4th Generation ECRIS and Application to Cyclotrons

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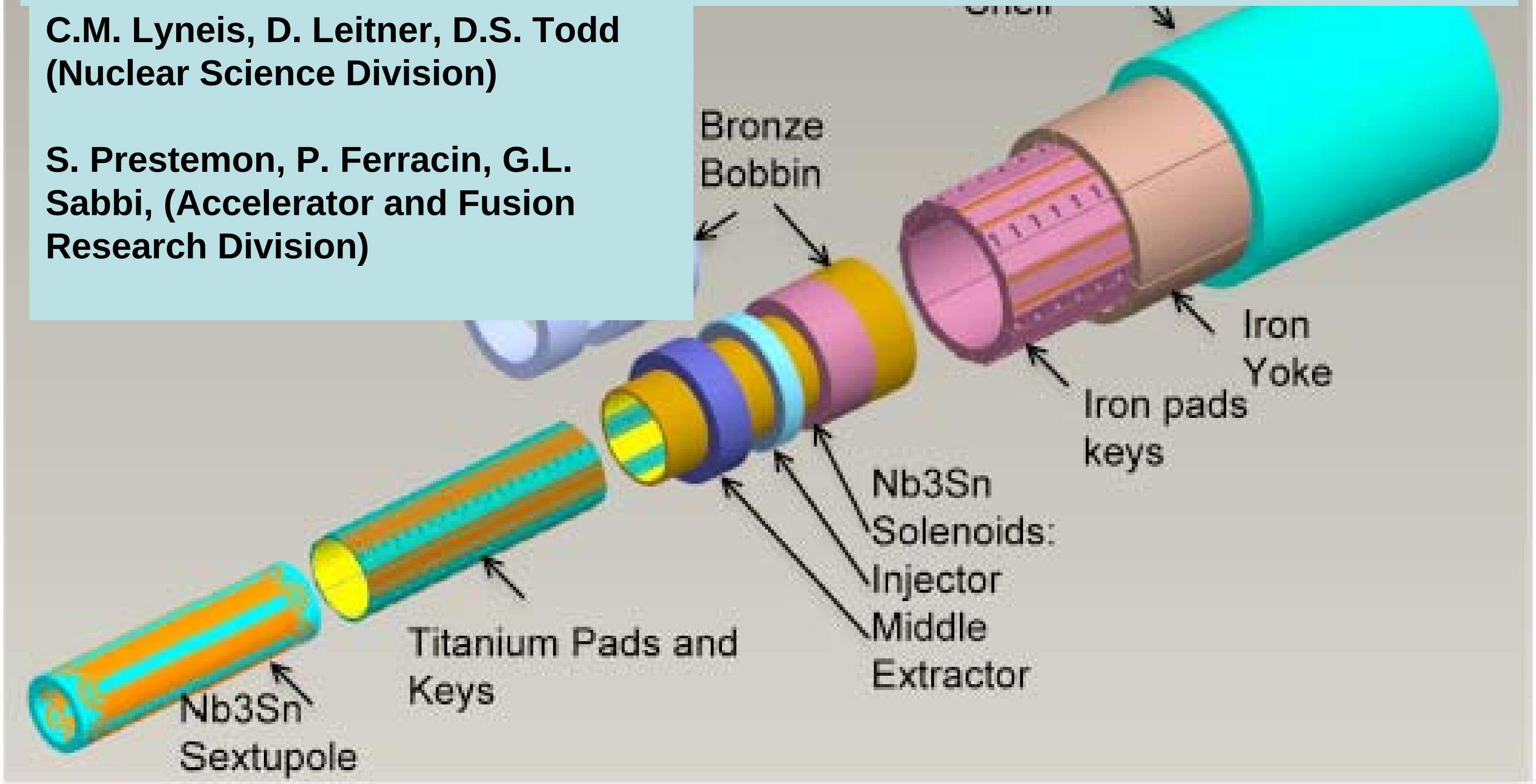
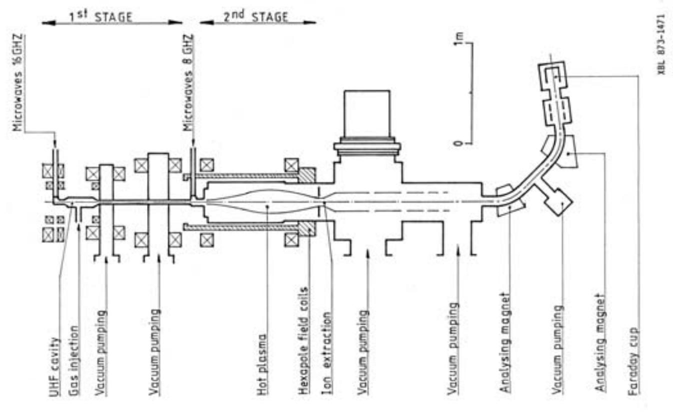


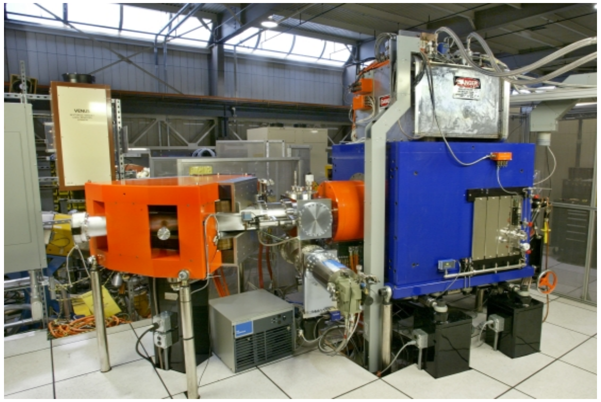
ECR ion sources have made remarkable improvements over the last few decades

Supermafios (Geller, 1974)
15 eμA of O^{6+}



Factor
200
increase

VENUS (2007) 28 GHz
2850 eμA of O^{6+}



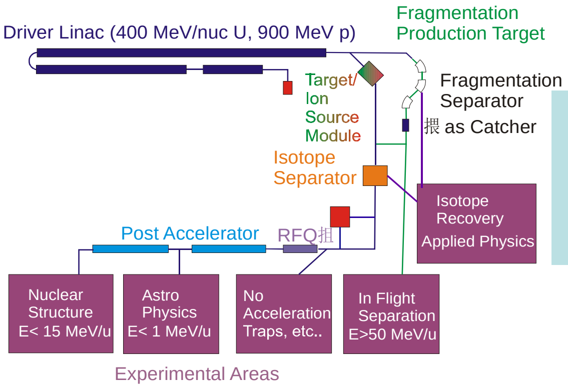
Generation 1.0
f≤10 GHz

Generation 2
10 < f ≤ 20 GHz

Generation 3.0
20<f<40 GHz

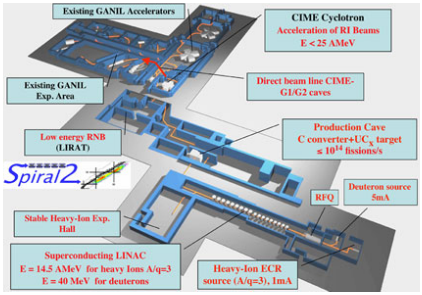
Demand for increased intensities of highly charged heavy ions continues to grow

FRIB
MSU, USA



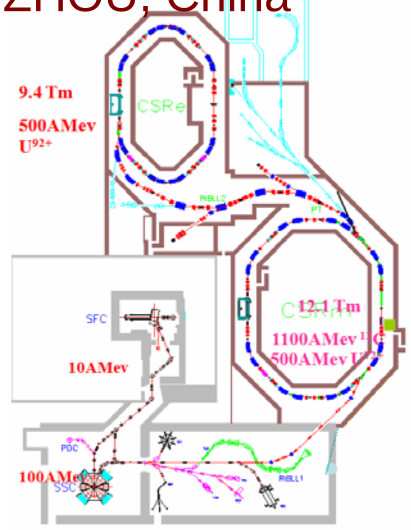
270 eμA U^{33+}
and
270 eμA U^{34+}

SPIRAL 2, GANIL, France



1mA Ar^{12+}

IMP HIRFL, LANZHOU, China



750 μA Bi^{35+}

RIKEN, Japan

525 eμA U^{35+}

Present Performance of 3rd Generation Sources

Ion	Intensity eμA	Source
Ar^{12+}	860	VENUS
Xe^{27+}	455	SECRAL
Bi^{30+}	225	VENUS
Bi^{41+}	22	SECRAL
U^{33+}	205	VENUS

Projected Requirements

Ion	Intensity eμA	Project
Ar^{12+}	1000	Spiral 2-GANIL
Bi^{35+}	750	IMP HIRFL
U^{33+}	270	FRIB
U^{35+}	525	HRIBF- RIKEN

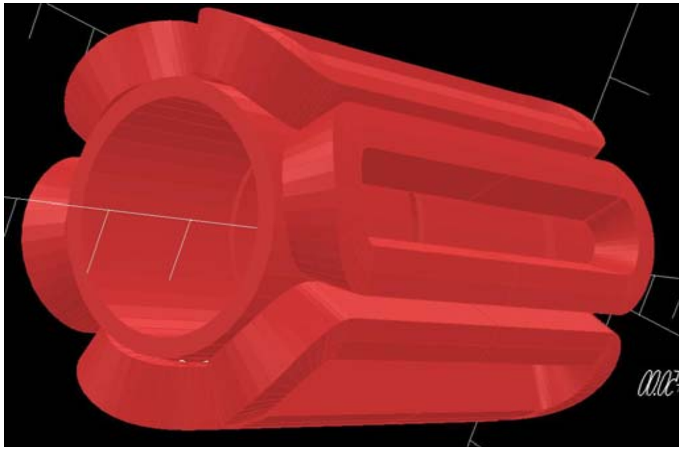
Third Generation Superconducting ECR Sources

- SuSI MSU
- SC-ECR RIKEN
- ------------------------
- SECRAL IMP
- VENUS LBNL

SECRAL*, IMP, Lanzhou, China

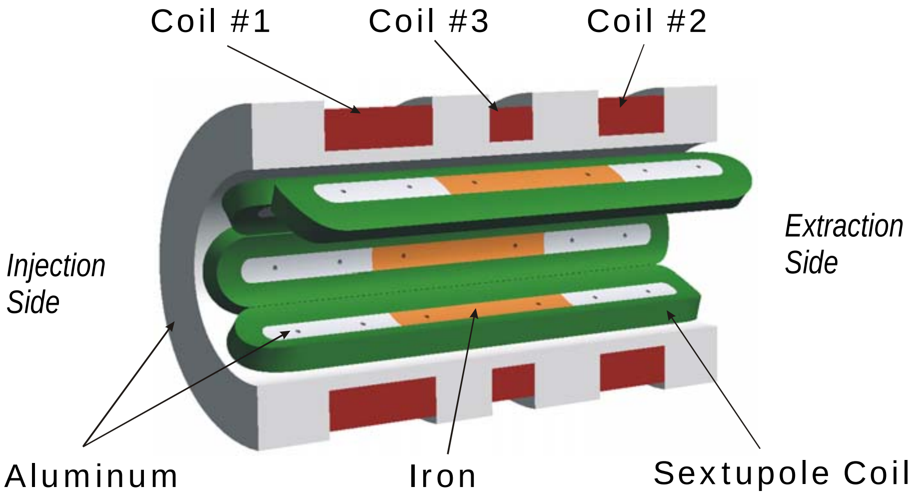
In operation at 18 and 24 GHz

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

ECREVIS, SERSE, SUSI, MS-ECRIS, RIKEN SC-ECR

•

Standard Model for ECR ion sources

Frequency scaling $n_e \ \alpha \ \ \omega_{rf}^2$

$$B_{ecr} = \frac{m_e \, \omega_{rf}}{q_e}$$

Confinement criterion at 28 GHz

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

B_{inj} ~3 - 4 B_{ecr} on axis

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

B_{min} ~ 0.5-0.8 B_{ecr} on axis

$I \propto \boldsymbol{\omega_{rf}}^2/m$

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

Enhancements

Electron sources (Bias Probe, Electron Gun, Plasma First Stage, Wall Coatings)

2 Frequency Heating

Solids → Ovens, Direct Insertion, Sputtering

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

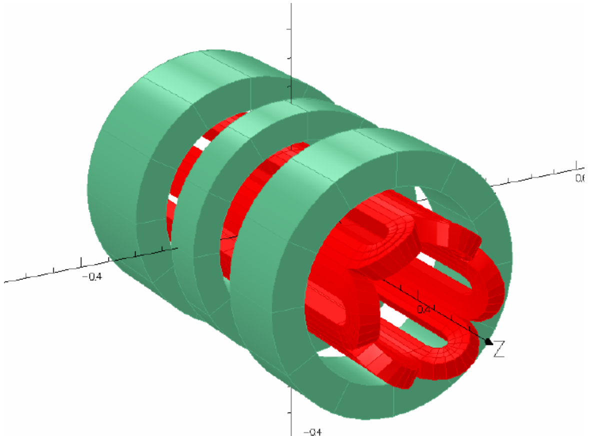
ECR Coil Layouts

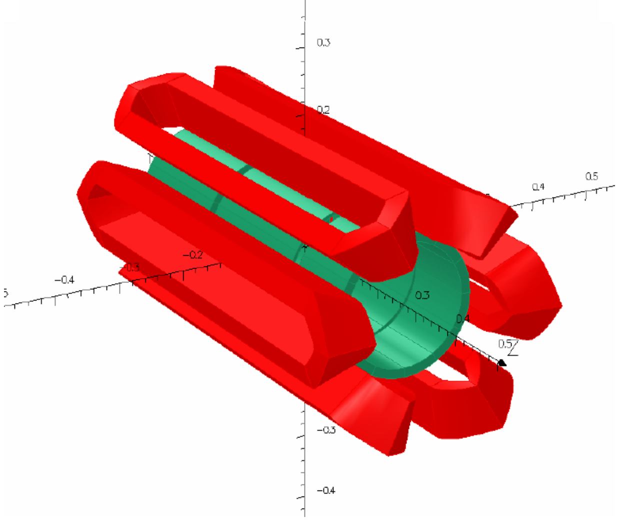
Sextupole-in-solenoid:

- ☺ Minimizes the peak field in the sextupole
- ☹ Solenoid field causes strong asymmetric forces on the sextupole coil ends

Solenoid in sextupole:

- ☺ Minimizes the influence of the solenoid on the sextupole coil field and forces
- ☺ More compact
- ☹ Higher field in the sextupole coil (larger radius)
- ☹ Strong forces on the solenoid coils
- ☹ Iron contribution less effective at high field

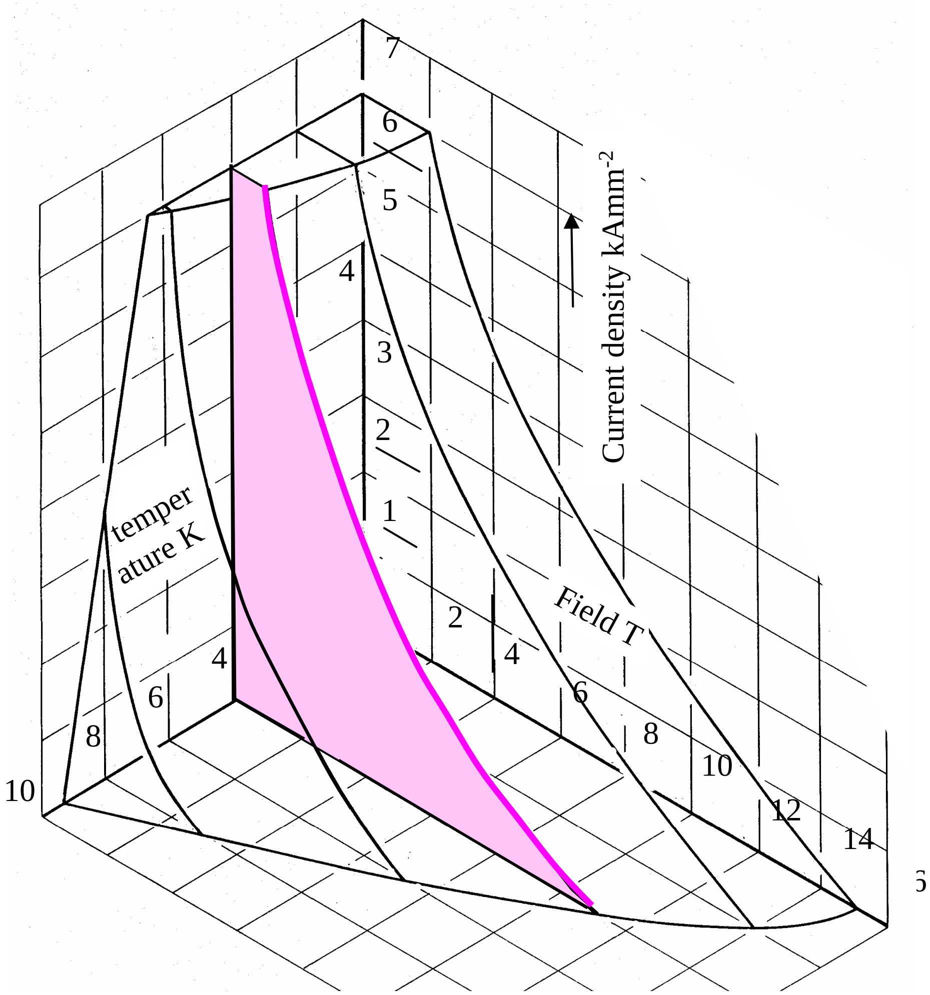


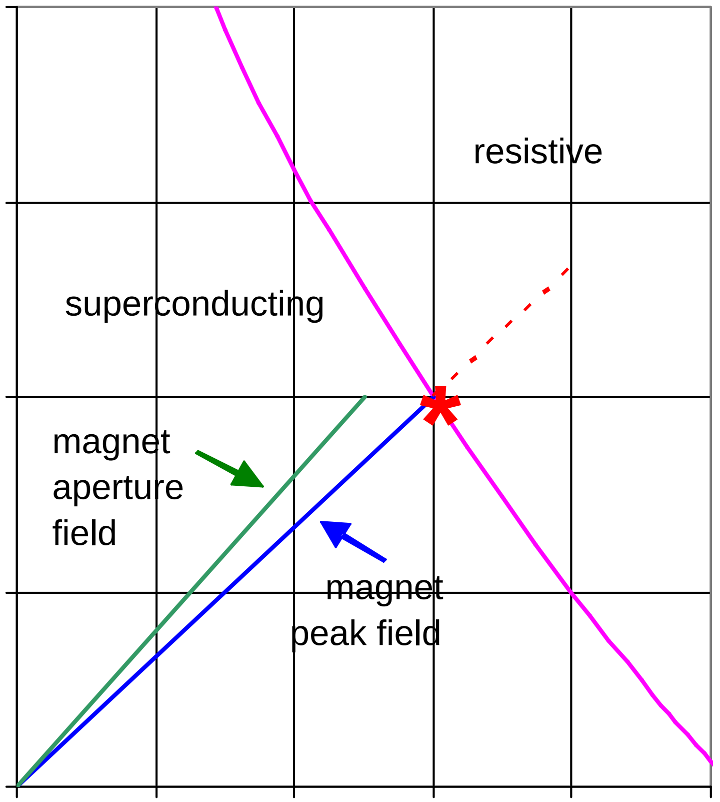


LBNL group chose the Sextupole-in-Solenoid because it has the potential to reach higher magnetic fields

Superconducting Magnets

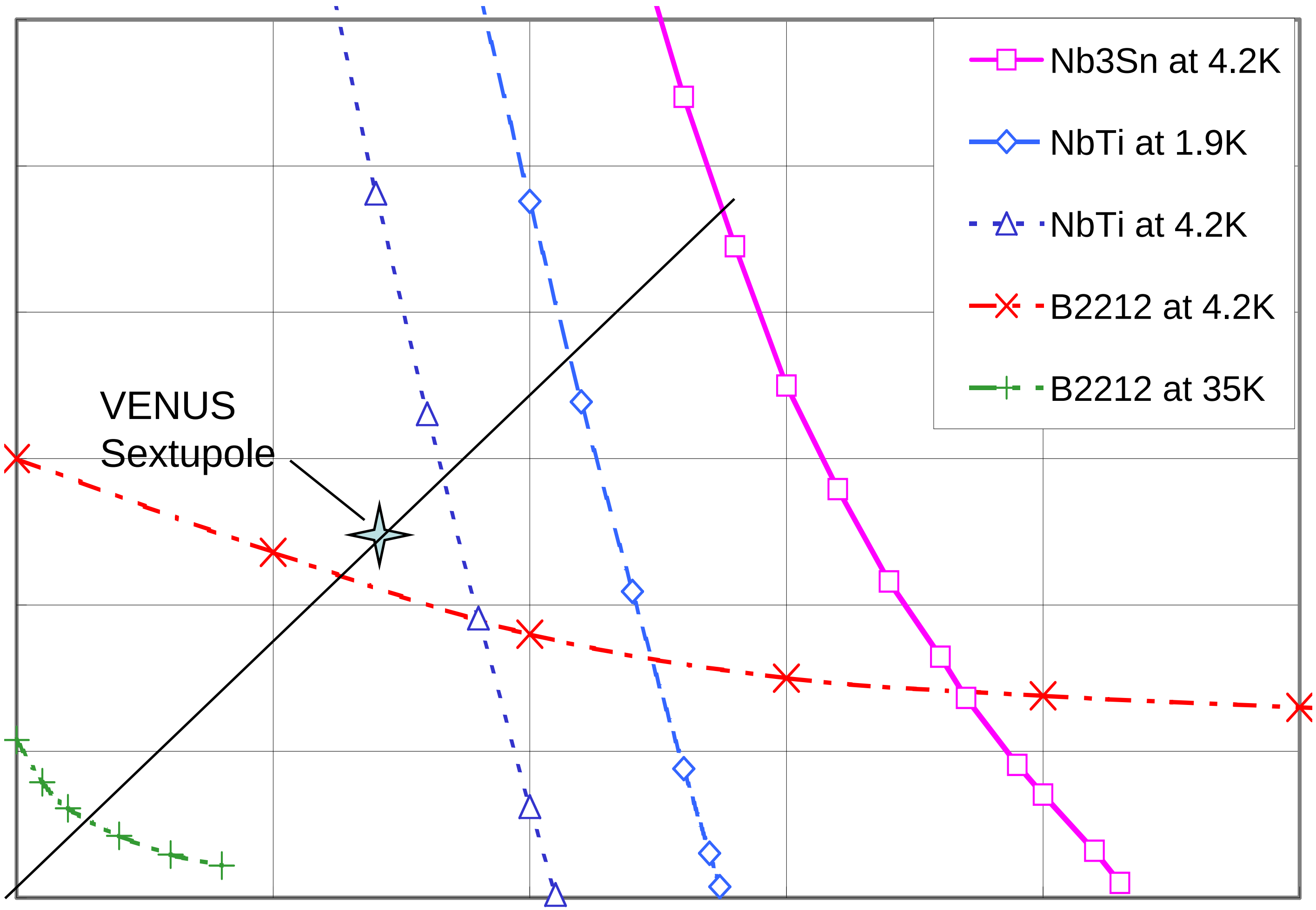
Critical line and magnet load lines





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

Engineering Current Densities for various materials



LBNL Design Effort for a 56 GHz ECR

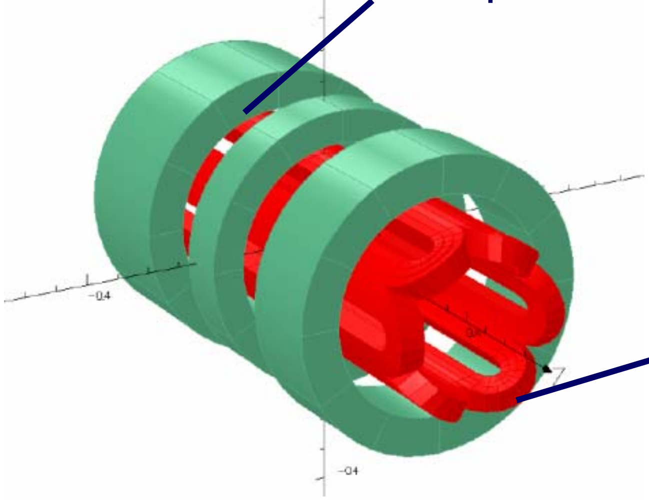
- LBNL Supercon group is developing Nb_3Sn magnets (dipoles and quadrupoles for the LHC Upgrade)

- Supercon and the 88-Inch Cyclotron ECR group developed the VENUS magnet structure

- LBNL R&D funds have supported a preliminary design effort for a Nb_3Sn ECR magnet structure for a 4^{th} Generation ECR ion source

Sextupole-in-Solenoid for 56 GHz: Clamping Structure

Maximum peak field on the coil (15.1 T, 862 A/mm^2)



There are two limits to the maximum achievable field with this design

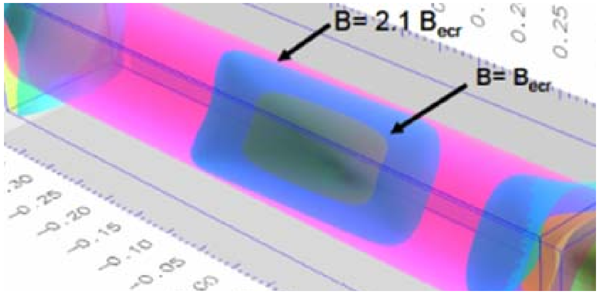
Maximum force on the end point (up to 175 MPa)

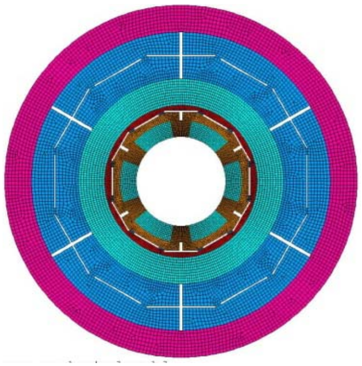
To control these forces

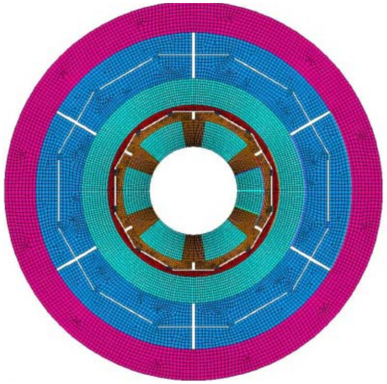
- In the end region each layer is subdivided in two blocks of conductors separated by end-spacers.
- The number of turns per block and the relative axial position of the end spacers were optimized to reduce the peak field in the end region.
- The coils are lengthen to reduce the peak field
- Shell type support structure

Magnetic Design

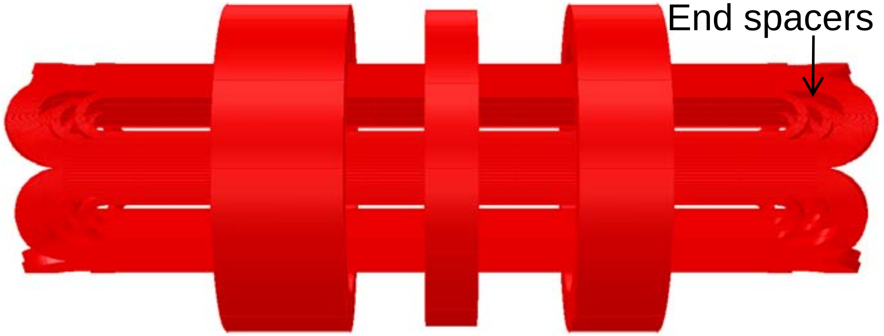
- Cos (3θ) sextupole winding, end spacers
- Keystone Rutherford cable, 15 mm wide
- Two and four layer options:



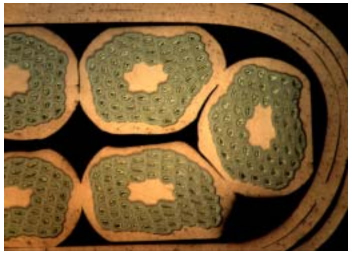


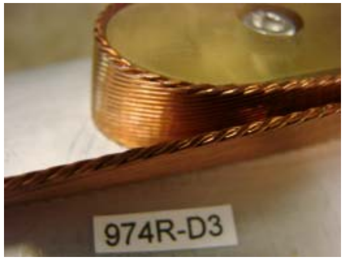


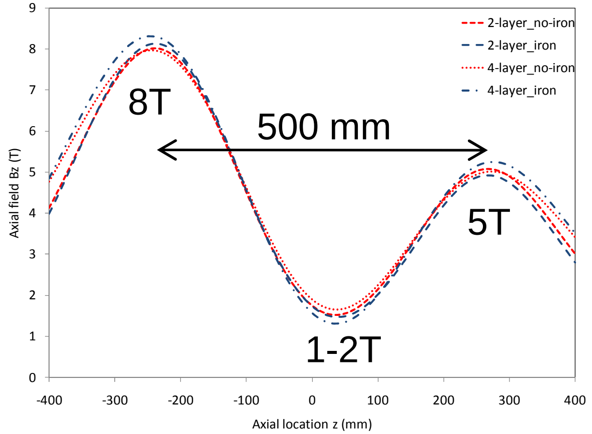
2-layer sextupole   4-layer sextupole

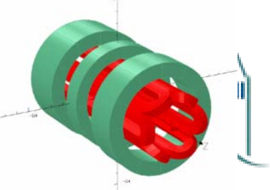


Prototype cable

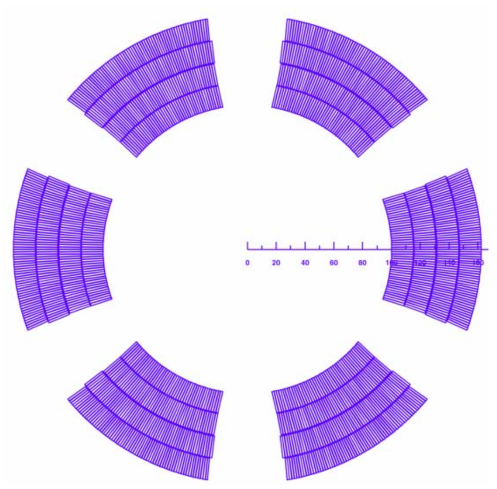








Sextupole design concepts



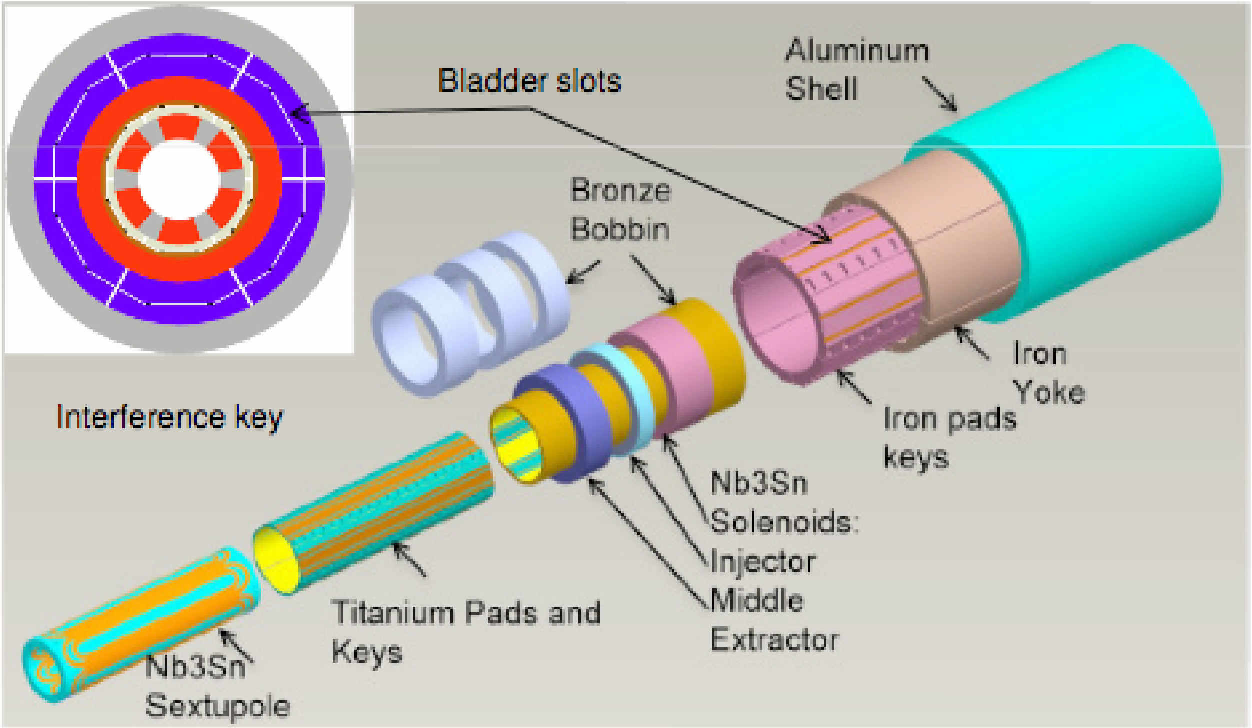
- 4-layer coils using cables (675 conductors/coil)
- The same cable design is currently used by the LARP program to develop high field quadrupoles for future LHC luminosity upgrades (peak fields 15 T)

Cable properties	
Strand Dia	0.8 mm
Fill factor	~ 33%
No strands	35
Cable	~ 15.2x1.5 mm

- The cable design requires high 8.2kA current leads, the 56 GHz cryostat will most likely require He filling during operation.

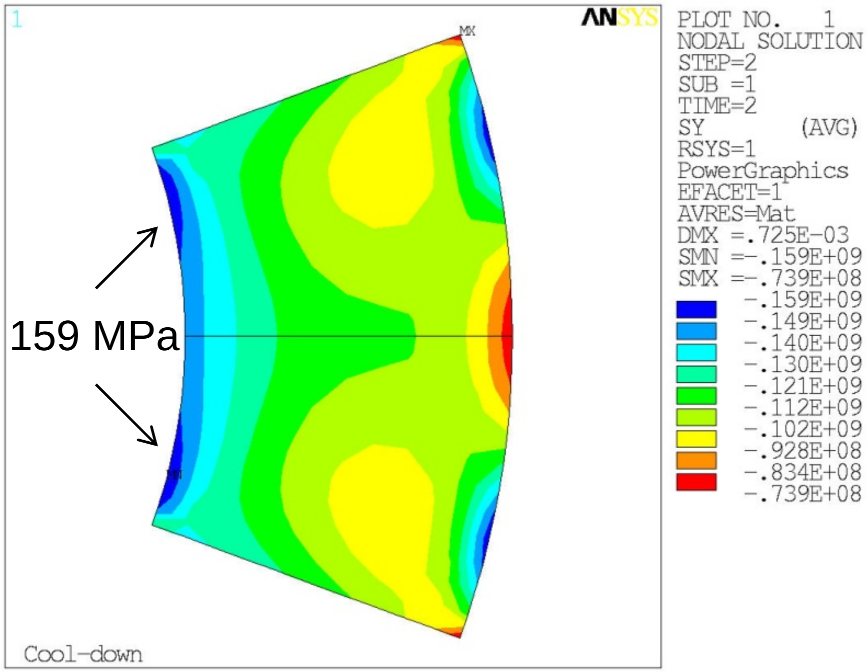
Shell-based Mechanical Structure

- Primary mechanical support is provided by a thick Aluminum shell
- Assembly (warm) pre-load by pressurized bladders and interference keys
- Pre-load increase at cool-down due to shell-yoke differential contraction
- The coils remain in compression up to the operating point



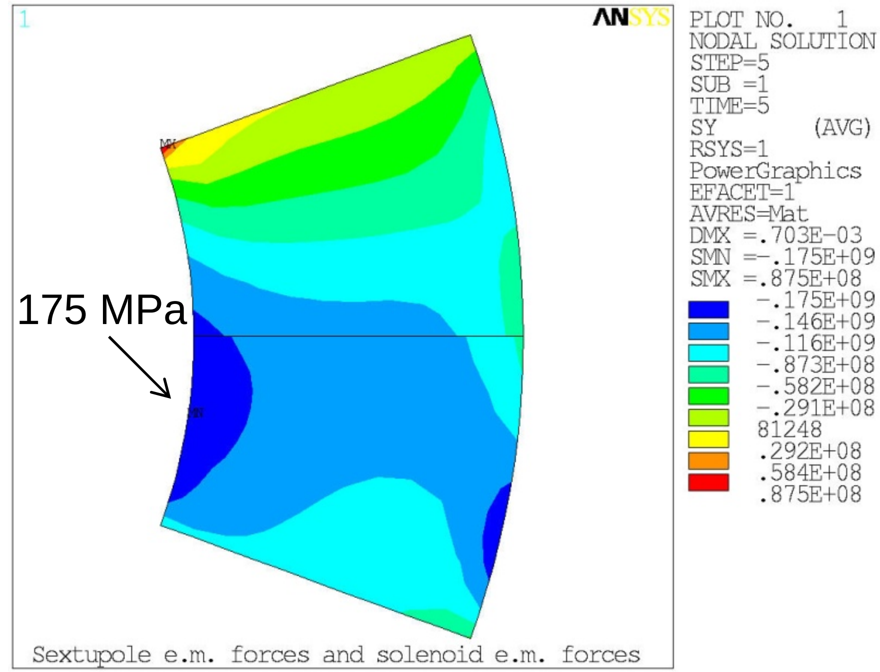
Sextupole coil stresses for 56 GHz

After cool-down



- Solenoid intercepts 50% of compressive the force
- Maximum stress 159 MPa in the “solenoid center” region

At the operating point



- Asymmetric stress profile in the “solenoid end” region
- Maximum stress 175 MPa

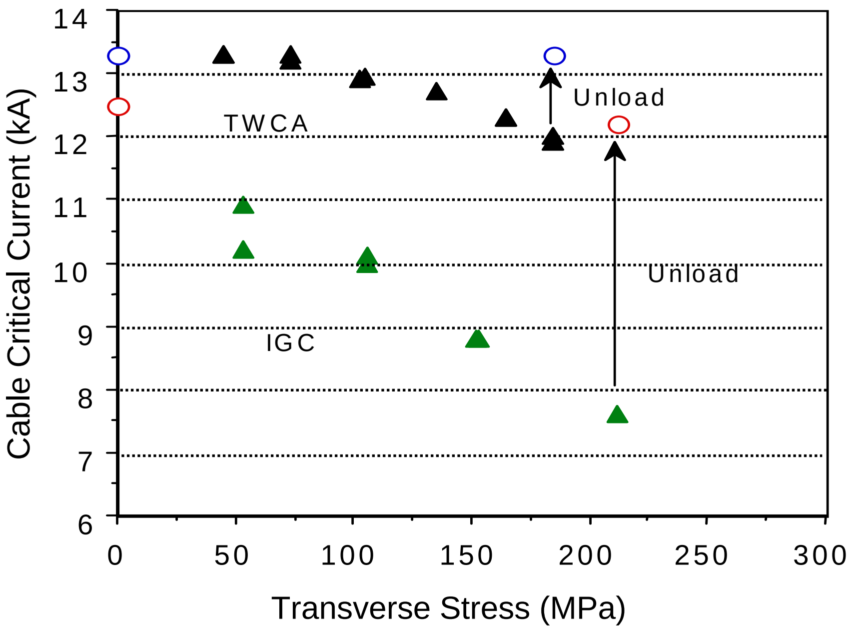
Nb_3Sn Challenges

Brittleness:

- React coils after winding
- Epoxy impregnation

Strain sensitivity:

- Mechanical design and analysis to prevent degradation under high stress

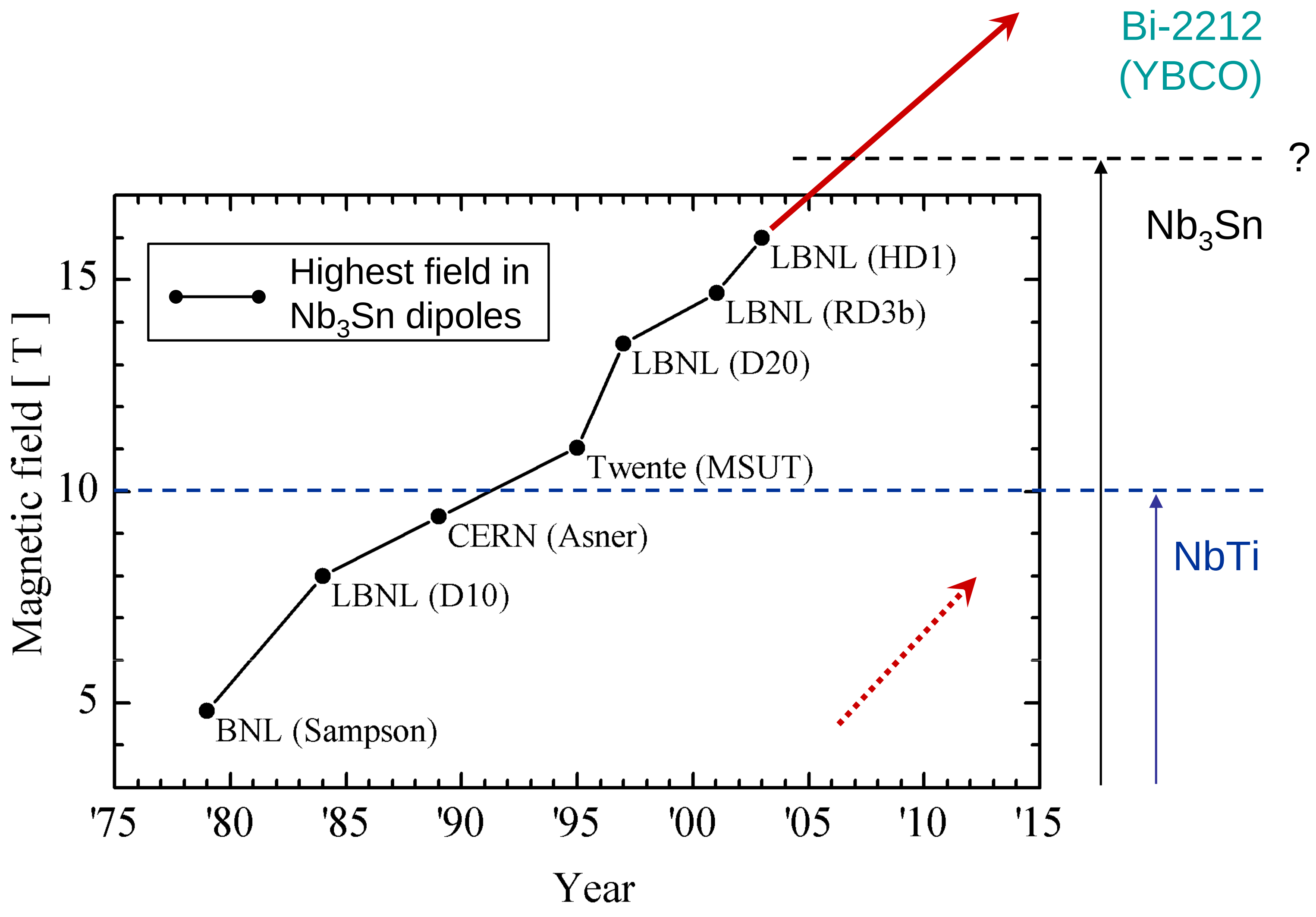


Material	NbTi	Nb_3Sn
Dipole Limit	10-11 T	16-17 T
Reaction	Ductile	~675^{0}C
Insulation	Polymide	S/E Glass
Coil parts	G-10	Stainless
Axial Strain	N/A	< 0.03 %
Transverse stress	N/A	< 200 MPa

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 ~ $n_e V$ 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 significantly more cryo-cooling power.

Progress in Maximum Field



• Why is this the time to be developing a 4th Generation ECR Ion Source?

• Heavy ion driver requirements are beyond the reach of 3rd Generation Source performance

• The R&D time needed for a new generation source is quite long. Example: VENUS (9 years from proposal to 28 GHz operation)

• High Energy Physics is driving the technology for Nb3Sn magnets—LHC upgrade—Nuclear physics can take advantage of these developments

• While the magnets are the most demanding technical challenge—The design studies show it is feasible to build an 4th Generation source at f ≥ 50 GHz

• The cost of such a source should only be about 2 or 3% of the cost of a state-of-the-art Rare Isotope Beam facility

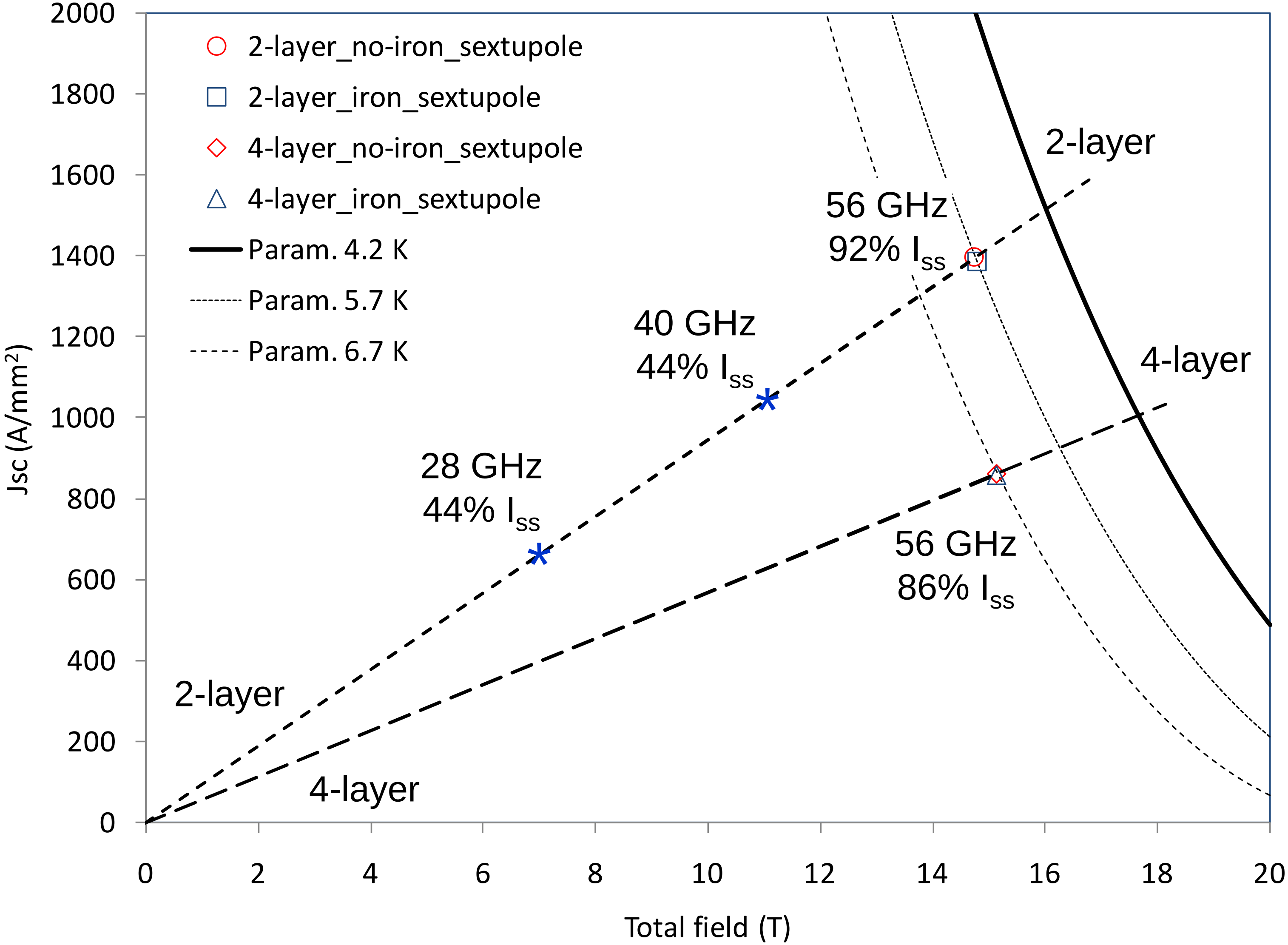
4th Generation ECR Ion Source

- 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
- Next step, construction of a prototype Nb_3Sn ECR ion source magnet structure for 56 GHz

ECRIS-56 A new twist on an old idea!
“… we propose a bolder extrapolation.
…With a 56 GHz generator, TRIPLEMAFIOS should furnish up to U^{50+} ions!”

Richard Geller, IEEE-Trans NS-23, 1976

Operational Conditions

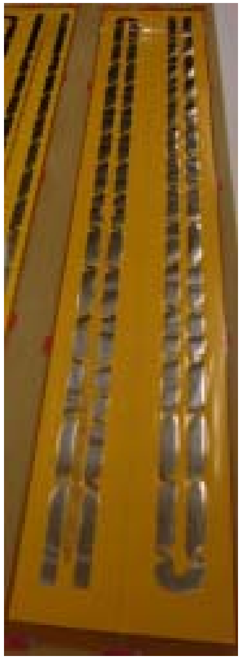


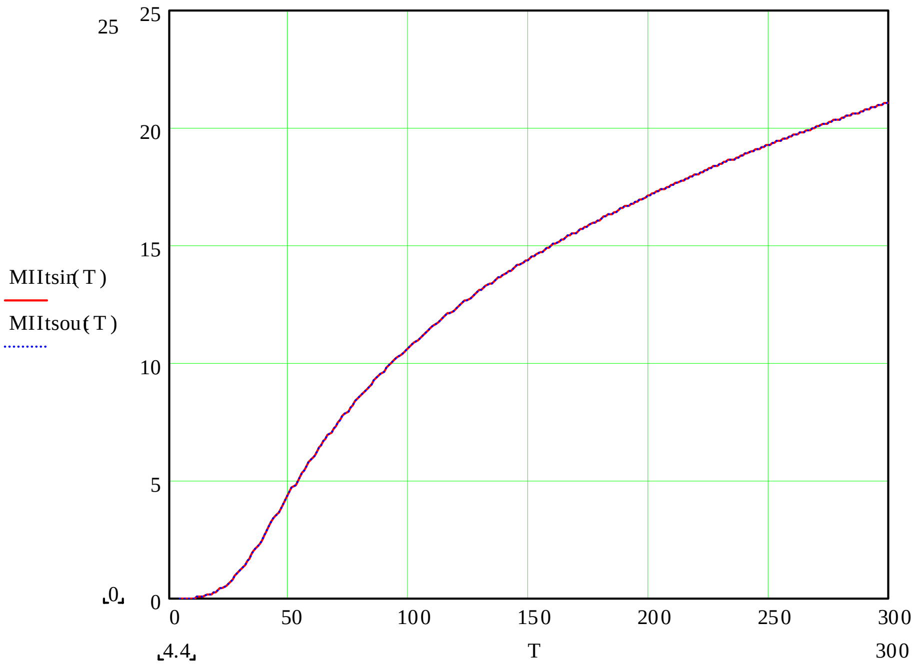
Quench Protection

Design parameters: 2-layer design: I_{op}=13.2kA; L= 33mH; U=2.9MJ
4-layer design: I_{op}= 8.2kA; L=163mH; U=5.5MJ

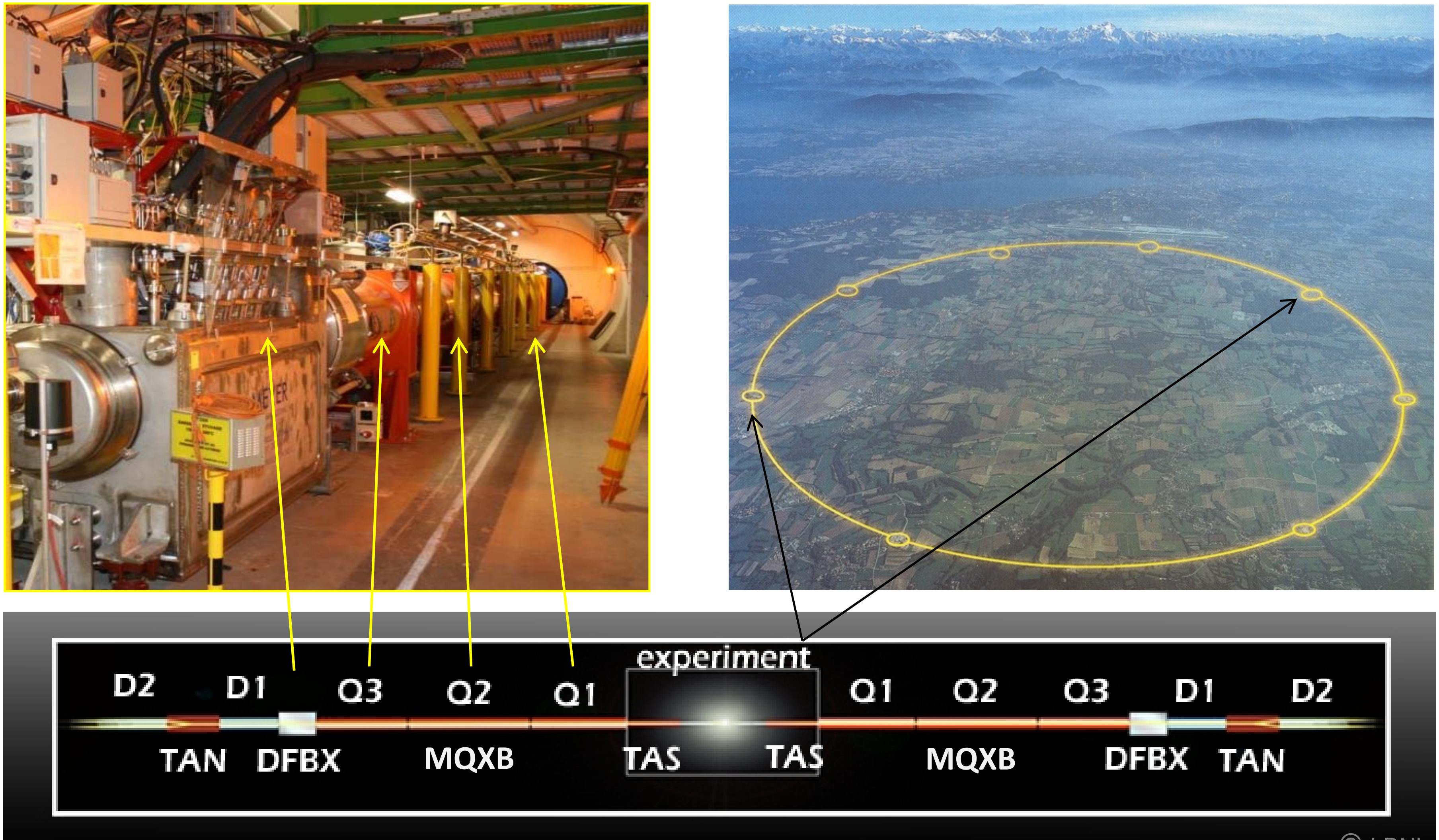
Active protection and full heater coverage is required:

- T_{max} for 100% heater coverage: 390K (2-layer); 260K (4-layer)
- T_{max} for 75% heater coverage: 430K (2-layer); 280K (4-layer)

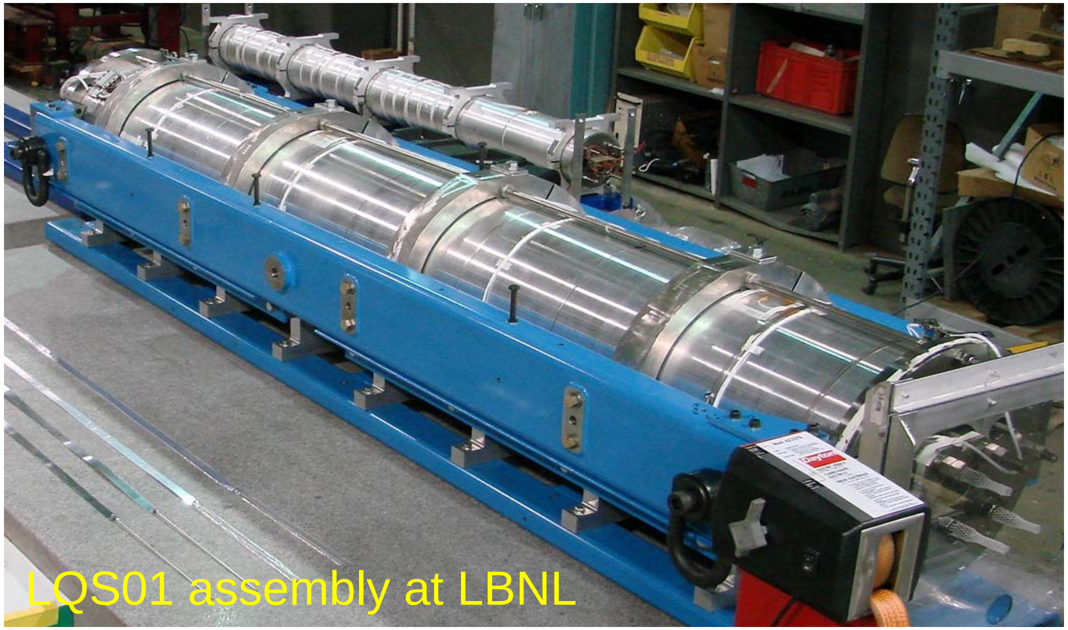


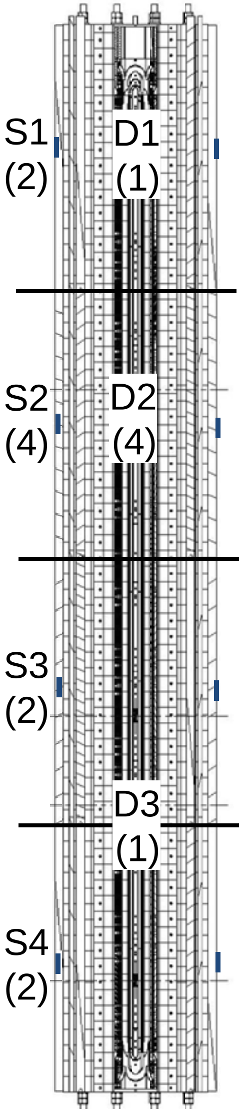
Nb_3Sn Magnets for the LHC Upgrades



Long Quadrupole Shell (LQS)

- TQ length scale-up from 1 m to 4 m
- Coil Fabrication: BNL+FNAL
- Coil and magnet instrumentation: LBNL
- Mechanical structure and assembly: LBNL
- Test: FNAL (November 2009)
- Target gradient 200 T/m



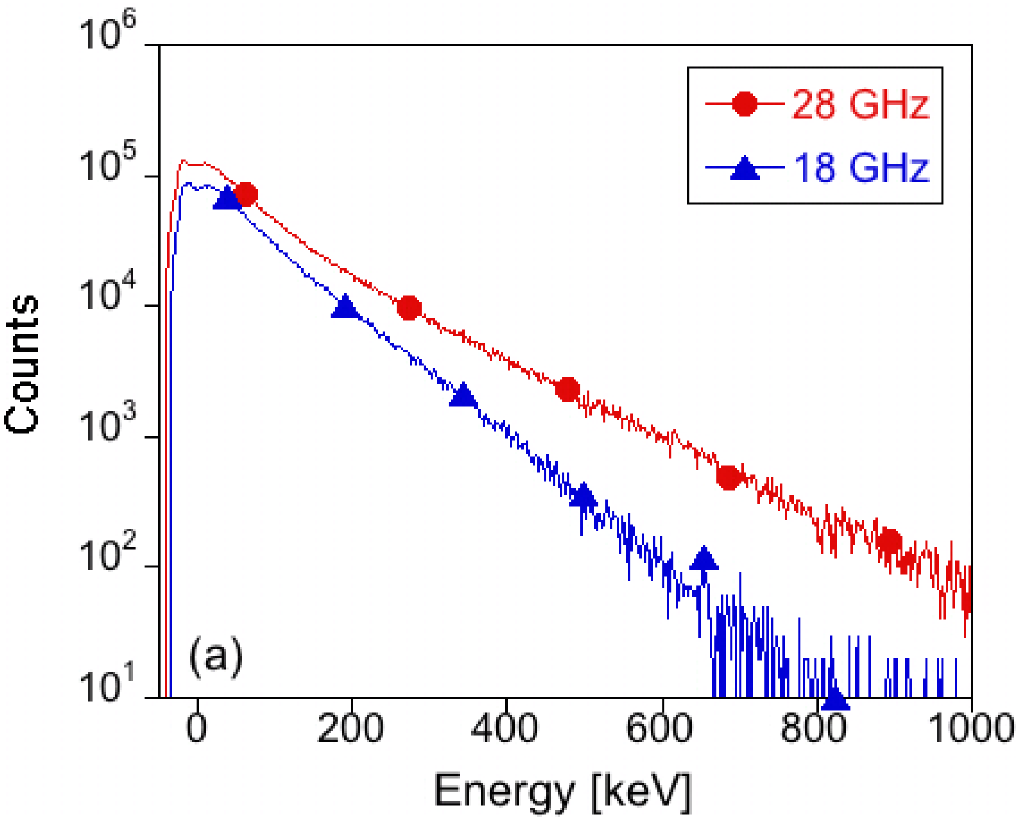


Summary

- The magnet requirements for 56 GHz operation are challenging but feasible using Nb_3Sn conductor
- Design tools and fabrication technology are available
- Sextupole-in-solenoid preferred to achieve the highest field
- Shell based support structures are suitable to provide the required pre-load and prevent conductor motion at all coil locations
- Next step: detailed engineering design and prototype fabrication
- Nb_3Sn properties also provide key advantages in the field range accessible to NbTi

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

New VENUS Plasma Chamber with X-ray Shielding and Increased Water Cooling

Bremsstrahlung heating of the cryostat
H_b = 0.1 to 0.15W/kW for Bmin/Becr=50 %
H_b=0.25 to 1.6 W/kW for Bmin/Bec=72%