Superconducting Magnets for Particle Detectors

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The Roots of the LHC Technology:

CERN Centennial Superconductivity Symposium,

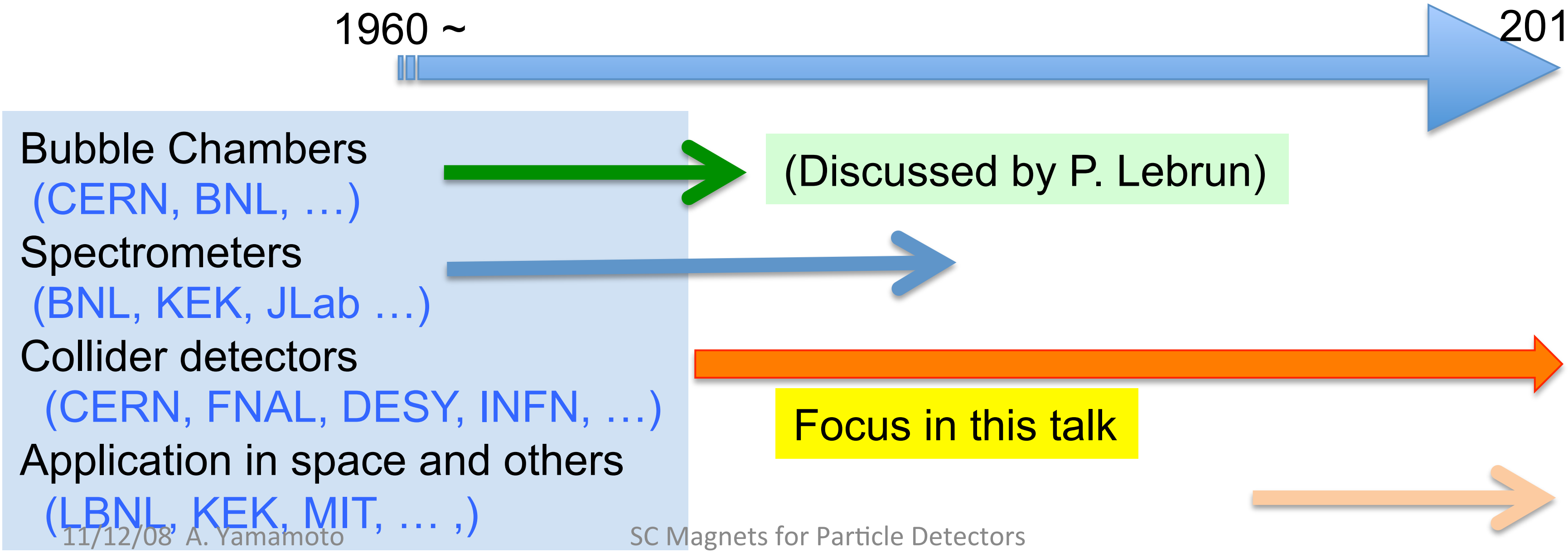
CERN, 8th December, 2011

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
- Future prospects

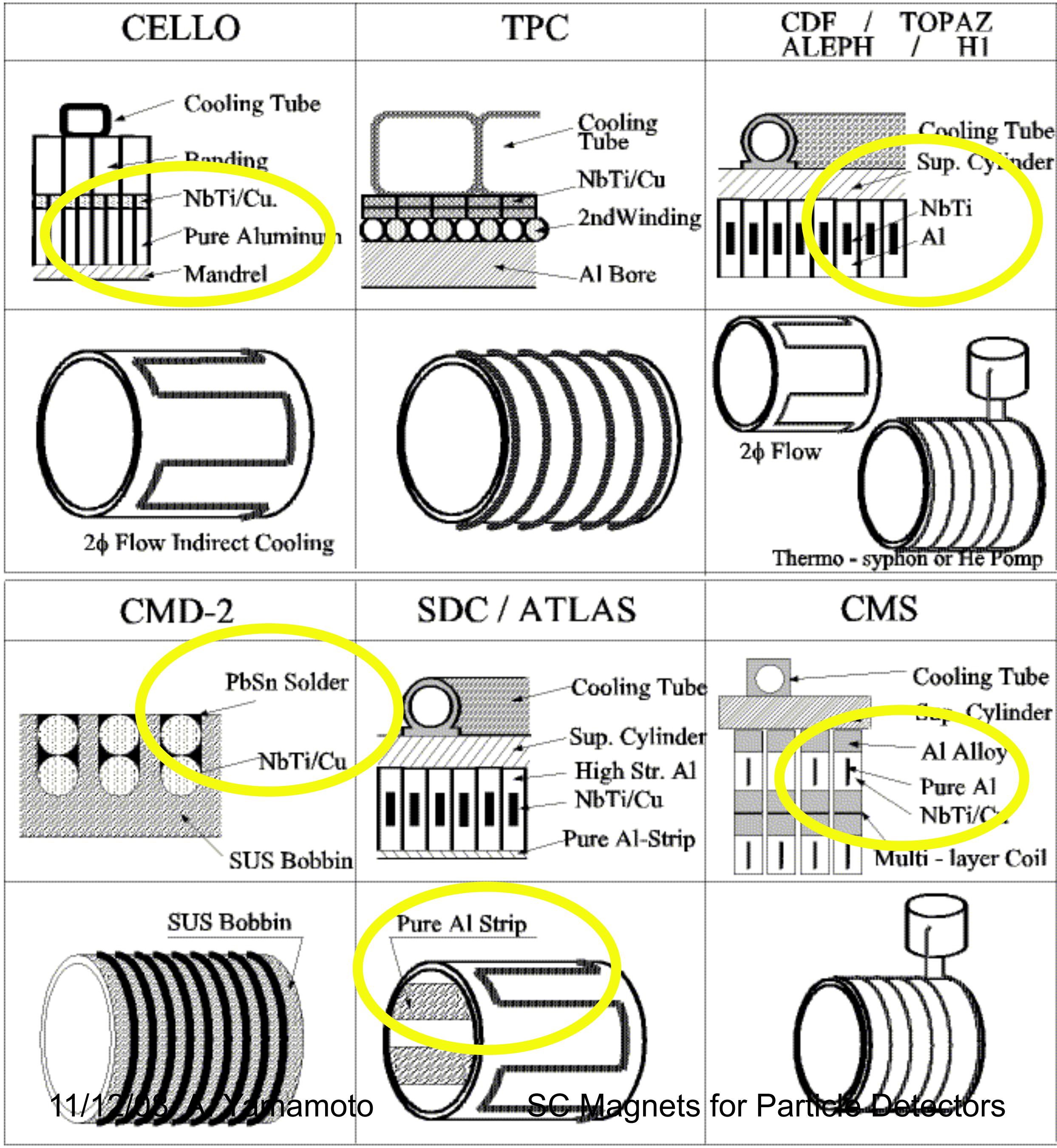
Progress in Superconducting Magnets for Particle Detectors

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



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)



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

Basic Relations with Detector Magnet

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

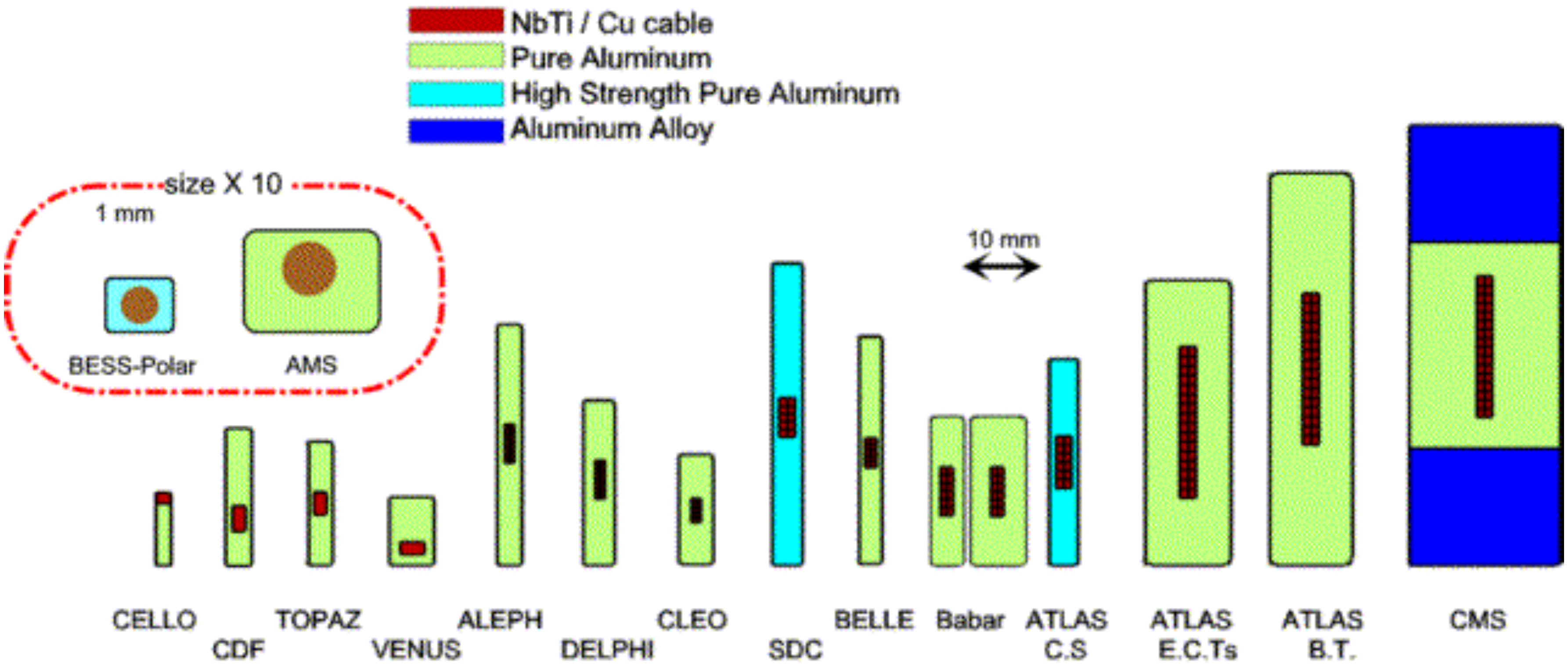
- **Magnetic Field:** $\text{rot } B = \mu_0 J$
- **Stored Energy:** $E = 1/2\mu_0 \text{ Int. } B^2 \, dv$
- **Coil Mass:** $M = V_{coil}\,\gamma$
- **Pressure:** $p = B^2/2\mu_0$
- **Hoop Stress:** $\sigma_{hoop} = (R/t) \cdot p$
- **Wall thickness:** $t = (R/\sigma_h) \cdot p$
- **E/M ratio:** $E/M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

•B:	magnetic field
•μ_0:	magnetic permeability
•V_{field}:	magnetic volume
•V_{coil}:	coil volume
•.γ:	effective density
•.σ_{hoop}:	hoop stress
•R:	coil radius
•t:	coil thickness

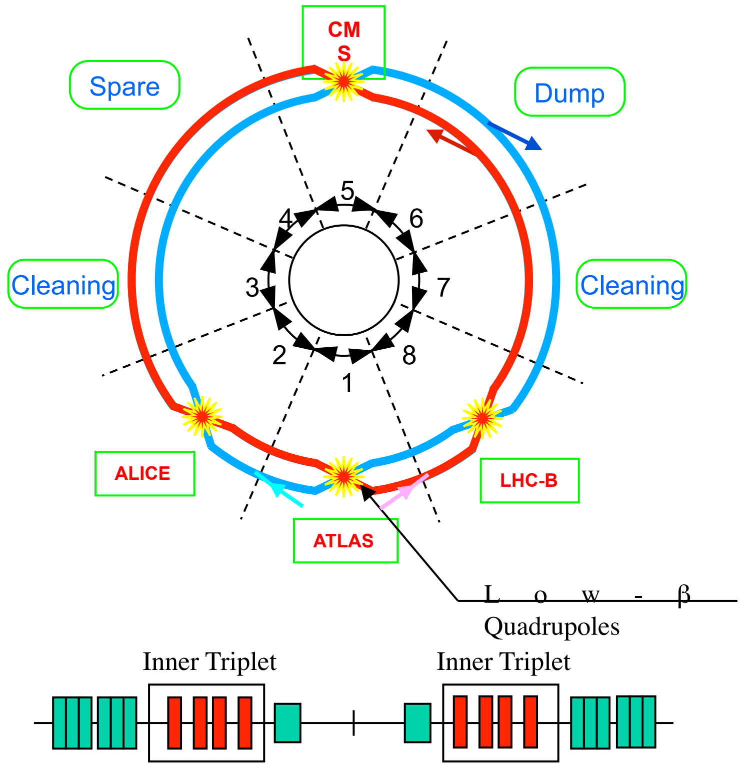
Superconducting Detector Solenoid Mechanics and Thermal Balance

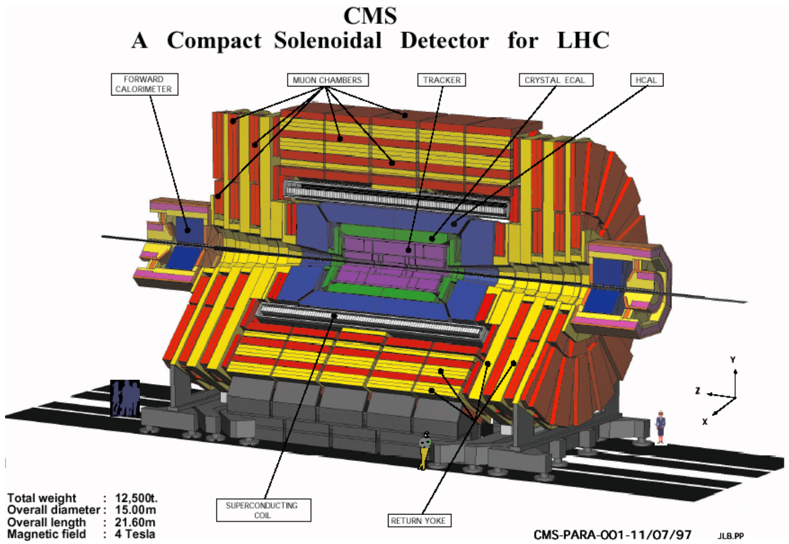
- Material: $t \propto RB^2/(E/M) \propto RB^2 \gamma / \sigma_h$
  - **E/M (Stored Energy/ Cold Mass) to be higher**
  - **Superconductor to be stronger and lighter**
- Stored Energy Absorption in case of Quench
  - Fast quench propagation >> Less thermal stress

Progress of Al-stabilized SC



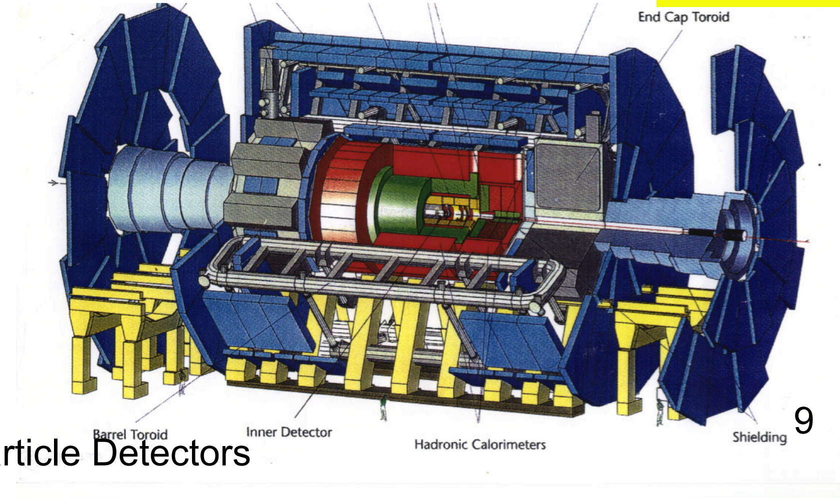
Status: Collider Detector Magnets
CERN-LHC Experiments





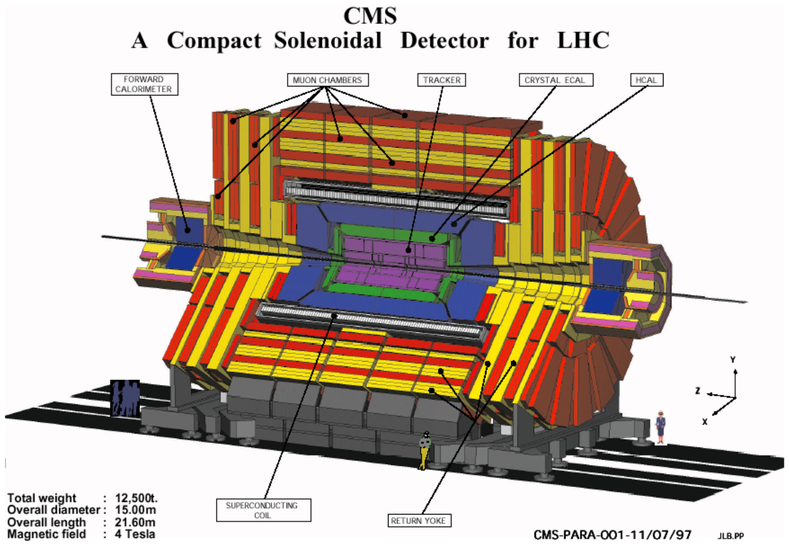
CMS

ATLAS



Status: Collider Detector Magnets
CERN-LHC Experiments

- 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
  - **$dp/p \sim \{B \cdot R\}^{-1}$**

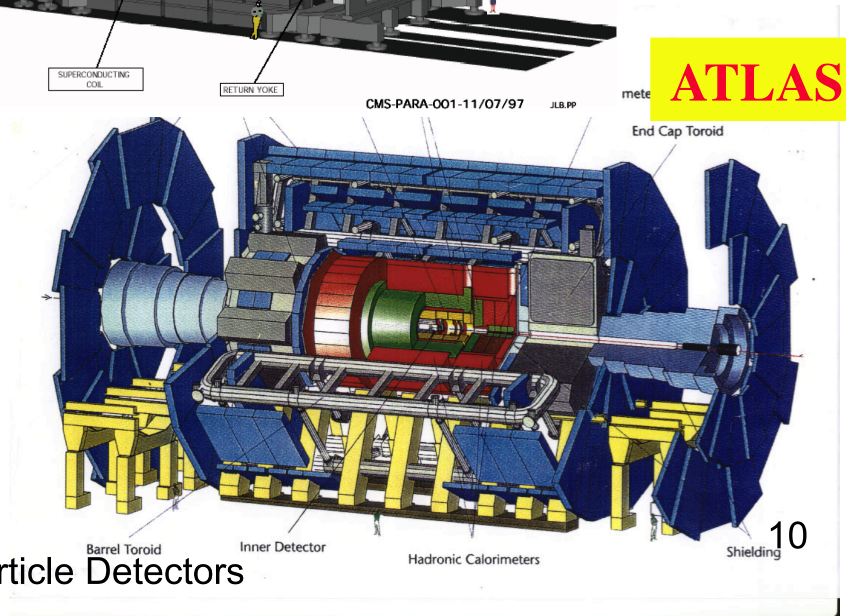


CMS

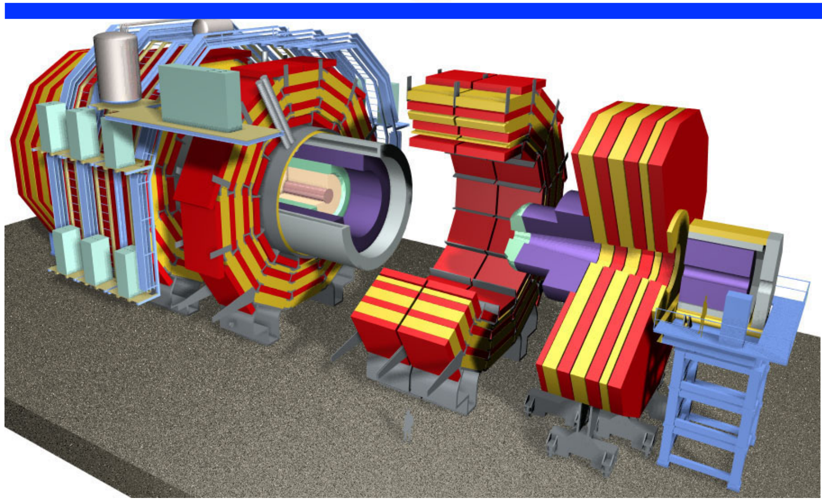
- ATLAS: toroid
- Good resolution in forward direction
- Saggita and deflection in toroid

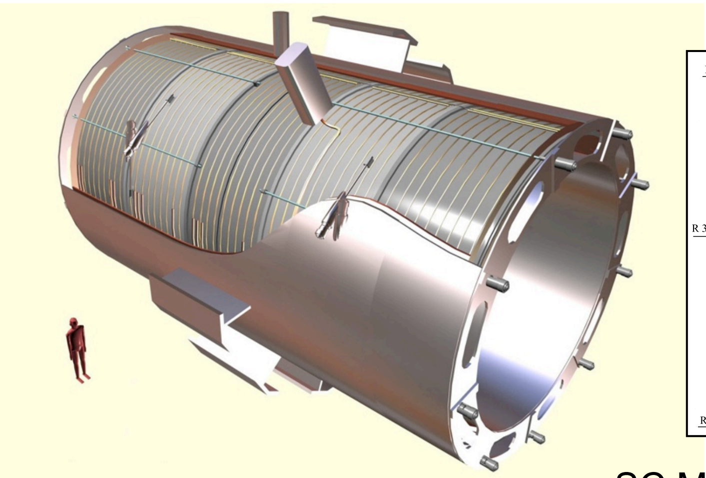
  $dp/p \sim \{B_\phi \cdot R_i \cdot \ln(R_i/R_o) / \sin\theta\}^{-1}$

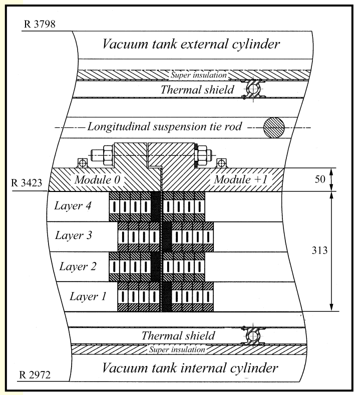
ATLAS



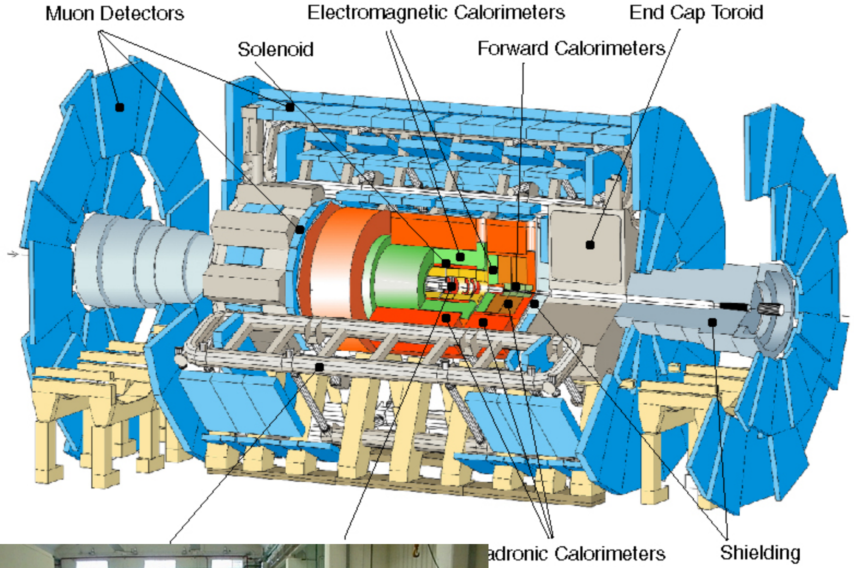
CMS
High Field and Compact

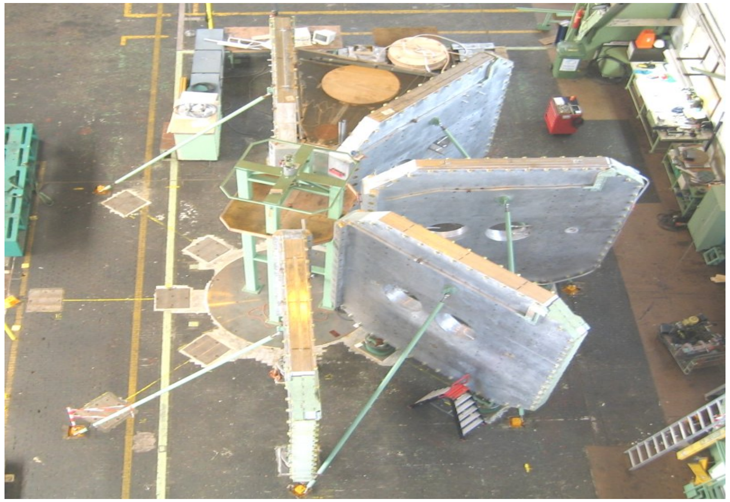


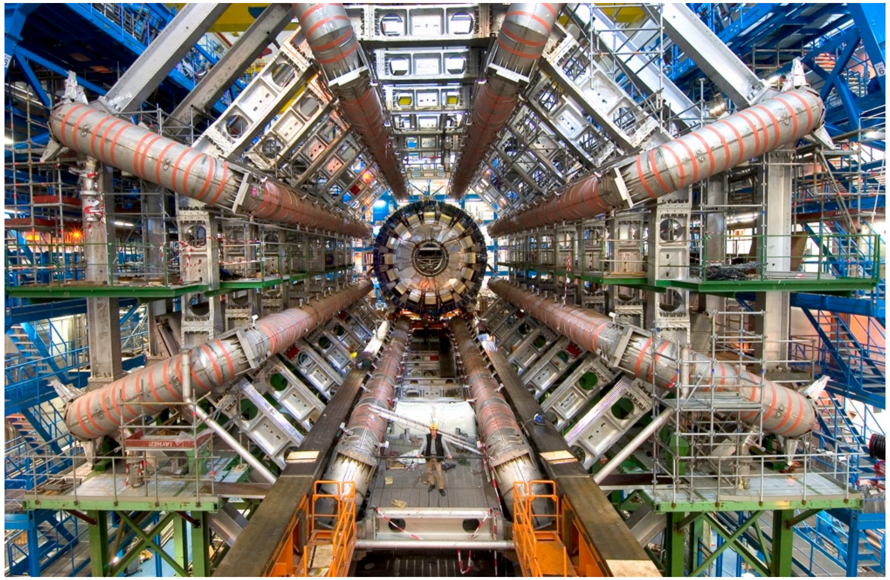




ATLAS Toroidal Magnet System

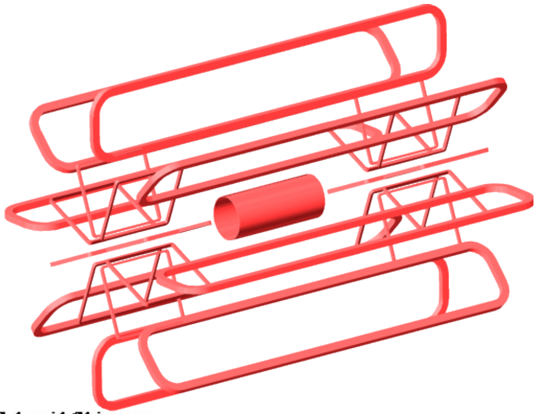


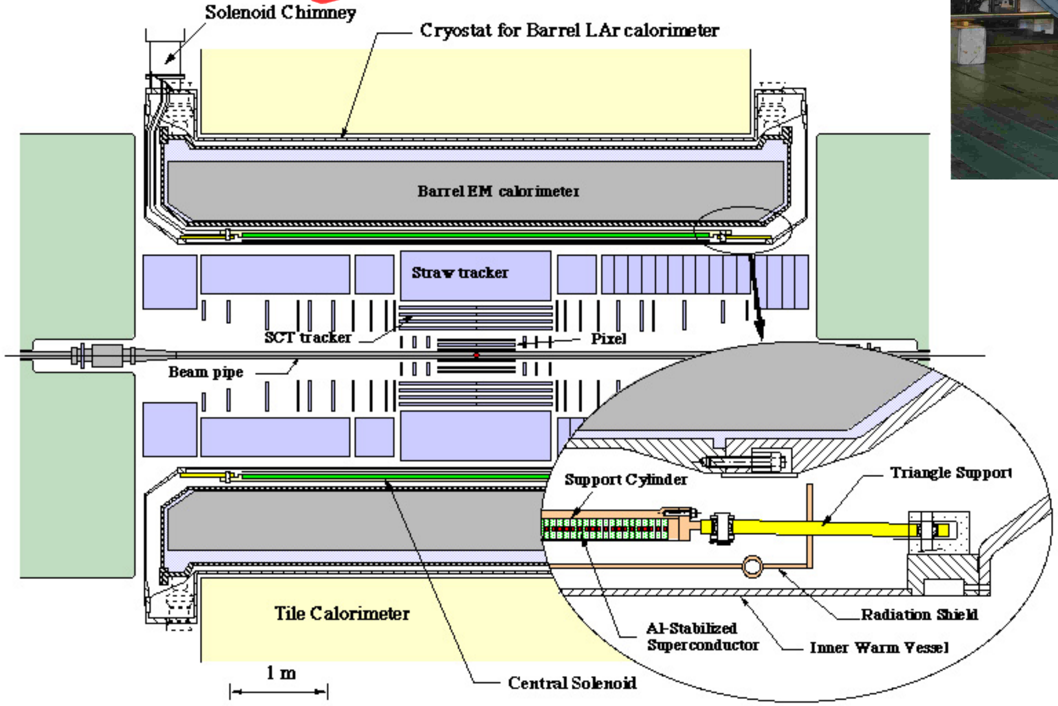


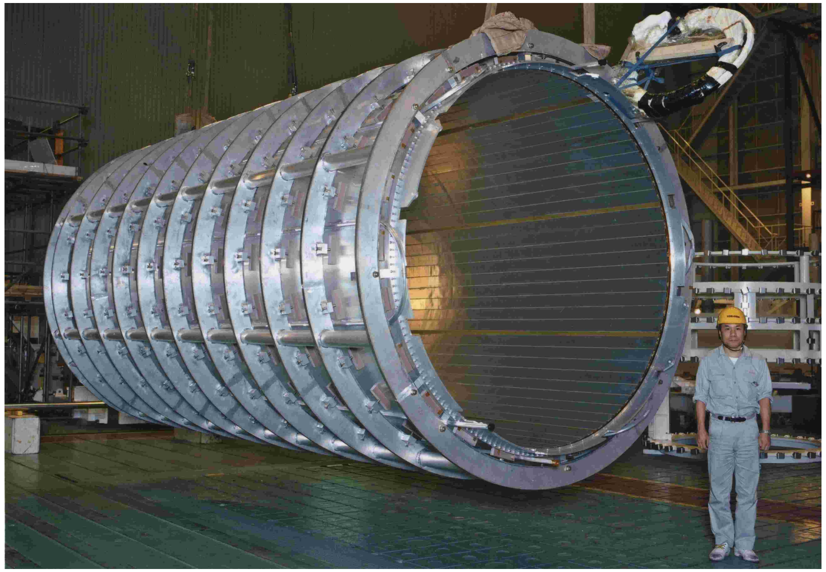


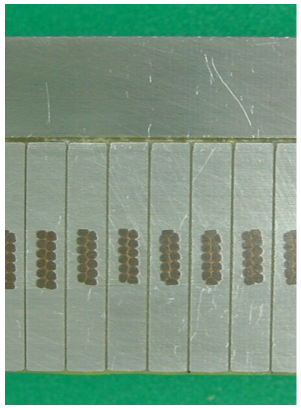
width: 44m
diameter: 22m
weight: 7000t

ATLAS Central Solenoid





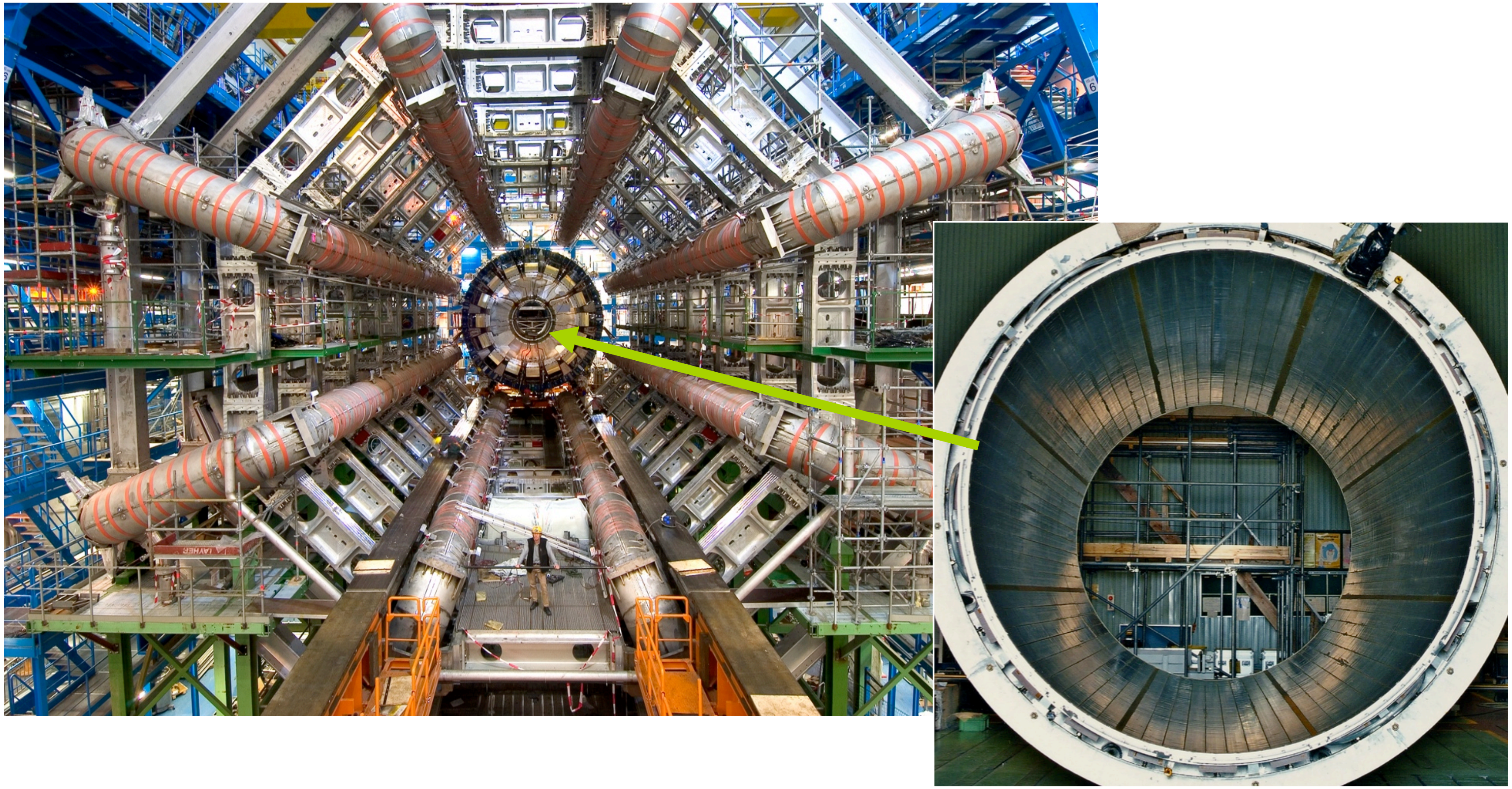




Thin coil
High-strength
Al-stabilizer

30 mm

Installation of ATLAS Central Solenoid



Solenoid

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

Energy / Mass Ratio

- Magnetic Field: rot B = $\mu_0 J$
- Stored Energy: $E = 1/2\mu_0 \int B^2\, dv$
- Coil Mass: $M = V_{coil} \infty \gamma$
- 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: $E/M = (B^2/2\mu_0) \cdot R/2\gamma$**

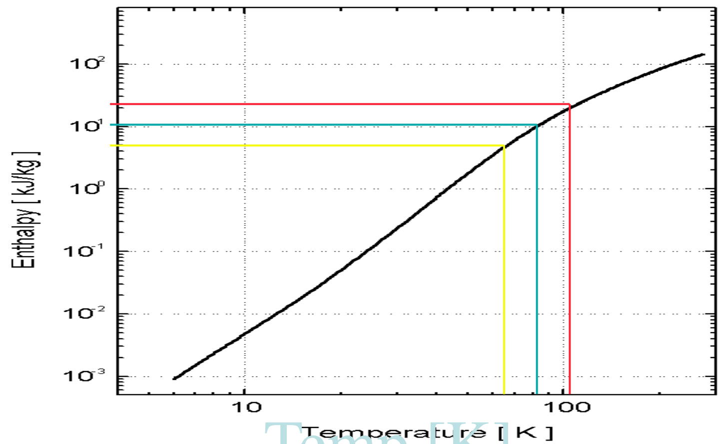
  $= \sigma_h/2\gamma$

B:	magnetic field
μ_0:	permeability
V_{field}:	magnetic volume
V_{coil}:	coil volume
γ:	effective density
σ_{hoop}:	hoop stress
R:	coil radius
t:	coil thickness

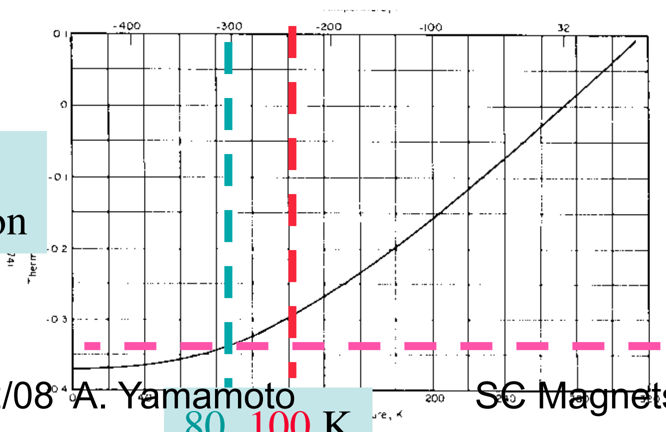
E/M : Stored Energy / Cold Mass

A Scaling Parameter to optimize Coil Design

Entharpy



Thermal Expansion



80, 100 K

Enthalpy

H = E/M = Integral {Cp dt}

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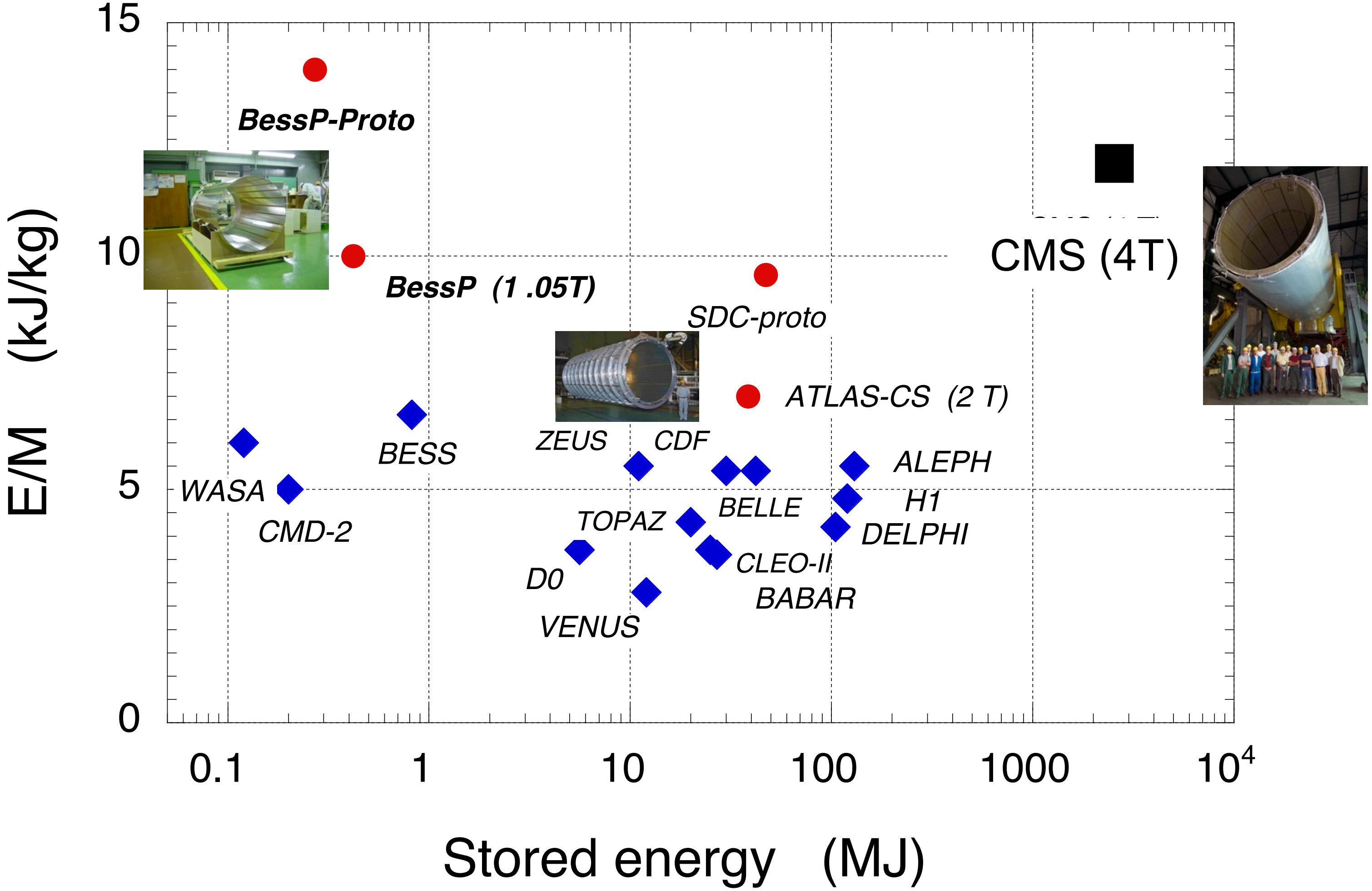
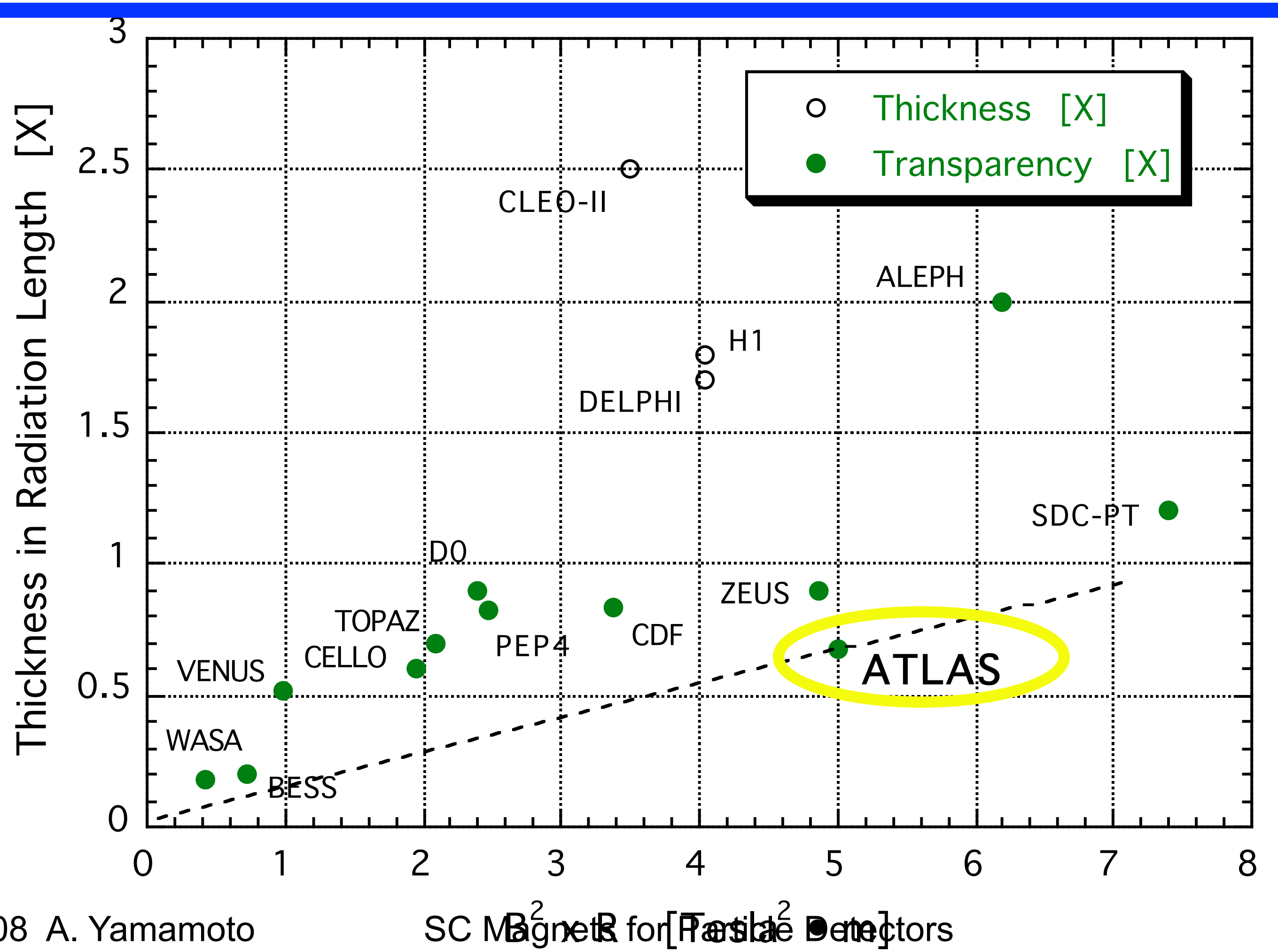
20 kJ/kg	**~100 K**
10 kJ/kg	**~ 80 K**
5 kJ/kg	**~ 65 K**

Peak Temperature with homogeneous energy dump

Stored Energy to Mass Ratio

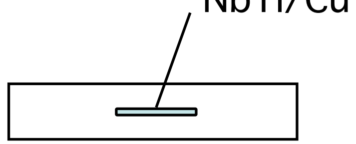


Radiation Thickness of Various Solenoids



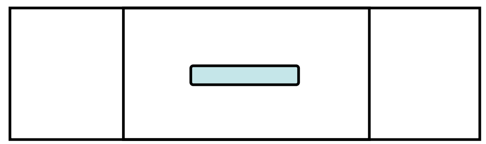
Two Approaches to Stabilization High-Strength Al-Stabilizing

- **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

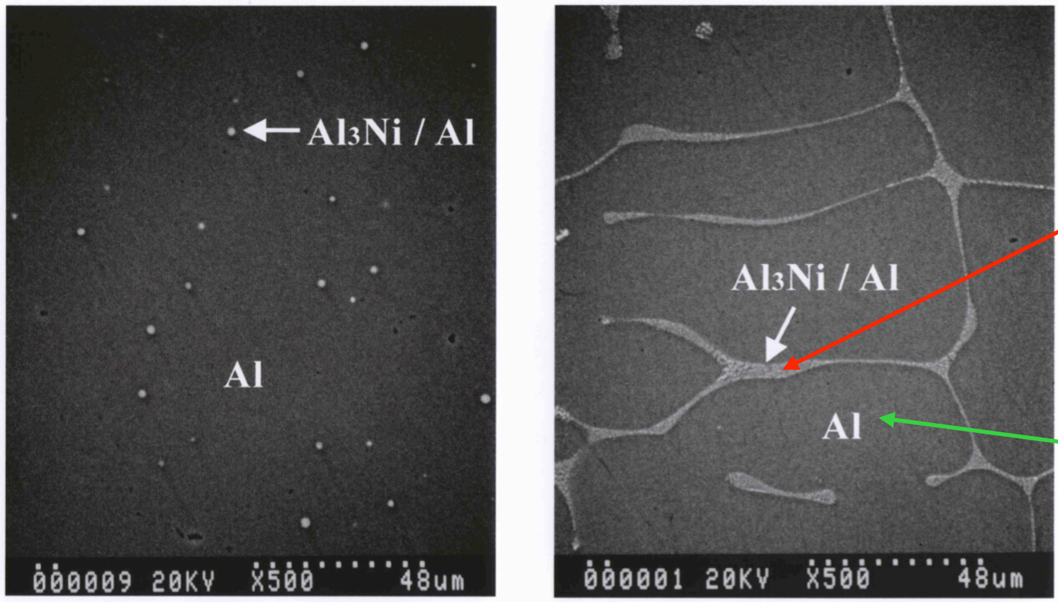


Alloy / Pure-Al / Alloy

Hybrid

Composite structure formed by
Micro-alloying and precipitation

Ni>> High



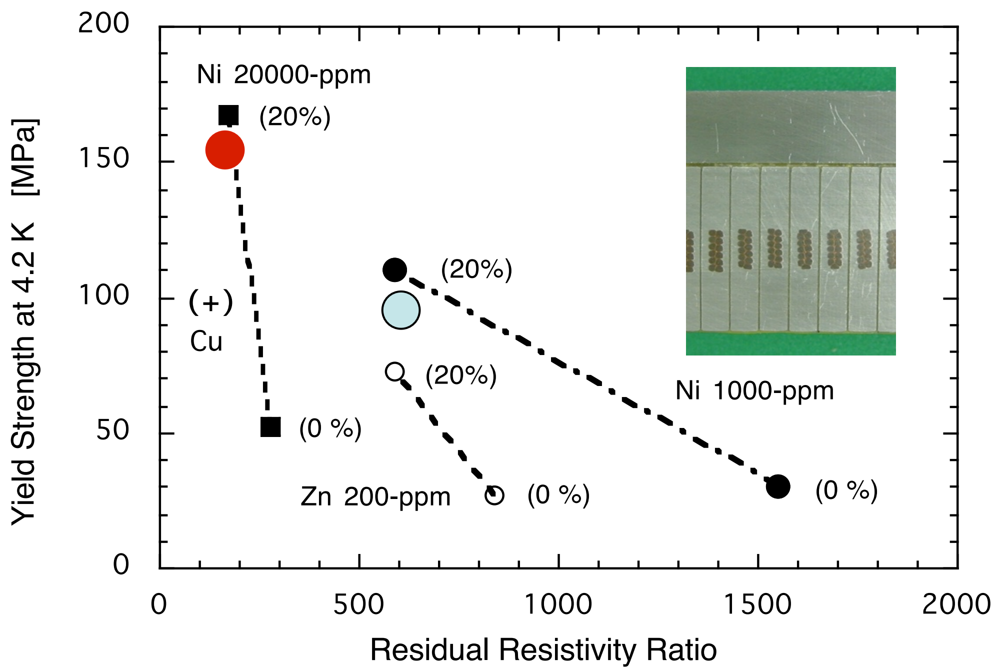
a) Al-0.1wt%Ni Alloy   b) Al-0.5wt%Ni Alloy

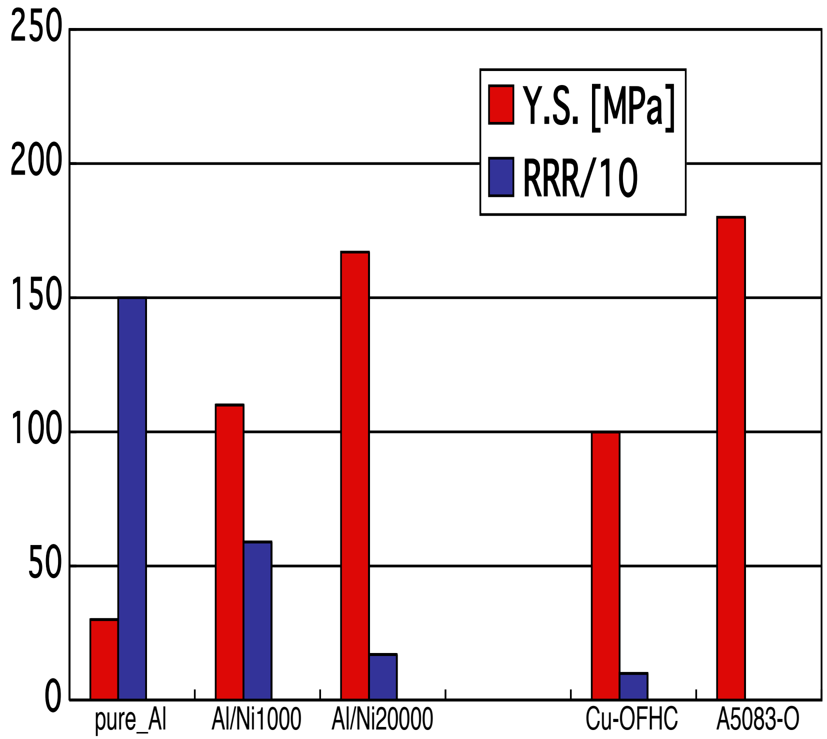
0.1%   0.5%

Al_3Ni precipitated
Contributes as structural component

Pure-Al region
Keep low resistivity

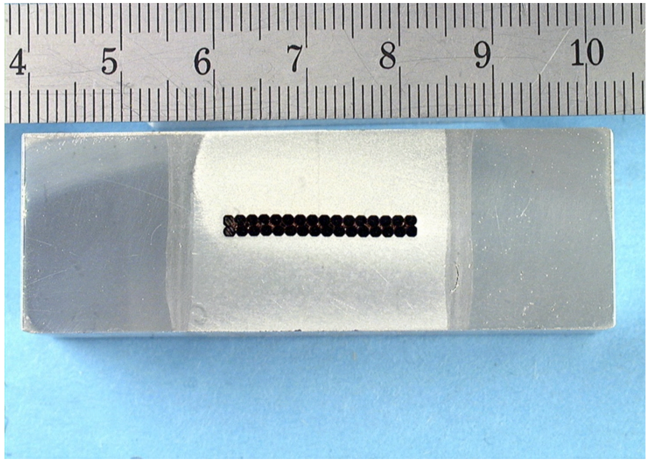
High-strength Al-stabilizer

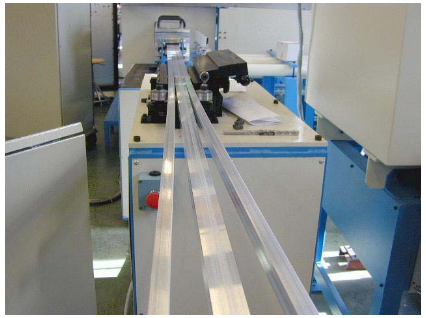


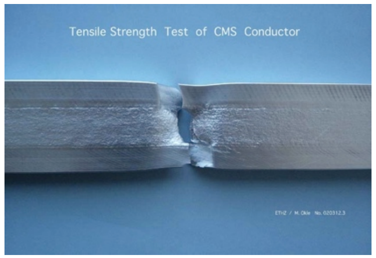


Micro-alloying + Cold-work (area reduction) hardening
Ni 0.1 ~ 2 % + 15~20 % Cold-work

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)

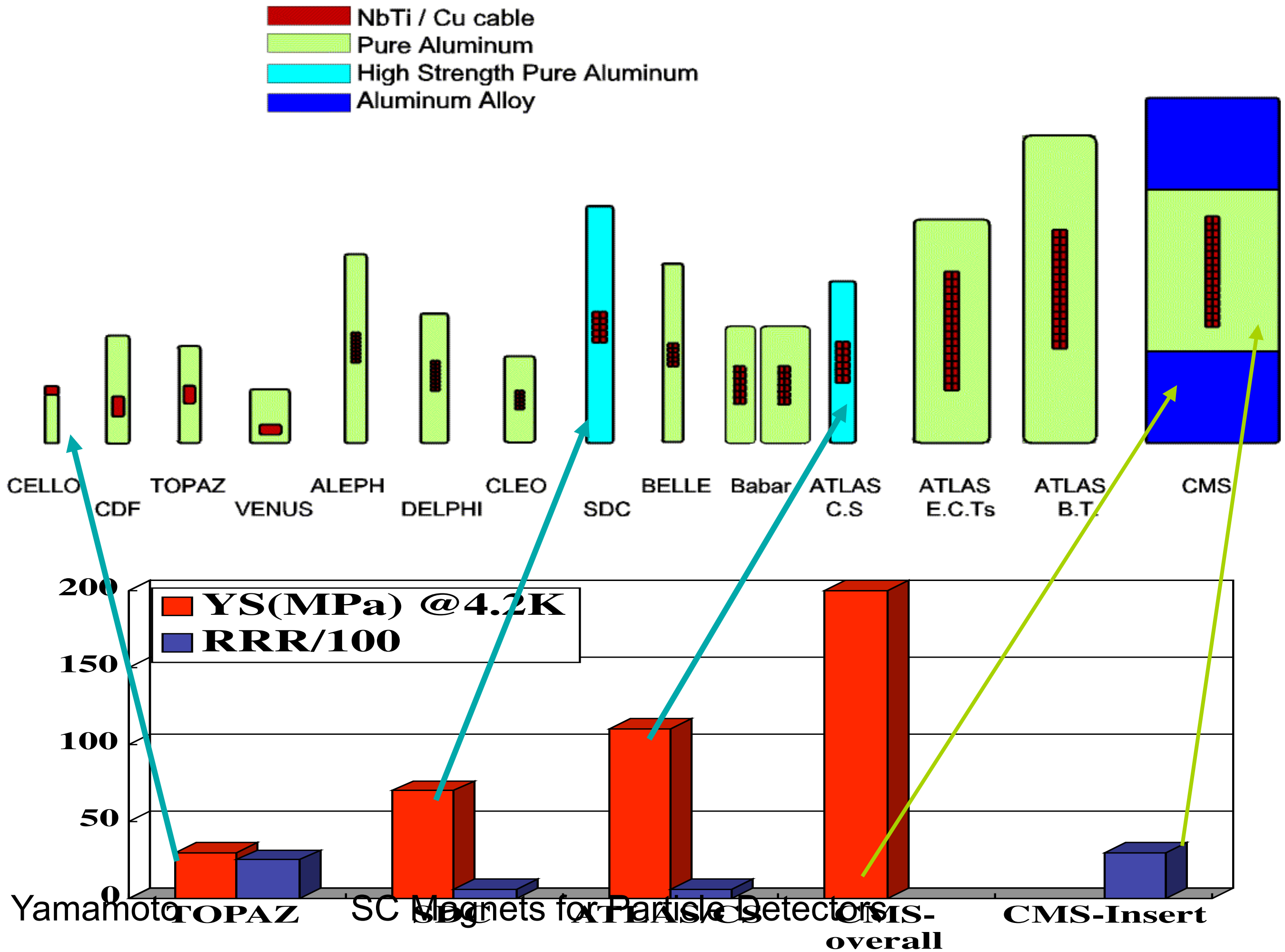
Electrical properties of inserts

RRR :

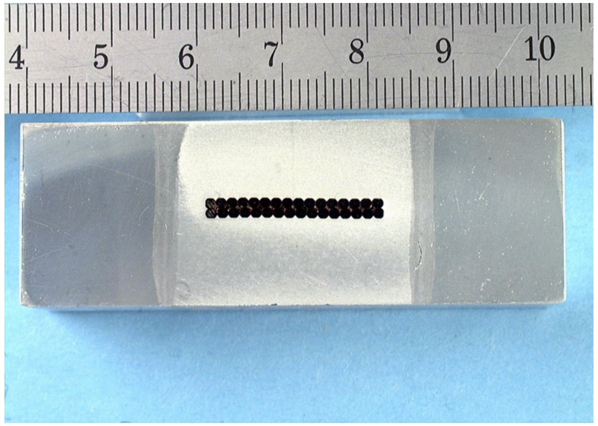
3020	**@ 0 T**
1134	@ 1 T
977	**@ 5 T**

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

Progress of Al-Stabilizer Superconductor in Colliding Detector Magnets



Further Development for Al-Stabilizer Superconductor

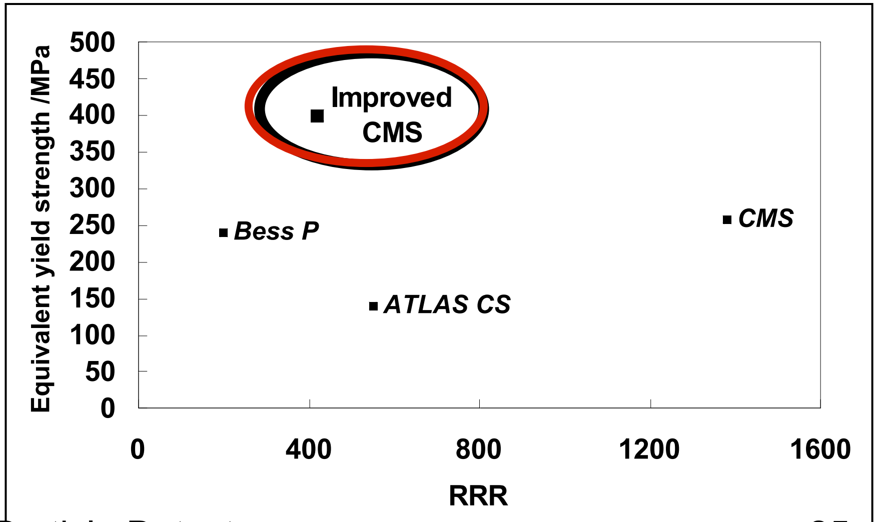


- Energy Frontier Collider Detector
  - Field： > 5 Tesla
  - Scale： Diameter, ～10m

- Further reinforcement

  - ATLAS H.S. stabilizer
    - Ni-0.5 ~ 1 %
  - CMS-Hybrid Support
    - A6058 -->> A7020

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

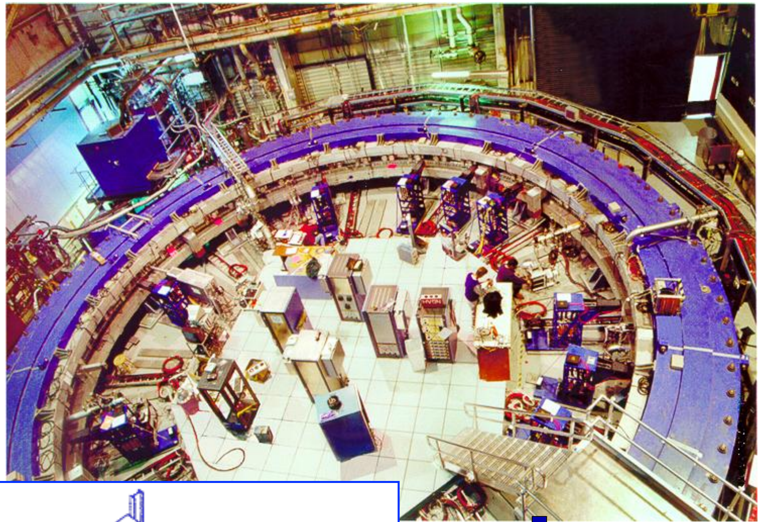


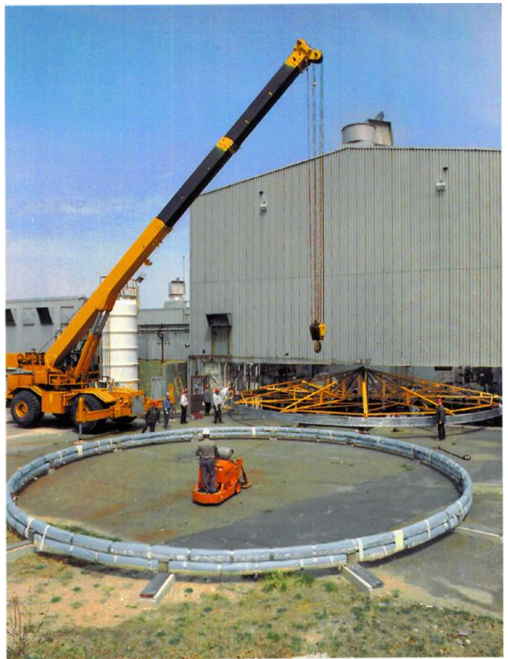
Guide Lines Suggested for Future Detector Magnets (ILC/CLIC)

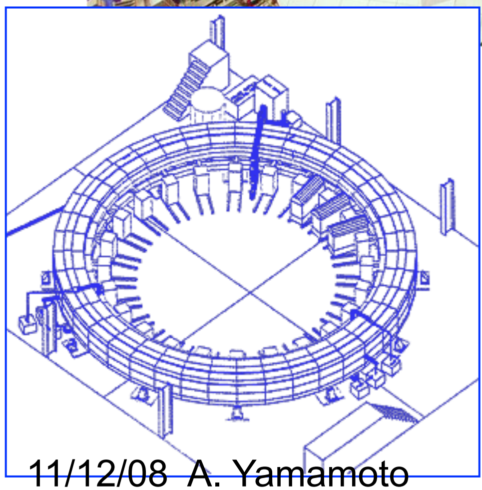
- NbTi superconductor at Bc = 5 T or smaller,
  - T-margin >> 1 K for reliable operation
- Al-stabilized superconductor
  - High strength Al-stabilizer inevitably important for practical magnet design with E/M ratio of 10-12 kJ/kg
  - Quench protection with ~ 50 % energy extraction.

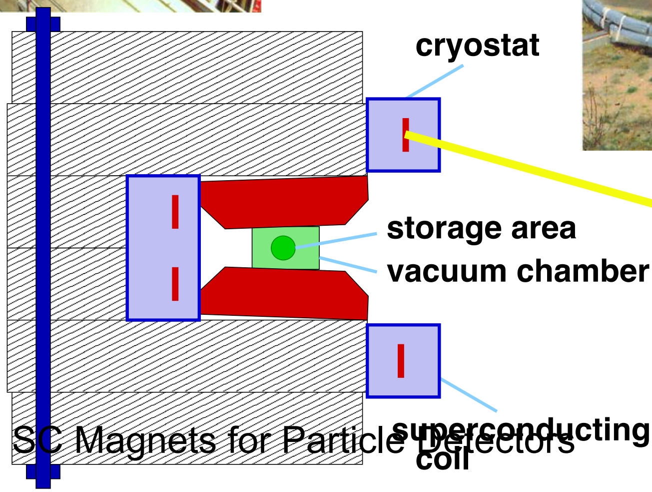
An Application for Superconducting Muon Storage Ring

for Muon G-2 Measurement at BNL

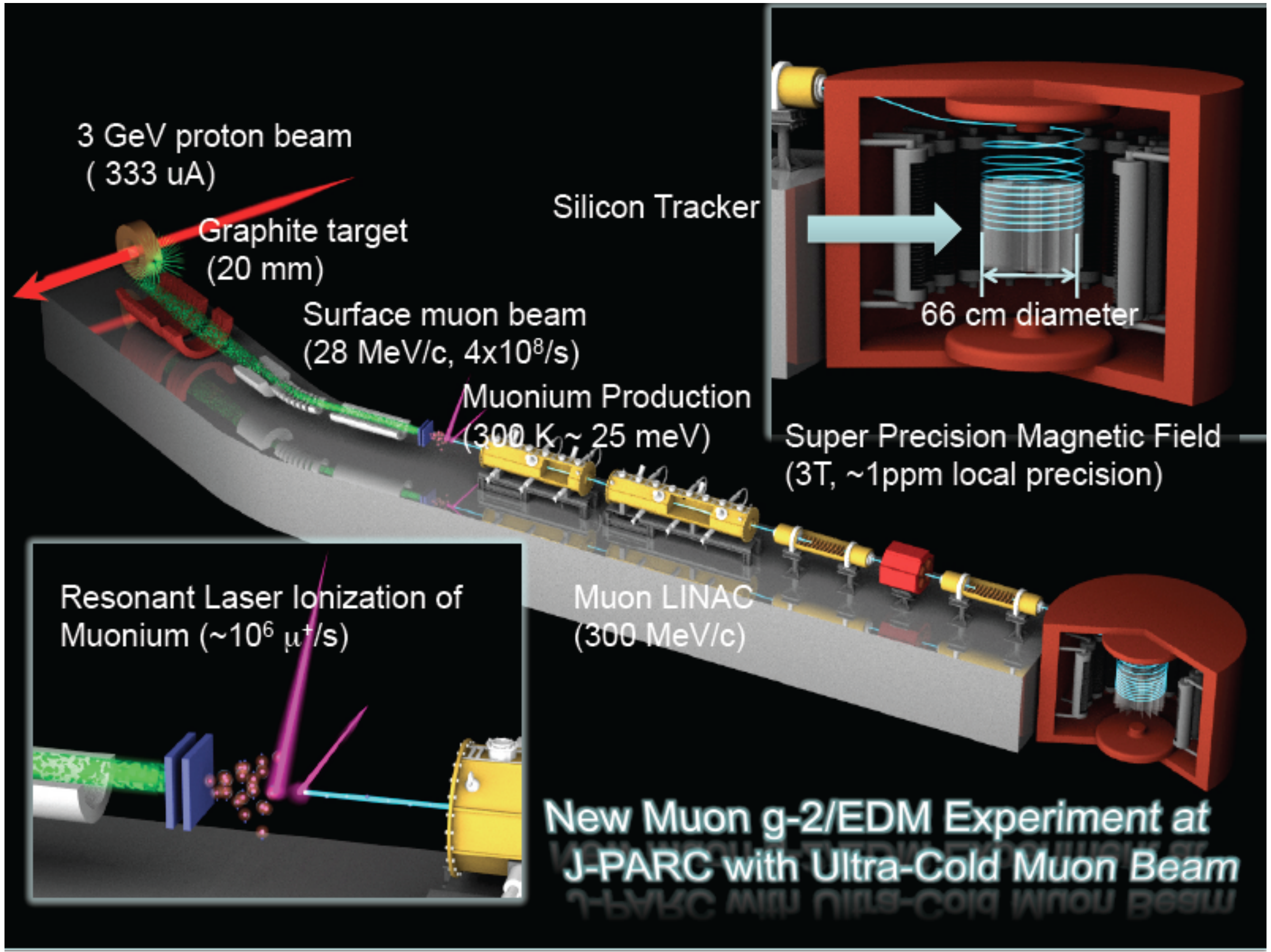








A New muon g-2 Experiment



Pion Capture Solenoids for Intense Muon Beam Experiments

High Intensity Muon Source

for muon-electron conversion experiment: such as: Mu2E, COMET, …

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:

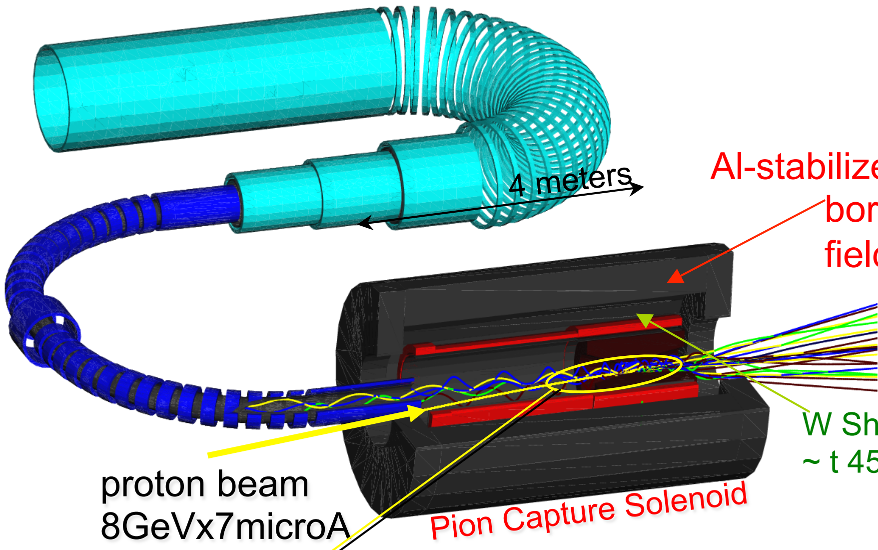
- Nuclear heating in SC coils
- Irradiation damage in stabilizer, etc.

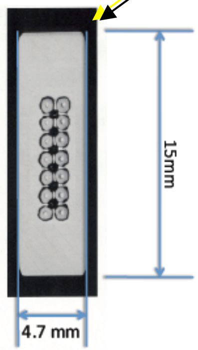
Aluminum stabilizer

- "Transparent" to particles

  →Lower heat load, smaller bore for shielding
- Perfect recovery from irradiation damage by thermal cycle to room temp.

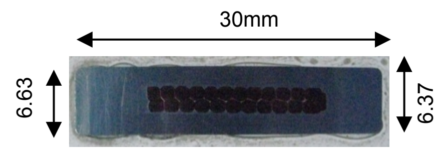
  →Stable operation





Design parameters for COMET

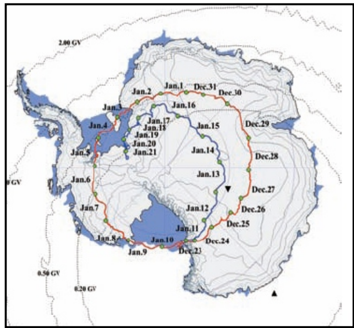
- Size: 4.7x15mm
- Proof strength of Al@4K: >85MPa
- RRR@0T: >500
- Al/Cu/SC: 7.3/0.9/1
- 14 SC strands: 1.15mm dia.



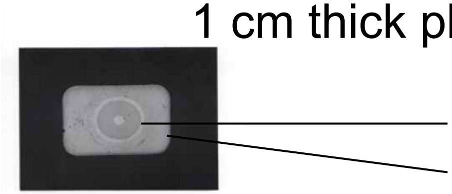
Mu2e-design-based conductor (2010)

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



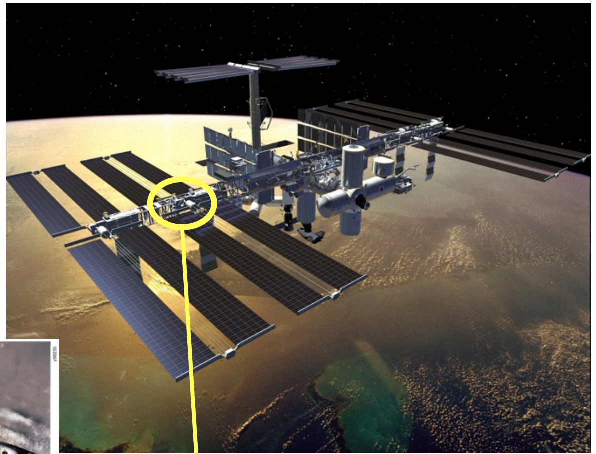
Equivalent mass with
1 cm thick plastic scintillator

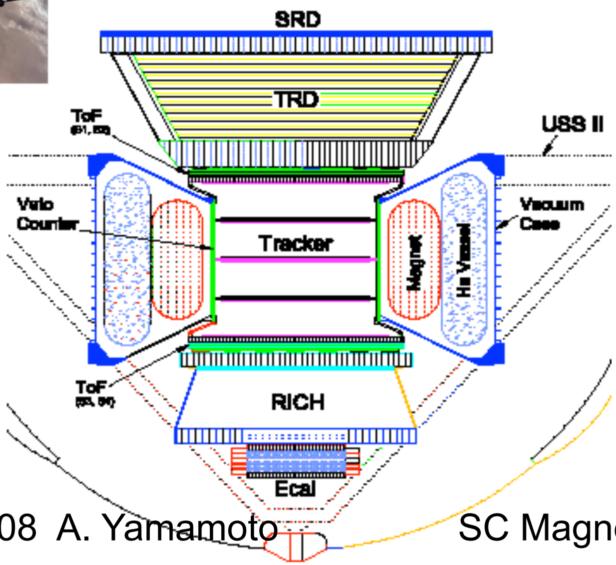


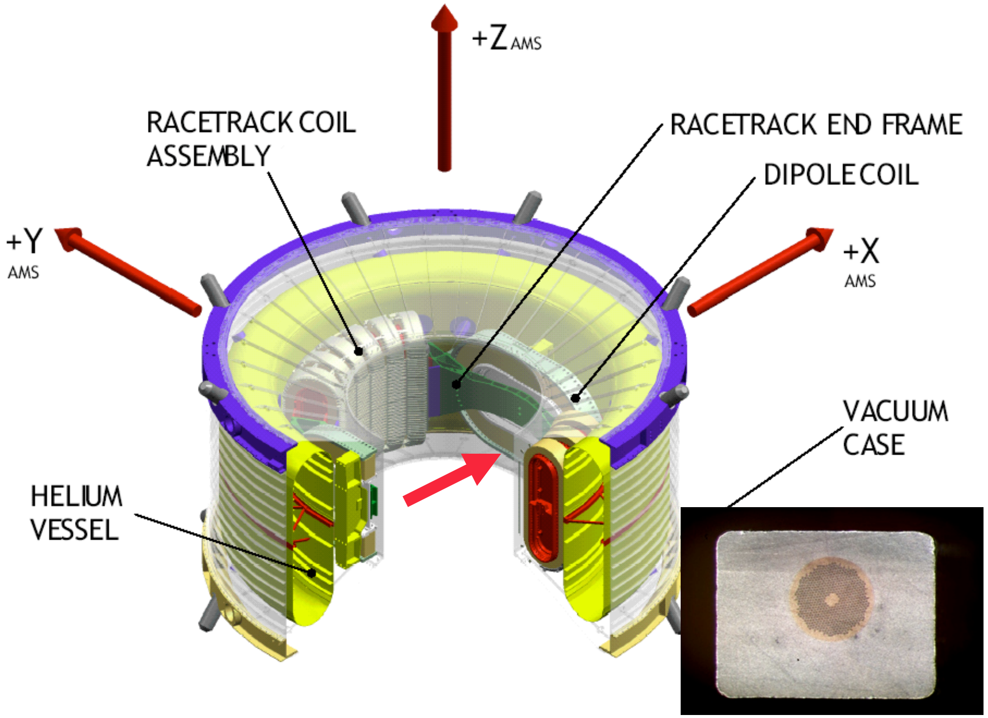
NbTi superconudctor
Al-stabilizer
>> High strength and Low R

AMS developed Al-stabilized SC coil,

but not applied in the scientific flight





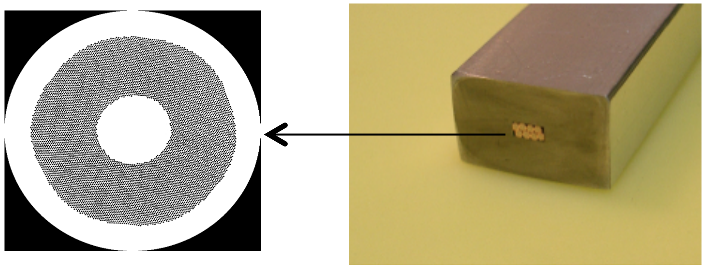


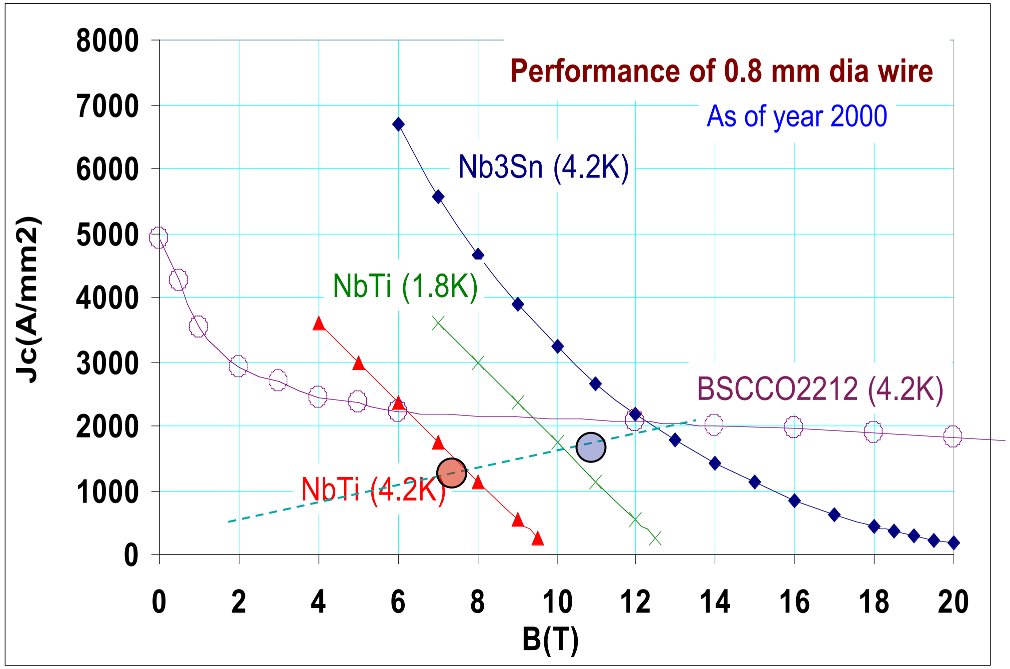
Active Dipoles and Helmholtz coils to cancel global magnetic moment.

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

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 a *'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.

Progress in Detector Magnets

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

Momentum Analysis with Magnetic Field

- Bending with magnetic field

  Deflection:

  $\tan \theta = \sim \theta$

  $= L/\rho = e\, B\, L/\, \mathbf{p}$

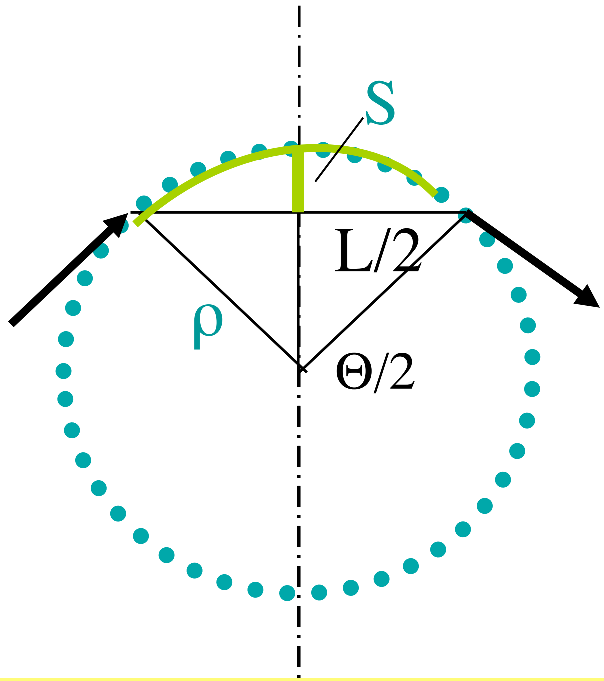
  Sagitta:

  $S \sim (1/8)\, e \bullet B \bullet L^2 / p$

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

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

>> S = .3 ÷ 8 ÷ 1 = 37.5 mm



$S = \rho(1\text{-}\cos \theta/2)$

Taylor Expansion,

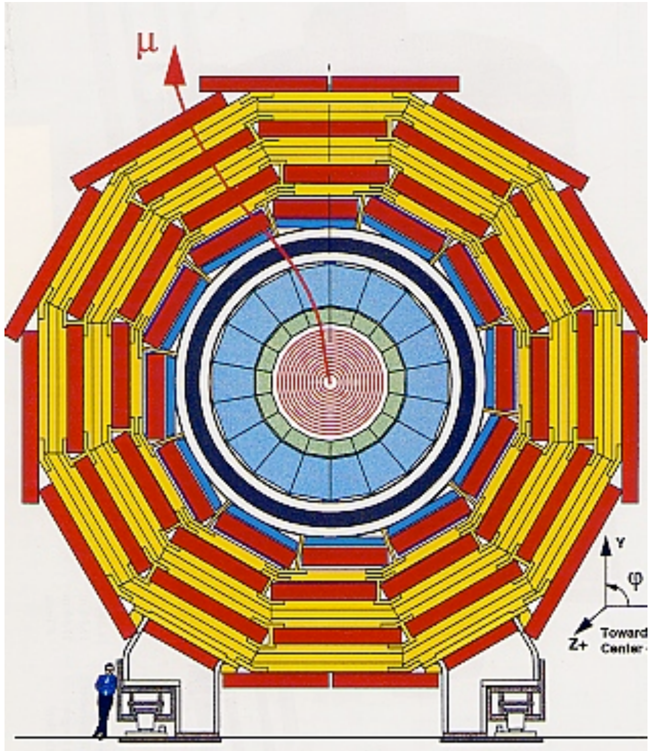
$\cos(\theta) = 1 - (\theta/2)^2/2! + (\theta/2)^4/4!$

$S = \sim \rho\, \theta^2 / 8 = eBL^2/8p$

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

CMS: Solenoidal Field

- Axial, Uniform Field
- Self Supporting
- Iron Return Yoke
- Field inside the solenoid
  - Sagitta measurement
  - **dp/p ~ $\{B \bullet R^2\}^{-1}$**

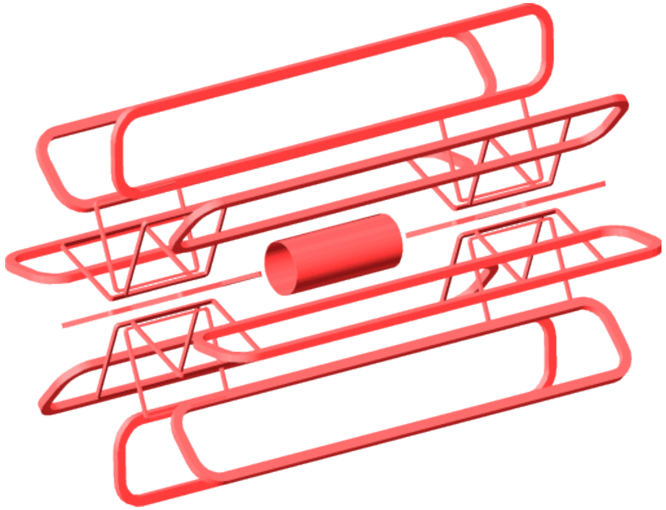


- Deflection angle outside the solenoid
  - **dp/p ~ $\{B \bullet R\}^{-1}$**

ATLAS: Toroidal Field

Self Closed Field

Field only at Detector Region



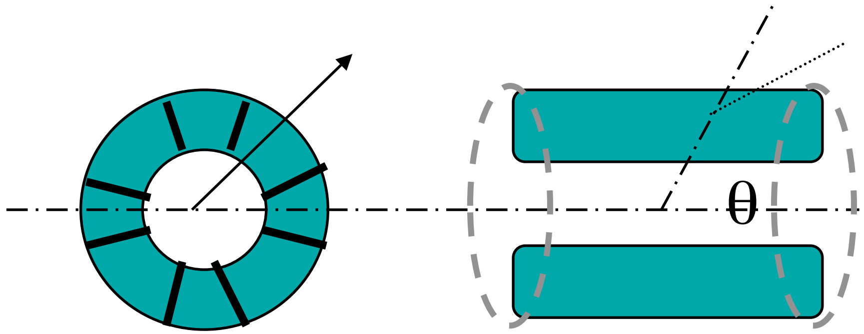
Field : proportional to R^{-1}

6~ 8 coils in practical design

Largre field in the coil

Sophisticated support structure

to keep self balance



Saggita and deflection

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

More Powerful Deflection in forward/backward direction

Basic Relations with Detector Magnet

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

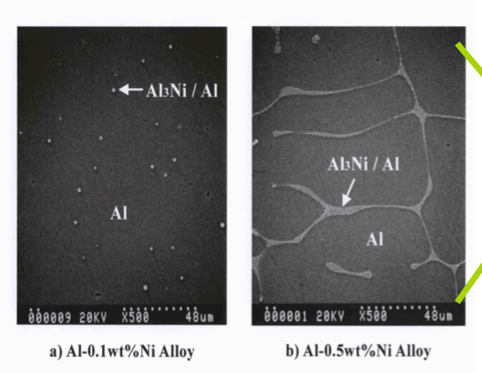
- **Magnetic Field:** $\mathrm{rot}\ B = \mu_0 J$
- **Stored Energy:** $E = 1/2\mu_0 \ \mathrm{Int.}\ B^2\, dv$
- **Coil Mass:** $M = V_{coil}\, \gamma$
- **Pressure:** $p = B^2/2\mu_0$
- **Hoop Stress:** $\sigma_{hoop} = (R/t) \cdot p$
- **Wall thickness:** $t = (R/\sigma_h) \cdot p$
- **E/M ratio:**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

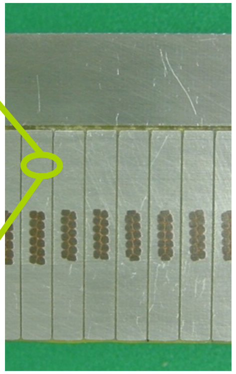
•B:	magnetic field
•μ_0:	magnetic permeability
•V_{field}:	magnetic volume
•V_{coil}:	coil volume
•.γ:	effective density
•.σ_{hoop}:	hoop stress
•R:	coil radius
•t:	coil thickness

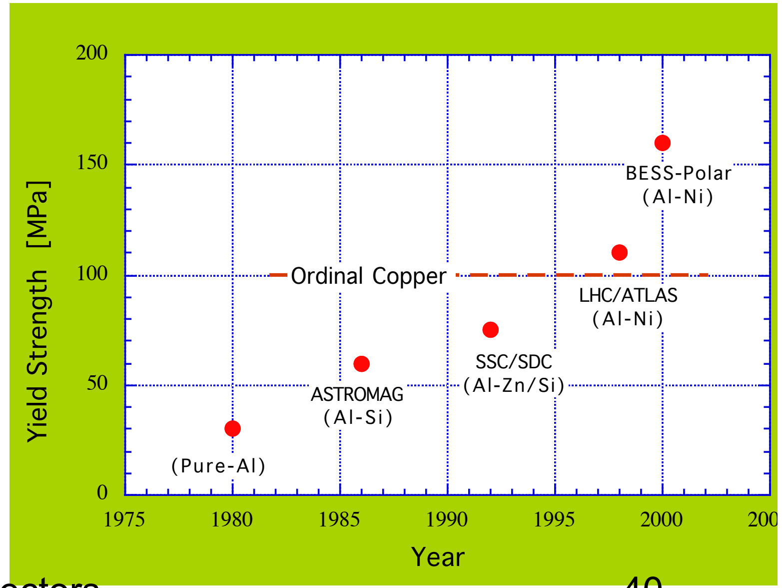
High-strength Al-Stabilizer Uniform reinforcement

- Highest B with minimizing wall material:

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

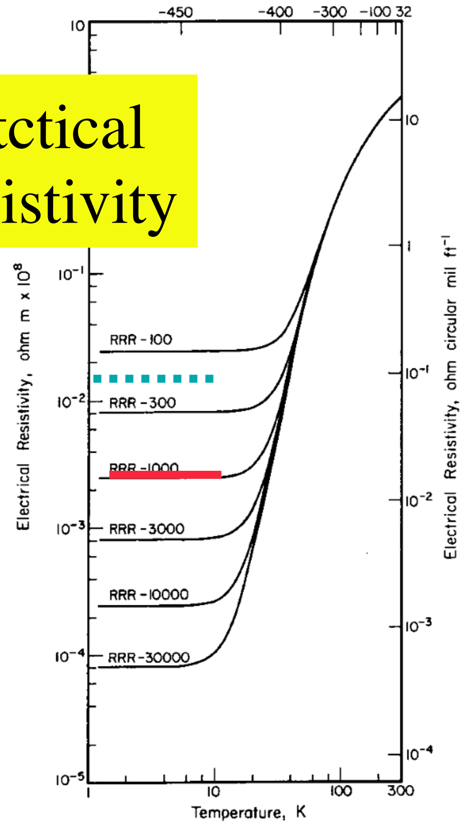




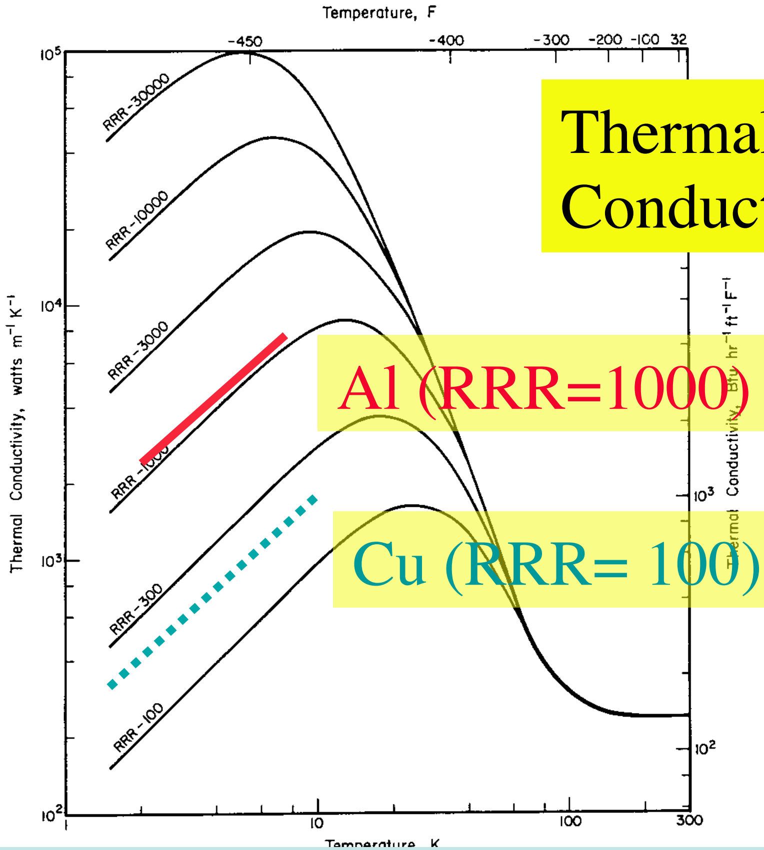


Characteristics of Aluminum

Eletctical Resistivity



Thermal Conductivity



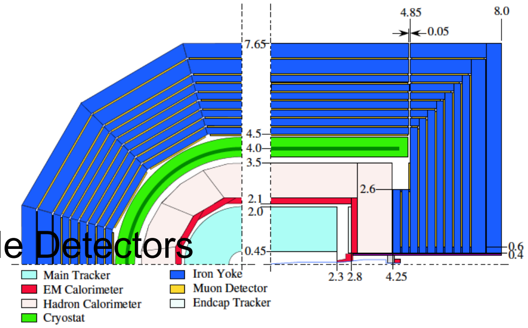
Al (RRR=1000)

Cu (RRR= 100)

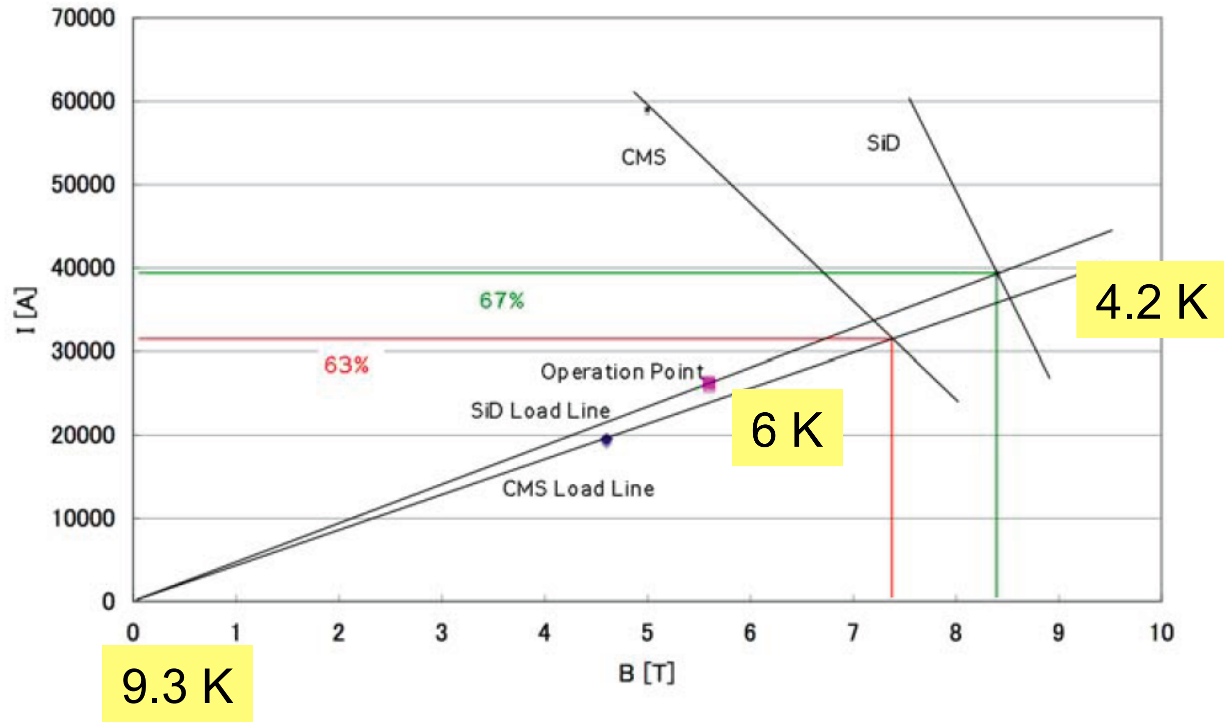
Aluminum may provide very wide range characteristics depending on the purity (or RRR)

ILC Detector Magnets
Possible Design Parameters

		LHC		ILC /CLIC	
	unit	ATLAS-CS	CMS	ILD	SiD
Mag. Field	T	2	4	3.5	5
Diameter	m	2.5	6.5	8	5.3
Coil thick.	m	0.045	0.3		0.4
Length	m	5.4	12.5	8.9	5
St. Energy	GJ	0,04	2.6		1.4
E/M	kJ/kg	7	12	~ 12	12



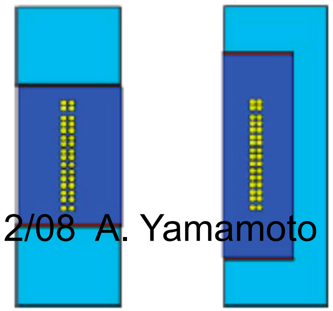
NbTi Superconductor Faces Limit imposed by Temperature Margin

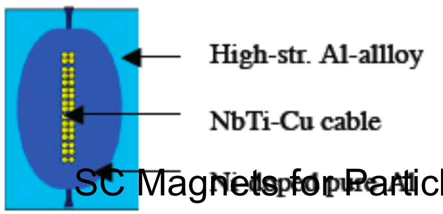


- A load line ratio of < 70 % should be kept to maintain a temperature margin of >> 1 K.
- The practical limit of NbTi is to provide a useful field of 5 T

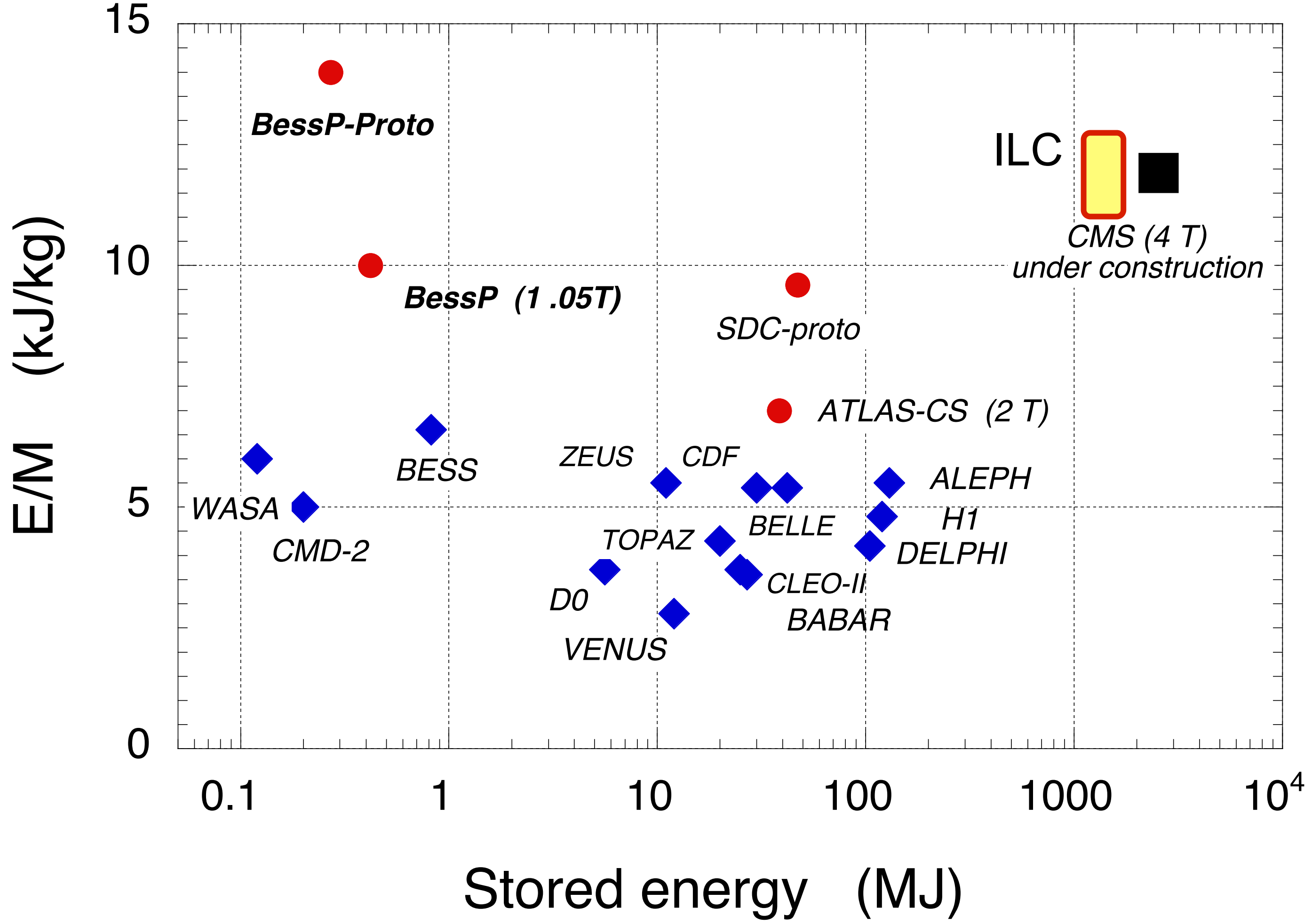
Further Optimization on Strength and RRR

	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





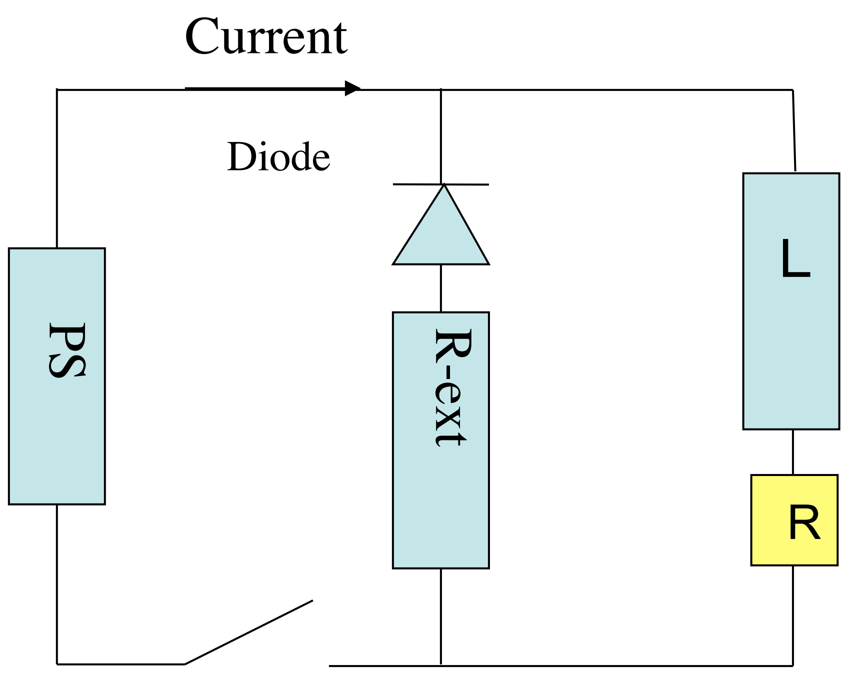
E/M Ratio Expected at ILC Solenoids



Practical Energy Extraction

for effective reduction of E/M ratio

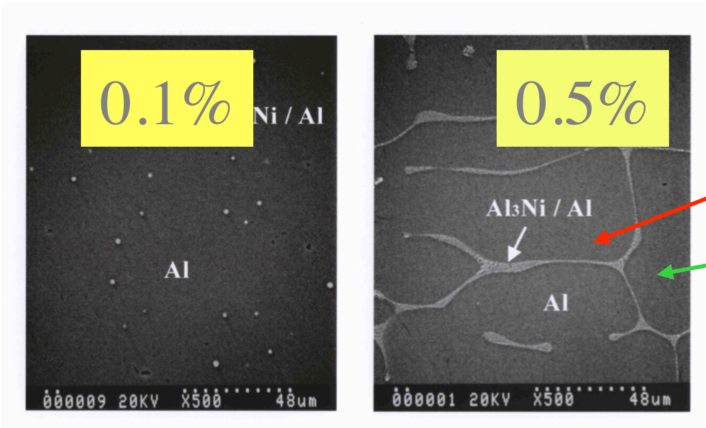
- Immediate switch off and
  - Extraction of energy into external dump resister
  - Lower energy dump into coil
  - Lower peak temperature
- Reliability to be very important
  - Voltage limit across R-ext



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

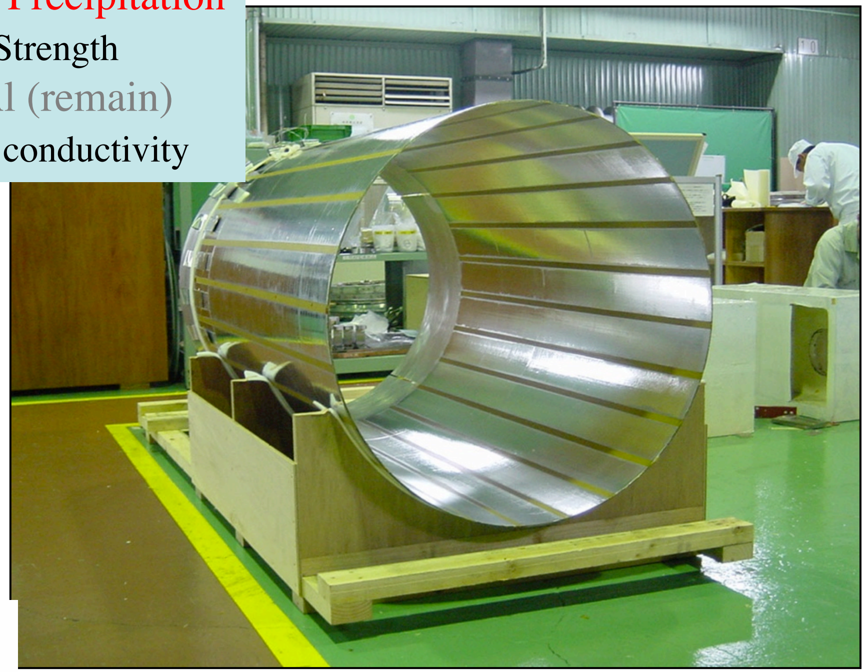
An Extremely Thin Solenoid

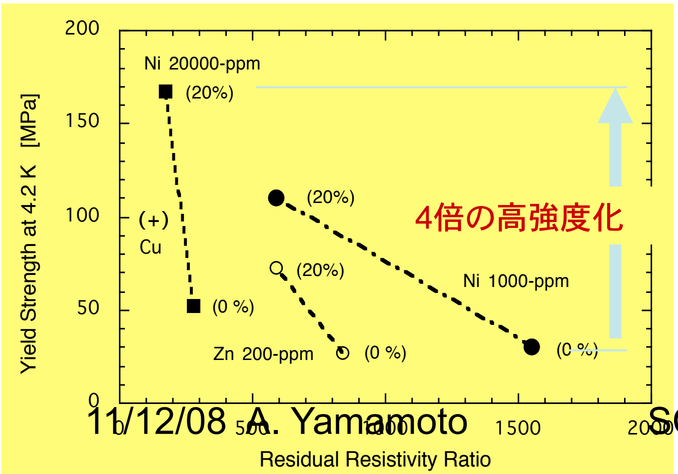
BESS-Polar : Bc = 1 T, D = 0.9 m, t = 3 mm, X = 0.1 Xo

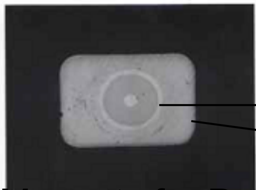


a) Al-0.1wt%Ni Alloy
b) Al-0.5wt%Ni Alloy

Al_3Ni Precipitation
High Strength
Pure Al (remain)
High conductivity







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