NbTi and Nb_3Sn Superconducting Undulator Designs

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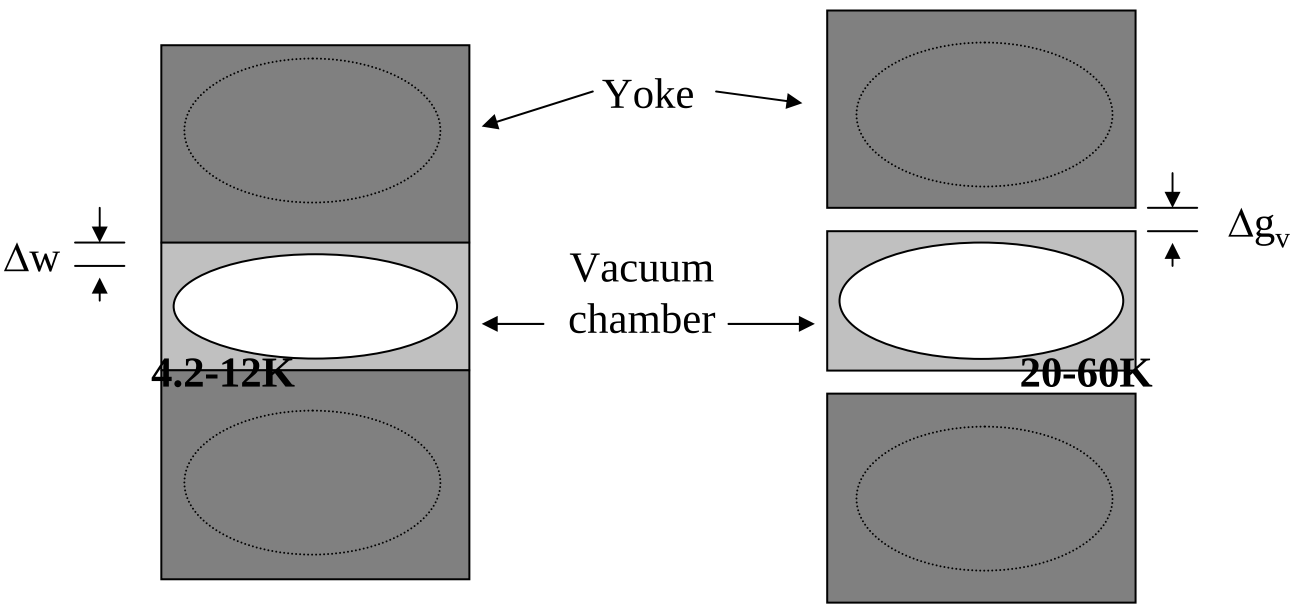
Outline

- Motivation
- Critical current density models
  - Field and temperature dependence
- Limits on attainable average current density
- Heat loads on SCU’s
  - Review of key sources
  - Estimated image-current heating for sample rings
- Model for cryocooler performance
- Estimated undulator performance vs gap
- Summary

Cryogenic design options

- Vacuum chamber and magnet can be thermally linked; magnet and chamber operate at 4.2-12K
- Vacuum chamber and magnet can be thermally isolated; chamber operates at intermediate temperature (30-60K); magnet is held at 4.2K

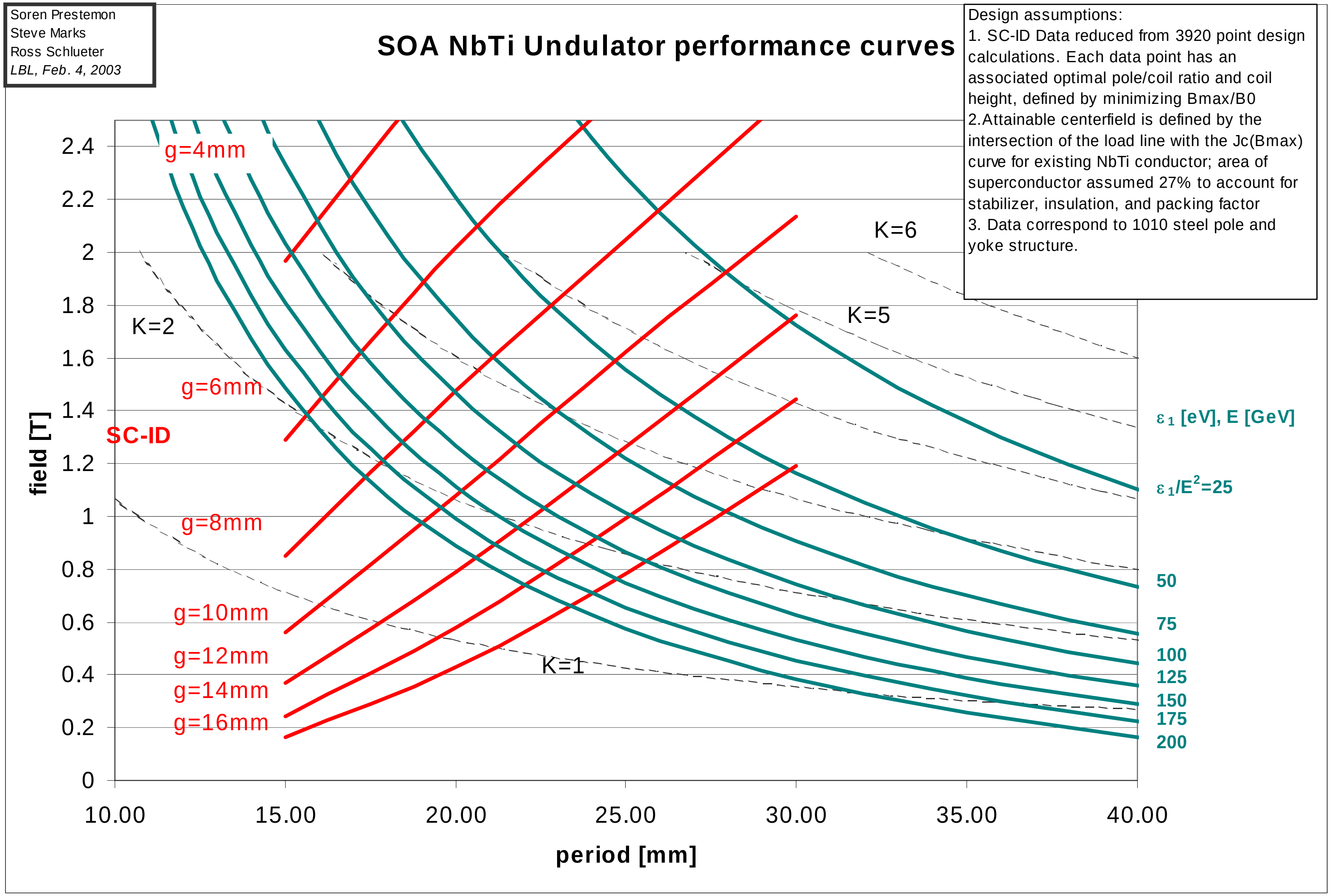


Aggressive spacings:

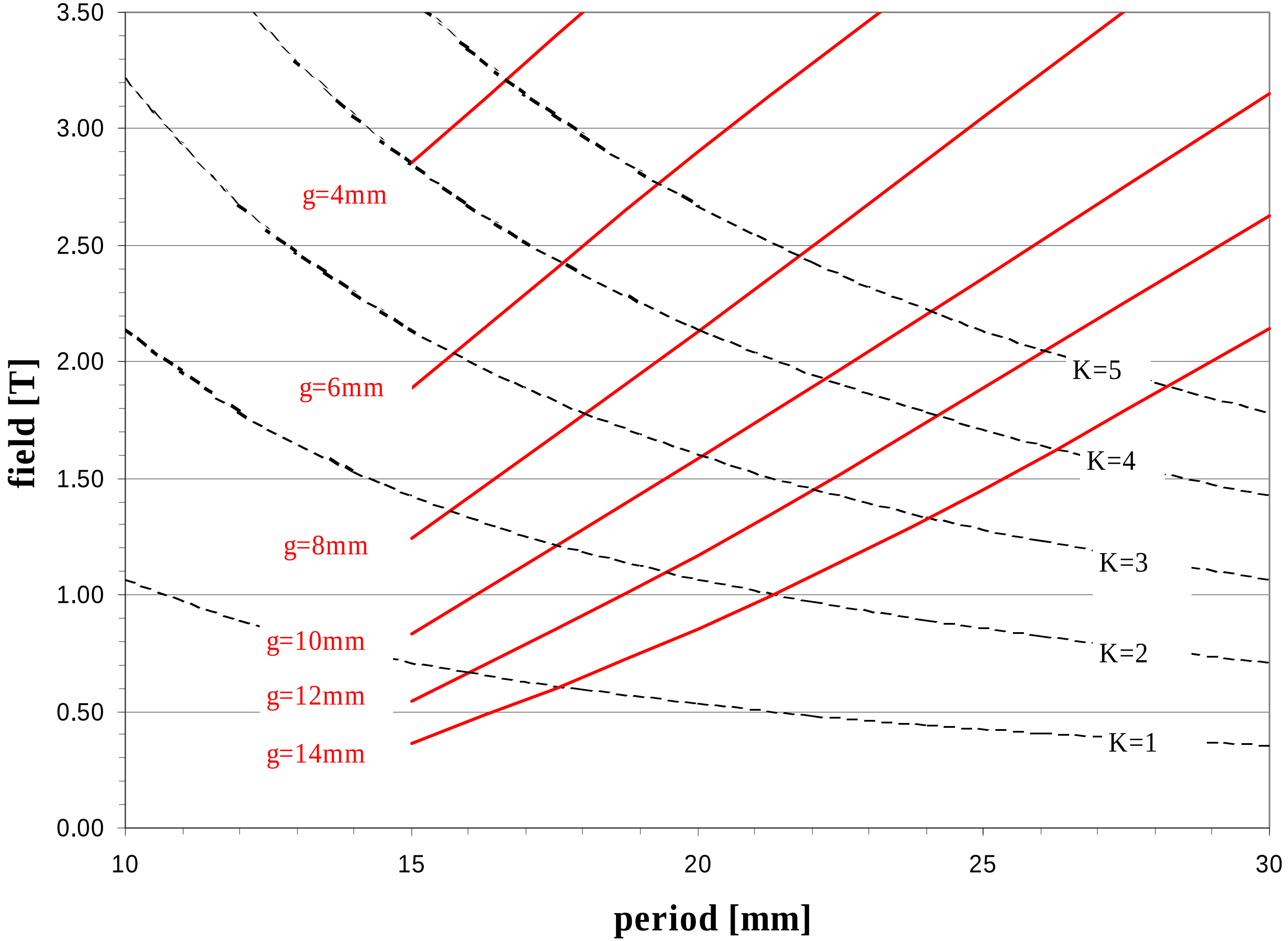
Δw~0.75mm

Δg_v~1mm

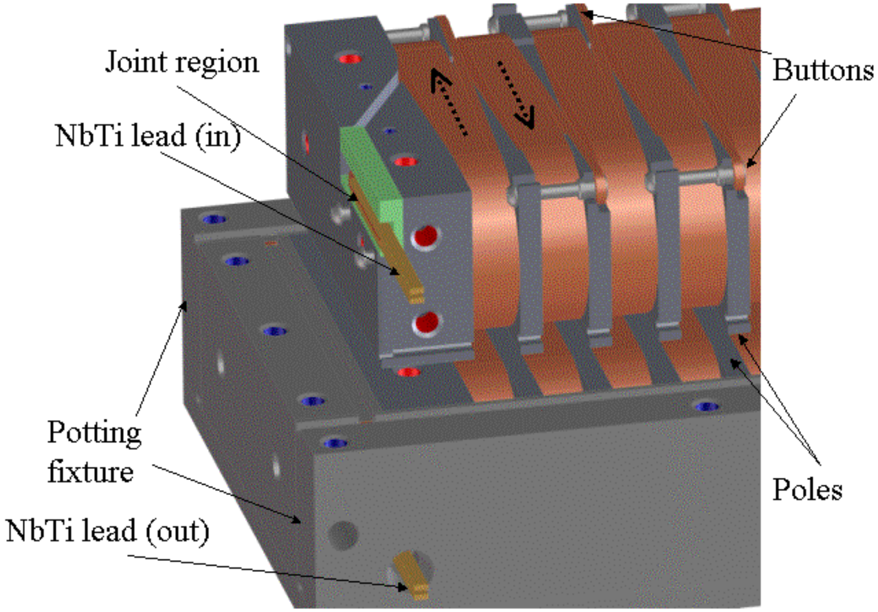
Calculated performance curves for NbTi conductors

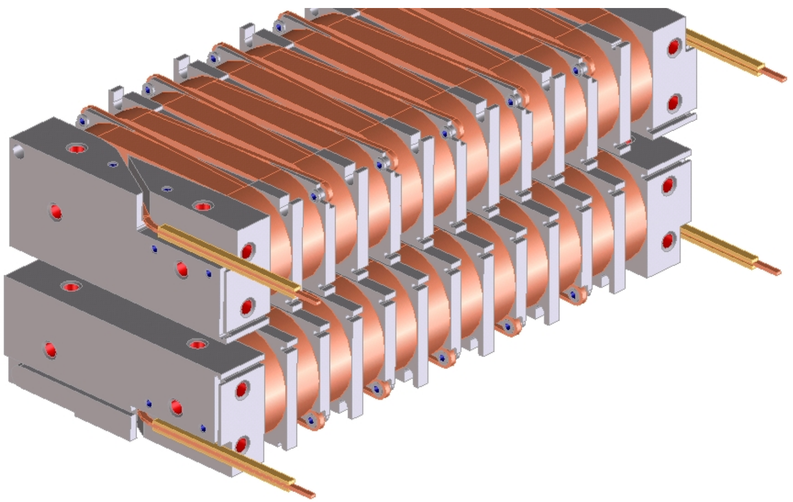


Calculated performance curves for Nb3Sn conductors

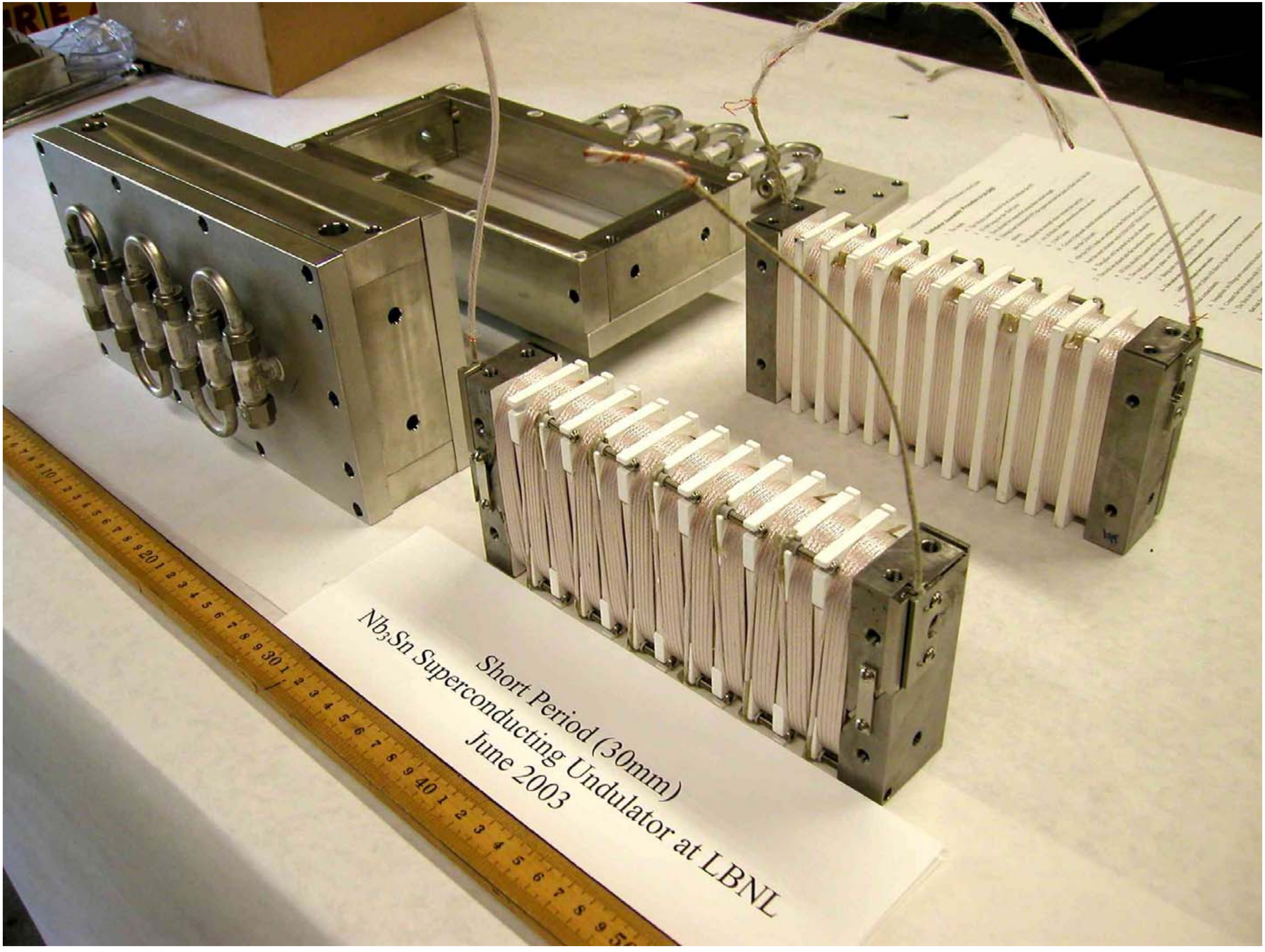


Prototype design





Coil Geometry	
λ [mm]	30
p_w [mm]	4.8
c_w [mm]	10.2
c_h [mm]	5.4
y_h [mm]	28
Average turn length [mm]	21.9
Turns/layer	5
Number of layers	5
Conductor	
Strand diameter [mm]	0.48
Number of strands in cable	6
Cable width (bare) [mm]	1.75
Cable height (bare) [mm]	0.90
Insulation thickness [mm]	0.065
Cu:SC	1.08:1
RRR	21
Cabling packing factor	0.72
Overall SC fraction	0.24
$J_c(5.9\mathrm{T}, 4.2\mathrm{K})$ [A/mm^2]	6115
Anticipated performance (gap=10 mm)	
B_0 [T]	3.2
B_{max} [T]	5.9
I_{max} [A]	3200
E (stored energy/period) [J]	2000


Short Period (30mm)
Nb3Sn Superconducting Undulator at LBNL
June 2003

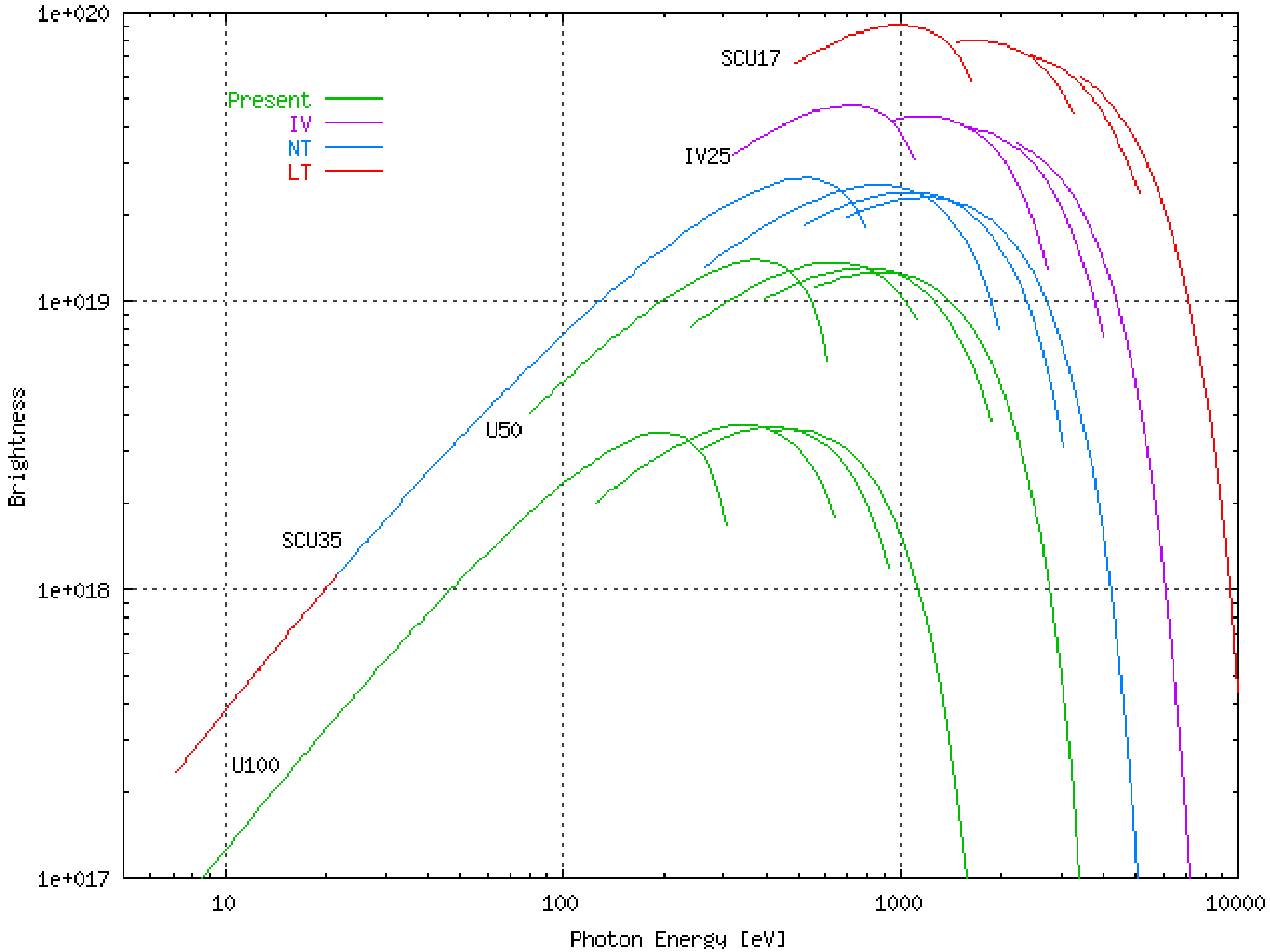
SCU's at ALS

ALS	
$E_e = 1.9$ GeV	
$I = 0.4$ A	
$L = 4.5$ m	
$\sigma_x = 0.26\,\text{mm}$	
$\sigma_{x'} = 0.023\,\text{mrad}$	
$\sigma_y = 0.023\,\text{mm}$	
$\sigma_{y'} = 0.006\,\text{mrad}$	

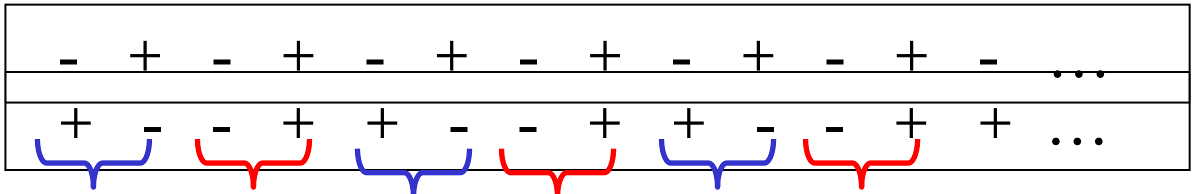
SCU's at the ALS

- Why should we be interested in SCU's?
  - Higher fields, shorter periods
    - Increased brightness and/or shorter devices
    - Extended spectral range

- IV
  - $g_m = 5$ mm
- NT
  - $g_m = 10$ mm (4.2 K)
  - $g_v = 7$ mm (20 K)
  - NbTi
- LT
  - $g_m = 8$ mm (4.2 K)
  - $g_v = 5$ mm (20 K)
  - Nb_3Sn



Regular pattern
Period-doubled



Critical Current Modeling

$b = B / B_{c2}$

$t = T / T_{c0}$

$$\begin{cases} T_{c0}(\varepsilon) = T_{cm} S(\varepsilon)^{1/w} \\ B_{c2}(T,\varepsilon) = B_{c2m} S(\varepsilon) \beta(T,\varepsilon) \end{cases}$$

Nb_3Sn $$J_c(B,T,\varepsilon) = C_0 \beta(T,\varepsilon)^{\nu} K(T,\varepsilon)^{-\gamma} S(\varepsilon) f(b) / B$$

Strain dependence

$$S(\varepsilon) = 1 - a\,|\,\varepsilon\,|^{u}$$

$$a = 900\ (\varepsilon \le 0), 1250\ (\varepsilon > 0)$$

$$u = 1.7$$

NbTi $$J_c(B,T) = C_0 \left(1 - t^n\right)^{\gamma} f(b) / B$$

$$B_{c2}(T) = B_{c2m}\left(1 - t^n\right)$$

$$f(b) = b^p (1-b)^q \qquad \beta(T,\varepsilon) = (1-t^2) K(T,\varepsilon) \qquad K(T,\varepsilon) = 1 - 0.31 t^2 (1 - 1.77 \ln(t))$$

TABLE 1. Material and fit parameters for NbTi and Nb3Sn superconductors

Material	B_{c2m} [T]	T_{cm} [K]	n	υ	γ	p	q	w	C_0 [AT/mm^2]
NbTi	~14	~9.3	1.7	-	2	0.6	1	-	~75000
Nb_3Sn	~30	~18	(2)	2	1	0.5	2	3	~28000

Godeke, A., Ten Haken, B., and H.J. Ten Kate, H., IEEE Trans. on Applied Superconductivity, Vol. 9, No.2, June 1999

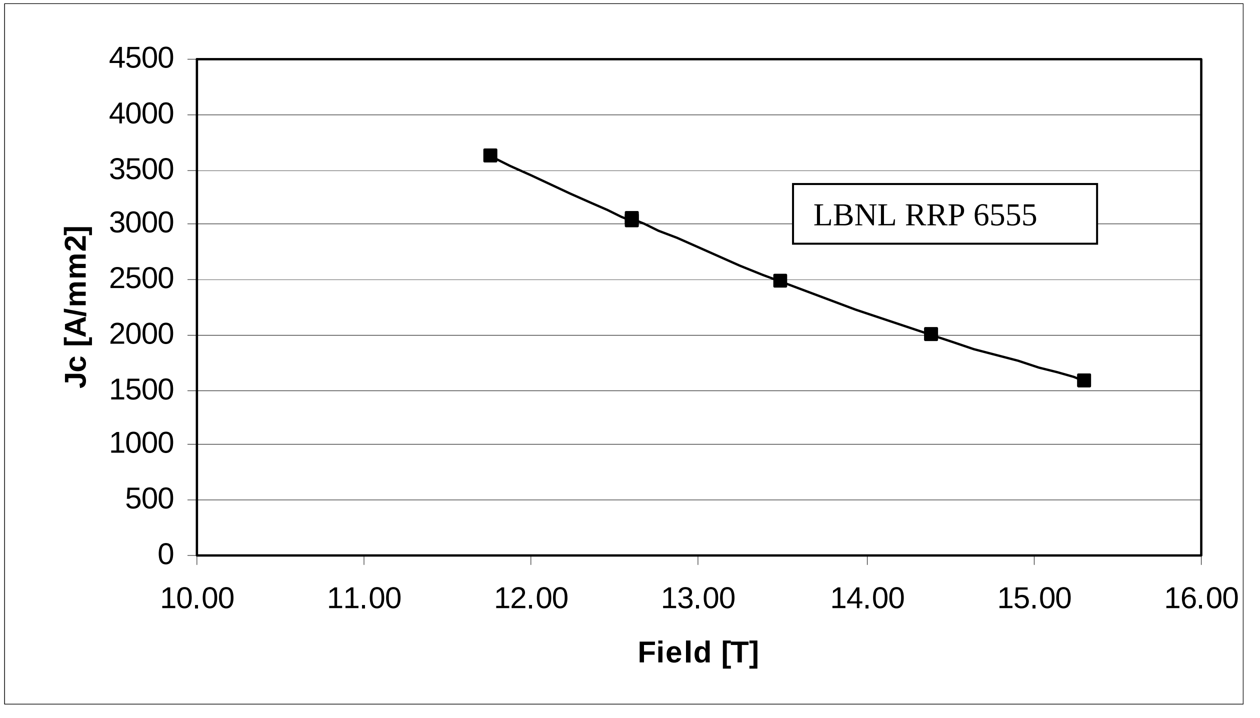
Ten Haken, B., Godeke, A. and H. J. Ten Kate, H., Journal of Applied Physics, Vol. 85, No. 6, March 1999

Green, M. A., IEEE Trans. on Magnetics, 25 (2), 1989.

Summers, L. T., et al., IEEE Trans. on Magnetics, 27(2), p. 2041, 1991.

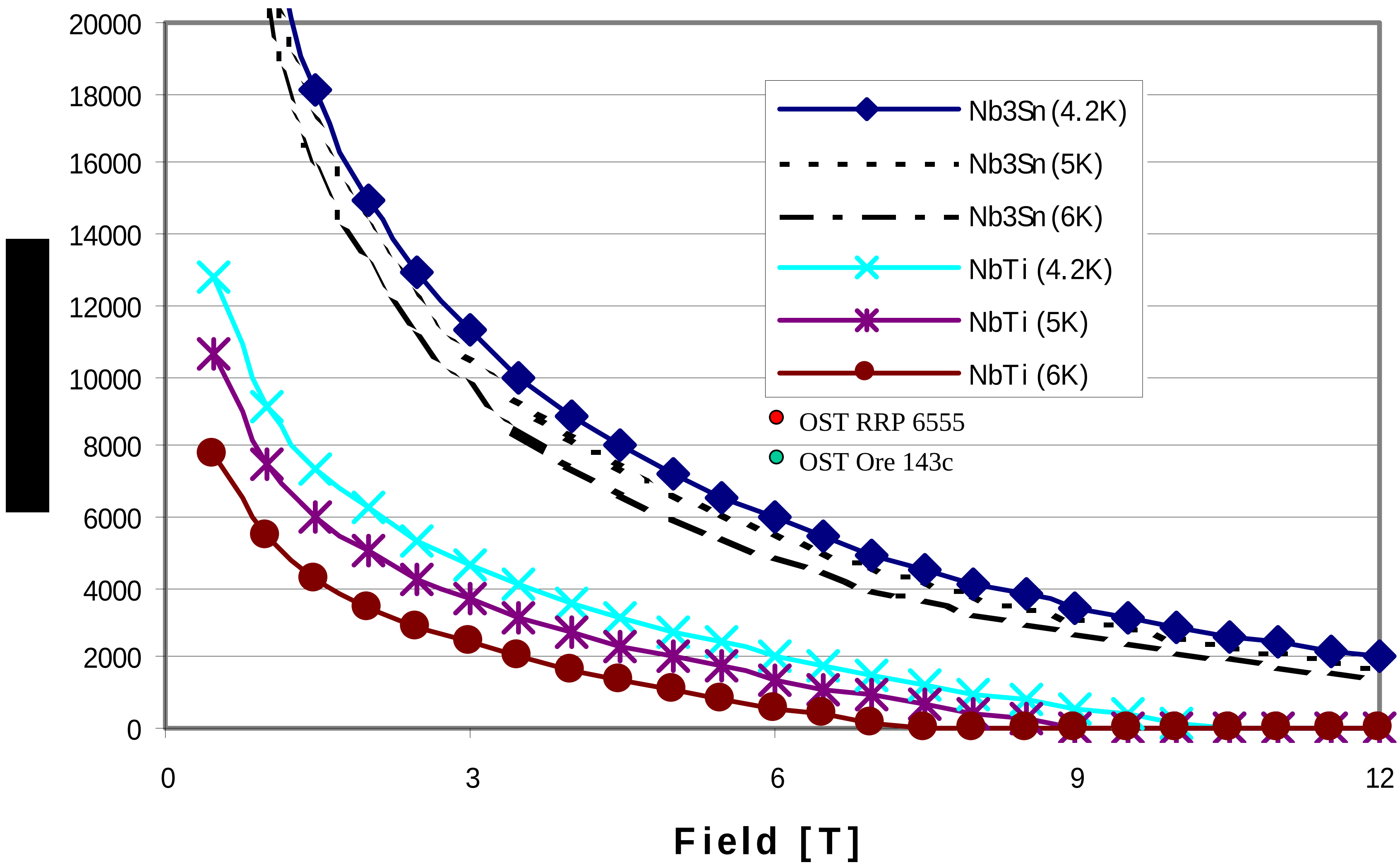
Example performance data

TABLE 2. Examples of superconductor performance. Values are for 4.2K.			
Material	**Jc (12 T) A/mm2**	**Jc (6T) A/mm2**	**Comments**
Nb_3Sn, OST RRP 6555 [8]	~3100	~8900	Strand for LBNL HD-1 dipole prototype
Nb_3Sn, OST ORe 143c	~2400	~7100	Strand for LBNL RD-3c dipole prototype [9]
Nb_3Sn, OST ORe 0021B14B	~2000	~6000	Used in LBNL SCU prototype
NbTi, Industrial sampling (Lee, 2002)	-	~2100	Available in long lengths
NbTi, APC, Heussner et al. (UW-ASC) [10]	-	~2900	R&D effort, high Cu:SC



Heussner, R. W., Marquardt, J. D., Lee, P. J., and Larbalestier, D. C., Applied Physics letters, 70(7), February 1997

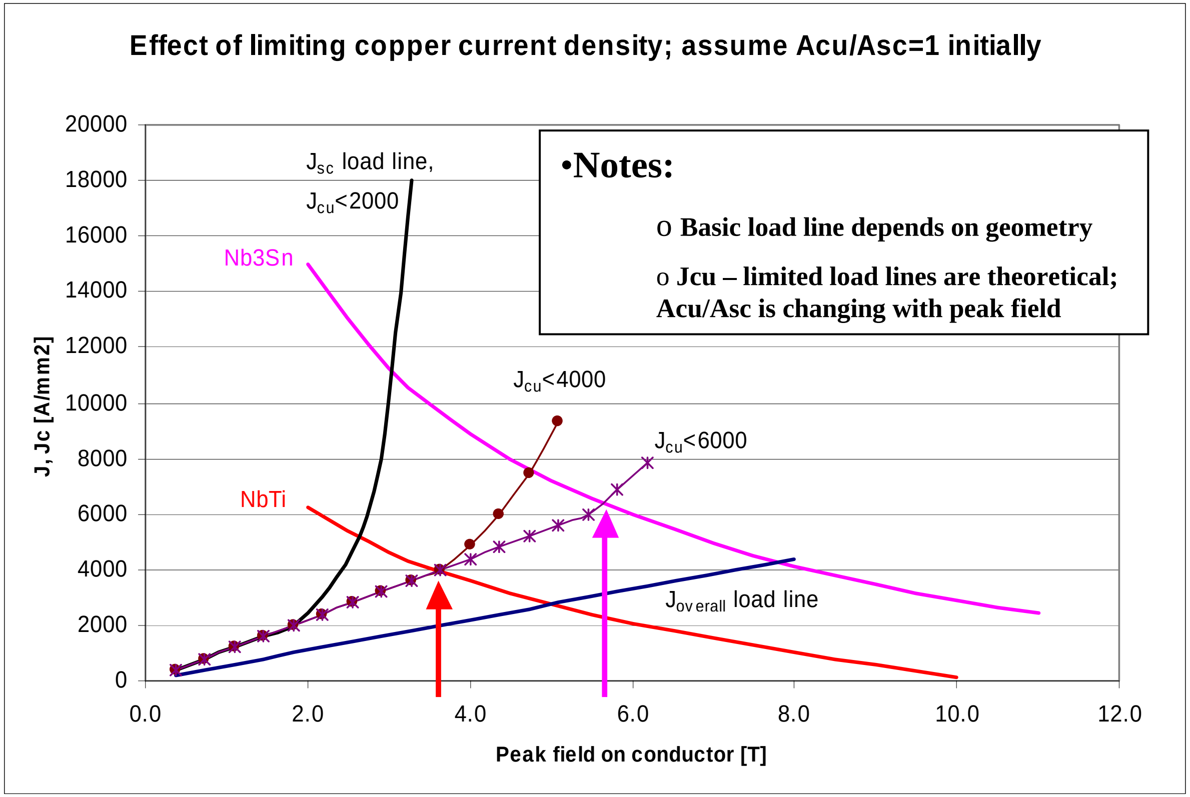
Affect of temperature on critical current density



Limits on attainable average current density

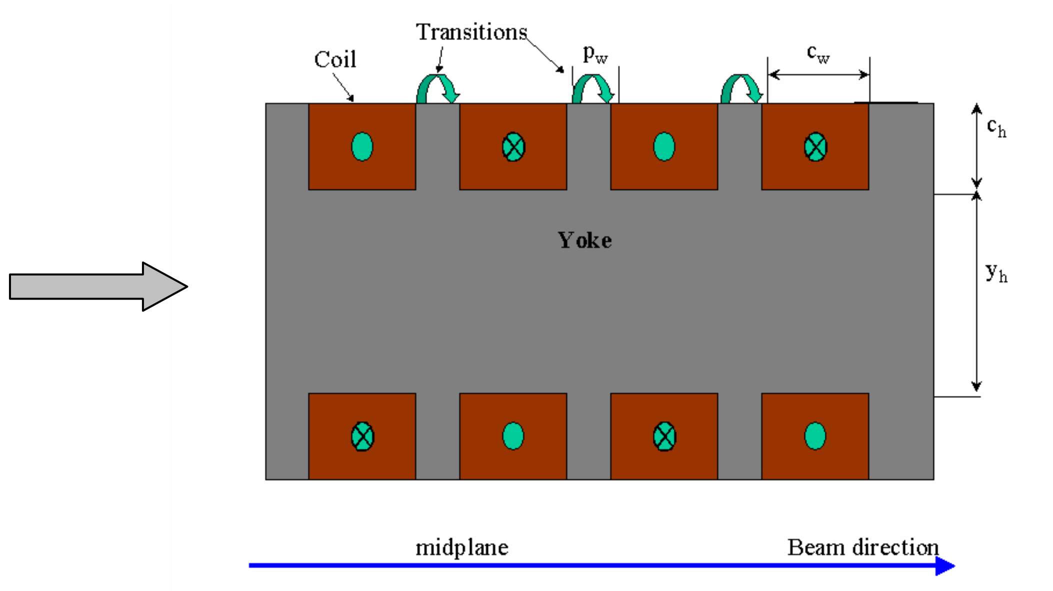
- Conductor needs copper for *stability* from flux-jumps, and for *protection* during a quench
- Conductor insulation must support quench voltage (typically <1kV), and must support manufacturing requirements
- Conductor shape, wire tension, coil form, etc. dictate packing factor
- Larger conductor minimizes A_{ins}/A_{tot}, but increases heat load through leads

- SCU's have "low" peak field on conductor; we must be able to handle high J_{cu} values during a quench in order to take advantage of modern advanced superconductors



Optimal designs

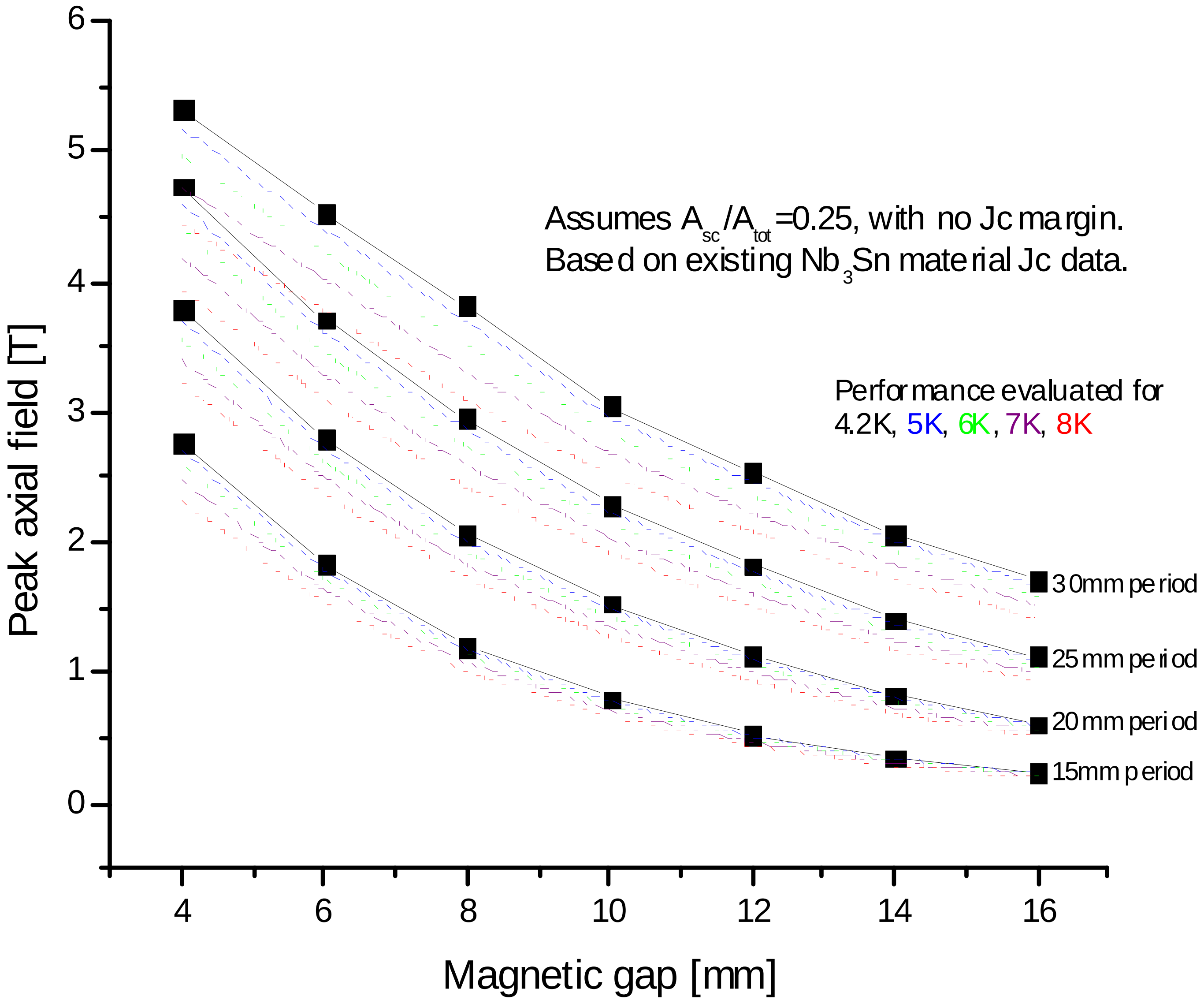
λ	Undulator period
h	Magnetic half gap (gap = $2h$)
p_w	Pole width (beam direction)
c_w	Coil width (beam direction)
c_h	Coil thickness
y_h	Yoke thickness
r_{pc}	$= p_w / c_w$
J_{av}	Engineering, or overall, current density
J_{sc}	Superconductor current density
J_{cu}	Copper current density (e.g. during a quench)
B_0	Peak field on the axis
B_{max}	Peak field on the conductor
K	$= eB\frac{\lambda}{2\pi mc} = 0.934\lambda[cm]B[T]$



For any gap, period, and J_{av}, there is an optimal set c_w, c_h, p_w that minimizes B_{max} / B_0. From these, “optimal load lines” can be determined.

Peak performance for an actual device is derived from J_c data and the superconductor cross section, which is used to relate J_{av} to J_{sc}. The peak attainable field B_0 is defined by the intersection of the “optimal load lines” with the J_c curve, i.e. when $J_{sc} = J_c(B_{max})$.

Performance curves for Nb_3Sn SCU's



Heat sources for SCU's

We concentrate on these (applies to the first two items)

- Traditional cryogenic loads: $Q_{static} = Q_{cond} + Q_{leads} + Q_{walls}$ (□ 1W)
- Image current heating: proportional to 1/*h*, *h*=half-gap; function of beam parameters
- Synchrotron radiation: needs to be masked
- Other
  - Electron cloud
  - Diverse beam RF

See *Welch, J., Workshop on Superconducting Undulators and Wigglers, ESRF, July 2003* for an overview of potential sources

Beam heating

1. Podobedov, B., Workshop on Superconducting Undulators and Wigglers, ESRF, July 2003
2. Eric Wallen, Workshop on Superconducting Undulators and Wigglers, ESRF, July 2003
3. Caspers, F., Morvillo, M., Ruggiero, F. and Tan, J., LHC Project Report 307, CERN, August 1999

$$Q_{im} = \alpha \frac{I^2 l_s}{h(l_b)^{5/3}} Z_0^{2/3} (\rho \lambda_e)^{1/3}$$

l_s is the bunch spacing,
l_b is the bunch length
h is the half-gap
Z_0 is the free-space impedance,
α is a constant, based solely on the vacuum chamber geometry.

(Extreme anomalous skin effect; heating no longer a function of RRR or of frequency)

$$\sigma = \frac{ne^2\tau}{m} \rightarrow \lambda_e = v_f \tau$$

electron charge e [C]	1.602E-19			
electron mass [kg]	9.1E-31			
	Cu	Al	Ag	Au
resistivity (ρ) [Ohm-m]	1.74E-08	2.68E-08	1.59E-08	2.46E-08
conductivity [1/Ohm-m]	5.75E+07	3.73E+07	6.29E+07	4.07E+07
electron density [1/m^3]	8.54E+28	1.81E+29	5.85E+28	5.90E+28
electron velocity on Fermi surface [m/s]	1.57E+06	2.02E+06	1.39E+06	1.39E+06
collision time [s]	2.39E-14	7.33E-15	3.81E-14	2.44E-14
mean-free path length (l) [m]	3.75E-08	1.48E-08	5.30E-08	3.40E-08
ρ*l [Ohm-m^2]	6.52E-16	3.97E-16	8.43E-16	8.35E-16

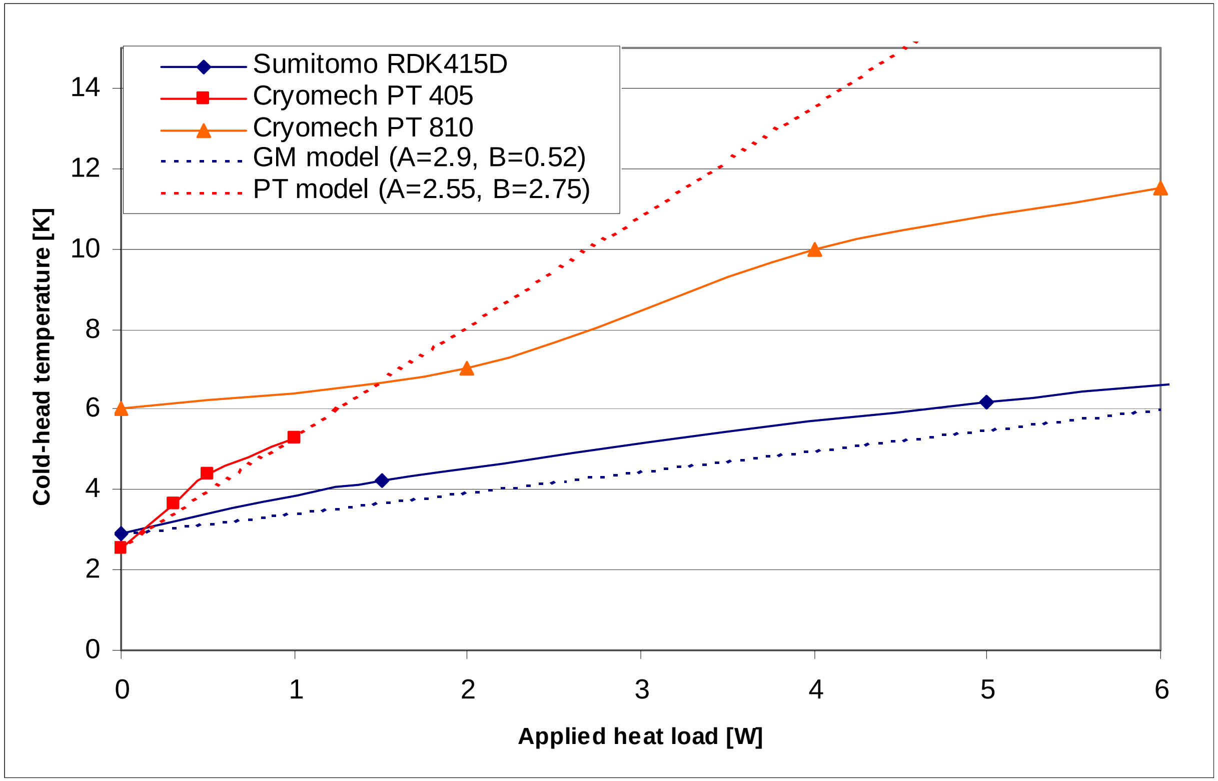
Source: Intro to Solid State Physics, 5th edition, C. Kittel

Image Current heating estimates

Estimates of RF heating for different rings, using different vacuum chamber surface materials. Estimates are derived using the Piwinski formulation as developed by Boris Podobedov.
Note: BNL device is 2m; ALS devices assume 1.5m; Max-Lab and ESRF data correspond to 1m devices.

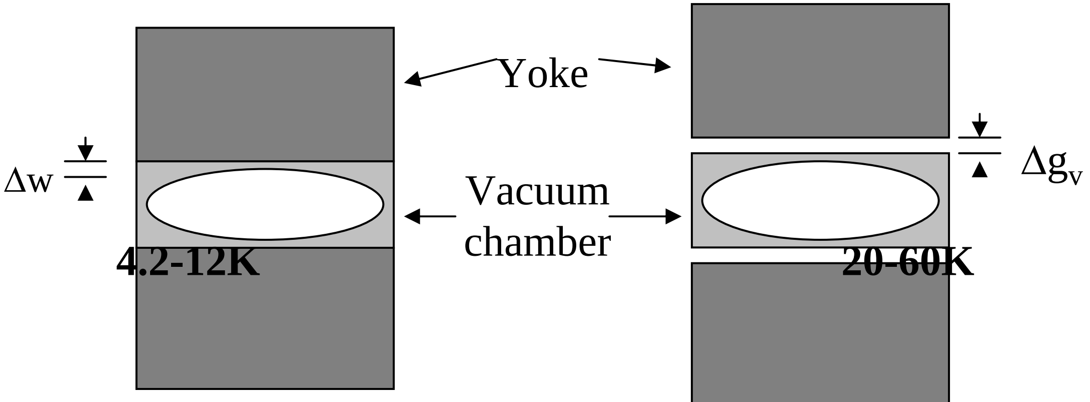
	Cu		Al		Ag		Au	
	300K	***4.2K***	***300K***	***4.2K***	***300K***	***4.2K***	***300K***	***4.2K***
Boris example (BNL)	51.89	9.84	64.70	8.32	49.83	10.69	61.94	10.66
ALS present	3.94	0.66	4.91	0.56	3.78	0.71	4.70	0.71
ALS 2-bunch present	11.08	1.85	13.81	1.56	10.64	2.01	13.22	2.00
ALS upgrade	13.19	2.20	16.45	1.86	12.67	2.39	15.75	2.38
ALS upgrade - X	25.59	4.60	31.91	3.88	24.57	4.99	30.55	4.98
ALS upgrade 2-bunch X	21.49	3.86	26.80	3.26	20.63	4.19	25.65	4.18
Max-Lab II	0.73	0.13	0.90	0.11	0.70	0.14	0.87	0.14
ESRF uniform	1.95	0.31	1.95	0.31	1.95	0.31	1.95	0.31
ESRF 16-bunch	6.59	0.91	6.59	0.91	6.59	0.91	6.59	0.91
ESRF 1-bunch	2.77	0.36	2.77	0.36	2.77	0.36	2.77	0.36

Cryocooler performance



- Consider two linear relations to demonstrate the effect of cooling power on performance:
  - The RDK is a GM-type cooler, capable of 1.5W at 4.2K
  - The PT405 is a pulse-tube capable of 0.5W at 4.2K

$$T(Q) \approx T_0 + aQ$$

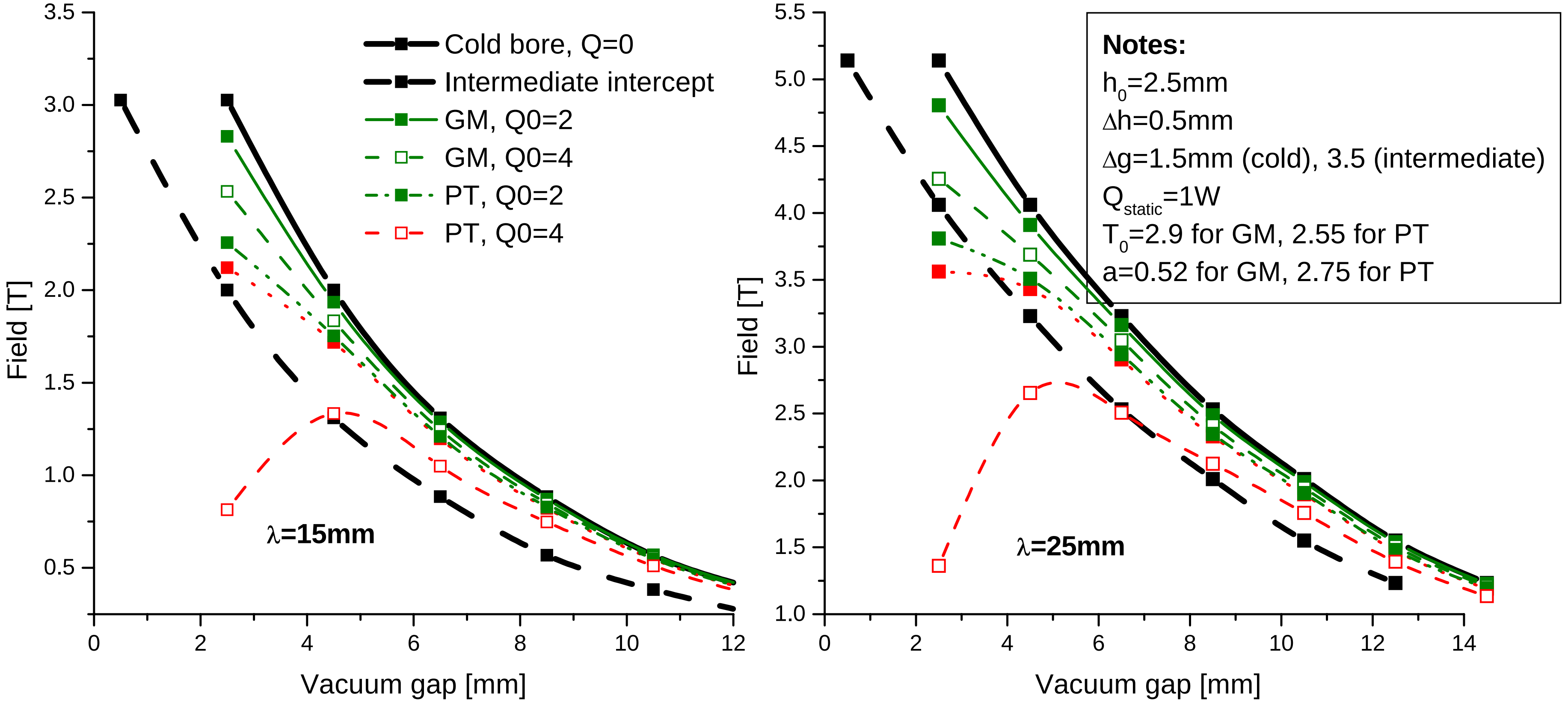


Performance curves

Based on a coupling of the image current heating and cryocooler performance

$$Q = Q_{static} + Q_{im} = 1 + Q_0 \frac{2.5}{h}$$

$$T(Q) \approx T_0 + aQ$$



Conclusions

- Nb_3Sn has superior performance compared to that of NbTi at all temperatures, specifically both at 4.2K and higher.
- For operating conditions with low beam heat-loads a cold-bore Nb_3Sn design yields best performance.
- Unlike NbTi, Nb_3Sn retains significant J_c for temperatures of 10K or higher, making operation at such temperatures of interest cryocooler-based systems when beam heat loads are expected.
- For high heat load scenarios, intercept temperature designs must be considered.