Superconducting Technology for Future Collider Detectors

Akira Yamamoto
(KEK and CERN)

A talk prepared for MuC Detector Magnet WS, Oct. 5, 2023
- based on the talk at TIPP2023, Sept. 8, 2023 -

https://indico.cern.ch/event/1324236/

Original Talk given at TIPP2023

Superconducting Technology for Future Colliders and Detectors

Akira Yamamoto
(KEK and CERN)

A plenary talk, TIPP 2023, Cape Town
September 8, 2023

https://tipp2023.org/

A. Yamamoto, 2023/09/08 1

References:

Overview:

- V. Shiltsev and F. Zimmermann, Modern and Future Colliders, Rev. Mod. Phys. 93 (2021) 015006.

LDG Report for ESPPU-2020: European Strategy for Particle Physics Update (ESPPU-2020): https://arxiv.org/abs/2201.07895

- N. Mounet (Editor), “European Strategy for Particle Physics, Accelerator R&D Roadmap”, CERN Yellow Report, CERN 2022-001. (2022),

LDG: Community Report on the Accelerator Roadmap at Acc. R&D Workshop, INFN Frascatti, **July 2023**: https://agenda.infn.it/event/35579/

- U. Bassler, “A portfolio of HEP Colliders”,
- G. Bisoffi and P. Mcintosh, et al., “RF achievements and plans”,
- A, Siemko, “High field magnet R&D programme status of HFM within the accelerators roadmap”.
- J.G. M.Jimenez, “Magnet developments for future physics programmes”,

FCC-week 2023, June 7: https://indico.cern.ch/event/1202105/timetable/

- B. Auchmann, “Future HFM R&D directions”.
- A. Ballarino, “HTS developments”.

US Snowmass’21 Report (2023) : https://iopscience.iop.org/journal/1748-0221/page/snowmass21

- T. Roser et al., “On the feasibility of future colliders”, Snowmass’21 Implementation Task Force, 2023 JINST **18**, P05018 (2023).
- S. Belomestnykh amd S. Posen, I., “Key directions for research and development of superconducting radio frequency cavities”, arXiv:2204.01178.
- S. Belomestnykh et al., “Acceleraor technology R&D: Report of AF7-rf Topical Group for Snowmas’21, arXiv:2208.12368
- M. Mentink, K. Sasaki et al., “Superconducting detector magnets for high energy physics”, 2023 JINST 18, T06013 (2023).

US-P5 Townhall (2023): https://indico.slac.stanford.edu/event/7992/overview

- S. Gourlay, T. Raubenheimer, and V. Shiltsev , “Snowmass’21 Accelerator Frontier”
- S. Belomestnynkh, “ILC and SRF “ (not uploaded).
- S, Prestemon, “Magnets for energy frontier colliders”, US-P5 Townhall meeting, May 2023.

AFAD-2023:

- K. Umemori, “Development of SRF technology at KEK-iCASA” Asian Forum for Accs & Detectors 2023.

Outline

- **Introduction :**
  - Future Colliders baaed on **S**uper**c**onducting (Sc) Technology
- **Sc Technology for Colliders:**
  - Sc RF Cavities
  - Sc Magnets
- **Sc Technology for Detector Magnets**
- **Summary**

Future Colliders based on Sc Acc. Technology

Courtesy:
ILC
FCC-ee, -hh
CEPC/SPPC
MC
EIC

<u>Linear Colliders</u>:

ILC e+e- (250 GeV → 1 TeV) :
- **SRF:** for High-Q (10^{10}) and high-G (**31.5 → 45 MV/m**)
- Highest efficiency and AC-power balance

CLIC e+e- (380 GeV → 3 TeV) :
- **NRF:** Very high G (100 MV/m)

<u>Circular Colliders :</u>

FCC-e+e- (90 → 350 GeV):
- **SRF: (400 – 800 MHz, 20 ~ 30 MV/m)**

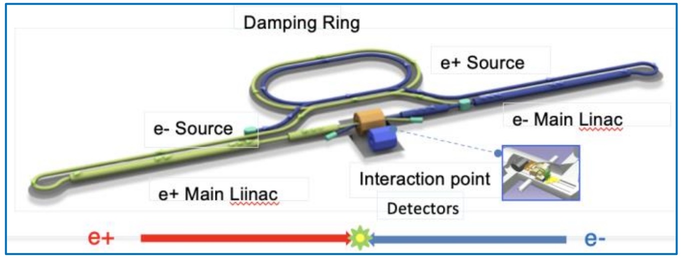
FCC-hh (80 -120 TeV):
- HF SC magnets (SCM: **14 – 20 T**)
- **SRF: (400, 800 MHz)**

CEPC e+e- (90 - 240 GeV):
- **SRF:** (0.65, 1.3 Ghz, 5 – 30 MV/m)

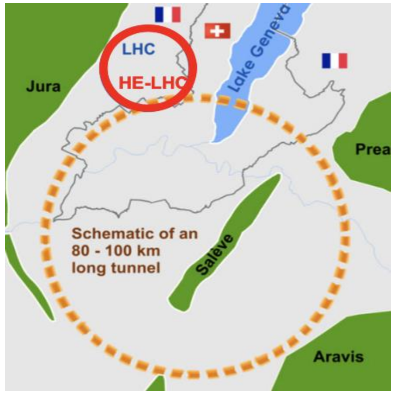
SPPC- pp (75 - 125 TeV):
- HF SCM (**12 -20** T)

EIC Ion•e-(275/100 GeV/n v.s. 18 GeV, approved)
- **SCM and SRF**

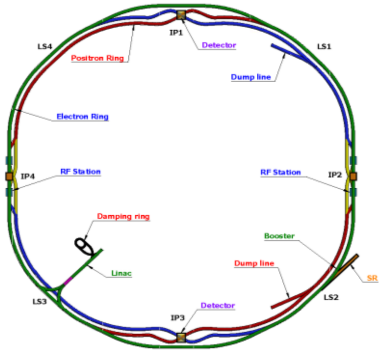
MC μ+μ– (3 – 14 TeV)
- SRF (1, 3 GHz, 30 MV/m, HF solenoid (≥ 40 T, Dipole, 16 T).



ILC

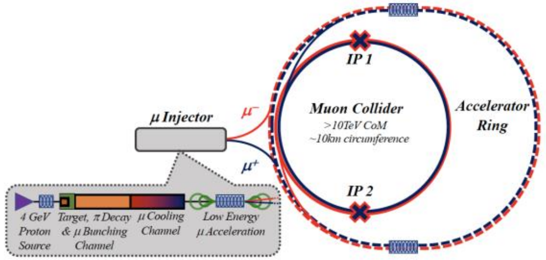


FCC-ee / -hh

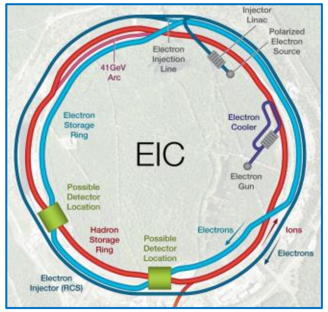


CEPC / SPPC

Ref.: T. Resiak, TIPP23, Thu., F5



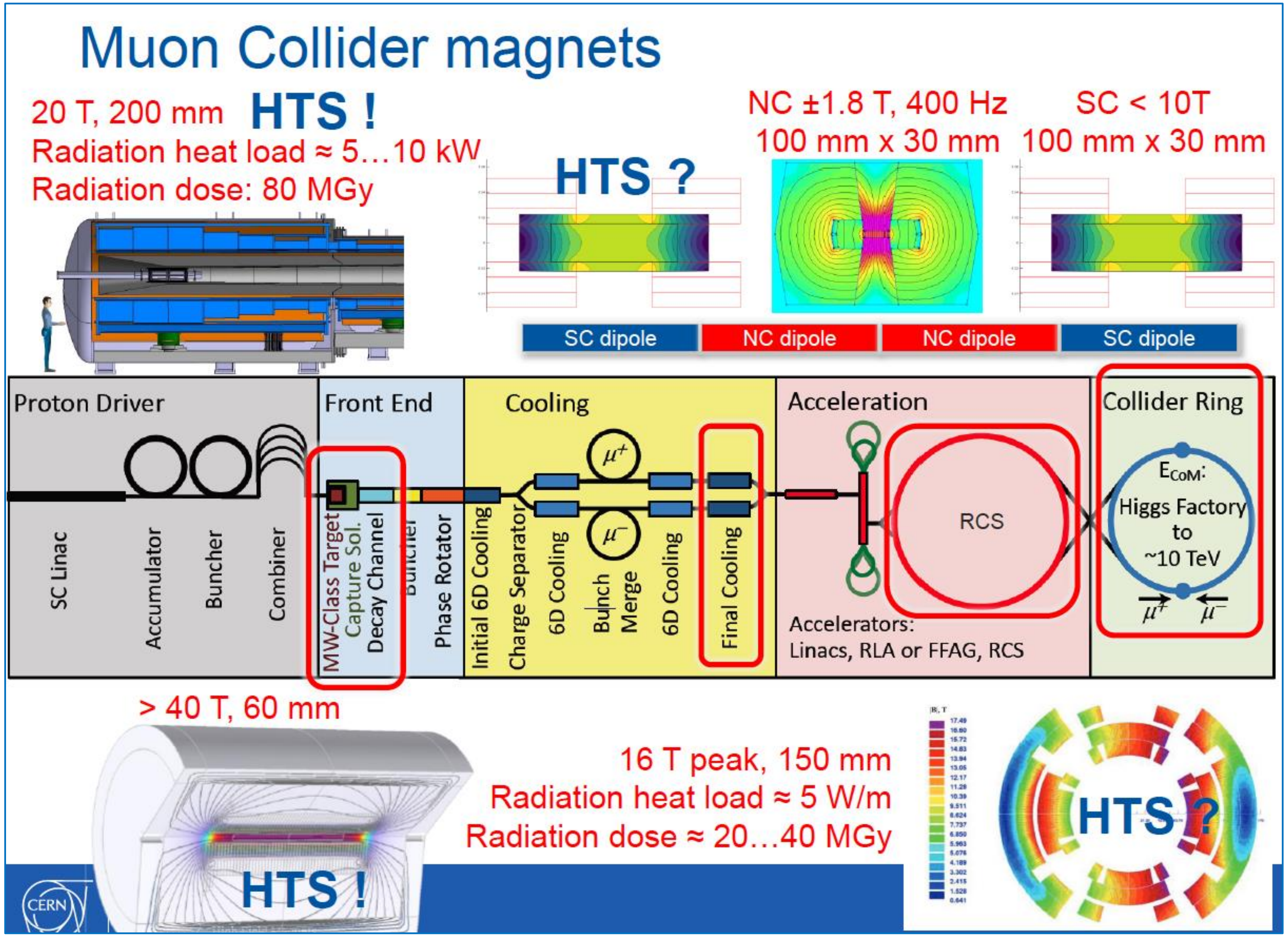
MC



EIC

A new/revived Direction for Muon Collider:

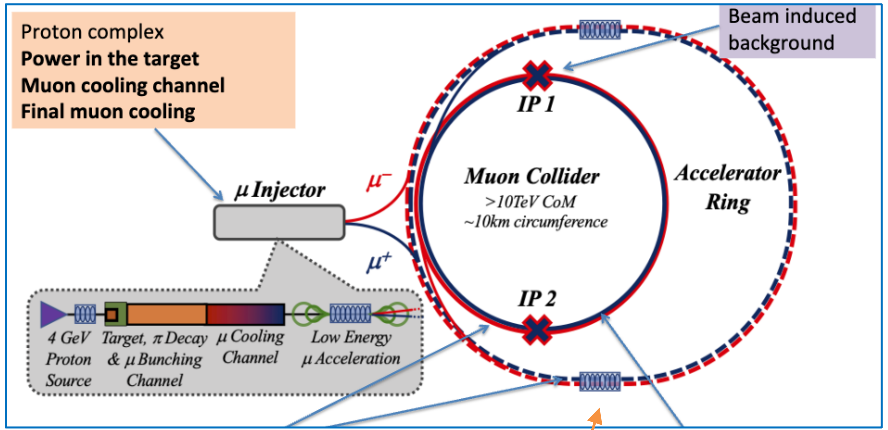
Courtesy: D. Schultz,
Luca Bottura, A. Grudiev



SRF Cavities

Acceleration:

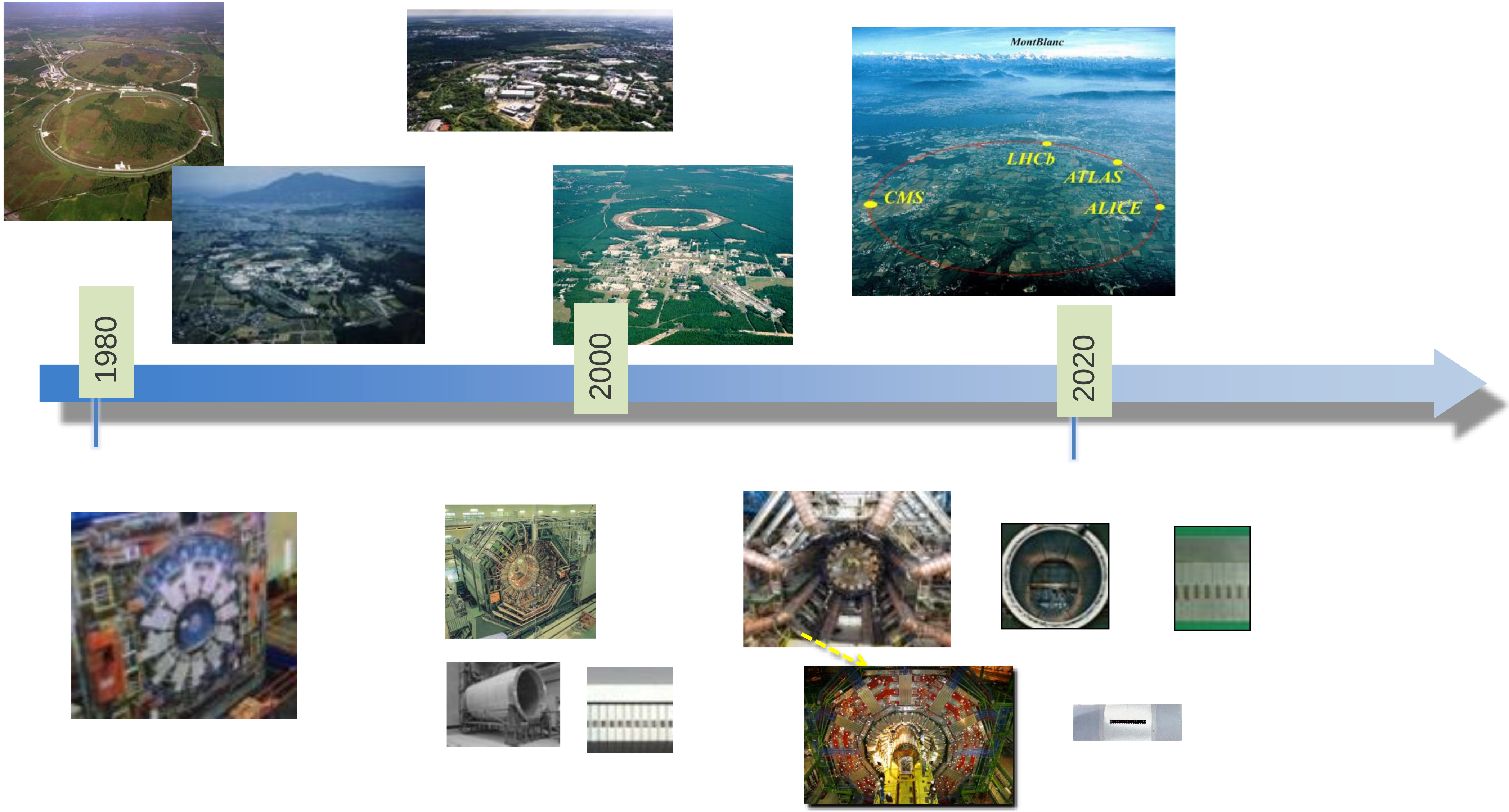
- 1.3 GHz, - 31.5 MV/m



Outline

- **Introduction :**
  - Future Colliders, relying on Superconducting (SC) Technology
- **SC Technology for Colliders:**
  - Superconducting RF Cavities (Acc. Structure)
  - Superconducting Magnets
- **Superconducting Detector Magnets (SC-DM)**
- **Summary**

Advances in SC Detector Magnets for Colliders



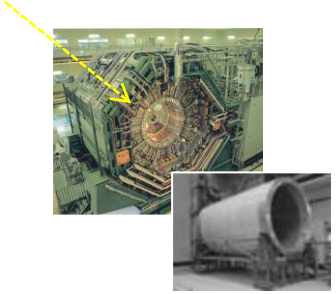
Tevatron: CDF

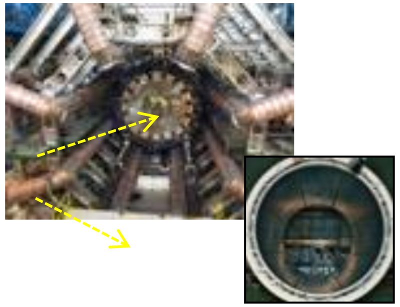
Tristan; Topaz, Venus, Amy

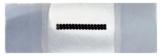
LHC: ATLAS, CMS

Advances in Detector Solenoids

Experiment	Laboratory	R (m)	B (T)	I (kA)	X (X_0)	E/M (kJ/kg)	E (MJ)	Year	Ref.
PLUTO	DESY	0.75	2.2	1.3	4.0	2.3	4.1	1972	18
ISR point 1	CERN	0.85	1.5	2	1.1	1.8	3.0	1977	19
CELLO	Saclay/DESY	0.85	1.5	3	0.6	5.0	7.0	1978	20
PEP4/TPC	LBL/SLAC	1.1	1.5	2.27	0.83	7.6	11	1983	21
CDF	KEK/FNAL	1.5	1.6	5	0.84	5.4	30	1984	22
TOPAZ	KEK	1.45	1.2	3.65	0.70	4.3	19	1984	23
VENUS	KEK	1.75	0.75	4	0.52	2.8	11.7	1985	24
AMY	KEK	1.2	3	5	N/A	N/A	40	1985	25
CLEO-II	Cornell	1.55	1.5	3.3	2.5	3.7	25	1988	26
ALEPH	Saclay/CERN	2.75	1.5	5	2.0	5.5	136	1987	27
DELPHI	RAL/CERN	2.8	1.2	5	1.7	4.2	110	1988	28
ZEUS	INFN/DESY	1.5	1.8	5	0.9	5.2	10.5	1988	29
H1	RAL/DESY	2.8	1.2	5	1.8	4.8	120	1990	28
BESS	KEK	0.5	1.2	0.38	0.2	6.6	0.25	1990	30
WASA	KEK/Uppsala	0.25	1.3	0.9	0.18	6	0.12	1996	31
BABAR	INFN/SLAC	1.5	1.5	6.83	0.5	N/A	27	1997	32
D0	FNAL	0.6	2.0	4.85	0.9	3.7	5.6	1998	33
BELLE	KEK	1.8	1.5	4.16	N/A	5.3	37	1998	34
ATLAS-CS	KEK/CERN	1.25	2.0	7.8	0.66	7.1	38	2001	35
BESS-polar	KEK	0.45	1.0	0.48	0.156	9.2	0.34	2005	36
CMS	CMS/CERN	3.0	4.0	19.5	N/A	12	2600	2007	37
BESIII	IHEP (China)	1.45	1.0	5	N/A	2.6	9.5	2008	38
CMD-3	BINP	0.35	1.5	1	0.085	8.2	0.31	2009	39

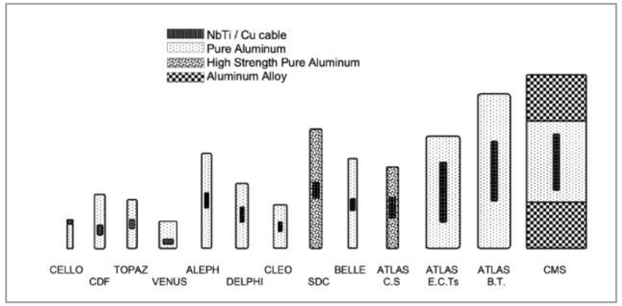


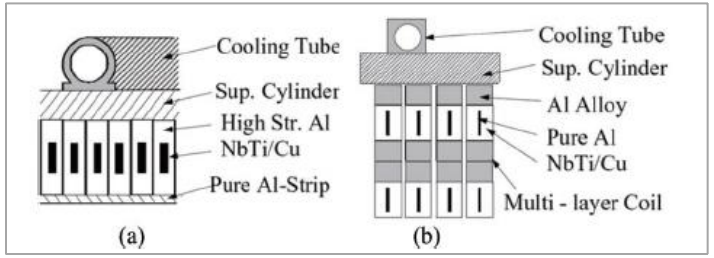



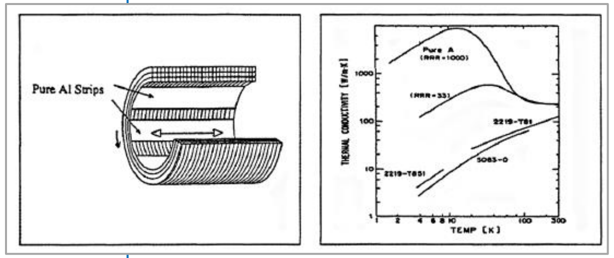
Technology Advances for Detector Magnets

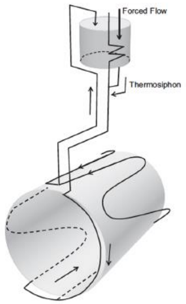
Table 1. Advances in thin/transparent solenoid magnet technology.

Technology	First Detector of the technology implemented
Al-stabilized superconductor (soldered) and indirect/conduction cooling	ISR [2], CELLO [3]
Secondary winding and quench back	PEP4-TPC [4]
Co-extruded Al-stab. superconductor	CDF [5]
Inner winding	TOPAZ [6]
Peak field on strand	5.4
CFGP outer vacuum vessel/wall	VENUS [7]
Thermo-siphon and indirect cooling	ALEPH [8], DELPHI [9]
2-layer coil and grading	ZEUS [10], CLEO [11]
Al-stabilizer w/ Zn, and Isogrid vacuum vessel	SDC-Prototype [12]
Shunted coil w/ conductor soldered to mandrel	CMD-2 [13]
High-strength Al-stabilizer w/ Ni micro-alloying and fast quench propagation w/ pure-Al strips and heater	ATLAS [14]
Hybrid conductor configuration using EBW	CMS [15]
Self-supporting coil with no outer support cylinder	BESS-Polar [16]

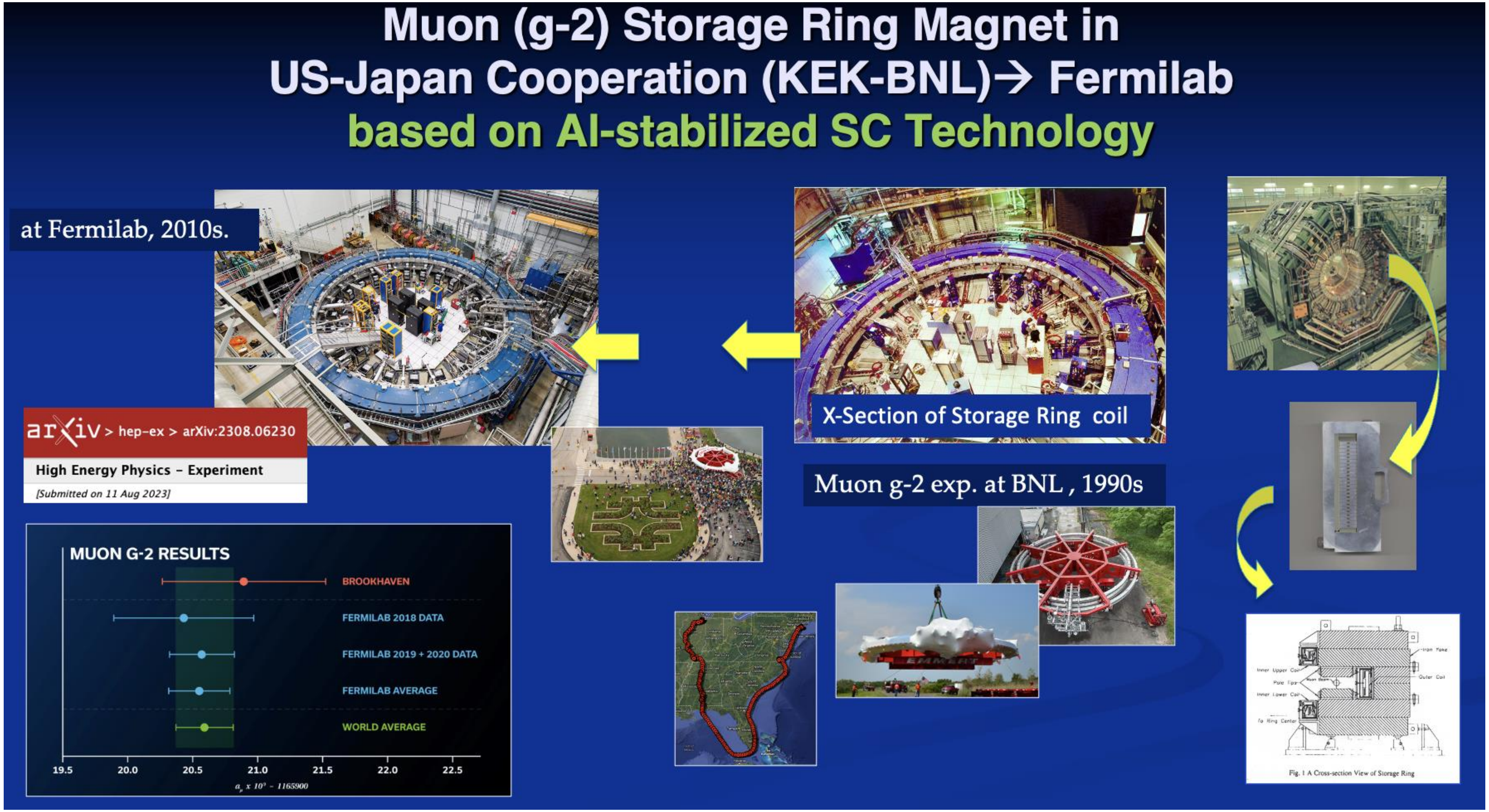




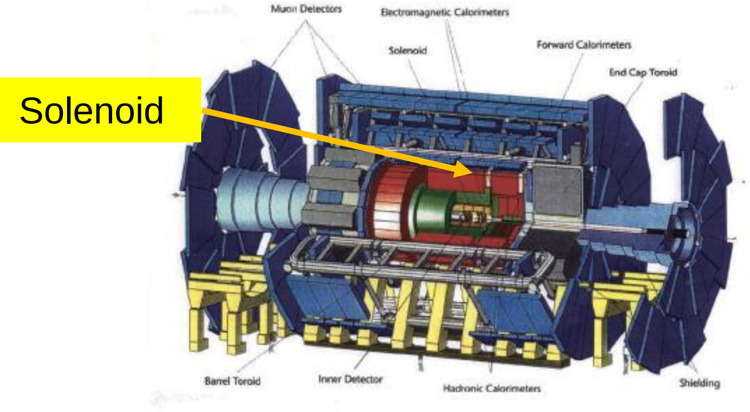




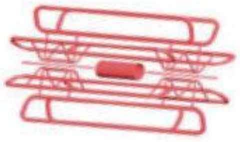
A Spin-out of the Al-SC Technology



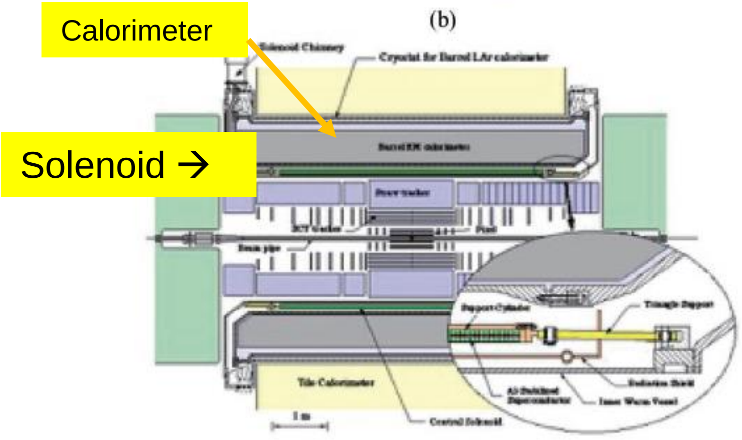
Status: LHC, ATLAS and CMS Detector Magnets



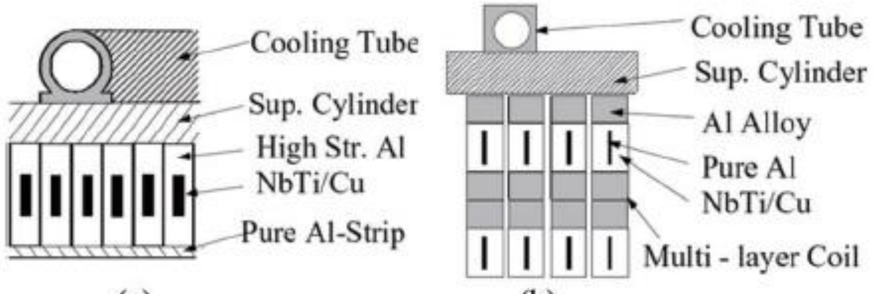
(a)



(b)



ATLAS-CS, placed inside Calorimeter



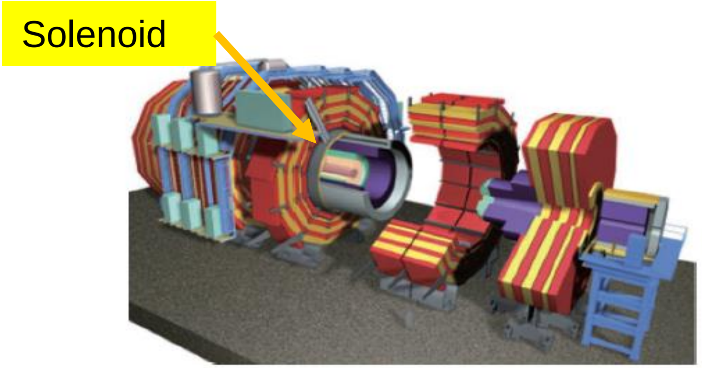
(a) (b)

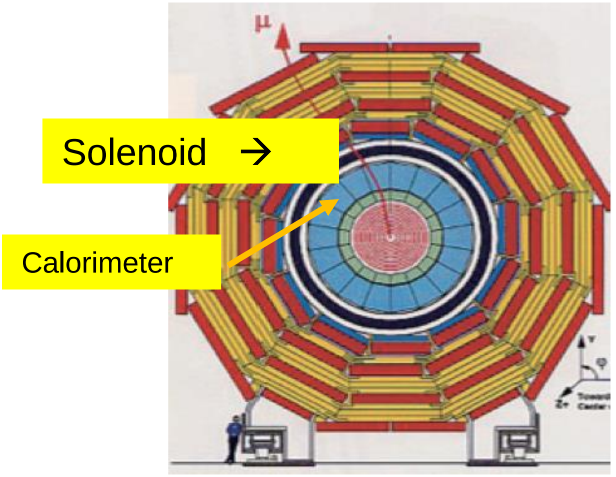
Al-stabilized SC:

Serving an essential role for:

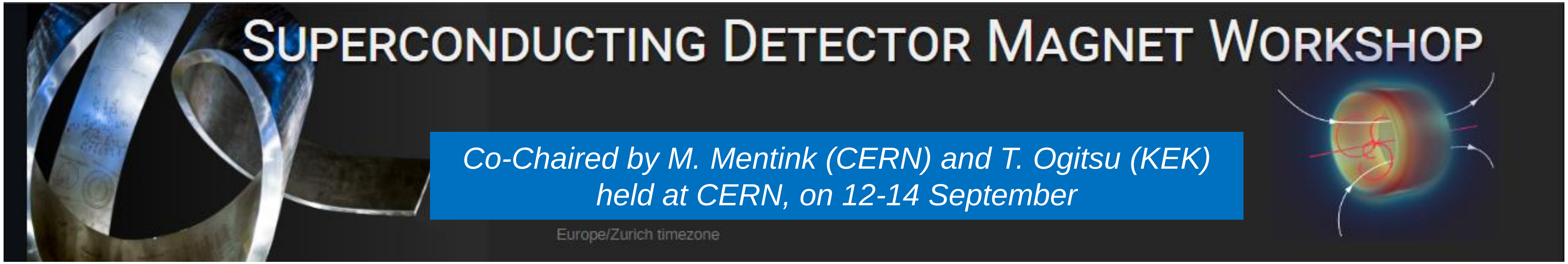
- **B field w/ Large volume**
- **Reliable operation**
- **Particle passing through**

We need to prepare for Future Programs





CMS Solenoid placed outside alorimeter



Motivation:

- Preparing **SC Detector Magnets technology,, for future Colliders**
- **Re-establishing: Al-stabilized SC technology, as a critical issue**

Future Colliders and Physics Experiments
Expected

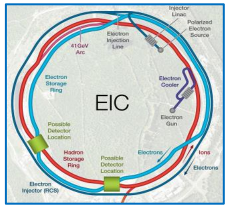
Future proposed particle physics experiments being studied: from LDG Accelerator R&D Report, CERN 2022-001

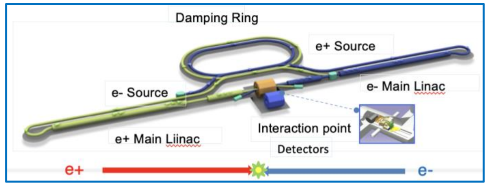
< 2030	2030-2035	2035-2040	2040-2045	> 2045
SPS fixed target Other fixed target; FAIR (hep) Belle II ALICE LS3 PIP-II/DUNE/Hyper-K	ALICE 3 LHCb (≥ LS4) EIC LHeC	ILC	FCC-ee CLIC	FCC-hh FCC-eh Muon Collider Plasma Collider

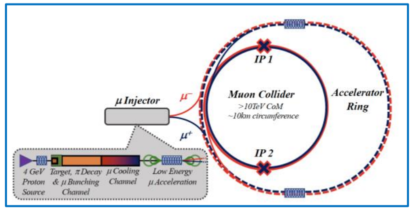
2007 ~ 2022

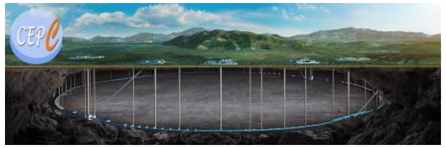
COMET, Mu2e

Other phys. Experiments: Mu2e, G-2 (fnal), Comet, G-2)J-Parc), BabyAXIO, AXIO (desy)



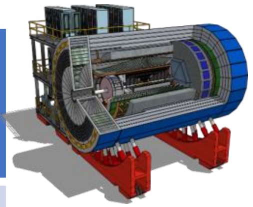




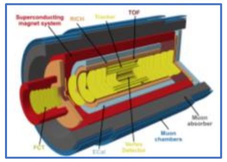


Future Particle Detector Plans proposed

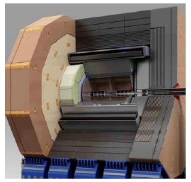
Subject / Project	Institutes in charge
The Electron-Ion Collider (EIC)	BNL / JLab
International Linear Collider –ILD (ILC-ILD)	ILC-IDR
International Linear Collider - SiD (ILC-SiD)	SLAC
Compact Linear Collider (CLiC)	CERN
Leptron Future Circular Collider (FCC-ee)	CERN
Hadron Future Circular Collider (FCC-hh)	CERN
Circular Electron Positron Collider (CEPC)	IHEP
A Large Ion Collider Experiment 3 (ALICE-3)	CERN
Muon to Electron (Mu2e)	ermilab
Muon Experiments in Japan	KEK
antiProton ANihilation at Darmstadt (PANDA)	GSI
Baby International Axion Observatory (BabyIAXO)	DESY
MAgnetized Disc & Mirror Axion eXp. (MADMAX)	CEA for DESY
Alpha Magnetic Spectrometer 100 (AMS-100)	Rheinish West.

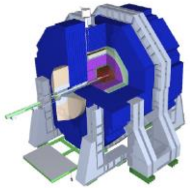


EIC

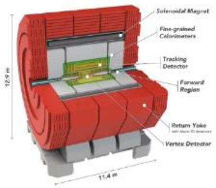


ALICE-3

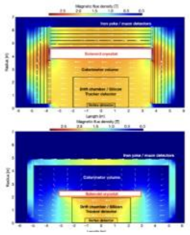




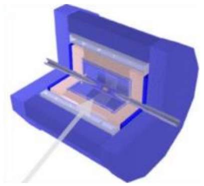
ILC-ILD /SiD



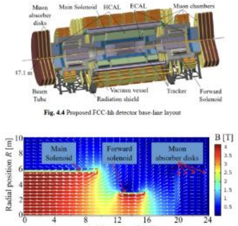
CLIC



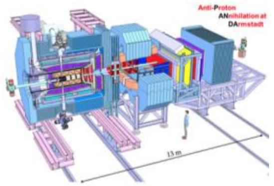
FCC-ee



CEPC

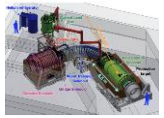


FCC-hh

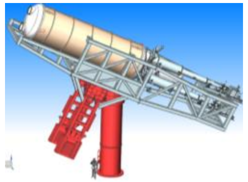


PANDA

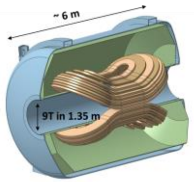
Mu2e



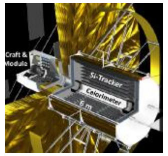
Comet



BabyIAX0



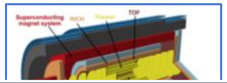
MadMax



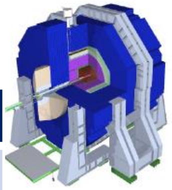
AMS100

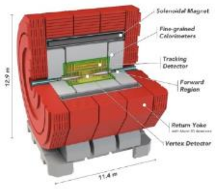
Future Particle Detector Plans proposed

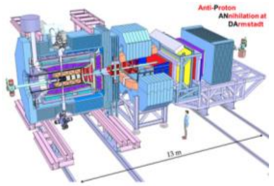
Subject / Project	Institutes in
The Electron-Ion Collide	
International Linear Colli	
International Linear Colli	
Compact Linear Collider	
Leptron Future Circular (	
Hadron Future Circular (	
Circular Electron Positro	
A Large Ion Collider Exp	
Muon to Electron (Mu2e	
Muon Experiments in Ja	
antiProton ANihilation at	
Baby International Axion	
MAgnetized Disc & Mirro	
Alpha Magnetic Spectro	

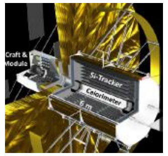

Experiments	Site	B [T}	Size, ID x L [m]	Note
EIC-Detector	BNL	1.5~3	2.5~3.2 x 8.5	Solenoid
ILC-ILD	Japan	4	6.88 X 7.35	Solenoid
ILC-SiD	Japan	5	5 X 5	Solenoid
CLIC-ILD	CERN	4	6.8 X 8.3	Solenoid
CLIC-SiD	CERN	5	5.4 X 6.5	Solenoid
CLIC	CERN	4	7 X 8.3	Solenoid
FCC-ee IDEA	CERN	2	4.2 X 6.0	Solenoid
FCC-ee CLD	CERN	2	7.4 X 7.4	Solenoid
FCC-hh	CERN	4	10 X 20	Solenoid
ALICE-3	CERN	2	3 x 7.5	Solenoid
M2e	Fermilab	5 ~ 2.5	1.5 X 4	Production
Muon-g-2	Fermilab	1.473	0.09 X 14.22 ▪ 2π	Storage solenoid
COMET	J-PARC	5 ~ 3	1.3 X 1.6	Capture Sol.
Muon-g-2	J-PARC	3	0.66 X 0.33	Solenoid
BabyAXIO	DESY	2	0.7 X 10	D. Racetrack
IAXO	DESY	5 - 6	5 X 25	Toroid
Panda	GSI	2	1.8 x 3.1	Solenoid
Madmax	DESY	9	1.35 x 1.2	Dipole


LD /SiD


CLIC


PANDA


Comet


AMS100

Courtesy: B. Cure, Y. Makida

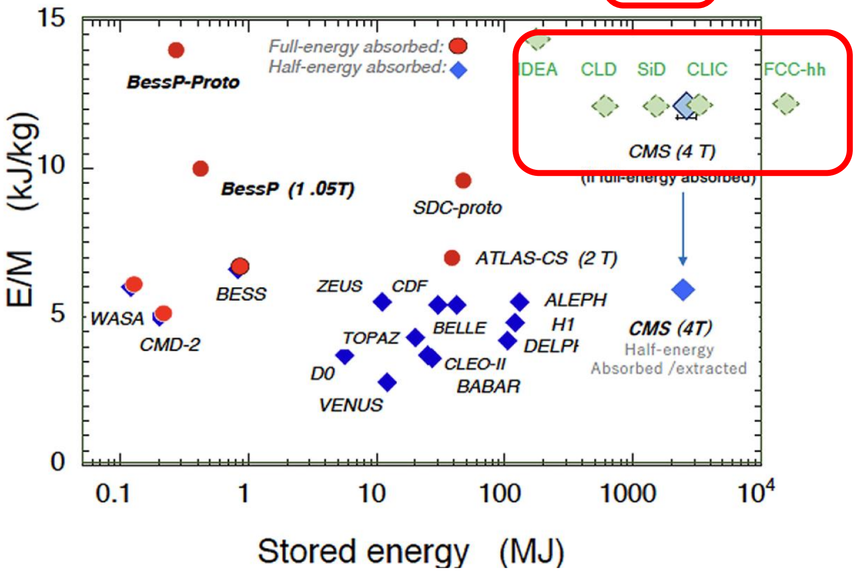
Al-stabilized Superconductor, reinforced, required

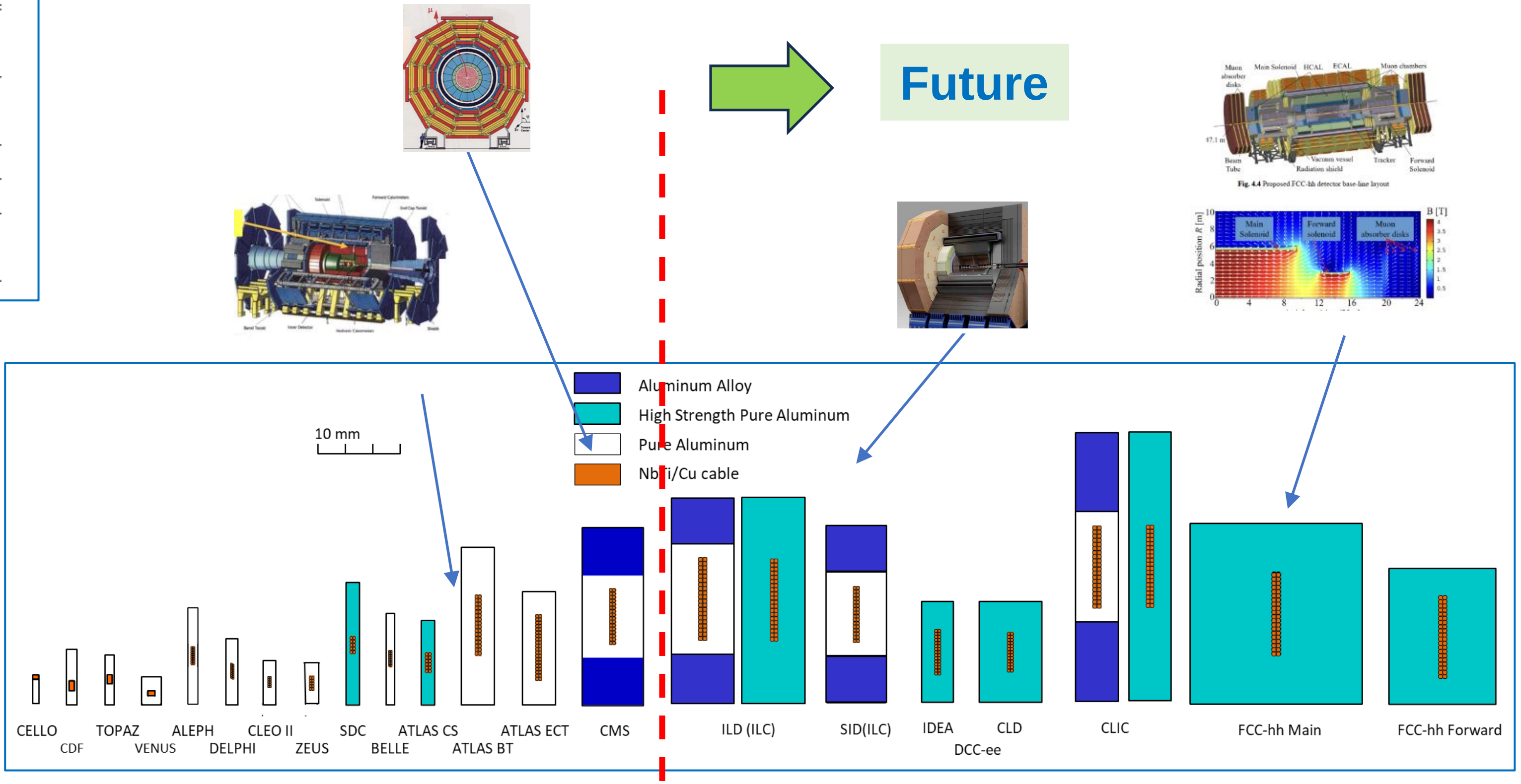
All future solenoids need **Al-stabilized** and reinforced superconductor:

- **Large solenoids → high B** resulting large stored **Energy, and with small Mass**
  → high E/M → reinforcement crucially important

Table 4. The proposed design parameters for the detector solenoids for future projects.

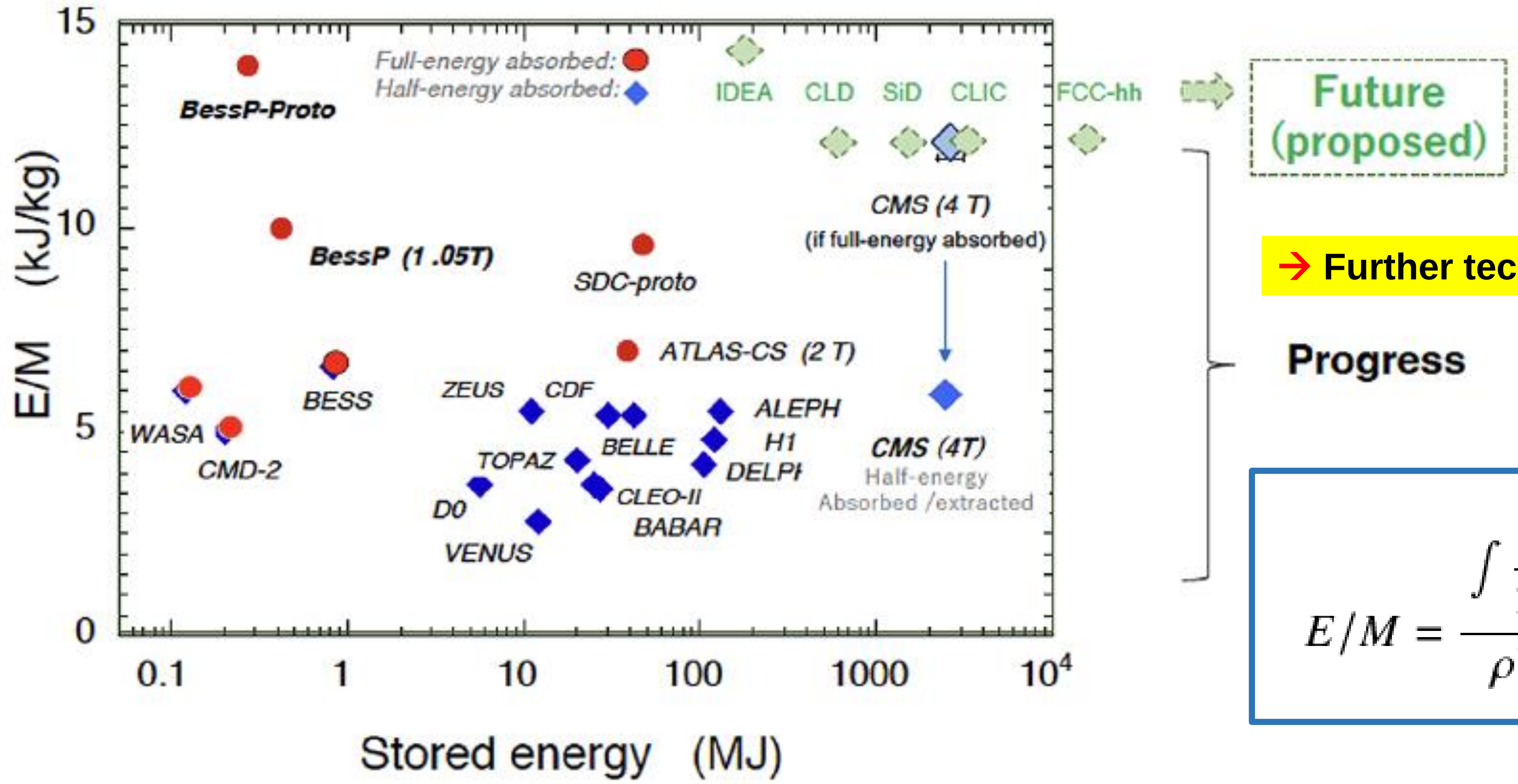
Projects	Magnet	B_c (T)	InnerR (m)	Length (m)	E/M (kJ/kg)	Stored energy (GJ)
FCC-ee	IDEA	2	2.24	5.8	14	0.17
	CLD	2	4.02	7.2	12	0.6
FCC-hh		4	5	20	11.9	13.8
CLIC		4	3.65	7.8	13	2.3
ILC	ILD	4	3.6	7.35	13	23
	SID	5	2.5	5	12	1.4





M. Mentink, K. Sasaki et al., JINST113P 0323 (2023)

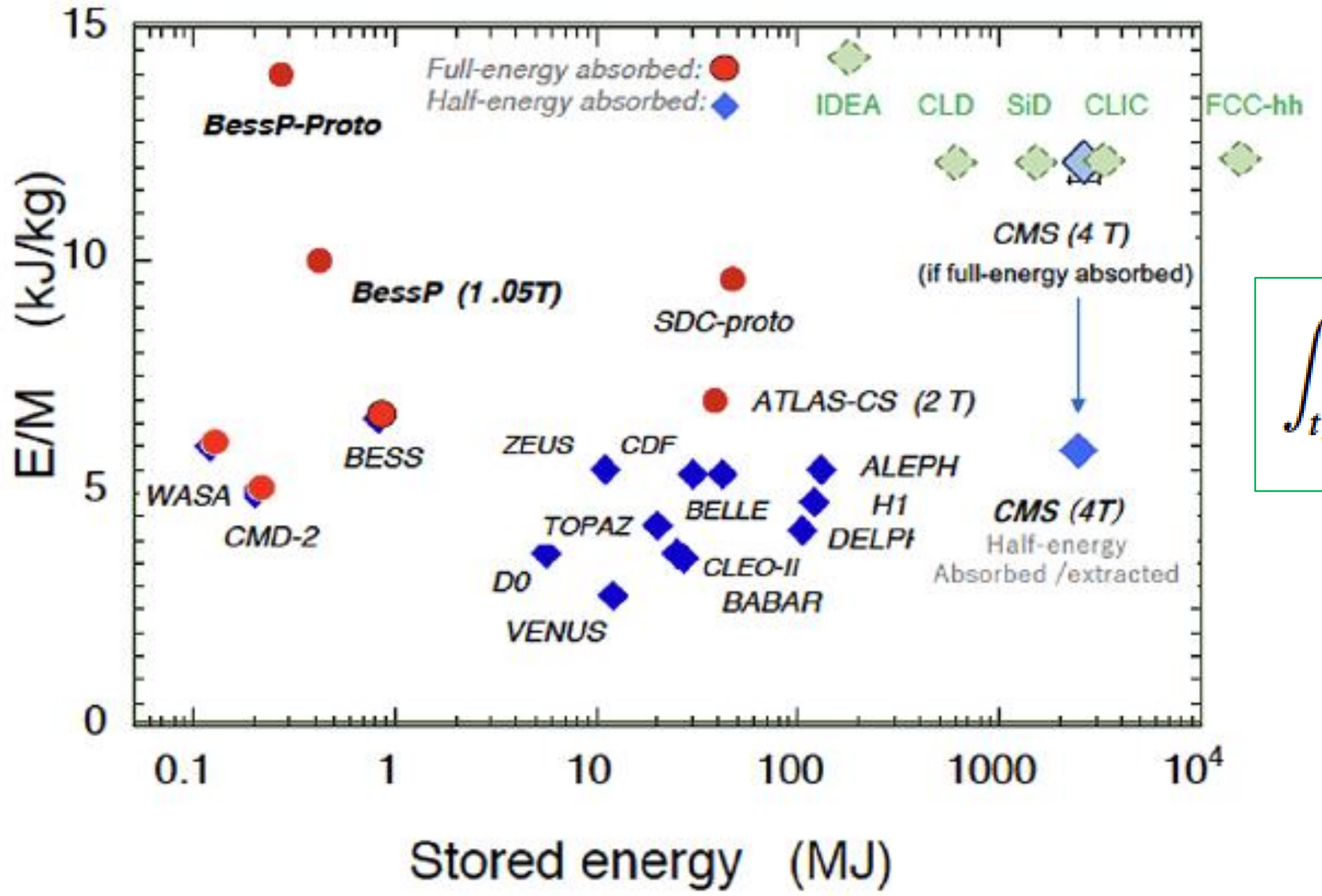
Advances and Prospect in E/M ratio for Future



→ **Further technology required**

$$E/M = \frac{\int \frac{B^2}{2\mu_0} dv}{\rho V_{coil}} = \frac{\sigma_h}{2\rho},$$

Advances and Prospect in E/M ratio for Future



$$t = \frac{B^2}{2\mu_0}\frac{1}{\sigma_h}.$$

$$\int_{t_{quench}}^{t_{end}} j^2 dt = \int_{T_0}^{T_{max}} \frac{C_{p\ ave}}{\rho_{ave}} dT,$$

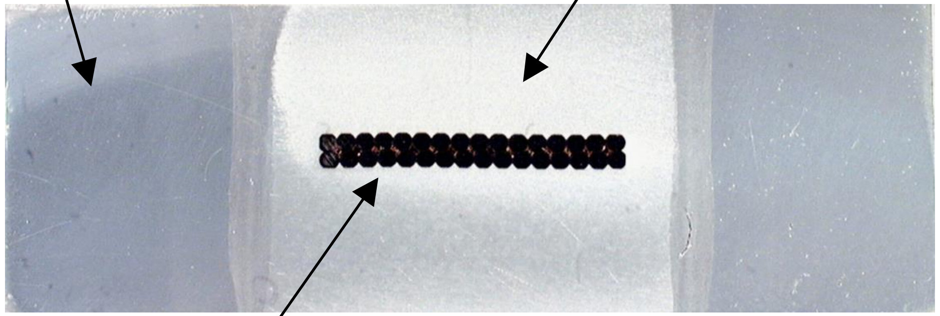
$$E/M = \frac{\int \frac{B^2}{2\mu_0} dv}{\rho V_{coil}} = \frac{\sigma_h}{2\rho},$$

Longer Time-scale: Aluminum-stabilized conductor technology

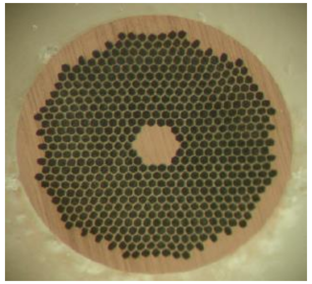
- **The aluminum-stabilized Nb-Ti/Cu (SC) conductor is the traditional workhorse**
  - that is used in nearly all superconducting detector magnets.
- Al-based SC conductors give strong performance needed for SC detector magnets:
  - Significant heat capacity for a given amount of weight
  - Excellent electrical and thermal conductivity at 4 K (pure or nickel-doped aluminum)
  - Very good mechanical properties (nickel-doped aluminum or aluminum-alloy)
  - Affordable, in combination with superconducting Nb-Ti/Cu Rutherford cables

→ **However, in recent years, commercial availability has been an issue**

→ **Can we obtain it? Do viable alternatives exist?**

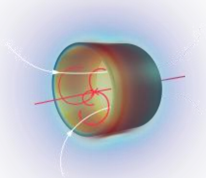


Courtesy: The CMS collaboration



Cross-section of a Nb-Ti/Cu strand used in the CMS conductor (Blau et al, "The CMS conductor", IEEE Trans 2002)

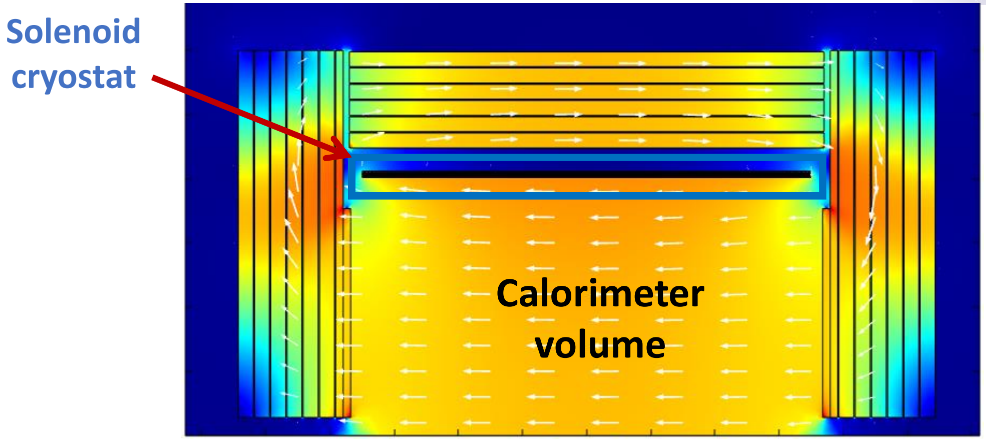
Future Circular Collider FCC-ee: IDEA and CLD



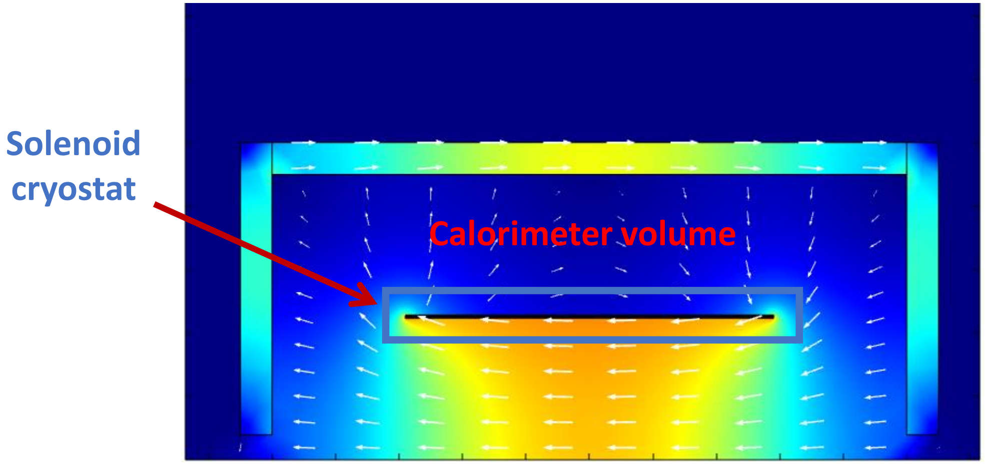
	Detector solenoid #1	Detector solenoid #2
Warm bore diameter [m]	8.0	4.0
Cold mass length [m]	7.0	5.8
Magnetic field in the centre [T]	2.0	2.0
Stored magnetic energy [MJ]	600	170

Magnet parameters

- Presentation by N. Deelen (CERN)
- For the FCC-ee project, proposed to be hosted at CERN, with operation foreseen to start in 2045, featuring electron-position collisions
- Two solenoid types (For “IDEA” and “CLD”) detectors
    - One solenoid, featuring 2 T over a free bore of 8.0 meters, and a cold mass length of 7.0 meters, no transparency requirement
    - One solenoid, featuring 2 T over a free bore of 4.0 meters, and a cold mass length of 5.8 meters, with transparency requirement
- Conductor: Reinforced aluminum-stabilized Nb-Ti/Cu conductor



CLD detector, featuring a 2 T solenoid

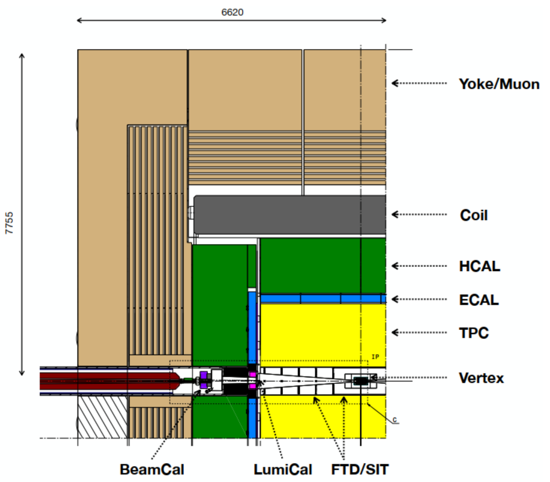


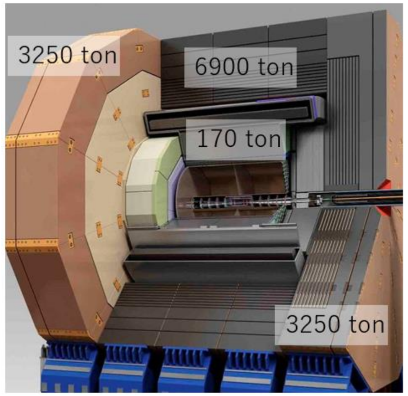
IDEA detector, featuring a transparent 2 T solenoid

International Linear Collider: ILC-ILD

	Detector solenoid
Warm bore diameter [m]	6.9
Cold mass length [m]	7.35
Magnetic field in the centre [T]	4.0
Stored magnetic energy [MJ]	2300

Magnet parameters

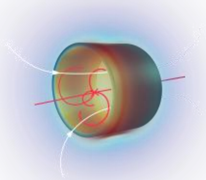




ILC-ILD detector featuring a 4 T superconducting solenoid

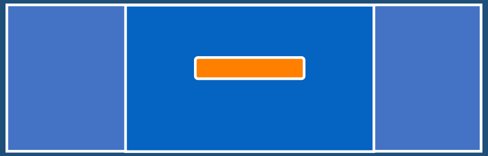
- Presentations by K. Buesser (DESY) and Y. Makida (KEK)
- For the International Linear Collider project, proposed to be hosted in Japan
- Featuring a superconducting solenoid, with 4 T over a 6.9 m warm bore diameter, and a 7.35 m cold mass length, stored magnetic energy of 2300 MJ
- With optional “Detector-Integrated-Dipole” coil wound on top of the solenoid
- Conductor: Foresees to use a reinforced aluminum-stabilized Nb-Ti/Cu conductor

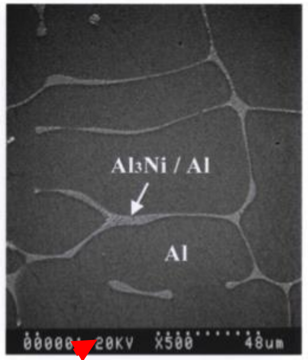
Ultimate effort for maximizing the peroformance



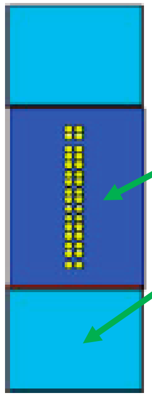
- **Reinforcement of Al**
  - **with keeping low resistivity**
- **Uniform reinforcement**
  - **Micro-alloying and cold work**
  - **ATLAS-CS**

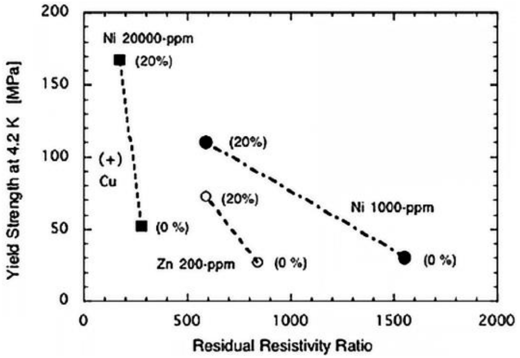
- **Hybrid reinforcement**
  - **Welding Al-Alloy with pure-Al**
  - **CMS**



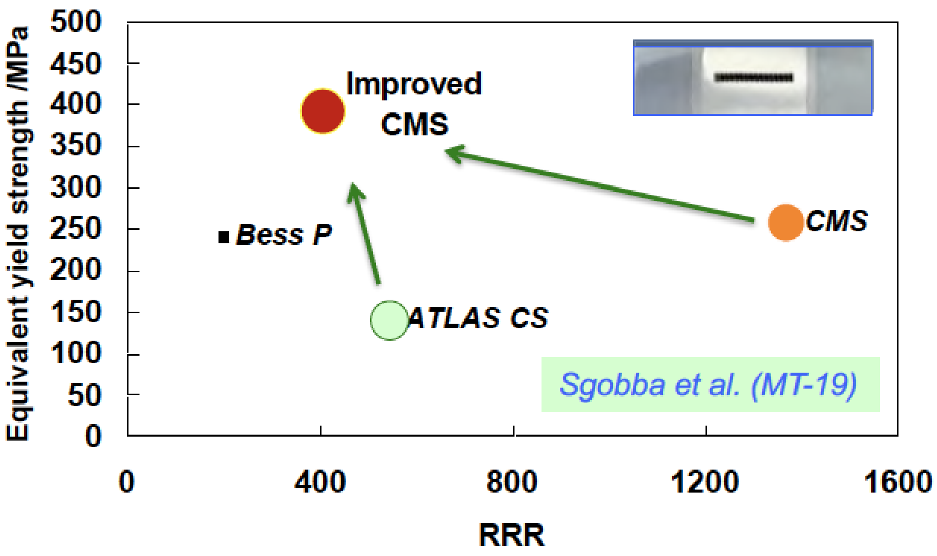


b) Al-0.5wt%Ni Alloy





	Rein-force	Feature	Al Y. S. (MPa)	Full cond. Y.S.	Full cond. RRR
ATLAS-CS	Uniform	Ni-0.1% Al	110 MPa	146 MPa	590
CMS	Hybrid	Pure-Al & A6082-T6	26 / 428	258	(1400)
Future	**Hybrid**	**Ni-Al & A6082-T6**	**110 / 428**	**300**	**400**
Future	**Hybrid**	**Ni-Al & A7020-T6**	**110 / 677**	**400**	**400**



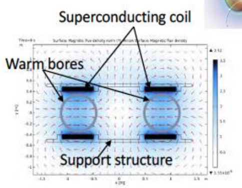
Urgent Near Future Programs :

BabyIAXO

	Detector dipole
Warm bore diameter [m]	2x 0.7
Cold mass length [m]	11
Magnetic field in the centre [T]	2.0
Stored magnetic energy [MJ]	40

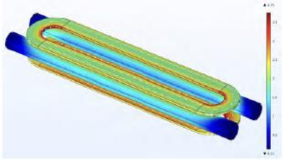
Magnet parameters

BabyIAXO detector

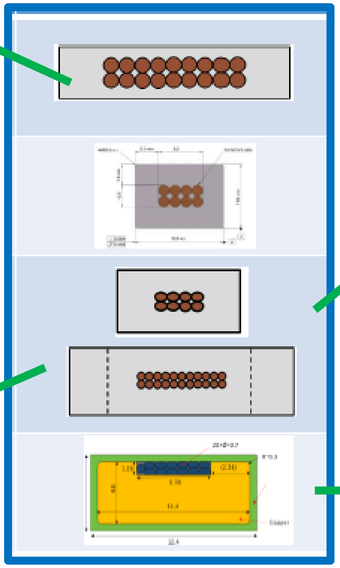


Magnetic field in cross-section

- Presentation by U. Schneekloth (DESY)
- BabyIAXO detector, for studying axions emanating from the sun
- Featuring a superconducting common-coil dipole with a 2 T transverse magnetic field in two 0.7 meter warm bores of 11 meters length
- Conductor: Featuring an aluminum-stabilized Nb-Ti/Cu conductor



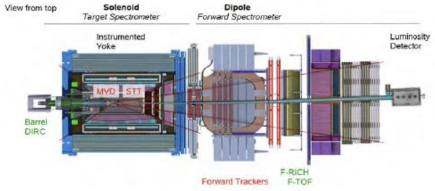
Common-coil dipole, with counter-flowing current in two superconducting race-track coils



The PANDA detector

	Target spectrometer solenoid
Warm bore diameter [m]	1.8
Cold mass length [m]	~3.1
Magnetic field in the centre [T]	2
Stored magnetic energy [MJ]	22

Magnet parameters



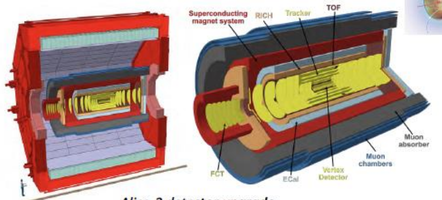
The PANDA detector layout

- Presentation by L. Schmitt (GSI)
- For fixed-target anti-matter physics at FAIR, foreseen to start operation by 2029
- With strong involvement of various Russian institutes, including the Budker Institute of Nuclear Physics
- Featuring a 2 T superconducting solenoid, with a stored magnetic energy of 22 MJ
- Conductor: Aluminum-stabilized Nb-Ti/Cu conductor technology, under development through a R&D effort by Russian institutes and industry (BINP, VNIINM Bochvar, VNIIKP, SARKO)

Alice-3

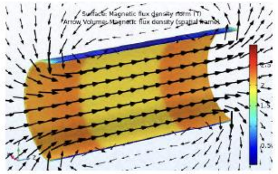
	Detector solenoid
Warm bore diameter [m]	3
Cold mass length [m]	7.5
Magnetic field in the centre [T]	2
Stored magnetic energy [MJ]	130

Magnet parameters



Alice-3 detector upgrade

- Presentation by W. Riegler (CERN)
- Planned to be installed by LS4 (which is currently foreseen to start in 2033)
- Featuring a superconducting solenoid, with 2 T in the center and additional windings at the end to augment bending power for high-pseudo-rapidity particles
- Also featuring a forward (superconducting) dipole
- Conductor: Proposal to use a reinforced aluminum-stabilized conductor



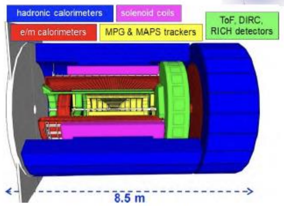
Magnetic field configuration

The Electron-Ion Collider

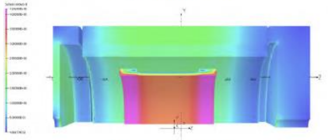
	Detector solenoid #1	Detector solenoid #2
Warm bore diameter [m]	2.8	3.2
Cold mass length [m]	3.5	3.6
Magnetic field in the centre [T]	2.0	3.0
Stored magnetic energy [MJ]	46	~150

Magnet parameters

- Presentation by R. Rajput-Ghoshal (Jefferson Lab)
- For the Electron-Ion Collider project to be hosted at BNL, with full project finalization foreseen by 2034
- Two superconducting detector solenoids, for two interaction points:
  - #1: 2 T in solenoid with a 2.8 meter warm bore diameter and a 3.5 meter cold mass length
  - #2: 3 T in solenoid with a 3.2 meter warm bore and a 3.6 meter cold mass length
- Conductor:
  - Solenoid #1, initial preference for reinforced aluminum-stabilized Nb-Ti/Cu, but copper-stabilized conductor can work as well
  - Solenoid #2, a reinforced aluminum-stabilized Nb-Ti/Cu conductor is foreseen



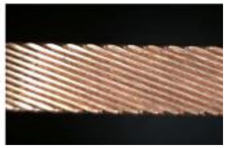
Detector solenoid #1



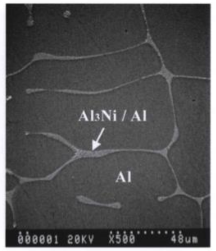
Detector solenoid #2

Al-Stabilized SC Technology to be re-established

- **NbTi/Cu SC and Cable production: remaining:**
  - SC strand: industry
  - Cable: CERN, FNAL, LBNL, and industry*.

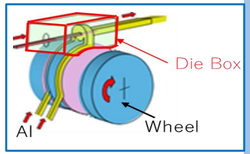


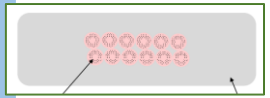
- **Al-stabilizer reinforcement remaining:**
  - with micro-alloying and cold work remain feasible
  - Industrially available in Japan.

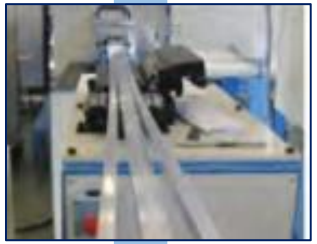


b) Al-0.5wt%Ni Alloy

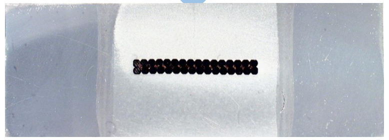
- **Al-NbTi/Cu co-extrusion technology :disappearing:**
  - All the experienced industrial facilities have been shut-downed and dismantled,
  - Toly E. (in China) started the development with aiming for the CEPC detector solenoid. The progress sounds promising and needs to watch further progress.
  - The technology shall be widely transferred to the industry to maintain production capability







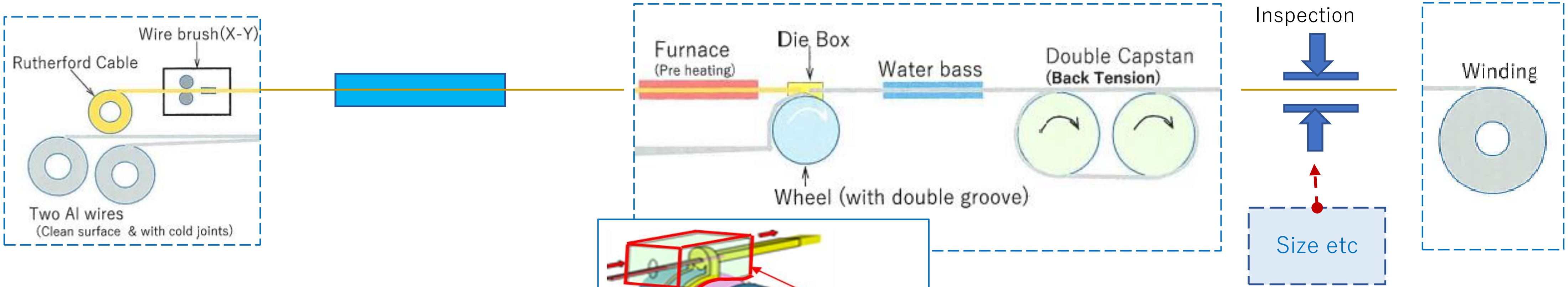
- **EBW for conductor reinforcement: remaining:**
  - Technology kept at TECHMETA in France

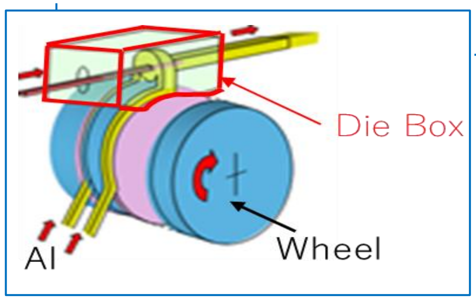


Courtesy; Toly and Hitachi

A Critical Issue: Co-extrusion for Al-stab.SC

NbTi/Cu cable Al-wire	Brushing (x, Y)	U-Sonic Cleaning	Pre-heating	Co-extrusion	Water-cooling	D-capstan or Caterpillar	Winding / Spooling	Inspection QA





- All experienced supplier's facilities **shut-down in past 10 years**

- Except for A company, **Toly Electric,** in China, is starting new R&Ds (for CEPC?)
- We need to prepare for other capabilities

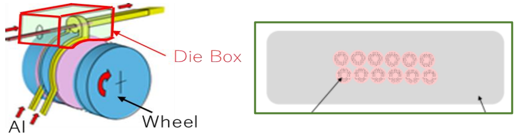
We need to action it, NOW ?

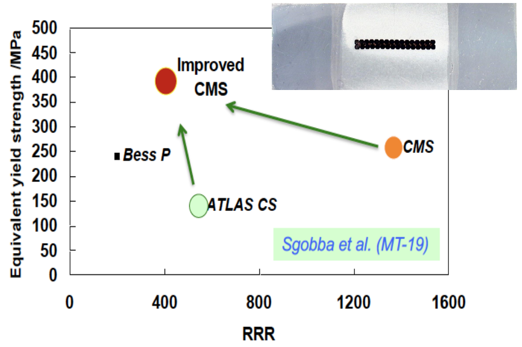
Urgent Action Required:

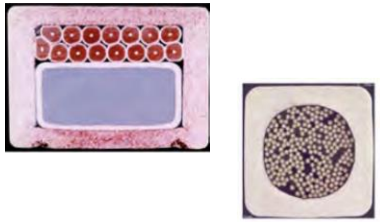
- **Al-stabilized superconductor technology** needs to be resumed,
  - **"Co-extrusion technology"** of Al-stabilizer to be resumed, and
  - "Hybrid-structure technology" by using electron beam welding (EBW)
  - **Laboratory's leading effort very important** to advance the technology
- CERN is now working for establishing a program on coextrusion process for Al-stab SC with institutional and industrial partners.

Remarks:

- It will be **needed** to investigate **backup solutions** such as:
  - soldering technology of NbTi/Cu conductor with Cu-coated Al-stabilizer, and/or CICC. ,,,
- It will be encouraged to investigate Al-stabilized HTS for specofoc applications



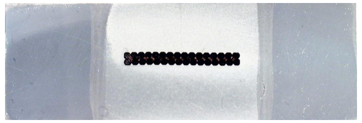


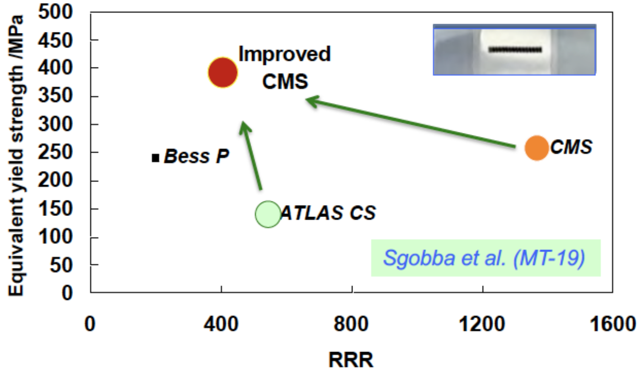


Future Direction and Back-up/Alternate SC Solutions

Issue: Al-stabilized Superconductor:

- No industrial production available, as current status,
- Development to be resumed
  Urgent requests from EIC, BabyIAXO, …
- Laboratory-Industry cooperation inevitable. For
  - **Co-extrusion** technology and/or
  - Soldering technology as backup

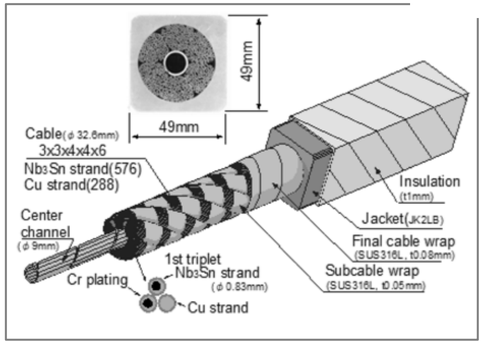




Back-up Solution: Alternate Superconductor :

Conductor-In-Conduit-Conductor (CICC)

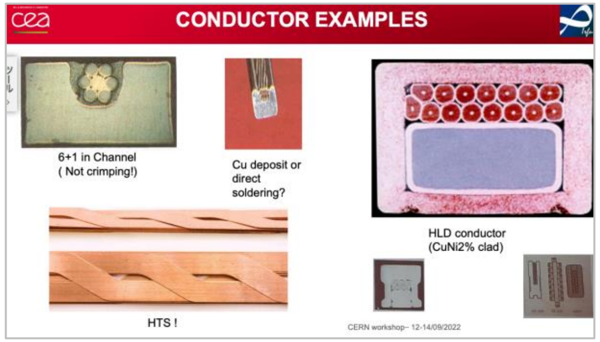
- It may be applicable in most detector solenoid design, if no request of “transparency”.
- A proposal to apply CICC to ILC-SiD, with no request for ”transparency”.
- It is Important to study the feasibility, and to learn experiences integrated in the ITER project.



WIC: (Wire-in Channel)

High Temperature Superconductor (HTS)

- HTS application proposed by AMS-100,
- The feasibility to be investigated.



Outline

- **Introduction :**
  - Future Colliders, relying on Superconducting (SC) Technology
- **SC Technology for Colliders:**
  - Superconducting RF Cavities (Acc. Structure)
  - Superconducting Magnets
- **Superconducting Detector Magnets (SC-DM)**
- **Summary**

Summary

- **Acc. SRF Technology :**
  - **Nb-bulk** (for > 1 GHz) :High-G (> 45 MV/m) and High-Q (> 3E10) w/ optimizing the surface process, High-G (> 50 MV/m w/ travelling wave SRF
  - **Thin-Film** (to be combined with Nb → Cu substrate) : New material such as NB_3Sn to improve performance to reach > 50 MV/m .
- **Acc. Magnet Technology:**
  - **Nb_3Sn** toward **14 + (toward 16) T,** w/ higher Jc, **mechanical property**, field quality, training quenches,,
  - **Nb_3Sn + HTS-insert**" be inevitably required, for **16 T and beyond**, and cost effective HTS will be essentially required for practical accelerator applications.

- **Detector Magnet Technology :**
  - **Al-stabilized superconductor technology** needs to be revived, and urgently required !
  - **CERN** is acting to **re-establish the technology** in close cooperation with industry. → *Talk by B. Cure.*
  - Conduction cooling technology is another important concept for particle detector to minimize particle interaction in the SC magnet system.
  - Alternate technologies need to be investigated, depending on the time constraint.

Superconducting technology is essential for Future Colliders & Detectors !!

Reserved

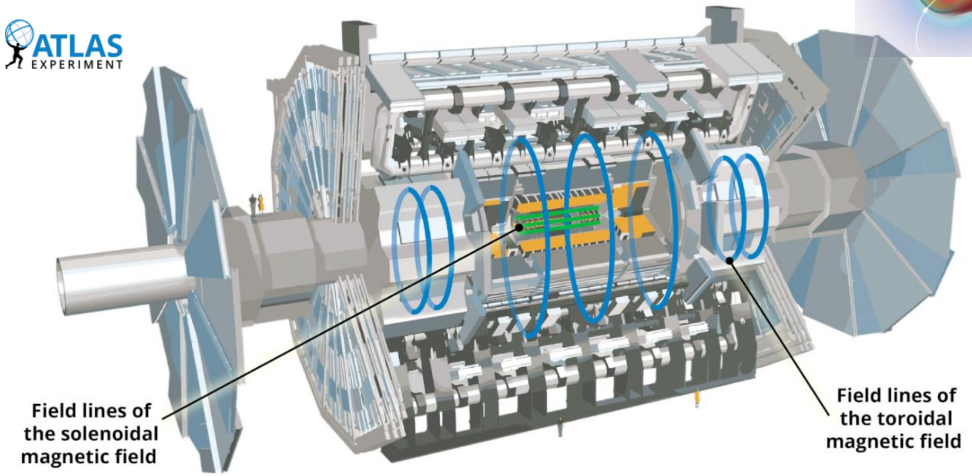
Background: Historical experiences of the ATLAS and CMS magnet projects

Very large superconducting detector magnet projects!

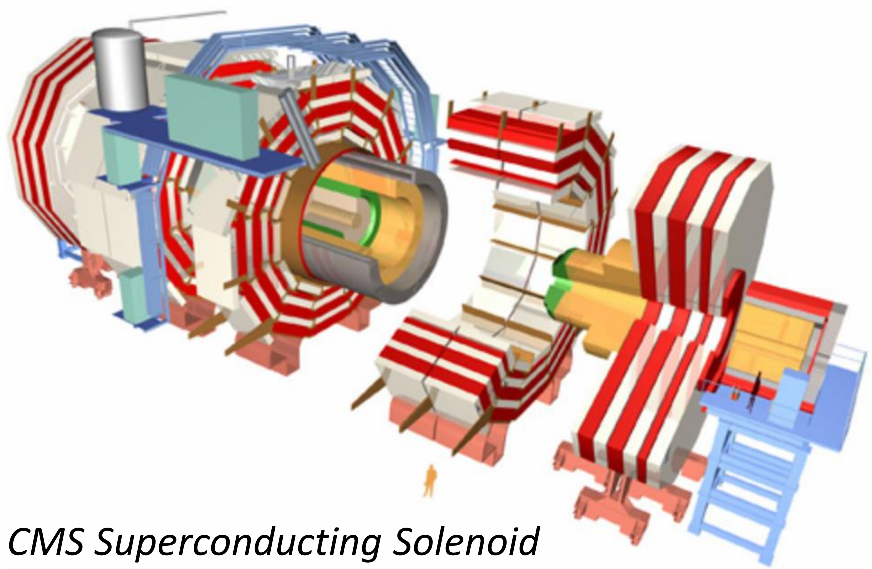
- Time-scale for engineering design and validation effort, the construction, and the commissioning: More than 15 years each
- Production of components (conductor, coils, support structure, etc) in industry, and subsequent assembly at CERN
- Designed, constructed, commissioned, and maintained with strong support from multiple institutes:
  - ATLAS: CEA-Irfu, KEK, INFN-LASA, RAL, NIKHEF, JINR-Dubna, IHEP-Protvino, ITAM Novosibirsk, CERN
  - CMS: CEA-Irfu, ETH Zurich, INFN Genoa, University of Wisconsin, Fermilab, ITEP Moscow, CERN

Important lessons:

- For large superconducting detector magnets a long-term strategy is needed
- **The historical importance of collaboration is evident**



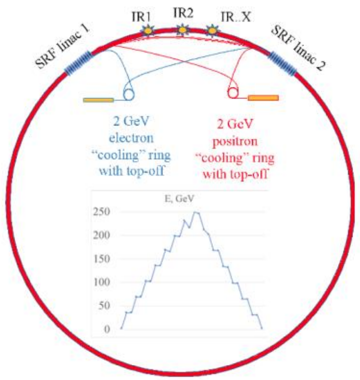
ATLAS Superconducting magnets

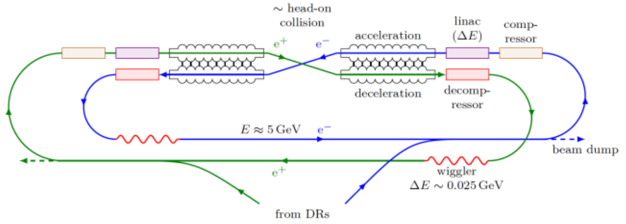


CMS Superconducting Solenoid

Higgs Factory Summary (from Snowmass)

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC[3] (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC[1,3] (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC[3] (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory[3]	0.13	0.01	>10	19-24	4-7	200





T. Roser et al, https://iopscience.iop.org/article/10.1088/1748-0221/18/05/P05018