Superconducting Magnets for Particle Detectors

Akira Yamamoto (KEK)

Presented at

The Roots of the LHC Technology:

CERN Centennial Superconductivity Symposium,

CERN, 8th December, 2011

Outline

- Progress in SC Magnets for particle detectors
- LHC detector magnets as state-of-art technology
- Toward a dream:
  - Transparent magnetic field
  - Al-stabilized superconductor as a key technology
- Application in space science and muon physics
- Summary

Progress in Superconducting Magnets for Particle Detectors

- Features:
  - Higher field
  - Energy saving
  - Compact and 'Transparent magnetic field'

1960 ~ 2010

Bubble Chambers
(CERN, BNL, …)
(Discussed by P. Lebrun)

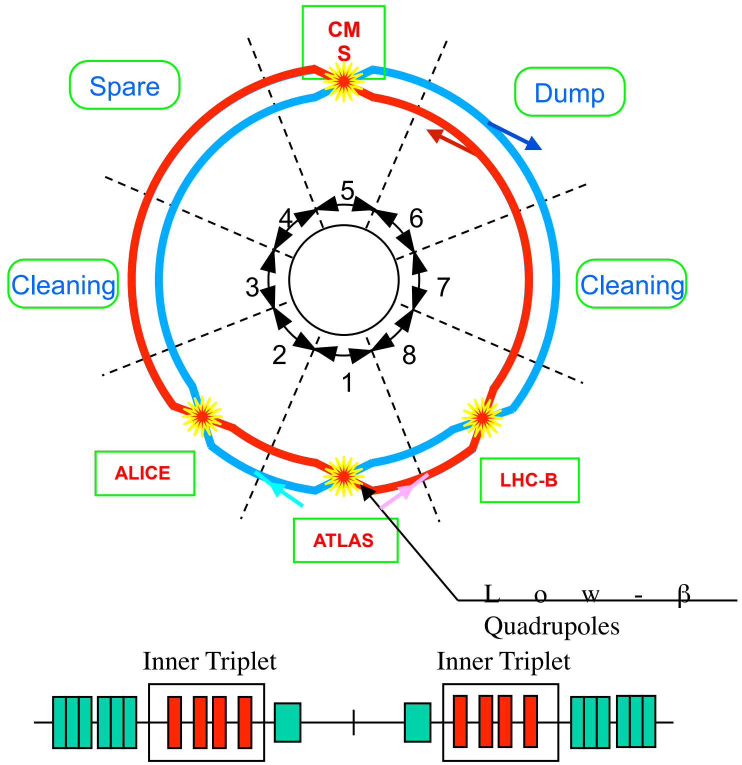
Spectrometers
(BNL, KEK, JLab …)

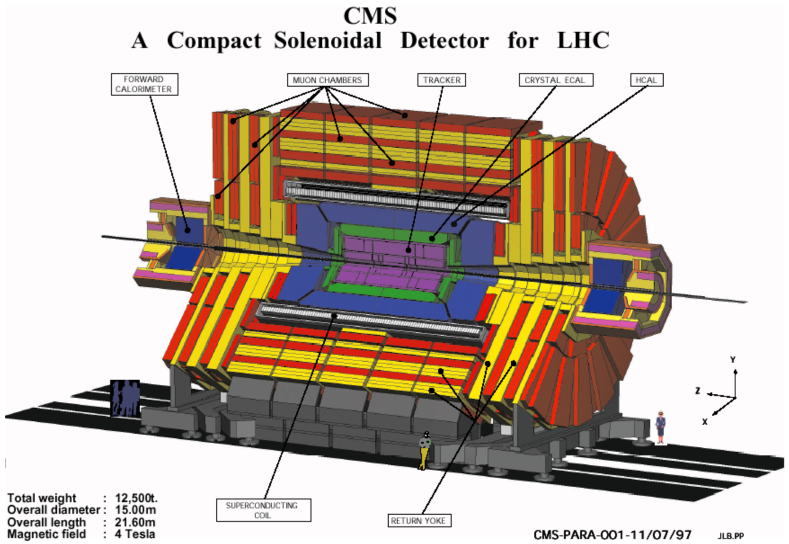
Collider detectors
(CERN, FNAL, DESY, INFN, …)
Focus in this talk

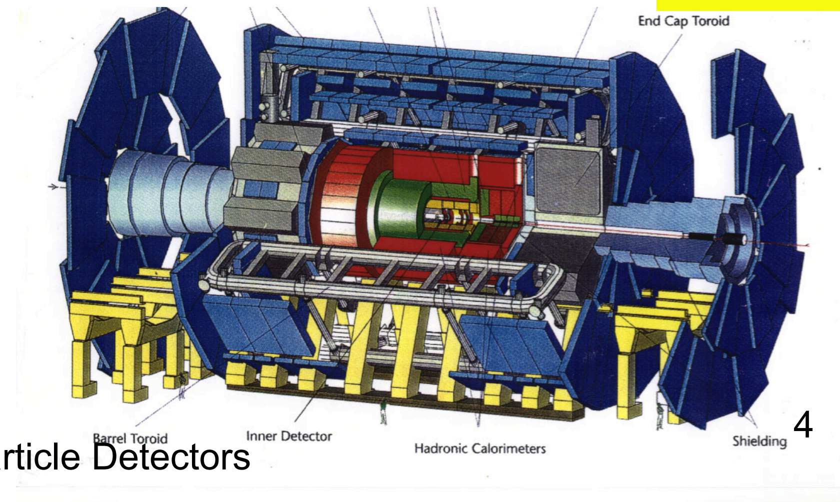
Application in space and others
(LBNL, KEK, MIT, … ,)

Collider Detector Magnets

CERN-LHC: CMS and ATLAS

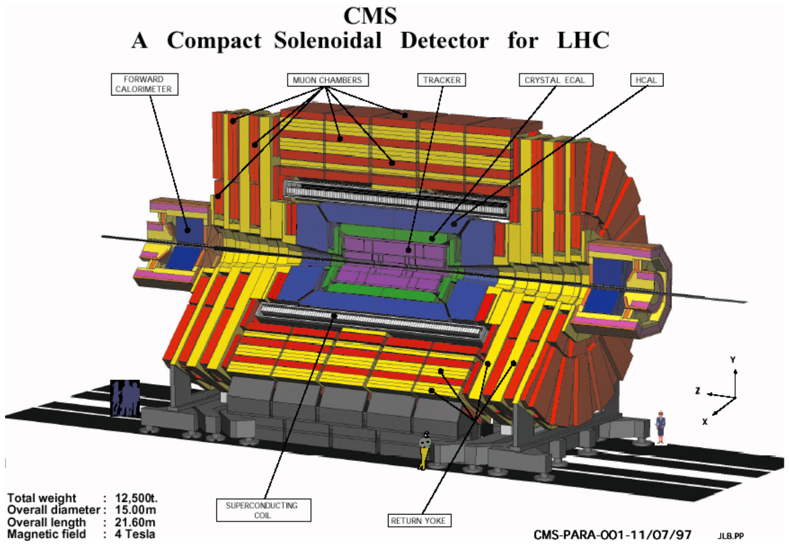






Collider Detector Magnets Features

- CMS: solenoid
- Strong and uniform field
- Field inside the solenoid
  - Sagitta measurement
  - $dp/p \sim \{B \cdot R^2\}^{-1}$
- Deflection angle outside the solenoid
  - $dp/p \sim \{B \cdot R\}^{-1}$

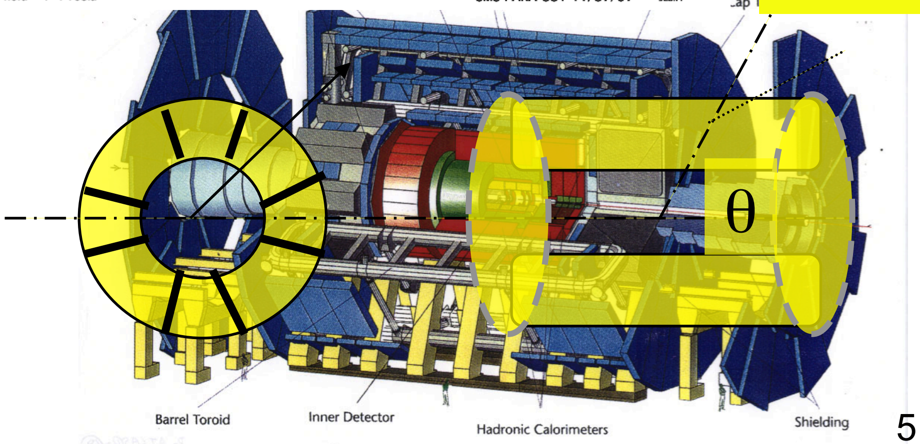


CMS

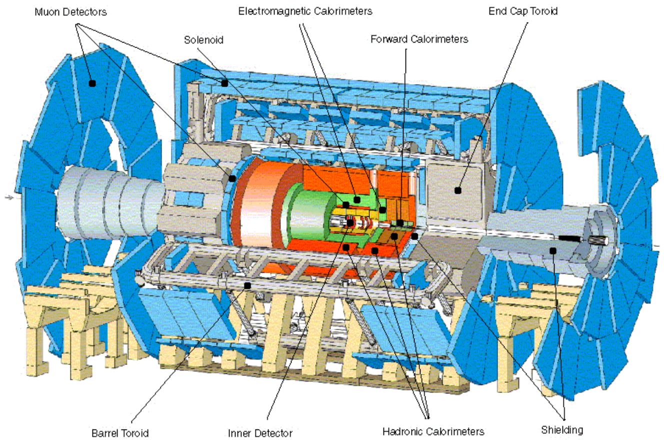
- ATLAS: toroid
- Good resolution in forward direction
- Saggita and deflection in toroid

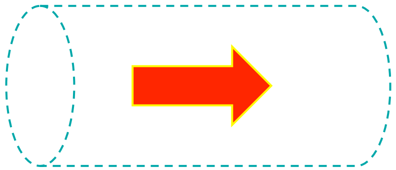
$dp/p \sim \{B_\phi \cdot R_i \cdot \ln(R_i/R_o) / \sin\theta\}^{-1}$

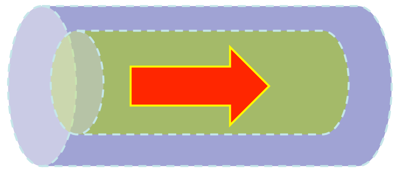
ATLAS

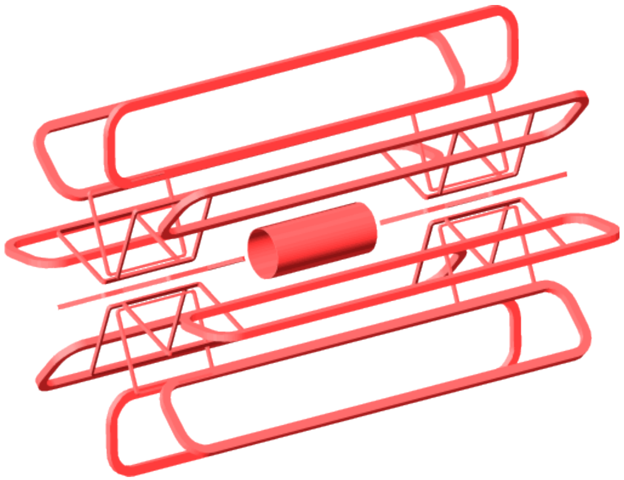


Transparent Magnetic Field
A keyword in Physics Experients







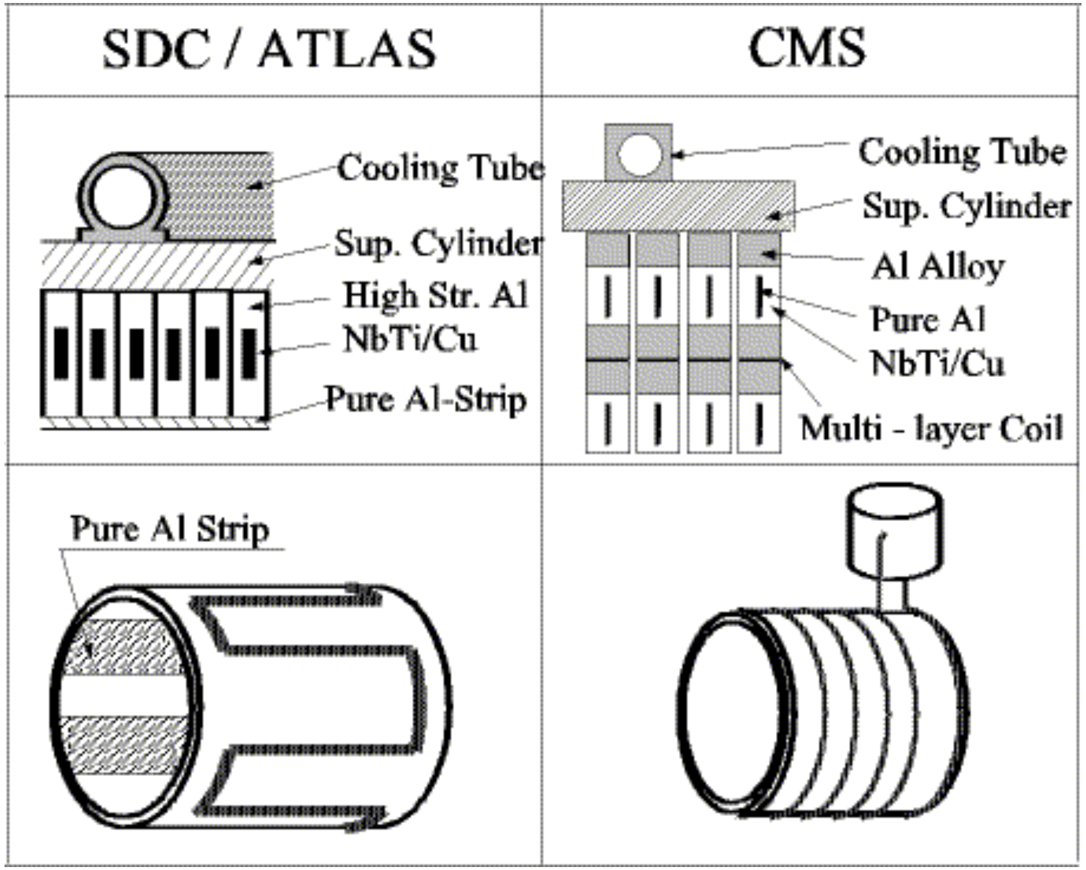


- ***Physicist Dream !!***
  - Only magnetic field !!
- ***Engineering Approach***
  - High current density
    - **Superconducting Magnet**
  - Low-Z material
    - **Al-stabilized superdonductor**
  - Minimum structure
    - **Indirect cooling**

Progress in Collider Detector Magnets

Experiment --Lab.		B [T]	R (or L) [m]	E [MJ]	X [Xo]	E/M [kJ/kg]:	Technical Remark	(Year)
ISR	CERN	1.5	1.1				Al-soldered to S/C	(1977)
CELLO	CEA/DESY	1.5	0.85		0.6		Indirect cooling	(1978)
*PEP4	LBL	1.5	1.1	---	0.83		Cu stab, Q-back	(1983)
CDF	TU/FNAL	1.5	1.5	30	0.84	5.4	Al co-extrusion	(1984)
TOPAZ	KEK	1.2	1.45	20	0.70	4.3	Inner coil winding,	(1984)
VENUS	KEK	0.75	1.75	12	0.52	2.8	CFRP vac. shell,	(1985)
AMY	KEK	3	1..2	40			Hybrid of Cu/Al stab.	(1985)
CLEO-II	Cornell	1.5	1.55	25	2.5	3.7	Double layer	(1988)
ALEPH	CEA/CERN	1.5	2.75	130	2.0	5.5	Thermo-siphon	(1987)
DELPHI	RAL/CERN	1.2	2.8	109	1.7	4.2	LHe-pump cooling	(1988)
ZEUS	INFN/DESY	1.8	1.5	11	0.9	5.5	Current grading,	(1988)
H1	RAL/DESY	1.2	2.8	120	1.8	4.8		(1990)
(BESS)	KEK	1.2	0.5	1	0.2	6.6	Thin-Al,Pure-Al strip	(1990)
*CMD-2	BINP	1.2	0.36	---	0.38	5	Current shunting	(1990)
(G-2)	BNL/KEK	1.5	6	---			One-ring dipole	(1995)
WASA	KEK/Uppsala	1.3	0.25	---	0.18	6	Thinnest	(1996)
SDC-prt	KEK/Fermi	1.5 (2)	1.85	1.2	9.6	High-st. Al, Isogrid	(1993)	
CLOE	INFN	1.5	1.x	---	---			(1997)
BABAR	INFN/SLAC	1.5	1.5	27	---			(1997)
D0	Fermi*	2.0	0.6	5.6	0.9	3.7	Conforming of Al	(1998)
BELLE	KEK*	1.5	1.8	42	---	5.3		(1998)
BES-III	IHEP	1.0	1.45	9.5	---			(200_)
ATLAS-CS		2	1.3	38	0.66	7	High St.Al-stabil.	(2001)
ATLAS-BT		1	4.7-9.8	1080	---		Toroid	(2006)
ATLAS-ET		1	0.83-5.4	2x250	---		Toroid	(2007)
CMS		4	6	2,600	---	12	Hybrid conductor	(2005)

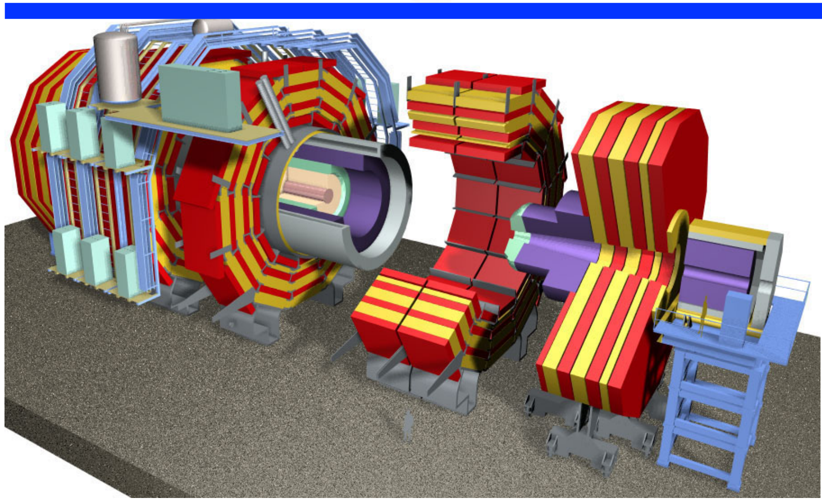
Recent Progress in Detector Magnet Design

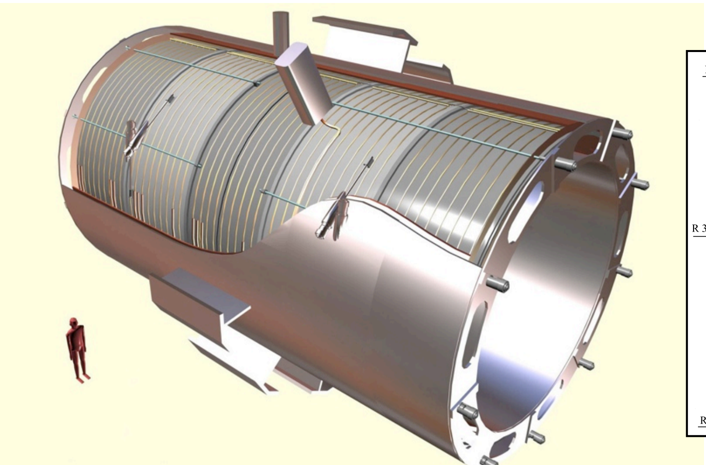


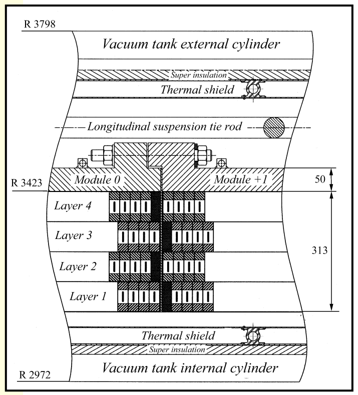
Uniformly reinforced Superconductor

Hybrid conductor with EB welding

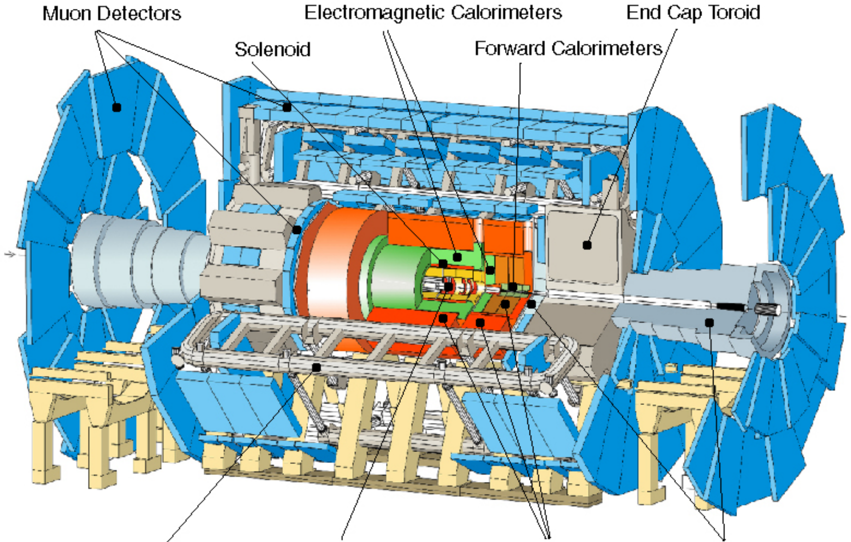
CMS
High Field and Compact

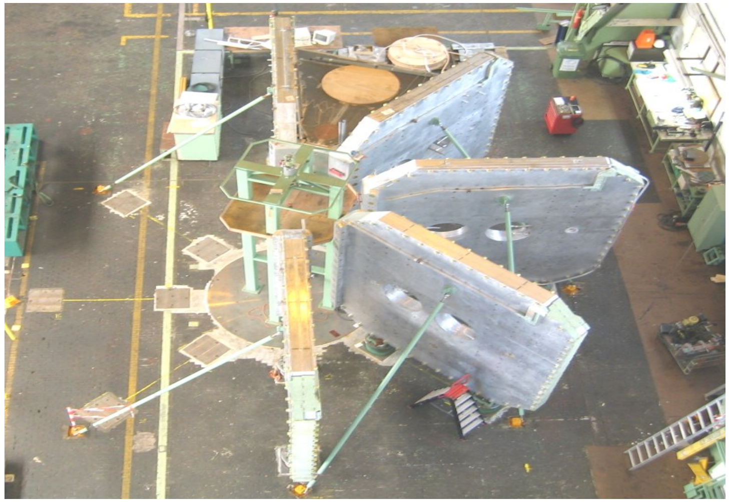


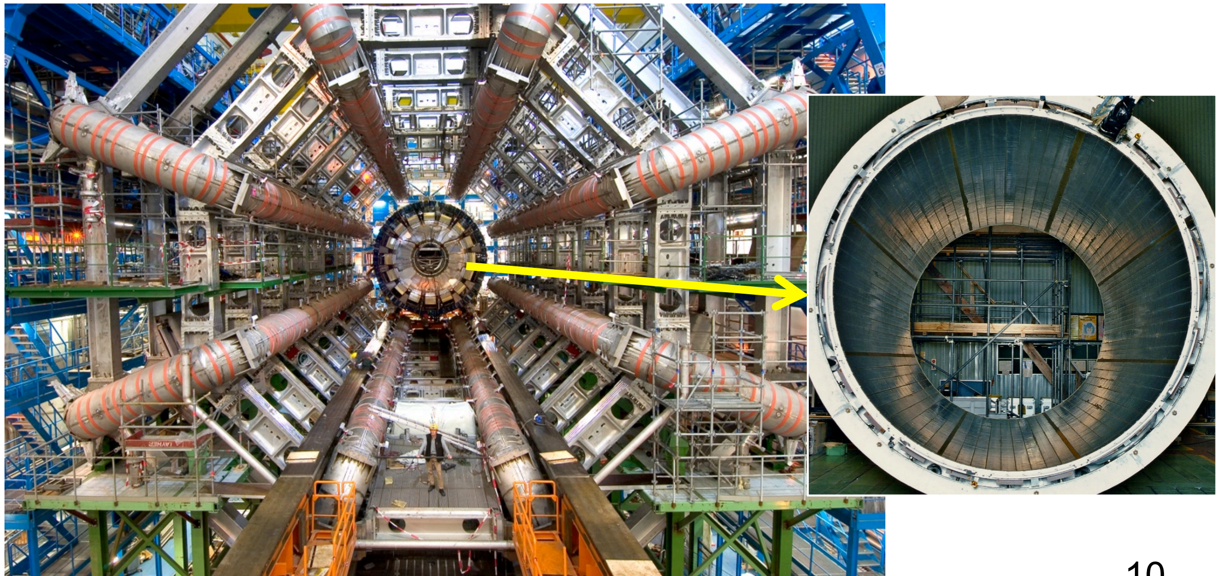




ATLAS Toroidal Magnet System

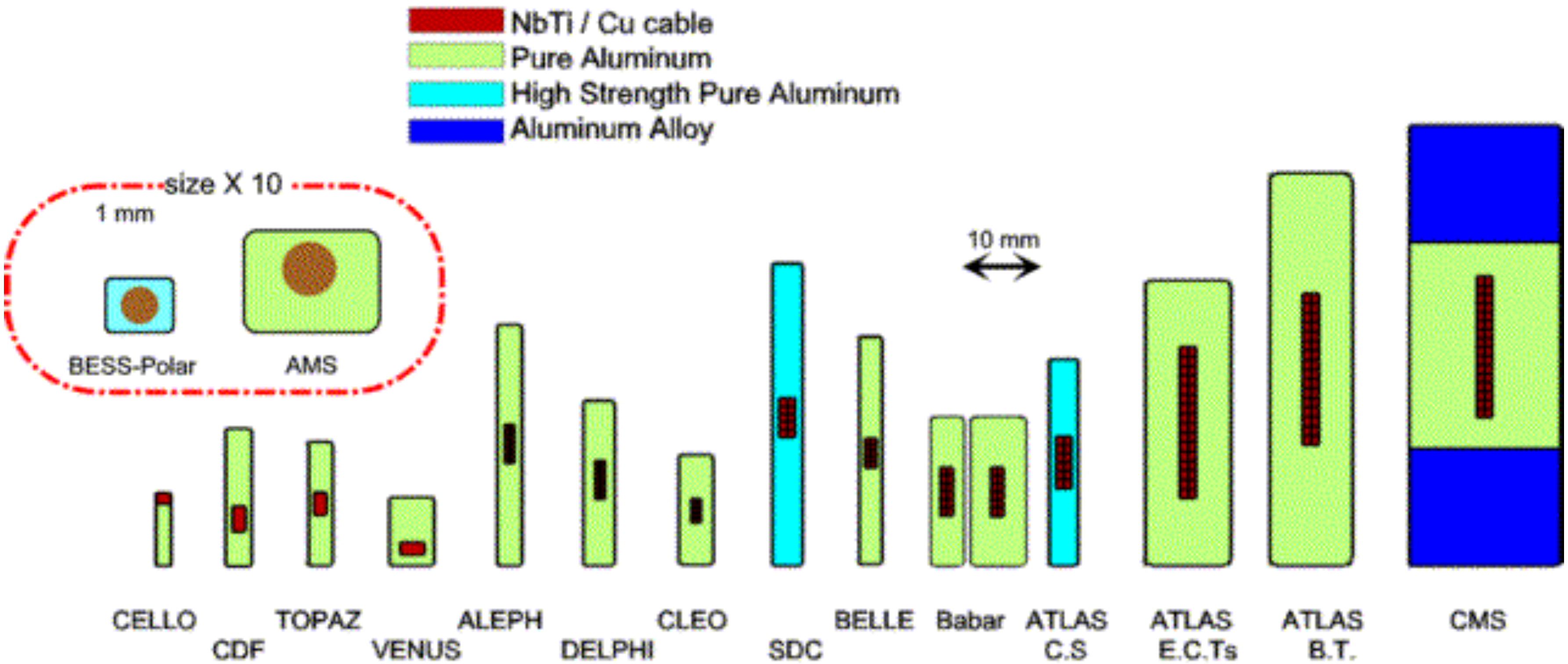






width: 44m
diameter: 22m
weight: 7000t

Progress of Al-stabilized SC

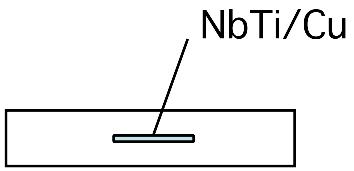


Transparency, Mechanics and Thermal Balance in Detector Solenoid

- 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**
- Stored Energy Absorption in case of Quench
  - Fast quench propagation >> Less thermal stress

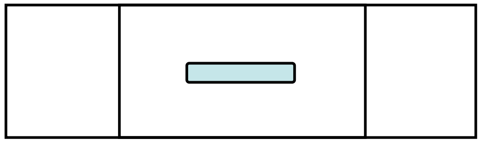
Two Approaches to Stabilization High-Strength Al-Stabilizing

- **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 Micro-alloying

Uniform



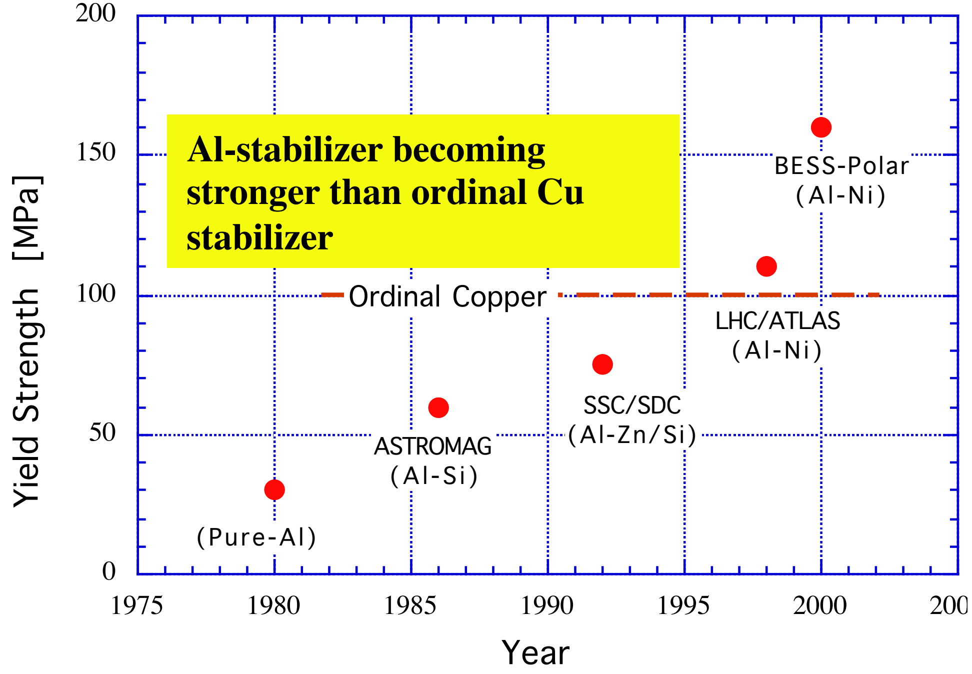
Alloy / Pure-Al / Alloy

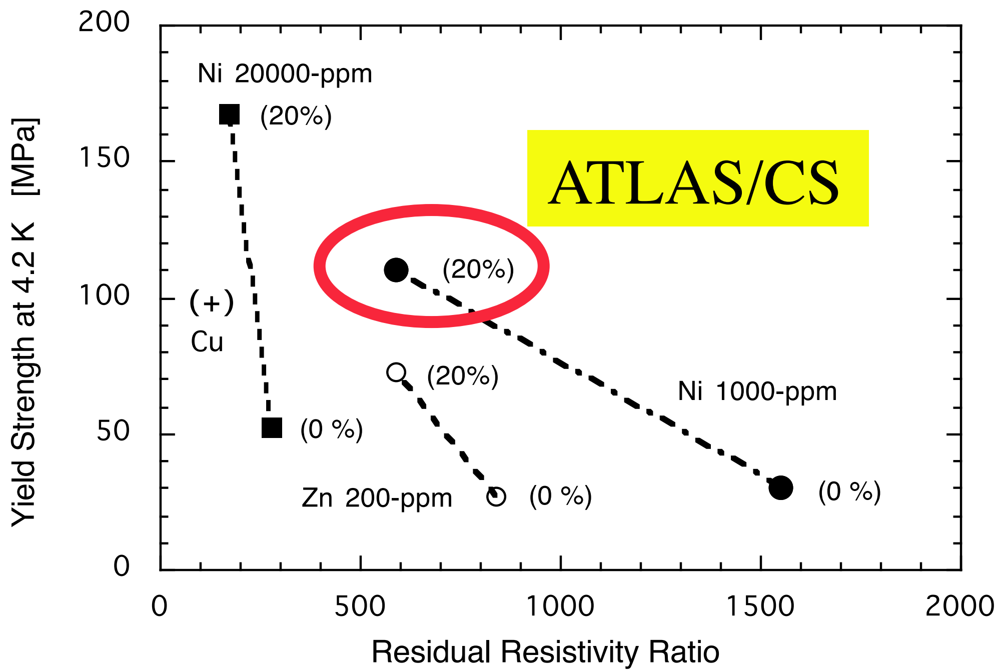
Hybrid

Micro-alloying with pure-Al

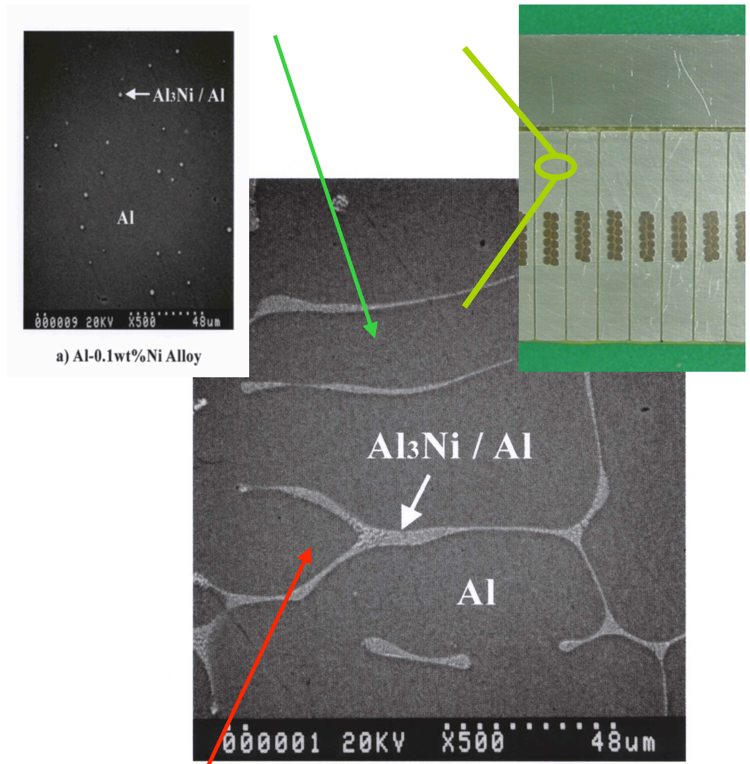
Additve metal contribution	A	Dens.	Solubility		resistivity (in solution / crystal.)	
		[g/cm³]	[w-%]		[10^{-12} Ωm/wppm]	
Solid solution:						
Si		28	2.6	1.65	0.7	0.088
Zn	65	7.1	83 @ 400C		0.10	0.023
Crystallization / Precipitation:						
Ni	59	8.8	0.05	@640C	0.81	0.061
			<0.006	@<500C		

Ni: Best reinforcement with keeping Low resistivity.



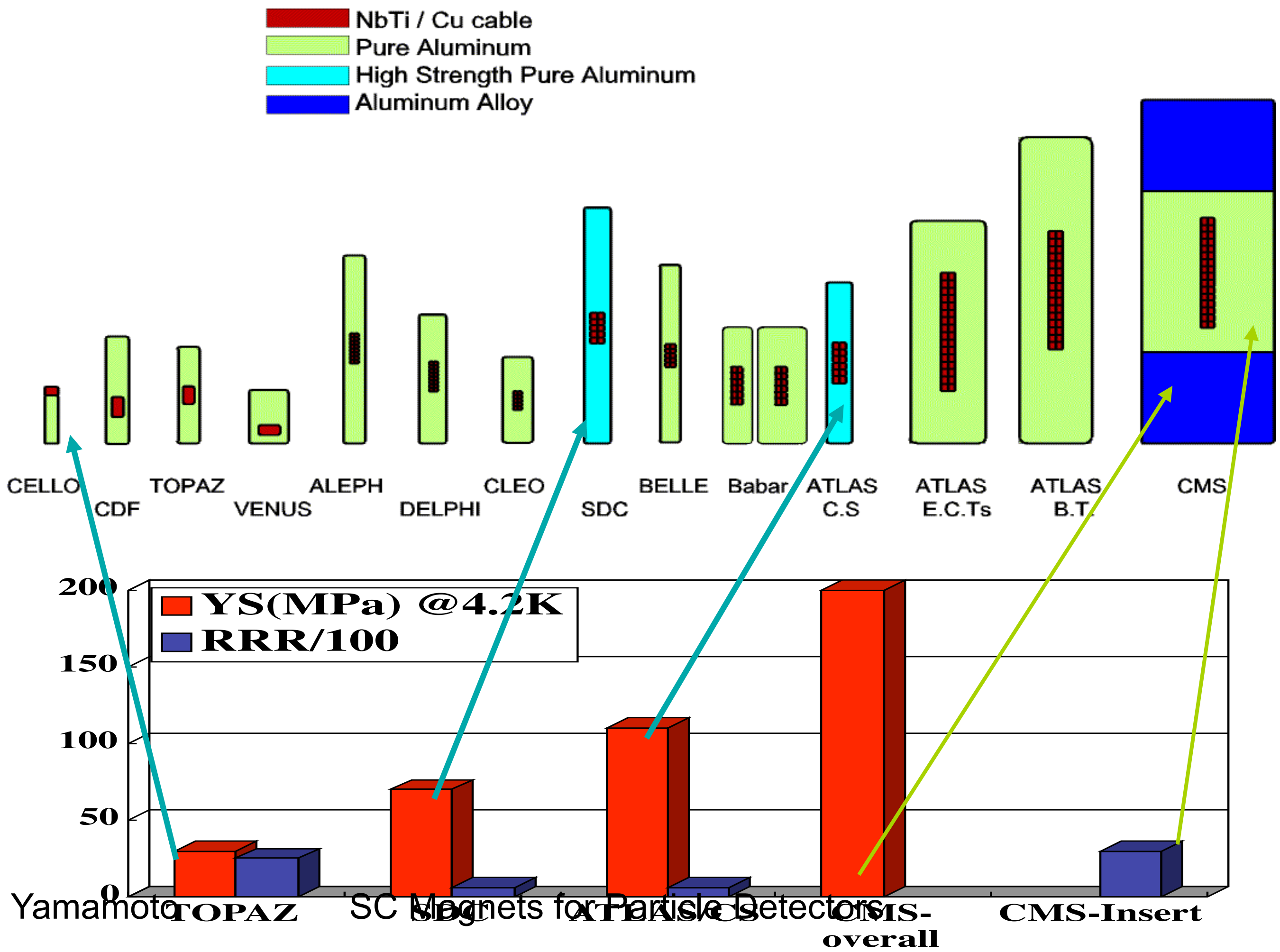


Pure-Al region
Keep low resistivity



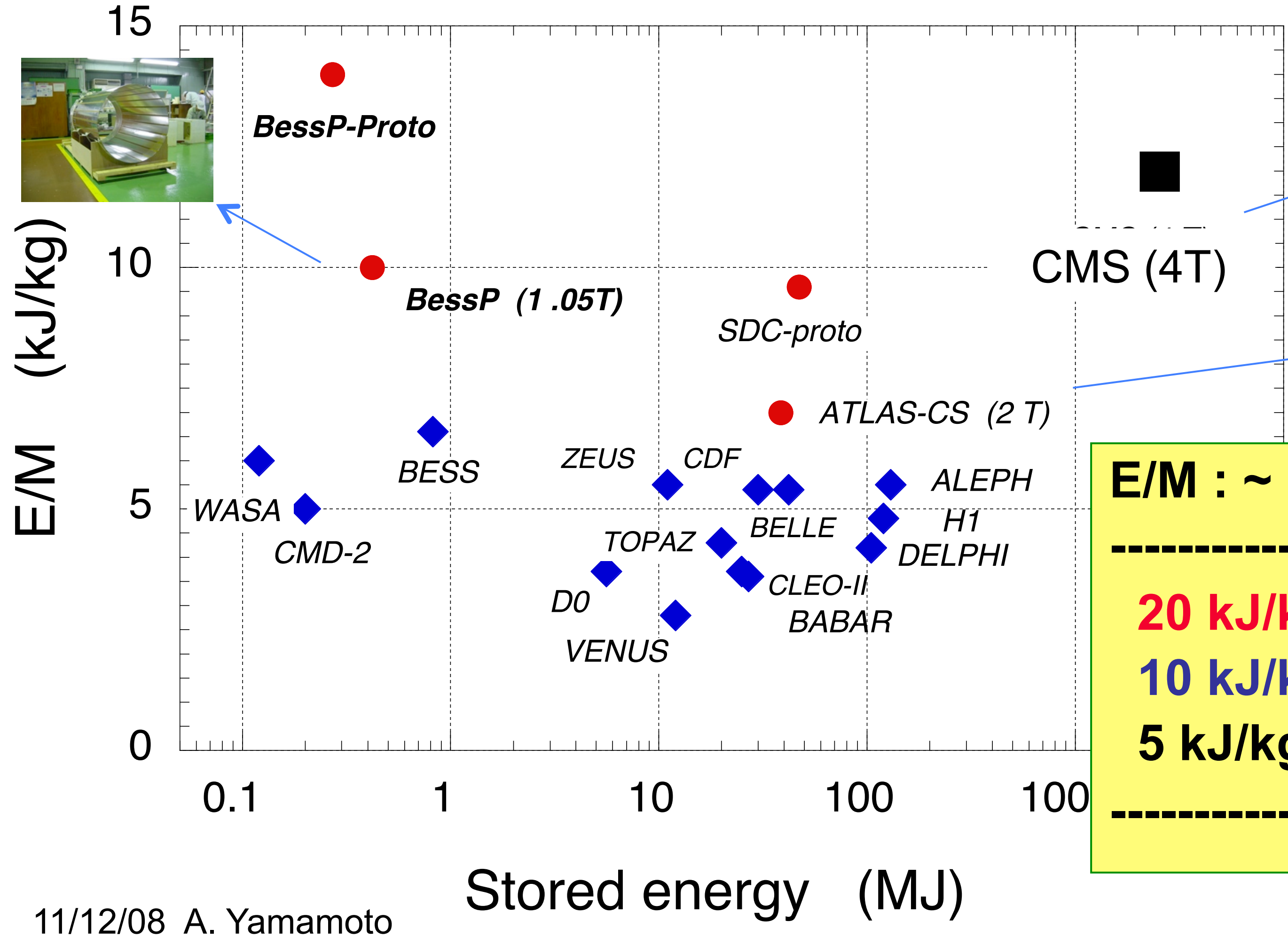
Al_3Ni precipitated
Contributes as structural component

Progress of Al-Stabilizer Superconductor in Colliding Detector Magnets



Stored Energy to Mass Ratio

E/M = $(B^2/2\mu_0) \cdot R/2\gamma$ = ~ $\sigma_h/2\gamma$

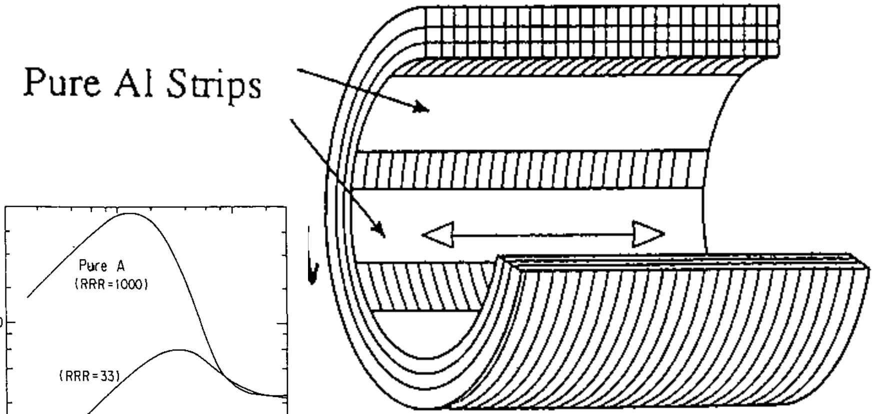


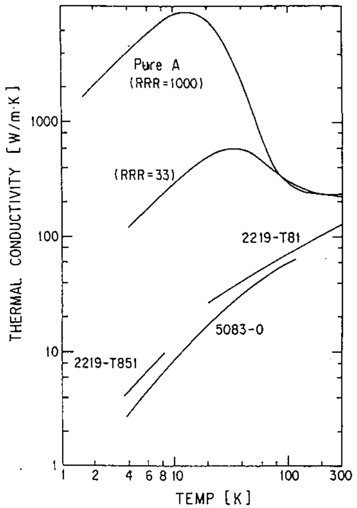
E/M : ~ Enthalpy

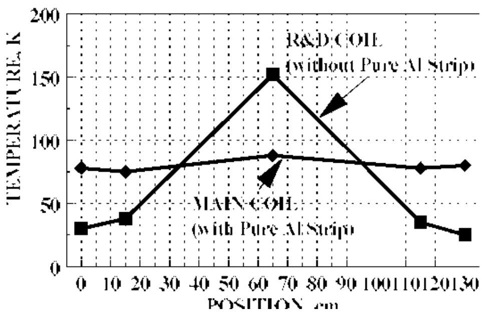
---

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

Fast Quench Propagation by using pure-Al Strips







Circumf. Velocity:

$$V\phi = (J/\gamma C) \cdot \{L_0 T_s/(T_s - T_c)\}^{1/2}$$

Axial Velocity:

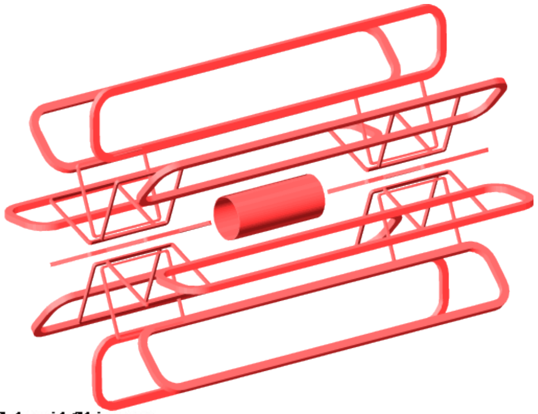
$$V_z = (k_z/k_\phi)^{1/2} \cdot v_\phi$$

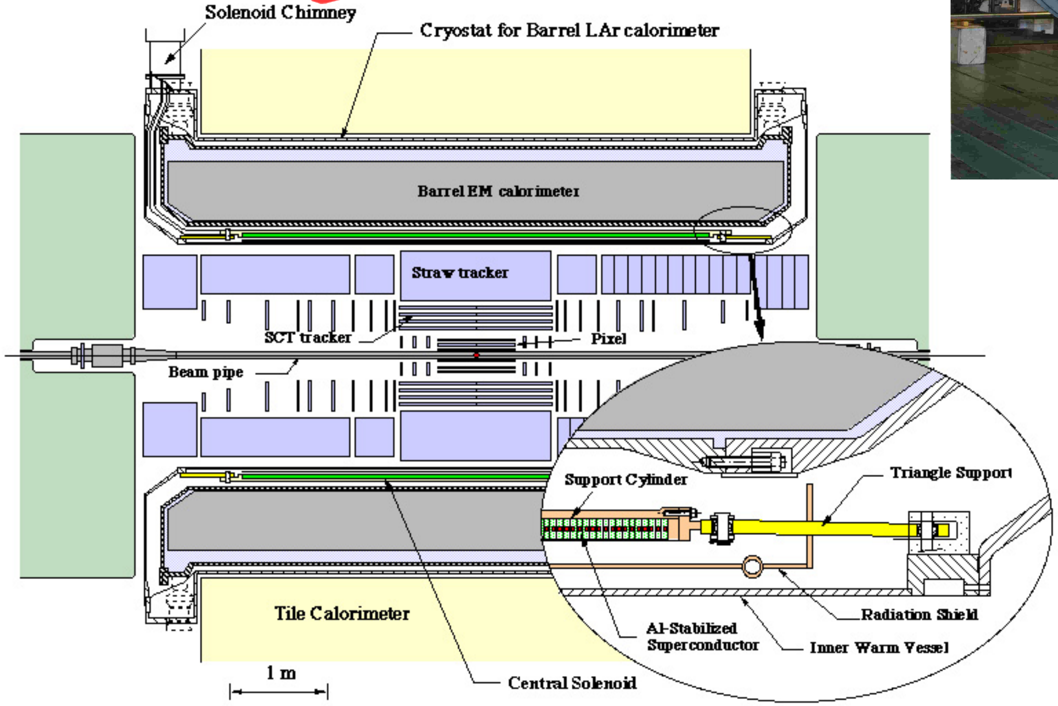
To improve Z propagation;

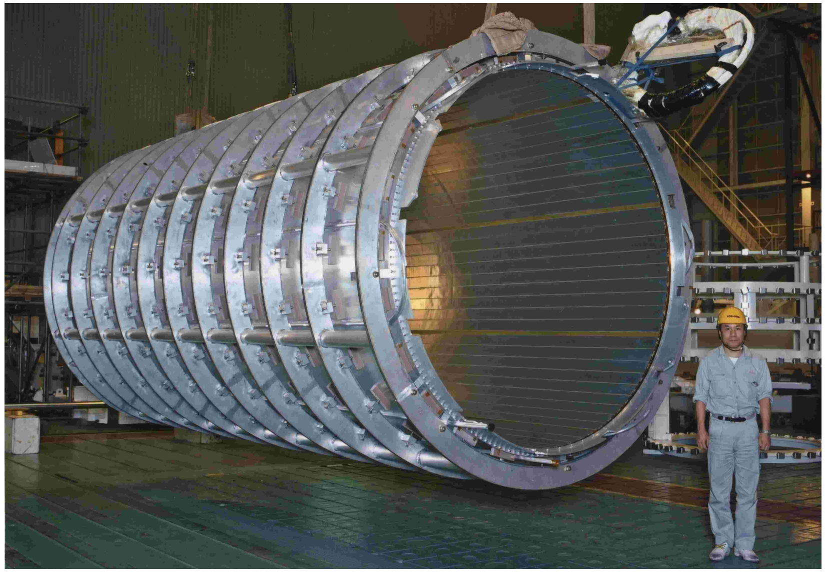
Axial Pure Al-strip useful !!

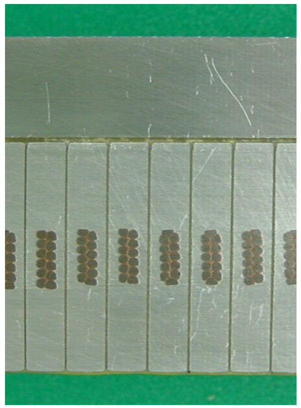
Axial Pure-Al strip useful to homogenize Coil temperature and may allow higher E/M ratio

ATLAS Central Solenoid





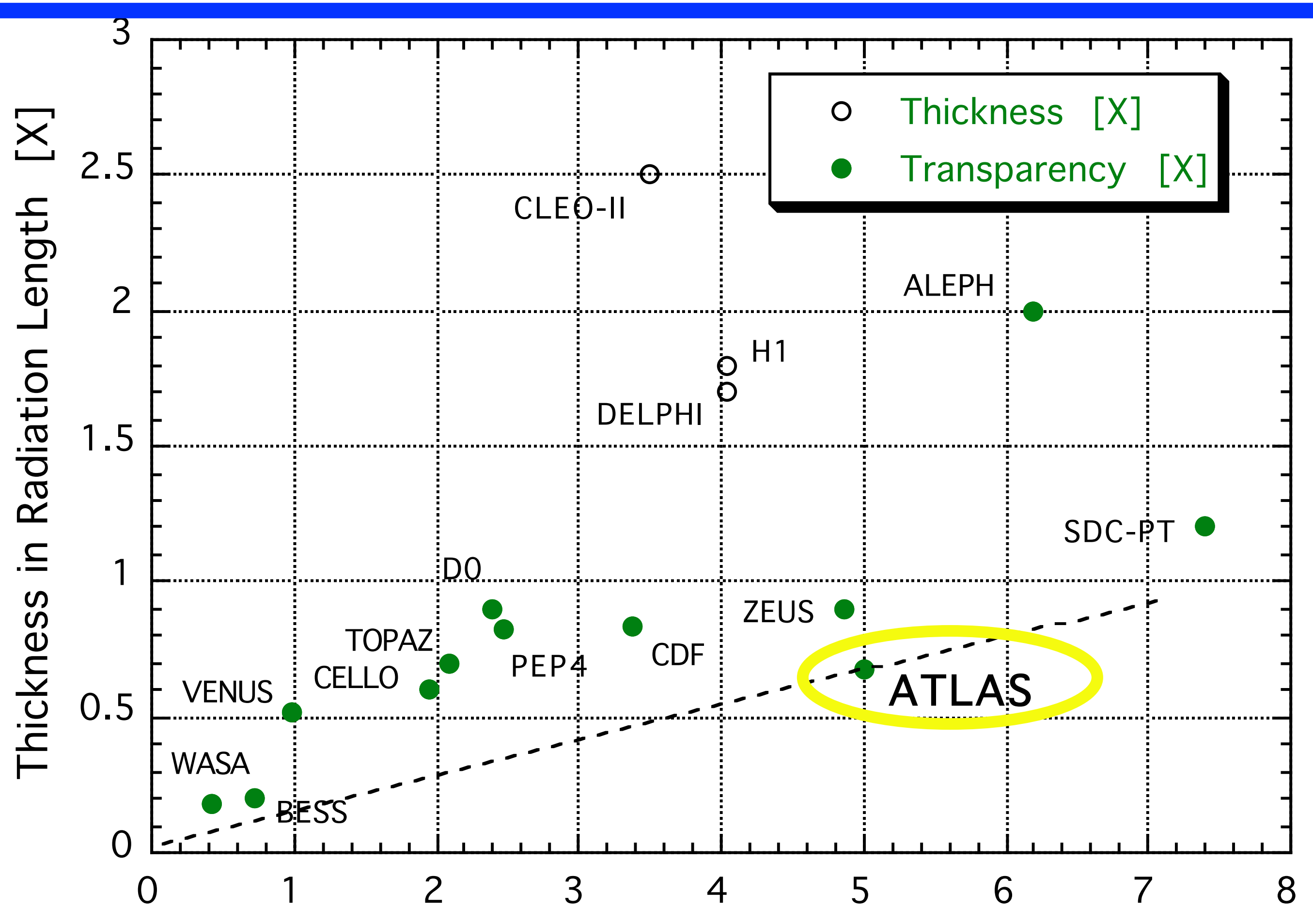




Thin coil
High-strength
Al-stabilizer

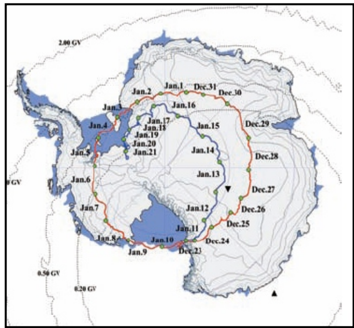
30 mm

Radiation Thickness of Various Solenoids

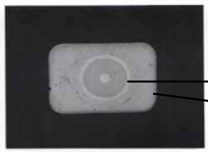


A Thin Solenoid for Cosmic-ray Observation in Scientific Ballooning over Antarctica

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



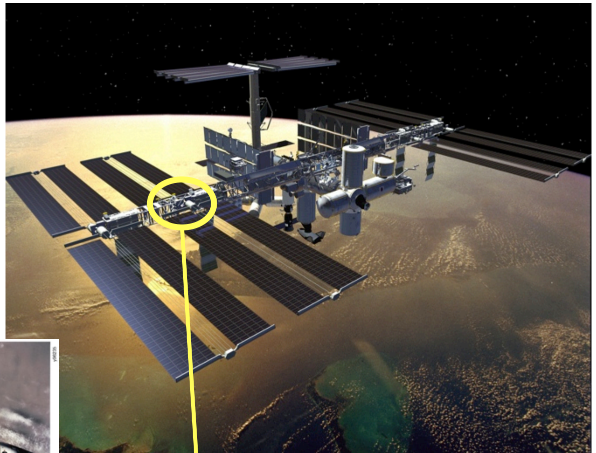
Equivalent mass with
1 cm thick plastic scintillator

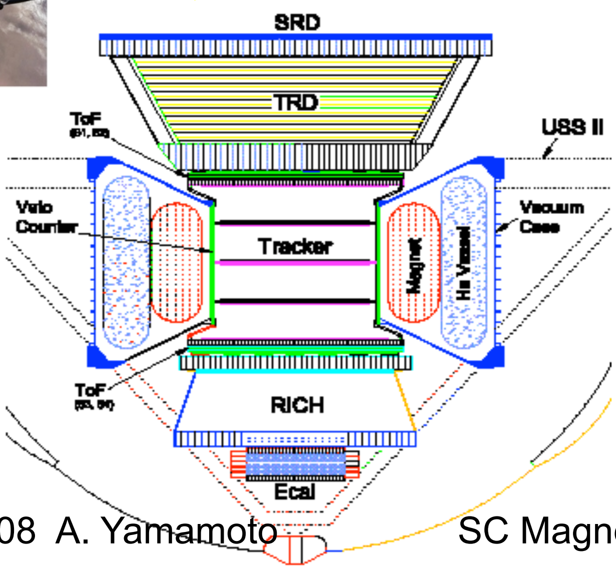


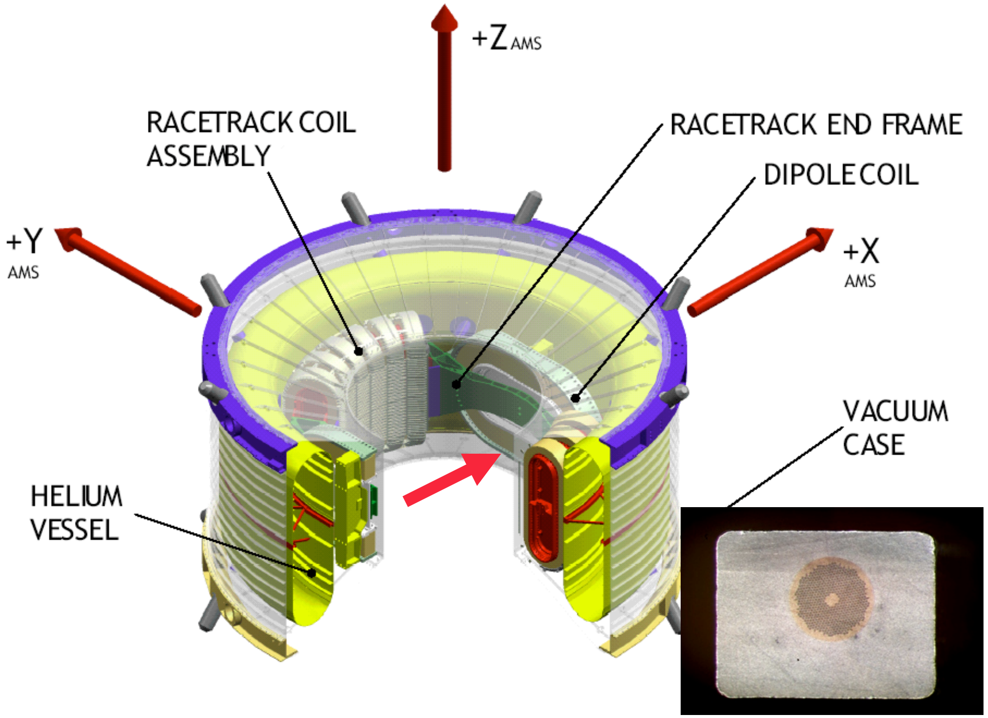
>> High strength and Low R

AMS developed Al-stabilized SC coil,

but not applied in the scientific flight





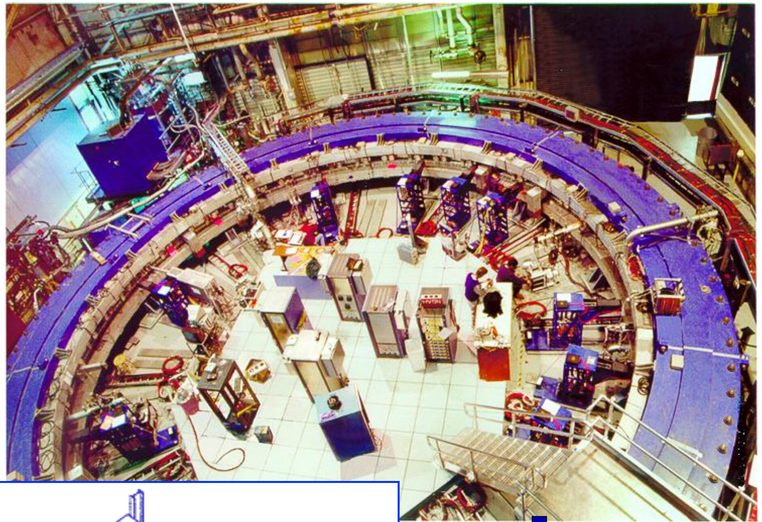


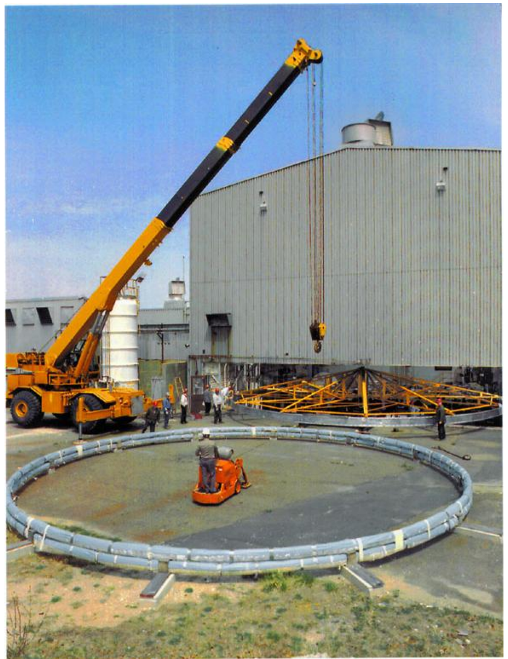
Active Dipoles and Helmholtz coils to cancel global magnetic moment.

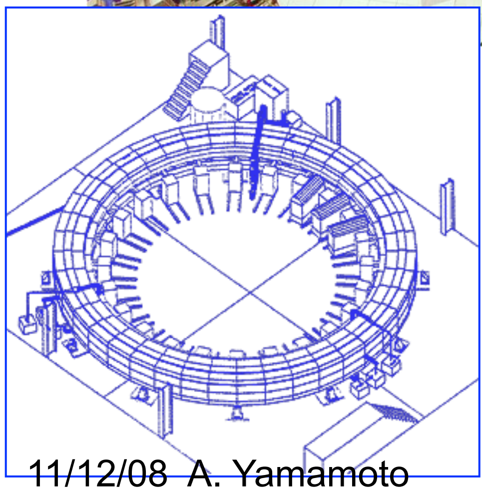
Bertrand Blau et al., MT-17, IEEE AS, 2001

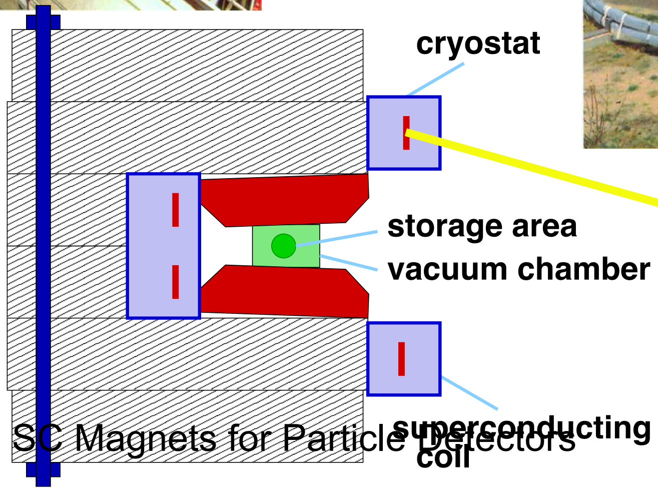
An Application for Superconducting Muon Storage Ring

for Muon G-2 Measurement at BNL

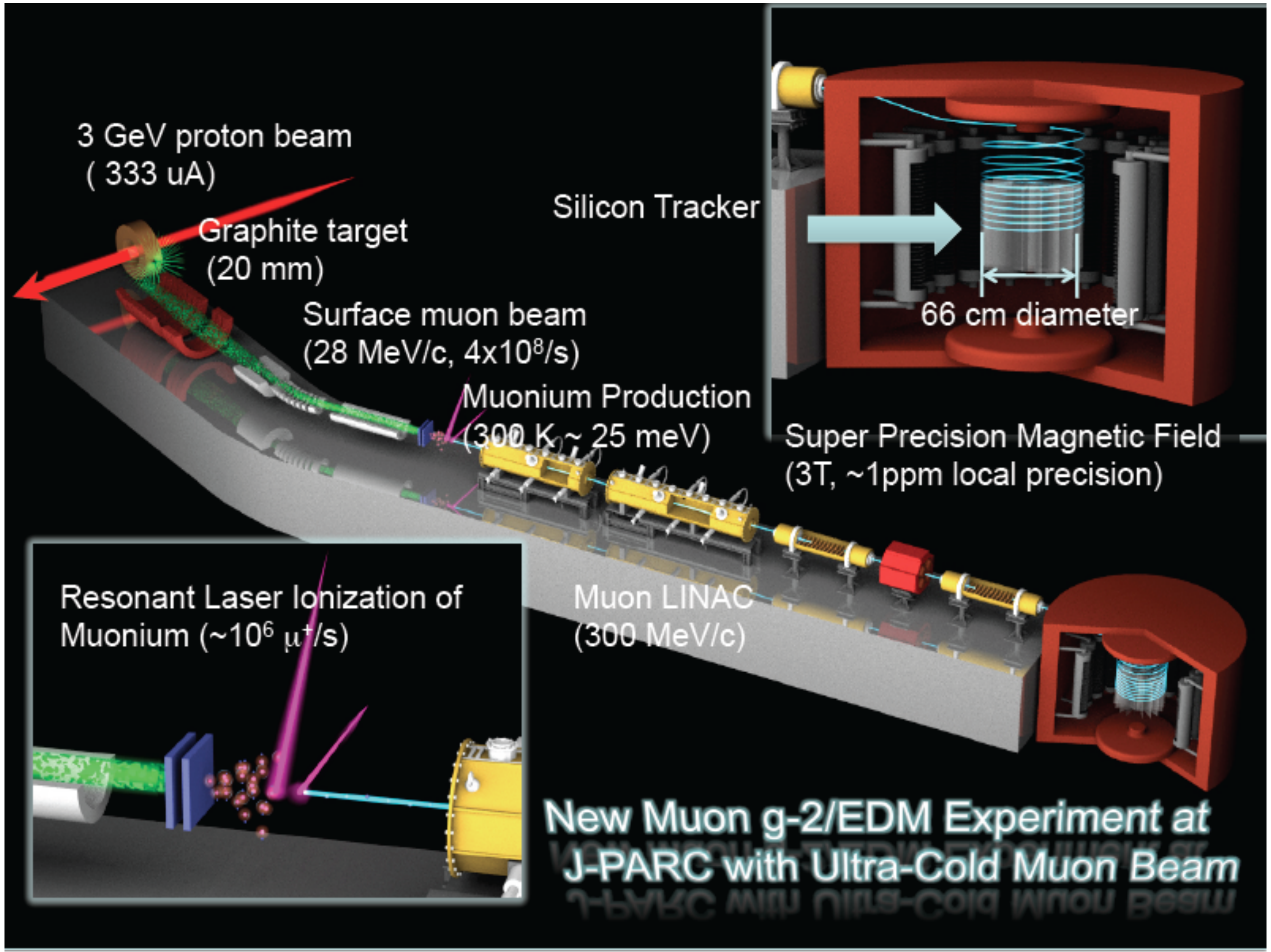








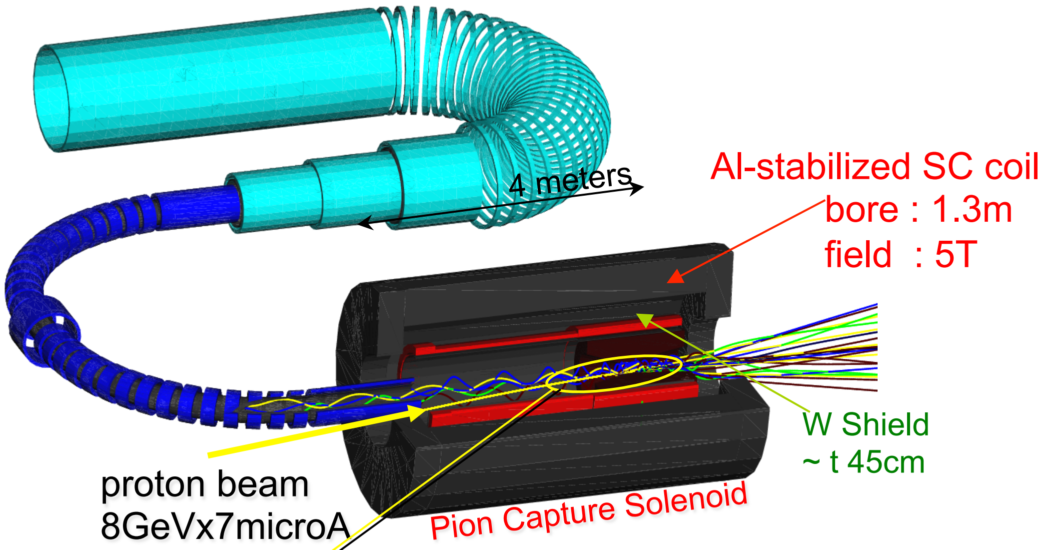
A New muon g-2 Experiment



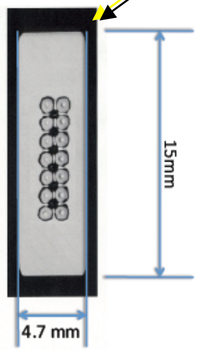
Pion Capture Solenoids for Intense Muon Beam Experiments

High Intensity Muon Source
for muon-electron conversion experiment:
such as: Mu2E (Fermilab), COMET (KEK), …

Requirements on SC solenoid:
- Large acceptance to capture pions
- High field on the target
- Severe radiation from the target
  - Max. neutron fluence: ~10^{21} n/m^2

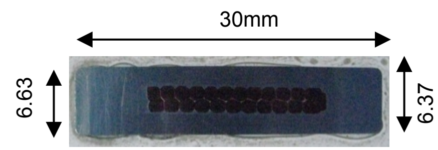


Irradiation causes:
- Nuclear heating in SC coils
- Irradiation damage in stabilizer, etc.



Design parameters for COMET
- Size: 4.7x15mm
- Proof strength of Al@4K: >85MPa
- RRR@0T: >500
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.

Aluminum stabilizer
- "Transparent" to particles
  →Lower heat load, smaller bore for shielding
- Perfect recovery from irradiation damage by thermal cycle to room temp.
  →Stable operation

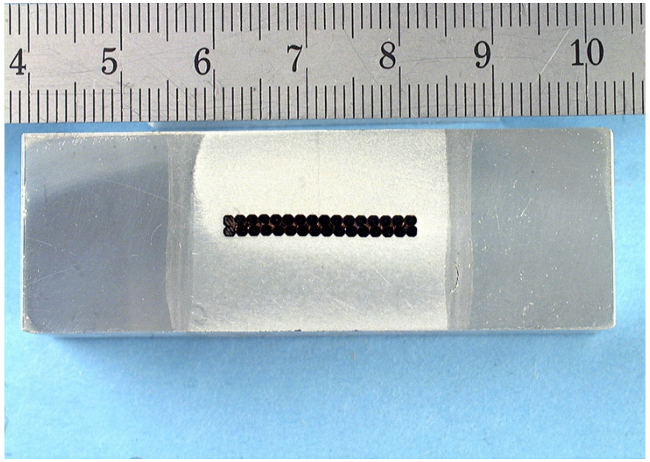


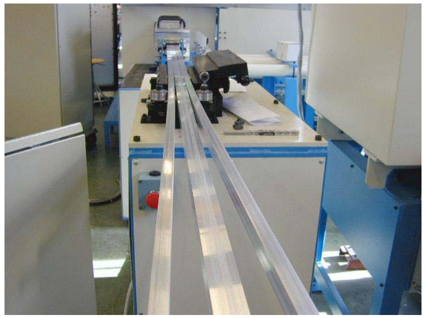
Mu2e-design-based conductor (2010)

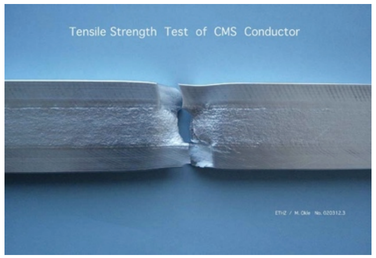
Guide Lines Suggested for Future Detector Magnets (ILC/CLIC)

- 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.

CMS with Hybrid Structure (5N-Al/AA6082)







Overall mechanical strength

Y.S . :

130 MPa @ 300 K before curing

180 MPa @ 300 K after curing

(**258** MPa @ 4.2 K, estimated)

Electrical properties of inserts

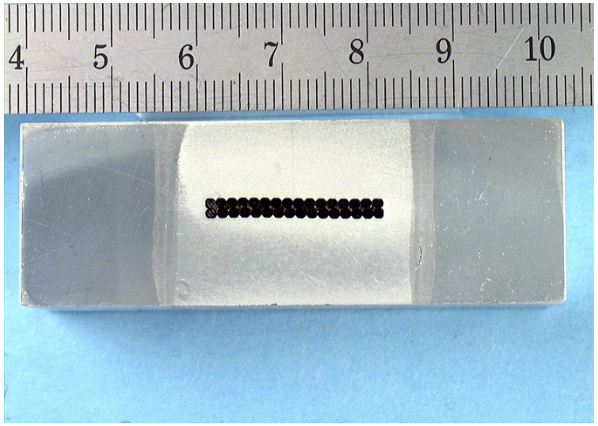
RRR :

3020	**@ 0 T**
1134	@ 1 T
977	**@ 5 T**

B. Cure, B. Blau. A. Herve, et al, this conference

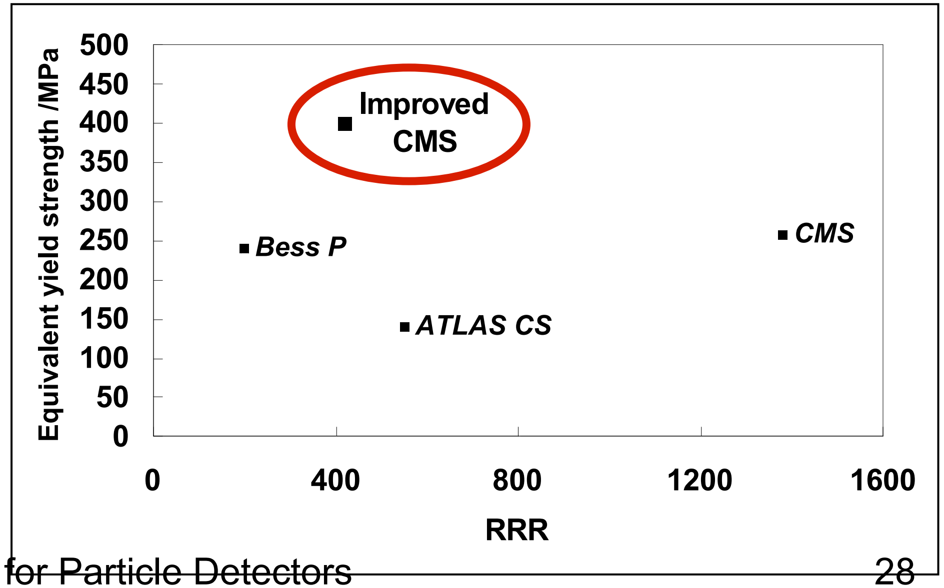
Further Development for Al-Stabilized Superconductor

CMS / ATLAS / ILC / CLIC magnet collaboration



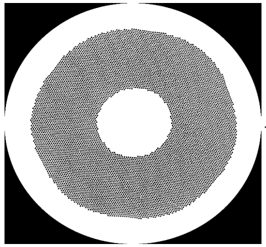
- Energy Frontier Collider Detector
  - Field : > 5 Tesla
  - Scale : Diameter, ～10m
- Further reinforcement
  - ATLAS H.S. stabilizer
    - Ni-0.5 ~ 1 %
  - CMS-Hybrid Support
    - A6058 -->> A7020

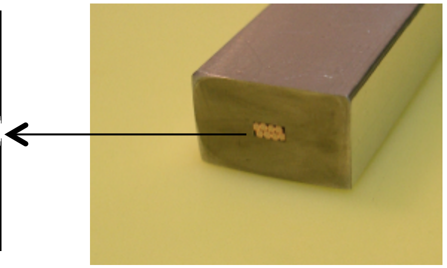
Y.S.(0.2%) = 400 MPa
RRR = ~ 400

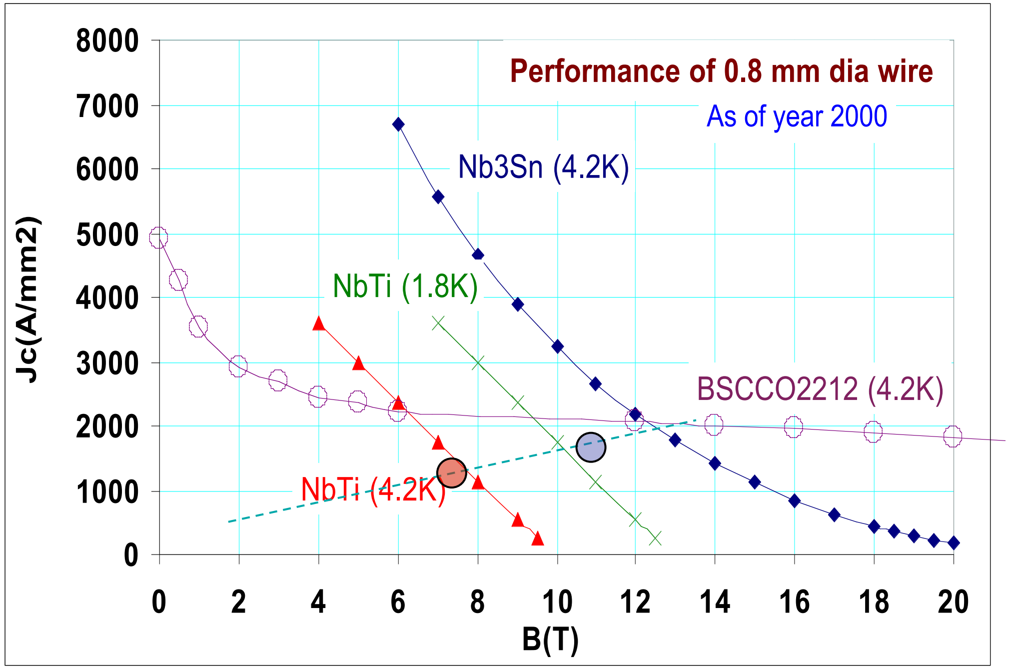


Toward Higher Field

- Al-stabilized Nb3Sn/Nb3Al Solenoid beyond 10 T
- An R&D expected in cooperation with NIFS.







- The possibility of using NB3Sn/Nb3Al must be investigated

Summary

- There has been great progress in superconducting magnets for particle detectors using Al-stabilized superconductor technology to give the best chance to realize/approach a *'pure (transparent) magnetic field'.*
- The LHC detectors magnets are the result of a successful development program and currently are functioning using state of the art technology.
- NbTi Al-Stabilized superconductor may still be used for future detector magnets when:
  - Useful magnetic field of **5 T** as an ultimate field,
  - E/M ratio of < **~ 12 kJ/kg** with protection of energy extraction
- Detector magnets beyond 5T require further R&D on Nb3Sn/Nb3Al and HTS conductors.

Superconducting Detector Magnets at LHC

Experiment	B [T]	R [m]	E [GJ]	E/M [kJ/kg]	Remark
ATLAS					
CS	**2.0**	**1.25**	**0.04**	**7**	**High-Strength Al** **Thin solenoid (0.7 Xo)**
BT	**~1**		**1.08**	**3**	8 lumped coil in largest single cold mass.
ET	**~1**		**2x0.25**	**1.6**	
CMS	**4.0**	**3.2**	**2.6**	**12**	**Hybrid-conductor** **Largest store energy**

ATLAS CS, BT, and CMS successfully in operation