Advances and Challenges in Energy-Frontier Particle Accelerator Technology

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AMICI Industry Forum, Brussels, 17-18 September, 2019

Digested from a report at CERN Open Symposium on EPPSU, Granada, May, 2019
https://indico.cern.ch/event/808335/timetable/#20190513.detailed

Outline

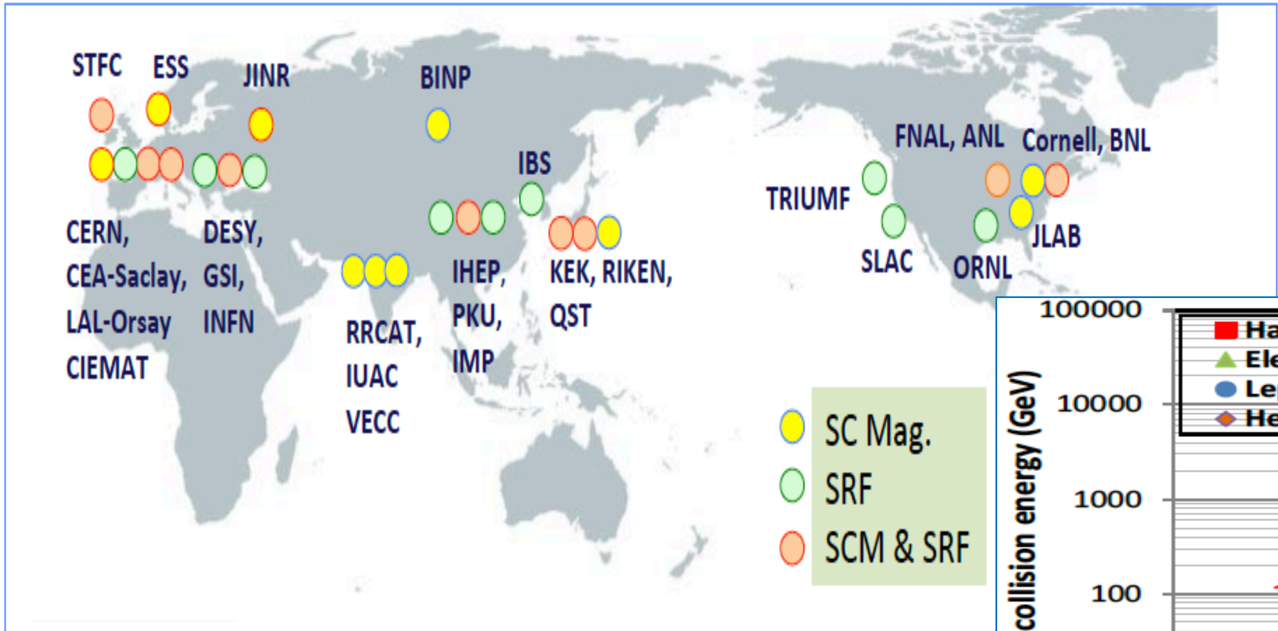
- Introduction

- **State of the Art in Accelerator Technologies,** focusing on
  - Nano-beam, (in Appendix)
  - Superconducting Magnet and Superconducting/Normal-conducting RF

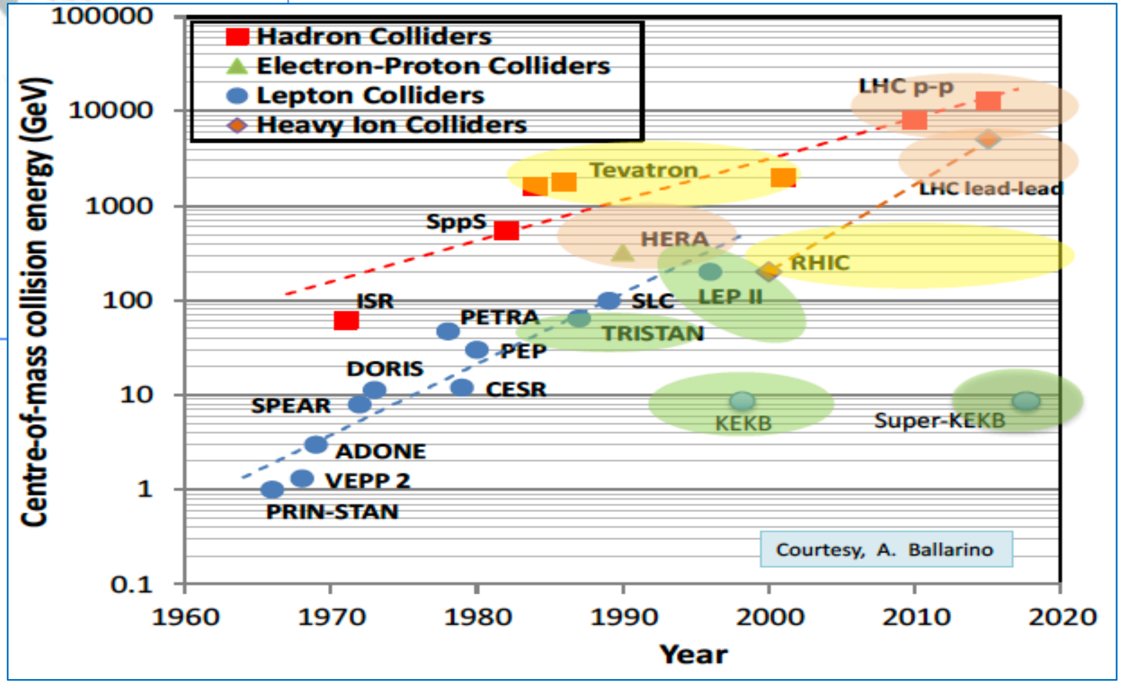
- **Challenges for future**

- **Summary**

Frontier Accelerators based on SC Technology



Courtesy, A. Ballarino



High-energy and **High-Intensity** frontier accelerators are relying on superconductivity as core technology to be focused in this talk.

Advances in Accelerator Technology Frontiers

Type	Acclerator	Op. Years	Beam Energy (TeV)	B [T]	E [MV/m]	Pioneering/Key Technology
CC hh	**Tevatron**	1983-2011	2 x 0.5	**4 T**		Superconducting Magnet (SCM)
	HERA	1990 -2007		**4.68 T**		SCM, e-p Collider,
	RHIC	2000 ~		**3.46 T**		SCM
	SPS **LHC** **HL-LHC**	1981-1991 2008 ~ Under constr.	2 x 0.42 2 x (6.5 **>> 7)**	**(NC mag.)** **7.8T -->8.4** **11~12**		P-bar Stochastic cooling SCM (NbTi) at 1.8 K, **SRF** SCM (Nb_3Sn), **SRF**, e-cooling
CC ee	**TRISTAN**	1986-1995	2 x 0.03		**5**	**SRF** (Nb-bulk), SCM-IR-Quad (NbTi)
	LEP	1989-2000	2 x 0.55		**5**	**SRF** (Nb-Coating) , SCM-IRQ
	KEKB **Super-KEKB**	1998~2010 2018 ~	0.002+0.008 0.004+0.007		**5** **5**	Luminosity, **SRF** Crabbing, SCM-IRQ Luminosity, Nano-beam, SCM-IRQ
LC ee	**SLC/PEP-II**	1988/98~2009	2 x 0.5			**Normal conducting RF**
	(Eu-XFEL)	(2018 ~)	(0.0175)		**(23.6)**	SRF (Nb-bulk)

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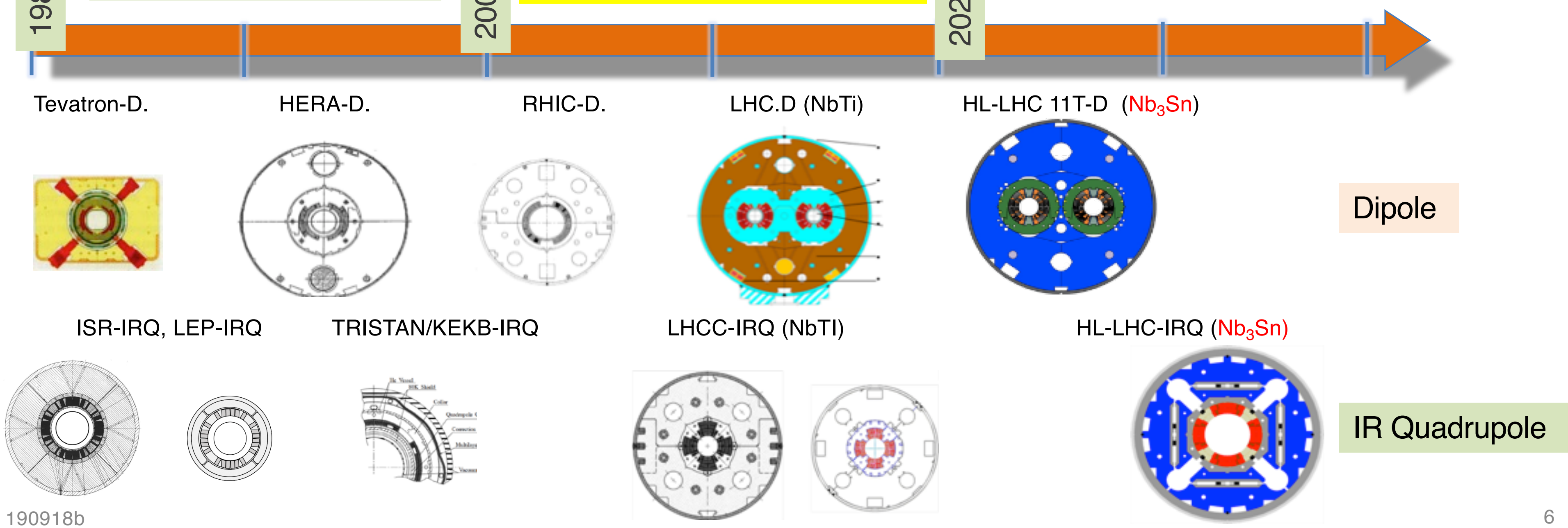
Advances in SC Magnets for Accelerators

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*

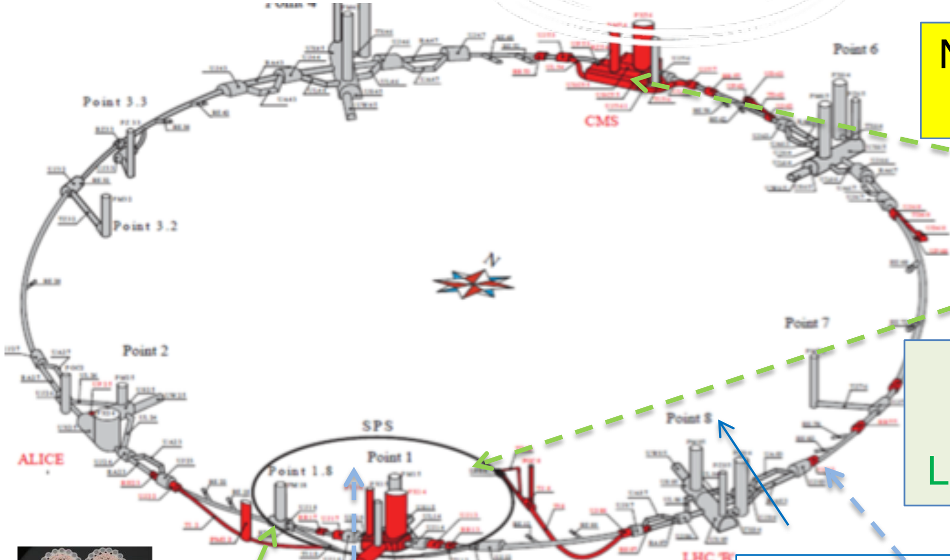
Under Construction
- **FAIR (GSI) ………** *Fast-cycleShnchr.*
- **HL-LHC (CERN)**
- **NICA (JINR)**

Future:
- **EIC (e-Ion)**
- **FCC**-hh / HE-LHC
- **SppC**



Courtesy, L. Rossi, E. Todesco

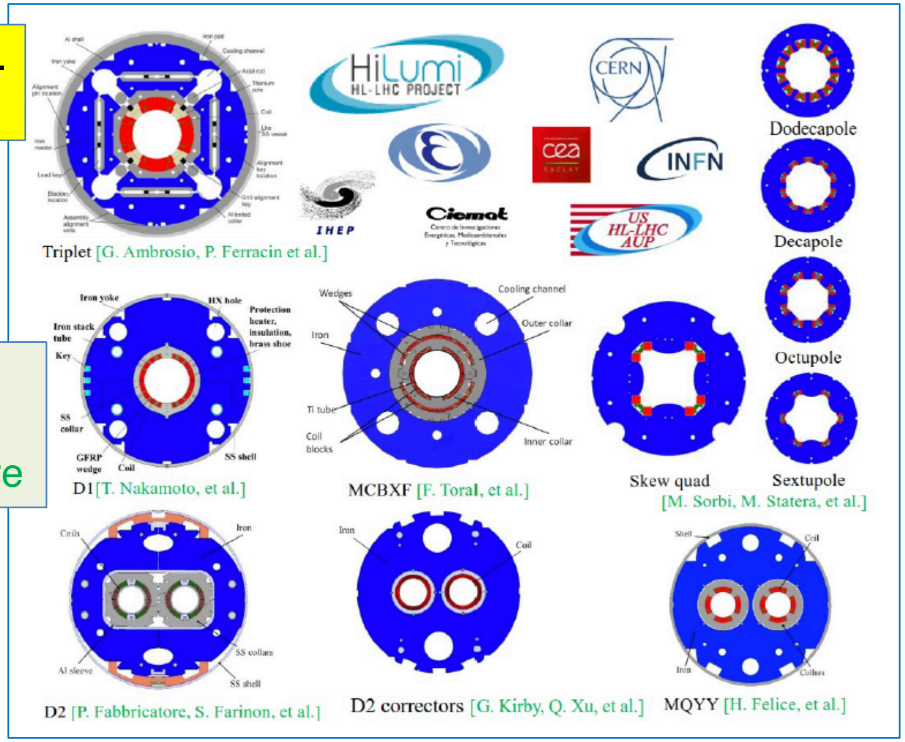
NbTi, Nb_3Sn Superconducting Magnets and MgB_2 SC Links for HL-LHC

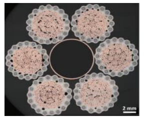


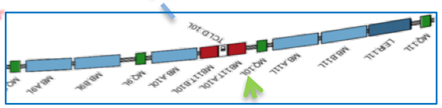
Nb_3Sn Quad. (MQXF)

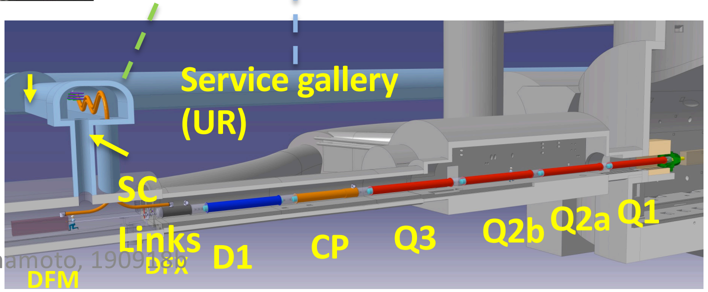
NbTi Mag. (D1, and …)

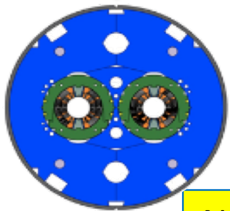
Large aperture











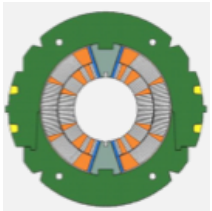
Nb3Sn Dipoles w/ Collimator

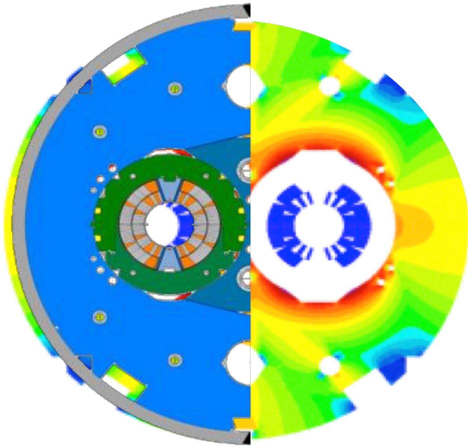
Discussed by L. Rossi

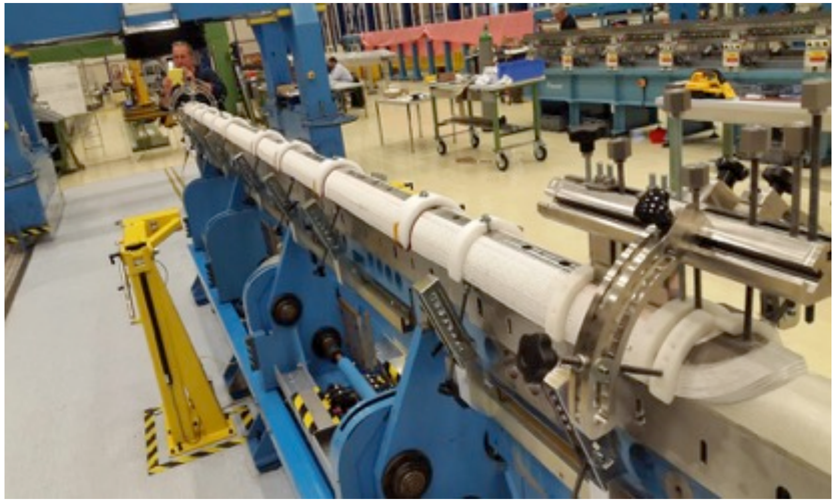
Courtesy, A. Devred, F. Savary, G. Willering

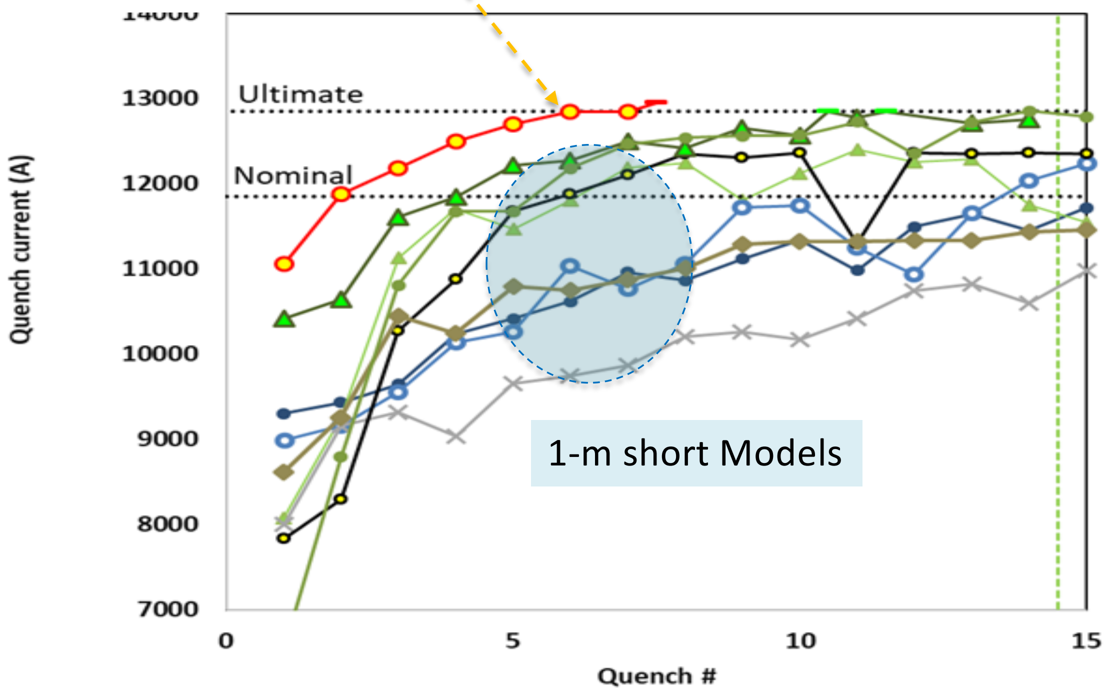
HL-LHC, 11T Dipole Magnet

- The 1st Series, 5.5 m long Dipole, powered as a single aperture in the initial test: Reached
  - **Bc = 11.2 T (at nominal current)**
    I-nominal, after 1 quench,
  - Bc = 12.1 T (at ultimiate current)
    I-ultimate) after 6 quenches.





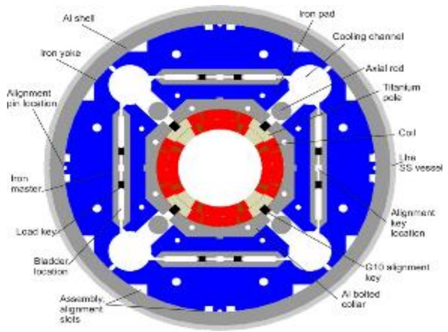




A. Yamamoto, 190918b

Nb_3Sn Quadrupole (MQXF) at IR

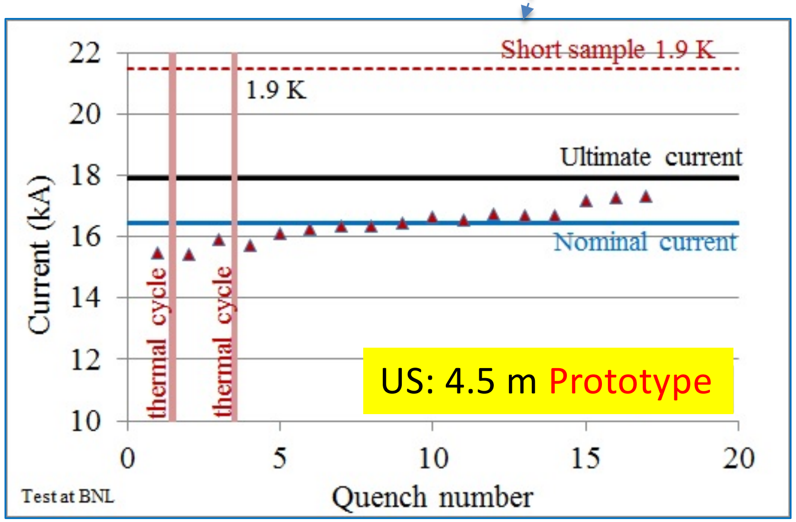
Courtesy,
G. Ambrosio, G. Chlachidze
E. Todesco, P. Ferracin

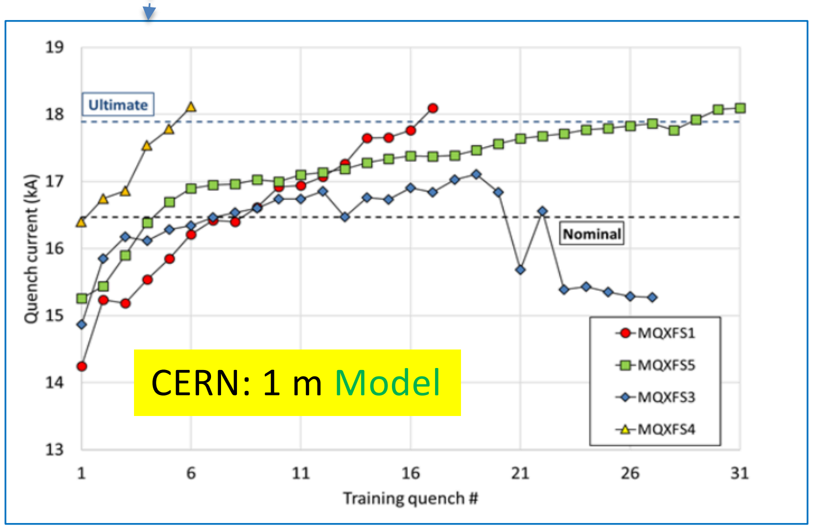


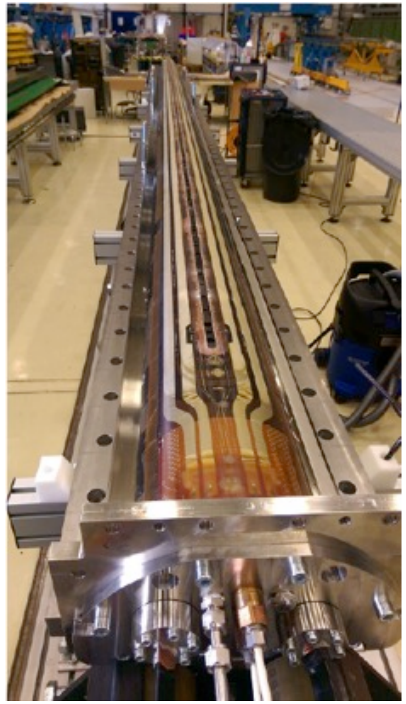
US: 4.5 m Prototype:
- Completed and tested

CERN: 1-m short Models:
- Successfully demonstrated the performance

CERN: 7 m Prototype under development







CERN: 7 m long prototype under development

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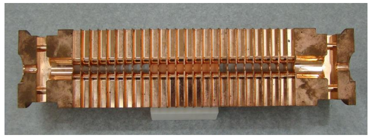
- **Challenges for future, focusing on**
  - Superconducting Technologies for future Lepton and Hadron Colliders
- **Summary**

Courtesy: W. Wuensch

Features of Normal conducting and Superconducting RF

Normal conducting (CLIC)	Superconducting (ILC)
Gradient: 72 to 100 MV/m - Higher energy reach, shorter facility	Gradient: 31.5 to 35 (to 45) MV/m, - Higher efficiency, steady state beam power from RF input
Frequency: 12 GHz - High efficiency RF peak power - Precision alignment & stabilization to compensate wakefields	Frequency: 1.3 GHz - Large aperture gives low wakefields
Q_0: order $< 10^5$, - Resistive copper wall losses compensated by strong beam loading – 40% steady state rf-to-beam efficiency	Q_0: order 10^{10}, - High Q - losses at cryogenic temperatures
Pulse structure: 180 ns / 50 Hz	Pulse structure: 700 μs / 5 Hz
Fabrication: - driven by micron-level mechanical tolerances	Fabrication - driven by material (purity) & clean-room type chemistry
- High-efficiency RF peak power production through klystrons and two-beam scheme	- High-efficiency RF from long-pulse, low-frequency klystrons

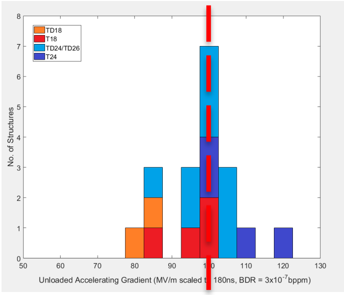


Courtesy: W. Wuensch

Normal Conducting Linac Technology Landscape

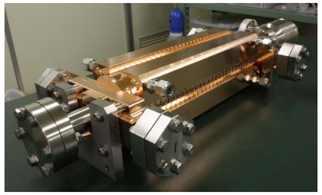
Components:

Laboratory with commercial
- **Accelerating structures**
- pulse compressors
- alignment
- Stabilization, etc.



~ 100 (+/-20) MV/m

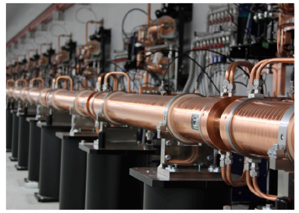
Full commercial supply
- X-band klystrons
- solid state modulator,



Systems Facilities:
(100 MeV-range)

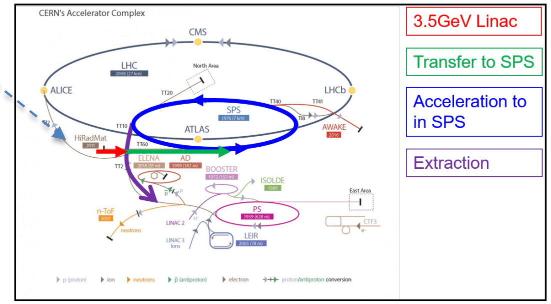
- XBoxes at CERN
- (NEXTEF KEK)
- Frascati
- NLCTA SLAC
- Linearizers at Electra, PSI, Shanghai and Daresbury
- Test stand at Tsinghua
- Deflectors at SLAC, Shanghai, PSI and Trieste
- NLCTA
- SmartLight
- FLASH

C-band (6 GHz),
low-emittance
GeV-range facilities
Operational:
- **SACLA**
- **SwissXFEL (8 GeV)**



X-band (12 GHz)
GeV-range facilities
Planning:
- **Eu-Praxia**
- **e-SPS**
- **CompactLight**

CLIC



Advances in SRF Technology for Accelerators

Progress (1988~)
- TRISTAN
- LEP-II
- HERA
- CEBAF
- CESR
- KEKB
- BES
- cERL

In Operation/Construction:
- **SNS: 1 GeV**
- **CEBAF 12 GeV → 80**
- **ISAC-II, ARIEL**
- **Super-KEKB**
- **Eu-XFEL → 800**

Under Construction:
- **LCLS-II → 300**
- **FRIB → 340**
- **PIP-II → 115**
- **ESS→ 150**
- **Shine → 600**

To be realized:
- HL-LHC-Crab → 20
- EIC
- **ILC-250 → 8,000**
- FCC
- CEPC/SPPS

1980 — 2000 — 2020








> **2,000** SRF cavities realized, in last 10 years !

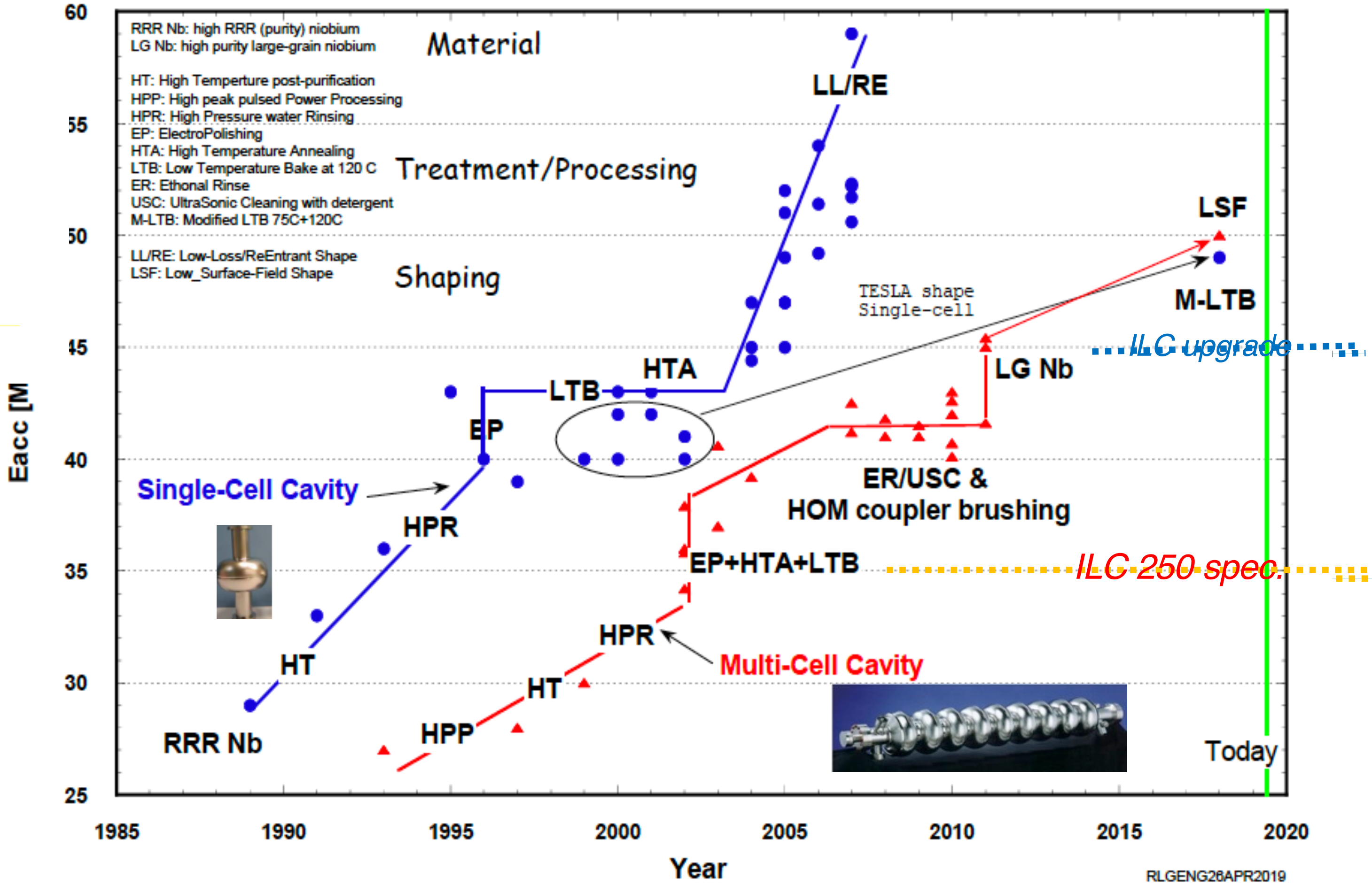
Courtesy: R. Geng,

Advances in L-band (~ 1GHz) SRF Cavity Gradient

Field Gradient | Surface | Material

$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$

Thermal conductance | Surface, | Shape



A. Yamamoto, 190918b

Courtesy, H. Weise, N. Walker

European XFEL, SRF Linac Completed and in Operation

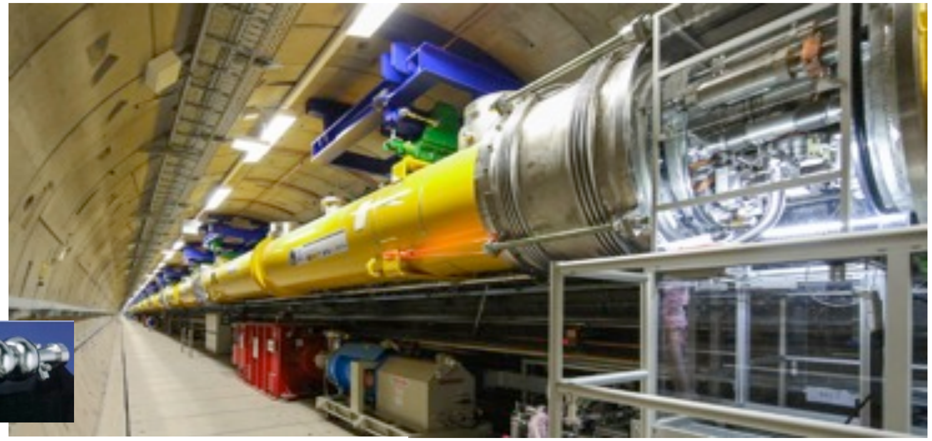
URL: http://www.desy.de/news/news_search/index_eng.html

2018/07/17

Back

European XFEL accelerator reaches its design energy

Accelerator accelerates electrons to 17.5 GeV for the first time



Progress:

2013: Construction started

2016: E- XFEL Linac completion

2017: E-XFEL beam start

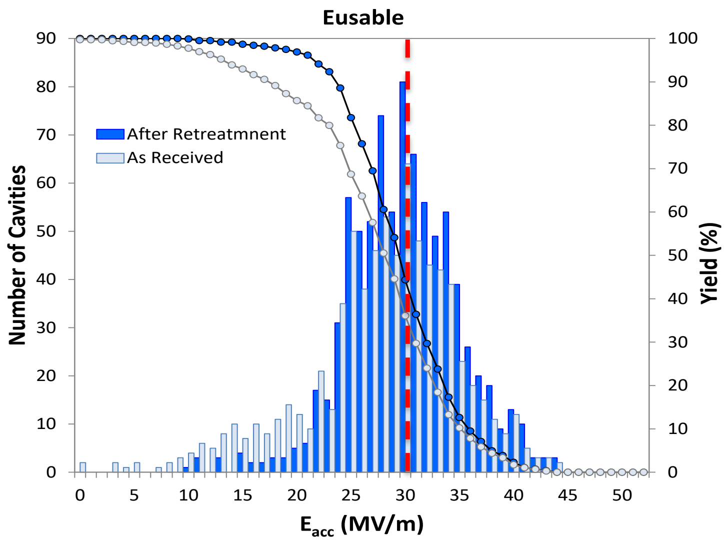
2018: 17.5 GeV achieved

1.3 GHz / 23.6 MV/m

800+4 SRF acc. Cavities

100+3 Cryo-Modules (CM)

: ~ 1/10 scale to ILC-ML



After Re-treatment:

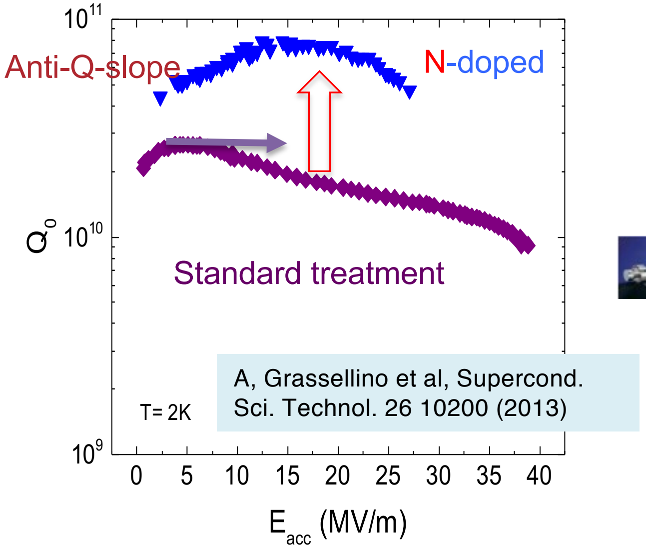
E-usable: 29.8 ± 5.1 [MV/m]

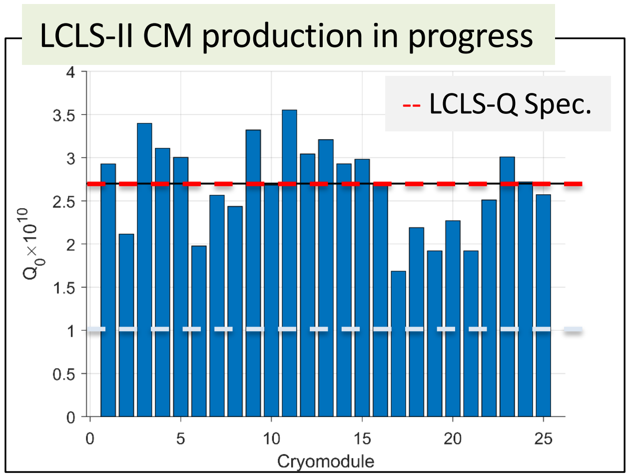
>10 % (47/420, RI) cavities exceeding 40 MV/m

A. Yamamoto, 190918b

Courtesy, M. Ross

LCLS-II SRF Linac (SLAC/Fermilab/JLab Collaboration)





1 km SCRF-CW Linac

- > x 2 **Q** achieved,
- N-doping at 800C,discovered by A. Grasellino et al.

SRF e-Linac Parameters

Beam: 4 (+ 4) GeV, up to 0.3 mA

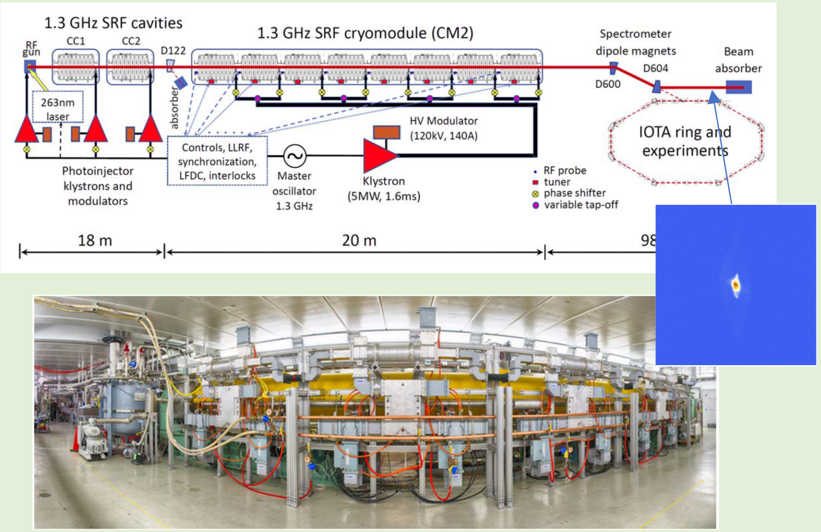
SRF cavity:

- Frequency : 1.3 GHz, CW
- G: 18 ~21 MV/m
- Q: > 2.7 e10 (av.)
- # cavity = 280 (+160)
- # CM 35 (+20)

To be completed in 2020 (~2026)

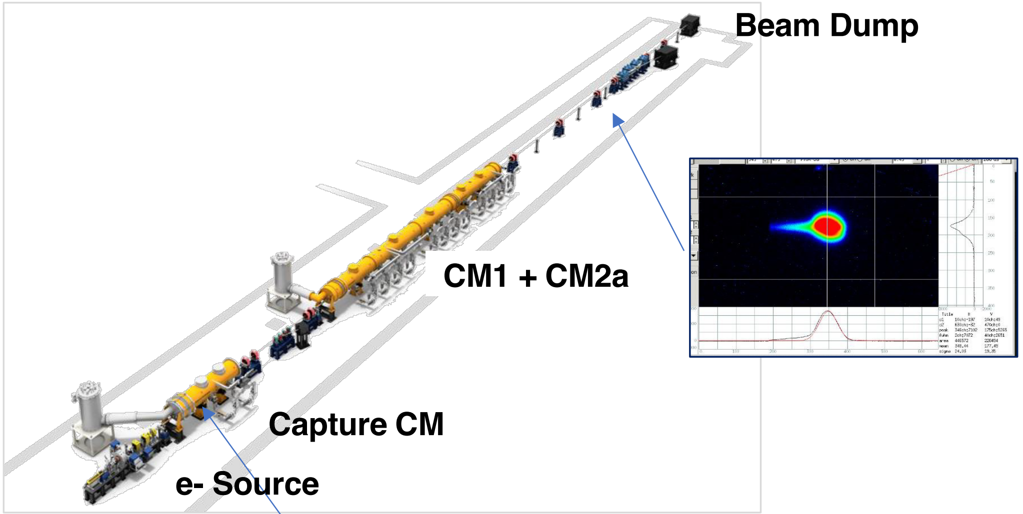
Courtesy: V. Shiltsev, S. Michizono

Fermilab, KEK achieving ILC Gradient Goal ≥ 31.5 MV/m with beam



Beam Acc. : 260 MeV by 8 Cavities,
<G> = 32.3 MV/m

Fermilab-FAST Progress, 2017



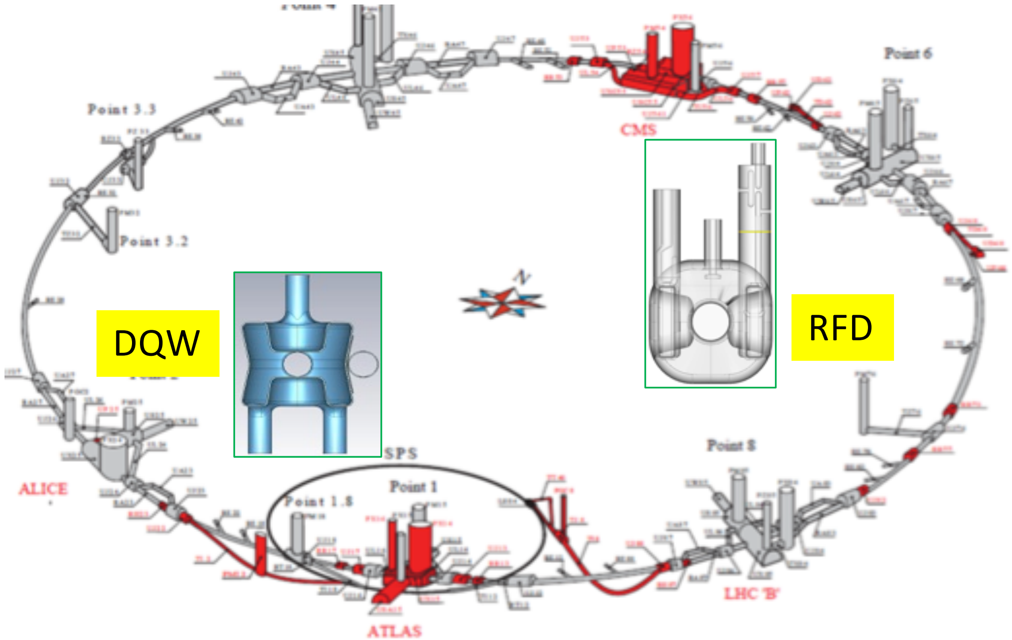
Beam Acc. : 230 MeV by 7 Cavities,
<G> = 32 MV/m

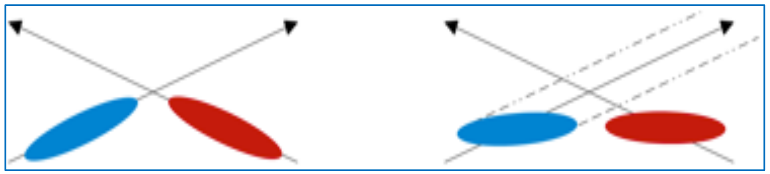
KEK-STF2 Progress, 2019

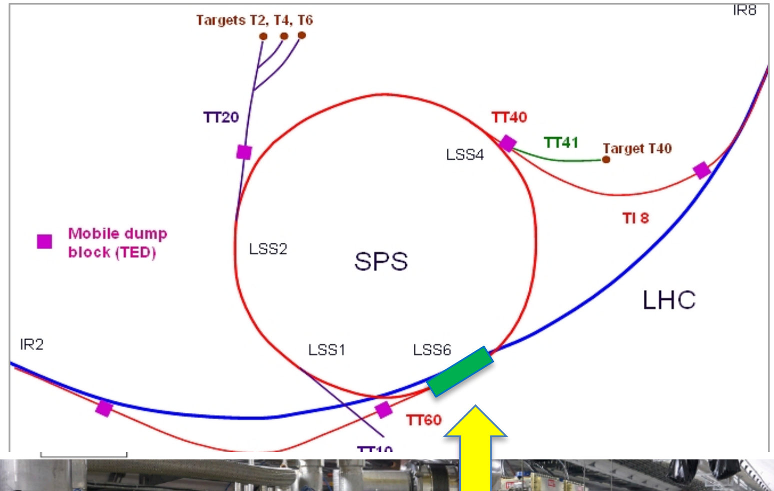
Nb SRF Crab Cavities for HL-LHC

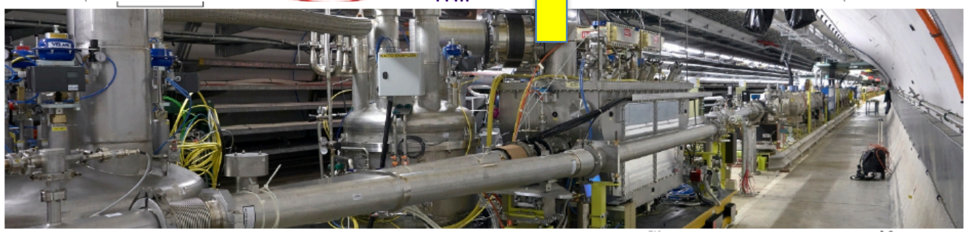
Courtesy,
R. Calaga, O. Capatina,
A. Ratti, L. Ristori

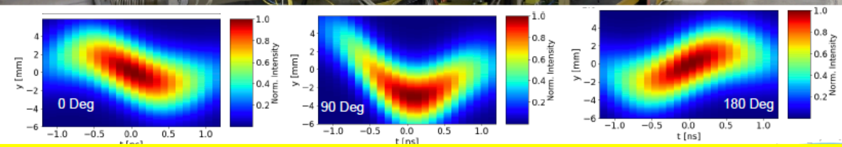
CERN, US-AUP, STFC, TRIUMF Collaboration











Crabbing p beam demonstrated at SPS, 2018

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Future Colliders to be "Green Accelerators"

Linear Colliders (energy extendable):

ILC- e+e- (2 x 125 → 1000 GeV) :

- SRF beam acceleration, High efficiency

CLIC- e+e- (2 x 190 → 3000 GeV) :

- NRF two beam acceleration,

Circular Colliders (max. energy fixed):

FCC-e+e- (2 x 175 GeV):

- SRF beam acceleration and compensation for synchrotron radiation

FCC-hh (2 x 50 TeV):

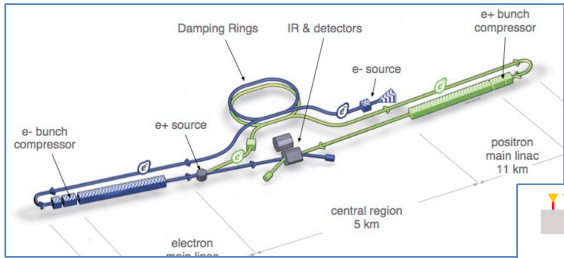
- SC magnets to handle circulating beam
- SRF beam acceleration

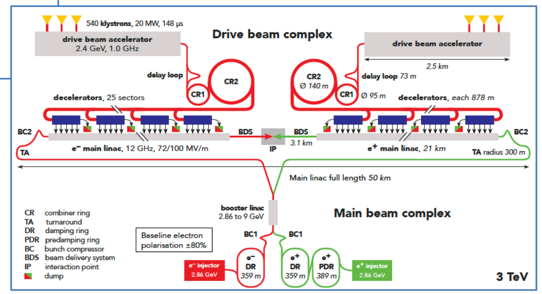
CEPC e+e- (2 x 120 GeV):

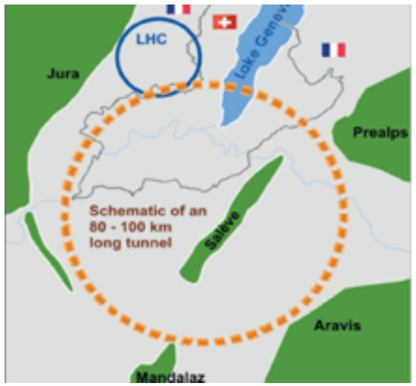
- SRF beam acceleration, in particular, for compensation for synchrotron radiation

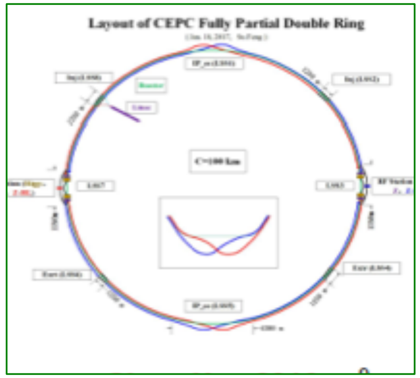
SPPC- pp (2 x 50 GeV):

- SC magnets to handle circulating beam
- SRF beam acceleration









Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CC hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CC ee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10 – 20 (0.4 - 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 – (40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LC ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	4.8- 5.3 (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

*Cost estimates are commonly for "**Value**" (material) only.

Technical Challenges in Energy-Frontier Colliders proposed

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		filled)	120			TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
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LC ee	ILC	TDR update	(-1)	(– 4.9)	(– 300)	(for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC		(– 3)	(– 6)	160 (– 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

Major Technical Challenges:

Hadron Colliders:

- High-field magnet
- Energy management

Lepton Colliders:

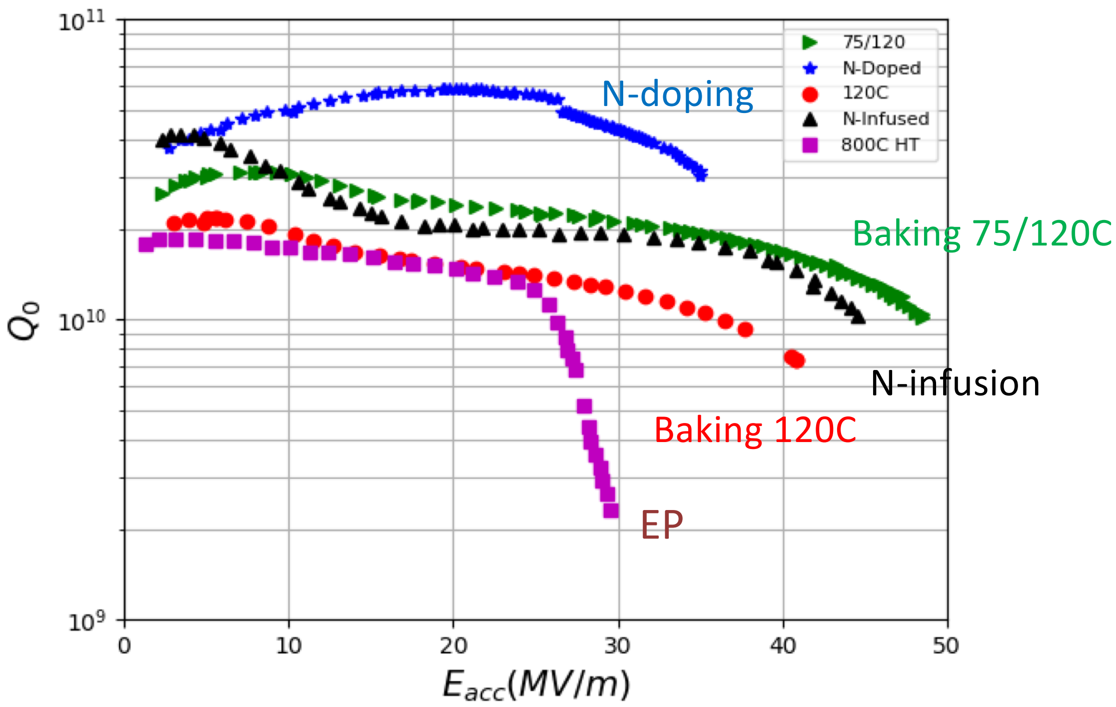
- SRF cavity: High-Q and -G (to prepare for upgrade)
- NRF acc. Struct.: large scale, alignment, tolerance, timing
- Energy management

A. Yamamoto, 190918b

*Cost estimates are commonly for "**Value**" (material) only.

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

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

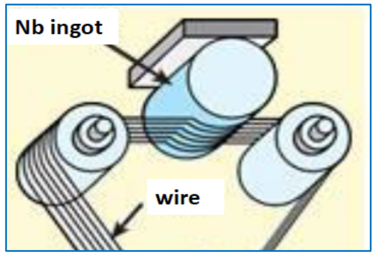


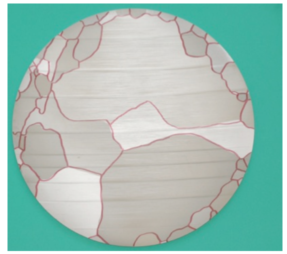
- **N-doping** (@ 800C for ~a few min.)
  - Q >3E10, G = 35 MV/m
- **Baking w/o N** (@ 75/120C)
  - Q >1E10, G =49 MV/m (Bpk-210 mT)
- **N-infusion** (@ 120C for 48h)
  - Q >1E10, G = 45 MV/m
- **Baking w/o N** (@ 120C for xx h)
  - Q >7E9, G = 42 MV/m
- **EP** (only)
  - Q >1.3E10, G = 25 MV/m

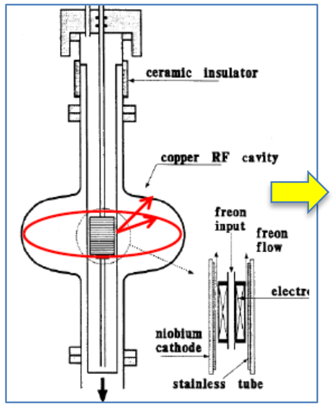
- **High-Q** by **N-Doping** well established, and
- **High-G** by N-infusion and **Low-T baking** still to be understood and reproduced, worldwide.

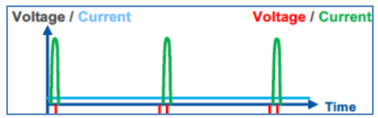
Challenges in SRF Cavity Technology

- **Bulk-Nb:**
  - **High-G and -Q optimization**
    - Low-T treatment w/ or w/o N-infusion.
  - **Large-Grain (LG) directly sliced from ingot**
    - For possible less contamination and cost-reduction
- **Thin-film Coating**
  - **Nb thin-film** coating on **Cu**-base cavity structure
    - Important for lower frequency and/or low-beta application.
    - A New approach to realize flatter Q-slope (higher-Q)
    - **H**igh **P**ower **I**mpulse **M**agnetron **S**puttering (HiPIMS) , instead of
    - **DC M**agnetron **S**puttering (DCMS)
  - **Nb_3Sn** / **MgB_2** film coating on **Nb** or **Cu**
    - To reach much higher G, with higher B_c (B_{sh})





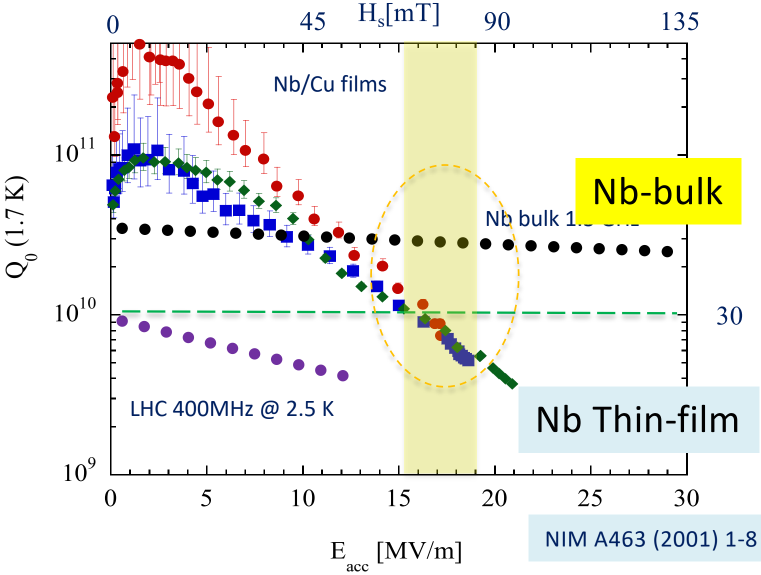




Courtesy: S. Calatroni

DC Magnetron Sputtered Nb/Cu Films

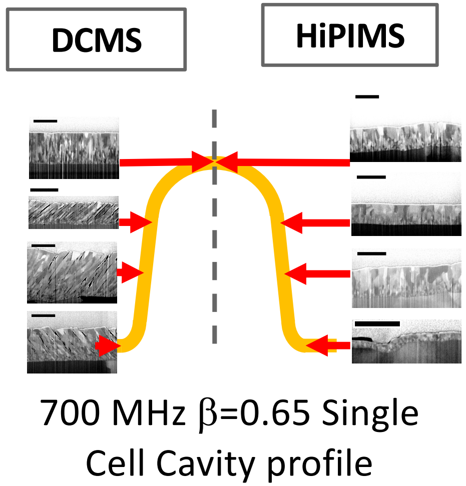
1.5 GHz Nb/Cu cavities, sputtered with Kr @ 1.7 K (Q_0=295/R_s)

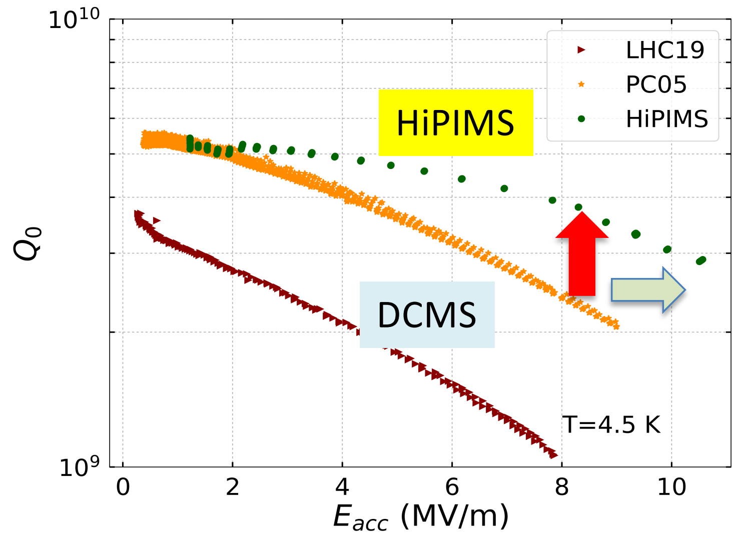


NIM A463 (2001) 1-8

HiPIMS coatings – QPR Sample

To be important challenge for < 600 MHz (FCC)





- Q = 1×10^{10} @ 15 MV/m, for thin-film cavities:
  - competitive option in several future projects.
- R&D focused on:
  - improving the "slope"

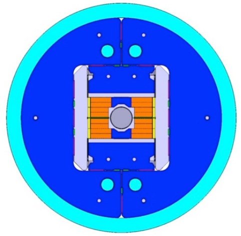
- HiPIMS Nb/Cu to be comparable to bulk Nb on quadrupole resonator sample at 400, 800 and 1,300 MHz.
  - To be discussed more by M. Benedikt (in Acc. Session).
- Q-slope seems to be flatter
  --> High-Q, resulting **Power Saving**,
- Projected performance > 2x better than LHC specifications

Outline

- Introduction
- State of the Art in Accelerator Technology, focusing on
- Challenges for future, focusing on
  - **Superconducting technology** for future Lepton and Hadron Colliders
  - **Energy Management**
- Summary

Courtesy: G. De Rijk, A. Devred

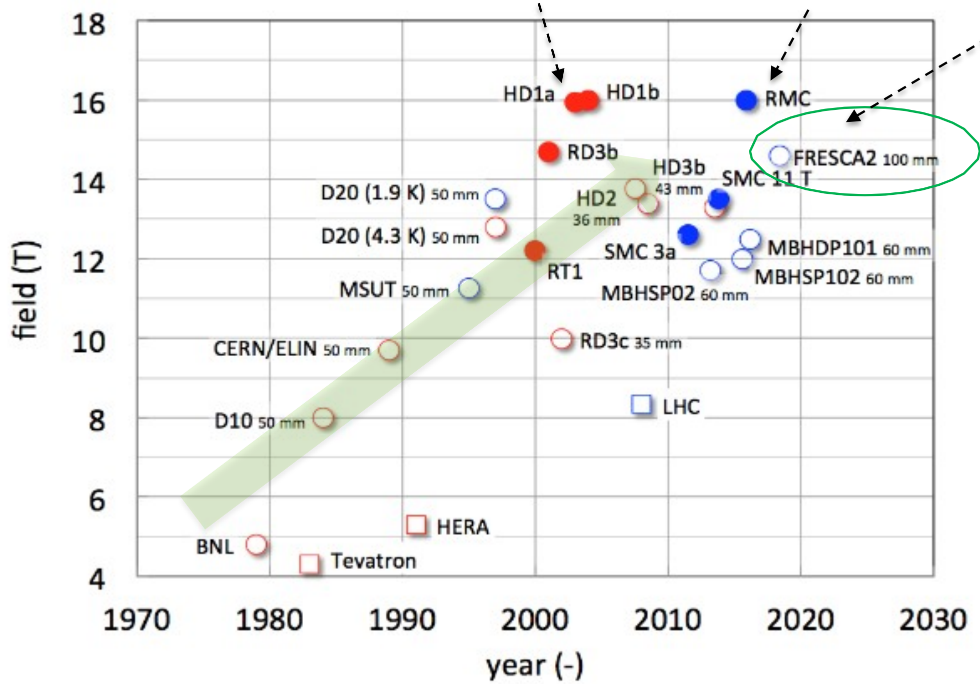
Advances in Nb_3Sn Magnet Development

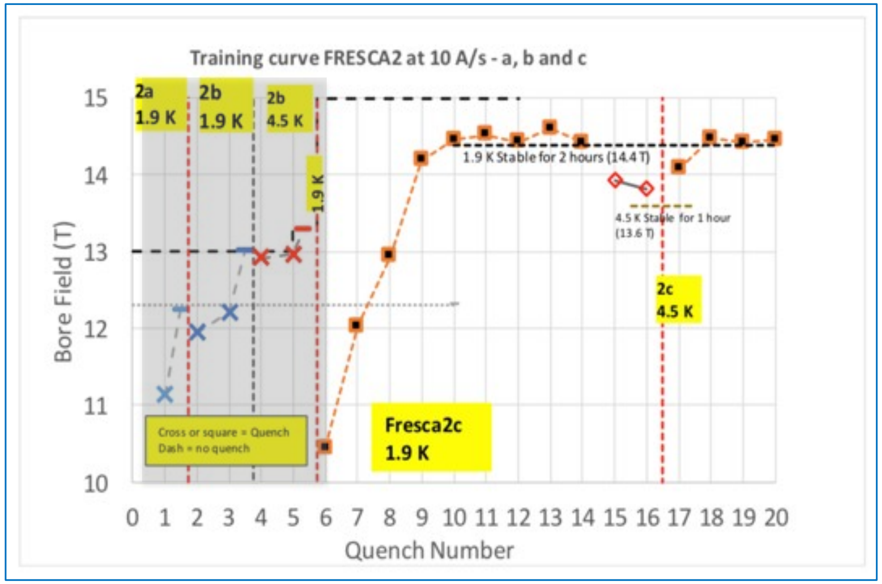


2003: LBNL HD1
(16 T at 4.2 K)

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)





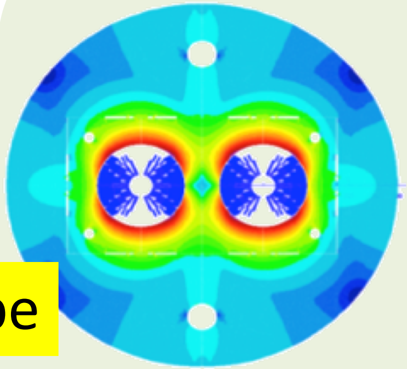
Courtesy, M. Benedikt, L. Bottura, D. Tommasini, S. Prestemon

FCC hh ee he

16 T Dipole R&Ds in Europe and US

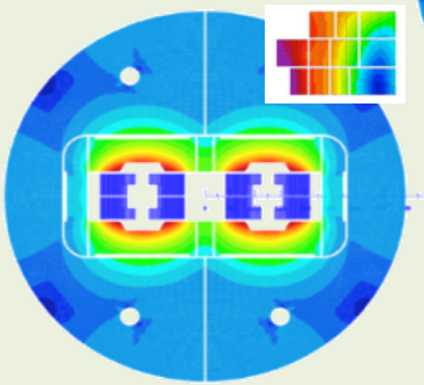
Europe

Cos-θ

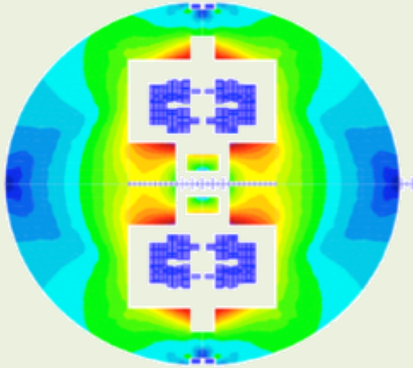


EuroCirCol A key to New Physics

Blocks



Common coils



Pioneering work at BNL

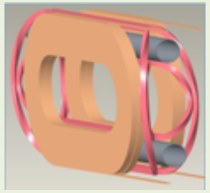
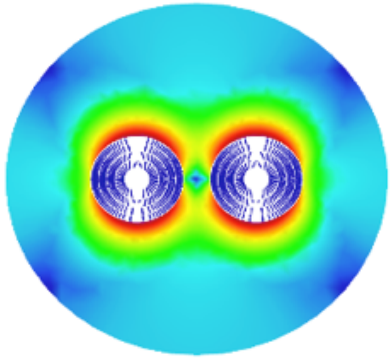


CHART2
Swiss Acc. Research & Technology

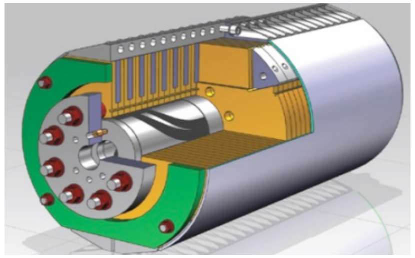
Canted Cos-θ (CCT)

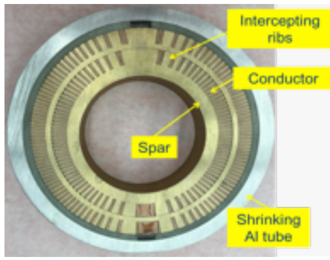


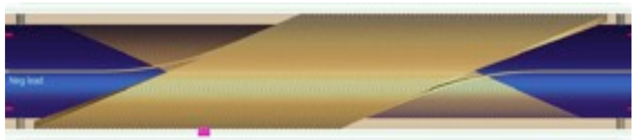
US

U.S. MAGNET DEVELOPMENT PROGRAM

Cos-θ







CCT,
Pioneering work at LBNL

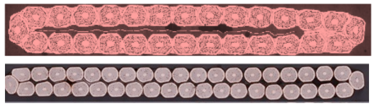
Courtesy: S. Prestemon S. Belomstnykh

US-DOE MDP taking Steps to realize 16 T

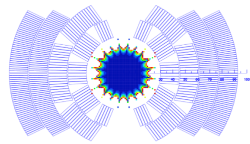
MDP Goals:

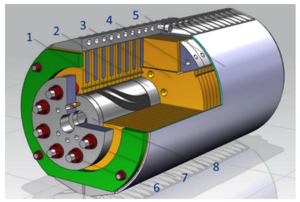
1. Explore Mb_3Sn magnet limit
2. Demonstrate HTS magnet (5 T – self fied)
3. Investigate fundamentals for performance and cost reduction
4. Pursue Nb3Sn and HTS conductor R&D

- **Step 1:** (we are here in 2019)
  - Realize 14 T w/ mechanical design for 16 T
  - Will be **tested soon (2019).**
- **Step 2:**
  - Realize 15 T w/ pre-stress optimization
- Step 3:
  - Challenge to realize 16 T, with SC conductor satisfying 1,500 A/mm2 and sufficiently controlled mechanical design



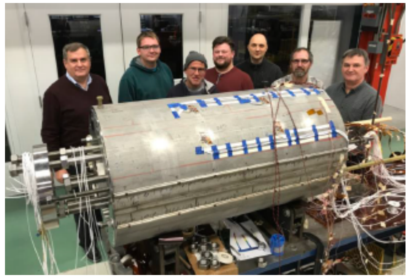
L1-L2: 28 strands, 1 mm RRP 150/169
L3-L4: 40 strands, 0.7 mm RRP 108/127





Before test, at Fermilab

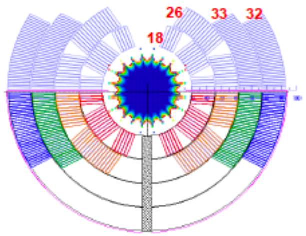
US-MDP 15 T Dipole : Exceeding 14 T



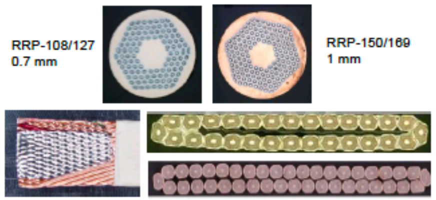
U.S. MAGNET DEVELOPMENT PROGRAM

15 T Dipole design

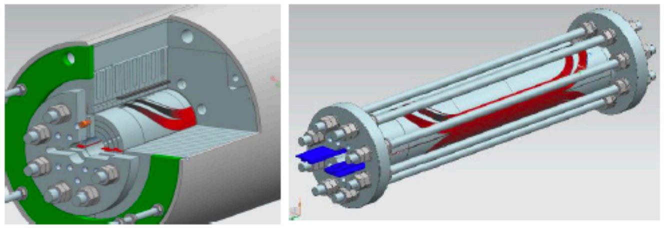
➢ **Coil** (V.V. Kashikhin et al.):
- 60-mm aperture, 4-layer graded coil
- W_{sc} = 68 kg/m/aperture



➢ **Cable** (E. Barzi et al.):
- L1-L2: 28 strands, 1 mm RRP150/169
- L3-L4: 40 strands, 0.7 mm RRP108/127
- 0.025 mm x 11 mm SS core
- Insulation: E-glass tape

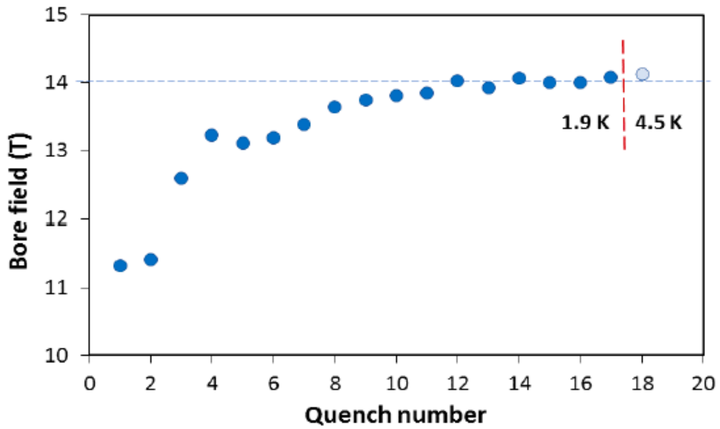


➢ **Innovative mechanical structure** (I. Novitski et al.):
- Thin StSt coil-yoke spacer
- Vertically split iron laminations
- Aluminum I-clamps
- 12-mm thick StSt skin
- Thick end plates and StSt rods
- Cold mass OD<610 mm



U.S. MAGNET DEVELOPMENT PROGRAM

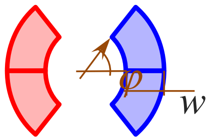
Maximum field achieved



- First quenches above 11 T
- Maximum bore field at 4.5 K
  - measured 14.10±0.04 T
  - calculated (COMSOL, V.V. Kashikhin) 14.112 T

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 !!

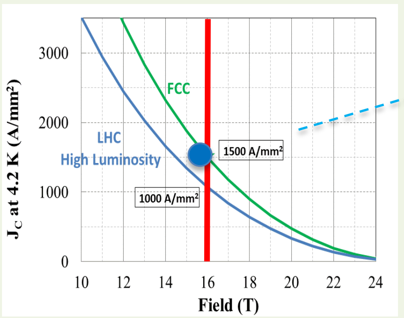
$$B = \frac{2\mu_0}{\pi} J w \sin(\phi)$$

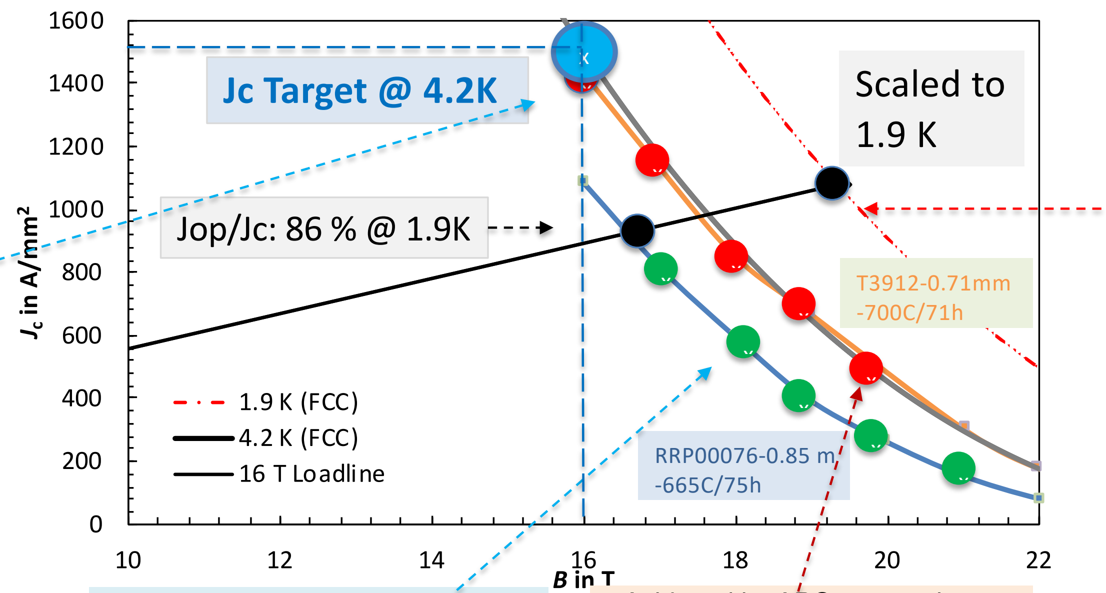
Main development Target:

- **J_c (16T, 4.2K) > 1500 A/mm²**
  - 50% higher than HL-LHC

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)

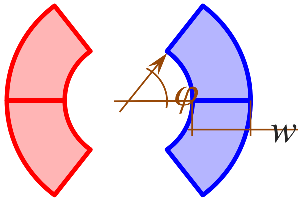
- Achieved by APC approach: X. Xu et al (Fermilab)

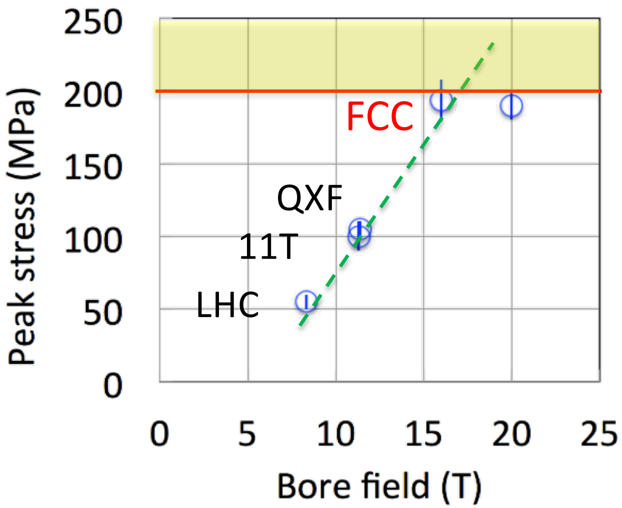
https://arxiv.org/abs/1903.08121

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

Courtesy: L. Bottura, A. Devred

Mechanical Constrain to consider Operating Margin



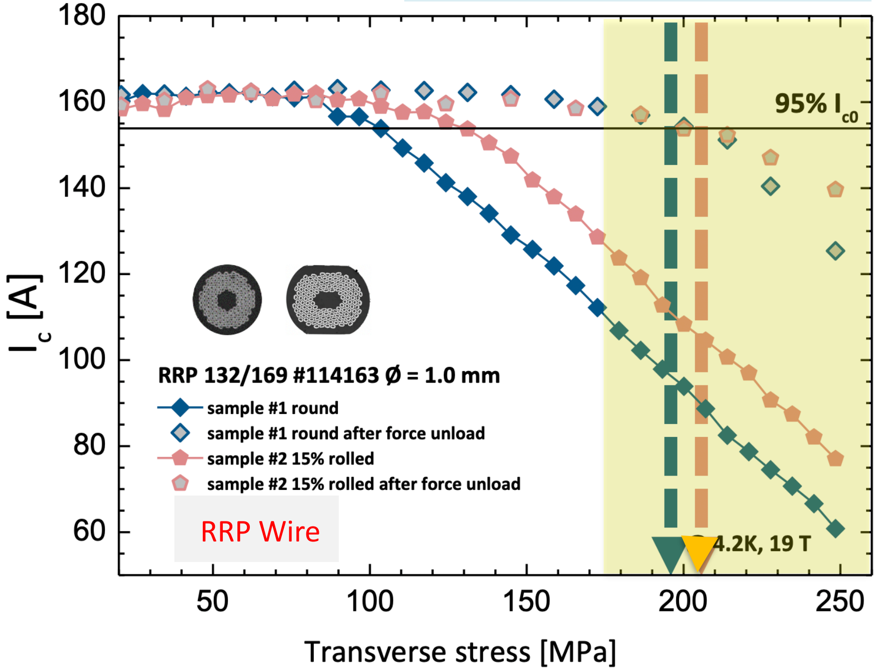


$$F \propto B^2, \quad w \propto \frac{B}{J} \quad \longrightarrow \quad \sigma \approx \frac{F}{w} \propto JB$$

or

$p \sim B^2$

Measurement at Univ. Geneve

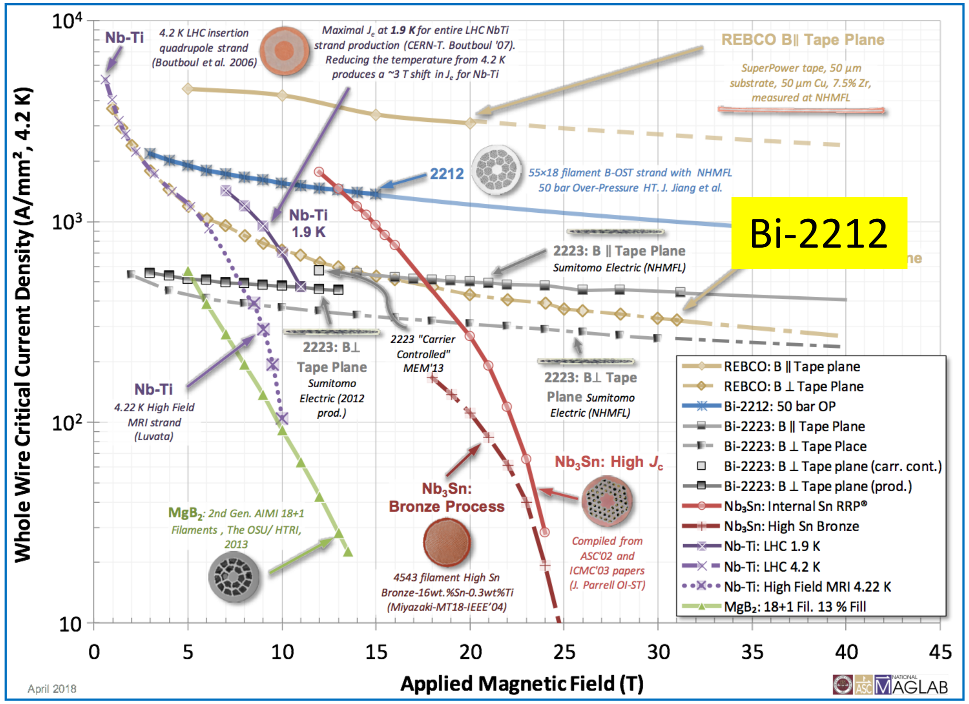


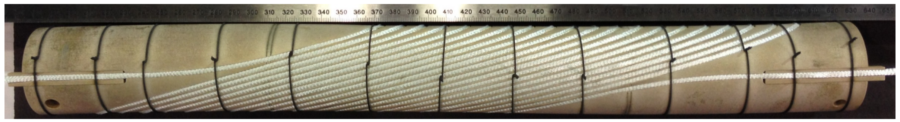
Attention, I_c (J_c) reduction:

- reversible at <150 MPa (~15% at 11.6 T),
- irreversible at >170 MPa.

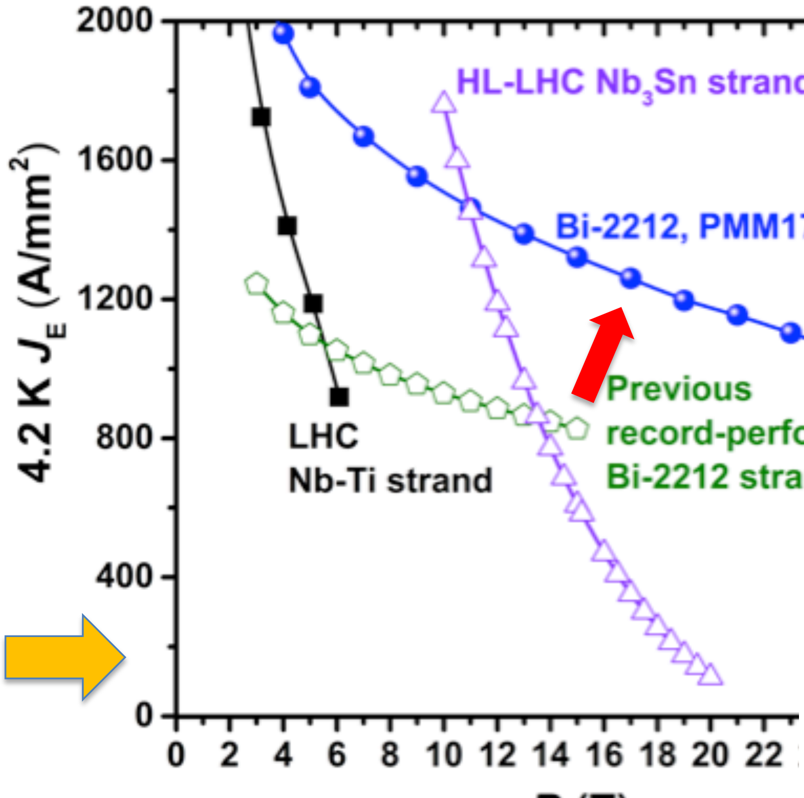
as a critical constraint because of fundamental mechanical property.

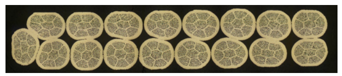
Prospect for HTS in focus to Bi2212 in the US





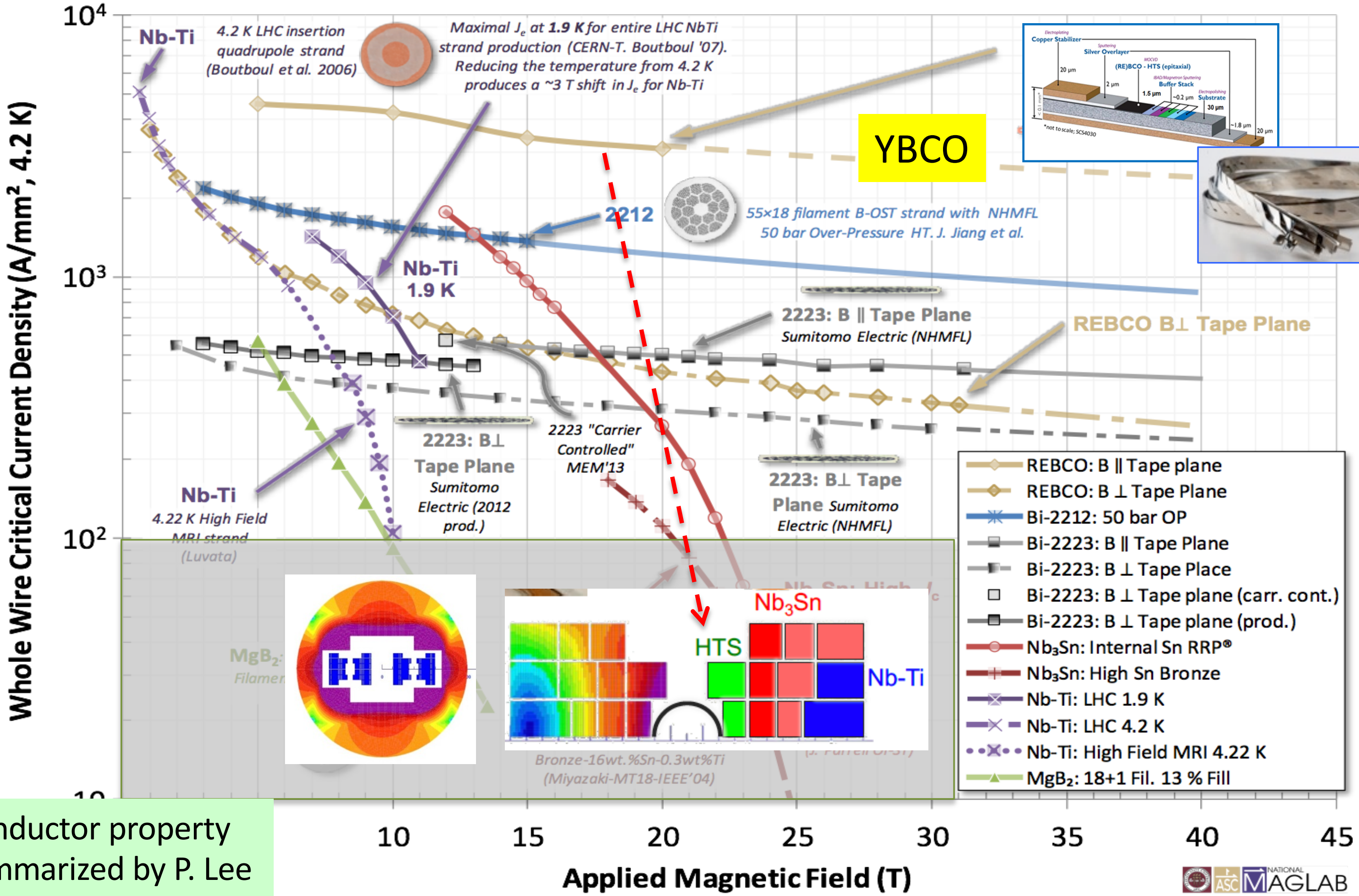
Application expected for CCT by using B2212





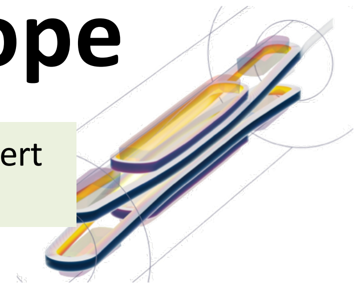
Courtesy, P. Lee, L. Rossi, G. De RIjk

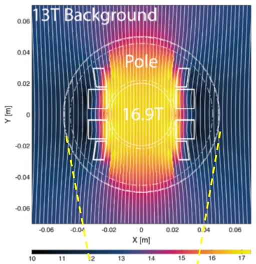
HTS, Rebco (YBCO) SC/Magnet in Europe



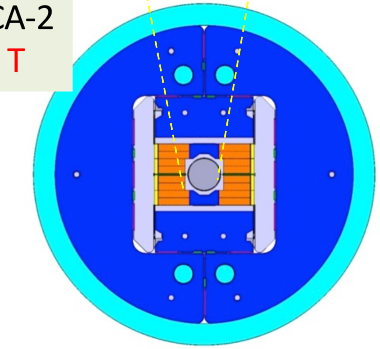
Conductor property summarized by P. Lee

HTS-Insert
3~5 T





FRESCA-2
13-14 T



Eucard2: HTS-insert to be tested in 2019
(3-5) + (13-14)T : > 16 T

Courtesy: Ph. Lebrun, S. Claude

Key Issues in Energy Management

in both Energy- and Intensity-frontier Accelerators

- **Energy Saving**
  - Superconducting technology (partly covered in this talk)
- **System Efficiency Improvement**
  - Power system efficiency
  - RF modulator and Klystron,
    - Two beam acceleration
  - Cryogenics system efficiency
    - Depending on operational temperature (such as SR heat removal by Ne=He cycle)
  - Efficient beam dynamics
    - Low-emittance/nano-beam,
  - Novel, accelerator scheme
- **Dynamic Energy Balance**
  - **Power** (W) to **Energy** (W-hour) efficiency
  - Dynamic operation in best optimized season/day/time.
  - Re-use/Recycling energy in cooperation with wider community

Outline

- **Introduction**
- **State of the Art in Accelerator Technology, focusing on**
- **Challenges for future, focusing on**
  - Superconducting technology for future Lepton and/or **Hadron Colliders**
- **Comments on**
  - **Complementarity of Energy-Frontier and Intensity-Frontier, and Energy Management**
- **Summary**

Personal Prospect (1/2)

- Accelerator Technologies are ready to go forward for **lepton colliders** (ILC, CLIC, FCC-ee, CEPC), focusing on the Higgs Factory **construction to begin in > ~5 years.**
- SRF accelerating technology is well **matured** for the realization including cooperation with industry.

- Continuing R&D effort for higher performance is very important for future project upgrades.
  - **Nb-bulk, 40 – 50 MV/m**: ~ 5 years for single-cell R&D and the following 5 – 10 years for 9cell cavities statistics to be integrated. Ready **for the upgrade**, **10 ~ 15 years.**

Personal Prospect (2/2)

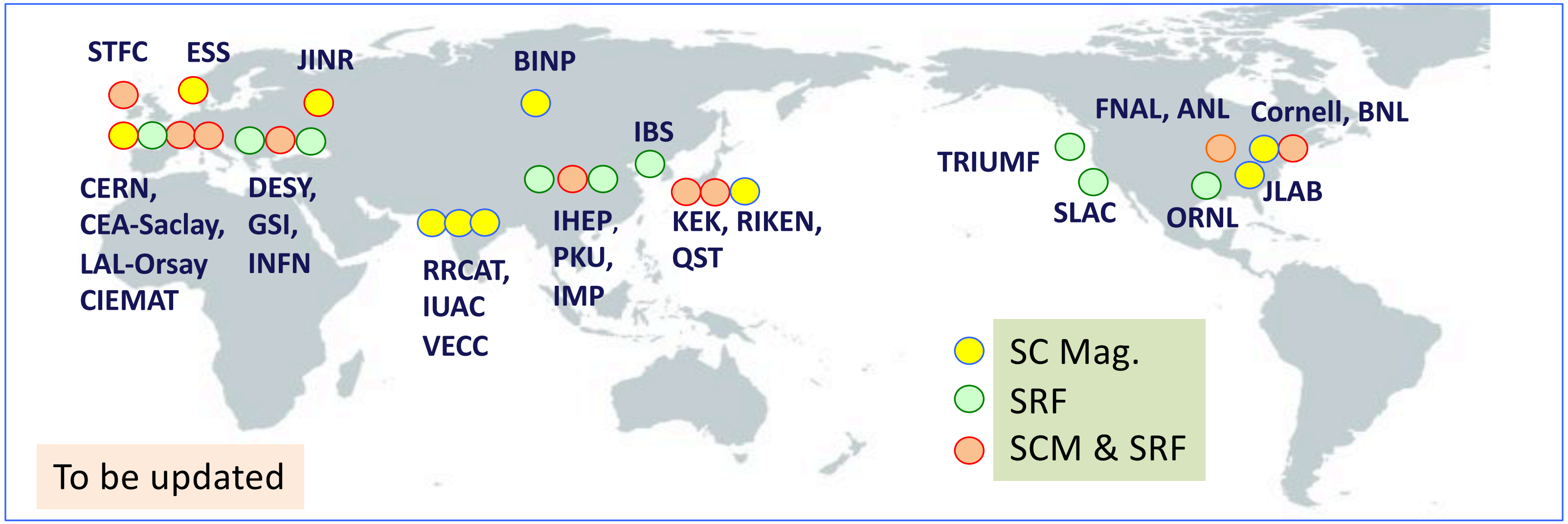
- Nb_3Sn superconducting magnet technology for hadron colliders, still requires **step-by-step** development to reach **14, 15, and 16 T**.
- It would require the following **time-line** (in my personal view):
  - **Nb_3Sn, 12~14 T:** 5~10 years for short-model R&D, and the following 5~10 years for prototype/pre-series with industry. It will result in **10 – 20 yrs** for the construction to start,
  - **Nb_3Sn, 14~16 T:** 10-15 years for short-model R&D, and the following 10 ~ 15 years for protype/pre-series with industry. It will result in **20 – 30 yrs** for the construction to start, (consistently to the FCC-integral time line).
  - **NbTi , 8~9 T:** proven by LHC and **Nb_3Sn, 10 ~ 11 T** being demonstrated. It may be feasible for the construction to begin in > ~ 5 years.
- **Continuing R&D effort** for high-field magnet, present to future, should be critically **important**, to realize highest energy frontier hadron accelerators in future.

Personal View on Relative Timelines

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF—LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collier (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction		Operation			Upgrade
12~14T Nb_3Sn	Short-model R&D		Proto/Pre-series	Construction		Operation	
14~16T Nb_3Sn	Short-model R&D			Prototype/Pre-series		Construction	

Note: **LHC experience**: **NbTi (10 T)** R&D started in 1980's --> (**8.3 T)** Production started in late 1990's, in **~ 15 years**

Global Future of the Superconducting Technology for Particle Accelerators,



Future projects/Studies to be realized / anticipated

- Particle/Nuclear Phys.: ILC, FCC/HE-LHC, CEPC-SppC, JLEIC / eRHIC, and …
- Photon Science: CW-XFEL, and …
- Neutron Sources: CSNS, and …
- Medical Applications: Therapy, and further to be extended
- Industrial Applications: to be extended

Summary

- **Superconducting technology will be inevitable** to approach any energy/power frontier particle accelerators, increasing energy and saving power consumption, (**Green Accelerators**).

- **High-field (> 10 T) magnet technology** is being **matured** with Nb3Sn superconductor, to be applied in real projects, and further investment and cost-saving will be inevitably required for far future energy/power frontier. HTS needs to be matured in magnet technology and the cost saving in mass production will be a key for future accelerator application.

- **SRF technology** has been much **advanced** in past 20 years, **with bulk Nb** technology. **Thin-film** science and technology **will be a key** for extending the field gradient and for saving cooling power in future application expansion, as well as ERL SRF technology.

- The superconducting technology will be extended to wide range of science and technology including Pphoton science, Spallation neutron sources, Medical application, and further **industrial** applications.

Acknowledgments

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  - *CEPC-SPPC study at IHEP, and*
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    - *Fermilab, LBNL, BNL, JLab, Cornell, SLAC, CERN, CEA-Saclay, LAL-Orsay, DESY, STFC, ESS, KEK, ...*

GARD-SRF

CEPC/SPPC

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Reserved

Outline

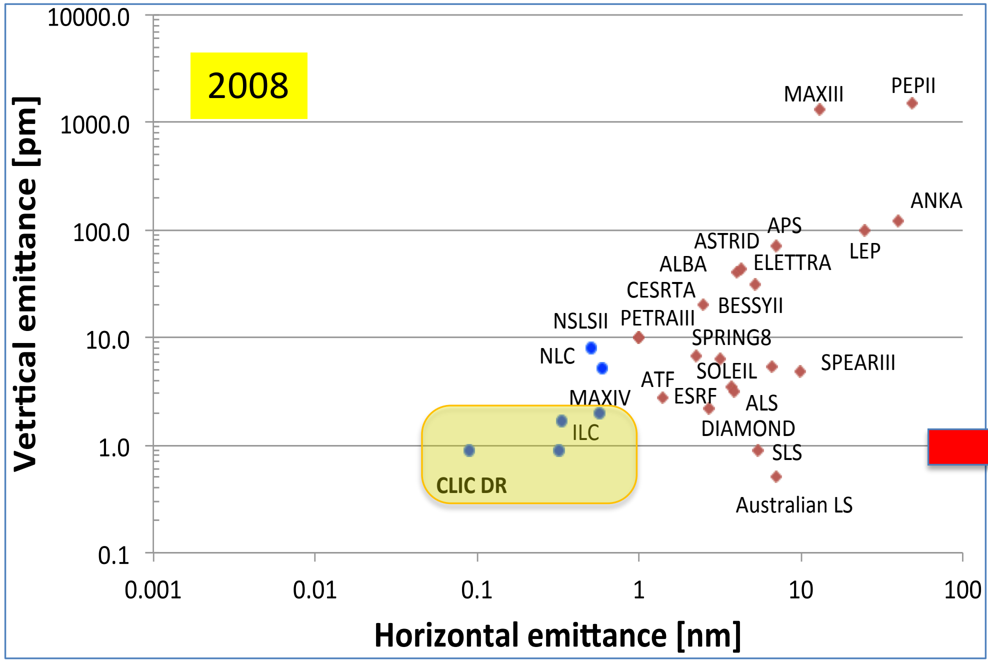
- **Introduction**
- **State of the Art in Accelerator Technologies**, focusing on
  - **Nano-beam**,
  - Superconducting Magnet and Superconducting/Normal-conducting RF
- **Challenges for future, focusing on**
  - Superconducting technologies for future Lepton and Hadron Colliders
- **Summary**

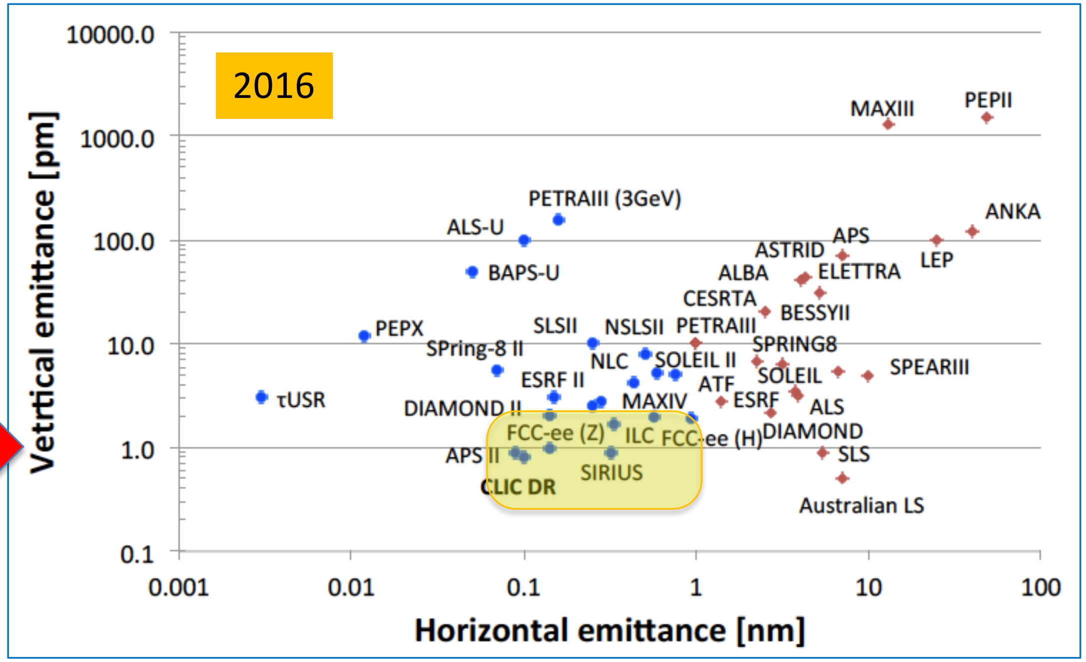
Courtesy: S. Stapnes

Low-emittance achieved in past 10 years

to be discussed more by V. Shelitsev and S. Stapnes

- **Low emittance beam** sufficiently advanced for future colliders





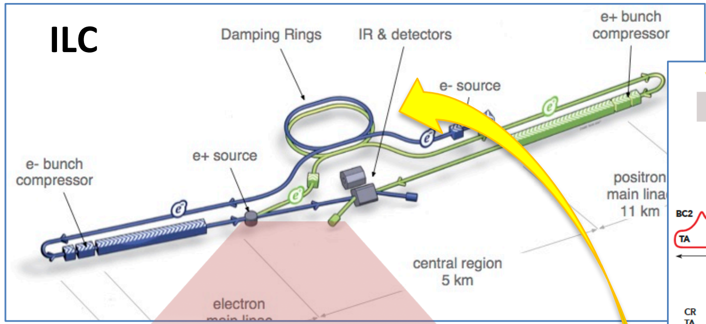
ATF/ATF2: Accelerator Test Facility

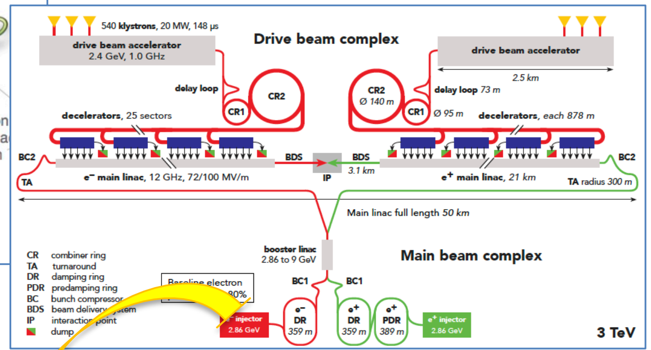
Courtesy: N. Terunuma

to be discussed more by V. Shelitsev and S. Stapnes

Develop nano-beam technology for ILC/CLIC

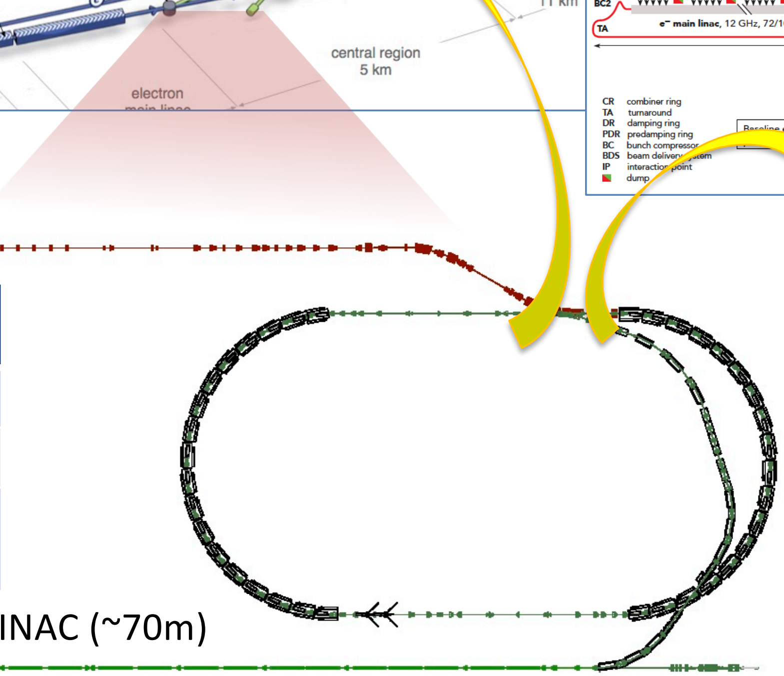
- Goal: Realize small beam-size and theStabilize beam position





FF: Nano beam-size

	B Energy [GeV]	Vertical Size
ILC-250	125	7.7 nm
CLIC-380	190	2.9 nm
ATF2 (achieved)	1.3	41 nm (-->8 nm eq. at ILC)



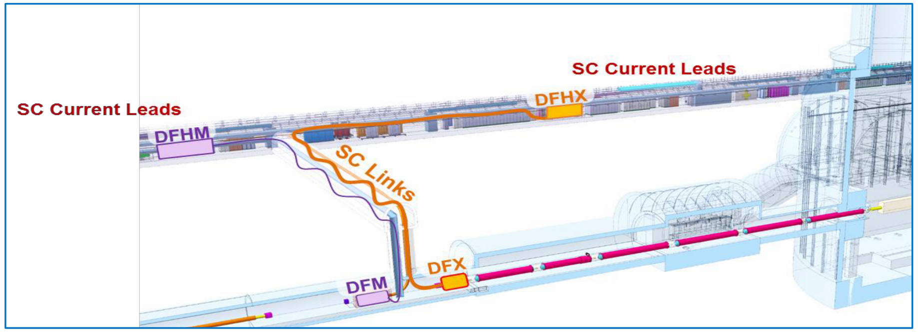
Damping Ring (140m)
Low emittance e- beam

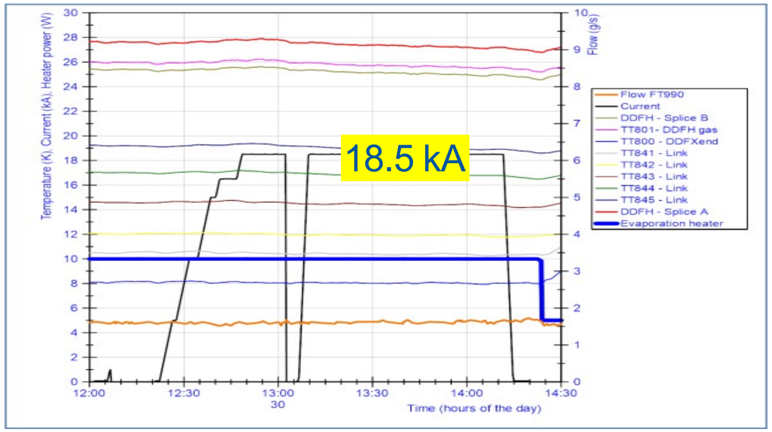
1.3 GeV S-band e- LINAC (~70m)

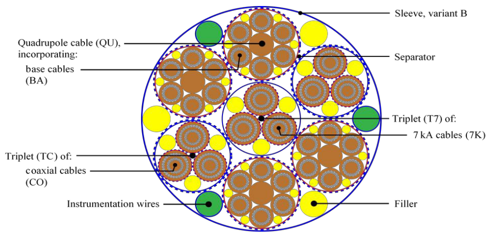
A. Yamamoto, 190918b

MgB_2 18.5 kA Superconducting Link Demonstrated

- Innovative system supplying current to Interaction Region magnets.
- Several circuits in parallel with lengths in excess of 100 m.
- Multi-stage MgB_2 cable carrying up to ~129 kA @ 25 K, cooled by forced flow of GHe at 4.5-17 K,

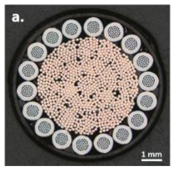




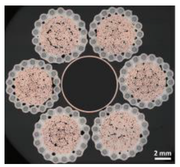


Layout of SC link cable

3 kA (6.5 mm)



18 kA (19 mm)



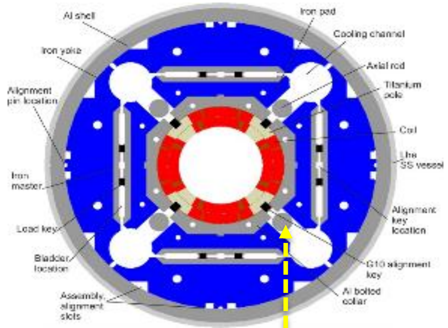
A demonstrator (2 x 60-m long, 18 kA cables) tested in Dec. 2018, exceeding requirements
- T_{CS} at 18 kA of 31.3 K

CERN and US-LARP/AUP Cooperation for Nb_3Sn IR Quadrupoles

LARP

US HL-LHC AUP

- **US-LARP Collaboration** taking a critical role for leading R&D:
  - **Magnet science and technology**
  - **Nb3Sn** accelerator magnet-technology beyond 10 T,
    - overcoming the very brittle feature (like ceramic),
    - with winding, reacting, and impregnating, and
  - **Mechanical structuring w/ Bladder technology** for
    - Rigid support of ***magnetic pressure*** proportional to **B^2**,

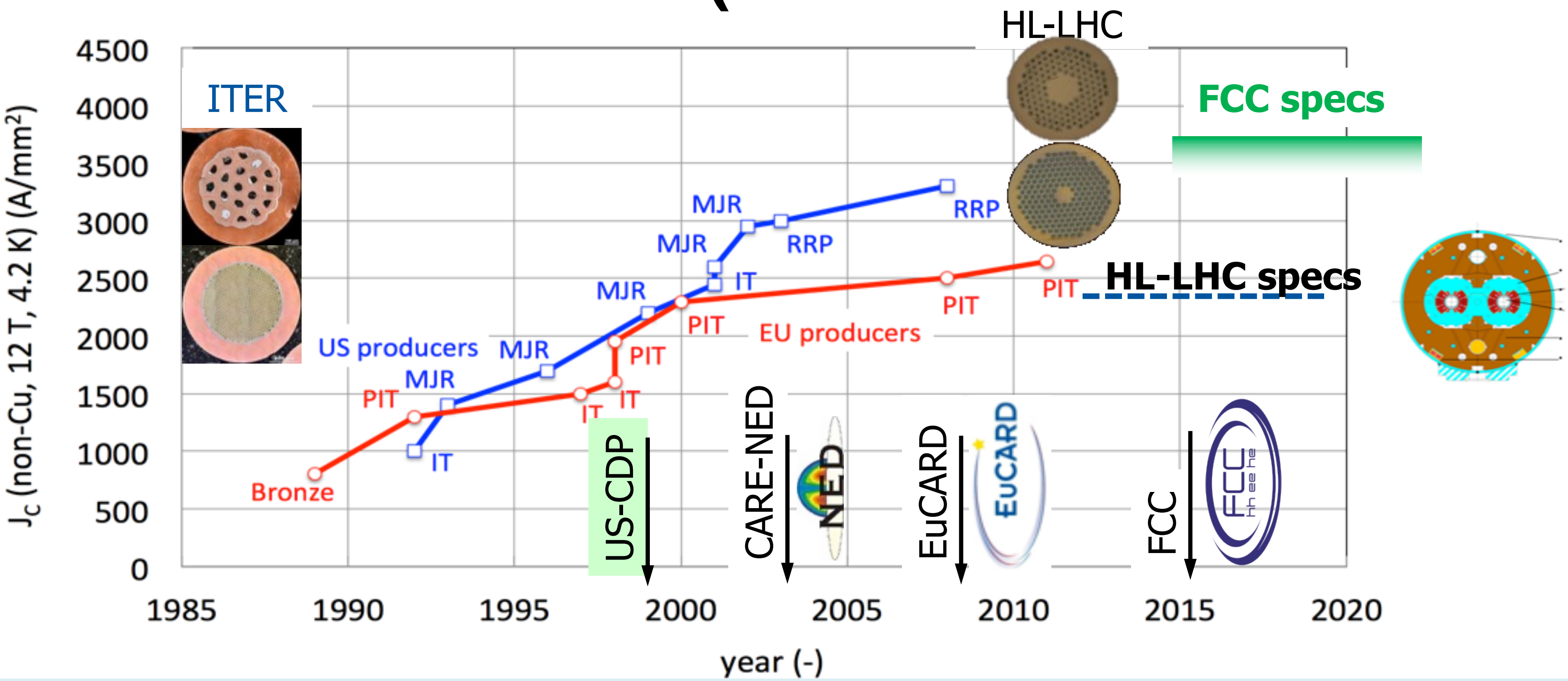


- **CERN** leading HL-LHC global collaboration and qualifying the Nb_3Sn accelerator magnet technology:
  - Experienced with the project realization for future collider accelerators.

Bladder, as a key technology

Courtesy, G. de Rijk

Nb_3Sn Conductor development for Accelerators (1998 ~)

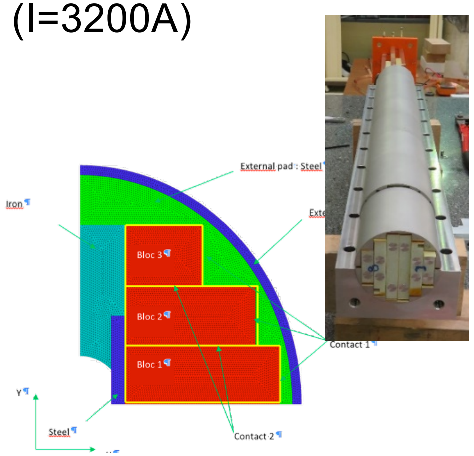


After 10 years of development, the US and EU development gave us the Nb_3Sn conductor for HILUMI.

Three HTS/Rebco Inserts (CERN-Europe Cooperation)

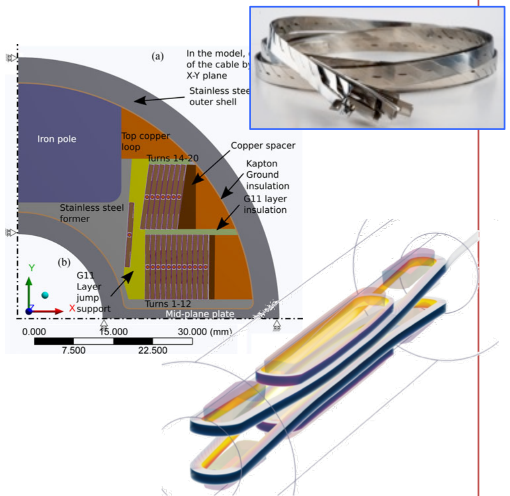
EuCARD1: insert
(CEA-CNRS-CERN),

racetrack,
ReBCO 4 tape stack cable,
stand alone tested Sept 2017:
Reached 5.37 T @ 4.2K
(I=3200A)



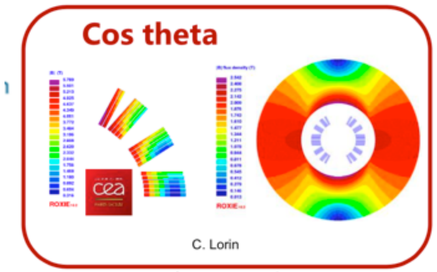
EuCARD2: Feather-M2
(CERN),

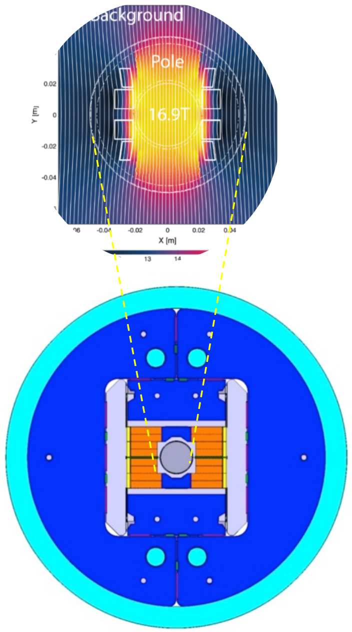
flared Ends coil
ReBCO, Roebel cable,
stand alone tested Apr 2017:
Reached 3.37 T @ 4.2K
(I=6500A)



EuCARD2: cosΘ insert
(CEA),

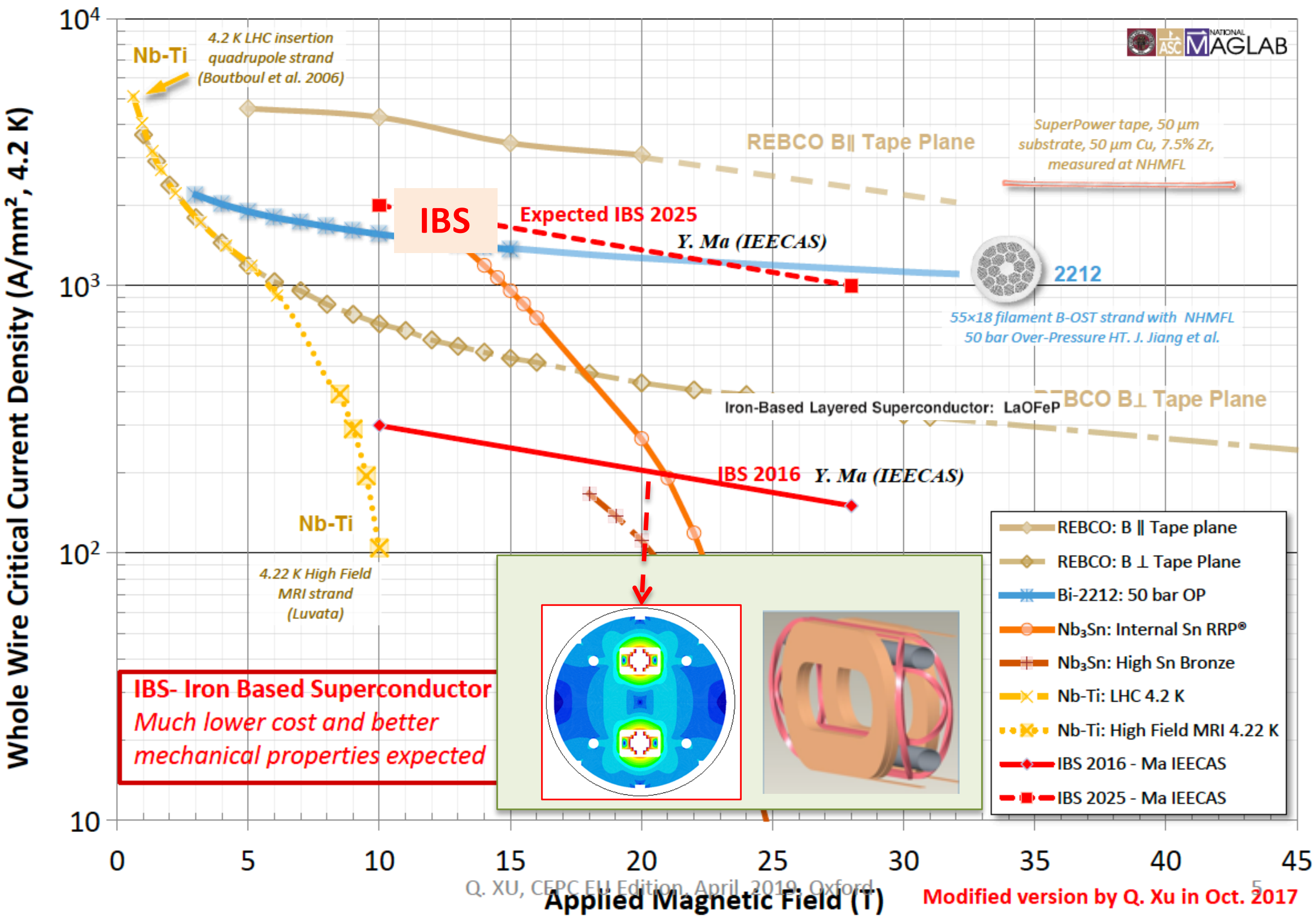
cosΘ coil,
ReBCO, Roebel cable,
being fabricated,
stand alone test in autumn 2019





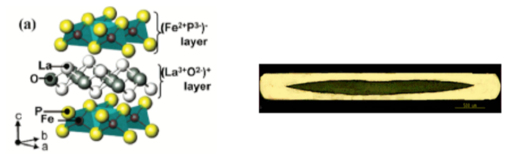
Eucard2+ HTS-insert to be tested in 2019

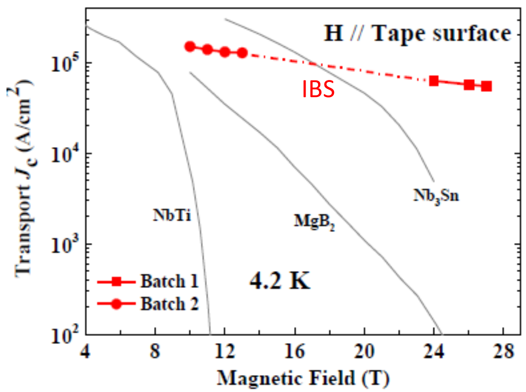
HTS/IBS SC and Magnet in China



Y. Kamihara et al.,

Iron-Based Layered Superconductor: LaOFeP





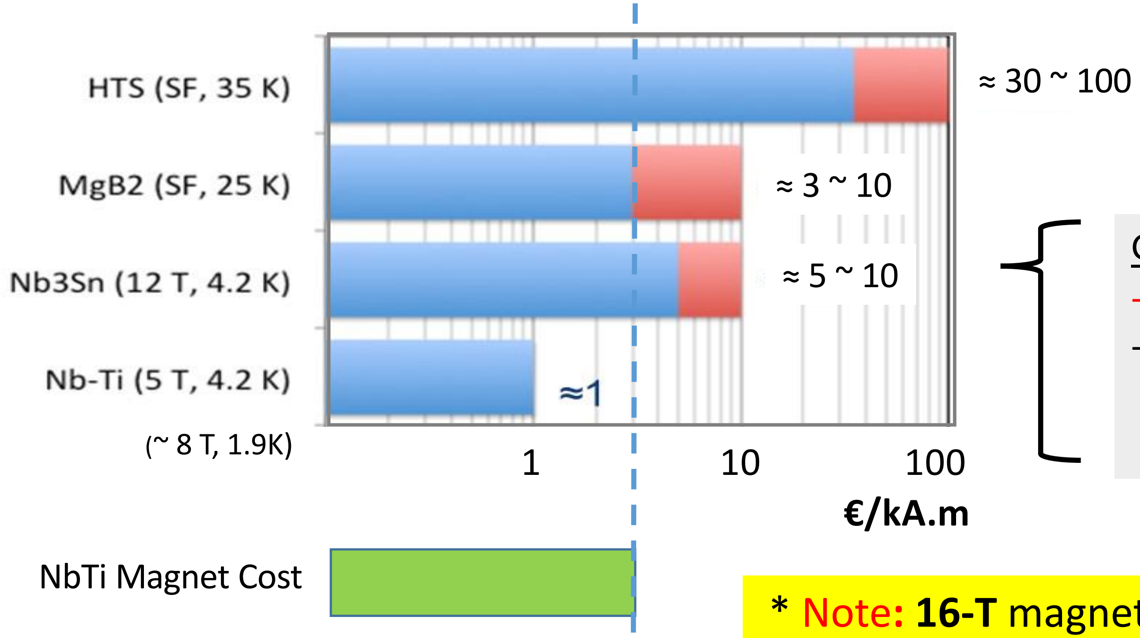
Y. Mao et al., Supercond. Sci. Technol. 31 (2018) 015017

Iron Based Superconductor (IBS) development in China toward 12 --> 24 T

Courtesy: F. Bordry, L. Bottura, A. Devred

Relative Cost Comparison for High-field SC and Magnet

- An approach for cost consideration:
  - Superconductor cost to be 30 % of the total cost for the LHC NbTi dipole magnet assembled.
  - It gives a general guideline for acceptable superconductor cost.
  - The currently available HTS cost is still too far, exept for Iron-based-SC (IBS) potential



Goal for Nb_3Sn for FCC or HE-LHC:

- **3.5 €/kA.m at 16 T and 1.9 K**
- Corresponding to 500...600 **€**/kg,
  - a factor 2.5 ~ 3 lower than the present cost 1300 ~ 1500 EUR/kg for HL-LHC (RRP)

* Note: **16-T** magnet requires **x 2** conductor to that of **14 T.**

Courtesy: F. Bordry, S. Gilardoni

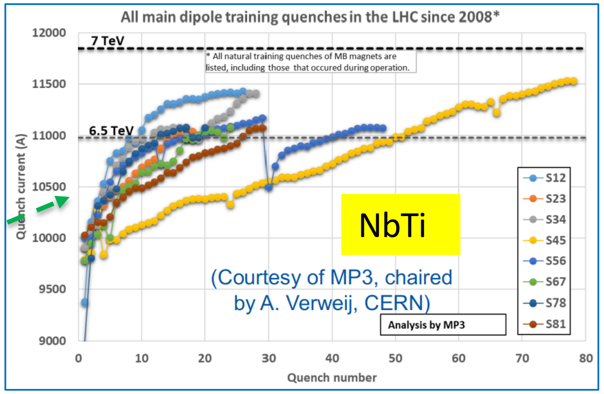
List of Challenges in Vacuum, Target, Collimator, and Beam Dump

- **Vacuum:**
- **Target :**
  - In general High cumulated radiation doses and radiation damage on materials
- **Collimators**
  - Absorb large amount of energy deposition without long term damage
  - Thermo-mechanical and temperature management with innovative techniques
  - Material with high mechanical resistance to impact and high electrical conductivity
- **Dumps:**
  - sustain single impact of full beam without compromising the overall material integrity.
  - How power dump with 3~5 MW/beam, DC, in LCs.

Summary: State of the Art – RF and SC Magnet

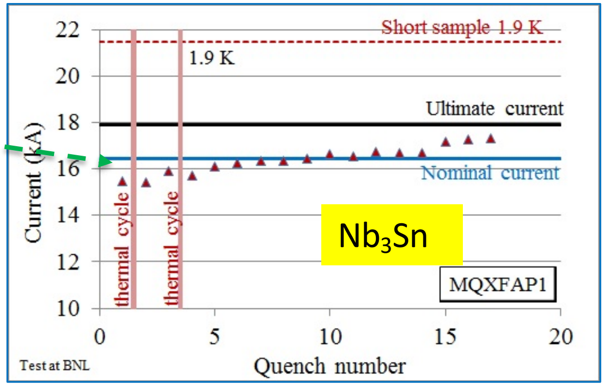
NRF and SRF:

- **NRF** CLIC R&D (~ 12 GHz) : 70 ~ 100 MV/m
- **SRF** Eu-XFEL (1.3 GHz, 9-cell cavity) : 30 MV/m (+/- 20%)
- **SRF** KEK-B (Crab cavity); experienced, and CERN-SPS demonstrated



SC Magnet:

- **NbTi:** ~ 8 T at 1.9 K experienced at LHC. **Re-training** aft. thermal cycling (TC) still an issue
- **Nb3Sn:** ~ 11 T at 1.9 K in progress. **Good memory** after TC, and more statistic anticipated.



Note: Loadline-ratio, should be carefully determined.

Summary: Challenges - SRF and SC Magnet

- **Superconducting RF:**
  - Nb-bulk (for > 1 GHz)
    - High-Q (> 3E10) and High-G (> 45 MV/m) , w/Low-T treatment w/ or w/o N-infusion.
    - Large-Grain SRF cavity for cleaner condition with cost-reduction,
  - Thin-Film (for wider applications)
    - Thin-film on Nb to improve effective B_{sh}, resulting higher gradient, and further Potential
    - New material such as NB_3Sn/MgB_2 to drastically improve performance.
- **Superconducting Magnet:**
  - Nb3Sn requires much longer steps to reach 16 T, for improvement of SC current density, **mechanical property**, field quality control, training quenches, magnet protection, and industrialization.
  - "Nb3Sn + HTS-insert" be inevitably required, beyond 16 T, and cost effective HTS will be essentially required for practical accelerator applications.