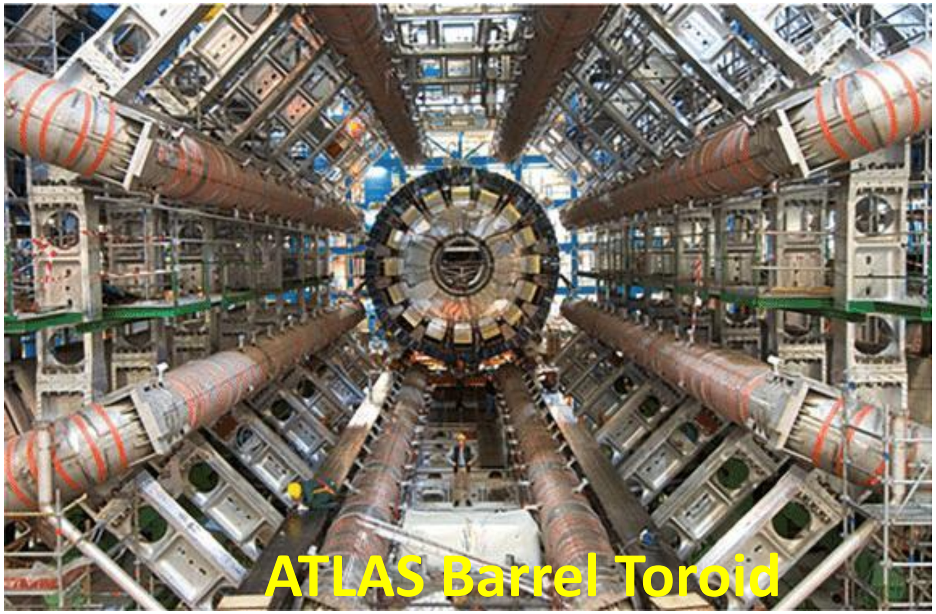
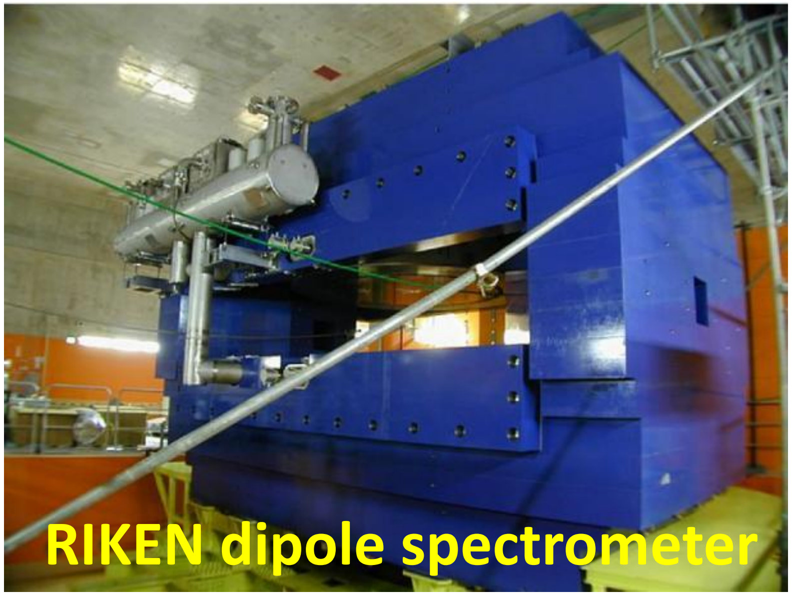




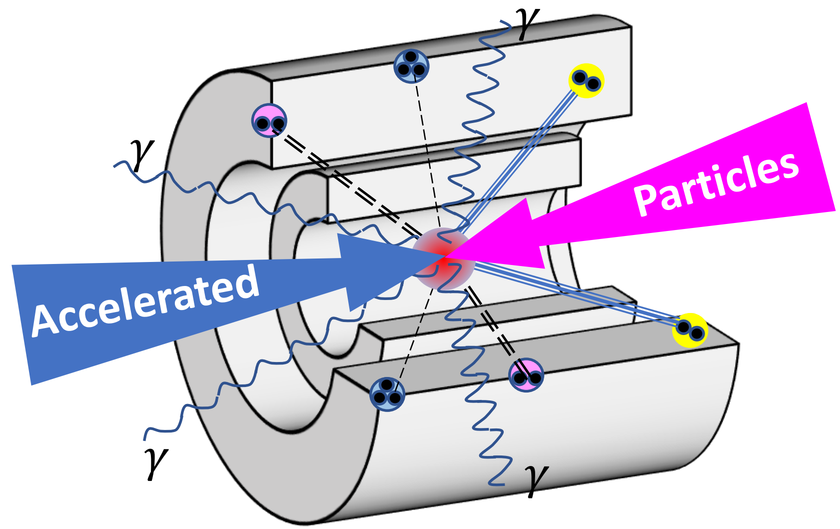
Superconducting Detector Magnet

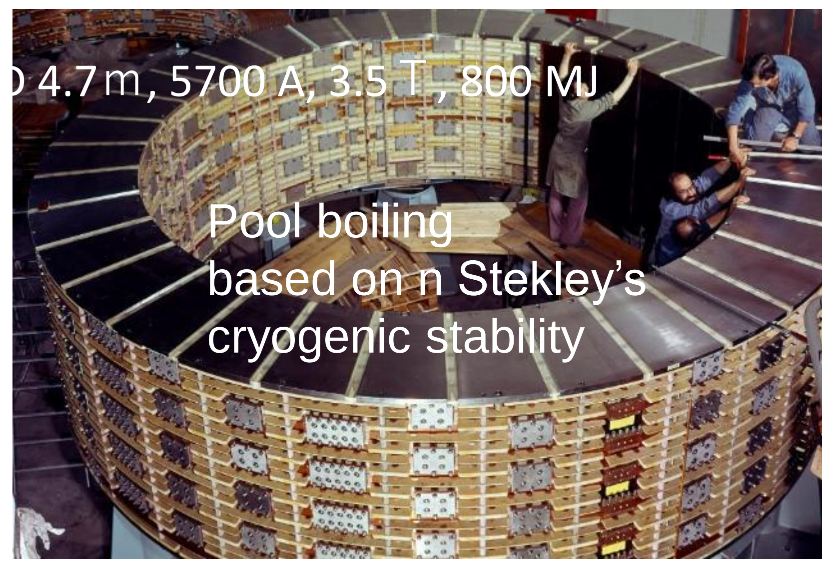
2026/2/4

KEK Yasuhiro Makida

Introduction(1)

- To discover new elementary particles
  - Accelerator produces new particles from high energy cluster generated by collisions of accelerated particles known as proton, electron, positron.
  - Detector analyzes shower of produced particles.
- Particle detector with magnetic field is effective.
  - Momentum measurement.
  - Polarity (Matter or Antimatter) identification.
- Large volume with magnetic field is created to measure trajectory of particles.
- Implement SC magnet for detector started around 1970.
  - for LH_2 bubble chamber.
    - 12-foot BC magnet in 1969 at Argonne
    - BNL(1970), FNAL(1973), CERN(1972) ...



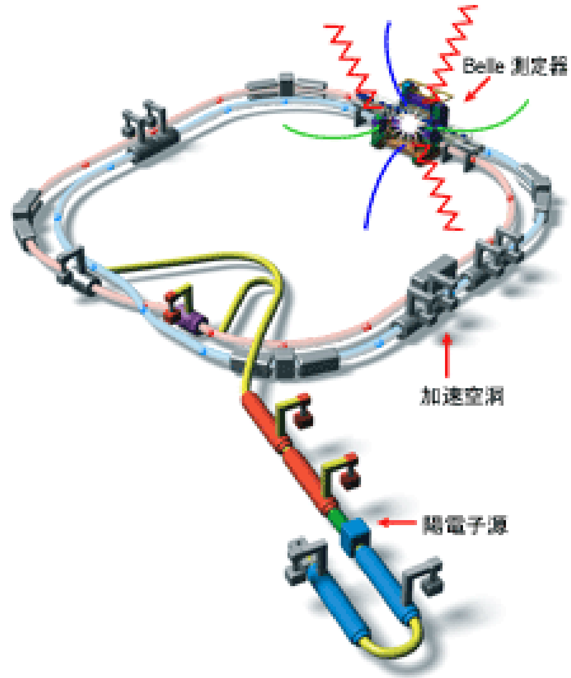


BEBC SC coil made in 1970

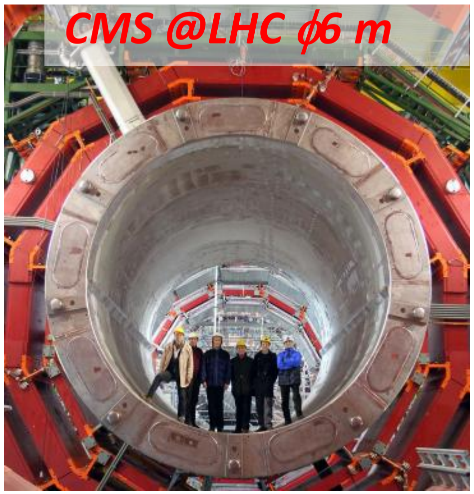
From CERN Courier December 2005

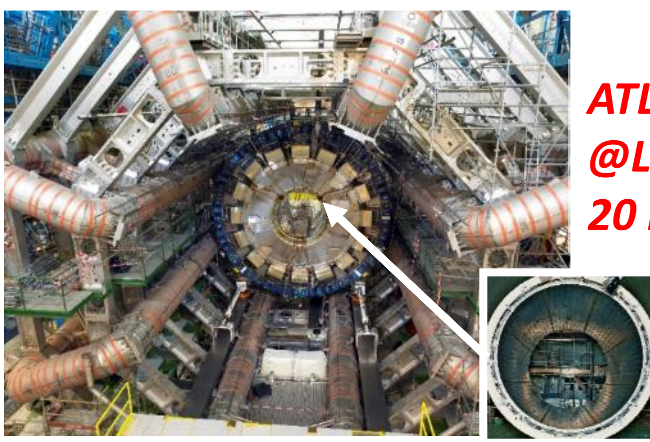
Introduction(2)

- Development of Detector SC magnets.
  - Huge detector magnets for the energy frontier accelerator experiments have been developed.

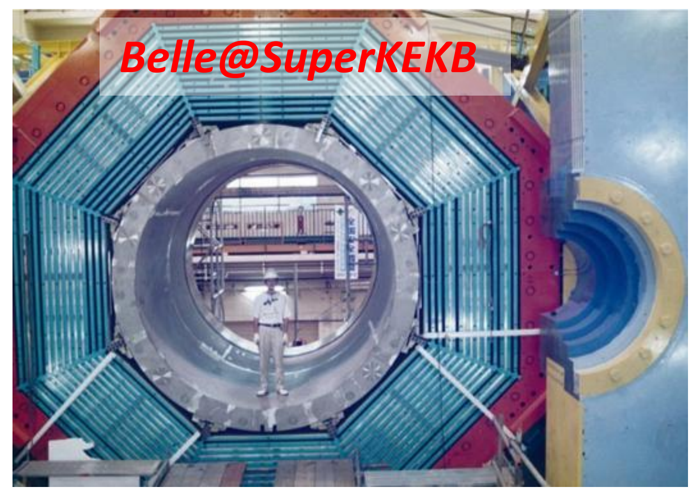


https://www2.kek.jp/ja/newskek/2007/sepoct/kekb3.html





ATLAS solenoid & toroid @LHC
20 m wide & ϕ2,5 m



Introduction(3)

Except EF experiments,

- Many kinds of Detector magnets have been developed for many accelerator experiments, nuclear and material etc.
    - Cryocooler promote SC detector magnet.
    - For cosmic observation, SC magnet ballooning through sky.
- **This lecture explains technical features of detector SCM.**

. Imazato, et al, Proceedings of MT-11

K. Aoki, TEION KOGAKU, 45,4, p191

T. Inagaki, Cryogenics, vol. 24, no. 2, p. 83

W. Ootani et al. : IEEE Trans. on Appl. Super. 14 2 (2004) 568

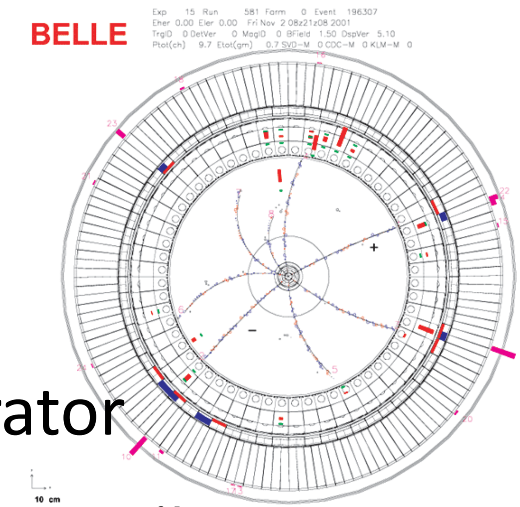
Y. Sato et al. : Proc. of the 15th Int. Conf. on Magnet Technology (MT-15) (1998) 262

OUTLINES

1. Charged particles in a magnetic field.
2. Type and features of magnetic spectrometer.
3. Thin solenoid type magnet
   1. E/M ratio
   2. Aluminum stabilized superconductor
   3. Coil manufacture (Direct internal winding)
   4. Conductive cooling
   5. Quench protection
   6. Cryostat
4. Future plans

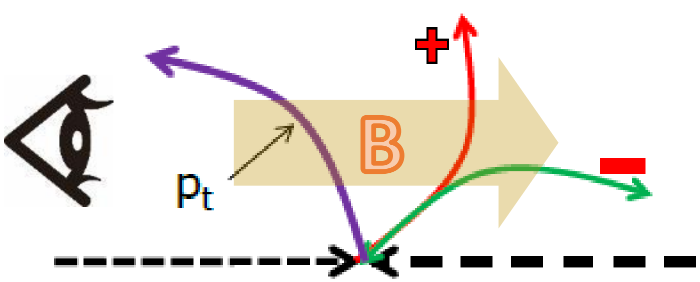
Charged particles in a magnetic field.(1)

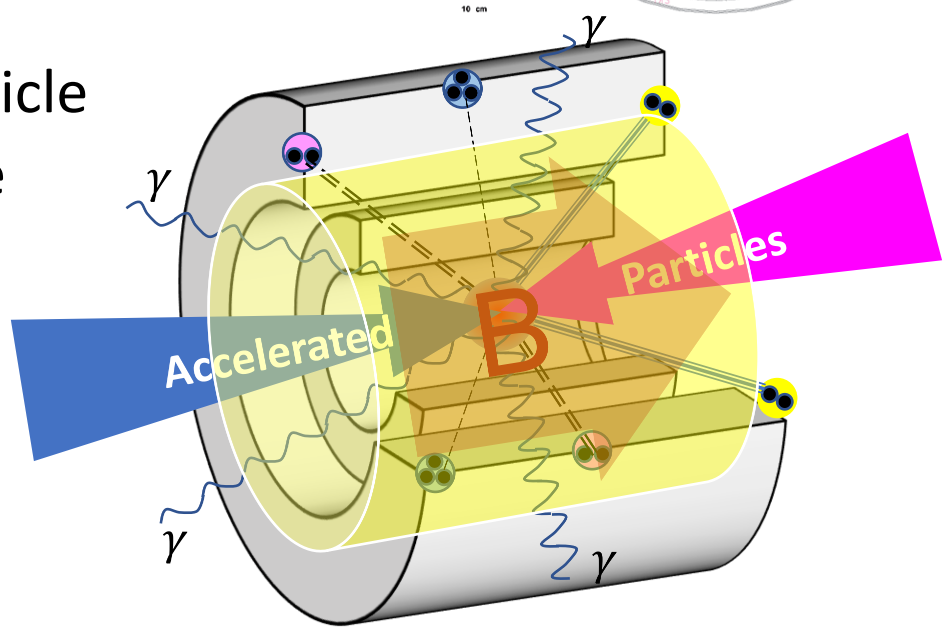
- How to analyze the shower of particles ? We need:
  - Track reconstruction in trackers
  - Energy measurement in calorimeters
  - Charge identification in magnetic field
  - Momentum measurement in magnetic field



- Detector magnet is in fact, magnetic separator

  Information yield:
  - anticlockwise -> positive particle
  - clockwise -> negative particle
  - curvature -> momentum





Charged particles in a magnetic field(2)

A particle with mass m, charge q, velocity $\boldsymbol{v}$ will be deflected in a magnetic field $\boldsymbol{B}$. (Lorentz force)

$$\boldsymbol{F} = \dot{\boldsymbol{p}} = m\dot{\boldsymbol{v}} = q(\boldsymbol{v} \times \boldsymbol{B}) \ \rightarrow \dot{\boldsymbol{v}} = \frac{q}{m}(\boldsymbol{v} \times \boldsymbol{B})$$

Now $B_1 = B_2 = 0, B_3 = B > 0$ and $\boldsymbol{v}_T = v_1\boldsymbol{e}_1 + v_2\boldsymbol{e}_2, \quad \boldsymbol{v}_\parallel = v_3\boldsymbol{e}_3$

This solution describes a rotating velocity vector $\boldsymbol{v}_T$ in the plane perpendicular to $\boldsymbol{B}$.

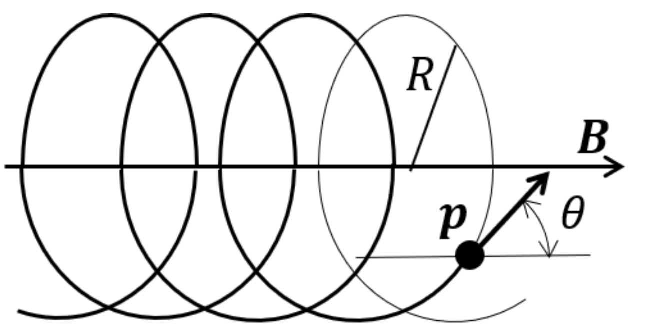
$$v_1 = v_T \cos\left(\frac{Bq}{m}t + \psi_0\right), \ v_2 = -v_T \sin\left(\frac{Bq}{m}t + \psi_0\right), v_3 = v_\parallel$$

Integration yields the particle trajectory.

$$x_1 = v_T \frac{m}{Bq} \sin\left(\frac{Bq}{m}t + \psi_0\right) + x_{10}$$

$$x_2 = v_T \frac{m}{Bq} \cos\left(\frac{Bq}{m}t + \psi_0\right) + x_{20}$$

$$x_3 = v_\parallel t + x_{30}$$



This is the representation of a helix which lines on a cylinder surface coaxially with the magnetic field. Its projection onto the plane perpendicular to $\boldsymbol{B}$ describes a circle with radius

$$R = \sqrt{(x_1 - x_{10})^2 - (x_2 - x_{20})^2} = \frac{mv_T}{|q|B} = \frac{p_T}{|q|B}, \quad \sin\theta = \frac{p_T}{p}$$

Charged particles in a magnetic field(3)

$$p_T = |q|BR, \qquad p = \frac{p_T}{\sin\theta}$$

p_T:momentum perpendicular to B, p: total momentum

Employing the reconstructed radius of curvature R and slope θ of the helix, the transverse and the total momentum can be determined.

For practical use in the high energy physics, transvers momentum can also be written

$p_T = 0.3|z|BR$ We are often confused by the coefficient 0.3.

where the quantities are given in the following **units**, $\boldsymbol{p_T}$ **in [GeV/c],** B in [T], R in [m]

z is the particle charge in units of elementary charge, $\boldsymbol{z = q/1.602 \times 10^{-19}}$ in $[\boldsymbol{e}]$.

For the conversion , we use [Tesla]=[Volt ▪ sec/m²] and velocity of light

$c \approx 0.3 \times 10^9$[m/sec]

$\nabla \times \vec{E} = -\partial\vec{B}/\partial t$

$$\left[\frac{GeV}{c}\right] = \frac{[GeV]}{0.3 \times 10^9 [m/sec]} = \frac{1}{0.3}\left[\frac{eV sec}{m}\right] = \frac{1}{0.3}[eTm]$$

The factor 0.3 occurs whenever we change from momentum unit from eV/c to eV s/m. The latter would be a normal SI unit if e is expressed in units of coulomb, but in most cases in high energy physics, e cancels out when writing charges in unit of e.

The trajectory of particle with a momentum of 0.3 [GeV/c] has a curvature radius of 1 [m] in a field of 1 [T].

Charged particles in a magnetic field(4)

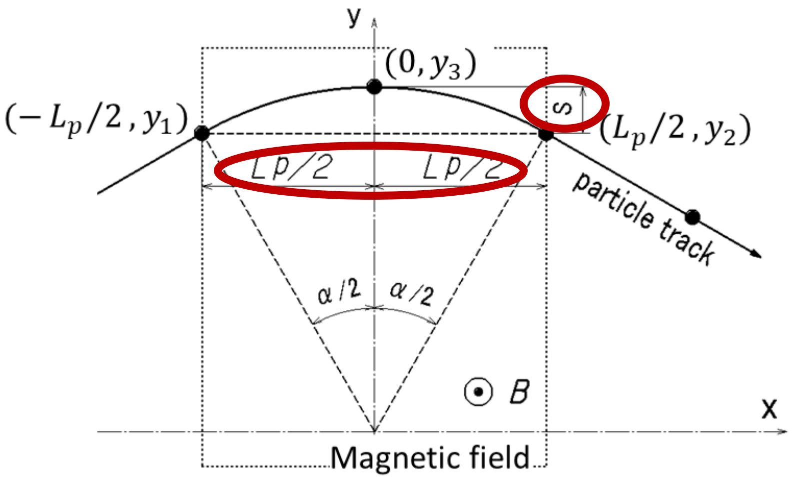
In actual particle detectors, the transverse momentum component p_T is determined from the curvature radius R at a small deflection angle α.
The measurement of p_T boils down to the determination of the **sagitta s, that is, largest perpendicular distance of the trajectory from the connecting line between the particle's entrance into and exit from the magnetic field volume L_p** (arm).
According to the figure, the following relations for the curvature radius, sagitta and arm are obtained.

$$\frac{R-s}{R} = \cos\frac{\alpha}{2} \approx 1 - \frac{1}{2}\left(\frac{\alpha}{2}\right)^2 = 1 - \frac{\alpha^2}{8}$$

and $\frac{L_p}{2R} = \sin\frac{\alpha}{2} \approx \frac{\alpha}{2}$

then $s \approx \frac{L_p^2}{8R}$, $\quad p_T = \frac{0.3}{8}\frac{L_p^2 B}{s}|z|$

where p_T[GeV/c], L_p [m], s[m], B[T] and $z[e]$



Resolution of momentum p_T depends on the sagitta s.
But its precision is limited due to the particle detectors' performance.
So, keeping the resolution of s for higher collision energies, so higher momentum, requires to scale up L_p.
The larger L_p needs the larger SCM .
Detector magnet tends to have large aperture.

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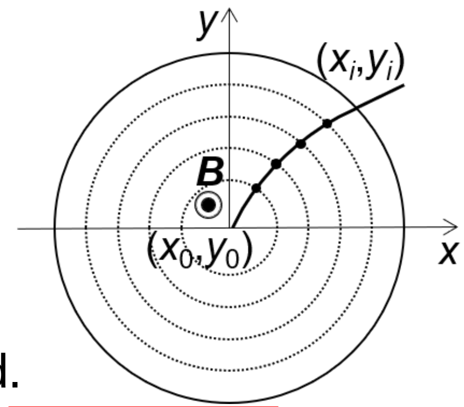
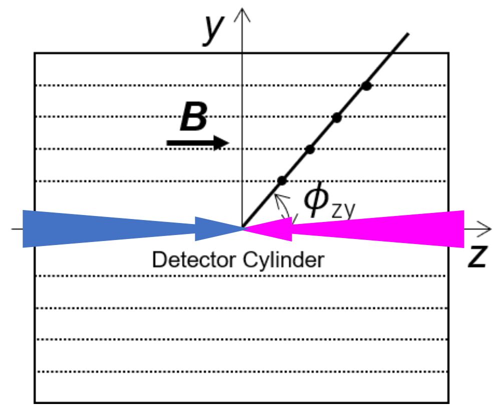
Type and features of magnetic spectrometer.(1)

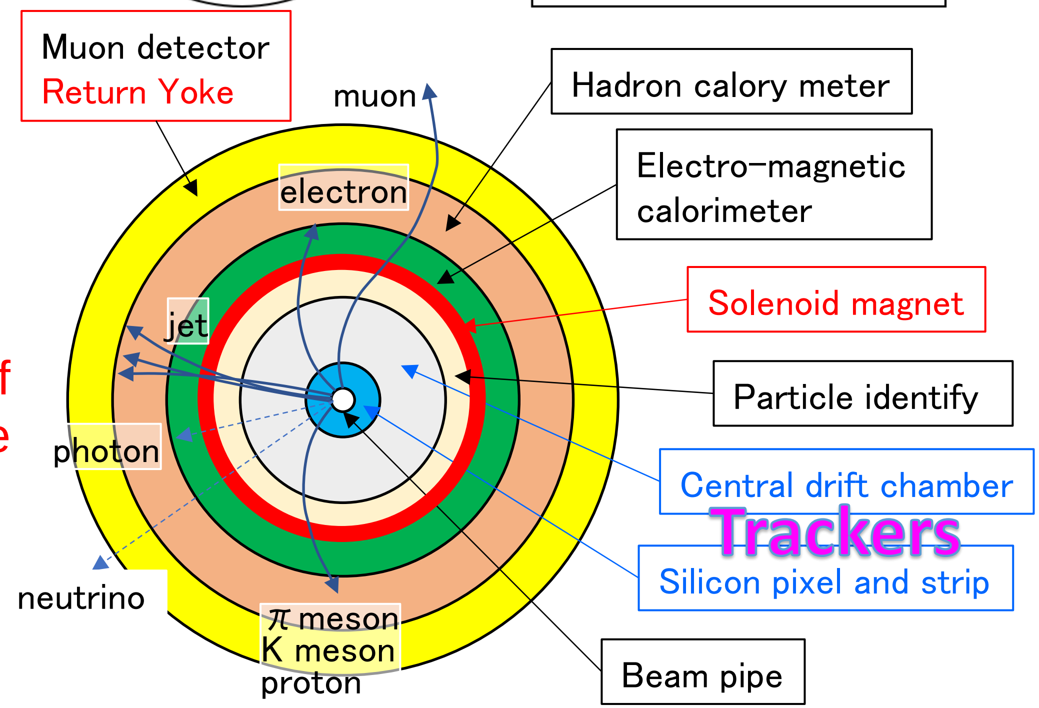
Magnetic Spectrometer Type Solenoid, Dipole, Toroid and Combination

Solenoid Type

- Many collider experiments have chosen solenoid type detectors.
  - VENUS,TOPAZ, AMY, Belle (KEK)
  - CDF, D0 (FNAL), Babar (SLAC)
  - ALEPH, DELPHI, ATLAS CS, CMS (CERN)
- The beam injects parallel with B field.
- Beam collision point is at the center of solenoid and its magnetic field.
- Sub-detectors are arranged concentrically.
- A set of tracking sub-detectors encloses the collision point to observe the deflections or decays of particles without dependence on the azimuth. It's called "4π detector".
- The solenoid is enclosed with iron return yoke which make a magnetic circuit and increase total weight.
    - CMS 14000 ton, ATLAS 7000 ton



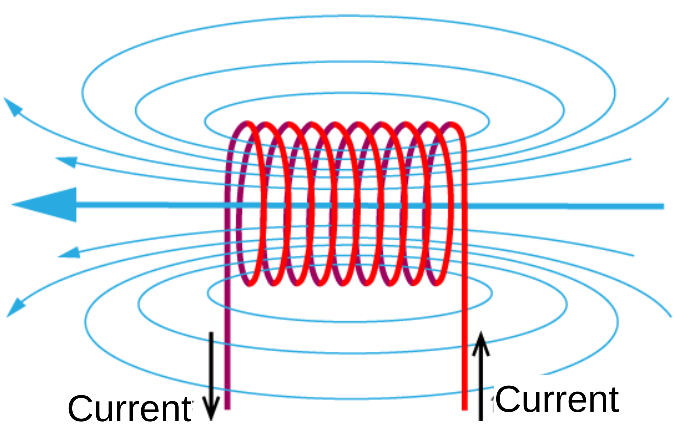


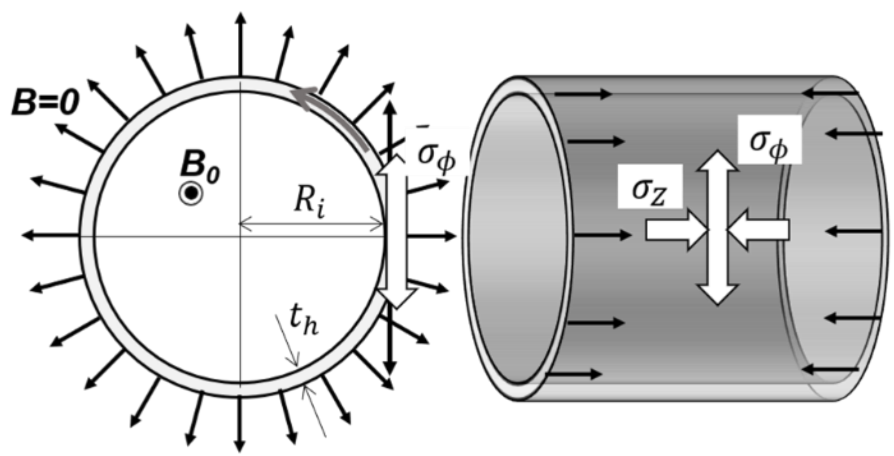


Type and features of magnetic spectrometer(2)

Features of solenoid coil

- Maximum field B_{peak} in the coil might be 1.2 times of the center field B_0. In case of dipole coil $B_{peak}/B_0 > 2,$ toroidal coil $B_{peak}/B_0 \sim 4$,. So, solenoid is more effective.
- A cylindrical winding is simple and free-standing.
- Air core (no iron) solenoid EMF is comprised of the hoop force and axial compression force . It is closed coil inside.
- So, the coil can be thin, light and transparent due to simple EMF.
- Resolution for particles around beam axis is low, because magnet field is parallel with their flight direction.

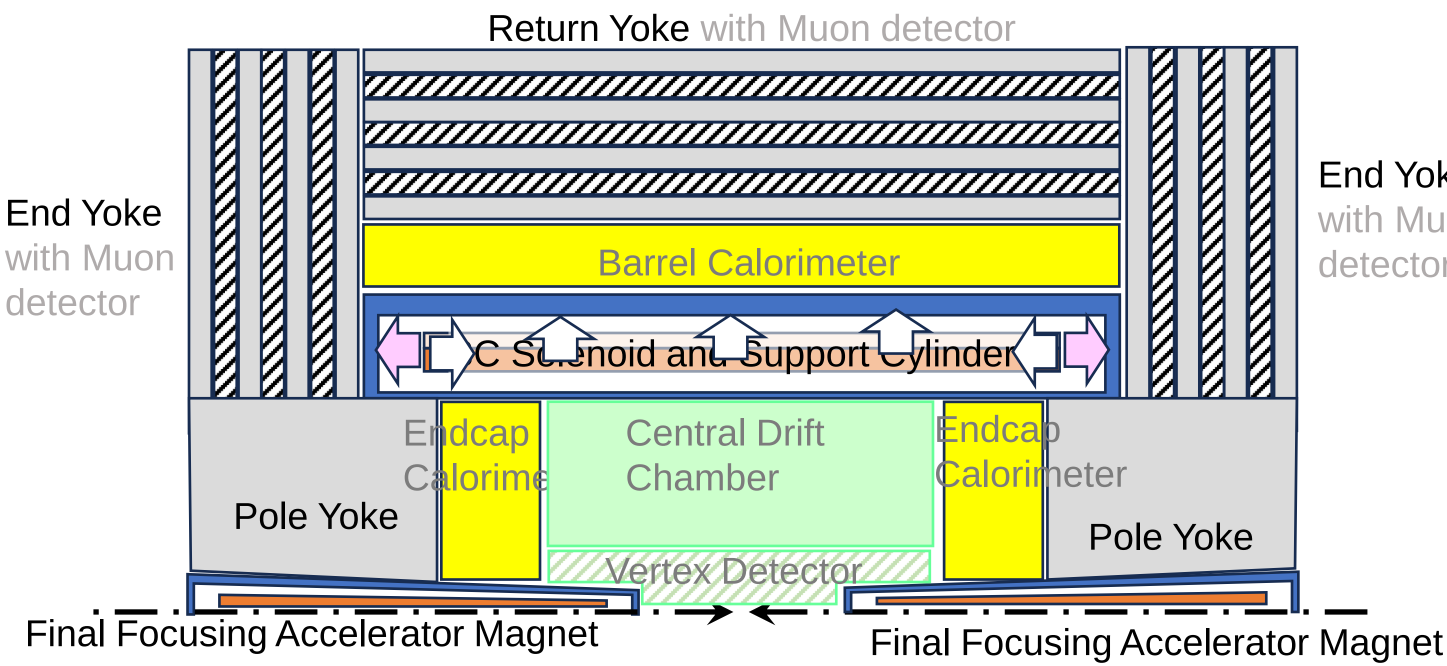




Type and features of magnetic spectrometer(3)

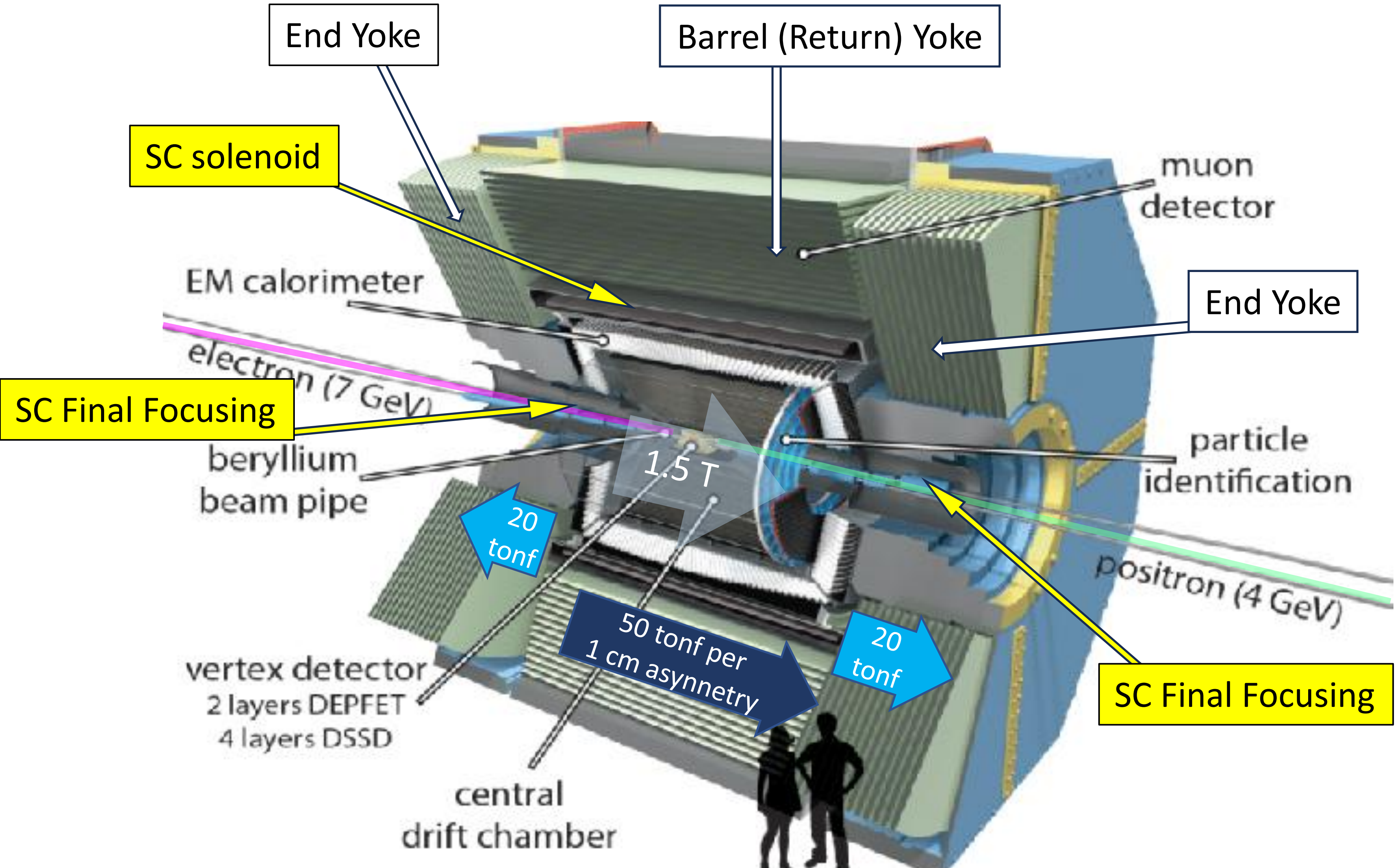
Features of solenoid type

- The actual detector solenoid is enclosed within a heavy iron yoke, and the magnetic field distribution and electromagnetic forces are affected by it.
- The uniformity of the internal magnetic field up to about 2 Tesla is affected by the shape of the Pole Yoke. FEM code needs to optimize it shape.
- EMF on solenoid in typical detector configuration.
  - Inside coil : hoop force.
  - Asymmetric arrangement causes resultant force of attraction between the iron yoke and coil. This need external support.



Type and features of magnetic spectrometer(4)

Solenoid type example : Belle II in SKEKB

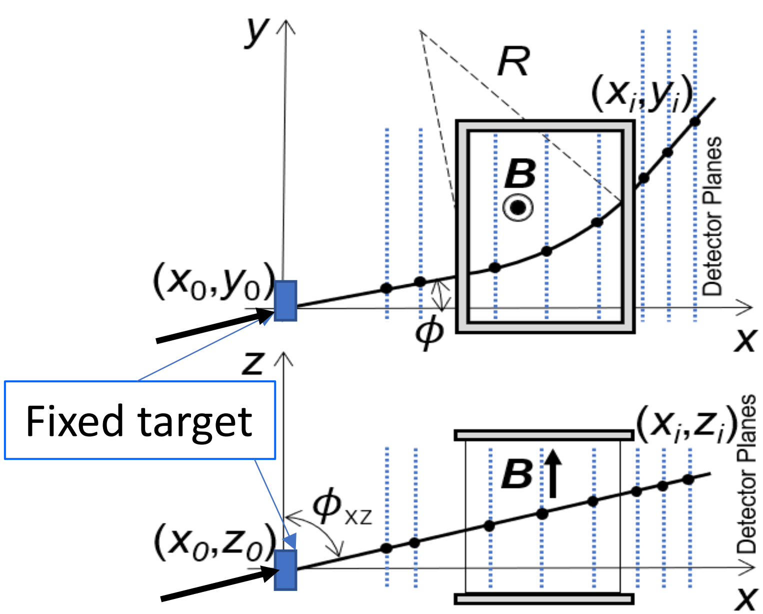


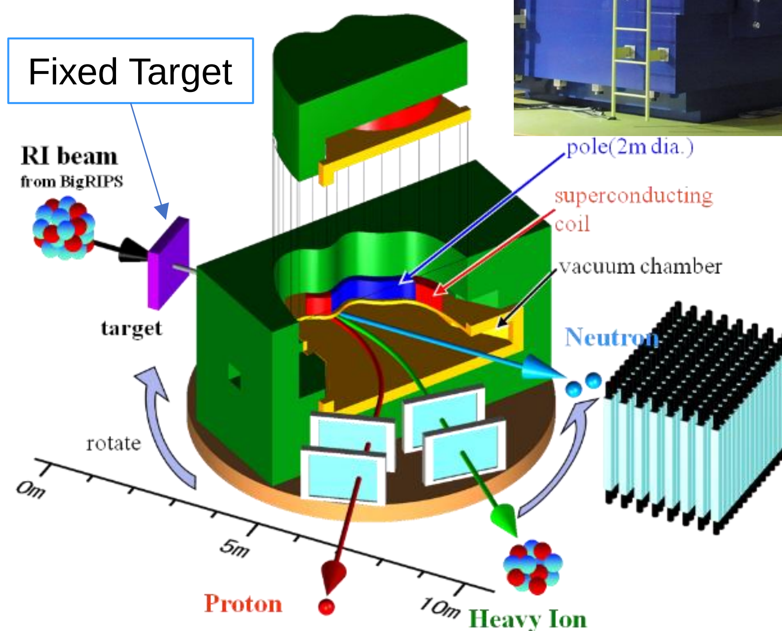
Axial supports rod in cryostat withstand 50 tonf tension and compression

Type and features of magnetic spectrometer(5)

Dipole (Forward) type (Two coil type)

- The Dipole type spectrometers are mainly chosen for the experiments using fixed targets.
- A dipole magnet is placed at the downstream side of a fixed target and generates a vertical magnetic field domain with the beam axis. Because the particles produced at the target move preferentially into the forward direction within a narrow solid angle.
- $B_{peak}/B_0 > 2$





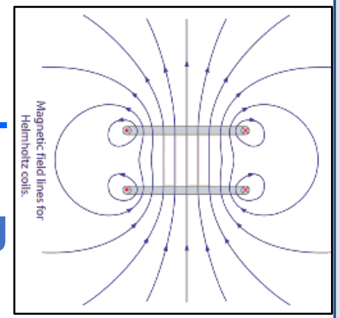
SAMURAI spectrometer @ RIKEN

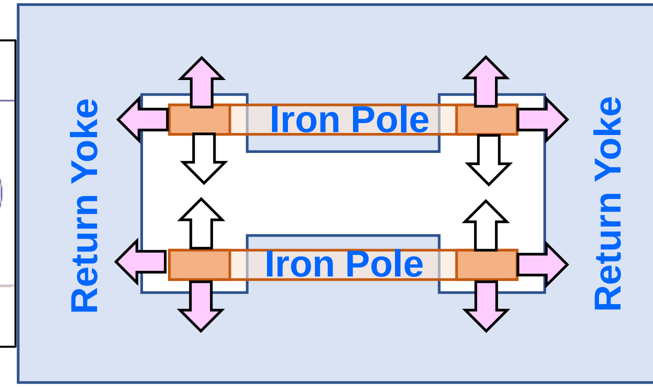
3 T@563 A https://ribf.riken.jp/~yshimizu/index.php?SAMURAI

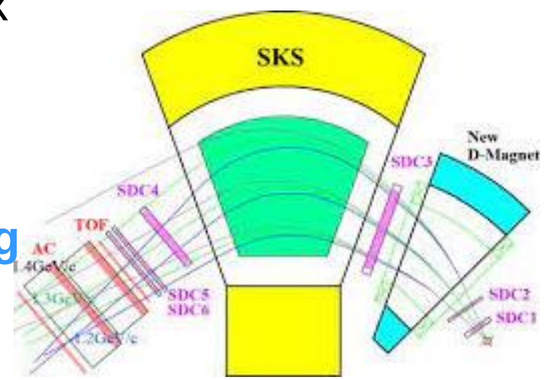
Type and features of magnetic spectrometer(6)

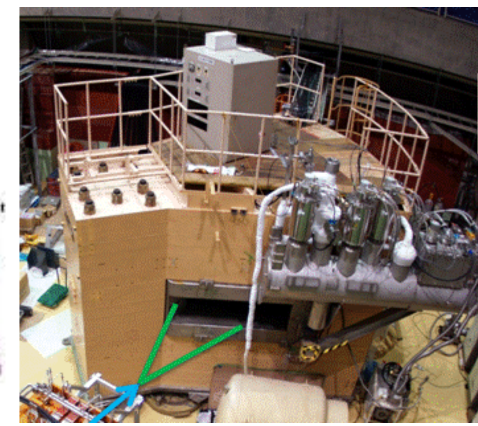
Features of dipole coil

- Field distribution at effective zone depends on the shape of **iron pole**.
- To improve its acceptable aperture, **fan-shaped** or **saddle-shaped** coil might be chosen. But they need a **reinforcing structure** to keep their forms.
- EMF: An attractive force acts between the two coils w/o iron yoke. A complex attractive force acts toward the iron yoke.
- If the two coils are not mechanically integrated; they are **not free standing** but needs some additional external support structure.

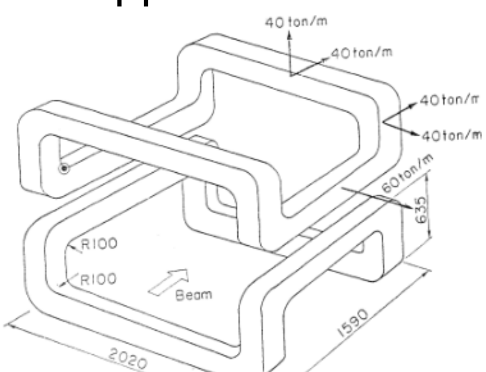








SC. Kaon Spectrometer @ J-PARC **Fan-shaped** coil.

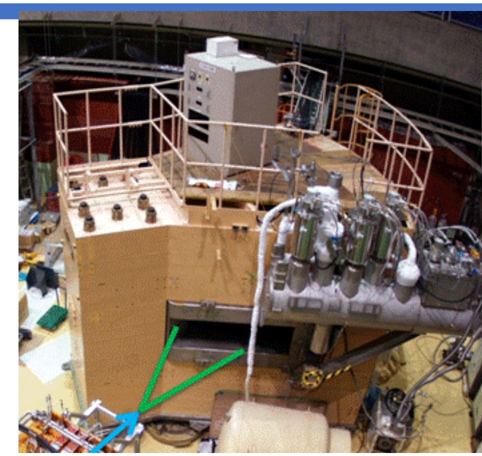


BENKEI spectrometer @ KEK 12GeV **Saddle-shaped** coil.

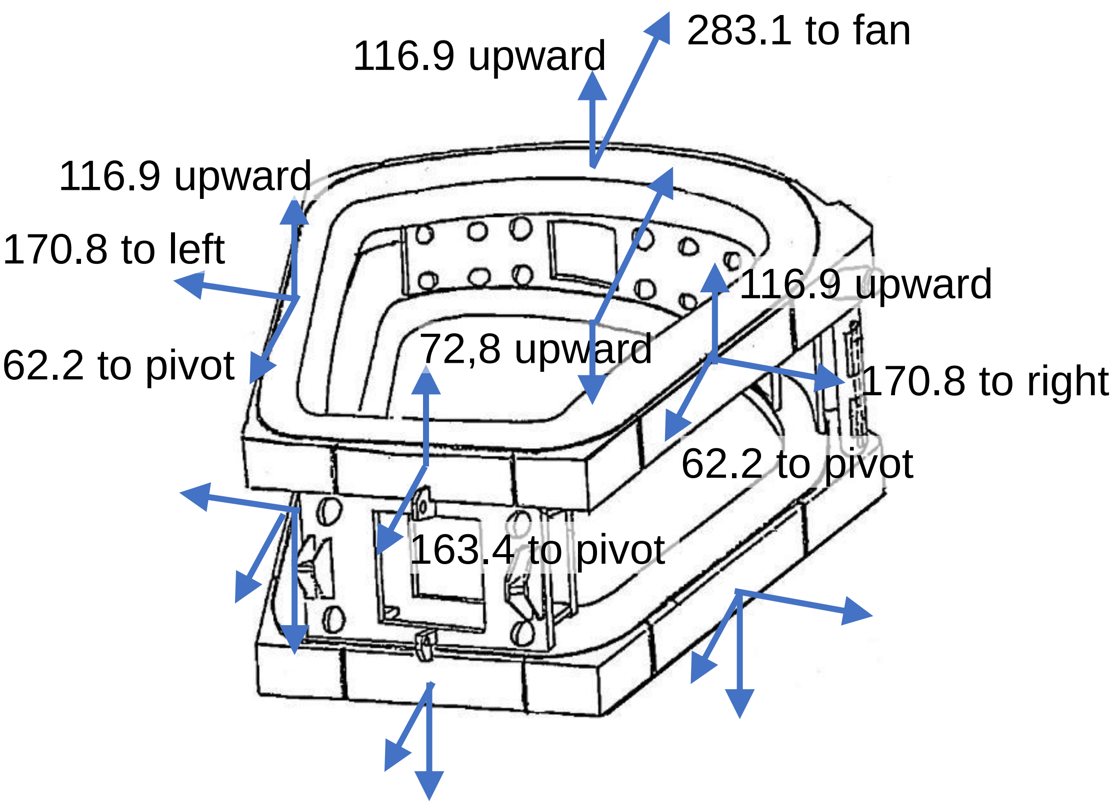
Type and features of magnetic spectrometer(7)

Dipole type example (SKS magnet in J-PARC)

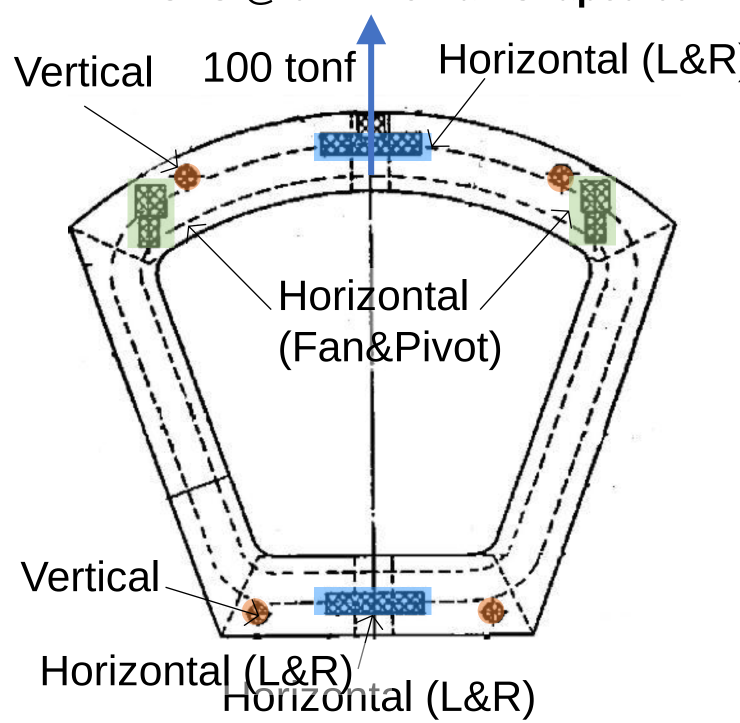
- EMF: A complex attractive force acts toward the iron yoke.
    - The two coils are mechanically integrated.
    - Vertical EMF is balances.
    - Horizontal EMF needs external support and structure.



SKS @ J-PARC **Fan-shaped** coil.



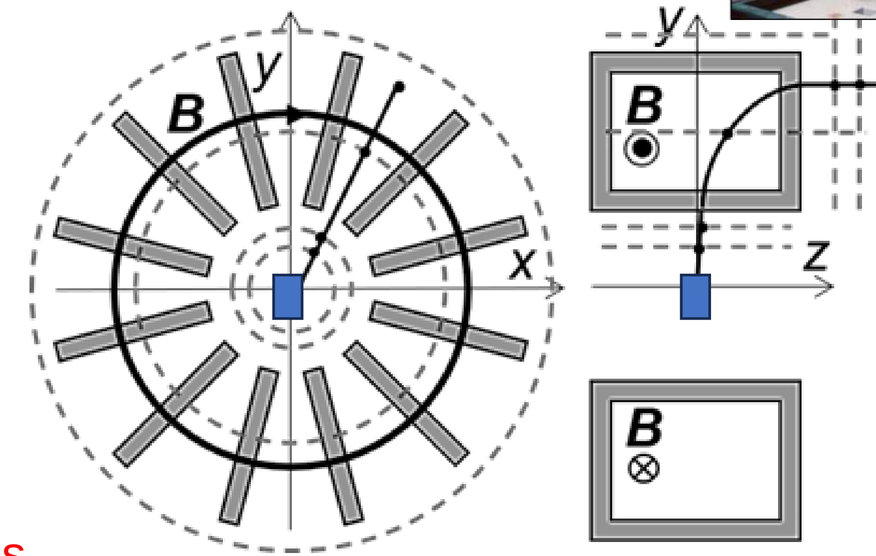
SKS cold mass (Coil, Coil Structure and LHe vessel



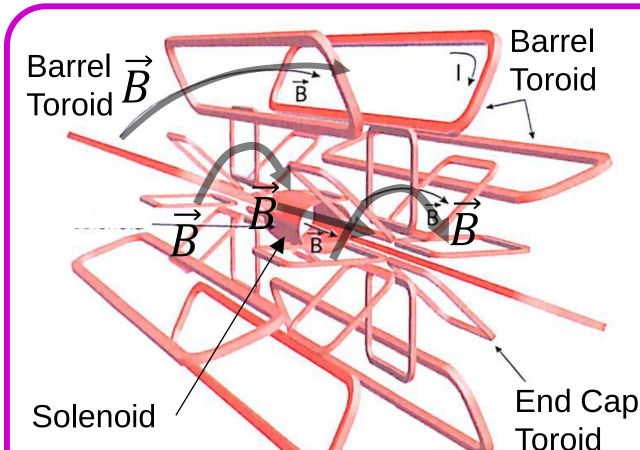
Type and features of magnetic spectrometer(6)

Toroidal type

- This type observe particles going perpendicular to the beam injection with large solid angle.
- *B*=0 at the target or the collision.
- Induce large magnetic domain with relatively smaller coil than simple solenoid coil.
- In case of ATLAS detector, a solenoid induce field around the collision point and three toroidal coils induce huge field domain far away.

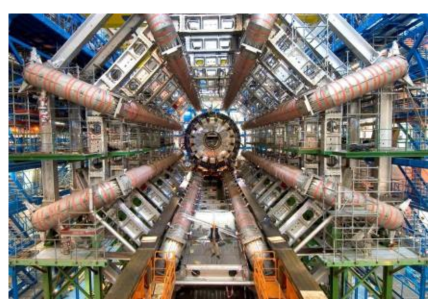


ATLAS

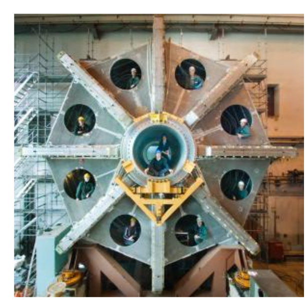


4 Magnets Com

Barrel Toroid



Endcap Toroid

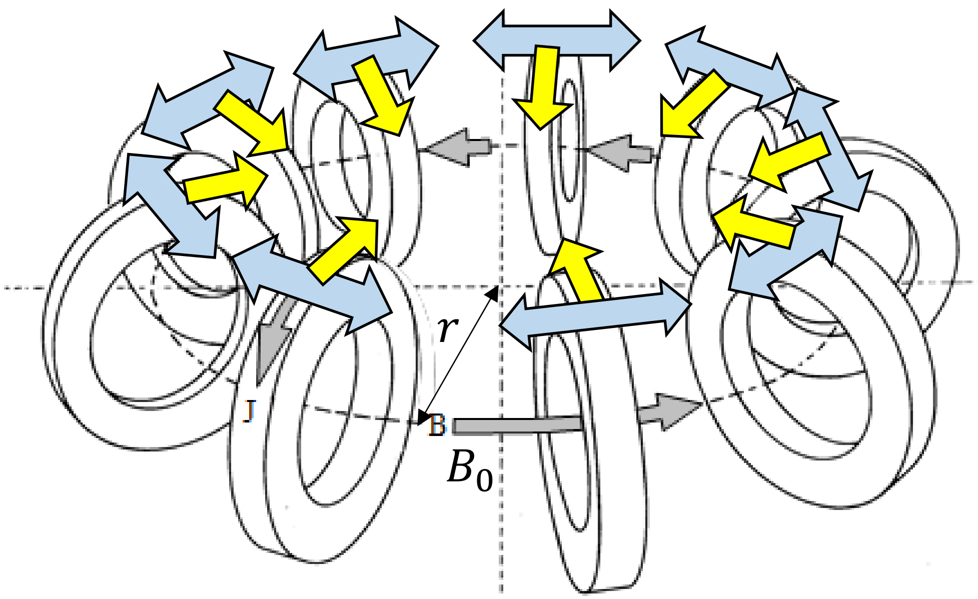


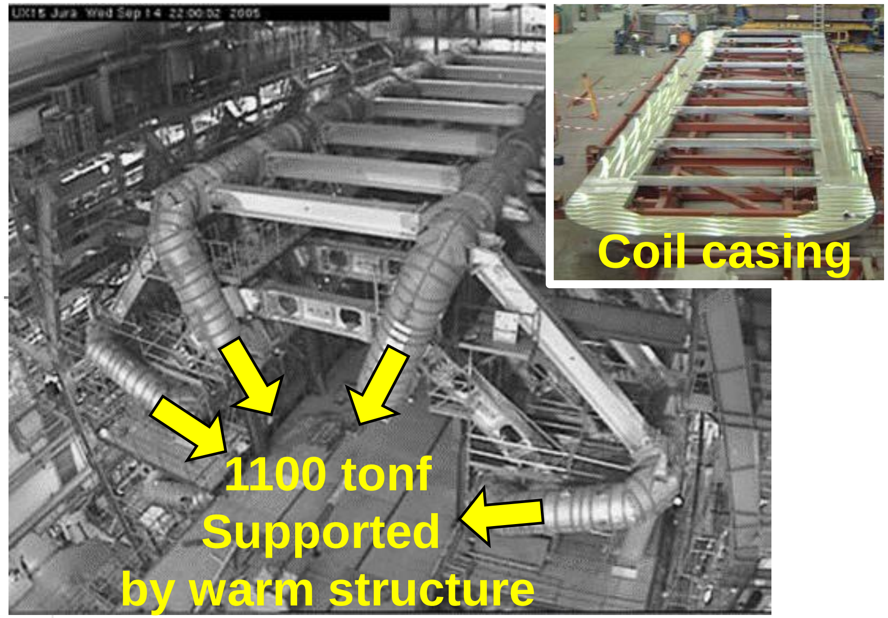
Central Solenoid

Type and features of magnetic spectrometer(6)

Feature of Toroidal Coil

- Only set of coils complete magnetic circuit without Iron.
- Field inside torus has $B = \mu_0 NI/2\pi r$, 1/*r* dependence.
- $B_{peak}/B_0 \approx 4$.
- As the EMF does not remain in the coil inside, strong additional structure is necessary.
  - Each coils attracts each other, then a centripetal force is induced, which should be supported by external structure.
  - Each coil needs restrain additional structure to keep it shape. Otherwise, the coil will be D-shaped, like a tokamak coil.



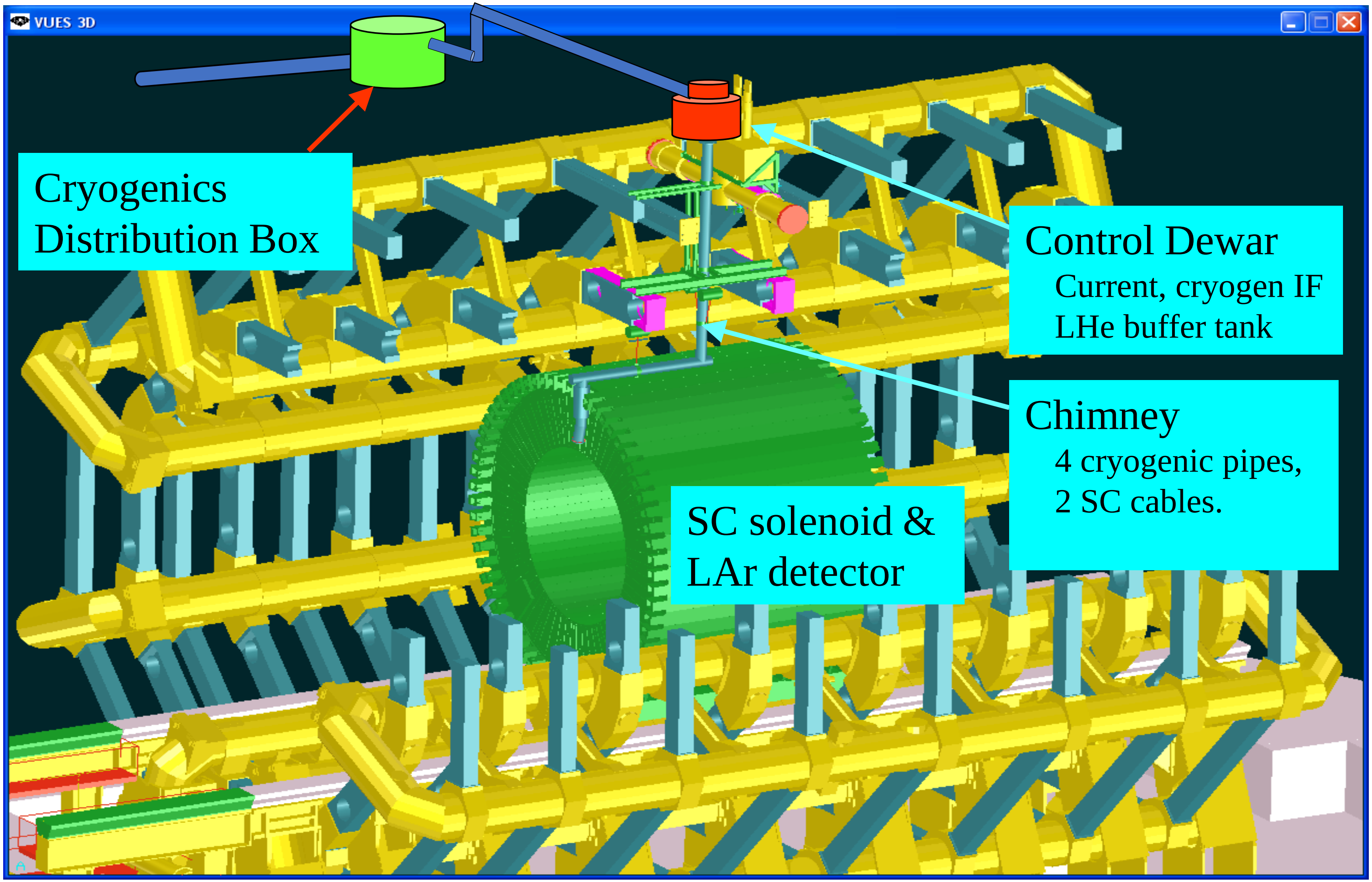


Feature of Detector Magnets

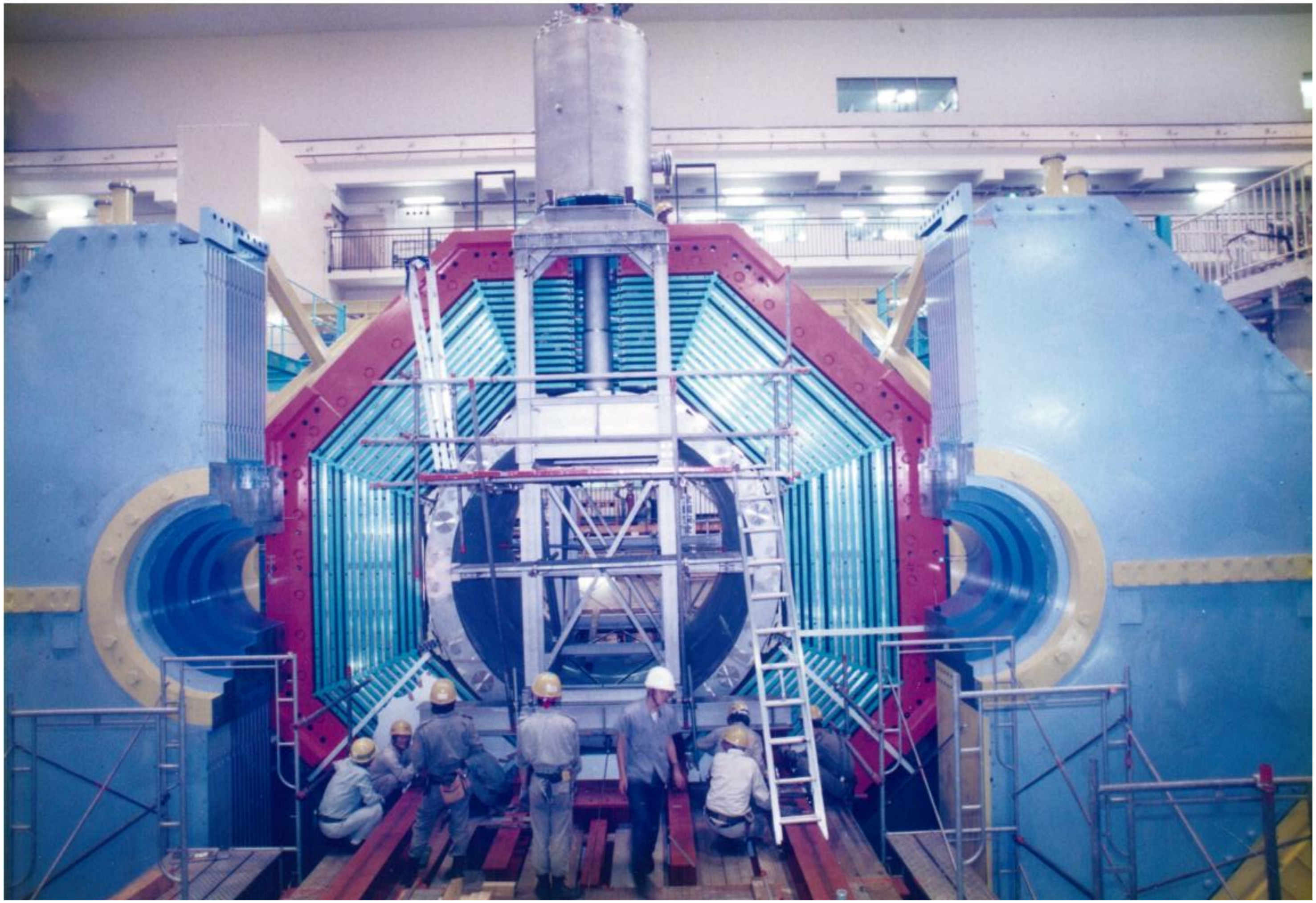
- For momentum resolution and large acceptance, the magnets arise large BL_0^2 domain.
- For physics scientist need *B*, not the magnet (!).
  - To minimize particle scattering, **minimizing mass** → Material?: in general, all Al with low density is appreciate.
  - Especially when the calorimeters are put outside the solenoid, transparency through the magnet wall is essential.
  - Minimum lost sphere for magnet services and supporting structures (next page).
- Unique and not replaceable.
  - Very robust design with large margins and high level of redundancy
- Magnet field < 5 T, NbTi is fine.

The latter part of this lecture would mainly introduce various elementary technologies for thin solenoid.

Example of minimum sphere for services :
Chimney port including cooling flow and current for ATLAS Central Solenoid



Example of minimum sphere for services :
Narrow chimney port including cooling flow and current for Belle Solenoid



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Transparency X_0

- Thinness is defined in terms of interaction lengths, absorption lengths and radiation lengths.
  - Discussion of interaction lengths must identify which particle, and absorption lengths must identify which particle and its energy.
- The most common definition of thinness uses **radiation lengths**.
  - It is defined as the mean length (in mm) into the material at which the energy of an electron is reduced by the factor 1/e. Euler's number e
  - Thickness $X_0 = t_{physical}/L_{rad}$
- Larger particle energy → larger magnet → thicker magnet wall.→ X_0 is not a fair evaluation metric for thinness.

Material	Radiation Length L_{rad} (mm)
Epoxy	~280
Aluminum	88.9
Titanium	37.2
Iron	17.6
Copper	14.3
Niobium	~11.8

by M.A. Green, LBNL-40185, UC-414

atomic number

$$L_{rad} = 158\frac{Z^{-0.7}}{\gamma_0} \propto \gamma_0^{-1}$$

density

An index of thin solenoid performance : E/M ratio

- Performance index :

$$E/M \text{ ratio} = \frac{\text{Stored Magnetic Energy}}{\text{Cold Mass}} [kJ/kg]$$

Cold Mass = Coil winding +EMF support structure (support cylinder)
＋Cooling pipes and LHe vessel

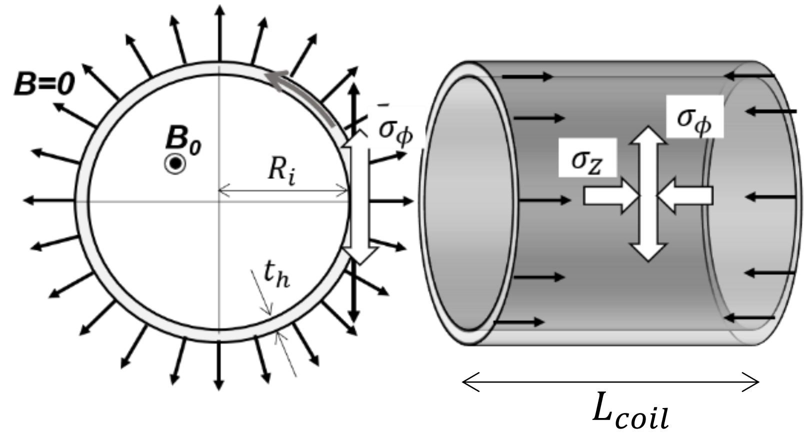
- Consideration stored energy and stress analysis in solenoid.

$$E = \frac{B_0^2}{2\mu_0}\left(\pi R_i^2 L_{coil}\right)$$

$$\sigma_\phi = \frac{{B_0}^2}{2\mu_0}\frac{R_i}{t_h} \quad \text{hoop stress}$$

$$M = 2\pi R_i L_{coil} t_h \gamma_0$$

$$E/_M = \frac{\sigma_\phi}{2\gamma_0}$$



- The larger E/M→ The higher stress σ_ϕ and lower density γ_0
→ Thinner
- Aluminum and its alloy are main material.

E/M ratio from thermal viewpoint

- Another explanation about E/M from thermal viewpoint.

  If whole magnetic energy stored in the magnet E could be absorbed by the magnet mass (cold mass), uniform temperature rise θ_Q corresponds to E/M .

  $$E = M\left(h(\theta_Q) - h(\theta_0)\right)$$

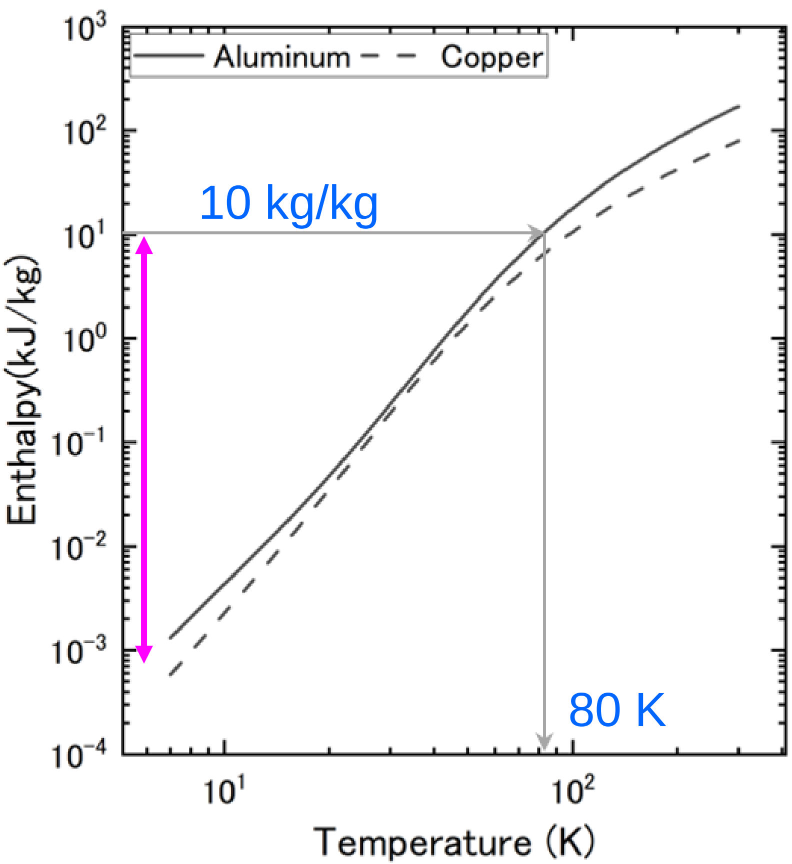
- E/M = 10 kJ/kg, then θ_Q = 80 K

  Main material is AL.

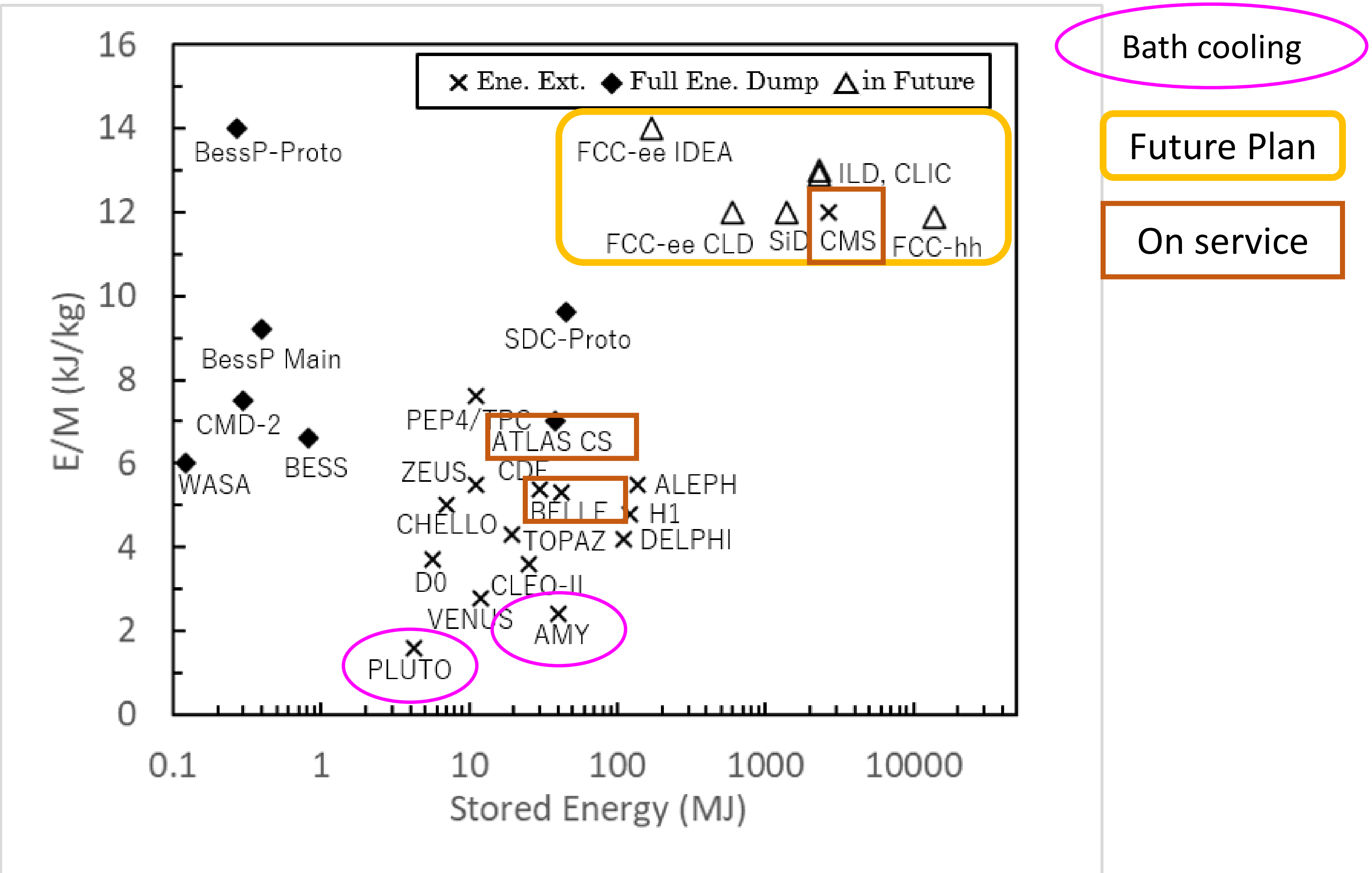
- Actually, in case of quench,
  - Nonuniform E absorption in the coil increase higher temperature.
  - In worst case, Hot Spot break out.
  - Higher E/M means:

    ✓higher quench damage risk,

    ✓E/M > 7 kJ/kg needs active QP.



E/M ratio of detector magnets

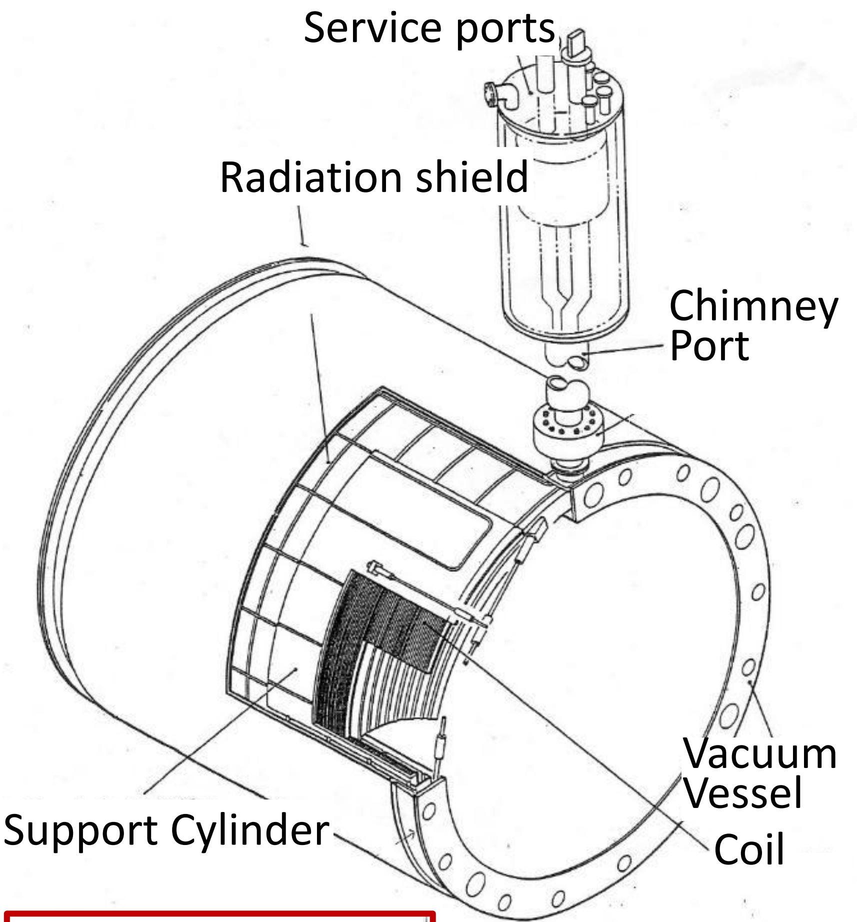


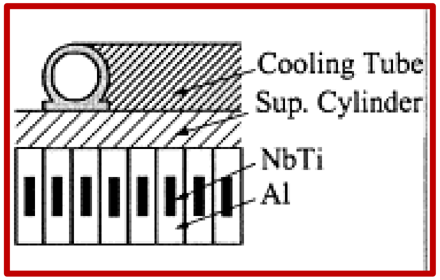
Higher E/M can achieve by light and strong material

Technical history for transparent solenoid

Technical elements for transparent solenoid

Technical elements	Introduced to
Aluminum stabilized SC	
Conduction cooling	ISR, CELLO
Co-extrusion for Al clad.	CDF
Direct internal winding	TOPAZ
Thermo-syphone circulation	ALEPH, DELPHI
CFRP vacuum vessel	VENUS
Pure Al strip quench propagator	
Honeycomb vacuum vessel	BESS
Zn doped reinforced Al	SDC-P
Non insulation conductor	CMD-2
Ni doped reinforced Al	ATLAS
Al alloy welded	CMS
W/o outer support cylinder	BessPolar





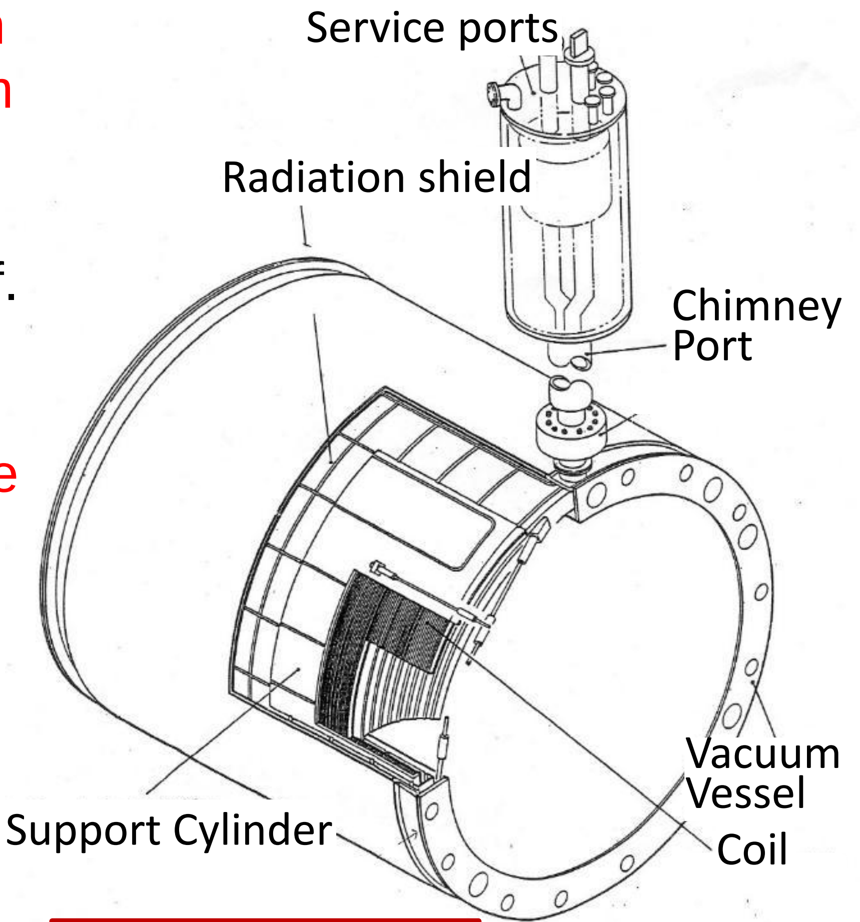
Coil wound with aluminum stabilized superconductor is surrounded support cylinder. Coil is cooled through its own thermal conductivity from cooling pipes on the outer support cylinder.

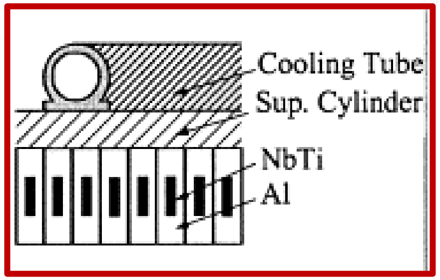
Technologies for transparent solenoid

- Aluminum clad NbTi/Cu cable.
- A solenoid coil windings surrounded with outer support cylinder made of aluminum alloy. It is impregnated with resin to integrate a cylinder so-called cold mass.
- EMF is supported by the cold mass itself.
- The cold mass is cooled by LHe flow in the tubes on the support cylinder with its own thermal conduction. There is no LHe vessels containing the cold mass.
- There is no mandrels inside of the coil windings.

Secondary effect

- Light weight cold mass. Smaller heat capacity. Smaller heat leak through the support structure.
- Slow pressure rise after quench because of conductive heat transfer. So quench protection for cryogenic system has ample time.





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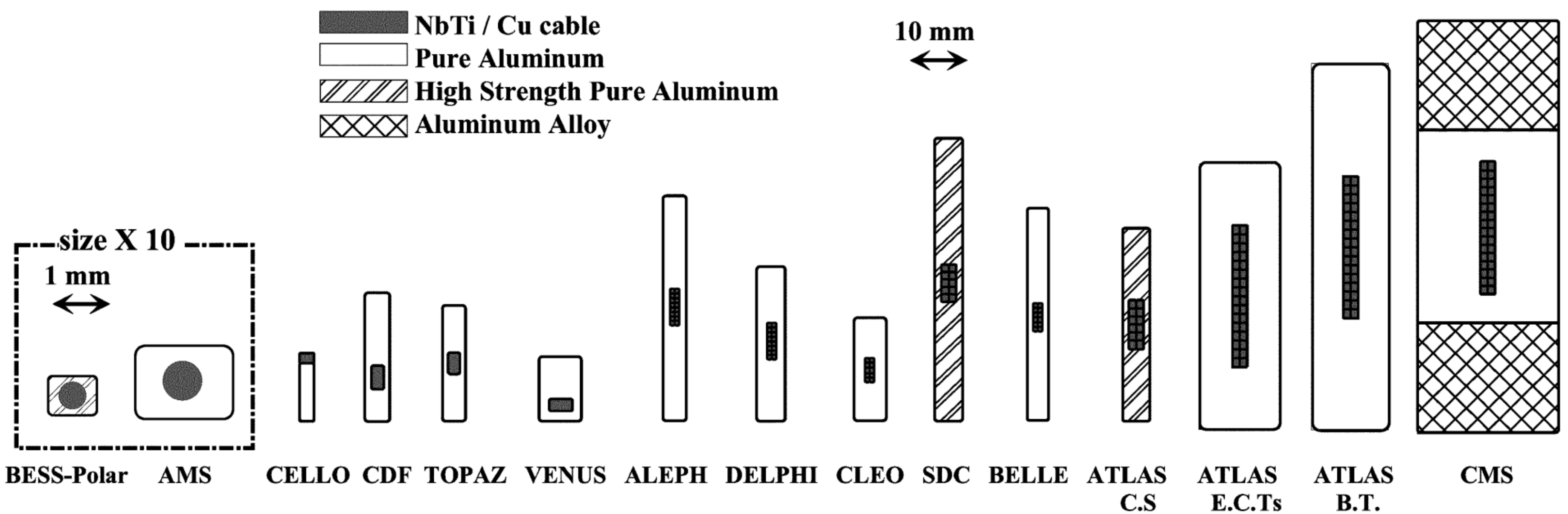
Aluminum stabilized superconductor

Pure aluminum clad NbTi/Cu cable with large cross-sectional ratio.

- Developed for mainly conduction cooling detector magnet. Al clad conductor has lower resistivity and larger thermal capacity.
  - absorbing the disturbance in the coil. Enthalpy stability.
  - moderating temperature rise and voltage rise after quench, which make a time for quench protection.
- Density of Al is <1/3 that of Cu. Longer radiation length, Transparent
- Advanced Al stabilizer has mechanical strength.

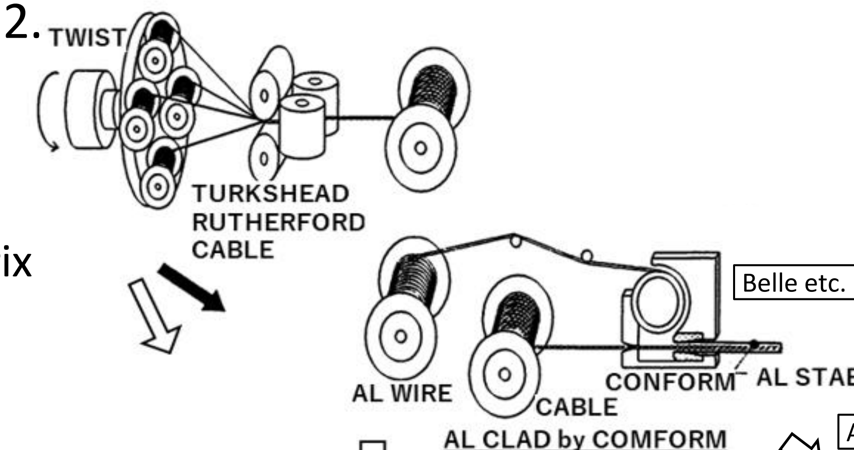


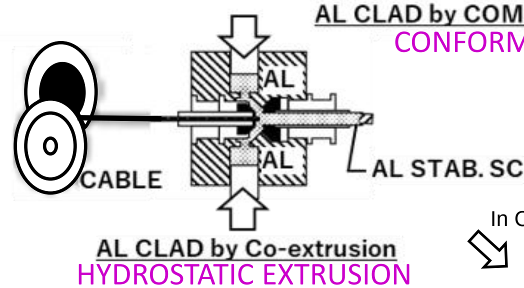
Al clad process

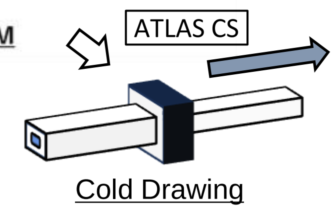
① NbTi / Cu cable with Cu ratio 0.8~1.2.

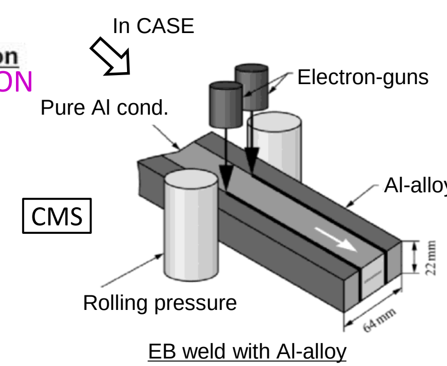
② Clothing Al
- hydrostatic extrusion machine or conform machine.
- A kind of friction welding b/w Cu matrix and Al.
- 1μm diffusion layer, > 30 MPa shear strength, ~10^{-11}Ω-m resistance

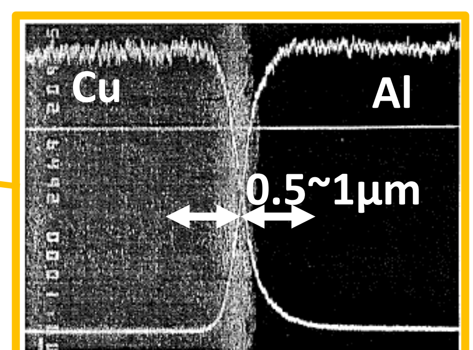
③ Cold Drawing
- Precise coil outline with tolerance of < 0.05 mm
- Work hardening of Al



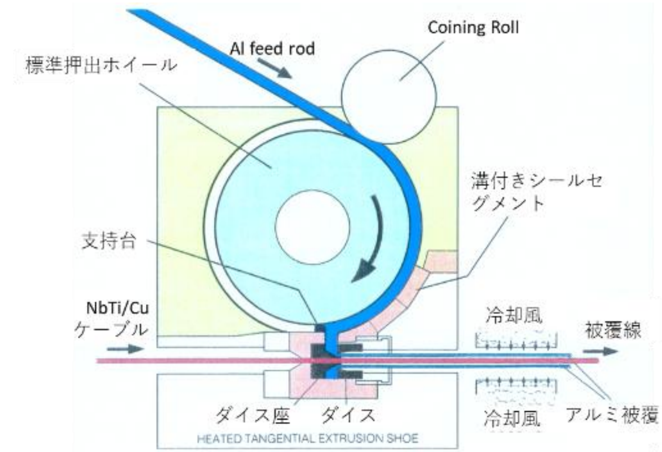


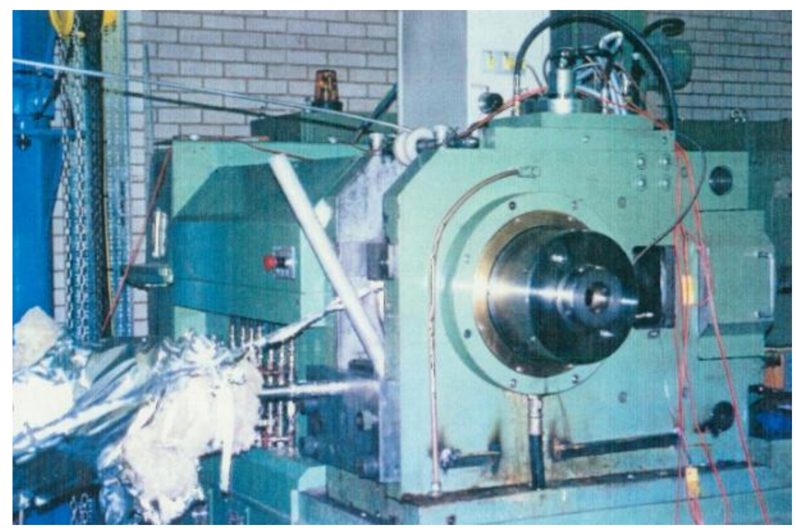






Hydrostatic extrusion machine





Conform extrusion machine

Function of Al Stabilizer: Stability and Quench protection

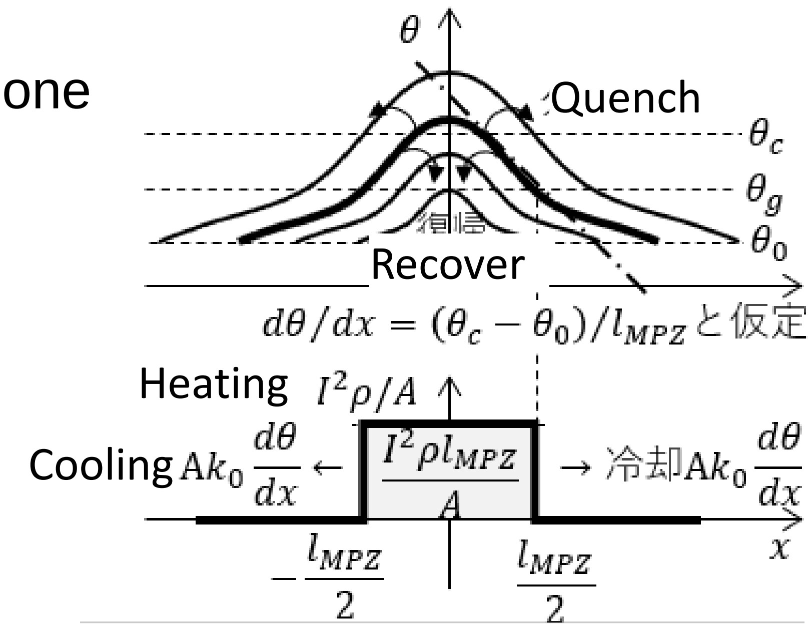
Index of stability ：MPZ-MQE

- Balance b/w heat generation in normal zone and conduction cooling to SC zone.

$$I^2 \frac{\rho l_{MPZ}}{A} = 2Ak_0 \frac{(\theta_c - \theta_0)}{l_{MPZ}}$$

$$l_{MPZ} = \left(2L_0\theta_0(\theta_c - \theta_0)\right)^{\frac{1}{2}} \frac{A}{\rho I}$$

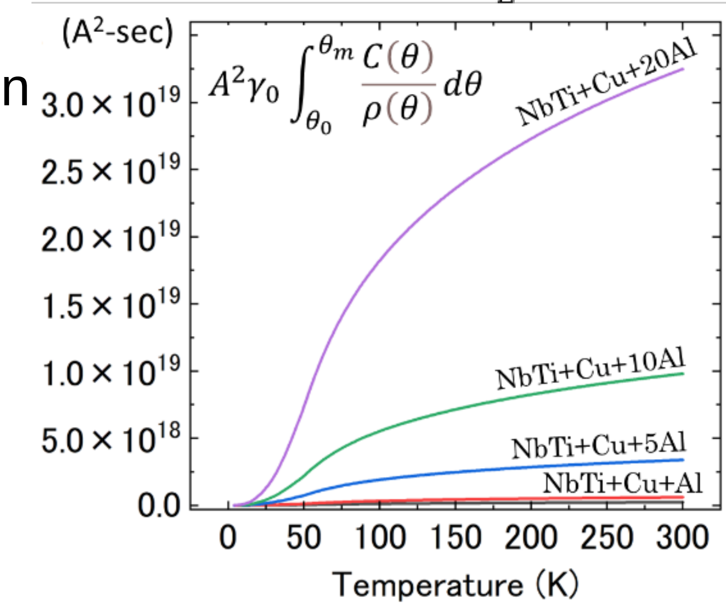
$$E_{MQE} = \{2k_0(\theta_c - \theta_0)\}^{\frac{1}{2}} \gamma_0 \Delta h \frac{A^2}{\rho I}$$



Quench protection: Hot spot

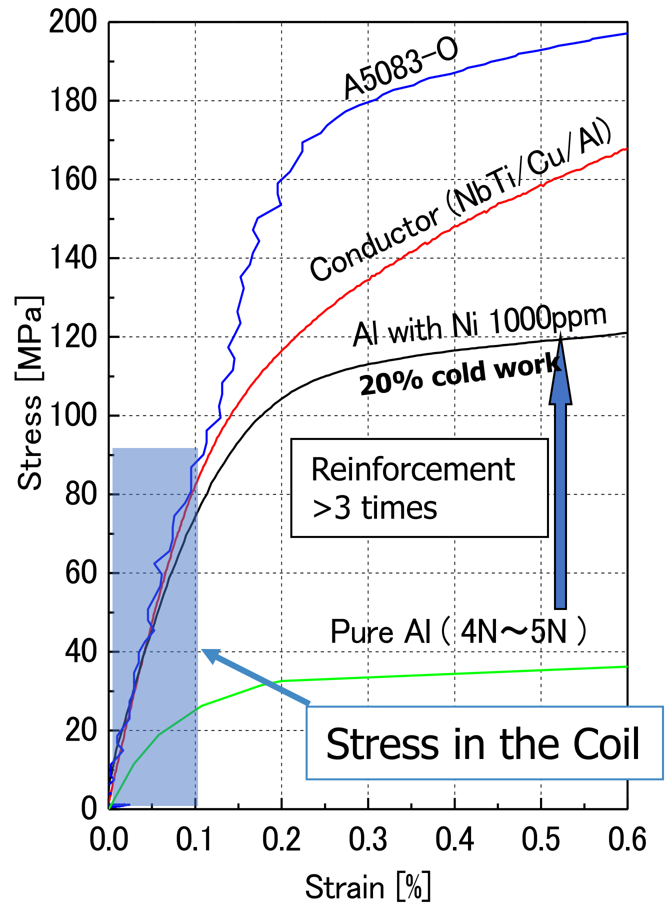
- Adiabatic temperature rise at quench origin

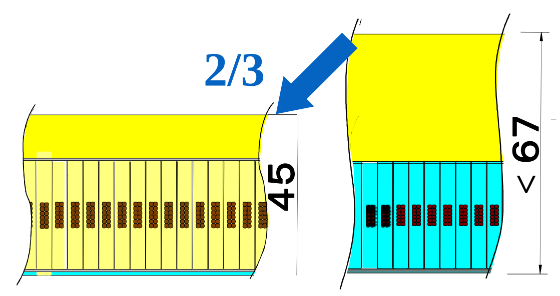
$$\int_0^{\infty} I(t)^2 dt = A^2 \gamma_0 \int_{\theta_0}^{\theta_m} \frac{C(\theta)}{\rho(\theta)} d\theta$$



Mechanical Advanced Al stabilizer

- In solenoid, hoop EMF is supported by the outer support cylinder with Al alloy and the winding conductor itself.
  - Yield strength :
    ~ 30 MPa in pure Al
    ~ 180 MPa in A5083 alloy.
  - Mainly support cylinder keep hoop EMF.
- Improvement of mechanical strength of Al stabilizer can shear the EMF.
  - Keeping low resistance.
  - Applied to ATLAS CS
    1. 99.999% Al doped with 1000 ppm Ni
    2. Cold drawing at reduction rate of 20 %



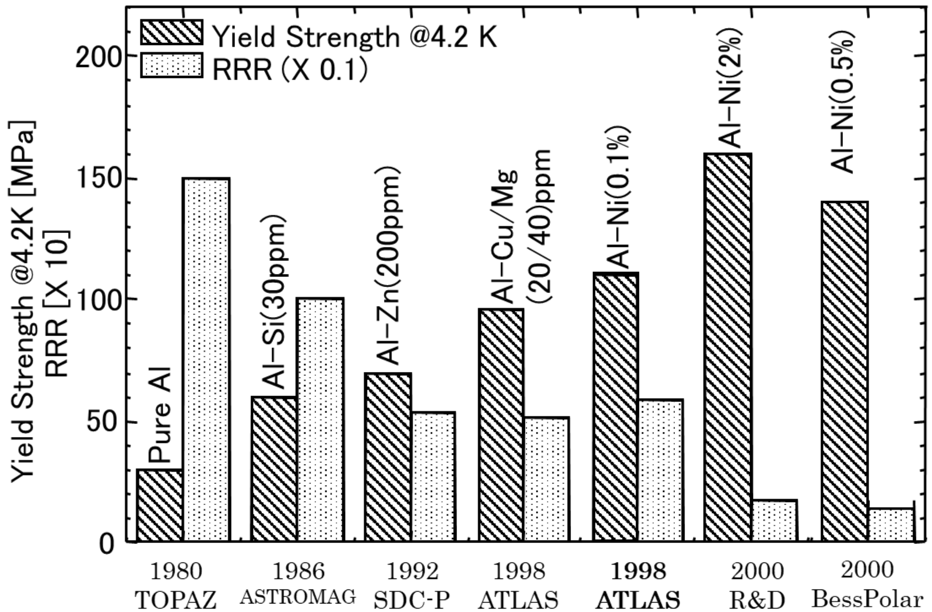


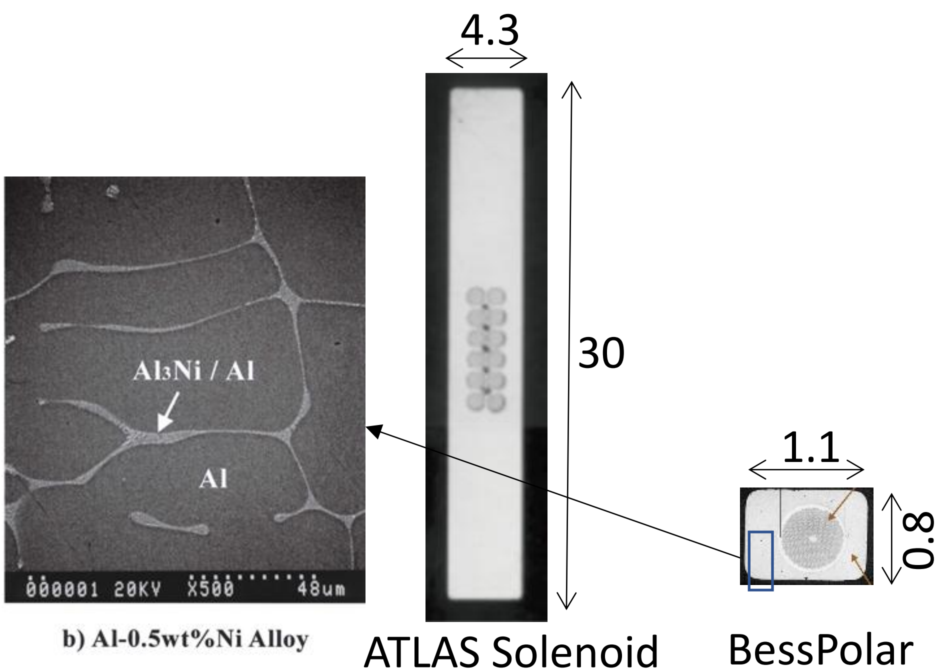
ATLAS with high strength conductor

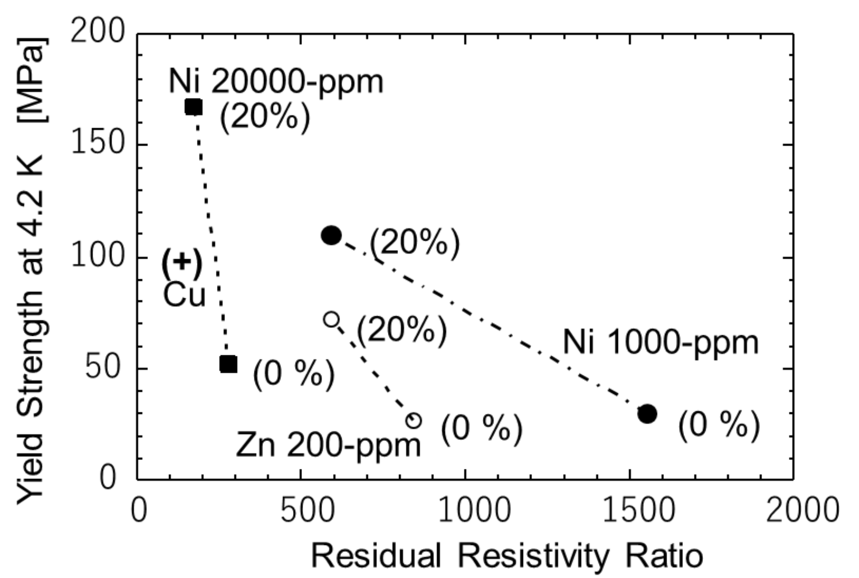
Design based on Belle

R&D for mechanical improvement

- Ni doped Al shows desirable balance of RRR and Yield Strength.
- Addition of Ni and following cold work create Al3Ni intermetallic compound network in pure Al bulk like a kind of composite.
- Al3Ni network increases mechanical strength and pure Al part keeps low resistance.



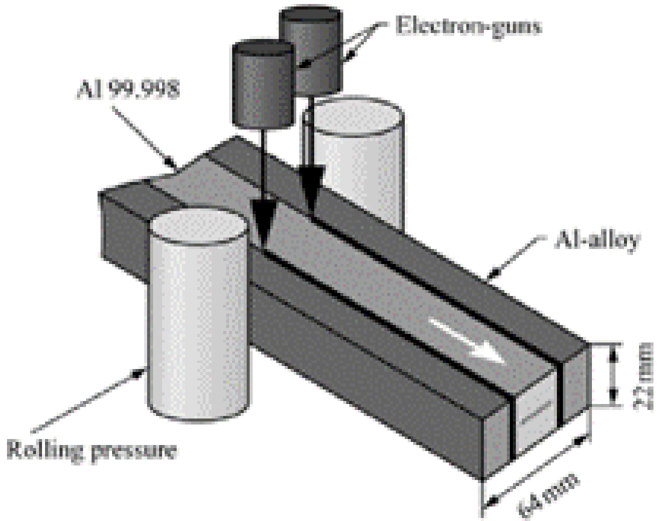


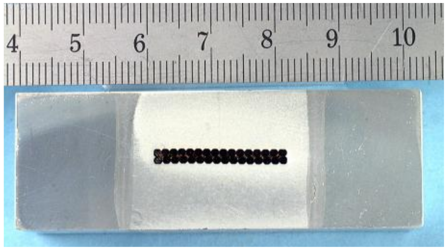


Another approach mechanical improvement

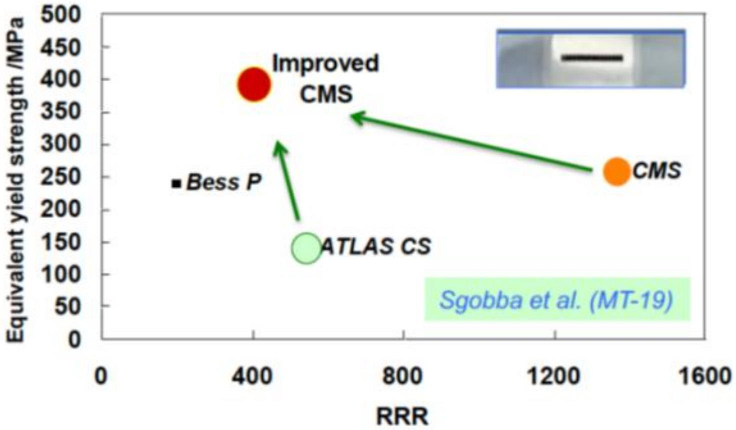
Adding Al alloy (CMS solenoid)

- Al alloy bars（AW6082）are electron beam welded.
- Equivalent yield strength 250 MPa.





More reinforced conductor with combination of high strength pure Al and Al-alloy.



Currently, there is no industrial availability of the co-extrusion process, because small demand is not commercially attractive..

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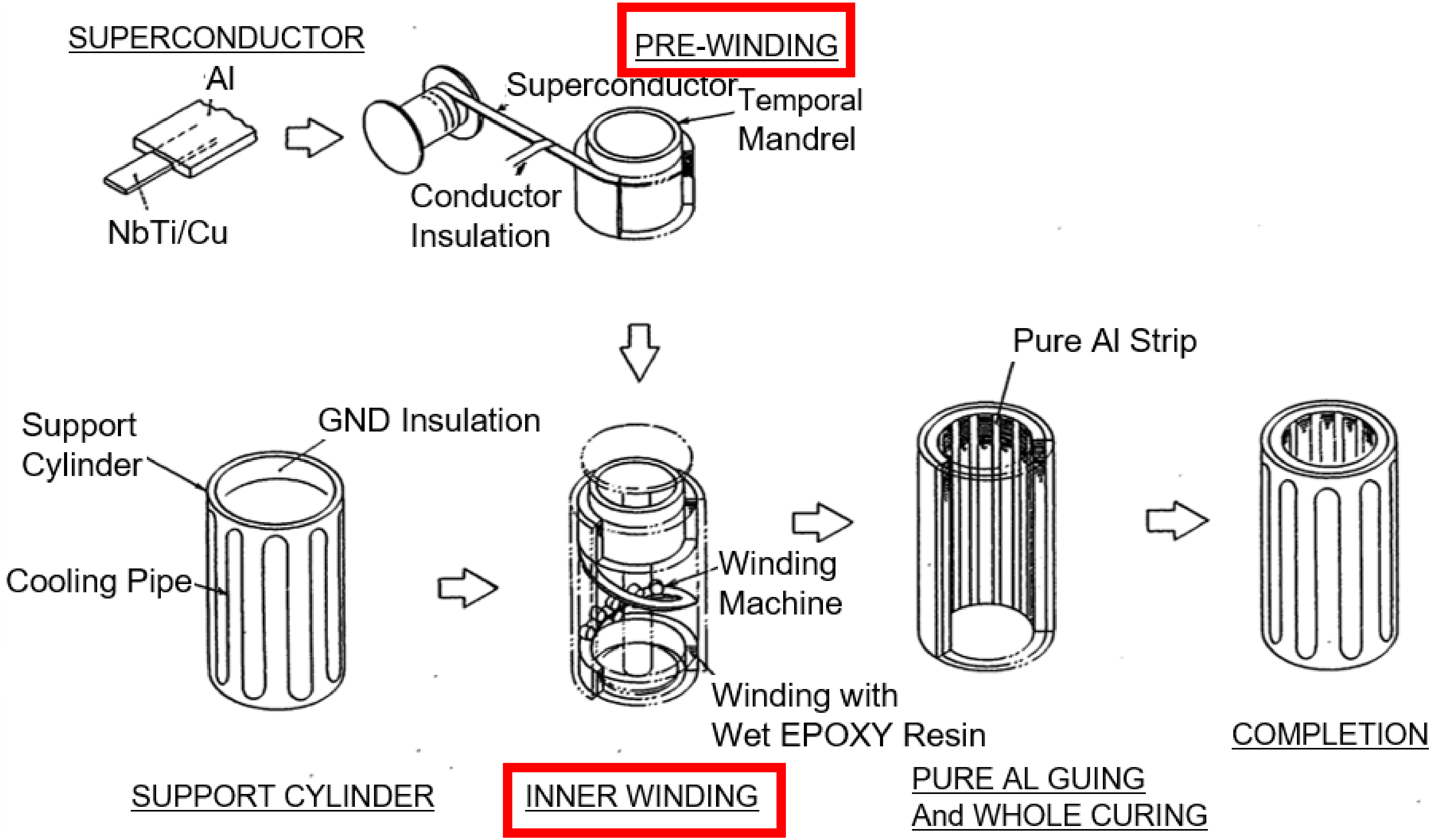
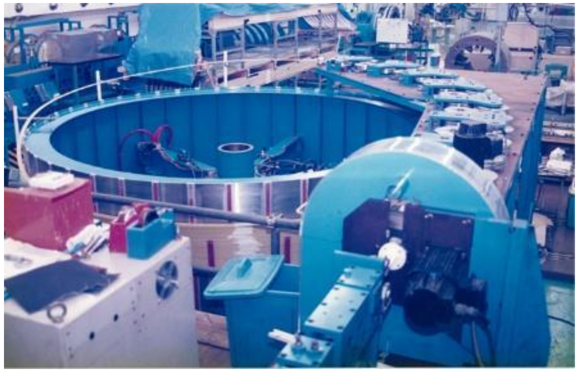
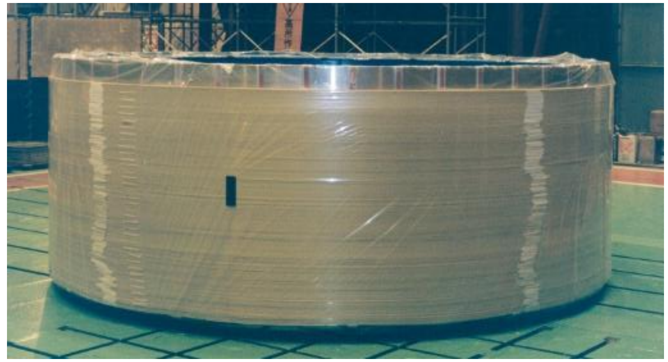
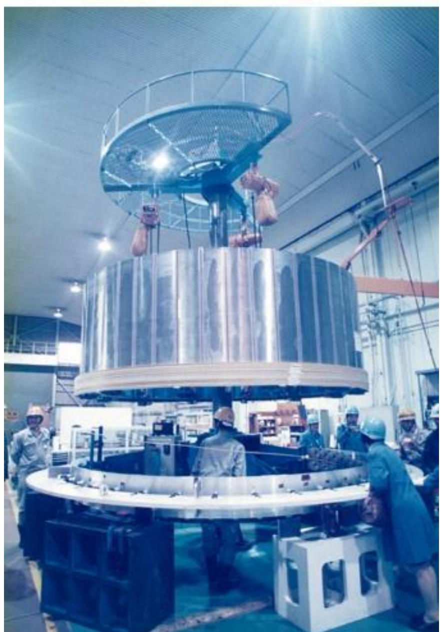
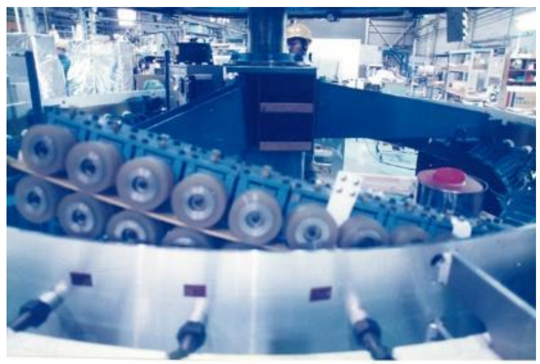
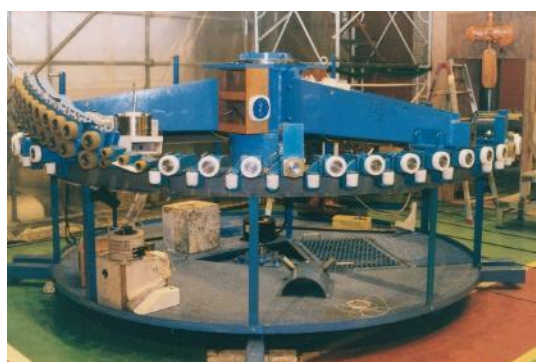
Coil Manufacture Process



Photos of Belle solenoid manufacture.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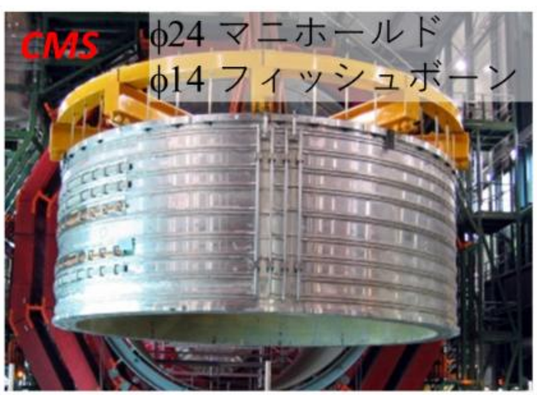
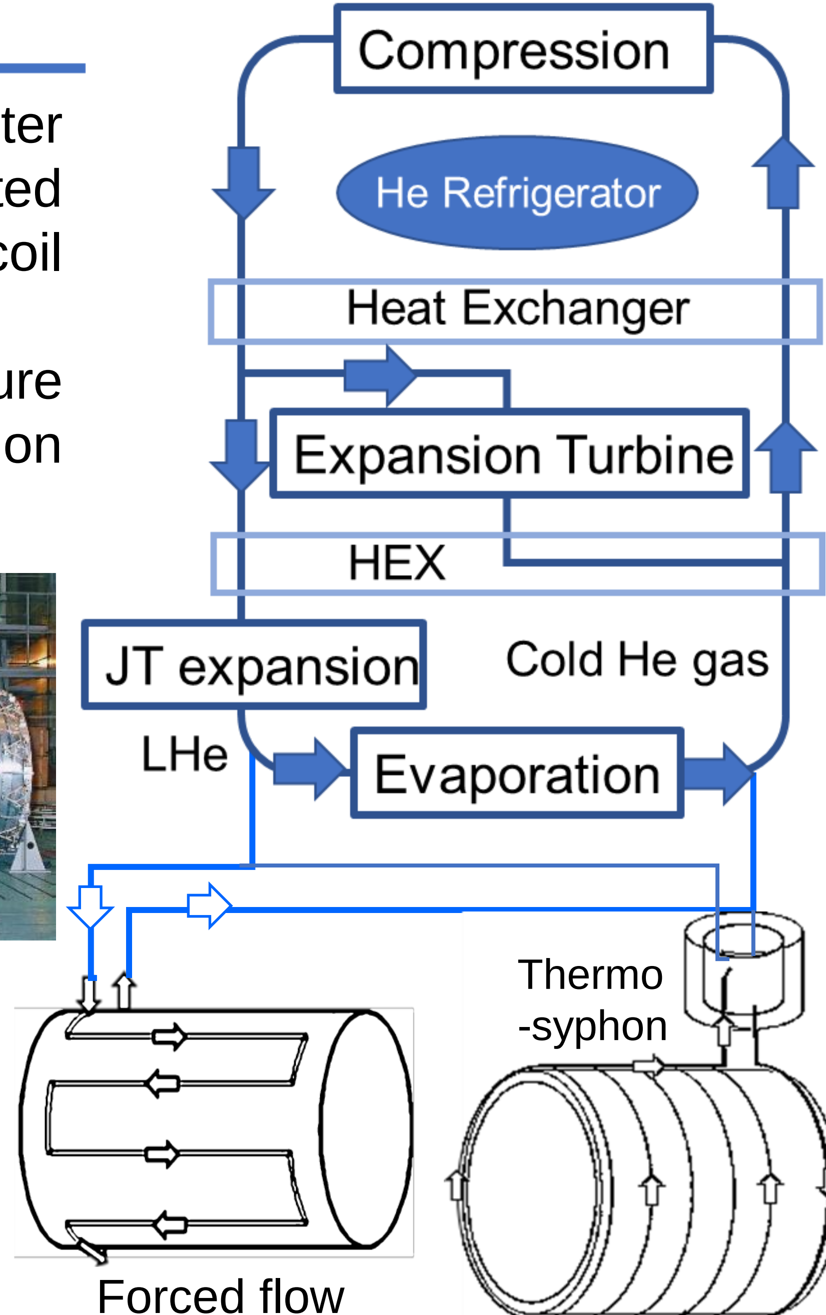
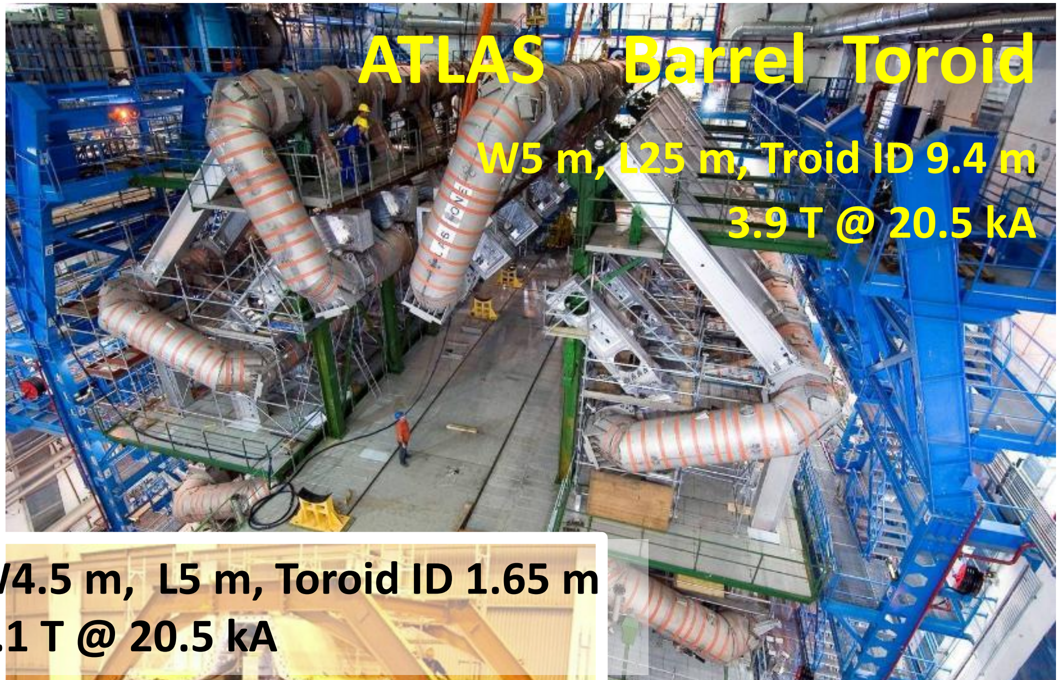
Conduction cooling

- Serpentine tubes are welded on outer surface of the support cylinder. Saturated (2 phase) LHe flow cools the whole coil through its conduction.
- 2P flow is driven by compressed pressure (forced flow) or by natural convection (thermo-syphon).





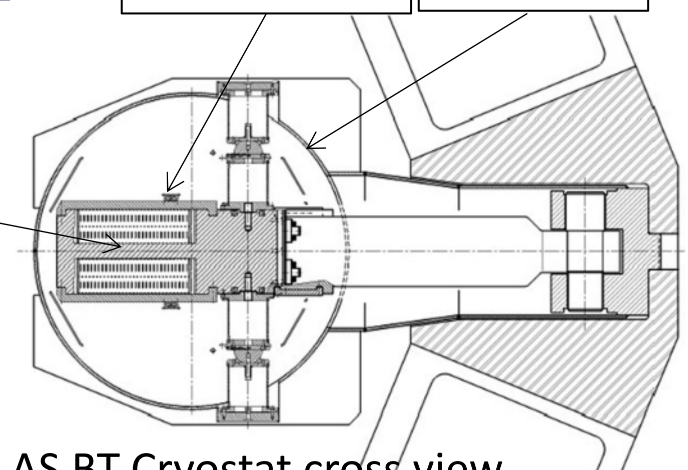
Conduction cooling for toroidal coil



W4.5 m, L5 m, Toroid ID 1.65 m
4.1 T @ 20.5 kA

ATLAS End Cap Troid

All coils are conduction cooling.



ATLAS BT Cryostat cross view

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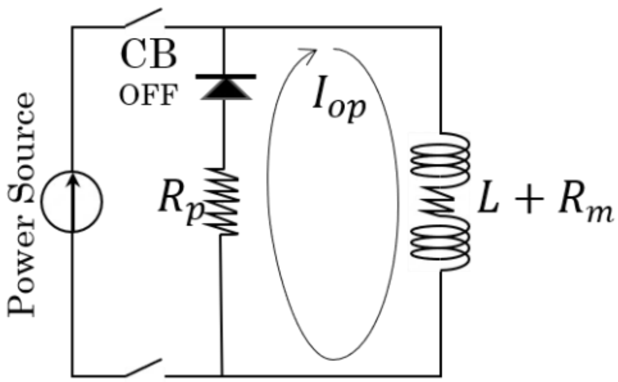
Quench Protection

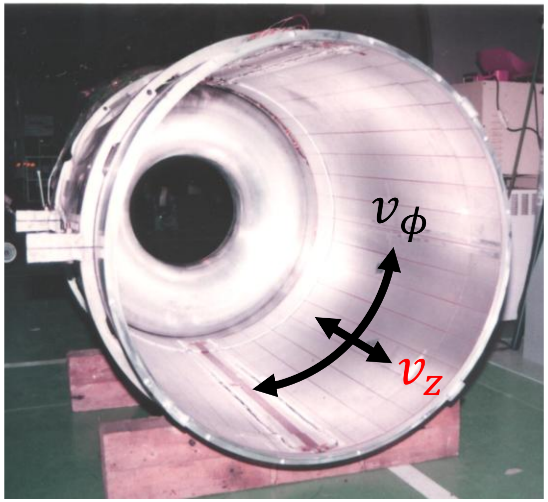
- Basic policy on quench protection is how fast the current at the quench origin is lowered to keep a temperature rise low enough.
- The current is lowered with a time constant of $\tau_m = L/\left(R_p + R_m\right)$.
- Terminal voltage $R_P I_{op}$ limit restricts larger protection resistor R_p.
- Larger normal zone expansion makes larger R_m. And mixture of $L\,dI_{op}/dt + R_m I_{op}$ restricts large internal voltage.

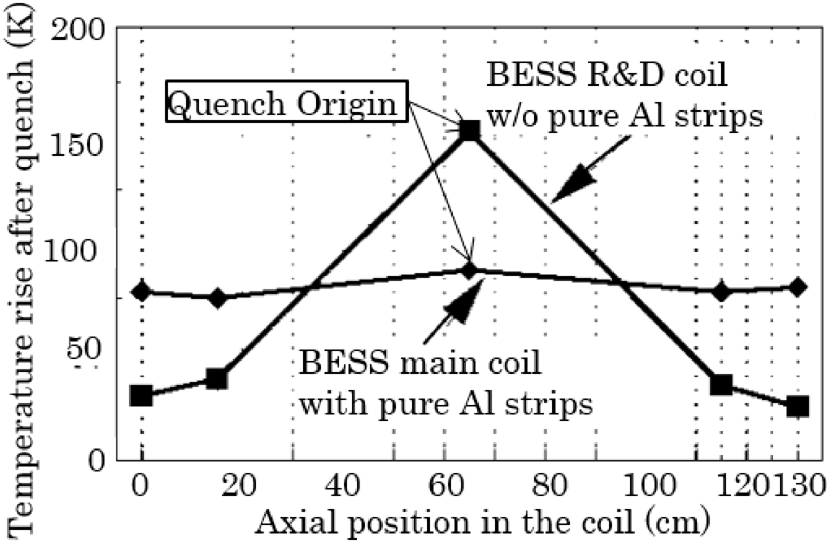


Fast quench propagation with pure Al strips.

$$v_\phi = \frac{j_e}{\gamma C}\left(\frac{L_0\theta_s}{\theta_s - \theta_0}\right)^{\frac{1}{2}}$$

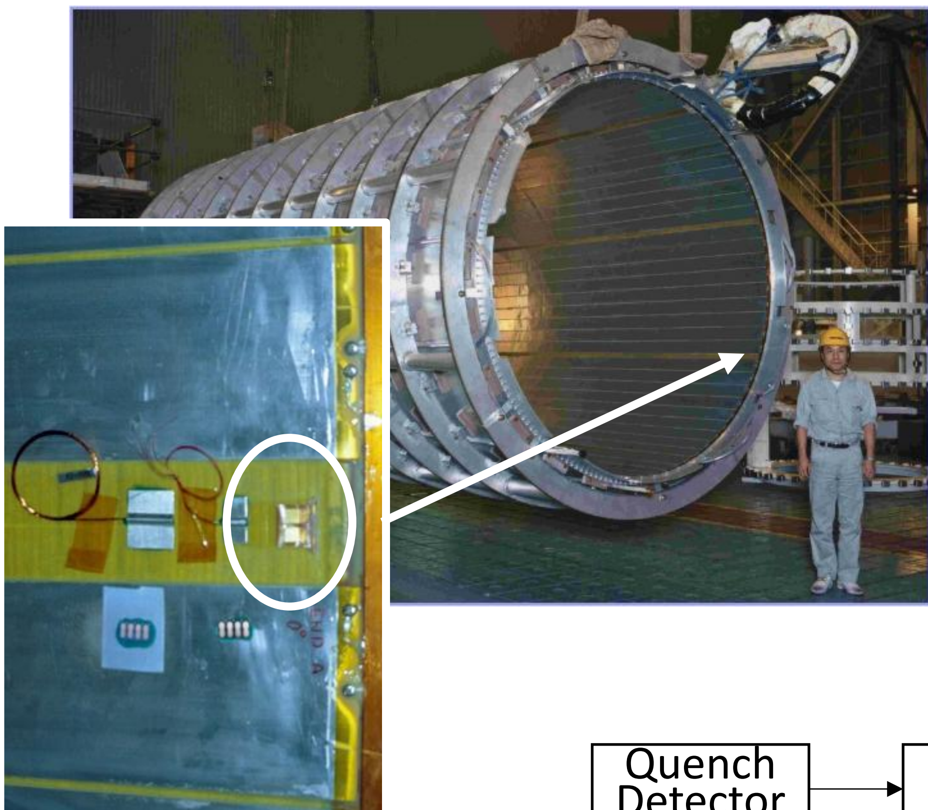
$$v_z = \left(\frac{k_z}{k_\phi}\right)^{\frac{1}{2}} v_\phi$$

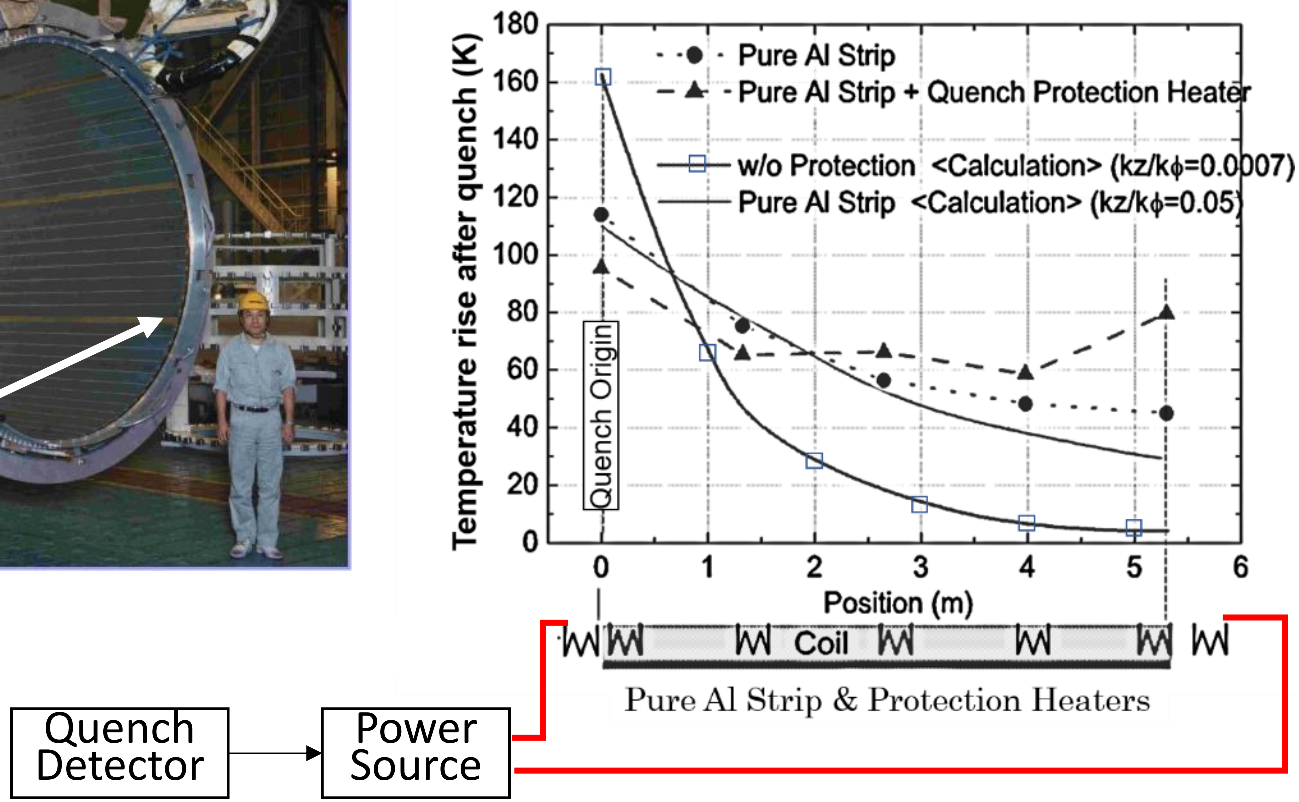




Quench Protection Heaters (QPH)

- Fast quench propagation in ATLAS CS is implemented with pure Al strips and distribution of protection heaters.
- Normal zones are generated earlier than quench propagation.
- Quench propagation is suspended at the divided coils in sprit solenoids, dipole coils and toroidal coils. Protection hears are necessary.

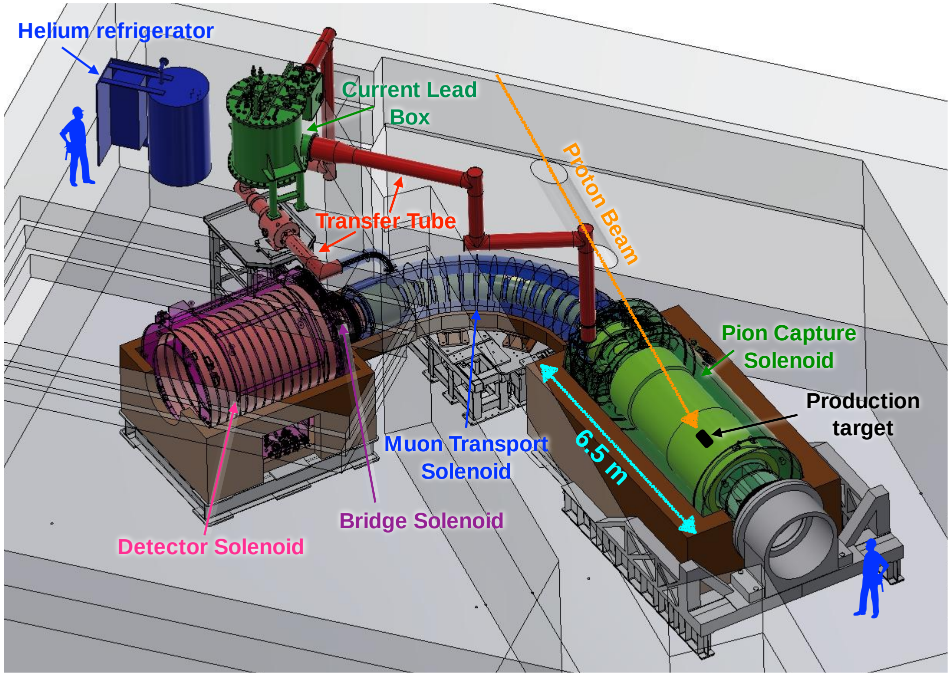


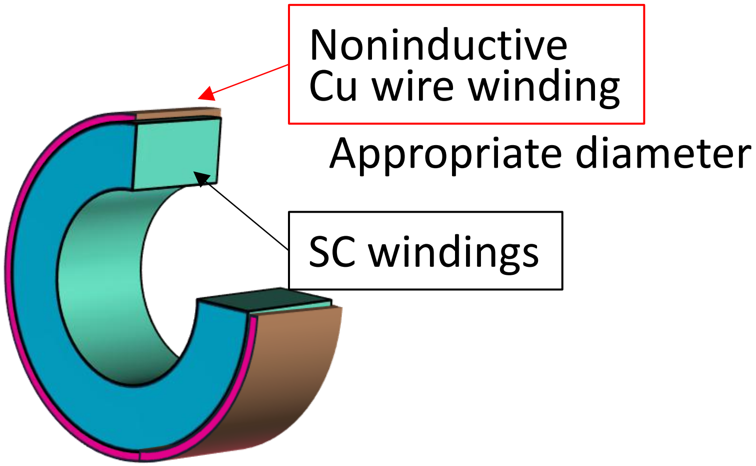


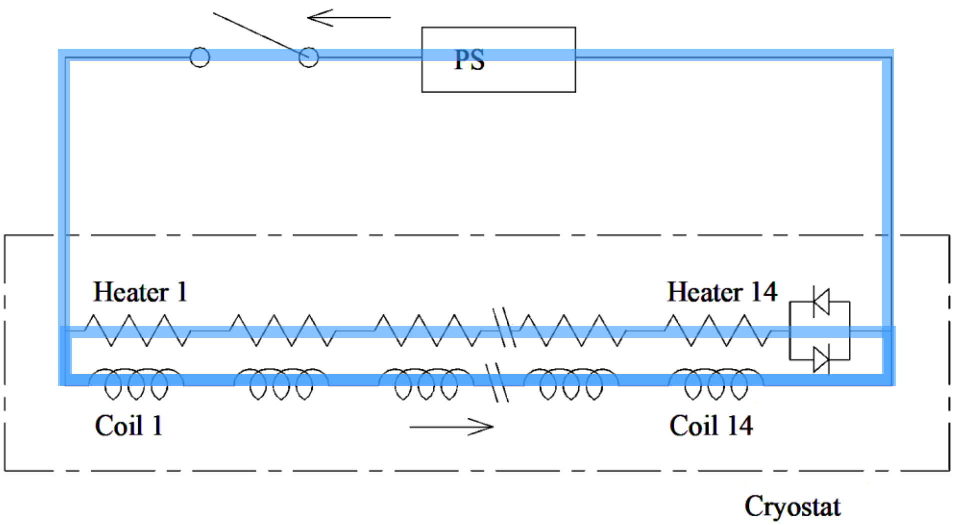
External power source fires the QPH

QPH fired by operation current

- Cu conductor with appropriate cross section is wound in noninductive manner outside of SC windings.
- When a quench is detected, PS is cut off and charged current from PS is switched into the Cu winding to heat up SC winding.
- Example: for 190A magnet, ϕ1.5 mm Cu wire is wound.







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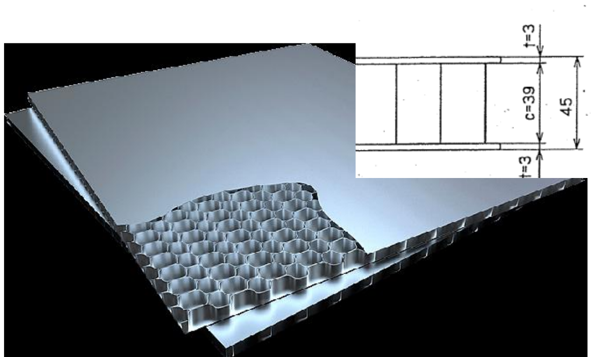
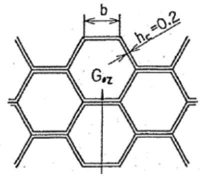
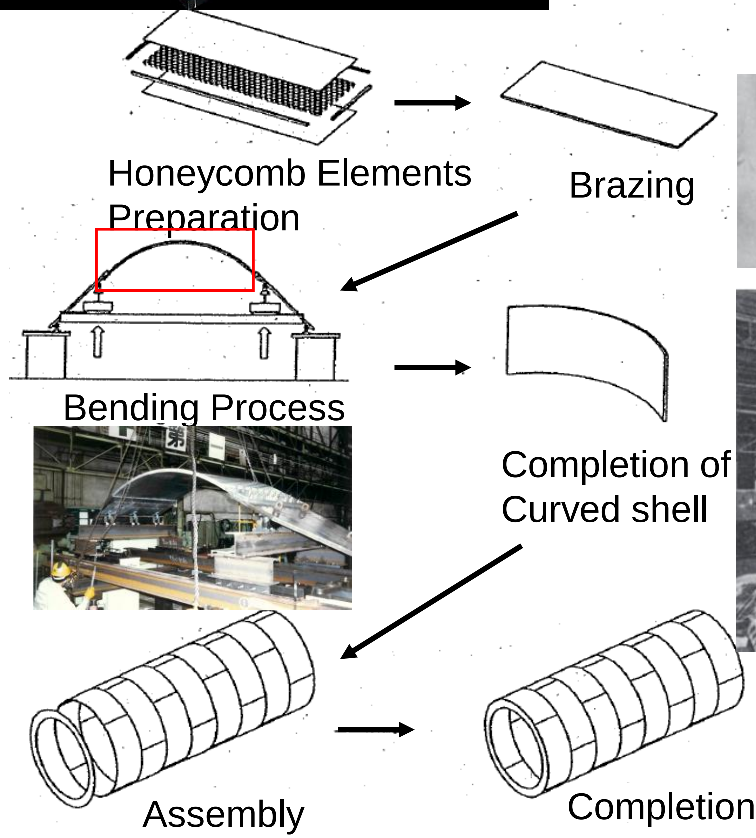
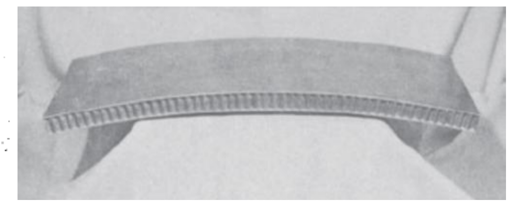
Mass reduction at VV with honeycomb plate





- Outer vacuum cylindrical vessel is applied external pressure of 100 kPa.
- It need to have a large enough bending rigidity. it becomes thick cylinder.
- Al-honeycomb plates can get enough rigidity with saving actual thickness.
- KEK made a ϕ4.1 m,L 2.1 m Al-honeycomb VV.





	3-point bending (bending roller)	4-point bending
Condition		
Shearing force distribution		
Bending moment distribution		
Cores collapsed	Occurs	None

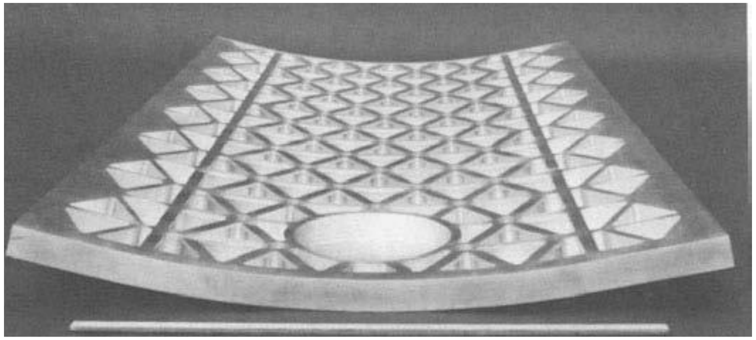
I. Ohno et al.," Brazed honeycomb vessel r&d for the SDC solenoid magnet," Supercollider 5, New York, 1994

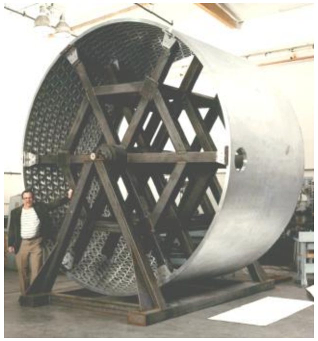
H. Yamaoka et al.,"Development of a brazed-aluminum-honeycomb vacuum vessel for a thin superconducting solenoid magnet," Adv. Cryogenic Eng., Vol. 39, p.1983, 1994.

Mass reduction at VV with other method

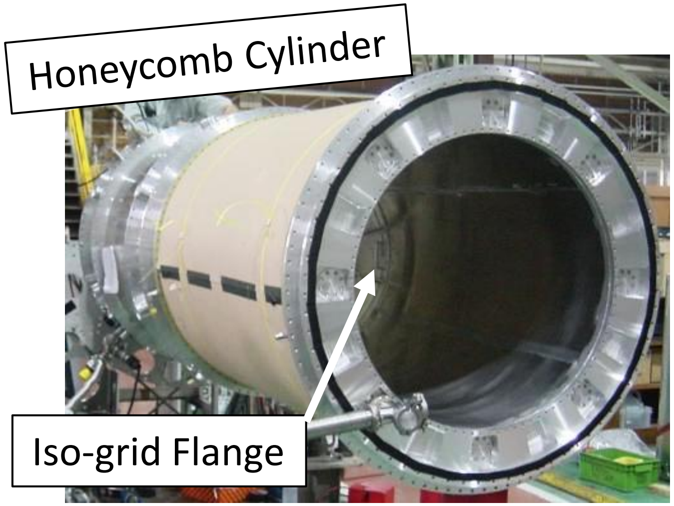
Iso-grid structure

- Iso-grid is a type of partially hollowed-out structure formed usually from a single metal plate (or face sheet) with triangular integral stiffening ribs (often called stringers) to save its weight.
- Honeycomb is more effective for saving weight, but shape of iso-grid has more flexibility.
- End flange, service ports etc. is applied iso-grid structure..





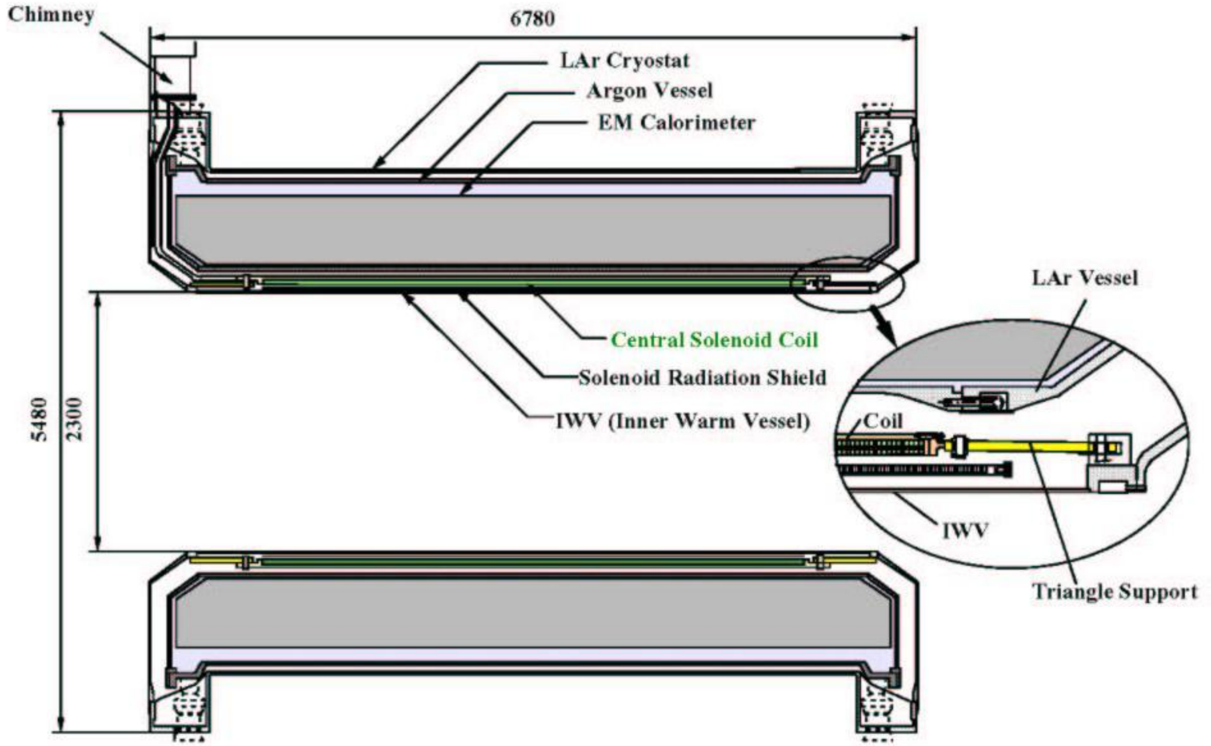
	Bulk plate	Iso-grid	Honeycomb
Material	A5083	5083-h32	A6951/4045-T6
Thickness(mm)	27	46	46
Skin thickness (mm)	(27)	4.0	3.0+3.0
Effective thickness (mm)	27	11	7
Relative weight	1	0.4	0.26
Transparency (Xo)	0.303	0.123	0.079

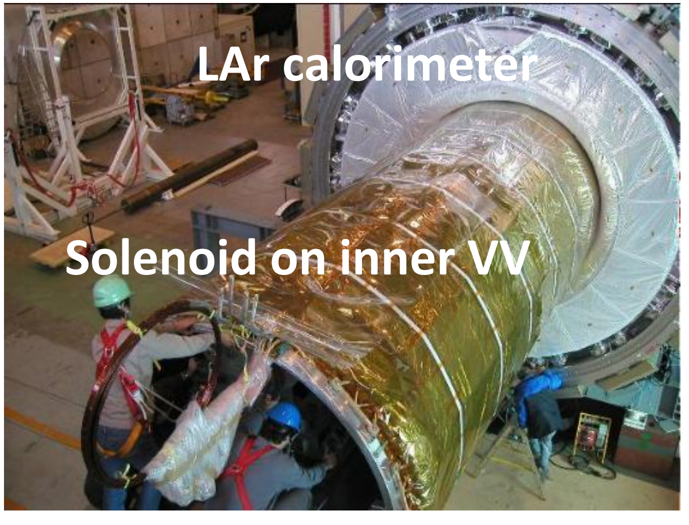


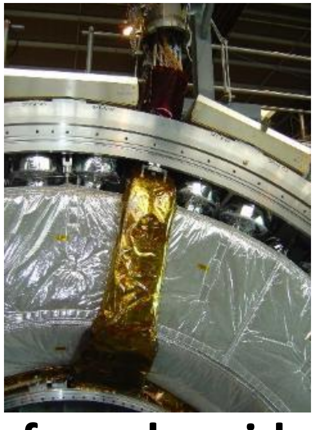
BESS Solenoid

https://indico.cern.ch/event/727555/contributions/3431121/attachments/1869146/3074972/20190626-TenKate-FCC-wk-2019-Brussel-FCC-Detector-Magnets.pdf

Common V.V with outer cryogenic calorimeter





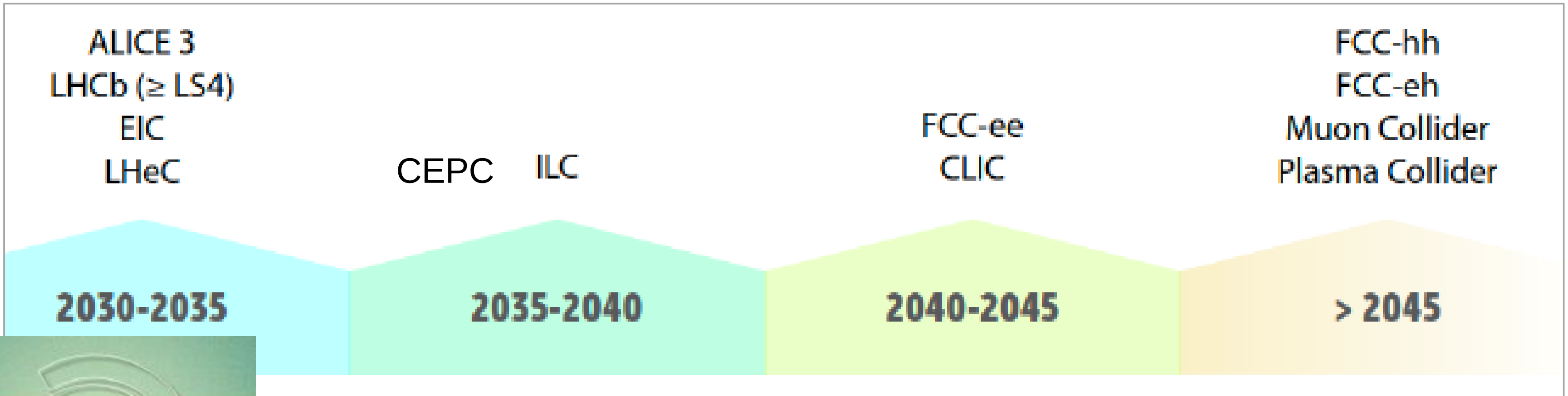


Service line for solenoid

OUTLINES

1. Charged particles in a magnetic field.
2. Type and features of magnetic spectrometer.
3. Thin solenoid type magnet
    1. E/M ratio
    2. Aluminum stabilized superconductor
    3. Coil manufacture (Direct internal winding)
    4. Conductive cooling
    5. Quench protection
    6. Cryostat
4. Future plans

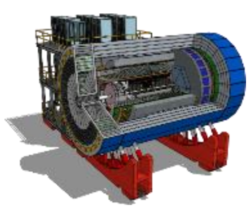
Future huge detector magnets for Energy Frontier

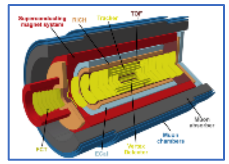


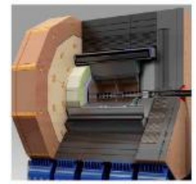
European Strategy
Laboratory Directors Group

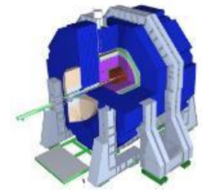
Projects	Energy (GeV)	Magnet	B_0 (T)	Inner D (m)	Length (m)	E/M (kJ/kg)	Stored Ene.(GJ)
ILC	250-500	ILD	4	7.2	7.35	13	2.3
		SID	5	5.0	5	12	1.4
CLIC	380 → 3000	CLICdet	4	7.3	7.8	13	2.3
FCC-ee	88-95 →365	IDEA	2	4.5	5.8	14	0.17
		CLD	2	8.5	7.2	12	0.6
FCC-hh	100 TeV		4	10	20	11.9	13.8
CEPC	240		3	7.3	7.6	15	1.54

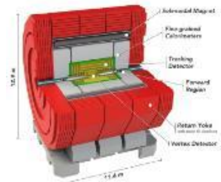
Detector magnet projects for existing & future colliders, non-colliders and space experiments

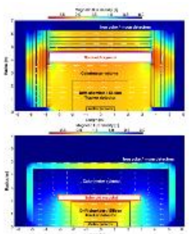

EIC

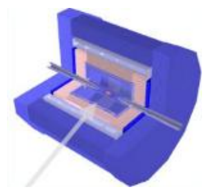

ALICE-3

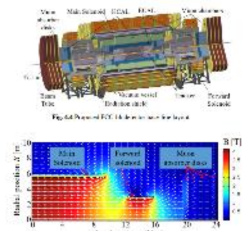

ILC-ILD

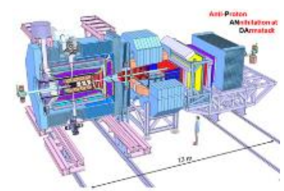

ILC-SiD


CLIC

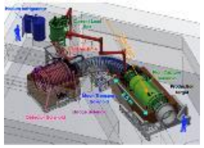

FCC-ee


CEPC


FCC-hh


PANDA


Mu2e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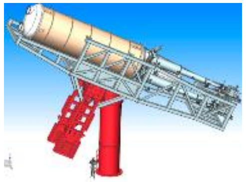
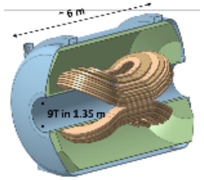
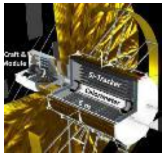
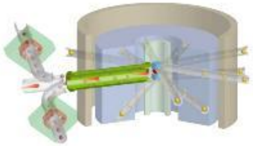
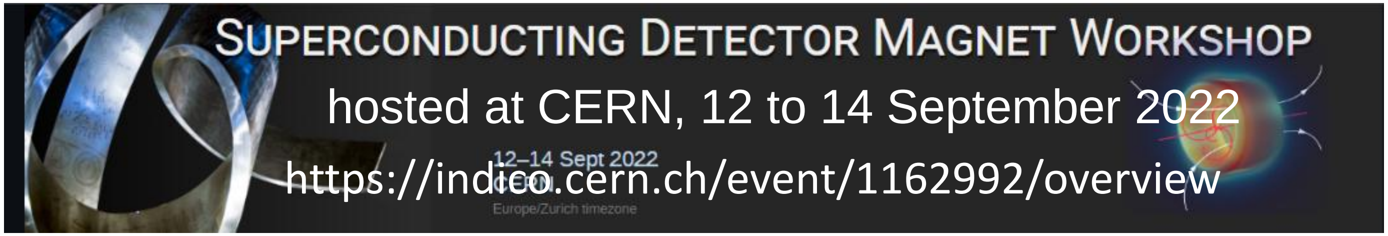

BabyIAXO



MadMax

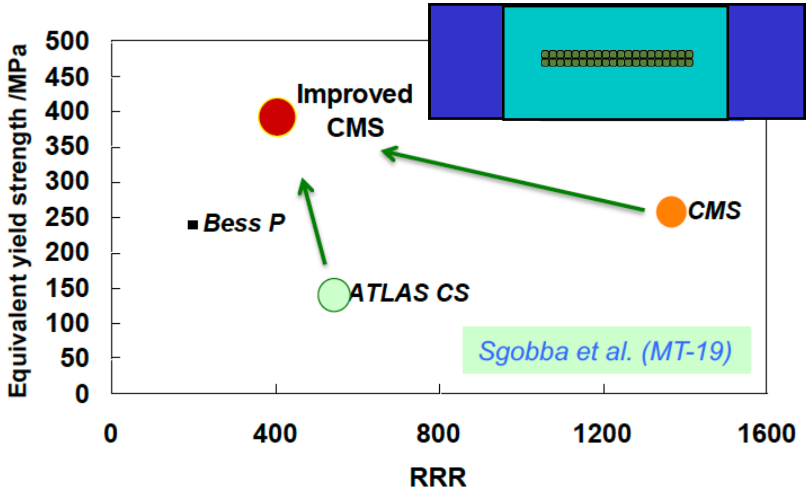

AMS100

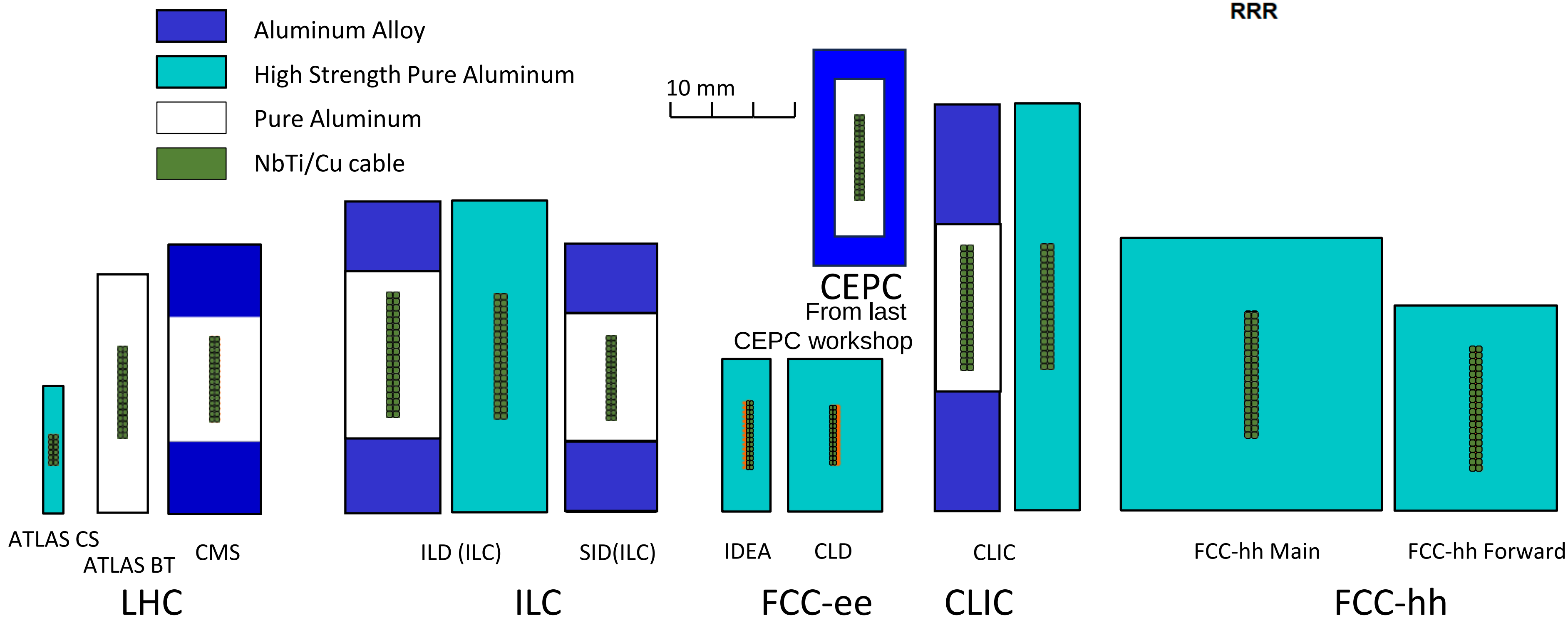

J-Parc MLF



Al stab. conductor mechanically reinforced

- More reinforced conductor with combination of high strength pure Al and Al-alloy.
- **Currently, all experienced factory withdrawn from the production of aluminum-stabilized superconductor in Japan.**





Summary of this lecture

Roles, features and technologies of SC magnet for detectors are explained.

- Magnetic field curves trajectory of particle, which indicates its momentum and polarity.
- Magnets have variety shapes, solenoid, dipole, toroid and their combination.
- Large field area BL_0^2 and wide solid angle for particle detectors.
- Especially, for energy fronter colliders, thin SC solenoids with a solid angle of 4π have been developed.

Technologies for thin solenoid:

- Minimize particle scattering & mass of magnet. Al and its alloy is main material.
- NbTi SC cable clad with pure Al stabilizer → Mechanical advanced Al stabilizer.
- Conduction cooled coil without a LHe vessel.
- Pure Al quench propagator or distribution of heaters protect coils against quench.
- Al honeycomb and iso-grid structure for outer vacuum cylinder to reduce effective thickness.

In future, huger detector magnets has been considered for EF collider.

Back-up

Introduction(4)

History of High Energy Physics Detector Magnets

- 1969 CERN –BEBC, Big European Bubble Chamber (solenoid)
- 1972 CERN –Omega magnet (large aperture dipole)
- 1977 CERN/ISR –Solenoid *Al stabilized superconductor*
- 1978 DESY –**CELLO (solenoid)** *Pioneer of thin solenoid*
- 1983 SLAC/PEP4 –TPC solenoid
- 1985 KEK/TRISTAN –TOPAZ, VENUS, AMY (solenoids)
- 1988 CERN/LEP –ALEPH, DELPHI (solenoids)
- 1990 DESY/HERA –ZEUS (solenoid)
- 1997 KEKB/KEK – **Belle (solenoid)** *Woking now*
- 1997 SLAC –BABAR (solenoid)
- 2004 KEK –BESS-Polar (ultra-thin solenoid)
- 2007 CERN/LHC –**CMS (solenoid), ATLAS (Toroids, solenoid).** *Woking now*

T. M. Taylor, CERN Summer Student Lecture, 2006
Y. Makida added “Belle” at ASSCA2023 Lecture.

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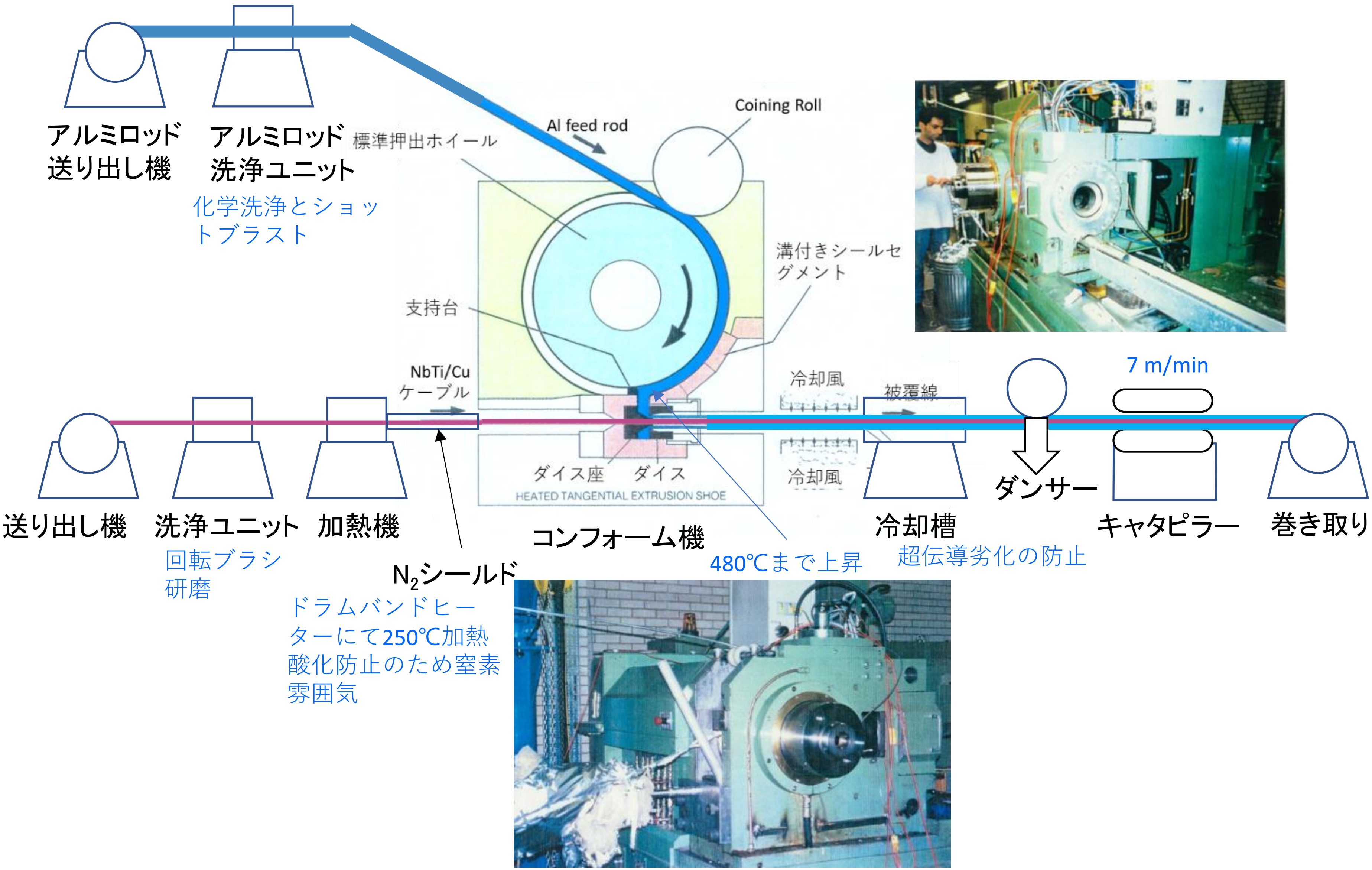
Main parameters of detector magnet

Detector Name	Laboratory	B (T)	A.D. (m)	L (m)	Energy (MJ)	E/M (kJ/kg)
PLUTO*	DESY	2.2	1.4	1.05	4.25	1.6*
CELLO	DESY/Saclay	1.5	1.5	4.02	7	5.0
PEP4/TPC	SLAC/LBL	1.5	2.04	3.84	11	7.6
CDF	FNAL/Tsukuba	1.5	2.86	5.07	30	5.4
D0	FNAL	2	1.07	2.7	5.6	3.7
CLEO-II	Cornell	1.5	2.9	3.8	25	3.6
ALEPH	CERN/Saclay	1.5	5.0	6.3	136	5.5
DELPHI	CERN/RAL	1.2	5.2	7.4	109	4.2
ZEUS	DESY/INFN	1.72	3.0	2.85	11	5.5
H1	DESY/RAL	1.2	5.2	5.75	120	4.8
TOPAZ	KEK	1.2	2.72	5.4	19.5	4.3
VENUS	KEK	0.75	3.4	5.64	12	2.8
AMY*	KEK	3.0	2.2	1.54	40	2.4*
Belle	KEK	1.5	3.6	4	42	5.3
ATLAS (CS)	CERN/KEK	2	2.3	5.3	38	7
CMS	CERN	4	6	12.5	2670	12
BESS	KEK	1.2	0.85	1.0	0.82	6.6
BESS-Polar	KEK	0.8	0.8	1.0	0.40	9.2

Layout of clothing process

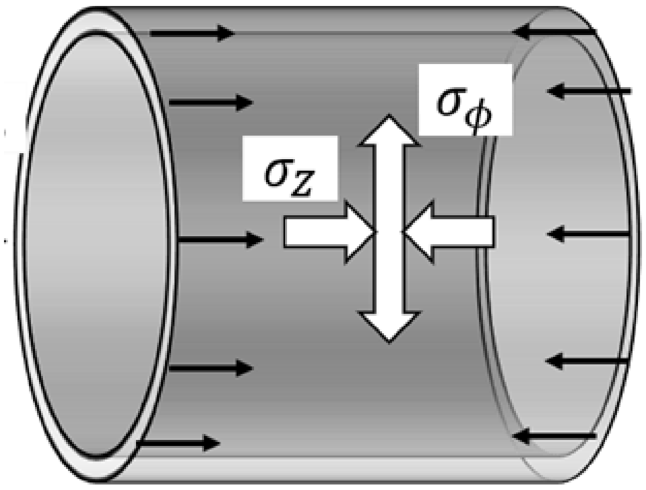


EMF and Stress in a solenoid

In actual designing, stress intensity or von Mises stress calculated by FEM is $< \sigma_{allow}$ are checked.

Stress Intensity: $\sigma_{int} \approx \sigma_\phi - \sigma_Z$

von Mises: $$\sigma_{eq} = \left\{\frac{1}{2}\left[(\sigma_\phi - \sigma_Z)^2 + {\sigma_Z}^2 + {\sigma_\phi}^2\right]\right\}^{1/2}$$



ATLAS solenoid Stress distribution