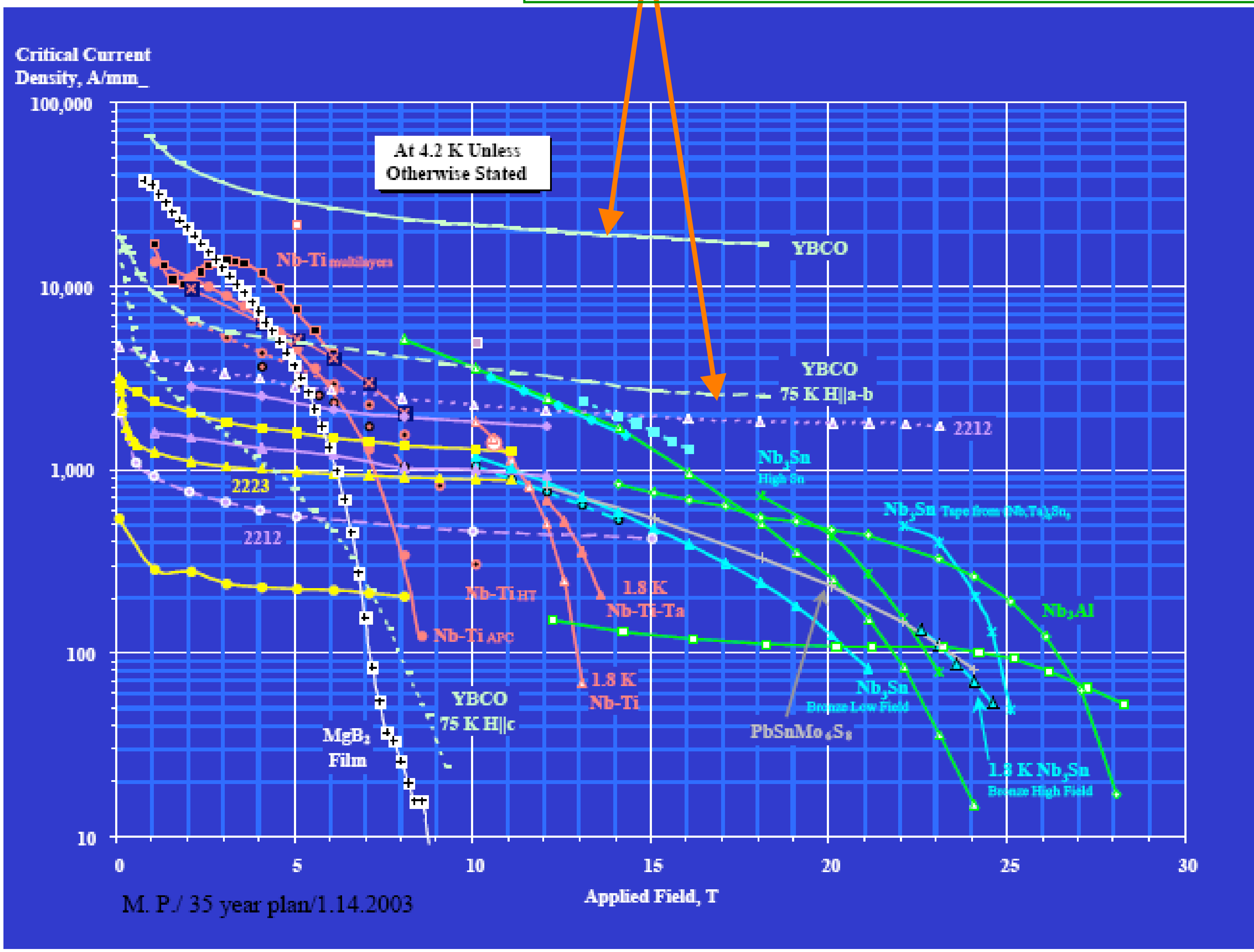
Advanced Magnet Technology for Future Fusion Machines

Leslie Bromberg, Joseph V. Minervini and Joel H. Schultz

ARIES MEETING
Madison WI
May 28-29, 2008

HTS

YBCO not only higher J_c, but relatively flat out to 30 T; O(M) more scalability than LTS or G1 HTS



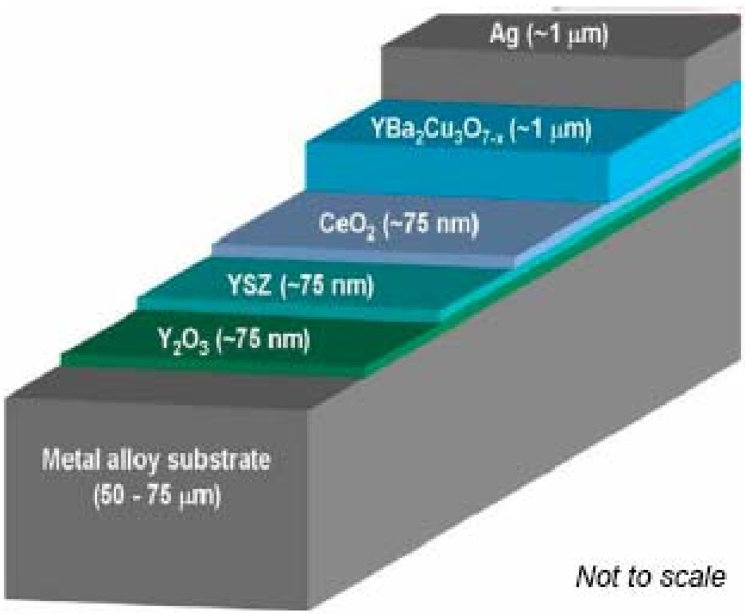
Probably any toroidal concept can be scaled down to 1/3 or 1/4 scale (1/27 or 1/64 volume); prove out advanced physics and advanced magnets with same prototype

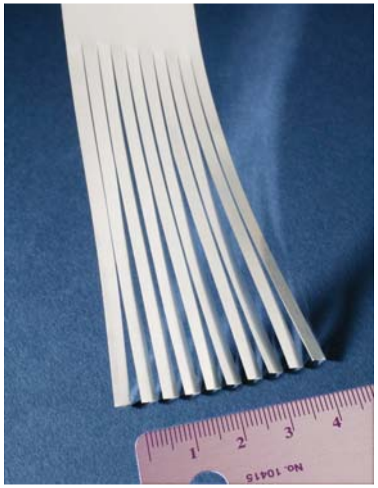
2nd Generation YBCO Coated Conductor Architecture

RABiTS / MOD 2G Strip Architecture

- **Substrate: Ni-5%W alloy**
  - Deformation texturing
- **Buffer stack: Y_2O_3/YSZ/CeO_2**
  - High rate reactive sputtering
- **YBCO**
  - Metal Organic Deposition of TFA
- **Ag**
  - DC sputtering

Width: 1 cm → 4 cm → 10 cm

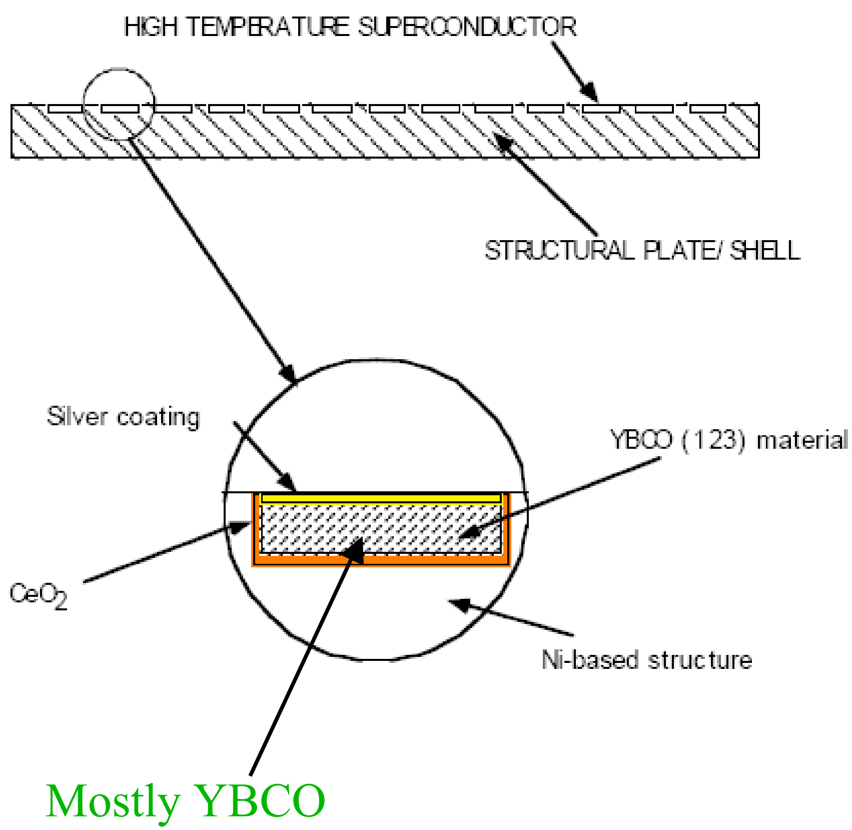




Wider strips increase manufacturing throughput and reduce cost

High Current SC Development

ARIES-AT thick YBCO TF conductor



ARIES-AT uses YBCO as best future conductor

used as 9 T insert in 27 T solenoid (2007)

- No commercial HTS application requires more than 500 A
- ARIES conductors will not be developed independently by industry

High current HTS conductors must be developed by the fusion program

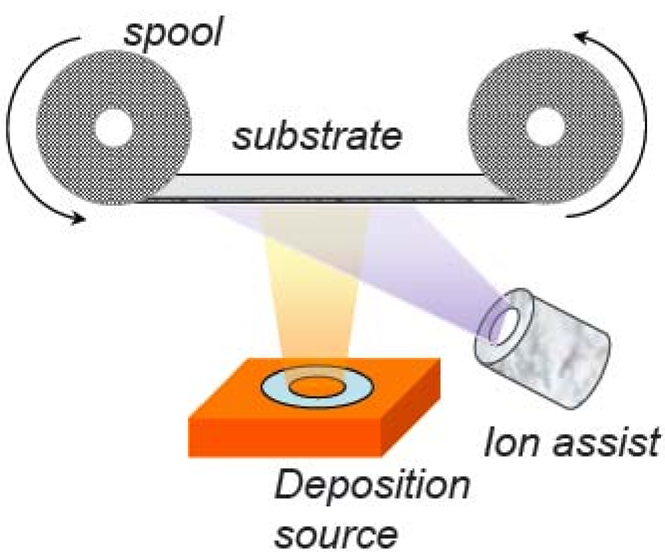
- as high I CICC conductors were

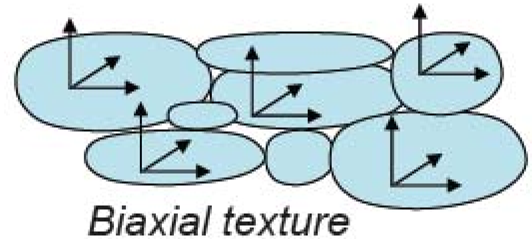
YBCO manufacturing/Superpower

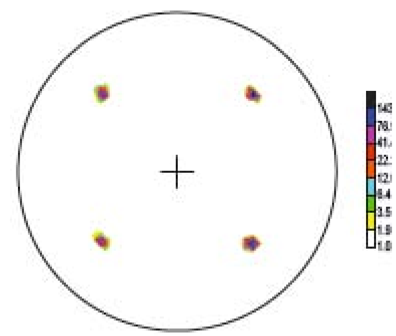
SuperPower Inc.

Ion Beam Assisted Deposition (IBAD) – A technique to produce single crystal films on polycrystalline or amorphous substrates

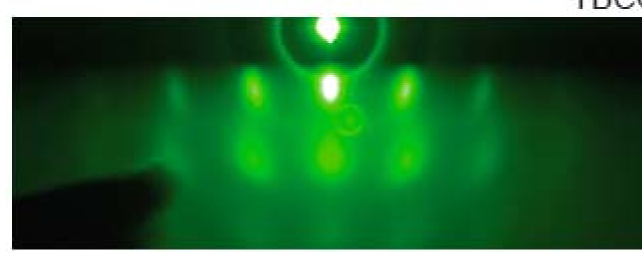
- Essentially, any substrate can be used – stainless steel, nickel alloys, glass, polymer …(room temperature process)
- Biaxial texture achieved in certain conditions of ion bombardment resulting in grain-to-grain misorientation in film plane of about 5 degrees !
- Only 10 nm of IBAD film is needed – very fast process !







YBCO(113)

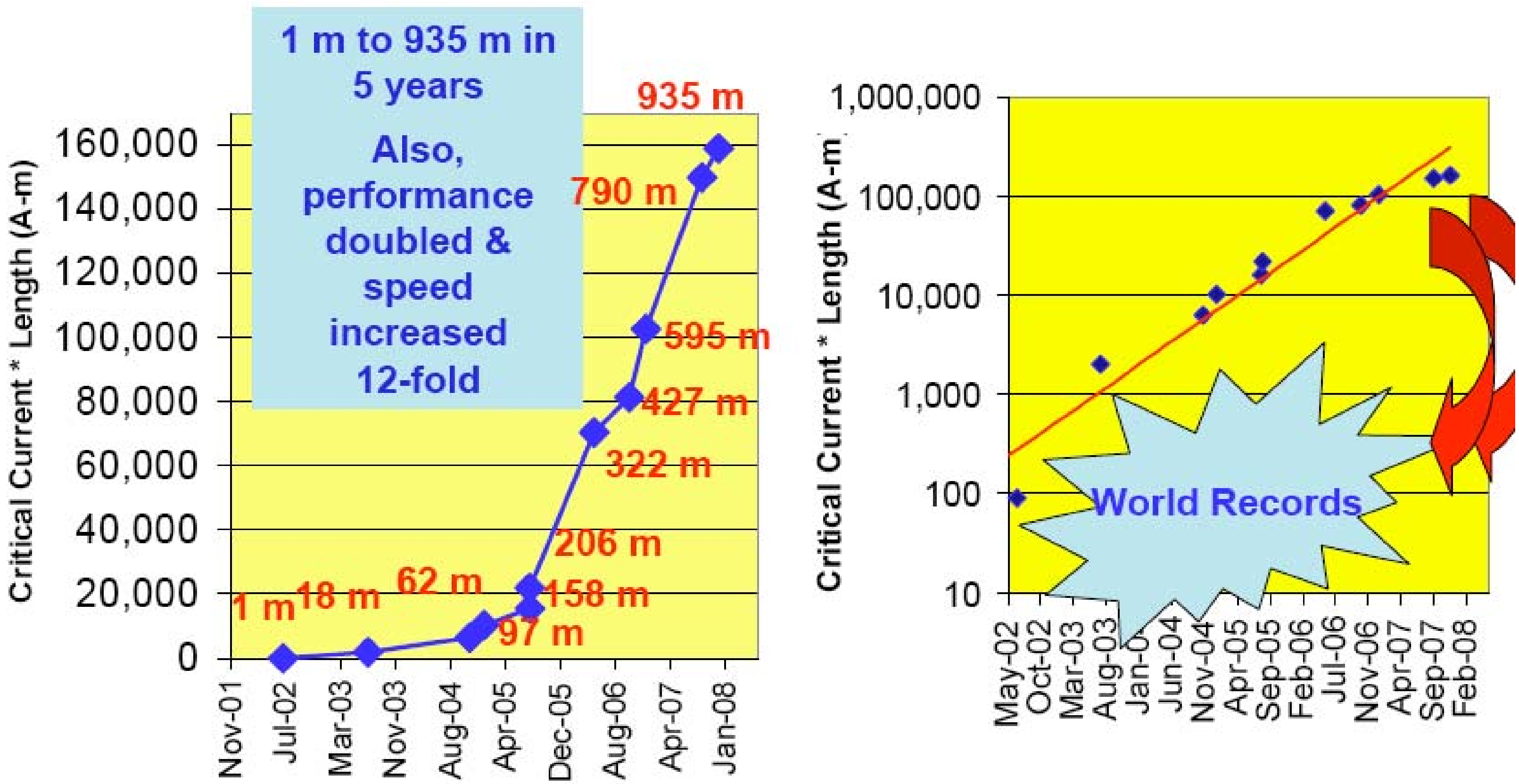


SVC Annual Technical Conference, Chicago, April 19 – 24, 2008

YBCO material

SuperPower

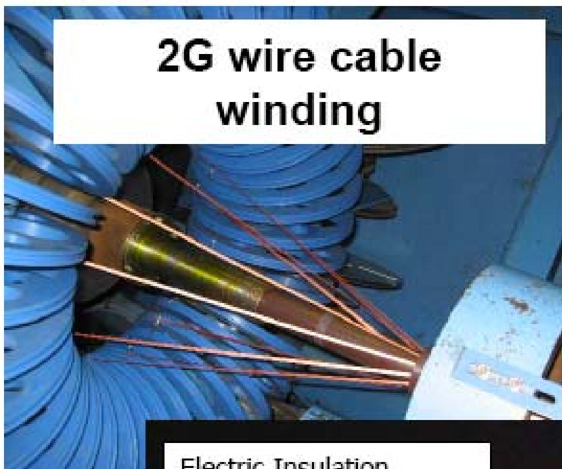
Remarkable progress in thin film HTS wire scale-up over the last 5 years

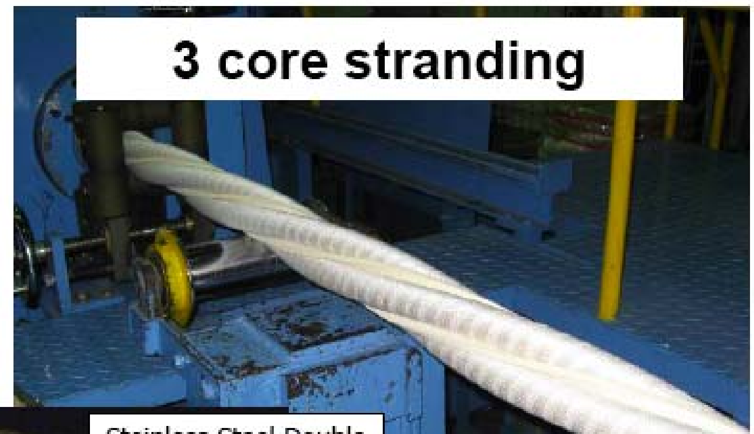


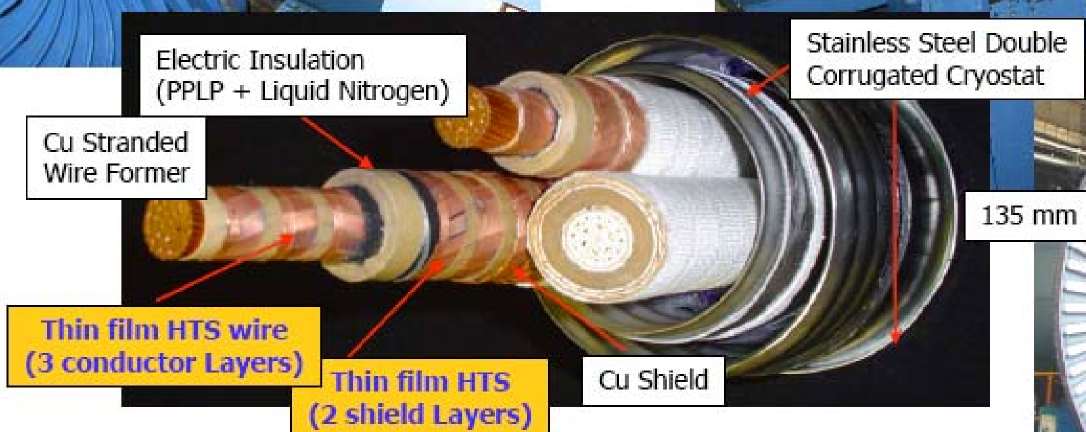
YBCO is a real material

SuperPower Inc.

30 m cable was manufactured & tested by Sumitomo Electric with ~ 10,000 m of our thin film HTS wire







SUMITOMO ELECTRIC

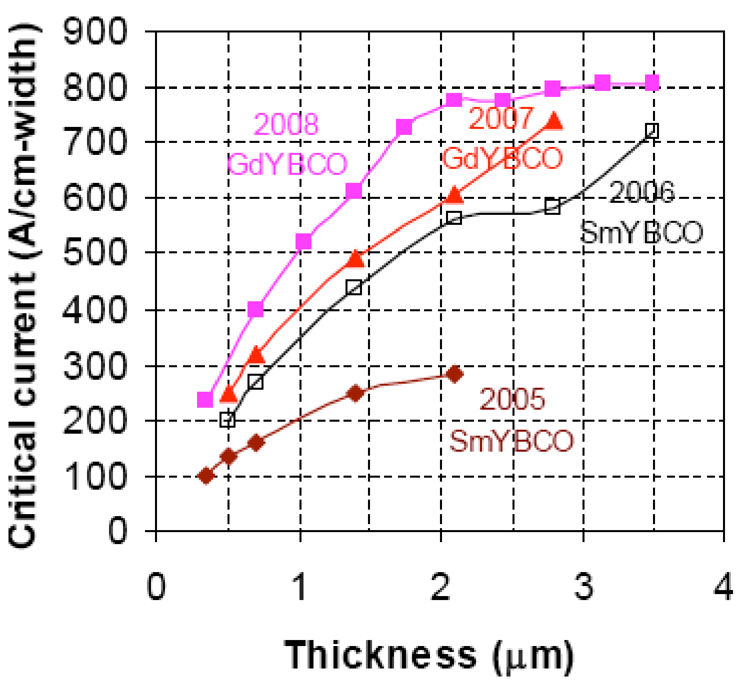
Ingenious Dynamics

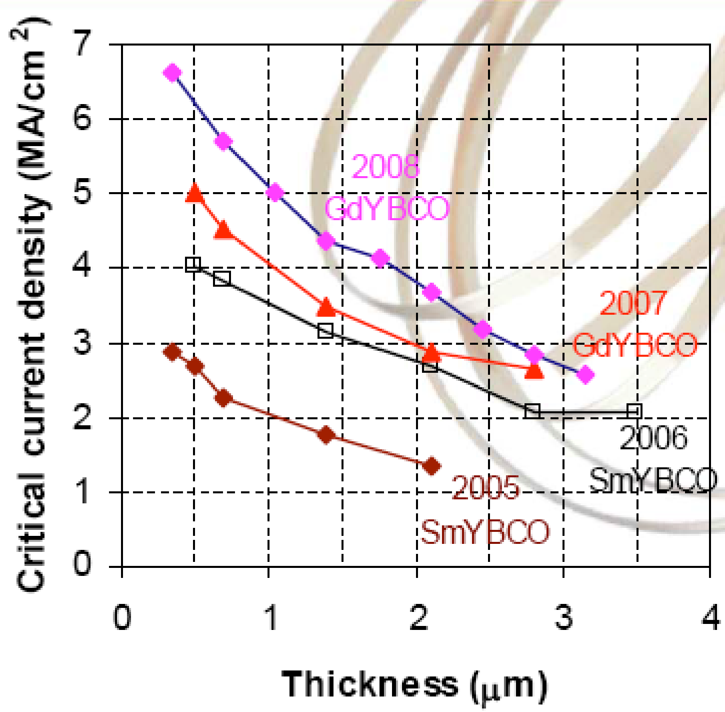
SVC Annual Technical Conference, Chicago, April 19 – 24, 2008

Thickness 'barrier' being overcome using nanoparticle additives

- t > 10 μm undemonstrated, but may be possible

Capability of 320 A in 4 mm widths achieved !





Over 1.2 m length,
Ic = 964 A = 803 A/cm,

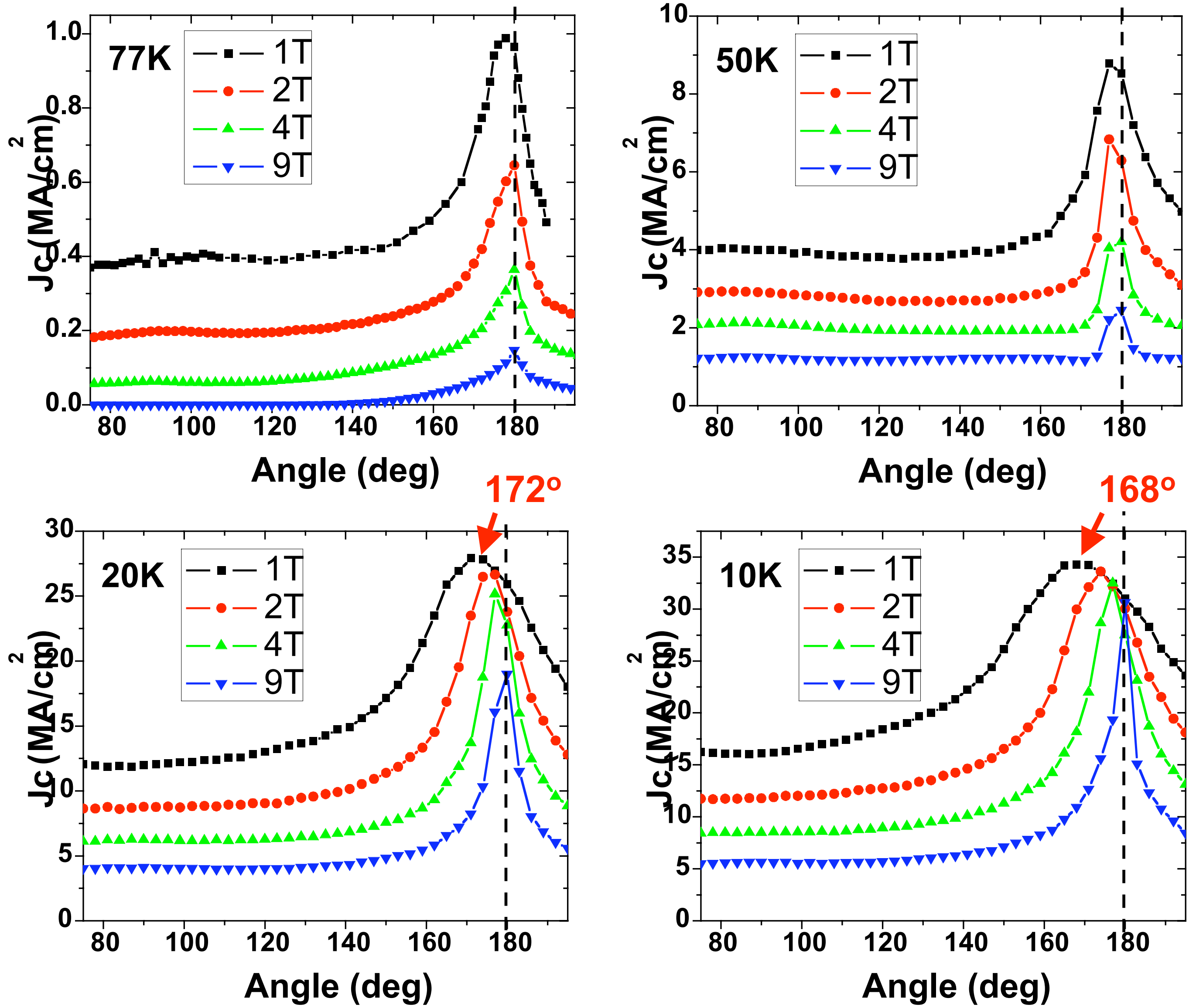
Ic measurement using continuous dc current (no pulsed current) across entire tape width of 12 mm No patterning

3.5 μm film made in 10 passes: **Ic = 964 A = 803 A/cm (Jc = 2.06 MA/cm²)**

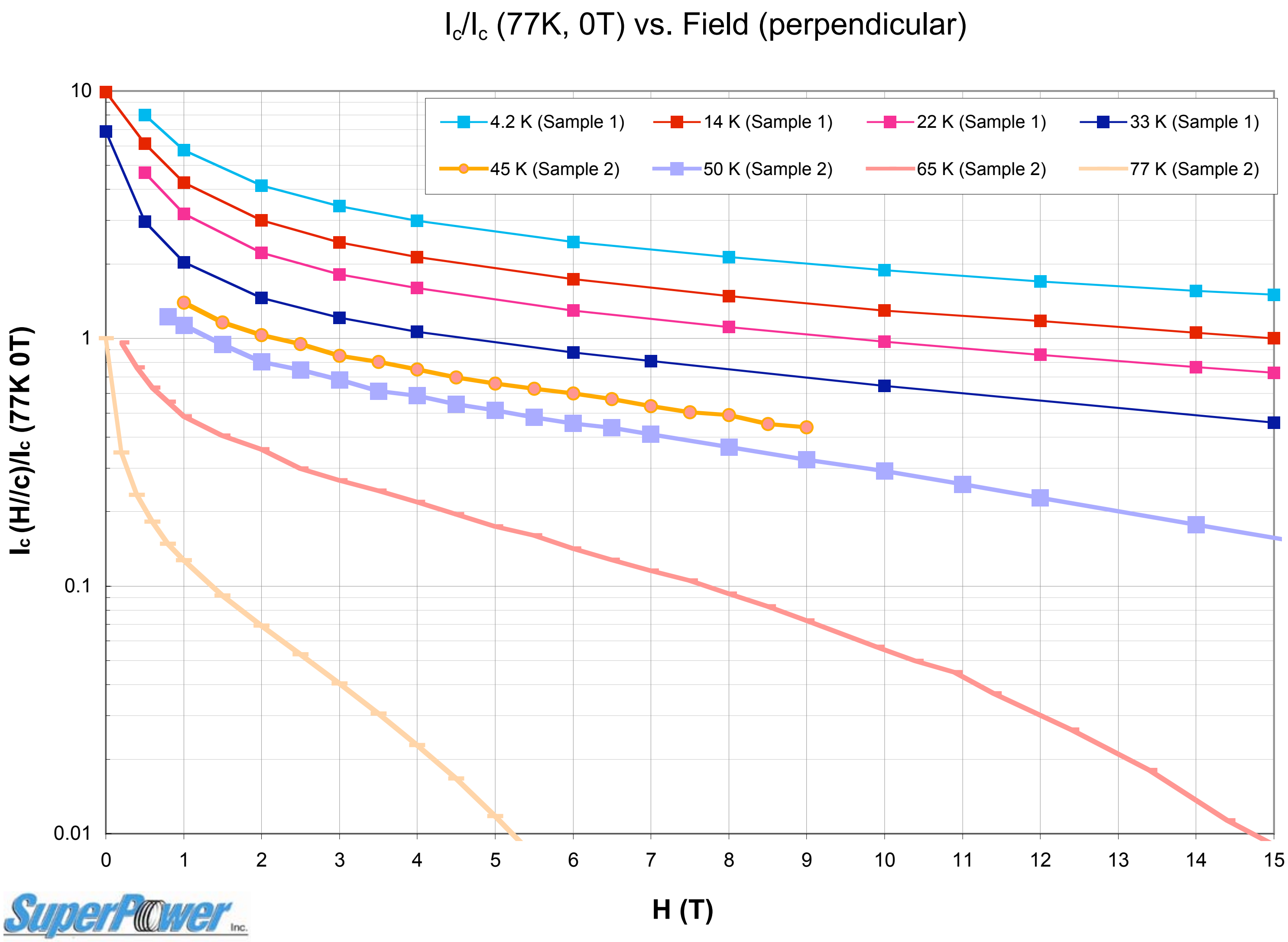
2.1 μm film made in 6 passes: **Ic = 929 A = 774 A/cm (Jc =3.68 MA/cm²)**

Technology &
Engineering Division

YBCO/Superpower-Philips



YBCO/Superpower-Philips



SuperPower Inc.

Once a marginal level of performance is achieved by HTS wire, demonstration devices can be built, but the cost-performance ratio must be reduced for market entry and commercialization.

Technology Attributes	Near-Term Goals (present – 2007)	Mid-Term Goals (2008 – 2011)	Long-Term Goals (2012 – 2016)
Critical current	250 A/cm, 77 K, sf 125 A/cm, 65 K, 2 T	500 A/cm, 77 K, sf 250 A/cm, 65 K, 2 T	1000 A/cm, 77 K, sf 500 A/cm, 65 K, 2 T
Cost/Performance Ratio	$400/kA-m, 77 K, sf $800/kA-m, 65 K, 2 T	$50/kA-m, 77 K, sf $100/kA-m, 65 K, 2 T	$10/kA-m, 77 K, sf $20/kA-m, 65 K, 2 T
Wire Length	100 m	1000 m	>1000 m
AC Losses	1 – 2 W/m	0.5 – 1.0 W/m	< 0.50 W/m

Source: NCI Analysis, Southwire, DOE.

HTS TF coils???

- Conductor on plates
  - As in ARIES AT with HTS materials
  - Probably has to operate at temperatures around 60-70 K
  - Improvement on superconductor material is impressive
    - Two major suppliers in the US, using different technologies for second generation

HTS magnets

- How does the use of HTS change the design?
  - Cooling…
    - Either gaseous He or liquid nitrogen, or “dry”
  - Protection
    - Very difficult for HTS materials (difficult to monitor whether the magnet quench).
    - Fundamentally different design process: design to no quench
    - If quench, internal dump
    - Achieved using AC magnetic field that heat the superconductor
      - no inductive coupling to the main toroidal field magnet, thus reducing reactive power
        - Patent application (presently licensed for protection of superconducting cyclotrons for proton beam therapy)

Operation

- Tapes are expected to carry about 250-1000 A/cm
  - Commercially available in long lengths with ~250 A/cm
- Technology available for 500 A/cm, with ultimate goal 1000 A/cm
- Difficult to achieve very large currents, unless large number of tapes are combined

- New concept of quench detection/protection allows the use of low current in the winding pack.
- Design with currents on the order of 1000 A, with magnets in series

Charging time?

- 1000 A max current
- 2000 V max voltage

- Energy in TF ~ 50 GJ

- Charge magnet in about 1 day (10^5 seconds)

ANCILLIARIES COST

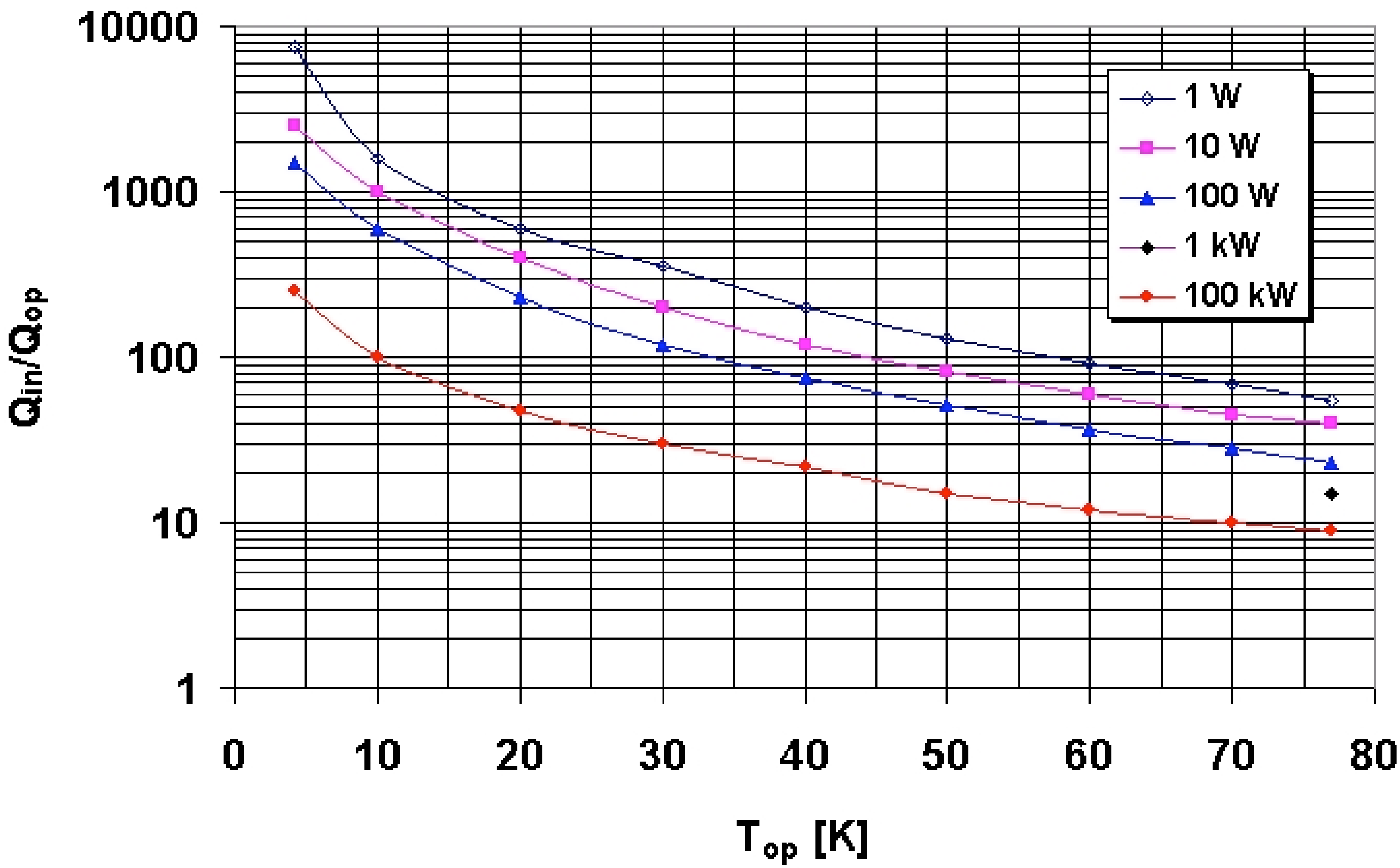
- When the cost of the magnets are 100M$ and higher, lots of other costs are not important
- Magnet costs have reduced to the point where they are NOT negligible, and should include them now:
  - Refrigerators
    - Efficiency ~ 25% of Carnot for large units
  - Current leads
    - Refrigeration losses
      - 100 W_{th}/kA at intermediate temperature (~ 70K)
      - 0.1 W_{th}/kA to low temperature (~4 K)
      - Superconducting leads (from intermediate temperature to 4K)

Refrigeration loads

- Dominant refrigeration load due to radiation on 4 K magnets
- Additional thermal loads:
  - Leads
    - To 4 K : 0.1 W/kA per lead
    - To 70 K: 75 W/kA per lead
    - Number of leads depends on protection (number of circuits for dump)
  - Support loads are not very large

Technology & Engineering Division

Refrigeration efficiency



Cryo-refrigerator Costs - 4K

Component	Units	Relative Cost
Helium refrigerator (Compressor/ cold box)	(k$/K)	$(63\ \text{k\\$}/T_{inlet})(Q_{cap,W})^{0.7}$
Compressor/ cold box	(pu)	1
Dewars and surge tanks	(pu)	0.02
Piping and installation	(pu)	0.1
Recovery system	(pu)	0.04
LN2 system	(pu)	0.03
Engineering	(pu)	0.05
Buildings	(pu)	0.09
Subtotal	(pu)	0.33 CC

Intermediate refrigerator (~ 70 K)

HTS Technology Platforms » Cryogenics & Cryostats › *Timing*

Efficiency, reliability and cost of cryogenics are important components of life cycle cost for an HTS device; improving these factors will increase the likelihood HTS devices will be commercially successful.

Technology Attributes		Near-Term Goals (present – 2007)	Mid-Term Goals (2008 – 2011)	Long-Term Goals (2012 – 2015)
Cryogenics	Carnot Efficiency	12% @ 65 K	20% @ 65 K	30% @ 65 K
	Reliability	95%	99%	> 99.9%
	Cost	$100/W @ 65K	$60/W @ 65K	$25/W @ 65K

©2006 Navigant Consulting, Inc.
HTS Market Readiness Review – August 2006

More on costs…

The Snowmass '99 Plan

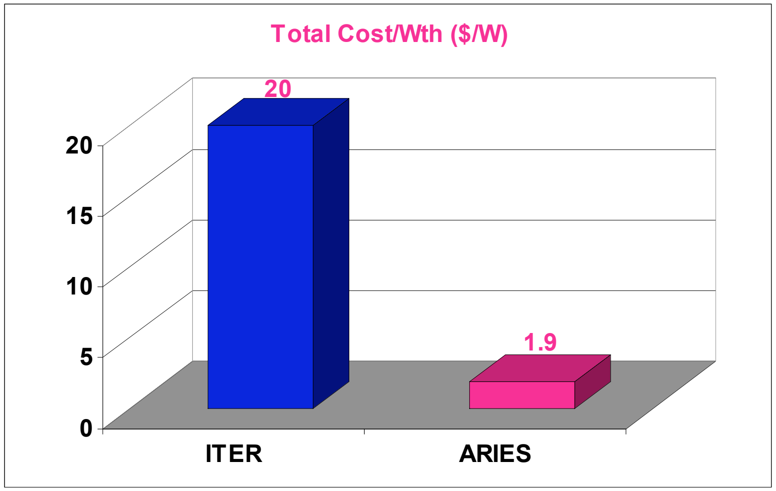
- Unanimous consensus of fusion magnet community
  - conclusions repeated, Snowmass 2002 but never implemented
- Broad-front attack: Improve the Figure of Merit of each magnet subsystem

FOM	**Units**	**ITER**	**Goal**
J_c(12 T, 4.2 K)	(A/mm^2)	700	2,000
$\sigma_{allow, steel}$	(MPa)	400	800
$E_{allow,ins}$	(V/mm)	2,000	4,000
T_{op}	(K)	4.5	10
P_{leads}	(W/kA)	1.0	0.1

Factor of > 2 in FOM's for each subsystem should improve overall size/economics of magnet system by > 2

Technology &
Engineering Division

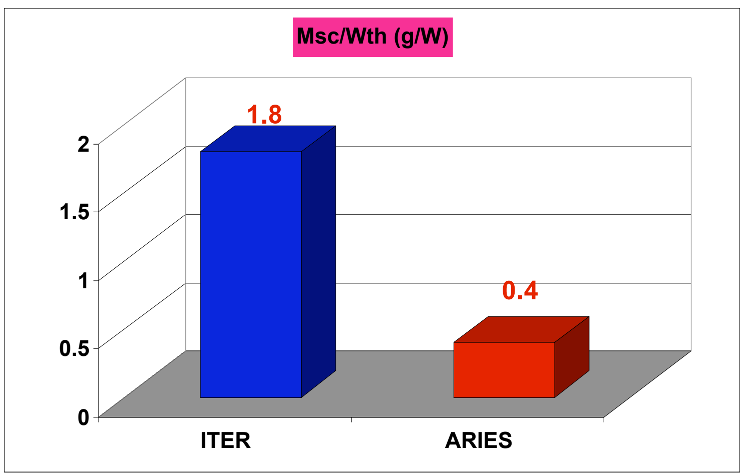
ARIES HTS/ITER



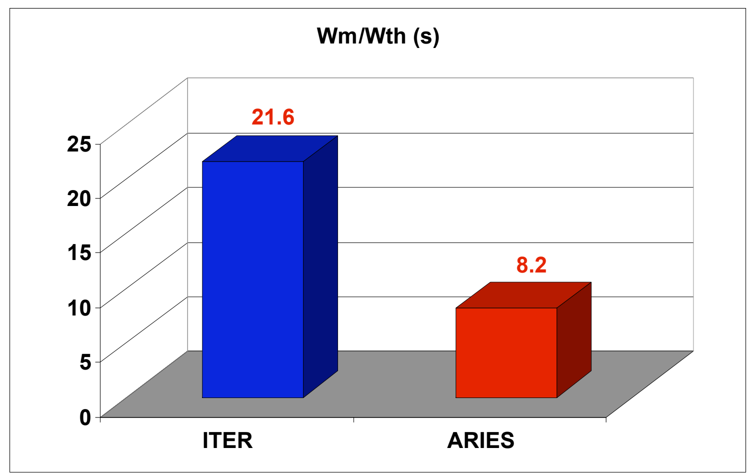
Specific Cost: ARIES 10 x better

Need superconductor that's O(M), e.g. 4.5 x higher J_e than ITER at same field, higher T

(Saving refrigeration not enough)



Specific Mass: ARIES 4.5 x better



Specific Energy: ARIES 2.6 x better

Conductor	Self-supporting PF coils		
	1st of a kind		**10th of a kind**
Strands	25.4	IM	12.7
Coat	6	LCE	2.3
Cabling	13.6	LCE	5.2
Waste	11.3		0
Sheath	5.3	LCE	2
Encapsulation	3.7	LCE	1.4
Additional material	0.9		0
Conductor subtotal	**66.3**		**23.8**
$/ kA m			1
(8 T)			
Winding pack			
Insulation	2.2	LCE	0.8
Tooling	4.2		0
Winding	50.9	LCE	19.6
Dummies	7.1		0
Heat treatment	0.7	LCE	0.3
Leads	1.2	LCE	0.4
Winding pack subtotal	**132.6**		**44.9**
$/ kA m			1.9
Unit cost, $/kg			88
Support	19.4	LCE	7.5
Engineering	43.6		0
Hardware / engineerin	**195.6**		**52.4**
Contingency	58	20%	10.5
PACE direct	253.6		62.9
PACE G&A	22.6	10%	6.3
OPEX	8.7		0
TC in M$	**285**		**69.2**

PSFC

Technology & Engineering Division

Near term low temperature superconductor

Topical Review

Table 5. Cost analysis for Nb_3Sn magnet conductors with $d_s = 0.8$ mm diameter and $R = 1.0$. Alloy compositions are given by mass.

			Internal Sn HEP			
Strand type	Bronze	Int. Sn ITER	c. 2000	c. 2003	Var. 1	Var. 2
(A) Materials and geometry						
Superconductor	Nb1Ta	Nb7.5Ta	Nb7.5Ta	Nb7.5Ta	Nb	Nb + Nb47Ti
Stabilizer	Cu	Cu	Cu	Cu	Cu	Cu
Reactants	Cu16Sn1Ti	Sn3Ti	Sn3Ti	Sn	Sn3Ti	Sn
Diffusion barrier	Ta40Nb	Ta40Nb	Ta40Nb	Nb	Nb	Nb
Ancillary materials[a]	—	Cu	Cu	Cu	Cu	Cu
Reactants area fraction (%)	30	10	10	13	13	13
Diffusion barrier area fraction (%)	7	10	10	8	8	8
Ancillary materials area fraction (%)	—	15	10	4	4	4
Superconductor area fraction[b] (%)	13	15[d]	20[d]	25[d]	25[d]	25[d]
Composite strand density (g cm^{-3})	9.4	9.1	9.1	8.7	8.6	8.6
Composite strand density (g m^{-1})	4.7	4.6	4.5	4.4	4.3	4.3

(D) Cost indices						
Raw materials (\$ kg^{-1})	106	89	114	96	90	73
Raw materials (\$ m^{-1})	0.50	0.32	0.55	0.43	0.40	0.32
relative to LHC strand	2.7	1.8	3.0	2.4	2.2	1.7
Raw materials (\$ kA^{-1} m^{-1})						
10 T	2.00	1.50	0.61	0.35	0.32	0.26
12 T	2.60	1.80	0.94	0.56	0.52	0.42
15 T	4.30	3.50	1.70	1.00	0.97	0.78
20 T	12.00	16.00	6.90	4.20	3.90	3.13
Scaled cable @ 12 T (\$ kA^{-1} m^{-1})	15	27	9.00	6.80	6.30	5.10

Costs of high field superconducting strands for particle accelerator magnets, L.D. Cooley, et al, *Supercond. Sci Techn* **18** (2005)

Table 3. Purchase data for selected high field magnet strands from projects during the past 10 years. 'MJR' refers to the modified jelly-roll process used by Oxford Instruments—Superconducting Technology (OST). 'RRP' refers to the restacked-rod process also used by OST. 'PIT' refers to strands made by the powder-in-tube technique. Critical current density refers to typical values calculated for the non-stabilizer area and as obtained for short samples. Operating current densities are typically 10% lower.

Strand type	d_s (mm)	R	J_c (12 T, 4.2 K) (A mm^{-2})	\$ kg^{-1}	\$ m^{-1}	\$ kA^{-1} m^{-1}
Nb_3Sn						
ITER bronze	0.81	0.30	750, low loss	740	3.47	11.90
ITER int. Sn	0.81	1.5	875, low loss	650–1000	2.98–4.59	14.49–22.29
MJR, c. 2000	0.80	1.0	2200	930	4.22	7.67
MJR, c. 2002	0.80	1.0	2900	1030	4.64	6.40
RRP, c. 2003	0.80	0.86	3000	1030	4.62	5.72
PIT, c. 2001	1.0	1.0	1800	3110	20.50	28.94
Bi-2212						
PIT, c. 2002	0.80	2.8	2000	3470	15.00	57.00

PSFC

Technology & Engineering Division

Nb_3Sn

	Bronze	Int. Sn	R&D-A	R&D-B	R&D-C	Low-Cu
	4.2 K	4.2 K	4.2 K	4.2 K	4.2 K	4.2 K
Strand raw cost, $/kg	*$146.30*	*$97.30*	*$97.30*	*$102.45*	*$94.25*	*$168.05*
Strand raw cost, $/m	*$0.67*	*$0.43*	*$0.43*	*$0.46*	*$0.42*	*$0.74*
Strand cost relative to LHC Nb-Ti	2.5	1.6	1.6	1.7	1.6	2.8
Production cost scaling factor	450%	1190%	830%	830%	830%	830%
Relative to LHC Nb-Ti	2.0	5.3	3.7	3.7	3.7	3.7
Scaled strand cost, $/kg	*$658.37*	*$1,157.87*	*$807.59*	*$850.34*	*$782.28*	*$1,394.82*
Recent purchase prices, $/kg		$1,060				
Scaled strand cost, $/m	*$3.02*	*$5.14*	*$3.58*	*$3.80*	*$3.47*	*$6.17*
Cabling cost, $/m	*$3.00*	*$3.00*	*$3.00*	*$3.00*	*$3.00*	*$3.00*
Scaled cable cost, $/m	*$111.65*	*$188.03*	*$132.05*	*$139.84*	*$128.01*	*$138.73*
Cable final performance index at field, $/kA-m						
5	*$3.66*	*$1.93*	*$1.35*	*$1.43*	*$1.31*	*$1.39*
8	*$6.53*	*$3.55*	*$2.50*	*$2.64*	*$2.42*	*$2.57*
10	*$9.14*	*$4.76*	*$3.35*	*$3.54*	*$3.24*	*$3.45*
12	*$12.19*	*$7.70*	*$5.41*	*$5.73*	*$5.24*	*$5.58*
Scanlan data	*$11.90*	*$7.74*		*$5.74*		
15	*$20.32*	*$14.44*	*$10.14*	*$10.74*	*$9.83*	*$10.46*
20	*$67.73*	*$57.76*	*$40.56*	*$42.96*	*$39.32*	*$41.84*

PSFC
Technology & Engineering Division

Powder In Tube (PIT)

	Nb_3Sn 4.2 K	Bi2212 4.2 K	MgB_2 4.2 K	H-Nb_3Sn 4.2 K	H-MgB_2 4.2 K
Strand raw cost, $/kg	$83.50	$214.21	$252.59	$83.50	$19.50
Strand raw cost, $/m	$0.35	$0.93	$1.01	$0.36	$0.06
Strand cost relative to LHC Nb-Ti	1.3	3.5	3.8	1.4	0.2
Production cost scaling factor	825%	805%	225%	225%	225%
Relative to LHC Nb-Ti	3.7	3.6	1.0	1.0	1.0
Scaled strand cost, $/kg	$688.88	$1,724.39	$568.33	$187.88	$43.88
Recent purchase prices, $/kg					
Scaled strand cost, $/m	$2.90	$7.49	$2.27	$0.82	$0.13
			$0.50		
Cabling cost, $/m	$3.00	$3.00	$3.00	$3.00	$3.00
Scaled cable cost, $/m	$107.31	$272.53	$84.71	$32.53	$7.76
Cable final performance index at field, $/kA-m					
5	$2.06	$29.82	$2.96	$0.32	$0.24
8	$3.66	$32.53	$8.88	$0.59	$0.53
10	$5.17	$35.26	$29.60	$0.78	$0.95
12	$7.41	$35.79	$74.00	$1.27	$1.91
Scanlan data				$1.50	
15	$12.56	$37.67	$2,219.94	$2.38	$9.53
20	$65.92	$39.76	(>Hc2)	$9.40	(>Hc2)

PSFC

Technology & Engineering Division

Cost comparison

Previous suggested costing of SC

- NbTi
  - Presently: 1-2 \$/kA m — 0.6 \$/kA m (@ 5T)
- Nb_3Sn
  - Today: 10-20 \$/kA m
  - Near term: 5 \$/kA m
  - Expected: 1-2 \$/kA m — 1.5 \$/kA m (@12 T)
- YBCO
  - Presently: 600 \$/kA m — 36 \$/kA m (2212 @ 12T)
  - Guessed: 10-20 \$/kA m
  - Expert opinion: 20 \$/kA m

  - Evaluation of costing using model/data from Coley/BNL (June 2003) for low Tc and Navigant Consulting for HTS

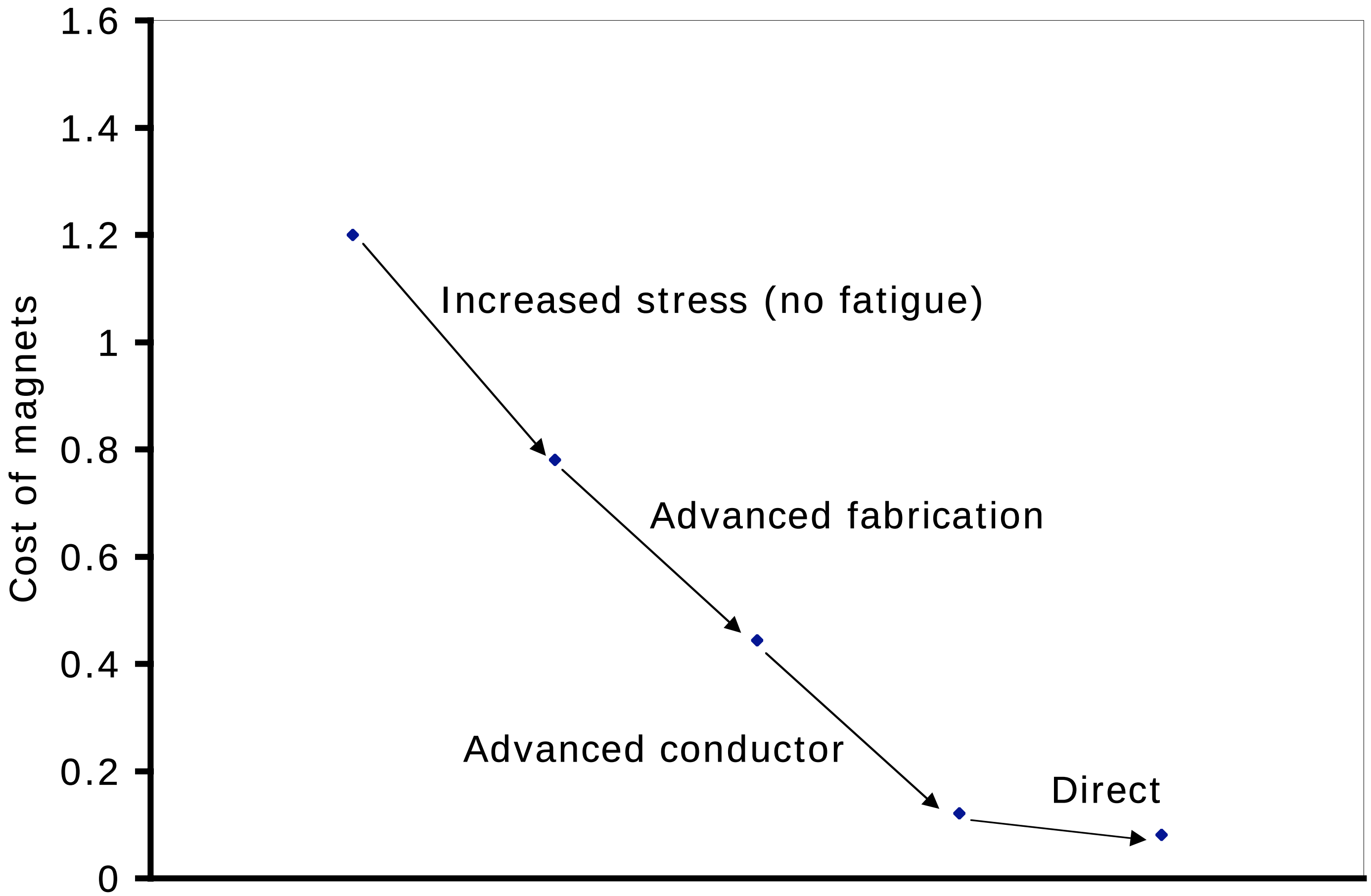
STRUCTURE

- Higher stresses allowed in ARIES than in ITER because of lack of fatigue and less conservative approach (lower margins)
- Decrease in costs due to innovative manufacturing of the structure
  - Cost of development the technology of additive manufacturing being borne by other fields
    - Aerospace
    - Consumer markets (mainly plastics)
  - However, potential synergism of rapid prototyping with magnet manufacturing needs to be funded through DOE (either HEP, NP or fusion)
    - As in ARIES AT (HTS), deposition of SC on structural plates
    - Integration with cooling, current leads, joints between elements

Cost of structure

- Reduction of amount of material by ~ 2 (800 MPa vs 400 MPa)
- Reduction of material cost by switching from high cost Ni-based alloy to SS (another factor of 2)
- Reduction of construction material by an additional factor.
- Net cost of structure ~ $20 /kg vs close to $100 /kg for other studies

Technology implication to magnet costs



Conclusions

- Superconducting magnets can be made more compact, less expensive by focused base R&D program
  - Both incremental as well as revolutionary approaches should be investigated
  - To achieve the goal, aggressive magnet program is required, as not all aspects required for fusion are being investigated by HEP program (which anyway was devastated at the same time as the ITER program)
- However, Magnet Base Program is disappearing in the US