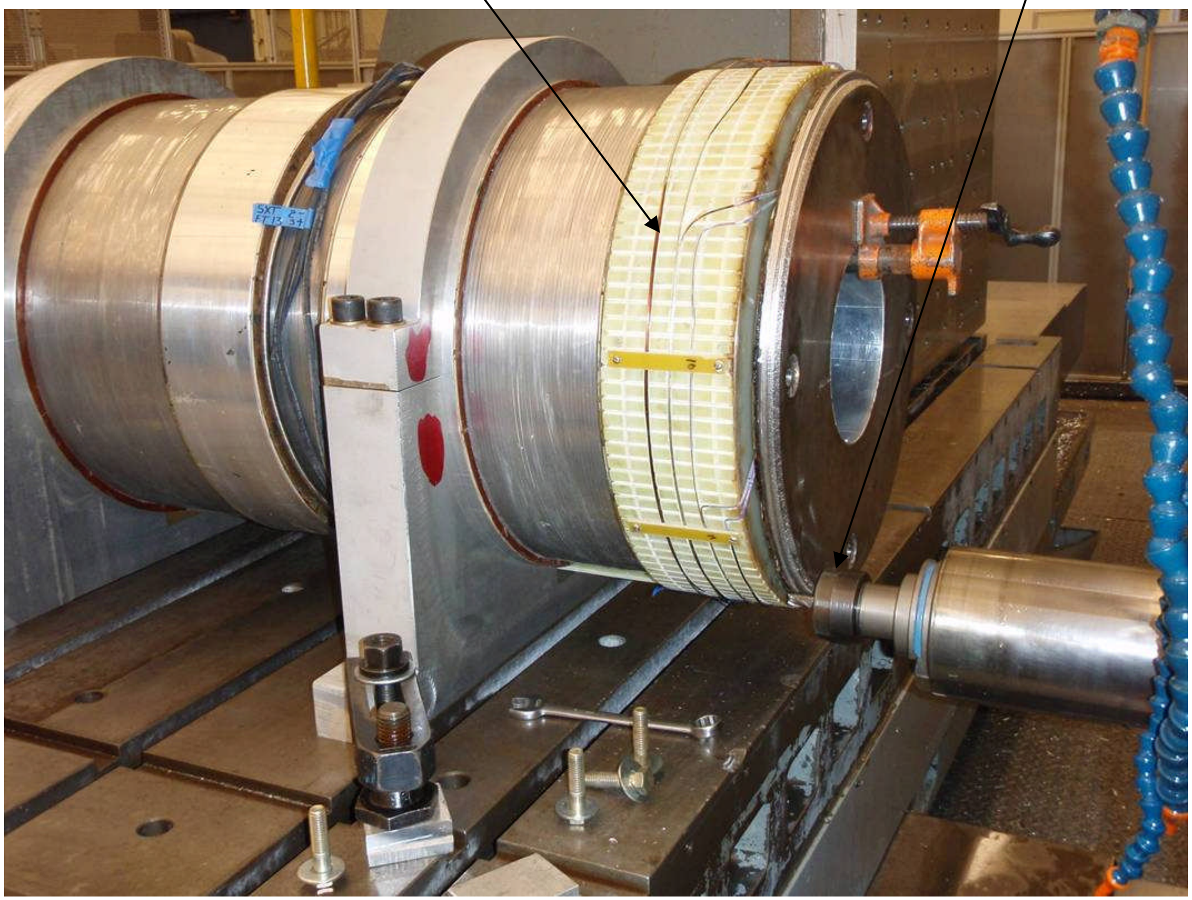
Coil assembly extracted

Lower cryostat opening set-up

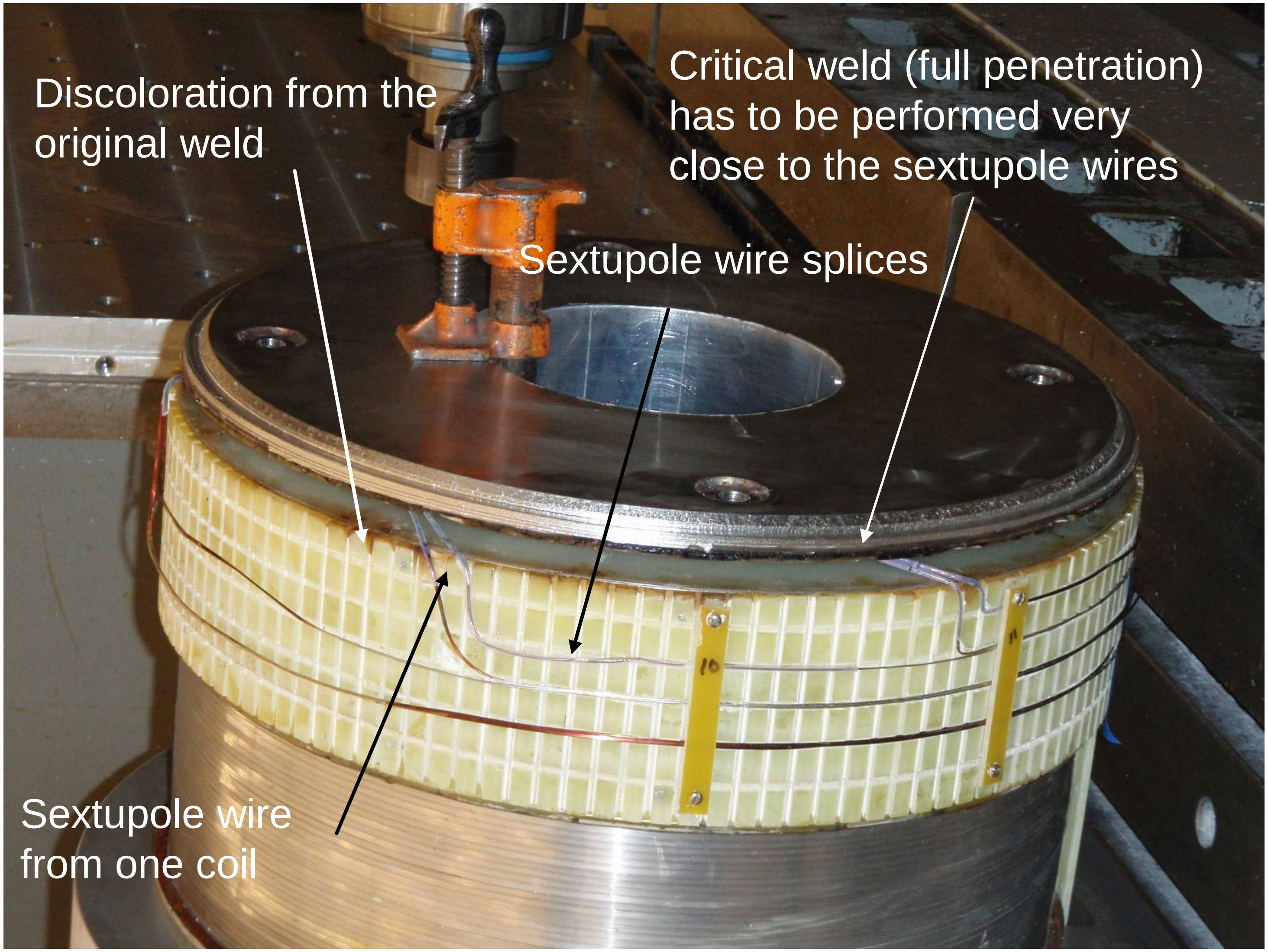
Preparation for the critical weld close to the sextupole wires

Large sextupole flange is prepared for welding

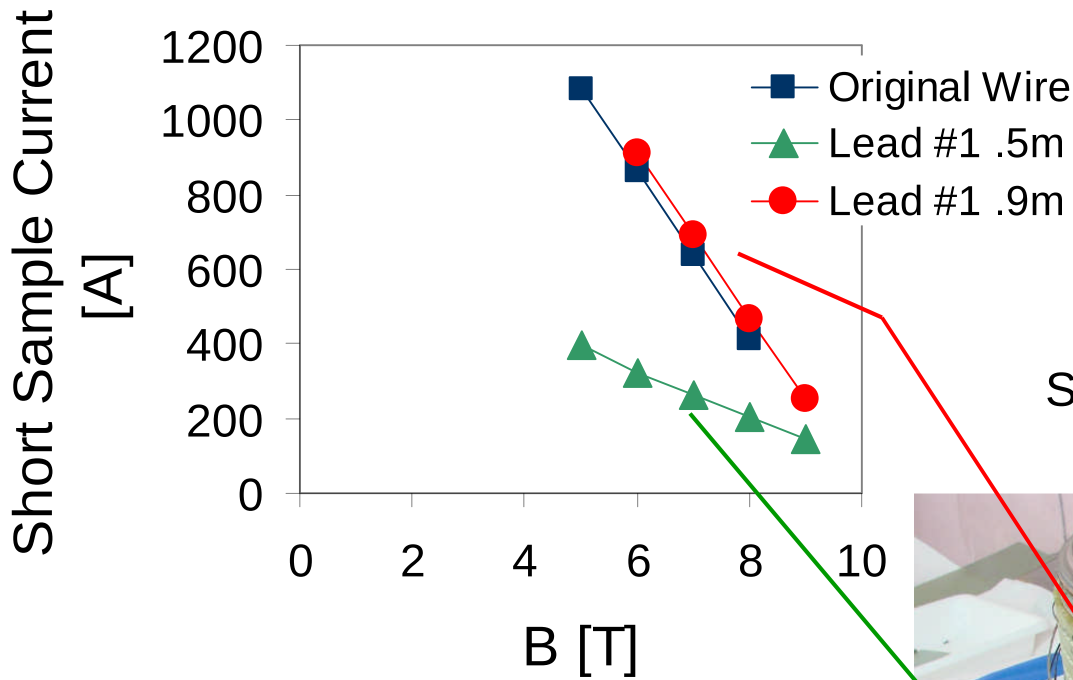
Sextupole wire guide

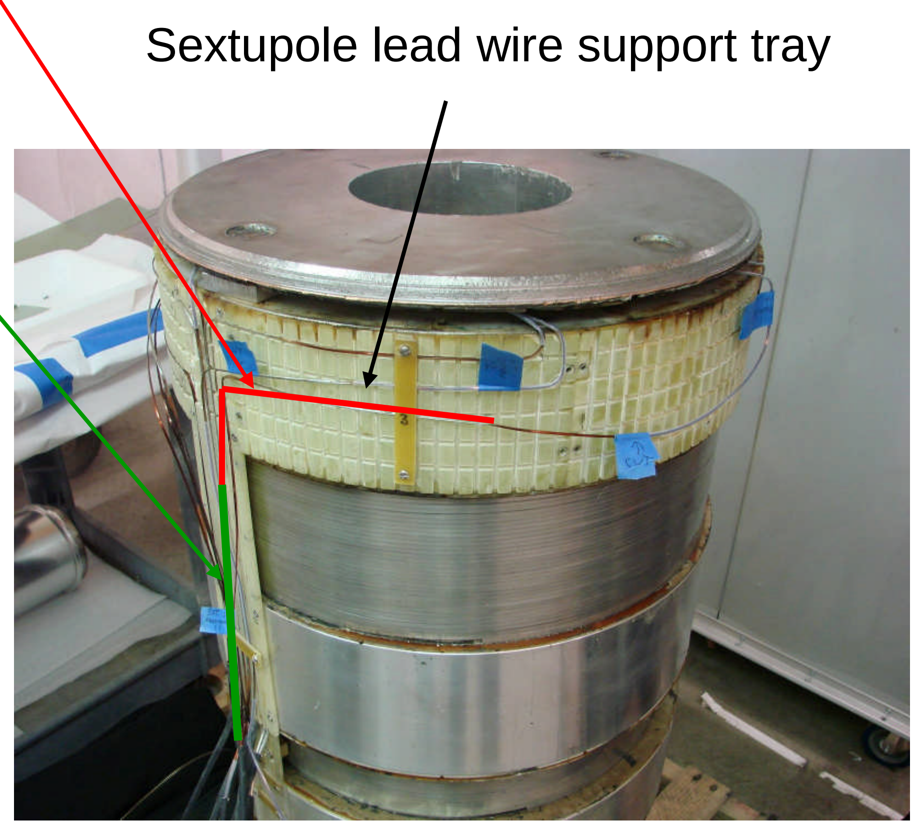


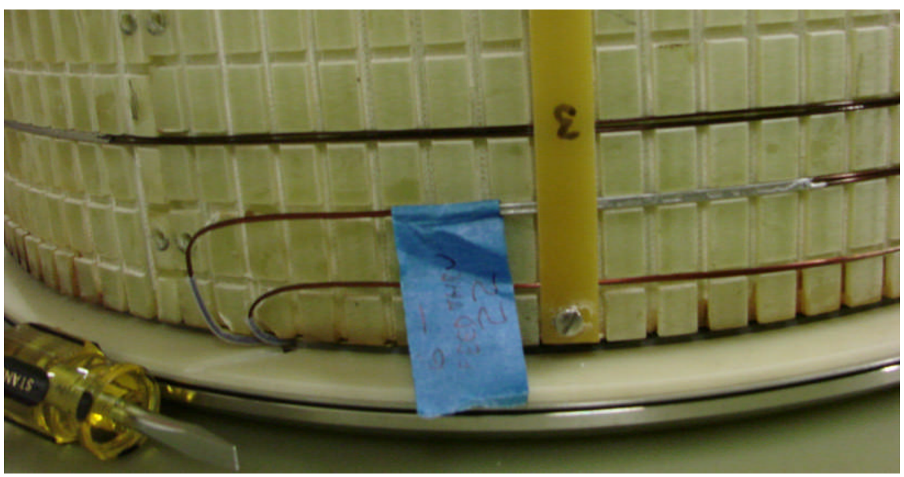
Preparation for the critical weld close to the sextupole wires



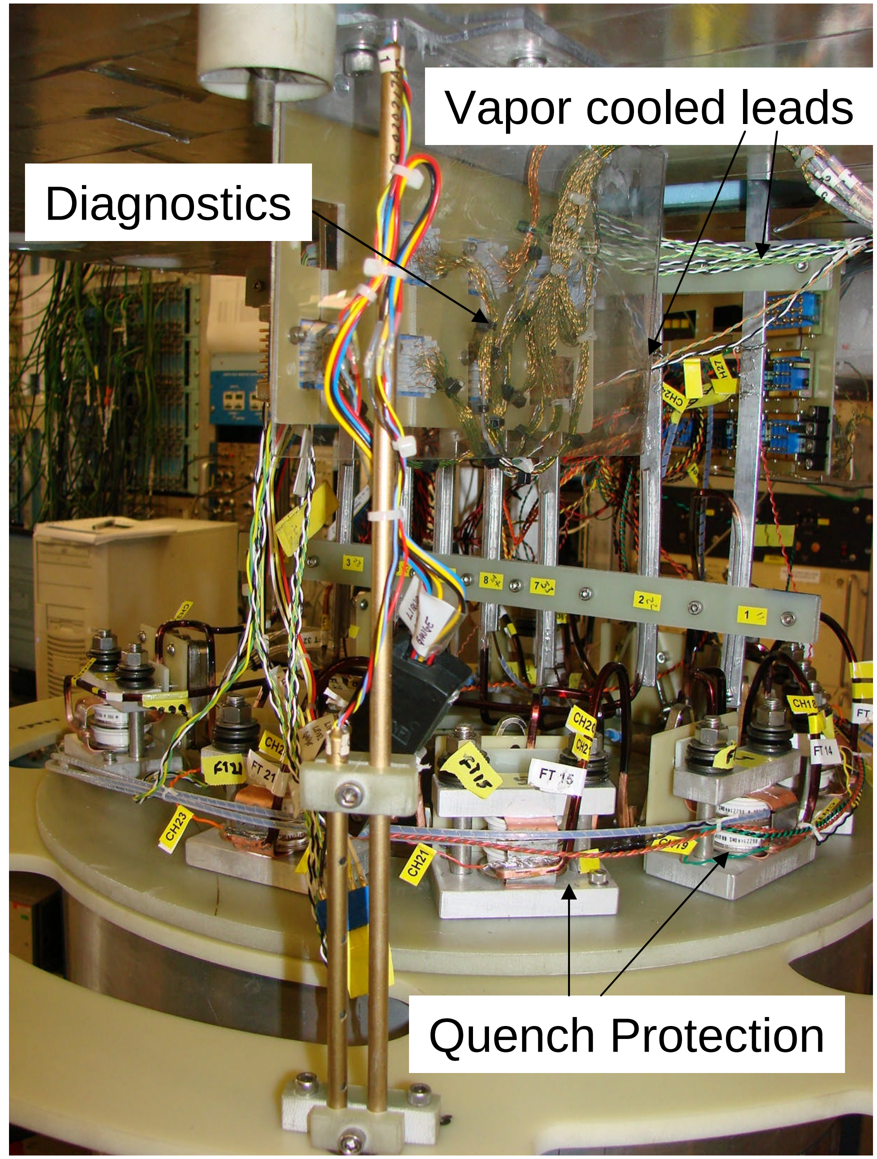
Short Sample tests confirmed that the remaining lead wire has not been damaged







VENUS Cold Test Preparations 9/10/2008 after lead repair



VENUS Cold Test 9/12/2008 after lead repair

- The VENUS magnet was energized to full excitation current without quenches.
- Ramp 1: Solenoids
- Ramp 2: Sextupole
- Ramp 3: all magnets together

4.1 T and 3.2 T (axial), 2.1 T radial reached

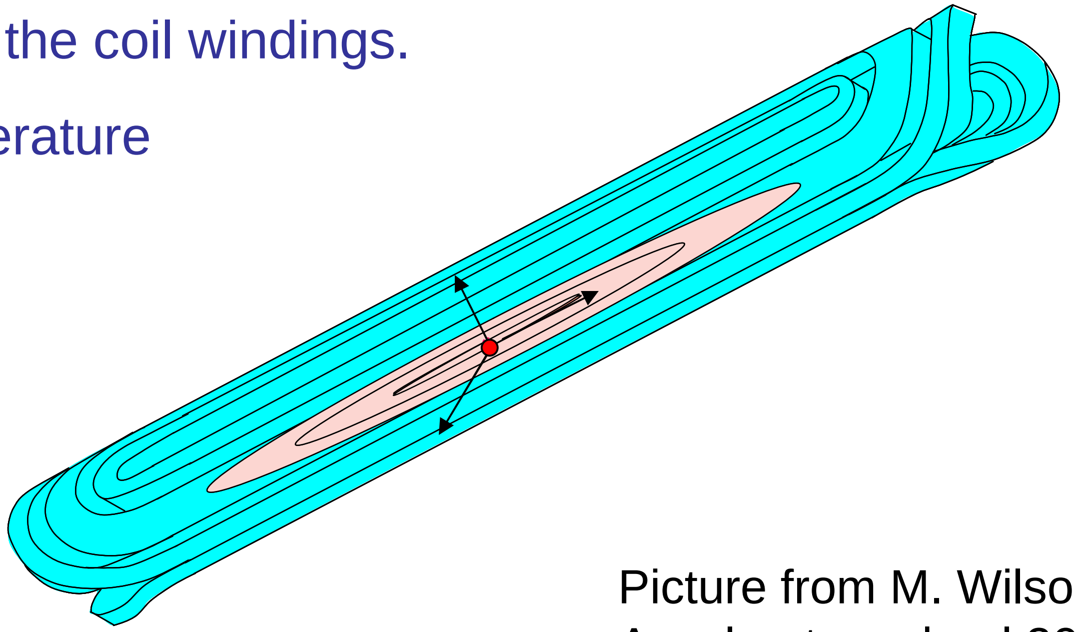
The VENUS magnet is fully functional again!

Lead Quench versus Coil Quench

- During training and commissioning (2000) the VENUS magnet has quenched about 15 times
- None of this quenches caused any damage to the magnet
- What happened this time?

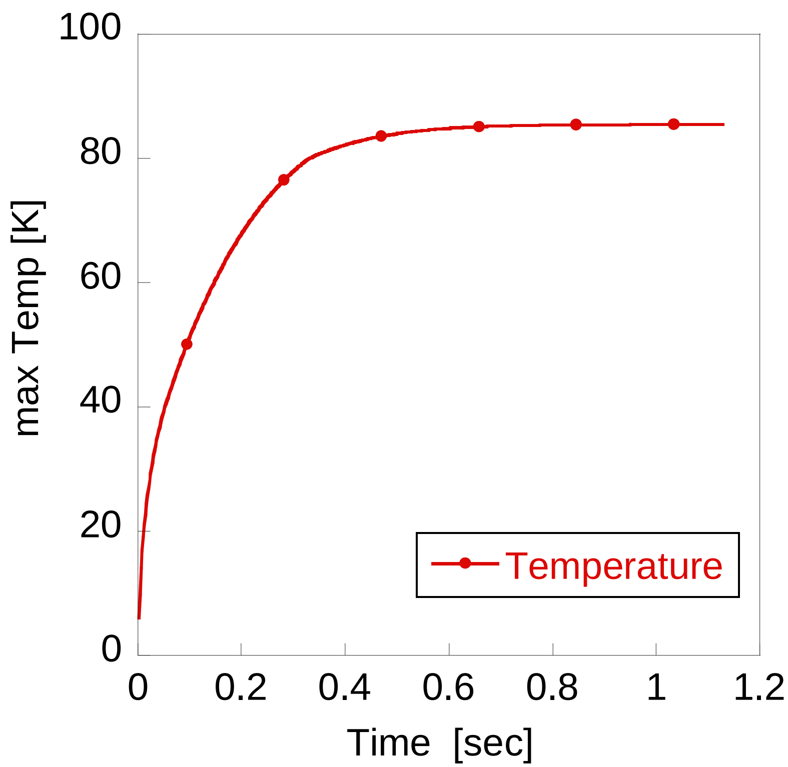
Quench process (VENUS Sextupole Coil)

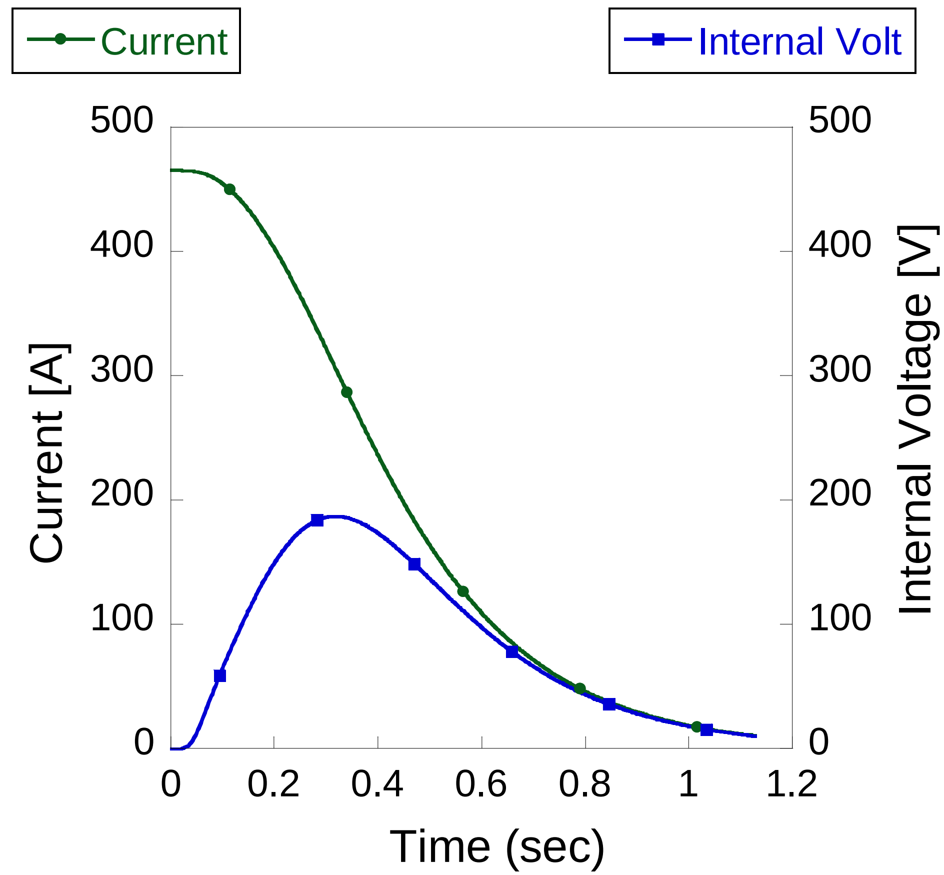
- A resistive region starts at 1 point of the superconducting coil
- The quench grows three dimensional via combined effects of Joule heating and thermal conduction
- stored energy ½LI^2 of the magnet (150kJ) is dissipated as heat
- Voltage grows rapidly and triggers quench protection diodes to short and PS are turned off, but the stored energy is mainly dissipated inside the coil windings.
- Critical: Maximum temperature reached in the coil/wire



Picture from M. Wilson,
Accelerator school 2006

Maximum temperature inside one sextupole coil during a quench



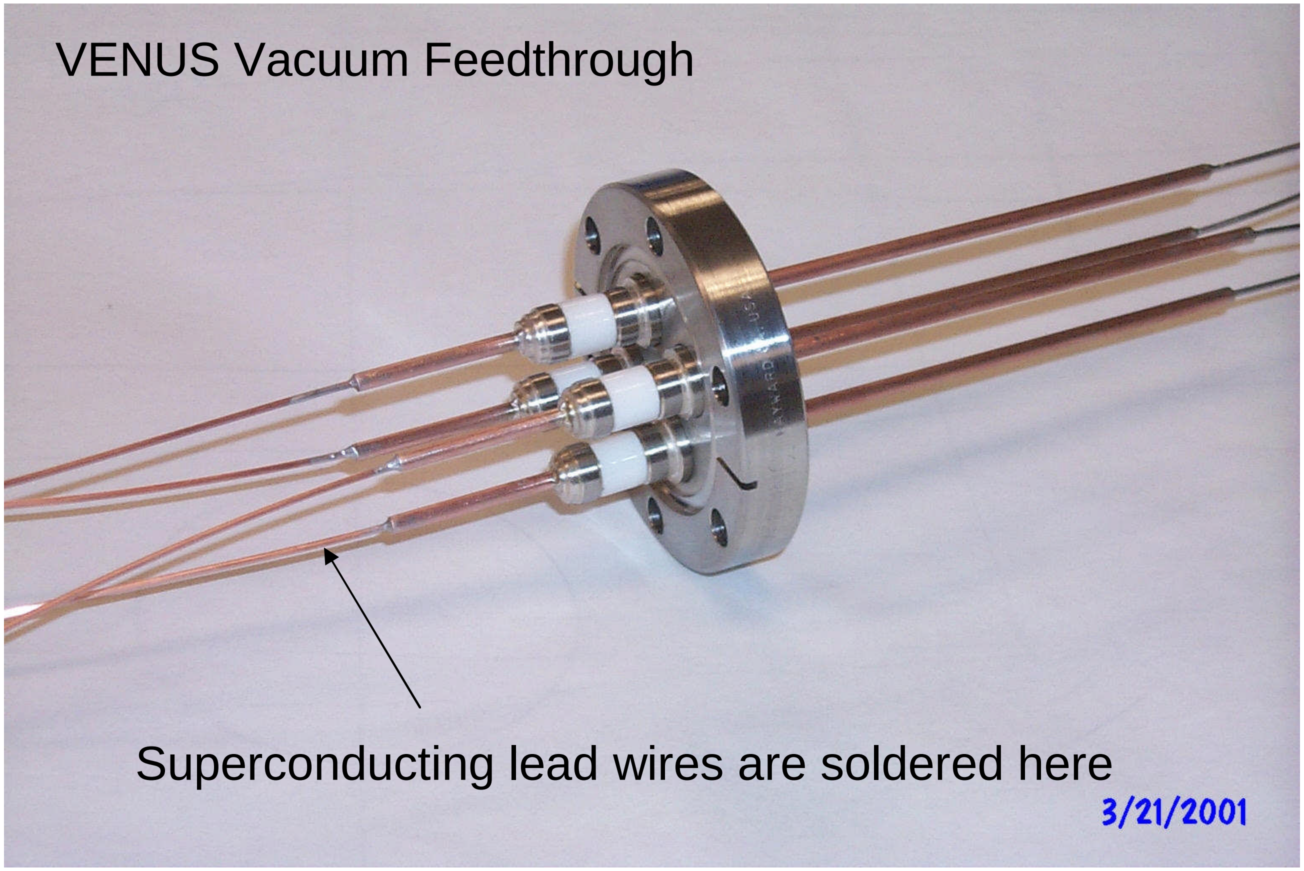


Within .5 to .7 sec the coil reaches its peak voltages, the current decreases rapidly
The coil reaches its maximum temperature of 80 to 120 K.

The coil is self protected in case of a quench

Quench of a lead

- Typically starts at a non superconducting solder joint (10-20 nOhm)
- In the case of VENUS there is a solder joint to the vacuum feed through of the helium vessel
- Most likely cause is insufficient cooling



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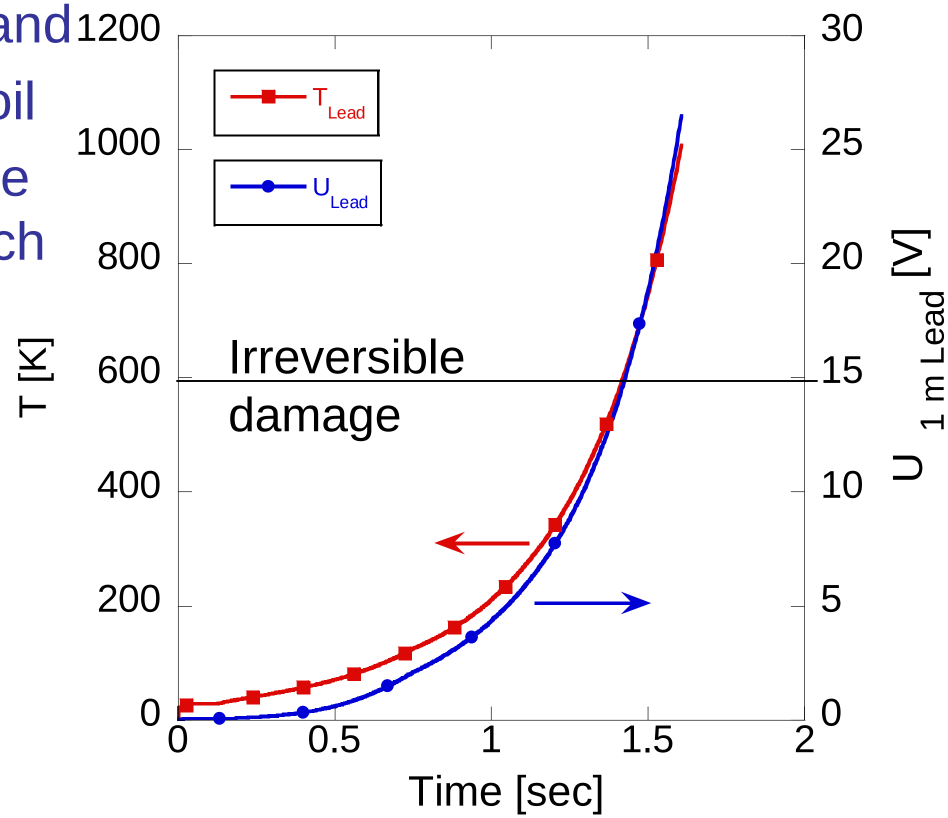
Superconducting lead wires are soldered here

Lead Quench

- Quench region grows only linear and
- Grows is slower than inside the coil
- Temperature grows rapidly, but the voltage grows slow until the quench reaches the coil.
- Quench is further stalled once the liquid helium level is reached
- Once the wire is burned the high internal voltage of the quenching coil initiates an arc plasma which causes further damage to the leads.



Bottom Line

Needs to be avoided under all circumstances

Mitigations of lead quenches – Three possible approaches

- Reinforce the wire with enough copper to prevent heating damage under all circumstances (even loss of helium)
  - Disadvantage: Stalls quench, can lead to burn out in the adjacent section or the coil edge
- **Design an active quench protection system (future 3rd and 4th Generation ECR ion sources)**
  - Have voltage taps on the solder joints to detect a quench as early as possible
  - Use heaters around the coil to quench the cold mass as quickly as possible
  - Use external resistor to dissipate the stored energy
- **VENUS approach**
  - Design the leads to ensure a big superconducting margin of the wire (VENUS wire has a short sample limit > 1 kA at 2 T)
  - Double the leads (increase SC margin and cross section)
  - Interlock the liquid helium level
  - Maximize the vapor cooling and liquid contact of the lead wire

Next Steps

- After the successful cold test the VENUS magnet will be reinserted into the cryostat
- The lower cryostat helium vessel welded
- The upper cryostat reconstructed
- Reinstallation on the 88-Inch vault roof
- Re-commissioning is expected to be started early 2009 – 1 year after the failure

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Conclusions

- 3rd Generation sources fulfill their intensity promises
  - The performances are still increasing with power, 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+}
- Lead quench in the VENUS source has been analyzed
  - Concluded that the coil design is self protected in the case of a quench (maximum temperature are below 120K)
  - Dynamic of a lead quench is very different from a coil quench
  - Lead quenches need to be considered for the design of a superconducting ECR ion source
- VENUS magnet has been repaired and reaches full field after the repair without any training quenches