Survey of measuring facilities in EU laboratories

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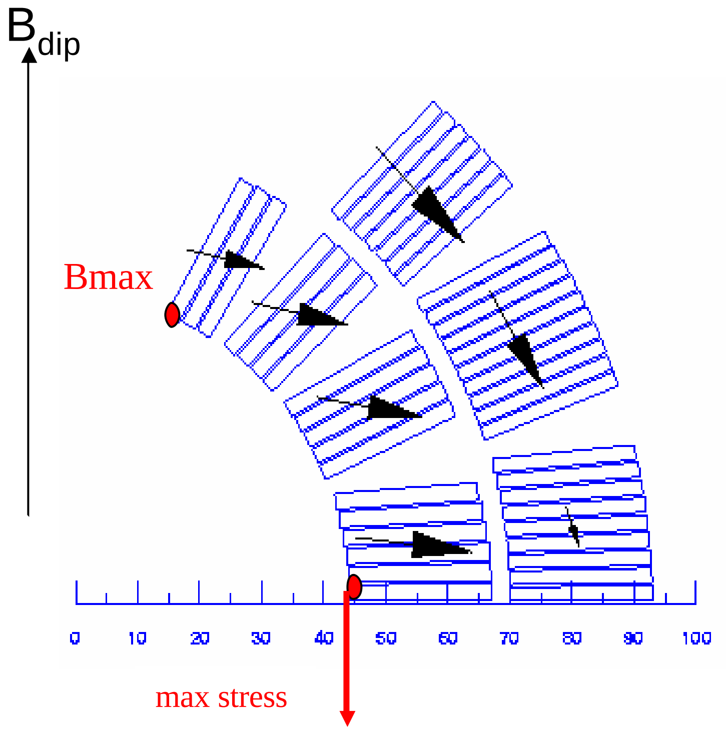
•focus on A15
•high currrent (density) conductors (cables)

Conductor R&D in Europe dedicated to or attractive for accelerator magnets

- NbTi : performance limits reached with LHC
- coated YBCO: very challenging, rapid improvements, applications in 5-10 years
- Nb_3Al: little EU activity, mainly US and Japan
- EU(3rd, 4th and 5th FP) + national programs on BSCCO (many 10's M€)
  - mainly BSCCO(2223)
  - focus on AC power applications and related issues
  - no approved 6th FP program despite a lively and competent R&D community
  - tape geometry not attractive for acc. magnets, large filaments
  - expensive ($/m/kA), relatively underperforming, I_c strain sensitive

- MgB_2 : very challenging, possibly also at high fields
- national programs in many countries since 2-3 years
- one (1) EU program: HIPERMAG, 2.5 M€, 13 (!) partners, 3 years program,
- mainly material science oriented

- Nb_3Sn:
- R&D driven by EFDA/ITER program, beautiful conductors, moderate I_c, low losses (d_f, R_c), $I_c(\varepsilon_{//})$, CICC
- only Bochvar and Univ. of Geneva have reported on more fundamental material aspects
- CERN-UT(dipole) and CEA (quad) programs, mainly technology oriented, modest resources for conductor development manufacturers
- CARE-NED, 3 years program (1 M€), 5 partners, Nb_3Sn acc. dipole magnet

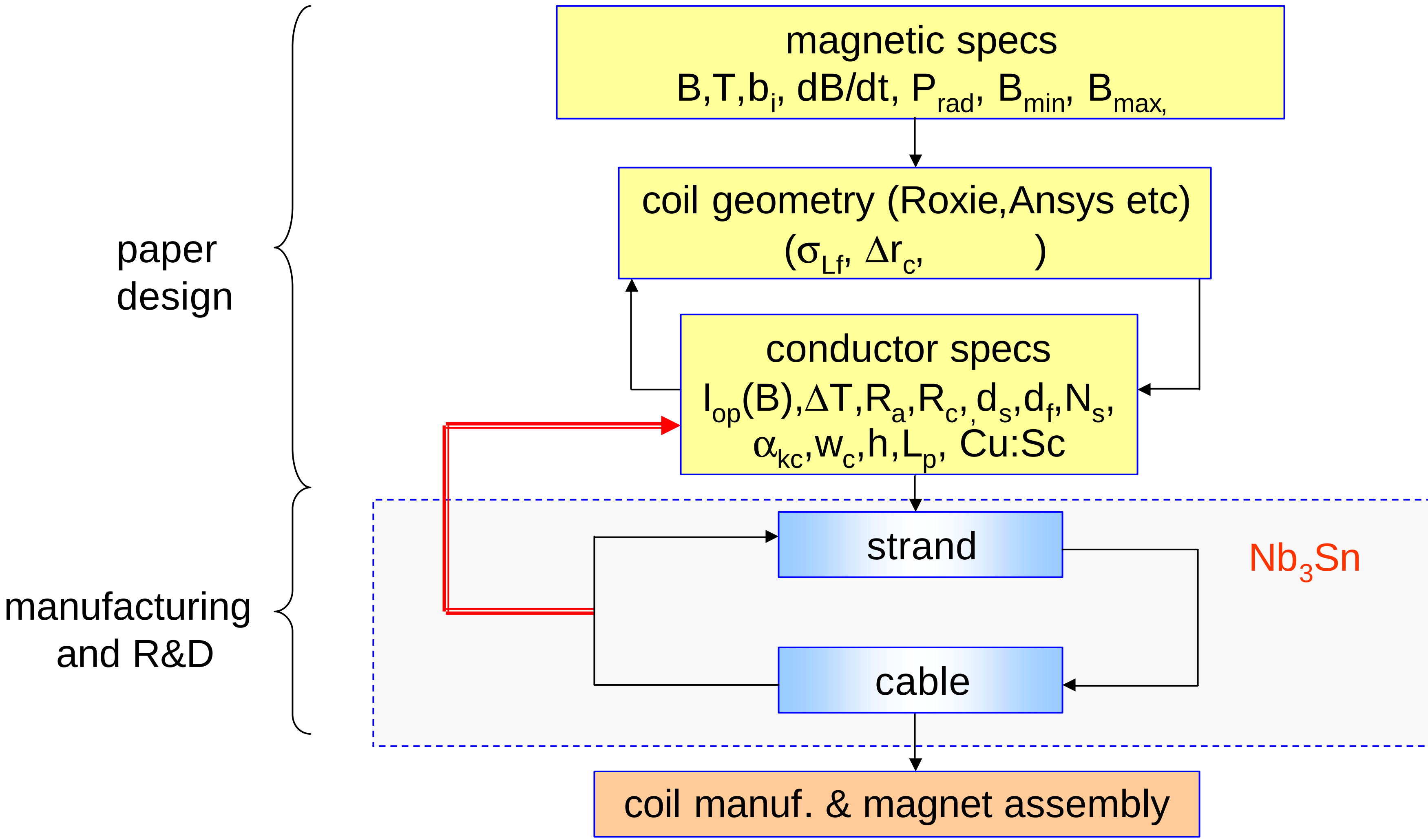


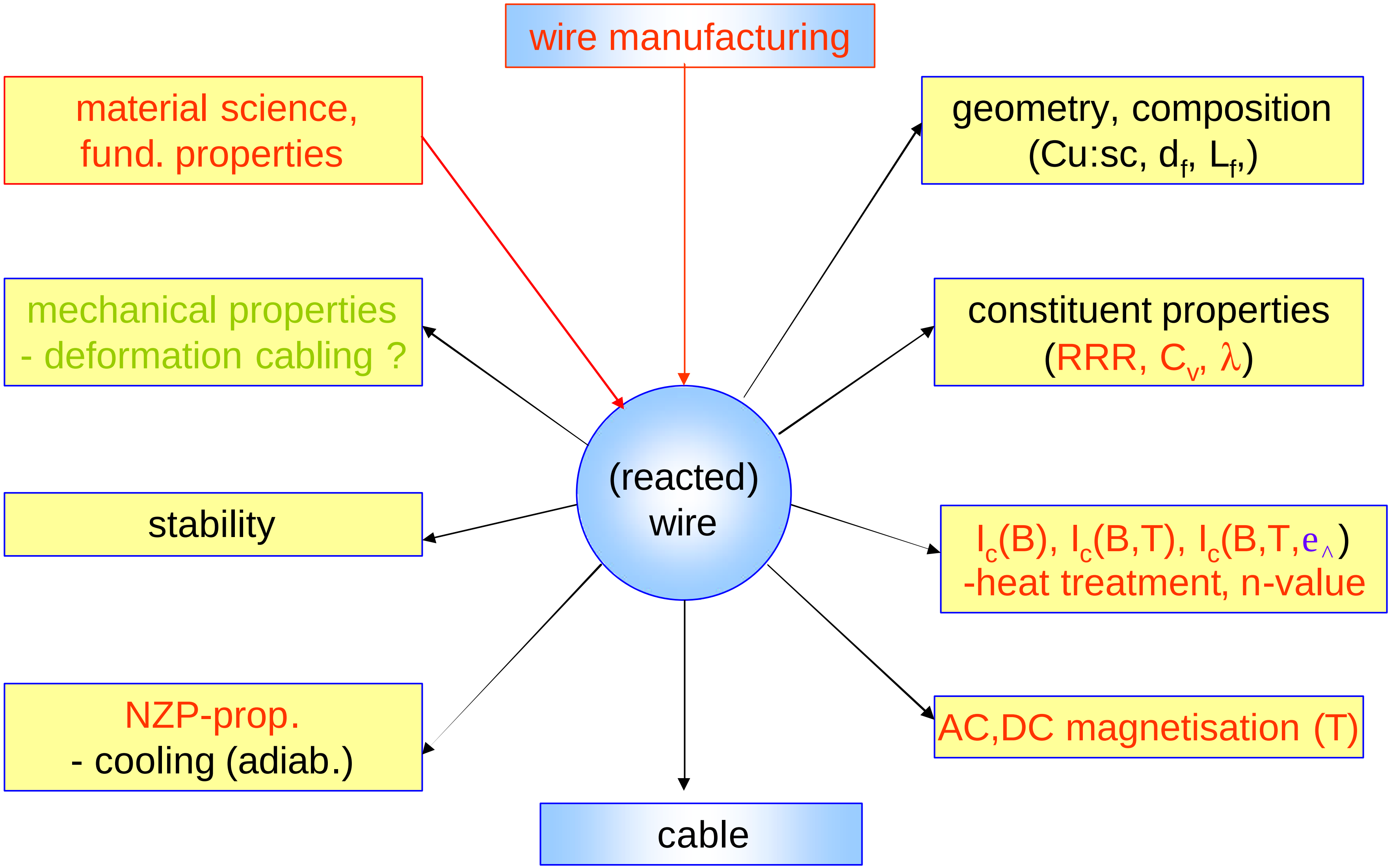
main stress perp. to wire/cable

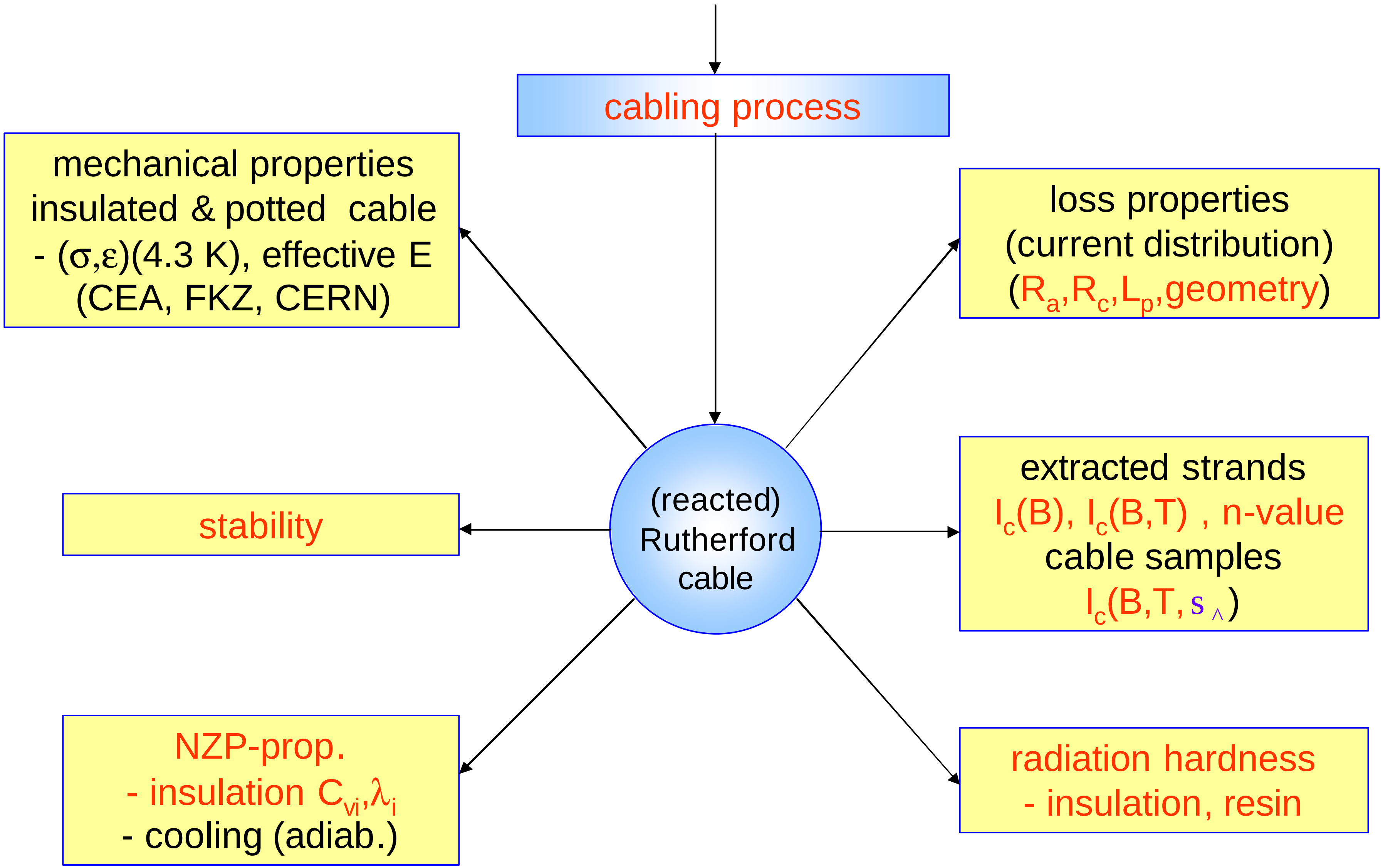
NED reference parameters

- 15T at 4.3 K
- bore ~ 80 mm
- J_{cnCu} ~ 1500 A/mm^2 @ 15 T
- Rutherford cable with SS core
- probably fully resin impregnated
- wind and react route (HT ~650 ^{0}C)

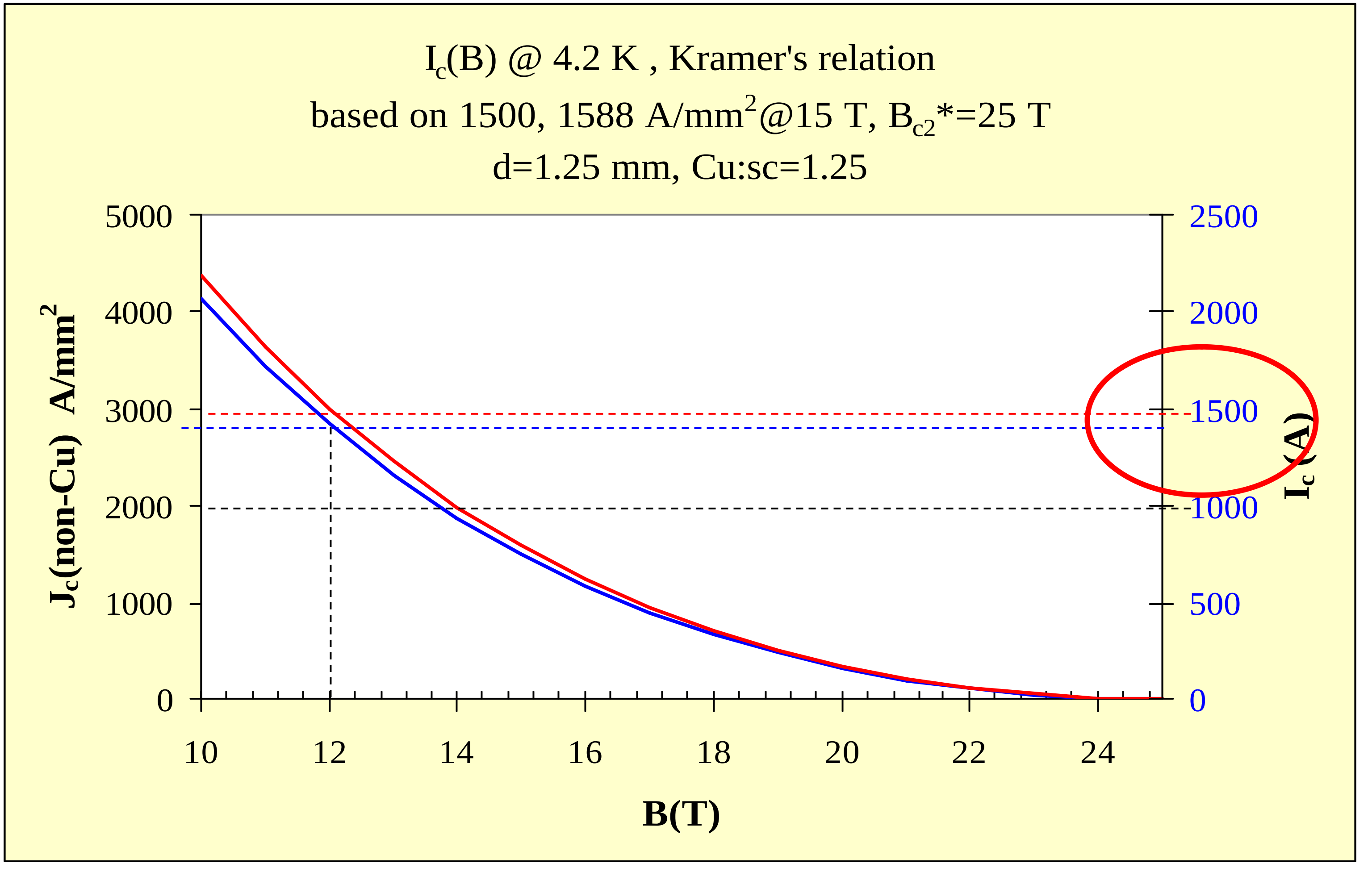
In NED no coil will be manufactured


paper
design
manufacturing
and R&D
magnetic specs
B, T, b_i, dB/dt, P_{rad}, B_{min}, B_{max},
coil geometry (Roxie,Ansys etc)
(σ_{Lf}, Δr_c,)
conductor specs
$I_{op}(B)$,ΔT,R_a,R_c,,d_s,d_f,N_s,
α_{kc},w_c,h,L_p, Cu:Sc
strand
cable
Nb_3Sn
coil manuf. & magnet assembly


wire manufacturing
material science,
fund. properties
geometry, composition
(Cu:sc, d_f, L_f,)
mechanical properties
- deformation cabling ?
constituent properties
(RRR, C_v, λ)
(reacted)
wire
stability
I_c(B), I_c(B,T), I_c(B,T,$e_\wedge$)
-heat treatment, n-value
NZP-prop.
- cooling (adiab.)
AC,DC magnetisation (T)
cable


cabling process
mechanical properties
insulated & potted cable
- (σ,ε)(4.3 K), effective E
(CEA, FKZ, CERN)
loss properties
(current distribution)
(R_a,R_c,L_p,geometry)
stability
(reacted)
Rutherford
cable
extracted strands
$I_c(B)$, $I_c(B,T)$, n-value
cable samples
$I_c(B,T,s_{\wedge})$
NZP-prop.
- insulation C_{vi},λ_i
- cooling (adiab.)
radiation hardness
- insulation, resin

Wire I_c measurements (1)



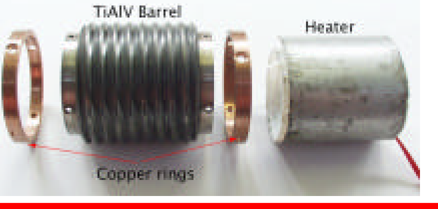
Requirements

Preparation

- HT at ~650 ^{0}C (inert gas, vacuum)
- avoid sample transfer after HT
- enable extracted strand meas.
- standard procedures

Facility

- I~1000 A (DC)
- B > 14 T
- T = 1.8 K, 4.2 K
  or variable (ΔT < 0.05 K)
- I_c criterion 10 μV/m (range 1-50 μV/m)



courtesy P.L. Bruzzone (EPFL-CRPP)

Though little reported experience in Europe with such high-current wires, facilities (though not always with HT facility) are operational in:

Austria, UK, France, Russia, Germany, Slovak Republic, Netherlands, Switzerland, Italy

both manufacturers and institutes/universities

NED: lab. intercomparison, establish standard protocol and procedures

EU-facilities — Wire constituents (+ cable insulation) $C_v(T)$, $\lambda(T)$, RRR

	$C_v(T)$	$\lambda(T)$	remarks
Univ. of Geneva (in home dev. facility)	X		small samples
Univ. of Southampton (PPMS)	X	X	
Joh. Keppler Inst. (PPMS)	X	X	
CEA		X	ins. cable stack (1.8K)
UT		X	idem (4.3 K)
INFN-LASA		X	idem (4.3 K)

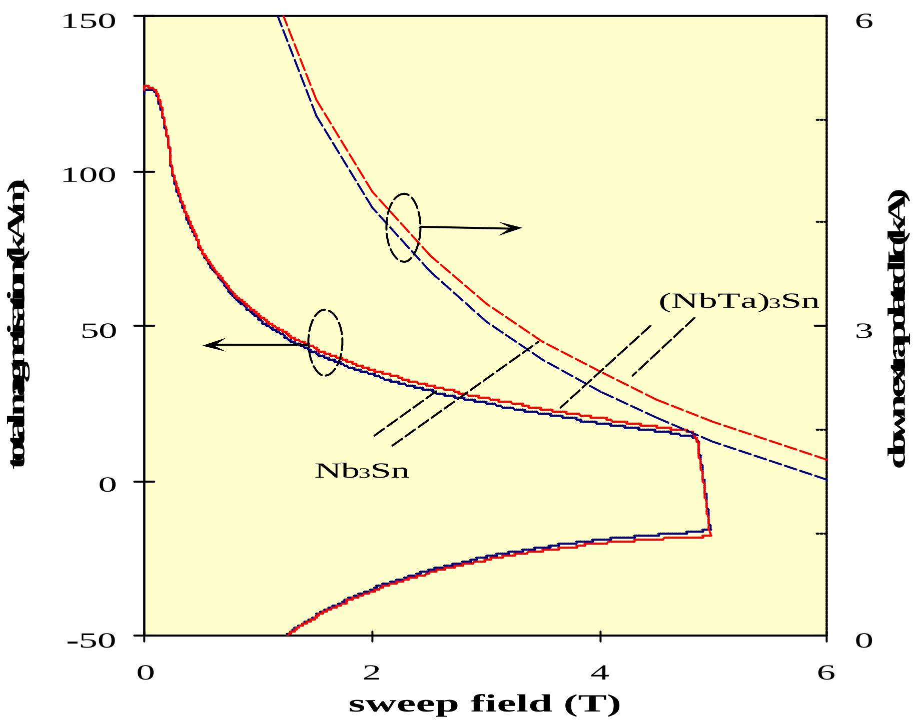
RRR: many laboratories and manufacturers

- Establishment of a data base containing indisputable data of material properties
- NED: dedicated but small program on insulation development and characterisation (heat transfer and λ(T) measurements at CEA,, electrical and mechanical properties, handling, if possible radiation hardness)

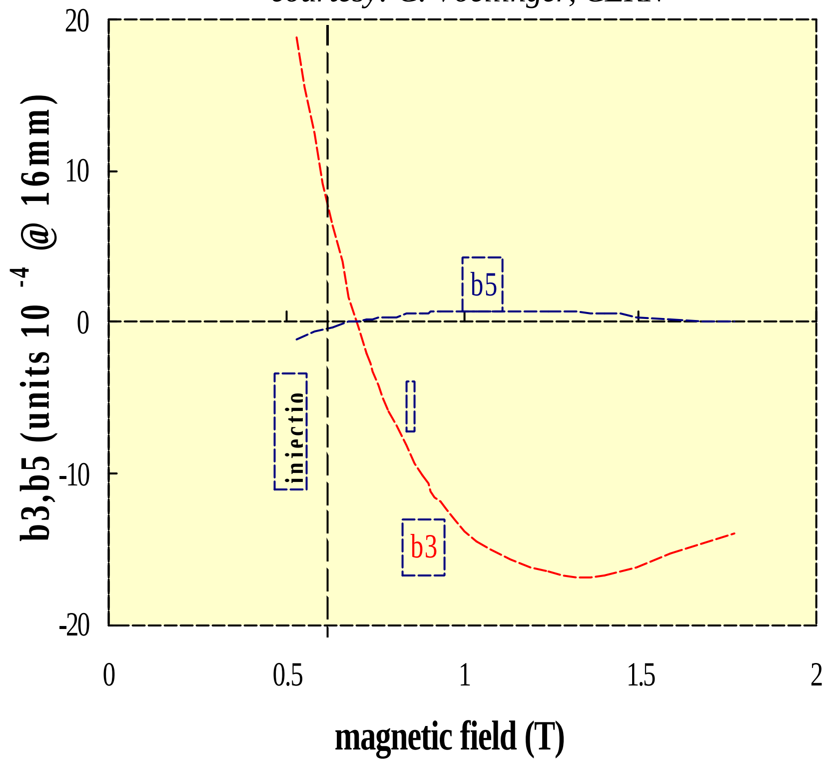
wire magnetisation measurements (1)

Filament magnetisation affects:

•DC: field errors, especially at low fields
 - filament magnetisation couples to cable coupling currents with long time constants ~10^3 s (BICCs) → decay and snap-back of field errors during injection in LHC



courtesy: C. Voellinger, CERN



wire magnetisation measurements (2)

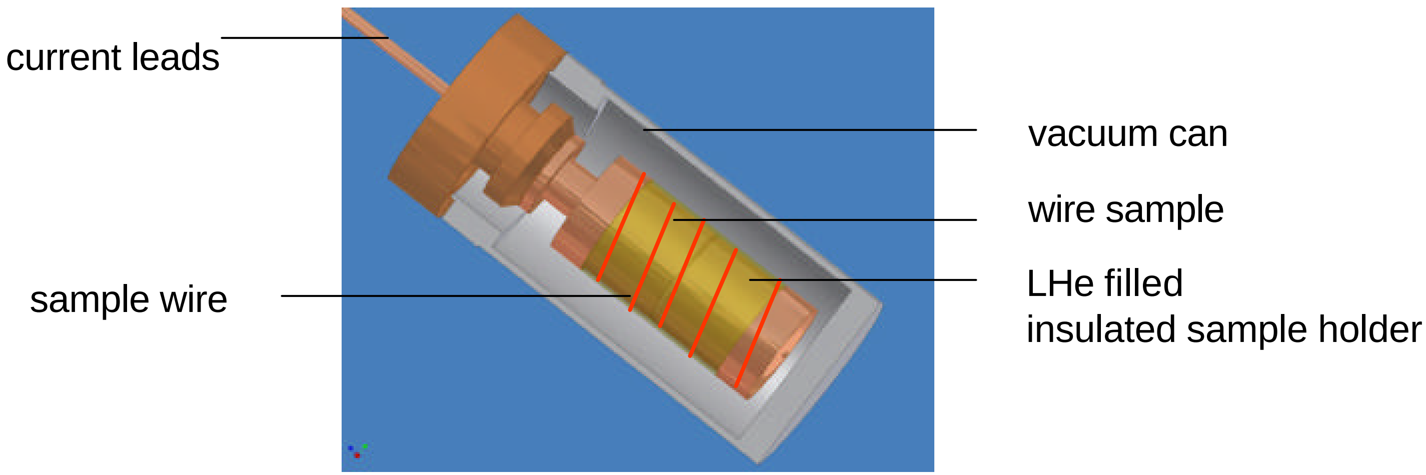
- AC: coil temperature (stability) by filament magnetisation and coupling current losses in the matrix, especially important at high dB/dt (GSI :1-4 T/s)

- several laboratories use different techniques (VSM, pick-up coils, SQUID) for quasi-DC and AC-loss measurements at relevant field strengths (< 3T), 4.3 K and dB/dt (0.01-1 T/s)

- differences of 20 % between laboratories due to calibration or sample geometry

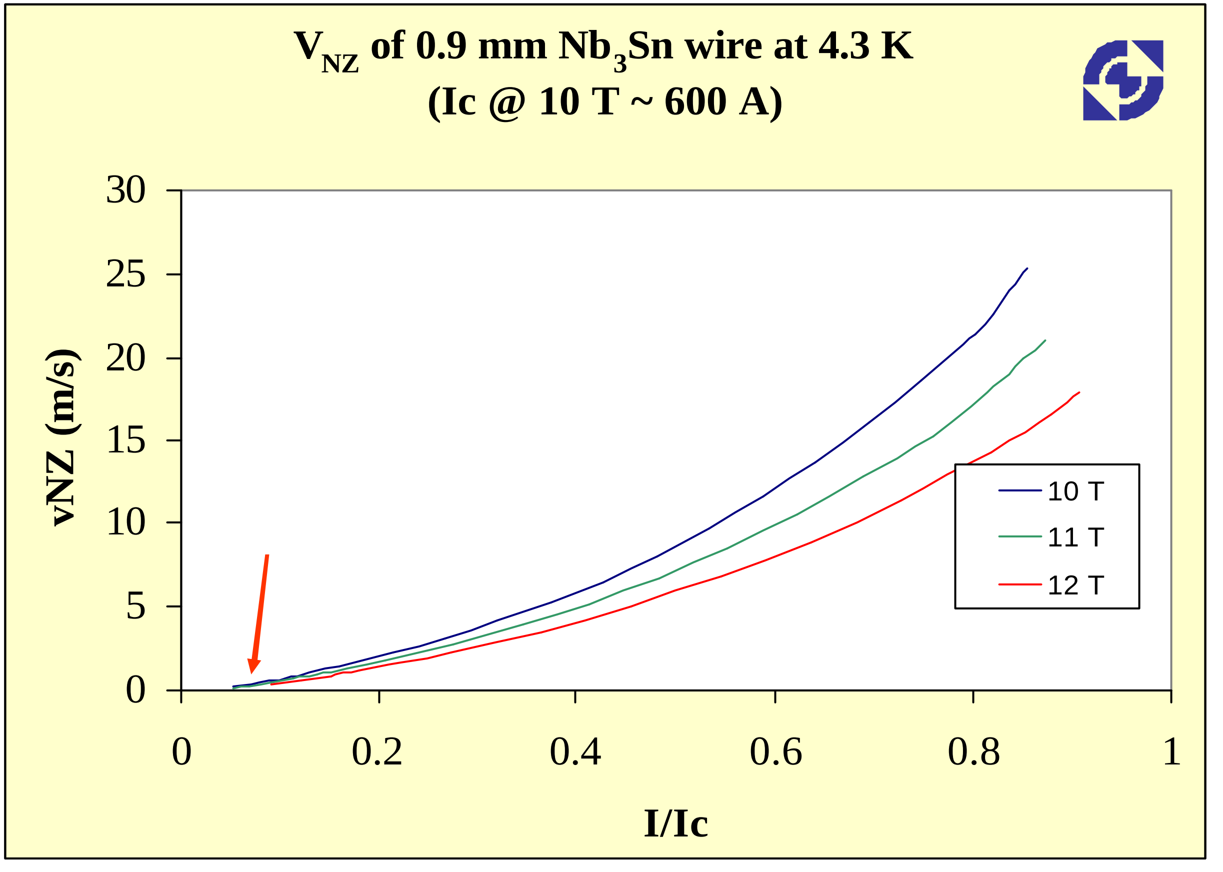
- for protection of any coil a priori knowledge about normal zone propagation properties is mandatory
- Wilson's nearly adiabatic formulae are not valid for Nb_3Sn conductors: overestimation > 30 % (linear heating function between T_{cs} and T_c (B) is inadequate)
- improved simulations rely on constituent properties; experimental validation of v_{nz} and T_{max} remains essential

Possible arrangement (UT)



- B_a, current, heaters, thermometers, voltage taps

NZP measurements wire (2)



Facilities available (but not all operational presently):
CEA, FZK, UT, CERN

$I_c(\varepsilon_{//})$ measurements wire

	EPFL,FZK, Kurchatov	Univ. of Durham	UT	Univ. of Geneva
sample configuration	Straight	helical CuBe Walter's spring	1: U-device 2: Ti "pacman": circle 3: periodical bending	Helical Ti Walter's spring
strain range	ε>0	-1 % < ε < 1 %	2: - 1 % < ε < 1 %	-0.5 %< ε< 1 %
max. field (T)	11,13,13	18	12 (15)	17 (20)
operating temperature (K)	> 4.3	> 1.8	4.3	>1.8
sample length (m)	~0.1	1	2: 0.15 (0.25)	0.6
(σ,ε)	yes	no	no	yes

1 - beautiful experiments, nice results, lots of discussion , relevant for ITER and solenoids

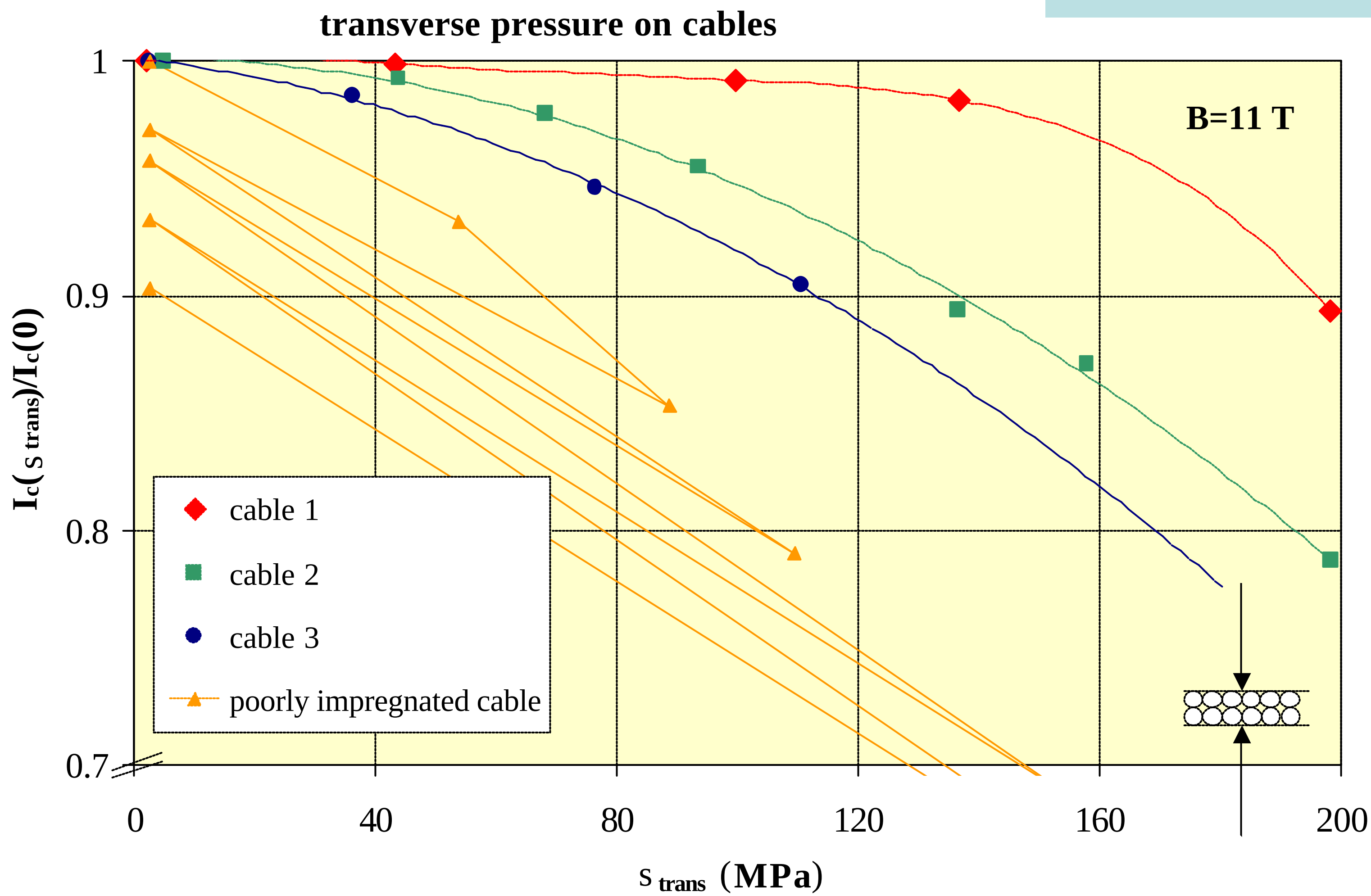
2 – practically interesting: in what state is the superconductor at powering, what is corresponding (σ,ε) – relation ?

3 – ITER: (periodical) bending appears (more) relevant

For accelerator magnets: little relevance !
Regarding stress distribution and cable geometry focus should be on $I_c(\sigma,\varepsilon)_{\perp}$

Cable $I_c(B, \sigma_\perp)$ measurements (1)

- PSI: *Pasztor et al*
- UT



•cabling of high current density wires into high compacted, cored Rutherford cables often results in filament damage or wire breakage (>>10 % current degradation)

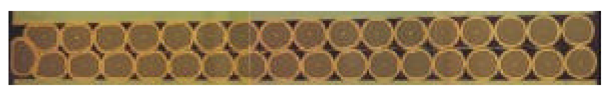
•a good performing wire does not imply a good cable

•relation between mechanical properties of strand and cabling degradation not well understood and unpredictable

•cabling demands highly skilled people and is certainly not a straightforward step

•cabling of newly developed wires should be learned by exploring the parameter space (width, thickness, pitch, keystone angle, mechanical rigidity, core tension/behaviour), followed by microscopic cross sectional inspection/extracted strand measurements

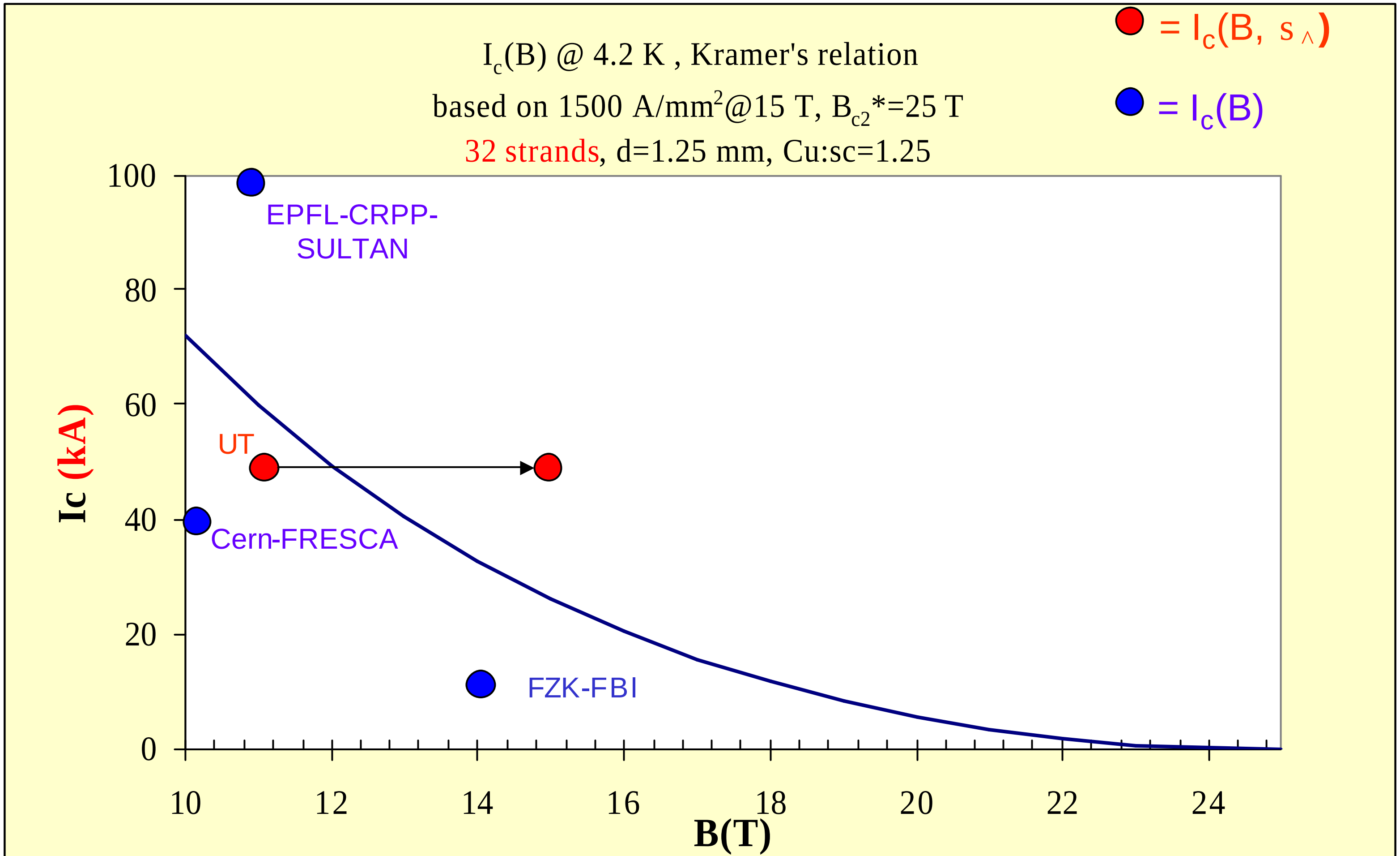
•another iteration step of wire manufacturing or cabling may be necessary



This process requires an experimental cabling facility which is at present not available in Europe (though visiting LBNL is not really a punishment)

Cable I_c(B, s ∧) measurements (1)

- Extracted strand measurements before cable measurement delicate, but preferable



EU-facilities Cable $I_c(B, \sigma_\perp)$/NZP/stab. measurements (2)

	CRPP SULTAN	Cern FRESCA	UT		FZK FPI
current supply	cold transformer	RT-PS or cold transformer	cold transformer		RT-PS
max. DC current (kA)	100	40	45		10
max. field (T)	11 solenoidal	10 dipole	15 soldenoidal		14 split pair
operating temperature (K)	> 4.3 forced flow He	1.8 or 4.3	4.3		4.3
max. field region/ sample length (m)		2 x 0.8	0.04 (U-shape)	0.6 (helical)	0.6
$\sigma_\perp$ (MPa)	RT prestress possible	RT prestress < 100	< 250	-	axial tensile stress only
NZP/stability meas.	yes	yes	no	no	possibly
experience/capability current distribution meas.	yes/yes	yes/yes	yes/no	yes/no	?
additional features	- AC field 0.4 T 0.01-6 Hz - 3 T pulse field	- Hall sensors curr. distr. meas.	-	-	-
sample preparation/ sample mounting	demanding/ **very demanding**	demanding/ easy	demanding / easy	demanding/ easy	demanding/ **demanding**

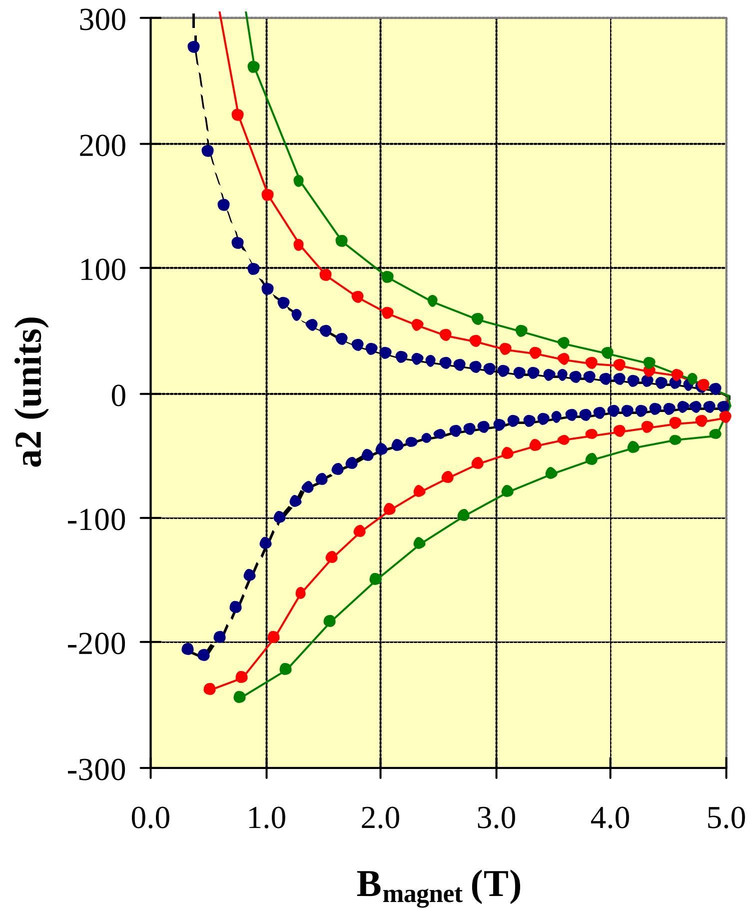
•Due to dB/dt coupling currents between strands in cable are generated (NCC (τ<1 s), BICC ($\tau \sim 10^3$ s)

• both generate undesired field errors and at high dB/dt also significant losses

• amplitude mainly controlled by R_c, the resistance between crossing strands

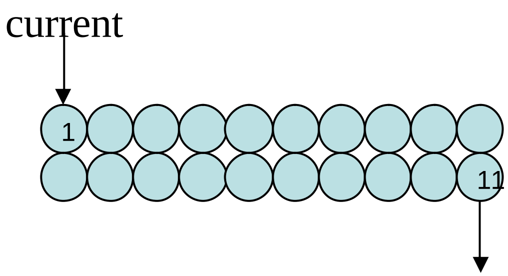
⇒ control of R_c imperative

- LHC (10 mT/s): $R_c \sim 15\ \mu\Omega$
- GSI (1-4 T/s): $R_c \sim 1 - 10\ m\Omega$



Very low Rc ~ 1 μΩ: sintering during HT
→ insert 20 μm stainless steel core in cable

Measuring R_c



Direct V-I method (4.3 K, $\sigma_{\perp}$) (A. Verweij-CERN)

- measure V(1,i)
- derive R_c from voltages and V- profile

• especially in cored cables the method is not always accurate but gives a good indication for the R_c range

• routinely carried out at CERN for quality control LHC cables

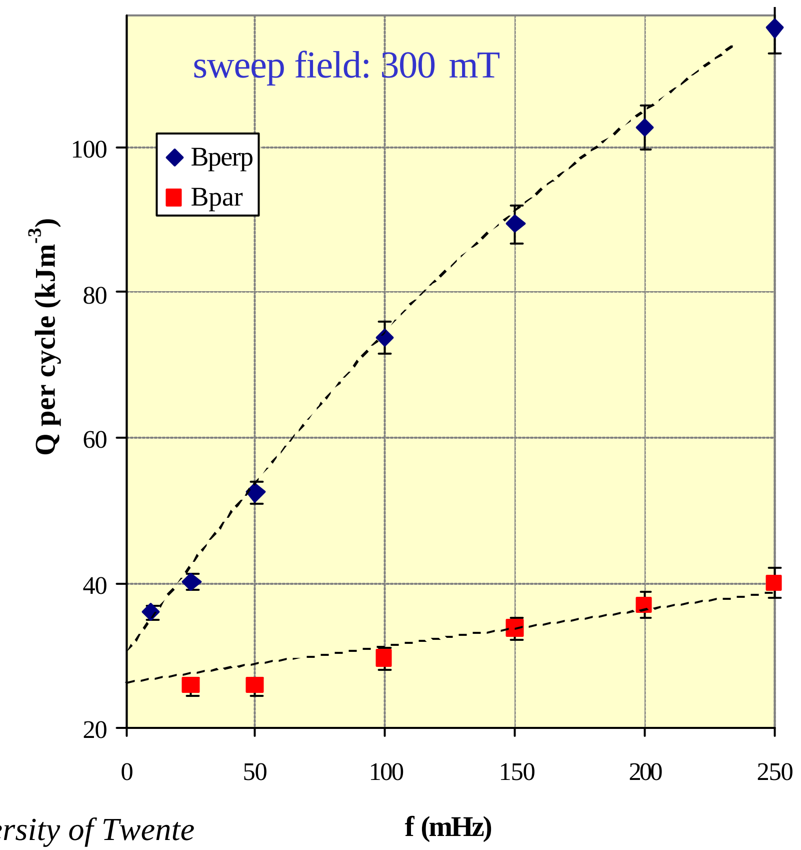
• possible at many places

• very attractive to study R_c evolution under cyclic loading
- UT: full size ITER cables: 4.3K, 3x3x30 cm, 800 kN, 4.3 K, electrical loss measurements
- also possible at FZK: 4.3 K, 600 kN press
  CEA: 4.3 K, 150 kN press

Measuring R_c

- Indirect measurement by deriving R_c from (electric, calorimetric) loss measurements
- Cable stack under representative RT pre-stress

calorimetric loss data



- ITER has been the driver for Nb_3Sn actvities in Europe
  - beautiful facilities for dedicated conductor research
  - wire manufacturers are still improving their conductors

- little (reported) R&D programs on more fundamentally oriented material aspects (grain size formation, Sn gradients)

- the NED program will only moderately contribute to
  - conductor development
  - magnet R&D

- facilities for conductor characterisation (wires/cables) are adequate except for:
  - a facility to perform routinely cable $I_c(B,\sigma)$/NZP/stability measurements and R&D (follow-up FRESCA)
  - an R&D cabling machine that is not occupied by LHC !