# Superconducting Magnets
## for ILC Detectors

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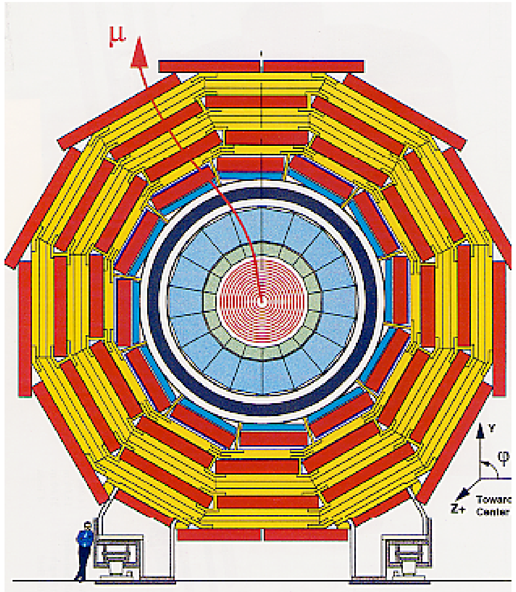
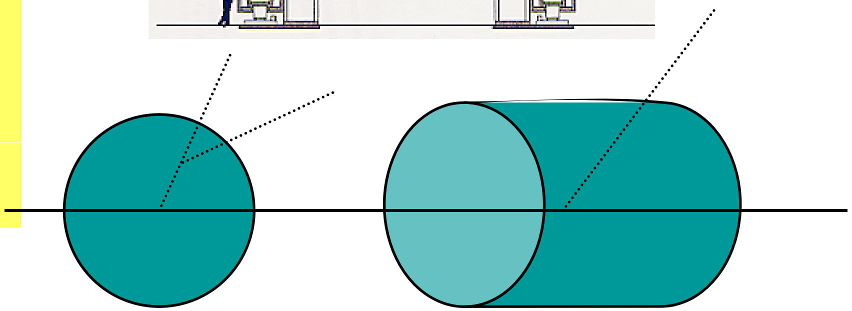
# Outline

- Status of Collider Detector Magnets
- ILC Detector Magnets
  - Possible Guide Line and Design Parameters
- Development/Investigation to be made
  - Conductor
  - Cryogenics for push-pull detector layout
- Summary

# Solenoidal Field

- Uniform, axial magnetic field
- Self supporting supporting
- Sagitta measurement inside magnetic field
  - **$dp/p \sim \{B \cdot R^2\}^{-1}$**
- Deflection angle measurement outside mag. field
  - **$dp/p \sim \{B \cdot R\}^{-1}$**



**Larger radius generally efficient**

# Momentum Analysis with Magnetic Field

- Bending with magnetic field

  Deflection:

  tan θ = ~ θ

  • = L/ρ = e B L/ **p**

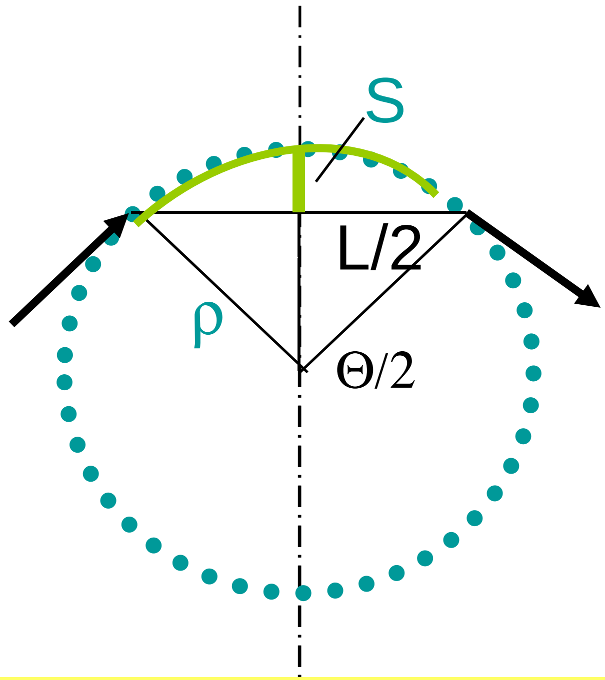
  Sagitta:

  S ~ (1/8) e • B • $L^2$ / p

  dp/p = ds/s ~ $B(L)^{-2}$

**L = 1 m, B = 1 T, L = 1 m, P = 1 GeV/c**

**>> S = .3 ÷ 8 ÷ 1 = 37.5 mm**




S = ρ(1-cos θ/2)

Taylor Expansion,

cos (θ) = 1 - $(\theta/2)^2/2! + (\theta/2)^4/4!$

S = ~ ρ $\theta^2$ / 8 = $eBL^2/8p$

S [m] = $0.3BL^2/8p$ [B:T, L: m, p: GeV/c]

# Basic Relations with Detector Magnet

- **Saggita:** $dp/p \sim \{B \bullet R^2\}^{-1}$
- **Deflection:** $dp/p \sim \{B \bullet R\}^{-1}$

- **Magnetic Field:** $\text{rot } B = \mu_0 J$
- **Stored Energy:** $E = 1/2\mu_0 \text{ Int. } B^2 \, dv$
- **Coil Mass:** $M = V_{coil} \, \gamma$
- **Pressure:** $p = B^2/2\mu_0$
- **Hoop Stress:** $\sigma_{hoop} = (R/t) \bullet p$
- **Wall thickness:** $t = (R/\sigma_h) \bullet p$
- **E/M ratio:** $E/M = (B^2/2\mu_0) \bullet R/2\gamma$
  $= \sigma_h/2\gamma$

| | |
|---|---|
| •B: | magnetic field |
| •$\mu_0$: | magnetic permeability |
| •$V_{field}$: | magnetic volume |
| •$V_{coil}$: | coil volume |
| •.$\gamma$: | effective density |
| •.$\sigma_{hoop}$: | hoop stress |
| •R: | coil radius |
| •t: | coil thickness |

# Superconducting Detector Solenoid Mechanics and Thermal Balance

- Material $t \propto RB^2 / (E/M) \propto RB^2 \gamma / \sigma_h$
  - **E/M (Stored Energy/ Cold Mass)** **to be higher**
  - **Superconductor to be stronger and lighter**
- Uniform Energy Absorption in case of Quench
  - Fast quench propagation >> Less theral stress

# Progress in Detector Magnets

Table 1. Progress of detector solenoid magnets in high energy physics.

| Experiment | Lab. | B [T] | R [m] | Length [m] | Energy [MJ] | X [Xo] | E/M [kJ/kg]: |
|---|---|---|---|---|---|---|---|
| CDF | Tsukuba/Fermi | 1.5 | 1.5 | 5.07 | 30 | 0.84 | 5.4 |
| TOPAZ* | KEK | 1.2 | 1.45 | 5.4 | 20 | 0.70 | 4.3 |
| VENUS* | KEK | 0.75 | 1.75 | 5.64 | 12 | 0.52 | 2.8 |
| AMY* | KEK | 3 | 1.29 | 3 | 40 | # | |
| CLEO-II | Cornell | 1.5 | 1.55 | 3.8 | 25 | 2.5 | 3.7 |
| ALEPH* | Saclay/CERN | 1.5 | 2.75 | 7.0 | 130 | 2.0 | 5.5 |
| DELPHI* | RAL/CERN | 1.2 | 2.8 | 7.4 | 109 | 1.7 | 4.2 |
| ZEUS | INFN/DESY | 1.8 | 1.5 | 2.85 | 11 | 0.9 | 5.5 |
| H1 | RAL/DESY | 1.2 | 2.8 | 5.75 | 120 | 1.8 | 4.8 |
| BABAR | INFN/SLAC | 1.5 | 1.5 | 3.46 | 27 | # | 3.6 |
| D0 | Fermi | 2.0 | 0.6 | 2.73 | 5.6 | 0.9 | 3.7 |
| BELLE | KEK | 1.5 | 1.8 | 4 | 42 | # | 5.3 |
| BES-III+ | IHEP | 1.0 | 1.45 | 3.5 | 9.5 | # | 2.6 |
| ATLAS-Central Solenoid | ATLAS/CERN | 2.0 | 1.25 | 5.3 | 38 | 0.66 | 7.0 |
| ATLAS-Barrel Toroid+ | ATLAS/CERN | 1 | 4.7-9.75 | 26 | 1080 | --- | |
| ATLAS-End-cap Toroid+ | ATLAS/CERN | 1 | 0.825-5.35 | 5 | 2 x 250 | --- | |
| CMS+ | CMS/CERN | 4 | 6 | 12.5 | 2600 | # | 12 |

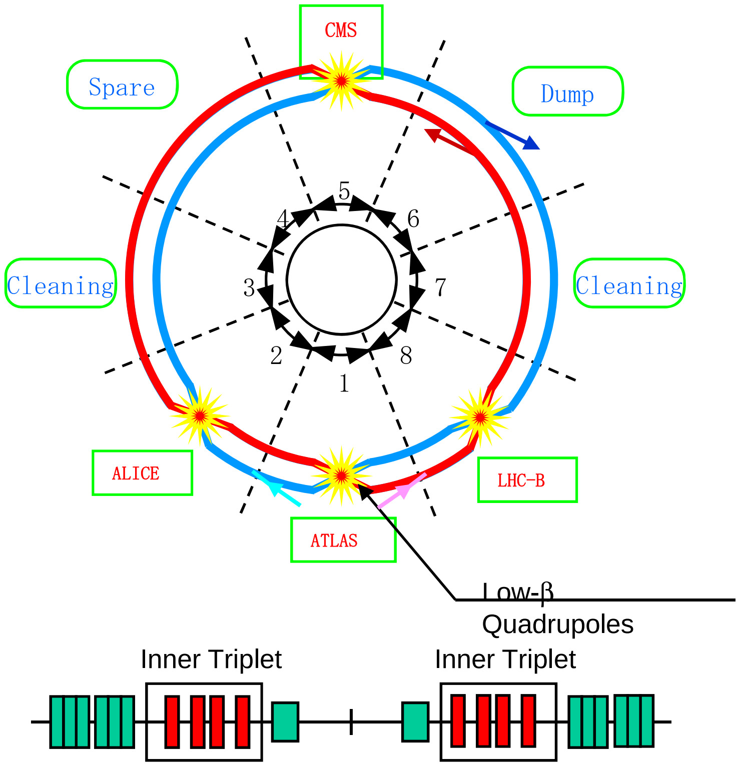
* operation complete,

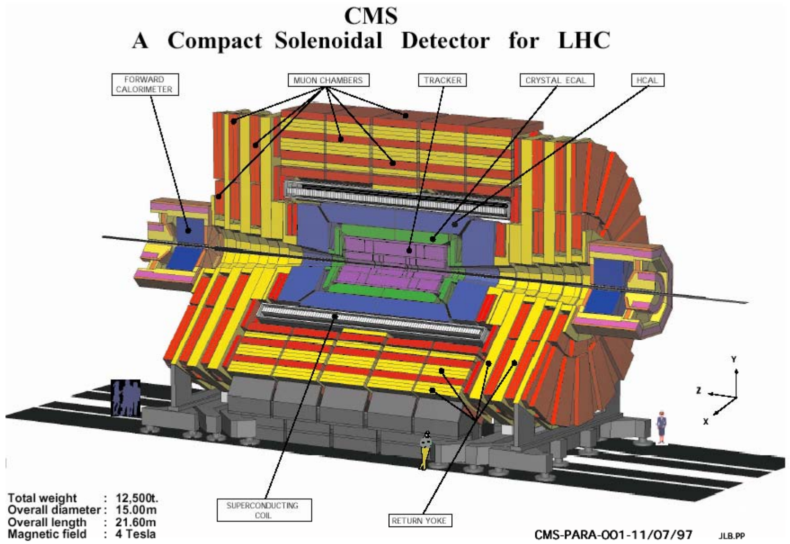
+ detector under construction

# EM calorimeter inside solenoid, so small radiation length, X, not a goal,

# Status: Collider Detector Magnets

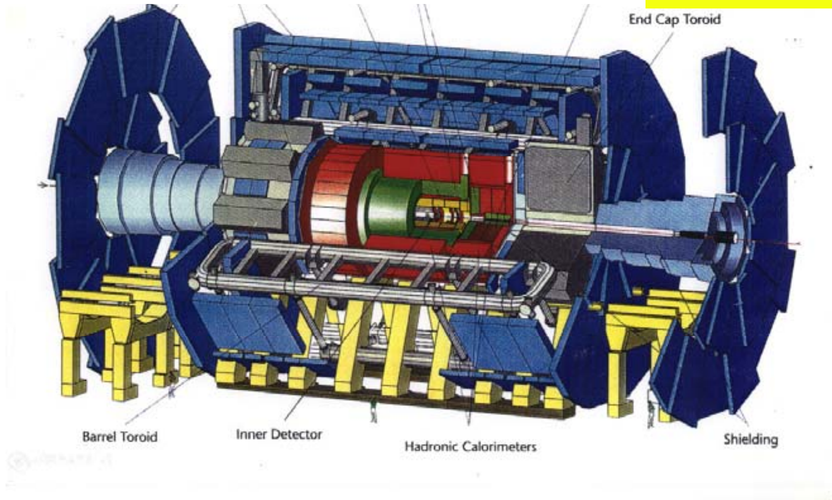
## CERN-LHC Experiments



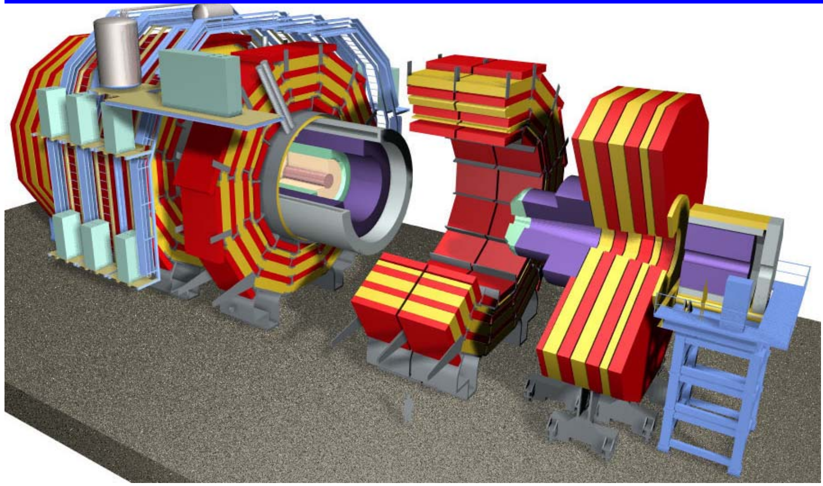



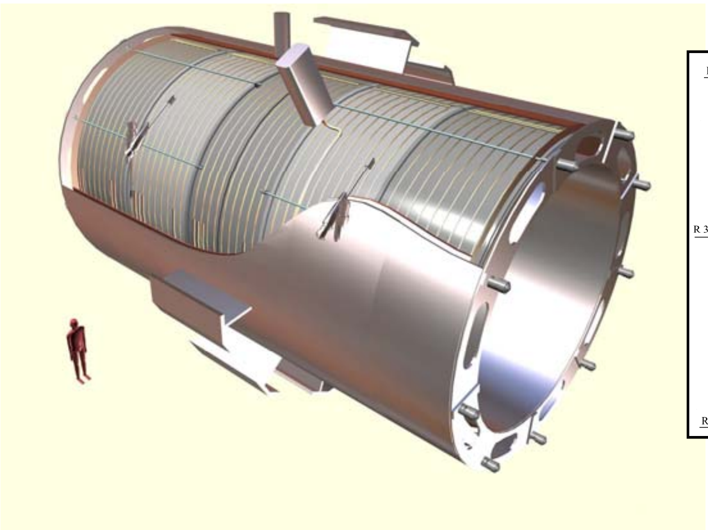

CMS

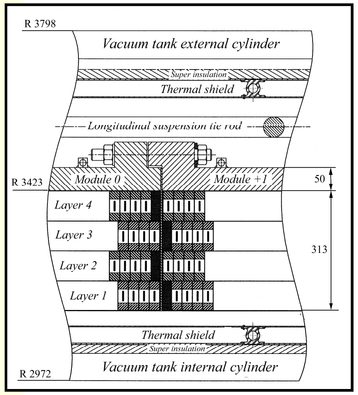
ATLAS



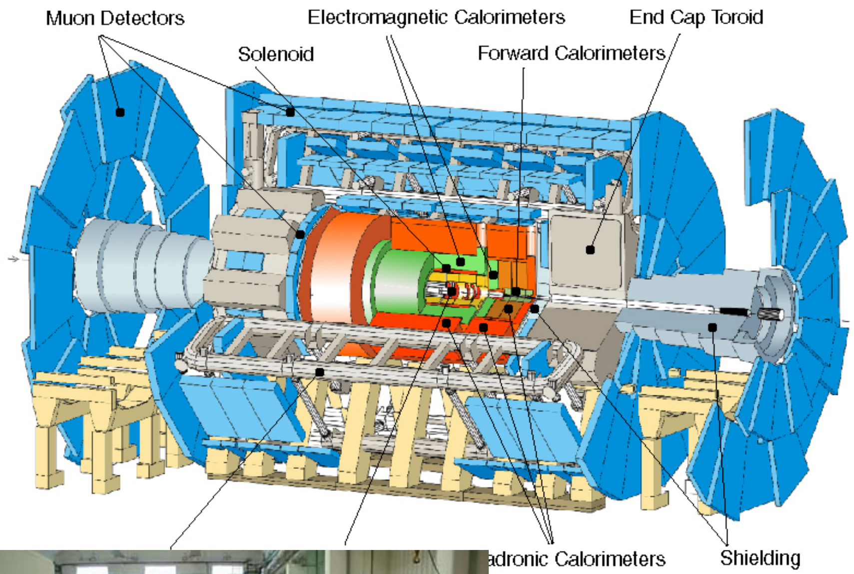
# CMS
# High Field and Compact

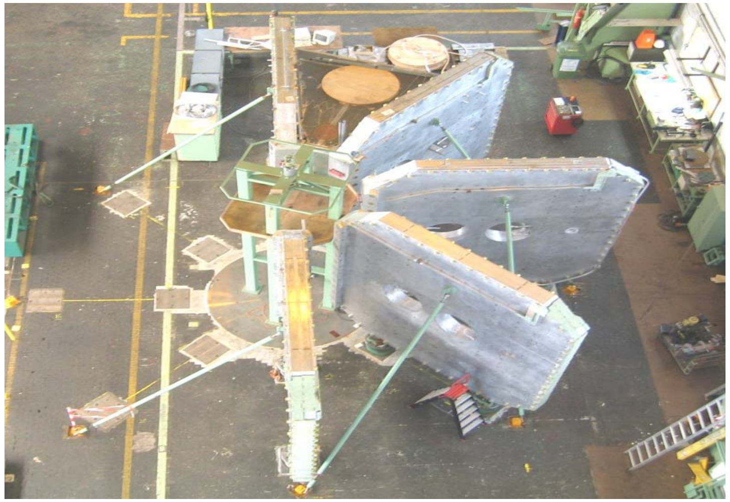


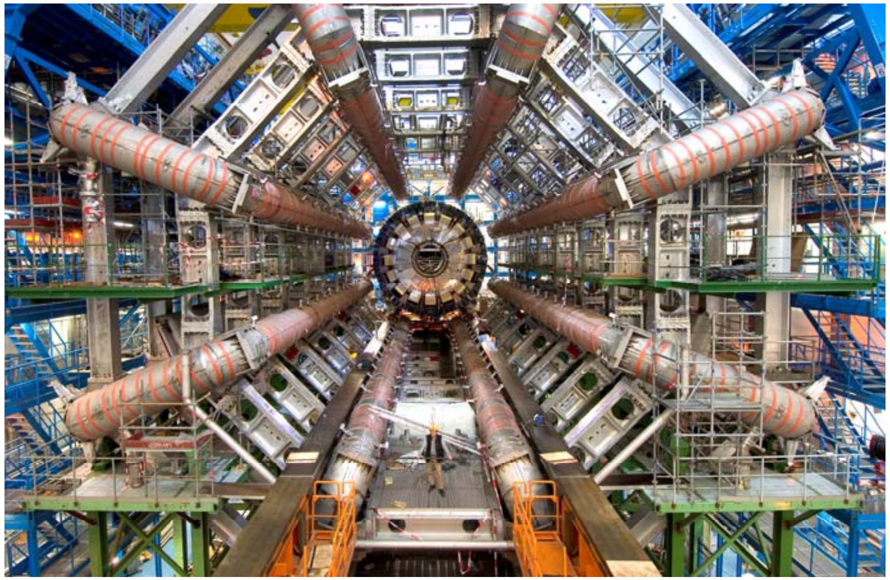




# ATLAS Toroidal Magnet System

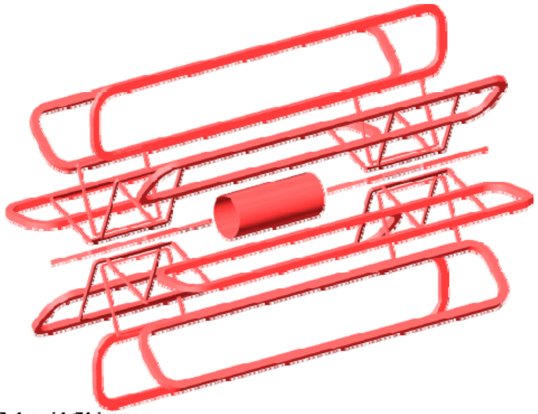


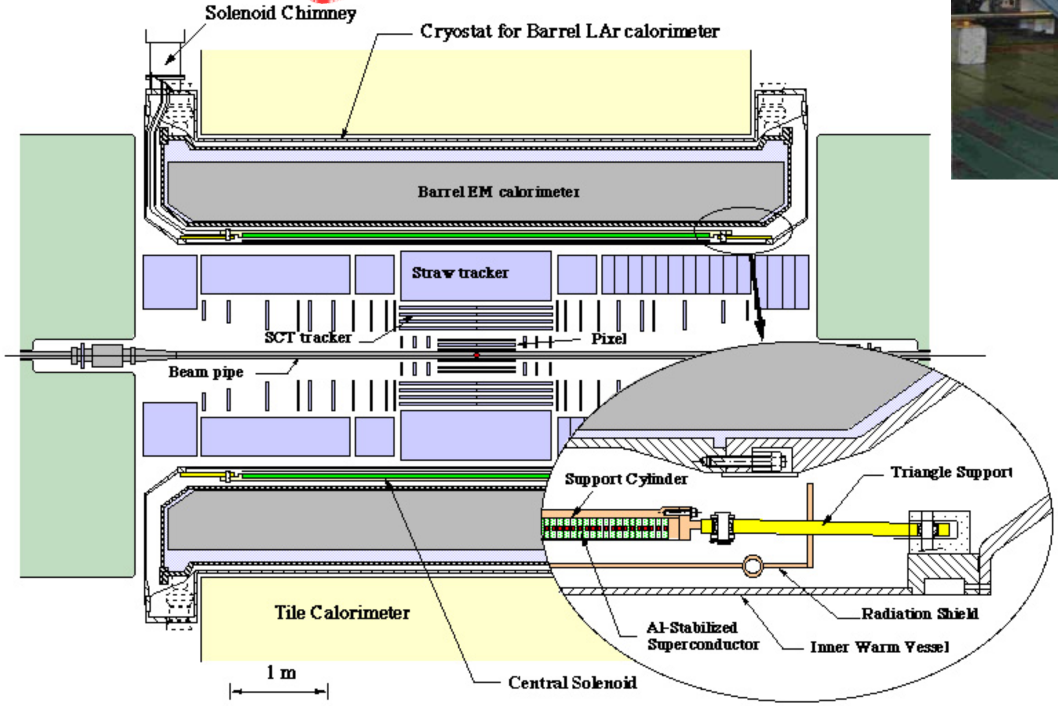



width: 44m
diameter: 22m
weight: 7000t

# ATLAS Central Solenoid

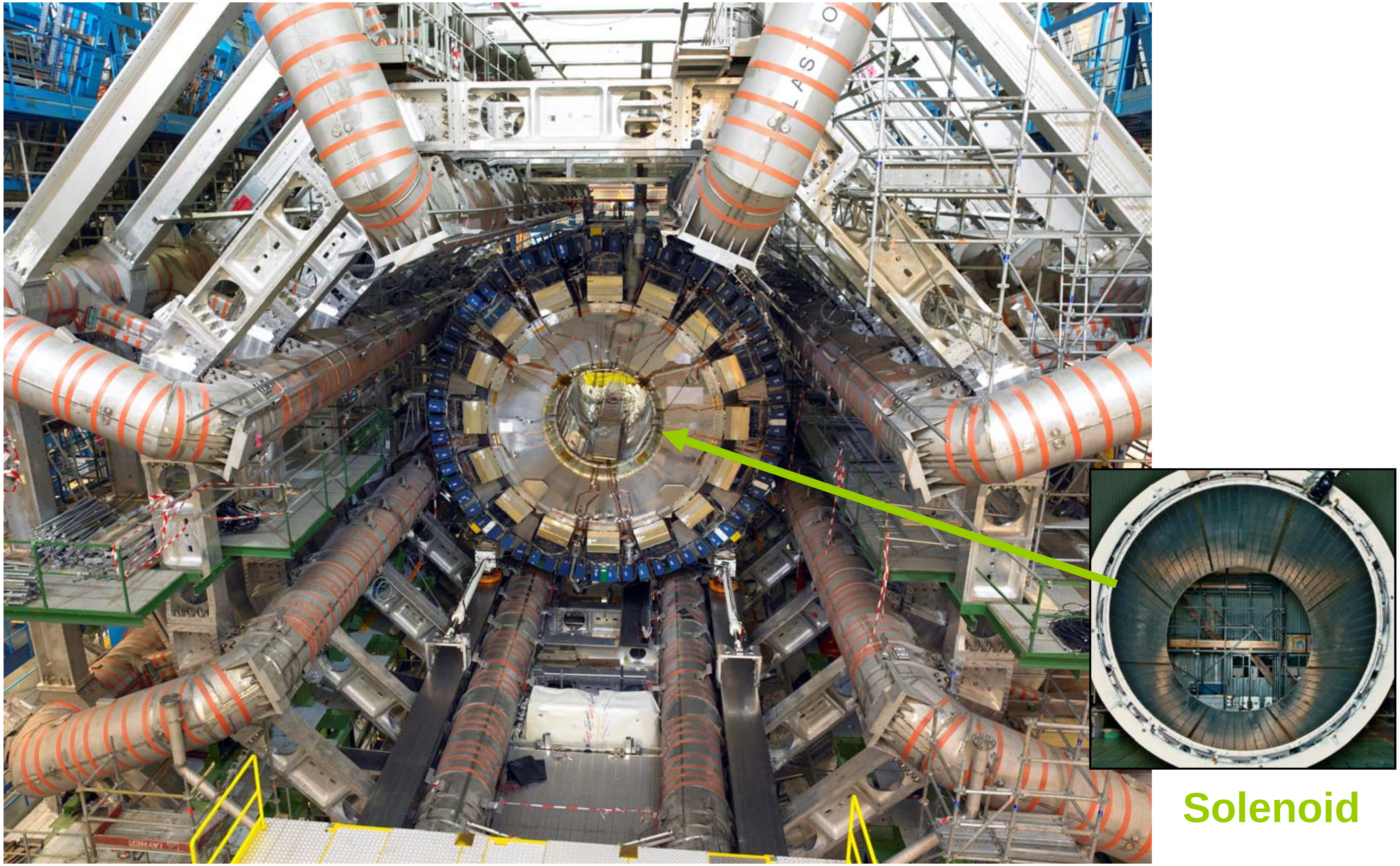





Thin coil
High-strength
Al-stabilizer

30 mm

# ATLAS Central Solenoid installed



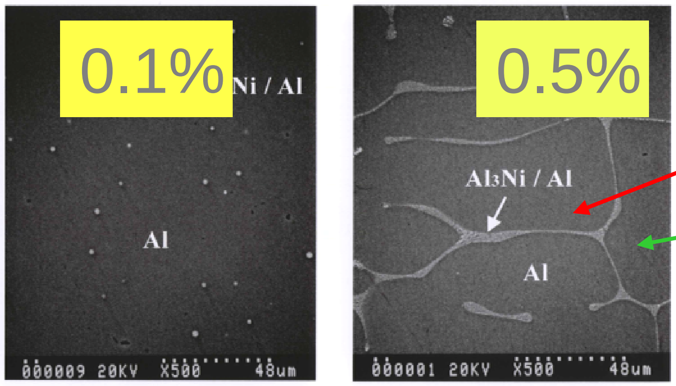
# Superconducting Detector Magnets at LHC

| Experiment | B [T] | R [m] | E [GJ] | E/M [kJ/kg] | Remark |
|---|---|---|---|---|---|
| **ATLAS** | | | | | |
| **CS** | **2.0(2.1)** | **1.25** | **0.04** | **7** | **High-St. Al, no-cryo** <br> **Thin solenoid (0.7 Xo)** |
| **BT** | **~1** | | **1.08** | **3** | **8 split, Largest** |
| **ET** | **~1** | | **2x0.25** | **1.6** | **Single cold mass** |
| **CMS** | **4.0** | **3.2** | **2.6** | **12** | **Hybrid-conductor** |

**ATLAS CS, BT, and CMS successfully commissioned**

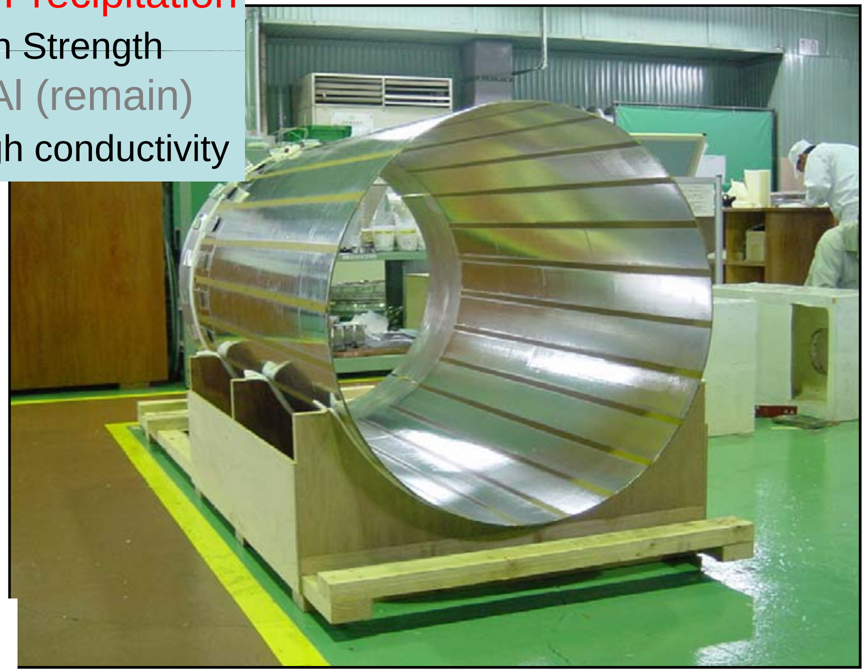
# An Extremely Thin Solenoid

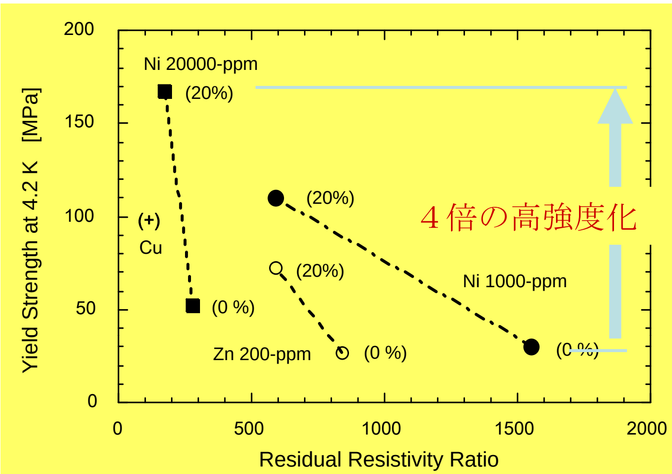
BESS-Polar : Bc = 1 T, D = 0.9 m, t = 3 mm, X = 0.1 Xo

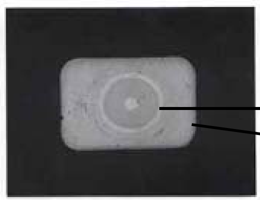



a) Al-0.1wt%Ni Alloy    b) Al-0.5wt%Ni Alloy

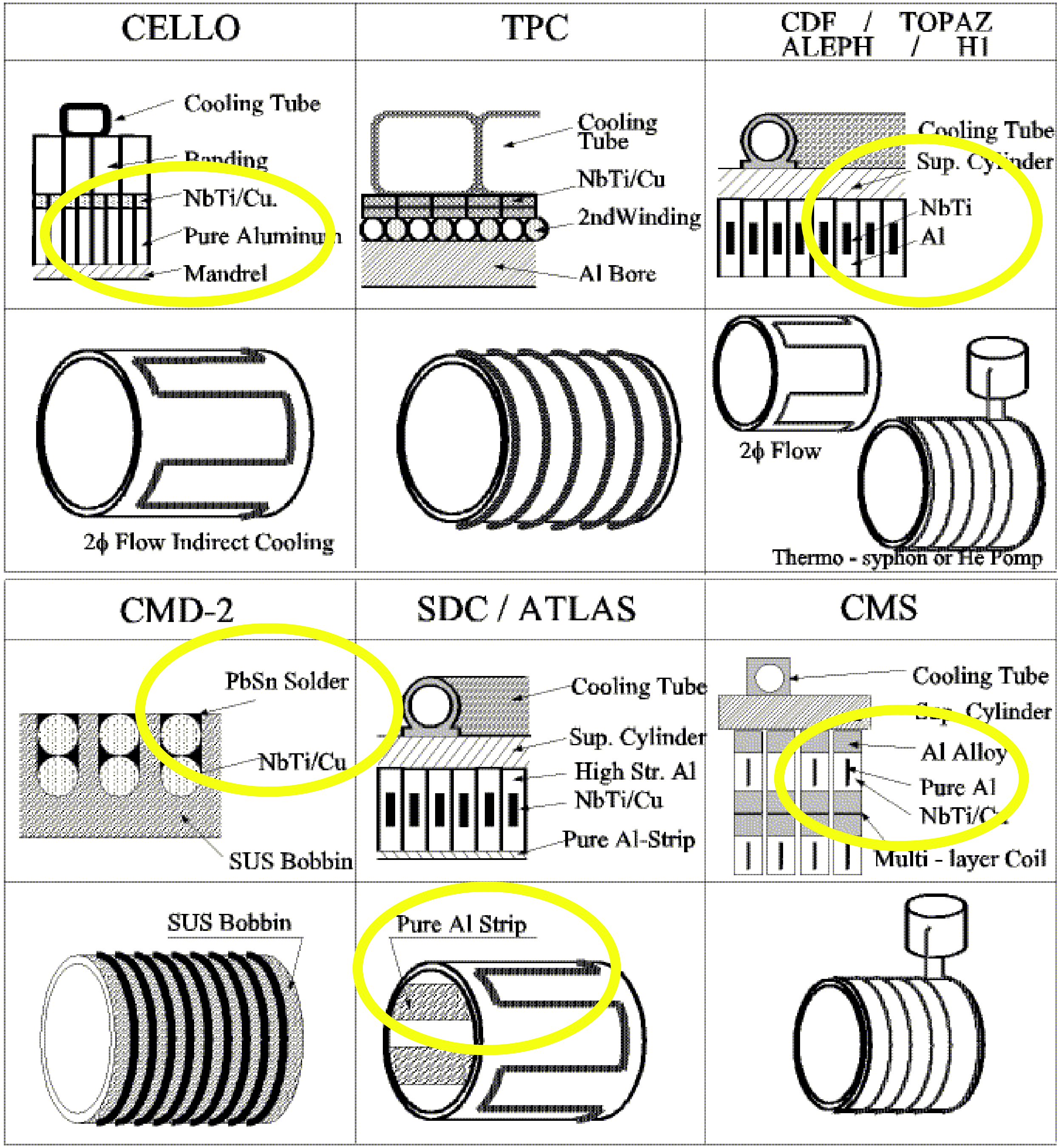
$Al_3Ni$ Precipitation
High Strength
Pure Al (remain)
High conductivity





NbTi superconudctor
Al-stabilizer
>> High strength and Low R




Recognized events;

CDF
Al-co-extrusion,

TOPAZ
Inner winding

Aleph/Dephi
Thermo-syphone/Pump

Zeus/Cleo
Two layer, Grading

BESS/SDC/ATLAS-CS
Pure-Al strip

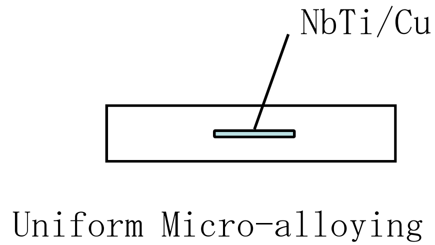
SDC/ATLAS-CS
High strength Al stab.

CMS
Hybrid conductor

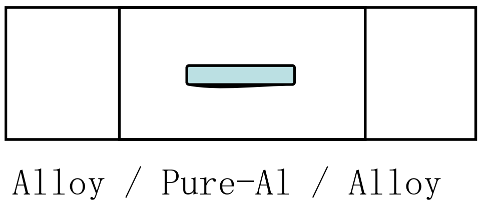
BESS-P
Self supporting

# Two Approach for High-Strength Al-Stabilizing

- **Reinforcement of Al**
  - **with keeping low resistivity**
- **Uniform reinforcement**
  - **Micro-alloying and cold work**
  - **ATLAS-CS**
- **Hybrid reinforcement**
  - **Welding Al-Alloy with pure-Al**
  - **CMS**




Uniform

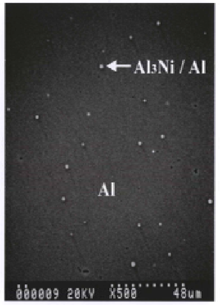



Hybrid

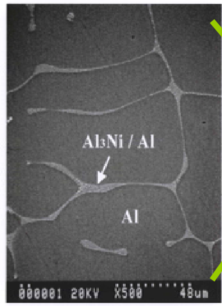
# High-strength Al-Stabilizer
# Uniform reinforcement

- Highest B with minimizing wall material:

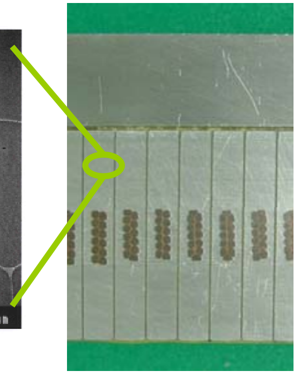
- High strength superconductor
  - Ni-doped Al-stabilizer:
    - mechanical reinforcement
    - Low electrical resistance,

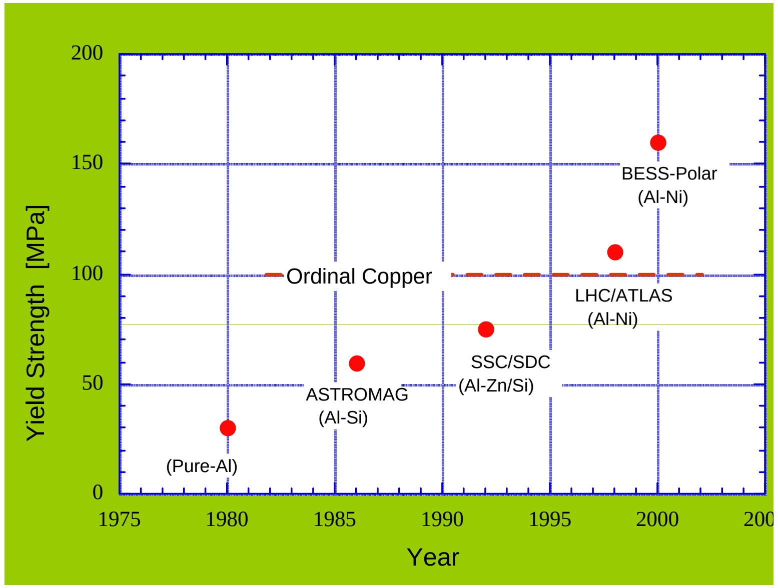


a) Al-0.1wt%Ni Alloy

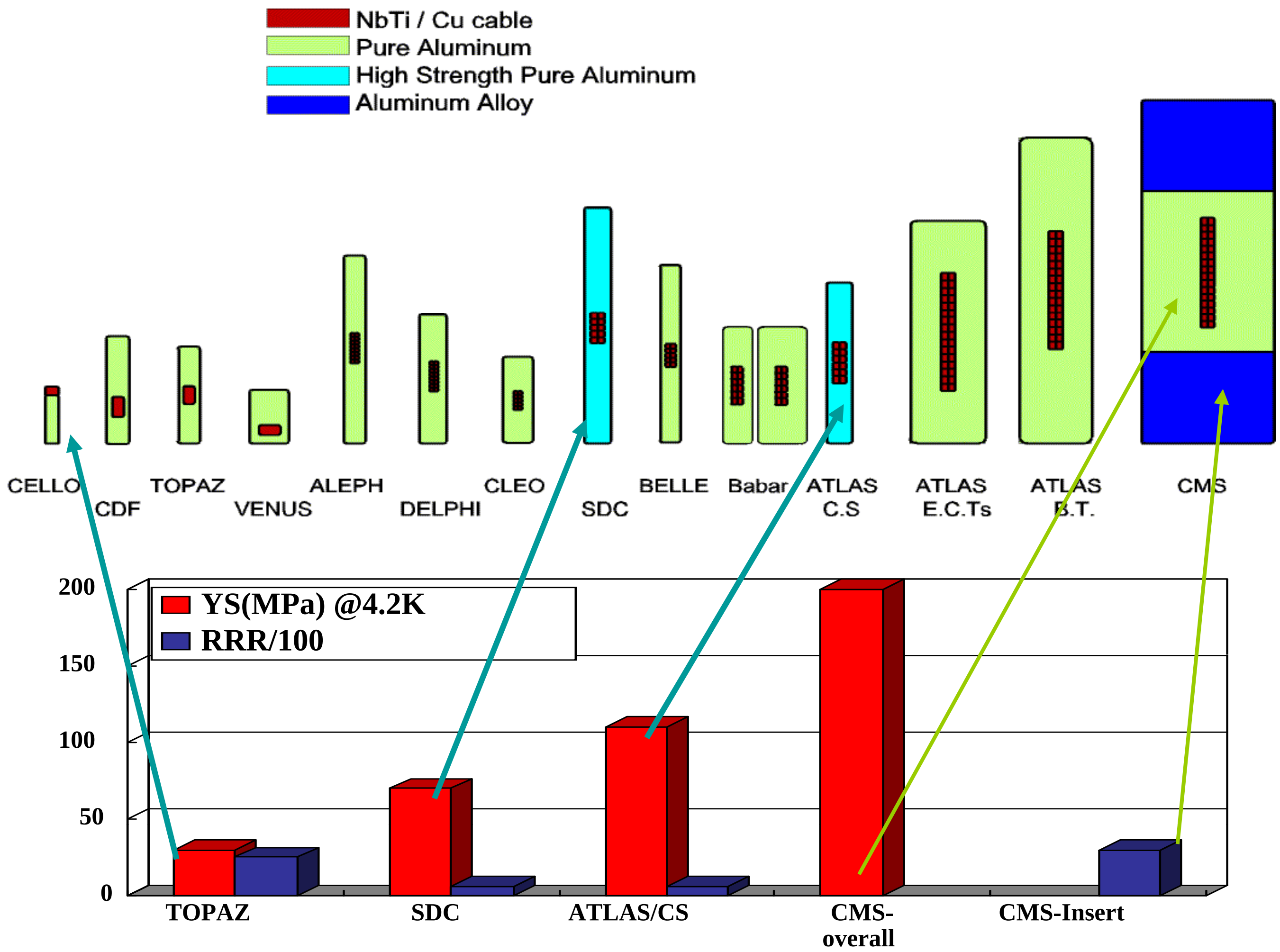


b) Al-0.5wt%Ni Alloy





# Progress of Al-Stabilizer Superconductor in Colliding Detector Magnets



# Basic Relations with Detector Magnet

- **Saggita:** **$dp/p \sim \{B \cdot R^2\}^{-1}$**
- **Deflection:** **$dp/p \sim \{B \cdot R\}^{-1}$**

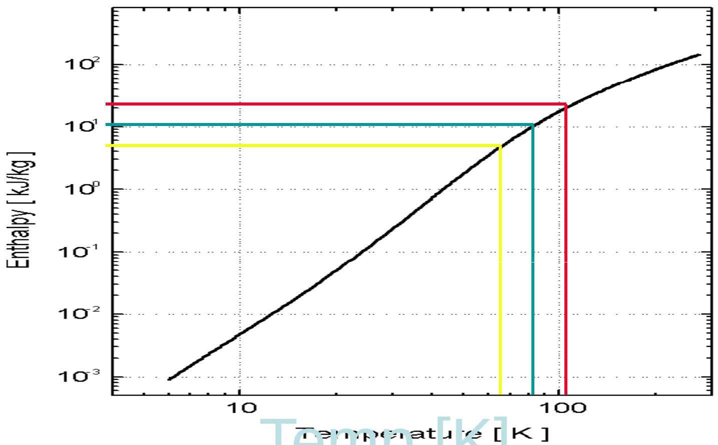
- **Magnetic Field:** **$rot\ B = \mu_0 J$**
- **Stored Energy:** **$E = 1/2\mu_0\ Int.\ B^2\ dv$**
- **Coil Mass:** **$M = V_{coil}\ \gamma$**
- **Pressure:** **$p = B^2/2\mu_0$**
- **Hoop Stress:** **$\sigma_{hoop} = (R/t) \cdot p$**
- **Wall thickness:** **$t = (R/\sigma_h) \cdot p$**
- **E/M ratio:** **$E/M = (B^2/2\mu_0) \cdot R/2\gamma$**
  **$= \sigma_h/2\gamma$**

| | |
|---|---|
| •B: | magnetic field |
| •$\mu_0$: | magnetic permeability |
| •$V_{field}$: | magnetic volume |
| •$V_{coil}$: | coil volume |
| •.$\gamma$: | effective density |
| •.$\sigma_{hoop}$: | hoop stress |
| •R: | coil radius |
| •t: | coil thickness |

# E/M : Stored Energy / Cold Mass

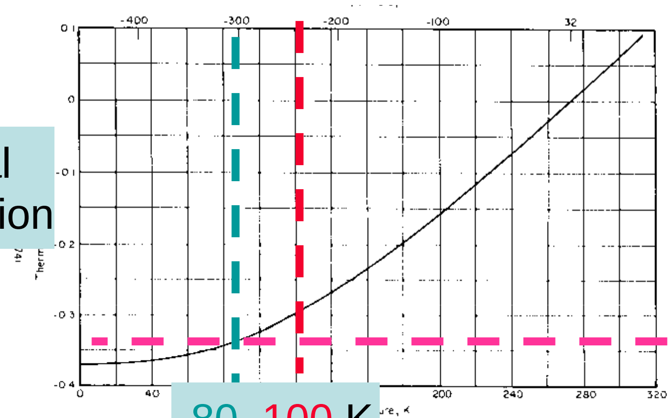
## A Scaling Parameter to optimize Coil Design

Entharpy




Temp [K]

Thermal Expansion




80, 100 K

**Enthalpy**

**H = E/M = Int. Cp dt**

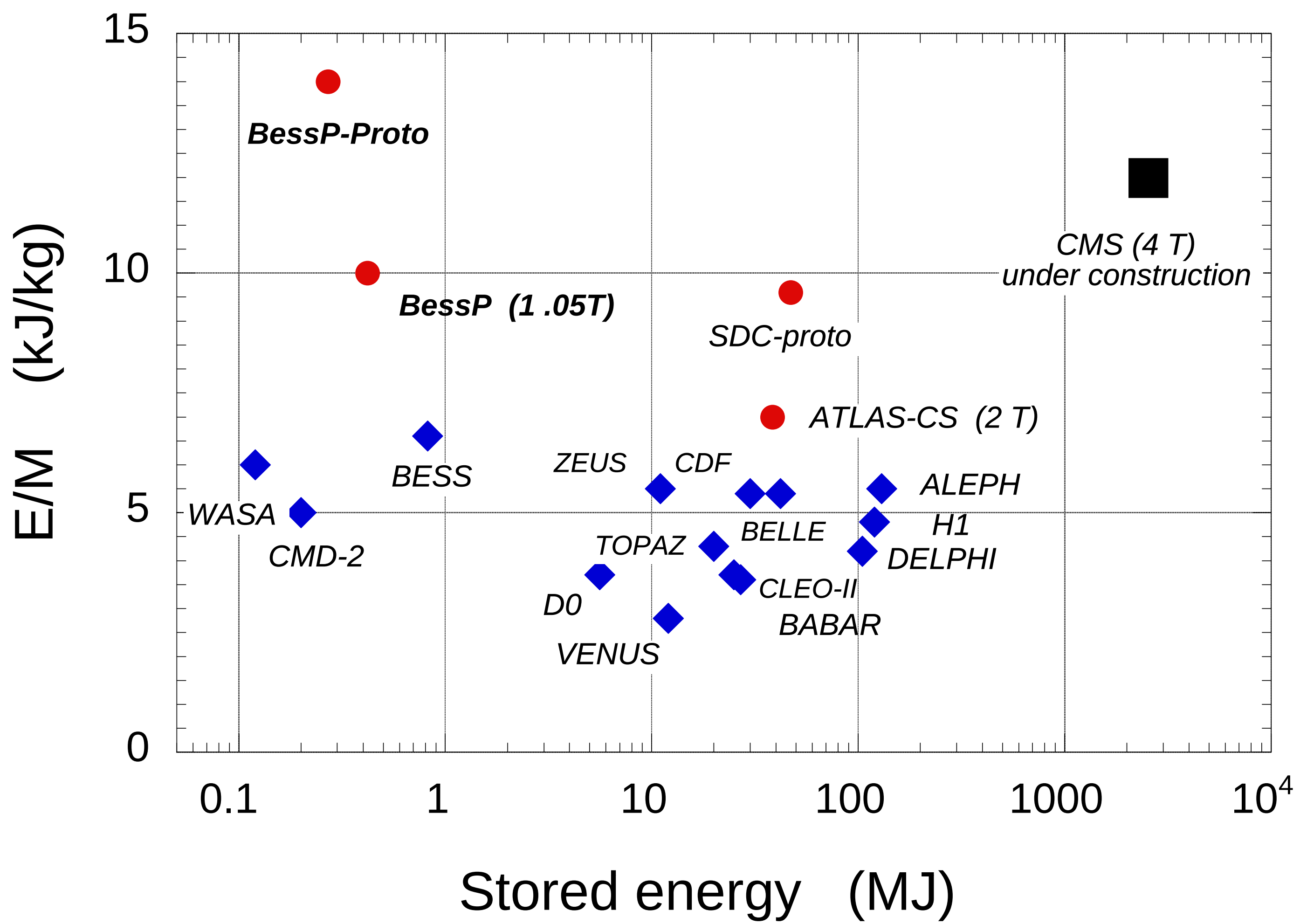
**--------------------------------**

| | |
|---|---|
| **20 kJ/kg** | **~100 K** |
| **10 kJ/kg** | **~ 80 K** |
| **5 kJ/kg** | **~ 65 K** |

**--------------------------------**

**Peak Temperature with homogeneous energy dump**

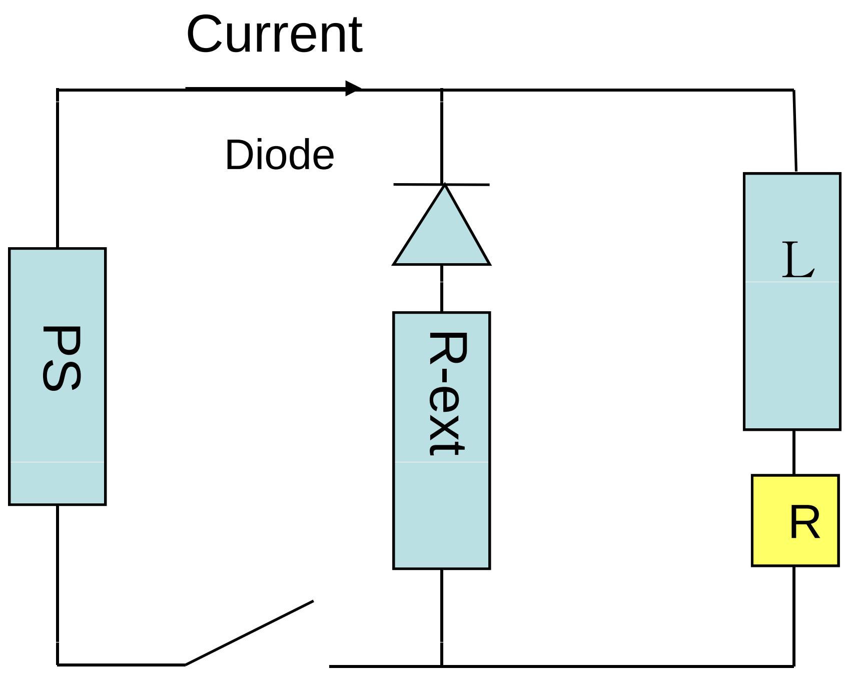
# E/M Ratio achieved



# Partical Energy Extraction

## for E/M ratio practically reduced

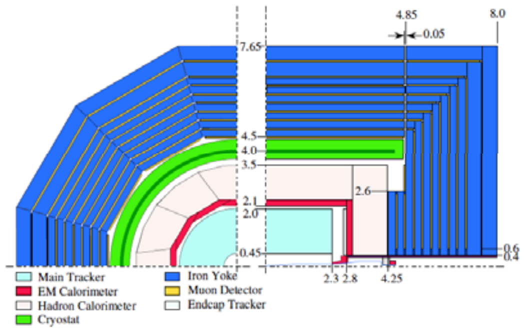
- Immediate switch off and
  - Extraction of energy into external dump resister
  - Lower energy dump into coil
  - Lower peak temperature
- Rreliability to be very imprtant
  - Voltage limit across R-ext




Decay Time constant $L/(R_{ext} + R_{coil})$

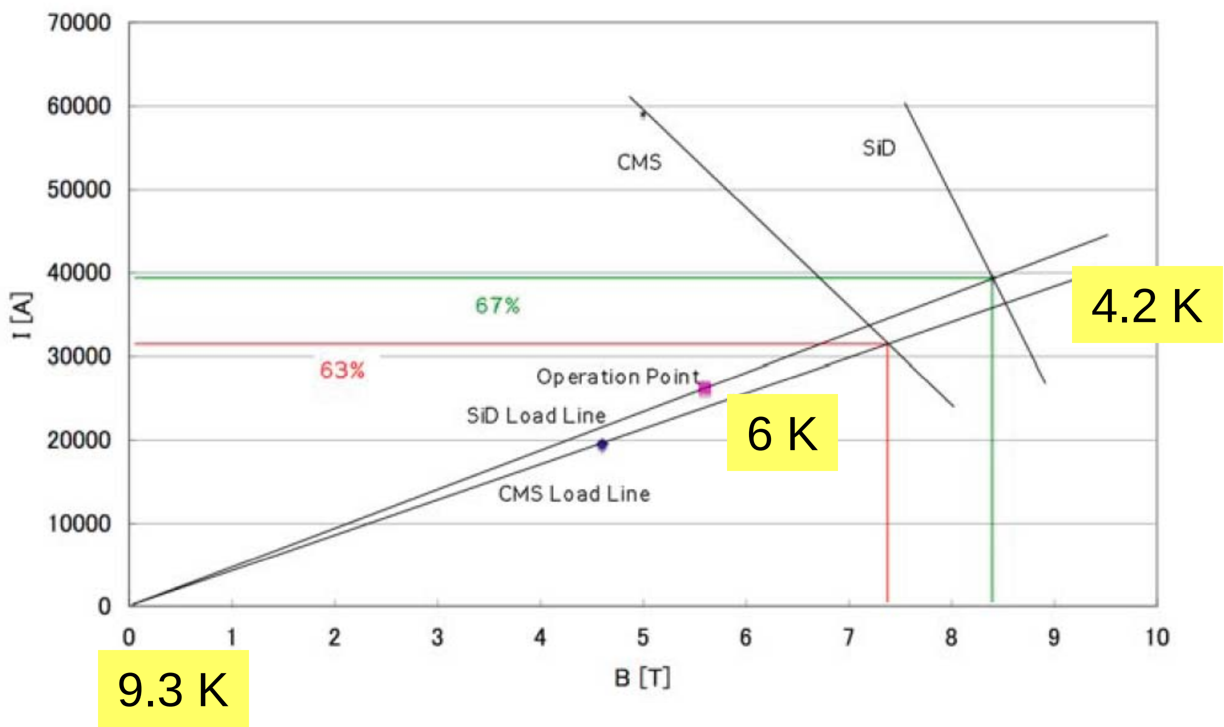
# ILC Detector Magnets
# Possible Design Parameters

| | | LHC | | ILC | | | |
|---|---|---|---|---|---|---|---|
| | unit | ATLAS-CS | CMS | GLD | LDC | SiD | 4th |
| Mag. Field | T | 2 | 4 | 3 | 4 | 5 | 3.5/-1.5 |
| Diameter | m | 2.5 | 6.5 | 8 | 6.3 | 5.3 | 6 / 11 |
| Coil thick. | m | 0.045 | 0.3 | ~0.4(0.7*) | ~0.3 | 0.4 | |
| Length | m | 5.4 | 12.5 | 8.9 | 6,6 | 5 | 11 |
| St. Energy | GJ | 0,04 | 2.6 | 1.6 | 1.7 | 1.4 | 5.7 |
| E/M | kJ/kg | 7 | 12 | ~ 20 (12*) | 13 | 12 | |




* Revision suggested

# NbTi Superconductor Facing Limit with Temperature Margin



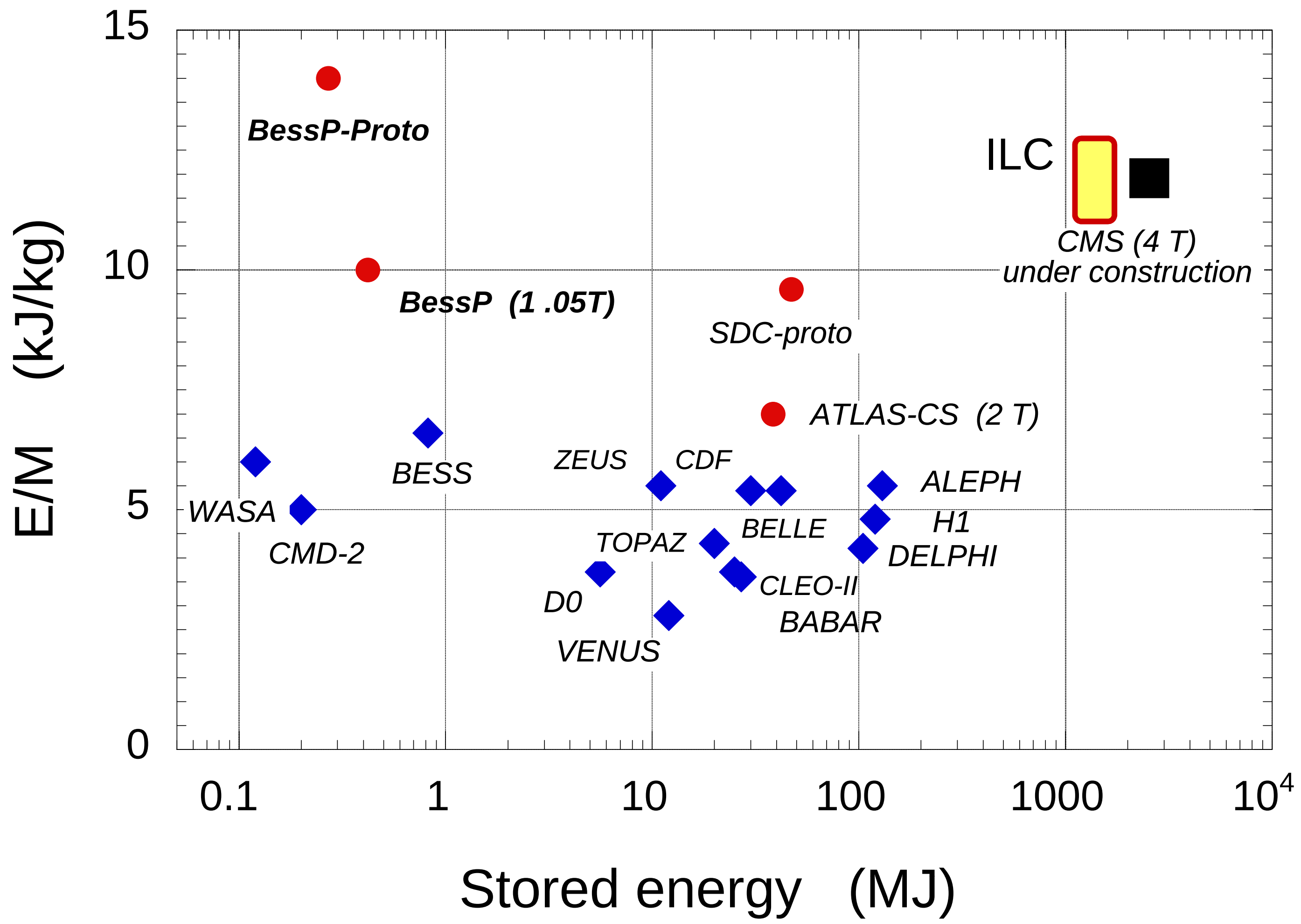

- A load line ratio of < 70 % should be kept to keep a temperature margin of >> 1 K.
- A useful field of 5 T reaching the practical limit of NbTi

# Guide Lines Suggested for ILC Detector Magnets

- NbTi superconductor at Bc = 5 T or smaller,
  - T-margin >> 1 K for reliable operation
- Al-stabilized superconductor
  - High strength Al-stabilizer inevitably important for practical magnet design with E/M ratio of 10-12 kJ/kg
  - Quench protection with ~ 50 % energy extraction.

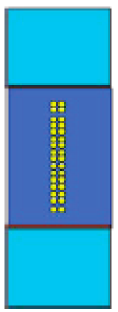
- Three detector solenoids may be similarly designed.
- The 4th concept requires much engineering.

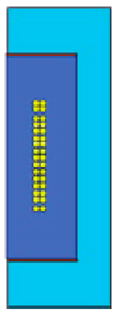
# E/M Ratio Expected at ILC Solenoids

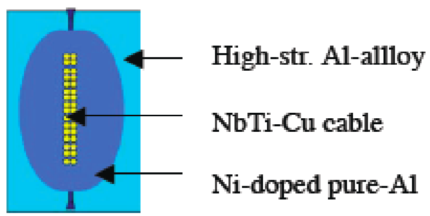


# Further Optimization on Strength and RRR

| | Rein-force | Feature | Al Y. S. (MPa) | Full cond. Y.S. | Full cond. RRR |
|---|---|---|---|---|---|
| LHC ATLAS-CS | Uniform | Ni-0.5% Al | 110 MPa | 146 MPa | 590 |
| LHC CMS | Hybrid | Pure-Al & A6082-T6 | 26/428 | 258 | 1400 |
| Future | Hybrid | Ni-Al & A6082-T6 | 110/428 | 300 | 300 |
| Future | Hybrid | Ni-Al & A7020-T6 | 110/677 | 400 | 300 |



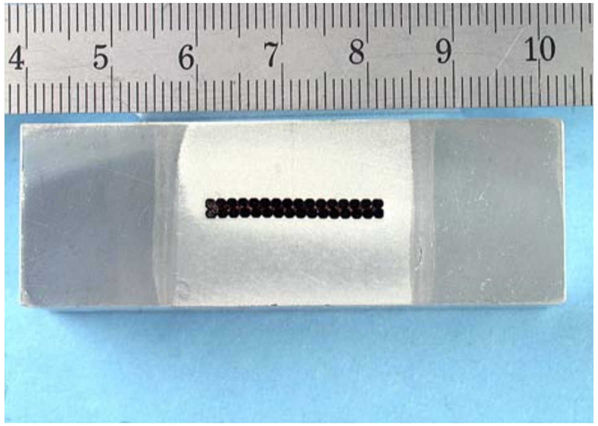


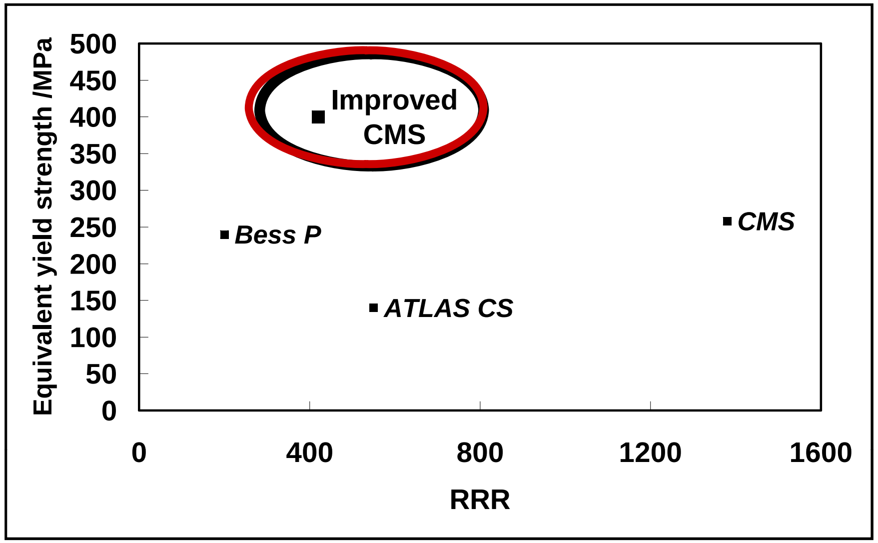



# Further Development for Al-Stabilizer Superconductor

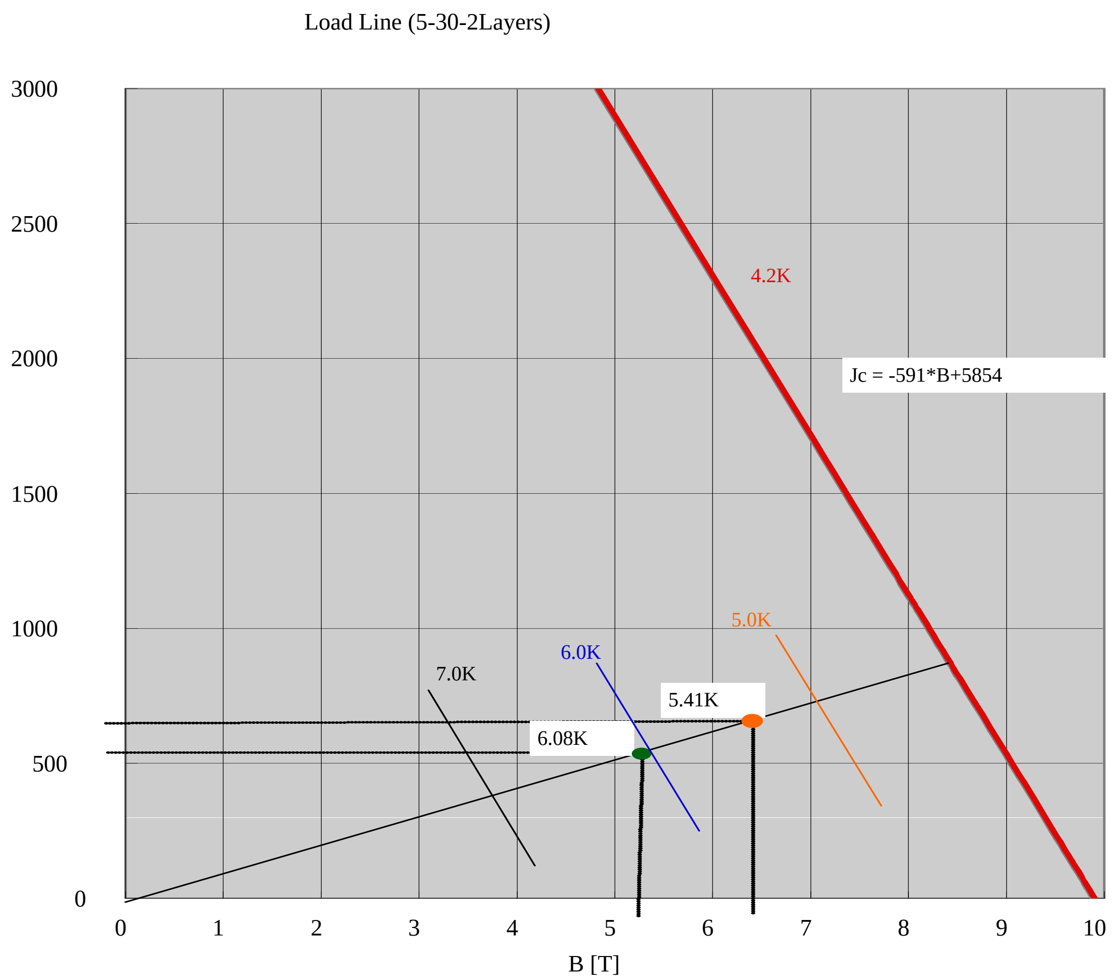
- Energy Frontier Collider Detector
  - Field > 5 Tesla
  - Scale Diameter, 10m
- Further reinforcement
  - ATLAS H.S. stabilizer
    - Ni-0.5 ~ 1 %
  - CMS-Hybrid Support
    - A6058 -->> A7020

Y.S.(0.2%) = 400 MPa
RRR = ~ 400



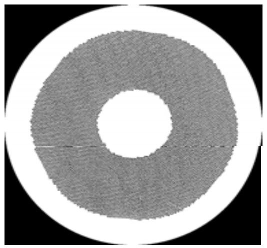
# Limit of NbTi Application practically at < 6 T

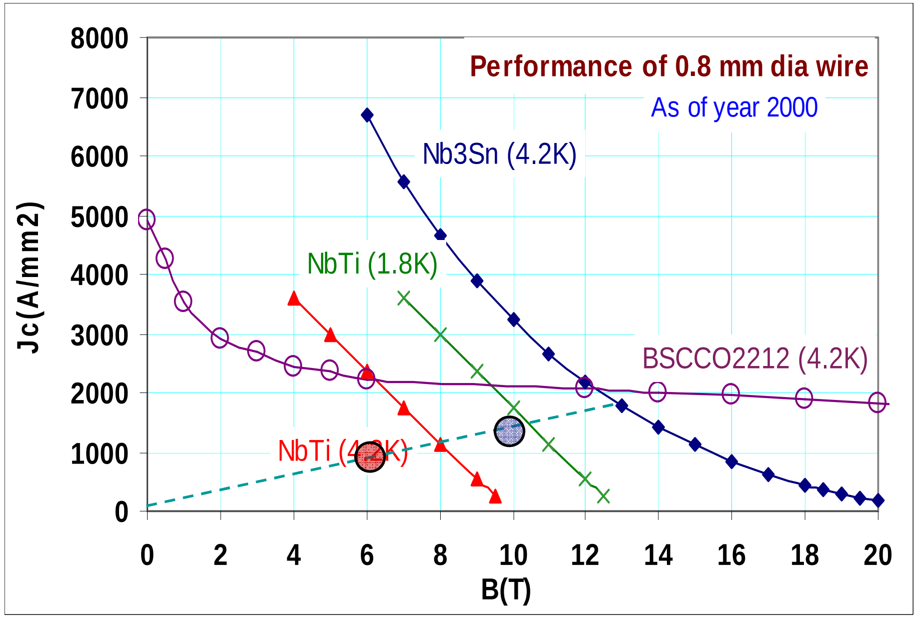



Load Line Ratio kept < 70 % to reserve T-margin > 1 K

# Toward Higher Field

- **Al-stabilized Nb3Sn/Nb3Al Solenoid beyond 10 T**
- **An R&D may be proposed in cooperation with NIFS.**






**Nb3Sn/Nb3Al Application Necessary to be investigated**

# Push-pull Design for Detector Magnets and Cryogenics

▪ Detector magnet system needs to be movable together with :

– Magnet power supply (~ 20 kA, DC),

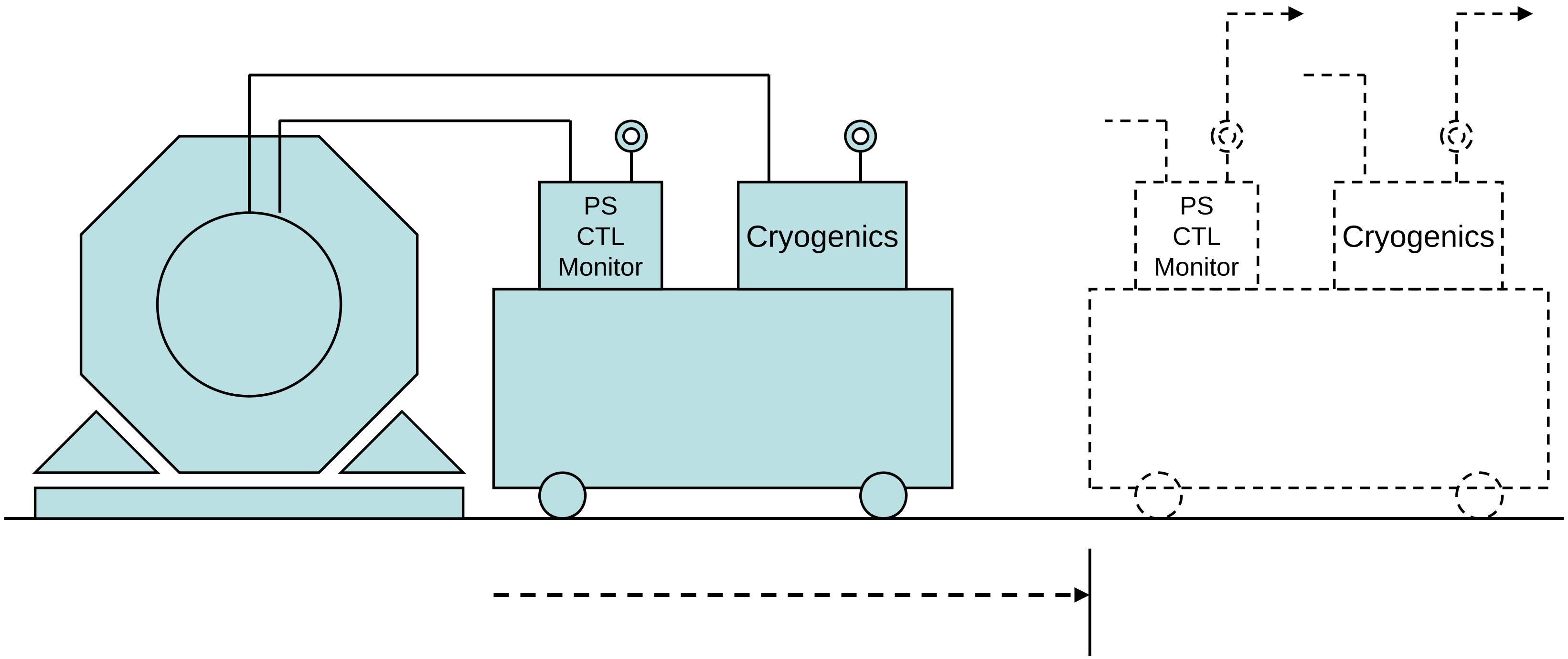
– Cryogenics (Cold-box), and

– Control system (control, monitor, safety interock etc),

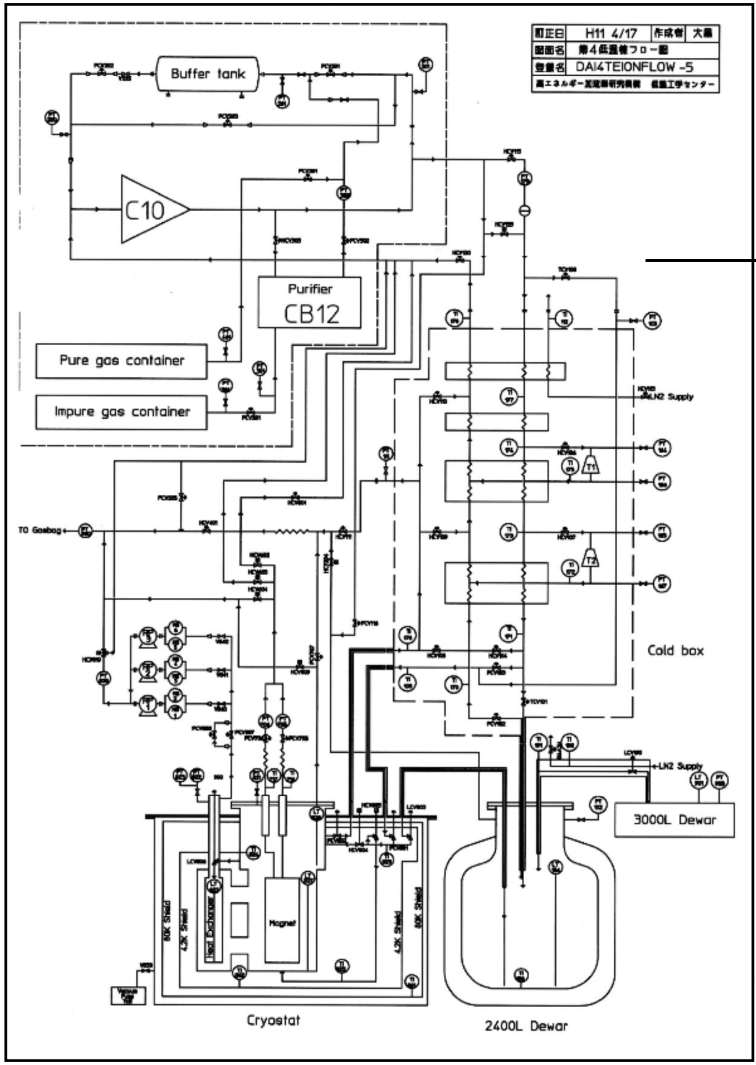
On the platform.

- Connections/reconnections required for components working at room temperature

# Concept of Pushpull Detector System with SC Magnet and Cryogenics



# Cryogenics Flow Diagram




Fixed at Room Temp.
Compressors etc.

Disconnection needed

Movable cold part

Cryogenics
Cold box
Control dewar

Magnet

# Possible Move-in/out Time

| | Day 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Stop steady op.,B-off,<br>Cryo. cold-box warm-up, | | | | | | | | | | |
| Seal-off & disconnect pipe and cables | | | | | | | | | | |
| Move-in/-out | | | | | | | | | | |
| Reconnect pipes and cables | | | | | | | | | | |
| Check safety<br>(leak tight, interock) | | | | | | | | | | |
| Cryogenics re-start cool-down, | | | | | | | | | | |
| Check safety at cold, &<br>pre-excitation test | | | | | | | | | | |
| Re-start detector run | | | | | | | | | | |

One week would be a reasonable time for
such critical operation for high-pressure gas system

# Summary

- ILC detector magnets may be built by using NbTi Al-stabilizer superconductor
  - Magnetic field of **5 T** as an ultimate field,
  - E/M ratio of < **~ 12 kJ/kg**
  - With energy extraction of 50 % in case of quench,

- **Push-pull** design acceptable, with assming a transition period of a week

- Detector magnets beyond 5 T requires further R&D by using Nb3Sn/NbsAl and HTS.