Synergies between Accelerator and Fusion Conductors

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E. Salpietro
EFDA Garching

- Introduction
- Cable in conduit conductor development for ITER
- EFDA dipole: synergy of accelerator and fusion conductor concept
- Dipole HF conductor: performance vs. void fraction and shape
- Dipole LF conductor: performance vs. shape and twist pitch
- Summary

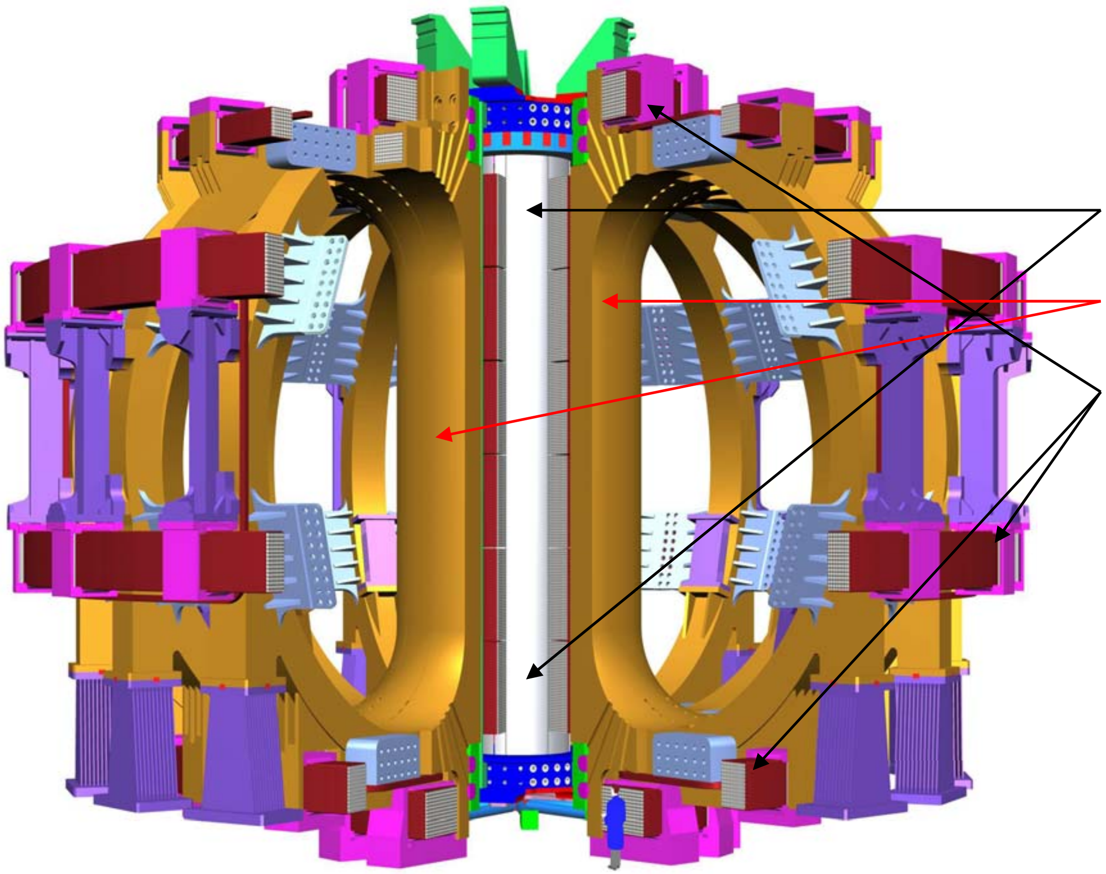
Introduction

- The main driver for accelerator and fusion applications are different
- **Fusion:** large volume, energy and required stability
- **Accelerator:** maximisation of current density, field homogeneity

- First conductors were flat cables for both type of applications
- First accelerator type magnet in late 60's made of Nb_3Sn (W.B. Sampson, BNL)
- IMP with silver plated Nb_3Sn ribbons (Oak Ridge) in late 60's
- Around 1970 stability issues solved (multifilament, twisting) at RAL → "Rutherford type" cable
- T-7 and T-15 with forced flow and flat cable embedded in Cu (Kurchatov, 1970's), LCT in the 80's

While the cable concept for the accelerator remained unchanged the CICC concept was introduced into fusion in the 80's

ITER – Magnets System



	Field (T)	*Current (kA)*
CS coil	13	45
TF coil	11.8	68
PF coil	4 – 6	50
Correction coil	< 5	10
Cryostat feedthrough	< 4	≤ 68
Current lead	< 30 mT	≤ 68
External current feeder	~ mT	≤ 68

41 GJ (TF only) vs. 10.5 GJ magnetic energy in the 27 km Tunnel of the Large Hadron Collider at CERN

Fusion – Cable-in-Conduit

*Main arguments **pro** CICC*

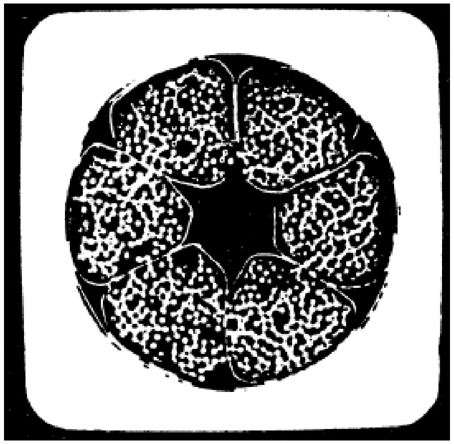
- High amperage conductor with large heat removal capability
  (large ampere turns, acceptable voltages, AC loss, nuclear heat)
- Forced flow cooling
  (only option for large magnets with large stored energy)
- High stability
  (local disturbances and peak loads)
- High mechanical strength
  (outer jacket acts as a structural material)
- Flexible design
  (number of strands, cabling pattern, cooling channel, shape, …)

*Main arguments **contra** CICC*

- Low current density
  (not a major issue for fusion magnets)
- Performance prediction
  (complex impact of strand/conductor parameters on final performance)

ITER – CICC Development

- In 1992 a project was planned under NET to build a coil made of different high amperage Nb_3Sn conductors (circular in square, rectangular, braid, twist, …). Activity was stopped due to start of ITER EDA phase.
- The early 90's first circular NET/ITER CICC were tested (40 kA current).

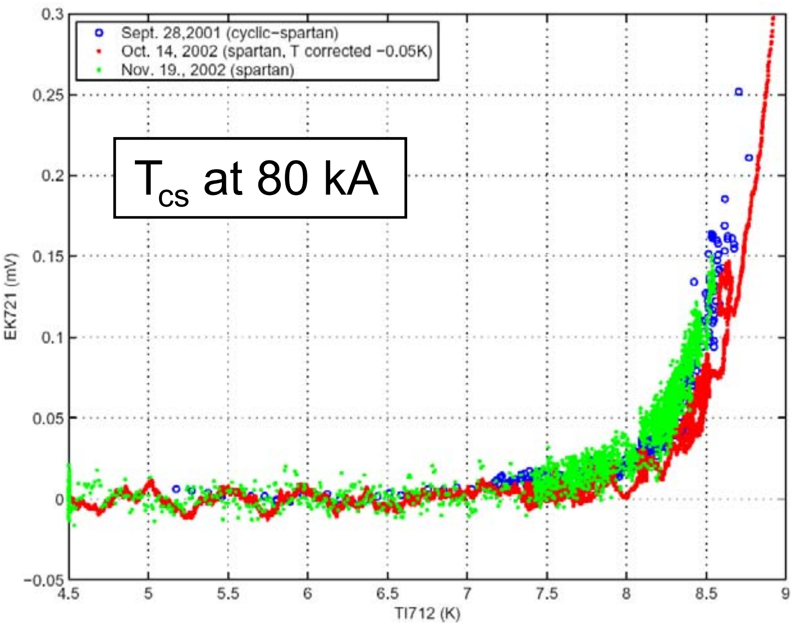


[D. Bessette et al., IEEE Trans. Magnetics 30, 2038-2041 (1993)]

- After assessing several options (cabling pattern, conduit material, central channel…) **Model Coils** (TFMC, CSMC) and **Insert coils** were built and tested 2001/2002.

ITER TF – TFMC Results

	ITER TF	TFMC
Peak field (T)	11.8	9.9
Conductor current (kA)	68	80
Number of turns	134	98
No. of double pancakes	7	5
Stored magnetic energy (MJ)	41,000	80 (337 with LCT)
Coil height (m)	12.6	4.6
Total coil weight	310	40



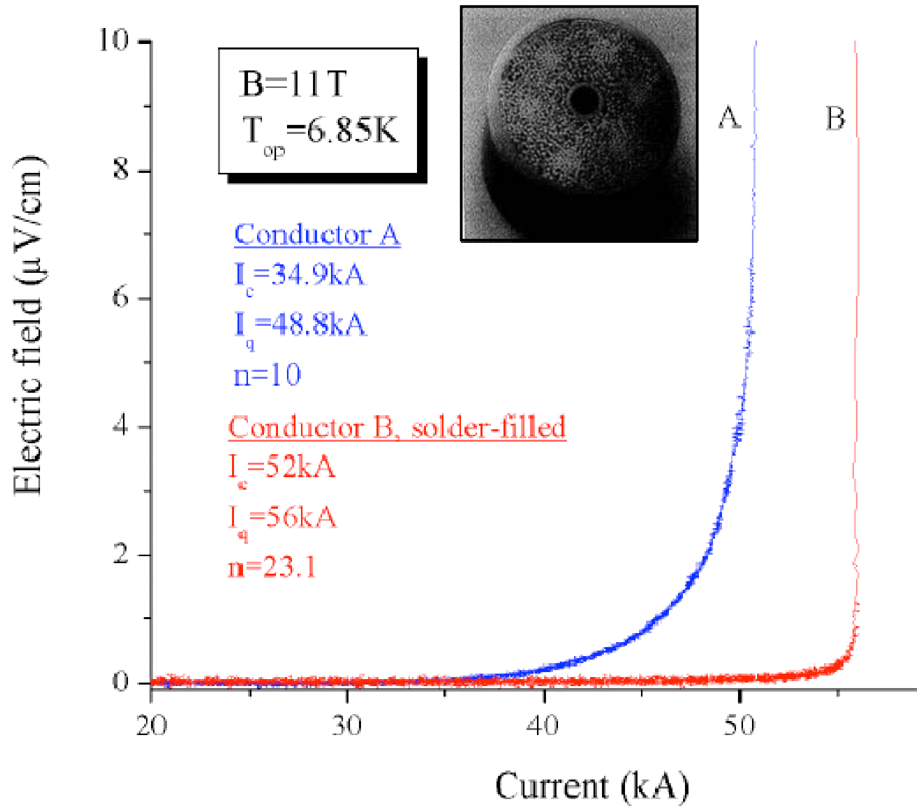
[J.L. Duchateau, CEA]

- TFMC exceeded design values
- No degradation with cycling
- Conductor performance in coil **less** (~15 %) than expected from single strand or Sultan short sample tests
- Degradation shows a BI load dependence →

[A. Ulbricht et al., Fus. Eng. Des. 73, 189-327 (2005)]

ITER TF – **Conductor**

- **Transverse load** (bending) identified as main cause of degradation



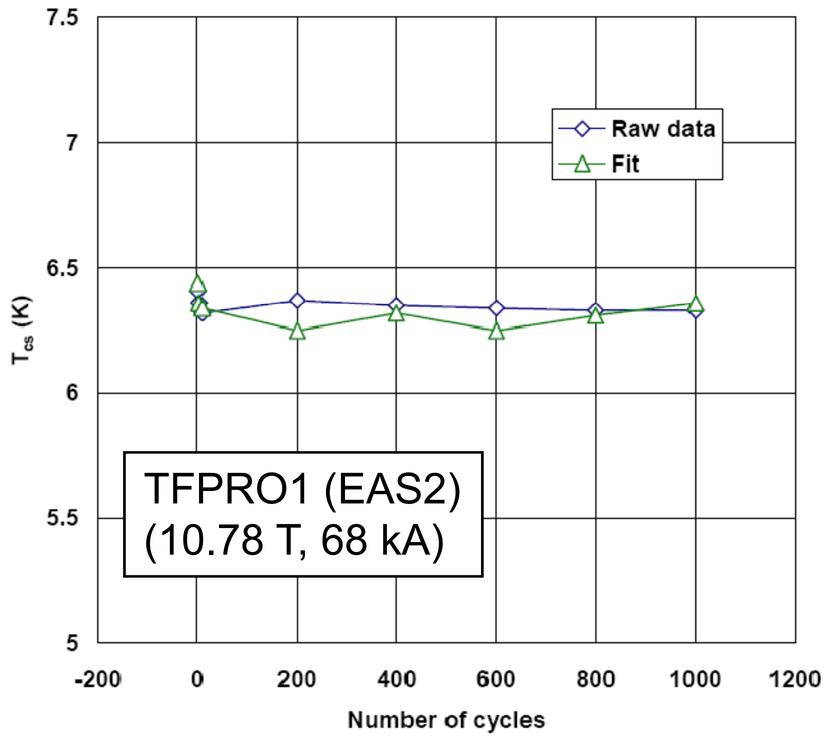
- Ti-jacket, Ti cooling tube
- 588(sc)+924(Cu) strands
- 0.7 mm diameter
- Braided primary stage (14+15)
- 37% void fraction
- Solder filled into conductor B after reaction
- Conductor B performed at expected limit

[P. Bruzzone et al., IEEE Trans. Appl. Supercond. 14, 1527-1530 (2004)]

ITER TF – Conductor

- Level of degradation depending on strand type (strain sensitivity, irreversible strain limit) but exact dependence not fully understood yet
- Updated design with more strands and **lower void fraction**
- First short sample tests in Sultan successful:

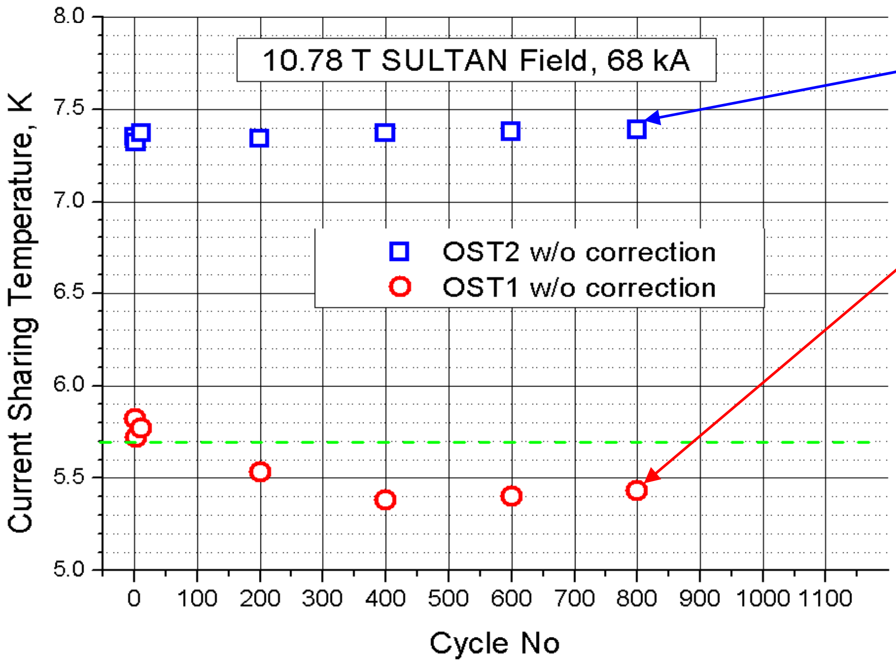
Number of Nb_3Sn strands	900
Total number of strands	**1422**
Strand diameter (mm)	0.82
Strand Cu ratio	1
Void fraction (%)	30
Jacket thickness (mm)	1.6 (2)
Conductor diameter (mm)	43.7



[R. Wesche, CRPP]

ITER TF – Conductor

- **Cable twist pitch** length specification increased after TFPRO2 result:



OST2: **28.5 %** void fraction
long twist pitches

OST1: **30 %** void fraction
reference twist pitch

- OST2 shows outstanding performance
- OST1 and OST2 strands almost identical design
- Excellent conductor OST2 uses OST2 strand which shows worse Jc strain behavior

- Longer twist pitch lengths and lower void fraction leads to significantly better performance in TFPRO2

*→ **Qualification with final TF spec in 2008***

Conclusions

- Successful conductor design was developed for the TF coils
- CS conductor is being finalised and qualified as well
- Performance extrapolation from single strand/subsize conductor is difficult and not reliable:
  void fraction, twist pitch and strand type play important role for the final conductor performance
- Full size conductor tests essential for qualification

Advanced Fusion CICC

- Compared to high field HEP conductors the ITER conductors are **less efficient** in view of current carrying capability

- The main reasons:
  1) Fusion type strands have **much less J_c** than HEP strands (1000 vs. 3000 A/mm^2 at 12 T, 4.2 K)
  2) Fusion CICC due to thermal mismatch between steel jacket and cable, J_c is reduced by about **50 %** (less for CS conductor)
  3) Transverse load (bending) on unsupported portions of strand normally adds a degradation of at least 10 %

- Some effects are unavoidable (lower conductor J_c due to coolant, copper for protection and jacket) but improvements are possible…

Attempt to merge accelerator and fusion conductor concepts:

The EFDA Dipole Conductors

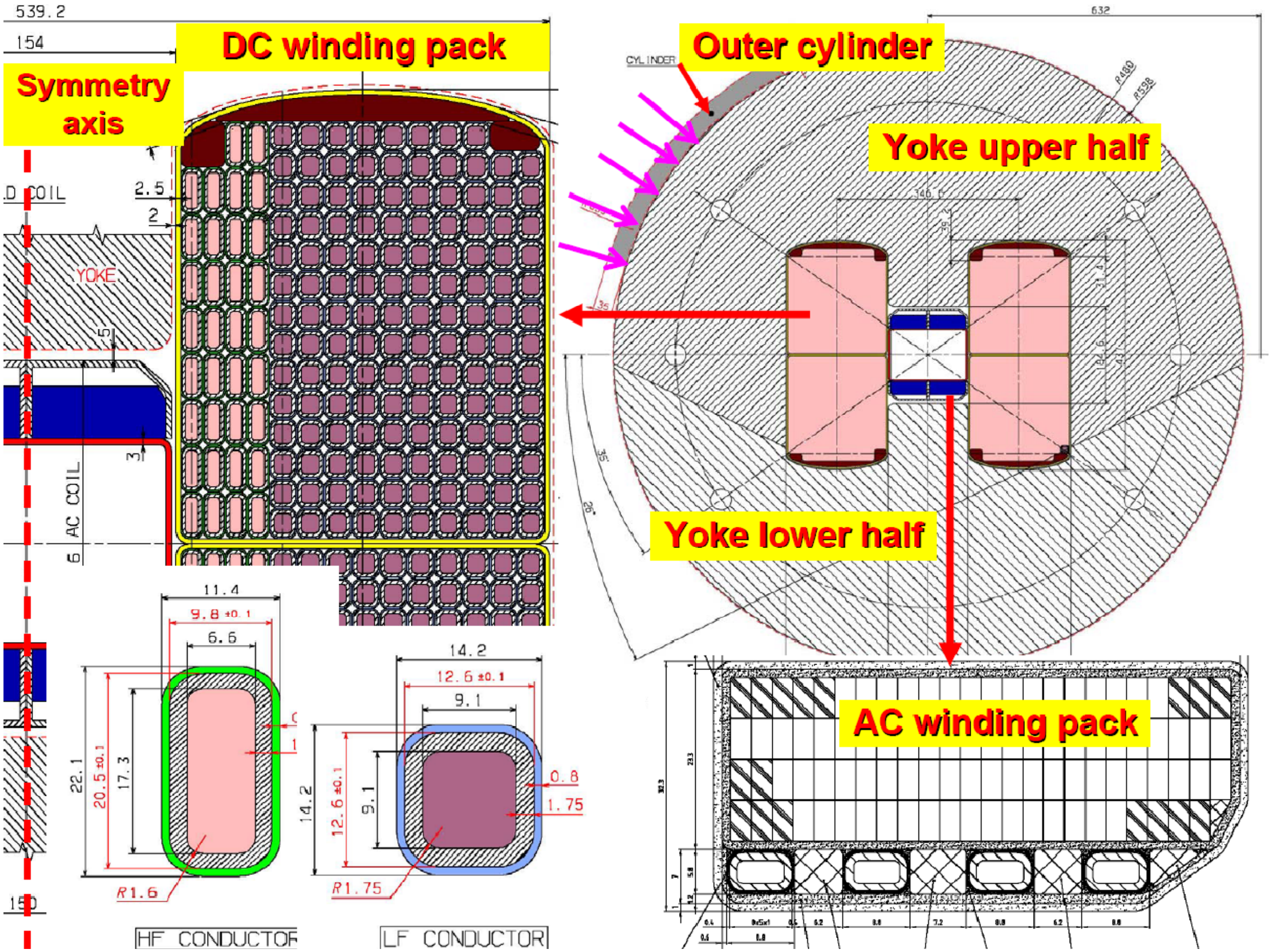
Advanced CICC Design

In order to improve performance, we can combine accelerator and fusion conductor technology

- Following the Nb_3Sn strand development in HEP (high J_c with smaller filaments) a CICC was designed and tested for the EFDA dipole project.
- The combination of high J_c strands and CICC provides a conductor design with high current density, stability and cooling power.
- Intrinsic instability of high J_c strands is stabilised by direct cooling.
- The high performance strands (J_c ~ 2500 A/mm^2 at 12 T and 4.2 K) have a similar J_c vs. strain dependence but are more prone to bending strain (A. Nijhuis, Twente University).

Parameters such as void fraction and twist pitch must be properly selected to obtain a robust conductor design

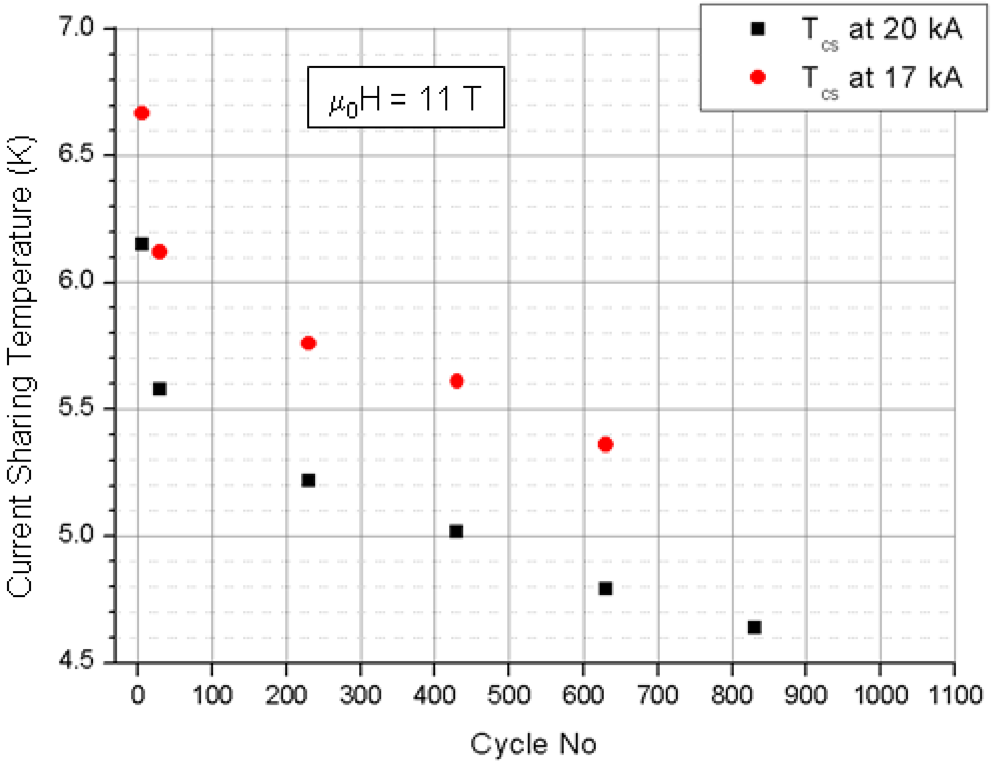
EFDA Dipole



[A. Portone et al., presented at MT20, Philadelphia, accepted for publication in IEEE Trans. Appl. Supercond. 18]

EFDA Dipole – High Field

- Based on successful dipole pre-prototype results[1], the dipole conductors were designed



Conductor	HF1
Cable pattern	(3x3)x4x4
Cu/non Cu strand	(0/9)x4x4
Sc strand number	144
Jacket thickness (mm)	1.65
Outer conductor dimensions (mm)	15.82 x 13.23
Void fraction (%) (calculated)	**35**

- Initial performance was lower than expected but acceptable
- Continuous degradation with cycling
- Explanation: neither cumulative nor single strand load were critical

  → **strand support?**

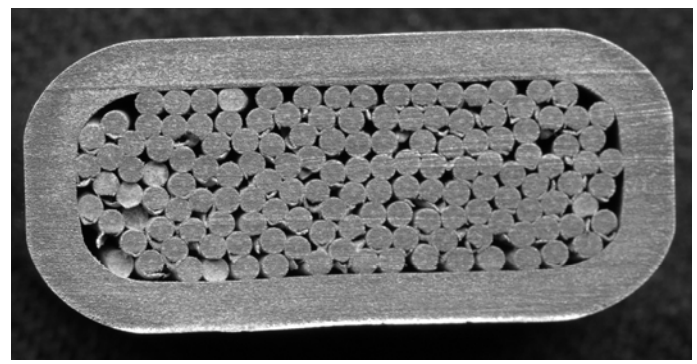
[1][P. Bruzzone et al., IEEE Trans. Appl. Supercond. 16, 894-897 (2006)]

EFDA Dipole – **High Field**

- Void fraction and twist pitches were based on typical values as used in fusion CICC
- Continuous degradation with cycling is a clear sign of filament cracking due to excessive transverse load

HF Sample 1
(test without solder)

increase of strand → support

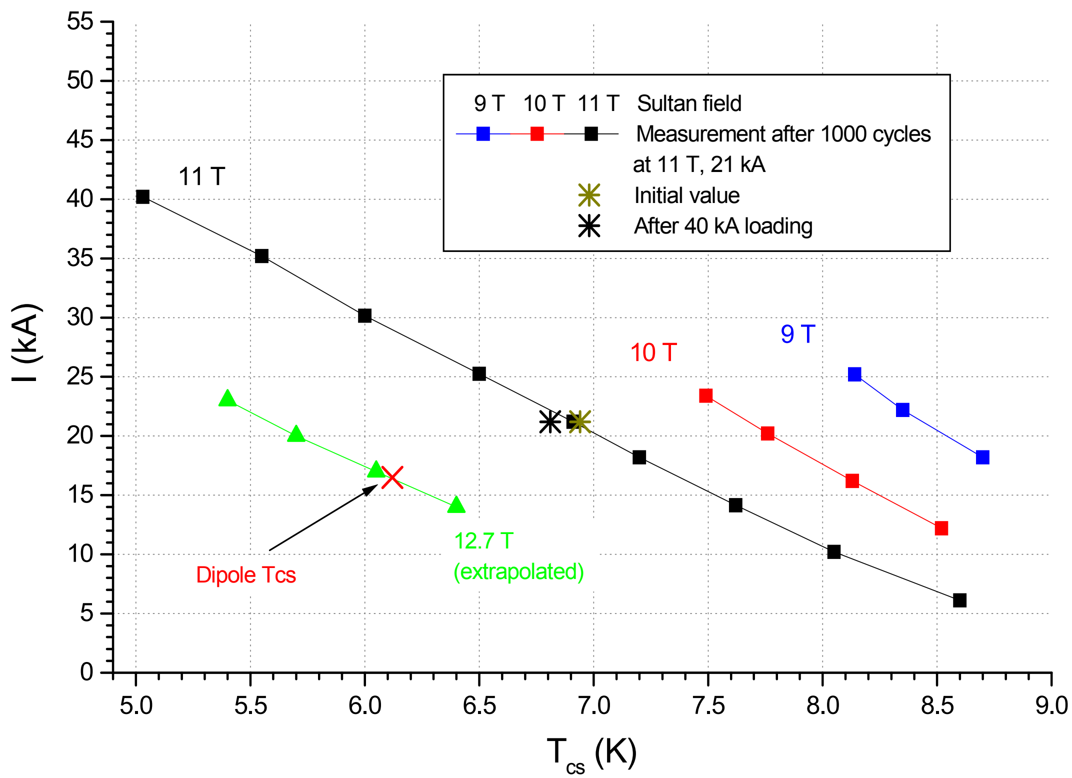


HF Sample 2

Identical cable was tested in a flatter conductor and with a lower void fraction of ***30 %*** *→*

[A. Vostner et al., presented at MT20, Philadelphia, accepted for publication in IEEE Trans. Appl. Supercond. 18]

EFDA Dipole – High Field



- Max non Cu J_c: **1080 A/mm²**
  Dipole $J_{c,op}$: 460 A/mm² (12.7 T)
  ITER $J_{c,op}$: 286 A/mm² (11 T)
- Max Cable J_c: **540 A/mm²**
  Dipole cable $J_{c,op}$: 230 A/mm² (12.7 T)
  [ITER cable $J_{c,op}$: 53 A/mm² (11 T)]
- Operating single strand load:
  dipole: 2.3 kN/m
  ITER: 0.9 kN/m
- Cycling up to 30 (and 40) kA

With these modifications the conductor worked as expected from single strand extrapolation

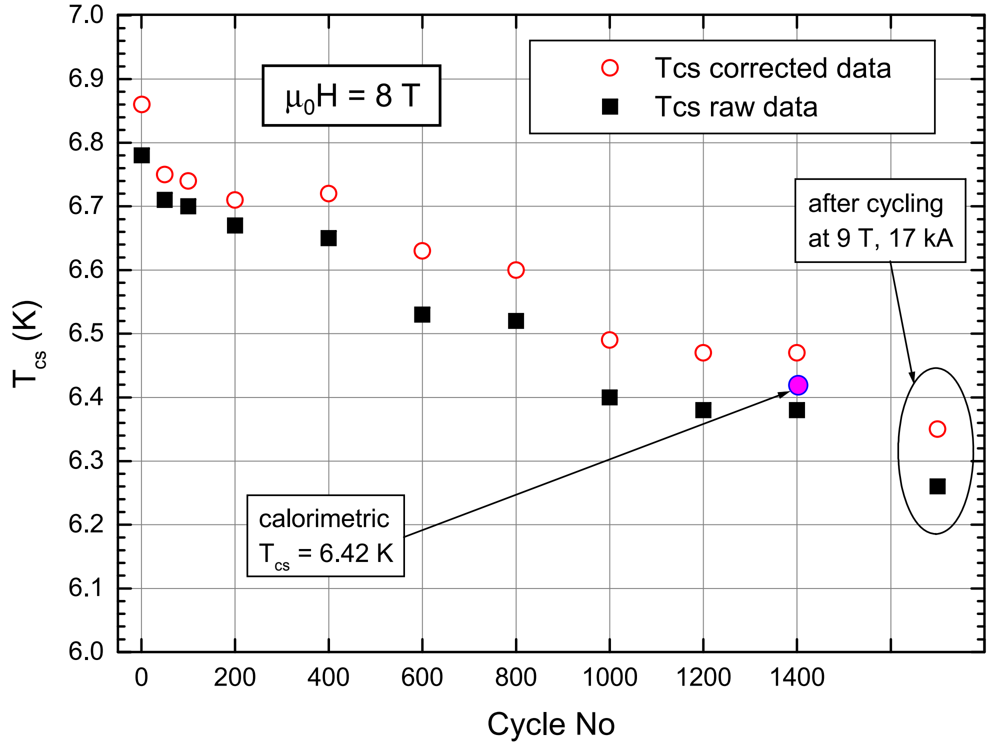
LOW FIELD CONDUCTOR

- First LF test sample showed same behavior as the HF conductor sample: severe degradation with cycling
- Following the successful test of the HF conductor, the void fraction was reduced for the square LF as well.
- Shape (square), cable (twist pitch) and jacket remained identical. Only the compaction was increased.

EFDA Dipole – **Low Field**

- Initial performance 20 % below model expectation (i.e. 0.5 – 0.6 K)
- After 1000 cycles at 8 T steady state performance with further loss of ~15 %
- Single strand load **2.83 kN/m!**

Sample	PITSAM2
Cable pattern	(3x3)x3x4
Cu/non Cu strand	(5/4)x3x4
Sc strand number	48
Cu strand number	60
Twist pitch	58 mm/95 mm/139 mm/213 mm
Jacket thickness (mm)	1.75
Outer conductor dimensions (mm)	12.6 x 12.6
Void fraction (%)	30



- **Significant improvement compared to the first LF sample (void fraction ~37 %)**
- **Performance ok (B_{max} of LF2 ~7.8 T) but NOT as good as the HF conductor**

→ ***Void fraction is a critical parameter but not the only one***

EFDA Dipole – **Low Field**

- As demonstrated by last series of ITER TF conductor samples and the dipole HF samples, twist pitch and conductor shape have a significant impact as well.
- Small (and fast) R&D activity to address this issue. As strand, the EFDA dipole strand (OST) was used as the strand is more sensitive to bending than other available strands so that the effect should be larger.
- As conductor the EFDA dipole LF was selected (all parts available and easier sample manufacture)
- Test series covers:
  - -) **3 different twist pitches** but identical conductor shape and void fraction
  - -) **2 different shapes** but identical cable and void fraction

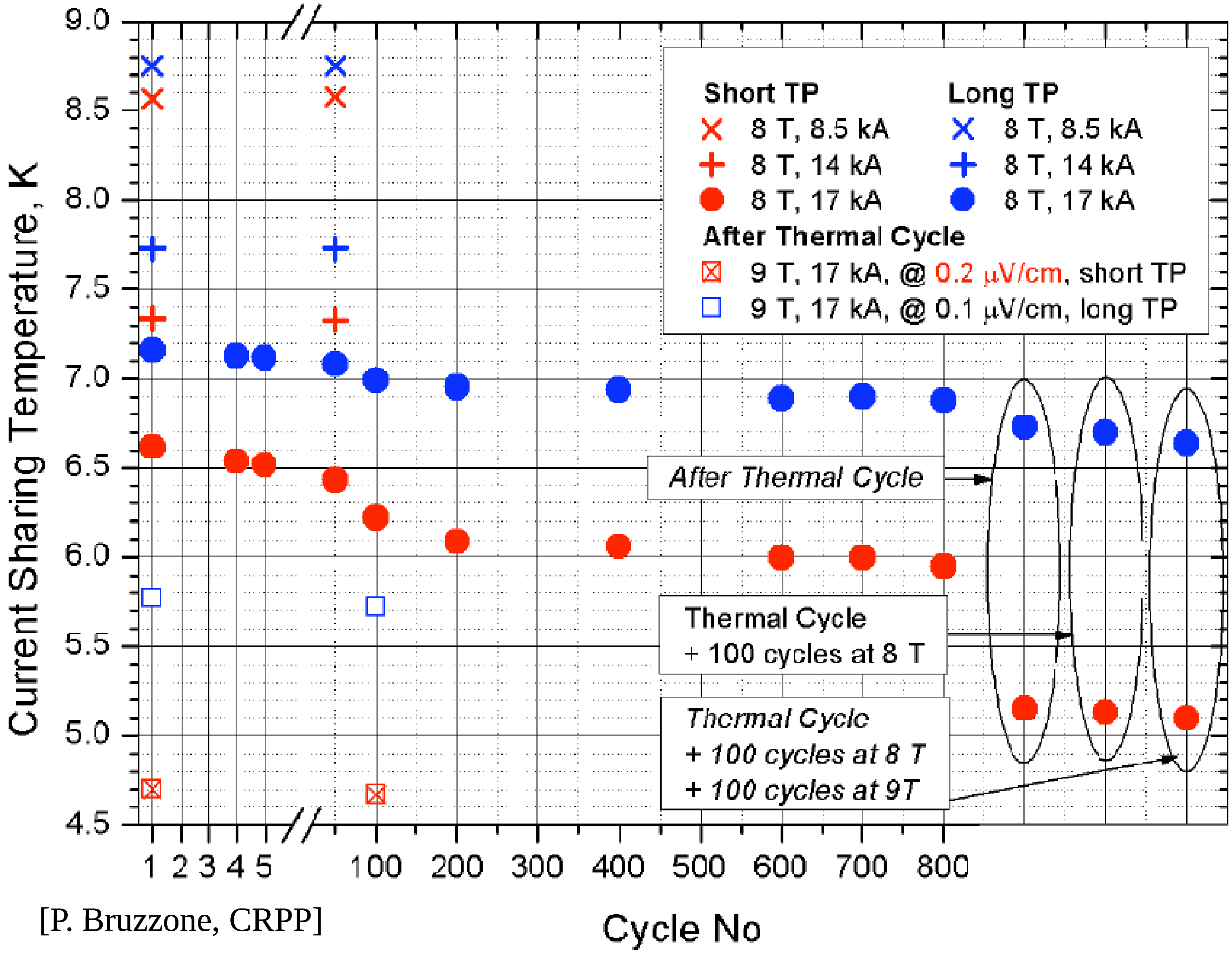
EFDA dipole LF conductor (12.6 x 12.6 mm)

EFDA Dipole – Low Field

Sample	PITSAM2	PITSAM3	PITSAM5	
Cable pattern	(3x3)x3x4	(3x3)x3x4	(3x3)x3x4	
Cu/non Cu strand	(5/4)x3x4 triplet1: 1 Cu/2 sc triplet2: 2 Cu/1 sc triplet3: 2 Cu/1 sc	(5/4)x3x4 triplet1: 1 Cu/2 sc triplet2: 2 Cu/1 sc triplet3: 2 Cu/1 sc	(5/4)x3x4 triplet1: 1 Cu/2 sc triplet2: 2 Cu/1 sc triplet3: 2 Cu/1 sc	
Sc strand number	48	48	48	
Cu strand number	60	60	60	
Strand diameter	0.81 mm Cr plated	0.81 mm Cr plated	0.81 mm Cr plated	
Twist pitch			Short TP	Long TP
	58 mm	58 mm	33.6 mm	83 mm
	95 mm	95 mm	94.6 mm	140 mm
	139 mm	139 mm	139 mm	192 mm
	213 mm	213 mm	213 mm	213 mm
Outer conductor dimensions (mm)	12.6 x 12.6	15.4 x 10.5	12.6 x 12.6	
Void fraction (%)	30	30	30	

Reference TP **Reference TP** **Short/Long TP**

Low Field – Pitsam5

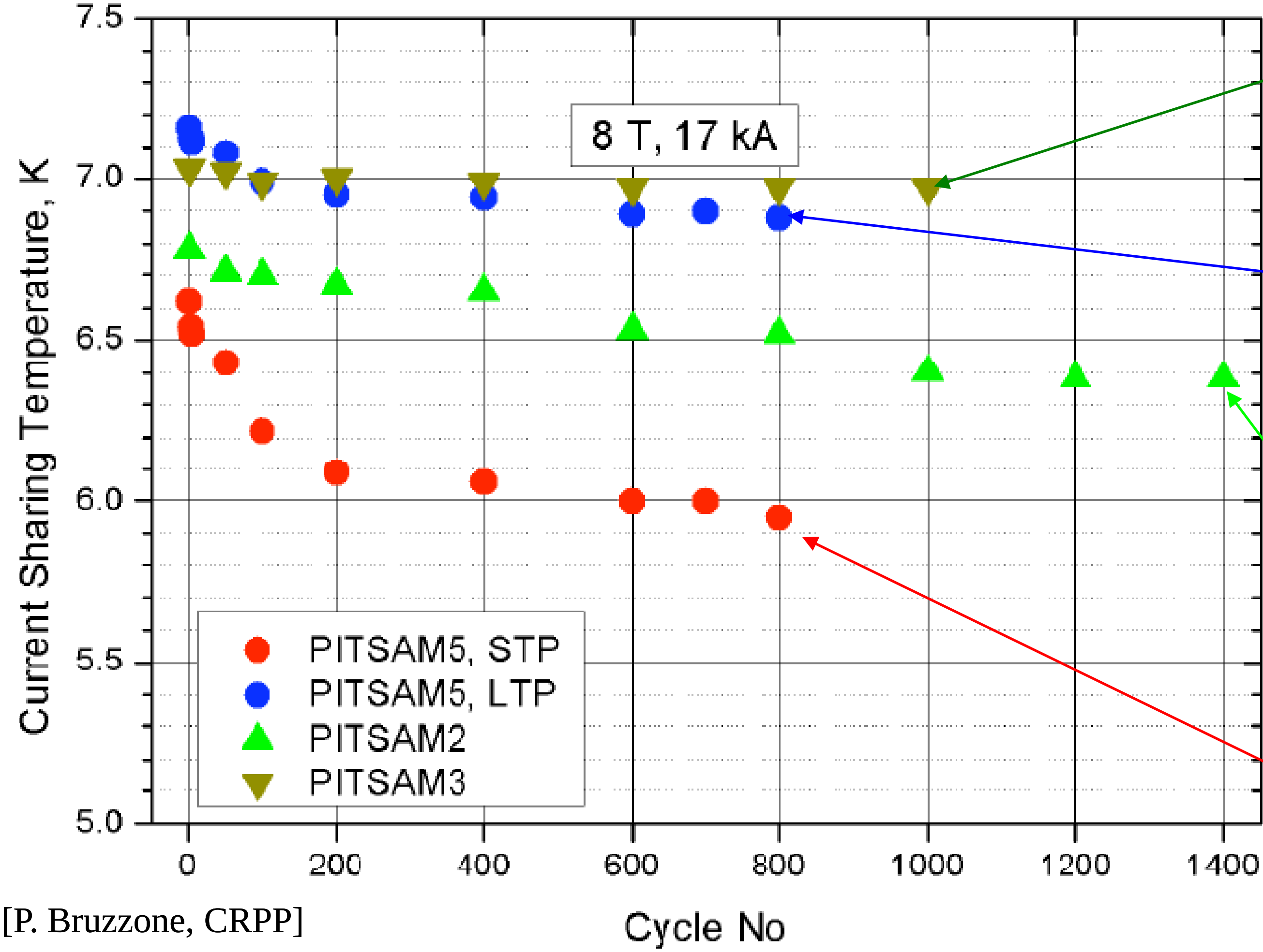


[P. Bruzzone, CRPP]

- Long TP much better from the beginning
- Less degradation with cycling for Long TP
- Difference in T_{cs} after cycling ~1 K
- Severe degradation of Short TP after warm up cycle

Long TP much better performance than Short TP

Twist Pitch – Short vs. Long



[P. Bruzzone, CRPP]

- PITSAM3 reference TP rectangular (1.5)
- PITSAM5 LTP first 3 stages like ITER TF (long) square
- PITSAM2 reference TP square
- PITSAM5 STP first stage 33 mm square

Performance "scales" with twist pitches but rectangular shape has similar effect than long twist pitch

Strand vs. Conductor

- Extrapolation from single strand data
- "Equivalent" longitudinal strain: -0.65 %
- PITSAM5 Short TP
  Initial value: 75 %
  After cycling: 60 %
  After warm up: 50 %
- PITSAM2 Reference TP
  Initial value: 82 %
  After cycling: 70 %
  After warm up: n.m.
- PITSAM5 Long TP
  Initial value: 90 %
  After cycling: 78 %
  After warm up: 75 %
- PITSAM3 Reference TP (rectangular)
  Initial value: 85 %
  After cycling: 82 %
  After warm up: 75 %

Same performance achieved with two different approaches

*Performance of **Long TP rectangular** conductor?*

Conclusions 1/2

- Even with a high J_c strands it is possible to design a successful CICC with steel jacket
- For this type and size of strand and conductor
  1) lower void fraction
  2) long twist pitch
  3) rectangular shape

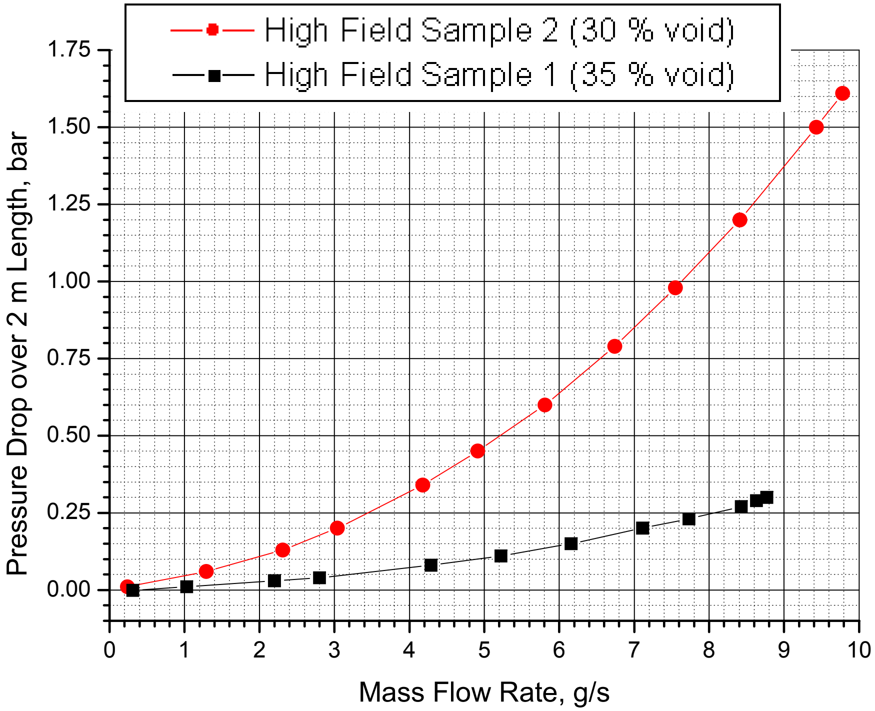
  significantly improves the conductor performance.
- All three parameters increase strand support.
- Rectangular shape “generates” similar effect as longer twist pitch

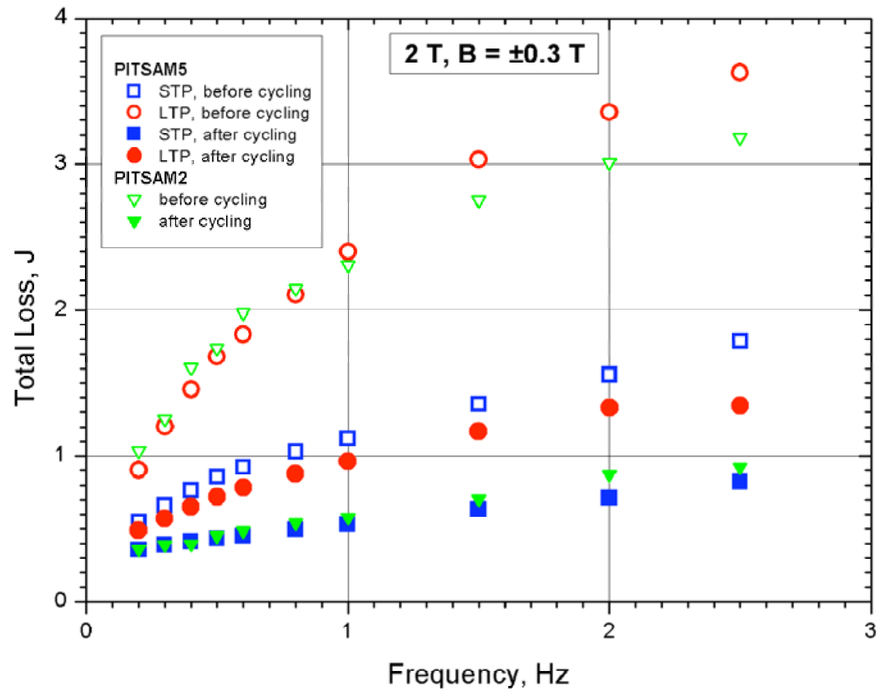
Conclusions 2/2

- These effects may be less important for strands with higher bending tolerance (e.g. TFPRO1)
- Dipole conductor (144 strands) is much smaller than ITER conductors but demonstrates the potential of Nb_3Sn conductors
- Next step in progress:
  NHFML Tallahassee will test a CICC conductor 3 x bigger than the EFDA HF dipole using identical strand, same void fraction and similar elm pressure

Drawbacks

Reduction of void fraction reduces cooling capacity (higher pressure drop) and increases AC losses





Dipole conductor design improvements not applicable to all conductor types (e.g. ITER CS conductor)

Summary

- Fusion magnets use cable in conduit conductors
- Advantages are: large energy margin
  low AC losses
  high mechanical strength
- Disadvantages are: unsupported cable
  thermal mismatch (with steel)
  lower current density
- Using high J_c strand, lower void fraction and longer twist pitch can mitigate most of the disadvantages
- This has been implemented into the dipole (and ITER) conductors
- Future:
  1) use lower thermal contraction material for the jacket
  2) cable size scale up towards dimensions relevant fusion magnets

Is the CICC concept applicable to large high field HEP magnets?

Acknowledgement

- P. Bruzzone, B. Stepanov, R. Wesche (CRPP Villigen)
- A. della Corte, U. Besi-Vetrella (ENEA Frascati)
- A. Baldini, M. Cervasio, G. Masciarelli (Luvata Fornaci di Barga)
- D. Bessette, A. Devred (ITER IO Cadarache)
- J.L. Duchateau (CEA Cadarache)