Superconducting Undulators for the Next Generation of Synchrotron Radiation Sources

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A joint effort by:

ALS Engineering & AFRD Supercon

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With much input/support from ALS groups:

Acc. Physics, Experimental Systems, and Scientific Support

David Robin, Christoph Steier, Howard Padmore, Zahid Hussain

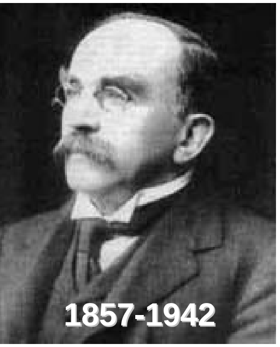
Outline

- Introduction: Insertion devices as Synchrotron Radiation Sources
- A brief review of the historical role of superconducting insertion devices
  - Examples of devices used or in use
- Technology development
  - Performance motivation
  - Technical considerations
  - Competing technologies
- Where we are now - current development
- Outstanding issues for diverse applications

Synchrotron radiation

First derived using classical mechanics, prior to the theory of relativity!

Thanks to Fernando Sannibale and David Robin, Fund. of Acc. Phys. course, USPAS, Phoenix, Jan 2006



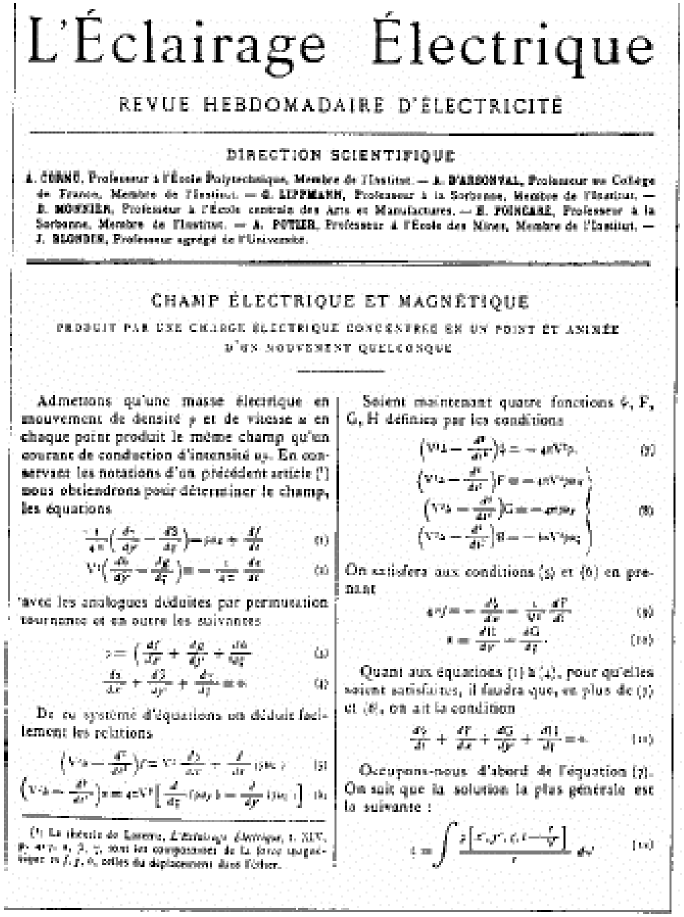
Joseph Larmor

Alfred Lienard

1898 Liénard:

ELECTRIC AND MAGNETIC FIELDS PRODUCED BY A POINT CHARGE MOVING ON AN ARBITRARY PATH

(by means of retarded potentials)



L'Éclairage Électrique

REVUE HEBDOMADAIRE D'ÉLECTRICITÉ

DIRECTION SCIENTIFIQUE

A. CORNU, Professeur à l'École Polytechnique, Membre de l'Institut. — A. D'ARSONVAL, Professeur au Collège de France, Membre de l'Institut. — G. LIPPMANN, Professeur à la Sorbonne, Membre de l'Institut. — D. MONNIER, Professeur à l'École centrale des Arts et Manufactures. — H. POINCARÉ, Professeur à la Sorbonne, Membre de l'Institut. — A. POTIER, Professeur à l'École des Mines, Membre de l'Institut. — J. BLONDIN, Professeur agrégé de l'Université.

CHAMP ÉLECTRIQUE ET MAGNÉTIQUE

PRODUIT PAR UNE CHARGE ÉLECTRIQUE CONCENTRÉE EN UN POINT ET ANIMÉE D'UN MOUVEMENT QUELCONQUE

Admettons qu'une masse électrique en mouvement de densité ρ et de vitesse u en chaque point produit le même champ qu'un courant de conduction d'intensité $u\rho$. En conservant les notations d'un précédent article [1] nous obtiendrons pour déterminer le champ, les équations

avec les analogues déduites par permutation tournante et en outre les suivantes

$$\frac{d\alpha}{dx} + \frac{d\beta}{dy} + \frac{d\gamma}{dz} = 0 \qquad (4)$$

De ce système d'équations on déduit facilement les relations

[1] La théorie de Lorentz, L'Éclairage électrique, t. XIV, p. 417; α, β, γ, sont les composantes de la force magnétique et f, g, h, celles du déplacement dans l'éther.

Soient maintenant quatre fonctions ψ, F, G, H définies par les conditions

On satisfera aux conditions (5) et (6) en prenant

Quant aux équations (1) à (4), pour qu'elles soient satisfaites, il faudra que, en plus de (7) et (8), on ait la condition

$$\frac{d\psi}{dt} + \frac{dF}{dx} + \frac{dG}{dy} + \frac{dH}{dz} = 0. \qquad (11)$$

Occupons-nous d'abord de l'équation (7). On sait que la solution la plus générale est la suivante :

Fig. 1. First page of Liénard's 1898 paper.

Insertion devices as Synchrotron Radiation Sources

- The first storage rings were designed for high-energy physics
  - As energy of electrons was increased, energy was observed to be lost in the form of radiation – synchrotron radiation
  - Key limitation to modern HEP accelerators (one of the motivators for proton rings, and the need to switch to linear colliders for leptons…)
- "2nd generation" sources were rings devoted to SR generation, essentially using the bend magnets as sources (examples: NSLS, ANKA, Spear II, …)

1943: Synchrotron invented by Oliphant
1945: Vekslar, McMillen invent the synchrocyclotron and Betatron
1947: synch. rad. observed at 70Mev GE synchrotron
1949: Wilson et al. first stored beam in a synchrotron
1952: Courant and Snyder develop strong focusing;
already patented by Christofilos!
1959: CERN PS operational
1960: Brookhaven AGS operational
1972: Spear completed (leads to J/Psi discovery,…)

IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

SPEAR II PERFORMANCE*

SPEAR Group†
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305
(Presented by J. M. Paterson)

"… In parallel with the high energy physics program, the Stanford Synchrotron Radiation Project has a large continuing program of ultraviolet and x-ray research.[8] "

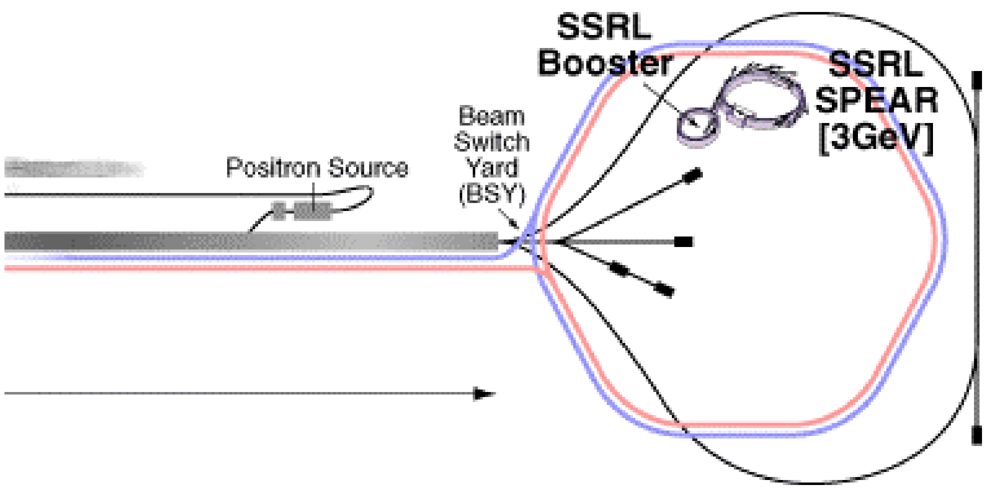
1990: SPEAR is used exclusively for SR production

IEEE 1998

SPEAR III – A BRIGHTER SOURCE AT SSRL*

R. Hettel, R. Boyce, S. Brennan, J. Corbett, M. Cornacchia, W. Davies-White, A. Garren, A. Hofmann, C. Limborg, Y. Nosochkov, H.-D. Nuhn, T. Rabedeau, J. Safranek†, H. Wiedemann
Stanford Synchrotron Radiation Laboratory, SLAC, Stanford, CA 94309

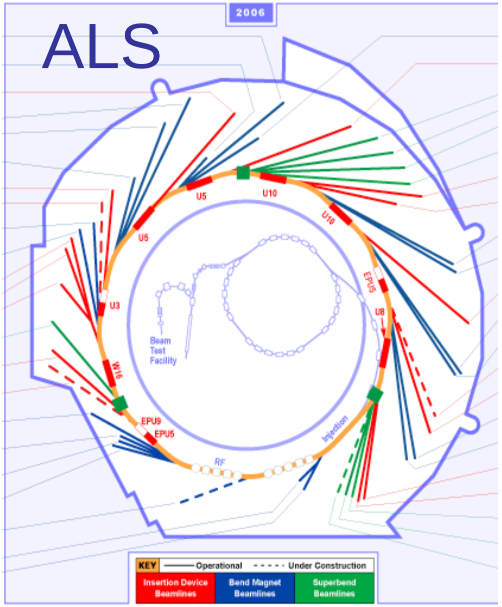
"… By replacing the magnets and vacuum chamber for the 3 GeV SPEAR II storage ring, the natural emittance of the machine can be reduced from 130 to 18 nm-rad and the stored current can be raised from 100 to 200 mA with a 50 h lifetime. This configuration increases focused photon flux for insertion device beamlines by an order of magnitude and the photon brightness for future undulators would exceed 10^{18} at 5 keV. …"



Dedicated SR sources

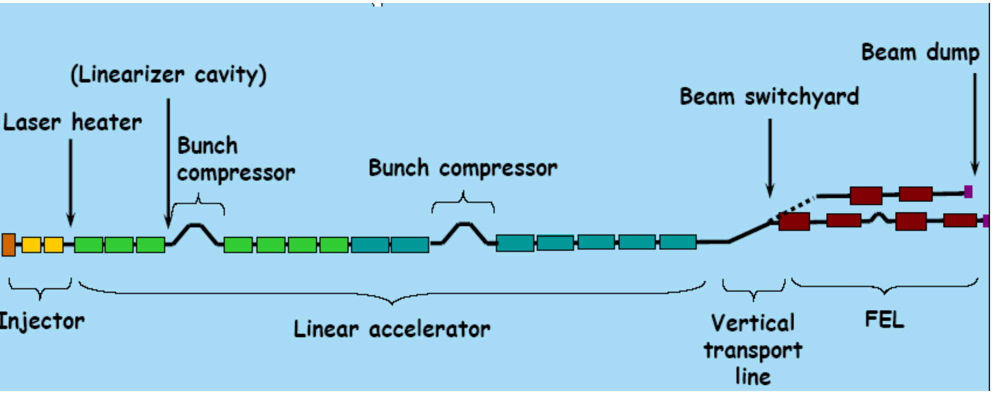
- "3rd generation" sources designed for use of special magnetic systems, "insertion devices", (ID's), into the straight sections of storage rings to generate specific radiation properties tailored to the beamline science needs. (Examples: ALS, Spear III, APS, ESRF,…)
  - Accelerator physics: - ID's should not impact the stored beam – want scalability, ability to exchange devices, etc
  - Scientific users: - ID's tailored to science need, e.g. flux or brightness over a given energy range, polarization control, etc.

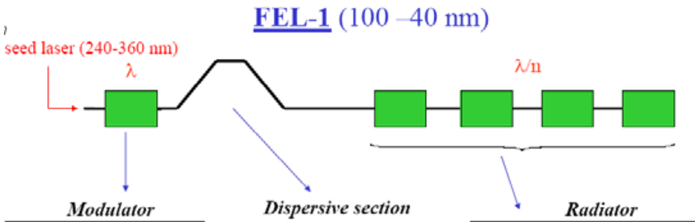
Note: almost all 2nd generation rings now incorporate ID's to enhance their science capabilities



- "4th generation" sources are currently being built – FEL's & ERL's. (examples: LCLS, DESY XFEL, Fermi at Elettra, 4GLS …)
  - Electron bunch passage through "Insertion device" generates synchrotron radiation, which in turn modulates the electron bunch energy; cycle can be repeated down to a final ID section that "radiates" the resulting micro-bunched beam coherently

Example: Fermi@Elettra workshop 2005: J. Corlett, G. De Ninno





Modulator

Parameter	Value
Type	Planar
Structure	One segment
Period	16 cm
K	3.9 - 4.9
Length	3.04 m

Dispersive section

Parameter	
R_{56}	~ 30 microns (40 nm)
Length	~ 1 m

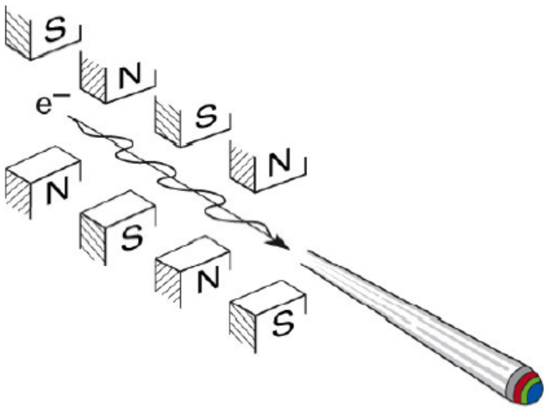
Radiator

Radiator	Value
Type	Apple
Structure	Segmented
Period	6.5 cm
K	2.4 - 4
Segment length	2.34 m
Break length	1.06 m
Total length	12.48 m

Total length FEL-1 ~ 16.5 m

Undulator and Wiggler characteristics: Field properties

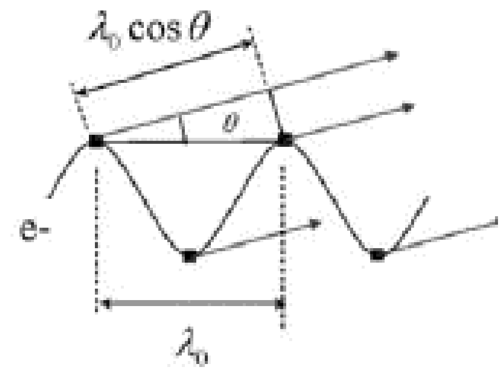
- These are magnetic devices generating fields transverse to the passing charged particles, usually designed to be inserted into a ring to generate synchrotron radiation
  - Fields can be “planar”, helical, or variable
  - Planar devices exhibit vertical focusing
  - $\Rightarrow$ There is always some coupling of device to beam-physics



- Fields are characterized by oscillation period and field strength
  - Strength parameter K distinguishes radiation properties

$$x = -a\cos(2\pi z/\lambda_u); \quad ev \times B = m_e v^2/\rho$$

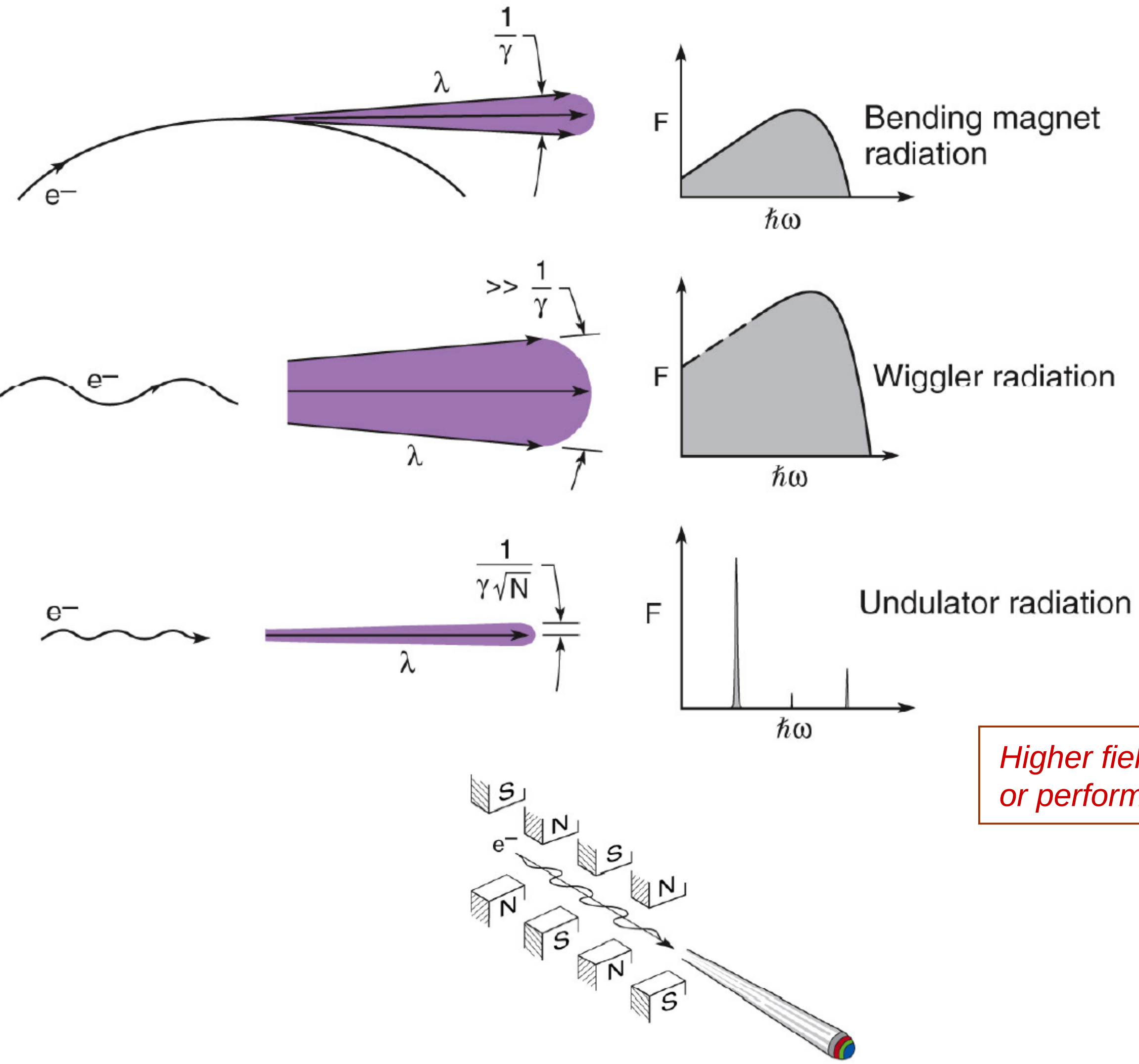
$$\Rightarrow (dx/dz)_{\max} \overset{def}{=} K/\gamma \quad \Rightarrow \quad K = \frac{eB\lambda_u}{2\pi m_0 c} = 0.934\lambda_u[cm]B[T]$$



Brian Kincaid, JAP 1977;
See R. Schlueter, Res. Memo 88-57, LLNL 1988 for wiggler field harmonics and focusing

Undulator and Wiggler characteristics: Radiation properties

From David Attwood,
Introduction to Synchrotron Radiation



Continuous spectrum characterized by

ε_c = critical energy

ε_c(keV) = 0.665 B(T)E²(GeV)

$$P[kW] = 0.633 E^2[GeV]\, B^2[T]\, I[A]\, L[M]$$

Higher field results in higher critical energy, more power

$$\varepsilon_1\,(\text{keV}) = \frac{0.95\, E^2\,[\text{GeV}]}{\lambda_u\,[\text{cm}]\,(1 + \frac{K^2}{2})}$$

Quasi-monochromatic spectrum with peaks at lower energy than a wiggler

Higher field for same period results in larger spectral range, or performance can be leveraged to increase brightness

Example applications

- Synchrotron radiation sources for soft / hard x-rays
  - Large number of lights sources worldwide (and quickly growing!)
  - Number of free electron laser projects underway
  - Figure of merit is typically brightness (ph./s/mm^2/mr^2/0.1%bw)

  Higher performance yields higher brightness and/or increased spectral range, or access to higher energy photons
- Damping rings
  - Emittance is reduced proportional to synchrotron radiation power
  - Figure of merit is SR source power => wigglers

  Higher field yields higher power: $P \sim B^2$
- Positron source for ILC
  - Positrons generated from pair-production
  - Polarized positrons from circular pol. radiation
  - Figure of merit is photon flux

  } *Helical undulator*

  Higher performance yields higher positron production, shorter undulator length

A brief review of the historical role of superconducting insertion devices

Ancient history

- The first undulators proposed were superconducting
  - 1975, undulator for FEL experiment at HEPL, Stanford
  - 1979, undulator on ACO
  - 1979, 3.5T wiggler for VEPP

Superconducting helically wound magnet for the free-electron laser

Rev. Sci. Instr., 1979

L. R. Elias and J. M. Madey

High Energy Physics Laboratory, Stanford University, Stanford, California 94305

(Received 12 April 1979; accepted for publication 18 May 1979)

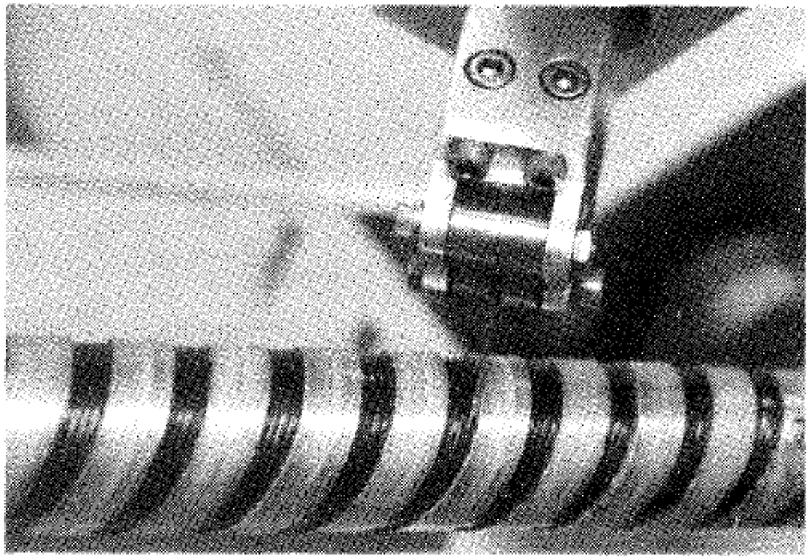


FIG. 5. Wire winding tool and partially completed magnet.

IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

GAIN MEASUREMENT ON THE ACO STORAGE RING LASER

D.A.G. Deacon[a], J.M.J. Madey[a], K.E. Robinson[a], C. Bazin[b], M. Billardon[c], P. Elleaume[d], Y. Farge, J.M. Ortéga[c], Y. Pétroff, M.F. Velghe[e].

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Superconducting undulator development

The naissance of RE permanent magnets

- In the 1980's and 1990's:
  - Klaus Halbach and others quickly and effectively developed permanent magnet undulators - largely stalled further development of SCU's
  - Planar, elliptical, quasi-periodic…

NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 1-10; © NORTH-HOLLAND PUBLISHING CO.

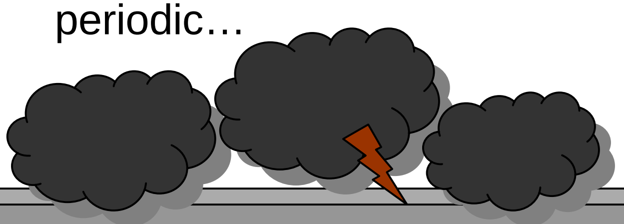
DESIGN OF PERMANENT MULTIPOLE MAGNETS WITH ORIENTED RARE EARTH COBALT MATERIAL*

K. HALBACH

University of California, Lawrence Berkeley Laboratory, Berkeley, CA 94720, U.S.A.

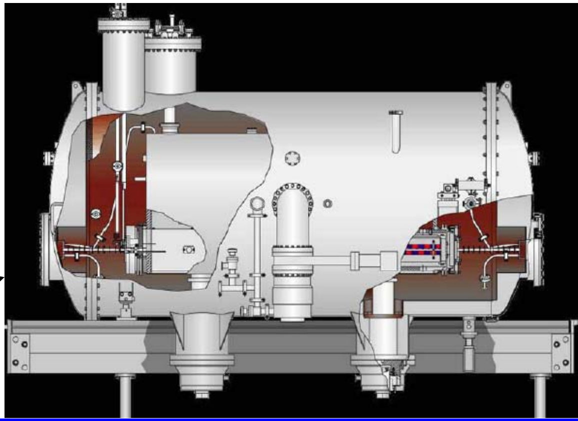
Received 20 August 1979

By taking advantage of both the magnetic strength and the astounding simplicity of the magnetic properties of oriented rare earth cobalt material, new designs have been developed for a number of devices. In this article on multipole magnets, special emphasis is put on quadrupoles because of their frequent use and because the aperture fields achievable (1.2–1.4 T) are rather large. This paper also lays the foundation for future papers on: (a) linear arrays for use as "plasma buckets" or undulators for the production of synchrotron radiation; (b) structures for the production of solenoidal fields; and (c) three-dimensional structures such as helical undulators or multipoles.



But the dark ages for SCID's…

- Nevertheless, some progress continued on superconducting wigglers and undulators
  - E.g Budker >11 devices, NbTi, Nb3Sn
  - First (?) cold-bore ID (wiggler) installed at MaxLab



Sampling of superconducting insertion devices

Location	λ [mm]	Year	Gap (mag.) [mm]	Gap (vac.) [mm]	Vac. T. [K]	B [T]	Type	Comments
Anka/Accel	14	2003	5		4.2	1.35	U	Variable gap device
SRRC / Wang NMR	60	2003	18		20		W	
Elettra / BINP	64	2002	16.5	11	20	3.5	W	RF heating renders inoperable
Max-lab	61	2002	12	10.2	4.2	3.54	W	Beam-heating higher than expected;
SRRC/Wang NMR	-	2002	55	20	300	6	WS	
Bessy II/ ACCEL	-	2002		30	300	6	WS	Operating; cryocooler insufficient, uses cryogens
Bessy II/BINP	172	2001	52	32	300	7.0	WS	Problems with cryogenics; not operating
Bessy II/BINP	172	2002	52	32	300	7.0	W	RF liner did not work
NSLS	26	1994	8.6			0.82	W	(see NSLS und. Below)
NSLS	18	1994	8.6			0.54	U	Attained field; attempted shimming with additional Sc circuits; problems with complicated field quality controls, cryogenics
SRRC	10	2000	2			1.39	U	
Firfel	10		2		4.2	1.07	U, St	
BNL (HGFEL)	18		8			0.54	U	
BNL (ATF)	8.8		4.4			0.66	U	

Pushing the limits of technology

- Permanent magnet ID’s are now mature
  - Pure magnet -> hybrid systems -> in-vacuum devices
  - Elliptically polarizing undulators (EPU’s)
  - Quasi-periodic undulators and EPU’s
  - Continue to make progress through material improvement

The age of enlightenment…

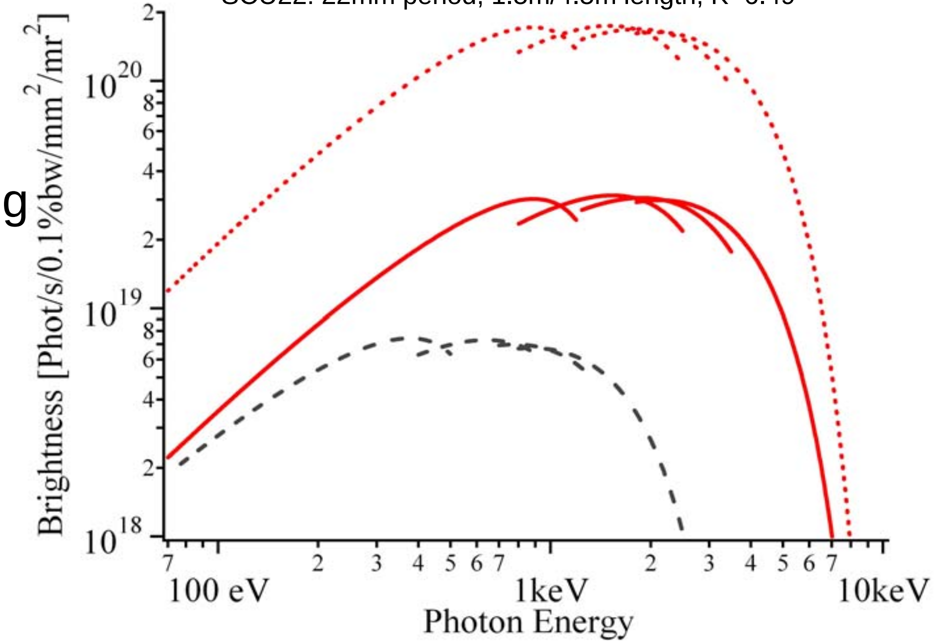
Recent renewed interest in superconducting undulators

- Potential to enhance the brightness and/or spectral range available to users
- Leverage significant development in superconductors and superconducting magnet technology

ALS upgrade parameters

U50: 50mm period, 4.5m length, K=3.97

SCU22: 22mm period, 1.5m/4.5m length, K=6.49



Undulator evolution

ALS U50 (1993)

Hybrid permanent magnet technology

ALS EPU50 (1998)

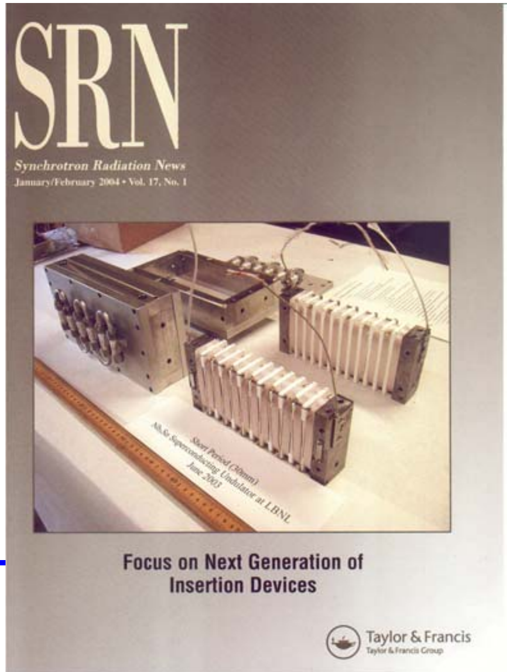
Pure permanent magnet technology, Elliptically polarizing capability

Spring8 IVUN (2000)

Small gap In-vacuum device

ALS SCU (200?)

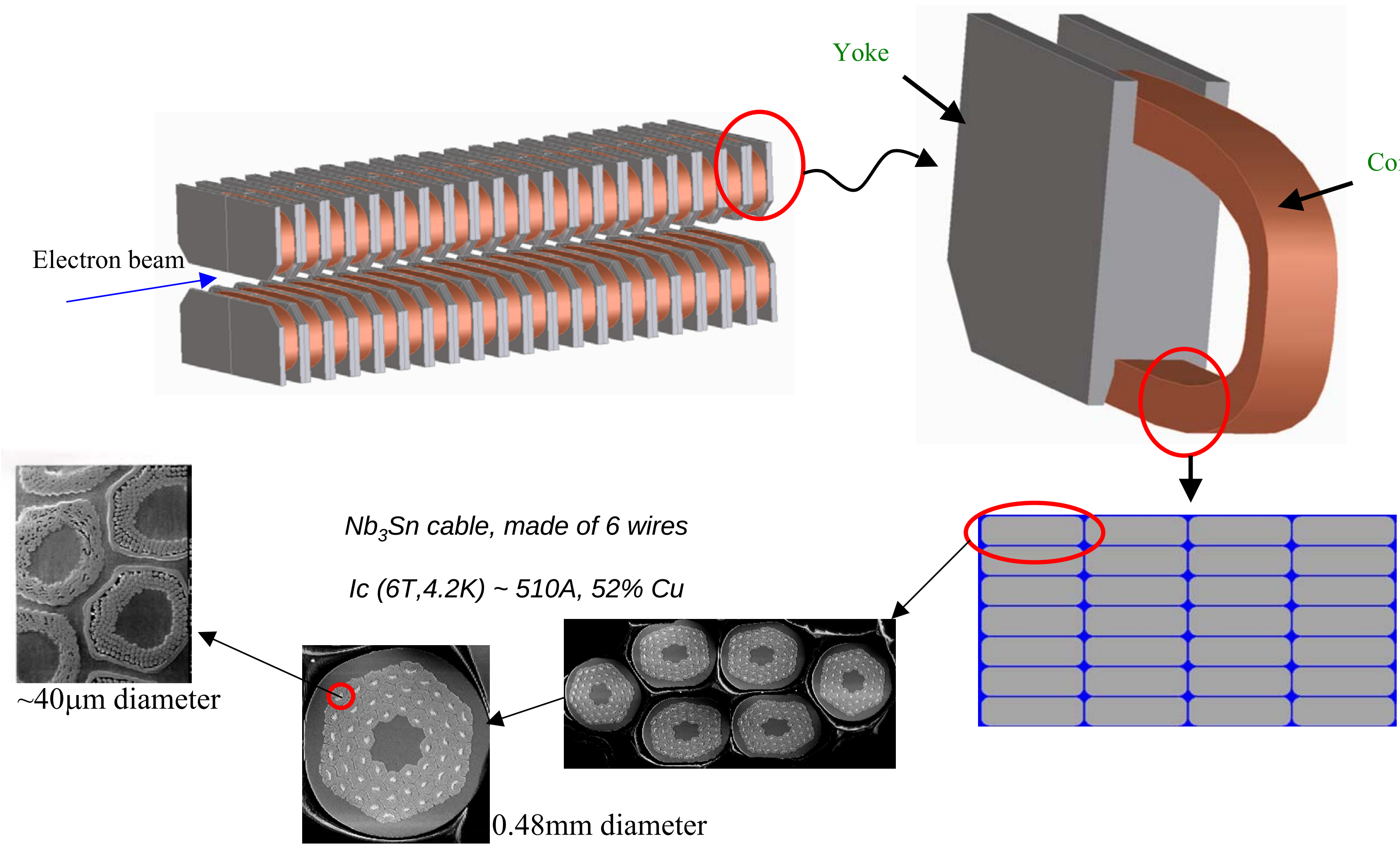
Nb_3Sn superconducting undulator



Technological development of SCU's at LBNL

- Performance motivation – why consider superconducting devices?
- Technical considerations
- Example projected performance and competing technologies

Superconducting undulators – general approach

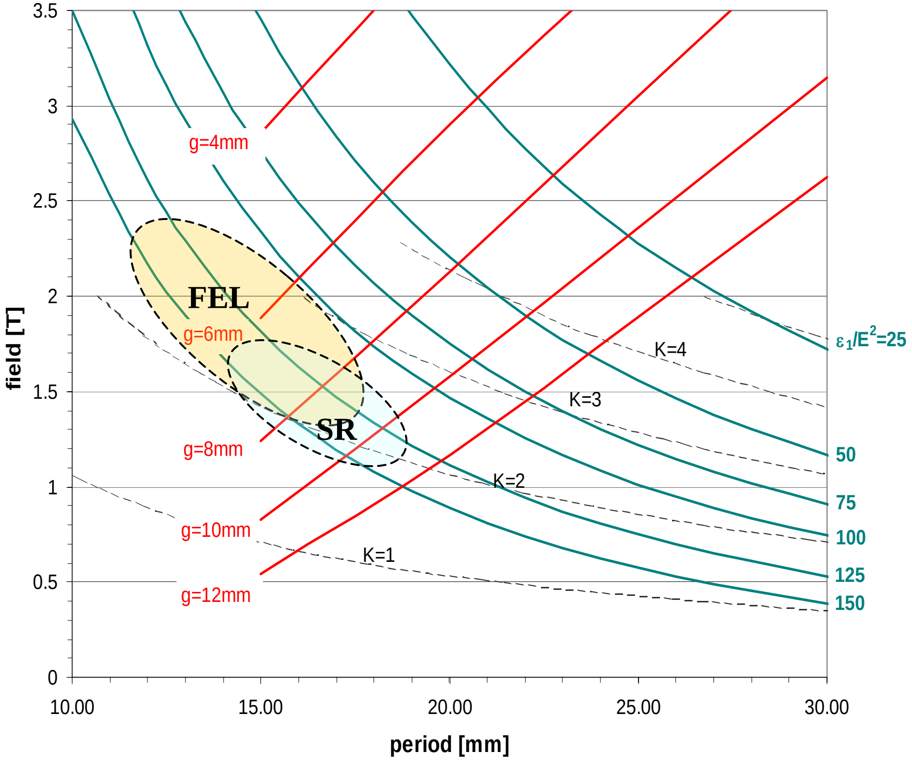


Performance considerations

Motivation for Nb_3Sn SCU's

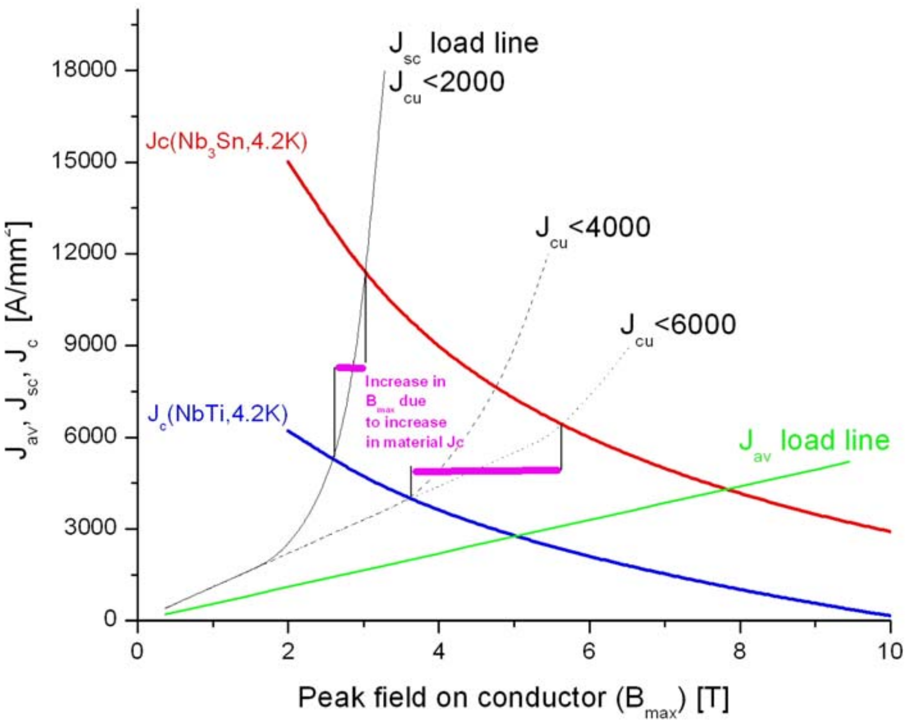
- **Motivation for SCU's**
  - Promises the best performance, in terms of spectral range and brightness, compared to competing technologies (PM, PM hybrid, Cryo-PM, …)

Nb3Sn superconducting undulator performance curves



- **Motivation for Nb_3Sn**
  - Low stored energy in magnetic system
    - "break free" from J_{cu} protection limitation
  - Take advantage of high Jc, low Cu fraction in Nb_3Sn
  - "High" T_c (~18K) of Nb_3Sn provides temperature margin for operation with uncertain/varying thermal loads

=> LBNL pioneered the use of Nb_3Sn for SCU's



Key design issues: application concerns

- Field quality requirements dictated by:
  - Beam physics
    - Beam path (steering, displacement)
    - focusing, dynamic effects
  - Radiation properties
    - phase error minimization for higher harmonics
    - trajectory straightness for FEL applications

- Operating conditions must be met
  - User radiation spectrum or power requirements
  - Acceptable impact on storage ring
  - Cryogenics must be compatible with facility

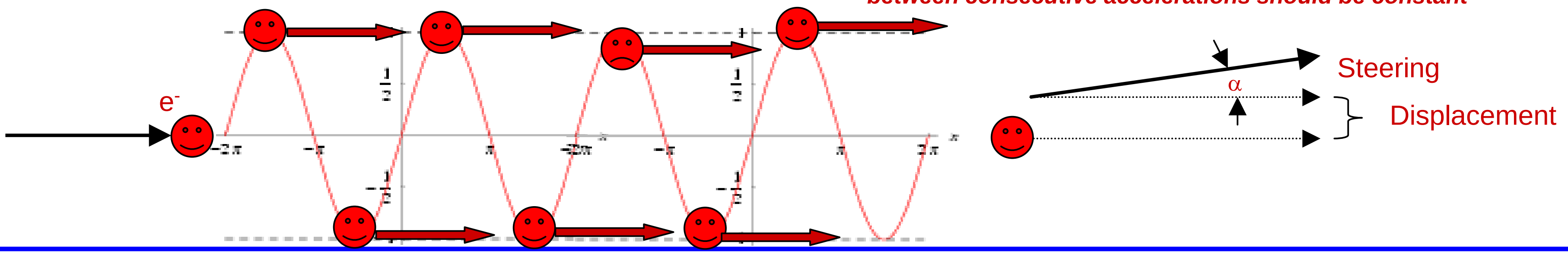
Technical issues with superconducting ID's

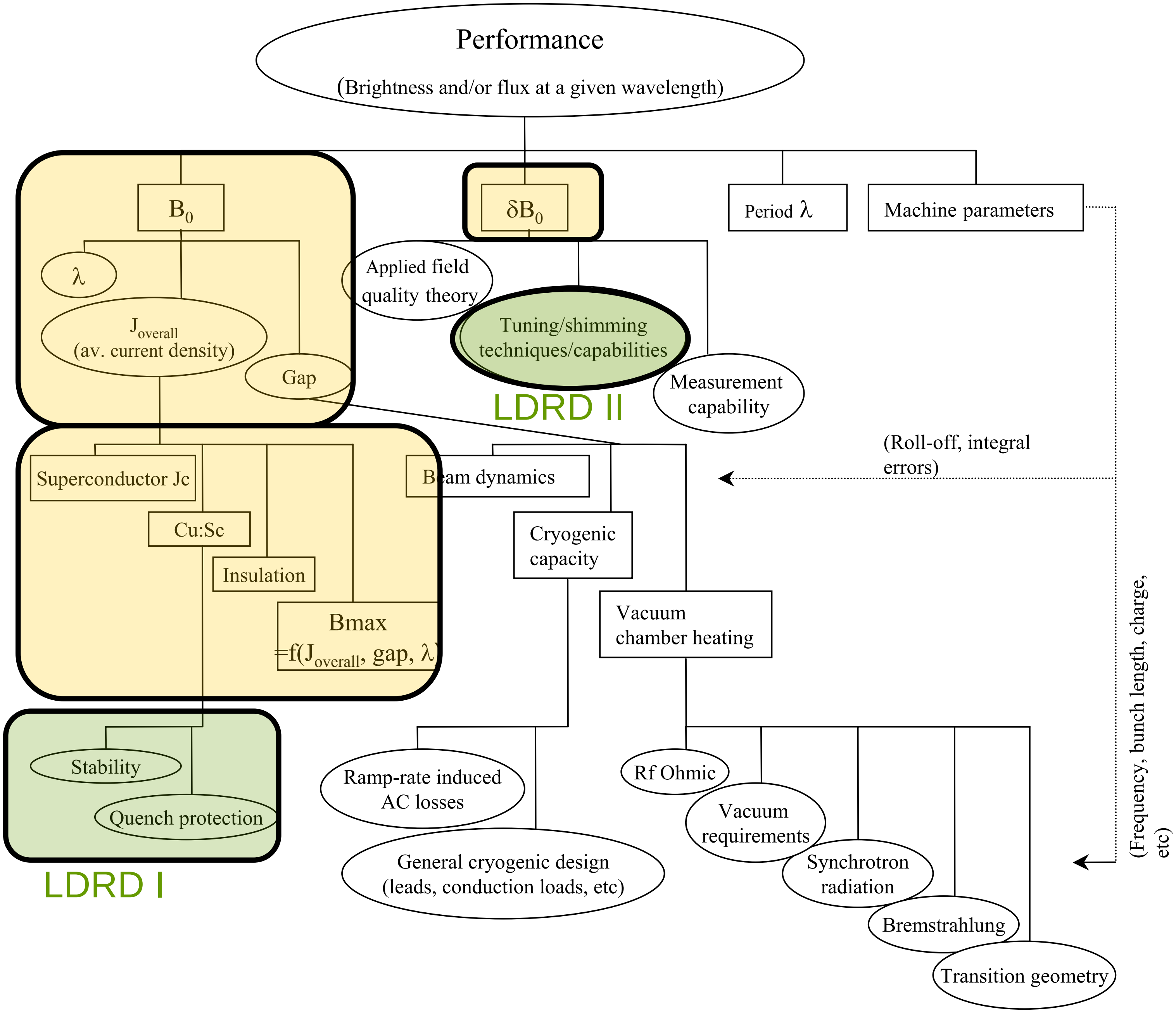
- ***"Low" peak conductor fields => high current densities***
  - Low-field instability issues
  - Quench protection must accommodate extremely high Cu current densities
  - Small conductor size required for reasonable currents => poor fill factor
- ***Cryogenic issues***
  - Beam-based heating
    - Image-currents
    - Synchrotron radiation
    - Other…
  - Traditional loads (conduction and thermal radiation)
- ***Phase-correction***
  - May need active correction due to dual regime (saturated and unsaturated poles)
    - Application-dependent
- ***Magnet measurement system***
  - Must work with cold magnet
  - Need integral measurements for beam displacement and steering determination
  - Need Hall-probe data with sufficient accuracy for phase-error determination

See "**Workshop on Superconducting Undulators & Wigglers", ESRF**

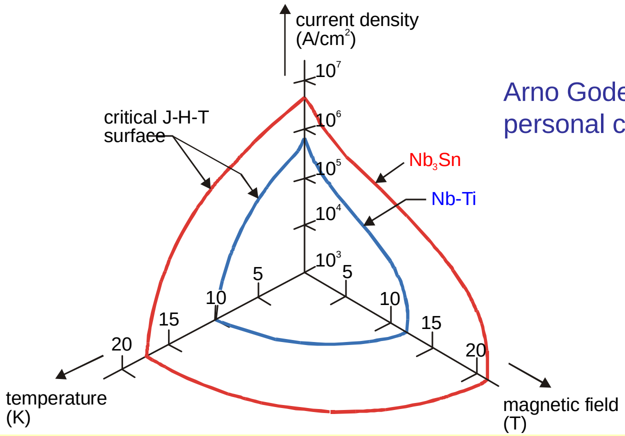
http://www.esrf.fr/Acelerators/Conferences/ID_Workshop

EM pulses must be in phase: distance traveled by electron between consecutive accelerations should be constant




Performance
(Brightness and/or flux at a given wavelength)
B_0
δB_0
Period λ
Machine parameters
λ
Applied field quality theory
$J_{overall}$ (av. current density)
Tuning/shimming techniques/capabilities
Gap
Measurement capability
LDRD II
(Roll-off, integral errors)
Superconductor Jc
Beam dynamics
Cu:Sc
Cryogenic capacity
Insulation
Vacuum chamber heating
Bmax $=f(J_{overall}, gap, \lambda)$
(Frequency, bunch length, charge, etc)
Stability
Quench protection
Ramp-rate induced AC losses
Rf Ohmic
Vacuum requirements
General cryogenic design (leads, conduction loads, etc)
Synchrotron radiation
Bremstrahlung
Transition geometry
LDRD I

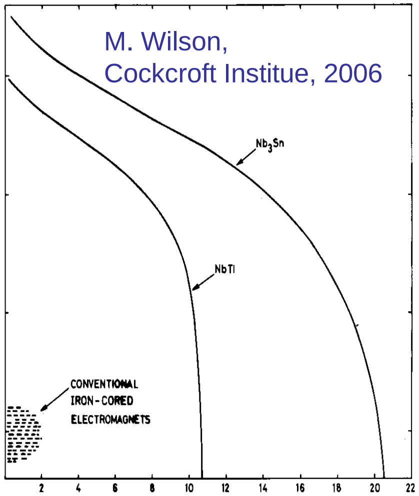
Low-temperature superconductors of interest: NbTi with Artificial Pinning (APC), Nb_3Sn



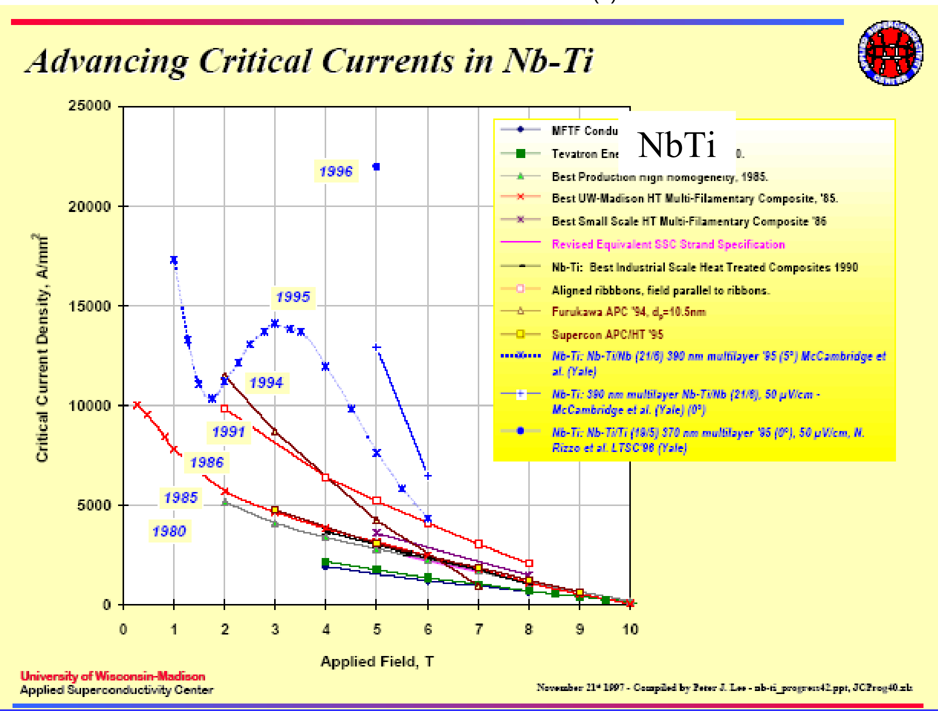
Arno Godeke, personal communication

Nb_3Sn

Note: High temperature superconductors (HTS) and existing versions of MgB_2 do not (yet) carry sufficient current, at any temperature, to compete with PM undulators



M. Wilson, Cockcroft Institute, 2006



R. Scanlan and D. Dietderich
IEEE Trans. Applied Supercond., Vol. 13, No 2, June 2003

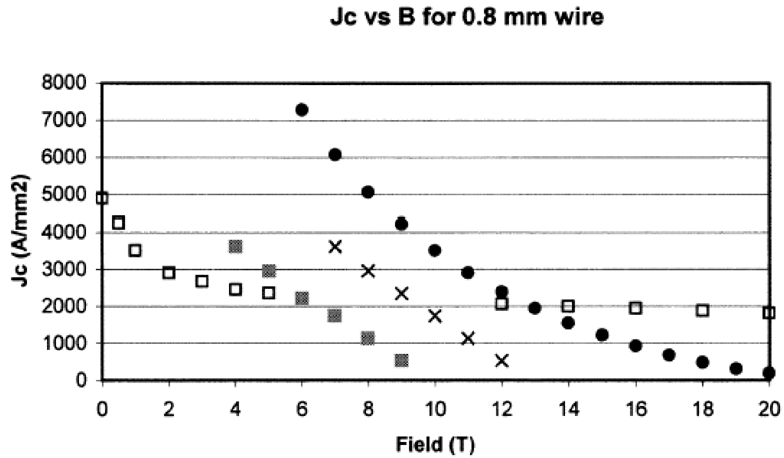
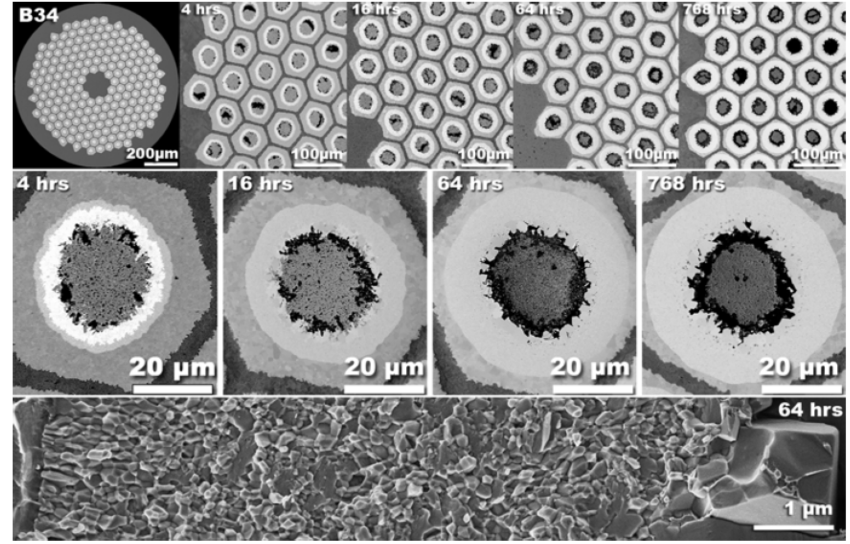


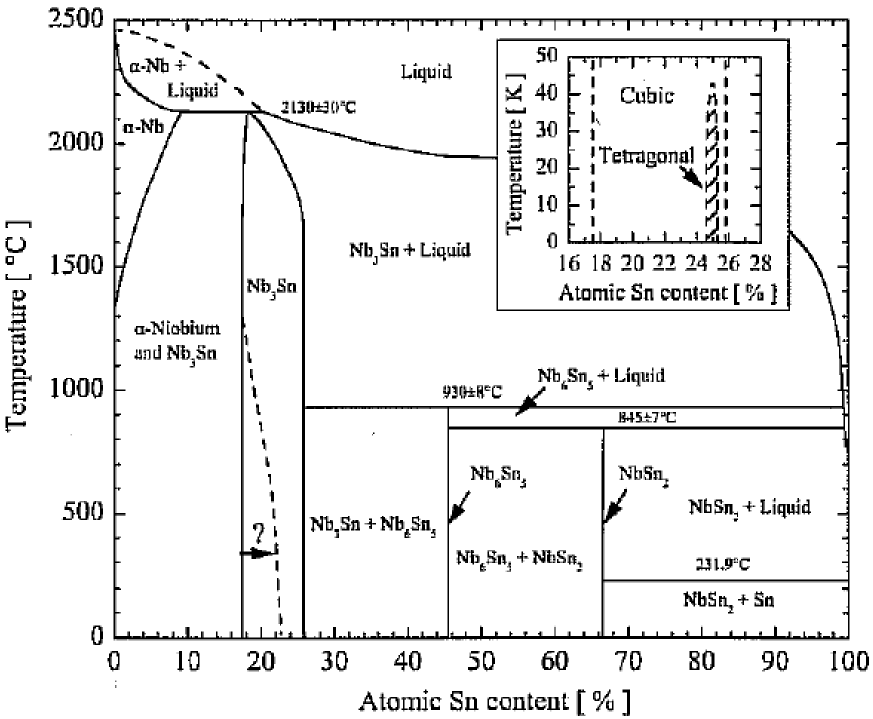
Fig. 5. Critical current vs. field for high field superconductors—Bi-2212 (open squares), Nb_3Sn (triangles), NbTi at 4.2 K (solid squares), and NbTi at 1.8 K (crosses). The crossover for Bi-2212 and Nb_3Sn is about 13 T on the basis of J_c. However, the practical crossover is still higher, due to the large volume fraction of Ag matrix required in the fabrication on the Bi-2212 wire at present.

Nb_3Sn superconductors

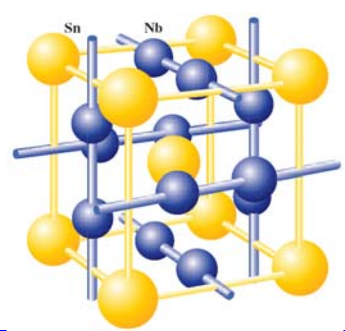


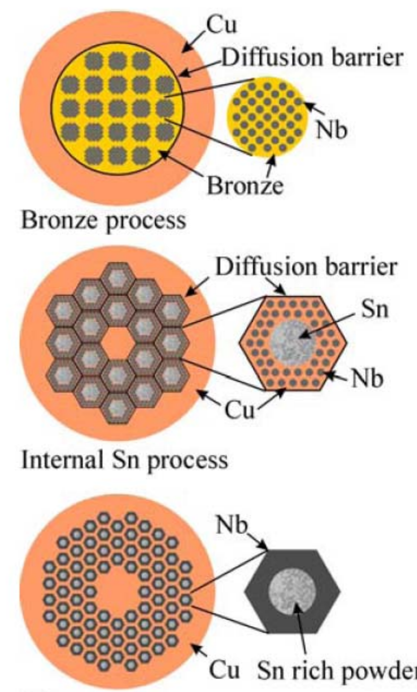
- These are intermetallic compounds, in an A15 structure; A15 is a **brittle** crystal structure
- Requires a fabrication process providing the appropriate composition and A15 development
- Process must not jeopardize **quality of stabilizer** in conductor (typically Cu)
- Requires heat treatment to **~650C**

=> Have significant impact on magnet design and fabrication!



See Thesis of
Arno Godeke
for an excellent
review of Nb3Sn
(source of these plots)





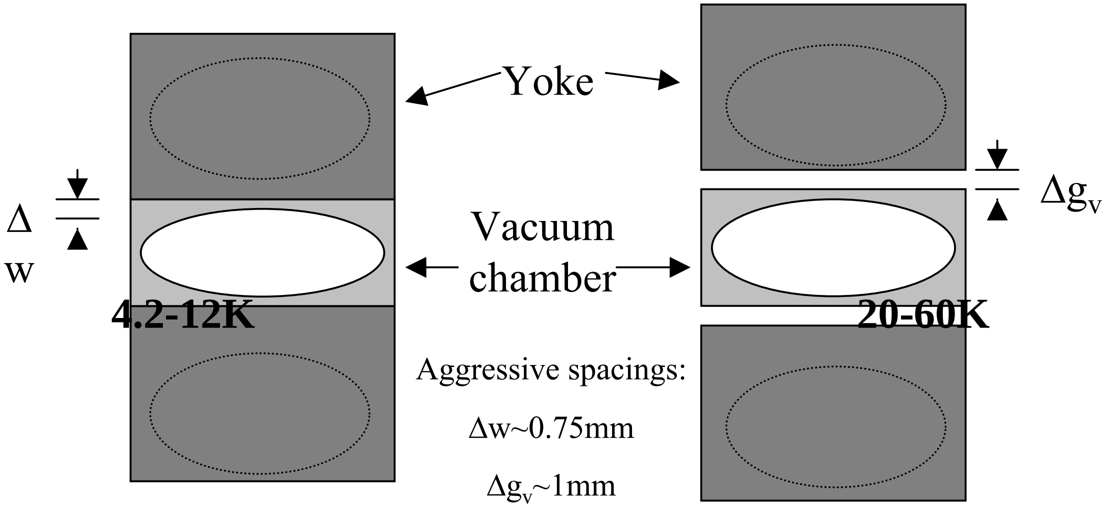
Cryogenic design options

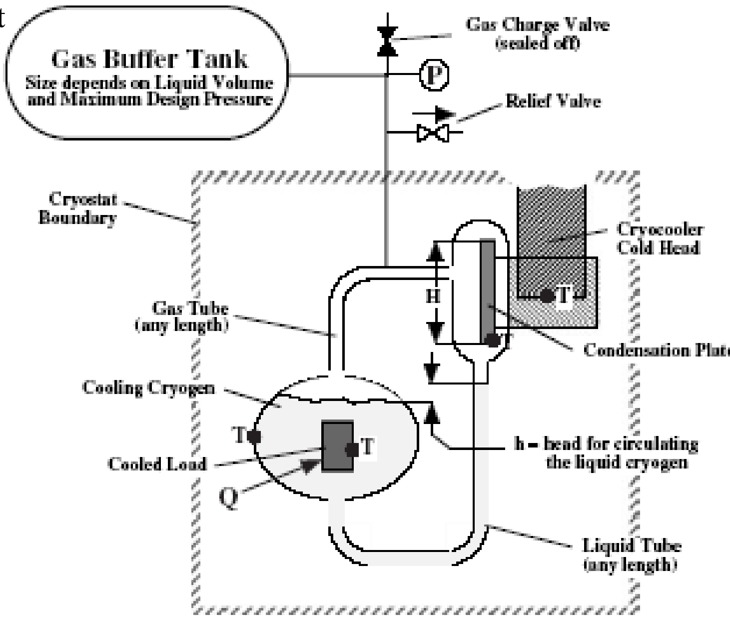
- Can use liquid cryogens or cryocoolers
  - Liquid cryogen approach requires liquifier + distribution system or user refills
  - Cryocoolers require low heat load and (traditionally) incur temperature gradients through conduction path and impose vibrations from GM cryocooler
    - Limits operating current due to current-lead heat load (despite HTS leads; typical limit is <1kA)
    - Solution: heat pipe approach (C. Taylor; M. Green)
- Need to know the heat loads under all operating regimes

M. Green, Supercond. Sci. Tech.16, 2003
M. Green et al, Adv. in Cryogenic Eng., Vol. 49

•Vacuum chamber and magnet can be thermally linked; magnet and chamber operate at 4.2-8K

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





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 = bunch spacing,
l_b = bunch length
h = half-gap
Z_0 = 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)

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

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

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

	Cu		**Al**	
	300K	***4.2K***	***300K***	***4.2K***
Boris example (BNL)	51.89	9.84	64.70	8.32
ALS present	3.94	0.66	4.91	0.56
ALS 2-bunch present	11.08	1.85	13.81	1.56
ALS upgrade	13.19	2.20	16.45	1.86
ALS upgrade - X	25.59	4.60	31.91	3.88
ALS upgrade 2-bunch X	21.49	3.86	26.80	3.26
Max-Lab II	0.73	0.13	0.90	0.11
ESRF uniform	1.95	0.31	1.95	0.31
ESRF 16-bunch	6.59	0.91	6.59	0.91
ESRF 1-bunch	2.77	0.36	2.77	0.36

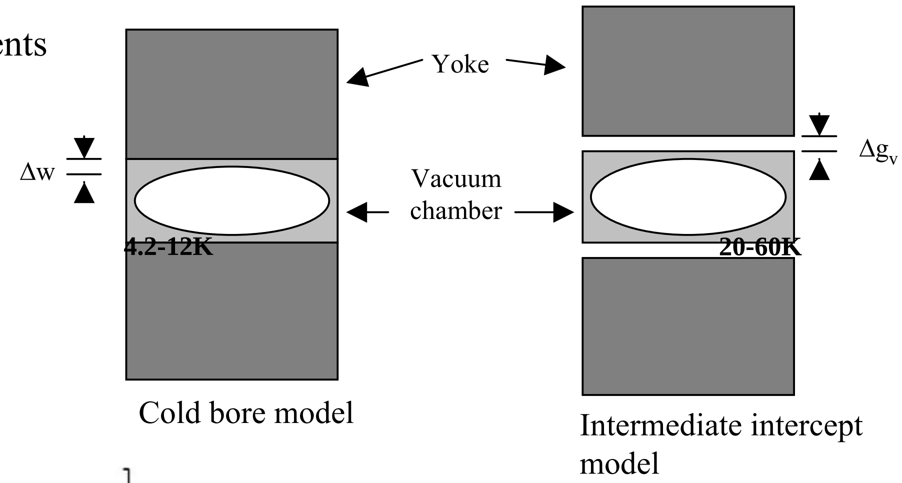
Beam heating impact on performance

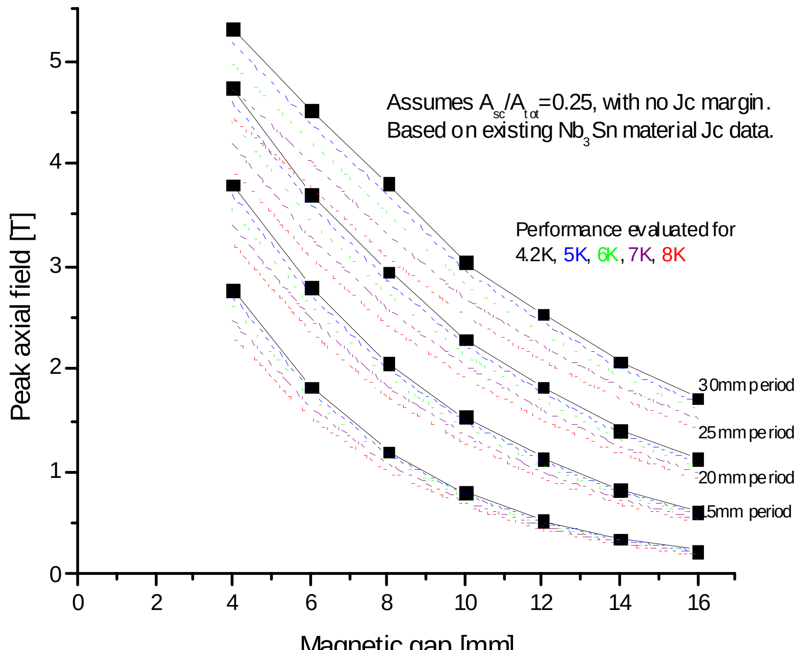
- In synchrotron rings, image current heating impacts design
- In FEL's, low duty-factor typically implies low image currents
  - → Other heating sources will dominate

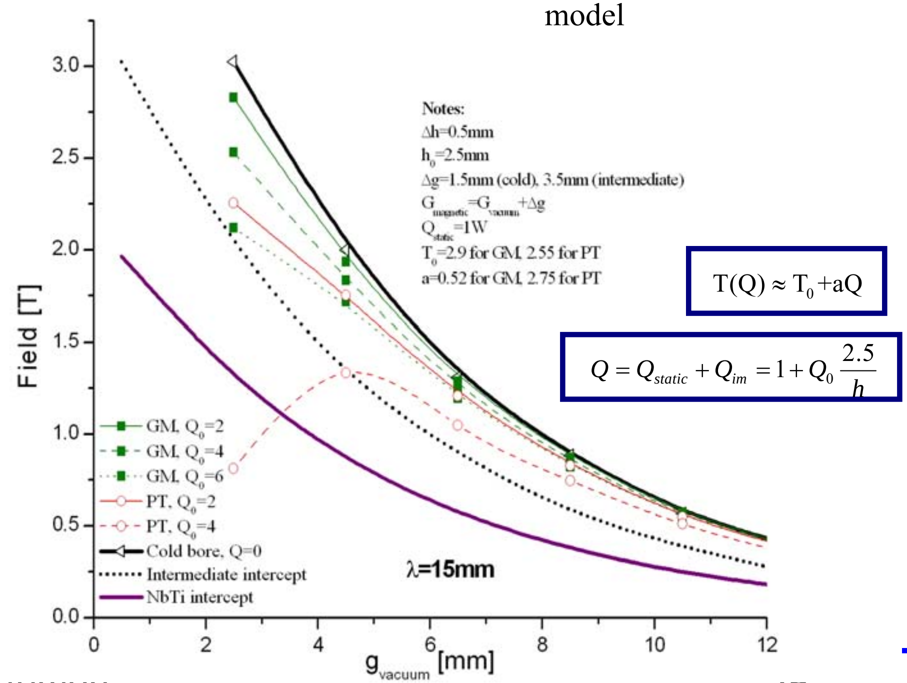
$$Q_{im} = \alpha \frac{I^2 l_s}{h(l_b)^{5/3}} Z_0^{2/3} (\rho \lambda_e)^{1/3}$$

Cold, extreme anomalous skin effect regime:
ALS: ~ 2 W/m
LCLS: ~ 3.e-4 W/m

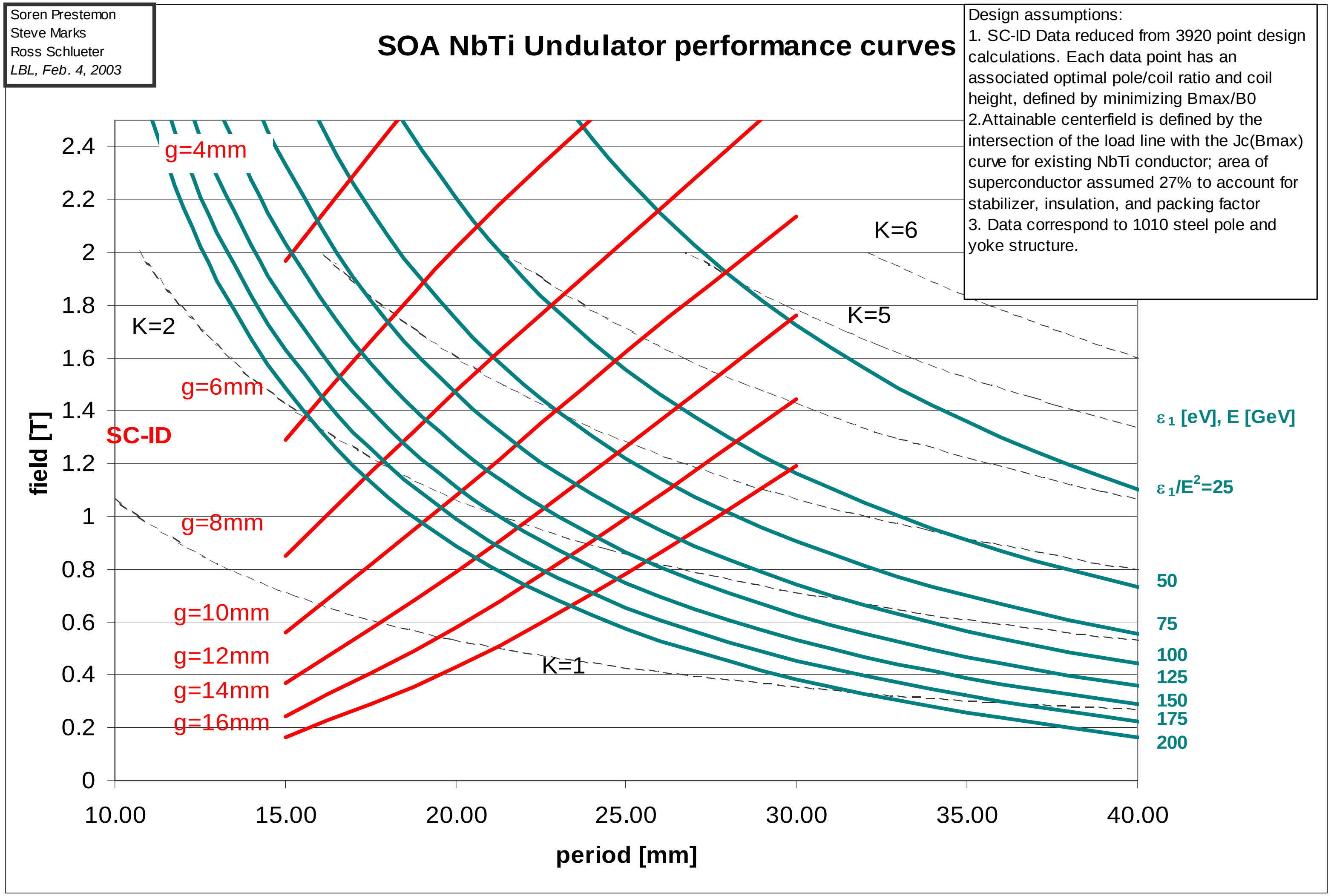
***Ref: Boris Podobedov**, Workshop on Superconducting Undulators and Wigglers, ESRF, June, 2003*



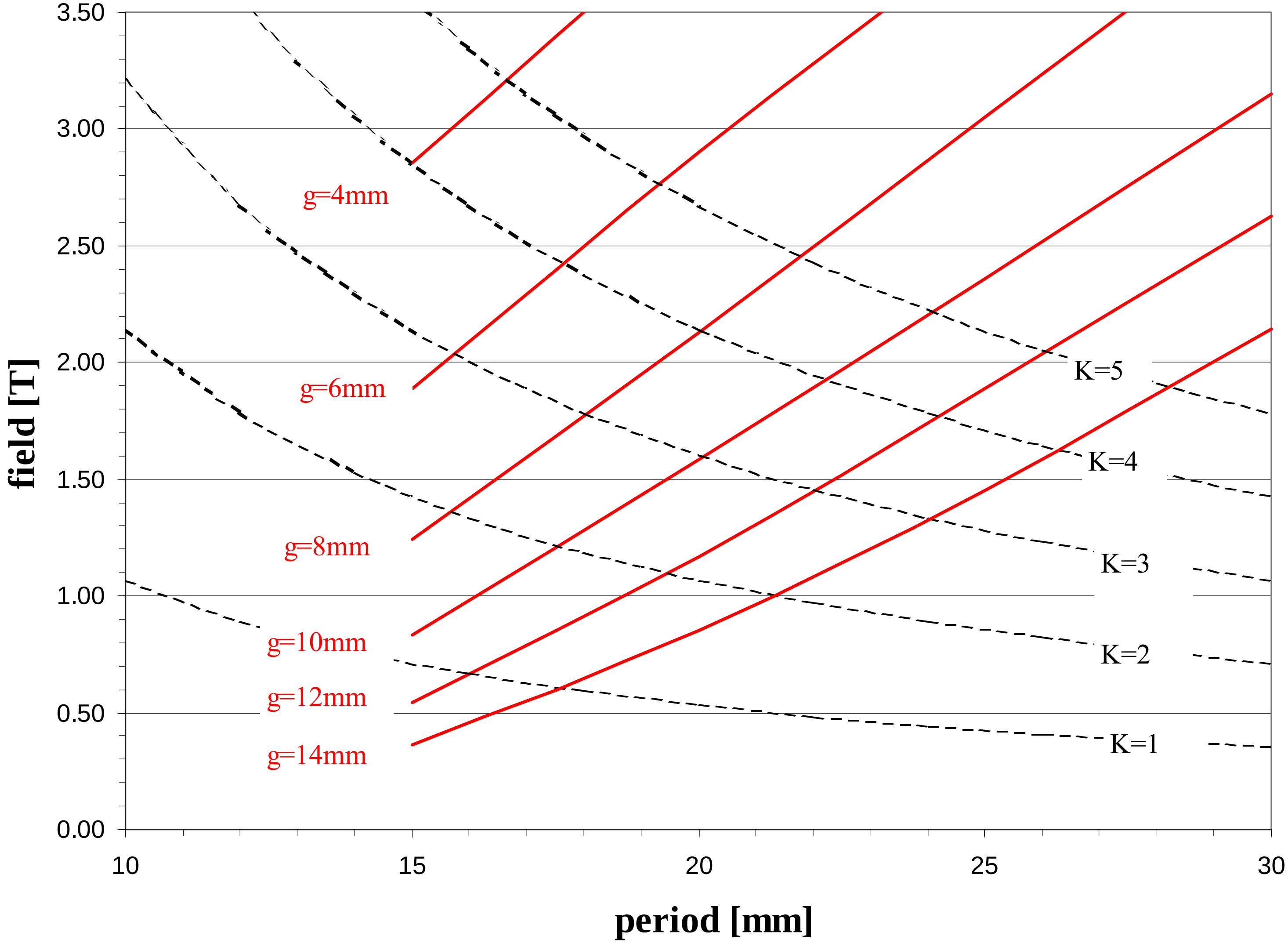




Calculated performance curves for NbTi conductors

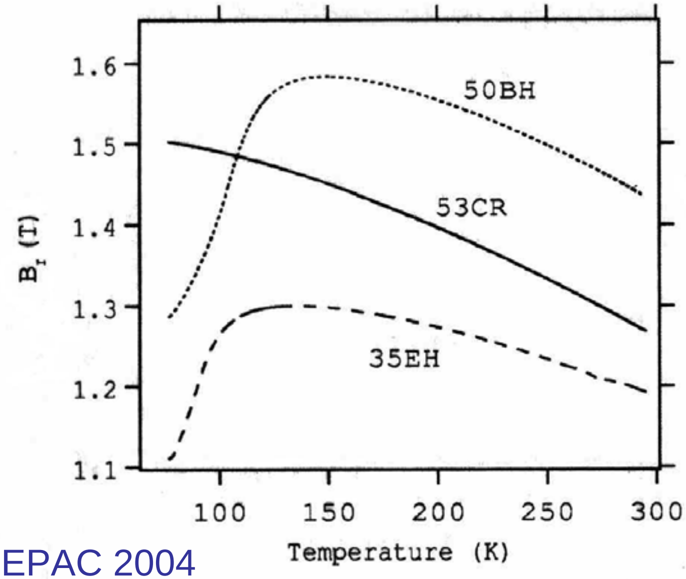


Calculated performance curves for Nb_3Sn conductors



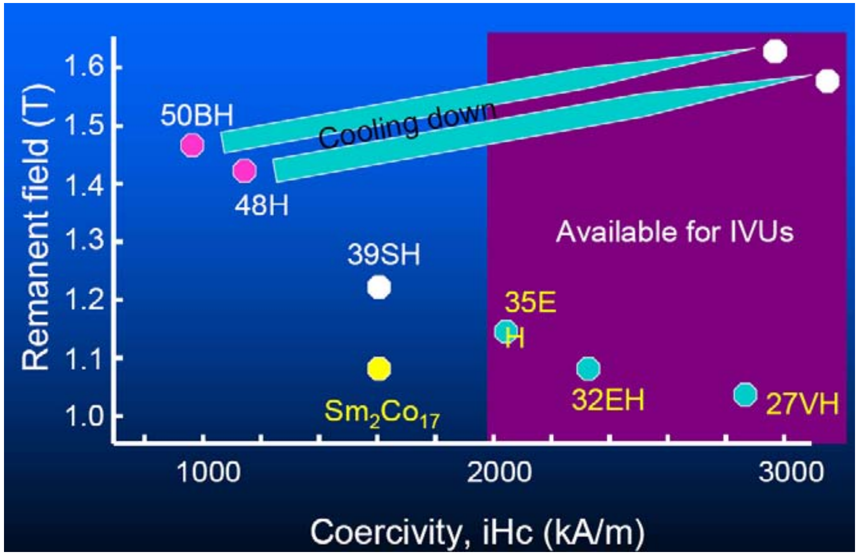
Competing technologies

- Permanent magnet devices (pure and hybrid, in-vacuum) are mature and formidable technologies – far exceeding performance of resistive magnet devices
- Spring-8 pioneered, ESRF doing R&D on cryogenically cooled versions of in-vacuum PM devices
  - Br increases ~10% from 300K to 100K
  - Coercivity increases 500% from 300K to 100K!
  - Significant field increase by switching to new material



Kitamura, EPAC 2004

- Issues:
  - Demagnetization during bakeout
    - 120C bakeout untenable due to low coercivity
  - Phase errors during cooldown
    - temperature gradients
    - Differential expansion of materials
  - Possibility of radiation damage
    - little radiation damage information at cryogenic temperatures



Magnetic gaps and lengths
Example: future insertion devices at the ALS

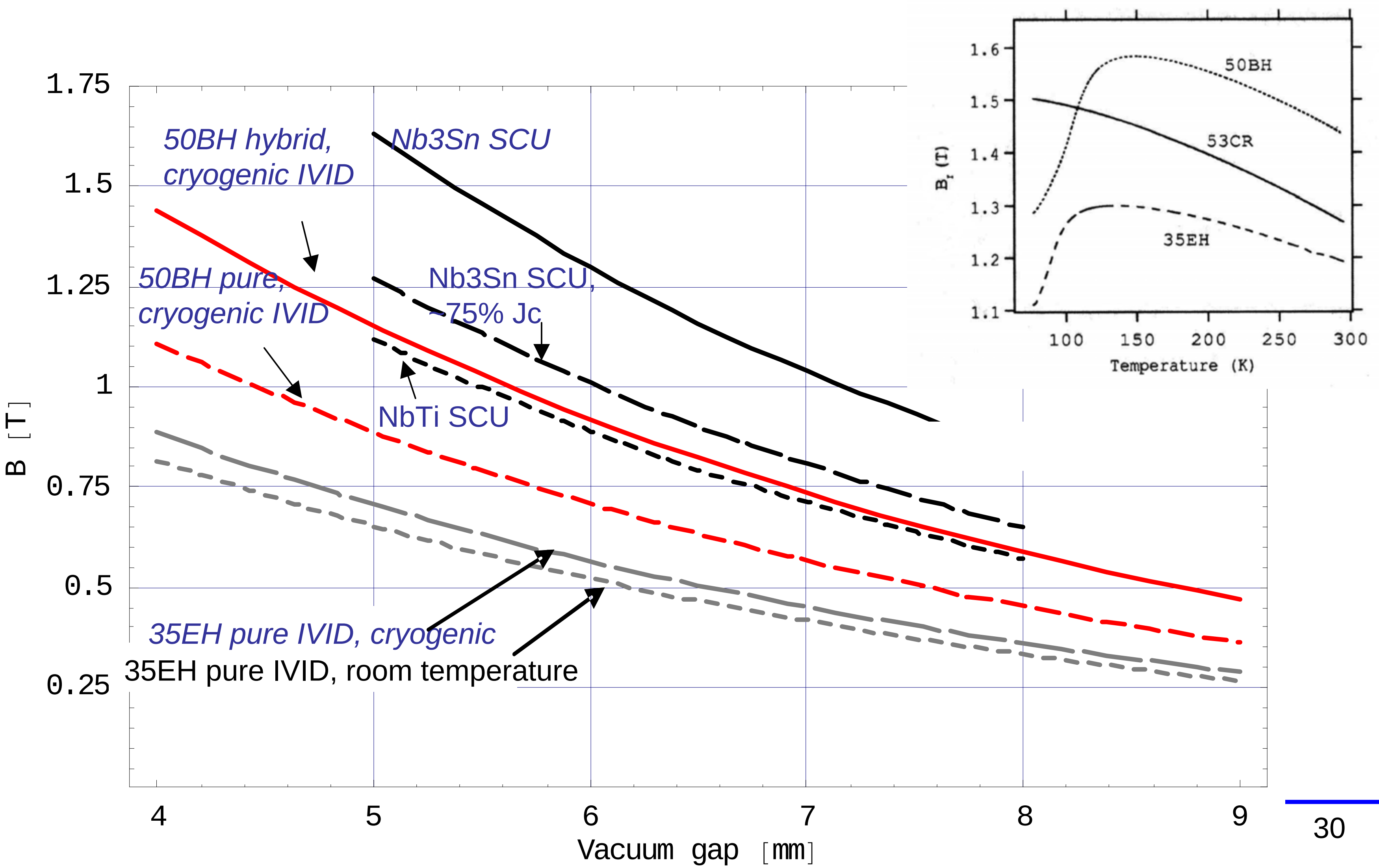
- Gaps, assuming 5mm vacuum aperture:
  - PM, PM-EPU: 7.3mm (1mm wall thickness, existing controls spacings; could be reduced, but risk increases – no hard stops, chance of hitting chamber…)
  - IV, *IV-EPU:* 5.4mm (0.4mm needed for controls, RF foil)
  - *SCU, SC-EPU*: 6.6mm (0.75mm wall thickness)
- Lengths:
  - PM: 2m (extend devices from current 1.85m by eliminating end chicanes & chambers)
  - IV: 1.62m (lose 360mm compared to PM on each side due to RF transitions)
  - SCU, SC-EPU: 1.6m ("cold-bore" operation; RF transitions do not move, but need space for thermal transitions; this is a reasonable estimate)
  - IV-EPU: 1.55m (RF transitions are a definite concern; this is an optimistic guess)

Note: technologies in blue are theoretical or in R&D

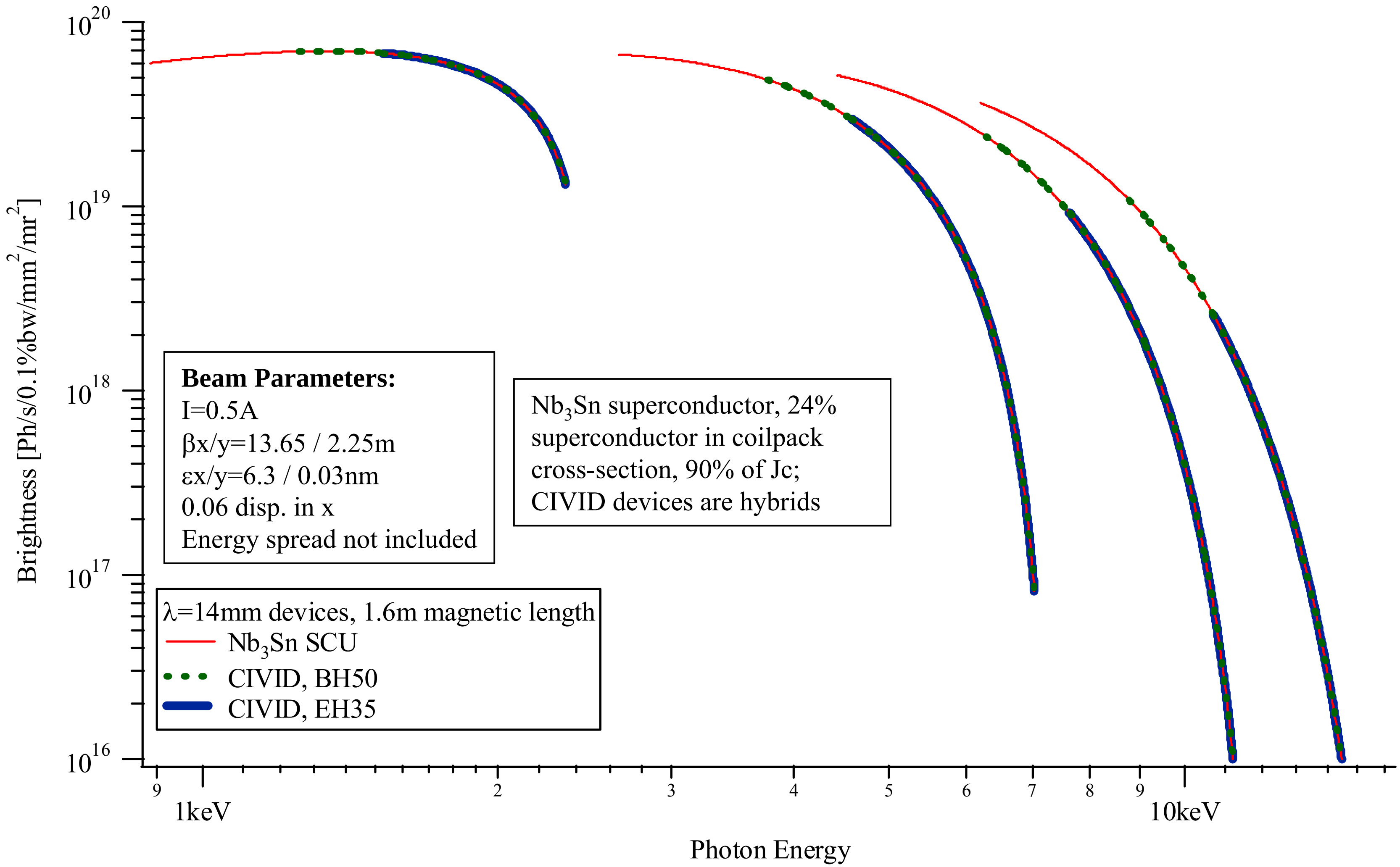
Field strength capability for IVID, cryo-IVID, and SCU

Options
calculated for λ=14mm

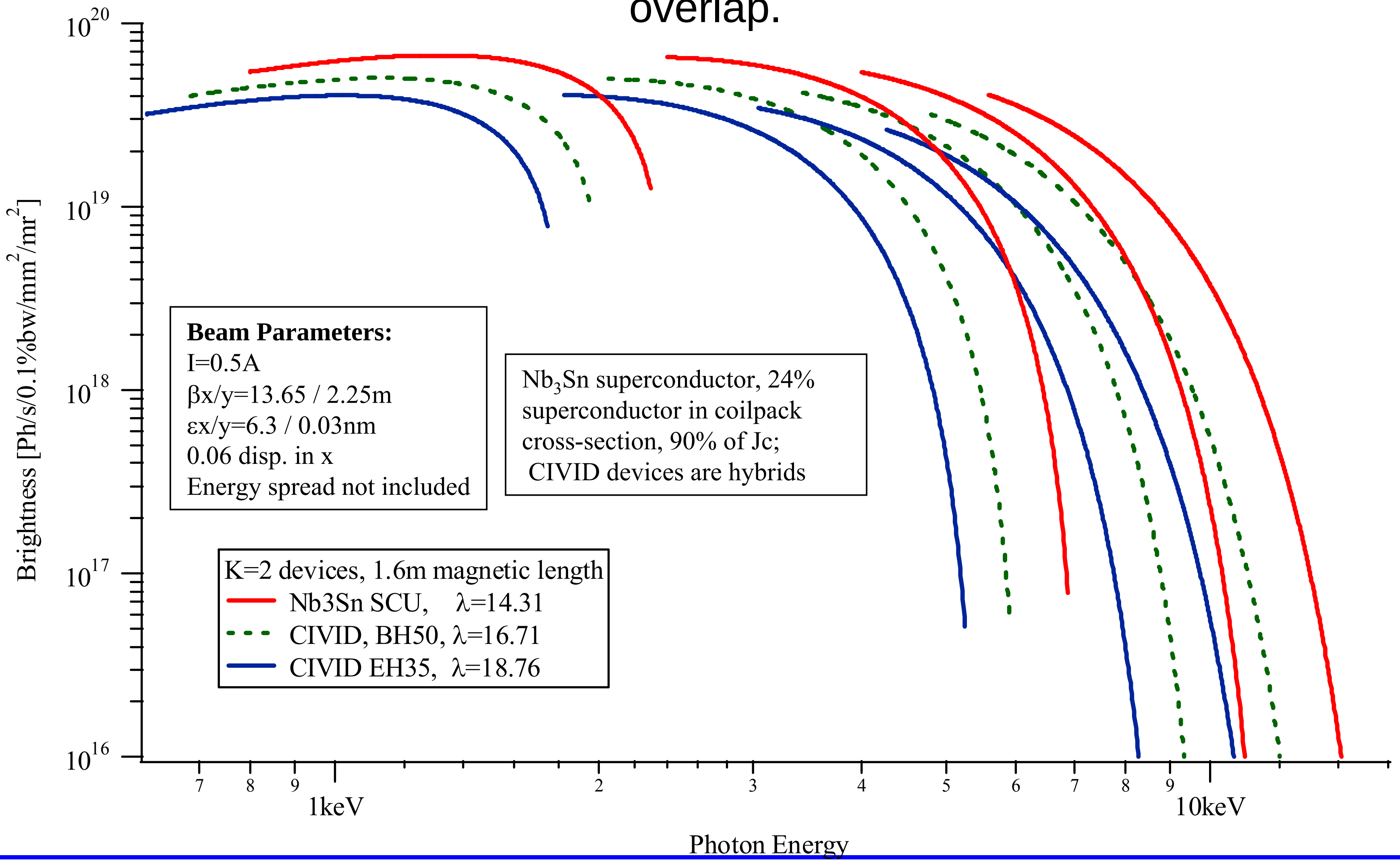
Cryogenic IVID data from Kitimura et al.



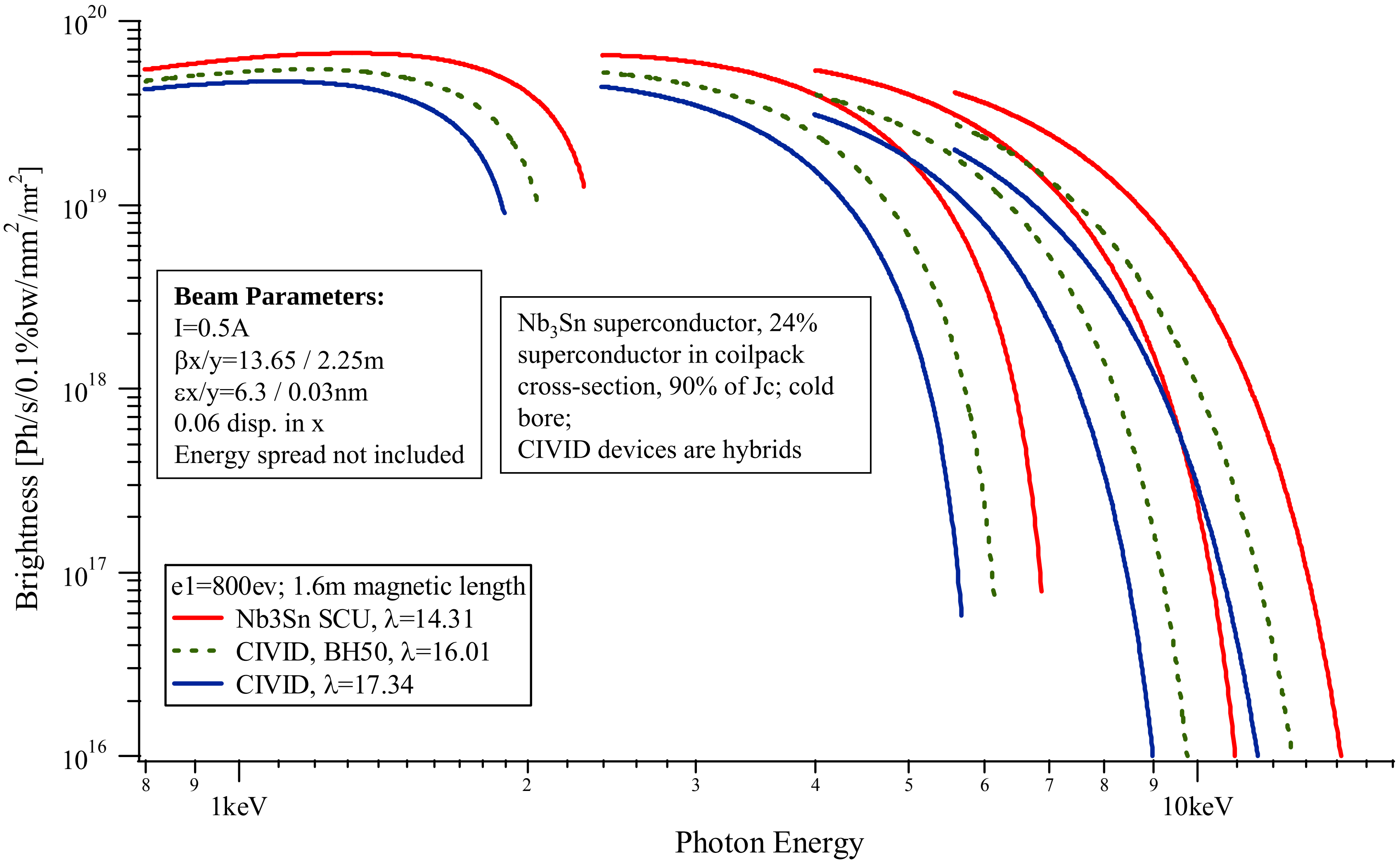
Brightness plots for devices based on different technologies with fixed period = 14mm.



Brightness plots for devices based on different technologies, with fixed K=2
(the device period is defined by the technology) to provide harmonic overlap.



Brightness plots for devices based on different technologies
Device periods are defined to yield ε_1=800eV



Ongoing R&D

- USA
  - LBNL (Nb_3Sn undulator prototypes)
    - two consecutive LDRD's – 30mm, 14.5mm period
    - WFO for APS – 14.5mm period: reached short sample
    - Conceptual design of SC-EPU
  - Argonne (NbTi, now considering Nb_3Sn)
    - Contracted with LBNL to demonstrate Nb_3Sn performance
    - WFO with NHMFL to design/fab Nb_3Sn prototypes, investigate alternative designs, develop cryogenic design
  - BNL
    - Investigating APC conductors; looking at variable-polarization SCU's
    - built and commissioned vertical test facility for detailed magnetic measurements
- Europe (only NbTi undulators so far…)
  - Accel collaborating with Anka – NbTi device operating in ring
  - Multi-lab collaboration (ESRF, Anka, …?) working with Accel
  - Maxlab looking at various SCU configurations
  - Maxlab, Bessy, ESRF, Elettra
    - much recent experience with SC wigglers
  - Daresbury – ILC helical undulator prototype
- Asia
  - Taiwan (installed WangNMR wigglers)

List indicative, not complete…

See www.esrf.fr/Accelerators/Conferences/ID_Workshop/
And http://www.desy.de/wus2005/

Now a look at LBNL R&D…

LBNL Nb_3Sn Undulator R&D

Collaboration of AFRD & Engineering Div.

Considered for ALS applications:

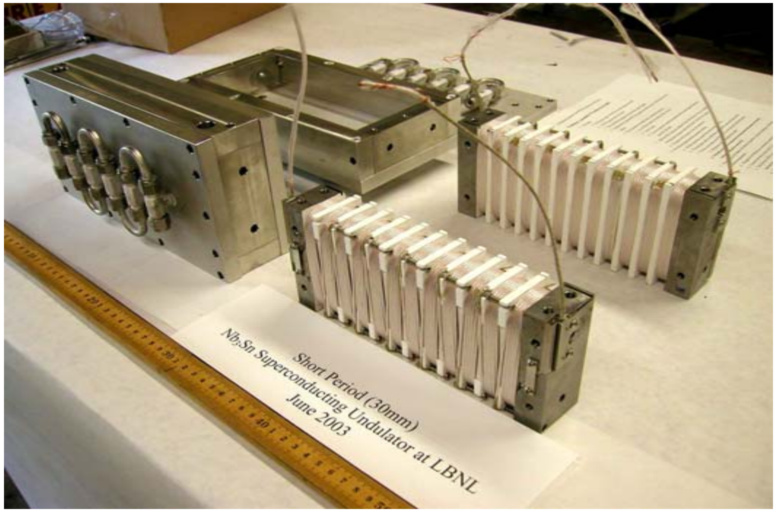
- Radiator for femto-slicing experiment
- Source for protein crystallography

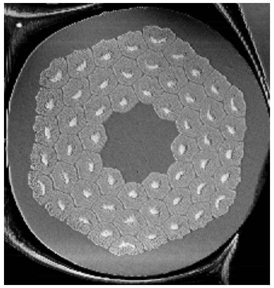
LDRD results (2003-04):

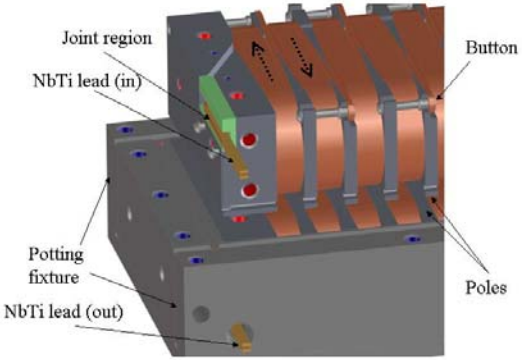
- Two prototypes using 6-strand cable
- 30mm period prototype; 80% of Jc
- 14.5mm period prototype: ~75% Jc

WFO (2005-06, for Argonne Nat. Lab):

- Test single strand conductor
- Design and fabrication improvements
- Reached short sample Jc in 4 quenches







Review of LBNL LDRD prototypes

- Two prototypes were designed, fabricated, and tested:
  - A 6 period, 30mm period device; *collaboration with WangNMR*
  - A 12 period, 14.5mm period device

- First prototype reached a peak current of ~2200A (~65% Jc); almost all quenches initiated near one splice
  - One-half of undulator was removed from the circuit
    - *Eliminated the bad region from the system*
    - *Significantly modified the magnetic system, but not the coil-field characteristics*
  - New test yielded 11 quenches, varying from 2379 to 2662A (~80% Jc)
    - *Very little sign of training*
    - *Quench triggers varied (some stick slip, some flux-jump), as did initiation locations*
    - *No discernable ramp-rate dependence*

  => Demonstrated quench Jcu>4000A/mm2 can be safely protected
- Prototype 2 test considered trim coil performance and quench performance
  - Trim coil performed as expected
    - *Can provide >1% field perturbation at all fields*
    - *Magnitude sufficient for use as active phase error correction element*
  - Quench test resulted in 2 quenches at ~2600A (~70%Jc).
    - *Both quenches located near the same splice*
    - *Flux jump signature suggests either large Deff or heating from epoxy cracking*

  => Demonstrated trim coil technique providing sufficient phase error correction

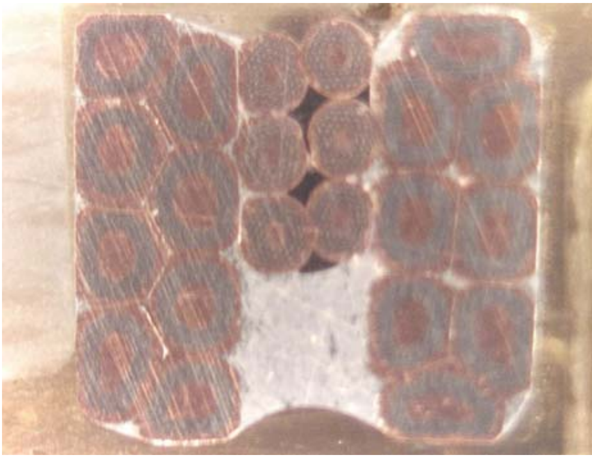
LDRD II prototype

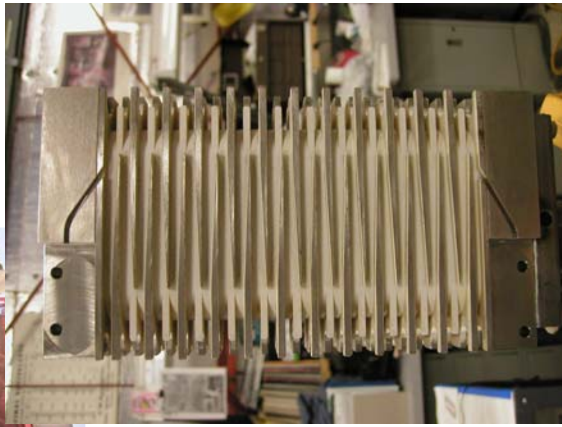
Nb3Sn-NbTi joint

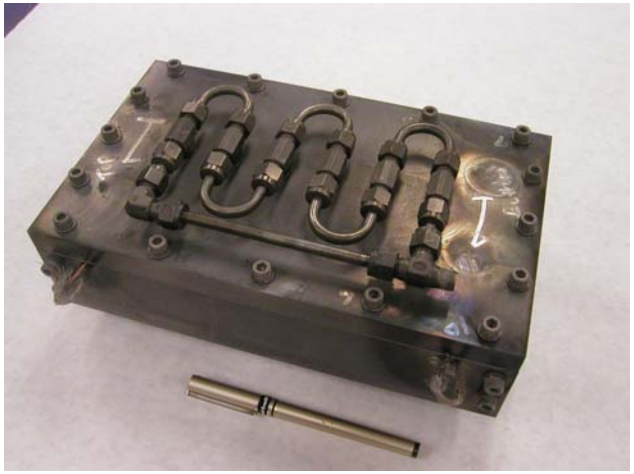
Yoke/pole and lead-in/lead-out

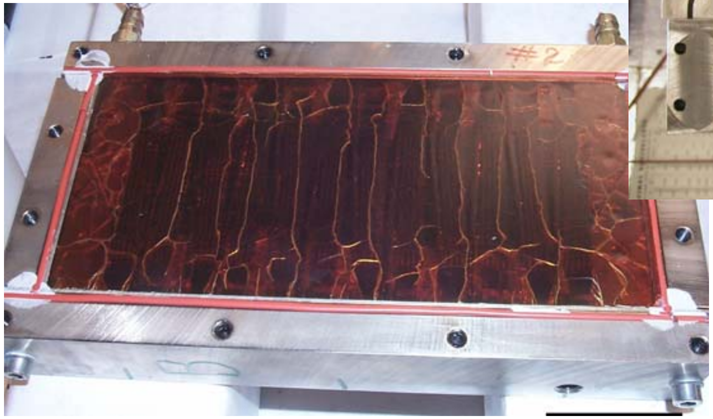
Potting issues (from LDRD I prototype)

Reaction chamber



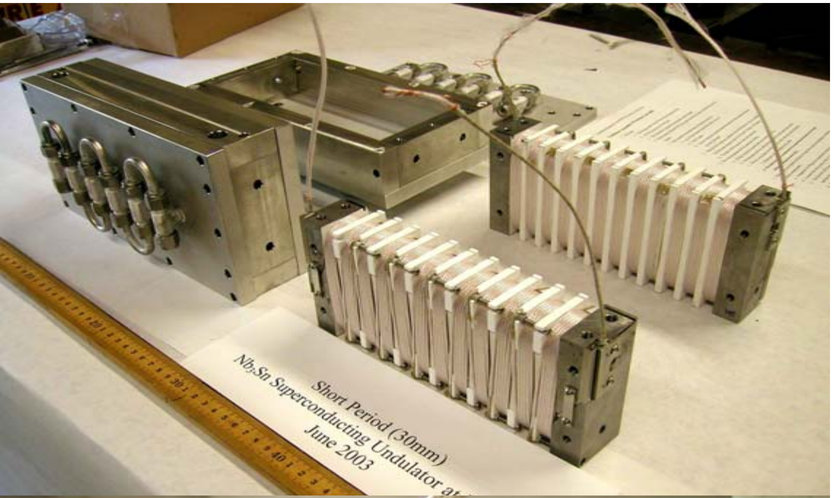




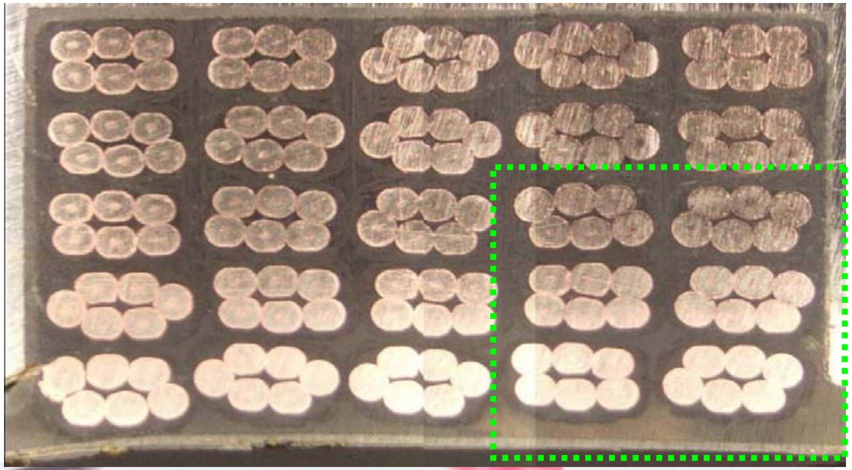


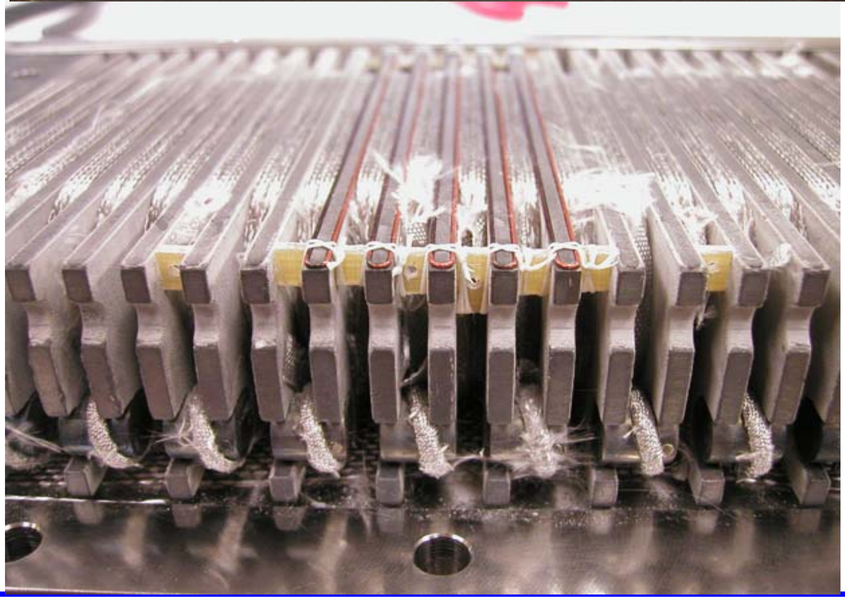
Review of LBNL prototypes

Prototype I
30mm period



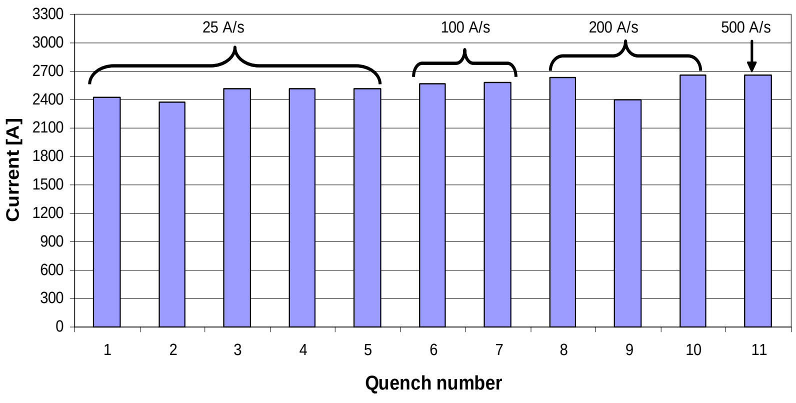
Prototype II
14.5 mm period

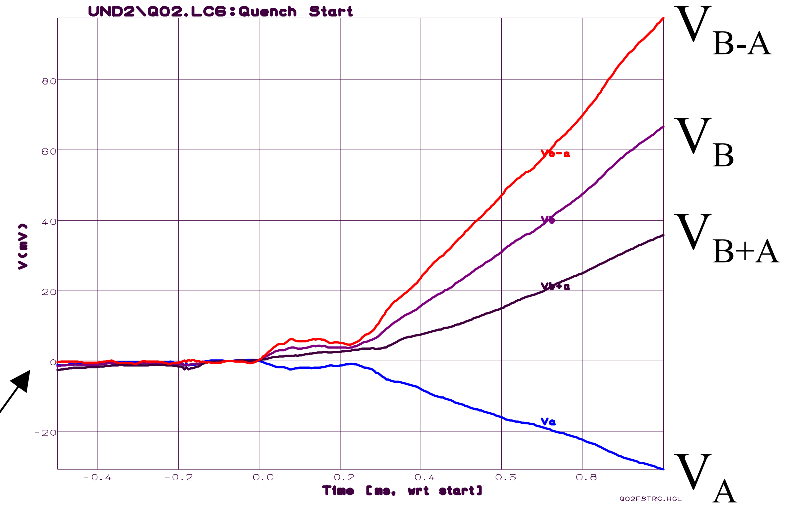




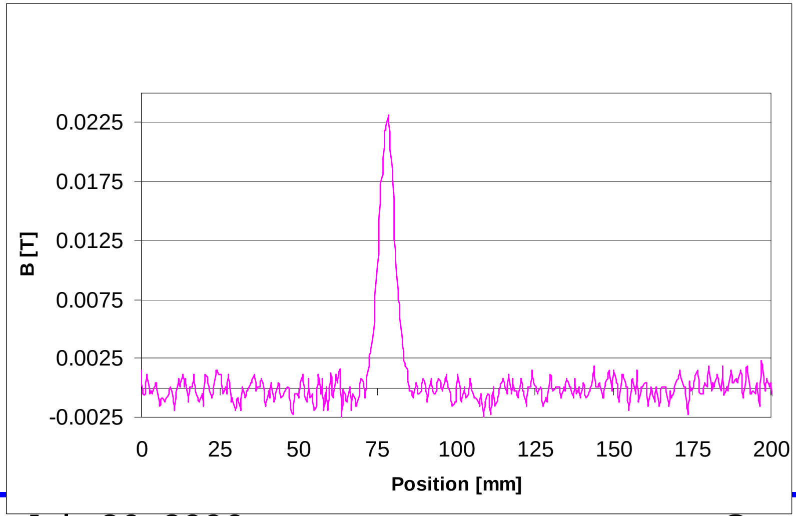
LDRD I&II prototype test results

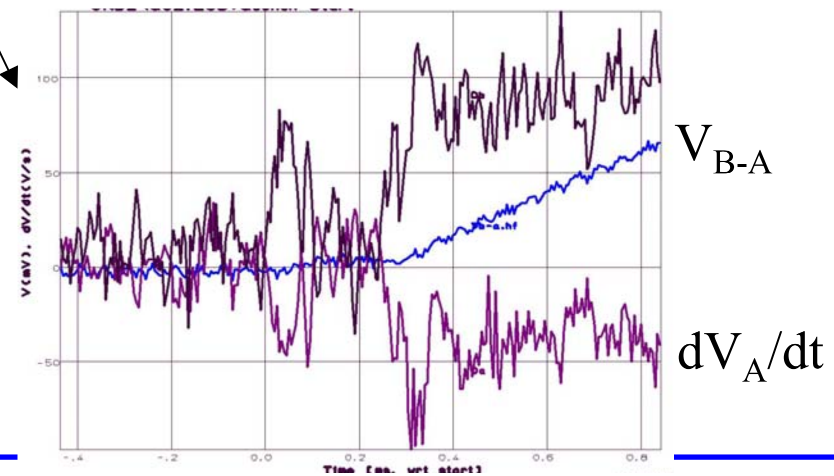
Prestemon et al., *IEEE Trans. on App. Supercond., June 2005*





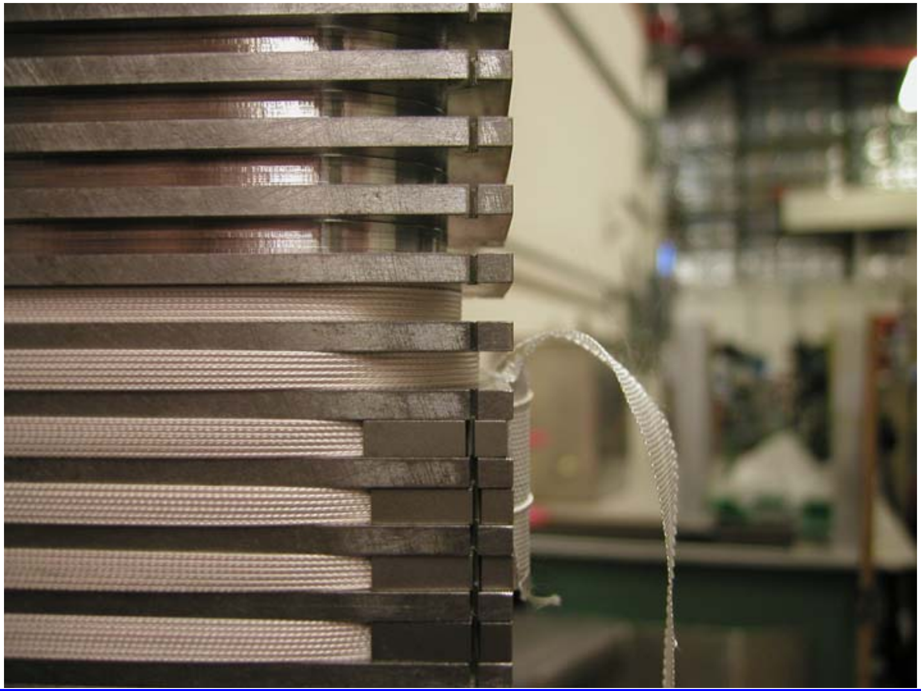
Flux-jump signature





Review of LBNL prototypes

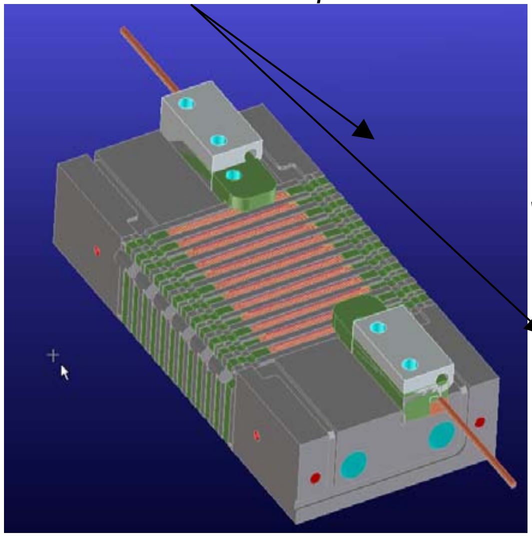
- *Prototype 3: funded by Argonne to demonstrate Nb_3Sn technology*
  - *Incorporated design modifications*
    - *End shoes to eliminate large areas of epoxy/glass*
    - *Increased RRR to reduce danger of low-field instability, from ~20 to ~100*
  - *A second prototype was designed to incorporate strand with trial ceramic insulation*
    - *Some sections of ceramic insulation are quite good - ~10-20 microns, good adhesion*
    - *A number of bare sections precluded use in an actual magnet prototype*
    - *Winding behavior of test section was reasonable*

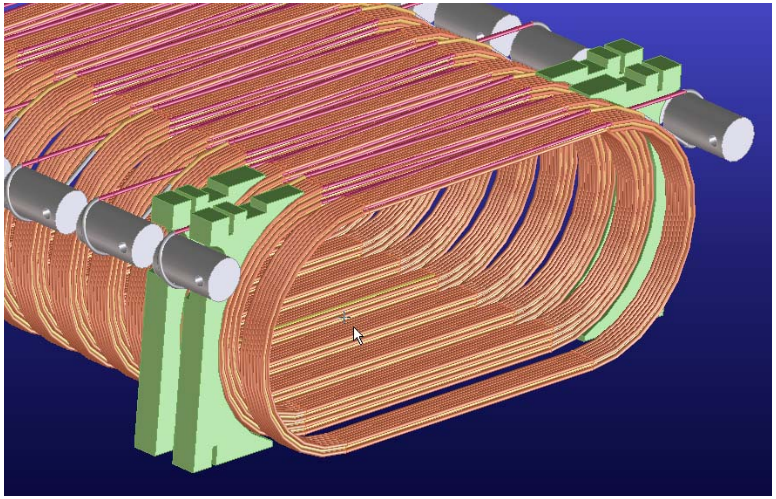


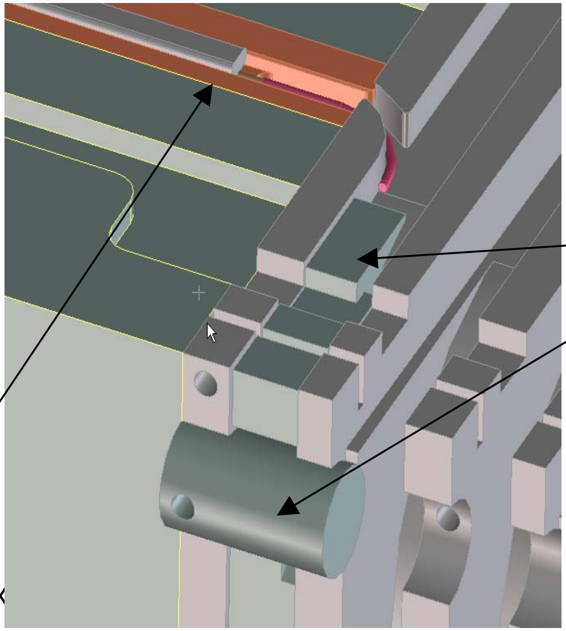
Design features of prototype III

Stainless steel end-pieces

Pole-Yoke







End-shoe

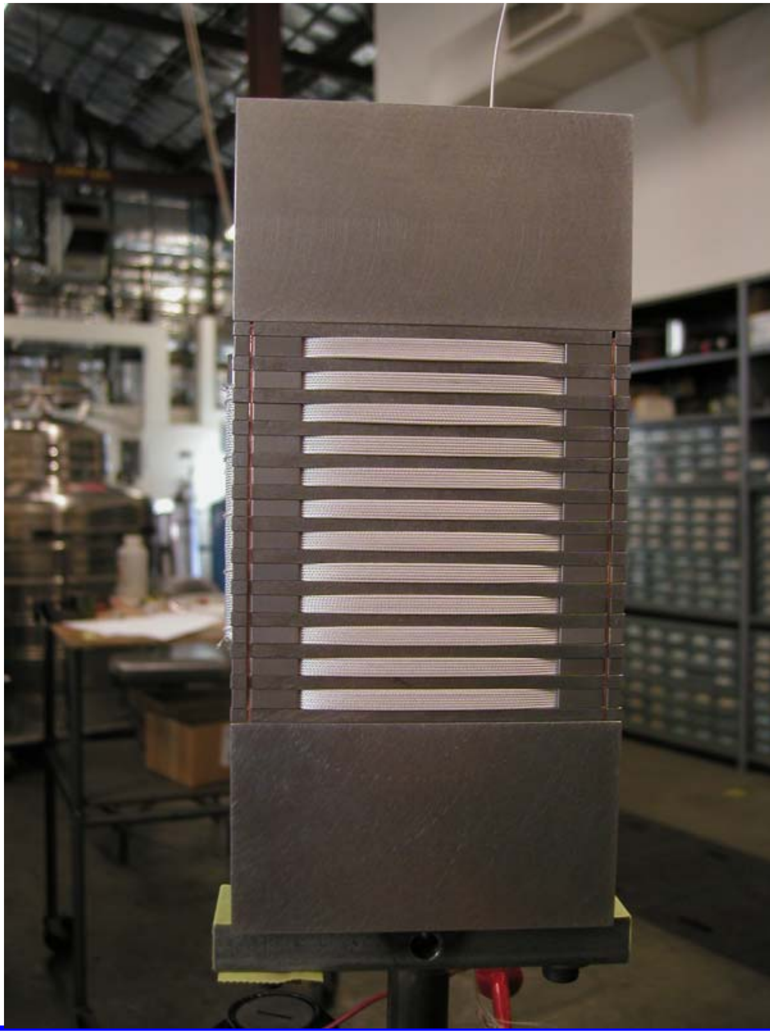
Button

Joint solder box

LBNL Prototype III Undulator-half (APS-funded) prototype during/after winding

-Note use of endshoes to eliminate voids and provide mechanical support.

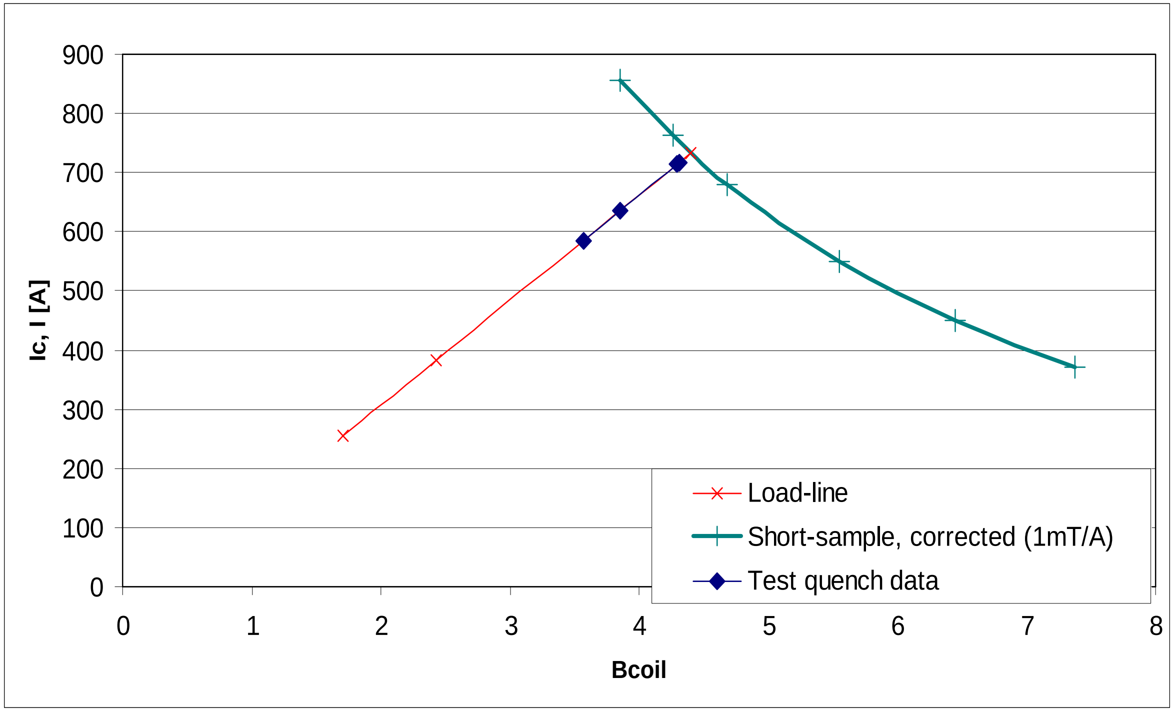
-Voltage taps are located at each coilpack



Prototype III undulator quench performance

- Five quenches:
  - 585A, 585A, 635A, 717A, 714A
  - At 717A:
    - Jsc=8250A/mm2
    - Jcu(quench)=7600A (self-protected)
    - Jav=1760A/mm2 (using full pocket size)

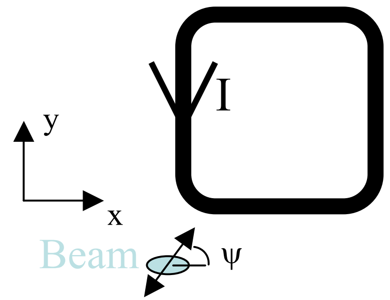
} *Record parameters*

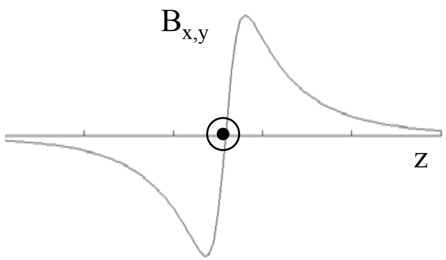


Polarization control

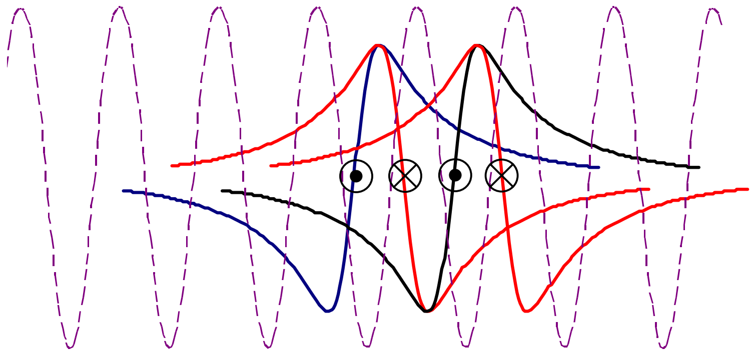
Generating variable linear polarization

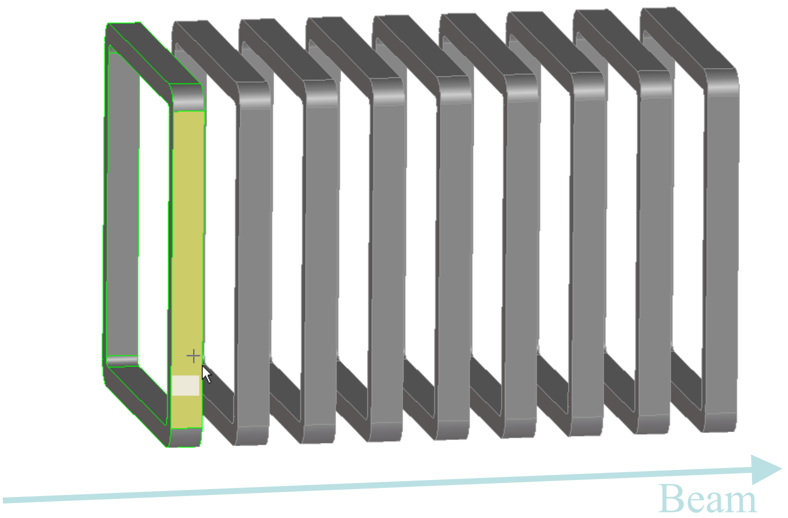
- A coil as shown generates antisymmetric B_x and B_y field profiles in z about the coil. The fields are largely on a plane of angle ψ that is a function of the coil gap and x-offset.





- A series of such coils in z, separated by $\lambda/2$ with alternating current directions, generates $B_x(z)$ and $B_y(z)$ fields that are periodic with equal phase shift.

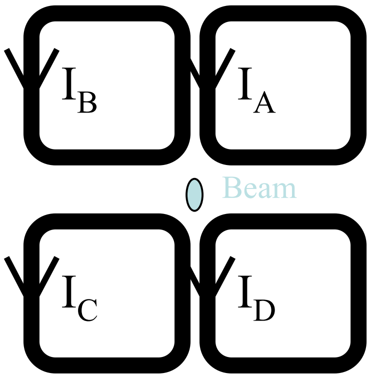




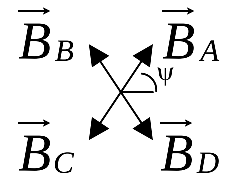
Polarization control

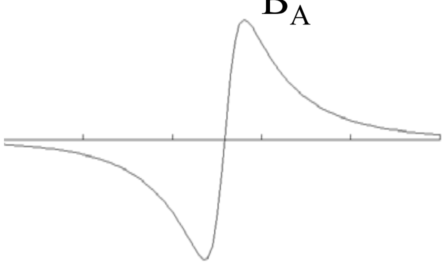
Generating variable linear polarization

- Consider a 4-quadrant array of such coil-series.
  - If I_C=-I_A, Coils A and C generate additive –fields.
  - Set I_C=-I_A, I_D=-I_B; Independent control of I_A and I_B provides full linear polarization control.



For $I_A=I_B=I_C=I_D$:





Independent control of I_A and I_B provides variable linear polarization control

- If $I_A=I_B$, vertical field, horizontal polarization
- If $I_A=-I_B$, horizontal field, vertical polarization

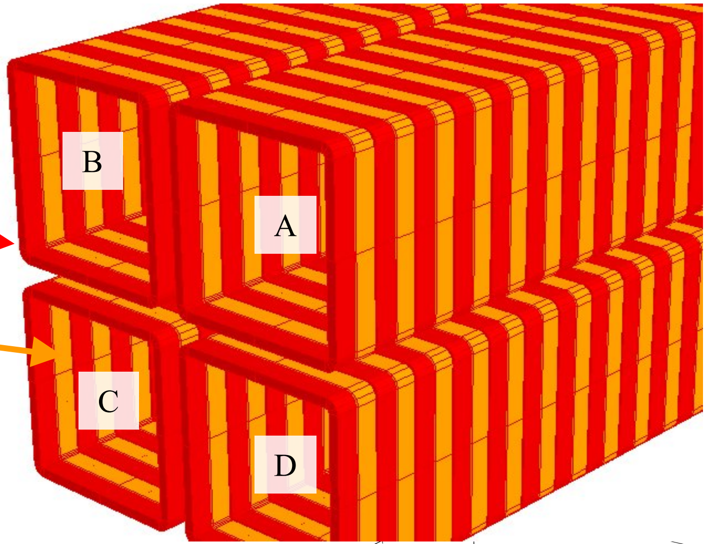
Polarization control

Generating variable elliptic polarization

- Add a second 4-quadrant array of such coil-series, offset in z by $\lambda/4$ (coil series α and β)
- With the following constraints the eight currents are reduced to four independent degrees of freedom:

$$I_C^\alpha = -I_A^\alpha, \quad I_D^\alpha = -I_B^\alpha$$

$$I_C^\beta = -I_A^\beta, \quad I_D^\beta = -I_B^\beta$$



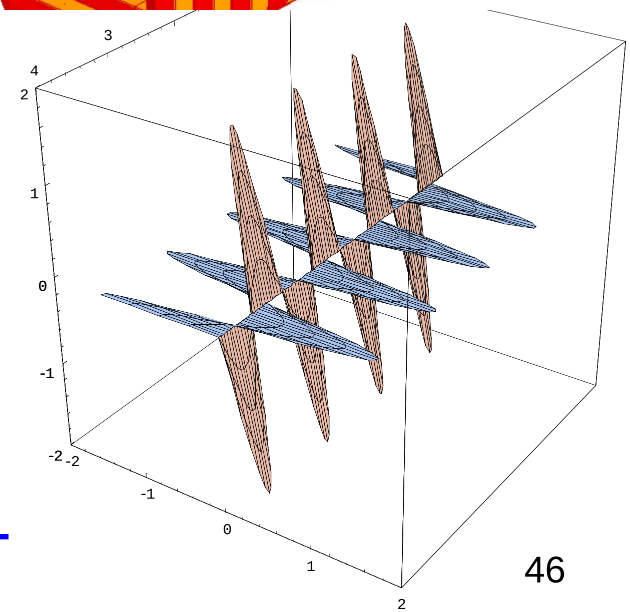
- The α and β fields are 90° phase shifted, providing full elliptic polarization control via

$$\vec{B}^\alpha(I_A^\alpha, I_B^\alpha; z), \quad \vec{B}^\beta(I_A^\beta, I_B^\beta; z):$$

$$\begin{pmatrix} B_x^\alpha \\ B_y^\alpha \end{pmatrix} = \eta \left\{ \begin{pmatrix} \text{Cos}(\psi) & -\text{Cos}(\psi) \\ \text{Sin}(\psi) & \text{Sin}(\psi) \end{pmatrix} \begin{pmatrix} I_A^\alpha \\ I_B^\alpha \end{pmatrix} \right\} \text{Sin}\left(\frac{2\pi z}{\lambda}\right)$$

$$\begin{pmatrix} B_x^\beta \\ B_y^\beta \end{pmatrix} = \eta \left\{ \begin{pmatrix} \text{Cos}(\psi) & -\text{Cos}(\psi) \\ \text{Sin}(\psi) & \text{Sin}(\psi) \end{pmatrix} \begin{pmatrix} I_A^\alpha \\ I_B^\alpha \end{pmatrix} \right\} \text{Sin}\left(\frac{2\pi z}{\lambda} - \frac{\pi}{2}\right)$$

Note: $B_{x,y}^\alpha = \sum_n a_{n;x,y} \sin\left(\frac{2\pi n x}{\lambda}\right)$; typically $\frac{a_3}{a_1} < 2\%$



With some switching… *enhanced spectral range*

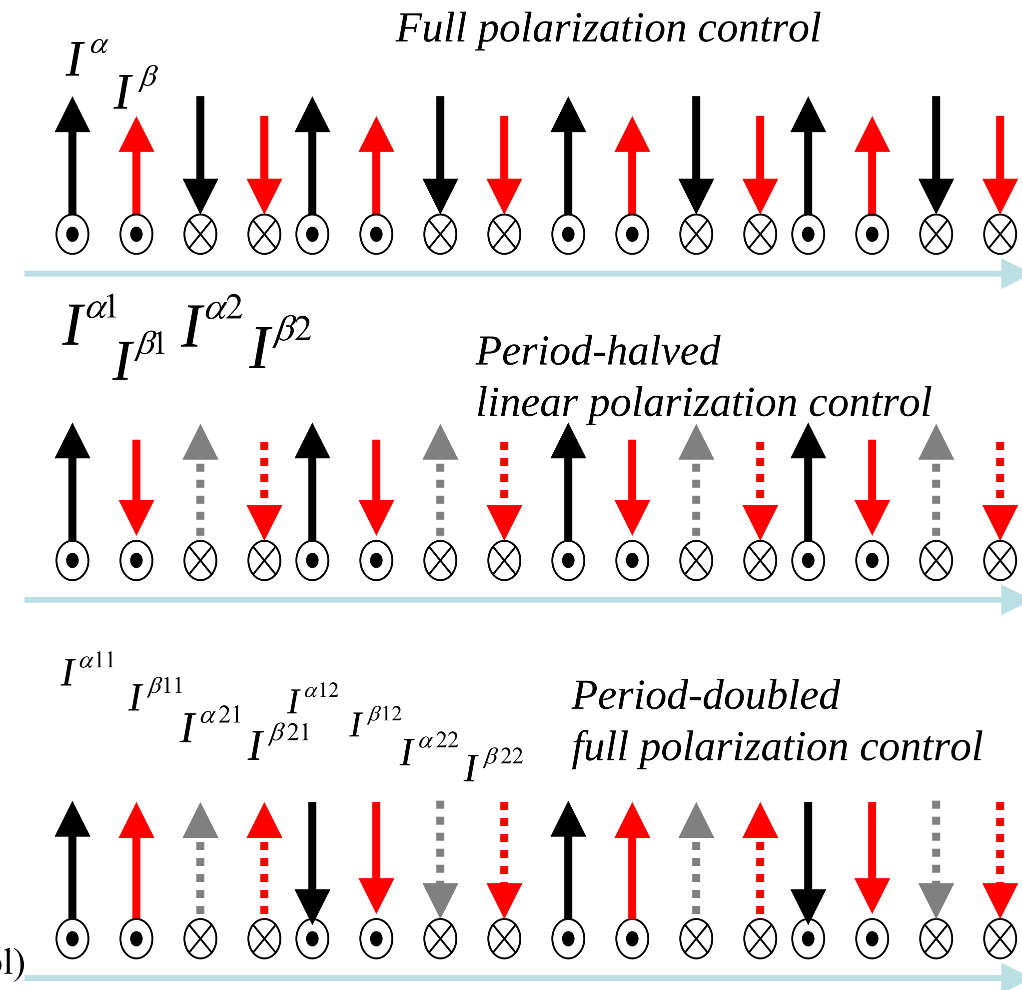
- Separating the coils in the α (and β) circuit into two groupings allows for period-halving:

$$\left.\begin{array}{l} I^{\alpha 1} = -I^{\alpha 2} \\ I^{\beta 1} = -I^{\beta 2} \end{array}\right\}$$ Previous (full polarization control)

$$\left.\begin{array}{l} I^{\alpha 1} = I^{\alpha 2} \\ I^{\beta 1} = I^{\beta 2} = -I^{\alpha 1} \end{array}\right\}$$ Period-halved linear mode (variable linear, no elliptic)

- Going further… separating the coils in the $\alpha 1$ (and $\alpha 2$, $\beta 1$, $\beta 2$) circuit into two groupings allows for period doubling:

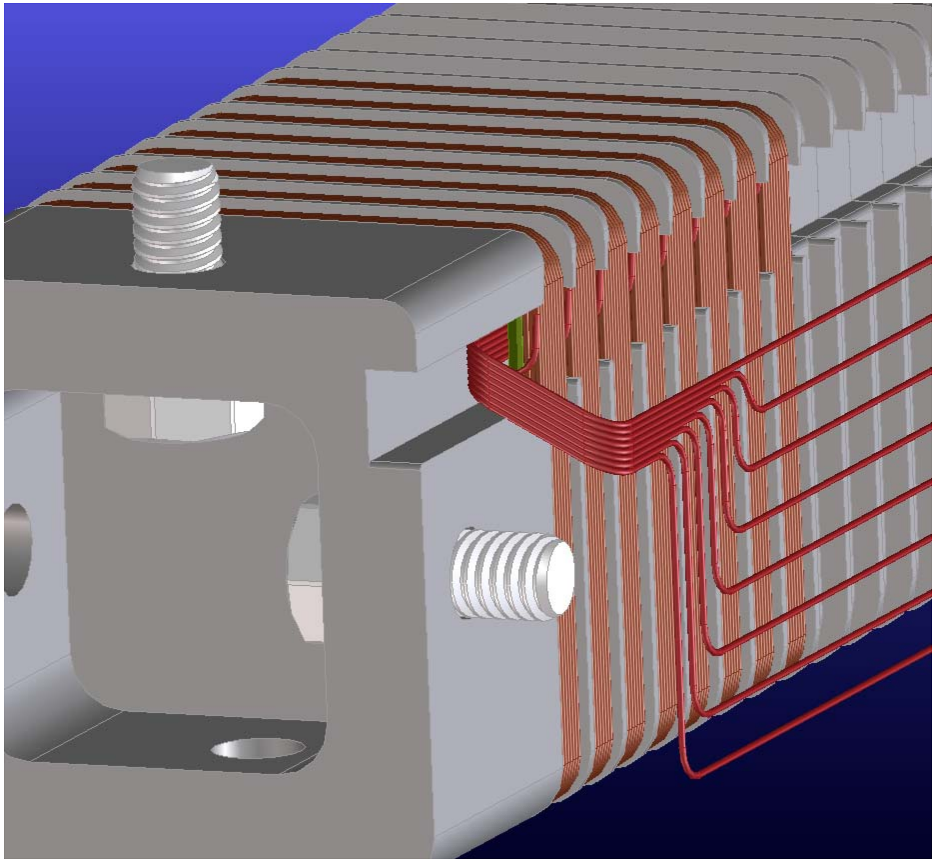
$$\left.\begin{array}{l} I^{\alpha 11} = I^{\beta 11} = -I^{\alpha 12} = -I^{\beta 12} \\ I^{\alpha 21} = I^{\beta 21} = -I^{\alpha 22} = -I^{\beta 22} \end{array}\right\}$$ Period-doubled (Full polarization control)

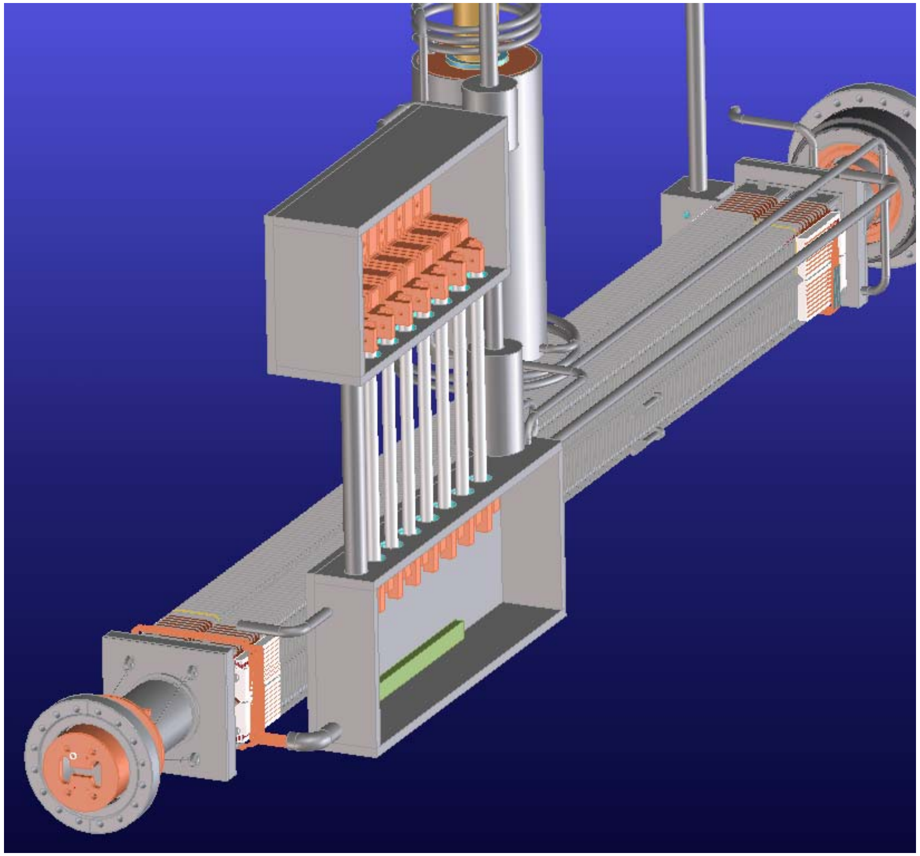


NOTE: Two power supplies (A, B) needed for linear polarization control; four needed for full (linear+elliptic) polarization control; switching network could provide access to the above regimes

A conceptual design for the LBNL SC-EPU with minimal joints

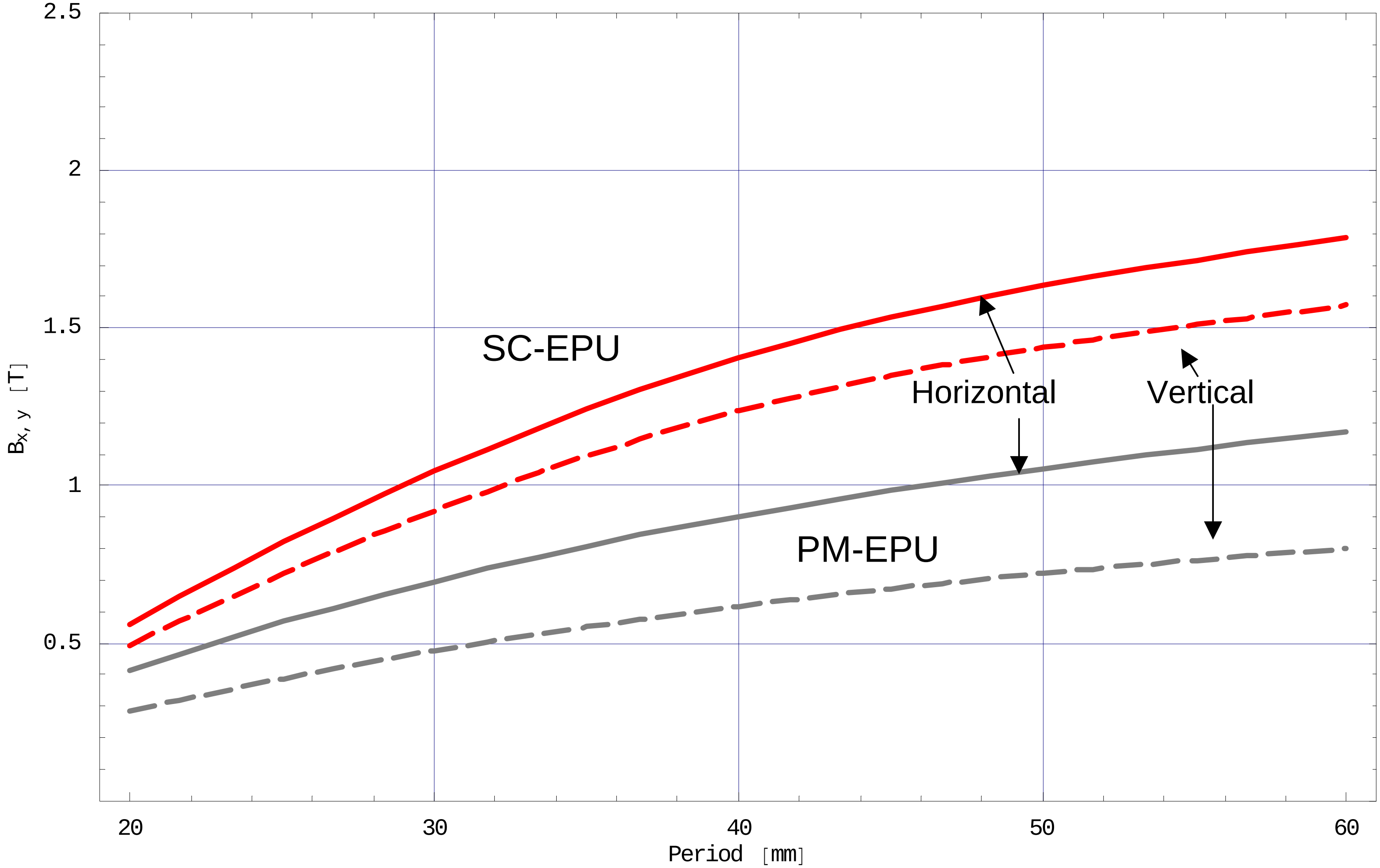
- Cryocooled using heat-pipe approach
- Performance limited by AC losses (dB/dt-induced heating) of coil
- Period halving/doubling requires “switchyard” – superconducting switch needs to be demonstrated



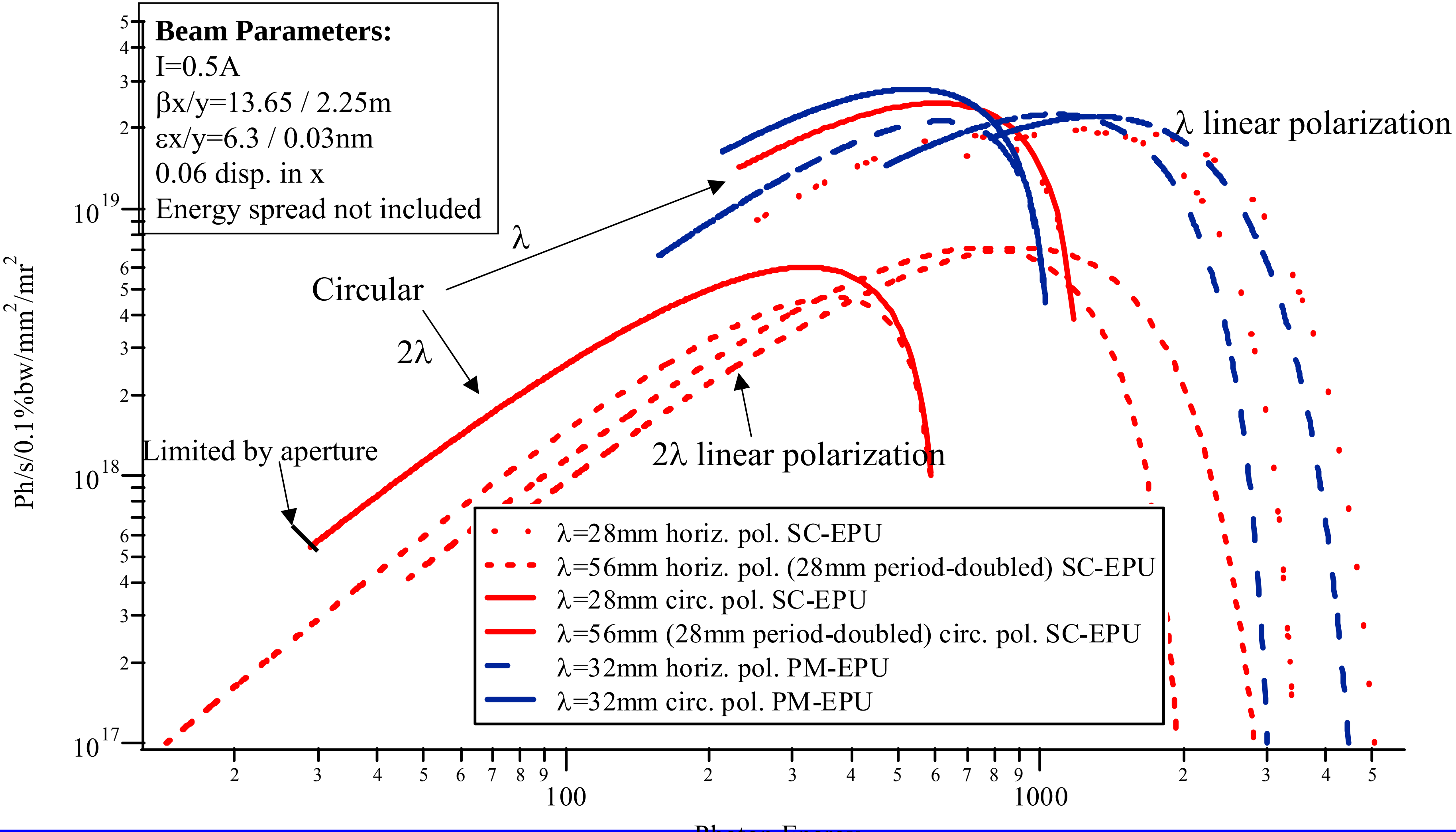


Superconducting elliptically polarizing undulator

Nb_3Sn superconductor, 24% superconductor in coilpack cross-section, 90% of Jc, vacuum gap=5mm (magnetic gap=9.9mm for PM-EPU, 7.9mm for SC-EPU)

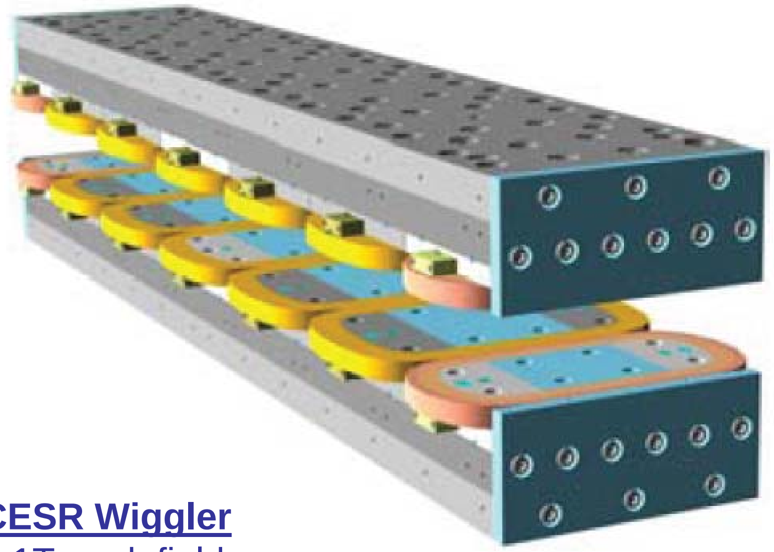


Spectral range and Brightness of example SC-EPU λ=28mm device and PM-EPU λ=32mm



Other applications of Superconducting insertion devices

- Modulators and radiators for FEL's
  - May serve to shorten length of FEL
  - Access shorter wavelength radiation
  - Main issues:
    - tight requirement on beam trajectory
    - Long lengths overall
- Wigglers for damping rings
  - CESR, ILC, …
- Undulator for ILC positron source



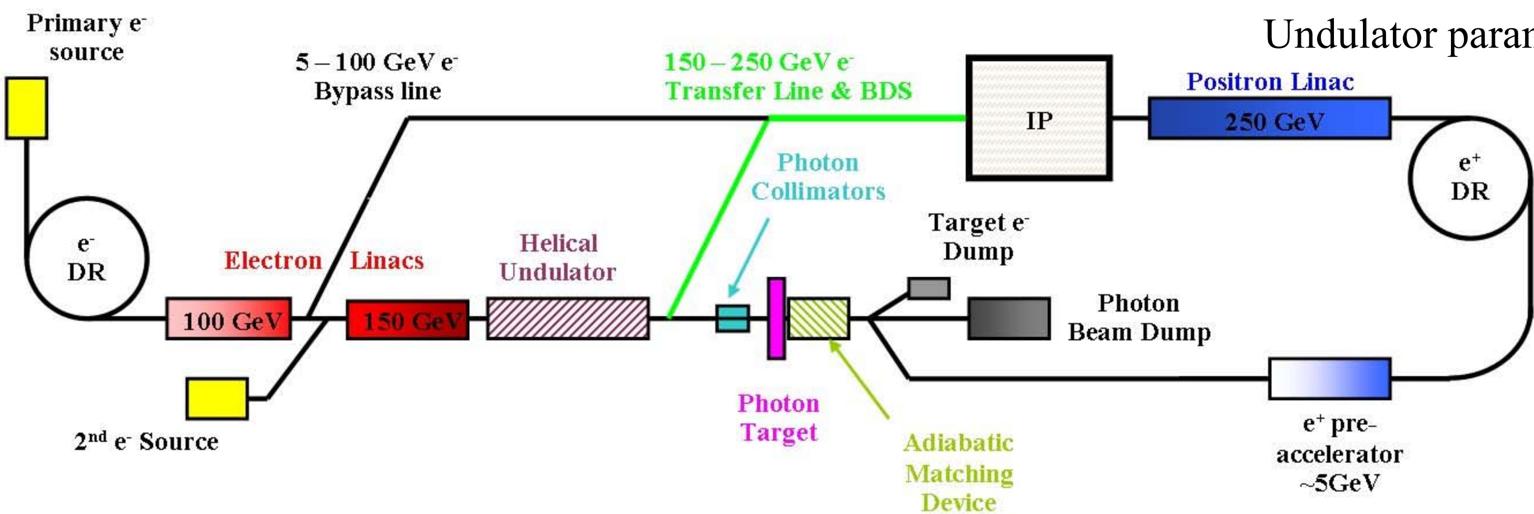
CESR Wiggler
2,1T peak field
9cm horizontal uniform aperture
40cm period
7.62cm pole gap, 5cm vertical beam aperture

Baseline wigglers for ILC damping ring

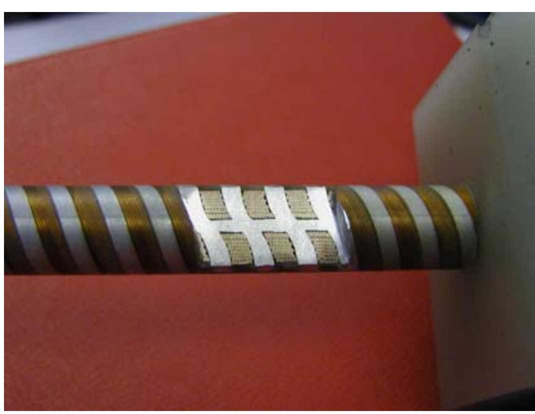
ILC Positron Source

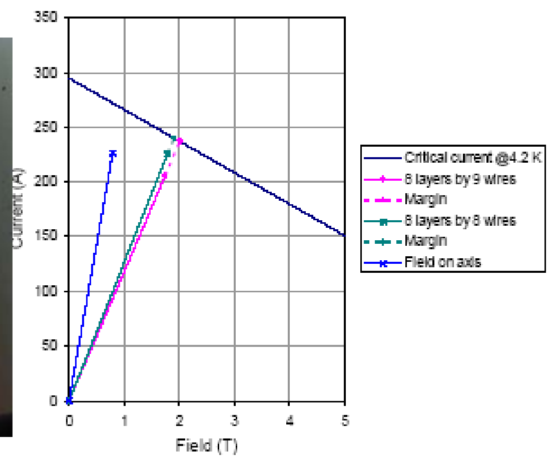
Parameter	Value	Units
Period	10	mm
Peak field	1.1	T
Type	Helical	-
Length	100-200	m
Max Photon Beam Power	95	kW

Undulator parameters (ideal)



First NbTi prototype, EUROTeV-heLiCal collaboration





Magnet features & parameters:

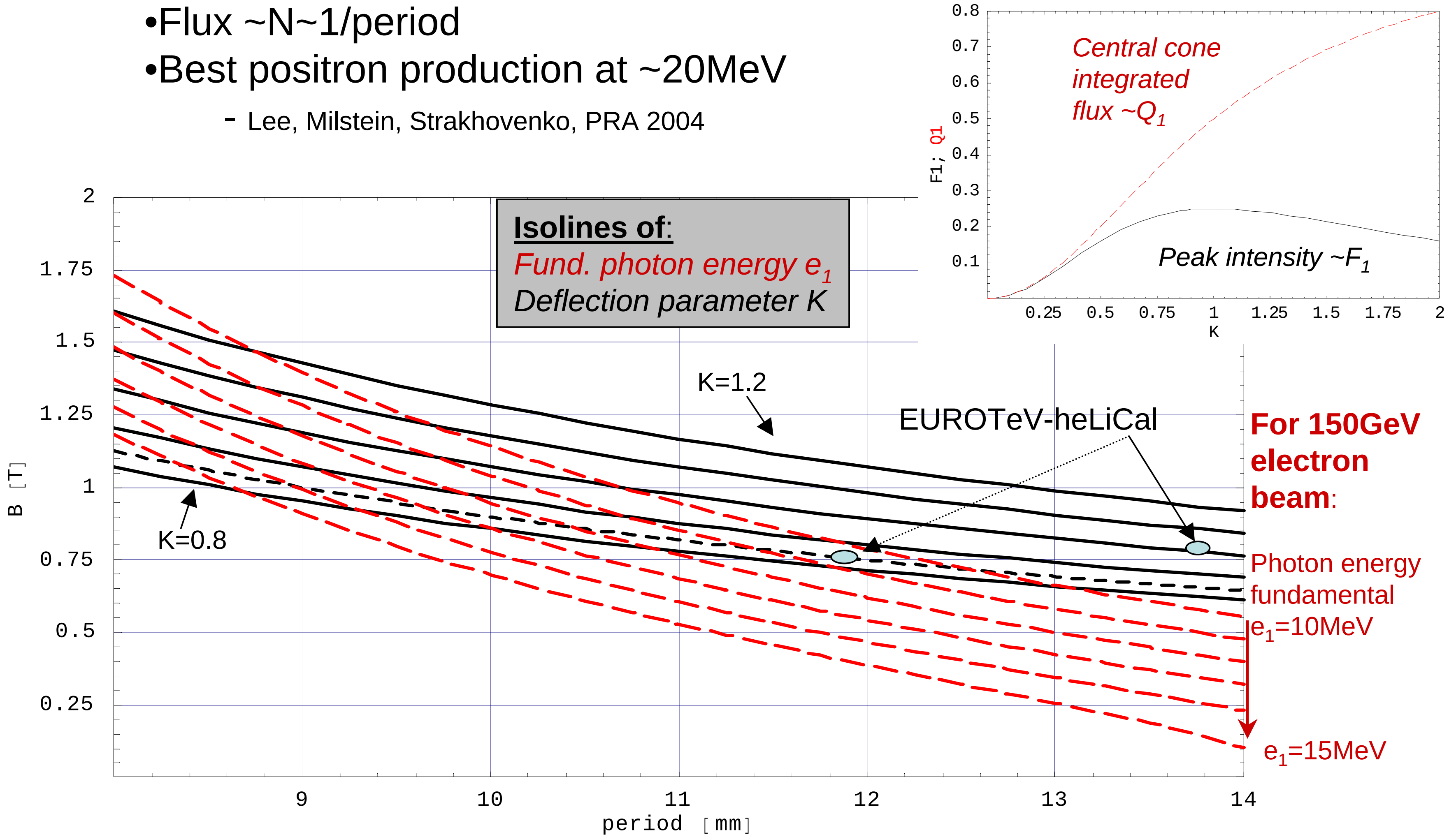
- Conductor: NbTi. 0.44 mm diam.
- Groove size: 4x4 mm
- Test: achieved 0.8 T on axis

ɿs:

ɿushenkov et al., Proceedings of PAC 2005
et al, Proceedings of EPAC 2004

Motivation for shorter period, higher field

- Flux ~N~1/period
- Best positron production at ~20MeV
  - Lee, Milstein, Strakhovenko, PRA 2004

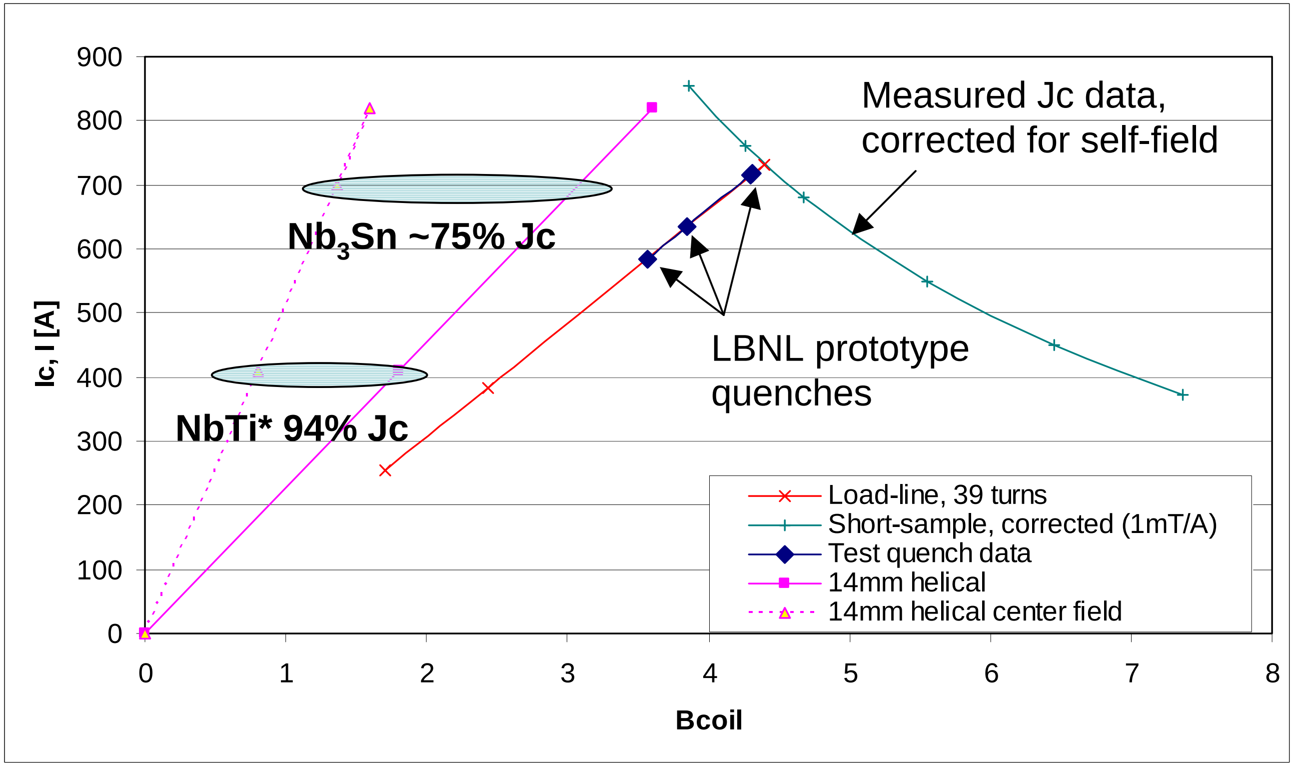


Relevance to ILC Design

- Use same load-line data, apply same Nb_3Sn conductor as LBNL prototype
  - Cross section close match (~4x4mm^2 vs 15.90mm^2 for LBNL prototype)
  - Assume 39 turns of ϕ=0.48mm
- Reasonable operating point at 700A => 3.07 T on coil, 1.37 T on-axis, K=1.78
- This performance can be used to reduce period increase positron production

1.4 T

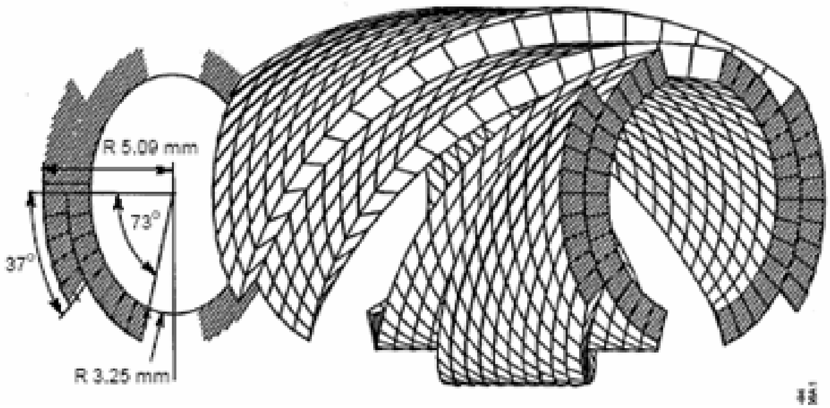
0.8 T



*1000A/mm2 J_{av} converted to current for comparison; actual conductor operated at 226A

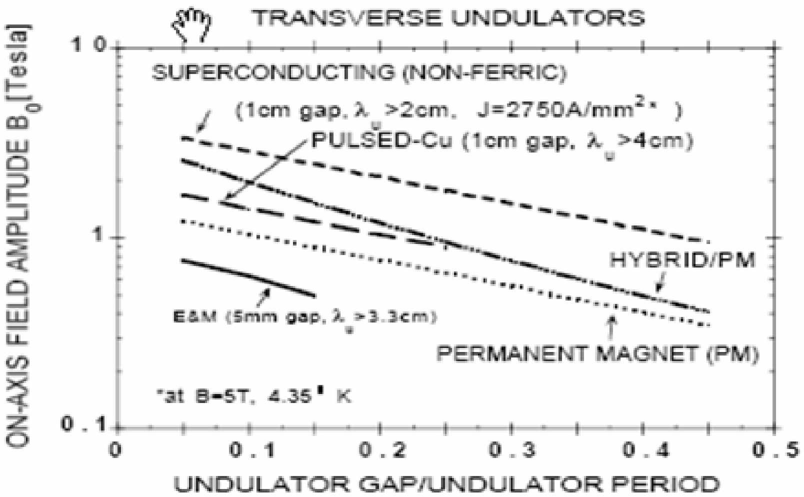
LBNL-SLAC Helical Undulator Design

- **Shell-type cross-section geometry**
- **Motivated by LCLS design studies**
- **Specialized optimization code available**



<u>LBNL Publications</u>:

- S. Caspi, "Magnetic Field Components in a Sinusoidally Varying Helical Wiggler. LBL-35928 July, 1994
- S. Caspi, "Stored Energy in a Helical Undulator", LBL SC-MAG-474, 1994.
- S. Caspi, "Magnetic Field Components in a Helical Dipole Wiggler with Thick Windings", LBL, 1994
- S. Caspi, "A Superconducting Helical Undulator for Short Wavelength FELs", LBL Report SC-MAG-475, 1994.
- S. Caspi, R. Schlueter, R. Tatchyn, "High Field Strong Focusing Undulator Designs for X-ray Linac Coherent Light Source (LCLS) Applications". SLAC-Pub 95-6885. PAC 1995.
- S. Caspi and C. Taylor , "An experimental superconducting helical undulator", NIMA Volume 375, 1996
- R. Tatchyn, et al, "R&D toward a linac coherent light source (LCLS) at SLAC", NIMA, Vol. 375, 1996.



LBNL Nb_3Sn Undulator Publications

Papers:

- Prestemon, S. et al. “Design and evaluation of a short period Nb3Sn superconducting undulator prototype”, Presented at PAC2003, Portland, Oregon, May 2003. Proceedings, PAC2003
- M. A. Green, D. R. Dietderich, S. Marks, S. O. Prestemon, “Design Issues for Cryogenic Cooling of Short Period Superconducting Undulators”, presented at CEC-ICMC, Anchorage, Alaska, Sept. 22-26, 2003. Advances in Cryogenic Engineering, AIP, Vol. 49, p 783-790.
- Prestemon, S.; Dietderich, D.;Marks, S.;Schlueter, R. , “NbTi and Nb3Sn superconducting undulator designs”, presented at SRI 2003, San Francisco, Aug. 2003. Synchrotron Radiation Instrumentation, AIP, vol. 705, p 294, 2004.
- Ross Schlueter, Steve Marks, Soren Prestemon, and Daniel Dietderich, “Superconducting Undulator Research at LBNL”, Synchrotron Radiation News, January/February 2004, Vol. 17, No. 1.
- S. O. Prestemon, D. R. Dietderich, S. E. Bartlett, M. Coleman, S. A. Gourlay, A. F. Lietzke, S. Marks, S. Mattafirri, R. M. Scanlan, R. D. Schlueter, B. Wahrer, B. Wang, “Design, Fabrication and Test Results of Undulators Using Nb3Sn Superconductor”, IEEE Transactions on Applied Superconductivity, June 2005 (Presented at ASC 2004, Jacksonville, Fl.)
- S. Prestemon, R. Schlueter, S. Marks, D. Dietderich, “Superconducting Undulators with Variable Polarization and Enhanced Spectral Range”, presented at MT19, Sep. 18-23, 2005, Genoa, Italy

Presentations:

- K. Robinson, “Superconducting Undulator R&D Collaboration Program in the United States”, Workshop on Superconducting Undulators & Wigglers, Grenoble, France, 1 July, 2003. http://www.esrf.fr/NewsAndEvents/Events/Workshop30-06-03/
- S. Prestemon, D. Dietderich, S. Gourlay, P. Heimann, S. Marks, G. L. Sabbi, R. Scanlan, R. Schlueter “Superconducting R&D at LBNL”, Workshop on Superconducting Undulators & Wigglers, Grenoble, France, 1 July, 2003. http://www.esrf.fr/NewsAndEvents/Events/Workshop30-06-03/
- S. Prestemon, D. Dietderich, S. Marks, R. Schlueter, “Nb3Sn Superconducting Undulator Designs: performance Issues and Design Concepts”, Workshop on Undulator systems for X-FELs (WUS2005), June 6-8, 2005 DESY Hamburg, Germany
- S. Prestemon, “Superconducting Undulators and Wigglers”, Workshop on Acceleratror Magnet Design and Optimization, CERN, Geneva, April 3-6, 2006

Summary

- Superconducting insertion devices have a long and varied history in accelerators and light sources, starting with the first FEL's
- A large number of wigglers have been built, installed, and characterized in diverse rings
  - First cold-bore devices are in operation
  - Worth considering conductor options based on thermal issues
- Superconducting undulators are under development
  - First devices starting to be installed
  - Need high J_e to justify the technology against mature PM devices
  - Image current heating is an issue – need thermal management
  - Phase error correction methods not fully developed – needed for high harmonics

- Experience at LBNL with Nb_3Sn has been successful
  - High quench J_{cu} can be handled – allows low Cu fraction, high Jc superconductors
  - We have demonstrated a possible phase error correction element
  - **Short-sample has been obtained**