US Snowmass'21 process and perspectives

Tor Raubenheimer, SLAC
on behalf of Snowmass AF conveners: S. Gourlay, V. Shiltsev, and me

FCC Week
June 28 – July 2, 2021

U.S. DEPARTMENT OF ENERGY | Stanford University

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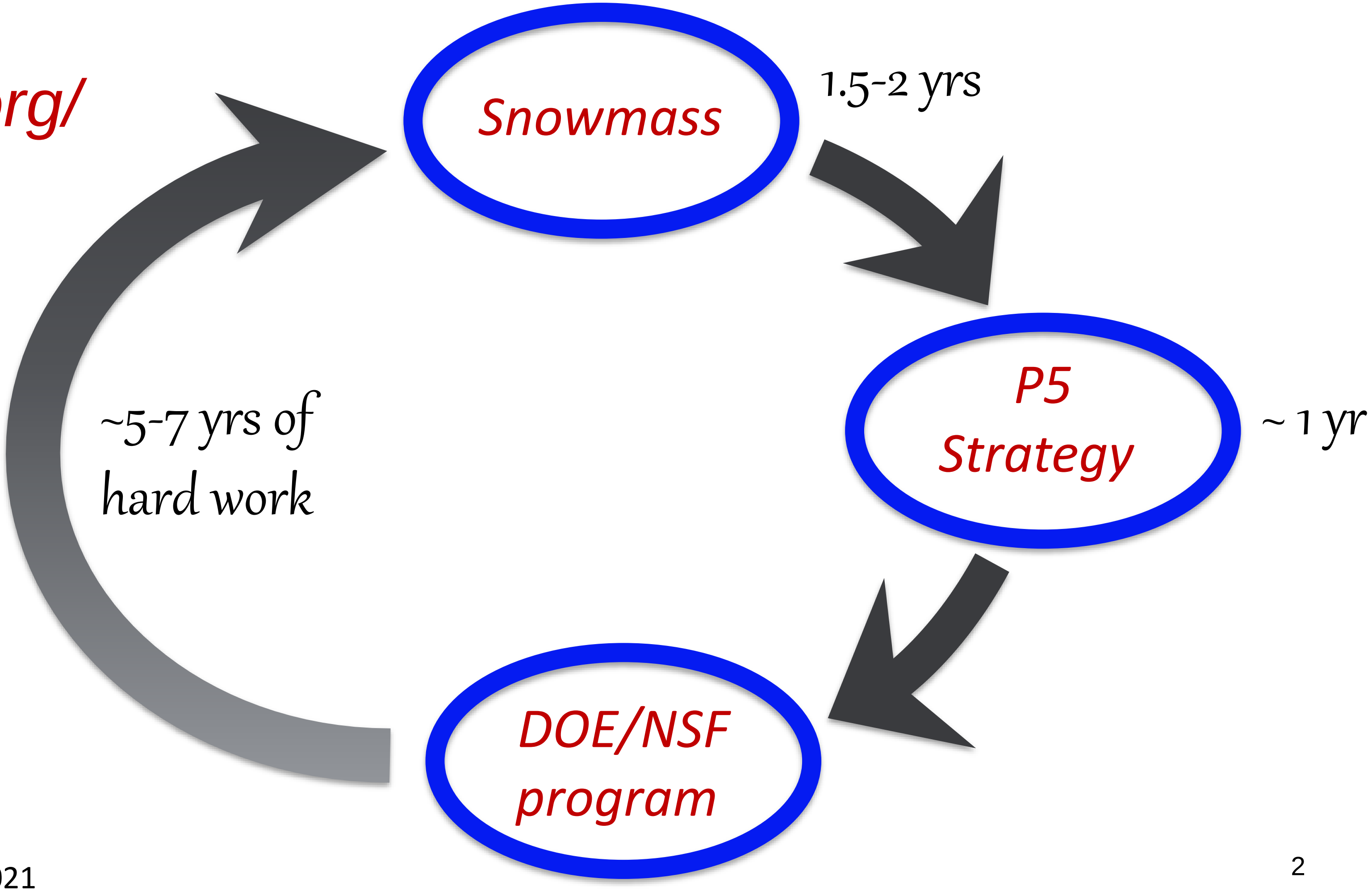
What is Snowmass?

"Snowmass is a particle physics community study"

https://www.snowmass21.org/

Provides input to P5 (Particle Physics Project Prioritization Panel) which develops a strategy for the US HEP program



Large US Accelerator Construction Projects

Many large accelerator projects across the United States:

- High Energy Physics:
  - High Luminosity LHC upgrade (~0.5B, ~2026)
  - Long-Baseline Neutrino Facility / PIP-II (~4B, 2030)
- Nuclear Physics:
  - Facility for Rare Ion Beams (~0.6B, 2022)
  - Electron-Ion Collider (~2B, 2031)
- Basic Energy Sciences:
  - Argonne Photon Source Upgrade (~1B, 2026)
  - Advanced Light Source Upgrade (~0.5B, 2026)
  - LCLS-II / LCLS-II High Energy (~2B, 2030)
  - SNS Power Upgrade and Second Target Station (~0.3B, 2027 / ~1B, 2030+)

US High Energy Physics Accelerator R&D Subpanel

Guided by 2015 Accelerator R&D Subpanel Report:

Near-term goals:

- PIP-II → LBNF / DUNE
- HL-LHC
- ILC e+/e- collider

Mid-term goals:

- Multi MW proton accelerator
- Very high energy proton-proton collider
- TeV-scale upgrade of ILC

Long-term goals:

- Multi-TeV e+/e- collider
- Neutrino factory

US HEP Accelerator Mid- and Long-term R&D Focus

US largely focused on accelerator technology R&D

- High Field magnet and High Gradient RF development as well as other technology development has been ongoing in part to support ILC and a high energy pp collider

US was heaving engaged in Linear Collider R&D from 1980 → 2008

- Refocused on SRF technology for cost reduction

Strong advanced acceleration programs

- No concept for a collider at this time but focused on fundamental demonstrations

Muon Accelerator Program (MAP) from 2011 to 2015

- Examined feasibility of MC subsystems but redirected before looking at integration

Snowmass’21: Frontiers and Topical Groups

10 Frontiers	80 Topical Groups
Energy Frontier	Higgs Boson properties and couplings, Higgs Boson as a portal to new physics, Heavy flavor and top quark physics, EW Precision Phys. & constraining new phys., Precision QCD, Hadronic structure and forward QCD, Heavy Ions, Model specific explorations, More general explorations, Dark Matter at colliders
Frontiers in Neutrino Physics	Neutrino Oscillations, Sterile Neutrinos, Beyond the SM, Neutrinos from Natural Sources, Neutrino Properties, Neutrino Cross Sections, Nuclear Safeguards and Other Applications, Theory of Neutrino Physics, Artificial Neutrino Sources, Neutrino Detectors
Frontiers in Rare Processes & Precision Measurements	Weak Decays of b and c, Strange and Light Quarks, Fundamental Phy[illegible]eriments. Baryon and Lepton Number Violation, Charged Lepton Flavor Violation [illegible]es, Hadron spectroscopy
Cosmic Frontier	Dark Matter: Particle-like, Dark Matter: Wave-lik[illegible] Energy & Cosmic Acceleration: The Modern Universe, Dark [illegible]mic Dawn & Before, Dark Energy & Cosmic Acceleration: Complemen[illegible]
Theory Frontier	String theory, quantum gr[illegible]ry techniques, CFT and formal QFT, Scattering amplitudes, Lattice [illegible] precision physics, Collider phenomenology, BSM model building, Astr[illegible]uantum information science, Theory of Neutrino Physics
Accelerator Frontier	Be[illegible]on, Accelerators for Neutrinos, Accelerators for Electroweak and Higgs [illegible]celerators for Physics Beyond Colliders & Rare Processes, Advanced [illegible]celerator Technology R&D: RF, Magnets, Targets/Sources
Instrumentatio[illegible]	[illegible]s, Photon Detectors, Solid State Detectors & Tracking, Trigger and DAQ, Micro Pattern Gas [illegible], Calorimetry, Electronics/ASICS, Noble Elements, Cross Cutting and System Integration, Radio [illegible]ction
Computational [illegible]	Experimental Algorithm Parallelization, Theoretical Calculations and Simulation, Machine Learning, Storage and processing resource access (Facility and Infrastructure R&D), End user analysis
Underground Facilities and Infrastructure Frontier	Underground Facilities for Neutrinos, Underground Facilities for Cosmic Frontier, Underground Detectors
Community Engagement Frontier	Applications & Industry, Career Pipeline & Development, Diversity & Inclusion, Physics Education, Public Education & Outreach, Public Policy & Government Engagement

30 Frontier conveners, ~250 Topical Group conveners,
>40 Inter-Frontier Liaisons, ~25 Early Career Liaisons

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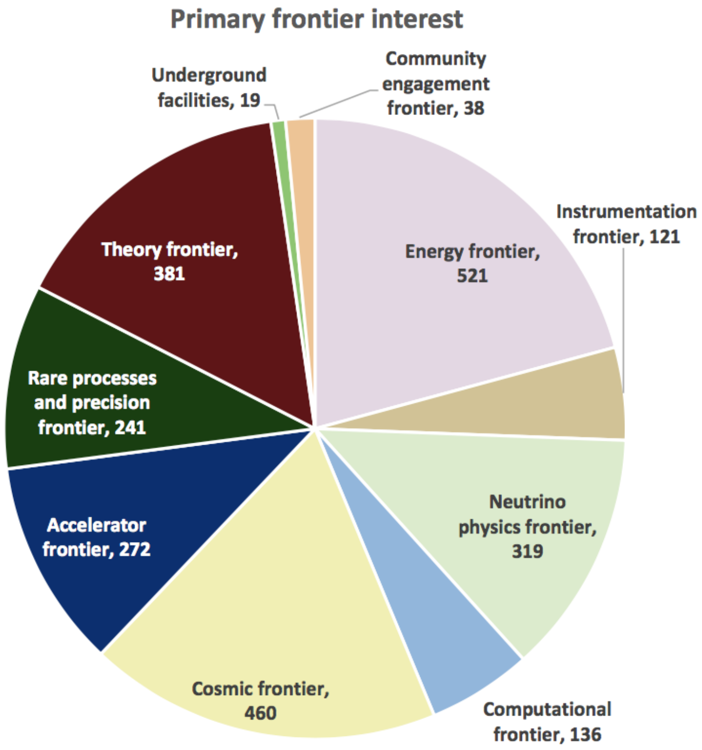
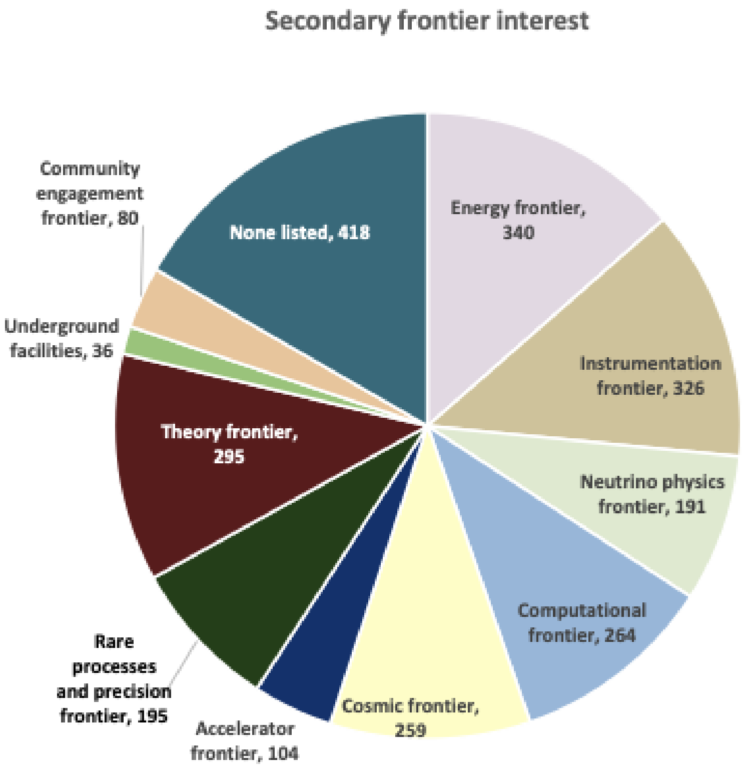
Snowmass *Community Planning Meeting*: Oct 5-8, 2020

~3,000 participants

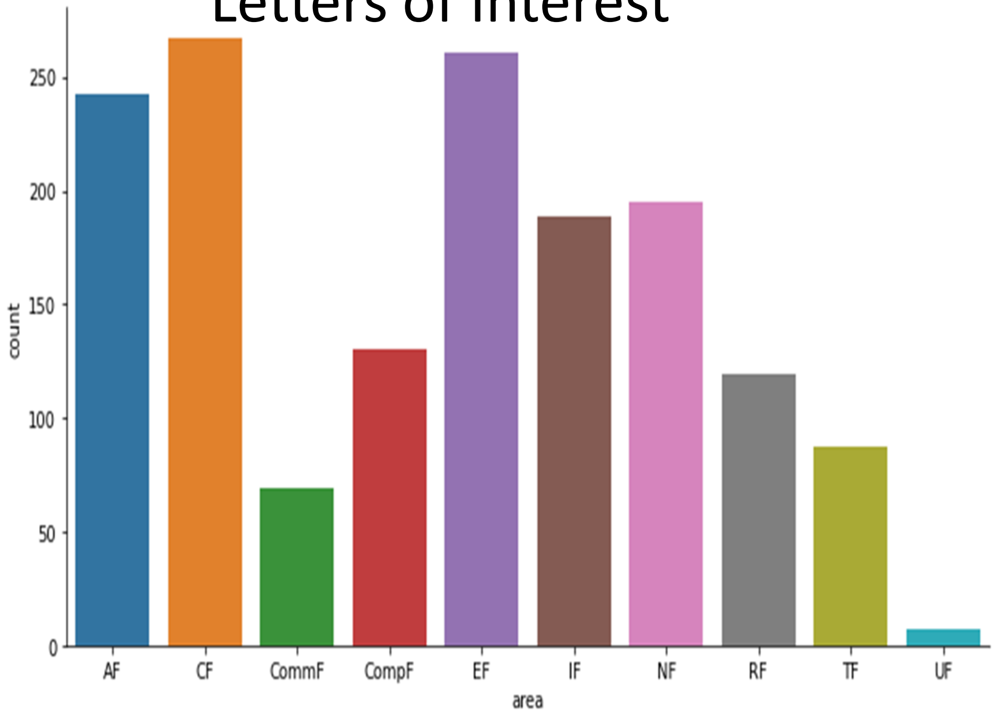
~650 outside the North America Time Zone

(Note that 11am-4pm U.S. Central time was inconvenient – very inconvenient for many countries)





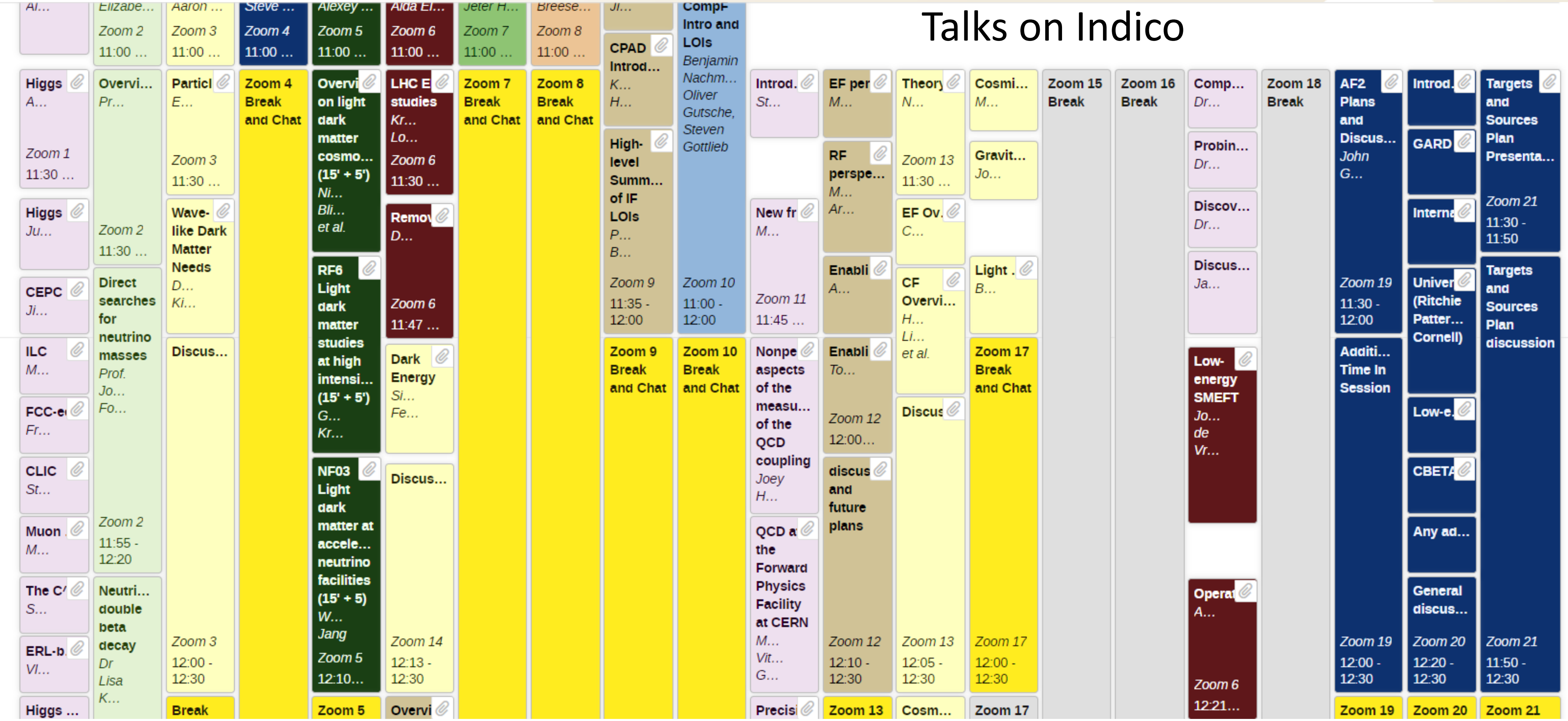
Letters of Interest



>120 related to FCCee

Community Planning Meeting Sessions (Oct, 2020)

Talks on Indico



Two days packed with parallel sessions

= EF = TF = AF

Snowmass Energy and Theory Frontiers

Topical Group	Co-Conveners
EF01: EW Physics: Higgs Boson properties and couplings	Sally Dawson (BNL), Andrey Korytov (U Florida), Caterina Vernieri (SLAC)
EF02: EW Physics: Higgs Boson as a portal to new physics	Patrick Meade (Stony Brook), Isobel Ojalvo (Princeton)
EF03: EW Physics: Heavy flavor and top quark physics	Reinhard Schwienhorst (MSU), Doreen Wackeroth (Buffalo)
EF04: EW Physics: EW Precision Physics and constraining new physics	Alberto Belloni (Maryland), Ayres Freitas (Pittsburgh), Junping Tian (Tokyo)
EF05: QCD and strong interactions:Precision QCD	Michael Begel (BNL), Stefan Hoeche (FNAL), Michael Schmitt (Northwestern)
EF06: QCD and strong interactions:Hadronic structure and forward QCD	Huey-Wen Lin (MSU), Pavel Nadolsky (SMU), Christophe Royon (Kansas)
EF07: QCD and strong interactions: Heavy Ions	Yen-Jie Lee (MIT), Swagato Mukherjee (BNL)
EF08: BSM: Model specific explorations	Jim Hirschauer (FNAL), Elliot Lipeles (UPenn), Nausheen Shah (Wayne State)
EF09: BSM: More general explorations	Tulika Bose (U Wisconsin-Madison), Zhen Liu (Maryland), Simone Griso (LBL)
EF10: BSM: Dark Matter at colliders	Caterina Doglioni (Lund), LianTao Wang (Chicago)

Many Topical Groups in both the Energy and the Theory Frontiers strongly coupled to FCC-ee physics case

Snowmass Accelerator Frontier – Key Questions

1. What is needed to advance the physics?
2. What is currently available (state of the art) around the world?
3. What new accelerator facilities could be available on the next decade (or next next decade)?
4. What R&D would enable these future opportunities?
5. What are the time and cost scales of the R&D and associated test facilities as well as the time and cost scale of the facilities?

Accelerator Frontier: Topical Groups

- AF1: Beam Physics and Accelerator Education
- AF2: Accelerators for Neutrinos
- AF3: Accelerators for EW/Higgs
- AF4: Multi-TeV Colliders
- AF5: Accelerators for PBC and Rare Processes
- AF6: Advanced Accelerator Concepts
- AF7: Accelerator Technology R&D

Subgroup 1 :Magnets
Subgroup 2: RF
Subgroup 3: Sources and Targets

Plus the **Accelerator Implementation Task Force** to help compare technical readiness and cost scales of different approaches

329 Acc. Frontier LoIs (incl.71 joint - EF, NF, RPF, …)

AF1: Beam Physics and Accelerator Education	61 (14)
AF2: Accelerators for Neutrinos	18 (5)
AF3: Accelerators for EW/Higgs	32 (4)
AF4: Multi-TeV Colliders	56 (10)
AF5: Accelerators for PBC and Rare Proc.	37 (22)
AF6: Advanced Accelerator Concepts	71 (5)
AF7: Accelerator Technology R&D	137 (6)

Highlights – Joint AF/EF Workshop on Future Colliders

Day 1: https://indico.fnal.gov/event/43871/

9:00 AM	→ 9:10 AM	**Introduction: goals, format, etc**
9:10 AM	→ 9:25 AM	**FCCee** **Speaker**: Katsunobu Oide (KEK)
9:25 AM	→ 9:40 AM	**CepC** **Speaker**: Yu Chenghui
9:40 AM	→ 9:55 AM	**ILC** **Speaker**: Shinichiro MICHIZONO (KEK)
9:55 AM	→ 10:10 AM	**CLIC** **Speaker**: Steinar Stapnes (FNAL)
10:10 AM	→ 10:25 AM	**EIC** **Speaker**: Christoph Montag (BNL)
10:25 AM	→ 10:40 AM	**LHeC** **Speaker**: Oliver Bruning (CERN)
10:40 AM	→ 10:55 AM	**HE-LHC** **Speaker**: Frank Zimmermann (CERN)
10:55 AM	→ 11:10 AM	**SppC** **Speaker**: Jingyu Tang (Institute of High Energy Physics)
11:10 AM	→ 11:25 AM	**FCChh** **Speaker**: Michael Benedikt

Day 2: https://indico.fnal.gov/event/43872/

9:00 AM	→ 9:10 AM	**Introduction: gioals, format, etc**
9:10 AM	→ 9:30 AM	**Cold NC-Linear Collider** **Speaker**: Emilio Nanni (SLAC National Accelerator Laboratory)
9:30 AM	→ 9:50 AM	**ERL based FCCee** **Speaker**: Thomas Roser (BNL)
9:50 AM	→ 10:10 AM	**Gamma-Gamma Higgs factories** **Speaker**: Frank Zimmermann (CERN)
10:10 AM	→ 10:30 AM	**Plasma-Laser WFA 1 TeV +** **Speaker**: Carl Schroeder (Lawrence Berkeley National Laboratory)
10:30 AM	→ 10:50 AM	**Plasma-Beam WFA 1 TeV +** **Speaker**: Spencer Gessner
10:50 AM	→ 11:10 AM	**Structure-beam WFA 1 Tev +** **Speaker**: John Power (Argonne National Lab)
11:10 AM	→ 11:30 AM	**Muon Coliders: Higgs Factory and 3-14 TeV** **Speaker**: Daniel Schulte (CERN)
11:30 AM	→ 12:10 PM	**Discussion/ Q&A**

Highlights from the Snowmass Accelerator Frontiers

AF1 – has been running a series of physics of Ultimate Beams and what are the fundamental limits of accelerator technology

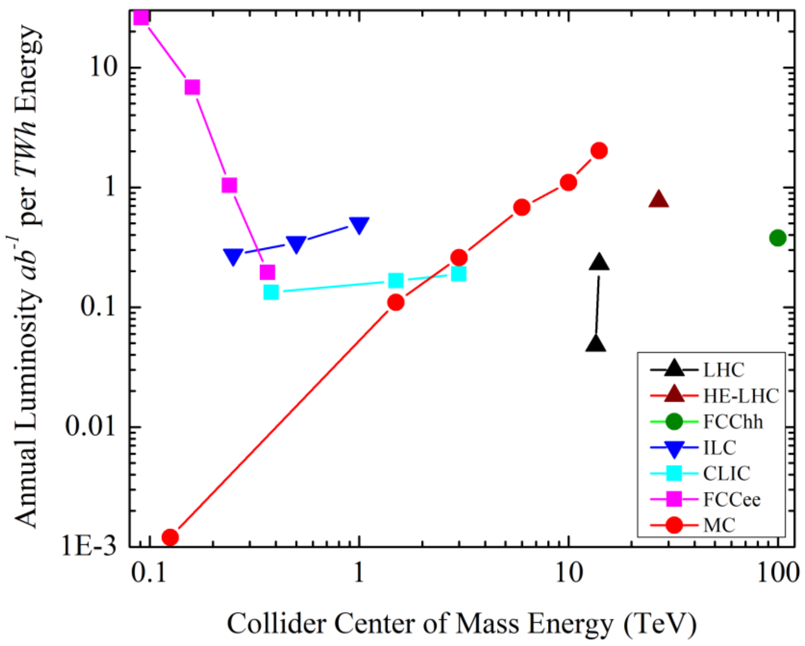
AF3 – looking broadly at Higgs factories from e+/e-, γ/γ, μ+/μ-

AF4 – considering multiple paths to high energy including e+/e-, γ/γ, μ+/μ- and p/p; lots on enthusiasm for μ+/μ- in part because of potential to fill in the gap from 3-14 TeV with US MC Forum and Int. MC Collab.

AF5 – working on many small or moderate scale proposals

AF6 – working to understand options to upgrade a more conventional linear collider as well as limits of plasma acceleration

AF7 – 3 subgroups exploring limits of accelerator technology (many efforts supported in part by US-Japan)



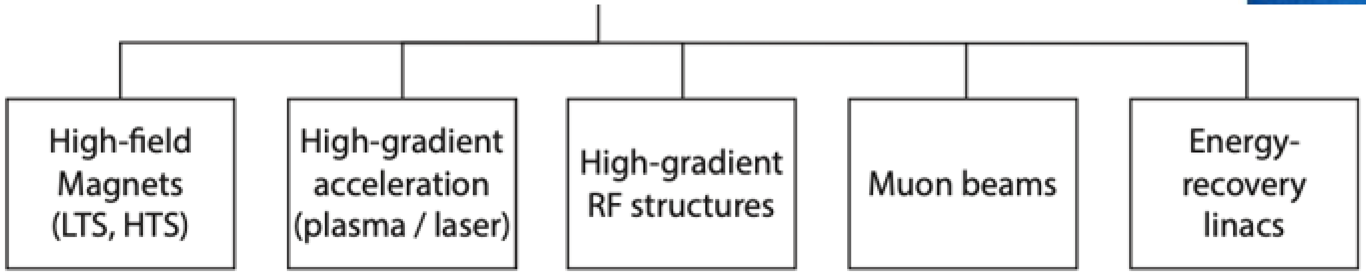
European Planning

ESPP describes strategy for particle physics in Europe and their contributions world-wide

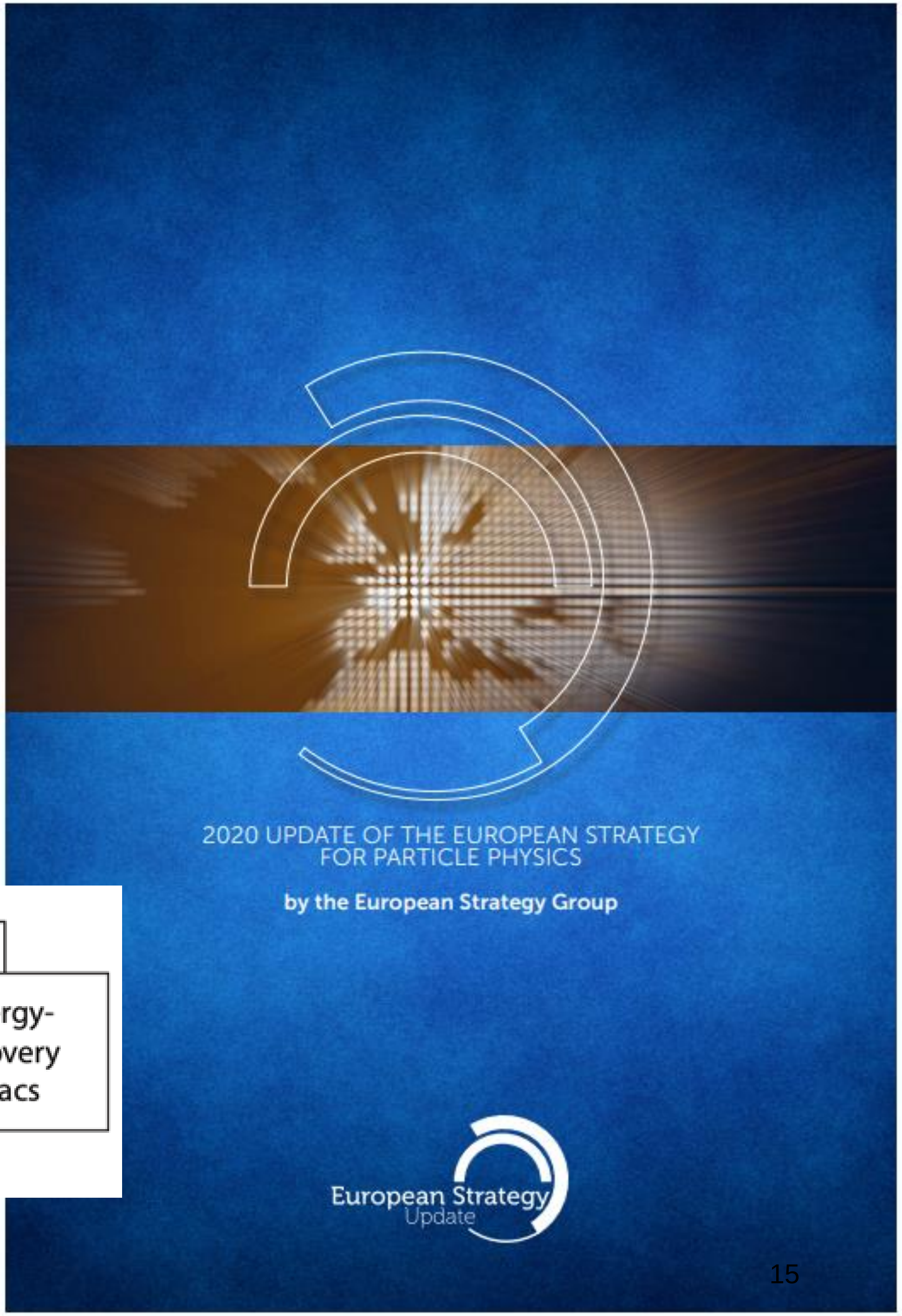
Immediate outcome → Accelerator R&D Task Forces reporting to Lab Directors Group (LDG) and CERN Council

Address the question of what are the most promising Accelerator R&D activities for HEP

5 Targetted Accelerator R&D Expert Panels



Snowmass AF participants are active on all the LDG panels



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AF Implementation Task Force

Key question for Snowmass'21 Accelerator Frontier to address: *"…What are the time and cost scales of the R&D and associated test facilities as well as the time and cost scale of the facility?"*

A large number of possible accelerator projects: ILC, Muon Collider, gamma-gamma and ERL options, a large circumference electron ring, and a large circumference hadron ring amongst others.

Comparison of the expected costs (using different accounting rules), schedule, and R&D status for the projects.

The *Accelerator Implementation Task Force* comprises of 12 world-renowned accelerator experts from Asia, Europe and US and two representatives of the *Snowmass Young*; it is chaired by Thomas Roser (BNL) and charged with developing metrics and processes to facilitate a comparison between projects (see next slide).


Thomas Roser (BNL, Chair)


Philippe Lebrun (CERN)


Steve Gourlay (LBNL)


Tor Raubenheimer (SLAC)


Katsunobu Oide (KEK)


Jim Strait (FNAL)


Sarah Cousineau (ORNL)


Marlene Turner (LBNL)


Spencer Gessner (SLAC)


Vladimir Shiltsev (FNAL)


Reinhard Brinkmann (DESY)


John Seeman (SLAC)

Implementation Task Force: Charge

1. Develop the metrics to compare projects' cost, schedule/timeline, technical risks (readiness), operating cost and environmental impact, and R&D status and plans;
2. Select the accelerator projects to be evaluated (provided by the AF topical groups);
3. Work with the proponents of the selected accelerator projects to evaluate them against the metrics from item 1;
4. Consider the ultimate limits of various types of colliders: e+/e-, p/p, mu+/mu-;
5. Consider limits and timescales due to accelerator technology for various types of colliders: e+/e-, p/p, mu+/mu-;
6. Lead the evaluation of the different HEP accelerator proposals and inform and communicate with the Snowmass'21 AF, EF, NF and TF;
7. Document the metrics, processes, and conclusions for the *Snowmass'21* meeting in the Summer 2022; write and submit a corresponding White Paper.

Focused on HEP Colliders

Large US Accelerator Construction Projects

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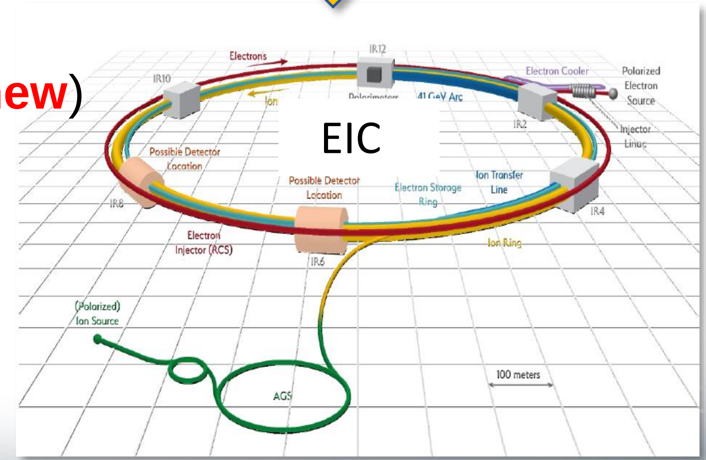
  - SNS Power Upgrade and Second Target Station (~0.3B, 2027 / ~1B, 2030+)

EIC Design Overview

Design based on **existing RHIC Complex**
RHIC is well maintained, operating at its peak

- **Hadron storage RHIC Yellow Ring 40-275 GeV (existing)**
  - 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance 1.5 nm
  - strong cooling (coherent electron cooling)
- **Electron storage ring 2.5–18 GeV** (**new**)
  - many bunches,
  - large beam current, 2.5 A ➔ 9 MW S.R. power
  - S.C. RF cavities
- **Electron rapid cycling synchrotron 0.4- 18GeV** (**new**)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (**new**)
  - $L = 10^{34} cm^{-2} s^{-1}$
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation



Electron-Ion Collider (EIC)

EIC electron ring has many similar challenges

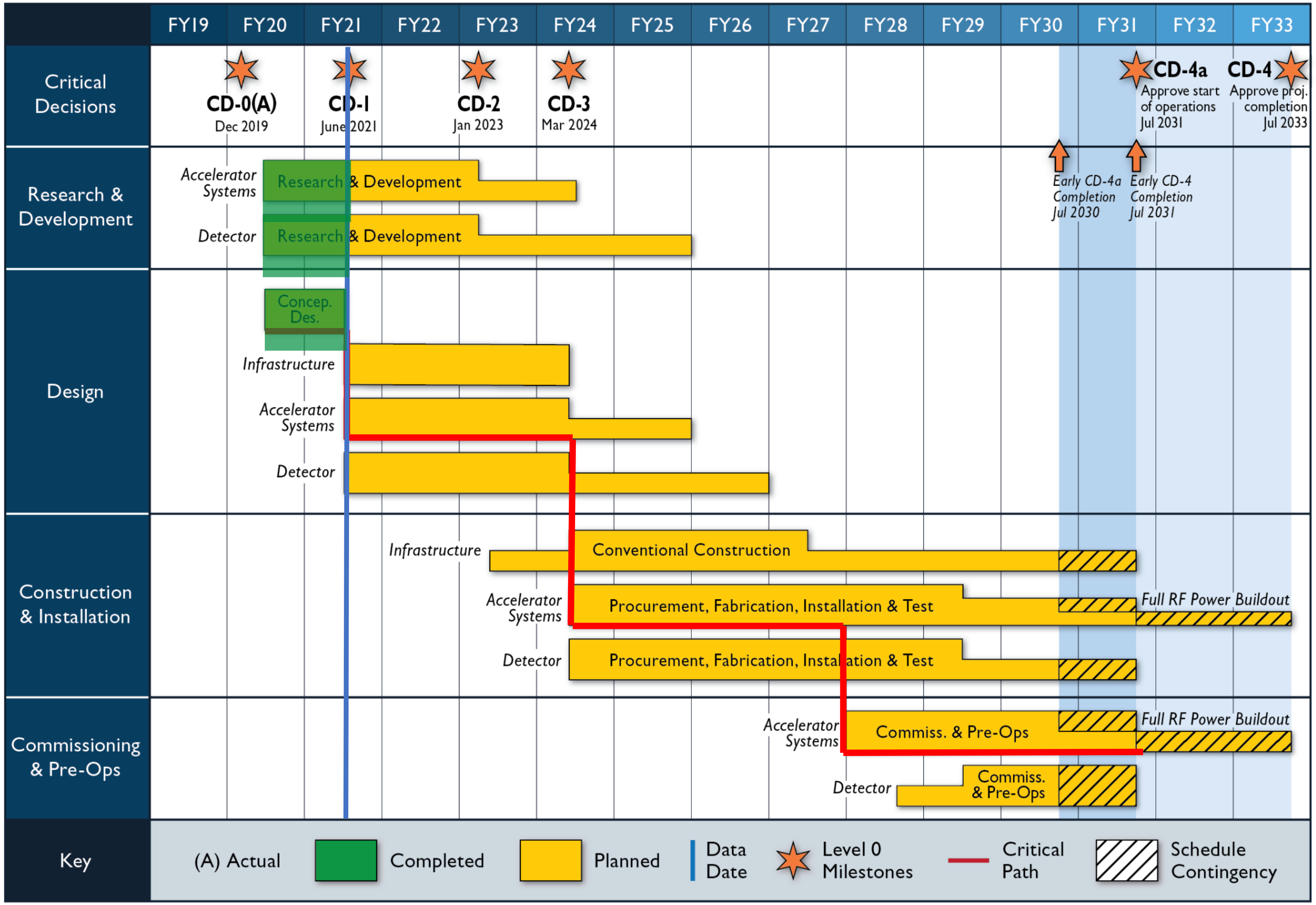
- SRF cavities and power sources
- Vacuum systems with intense synchrotron radiation
- Collective effects and impedance models
- Interaction region design and SC IR magnets

NSLS-II, EIC & FCC-ee beam parameters

	NSLS-II	EIC	FCC-ee-Z
Beam energy [GeV]	3	10 (18)	45.6 (80)
Bunch population [10^{11}]	0.08	1.7	1.7
Bunch spacing [ns]	2	10	15, 17.5 or 20
Rms bunch length [mm]	4.5 - 9	10	3.5 from SR 12 incl. BS
Beam current [A]	0.5	2.5 (0.27)	1.39
RF frequency [MHz]	500	591 or 394	400
SR power / beam /meter [W/m]	900	7000	600
Critical photon energy [keV]	2.4	9 (54)	19 (100)

Courtesy Frank Zimmermann

EIC Schedule

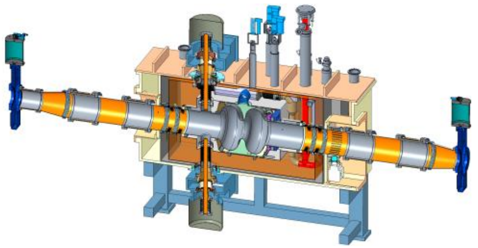


Completion roughly 10 years before FCCee

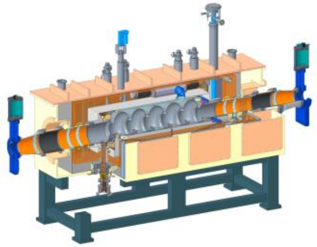
Courtesy Ferdinand Willeke

Electron-Ion Collider

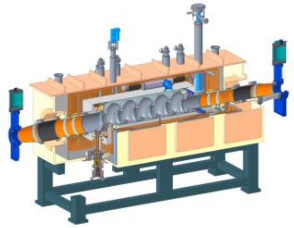
EIC RF systems



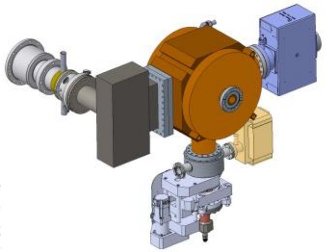
Electron - 591 MHz electron storage cavity



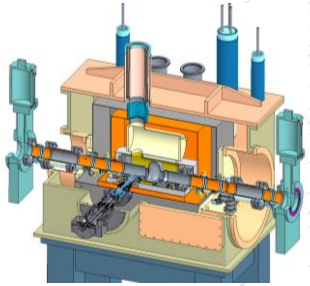
Hadron - 591 MHz bunch compression cavity



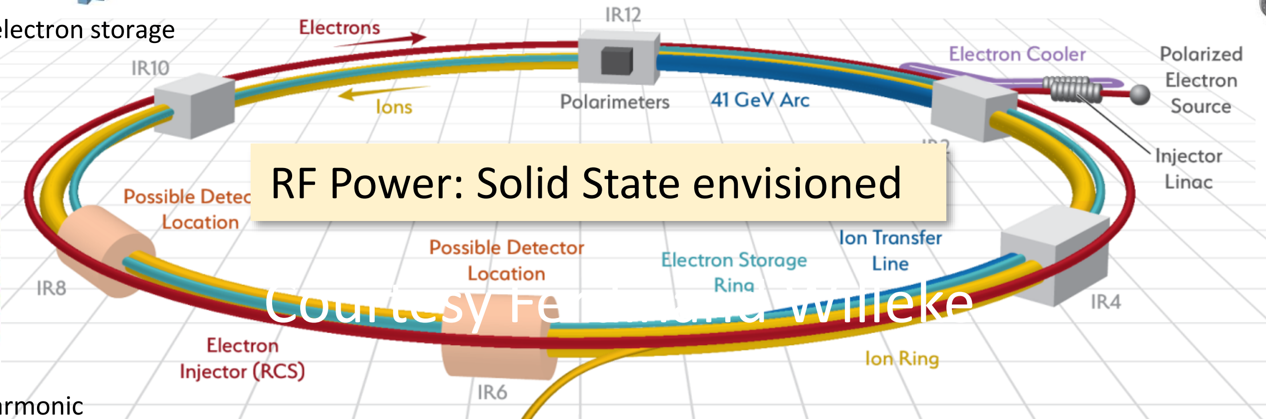
Hadron Cooling - 591 MHz acceleration cavity



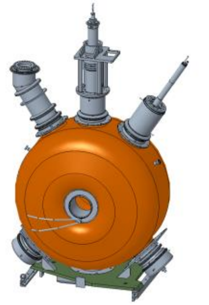
Injector - 571 MHz bunch compression cavity



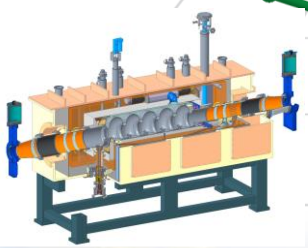
Electron - 1773 MHz 3rd harmonic cavity



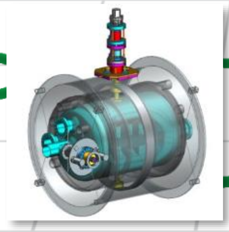
RF Power: Solid State envisioned



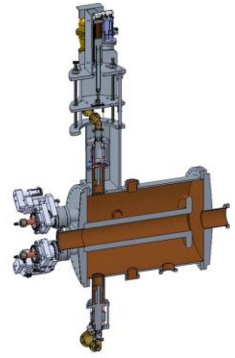
Hadron - 197 MHz bunch compression cavity



Rapid Cycling Synchrotron - 591 MHz acceleration cavity



197MHz/394MHz Crab cavities

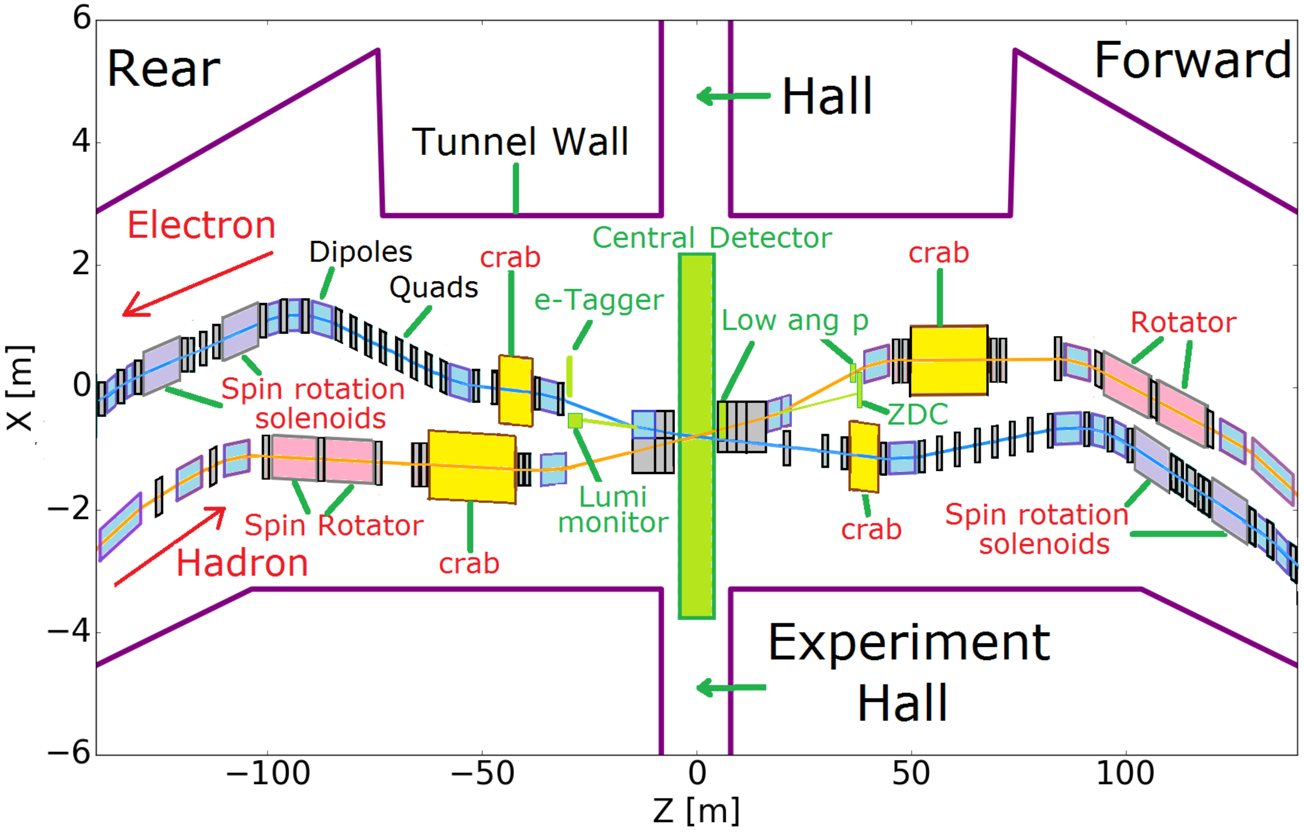


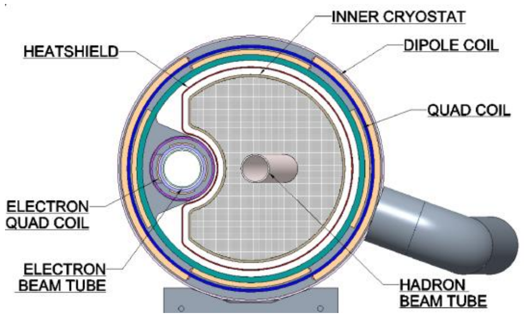
Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity

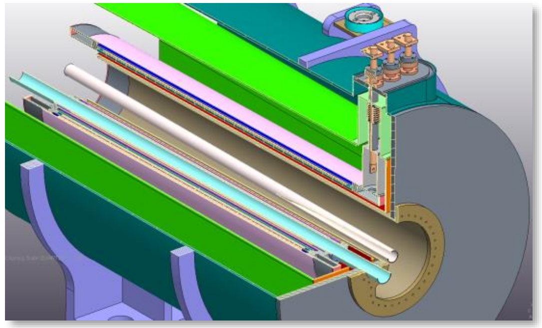
Hadron – 24.5 MHz acceleration cavity

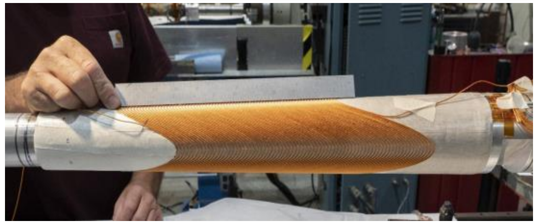
Courtesy Ferdinand Willeke

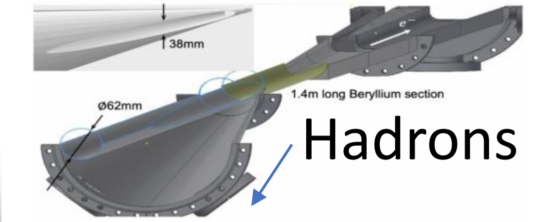
EIC Interaction Region









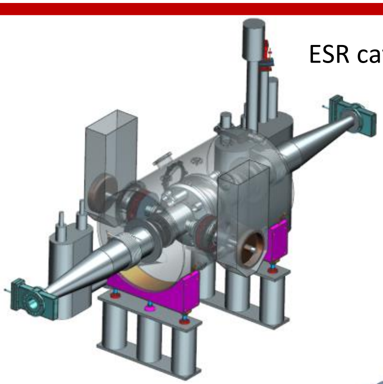


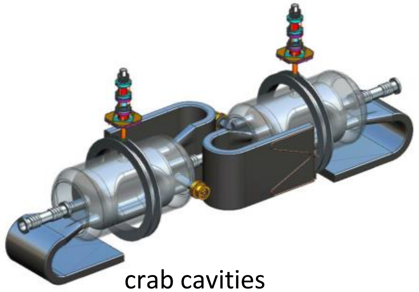
Courtesy Ferdinand Willeke

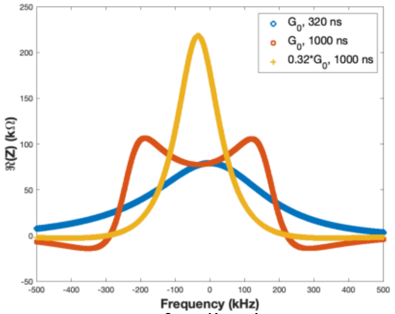
Synergies between EIC and FCC

Courtesy R. Rimmer
FCC week 2021

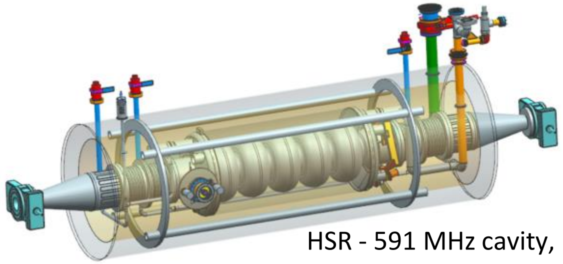
- High-power SRF systems
  - ESR, HSR, Crabbing, RCS
  - High energy electron cooling ERL
- SRF system stability, transients, noise
- Critical component R&D
  - High power couplers
  - HOM absorbers
  - RF power sources
- Advanced structure R&D
- New materials


ESR cavities


crab cavities



RF feedback

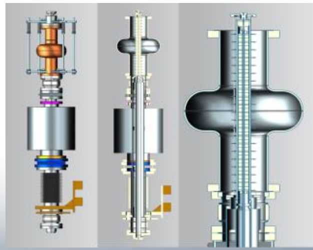

HSR - 591 MHz cavity, RCS, cooler ERL


Solid state amplifiers

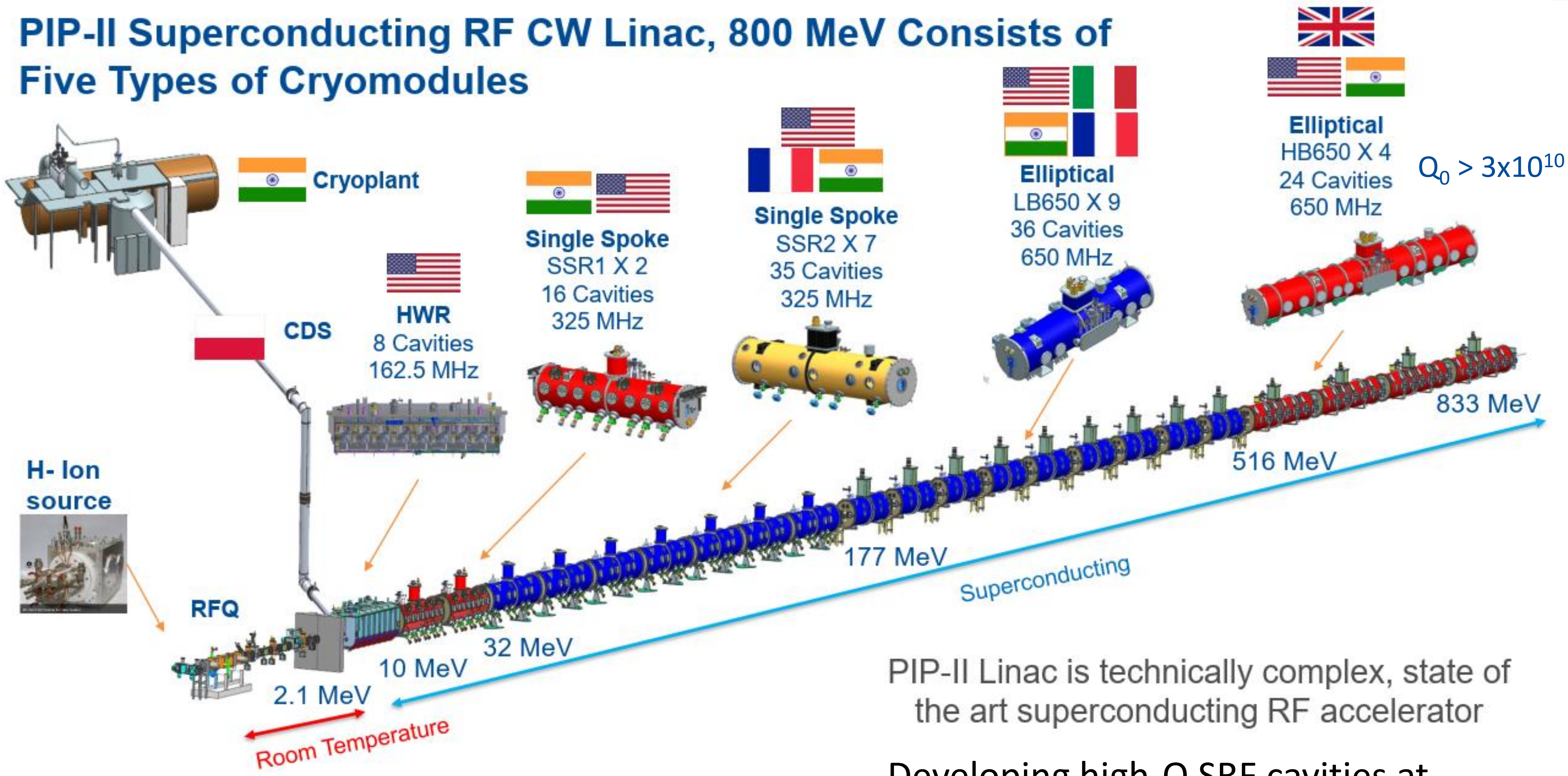

High-power couplers


HOM absorbers


Advanced cavity concepts


New materials

PIP-II at Fermilab



Developing high-Q SRF cavities at 650, 800, and 1300 MHz

Fermilab Magnet and SRF Technology & FCC

Ready to develop concrete plans for the FCC-ee accelerator technology roadmap

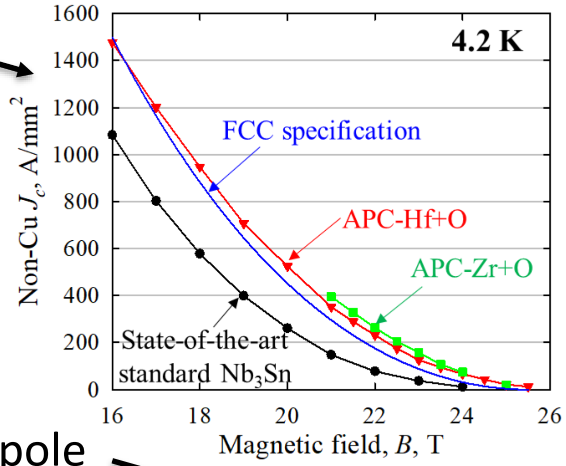
- Lots of synchrotron radiation losses => Requires a very large high Q SRF machine
- New Fermilab discoveries – "mid-T bake" - can be directly implemented for high Q SRF

Fermilab magnet and SRF R&D programs are highly synergistic with ambitious goals of FCC-hh and -ee

- Nb_3Sn conductor R&D (Xu ECA)
- High field magnet R&D (14.5 T record)
- High Q_0 SRF R&D (existing collaboration with CERN)

Eager for opportunities for dedicated R&D programs

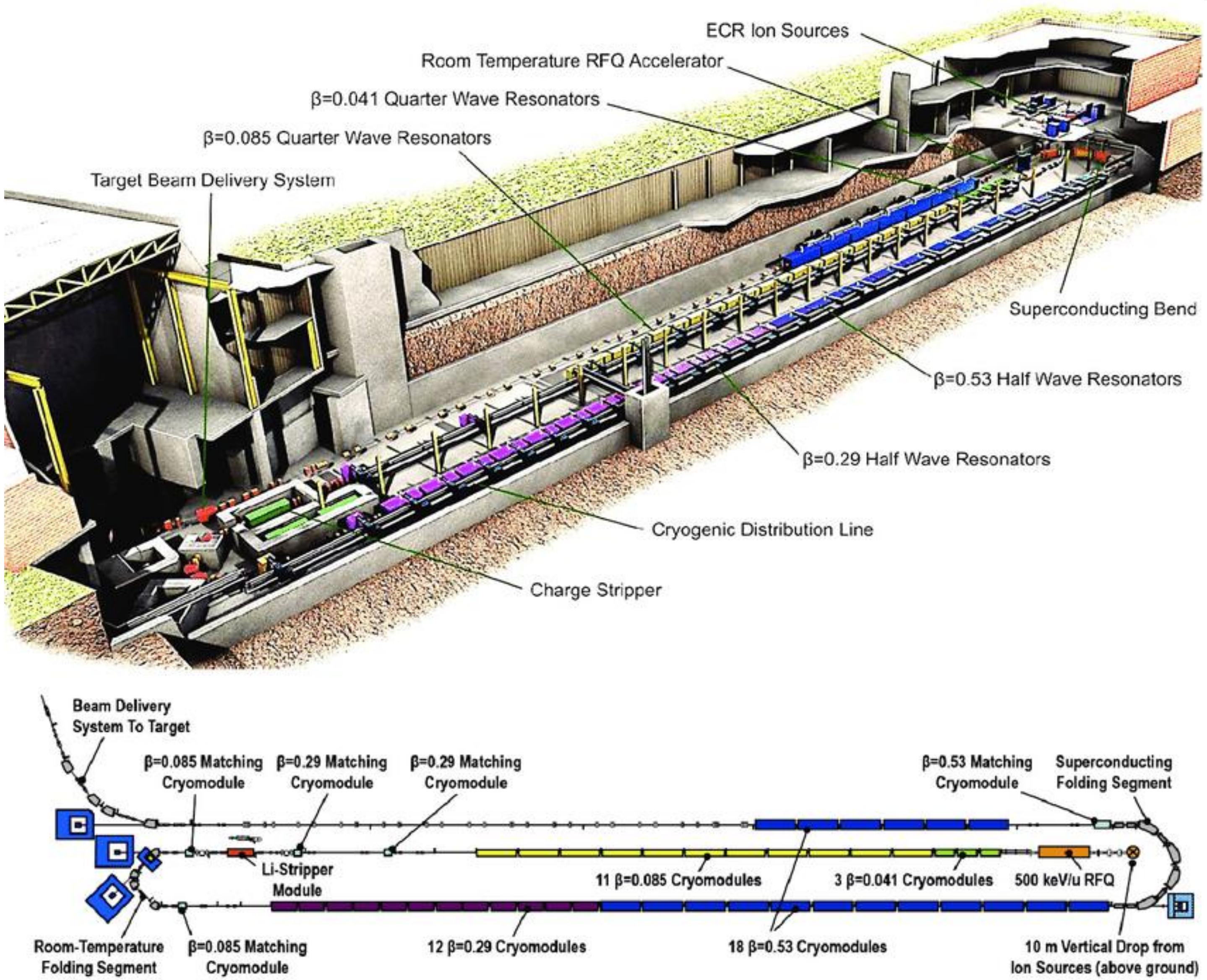
Fermilab Nb_3Sn conductor with APCs exceeding FCC J_c spec for first time



Fermilab 14.5 T Dipole

800 MHz cavity R&D with CERN & JLab

Facility for Rare Ion Beams (FRIB)



Over 200 SRF cavities operating at 322 MHz with plans to further extend the linac

Extensive use of Solid-State RF amplifiers

Developed substantial SRF infrastructure

BOLDVISIONARYREAL PEOPLESCIENCEIMPACT

Summary

Snowmass is a community-driven process:

- Provides input for US strategy development by P5 (Particle Physics Project Prioritization Panel) committee
- Important to engage in the process to ensure that all options are considered
- Visit the Snowmass wiki page (https://www.snowmass21.org/) to find out the best place to contribute

The US is engaged in a number of large accelerator projects in High Energy Physics, Nuclear Physics, and Photon & Neutron Science

- Many common problems in accelerator physics and technology development
- US program has strong accelerator technology R&D program
- Enthusiasm in US labs to develop these collaborative opportunities on FCC