Conceptual Design of a 56 GHz ECR Ion Source Magnet Structure

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LBNL

Contributing authors

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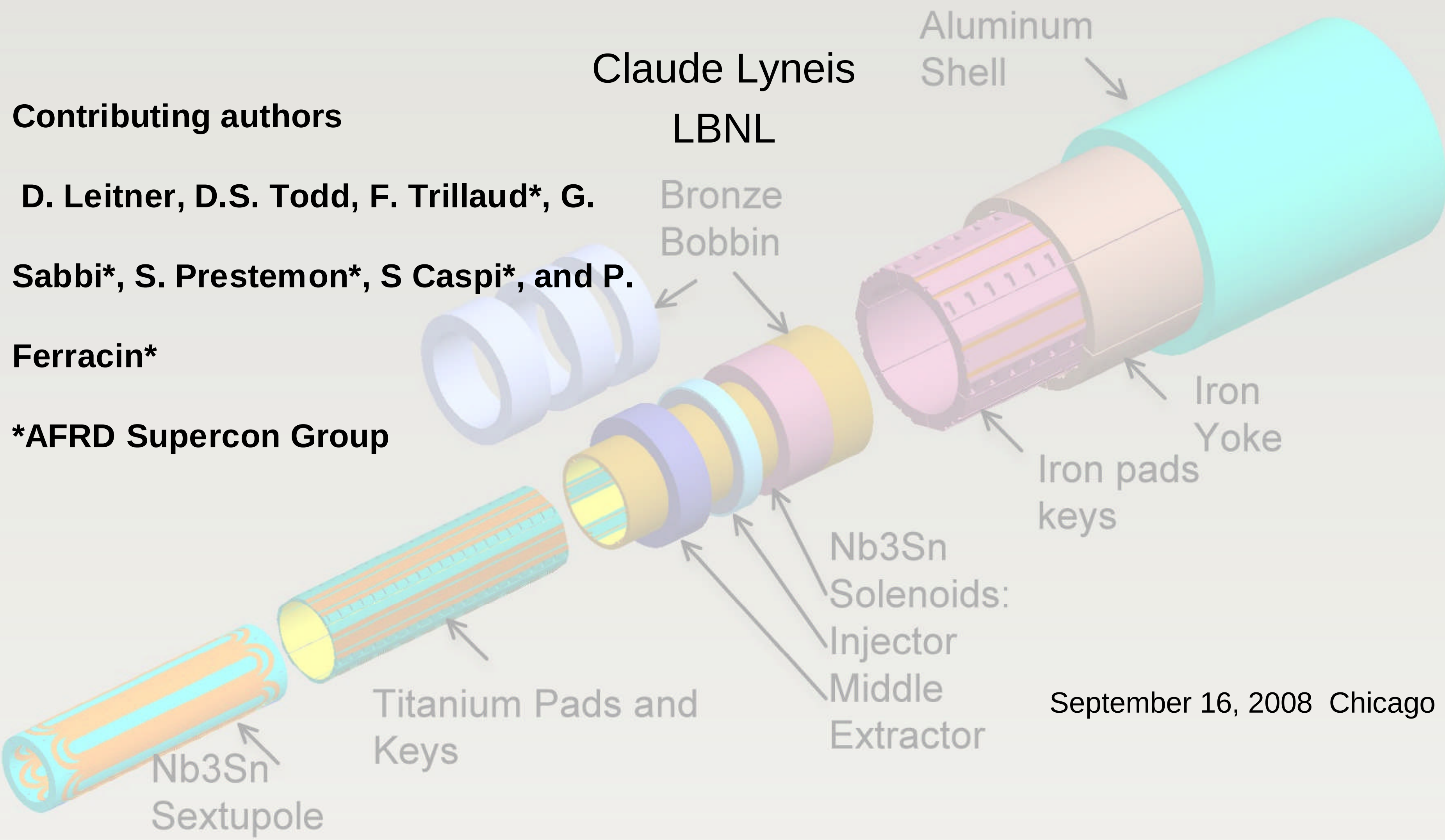
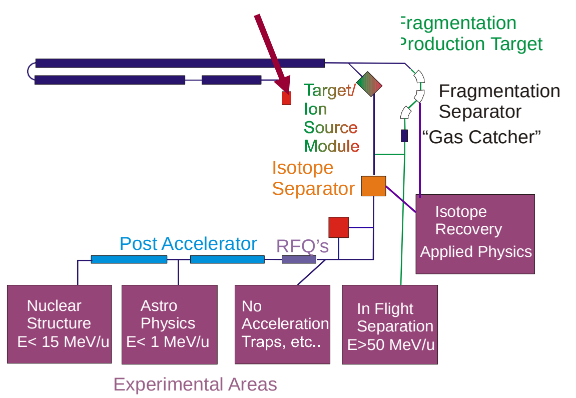
***AFRD Supercon Group**

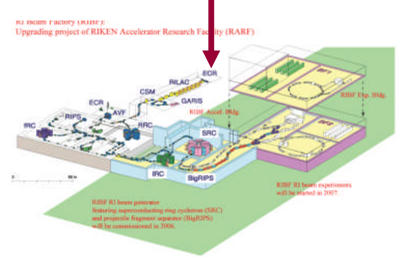


September 16, 2008 Chicago

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

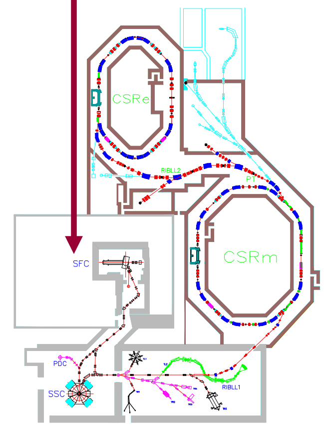


SC-ECRIS,
RIKEN, Japan



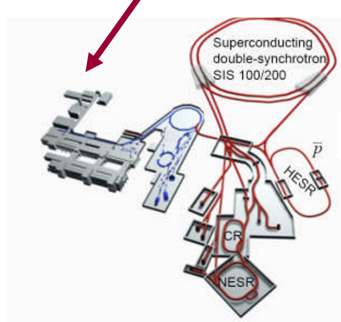
525 eμA U^{35+}

SECRAL,
Lanzhou, China
H. Zhao

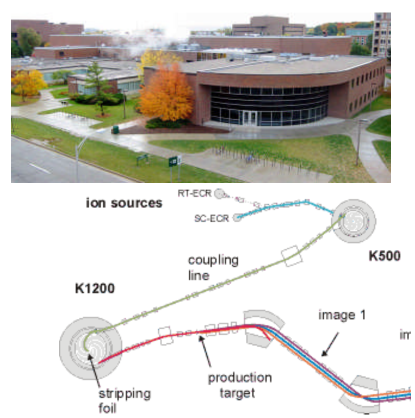


50-100 eμA U^{41+}

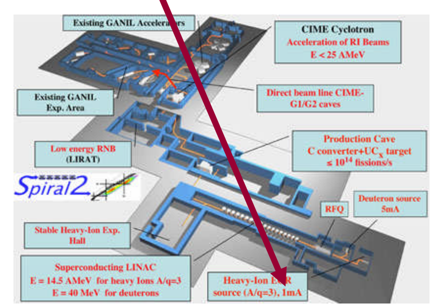
MS ECRIS
GSI, Germany



SuSI
NSCL,USA



SPIRAL 2,
GANIL, France



1mA Ar^{12+}

Conceptual Design for 56 GHz

- ECR physics and scaling
- Superconducting Magnet Technology
  - NbTi and Nb_3Sn
  - Lorentz force and clamping
  - Magnet design
- Other Challenges at 56 GHz
- Next step

Evolution of High Charge State ECR ion sources

- In the Beginning Supermafios in 1974-1977

- First generation 6 to 10 GHz sources
  - Minimafios, ECRVIS , LBL ECR, RT-ECR, SC-ECR …
- Second generation 14 to 18 GHz
  - CAPRICE, AECR-U, ………
  - RIKEN 18 GHz
  - SERSE 18 GHz Superconducting
  - A-PHOENIX
  - GTS 18 GHz Grenoble

  Generation 2.5
- Third Generation 20 to 35 GHz
  - VENUS Operating at 28 GHz Berkeley
  - SECRAL Operating at 18 GHz Lanzhou
  - MS-ECRIS Under construction for 28 GHz for FAIR
  - RIKEN SC-ECR Under construction for 28 GHz for RIBF
  - MSU-NSCL SUSI Under commissioning at 18 GHz
- Fourth Generation 40 to 60 GHz--Future

Standard Model for ECR ion sources

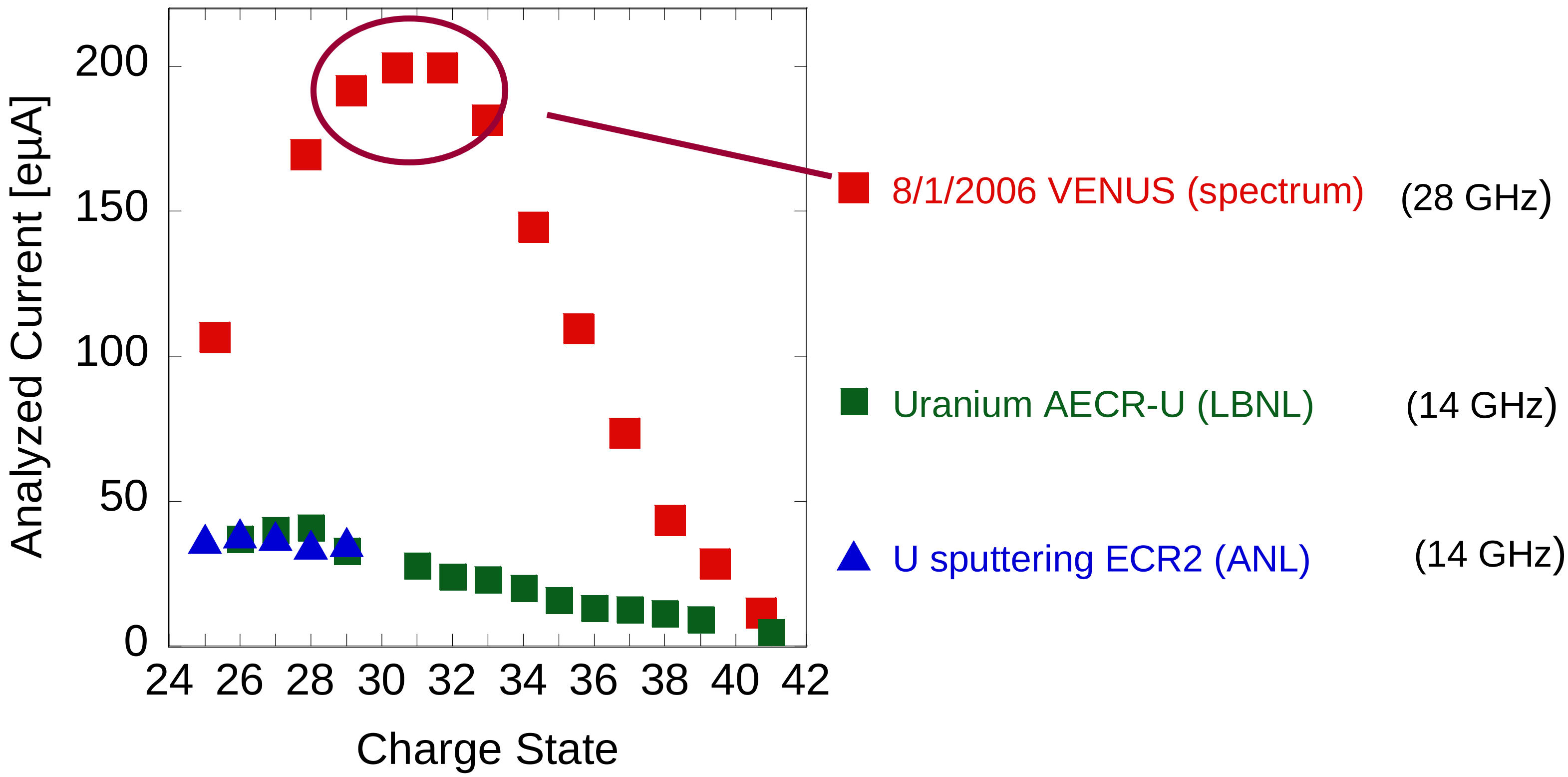
Frequency scaling $n_e \sim \omega_{rf}^2$ $I \propto \omega_{rf}^2/M$

ECR Resonance $B_{ecr} = \dfrac{m_e\,\omega_{rf}}{q_e}$ $B_{ecr}\,(\text{in T}) = \dfrac{f_{rf}(\text{in GHz})}{28}$

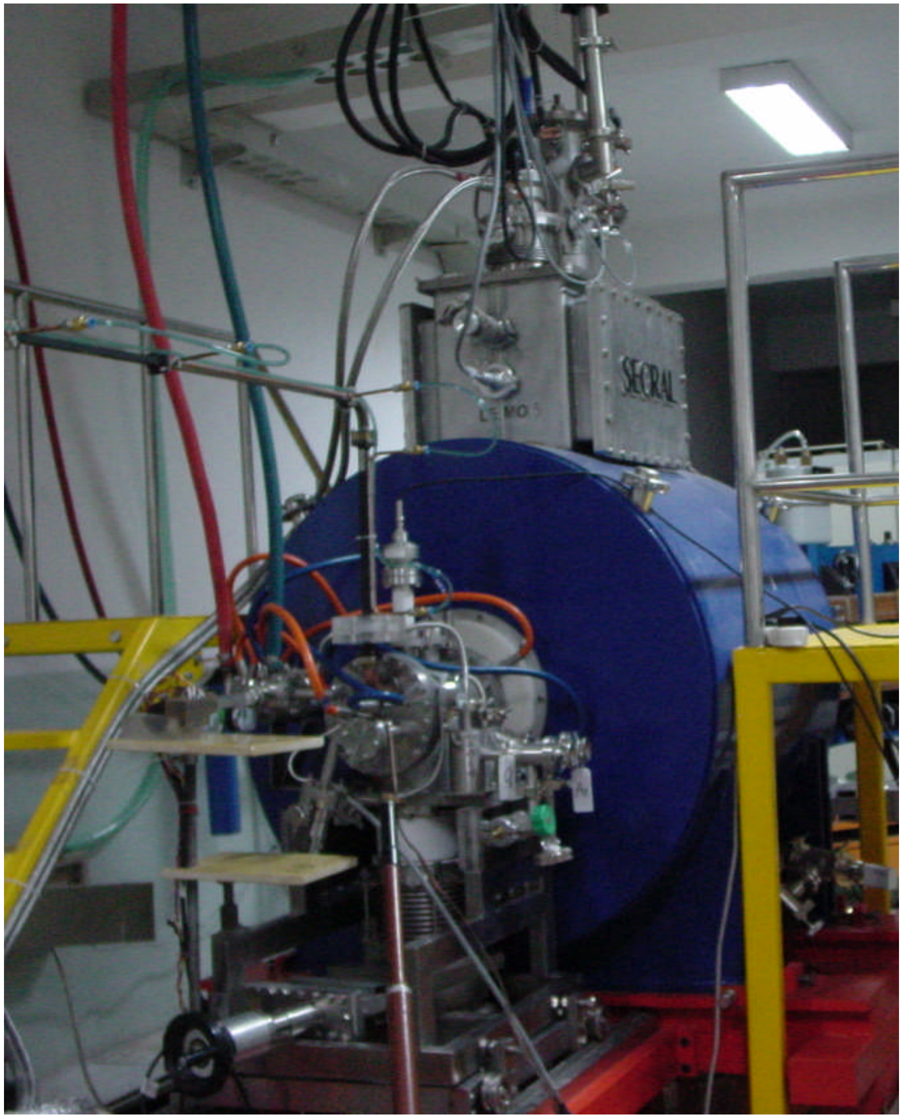
Confinement criterion	28 GHz	56 GHz
Bconf $\geq 2\, B_{ecr}$ at walls	2 T	4 T
$B_{inj} \sim 3 - 4\ B_{ecr}$ on axis	3-4 T	6-8 T
$B_{rad} \geq 2\, B_{ecr}$ on the walls	2 T	4 T
$B_{min} \sim 0.5\text{-}0.8\ B_{ecr}$ on axis		

High intensity uranium performance
14 and 28 GHz operation

Comparison of the highest intensity uranium beam obtained with VENUS to other sources

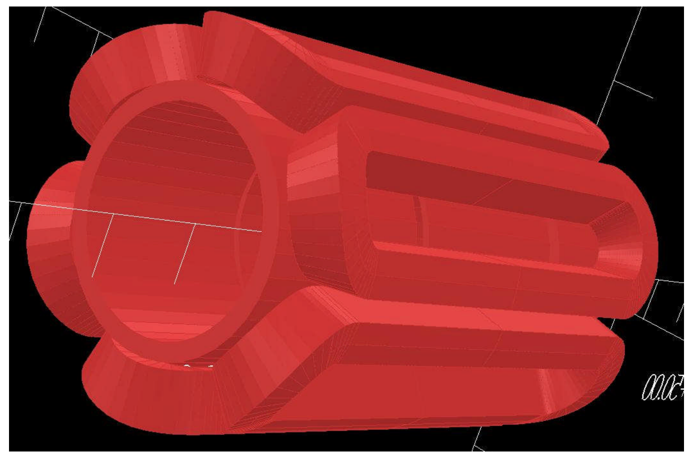


SECRAL*, IMP, Lanzhou, China



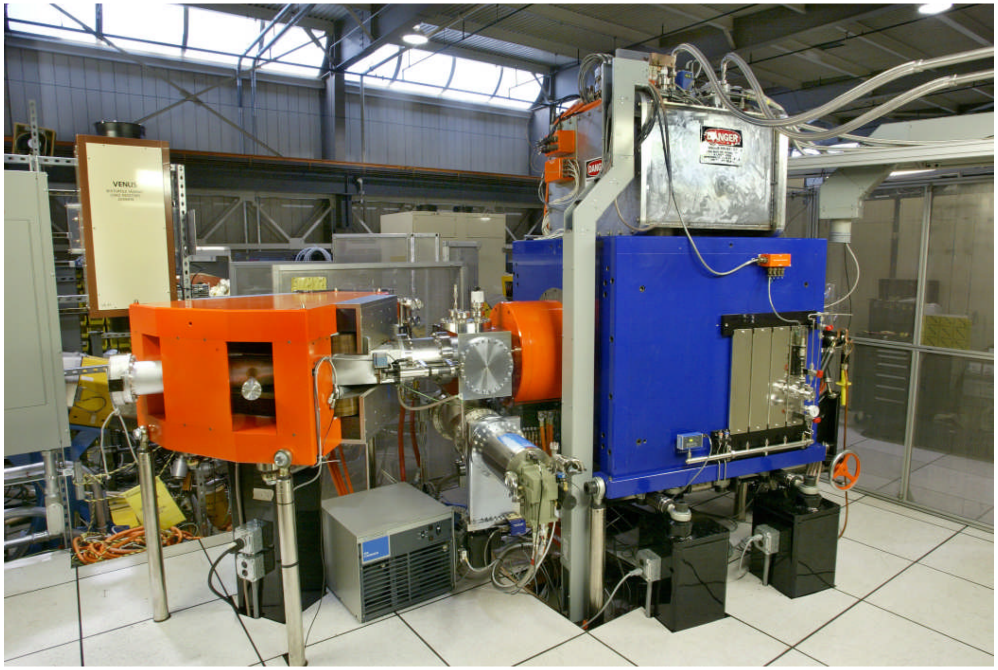
In operation at 18 GHz

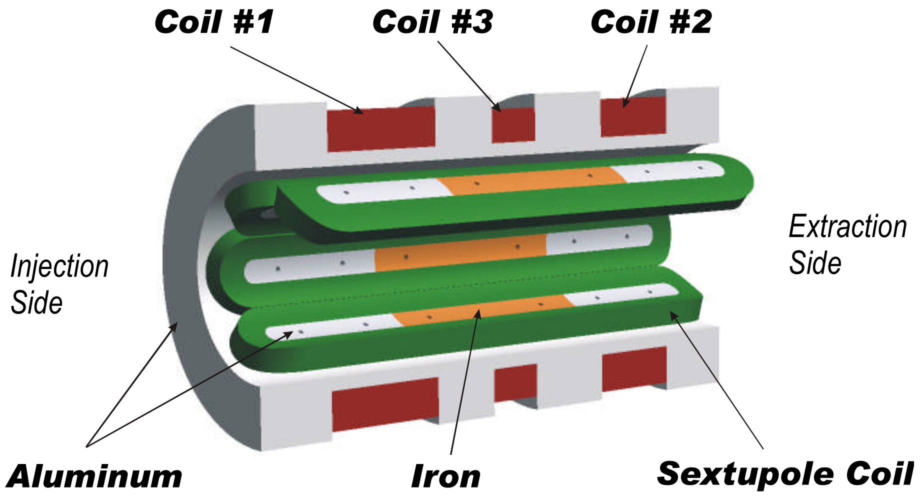
3.7 T axial, 2 Tesla radial



Solenoid-in-Sextupole

VENUS 28 GHz





Sextupole-in-Solenoid

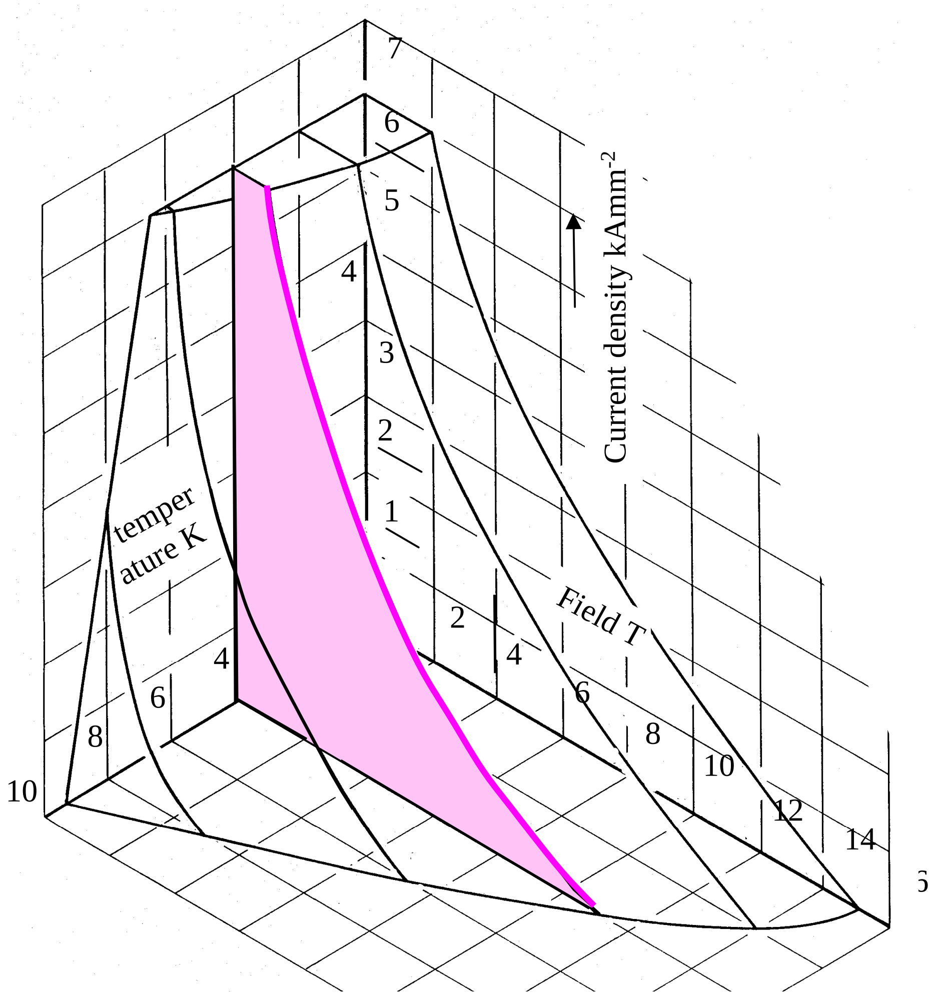
Achieved magnetic fields
Binj ≤4 T, Bext ≤ 3 T, Brad≤2.2 T

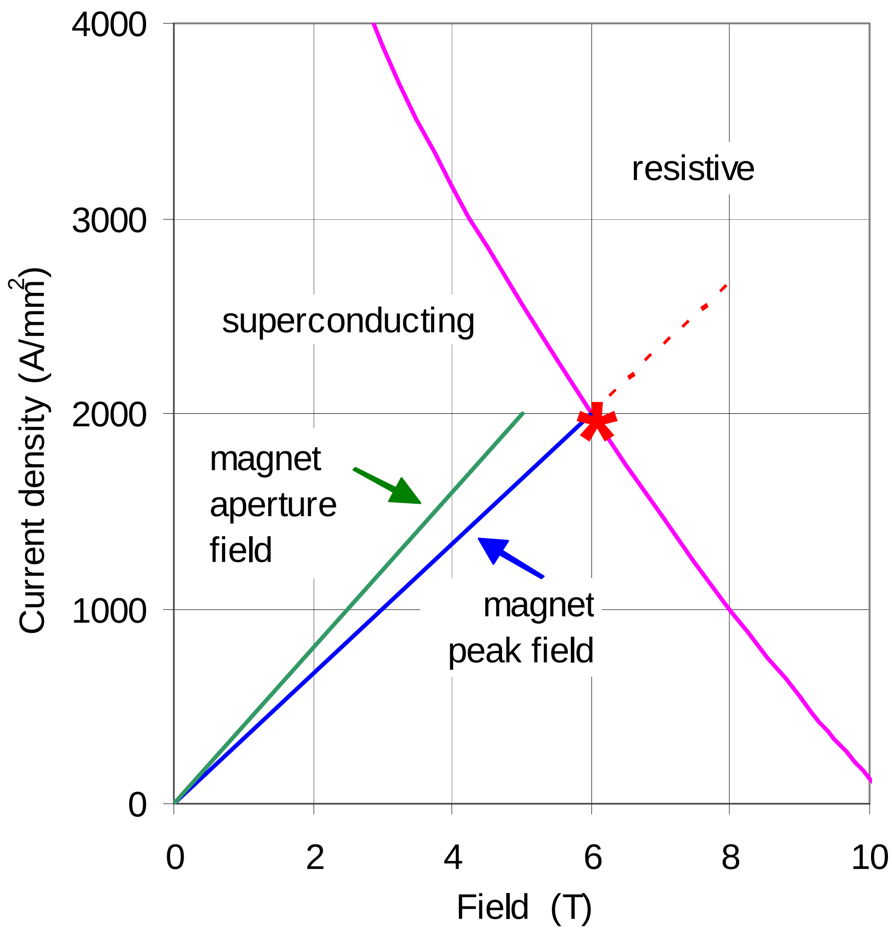
Operating at 28 GHz

•

Superconducting Magnets

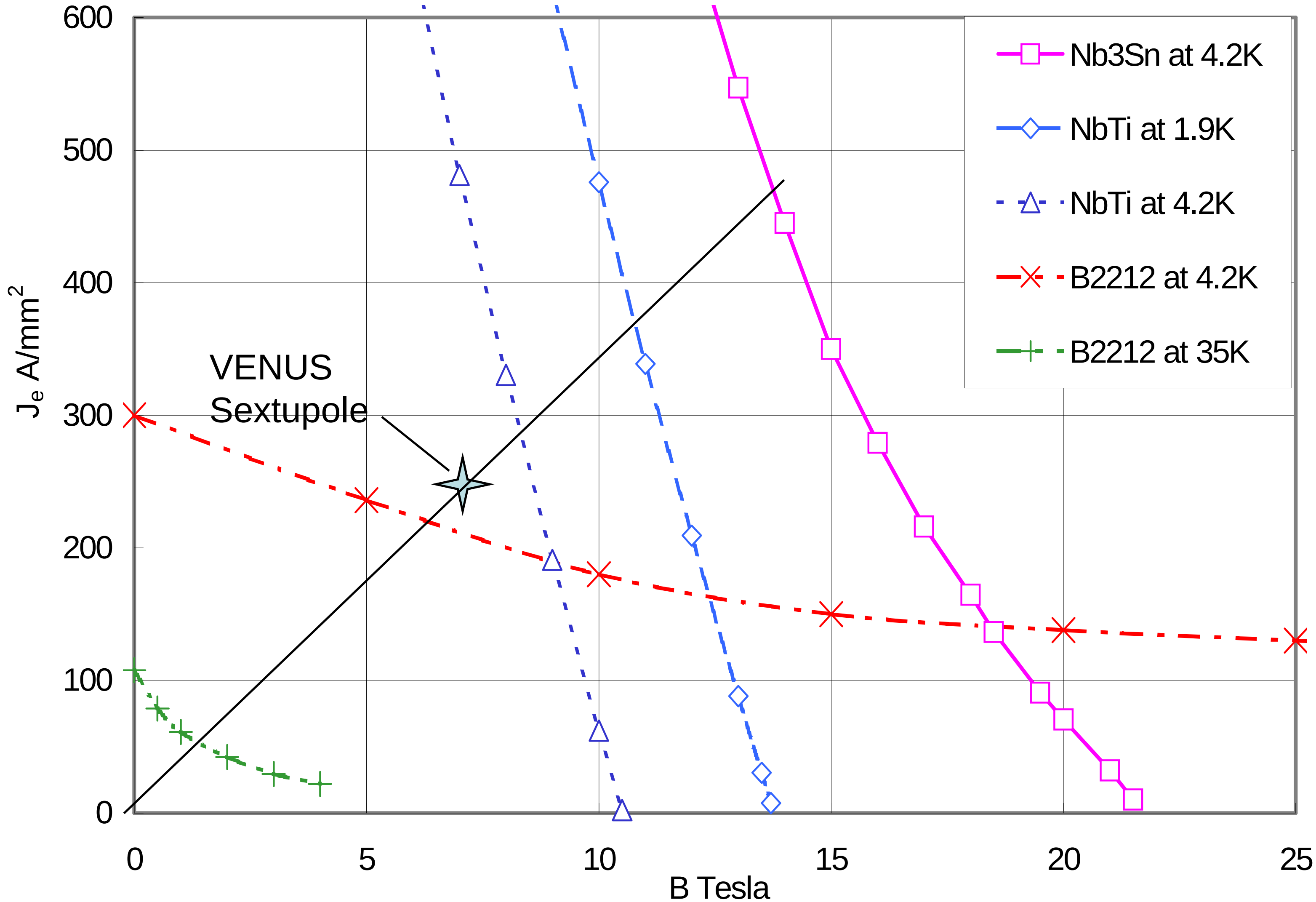
Critical line and magnet load lines



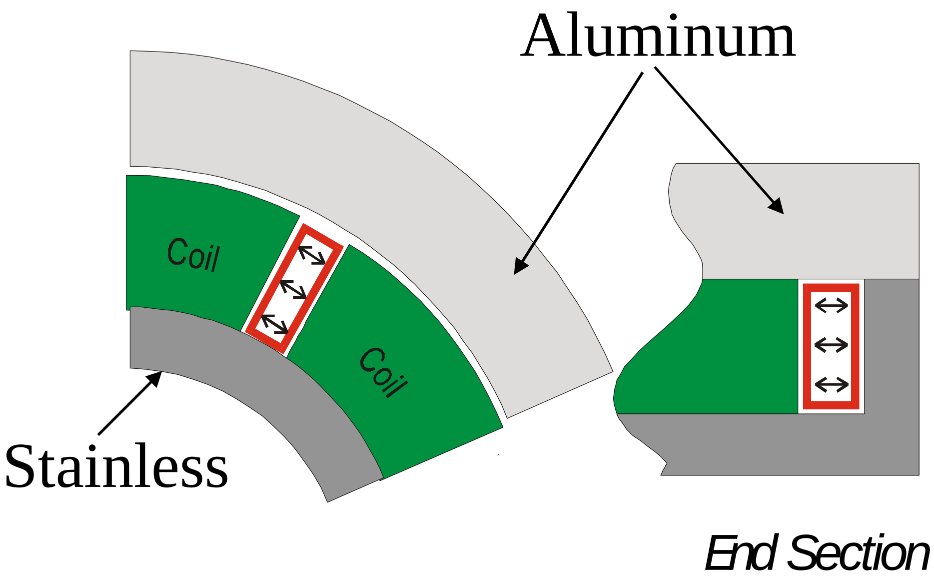


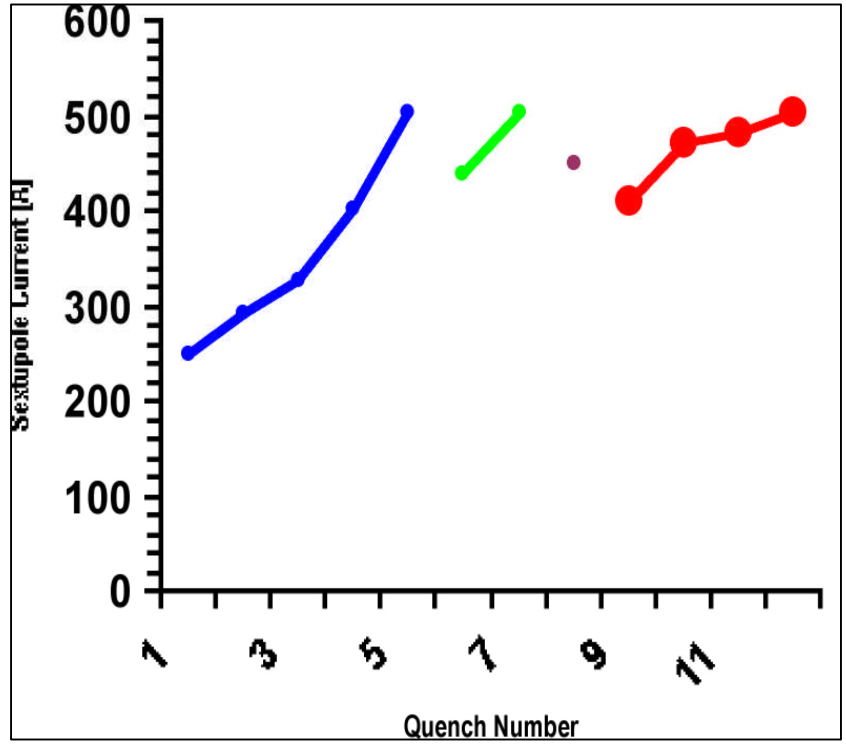
we expect the magnet to go resistive ***'quench'*** where the peak field load line crosses the critical current line *

Some engineering current densities and material properties



Sextupole Coil Clamping in VENUS





- Stainless steel bladders pressurized with low an indium alloy put the coils stress
- The large aluminum ring contracts as it cools to helium temperature, which **prestress** the coils.

- Magnet trained rapidly to full field
- No retraining required after warm-up

ECRIS-56 Magnet Design Study*

- R&D conceptual design
  - Magnet configurations
    - Sextupole-in-Solenoid or Solenoid-in-Sextupole
  - Superconducting materials evaluation
  - Magnetic design optimization
  - Structural design concepts

- Leverage the experience gained with VENUS
  and the high field magnet program at LBNL focused on LARP**

*__Design of a Nb3Sn magnet for 4th generation ECR ion source__, S. Prestemon et al,
Applied Superconductivity Conference, Aug 2008, to be published

** LARP LHC Advanced Research Project

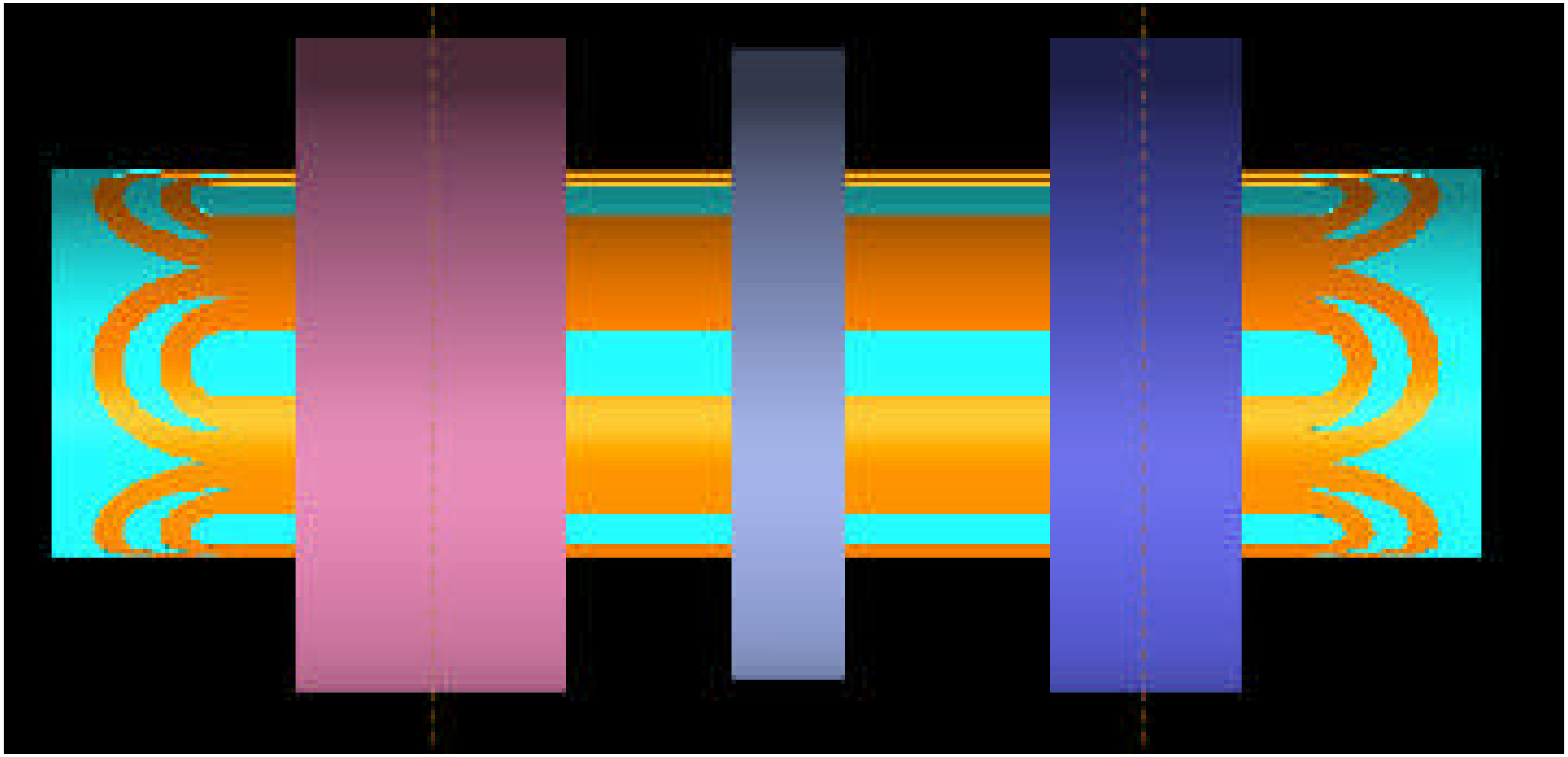
Design Decision 1
Sextupole-in-Solenoid or Solenoid-in-Sextupole for 56 GHz?

- 3 D magnetic models were made for these two coil configurations using the designs of VENUS and SECRAL as guides.
- Sextupole-in-Solenoid minimize sextupole field but solenoid fields exert large forces on the sextupole ends
- Solenoid-in-Sextupole minimizes solenoid field at sextupole but requires higher sextupole field and sextupole field generates large fields on the solenoid

- Solenoid-in-Sextupole produces local magnetic fields beyond the critical current for Nb_3Sn materials

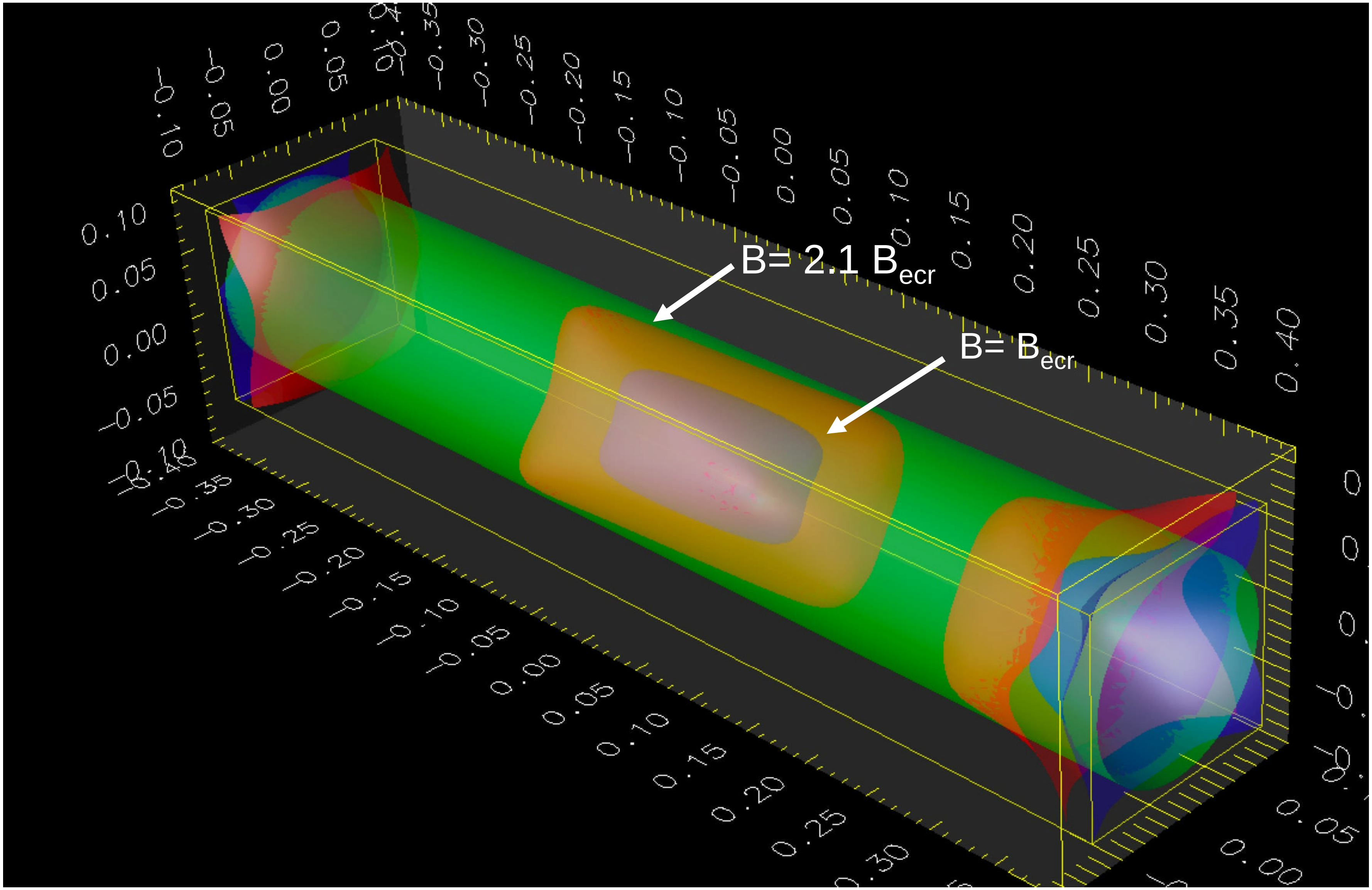
- Therefore the design focused on Sextupole-in-Solenoid (VENUS type)

VENUS-56w Magnetic Model

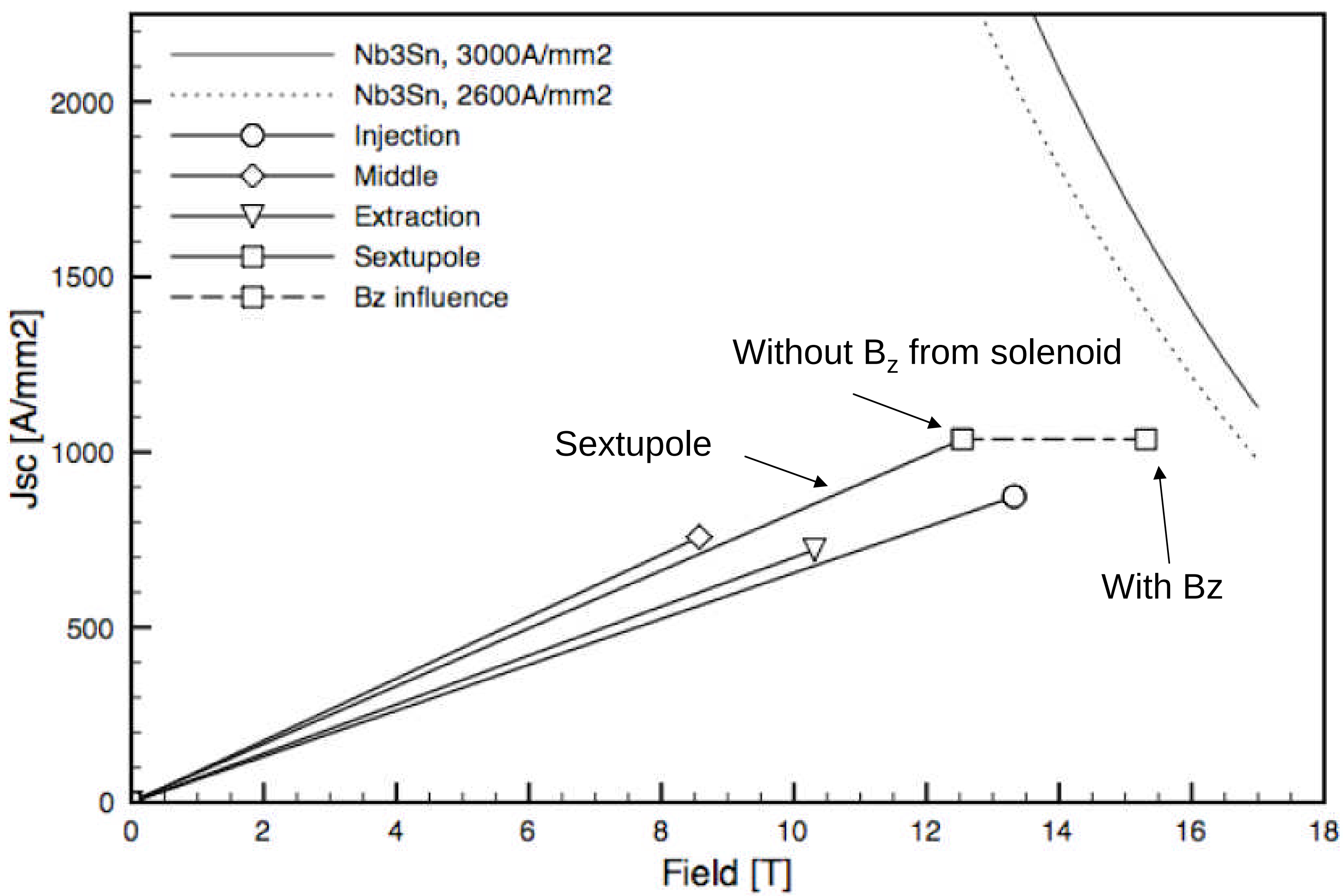


- Sextupole-in-Solenoid
- Sextupole ends extended
- Sextupole coils cross section increased over VENUS design
- Solenoid coils moved to larger radius

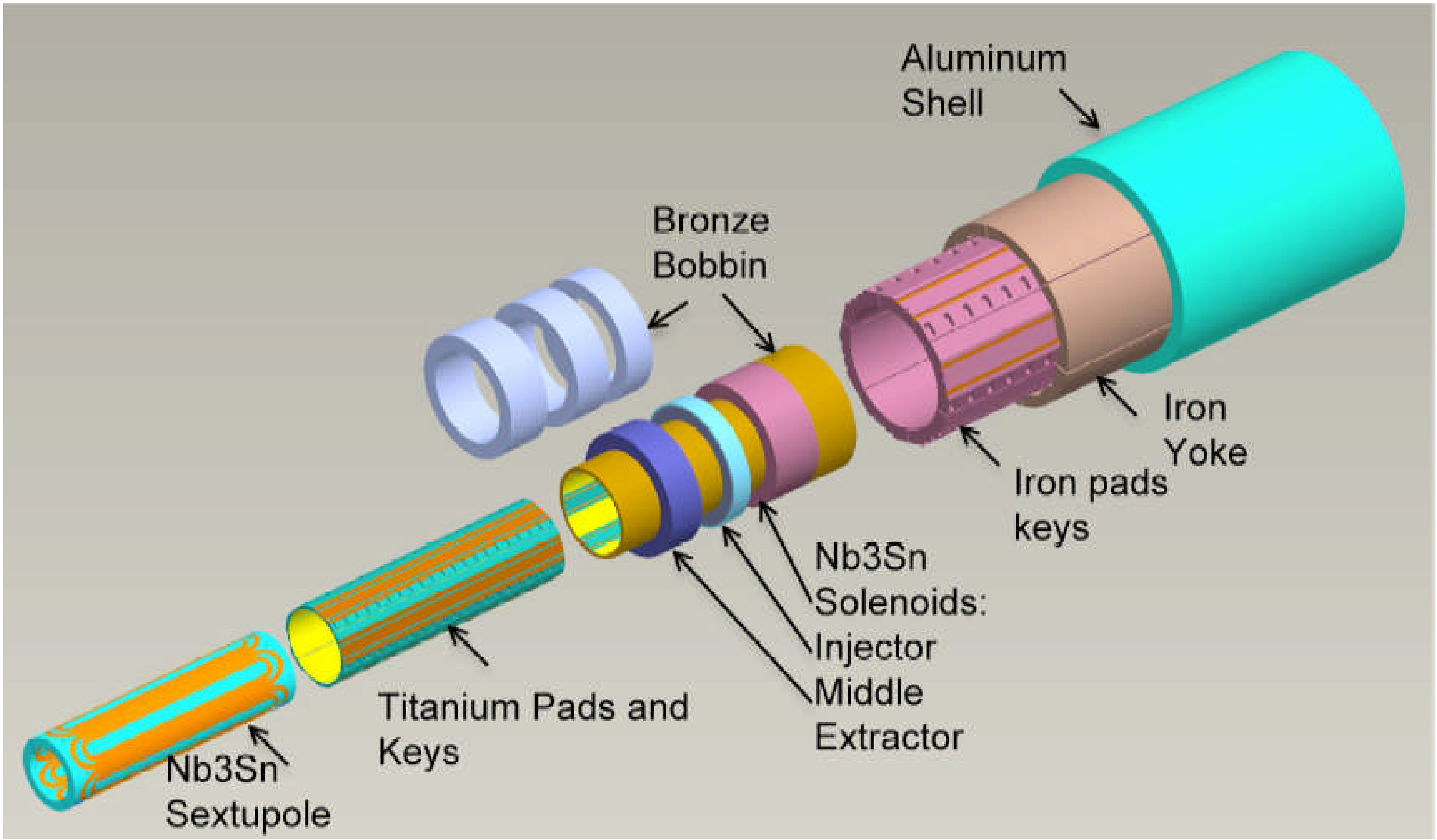
VENUS 56w
Closed Magnetic surfaces for 56 GHz



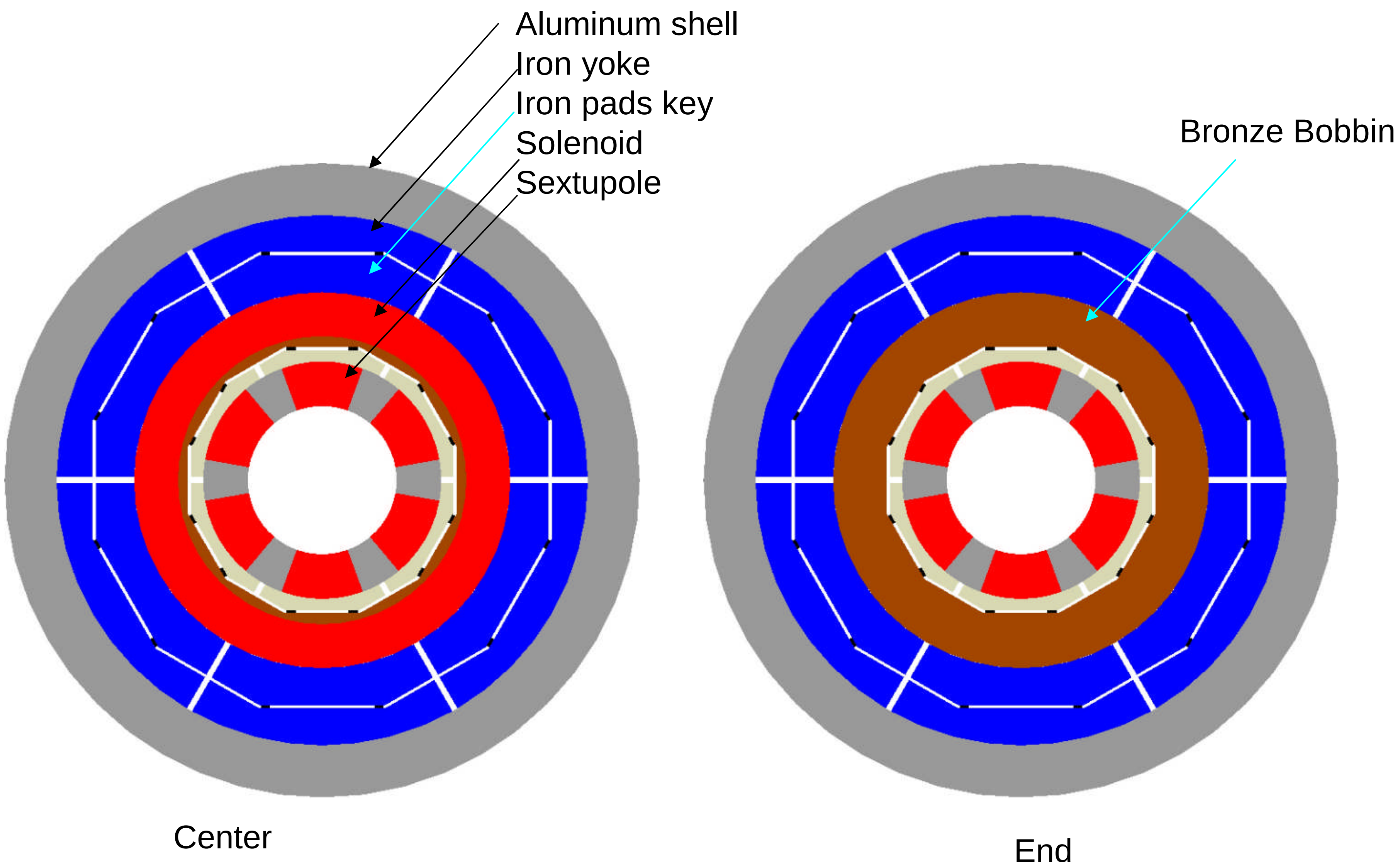
Calculated load lines for VENUS-56w



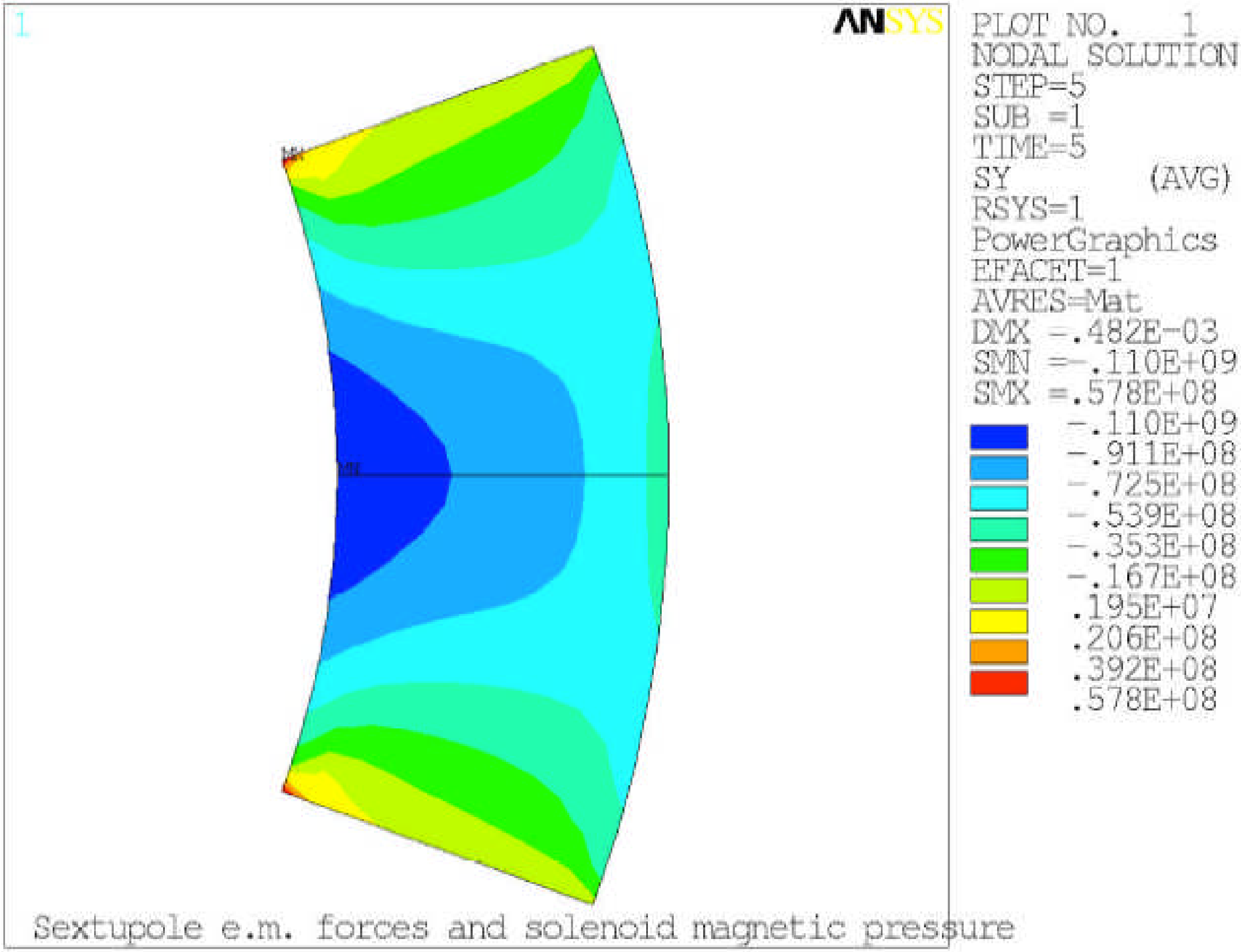
Structure to prestress coils to minimize conductor movement



Mechanical model center and end

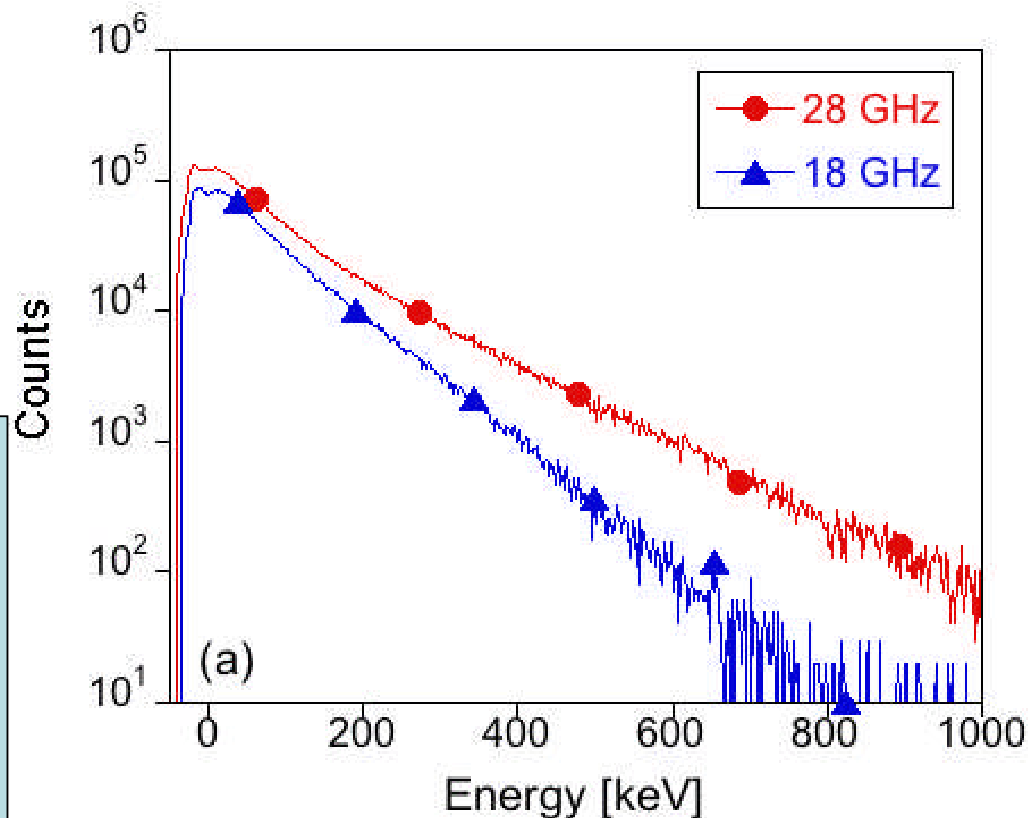


Axial Stress Distribution in Sextupole



VENUS Bremsstrahlung Measurements

- Measurements of axial bremsstrahlung at 18 and 28 GHz
- B fields are scaled by frequency
- B_{min}/B_{ecr} =70%
- RF input power 1.5 kW

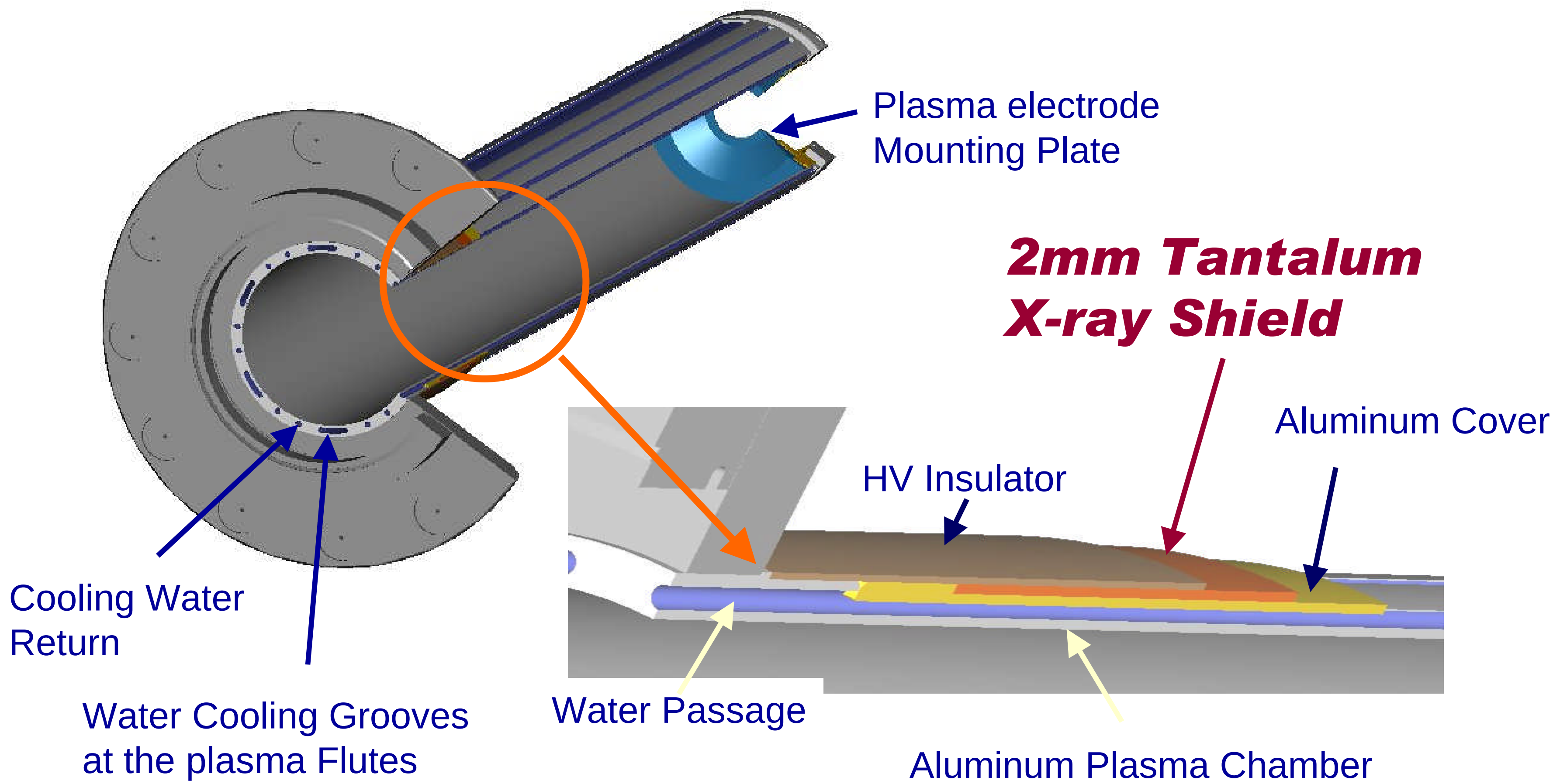


- Bremsstrahlung is more intense at 28 GHz
- Much larger high energy tail at 28 GHz
- Cryostat shielding is ineffective above 500 keV
- Mean electron energy increases with RF frequency Alain Girard (2000)

More shielding and
4 K cooling will be required
for 56 GHz

Plasma Wall Design and X-ray Shield Will Be A Greater Challenge at 56 GHz

VENUS (28GHz) Plasma Chamber with X-ray Shielding and Increased Water Cooling



Microwave Power at 56 GHz

- Gyrotrons producing at 53, 60 and 70 GHz can produce 200 kW at 100 ms pulse length.
- These can be “derated” to run cw at 30 kW
- At present there is no “laboratory scale” cw gyrotron commercially available
- We would need laboratory industrial collaboration

- No fundamental issue, but this is an area where development would be required.

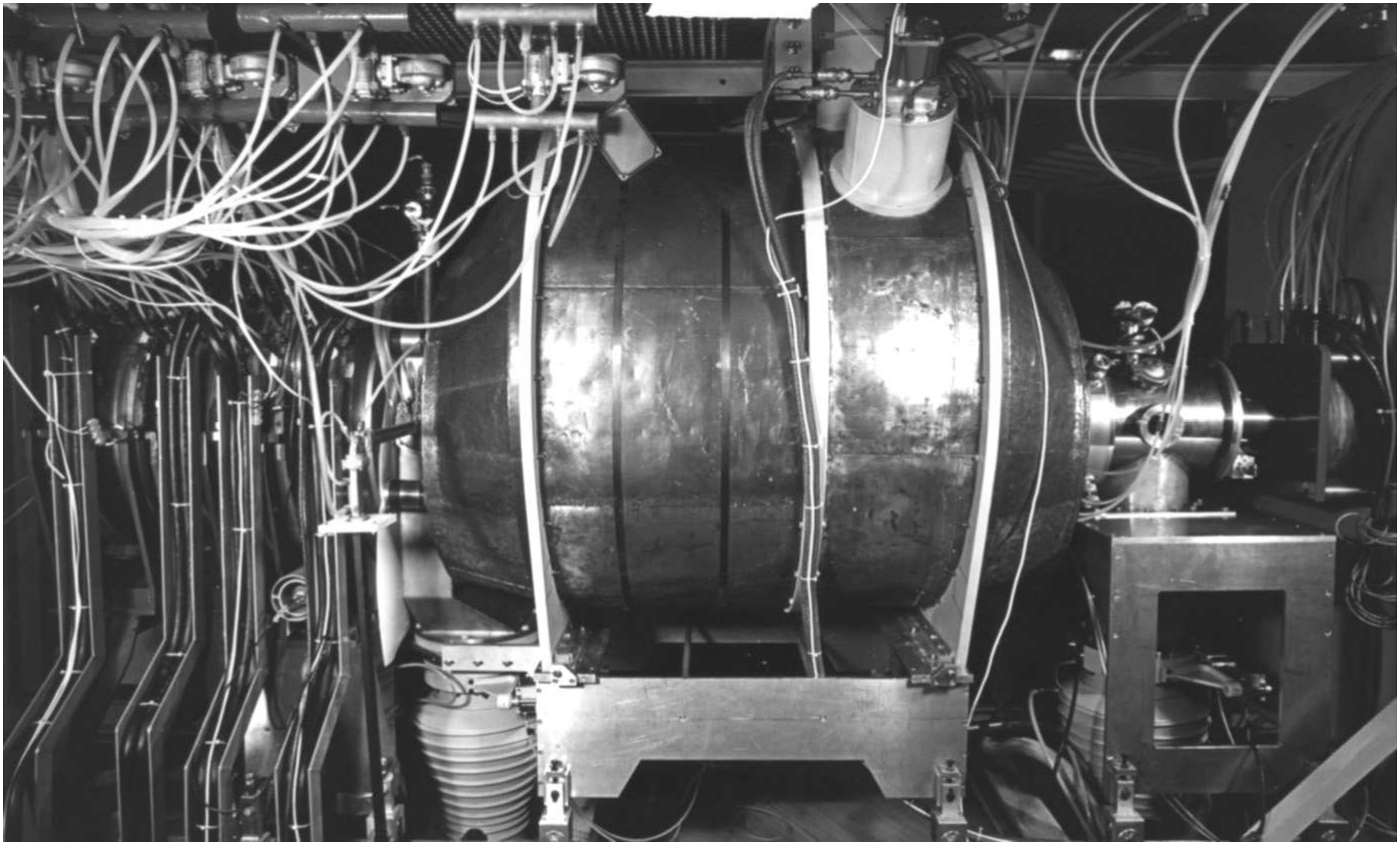
4th Generation ECR Ion Source

- As Geller predicted, frequency scaling promises us higher intensity and higher charge states
- There are technical challenges, but there are no “show stoppers”
- The design and construction of a magnet structure for a 4th Generation ECR is the most challenging task
- An “aggressive” preliminary analysis indicates construction of a 56 GHz ECR is feasible
- Next step--An engineering design study followed by construction of a prototype Nb_3Sn ECR ion source magnet structure for 56 GHz

- A 56 GHz ECR would be a major project with worldwide impact
- Community support and interest is important to continue this project

Back up Slides

ECREVIS Louvain-la-Neuve circa 1983



First successful SC ECR---Designed as superconducting version of SuperMAFIOS

MSU SC ECR 1990 to present

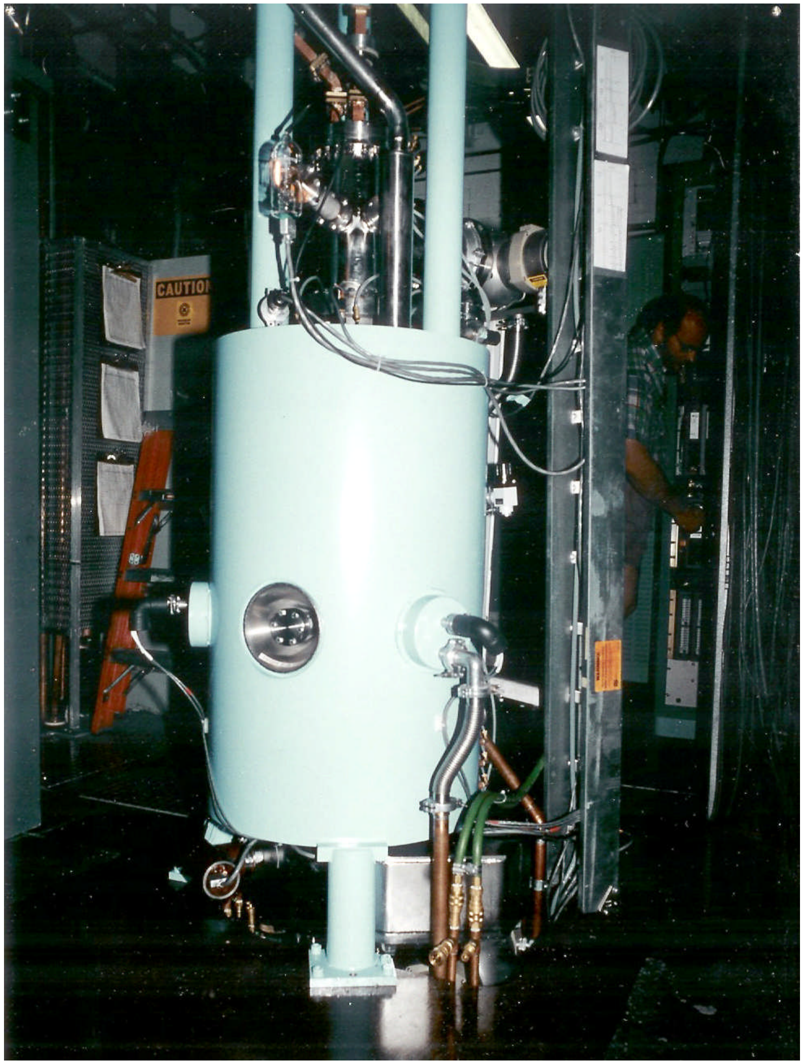
First vertical superconducting ECR

Most years in operation

Designed for 6 and 14 GHz

High B-mode demonstration at 6 GHz

Sextupole field too low for 14 GHz
(Quenching)



SERSE at INFN Catania

FIGURE 4. SERSE, the superconducting ECR ion source at INFN-LNS.

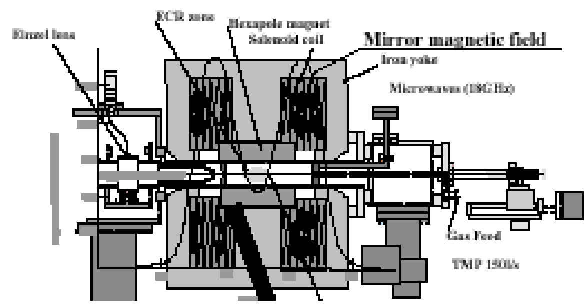
Superconducting ECR for 18 GHz
Tested at 28 GHz

- Demonstrated frequency scaling
- $I \sim f^2$, from 18 GHz to 28 GHz
- $P \geq 3$ kW
- Optimum B_{rad} at 28 GHz > 1.45 T

Magnetic fields and magnet technologies for 18, 28 and 56 GHz ECRIS

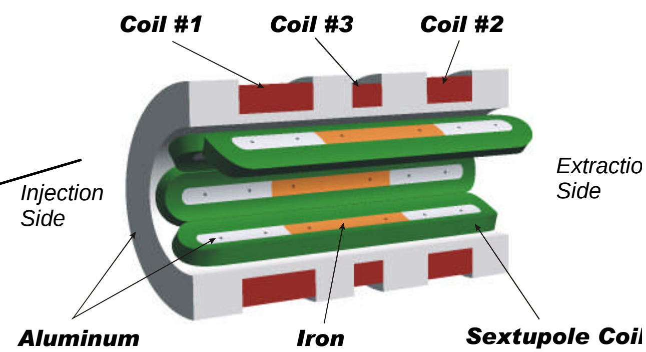
Optimum magnetic field (ECR Standard Model)

	18 GHz	28 GHz	56 GHz
B_{inj}	2-3 T	3-4 T	6-8 T
B_{min}	0.5 T	0.8 T	1.6 T
B_{ext}	1.3 T	2.0 T	4.0 T
B_{wall}	1.3 T	2.0 T	4.0 T



14 GHz, room temperature copper coils with iron yoke and permanent magnet sextupole are sufficient

18 GHz, room temperature copper coils with iron yoke and permanent magnet sextupole are at their limit

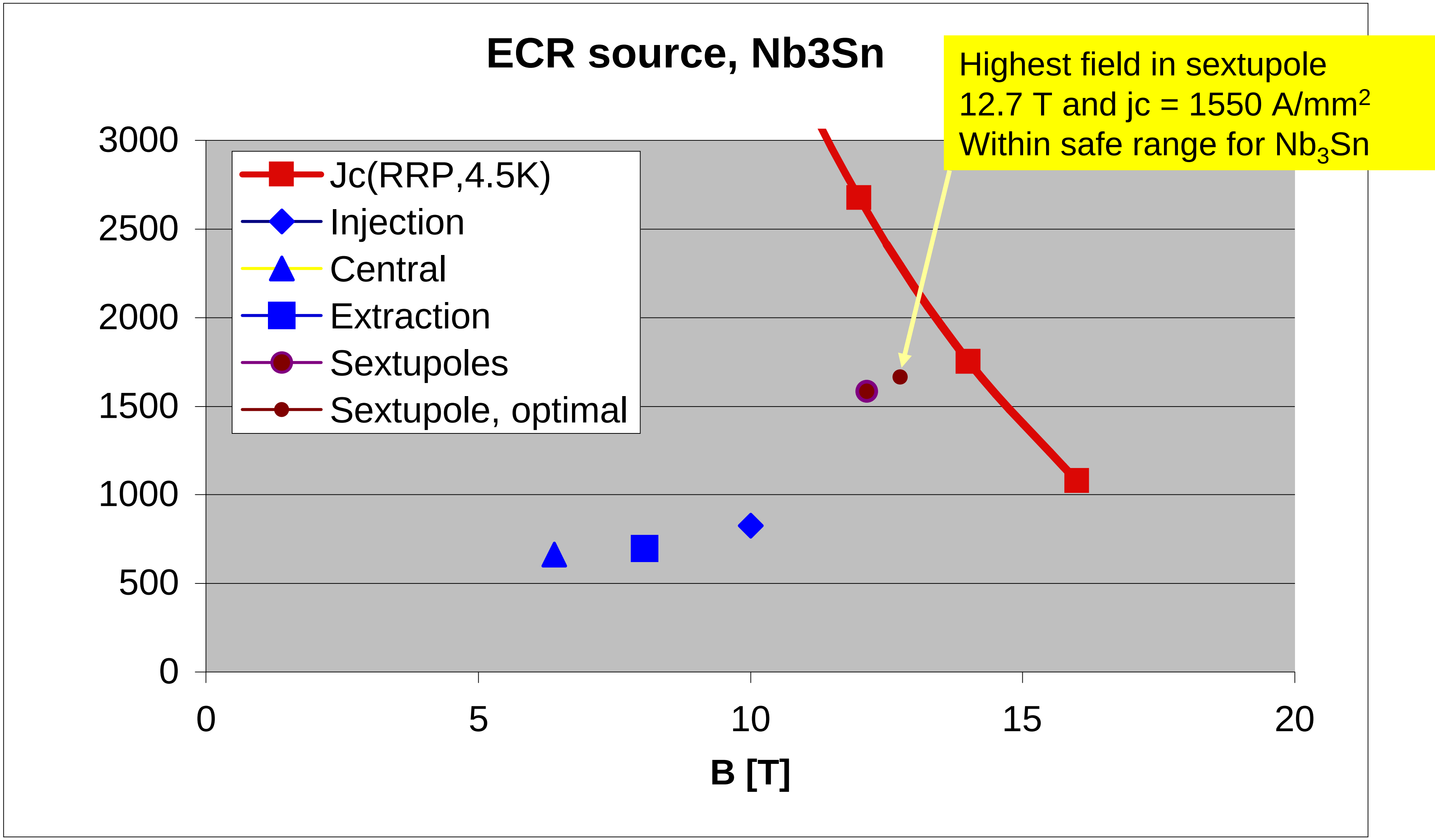


28 GHz superconducting NbTi solenoid and sextupole coils can produce the optimum fields

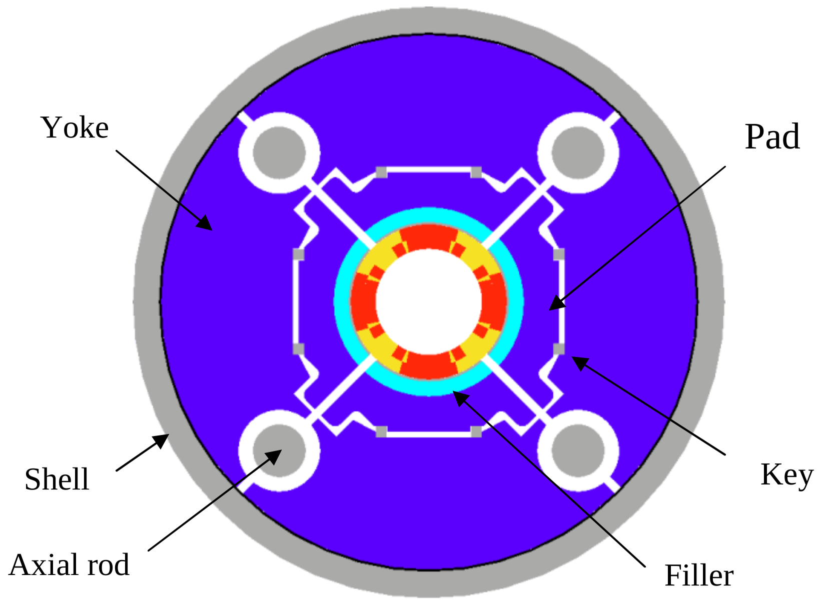
56 GHz superconducting Nb_3Sn solenoid and sextupole coils will be needed

?

Model calculation for Venus coil configuration for 56 GHz operation



LARP Technology Quad – Shell (TQS)



• Aluminum shell and axial rods: low assembly pre-load, large cool-down gain

• Accurate control of assembly pre-load using pressurized bladders and keys

• Need to quantify conductor degradation under high coil stress → cable testing

• FEA shows that 3D effects have a significant impact on actual coil stresses

• The inter-coil forces for ECRIS-56 will be about 4 times as great as for the VENUS magnet.

• The LARP technology quadrupole clamping is not directly applicable to an ECR magnet structure.

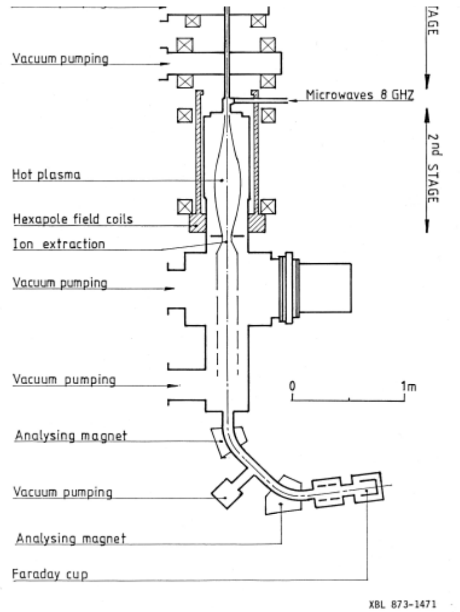
ECRIS-56 --Other Challenges

- Gyrotrons at 53, 60 and 70 GHz at 200 kW for 100 ms can be run at 30 kW cw. "No problem" to extend to 50 kW cw.
- Power requirements and chamber cooling
  - Total RF power ~ n_eV or ~ f^2*V. VENUS at 1 kW/liter has not reached the saturation power density
  - The heat deposition on the plasma wall is highly non-uniform and 'burnout" is a concern.
- Bremsstrahlung heating of the cryostat will require more cryocooling power.

Electron Cyclotron Resonance Ion Source Development

Supermafios (Geller, 1974)

15 eμA of O^{6+}



Power consumption 3 MW

Solenoid, Sextupole, Axial Extraction

VENUS (2004)

>2000 eμA of O^{6+}

Power consumption 100 kW

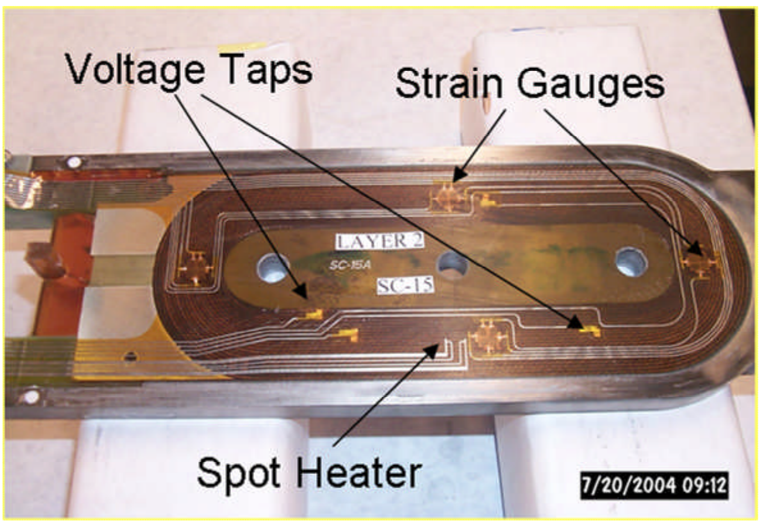
Solenoid, Sextupole, Axial Extraction

LBNL Supercon Group is the lead lab in the development of Nb_3Sn magnets and cables

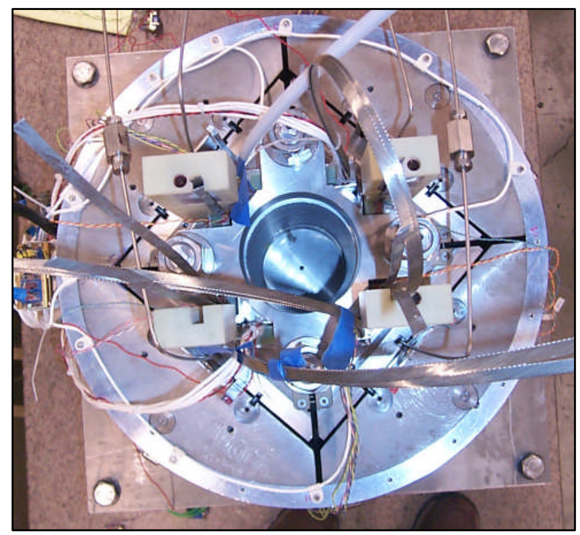
Nb_3Sn magnets are currently develop for LARP (LHC Accelerator Research Program)

LARP

SC Coil

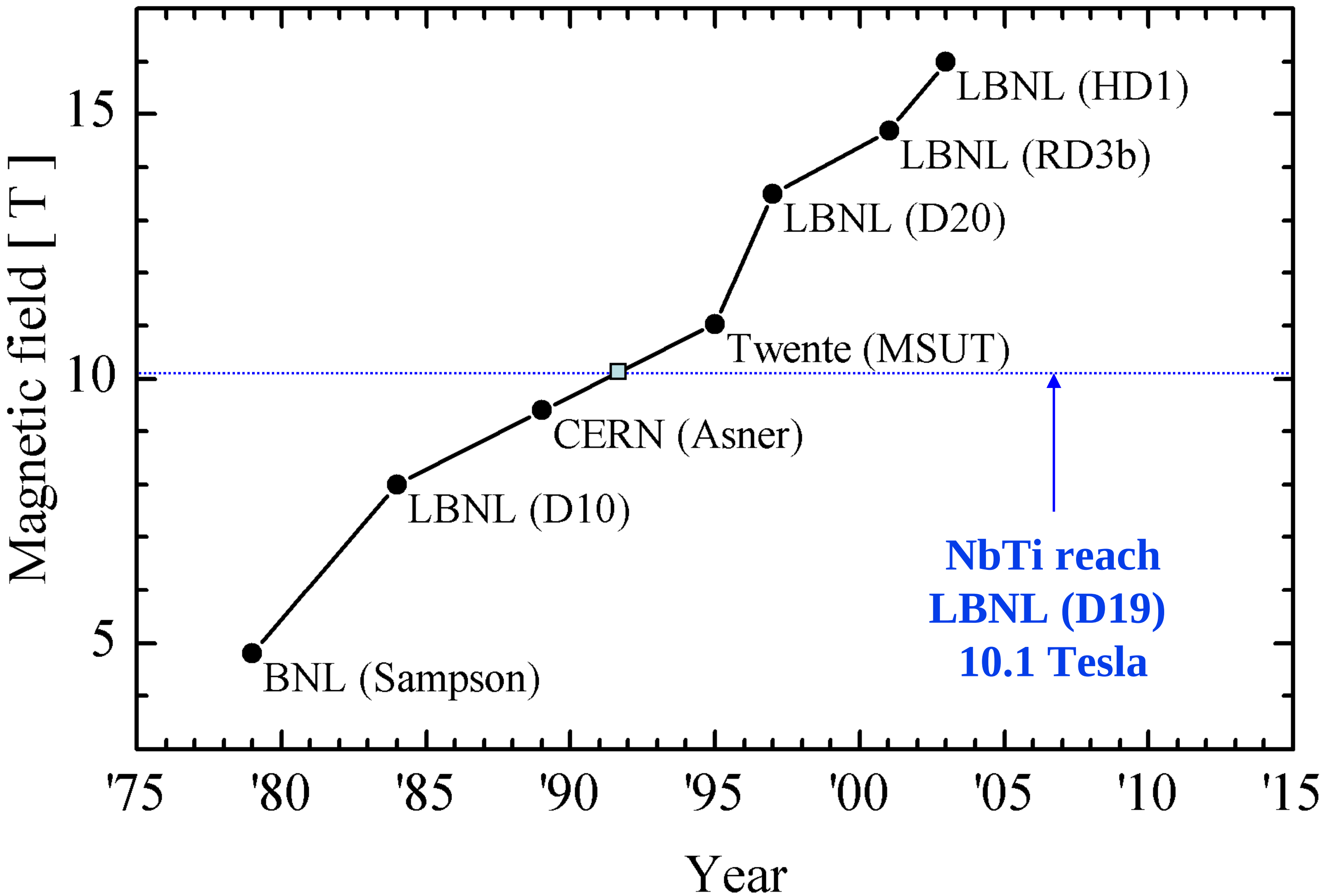


SQ Quadrupole

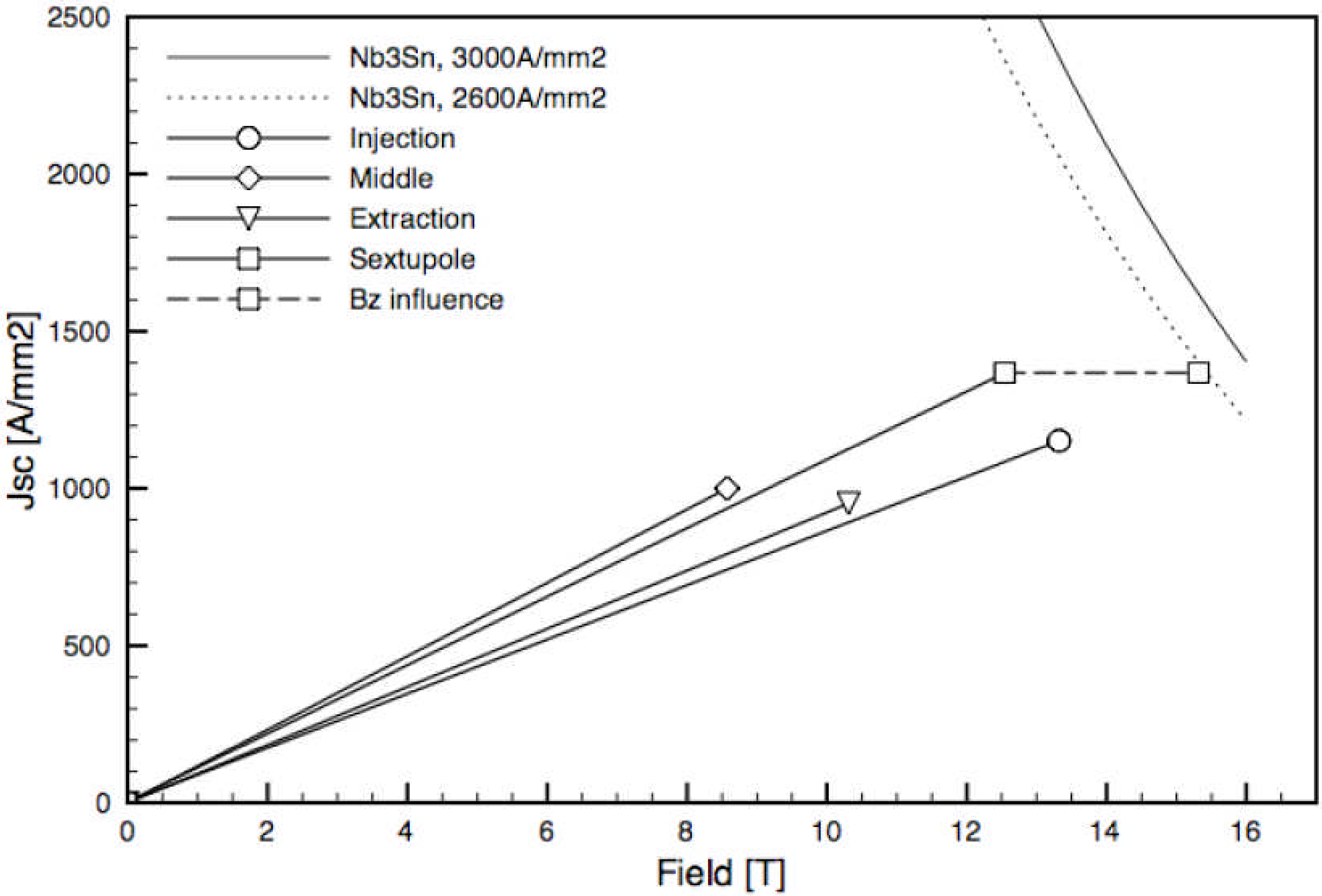


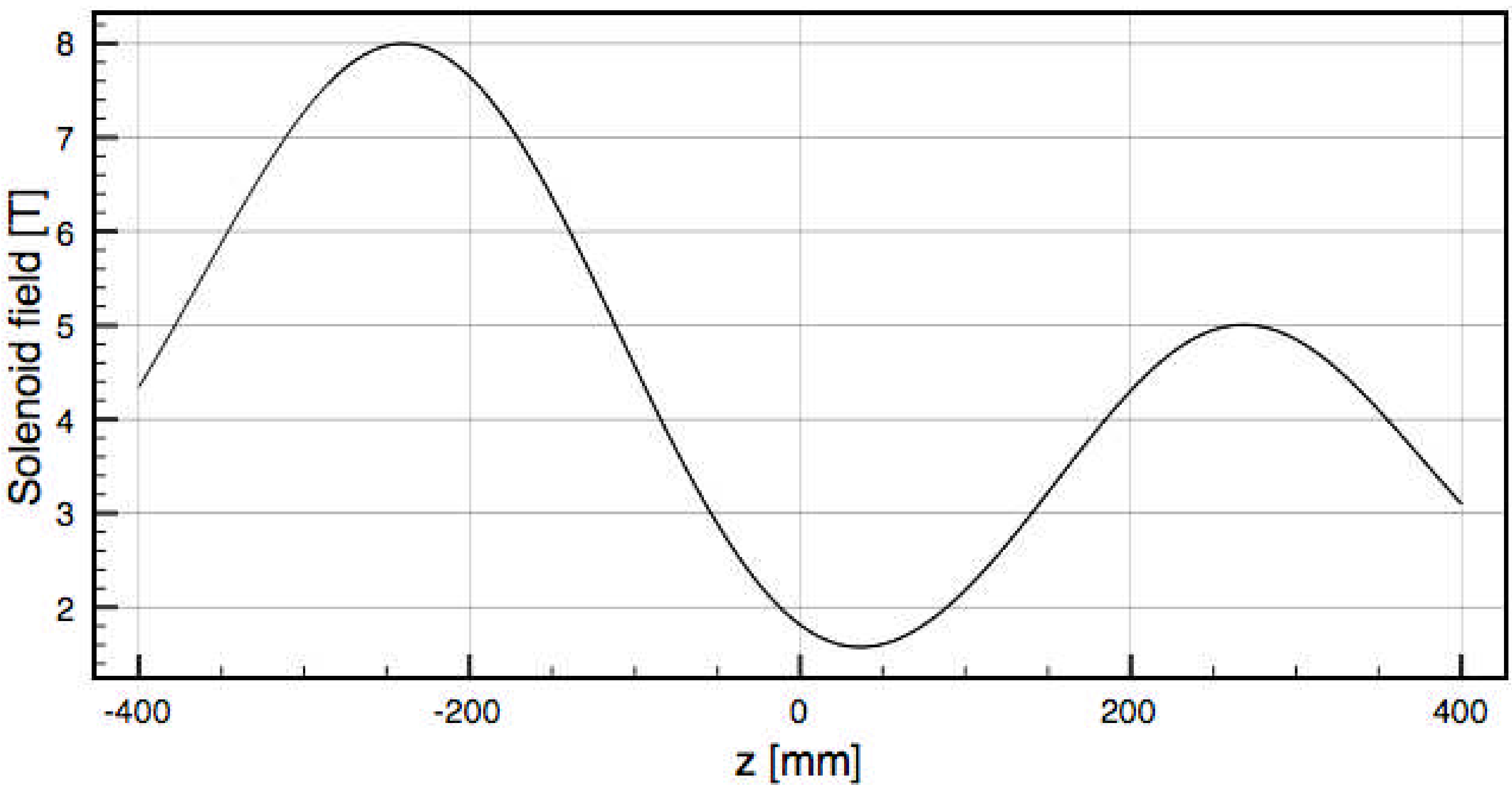
Sub-scale Magnet Series

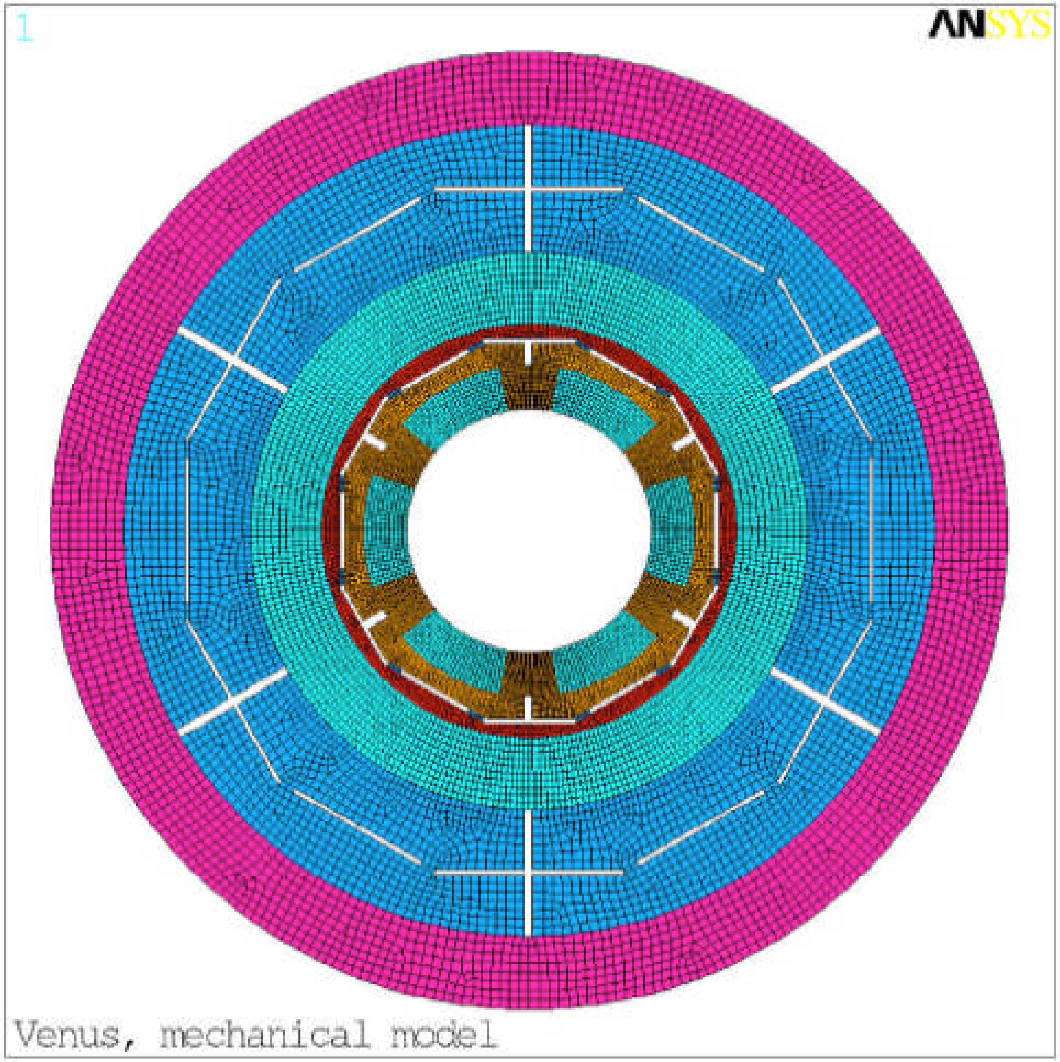
Maximum magnetic field in superconducting magnet coils

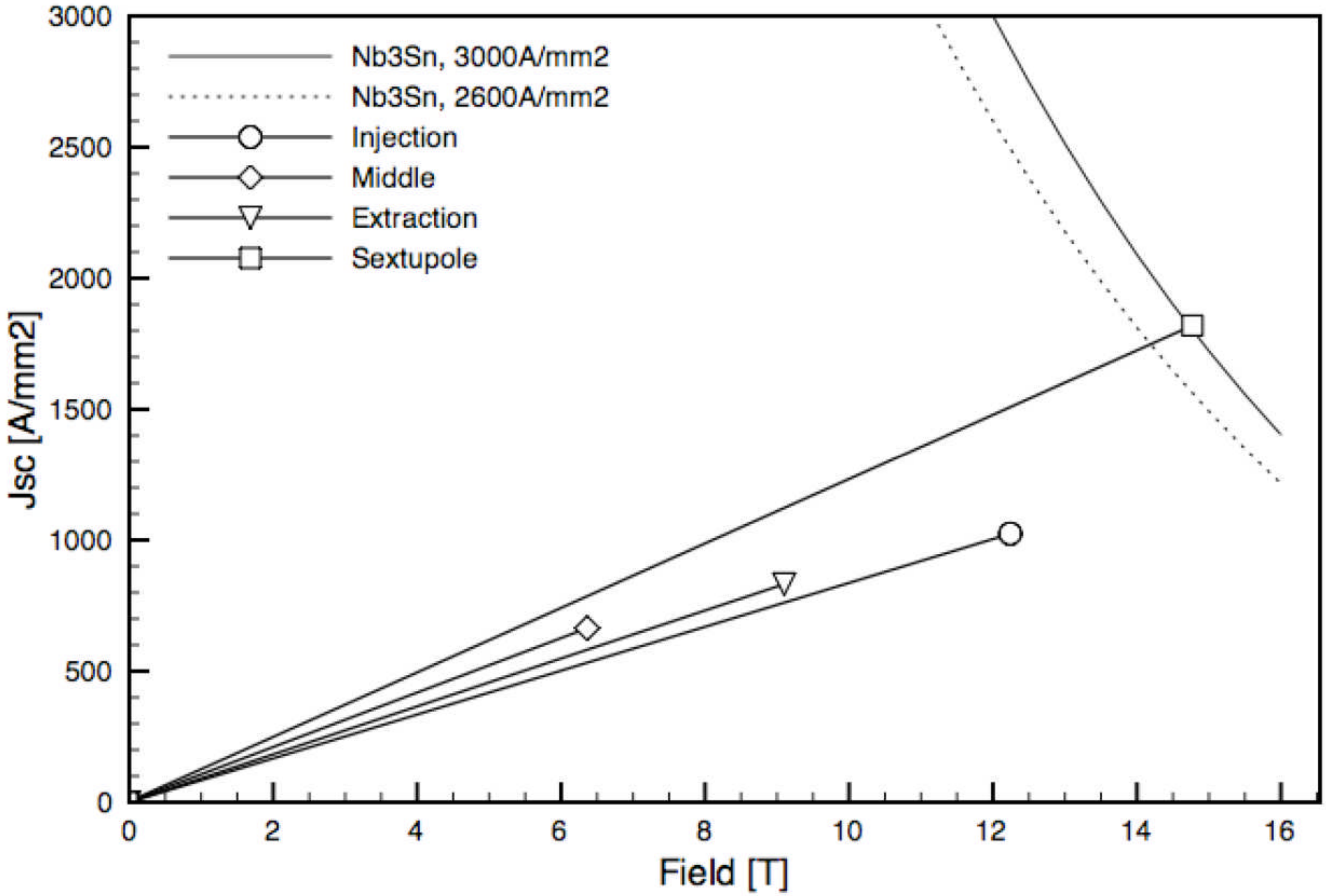


VENUS-56 Load line

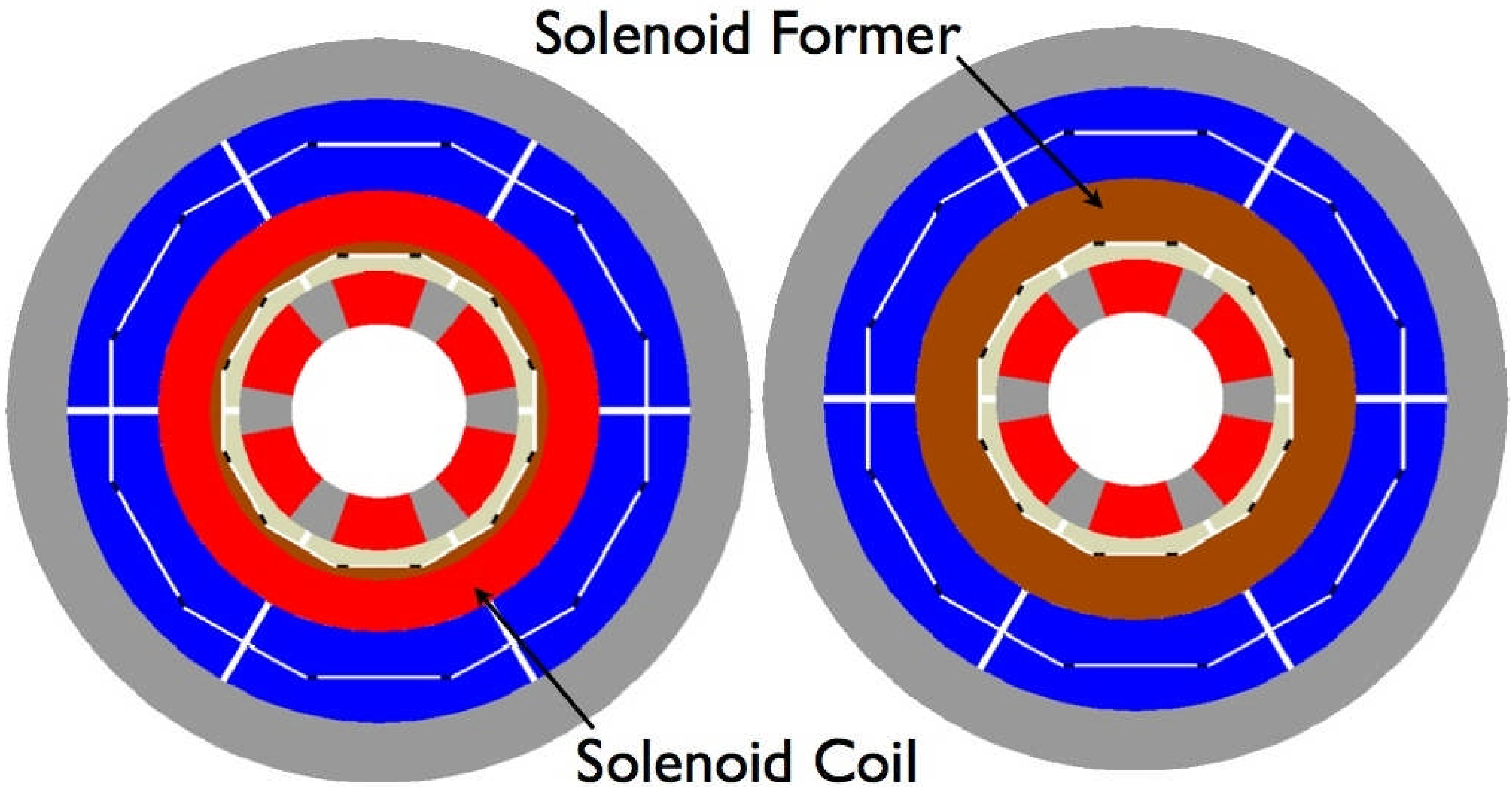


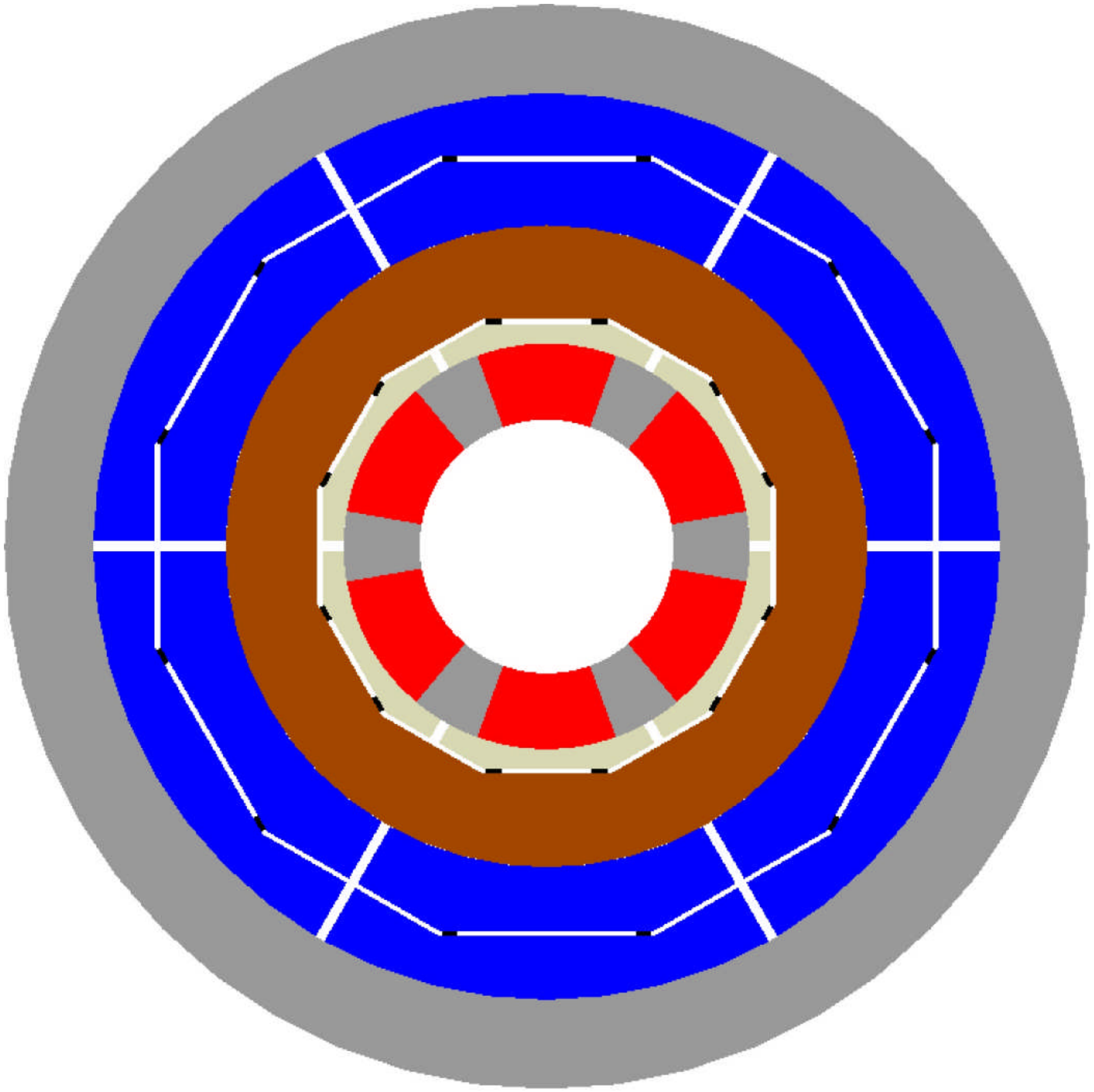

8
7
6
5
4
3
2
Solenoid field [T]
-400
-200
0
200
400
z [mm]

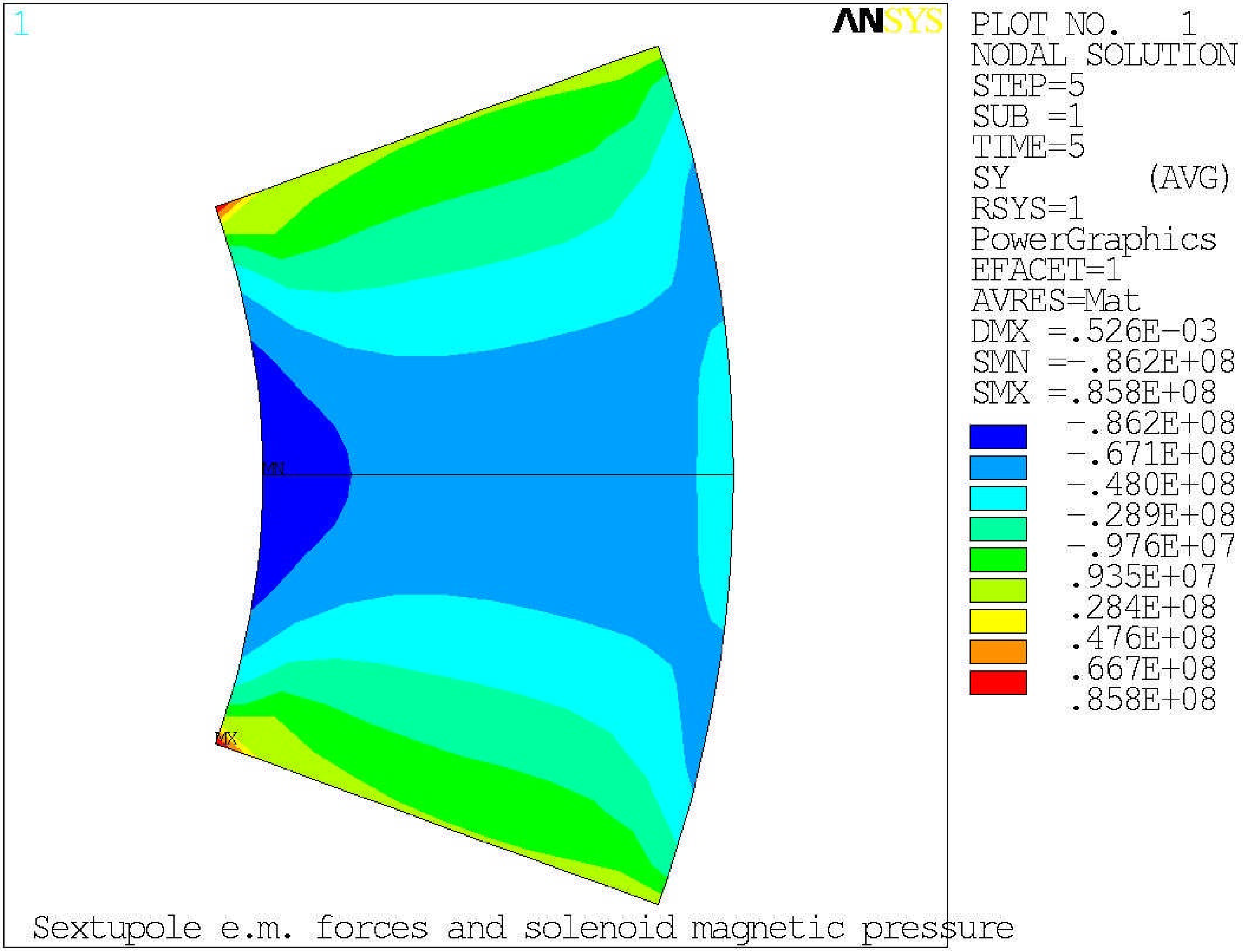

1
ANSYS
Venus, mechanical model



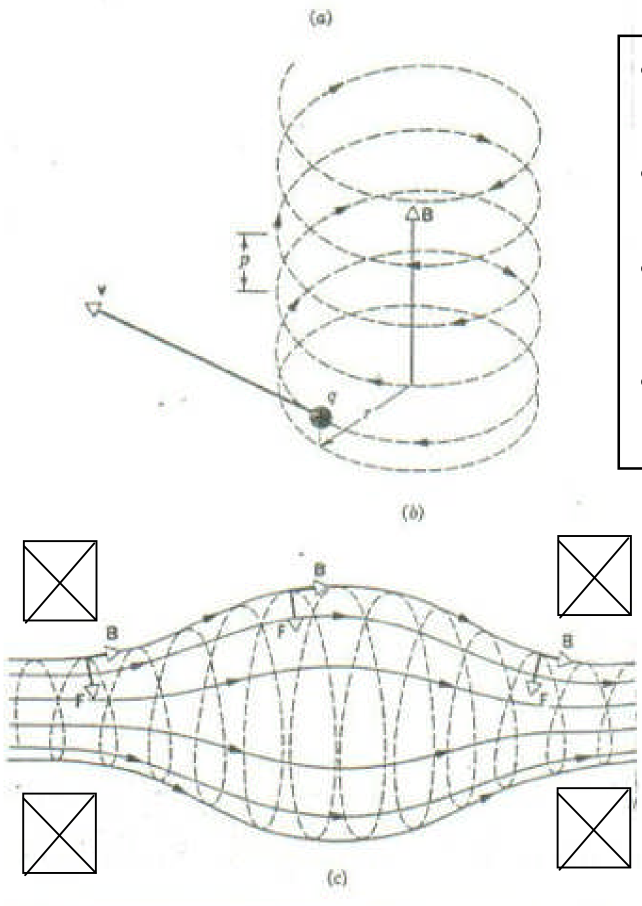
Nb3Sn, 3000A/mm2
Nb3Sn, 2600A/mm2
Injection
Middle
Extraction
Sextupole
Jsc [A/mm2]
Field [T]
3000
2500
2000
1500
1000
500
0
0
2
4
6
8
10
12
14
16


Solenoid Former
Solenoid Coil



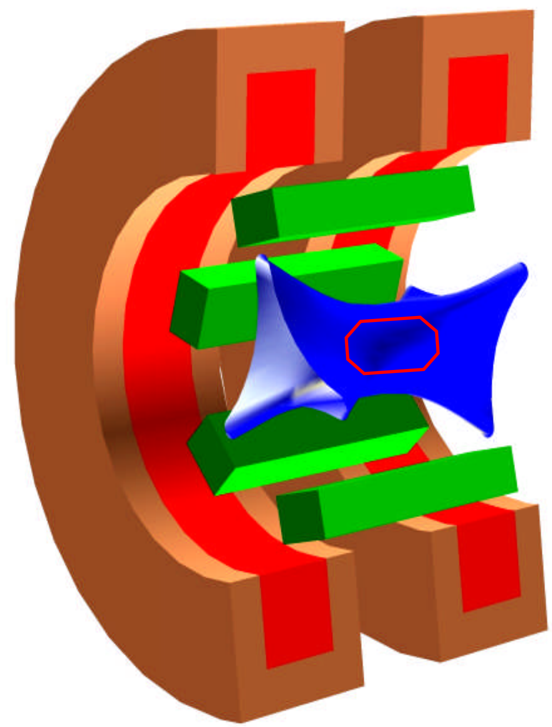

1
ANSYS
PLOT NO. 1
NODAL SOLUTION
STEP=5
SUB =1
TIME=5
SY (AVG)
RSYS=1
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.526E-03
SMN =-.862E+08
SMX =.858E+08
-.862E+08
-.671E+08
-.480E+08
-.289E+08
-.976E+07
.935E+07
.284E+08
.476E+08
.667E+08
.858E+08
MN
MX
Sextupole e.m. forces and solenoid magnetic pressure

Electron Cyclotron Resonance and Magnetic Confinement



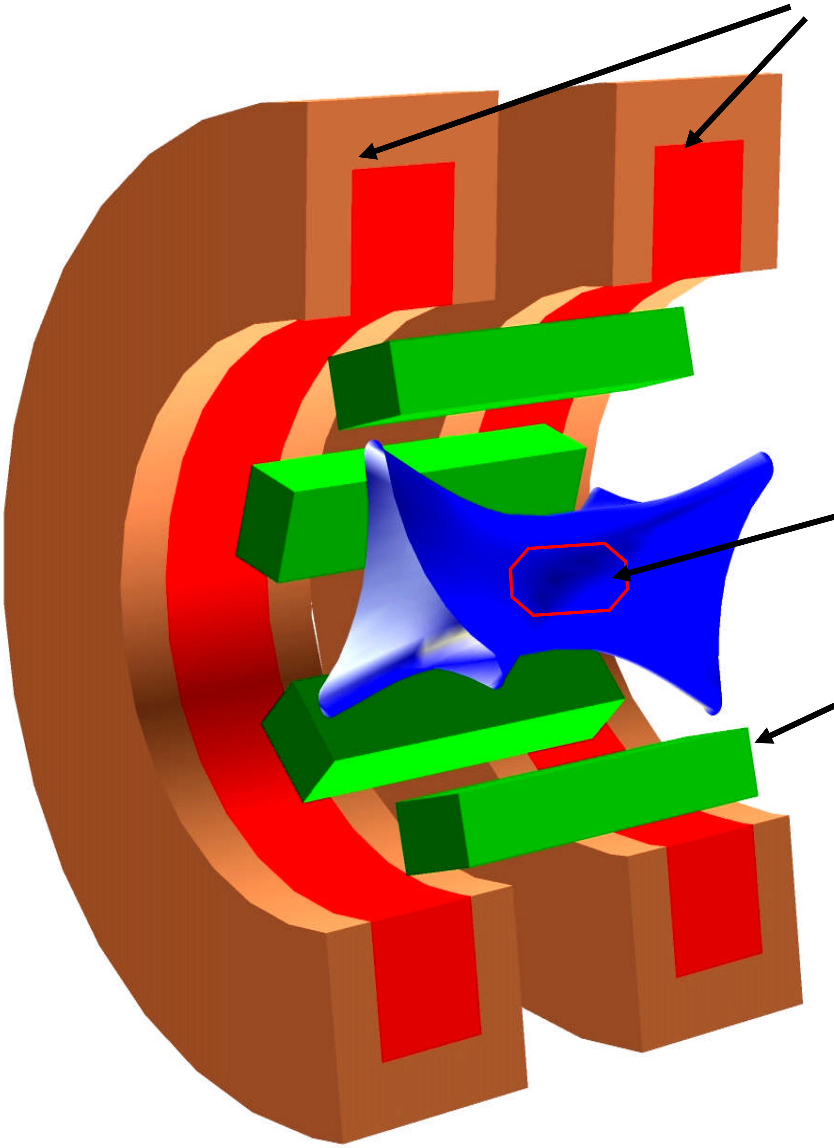
- Electron cyclotron frequency
- $\omega_{ecr} = eB/m_e$
- 28 GHz ~ 1 Tesla
- Magnetic mirror can trap electrons a long the axis

Mirror confinement



High Charge ECR confinement
Minimum B configuration

Minimum-B field Confinement



Solenoid Coils

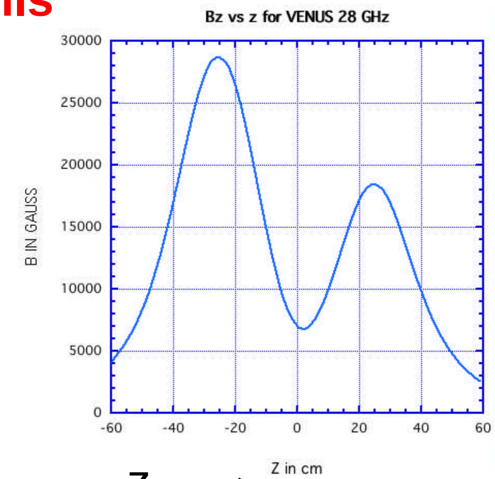
ECR Zone

$B_{ecr} = \omega_{rf} m_e / e$

Sextupole

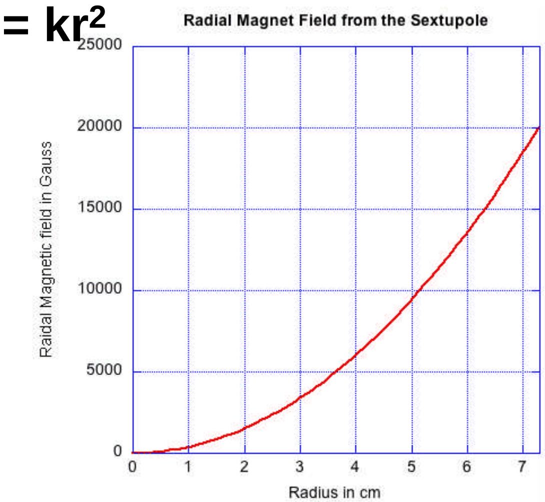
$B_{radial} = kr^2$

Axial field



z →

Radial field



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Fourth Generation ECR Ion Sources

ECRIS-56

- Model calculations for 4th Generation source
- Choose 56 GHz (2 times 28)
- Conventional coil geometry

For a 56 GHz ECR $B_{ecr} = 2$ T

Confinement criterion

$B_{conf} \geq 2\, B_{ecr}$ at walls

$B_{inj} \sim 3\, B_{ecr}$ on axis

$B_{rad} \geq 2\, B_{ecr}$ on the walls

ECRIS-56

$B_{inj} \sim 6$ T

$B_{ext} = 4$ T

$B_{rad} = 4$ T

ECRIS-56 Magnetic field is a challenge

Acknowledgements

- Slides from
  - D. Leitner, S. Gammino, T. Nakagawa, P. Zavodsksy , H.W. Zhao, N Angert,