Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

SC technology for future HEP particle accelerators

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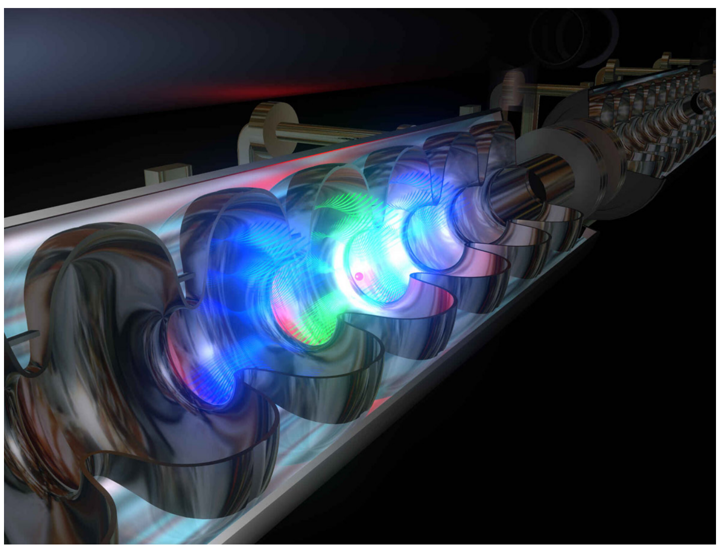
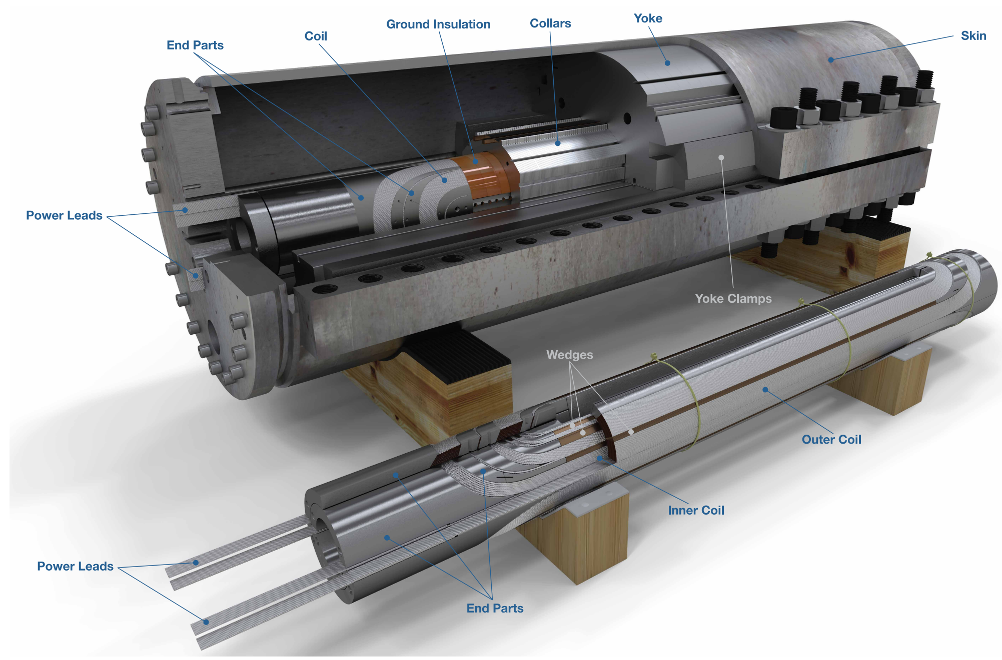
Outline

- Introduction: Future HEP particle accelerators and superconducting (SC) technology
- Superconducting RF (SRF) technology challenges for future lepton colliders: ILC; FCC-ee/CEPC
- High-field SC magnet technology needs for future hadron colliders: FCC-hh/SppC
- Summary



TESLA SRF cavity



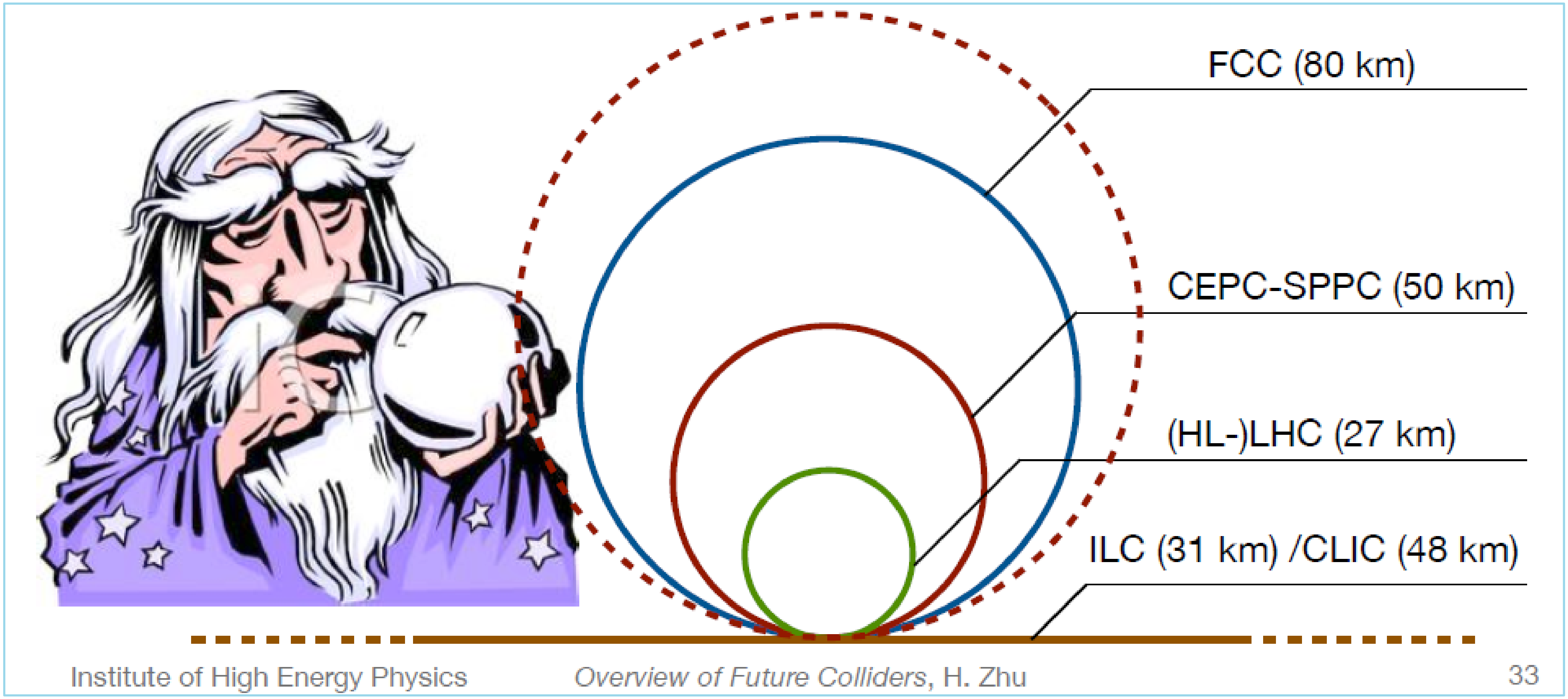
Short model of a SC magnet

Introduction

- Superconducting radio frequency accelerating cavities and High-field superconducting magnets and are a cornerstone technologies of future high-energy particle accelerators.
- Due to short time allotted for the talk, I will address only future HEP colliders, which present most challenging demands.
- Future generation of lepton colliders will require RF systems to be “affordable” and able to support high luminosity.
- The former necessitates cavities operating at high accelerating gradients (acceleration system length) with low cryogenic losses (high quality factor). The latter means supporting very high beam currents (higher order mode damping) and delivering very high power to the beams (RF power couplers).
- Next hadron colliders require a step up from the state-of-the-art accelerator-grade SC magnet technology: from 11 T (HL-LHC) to 16 T or even 20 T.
- In this talk I will briefly discuss state of the art of these two technologies, outline how they enable future generation of HEP colliders and discuss challenges.

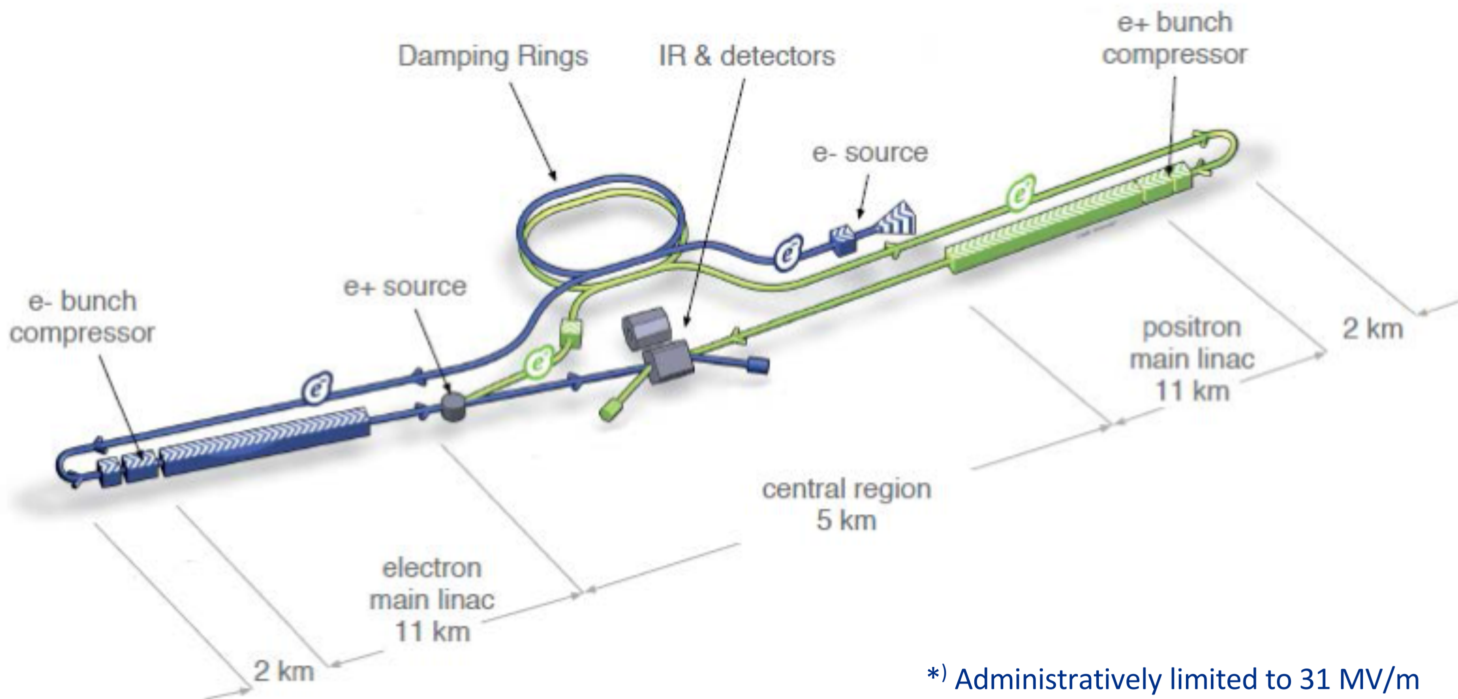
Future colliders: scale of the problem

- SRF: 800 cavities at 23.6 MV/m for EXFEL *vs.* 16,000 cavities at 31.5 MV/m for ILC
- SRF: 22 MW SR power for LEP2 *vs.* 100 MW SR power for FCC-ee
- SC magnets: 27 km LHC *vs.* 80 to 100 km FCC
- SC magnets: 11 T Nb_3Sn for HL-LHC *vs.* 16 T Nb_3Sn / 20T hybrid for FCC-hh/SppC



SRF technology for ILC: state of the art

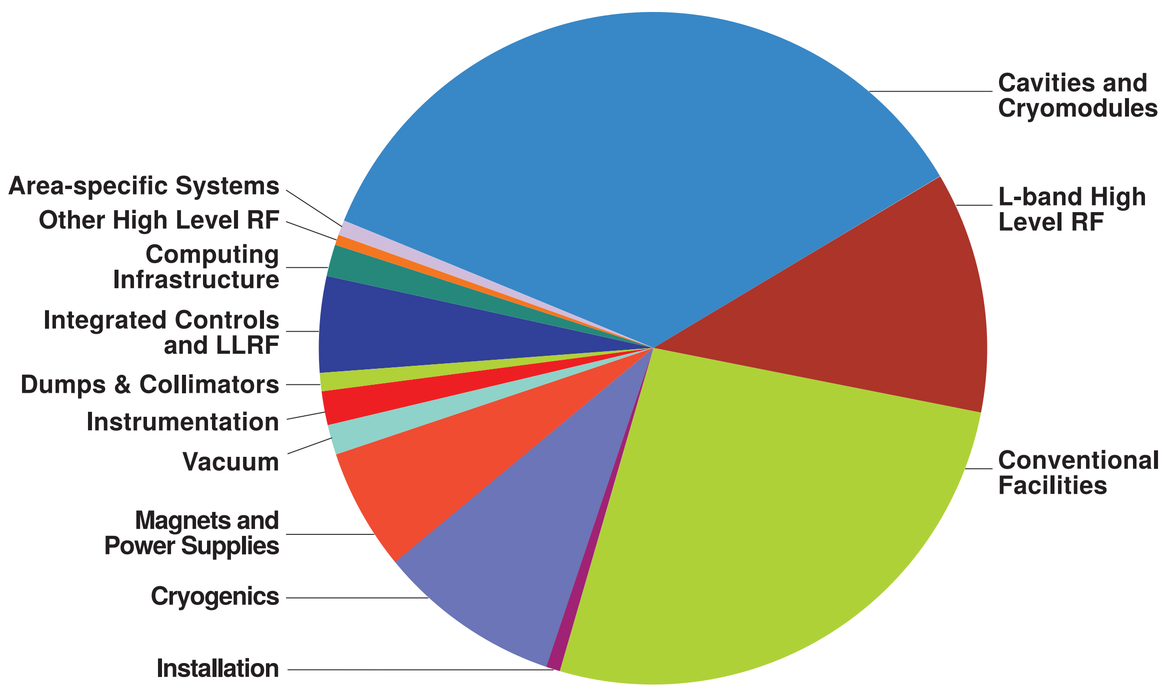
- The ILC TDR specs, 31.5 MV/m with Q > 10^{10} and 90% yield, have been demonstrated on a small scale.
- Average gradient of XFEL cryomodules is 27.9 MV/m* with only 5 of 98 tested CM modules below spec (23.6 MV/m).
- Field emission (FE) is still an issue at high gradients.
- ILC cost is still a big concern for funding agencies.



*) Administratively limited to 31 MV/m

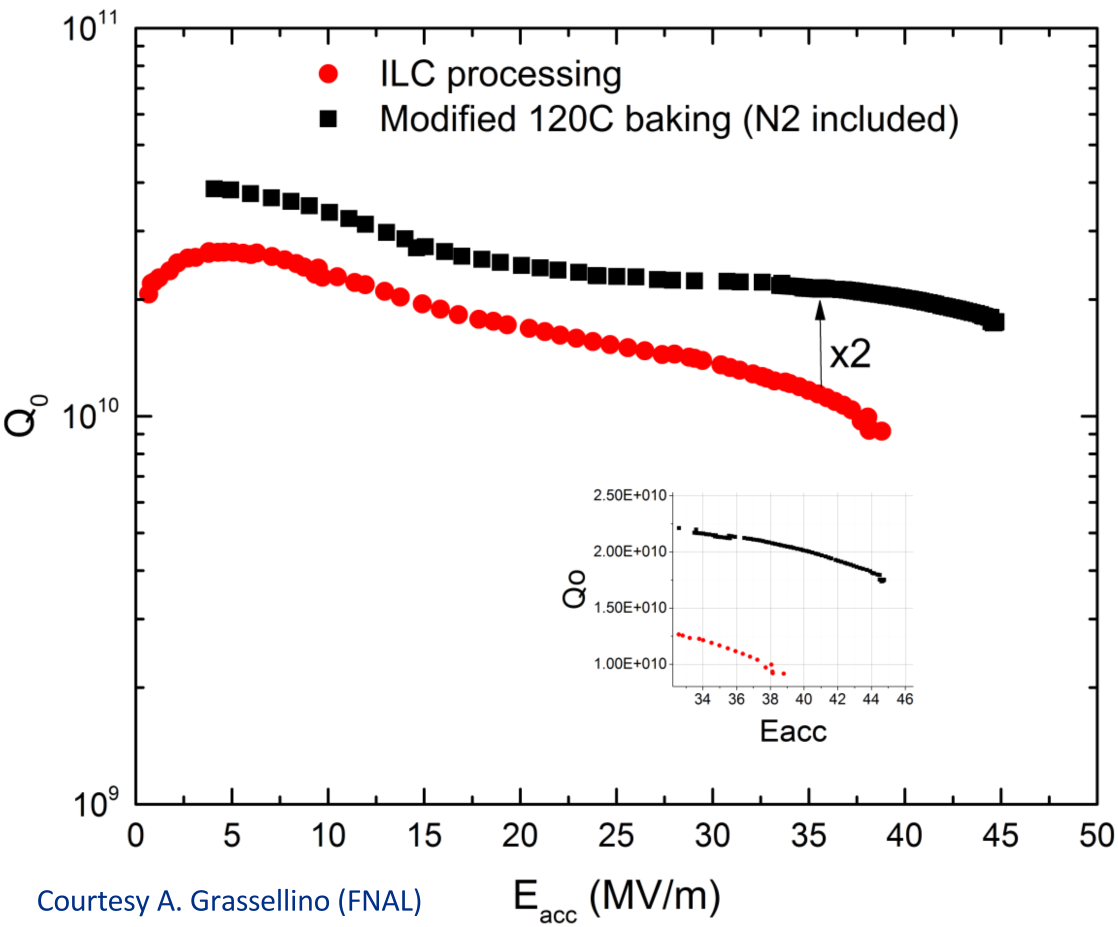
SRF technology for ILC: path to cost reduction

- From the ILC TDR: "[the cost] is dominated by the SRF components and related systems, together with the conventional facilities. These two elements account for 73% of the total. The main linac itself corresponds to 67% of the total project."
- Reducing the main linac cost is the most efficient way to bring the ILC cost down.
- Possible directions for short-term R&D: improve accelerating gradient and cavity Quality factor (Q); reduce cost of cavity and component fabrication; simplify cavity treatment. Long-term R&D would concentrate on alternative materials, e.g. Nb_3Sn.



Main Linac Cost Breakdown from ILC TDR

Recent R&D progress on high Q / high gradient: "standard" vs "N infused" cavity surface treatment



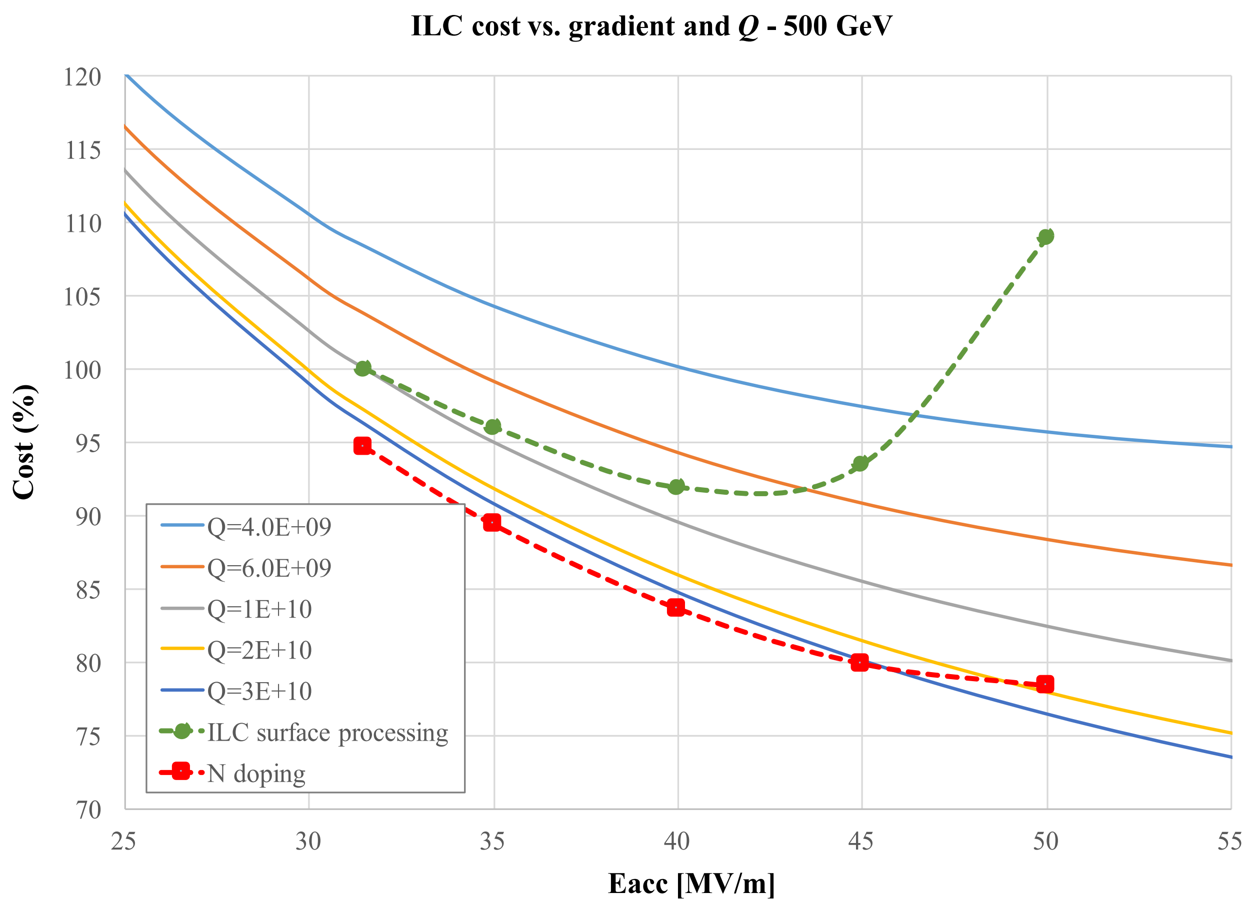
Courtesy A. Grassellino (FNAL)

Increase in Q by a factor of two
Increase in gradient ~15%

- FNAL recently demonstrated (on single-cell cavities) a new treatment, which utilizes "nitrogen infusion".
- Achieved so far:
  - 45.6 MV/m → 194 mT
  - with Q ~ $2 \cdot 10^{10}$!
- Systematic effect observed on several cavities.
- R&D to focus on :
  - Optimize the recipe;
  - Implement and demonstrate improvement with statistics on nine cells cavities;
  - Better understanding and mitigation of FE;
  - Demonstrate preservation of performance in cryomodule;
  - Transfer technology to industry.

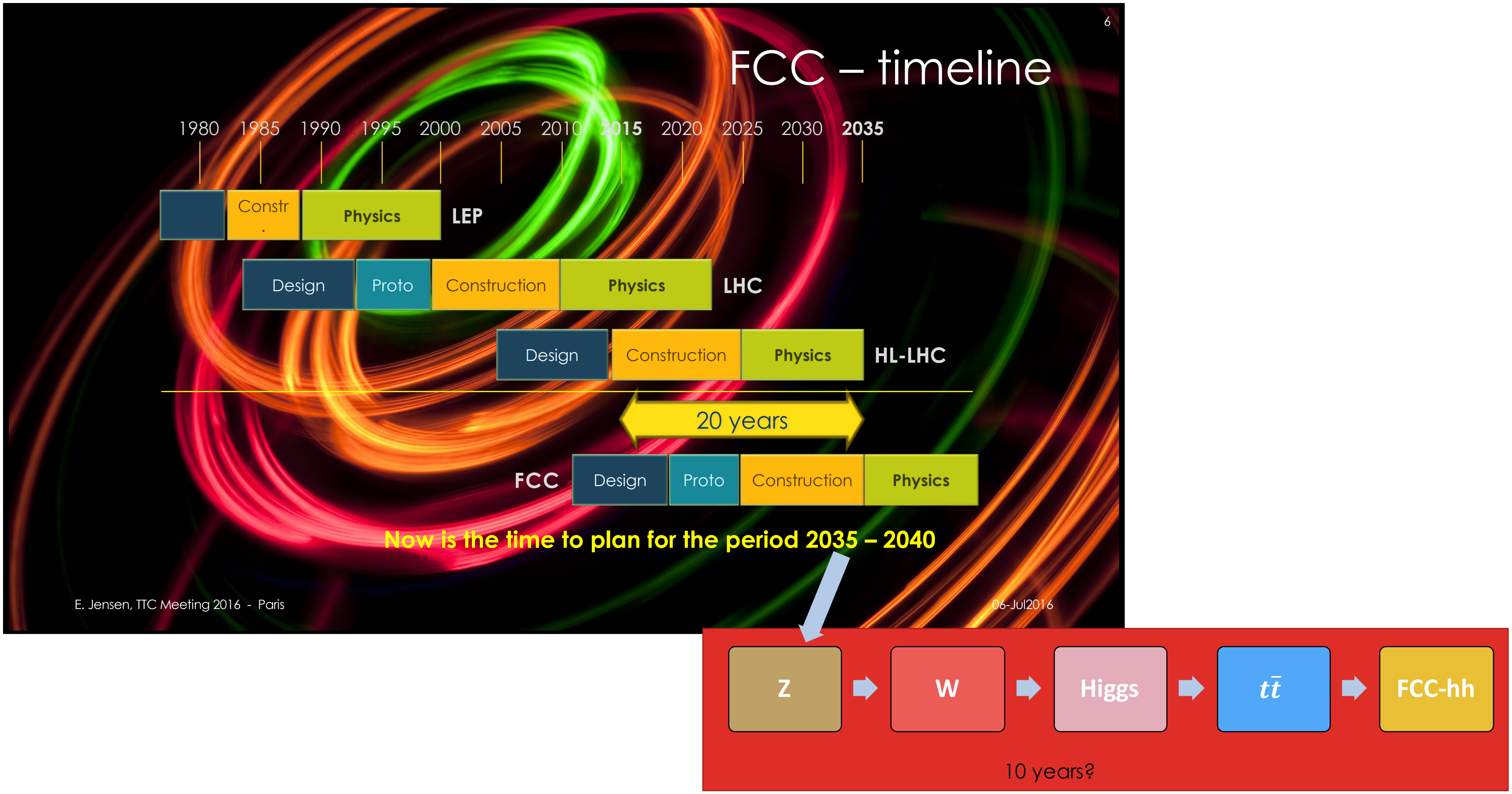
Potential ILC cost reduction

- A cost model based on the ILC TDR and new progress in the SRF technology on cavity achievable efficiency (Q) and acceleration (E_{acc}), showing potential cost reduction up to 20%.



Future circular lepton colliders

- Future e^+e^- colliders, FCC-ee and CEPC, are considered as a potential first step toward hadron colliders FCC-hh and SppC, *a la* LEP before LHC.



Parameters of the circular lepton colliders

- SRF systems for these machines will have to deal with very high RF power, high beam currents and strong HOM damping.

"Ampere-class" machine

parameter	FCC-hh	FCC-ee					CEPC	LEP2
Physics working point		Z		WW	ZH	$t\bar{t}$	H	
energy/beam [GeV]	50,000	45.6		80	120	175	120	105
bunches/beam	9,460	30180	91500	5260	780	81	50	4
bunch spacing [ns]	25	7.5	2.5	50	400	4000	3600	22000
bunch population [10^{11}]	1.1	1.0	0.33	0.6	0.8	1.7	3.8	4.2
beam current [mA]	500	1450	1450	152	30	6.6	16.6	3
$\mathcal{L}$/IP $[(\mathrm{nb}\cdot\mathrm{s})^{-1}]$	50	2100	900	190	51	13	20	0.012
energy loss/turn [GeV]		0.03	0.03	0.33	1.67	7.55	3.1	3.34
Bunch length σ [mm]	75	0.9	1.6	2	2	2.1		
synchrotron power [MW]	6			100			103	22
RF voltage [GV]	0.032	0.4	0.2	0.8	3.0	10	6.9	3.5

Courtesy E. Jensen (CERN)

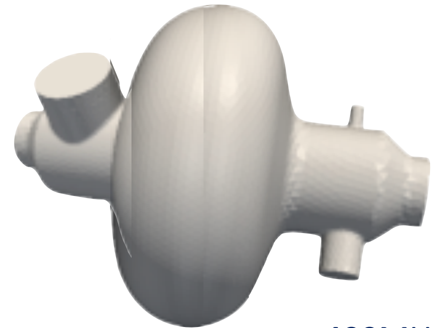
short bunches

"high gradient" machines

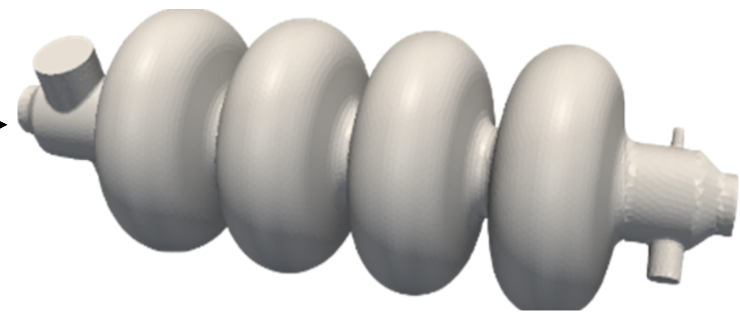
SRF technology for FCC-ee

- Parameters of the FCC-ee options cover very wide range and cannot be satisfied with one SRF system design.
- At the “high current” end, where the total voltage is relatively small, the design will be determined by strong HOM damping requirements and RF power couplers. Hence, single-cell cavity design. The gradients will be moderate (4-5 MV/m). Nb/Cu at 4 K is OK.
- At the “high gradient” end, the total voltage is large and the design will be driven by optimization of the accelerating gradient in CW mode of operation. The number of cells per cavity will be limited to 4-5 to ensure adequate HOM damping. Nb/Cu or other alternatives (Nb_3Sn?) are under consideration, but require R&D.

Higher currents

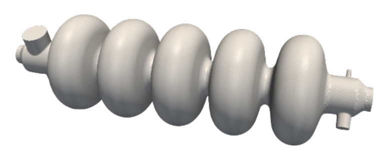


400MHz, 1 cell, Nb/Cu



400MHz, multi-cells, Nb/Cu

Higher gradient

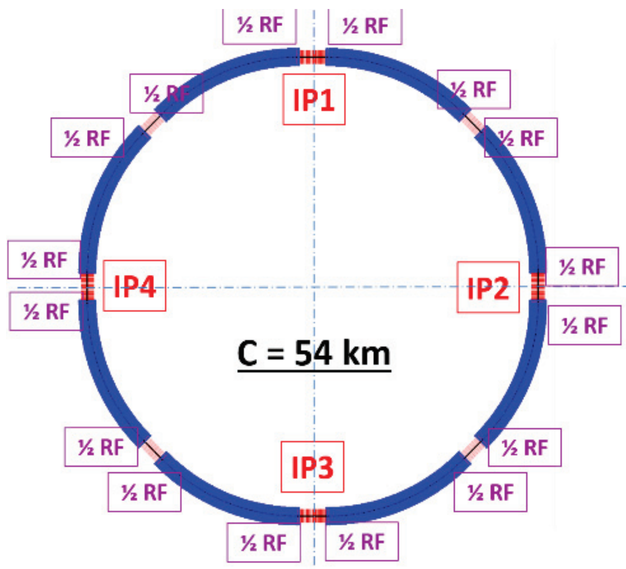


800MHz, multi-cells, Nb/Cu - bulk Nb

Courtesy E. Jensen (CERN)

SRF technology for CEPC

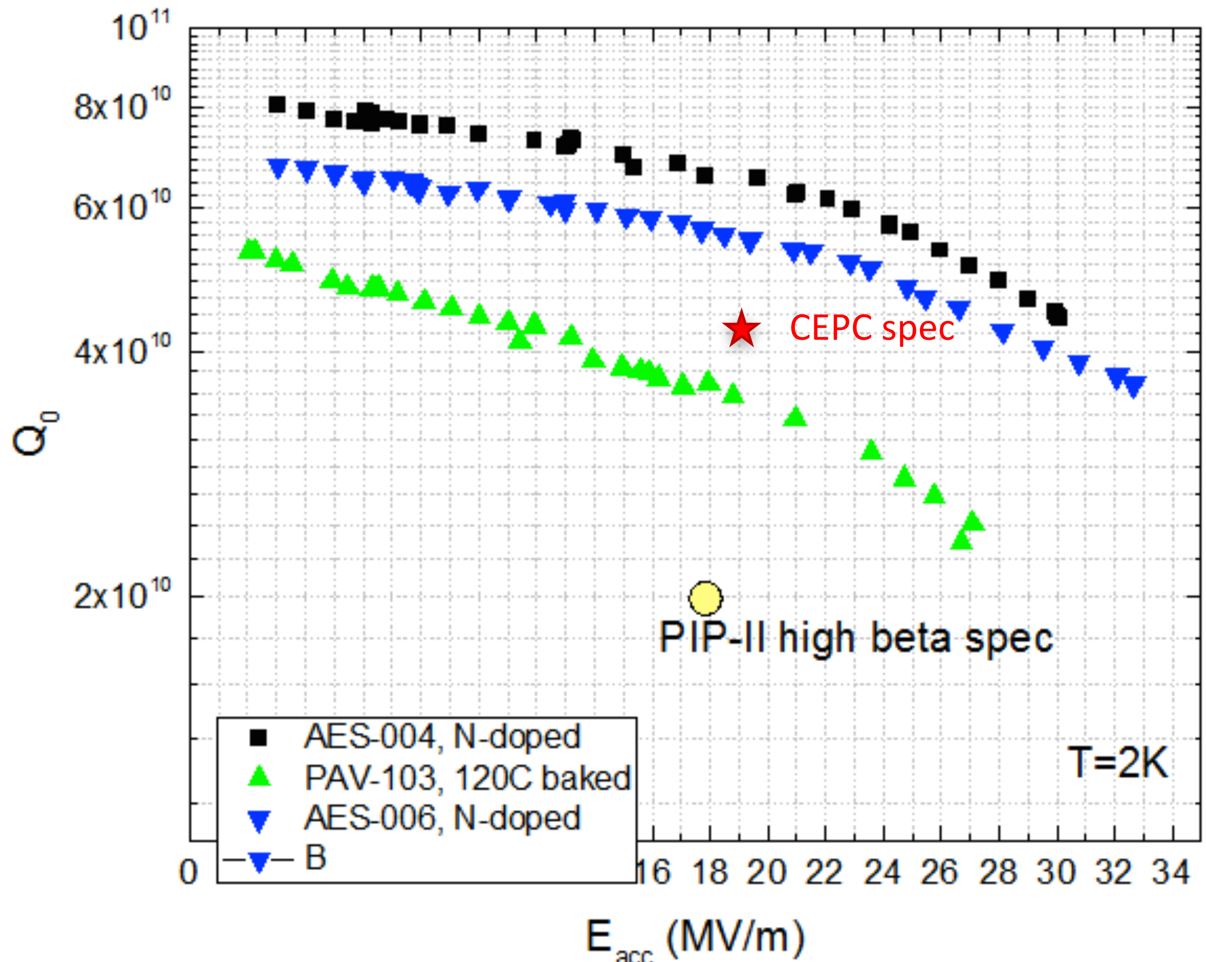
- CEPC's main physics goal is operation at 240 GeV center-mass energy as a Higgs factory.
- The collider RF system will consist of 384 650-MHz 5-cell SRF cavities operating at 19.3 MV/m with *Q* of $4{\cdot}10^{10}$.
- Nitrogen doping and magnetic flux expulsion technologies will be used to support high *Q*.
- Thin film SRF technology, e.g. Nb_3Sn is under consideration as possible alternative.



CEPC layout from J. Y. Zhai, et al., SRF2015

Nitrogen doping for 650 MHz

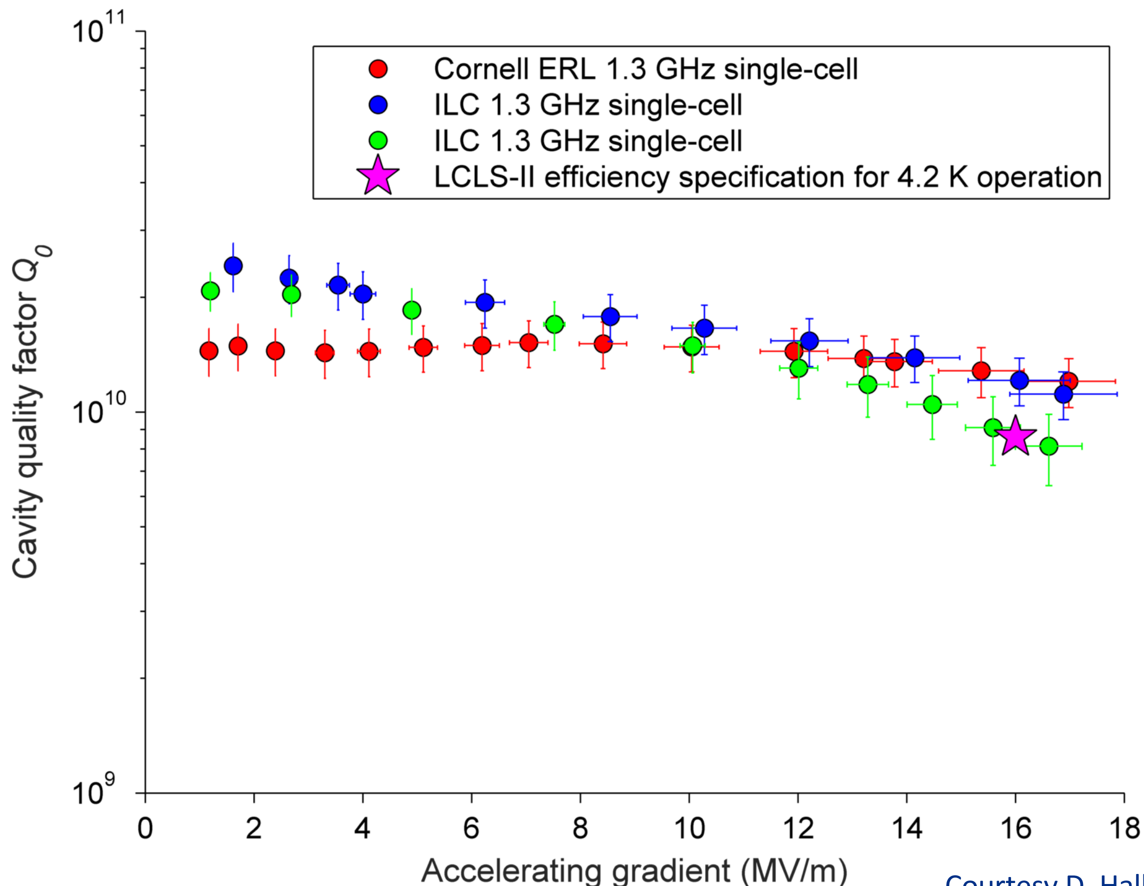
- Applying nitrogen doping to 650 MHz ($\beta = 0.9$) leads to doubling Q compared to 120°C bake (standard surface treatment ILC/XFEL), ~$7 \cdot 10^{10}$ at 2 K – world record at this frequency.



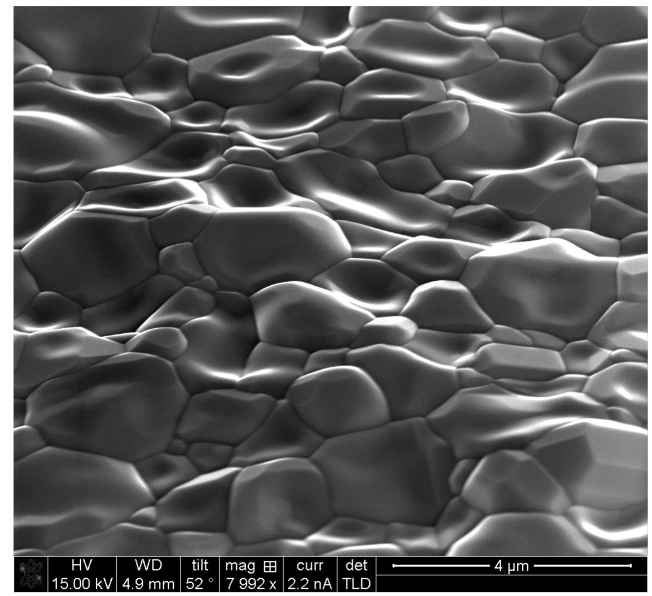
Courtesy A. Grassellino (FNAL)

Nb_3Sn SRF cavity R&D

- R&D on 1.3 GHz single-cell cavities at Cornell: Recent test results consistently demonstrate gradients >16 MV/m with Q > 10^{10} at 4.2 K.
- Very promising for future colliders. Next steps: extend this technology to multi-cell cavities and lower frequencies.



Courtesy D. Hall and M. Liepe (Cornell)



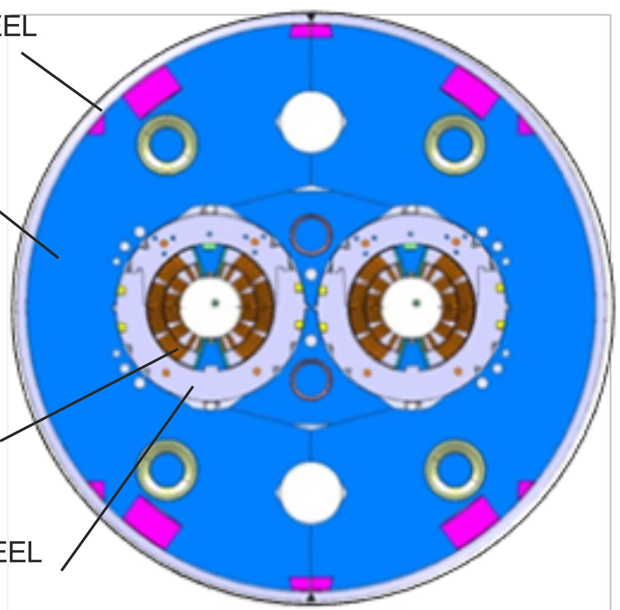
Nb_3Sn cavity surface
Courtesy Cornell University

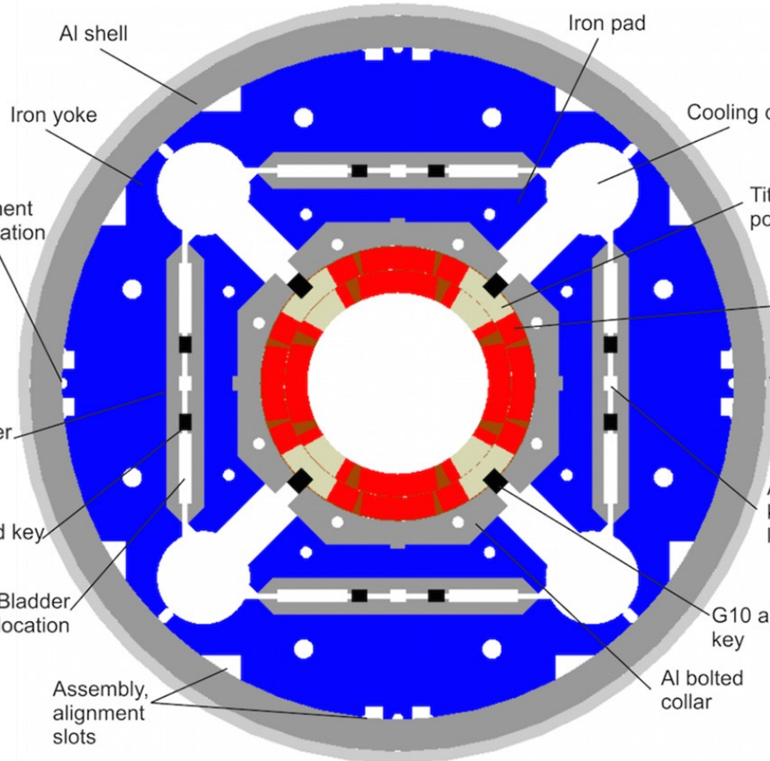
High-field SC magnet technology for future hadron colliders

- Proposed future hadron colliders – HE-LHC, FCC-hh, SppC – require developing SC magnet technology beyond state-of-the-art.
- State-of-the-art accelerator magnet technology will be utilized in HL-LHC and is based on 11-T class Nb_3Sn magnets.
- HE-LHC and FCC-hh plan to use 16 T magnets while SppC would need 20 T magnets.
- The former can be developed using Nb_3Sn technology while the latter would need to use HTS, most likely in a hybrid magnet configuration.
- In both cases cost reduction for Nb3Sn and HTS superconductor is mandatory to make the projects affordable.
- U.S. DOE is establishing a national Magnet Development Program (MDP) to develop SC magnet technology suitable for future energy-frontier colliders.

11-T class magnets for HL-LHC

- Nb_3Sn dipole for LHC collimation system upgrade
  - 60 mm aperture
  - B_{nom} = 11.2 T at I = 11.85 kA
  - cold mass cross-section is compatible with the LHC MB

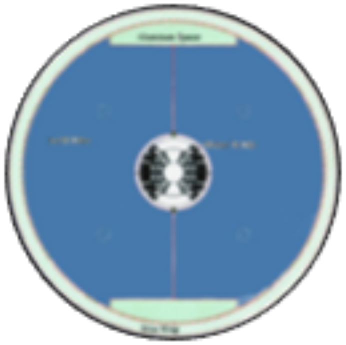




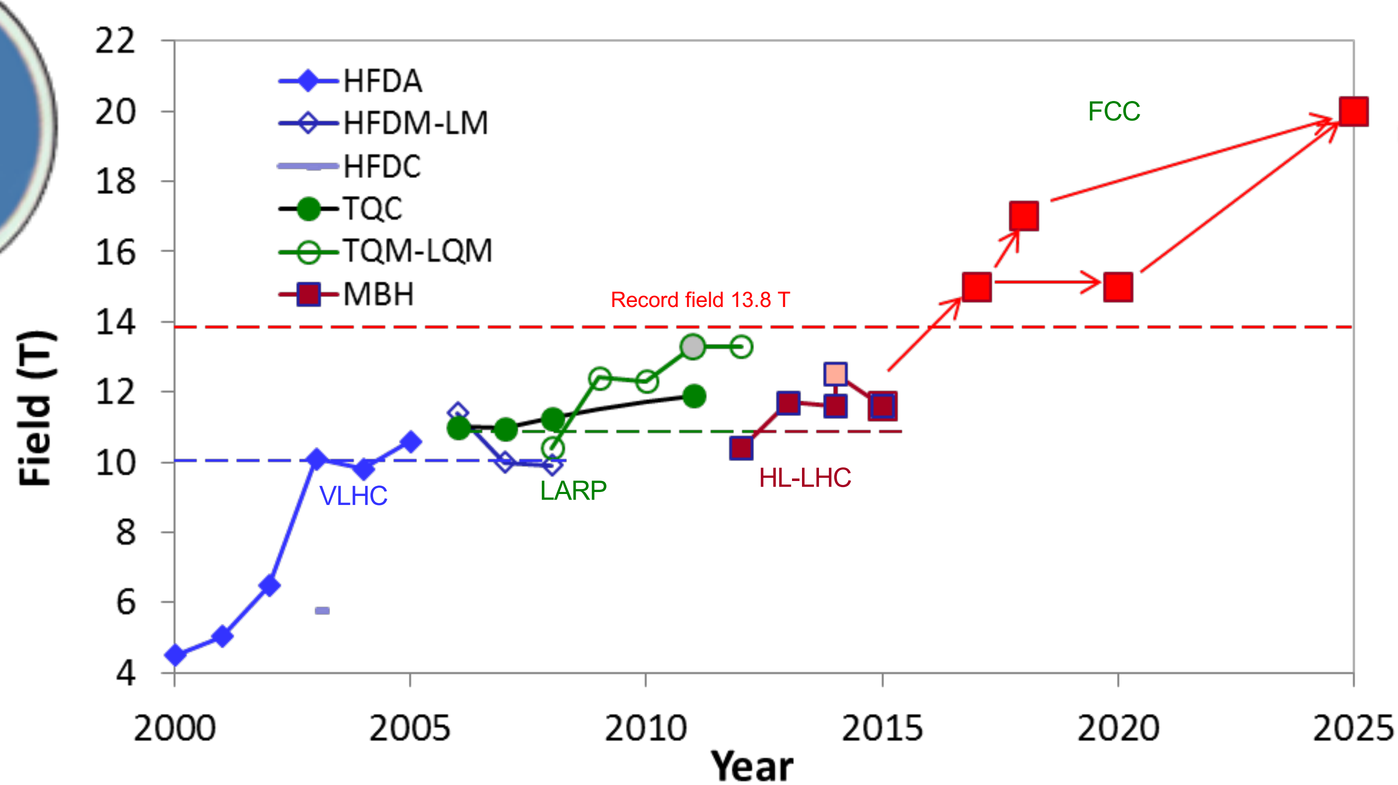
- Nb_3Sn IR quadrupole for LHC luminosity upgrade
  - 150 mm aperture
  - G_{nom} = 140 T/m at 17.5 kA

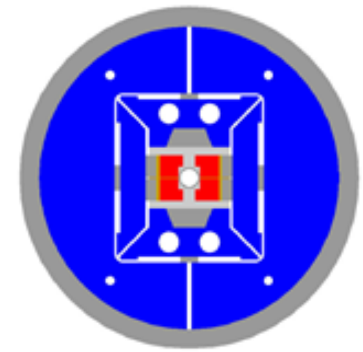
Courtesy A. Zlobin (FNAL)

Timeline for high-field accelerator magnet R&D

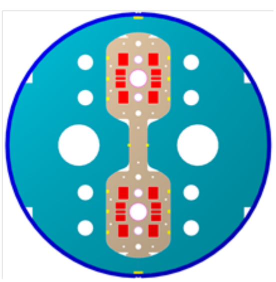


D20 (LBNL)
50 mm dipole
13.5 T (1997)

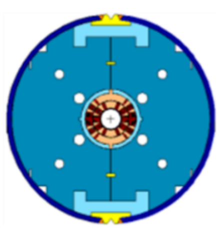




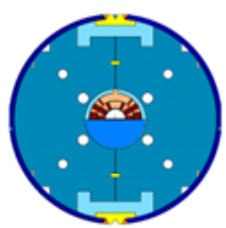
HD2 (LBNL)
35 mm dipole
13.8 T (2008)



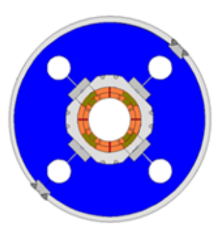
HFDC (R&W)
40 mm 10 T dipole



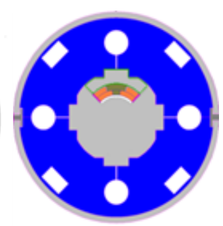
HFDA
43.5 mm
10 T dipole



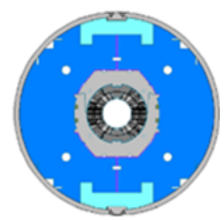
HFDM-LM
Dipole mirror



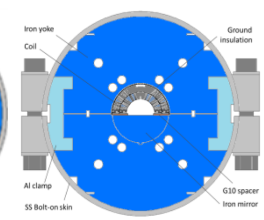
TQC
90 mm 200 T/m
quadrupole



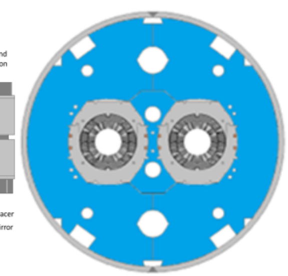
TQM-LQM
Quadrupole
mirror



MBHSP
60 mm 11 T dipole



MBHSM
Dipole mirror



MBHDP
60 mm 11 T dipole

Courtesy A. Zlobin (FNAL)

Magnet Development Program

- This is a generic R&D program designed to achieve 4 goals and address the driving questions.

US Magnet Development Program (MDP) Goals:

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

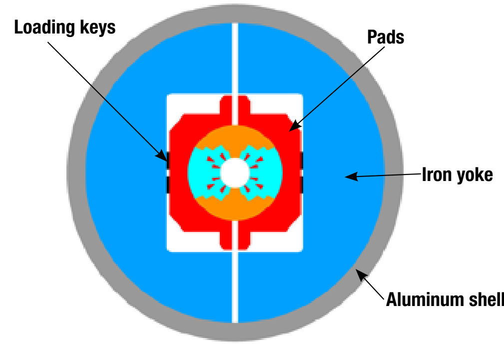
Support the above efforts by addressing fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

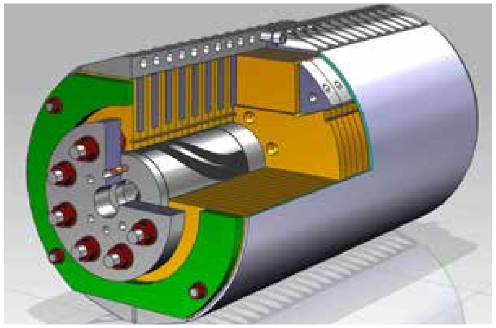
GOAL 4:

Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

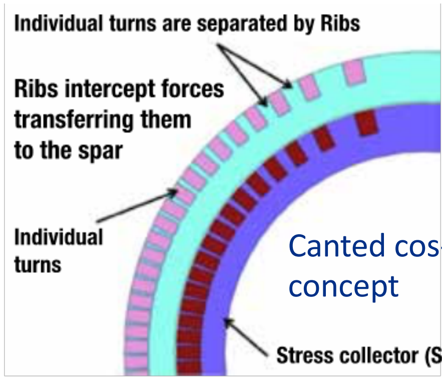
TABLE 1: **Driving Questions**

	Driving questions related to the ***ultimate performance limits*** **of high-field accelerator magnets**
1	What is the nature of accelerator magnet training? Can we reduce or eliminate it?
2	What are the drivers and required operation margin for Nb_3Sn and HTS accelerator magnets?
3	What are the mechanical limits and possible stress management approaches for Nb_3Sn and 20 T LTS/HTS magnets?
4	What are the imitations on means to safely protect Nb_3Sn and HTS magnets?
	Driving questions related to ***cost and operational considerations*** **of high-field accelerator magnets**
5	Can we provide accelerator quality Nb_3Sn magnets in the range of 16 T?
6	Is operation at 16 T economically justified? What is the optimal operational field for Nb_3Sn dipoles?
7	What is the optimal operating temperature for Nb_3Sn and HTS magnets?
8	Can we build practical and affordable accelerator magnets with HTS conductor(s)?
9	Are there innovative approaches to magnet design that address the key cost drivers for Nb_3Sn and HTS magnets that will shift the cost optimum to higher fields?
	Driving question related to ***conductor development*** **for high-field accelerator magnets**
10	What are the near and long-term goals for Nb_3Sn and HTS conductor development? What performance parameters in Nb_3Sn and HTS conductors are most critical for high field accelerator magnets?





Baseline cos-theta design



Canted cos-theta concept

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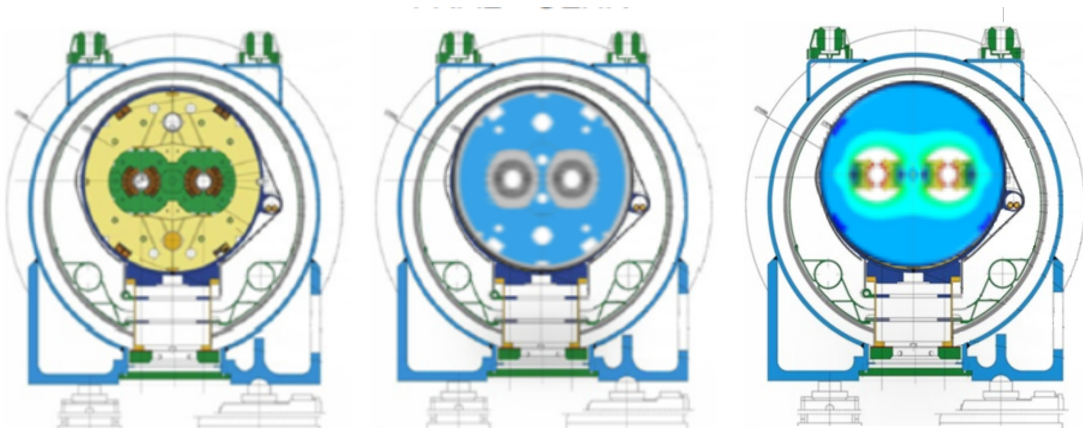
Magnet cost reduction strategy



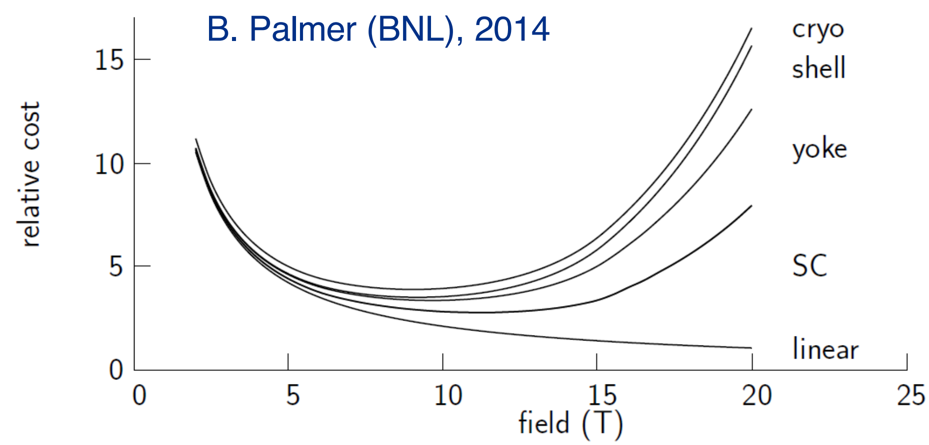
LHC, 56 mm
8.3 T, 1.9 K

LHC, 60 mm
11 T, 1.9 K

FCC, 50 mm
16 T, 1.9-4.3 K

Relative costs of components

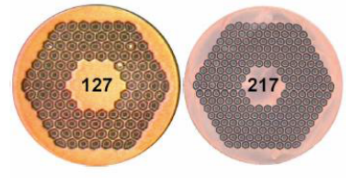
The plot is of the accumulated costs. The labeled part costs are thus represented by the spaces between the lines.



- Reduce magnet cross-section
- Increase magnet length
- Reduce component cost
- Reduce labor
- Improve performance - margin, B_{op}, T_{op}

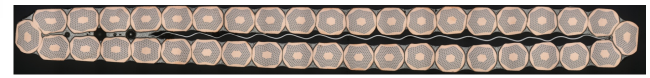
Conductor R&D program

- Nb_3Sn strand and cable
  - Internal Tin, Powder-In-Tube wires → Rutherford cable

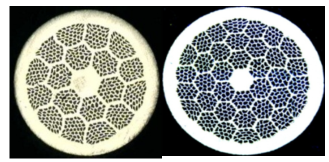


Nb_3Sn RRP strand, OST

40-strand Nb3Sn Rutherford cable



- HTS conductor and cable
  - Bi-2212 wire → Rutherford cable
  - ReBCO tape → ROEBEL cable or CORC



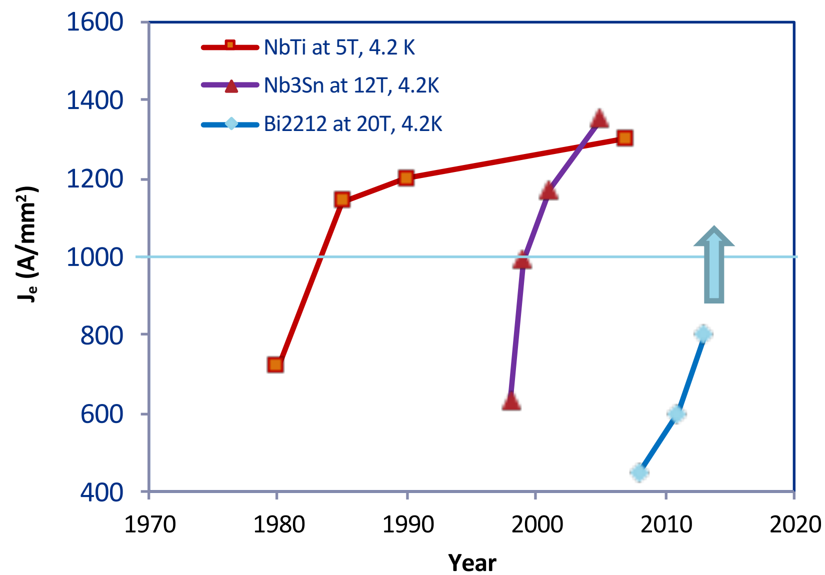
Bi2212 PIT strand, OST

24-strand HTS Rutherford cable

ROEBEL cable

Cable On Round Core (CORC)

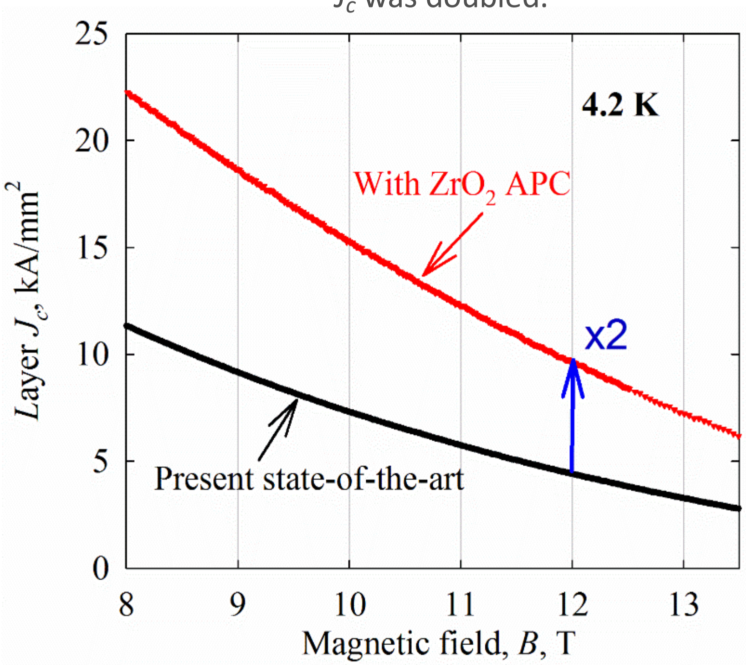
- Objective: improve J_e and reduce cost



A new generation of Nb_3Sn conductors

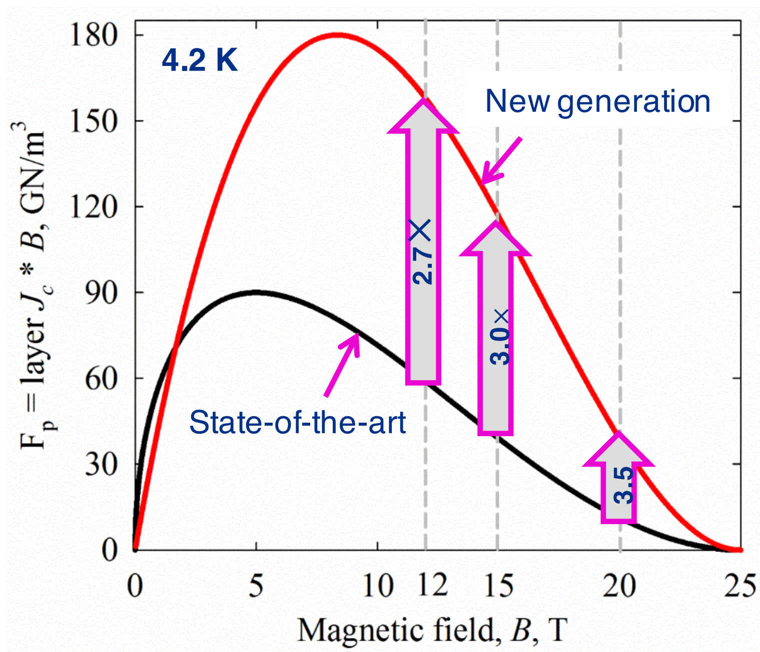
- The key factor of Nb_3Sn conductors for 16 T Nb_3Sn magnets: critical current density, J_c
  - **What we have:** J_c (15 T) = 1300-1500 A/mm² for present state-of-the-art.
  - **What we need:** J_c (15 T) = 2000-3000 A/mm² for fabricating 16 T magnets economically.
- We need 50-100% improvement of 15 T J_c over present Nb_3Sn conductors.
- How can we achieve such an improvement when J_c of Nb_3Sn have plateaued for nearly two decades?

A new technique:
by generating ZrO_2 artificial pinning centers (APC), J_c was doubled.



X. Xu *et al.*, *Adv. Mater.* **27**, 1346-50, 2015.

More improvement by further optimization:
add titanium dopant.



15 T J_c can be improved by a factor of 3.

- This new Nb_3Sn has sufficient J_c for fabricating 16 to18 T magnets.
- Its J_c at 20 T matches HTS.

Next steps:

1. Extend this technology to practical conductors.
2. Further optimization.

Summary

- Future energy-frontier colliders require advances in SC technology beyond state-of-the-art.
- Cost reduction is very important aspect of R&D aimed at developing this technology
- Electron-positron colliders will require large-scale SRF installations, e.g. 16,000 cavities for ILC.
- Recent advances – nitrogen doping and nitrogen infusion, magnetic flux expulsion – demonstrate that there is still room for improvement using bulk Nb.
- Further progress can be achieved with thin film techniques, especially Nb_3Sn cavities.
- High-field SC magnet technology is a cornerstone for future hadron colliders, which require fields of 16 to 20 T, beyond state-of-the-art.
- R&D goals here include exploring performance limits of Nb_3Sn; developing 16-T class accelerator quality magnets; pursuing Nb_3Sn and HTS conductor development to increase performance and reduce cost.