Draft: 190512

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

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, S. Gilardoni, 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, M. Sugano, T. Taylor, L. Evans, L. Revkin, C. Biscari, and V. Shiltsev, for their kindest cooperation to provide various information and discussions.*

CEPC/SPPC

Outline

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

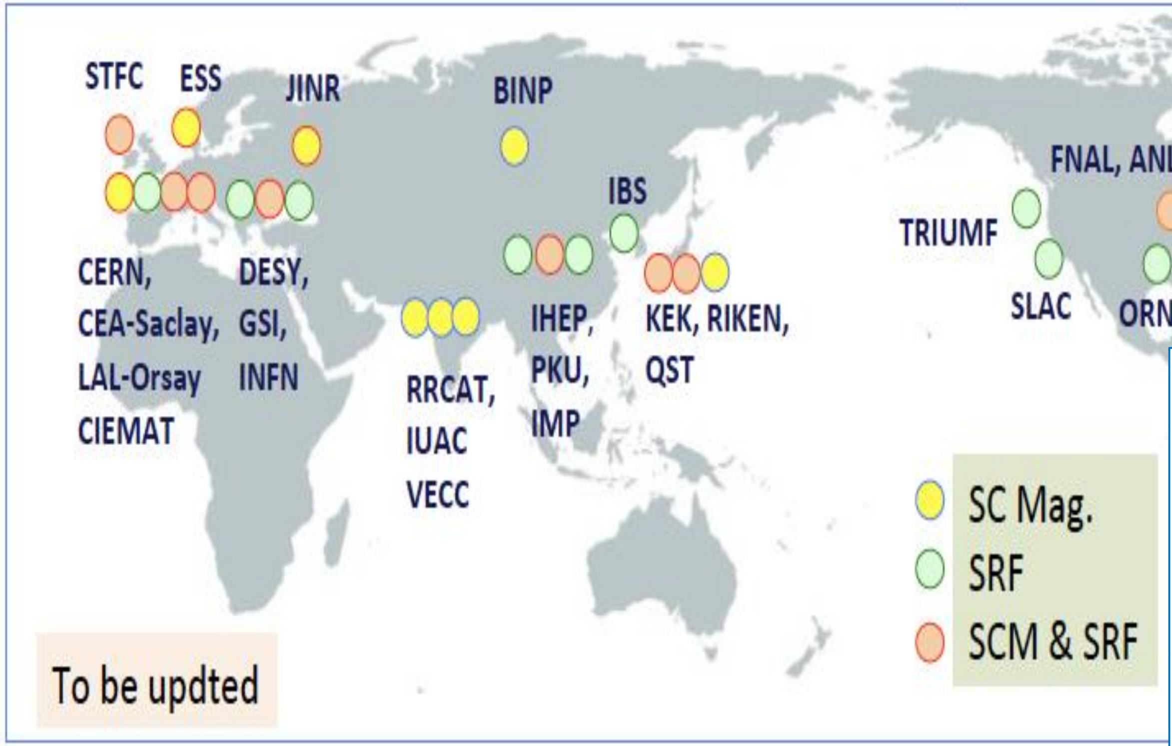
- **State of the Art in Accelerator Technologies, focusing on**
  - Nano-beam*, Superconducting Magnet and RF, and Normal-conducting RF

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

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

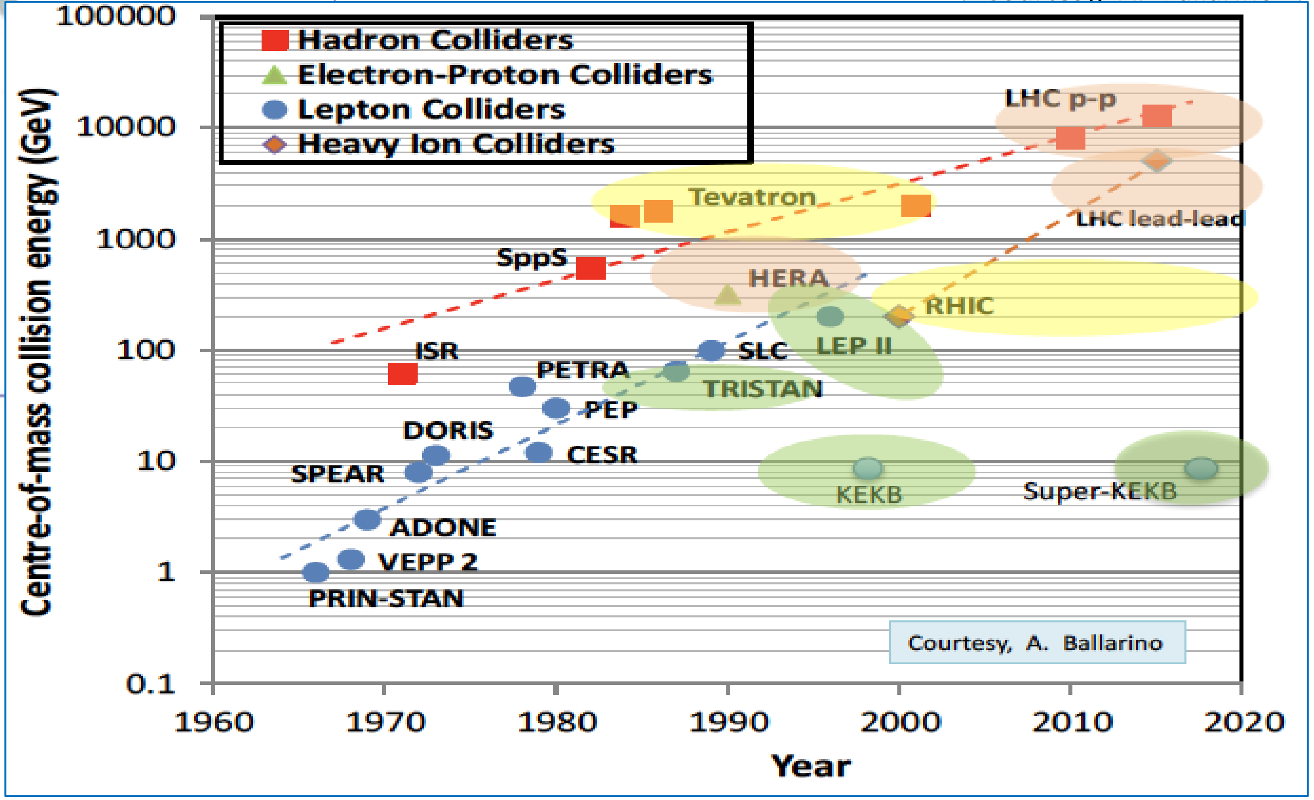
- **Summary**

Frontier Accelerators based on SC Technology



To be updted

Courtesy, A. Ballarino



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)

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**

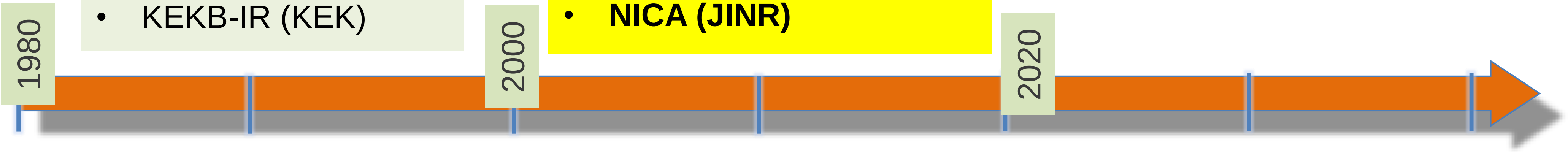
Advances in SC Magnets for Accelerators

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*

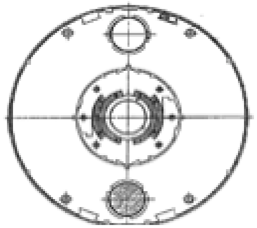
Under Construction
- **FAIR (GSI) ………** *Fast-cycleShnchr.*
- **HL-LHC (CERN)**
- **NICA (JINR)**

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

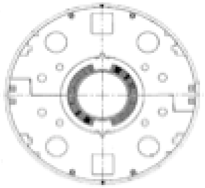


Tevatron-D.

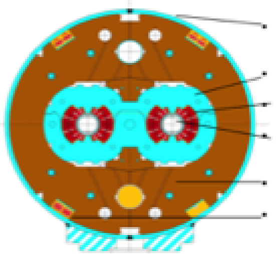
HERA-D.



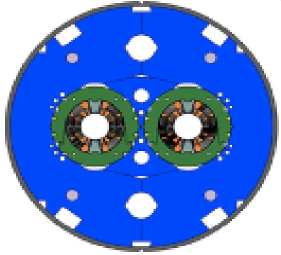
RHIC-D.



LHC.D (NbTi)

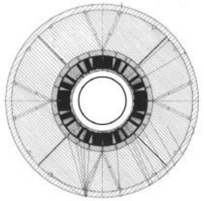


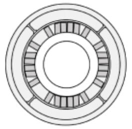
HL-LHC 11T-D (Nb_3Sn)



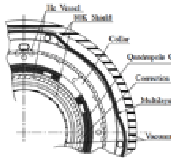
Dipole

ISR-IRQ, LEP-IRQ

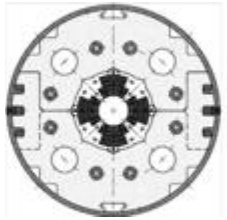




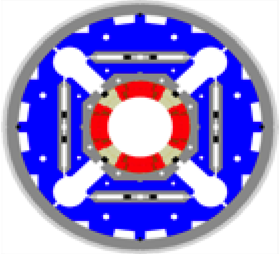
TRISTAN/KEKB-IRQ



LHCC-IRQ (NbTI)



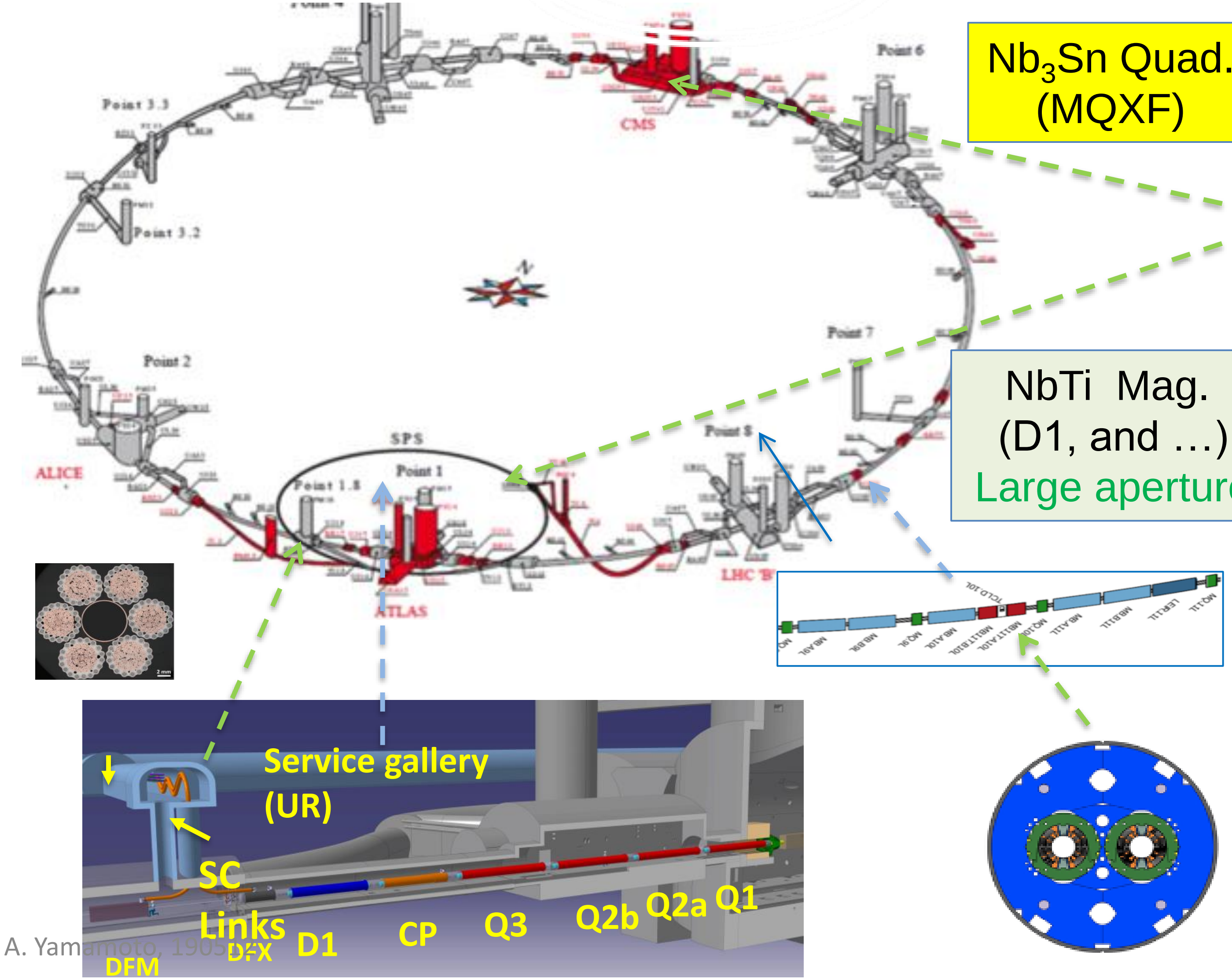
HL-LHC-IRQ (Nb_3Sn)



IR Quadrupole

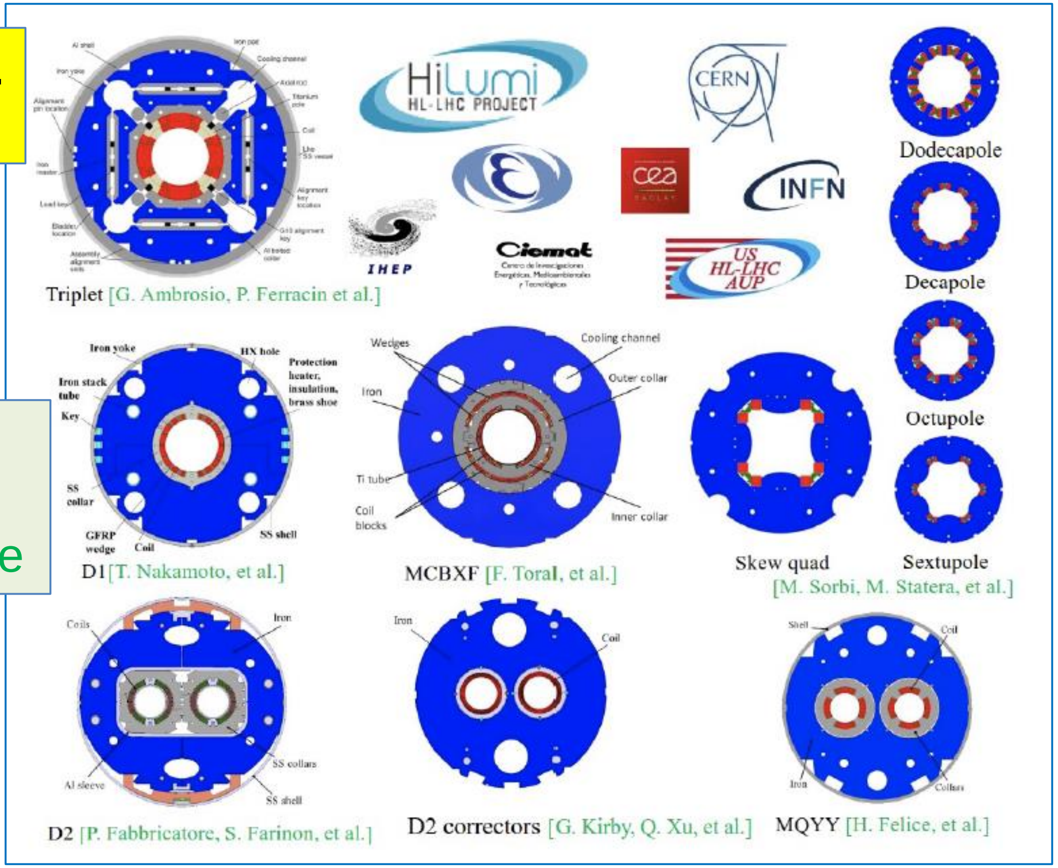
Courtesy, L. Rossi, E. Todesco

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



Nb_3Sn Quad.
(MQXF)

NbTi Mag.
(D1, and …)
Large aperture


Triplet [G. Ambrosio, P. Ferracin et al.]

Dodecapole

Decapole

Octupole

D1 [T. Nakamoto, et al.]

MCBXF [F. Toral, et al.]

Skew quad

Sextupole

[M. Sorbi, M. Statera, et al.]

D2 [P. Fabbricatore, S. Farinon, et al.]

D2 correctors [G. Kirby, Q. Xu, et al.]

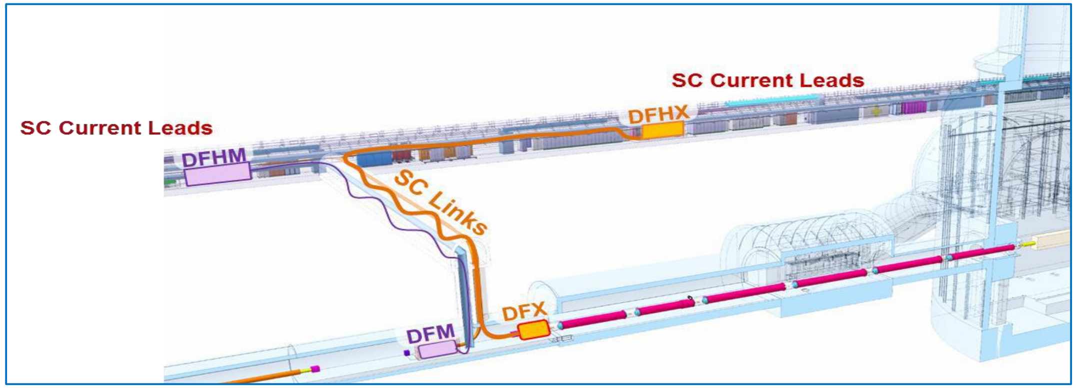
MQYY [H. Felice, et al.]

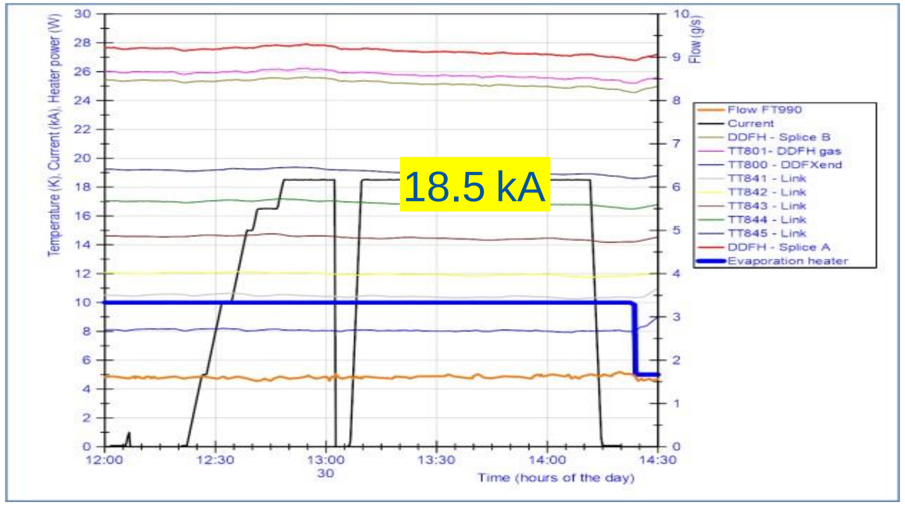
Nb3Sn Dipoles w/ Collimator

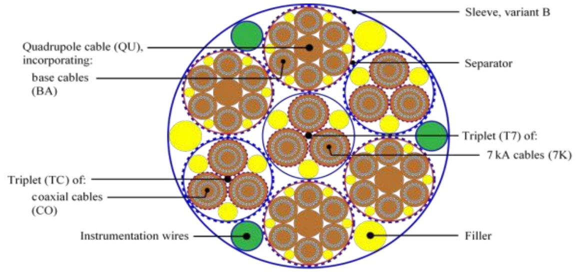
Courtesy: A. Ballarino,

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,

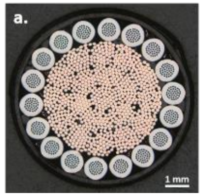




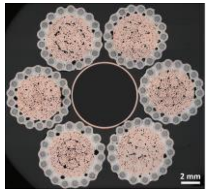


Layout of SC link cable

3 kA
(6.5 mm)



18 kA
(19 mm)

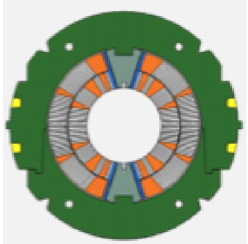


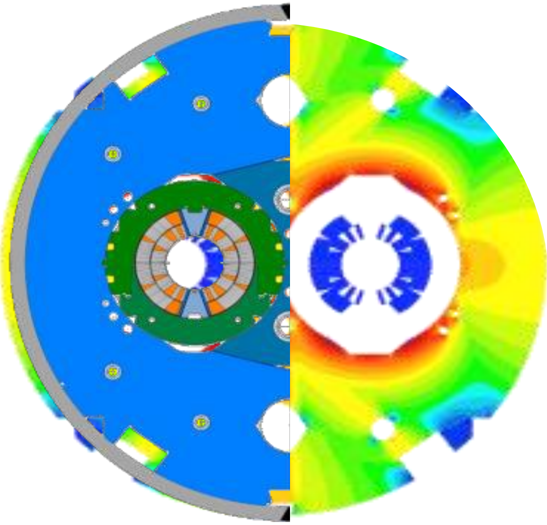
A demonstrator (2 x 60-m long, 18 kA cables) tested in Dec. 2018, exceeding requirements
- T_{CS} at 18 kA of 31.3 K

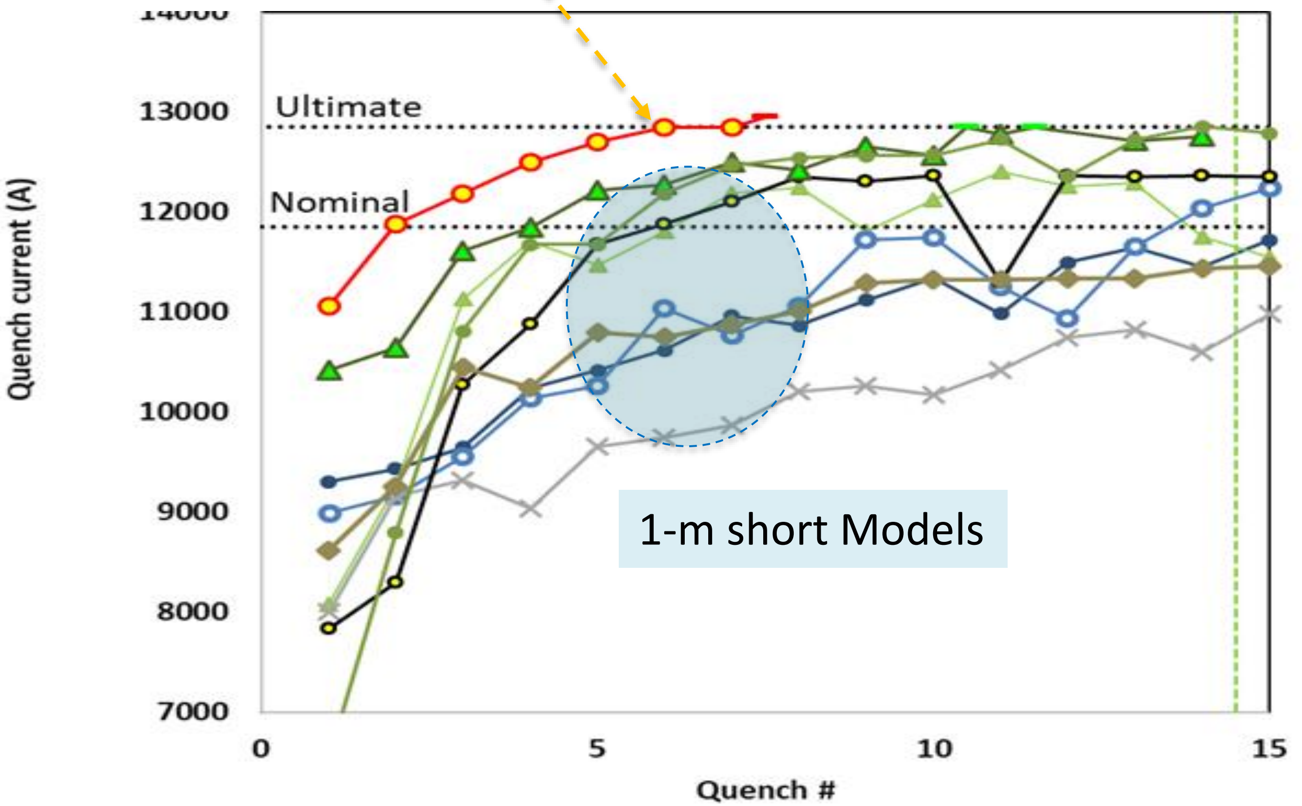
Courtesy, A. Devred, F. Savary, G. Willering

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.



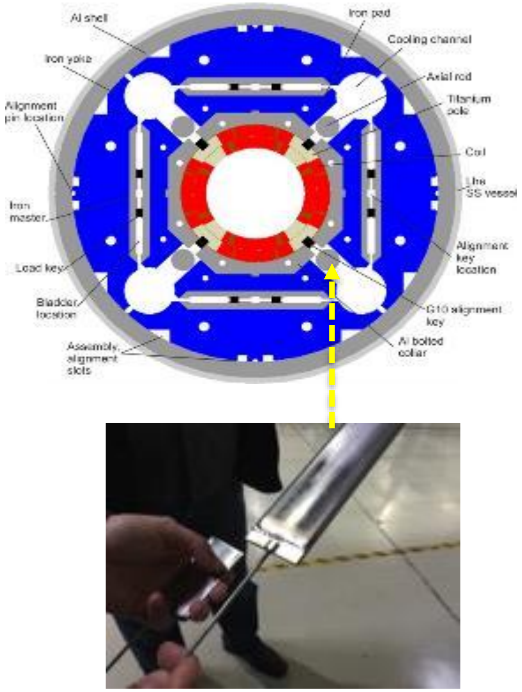




CERN and US-LARP/AUP Cooperation for Nb_3Sn IR Quadrupoles

- **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** ,

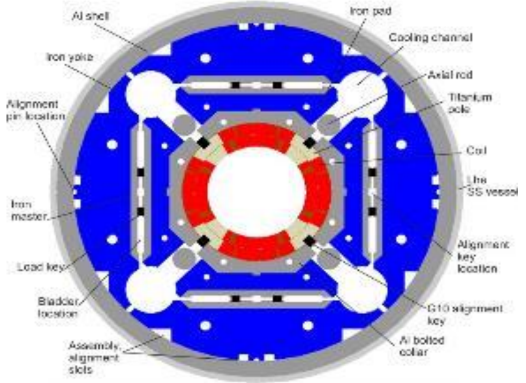
- **CERN** leading HL-LHC global collaboration and qualifying the Nb_3Sn accelerator magnet technology:
  - Experienced with the project realization for future collider accelerators.



Bladder, as a key technology

Nb$_3$Sn Quadrupole (MQXF) at IR

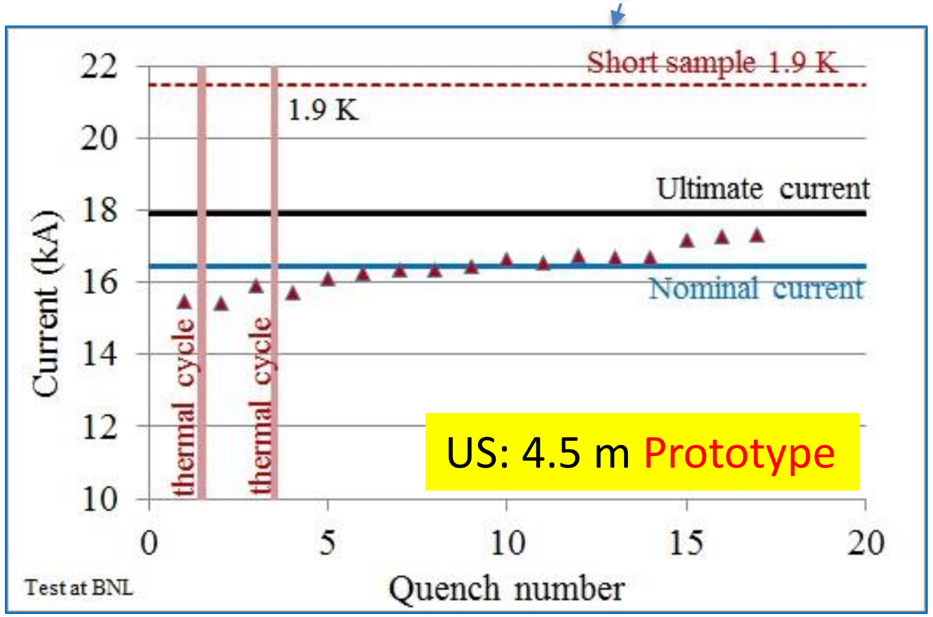
Courtesy,
G. Ambrosio, G. Chlachidze
E. Todesco, P. Ferracin



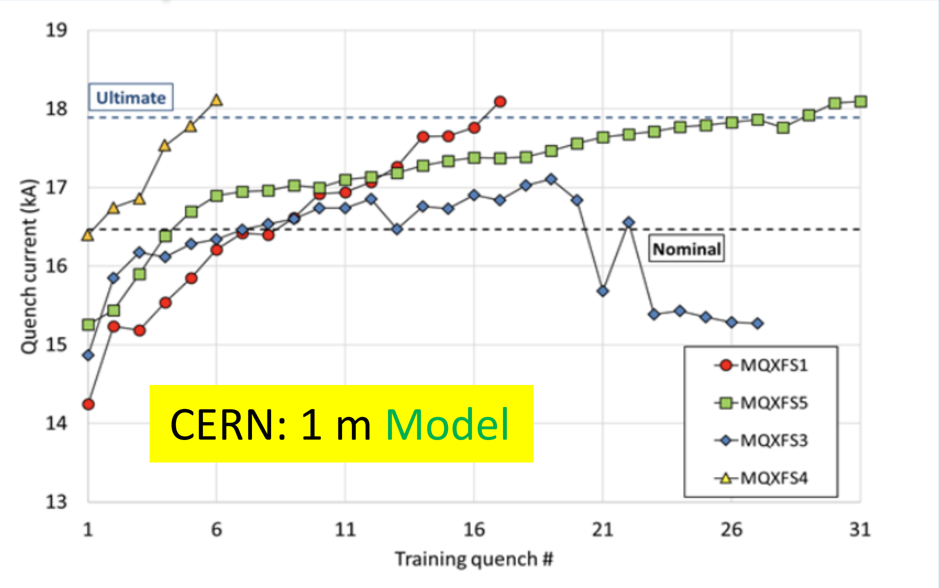
US: 4.5 m Prototype:
- Completed and tested

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

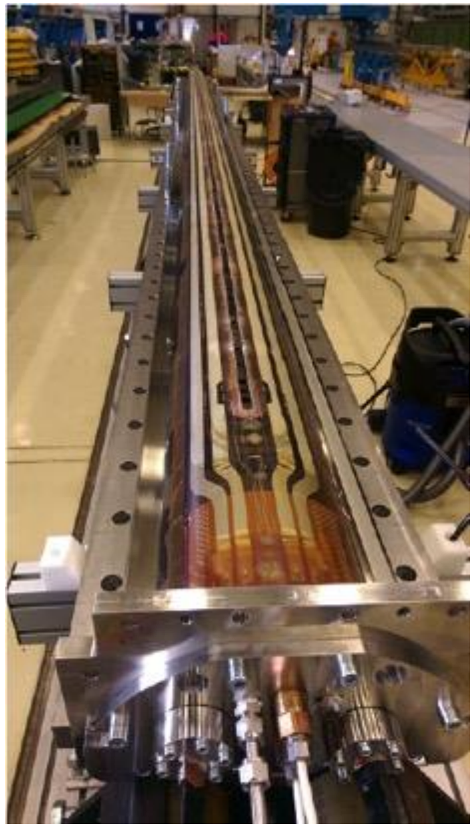
CERN: 7 m Prototype under development



US: 4.5 m Prototype



CERN: 1 m Model



CERN: 7 m long prototype under development

A. Yamamoto, 190512

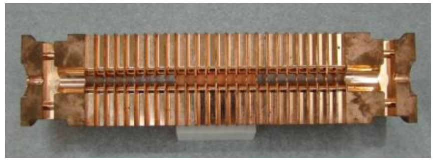
Outline

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

Courtesy: W. Wuensch

Features of Normal conducting and Superconducting RF

Normal conducting (CLIC)	Superconducting (ILC)
Gradient: 72 to 100 MV/m - Higher energy reach, shorter facility	Gradient: 31.5 to 35 (to 45) MV/m, - Higher efficiency, steady state beam power from RF input
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



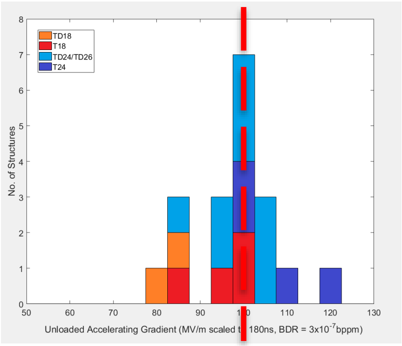
A. Yamamoto, 190512

Courtesy: W. Wuensch

Normal Conducting Linac Technology Landscape

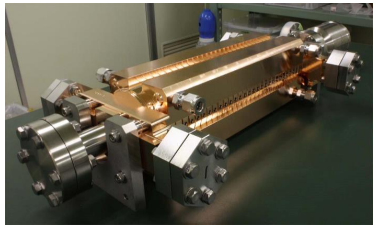
Components:

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



~ 100 (+/-20) MV/m

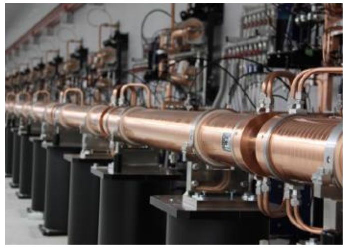
Full commercial supply
- X-band klystrons
- solid state modulator,



Systems Facilities:
(100 MeV-range)

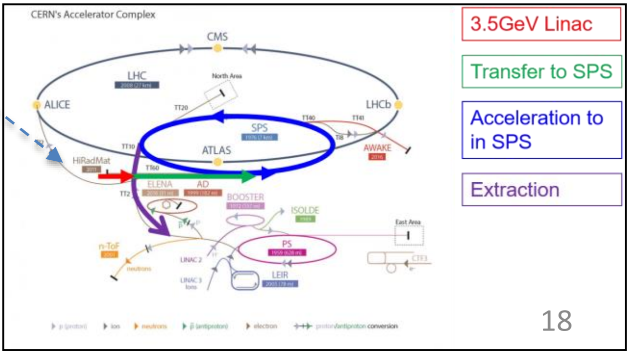
- XBoxes at CERN
- (NEXTEF KEK)
- Frascati
- NLCTA SLAC
- Linearizers at Electra, PSI, Shanghai and Daresbury
- Test stand at Tsinghua
- Deflectors at SLAC, Shanghai, PSI and Trieste
- NLCTA
- SmartLight
- FLASH

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

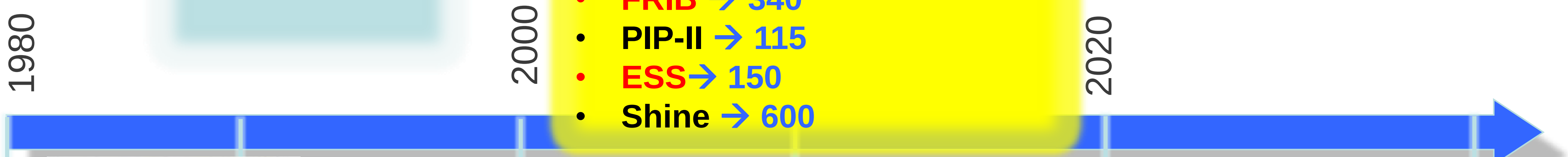


X-band (12 GHz)
GeV-range facilities
Planning:
- **Eu-Praxia**
- **e-SPS**
- **CompactLight**

CLIC



Advances in SRF Technology 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



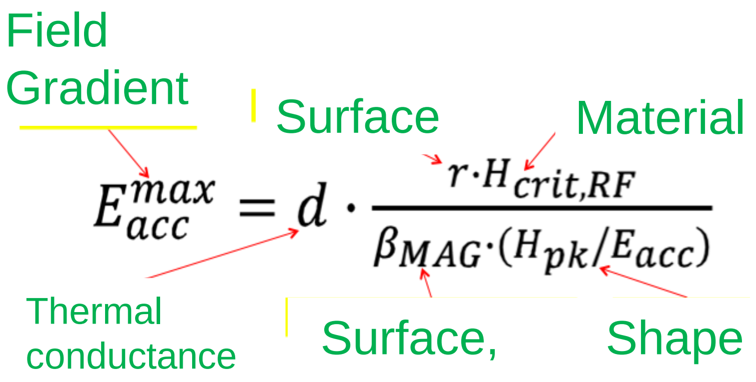




> **2,000** SRF cavities realized, in last 10 years !

Courtesy: R. Geng,

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



Field Gradient

Surface

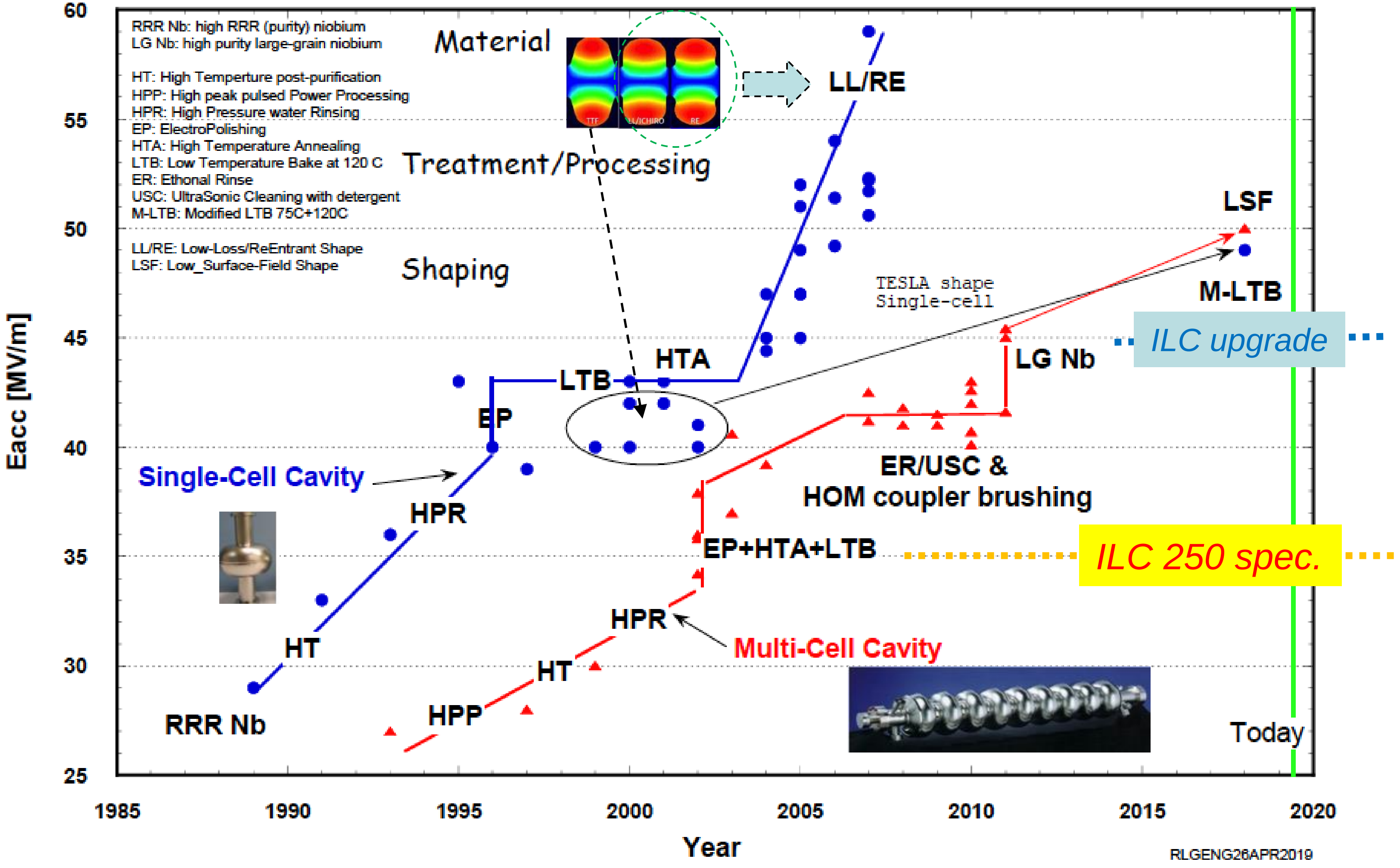
Material

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

Thermal conductance

Surface,

Shape



RRR Nb: high RRR (purity) niobium
LG Nb: high purity large-grain niobium

HT: High Temperture post-purification
HPP: High peak pulsed Power Processing
HPR: High Pressure water Rinsing
EP: ElectroPolishing
HTA: High Temperature Annealing
LTB: Low Temperature Bake at 120 C
ER: Ethonal Rinse
USC: UltraSonic Cleaning with detergent
M-LTB: Modified LTB 75C+120C

LL/RE: Low-Loss/ReEntrant Shape
LSF: Low_Surface-Field Shape

A. Yamamoto, 190512

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

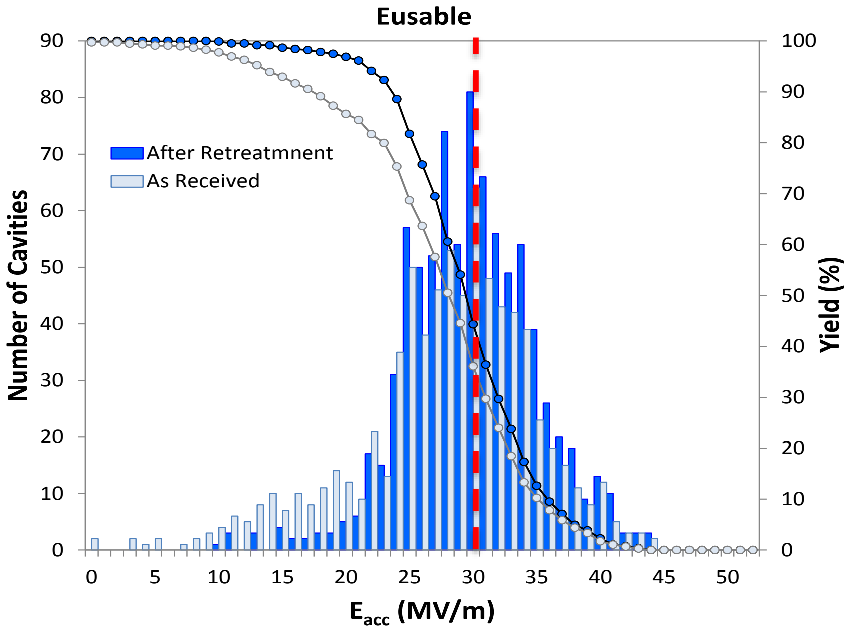
Progress:

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

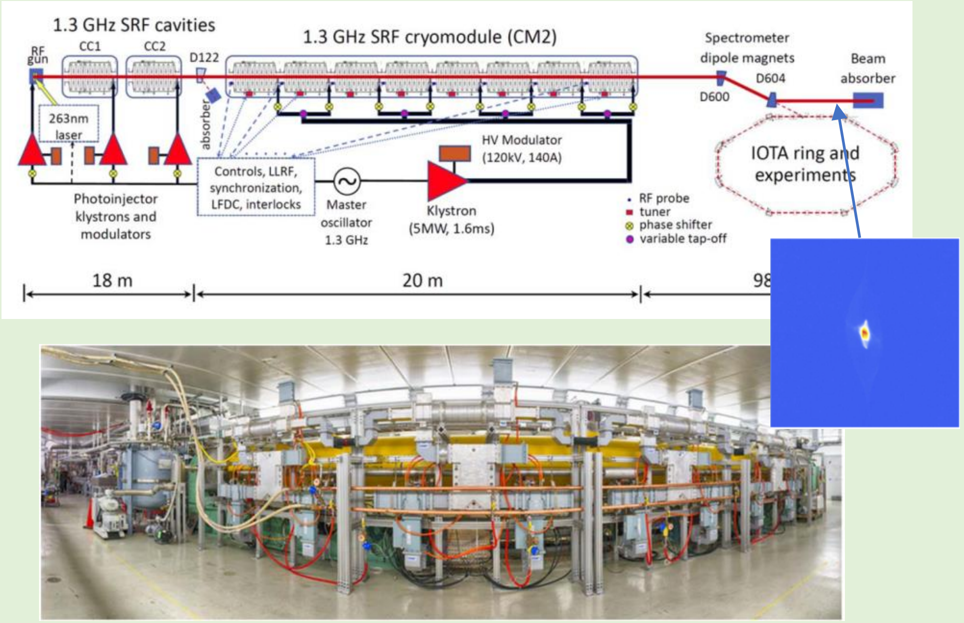
After Re-treatment:

E-usable: 29.8 ± 5.1 [MV/m]

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

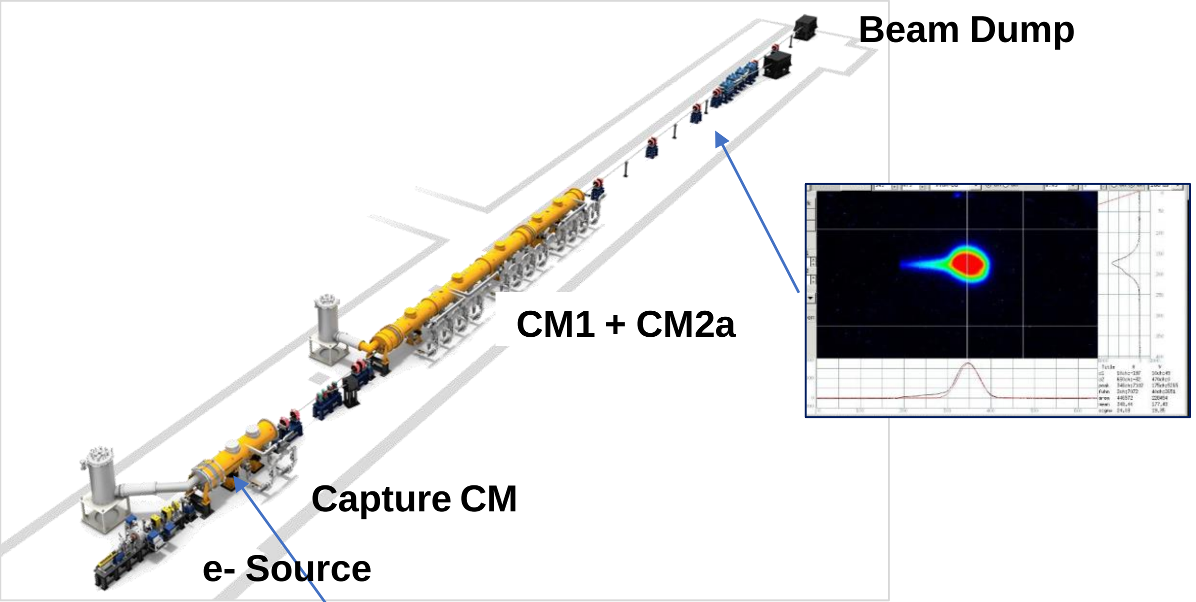
Courtesy: V. Shiltsev, S. Michizono

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

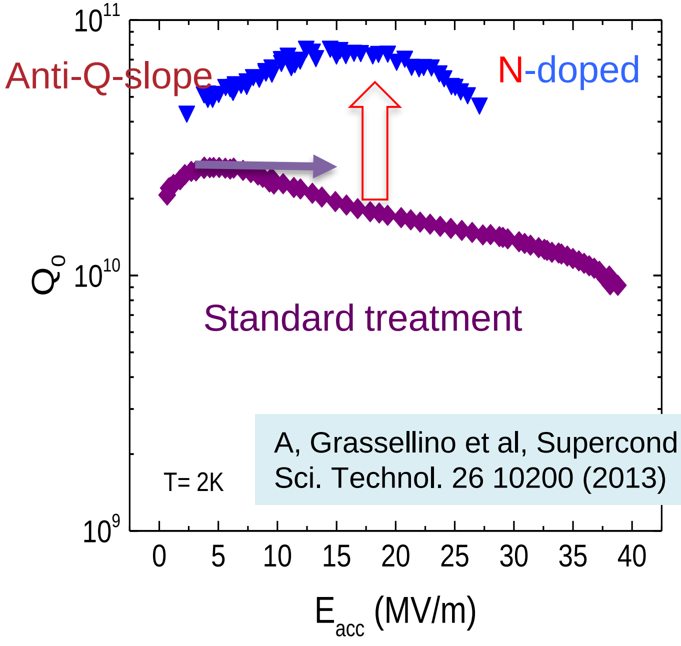


Beam Acc. : 230 MeV by 7 Cavities,
<G> = 32 MV/m

KEK-STF2 Progress, 2019

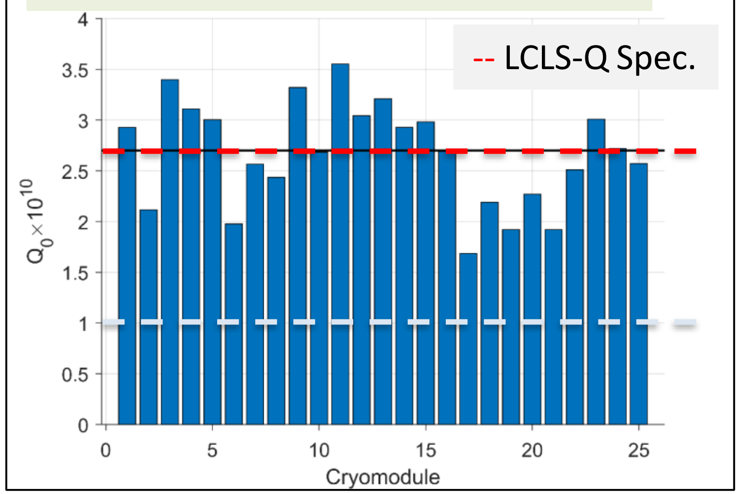
Courtesy, M. Ross

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:

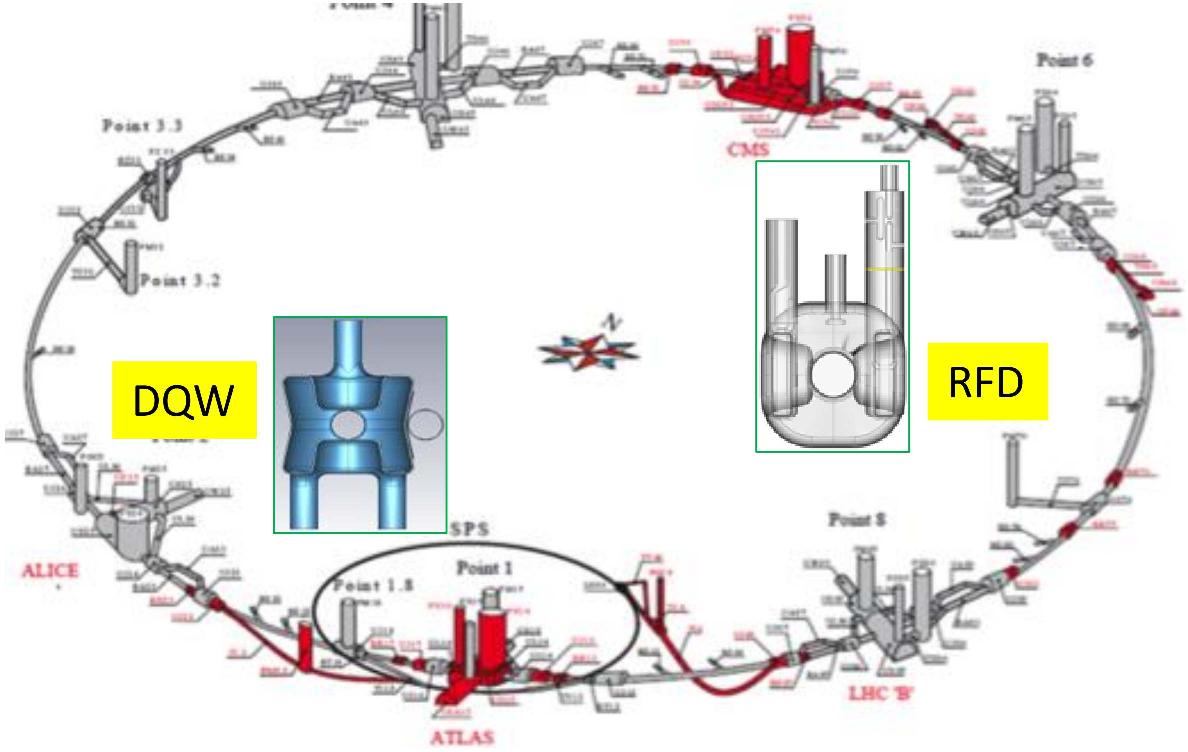
- Frequency : 1.3 GHz, CW
- G: 18 ~21 MV/m
- Q: > 2.7 e10 (av.)
- # cavity = 280 (+160)
- # CM 35 (+20)

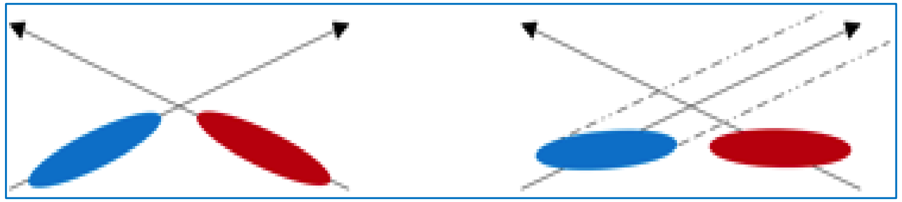
To be completed in 2020 (~2026)

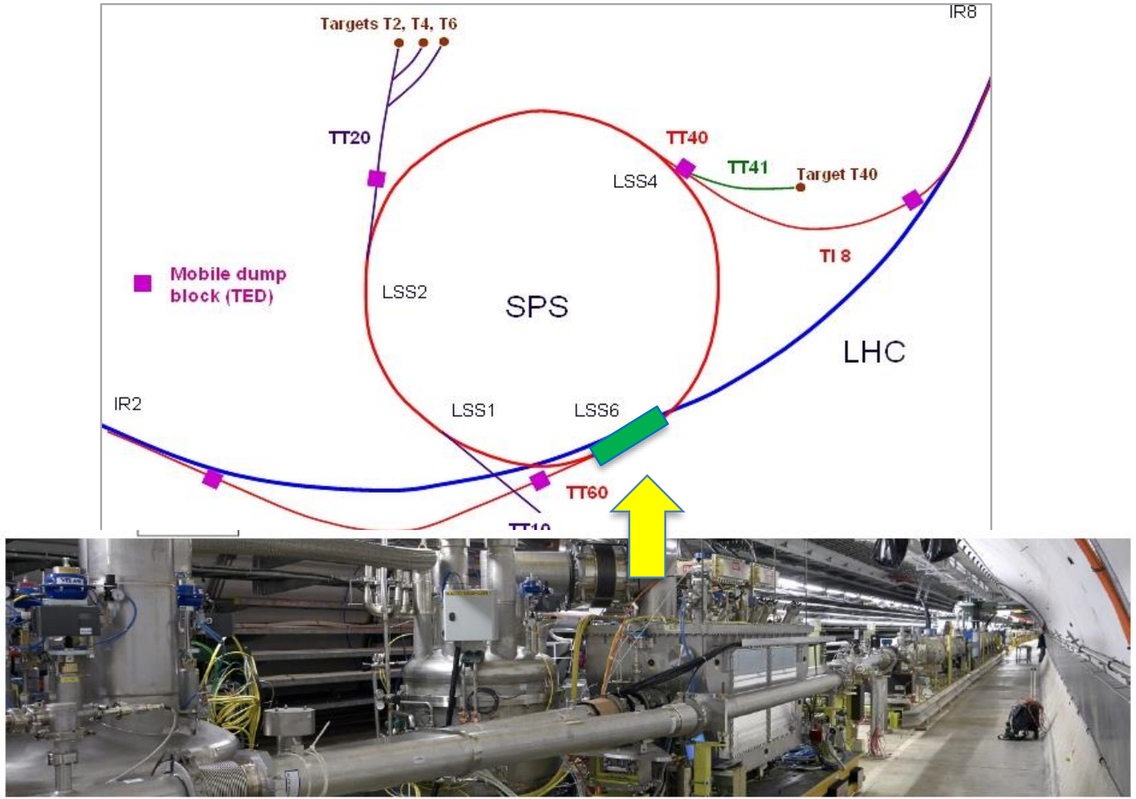
Nb SRF Crab Cavities for HL-LHC

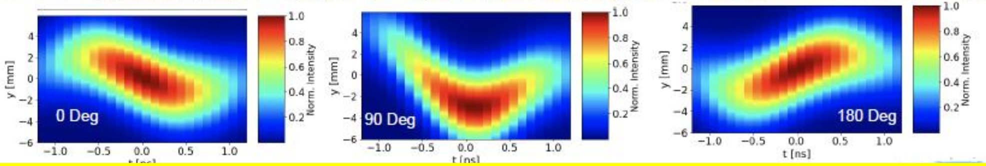
Courtesy,
R. Calaga, O. Capatina,
A. Ratti, L. Ristori

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]	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

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]	[illegible] filled)	[illegible] 120			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]		(0.[illegible]	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
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

Major Technical Challenges:

Hadron Colliders:

- High-field magnet
- Energy management

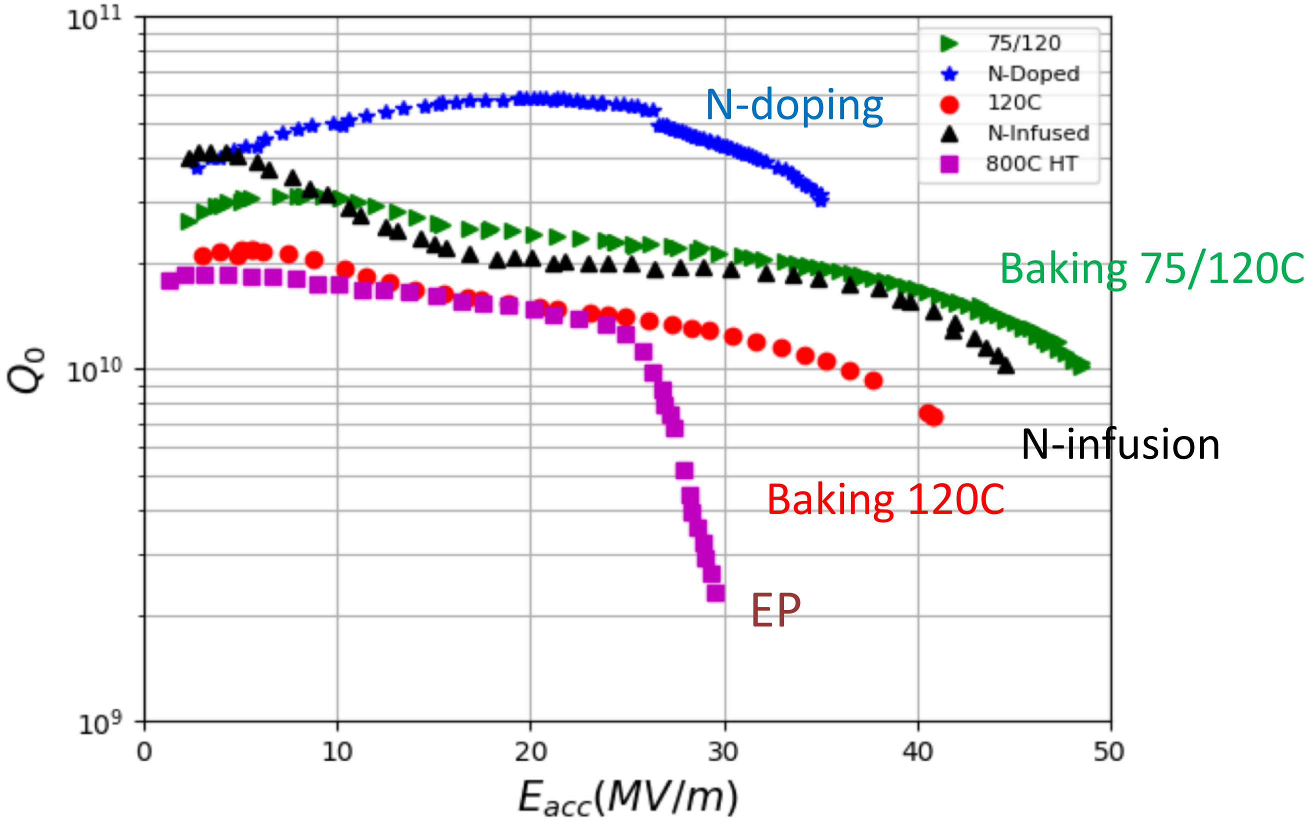
Lepton Colliders:

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

A. Yamamoto, 190512

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

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

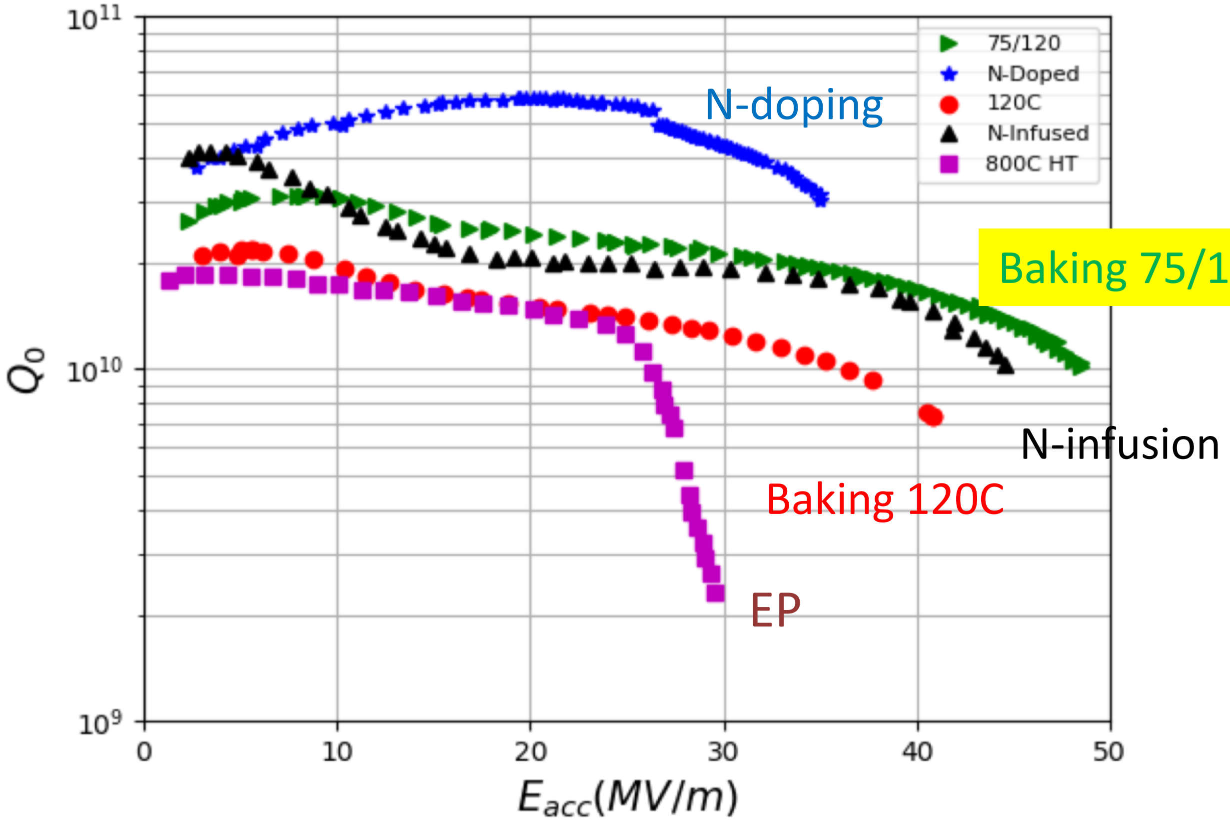


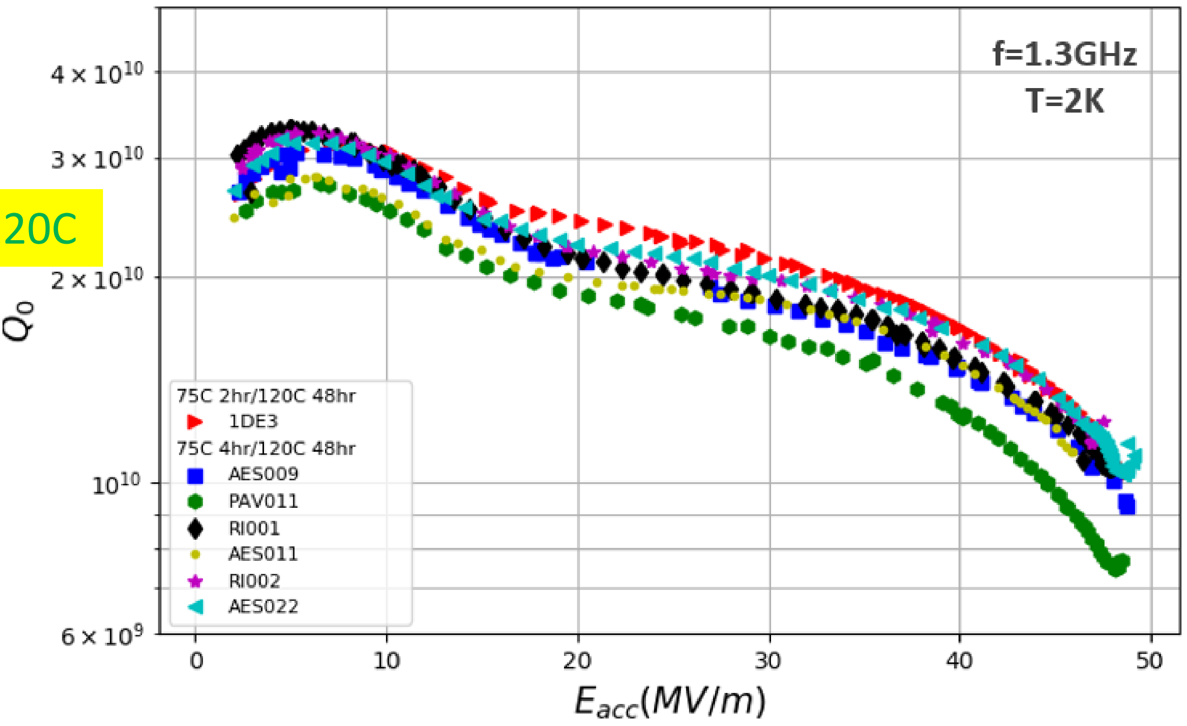
- **N-doping** (@ 800C for ~2 min.)
  - Q >3E10, G = 35 MV/m
- **Baking w/o N** (@ 75/120C)
  - Q >1E10, G =49 MV/m (Bpk-210 mT)
- **N-infusion** (@ 120C for 48h)
  - Q >1E10, G = 45 MV/m
- **Baking w/o N** (@ 120C for xx h)
  - Q >7E9, G = 42 MV/m
- **EP** (only)
  - Q >1.3E10, G = 25 MV/m

- **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)

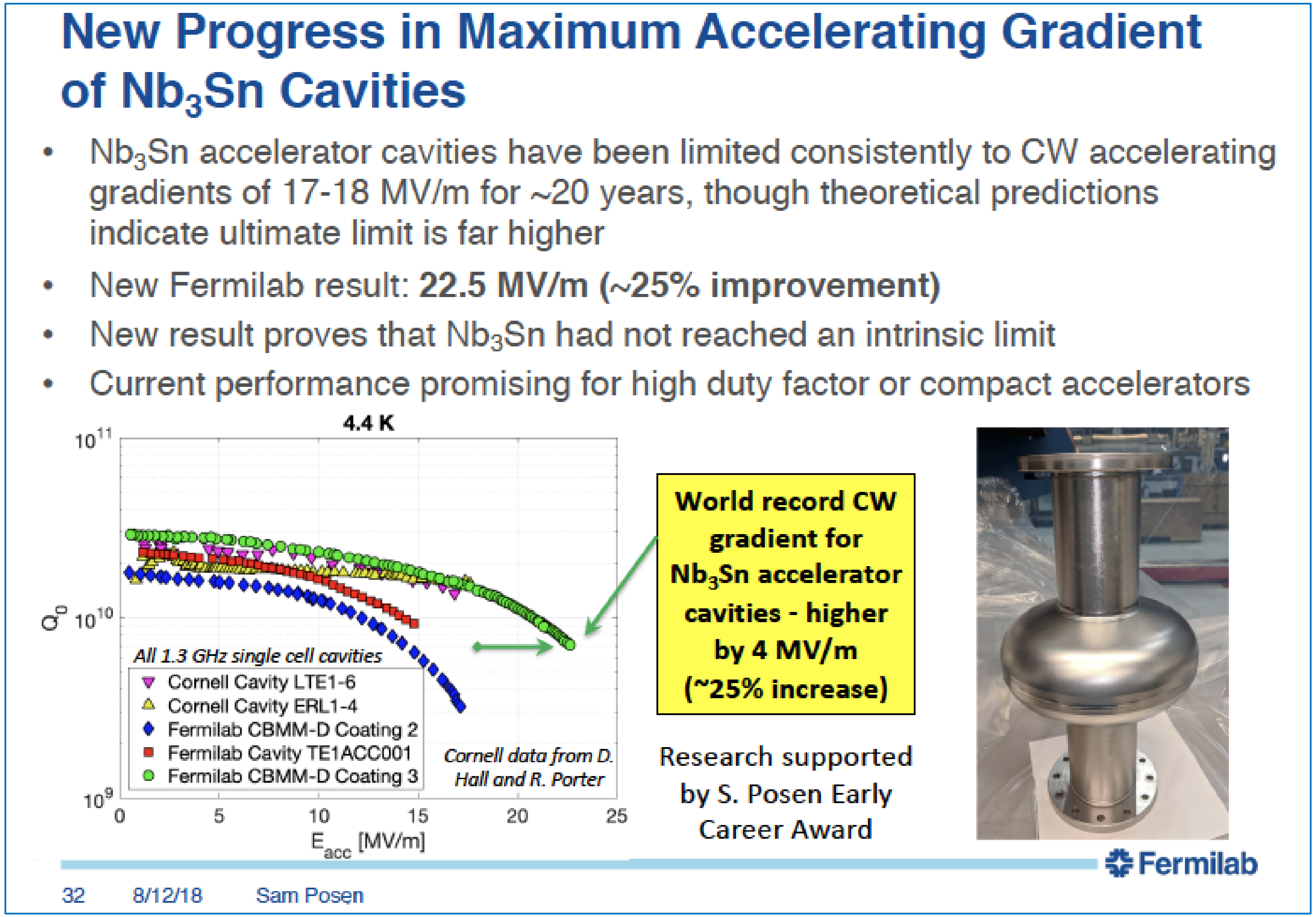
https://arxiv.org/abs/1806.09824

- Performance at **Fermilab** confirmed by **Cornell**, **DESY**, and **JLab.**

Courtesy: A. Grasselion, S. Posen

Progress in Nb_3Sn-Coating Research

reported at Fermilab 1-day Workshop, May 2019



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

Cornell data from D. Hall and R. Porter

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

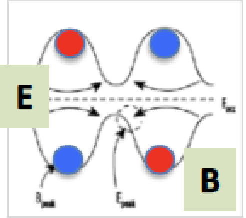
Research supported by S. Posen Early Career Award

Fermilab

32 8/12/18 Sam Posen

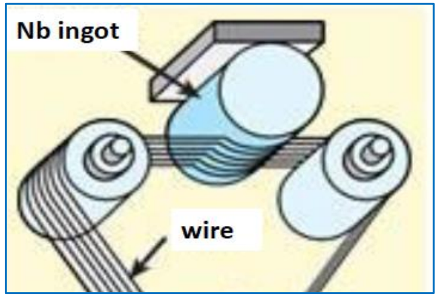
B_{sh} = practical limit for SRF

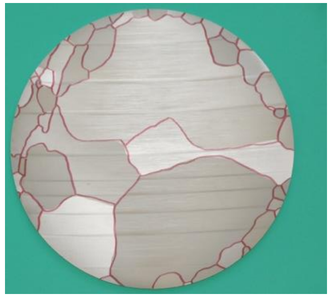
- $Bs_{sh\text{-}Nb}$: 210 mT
- $Bs_{sh\text{-}Nb3Sn}$: 430mT
- $Bs_{sh\text{-}MgB2}$: 310mT

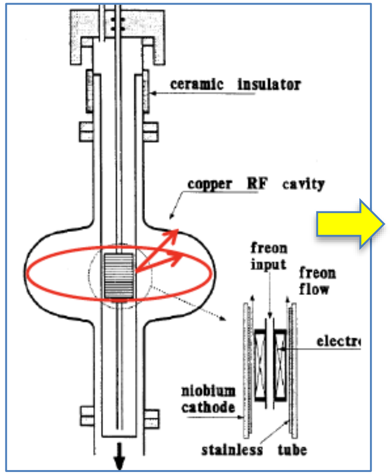


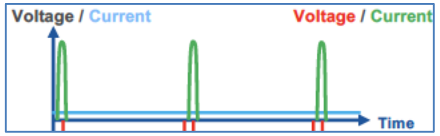
Challenges in SRF Cavity Technology

- **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 **I**mpulse **P**ower **M**agnetron **S**puttering (HiPIMS) , instead of
    - **DC M**agnetron **S**puttering (DCMS)
  - **Nb_3Sn** / MgB_2 film coating on Nb or Cu
    - To reach much higher G, with higher B_c (B_{sh})





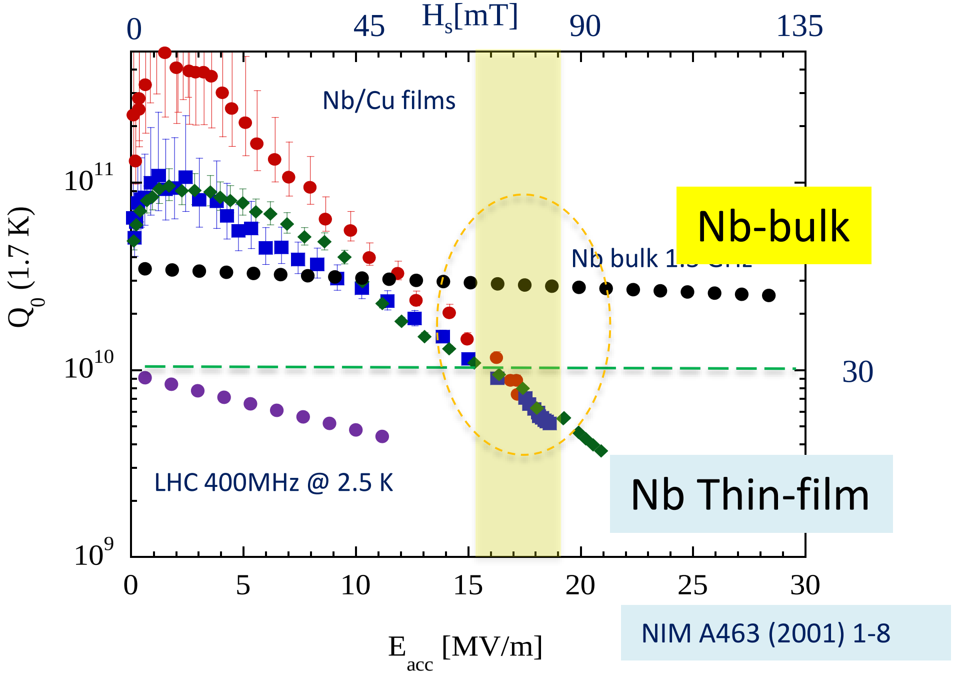




Courtesy: S. Calatroni

DC Magnetron Sputtered Nb/Cu Films

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

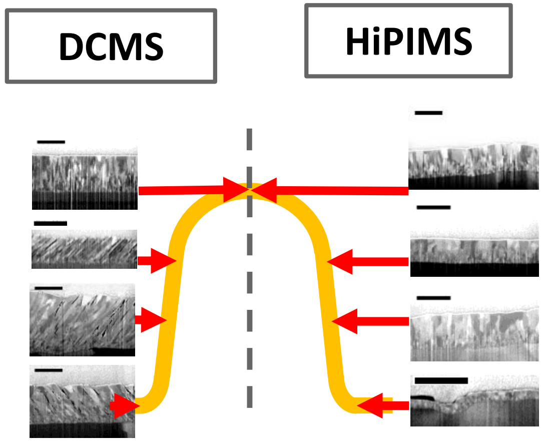


NIM A463 (2001) 1-8

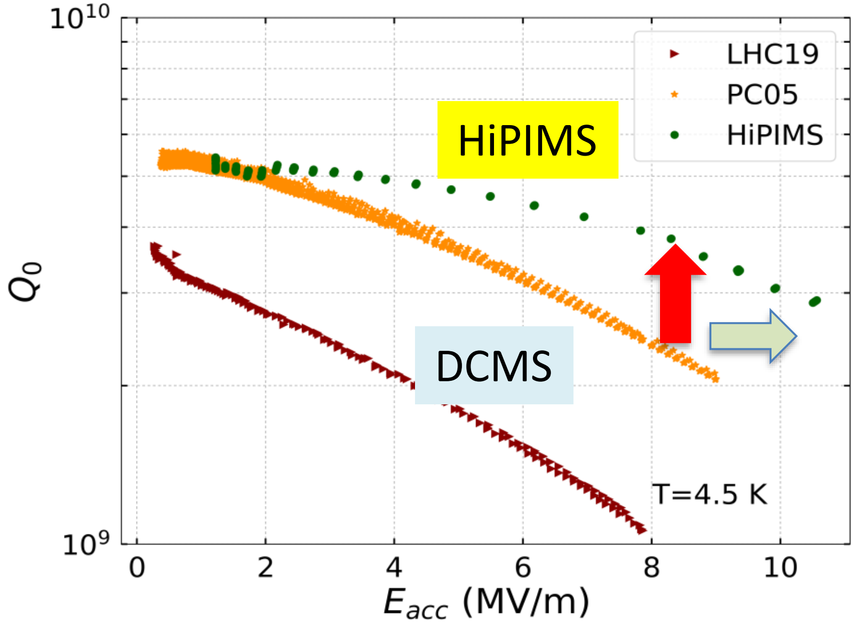
- Q = 1×10^{10} @ 15 MV/m, for thin-film cavities:
  - competitive option in several future projects.
- R&D focused on:
  - improving the "slope"

HiPIMS coatings – QPR Sample

To be important challenge for < 600 MHz (FCC)



700 MHz β=0.65 Single Cell Cavity profile



- HiPIMS Nb/Cu to be comparable to bulk Nb on quadrupole resonator sample at 400, 800 and 1,300 MHz.
- Q-slope seems to be flatter

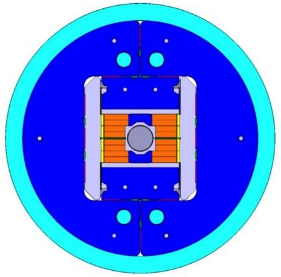
  --> High-Q, resulting **Power Saving**,
- Projected performance > 2x better than LHC specifications

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 **Hadron Colliders**
- **Summary**

Courtesy: G. De Rijk, A. Devred

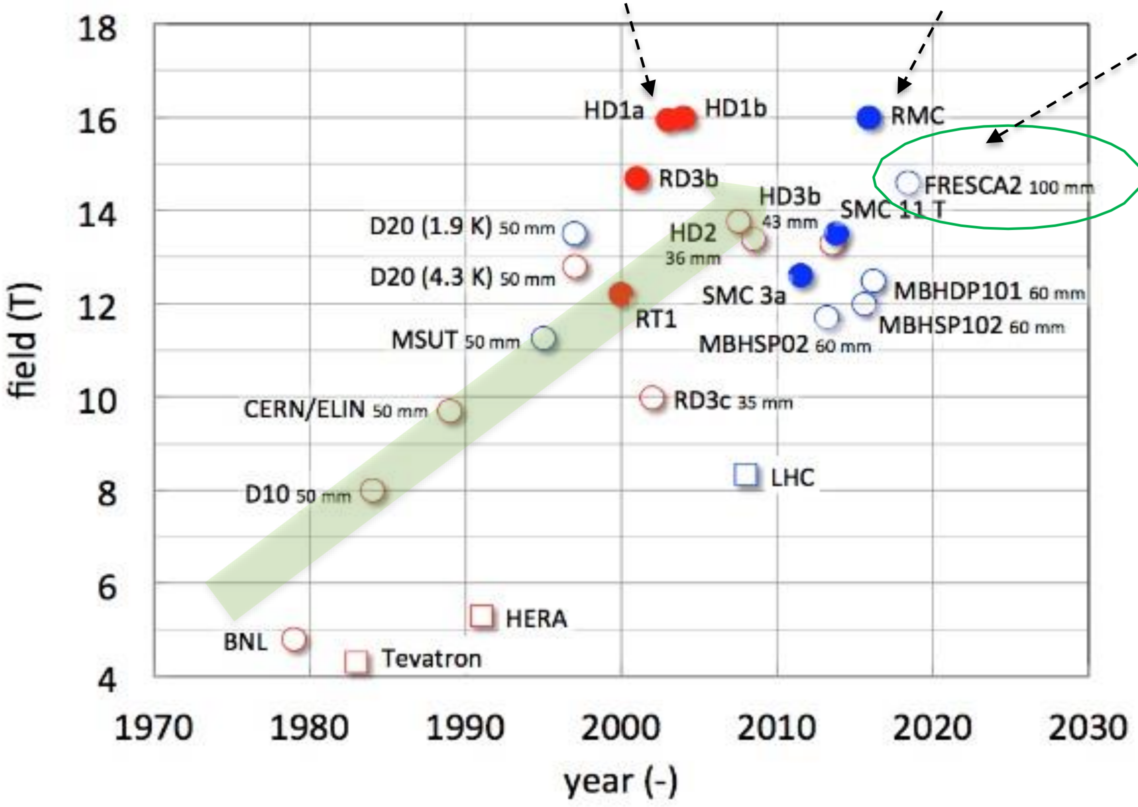
Advances in Nb_3Sn Magnet Development

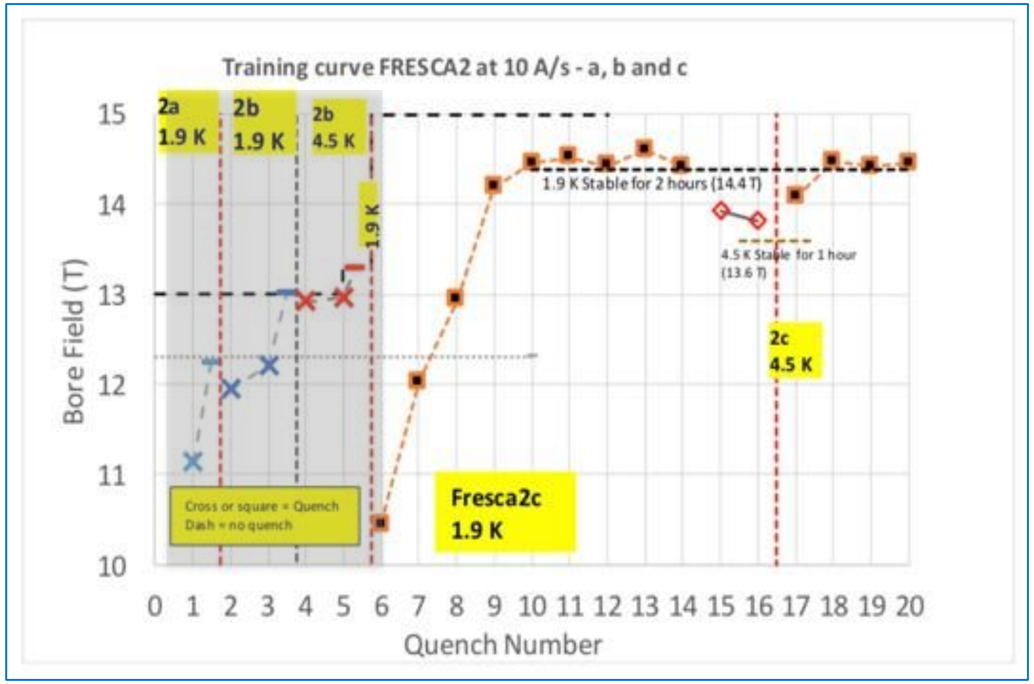


2003: LBNL HD1
(16 T at 4.2 K)

2015:CERN RMC
(16.2 T at 1.9 K)

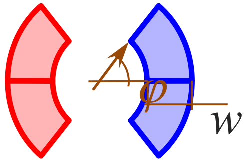
2018: FRESCA2
(100 mm aperture, 14.6/14.95 T bore/peak at 12.1 kA. 1.9 K)





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

Nb_3Sn Conductor Progress



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

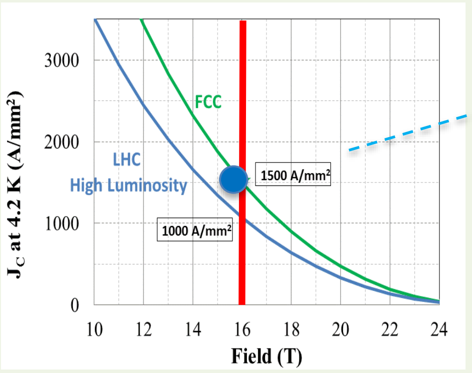
$$B = \frac{2\mu_0}{\pi} J w \sin(\phi)$$

Main development Target:

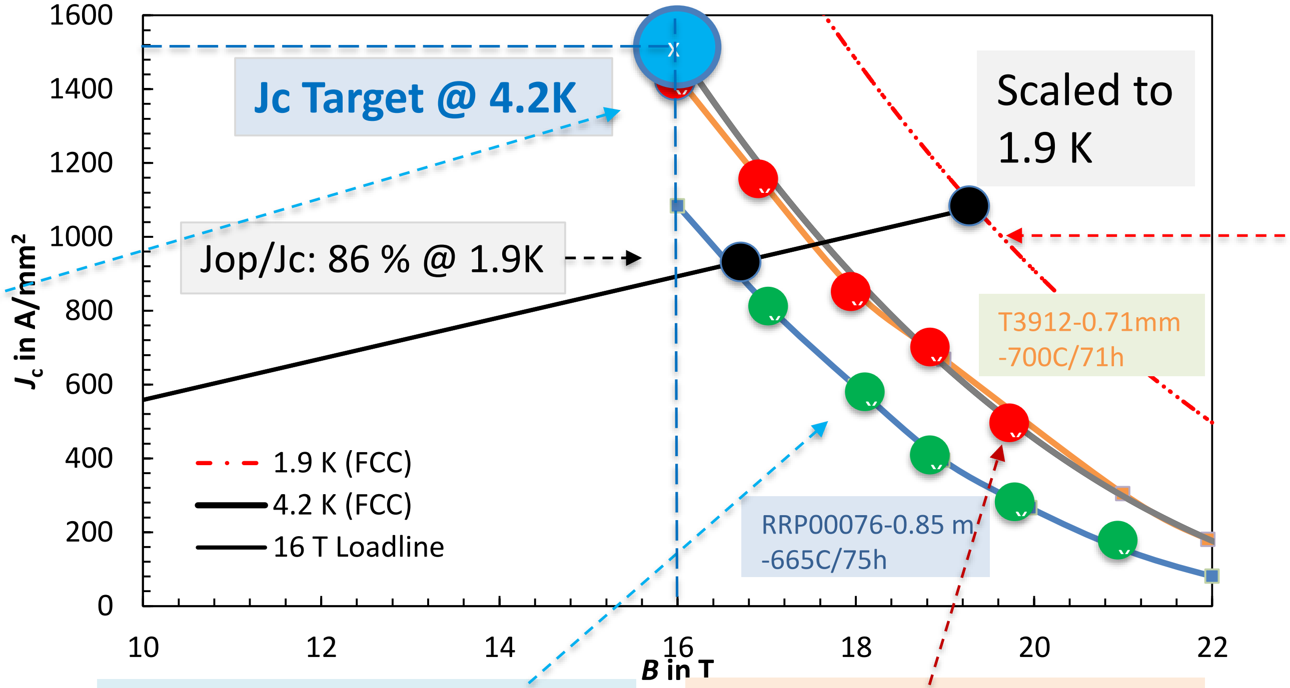
- **J_c (16T, 4.2K) > 1500 A/mm²**
  - 50% higher than HL-LHC

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



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

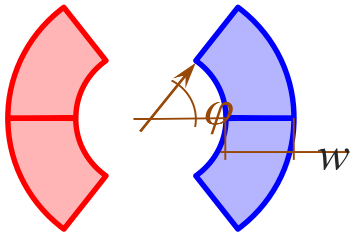
● Achieved by APC approach: X. Xu et al (Fermilab)

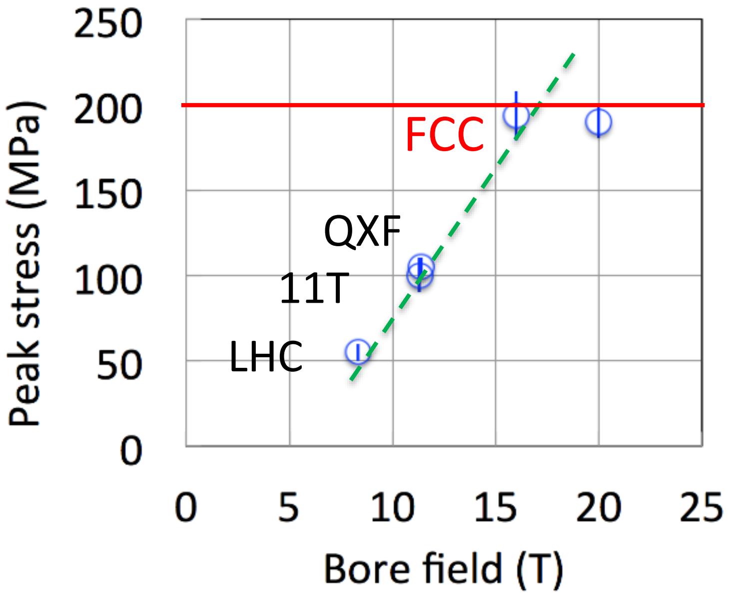
https://arxiv.org/abs/1903.08121

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

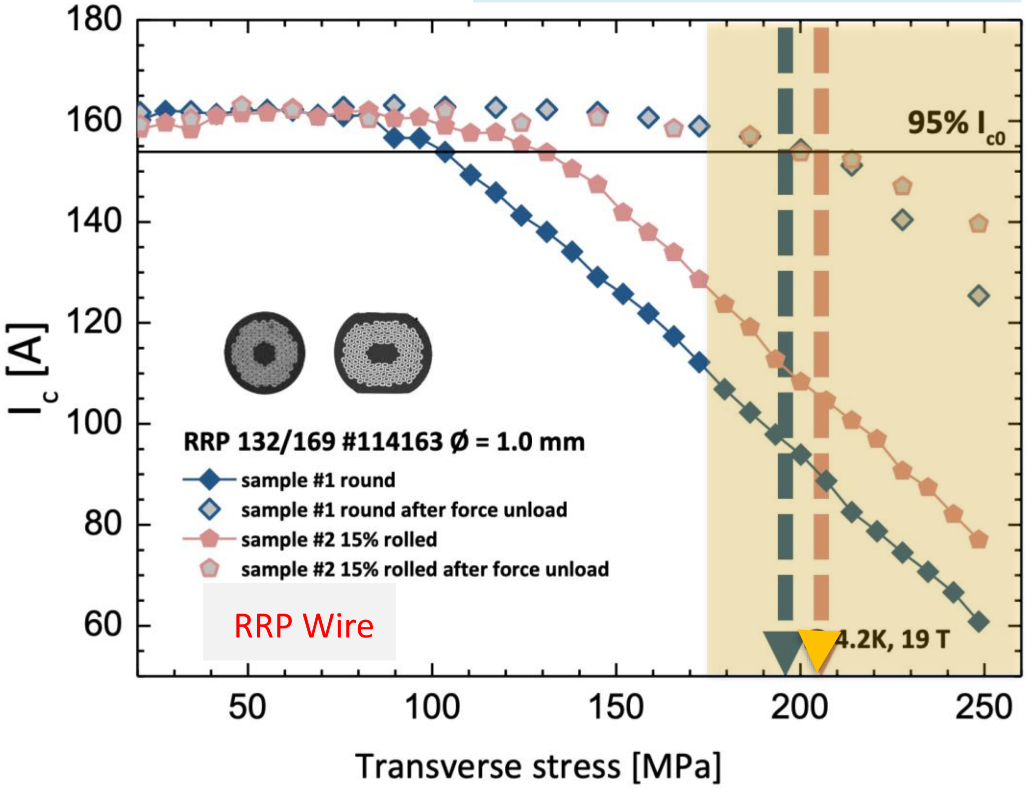
Courtesy: L. Bottura, A. Devred

Mechanical Constrain to consider Operating Margin





Measurement at Univ. Geneve



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

or

$p \sim B^2$

Attention, I_c (J_c) reduction:

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

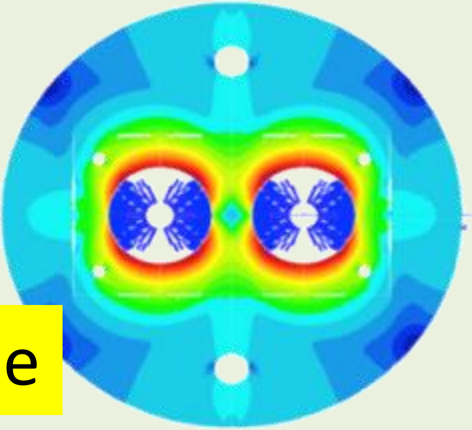
as a critical constraint because of fundamental mechanical property.

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

16 T Dipole R&Ds in Europe and US

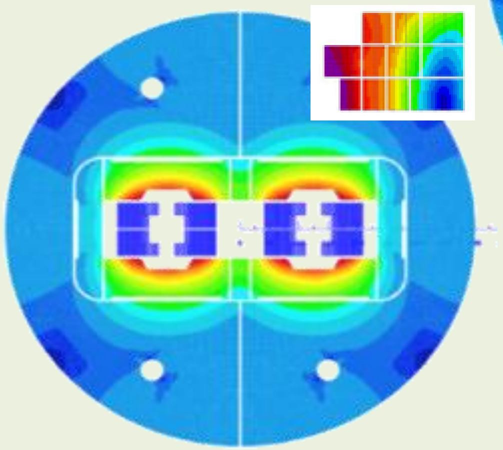
Europe

Cos-θ

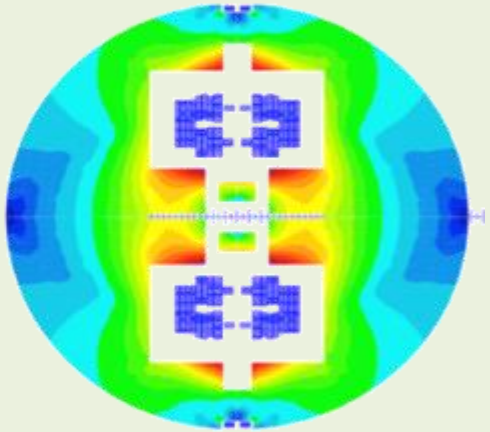


EuroCirCol
A key to New Physics

Blocks



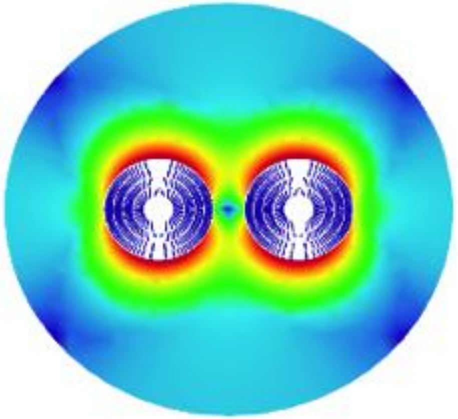
Common coils



Pioneering work at BNL

CHART2
Swiss Acc. Research & Technology

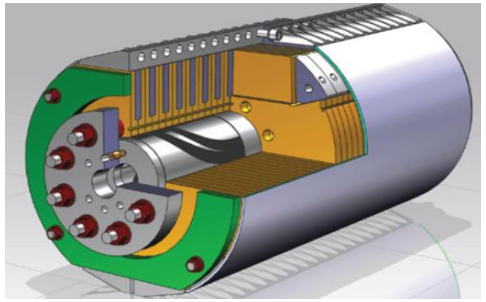
Canted Cos-θ (CCT)

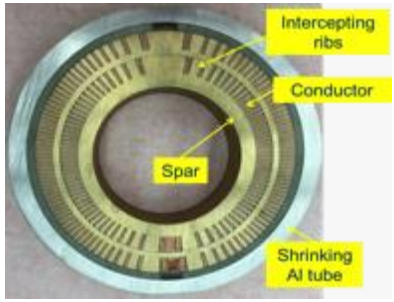


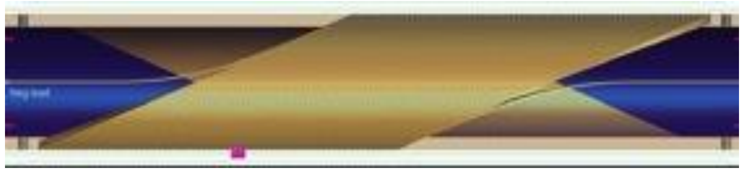
US

U.S. MAGNET DEVELOPMENT PROGRAM

Cos-θ







CCT,
Pioneering work at LBNL

Courtesy: S. Prestemon S. Belomstnykh

US-DOE MDP taking Steps to realize 16 T

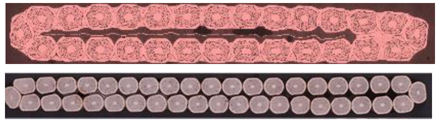

The U.S. Magnet Development Program Plan

U.S. MAGNET DEVELOPMENT PROGRAM

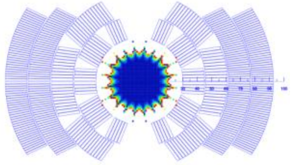
MDP Goals:
1. Explore Mb_3Sn magnet limit
2. Demonstrate HTS magnet (5 T – self fied)
3. Investigate fundamentals for performance and cost reduction
4. Pursue Nb3Sn and HTS conductor R&D

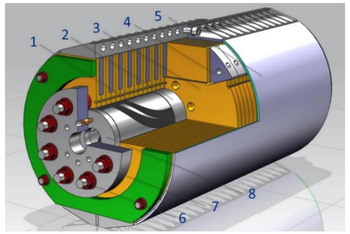
See Appendix

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

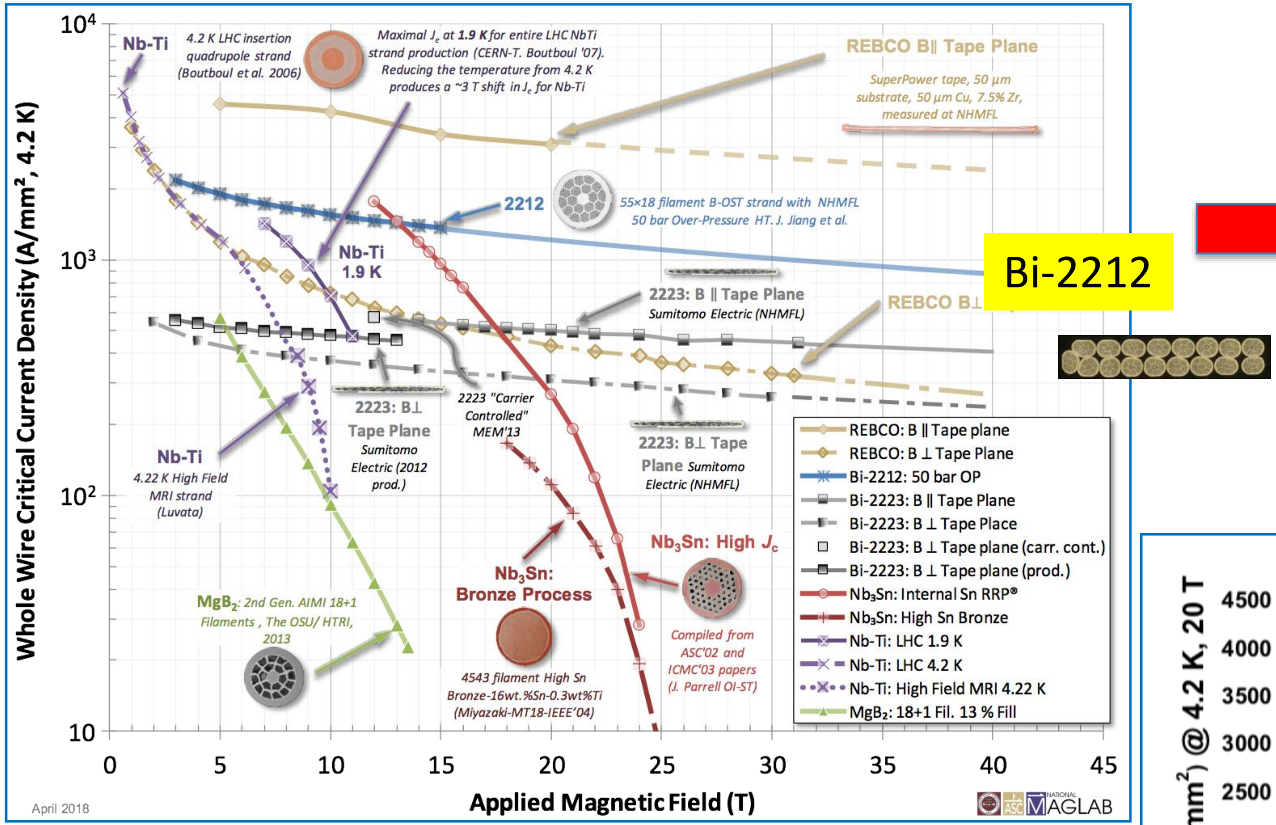




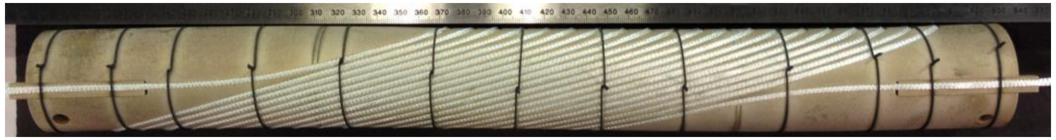

Before test, at Fermilab

Courtesy, P. Lee, S. Prestemon

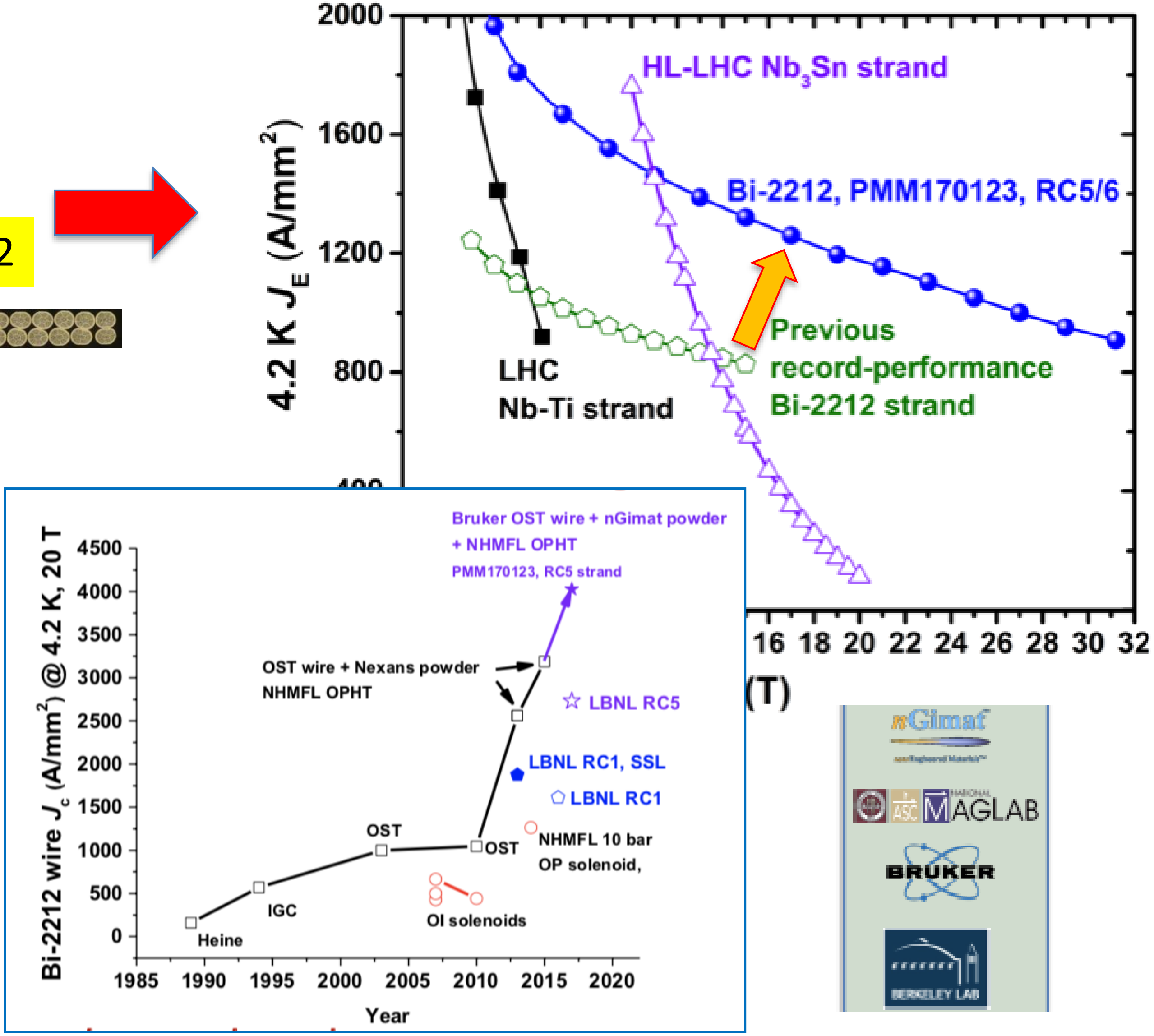
HTS, focusing on Bi2212 in the US



Bi-2212



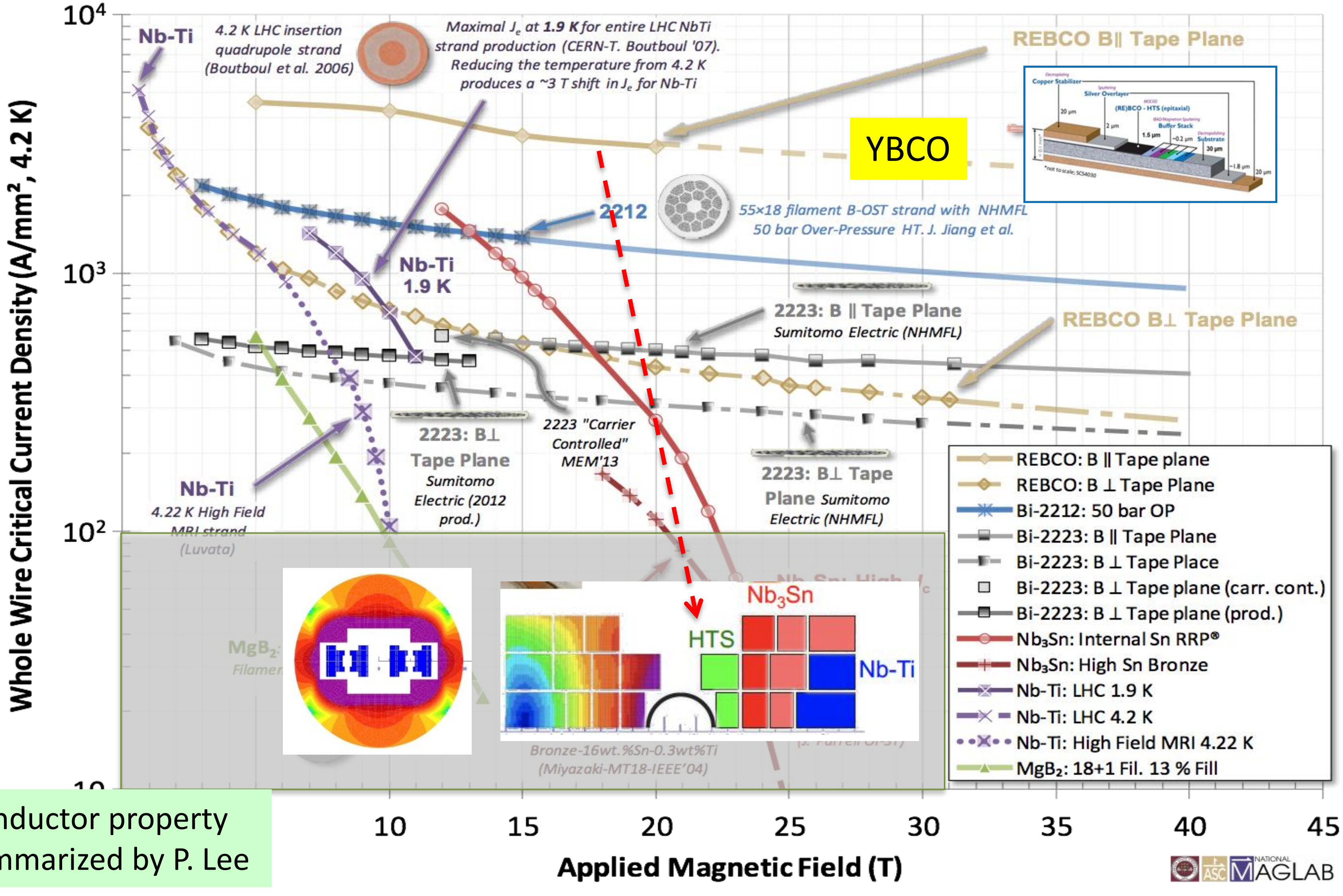
Application expected for CCT by using B2212

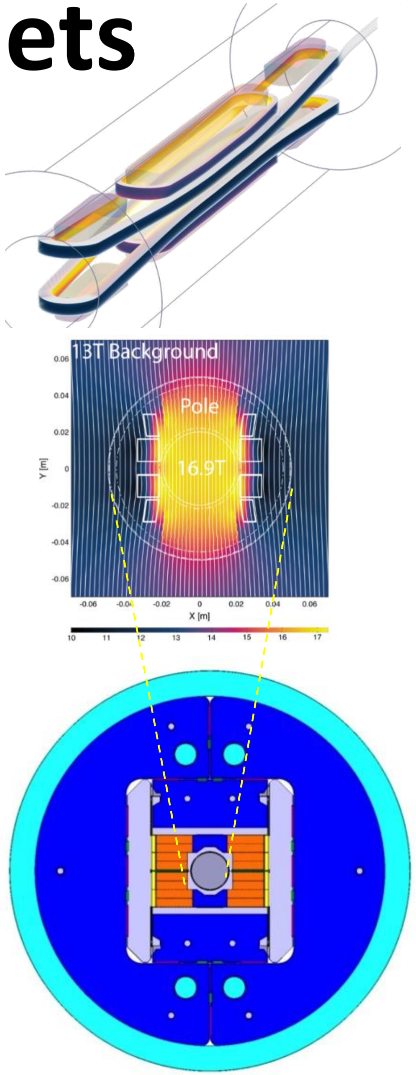


A. Yamamoto, 190512

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

High-Field Superconductor and Magnets

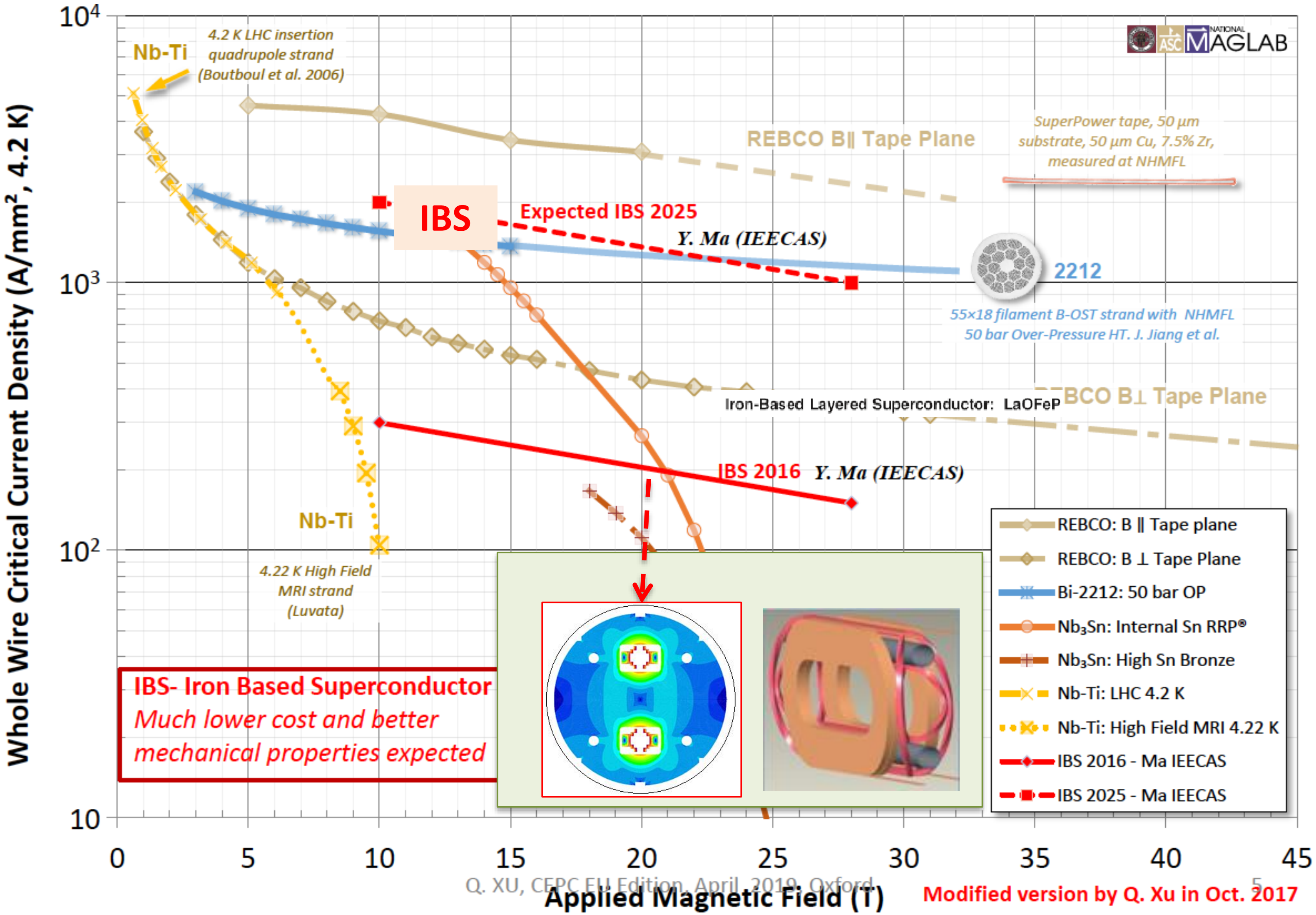




Conductor property summarized by P. Lee

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

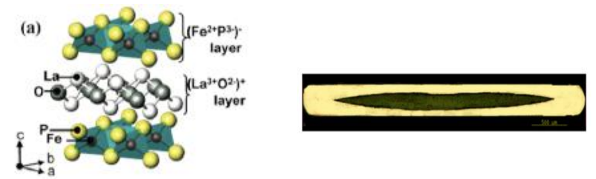
High-Field Superconductor and Magnet with IBS in China

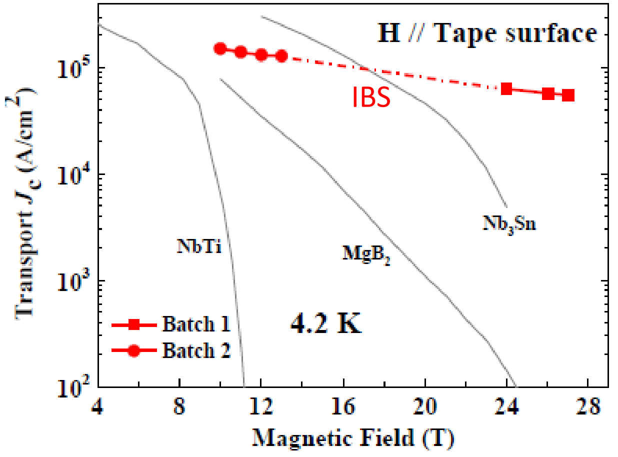


Modified version by Q. Xu in Oct. 2017

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

Iron-Based Layered Superconductor: LaOFeP





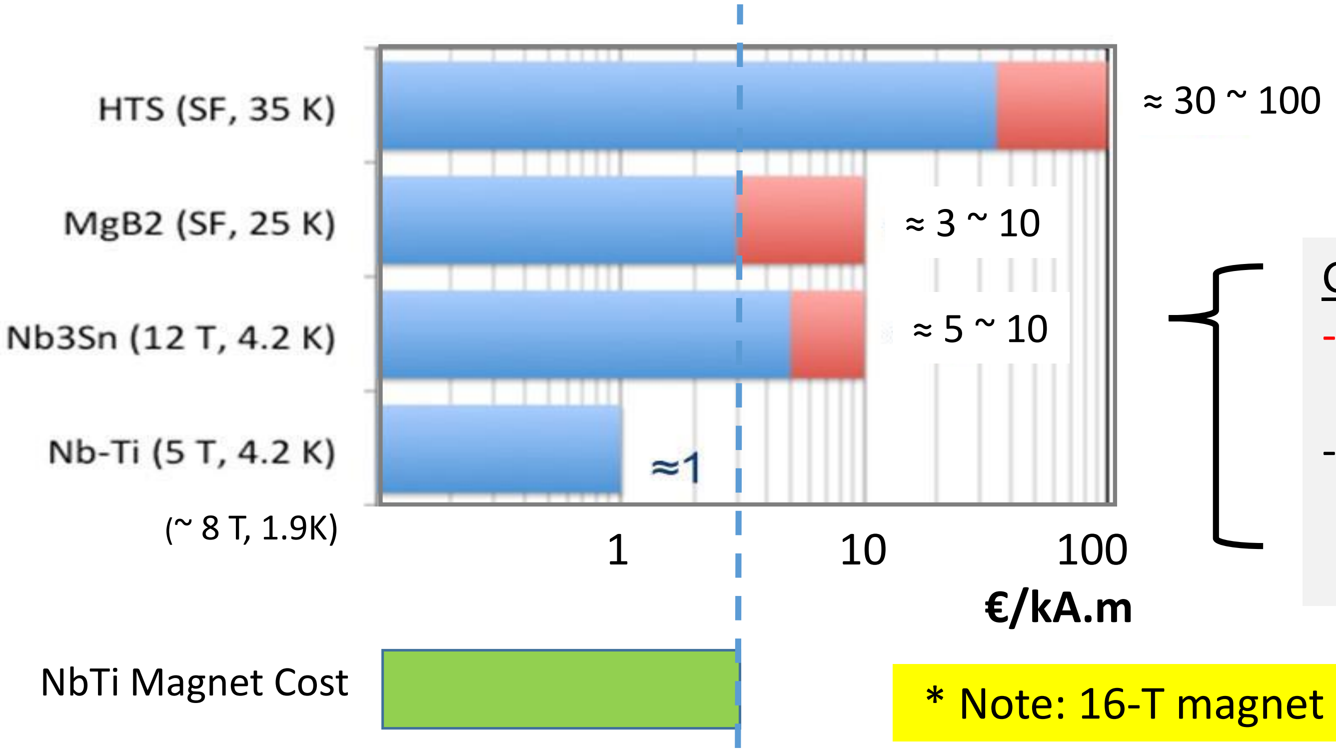
Y. Mao et al., Supercond. Sci. Technol. 31 (2018) 015017

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

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

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$_3$Sn 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.

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

- **Vaccum:**

- **Target for future high intensity facilities challenges:**
  - CERN specific requirements : ~355 kW average power, 2.5 MW pulse power , and extraction from SPS without increasing losses.
  - In general High cumulated radiation doses and radiation damage on materials

- **Collimators**
  - Absorb large amount of energy deposition without long term damage
  - Thermo-mecanical and temperature management with innovative production 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.
  - CLIC/ILC requirement: 3~5 MW/beam, DC, in main dump,

More in Appendix

Outline

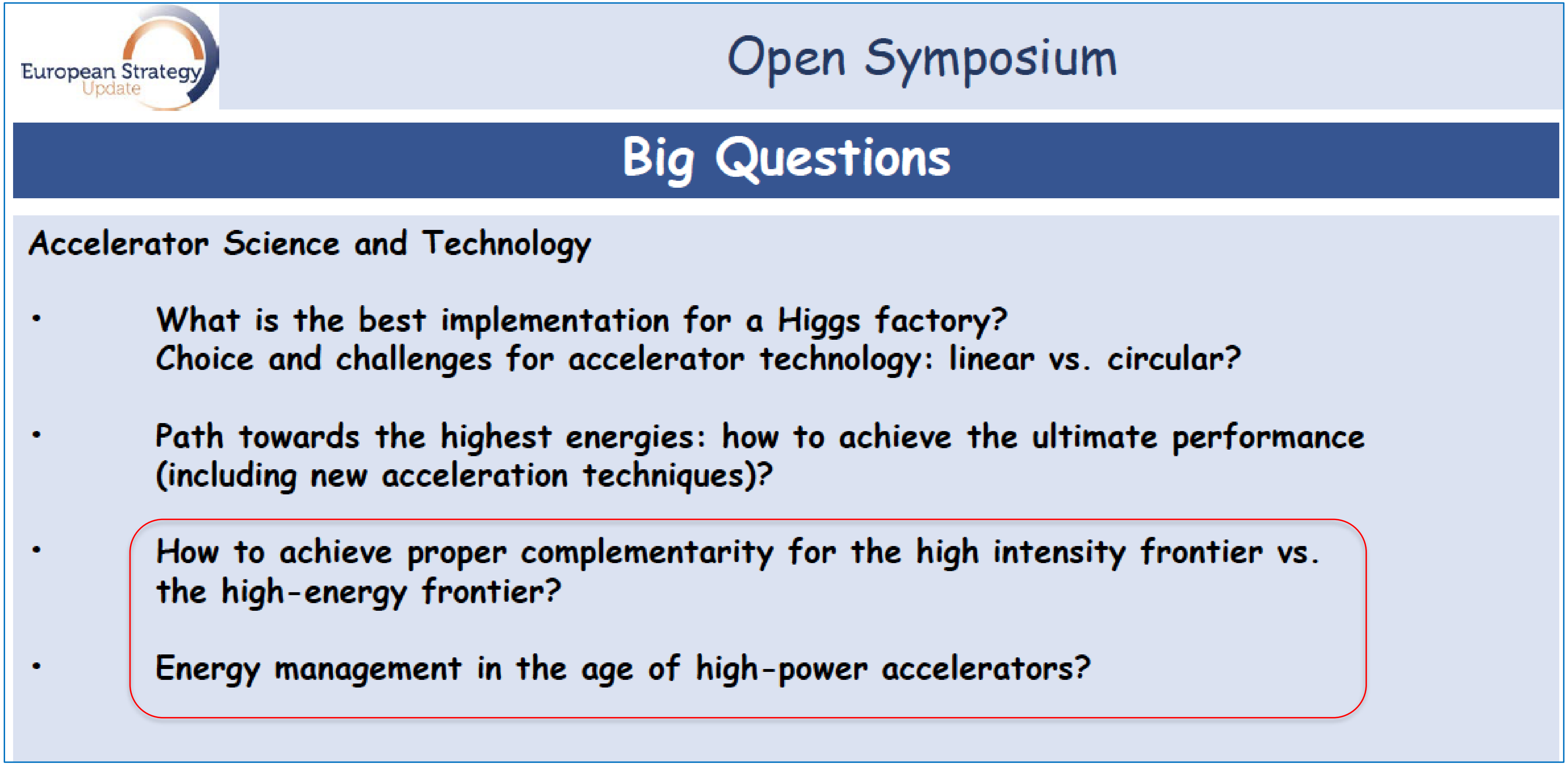
- **Introduction**
  - Advances in Accelerator Technology in Particle Physics
- **State of the Art in Accelerator Technologies, focusing on**
  - Nano-beam, Superconducting Magnet and RF, and Normal-conducting RF
- **Challenges for future, focusing on**
  - Key technologies and energy management for 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)



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

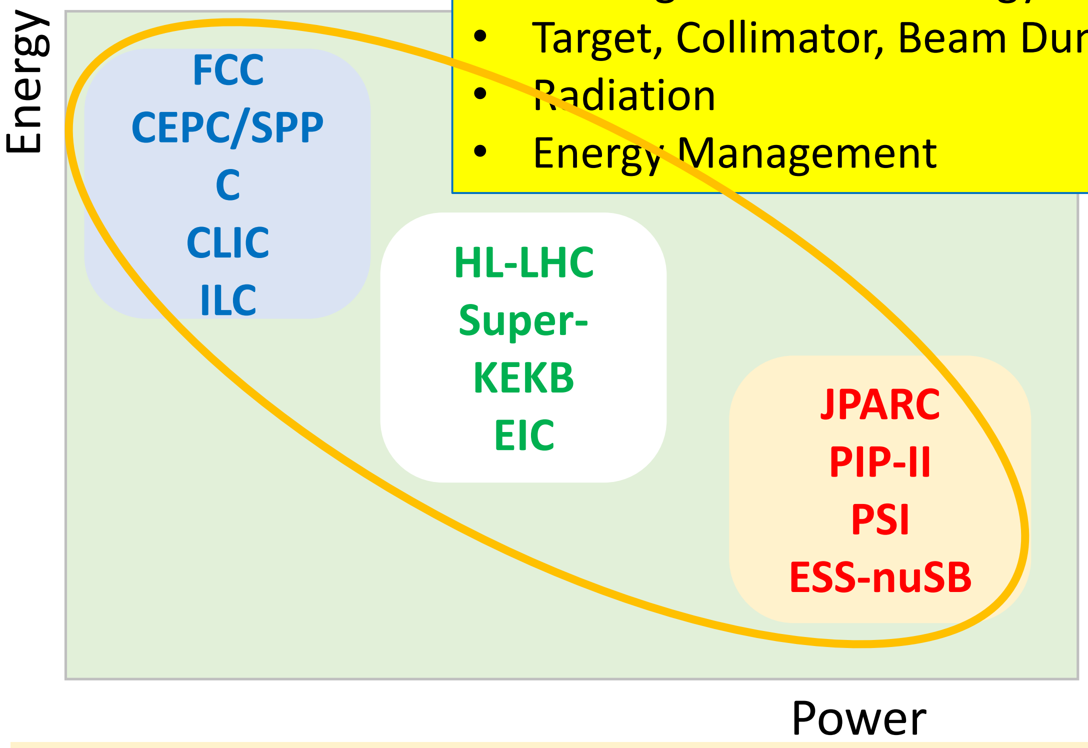
Intensity – Acc.	Energy [GeV]	Power [MW]	Acc. Tech. Feature	SC Tech.
SPS*	**450**		Synchrotron	
Fnal M. Injector	**120**	**0.7**	Synchrotron	
J-PARC*	**3** **30**	**1** **0,49 ~ 1.3**	Linac/Synchr Ext. Beam	**SCM**
PIP-II	**60 -120**	**.2**	Linac (SRF) Synchrotron	**SRF**
PSI-HIPA*	**0.59**	**1.4**	Cycrotron	
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, 190512

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)
    - Magnet --> high field
    - RF cavity -> High-G and High-Q
- **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
    - 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, and SRF:

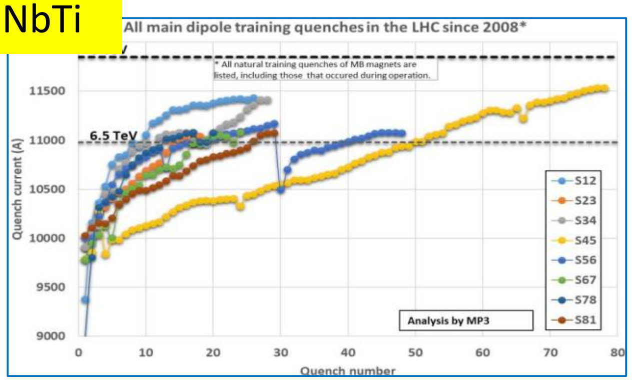
- NRF (~ 12 GHz, 20 cm unit): (CLIC R&D: 12 GHz): 70 ~ 100 MV/m
- SRF (1.3 GHz, 9-cell cavity): (Eu-XFEL) : 30 MV/m,
- SRF (Crab cavity); Experienced at KEK-B, an at CERN-SPS

SC Magnet:

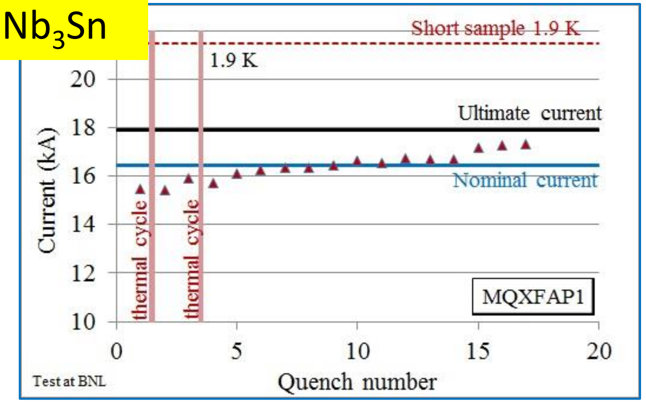
- NbTi: LHC (Main Dipole)
  - B_{bore} = ~ 8 T at 1.9 K . Re-training aft. thermal cycling (TC) still a major issue
- Nb3Sn: HL-LHC (11 T Dipole)
  - B_{bore} = ~ 11 T at 1.9 K. Good memory after TC, but more statistic needed

Note: Loadline-ratio, however, should be conservative

NbTi



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)
    - 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)

- RF 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.

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

<table>
<tr><th>Timeline</th><th>~ 5</th><th>~ 10</th><th>~ 15</th><th>~ 20</th><th>~ 25</th><th>~ 30</th><th>~ 35</th></tr>
<tr><td colspan="8">Lepton Colliders</td></tr>
<tr><td>SRF-LC/CC</td><td>Proto/pre-series</td><td colspan="2">Construction</td><td colspan="2">Operation</td><td colspan="2">Upgrade</td></tr>
<tr><td>NRF—LC</td><td>Proto/pre-series</td><td colspan="2">Construction</td><td colspan="2">Operation</td><td colspan="2">Upgrade</td></tr>
<tr><td colspan="8">Hadron Collier (CC)</td></tr>
<tr><td>8~(11)T
NbTi /(Nb3Sn)</td><td>Proto/pre-series</td><td colspan="2">Construction</td><td colspan="3">Operation</td><td>Upgrade</td></tr>
<tr><td>12~14T
Nb_3Sn</td><td colspan="2">Short-model R&D</td><td>Proto/Pre-series</td><td colspan="2">Construction</td><td colspan="2">Operation</td></tr>
<tr><td>14~16T
Nb_3Sn</td><td colspan="2">Short-model R&D</td><td colspan="3">Prototype/Pre-series</td><td colspan="2">Construction</td></tr>
</table>

Note: LHC magnet R&D, **NbTi for 10 T at 1.9 K**, started in 1980’s and the production started in late 1990’s, in **~ 15 years**

Appendix

-

Personal Prospect (2/3)

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

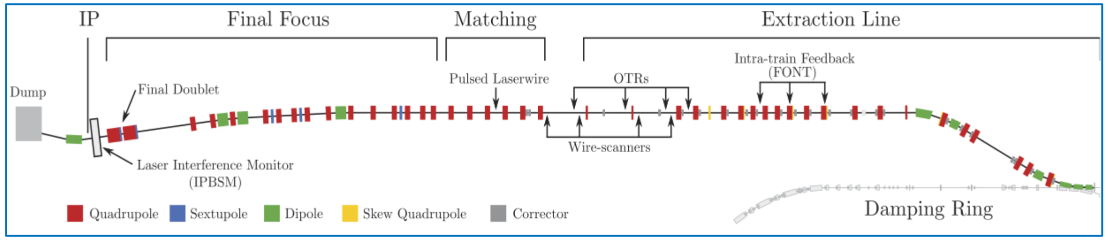
Progress in FF Beam Size and Stability at ATF2

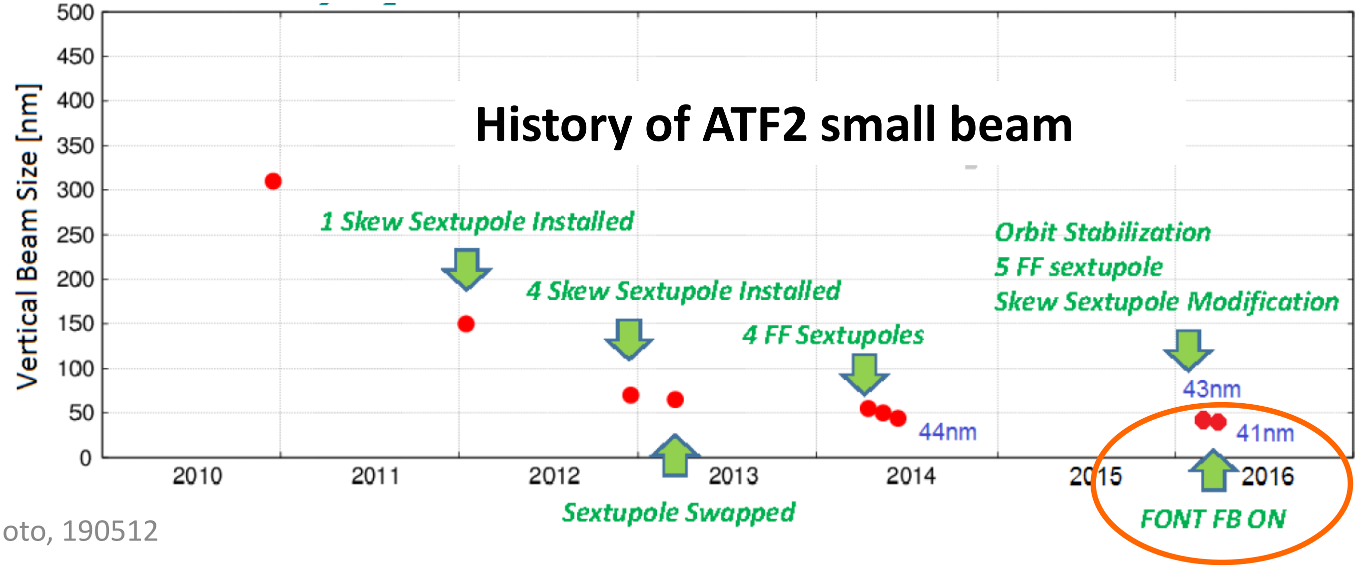
Goal 1: Establish the FF method with same optics and comparable beamline tolerances

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

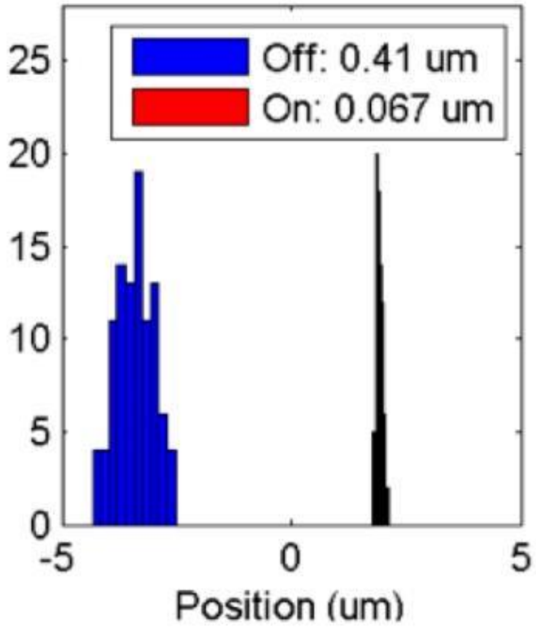
Goal 2: Develop nm position stabilization at FF:

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





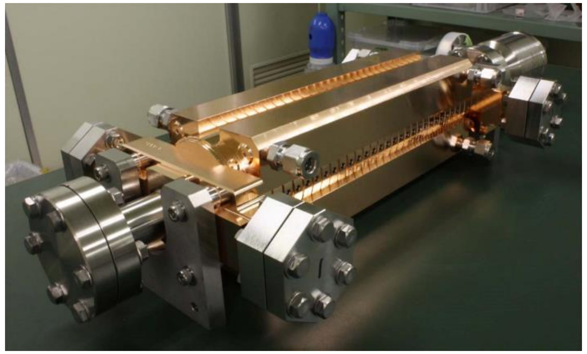
Nano-meter stabilization at FF

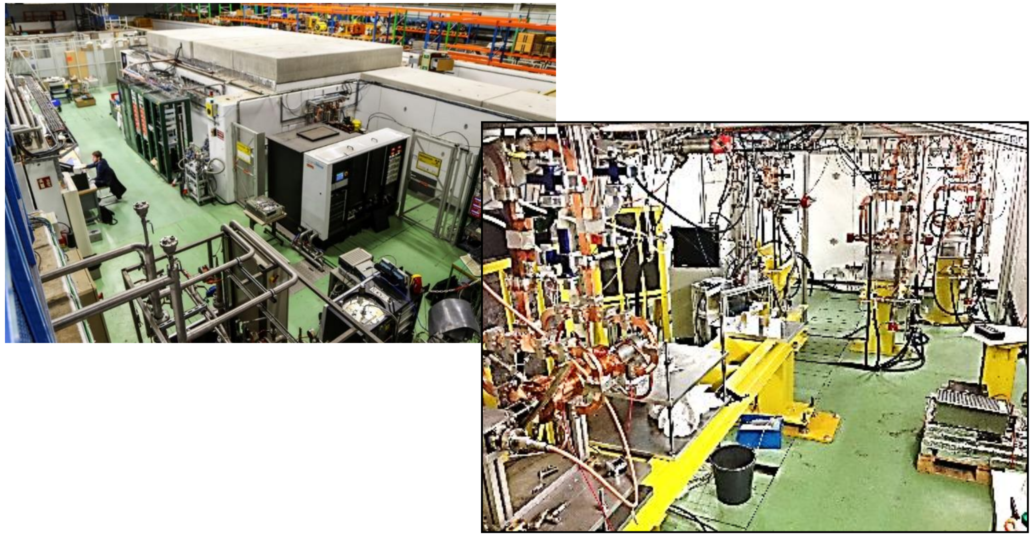


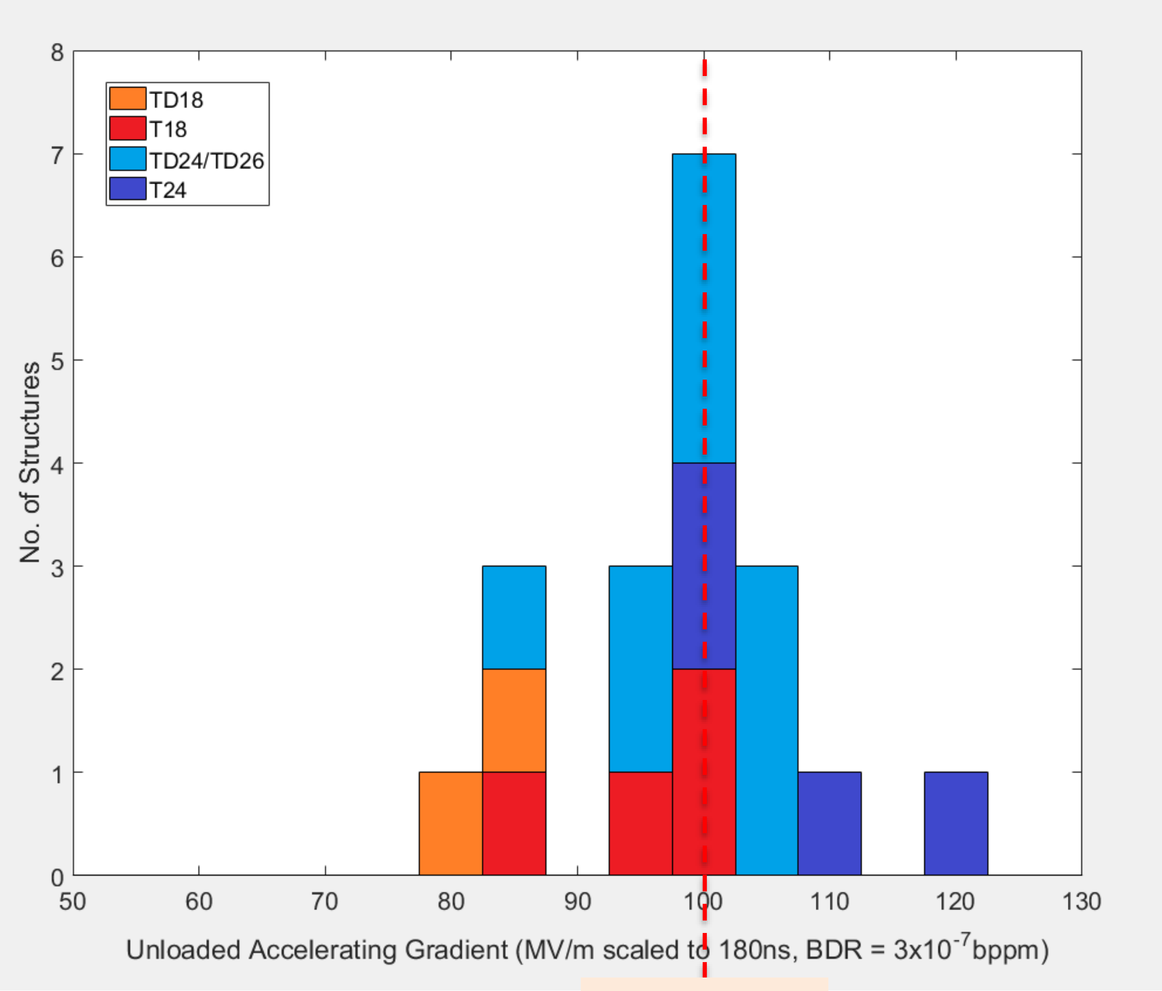
Curtesy: S. Stapnes, P. Barlow, W. Wuensch

Progress in Normal Conducting RF Acc. Structure

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





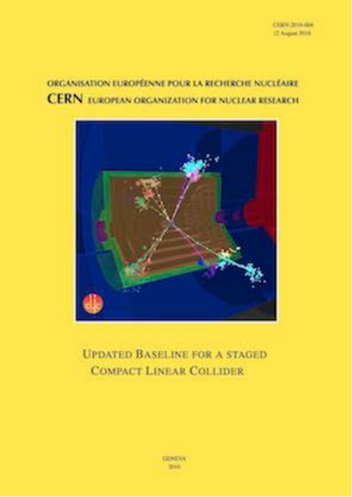


100 MV/m

A. Yamamoto, 190512

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

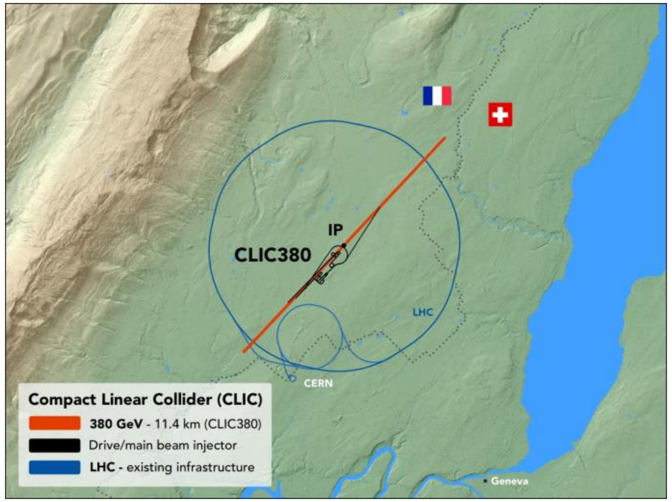
NRF Technology for CLIC-380 and beyond

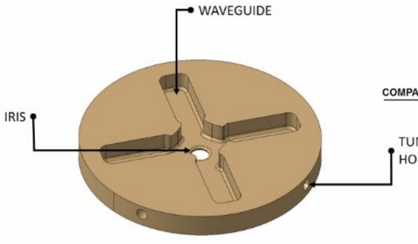


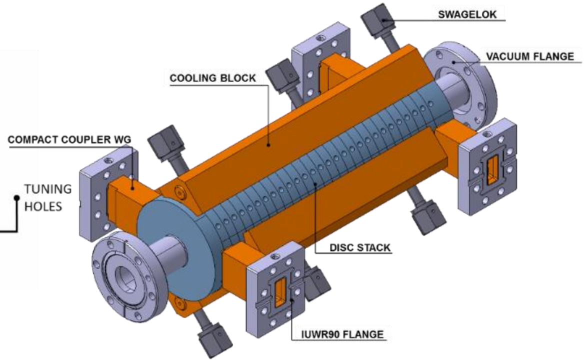
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

UPDATED BASELINE FOR A STAGED
COMPACT LINEAR COLLIDER

GENEVA
2016







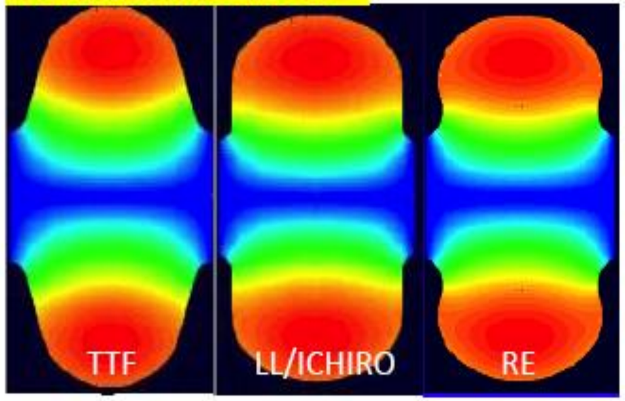
- Linear e^+e^- collider, staged **$\sqrt{s}$ = 0.38 TeV**
- **70 MV/m** accelerating gradient needed for compact (~11 km) machine based on :
  - normal-conducting accelerating structures
  - two-beam acceleration scheme
- **Issue remaining:**
  - Power efficiency at higher energies
  - Large scale production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

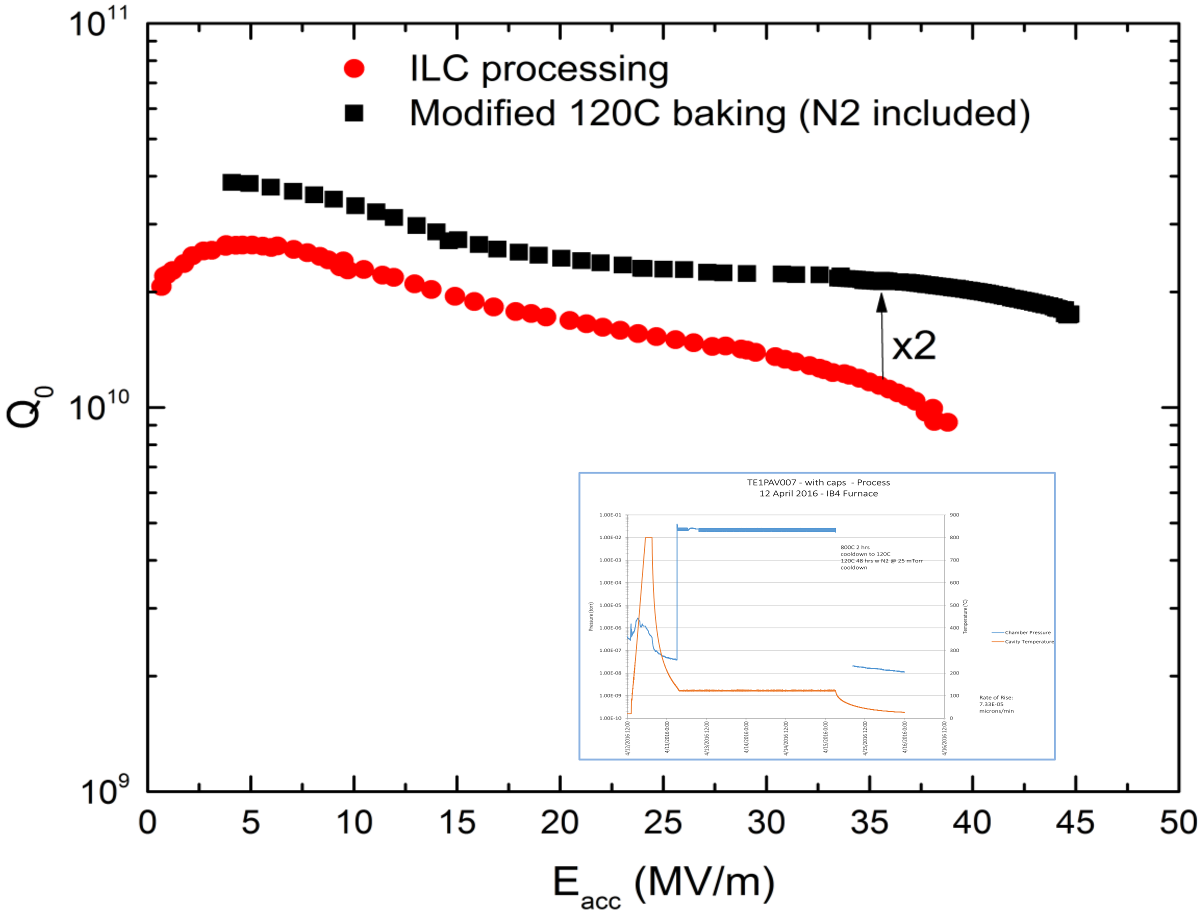


from J.Sekutowicz lecture Note

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

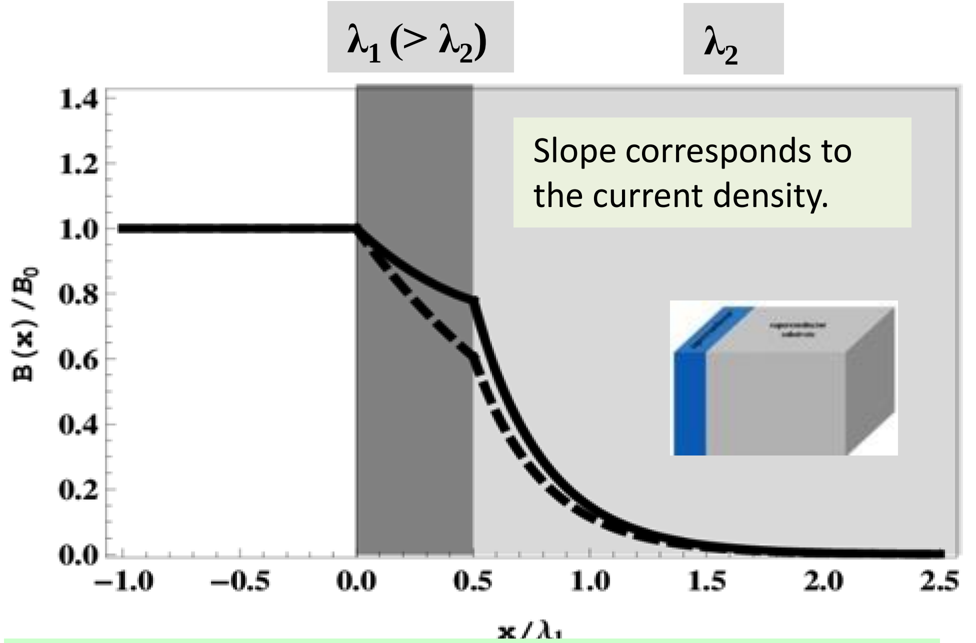
arXiv:1701.06077

- 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.



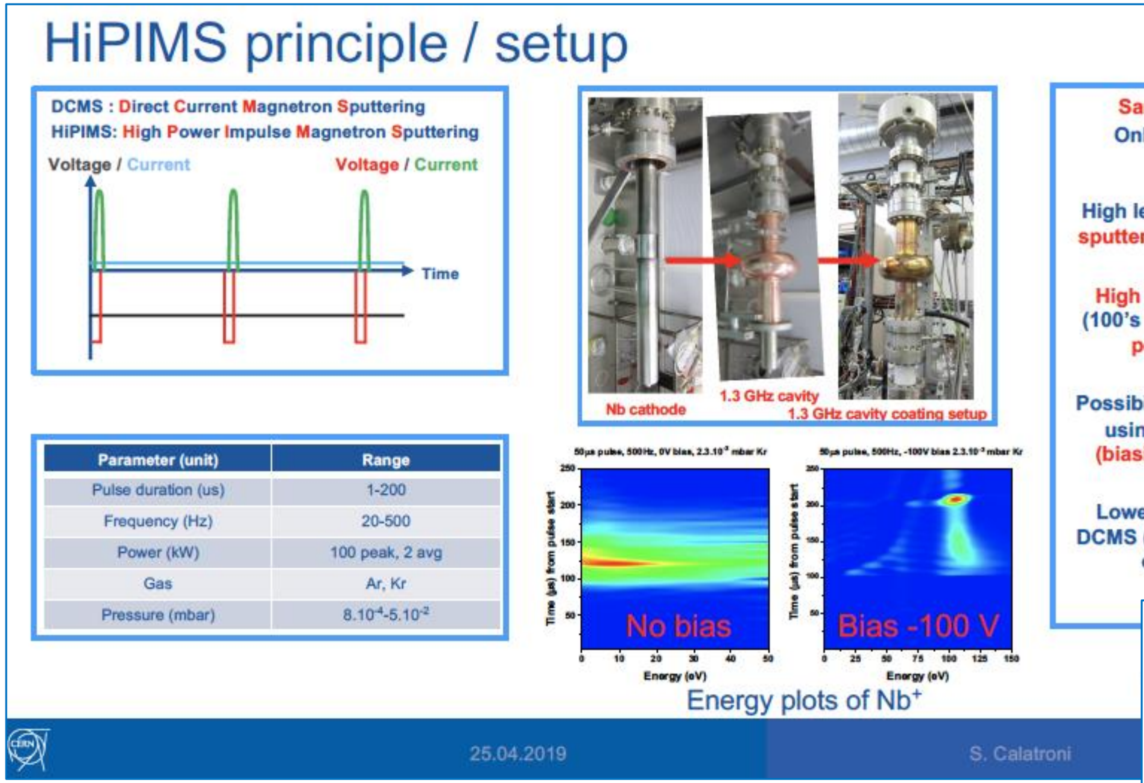
Slope corresponds to the current density.

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

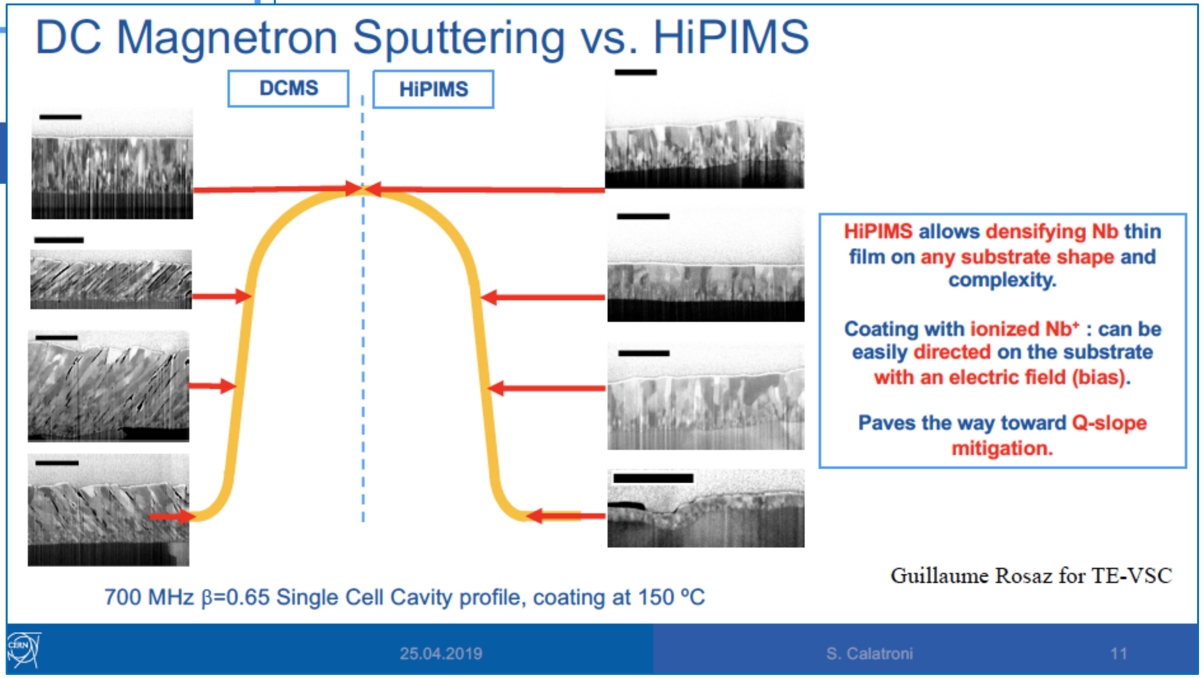
High level of ionization of the sputtered species (up to 70%)

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)

25.04.2019 S. Calatroni



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.

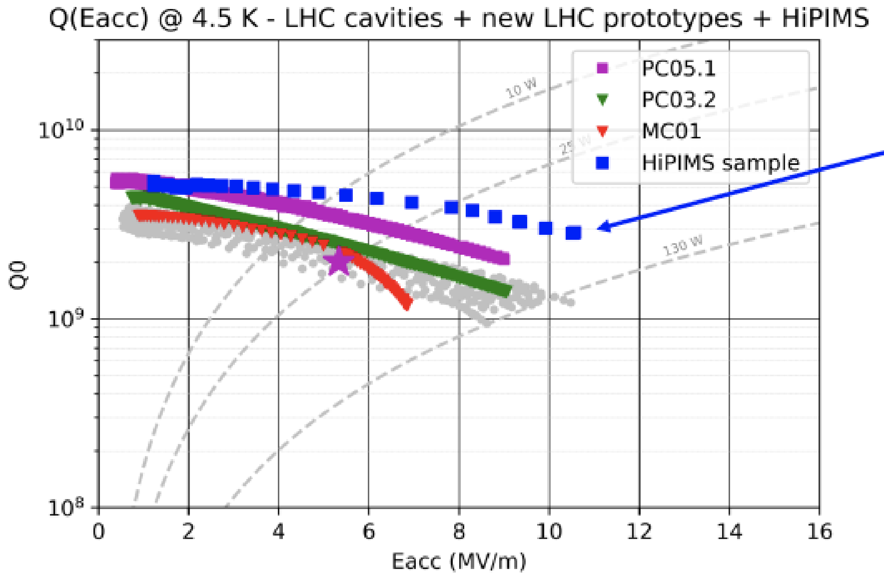
Guillaume Rosaz for TE-VSC

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

25.04.2019 S. Calatroni 11

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

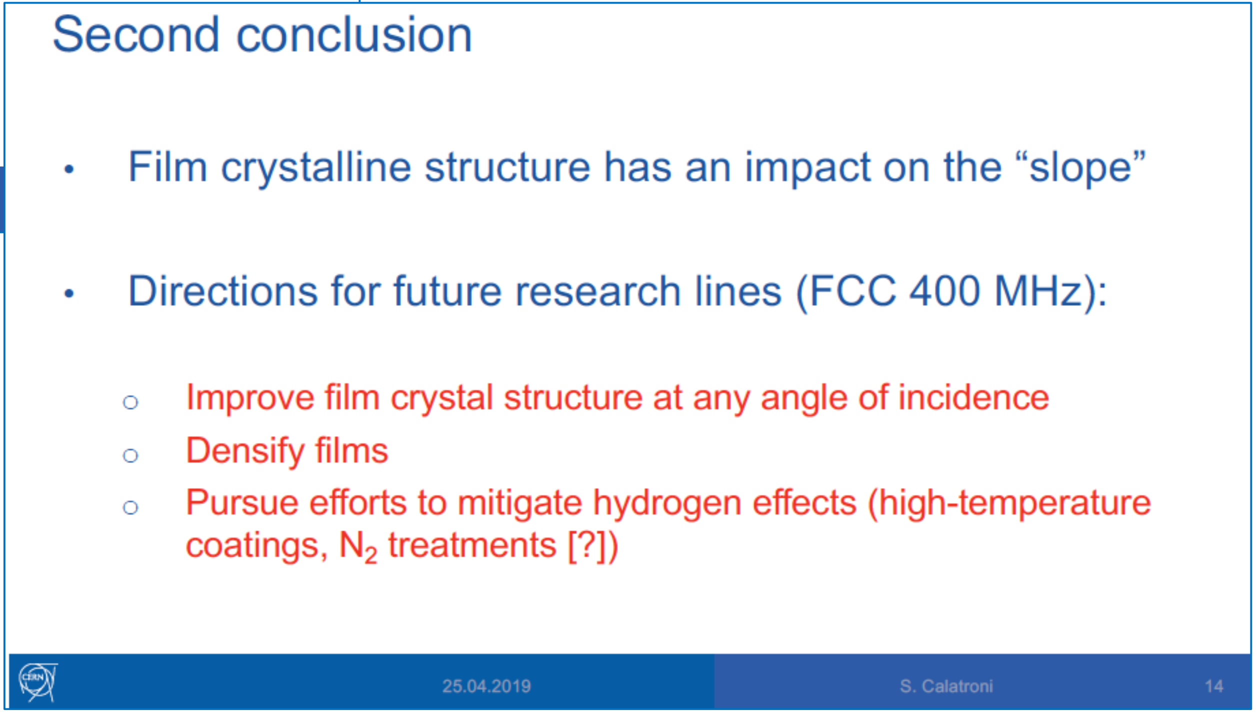
Q-slope phenomenon strongly suppressed and support the effort to evolve this technology into real cavities.

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 [?])

25.04.2019

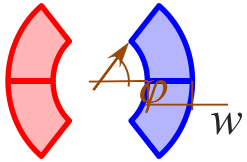
S. Calatroni

14

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

Nb_3Sn conductor program

Figures to be updated



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

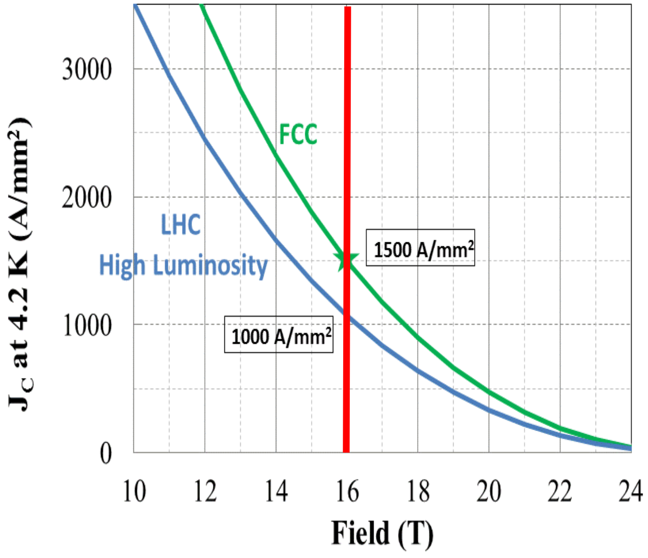
- **Nb_3Sn** is one of the **major cost & performance** factors for FCC-hh
- **Highest attention** is given

Main development goals:

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

Global cooperation:

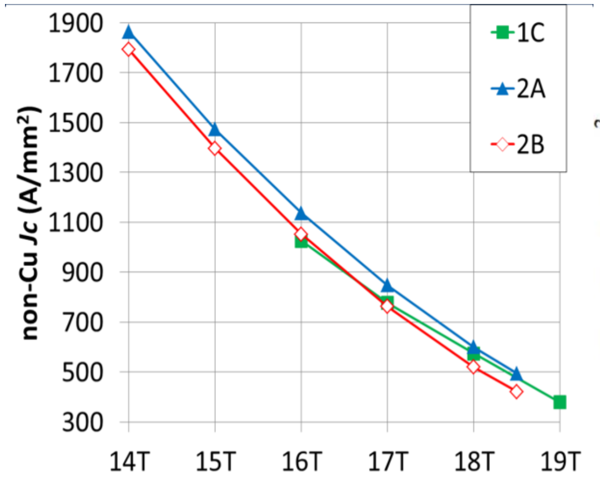
- CERN/KEK/Tohoku/JASTEC/Furukawa
- CERN/Bochvar High-tec. Res. Inst
- CERN/KAT
- CERN/Bruker
- T.U. Vienna, Geneve U., U. Twente,
- Florida S.U. - Appl. Superc. Center
- New US-DOE-**MDP**



Requirement (FCC)

Non-Cu

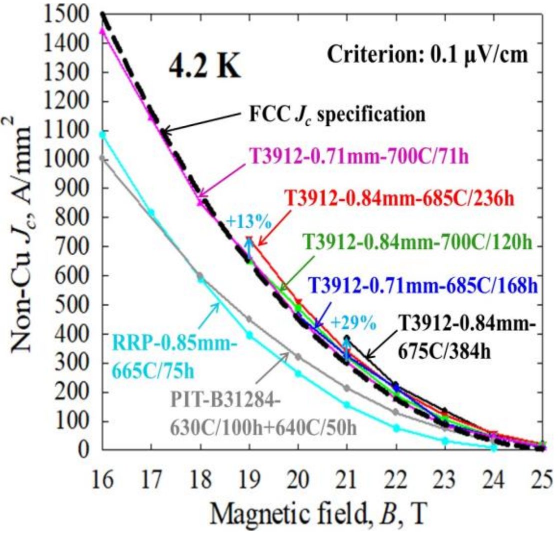
J_c : 1,137 A/mm² @16T



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

Non-Cu

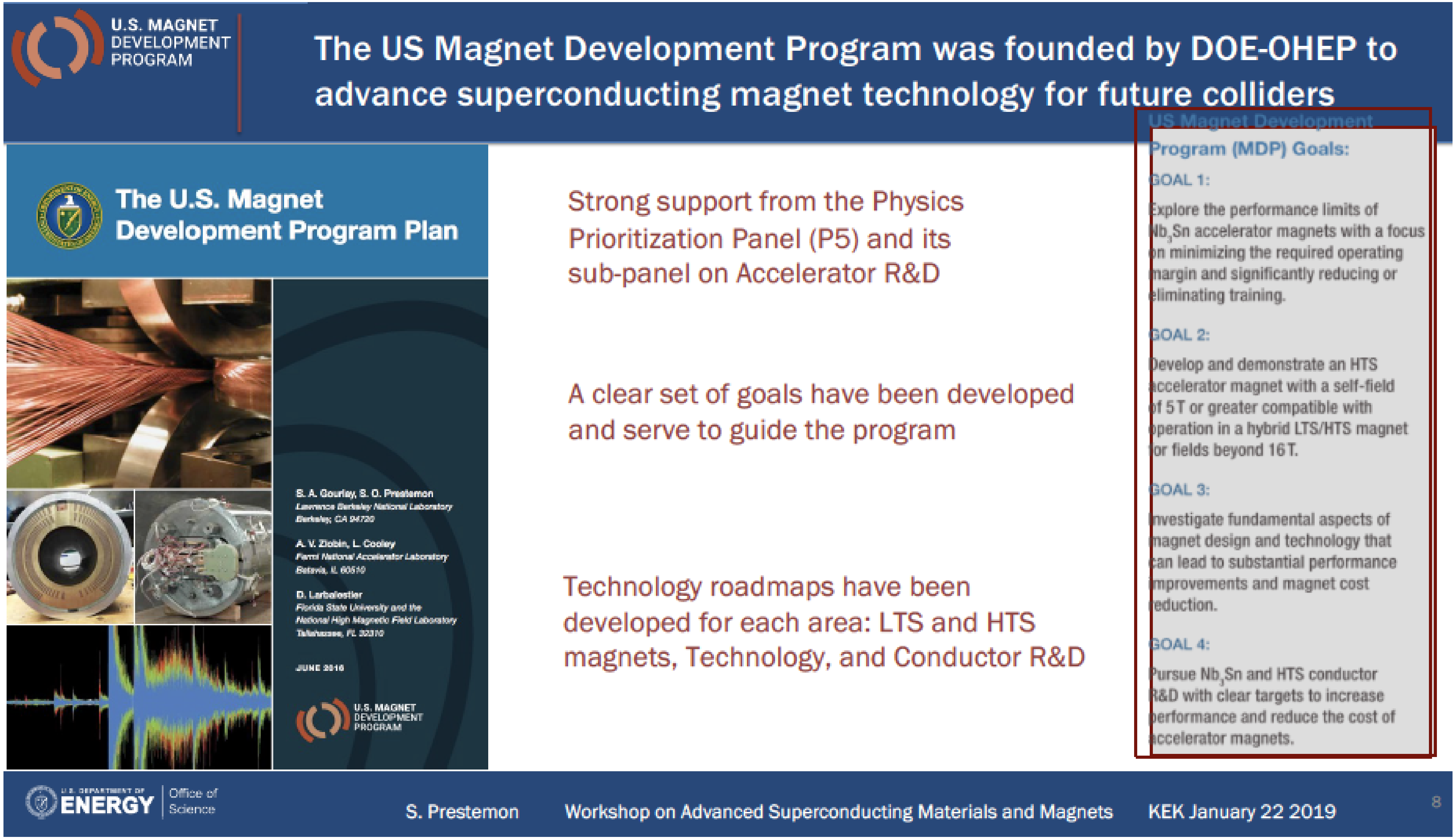
J_c : ~ 1,450 A/mm² @16T



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

https://arxiv.org/abs/1903.08121

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

The U.S. Magnet Development Program Plan

S. A. Gourlay, S. O. Prestemon
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory
Batavia, IL 60510

D. Larbalestier
Florida State University and the
National High Magnetic Field Laboratory
Tallahassee, FL 32310

JUNE 2016

U.S. MAGNET
DEVELOPMENT
PROGRAM

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.

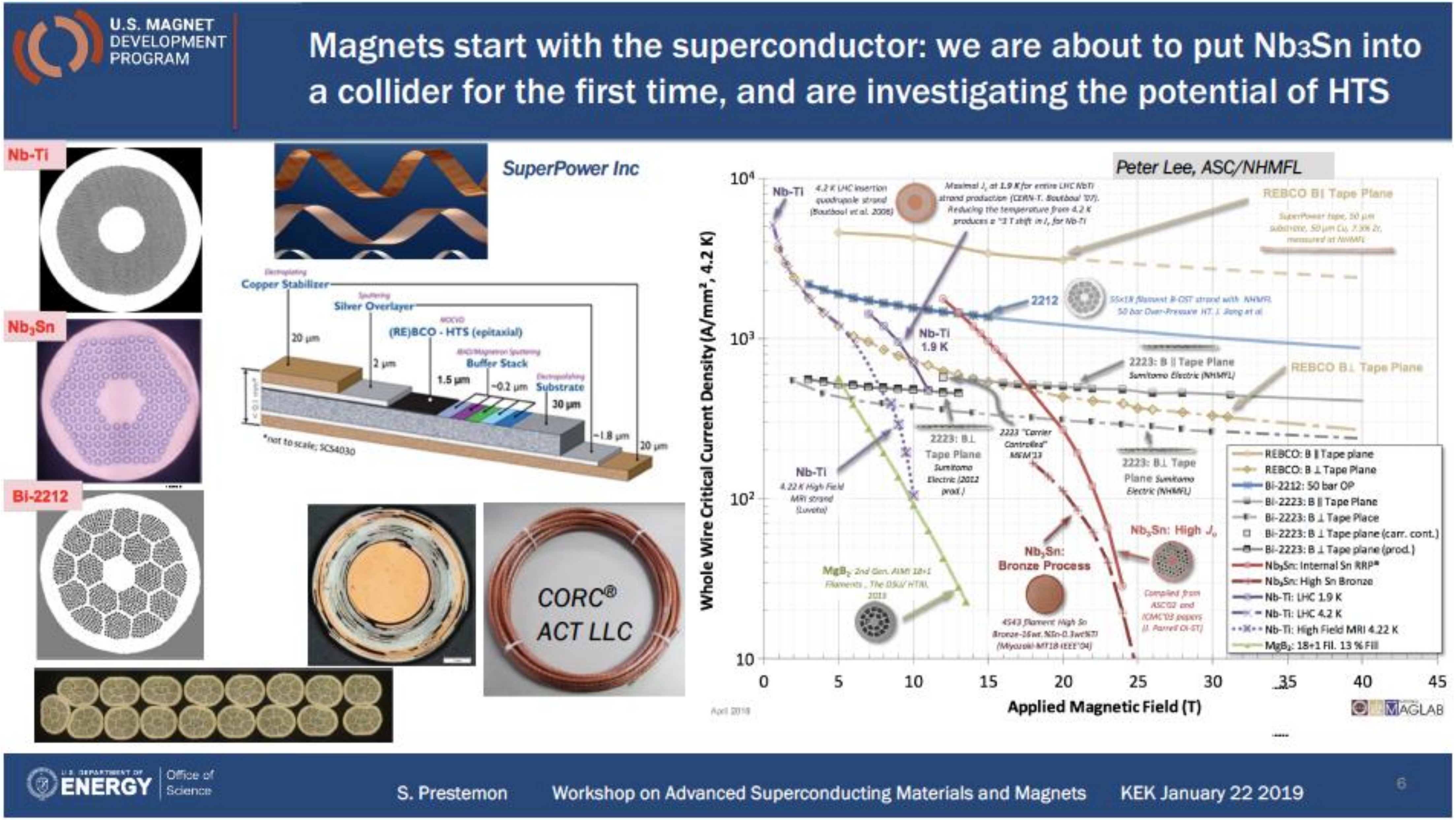
GOAL 4:

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

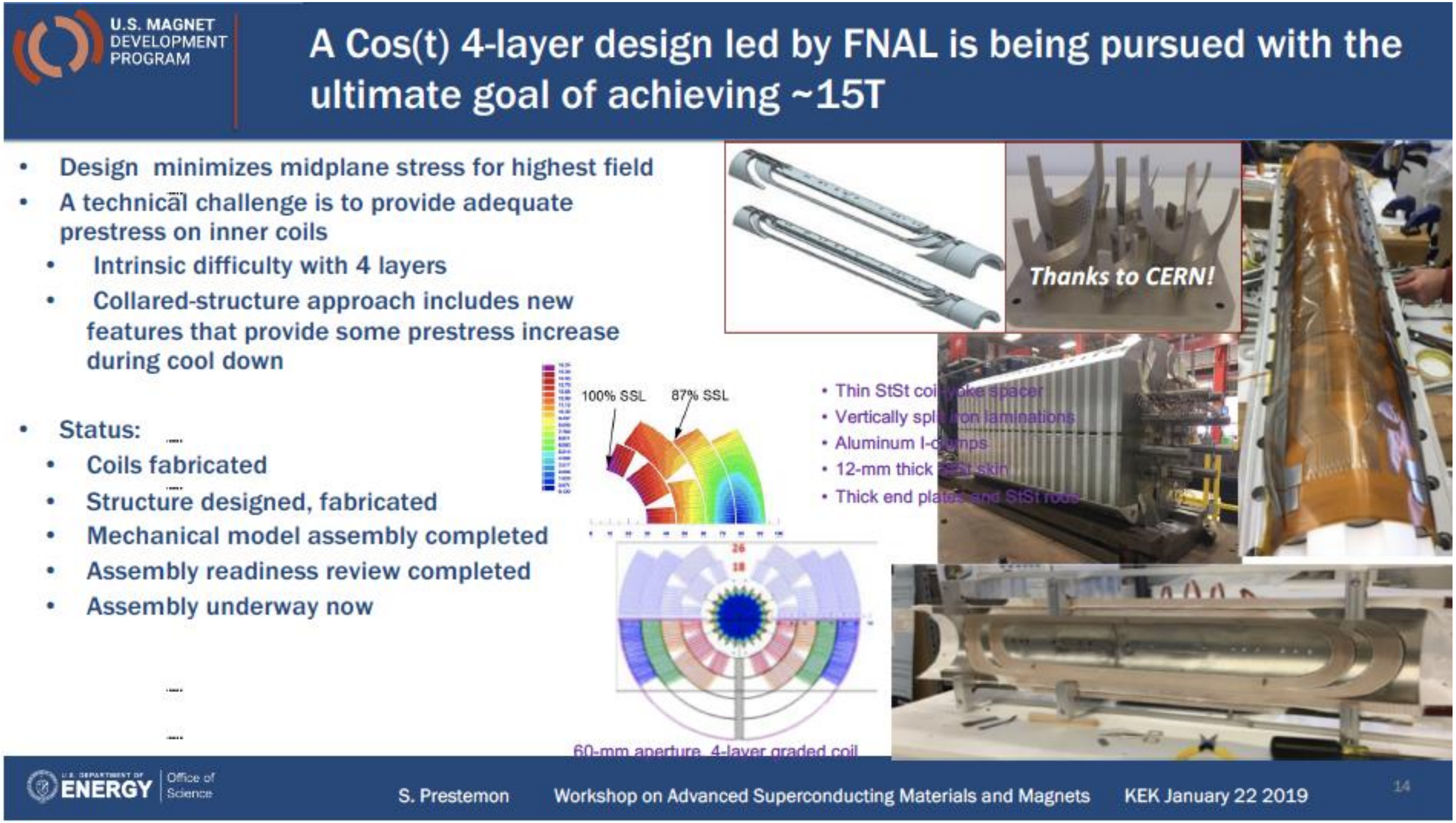


U.S. MAGNET DEVELOPMENT PROGRAM

Magnets start with the superconductor: we are about to put Nb3Sn 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



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

- Thin StSt coil-yoke spacer
- Vertically split iron laminations
- Aluminum I-clamps
- 12-mm thick StSt skin
- Thick end plates and StSt rods

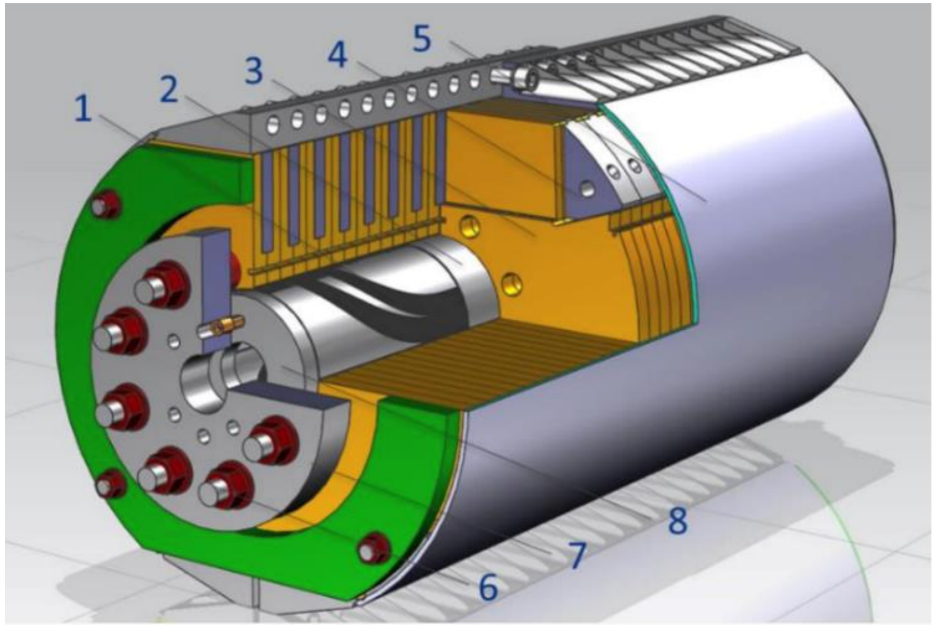
60-mm aperture, 4-layer graded coil

U.S. DEPARTMENT OF ENERGY Office of Science S. Prestemon Workshop on Advanced Superconducting Materials and Magnets KEK January 22 2019 14

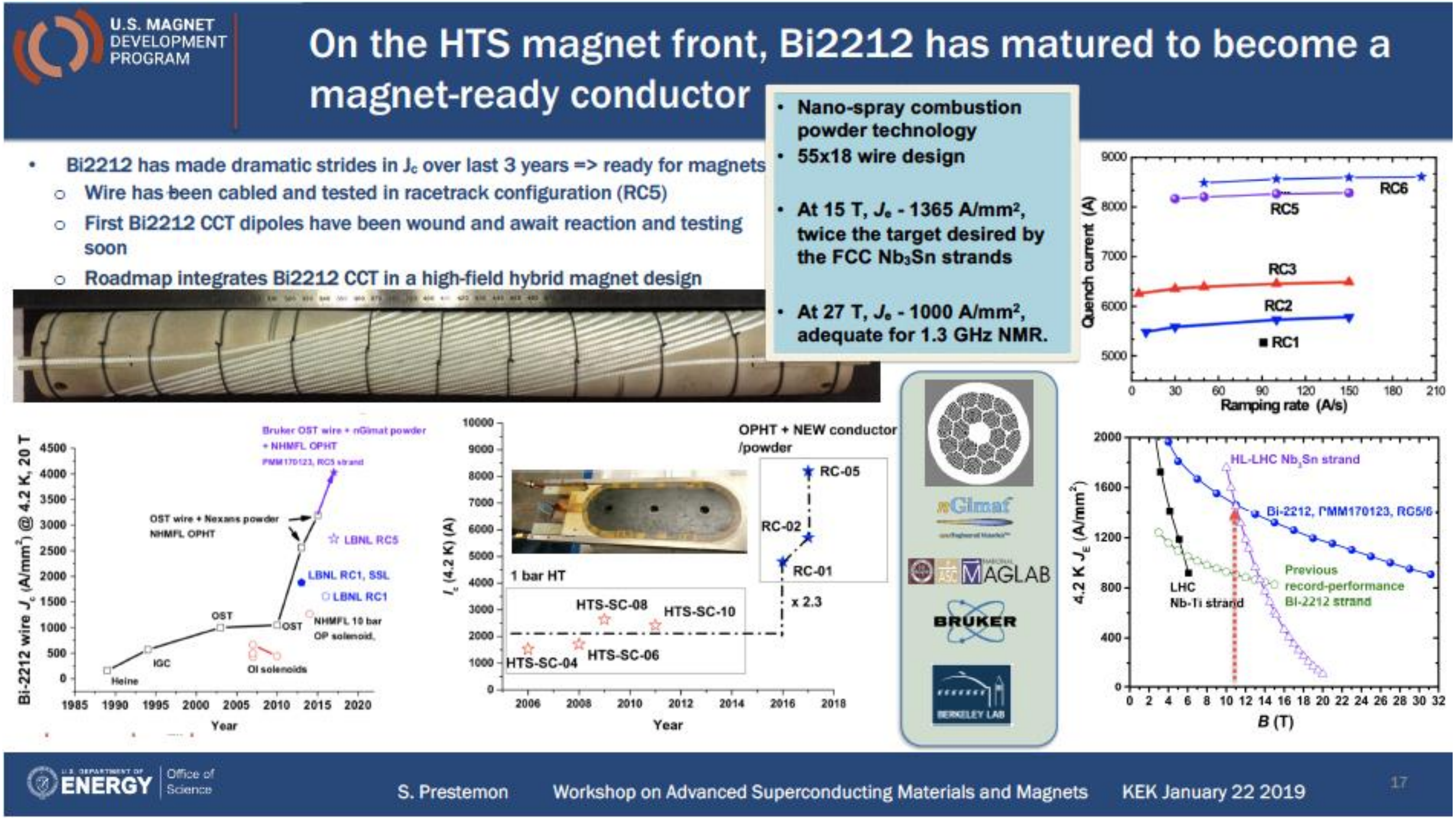
Courtesy: S. Belomstnykh

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



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.**

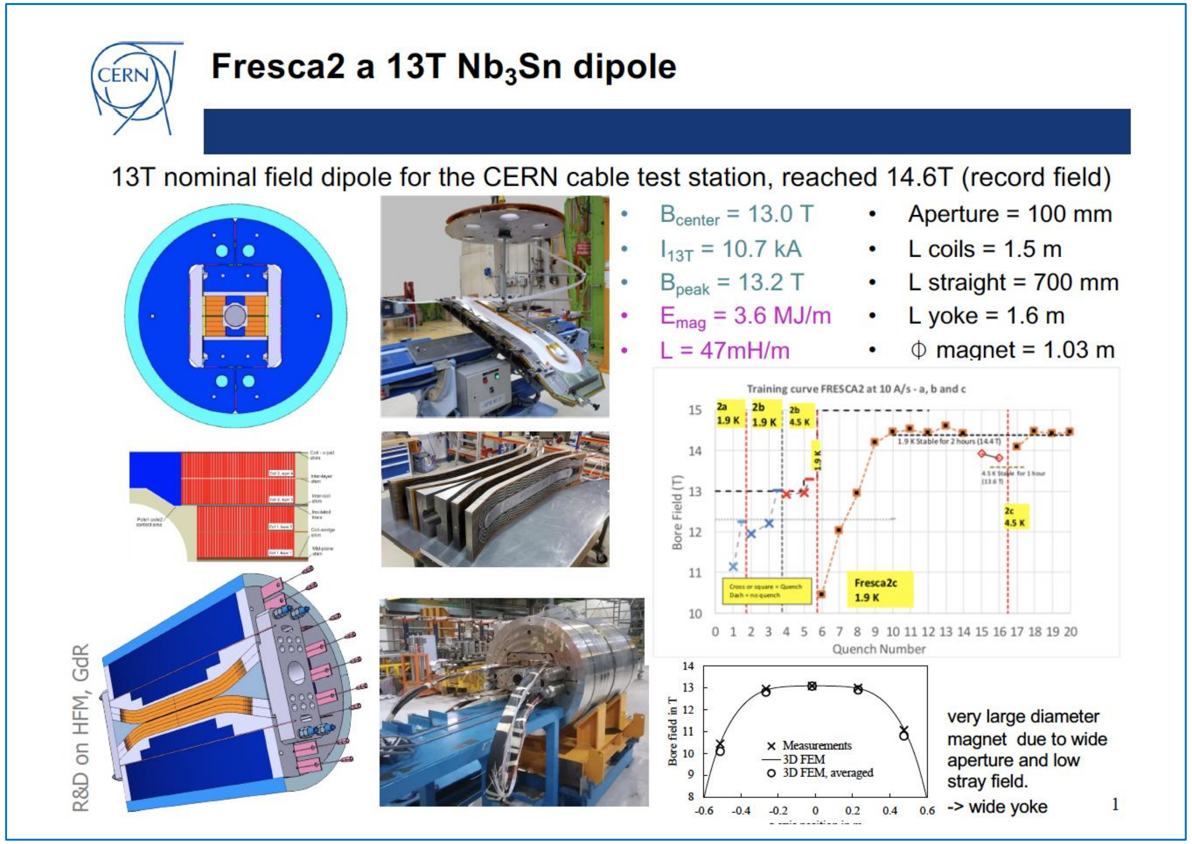
U.S. DEPARTMENT OF ENERGY | Office of Science

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

17

Courtesy: G. de Rick

FRESCA2 + HTS-Insert



Fresca2 a 13T Nb_3Sn dipole

13T nominal field dipole for the CERN cable test station, reached 14.6T (record field)

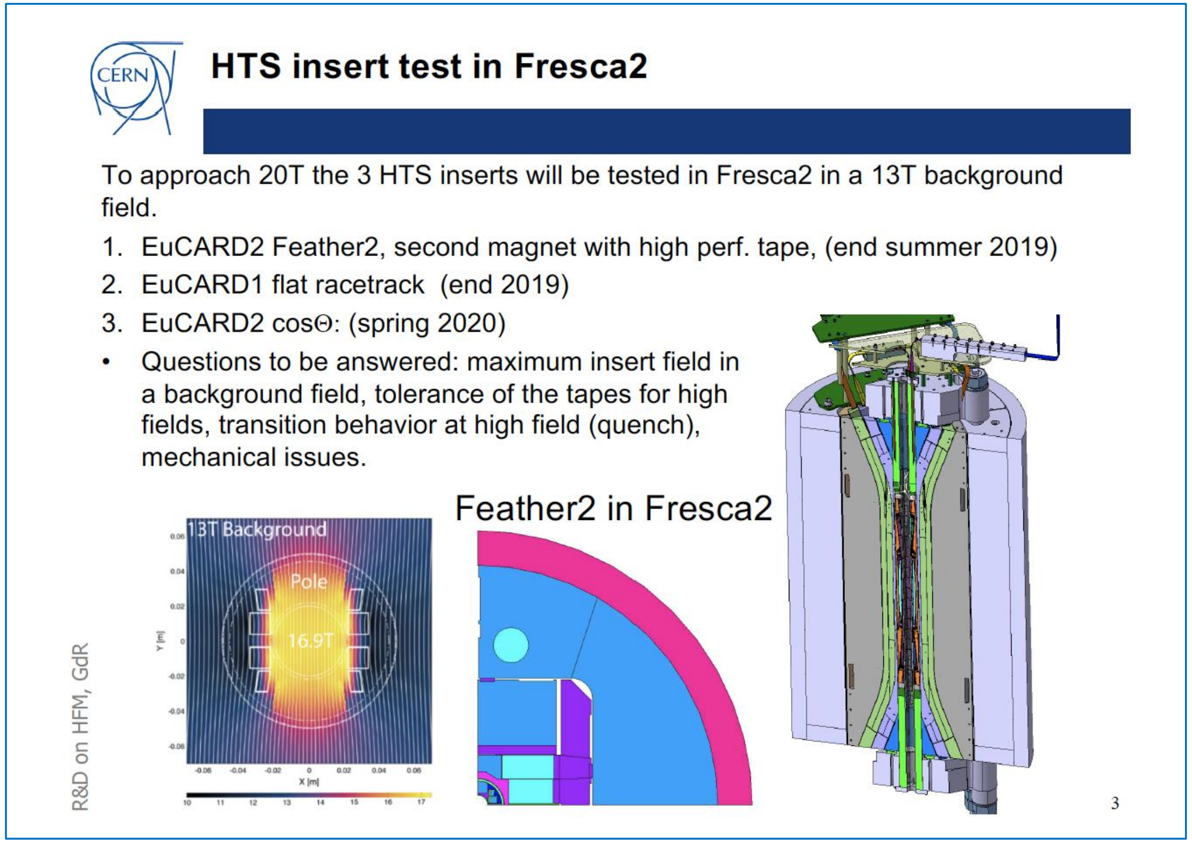
- B_{center} = 13.0 T
- I_{13T} = 10.7 kA
- B_{peak} = 13.2 T
- E_{mag} = 3.6 MJ/m
- L = 47mH/m

- Aperture = 100 mm
- L coils = 1.5 m
- L straight = 700 mm
- L yoke = 1.6 m
- Φ magnet = 1.03 m

very large diameter magnet due to wide aperture and low stray field.
-> wide yoke

R&D on HFM, GdR

1



HTS insert test in Fresca2

To approach 20T the 3 HTS inserts will be tested in Fresca2 in a 13T background field.

1. EuCARD2 Feather2, second magnet with high perf. tape, (end summer 2019)
2. EuCARD1 flat racetrack (end 2019)
3. EuCARD2 cosΘ: (spring 2020)

- Questions to be answered: maximum insert field in a background field, tolerance of the tapes for high fields, transition behavior at high field (quench), mechanical issues.

Feather2 in Fresca2

R&D on HFM, GdR

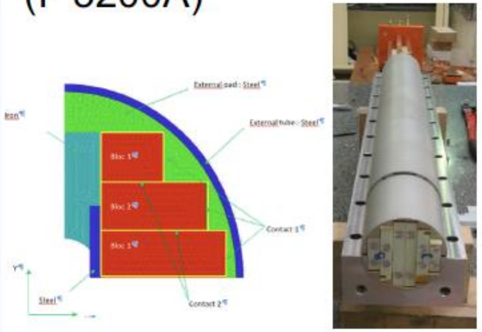
3

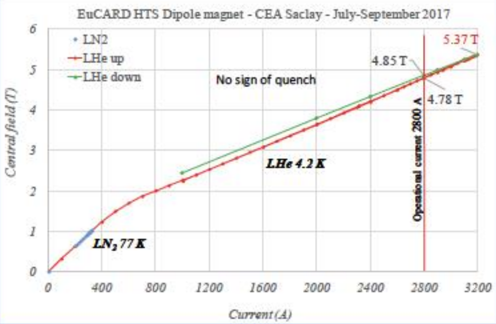
Courtesy: G. de Rick

Three HTS inserts (CERN and collaborations)

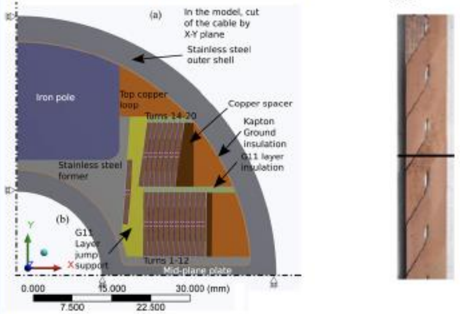
R&D on HFM, GdR

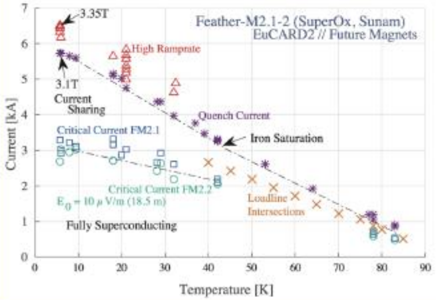
EuCARD1: insert (CEA-CNRS-CERN), flat racetrack, ReBCO 4 tape stack cable,stand alone tested Sept 2017: Reached 5.37 T @ 4.2K (I=3200A)



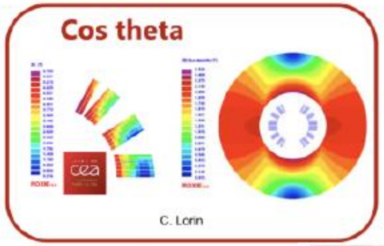


EuCARD2: Feather-M2 (CERN), flared ends coil ReBCO, Roebel cable, First magnet (low perf tape), stand alone tested Apr 2017: Reached 3.37 T @ 4.2K (I=6500A)





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

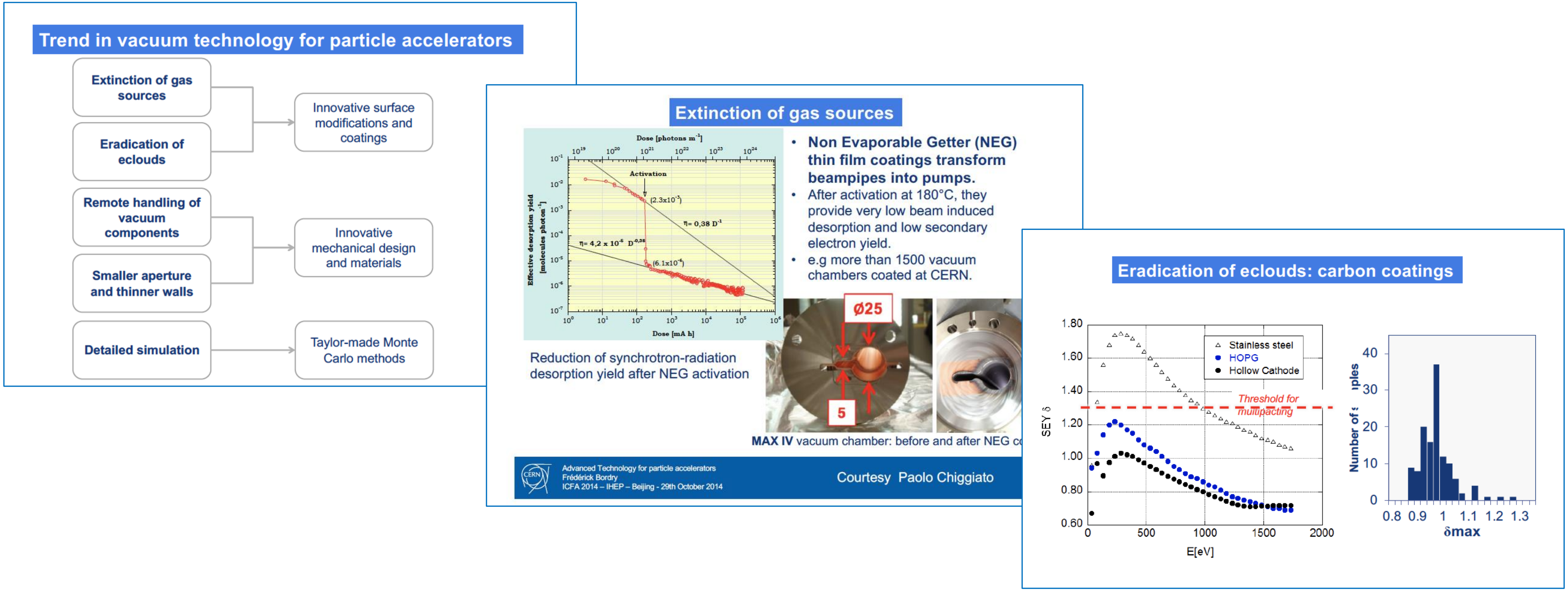


Design parameters (**SuperPower** Cable)

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



Trend in vacuum technology for particle accelerators

Extinction of gas sources
Eradication of eclouds
→ Innovative surface modifications and coatings

Remote handling of vacuum components
Smaller aperture and thinner walls
→ Innovative mechanical design and materials

Detailed simulation → Taylor-made Monte Carlo methods

Extinction of gas sources

Reduction of synchrotron-radiation desorption yield after NEG activation

- **Non Evaporable Getter (NEG) thin film coatings transform beampipes into pumps.**
- After activation at 180°C, they provide very low beam induced desorption and low secondary electron yield.
- e.g more than 1500 vacuum chambers coated at CERN.

MAX IV vacuum chamber: before and after NEG c

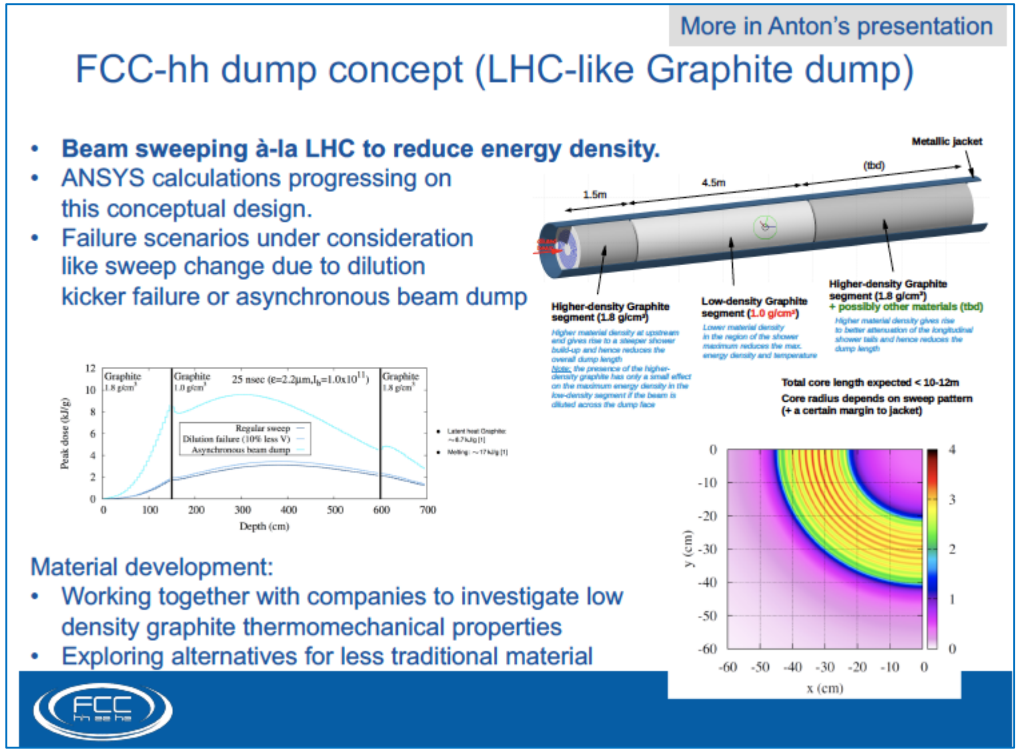
Advanced Technology for particle accelerators
Frédérick Bordry
ICFA 2014 – IHEP – Beijing - 29th October 2014

Courtesy Paolo Chiggiato

Eradication of eclouds: carbon coatings

Courtesy: S. Gilardoni

Beam Dump and Collimators for FCC-hh– a first insight



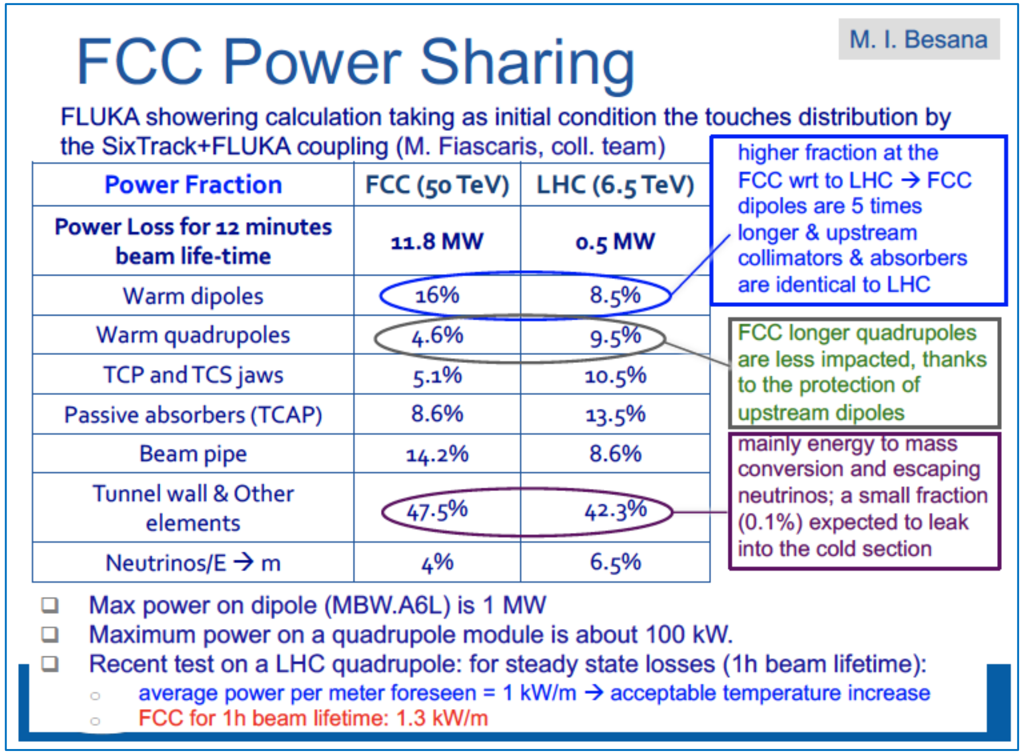
More in Anton's presentation

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



M. I. Besana

FCC Power Sharing

FLUKA showering calculation taking as initial condition the touches distribution by the SixTrack+FLUKA coupling (M. Fiascaris, coll. team)

Power Fraction	FCC (50 TeV)	LHC (6.5 TeV)
Power Loss for 12 minutes beam life-time	11.8 MW	0.5 MW
Warm dipoles	16%	8.5%
Warm quadrupoles	4.6%	9.5%
TCP and TCS jaws	5.1%	10.5%
Passive absorbers (TCAP)	8.6%	13.5%
Beam pipe	14.2%	8.6%
Tunnel wall & Other elements	47.5%	42.3%
Neutrinos/E → m	4%	6.5%

higher fraction at the FCC wrt to LHC → FCC dipoles are 5 times longer & upstream collimators & absorbers are identical to LHC

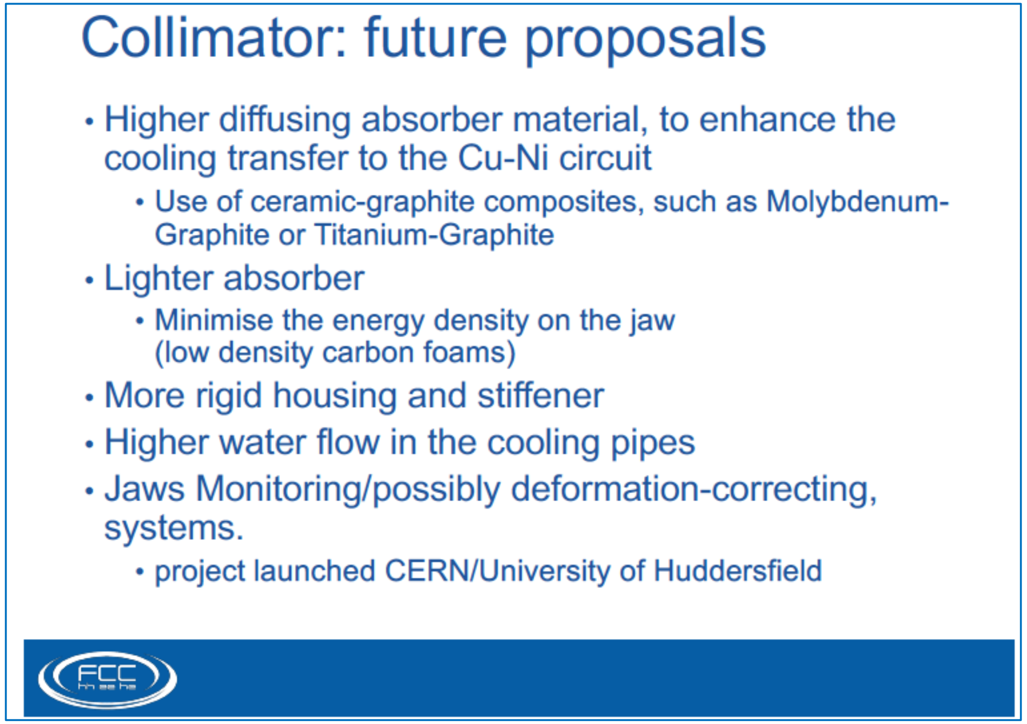
FCC longer quadrupoles are less impacted, thanks to the protection of upstream dipoles

mainly energy to mass conversion and escaping neutrinos; a small fraction (0.1%) expected to leak into the cold section

☐ Max power on dipole (MBW.A6L) is 1 MW
☐ Maximum power on a quadrupole module is about 100 kW.
☐ Recent test on a LHC quadrupole: for steady state losses (1h beam lifetime):
  ○ average power per meter foreseen = 1 kW/m → acceptable temperature increase
  ○ FCC for 1h beam lifetime: 1.3 kW/m

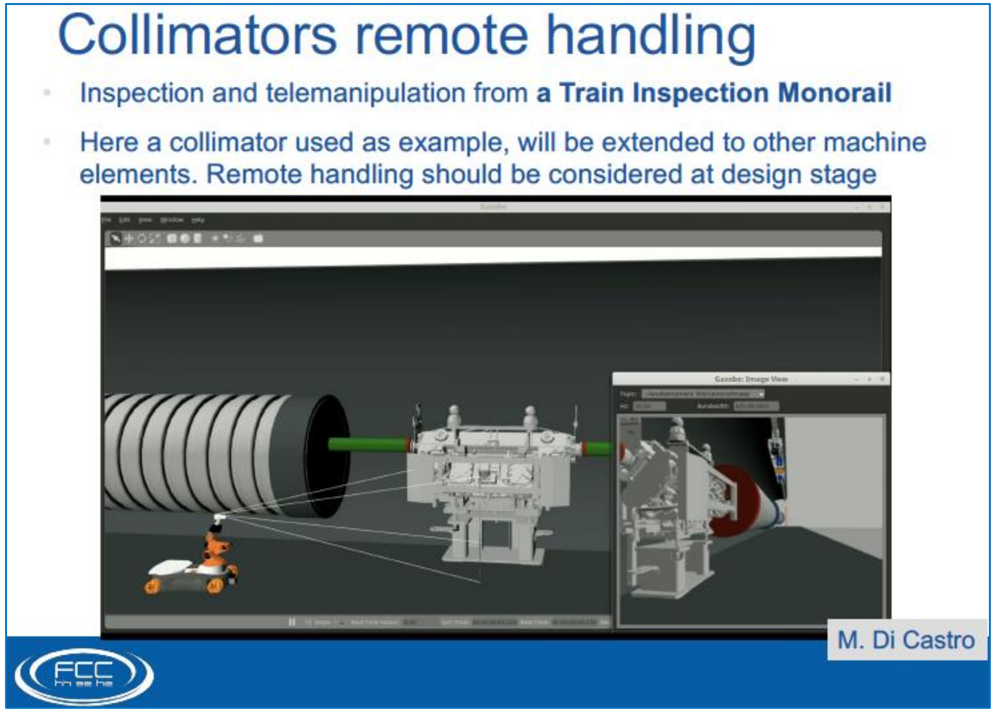
Courtesy: S. Gilardoni

Collimator: Future Proposal



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



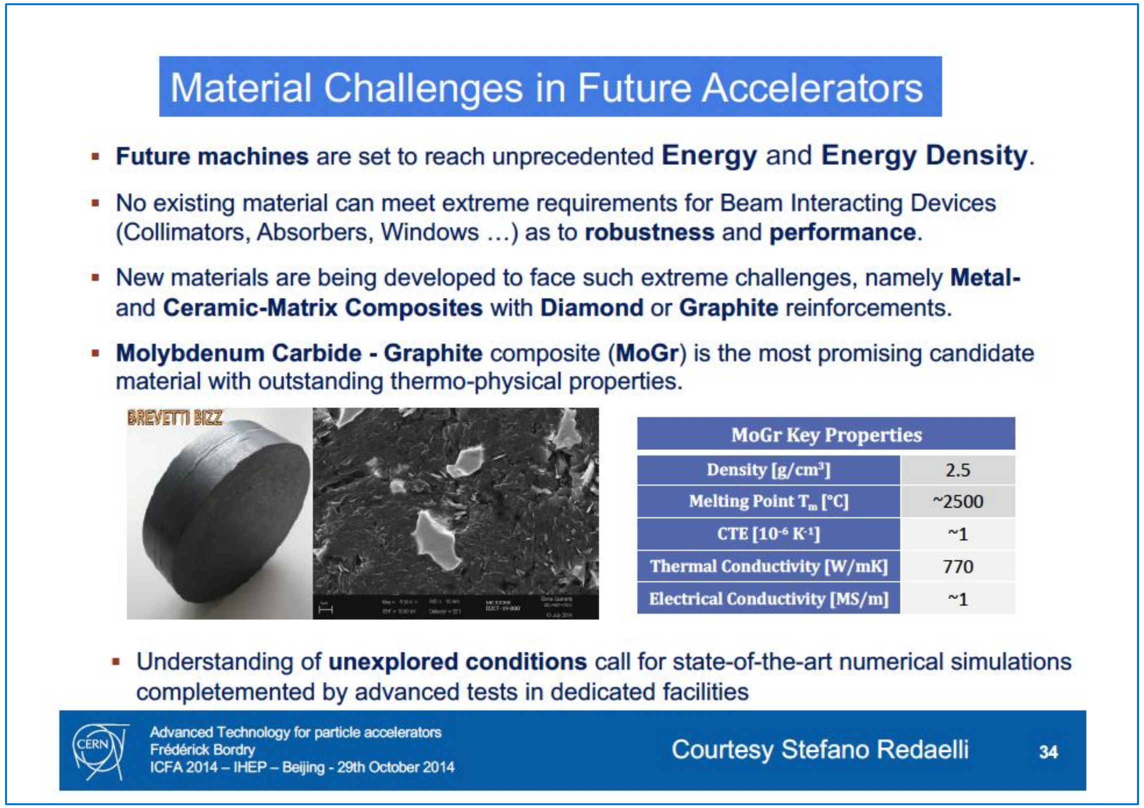
Collimators remote handling

- Inspection and telemanipulation from **a Train Inspection Monorail**
- Here a collimator used as example, will be extended to other machine elements. Remote handling should be considered at design stage

M. Di Castro

Courtesy: F. Bordry

Technical Challenges: 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.

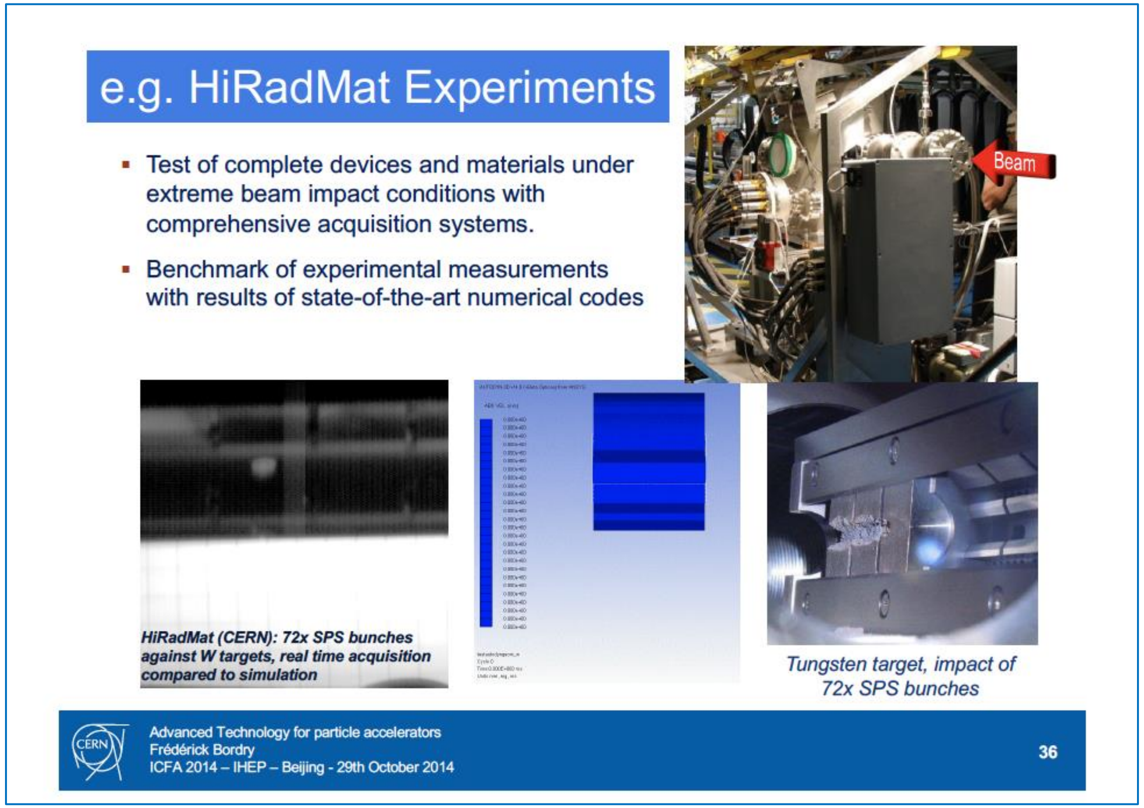
MoGr Key Properties	
Density [g/cm³]	2.5
Melting Point T_m [°C]	~2500
CTE [10^{-6} K^{-1}]	~1
Thermal Conductivity [W/mK]	770
Electrical Conductivity [MS/m]	~1

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

Advanced Technology for particle accelerators
Frédérick Bordry
ICFA 2014 – IHEP – Beijing - 29th October 2014

Courtesy Stefano Redaelli

34



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

Advanced Technology for particle accelerators
Frédérick Bordry
ICFA 2014 – IHEP – Beijing - 29th October 2014

36

Courtesy: N. Saito

R a D I A T E

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)

Thermal analysis of Al alloy

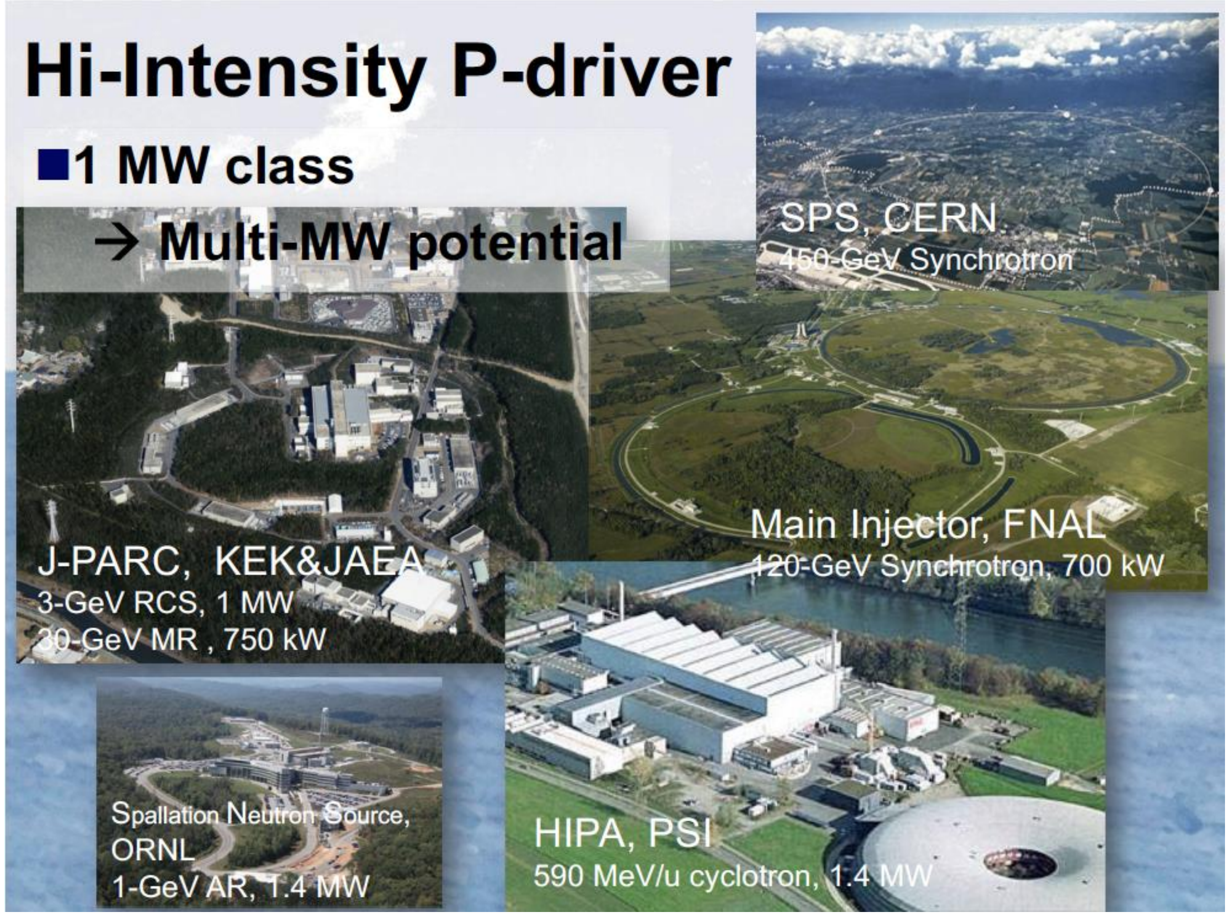
NuMI graphite broken target
Post-Irradiation Examination (PIE)
at PNNL: Swelling effect observed

New Irradiation Run at BNL (2017 February ~)

2016～...（予定）

Courtesy: N. Saito

Intensity Frontier Accelerators



Hi-Intensity P-driver

- **1 MW class**
  - **→ Multi-MW potential**

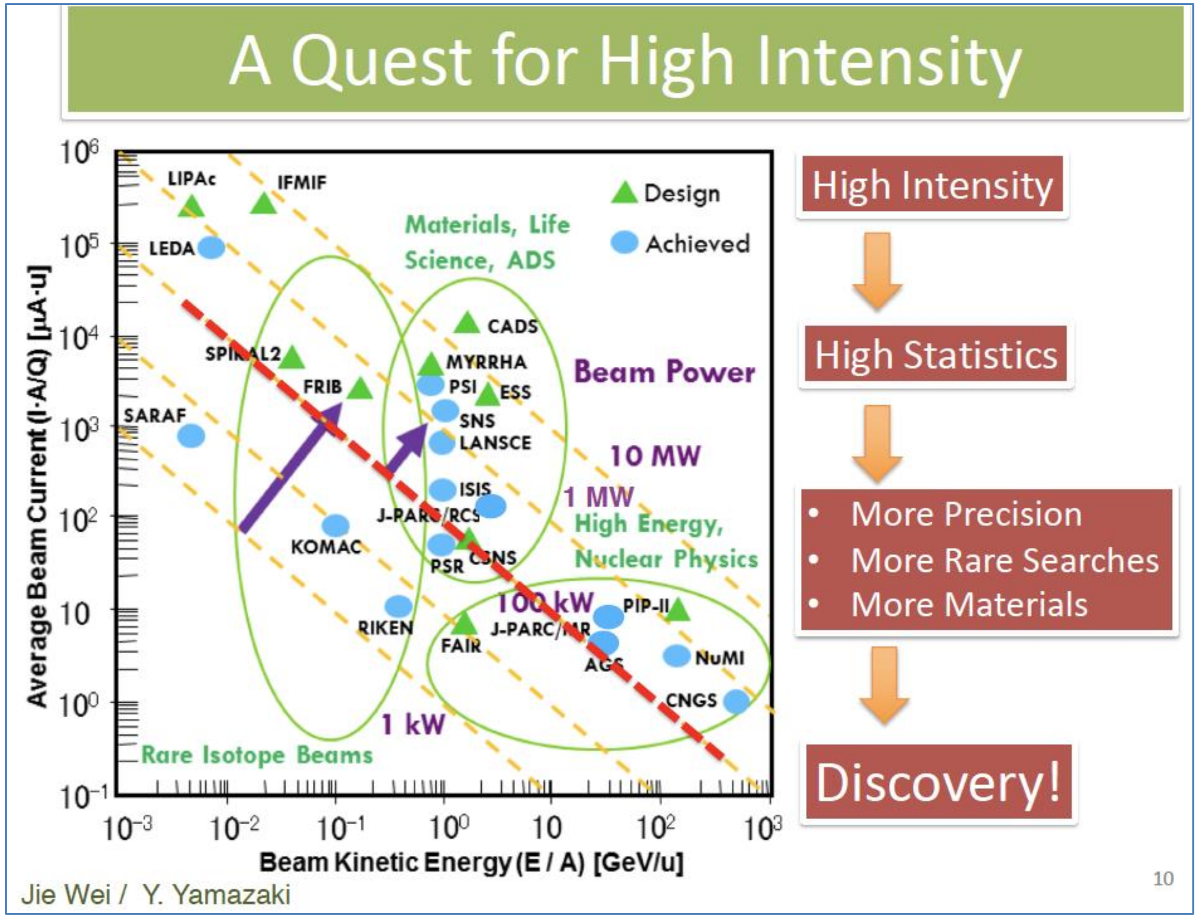
SPS, CERN
450-GeV Synchrotron

Main Injector, FNAL
120-GeV Synchrotron, 700 kW

J-PARC, KEK&JAEA
3-GeV RCS, 1 MW
30-GeV MR , 750 kW

Spallation Neutron Source, ORNL
1-GeV AR, 1.4 MW

HIPA, PSI
590 MeV/u cyclotron, 1.4 MW



A Quest for High Intensity

High Intensity

High Statistics

- More Precision
- More Rare Searches
- More Materials

Discovery!

Jie Wei / Y. Yamazaki

10

US Electron-Ion Collider

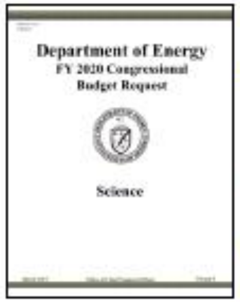
National Academy of Sciences : 2018 Assessment of US EIC

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


AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE

"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?"


Department of Energy
FY 2020 Congressional
Budget Request

Science

US DOE Budget Justification

Volume 4, Page 272:

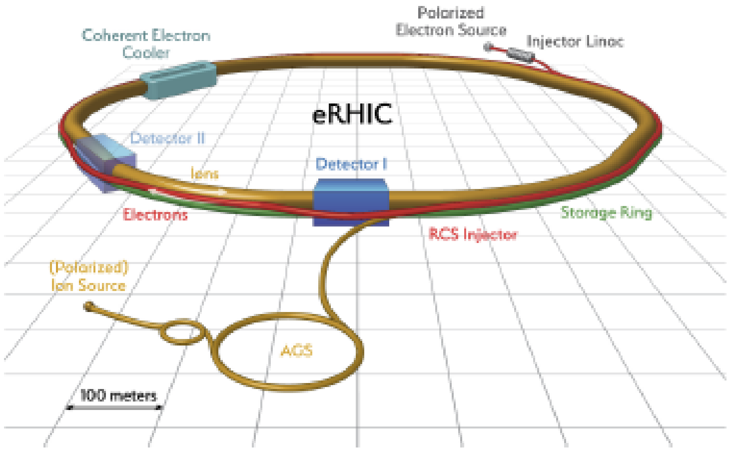
"..(EIC)..Critical Decision-0, Approve Mission Need, is planned for FY 2019."

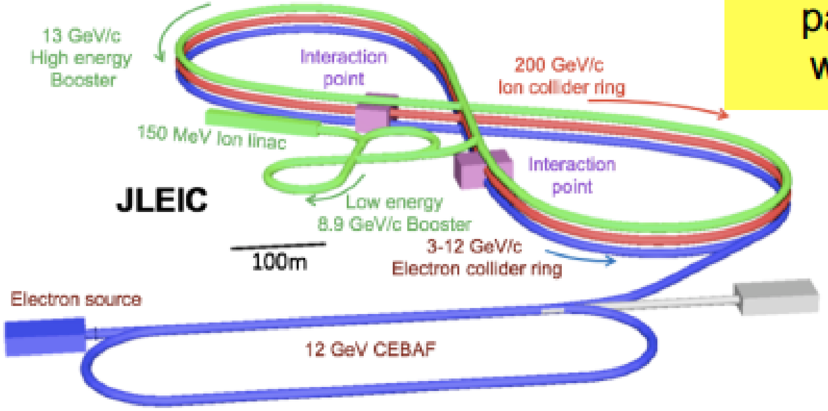
Two realization concepts being developed.
Realization could be as early as 2028-2030.

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

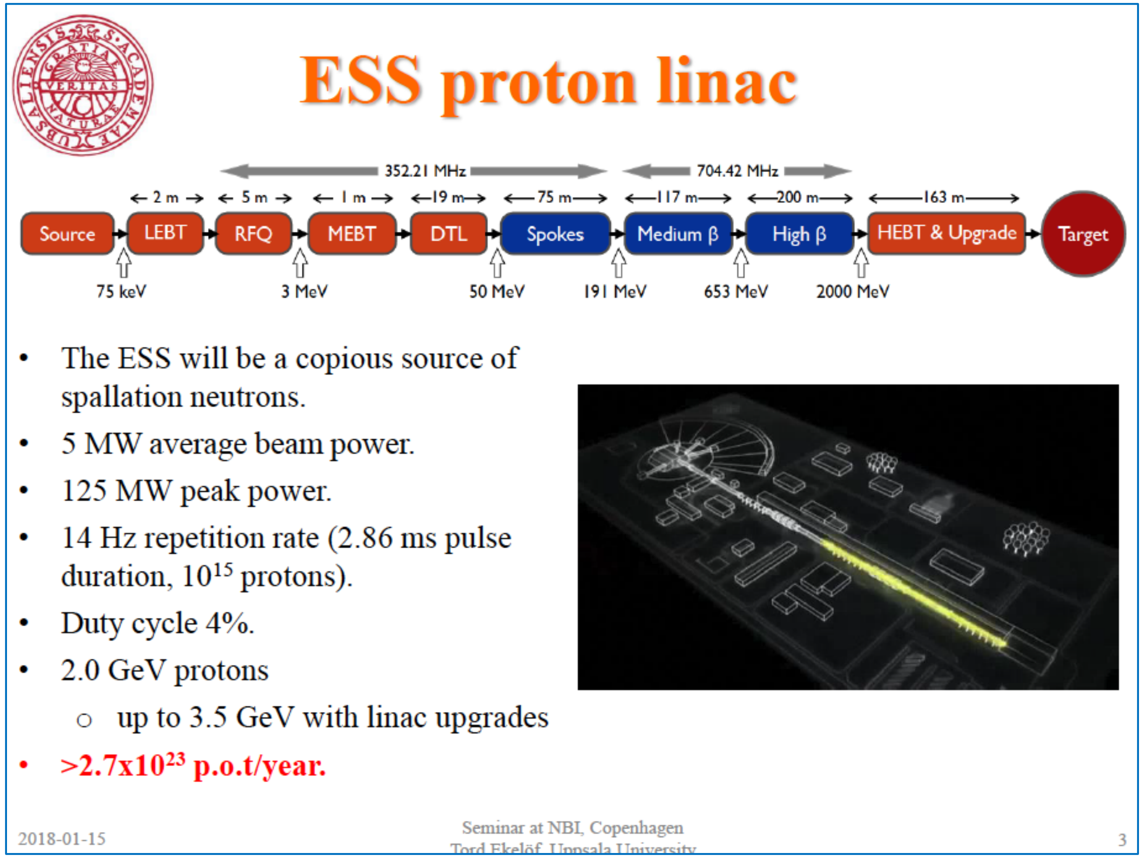
Common areas of synergy with European projects:

- 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

Courtesy: R. Garoby

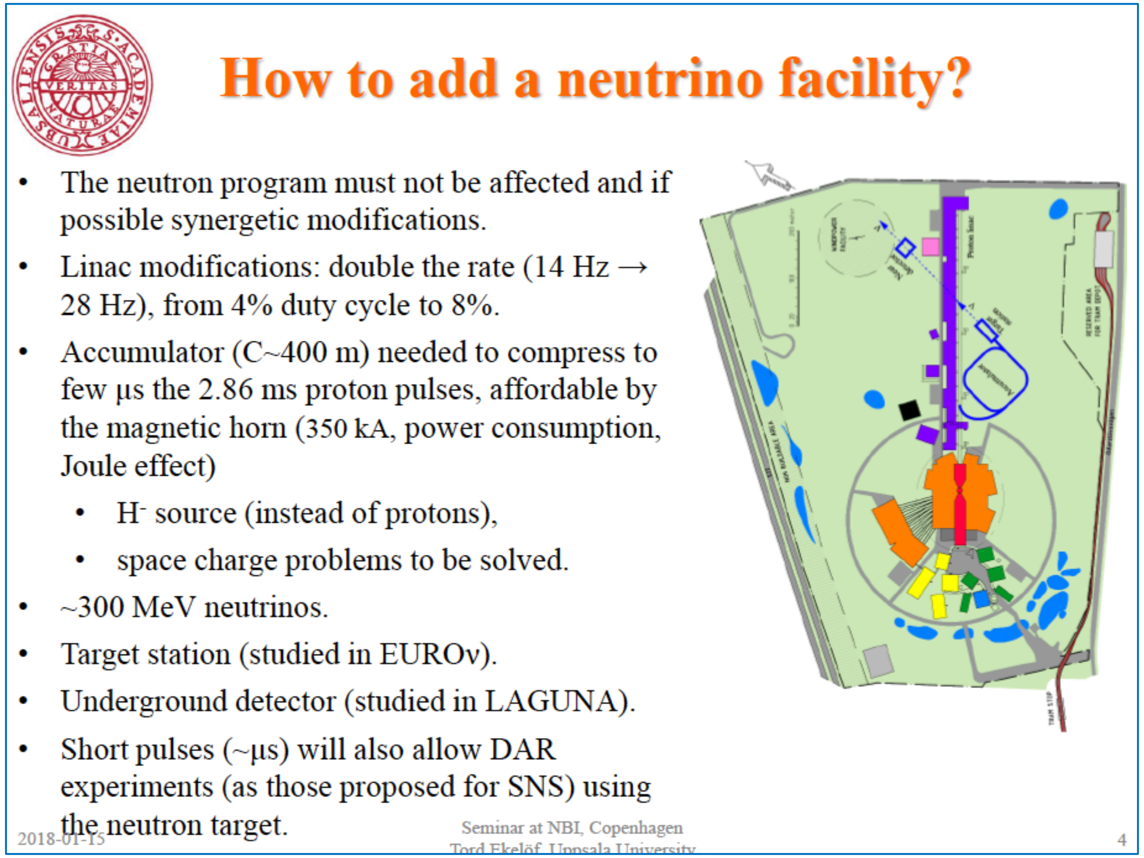
ESSnuSB: An Intensity-frontier ACC. for PP in future



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

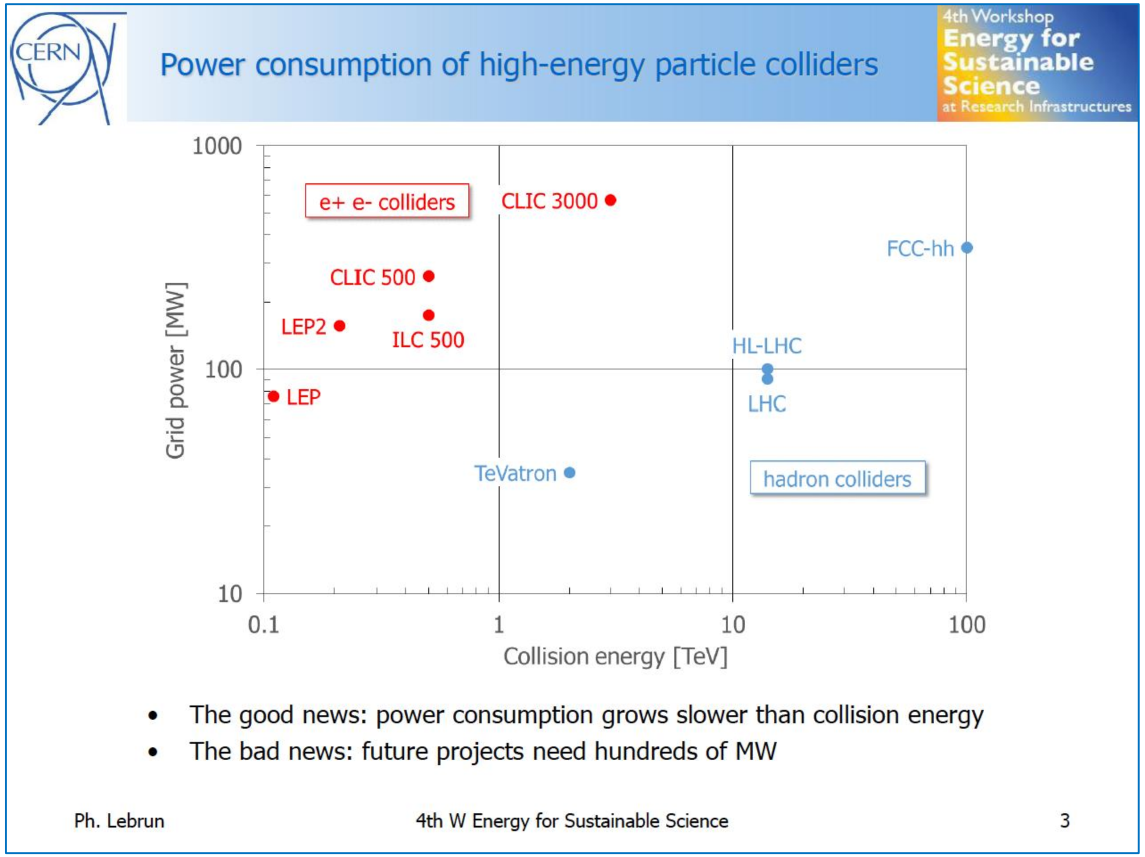


How to add a neutrino facility?

- 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.

2018-01-15 Seminar at NBI, Copenhagen Tord Ekelöf, Uppsala University 4

Energy Efficiency and Management in Accelerators



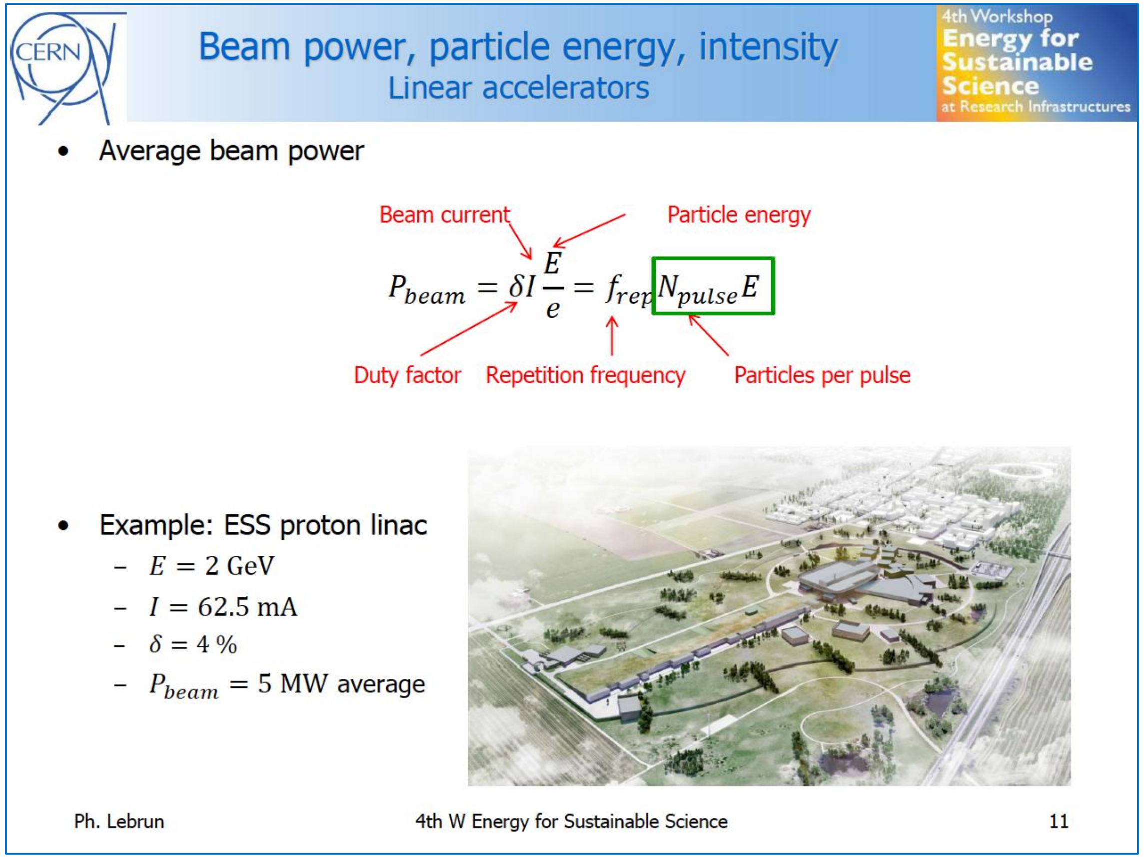
CERN

4th Workshop Energy for Sustainable Science at Research Infrastructures

Power consumption of high-energy particle colliders

- 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



CERN

4th Workshop Energy for Sustainable Science at Research Infrastructures

Beam power, particle energy, intensity

Linear accelerators

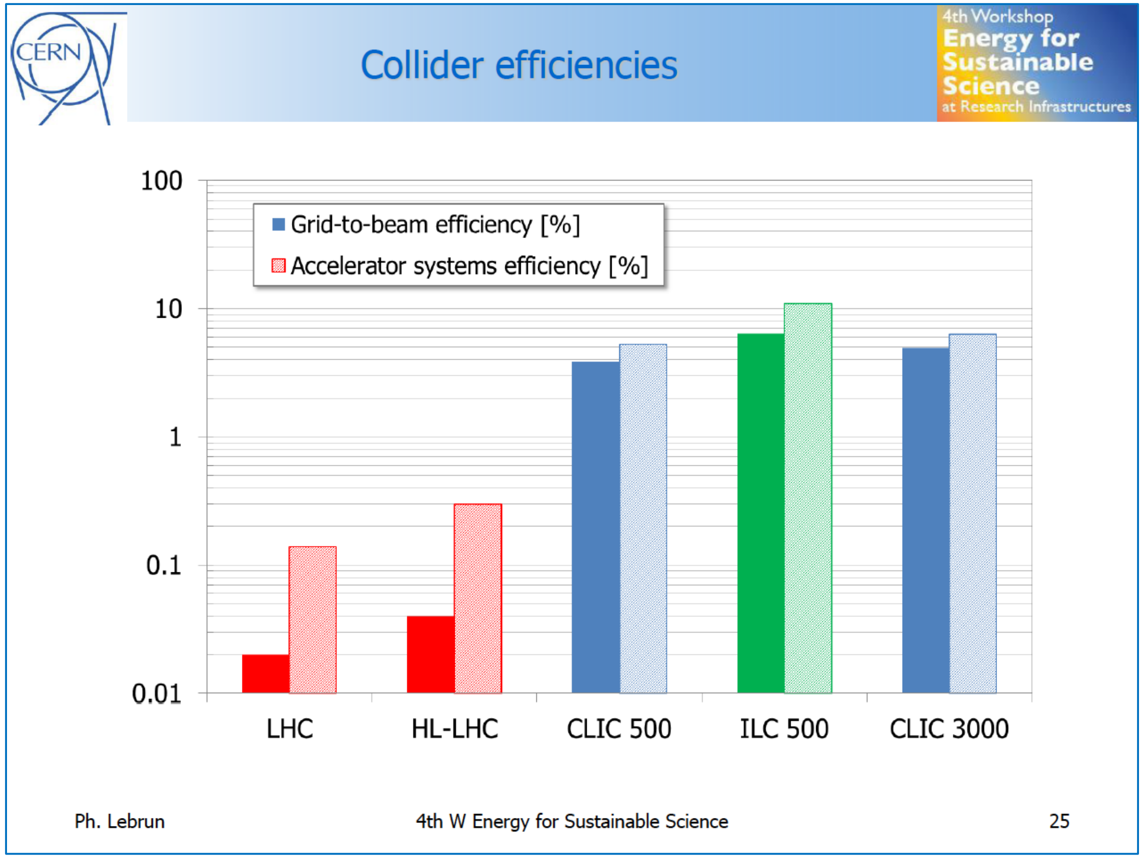
- Average beam power

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

- 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

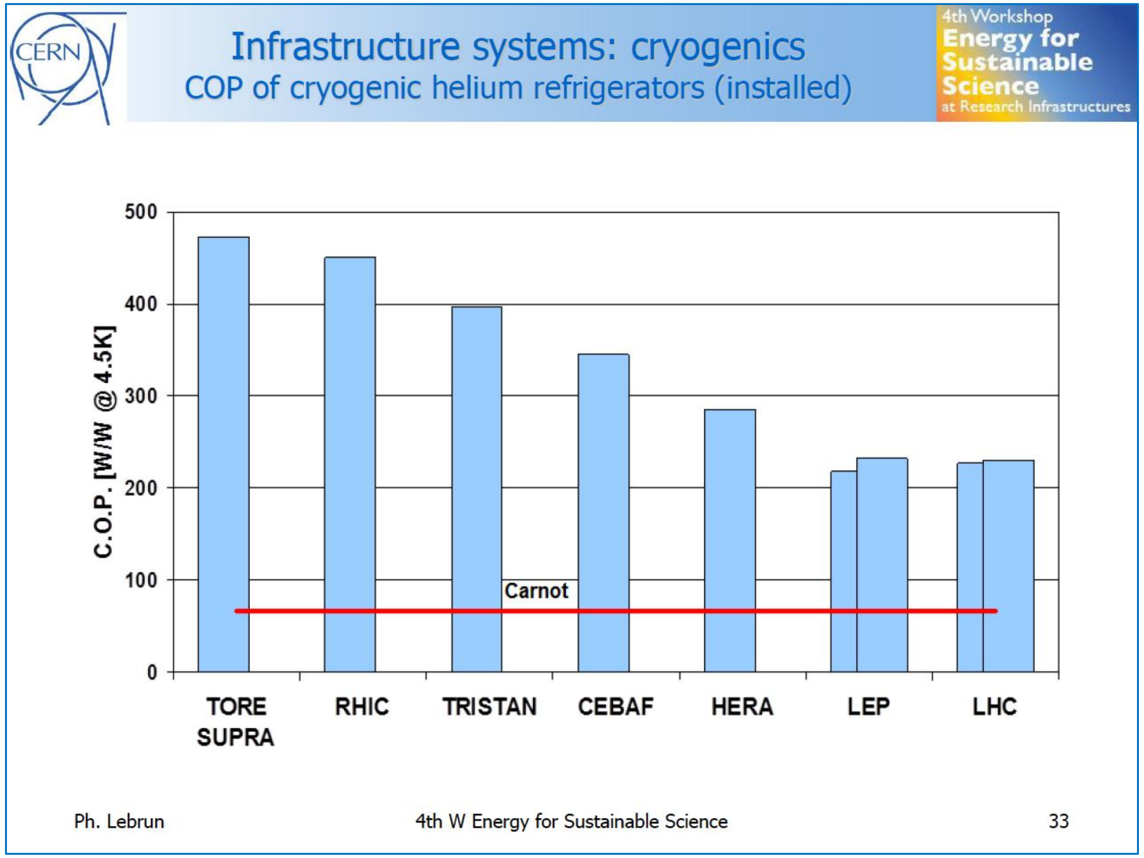
Energy Efficiency and Management in Accelerators



Collider efficiencies

4th Workshop
Energy for Sustainable Science
at Research Infrastructures

Ph. Lebrun 4th W Energy for Sustainable Science 25



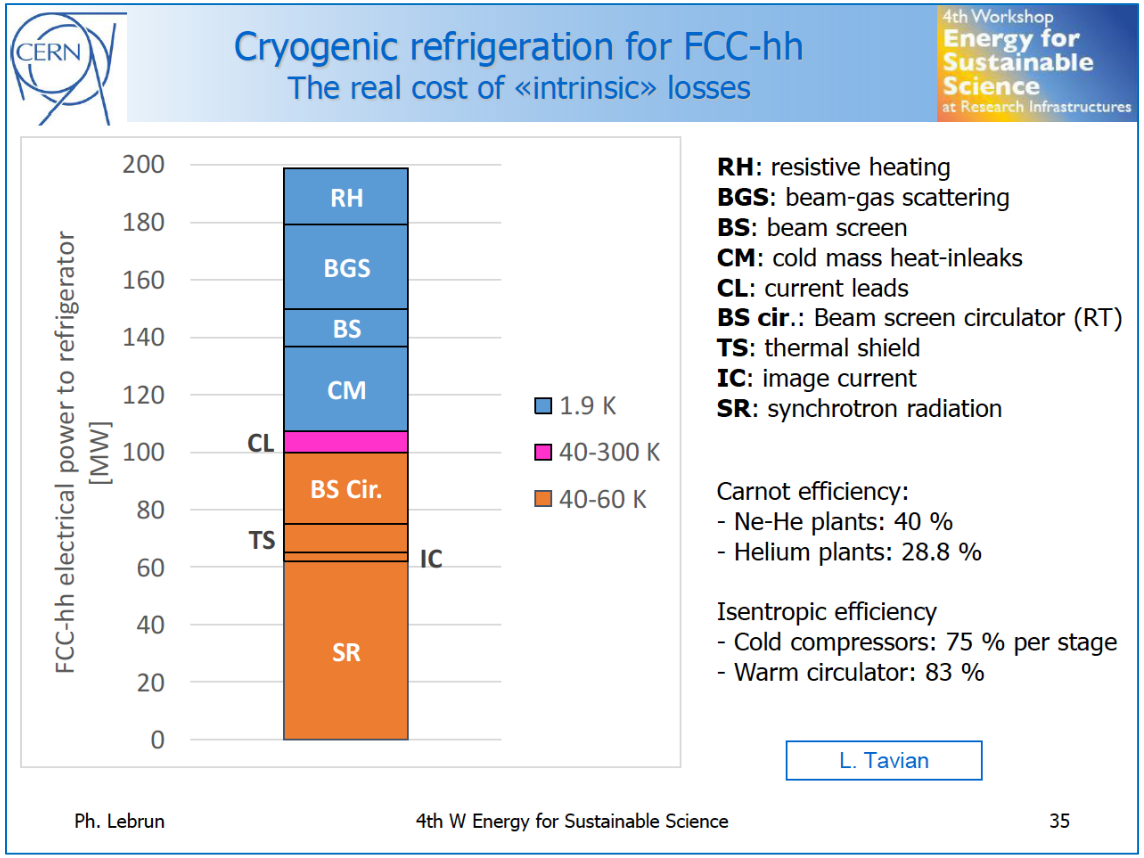
Infrastructure systems: cryogenics

COP of cryogenic helium refrigerators (installed)

4th Workshop
Energy for Sustainable Science
at Research Infrastructures

Ph. Lebrun 4th W Energy for Sustainable Science 33

Energy Efficiency and Management in Accelerators



CERN

4th Workshop Energy for Sustainable Science at Research Infrastructures

Cryogenic refrigeration for FCC-hh

The real cost of «intrinsic» losses

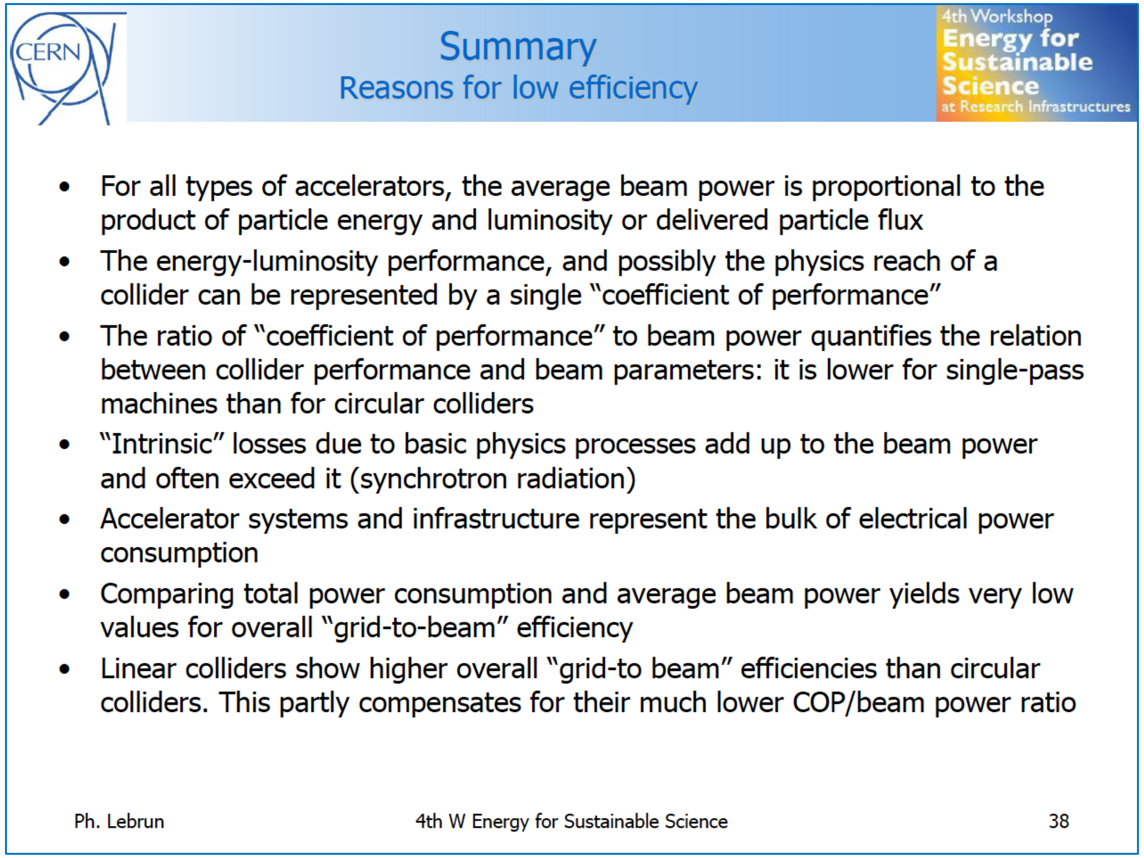
RH: resistive heating
BGS: beam-gas scattering
BS: beam screen
CM: cold mass heat-inleaks
CL: current leads
BS cir.: Beam screen circulator (RT)
TS: thermal shield
IC: image current
SR: synchrotron radiation

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



CERN

4th Workshop Energy for Sustainable Science at Research Infrastructures

Summary

Reasons for low efficiency

- 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

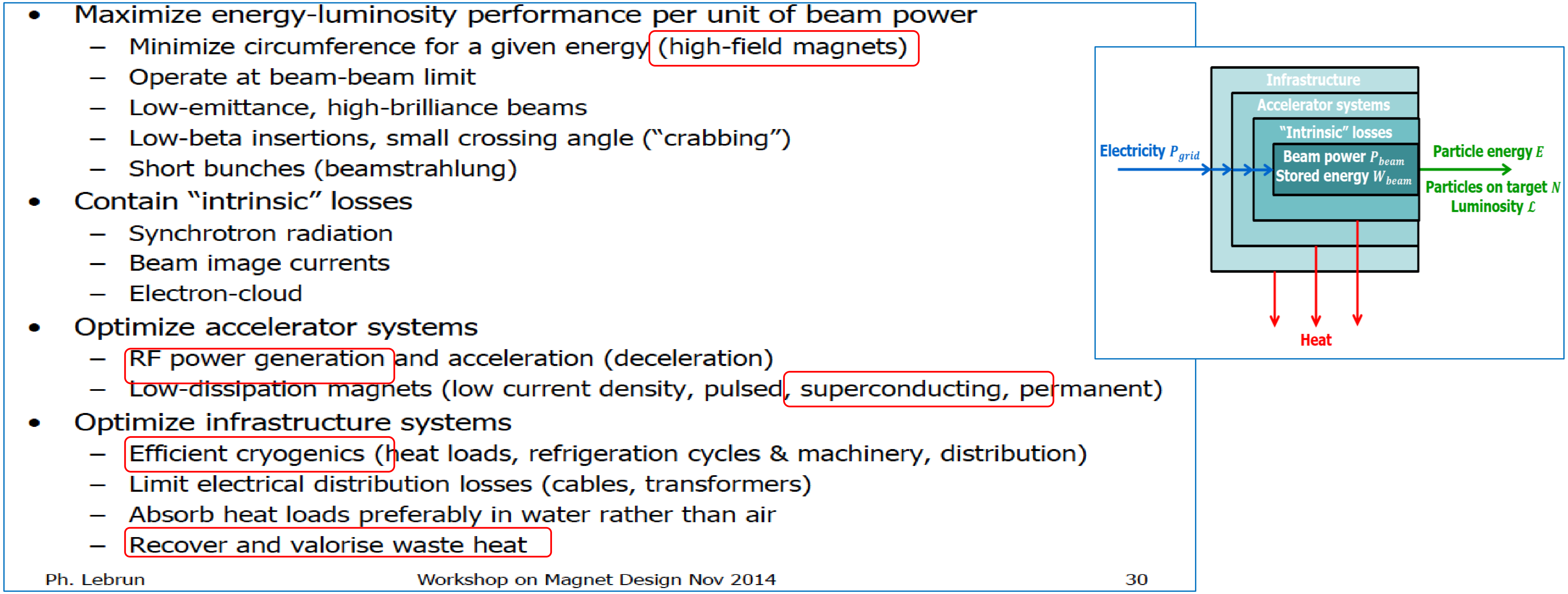
Ph. Lebrun 4th W Energy for Sustainable Science 38

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