Draft: 190505b

State of the Art and Challenges in Accelerator Technologies – Past and Present

Akira Yamamoto
(CERN and KEK)

A Plenary Talk at CERN Council Open Symposium on the Update of European Strategy for Particle Physics (ESPP)
13-16 May, 2019 – Granada, Spain

Open Symposium on the Update of European Strategy for Particle Physics

13 – 16 May, 2019

https://cafpe.ugr.es/eppsu2019/venue.html

Monday Plenary Session

30' - State of the Art and Challenges in Accelerator Technology — Past and Present – Akira Yamamoto (CERN/KEK)

- HEP today
- Technology - mainly rf and magnets
- Lessons learnt

30' - Future - path to very high energies - Vladimir Shiltsev (Fermilab)

Outline

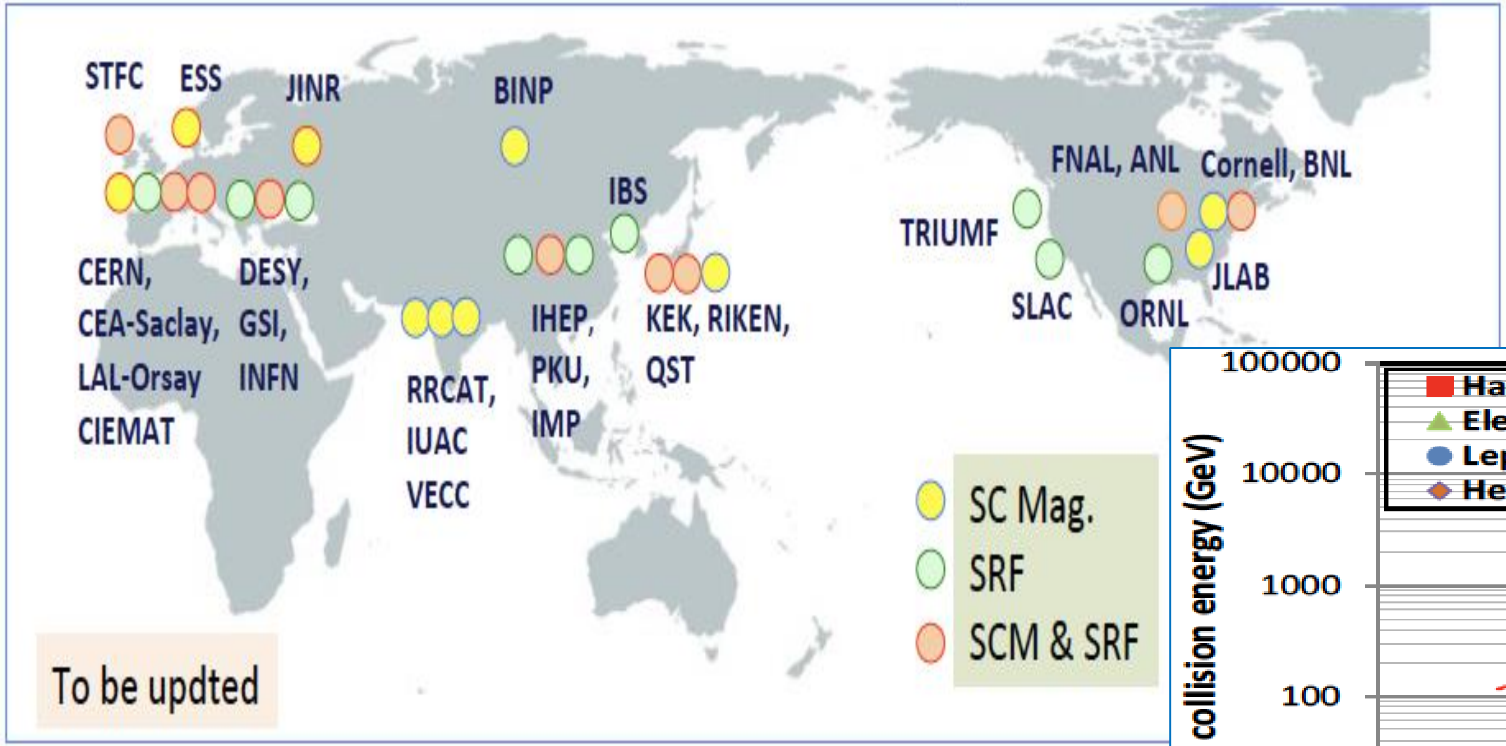
- **Introduction**
  - Advances in Accelerator Technology in Particle Physics

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

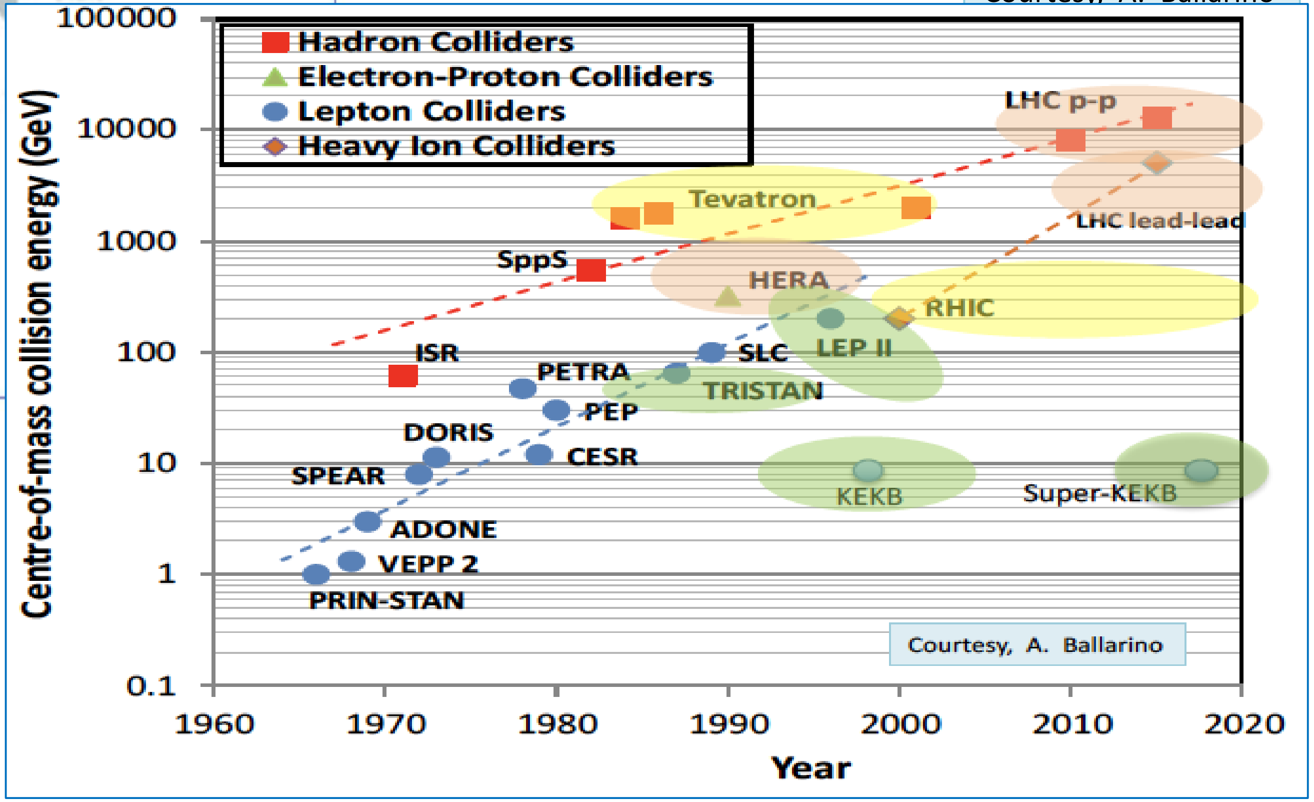
- **Challenges for future**
  - Superconducting Technologies for future Lepton and Hadron Colliders

- **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.

Accelerator Technologies advanced in Particle Physics

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 0.003+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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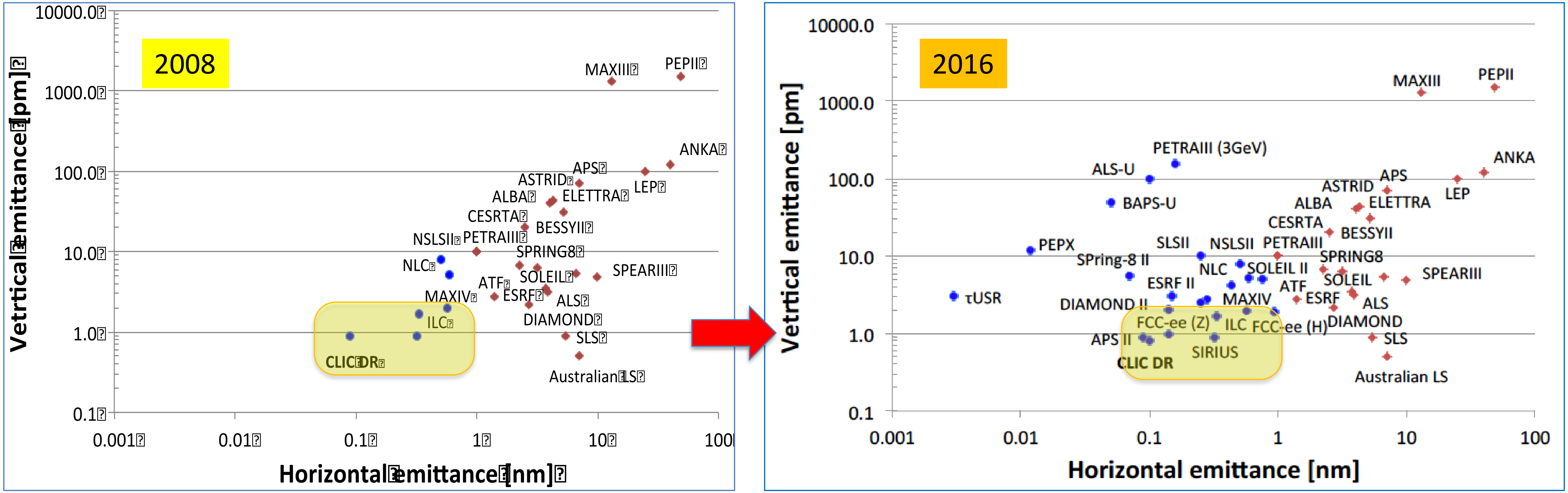
  - **Nano-beam**, Superconducting Magnet and RF, and Normal-conducting RF
    - **>>> To be discussed by V. Shiltsev and S. Steinar, and the information in Appendix**
- **Challenges for future, focusing on**
  - Superconducting technologies for future Lepton and Hadron Colliders
- **Summary**

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



More to be discussed by V. Shlitsev in next talk

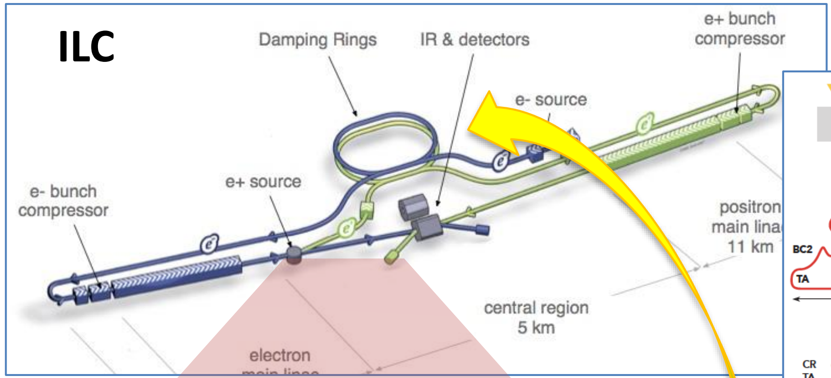
ATF/ATF2: Accelerator Test Facility

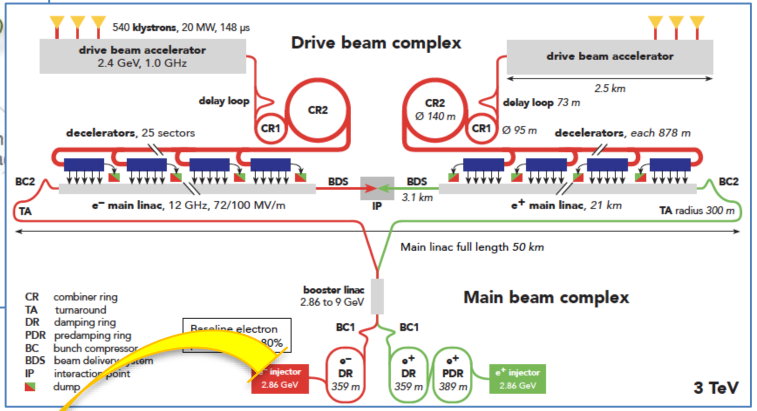
Courtesy: N. Terunuma

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

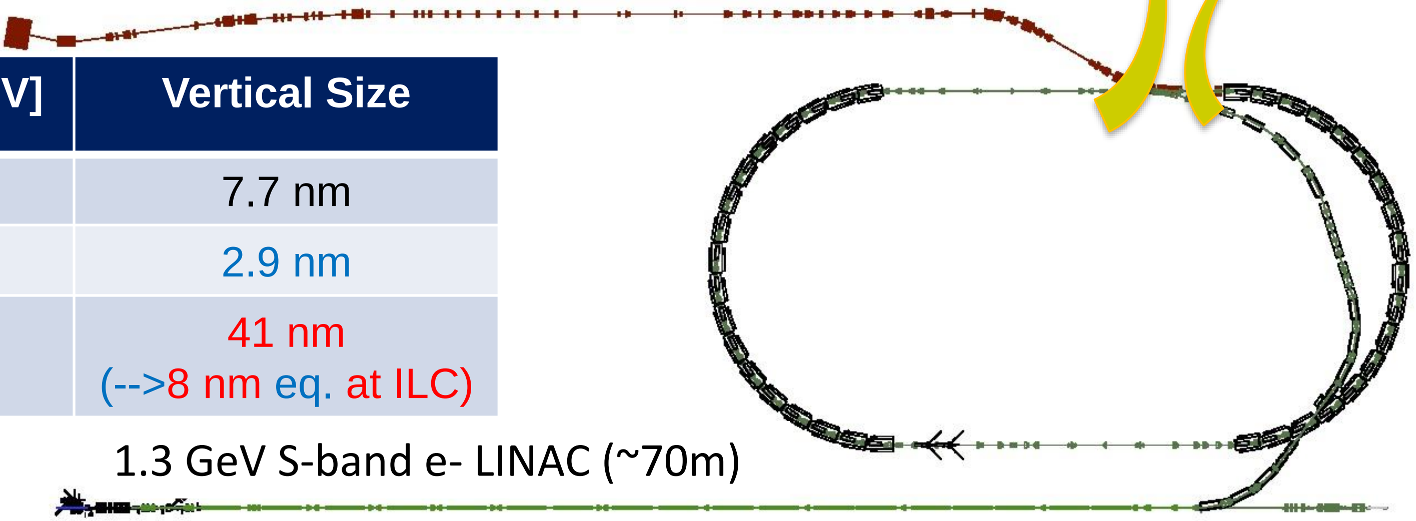
Develop nano-beam technology for ILC/CLIC

- 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)

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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*

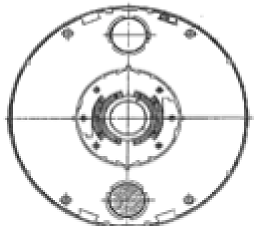
Under Construction
- FAIR (GSI) ……… *Fast-cycleShnchr.*
- HL-LHC (CERN)
- NICA (JINR)

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

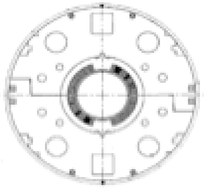
1980 — 2000 — 2020

Tevatron-D.

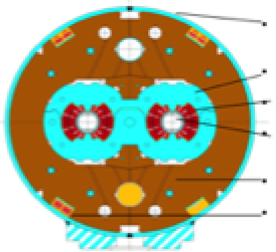
HERA-D.



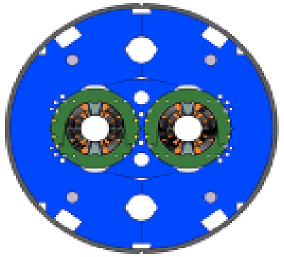
RHIC-D.



LHC.D (NbTi)

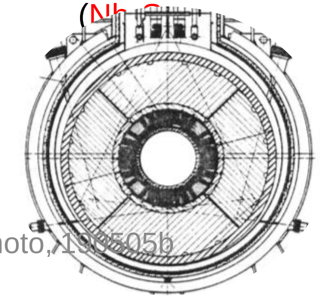


HL-LHC 11T-D (Nb_3Sn)

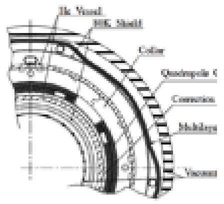


11 T Dipole

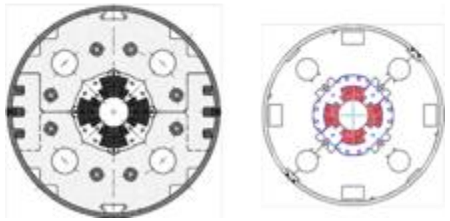
ISR-IRQ



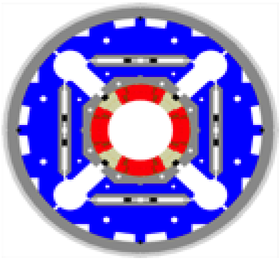
TRISTSN/KEKB



LHCC-IRQ (NbTI)



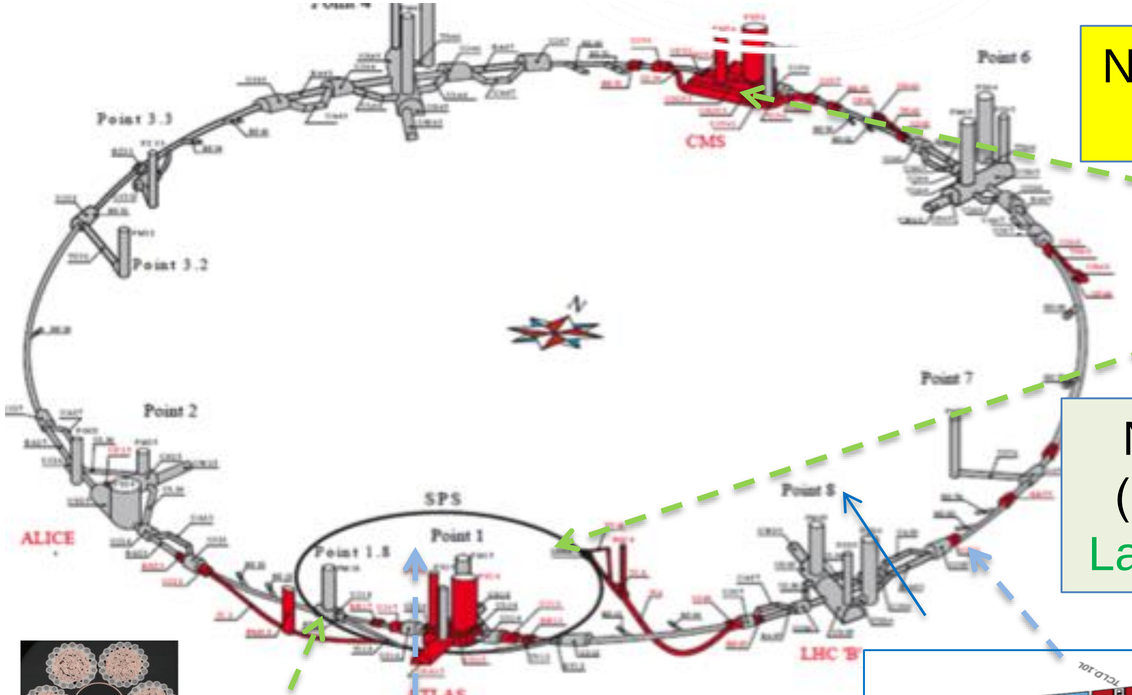
HL-LHC-IRQ



IR Quadrupole

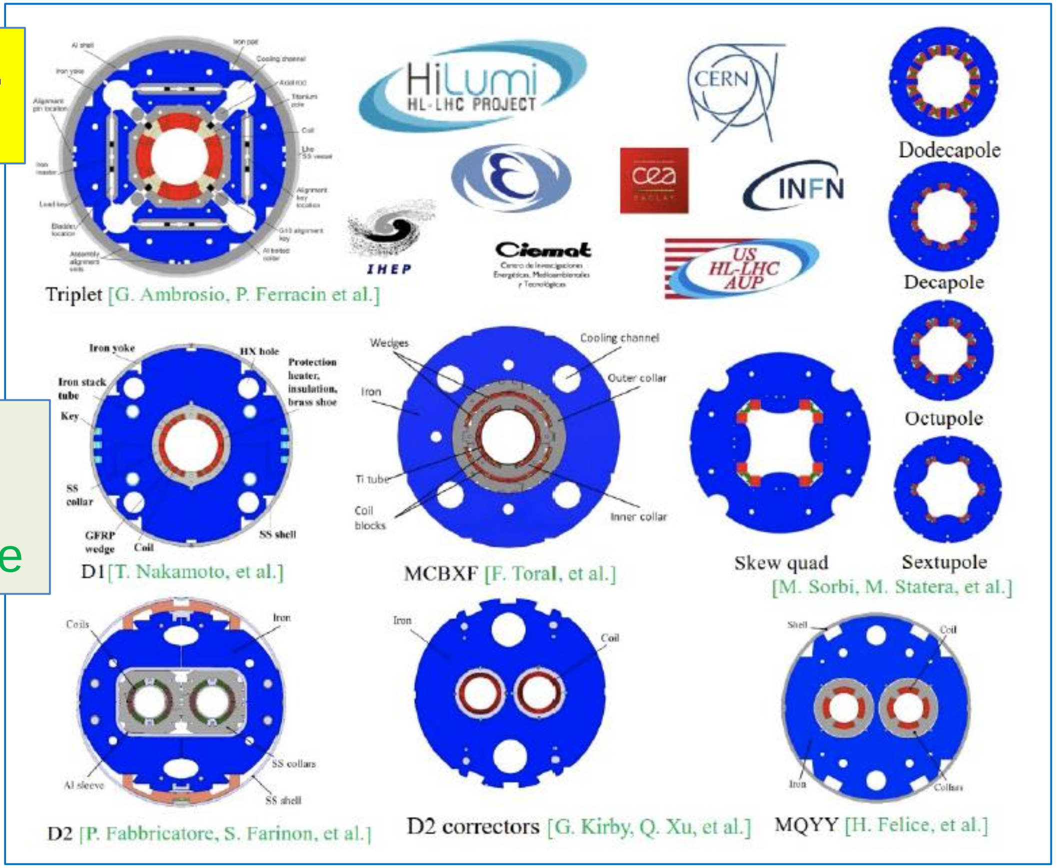
Courtesy, L. Rossi, E. Todesco

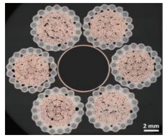
NbTi, Nb_3Sn Superconducting Magnets and MgB_2 SC Links for HL-LHC

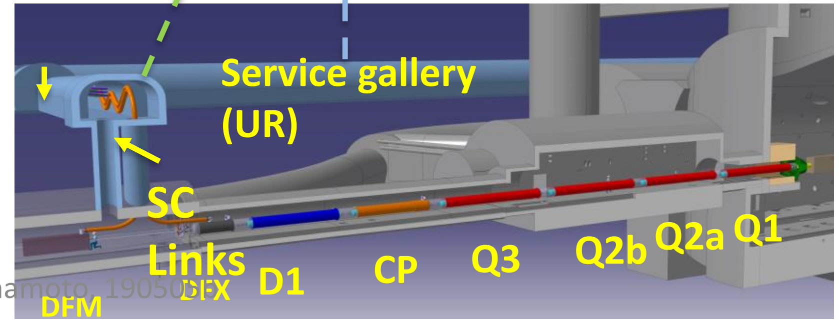


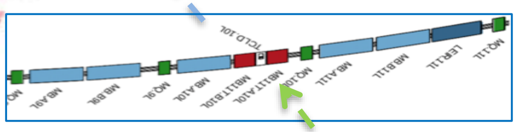
Nb_3Sn Quad.
(MQXF)

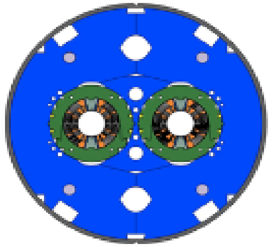
NbTi Mag.
(D1, and …)
Large aperture









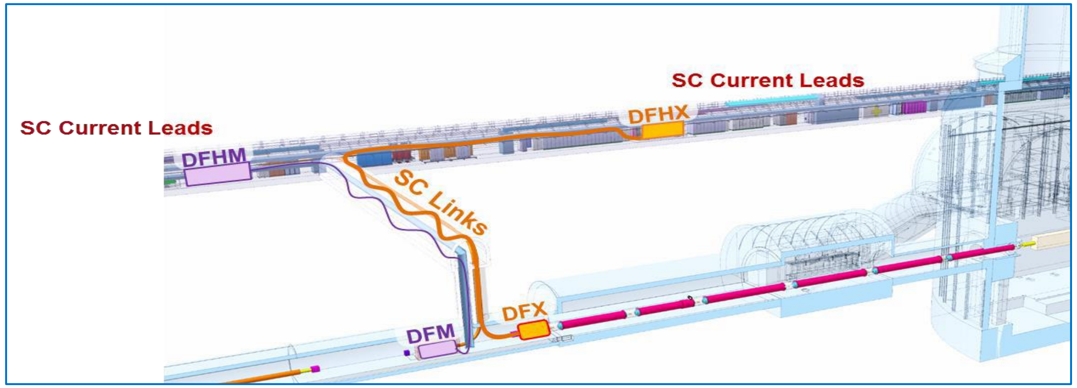


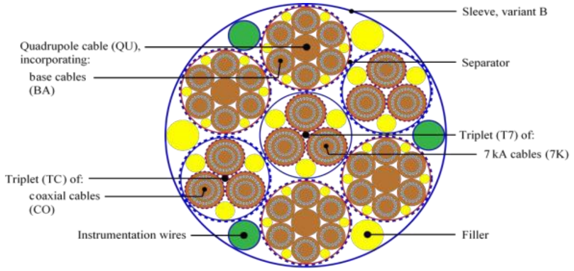
Nb3Sn Dipoles w/ Collimator

Courtesy: A. Ballarino,

MgB_2 18.5 kA Superconducting Link Demonstrated

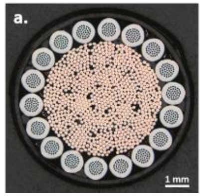
- Innovative system supplying current to Interaction Region magnets.
- Several circuits in parallel with lengths in excess of 100 m.
- Multi-stage MgB_2 cable carrying up to ~129 kA @ 25 K, cooled by forced flow of GHe at 4.5-17 K,



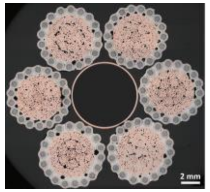


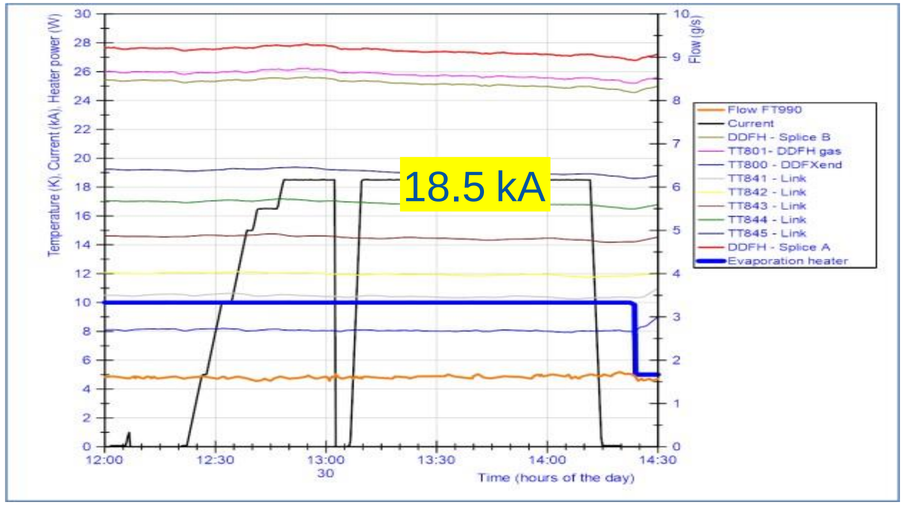
Layout of SC link cable

3 kA (6.5 mm)



18 kA (19 mm)

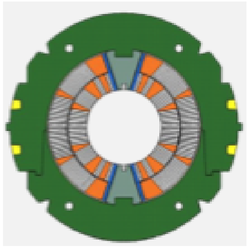


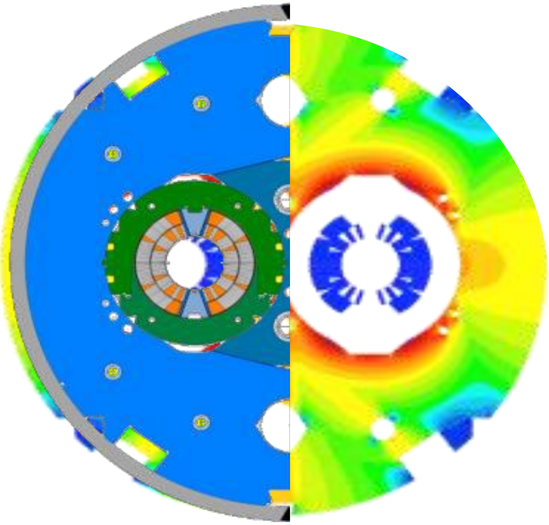


A demonstrator (2 x 60-m long, 18 kA cables) tested in Dec. 2018, exceeding requirements
- T_{CS} at 18 kA of 31.3 K

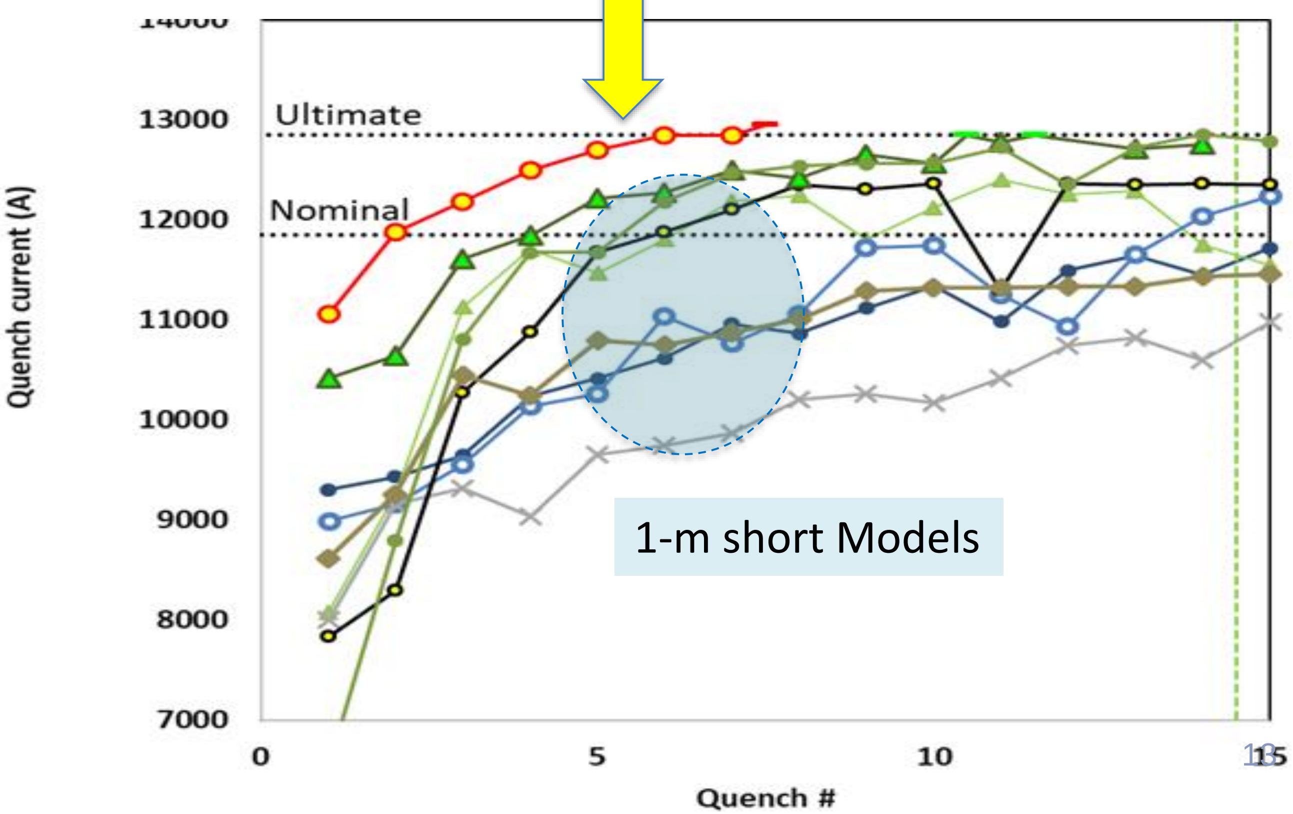
Courtesy, A. Devred, F. Savary, G. Willering

HL-LHC, 11T Dipole Magnet



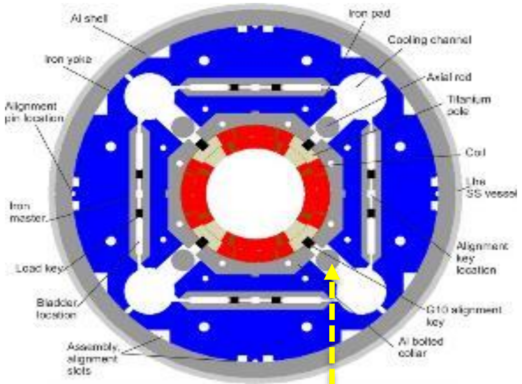


- **The 1st Series, 5.5 m long Dipole, powered as a single aperture in the initial test: Reached**
  - **Bc = 11.2 T (at nominal current)**
    I-nominal, after 1 quench,
  - Bc = 12.1 T (at ultimiate current)
    I-ultimate) after 6 quenches.



CERN and US-LARP/AUP Cooperation for Nb3Sn IR Quadrupoles

- **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**,

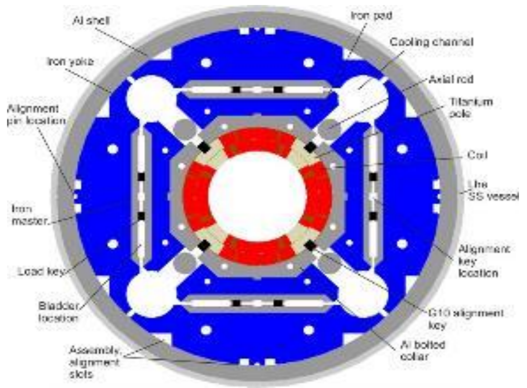


Bladder, as a key technology

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

Nb_3Sn Quadrupole (MQXF) at IR

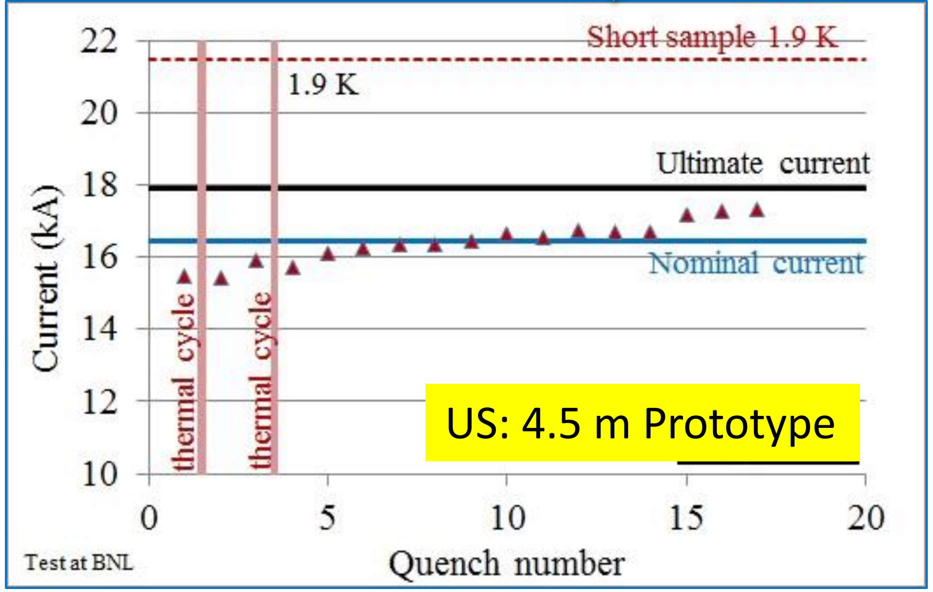
Courtesy,
G. Ambrosio, G. Chlachidze
E. Todesco, P. Ferracin

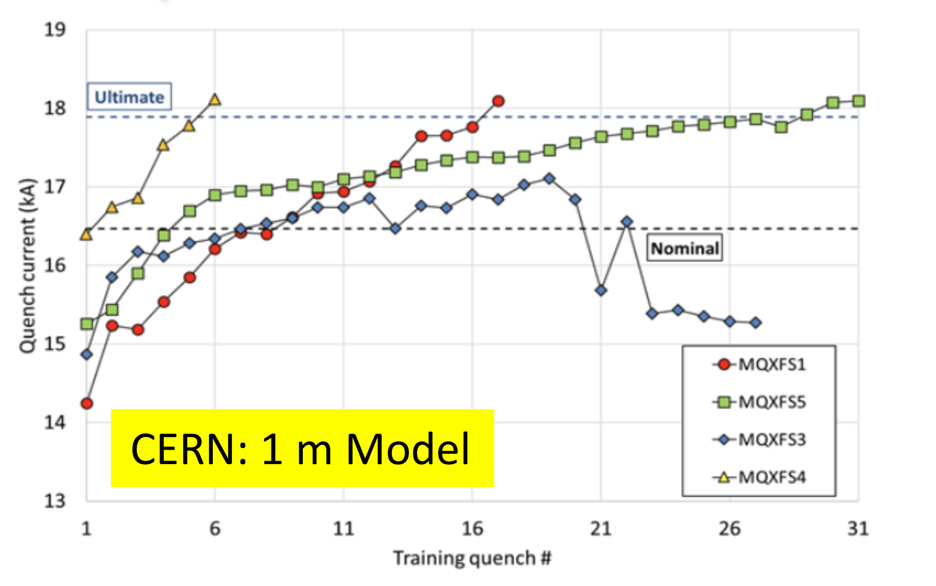


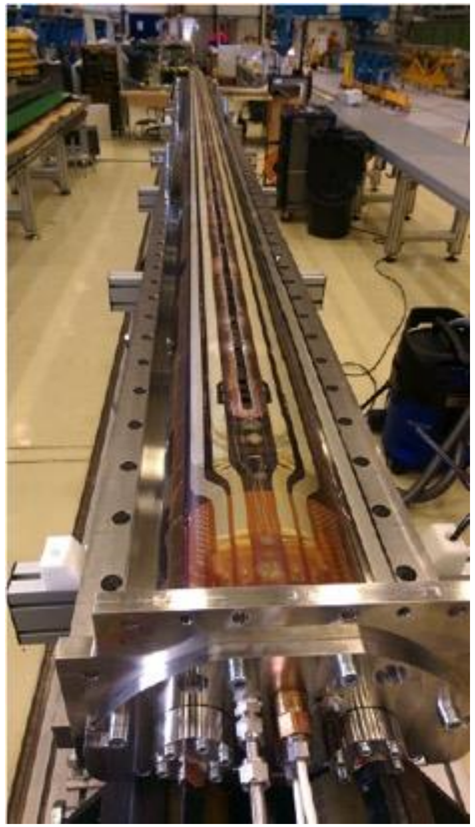
US: 4.5 m Prototype:
- Completed and tested

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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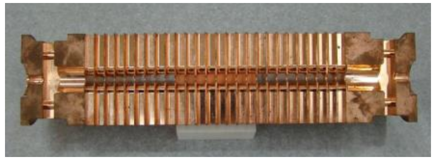
Courtesy: W. Wuensch

Features of Normal- 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 power efficiency, more steady state beam power from rf input power
RF Frequency: 12 GHz - High efficiency RF peak power - Precision alignment & stabilization to compensate wakefields	RF Frequency: 1.3 GHz - Large aperture gives low wakefields
Q@: order < 10^5, - Resistive copper wall losses compensated by strong beam loading – 40% steady state rf-to-beam efficiency	Q@: order 10^{10}, - High Q - losses at cryogenic temperatures
Pulse structure: 180 ns / 50 Hz	Pulse structure: 600 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 long-pulse, low frequency klystrons and two-beam scheme	- High-efficiency rf also from long-pulse, low-frequency klystrons

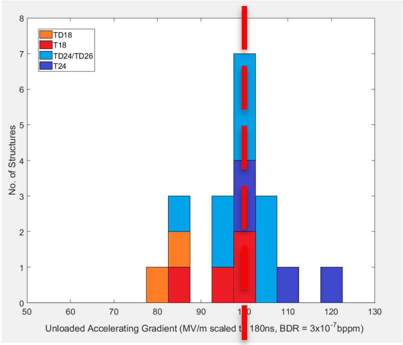


Courtesy: W. Wuensch

Normal Conducting Linac Technology Landscape

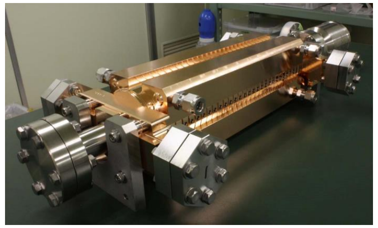
Components:

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



~ 100 (+/-20) MV/m

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

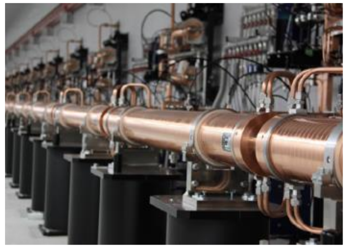


Systems Facilities:
(100 MeV-range)

- 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**

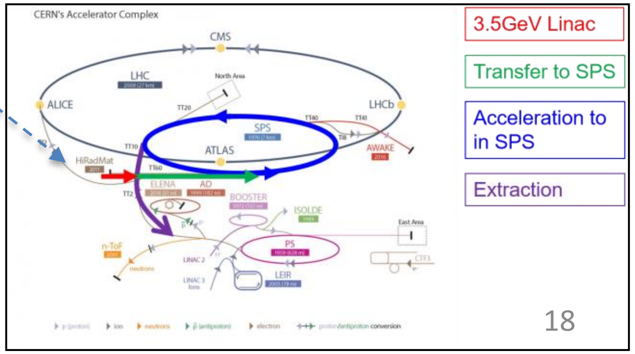
Operational:
- **SACLA**
- **SwissFEL (8 GeV)**



X-band (12 GHz) **GeV-range facilities**

Planning:
- **Eu-Praxia**
- **eSPS**
- **CompactLight**

CLIC



Advances in SRF Technology and Accelerators

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

In Operation: → # cavities
- 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 !

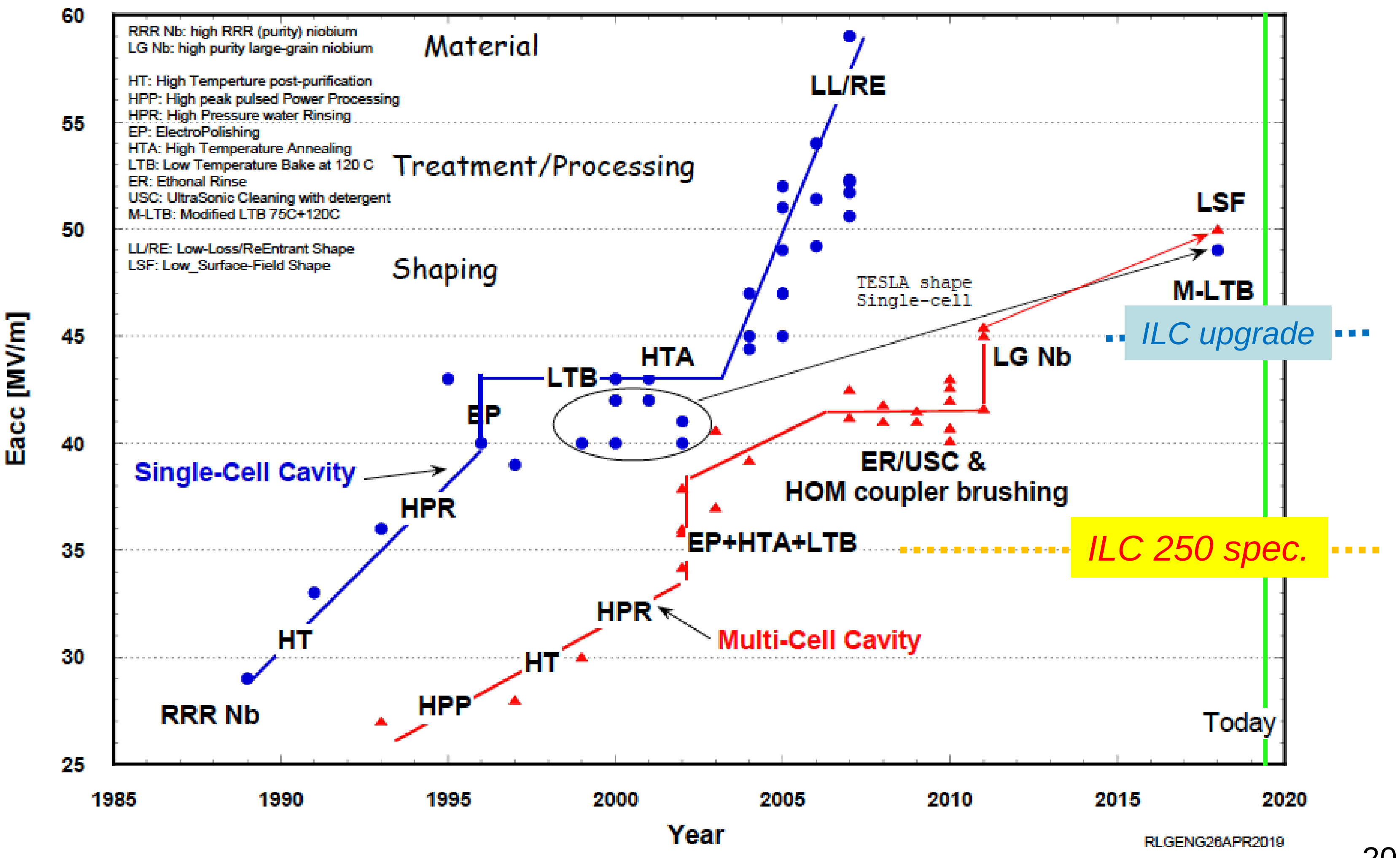
Courtesy: R. Geng,

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



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Courtesy, H. Weise, N. Walker

European XFEL, SRF Linac Completed

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

2018/07/17

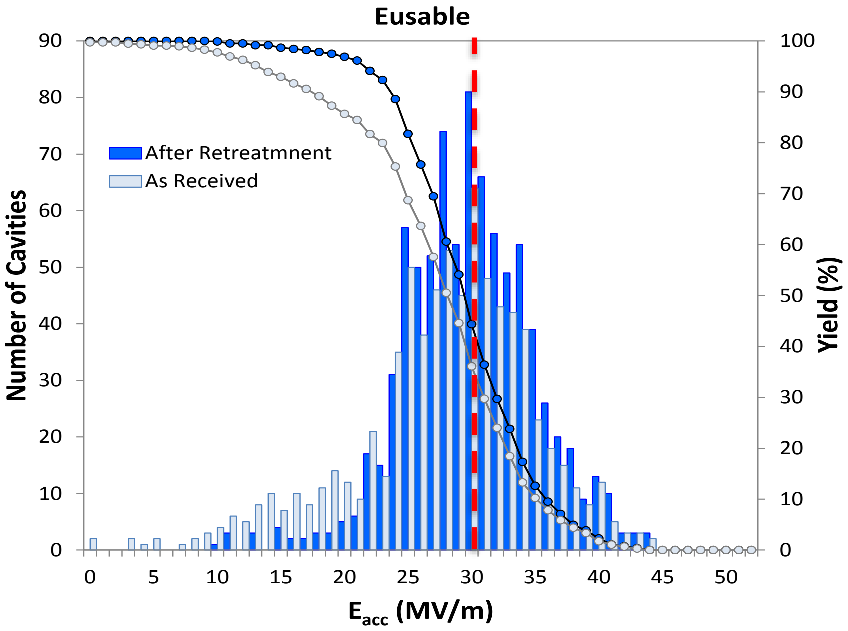
Back

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 Retreatment:
E-usable: 29.8 ± 5.1 [MV/m]

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

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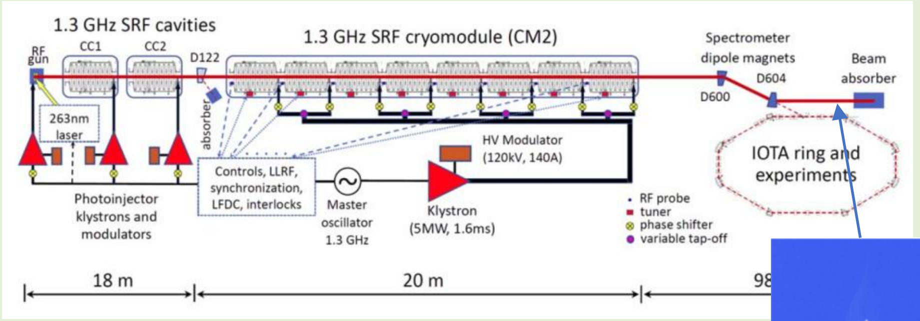
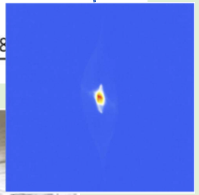
Courtesy: V. Shiltsev, S. Michizono

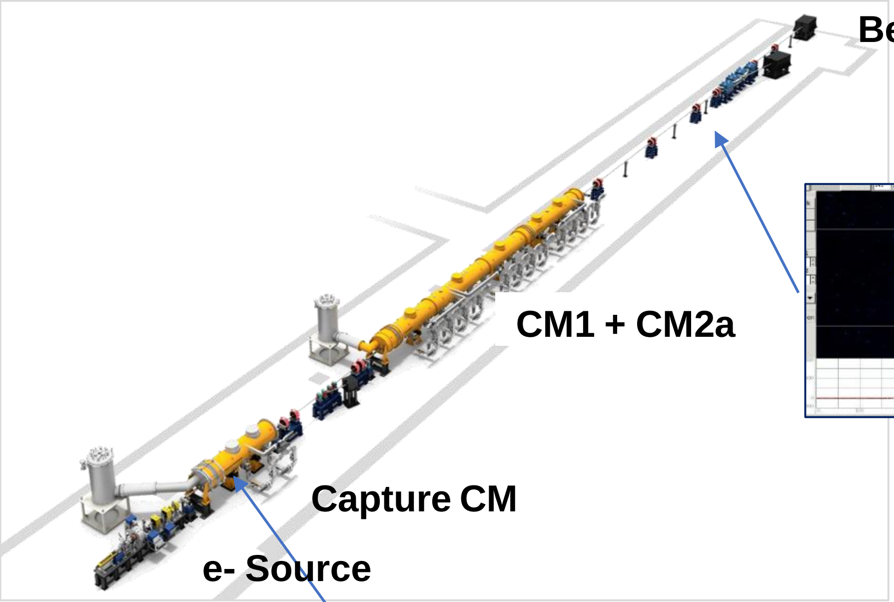
Fermilab, KEK achieving ILC Gradient Goal ≥ 31.5 MV/m with beam

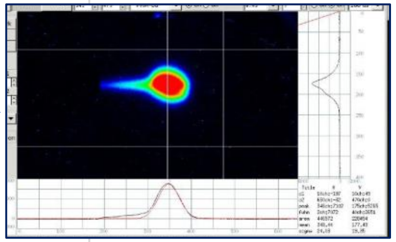




Beam Acc. : 260 MeV by 8 Cavities,
<G> = 32.3 MV/m

Fermilab-FAST Progress, 2017



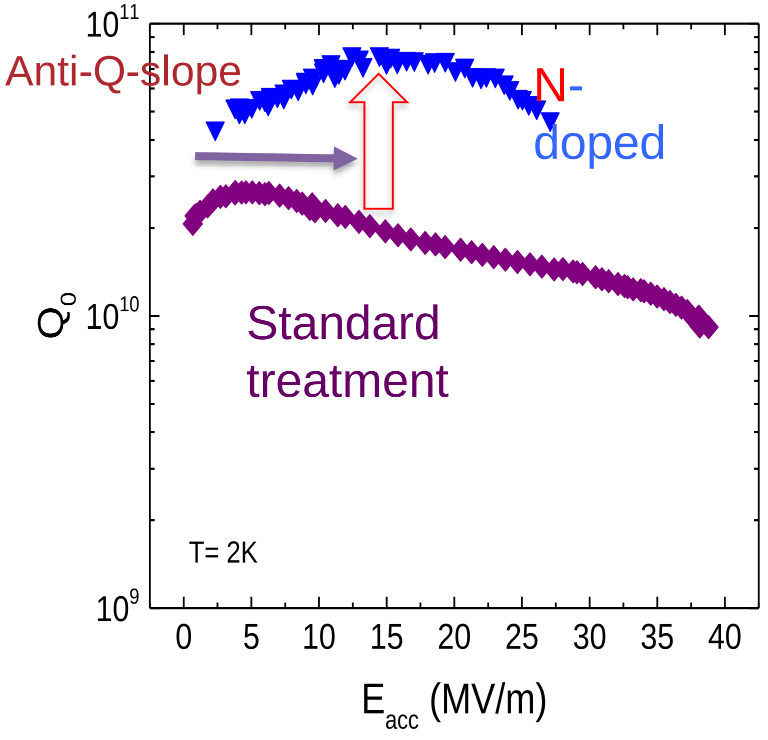


Beam Acc. : 230 MeV by 7 Cavities,
<G> = 32 MV/m

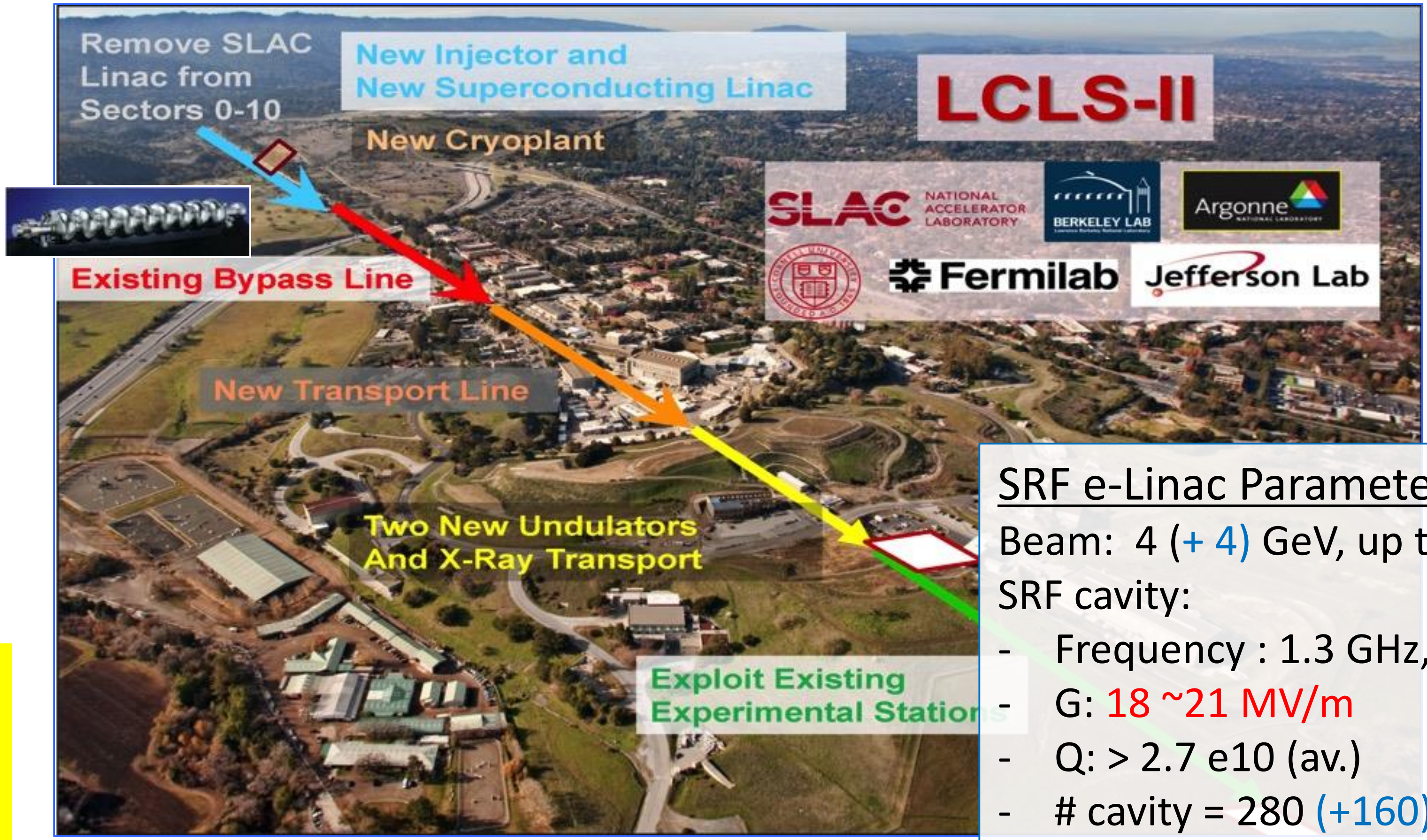
KEK-STF2 Progress, 2019

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., (Fermilab)

A. Grasselino et al, Supercond. Sci. Technol. 26 10200 (2013)

SRF e-Linac Parameters

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

SRF cavity:

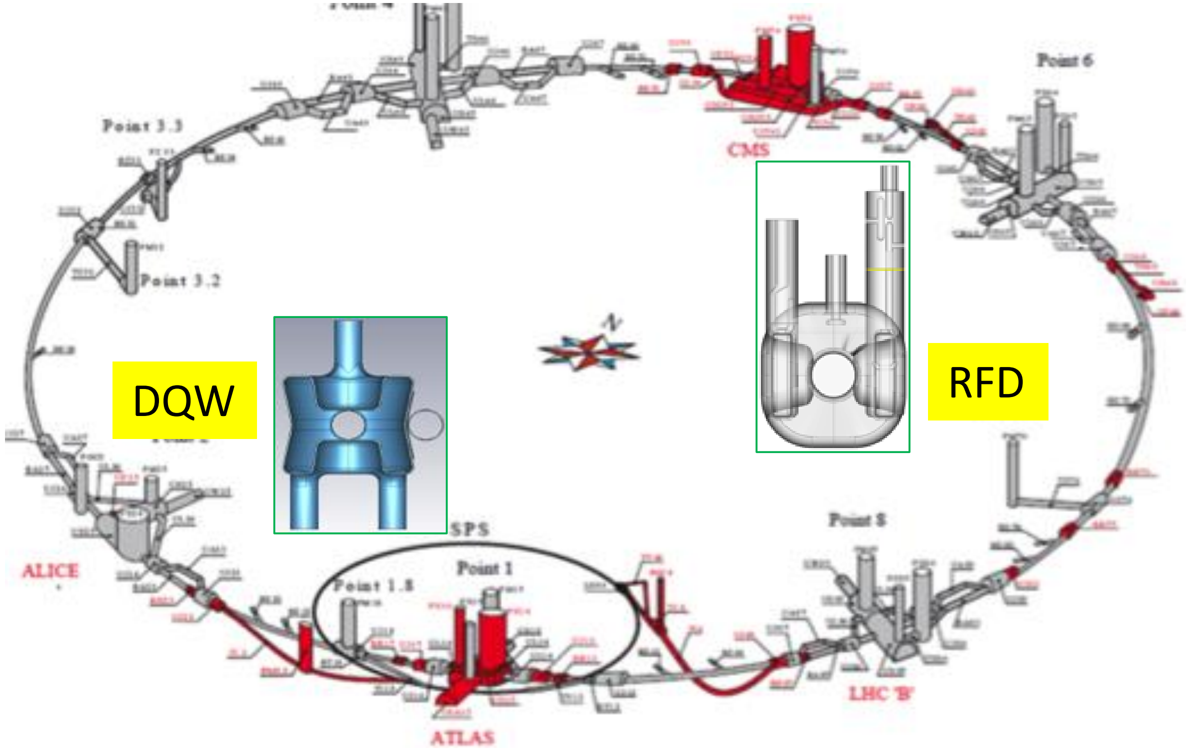
- Frequency : 1.3 GHz, CW
- G: 18 ~21 MV/m
- Q: > 2.7 e10 (av.)
- # cavity = 280 (+160)
- # CM 35 (+20)

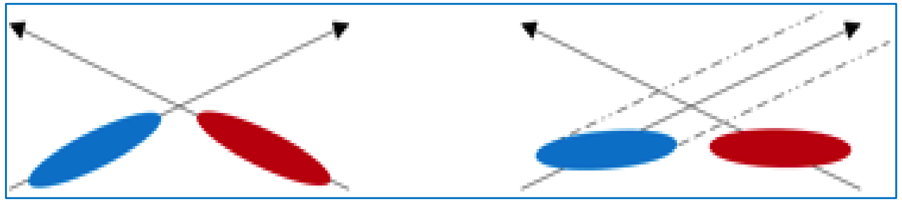
To be completed in 2020 (~2026)

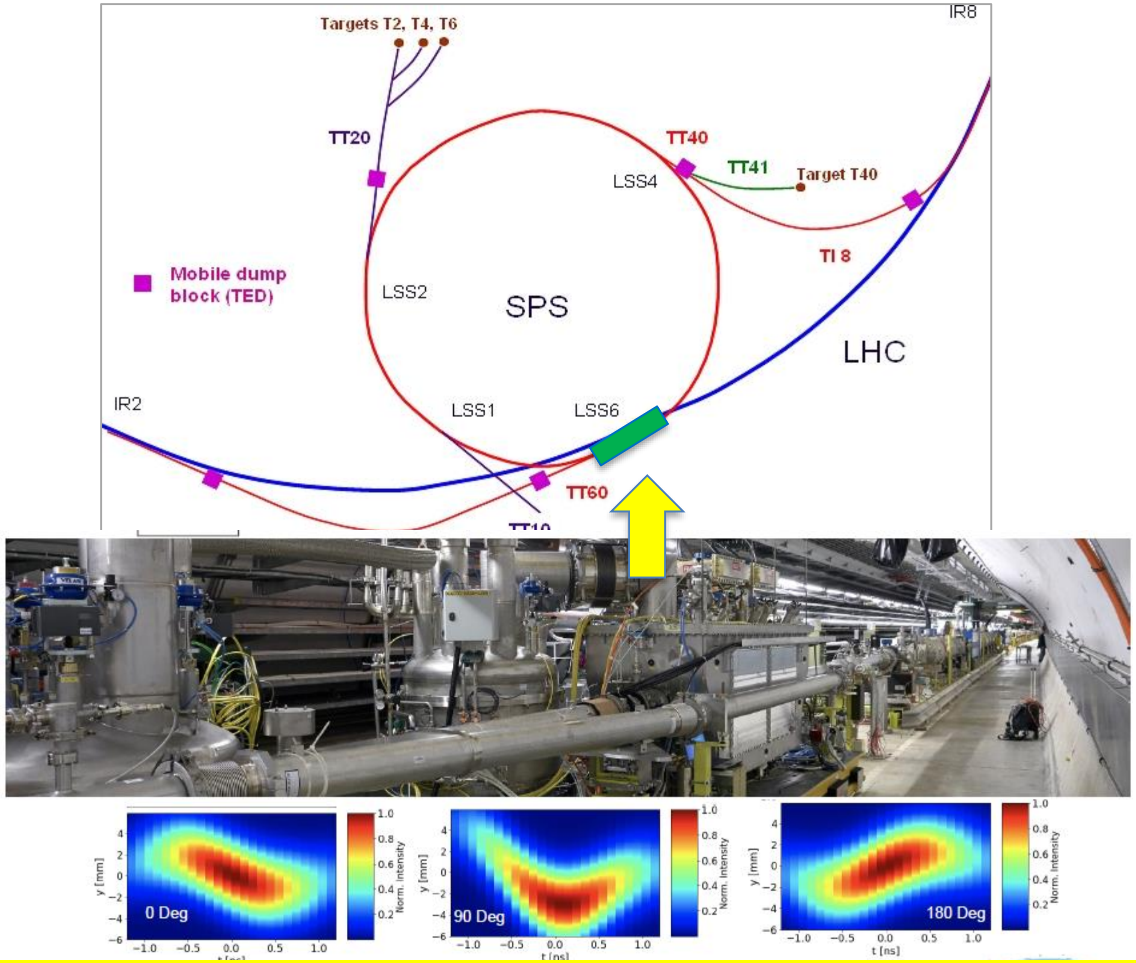
Nb SRF Crab Cavities for HL-LHC

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

CERN, US-AUP, STFC, TRIUMF Collaboration







Crabbing p beam demonstrated at SPS, 2018

Outline

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

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	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 [BCHF]		5~10 (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)	5.3 [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 [BCHF]		72 – 100 (12)	Large scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

A. Yamamoto, 190505b

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	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
	[illegible]	(to be filled)	[illegible] 120	[illegible]	[illegible]	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
C C ee	FCC-ee	[illegible]	[illegible] – 0.37	[illegible]60 – 31	260 – 350	10.5 [BCHF]		(0.[illegible] – 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - [illegible] (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
L C ee	ILC	TDR update	[illegible] (-1)	[illegible] (– 4.9)	[illegible] (– 300)	[illegible] [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	[illegible]	[illegible] (- 3)	[illegible] (- 6)	160 (- 580)	5.9 [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:

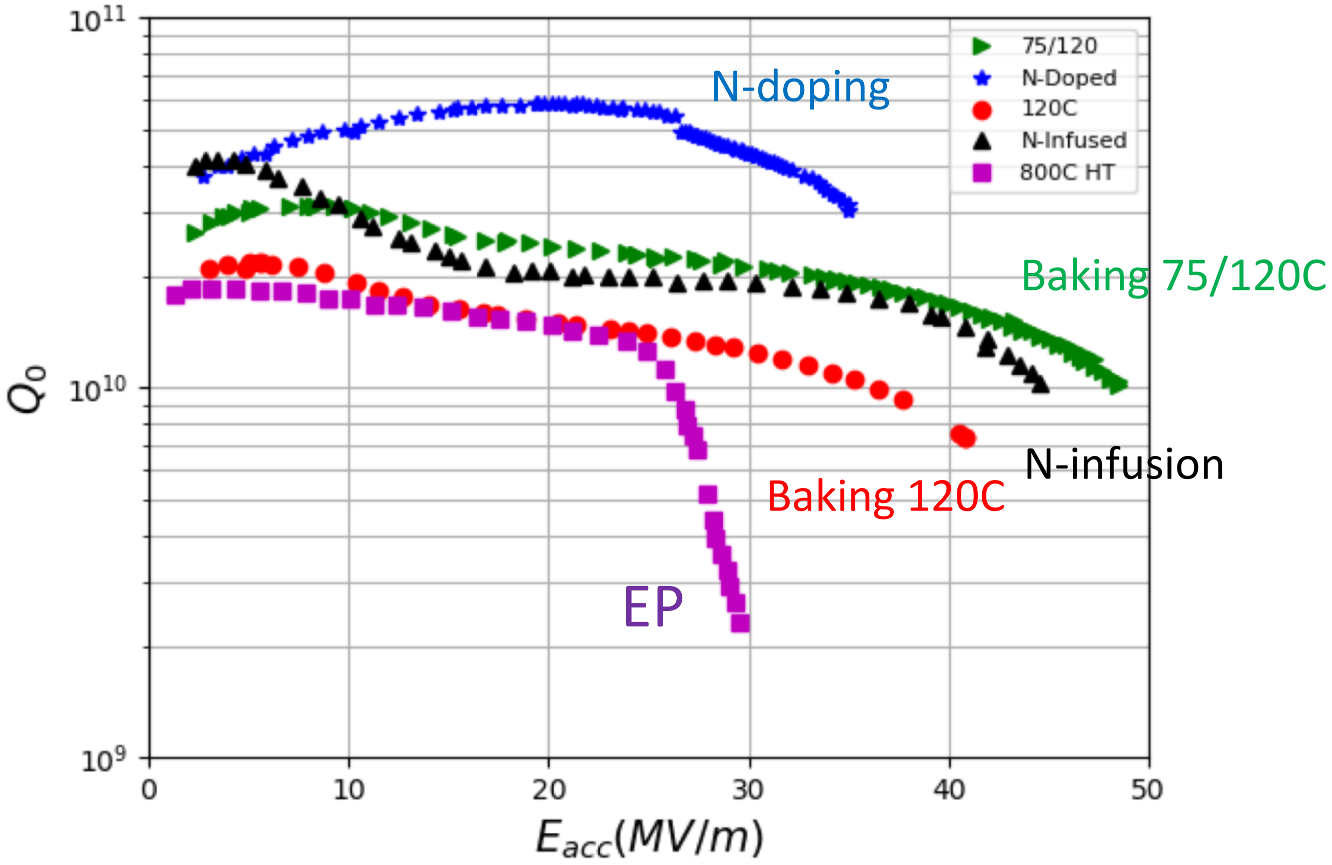
- High-field magnet
- Energy management

Lepton Colliders:

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

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

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

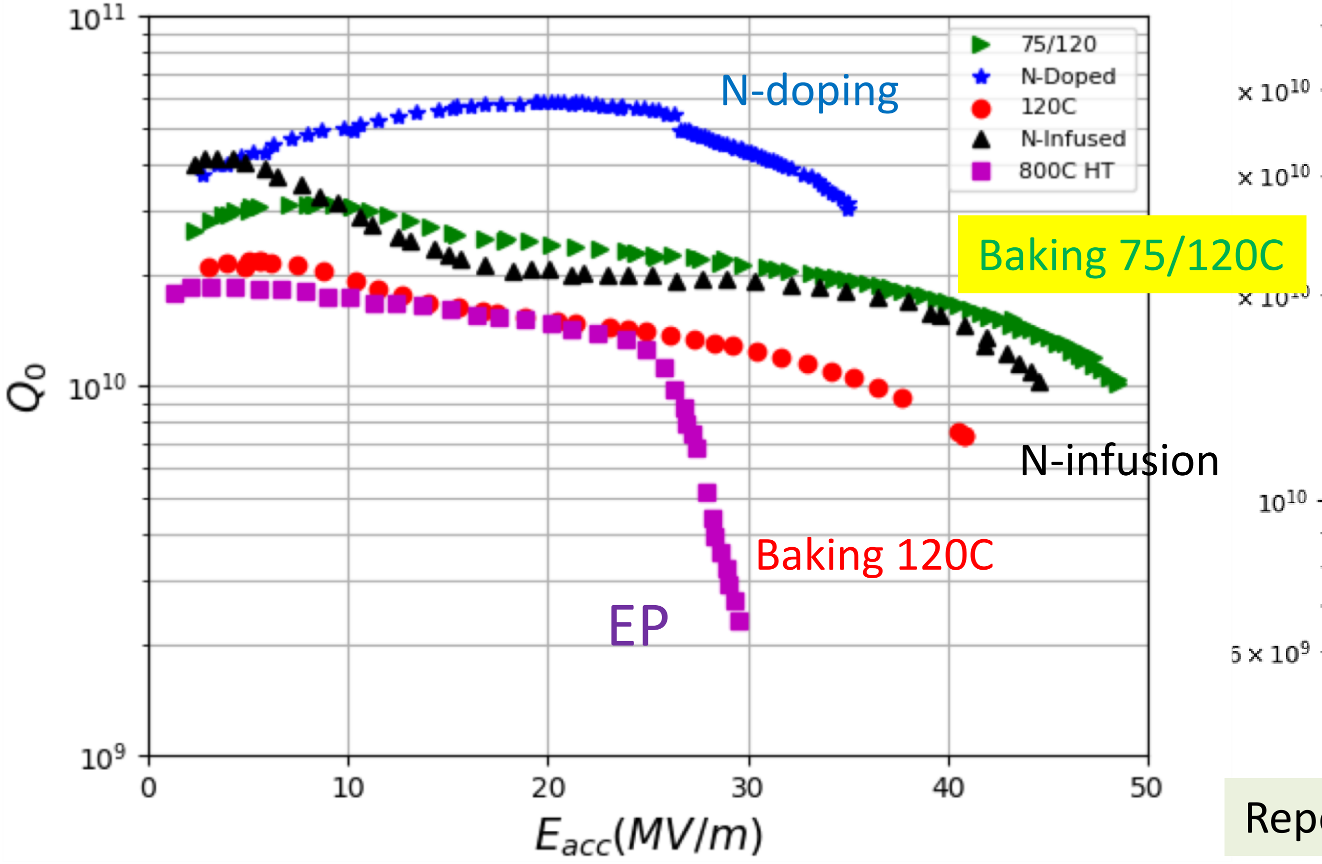


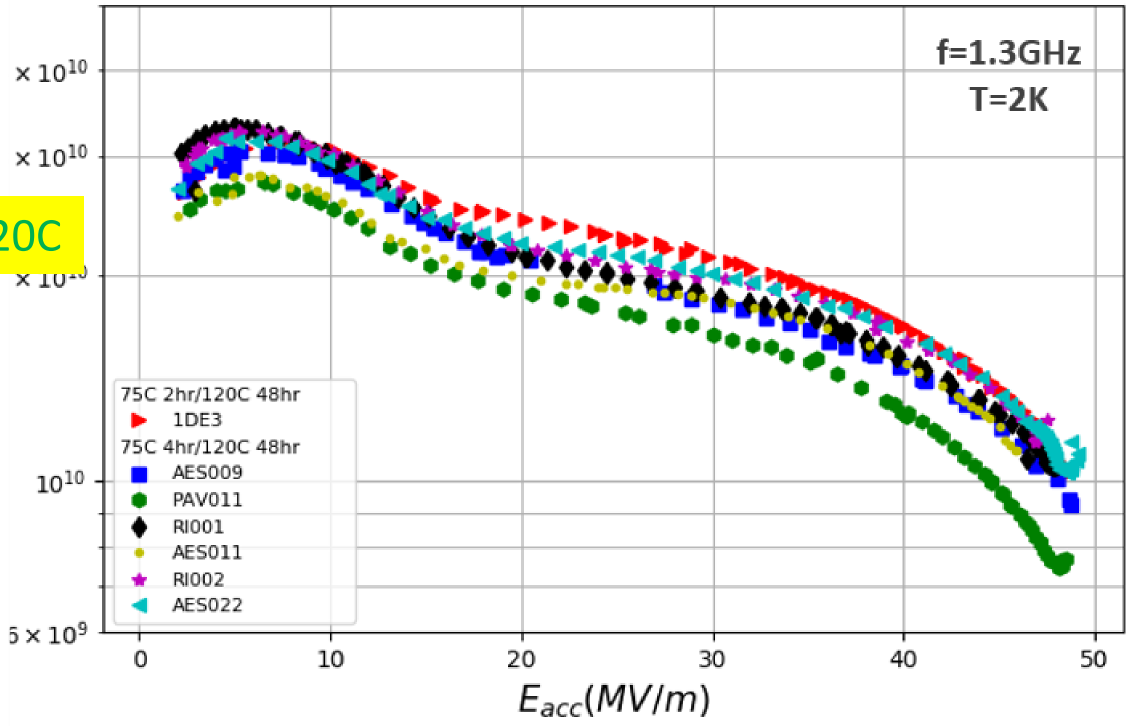
- N-doping (@ 800C for 48h)
  - Q>3E10, 35 MV/m
- **Baking w/o N (@ 75/120C)**
  - Q>1E10, 49 MV/m (Bpk-210 mT
- N-infusion (@ 120C for 48h)
  - 1E10, 45 MV/m
- Baking w/o N (@ 120C for xx h)
  - 7E9, 42 MV/m
- EP (only)
  - 1.3E10, 25 MV/m

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

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

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





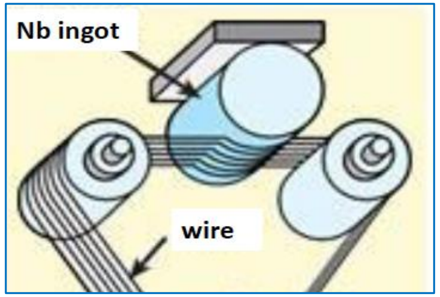
Repeated on second cavity TE1AES009 (fine grain, AES, WC)

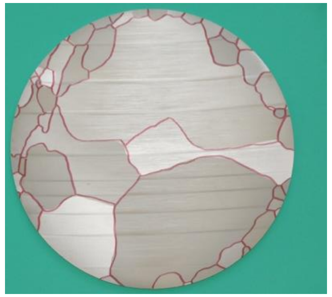
The performance also confirmed by Cornell, JLab, and DESY, and expected to be confirmed by other laboratories

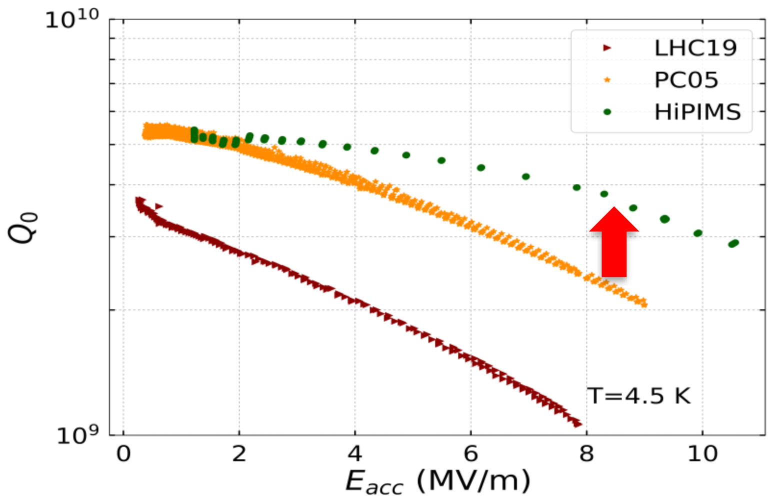
https://arxiv.org/abs/1806.09824

Challenges in SRF Cavity Technology

- **Bulk-Nb: High-G and High-Q optimization**
  - Low-T treatment w/ or w/o N-infusion.
- **Bulk-Nb: Large-Grain directly sliced from ingot**
  - For possible less contamination and cost-reduction
- **Thin-film Coating**
  - Nb thin film coating on Cu-base cavity structure
  - Nb3Sn/MgB2 film coating on Bulk-Nb or Cu structure
    - Much higher G, w/ high-Bc (Bsh)
    - Important for lower frequency and/or low-beta application.
      - A New approach by using **High Impulse Power Magnetron Sputtering** (HiPIMS) , instead of **DC Magnetron Sputtering** (DCMS), resulting flatter Q-slop, resulting better thermal efficiency.



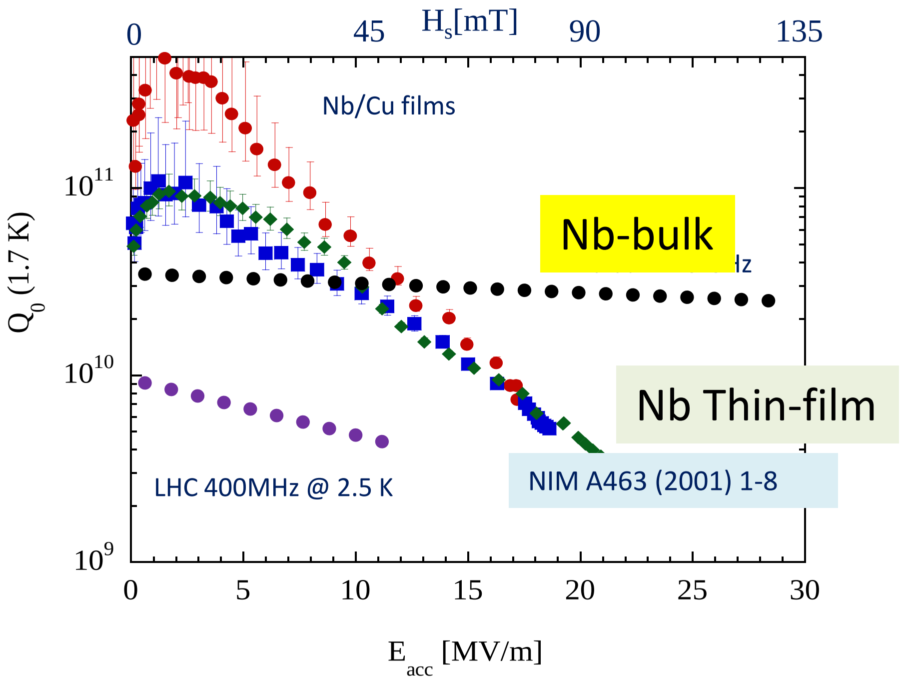




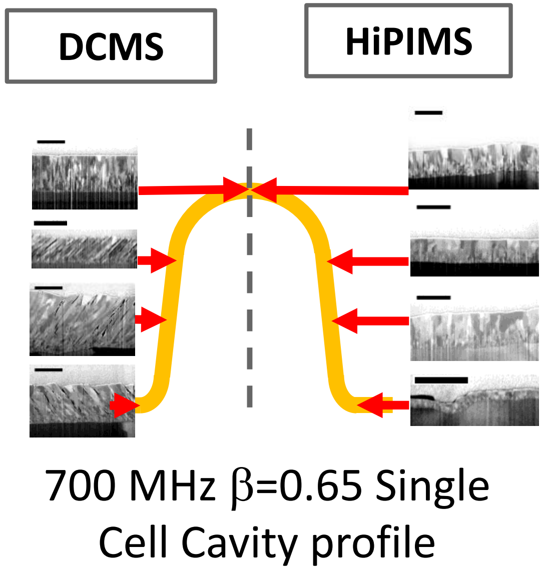
Courtesy: S. Calatroni

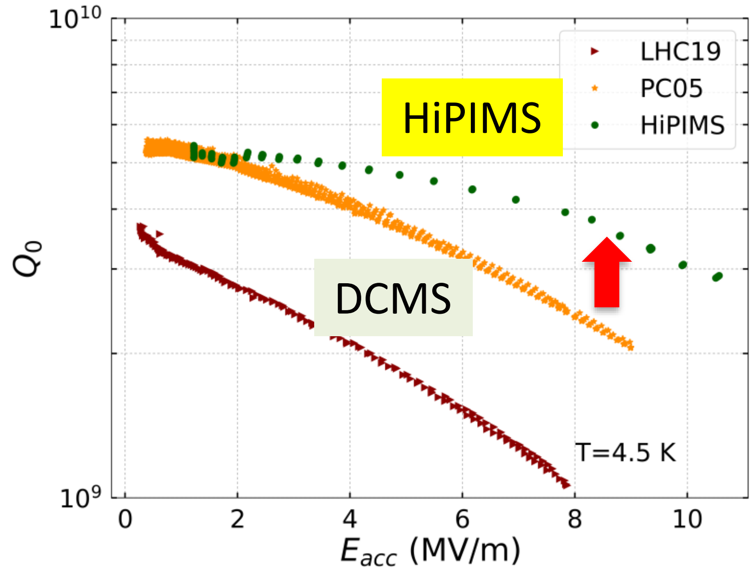
DC Magnetron Sputtered Nb/Cu Films

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



HiPIMS coatings – QPR Sample





- Q = $1x10^{10}$ @ 15 MV/m is a value that would make film cavities a competitive option in several future projects.
- Current R&D is focussed on improving the "slope", applying films to new geometries, new materials

- HiPIMS Nb/Cu films appear to be comparable to bulk Nb on quadrupole resonator sample at 400MHz, 800MHz and 1.2GHz.
- Q-slope phenomenon seems to disappear and support the effort to evolve this technology into real cavities, and High-Q resulting **Power Saving**,
- Projected performance > 2x better than LHC specifications

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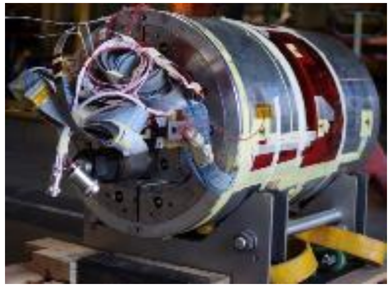
  - **Superconducting technology** for future Lepton and **Hadron Colliders**

- **Summary**

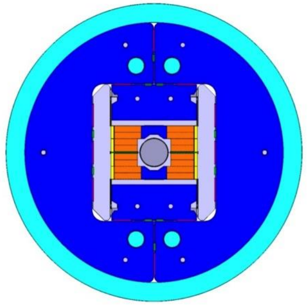
Courtesy: G. De Rijk, A. Devred

Advances in Nb_3Sn Magnet Development

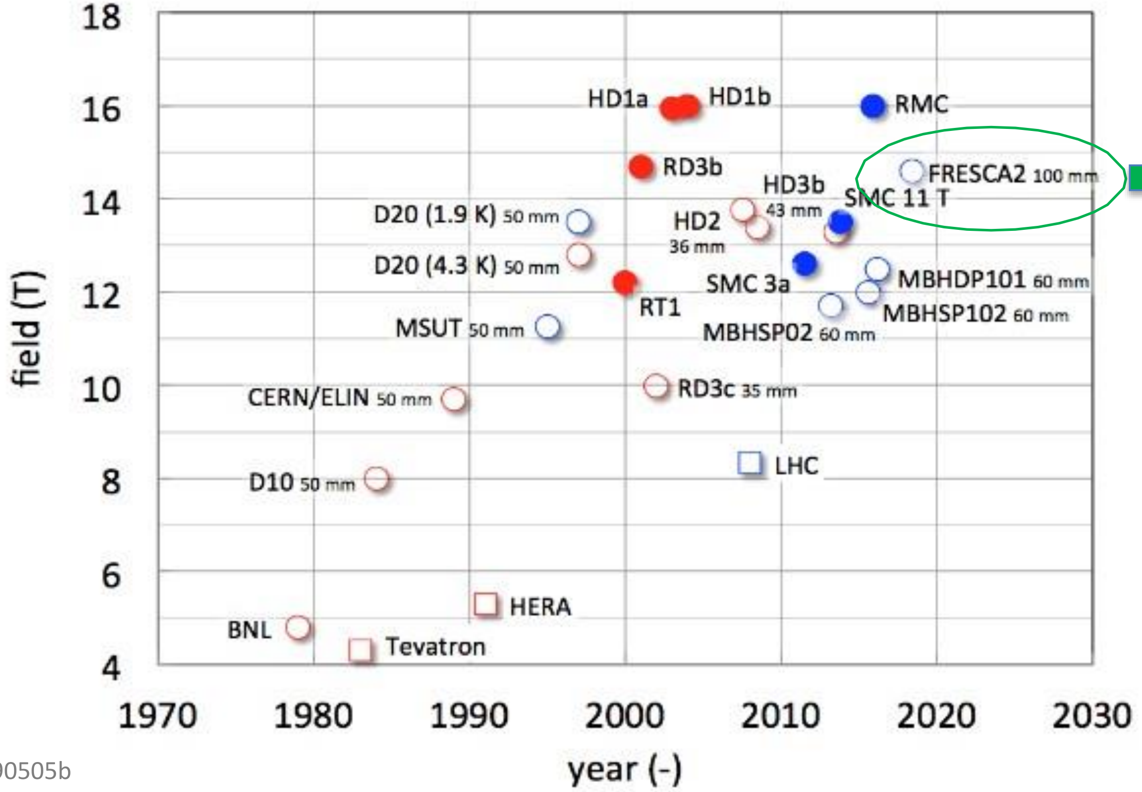
2003: LBNL HD1
(16 T at 4.2 K)

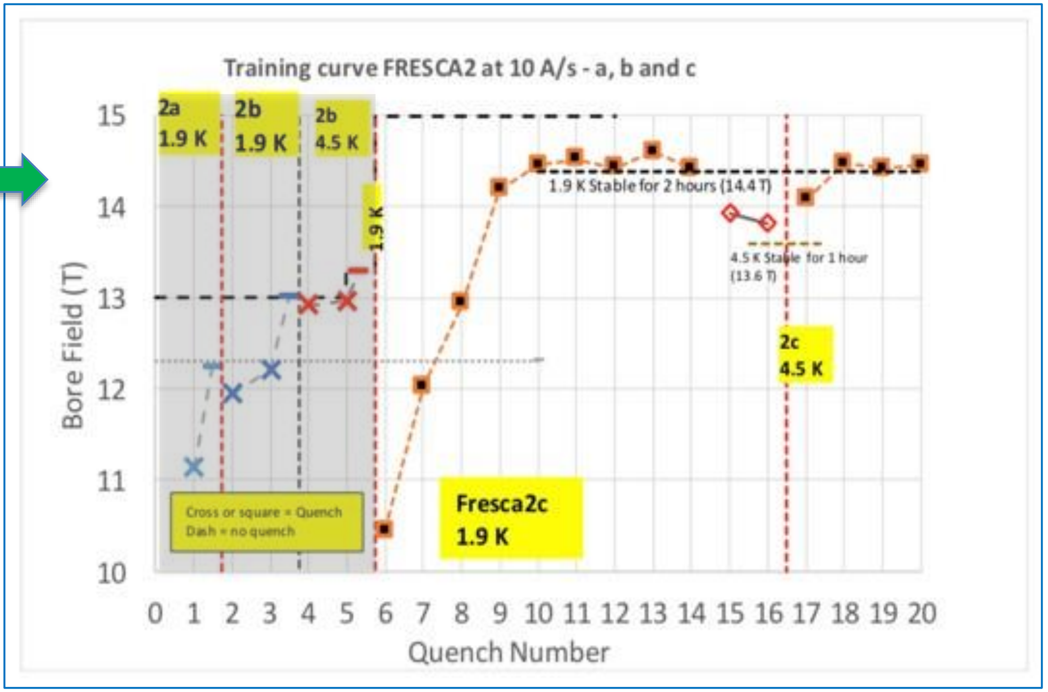


2015:CERN RMC
(16.2 T at 1.9 K)



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

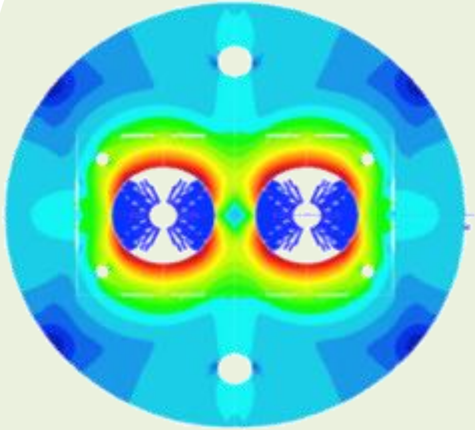




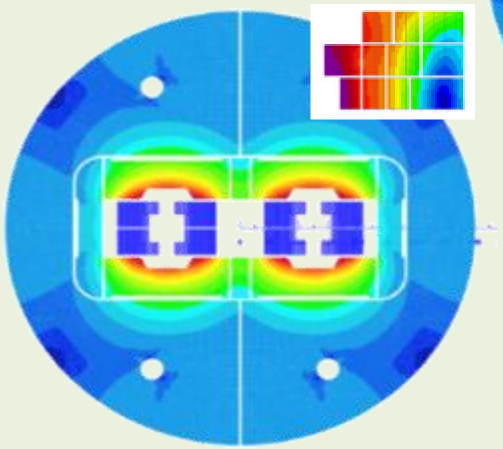
Courtesy, M. Benedikt, L. Bottura, D. Tommasini, S. Prestemon

16 T Dipole Options and R&D Cooperation

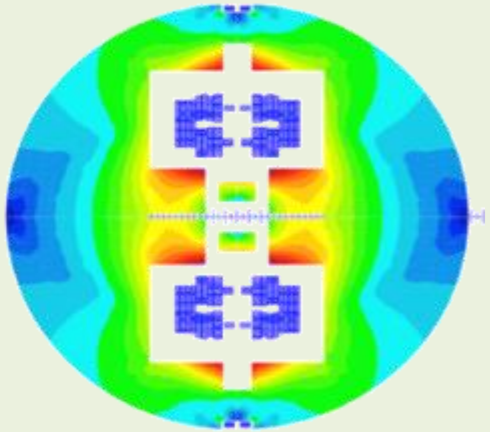
Cos-θ



Blocks



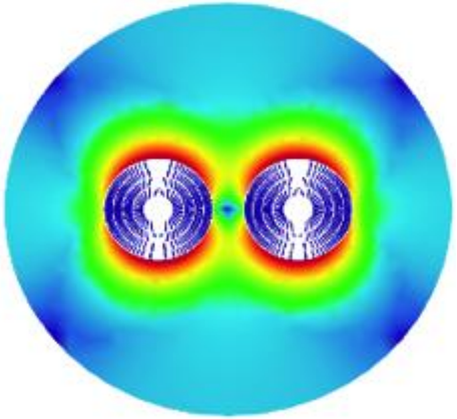
Common coils



Pioneering work at BNL

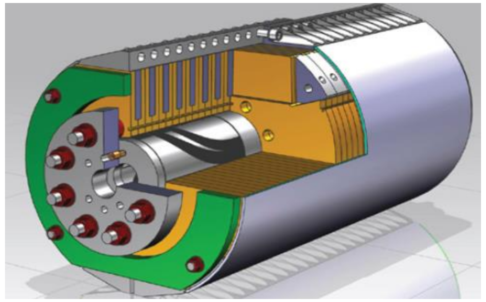
CHART2
Swiss Acc. Research and Technology
See; Appendix

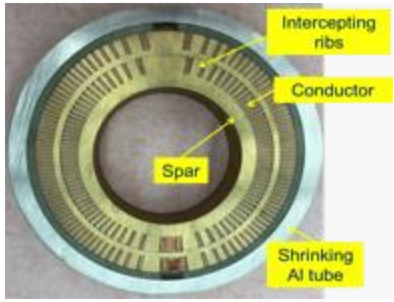
Canted Cos-θ (CCT)

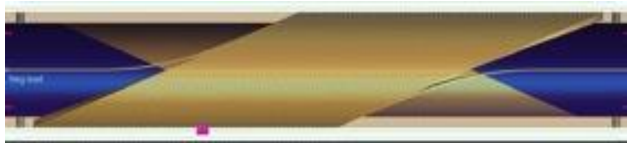


U.S. MAGNET DEVELOPMENT PROGRAM

Cos-θ



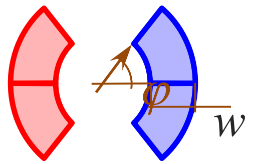




CCT,
Pioneering work at LBNL

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

Nb_3Sn Conductor Progress



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

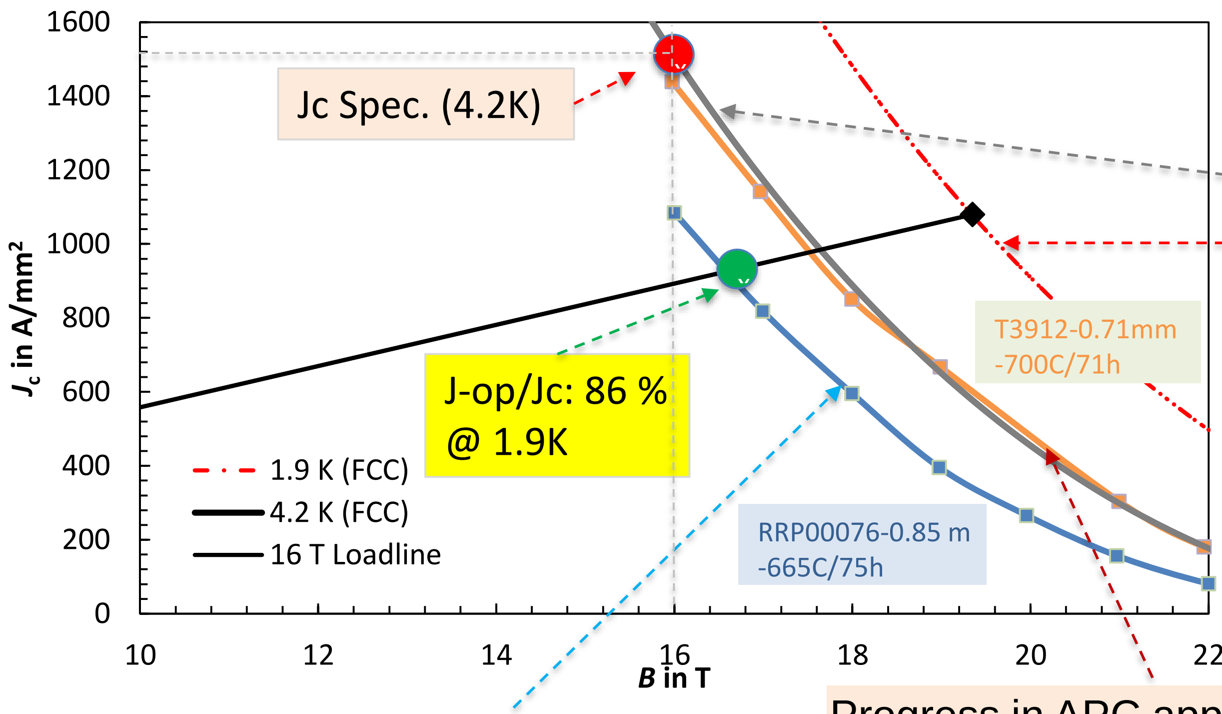
- **Artificial Pinning Center (APC)** approach has been successful, for
- J_c (16T, 4.2K) to have reached ~ 1500 A/mm² in pure research,
- Industrialization and cost-reduction is yet to come !!

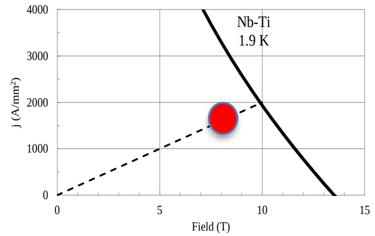
Main development goals:

- **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





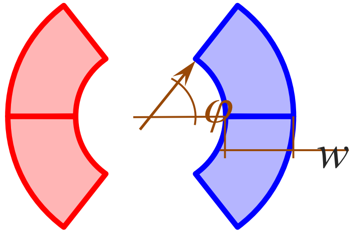
Progress in Ternary Add. Approach:
K. Saito/T. Ogitsu et al. (JASTEC/KEK)

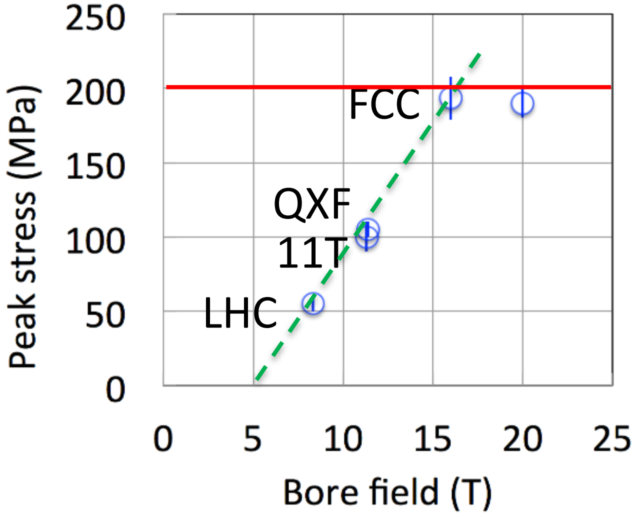
Progress in APC approach:
X. Xu et al (Fermilab)

https://arxiv.org/abs/1903.08121

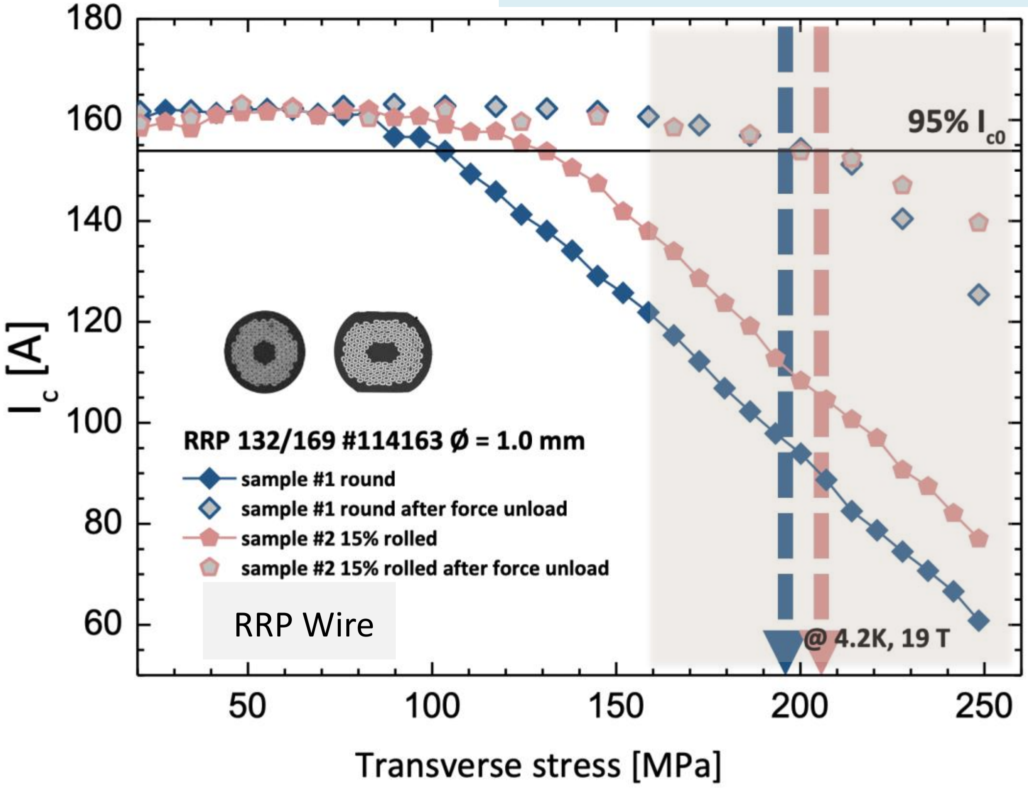
Courtesy: L. Bottura, A. Devred

Mechanical Constrain to consider Operating Margin





Wire Measurement @Univ. Geneve



$$F \propto B^2$$

$$w \propto \frac{B}{J}$$

$$\rightarrow \quad \sigma \approx \frac{F}{w} \propto JB$$

Magnetic pressure (p):
-- Mechanical stress (σ)

- Reversible I_C reduction already at 150 MPa (~15% at 11.6 T);
- Irreversible I_C degradation onset, around at 160-170 MPa.

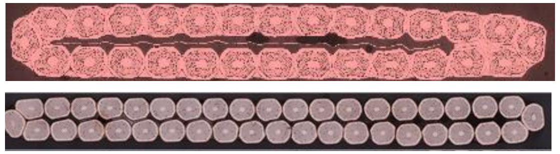
MDP taking Steps to realize 16 T

MDP Goals:

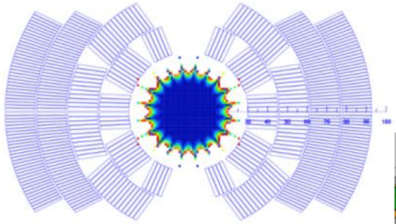
1. Explore Mb_3Sn magnet limit
2. Demonstrate HTS magnet (5 T – self fied)
3. Investigate fundamentals for performance and cost reduction
4. Pursue Nb3Sn and HTS conductor R&D

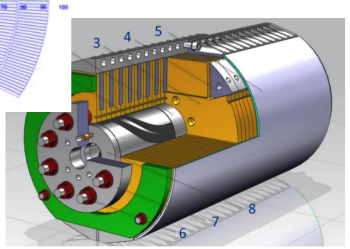
See Appendix

- **Step 1:** We are here in 2019
  - Realize 14 T w/ mechanical design for 16 T
- 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

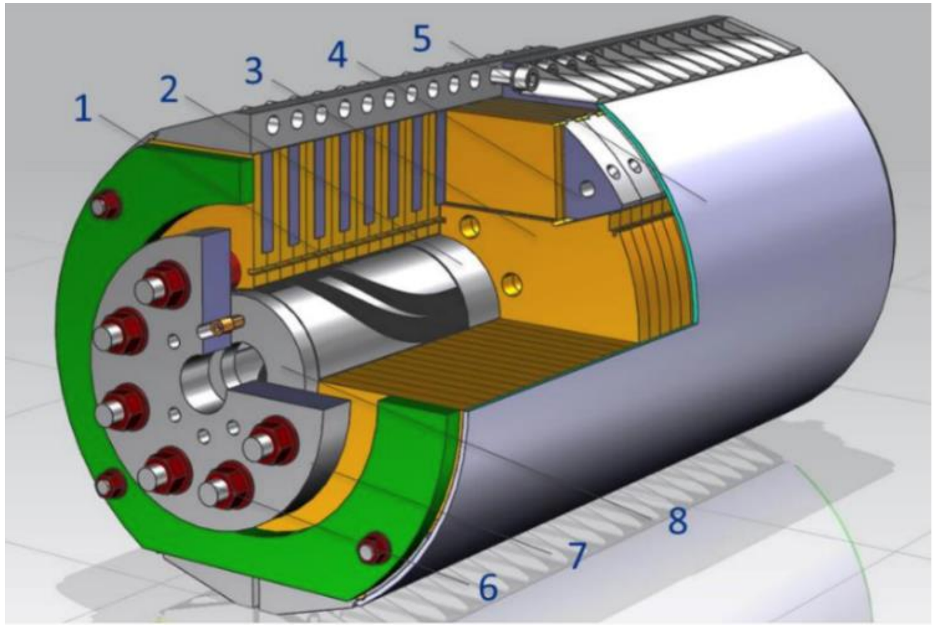




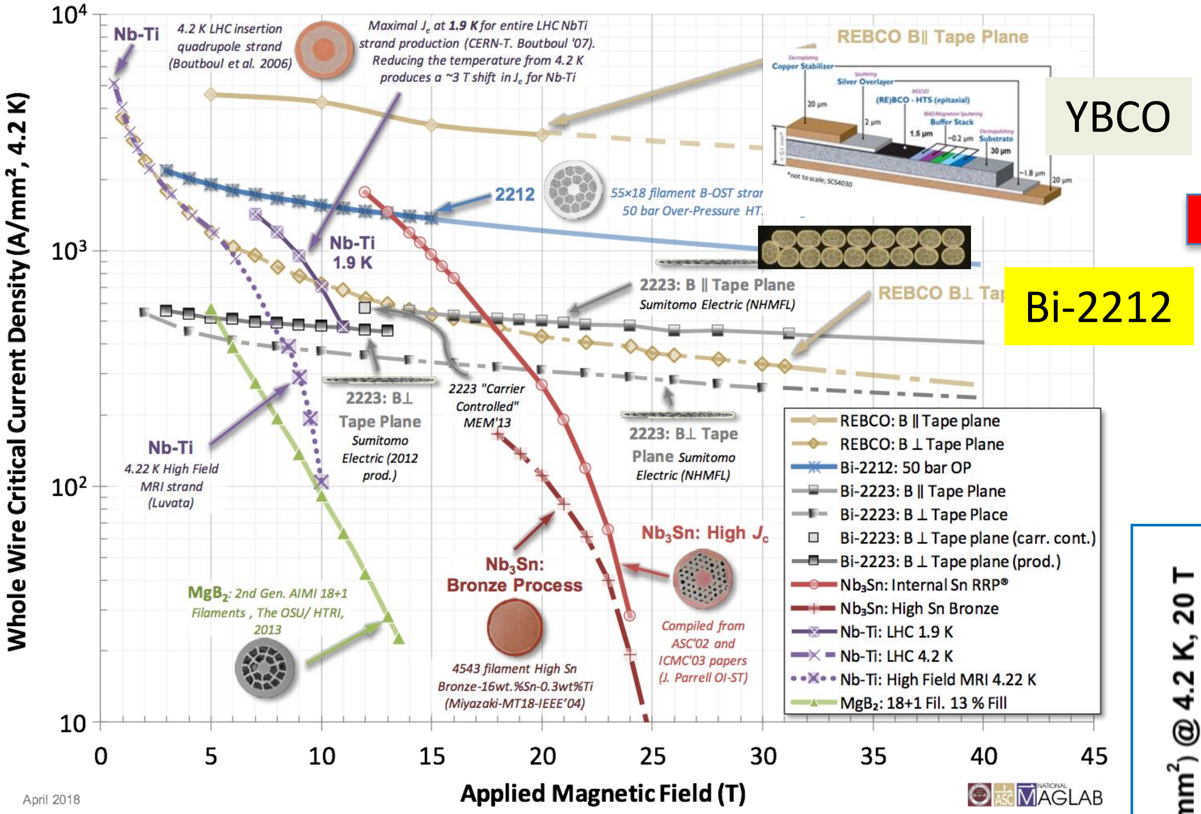
Courtesy: S. Belomstnykh

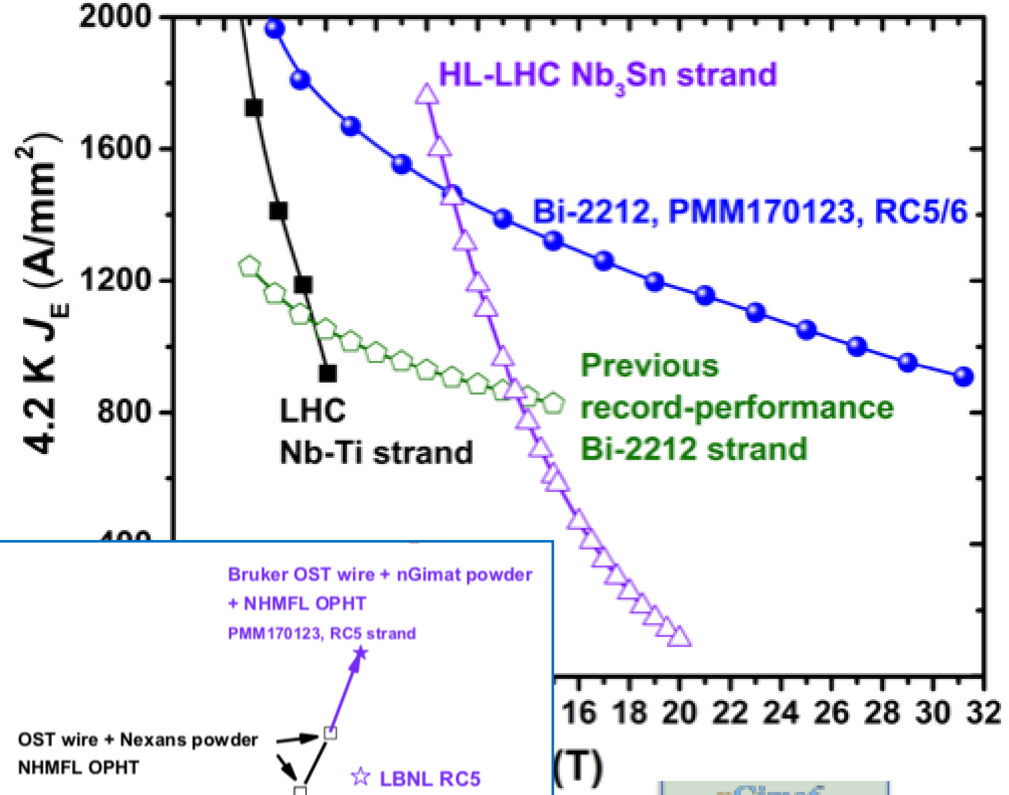
MDP: SC Magnet R&D at Fermilab: 15 T Dipole

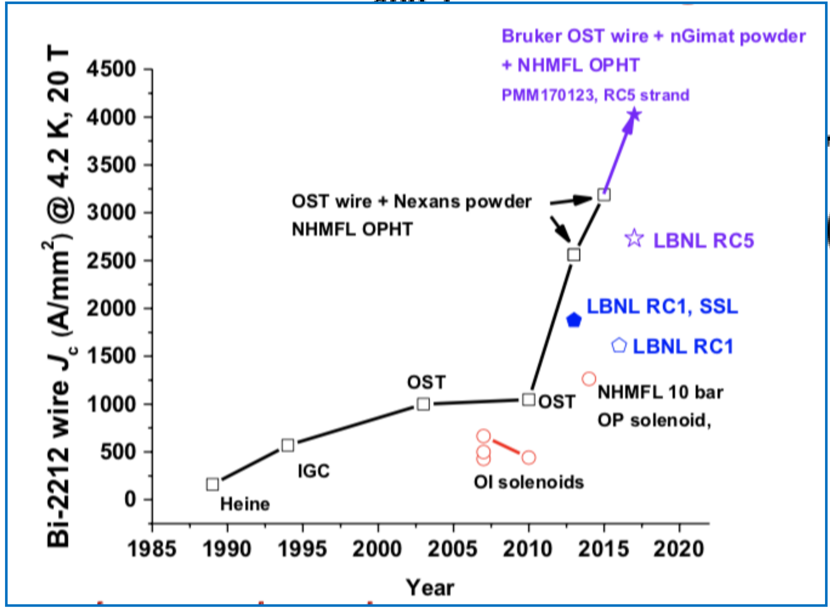
- The 15 T dipole demonstrator magnet assembly is finished
- The dipole is in being prepared for the first test expected to start in a week

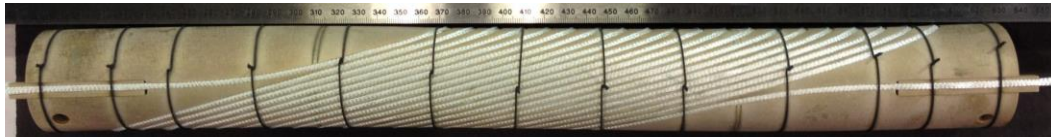


HTS Superconductor, focusing on Bi2212 (in MDP)





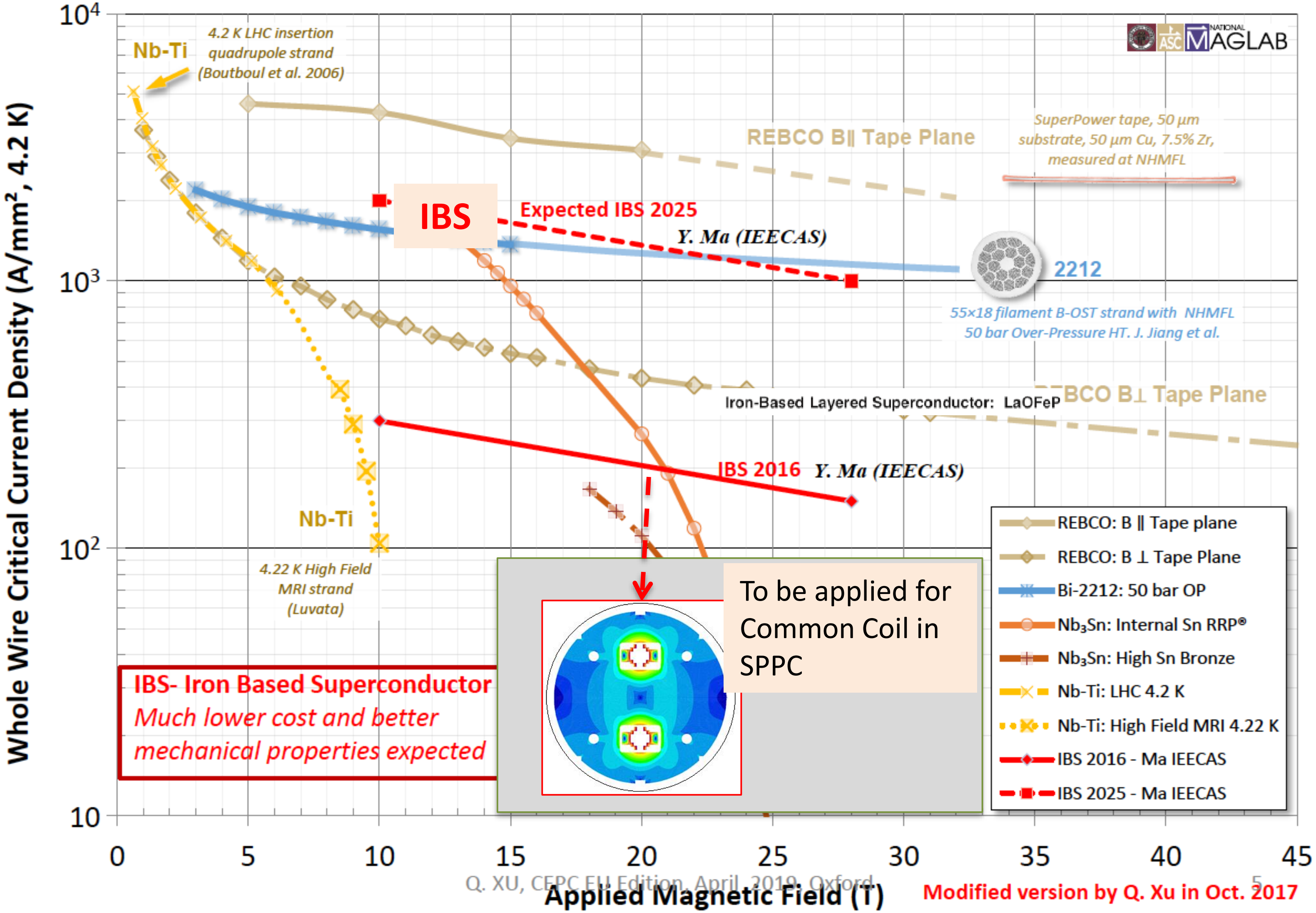




Application expected for CCT coil

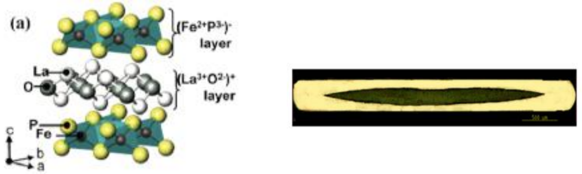
Courtesy, P. Lee, Q. Xu

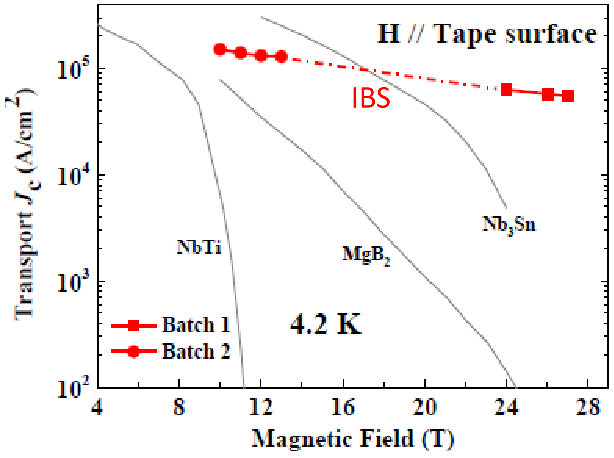
High-Field Superconductor and Magnets, focusing on IBS



Y. Kamihara et al., J|A|C|S COMMUNICATIONS Published on Web 07/15/2006

Iron-Based Layered Superconductor: LaOFeP



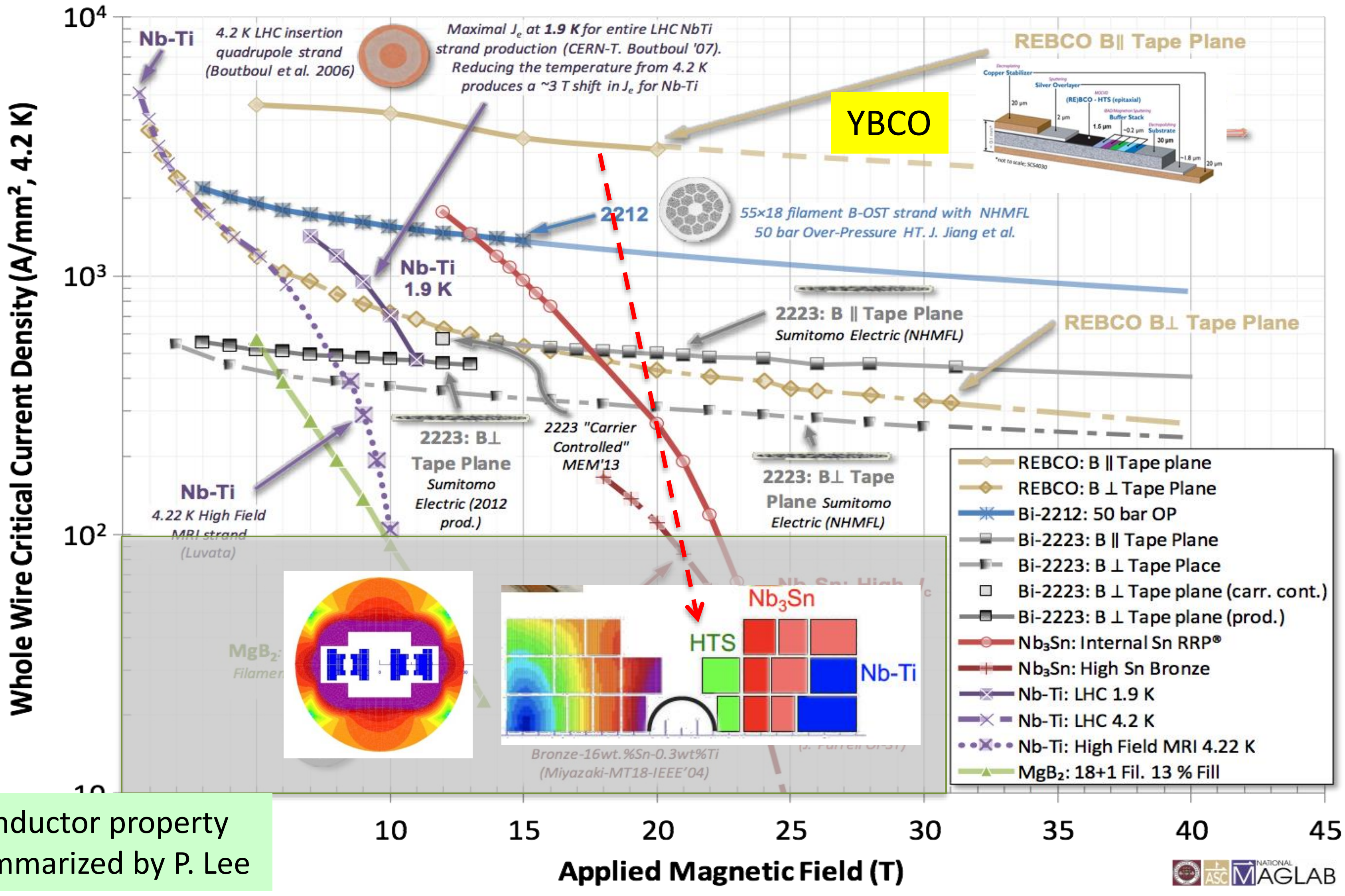


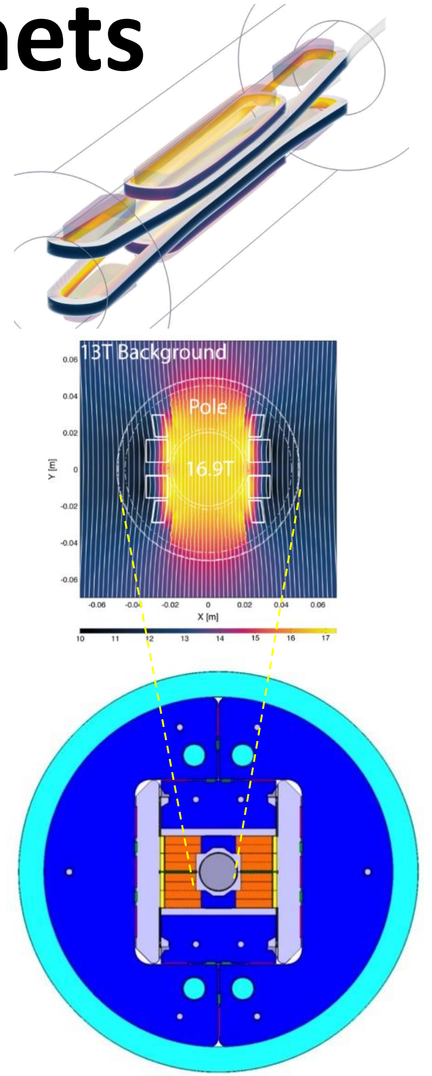
Y. Mao et al., Supercond. Sci. Technol. 31 (2018) 015017

Iron Based Superconductor (IBS) in China.

A. Yamamoto, 190505b

High-Field Superconductor and Magnets





Conductor property summarized by P. Lee

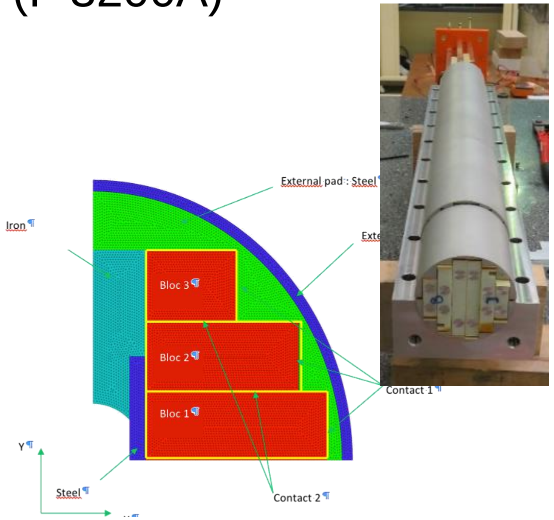
Eucard2: HTS-insert to be tested in 2019
3~5 + 13.5 T : > 16 T

Courtesy: G. De Rijk

Three HTS inserts (CERN and Collaborations)

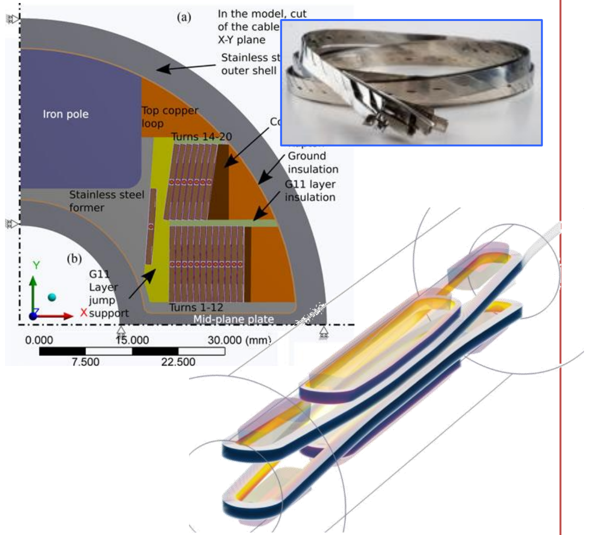
<u>EuCARD1</u>: insert (CEA-CNRS-CERN),

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



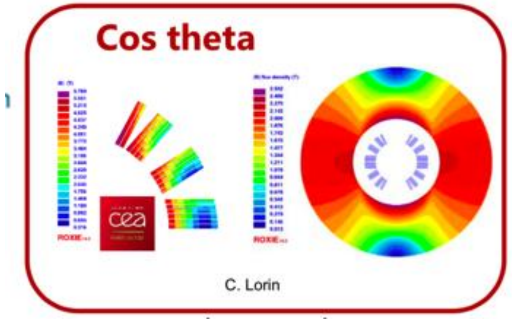
<u>EuCARD2: Feather-M2</u> (CERN),

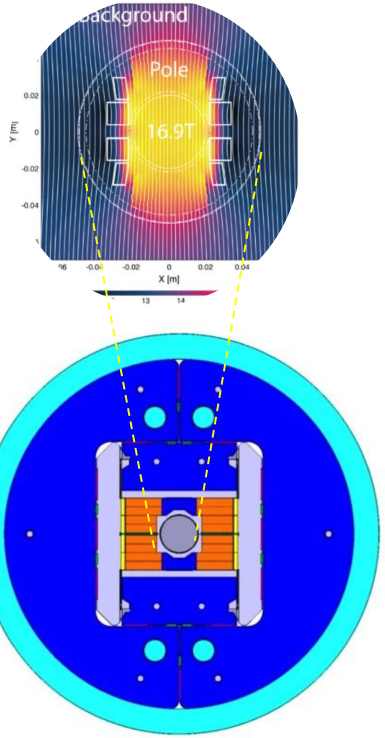
flared ends coil ReBCO,
Roebel cable,
stand alone tested Apr 2017:
Reached 3.37 T @ 4.2K (I=6500A)



<u>EuCARD2: cosΘ insert</u> (CEA),

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

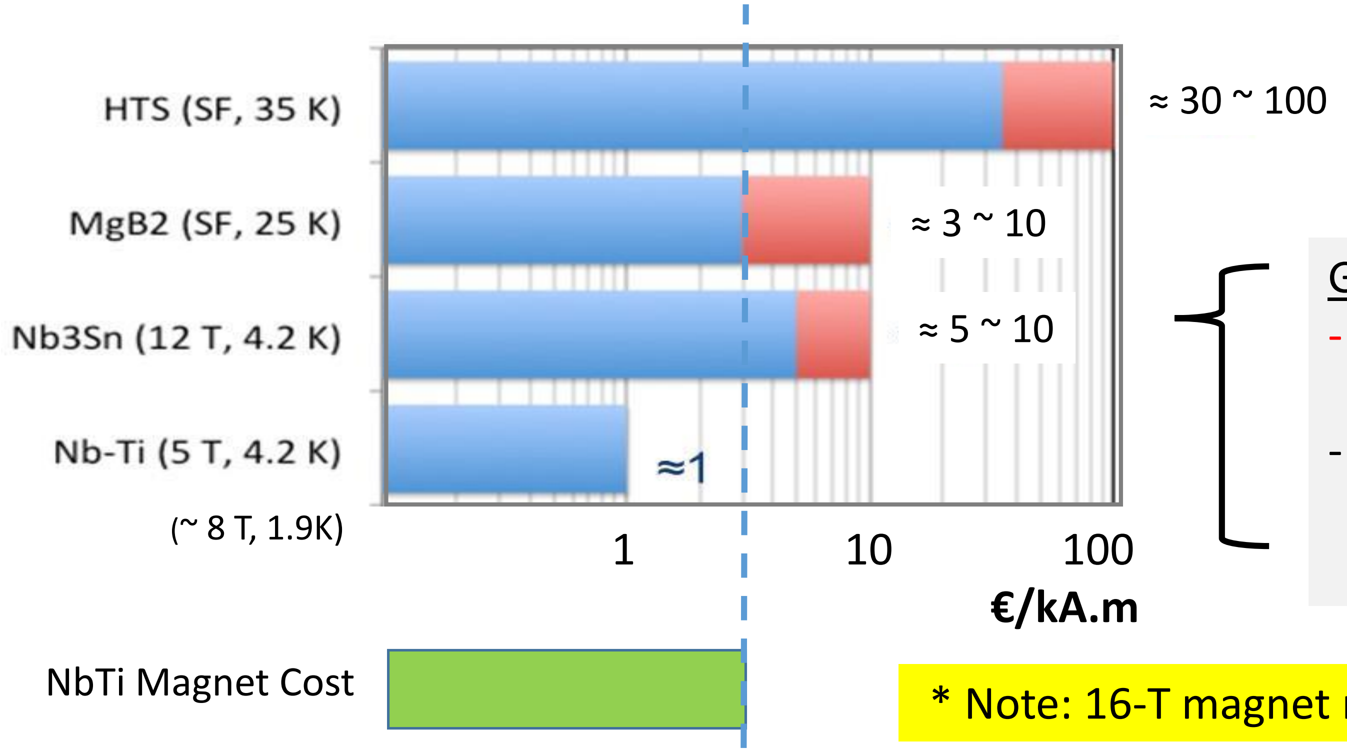




Eucard2+ HTS-insert to be tested in 2019

Some Cost References for High-field Conductors

- 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.

Further challenges in Accelerator Technologies

- Vacuum,
- Targetting,
- Beam collimator,
- Beam dump,
- Radiation hardness,
- Others

Some Information in Appendix

Outline

- **Introduction**
  - Advances in Accelerator Technology in Particle Physics
- **State of the Art in Accelerator Technologies, focusing on**
  - Nano-beam, Superconducting Magnet and RF, and Normal-conducting RF
- **Challenges for future, focusing on**
  - Key technologies and energy management for future Lepton and Hadron Colliders
- **Comments on**
  - **Complementarity for Energy-Frontier vs. Intensity-Frontier, and Energy Management**
- **Summary**

Questions given by EPPSU2020 Acc. Session Conveners:

Lenny Rivkin (PSI) and Caterina Biscari (ALBA)

European Strategy Update

Open Symposium

Big Questions

Accelerator Science and Technology

- What is the best implementation for a Higgs factory?
  Choice and challenges for accelerator technology: linear vs. circular?
- Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?
- How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?
- Energy management in the age of high-power accelerators?

Courtesy: N. Saito, S. Belomestnykh, R. Garoby

Intensity frontier vs. Energy frontier

Intensity – Acc.	Energy [GeV]	Power [MW]	Acc. Tech. Feature	SC Tech.
SPS*	450		Synchrotron	
Fnal M. Injector	120	0.7	Synchrotron	
J-PARC*	3 30	1 0,49 ~ 1.3	Linac/Synchr Ext. Beam	SCM
PIP-II	60 -120	.2	Linac (SRF) Synchrotron	SRF
PSI-HIPA*	0.59	1.4	Cycrotron	
FAIR (SIS100)	29	0.2	Synchrotron	SCM
(ESS) ESSnuSB *	2 2	2 ~ 5 (+5) 2 x 5	Linac	SRF
CEBAF	12	1	LINAC+Ring	SRF
Super-KEKB		---	Collider	
HL-LHC	2 x 7,000	---	Collider	SCM. SRF
EIC*		---	Collider	SCM, SRF

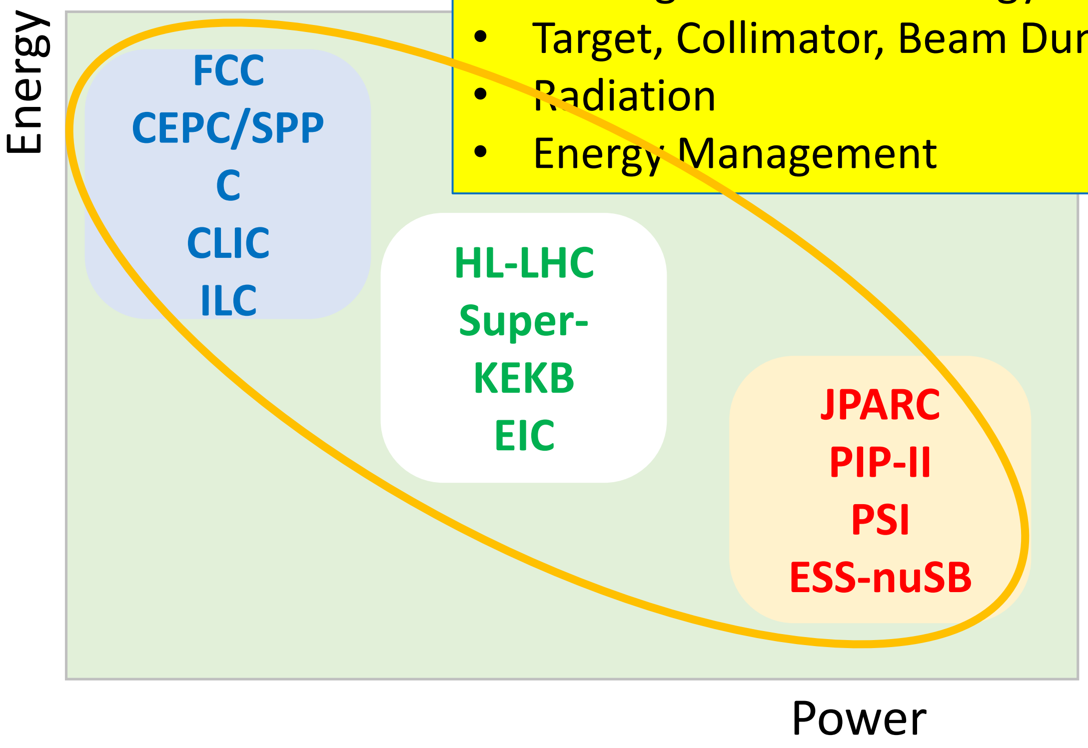
* More in Appendix

A. Yamamoto, 190505b

Discussed by V. Shiltsev in Parallel Session

Common Issues:

- SC Mag. & SRF technology
- Target, Collimator, Beam Dump
- Radiation
- Energy Management



Science is complementary, and
Technology is based on common core technology,
Let us work together and maximize synergy !!

Courtesy: Ph. Lebrun, S. Claude

Energy Management

Major issue in Energy- and Intensity-frontier Accelerators

- **Energy Saving**
  - Superconducting technology (partly covered in this talk)
    - Magnet
    - RF cavity -> further contribution by High-G and High-Q
- **System Efficiency Improvement**
  - Power system efficiency (to be covered by E. Jensen in Acc. Session)
    - RF modulator, Klystron,
    - Two beam acceleration
  - Cryogenics system efficiency
    - Further optimization depending on the operational temperature (eg; Ne-He refrigerator for SR heat removal)
  - Efficient beam dynamics (to be covered by V. Shiltsev)
    - Low-emittance/nano-beam,
  - Novel, further efficient accelerator scheme (to be covered by V. Shiltsev)
- **Dynamic Energy Balance**
  - Important issue: not power (W) efficiency, but energy (W-hour) efficiency
  - Accelerator operation in best harmonized condition in season/day/time.
  - Energy re-use/recycling more communicated with surrounding community/industry

More in Appendix

Outline

- **Introduction**
  - Advances in Accelerator Technology in Particle Physics

- **State of the Art in Accelerator Technology, focusing on**
  - Nano-beam, Applied Superconductivity, and RF

- **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**

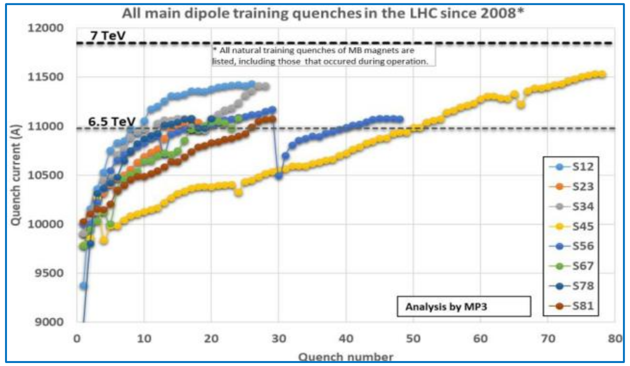
- **Summary**

Summary: State of the Art – RF and SC Magnet

NRF, SRF:

- NRF (~ 12 GHz, 20 cm unit):
  - E (CLIC R&D: 12 GHz): 70 ~ 100 MV/m
- SRF (1.3 GHz, 9-cell cavity)
  - <E> (Eu-XFEL) : 30 MV/m, (~ 800 cavities)
- SRF (Crab cavity)
  - Experienced at KEK-B, and demonstrated at CERN-SPS

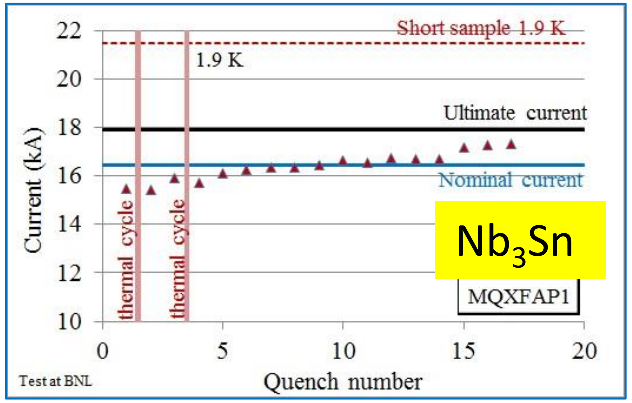
NbTi



SC Magnet:

- NbTi: LHC (Main Dipole)
  - B_{bore} = ~ 8 T at 1.9 K
  - Re-training aft. thermal cycling (TC) still a critical issue
- Nb3Sn: HL-LHC (11 T Dipole)
  - B_{bore} = ~ 11 T at 1.9 K
  - Good memory after TC, but more statistic needed
  - Loadline-ratio, however, should stay lower (< 80%)

Nb_3Sn



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)
    - Potential thin-film on Nb to improve effective Bsh, resulting higher gradient, and further Potential for new SC material such as NB3Sn/MgB2 to much/drastically improve Bc.
- **Superconducting Magnet:**
  - Nb3Sn technology, to reach 16 T, requires much longer steps for much improvement of SC current density, mechanical property, control for field quality and limited training quenches, and industrialization effort.
  - "Nb3Sn + HTS-insert" technology will be required, beyond 16 T, and cost effective HTS will be essentially required for practical accelerator applications.

Personal Prospect

- Accelerator Technologies are ready to go forward for lepton colliders (ILC, CLIC, FCC-ee, CEPC), focusing on the Higgs Factory to start the construction in 5 ~ 7 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_3Sn high-field superconducting magnet, as a core technology for energy-frontier hadron colliders, still requires step-by-step development efforts to reach 14, 15, and 16 T.
- A field range of 14 -16 T, with accelerator quality, would requires much longer time:
  - 12~14 T, 5~10 years for short model work, and next 5~10 years for prototype/pre-series work in cooperation with industry, resulting 10 – 20 yrs to reach the production stage
  - 14~16 T: 10-15 years for short model work, and next 10 ~ 15 years for protype/pre-series work in cooperation with industry, resulting 20 – 30 yrs to reach the production stage, It would be consistent with the FCC- integral time scale.
- NbTi Superconducting magnet technology at 8~9 T is well proven with LHC, and Nb_3Sn magnet at 10 – 11 T is being demonstrated with HL-LHC. A hadron collier with either technology should be practical to start the construction in 5 ~ 7 years.
- Continuing R&D effort for the high-field magnet, present to future, should be critically important, to realize highest energy frontier hadron accelerators in future.

- High-energy and Intensity-frontier needs to work together on energy management including energy-efficiency improvement, energy-saving, energy-recycling, in wider networks with surrounding communities.

Personal View for possible, 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	

Acknowledgments

- ***This talk has been prepared in communication with***
  - *HiLumi-LHC, and US-LARP/AUP collaboration*
  - *Euro-CirCol (FCC study body),*
  - *EUCARD-2 succeeded by ARIES,*
  - *US-DOE Magnet Development Program (MDP),*
  - *US-General Accelerator SRF R&D program (GARD-SRF),*
  - *Tesla Technology Collaboration (TTC), European XFEL, and LCLS-II,*
  - *Linear Collider Collaboration (LCC) for ILC and CLIC ,*
  - *FCC Study at CERN,*
  - *CEPC-SPPC study at IHEP, and*
  - *SC magnet and SRF accelerator laboratories:*
    - *Fermilab, LBNL, BNL, JLab, Cornell, SLAC, CERN, CEA-Saclay, LAL-Orsay, DESY, STFC,KEK, …*

GARD-SRF

- ***Special thanks to***: *F. Bordry, L. Rossi, S. Steinar, J. M. Jimenez. L. Bottura, A. Devred, G. De Rijk , A. Ballarino, E. Todesco, D. Tommasini, F. Savary, D. Schoeling, E. Jensen, W. Wuensch, S. Cataloni, B. Foster, B. List, N. Walker, H. Weise, S. Prestemon S. Belomestnkh, A. Grassellino, H. Padamsee, M. Ross, N. Saito, S. Michizono, K. Yokoya, N. Terunuma, T. Ogitsu, T. Taylor, L. Evans, L. Revkin, C. Biscari, and V. Shiltsev, for their kindest cooperation to provide various information and discussion.*

CEPC/SPPC

Appendix

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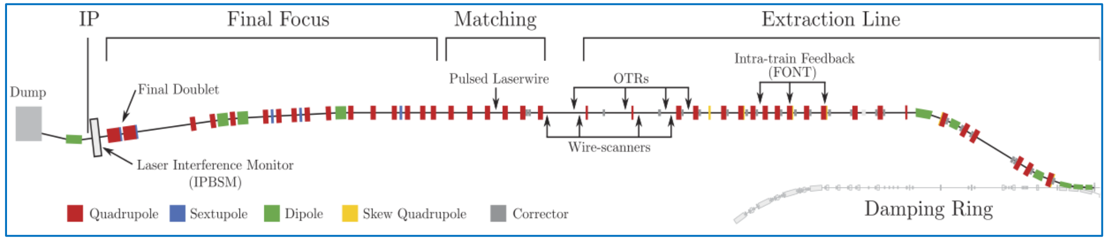
Progress in FF Beam Size and Stability at ATF2

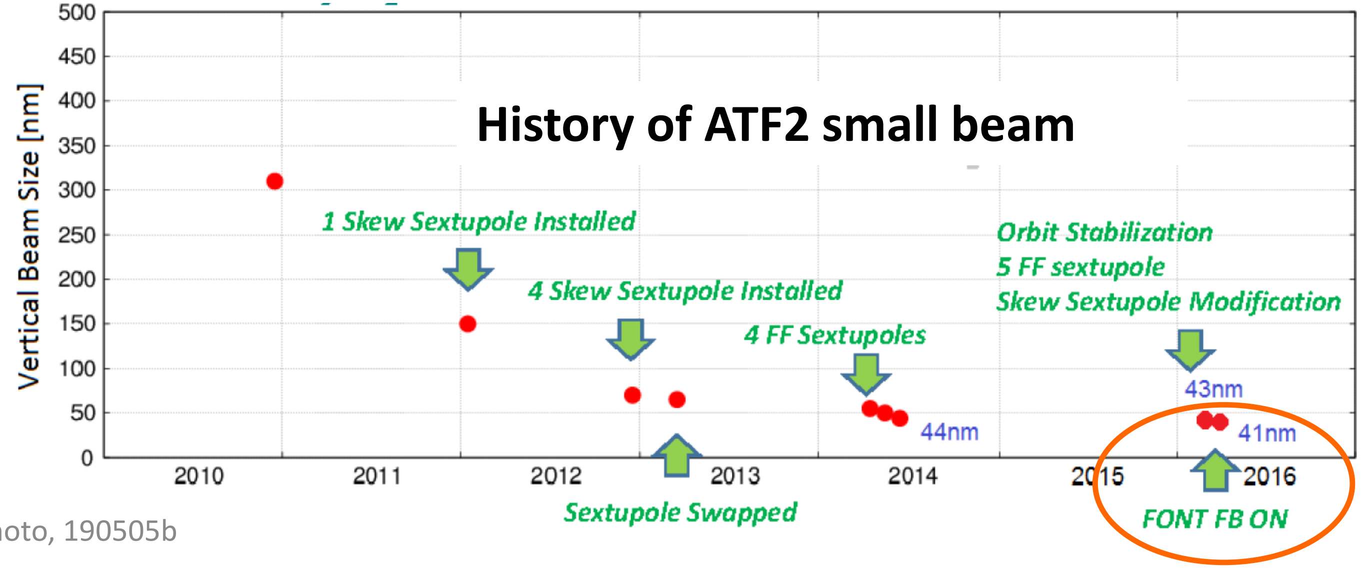
Goal 1: Establish the FF method with same optics and comparable beamline tolerances

- ATF2 Goal : 37 nm → 7.7nm@ILC250GeV
    - Achieved **41 nm** (2016)

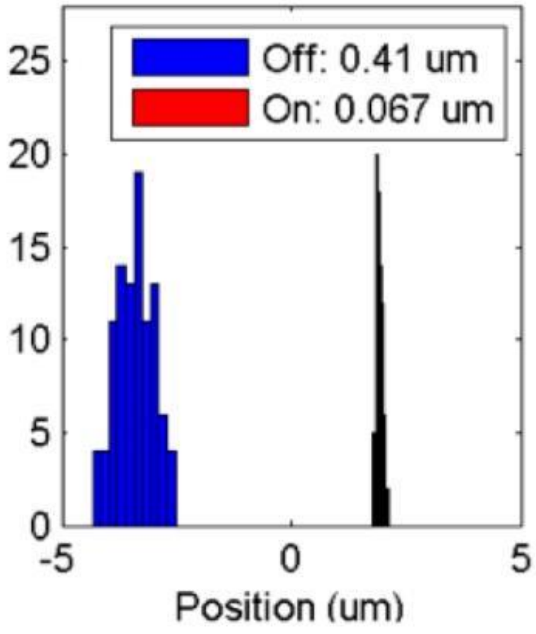
Goal 2: Develop nm position stabilization at FF:

- **FB latency 133 ns achieved** (target: < 300 ns)
- **positon jitter at IP: 410 → 67 nm (2015)** (limited by the BPM resolution)





Nano-meter stabilization at FF

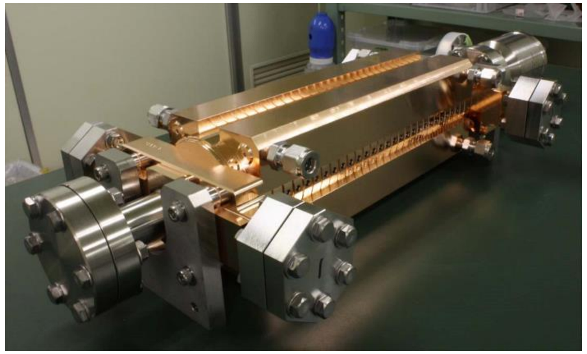


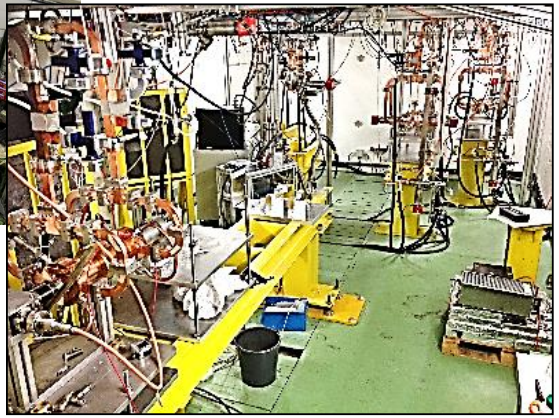
A. Yamamoto, 190505b

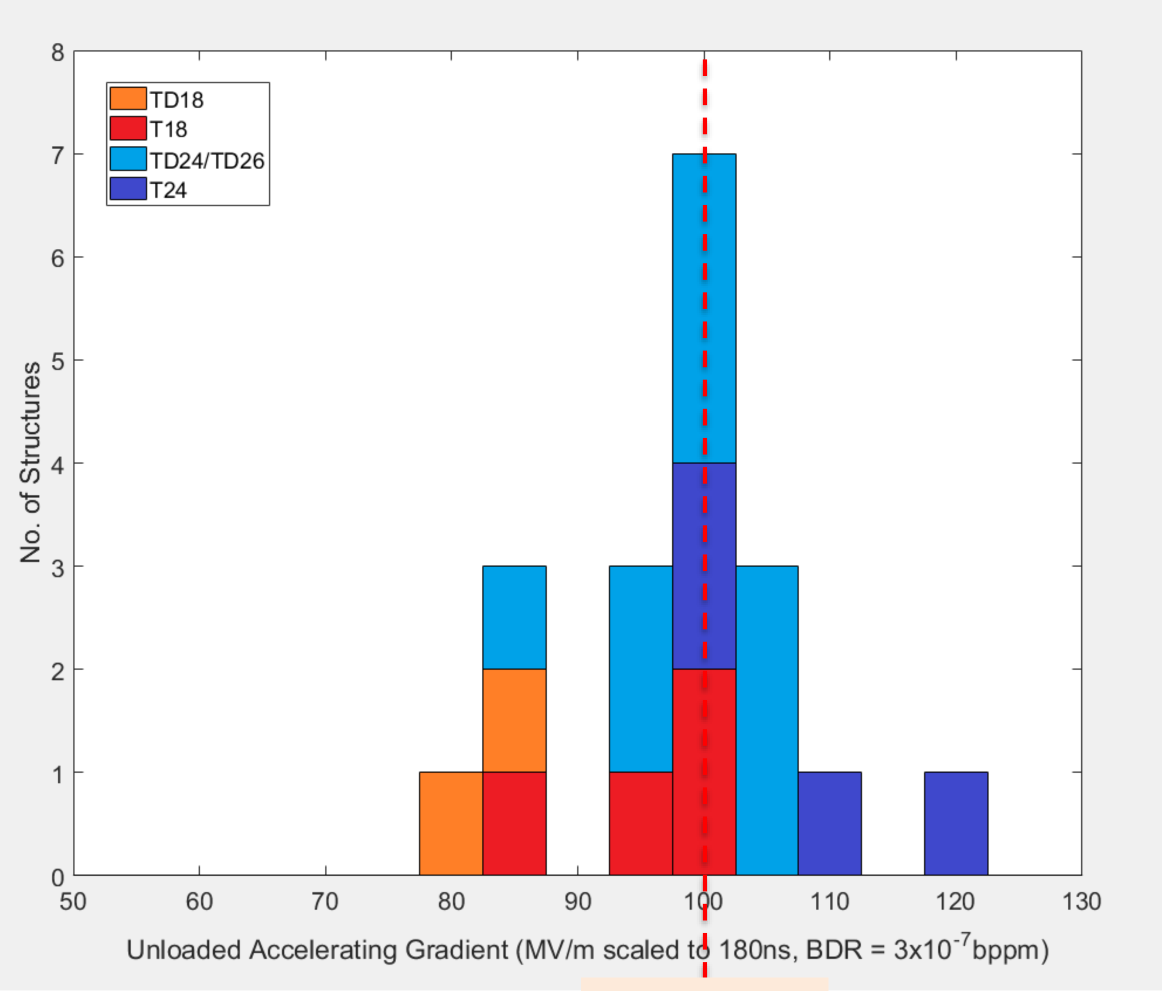
Curtesy: S. Stapnes, P. Barlow, W. Wuensch

Progress in Normal Conducting RF Acc. Structure

- **Achieved 100 MV/m gradient in main-beam RF cavities**

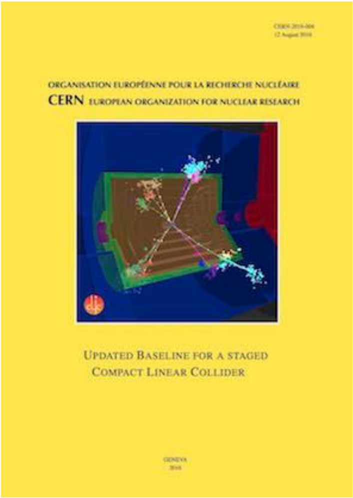


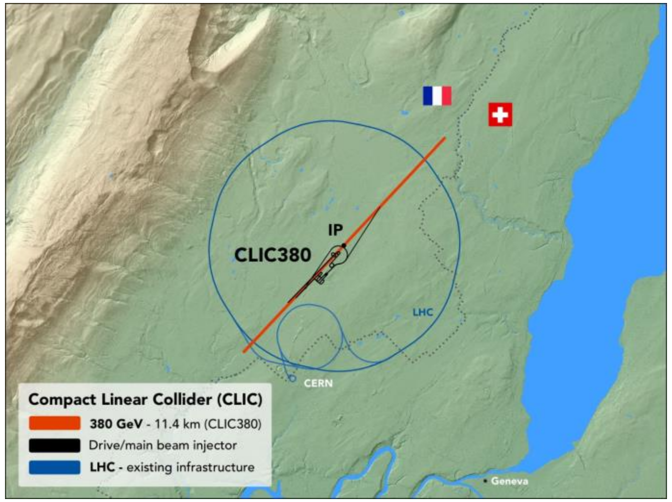




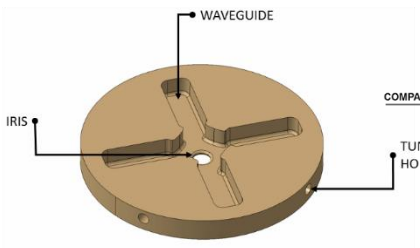
Curtesy: S. Stapnes, P. Barlow, W. Wuensch

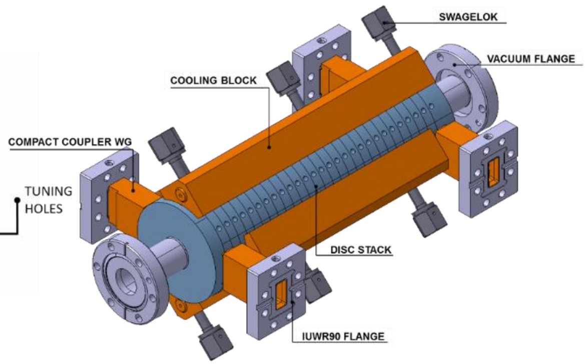
NRF Technology for CLIC-380 and beyond





- Linear e^+e^- collider, staged **$\sqrt{s}$ = 0.38 TeV**
- **70 MV/m** accelerating gradient needed for compact (~11 km) machine based on :
  - normal-conducting accelerating structures
  - two-beam acceleration scheme
- **Issue remaining:**
  - Power efficiency at higher energies
  - Large scale production experience for Acc. Structures
  - System-level alignment and stabilization



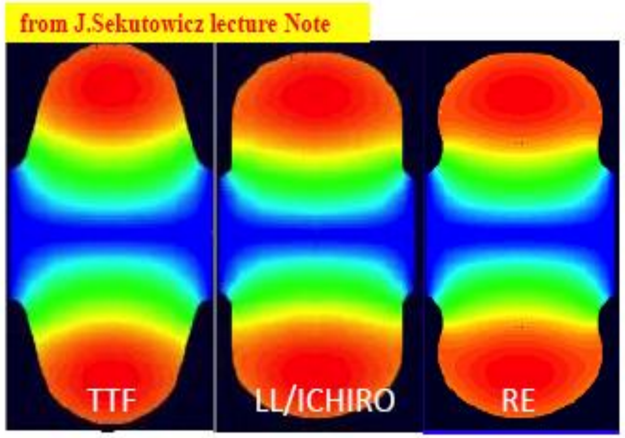


Better Cavity Shapes to Beat the Limit:

Lower H_{pk} even if you have to raise E_{pk}

$$E_{acc} = \frac{H_{CR}^{RF}}{H_{pk}/E_{acc}}$$

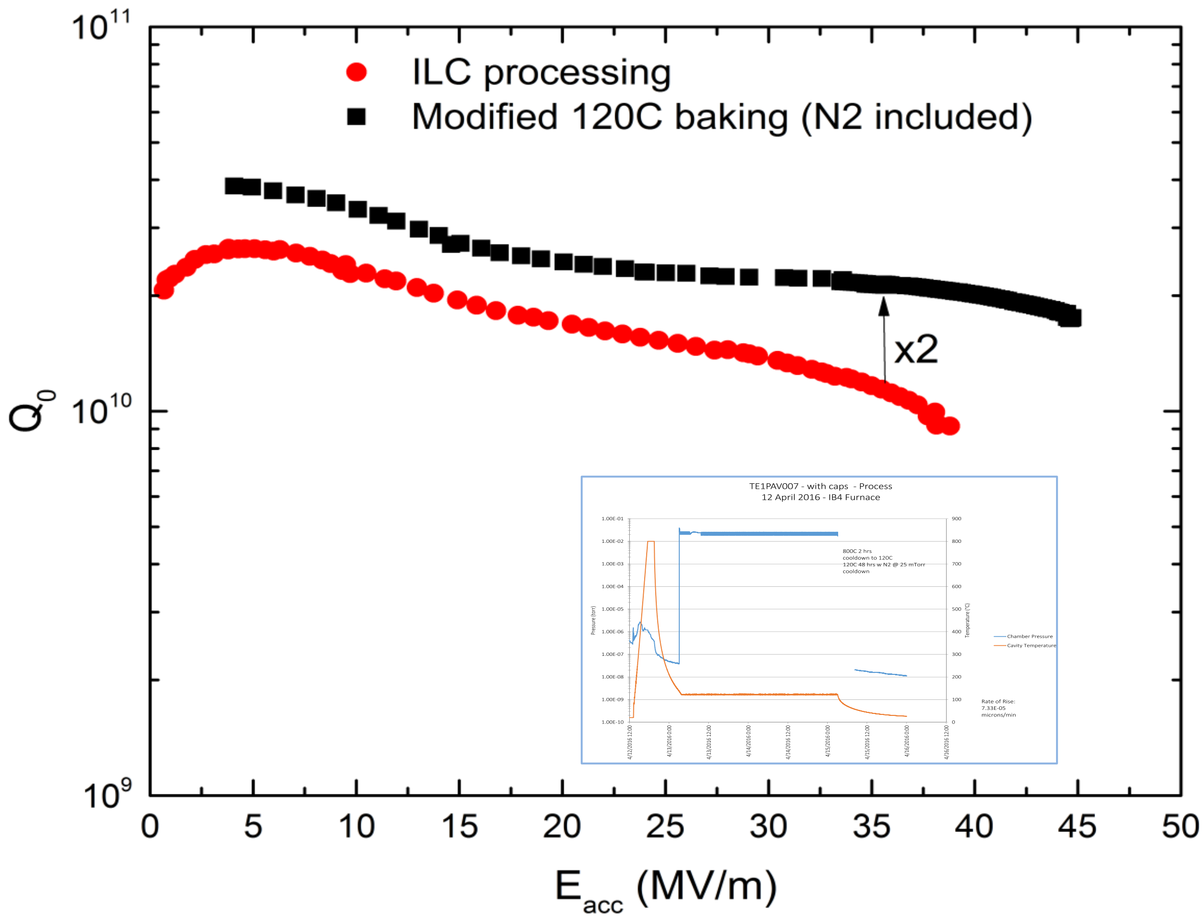
TTF: TESLA shape
Reentrant (RE): Cornell Univ.
Low Loss(LL): Jlab/DESY
LL/ICHIRO: KEK
Low Surface field(LSF): SLAC/Jlab



Shape	TTF	LL/Ichiro	RE	LSF
D-iris [mm]	70	60	60	60
Ep/Eacc	1.98	2.36	2.28	1.98
Hp/Eacc [Oe/MV/m]	41.5	36.1	35.4	37.1
G*R/Q [Ω^2]	30840	37970	41208	36995
Eacc-max [MV/m]	42.0	48.5	49.4	47.2

Courtesy, A. Grassellino

“N infusion” during 120C bake, improving both G and Q



Achievements at Fermilab:

G-max = 45.6 MV/m →194 mT

Q (at 35 MV/m) : ~ 2.3e10

Improvements:

G : ~ 15 %

Q : x 2 → Cryogenics saving

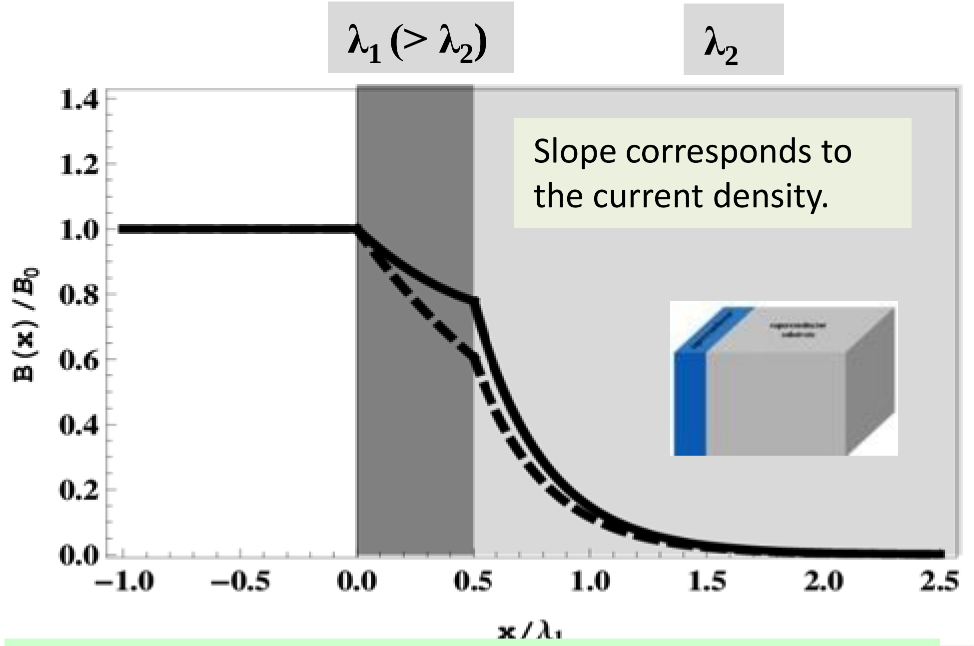
arXiv:1701.06077

- The recipe discovered and demonstrated at **Fermilab** (by A. Grassellino et al.).
- Global collaboration extends the R&D and demonstrate the statistics.
- US-DOE and JP-MEXT support the cost-reduction R&D based on the N-infusion technology.

Courtesy, R. Laxdal, T. Kubo

Possible Consideration and Models

- 120C bake is known to manipulate mean free path at very near surface (~nm) on clean bulk Nb.
- The Nitrogen (N) infusion is a variation of the 120 C bake where N dopes the near surface w/o working lossy nitrides.
- A dirty (doped) layer at the surface seems beneficial in order to increase the quench field above Bc1.



Surface current is suppressed:

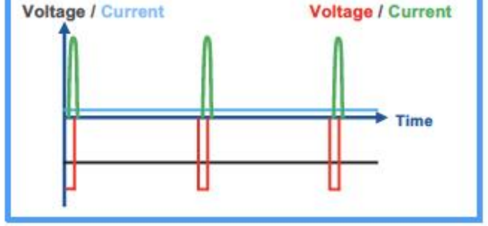
- means an enhancement of the field limit, because of the theoretical field limit to be determined by the current density.

- C.Z. Antoine, et al. APL 102, 102603 (2013).
- T. Kubo et al, Appl. Phys. Lett. 104, 032603 (2014).
- A. Gurevich, AIP Advances 5, 017112 (2015).
- T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017) .. (Figure above)

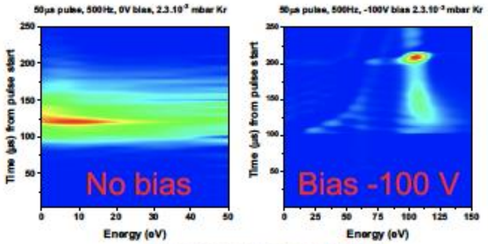
Courtesy: S. Cteroni

HiPIMS principle / setup

DCMS : Direct Current Magnetron Sputtering
HiPIMS: High Power Impulse Magnetron Sputtering



Parameter (unit)	Range
Pulse duration (us)	1-200
Frequency (Hz)	20-500
Power (kW)	100 peak, 2 avg
Gas	Ar, Kr
Pressure (mbar)	8.10^{-4}-5.10^{-2}



Energy plots of Nb^{+}

Same setup as DCMS
Only the power supply changes

High level of ionization of the sputtered species (up to 70%)

High instantaneous power (100's kW) for same average power as in DCMS.

Possibility to densify the layer using a negative voltage (biasing) on the substrate.

Lower coating rate than in DCMS (ions re-attracted at the cathode surface)

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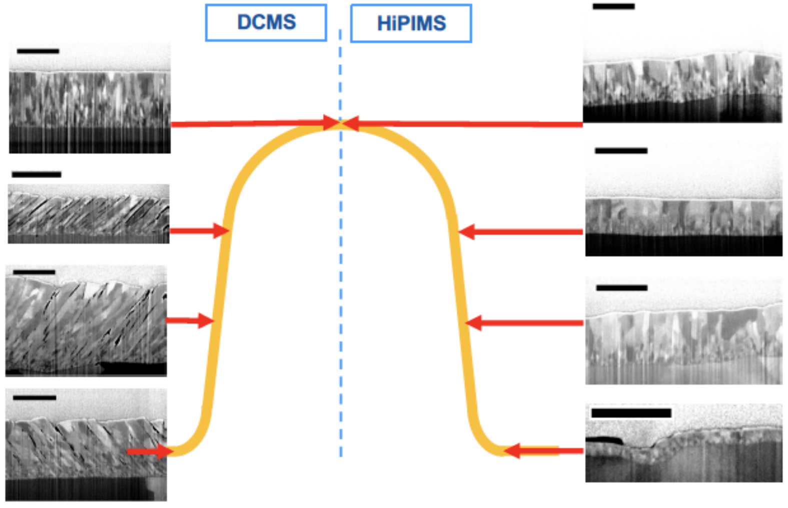
DC Magnetron Sputtering vs. HiPIMS



HiPIMS allows densifying Nb thin film on any substrate shape and complexity.

Coating with ionized Nb^{+} : can be easily directed on the substrate with an electric field (bias).

Paves the way toward Q-slope mitigation.

Guillaume Rosaz for TE-VSC

700 MHz β=0.65 Single Cell Cavity profile, coating at 150 °C

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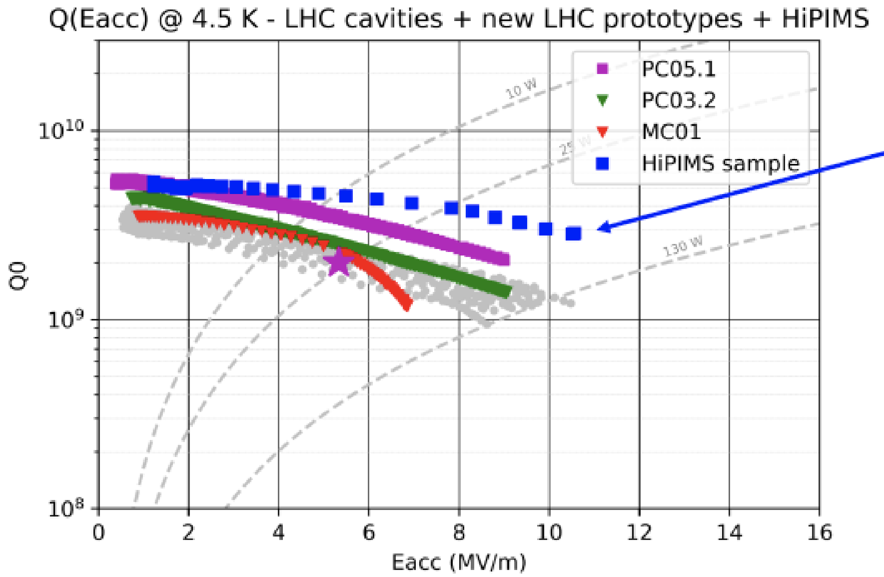
Courtesy: S. Cteroni

State of the art biased HiPIMS coatings: QPR sample



Extrapolation of surface resistance of biased HiPIMS Nb/Cu film as measured at 400 MHz with quadrupole resonator, to the LHC cavity geometry

Q-slope phenomenon strongly suppressed and support the effort to evolve this technology into real cavities.

Projected performance > 2x better than LHC specifications

G. Rosaz,

25.04.2019 S. Calatroni

Second conclusion

- Film crystalline structure has an impact on the "slope"
- Directions for future research lines (FCC 400 MHz):
  - Improve film crystal structure at any angle of incidence
  - Densify films
  - Pursue efforts to mitigate hydrogen effects (high-temperature coatings, N_2 treatments [?])

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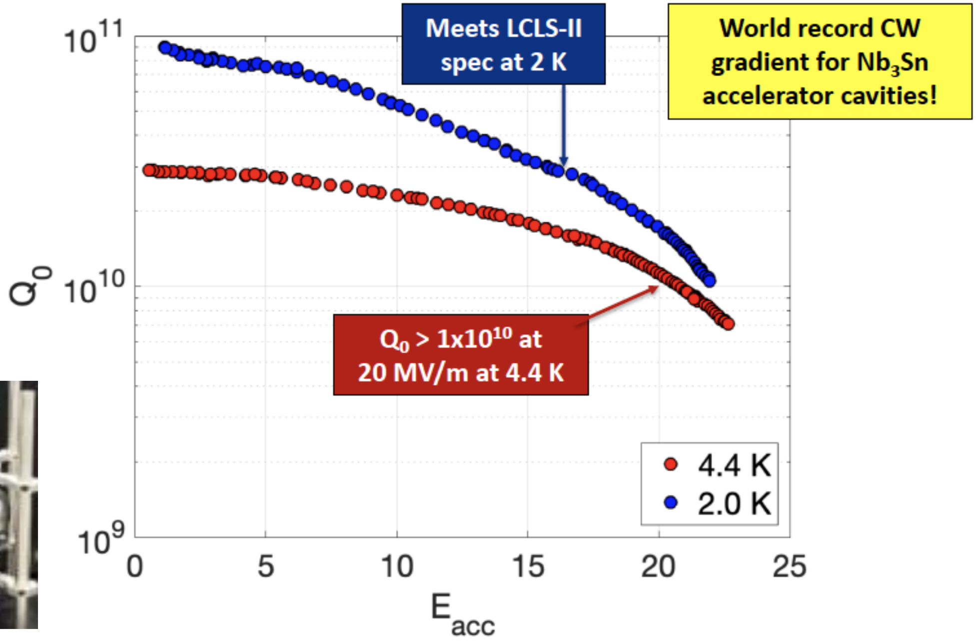
Progress in Nb_3Sn-Coating Research

reported at TTC meeting, Vancouver, Feb. 2019

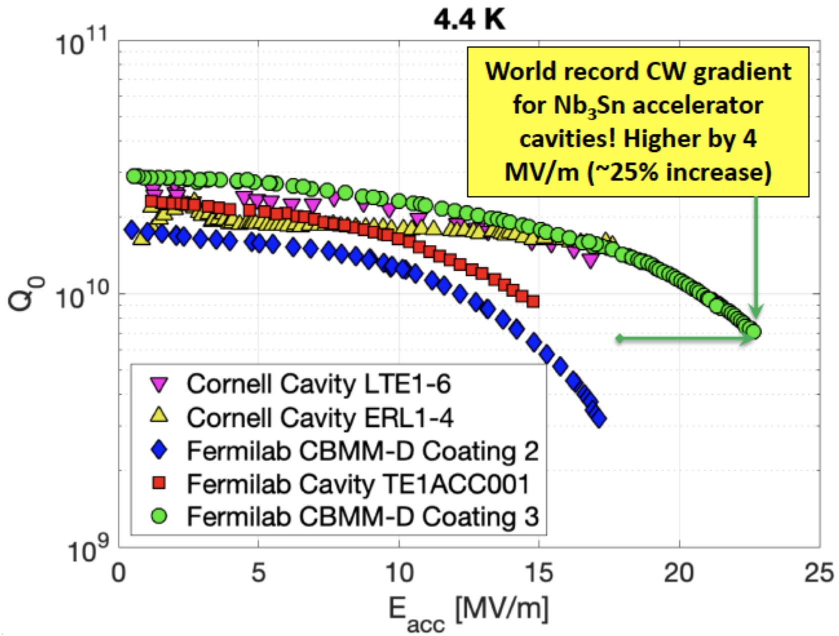
New Progress in Nb_3Sn: Fermilab 1.3 GHz Cavity



21 8/12/18 Sam Posen

Comparison to Other Cavities

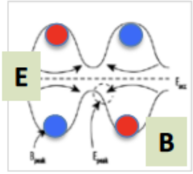
Cornell data from D. Hall and R. Porter



Fermilab

B_{sh} = practical limit for SRF

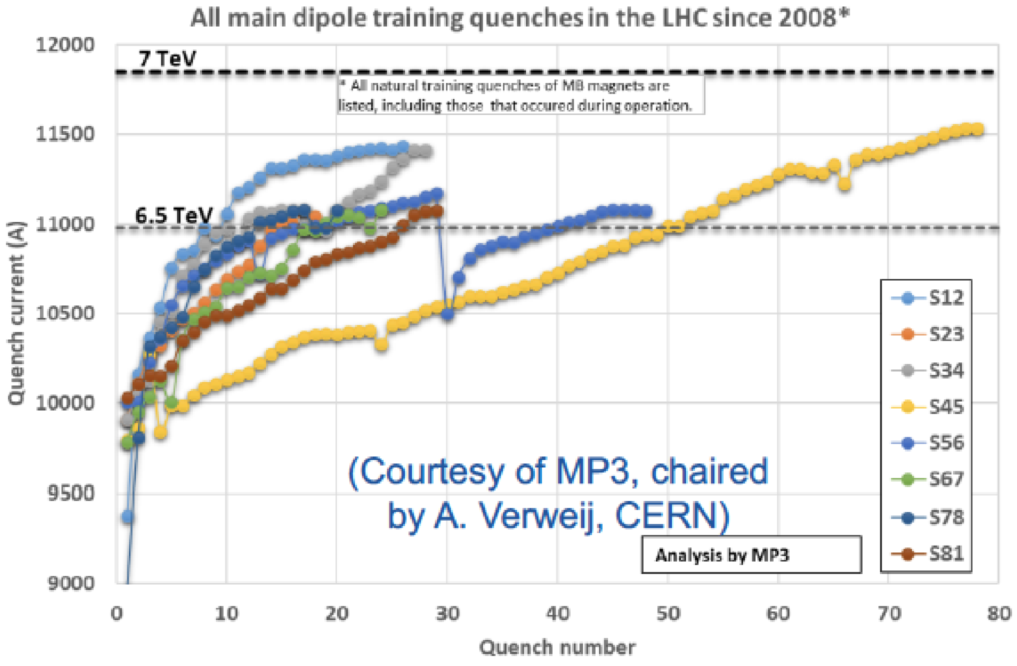
- $Bs_{sh\text{-}Nb}$: 210 mT
- $Bs_{sh\text{-}Nb3Sn}$: 430mT
- $Bs_{sh\text{-}MgB2}$: 310mT



Training Quench in NbTi Magnets (LHC)

Nb–Ti Work Horse: the LHC

- LHC remains the largest superconducting magnet system ever assembled and is now operating reliably at 6.5 TeV, corresponding to a dipole magnet current of 10,980 A and a bore/peak field of 7.73/7.95 T.



(Courtesy of MP3, chaired by A. Verweij, CERN)

- Although all magnets were cold tested prior to tunnel installation, a training campaign is required after each warm-up/cool-down.
- Bringing the machine up to 7 TeV (11,850 A and a bore/peak field of 8.33/8.57 T) is expected to require several hundred quenches.

CERN 8 April 2019 4

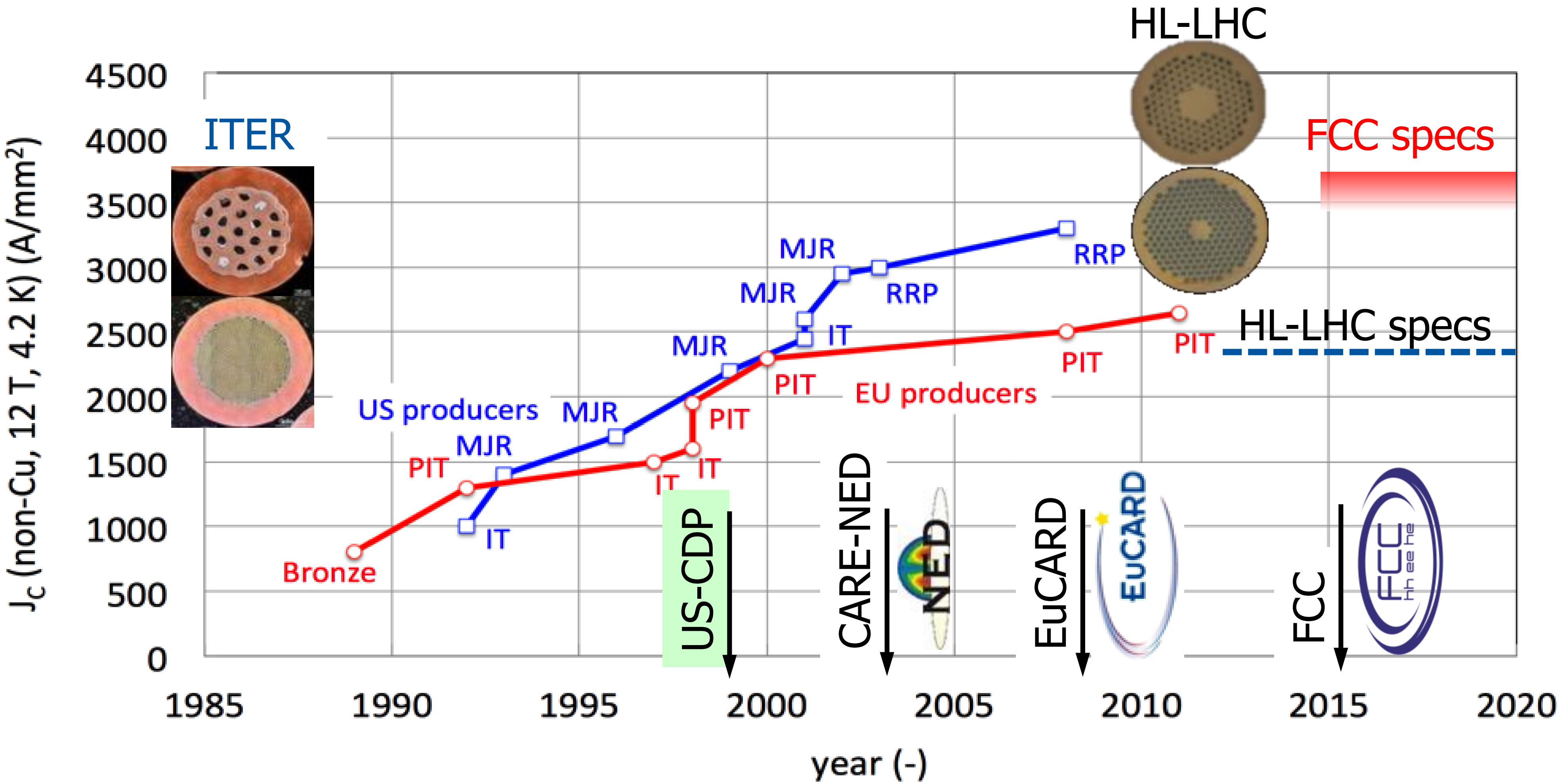
CHART2 – Swiss Accelerator Research and Technology

- Mission with regard to applied superconductivity:
  - Develop a sustainable and Swiss-based expertise in applied superconductivity and superconducting magnets for HEP, in view of a possible FCC-hh or HE-LHC. This shall be anchored in the existing institutes and universities, and further developed thanks to additional recruitment and hands-on training of applied scientists and technicians in the practical objectives described below (R&D, prototyping and testing).
- High-field magnets:
  - *prove (or disprove) CCT technology for Nb_3Sn 16-T dipoles,*
  - *develop an up to 2-m-long high-field demonstrator – possibly of different coil geometry.*
  - contribute to the development of Nb_3Sn conductors that match the performance targets […] and of the cable optimization and test.
- HTS magnets:
  - develop technologies for HTS based accelerator magnets,
  - design, build, and test an HTS variant of the SLS 2.0 superbend magnet.
  - design, build, and test several periods of an HTS undulator magnet.
- Infrastructure:
  - To establish the infrastructure needed to build and test all aspects of FCC-hh, HE-LHC magnets and other SC accelerator magnets.

Infrastructure | Enabling Technologies | Wire R&D | LTS Magnet R&D | HTS Magnet R&D | HFM Demonstrator

Courtesy, G. de Rejk

Conductor development (1998-2008)

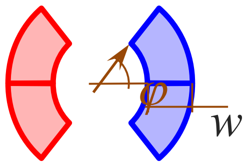


after 10 years of development the US and EU development gave us the Nb_3Sn conductor for HILUMI.

Courtesy, A. Ballarino, A. Devred, T. Ogitsu

Nb_3Sn conductor program

Figures to be updated



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

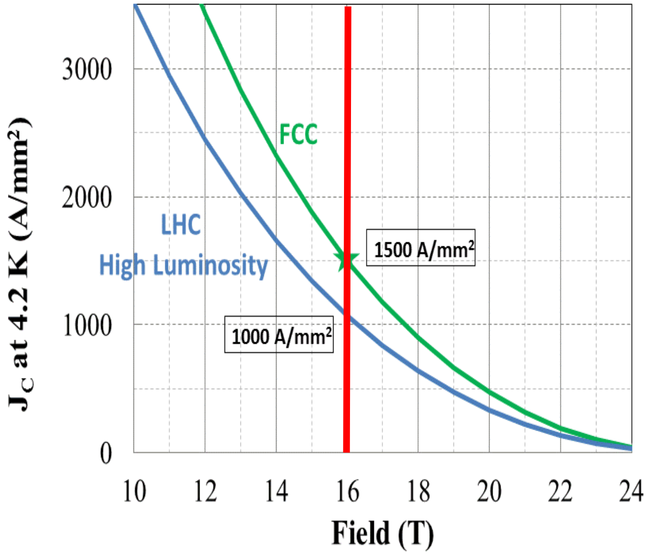
- **Nb_3Sn** is one of the **major cost & performance** factors for FCC-hh
- **Highest attention** is given

Main development goals:

- **J_c (16T, 4.2K) > 1500 A/mm^2**
  - 50% higher than HL-LHC

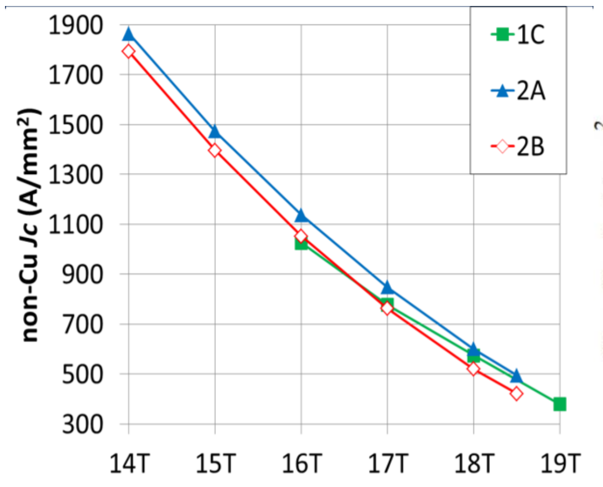
Global cooperation:

- 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
- New US-DOE-**MDP**



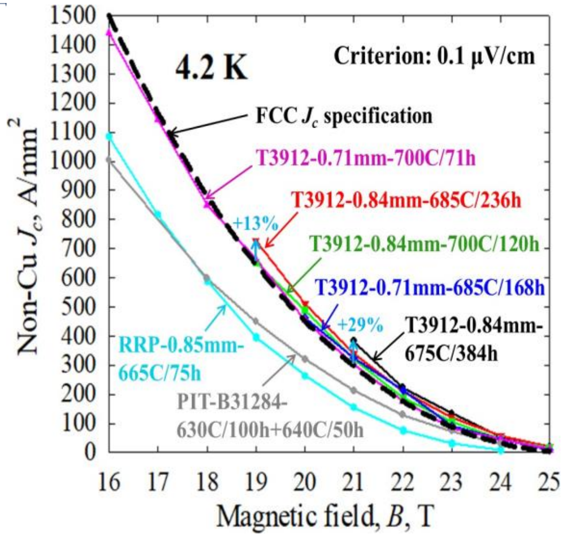
Requirement (FCC)

Non-Cu
J_c : 1,137 A/mm^2 @16T



Ternary add. Approach:
K. Saito et al. (JASTEC/KEK)

Non-Cu
J_c : ~ 1,450 A/mm^2 @16T



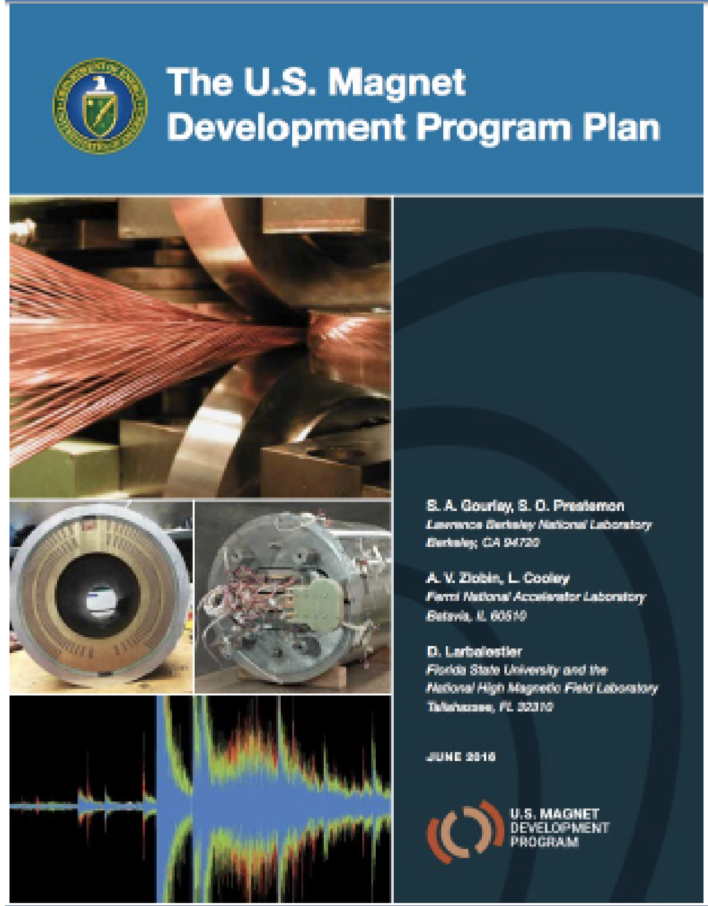
Artificial Pinning Center (APC) approach:
X. Xu et al (Fermilab)

https://arxiv.org/abs/1903.08121

Courtesy: S. Prestemon

U.S. MAGNET DEVELOPMENT PROGRAM

The US Magnet Development Program was founded by DOE-OHEP to advance superconducting magnet technology for future colliders



Strong support from the Physics Prioritization Panel (P5) and its sub-panel on Accelerator R&D

A clear set of goals have been developed and serve to guide the program

Technology roadmaps have been developed for each area: LTS and HTS magnets, Technology, and Conductor R&D

US Magnet Development Program (MDP) Goals:

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:

Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

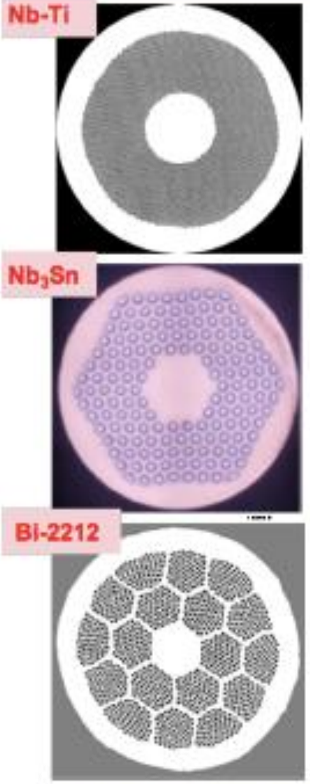
U.S. DEPARTMENT OF ENERGY | Office of Science

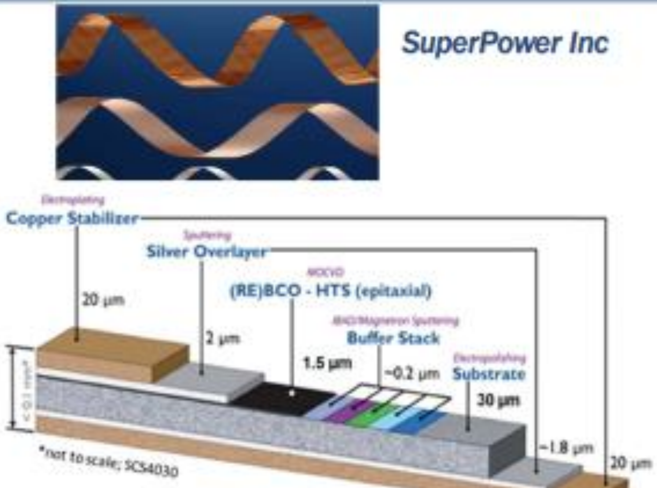
S. Prestemon   Workshop on Advanced Superconducting Materials and Magnets   KEK January 22 2019   8

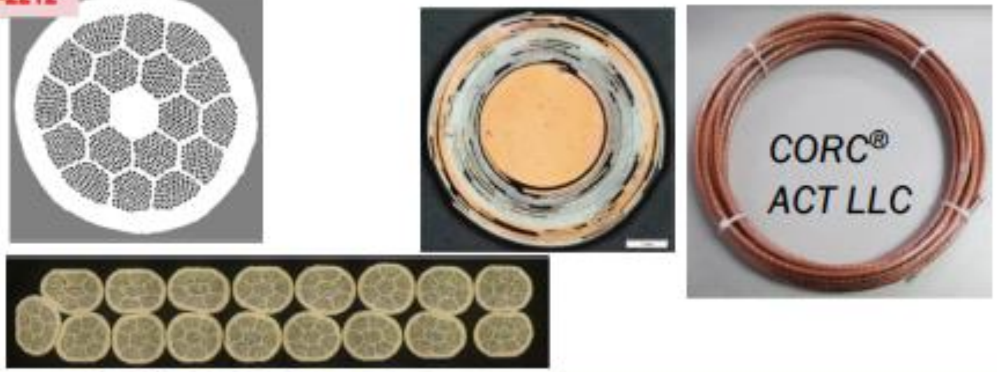
Courtesy: S. Prestemon

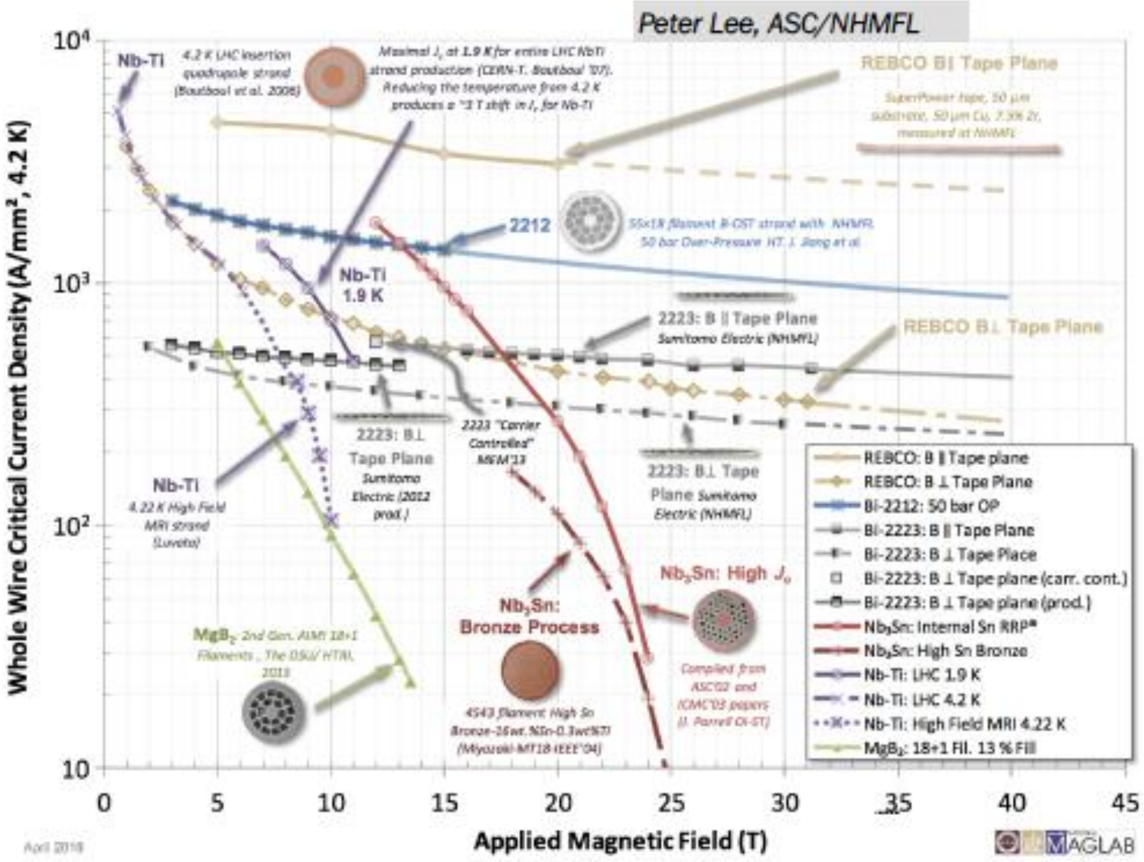
U.S. MAGNET DEVELOPMENT PROGRAM

Magnets start with the superconductor: we are about to put Nb_3Sn into a collider for the first time, and are investigating the potential of HTS









U.S. DEPARTMENT OF ENERGY | Office of Science

S. Prestemon   Workshop on Advanced Superconducting Materials and Magnets   KEK January 22 2019   6

Courtesy: S. Prestemon

U.S. MAGNET DEVELOPMENT PROGRAM

A Cos(t) 4-layer design led by FNAL is being pursued with the ultimate goal of achieving ~15T

- Design minimizes midplane stress for highest field
- A technical challenge is to provide adequate prestress on inner coils
  - Intrinsic difficulty with 4 layers
  - Collared-structure approach includes new features that provide some prestress increase during cool down
- Status:
  - Coils fabricated
  - Structure designed, fabricated
  - Mechanical model assembly completed
  - Assembly readiness review completed
  - Assembly underway now

60-mm aperture, 4-layer graded coil

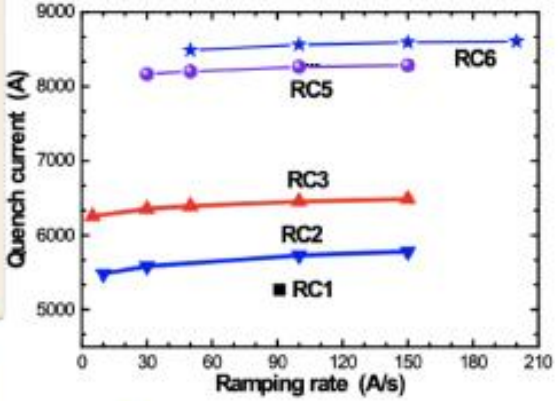
Courtesy: S. Prestemon

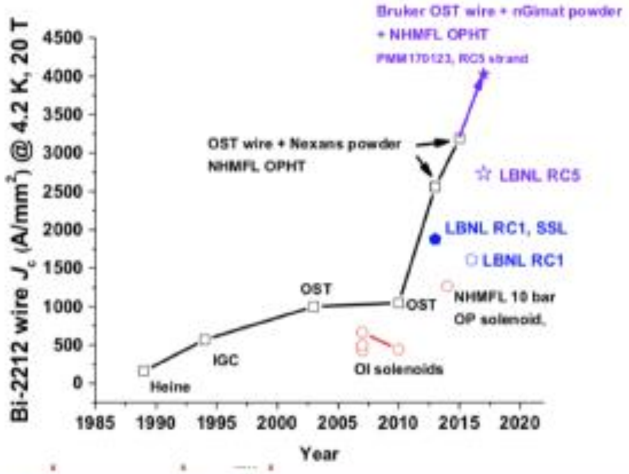
U.S. MAGNET DEVELOPMENT PROGRAM

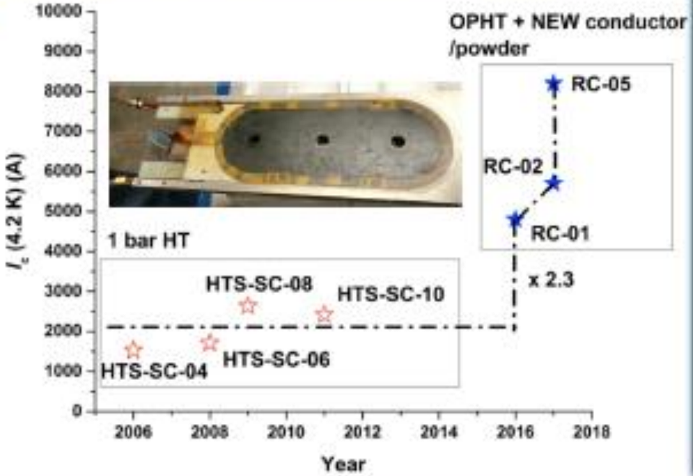
On the HTS magnet front, Bi2212 has matured to become a magnet-ready conductor

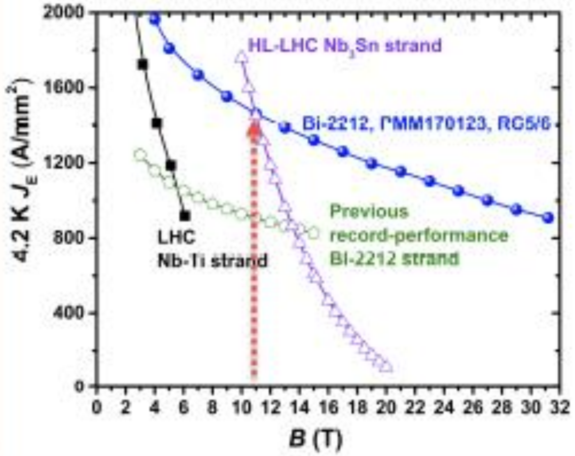
- Bi2212 has made dramatic strides in J_c over last 3 years => ready for magnets
  - Wire has been cabled and tested in racetrack configuration (RC5)
  - First Bi2212 CCT dipoles have been wound and await reaction and testing soon
  - Roadmap integrates Bi2212 CCT in a high-field hybrid magnet design

- **Nano-spray combustion powder technology**
- **55x18 wire design**
- **At 15 T, J_e - 1365 A/mm², twice the target desired by the FCC Nb_3Sn strands**
- **At 27 T, J_e - 1000 A/mm², adequate for 1.3 GHz NMR.**



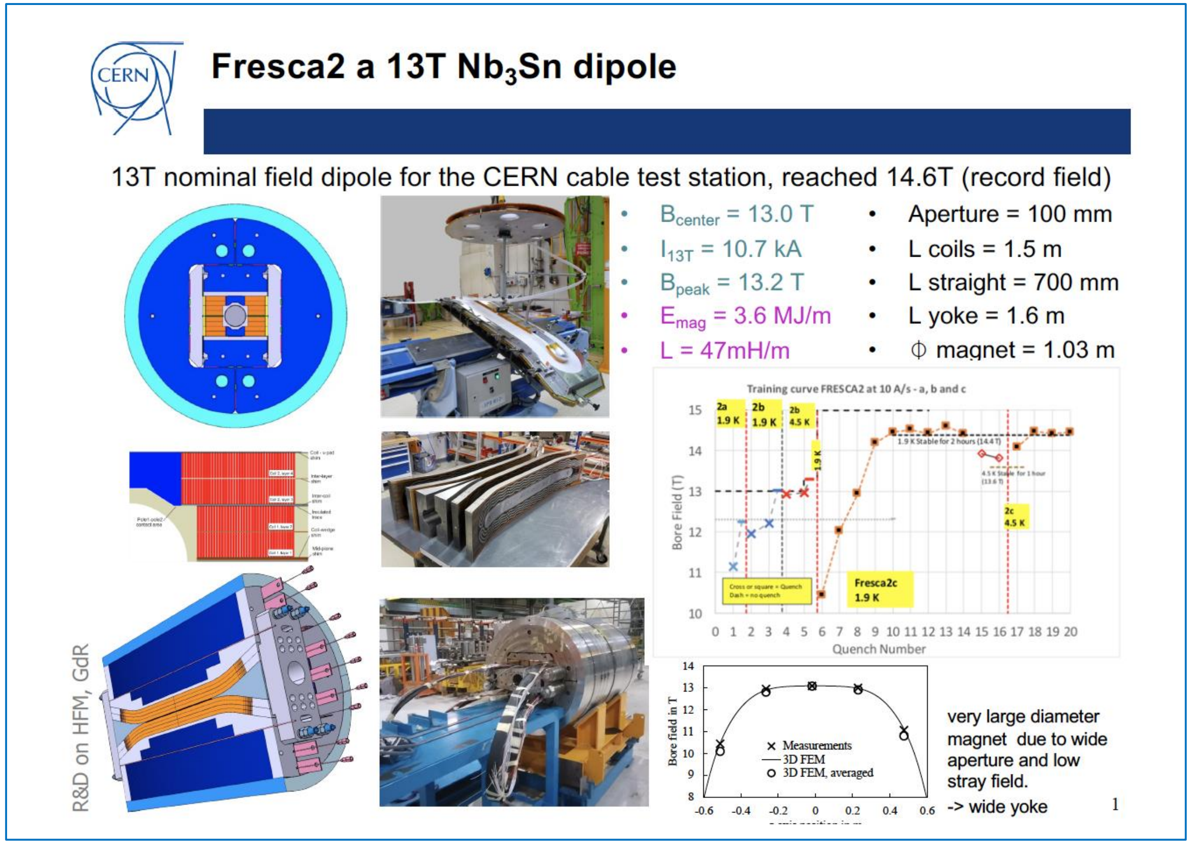


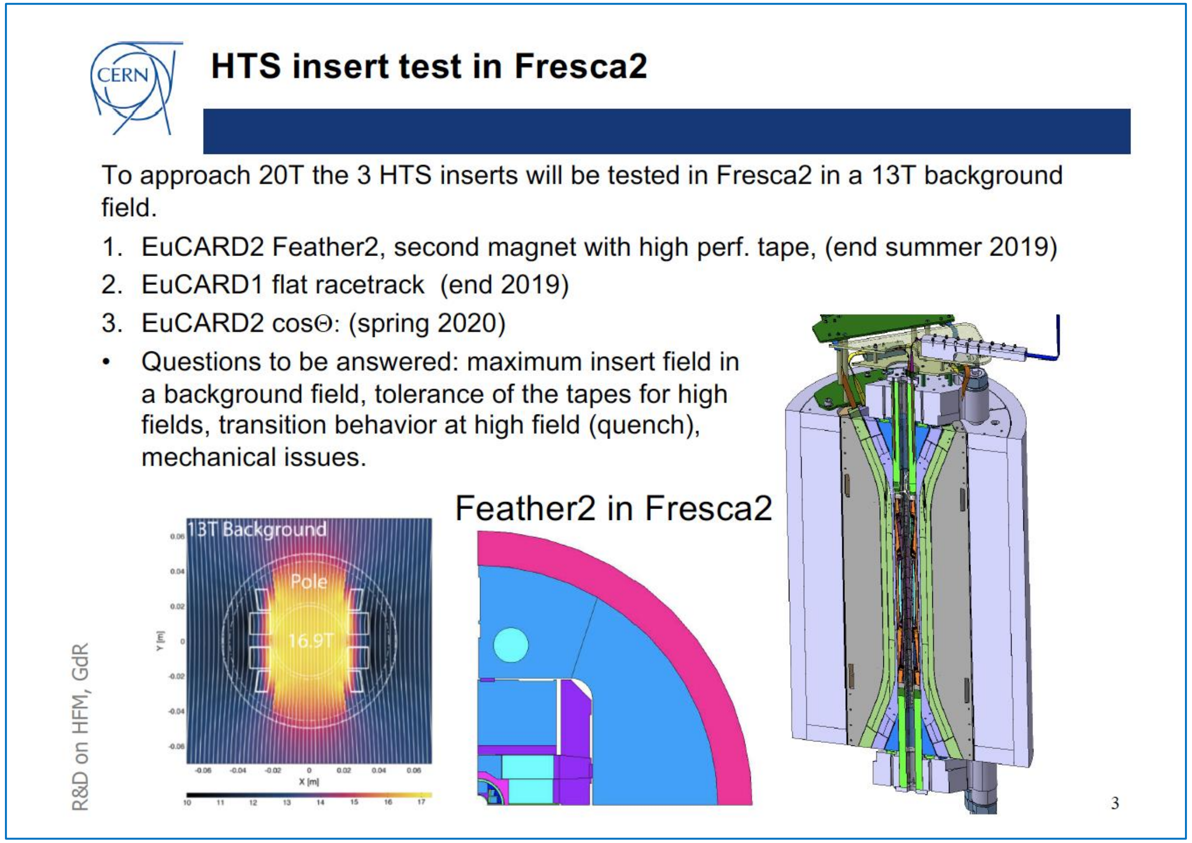




Courtesy: G. de Rick

FRESCA2 + HTS-Insert



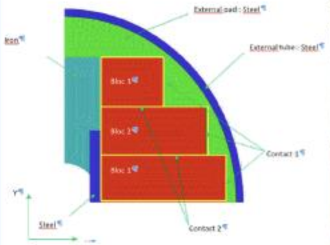


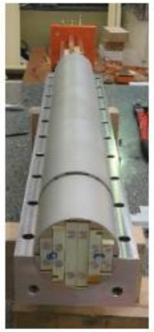
Courtesy: G. de Rick

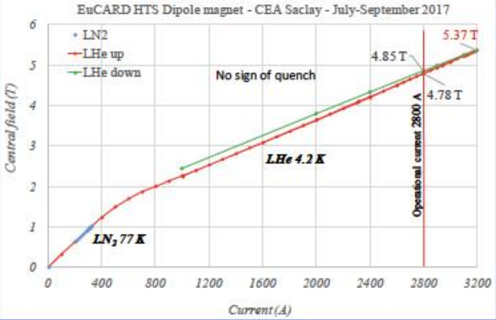
Three HTS inserts (CERN and collaborations)

R&D on HFM, GdR

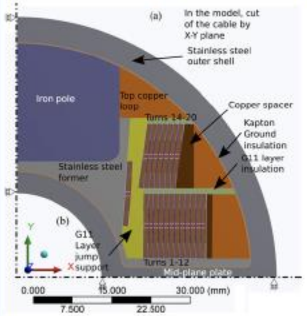
EuCARD1: insert (CEA-CNRS-CERN), flat racetrack, ReBCO 4 tape stack cable,stand alone tested Sept 2017: Reached 5.37 T @ 4.2K (I=3200A)

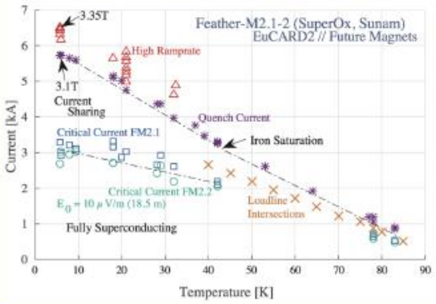




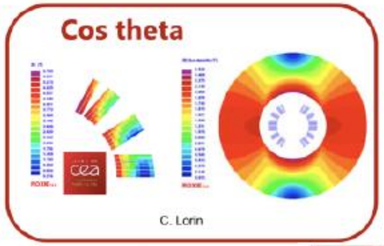


EuCARD2: Feather-M2 (CERN), flared ends coil ReBCO, Roebel cable, First magnet (low perf tape), stand alone tested Apr 2017: Reached 3.37 T @ 4.2K (I=6500A)





EuCARD2: cosΘ insert (CEA), cosΘ coil, ReBCO Roebel cable, being fabricated, stand alone test in autumn 2019

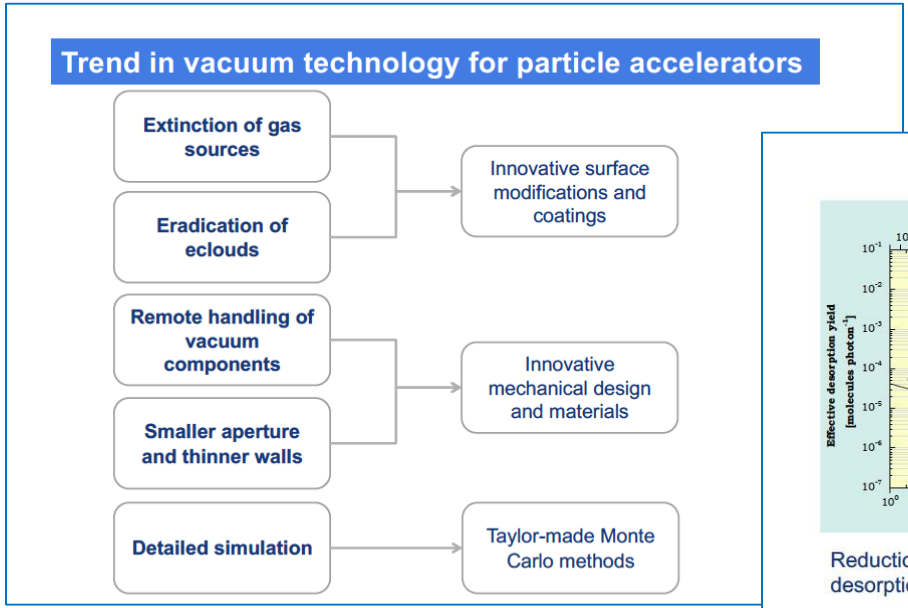


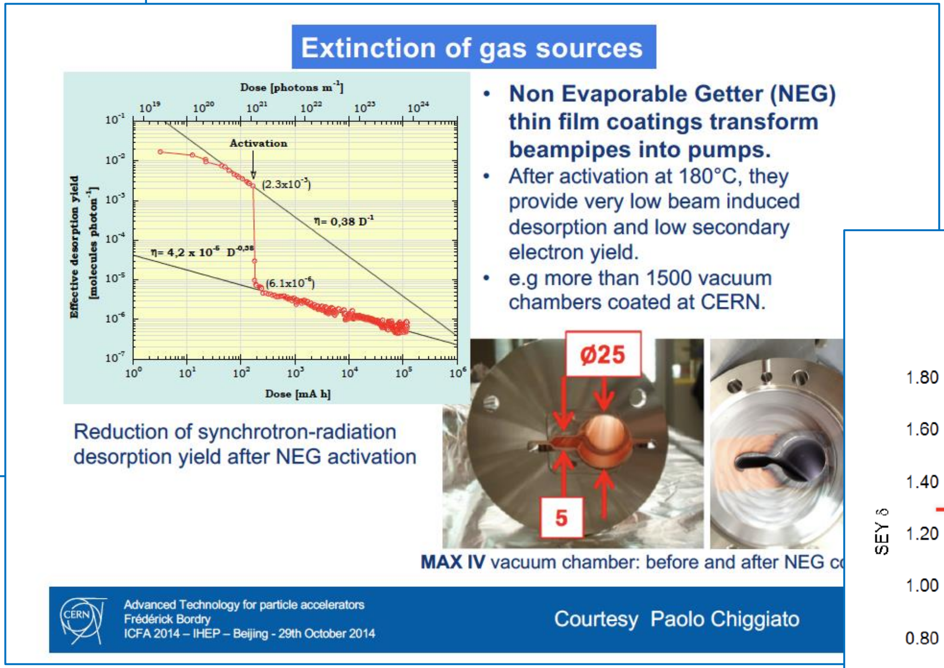
Design parameters (**SuperPower** Cable)

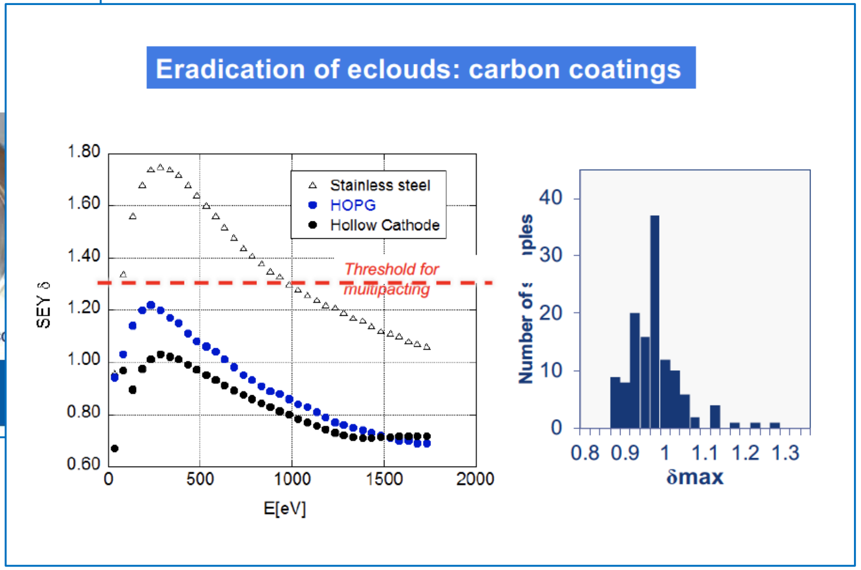
Layout	Unit	Cosθ B
Iop	kA	10.06
Bop	T	5
Bpeak	T	5.8
Ic	kA	15.2
LL margin	(%)	34
T margin	K	30
Sd. inductance	mH/m	0.73
coil inner radius	mm	24
yoke inner radius	mm	50
yoke outer radius	mm	110
Nb. of turns	-	17
Unit len. of cond.	m	24

Courtesy: F. Bordry

Technical Challenge: Vacuum





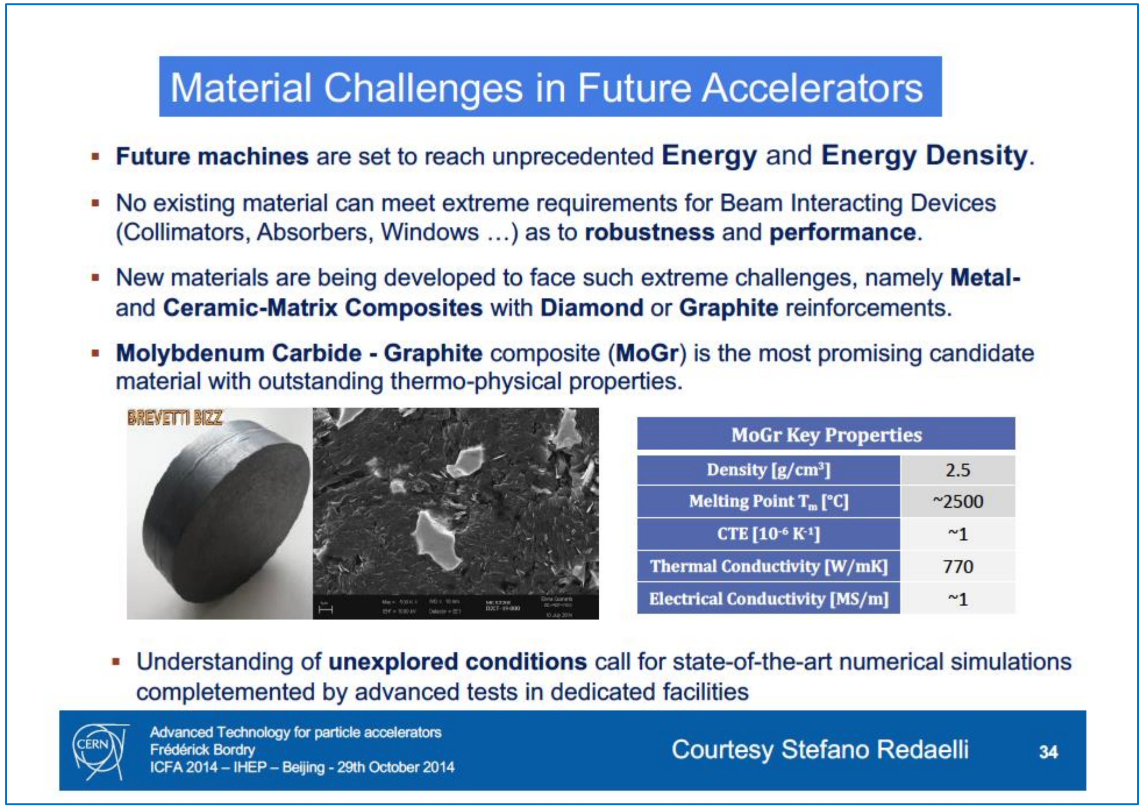


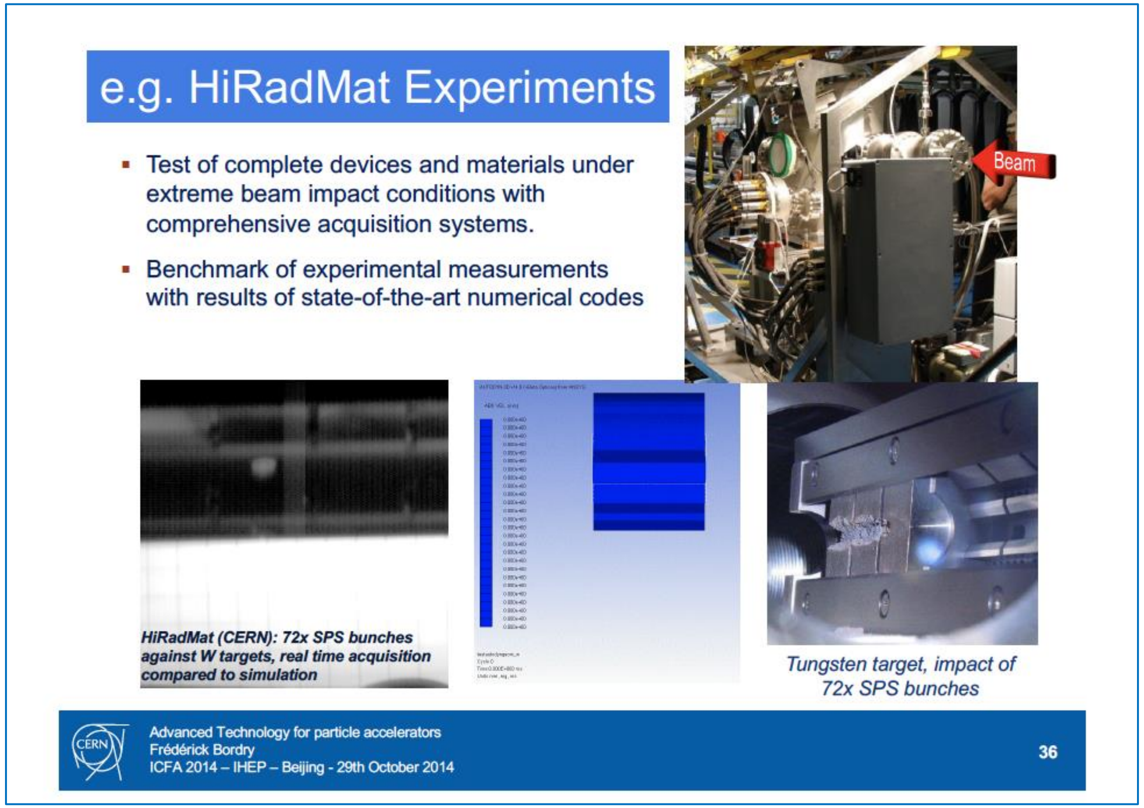
Challenges in Target, Collimator, and Beam Dump

- To be filled:

Courtesy: F. Bordry

Technical Challenges: Radiation Hardness

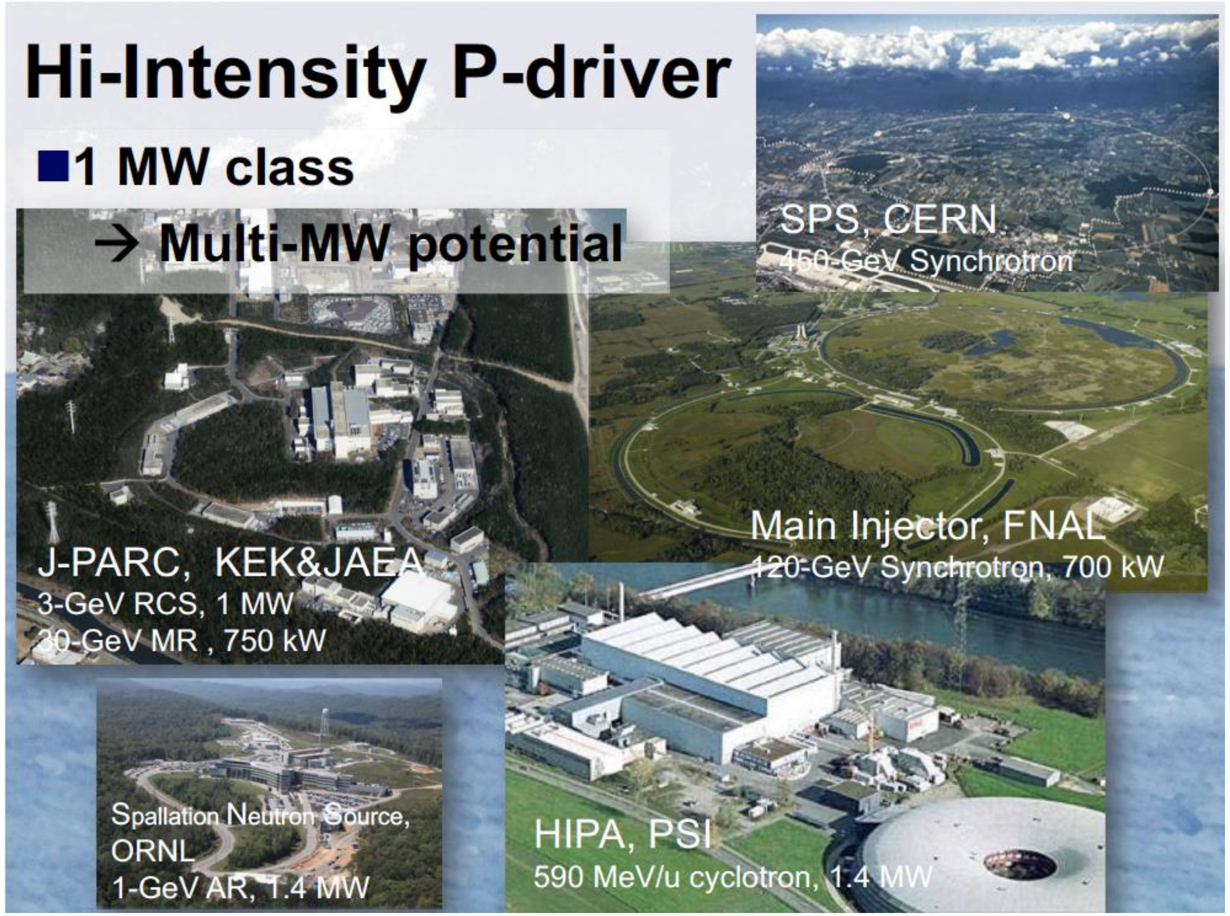


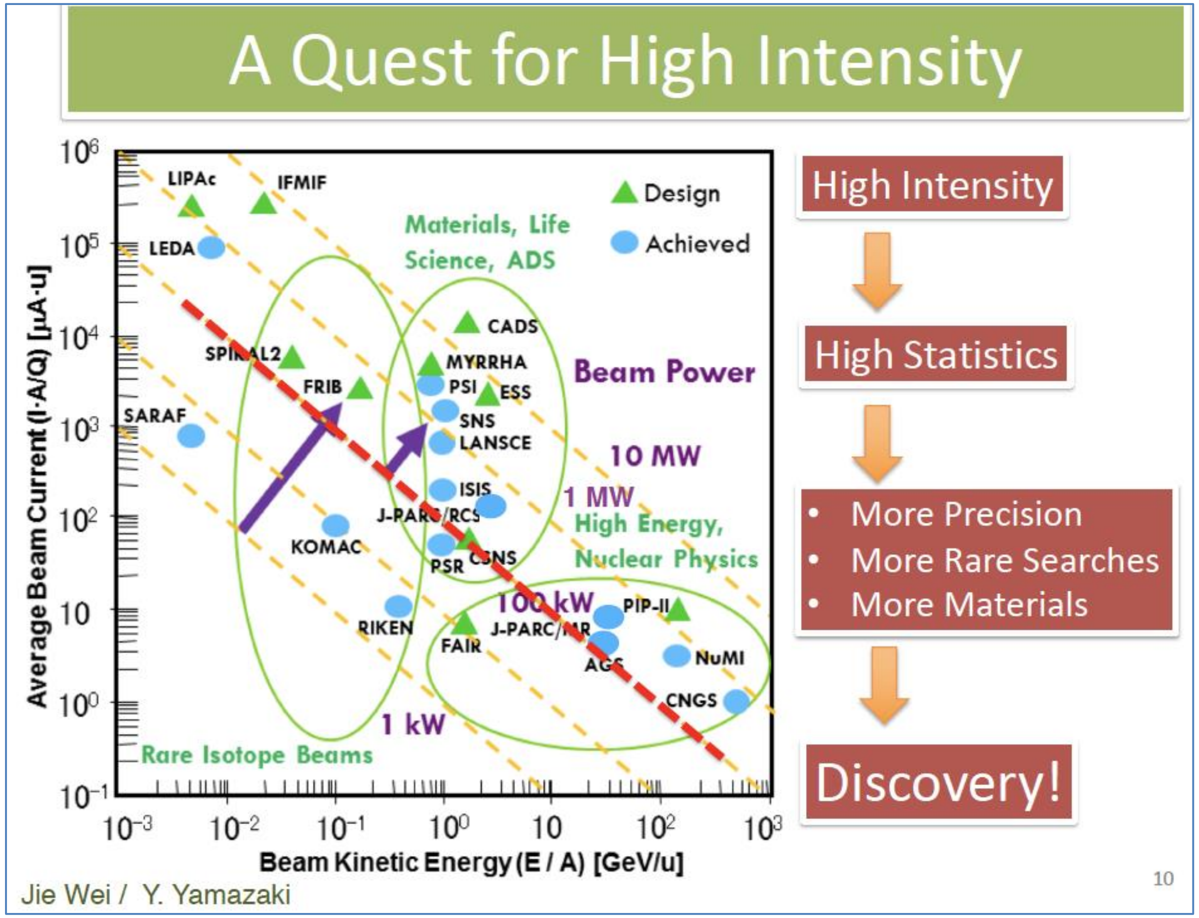


Courtesy: N. Saito

Courtesy: N. Saito

Intensity Frontier Accelerators





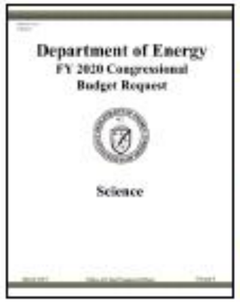
US Electron-Ion Collider

National Academy of Sciences : 2018 Assessment of US EIC

The committee finds **the scientific case compelling, fundamental and timely.**

"EIC can address three profound questions..

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense system of gluons?"



US DOE Budget Justification

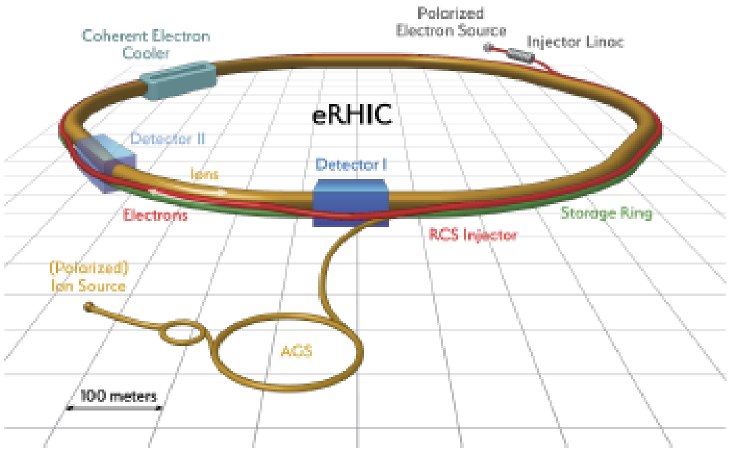
Volume 4, Page 272:
"..(EIC)..Critical Decision-0, Approve Mission Need, is planned for FY 2019."

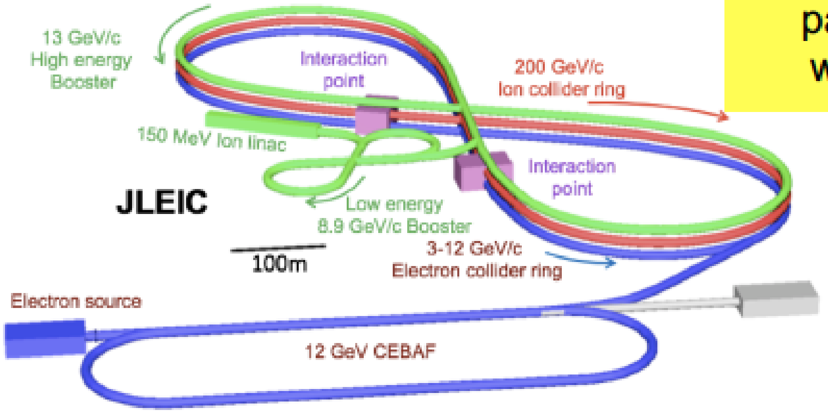
Two realization concepts being developed.
Realization could be as early as 2028-2030.

Requirements from the EIC Whitepaper

- Highly polarized (~70%) electron and nucleon beams [as well as light ions]
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from ~20 - ~100 GeV, upgradable to ~140 GeV
- High collision luminosity ~$10^{33\text{-}34}$ cm^{-2} s^{-1}
- Possibilities of having more than one interaction region

EIC Accelerator Sci Tech & Synergies with European projects





Accelerator R&D ongoing with strong cooperation between several DOE labs under DOE NP guidance

Collaboration from international partners is welcome!

Common areas of sci-technological advances:

- Unprecedented collider that needs to maintain high luminosity and high polarization
- Combine challenges of Super-B factories & hadron colliders
- Crab cavities, hadron beam cooling, high field magnets for the interaction points

Common areas of synergy with European projects:

- HL-LHC and EIC crab cavities
- PERLE ERL and ERL for hadron cooling
- High voltage DC cooling for EIC and for HESR/FAIR GSI
- Nb3Sn and thin film cavities for cost-effective SRF
- Highly HOM-damped SRF cavities
- IR SC magnets for HE-LHC, FCC, EIC
- General accelerator beam dynamics and simulations

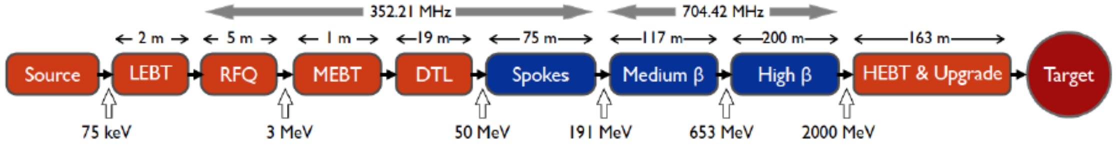
EIC accelerator technology development is synergistic with the projects (HL-LHC, HE-LHC, FCC, etc.) discussed within the European Strategy update process.
Encourage creating a global world-wide collaboration on EIC accelerator and machine-detector interface R&D

2

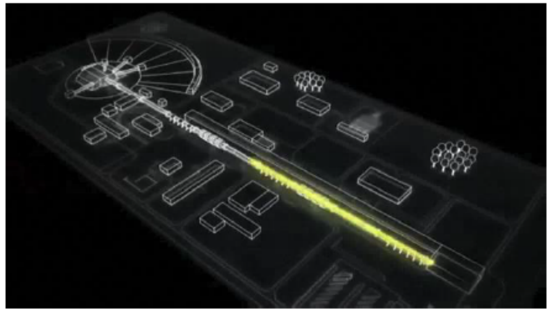
Courtesy: R. Garoby

ESSnuSB: An Intensity-frontier ACC. for PP in future

ESS proton linac



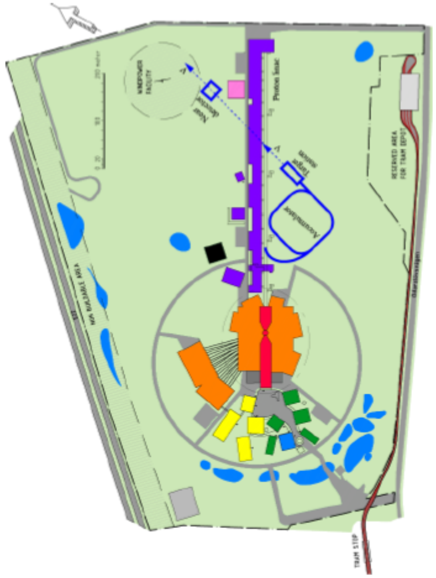
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**



2018-01-15 Seminar at NBI, Copenhagen Tord Ekelöf, Uppsala University 3

How to add a neutrino facility?

- The neutron program must not be affected and if possible synergetic modifications.
- Linac modifications: double the rate (14 Hz → 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few µs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
  - H^- source (instead of protons),
  - space charge problems to be solved.
- ~300 MeV neutrinos.
- Target station (studied in EUROν).
- Underground detector (studied in LAGUNA).
- Short pulses (~µs) will also allow DAR experiments (as those proposed for SNS) using the neutron target.



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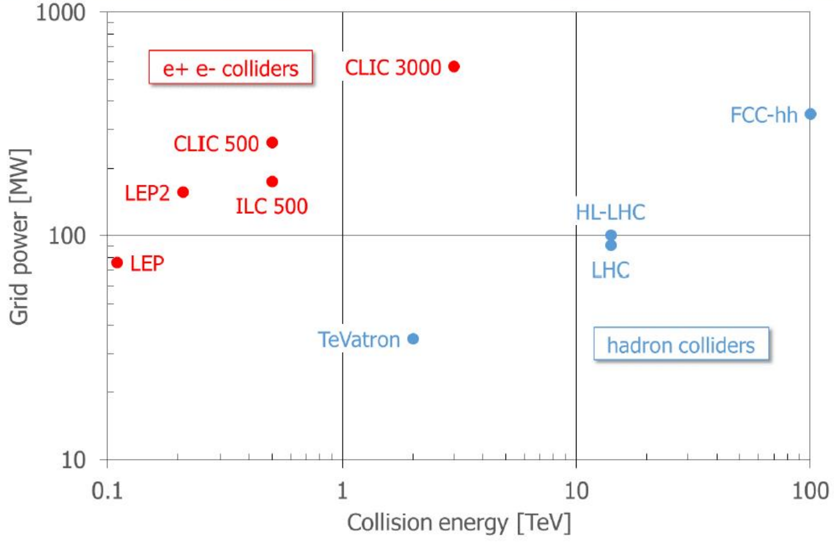
Energy Efficiency and Management in Accelerators

Power consumption of high-energy particle colliders

4th Workshop Energy for Sustainable Science at Research Infrastructures



- The good news: power consumption grows slower than collision energy
- The bad news: future projects need hundreds of MW

Beam power, particle energy, intensity

Linear accelerators

4th Workshop Energy for Sustainable Science at Research Infrastructures

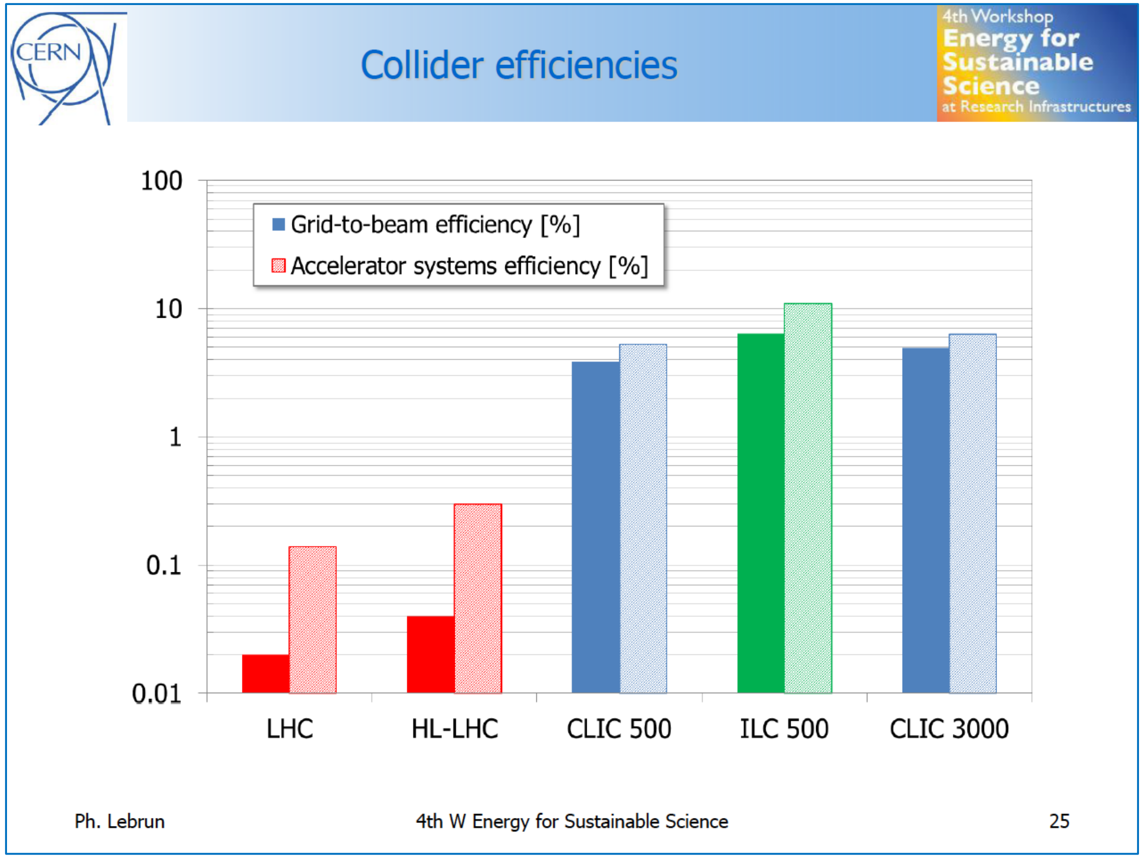
- Average beam power

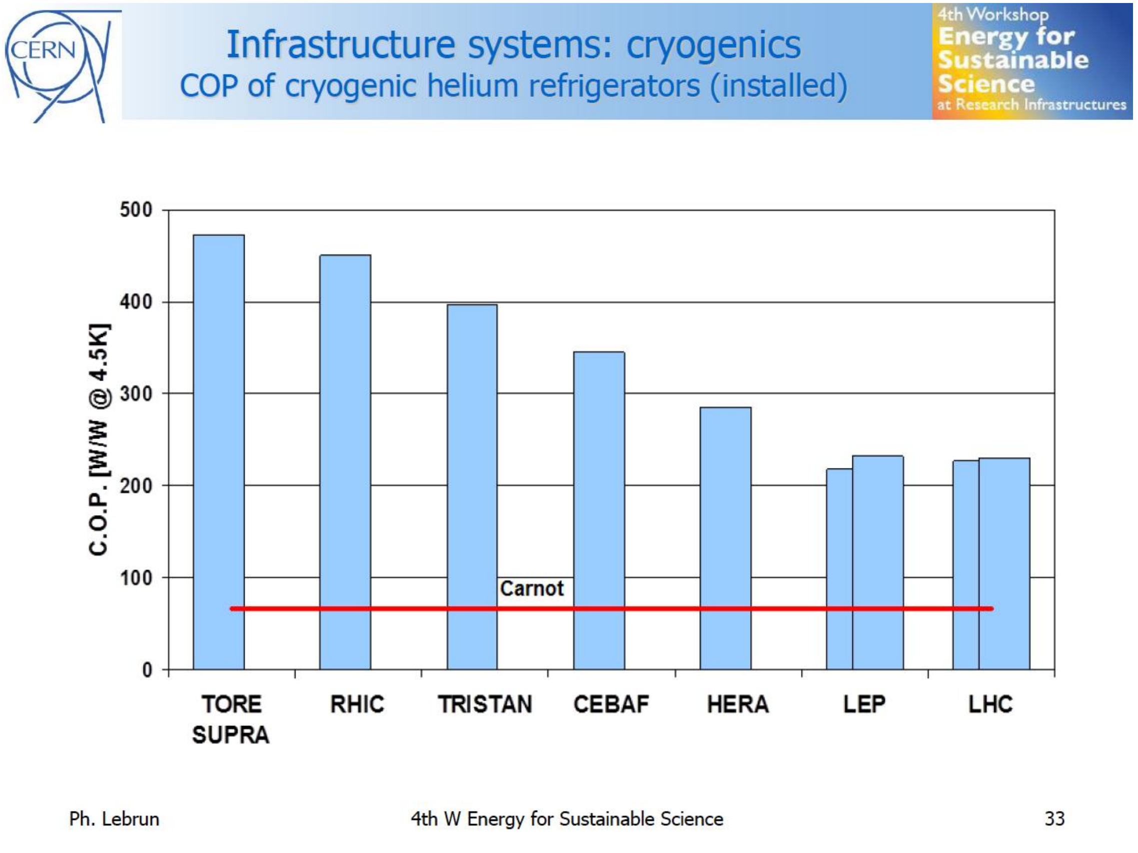
$$P_{beam} = \delta I \frac{E}{e} = f_{rep} N_{pulse} E$$

Beam current; Particle energy; Duty factor; Repetition frequency; Particles per pulse

- Example: ESS proton linac
  - $E = 2$ GeV
  - $I = 62.5$ mA
  - $\delta = 4\ \%$
  - $P_{beam} = 5$ MW average

Energy Efficiency and Management in Accelerators

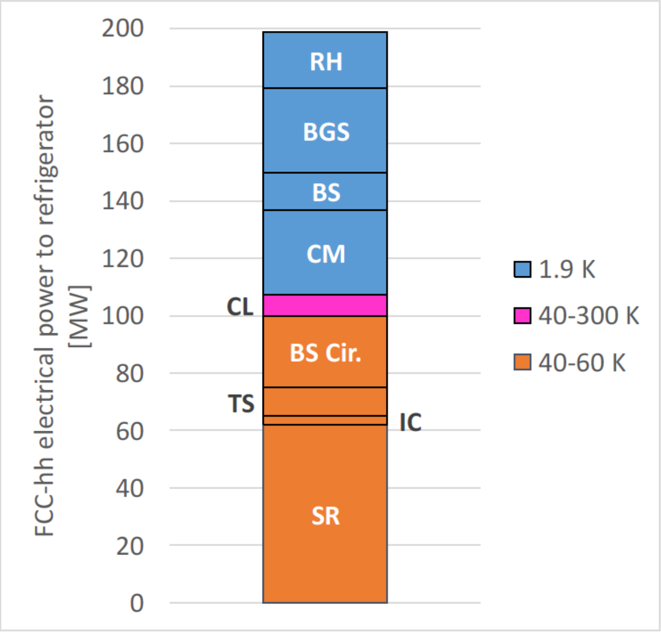




Energy Efficiency and Management in Accelerators

Cryogenic refrigeration for FCC-hh
The real cost of «intrinsic» losses

4th Workshop Energy for Sustainable Science at Research Infrastructures



RH: resistive heating
BGS: beam-gas scattering
BS: beam screen
CM: cold mass heat-inleaks
CL: current leads
BS cir.: Beam screen circulator (RT)
TS: thermal shield
IC: image current
SR: synchrotron radiation

Carnot efficiency:
- Ne-He plants: 40 %
- Helium plants: 28.8 %

Isentropic efficiency
- Cold compressors: 75 % per stage
- Warm circulator: 83 %

L. Tavian

Ph. Lebrun 4th W Energy for Sustainable Science 35

Summary
Reasons for low efficiency

4th Workshop Energy for Sustainable Science at Research Infrastructures

- For all types of accelerators, the average beam power is proportional to the product of particle energy and luminosity or delivered particle flux
- The energy-luminosity performance, and possibly the physics reach of a collider can be represented by a single "coefficient of performance"
- The ratio of "coefficient of performance" to beam power quantifies the relation between collider performance and beam parameters: it is lower for single-pass machines than for circular colliders
- "Intrinsic" losses due to basic physics processes add up to the beam power and often exceed it (synchrotron radiation)
- Accelerator systems and infrastructure represent the bulk of electrical power consumption
- Comparing total power consumption and average beam power yields very low values for overall "grid-to-beam" efficiency
- Linear colliders show higher overall "grid-to beam" efficiencies than circular colliders. This partly compensates for their much lower COP/beam power ratio

Ph. Lebrun 4th W Energy for Sustainable Science 38

Courtesy: Ph. Lebrun, V. Shiltsev

Energy Management

to be discussed by E. Jensen (Acc. Session)

A reference: Outlook – Strategies pointed out by Ph. Lubrun (EUCARD2 study)

- Maximize energy-luminosity performance per unit of beam power
  - Minimize circumference for a given energy (high-field magnets)
  - Operate at beam-beam limit
  - Low-emittance, high-brilliance beams
  - Low-beta insertions, small crossing angle ("crabbing")
  - Short bunches (beamstrahlung)
- Contain "intrinsic" losses
  - Synchrotron radiation
  - Beam image currents
  - Electron-cloud
- Optimize accelerator systems
  - RF power generation and acceleration (deceleration)
  - Low-dissipation magnets (low current density, pulsed, superconducting, permanent)
- Optimize infrastructure systems
  - Efficient cryogenics (heat loads, refrigeration cycles & machinery, distribution)
  - Limit electrical distribution losses (cables, transformers)
  - Absorb heat loads preferably in water rather than air
  - Recover and valorise waste heat

Ph. Lebrun Workshop on Magnet Design Nov 2014 30