Prospects for Future Colliders
and
Advanced Accelerator Technologies
- with Applied Superconductivity -

Akira Yamamoto
(KEK and CERN)

To be presented at the Future Colliders Session, LHCP2021
9 June 2021

Outline

- Overview of Future Colliders
  - Lepton Colliders for Higgs Factory, and Hadron Colliders for energy frontier

- Advanced Technologies for Future Colliders
  - Nano-beam and NRF/SRF technology
  - High-field Superconducting Magnet technology

Future Colliders based on SC Technology (See full list in next pages)

Linear Colliders:

ILC e+e- (250 GeV → 1 TeV) :

- **SRF:** for High-Q (10^{10}) and high-G (31.5 MV/m)
- Highest efficiency and AC-power balance

CLIC e+e- (380 GeV → 3 TeV) :

- **NRF:** Very high G (100 MV/m) for energy frontier with compactness

Circular Colliders :

FCC-e+e- (90 → 350 GeV):

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

FCC-pp (2 x 50 TeV):

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

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

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

SPPC- pp (75 TeV):

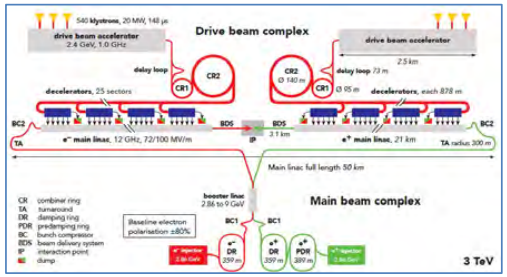
- High-field SCM (12 T) for energy frontier
- **SRF:** beam acceleration

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

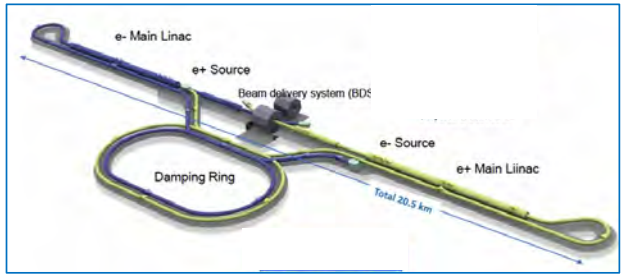
- **SCM and SRF**

MC μ+μ– (3 – 14 TeV)

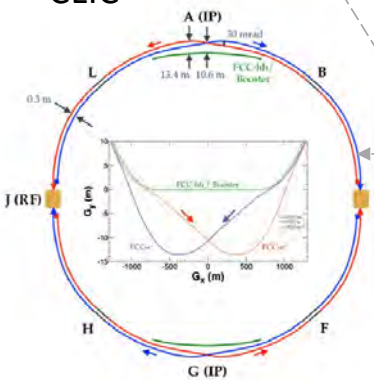
- SRF and NRF with very high-field SCM
- Higher efficiency at > 3 TeV, although short life-time.



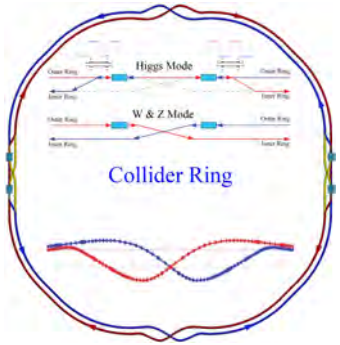
CLIC



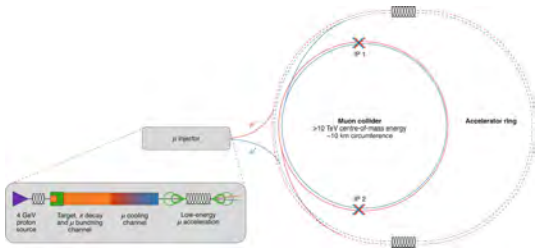
ILC



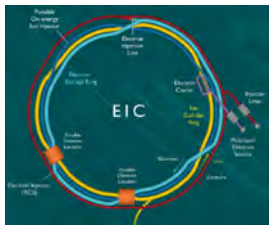
FCC-ee/-hh



CEPC/SPPC



MC



EIC

Future Colliders based on SC Technology (see full list in next pages)

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

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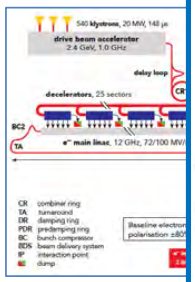
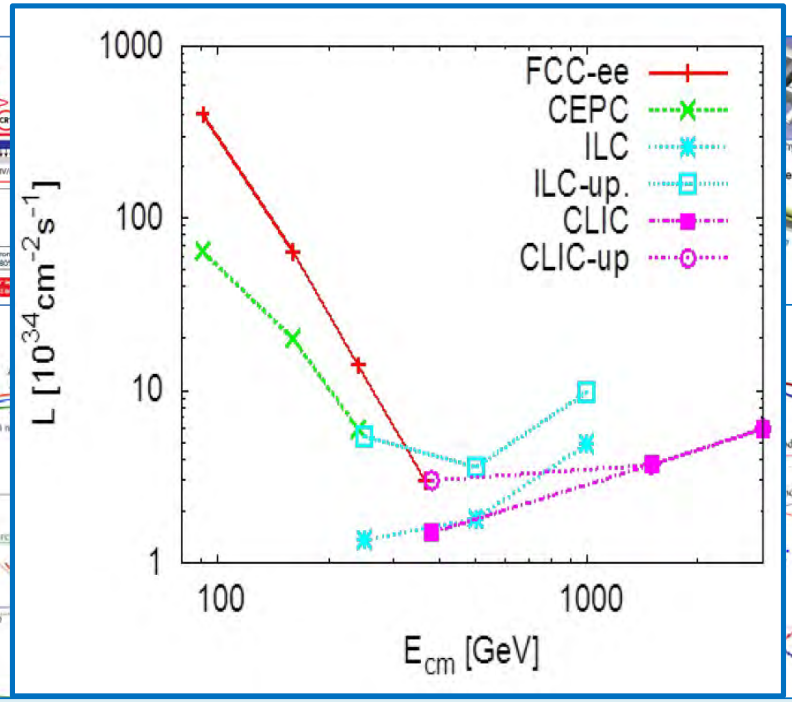
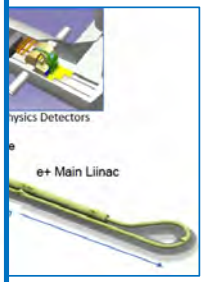
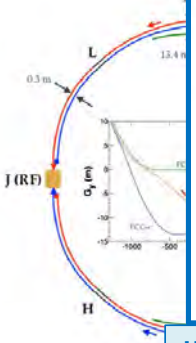


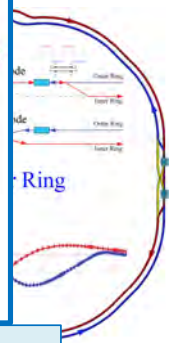
CLIC



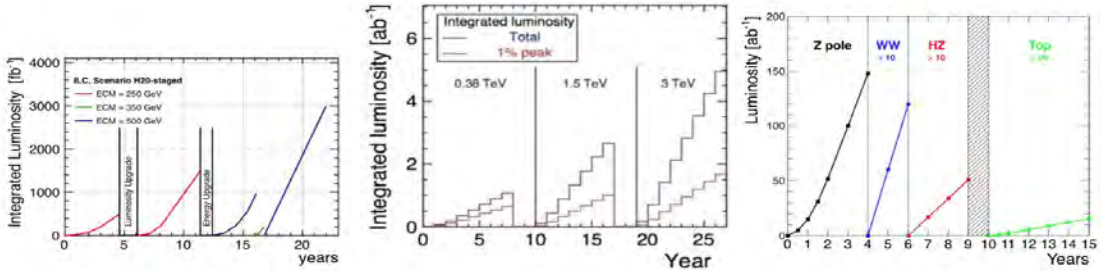


ILC





ILC CLIC FCC-ee



ESPPU-Physics-Briefing Book, (2019)

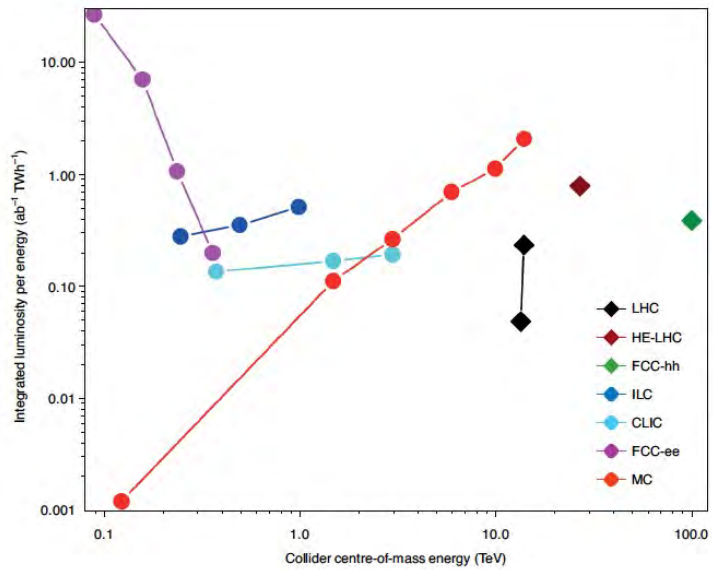
Luminosity normalized by AC-Plug Power

- Circular Colliders may be efficient in lower energy region below 250 GeV (COM),
- Linear Colliders may have advantage in an energy region above 250 GeV,
- Muon Collider may become a potential options above 1 TeV

Project	Type	Energy (TeV, c.m.e.)	N_{det}	$\mathcal{L}_{int}$ (ab^{-1})	Time (yr)	Power (MW)
ILC	e^+e^-	0.25	1	2	11	129
		0.5	1	4	10	163(204)
		1	1			300
CLIC	e^+e^-	0.38	1	1	8	168
		1.5	1	2.5	7	370
		3	1	5	8	590
CEPC	e^+e^-	0.091 and 0.16	2	16 + 2.6	2 + 1	149
		0.24	2	5.6	7	266
FCC-*ee*	e^+e^-	0.091 and 0.16	2	150 + 10	4 + 1	259
		0.24	2	5	3	282
		0.365 and 0.35	2	1.5 + 0.2	4 + 1	340
LHeC	ep	1.2	1	1	12	(+100)
HE-LHC	pp	27	2	20	20	220
FCC-*hh*	pp	100	2	30	25	580
FCC-*eh*	ep	3.5	1	2	25	(+100)
Muon collider	$\mu\mu$	14	2	50	15	290

→ **110 (updated)**

V. Shiltsev and F. Zimmermann,
Rev. Mod. Phys. Vol. 93, No. 1, Jan-March 2021)

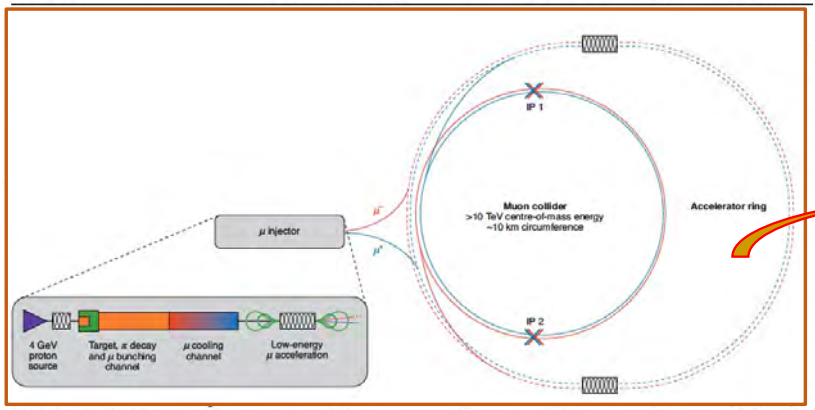


K. Long, D. Lucchesi, M. Palmer, N. Pastrone, D. Schulte, and V. Shiltsev,
Nature Physics 17, March , p289-292, 2021.

Luminosity normalized by AC-Plug Power

- Circular Colliders may be efficient in lower energy region below 250 GeV (COM),
- Linear Colliders may have advantage in an energy region above 250 GeV,
- Muon Collider may become a **unique/potential options in multi TeV (→ Nadia Pastrone's talk)**

Project	Type	Energy (TeV, c.m.e.)	N_{det}	$\mathcal{L}_{int}$ (ab^{-1})	Time (yr)	Power (MW)
Muon collider	$\mu\mu$	14	2	50	15	290



V. Shiltsev and F. Zimmermann,
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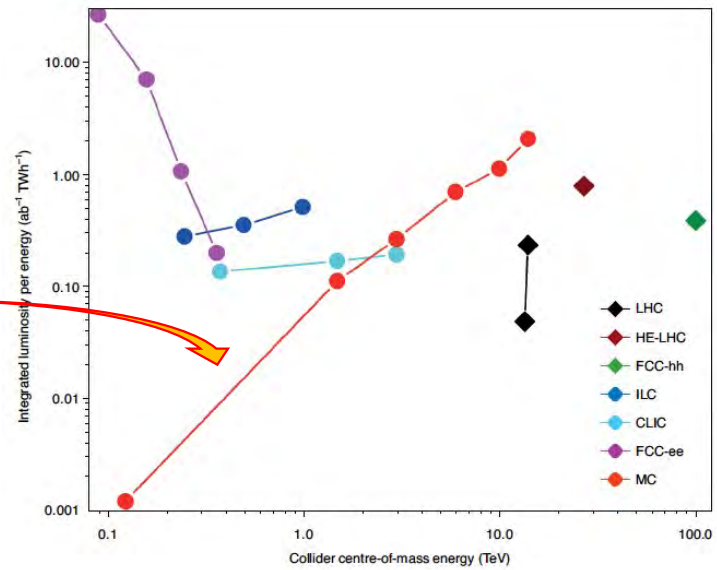

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Summary of Lepton Colliders

V. Shiltsev and F. Zimmermann,
Rev. Mod. Phys. Vol. 93, No. 1, 2021.

TABLE V. Tentative parameters of selected future e^+e^- high-energy colliders.

Species	FCC-*ee* (Benedikt *et al.*, 2019a) e^+e^-			CEPC (CEPC Study Group, 2018) e^+e^-		ILC (Aihara *et al.*, 2019) e^+e^-		CLIC (Aicheler *et al.*, 2019) e^+e^-	
Beam energy (GeV)	45.6	120	183	45.5	120	125	250	190	1500
Circumference, length (km)		97.75		100		20.5	31	11	50
Interaction regions		2 or 4		2		1		1	
Integrated luminosity/expt. (ab^{-1}/yr)	26	0.9	0.17	4	0.4	0.2	0.3	0.2	0.6
Peak luminosity (10^{34} cm^{-2} s^{-1})	230	8.5	1.55	32	3	1.4	1.8	1.5	5.9
Repetition rate (Hz, f_{rev} for rings)		3067		3000		5		50	
Polarization (%)	≥ 10	0	0	5–10	0	80, 30% (e^-, e^+)		80%, 0%	
Time between collisions (μs)	0.015	0.75	8.5	0.025	0.68	0.55	0.55	0.0005	0.0005
Energy spread (rms, 10^{-3})	1.3	1.65	2.0	0.8	1.3	1.9, 1.5 (e^-,e^+)	1.2, 0.7 (e^-,e^+)	3.5	3.5
Bunch length (rms, mm)	12.1	5.3	2.5	8.5	4.4	0.3	0.3	0.07	0.044
Normalized rms emittance (H,V μm)	24, 0.09	148, 0.3	520, 1.0	16, 0.14	284, 0.6	5, 0.035	10, 0.035	0.9, 0.03	0.66, 0.03
β^* at IP (H,V cm)	15, 0.08	30, 0.1	100 0.16	20, 0.1	36, 0.15	1.3, 0.041	2.2, 0.048	0.8, 0.01	0.69, 0.007
Horizontal IP beam size (μm)	6.4	14	38	6.0	21	0.52	0.47	0.15	0.04
Vertical IP beam size (nm)	28	36	68	40	60	8	6	3	1
Full crossing angle (mrad)		30		33		14		20	
Crossing scheme		Crab waist		Crab waist		Crab crossing		Crab crossing	
Piwinski angle Φ	28.5	5.8	1.5	23.8	2.6	0		0	
Beam-beam parameter ξ_y (10^{-3})	133	118	128	79	109				
rf frequency (MHz)	400	400	400 and 800	650	650	1300	1300	11 994	11 994
Particles per bunch (10^{10})	17	18	23	8	15	2	2	0.52	0.37
Bunches per beam	16 640	328	48	12 000	242	1312	1312	352	312
Average beam current (mA)	1390	29	5.4	461	17.4	0.021	0.021	0.014	0.009
Injection energy (GeV)	On energy (top up)			On energy (top up)		5.0 (linac)		9.0 (linac)	
rf gradient (MV/m)	1.3	9.8	19.8	3.6	19.7	31.5	31.5	72	100
SR power loss (MW)		100		33.5	60				

Summary of Hadron Colliders

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TABLE VII. Tentative parameters of selected future high-energy hadron and muon colliders. Parameters of the $\mu^+\mu^-$ Higgs factory are given for reference only. An estimate for SppC ac power is not yet available.

	HE-LHC	FCC-hh	SppC	$\mu\mu$ collider		
Species	pp	pp	pp		$\mu^+\mu^-$	
Beam energy (TeV)	13.5	50	37.5	0.063	3	7[a]
Circumference (km)	26.7	97.75	100	0.3	6	26.7
Interaction regions	2 (4)	4	2	1	2	2
Peak luminosity (10^{34} cm^{-2} s^{-1})	15	5 – 30	10	0.008	12	33
Integrated luminosity per expt. (ab^{-1}/yr)	0.5	0.25–1.0	~0.4	0.001	1.0	3
Time between collisions (μs)	0.025	0.025	0.025	1	20	90
Events per crossing	800	170 – 1000	~300	...	...	...
Energy spread (rms, 10^{-3})	0.1	0.1	0.2	0.04	1	1
Bunch length (rms, mm)	80	80	75.5	63	2	1
IP beam size (μm)	6.6	6.8 (initial)	6.8 (initial)	75	1.5	0.6
Injection energy (GeV)	1300	3300	2100		On energy	
Transverse emittance (rms normalized, μm)	2.5	2.1 (initial)	2.4 (initial)	200	25	25
β^*, amplitude function at IP (cm)	45	110 – 30	75	1.7	0.25	1
Beam-beam tune shift/ IP (10^{-3})	5	5 – 15	7.5	20	90	100
rf frequency (MHz)	400	400	400/200	805	805	805
Particles per bunch (10^{10})	22	10	15	400	200	200
Bunches per beam	2808	10 600	10 080	1	1	1
Average beam current (mA)	1120	500	730	640	16	4
Length of standard cell (m)	137	213	148	...	...	...
Phase advance per cell (deg)	90	90	90	...	...	...
Peak magnetic field (T)	16	16	12 (24)	10	10	16
SR power loss/beam (MW)	0.1	2.4	1.2	0	0.07	0.5
Longitudinal damping time (h)	3.6	1.1	2.4	...	...	...
Initial burn-off time (h)	3.0	17 – 3.4	13	...	...	...
Total facility ac power (MW)	200	580	...	200	270	290
Novel technology	16 T magnets	16 T magnets	HTS magnets	μ production/10–16 T magnets		

[a]The 14 TeV c.m.e. muon collider design has not yet been completed; the numbers are a projection (Neuffer and Shiltsev, 2018).

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC- Power [MW]	E: [MV/m] [GHz]	B [T]	Major Challenges in Technology
LC ee	ILC	TDR update	0.25 -1	1.35 (~ 4.9)	110 (~ 300)	31.5 – 45 [1.3]		High-G and high-Q SRF cavity, Higher-G for future upgrade including new material, Nano-beam stability
	CLIC	CDR	0.38 - 3	1.5 (~ 6)	160 (~ 580)	72 – 100 [12]		Acc. Structure, Large-scale production, Two-beam acceleration in a prototype scale, Precise alignment and stabilization.
CC ee	FCC-ee	CDR	0.09 ~ 0.38	460 ~ 31	260 ~ 350	10 – 20 [0.4 - 0.8]		High-Q SRF cavity at < GHz, Nb thin-film Coating, Synchrotron Radiation absorption, Energy efficiency (RF efficiency).
	CEPC	CDR	0.046 - 0.24	32 ~ 5	150 ~ 270	20 – 40 [0.65]		High-Q SRF cavity at < GHz, LG Nb-bulk/thin-film, Synchrotron Radiation constraint, Low-field magnet with high-precision.
CC hh	FCC-hh	CDR	~ 100	5 ~ 30	580		16	High-field SC magnet - Nb3Sn (+HTS): high Jc, mechanical stress sustainability Energy management
	SPPC	CDR	70	10	---		12	High-field SC magnet - IBS: High Jc, stress sustainability, energy management
CC mm	MC		0.12 ~ 14	0.008~33	200 ~290	tbd [tbd]	10 ~ 20	Short lifetime, cooling, High-field SCM, RF in strong magnetic field, ….

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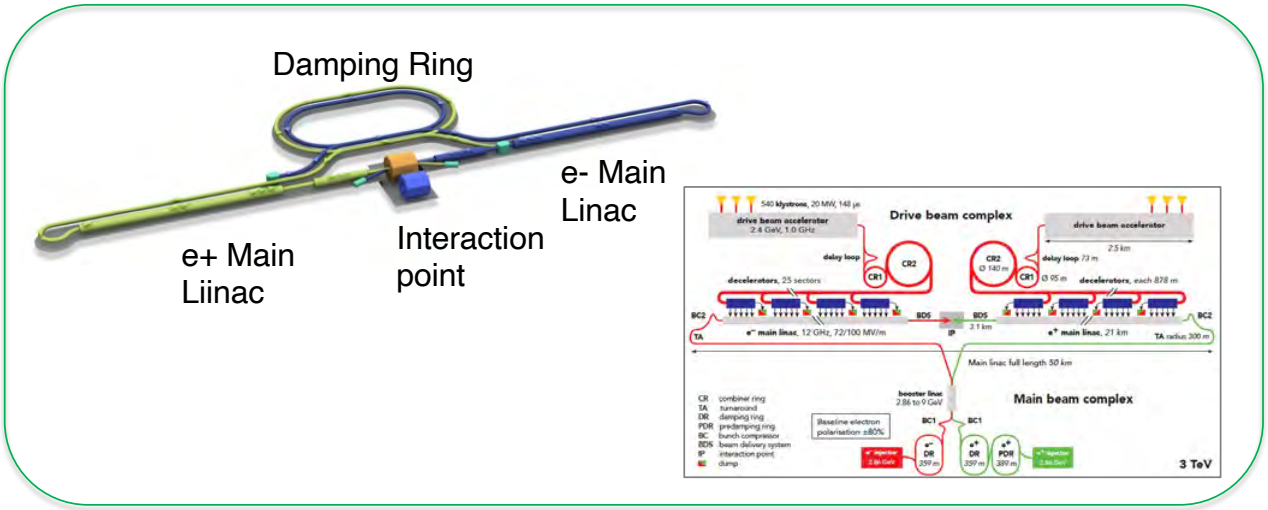
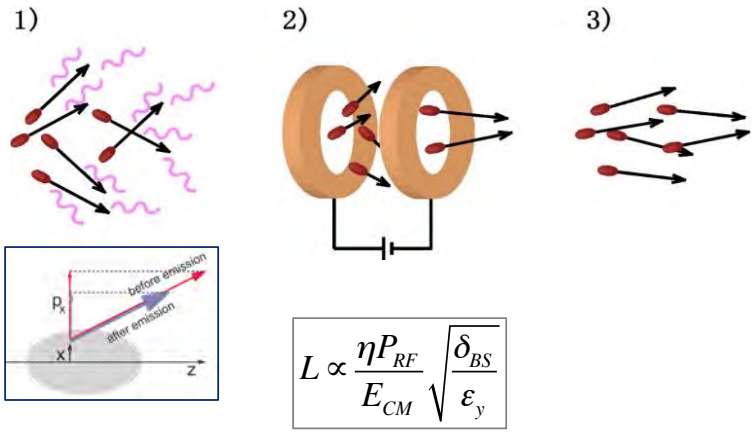
- Advanced Technologies for Future Colliders
  - **Nano-beam** and **NRF/SRF** technology for **L**epton **C**olliders
  - **High-field Superconducting Magnet** technology for **H**adron Colliders

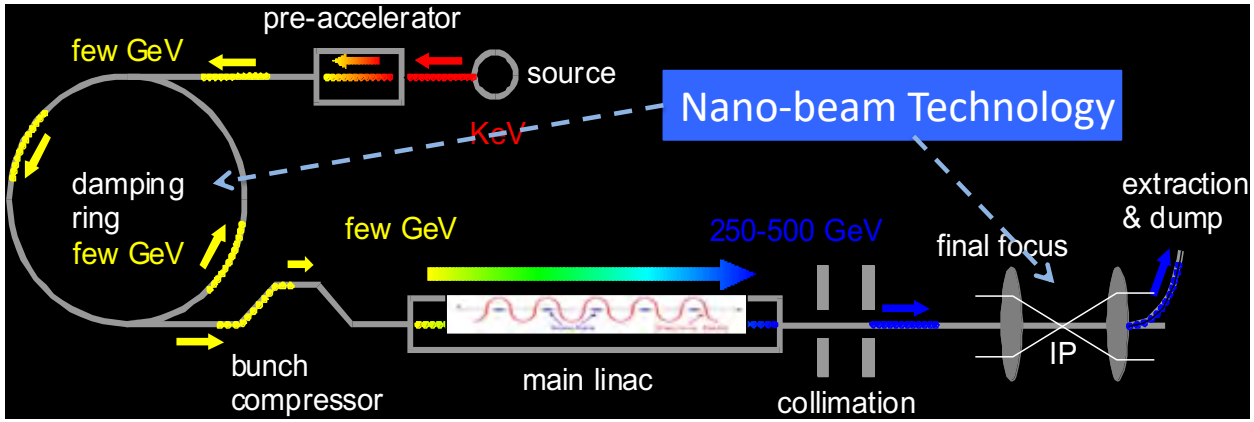
Nano Beam: Key Technology at ILC and CLIC



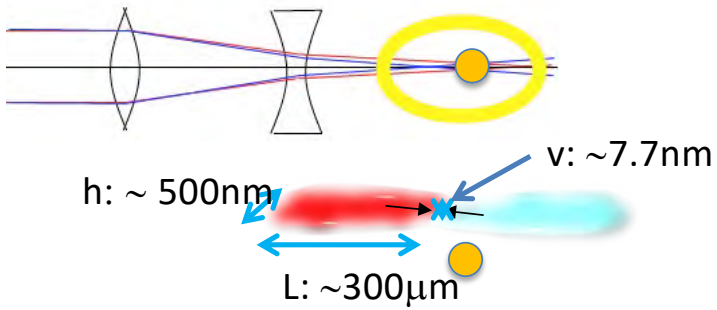
Damping Ring: Low Emittance



$$L \propto \frac{\eta P_{RF}}{E_{CM}} \sqrt{\frac{\delta_{BS}}{\varepsilon_y}}$$



Beam Delivery System: Small Beam Size



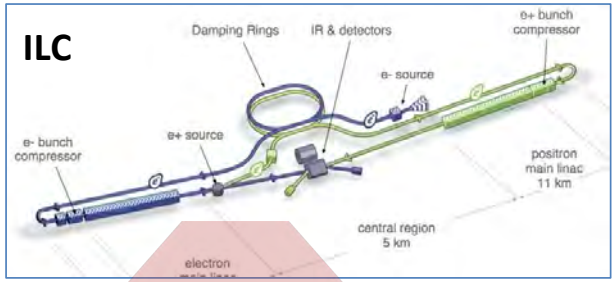
Courtesy: N. Terunuma

ATF: Accelerator Test Facility, hosted at KEK

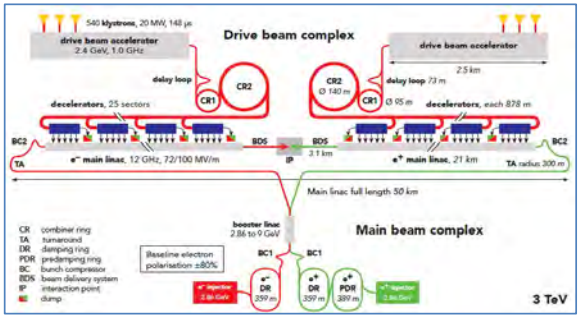
Advancing nano-beam technology for ILC/CLIC

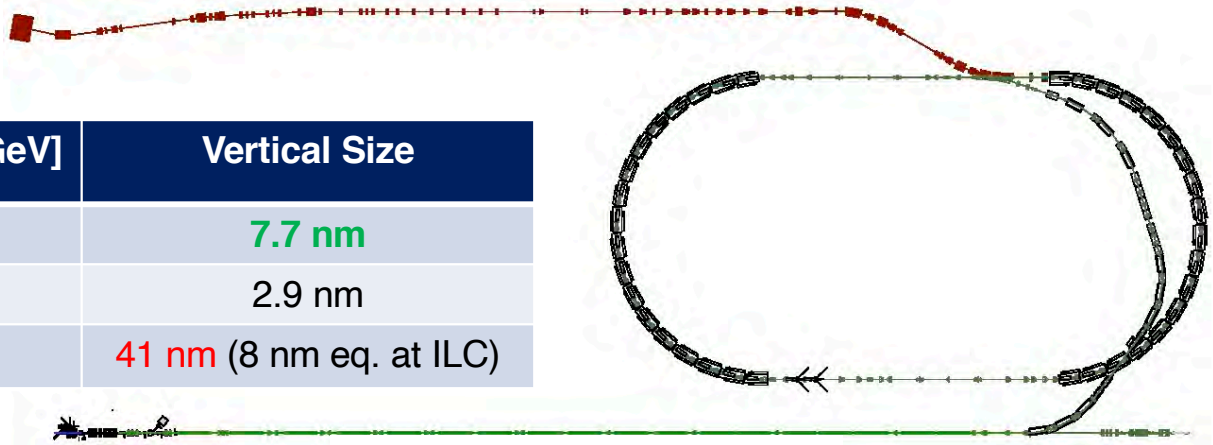
- To Realize small beam-size and Stabilize beam position

ILC



CLIC





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

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

Courtesy: N. Terunuma

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Advancing nano-beam technology for ILC/CLIC

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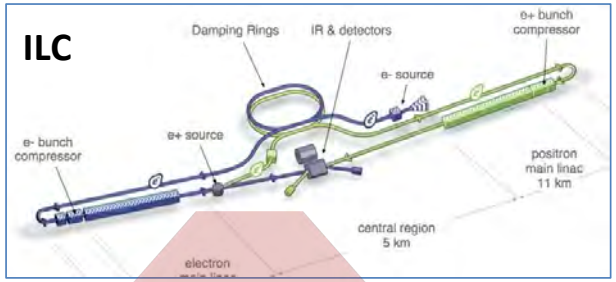
ILC



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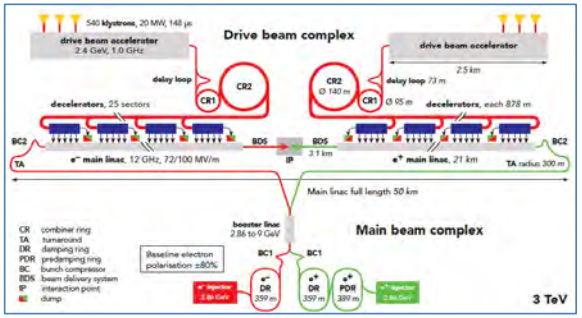

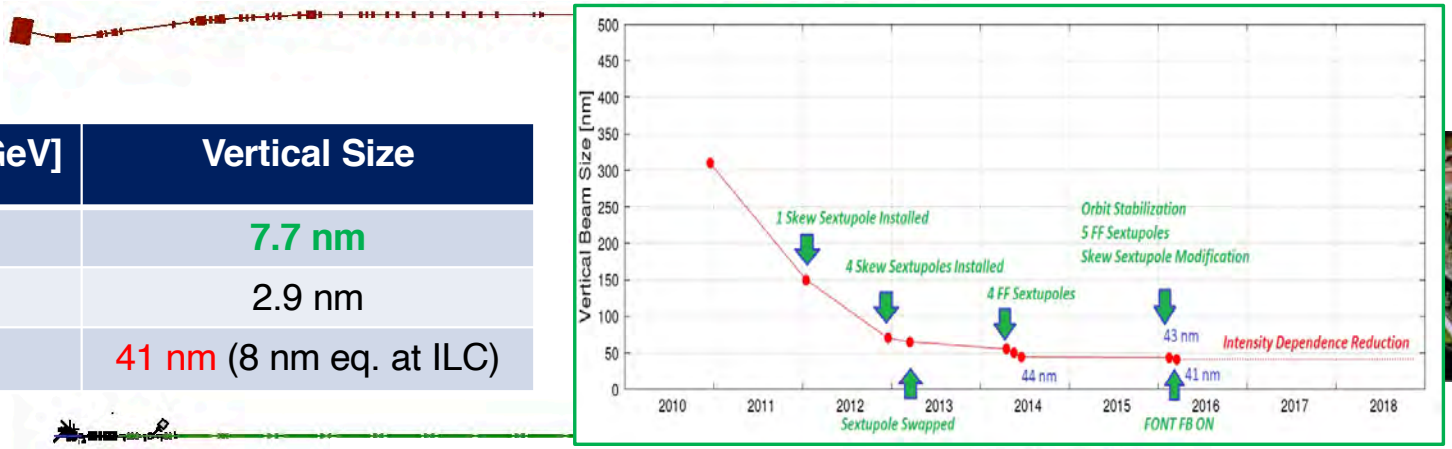

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1.3 GeV S-band e- LINAC (~70m)

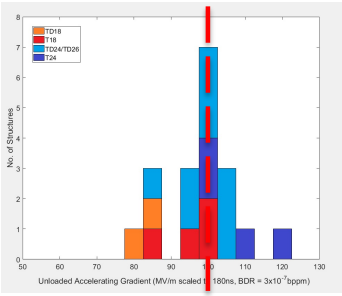
Courtesy: W. Wuensch

CLIC: Normal Conducting Linac Technology Landscape

Components:

Laboratory with commercial

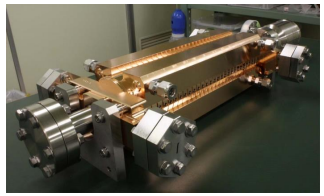
- **Accelerating structures**
- pulse compressors
- alignment
- Stabilization, etc.



~ 100 (+/-20) MV/m

Full commercial supply

- X-band klystrons
- solid state modulator,

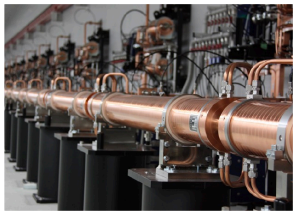


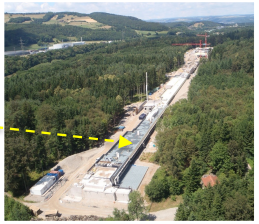
Systems Facilities:
(100 MeV-range)

- 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:

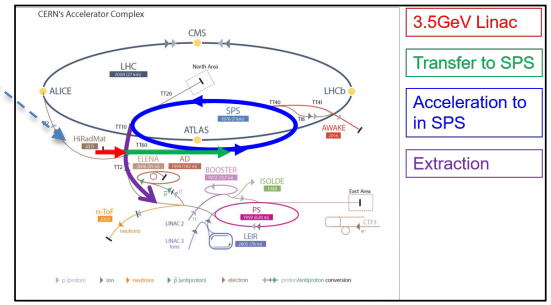
- **SACLA**
- **SwissXFEL (8 GeV)**





X-band (12 GHz)
GeV-range facilities
Planning:

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



CLIC

Discussed byS. Stapnes
See Appendix. P. 58059.

Courtesy: S. Michizono

~ 1.3 GHz SRF Accelerators, worldwide

European XFEL
(in operation, 2017~)

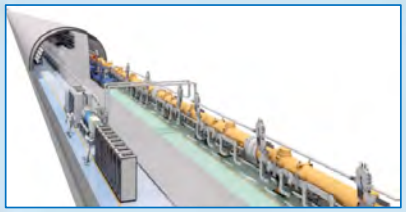
800 cavities
100 CMs
17.5 GeV (Pulsed)

ESS (0.8 GHz)
(under construction)

SHINE
(under construction)

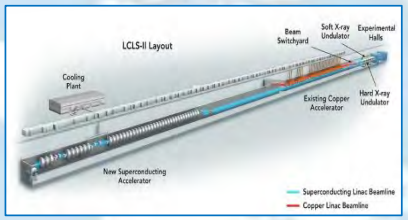
~600 cavities
75 CMs
8 GeV (CW)

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



ILC (planned)

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

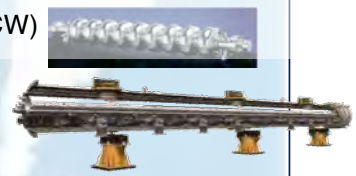


LCLS-II -HE
(under construction)

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

JLab-CEBAF(1.5 GHz)
(in operation)

40 CMs
6~12 GeV(CW)



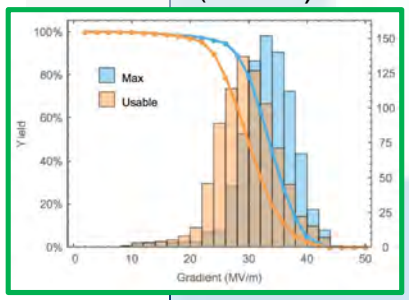
~ 2,000 1.3 GHz SRF cavities being realized, even in these 10 years !

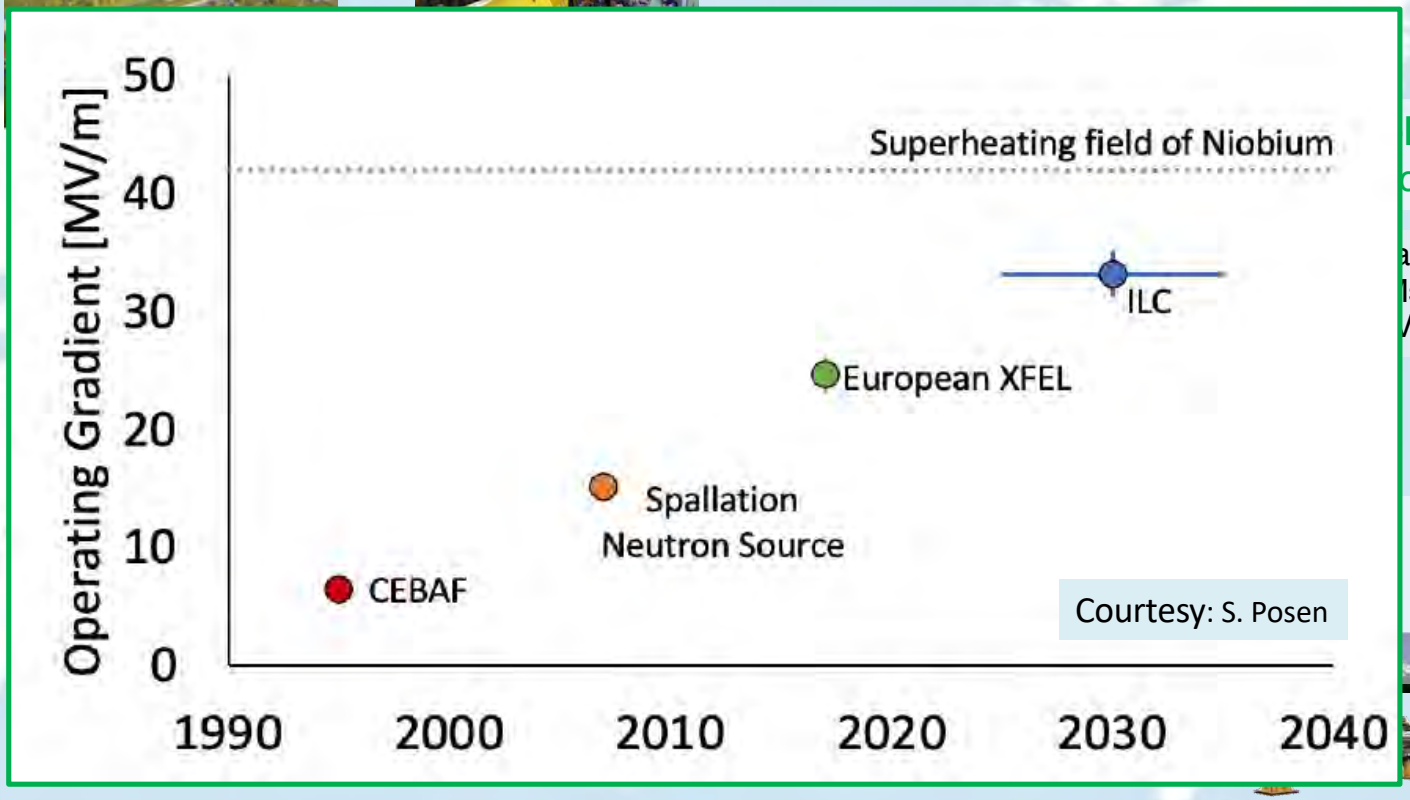
Courtesy: S. Michizono

~ 1.3 GHz, SRF Accelerators, worldwide

European XFEL
(in operation, 2017~)

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





Courtesy: S. Posen

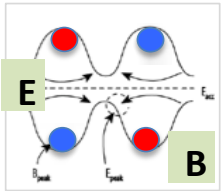
II
construction)

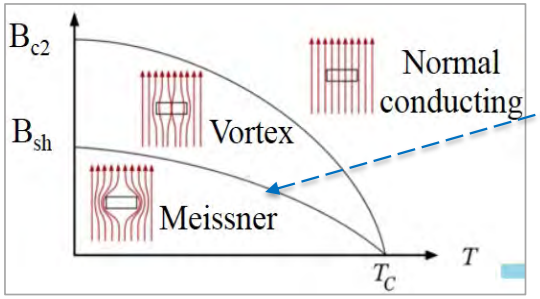
avities
ls
/ (CW)

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

Courtesy, S. Posen

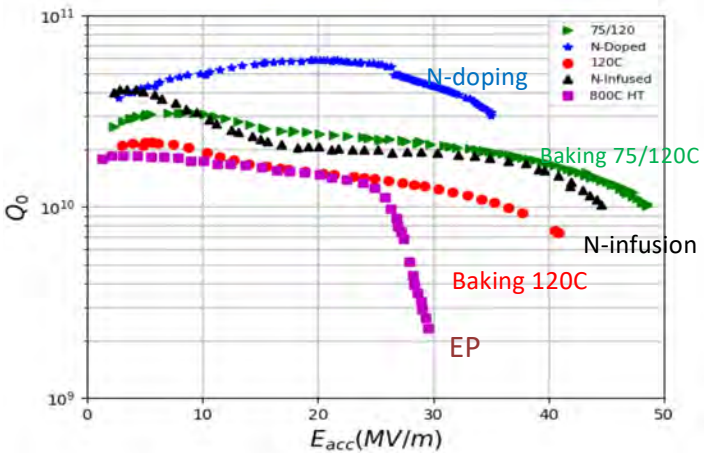
Recent Progress in SRF Technology





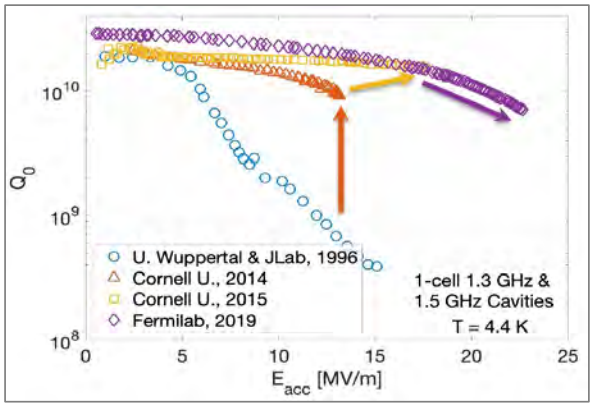
SRF cavity → w/ Meissner state

- B_{sh} = practical limit for SRF
- Bsh = 0.8 ~ 1.2X Bc_1
  - $Bs_{sh\text{-}Nb}$: 210 mT
  - $Bs_{sh\text{-}Nb3Sn}$: 430mT



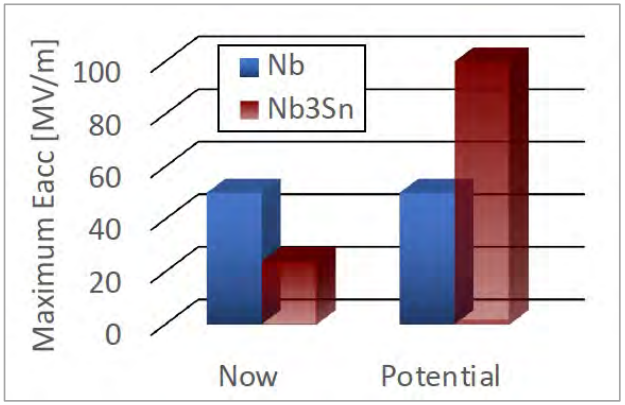
High-Q and High-G efforts in progress.

A. Grassellino, TTC Meeting, TRIUMF, Feb., 2019



Nb_3Sn progress at Fermilab.

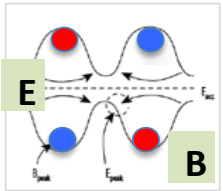
S. Posen et al., SUST, 34, 02507 (2021)

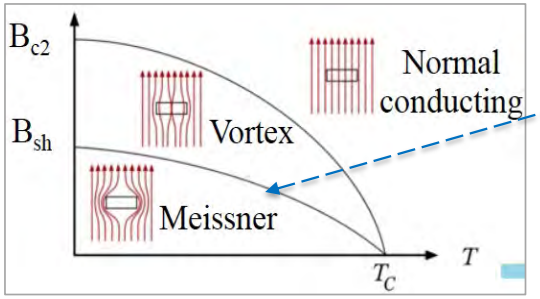


Nb_3Sn Potential in high-G future

Courtesy, S. Posen

Recent Progress in SRF Technology





SRF cavity → w/ Meissner state

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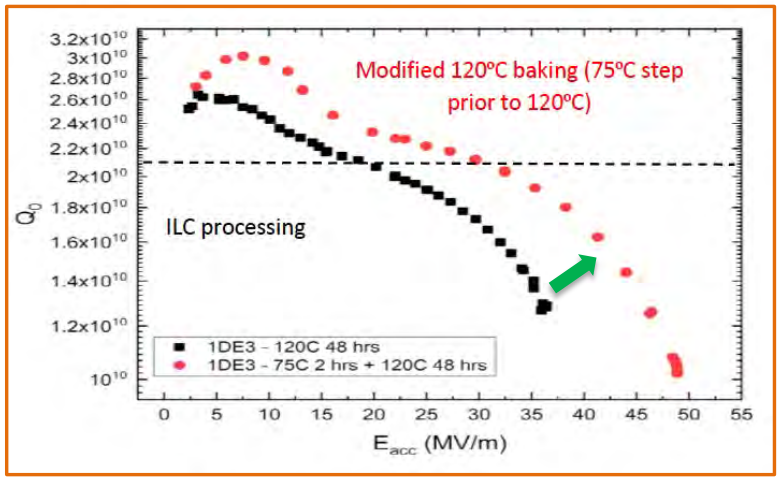
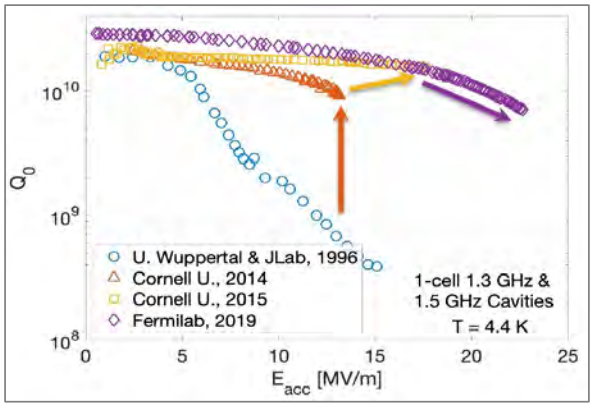
  - $Bs_{sh\text{-}Nb}$: 210 mT
  - $Bs_{sh\text{-}Nb3Sn}$: 430mT

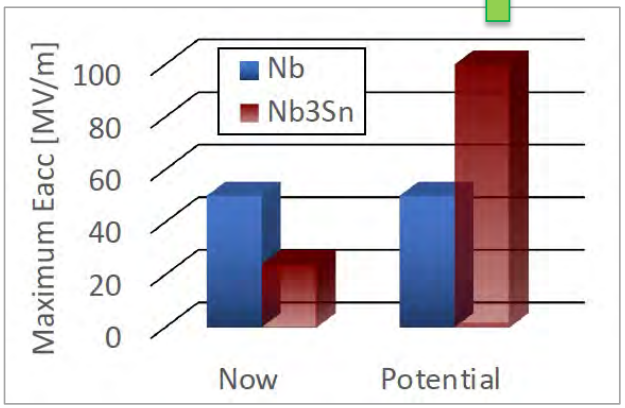
x2



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



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



Nb_3Sn Potential in high-G future

Prospects for Advanced Technologies in Future Lepton Colliders

- Accel Technologies of Nano-beam and RF 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 technology has been well **matured** for the realization including cooperation with industry, based on Euro-XFEL project successfully constructed and in stabke operation.
- SRF high-G R&D effort needs to be extended for future upgrades.
  - **Nb-bulk, 40 – 50 MV/m and Nb3Sn, > 50 MV/m:** ~ 5 years for single-cell R&D and the following 5 – 10 years for 9cell cavities statistics, **in long term scope.**

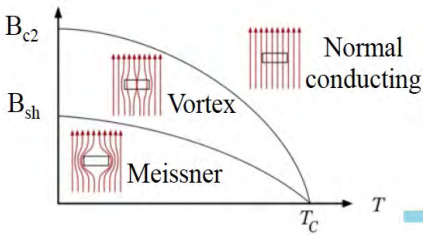
Outline

- Overview of Future Colliders
  - Lepton Colliders for Higgs Factory, and Hadron Colliders for energy frontier

- Advanced Technologies for Future Colliders
  - **Nano-beam** and **NRF/SRF** technology for **L**epton **C**olliders
  - **High-field Superconducting Magnet** technology for **H**adron Colliders

Progress in SC Accelerator Magnet Development

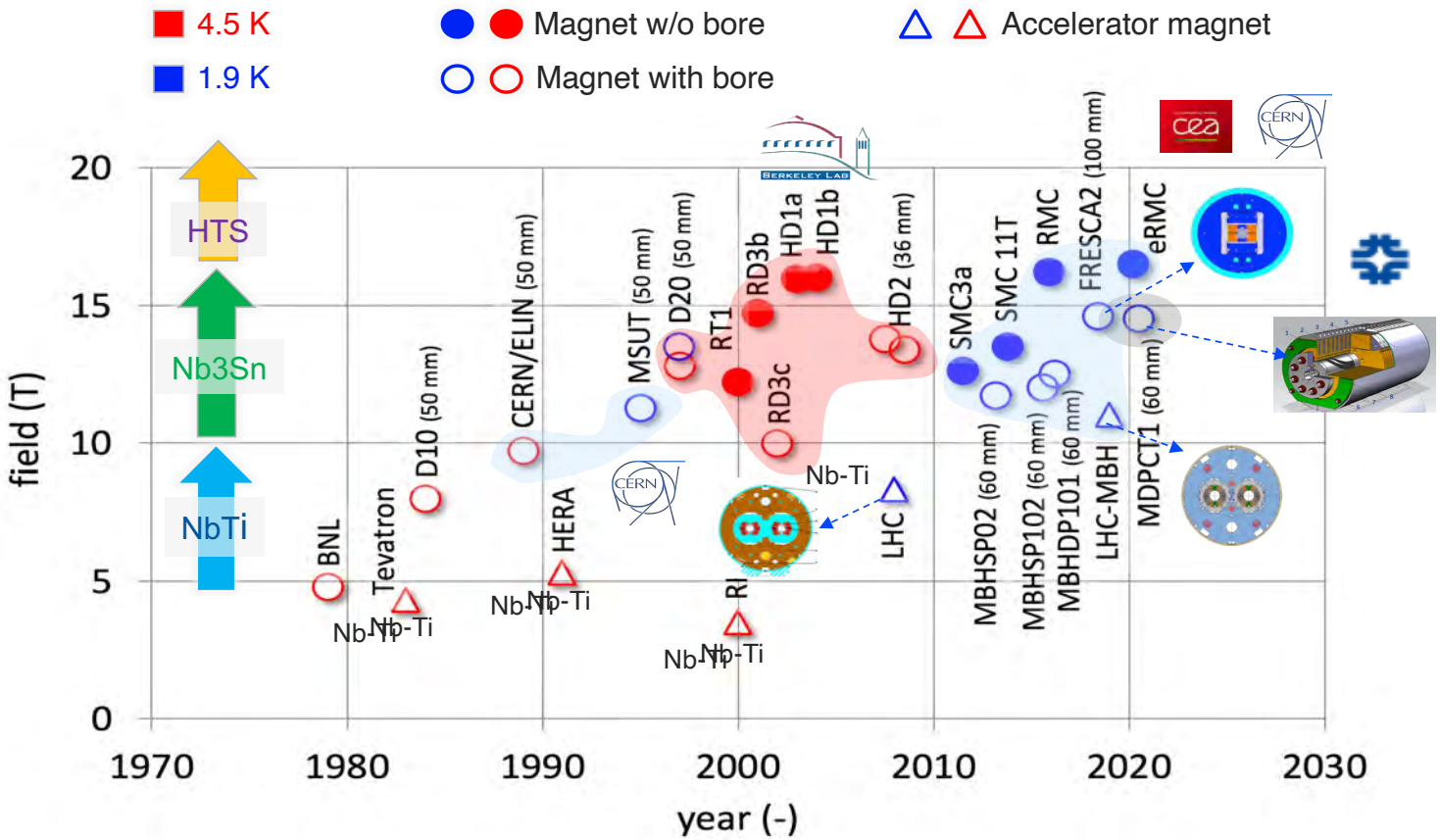
Courtesy, L. Bottura



SCM: in vortex state < Bc2

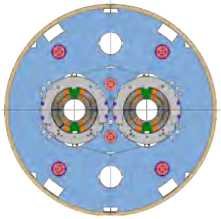
- Nb_3Sn (Bc2, Tc) : 21.5 T , 18 K
- NbTi (Bc2, Tc) : 11.5 T, 9.5 K

Progress in HTS
→ Appendix



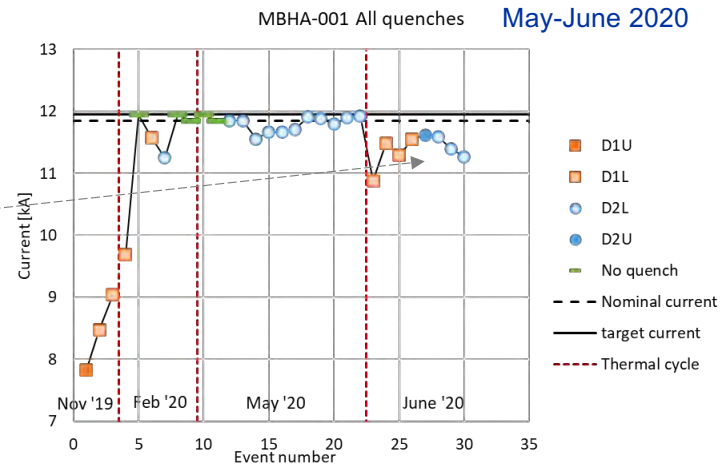
Courtesy: A. Devred, G. Willering

Performance of series S1 to S4



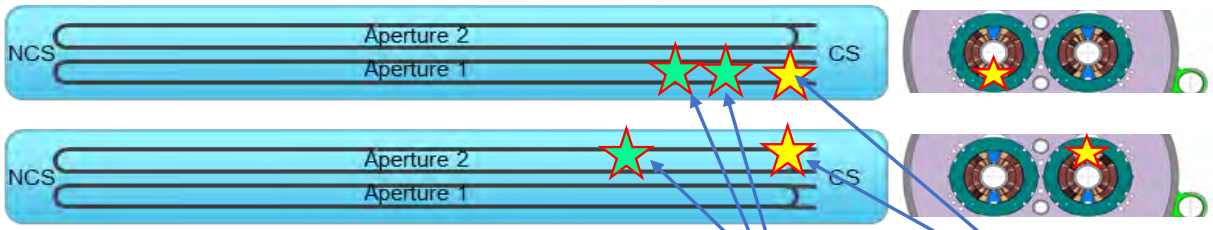
- S1 met **specified performance.**
- S2, S4 showed degradation after thermal cycles

S2:
May-June 2020



S2 – MBHA-001

S4 – MBHB-003

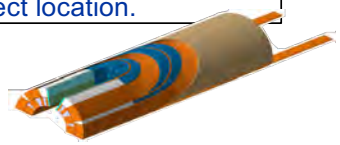


Ap 1 Lower

Ap 2, upper

Additional quench locations related to, but away from defect location.

Quench location at defect location.



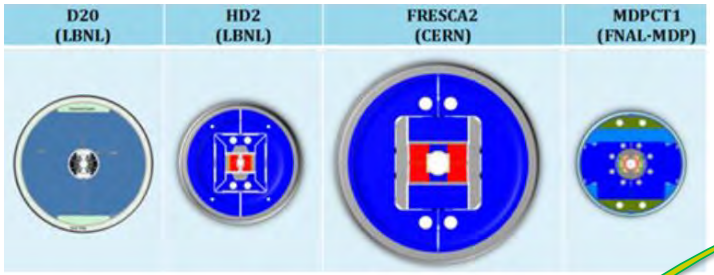
Root-Cause Analysis
(in progress)

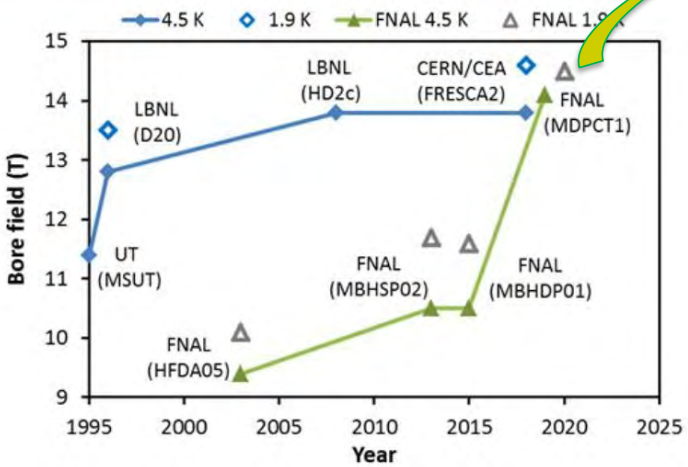
- V-I Characteristics,
- Themo-Mech. Analysis,
- X-ray Tomography,
- Others,

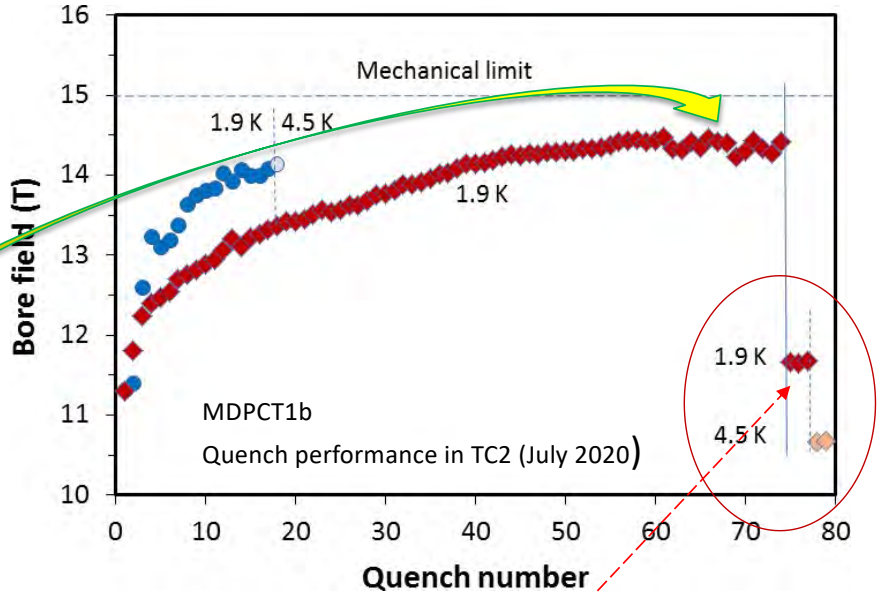
Courtesy: A. Zlobin

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

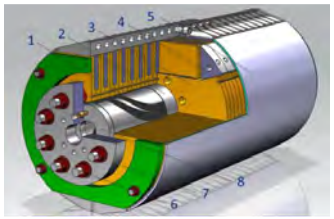
TC2 test target: *achieve ~14.5 T in magnet aperture @1.9 K*

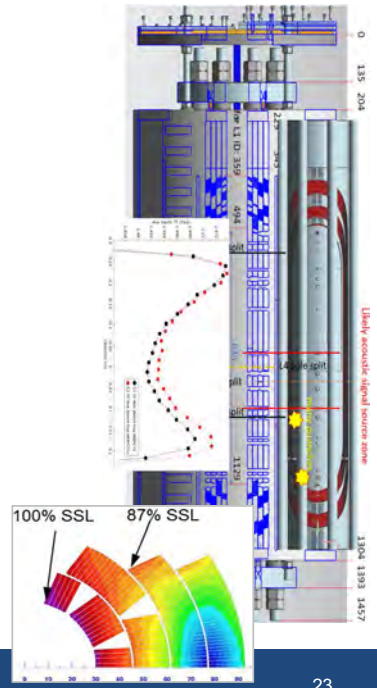






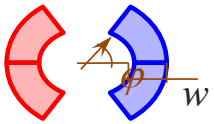
- No retraining, all quenches in coil 5, RE, pole turn
- MDPCT1b reached its conductor limit at both temperatures
- 18% performance degradation wrt TC1





Courtesy: L. Bottura, A. Devred

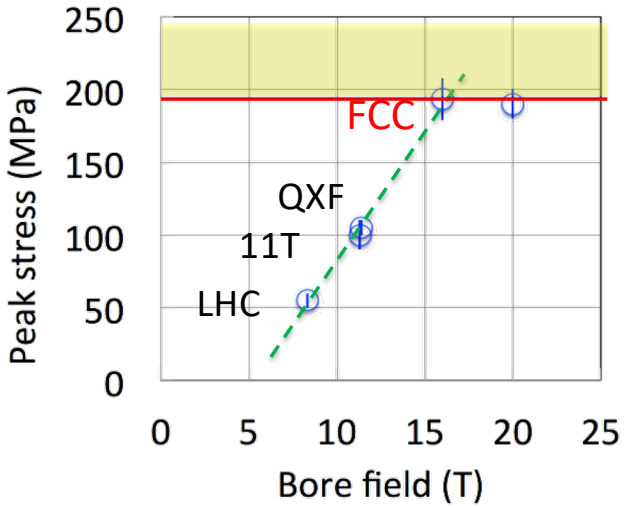
Mechanical Constrain to consider Operating Margin



$$F \propto B^2$$

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

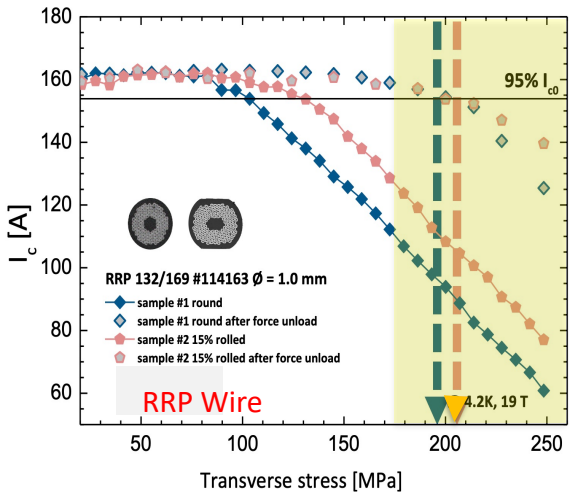
$$\sigma \approx \frac{F}{w} \propto JB \quad \sim B^2$$



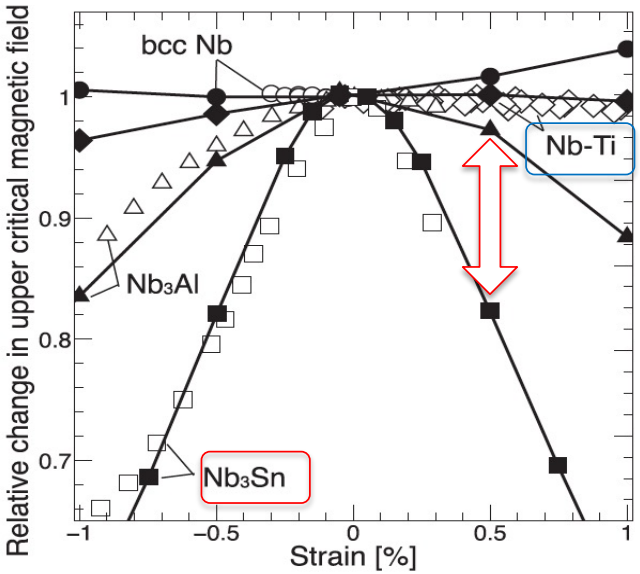
Attention : I_c (J_c) reduction:

- irreversible above～170 MPa.

Measurement at Univ. Geneve



- **Large Impact** of Strain on Jc, reduction,
- Nb3Sn superconductor much different from **NbTi**



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

Prospects on HF Superconducting Magnet Development

- **Magnetic Field:**
  - **Nb3Sn** dipole field of **16 T** with accelerator quality remains as an ambitious target.
  - **Mitigation of Degradation** becomes a critical issue,
    - as lessons learned from the (full scale) **HL-LHC 11T and US-MDP 15 T** model dipoles.
    - degradations experienced at the axial coil ends, possibly caused by combined stress/strain and/or the local enhancement.
  - Step-wise development encouraged:
    - **≥ 14 T:** Acc. Acc. quality models, w/ sufficient SC margin (≤ ~ 80 % to Nb_3Sn SSL) to explore ultimate potential of Nb_3SN (LTS),
    - **Toward 16 T:** short model, hopefully with Nb_3Sn alone, and with potential backup with HTS,
    - In parallel, **12 T,** robust, and accelerator quality prototype magnet, aiming at industrial participation and the production readiness to be demonstrated.

- **Superconductor and Insulation:**
  - **Nb_3Sn**: stress/strain sustainability needs to be prioritized, in balance with the critical current density (J_c) and specific heat (C_p), and
  - **HTS**: as insert beyond the Nb_3Sn ultimate limit,
  - **Electrical insulation** sustainability including **epoxy-resin** under high mechanical **stress** and long-term **irradiation.**

Personal View for HFM Development and the Timeline

- Nb_3Sn superconducting magnet technology for hadron colliders, still requires **step-by-step** development to reach **14, 15, 16 T, and beyond**.
- It may require the following **time-line**:
  - **Nb_3Sn, 12~14 T:** 5~10 yrs for short-models, and + 5~10 yrs for proto/pre-series with industry.

    It will result in **10 – 20 yrs** for the construction to start,
  - **Nb_3Sn, 14~16 T:** 10-15 yrs for short-models, and +10 ~ 15 yrs for proto/pre-series with some backup

    It will result in **20 – 30 yrs** for the construction to start, (consistently to the FCC-integral timeline).
  - **Nb3Sn + HTS, > 16 T**: much more than 15 yrs for fundamental research and shot model development, and the following years for full scale prototype.
- **Continuing, patient R&D effort** for high-field magnet will be critically **important**, to realize energy frontier hadron accelerators in future.

Personal Scope for HFM Development Timeline

for reaching Accelerator Construction and Operation

Timeline	~ 10	~ 20	~ 30	
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series	**Construction**	**Operation**
14~16T Nb_3Sn	Short-model R&D	Prototype/Pre-series	**Construction**	
>16 T Nb_3Sn + **HTS**	Fundamental and Short Model R&D	Prototype/Pre-series		

Note: LHC experience: **NbTi (10 T)** R&D started in 1980's
--> **(8.3 T) Production** started in late 1990's, in **~ 15 years**
→ **LHC Operation** started in later 2000's, in ~ 25 years

Thank you for your attentions

Appendix

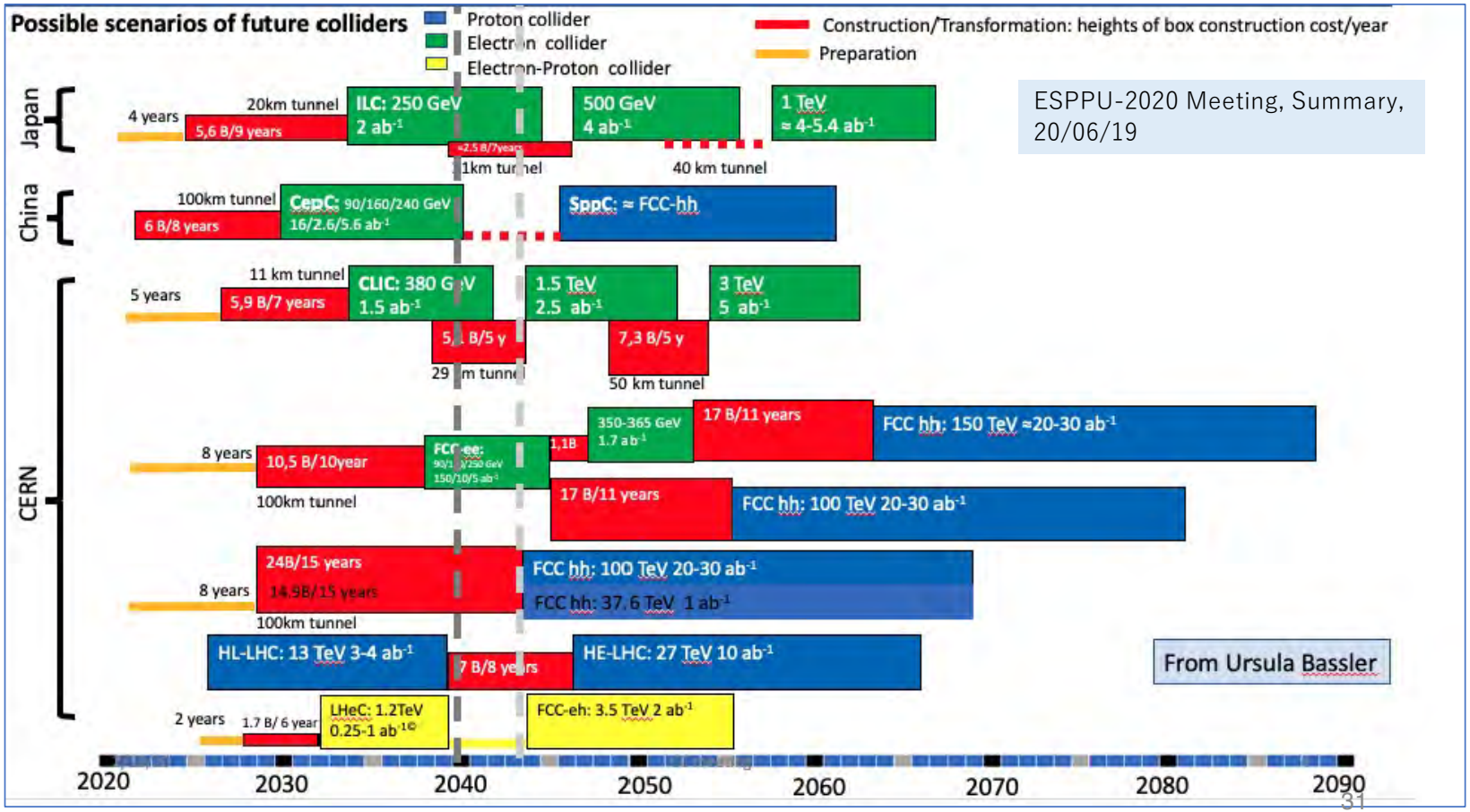
Approximate technically limited timelines of future large colliding beam facilities

V. Shiltsev and F. Zimmermann, Review of Modern Physics 93, 015006, 2021

	2020	2025	2030	2035	2040	2045
RHIC	*AA, pA, pp*					
EIC	TDR	Construction		20 GeV → 140 GeV		
LHeC	TDR	Construction		1.3 TeV		
(HL)-LHC		14 TeV				
CEPC	TDR	Construction	240 GeV	Z W		SppC
ILC	Pre-constr'n	Construction		250 GeV		500 GeV
CLIC	TDR, pre-constr'n	Construction		380 GeV		1.5 TeV
FCC-*ee*	TDR, pre-construction		Construction		Z W 240 GeV → 350 GeV	
HE-LHC	R&D, TDR, prototyping, pre-construction			Construction		27 TeV
FCC-*hh*	R&D, TDR, prototyping, pre-construction			Construction		100 TeV
Muon Collider	R&D, tests, TDR, prototyping, pre-construction			Construction		3 → 14 TeV
Plasma Coll.	R&D, feasibility studies, tests, TDR, prototyping, pre-construction				Construction	3 TeV

Possible Scenarios of Future Colliders
discussed in ESPPU-2019

- **ILC**
  - 0.25 to 1 TeV
- **CepC / SppC**
  - 0.09 to 0.24 / to ≥ 100 TeV
- **CLIC**
  - 0.38 to 3 TeV
- **FCC-ee / Fcc-hh**
  - 0.09 to 0.38 / to 100 TeV
- **HL-LHC / HE-LHC**
  - 14 / to 27 TeV



ESPPU-2020 Meeting, Summary, 20/06/19

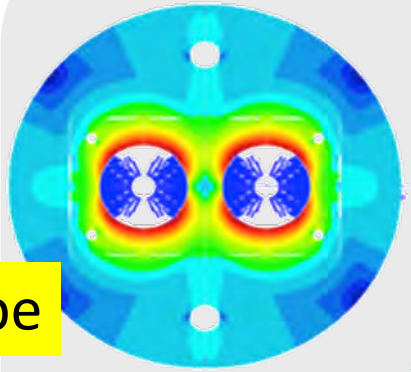
From Ursula Bassler

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

Multiple R&D Approaches for 16 T Dipole in Europe and US

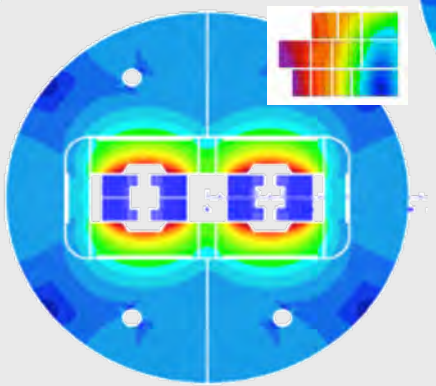
Europe

Cos-θ

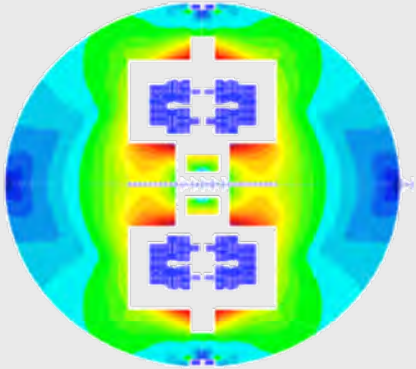


EuroCirCol
A key to New Physics

Blocks



Common coils

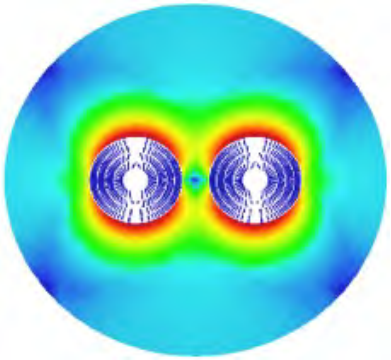


Pioneering work at BNL

FCC hh ee he

CHART2
Swiss Acc. Research & Technology

Canted Cos-θ (CCT)

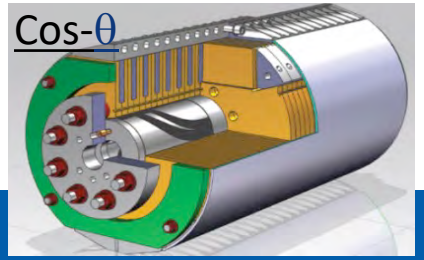


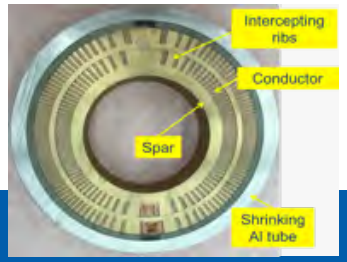
CCT,
Pioneering work at LBNL

US

U.S. MAGNET DEVELOPMENT PROGRAM

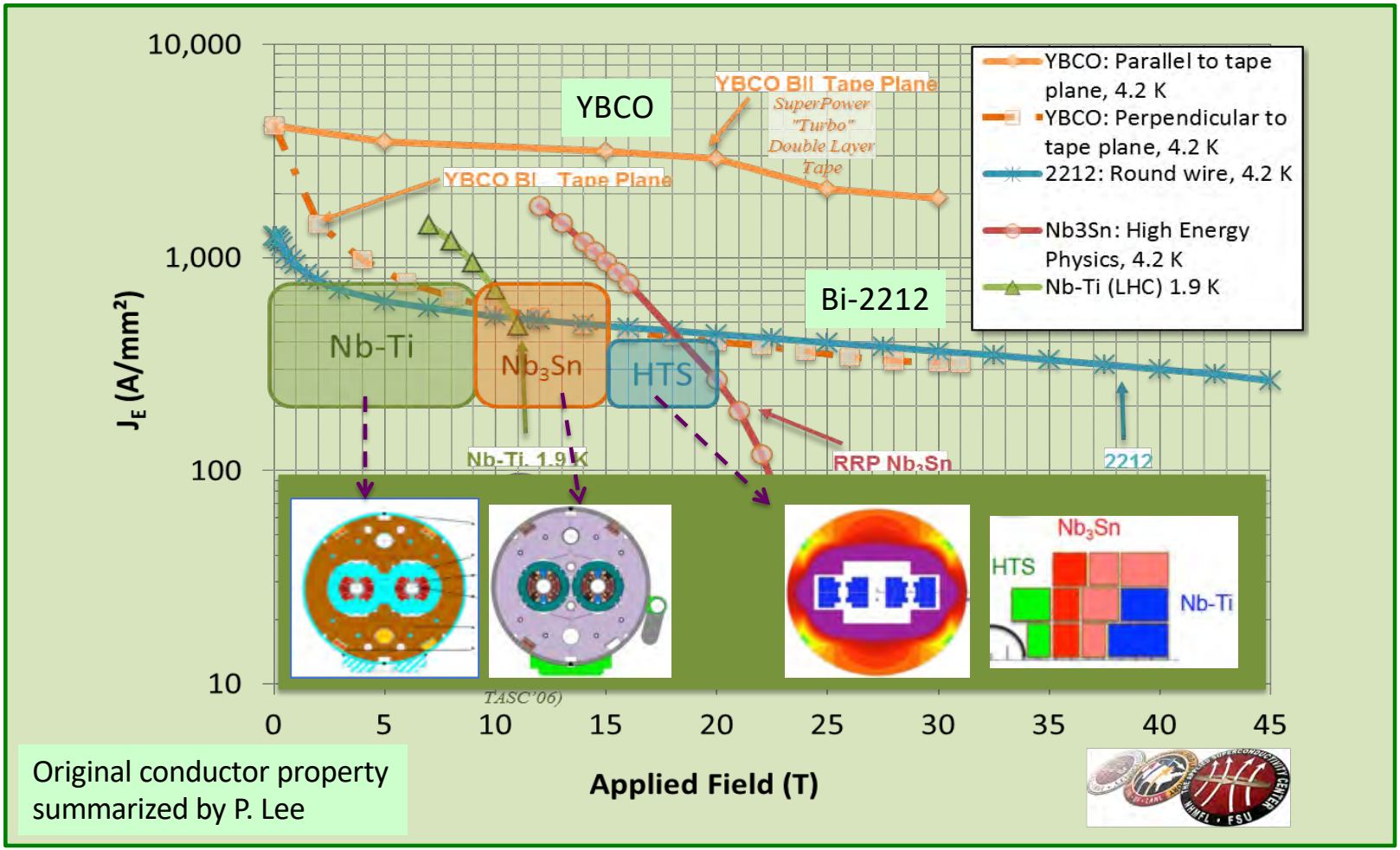
Cos-θ





Courtesy, P. Lee, L. Rossi

High-Field Superconductor and Magnets

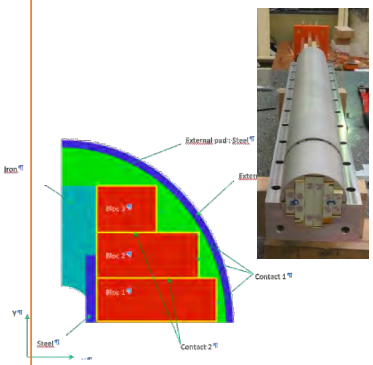


Original conductor property summarized by P. Lee

Progress in HTS SC magnet Development

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)