Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Update on the US decadal roadmap on SRF technology for HEP accelerators

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Outline

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- SRF and the next generation of HEP accelerators
- GARD SRF thrusts
- SRF facilities
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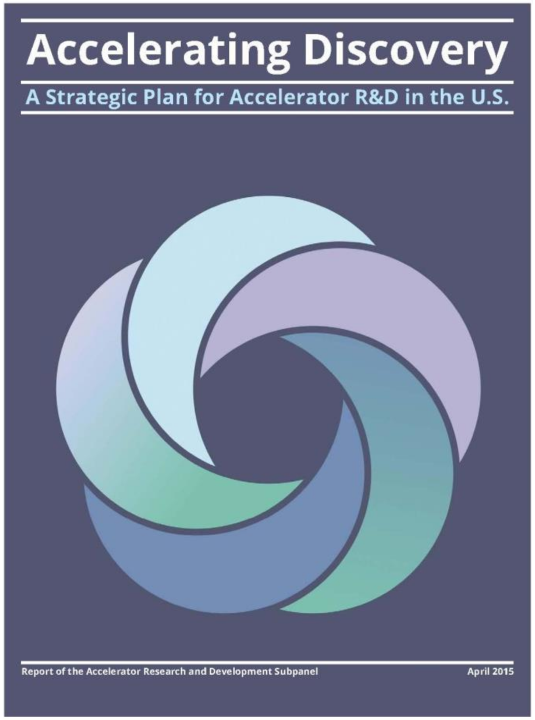
Introduction

- General Accelerator R&D Program (GARD) is a program within U.S. DOE Office of High Energy Physics, which is providing funding for cutting-edge medium- and long-term R&D in the physics and technology of particle accelerators and beams primarily aimed at supporting the High Energy Physics mission. However, very often the long-term generic work will also benefit other applications.



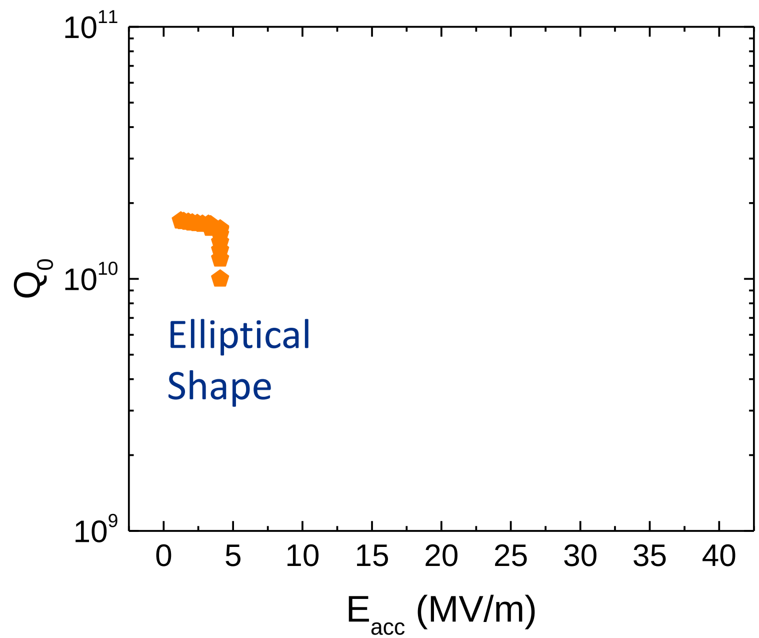
- Medium term accelerator R&D is defined as work performed in the support of possible new facilities or of upgrades to existing ones. A distinguishing characteristic of medium term R&D is that it applies to facilities that possess a reasonable conceptual idea for implementation.
- Long-term accelerator R&D refers to the development of ideas and underlying technologies that could support facilities for which we do not currently have an integrated implementing concept.
- Following the release of the HEPAP Accelerator R&D Subpanel report: “Accelerating Discovery—A Strategic Plan for Accelerator R&D in the U.S.” in April 2015, GARD has engaged its research community to address the Subpanel recommendations to develop research roadmaps for different areas.
- One of these roadmaps is being developed on RF Technology, which covers Superconducting RF, Normal Conducting RF, and RF Sources. The RF Technology roadmap is nearly complete and will be published soon. In this talk I will cover the SRF portion only.

SRF and the next generation of HEP accelerators

- Superconducting Radio Frequency is a cornerstone technology for many future particle accelerators including those for High Energy Physics experiments.
- One of the primary virtues of the SRF technology is that it is **now technically ready** to be used to build CW-capable accelerators of any energy, including multi-TeV.
- The practical limits to the SRF accelerator performance are set only by the ***budgetary constraints***. This technological maturity means that advances in achievable gradients and cavity quality factors (*Q's*) ***directly and immediately*** translate into advances in energy reach and/or intensity.
- Building the next generation of HEP accelerators would require efforts on a much larger scale than previously achieved. While the current state of the art technology can be used for these machines, advancing the technology beyond the state of the art is necessary to make the new facilities “affordable”, to improve their performance, and to allow for upgrades.
- ***SRF technology is now at the beginning of a new phase***. Recent developments and new ideas hold promise for potentially a **factor of 3 or more improvements** in achievable gradients and efficiency.
- An improvement factor of > 3 in gradients, with $Q > 3 \cdot 10^{10}$, could directly: increase the energy reach of a machine, making the physics reach much stronger; or make the same machine substantially cheaper (affordable).

SRF Performance Evolution

Courtesy A. Grassellino



1.3 GHz, 2 K

3 – 4 MV/m
Multipacting

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SRF Performance Evolution

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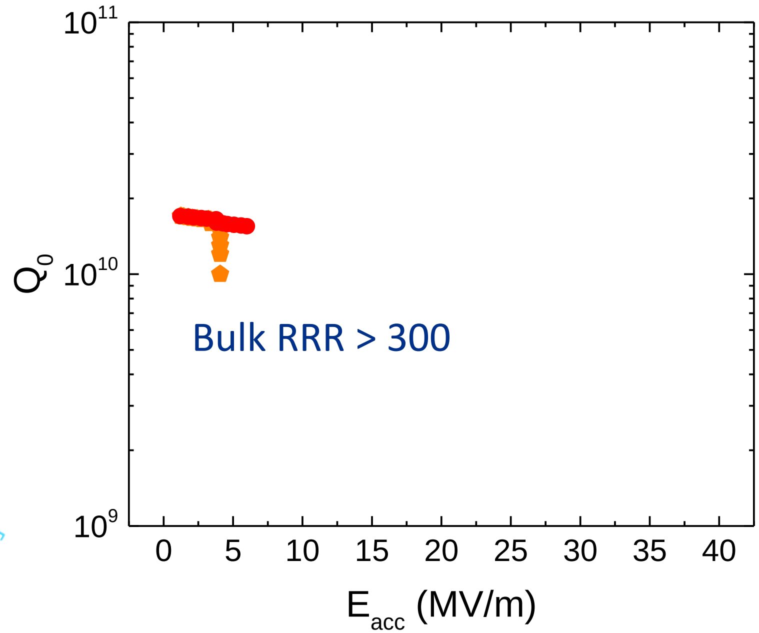
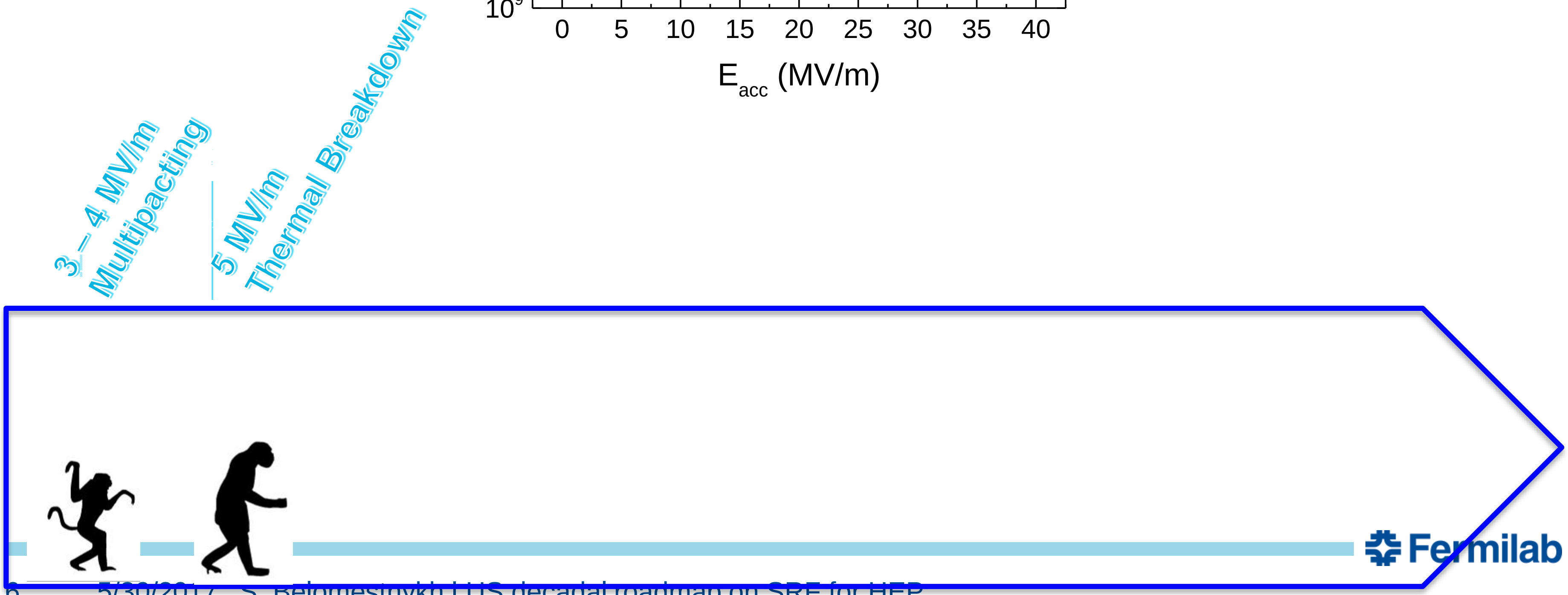


1.3 GHz, 2 K



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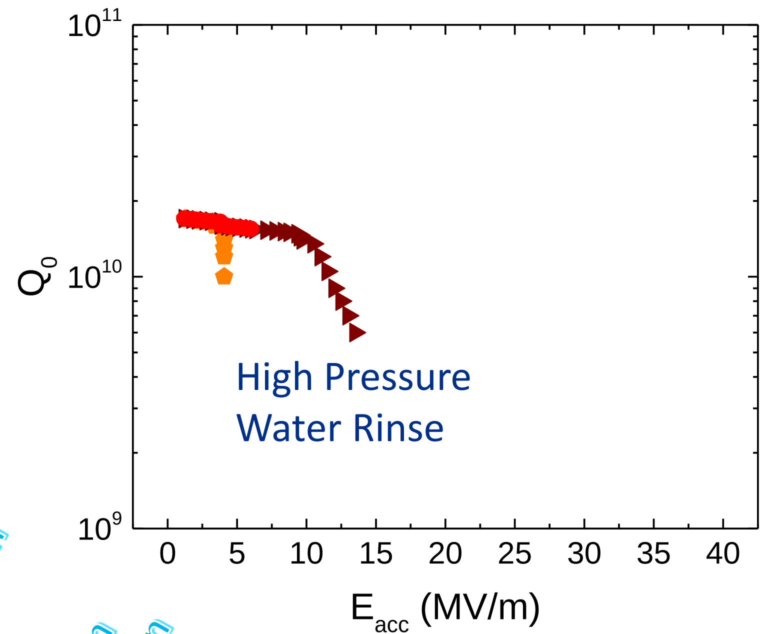

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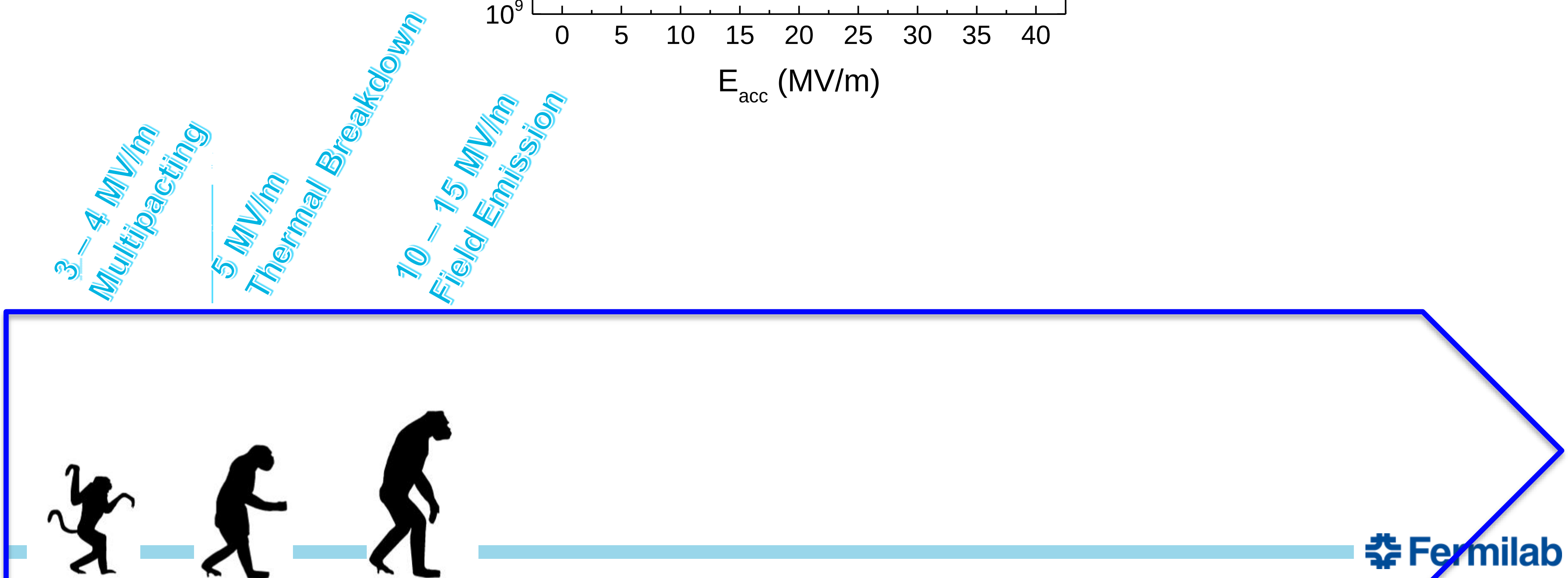

SRF Performance Evolution

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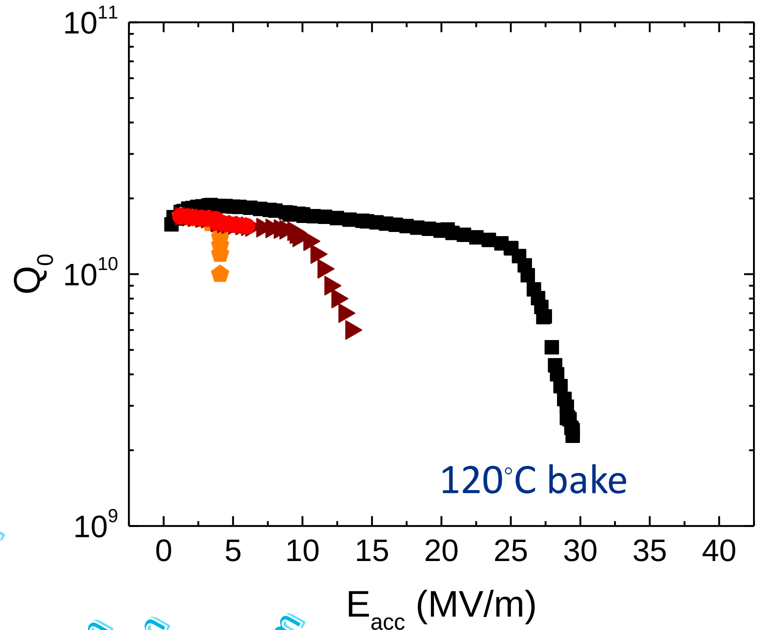


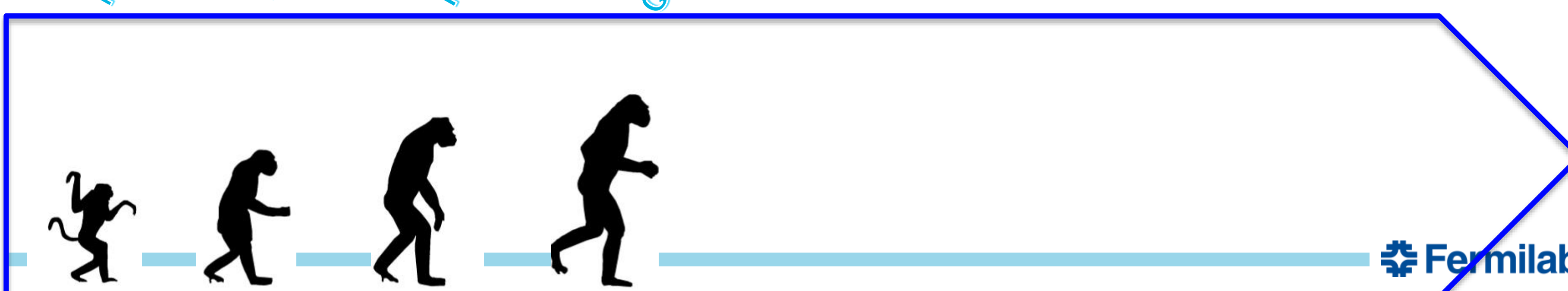
1.3 GHz, 2 K

3 – 4 MV/m
Multipacting

5 MV/m
Thermal Breakdown

10 – 15 MV/m
Field Emission

20 - 25 MV/m
High field
Q-SLOPE



SRF Performance Evolution

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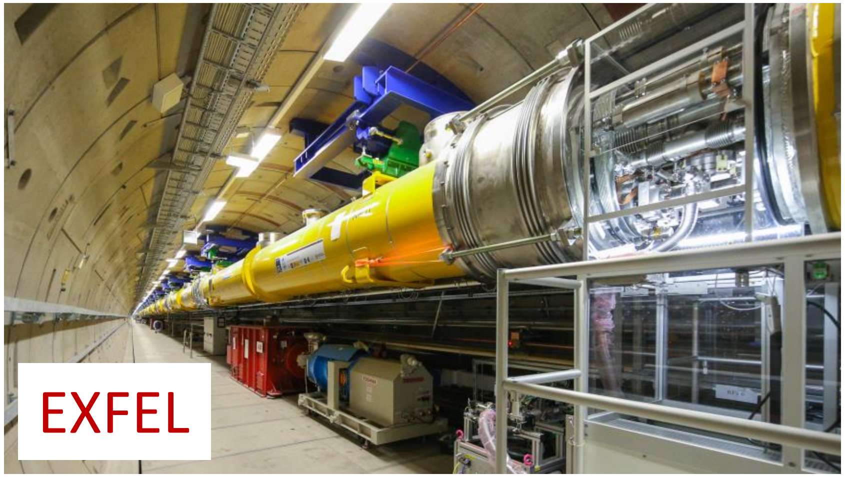

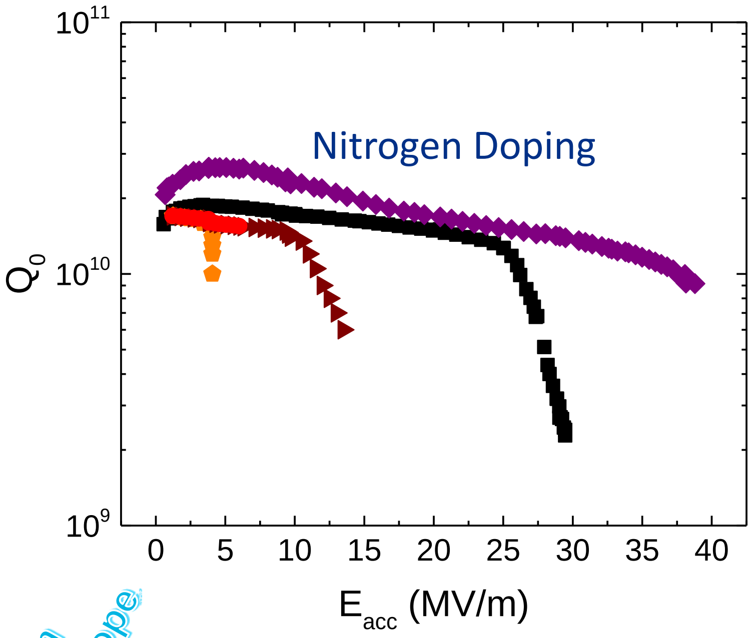

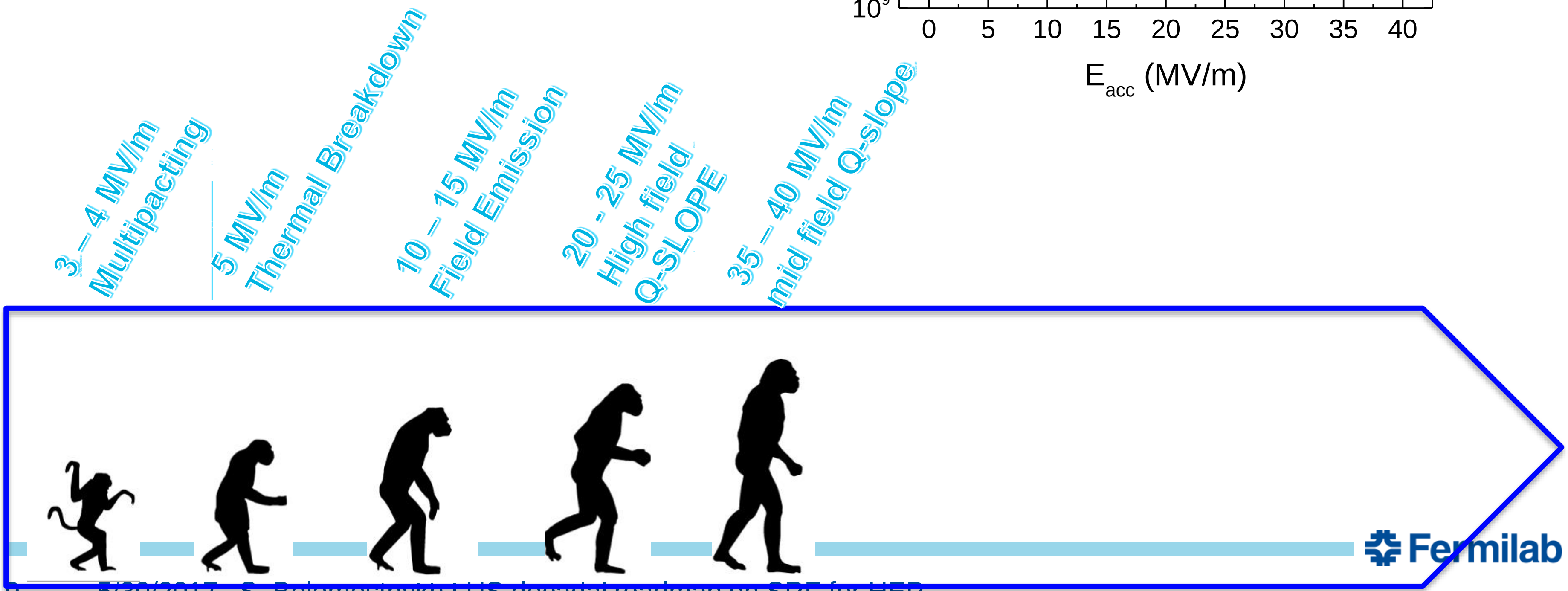

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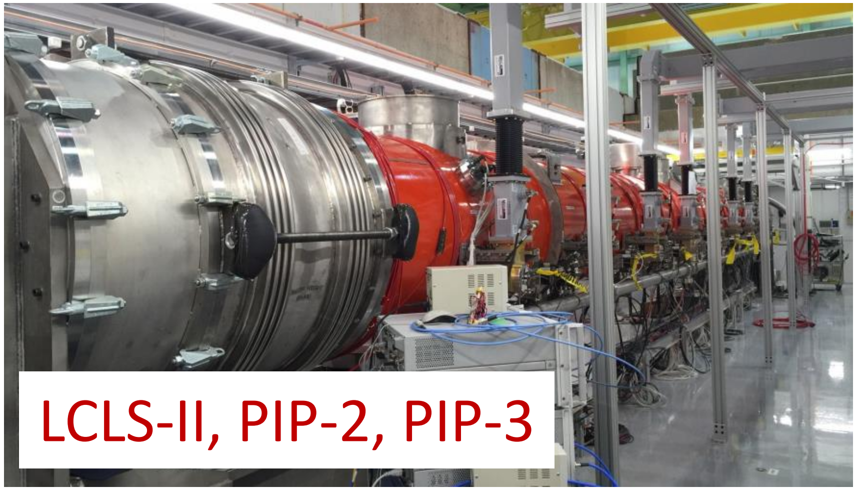
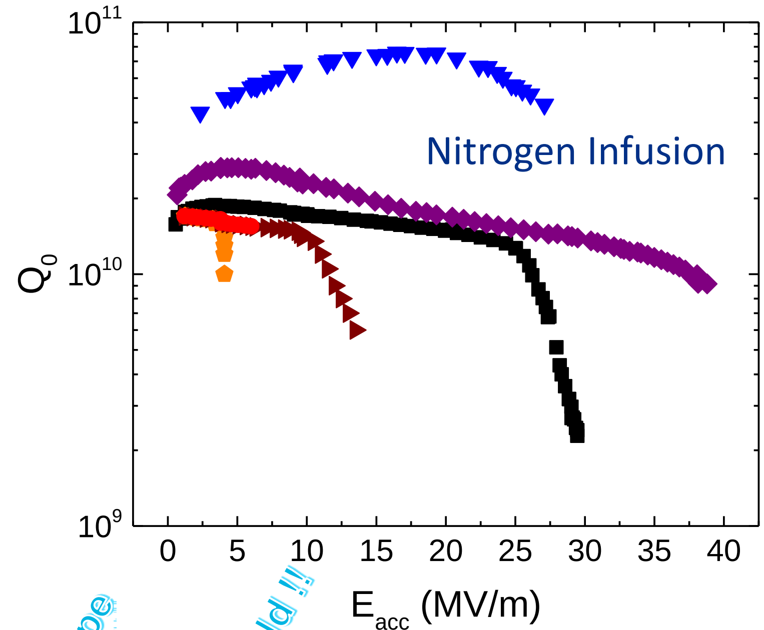




3 – 4 MV/m
Multipacting

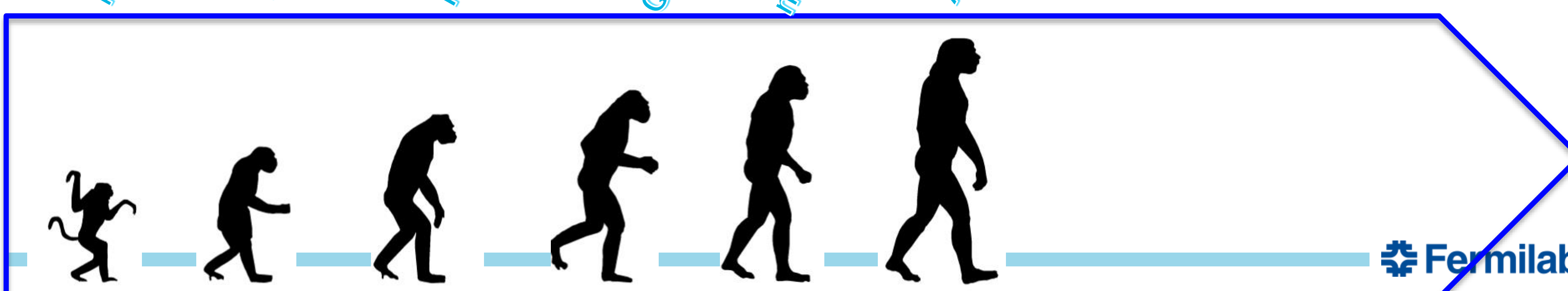
5 MV/m
Thermal Breakdown

10 – 15 MV/m
Field Emission

20 - 25 MV/m
High field
Q-SLOPE

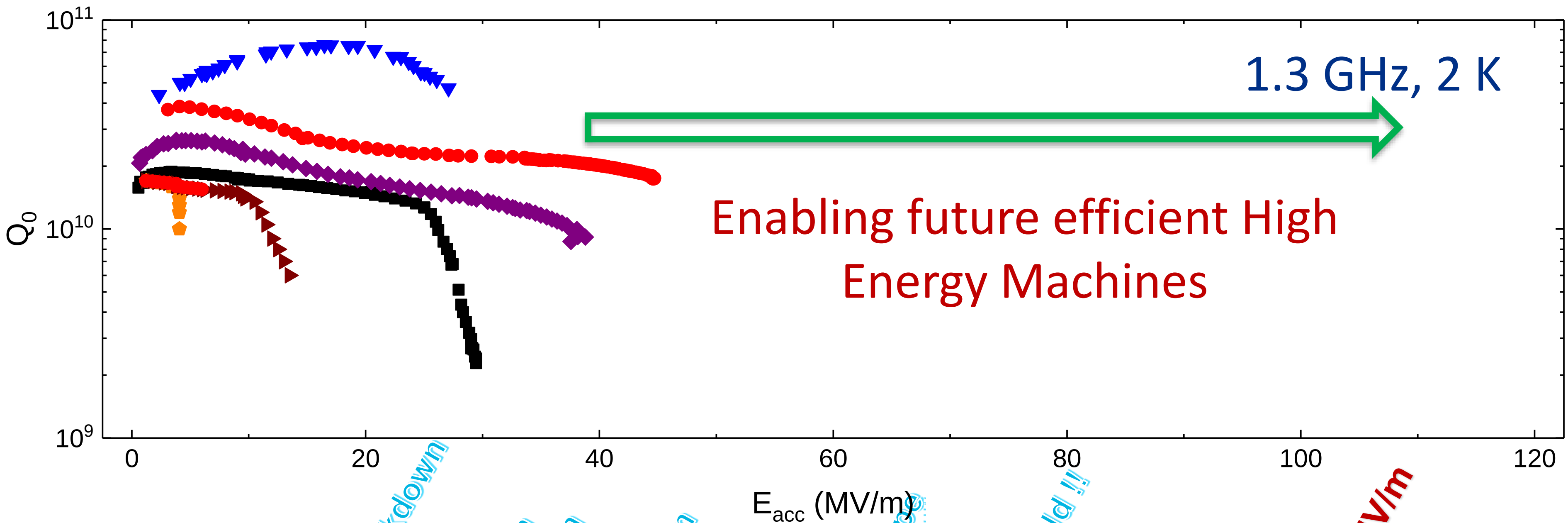
35 – 40 MV/m
mid field Q-slope

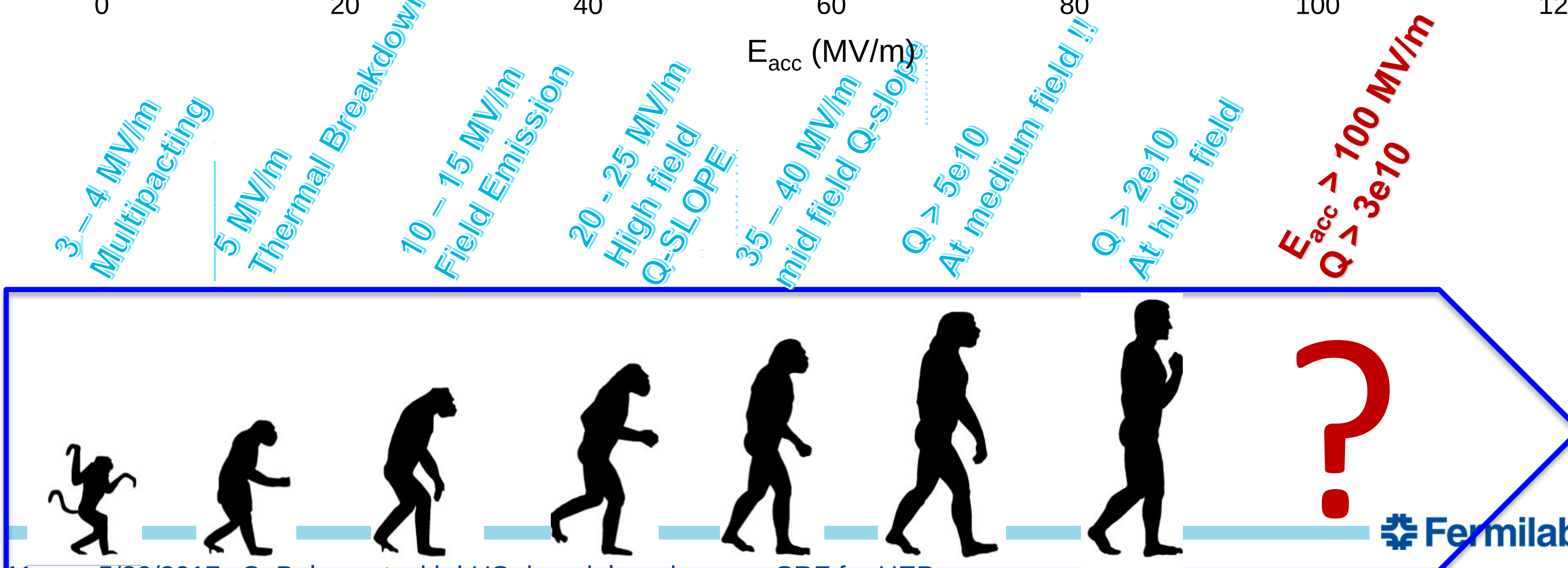
Q > 5e10
At medium field !!



SRF Performance Evolution

Courtesy A. Grassellino

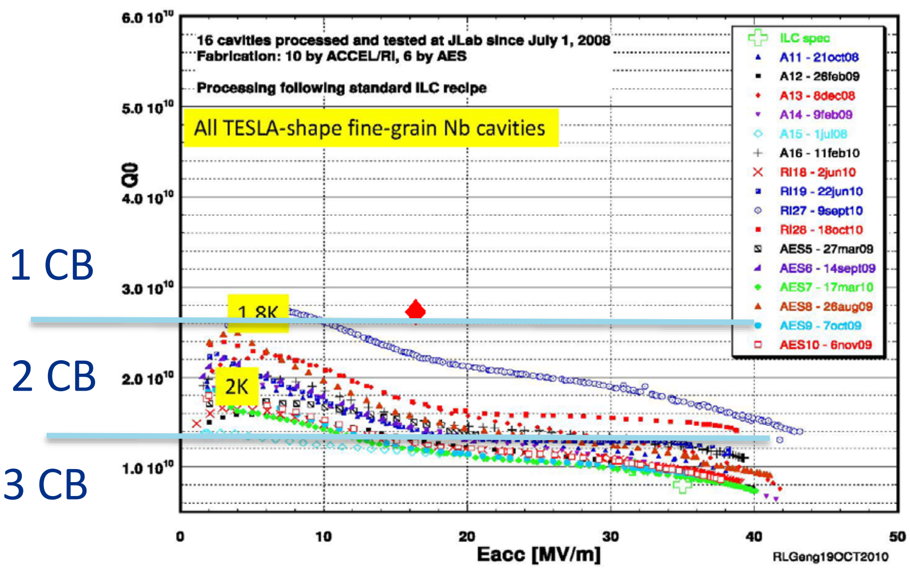




CW example: LCLS-II (relevant to PIP-II/PIP-III, FCC-ee,…)

- For LCLS-2 the cost of the linac is roughly the **same** order of magnitude as cost of refrigeration.

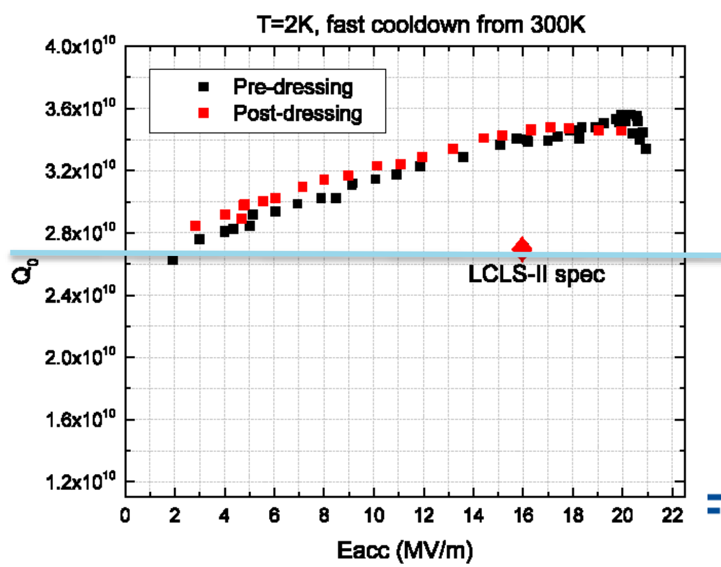
Motivation for High Q_0 R&D



"The best cavities of 2010"

The SRF world is changing

"The best dressed cavity of 2014" (so far)
TB9AES011



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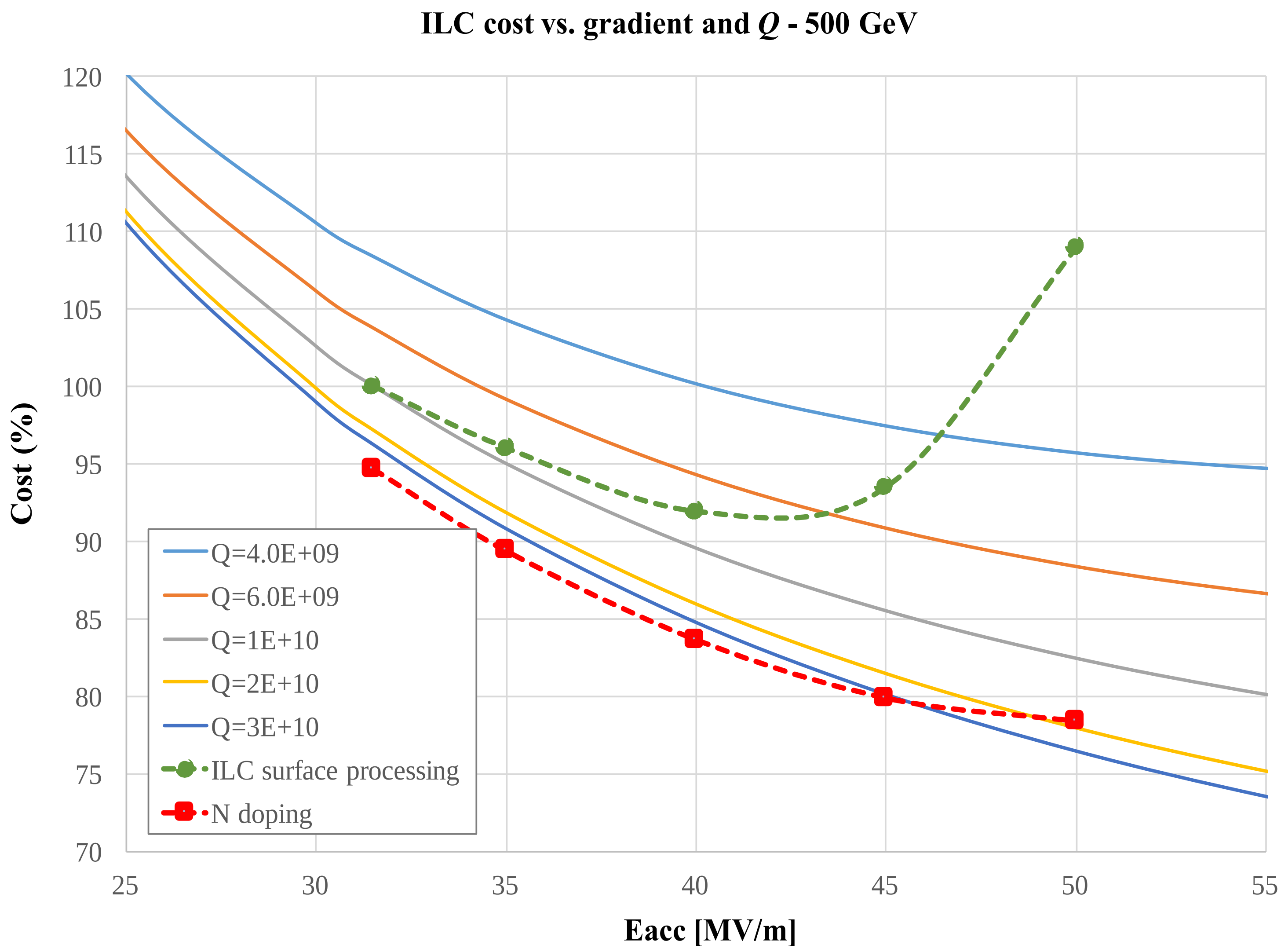
High gradients need High *Q*



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GARD SRF thrusts

- While there are many ideas on how to reduce costs of SRF machines, including material, fabrication and processing simplification, the clear cost driver is cavity performance.
- Therefore, we divided the roadmap into two main thrusts:

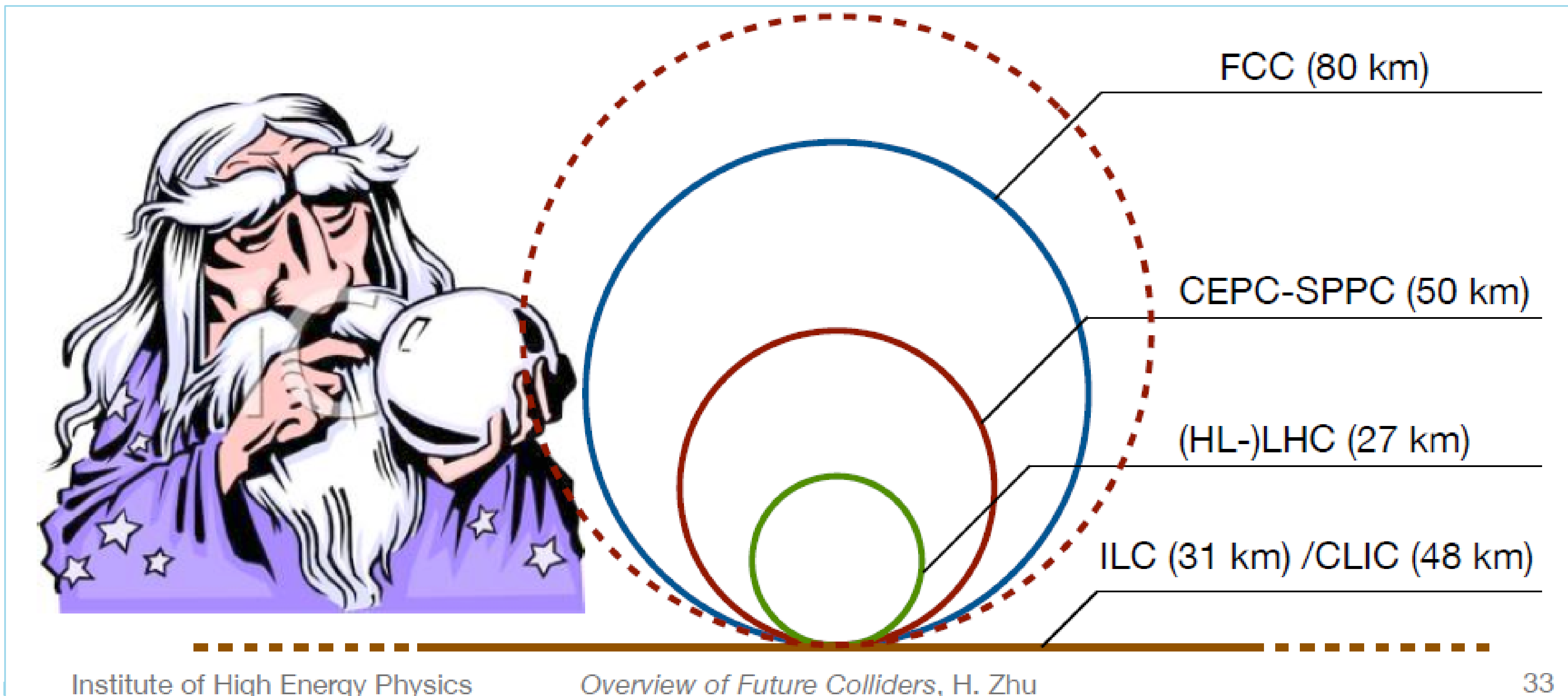
High *Q* frontier

High Gradient Frontier

- The pathways towards the accomplishments of High *Q* and High Gradient goals are exciting.

Next generation HEP accelerators

- The HEP accelerators **under consideration** are the *International Linear Collider* and a future *multi-TeV e+e- collider*, future circular colliders *FCC-ee, FCC-hh, FCC-eh, HE-LHC* at CERN, *CEPC/SppC* in China, and the SRF option for upgrading the Fermilab accelerating complex to a beam power over 2.4 MW, *PIP-III*.
- All these future machines would greatly benefit from the results of SRF R&D focused on delivering higher accelerating gradients and quality factors as well as developing “companion” technologies and synergistic SRF-NCRF R&D.



Alignment of SRF R&D and future machines

Main R&D

Doping and Flux Expulsion:
E_{acc} up to 70 MV/m with Q (2 K) > 3x10^{10}

Layered structures and advanced concepts on fundamental field limits: E_{acc} > 100 MV/m

Nb_3Sn: E_{acc} up to 90 MV/m with Q (4 K) > 3x10^{10}

Companion R&D

Field emission mitigation, Novel cavity shapes, RF sources, Ancillaries, Microphonics

PIP-II	ILC 1st Stage 250 GeV	PIP-III	ILC 2nd Stage	FCC-ee, CEPC	Multi-TeV *e+e-* Collider

Synergies: FELs, ADS, Quantum Computing, Compact Accelerators, etc.

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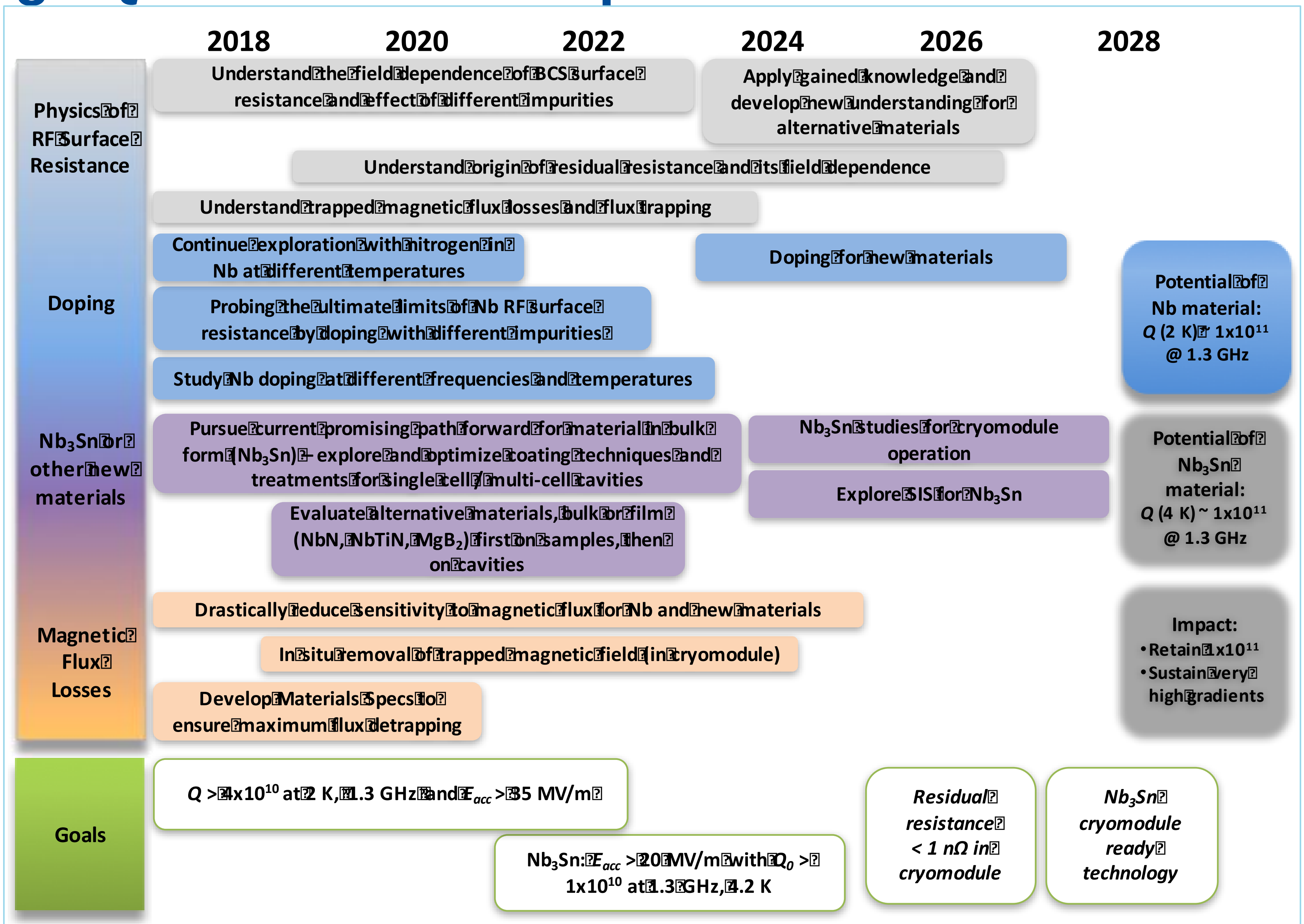
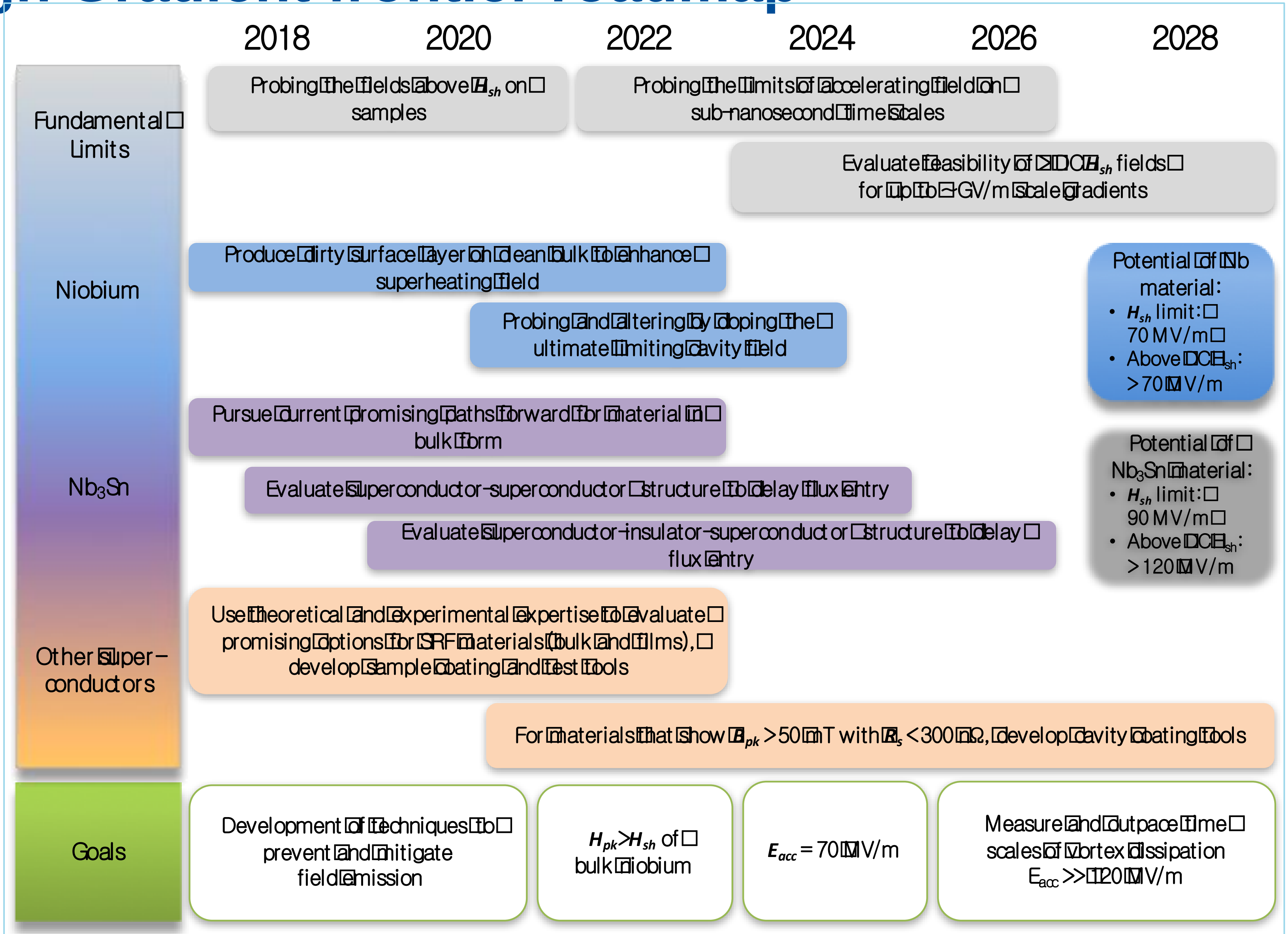
High *Q* frontier roadmap



High *Q* main directions

- Continue exploration of the effect of interstitial impurities on bulk Nb surface resistance;
- Study the effect of doping on the quality factor of cavities at different frequencies in the range of 650 MHz to 3.9 GHz;
- Develop fundamental understanding of the reverse field dependence of the BCS surface resistance and devise experiments towards validation of different theories;
- Develop understanding of mechanisms of trapping magnetic vortices and their contribution to the RF losses, and devise experiments towards validation of models;
- Develop understanding of 'intrinsic' residual resistance and its field dependence;
- Work towards amelioration of trapped vortices via innovative ideas: advanced magnetic shielding concepts, in situ flux removal, determine material properties/preparation for minimal pinning strength, etc.;
- Develop Nb_3Sn coating on single and multi-cell cavities of different frequencies;
- Investigate feasibility of other materials for high *Q*.

High Gradient frontier roadmap



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Common SRF roadmap elements

- New materials, films, multilayers
  - MgB_2, NbN, Nb_3Sn, other A15 superconductors (Nb_3Al, V_3Si etc.), zinc iron pnictides…
- Development of Nb_3Sn as practical SRF material
  - Nb_3Sn bulk films show promising results, recently demonstrating high *Q* out to medium fields at 4.2 K in R&D cavities.
  - More studies are needed to develop recipes that produce uniform, high quality films over a large surface area; to demonstrate the breakthrough potential of this material for pulsed high energy applications, we aim to achieve peak surface magnetic fields in pulsed mode that exceed the DC superheating field of niobium.
- Field emission mitigation
  - Field emission phenomenon could be a serious impediment to achieving high gradients. Special studies will have to be done in parallel with high gradient research to abate field emission in vertical tests and cryomodules.
- Microphonics and Lorentz Force Detuning compensation
- Novel SRF cavity shapes
  - R&D on new cavity shapes can further improve performance of SRF structures and HEP accelerators, up to 20% higher gradients for the same surface magnetic field.
  - Future HEP experiments require higher beam intensities and shorter cycle times of synchrotrons. Development of a new generation of fast frequency tuners for SRF cavities and new low-frequency cavity structures will be pursued.

SRF facilities

- While some infrastructure underpinning SRF research and development is already established at different U.S. national laboratories (ANL, FNAL, JLab, …) and universities (Cornell, Temple, Northwestern, …), new research directions requires new facilities or upgrading the existing ones.
- Facility utilization for SRF R&D:

SRF Facilities → / SRF R&D Topics ↓	Vertical cavity testing	Horizontal cavity testing	Cryomodule testing	High power pulsed testing	Materials science lab tools	Chemical & furnace treatment	Cleanroom	Compact accelerator	Coating systems	Quantum test bed facility
Surface resistance physics	Red				Red	Red	Red		Red	Red
Gradient limit physics	Red			Red	Red	Red	Red		Red	
Doping	Red	Yellow	Yellow		Red	Red	Red		Yellow	
Flux expulsion	Red	Yellow	Yellow		Red	Red	Red			
Nb_3Sn high gradient	Red	Yellow		Red	Red	Red	Red		Red	
Nb_3Sn high Q	Red	Red	Yellow		Red	Red	Red	Red	Red	
Other superconductors	Yellow				Red	Yellow	Yellow		Red	
Layered geometries	Red			Yellow	Red	Red	Red	Yellow	Red	
Field emission mitigation	Red	Yellow	Yellow	Red	Red	Red	Red			
Microphonics studies		Red	Red					Yellow		
New cavity shapes	Red	Red	Yellow	Yellow	Yellow	Red	Red	Yellow	Yellow	Yellow
Ancillaries		Red	Red					Red		
NCRF Synergies	Yellow			Red	Red	Yellow	Yellow		Yellow	

Legend: Red = Activity requires extensive use of facility; Yellow = Activity requires moderate use of facility

Summary

- SRF is the technology of choice for many new accelerators, including the next generation HEP machines.
- Recent exciting developments (N doping, N infusion, progress in Nb_3Sn, theoretical advances,…) indicate that there is a lot of potential to be uncovered. There are many new ideas to be explored.
- While the SRF community has a number of operating test facilities, validating new concepts will require new testing capabilities.
- New breakthrough can be quickly applied to accelerators (example: nitrogen doping at LCLS-II).