Magnet considerations for ARIES IFE

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ARIES Meeting

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ARIES IFE

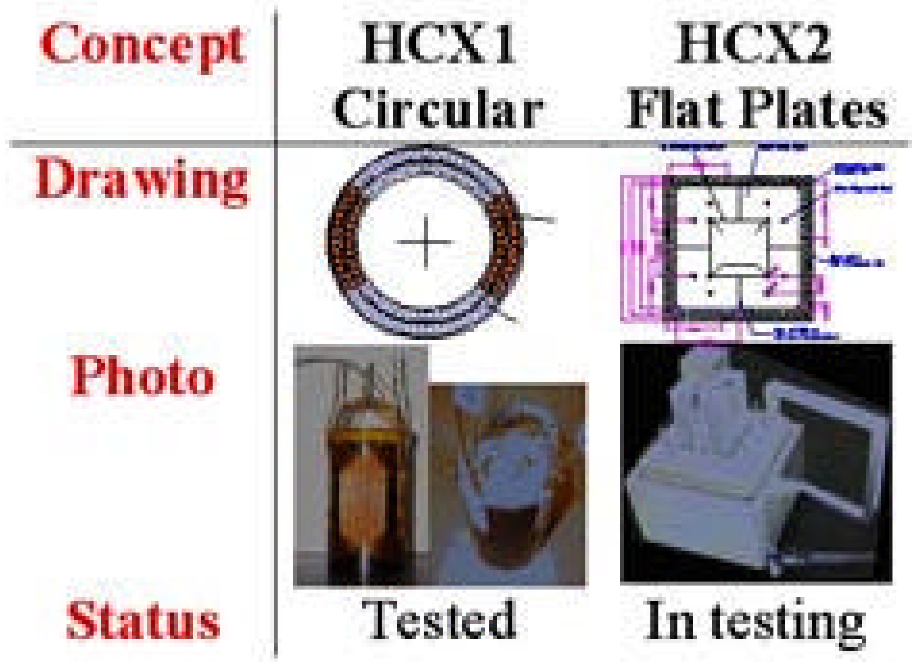
- Status of near term magnet development for IFE
  - High current transport experiment (low energy)
  - Acceleration section (medium energy acceleration)
- High temperature superconductor magnet options for IFE
- Insulation considerations

Present work in magnet community for IFE

- HCX (High Current Transport Experiment):
  - 800 m A x 1.6-2 MeV, front-end of:

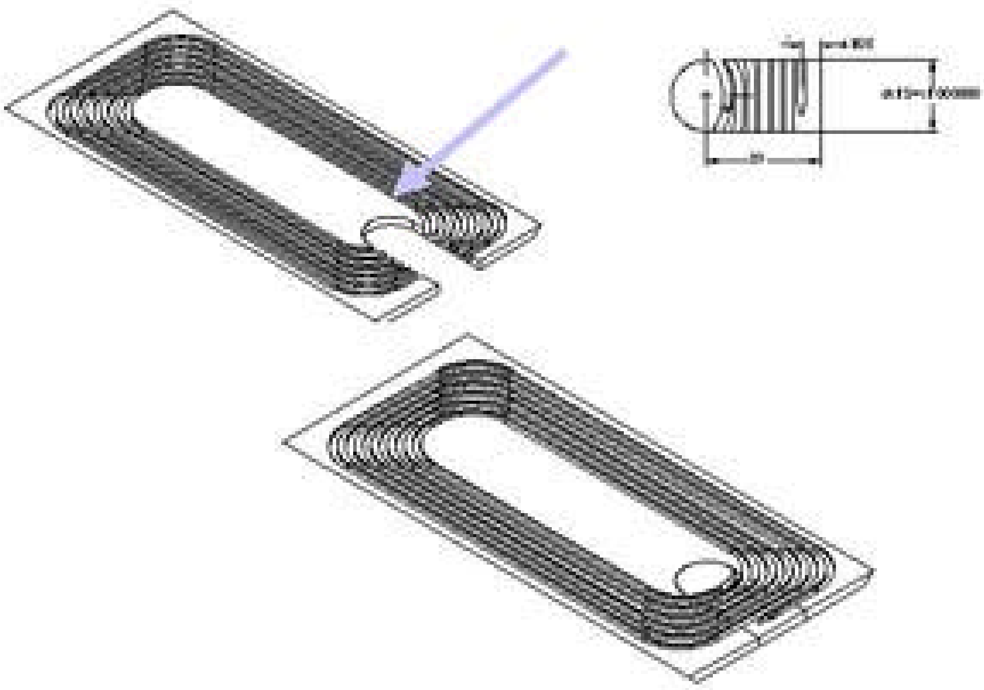
- IRE (Integrated Research Experiment):
  - 200 A x 200 MeV

    - Possible front-end of HIFSA commercial reactor:
    - 10 kA x 10 GeV)


Concept
HCX1 Circular
HCX2 Flat Plates
Drawing
Photo
Status
Tested
In testing

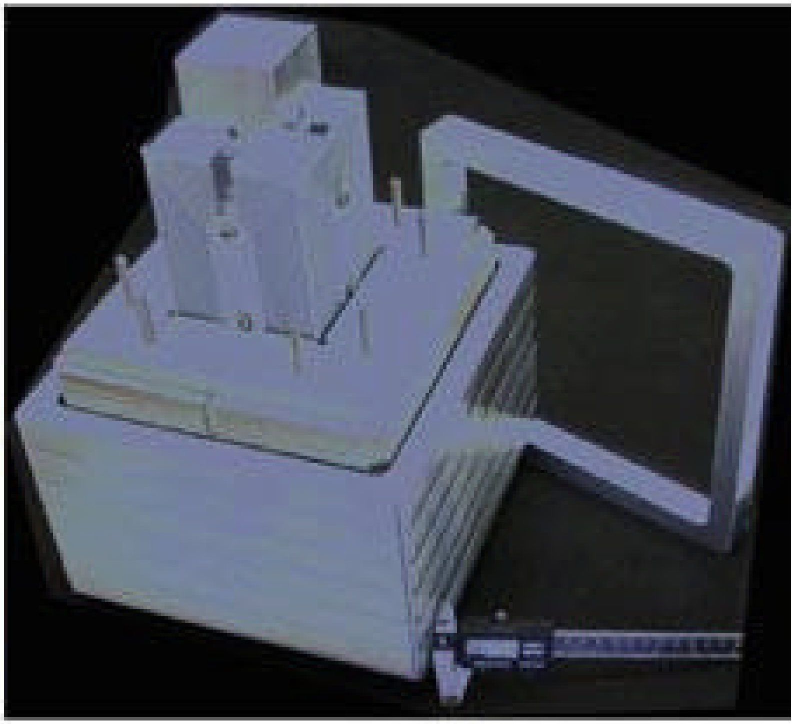
HCX cylindrical

HCX Plate racetrack

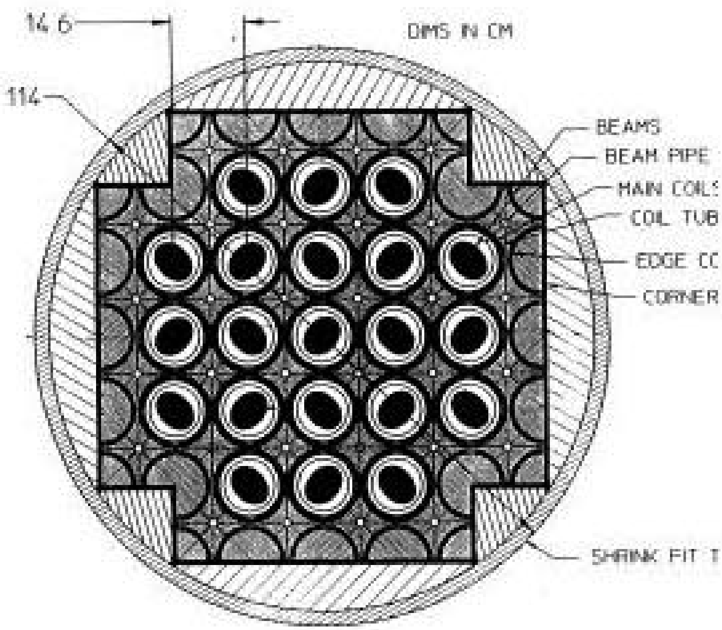


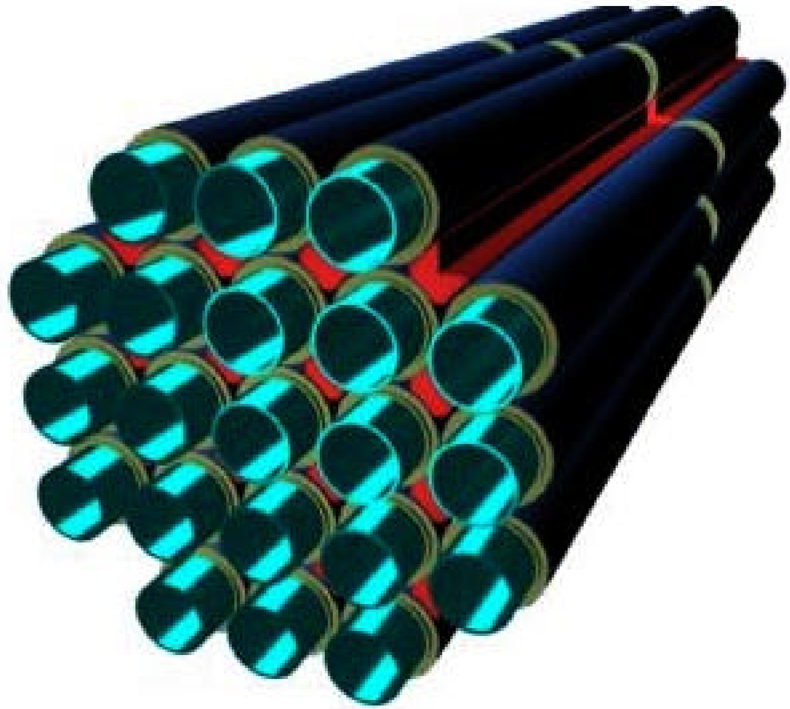
HCX

Plate racetrack

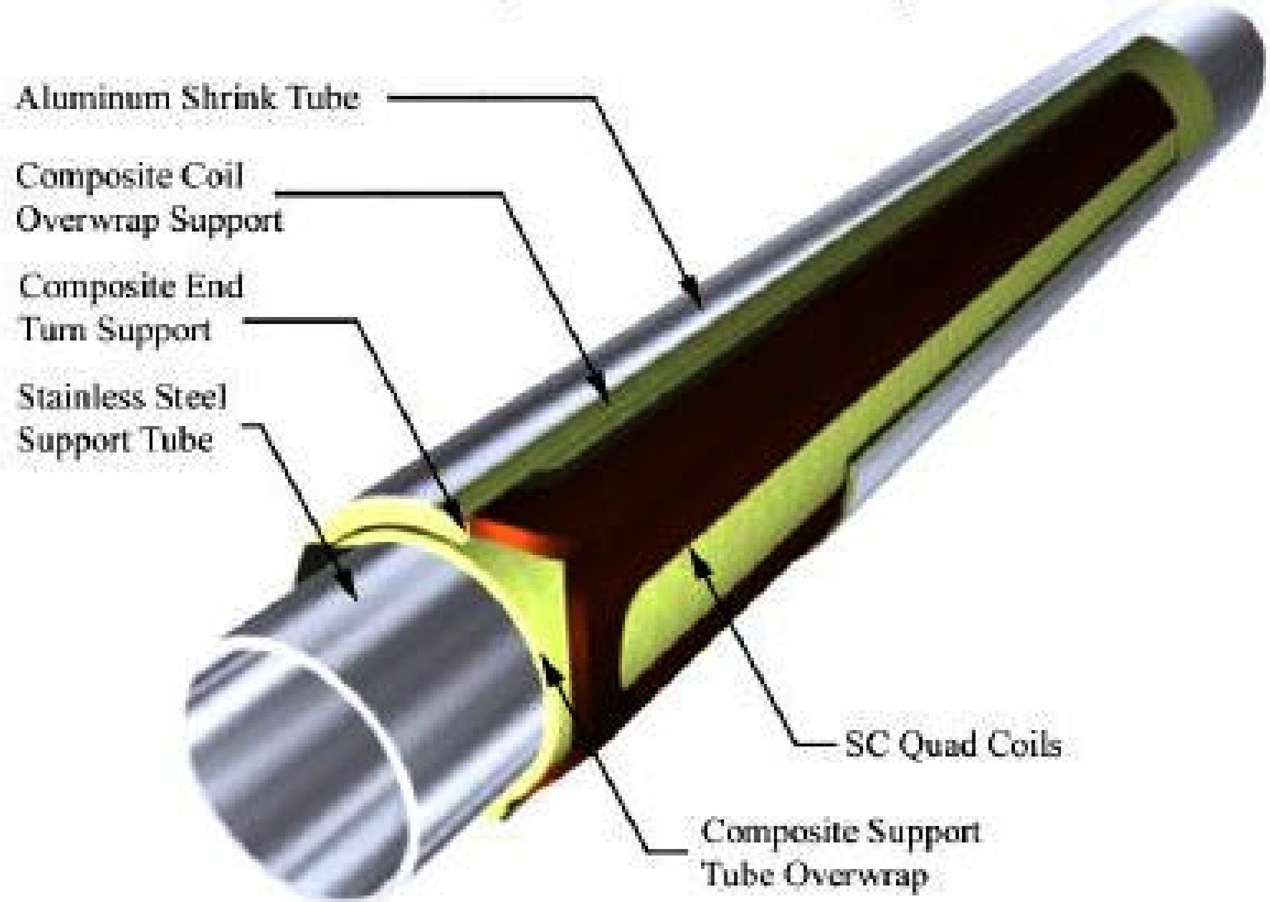


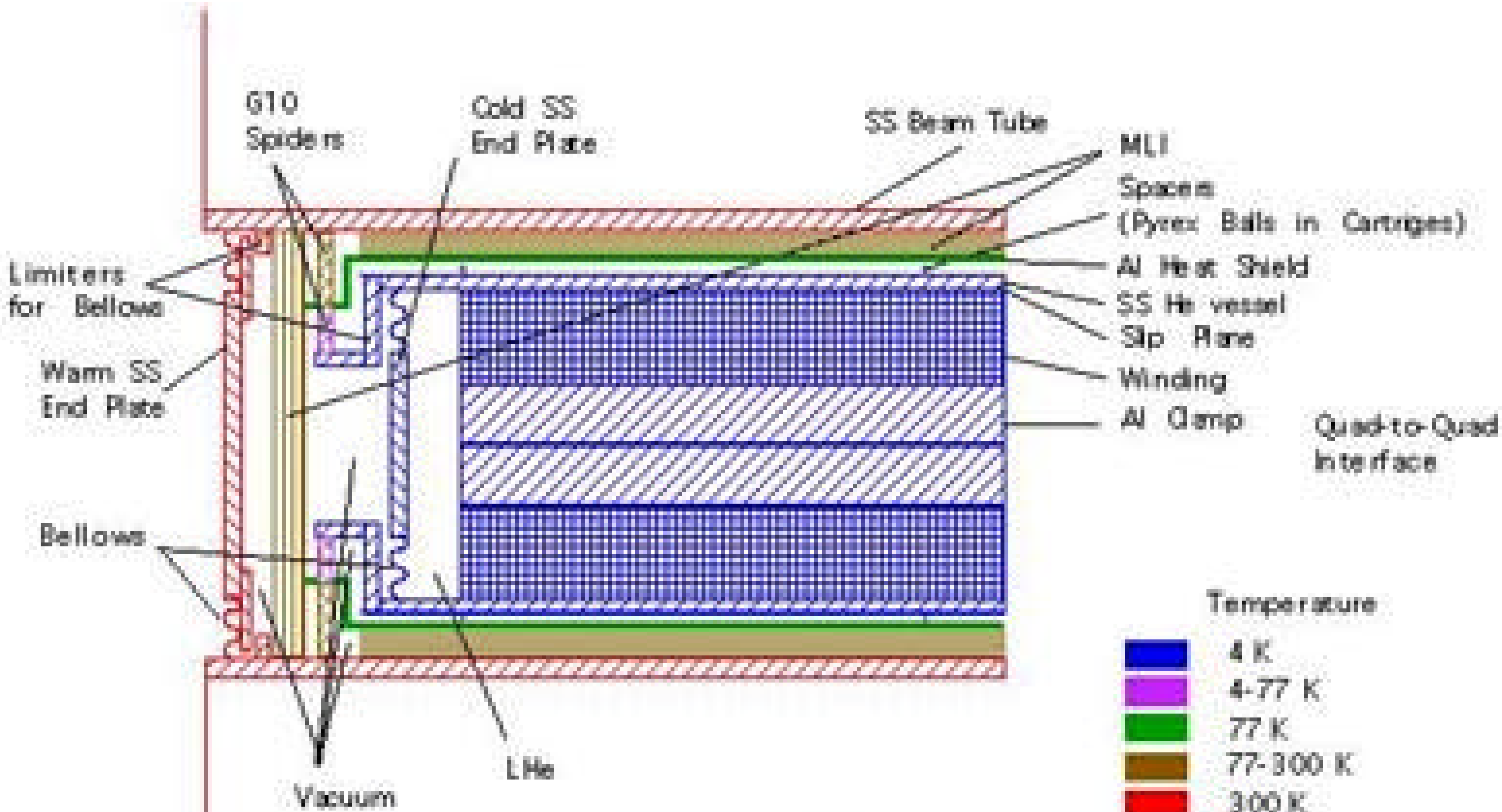
IRE design of array





Quad Coil Assembly





	P/quad	P/42quad_array	P/area
	(W)	(W)	(W/m^2)
LHe	0.12	4.95	0.27
LN2	0.85	35.75	1.93
RT	0.97	40.72	2.20

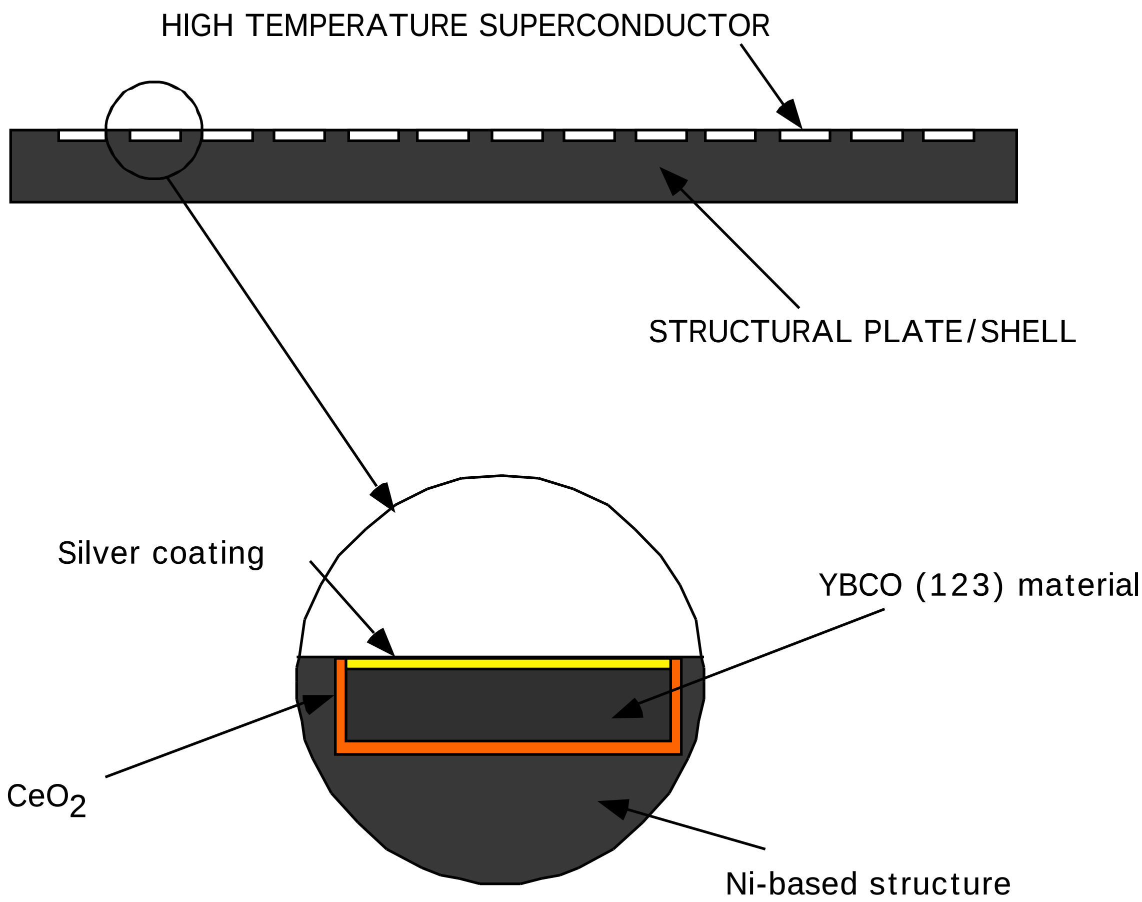
Implications of technology program for HU IFE final optics magnets

- For IFE with HI driver, cost minimization of magnet system is paramount

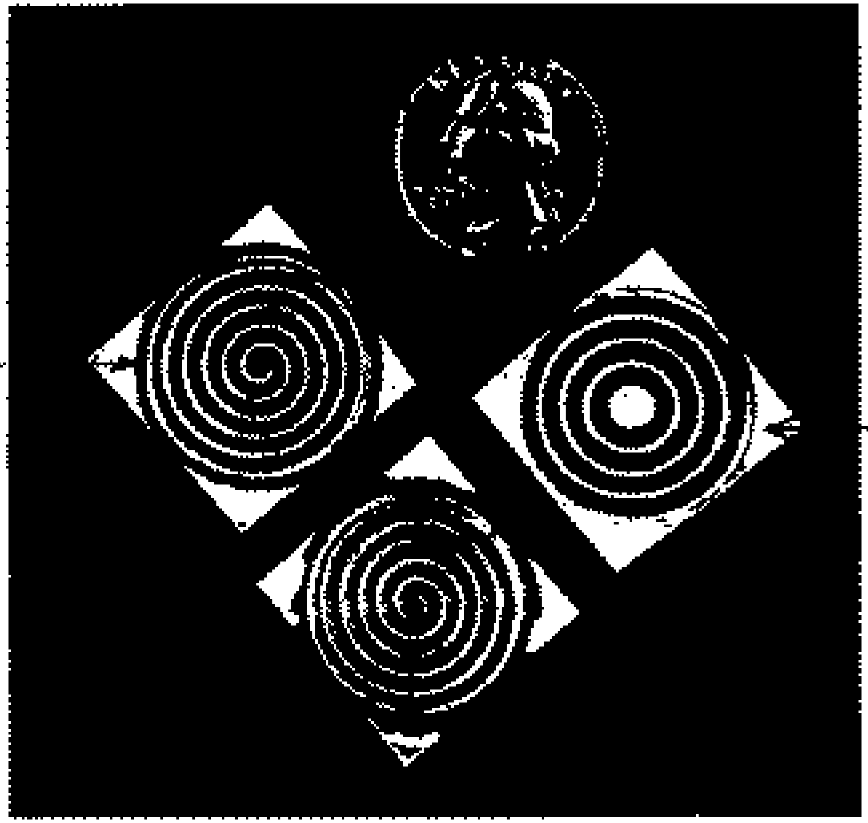
- Cost minimization of final optics by

  - Epitaxial techniques
  - High Tc to minimize quench requirements and cost of the cryogenic system (dry system)
  - Optimize structural requirements

IFE magnet construction
Epitaxial YBCO films



BSCCO 2212 layered pancakes on silver
(L. Bromberg, MIT, 1997)

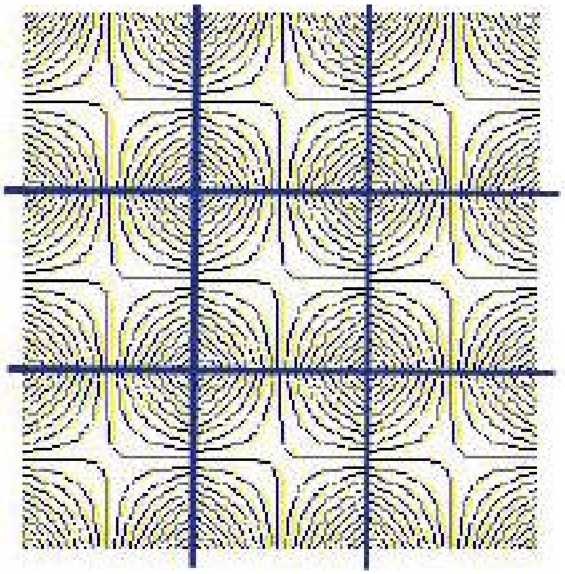


Magnet configuration options

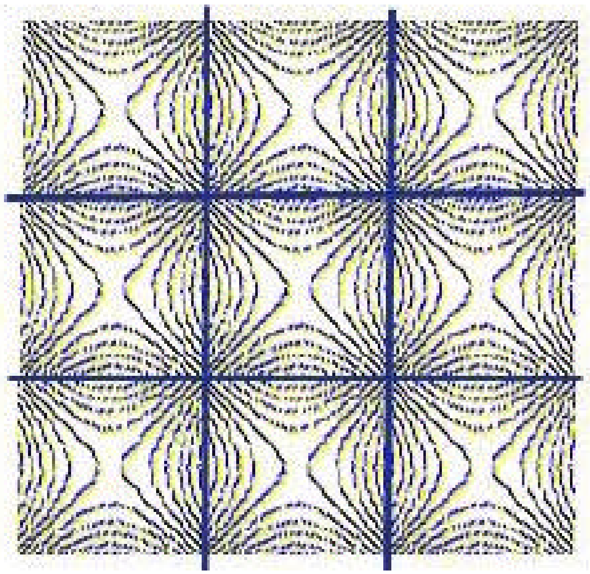
- Plate magnets, with superconductor on the surface of structural plates
- Two different arrangements are possible ($a = 0$ or $b = 0$)

$$\phi \sim r^2 (a \sin(2\theta) + b \cos(2\theta))$$

cos (2θ)



sin (2θ)



Current distribution in plate quad arrays

- The current density for the two cases is different
  - For the sin (2θ):
    - $|K_{wall}| = 4\,A\,x\,/\mu_o$ (on the x-wall), $-a < x < a$
    - $|K_{wall}| = 4\,A\,y\,/\mu_o$ (on the y-wall), $-a < y < a$
  - For the cos (2θ):
    - $|K_{wall}| = 4\,A\,a\,/\mu_o$
- In both cases, the magnetic field is:

$$|\,B\,| = 2\,A\;r$$

  - and the gradient is

$$|\,B\,|' = 2\,A$$

Current distribution in quad arrays

- Superconductor is deposited directly on structural plates
- Epitaxial techniques can be used to achieve desired current density for optimal quadrupole field generation
  - Deposition of superconducting material directly on structural substrate minimized motion of SC and heat generation
  - Insulation is achieved by depositing thin insulating layer between superconductor and substrate
    - Ce_2O is presently used in the manufacturing of YBCO tapes
      - For sin (2θ) arrays, SC is deposited with uneven spacing to simulate $K \sim x$ distribution
      - For cos (2θ) arrays, SC is deposited uniformly

Superconductor implications

- YBCO material is very sensitive to field orientation
  - preferred orientation of field is parallel to YBCO tape, (**B** || ab)
  - Preliminary critical current density: 10^{10} A/m^2

  - For sin (2θ) arrays, field is perpendicular to SC
  - For cos (2θ) arrays, field is parallel to SC

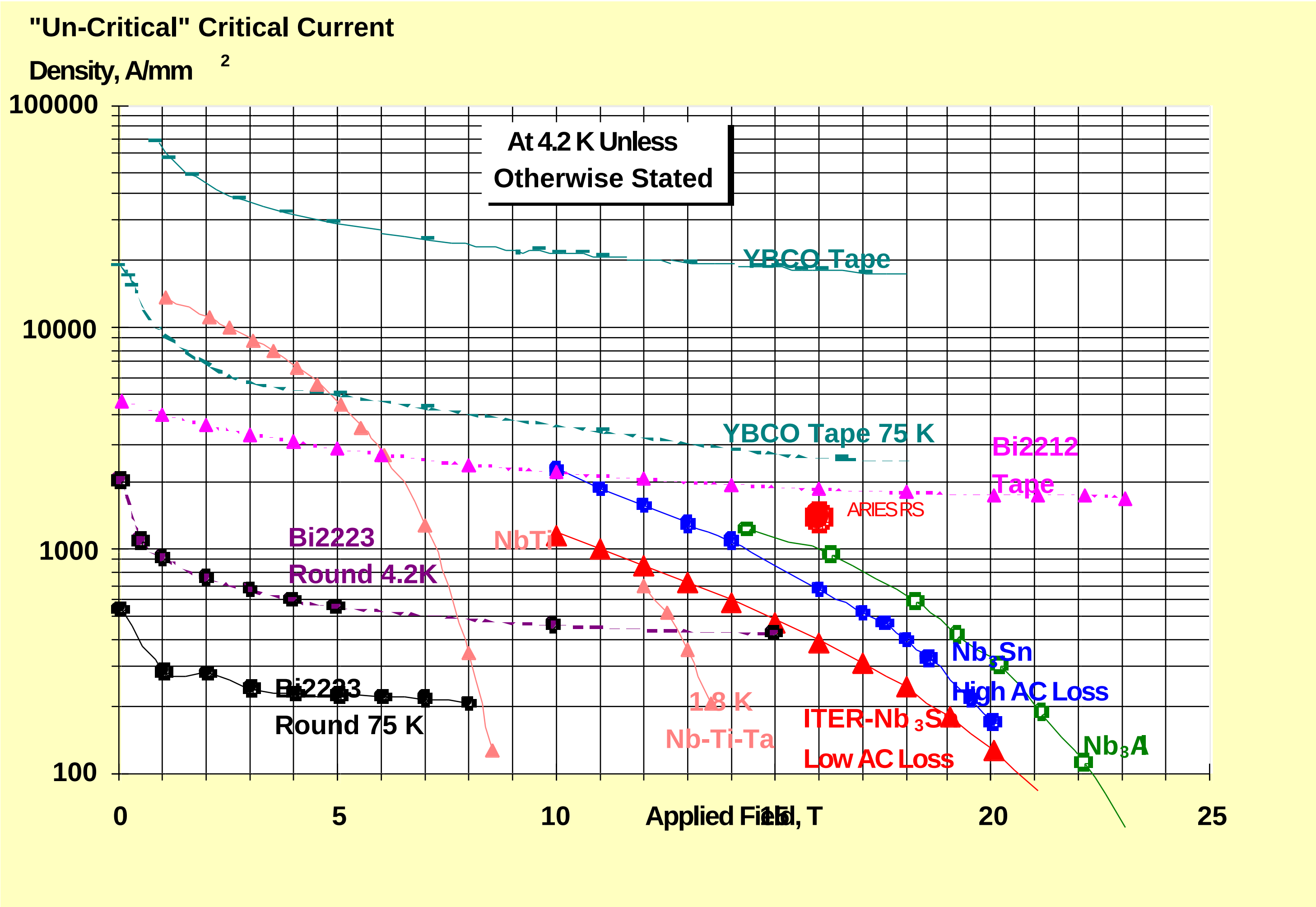
  - sin (2θ) requires non-uniform current density, which means that for similar average current density, peak is higher (for comparable thicknesses, current density is higher)
  - cos (2θ) requires uniform current density

Forces in Epitaxial quad arrays

- Because of symmetry, forces are mostly along the substrate (I.e., tension or compression, with almost no shear)
- For both sin (2θ) and cos (2θ) arrays:
  - $F = 4 A^2 a^3 / \mu_o$
  - $\sigma = F/t$ (t : thickness of structural plate)

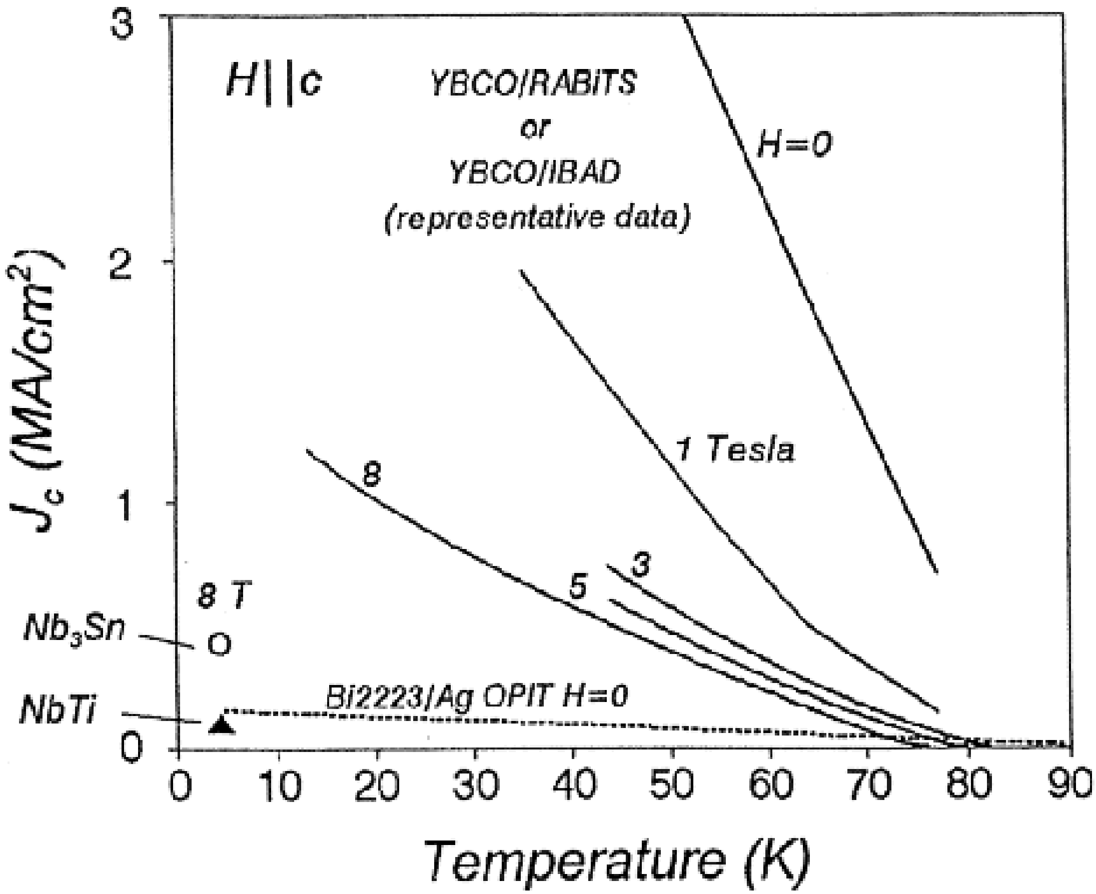
- To limit strain in SC to 0.2% (comparable to LTS), the maximum tensile stress in structure is ~500 MPa

HTS Superconductor options and comparison with LTS (YBCO tape at 4 K and at 75 K)



Courtesy of Lee, UW Madison

YBCO Current density with field in the "bad" direction (B||c) as a function of temperature



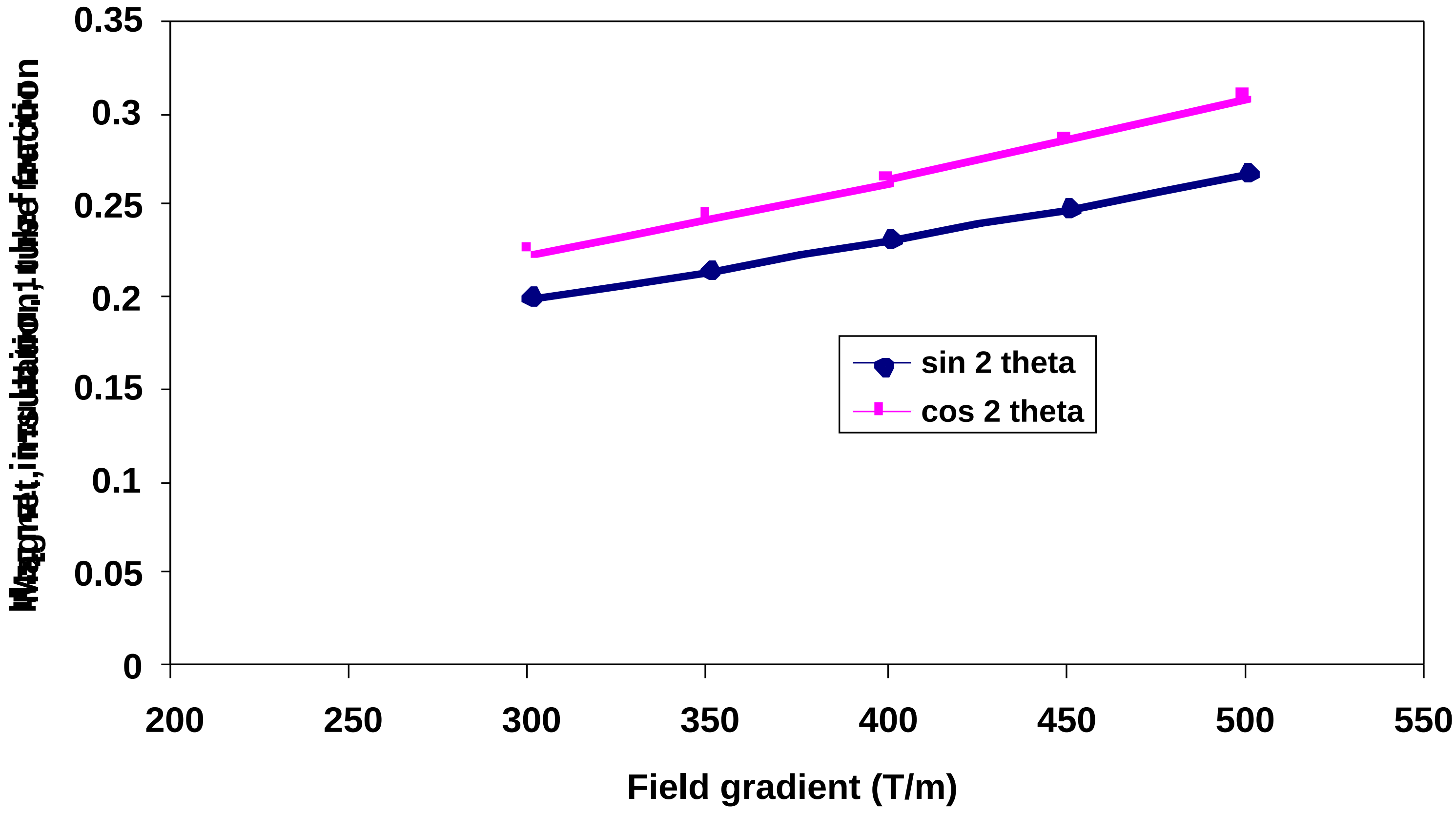
Typical Quad magnet design

Structure stress	Pa	5.00E+08
Current density	A/m^2	1.00E+10
Thickness of beam tube	m	1.00E-03
Thickness of MLI	m	0.002
Bmax	T	6
a	m	0.02
Field gradient	T/m	300
A	T/m	150
Structure thickness	mm	1.15E-03
Superconductor		
Current density (K)		
sin 2 theta	A/m	9.55E+06
cos 2 theta	A/m	1.91E+07
Thickness for 1.e6 A/cm^2		
sin 2 theta	m	9.55E-04
cos 2 theta	m	1.91E-03
Fraction of cell for magnet, insulation, beam tube		
sin 2 theta		0.202521
cos 2 theta		0.226394
Current, cos 2 theta		
number of turns per layer		10
number of plates, 10 microns YBCO		191
Current per turn	A	400
Current, sin 2 theta		
number of turns per layer		10
number of plates, 10 microns YBCO		95
Current per turn	A	400

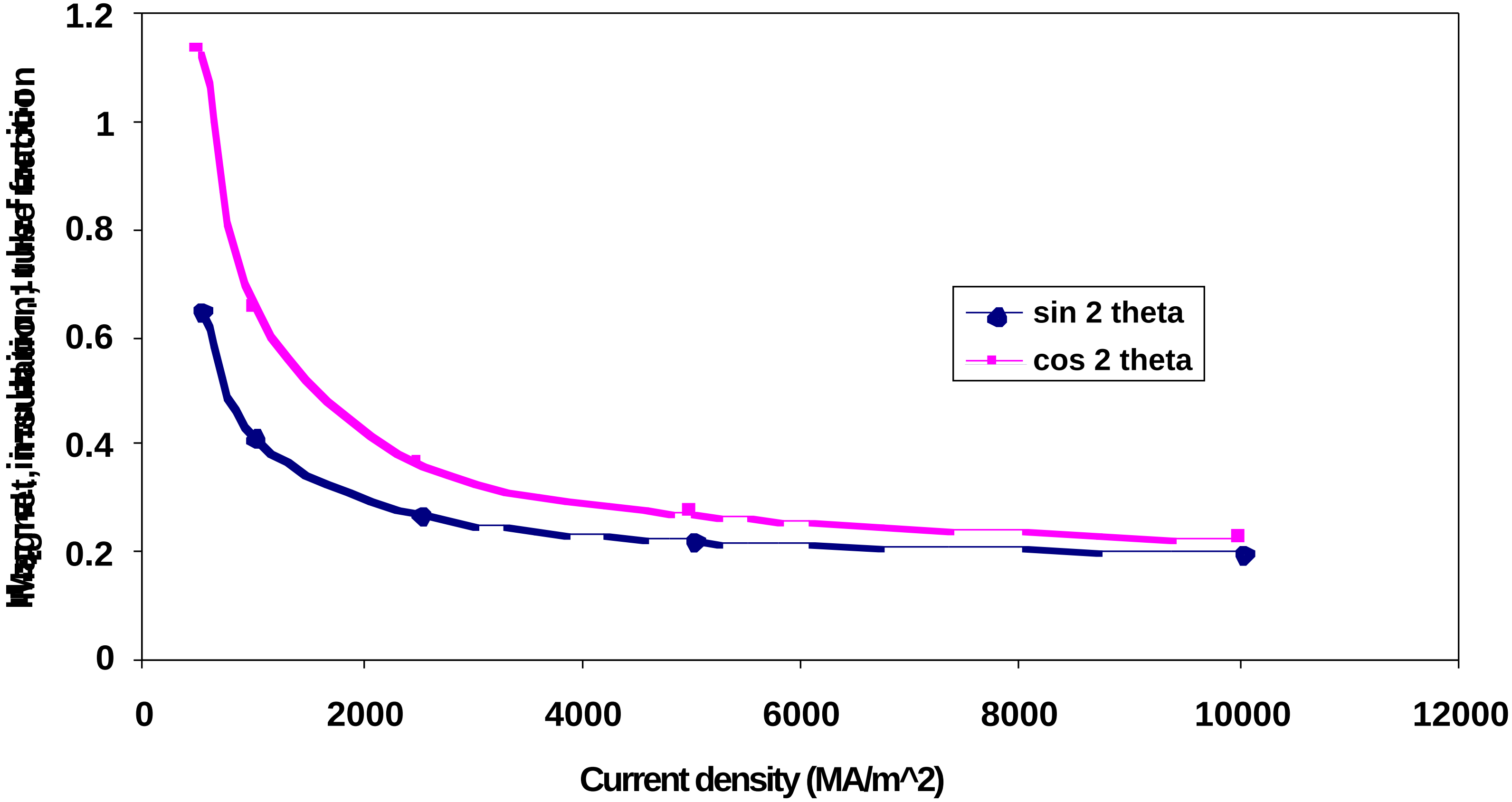
YBCO for IFE magnets

- Current density can be as high as 10^{10} A/m^2 (1 MA/cm^2) for fields as high as 9 T, a temperatures between 20 K and 77 K
  - At 9T (B || c), T < 20K
- Temperatures between 4 K and 77 K can be achieved by using dry system (no liquid coolant)
- Cooling is provided by conduction cooling to a cryocooler head.

Fraction of cell not allocated to beam (linear ratio, not area ratio)



Fraction of cell not allocated to beam
Field gradient = 300 T/m



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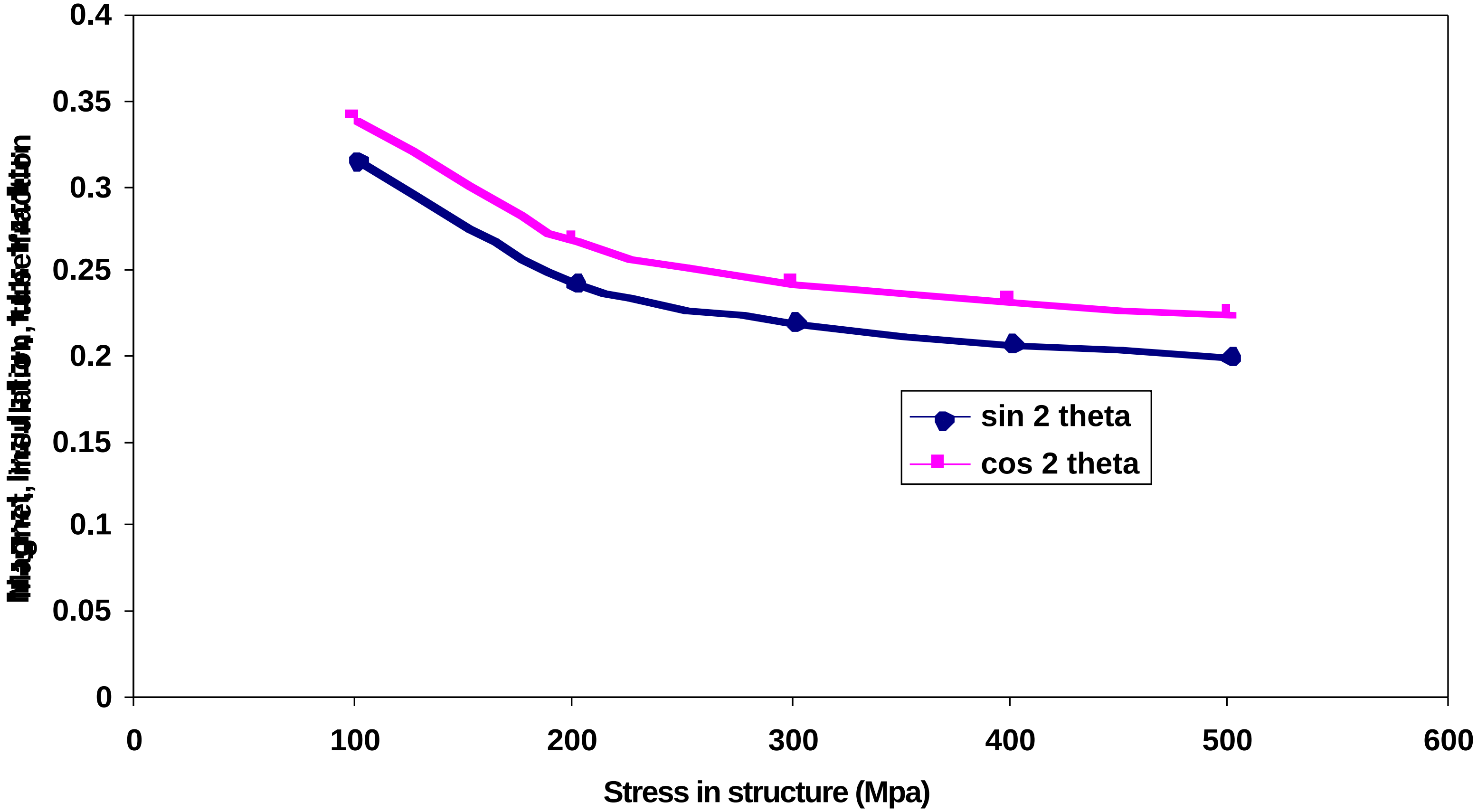
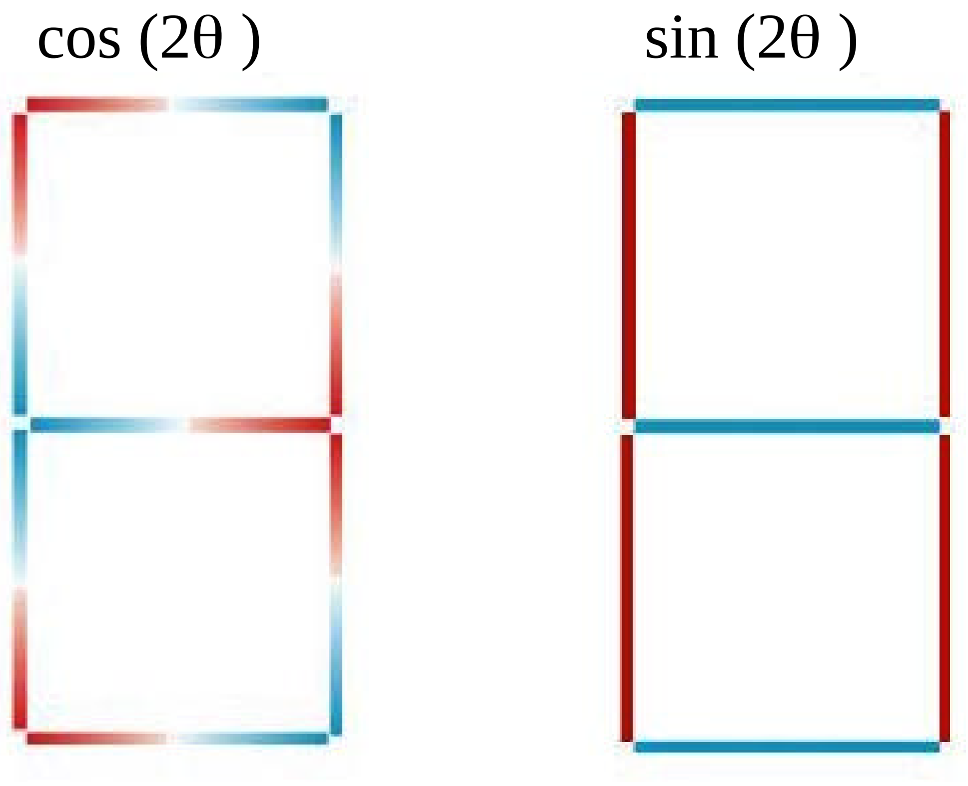
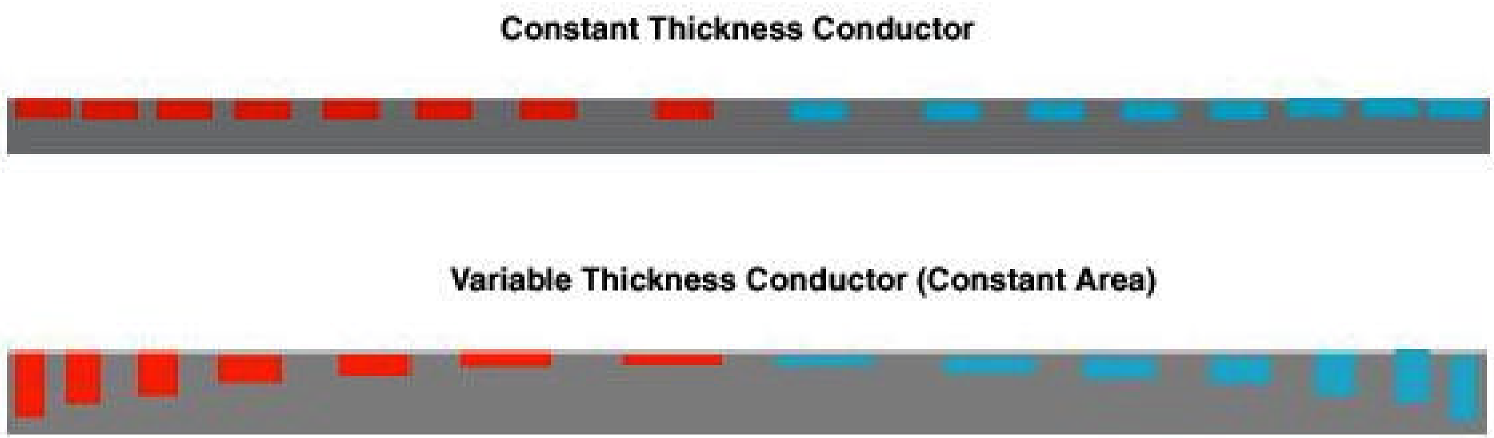


Current density
sin (2θ) and cos (2θ) quad arrays

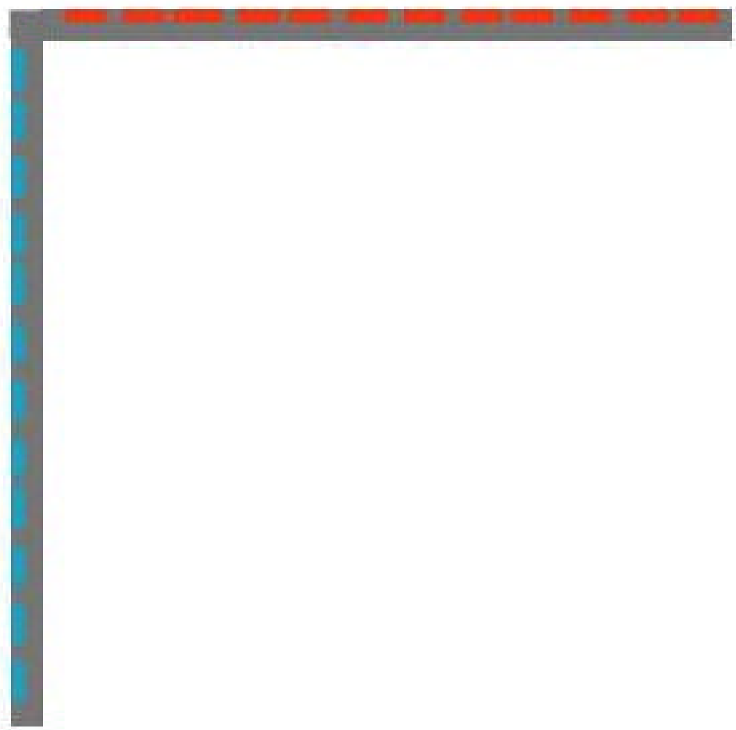


cos (2 θ) plate design options



sin (2θ) magnet section

(not planar due to current return!)

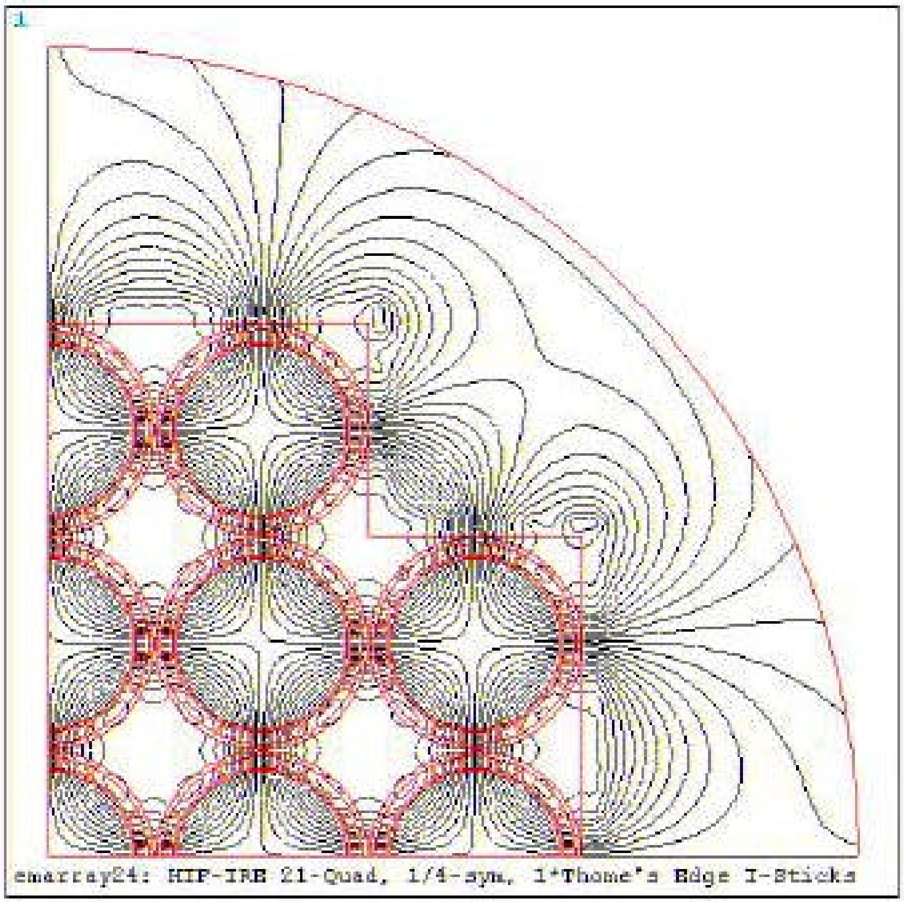


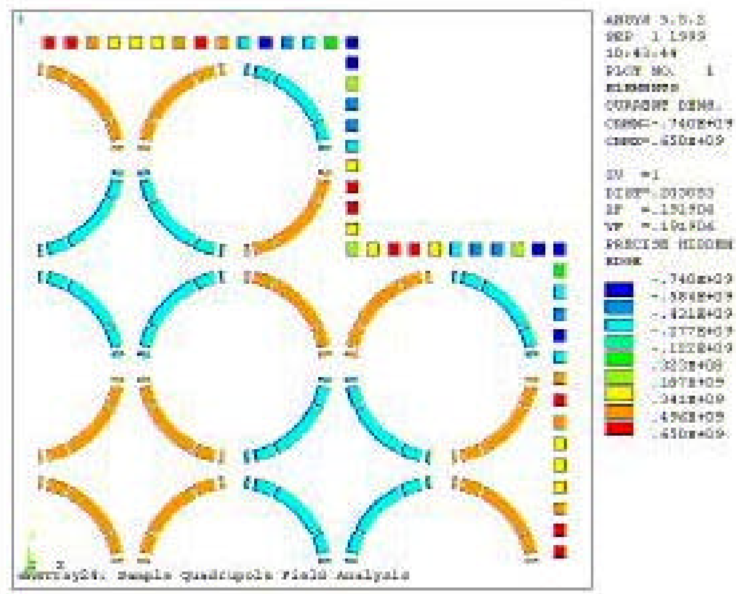
Magnet quench

- Energy in magnet is small (for both sin 2 theta and cos 2 theta):
  $E = 16 A^2 a^4 L / 3 \mu_o$ (L is the quad length)
- For typical magnets ($L \sim 1$ m), E ~ 20 kJ/quad
- If 100 quads are in parallel, 2 MJ per supply
- If single power supply, @400 A and 5 kV discharge, $\tau_{dump} \sim 1$ s
  - However, very high current density, magnet will self destroy at this very high current density
- Quench protection for HTS: passive, quench prevention by large thermal mass to avoid flux jumping, large heat release.

Edge conditions of the quad array

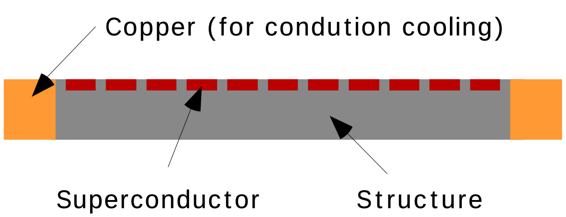
Current density of outermost quad array boundary modified to control field profile

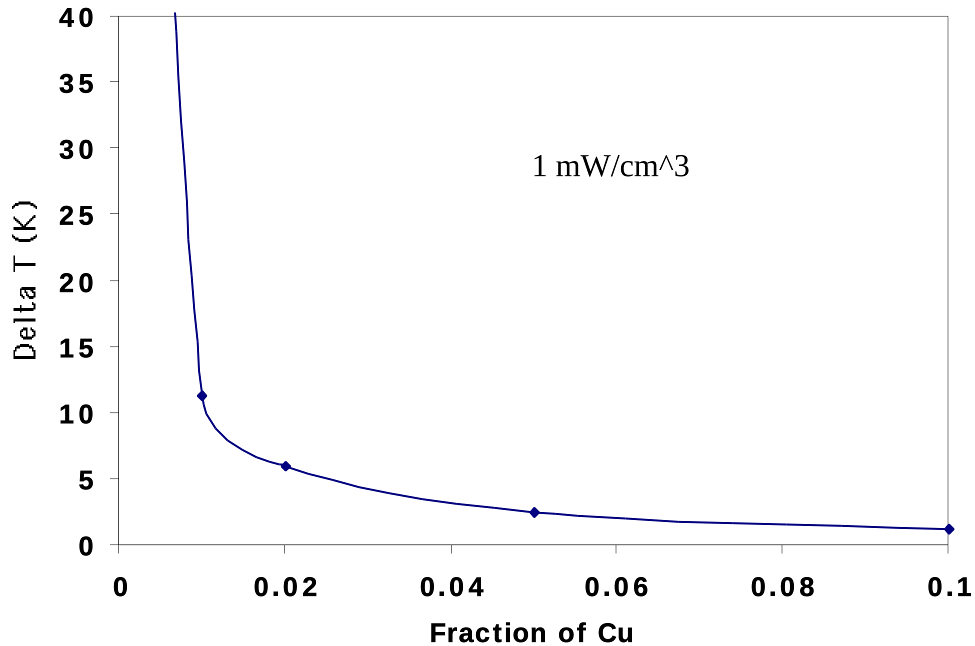




Coil Cooling

- Assuming that quads are only cooled at each end
  - If only Ni-based material, large temperature raise to midplane of quad ($\Delta T \sim 100$ K)
  - Cu placed in parallel to structural plates (bonded at the structural plate edges, to prevent warping)





Cryogenic advantages

- Due to good design (as in the IRE design shown above), operation at 77 K only slightly reduces the required thermal insulation gap
  - Little radiation from 77 K to 4 K
  - Support can be long without implication to radial build
  - Required distance determined by requirement of no contact between 4 K and 77 K
- Therefore, the use of HTS is not driven by cryogenic requirements.
- Cryogenic requirements substantially reduced by operation at ~ 77 K (by about a factor of 8, scaling from IRE design)
- Operation of HTS below 77 K by the use of cryocooler (dry operation)

Magnet assembly tolerance

- Epitaxial techniques allows the manufacturing of the YBCO plates with high precision (~ μm)
- Plates can be assembled to tolerances of 5 mils (0.12 mm)
- Plate supports can be assembled with 10 mil accuracy
- Magnet racetrack can be placed with 10 mils accuracy (0.25 mm) along the entire way of the plate (~ 1 m across, 1 m apart).

Advantages of plate quad arrays

- The forces are only in tension/compression in the plates
  - There are no loads that are perpendicular to the plates that need to be reacted in shear.
  - Very important consideration for insulator

- These forces are easy to react, and do not require the need of large inter-quad structure
  - The only structure is needed to control off-normal loads, gravity and for accurate positioning of the plates.

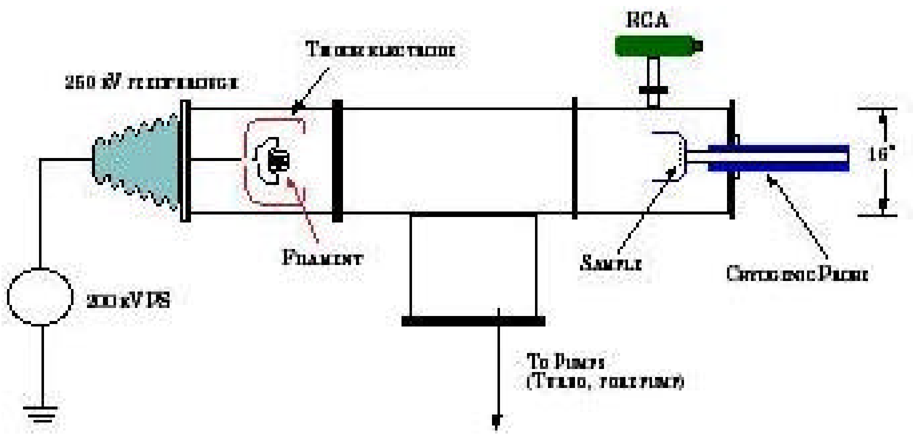
- The field is a perfect quadrupole field, with total absence (in the ideal conditions) of higher order components
  - Errors due to
    - misalignment
    - errors in plate manufacture
    - end-fields

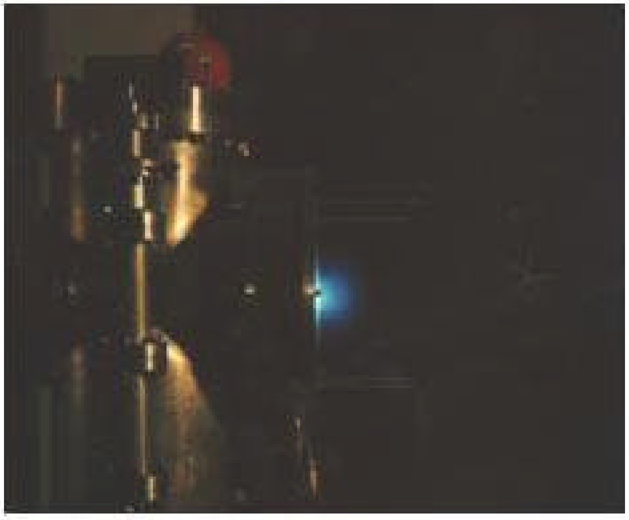
- Possibility for cheap manufacturing!

Irradiation considerations

- Final focusing magnets will experience high dose:
  - 40 MGray/year from γ's, 8 MGray/year from neutrons (Latkowski)
  - Very high peaking, ~10^5 – 10^6 (Sawan, 1981)
  - Very high instantaneous dose rate: 10^5 – 10^6 Gray/s

Irradiation testing of insulators at M.I.T.





- Irradiation damage to organics mainly due to radiochemistry, driven mainly by electrons
- Radiation facility consisting of:
  - E-beam unit (200 kV, 4 mA)
  - Capable of large dose rates (up to Grad/s)
  - Large sample capability (5cm x 5 cm)
  - Capable of cryogenic testing

Summary

- Design options for plate magnets for IFE quad final optics have been investigated
  - Use High temperature superconductor (YBCO)
  - sin (2θ) option requires angle elements (non-planar)
  - Epitaxial technique on flat plates, angle elements
  - Large number of elements, easily manufactured.

- Design algorithms were developed
  - Only for high temperature superconductor
  - Comparison to LTS in the near future

- Irradiation effect need to be determined
  - Lack of large shear between elements allows the possibility of all inorganic insulation
  - Very large dose rates