Synergies: Accelerators

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Outline

Timeline Highlights in Accelerator Developments for Future Higgs Factories

Recent Directives in Accelerator-Related Contributions to FCC-ee and the ILC

Selected Synergistic Developments in Accelerator Science and Technology

Potential Future US Contributions

US Accelerator Science and Technology Workforce

Summary

Timeline Highlights in Accelerator Developments for Future Higgs Factories

Timeline Highlight – 2013 Snowmass and 2014 P5 report

Science Driver #1: “Use the Higgs boson as a new tool for discovery”

Project-specific recommendation #1: “… **Complete the LHC** phase-1 upgrades **and continue the strong collaboration in the LHC with** the phase-2 **(HL-LHC) …”**

Project-specific recommendation #2: Motivated by the strong scientific importance of the **ILC** and the recent initiative in Japan to host it, **the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design** in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.

+ numerous recommendations on enabling R&D including

- **Support the discipline of accelerator science** through … Strengthen national laboratory-university R&D partnerships, leveraging their diverse expertise and facilities.
- **Pursue accelerator R&D with high priority** … Focus on outcomes and capabilities that will dramatically improve cost effectiveness **for mid-term and far-term accelerators.**

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Timeline Highlight – 2015 Strategic Plan for Acc. R&D in the US

"The Subpanel [excluded "short-term R&D for HL-LHC, PIP-II and ILC"] examined the accelerator R&D that is required to prepare for the future-generation accelerators envisioned by P5 … also **examined long-term R&D of exploratory nature aimed at developing … a multi-TeV e+ e- collider for energy frontier research** complementary to research at hadron colliders, and …"

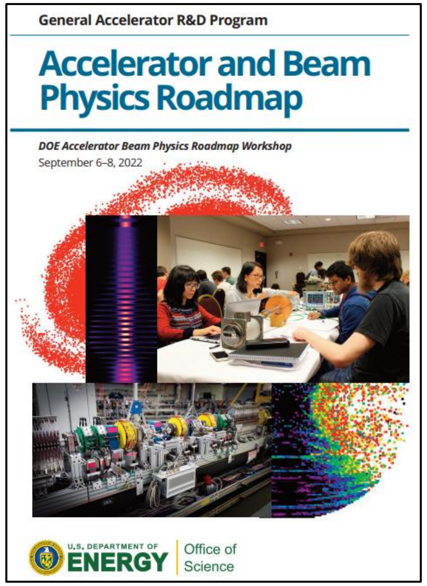
Reiterated the findings of the 2014 HEPAP Subcommittee on Workforce Development: "The **shortage of accelerator scientists** is apparent at the national labs…"

Provided **technology-specific recommendations** assuming three different (rather modest) funding scenarios two of which relate to OHEP funding under the General Accelerator Research and Development (GARD) program.

Timeline Highlight – 2022 Acc. and Beam Physics Roadmap

lead author: S. Nagaitsev

- addressed four grand challenges: beam intensity, quality, control and prediction
- described **roadmap for Accelerator and Beam Physics** for the GARD program
- reference for Snowmass



Timeline Highlight – 2022 Snowmass: Accelerator Frontier

conveners: S. Gourlay, T. Raubenheimer, V. Shiltsev

- 7 Topical Groups and multiple sub-groups
- preceded by **US FCCee planning panel** meetings with reference document

Timeline Highlight – 2023 (published): On the Feasibility of Future Colliders: Snowmass Implementation Task Force

lead author: T. Roser

comprehensive summary of both time and cost scales of

- accelerator-related R&D
- associated test facilities
- facility operations

with uniformly applied metrics to compare project cost, schedule/timeline, technical risk, operating costs, environmental impact, R&D status and plans

evaluated in four categories of colliders: Higgs factory colliders, lepton colliders with up to 3 TeV COM energy, colliders with 10 TeV or higher parton COM energy, lepton-hadron colliders

On the Feasibility of Future Colliders: Snowmass Implementation Task Force (here)

T. Roser (BNL), R. Brinkmann (DESY), S. Cousineau (ORNL), D. Denisov (BNL), S. Gessner (SLAC), S. Gourlay (LBNL/FNAL), P. Lebrun (ESI Archamps), M. Narain (Brown Univ.), K. Oide (KEK), T. Raubenheimer (SLAC), J. Seeman (SLAC), V. Shiltsev (FNAL), J. Strait (LBNL, FNAL), M. Turner (LBNL), L. Wang (Univ. Chicago)

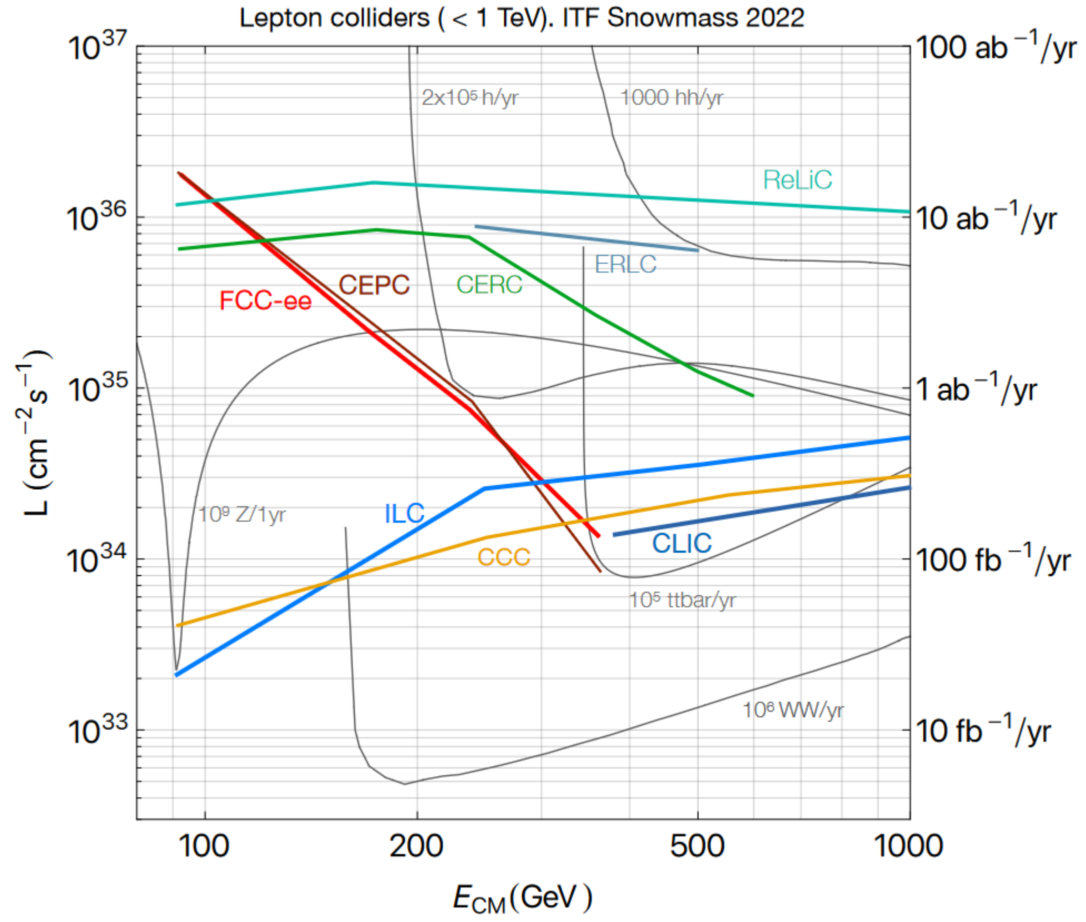


Figure 1. Peak luminosity per IP vs CM energy for the Higgs factory proposals as provided by the proponents. The right axis shows integrated luminosity for one Snowmass year (10^7 s). Also shown are lines corresponding to yearly production rates of important processes.

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II					1
CEPC-0.24	II					1
ILC-0.25	I					1
CCC-0.25	III					2
CLIC-0.38	II					1
CERC-0.24	III					2
ReLiC-0.24	V					2
ERLC-0.24	V					2
XCC-0.125	IV					2
MC-0.13	III					3
ILC-3	IV					2
CCC-3	IV					2
CLIC-3	II					1
ReLiC-3	IV					3
MC-3	III					3
LWFA-LC 1-3	IV					4
PWFA-LC 1-3	IV					4
SWFA-LC 1-3	IV					4
MC 10-14	IV					3
LWFA-LC-15	V					4
PWFA-LC-15	V					4
SWFA-LC-15	V					4
FCChh-100	II					3
SPPC-125	III					3
Coll.Sea-500	V					4

Table 9. Table summarizing the TRL categories, technology validation requirements, cost reduction impact and the judgement of performance achievability on technical components and subsystems for the evaluated collider proposals. Colors and categories are described above in Sec.3 and go from lighter/lower/easier to darker/higher/more challenging. The first column "Design Status" indicates current status of the design concepts: I - TDR complete, II - CDR complete, III - substantial documentation; IV - limited documentation and parameter table; V - parameter table. The last column indicates the overall risk tier category, ranging from Tier 1 (lower overall technical risk) to Tier 4 (multiple technologies that require further R&D).

Recent Directives in Accelerator-Related Contributions to FCC-ee and the ILC

2020 European Strategy for Particle Physics

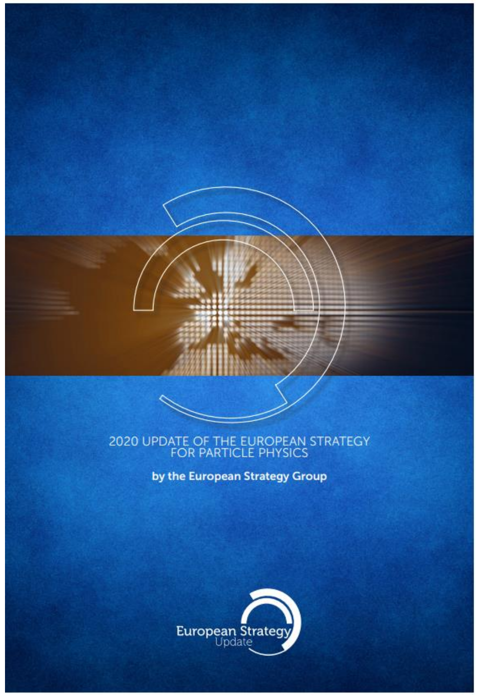
Identified as the highest-priority next collider an electron-positron Higgs factory.

- the particle physics community **should ramp up its R&D effort focused on advanced accelerator technologies**, in particular that for high-field superconducting magnets, including high-temperature superconductors

- The timely realisation of the **electron-positron International Linear Collider (ILC)** in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

- **Innovative accelerator technology** underpins the physics reach of high-energy and high-intensity colliders…

- The European particle physics community must **intensify accelerator R&D and sustain it with adequate resources…**



See also the European Strategy for Particle Physics Accelerator R&D Roadmap, published in Jan 2022.

The DOE national lab's participation in the FCC Feasibility Study was codified (under Addendum III to Accelerator Protocol III) in December 2020.

2023 P5 Report

From Executive Summary: The panel endorses an off-shore Higgs factory, located in either Europe or Japan, to advance studies of the Higgs boson …

- Recommendation #2 – Plan and start the following major initiatives **… an off-shore Higgs factory,** realized in collaboration with international partners…**The US should actively engage in feasibility and design studies**.

- Recommendation #6 - **Convene a targeted panel** with broad membership across particle physics **later this decade that makes decisions on the US accelerator-based program** at a time when major decisions concerning and off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed... The panel would consider the following:

  - The level and nature of US contribution in a specific Higgs factory including an evaluation of the associated schedule, budget, and risks once crucial information becomes available.
  - Mid- and large-scale test and demonstrator facilities in the accelerator and collider R&D portfolios.
  - …

OHEP responses for P5 recommendations will be presented at the upcoming HEPAP meeting on May 9-10, 2024.

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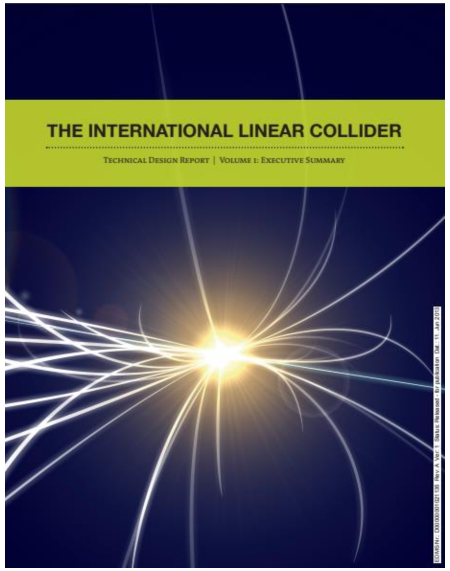
Strategic Developments for the ILC



The ILC TDR (Technical Design Report) was published in 2013.

In 2020, the International Committee for Future Accelerators (ICFA) appointed an **ILC International Development Team (IDT)**[1].

The IDT outlined the remaining technical preparations necessary before ILC construction[2]; e.g. work planned to be executed during the ILC Preparatory Phase through an ILC Pre-laboratory (ILC Pre-lab), an international laboratory organized to perform the work. Launching the ILC Pre-lab requires a level of international agreement that does not yet exist.

KEK and the IDT are initiating **the ILC Technology Network (ITN)**[3] – a global collaboration of laboratories who wish to contribute to ITN's purpose; i.e. execution of high priority tasks identified by the IDT from the work packages described in the ILC Pre-Lab Proposal with framework defined in 2023.

[1] https://linearcollider.org/ [2] https://zenodo.org/records/4884718 [3] https://linearcollider.org/wp-content/uploads/2023/09/IDT-EB-2023-00

DOE-HEP has indicated that DOE, or the DOE national labs, do not intend to formally join the ITN at this time, but support for related technologies, including workforce development efforts, are planned to be coordinated under the U.S.-Japan Cooperation Program.

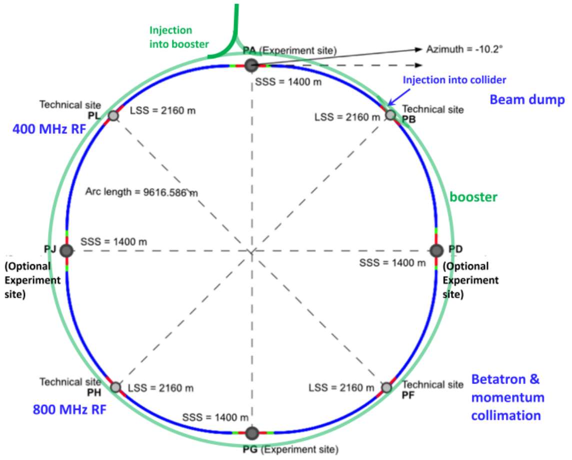
Selected Synergistic Developments in Accelerator Science and Technology

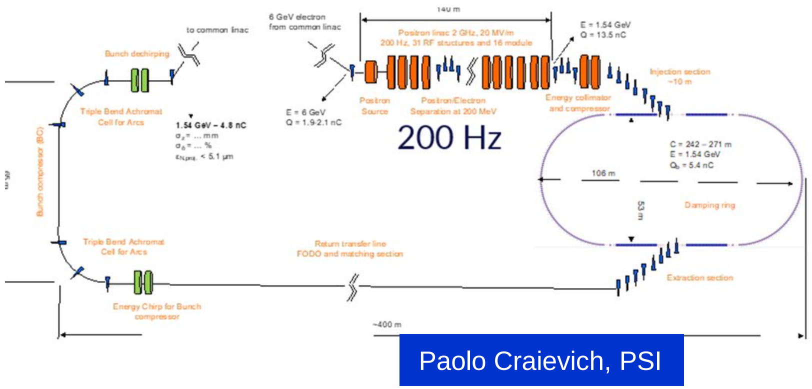
A few examples illustrating relevant US expertise and core capabilities.

FCC-ee / ILC – Present Layouts and Common Design Features

FCC-ee

- double ring e^+e^- collider
- asymmetric IR layout and optics to limit SR towards the detector
- 4 interaction points, 30 mrad crossing angle, crab-waist collisions



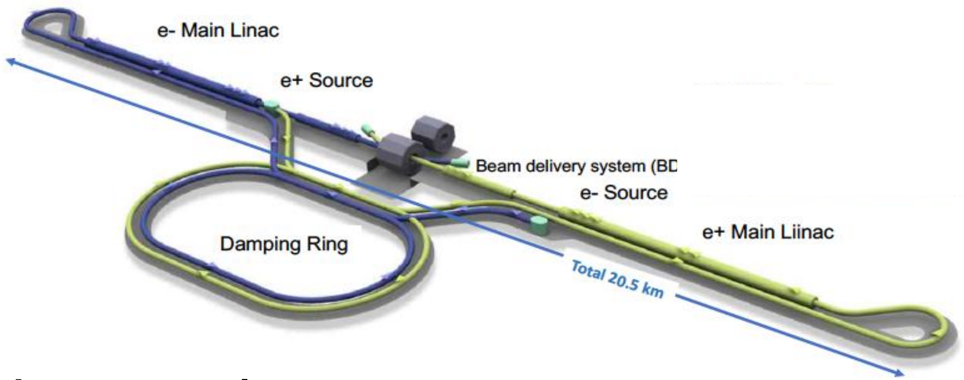


Injector complex (baseline)

- e- and e+ sources
- e- (6 GeV), e- (1.5 GeV) and common (20 GeV) linacs
- damping ring (1.5 GeV)
- common full-energy booster synchrotron (20 GeV to collision energy)

ILC

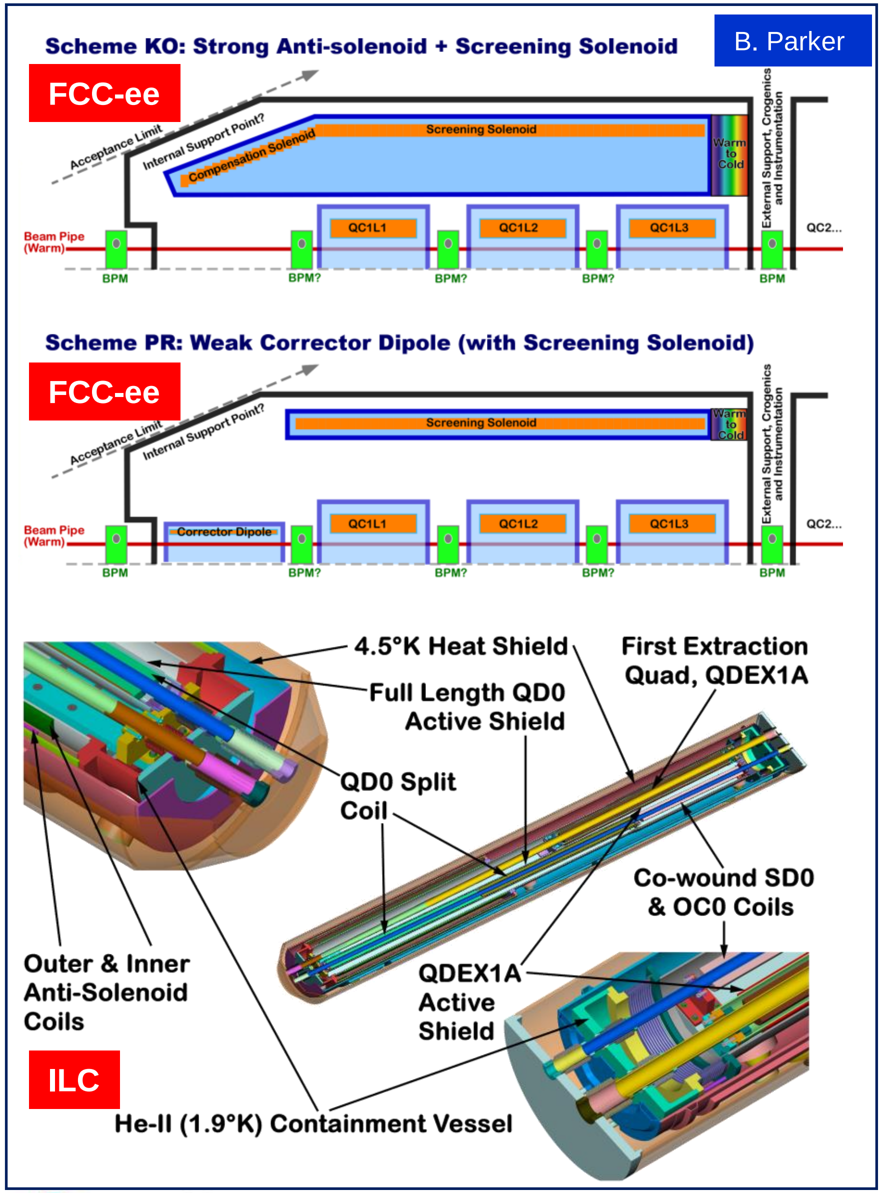
- double linac e^+e^- collider, separate e+ and e- linacs (250 GeV)
- beam delivery systems with demagnification optics
- 1 interaction point, 14 mrad crossing angle, crab cavities for head-on collisions



Injector complex

- e- and e+ sources (polarized)
- e+ (5 GeV) booster linac
- damping rings (5 GeV)

FCC-ee / ILC Synergies: Machine Detector Interface (MDI)



Beam properties at collision quite different, but commonalities exist:

Physics requirements
- detector stay clear (L* and forward angle)
- interplay with accelerator performance optimization

Mechanical engineering requirements
- beam pipe design (warm/cold transitions)
- cryostat support (from detector or external)
- detector installation and access requirements
- utility interfaces (cryogenics, leads etc.)

Overlapping requirements
- vibration mitigation (including interactions with beam-based trajectory feedback systems)
- instrumentation (luminosity and beam position monitors)
- radiation shielding (beamstrahlung and radiative Bhabhas)
- space constraints

Collective experience in past and future colliders is critical in advancing MDI optimization.

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FCC-ee / ILC Synergies: IR Quadrupole Stability

Courtesy Brett Parker

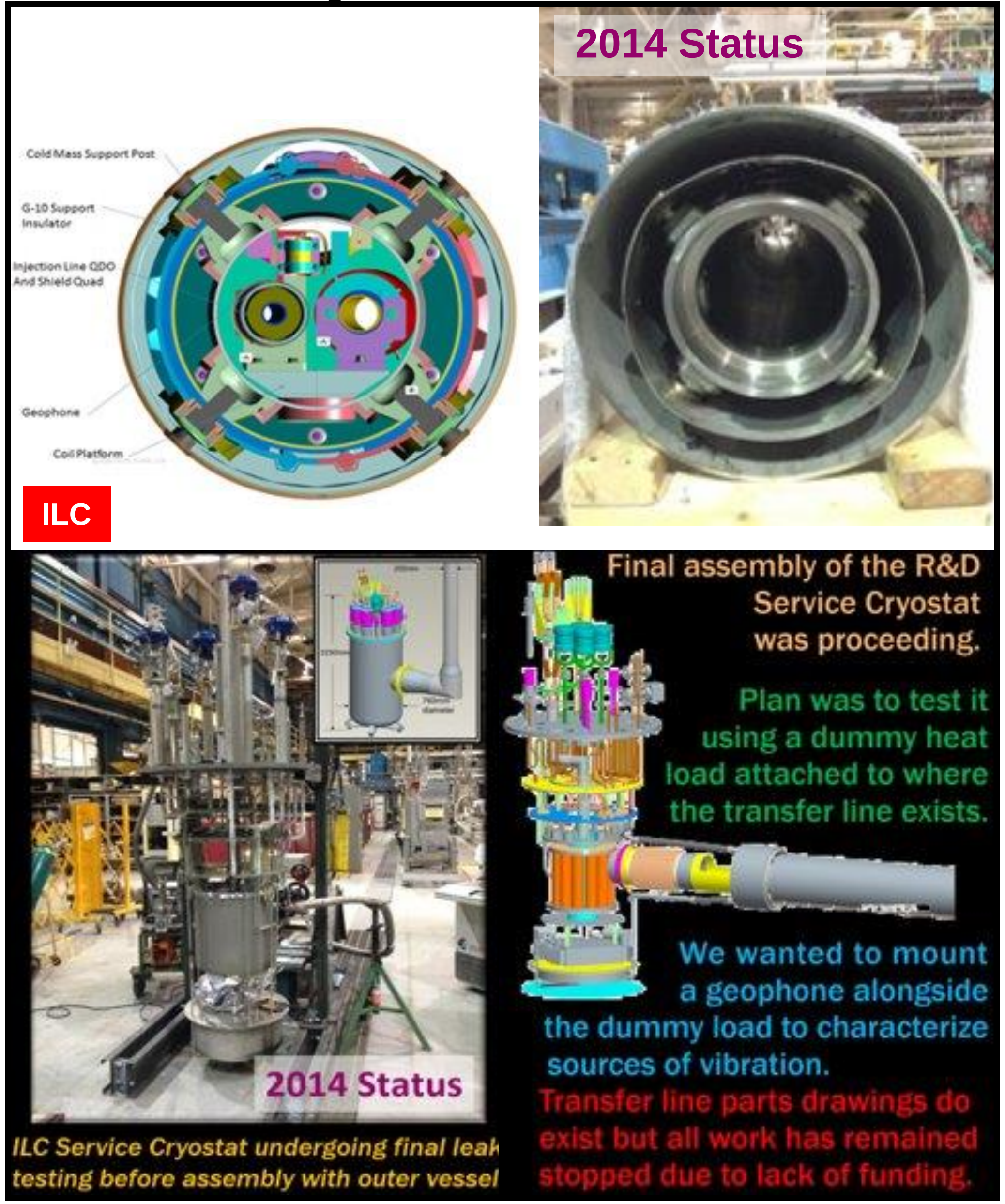
Nano-beam position stability requirements:

- ILC IP $\sigma_{vert} = 3\,nm$ $\rightarrow$ 50 nm stability with BB feedback
- FCC-ee $\sigma_{vert} = 35\,nm \rightarrow$ ~35 nm stability

Synergistic progress: demonstrate measurement accuracies well below requirements

- ILC prototype development (90% complete)
- SuperKEKB implementation (demonstrated "1 nm single-arm probe stability").
- highly relevant for FCC-ee and ILC

Repeat: collective experience in past and future colliders is critical in advancing MDI optimization.



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FCC-ee/ILC Synergies: Bulk Nb SRF Development

Courtesy Kellen McGee

- High-Q/High-gradient advancements to reduce overall cost of construction (length of ILC) or cooling (both ILC and FCC)
  - Moving away from complex N-doping process and exploring simpler and less costly low-($\sim 120℃$) and mid-($\sim 300℃$) temperature baking benefit FCC and ILC

1.3 GHz 9-cell baking treatment

- Modest R&D needed to bring sub-GHz bulk cavity performance to FCC 800 MHz spec (FCC-ee)
  - FCC-ee requirement of $Q_0 = 3 \times 10^{10}$ at 25 MV/m requires R&D to realize a consistent ~20% improvement over current sub-GHz cavity performance
- R&D in low-temperature baking and two-step baking shows potential to significantly increase 1.3 GHz cavity gradient, but more development needed to reach 50 MV/m+

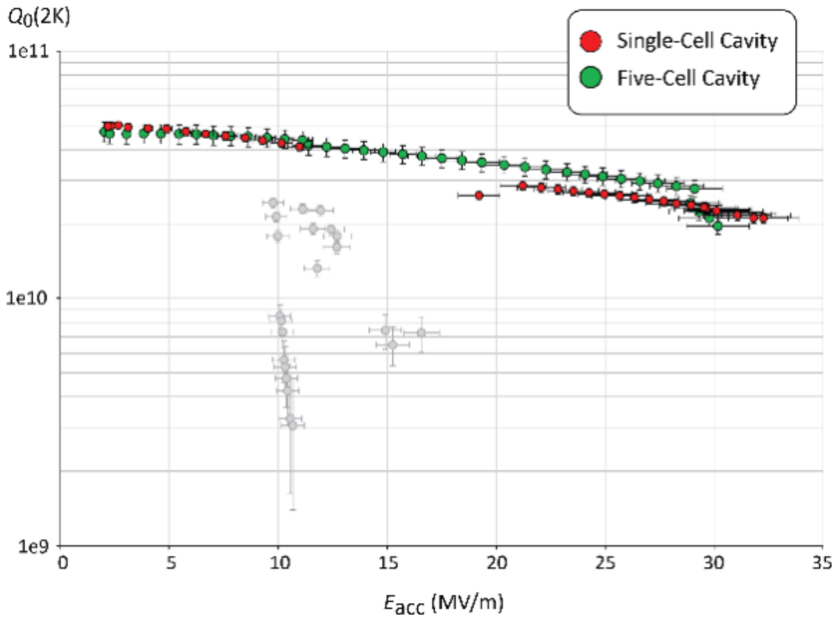

Figure 4: Combined VTA results for the five-cell and single-cell cavity as measured at 2 Kelvin.

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FCC-ee/ILC Synergies: Nb3Sn Development

Courtesy Kellen McGee

Current status of Nb3Sn at FNAL

- > 20 MV/m demonstrated in 1-cell
- 15 MV/m demonstrated in multicell

FCC gradient demonstrated in Nb3Sn sub-GHz cavities

- R&D needed to realize this performance in multicell cavities and the cryomodule context

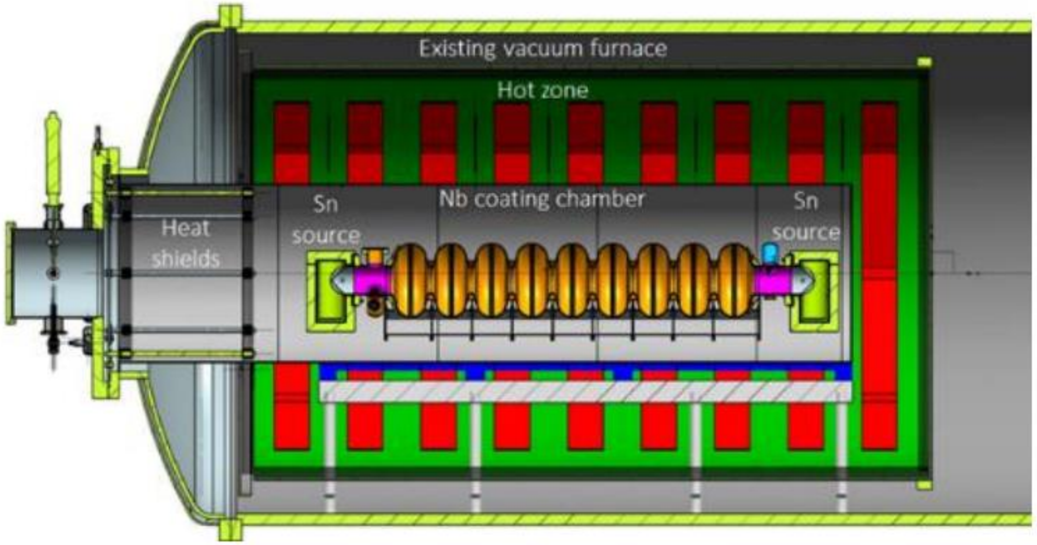
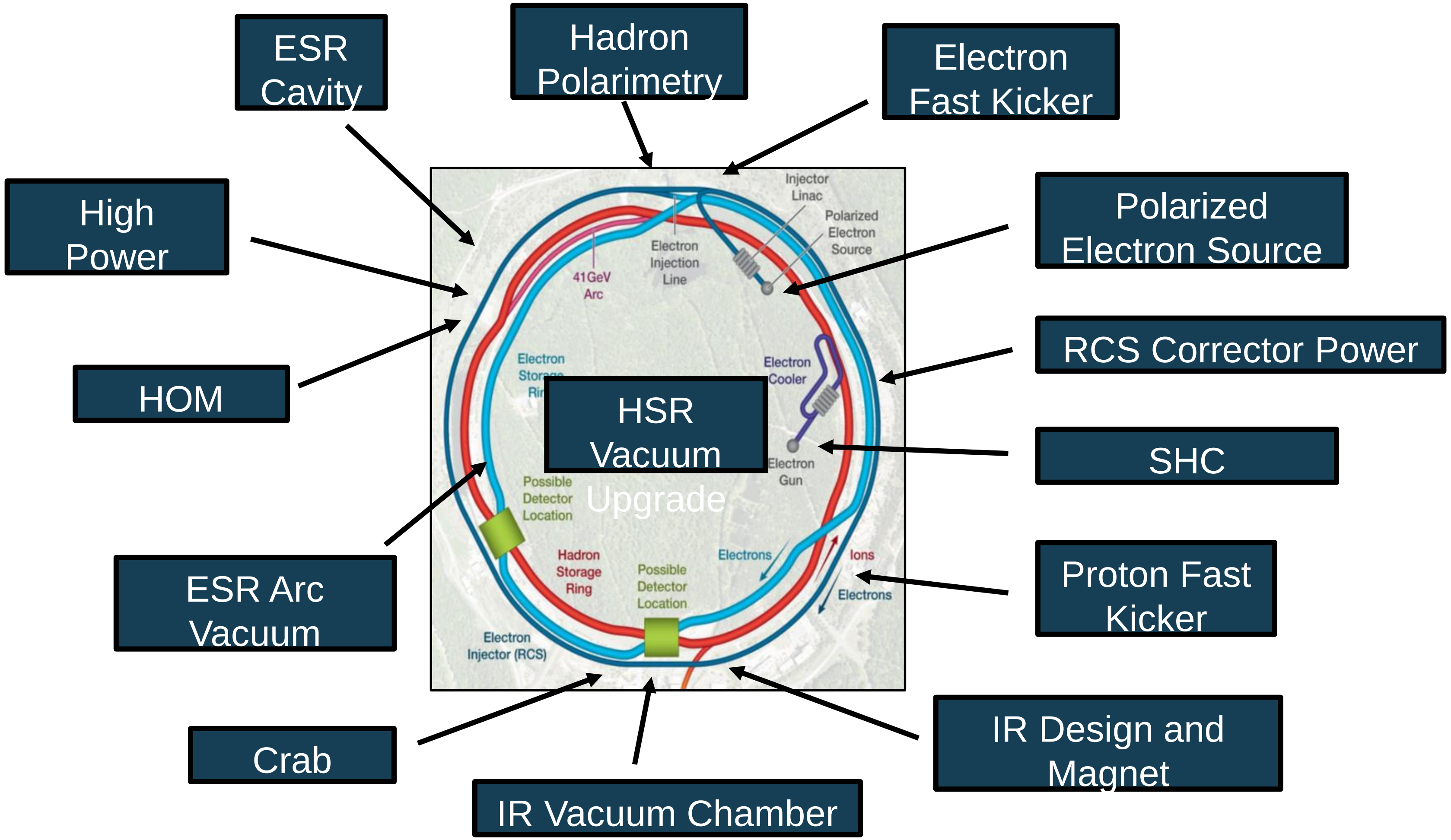


Figure 3: Horizontal furnace for Nb_3Sn multicell cavity coating at Fermilab.

Significant further R&D is needed to reach high gradients in 1.3 GHz Nb3Sn cavities for potential use in ILC

- Nb3Sn cavity processing and handling techniques also require R&D to enable consistent quality in ~16,000 cavities for ILC.

Synergies with the Electron Ion Collider (EIC)



The EIC Project **R&D** efforts support **innovative and critical conceptual designs** by providing an initial design process with calculations, simulations, and layouts… Thus, project **R&D** is very **focused on the needs of the project** to advance to manufacturing the state-of-the-art system components required for the EIC.

Courtesy Qiong Wu

- FCC-EIC Joint & MDI Workshop (Oct 2022) https://indico.cern.ch/event/1186798/
- EIC Workshop – Promoting Collaboration on the EIC (Oct 2020) https://indico.cern.ch/event/949203/

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Potential Future US Contributions

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US Contributions proposed by US-FCCee Planning Panel

Focus on

- projects needs (including cost and schedule reduction, power efficiency)
- US expertise and capabilities while still benefiting the US programs

US-FCCee Planning Panel

Panel Coordinators:
Tor Raubenheimer (SLAC/Stanford) and Vladimir Shiltsev (FNAL)

Machine Design:
Yunhai Cai (SLAC), John Byrd (ANL), Michiko Minty (BNL), Sergei Nagaitsev (JLab)

Magnet Systems:
Kathleen Amm (BNL), Steve Gourlay (FNAL), Soren Prestemon (LBNL)

RF Systems:
Sergey Belomestnykh (FNAL), Mark Kemp (SLAC), Matthias Liepe (Cornell)

Three main areas of potential contributions with several topics in each area identified

Area 1 – RF Systems
Area 2 – Magnets and Machine Detector Interface
Area 3 – Modeling, Design, Collimation, Polarization, Instrumentation

	ANL	BNL	FNAL	LANL	LBNL	JLab	SLAC	Universities
SRF cavities/CMs			■			■	■	Cornell, ODU ...
RF sources/modul.	■						■	IIT, Stanford
Copper RF linac	■			■			■	NIU, IIT
IR magnets		■	■		■			FSU, MIT, TAMU
Booster/MR magnets	■	■	■		■			
Beam Optics	■	■	■	■	■	■	■	Cornell, ...
Collimation		■	■				■	
Polarization		■	■			■		Cornell, UNM, ...
Instrumentation	■	■	■		■	■	■	many
Infrastructure	■	■	■	■	■	■	■	

Phases and deliverables defined

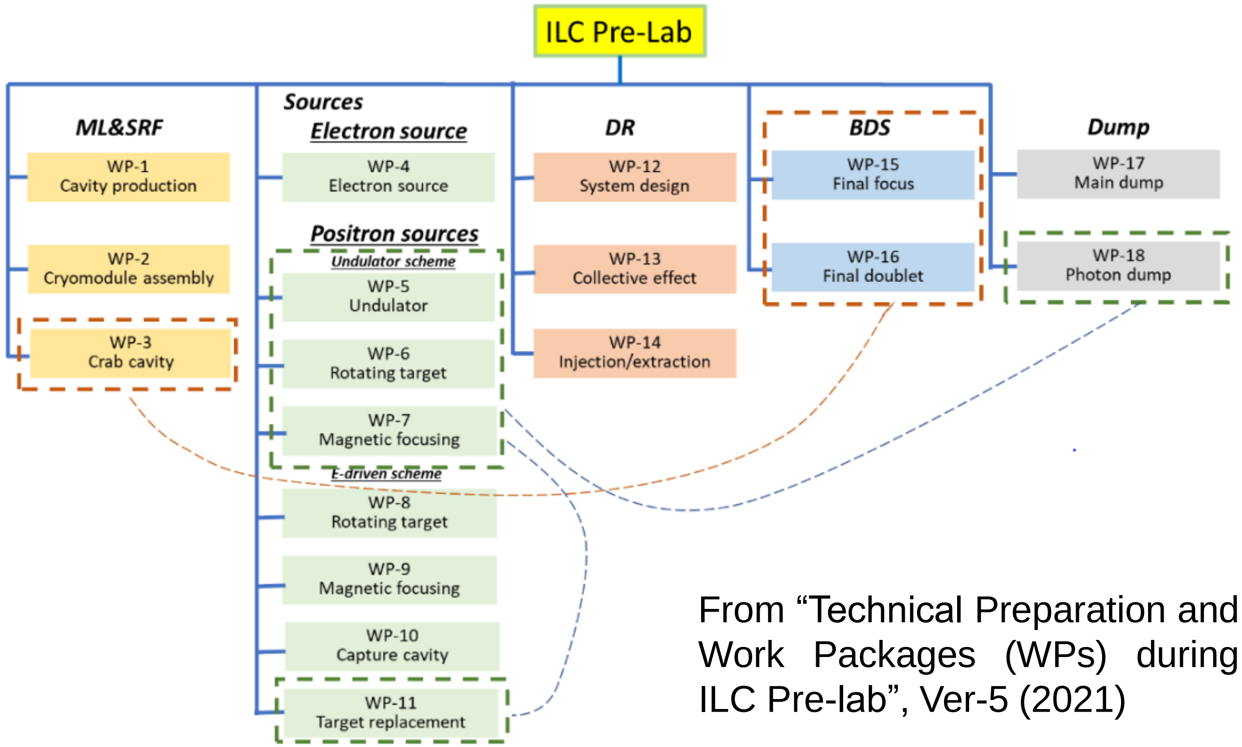
- technology R&D
- preliminary design and component prototyping
- system design and system prototyping
- preproduction models and fabrication

Comprehensive review pre-P5 performed.

US Accelerator Expertise Relevant to the ILC

- Major role, including leadership, of the worldwide Global Design Effort that led to the ILC Technical Design Report

- Contributions to the IDT-WG2 and to IDT-WG2's identification of accelerator-related activities for the ILC Pre-lab with IDT-WG2 US Member Affiliations – BNL(1), Cornell (1), FNAL (3), JLAB (2), ORNL (1), SLAC (3) + contributions from ANL, LBNL, and Old Dominion University



From "Technical Preparation and Work Packages (WPs) during ILC Pre-lab", Ver-5 (2021)

Similar to US expertise for the FCCee:

- extensive (multi-laboratory) experience in
  - beam optics and collective effects, beam delivery design and instrumentation
  - damping ring system and subsystem design (SRF, vacuum chambers, magnets, instrumentation, etc.)
- and core capabilities in
  - SRF (Cornell, FNAL, JLAB, SLAC)
  - final focus magnets (BNL, FNAL, LBNL)
  - polarized e-sources (BNL, Cornell, JLAB, SLAC)
- and in
  - undulators for polarized e+ sources
  - crab cavities
  - fast kickers

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US Accelerator S&T Workforce

Workforce Resources

United States Particle Accelerator School, USPAS supported by DOE HEP under GARD

Select institutes

- Center for Advanced Studies of Accelerators, CASA
- Cornell Laboratory for Accelerator-based ScienceS and Education, CLASSE, and the Center for Bright Beams (NSF)
- Center for Accelerator Science and Education, CASE, at Stony Brook University (HEP)
- MSU cryo-initiative – collaboration between FRIB and MSU College of Engineering (NP)
- Virginia Innovative Traineeships in Accelerators, VITA (DOE)

New DOE OS initiatives recognizing diminishing expertise in accelerator R&D, projects, and operation in the US and increased demand:

- Particle Accelerators for Science and Society and Workforce Training (2021)
- RENEW: Reaching a New Energy Sciences Workforce (2023)
- FAIR: Funding for Accelerated, Inclusive Research (2023)
- MIni-Workshop on Accelerator Scientist / Engineer Workforce of National Labs (2024)

Summary

Summary

The US Accelerator Physics community is proactive in strategic planning; select examples

- 2015 Strategic Plan for Accelerator R&D in the US
- 2022 Accelerator and Beam Physics Roadmap
- 2023 Snowmass Implementation Task Force on Feasibility of Future Colliders
- specific to an off-shore Higgs Factory
  - 2013 major contributions to the ILC TDR
  - 2022 US FCC-ee planning panel
  - 2023 strong engagement in the ILC Pre-Lab
- interest in other areas not covered here: sustainability (e.g. energy-efficient cryogenic systems and RF power sources), site-specific civil engineering design (with contributions already underway), as well as to future upgrades.

Continuity in engagement drives progress

- MDI: ILC → SuperKEKB → FCCee → ILC
- RF: all TESLA-like developments in SRF (including LCLS-II) for the ILC, FCCee and material science (e.g. for FCChh) and beyond

There is an increasing urgency in strengthening the US workforce in accelerator-based technology

2014 P5 report: “support the discipline of accelerator science”

2015 strategic plan: “shortage of accelerator scientists”

2024 dedicated DOE mini-workshop on Workforce in Accelerator Science and Technology

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The US Accelerator Physics community offers much expertise and has great interest in both R&D and in in-kind contributions for an off-shore Higgs Factory. Down-selection of contributions may be challenging.

Acknowledgements

Thank you to all whose collective contributions were represented here.

Special thanks, with contributions towards both FCCee and ILC initiatives, especially to Sergey Belomestnykh, Kellen McGee, Brett Parker and Alex Zaltsman.

For this talk also received much appreciated support for the ILC (Andy Lankford, ILC America's liaison) and Nikolay Solyak.

Am thankful for continuous and extended communications with Tor Raubenheimer, Vladimir Shiltsev, and Frank Zimmermann and would like to recognize Derun Li for strong support and guidance.