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

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in cooperation with SLAC and CPI

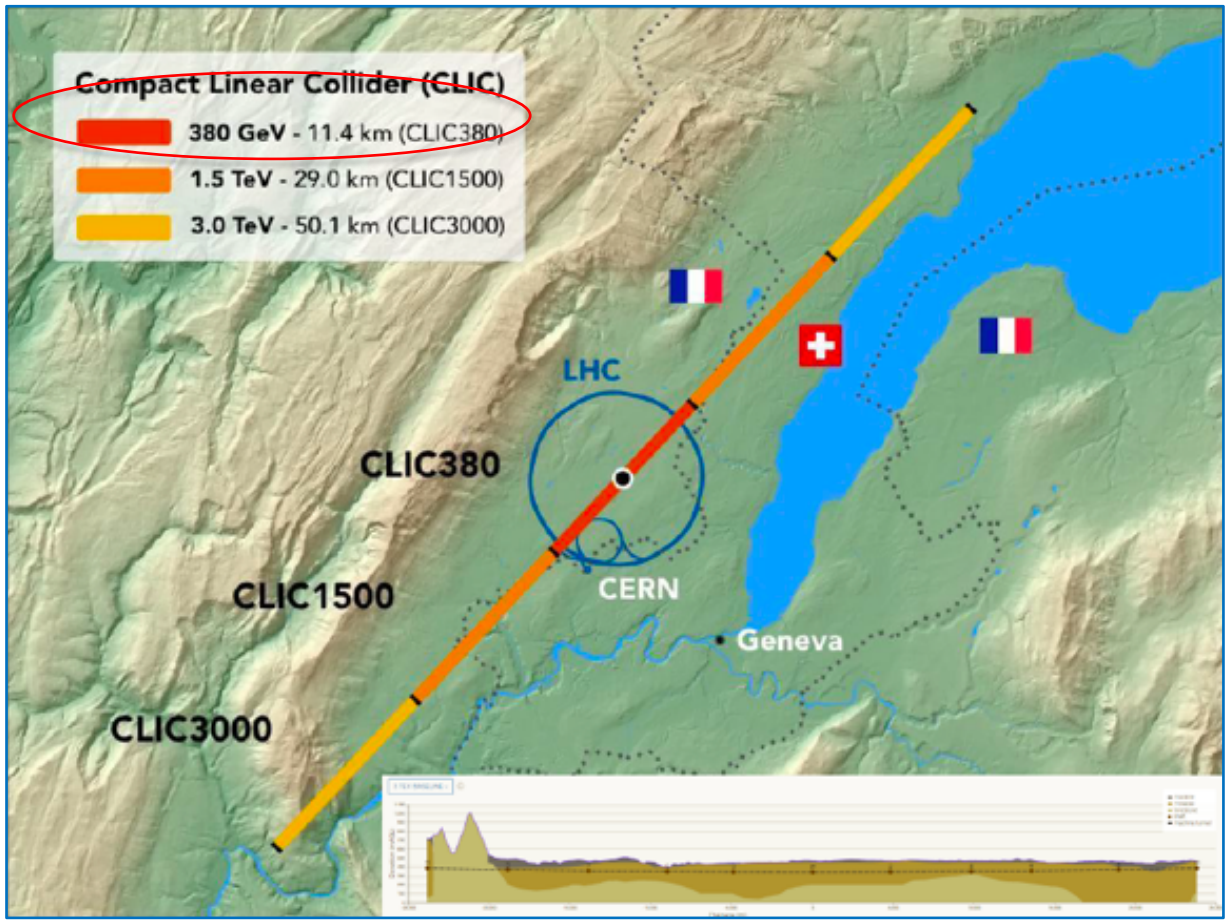
To be presented at CLIC-2019, 23 January, 2019

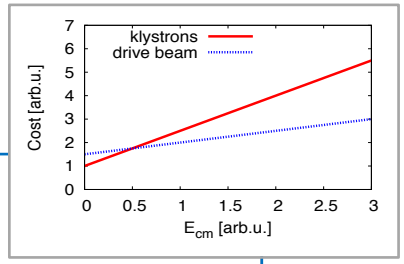
# Background and Objectives

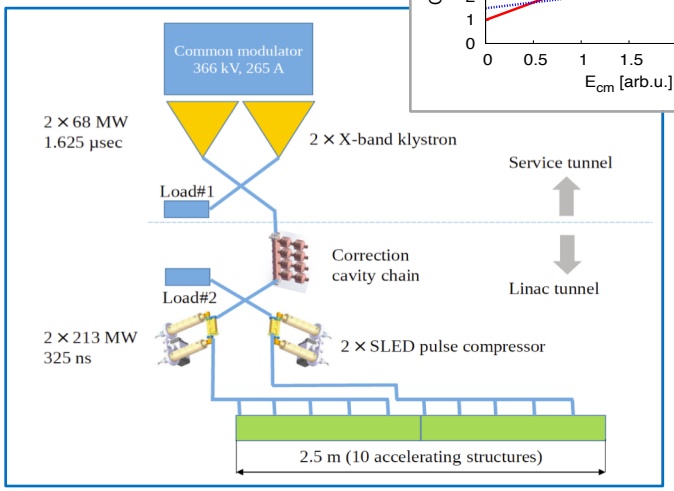
- The CLIC-380 staging scenario being studied at CERN,
- X-band (12 GHz) klystron-based accelerating scheme as a quick option.
- The X-band klystron requiring a beam-focusing solenoid and magnet field:
  - Bc = **~ 0.6** T in a warm bore-diameter of 0.24 m
- A Cu-based solenoid magnet, currently consuming
  - 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**

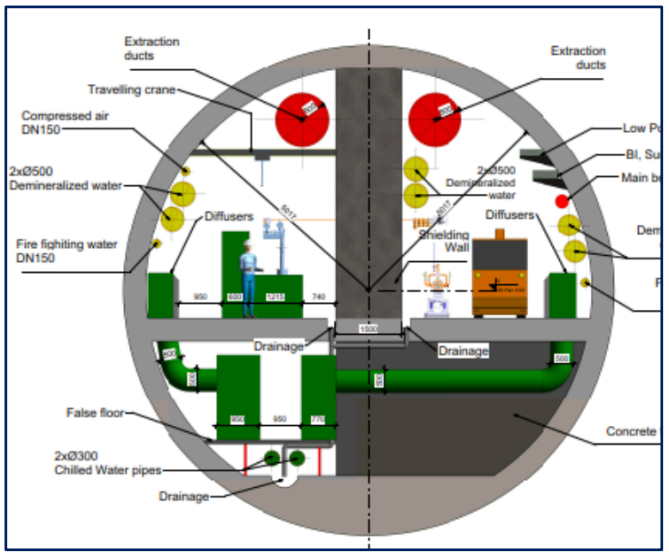
Courtesy: D. Shultz

# CLIC Staging Scenario at 380 GeV with X-band Klystrons

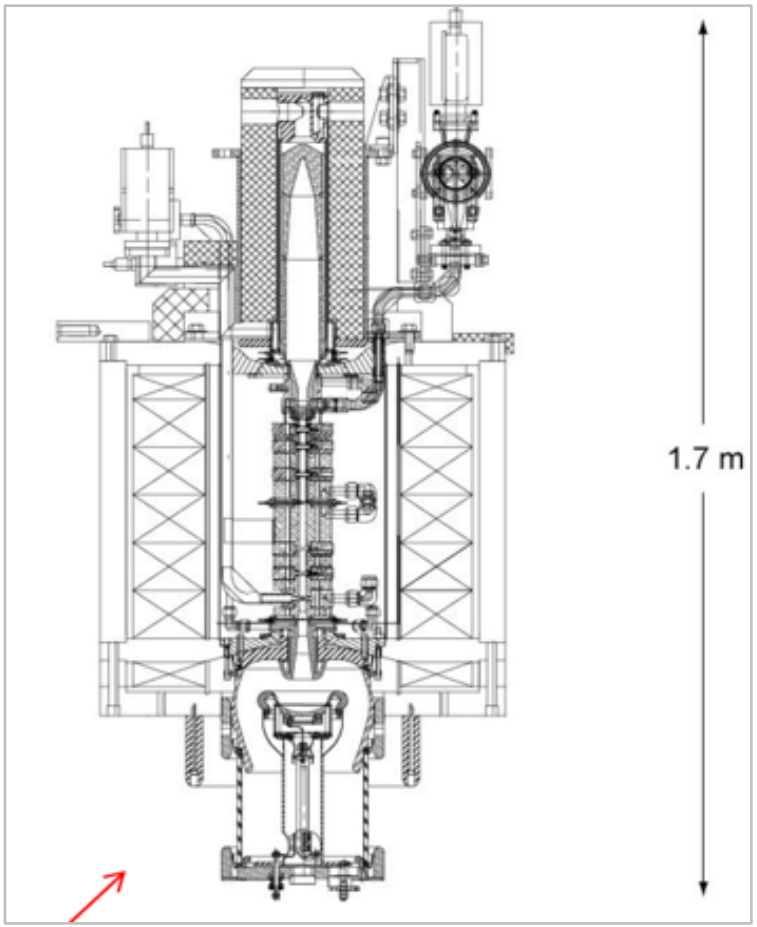


# X-band Klystron developed in cooperation of SLAC/CPI and CERN



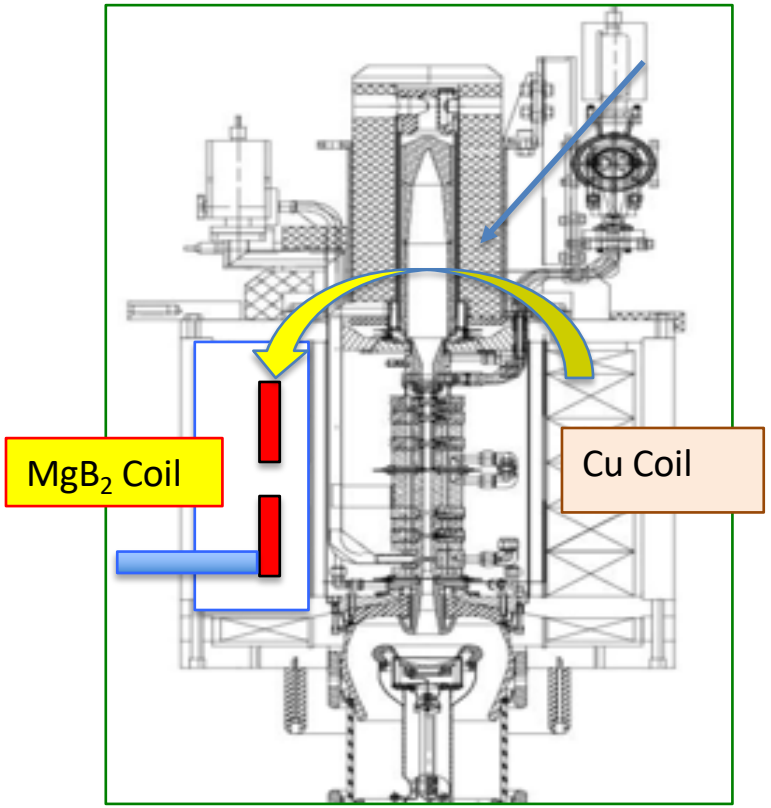

(~35V x 600 A )

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

# 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<br>13.5 W @ 80 K |
| AC Plug-Power | ≤ 3 kW<br>( < 1,5 kW/Klystron in case of a pair ) |




# A Possible Choice among SC Materials

| Material | $T_c$ [K] | $B_{c1}(0)$ [T] | $B_{sh}(0)$ [T] | $B_c(0)$ [T] | $B_{c2}(0)$ [T] | Pen. depth $\lambda(0)$ [nm] |
|---|---|---|---|---|---|---|
| NbTi | 9.2 ~9.5 | 0.067 | -- | -- | 11.5 ~ 14 | 60 |
| $Nb_3Sn$ | 18.3 | (0.05) | 0.43 | 0.54 | 28 ~30 | 80 |
| $MgB_2$ | 39 | (0.03) | 0.31 | 0.43 | 39 | 140 |
| $Bi_2Sr_2Ca_1Cu_2O_8$ (BSCCO-2212) | 94 | 0.025 | -- | -- | >100/30 | 1800 |

X 4 Tc

$$CoP = \frac{\theta_c}{\theta_h - \theta_c}$$

CoP = **1.3%** at 4.5 K (for NbTi operation)
= **5.8** at 20 K (for MgB2 operation)
$MgB_2$ provides an advantage of
x 4 higher thermal efficiency

# 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

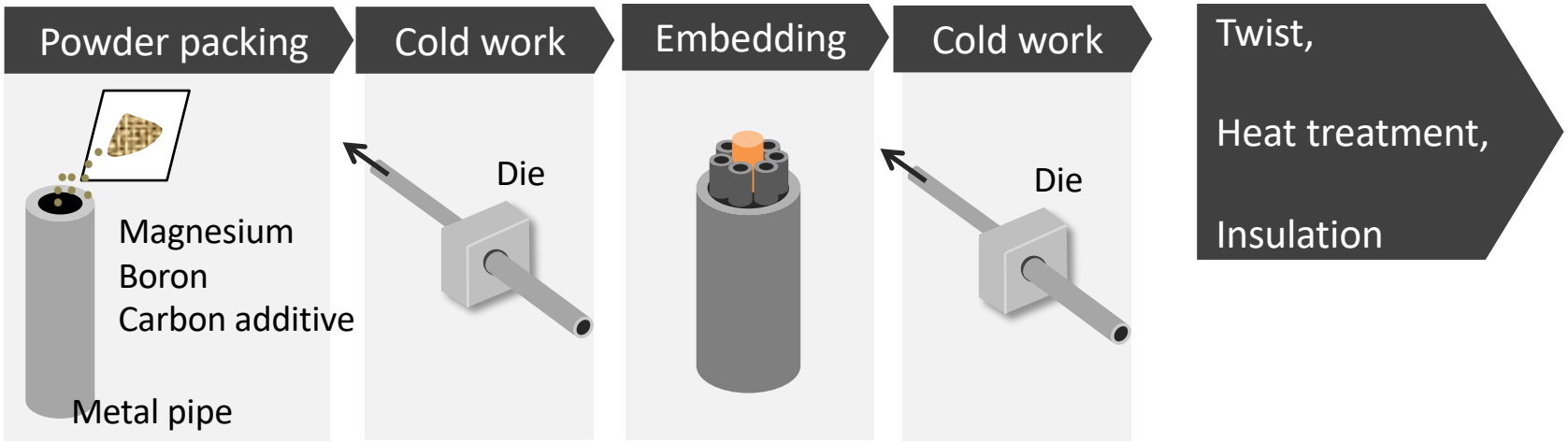
**2019:**

- 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.

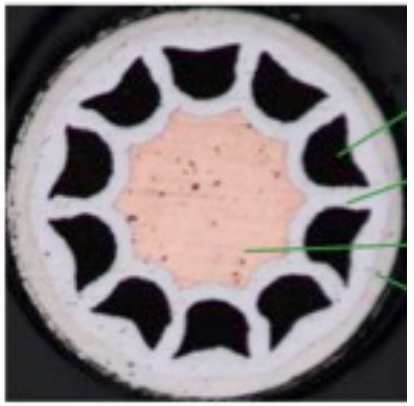
# $MgB_2$ Conductor Manufacturing Process



## Powder in Tube (PIT) method

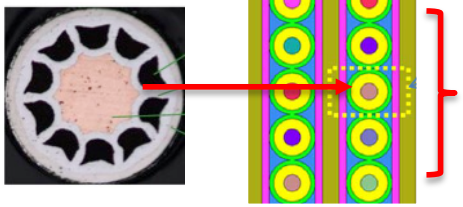


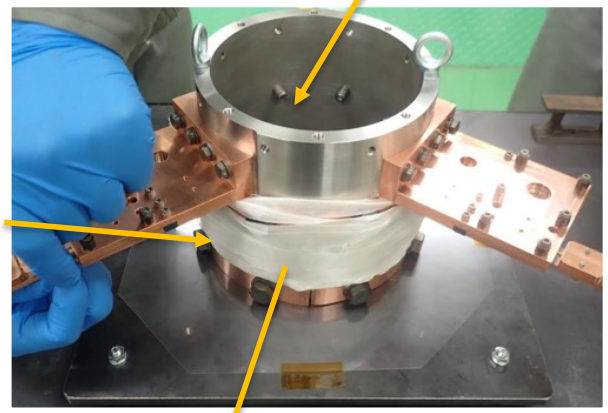

| | Hitachi, *in situ Process* |
|---|---|
| Powder | Mg + B + additive |
| Metal pipe & rod | Cu, Fe, Ni |
| Heat treatment temp. | Typically 600℃ |
| W&R or R&W | Mainly Wind & React |
| Insulation | Glass braid |

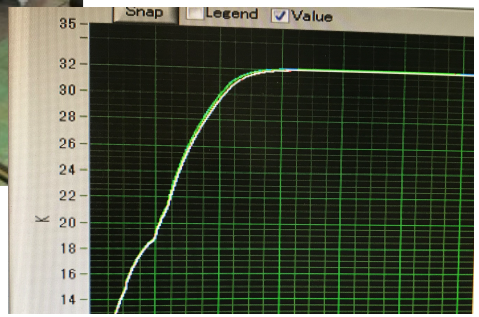


Φ0.67 $MgB_2$

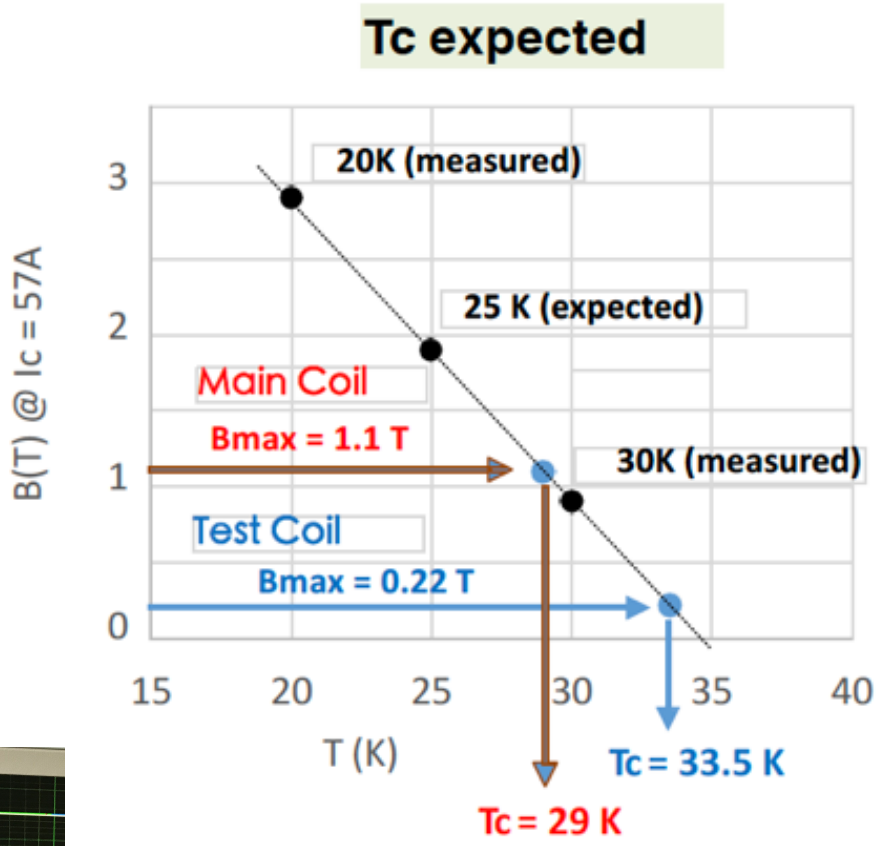
# $MgB_2$ Conductor Performance Test by using a small test coil, August, 2018



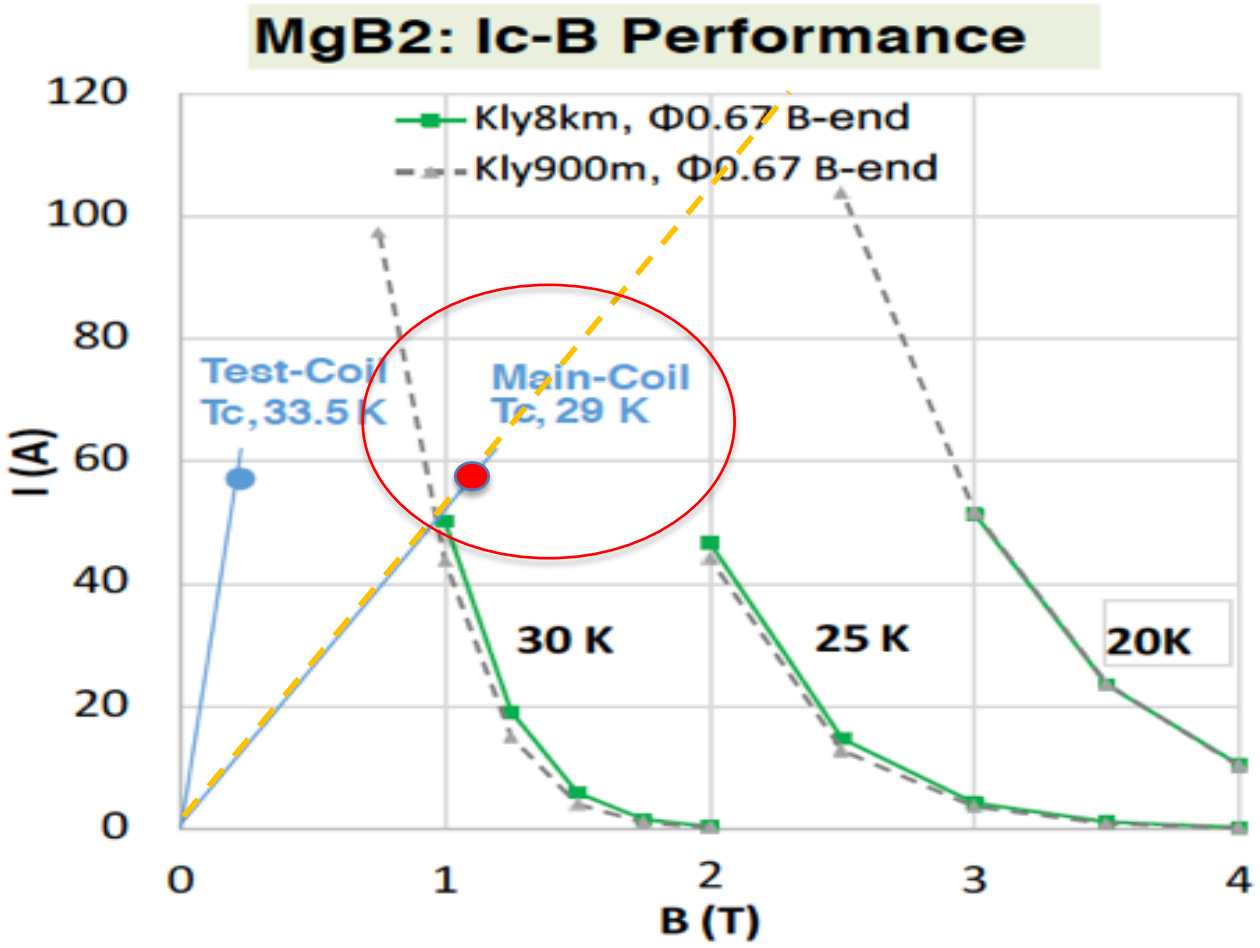




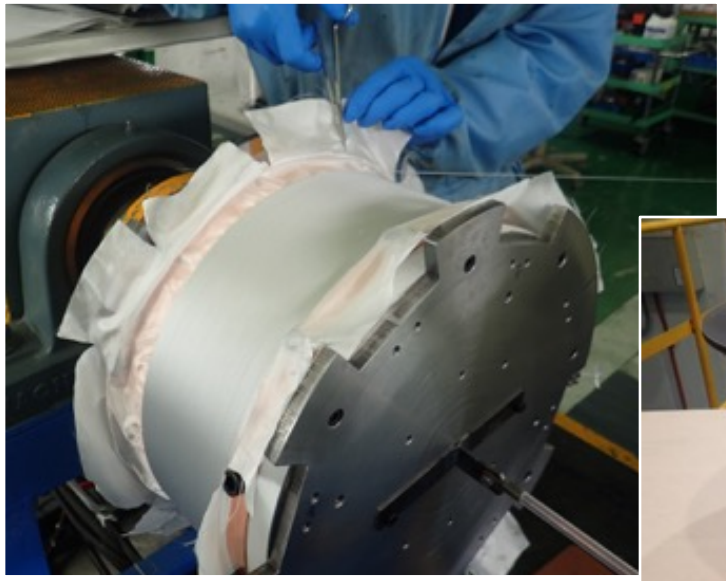

57 A @ 32 K, achieved



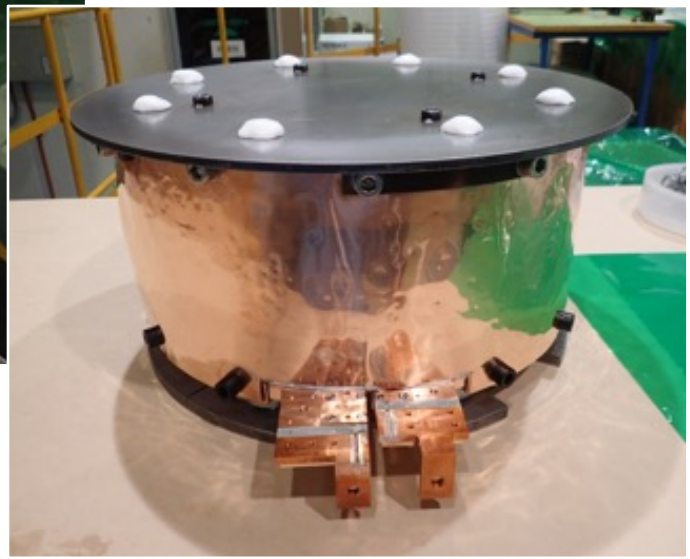
# Hitachi, MgB2 Conductor Performance



# Coil Winding, (Heat-treatment), and Epoxy-Resin Molding



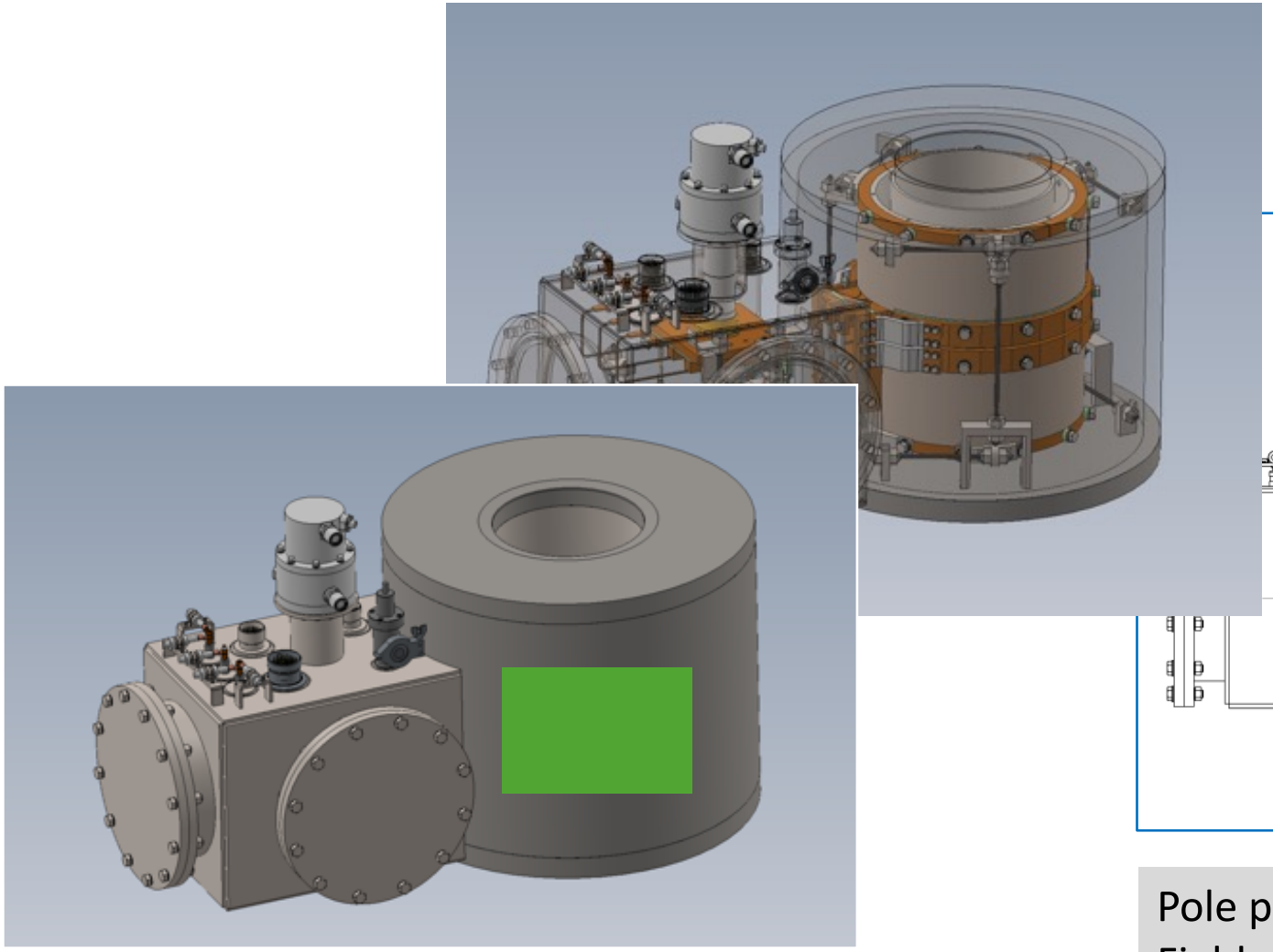
Coil Winding
using $MgB_2$ conductor
w/ glass-insulation

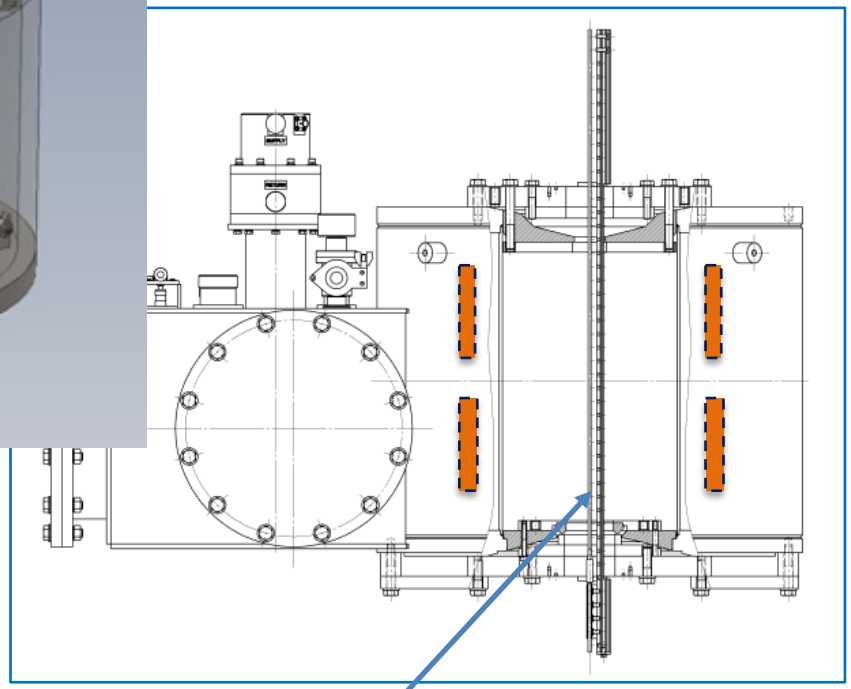


Coil w/ Cu conduction layer,
after Heat Treatment

Preparation for Resin Molding

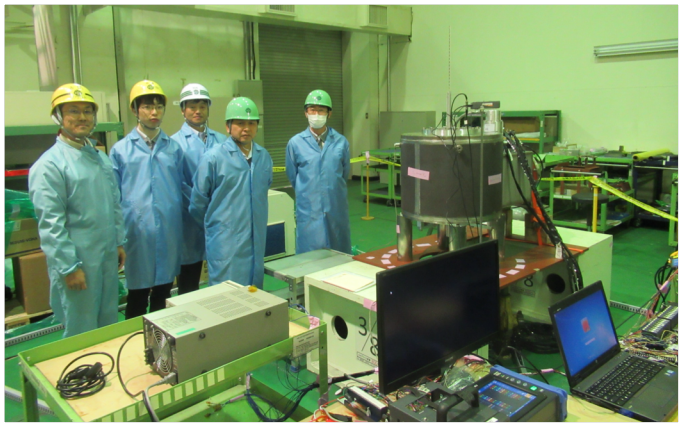
# Prototype Coil Assembly with Cryostat functioning as Flux-rerun Iron Yoke and Cryo-cooler

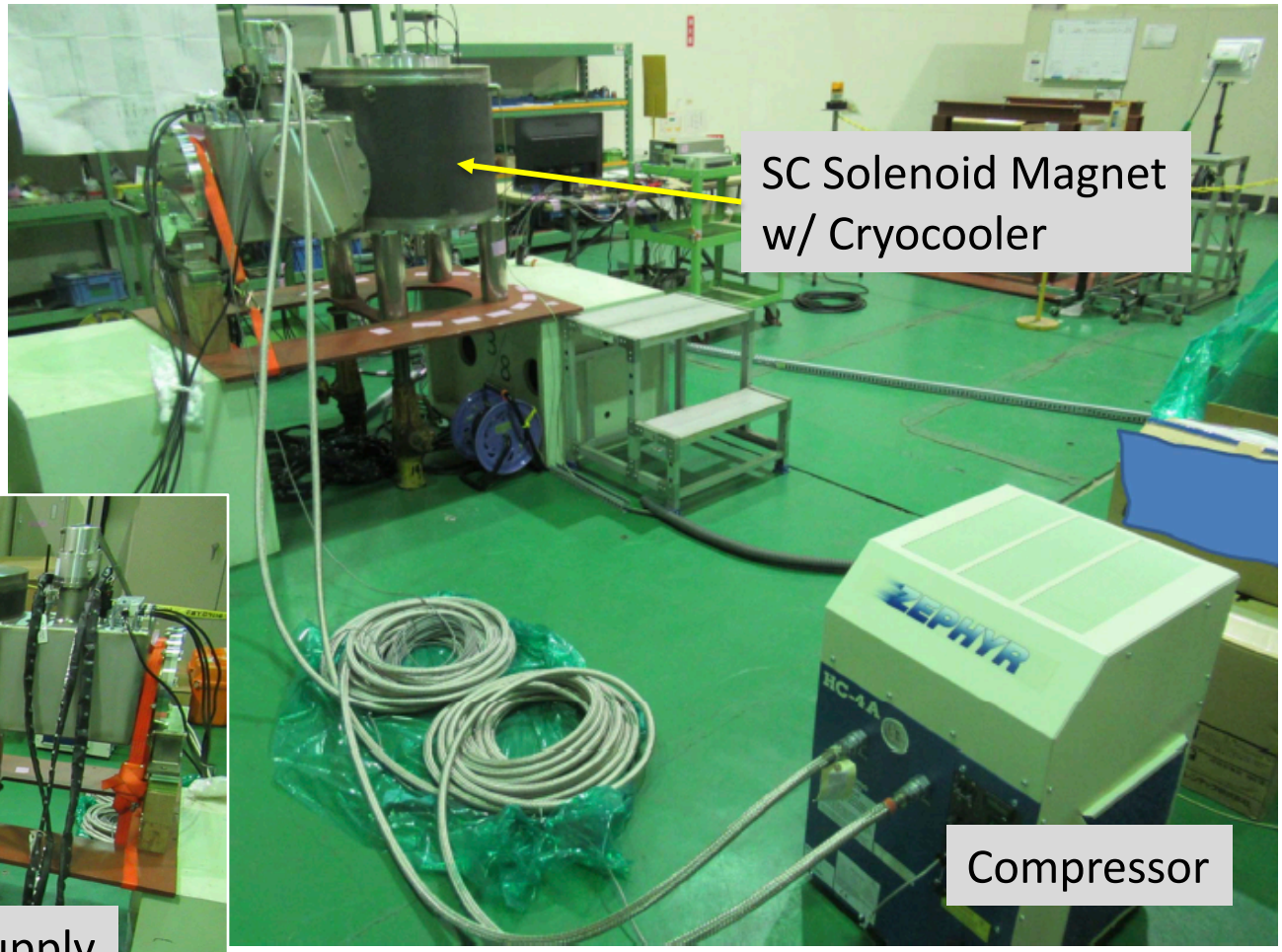


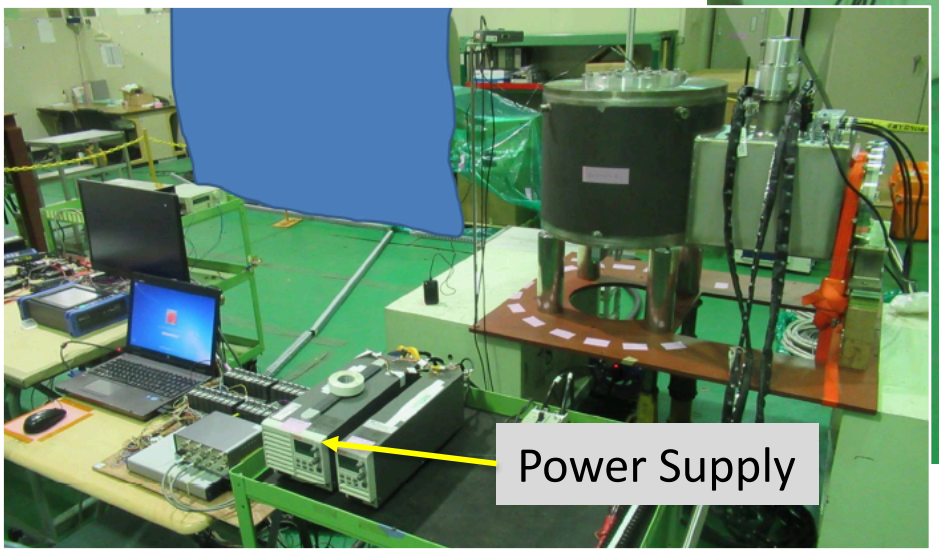


Pole pieces, and
Field profile measurement setup

# Solenoid Magnet Test Setup
# 7-8 Jan., 2019

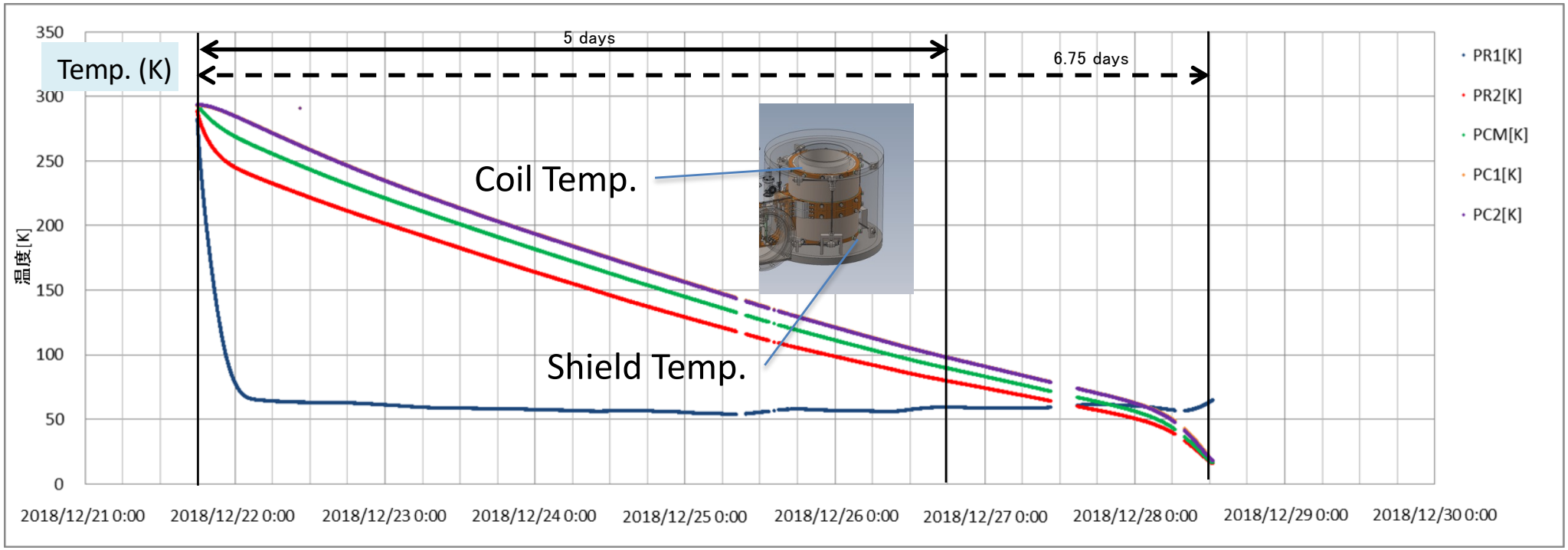




# Solenoid Coil Cool-down by using Cryocooler

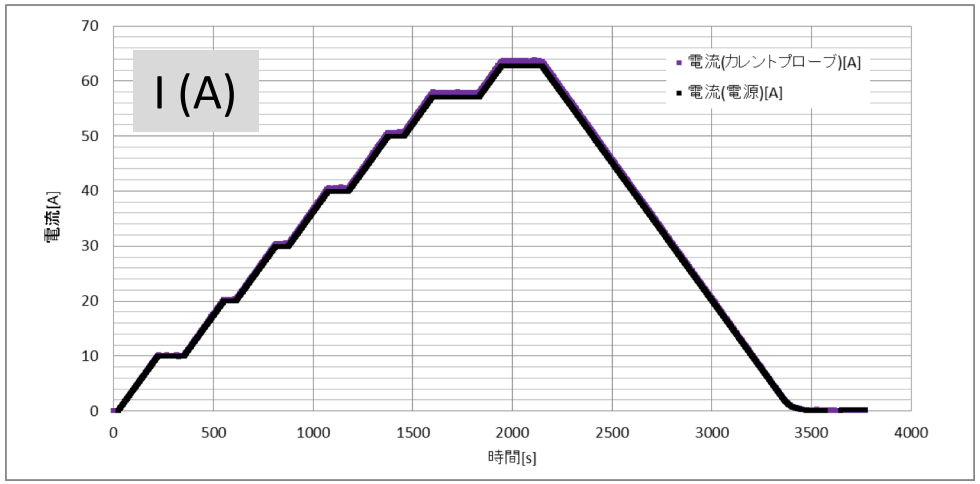
## in < 7 days

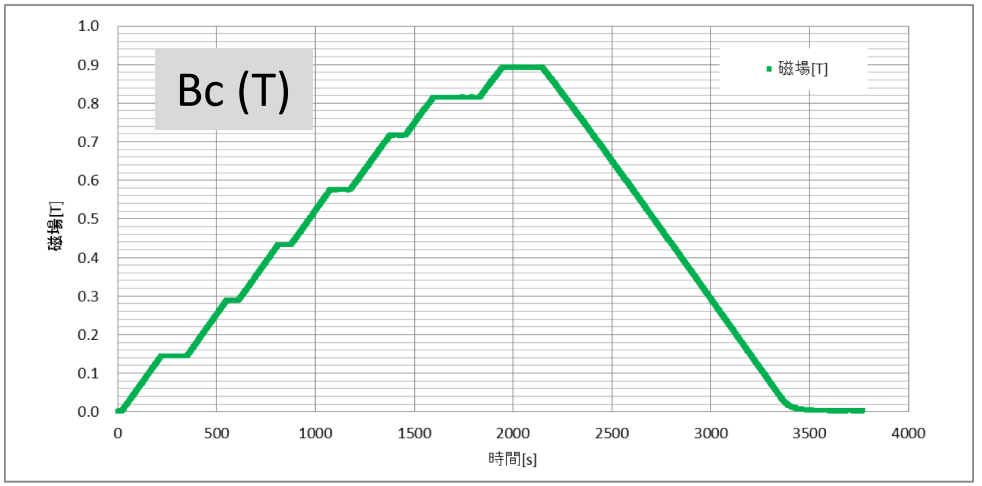


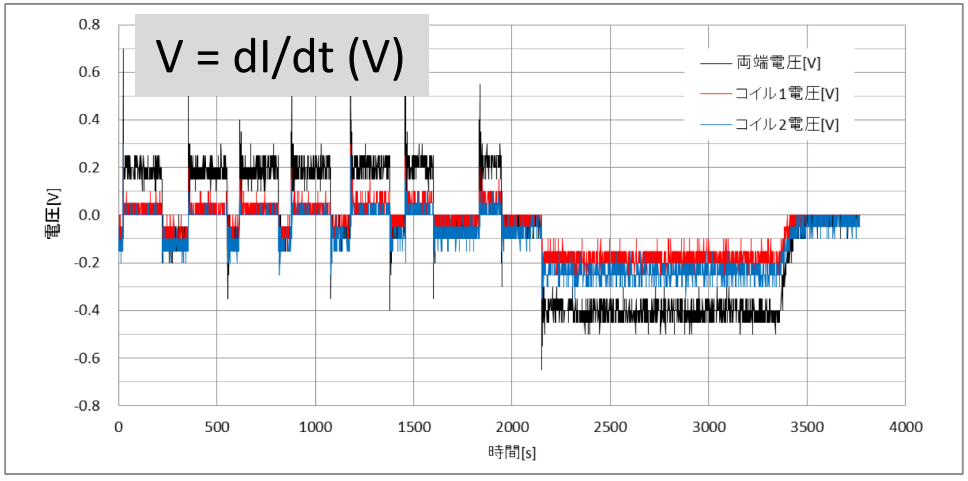

Time: (yr/mm/dd/hr)

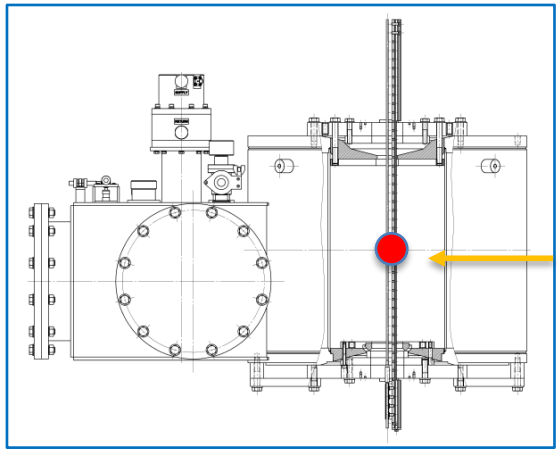
# Solenoid Excitation Test

# $B_c$ reached 0.9 T @ I = 62.7 A, 16 K



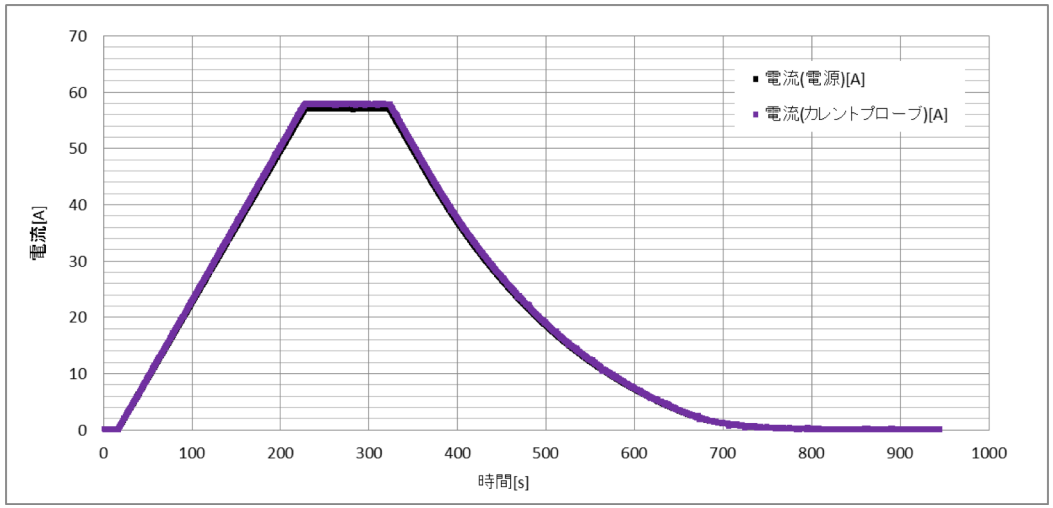



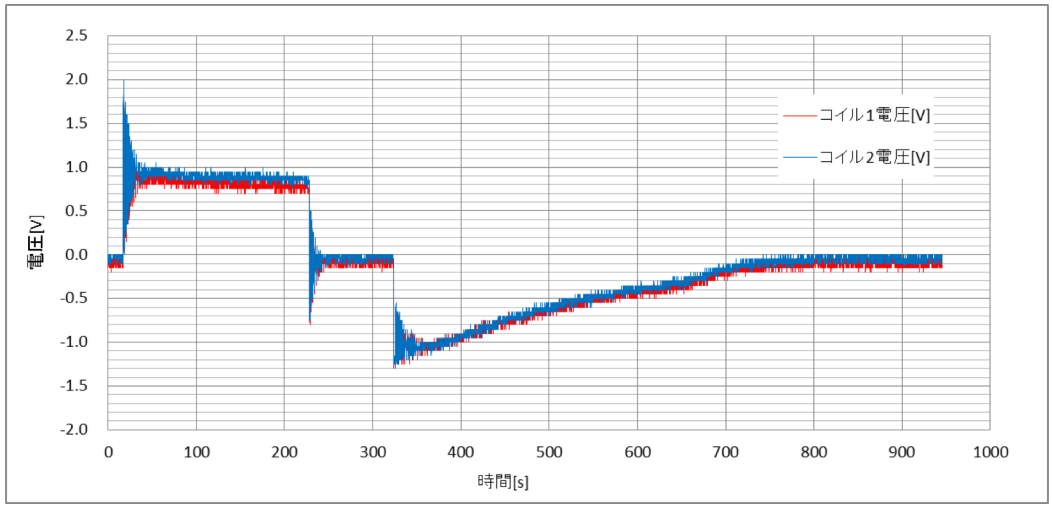



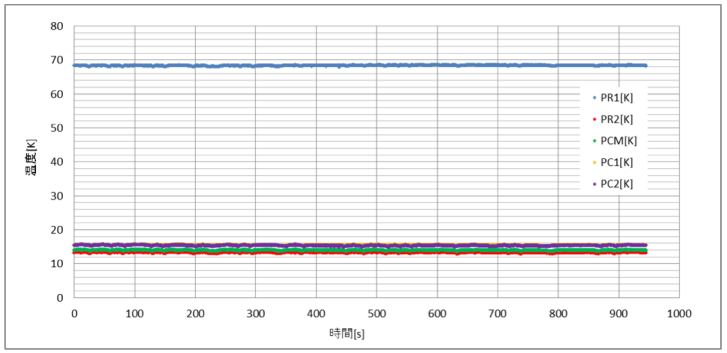



Bc (T)

# Excitation within 4 min. for ramping-up

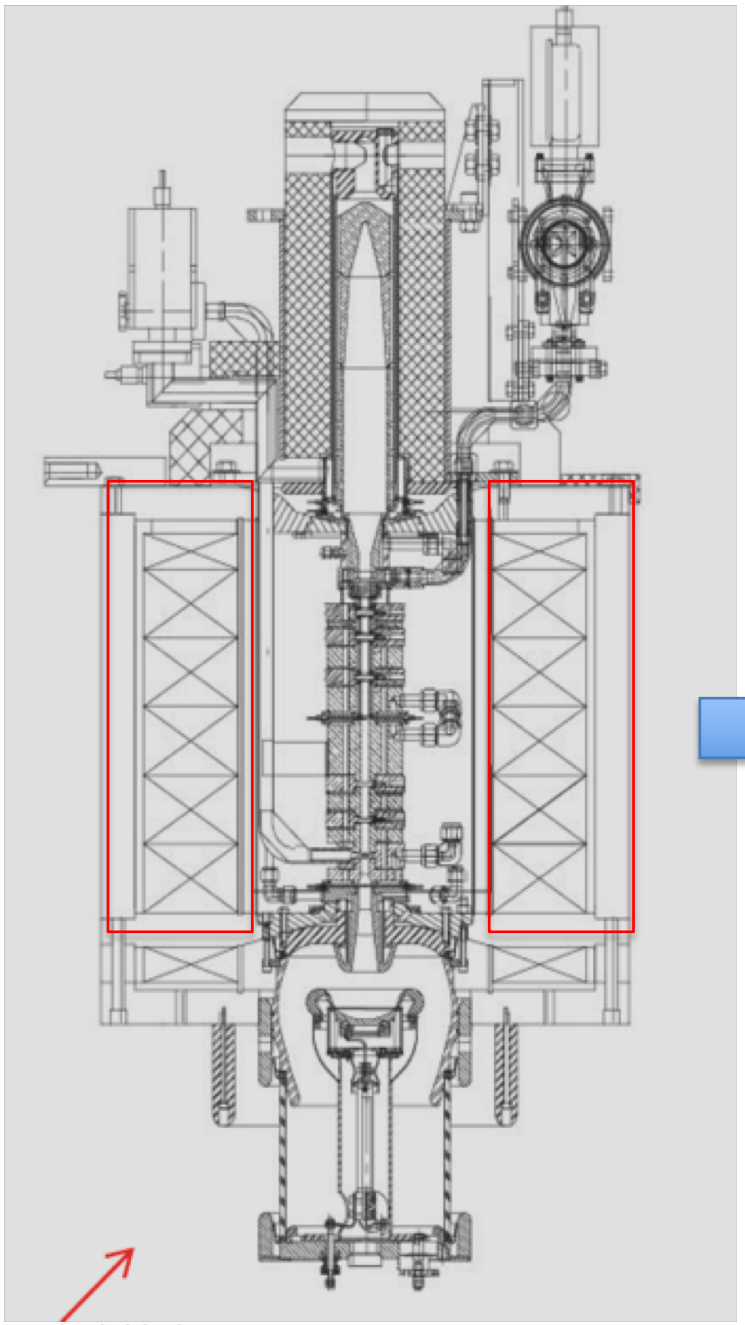


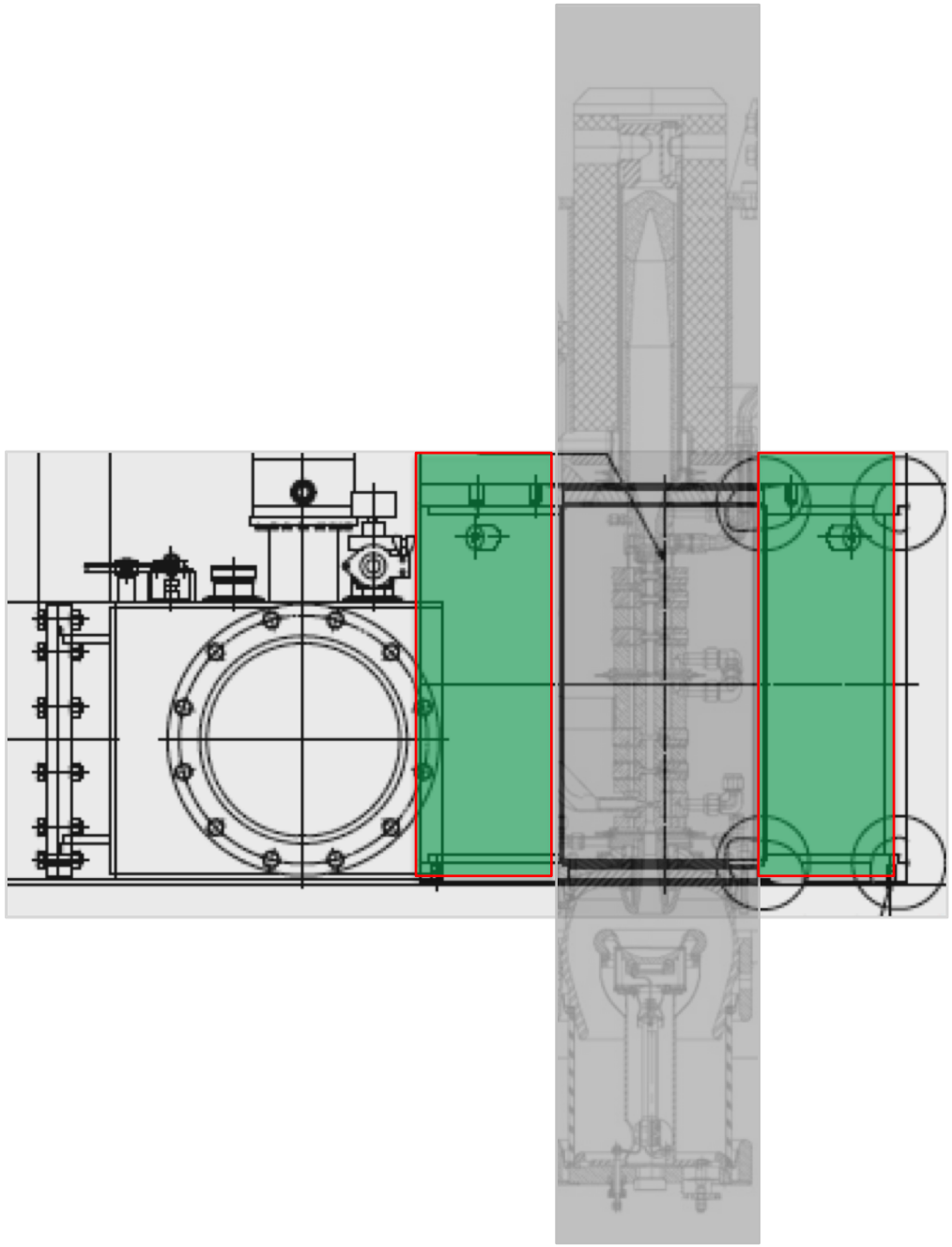



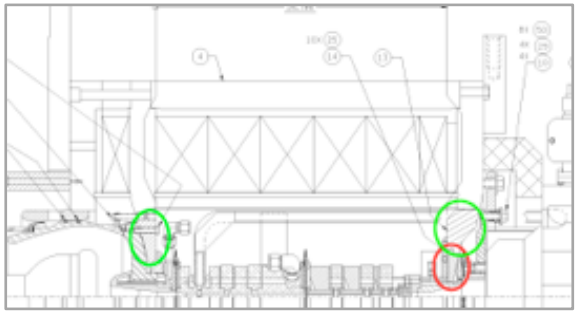

Temperature kept constant at 16 K

# Magnet Assembly w/ Klystron



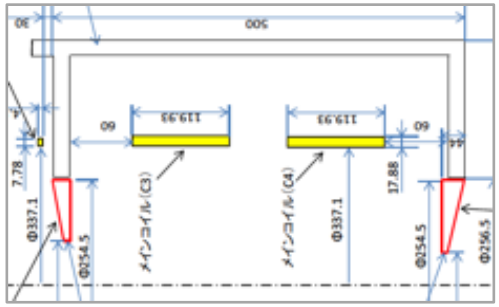


# Axial Magnetic Field Profile Comparison of Cu and SC Solenoids to be evaluated, soon

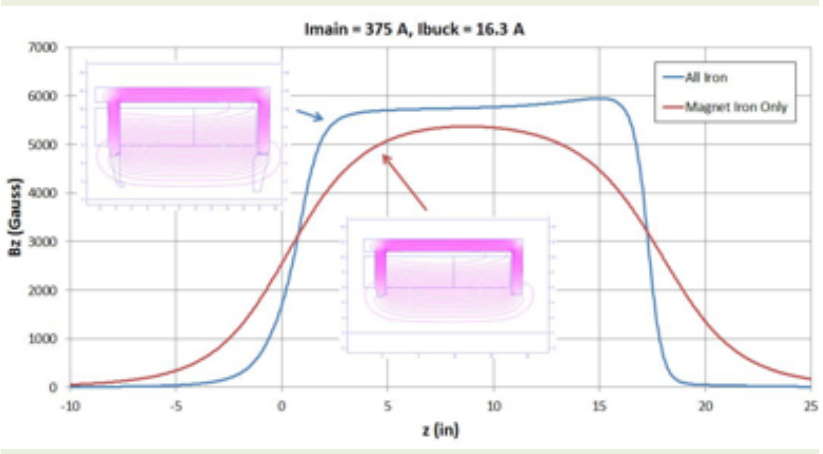


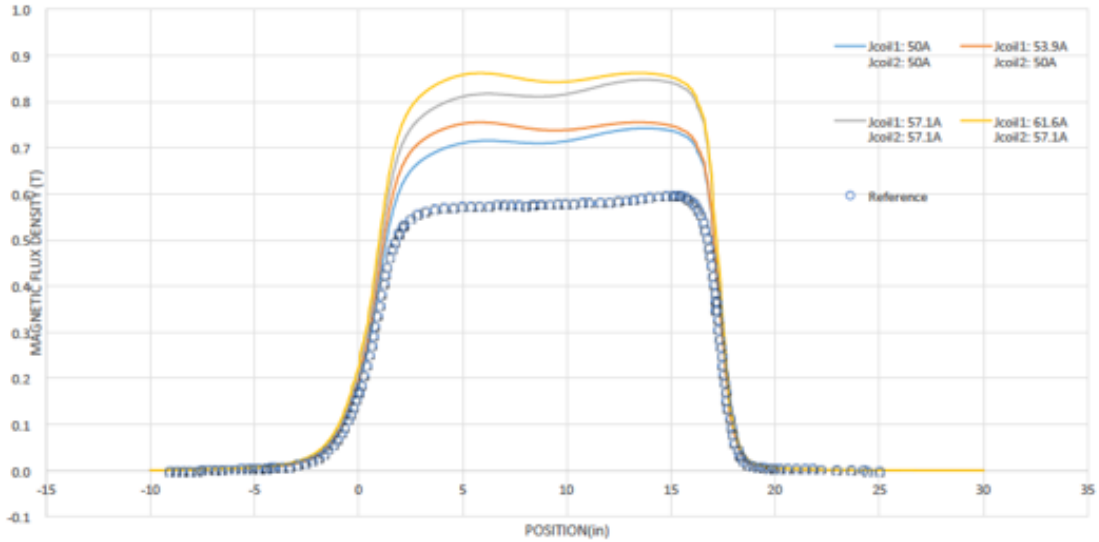
←Cu Solenoid

SC Solenoid →



Courtesy: j. Neilson



# Further Test Plan

2019:

| | |
|---|---|
| 1/7: | Cool-down completed |
| | Excitation started |
| (1/9~15: | Cryo-cooler maintenance) |
| 1/16~ : | Re-cooldown |

Further Plan:

| | |
|---|---|
| 1/23 | Excitation, quench safety, field meas. |
| 2/14~15: | Acceptance tests with CERN's participation |
| | --> confirming excitation, quench safety, field profile. |
| | --> instructing how to operate the magnet at CERN |
| 3/15: | Deliver to KEK (and soon Ship to CERN) |

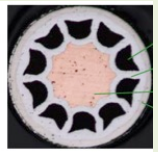
# Summary: Development of a Superconducting Solenoid for X-band Klystron beam-focusing

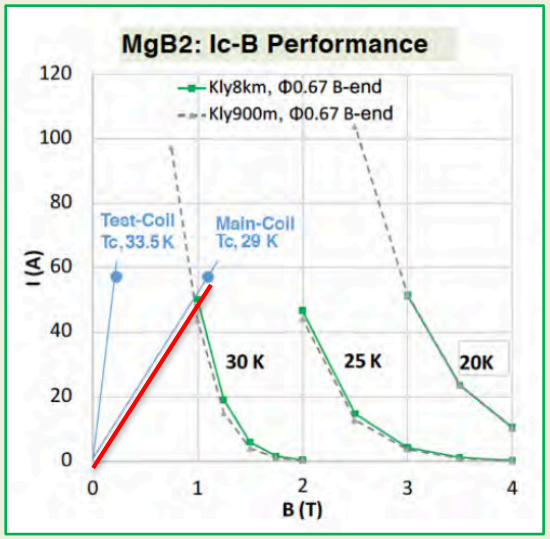
## Objective

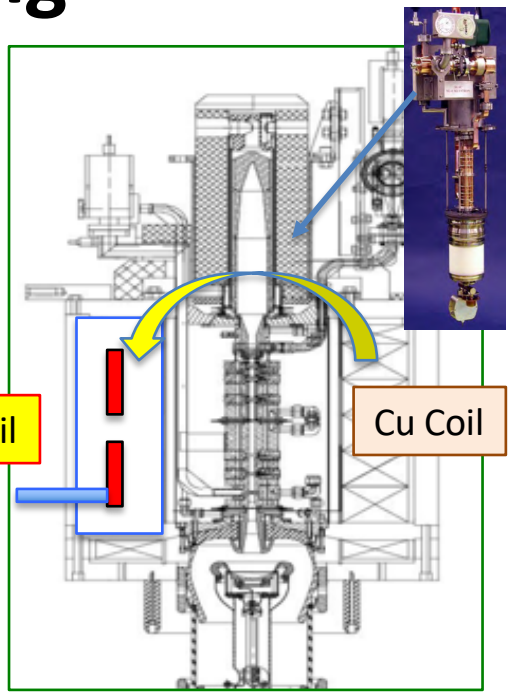
- SC-mag technology to be demonstrated for high-efficiency X-band Klystron for future linear accelerator applications

## Prototype SC Magnet Design:

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





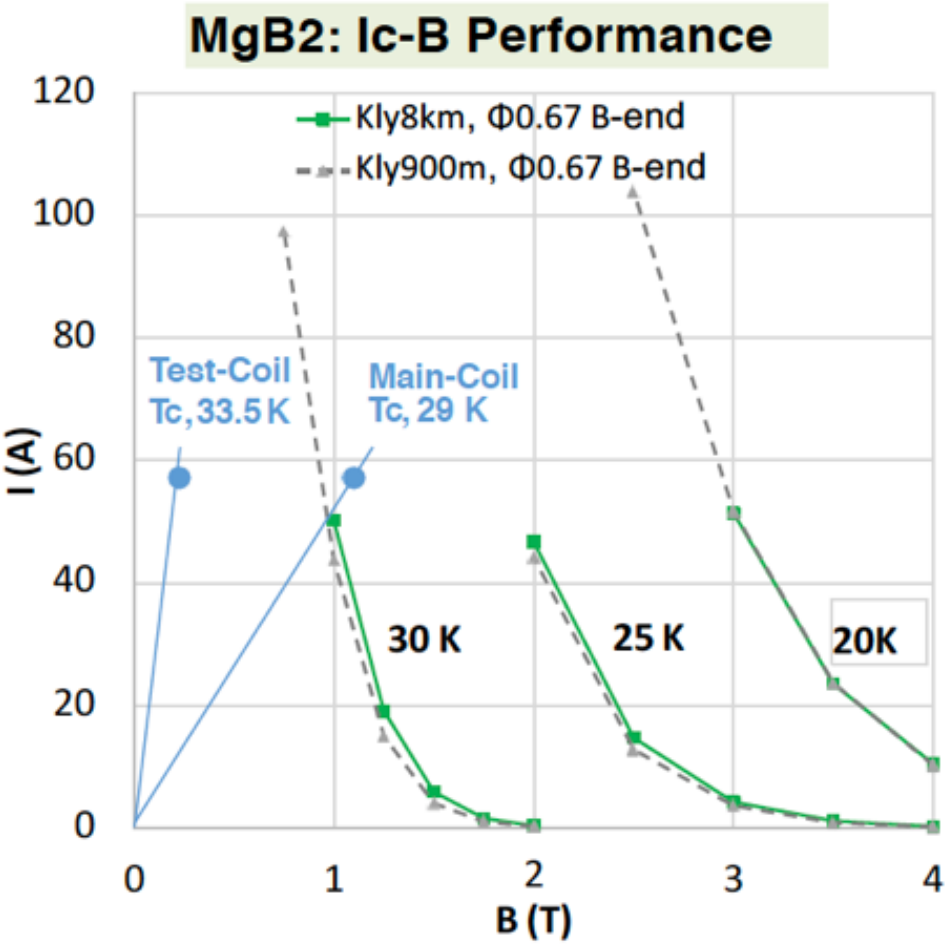



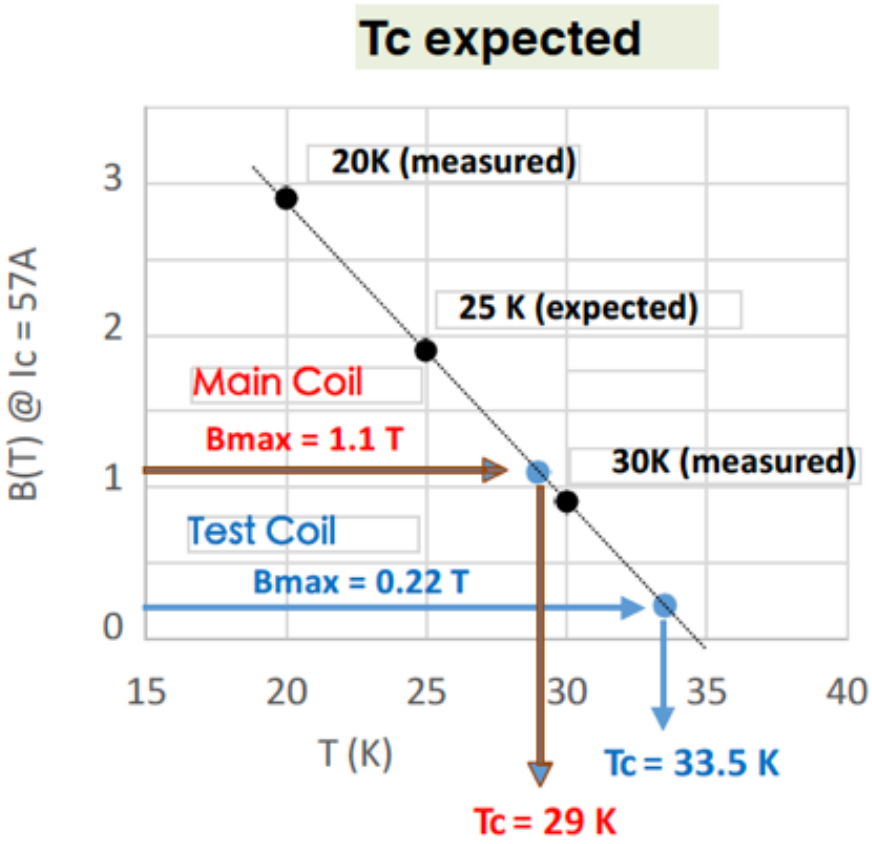

## Progress and Further Plan:

- $MgB_2$ conductor performance confirmed,
- Magnet fabrication completed,
- Magnet test in progress: Bc = 0.9 T achieved at 16 K
- Performance to be evaluated, with Klystron, at CERN in 2019.

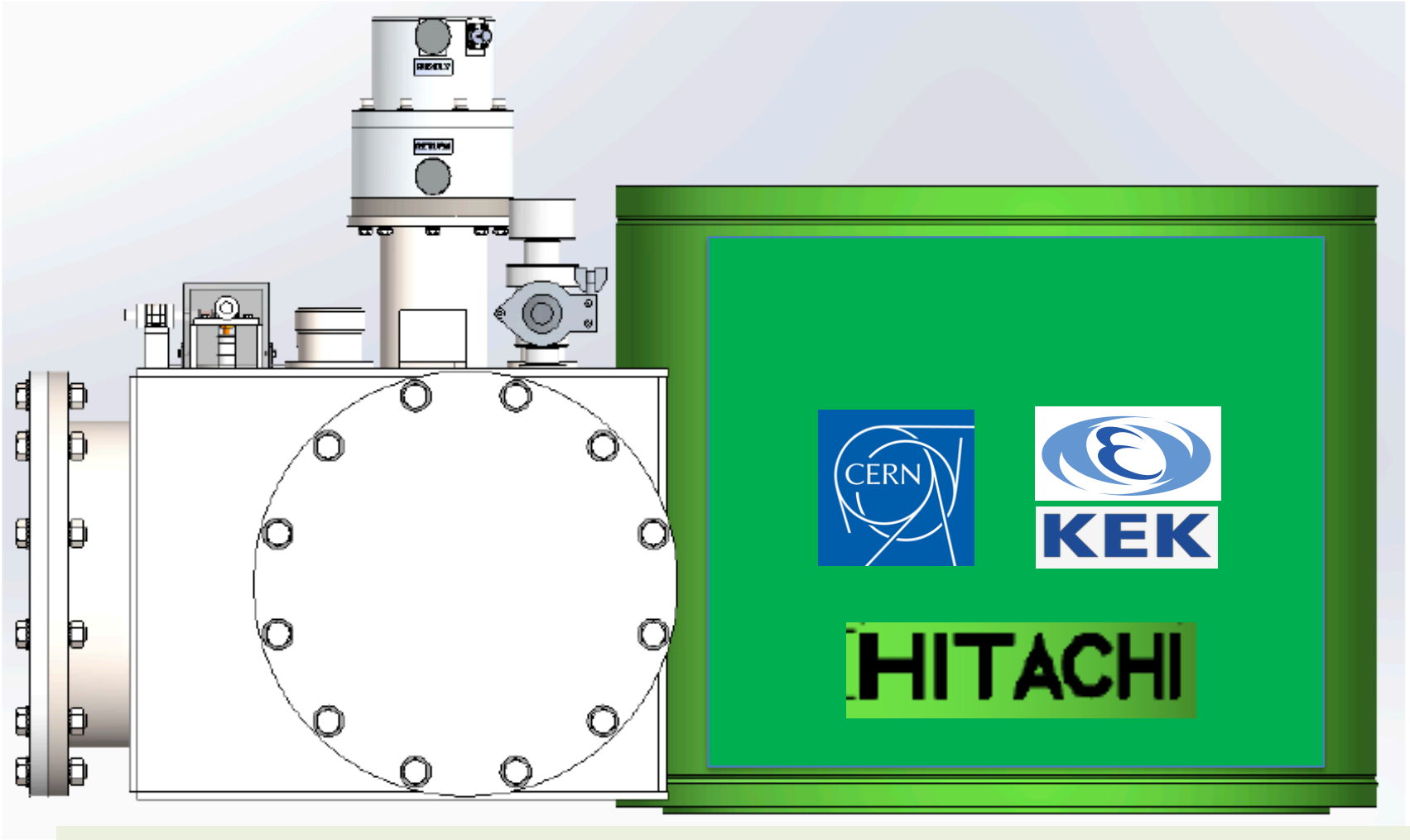
# Appendix

# Hitachi, MgB2 Conductor Performance



# 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)

# Cold-Head Performance Required

## CH-204 10K CRYOCOOLER SERIES

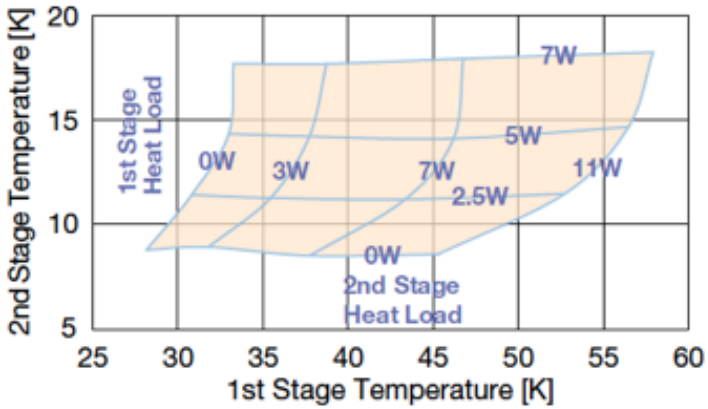
### Performance Specifications

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

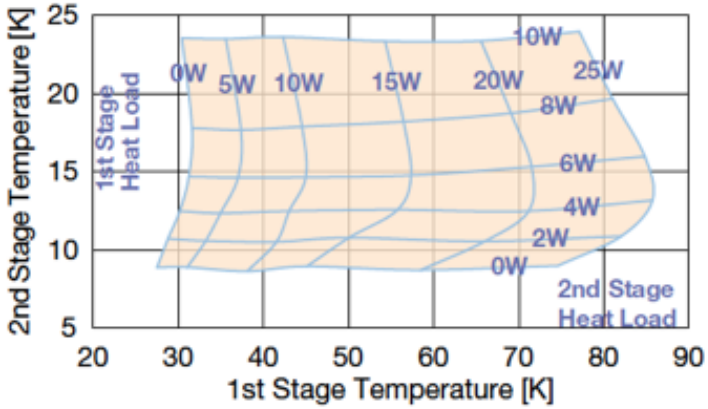
### Standard Scope of Supply

- 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

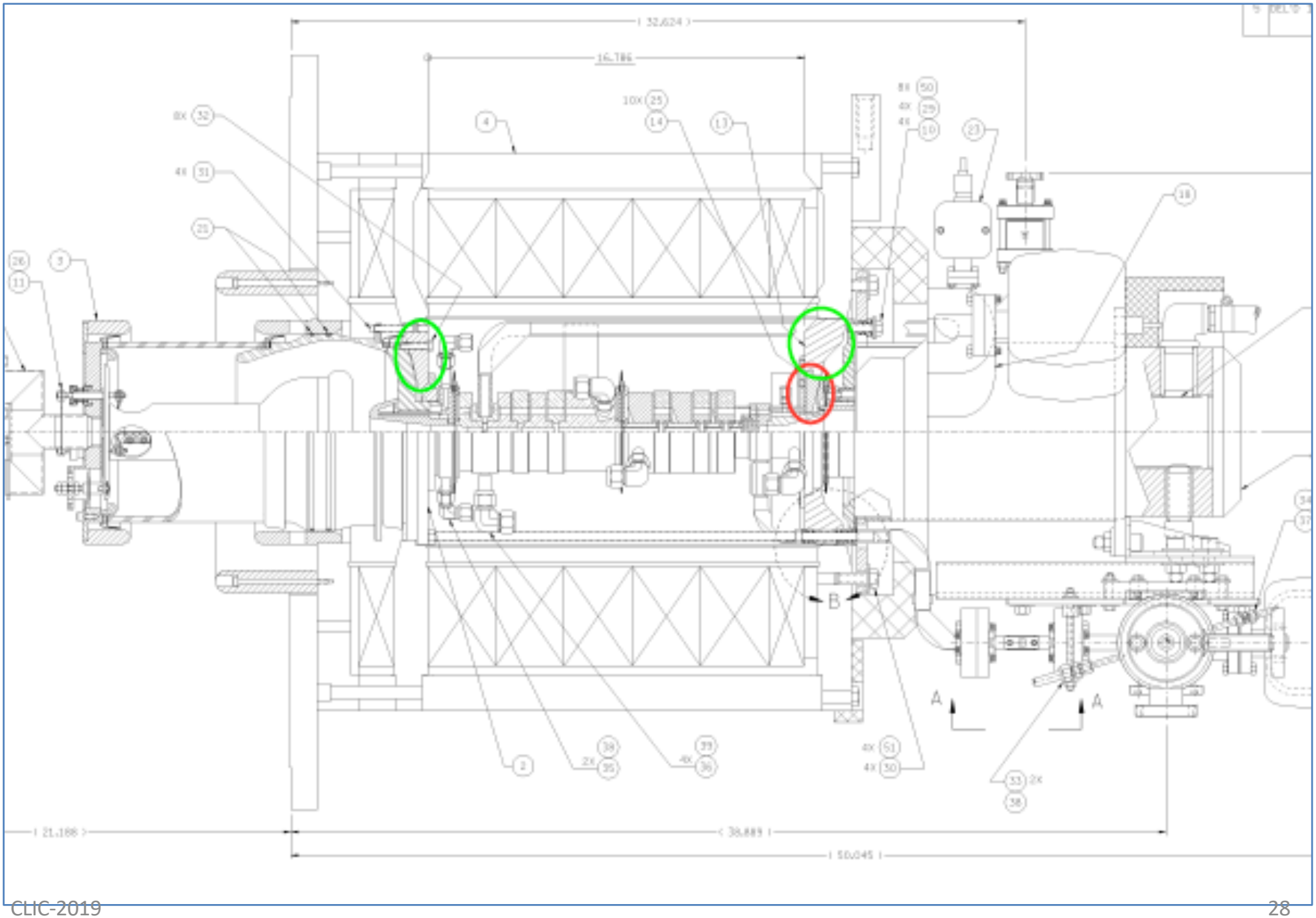
| CNA-11 | | Zephyr® | CNA-31 | | CSA-71A | CNA-61 | |
|---|---|---|---|---|---|---|---|
| B | C | | C | D | | C | D |
| Air Cooled | | Air Cooled | Air Cooled | | Air Cooled | Air Cooled | |
| 1 Phase 100 V, 50/60 Hz | 1 Phase 100, 120, 220, 230, 240 V, 50/60 Hz | 1 Phase 200 V, 220 V, 230/240 V, 50 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 (95 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 | |

# Cryo-Cooler Performance Required

http://www.shicryogenics.com//wp-content/uploads/2012/11/Cryocooler-Product-Catalogue.pdf

| Cold Head Model | | RDK-101D | RDK-305D | RDK-205D | RDK-408D2 | RDK-415D | RP-062B | RP-082B | CH-204N |
|---|---|---|---|---|---|---|---|---|---|
| 1st Stage Capacity | 50 Hz | 3.0 W @ 60 K | 15 W @ 40 K | 3.0 W @ 50 K | 40 W @ 43 K | 35 W @ 50 K | 30 W @ 65 K | 40 W @ 45 K | – |
| | 60 Hz | 5.0 W @ 60 K | 20 W @ 40 K | 4.0 W @ 50 K | 50 W @ 43 K | 45 W @ 50 K | 30 W @ 65 K | 40 W @ 45 K | – |
| 2nd Stage Capacity | 50 Hz | 0.1 W @ 4.2 K | 0.4 W @ 4.2 K | 0.5 W @ 4.2 K | 1.0 W @ 4.2 K | 1.5 W @ 4.2 K | 0.5 W @ 4.2 K | 1.0 W @ 4.2 K | 2.5 W @ 10 K |
| | 60 Hz | 0.1 W @ 4.2 K | 0.4 W @ 4.2 K | 0.5 W @ 4.2 K | 1.0 W @ 4.2 K | 1.5 W @ 4.2 K | 0.5 W @ 4.2 K | 1.0 W @ 4.2 K | 3.0 W @ 10 K |
| Minimum Temperature[1] | | <3.0 K | <3.5 K | <3.5 K | <3.5 K | <3.5 K | <3.0 K | <3.0 K | 6.5 K |
| Cooldown Time[1] | 50 Hz | <150 | <120 | <90 | <60 | <60 | <100 | <80 | 40 |
| | 60 Hz | <150 | <120 | <90 | <60 | <60 | <90 | <80 | 35 |
| Weight | | 7.2 kg (15.9 lbs.)[2] | 16.0 kg (35.3 lbs.) | 14.0 kg (30.9 lbs.) | 18.0 kg (39.7 lbs.) | 18.5 kg (40.8 lbs.) | 23.2 kg (51.2 lbs.) | 26.0 kg (57.3 lbs.) | 7.8 kg (17.2 lbs.) |
| Bakeable Option | | | | | | | | | ● |
| HC-4E1 | | | | | | | | | ● |
| CKW-21A | | | | ● | | | | | |
| HC-8E4 | | | | | | | | | ● |
| F-50L/H | | | | | ● | ● | ● | | |
| F-70LP/L/H | | | | | ● | ● | | ● | 3 |
| CNA-11B/C | | ● | | | | | | | |
| Zephyr® | | | | | | | | | ● |
| CNA-31C/D | | | ● | | | | | | |
| CSA-71A | | | | | ● | ● | | | |
| CNA-61C/D | | | | | ● | ● | | | |

| Cold Head Model | | RDK-408S2 | CH-202 | CH-204 | CH-208R | CH-208L | CH-210 | RDK-400B | CH-104 | CH-110 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1st Stage Capacity | 50 Hz | 35 W @ 45 K | 7.3 W @ 77 K | 13.5 W @ 80 K | 65 W @ 77 K | 28 W @ 77 K | 110 W @ 77 K | 54 W @ 40 K | 34 W @ 77 K | 175 W @ 77 K |
| | 60 Hz | 40 W @ 45 K | 8.8 W @ 77 K | 16.2 W @ 80 K | 80 W @ 77 K | 35 W @ 77 K | 120 W @ 77 K | 70 W @ 40 K | 42 W @ 77 K | 200 W @ 77 K |
| 2nd Stage Capacity | 50 Hz | 5.4 W @ 10 K | 1.8 W @ 20 K | 6.7 W @ 20 K | 6.0 W @ 20 K | 8.0 W @ 20 K | 6.0 W @ 20 K | N/A | N/A | N/A |
| | 60 Hz | 6.3 W @ 10 K | 2.2 W @ 20 K | 7.1 W @ 20 K | 7.5 W @ 20 K | 10.0 W @ 20 K | 7.0 W @ 20 K | N/A | N/A | N/A |
| Minimum Temperature[1] | | <7 K | 10 K | 10 K | 10 K | 10 K | 10 K | <25 K | <25 K | <25 K |
| Cooldown Time[1] | 50 Hz | <60 | 75 | 35 | 55 | 50 | 35 | <30 | <40 | 35 |
| | 60 Hz | <60 | 65 | 30 | 45 | 40 | 30 | <30 | <30 | 30 |
| Weight | | 17.2 kg (37.9 lbs.) | 6.8 kg (15.0 lbs.) | 7.8 kg (17.2 lbs.) | 11.6 kg (25.6 lbs.) | 11.8 kg (26.0 lbs.) | 13.8 kg (30.4 lbs.) | 16.0 kg (35.3 lbs.) | 7.9 kg (17.5 lbs.) | 13.7 kg (30.2 lbs.) |
| Bakeable Option | | | ● | ● | ● | ● | ● | | ● | ● |
| HC-4E1 | | | ● | ● | | | | | ● | 4 |
| CKW-21A | | | | | | | | | | |
| HC-8E4 | | | | ● | ● | ● | | | ● | 4 |
| F-50L/H | | ● | | | | | | ● | | |
| F-70LP/L/H | | | | 3 | ● | ● | ● | | 3 | ● |
| CNA-11B/C | | | | | | | | | | |
| Zephyr® | | | ● | ● | | | | | ● | 4 |
| CNA-31C/D | | | | | | | | | | |
| CSA-71A | | ● | | | | | | ● | | |
| CNA-61C/D | | ● | | | | | | ● | | |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16.786
21.188
38.889
50.045
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A
B

# e Klystron at the
# ental hall