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

Akira Yamamoto
(KEK and CERN)

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

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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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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

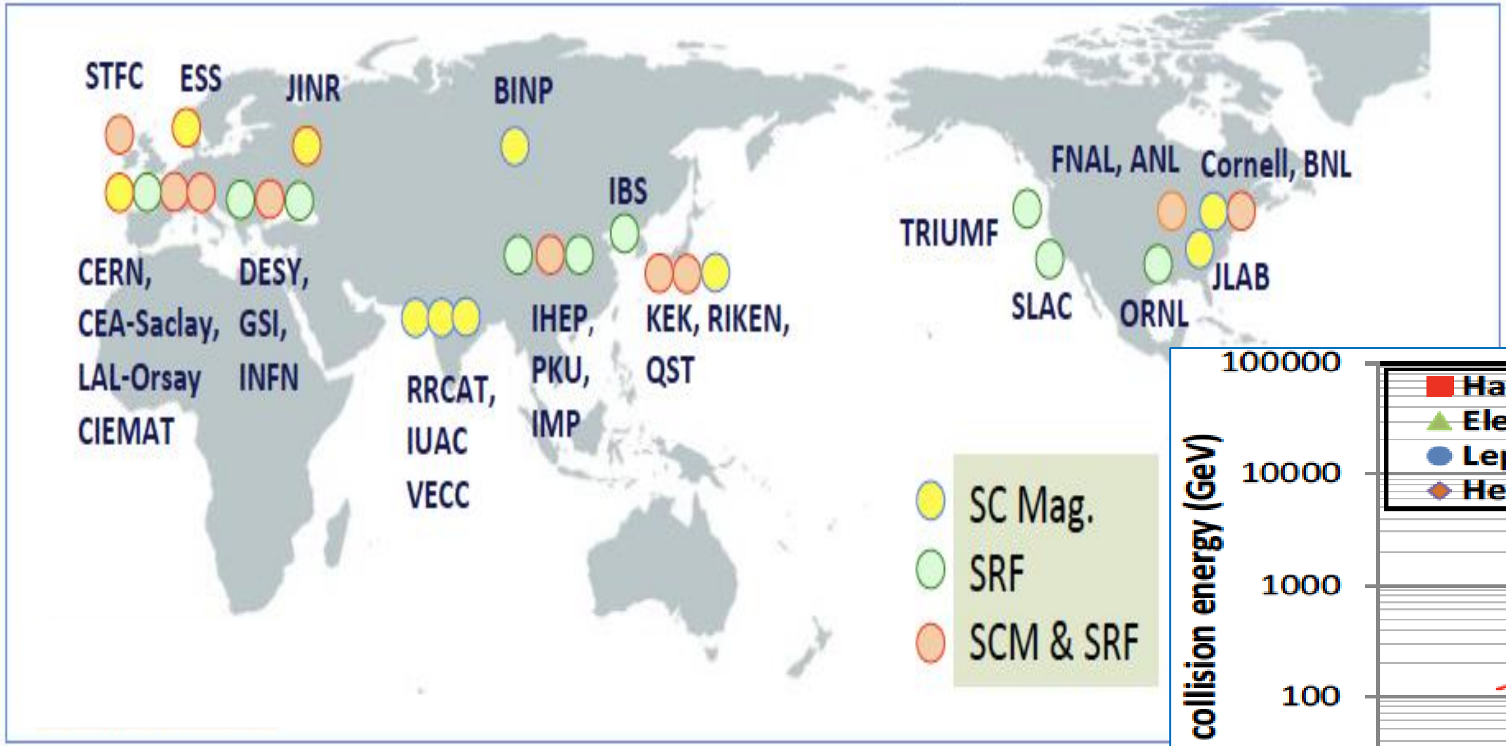
- **State of the Art in Accelerator Technologies, focusing on**
  - Nano-beam*, Superconducting Magnet and RF, and Normal-conducting RF

    * to be covered by V. Shiltsev and S. Stapnes

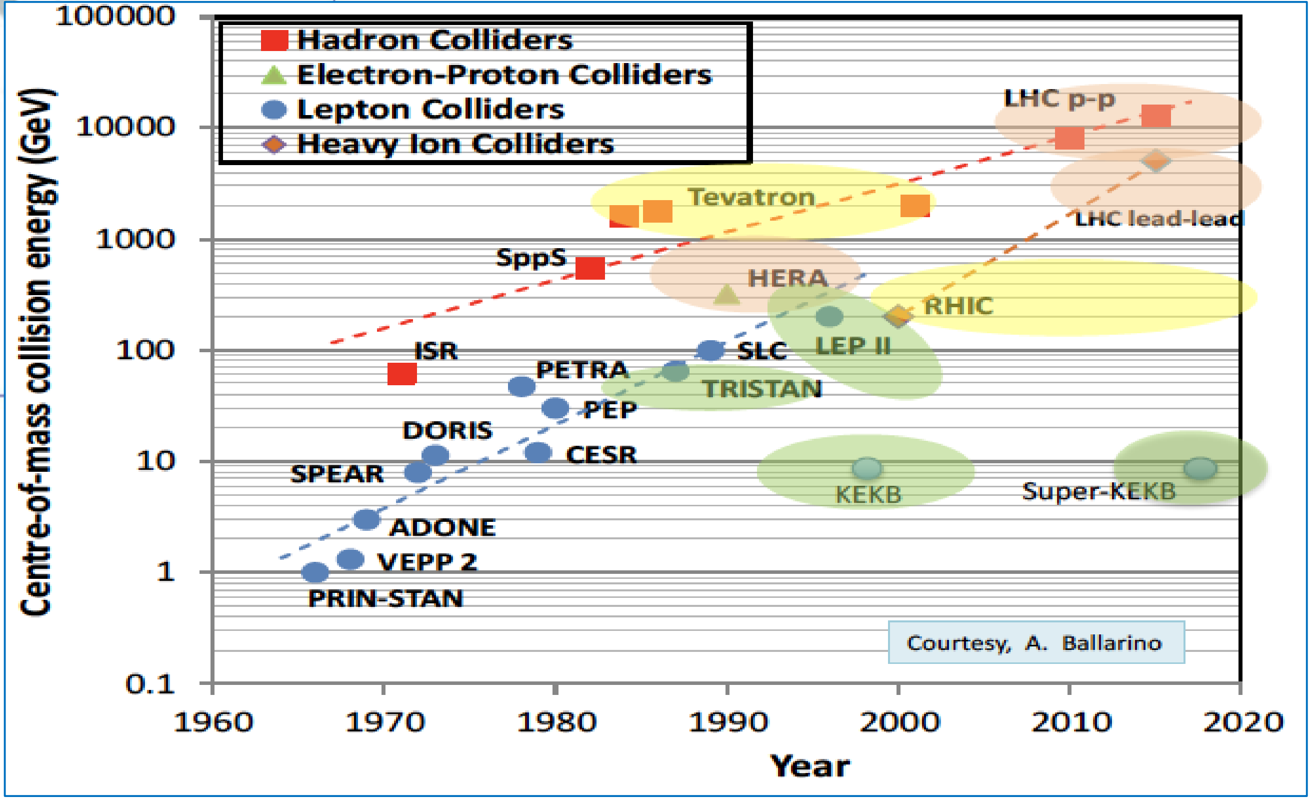
- **Challenges for future**
  - Superconducting Technologies for future Lepton and Hadron Colliders

- **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 0.004+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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    >>> To be discussed by V. Shiltsev and S. Steinar

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- **Summary**

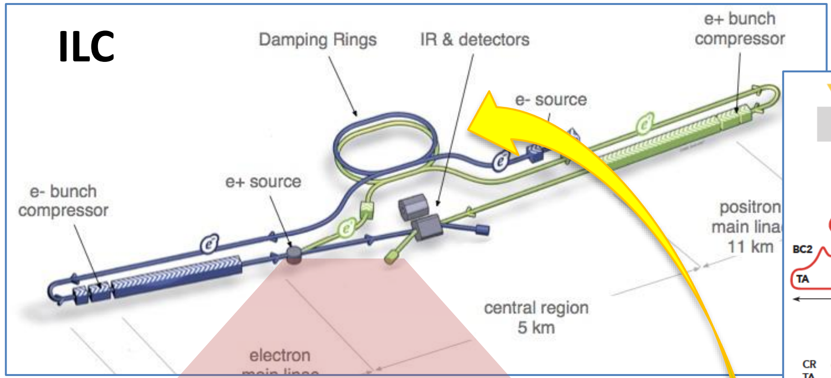
ATF/ATF2: Accelerator Test Facility

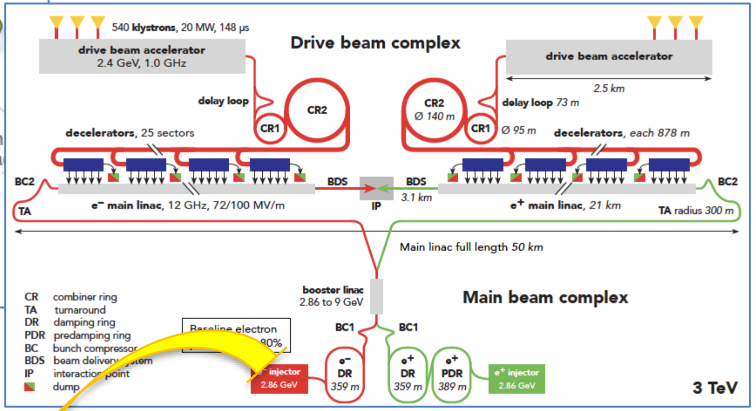
Courtesy: N. Terunuma

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

Develop nano-beam technology for ILC/CLIC

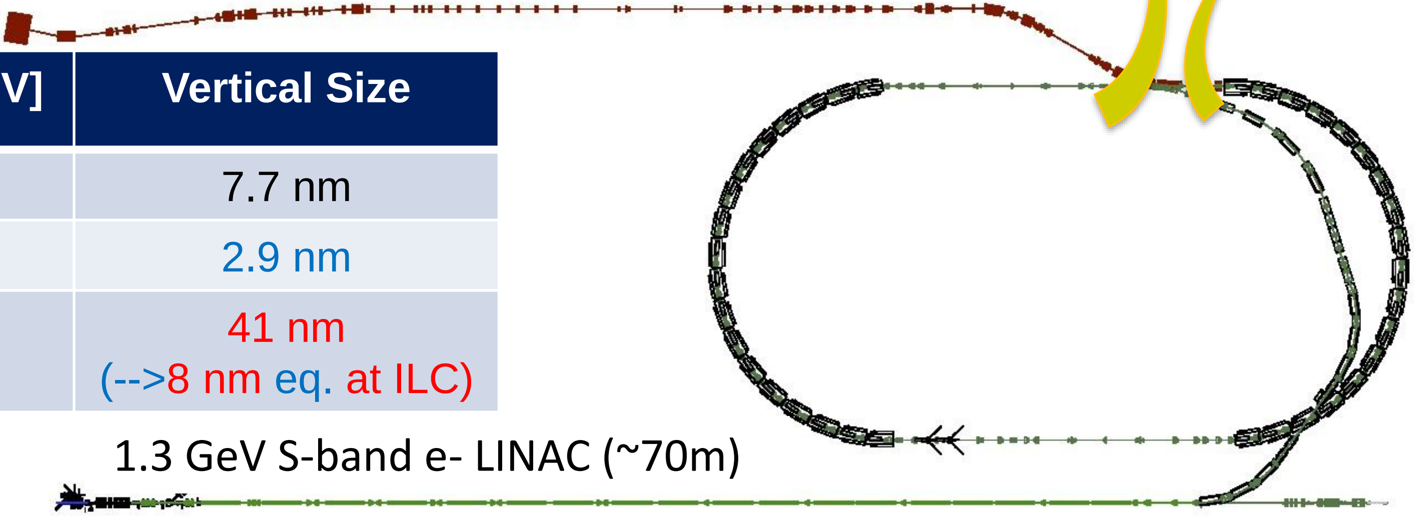
- Goal: Realize small beam-size and theStabilize beam position





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)



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

Damping Ring (140m)
Low emittance e- beam

See more, Appendix, p.56-56.

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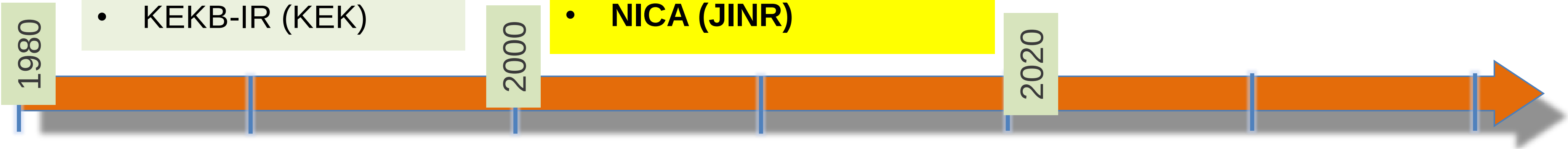
Advances in SC Magnets for Accelerators

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*

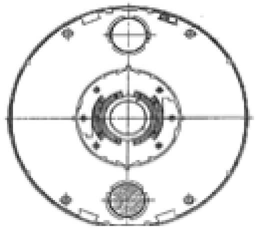
Under Construction
- **FAIR (GSI) ………** *Fast-cycleShnchr.*
- **HL-LHC (CERN)**
- **NICA (JINR)**

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

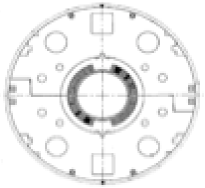


Tevatron-D.

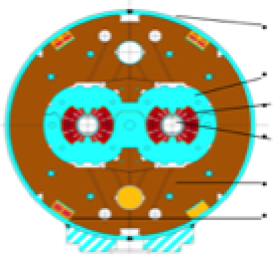
HERA-D.



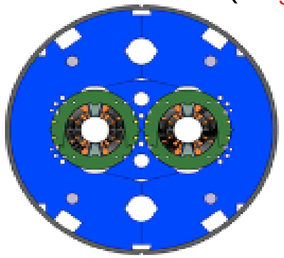
RHIC-D.



LHC.D (NbTi)

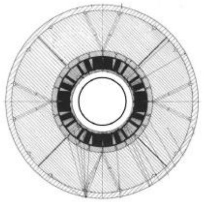


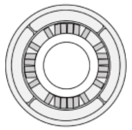
HL-LHC 11T-D (Nb_3Sn)



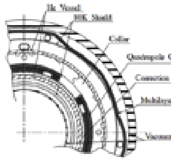
Dipole

ISR-IRQ, LEP-IRQ

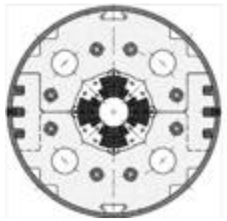




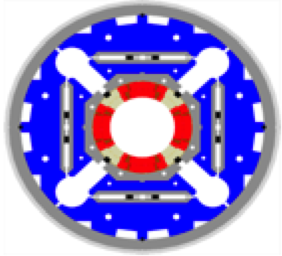
TRISTAN/KEKB-IRQ



LHCC-IRQ (NbTI)



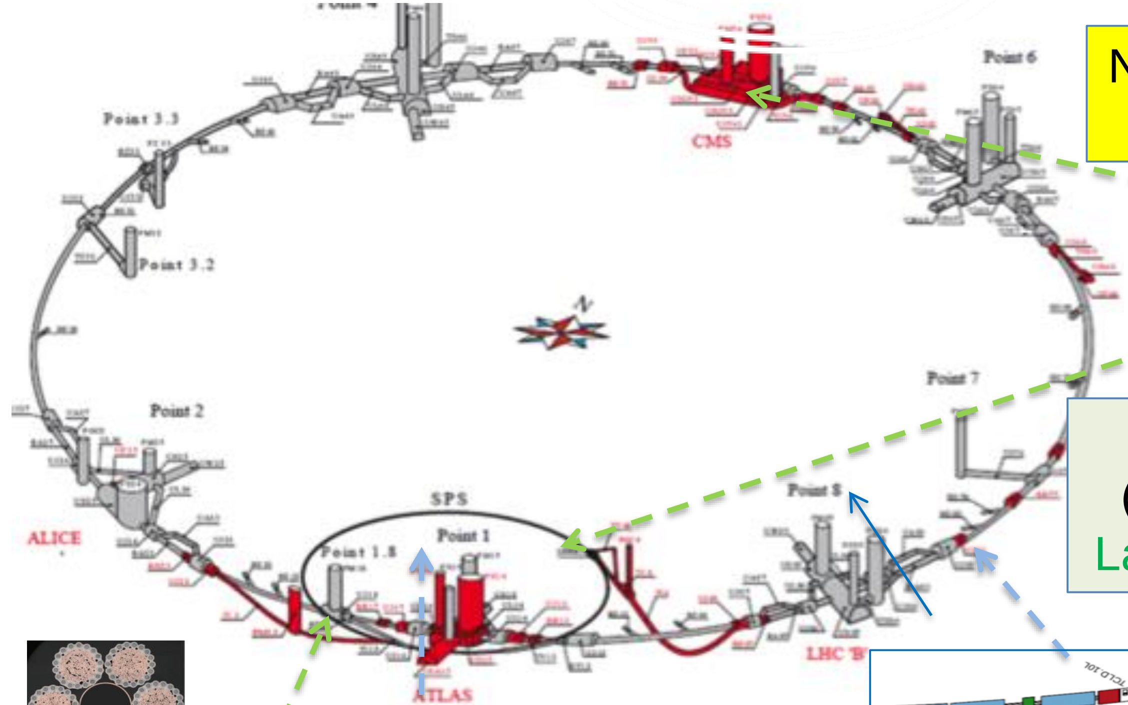
HL-LHC-IRQ (Nb_3Sn)



IR Quadrupole

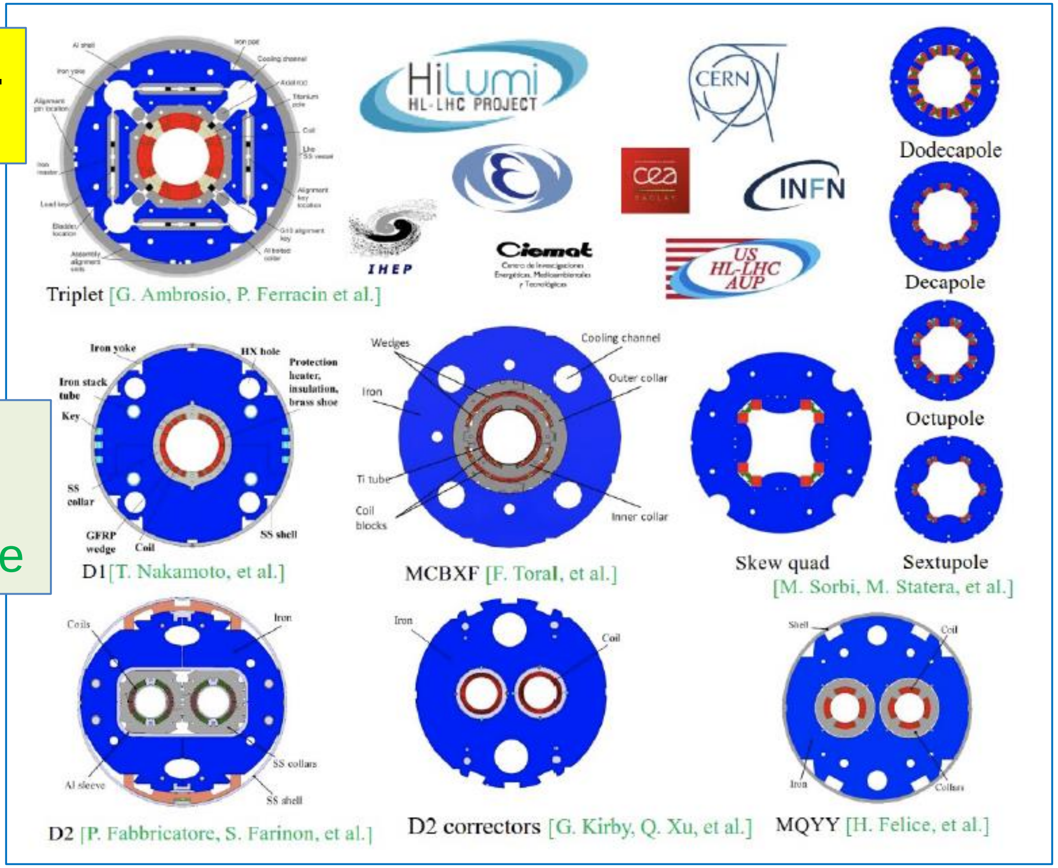
Courtesy, L. Rossi, E. Todesco

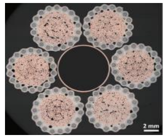
NbTi, Nb_3Sn Superconducting Magnets and MgB_2 SC Links for HL-LHC

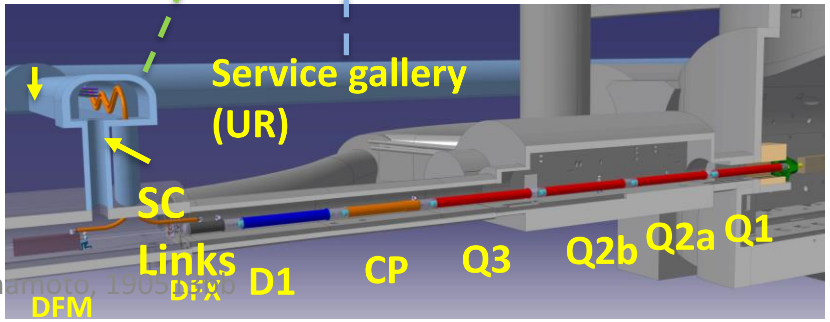


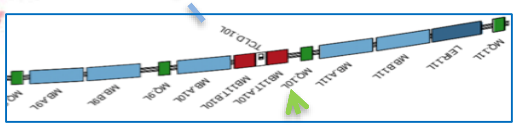
Nb_3Sn Quad. (MQXF)

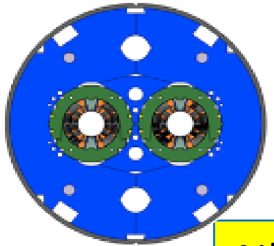
NbTi Mag. (D1, and …) Large aperture









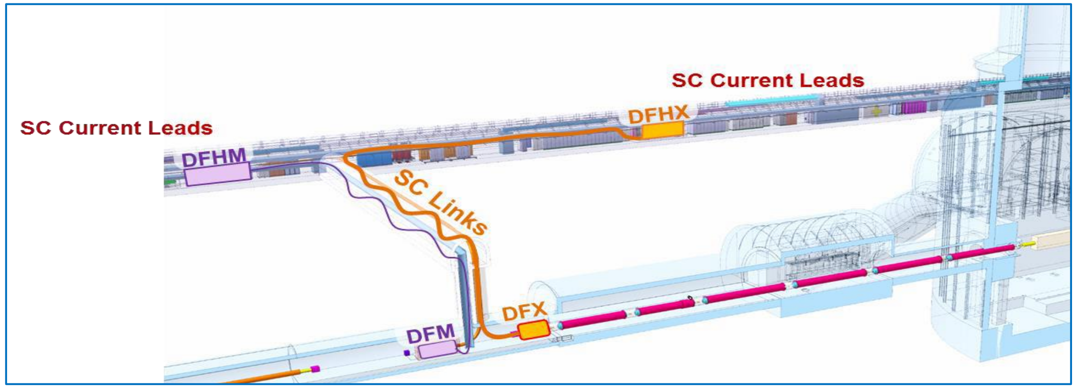


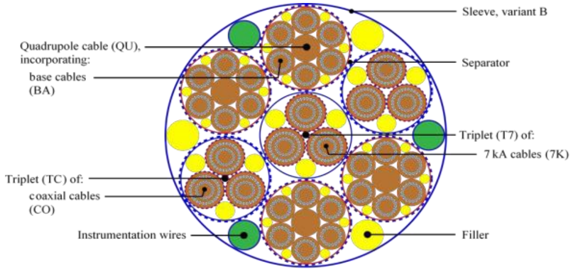
Nb3Sn Dipoles w/ Collimator

Discussed by L. Rossi

MgB_2 18.5 kA Superconducting Link Demonstrated

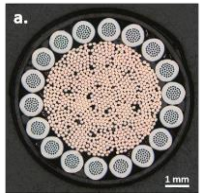
- Innovative system supplying current to Interaction Region magnets.
- Several circuits in parallel with lengths in excess of 100 m.
- Multi-stage MgB_2 cable carrying up to ~129 kA @ 25 K, cooled by forced flow of GHe at 4.5-17 K,



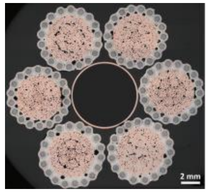


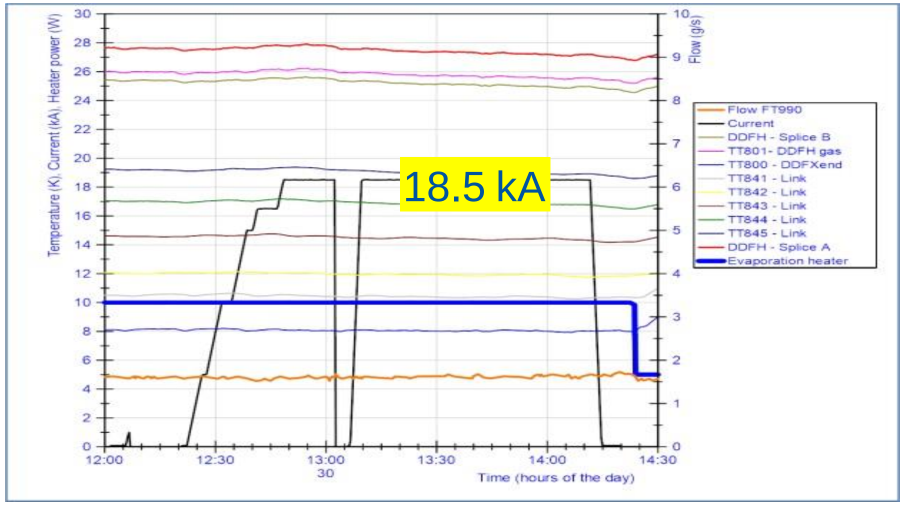
Layout of SC link cable

3 kA (6.5 mm)



18 kA (19 mm)

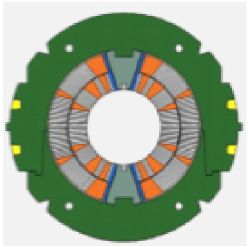


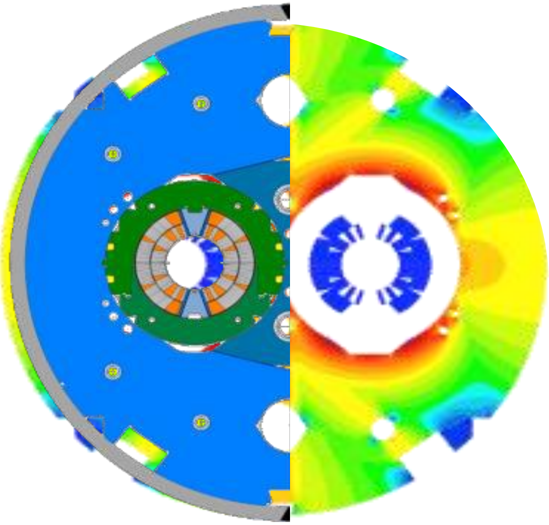


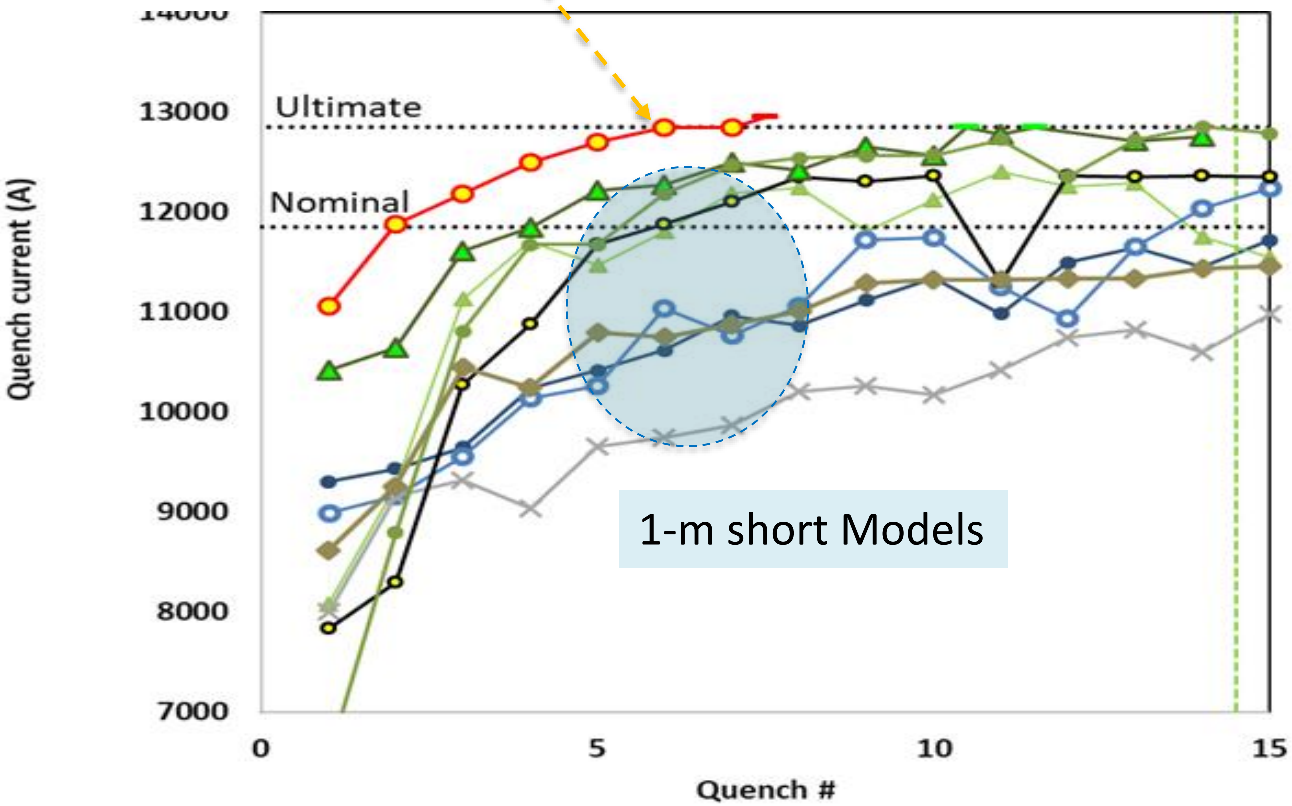
A demonstrator (2 x 60-m long, 18 kA cables) tested in Dec. 2018, exceeding requirements
- T_{CS} at 18 kA of 31.3 K

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.



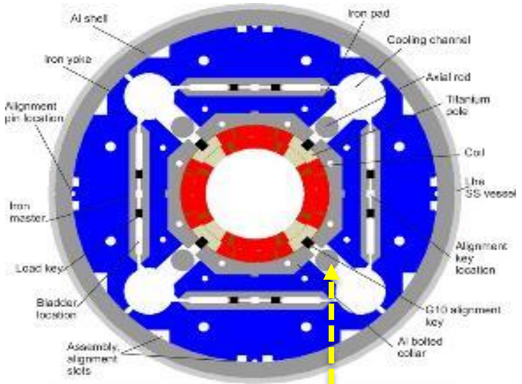




CERN and US-LARP/AUP Cooperation for Nb_3Sn IR Quadrupoles

- **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** ,

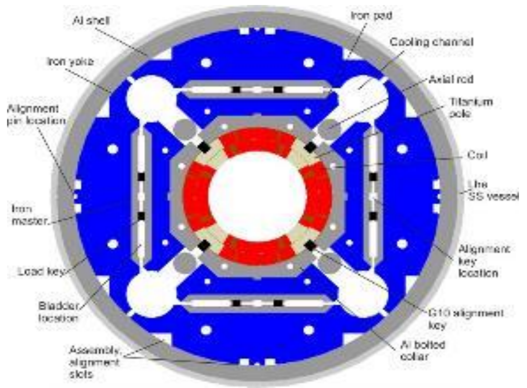
- **CERN** leading HL-LHC global collaboration and qualifying the Nb_3Sn accelerator magnet technology:
  - Experienced with the project realization for future collider accelerators.



Bladder, as a key technology

Nb_3Sn Quadrupole (MQXF) at IR

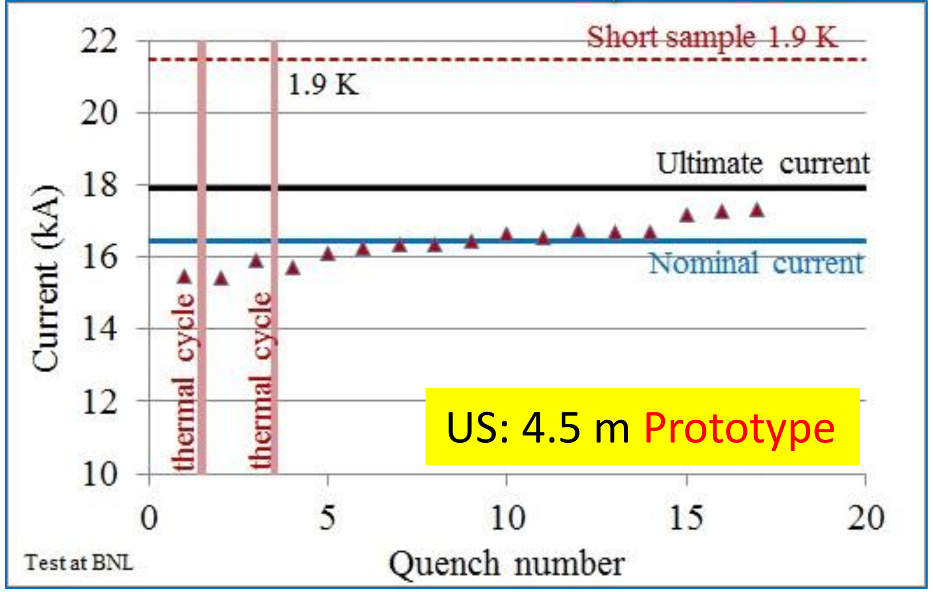
Courtesy,
G. Ambrosio, G. Chlachidze
E. Todesco, P. Ferracin

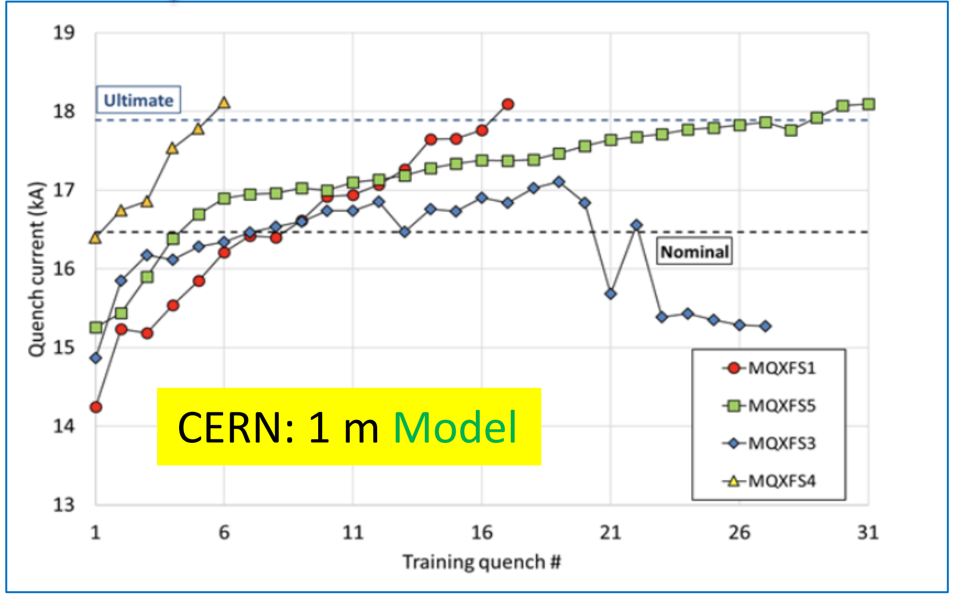


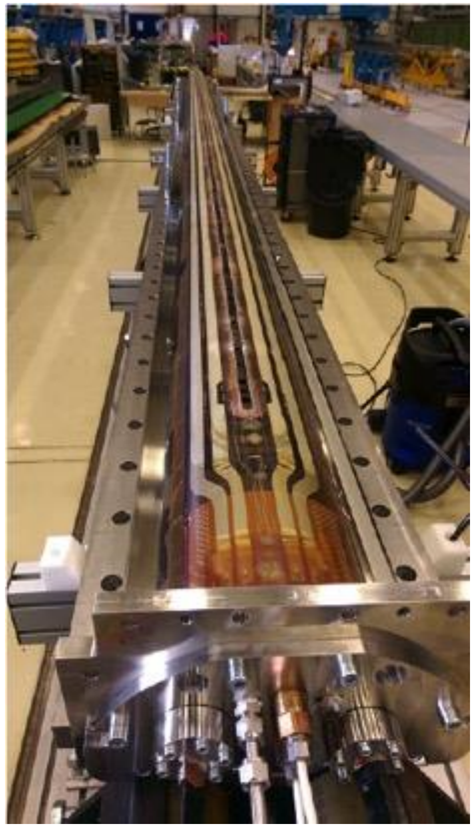
US: 4.5 m Prototype:
- Completed and tested

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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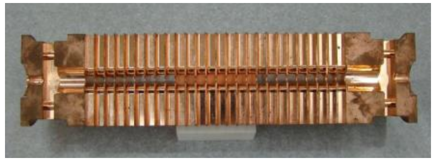
Courtesy: W. Wuensch

Features of Normal 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
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_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 long-pulse, low freq. klystrons and two-beam scheme	- High-efficiency RF also from long-pulse, low-frequency klystrons



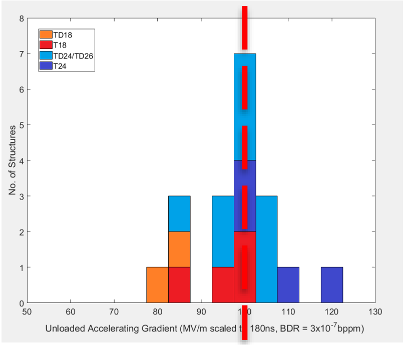
Courtesy: W. Wuensch

Normal Conducting Linac Technology Landscape

Components:

<u>Laboratory</u> with commercial

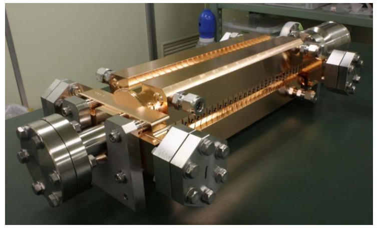
- **Accelerating structures**
- pulse compressors
- alignment
- Stabilization, etc.



~ 100 (+/-20) MV/m

<u>Full commercial</u> supply

- X-band klystrons
- solid state modulator,

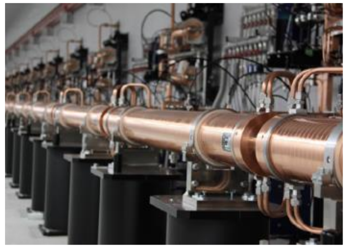


Systems Facilities:
(100 MeV-range)

- 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
<u>Operational:</u>

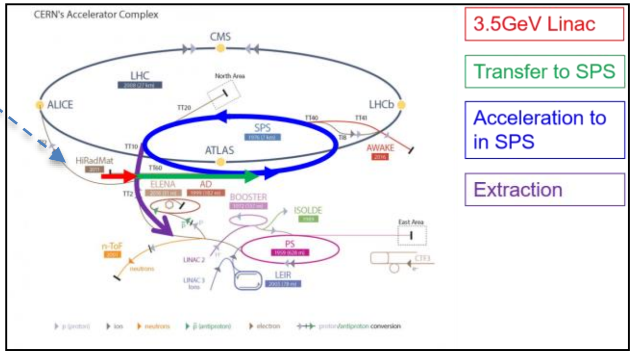
- **SACLA**
- **SwissXFEL (8 GeV)**



X-band (12 GHz)
GeV-range facilities
<u>Planning:</u>

- **Eu-Praxia**
- **e-SPS**
- **CompactLight**

CLIC



Discussed byS. Stapnes
See Appendix. P. 58059.

Advances in SRF Technology for 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 Gradient

Field Gradient

Surface

Material

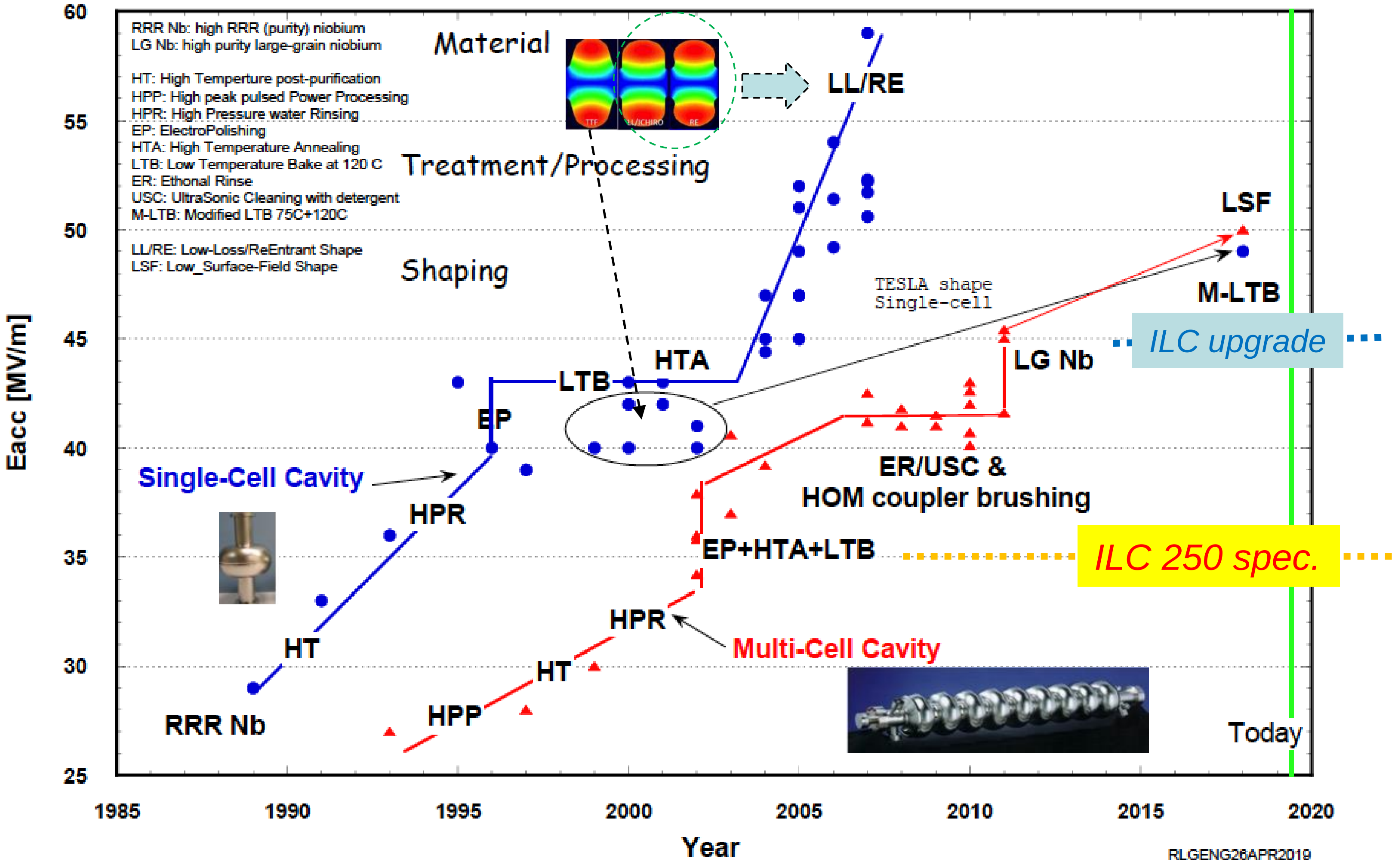
$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$

Thermal conductance

Surface,

Shape

See more, Appendix p.60.



A. Yamamoto, 190513bb

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

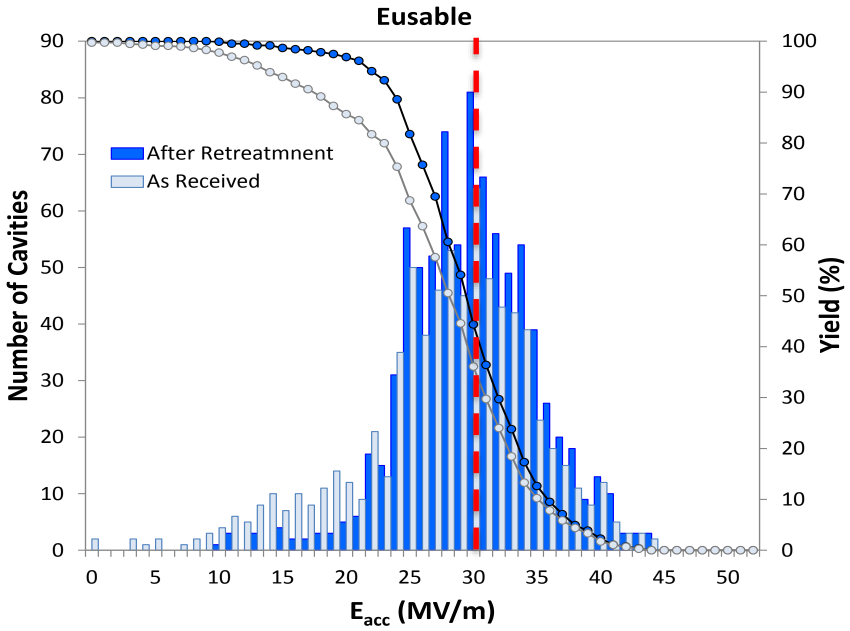
Back

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:

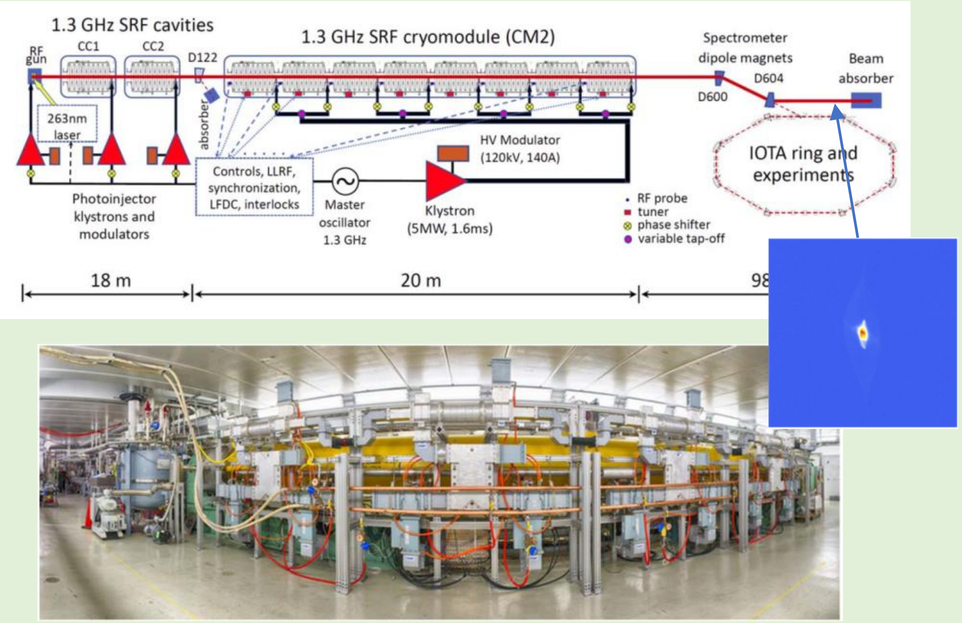
E-usable: 29.8 ± 5.1 [MV/m]

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

A. Yamamoto, 190513bb

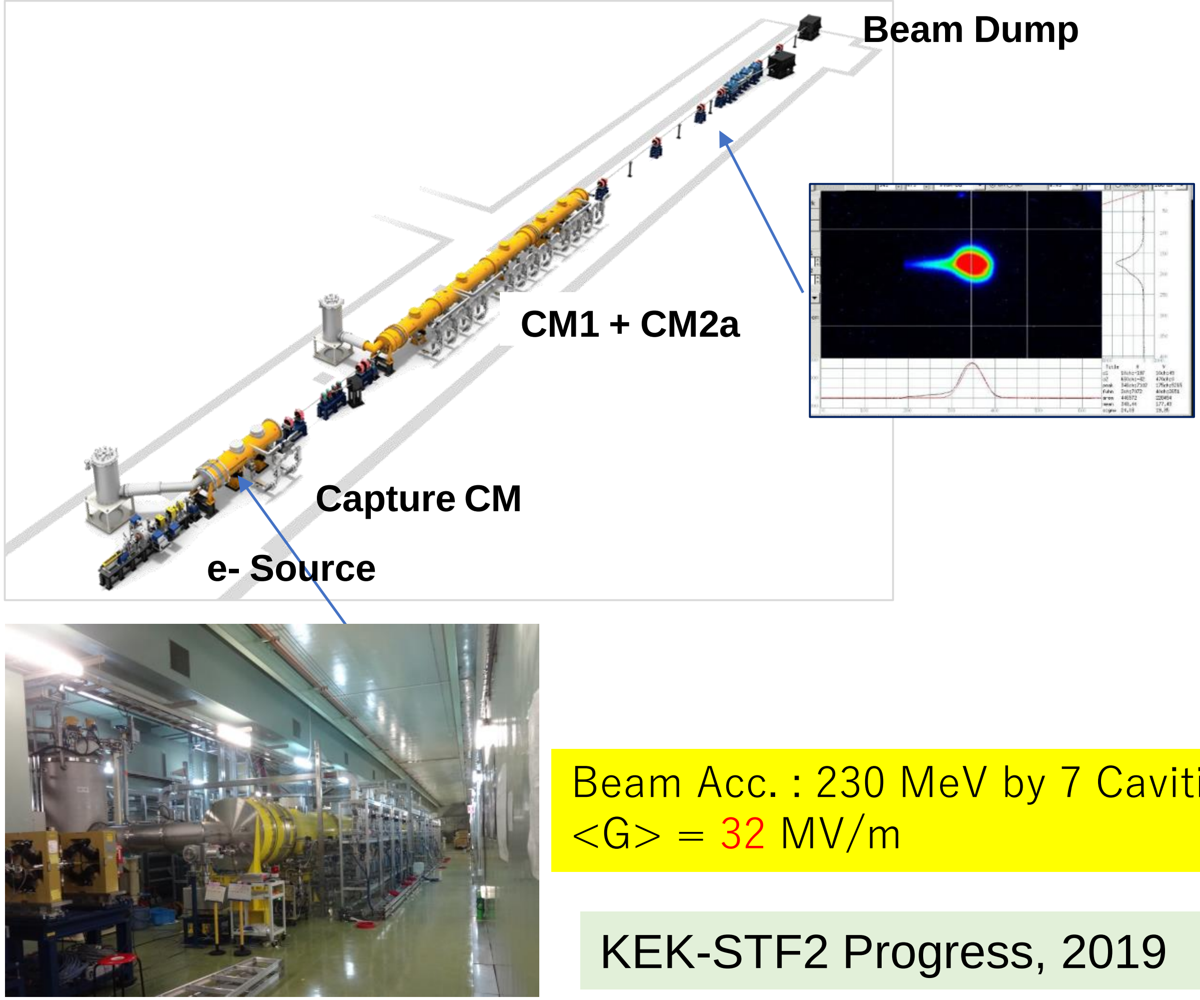
Courtesy: V. Shiltsev, S. Michizono

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

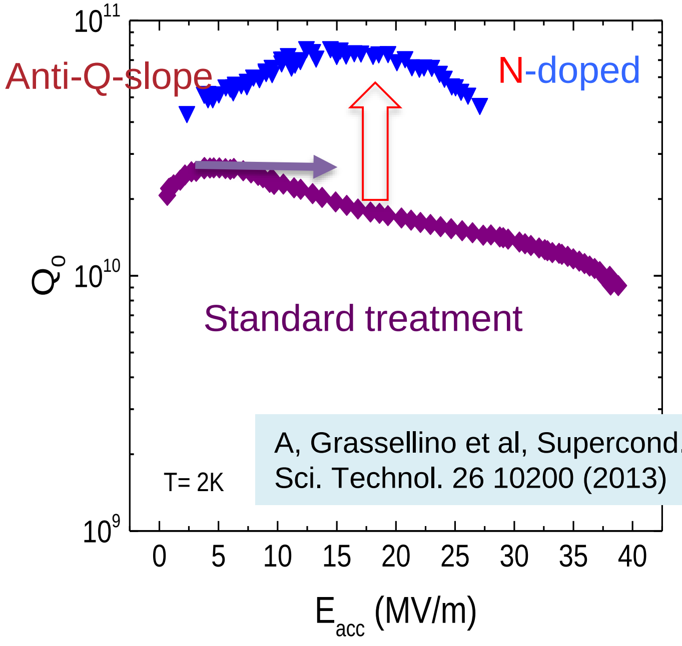


Beam Acc. : 230 MeV by 7 Cavities,
<G> = 32 MV/m

KEK-STF2 Progress, 2019

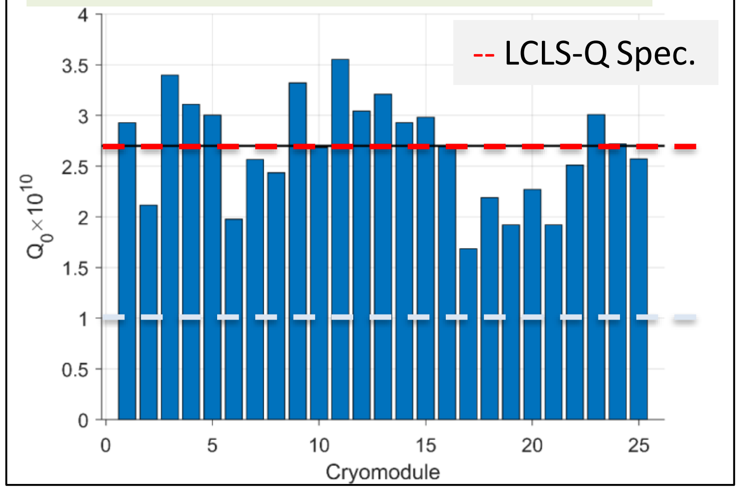
Courtesy, M. Ross

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



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

LCLS-II CM production in progress



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:

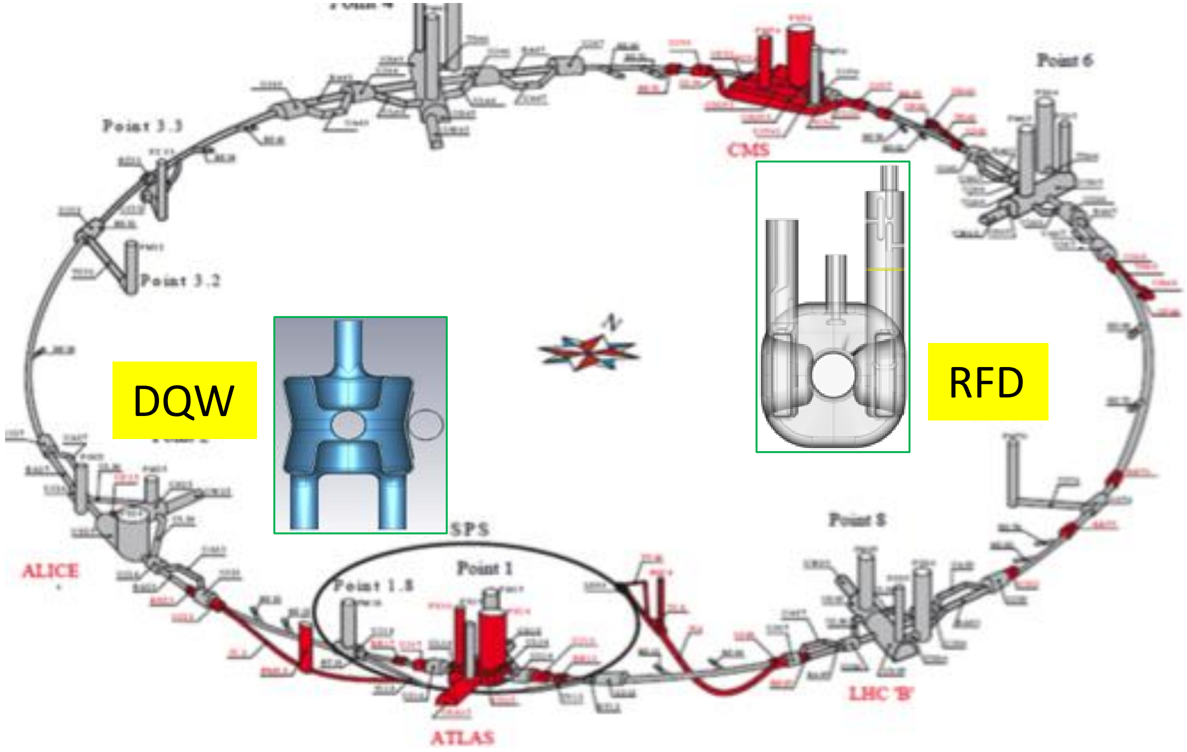
- Frequency : 1.3 GHz, CW
- G: 18 ~21 MV/m
- Q: > 2.7 e10 (av.)
- # cavity = 280 (+160)
- # CM 35 (+20)

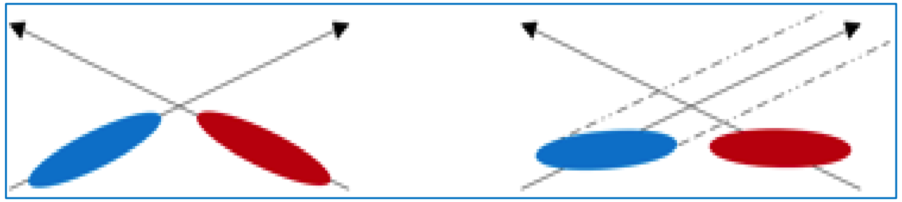
To be completed in 2020 (~2026)

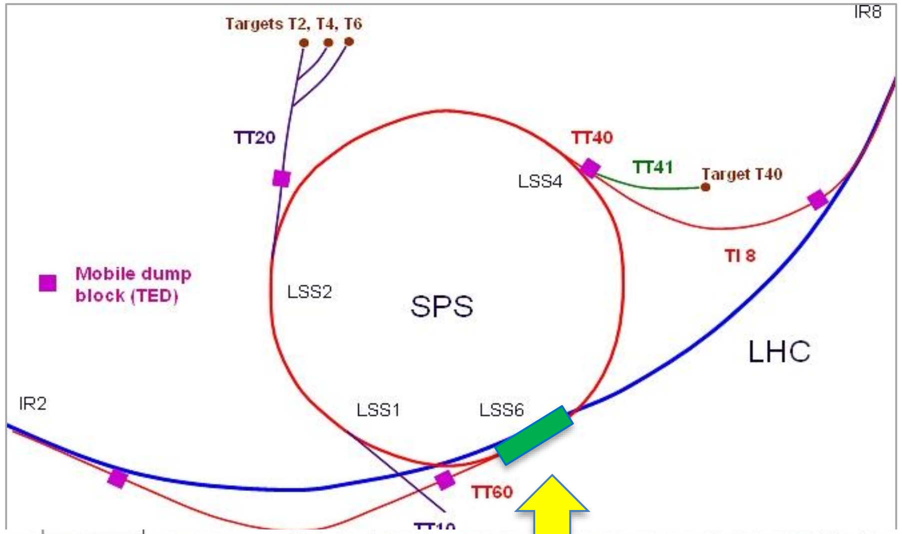
Nb SRF Crab Cavities for HL-LHC

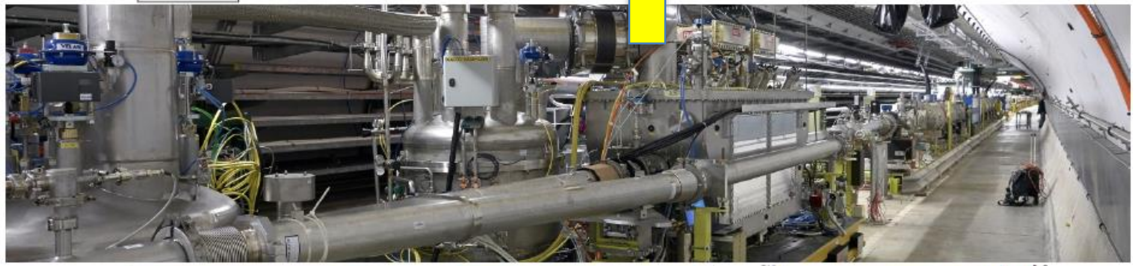
Courtesy,
R. Calaga, O. Capatina,
A. Ratti, L. Ristori

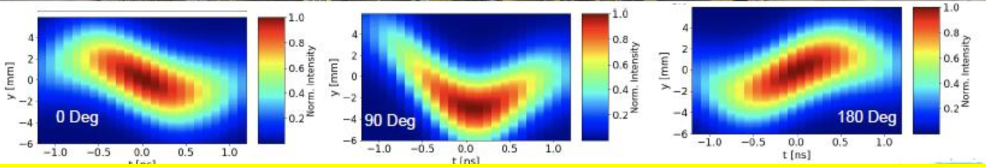
CERN, US-AUP, STFC, TRIUMF Collaboration











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]	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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	[illegible]	(to be filled)	[illegible] 120	[illegible]	[illegible]	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CCee	FCC-ee	[illegible]	0.37	60 – 31	260 – 350	10.5 +1.1 [BCHF]		[illegible]	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
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	CLIC	[illegible]	[illegible] (- 3)	[illegible] (- 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

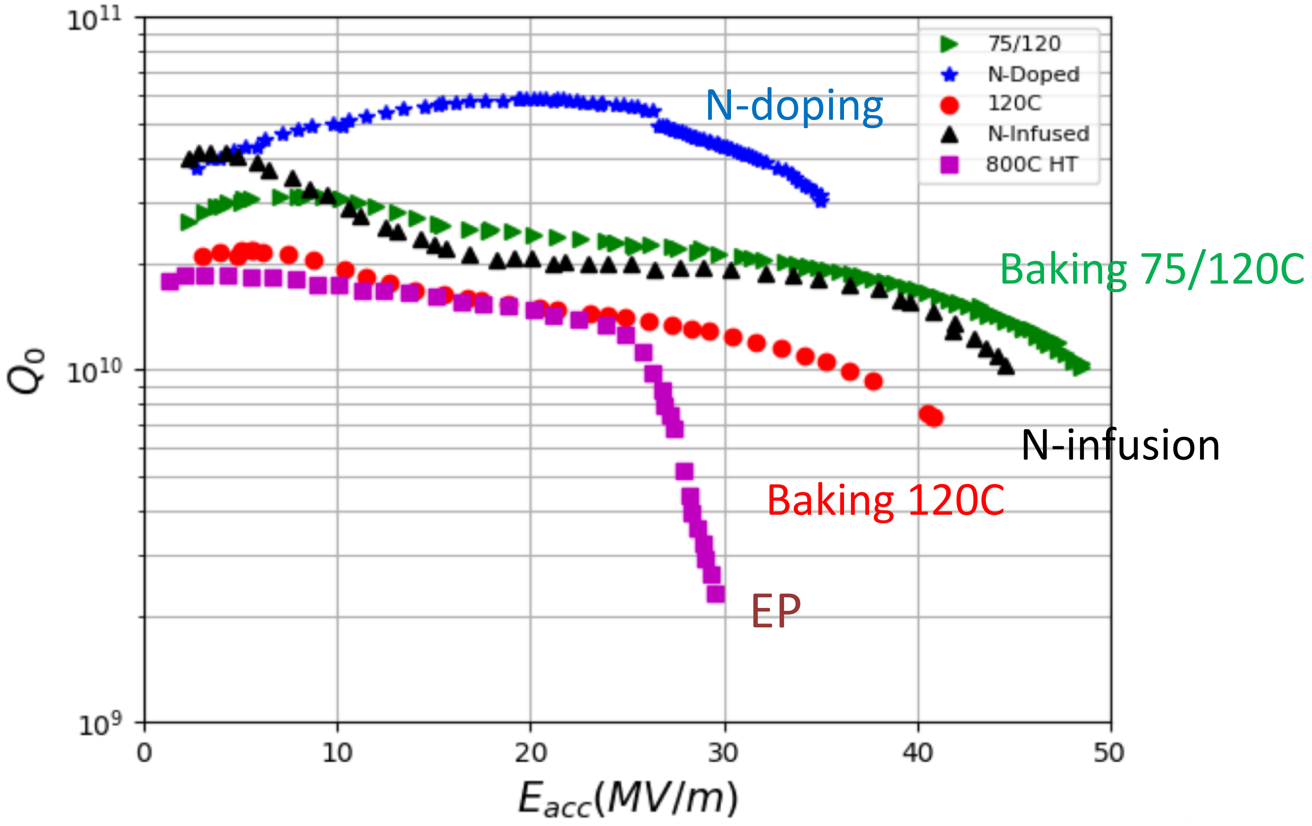
Lepton Colliders:

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

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

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

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

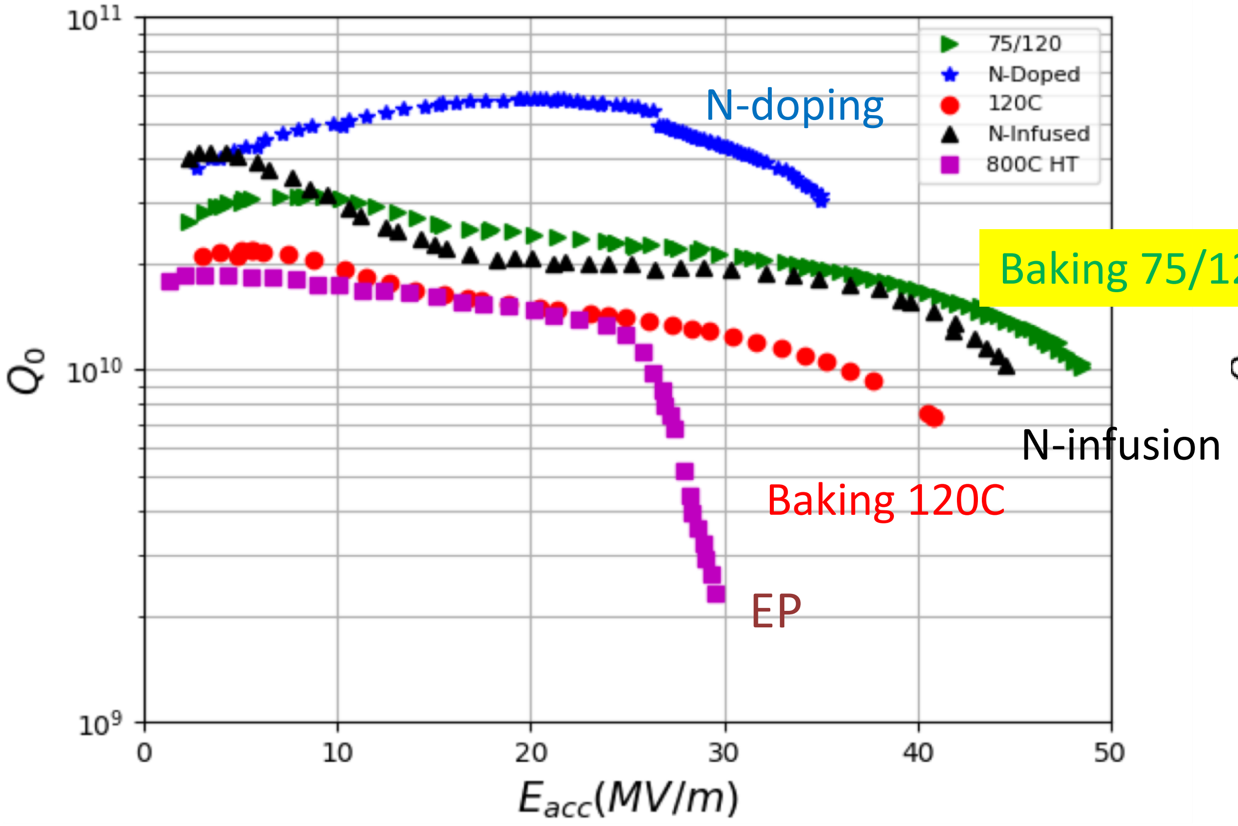


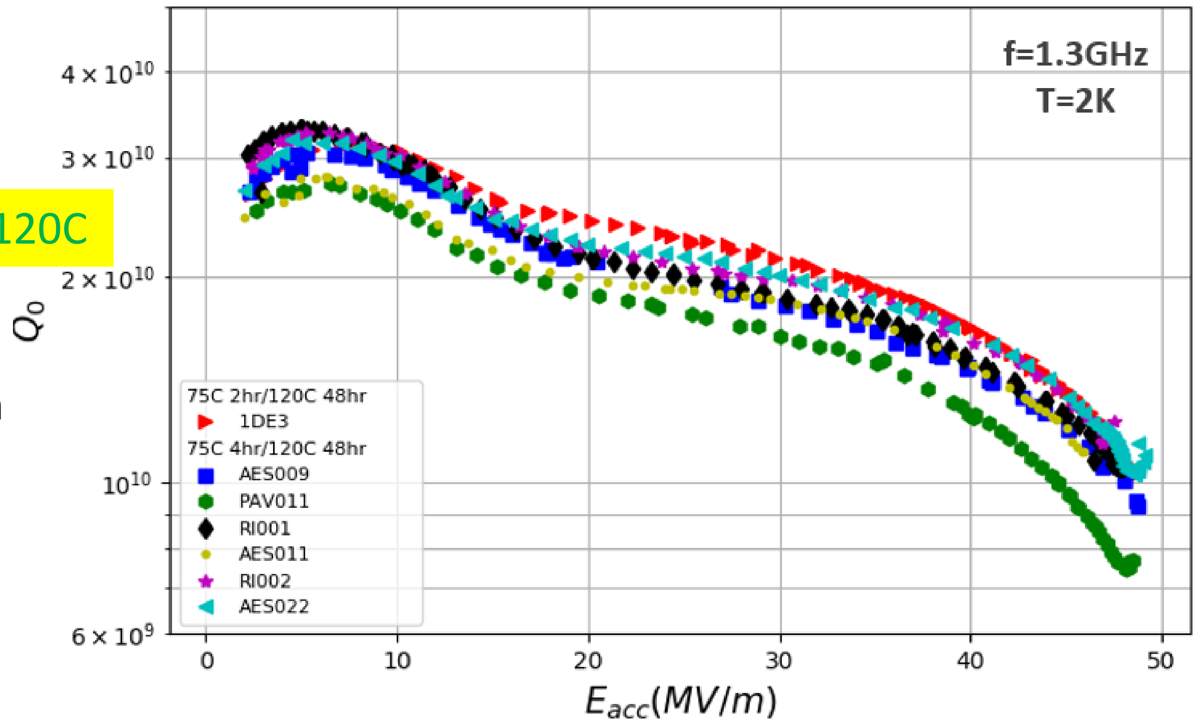
- **N-doping** (@ 800C for ~a few min.)
  - Q >3E10, G = 35 MV/m
- **Baking w/o N** (@ 75/120C)
  - Q >1E10, G =49 MV/m (Bpk-210 mT)
- **N-infusion** (@ 120C for 48h)
  - Q >1E10, G = 45 MV/m
- **Baking w/o N** (@ 120C for xx h)
  - Q >7E9, G = 42 MV/m
- **EP** (only)
  - Q >1.3E10, G = 25 MV/m

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

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

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





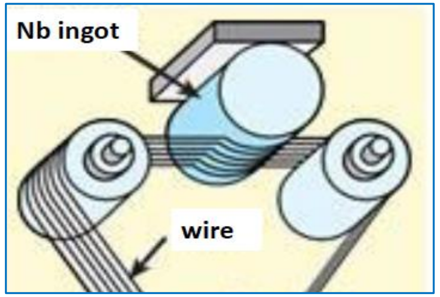
Repeated on second cavity TE1AES009 (fine grain, AES, WC)

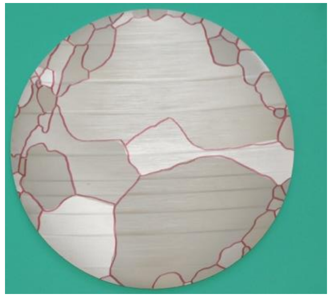
https://arxiv.org/abs/1806.09824

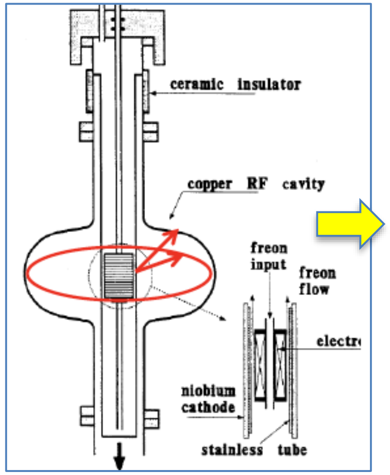
- Performance at **Fermilab** confirmed by **Cornell**, **DESY**, and **JLab.**
- See more, p. 61.

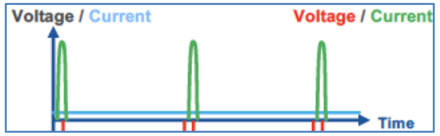
Challenges in SRF Cavity Technology

- **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})







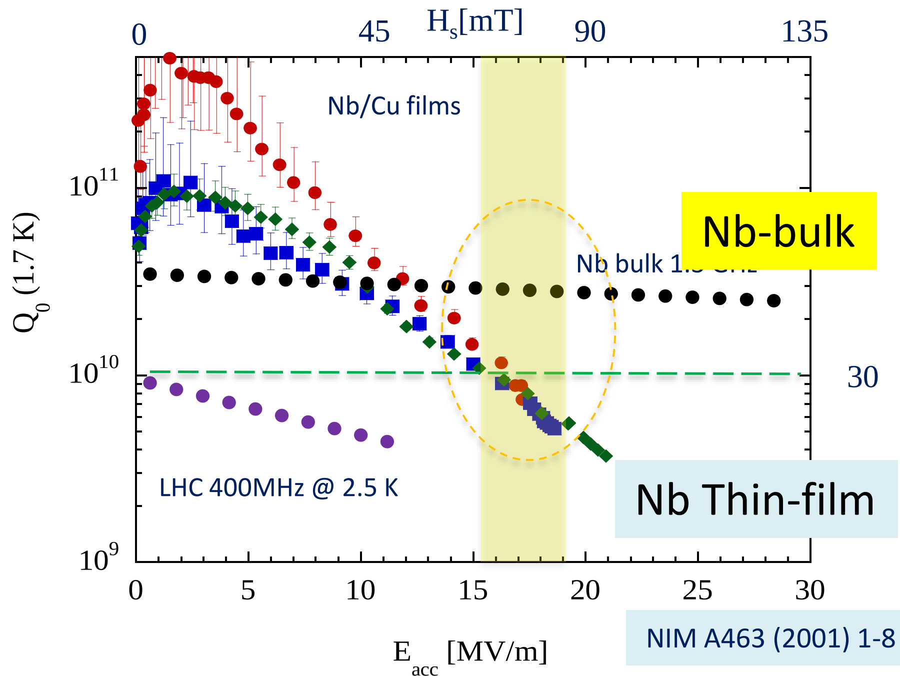


See more, Appendix: p. -62-64.

Courtesy: S. Calatroni

DC Magnetron Sputtered Nb/Cu Films

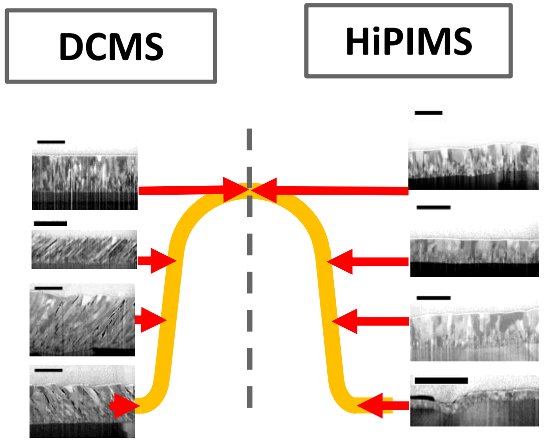
1.5 GHz Nb/Cu cavities, sputtered with Kr @ 1.7 K (Q_0=295/R_s)



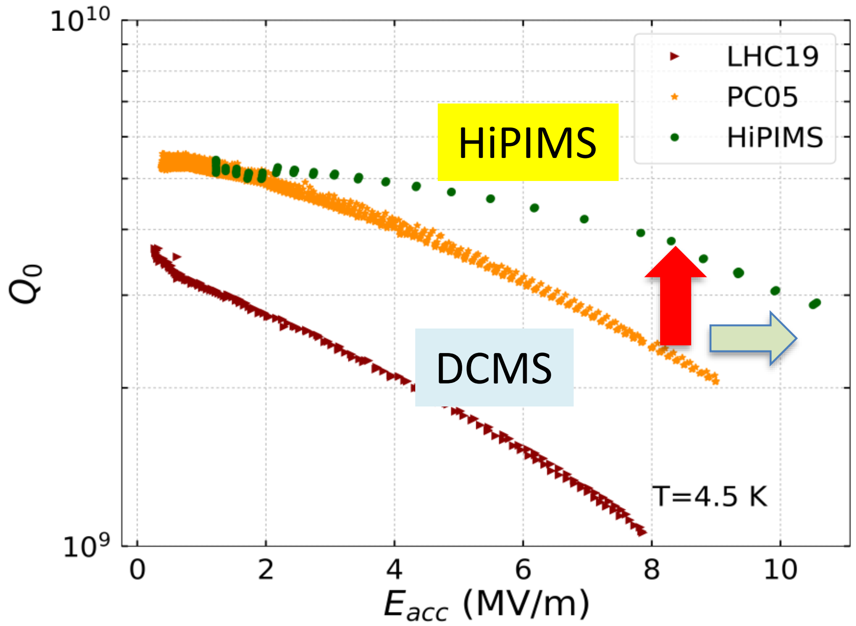
NIM A463 (2001) 1-8

HiPIMS coatings – QPR Sample

To be important challenge for < 600 MHz (FCC)



700 MHz β=0.65 Single Cell Cavity profile



- 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

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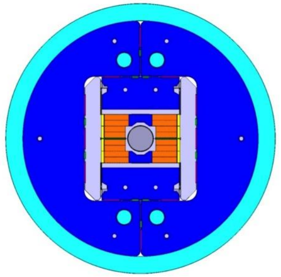
  - **Superconducting technology** for future Lepton and **Hadron Colliders**
- **Summary**

Courtesy: G. De Rijk, A. Devred

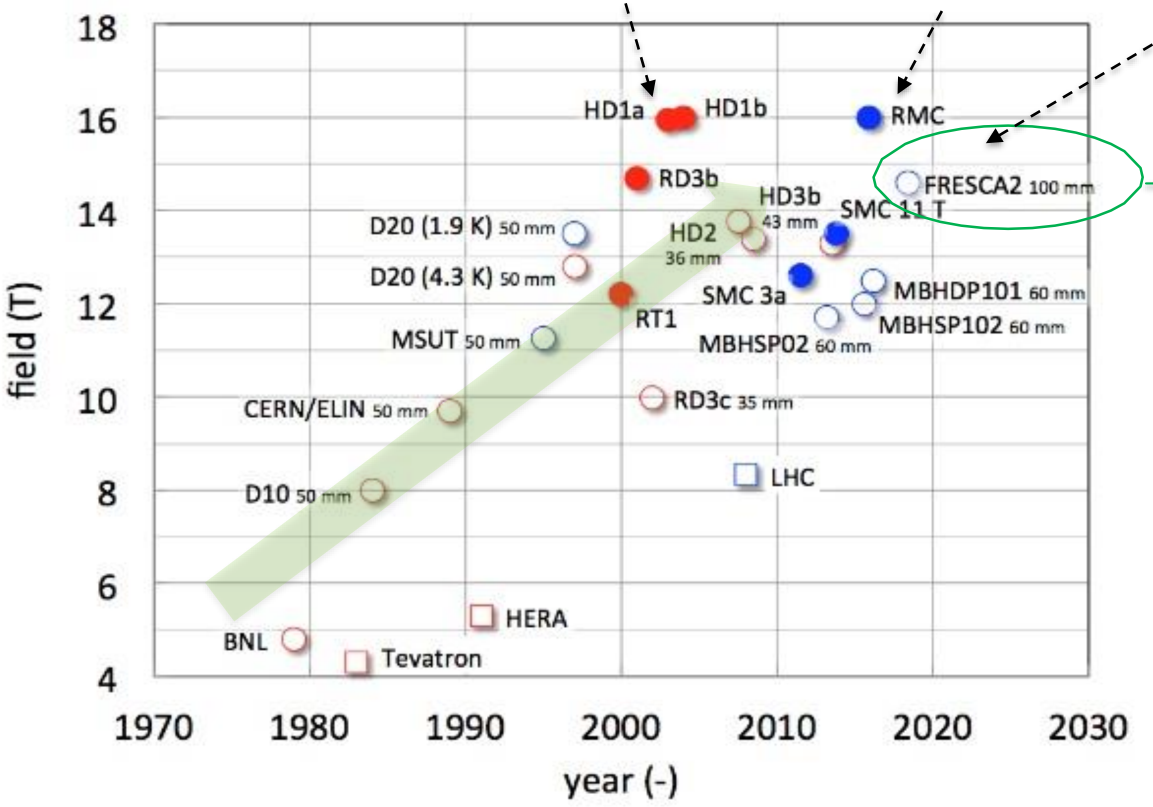
Advances in Nb_3Sn Magnet Development

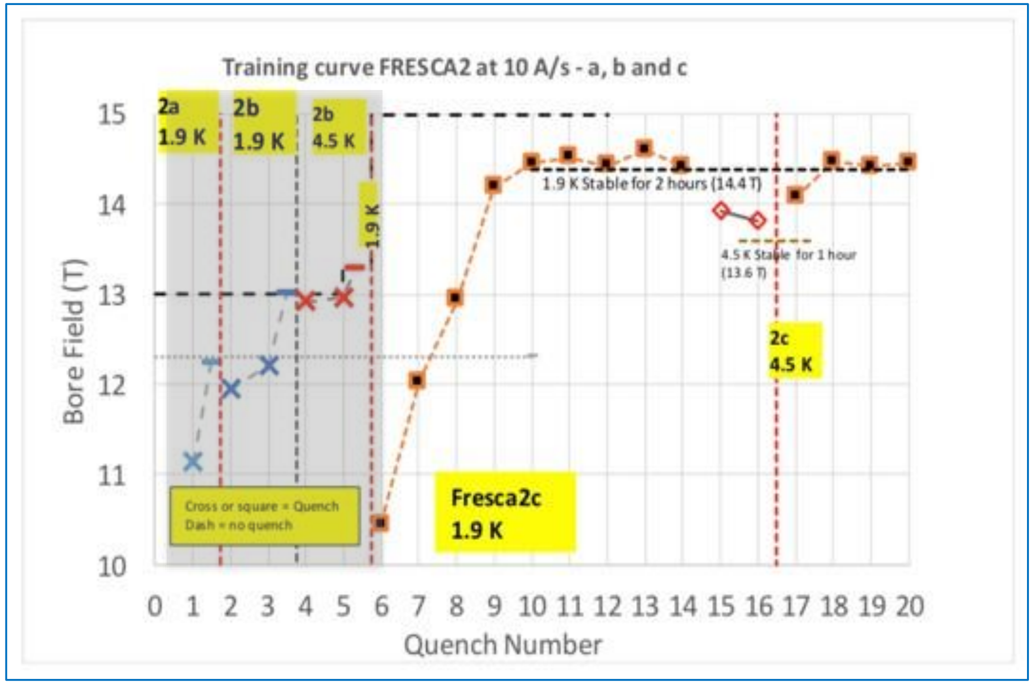


2003: LBNL HD1
(16 T at 4.2 K)

2015:CERN RMC
(16.2 T at 1.9 K)

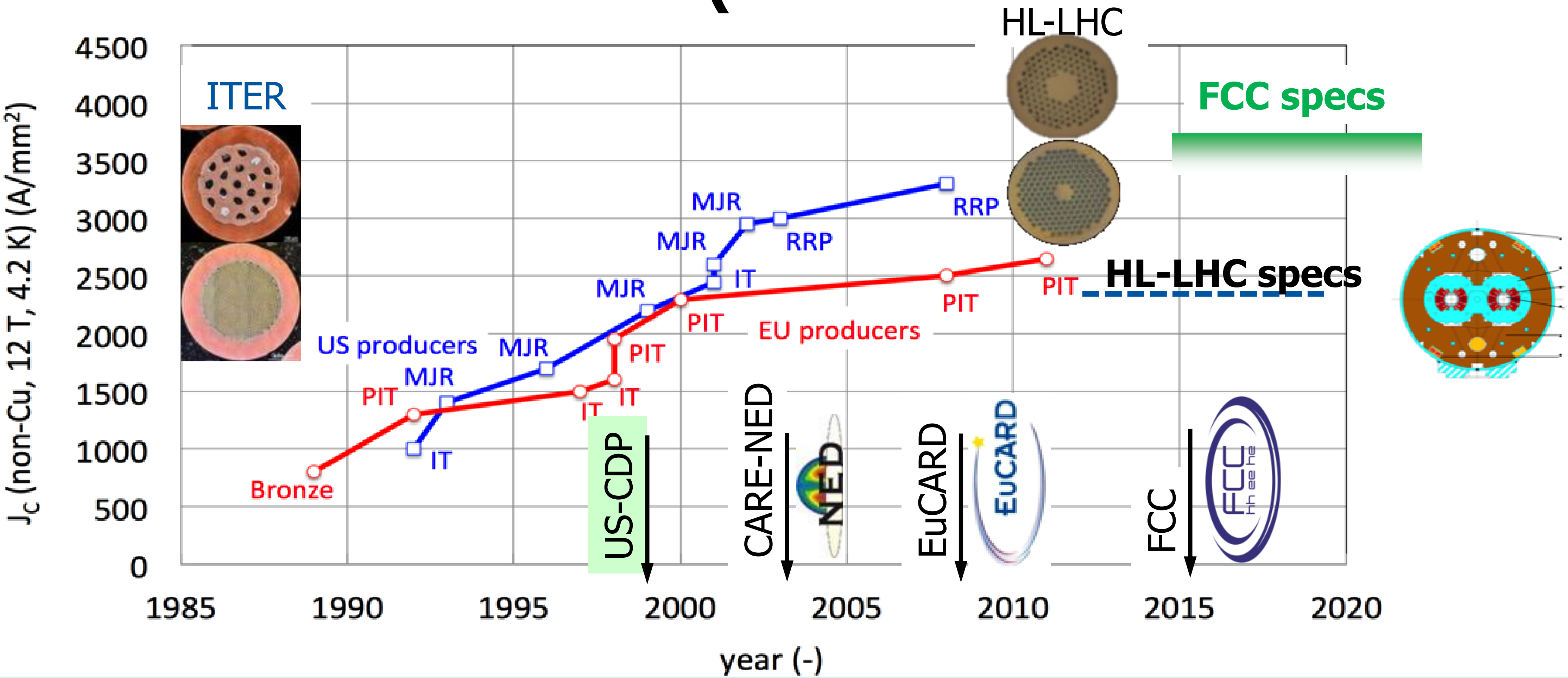
2018: FRESCA2
(100 mm aperture, 14.6/14.95 T bore/peak at 12.1 kA. 1.9 K)





Courtesy, G. de Rijk

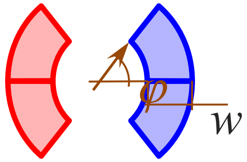
Nb_3Sn Conductor development for Accelerators (1998 ~)



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

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 !!

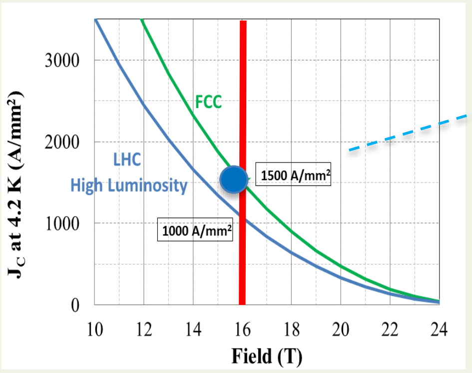
$$B = \frac{2\mu_0}{\pi} J w \sin(\phi)$$

Main development Target:

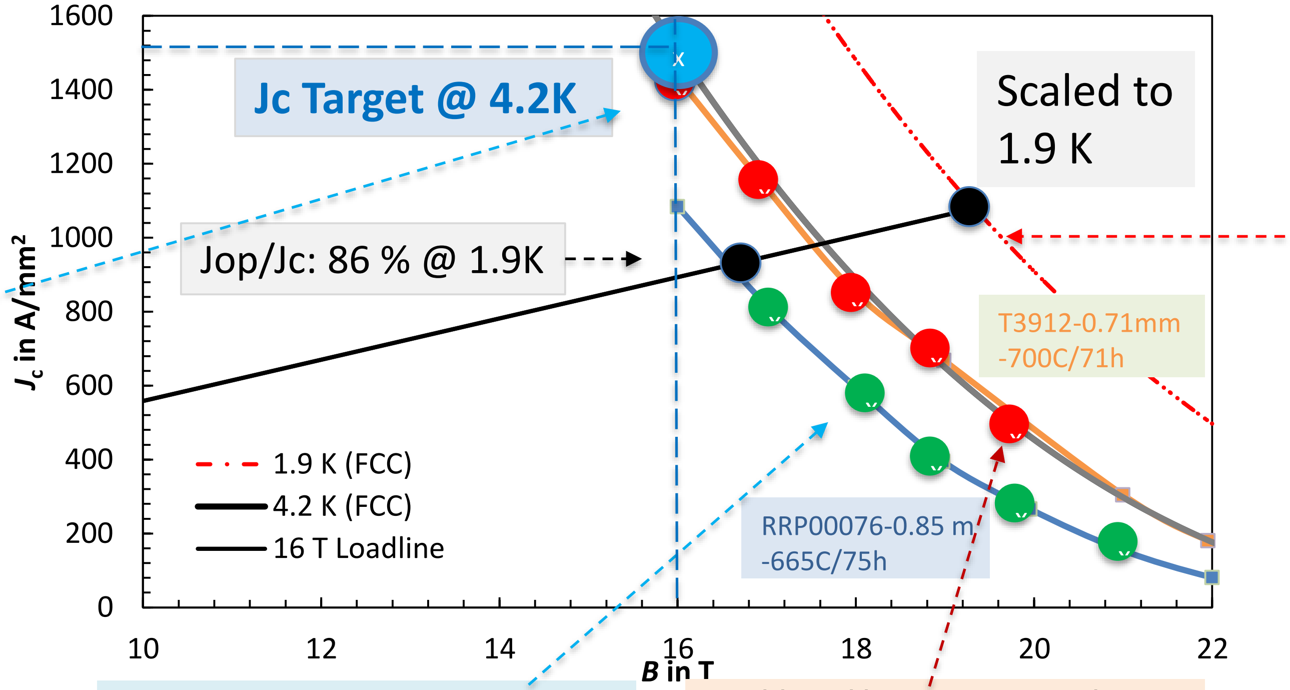
- **J_c (16T, 4.2K) > 1500 A/mm²**
  - 50% higher than HL-LHC

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

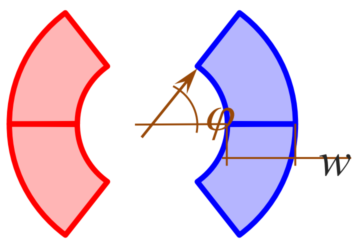
- Another ternary approach w/ Hf rto Nb4Ta in progress: S. Balachandran et al., https://arxiv.org/pdf/1811.08867.pdf

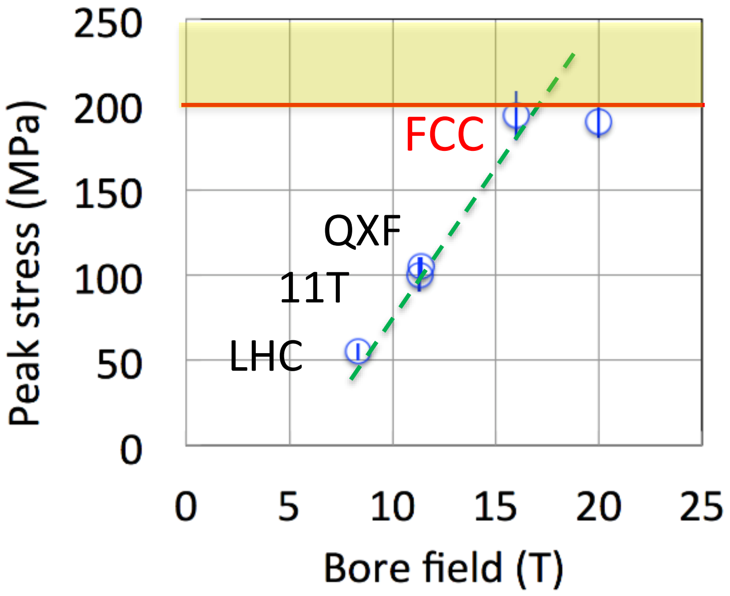
A. Yamamoto, 190513bb

See more, Appendix: p. 65.

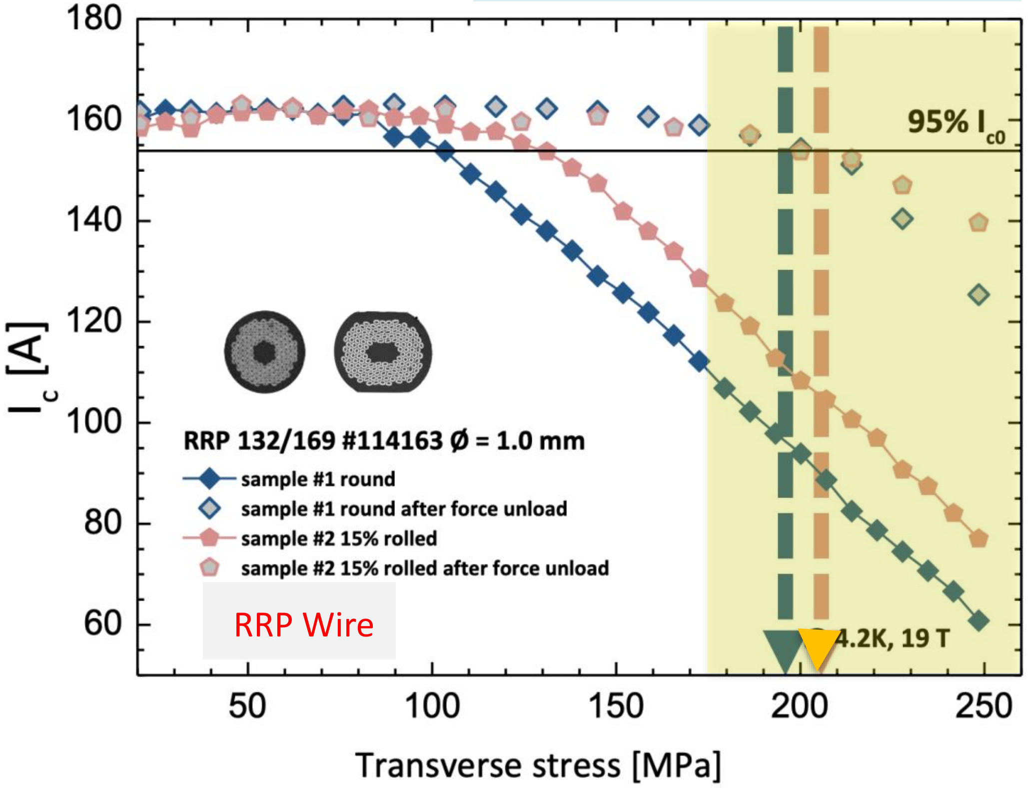
Courtesy: L. Bottura, A. Devred

Mechanical Constrain to consider Operating Margin





Measurement at Univ. Geneve



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

or

$$p \sim B^2$$

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.

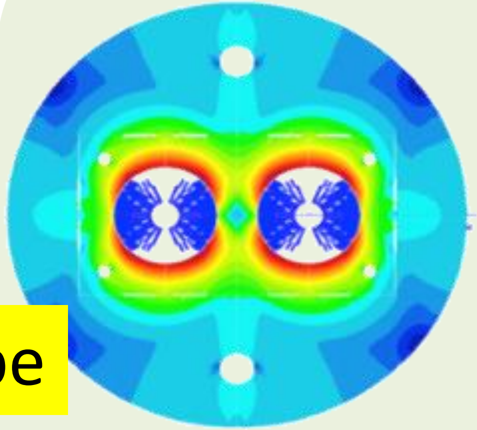
Courtesy, M. Benedikt, L. Bottura, D. Tommasini, S. Prestemon

16 T Dipole R&Ds in Europe and US

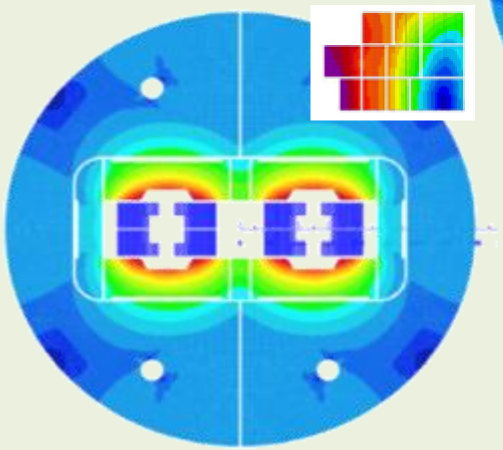
Europe

EuroCirCol — A key to New Physics

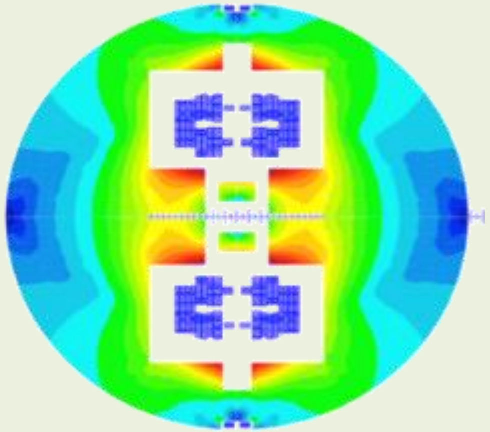
Cos-θ



Blocks



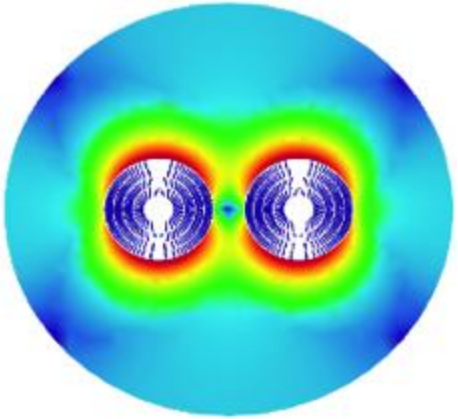
Common coils



Pioneering work at BNL

CHART2
Swiss Acc. Research & Technology

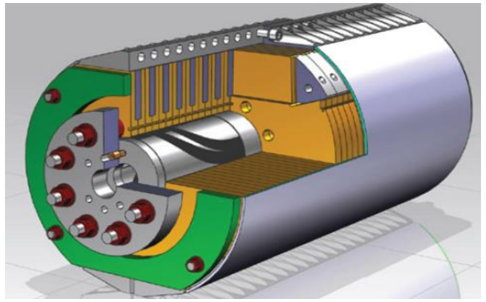
Canted Cos-θ (CCT)

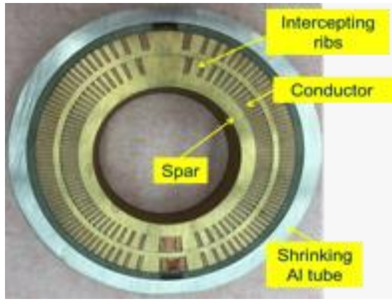


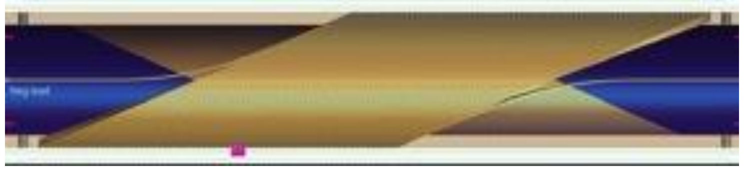
US

U.S. MAGNET DEVELOPMENT PROGRAM

Cos-θ







CCT,
Pioneering work at LBNL

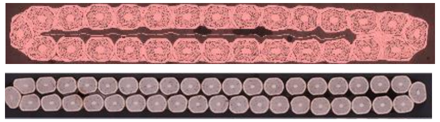
US-DOE MDP taking Steps to realize 16 T

MDP Goals:

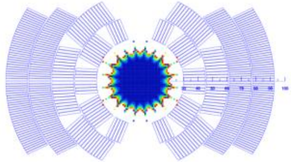
1. Explore Mb_3Sn magnet limit
2. Demonstrate HTS magnet (5 T – self fied)
3. Investigate fundamentals for performance and cost reduction
4. Pursue Nb3Sn and HTS conductor R&D

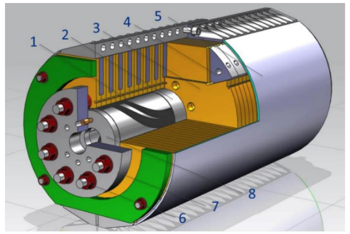
See Appendix: p66-69.

- **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

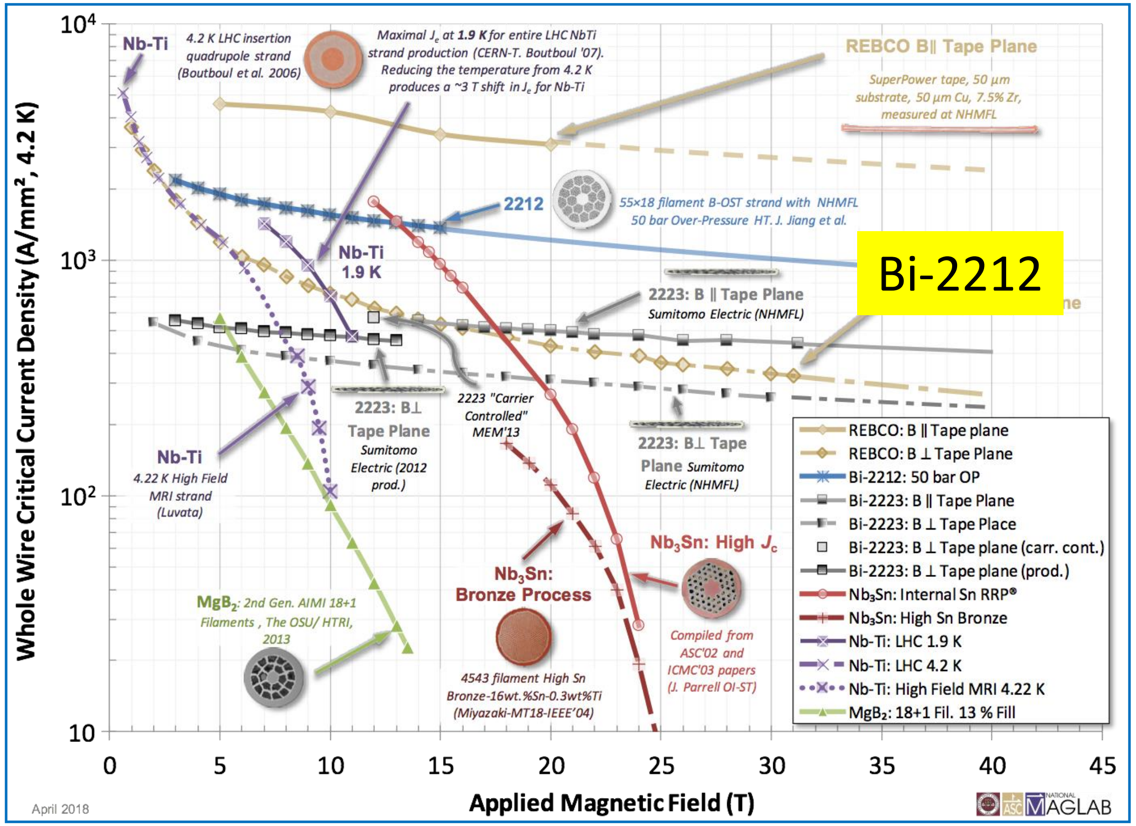


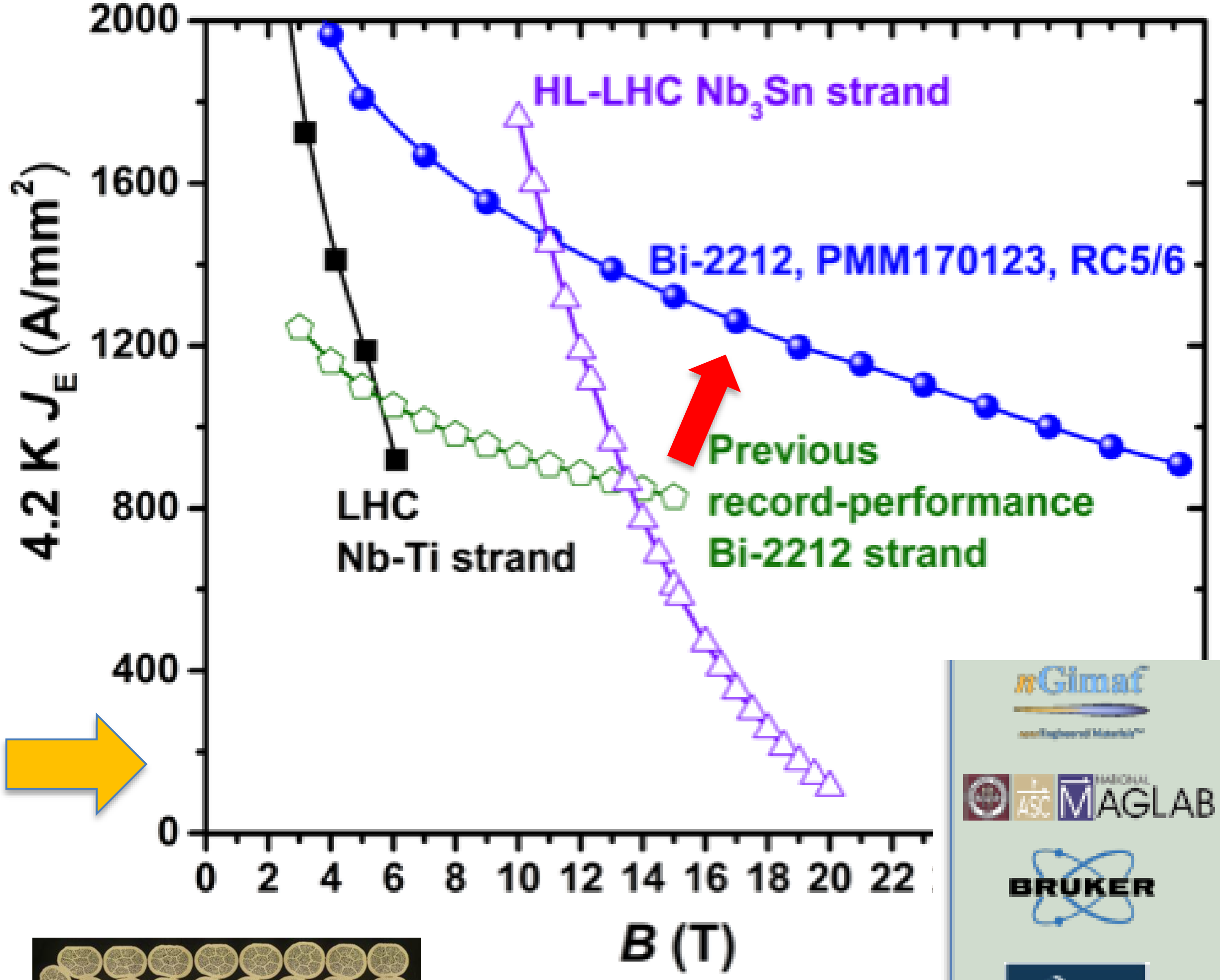


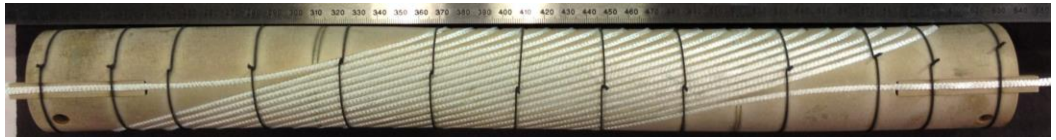
Before test, at Fermilab

Courtesy, P. Lee, S. Prestemon

HTS, focusing on Bi2212 in the US





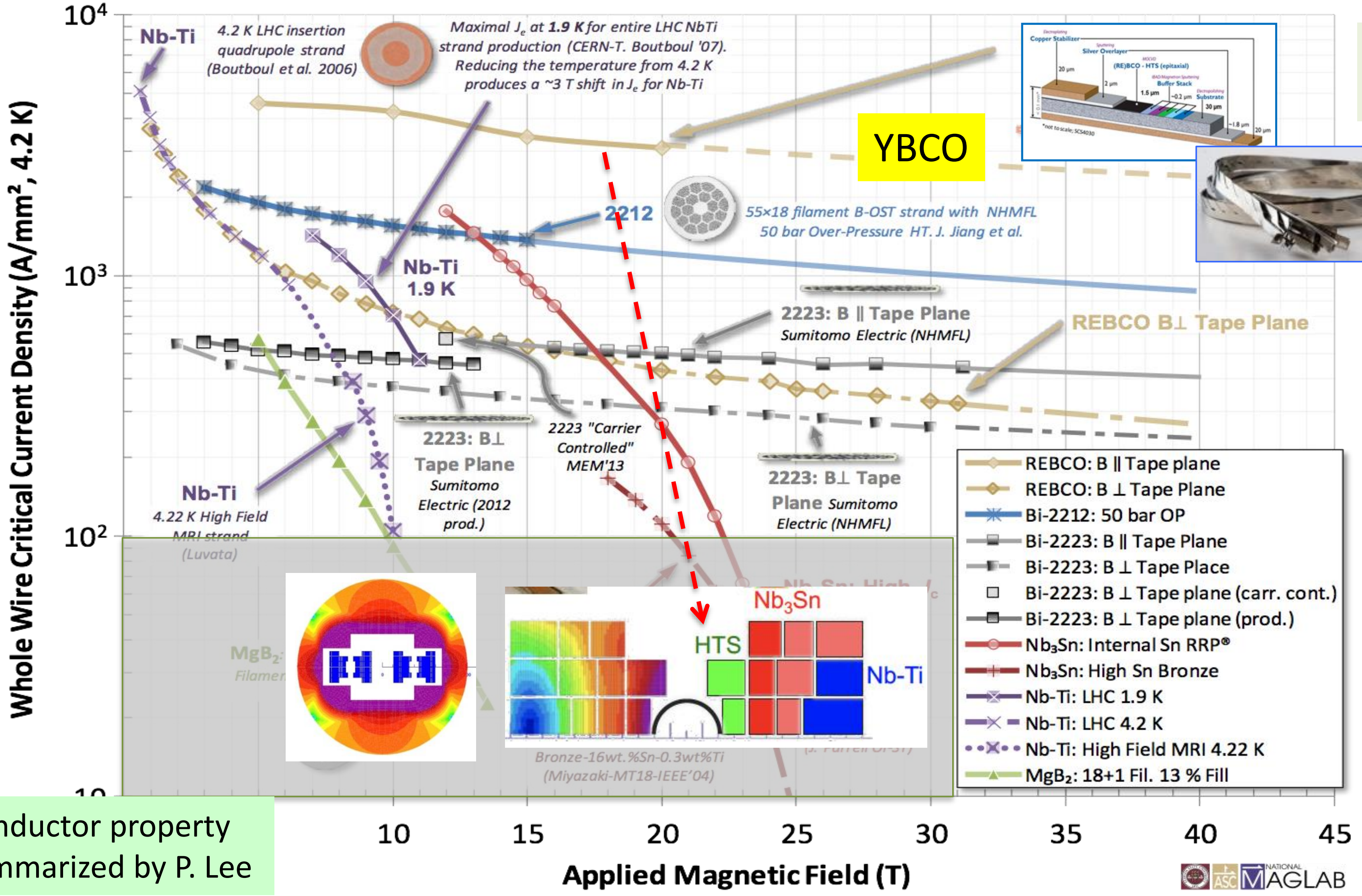


Application expected for CCT by using B2212

A. Yamamoto, 190513bb

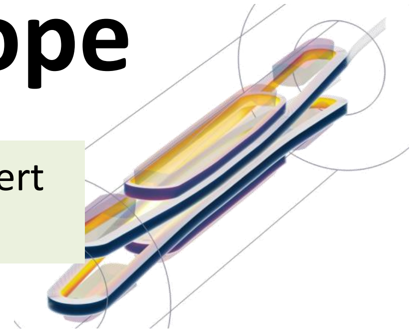
Courtesy, P. Lee, L. Rossi, G. De RIjk

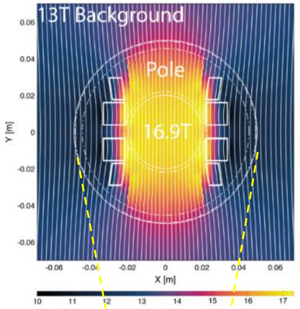
HTS/Rebco (YBCO) SC and Magnet in Europe



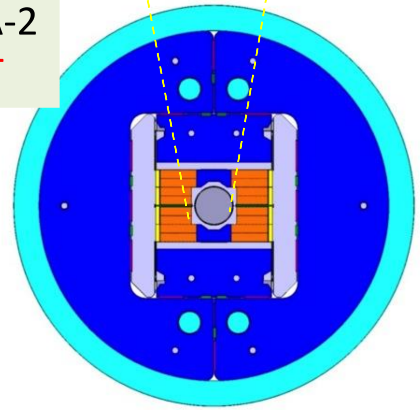
Conductor property summarized by P. Lee

HTS-Insert
3~5 T





FRESCA-2
13-14 T



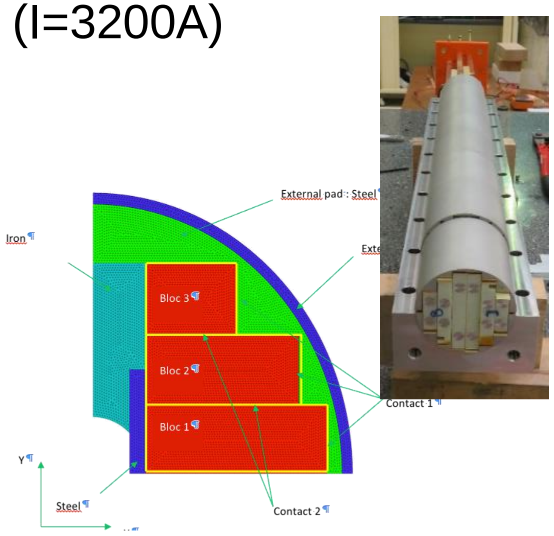
Eucard2: HTS-insert
to be tested in 2019
(3-5) + (13-14)T : > 16 T

Courtesy: G. De Rijk

Three HTS/Rebco Inserts (CERN-Europe Cooperation)

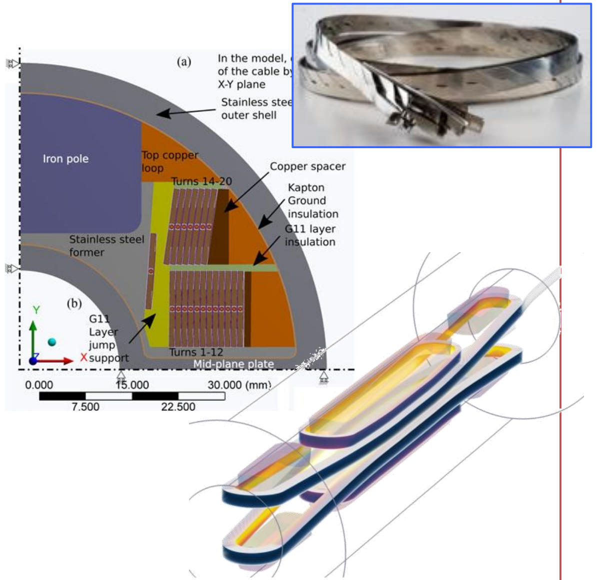
EuCARD1: insert
(CEA-CNRS-CERN),

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



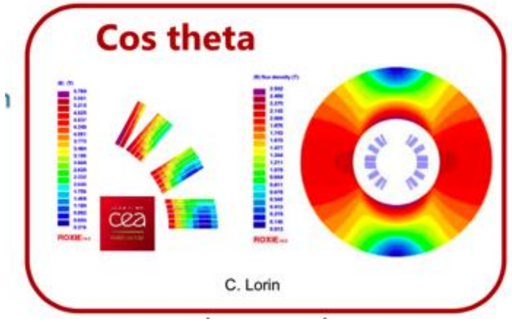
EuCARD2: Feather-M2
(CERN),

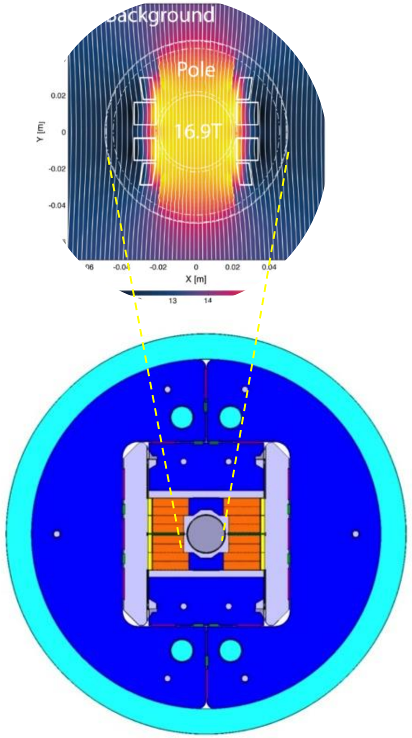
flared Ends coil
ReBCO, Roebel cable,
stand alone tested Apr 2017:
Reached 3.37 T @ 4.2K
(I=6500A)



EuCARD2: cosΘ insert
(CEA),

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



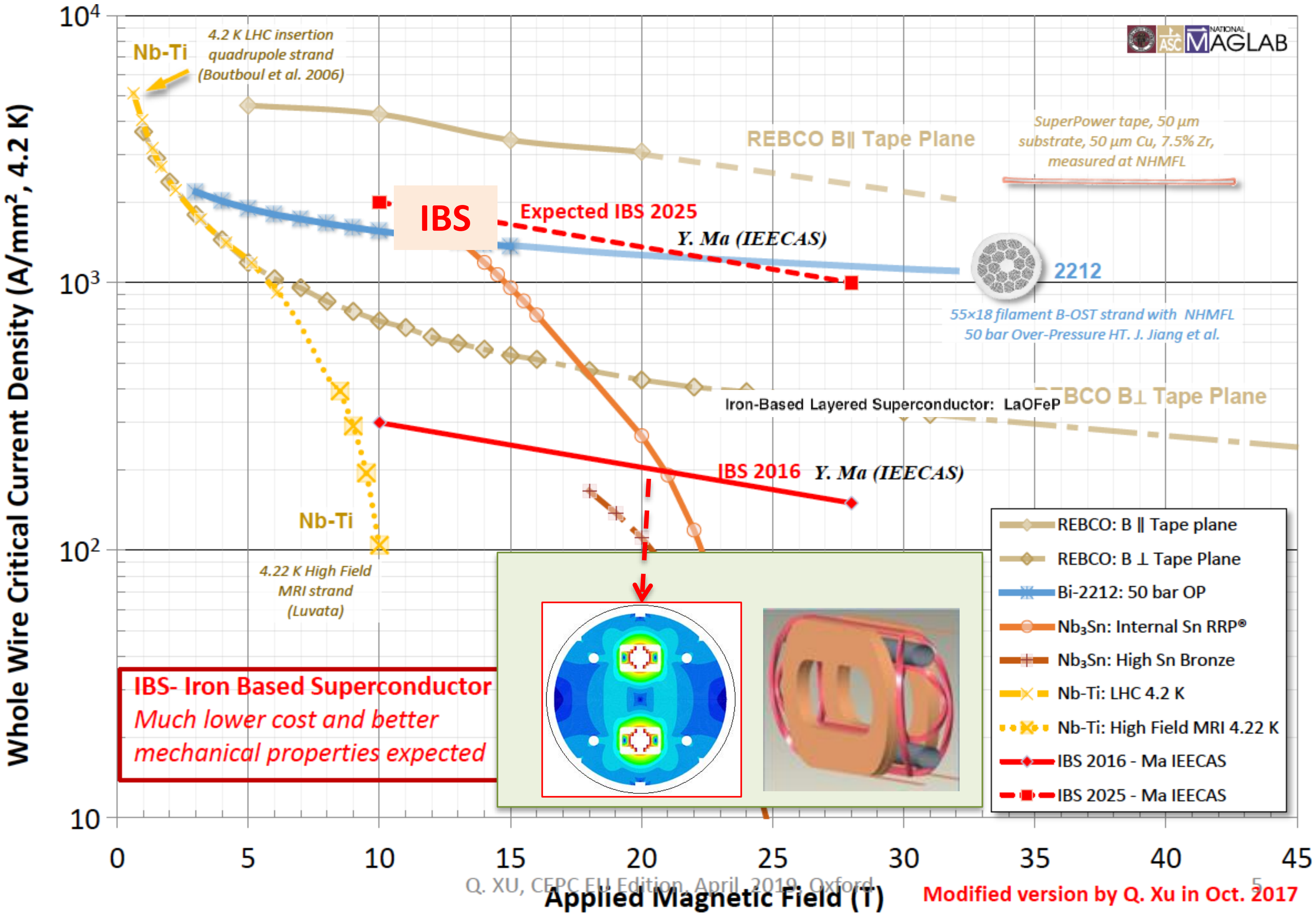


Eucard2+ HTS-insert to be tested in 2019

See more: Appendix: p. 71

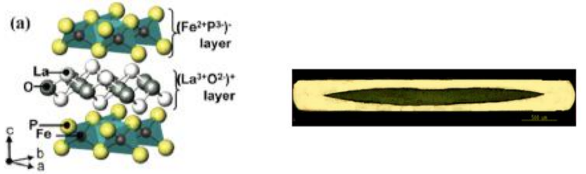
Courtesy, P. Lee, Q. Xu

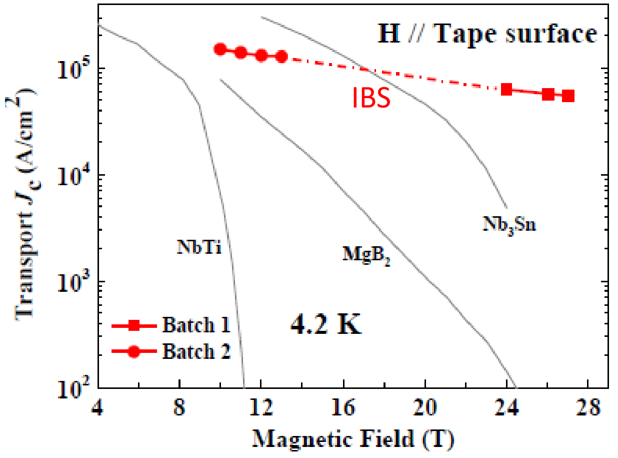
HTS/IBS SC and Magnet in China



Y. Kamihara et al., JACS Communications, Published on Web 07/15/2006

Iron-Based Layered Superconductor: LaOFeP



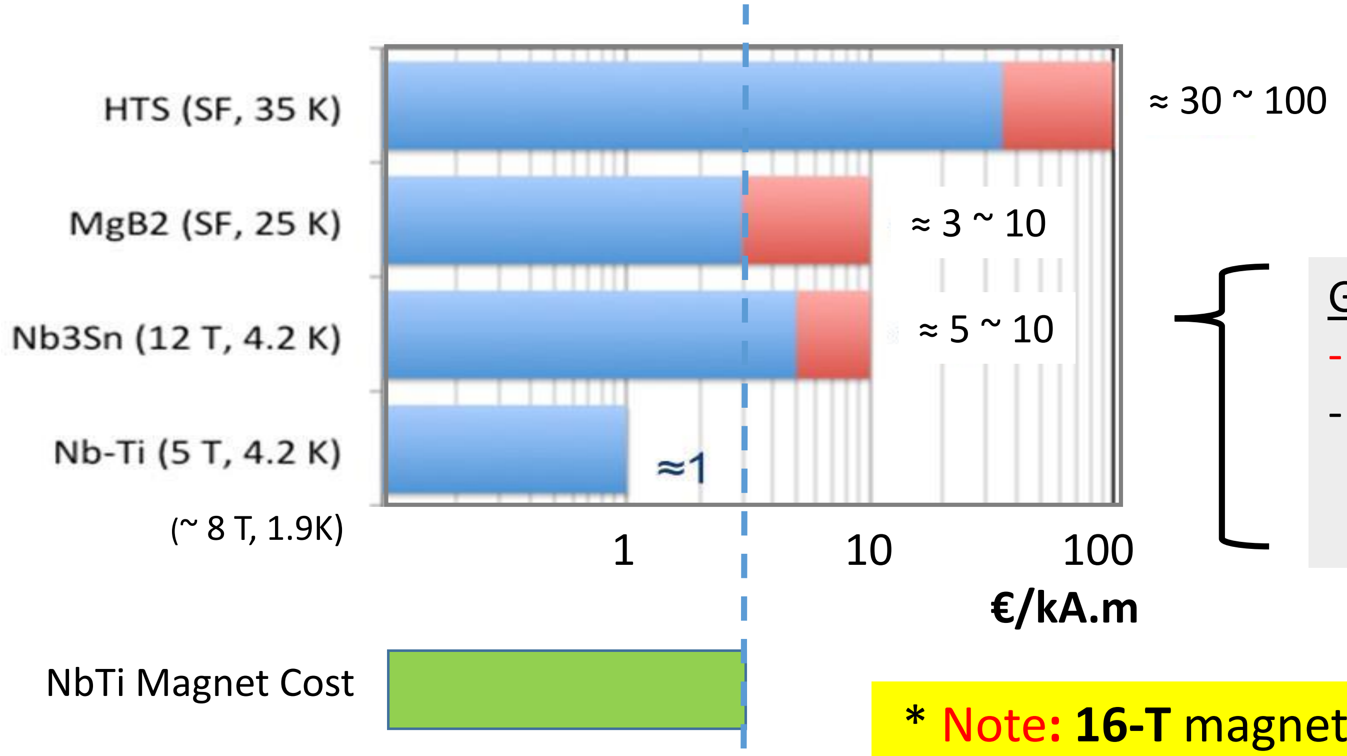


Y. Mao et al., Supercond. Sci. Technol. 31 (2018) 015017

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

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.

More in Appendix, p. 72-76.

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- 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

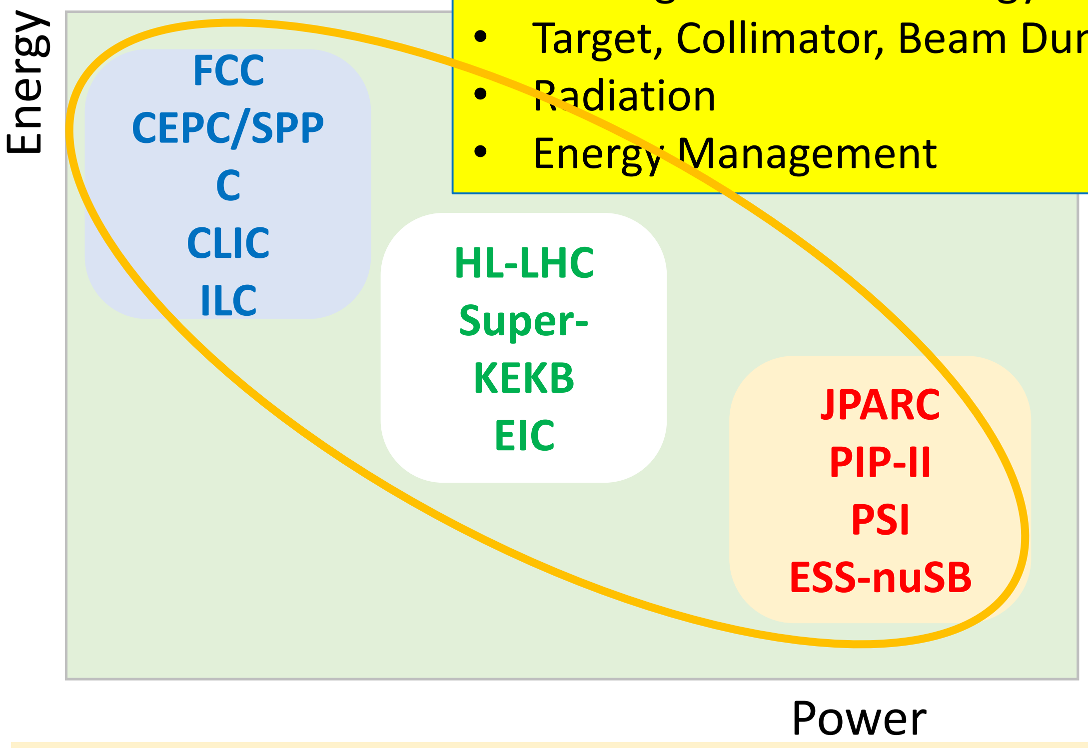
Intensity – Acc.	Energy [GeV]	Power [MW]	Acc. Tech. Feature	SC Tech.
SPS*	450		Synchrotron	
Fnal M. Injector	120	0.7	Synchrotron	
J-PARC*	3 30	1 0,49 ~ 1.3	Linac/Synchr Ext. Beam	SCM
PIP-II	60 -120	.2	Linac (SRF) Synchrotron	SRF
PSI-HIPA*	0.59	1.4	Cycrotron	
FAIR (SIS100)	29	0.2	Synchrotron	SCM
(ESS) 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

A. Yamamoto, 190513bb

* More in Appendix: p. 77-80.

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 technology,
- Let us work together and maximize synergy !!

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 (to be covered by E. Jensen in Acc. Session)
    - 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 (to be covered by V. Shiltsev)
    - Low-emittance/nano-beam,
  - Novel, accelerator scheme (to be covered by V. Shiltsev)
- **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

More in Appendix p.81 – 83.

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

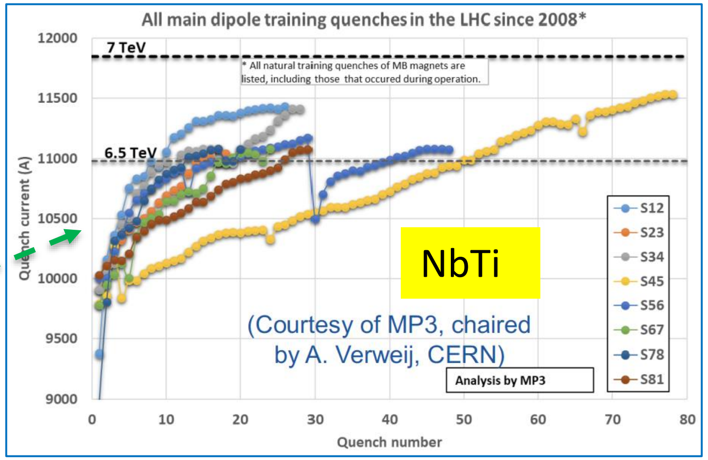
NRF and SRF:

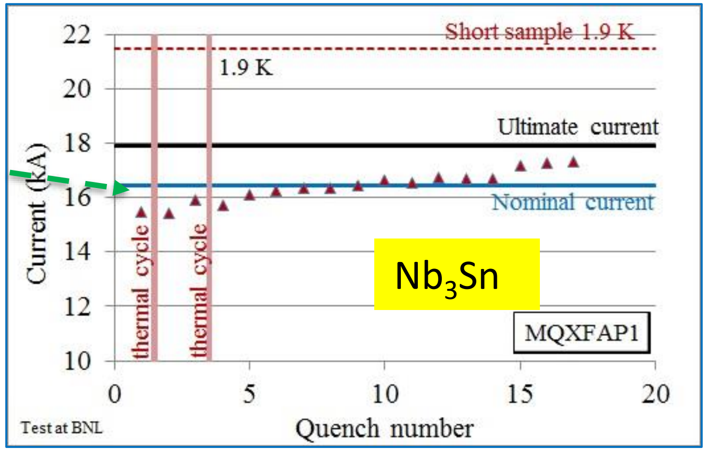
- **NRF** CLIC R&D (~ 12 GHz) : 70 ~ 100 MV/m
- **SRF** Eu-XFEL (1.3 GHz, 9-cell cavity) : 30 MV/m (+/- 20%)
- **SRF** KEK-B (Crab cavity); experienced, and CERN-SPS demonstrated

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.

General 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	Construction	Operation	Operation	Upgrade	Upgrade
NRF—LC	Proto/pre-series	Proto/pre-series / Construction	Construction	Operation	Operation	Upgrade	Upgrade
Hadron Collier (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction	Construction	Construction / Operation	Operation	Operation	Upgrade
12~14T Nb_3Sn	Short-model R&D	Short-model R&D / Proto/Pre-series	Proto/Pre-series	Construction	Construction	Operation	Operation
14~16T Nb_3Sn	Short-model R&D	Short-model R&D	Short-model R&D / Prototype/Pre-series	Prototype/Pre-series	Prototype/Pre-series	Construction	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**

Appendix

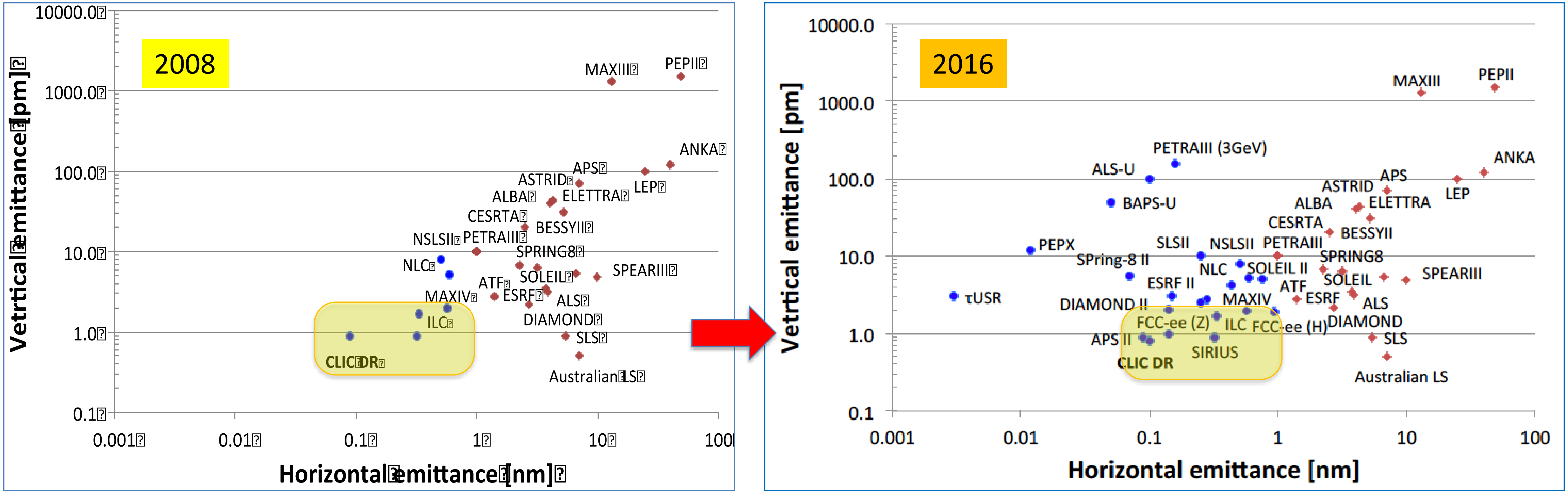
-

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

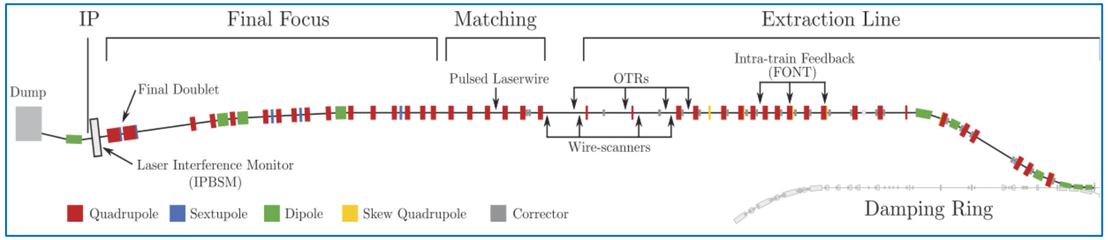
Progress in FF Beam Size and Stability at ATF2

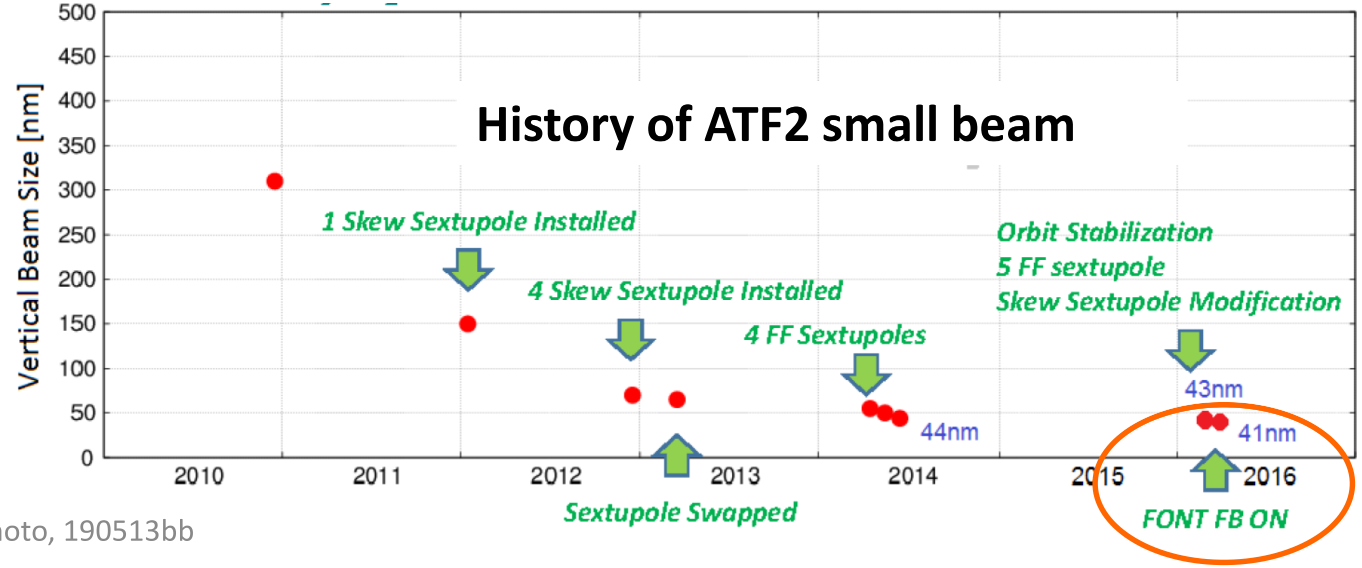
Goal 1: Establish the FF method with same optics and comparable beamline tolerances

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

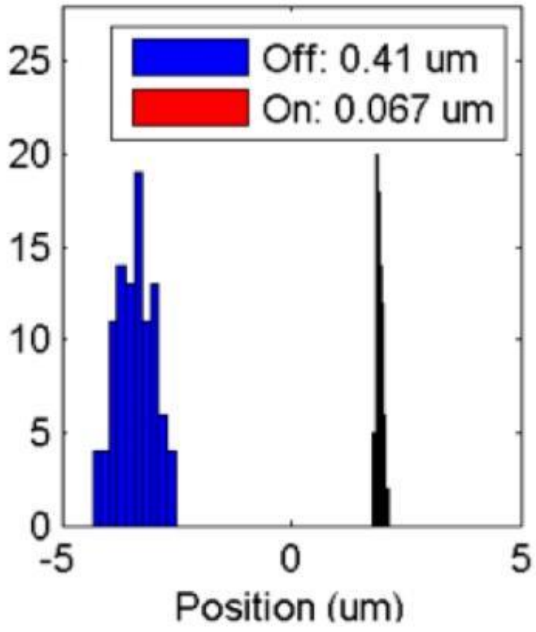
Goal 2: Develop nm position stabilization at FF:

- **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

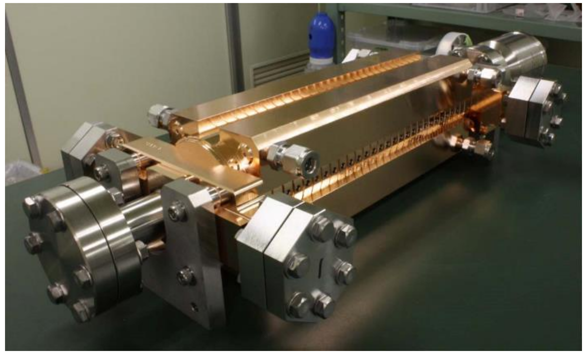


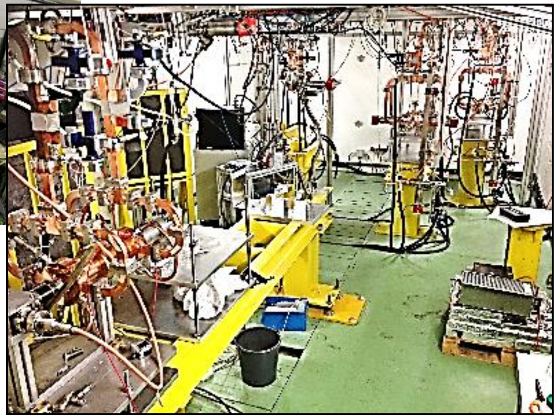
A. Yamamoto, 190513bb

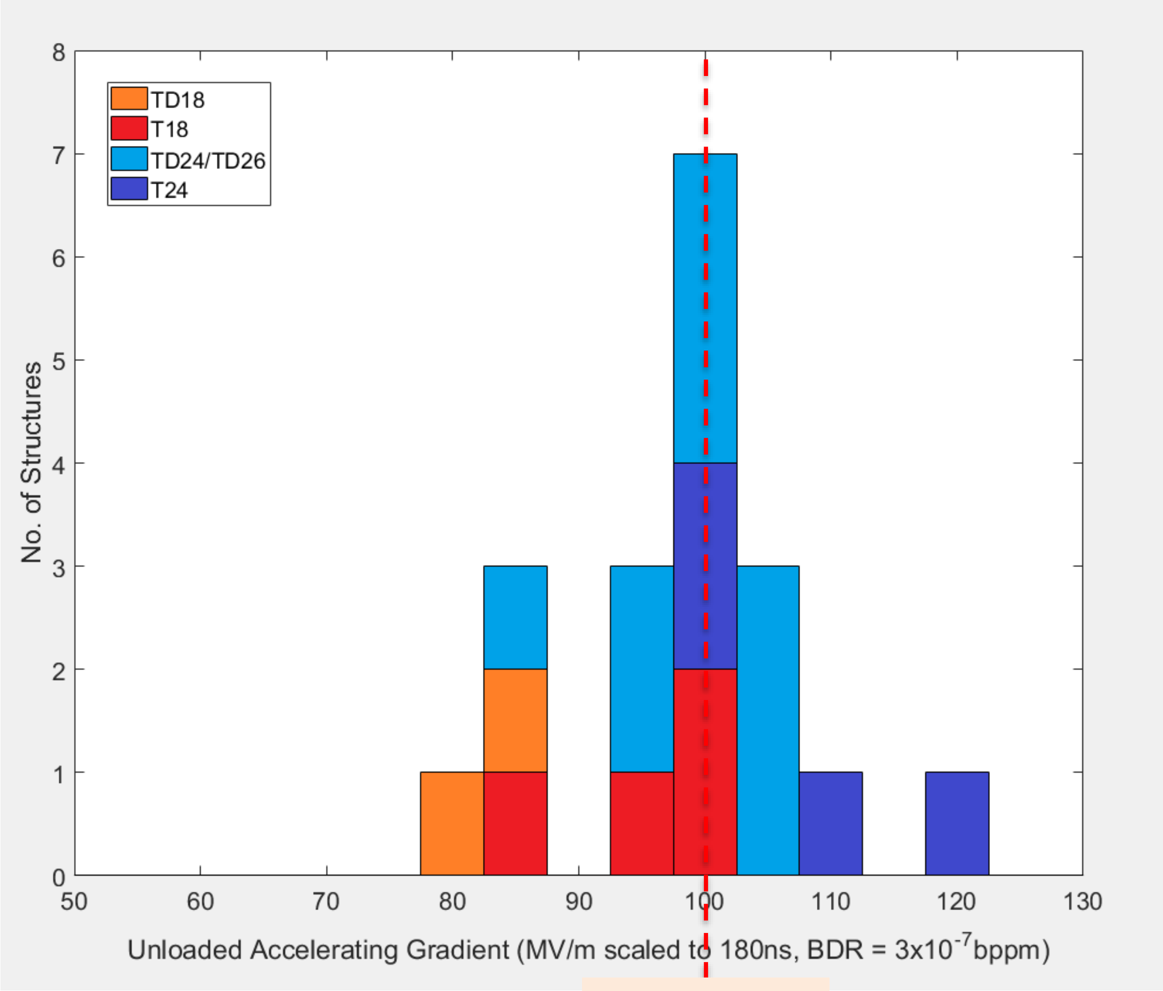
Curtesy: S. Stapnes, P. Barlow, W. Wuensch

Progress in Normal Conducting RF Acc. Structure

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



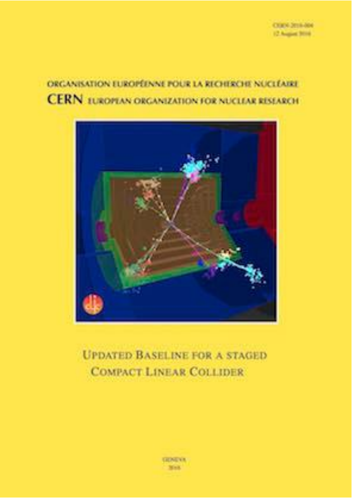


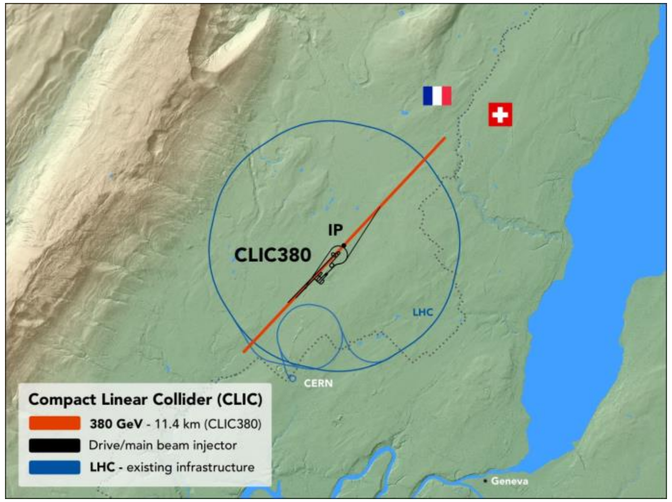


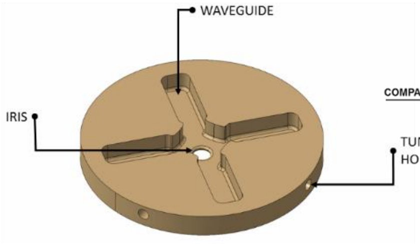
100 MV/m

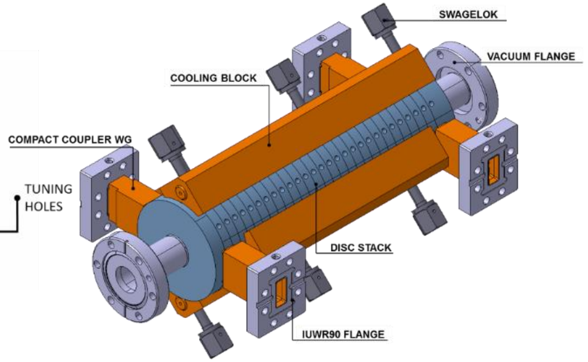
Curtesy: S. Stapnes, P. Barlow, W. Wuensch

NRF Technology for CLIC-380 and beyond









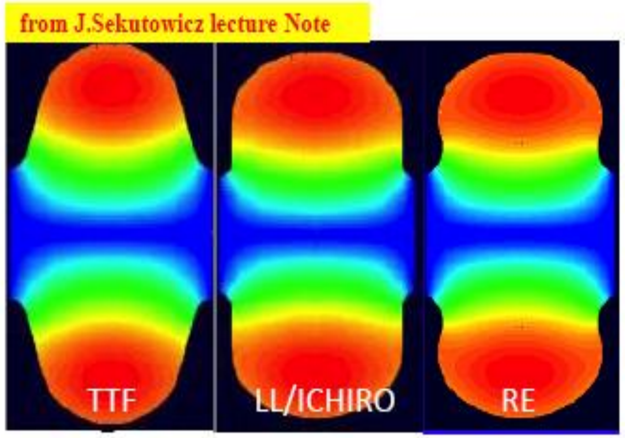
- Linear e^+e^- collider, staged **$\sqrt{s}$ = 0.38 TeV**
- **70 MV/m** accelerating gradient needed for compact (~11 km) machine based on :
  - normal-conducting accelerating structures
  - two-beam acceleration scheme
- **Issue remaining:**
  - Power efficiency at higher energies
  - Large scale production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

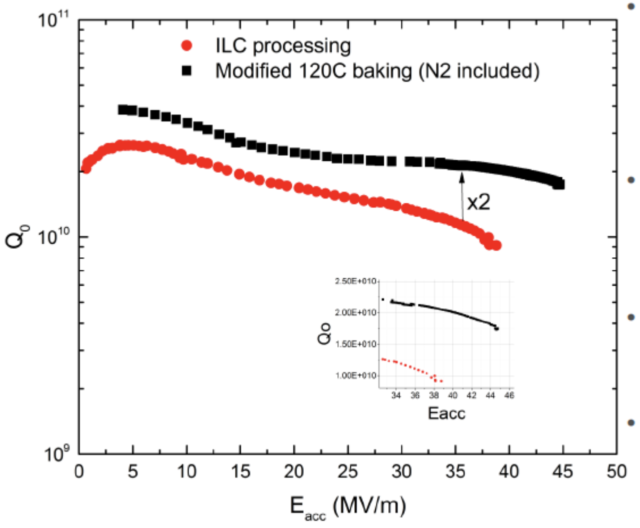


Shape	TTF	LL/Ichiro	RE	LSF
D-iris [mm]	70	60	60	60
Ep/Eacc	1.98	2.36	2.28	1.98
Hp/Eacc [Oe/MV/m]	41.5	36.1	35.4	37.1
G*R/Q [Ω^2]	30840	37970	41208	36995
Eacc-max [MV/m]	42.0	48.5	49.4	47.2

Coutesy: A. Agrassellino
Summarized in Fermilab WS, 190508

N-Infusion and New 75/120C Finding

Cavity performance progress at FNAL: "standard" vs "N infused" cavity surface treatment



Increase in Q by > a factor of two
Increase in gradient ~15%

- FNAL has demonstrated in 2017 a new treatment, which utilizes "nitrogen infusion", achieving
  45.6 MV/m → 194 mT
  with Q ~ 2x10[10]
- The idea is to nano-engineer the surface with a nitrogen enriched layer of some optimal depth (5-100nm)
- Jlab, has reproduced similar results on single cell cavities with Q >2e10 at 35 MV/m
- R&D work towards:
  - Best recipe for higher Q at high gradient
  - Robustness of process

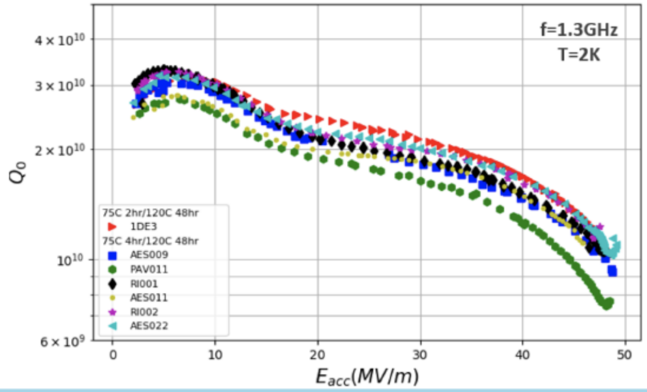
A Grassellino *et al* 2017 *Supercond. Sci. Technol.* **30** 094004

Fermilab

5/12/19 Grassellino - ILC Accelerator R&D

The new 75/120C findings - reproducibility

- We have recently focused our attention to the unexpected finding that a pre-120C bake step of ~4 hours at 75C seem to lead consistently to unprecedented accelerating gradients ~50 MV/m (220 mT, TESLA shape)
- However, under the ILC cost reduction effort, as we study more and more cavities, and exchange cavities worldwide, some new interesting findings are emerging in terms of Q and achievable accelerating gradient cooldown dependence



75/120C bake cavities

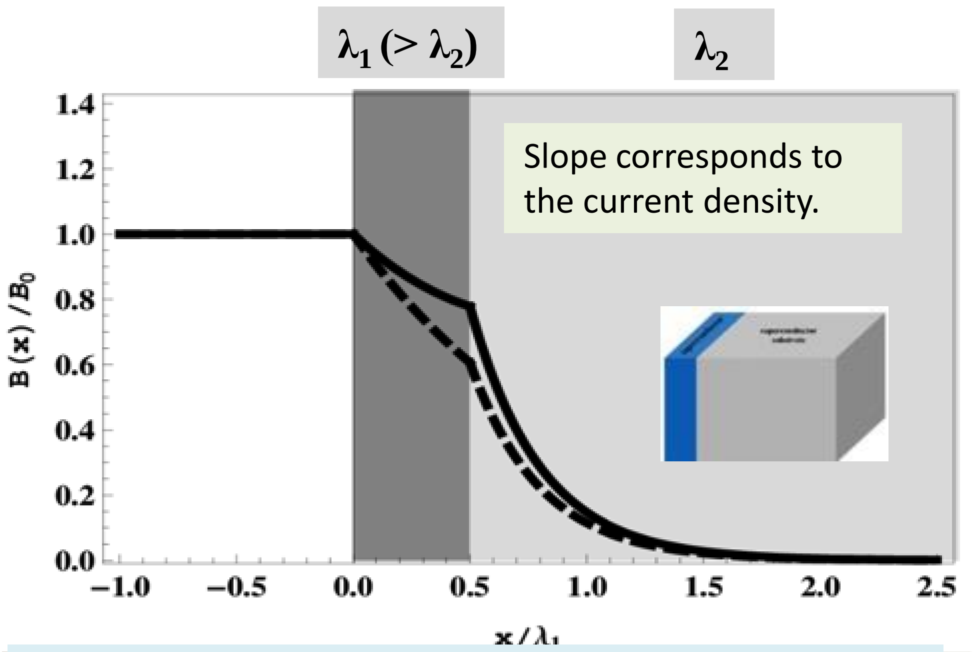
See Grassellino et al arXiv:1806.09824

Fermilab

Grassellino - ILC Accelerator R&D 5/12/19

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.



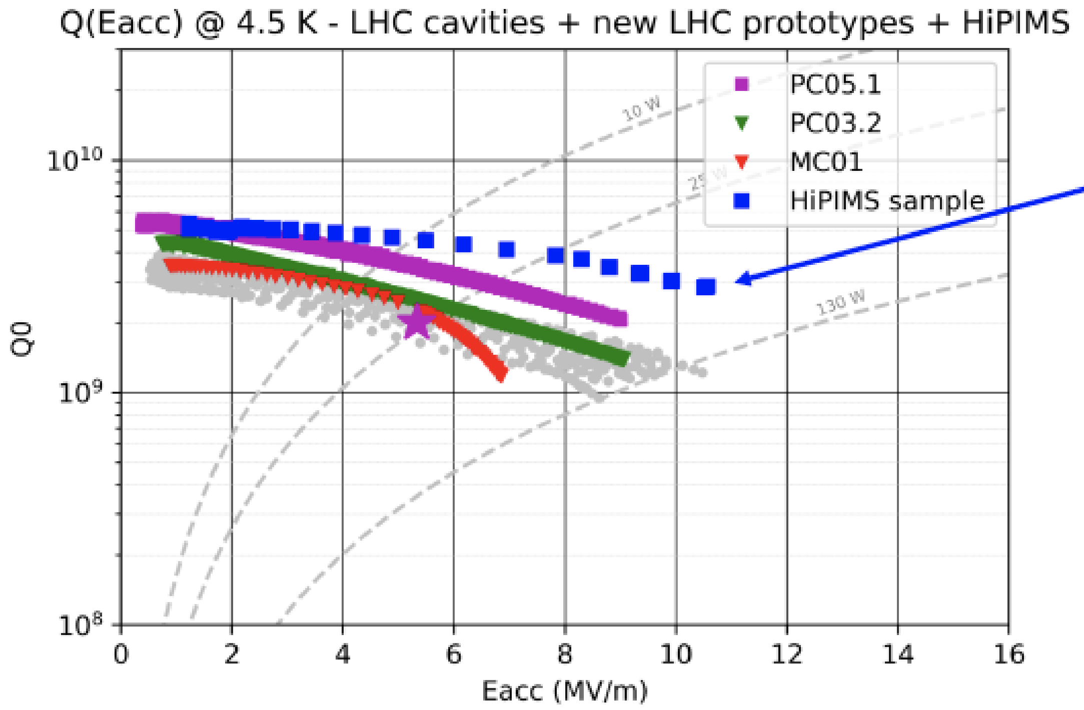
Surface current is suppressed:

- 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)

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, F. Peauger, M. Arzeo

25.04.20

- Film crystalline structure has an impact on the "slope"
- Directions for future research lines (FCC 400 MHz):

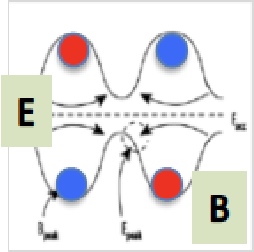
Courtesy: A. Grassellino, S. Posen

Progress in Nb_3Sn-Coating Research

reported at TTC meeting, Feb, Vancouver, and updated at Workshop at Fermilab, May, 2019

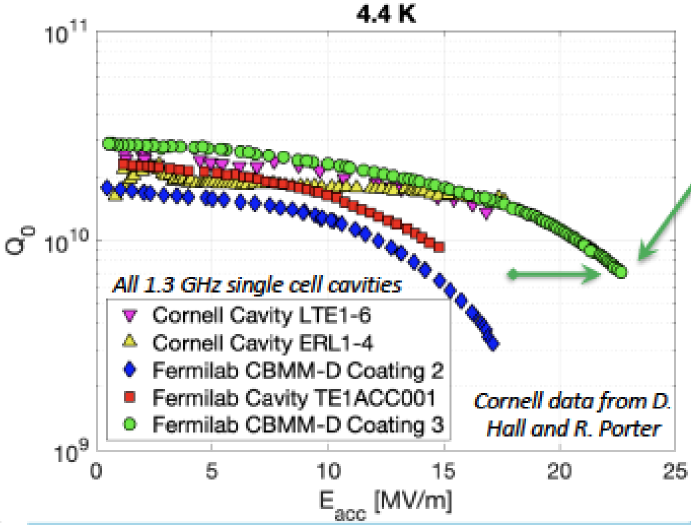
B_{sh} = practical limit for SRF

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



New Progress in Maximum Accelerating Gradient of Nb_3Sn Cavities

- Nb_3Sn accelerator cavities have been limited consistently to CW accelerating gradients of 17-18 MV/m for ~20 years, though theoretical predictions indicate ultimate limit is far higher
- New Fermilab result: **22.5 MV/m (~25% improvement)**
- New result proves that Nb_3Sn had not reached an intrinsic limit
- Current performance promising for high duty factor or compact accelerators

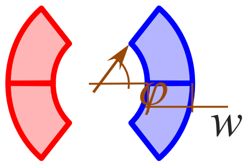


World record CW gradient for Nb_3Sn accelerator cavities - higher by 4 MV/m (~25% increase)

Research supported by S. Posen Early Career Award

Fermilab

32 8/12/18 Sam Posen



Nb_3Sn conductor program

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

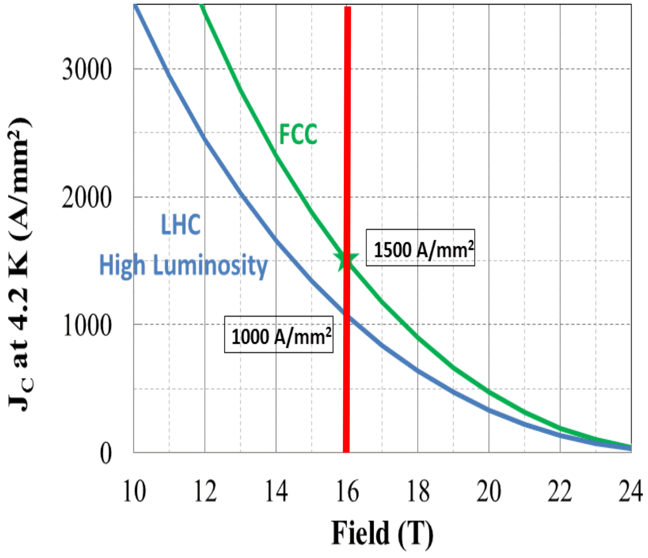
$$B = \frac{2\mu_0}{\pi} J w \sin(\phi)$$

Main development goals:

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

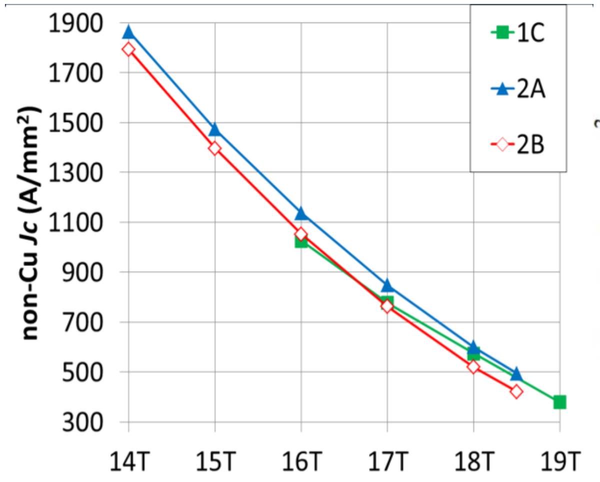
Global cooperation:

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



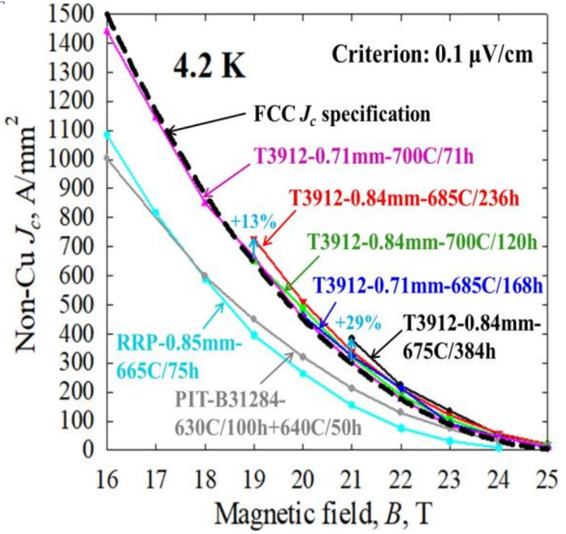
Requirement (FCC)

Non-Cu
J_c : 1,137 A/mm² @16T



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

Non-Cu
J_c : ~ 1,450 A/mm² @16T

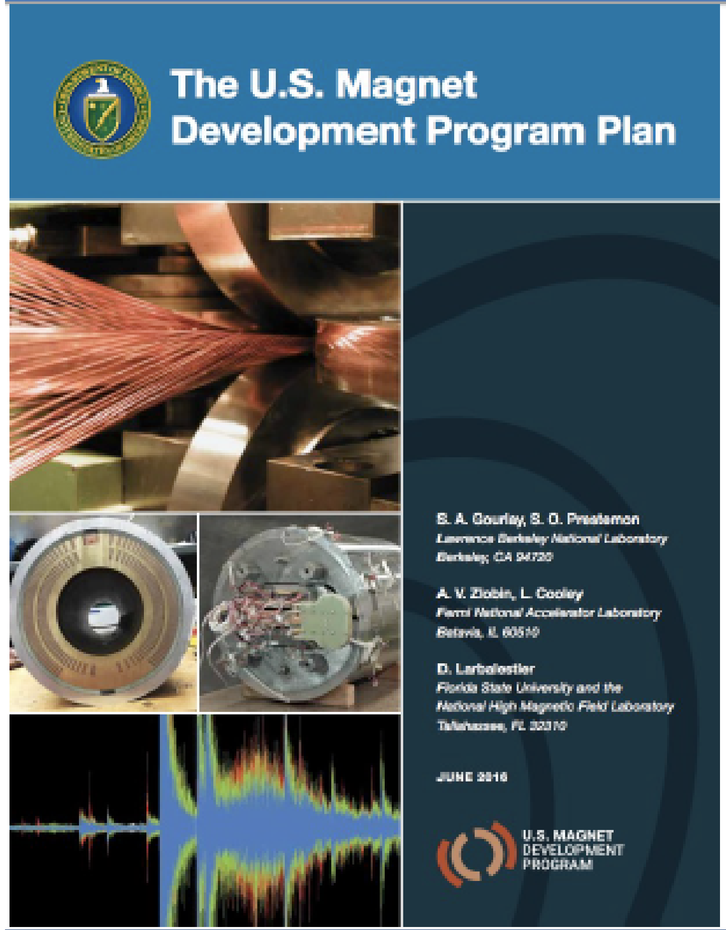


Artificial Pinning Center (APC) approach:
X. Xu et al (Fermilab)

https://arxiv.org/abs/1903.08121

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.

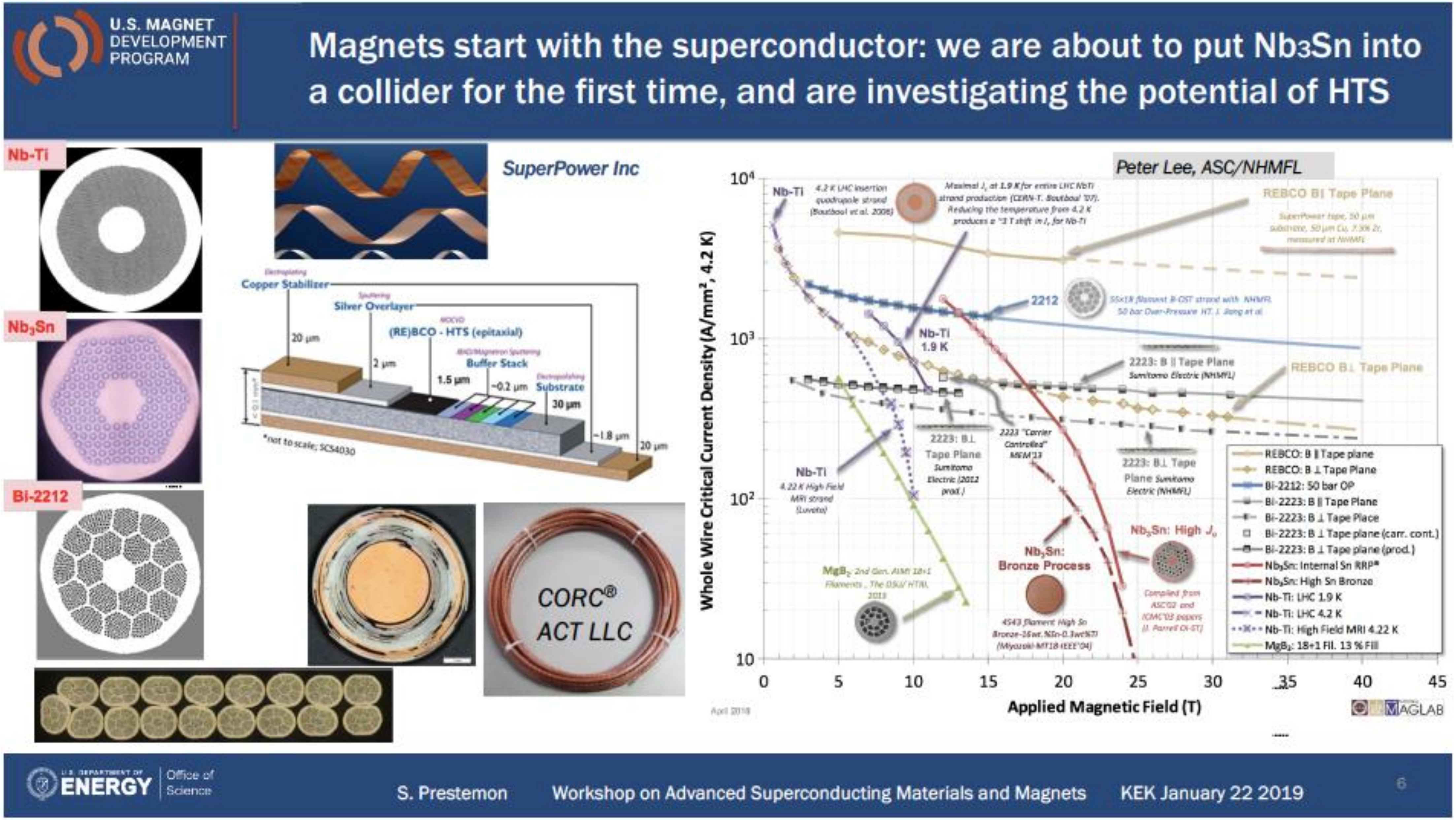
GOAL 4:

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



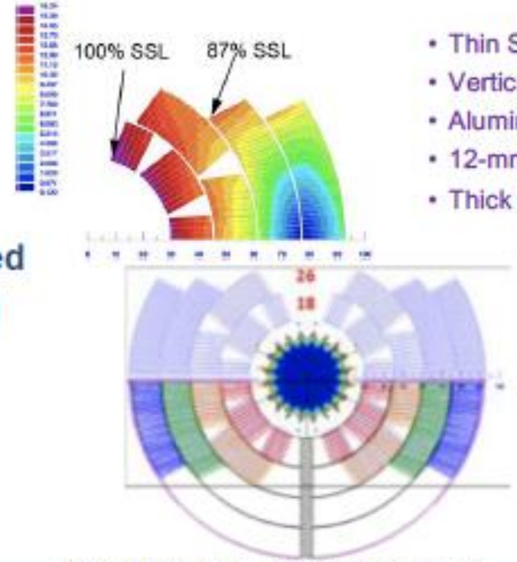
Courtesy: S. Prestemon

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

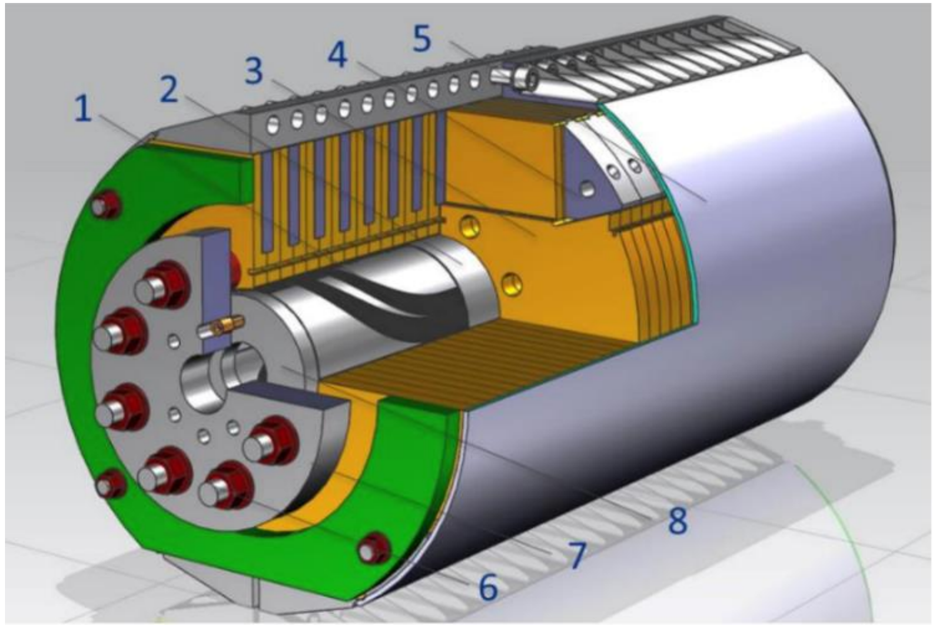


60-mm aperture, 4-layer graded coil

Courtesy: S. Belomstnykh

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

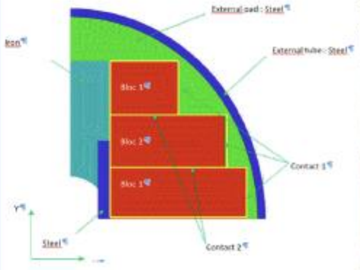
- The **15 T** dipole demonstrator magnet assembly is finished
- The dipole is in being prepared for the first test expected to start in May, 2019

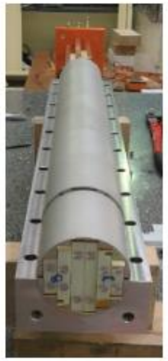


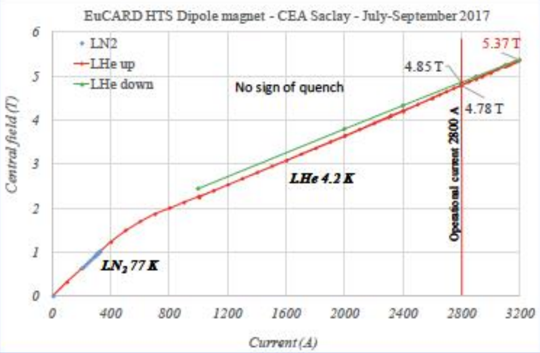
Courtesy: G. de Rick

Three HTS inserts (CERN and collaborations)

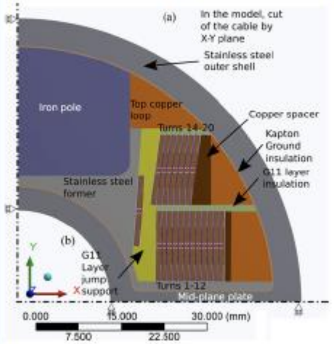
EuCARD1: insert (CEA-CNRS-CERN), flat racetrack, ReBCO 4 tape stack cable,stand alone tested Sept 2017: Reached 5.37 T @ 4.2K (I=3200A)

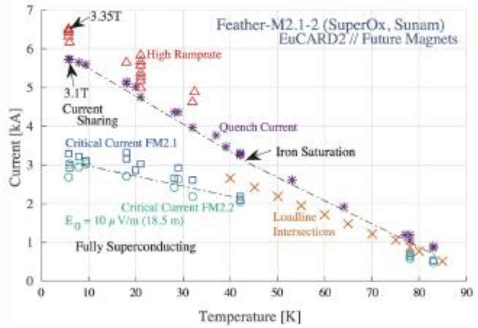




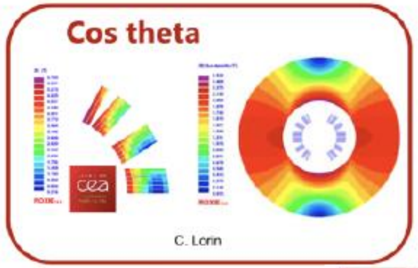


EuCARD2: Feather-M2 (CERN), flared ends coil ReBCO, Roebel cable, First magnet (low perf tape), stand alone tested Apr 2017: Reached 3.37 T @ 4.2K (I=6500A)





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



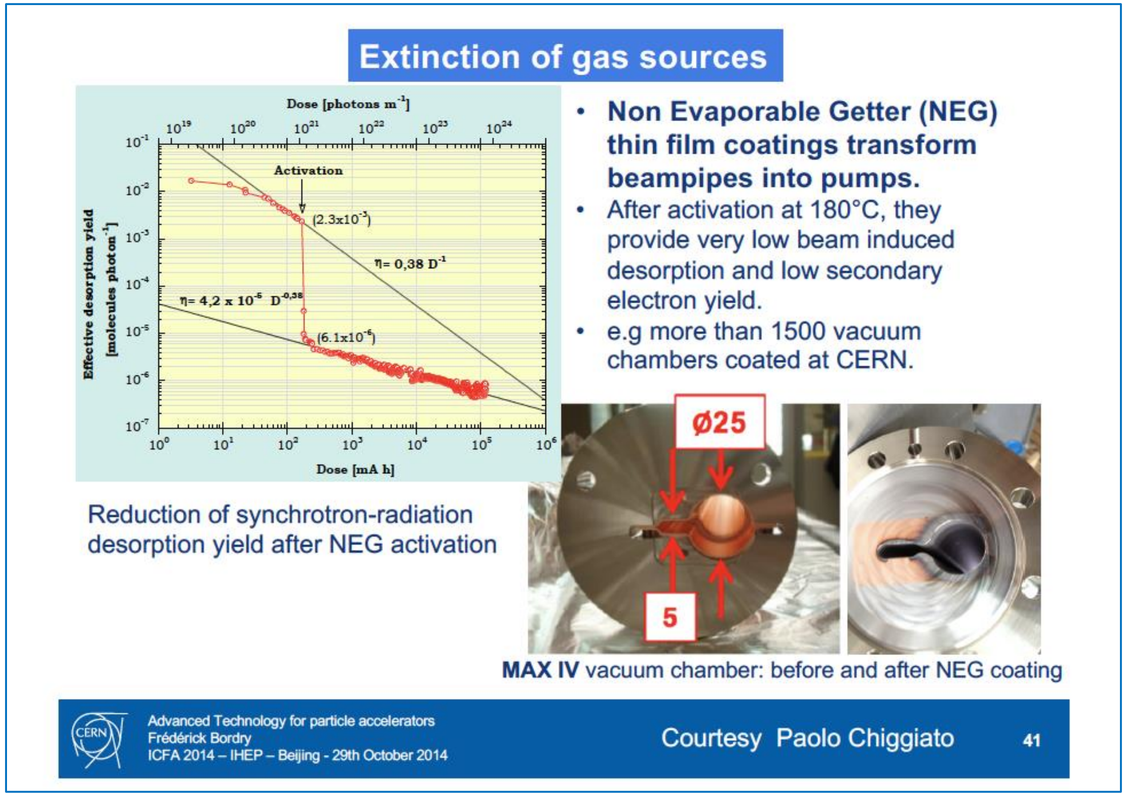
Design parameters (**SuperPower** Cable)

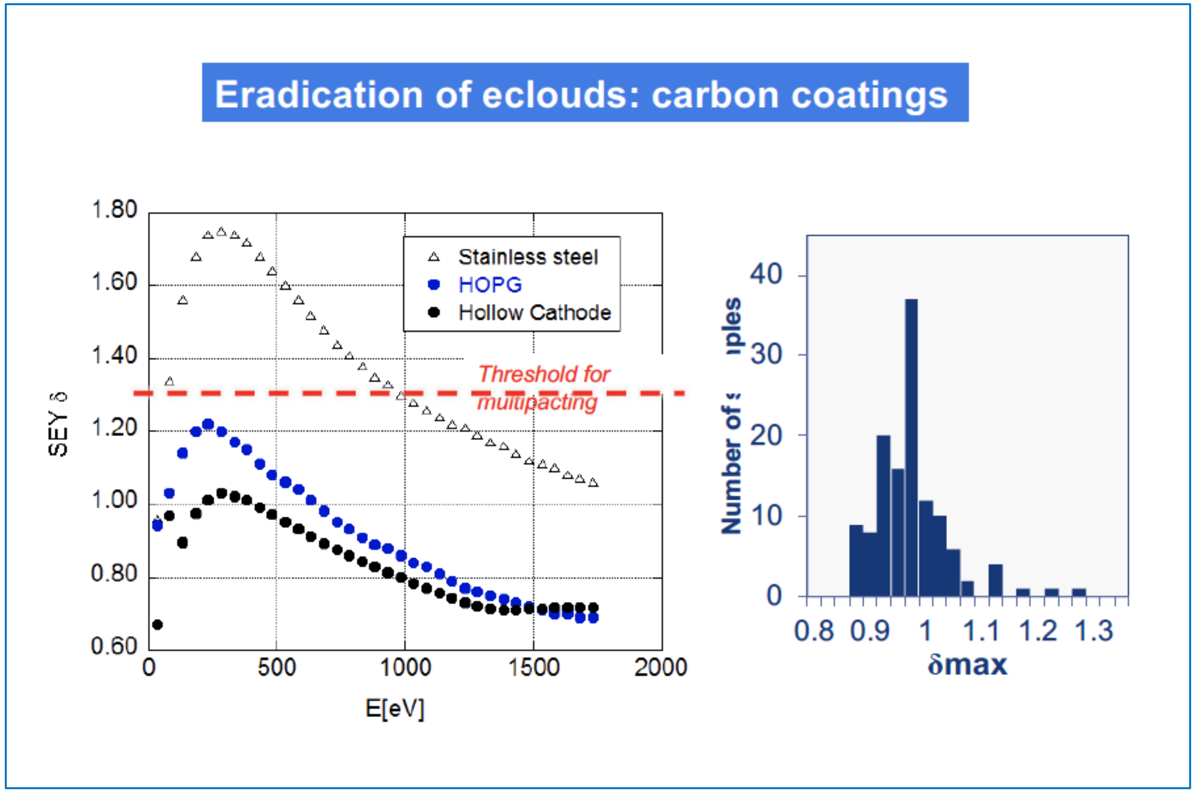
Layout	Unit	Cosθ B
Iop	kA	10.06
Bop	T	5
Bpeak	T	5.8
Ic	kA	15.2
LL margin	(%)	34
T margin	K	30
Sd. inductance	mH/m	0.73
coil inner radius	mm	24
yoke inner radius	mm	50
yoke outer radius	mm	110
Nb. of turns	-	17
Unit len. of cond.	m	24

R&D on HFM, GdR

Courtesy: F. Bordry

Vacuum





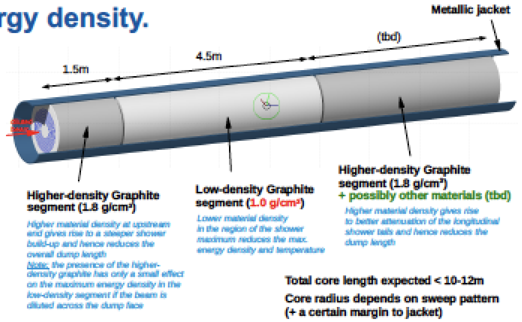
Courtesy: S. Gilardoni

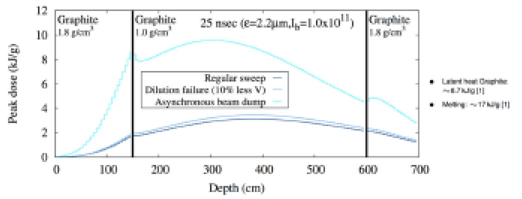
Beam Dump & Collimators for FCC-hh

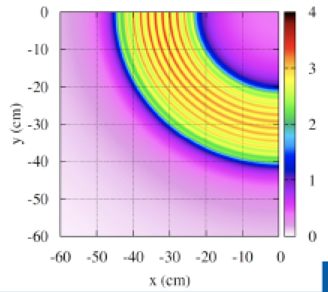
More in Anton's presentation

FCC-hh dump concept (LHC-like Graphite dump)

- **Beam sweeping à-la LHC to reduce energy density.**
- ANSYS calculations progressing on this conceptual design.
- Failure scenarios under consideration like sweep change due to dilution kicker failure or asynchronous beam dump







Material development:

- Working together with companies to investigate low density graphite thermomechanical properties
- Exploring alternatives for less traditional material

FCC hh ee he

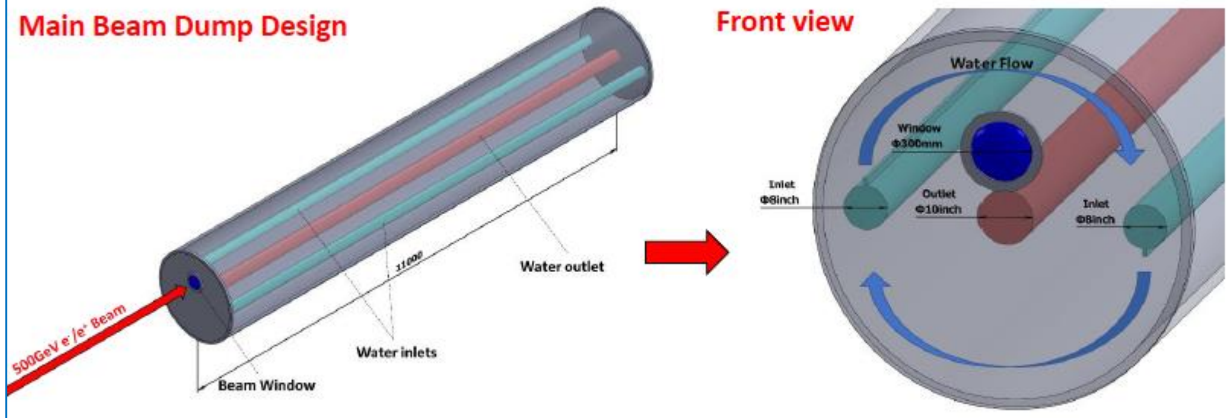
Collimator: future proposals

- Higher diffusing absorber material, to enhance the cooling transfer to the Cu-Ni circuit
  - Use of ceramic-graphite composites, such as Molybdenum-Graphite or Titanium-Graphite
- Lighter absorber
  - Minimise the energy density on the jaw (low density carbon foams)
- More rigid housing and stiffener
- Higher water flow in the cooling pipes
- Jaws Monitoring/possibly deformation-correcting, systems.
  - project launched CERN/University of Huddersfield

FCC hh ee he

ILC (CLIC) Beam Dump Concept

Main Beam Dump Design — **Front view**



【Beam Power @ 1TeV Beam operation】

- 500GeV × 2.79nC × 2450Bunches × 4pulses/sec : **13.7MW** + **20% safety margin** ≒ **17MW**

【Base Design】

- **Water power absorber** and **forced convection** to extract the heat.
  - * Water is compressed **1 MPa** ⇒ **boiling temp 180℃**
  - * Vortex water flow ⇒ Mass flow rate : **104.5kg/s** each inlet, flow velocity **2.17m/s**
- **1mm thick** Beam Window made of **Ti-6Al-4V**.

2017/10/25 　＊Base design of ILC Main Beam Dump : P. Satyamurthy, et.al., NIM A 679 (2012)

Beam dump parameters

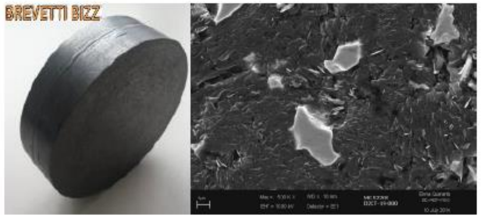
	TDR		250 GeV ILC
Center of mass energy (GeV)	500	1,000 (for future upgrade)	250
Beam energy(GeV)	250	500	125
Repetition (Hz)	5	4	5
Number of bunches	1312	2450	1312
Bunch interval (nsec)	554	366	554
Pulse width (msec)	0.727	0.897	0.727
Number of charges	$2x10^{10}$ (3.2nC)	$1.74x10^{10}$ (2.79nC)	$2x10^{10}$ (3.2nC)
Charges per pulse (μC)	4.20	6.83	4.20
Pulse current (mA)	5.78	7.61	5.78
Pulse energy (MJ)	1.05	3.41	0.53
Average power(MW)	5.25	13.7	2.63
Design：20% margin →		**17 MW**	20%

Courtesy: F. Bordry

Radiation Hardness

Material Challenges in Future Accelerators

- **Future machines** are set to reach unprecedented **Energy** and **Energy Density**.
- No existing material can meet extreme requirements for Beam Interacting Devices (Collimators, Absorbers, Windows …) as to **robustness** and **performance**.
- New materials are being developed to face such extreme challenges, namely **Metal-** and **Ceramic-Matrix Composites** with **Diamond** or **Graphite** reinforcements.
- **Molybdenum Carbide - Graphite** composite (**MoGr**) is the most promising candidate material with outstanding thermo-physical properties.

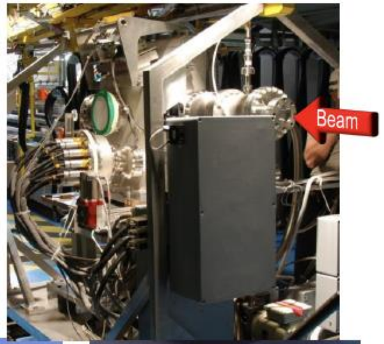


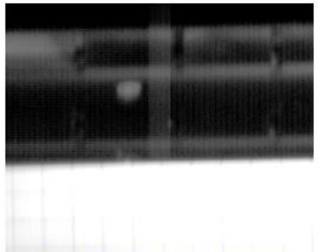
MoGr Key Properties	
Density [g/cm³]	2.5
Melting Point T_m [°C]	~2500
CTE [10^{-6} K^{-1}]	~1
Thermal Conductivity [W/mK]	770
Electrical Conductivity [MS/m]	~1

- Understanding of **unexplored conditions** call for state-of-the-art numerical simulations completemented by advanced tests in dedicated facilities

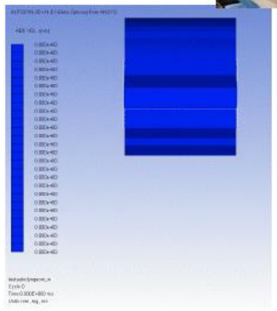
e.g. HiRadMat Experiments

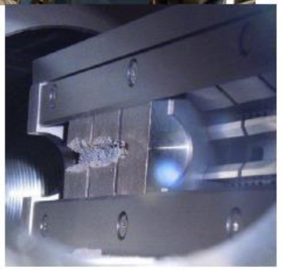
- Test of complete devices and materials under extreme beam impact conditions with comprehensive acquisition systems.
- Benchmark of experimental measurements with results of state-of-the-art numerical codes





HiRadMat (CERN): 72x SPS bunches against W targets, real time acquisition compared to simulation





Tungsten target, impact of 72x SPS bunches

Courtesy: N. Saito

RaDIATE

Radiation Damage In Accelerator Target Environments

radiate.fnal.gov

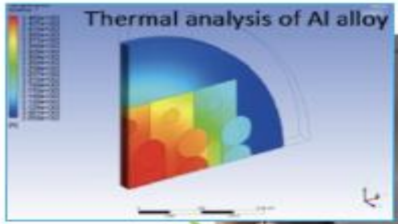
- High Intensity Accelerator requires investigation of radiation damage of target and beam window
- RaDIATE: an internat'l collab. of scientists and engineers from acc. and reactor facilities to solve the problems
- J-PARC has joined the team since 2014. MOU is in preparation

Neutrino Beam Window
Ti Alloy ~1x10^{21} pot
~1 Displacement Per Atom
(Existing data up to ~0.3DPA)

Fermilab | University of Oxford | Science & Technology Facilities Council | Brookhaven National Laboratory | Pacific Northwest National Laboratory | Los Alamos National Laboratory | FRIB | European Spallation Source | Oak Ridge National Laboratory | Ciemat | Argonne National Laboratory | CERN

2016~…(予定)

17



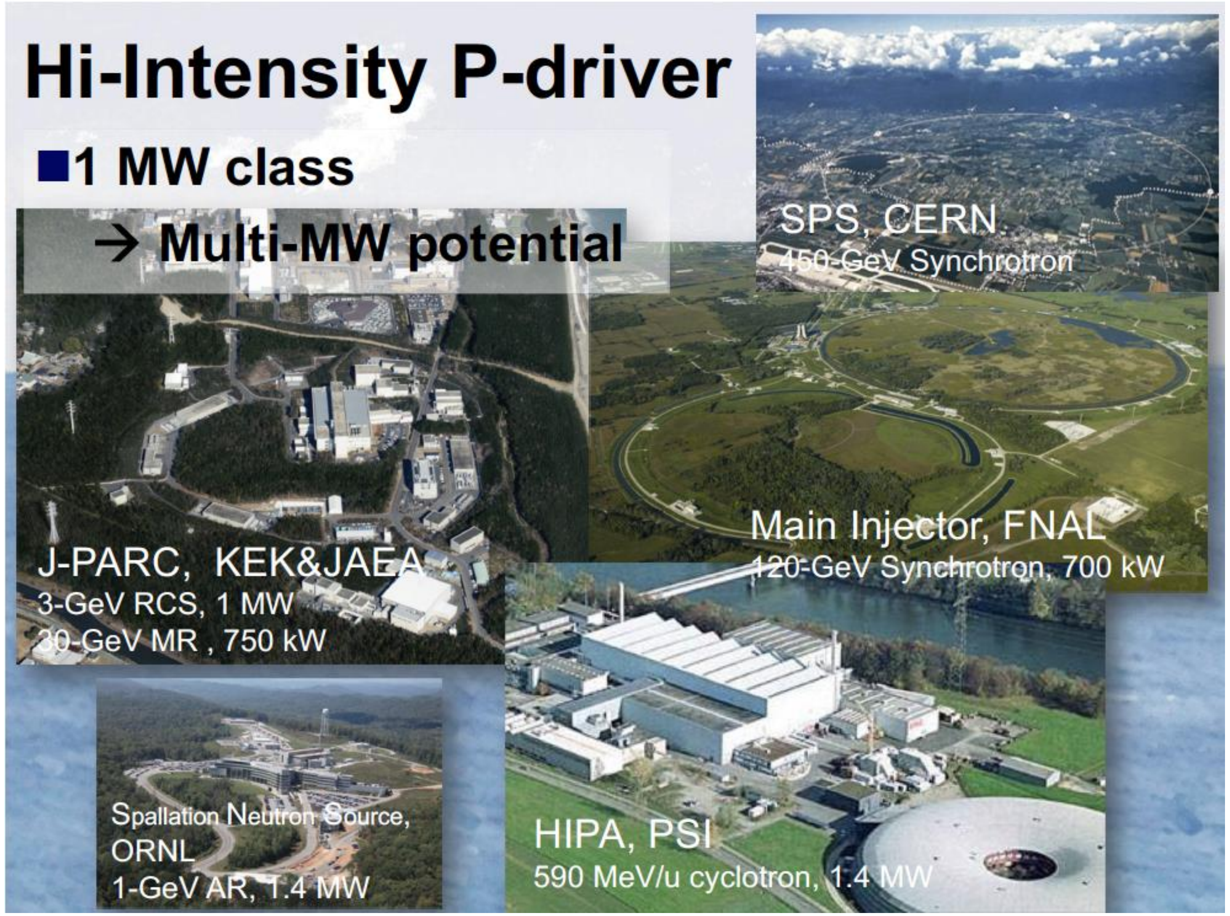
NuMI graphite broken target
Post-Irradiation Examination (PIE)
at PNNL: Swelling effect observed

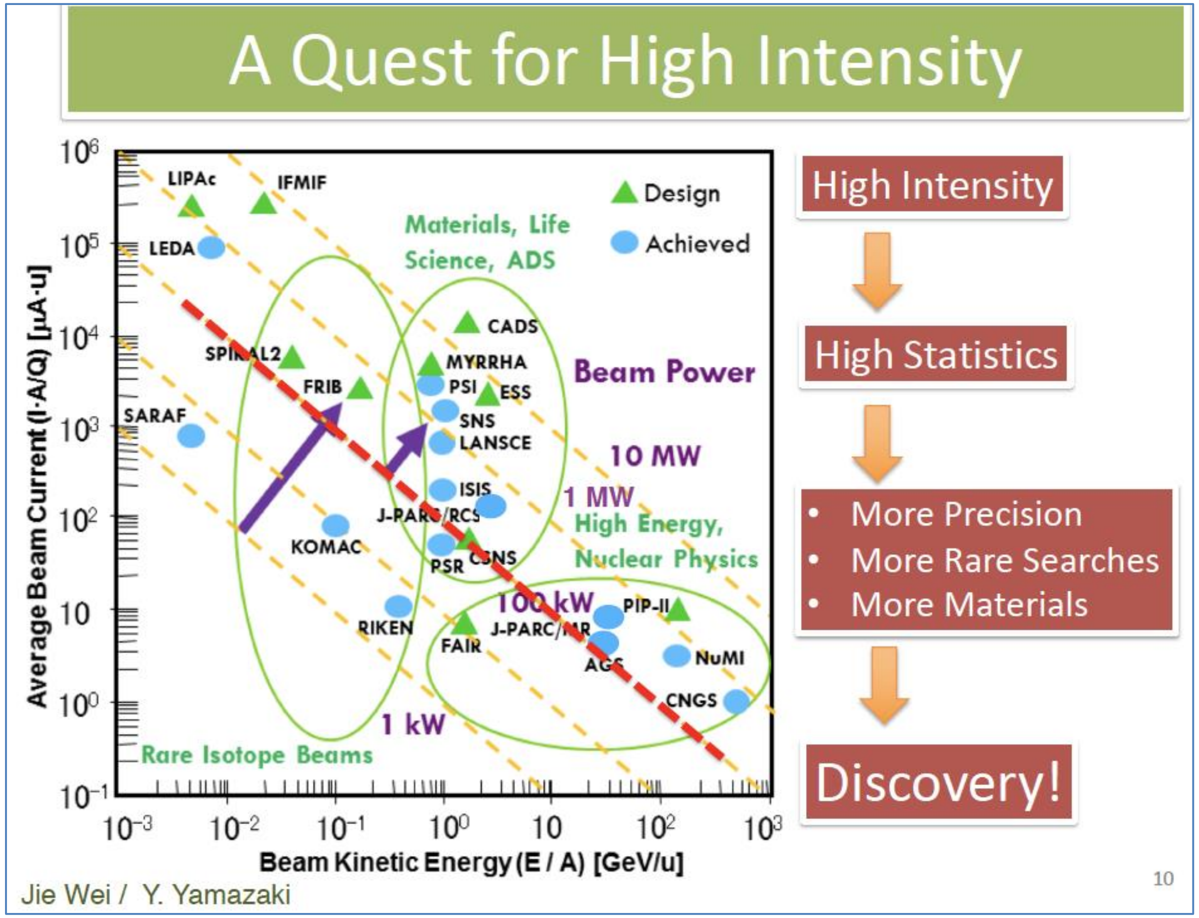
MIRAI Consortium

New Irradiation Run at BNL (2017 February ~)

Courtesy: N. Saito

Intensity Frontier Accelerators

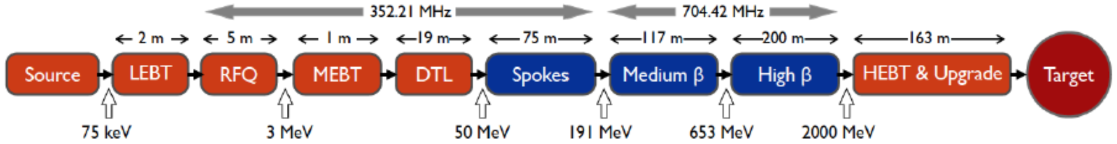




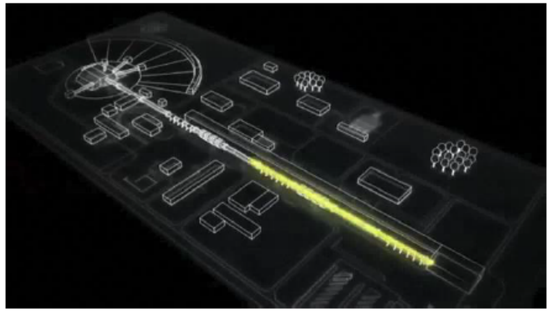
Courtesy: R. Garoby

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

ESS proton linac

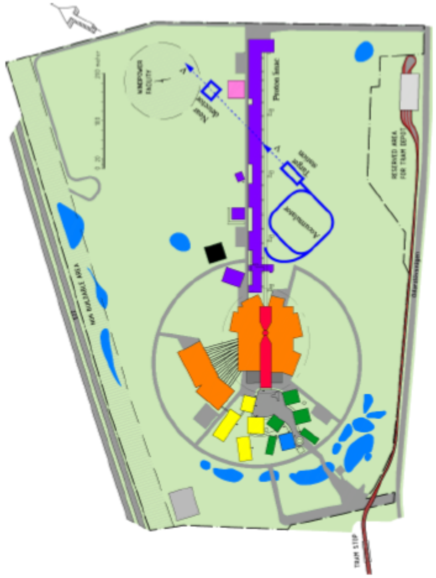


- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4%.
- 2.0 GeV protons
  - up to 3.5 GeV with linac upgrades
- **>2.7x10^{23} p.o.t/year.**



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.



Courtesy: A. Seryi

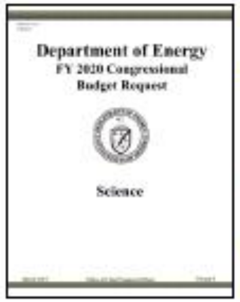
US Electron-Ion Collider

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."

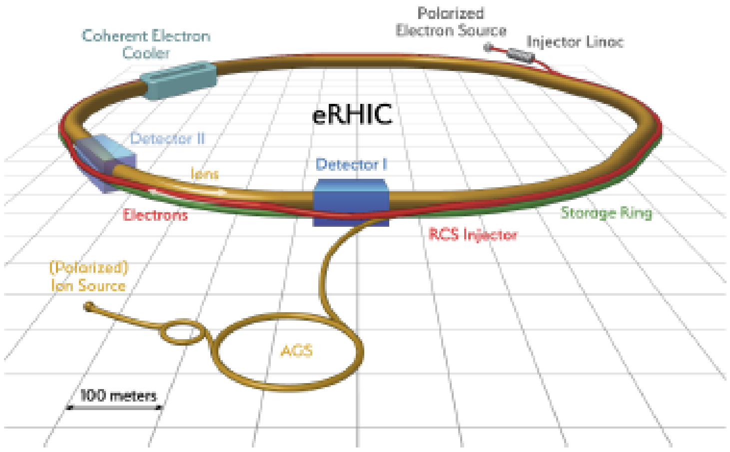
Two realization concepts being developed.
Realization could be as early as 2028-2030.

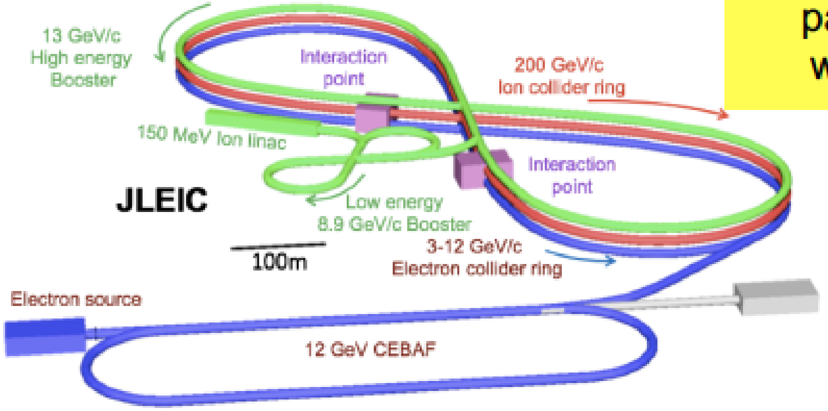
Requirements from the EIC Whitepaper

- 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

Courtesy: A. Seryi

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

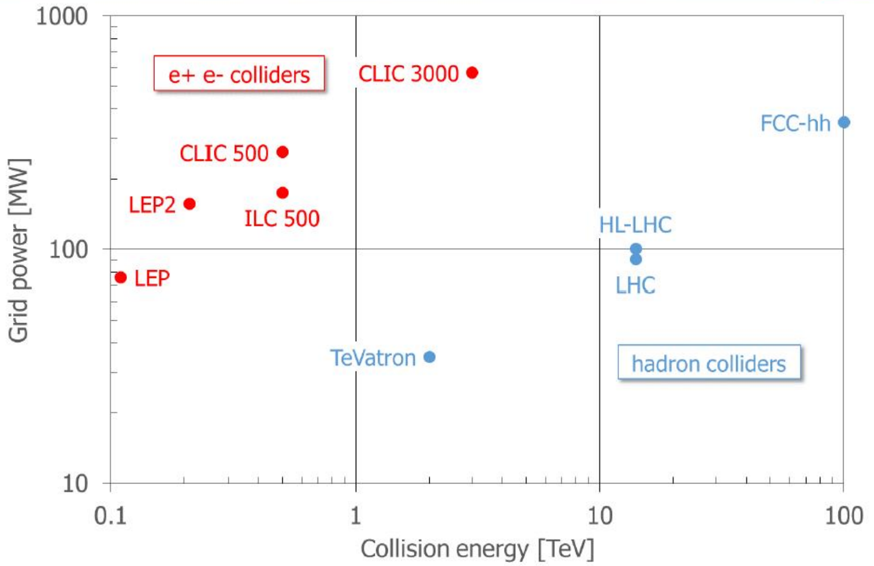
2

Courtesy: Ph. Lebrun

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

Ph. Lebrun 4th W Energy for Sustainable Science 3

Beam power, particle energy, intensity
Linear accelerators

4th Workshop Energy for Sustainable Science at Research Infrastructures

- Average beam power

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

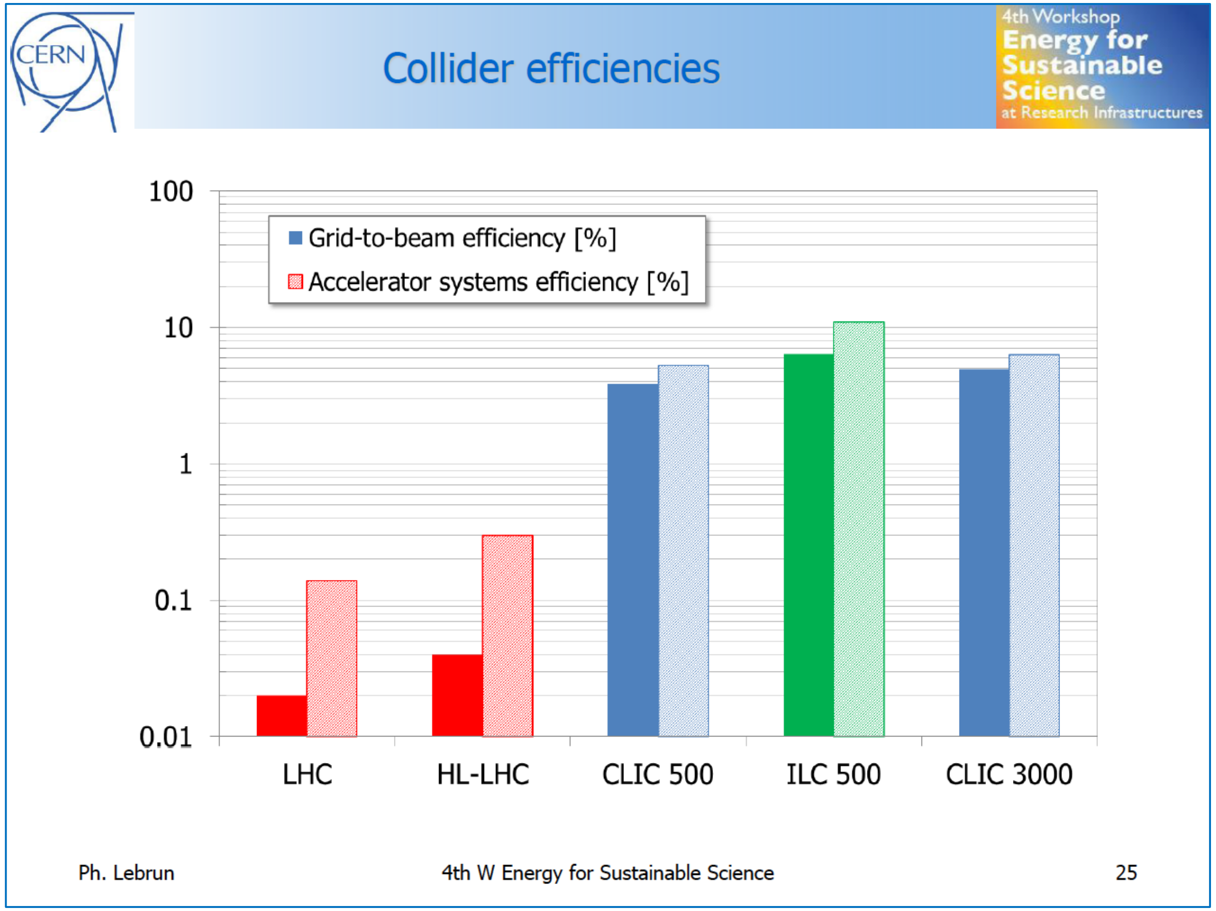
Beam current, Particle energy, Duty factor, Repetition frequency, Particles per pulse

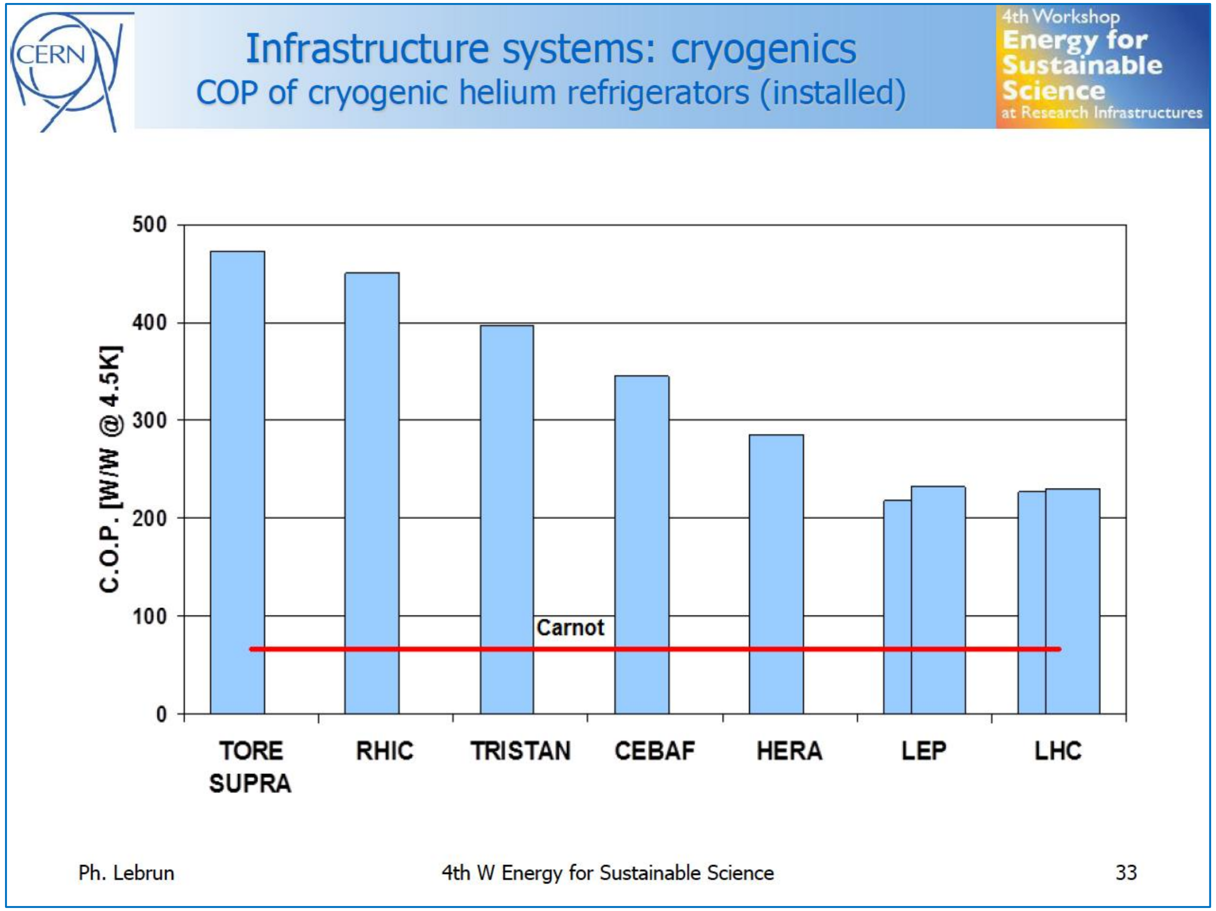
- Example: ESS proton linac
  - $E = 2$ GeV
  - $I = 62.5$ mA
  - $\delta = 4\ \%$
  - $P_{beam} = 5$ MW average

Ph. Lebrun 4th W Energy for Sustainable Science 11

Courtesy: Ph. Lebrun

Energy Efficiency and Management in Accelerators



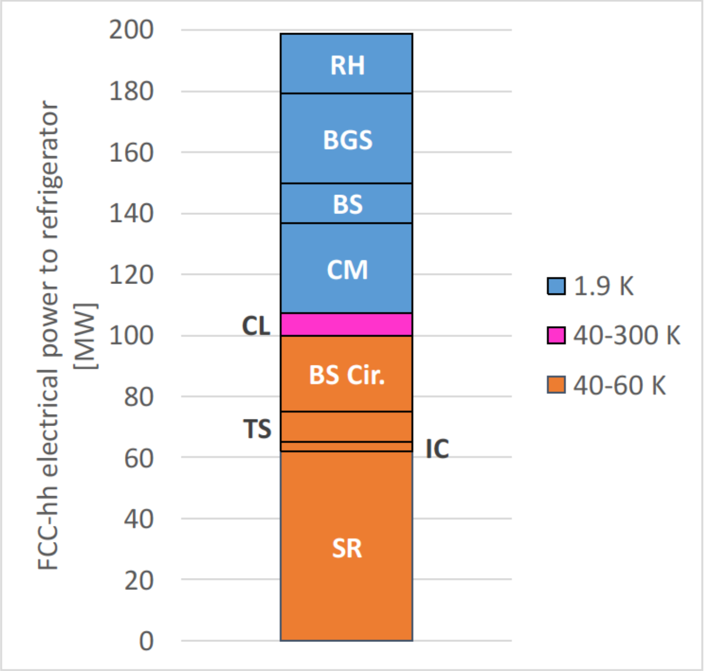


Courtesy: Ph. Lebrun

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

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Summary
Reasons for low efficiency

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- 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

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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

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