A Prototype of Superconducting Solenoid for 50 MW X –band Klystron

A. Yamamoto（KEK and CERN) and S. Michizono (KEK)
W. Wuench, I. Syratchev, G. Mcmonagle, N. Catalan-Lasheras, S. Calatroni, and S. Stapnes (CERN)
H. Watanabe, H. Tanaka, Y. Koga, S. Kido, T. Koga, and K. Takeuchi et al., (Hitachi)
in cooperation with SLAC and CPI

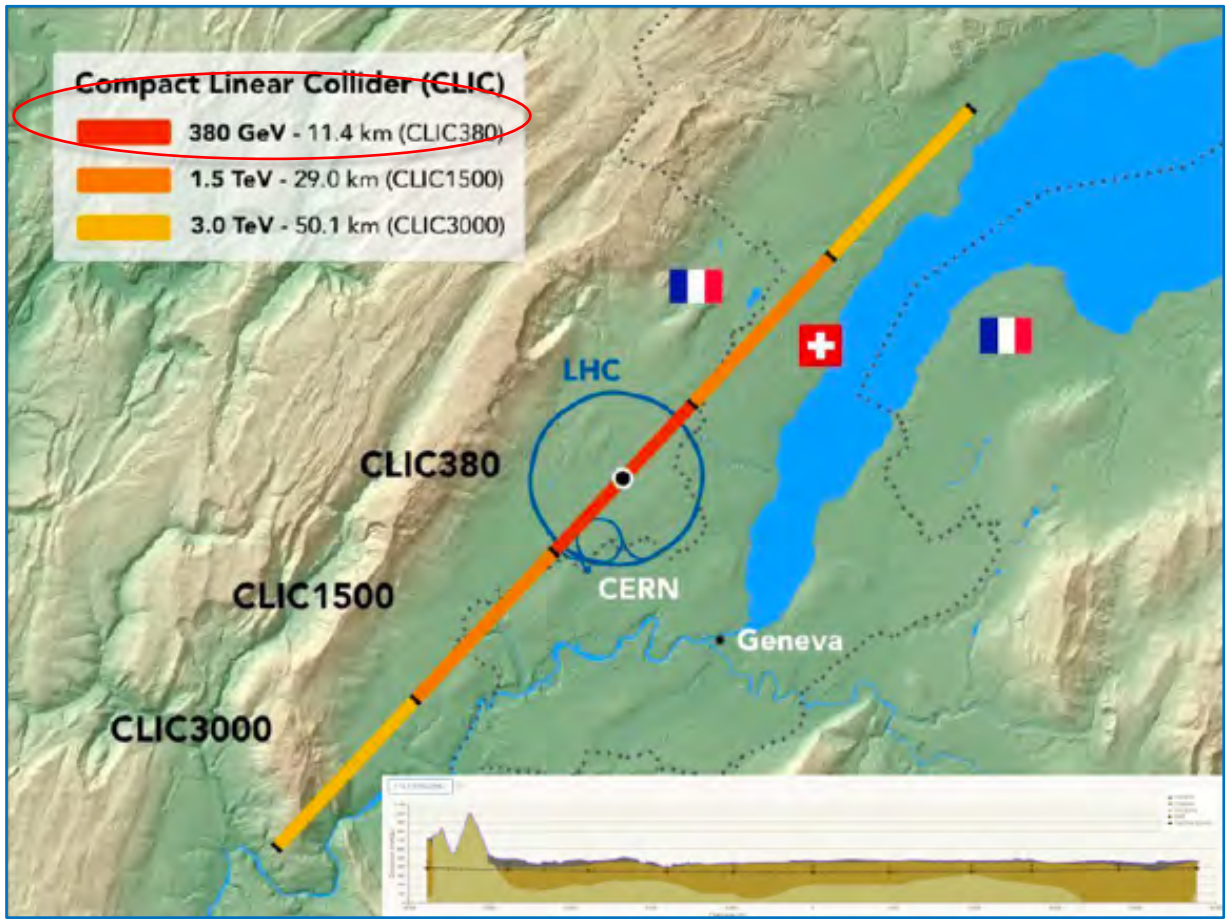
High-efficiency RF Workshop, Uppsala Univ., 18 June., 2019

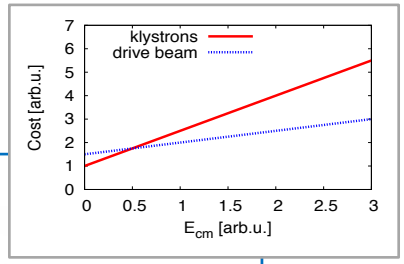
Background and Objectives

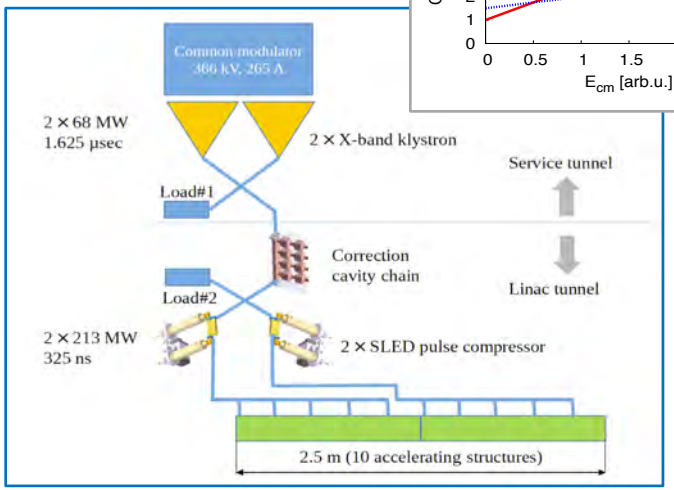
- The CLIC-380 staging scenario being studied at CERN,
- X-band (12 GHz) klystron-based accelerating scheme as a quick option.
- The X-band klystron requiring a beam-focusing solenoid and magnet field:
  - Bc = **~ 0.6** T in a warm bore-diameter of 0.24 m
- A Cu-based solenoid magnet, currently consuming
  - Power of **~20 kW/Klystron**, corresponding to **~ 100 MW** for ~ 5,000 Klystrons for CLIC-380.
- The superconducting magnet option may realize:
  - Power saving down to **< 2 kW**/Klystron (for , corresponding to **~ 10 MW**, for Cryogenics. **--> 90 % power saving**

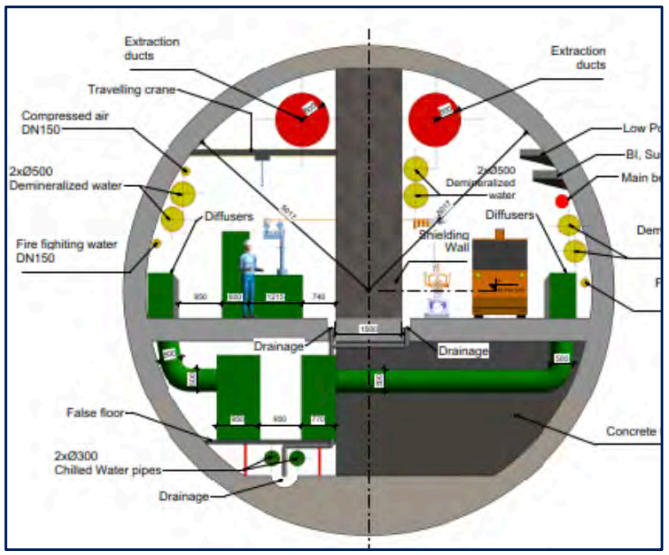
Courtesy: D. Shultz

CLIC Staging Scenario at 380 GeV with X-band Klystrons



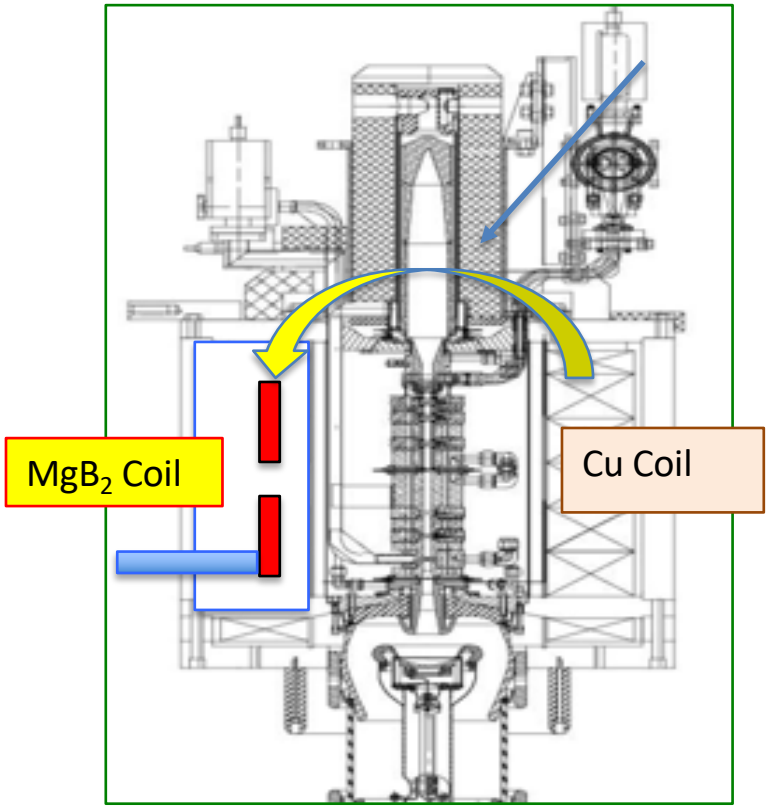




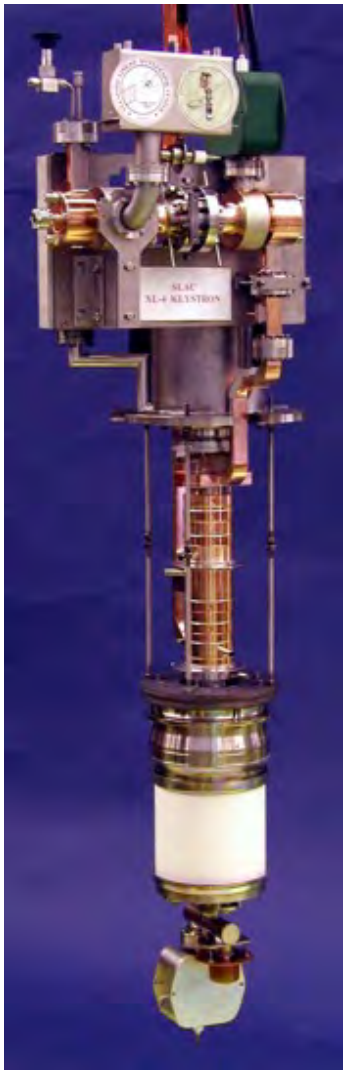


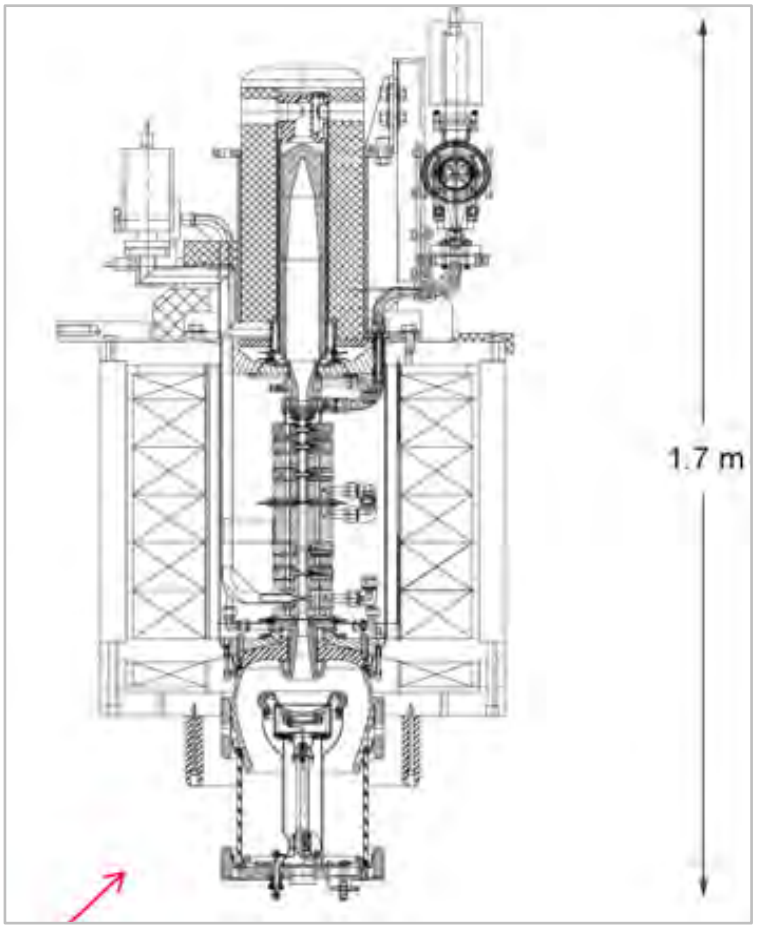
A SC Prototype Magnet proposed

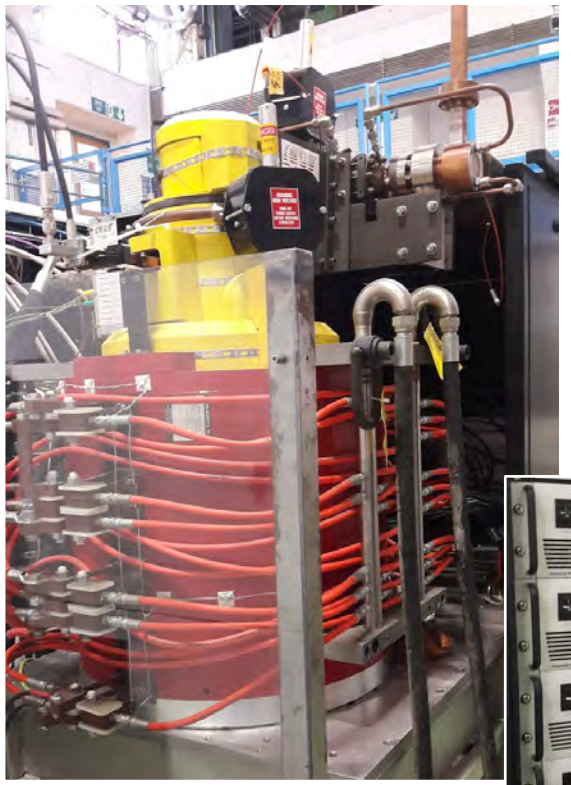
Design Parameters	
Superconductor * (T-operation)	MgB_2 (@ 20 K)
Current	50A/57.1 A (62.8 A)
Central field	0.7 T/0.8 T (0.9 T)
Stored energy	~ 10 kJ
Cryo-cooler applied	6.7 W @ 20 K 13.5 W @ 80 K
AC Plug-Power	≤ 3 kW (< 1,5 kW/Klystron in case of a pair)



X-band Klystron developed in cooperation of SLAC/CPI and CERN





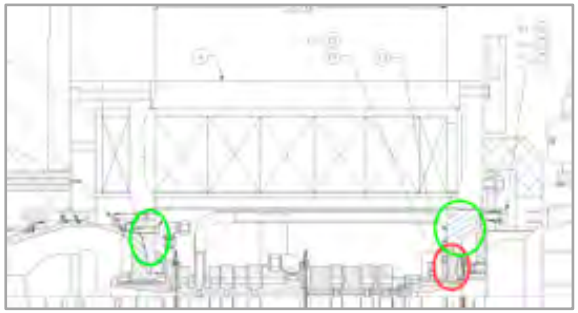


(~35V x 600 A)

F. Peauger *et al.*; A 12 GHz RF PS FOR THE CLIC STUDY; IPAC'10

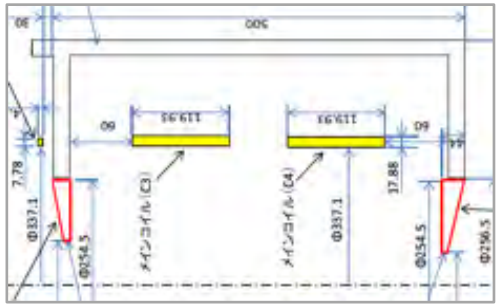
Solenoid: Power : ~ 20 kW,
→ ~ 50 % of total AC-plug Power

Axial Magnetic Field Profile Comparison of Cu and SC Solenoids to be evaluated, soon

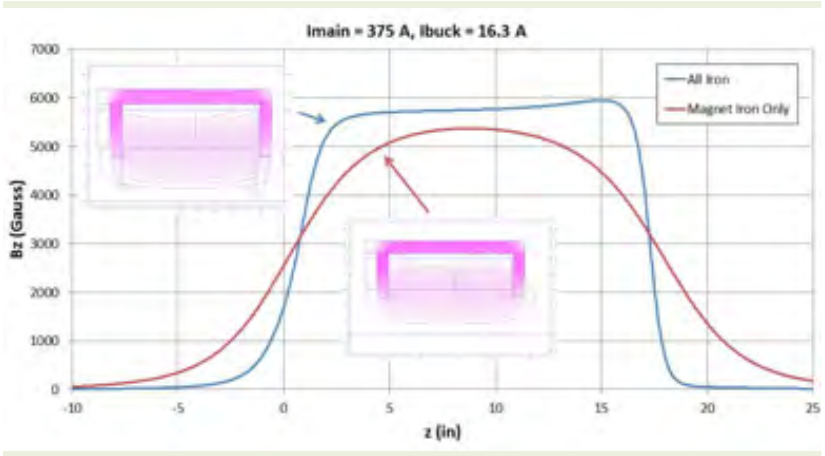


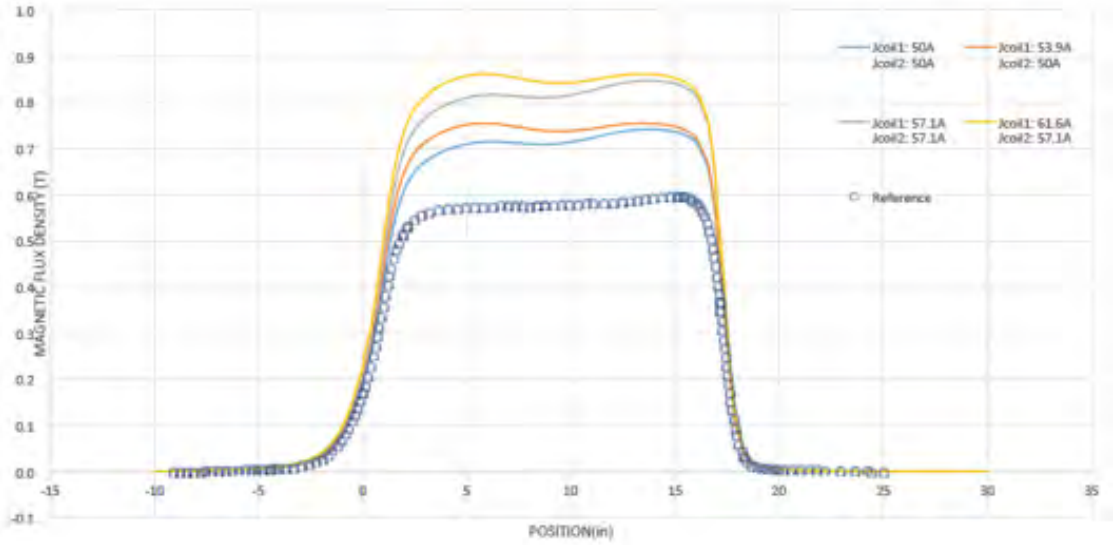
←Cu Solenoid

SC Solenoid →



Courtesy: j. Neilson





Technical Requirements for the Model Magnet

Subjects	Requirements/Parameters	Notes
Superconducting coil:		
Configuration	A twin solenoid	Epoxy-resin Impregnated & cooled by a Cryo-cooler
Central field	0.7 / 0.8 T	Field profile adjustable w/ trim-current in a half-coil
Operational Current	50 / 57.1 A (< 60 A)	Trim current of +/- 6 A in a half coil
Coil Inner Diameter	**340** mm	
Thickness including the coil mandrel	~ 18 mm (< 20 mm)	
Length	~ { 130 + center-gap+130 } mm	
Superconducting wire:		
Material configuration	MgB2 with Cu stabilizer	Cu area ratio > 17 %, and RRR (Cu, 40K) > 15
Insulation	Glass-braid	Adaptable for impregnation and heat-treatment
Heat treatment after coil-winding	600 deg. C, in Ar gas, for 12 hours	Required after coil winding
Cryostat:		
Warm bore diameter	**256** (+4, -0) mm	St. Steel, inner cylinder, for klystron installation
Outer diameter	628 (+/- 3) mm	Iron, yoke functioning as magnetic field returning
Length	516 (+/- 2) mm	
Cryo-cooler:		
Cold head	> 4 W @ 20 K, > 8W @ 80 K	SHI, CH204
Compressor	AC power < 3 kW, air-cooled	SHI, Zephyr

Progress in 2018/2019

2018:

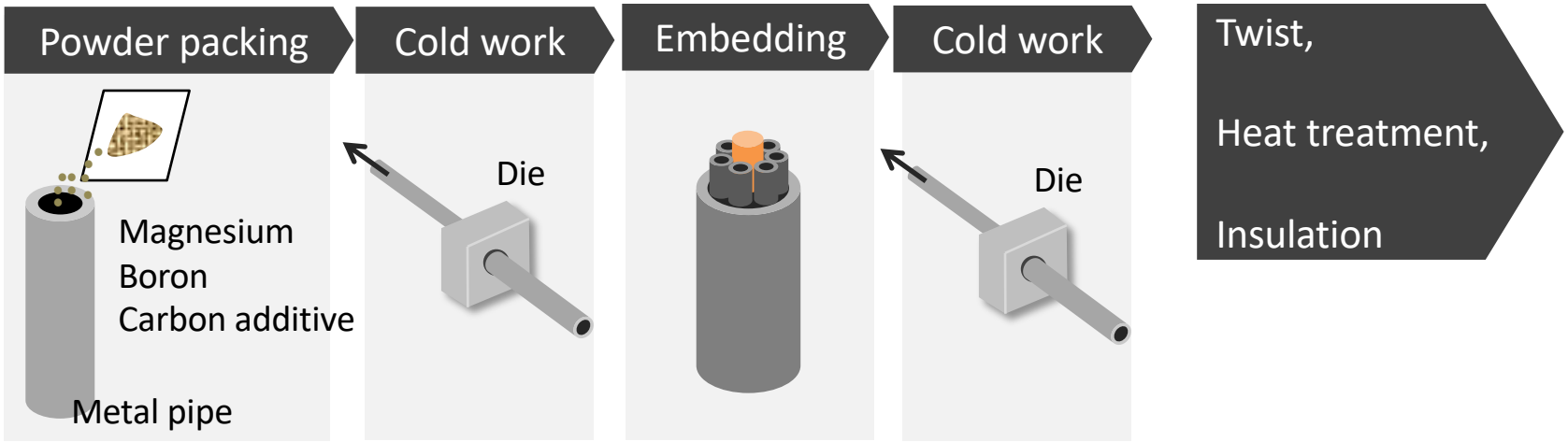
- **Jan:** MgB2 conductor fabrication started,
- **May:** A model magnet fabrication started,
- **Aug:** MgB2 conductor fabrication completed, including the performance test
  - Confirming $I_{op} \geq 50$ A, at 0.7 T, ≥ 20 K.
- **Sept:** Coil-winding started,
- **Oct:** Coil-winding and heat-treatment completed.
- **Nov:** Epoxy-resin impregnation
- Dec: Coil assembled with Cryostat and Cryocooler
- Dec: Magnet system complete, and Cool-down start

2019:

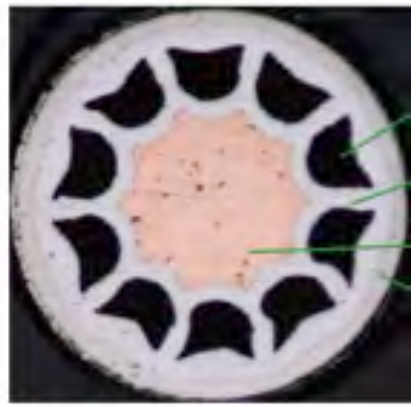
- Jan: Coil reached 16 K, and the 1st excitation reached Bc = 0.9 T, I = 62 A (max)
- Jan: Cryocooler failure and the investigation in progress.
- Feb: Acceptance tests including the full excitation up to Bc ≥ 0.9 T, field profile measurement, a quench-test at Tc ≥ 28 K, and emergency-safety test, with CERN participation.

MgB_2 Conductor Manufacturing Process

Powder in Tube (PIT) method

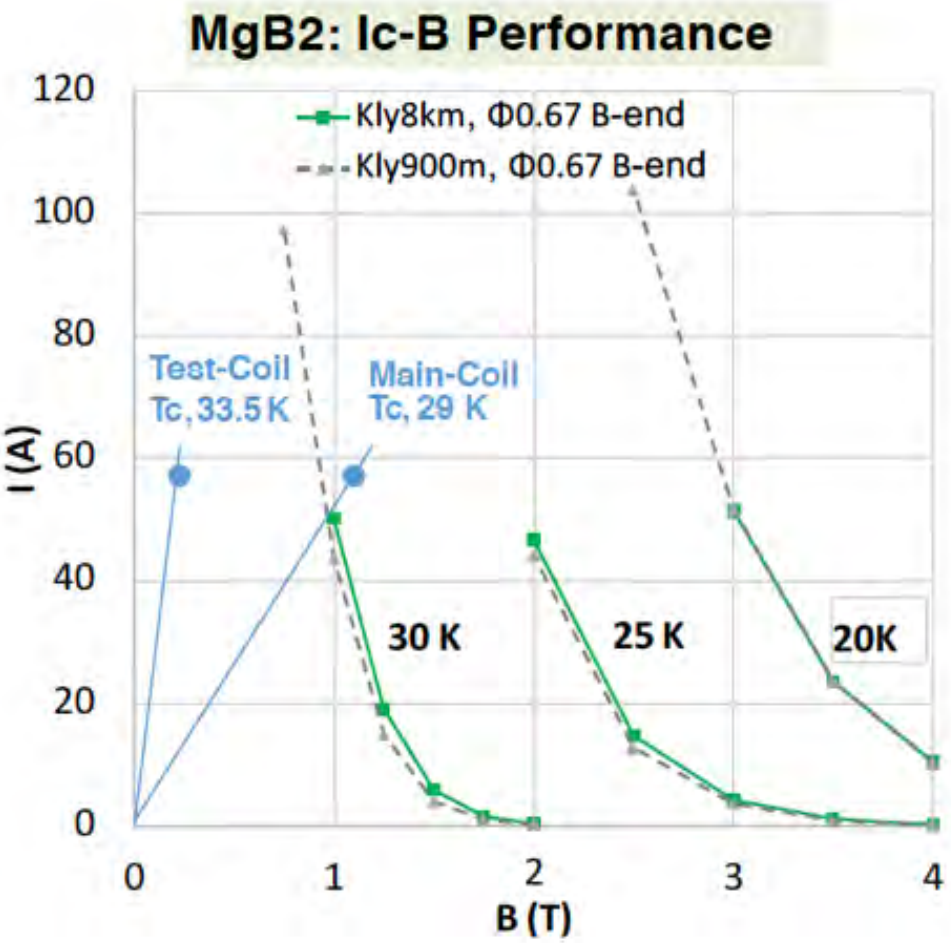


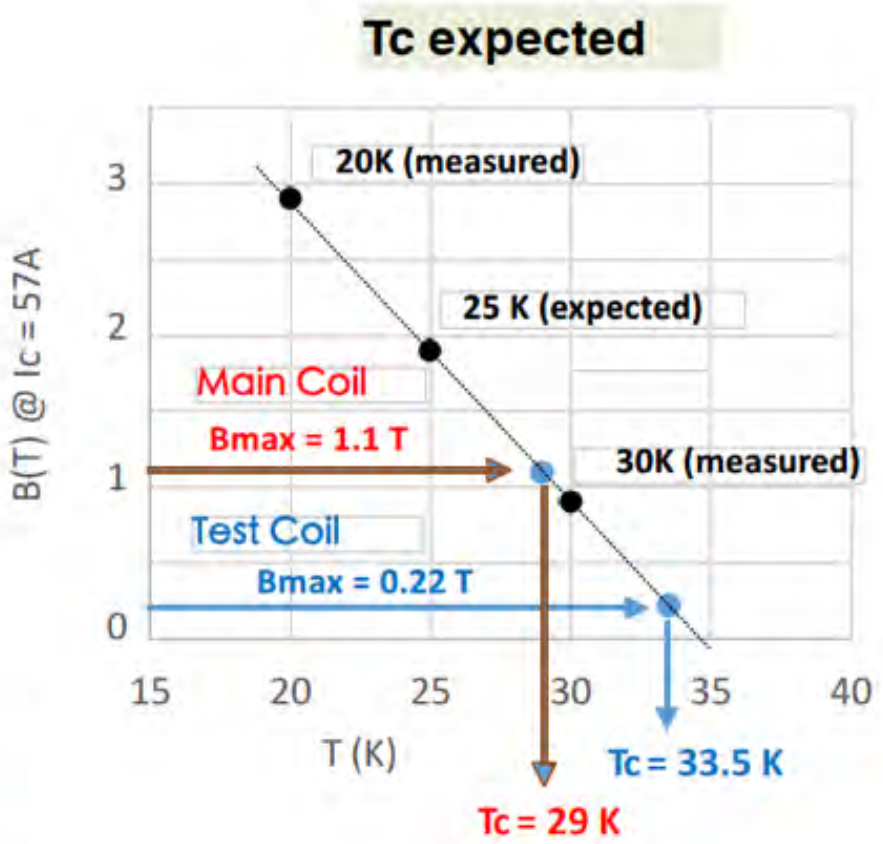
	Hitachi, *in situ Process*
Powder	Mg + B + additive
Metal pipe & rod	Cu, Fe, Ni
Heat treatment temp.	Typically 600℃
W&R or R&W	Mainly Wind & React
Insulation	Glass braid



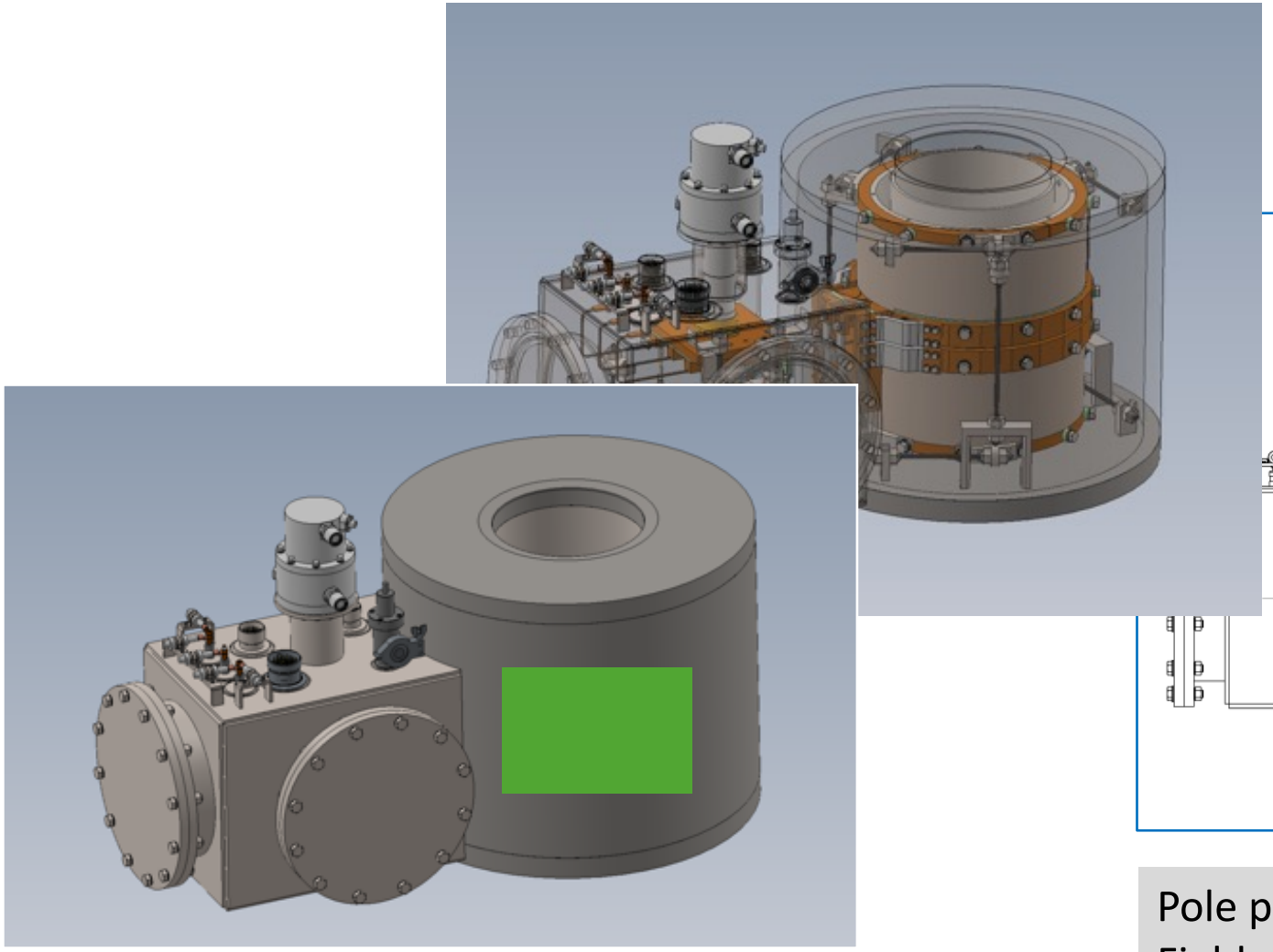
Φ0.67 MgB_2

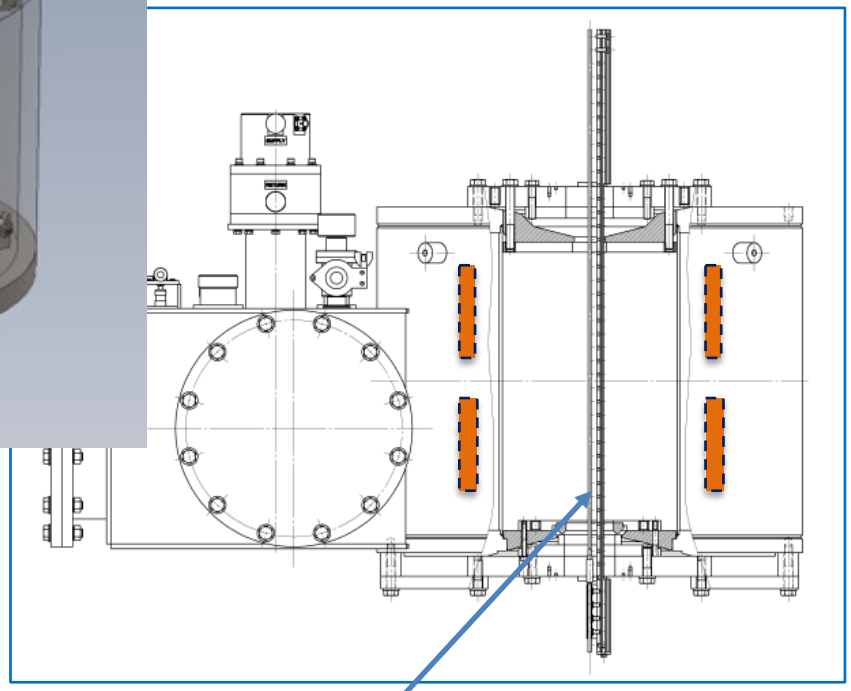
Hitachi, MgB2 Conductor Performance





Prototype Coil Assembly with Cryostat functioning as Flux-rerun Iron Yoke and Cryo-cooler

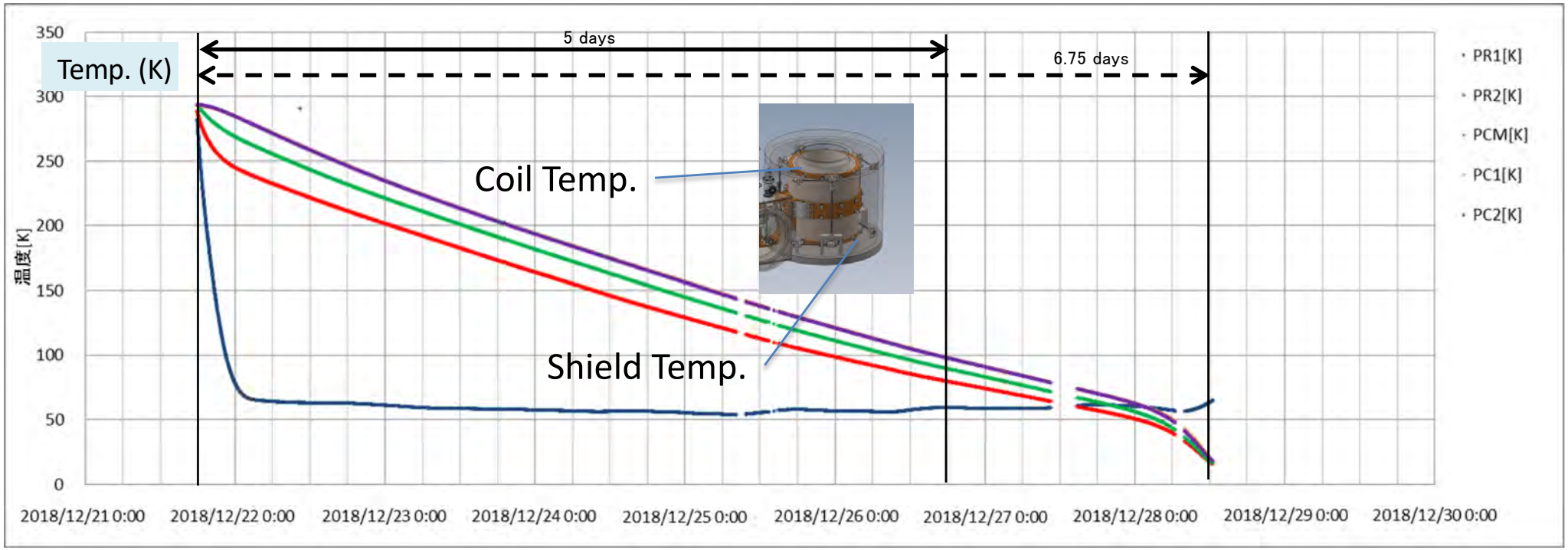




Pole pieces, and
Field profile measurement setup

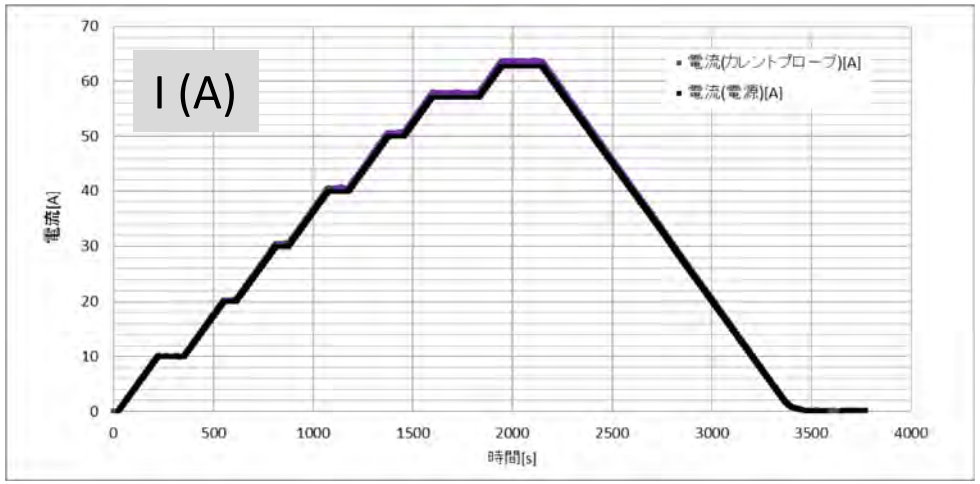
Solenoid Coil Cool-down by using Cryocooler

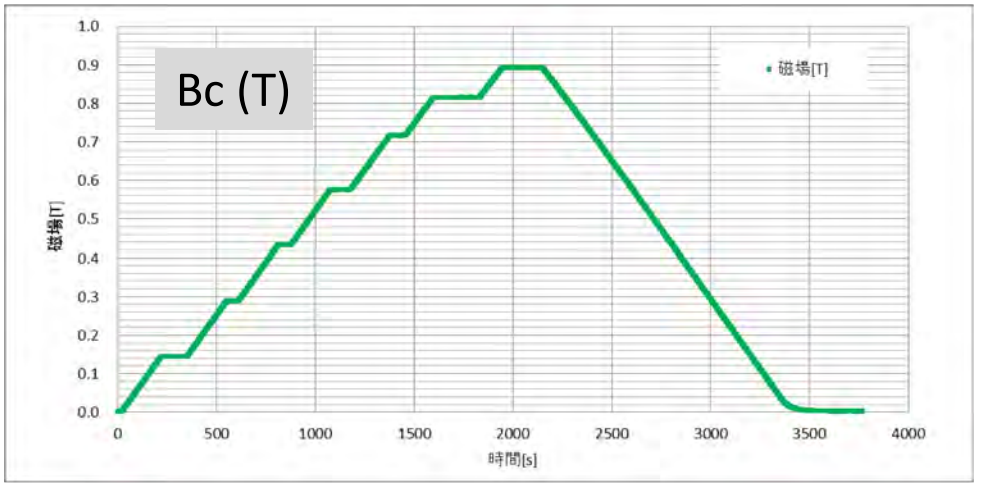
in < 7 days

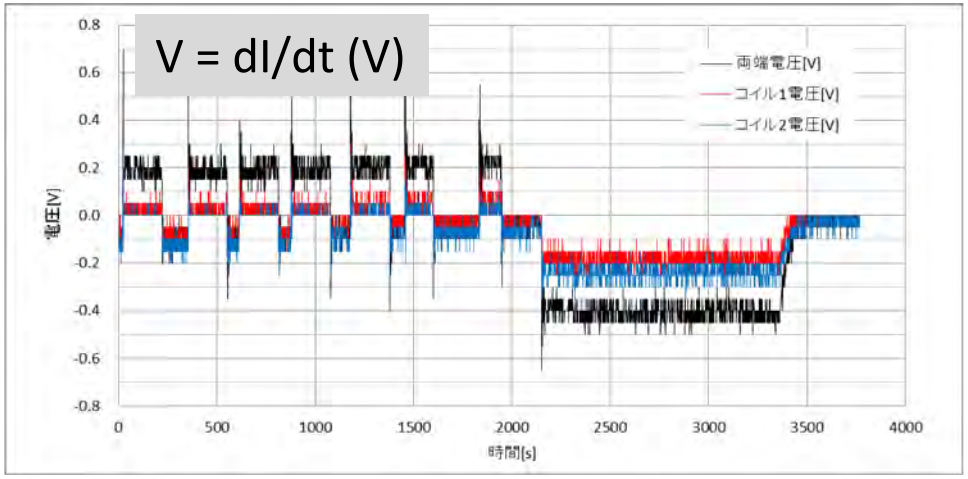


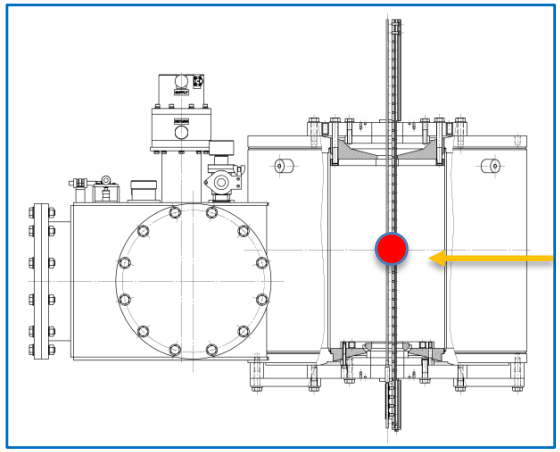
Time: (yr/mm/dd/hr)

Solenoid Excitation Test
B_c reached 0.9 T @ I = 62.7 A, 16 K

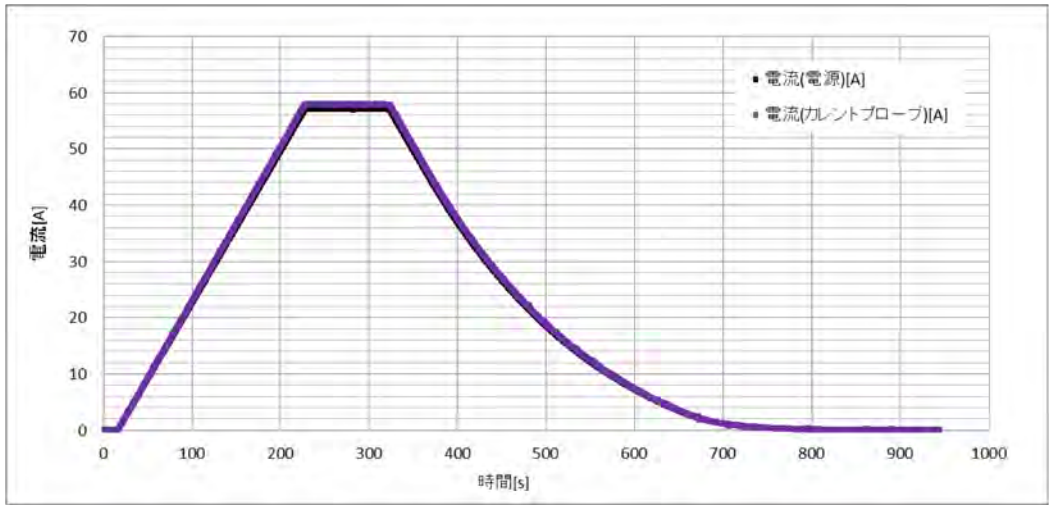


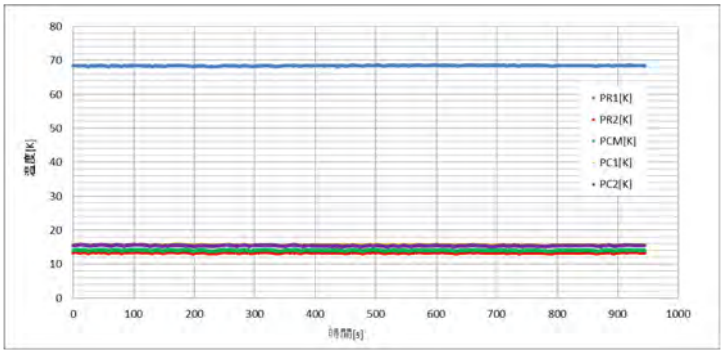


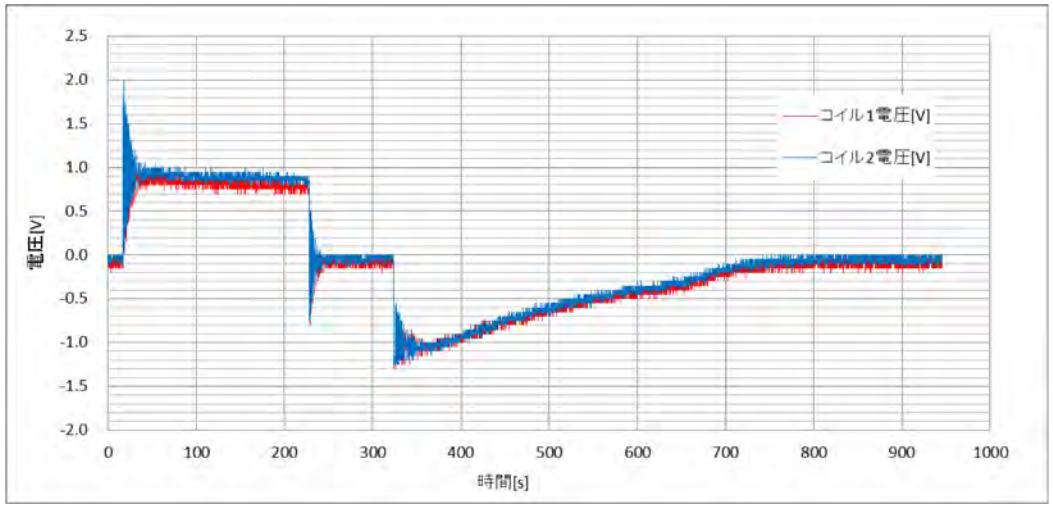




Excitation within 4 min. for ramping-up

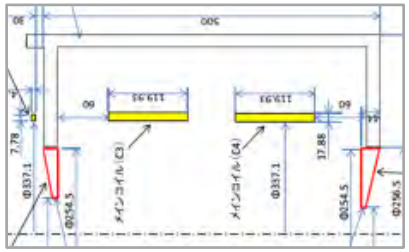


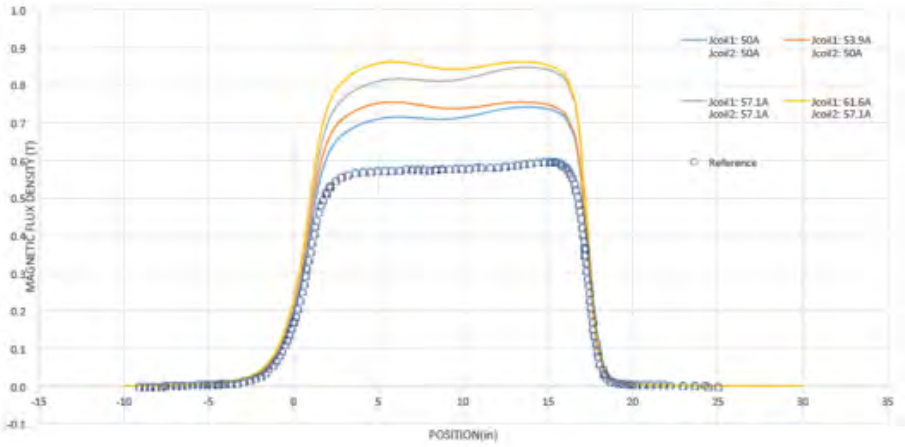




Temperature kept constant at 16 K

Field Profile Measurement





Expected

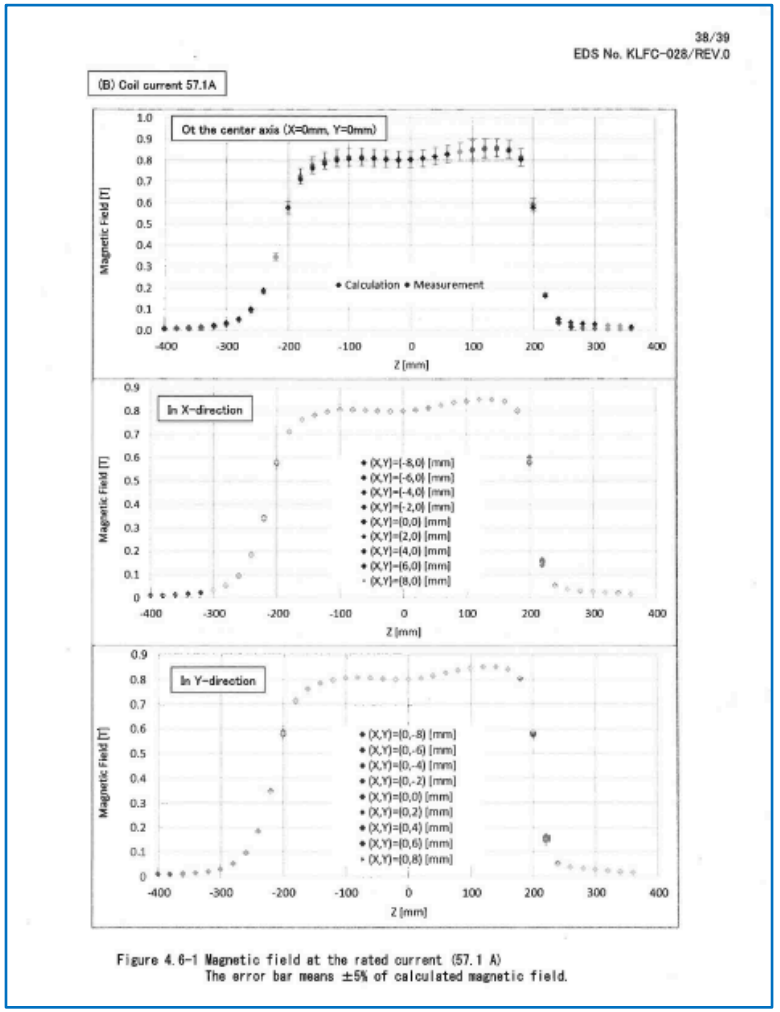


Figure 4.6-1 Magnetic field at the rated current (57.1 A)
The error bar means ±5% of calculated magnetic field.

Measureed

Quench Test w/ raising Coil Temperature at Bc = 0.8 T, I = 57 A, Tc = 29 K

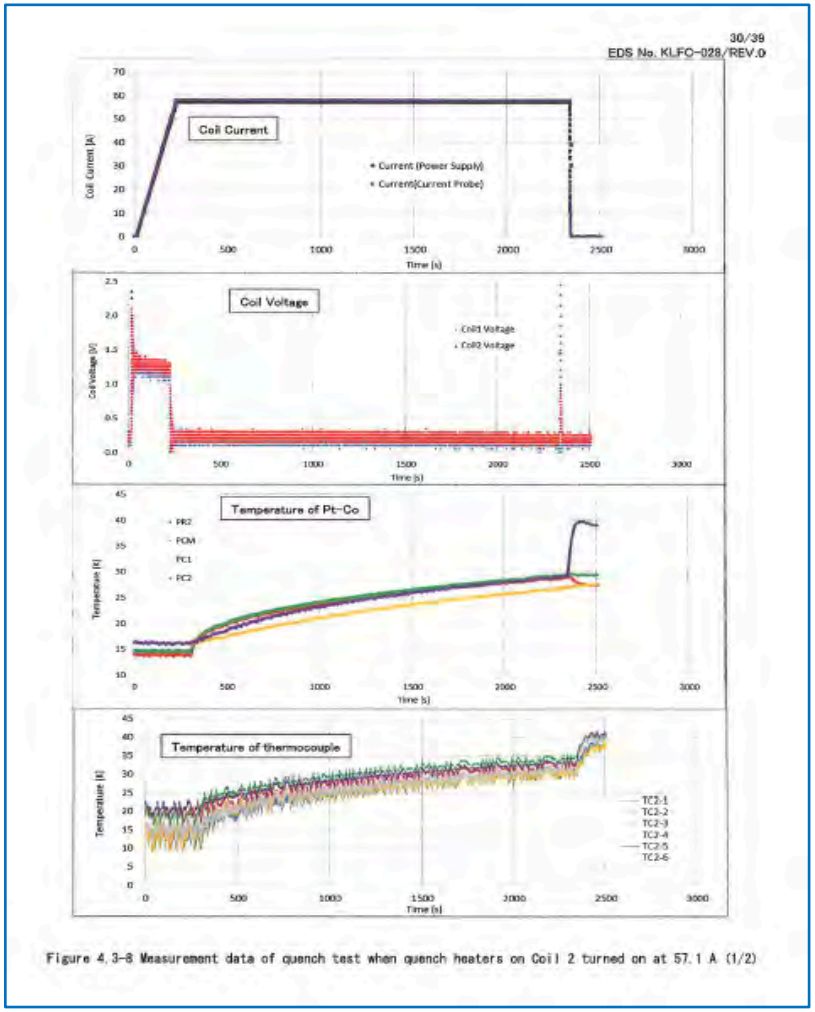


Figure 4.3-8 Measurement data of quench test when quench heaters on Coil 2 turned on at 57.1 A (1/2)

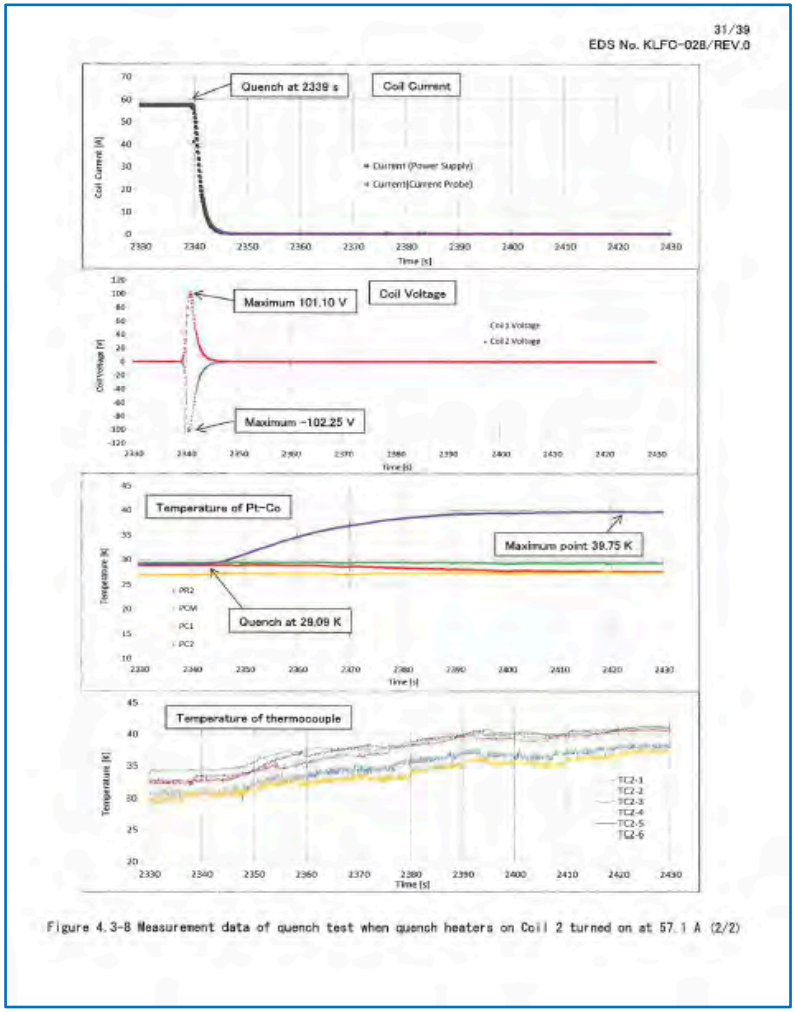


Figure 4.3-8 Measurement data of quench test when quench heaters on Coil 2 turned on at 57.1 A (2/2)

Quench Test w/ raising Coil Temperature at Bc = 0.9 T, I = 63 A, Tc = 28 K

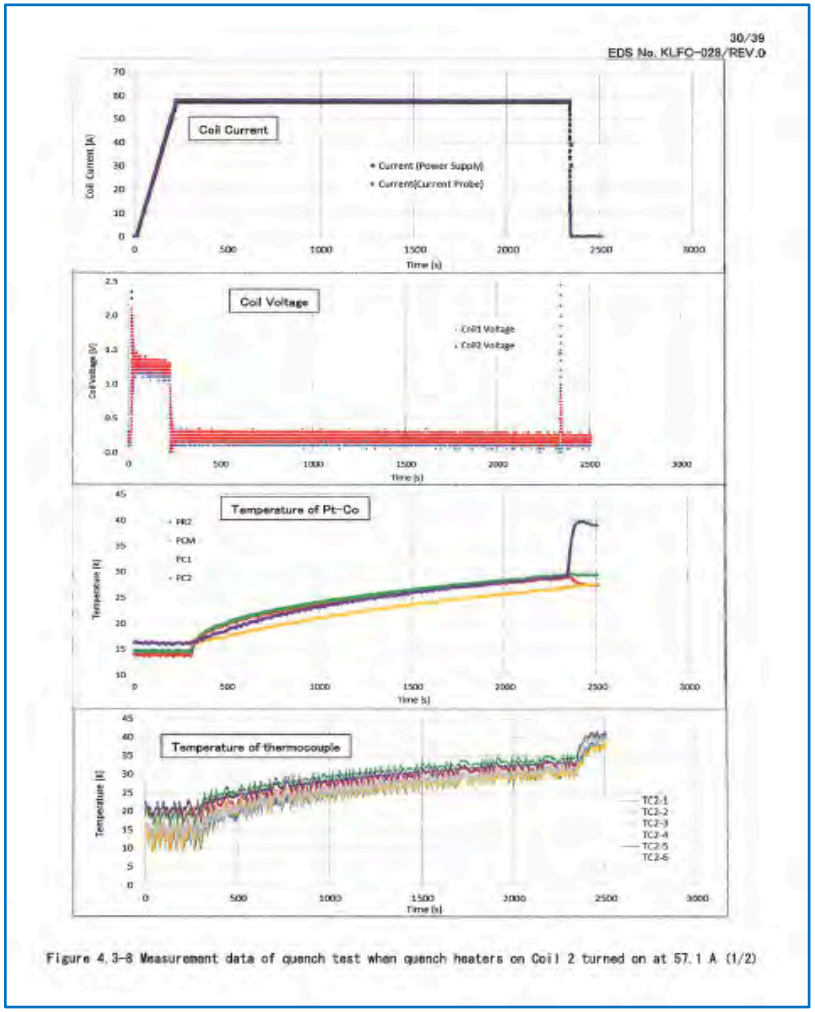


Figure 4.3-8 Measurement data of quench test when quench heaters on Coil 2 turned on at 57.1 A (1/2)

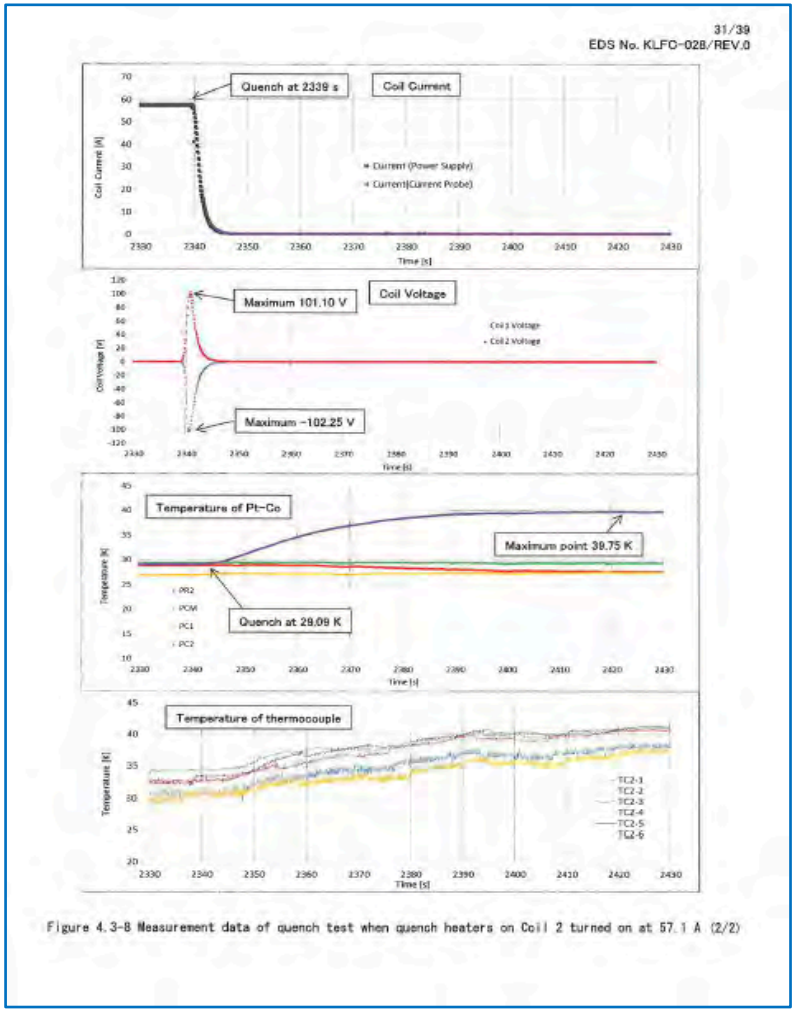
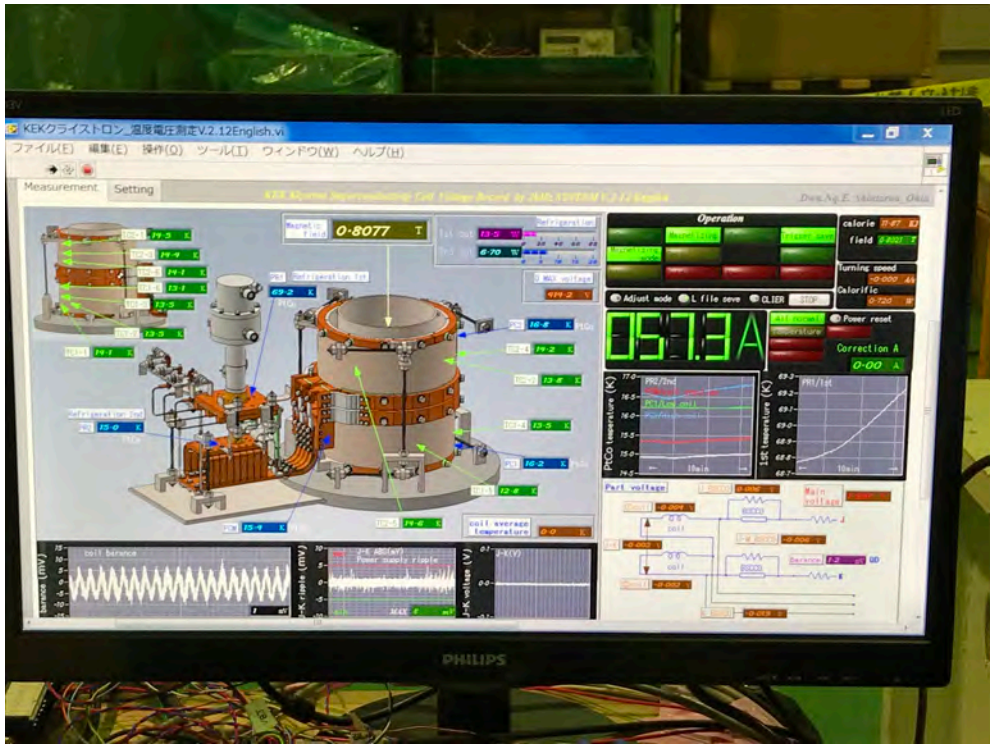
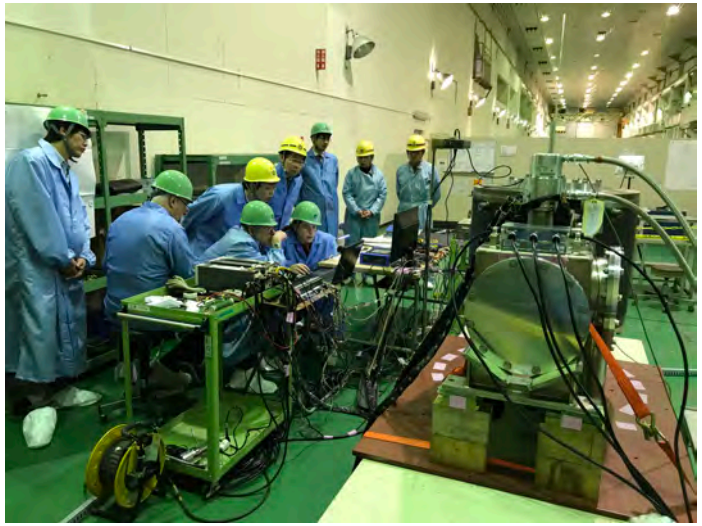


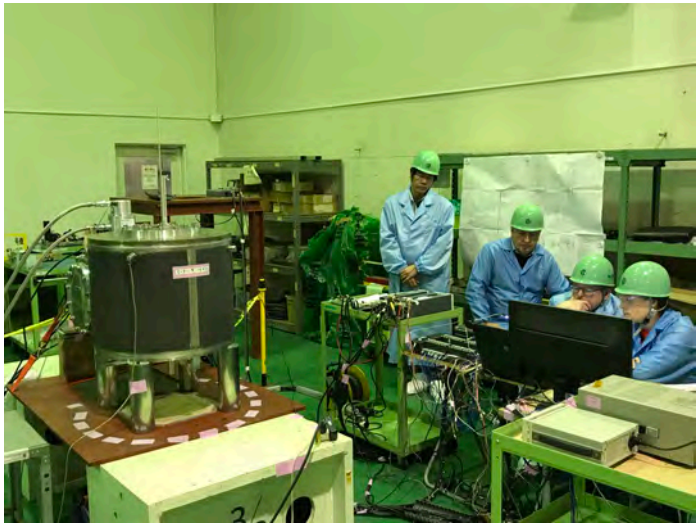
Figure 4.3-8 Measurement data of quench test when quench heaters on Coil 2 turned on at 57.1 A (2/2)

Acceptance Test at Hitachi
14 – 15 Feb., 2019



Acceptance Test at Hitachi
14 – 15 Feb., 2019





Acceptance Test at Hitachi
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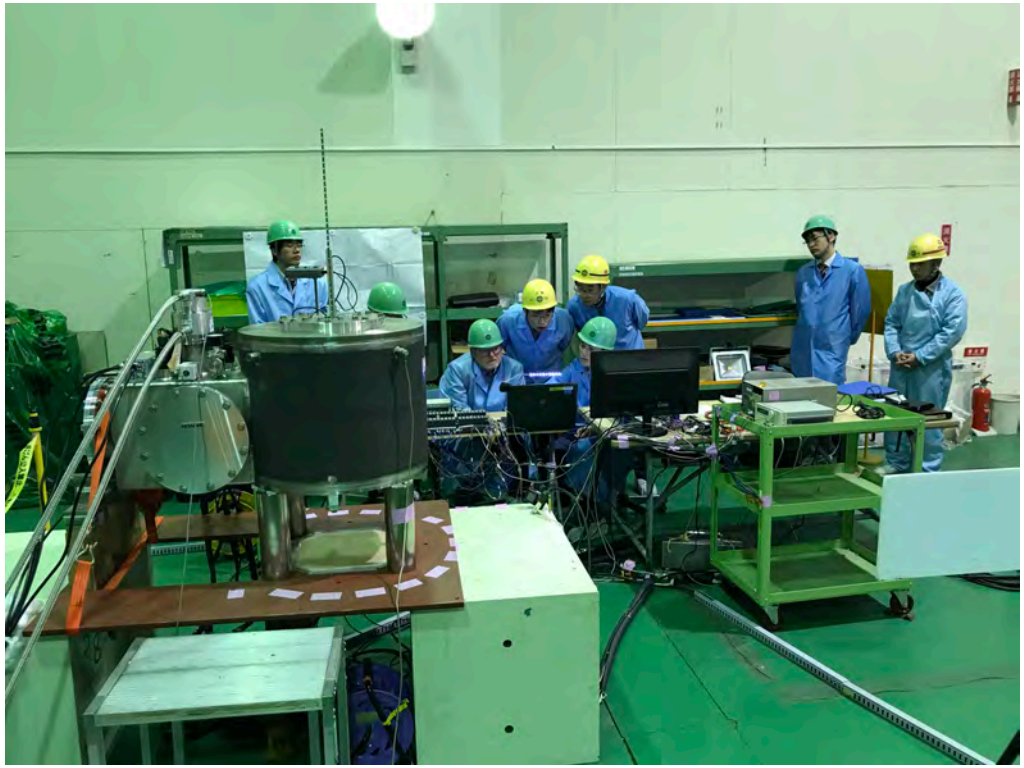
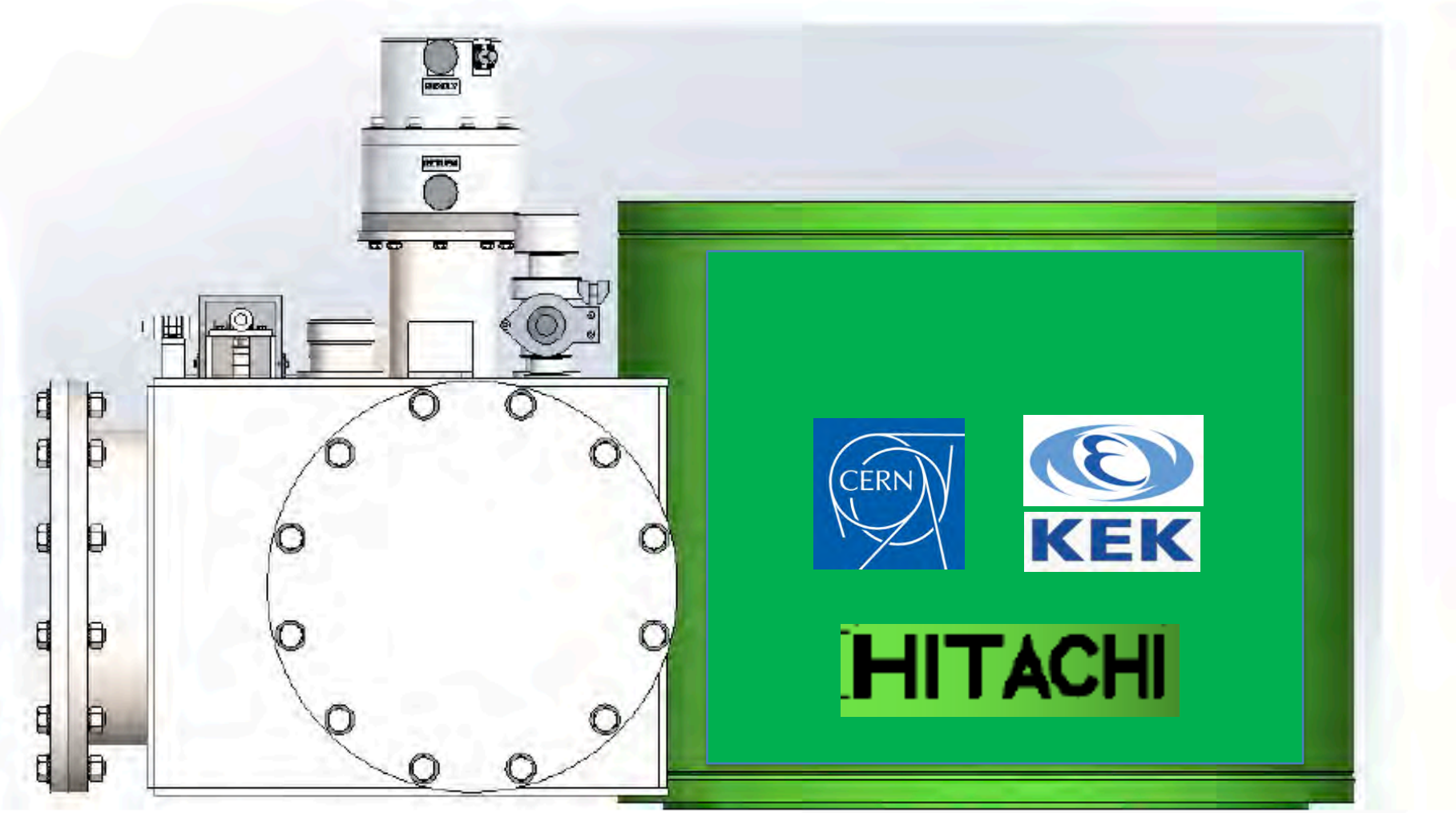


Acceptance Test Completed
15 Feb.. 2019

Logos: an update discussed

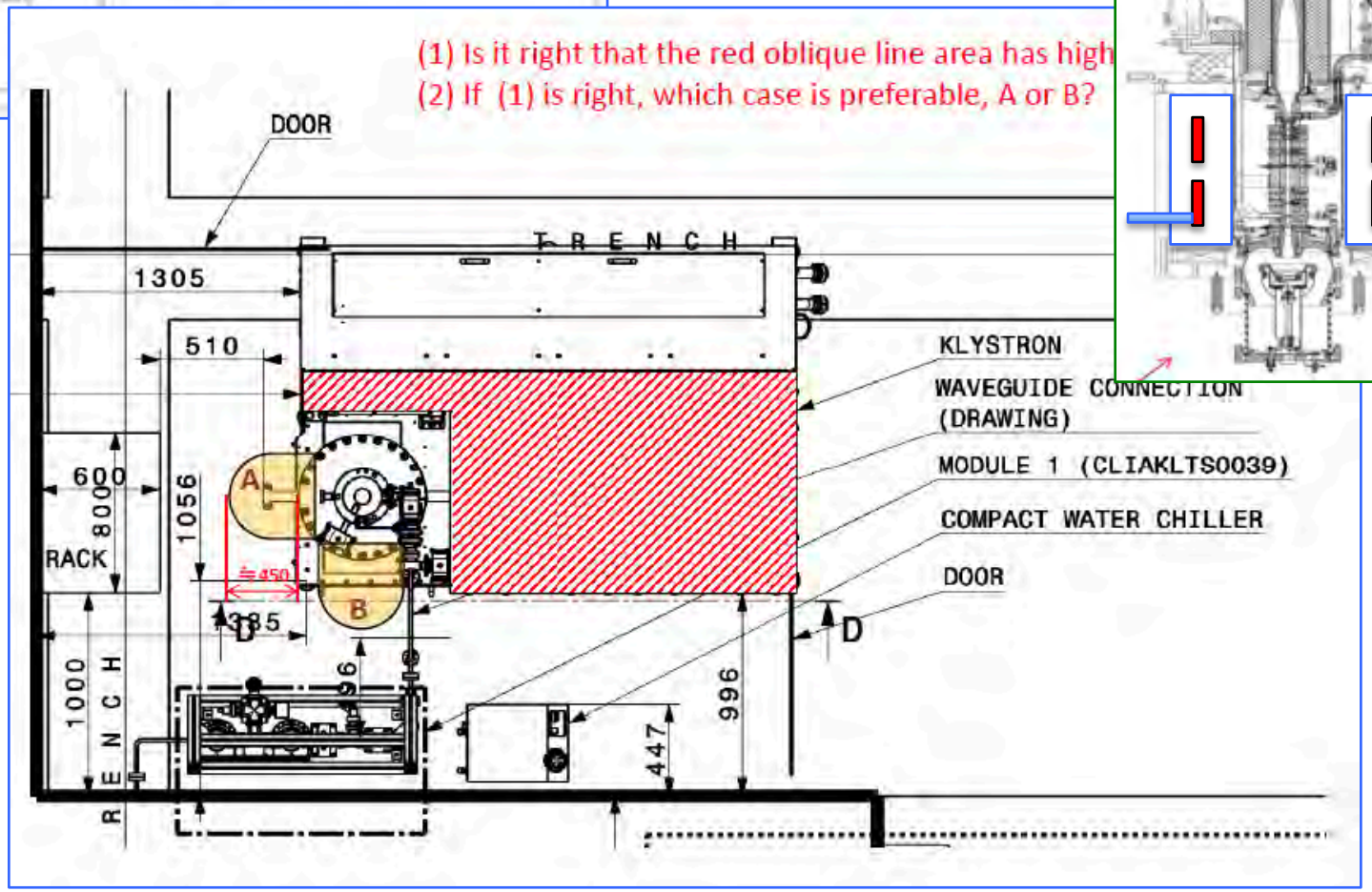


Locations: One on cylindrical yoke, and one on Service box (for different angles

Logo sizes: CERN, KEK : ~ 100 x 100 mm^2

Hitachi: ~ 35 x 200 mm^2 (to be discussed w/ Hitachi)

e Klystron at the
ental hall



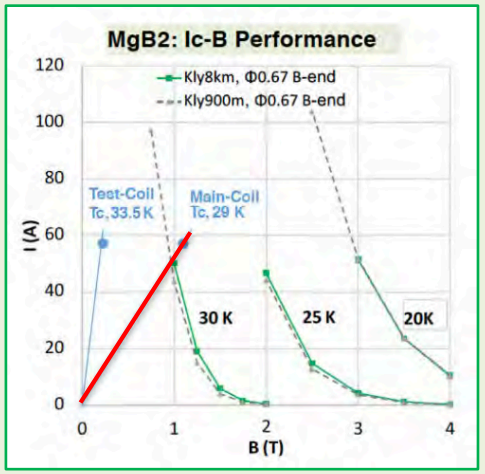
Summary: Development of a Superconducting Solenoid for X-band Klystron beam-focusing

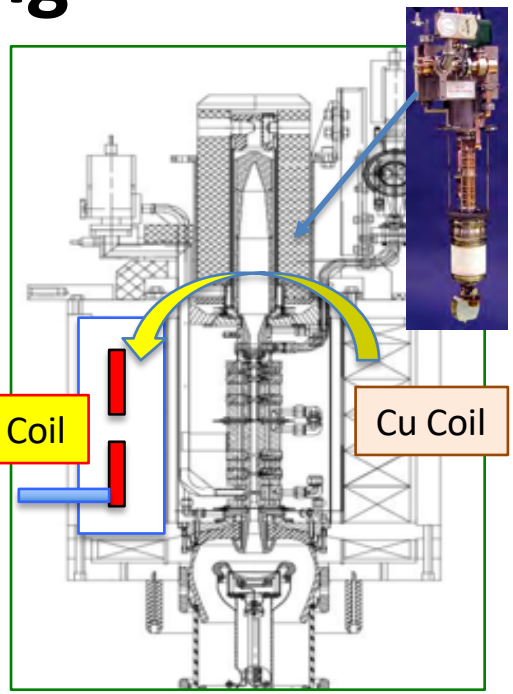
Objective

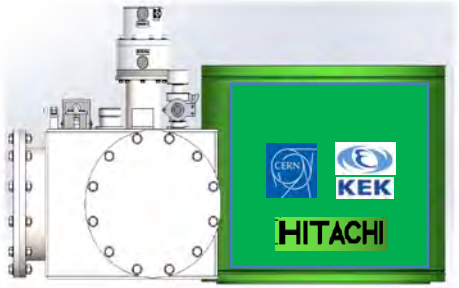
- SC-mag technology to be demonstrated for high-efficiency X-band Klystron for future applications

Prototype SC Magnet Design:

- Superconductor: **MgB_2**
- B_c: > **0.7 T** (at a warm bore aperture of ~ 0.24 m)
- T-operation: **20 K** or higher
- AC-plug power: < 3 kW
  - → **< 1.5 KW / Klystron, by pairing**
  - → **< 1/10 AC-power of Cu-Coil**







Progress and Further Plan:

- MgB_2 conductor performance confirmed,
- Magnet fabrication completed,
- Magnet Performance: **B_c = 0.9 T. at Tc =28 K, (AC-plug = 2.8 kW)**
- Performance to be evaluated, with Klystron, at CERN in 2019.

Appendix

Cold-Head Performance Required

CH-204 10K CRYOCOOLER SERIES

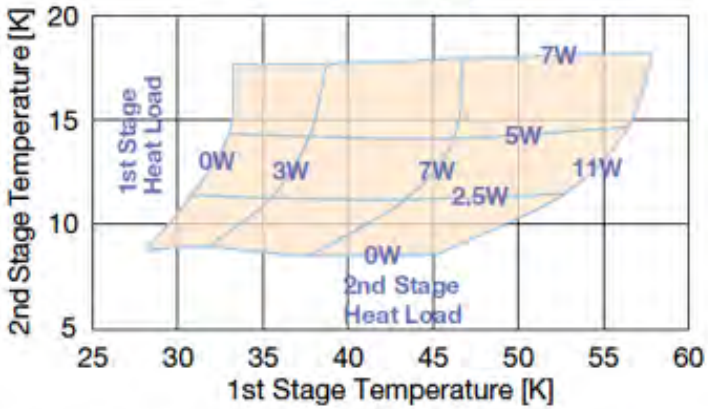
Performance Specifications

Power Supply Hz	50	60
2nd Stage Capacity Watts @ 20 K	6.7	7.1
1st Stage Capacity Watts @ 80 K	13.5	16.2
Maximum 2nd Stage Capacity Watts @ 20 K (No 1st Stage Load)	7.5	9.0
Cooldown Time to 20 K Minutes	35	30
Weight kg (lbs.)	7.8 (17.2)	
Maintenance Hours	13,000	

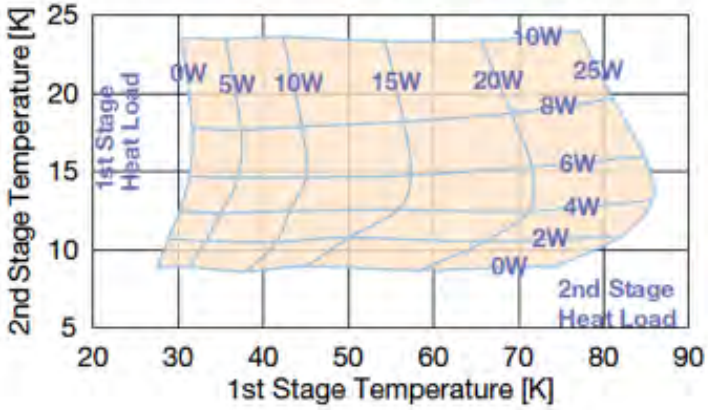
Standard Scope of Supply

- CH-204 Cold Head
- Zephyr®, HC-4E1, HC-8E4 or F-70L/H Compressor
- 3 m (10 ft.) Helium Gas Lines
- 3.5 m (11 ft.) Cold Head Cable
- Tool Kit

CH-204 Cold Head Capacity Map (50 Hz)



CH-204 Cold Head Capacity Map (60 Hz)



Cryo-Cooler Performance Required

COMPRESSOR OPTIONS

All SHI Cryocoolers and Pulse Tubes are driven by highly-efficient and reliable helium compressors. These compressors boast industry-leading 20,000 or 30,000 hour maintenance intervals, and are available in single-phase and three-phase, low and high voltage, and water and air-cooled versions.

To find the most compatible compressor for your cryocooler or pulse tube system, please refer to the individual product specifications in this catalogue or contact your local SHI Cryogenics Group sales office.

Compressor Model	HC-4E1	CKW-21A	HC-8E4	F-50		F-70		
				L	H	LP	L	H
Cooling	Water Cooled	Water Cooled	Water Cooled	Water Cooled		Water Cooled		
Electrical Supply	1 Phase 200 V, 230/240 V, 50 Hz 208/230 V, 60 Hz	3 Phase 200 V, 50/60 Hz	3 Phase 220 V, 50 Hz 220/230 V, 60 Hz	3 Phase 200 V, 50/60 Hz	3 Phase 380, 400, 415 V, 50 Hz 480 V, 60 Hz	3 Phase 200 V, 50/60 Hz		3 Phase 380-415 V, 50 Hz 480 V, 60 Hz
Power Consumption*	2.6 kW at 50 Hz 3.0 kW at 60 Hz	2.7-3.3 kW at 50 Hz 3.5-4.0 kW at 60 Hz	3.7 kW at 50 Hz 4.3 kW at 60 Hz	6.5-7.2 kW at 50 Hz 7.5-8.3 kW at 60 Hz		6.7-7.2 kW at 50 Hz 8.0-8.5 kW at 60 Hz	6.6-6.9 kW at 50 Hz 7.5-7.8 kW at 60 Hz	
Ambient Temperature	4-40 °C (40-104 °F)	5-35 °C (41-95 °F)	4-40 °C (40-104 °F)	5-35 °C (41-95 °F)		4-40 °C (40-104 °F)		
Cooling Water (Inlet)	2.7 L/min. (0.7 gal./min.) 4-27 °C (40-80 °F)	3.0-3.5 L/min. (1.8 gal./min.) 28 °C (82 °F)	5.7-9.5 L/min. (1.5-2.5 gal./min.) 4-21 °C (40-70 °F)	7-10 L/min. (1.8 gal./min.) 28 °C (82 °F)		6-9 L/min. (1.6-2.4 gal./min.) 5-25 °C (41-77 °F)		
Cooling Air	N/A	N/A	N/A	N/A		N/A		
Dimensions (HxWxD)	504 x 430 x 485 mm (19.8 x 16.9 x 19.1 in.)	461 x 400 x 450 mm (18.1 x 15.7 x 17.7 in.)	504 x 430 x 485 mm (19.8 x 16.9 x 19.1 in.)	591 x 450 x 588 mm (23.3 x 17.7 x 23.2 in.)		532 x 443 x 493 mm (20.9 x 17.4 x 19.4 in.)		
Weight	75 kg (165 lbs.) 82 kg (180 lbs.) w/ transformer	70 kg (155 lbs.)	75 kg (165 lbs.)	120 kg (264 lbs.)		100 kg (225 lbs.)		
Maintenance	30,000 Hours	20,000 Hours	30,000 Hours	30,000 Hours		30,000 Hours		

* Typical power consumption

CNA-11		Zephyr*	CNA-31		CSA-71A	CNA-61	
B	C		C	D		C	D
Air Cooled		Air Cooled	Air Cooled		Air Cooled	Air Cooled	
1 Phase 100 V, 50/60 Hz	1 Phase 100, 120, 220, 230, 240 V, 50/60 Hz	1 Phase 200 V, 220 V, 230/240 V, 50 Hz 220 V, 60 Hz	3 Phase 200 V, 50/60 Hz	3 Phase 380, 400, 415 V, 50 Hz 460, 480 V, 60 Hz	3 Phase 200 V, 50/60 Hz	3 Phase 200 V, 50/60 Hz	3 Phase 380, 400, 415 V, 50 Hz 460, 480 V, 60 Hz
1.2-1.3 kW at 50 Hz 1.3-1.5 kW at 60 Hz		3.0 kW at 50 Hz 3.4 kW at 60 Hz	3.8-4.6 kW at 50 Hz 4.8-5.6 kW at 60 Hz		6.5-7.2 kW at 50 Hz 7.5-8.3 kW at 60 Hz	7.5-8.0 kW at 50 Hz 8.5-9.2 kW at 60 Hz	
4-38 °C (39-100 °F)		4-32 °C (40-90 °F)	4-38 °C (39-100 °F)		5-35 °C (41-95 °F)	5-35 °C (41-95 °F) - Indoor 30-45 °C (22-113 °F) - Outdoor	
N/A		N/A	N/A		N/A	N/A	
2.7 m³/min. (95 cfm), 50 Hz 3.3 m³/min. (117 cfm), 60 Hz		20 m³/min. (706 cfm), 50/60 Hz	20.1 m³/min. (710 cfm), 50 Hz 23.0 m³/min. (812 cfm) 60 Hz		28 m³/min. (989 cfm), 50/60 Hz	29.7 m³/min. (1049 cfm), 50 Hz 29.8 m³/min. (1052 cfm), 60 Hz	
400 x 390 x 450 mm (15.7 x 15.3 x 17.7 in.)	610 x 390 x 450 mm (24.0 x 15.4 x 17.7 in.)	715 x 453 x 488 mm (28.2 x 17.8 x 19.2 in.)	901 x 520 x 520 mm (35.5 x 20.5 x 20.5 in.)		885 x 550 x 550 mm (34.8 x 21.7 x 21.7 in.)	630x270x570 mm (24.8 x 10.6 x 22.4 in.) 1050x910x400 mm (41.3 x 35.8 x 15.7 in.)	705x270x610 mm (27.8 x 10.6 x 24.0 in.) 1050x910x400 mm (41.3 x 35.8 x 15.7 in.)
42 kg (93 lbs.)	75 kg (165 lbs.)	102 kg (225 lbs.) 111 kg (245 lbs.) w/ transformer	95 kg (210 lbs.) 104 kg (229 lbs.)		140 kg (309 lbs.)	45 kg (99 lbs.)/ 115 kg (254 lbs.)	55 kg (121 lbs.)/ 115 kg (254 lbs.)
30,000 Hours		30,000 Hours	30,000 Hours		20,000 Hours	20,000 Hours	