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# Higgs-Energy LEptoN (HELEN) collider

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# Motivation

- ILC remains the most mature option (TDR level) for a Higgs factory. However, efforts to launch the project in Japan haven't yet been successful.
- Snowmass was a great opportunity for the HEP community to consider options for major collider facilities that can potentially be hosted in the United States.
- One of the several options proposed in the Snowmass White Paper is a linear collider based on high gradient SRF (in the range of 55 MV/m to 90 MV/m; standing wave or travelling wave structures).

**Future Collider Options for the US**

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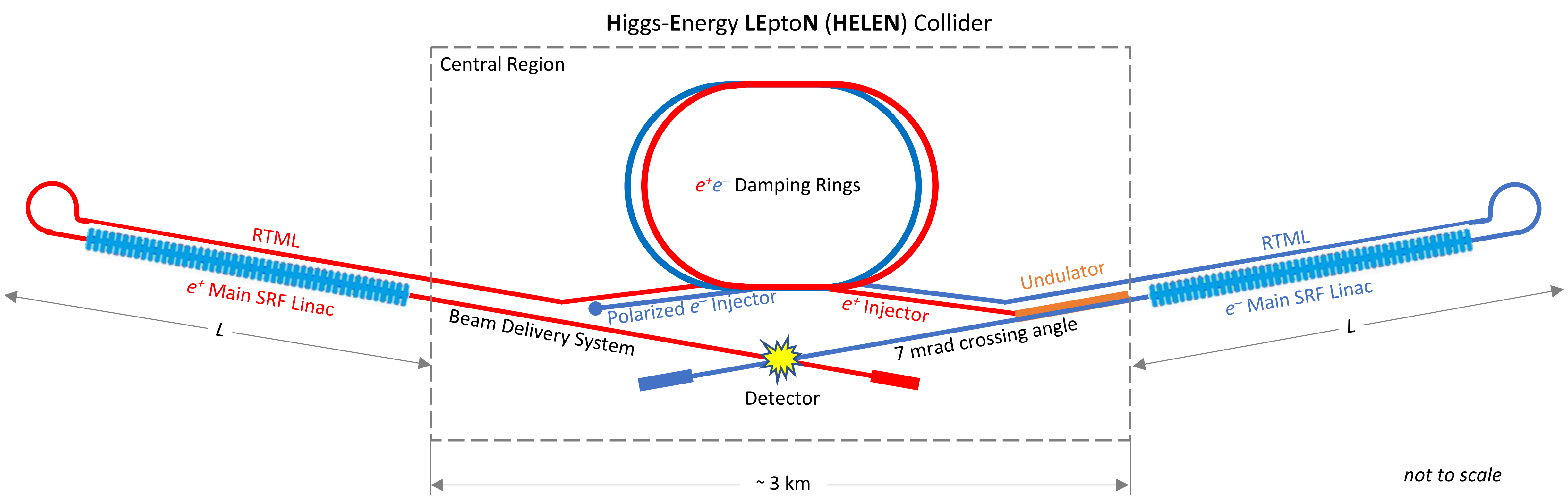
# Introduction: advances in SRF technology

- There continues to be steady progress in developing the SRF technology with accelerating gradients demonstrated up to 50 MV/m while the ILC design requires 31.5 MV/m.
- With an aggressive R&D program on **traveling wave SRF structures** and innovations in cavity surface treatments and processing, an accelerating gradient of about **70 MV/m** can possibly be reached within the next 2–3 years.
- Further, longer term, research on developing new SRF materials, specifically $Nb_3Sn$, could enable ultimate gradients of 90 MV/m and higher.

# HELEN collider

- Anticipating these advances, we proposed a **250 GeV $e^+e^-$ SRF linear collider (Higgs-Energy LEptoN collider, or HELEN collider)** that can be sited at Fermilab.
- With the use of existing infrastructure and facilities at Fermilab and much higher gradients, there could be significant cost reduction for the main linac relative to the ILC main linac cost.



# Baseline Design/Layout and Parameters

- While we considered 3 different advanced SRF technologies, a **traveling wave (TW) SRF operating at 70 MV/m is selected as the baseline option**.
- Most of the HELEN parameters (except for SRF) are identical to those of the ILC.

**Higgs-Energy LEptoN (HELEN) Collider based on advanced superconducting radio frequency technology**

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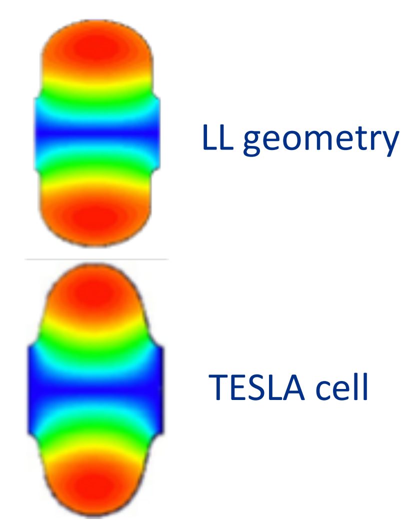
| Parameter | HELEN | ILC |
|---|---|---|
| CM energy $2\times E_b$ (GeV) | 250 | 250, 500 |
| Length (km) | 7.5 | 20.5, 31 |
| Interaction points | 1 | 1 |
| Integrated luminosity (ab$^{-1}$/yr) | 0.2 | 0.2, 0.3 |
| Peak lumi. $\mathcal{L}$ ($10^{34}$cm$^{-2}$s$^{-1}$) | 1.35 | 1.35, 1.8 |
| CM energy spread $\sim 0.4\delta_{BS}$ (rms, %) | 1 | 1, 1.7 |
| Polarization (%) | 80/30 ($e^-/e^+$) | 80/30 ($e^-/e^+$) |
| Rep.rate $f_{rep}$ (Hz) | 5 | 5 |
| Bunch spacing (ns) | 554 | 554 |
| Particles per bunch $N$ ($10^{10}$) | 2 | 2 |
| Bunches per pulse $n_b$ | 1312 | 1312 |
| Pulse duration ($\mu$s) | 727 | 727 |
| Pulsed beam current $I_b$ (mA) | 5.8 | 5.8 |
| Bunch length $\sigma_z$ (rms, mm) | 0.3 | 0.3 |
| IP beam size $\sigma^*$ (rms, $\mu$m) | H: 0.52<br>V: 0.0077 | H: 0.52, 0.47<br>V: 0.0077, 0.0059 |
| Emittance, $\varepsilon_n$ (rms, $\mu$m) | H: 5<br>V: 0.035 | H: 5, 10<br>V: 0.035, 0.035 |
| $\beta^*$ at interaction point (mm) | H: 13<br>V: 0.41 | H: 13, 11<br>V: 0.41, 0.48 |
| Full crossing angle $\theta_c$ (mrad) | 14 | 14 |
| Crossing scheme | crab crossing | crab crossing |
| Disruption parameter $D_y$ | 35 | 35, 25 |
| RF frequency $f_{RF}$ (MHz) | 1300 | 1300 |
| Accelerating gradient $E_{acc}$ (MV/m) | 70 | 31.5 |
| Effective gradient $E_{eff}$ (MV/m) | 55.6 | 21 |
| Total beam power (MW) | 5.3 | 5.3, 10.5 |
| Site power (MW) | 110 | 111, 173 |
| Key technology | TW SRF | SW SRF |

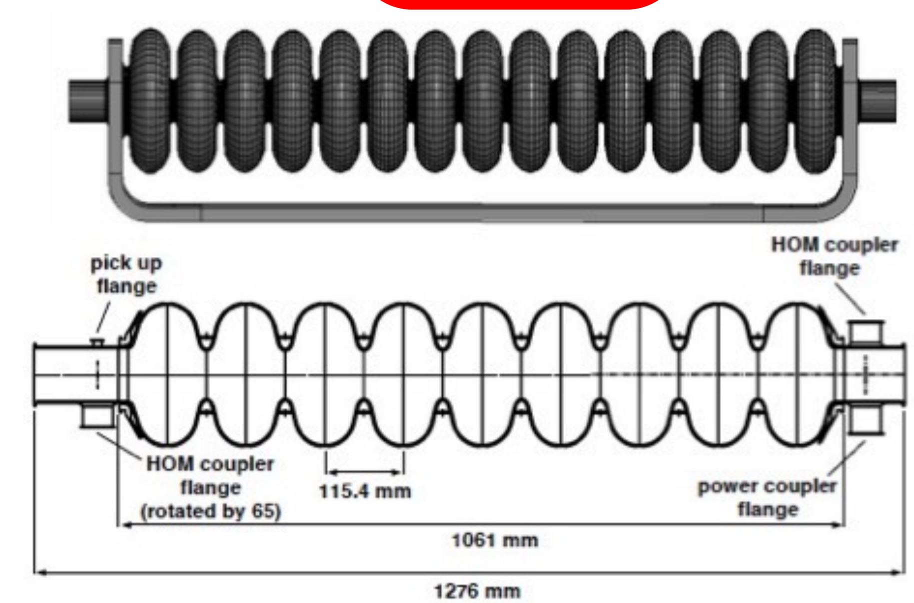
# Key technology: SRF

- **Advanced geometry standing wave (SW) structure operating at 55 MV/m**. Combing and advanced cavity shape and new treatment recipes should allow reaching accelerating gradients of ~60 MV/m. This version is essentially the ILC with different SRF cavities operating at higher gradient. Assuming the LSF accelerating structure operating at 55 MV/m, the HELEN collider would be 9.4-km long.
- *(Baseline)* **TW structure operating at 70 MV/m**. With accelerating structures about 2 times longer than the ILC (TESLA) cavities, the fill factor increases to 80.4% and the collider will be 7.5-km long.
- **$Nb_3Sn$ structure operating at 90 MV/m**. For this option, we assume the LSF-shape cavities operating at 90 MV/m at ~4.5 K. This shortens the collider length to 6.9 km.

| Parameter | Advanced SW | Traveling wave | $Nb_3Sn$ |
|---|---|---|---|
| Accelerating gradient (MV/m) | 55 | 70 | 90 |
| Fill factor | 0.711 | 0.804 | 0.711 |
| Real estate (effective) gradient (MV/m) | 39.1 | 55.6 | 64.0 |
| Cavity $Q$ ($10^{10}$) | 1.0 (2 K) | 0.69 (2 K) | 1.0 (4.5 K) |
| Active cavity length (m) | 1.038 | 2.37 | 1.038 |
| Cavity $R/Q$ (Ohm) | 1158 | 4890 | 1158 |
| Geometry factor $G$ (Ohm) | 279 | 186 | 279 |
| $B_{pk}/E_{acc}$ mT/(MV/m) | 3.71 | 2.89 | 3.71 |
| $E_{pk}/E_{acc}$ | 1.98 | 1.73 | 1.98 |
| Number of cavities | 4380 | 1527 | 2677 |
| Number of cryomodules | 505 | 382 | 309 |
| Collider length (km) | 9.4 | 7.5 | 6.9 |
| AC power for main linacs (MW) | 49 | 39 | 58 |
| Total collider AC power (MW) | 121 | 110 | 129 |



Comparison of SW SRF cavity shapes



The TW structure with a 105° phase advance per cell compared to the one-meter standing-wave TESLA structure

# Potential siting at Fermilab

- We have identified locations for a possible future linear collider at Fermilab: two 7-km diagonal options and a 12-km footprint with N-S orientation extending outside the site boundary but with the Interaction Region (IR) on site.
- A 250-GeV HELEN Higgs factory (HELEN-250) could potentially fit along either of two diagonals after further optimization of the collider.
- The 12-km N-S footprint can accommodate not only the 7.5-km-long (including 3 km of beam delivery system) HELEN-250 but would also allow extension of the main linacs to the center-of-mass energy of 500 GeV (HELEN-500).

# Collider baseline selection

The **TW option was selected as the baseline** for the following reasons:

- It is **the most efficient** in terms of AC power consumption and is on par with the ILC site power demand.
- It offers **the best cost saving**. Our preliminary estimate indicates that the cost savings (relative to the ILC main linac cost) are 13%, 26%, and 18% for the three technologies, respectively.

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*) $R/Q$ for TW is given for a 2.37-meter-long structure

- The traveling wave technology **can be demonstrated on a relatively short time scale**. With an aggressive R&D program and innovations in cavity surface treatments and processing, the required accelerating gradient can possibly be reached within the next 2–3 years. After that, another 2–3 years would be needed to build and test a demonstration cryomodule, possibly with beam at the Fermilab's FAST facility.

# Electrical power budget for the HELEN baseline

| System | AC power [MW] |
|---|---|
| $e^-$ source | 4.9 |
| $e^+$ source | 9.3 |
| DR's | 14.2 |
| RTML | 10.4 |
| ML cryogenics | 14.1 |
| ML RF | 24.8 |
| ML CF & utilities | 10.5 |
| BDS | 9.3 |
| Beam dumps | 1.2 |
| **Accelerator total** | **98.7** |
| IR/MDI | 5.8 |
| Main Campus | 2.7 |
| General margin | 3.3 |
| **Facility total** | **110.5** |

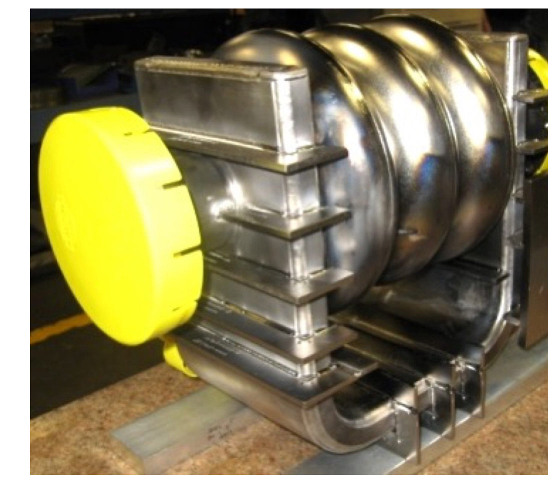
- The electrical power budget is based on the ILC model.
- All numbers should be identical to ILC except for the Main Linac cryogenics and RF, where HELEN would need about 2 MW less power for cryogenics and ~1 MW more for RF.

DR = Damping Ring; RTML = Ring To Main Linac; ML = Main Linac;
CF = Conventional Facilities; BDS = Beam Delivery System;
IR = Interaction Region; MDI = Machine-Detector Interface

# State of Proposal and R&D needs (5-10 years)

The major objectives of the accelerator R&D program should be on **advancing the TW SRF technology** toward demonstrating its feasibility and culminate in producing TDR

- Demonstrate the **feasibility of the TW SRF technology**:
  - test proof-of-principle 1.3 GHz TW cavity (several cells) and **demonstrate accelerating gradient of ~70 MV/m**
  - adapt an advanced cavity treatment techniques, so that high $\boldsymbol{Q} \sim \mathbf{10^{10}}$ can be achieved at high gradients
  - **design, build and test full-scale prototype cavities**; demonstrate performance needed for the HELEN collider
  - **design and build a prototype cryomodule** for TW SRF cavities
  - **verify the cryomodule performance** without beam on a test stand and with beam at Fermilab's FAST facility
- Design and optimize the HELEN linear collider accelerator complex
- Confirm the physics reach and detector performance for the HELEN beam parameters
- Publish **Conceptual Design Report** as modification of the ILC design **in 2–3 years**
- Prepare TDR after demonstrating the cryomodule performance, in ~ 5 years



Fabricated 3-cell TW cavity

# Summary

- If the ILC project in Japan will not gain traction, the expertise accumulated by the world's ILC community – in particular in the U.S. laboratories and universities (Cornell, Fermilab, JLAB, SLAC, ...) – would allow rapid developing, prototyping, and testing of new SRF cavities and cryomodules.
- Fermilab has capabilities that support the full cycle of R&D, production, and verification (including testing cryomodules with beam) at the SRF accelerator test facilities and FAST linac.
- If given high priority, the construction of the HELEN collider could start as early as 2031–2032 with first physics in ~ 2040.
- The HELEN collider can be upgraded to higher luminosities in the same way as was proposed for the ILC or to higher energies either by extending the linacs or with higher accelerating gradients as they become available.