Development of Superconducting Undulators

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- **LBNL contributors**
- Magnetic Systems
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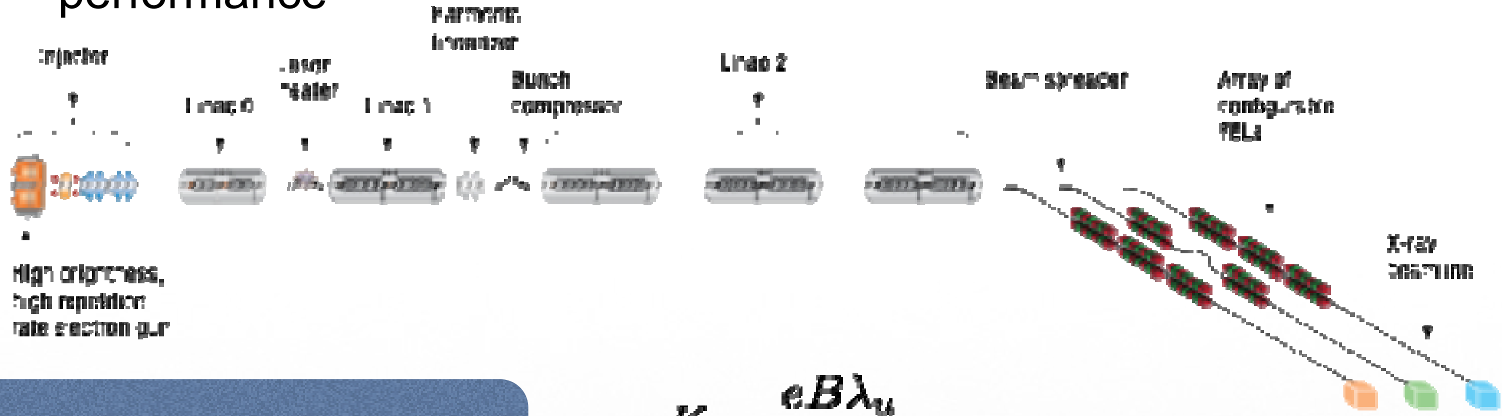
- Superconducting Magnet Program
  - ✓ *Daniel Dietderich, Shlomo Caspi*

Outline

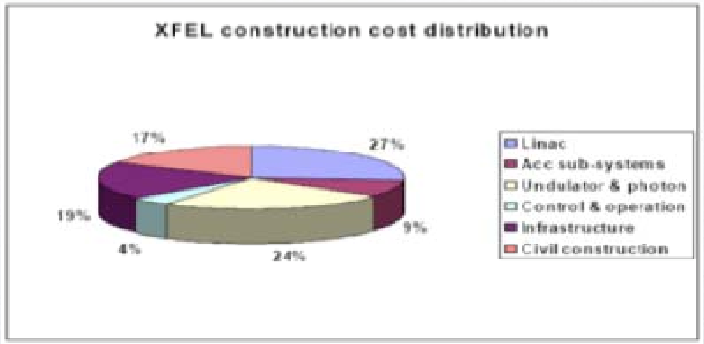
- Introduction
- Undulator development status:
  - ✓ Historical
  - ✓ Current
- Technical developments
  - ✓ Current developments and areas that need further research
- Future directions

- Undulator technology plays a critical role in FEL design and performance



$$K = \frac{eB\lambda_u}{2\pi mc}$$

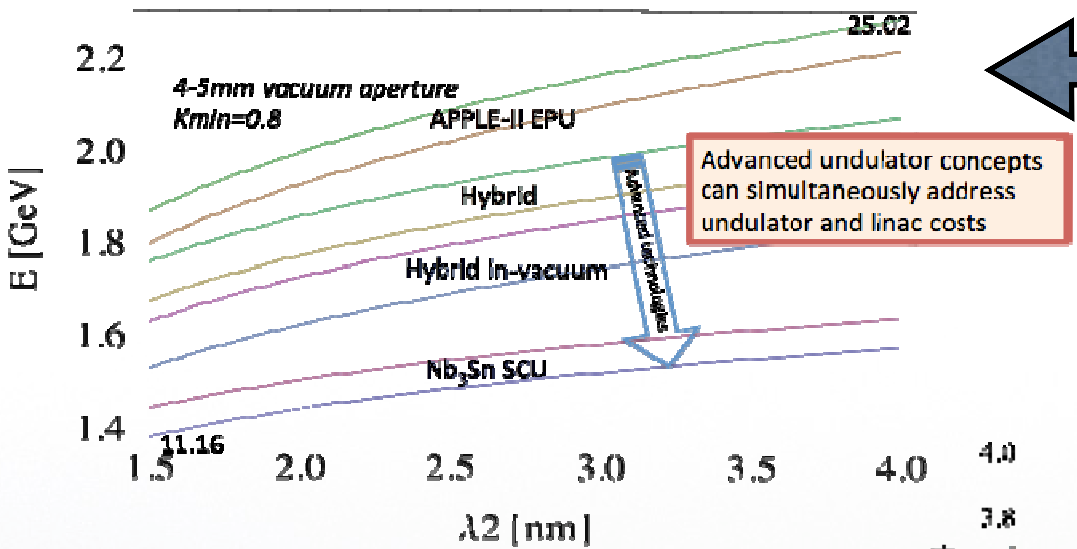
Lei Zang, Cockcroft Institute presentation



$$K_{max} = \left[2\left(\frac{\lambda_2 - \lambda_1}{\lambda_1}\right)\left(1 + \frac{K_{min}^2}{2}\right) + K_{min}^2\right]^{1/2}$$

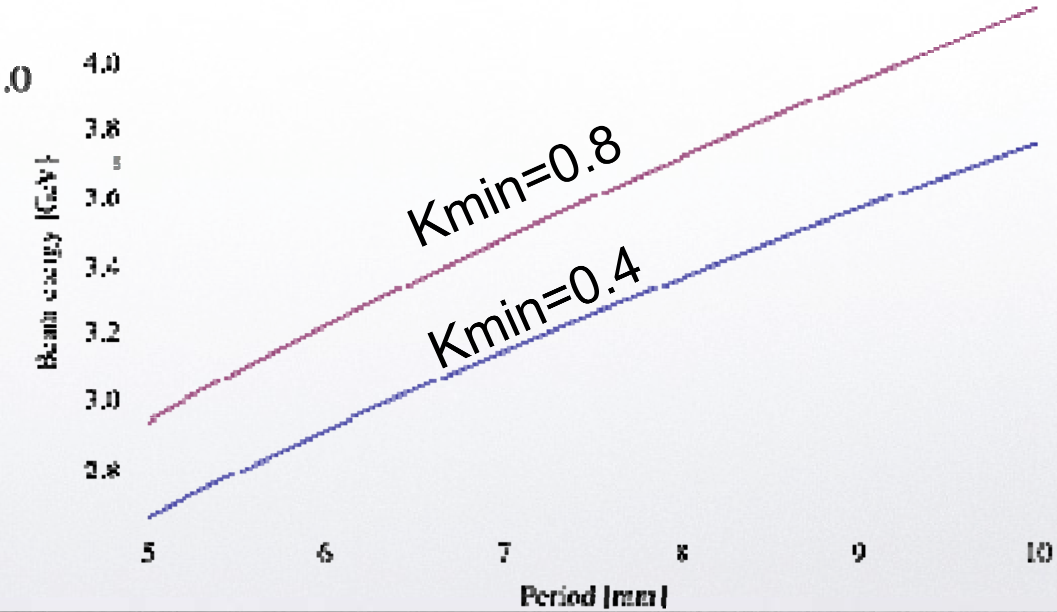
Tuning range ⇨ Undulator strength

Motivation: FEL's



Tunability for soft X-rays:
- Beam energy needed to access wavelength range 1nm<λ<λ2 for various technologies

Access to hard X-rays:
- Beam energy needed to access 1 angstrom for Kmin=0.4 and 0.8



SCU's: Motivation

- **Performance dominates in the >10mm period range**
  - ✓ Next closest competitor are cryogenic in-vacuum PM devices
  - ✓ Expect SCU's to be cheaper (ultimately)
    - ➡ No moving parts, material cheaper; cryogenics more expensive, but probably not significant if part of large SRF-linac facility
- **Performance appears strong in the <10mm period regime**
  - ✓ Outperforms hybrid PM devices
  - ✓ Need to:
    - ➡ Demonstrate performance
    - ➡ Understand and control tolerances
- **Maturity compared to other technologies**
  - ✓ PM>hybrid>in-vac.hybrid>CIVID>NbTi>Nb3Sn>HTS>SRF>plasma
  - ✓ But… measured SCU(NbTi) devices as APS and ANKA suggest SCU(NbTi) is in a close race with CIVID (excellent phase errors with SCU's)

- First undulators 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

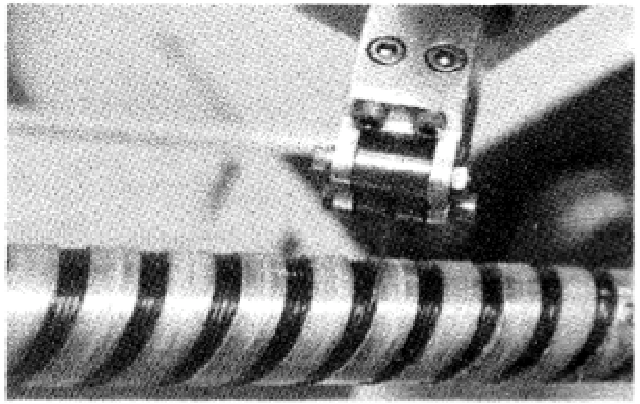


FIG. 5. Wire winding tool and partially completed magnet.

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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Karlsruhe/Mainz 1998
3.8mm period device

Superconducting undulators on rings

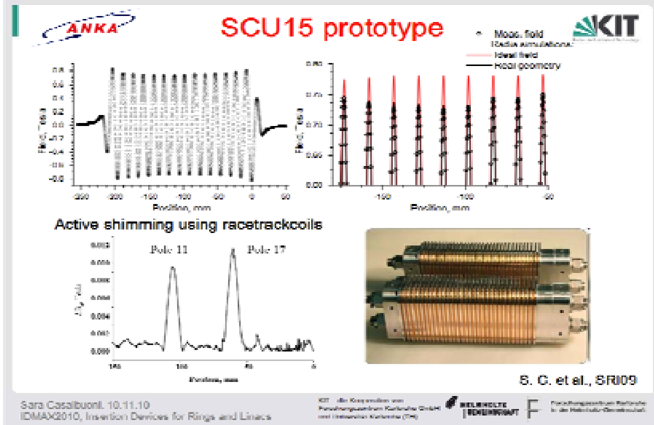
Location	λ [mm]	Year	Gap (mag.) [mm]	Gap (vac.) [mm]	Vac. wall temp. [K]	B [T]	Comments
Karlsruhe/Mainz	3.8	1998		2			
Anka/Accel	14	2003	5		4.2		Variable gap for beam-filling
NSLS	26	1994	8.6			0.82	(see NSLS und. Below)
NSLS	18	1994	8.6			0.54	Attained field; attempted shimming with additional Sc circuits; problems with complicated field quality controls, cryogenics
SRRC	10	2000	2			1.39	
Firfel	10		2		4.2	1.07	
BNL (HGFEL)	18		8			0.54	
BNL (ATF)	8.8		4.4			0.66	

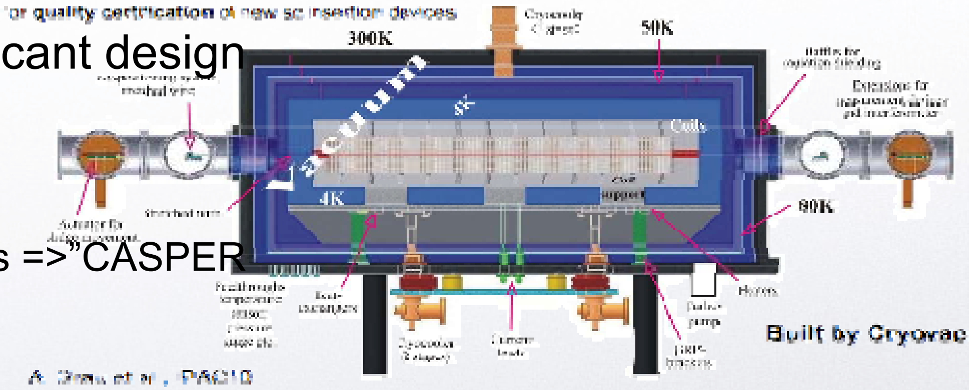
SCU's: Current status

- **NbTi Prototypes – full scale and subscale, demonstrate performance meets specs**
  - ✓ Phase errors quite low -Key is excellent quality control during fab.
  - ✓ No real implementation of shimming ; except LBNL proof of principle
  - ✓ Some variation from device to device; source not evident
- **Implementation of Nb3Sn at LBNL; only tentatively investigated elsewhere**
  - ✓ Would benefit from guidance on material and fabrication issues
  - ✓ Working with conductor vendors for optimal conductors
- **Cryogenics:**
  - ✓ Generally using cryocoolers, either with recondensers or via conduction
  - ✓ General uncertainty on heat load; evidence of unknown source; multiple calorimeters being designed and fabricated
- **Next steps**
  - ✓ First truly successful operation in a storage ring (Anka / APS / other?) needed
- **R&D areas**
  - ✓ Need to develop fully functioning measurement system
  - ✓ Need fully developed shimming approach
  - ✓ Need to develop sub-10mm period devices

SCU's: Active developments

- ANKA:
  - ✓ Steadily developing SCU's with industrial partners
  - ✓ First devices on ring
    - ➡ initially had performance issues, but getting better
    - ➡ providing critical input into design/implementation issues
  - ✓ More devices being designed/prototyped/built:
    - ➡ 15mm period device for NANO beamline
    - ➡ 15/45mm period undulator/wiggler device
  - ✓ ring requires variable gap device => significant design implications
  - ✓ R&D:
    - ➡ Improved measurements for shimming analysis =>"CASPER II"
    - ➡ understand beam heat loads => "COLDDIAG"
    - ➡ test performance of devices on the ring



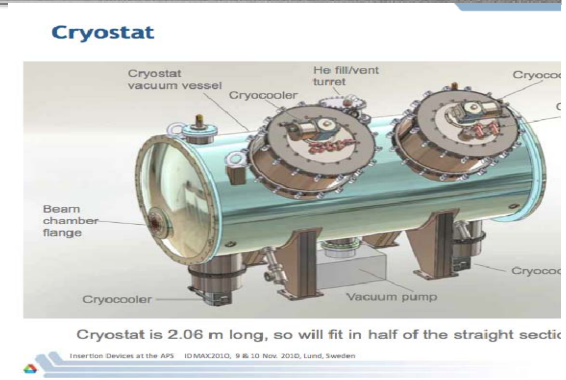


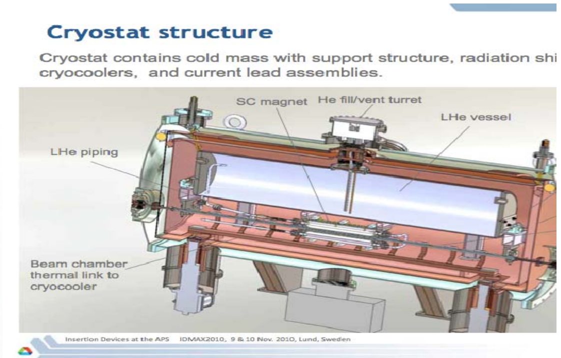
SCU's: Active developments

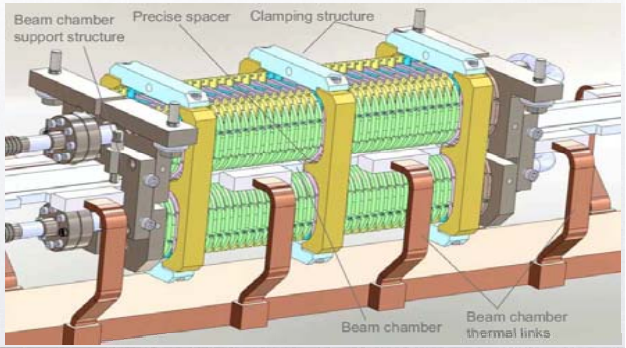
Y. Ivanyushenkov
Short-period undulator
workshop, LBNL, 2011

- APS:
  - ✓ Developing SCU's as a key component of an ongoing upgrade
  - ✓ Conservative, systematic approach being pursued
  - ✓ Addressing technical issues:
    - ➡ goal of having a first device in the ring within 1-2 years, and many (~8) more over the next few years

Prototype / Parameter	1	2	3	4	5	Assembly 1	Assembly 2
No of poles	10	10	10	10	10	42	42
Core/ pole material	Al/Al	Iron/Iron	Al/Al	Al/Al	Al/Al	Iron /Iron	Al/Iron
LHe test status	Tested	Tested	Used for impregnation study	Used for impregnation study	Used for impregnation study	Tested	Tested
Peak field						0.65 T @ 500 A	0.61 T @ 500 A
Phase error*						7.1°@ 500 A 3.3°@ 200 A	5.0° @ 500 A 3.0° @ 200 A
Spectral performance (phase errors included)						>75% of ideal in 3rd harmonic (60 keV); >55% of ideal in 5th harmonic (100 keV)	







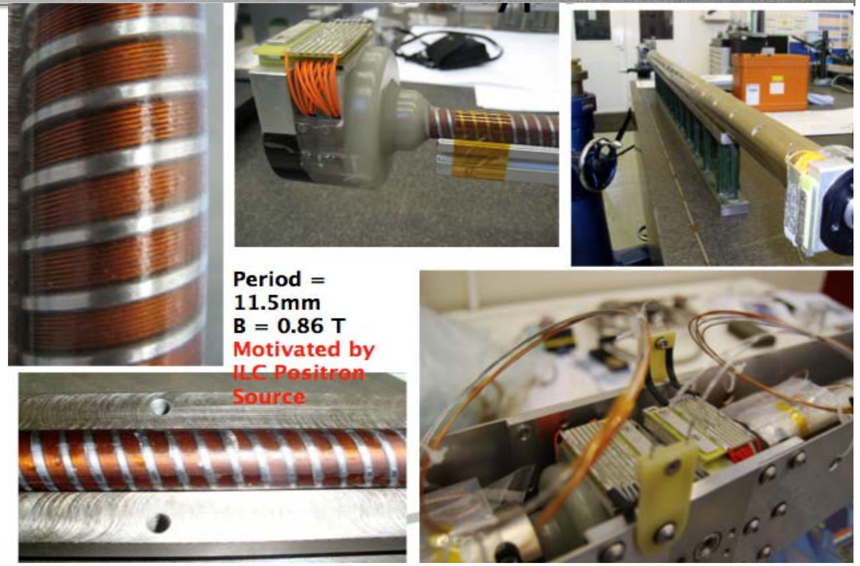
SCU's: Active developments

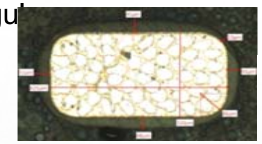
- Daresbury:

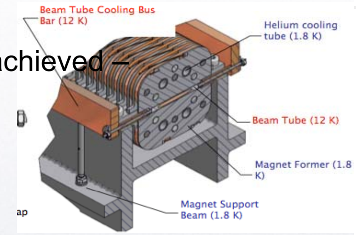
J. Clarke
Short-period undulator workshop, LBNL, 2011

✓ Significant development effort in bifilar helical undulator
  - focus on ILC positron production mechanism
  - numerous prototypes built and tested
  - full-length device built and tested - met field-strength requirement
  - no local field correction

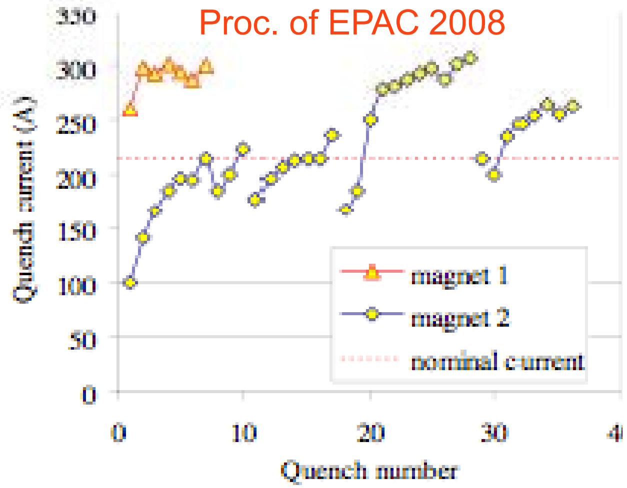
✓ Planar SCU's under development:
  - 15mm period, 2m device for Diamond
    - NbTi, Supercon Inc., Cu:SC=0.9:1, rectangu
    - 5mm vac. gap (12K chamber)
    - 1.8K operation
  - R&D plan:
    - Assemble the turret test rig and confirm the cooling powers expected are achieved
    - Construct a short magnet array to confirm tolerances are achieved – vertically test
    - If not, incorporate correction scheme?
    - Construct full length magnet
    - Assemble and test complete undulator
    - Install into Diamond (replace existing in- vac undulator), confirm cryo and magnetic performance





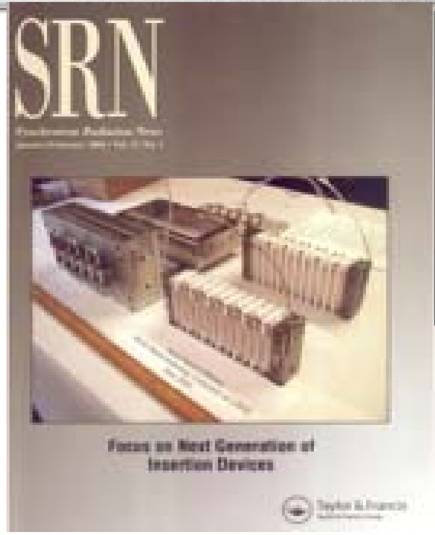


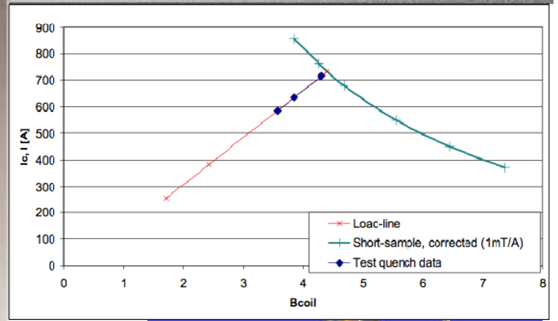
J. Clarke et al.
Proc. of EPAC 2008

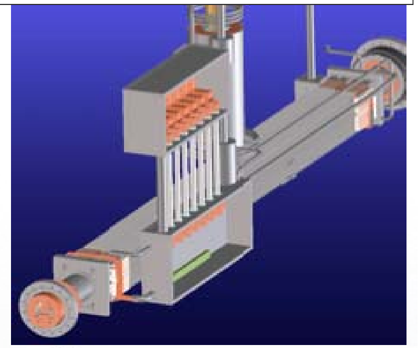


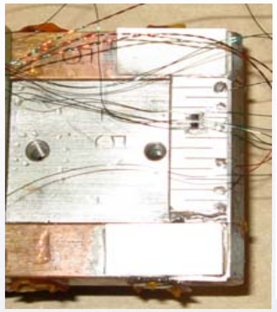
SCU's: Active developments

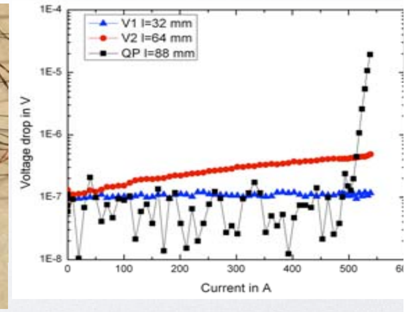
- LBNL:
  - ✓ Prototype planar SCU's using Nb_3Sn
    - ➡ 30mm and two 14.5mm period prototypes
  - ✓ Demonstration of shimming concept
  - ✓ Demonstration of cold-switching concept
    - ➡ allows +/-/0 current to a shim
    - ➡ will allow fast shimming of a device
    - ➡ will allow complex period-doubling electrical circuits
  - ✓ Development of an SC-EPU concept
  - ✓ Development and testing of pulsed wire measurement system
  - ✓ Development and component testing of YBCO tape undulator concept
  - ✓ Collaboration with SINAP on image-current calorimetry

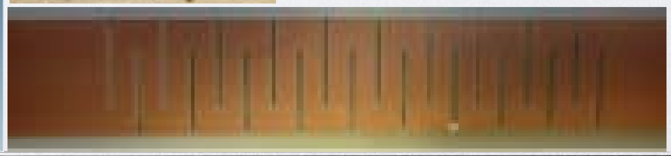


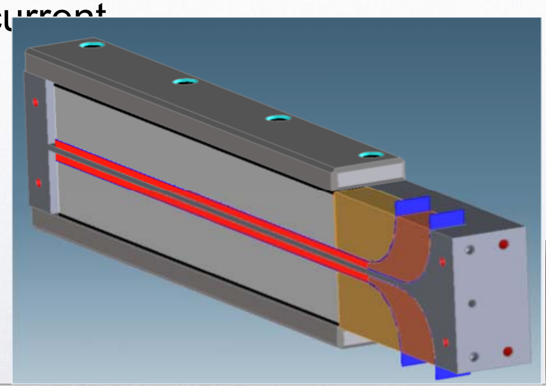


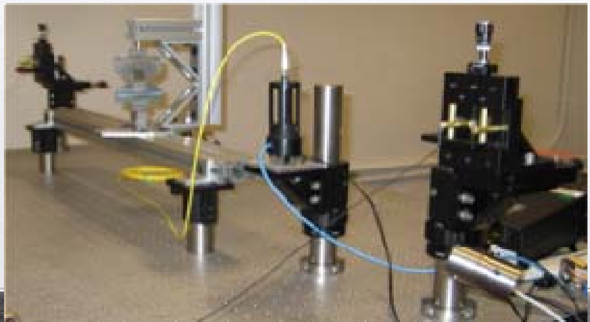






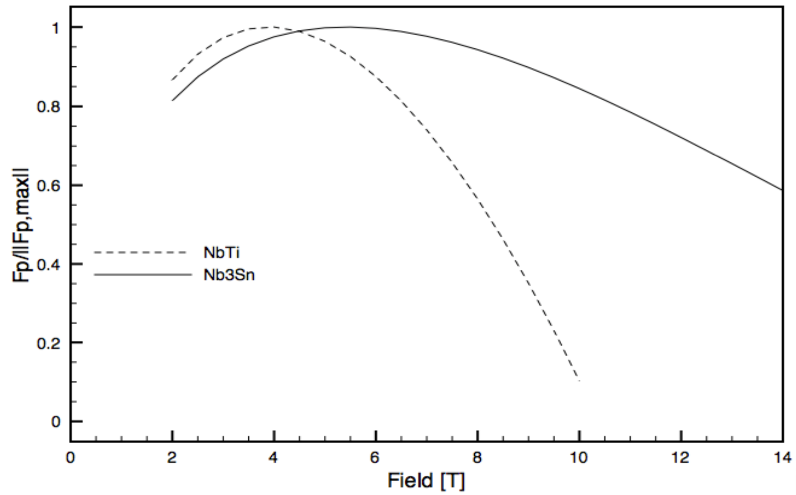


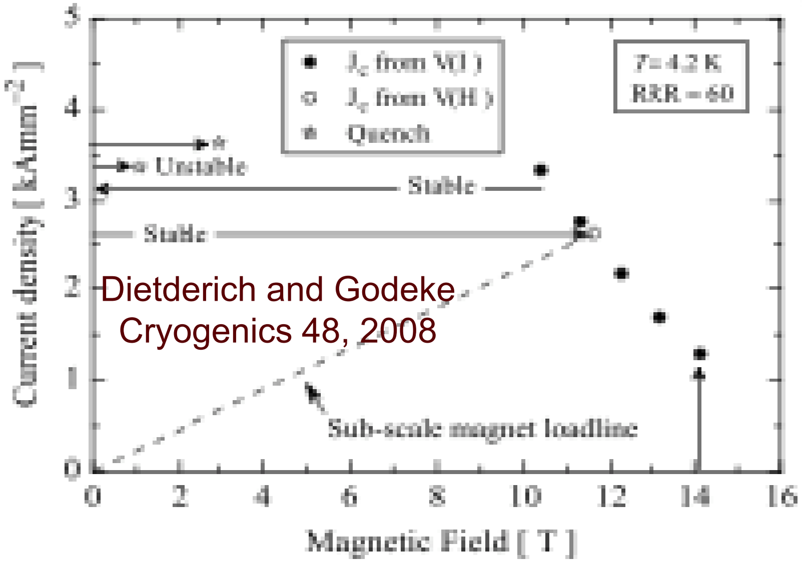




Technology developments: 1: Conductors

- The superconductor properties are the ***essential ingredient*** for high performance SCU's
  - ✓ Performance dictated by Jav => need high Jc
    - ➡ Need to minimize insulation and "stabilizer" cross-sections
  - ✓ For most undulator applications 2T<Bmax<4T
    - ➡ Leverage materials with strong pinning strength in this field range
    - ➡ Need to avoid low-field instabilities =>need small "filaments"

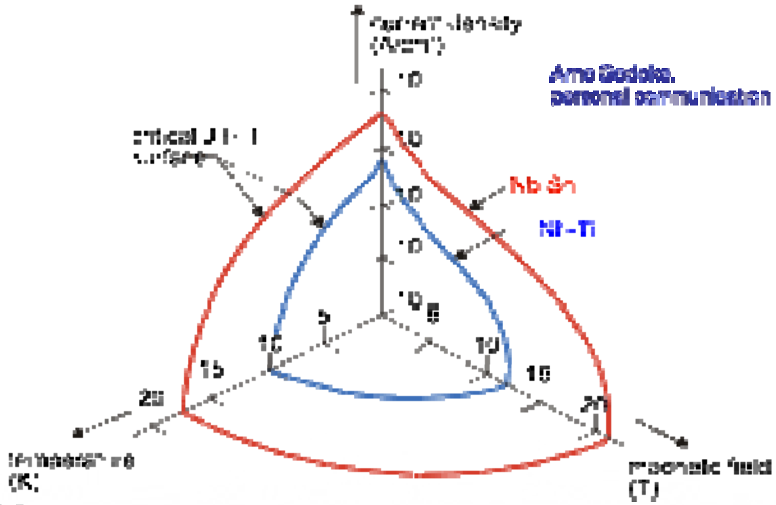


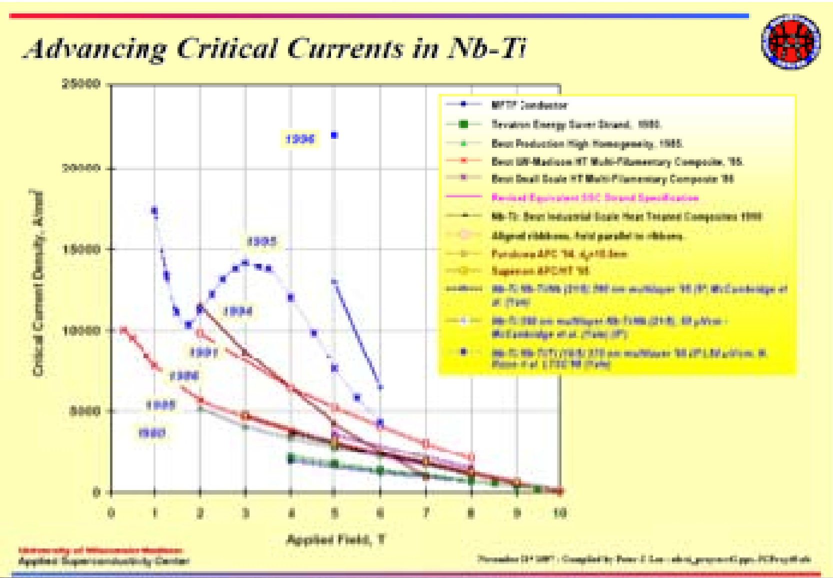


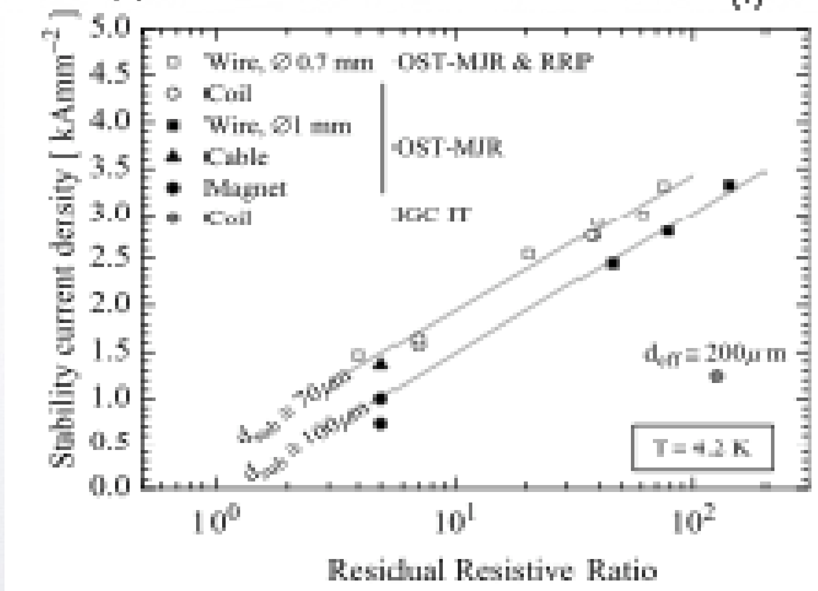
Dietderich and Godeke
Cryogenics 48, 2008

Conductors: LTS

- Commercially available materials:
  - ✓ NbTi: workhorse superconductor for Bmax<~9T
    - ➡ typically Jc is "low", Cu stabilizer fraction "high"
    - ➡ For SCU's, want Cu:Sc~1:1 or 1.3:1
  - ✓ APC NbTi: highly optimized NbTi material
    - ➡ excellent candidate for SCU's - optimal in 2-4T range
    - ➡ not readily available
  - ✓ Nb3Sn: ultimate performance
    - ➡ needs extra processing steps (Wind-and-react)

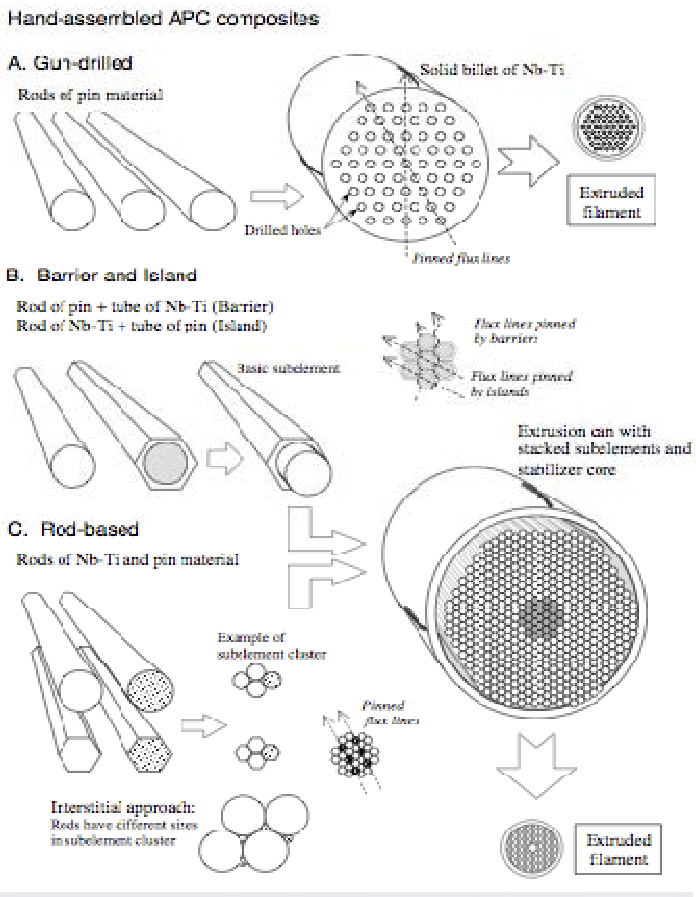


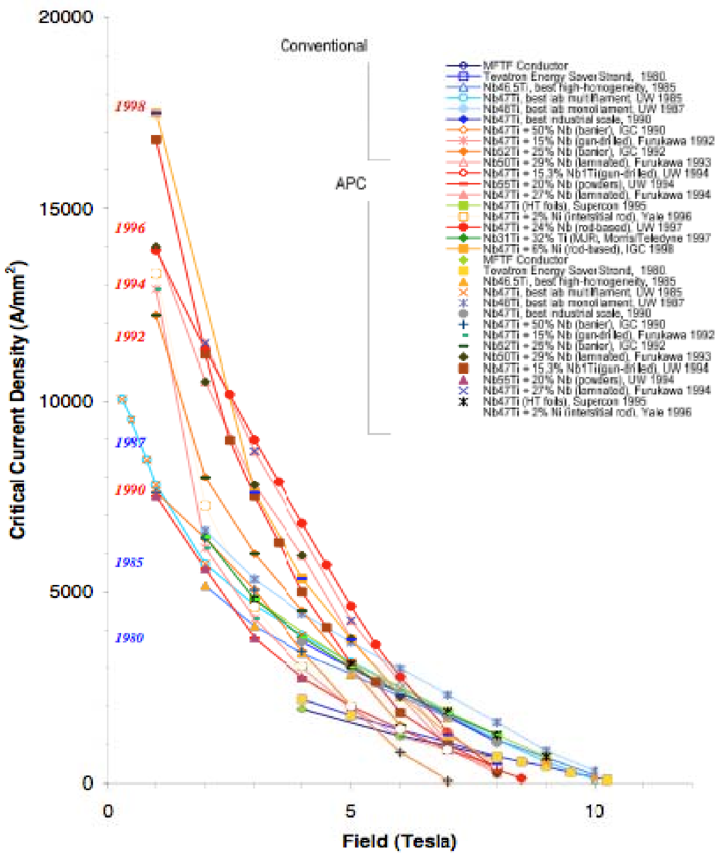


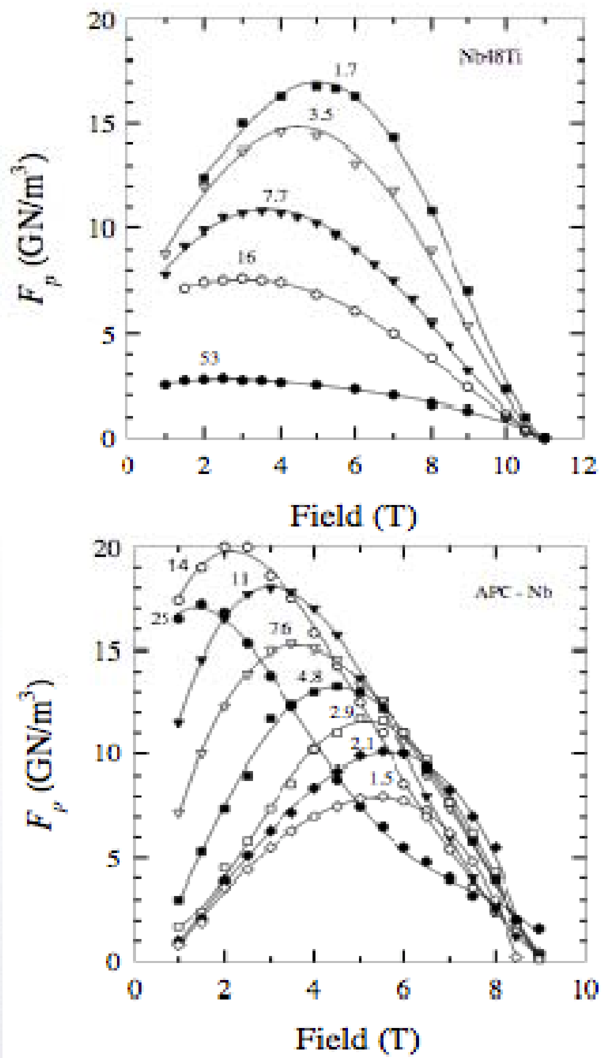


Conductors: Example APC-NbTi

L. D. Cooley and L. R. Motowidlo,
"Advances in high-field superconducting composites by addition of artificial pinning centres to niobium–titanium"
SUST 12 (1999)







Conductors: Example Nb_3Sn RRP

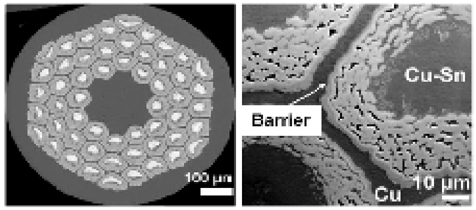
- Oxford Instruments

  ✓ Highest Jc Nb_3Sn material commercially available

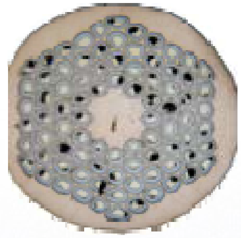
  ➡ Reducing filament size by increasing filament-count

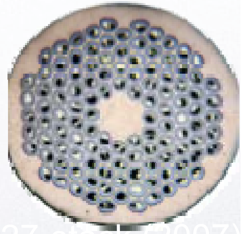
  ❖ Deff (0.7mm diameter wire) is ~40 microns

D. R. Dietderich and A. Godeke
Cryogenics 48 (2008)
MJR 54/61 stack

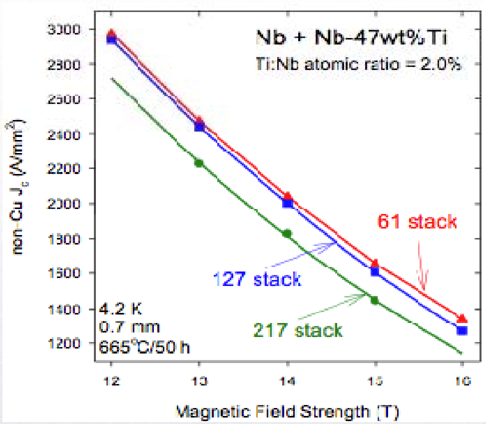


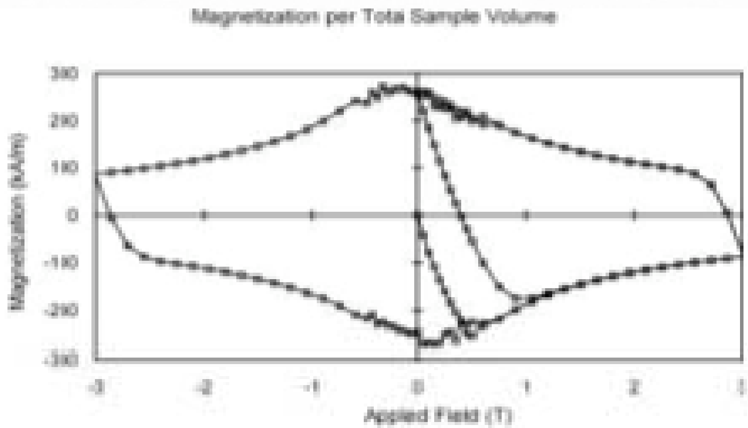
91 stack

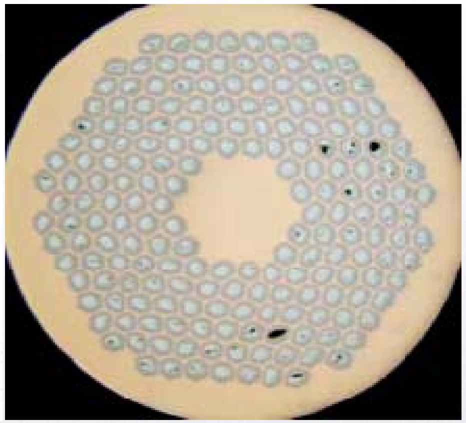




127 stack







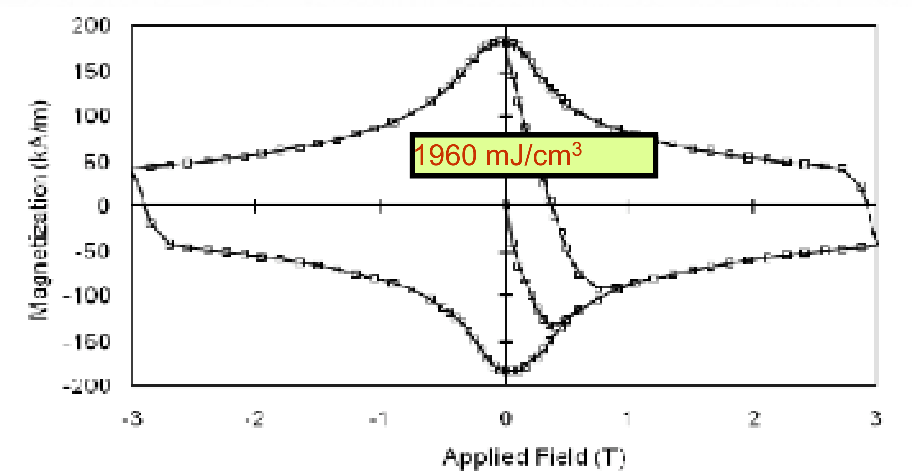
217 stack

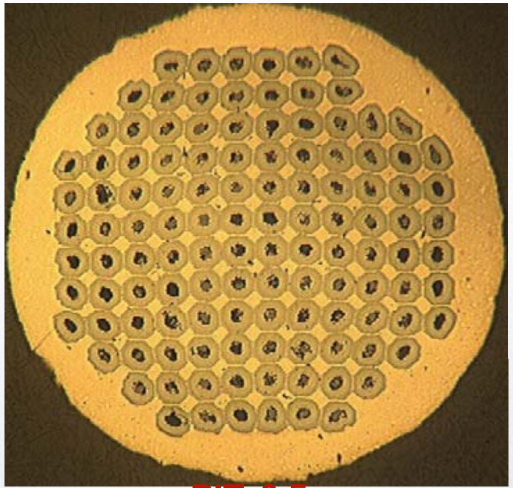
RRP process

Conductors: Example Nb3Sn PIT

- Supramagnetics

Conductor Design	Wire Diameter (mm)	Filament Diameter (μm)	Temp. (°C)	non-Cu J_c (A/mm²)	Critical Current (Amps)	Σ_{irr} (%)	RRR	non-Cu ac Losses (mJ/cm³)
120 OCT	0.5	31	675	1,988 @12T	191	0.58	-	-
"	0.759	47	650	2,649 @11.5T	588	-	48.5	-
"	0.5	31	625	2,617 @12T	251	0.74	-	1960



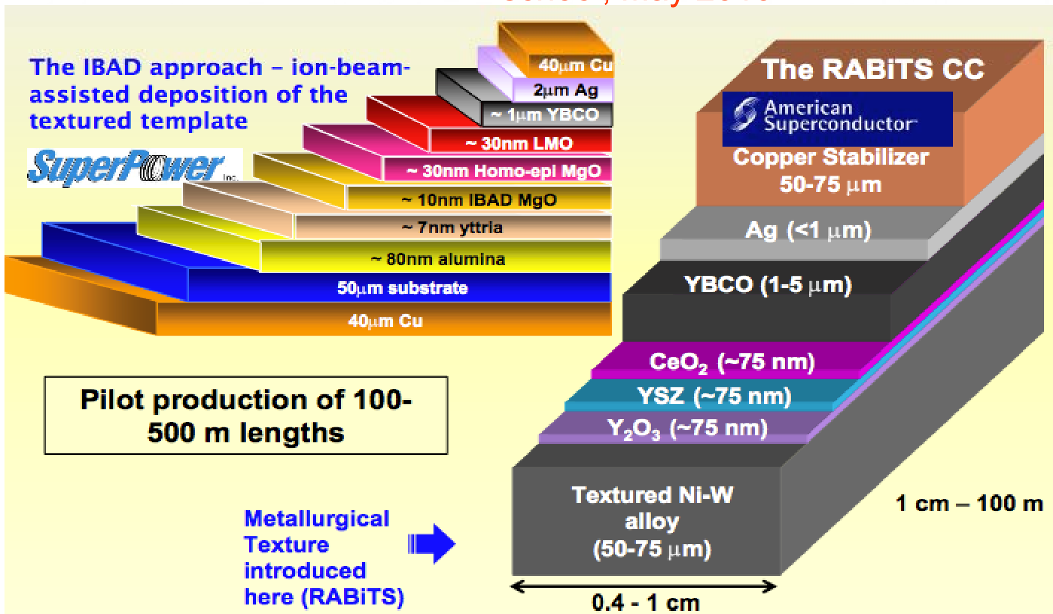


PIT, 0.5mm

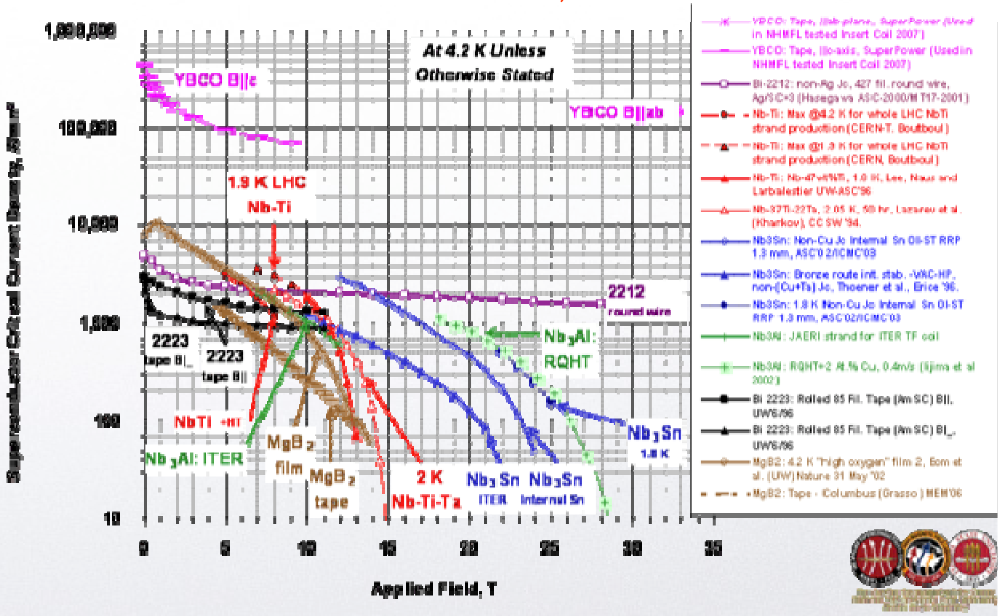
Conductors: Example YBCO

- "High temperature" superconductors:
  - ✓ carry supercurrent at temperatures as high as ~100K, or at high field (up to 100T or higher)
  - ✓ Current densities low at "high" temperature (e.g. 77K - LN)
  - ✓ Current density high at 4.2K (LHe)

D. Larbalestier, Maglab summer school, May 2010

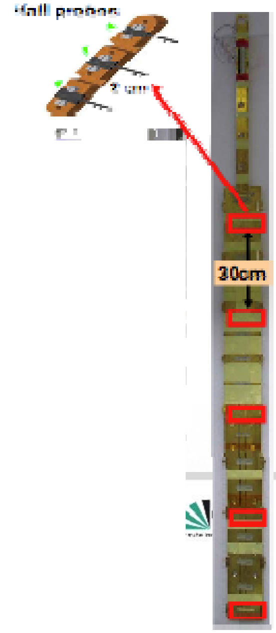


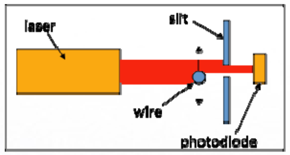
Peter Lee, NHMFL

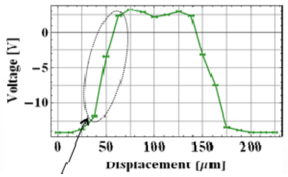


Technology developments: 2: Measurements

- Traditional Hall probe granite tables not applicable to SCU's
  - ✓ Modified Hall probe setups have been developed
    - Main issue is in determining accurate Hall probe location
  - ✓ Stretched wire integral methods can be applied
- Pulsed wire technique is being refined
  - ✓ provides fast determination of first and second integrals



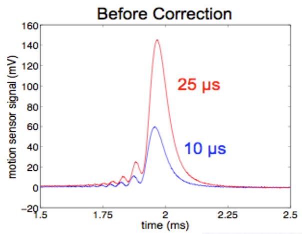


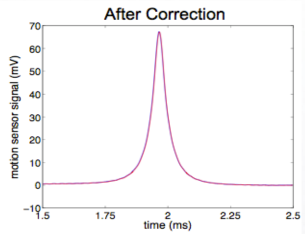


$$\hat{u}(t) = \frac{I_0}{2\mu}\int_{-\infty}^{+\infty} \frac{e^{i\omega\delta t}-1}{\omega^2\left(c+\kappa\frac{dc}{d\kappa}\right)}\bar{B}(\kappa)e^{-i\omega t}d\omega$$

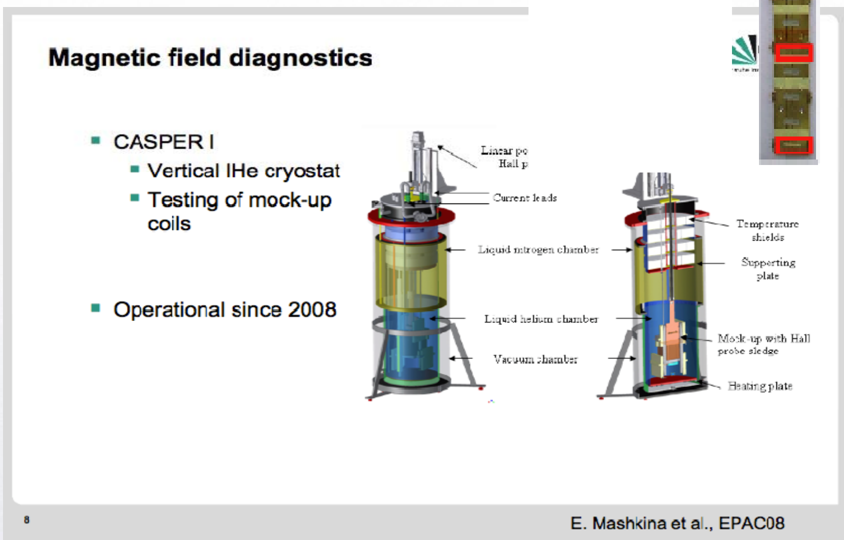
Dispersive wave motion: $\omega = \kappa c(\kappa)$

Undispersive wave motion: $\omega = \kappa c_0$



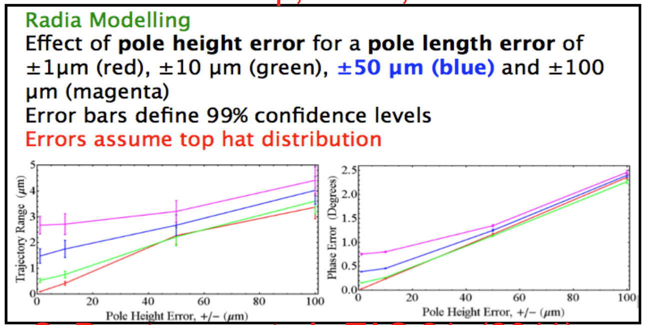


ANKA measurement setup "CASPER

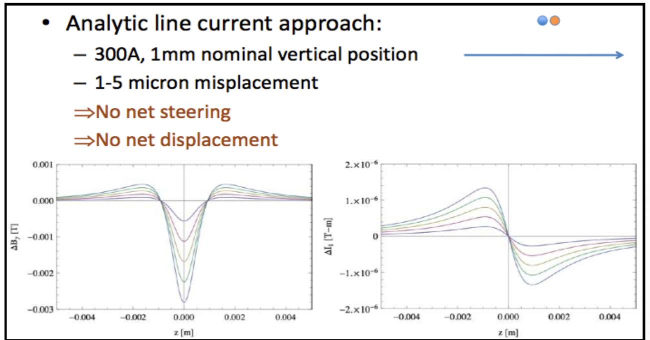


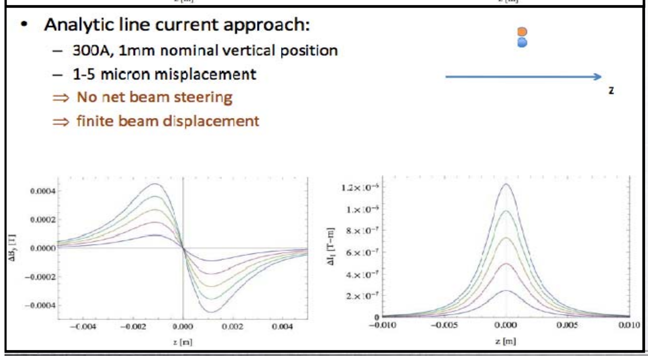
Technology developments: 3: Field quality and correction

J. Clarke, Short period undulator workshop, LBNL, 2011



S. Prestemon et al., TAS 21, (2011)





Two measurement technologies being pursued:

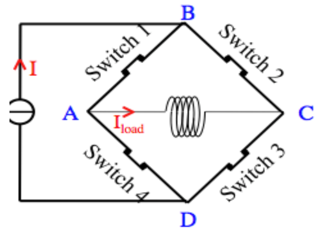
1) Hall probes in bores as small as 2-3mm diameter

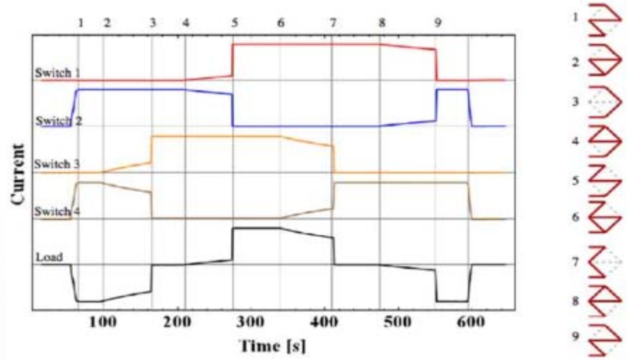
2) Pulsed wires in bores as small as 1 mm diameter

Key issue: ~25 micron vertical probe positioning in e.g. 10mm period undulator for dB/B ~ 10^-4;

- Need Probe in straight line to < 25 microns
- Undulator alignment to ~ 20 microns
- Quadrupole alignment to ~ 10 microns

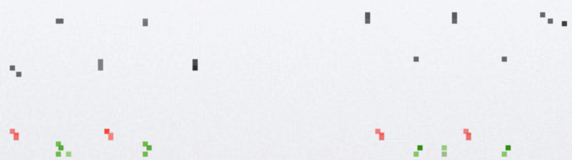
A. Madur et al. SRI 2009

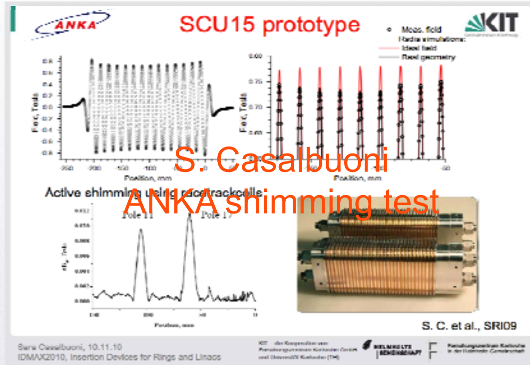




D. Wollman, EPAC 2008

Induction shimming concept





S. Casalbuoni

ANKA shimming test

Technology developments: 4: Wakefields and image currents

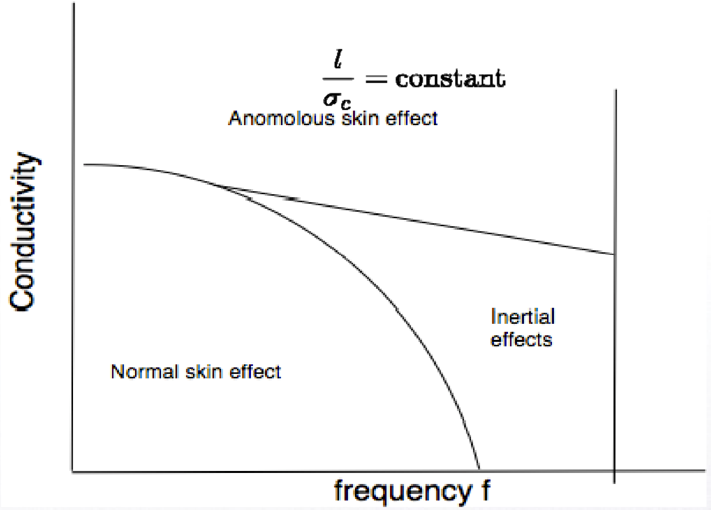
See Podobedov: PRSTAB 12, 2009

- "Cold-bore" operation results in highly-conductive surfaces (RRR can be very large)
  - ✓ impacts wakefields and image current heating of walls
- High conductivity => larger mean-free path ℓ
  - ✓ Anomolous skin effect (ASE) regime when ℓ> δ
  - ✓ Extreme ASE regime: ℓ>> δ and $k \ll k_p v_f/c$
  - ✓ High-frequency regime: $k \sim k_p v_f/c$

$$\delta = \sqrt{\frac{2}{Z_0 \sigma_c k}}$$

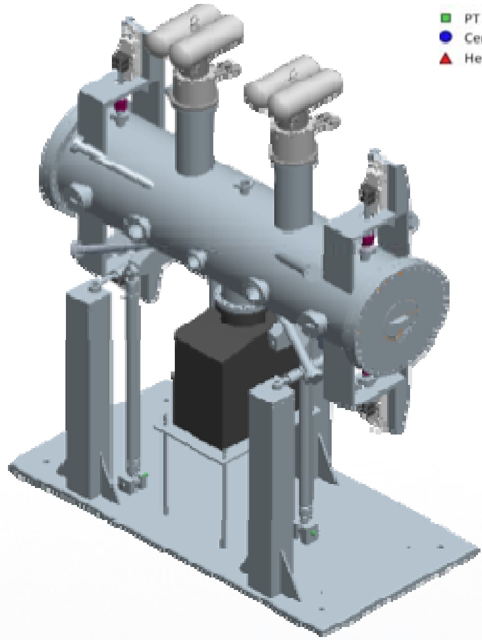
$$P/L|_{ASE} \propto \frac{I_{av}^2}{r\sigma_z^{5/3}}$$

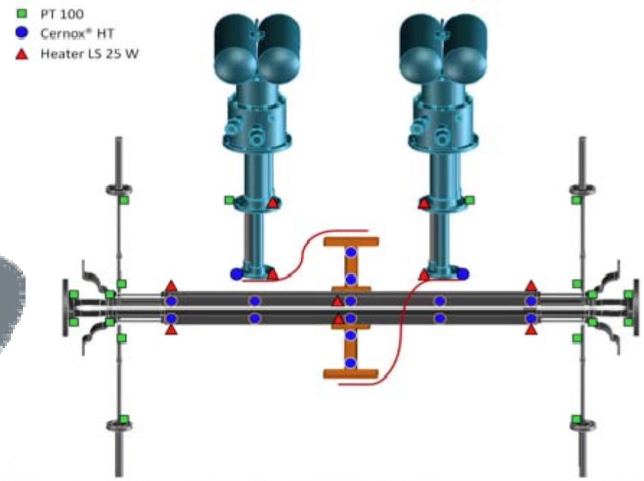
$$P/L|_{NSE} \propto \frac{I_{av}^2}{r\sigma_z^{3/2}\sqrt{\sigma_c}}$$



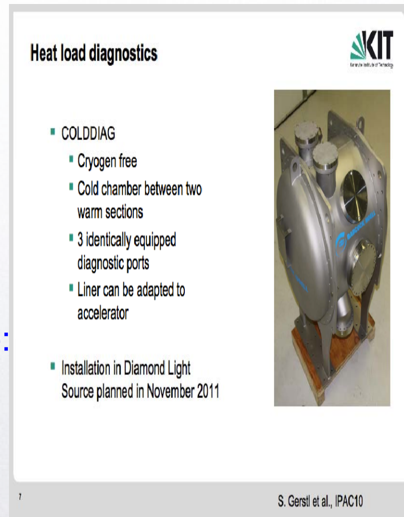
Measuring image currents

- Calorimetry:
  - ✓ SINAP/LBNL collaboration:
    - ➡ Measure heat loads via temperature gradients
    - ➡ Cooled by one or two cryocoolers
      - ❖ in-situ heaters:
        - constant-temperature operation
        - in-situ calibration checks
    - ➡ First installation planned summer 2012
    - ➡ Expect resolution <20mW
  - ✓ ANKA:
    - ➡ "COLDDIAG": cryogen-free measurements
    - ➡ passed factory and final acceptance test
    - ➡ first installation in Diamond Light Source
      - ❖ planned November 2011





Recent update (S. Casalbuoni):
- reached 4.8K on the liner
- reached 10^-9 mbar

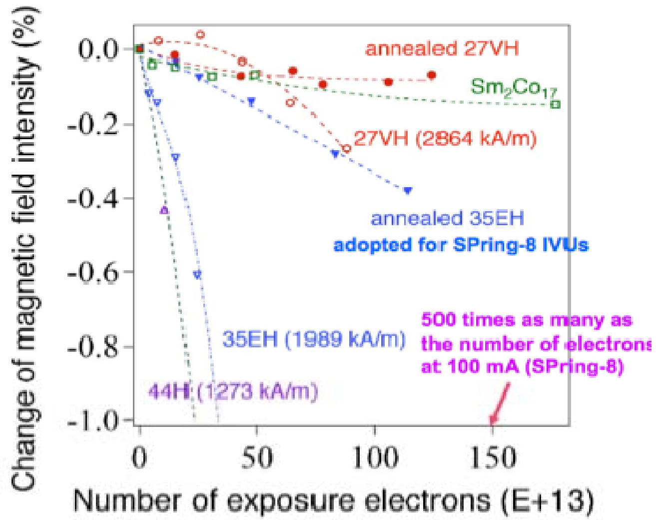

Heat load diagnostics

- COLDDIAG
  - Cryogen free
  - Cold chamber between two warm sections
  - 3 identically equipped diagnostic ports
  - Liner can be adapted to accelerator
- Installation in Diamond Light Source planned in November 2011

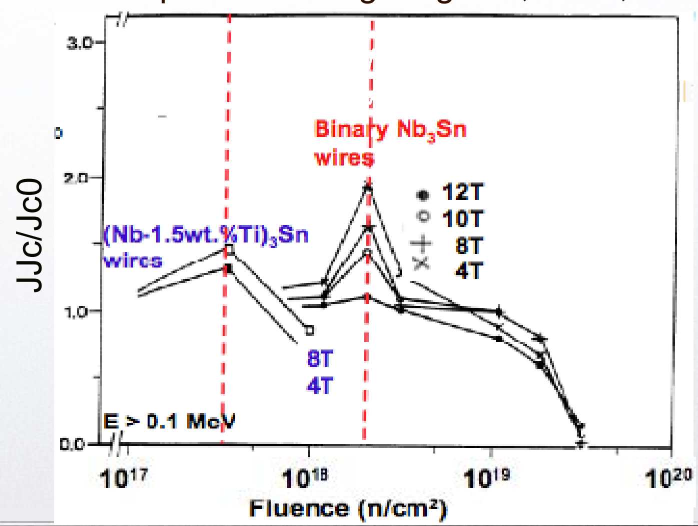
S. Gerstl et al., IPAC10

Technology developments: 5: Radiation tolerance

- High repetition-rate FEL's push the radiation limits of PM materials
  - ✓ Need to collimate beam, control halo
  - ✓ Sm_2Co_{17} dramatically better than NdFeB
- PM Radiation Damage
  - ✓ FLASH experiment suggested that only 10^4Gy gave 0.5% loss in B field of PM undulator
- SCU Radiation Damage
  - ✓ Primary concern is in epoxy used for potting coils, but much less susceptible than PMs
  - ✓ Should still be protected with collimation scheme
  - ✓ Commonly accepted dose limit for epoxies is 10^7 Gy - used in ITER (Fusion Technology Institute, Wisconsin)



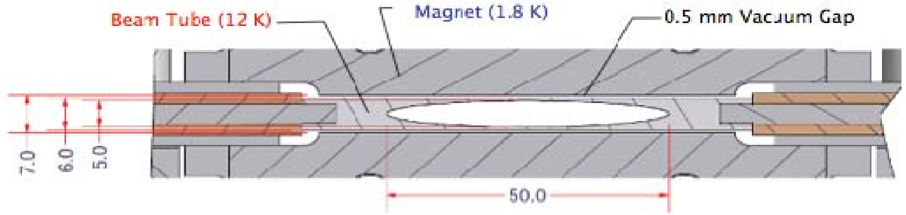
See Flukiger, 12 Course, Superconducting Magnets, Erice, 200



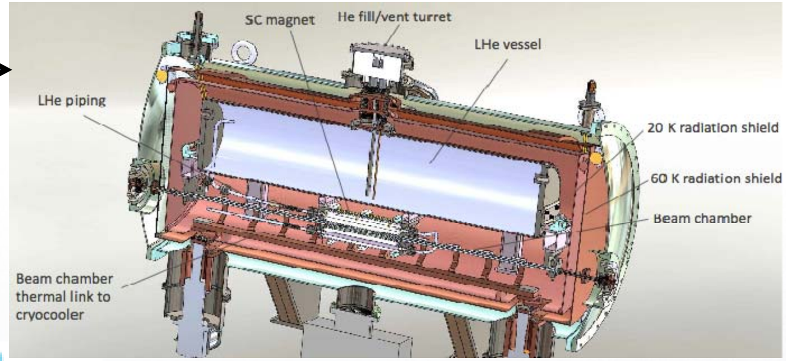
Technology developments: 6: Cryogenics

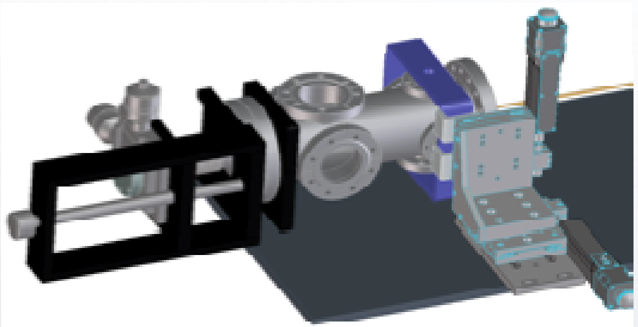
- Cold mass prototyping, R&D:
  - ✓ Liquid helium dewar
  - ✓ Cryogen-free system
- Storage ring application:
  - ✓ Liquid helium+liquifier
  - ✓ Liquid helium+cryocooler (“heat-pipe” approach)
  - ✓ Cryocooler (conduction)
- FEL applications:
  - ✓ Liquid helium+liquifier

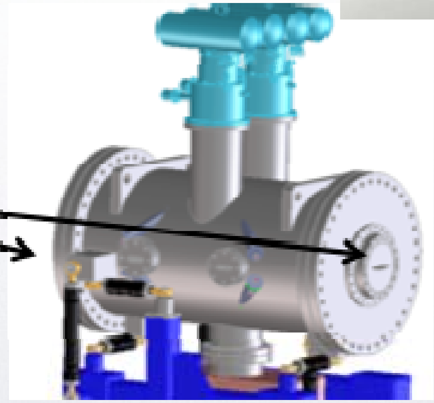
J. Clarke, Daresbury



Y. Ivanyushenkov, APS

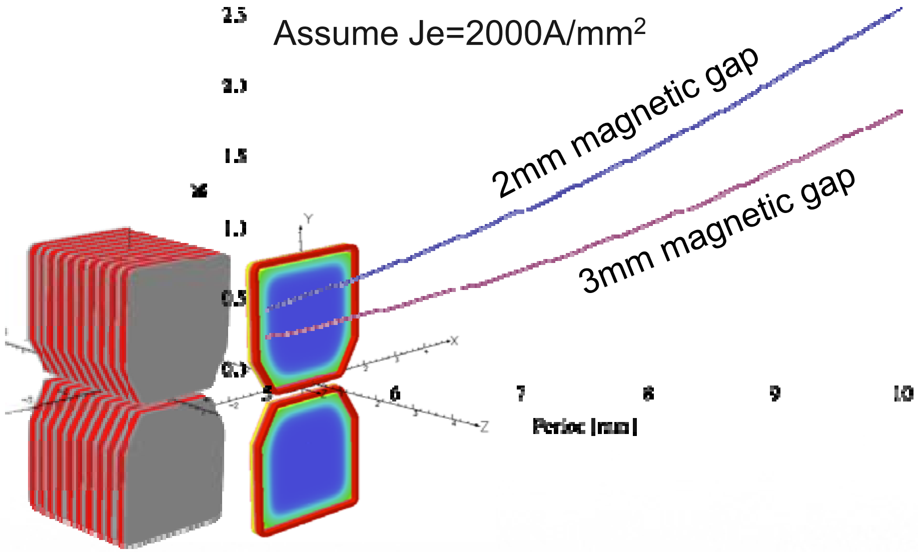


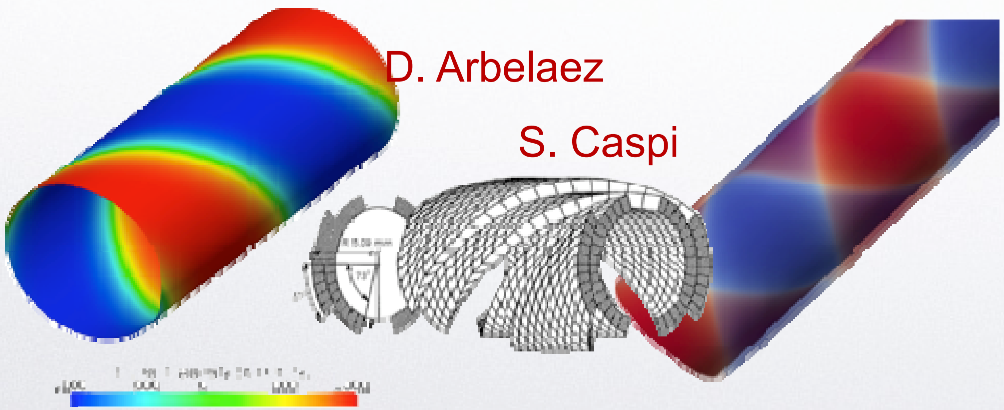


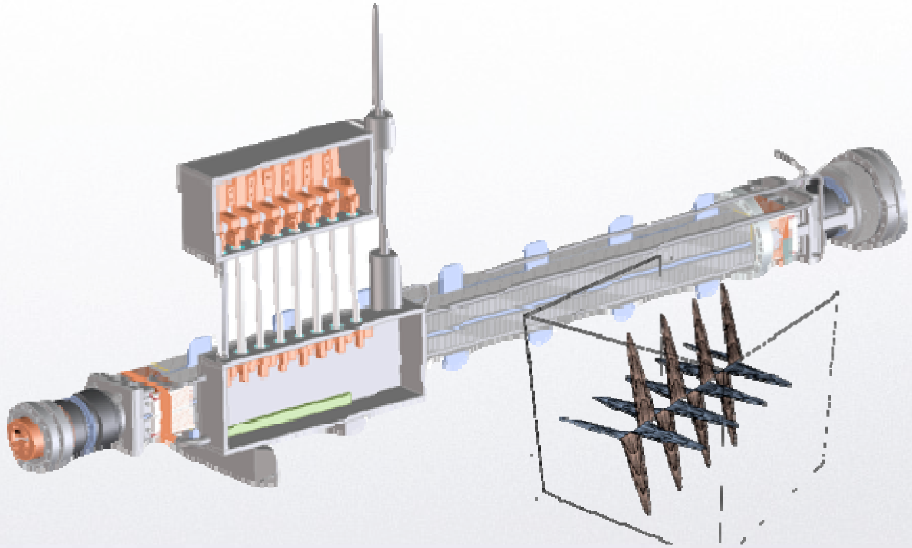


Future directions

- Strong pull for shorter-period devices: sub-cm
  - ✓ Recent workshop held at LBNL
- Some pull for bifilar helical devices
  - ✓ most efficient modulator design - shortest length FEL
  - ✓ not well-suited for laser-seeding
- Strong pull for variable polarization devices







Summary

- Significant progress in SCU development
- Real devices will soon be appearing on storage rings
- Field errors are quite low
  - ✓ controlled by fabrication tolerances
- R&D ongoing to address remaining issues
  - ✓ magnetic measurements
  - ✓ field correction
  - ✓ implementation issues (alignment, cryogenics,...)