FUSION
FOR
ENERGY

The European superconductors for ITER magnets

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Outline

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- Cabling
- Jacketing
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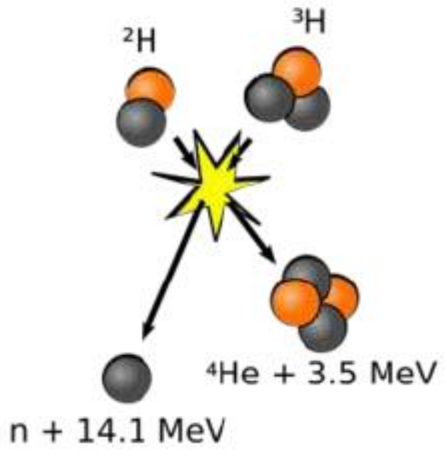
ITER Project: introduction

- **ITER** (International Thermonuclear Experimental Reactor) is an **international** project being built in the south of France (close to CEA of Cadarache).
- The main **purpose** of ITER is to demonstrate the technological **feasibility** of **fusion power**.
- **Fusion reaction**: fusion of light elements (as Deuterium, Tritium) to form heavier element while **releasing energy**, in a way similar to energy production in stars).

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He}\,(3.56\,\mathrm{MeV}) + \mathrm{n}\,(14.03\,\mathrm{MeV}) $$

- Aims to produce thermal power of **500 MW**, corresponding to **10 times** the power injected into plasma.
- ITER project driven by ITER IO and 7 parties (China, EU, India, Japan, Korea, RF, US).
- **Seven** parties established Domestic Agencies to manage their contributions (90% in-kind contribution of components and 10% in cash).
- **Fusion for Energy** (F4E) is the **Domestic Agency** of **EU** (45% of total project budget).
- **First plasma** scheduled for **December 2025** and plasma in D-T phase in 2035.

ITER Magnets: why?



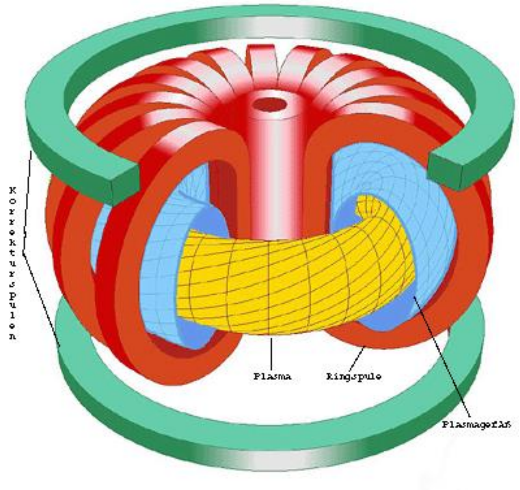
Fusion Reaction

- To get the fusion reaction very drastic conditions of density and temperature (~ **150 millions of ºC**!!) needed.
- In such conditions the matter state is **plasma** and it needs to be **confined** to keep conditions.
- What is needed in ITER Tokamak:

i. Creating a plasma current

ii. Holding the ions & electrons away from the wall forming a magnetic bottle

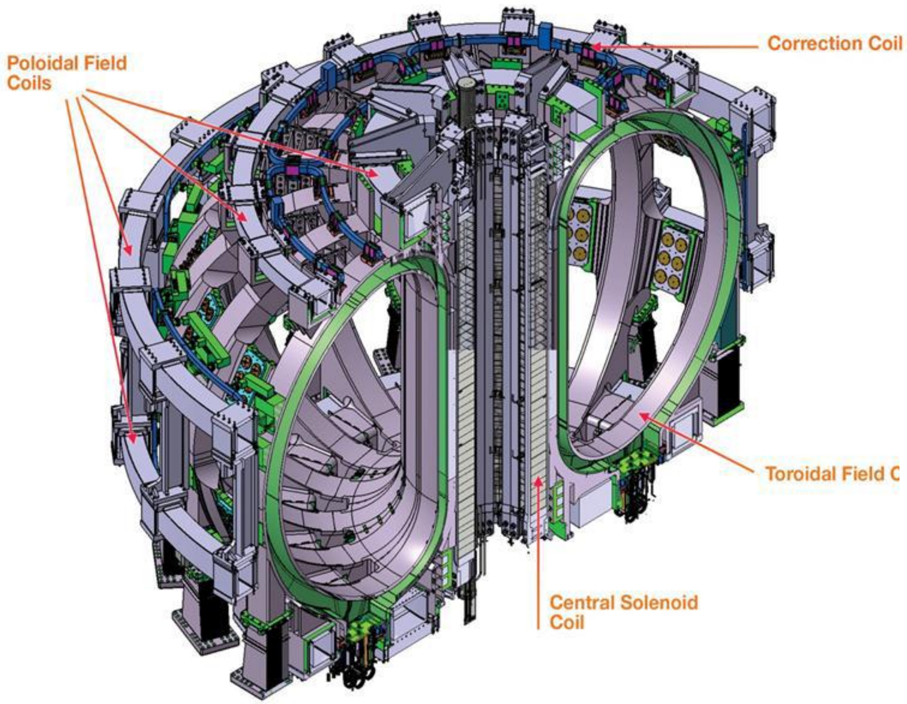
iii. Stopping energy/particle loss from the plasma

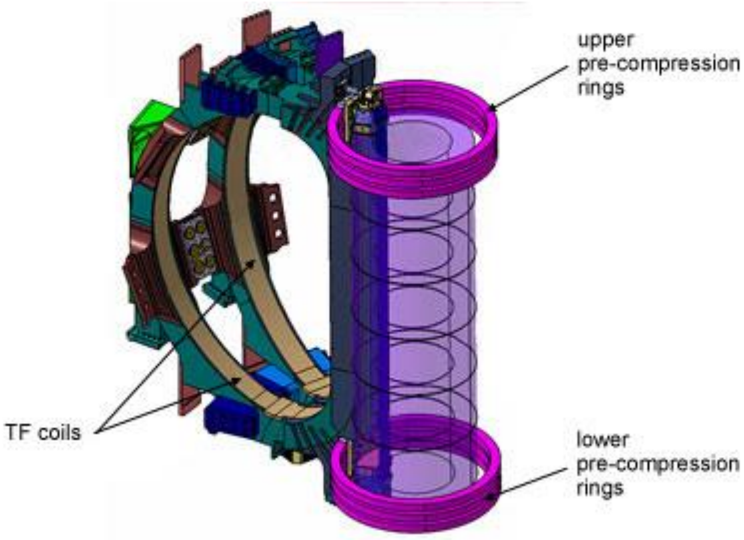


In **ITER Tokamak**:

- CS creates and drives the plasma current,
- TF coils squeezes the plasma to reach critical density for fusion reaction and
- PF coils shapes and stabilizes the plasma.
- In order to minimize power consumption and magnets dimensions **superconducting magnets** used at **~ 4 K**.

ITER Magnet system: what?





Needed for **ITER magnet system**:

- 19 (18+1 spare) Toroidal Field (TF) coils, 10 by EU, 9 by Japan
- 6 Poloidal Field (PF) coils, 1 by Russia, 5 by EU
- 1 Central Solenoid (CS) made of 6 modules, by US
- Correction Coils (CC), by China
- 9 Pre-Compression Rings (3 upper, 3 lower, 3 spares), EU

Total stored energy of 51 GJ for the ITER Magnet system!

European conductor contribution

F4E share to ITER magnet conductors:

- **27 TF conductor unit lengths** (~ 20 % of total) and extra super/dummy conductors (for about four TF coils): 19 regular lengths (760 m each) and 8 side lengths (415 m each). This needed about 97 tons of superconducting Nb_3Sn strand and 62 tons of Cu strand.

- **10 PF conductor unit lengths** (720 m each) and extra super/dummy conductors for PF6 (~ 11 % of Total for PF), which needed about 45 tons of superconducting NbTi strand.

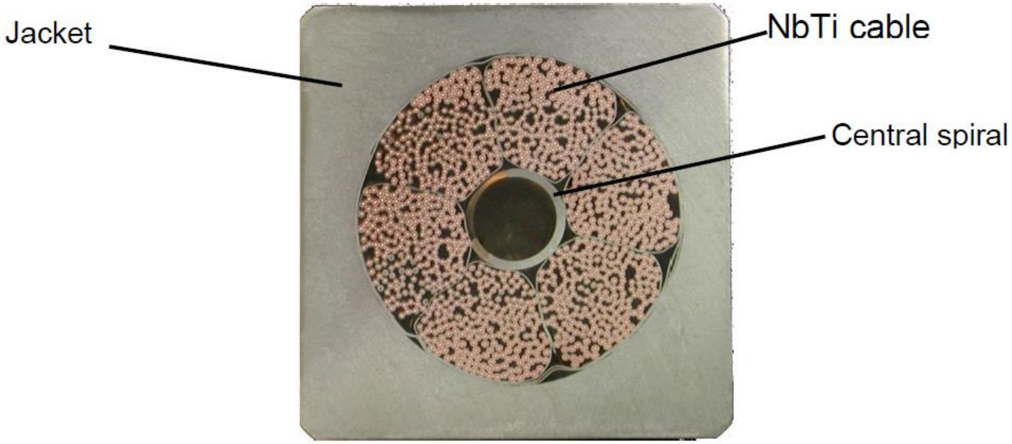
ITER TF conductors

- **TF** coil **operation**: **68 kA, 11.8 T, 5 K**
- TF superconductors are **Cable-In-Conduit Conductors** (CICCs).
- ~**1400 Nb_3Sn** superconducting and Cu strands cabled together (in 5 stages) with stainless steel wraps (for final cable and sub-cables) and around a central cooling spiral.
- Then **cable inserted** into circular long **jacket** made of butt-welded **austenitic stainless steel** to form final conductor.

Cable-In-Conduit Conductor for ITER TF

ITER PF6 conductors

- **PF6** coil **operation**: **52 kA, 6 T, 4.5 K**;
- All PF superconductors are CICCs as well.
- ~**1400 NbTi** superconducting strands cabled together (in 5 stages) with stainless steel wraps (for final cable and sub-cables) and around a central cooling spiral.
- Then cable inserted into **"round-in-square" long jacket** made of butt-welded AISI 316L stainless steel to form final conductor.



Cable-In-Conduit Conductor for ITER PF6 coil

TF conductor supply strategy

For TF conductor **4 supply and 3 characterization contracts**:

- BEAS contract (Germany) for the supply of 40 % of the Nb_3Sn SC strand.
- OST contract (USA) for the supply of 60 % of the Nb_3Sn SC strand (two contracts to mitigate risks).
- Luvata contract (Finland) for the supply of the copper strand.
- ICAS contract (Italy) for the cabling and the jacketing of the conductor), including all components but the strand.

ICAS is a consortium composed of ENEA (contract management), Tratos (cabling) and Criotec (jacketing).

- Durham University contract (UK) for the verification tests of the TF strand to cross-check supplier results on a regular way.
- Twente/Durham grant (NL/UK) for the strand extended characterization (critical current as function of T, B, strain).
- SULTAN contract for the testing of full conductor samples with SPC (CH) to validate various conductor production phases.

PF6 conductor procurement strategy

PF conductor procurement strategy based on PIA (Procurement Implementation Agreement, bi-lateral agreement with RF DA) for sake of synergy.

- EU PF6 NbTi strand and cables supplied by RF DA
- In exchange F4E in charge of jacketing 8 PF6 and 16 PF1 RF lengths
- NbTi strand produced at ChMP (Glazov, RF)
- PF cables manufactured at VNIIKP (Podolsk, RF) and shipped to EU.
- ICAS contract, used for TF conductor, for PF conductors (both PF1 and PF6, EU and RF), ICAS in charge to procure PF jacket sections.
- A contract for verification and extended strand characterization with Durham University.
- SULTAN contract for the testing of full conductor samples with SPC (Switzerland).

TF conductor: Copper strand

Cu strand – Luvata contract

- Contract for 62 t of Cr-plated Cu strand,
- As expected, **no problem** during the execution of this contract,
- **Very high RRR** values: RRR(average) = **363** (min. value of **280**),
- Production completed in advance (**6 months**!).
- However, **problem of strand storage** at the cabling supplier since copper fully produced and a few tons of Nb_3Sn manufactured before launching ICAS contract.

TF conductor: Nb_3Sn SC strand

For the fabrication of TF strand, **two main challenges**:

- **Before** ITER project, **worldwide Nb_3Sn** strand production: **~15ton/year**, more than **100 tons** per year have been needed for **ITER** and **~20t/year for EU** and two companies only: ***industrialization challenge***,
- **High strain sensitivity** due to **filament cracking** following **Lorentz** forces and **warm-up/cooldown** inducing thermo-mechanical loads on cable/jacket system in CICC. ***"Wind and React"***: heat treatment reaction done on TF WPs.

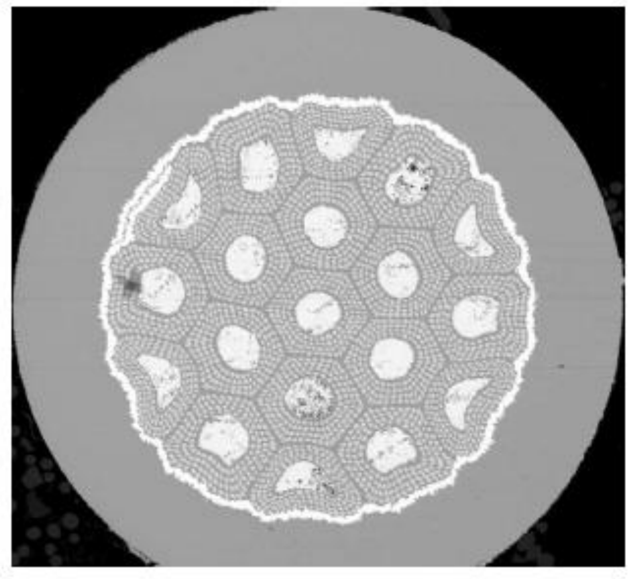
Main TF Nb_3Sn strand specification

Strand diameter	**0.820 ± 0.005 mm**
Strand twist pitch	**15 ± 2 mm**
Cr-plating thickness	**1-2 µm**
Strand piece length	**> 1000 m**
Cu/non-Cu ratio (vol.)	**1.0 ± 0.1**
Ic (12T, 4.22K)	**> 190 A**
n-value, 12T and 4.22K	**> 20**
RRR after HT	**> 100**
Strand hysteresis losses (± 3 T cycle)	**< 500 mJ/cm^3**

TF conductor: Nb_3Sn strand (OST)

Nb_3Sn strand – OST contract

- **59.7 t** of **Nb_3Sn** strand (~**60%** of total).



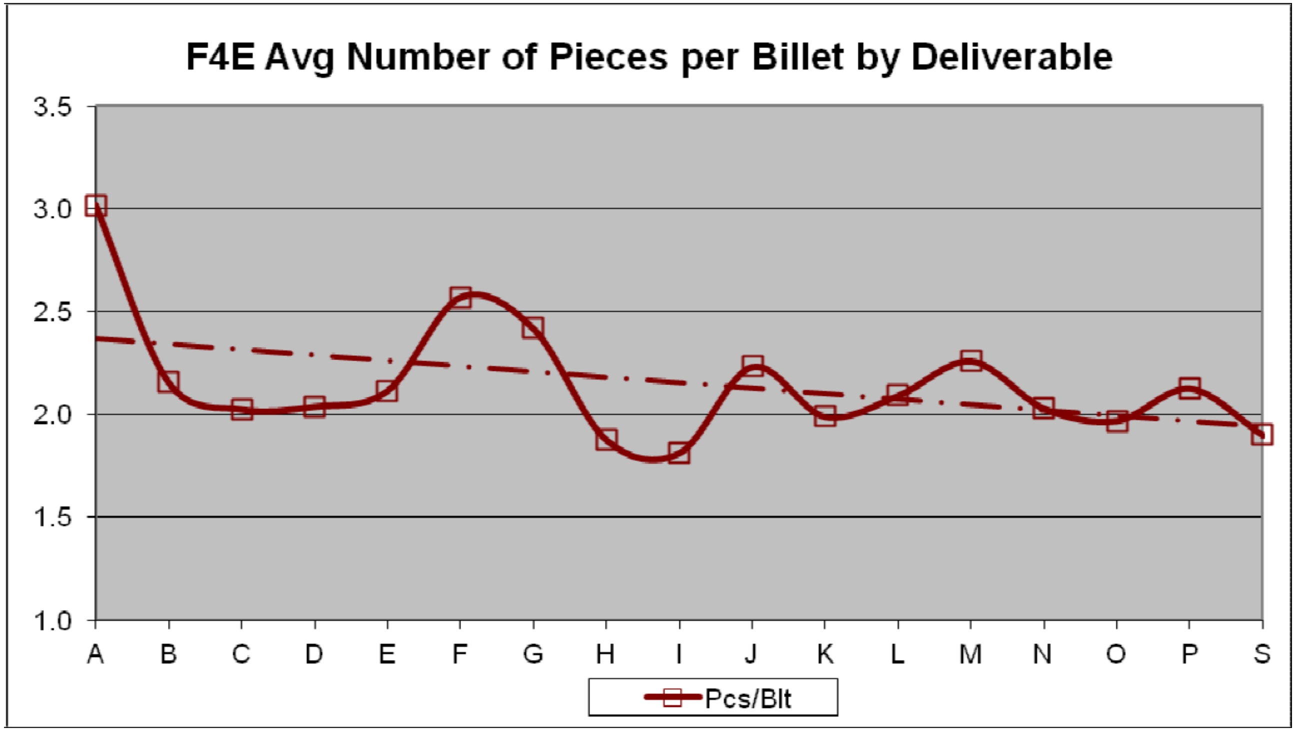
X-section of OST strand

- Produced by **Internal Tin** way
- **19** sub-elements per final billet
- **156 filaments** (142 Nb, 12 NbTi) per sub-element, **6µm**.
- **Ternary** Nb_3Sn (**Ti** doping)
- **Ta barrier** (diffusion), ~**8µm**.

- **1143** strand production **billets** needed for contract completion!

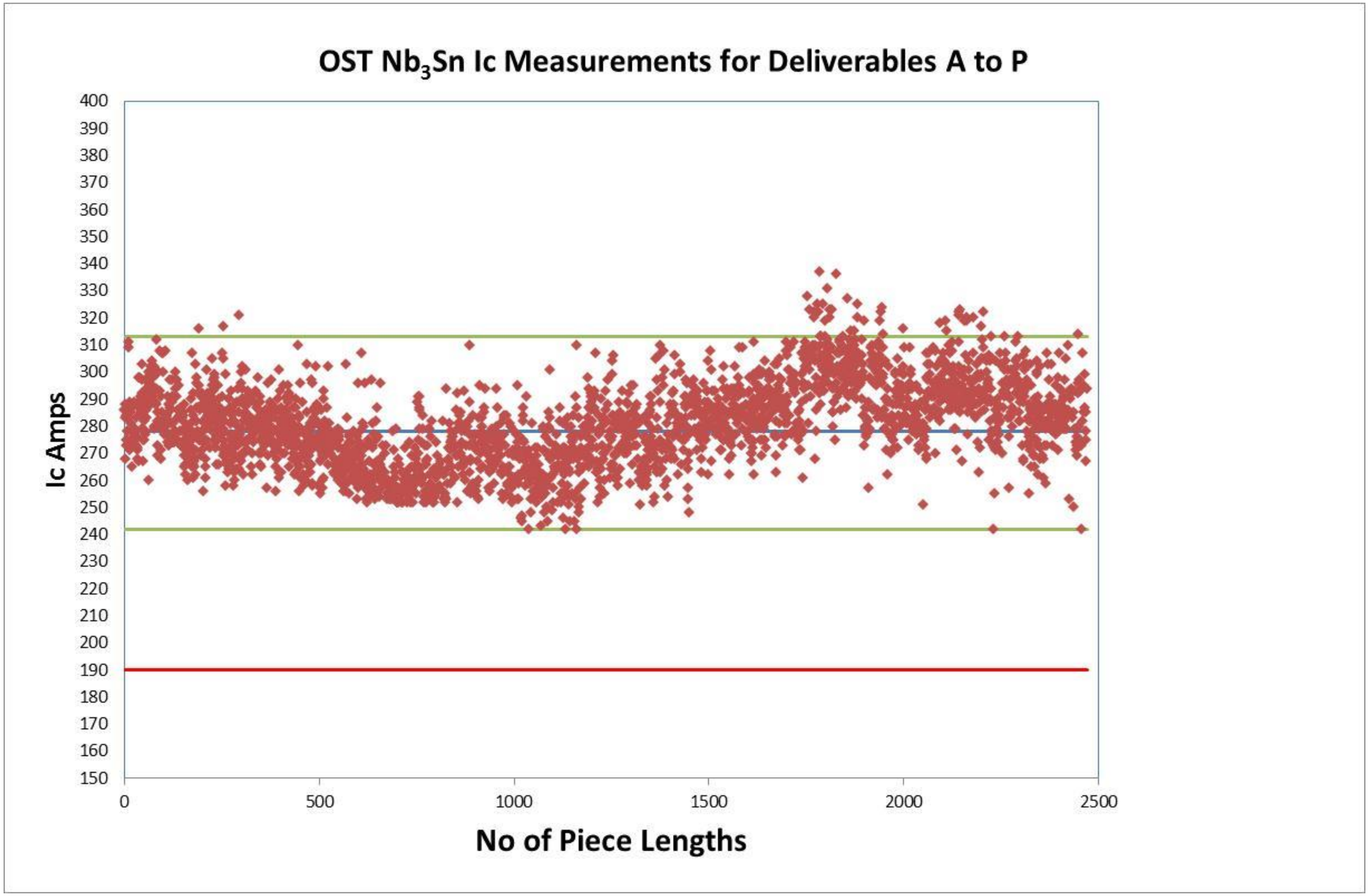
TF conductor: Nb_3Sn strand (OST)

- **Ramp up** phase took **13 months** (upgrade of facilities for mass production).
- During ramp up (first strand batch) several billets with low yield (< 50 %) due to Ta barrier and inclusions but **workability improved** quickly with the average **number of strand pieces** passing from **3** at the beginning to **2** per billet:



Nb_3Sn OST Deliverable A-P (60 t)
Ic values @ 4.22 K, 12 T, OST values

Average = 281 A
σ = 15 A

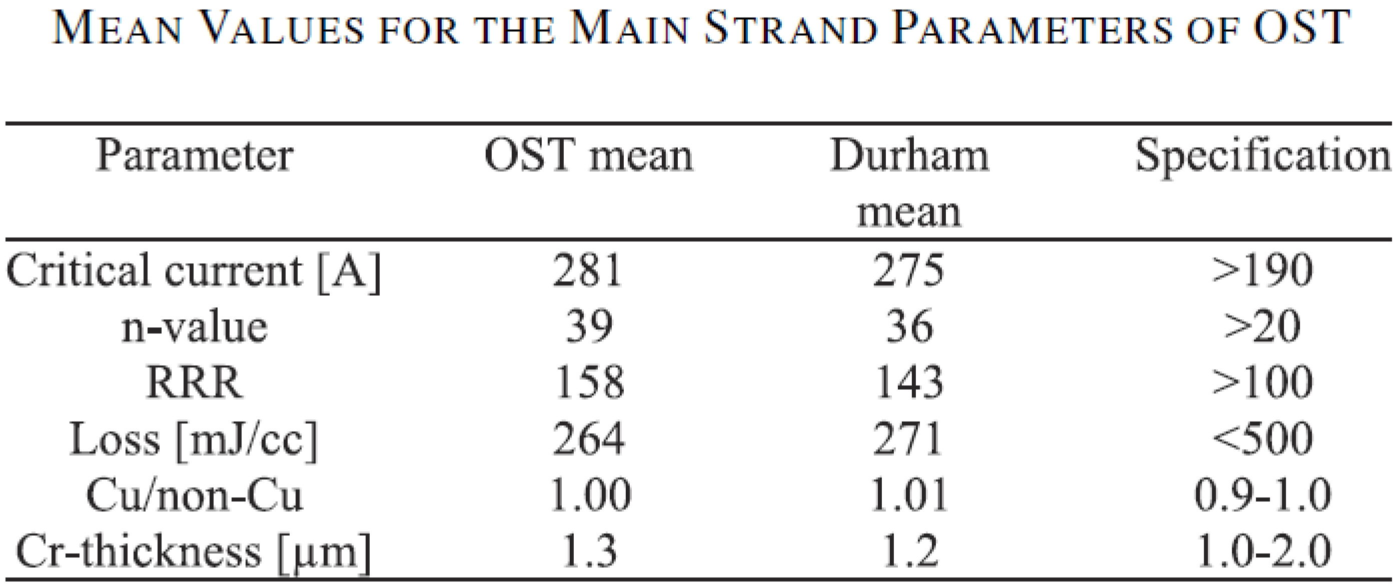


OST: Supplier data statistics (60 tons)

parameter	Ic [A]	n	RRR	Loss [mJ/cc]	Cu/non-Cu	Cr thickness [µm]
Average	281	39	158	264	1.00	1.3
Standard deviation	15	6	31	51	0.05	0.1

- **Critical current** in average **50% higher** than minimum **specified** value!
- All **loss values** within **specification** with the highest value being **19% below** the **maximum** specified value.

OST: Supplier data vs Durham (60 t)



MEAN VALUES FOR THE MAIN STRAND PARAMETERS OF OST

Parameter	OST mean	Durham mean	Specification
Critical current [A]	281	275	>190
n-value	39	36	>20
RRR	158	143	>100
Loss [mJ/cc]	264	271	<500
Cu/non-Cu	1.00	1.01	0.9-1.0
Cr-thickness [µm]	1.3	1.2	1.0-2.0

- In general, all parameters as measured **at OST consistent** with **Durham** measurements in average within a **few %**, to the **exception** of **RRR** where **DU** data **lower** by **9%** in average.

OST: RRR issue

- In general, **RRR** of **OST** strand was quite **high** (**158** in average) and this was **confirmed** by the **verification** measurements at Durham/Twente University.
- However, in the middle of the production, Durham measured for some billets **RRR out of spec** (< 100) whereas OST values were high as usual.
- Re-tests at both OST, Durham and Twente confirmed the **discrepancy** between OST and DU/UT values. Moreover, **US DA** verification measurements presented for some billets the **same** trend.
- Thorough investigations were launched. First, the **setups** have been cross-checked: OST and Durham appeared to be **consistent** on same physical samples within **very few %.**
- Then Heat Treatment has been considered. **OST** used **N_2** gas whereas **Durham** used **Ar**.

OST: RRR, heat treatment impact

- Two **~ 1 km lengths** have been cut **every 50 m** and adjacent samples have been reacted and tested at OST (1 under **Ar** and 1 under **N_2**) and reacted at CERN (under **vacuum**) and tested at DU. The results as averaged over the ~ 20 samples are quite surprising:

Strand	OST, N_2	OST, Ar	DU, vacuum (CERN)
F0796	144/11	81/16	88/21
F0825	146/14	131/18	134/17

RRR average and standard deviation over the length

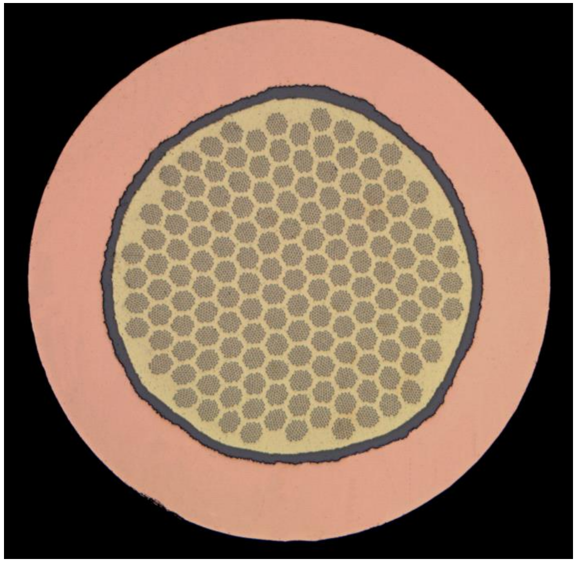
- Samples treated in **Ar** or **vacuum** provide quite **consistent** results. However, if samples reacted in **N_2** have a **higher RRR** than those in **Ar** for F0825 by **~ 10 %,** the discrepancy goes up to **78 %** for the other length…
- Last but not least this **RRR issue** was **localized** over **a few** batches.

OST: RRR, heat treatment impact (2)

- An analysis of oxygen residues present in heat treatments could explain discrepancy: **2 ppm for N_2** as compared to **10 ppm for Ar**.
- In addition, small oxygen amounts in N_2 gas could create at beginning of HT **oxide layer** on the strand able to act as a diffusion layer to **prevent** further **oxygen contamination** of the **copper** matrix.
- Anyway, OST changed the HT environment gas **from nitrogen to argon** till the end of the contract in order to be more conservative and **consistent** as well with **ASG**, the European TF coil manufacturers using Ar in HT of the TF double pancakes.

Nb_3Sn – Bruker EAS Contract

- **37.7 t** of **Nb_3Sn** strand (~**40%** of total)



X-section of Bruker EAS strand

- Manufactured by **Bronze Route**
- **151 sub-elements** per final billet
- **55 filaments** (NbTa), **3µm**, embedded in bronze matrix (CuSnTi) per sub-element.
- **Quaternary Nb_3Sn** (Ta and Ti doping)
- **Ta barrier** (diffusion barrier), 13µm.
- During drawing, intermediate annealing steps needed for the bronze due to work hardening: **long process**.

- **380 billets** needed for contract **completion**.

Nb_3Sn – Bruker EAS Contract

- **Ramp up** phase took **13 months** (upgrade of facilities for mass production).
- At the **beginning** of the strand **production**, **breakages** caused by foreign **particle** contamination: **problem rapidly solved**. Over the full production **2.8 piece lengths per billet** in average.
- More than **90 %** of billets with **yield > 80 %**: **good workability of the process.**
- Heat Treatment schedule: ITER technical specification for TF strand heat treatment foresees two options Cycle A and Cycle B:

Cycle A	***Cycle B***
– ***210 ˚C for 50 hrs,***	– ***210 ˚C for 50 hrs,***
– ***340 ˚C for 25 hrs,***	– ***340 ˚C for 25 hrs,***
– ***450 ˚C for 25 hrs,***	– ***450 ˚C for 25 hrs,***
– ***575 ˚C for 100 hrs,***	– ***575 ˚C for 100 hrs,***
– ***650 ˚C for 200 hrs.***	– ***650 ˚C for 100 hrs.***

Nb_3Sn – Bruker EAS Contract

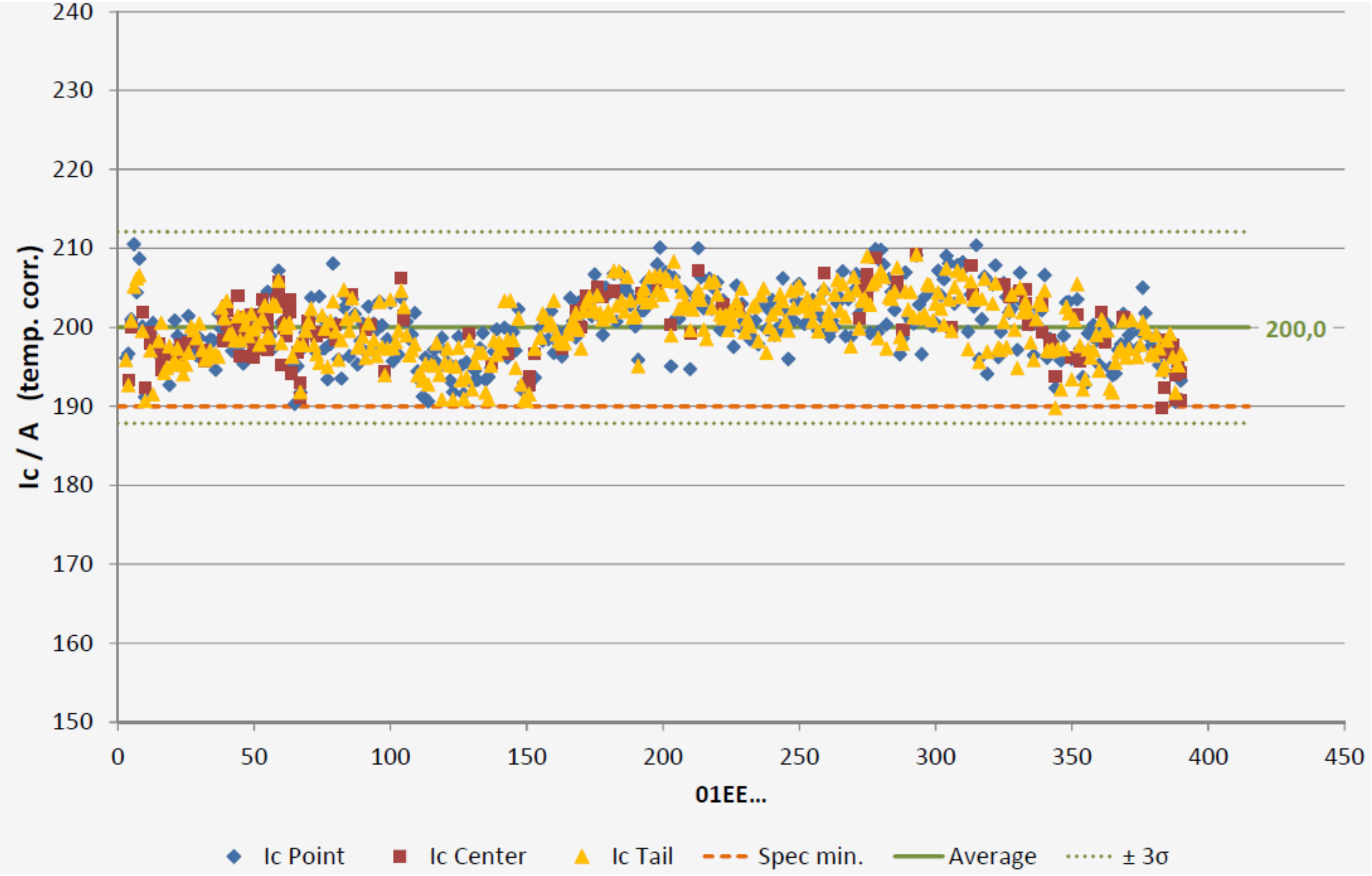
- However, both Cycles A and B provided strand Ic very close to specification (~ 190 A). In addition, qualification SULTAN conductor sample showed current sharing temperature ~ 5.9 K after cycling, near minimum specified value (5.7 K + 0.1 K error bar).
- Thus **HT modified**: HT schedule of **595 C/160 h + 620 C/320 h** typically provided strand **Ic ~ 200 A**.
- This HT schedule allowed to have all the billets produced (except two at the beginning of production) within critical current specification and all the SULTAN conductor samples tested to be just in specification (**Tcs ~ 5.8-5.9 K**).

Nb_3Sn BEAS deliverables A-Q (38 t)
Ic values @ 4.22 K, 12 T, BEAS data

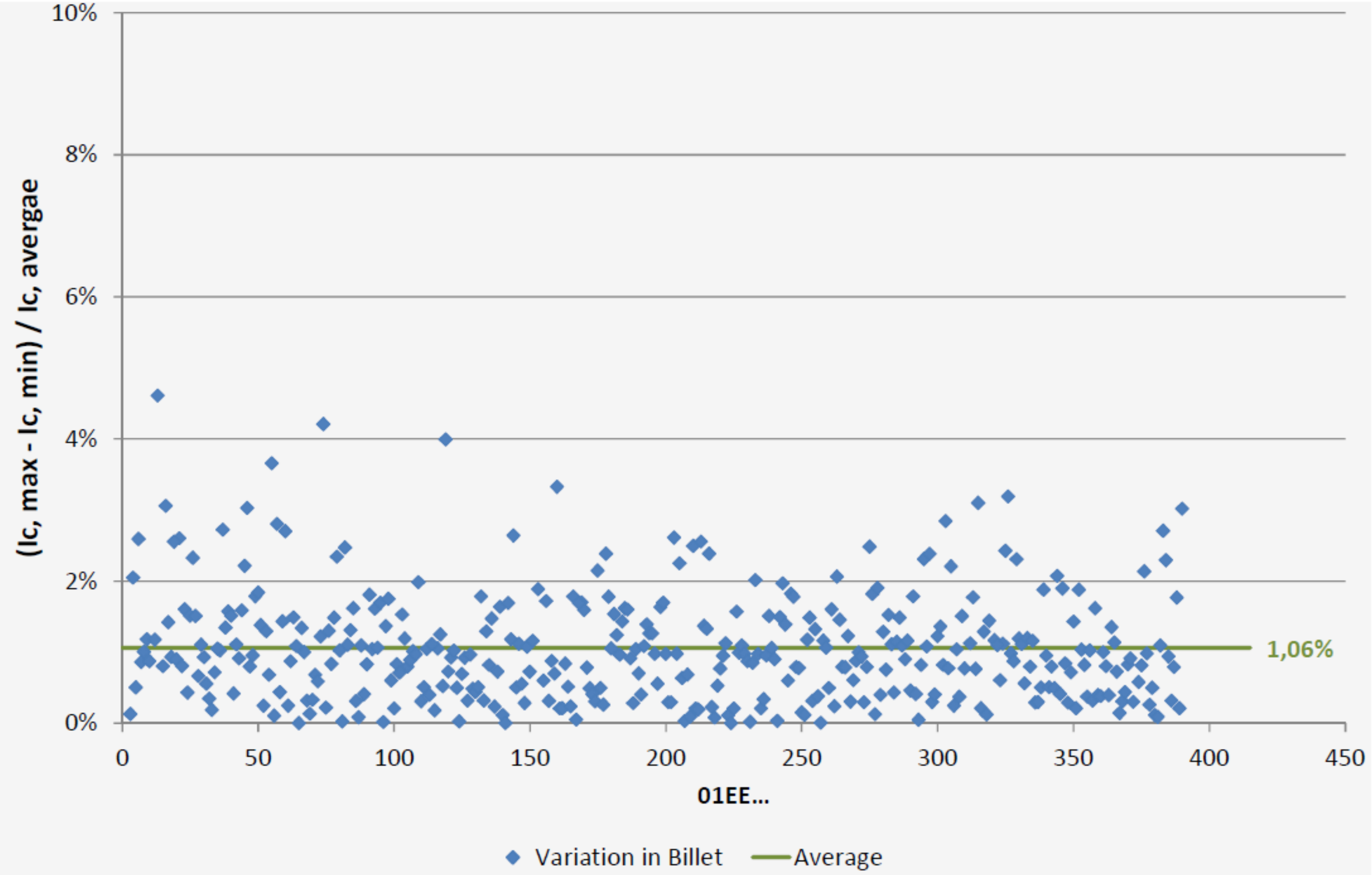
Average = 200 A

σ = 4 A

All values are within ± 5 %!!



BEAS: Ic variations within a single billet



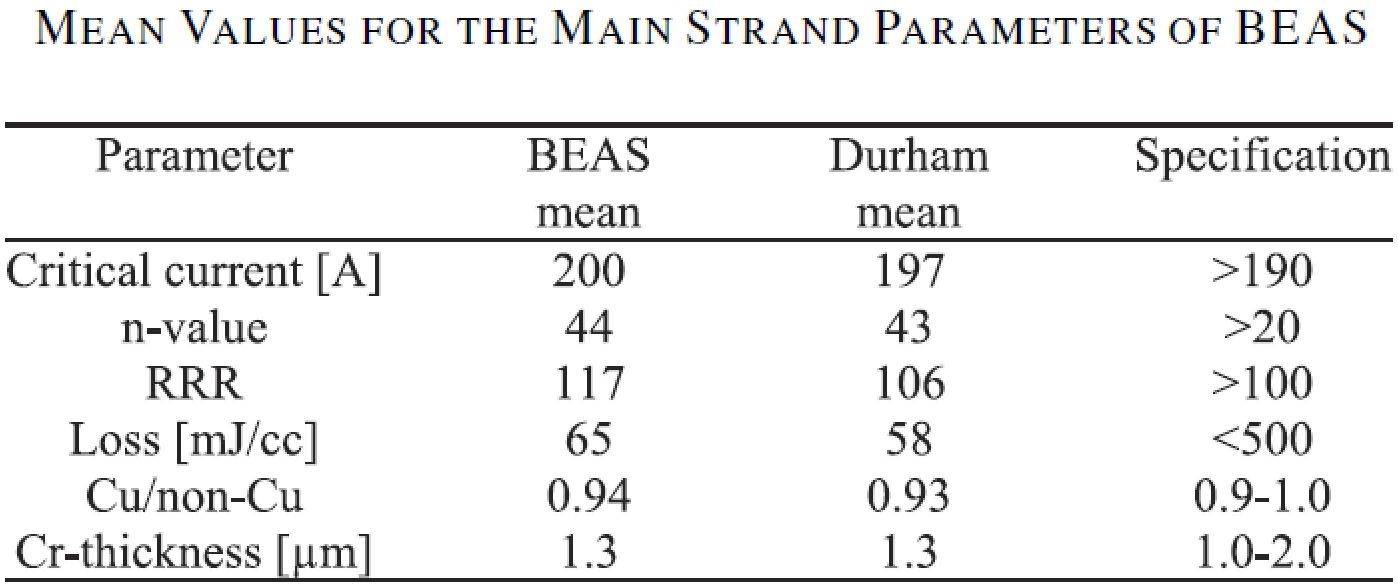
The critical current scatter for a given billet is within ± 2% and generally better than within ± 1%: remarkable!!

BEAS: Supplier data statistics (38 tons)

parameter	Ic [A]	n	RRR	Loss [mJ/cc]	Cu/non-Cu	Cr thickness [µm]
Average	200	44	117	65	0.94	1.3
Standard deviation	4	2	12	15	0.02	0.2

- Although Ic values close to minimum specification, **low variability** for all measurements **(± 5%**) and impressively **low scatter** for a given **billet** (generally within **± 1%**).
- **Ic scatter** for given billet **remarkable** since integrates testing setup reproducibility and repeatability, sample mounting and Cu/non-Cu variations along the billet.
- **RRR variability** in a billet obviously **larger** than that of Ic due to RRR sensitivity to local copper impurities or Ta barrier defects. Scatter within **10%** for most cases (can reach 30% in very few cases).
- **Losses very low** due to very **thin filaments** (~ 3µm) and relatively **low Jc**.

BEAS: Supplier data vs Durham (38 t)



MEAN VALUES FOR THE MAIN STRAND PARAMETERS OF BEAS

Parameter	BEAS mean	Durham mean	Specification
Critical current [A]	200	197	>190
n-value	44	43	>20
RRR	117	106	>100
Loss [mJ/cc]	65	58	<500
Cu/non-Cu	0.94	0.93	0.9-1.0
Cr-thickness [µm]	1.3	1.3	1.0-2.0

- Generally and in average, **BEAS and Durham data** are consistent within **few %**.
- However, for **RRR**, **Durham** values **lower** on average by almost **10%** than Bruker data. More explanations on next slide.

BEAS: RRR issue

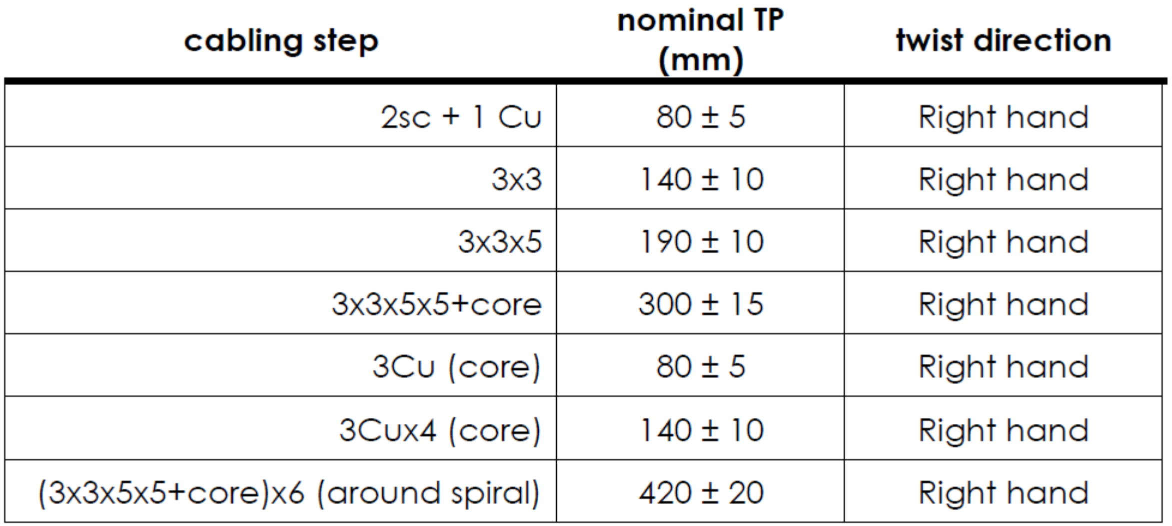
- There was an **issue** with **RRR** slightly **below specification** due to strand surface **contamination** during drawing but this issue has been quickly **solved** by BEAS.
- However, in this case too, there was a **discrepancy** of around **10 %** between the **supplier** and the **verification RRR** data where the supplier values were generally higher.
- Cross-checks made on same physical samples showed that BEAS, Durham and Twente setups provided data **consistent within 1-2 %.**
- Nevertheless, for batch E adjacent samples have been cut and:

  a. reacted and tested at BEAS (Ar)

  b. reacted and tested at Durham (Ar)

  c. reacted at CERN (vacuum) and tested at Twente
- In average the RRR of **BEAS** samples was **114**, whereas that of **Durham** samples was **102** and that of **Twente 93**….
- **Once again, impact of the environment during the heat treatment is decisive for RRR performance (interplay between atmosphere and contaminants).**

TF conductor: cabling at Tratos Cavi



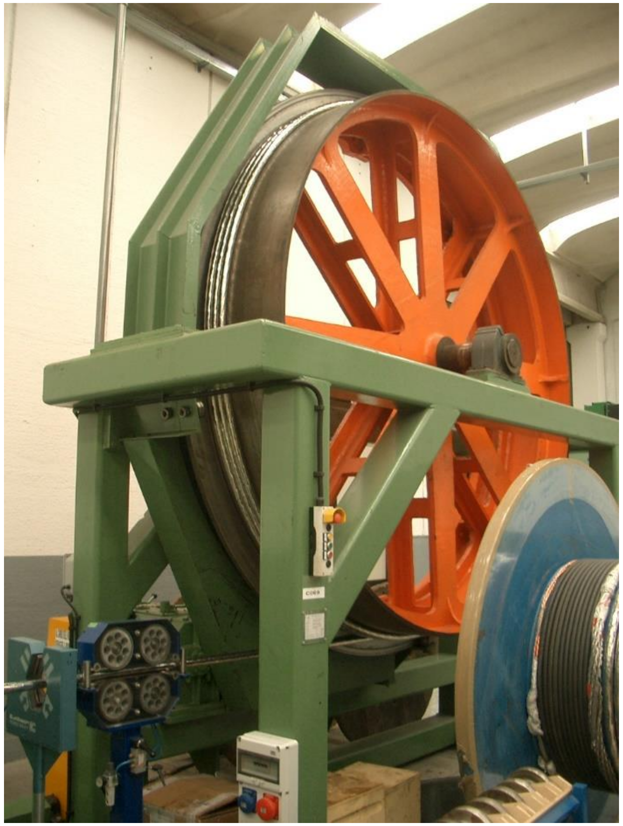
cabling step	nominal TP (mm)	twist direction
2sc + 1 Cu	80 ± 5	Right hand
3x3	140 ± 10	Right hand
3x3x5	190 ± 10	Right hand
3x3x5x5+core	300 ± 15	Right hand
3Cu (core)	80 ± 5	Right hand
3Cux4 (core)	140 ± 10	Right hand
(3x3x5x5+core)x6 (around spiral)	420 ± 20	Right hand

- **Triplets** (first cabling stage and Cu triplets) cabled on Machine A (**65 m/min**),
- Machine B for **stages 2 and 3** (**21** and **15 m/min**),
- Machine C for **last two stages** (typically **a few m/min**).
- On Machine C **pulling force** produced by a motorized **capstan** (OD 3000mm) at end of line. Pulling system, properly **balanced by brakes** of sub-cable de-spooling system: able of applying **very accurate payoff** tension **(<1 kg/strand**).

TF conductor: cabling at Tratos Cavi

- All components (but strand) supplied by supplier: spiral, wraps.
- **No serious technical** issue but BEAS **Bronze Route strand** more **difficult** to cable (bronze stiffer than copper): cabling qualification took more time for Bronze Route than for Internal Tin.

Final TF cable formation



Capstan (end of line)

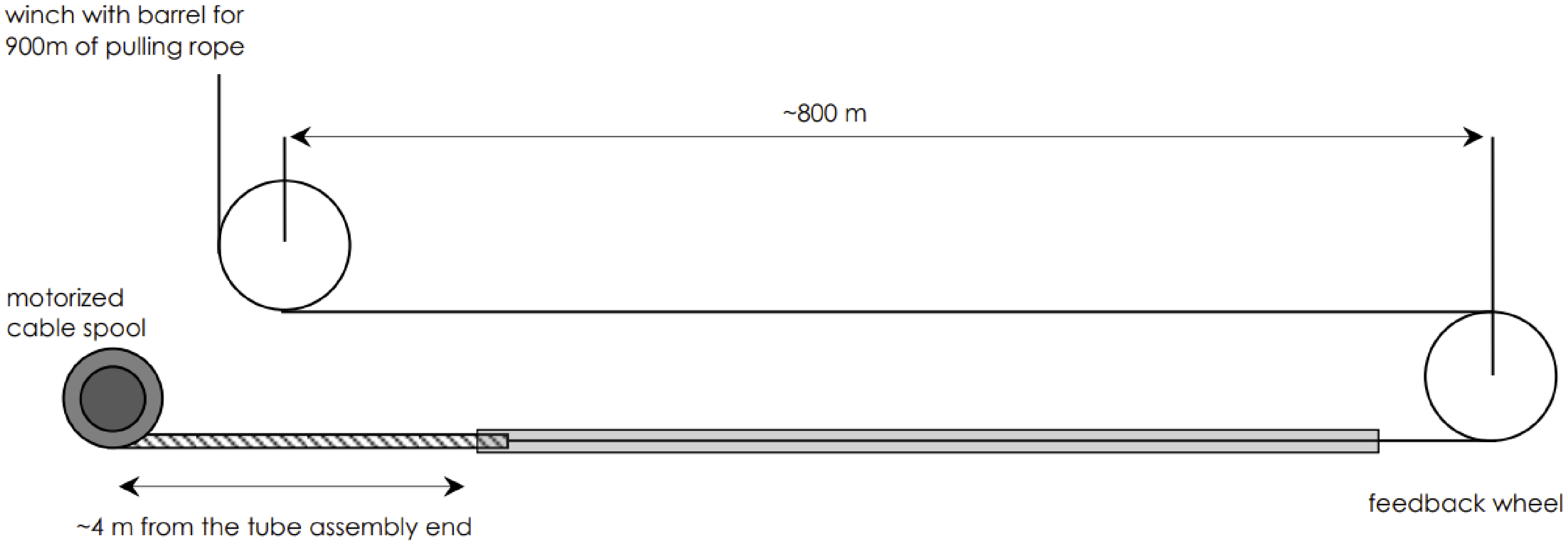
TF conductor: jacket assembly, Criotec

- **Jacket** sections (~13 m) **butt-welded** by a **TIG**, fully-automatic, orbital machine.
- **NDT** of weld (**endoscopic visual, X-ray, leak test, dye penetrant**).
- If NDT fine, jacket assembly pushed towards the jacketing line (800 m!!!) and new weld till full jacket length reached.

A view on the jacketing line (800 m)

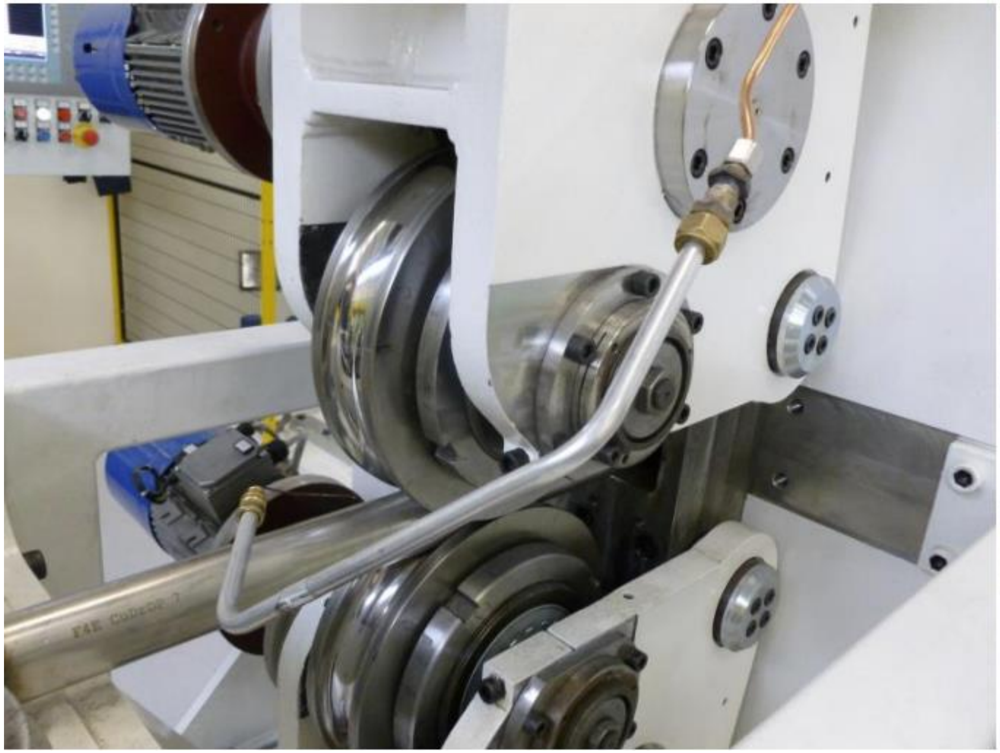
TF conductor: Cable insertion, Criotec

- Once the jacket **assembly completed**, the cable **insertion** can begin…
- The **cable** is then simply **inserted** into the conduit by pulling it by means of carbon fiber rope (**2-6 m/min**).
- **Maximum pulling** force around **40 kN** for 760m cable insertion and around **25 kN** for 415m cables.

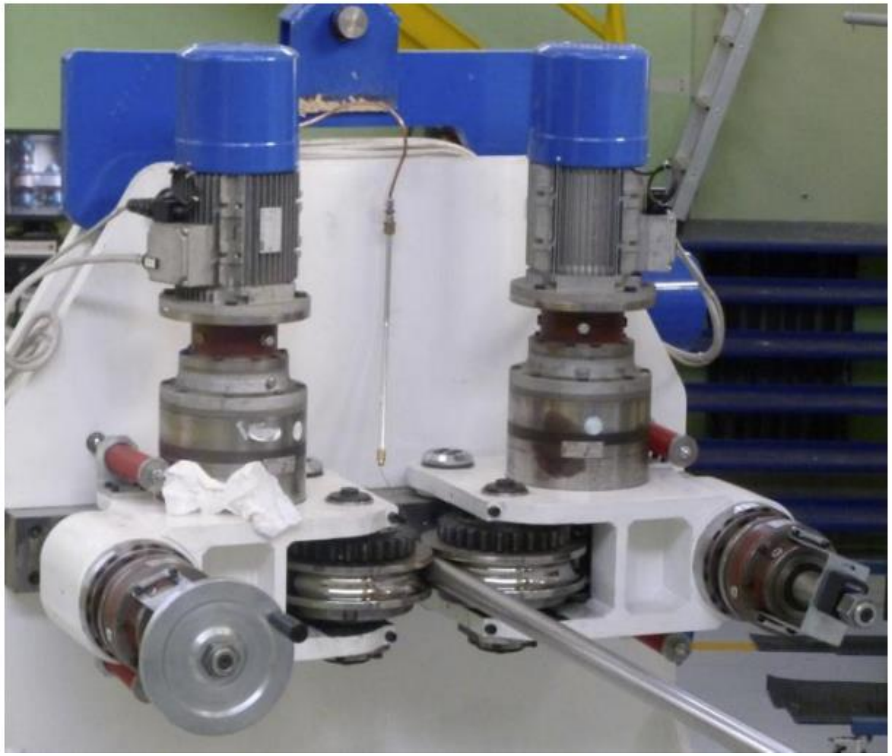


TF conductor: Compaction, Criotec

- After cable insertion, conductor **compacted** by means of dedicated compaction machine consisting of **3 pairs of rollers** (first for ovalization, second for compaction, third for shape correction back to circular).
- Typical speed for **compaction/spooling**: **1-3 m/min**.



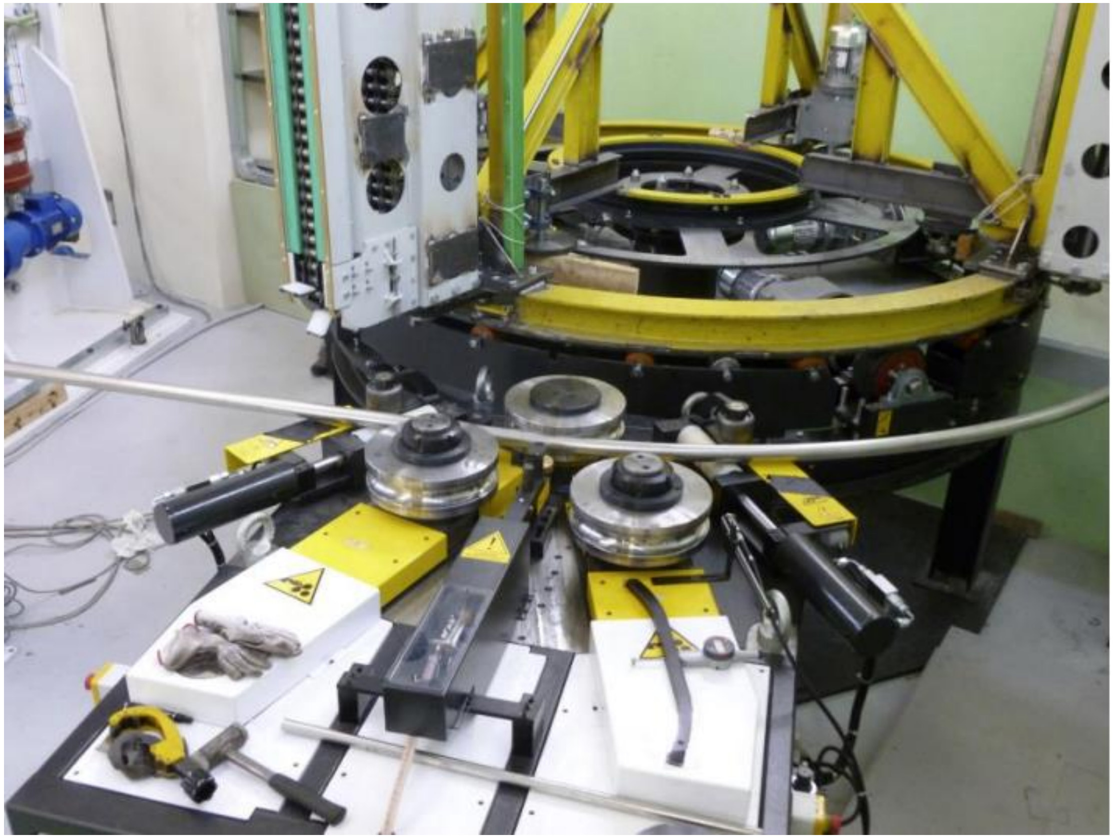
Second pair of compaction rollers



Third pair of compaction rollers

TF conductor: Spooling, Criotec

- At exit of compaction machine conductor enters bending machine to be properly **curved** and **spooled** (**4m inner diameter**).
- Dedicated **bending mach**ine consists of **three rollers**.



Bending machine for spooling

Final conductor

TF final conductor: global tests

- After conductor completion, **global tests** to be performed.
- Global tests:

1. **Dimensional** cross-check (OD **43.7 ± 0.3mm**)
2. **Dye Penetrant** testing of welds.
3. **Pressure** test (1 hour at 30 bar).
4. **Flow rate** and pressure drop measurements
5. **He leak** test (30 minutes at 30 bar).

- After **successful** testing of conductor length, conductor transferred to the transportation **jig**, **packed and shipped** to ASG, the European TF winding pack contractor.

Final conductor moving to ASG

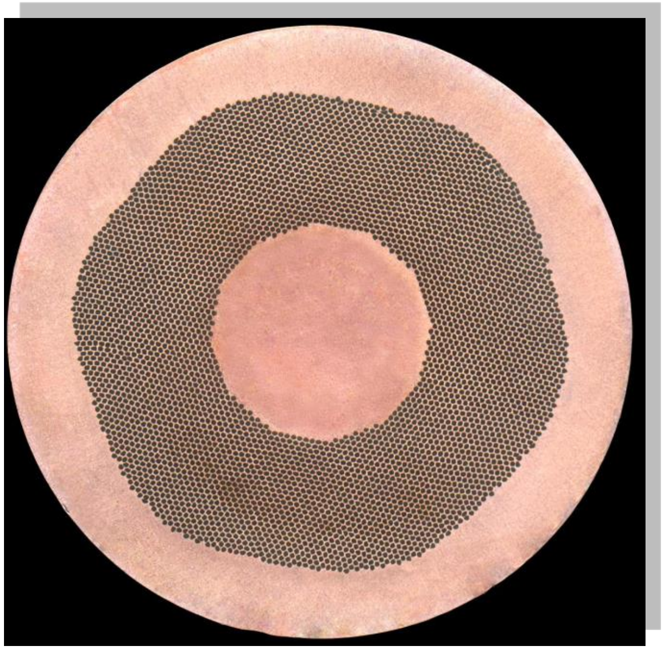
TF conductor: jacketing challenges

Before ITER project a single long length has been jacketed by Russia. However, no serious technical difficulties for TF jacketing but:

1. **Mechanical properties of jacket**: due to longer HT schedule for BEAS conductor, POSCO jacket have a maximum elongation slightly below specification (20 % minimum) for this HT. Therefore, **POSCO** jacket used for **50 %** of the lengths; new jacket supplier SMST has been qualified for second half: elongation of **30 %**! But schedule impact of several months (**not critical** for TF coils)…
2. **Transportation jigs**: since **no transportation jig** foreseen in the ITER technical specification, around a year necessary to agree between all the parties (ITER, F4E, ASG, ICAS) after contract signature.

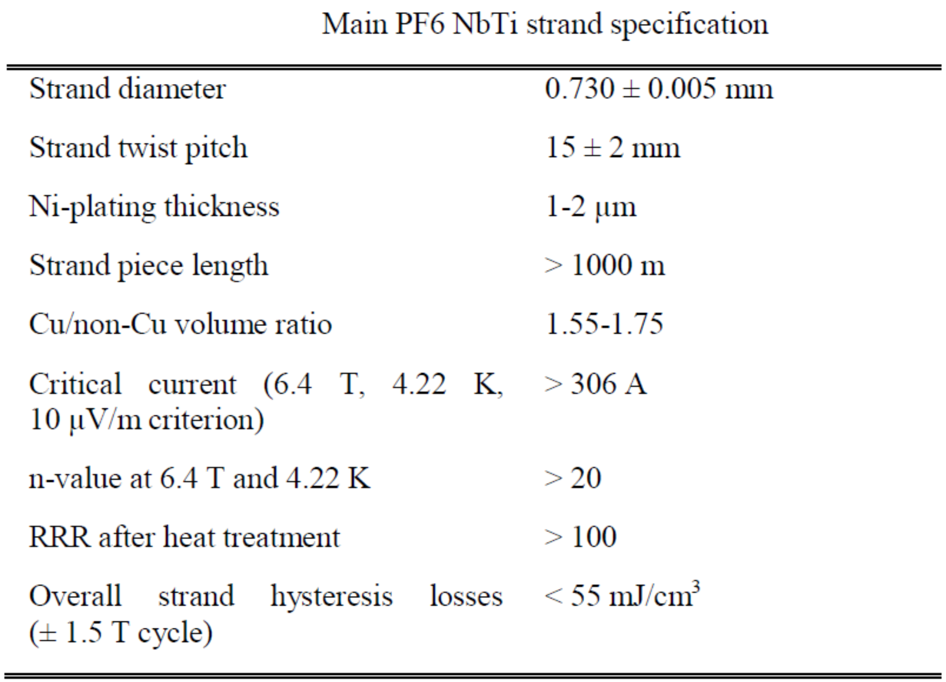
PF conductor: NbTi Strand

- Bi-lateral agreement: EU NbTi **strand** production (45 tons) by Russia.
- NbTi Strand manufactured by **Chepetsky Mechanical Plant** (Glazov, RF) and Ni-plated by **VNIIKP** (Podolsk, RF).
- Strand includes around **4500 NbTi filaments** (~**7 µm**, single stack).



Cross-section view of PF6 NbTi strand (courtesy RF DA)

PF conductor: NbTi Strand



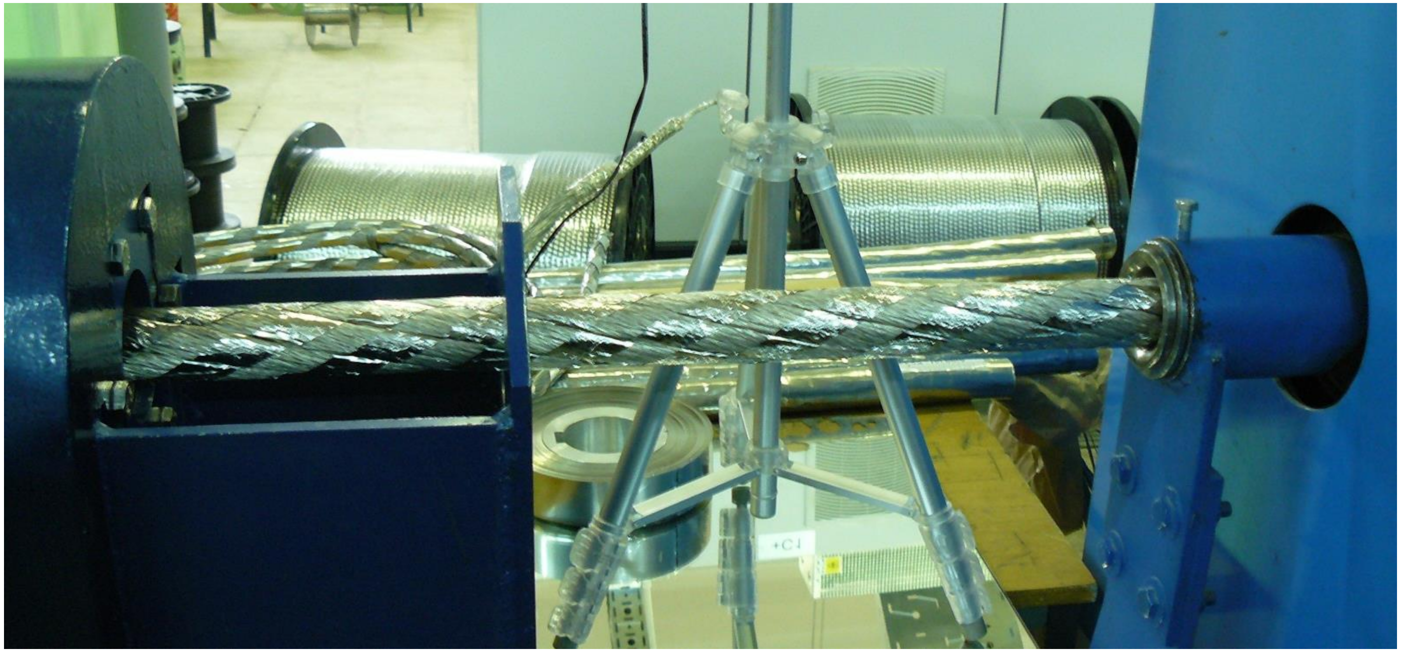
Main PF6 NbTi strand specification

Strand diameter	0.730 ± 0.005 mm
Strand twist pitch	15 ± 2 mm
Ni-plating thickness	1-2 μm
Strand piece length	> 1000 m
Cu/non-Cu volume ratio	1.55-1.75
Critical current (6.4 T, 4.22 K, 10 μV/m criterion)	> 306 A
n-value at 6.4 T and 4.22 K	> 20
RRR after heat treatment	> 100
Overall strand hysteresis losses (± 1.5 T cycle)	< 55 mJ/cm^3

- **317 billets** necessary for the full production.
- At **beginning** of production **three billets** discarded due to **low yield**.
- However, after ~1 year of production **89%** of billets had **yield > 80%**. **End** of production: **95%** of billets with **yield > 85%**.
- All supplier and verification data **within specification**!

PF conductor: Cables

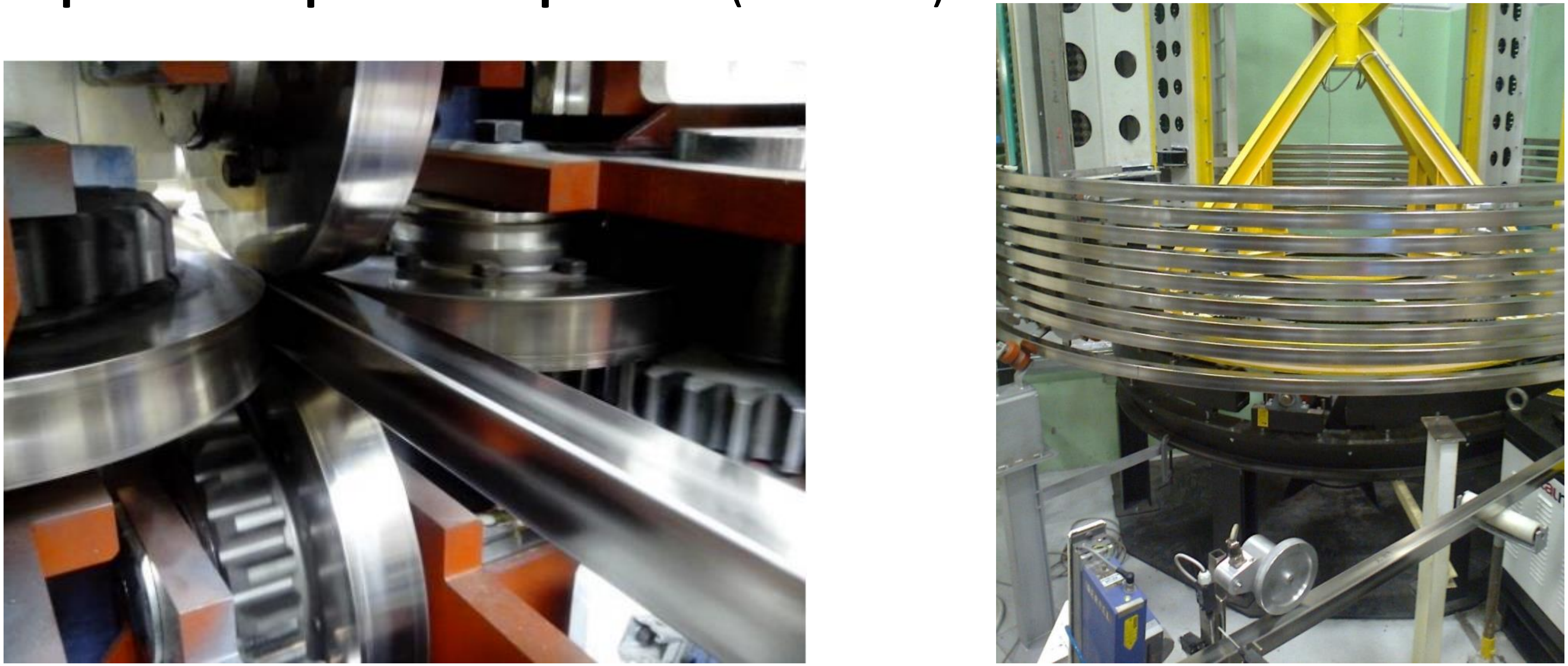
- EU PF6 cables managed by Russia; fabrication of the 5-stage cables at **VNIIKP** (Podolsk).
- Fabrication of **13 EU PF6 cables** (3 dummies + 10 production lengths) **completed** at the beginning of **2013**,
- **No big issue** during cable manufacturing.



Final cabling stage of a PF6 length

PF conductor: jacketing at Criotec

- PF6/PF1 cables shipped to Criotec for **insertion** and **compaction**.
- Process quite **similar** to that of **TF** conductor. Maximum pulling force around **27 kN** for PF6 cable **insertion**.
- **Dedicated compacting** machine for PF1/6 designed to perform the **square-to-square compaction** (4 rollers).



Compaction (left) and spooling (right) of a PF6 conductor length

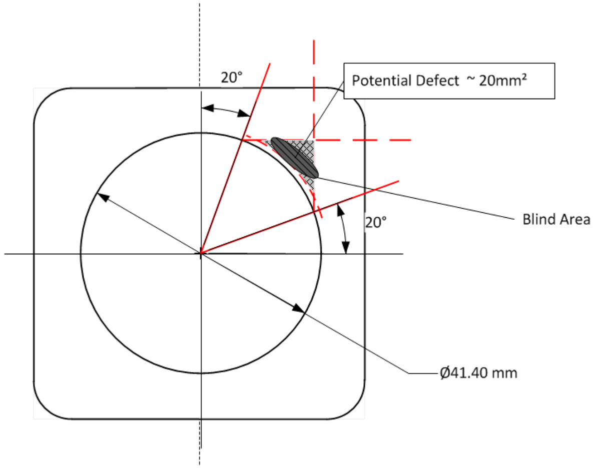
PF conductor jacketing: challenges

Technical challenges

1. PF jacket Non-Destructive Testing (NDT)

Due to the PF jacket section “round-in-square” **geometry** and despite **intensive efforts**, the Phase-Array Ultrasonic Testing (PAUT) had **difficulties** to detect **transverse defects** in **inner** surface **corner** areas; difficulties shared by CN PF and JA CS.

Therefore, an **Eddy Current Testing** (ECT) has been added to **PAUT**. Thanks to collaboration of all parties (SMST, ICAS, ISQ, CERN, IO CT, …) this combined testing provides **adequate solution** but **2** years, many technical discussions and trials to reach that.



PF conductor jacketing: challenges (2)

2. PF jacket assembly: welding

The PF jacket welding is a **complex process** (“round-in-square” **geometry**). Done with an **automatic TIG welding** machine. The welding **semi-automatic** procedure qualification lasted around **1 year**.

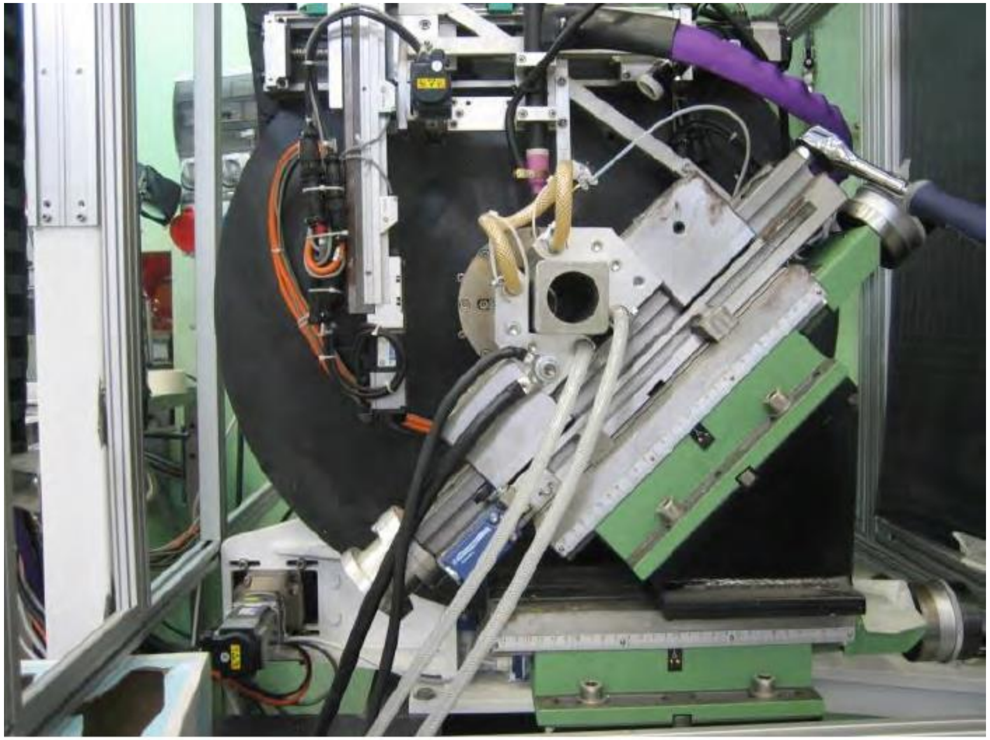


Figure 6. General view of the welding machine

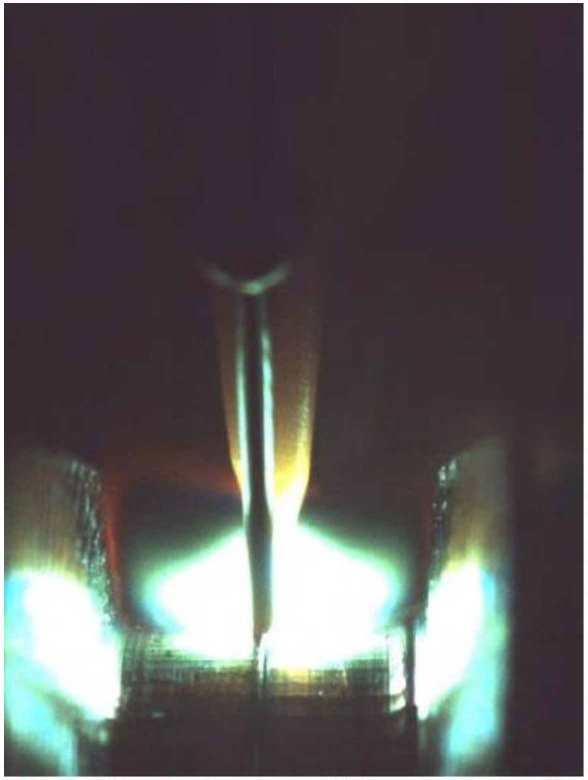


Figure 7b. electrode and filler wire during the very first pass

PF conductor jacketing: challenges (3)

Interface challenges

1. **PF cable storage**

Since the PF1/PF6 **cabling** well in **advance** regards to jacketing schedule **problem of cable storage**. Problem **solved** thanks to an **additional storage** at ICAS and **good will** of RF DA/VNIIKP to **postpone** cable **shipments** to Criotec.

2. **Transportation jigs**

since **no transportation jig** foreseen in the ITER technical specification, around **a year** necessary to **agree** between **all the parties** (ITER, F4E, RF DA, ASIPP, ICAS).

3. **Difficulties with customs**

First shipments of **PF6** conductors to **China** and **PF1** conductors to **Russia** characterized by **problems** during the **customs clearance**.

Some lessons from EU ITER conductors

1. Technical difficulties

- **Qualification** often **longer** than expected (**strand mass production**, **PF welding**),
- ***Be careful*** with Nb_3Sn strand **RRR** and with its **HT environment**!
- **PF** jacket **NDT** procedure should have been addressed in **advance**.

2. Interface issues (international complex project)

- **Storage crucial** (TF strand, cables, conductors): to be accounted for!
- Always **customs** difficulties (OST strand to Italy, PF cables from Russia to Italy, PF1 conductors to Russia and PF6 to China): more ***efforts*** to put on customs (***dedicated person*** on project level for example, organization of dummy shipments in advance),
- ***Interface requirements*** to be well ***defined*** to save time and money (TF/PF transportation jigs).

Conclusions

- The **TF** and **PF** conductor adventure in Europe lasted **9 years** (from **2009** with start of strand production to **2018** with the jacketing of last PF1 length for RF) and **hundreds of technical visits** at suppliers.
- **All TF** conductors already **wound** in 10 Winding Packs at ASG and **5 out of 10 TF coils** completed at SIMIC and **delivered to ITER**:

5th European TF coil delivered to ITER on 3rd of September 2021

Conclusions

- The 18 PF6 lengths have been wound and the **PF6 coil manufactured at ASIPP** (Hefei, China) following a European-China agreement.
- The **PF6 coil** has been shipped to F4E PF coils building in **ITER site** for cold testing (80 K) and final assembly, then **delivered to ITER in January 2021**:

The PF6 coil delivered to ITER in January 2021

Conclusions

- And then, in **April 2021**, **PF6 coil has been lowered into the ITER Tokamak pit**

The PF6 coil lifted for insertion into ITER pit in April 2021

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Last but not least I would like to acknowledge all EU conductor collaborators for their very professional work and collaborative way:

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- CERN
- KIT
- ISQ
- TWI
- RF DA
- ChMP and VNIIKP
- ITER IO

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