Technology path towards future colliders

Caterina Biscari
ALBA Synchrotron

ECFA-EPS Joint Session

Input to this talk mainly from Granada Symposium

Thanks to all those who submitted inputs, plus speakers, plus participants

Inputs to the Strategy on accelerators

- e+e- colliders
- hh colliders
- ep colliders
- FCC
- Gamma factories
- Plasma acceleration
- Muon colliders
- Beyond colliders
- Technological developments

Questions on Accelerator Science and Technology

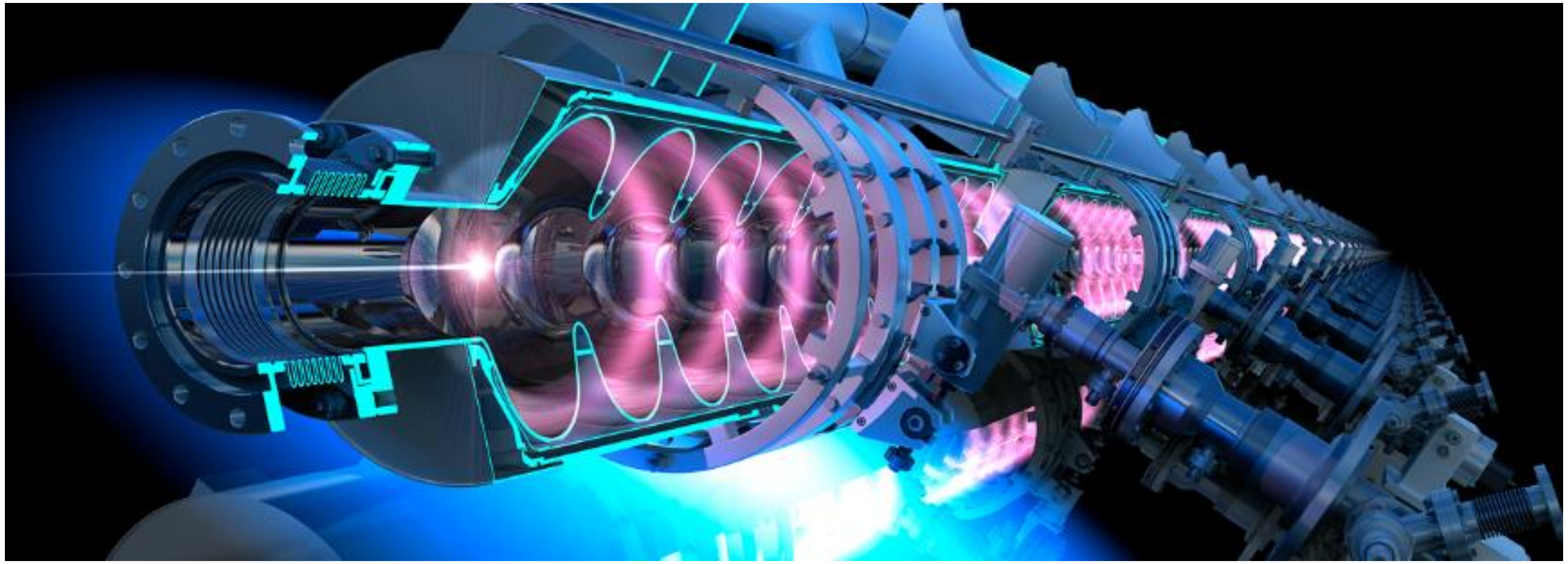
- Where is the best implementation for a Higgs factory?
- Choice and challenges for accelerator technology: linear vs. circular?
- Paths towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?
- How to achieve proper complementarity for the high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

Disclaimer

Only main technologies will be mentioned

Linear colliders technology highlights

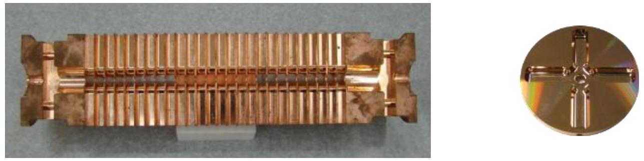
- rf cavities
- nanobeam



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, 190513bb

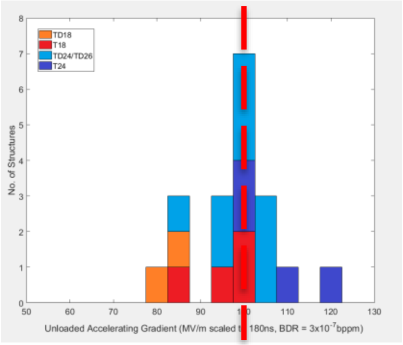
Normal Conducting Linac Technology Landscape

Courtesy: W. Wuensch

Components:

Laboratory with commercial

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

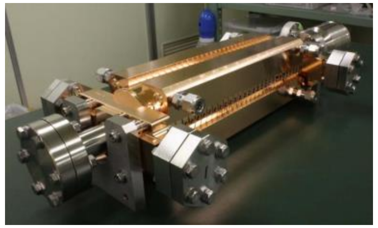


~ 100 (+/-20) MV/m

Full commercial supply

- X-band klystrons
- solid state modulator,

A. Yamamoto, 190513bb



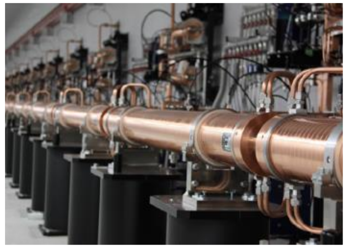
Systems Facilities:
(100 MeV-range)

- 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:

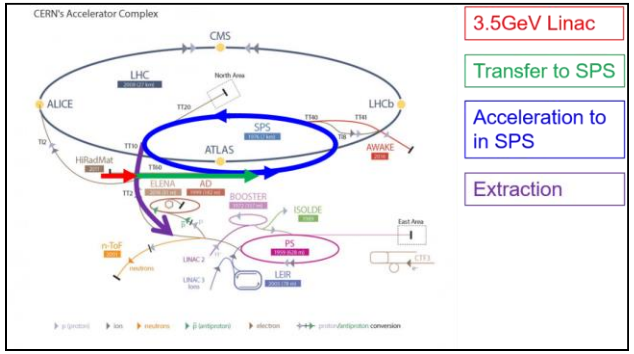
- **SACLA**
- **SwissXFEL (8 GeV)**



X-band (12 GHz)
GeV-range facilities

Planning:

- **EuPraxia**
- **e-SPS**
- **CompactLight**



CLIC

Advances in SRF Technology for Accelerators

Progress (1988~)

- TRISTAN
- LEP-II
- HERA
- CEBAF
- CESR
- KEKB
- BES
- cERL

In Operation: → # cavities

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

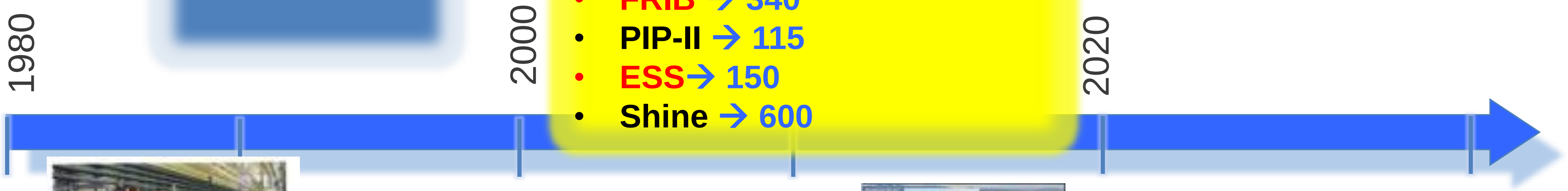
Under Construction:

- **LCLS=II → 300**
- **FRIB → 340**
- **PIP-II → 115**
- **ESS→ 150**
- **Shine → 600**

To be realized:

- HL-LHC-Crab → 20
- EIC

- **ILC-250 → 8,000**
- FCC
- CEPC/SPPS

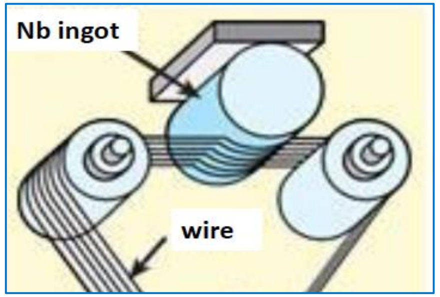


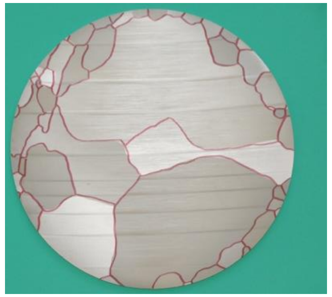
A. Yamamoto, 190513bb

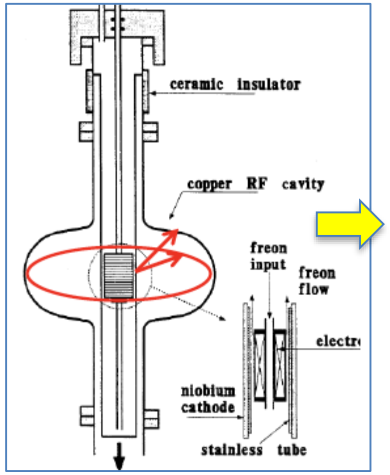
> **2,000** SRF cavities realized, in last 10 years !

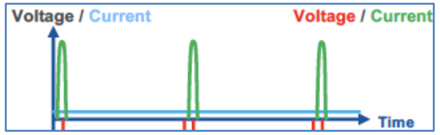
Challenges in SRF Cavity Technology

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









A. Yamamoto, 190513bb

RF technology

- Accelerator Technologies are ready to go forward for **lepton colliders** (ILC, CLIC, FCC-ee, CEPC), focusing on the Higgs Factory **construction to begin in > ~5 years.**
- SRF accelerating technology is well **matured** for the realization including cooperation with industry.
- Continuing R&D effort for higher performance is very important for future project upgrades.
  - **Nb-bulk, 40 – 50 MV/m**: ~ 5 years for single-cell R&D and the following 5 – 10 years for 9cell cavities statistics to be integrated. Ready **for the upgrade**, **10 ~ 15 years.**

FEL communities develop NC + SC rf cavities

- Operating (SwissFEL, EuXFEL,…)
- in construction (LCLS,…)
- in design stage

And so do ERL (PERLE,..)

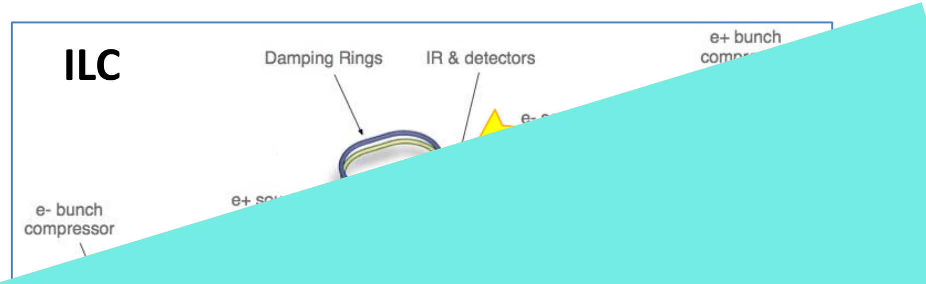
A. Yamamoto

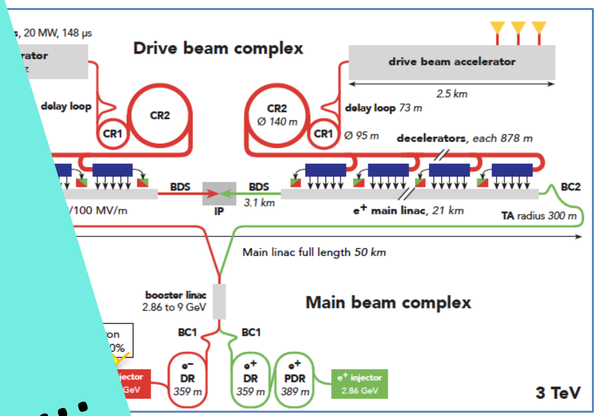
ATF/ATF2: Accelerator Test Facility

Courtesy: N. Terunuma

Develop nano-beam technology for ILC/CLIC

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

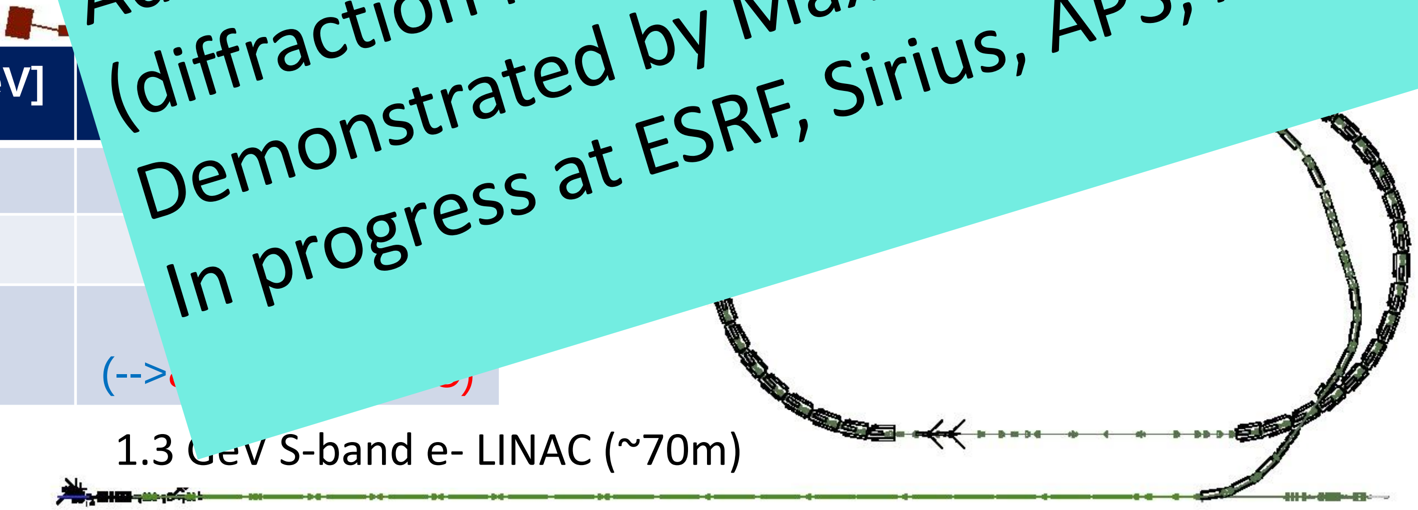




Advances in light sources
(diffraction limited storage rings)
Demonstrated by MaxIV
In progress at ESRF, Sirius, APS, ALS,….

FF: Nano bea

	B Energy [GeV]	
ILC-250	125	
CLIC-380	190	
ATF2 (achieved)	1.3	(-->



Damping Ring (140m)
Low emittance e- beam

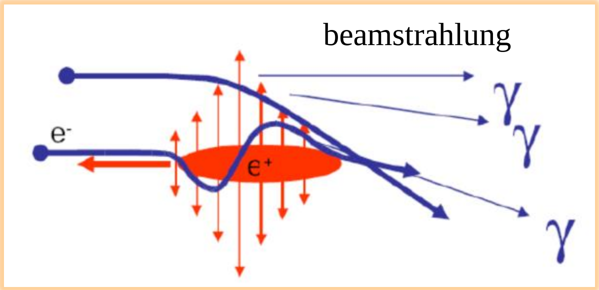
1.3 GeV S-band e- LINAC (~70m)

From A. Yamamoto, 190513bb

Challenges of Linear Colliders Higgs Factories

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y} \qquad \sim 10^{34}$$

Luminosity Spectrum
(Physics)



- $\delta E/E$ ~1.5% in ILC
- Grows with E: 40% of CLIC lumi 1% off $\sqrt{s}$

Beam Current
(RF power limited, beam stability)

- Challenging *e+* production (two schemes)
- CLIC high-current drive beam bunched at 12 GHz (klystrons + 1.4 BCHF)

Beam Quality
(Many systems)

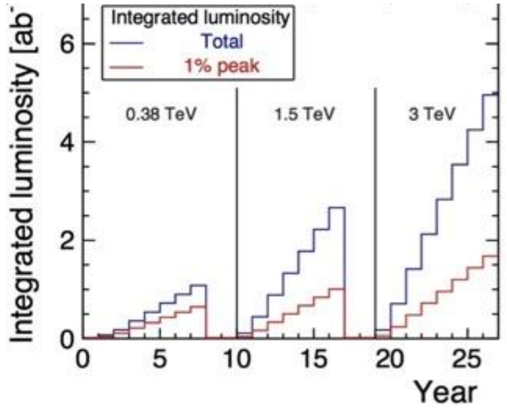
- Record small DR emittances
- 0.1 µm BPMs
- IP beam sizes

ILC 8nm/500nm
CLIC 3nm/150nm

Shiltsev | EPPSU 2019 Future Colliders

Overview of CLIC and ILC parameters

CLIC illustrations



CLIC y: 75% of 180 days

CLIC parameters

E: 380, 1500, 3000 GeV (L: 11-50 km)
Lum: 1.5-5.9 $10^{34\ -2}$ cm-2 s-1 *
Prep. phase 2020-2025
Constr.+comm. 7y, ready before 2035
Cost: CLIC-380: 5.9 BCHF,
Upgrades: deltas of 5 and 7 BCHF
Power: ~ 170 MW – 580 MW**

NCRF X-band now established and industrially available, used in small systems and being introduced in larger ones, relevant reference experience with C-band for larger systems (Swissfel).

ILC parameters

E: 250, 500, 1000 GeV (L: 20-40 km)
Lum: 1.35 (2.7) – 1.8(3.6) 10^{34} cm-2 s-1*
Prep. phase 2020-2023(4)
Constr.+comm. 9-10y, ready before 2035
Cost: ILC-250: 4.9-5.3 BILCU,
ILC-500: 8 BILCU (2012 $)
Power: ~ 130 – 300 MW

SCRF in extensive use in several FELs with parameters close to ILC parameters, the primary one being the E-XFEL at DESY. Technology optimization underway, linking to evolving SCRF R&D for grad. and Q.

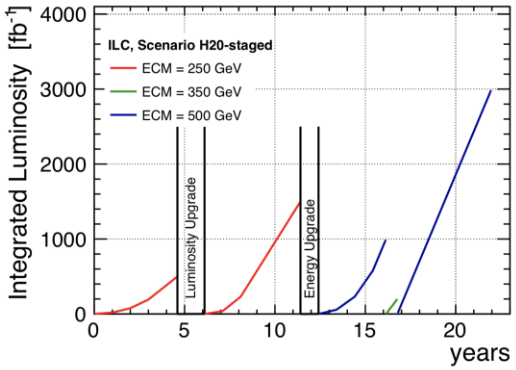
Staged approach to higher energies

Nanobeam addressed in design & specifications, benchmarked simulations, low emittance ring progress, extensive prototype and method development (for alignment, stabilization, instrumentation, algorithms and feedback systems, system and facility tests : FACET, light-sources, FELs, ATF2)
Extensive prototyping of all parts of these accelerators, for lab-test, use/test in test-facilities, light-sources or FELs (magnets, instrumentation, controls, vacuum, etc)

CERN hosted international project (follow LHC model)

Japan hosted international project, initial ideas about European capabilities available (link)

ILC illustrations



ILC y: 75% of 240 days

---

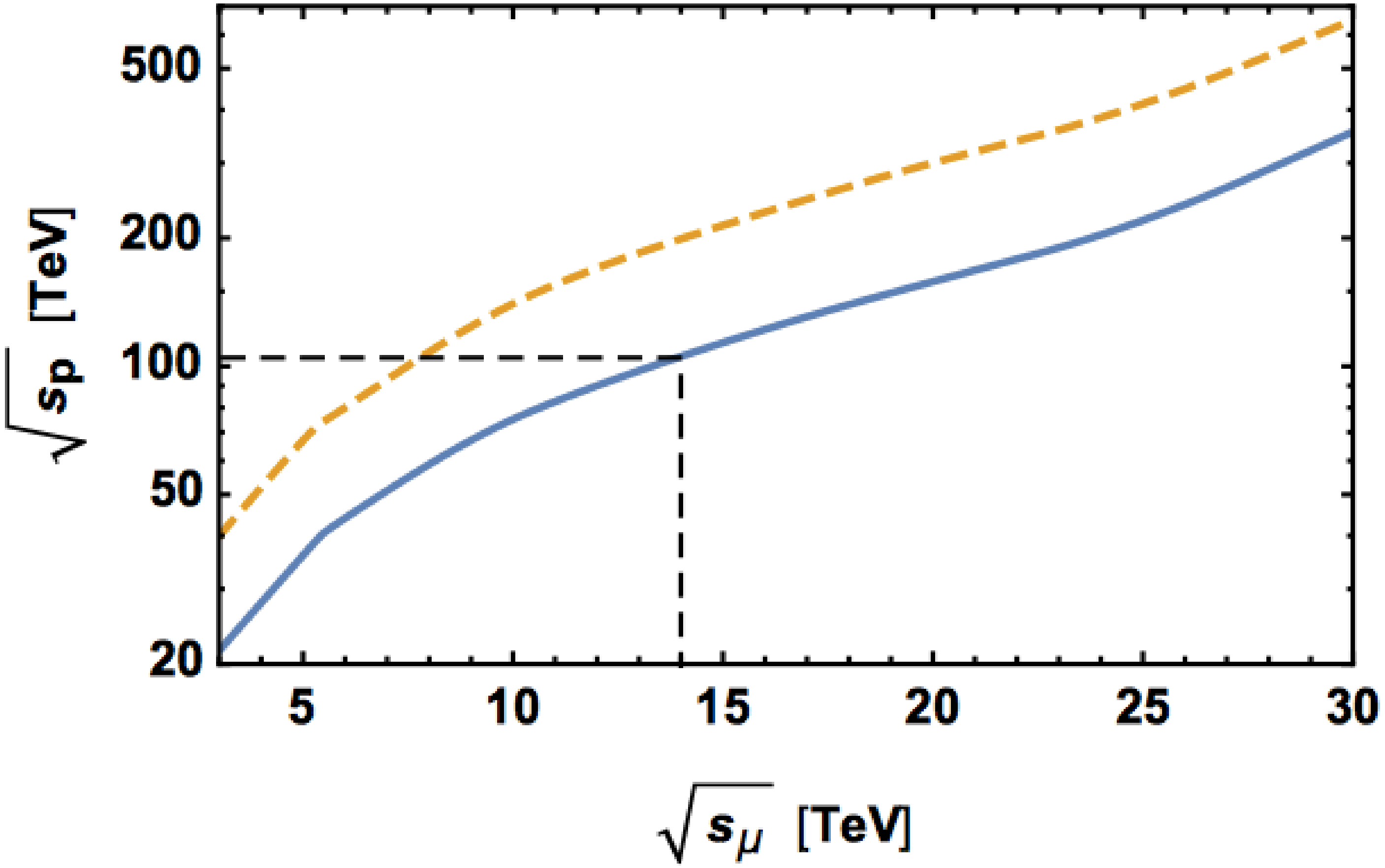
* Doubling by increasing frequency (to be) studied, ** Power at 1.5 and 3 TeV not updated from CDR 2012

Circular colliders technology highlights

- Size
- Synchrotron radiation
- High field magnets

Proton or lepton collisions

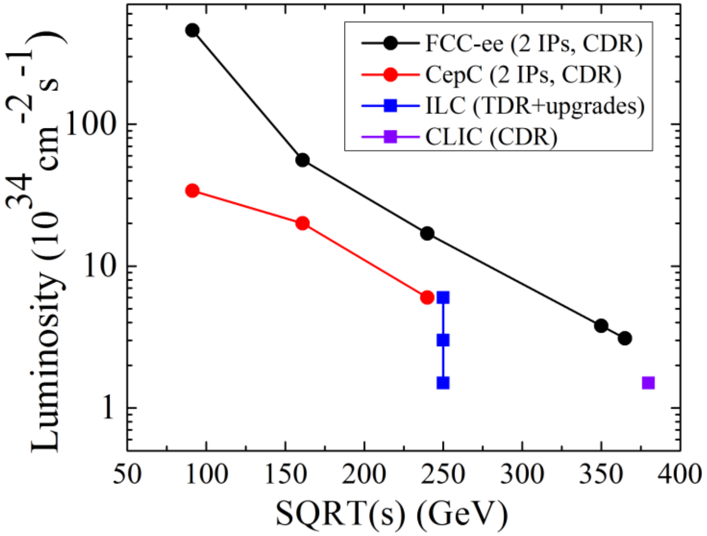
14 TeV lepton collisions
Are comparable to 100 TeV proton collisions



D. Schulte

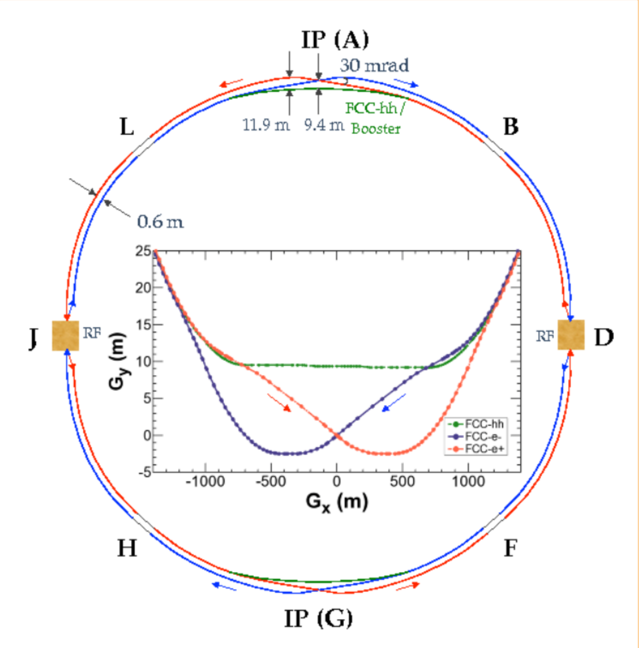
e+ e- colliders

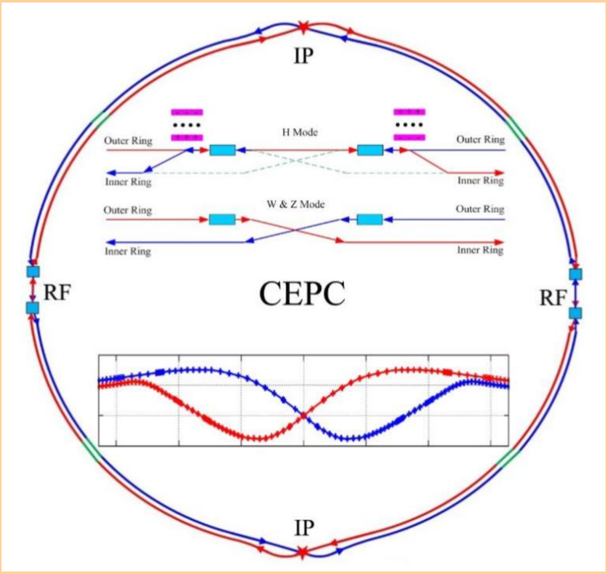
- Synchrotron radiation power, mitigated by long tunnel (100 km)
- Limit set to 100 MW @ FCC-ee (60 MW @ CepC) by limiting the current => L decreases as E increases
- new **beam-beam instability**; short beam lifetime => large acceptance



- High efficient RF sources:
  - Klystron 400/800 MHz η from 65% to >85%
- High efficiency SRF cavities:
  - 10-20 MV/m and high Q_0; Nb-on-Cu, Nb_3Sn
- Crab-waist collision scheme:
  - *Super KEK-B* nanobeams experience will help
- Energy Storage and Release R&D:
  - Magnet energy re-use > 20,000 cycles
- Efficient Use of Excavated Materials:
  - 10 million cu.m. out of 100 km tunnel

Shiltsev





Luminosity Challenge (e+ e-)

Luminosity cannot be fully demonstrated before the project implementation

- Luminosity is a feature of the facility not the individual technologies
- Have to rely on experiences, theory and simulation and foresee margins

FCC-ee and CEPC are based on experience from LEP, DAPHNE, KEKB, PEP II, superKEKB, …

- Gives confidence that we understand performance challenges
- New beam physics occurs in the designs,
  - e.g. beamstrahlung is unique feature of FCC-ee and CEPC
    - Identified and anticipated in the design, should be able to trust simulations
- **The technologies required are improved versions of those from other facilities**

Linear colliders are based on experiences from SLC, FELs, light sources, …

- Gives confidence that we understand the performance challenges
- Gives us confidence that we can do better than SLC
- Still performance goal more ambitious, e.g. **beam size of nm scale**
  - Creates additional challenges and requires additional technologies, e.g. stabilization
- **A part of the technologies are improved versions of those from other facilities**
- **Some had to be purpose-developed for linear colliders**

From D. Schulte

Maturity (e+e-)

- CEPC and FCC-ee, LHeC
  - Do not see a feasibility issue with technologies or overall design
  - But more hardware development and studies essential to ensure that the performance goal can be fully met
    - E.g. **high power klystrons, strong-strong beam-beam studies with lattice with field errors**, …
- ILC and CLIC
  - Do not see a feasibility issue with technology or overall design
  - Cutting edge technologies developed for linear colliders
    - **ILC technology already used** at large scale
    - **CLIC technology in the process of industrialization**
  - More hardware development and studies required to ensure that the performance goal can be full met
    - e.g. **undulator-based positron source**, BDS tuning, …
- Do not anticipate obstacle to commit to either CEPC, FCC-ee, ILC or CLIC
  - But a **review is required of the chosen candidate(s)**
  - More effort required before any of the projects can start construction

D. Schulte

pp colliders (+ ion-p, e-p)

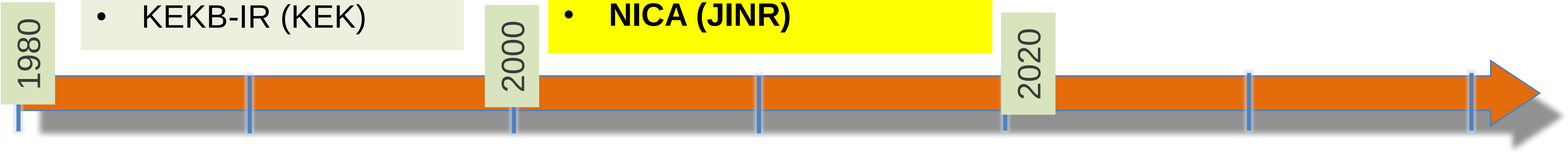
Advances in SC Magnets for Accelerators

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*

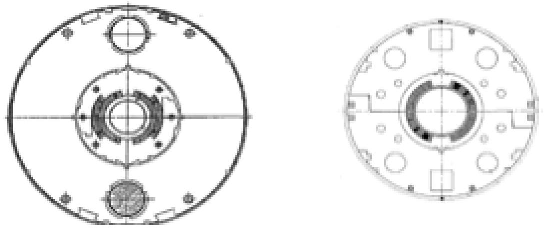
Under Construction
- **FAIR (GSI) ………***Fast-cycleShnchr.*
- **HL-LHC (CERN)**
- **NICA (JINR)**

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

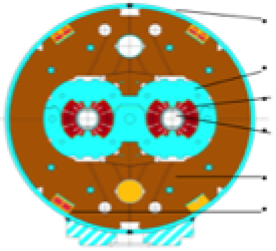


Tevatron-D.
HL-LHC 11T-D (Nb$_3$Sn)

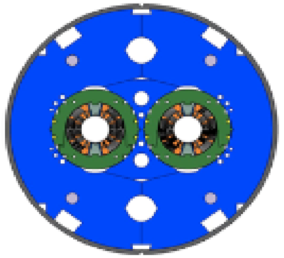
HERA-D.



RHIC-D.

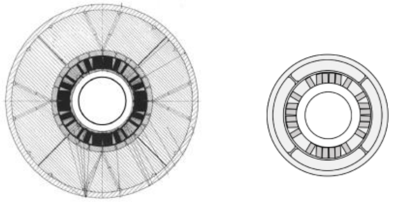


LHC.D (NbTi)

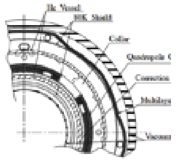


Dipole

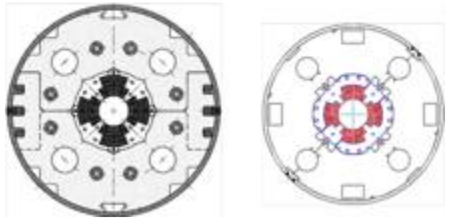
ISR-IRQ, LEP-IRQ
LHC-IRQ (Nb$_3$Sn)



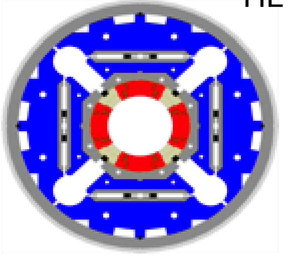
TRISTAN/KEKB-IRQ



LHCC-IRQ (NbTI)



HL-

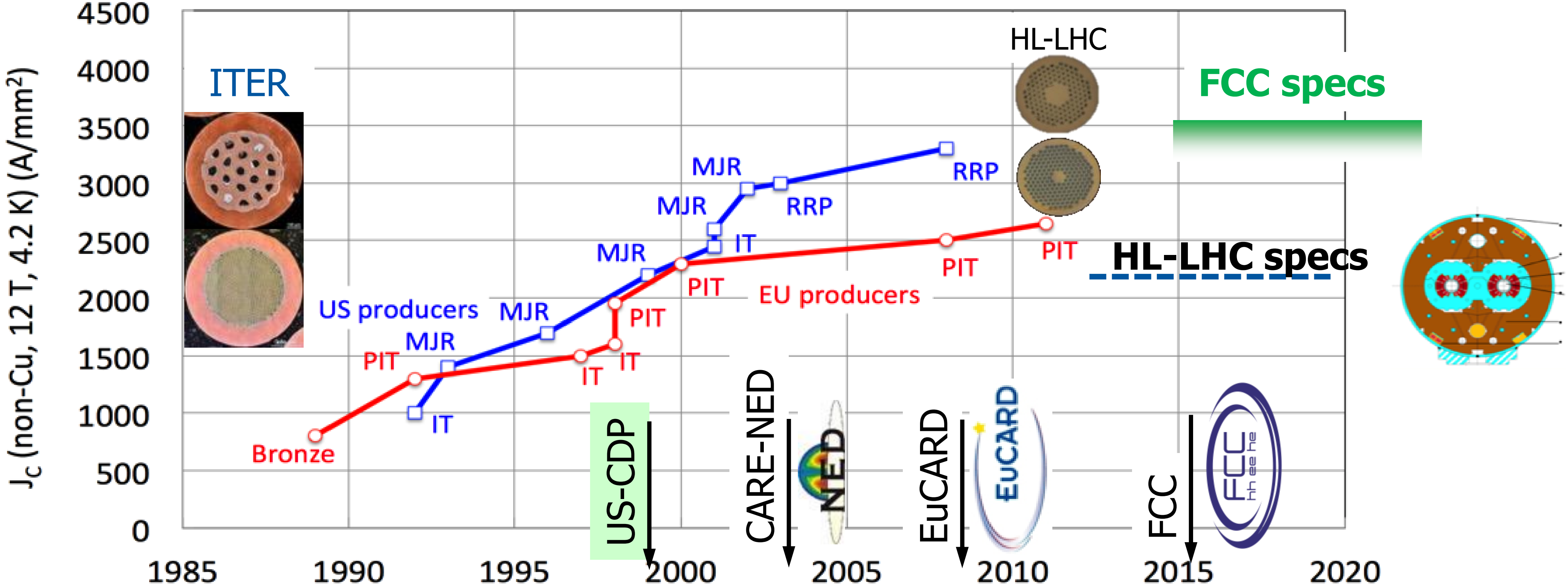


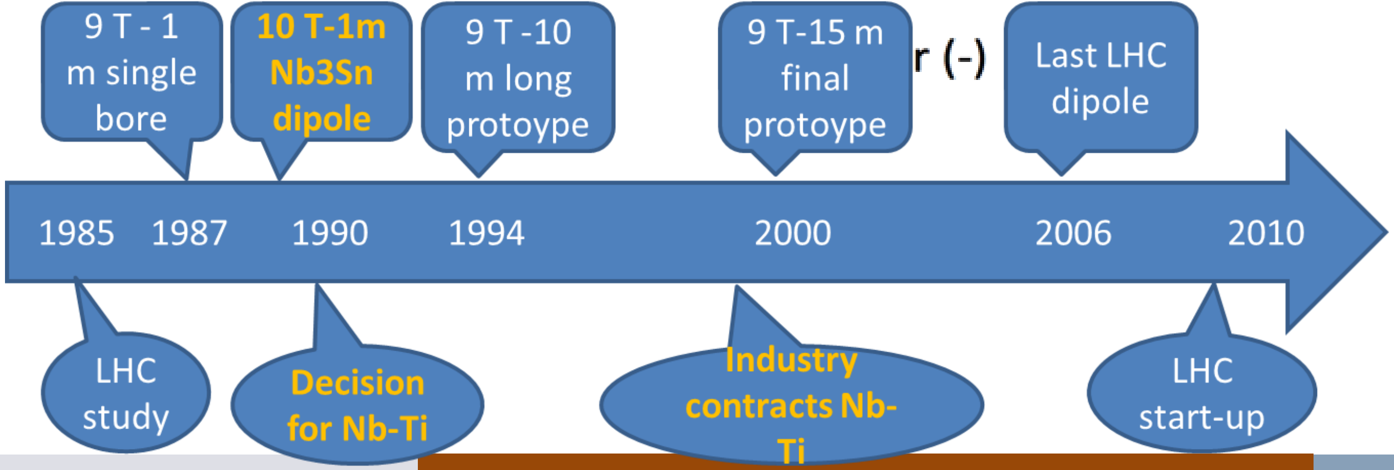
IR Quadrupole

A. Yamamoto

Nb$_3$Sn Conductor development for Accelerators (1998 ~)

Courtesy, G. de Rijk





9 T - 1 m single bore

10 T-1m Nb3Sn dipole

9 T -10 m long protoype

9 T-15 m final protoype

Last LHC dipole

1985 1987 1990 1994 2000 2006 2010

LHC study

Decision for Nb-Ti

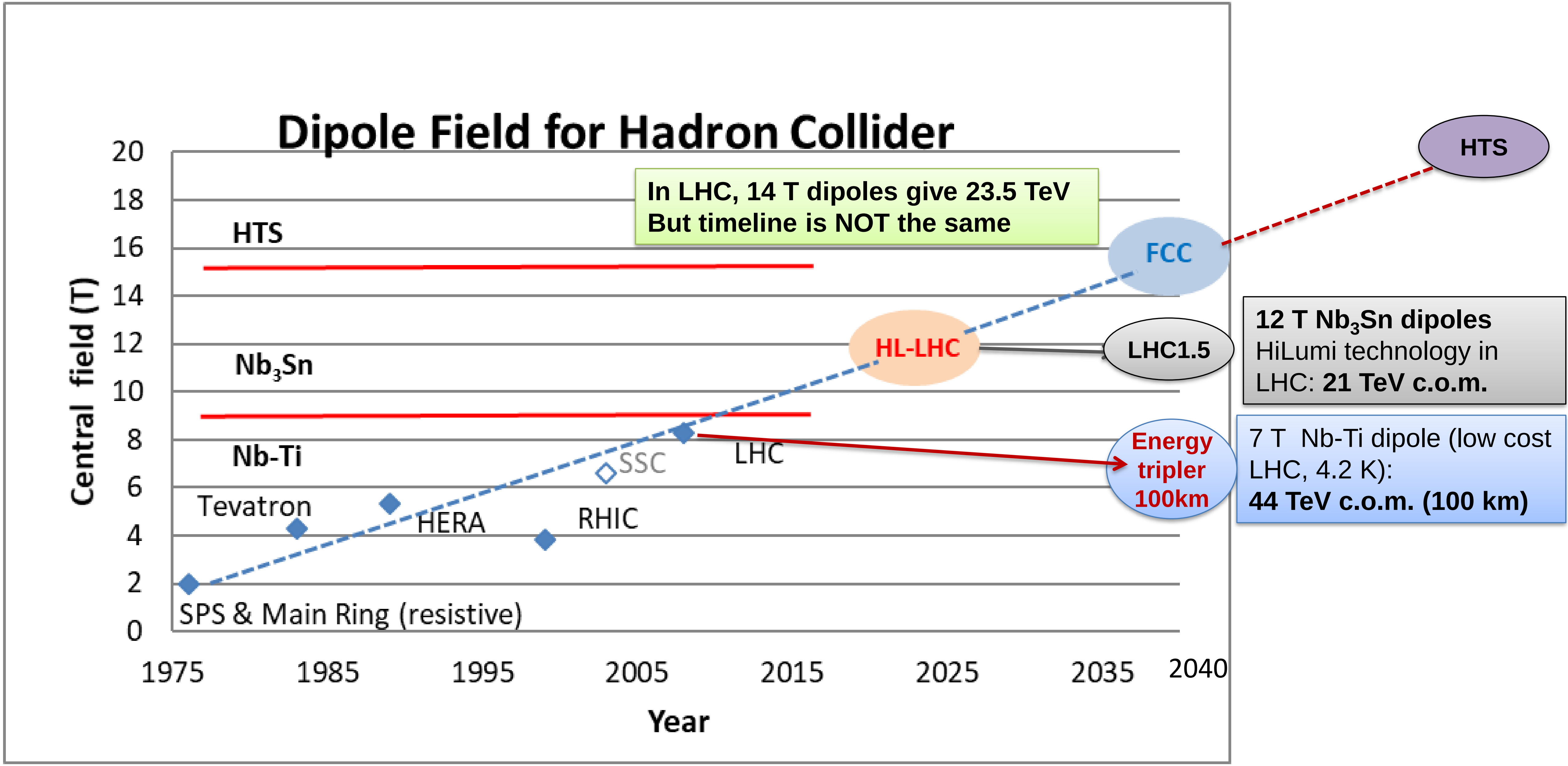
Industry contracts Nb-Ti

LHC start-up

After 10 years of development, the US and EU development produced the Nb$_3$Sn conductor for HILUMI

A. Yamamoto

High field magnet development



In LHC, 14 T dipoles give 23.5 TeV
But timeline is NOT the same

12 T Nb$_3$Sn dipoles
HiLumi technology in LHC: **21 TeV c.o.m.**

7 T Nb-Ti dipole (low cost LHC, 4.2 K):
44 TeV c.o.m. (100 km)

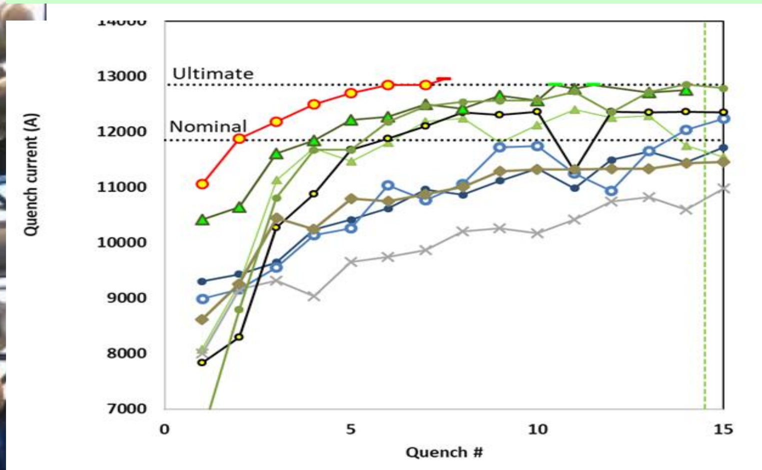
HL-LHC : 11 T magnets

HiLumi HL-LHC PROJECT

Bordry

11 T in full swing production: LS2 installation in 2020!
Great care given the stress sensitivity of Nb_3Sn

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 ultimate current)
I-ultimate) after 6 quenches.



+ Nb_3Sn Quadrupole (MQXF) at IR

US: 4.5 m Prototype:

- Completed and tested

CERN: 1-m short Models:

- Successfully demonstrated the performance

CERN: 7 m Prototype under development

+MgB_2 18.5 kA Superconducting Link Demonstrated

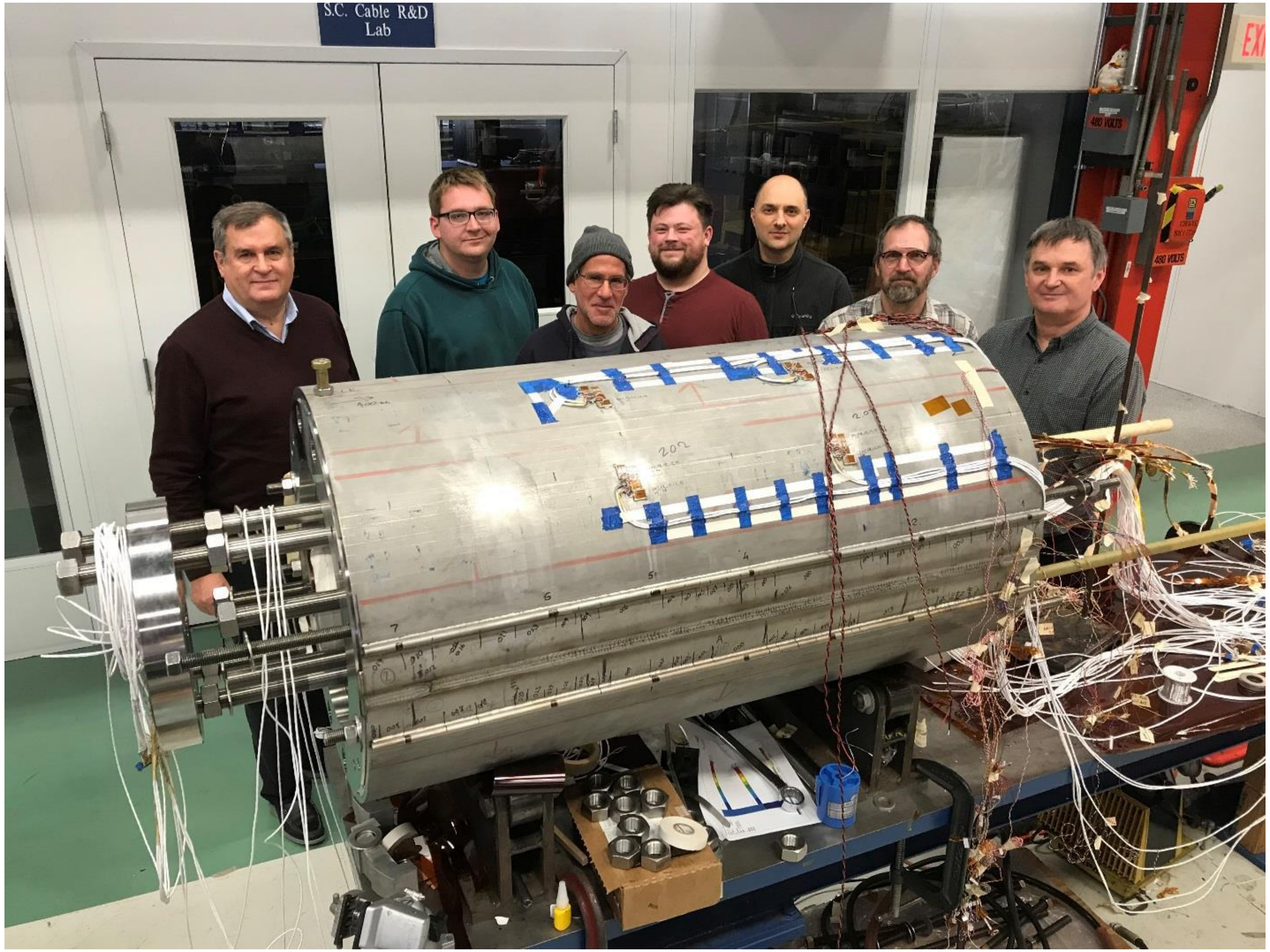
s.c. magnet technology

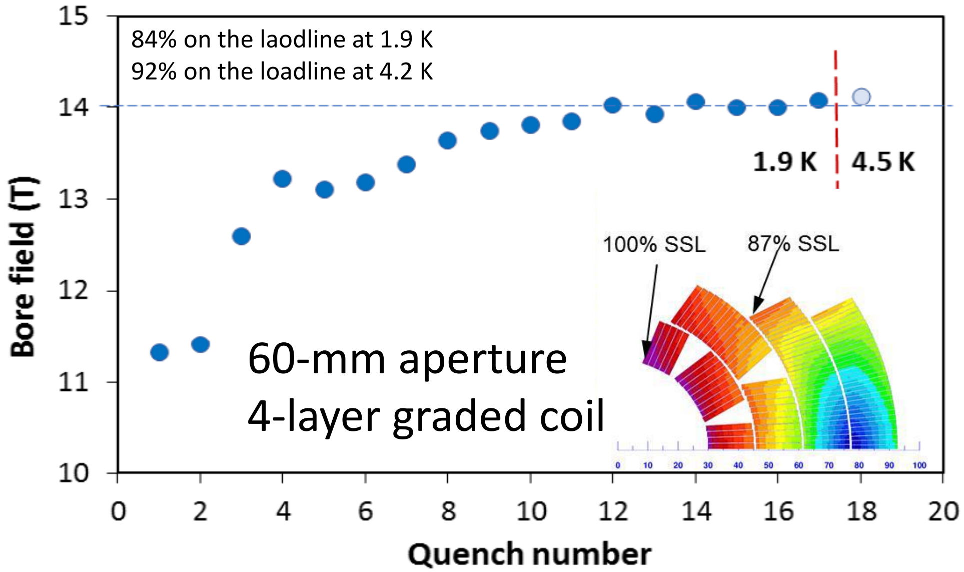
A. Yamamoto

- 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.

Intensify HTS accelerator magnet development

14 T magnet tested at FNAL!





- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T (as planned for the first stage)
- Second test foreseen in fall 2019 with additional pre-stress for 15 T

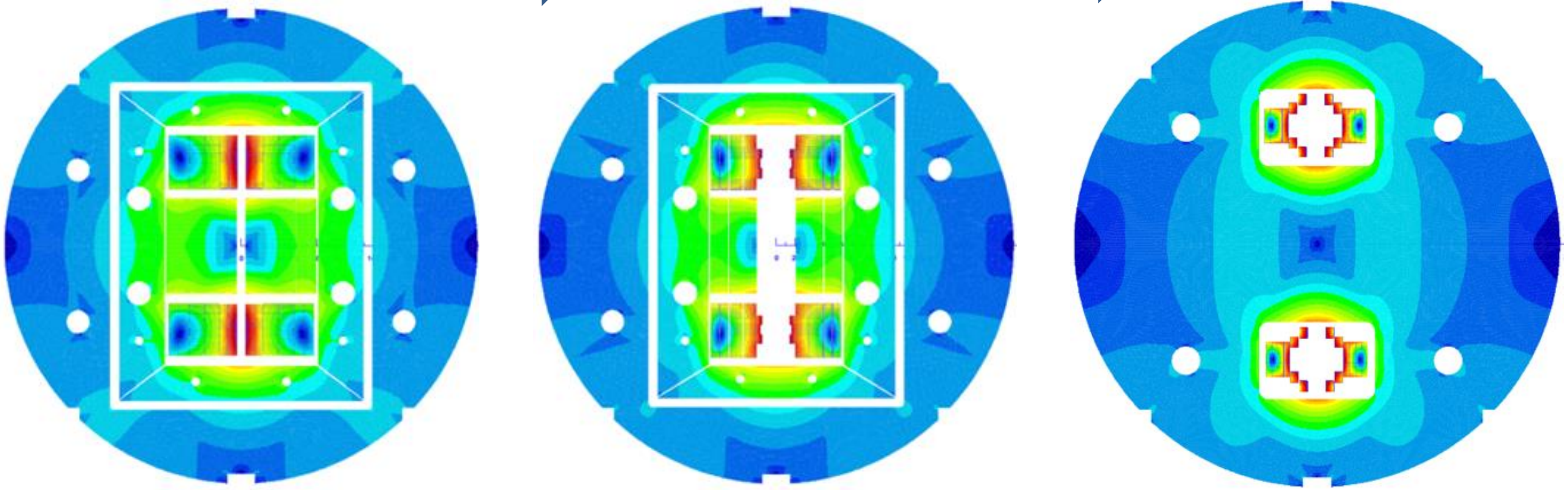
14 T magnet tested at FNAL!

- The difference between a 14 T and a 16 T magnet is very large, in terms of quantity of conductor needed, number of coils, and complexity of the construction. Though, on paper, a 16 T magnet is possible and is costing about twice the cost of a LHC magnet for twice the field. **Achieving such a construction on a large series may be extremely difficult**. A **two layer design** with a target field in the range of **12 T to 14 T** is considered by the magnet community present during the FCC week as 'consensus' for a collider in the next decades
- The design work has shown that all the considered options have a potential for FCC. This has motivated the **decision of exploring experimentally all options** to answer the outstanding questions of which design meets best the requirements, **which margin field level (~12-14 T)** should be selected
- In the last three years, the FCC Conductor Development Program coordinated by CERN has succeeded in engaging the **Japanese** (Jastec and Furukawa via the KEK coordination), the **Russian** (TVEL) and the **Korean** (KAT) companies in developing for the first time very high-performance **Nb_3Sn wire**. Critical current densities of up to **about 1250 A/mm^2 at 16 T** have been achieved, and kilometers length of wire have been produced in industry and delivered to CERN for first cabling trials
- In the **US,** the FCC current density target **(1500 A/mm^2 at 16 T)** has been achieved! Industrialization and cost reduction has yet to come

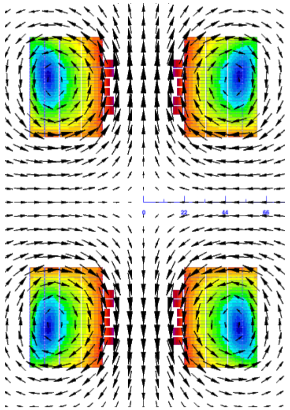
R&D of 12T Twin-aperture Dipole Magnet

R&D Roadmap for the next 10~15 years

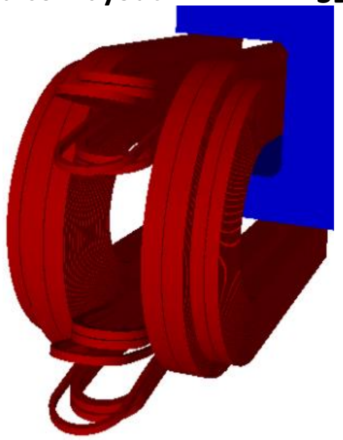
NbTi+Nb$_3$Sn, 2*ϕ10 aperture → **Nb$_3$Sn+HTS, 2*ϕ20 aperture** → **All HTS, 2*ϕ40 aperture**



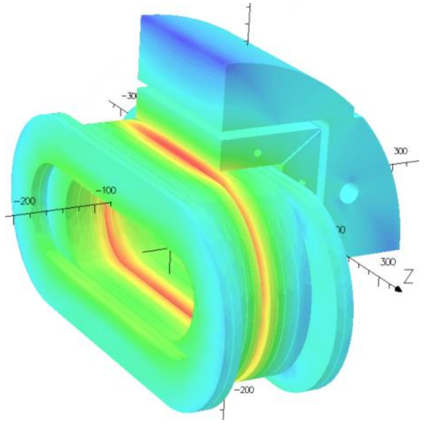
Magnetic flux distribution



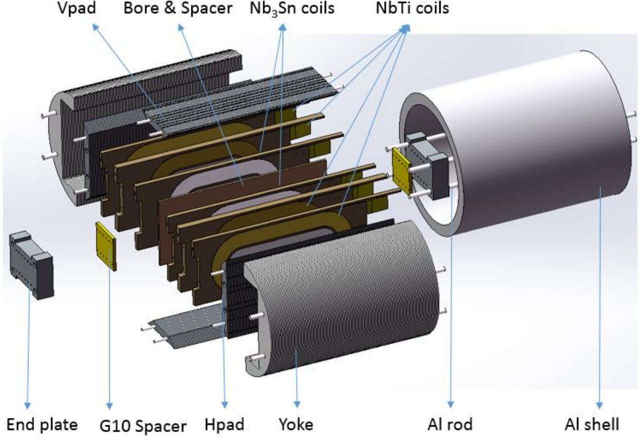
3d coil layout



3D magnetic field distribution



Components and assembly



Domestic Collaboration for HTS R&D

"Applied High Temperature Superconductor Collaboration (AHTSC)" formed in Oct. 2016. Including 18 institutions and companies in China. Regular meeting every 3 months.

- ***Goal :***

a) 1) *To increase the J_c of iron-based superconductor **(IBS)** by 10 times, reduce the cost to **20 Rmb/kAm @ 12T & 4.2K**, and realize the industrialization of the conductor;*

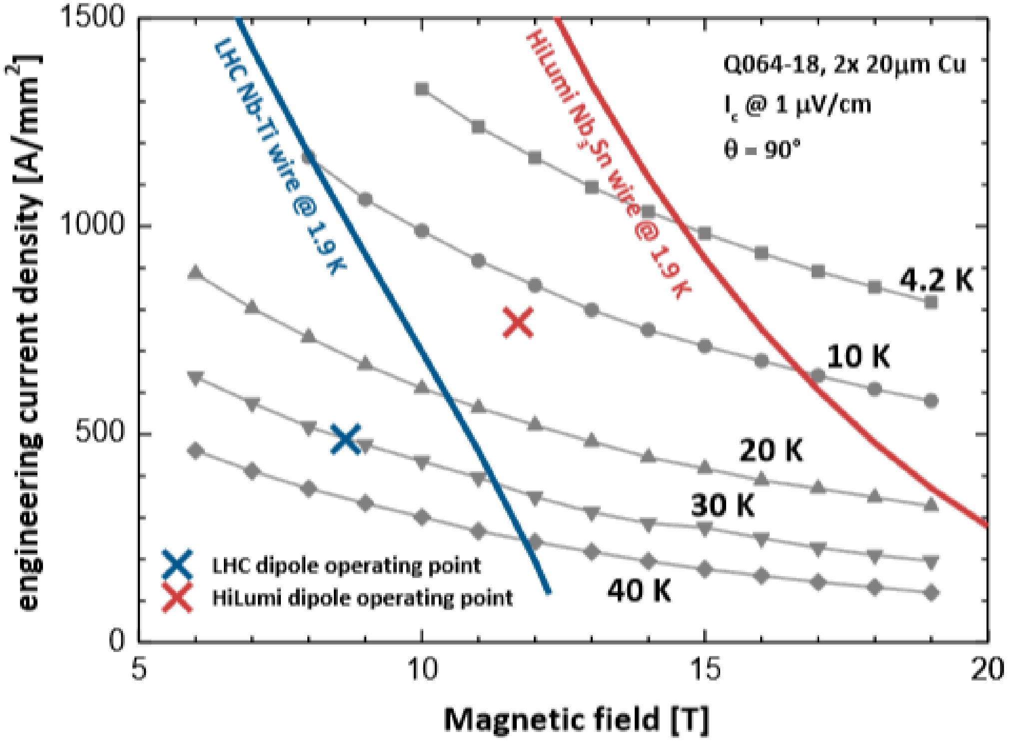
b) 2) *To reduce the cost of **ReBCO and Bi-2212** conductors to 20 Rmb/kAm @ 12T & 4.2K;*

c) 3) *Realization and Industrialization of IBS magnets and SRF cavities.*

- ***Working groups :*** *1) **Fundamental sciences** study; 2) **IBS** conductor R&D; 3) **ReBCO** conductor R&D; 4) **Bi-2212** conductor R&D; 5) **Performance** evaluation; 6) **Magnet and SRF** technology.*

HTS in Europe

Towards HTS-based dipoles operating at T >1.9 K ??



BRUKER tape Q064-18, 50μm stainless steel, 2x 20μm Cu, 2μm YBCO

Engineering current density in perpendicular field orientation

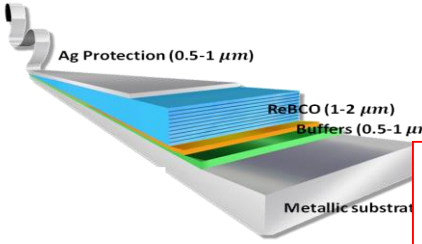
C. Senatore, FCC week

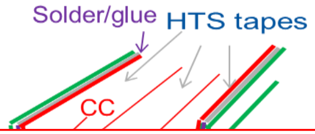
Summary

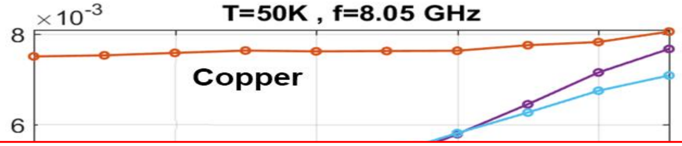
- High-J_e HTS conductors are setting the grounds for accelerator magnets in the 20 T range
- The ARIES R&D tapes with thinner substrate (50 μm stainless steel) from BRUKER exhibit very reproducible performance
- In spite of the tape shape, we got $J_e \approx 1150$ A/mm² @ 4.2 K, 19 T
- Fujikura new tape with EuBCO + BHO, with $J_e \approx 1300$ A/mm² @ 4.2 K, 19 T, is a commercial product
- SuperOx implemented a new composition and its new tape reached $J_e \approx 2000$ A/mm² @ 4.2 K, 19 T and 1000 A/mm² @ 20 K, 19 T
- In light of the present results, should we target also accelerator magnets operating at higher temperatures?

Beam vacuum systems:

HTS coated conductors for FCC-hh beam screen impedance reduction





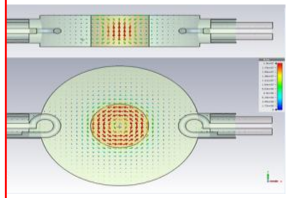


3 x improvement at 8 GHz compared to copper, expected 20
t 1 GHz ($f^{3/2}$)

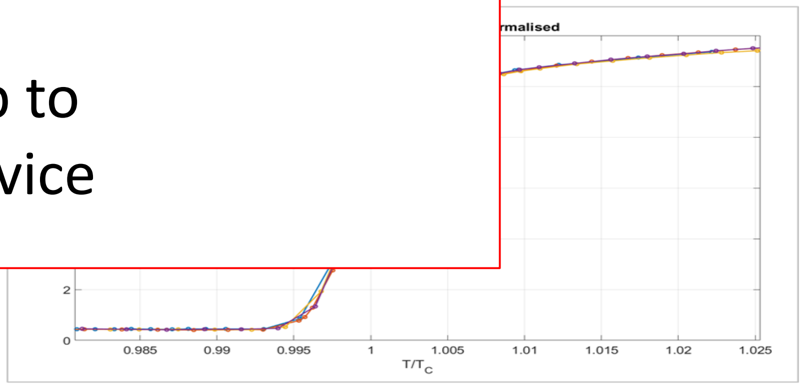
REBCO coated conductor
are layered structures on
flexible metallic substrate

All experiments on samples, supported by theoretical modelling, indicate that the Coated Conductors solution attains FCC-hh performance goals (impedance reduction in high magnetic field) and accelerator compatibility (e-cloud, SR radiation tolerance…)

Ready to undertake scaling-up to real-scale proof-of-concept device



r

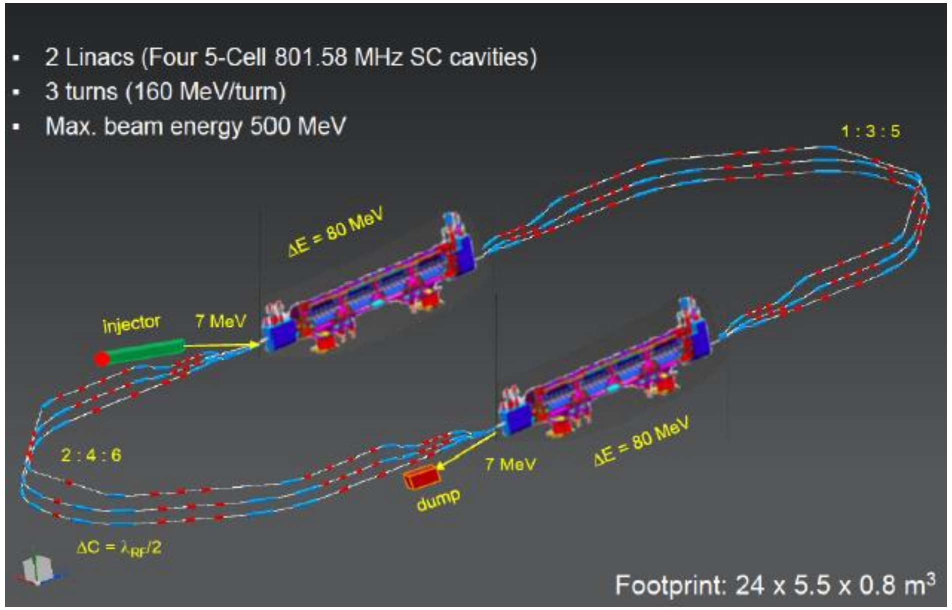


IFAE
Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA
BIST Barcelona Institute of Science and Technology
UPC
CommSensLab
EXCELENCIA MARÍA DE MAEZTU 2017 - 2020
ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA
EXCELENCIA SEVERO OCHOA
CSIC

FCC Week 2019 - Brussels

Energy Recovery Linacs

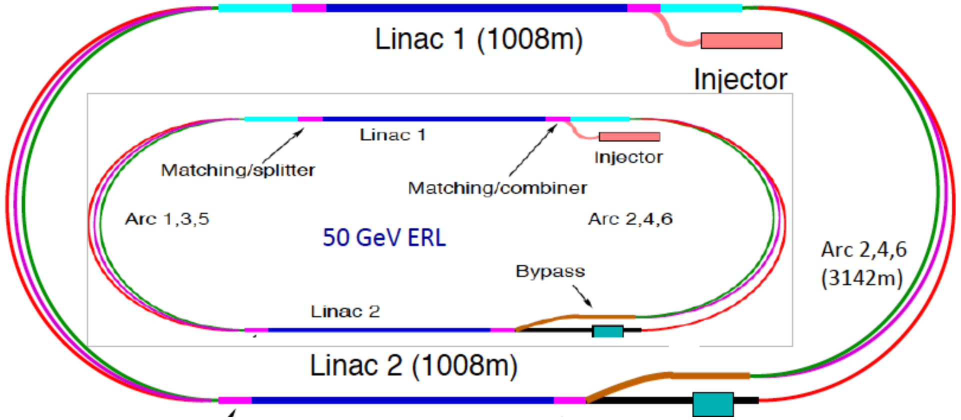
ERL: technology for possible applications in HEP, low energy and industrial areas



- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV

Footprint: 24 x 5.5 x 0.8 m^3

- Joint 802 MHz cavity development [LHeC+FCC]
- Very preliminary ideas on FCC-ee design with ERL technique: [extension to higher energy, less SR power, higher lumi > WW] Llatas, Litvinenko, Roser FCC Brussels



LHeC: 1 TeV ep collider with 10^{34} luminosity: P/10! Dump at injection. Possible injector to FCC-ee in recirculating mode [O.Bruening]

Existing test facilities

PERLE BINP, CERN, Daresbury, Liverpool, Jlab, Orsay+. Could be 6 GeV injector to FCC-ee →

ERLs in: Berlin, BINP, Cornell, Daresbury, Darmstadt, Jlab, KEK, Mainz..

High current and E ~ 1GeV: low energy physics [1000 x L(ELI)!, lithography, photofission

From M.Klein,

Technical Challenges in Energy-Frontier Colliders

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

A. Yamamoto, 190513bb

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

Technical Challenges in Energy-Frontier Colliders

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CC hh	*FCC-NbTi*	*(to be filled)*	*~ 100*	*< 30*			*~ 6*		*...Find the people who want to do it*
	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 – [illegible]	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CC ee	FCC-ee	CDR	0.18 – 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10 – 20 (0.4 - 0.8)	**High-Q SRF** cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	[illegible] – 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	[illegible] (-1)	[illegible] (– 4.9)	[illegible] (– 300)	[illegible] (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	[illegible]	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

A. Yamamoto, 190513bb

Major Technical Challenges:

Hadron Colliders:

- High-field magnet
- Energy management

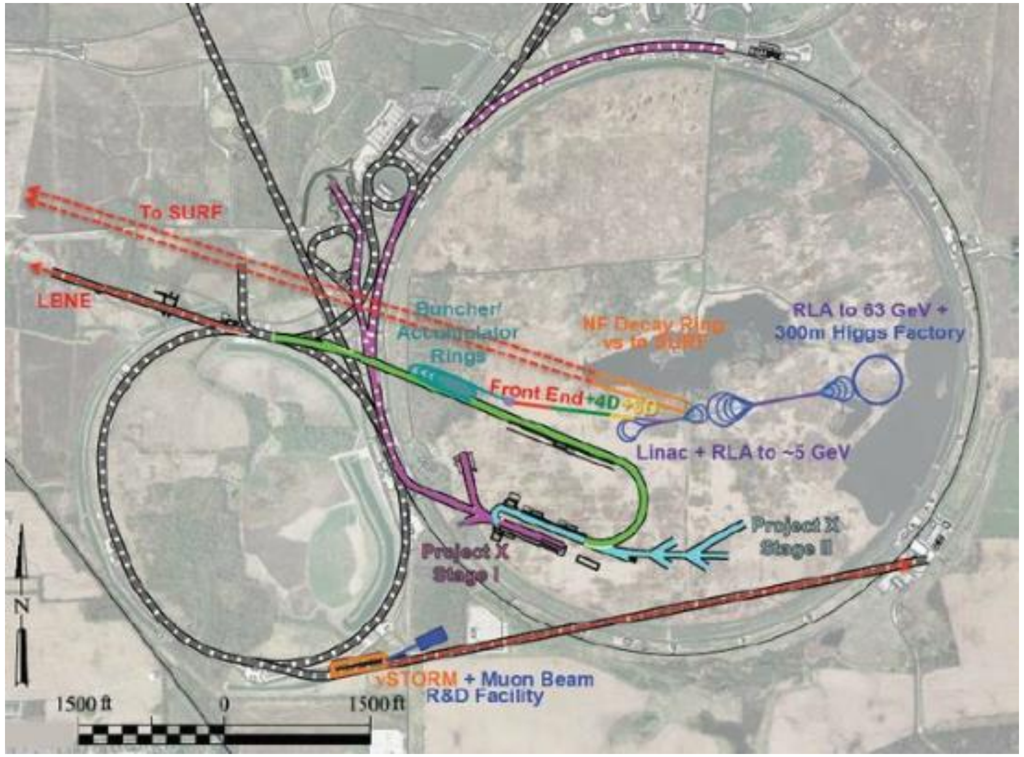
Lepton Colliders:

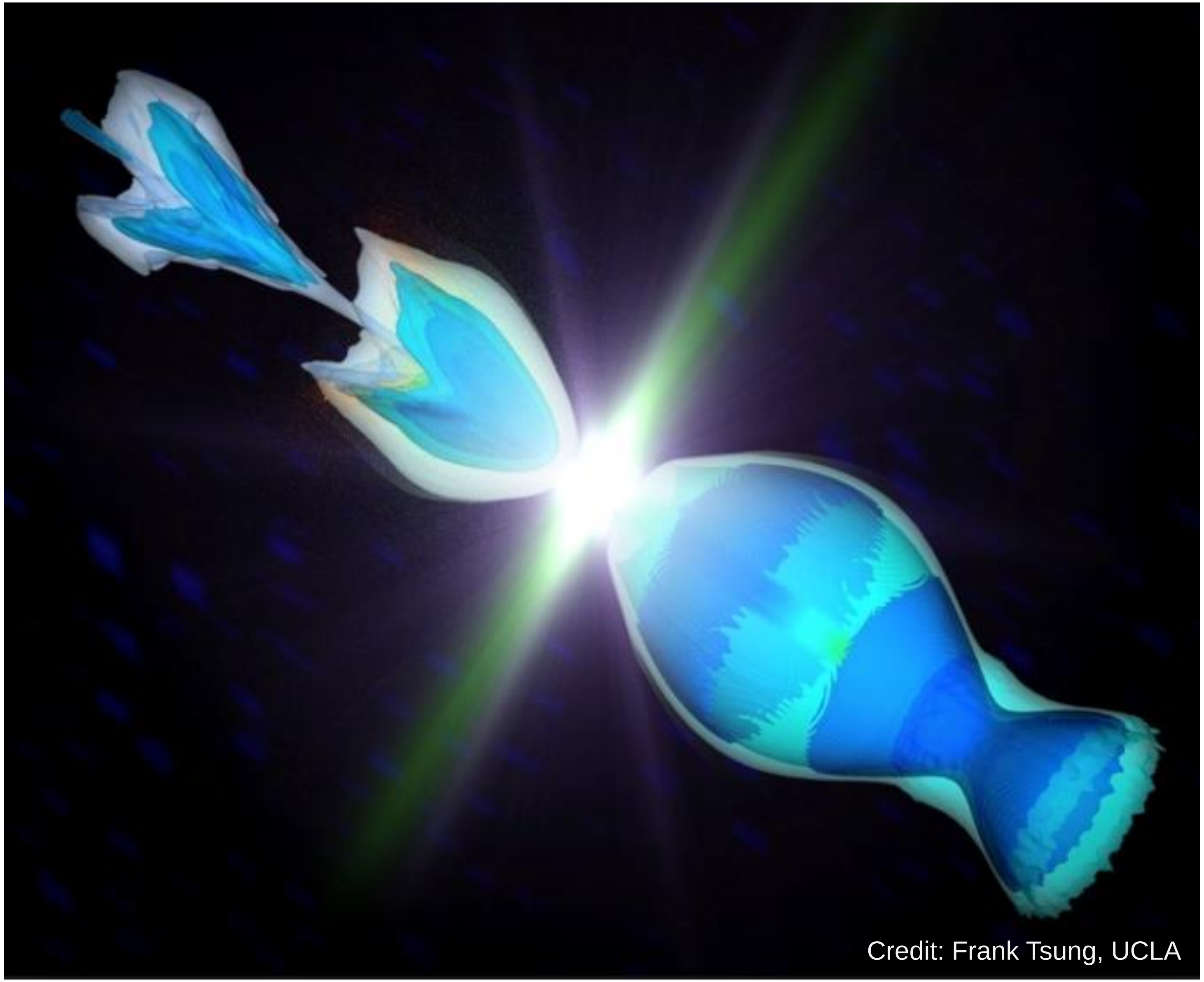
- SRF cavity: High-Q and -G (to prepare for upgrade)
- NRF acc. Struct.: large scale, alignment, tolerance, timing
- Energy management

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

Advanced technologies

- Muon collider
- Plasma acceleration

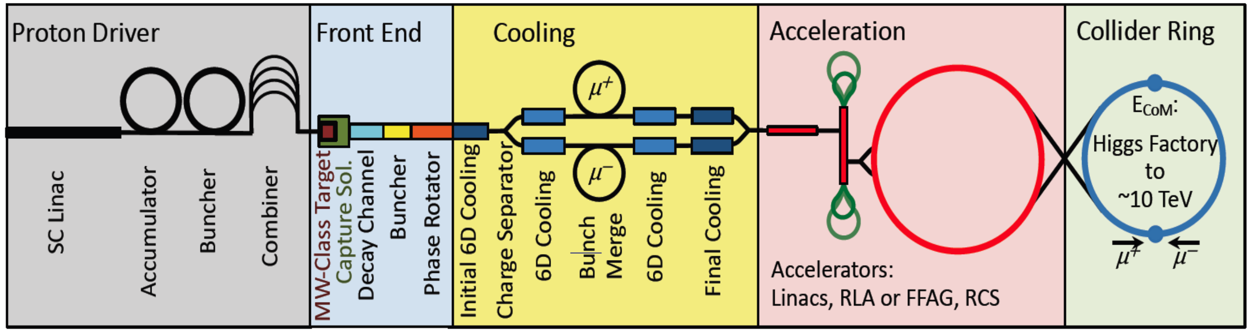




Credit: Frank Tsung, UCLA

Proton-driven Muon Collider Concept

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

Pions decay into muons that can be captured

Two schemes for μ production
- Proton (like in the figure)
- Positrons, still requiring consolidation

Muon Collider Parameters

		Higgs	Multi-TeV		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
b*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

D. Schulte

Answers to the Key Questions (D. Schulte)

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged on positron one
  - But at this moment **not mature enough for a CDR**, need a careful design study done with a coordinate international effort

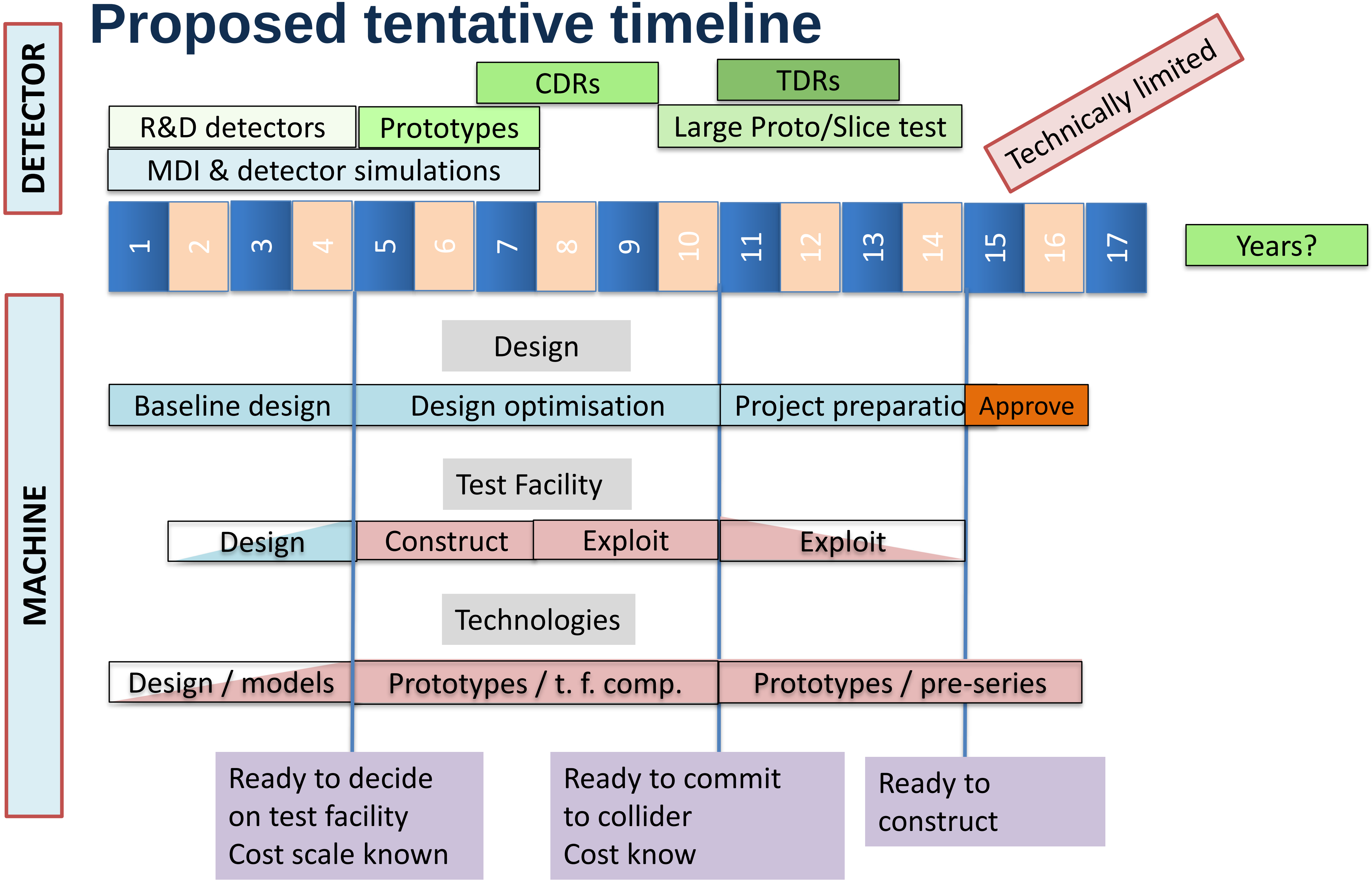
- **Is it worthwhile to do muon collider R&D?**
  - Yes, it **promises the potential to go to very high energy**
  - It **may** be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - **Should not miss this opportunity?**

- **What needs to be done?**
  - **Muon production and cooling is key** => A new test facility is required.
    - Seek/exploit synergy with physics exploitation of test facility (e.g. nuSTORM)
  - A conceptual design of the collider has to be made
  - Many components need R&D, e.g. fast ramping magnets, background in the detector
  - Site-dependent studies to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source
  - **R&D in a strongly coordinated global effort**

From D. Schulte

Muon Colliders, Granada 2019

Proposed tentative timeline



DETECTOR

R&D detectors

Prototypes

CDRs

TDRs

Large Proto/Slice test

MDI & detector simulations

Technically limited

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

Years?

MACHINE

Design

Baseline design

Design optimisation

Project preparatio

Approve

Test Facility

Design

Construct

Exploit

Exploit

Technologies

Design / models

Prototypes / t. f. comp.

Prototypes / pre-series

Ready to decide
on test facility
Cost scale known

Ready to commit
to collider
Cost know

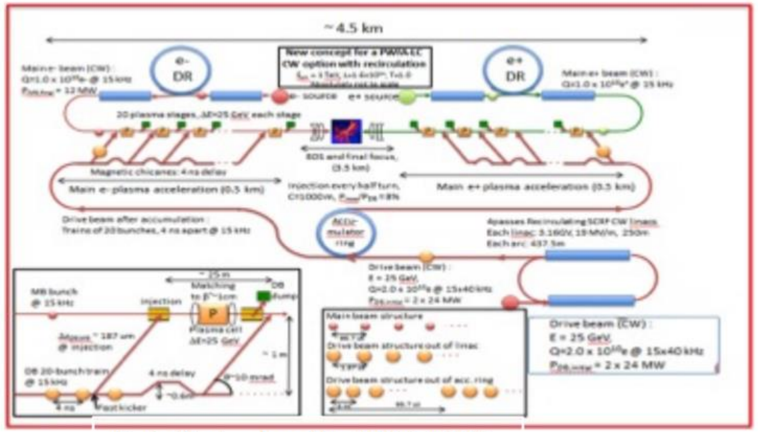
Ready to
construct

D. Schulte

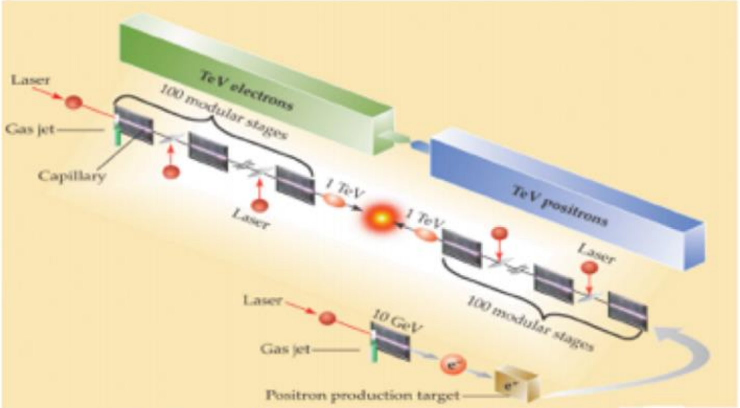
Plasma acceleration based colliders

Drive beams
Lasers: ~40 J/pulse
Electrons: 30 J/bunch
Protons: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams
Electrons: 10^{10} particles @ 1 TeV ~few kJ



E. Adli et. al.,arXiv:1308.1145



Leemans & Esarey, Phys. Today 63 #3 (2009)

Key achievements in last 15 years in plasma based acceleration using lasers, electron and proton drivers

- Focus is now **on high brightness beams, tunability, reproducibility, reliability, and high average power**

The road to colliders passes through **applications** that need compact accelerators (Early HEP applications, FELs, Thomson scattering sources, medical applications, injection into next generation storage rings …)

Many key challenges remain as detailed in community developed, consensus based roadmaps (ALEGRO, AWAKE, Eupraxia, US roadmap,…)

Strategic investments are needed:

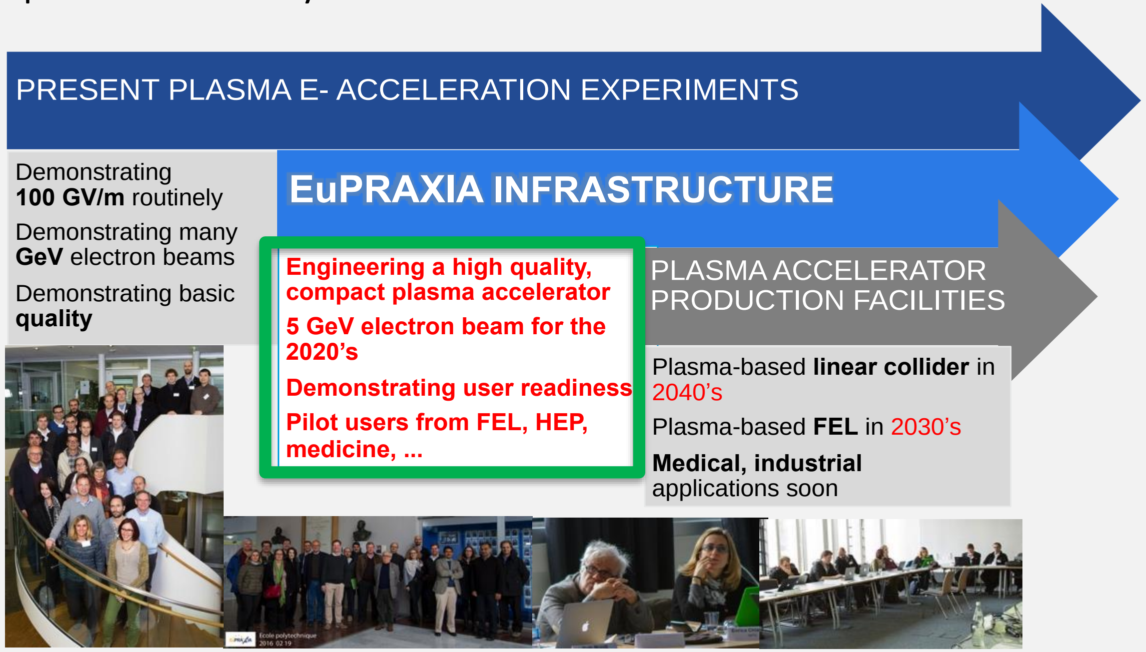
- **Personnel** – advanced accelerators attract large numbers of students and postdocs
- Existing **facilities** (with upgrades) and a few new ones (High average power, high repetition rate operation studies; fully dedicated to addressing the challenges towards a TDR for a plasma based collider)
- **High performance computing** methods and tools

Current initiatives of coordinated programs: EuPRAXIA, ALEGRO, AWAKE.

EuPRAXIA

Horizon 2020 EU design study funded in 2015.
Deliverable: Conceptual Design Report by Oct 2019

The EuPRAXIA Strategy for Accelerator Innovation:
The accelerator and application demonstration facility EuPRAXIA is the required intermediate step between proof of principle and production facility.



PRESENT PLASMA E- ACCELERATION EXPERIMENTS

Demonstrating **100 GV/m** routinely

Demonstrating many **GeV** electron beams

Demonstrating basic **quality**

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator

5 GeV electron beam for the 2020's

Demonstrating user readiness

Pilot users from FEL, HEP, medicine, …

PLASMA ACCELERATOR PRODUCTION FACILITIES

Plasma-based **linear collider** in 2040's

Plasma-based **FEL** in 2030's

Medical, industrial applications soon

ALEGRO

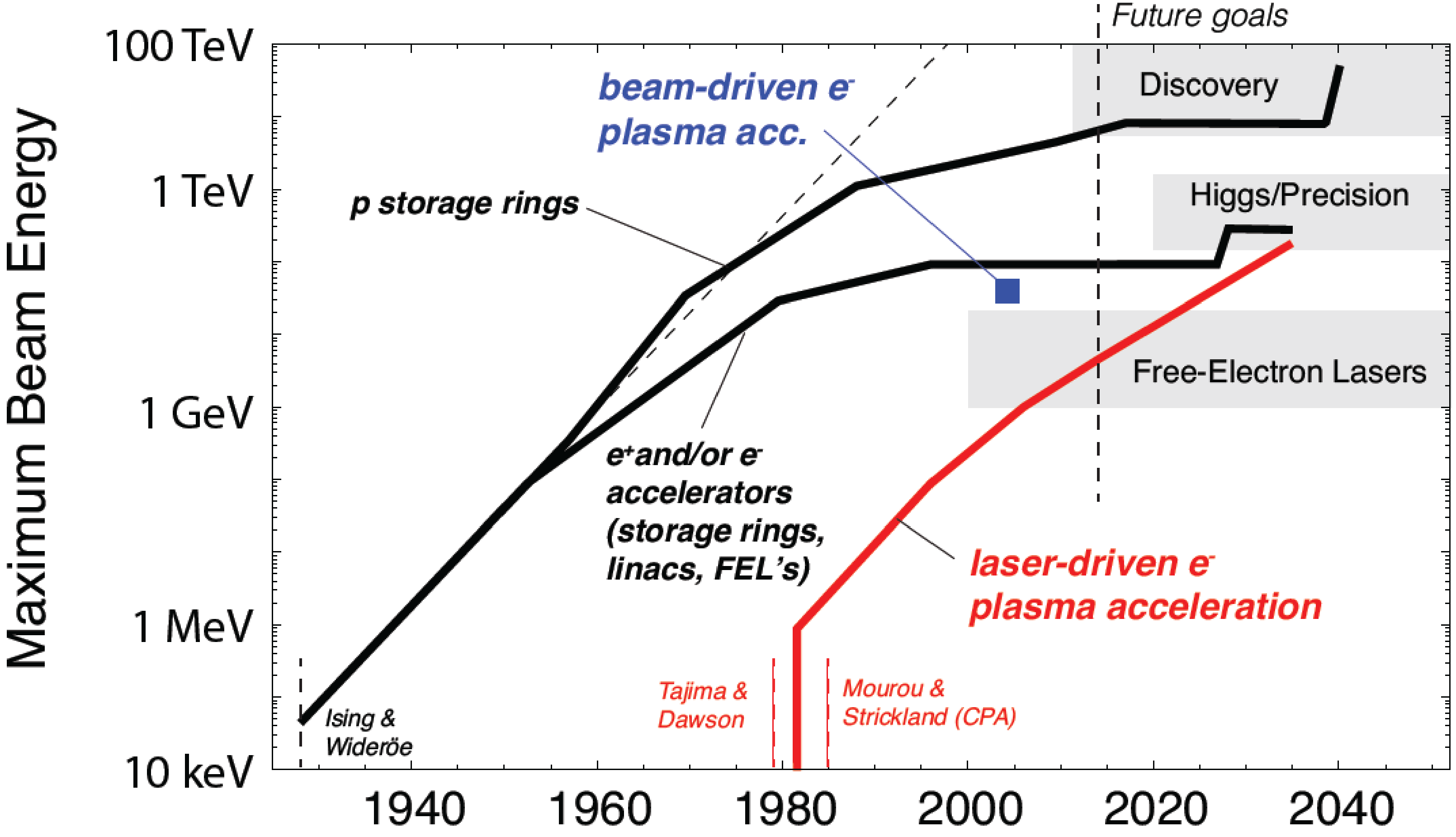
Advanced LinEar collider study GROup, ALEGRO: formed at initiative of the ICFA ANA panel in 2017.

Mission of the ALEGRO community:

- **Foster and trigger Advanced Linear Collider related activities** for applications of high-energy physics.
- **Provide a framework** to amplify international coordination, broaden the community, involving accelerator labs/institutes
- **Identify topics requiring intensive R&D and facilities**.

Goal:

- Long-term design of a e^+/e^-/gamma collider with up to 30 TeV: the **Advanced Linear International Collider (ALIC)**
- **Construction of dedicated Advanced and Novel Accelerators (ANA) facilities** are needed over the next 5 to 10 years in order to reliably deliver high-quality, multi-GeV electron beams from a small number of stages.
  - Today: Existing facilities explore different advanced and novel accelerator concepts and are proof-of-principle experiments.



ALEGRO delivered a document detailing the international roadmap and strategy of Advanced Novel Accelerators (ANAs).

Status of Today and Goals for Collider Application

	Current	Goal
Charge (nC)	0.1	1
Energy (GeV)	9	10
Energy spread (%)	2	0.1
Emittance (um)	>50-100 (PWFA), 0.1 (LFWA)	$<10^{-1}$
Staging	single, two	multiple
Efficiency (%)	20	40
Rep Rate (Hz)	1-10	10^{3-4}
Acc. Distance (m)/stage	1	1-5
Positron acceleration	acceleration	emittance preservation
Proton drivers	SSM, acceleration	Emittance control
Plasma cell (p-driver)	10 m	100s m
Simulations	days	Improvements by 10^7

Achieved Individually and NOT simultaneously

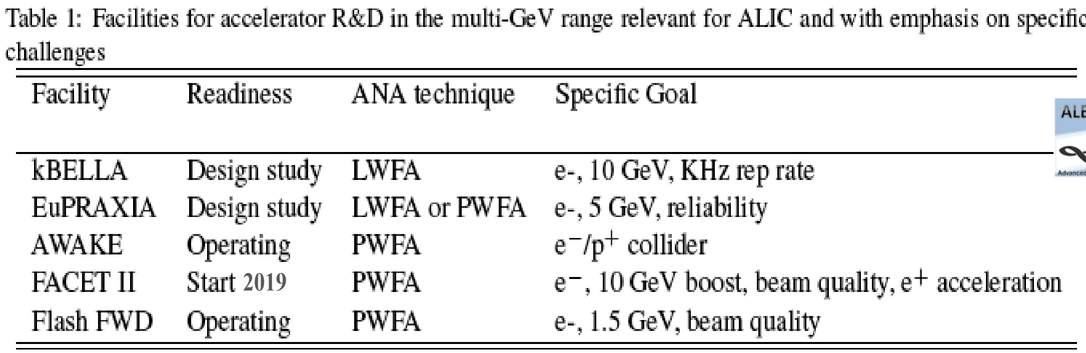


Table 1: Facilities for accelerator R&D in the multi-GeV range relevant for ALIC and with emphasis on specific challenges

Facility	Readiness	ANA technique	Specific Goal
kBELLA	Design study	LWFA	e-, 10 GeV, KHz rep rate
EuPRAXIA	Design study	LWFA or PWFA	e-, 5 GeV, reliability
AWAKE	Operating	PWFA	e^-/p^+ collider
FACET II	Start 2019	PWFA	e^-, 10 GeV boost, beam quality, e^+ acceleration
Flash FWD	Operating	PWFA	e-, 1.5 GeV, beam quality

Energy Efficiency

- Energy efficiency is not an option, it is a must!
- **Energy efficiency and energy management** must be addressed.
- Investing in dedicated R&D to improve energy efficiency pays off in terms of **savings and societal return** through development of technologies which serve the society at large.
- District heating, energy storage, magnet design, RF power generation, cryogenics, SRF cavity technology, beam energy recovery are areas where energy efficiency can significantly be improved.
- Higher-temperature high-gradient Nb/Cu accelerating cavities and highly-efficient RF power sources developed in the frame of the FCC-ee R&D programme will find numerous other applications; could improve the sustainability and performance for accelerators of nearly all types and sizes around the world.
- The resource-saving strategy includes studies to avoid water cooling wherever possible and developing schemes to supply waste heat to nearby consumers. A pilot program at LHC is on-going.
- The detailed technical design of the FCChh will also investigate energy recovery opportunities within the accelerator infrastructure, for example, by working with industrial partners on either storing heat for later use or its conversion into mechanical or electrical energy.

F*rom ESPPu Open Symposium, Granada*

E. Jensen: Energy Efficiency

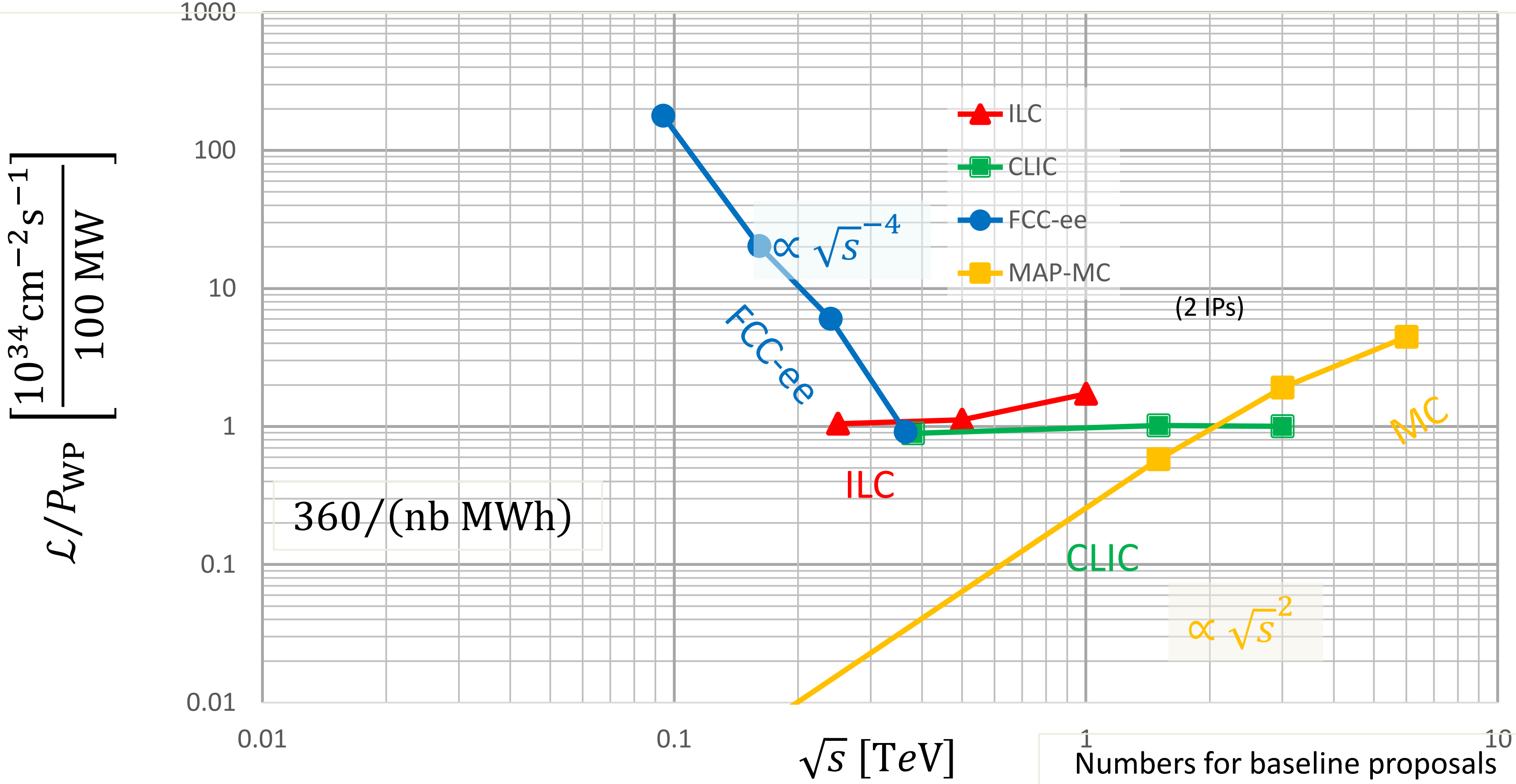
Example: He consumption @FCC-hh

- **Nelium** (Neon+ Helium) for cooling down to 40 + He for going to 1.9K
- The most power-hungry element @ FCC-hh is the cryogenic refrigeration system needed to cool the 16 T superconducting magnets down to 1.9 K.
- With respect to an LHC-class system, which would for an FCC-hh collider consume 290 MW of electrical power, the nelium technology and temperature choices lead to a reduction by 50 MW or 17% in the baseline configuration. **Slowly ramping up** the field of the magnets and with constant power substantially reduces the power demand, for all main dipoles from 270 MW for a constant-voltage ramp of 20 minutes to 100 MW for a constant-power ramp of 30 minutes.
- The external peak power demand during the ramp phase can be reduced further by **recovering the energy stored** in the superconducting magnets at the end of a cycle (50 MWh for the main dipoles), to buffer it locally, and **to reuse it** during the subsequent ramp-up. Losses in electricity transmission will be reduced by cooperating with industry to bring medium voltage DC distribution systems to market grade so that they can power the accelerator subsystems.
- R&D on **High efficiency klystrons** to go from 65% to 80% in power conversion efficiency (with LC communities)
- SC thin-film coating technology for operating high-gradient RF cavities at higher temperature, lowering the electricity need.
- Yearly energy consumption forecast of 4 TWh, compared to 1.4 TWh expected for the HL-LHC.

Figure of merit for proposed lepton colliders

Disclaimers:

1. This is not the only possible figure of merit
2. The presented numbers have different levels of confidence/optimism; they are still subject to optimisations



Numbers for baseline proposals

electricity cost ~200 euro per Higgs boson (F. Zimmerman)

Proposed HEP Projects and Grid Power Consumption

	ECM [TeV]	L / IP $[10^{34}cm^{-2}s^{-1}]$	P_{Grid} [MW]	power driving effects
FCC-ee (Z)	0.091	230	**259**	SR Power: 50MW/beam
FCC-ee (t)	0.365	1.5	**359**	SR power: 50MW/beam
FCC-hh	100	30	**580**	SR power: 2.4MW/beam @ 50K, cryogenics
ILC	1	4.9	**300**	beam power: 13.6 MW/beam, cryogenics
CLIC	3	5.9	**582**	beam power: 14 MW/beam
muon coll.	6	12	**270**	mu decay, 1.6MW/drive beam, cycling magnets, but scaling advantages, least developed

$$P_{\text{SR}} \propto \left(\frac{E}{E_0}\right)^4 \frac{1}{R}$$

$$L_{\text{lin.col.}} \propto H_D \sqrt{\frac{\delta_E}{\varepsilon_{y,n}}} P_{\text{beam}}$$

$$L_{\text{mu.col.}} \propto B \frac{N_0}{\varepsilon_n} \boxed{\gamma} P_{\text{beam}}$$

→ **need more R&D towards efficient concepts & technology, and energy management**

‘Traditional-technologies’ colliders

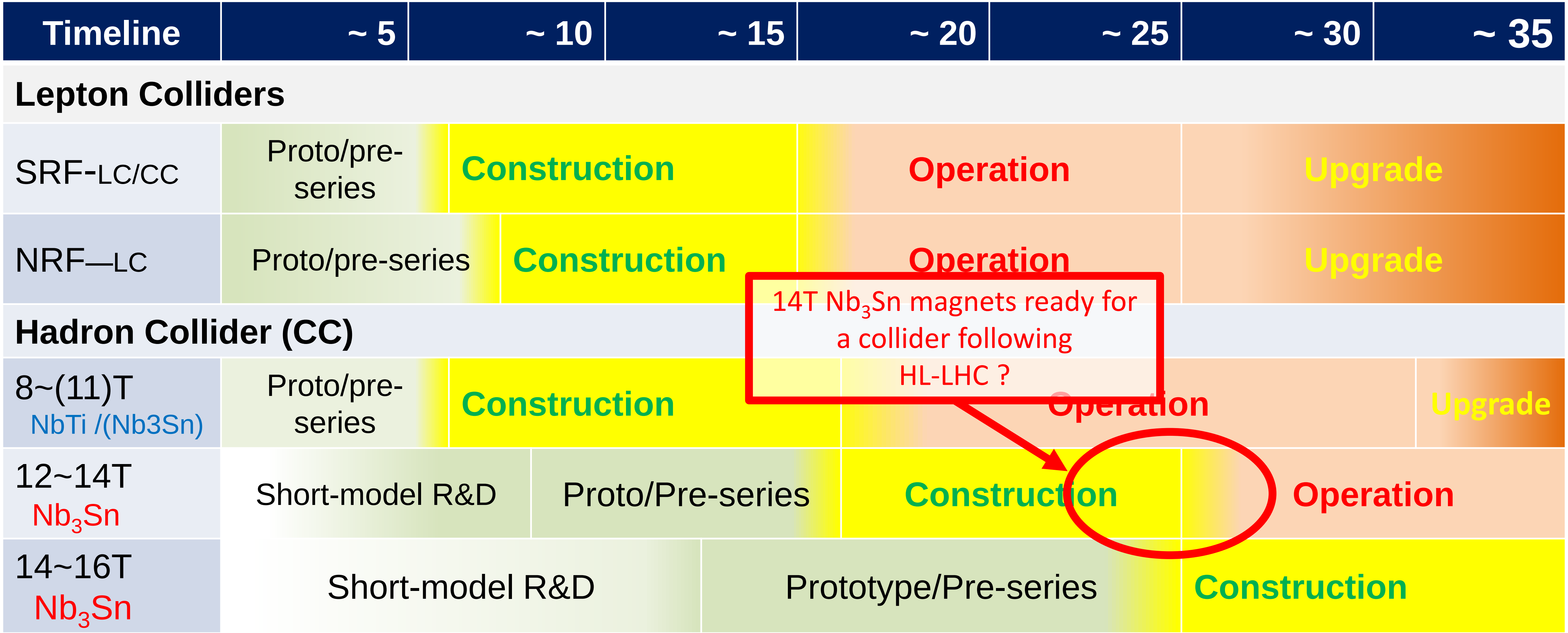
Comparisons

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	15+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
FCC-NbTi	*pp*	*37.5*	*10*	*20*	*240*	*14 GCHF (including tunnel)*
HE-LHC	pp	27	20	20		7.2 GCHF

new

D. Schulte

Personal (A. Yamamoto) View on Relative Timelines



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

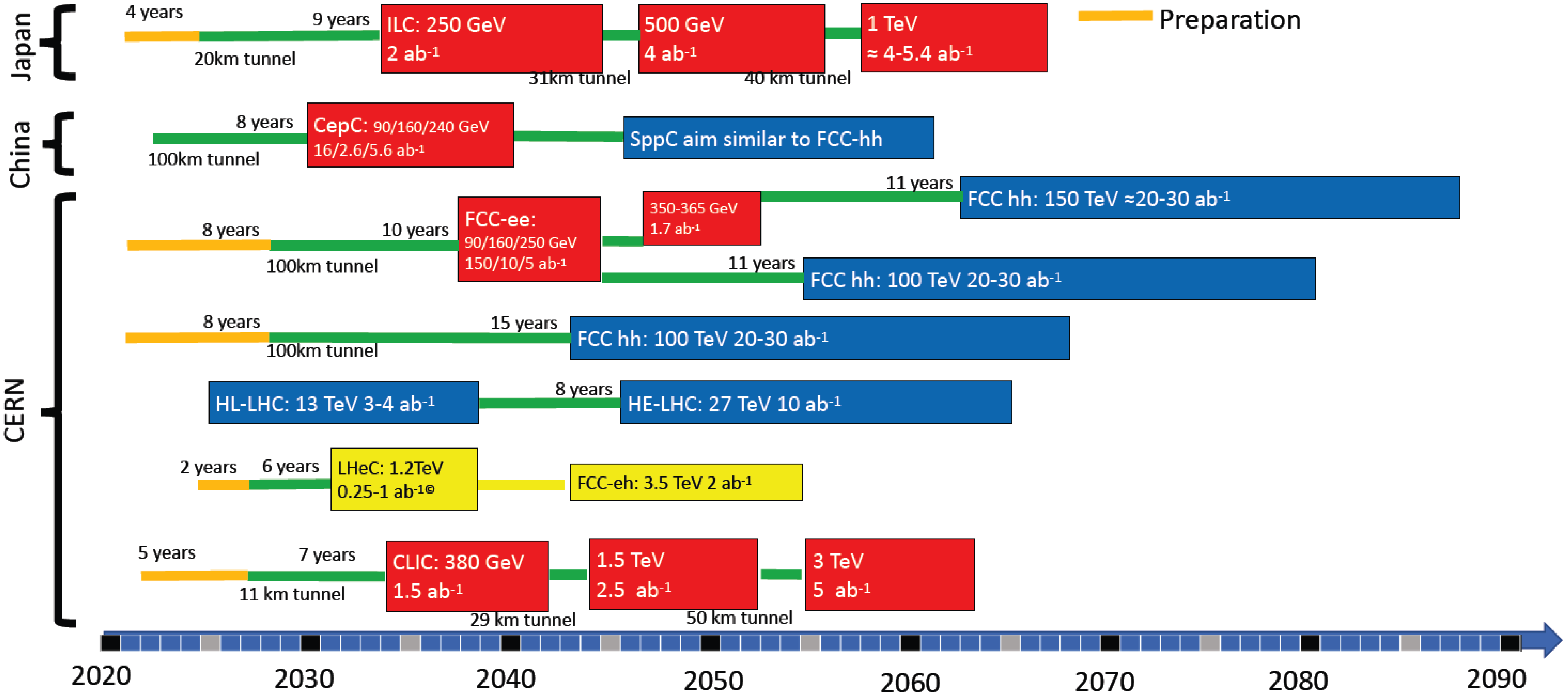
14T Nb_3Sn magnets ready for a collider following HL-LHC ?

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

A. Yamamoto

Possible scenarios of future colliders

🟦 Proton collider
🟥 Electron collider
🟨 Electron-Proton collider
▬ Construction/Transformation
▬ Preparation



Japan
4 years
9 years
20km tunnel
ILC: 250 GeV
2 ab^{-1}
31km tunnel
500 GeV
4 ab^{-1}
40 km tunnel
1 TeV
≈ 4-5.4 ab^{-1}

China
8 years
100km tunnel
CepC: 90/160/240 GeV
16/2.6/5.6 ab^{-1}
SppC aim similar to FCC-hh

CERN
8 years
10 years
100km tunnel
FCC-ee:
90/160/250 GeV
150/10/5 ab^{-1}
350-365 GeV
1.7 ab^{-1}
11 years
FCC hh: 150 TeV ≈20-30 ab^{-1}
11 years
FCC hh: 100 TeV 20-30 ab^{-1}

8 years
15 years
100km tunnel
FCC hh: 100 TeV 20-30 ab^{-1}

HL-LHC: 13 TeV 3-4 ab^{-1}
8 years
HE-LHC: 27 TeV 10 ab^{-1}

2 years
6 years
LHeC: 1.2TeV
0.25-1 ab^{-1}©
FCC-eh: 3.5 TeV 2 ab^{-1}

5 years
7 years
11 km tunnel
CLIC: 380 GeV
1.5 ab^{-1}
29 km tunnel
1.5 TeV
2.5 ab^{-1}
50 km tunnel
3 TeV
5 ab^{-1}

Special thanks to

Akira Yamamoto, Frank Zimmerman, Philip Burrows, Vladimir Shiltsev, Mike Seidel, Erk Jensen, Lucio Rossi, Daniel Schulte, Wim Leemans, Edda Gschwendtner, Mike Lamont, Michael Benedikt, Steinar Stapnes, Ursula Bassler, Fredry Bordry, Max Klein, plus many others

and

Lenny Rivkin

Back up slides

Expect Shortage of Expert Accelerator Workforce

- ***"Oide Principle"*** :

  1 Accelerator Expert

  can spend intelligently

  (only) ~1 M$ a year

- + it takes significant time to get the team together (XFEL, ESS)

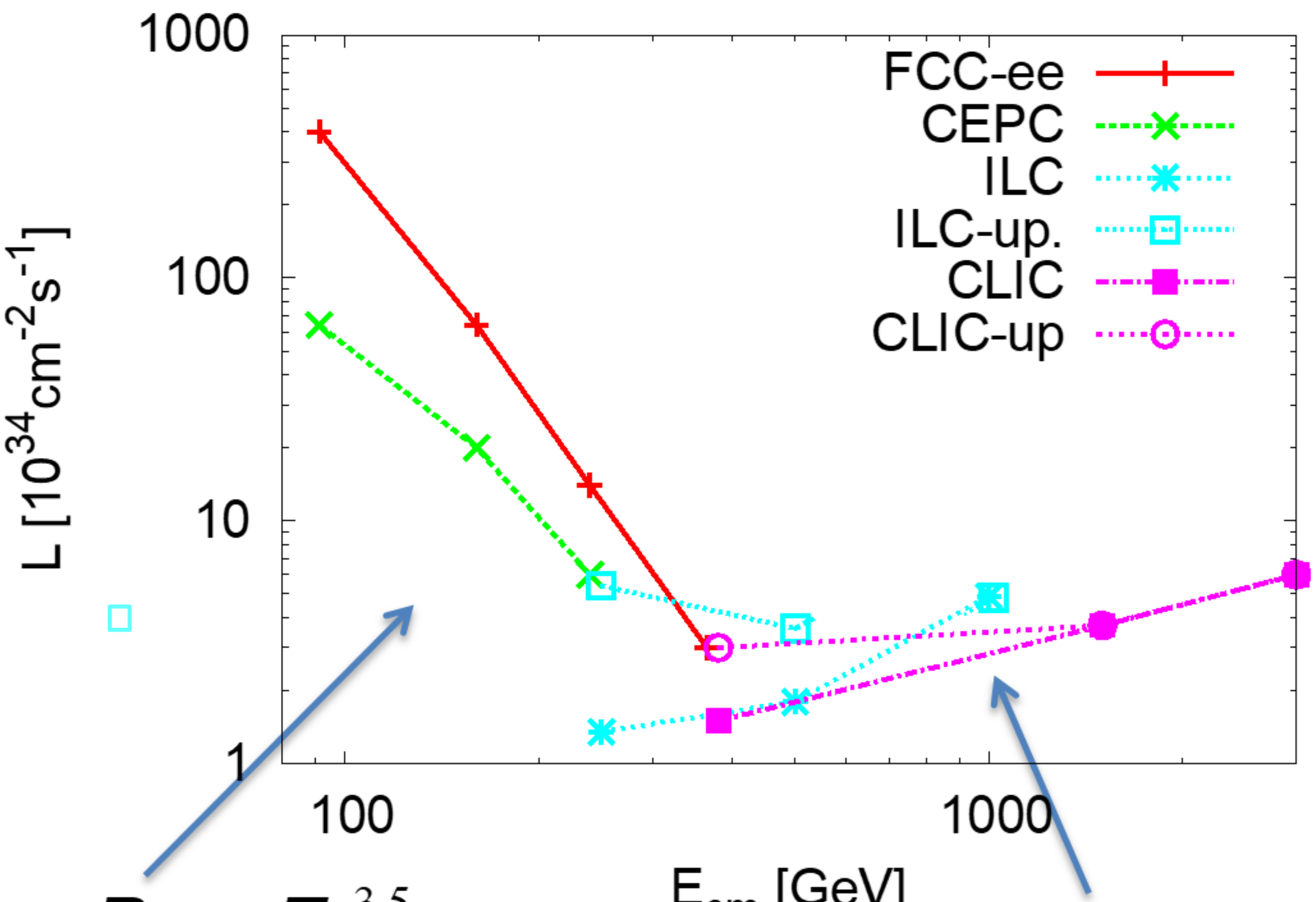
- Scale of the team: 10B$/10 years=1 B$/yr → need 1000 experts ← world's total now ~4500

K.Oide (KEK)

e+e- colliders

Ours is a very dynamic field!
(Luminosity upgrades for ILC, CLIC)

Luminosity per facility



$$L \propto P_{synrad} E_{cm}^{-3.5}$$

$$L \propto P_{RF} E_{cm}$$

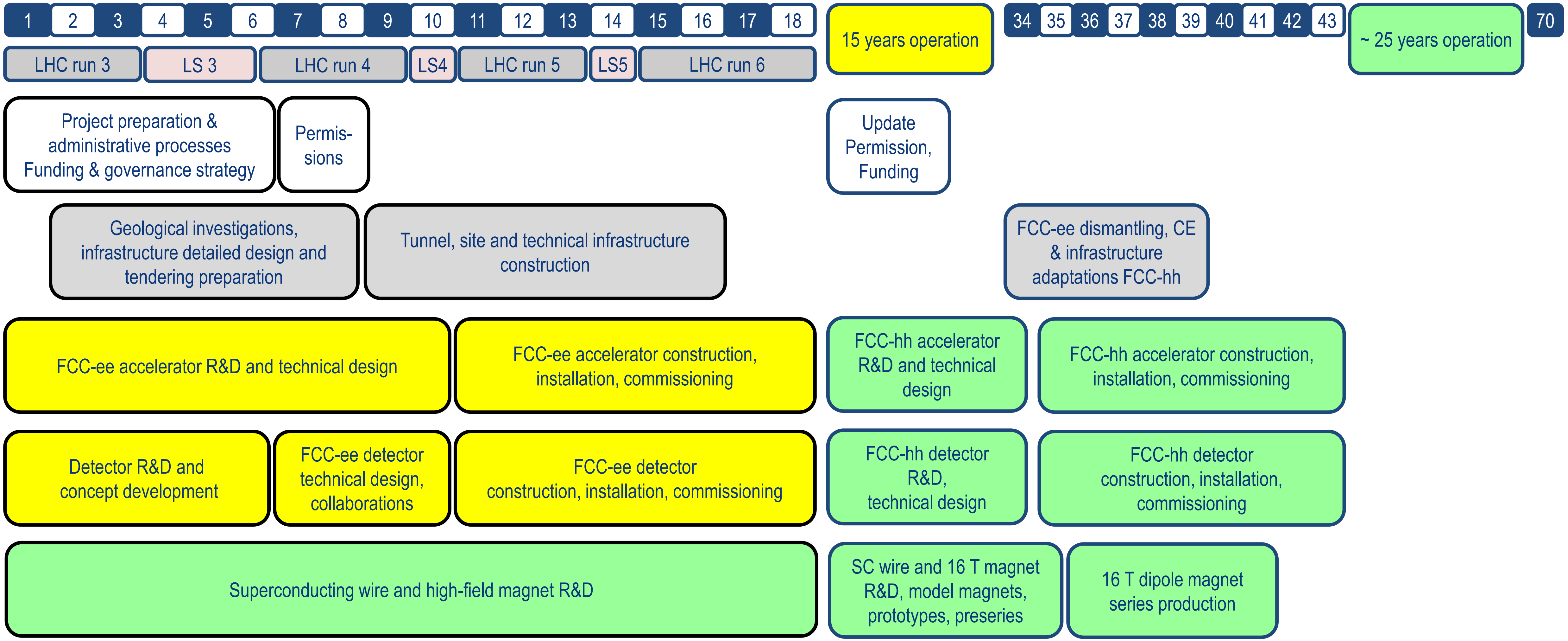
Proposed dates from projects

Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.

Project	**Start construction**	**Start Physics (Higgs)**
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

D. Schulte

FCC integrated project technical schedule



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

LHC run 3 | LS 3 | LHC run 4 | LS4 | LHC run 5 | LS5 | LHC run 6

15 years operation

34 35 36 37 38 39 40 41 42 43

~ 25 years operation

70

Project preparation & administrative processes Funding & governance strategy

Permis-sions

Update Permission, Funding

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Detector R&D and concept development

FCC-ee detector technical design, collaborations

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Superconducting wire and high-field magnet R&D

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

FCC integrated project is fully aligned with HL-LHC exploitation and provides for seamless continuation of HEP in Europe with highest performance EW factory followed by highest energy hadron collider.

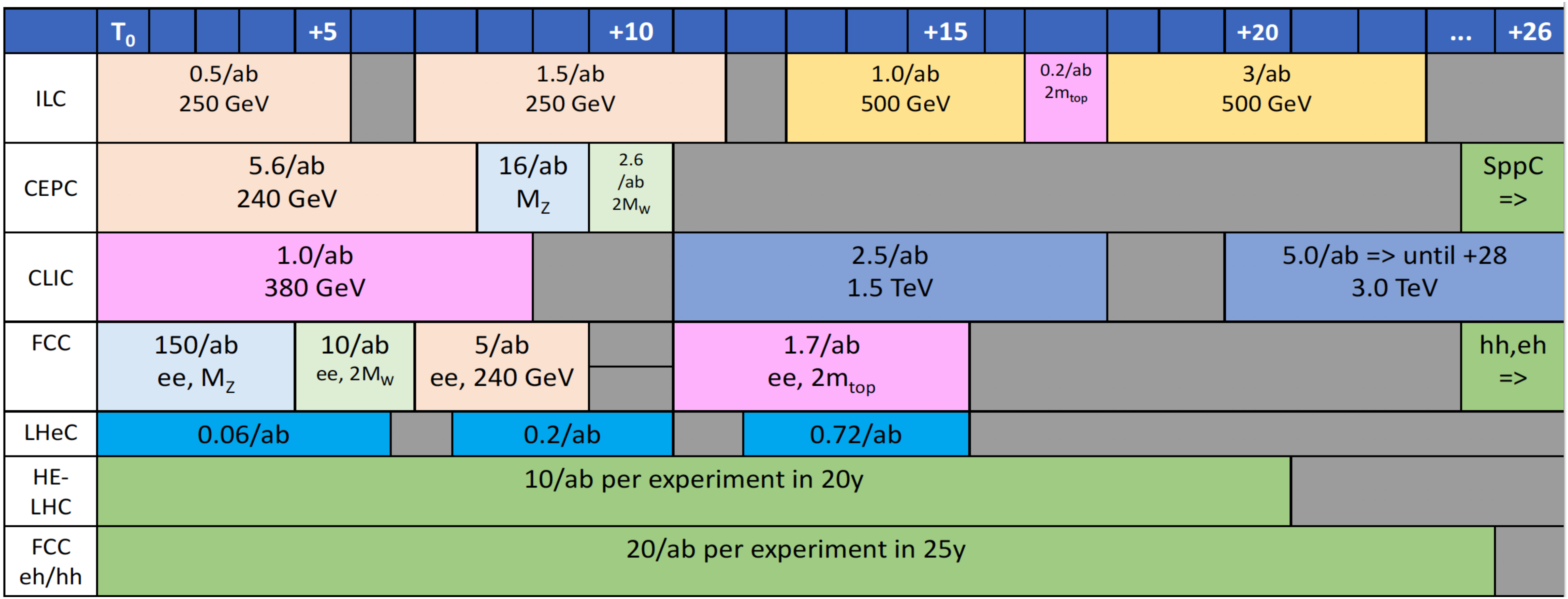
https://indico.cern.ch/event/727555/contributions/3447469/attachments/1867359/3071163/190624_Overview_of_the_FCC_Study_ap.pdf

ESG request for parameters of a lower-energy hadron collider

parameter	FCC-hh		FCC-hh-6T	HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		37.5	27	14	14
dipole field [T]	16		6	16	8.33	8.33
beam current [A]	0.5		0.6	1.1	1.1	0.58
synchr. rad. power/ring [kW]	2400		57	101	7.3	3.6
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	10 (lev.)	16	5 (lev.)	1
events/bunch crossing	170	1000	~300	460	132	27
stored energy/beam [GJ]	8.4		3.75	1.4	0.7	0.36

- **NbTi technology from LHC, magnet with single-layer coil providing 6 T at 1.9 K:**
  - → Corresponding beam energy 18.75 TeV or 37.5 TeV c.m.
  - → Significant reduction of synchrotron radiation wrt FCC-hh (factor 50) and corresponding cryogenic system requirements.
- **Luminosity goal 10 ab^{-1} over 20 years or 0.5 ab^{-1} annual luminosity:**
  - → Beam current 0.6 A or 20% higher than for FCC-hh, 1.2E11 ppb (FCC-hh: 1.0 ppb).
  - → Stored beam energy 3.75 GJ vs 8.4 GJ for FCC-hh.
- **Analysis of physics potential, technology requirements and cost ongoing.**

Proposed Schedules and Evolution



	T_0				+5					+10					+15					+20			...	+26
ILC	0.5/ab 250 GeV						1.5/ab 250 GeV						1.0/ab 500 GeV				0.2/ab $2m_{top}$	3/ab 500 GeV						
CEPC	5.6/ab 240 GeV							16/ab M_Z		2.6 /ab $2M_W$														SppC =>
CLIC	1.0/ab 380 GeV										2.5/ab 1.5 TeV									5.0/ab => until +28 3.0 TeV				
FCC	150/ab ee, M_Z				10/ab ee, $2M_W$		5/ab ee, 240 GeV				1.7/ab ee, $2m_{top}$													hh,eh =>
LHeC	0.06/ab						0.2/ab					0.72/ab												
HE-LHC	10/ab per experiment in 20y																							
FCC eh/hh	20/ab per experiment in 25y																							

D. Schulte