[Accelerator] R&D for future colliders

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In this talk I will discuss accelerator R&D topics critical for future colliders through the prism of recent P5 report. These colliders include circular and linear $e^+e^-$ Higgs factories, and longer-term options such as muon and hadron high energy colliders. As it is impossible to cover all possible R&D topics, I will discuss only the several key topics. I will start with P5 recommendations for future colliders, followed by a brief description of those colliders. Then the talk will cover R&D topics: beam optics & MDI, muon production, ionization muon cooling, high-filed superconducting magnets, and radio frequency technology. The choice of topics reflects my preference and in some cases ignorance, which I think is inevitable when one tries to cover such a broad subject 😊.
Acknowledgments

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- S. Michizono (KEK)
- V. Shiltsev (NIU)

and many others who directly or indirectly helped me to prepare this presentation
From Snowmass to P5

**Recommendation 2c:** An off-shore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements. The US should actively engage in feasibility and design studies. […]

**Recommendation 4a:** Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years […]

Wakefield concepts for a collider are in the early stages of development. A critical next step is the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout. This will provide an important yardstick against which to measure progress with this emerging technology path.

In the following I will consider only “conventional” colliders (ILC, FCC-ee & -hh) and muon collider
Scale and timeline for HEP colliders

Possible years to start collider operation:

- ILC
- FCC-ee: 2050
- Muon Collider: 2060
- FCC-hh: 2070
FCC-ee

- Stage 1 of the Future Circular Collider (FCC): an $e^+e^-$ Higgs factory, electroweak & top factory operating at highest luminosities ($Z, W, H, t\bar{t}$)
- Limited by 50 MW of synchrotron radiation per beam
- Two 90.7 km rings and booster in the same tunnel
- CDR (2018), Feasibility Study (2021-2025)
- Start operation in ~2045

$$L \left[ \text{cm}^{-2}\text{s}^{-1} \right] = 2.45 \cdot 10^{33} \cdot \frac{P_{SR}[\text{MW}]}{E_{\text{beam}}[\text{GeV}]} \cdot \frac{\rho[m]}{\beta_y^*[\text{m}]} \cdot R_{HG}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>WW</th>
<th>H (ZH)</th>
<th>ttbar</th>
</tr>
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<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
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<td>beam current [mA]</td>
<td>1270</td>
<td>137</td>
<td>26.7</td>
<td>4.9</td>
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<tr>
<td>number bunches/beam</td>
<td>11200</td>
<td>1780</td>
<td>440</td>
<td>60</td>
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<tr>
<td>bunched intensity [$10^{11}$]</td>
<td>2.14</td>
<td>1.45</td>
<td>1.15</td>
<td>1.55</td>
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<tr>
<td>SR energy loss / turn [GeV]</td>
<td>0.0394</td>
<td>0.374</td>
<td>1.89</td>
<td>10.4</td>
</tr>
<tr>
<td>total RF voltage 400/800 MHz [GV]</td>
<td>0.120/0</td>
<td>1.0/0</td>
<td>2.1/0</td>
<td>2.19/4</td>
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<tr>
<td>long, damping time [turns]</td>
<td>1158</td>
<td>215</td>
<td>64</td>
<td>18</td>
</tr>
<tr>
<td>horizontal beta* [m]</td>
<td>0.11</td>
<td>0.2</td>
<td>0.24</td>
<td>1.0</td>
</tr>
<tr>
<td>vertical beta* [mm]</td>
<td>0.7</td>
<td>1.0</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>horizontal geometric emittance [nm]</td>
<td>0.71</td>
<td>2.17</td>
<td>0.71</td>
<td>1.59</td>
</tr>
<tr>
<td>vertical geom. emittance [pm]</td>
<td>1.9</td>
<td>2.2</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>horizontal rms IP spot size [µm]</td>
<td>9</td>
<td>21</td>
<td>13</td>
<td>40</td>
</tr>
<tr>
<td>vertical rms IP spot size [nm]</td>
<td>36</td>
<td>47</td>
<td>40</td>
<td>51</td>
</tr>
<tr>
<td>beam-beam parameter $\xi_x / \xi_y$</td>
<td>0.002/0.0973</td>
<td>0.013/0.128</td>
<td>0.010/0.088</td>
<td>0.073/0.134</td>
</tr>
<tr>
<td>rms bunch length with SR / BS [mm]</td>
<td>5.6 / 15.5</td>
<td>3.5 / 5.4</td>
<td>3.4 / 4.7</td>
<td>1.8 / 2.2</td>
</tr>
<tr>
<td>luminosity per IP [$10^{34} \text{cm}^{-2}\text{s}^{-1}$]</td>
<td>140</td>
<td>20</td>
<td>5.0</td>
<td>1.25</td>
</tr>
<tr>
<td>total integrated luminosity / IP / year [ab$^{-1}$/yr]</td>
<td>17</td>
<td>2.4</td>
<td>0.6</td>
<td>0.15</td>
</tr>
<tr>
<td>beam lifetime rad Bhabha + BS [min]</td>
<td>15</td>
<td>12</td>
<td>12</td>
<td>11</td>
</tr>
</tbody>
</table>

* Site AC power is 290 MW at CM energy 240 GeV
FCC-ee key R&D topics

- RF system R&D: SRF at 400 MHz and 800 MHz, high-efficiency klystron R&D, Nb$_3$Sn SRF – to improve overall RF system efficiency. RF & cryogenics dominate the overall AC power consumption of the machine.
- MDI and final focus magnets, alignment, wakes
- Collider and booster beam optics
- Polarization studies and hardware design
- New $e^+e^-$ injector, possibly using cold copper technology (similar to C$^3$, compact & high gradient)
- Synergy with CEPC in China
International Linear Collider (ILC) is an $e^+e^-$ machine based on superconducting RF linac technology

- Accelerating gradient 31.5 MV/m (ave.) at $Q_0 = 10^{10}$
- ~8,000 9-cell cavities in ~900 cryomodules
- “Shovel-ready” design: TDR (2013)
- Energy is upgradeable with conventional Nb SRF technology to 500 GeV and to 1 TeV (45 MV/m, $Q_0 = 2 \times 10^{10}$) or with advanced SRF (traveling wave or Nb$_3$Sn)
- The first SRF cryomodule (full ILC specifications) operation with beam was demonstrated at FAST (Fermilab) in 2018

\[
L = \frac{P_{\text{beam}}}{E_{\text{beam}}} \cdot \frac{N_e}{4\pi\sigma^x\sigma^y} \cdot H_D
\]

---

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Unit</th>
<th>Initial</th>
<th>L Upgrade</th>
<th>Z pole</th>
<th>E / L Upgrades</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre of mass energy</td>
<td>$\sqrt{s}$</td>
<td>GeV</td>
<td>250</td>
<td>250</td>
<td>91.2</td>
<td>500</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\mathcal{L}$</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>1.35</td>
<td>2.7</td>
<td>0.21/0.41</td>
<td>1.5/3.6</td>
</tr>
<tr>
<td>Polarisation for $e^+/e^-$</td>
<td>$P_{\gamma}(\gamma_\gamma)$</td>
<td>%</td>
<td>80(30)</td>
<td>80(30)</td>
<td>80(30)</td>
<td>80(30)</td>
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<tr>
<td>Repetition frequency</td>
<td>$f_{\text{rep}}$</td>
<td>Hz</td>
<td>5</td>
<td>5</td>
<td>3.7</td>
<td>5</td>
</tr>
<tr>
<td>Bunches per pulse</td>
<td>$n_{\text{bunch}}$</td>
<td>1</td>
<td>1312/2625</td>
<td>1312/2625</td>
<td>1312/2625</td>
<td>2625</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$N_e$</td>
<td>10$^{10}$</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Linac bunch interval</td>
<td>$\Delta t_b$</td>
<td>ns</td>
<td>554</td>
<td>306</td>
<td>554/366</td>
<td>554/366</td>
</tr>
<tr>
<td>Beam current in pulse</td>
<td>$I_{\text{pulse}}$</td>
<td>mA</td>
<td>5.8</td>
<td>8.8</td>
<td>5.8/8.8</td>
<td>5.8/8.8</td>
</tr>
<tr>
<td>Beam pulse duration</td>
<td>$t_{\text{pulse}}$</td>
<td>$\mu$s</td>
<td>727</td>
<td>961</td>
<td>727/961</td>
<td>727/961</td>
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<tr>
<td>Accelerating gradient</td>
<td>$G$</td>
<td>MV/m</td>
<td>31.5</td>
<td>31.5</td>
<td>31.5</td>
<td>31.5</td>
</tr>
<tr>
<td>Average beam power</td>
<td>$P_{\text{ave}}$</td>
<td>MW</td>
<td>5.3</td>
<td>10.5</td>
<td>1.42/2.84$^3$</td>
<td>10.5/21</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>$\sigma^x_b$</td>
<td>mm</td>
<td>0.3</td>
<td>0.3</td>
<td>0.41</td>
<td>0.3</td>
</tr>
<tr>
<td>Norm. hor. emitt. at IP</td>
<td>$\gamma_{\varphi}$</td>
<td>$\mu$m</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Norm. vert. emitt. at IP</td>
<td>$\gamma_{\varphi}$</td>
<td>$\mu$m</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>RMS hor. beam size at IP</td>
<td>$\sigma^x_b$</td>
<td>mm</td>
<td>516</td>
<td>516</td>
<td>1120</td>
<td>474</td>
</tr>
<tr>
<td>RMS vert. beam size at IP</td>
<td>$\sigma^y_b$</td>
<td>mm</td>
<td>7.7</td>
<td>7.7</td>
<td>14.6</td>
<td>5.9</td>
</tr>
<tr>
<td>Luminosity in top 1%</td>
<td>$\mathcal{L}_{0.01}/\mathcal{L}$</td>
<td>%</td>
<td>73%</td>
<td>73%</td>
<td>99%</td>
<td>58.3%</td>
</tr>
<tr>
<td>Beamstrahlung energy loss</td>
<td>$\delta_{\text{b}}$</td>
<td>%</td>
<td>2.6%</td>
<td>2.6%</td>
<td>0.16%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Site AC power</td>
<td>$P_{\text{site}}$</td>
<td>MW</td>
<td>111</td>
<td>138</td>
<td>94/115</td>
<td>173/215</td>
</tr>
<tr>
<td>Site length</td>
<td>$L_{\text{site}}$</td>
<td>km</td>
<td>20.5</td>
<td>20.5</td>
<td>20.5</td>
<td>31</td>
</tr>
</tbody>
</table>

*AC plug-power may be further reduced (10 – 20%), if the RF (Klystron) and SRF/Cryogenics (Q-value) Efficiency may be improved.
ILC key R&D topics

While the ILC is at TDR ("shovel-ready") since 2013, some R&D is still ongoing to demonstrate beam parameters (nano-beams in ATF2 at KEK), further improve performance and demonstrate industrialization of the SRF linac, develop alternative concepts (e-linac-based positron source)

- SRF technology
- Nano-beam technology (damping ring and final focus)
- Positron source
FCC-hh

- Stage 2 of the Future Circular Collider: ~100 TeV, a natural continuation at energy frontier with $pp$ collisions and $ee$ option
- With FCC-hh after FCC-ee there will be significantly more time for high-field magnet R&D aiming at highest possible energies
- Start operation in ~2070

<table>
<thead>
<tr>
<th>parameter</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>collision energy cms [TeV]</td>
<td>81 - 115</td>
</tr>
<tr>
<td>dipole field [T]</td>
<td>14 - 20</td>
</tr>
<tr>
<td>circumference [km]</td>
<td>90.7</td>
</tr>
<tr>
<td>arc length [km]</td>
<td>76.9</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.5</td>
</tr>
<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>1</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
</tr>
<tr>
<td>synchr. rad. power / ring [kW]</td>
<td>1020 - 4250</td>
</tr>
<tr>
<td>SR power / length [W/m/ap.]</td>
<td>13 - 54</td>
</tr>
<tr>
<td>long. emit. damping time [h]</td>
<td>0.77 – 0.26</td>
</tr>
<tr>
<td>peak luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>~30</td>
</tr>
<tr>
<td>events/bunch crossing</td>
<td>~1000</td>
</tr>
<tr>
<td>stored energy/beam [GJ]</td>
<td>6.1 - 8.9</td>
</tr>
<tr>
<td>Integrated luminosity/main IP [fb$^{-1}$]</td>
<td>20000</td>
</tr>
</tbody>
</table>

* Estimated operating AC power is ~560 MW
FCC-hh key challenges and R&D topics

- High-field superconducting magnets: 14 - 20 T. The magnet technology will determine the energy reach of the machine.
- Power load on cold vacuum chamber in arcs from synchrotron radiation: 4 MW (~10^3 time higher than LHC) → cryogenics, vacuum.
- Stored beam energy: ~ 9 GJ (~10 times of HL-LHC) → machine protection.
- Pile-up in the detectors: ~1000 events/xing.
- R&D to reduce energy consumption (4 TWh/year) → cryogenics, HTS, beam current, ...
- Synergy with SppC in China.

Transfer lines proposed to be installed inside FCC-hh ring tunnel.
Muon collider

- Muon collider combines precision and energy reach needed to test the deepest questions of particle physics
- Smaller footprint than proton-proton-collider for the same pCM energy
- Muons are 207 times heavier than electrons and are not limited by synchrotron radiation
- BUT muons decay (2.2 µs lifetime at rest), hence must be accelerated rapidly
- 5-7 years of R&D to prepare a concept of demonstration facility

![Schematic layout of a 10-TeV muon collider complex](image)

**Tentative parameters based on U.S. Muon Accelerator Program (MAP) studies**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Higgs Factory</th>
<th>3 TeV</th>
<th>10 TeV</th>
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</thead>
<tbody>
<tr>
<td>COM Beam Energy</td>
<td>TeV</td>
<td>0.126</td>
<td>3</td>
<td>10</td>
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<tr>
<td>Collider Ring Circumference</td>
<td>km</td>
<td>0.3</td>
<td>4.5</td>
<td>10</td>
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<tr>
<td>Interaction Regions</td>
<td>ab⁻¹/year</td>
<td>0.002</td>
<td>0.4</td>
<td>4</td>
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<tr>
<td>Est. Integ. Luminosity</td>
<td>10³⁴ cm⁻² s⁻¹</td>
<td>0.01</td>
<td>1.8</td>
<td>20</td>
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<tr>
<td>Peak Luminosity</td>
<td>Hz</td>
<td>15</td>
<td>5</td>
<td>5</td>
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<tr>
<td>Repetition rate</td>
<td>µs</td>
<td>1</td>
<td>15</td>
<td>33</td>
</tr>
<tr>
<td>Time between collisions</td>
<td>µs</td>
<td>1</td>
<td>15</td>
<td>33</td>
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<tr>
<td>Bunch length, rms</td>
<td>mm</td>
<td>63</td>
<td>5</td>
<td>1.5</td>
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<tr>
<td>IP beam size σₓ, rms</td>
<td>µm</td>
<td>75</td>
<td>3</td>
<td>0.9</td>
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<tr>
<td>Emittance (trans), rms</td>
<td>mm-mrad</td>
<td>200</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>β function at IP</td>
<td>cm</td>
<td>1.7</td>
<td>0.5</td>
<td>0.15</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>MHz</td>
<td>325/1300</td>
<td>325/1300</td>
<td>325/1300</td>
</tr>
<tr>
<td>Bunches per beam</td>
<td>1</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Plug power</td>
<td>MW</td>
<td>~200</td>
<td>~230</td>
<td>~300</td>
</tr>
<tr>
<td>Muons per bunch</td>
<td>10¹²</td>
<td>4</td>
<td>2.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Average field in ring</td>
<td>T</td>
<td>4.4</td>
<td>7</td>
<td>10.5</td>
</tr>
</tbody>
</table>

![Higgs Factory](image)

\[ L = \frac{N_{+}N_{-}n_{eff}f_{rep}}{4\pi\sigma_x^*\sigma_y^*} \]

- The muon collider concept was developed by U.S. Muon Accelerator Program (2011-2016)
- In 2022 International Muon Collider Collaboration (IMCC) was formed, hosted by CERN
Muon collider key challenges and R&D topics

Challenges at each step of the muon collider chain of accelerators

- Proton driver: 1-4 MW beam power at 5-20 GeV; accumulate bunches with up to $10^{14}$ particle, compress to ns duration; deliver at 5-10 Hz rate
- Target must withstand beam power, will be immersed in a ~15 T SC solenoid with ~2 m aperture; muons to be captured for cooling
- Ionization cooling
- Muon acceleration: need to accelerate muon as fast as possible to reduce the loss of muons due to decay
- Collider ring: challenging MDI to suppress breakdown originating from muon decays
- Large variety of challenging magnets
- NC RF in high magnetic field
- SRF for fast acceleration
R&D synergies for future HEP colliders

- RF power efficiency
- SRF system

Examples of synergies with U.S. projects and accelerators:
- EIC (a NP machine in the DOE lingo): MDI, SRF, beam polarization, collective effects...
- PIP-II: SRF, proton driver
- LCLS-II: SRF
- LBNF: targetry
- SNS: proton driver

FCC-ee and –hh have many synergies with similar projects in China: CEPC and SppC

- Beam optics
- Collective effects
- MDI
- Machine efficiency
- High-field SC magnets

10 TeV Muon Collider

Off-shore Higgs Factory

~100 TeV Hadron Collider
Consider FCC-ee as an example

- The baseline beam optics of FCC-ee was established several years ago, then was adjusted to the new circumference and further improved recently.
- At the same time, significant work on an alternative lattice resulted in the LCCO (Local Chromatic Correction Optics, P. Raimondi) with:
  - Larger dynamic aperture with fewer magnets
  - Significant reduction of quadrupole and sextupole magnets’ length and strength
  - Simplified powering scheme
  - Lower energy loss due to SR (12%)
  - Reduced power consumption
  - Increased momentum acceptance
  - Relaxed tolerances
  - Work in progress
Beam optics, collective effects, machine design: FCC-ee IR

- Interaction region (IR), where accelerator and detector are connected (machine-detector interface, MDI), is a very complicated region in any collider.

- In FCC-ee the same IR will serve all energies, must have a flexible design with a detector field of 2 T. Very high luminosity of \( \sim 10^{36} \text{ cm}^{-2} \text{s}^{-1} \) at Z pole requires crab-waist scheme, nano-beams, and large crossing angle of 100 mrad. At \( t\bar{t} \) the IR must deal with synchrotron radiation (SR): critical energy below 100 keV constrains final focus optics, requires asymmetric bending.

- Two anti-solenoid inside the detector are needed to compensate the detector field.

- Special considerations (low material budget for central vacuum chamber alignment and stabilization) to accommodate luminosity monitor at Z to achieve \( 10^{-4} \) with low-angle Bhabhas.

- Beam pipe optimization to minimize beam impedance, SR masks, design BPMs, HOM absorbing bellows, cooling scheme, …
High power proton driver and target for muon collider

- MAP baseline design (based on simulations) calls for \( \sim 10^{14} \) protons/bunch with 1-3 ns bunch length
- MW-class target, an interface between the proton driver and front-end channel, must produce copious amounts of muons and be tolerant to MW beams
- Front end captures pions/muons
- \( \mu/p \) efficiency is 10-15% for each sign
- Thermal shock is a key parameter for survivability of high-power target
- Graphite, liq. lead and tungsten powder are currently considered, studies look promising
- Need: simulations, irradiation materials studies, pion yield measurements

<table>
<thead>
<tr>
<th>Proton beam energy</th>
<th>Neutron spallation source (ESS, SNS, CSNS)</th>
<th>Accelerator neutrino beam (T2K, CNGS, NuMI, SBN, LBNF)</th>
<th>Muon collider (MAP, IMCC design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (1-3 GeV)</td>
<td>Wide range (8-400 GeV)</td>
<td>Medium (5-20 GeV)</td>
<td>Extremely short (1-3 ns)</td>
</tr>
<tr>
<td>Short (105-700 ns)</td>
<td>Long (4.2-10.5 ( \mu s ))</td>
<td></td>
<td>High (( 10^{14} - 10^{15} ))</td>
</tr>
<tr>
<td>Medium (10^{13} – 1.5 \times 10^{14})</td>
<td>Medium (4.8 \times 10^{13} – 3.2 \times 10^{14})</td>
<td>Medium (5-15 Hz)</td>
<td>TBD</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>High (14-60 Hz)</td>
<td>Low (0.4-2 Hz)</td>
<td></td>
</tr>
<tr>
<td>Target material</td>
<td>Liq. Hg, W, Liq. Li, etc.</td>
<td>graphite</td>
<td></td>
</tr>
</tbody>
</table>
Ionization cooling

- Ionization cooling channel consists of 1,000+ muon cooling cells
- The cooling of muons requires very compact assembly of normal conducting RF cavities, superconducting solenoids, and either liquid hydrogen or LiH absorbers
- Large bore solenoids: from 2 T (1 m aperture) to 20+ T (0.05 m aperture)
- RF cavities (300-800 MHz) must operate in multi-tesla fields
- Absorbers (wedge-shaped) must tolerate large muon beam intensities
- Need to develop an end-to-end design with realistic cooling lattice that meets muon collider luminosity requirements
- Conceptual design of a demo facility

Schematic of the muon cooling demonstrator

https://doi.org/10.1140/epjc/s10052-023-11889-x
Magnet technology R&D

FCC-hh and muon collider require beyond state-of-the-art magnet technology

- High field dipoles – up to 17 T (and perhaps 20 – 24 T)
- Large aperture with fields up to 13 T (or more)
- (Very) fast ramping magnets
- Large aperture, high field solenoids (> 30 T)
- Large aperture interaction region quadrupoles

Conductor ultimately determines magnet performance

- High radiation environment
  - Radiation Damage
  - Heat deposition
- Manage stress

Conductor ultimately determines magnet performance

- Six different technological superconductors
  - Low Temperature Superconductors (LTS)
    - NbTi, Nb$_3$Sn, MgB$_2$
  - High Temperature Superconductors (HTS), also high field
    - Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Bi-2212 or BSCCO), Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ (Bi-2223), rare-earth Ba$_2$Cu$_3$O$_7$ (ReBCO)
  - Plus, a new family of iron-based superconductors (IBS), not yet commercially available
Potential conductor choices

**Nb$_3$Sn** has been around for many years
- After ~ half a century(almost) used for accelerator magnet – HiLumi LHC
- Max practical field ~ 14-15 T at 4.2 / 1.8 K
- Still possible improvements – $J_c$, high $C_p$
  - Work on increasing heat capacity of strands
  - Artificial Pinning Centers (X. Xu et al, MDP/FNAL)
- Demonstrate technology for large-scale accelerator deployment
  - Substantial CERN program to develop industrial capacity

**Bi-2212** has clear niche applications
- Several desirable properties: the only HTS available in the form of multifilamentary round wires, can be used to make Rutherford cable → high field quality
- High $J_c$ only at low temperature, no good for 20 K operation
- Expensive (75% silver) and cost reduction path not so clear
- Powder supply chain? – only 2 manufacturers worldwide

**ReBCO**
- Fusion can drive capacity and has substantially lowered cost of some architectures.
- Excellent $J_c(B)$ performance at elevated temperatures
- Available as flexible tape – not good for field quality?
- Prohibitively expensive, but can the cost be driven down?
- R&D to improve performance – and make into a magnet conductor

**Fe-based** could be game-changer
- Active R&D in China
- Worth pursuing in the U.S.?
- Potentially lower cost but performance not there yet
Magnet technology R&D for muon collider

**Capture Solenoid for Simultaneous mu+ & mu- Beams**
- Characteristics:
  - High field (15-20T)
  - Large bore (meter-scale)
  - Intense radiation environment – NC or HTS insert coil

**Muon Ionization 6-Dimensional Cooling Channel**
- Characteristics:
  - Solenoid-based cooling channel (LH₂/LiH absorbers)
  - RF cavities integral to focusing channel
  - Fields ranging from LTS to HTS conductor regime

**Muon Ionization Final Cooling Channel**
- Characteristics:
  - Emittance exchange channel for TeV-scale colliders – trade increased longitudinal beam emittance for smaller transverse emittance
  - Goal: 40-60 T HTS solenoids with d ~ 50mm

**Acceleration to the TeV Energy Scale for Muon Colliders**
- Characteristics:
  - Present baseline based on the use of Rapid Cycling Synchrotrons
  - Requires magnets capable of ~400Hz operation with B>1.5T
  - Novel magnets, suitable modeling, efficient power system

**Muon Collider Magnet Needs**
- Characteristics:
  - Decaying muon beams mean that luminosity is inversely proportional to circumference
  - 10T dipole ↔ 15-20T dipoles improves luminosity
  - Radiation environment
  - Challenging IR magnets

**HTS Magnet Development**
- Characteristics:
  - AMC (w/decaying beams) obtains the greatest performance enhancement of any HEP collider from HTS magnet technology
  - High quality HTS cables and magnets must be a priority
Radio frequency technology R&D thrusts

Three RF technology R&D thrusts

- Superconducting RF (SRF) technology will be used in all colliders that we discuss in this presentation. FCC-ee, ILC, and muon collider will have very large installations. Improving SRF cavity performance is critical.
- High-gradient normal conducting RF operating in high magnetic fields (Muon collider) as part of the ionization cooling
- High-efficiency RF sources (FCC-ee, ILC) to reduce overall AC power consumption of the machine
Improving the performance of bulk niobium cavities is achieved via surface treatment (only ~100 nm thick surface layer determines the performance)

- Higher quality factor cavities to reduce cryogenic load (all). Goals for FCC-ee: $Q_0 = 3 \times 10^{10}$ at $E_{\text{acc}} = 25$ MV/m for Booster initially, then $Q_0 = 6 \times 10^{10}$ at $E_{\text{acc}} = 25$ MV/m for Booster and collider for $t\bar{t}$ operation. Goal for ILC: improve $Q_0$ to $> 2 \times 10^{10}$ at $E_{\text{acc}} = 31.5$ MV/m for cost reduction and energy upgrade.

- Improve accelerating gradient (ILC, Muon collider) via surface treatment and novel cavity geometries (traveling wave SRF for ILC energy upgrade)

- Nb/Cu R&D for 400 MHz FCC-ee SRF
- Develop designs with well-suppress higher order modes for high intensity operation (FCC-ee, Muon collider)
- Develop alternative SRF superconductors – e.g., Nb$_3$Sn – for operations at higher temperatures and accelerating gradients (FCC-ee, ILC energy upgrade, Muon collider)
- Understand operation of SRF cavities in the vicinity of strong magnetic fields during muon acceleration and develop mitigation measures (Muon collider). Goals: $E_{\text{acc}} = 20$ MV/m at 325 MHz, 25 MV/m at 650 MHz, 38 MV/m at 1300 MHz
- Synergies with EIC, PIP-II, LCLS-II, CEPC, ...

### SRF R&D Goals

- **FCC-ee:**
  - $Q_0 = 3 \times 10^{10}$ at $E_{\text{acc}} = 25$ MV/m for Booster initially, then $Q_0 = 6 \times 10^{10}$ at $E_{\text{acc}} = 25$ MV/m for Booster and collider for $t\bar{t}$ operation. Goal for ILC: improve $Q_0$ to $> 2 \times 10^{10}$ at $E_{\text{acc}} = 31.5$ MV/m for cost reduction and energy upgrade.

### Single-cell HB650 (PIP-II shape) 650 MHz cavity after modified EP recipe and low-temperature bake

- **EP+120C _2K**
- **EP+120C_Low T**
- **EP _2K**
- **EP_Low T**

**Preliminary**

**9-cell 1300 MHz SRF cavities after 2-step low-temperature bake**

- **TB9AES011 June 2020**
- **TB9AC011 June 2020**
- **TB9AES003 Apr 2021**
- **TB9AC013 July 2021**
- **TB9AC006 Sep 2021**
- **TB9AES018 Oct 2021**
- **TB9R021 Dec 2021**
NCRF cavities in high magnetic fields

- Muon ionization cooling channel required 300-800 MHz RF cavities to operate in high magnetic fields from 2 to 20+ T
- A variety of parameters along the cooling channel: accelerating gradient, frequency, magnetic field, beam window thickness, etc.
- High-power, short-pulse RF power sources
- Considerable cavity R&Ds have been carried out in MAP and pre-MAP era to understand the RF breakdown in strong $B$ field and how to mitigate it
- For the field gradient demonstration: an 805 MHz MAP vacuum modular cavity and an 805 MHz high pressure hydrogen-filled cavity have achieved $\sim 50$ MV/m in a 3 T $B$ field
- The MICE 201 MHz cavity is a fully operational single cell cavity that has achieved the design gradient ($\sim 11$ MV/m) in a $\sim 0.2$ T $B$ field
- Much more needs to be learned about RF break down. Both simulations and experimental studies in a dedicated test facility are needed to explore different materials (e.g., aluminum, CuAg and other copper alloys, Be-coated copper,…) and magnetic field configurations.
- Cold copper technology might be a good choice, synergy with C$^3$ R&D
High-efficiency RF sources

- High-efficiency klystrons are needed to reduce overall AC power consumption of the machine
- CERN-led HEIKA collaboration is targeting to improve efficiency and performance of klystrons for various applications
- Example: the klystron efficiency upgrade from existing 65% to 80% would potentially save ~1 TWh in 10 years of FCC-ee operation
- Several options of klystron design improvements are explored, some in collaboration with industry
- An off-the-shelf Canon klystron was retrofitted and tested, showing significant improvement
Summary

- P5 recommended to actively engage in feasibility and design studies of two off-shore Higgs factories, ILC and FCC-ee
- Also, P5 recommended to support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies
- The collider designs are at different stages of maturity, but all require quite extensive R&D efforts covering a wide range of challenging topics from beam optics to MDI to beam polarization to positron production to muons ionization cooling high-field SC magnet and RF technologies…
- Any future collider will require very high AC power to operate, special attention should be given to R&D topics that would improve efficiency of various systems
- There are synergies between the colliders and with other projects and accelerators
- In this presentation I gave you just a snapshot of some R&D topics for future collider
- A lot of fun to be had when we begin R&D in earnest!
- BUT

We need funding, Uncle Sam!
Thank you!