Superconducting Technology for Accelerators Frontier

-- High-Field Magnet, SRF, and Cryogenics/Cryogen –

Akira Yamamoto
(KEK and CERN)

with special thanks to

E. Todesco, G. Apollinari, G. Ambrosio, A. Zlobin, Q. Xu, M. Ross, Y. Zhai, and S. Belomestnykh

for their kind cooperation

To be presented at HKUST IAS HEP Conference,
Hongkong, Feb.15 2023

Outline

- Introduction:
- Superconducting High-Field Magnet (HFM)
- Superconducting RF (SRF)
- Cryogenics / Cryogen
- Summary

Future Colliders based on SC Technology

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

Linear Colliders:

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) for energy frontier with compactness

Circular Colliders :

FCC-e+e- (90 → 350 GeV):

- **SRF:** with staging for efficient energy extension
    - Synchrotron radiation (SR) to determine the energy
- Highest luminosity at Z and H,

FCC-pp (100 TeV):

- High-field SC magnets (SCM: **16 T**) for energy frontier
- **SRF:** for acceleration for good energy balance w/ SR

CEPC e+e- (240 GeV):

- **SRF:** for acceleration,
    - Synchrotron radiation to determine the energy

SPPC- pp (75 - 125 TeV):

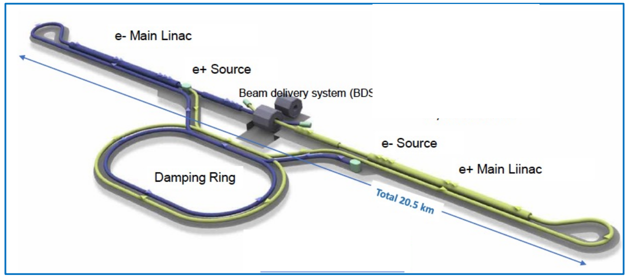
- High-field SCM (**12 -20** T) for energy frontier
- **SRF:** beam acceleration

EIC Ion•e-(275/100 GeV/n v.s. 18 GeV, under constr.)

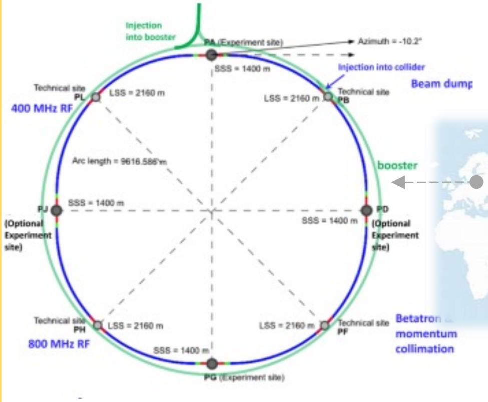
- **SCM and SRF**

MC μ+μ– (3 – 14 TeV)

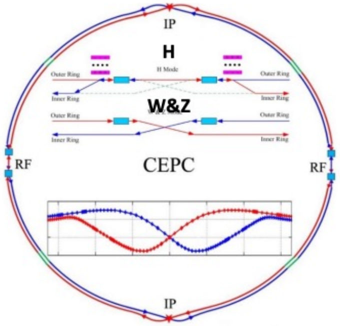
- SRF and NRF with very high-field SCM
- Higher efficiency at > 3 TeV, although short life-time.



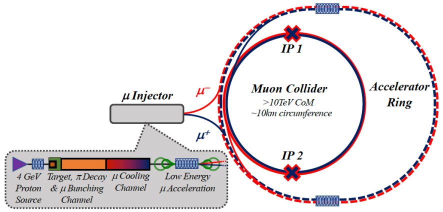
ILC



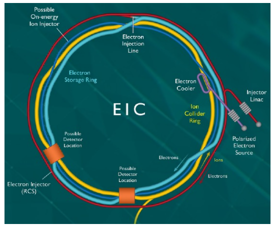
FCC-ee/-hh



CEPC/SPPC



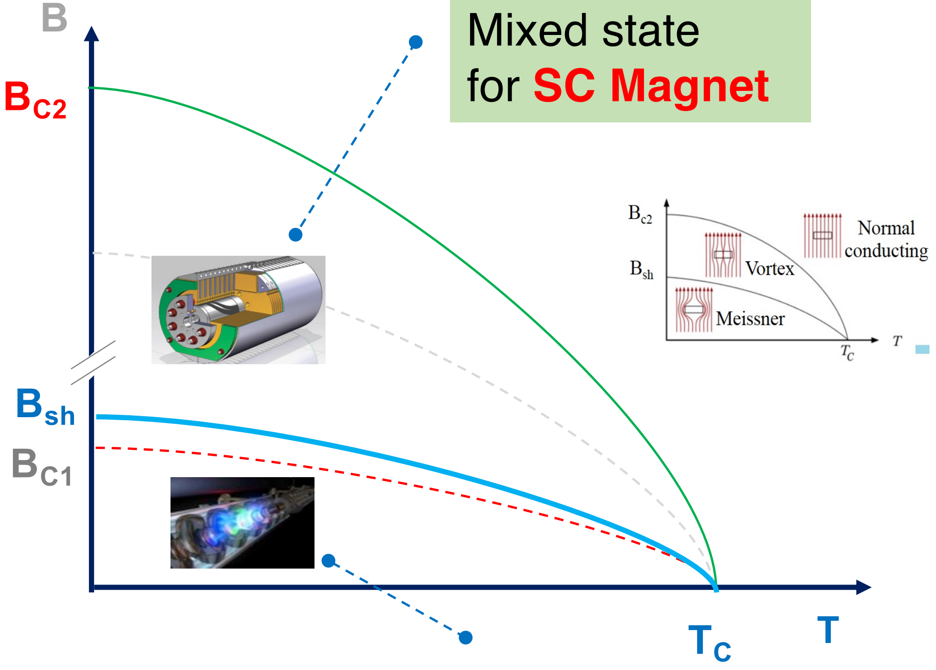
MC



EIC

Superconductor Applications for Accelerator Magnet and RF

Material	T_c [K]	$B_c(0)$ [T]	$B_{c1}(0)$ [T]	$B_{sh}(0)$ [T]	$B_{c2}(0)$ [T]
Nb	9.2	(0.25)	0.18	0.21	0.28
NbTi	~ 9.3	--	0.067	--	11.5 ~ 14
Nb_3Sn	~ 18.3	(0.54)	(0.05)	0.43	28 ~30
Application				RF	Magnet



Mixed state for **SC Magnet**

Meissner state For **SRF**

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Advances in SC Magnets for Accelerators

Past:
- ISR-IR
- Tevatron (Fermilab)
- TRISTAN-IR (KEK)
- HERA (DESY)
- Nuclotron (JINR)
- LEP-IR (CERN)
- KEKB-IR (KEK)

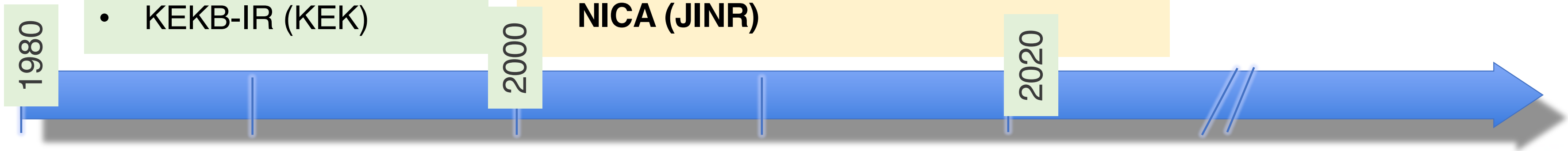
Present:
- **RHIC (BNL)**
- **LHC (CERN)**
- **SRC (RIKEN) …..** *SC-Cyclotron*

Under Construction
- **FAIR (GSI) ………** *Fast-cycle Shinchr.*
- **HL-LHC (CERN)**

NICA (JINR)

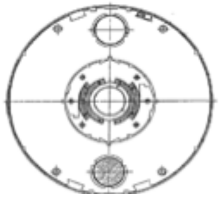
Future:
- **EIC (e-Ion)**

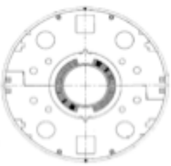
- **FCC-hh** / HE-LHC
- **SppC**

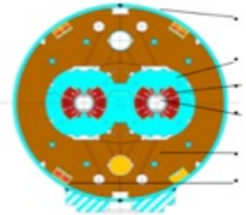


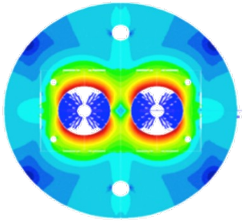
Dipole

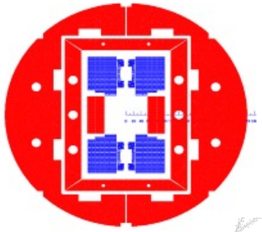

Tevatron-D.


HERA-D.

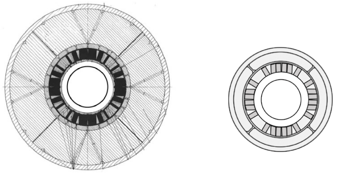

RHIC-D.

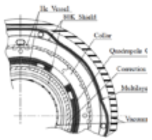

LHC.D (NbTi)

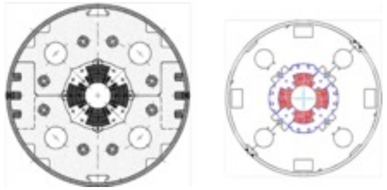

(FCC/-hh (Nb_3Sn))

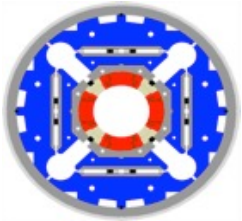

(SPPC (IBS))

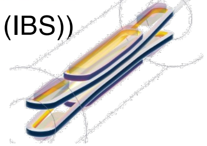
IR Quad.


ISR-IRQ, LEP-IRQ


TRISTAN/KEKB-IRQ


LHCC-IRQ (NbTI)


HL-LHC-IRQ (Nb_3Sn)


Insert (HTS)

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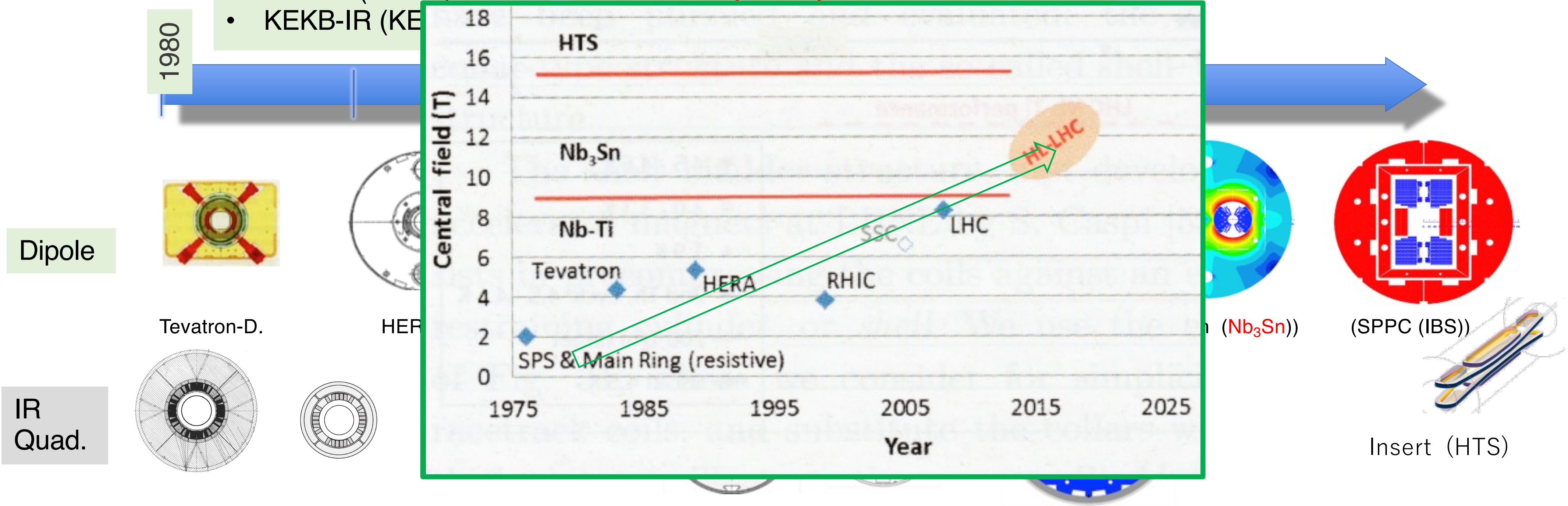
- **SppC**



ISR-IRQ, LEP-IRQ

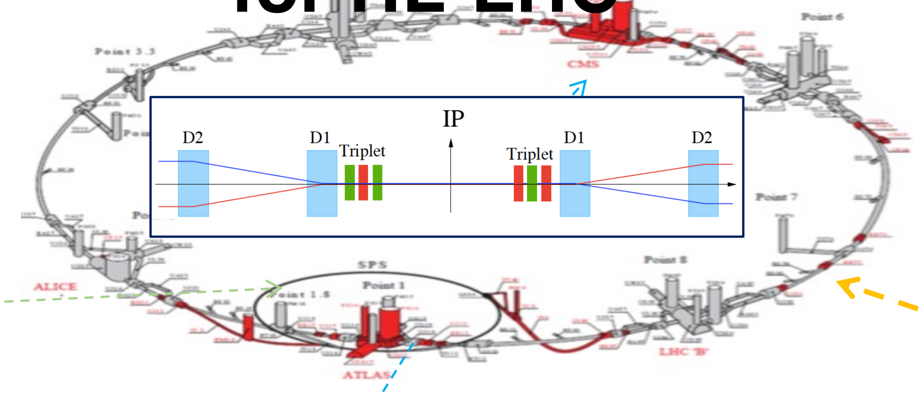
TRISTAN/KEKB-IRQ

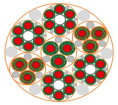
LHCC-IRQ (NbTI)

HL-LHC-IRQ (Nb$_3$Sn)

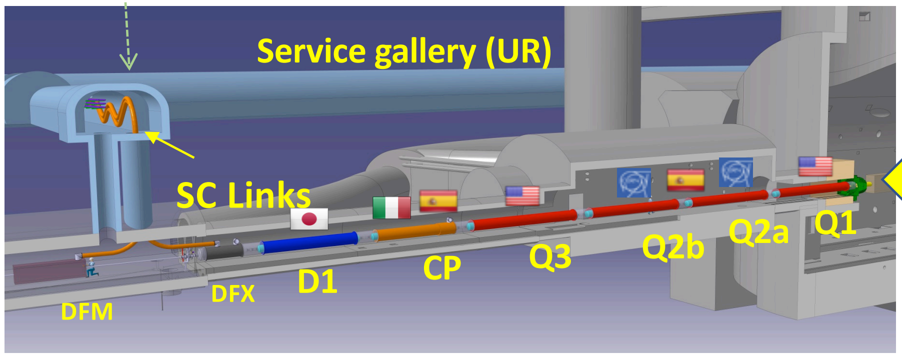
Courtesy, L. Rossi

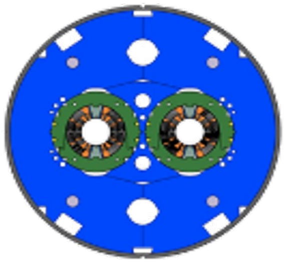
Nb$_3$Sn Superconducting Magnets, and MgB$_2$ SC Links for HL-LHC



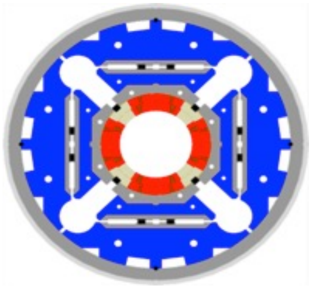


Supercond. Link; MgB$_2$

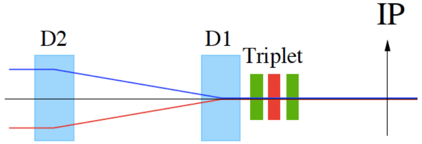




11t Dipole: Nb3Sn (postponed)



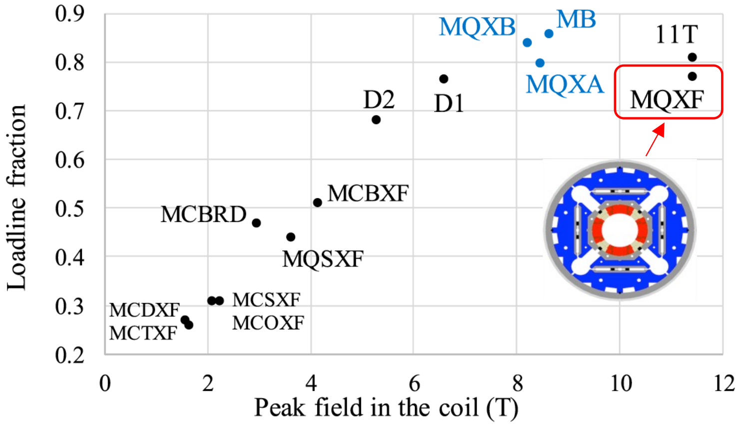
Quad. (MQXF): Nb3Sn,

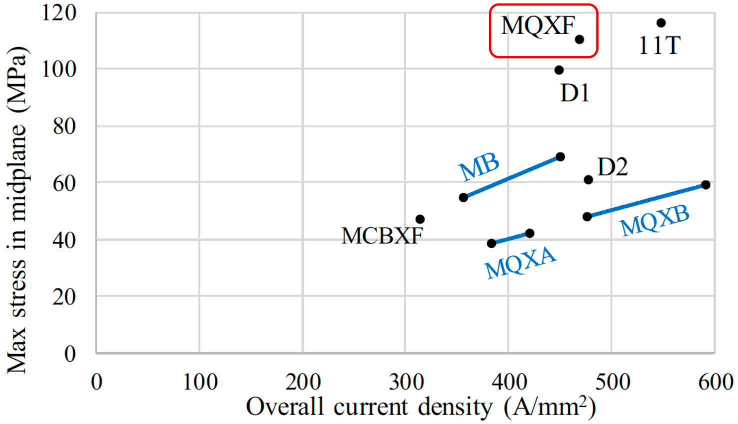


E. Todesco etl., SUST 34 (2021) 053001

HL-LHC IR Triplet (Q1~3) Parameters

Name:		**Q1/Q3**	**Q2**
Length	(m)	4.2	7.2
Coil design			
N. layers		2	
N. turns/pole		50	
Cable length/pole	(m)	431	721
Operational parameters			
Peak field^{f}	(T)	11.4	
Temperature	(K)	1.9	
Current	(kA)	16.230	
j overall^{g}	$(\mathrm{A\ mm}^{-1b})$	462	
Loadline fraction^{h}	(adim)	0.77	
Temperature margin	(K)	5.0	
Stored energy/m	$(\mathrm{MJ\ m}^{-1})$	1.17	
Inductance/m	$(\mathrm{mH\ m}^{-1})$	8.21	
Stored energy^{i}	MJ	4.91	8.37

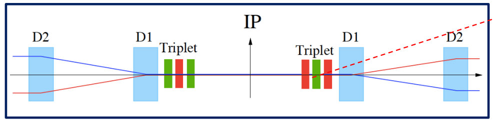


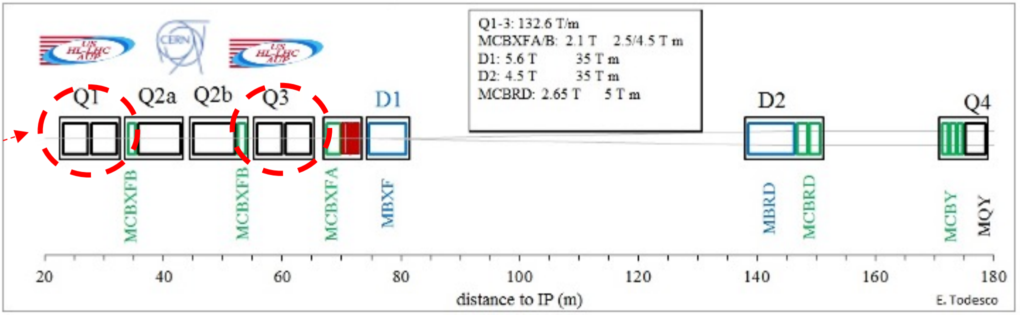


Courtesy: E. Todesco, G. Apollinari, G. Ambrosio

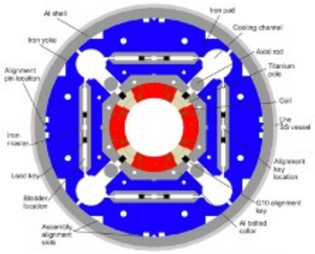
MQXFA (4.2 m) Series Production in Progress
Overview

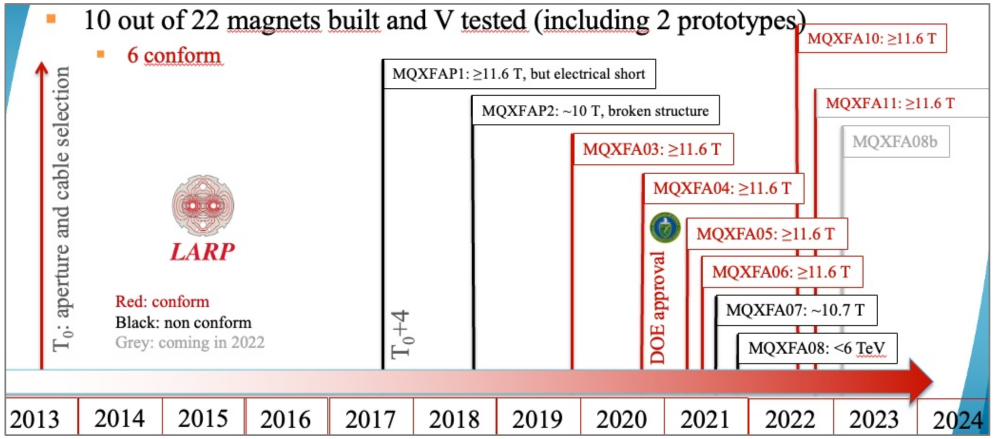
Series production:
2 x 2 x 4 + 4 = 20





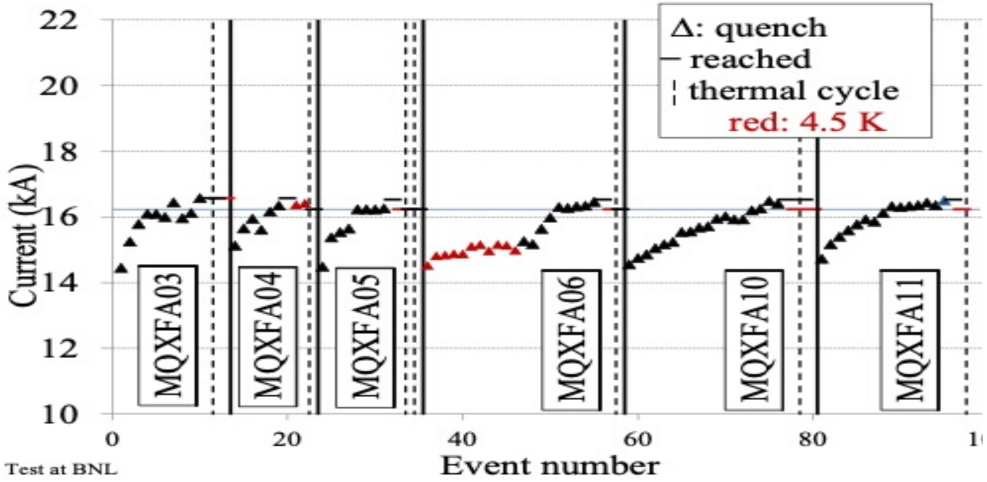
Q1-3: 132.6 T/m
MCBXFA/B: 2.1 T 2.5/4.5 T m
D1: 5.6 T 35 T m
D2: 4.5 T 35 T m
MCBRD: 2.65 T 5 T m





- 10 out of 22 magnets built and V tested (including 2 prototypes)
  - 6 conform

Red: conform
Black: non conform
Grey: coming in 2022

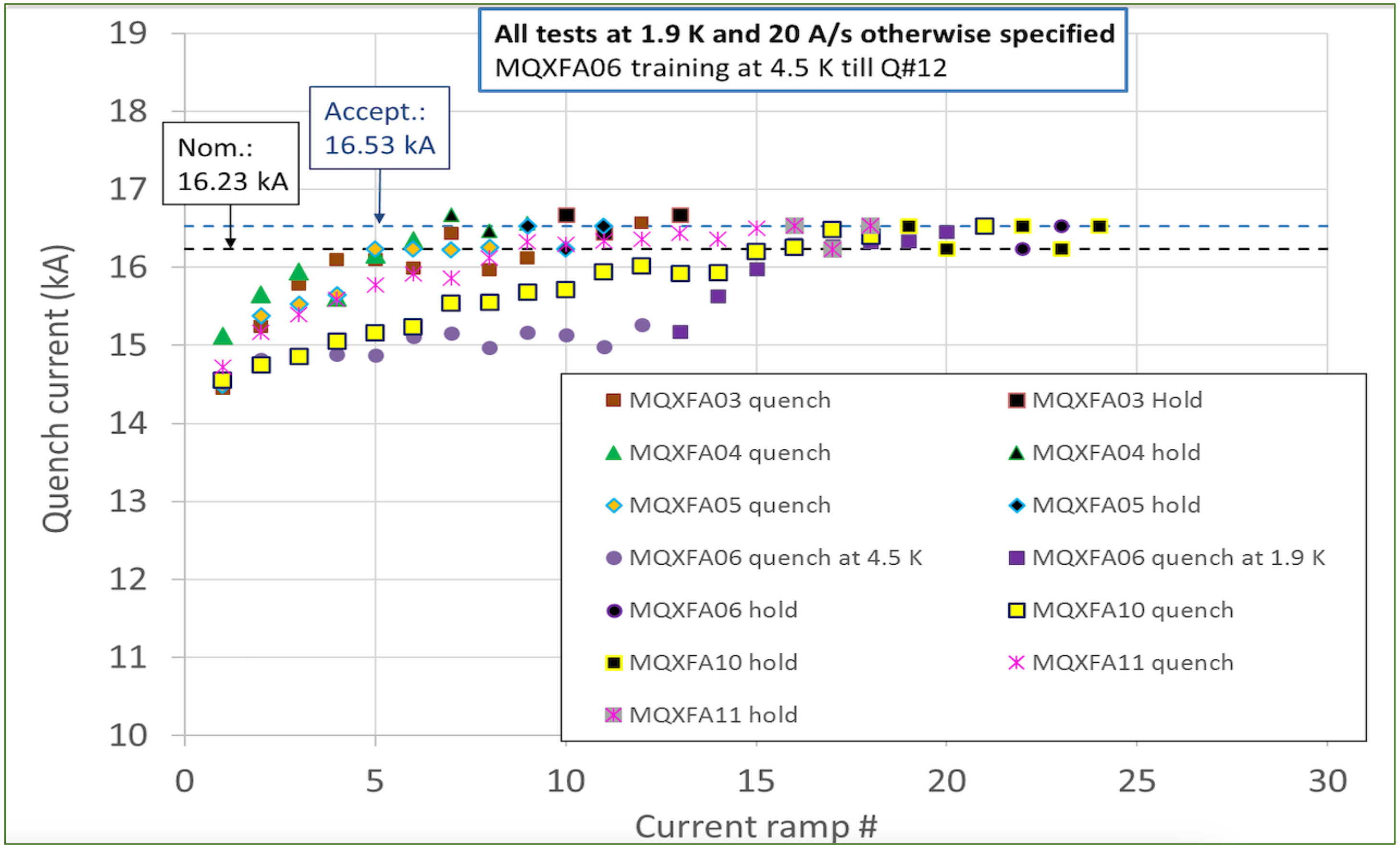


6 (out of 20) series-production magnets have been successfully completed.

Courtesy: G. Ambrosio et al.,

MQXFA (4.2 m) Series Production in Progress

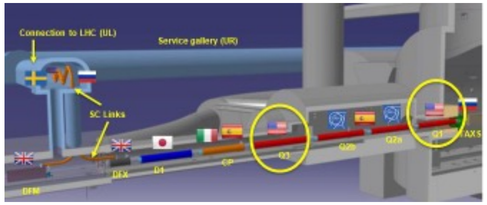
6 MQXFA magnets **reached the ultimate currents** and records of training quenches.



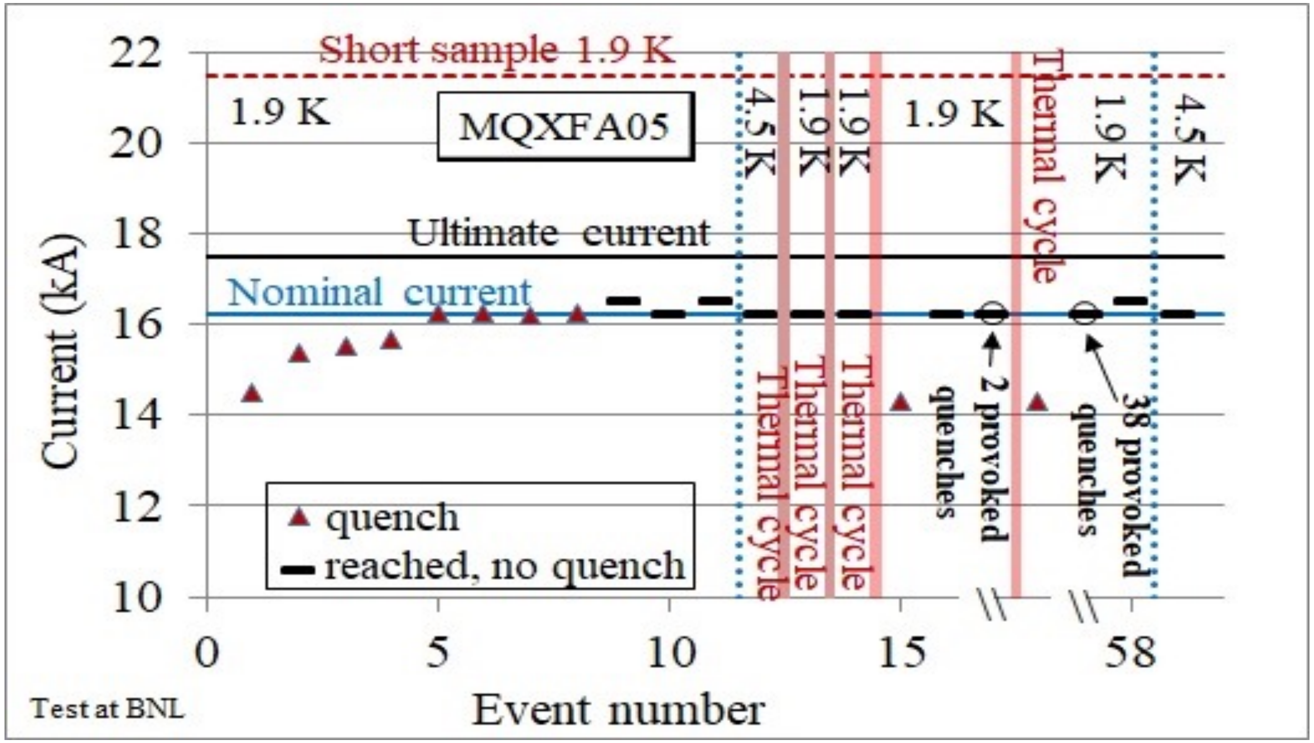
Courtesy: US HL-LHC AUP
G. Apollinari, G. Ambrosio et al.,

MQXFA05 (4.2 m) Endurance Tests

- **MQXFA** (w/ no LHe vessel) **successfully performed** the **endurance tests**,
- **No degradation** observed after **5 thermal ycles** and **50 quenches.**

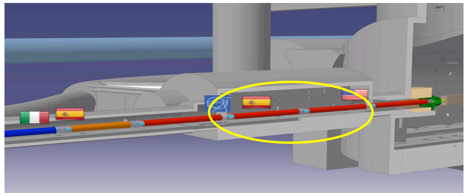


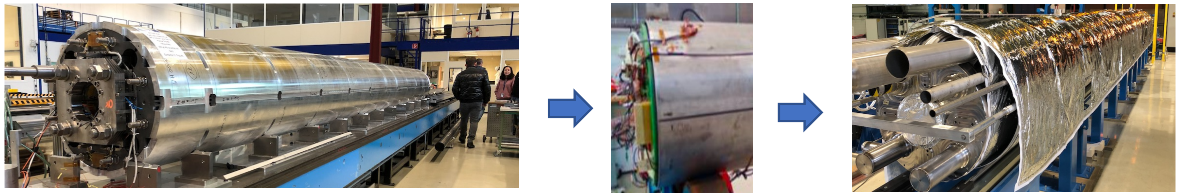
The MQXFA05 magnet enters the vertical cryostat at the Brookhaven National Laboratory for its endurance test (Image: BNL)



MQXFB02 (7.2-m) reached the Success

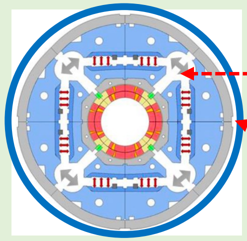
Courtesy: CERN HL-LHC-WP3
E. Todesco, S. Izquierdo Bermudes et al.



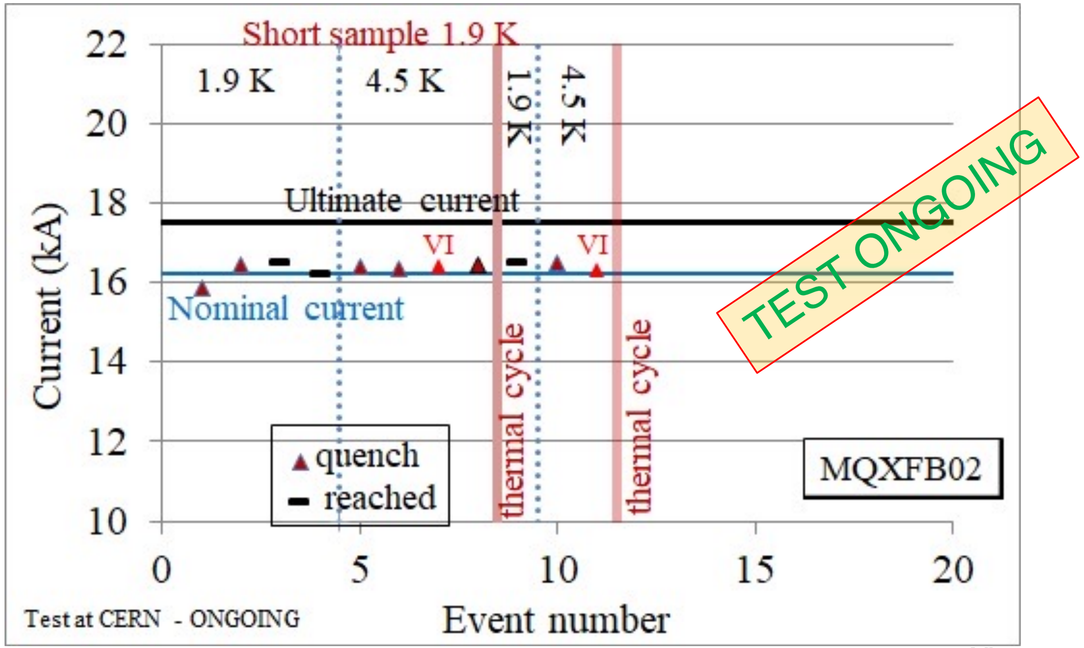


- MQXFB02 (QC improved) reached the **nominal plus 300 A** in the 1st powering cycle after **2 training** quenches.

- A new procedure was implemented to reduce the peak stress down to < **100 MPa,** during the magnet assembly
  - Note: succesful **short models** were asselbmed with peak stresses up to 140 MPa.
- LHe vessel welding procedure to minimize longitudinal friction/stress during thermal cycle.



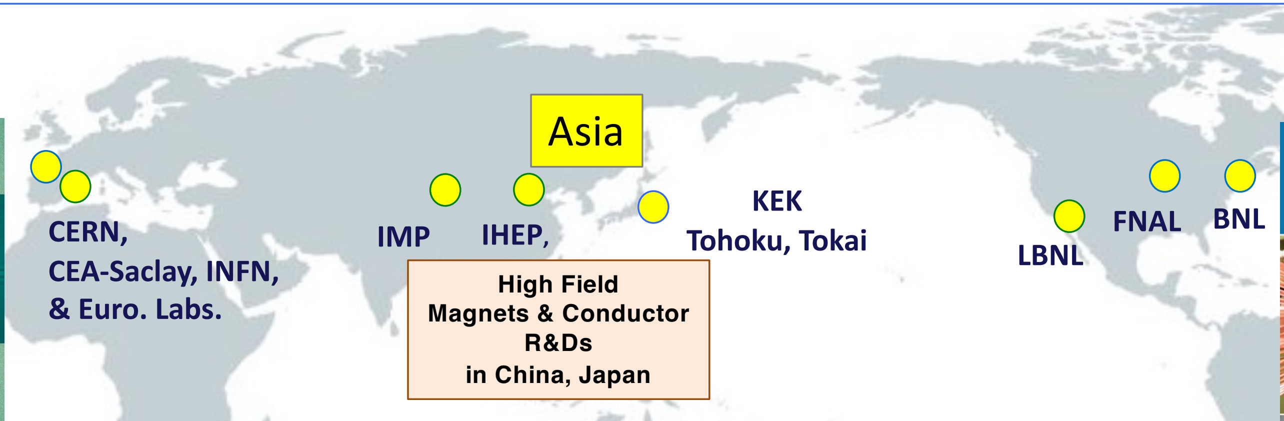
- New **bladders** implemented for magnet assembly,
- **SS-shell** with less friction to Al-shall



Global Efforts for High-Field SC Magnets for Future Energy Frontier Programs

Europe

CERN-LDG,
HF-Magnet WG



Asia

CERN,
CEA-Saclay, INFN,
& Euro. Labs.

IMP

IHEP,

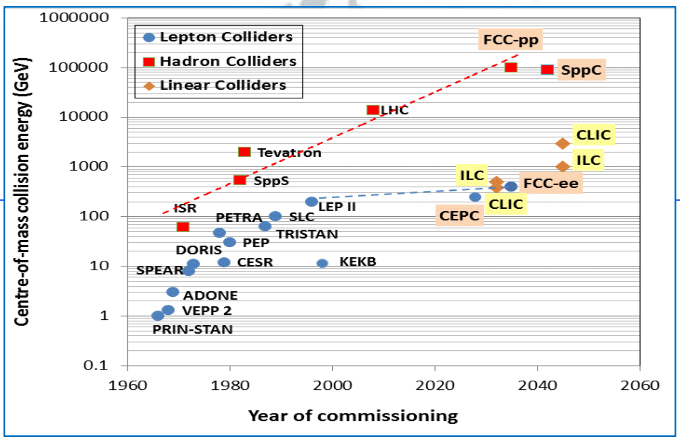
KEK
Tohoku, Tokai

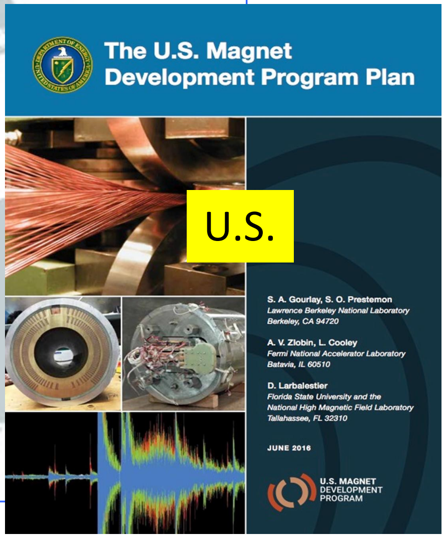
LBNL

FNAL

BNL

High Field
Magnets & Conductor
R&Ds
in China, Japan





The U.S. Magnet Development Program Plan

U.S.

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D. Larbalestier
Florida State University and the
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Tallahassee, FL 32310

JUNE 2016

U.S. MAGNET DEVELOPMENT PROGRAM

US-DOE Magnet Development Program

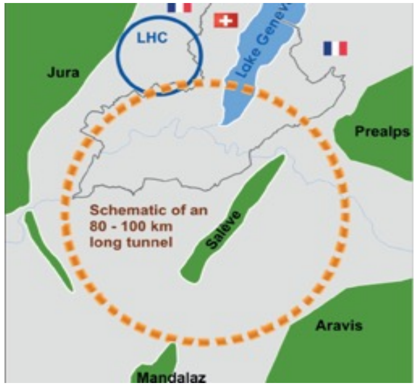
Courtesy, M. Benedikt, A. Siemko, D. Tommasini, S. Prestemon, A, Zrobin

Approaches for High Field Dipole Magnets

FCC

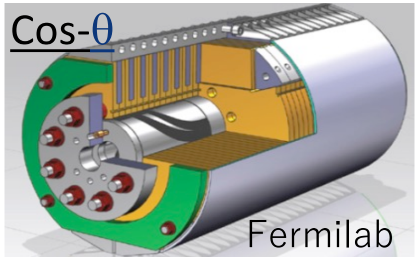
16 Tesla magnets

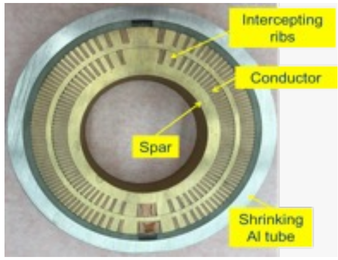
100 TeV c.o.m.

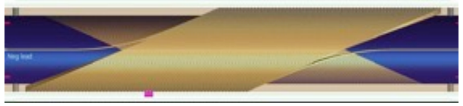


U.S. MAGNET DEVELOPMENT PROGRAM

Cos-θ







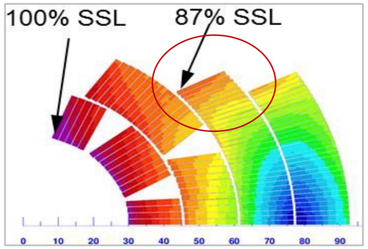
CCT,

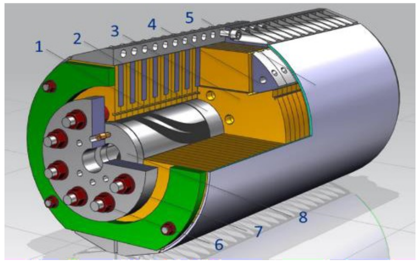
Pioneering work at LBNL

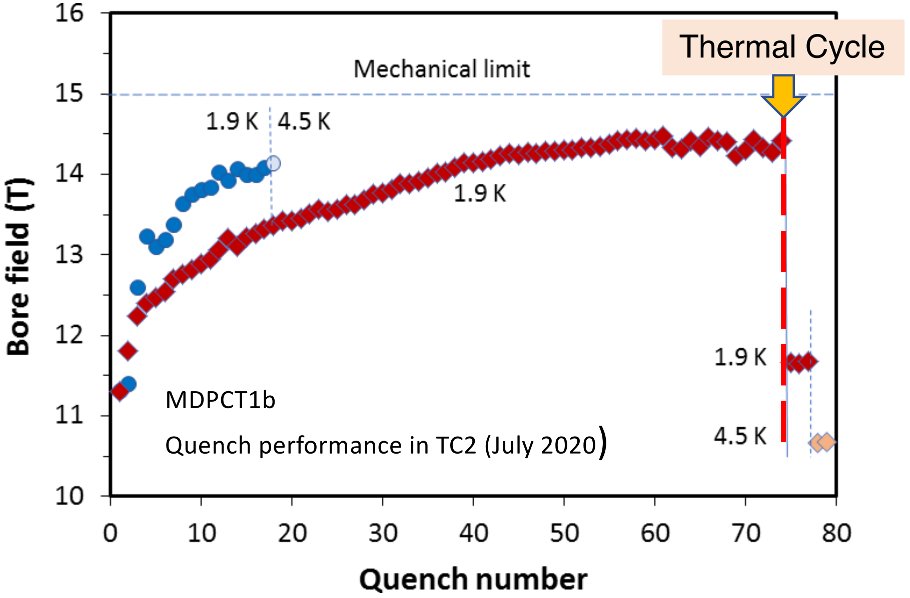
MDP-TAC Review
Courtesy: A. Zlobin

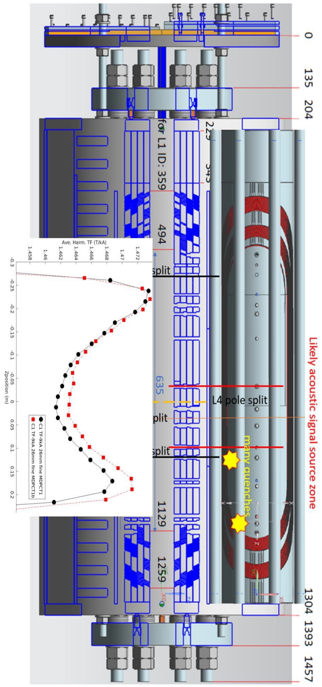
MDPCT1b: Quench performance in TC1 and TC2 (July 2020)

TC2 test target: *achieve ~14.5 T in magnet aperture @1.9 K*









- No retraining, all quenches in coil 5, RE, pole turn
- *MDPCT1b reached its conductor limit at both temperatures*
- *18% performance degradation after TC, wrt TC1*

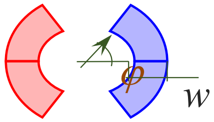
Courtesy: L. Bottura, A. Devred

Major Issue:
Mechanical Constraints affecting Operating Margin

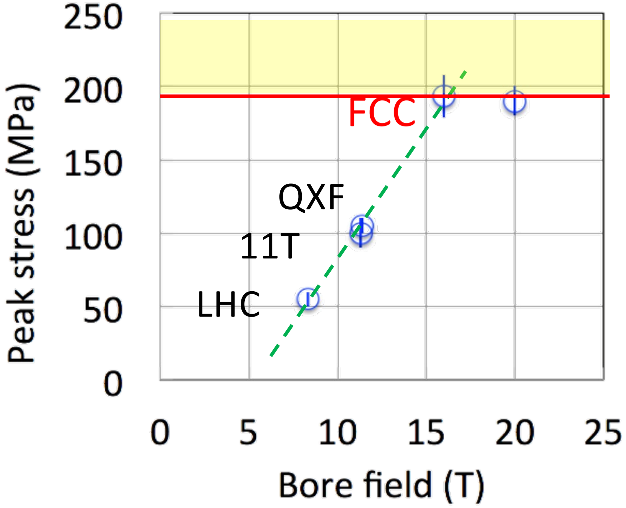
Large Impact of Strain on Jc, reduction,w/ Nb3Sn superconductor

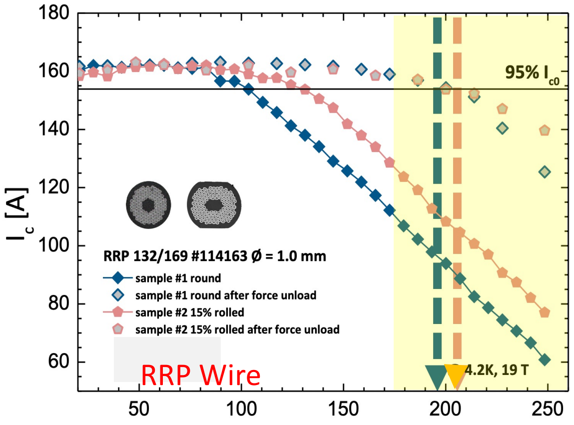
Attention： I_c (J_c) reduction:

- irreversible above～170 MPa.



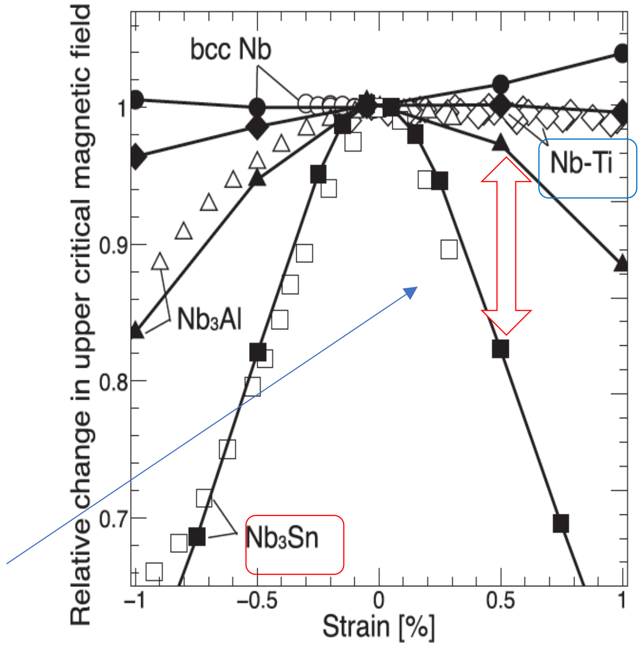
$$\left.\begin{aligned} F &\propto B^2 \\ w &\propto \frac{B}{J} \end{aligned}\right\} \rightarrow \sigma \approx \frac{F}{w} \propto JB \quad \sim B^2$$





Measurement at Univ. Geneve

A.Godeke, F. Hellman, H.H.J ten Kate, and M.G.T. Mentink et al.
Supercond. Sci. Technol. **31** (2018) 105011.

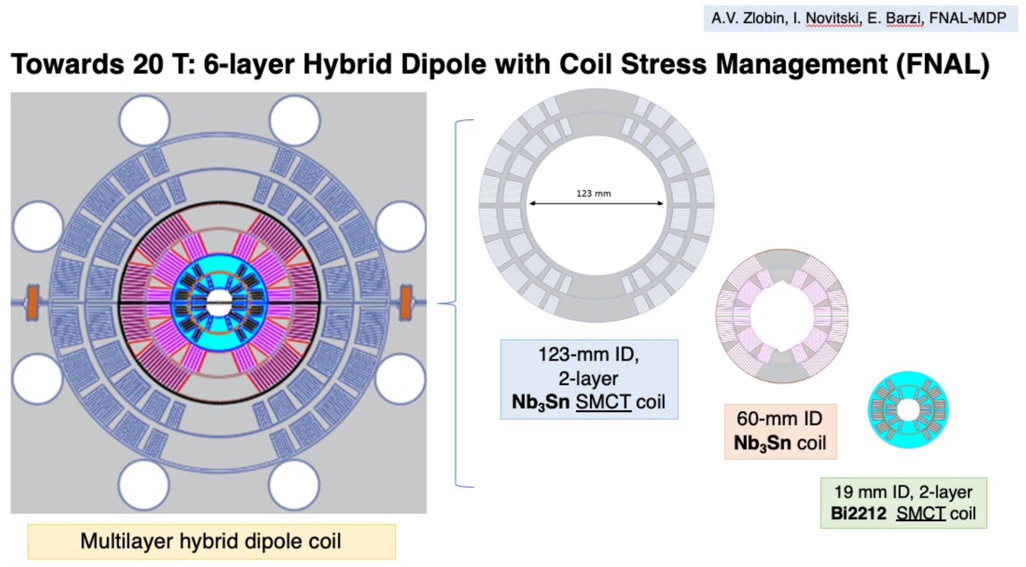


Courtesy: A.V. Zlobin

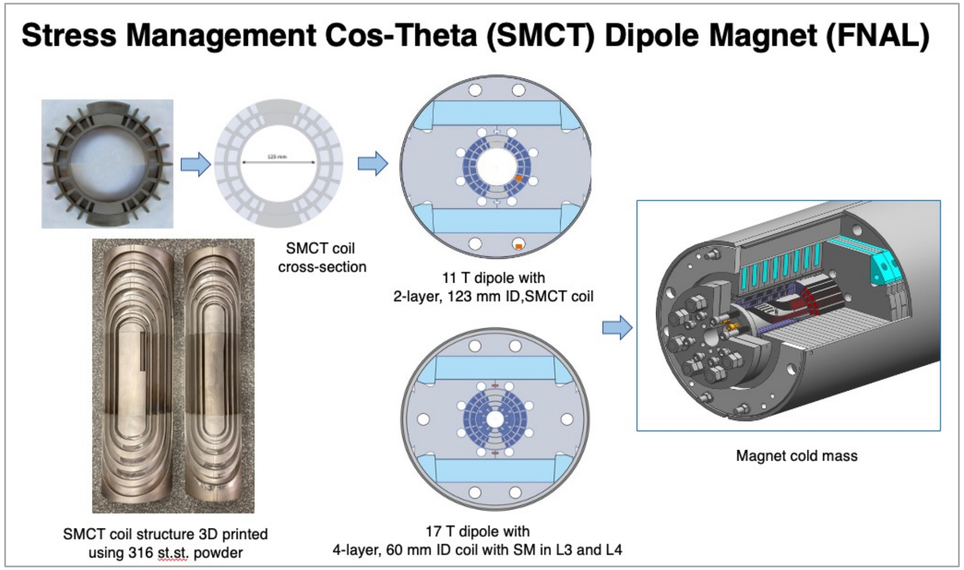
Stress Management Cos-Theta (SMCT) Dipole Magnet

as a next step of the 14.5 T Dipole program at FNAL, in progress

- The stress-management cos-theta (**SMCT**) coil/magnet is a new concept proposed and being developed at Fermilab in the framework of US-MDP program. The SMCT coil is wound into stainless-steel coil-winding structure providing grooves.
- The SMCT structure is used to reduce large coil deformations under the Lorentz forces and, thus, the excessively large strains and stresses in the coil.


A.V. Zlobin, I. Novitski, E. Barzi, FNAL-MDP

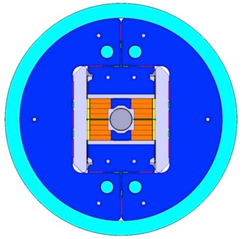
Towards 20 T: 6-layer Hybrid Dipole with Coil Stress Management (FNAL)


Stress Management Cos-Theta (SMCT) Dipole Magnet (FNAL)

A. Zlobin et al., Presented at ASC20222, and to be published in ASC-TAS.

Courtesy: G. De Rijk, A. Devred

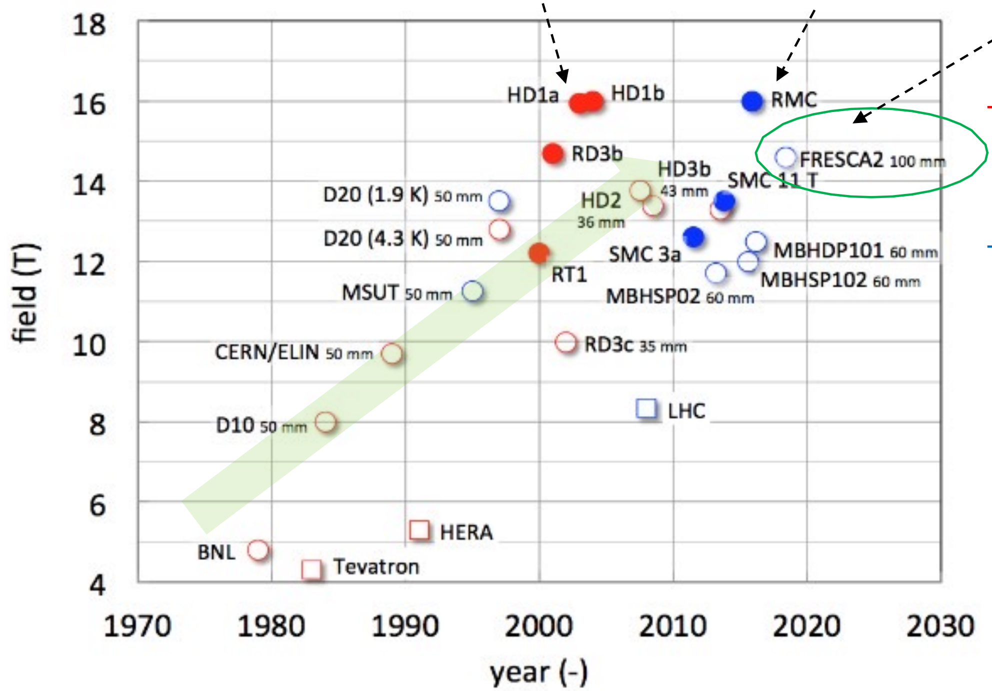
Advances in Nb_3Sn Magnet Development

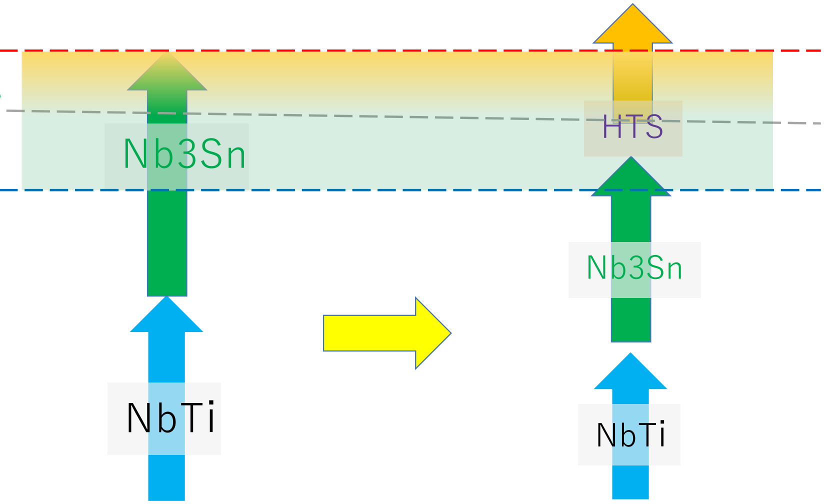


2003: LBNL HD1
(16 T at 4.2 K)

2015:CERN RMC
(16.2 T at 1.9 K)

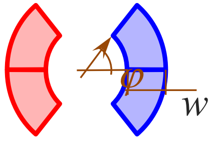
2018: FRESCA2
(100 mm aperture, 14.6/14.95 T bore/peak at 12.1 kA. 1.9 K)





Courtesy, A. Ballarino, X. Xu, T. Ogitsu, D. Schoerling

Nb_3Sn Conductor Progress

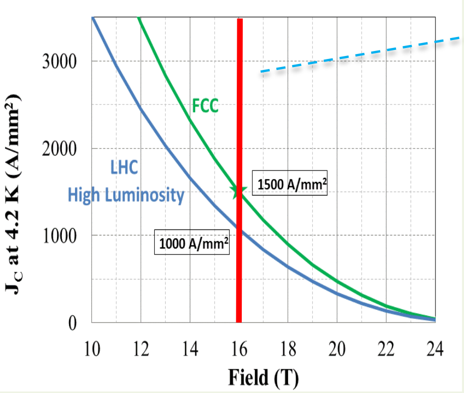


- **A**rtificial **P**inning **C**enter (**APC**) approach reached: **J_c** (16T, 4.2K) **~ 1500 A/mm²**
- **Mas-Production** and **cost-reduction** is yet to come !!

$$B = \frac{2\mu_0}{\pi} J w \sin(\phi)$$

Main development Target:

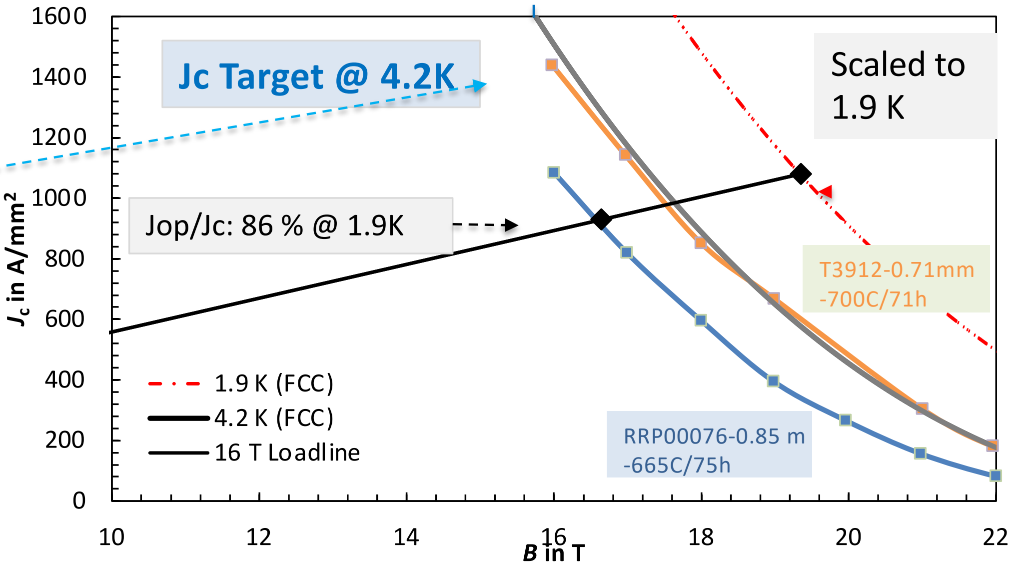
- **J_c (16T, 4.2K) > 1500 A/mm²**



Global cooperation:

CERN/KEK/Tohoku/JASTEC/Furukawa
- CERN/Bochvar High-tec. Res. Inst
- CERN/KAT
- CERN/Bruker
- T.U. Vienna, Geneve U., U. Twente,
- Florida S.U. - Appl. Superc. Center
- US-DOE-MDP, Fermilab

A. Ballarino et al., ASC-2018, DOI 10.1 109/IEEE TASC-2019, 2896469.



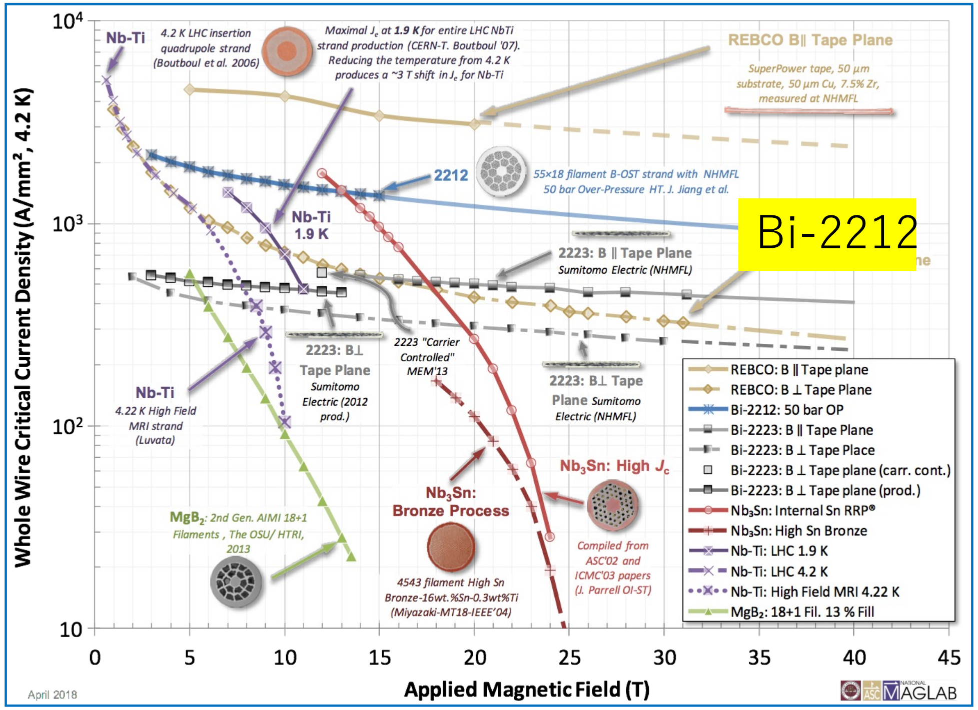
- Achieved by a ternary approach:
K. Saito/T. Ogitsu et al.
(JASTEC/KEK)

- Achieved by APC approach:
X. Xu et al (Fermilab)
https://arxiv.org/abs/1903.08121

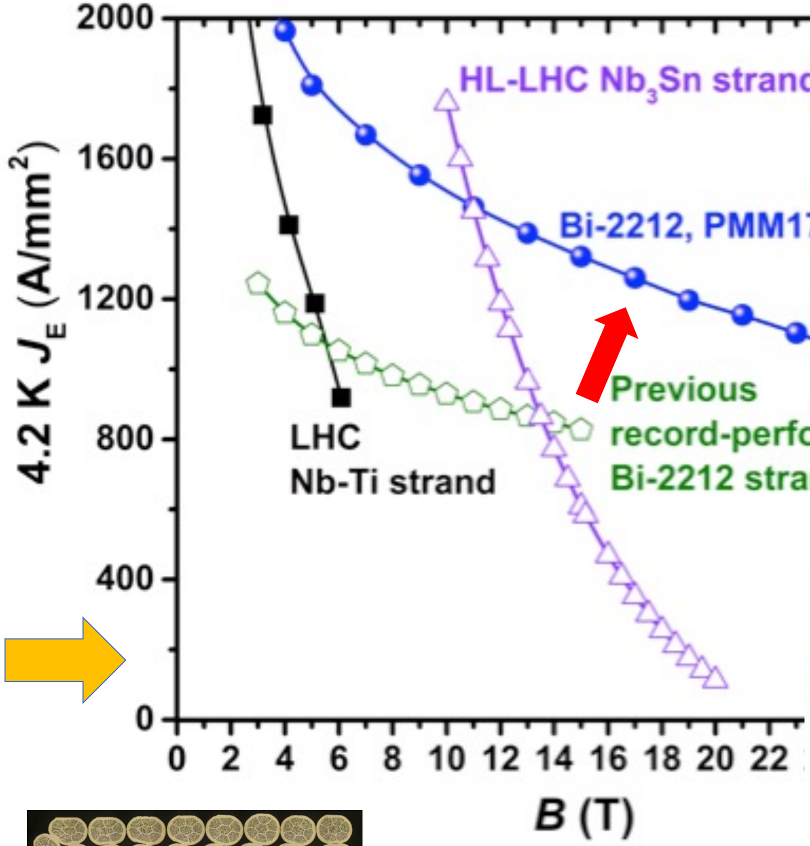
- Another ternary approach w/ Hf rto Nb4Ta in progress: S. Balachandran et al., https://arxiv.org/pdf/1811.08867.pdf

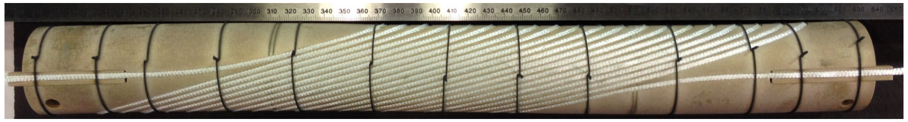
Courtesy, P. Lee, S. Prestemon

HTS, **focusing on Bi2212 in the US**



Bi-2212





Gimat
MAGLAB
BRUKER
BERKELEY LAB

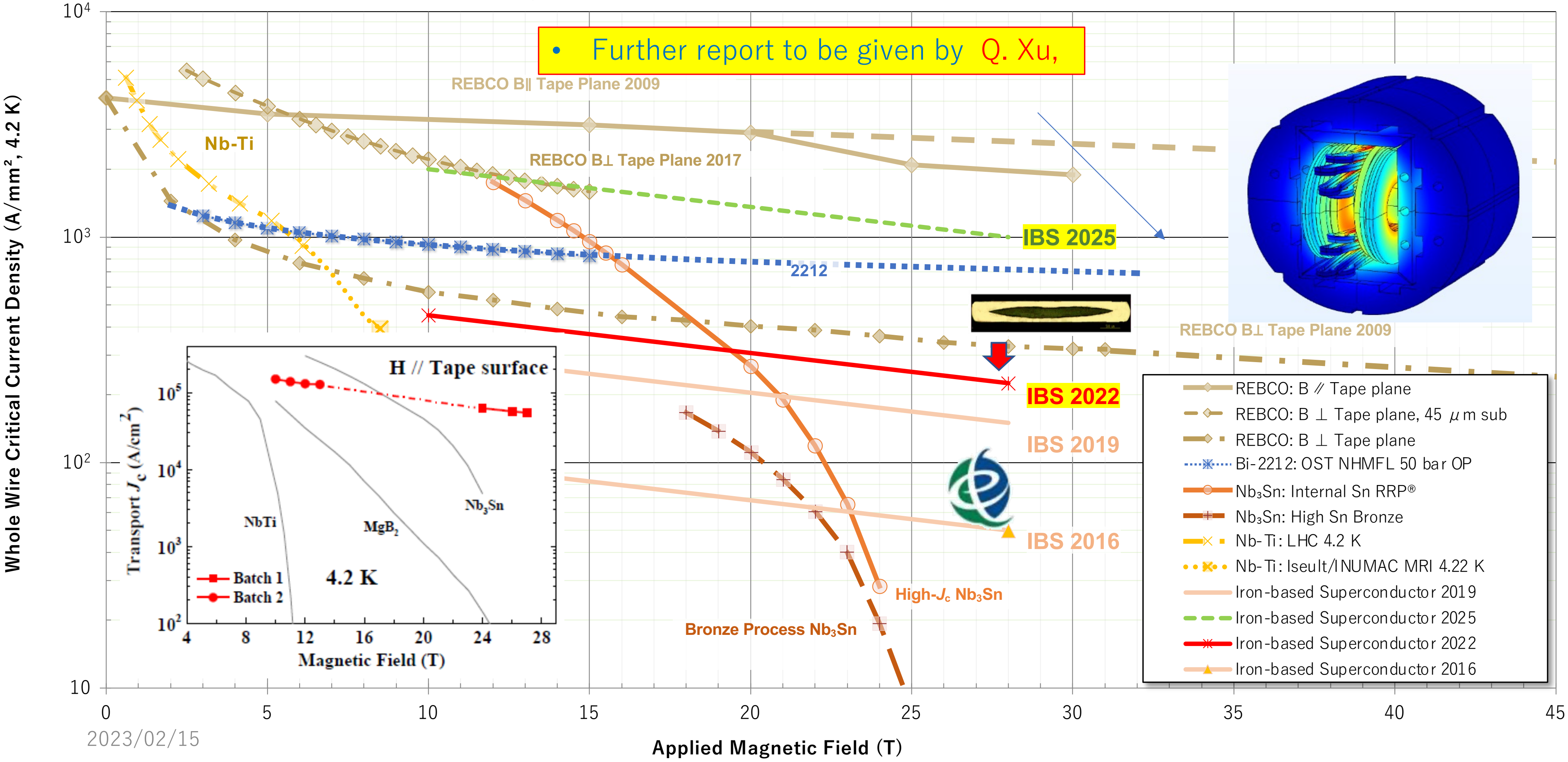
Application expected for CCT by using B2212

A. Yamamoto, 2021/3/23b

IBS Technology: Status and Outlook in China

Courtesy: Q. Xu

- Stainless-steel stabilized IBS tape achieved the highest J_e in 2022!
- The cost significantly reduced, and the mechanical properties raised .



- Further report to be given by Q. Xu,

Courtesy: Q. Xu

IBS Technology: Status and Outlook in China

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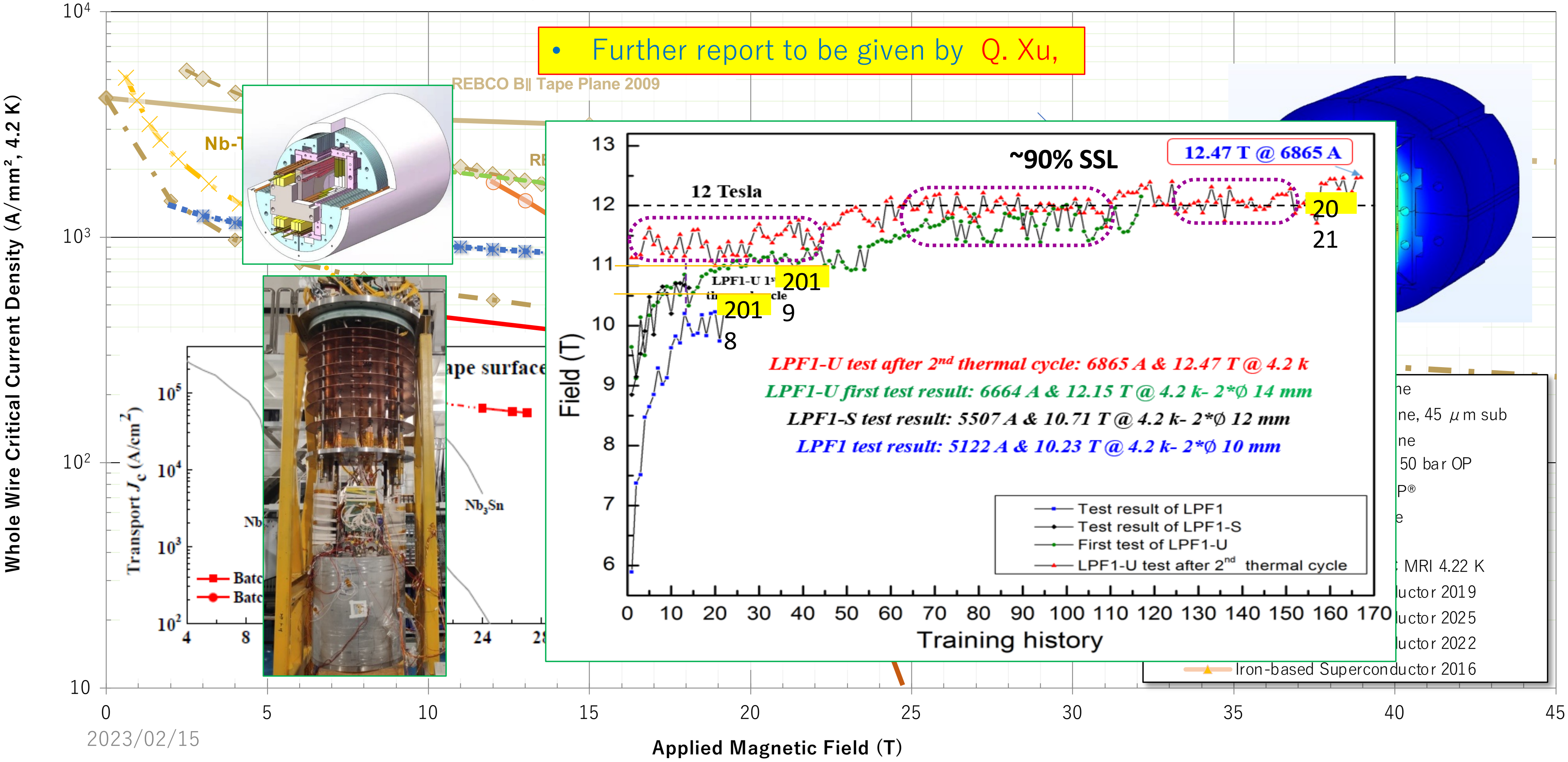
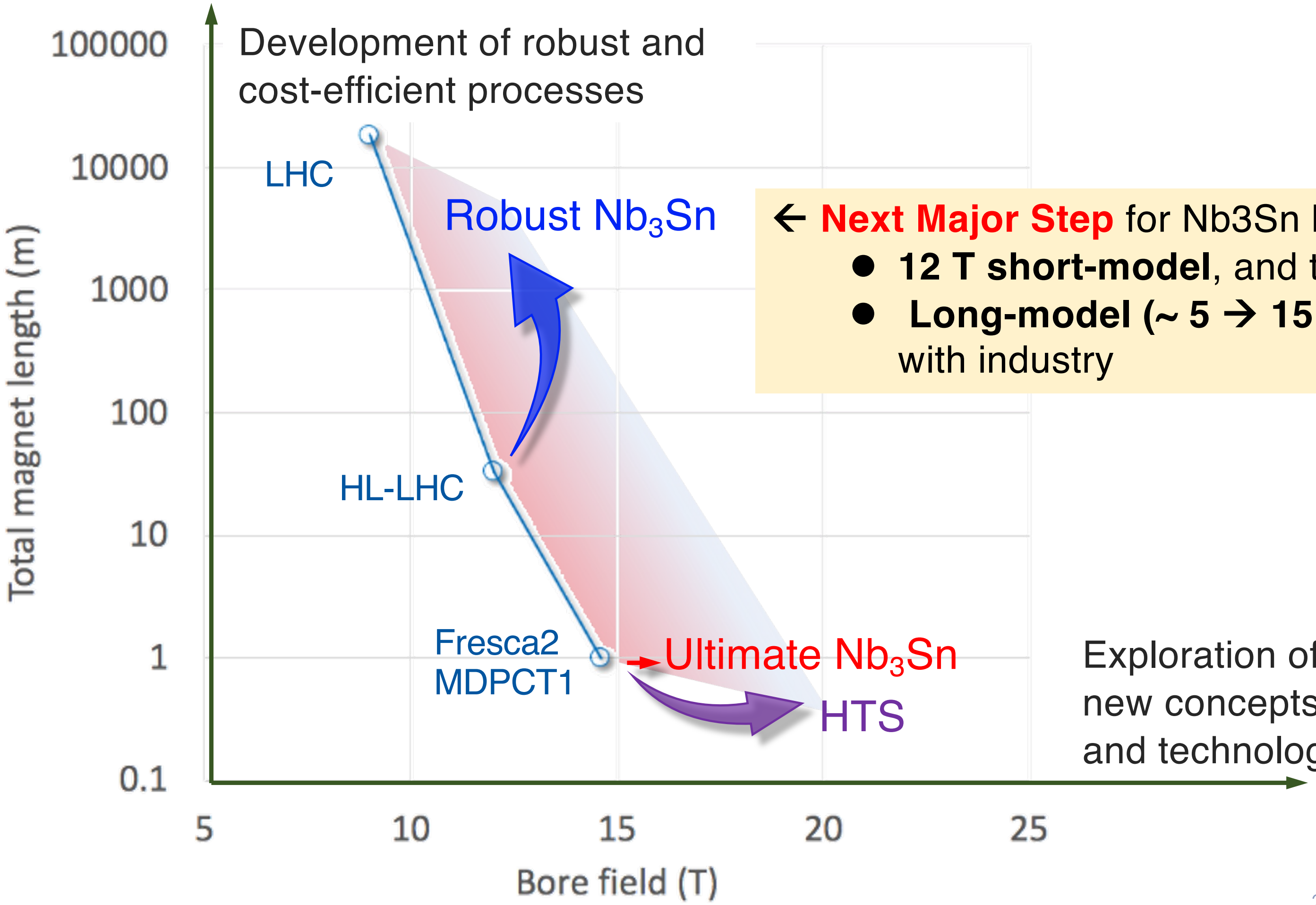


Courtesy: L. Bottura and LDG

High Field Magnet Development scoped by LDG



Development of robust and cost-efficient processes

Exploration of new concepts and technologies

← **Next Major Step** for Nb3Sn being proposed

- **12 T short-model**, and then
- **Long-model (~ 5 → 15 m)** in cooperation with industry

Prospect for HFM Development

Progress:

- We congratulate Nb_3Sn magnet technology is reaching to be applicable at 11~12 T in peak field, for a practical application: HL-LHC accelerator system/

Prospect:

- **High Field** magnet technology beyond 12 T requires **continuous and patient R&D efforts** to realize higher field and energy frontier accelerators:
  - **Nb_3Sn, 12~14 T: >~** 5 years for short-model R&D, the following >~ 5 years for prototype/pre-series. and further > **~ 10 yrs** for the construction start,
  - **Nb_3Sn (+HTS), 14~16 T:** >~ 10 years for short-model R&D, the following >~ 10 years for protype/pre-series, and further >~ **20 yrs** for the construction start,

ESPPU-2020, Physics Briefing Book, CERN-ESU-004, 30 Sept. 2019

Personal Prospect for the HF Magnet Development Timeline

Originally reported at ESPPU2020, CERN Open Symposium in Granada, 2019

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
14~16T Nb_3Sn (+HTS)	Short-model R&D		Prototype/Pre-series			**Construction**	
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		**Construction**		**Operation**	
~12T Nb_3Sn	Model/Proto /Pre-series	**Construction**		**Operation**			**Upgrade**

Note:
LHC experience:

	1980	1990	2000	2010
LHC MR, 8.3 T Dipoles (NbTi, 1.9 K, 15 m long, N = 1232)				
Short-Models	R&D start in early ('80) **Bc >10 T** realized ('88)		20 years	
Prototype ~ Pre-Series (3 x 10)		B_c 8.3T realized (~'95) (LL ratio: 86%)		
Production		Started (~'98)	Completed (~'06)	
LHC Operation at B_c			4T('09)	8T

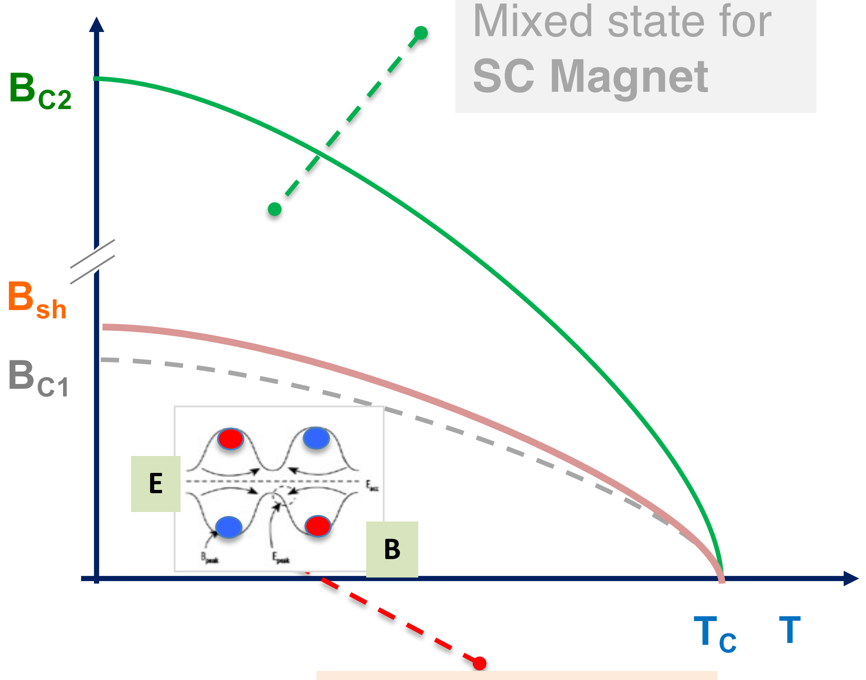
Outline

- Introduction:
- Superconducting High-Field Magnet (HFM)
- Superconducting RF (SRF)
- Cryogenics / Cryogen
- **Summary**

Pursued by T. Tajima
See: Appendix

Superconductor applicable for SRF Cavities

Material	T_c [K]	$B_{c1}(0)$ [T]	$B_{sh}(0)$ [T]	$B_{c2}(0)$ [T]
Nb	9.2	0.18	0.21	0.28
NbTi	9.2 ~9.5	0.067	--	11.5 ~ 14
Nb_3Sn	18.3	(0.05)	0.43	28 ~30
MgB_2	39	(0.03)	0.31	39
Important for:			RF	Magnet



Mixed state for
SC Magnet

Meissner state for
SRF

Courtesy: S. Michizono

~ 1.3 GHz SRF Accelerators, worldwide

European XFEL
(in operation, 2017~)

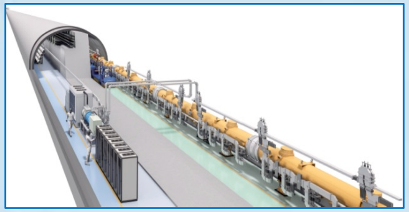
800 cavities
100 CMs
17.5 GeV (Pulsed)

ESS (0.8 GHz)
(under construction)

SHINE
(under construction)

~600 cavities
75 CMs
8 GeV (CW)

S1 Global:
DESY, Fermilab, KEK
8-cavity string Test,
2010



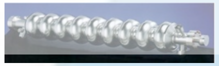
ILC (planned)

8,000 9-cell cavities
900 CMs
2 x 125 GeV (Pulsed)

LCLS-II -HE
(under construction)

-280+200 cavities
-35+25 CMs
- 4 +4 GeV (CW)

JLab-CEBAF(1.5 GHz)
(in operation)
40 CMs
6~12 GeV(CW)



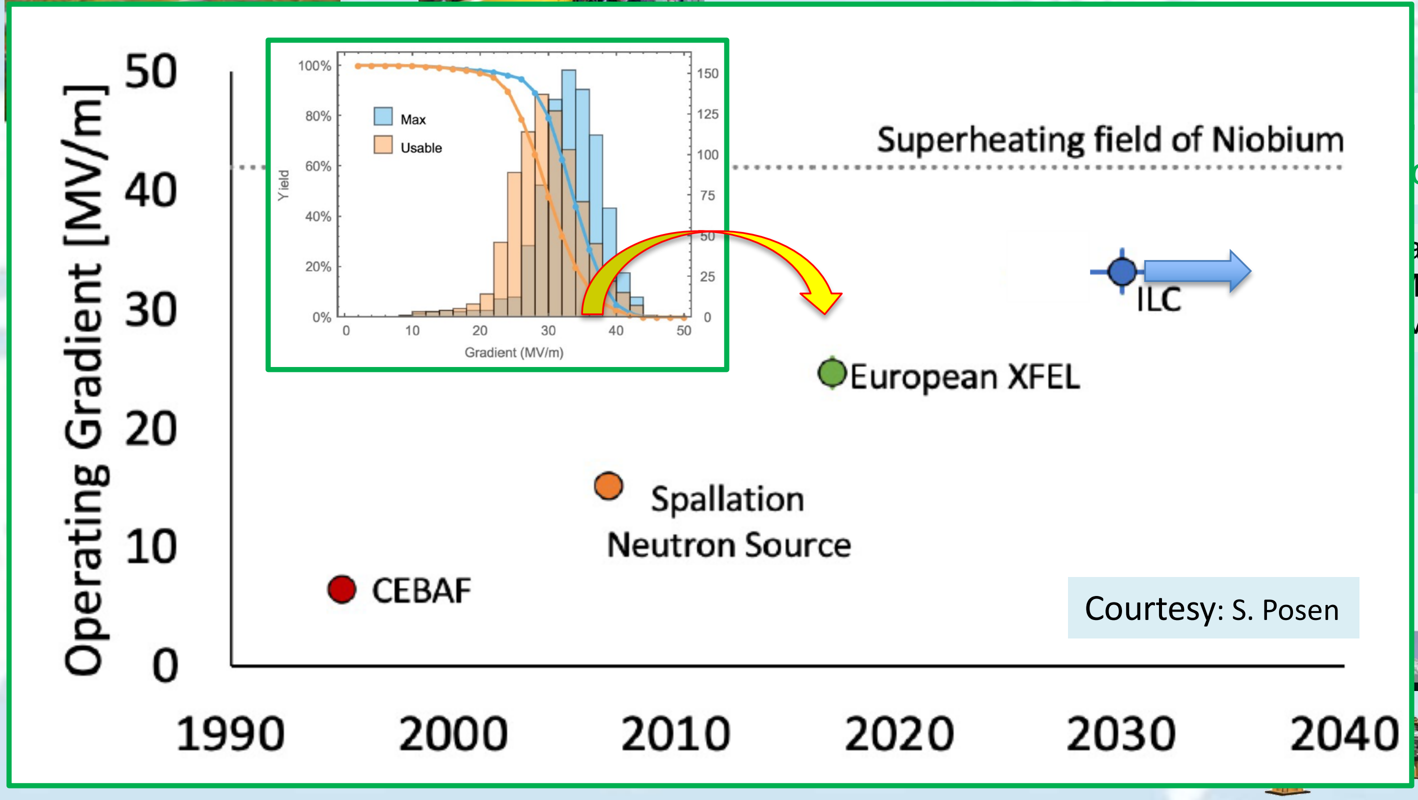
~ 2,000 1.3 GHz SRF cavities being realized, even in these 10 years **!**

Courtesy: S. Michizono

~ 1.3 GHz, SRF Accelerators, worldwide

European XFEL
(in operation, 2017~)

-800 cavities
-100 CMs
-17.5 GeV (Pulsed)



Courtesy: S. Posen

II
construction)

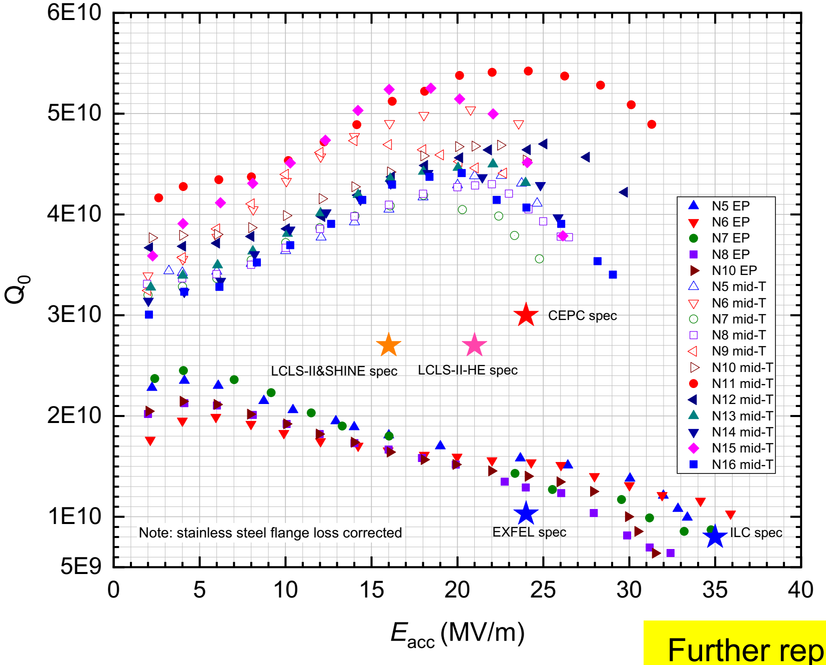
avities
ls
/ (CW)

~ **2,000** 1.3 GHz SRF cavities being realized, even in these 10 years !

Courtesy: J. Zhai

IHEP 1.3 GHz High-G & High-Q Cavity and Cryomodule

- Key technology R&D for FEL, CEPC booster and ILC
- 12 mid-T 9-cell cavities vertical test average Q 4.5E10@16-21 MV/m
- World's best high Q 1.3 GHz 9-cell cavity (N11): 5.4E10@21 MV/m, 4.9E10@31 MV/m
- 8 mid-T high Q 9-cell cavities integrated into cryomodule last year. 2 K module test ongoing.

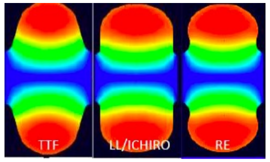


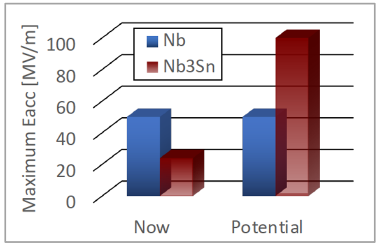
Further report to be given by J. Zhai

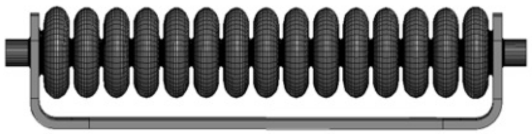
Courtesy: H. Padamsee

Future Prospects

- **Nb-based Standing Wave** (SW) TESLA type structure is
  - limited to a gradient of **~ 50 MV/m** by B_{sh} ~ 200 – 210 mT.
- **Advanced shape** cavities will be limited by **~ 60 MV/m**
  - Re-entrant, Low-Loss, Ichiro, Low Surface Field
  - Aiming at lower *Hpk/Eacc* (10-20%), but raise *Epk/Eacc* (15-20%)
- Advances material such as **Nb_3Sn**-based
  - Nb_3Sn, expecting Gradient limit up to **~ 80 MV/m**, at Bsh ~ 430 mT
- Explore the option of **Nb-based Traveling Wave** (TW) structures
  - Expecting Effective Gradient to be **~ 70 MV/m** or higher



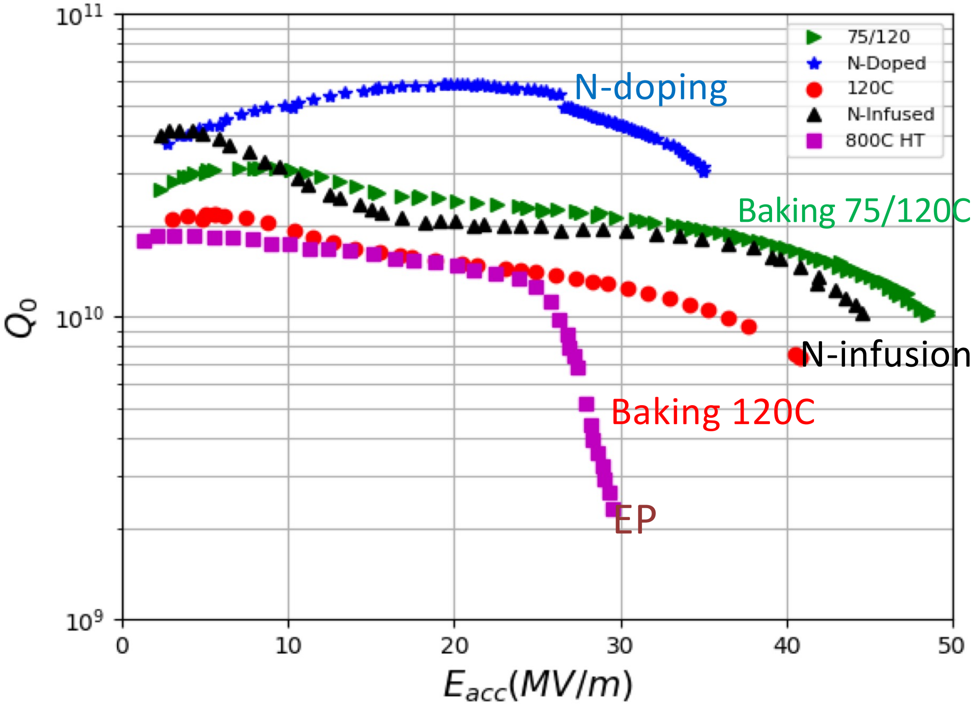




“**ILC:** The International Linear Collider -- Report to Snowmass 2021”, Aryshev *et al.*, arXiv:2203.07622 (15 March, 2022)

State of the Art in High-Q and High-G (1.3 GHz, 2K)

Courtesy: Anna Grassellino
- TTC Meeting, TRIUMF, Feb., 2019

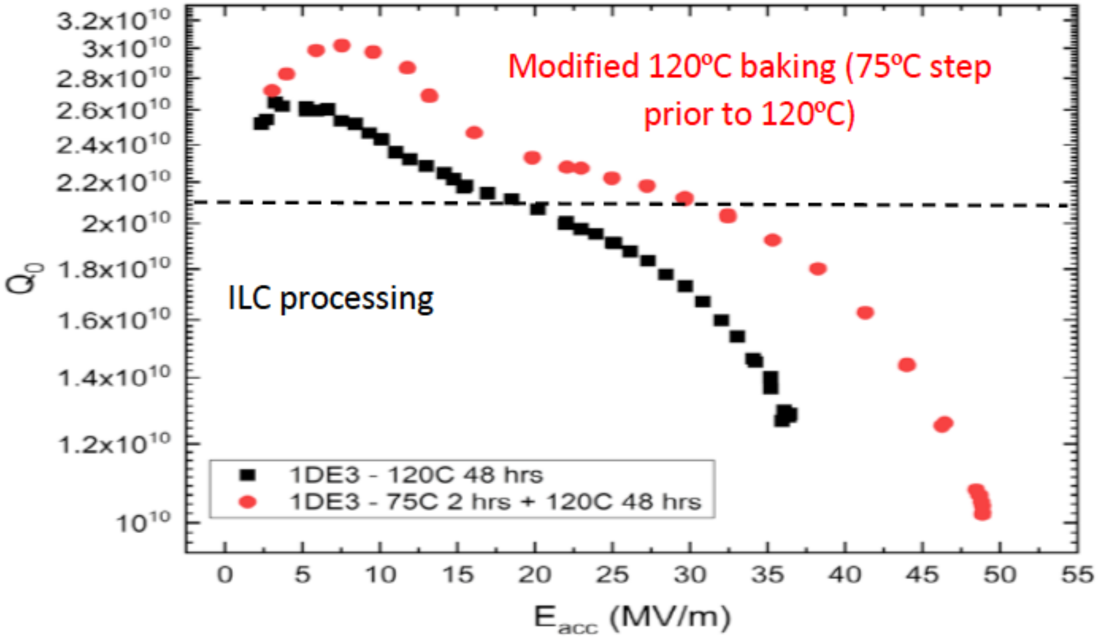


- **N-doping** (@ 800C for ~a few min.)
  - Q >3E10, G = 35 MV/m
- **2-step Baking w/o N** (@ 75/120C)
  - Q >1E10, G =49 MV/m (Bpk-210 mT)
- **N-infusion** (@ 120C for 48h)
  - Q >1E10, G = 45 MV/m
- **Baking w/o N** (@ 120C for xx h)
  - Q >7E9, G = 42 MV/m
- **EP** (only)
  - Q >1.3E10, G = 25 MV/m

- **High-Q** by **N-Doping** well established, and
- **High-G** by N-infusion and **Low-T baking** still to be understood and reproduced, worldwide.

State of the Art in High-Q and High-G (1.3 GHz, 2K)

Courtesy: Anna Grassellino
- TTC Meeting, TRIUMF, Feb., 2019



- **N-doping** (@ 800C for ~a few min.)
  - Q >3E10, G = 35 MV/m
- **2-step Baking w/o N** (@ 75/120C)
  - Q >1E10, G =**49 MV/m** (Bpk-210 mT)
- **N-infusion** (@ 120C for 48h)
  - Q >1E10, G = 45 MV/m
- **Baking w/o N** (@ 120C for xx h)
  - Q >7E9, G = 42 MV/m
- **EP** (only)
  - Q >1.3E10, G = 25 MV/m

- 2-Step Baking is a promising surface process for High E and High G, and to be further optimized.

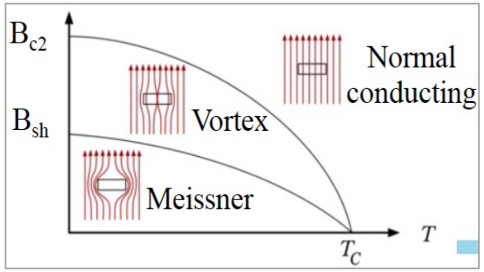
Courtesy, S. Posen

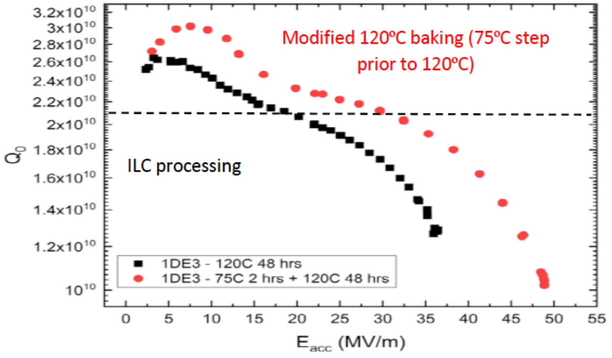
Recent Progress in SRF Technology

SRF cavity

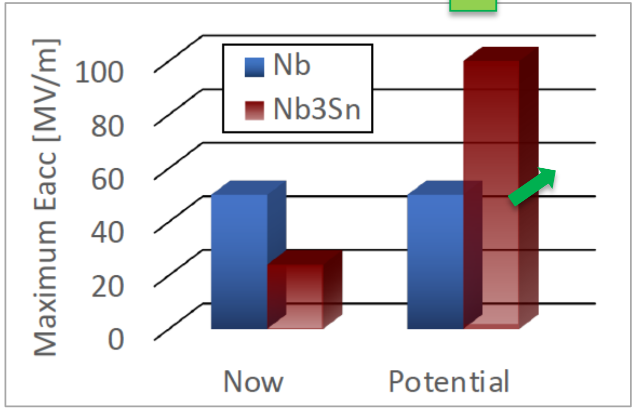
- B_{sh} = practical limit for SRF
  - Bs_{sh-Nb} : 210 mT
  - $Bs_{sh-Nb3Sn}$: 430mT

x2

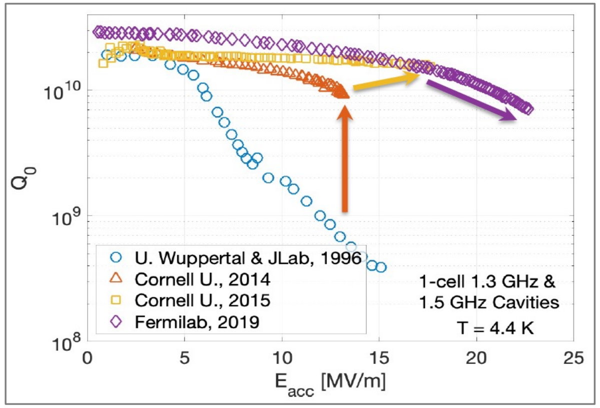




Progress at Fermilab: Nb, 75/120 bake
A. Grassellino et al., arXiv: 1806/09824



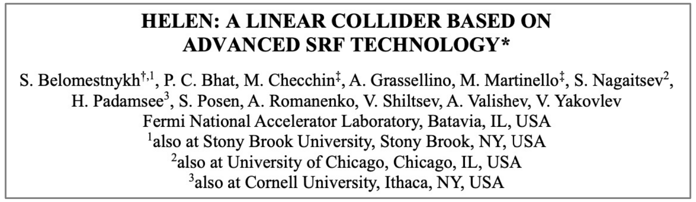
Nb_3Sn progress at Fermilab.
S. Posen et al., SUST, 34, 02507 (2021)



Nb_3Sn Potential in high-G future

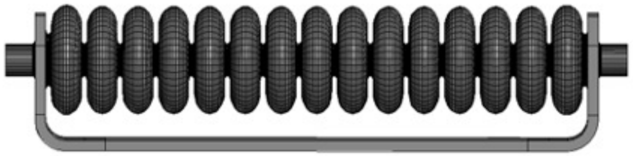
Courtesy: S. Belomestnykh

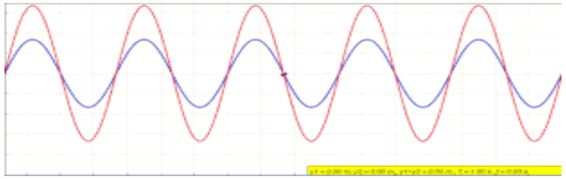
Traveling Wave Cavity Technology proposed for HELEN SRF Accelerator



HELEN: A LINEAR COLLIDER BASED ON ADVANCED SRF TECHNOLOGY*

S. Belomestnykh†,1, P. C. Bhat, M. Checchin‡, A. Grassellino, M. Martinello‡, S. Nagaitsev[2], H. Padamsee[3], S. Posen, A. Romanenko, V. Shiltsev, A. Valishev, V. Yakovlev
Fermi National Accelerator Laboratory, Batavia, IL, USA
[1]also at Stony Brook University, Stony Brook, NY, USA
[2]also at University of Chicago, Chicago, IL, USA
[3]also at Cornell University, Ithaca, NY, USA





- **Red** standing wave – High Peak Fields
- **Green** (acceleration) and **Blue** (Return) Waves are Travelling Waves - Lower peak fields
- Guide blue wave in a return wave-guide to avoid SW peak fields – attached to both ends

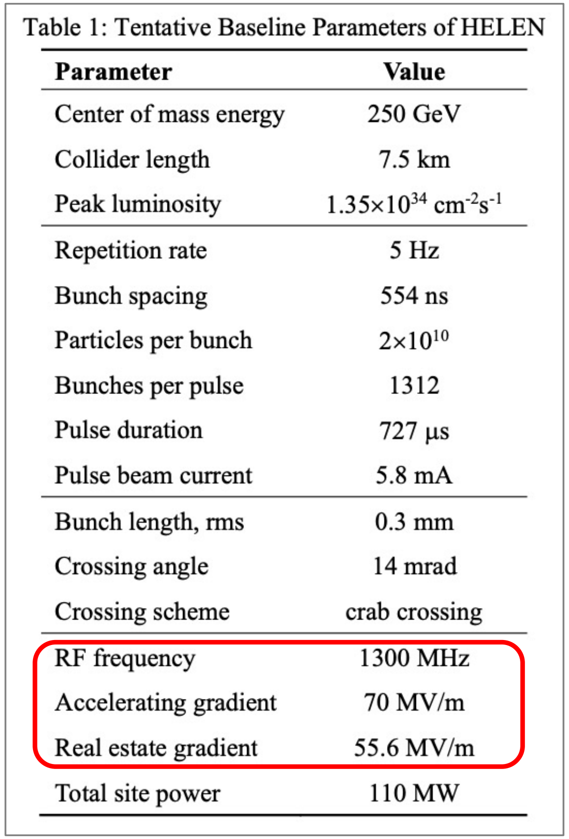


Table 1: Tentative Baseline Parameters of HELEN

Parameter	Value
Center of mass energy	250 GeV
Collider length	7.5 km
Peak luminosity	1.35×10^{34} cm^{-2}s^{-1}
Repetition rate	5 Hz
Bunch spacing	554 ns
Particles per bunch	2×10^{10}
Bunches per pulse	1312
Pulse duration	727 µs
Pulse beam current	5.8 mA
Bunch length, rms	0.3 mm
Crossing angle	14 mrad
Crossing scheme	crab crossing
RF frequency	1300 MHz
Accelerating gradient	70 MV/m
Real estate gradient	55.6 MV/m
Total site power	110 MW

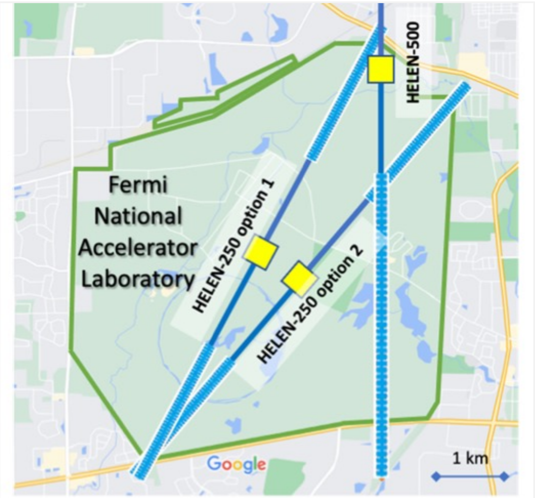
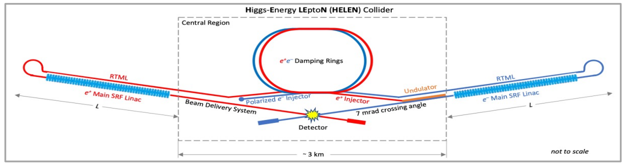


Figure 3: Options for HELEN collider at Fermilab.



https://doi.org/10.48550/arXiv.2209.01074

Prospects for Technologies for Future Lepton Colliders

- SRF technology has been well **advanced,** in cooperation with industry, based on **Euro-XFEL** successfully constructed and in stable operation since 2017, and further successful progress in LCLS-II SRF cavity production.

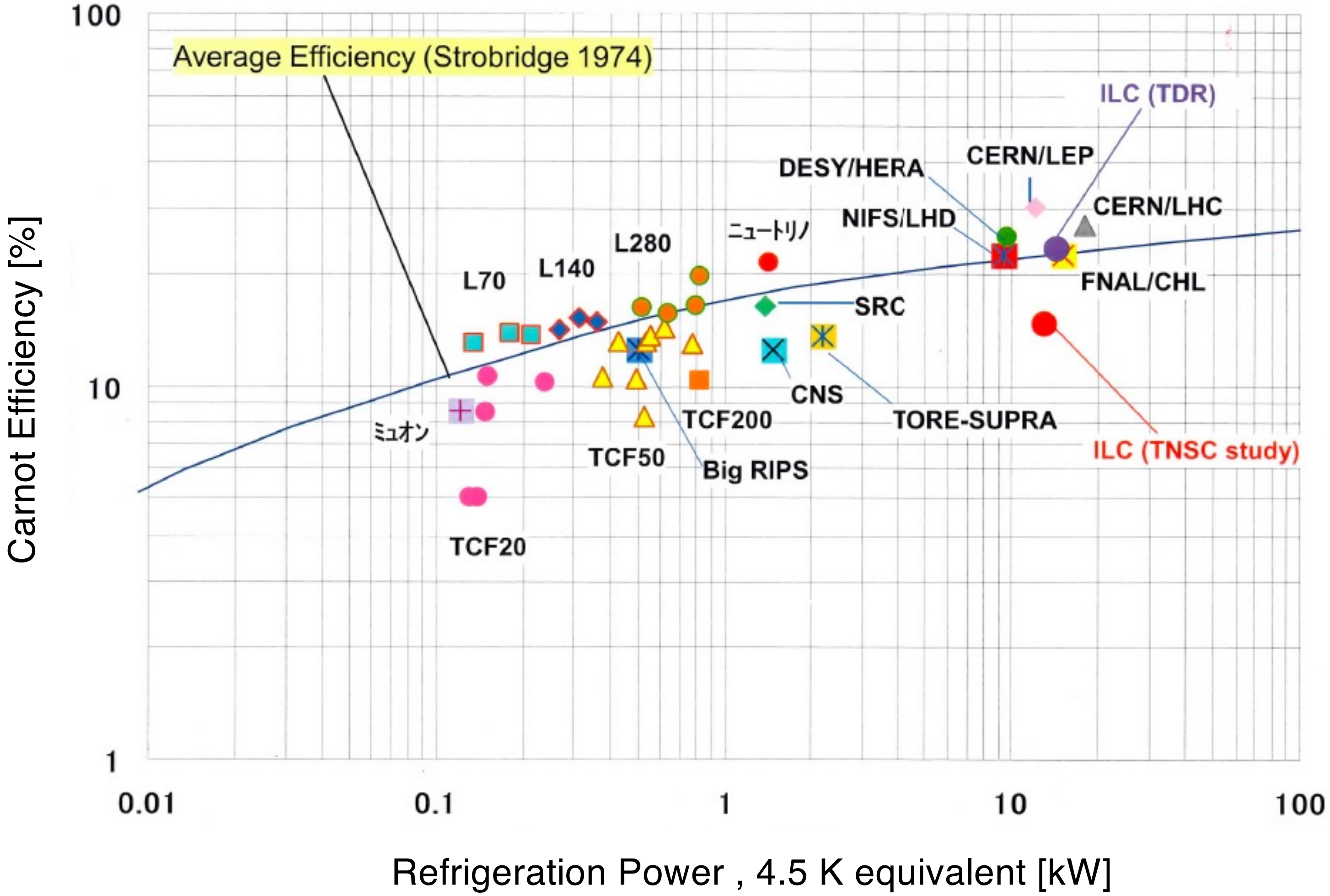
- SRF high-G and High-Q R&D effort needs to be extended for the future.
  - **Nb-bulk,** **E = 40 – 50 MV/m (SW), Q = 2 x 10^{10}**
  - **Nb_3Sn,** **> 50 MV/m**, and
  - **Nb-bulk,** **70 MV/m (TW)** in long term effort.

Outline

- Introduction:
- Superconducting High-Field Magnet (HFM)
- Superconducting RF (SRF)
- Cryogenics / Cryogen
- **Summary**

Courtesy: T. Okamura, *. Kaneda

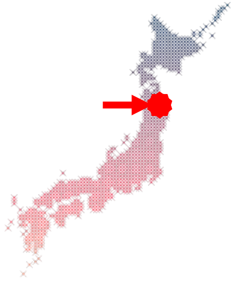
Worldwide He Cryogenic System and Carnot Efficiency

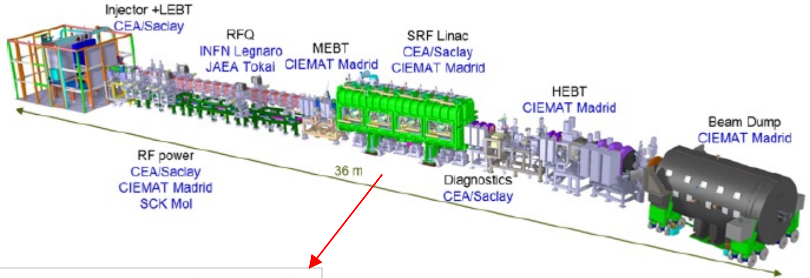


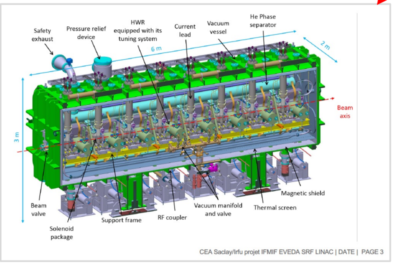
HPG System for Magnet and SRF

We are searching for a consistent HPGS Regulation Guideline

	QST-IFMIF: RIPac SRF-C	SLAC/FNAL: LCLS-II SRF-C
Mag—Vessel SRF-Cavity	ASME, BPVC Sect. VIII, Div.1	ASME BPC 31.1
Cryo-Piping	ASME BPC 31.1	ASME BPC 31.1
Refrigerator	Ref. Regulation	tbc

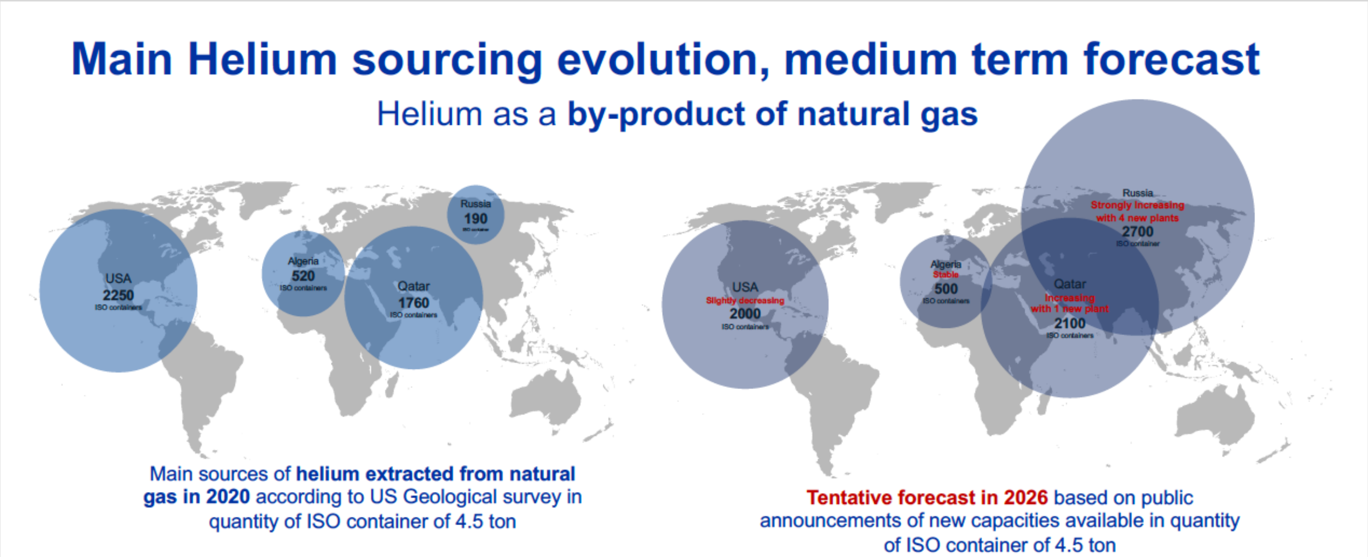






Courtesy: D. Delikaris

He Resource: Global Distribution



Main Helium sourcing evolution, medium term forecast

Helium as a **by-product of natural gas**

Main sources of **helium extracted from natural gas in 2020** according to US Geological survey in quantity of ISO container of 4.5 ton

Tentative forecast in 2026 based on public announcements of new capacities available in quantity of ISO container of 4.5 ton

Global resource and prospect:

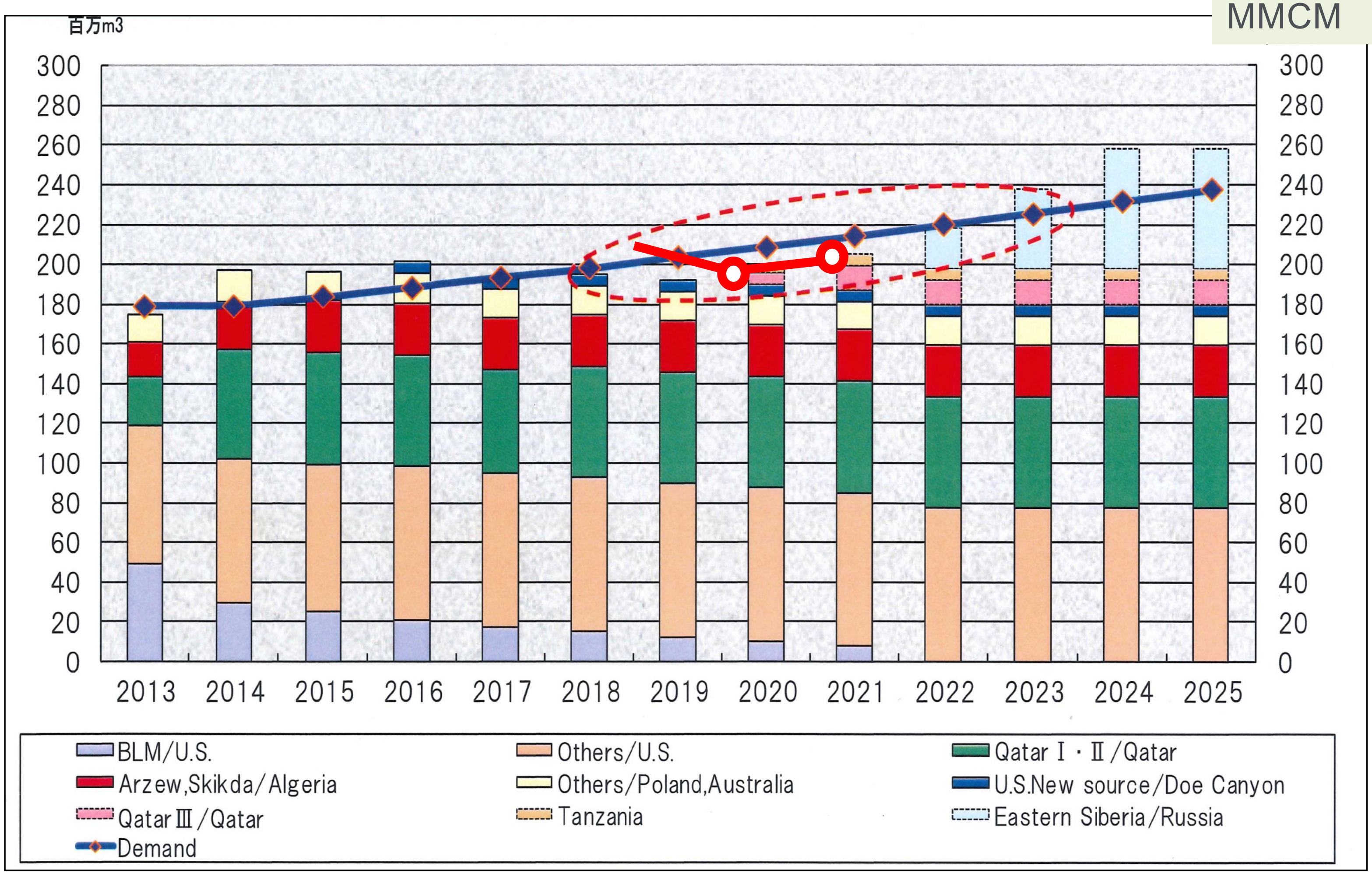
- Unbalanced production/demand (US BLM strategy, Technical and Geopolitical issues) affecting industrial and scientific customers, allocated to 60-70% of their demand
- Strong activities restart post Covid-19 pandemic
- Uncertainty on the effective world-wide production capacity and market access (countries restrictions)
- New helium production capacity (Qatar IV-V, Canada, Tanzania, South Africa) but for after 2025-2026

Supply and Demand Outlook as of 2019

Courtesy: R. Sagiyama

MMCM

MMCM：
Million cubic Meter



Real demand(I added from the latest data)

Outline

- Introduction:
- Superconducting High-Field Magnet (HFM)
- Superconducting RF (SRF)
- Cryogenics/Cryogen
- **Summary**

Challenges in Future Energy-Frontier Colliders

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	SRF E [MV/m] [GHz]	SCM B [T]	Major Challenges in Technology
LC ee	ILC	TDR update	0.25 -1	1.35, 2.7 (~ 4.9)	110, 138 (~ 300)	31.5 – 45 [1.3]		SRF cavity: High-G and high-Q Higher-G for future upgrade including new material, Nano-beam stability
	CLIC	CDR	0.38 - 3	1.5 (~ 6)	100 (~ 580)	72 – 100 [12]		Acc. Structure: High-precision, Large-scale production, Two-beam acceleration in a prototype scale, Precise alignment and stabilization.
CC ee	FCC-ee	CDR	0.09 ~ 0.38	460 ~ 31	260 ~ 350	10 – 20 [0.4 - 0.8]		**SRF cavity: High-Q** at < GHz, Nb thin-film Coating, Synchrotron Radiation absorption, Energy efficiency (RF efficiency).
	CEPC	CDR	0.046 - 0.24	32 ~ 5	150 ~ 270	20 – 40 [0.65]		SRF cavity: High-Q at < GHz, LG Nb-bulk/thin-film, Synchrotron Radiation constraint, Low-field magnet with high-precision.
CC hh	FCC-hh	CDR	~ 100	5 ~ 30	580	tbd	16	SC magnet : High-field - Nb3Sn (+HTS): high Jc, mechanical stress sustainability Energy management
	SPPC	CDR	75 - 125	10	---	tbd	12 - 24	SC magnet : High-field - IBS: High Jc, stress sustainability, energy management
CC mm	MC		0.12 ~ 14	0.008~33	200 ~290	≥ 30 0.8 ~1.3	10 -16 (> 40)	Short lifetime, cooling, SC magnet: High-field, RF in strong magnetic field, ….

Summary

- **Superconducting technology** will be inevitably required for future particle accelerators.

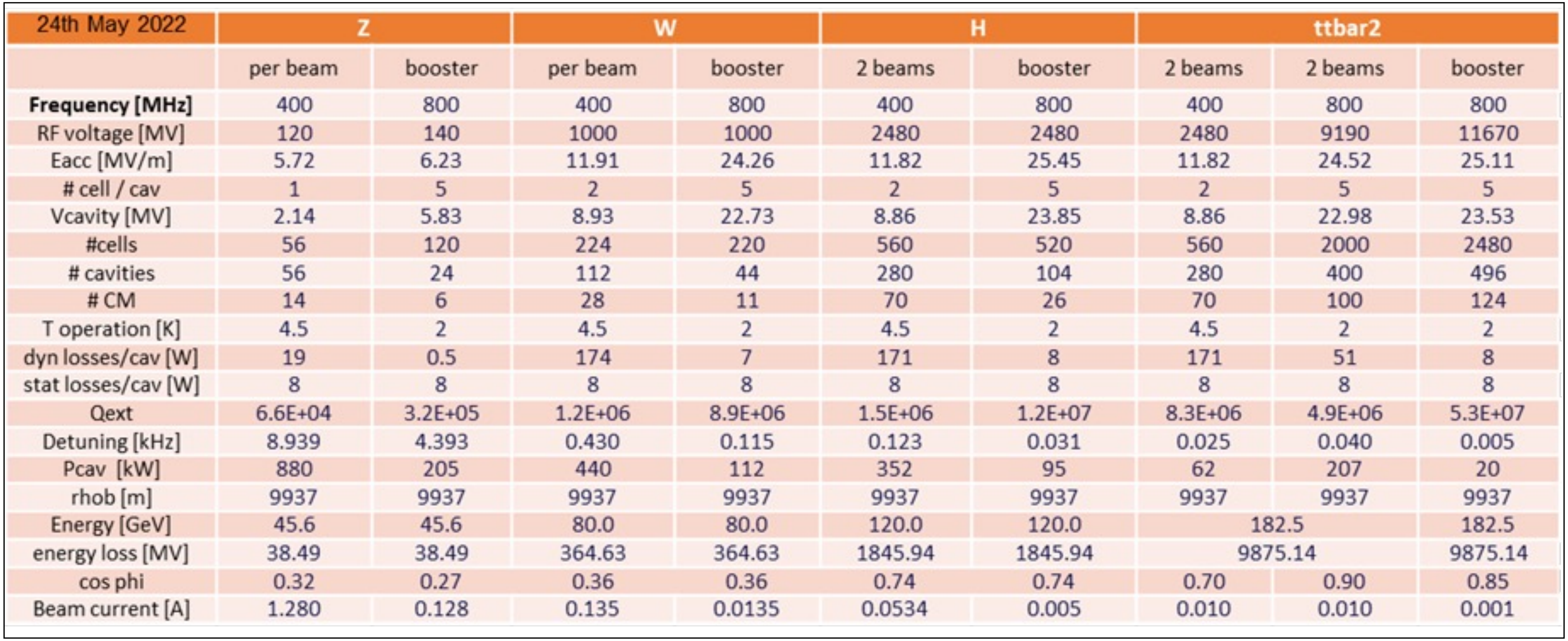
- **Encouraging progress on Nb3Sn magnet technology** reaching **11-12 T, applicable** for the HL-LHC accelerator system, and we may expect the higher field level of 14 T (+). We may need, however, further breakthrough, such as **Nb3Sn+HTS** to realize **16 T and beyond**, with satisfying the accelerator quality.

- **SRF technology** has much advanced, based on Euro-XFEL, LCLS-II, ESS, Shine, and other projects. It will provide **promising scope for future energy frontier colliders**.

- Further technical advances may be expected by using **Nb3Sn** technology and **Traveling Wave** technology.

reserved

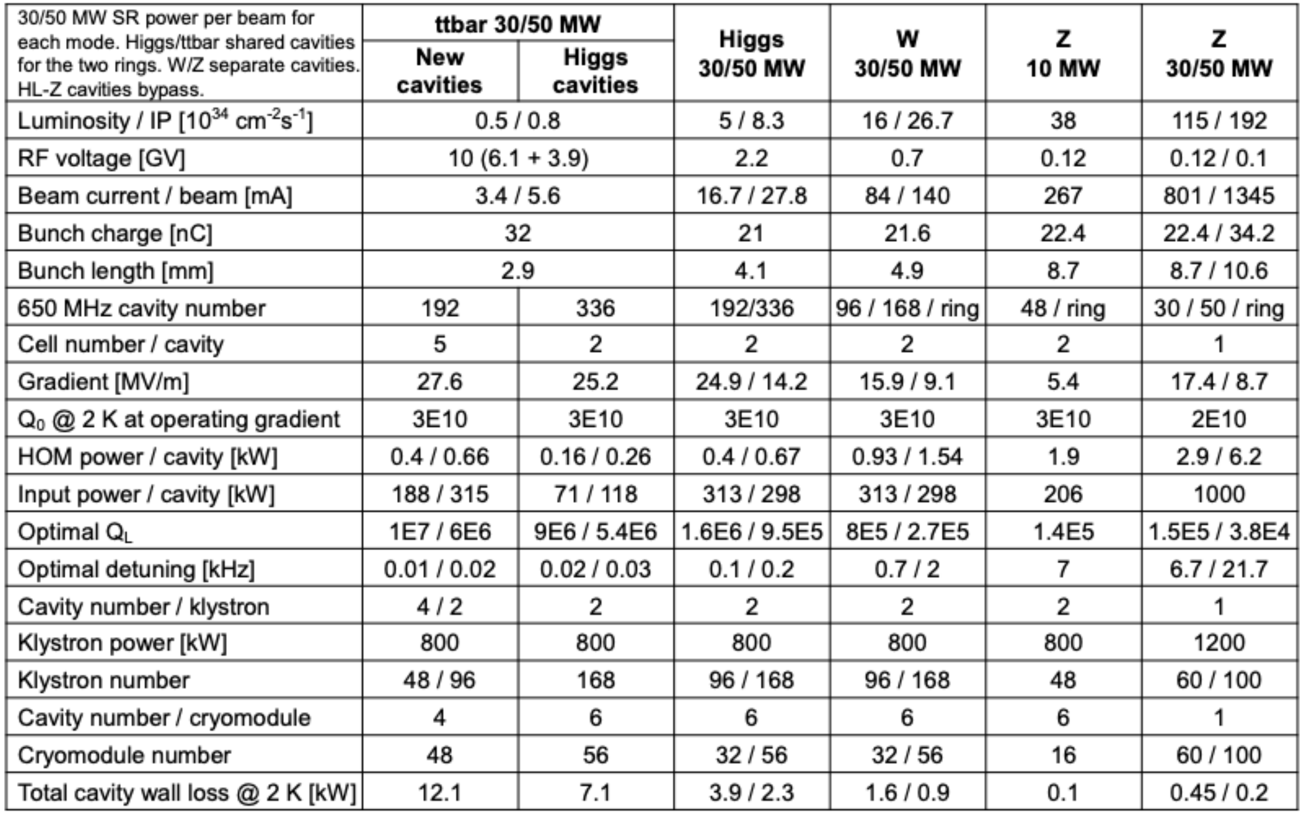
FCC-ee SRF Systems



24th May 2022	Z		W		H		ttbar2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1000	1000	2480	2480	2480	9190	11670
Eacc [MV/m]	5.72	6.23	11.91	24.26	11.82	25.45	11.82	24.52	25.11
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.83	8.93	22.73	8.86	23.85	8.86	22.98	23.53
#cells	56	120	224	220	560	520	560	2000	2480
# cavities	56	24	112	44	280	104	280	400	496
# CM	14	6	28	11	70	26	70	100	124
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	19	0.5	174	7	171	8	171	51	8
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.6E+04	3.2E+05	1.2E+06	8.9E+06	1.5E+06	1.2E+07	8.3E+06	4.9E+06	5.3E+07
Detuning [kHz]	8.939	4.393	0.430	0.115	0.123	0.031	0.025	0.040	0.005
Pcav [kW]	880	205	440	112	352	95	62	207	20
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9937
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5		182.5
energy loss [MV]	38.49	38.49	364.63	364.63	1845.94	1845.94	9875.14		9875.14
cos phi	0.32	0.27	0.36	0.36	0.74	0.74	0.70	0.90	0.85
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.005	0.010	0.010	0.001

Courtesy: Y. Zhai
HKUST IAS 2023

CEPC TDR 650 MHz RF Parameters (Collider Ring)



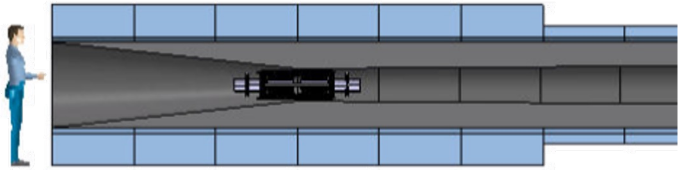
30/50 MW SR power per beam for each mode. Higgs/ttbar shared cavities for the two rings. W/Z separate cavities. HL-Z cavities bypass.	**ttbar 30/50 MW**		**Higgs 30/50 MW**	**W 30/50 MW**	**Z 10 MW**	**Z 30/50 MW**
	New cavities	**Higgs cavities**				
Luminosity / IP [10^{34} cm^{-2}s^{-1}]	0.5 / 0.8		5 / 8.3	16 / 26.7	38	115 / 192
RF voltage [GV]	10 (6.1 + 3.9)		2.2	0.7	0.12	0.12 / 0.1
Beam current / beam [mA]	3.4 / 5.6		16.7 / 27.8	84 / 140	267	801 / 1345
Bunch charge [nC]	32		21	21.6	22.4	22.4 / 34.2
Bunch length [mm]	2.9		4.1	4.9	8.7	8.7 / 10.6
650 MHz cavity number	192	336	192/336	96 / 168 / ring	48 / ring	30 / 50 / ring
Cell number / cavity	5	2	2	2	2	1
Gradient [MV/m]	27.6	25.2	24.9 / 14.2	15.9 / 9.1	5.4	17.4 / 8.7
Q_0 @ 2 K at operating gradient	3E10	3E10	3E10	3E10	3E10	2E10
HOM power / cavity [kW]	0.4 / 0.66	0.16 / 0.26	0.4 / 0.67	0.93 / 1.54	1.9	2.9 / 6.2
Input power / cavity [kW]	188 / 315	71 / 118	313 / 298	313 / 298	206	1000
Optimal Q_L	1E7 / 6E6	9E6 / 5.4E6	1.6E6 / 9.5E5	8E5 / 2.7E5	1.4E5	1.5E5 / 3.8E4
Optimal detuning [kHz]	0.01 / 0.02	0.02 / 0.03	0.1 / 0.2	0.7 / 2	7	6.7 / 21.7
Cavity number / klystron	4 / 2	2	2	2	2	1
Klystron power [kW]	800	800	800	800	800	1200
Klystron number	48 / 96	168	96 / 168	96 / 168	48	60 / 100
Cavity number / cryomodule	4	6	6	6	6	1
Cryomodule number	48	56	32 / 56	32 / 56	16	60 / 100
Total cavity wall loss @ 2 K [kW]	12.1	7.1	3.9 / 2.3	1.6 / 0.9	0.1	0.45 / 0.2

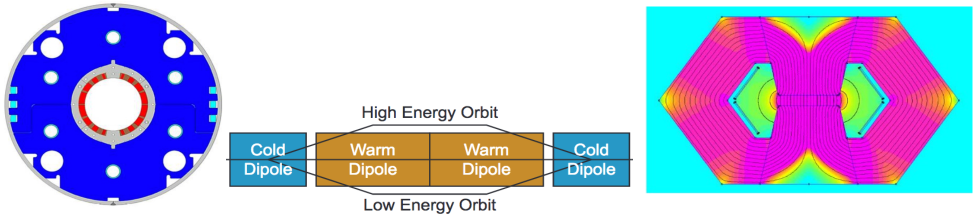
- ttbar and Higgs half filled with common cavities for two rings, W and Z with separate cavities for two rings.
- High luminosity Z upgrade use high current 1-cell cavity with RF bypass.
- Add more 2-cell cavities for Higgs 50 MW upgrade.
- Add 5-cell cavities for ttbar while using the original 2-cell Higgs cavities.
- Fundamental mode instability of Z-mode due to large detuning will be suppressed by RF feedback.
- No beam feedback needed for HL-Z because of deep damping 1-cell cavities.

MC Magnets: *Requirements and Challenges*

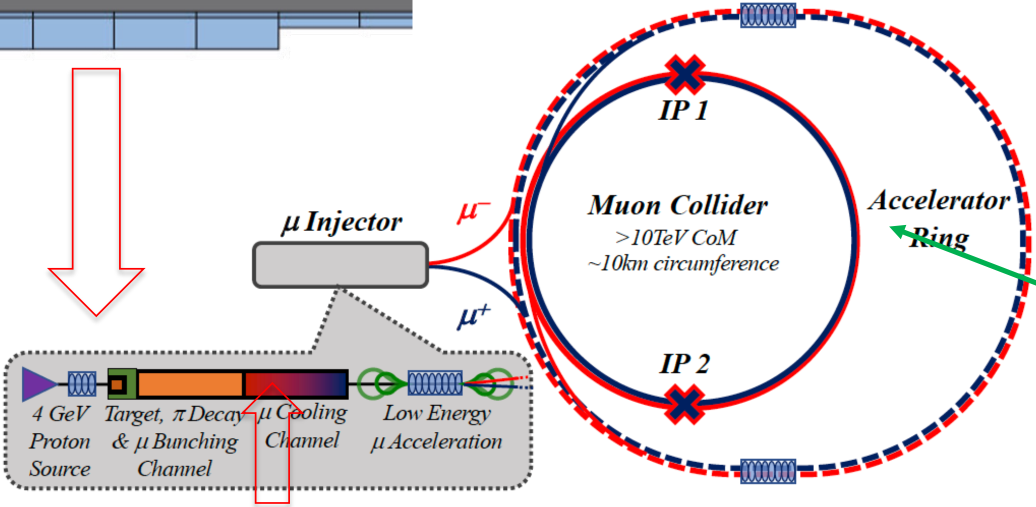
Courtesy: L. Bottura

a) Muon Generation:
20 T

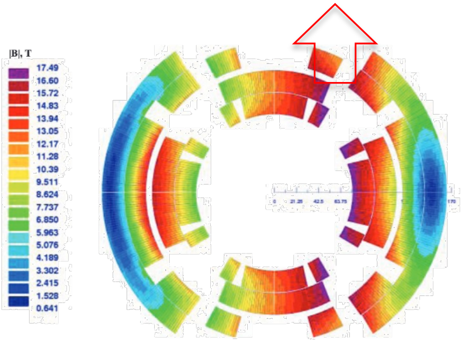




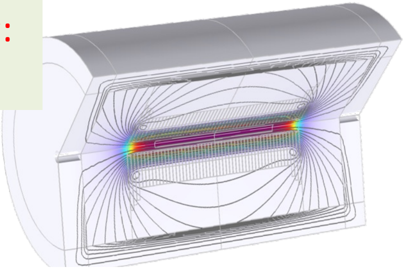
c) RCS Acceleration:
~ 10 T



d) Collider Ring:
16 T

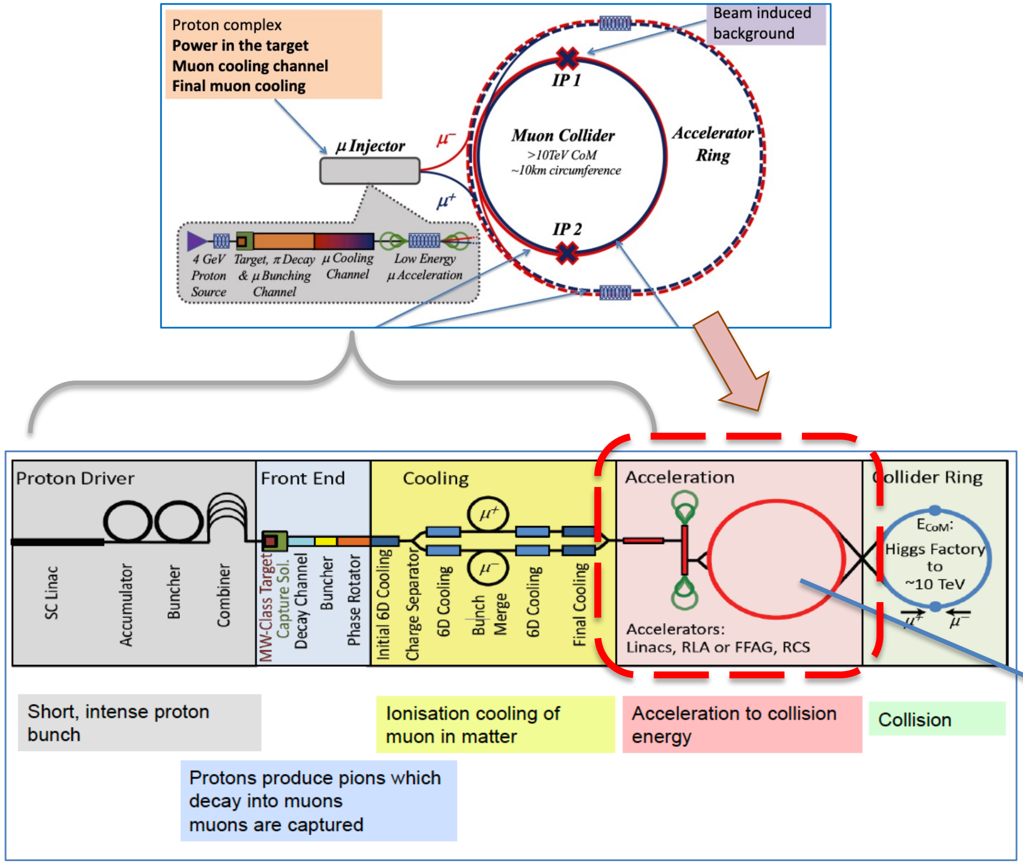


b) Final Cooling:
> 40 T



Courtesy: H. Damerau, F. Batsch

1.3 GHz, pulsed SRF Technology Applicable for the Muon Acceleration to Collision Energy



Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5

Multiple RF station along Acc. RIng with 1.3 GHz, pulsed SRF cavity (30 MV/m) being studied by F. Batsch et al.,