Workshop Goals,
Prospects for HEP SRF Accelerators in the US

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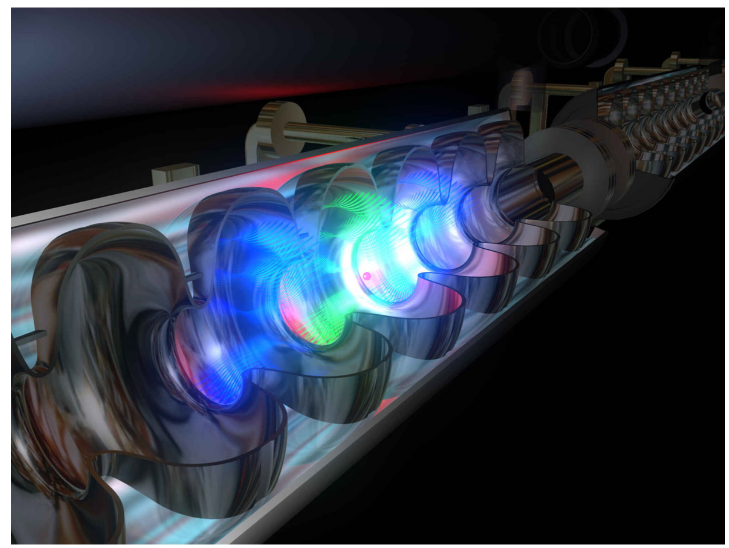
GARD-SRF Roadmap Workshop

9 February 2017

Outline

- Workshop goals and agenda
- Introduction: Future HEP particle accelerators and superconducting RF technology
- SRF challenges for HEP Intensity Frontier
- SRF technology challenges for HEP Energy Frontier: ILC; future circular colliders
- Synergies with NCRF
- Summary



TESLA SRF cavity

Workshop goals

- Discuss SRF R&D needed to support future HEP particle accelerators.
- Provide material for constructing a ten-year roadmap for SRF R&D:
  - Identify research thrusts;
  - Specify key milestones;
  - Specify research activities and parameters we would like to achieve;
  - Propose “stepping stone” facilities as intermediate steps toward future discovery facilities. Ideally, such facilities would be multi-purpose: to validate key R&D concepts and to serve broader user community (e.g. light source).
- A roadmap document will be developed after the workshop and presented to DOE in Germantown in early March.
- SRF and NCRF roadmaps will be combined into a single document for the RF Technology thrust.
- Similar effort in Advanced Accelerator Concepts resulted in Advanced Accelerator Development Strategy Report, published in 2016. The report is posted on the workshop Indico site.

GARD-SRF Roadmap Workshop at Fermilab

- Workshop agenda:
  - Plenary overview talks: Two talks on HEP physics requirements; Overviews from regions (Asia, Europe, USA); Report from NCRF workshop.
  - Round table on cost of SRF machines and cost reduction avenues.
  - WG1: Transformational routes for high gradient and Q → Ultimate Q and gradient limitations for SRF; New materials and surface structures; Fundamental understanding of SRF material properties.
  - WG2: Evolutionary developments → Nitrogen doping and infusion, other surface treatments; Nb3Sn cavity development; Thin film technology; Abatement of Field Emission.
  - WG3: RF ancillaries → RF power couplers, RF sources, HOM dampers, frequency tuners.
  - Discussion on future US facilities to validate R&D concepts.

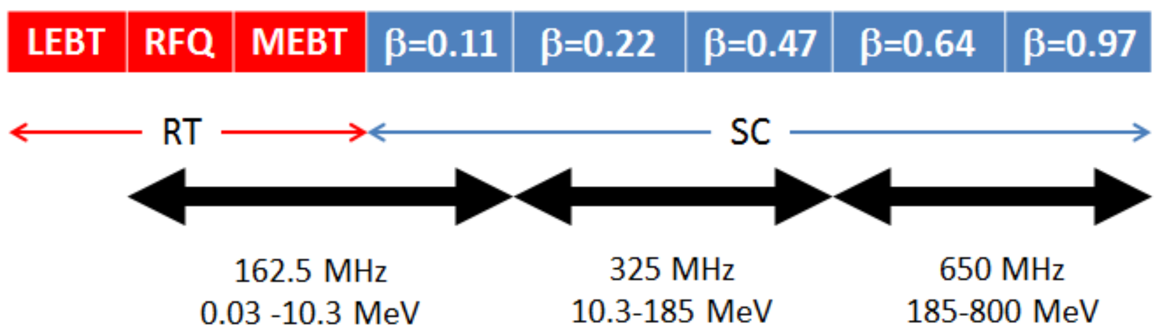
Introduction

- Superconducting radio frequency technology is a ***cornerstone technology*** for the next generation of high-energy particle accelerators.
- Future Intensity Frontier machine at Fermilab, PIP-III, will target > 2.4 MW proton beam power. One of the options under consideration is an 8-GeV SRF linac.
- Future generation of lepton colliders will require RF systems to be "***affordable***" and able to support ***high luminosity***.
- The former necessitates cavities operating shorter acceleration systems (***high accelerating gradient***) with lower 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***).
- In this talk I will briefly describe challenges to the SRF technology arising from the next generation of HEP accelerators, outline possible R&D paths and point out synergies with NCRF technology.

- *Leitmotif: cost, cost, cost …*

HEP Intensity Frontier: from PIP-II to PIP-III

- PIP-II, an upgrade of existing Fermilab accelerating complex, will bring the beam power to 1.2 MW.
- PIP-II 650 MHz cavities need further R&D on nitrogen doping to reach spec on *Q*.



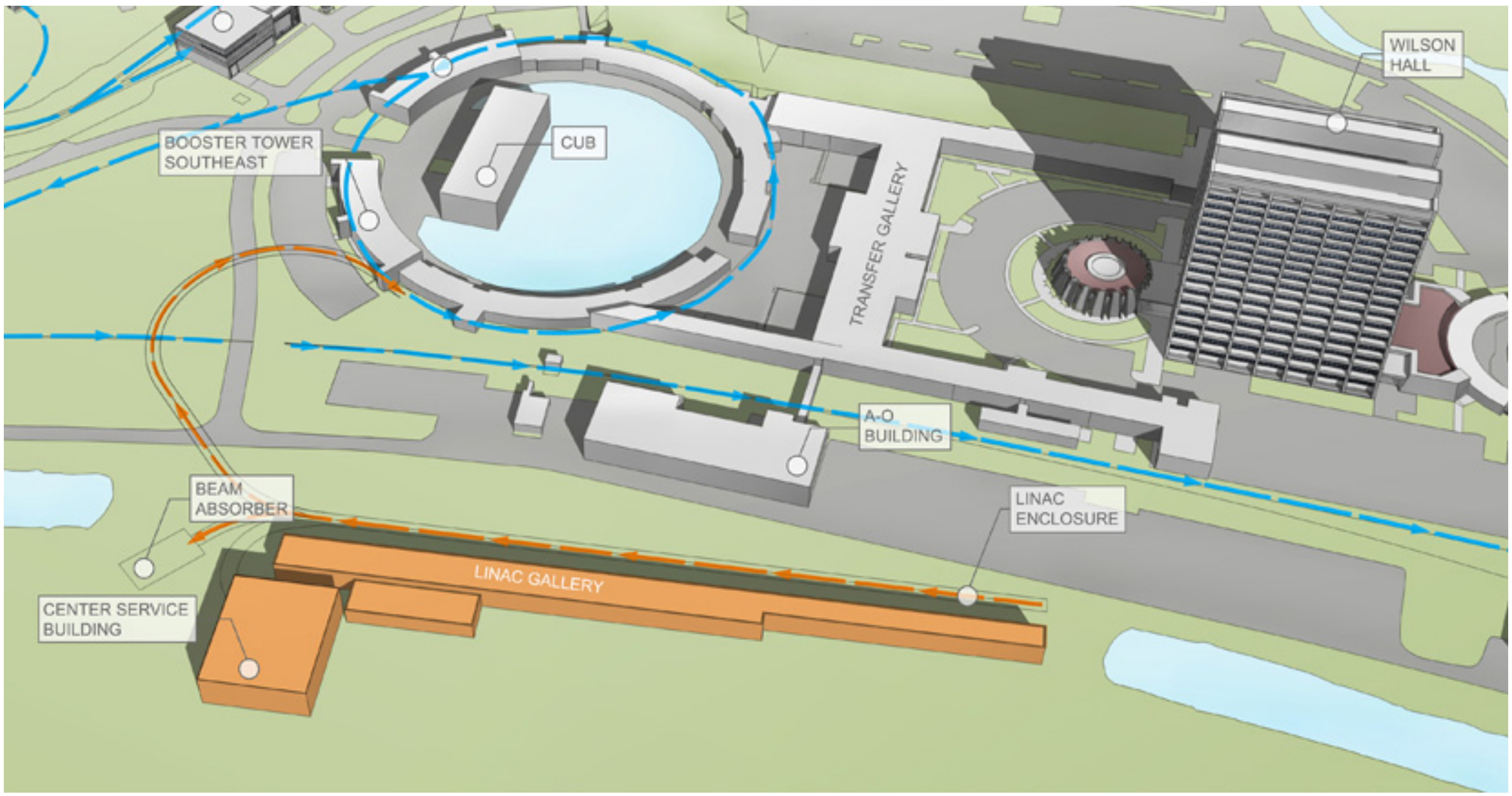
PIP-II Technology Map

General parameters of SC cryomodules

CM type	Cavities per CM	Number of CMs	Acc. gradient (MV/m)	CM length (m)	Q_0 at 2K (10^{10})	Surface resistance, (nOhm)	Loaded Q (10^6)
HWR	8	1	9.7	5.93	0.5	9.6 (2.75)	2.7
SSR1	8	2	10	5.2	0.6	14 ($10^{\#}$)	3.7
SSR2	5	7	11.4	6.5	0.8	14.4	5.8
LB650	3	11	15.9	3.9	2.15	8.9	11.3
HB650	6	4	17.8	9.5	3	8.7	11.5

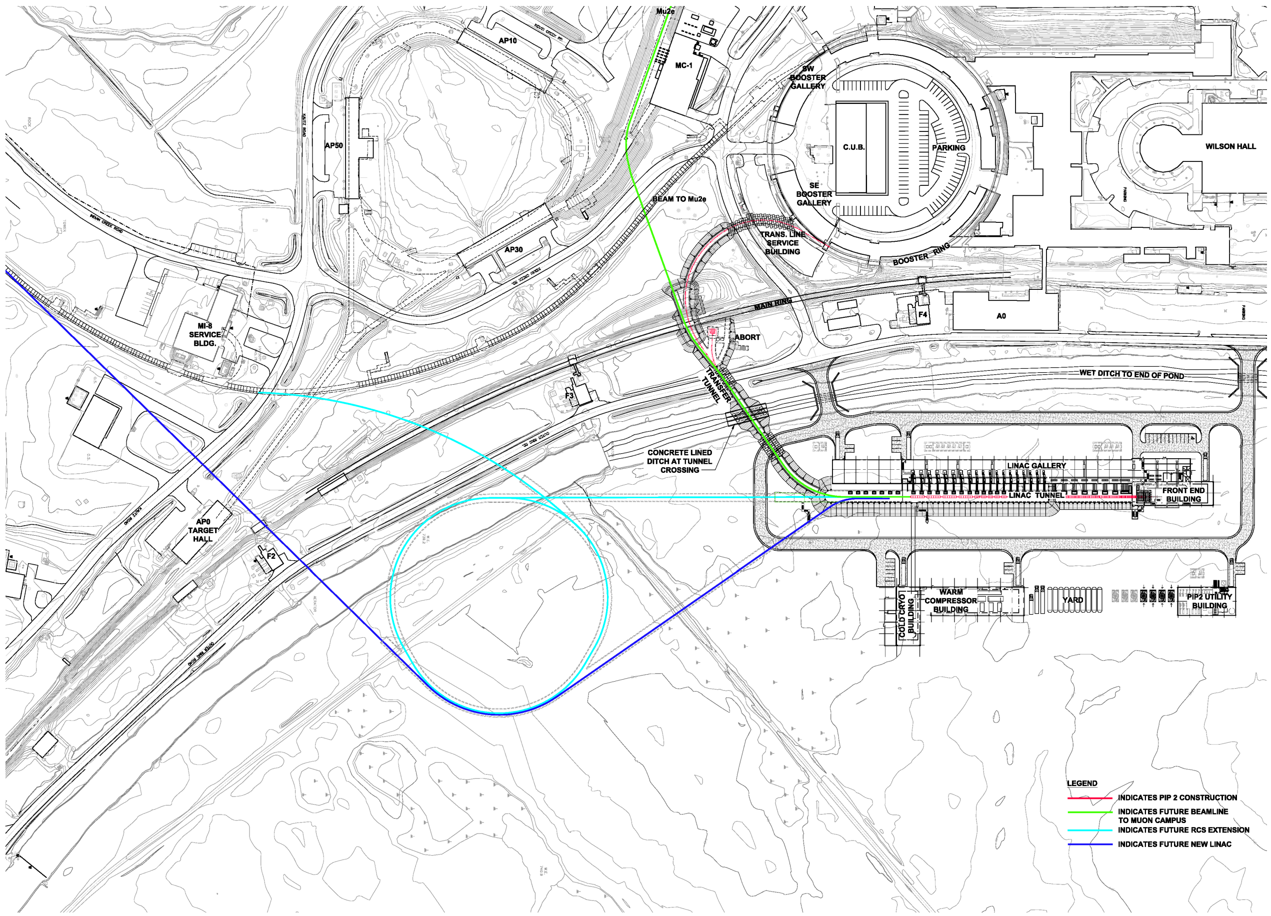
PIP-II Project

- PIP-II is now a project in CD0 stage. We expect to get CD1 by early next FY.
- PIP-II Project aims to provide 1.2 MW starting in 2025-26 with a new 800-MeV CW-capable superconducting linac.



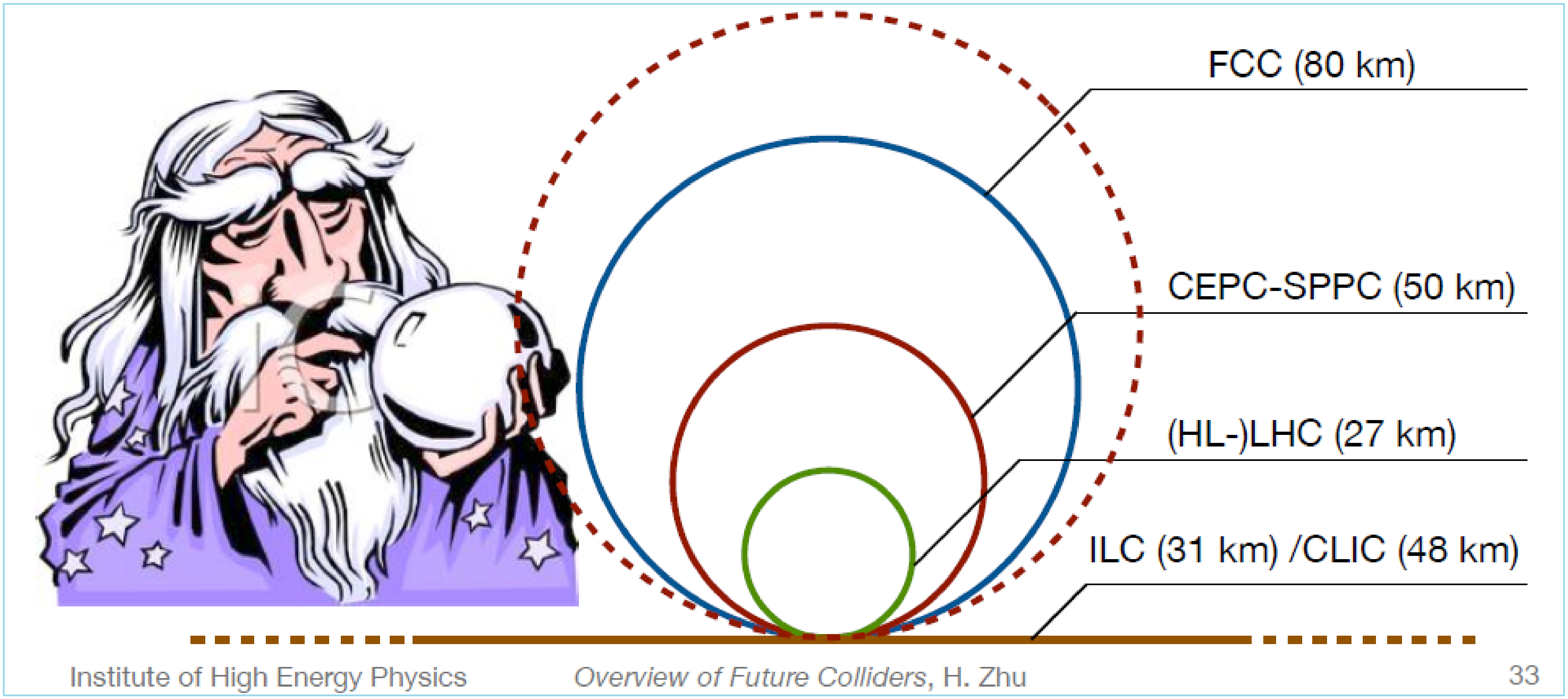
PIP-III

- Achieving 2+ MW will require replacement of the Booster with either a 6-8 GeV pulsed linac or a rapid cycling synchroton (RCS) fed by a ≥0.8 GeV linac.
- An SRF linac will operate at 650 MHz up to 3 GeV (CW-capable) and at 1.3 GHz up to 8 GeV (pulsed).
- Challenges for SRF: ***High Q*** for CW and ***high gradient*** for pulsed operation.



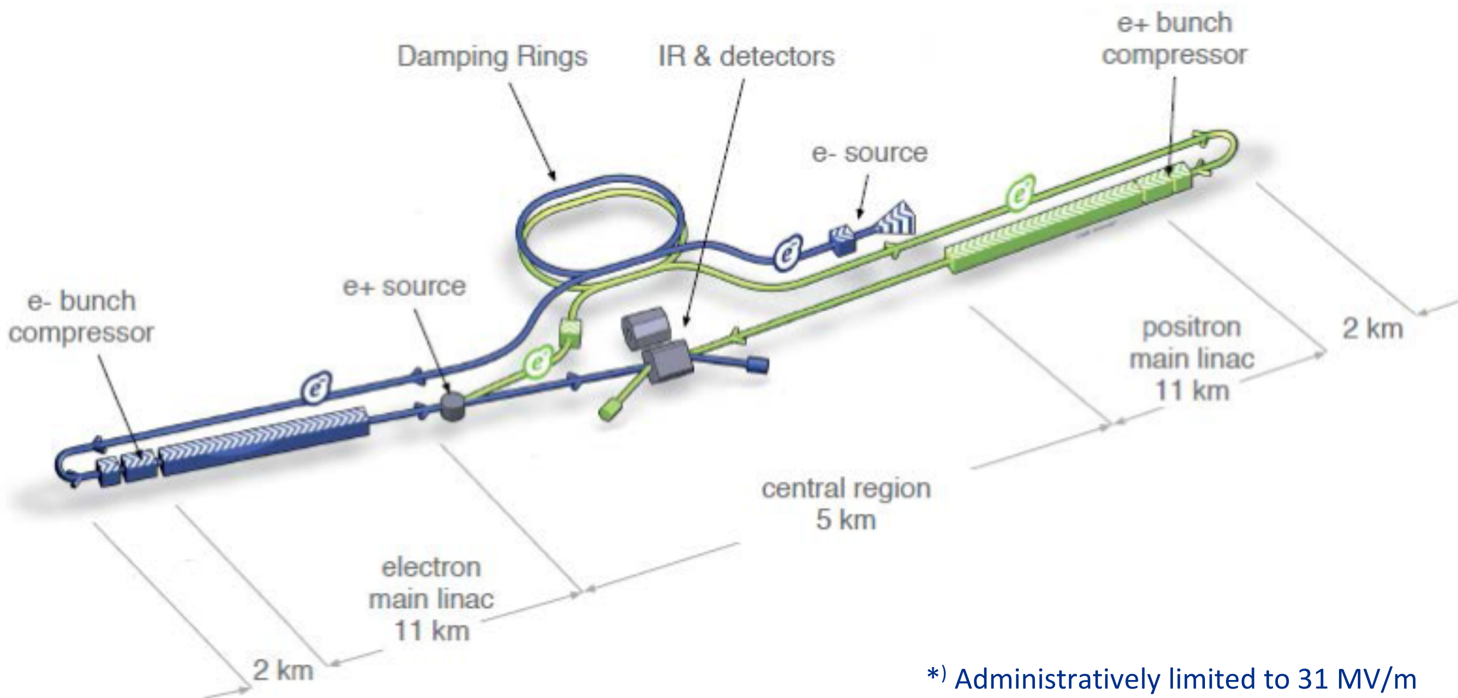
Future colliders: scale of the problem

- 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

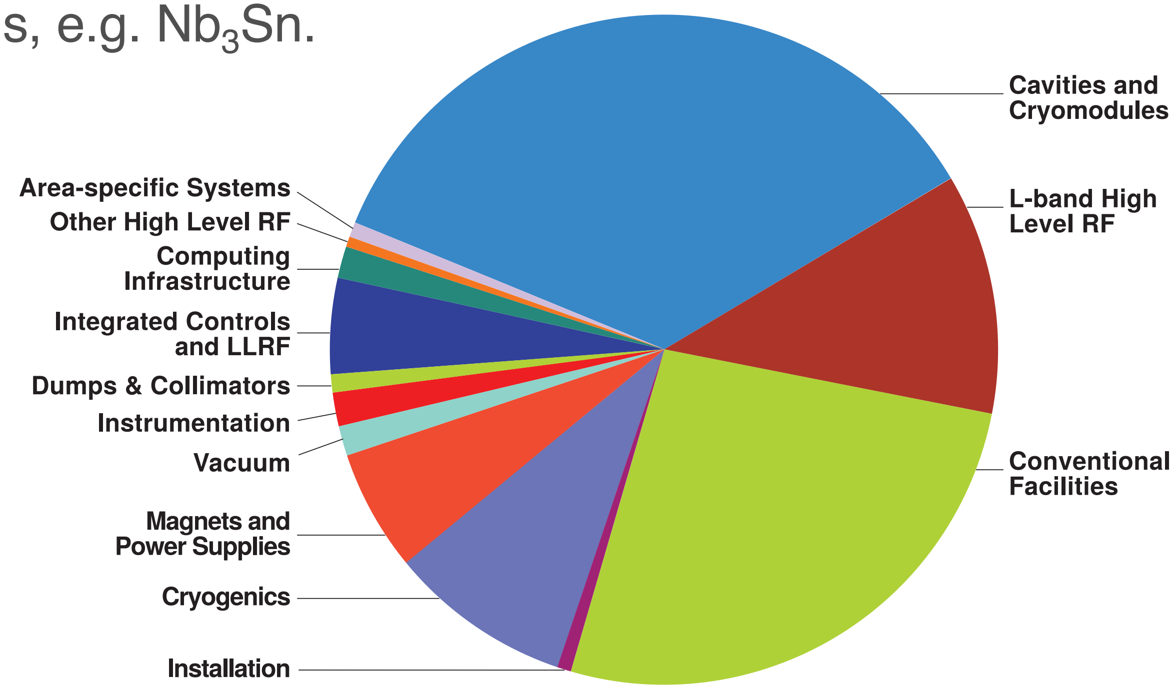
- The ILC TDR specs, 31.5 MV/m with $Q > 10^{10}$ and 90% yield, have been demonstrated on a small scale.
- Average gradient of XFEL cryomodules is 27.9 MV/m* with only 5 of 98 tested CM modules below spec (23.6 MV/m). The average Q factor is $\sim 1.4 \cdot 10^{10}$ at 20-23 MV/m.
- Field emission (FE) is still an issue at high gradients.
- ILC cost is still a major concern for funding agencies.



*) Administratively limited to 31 MV/m

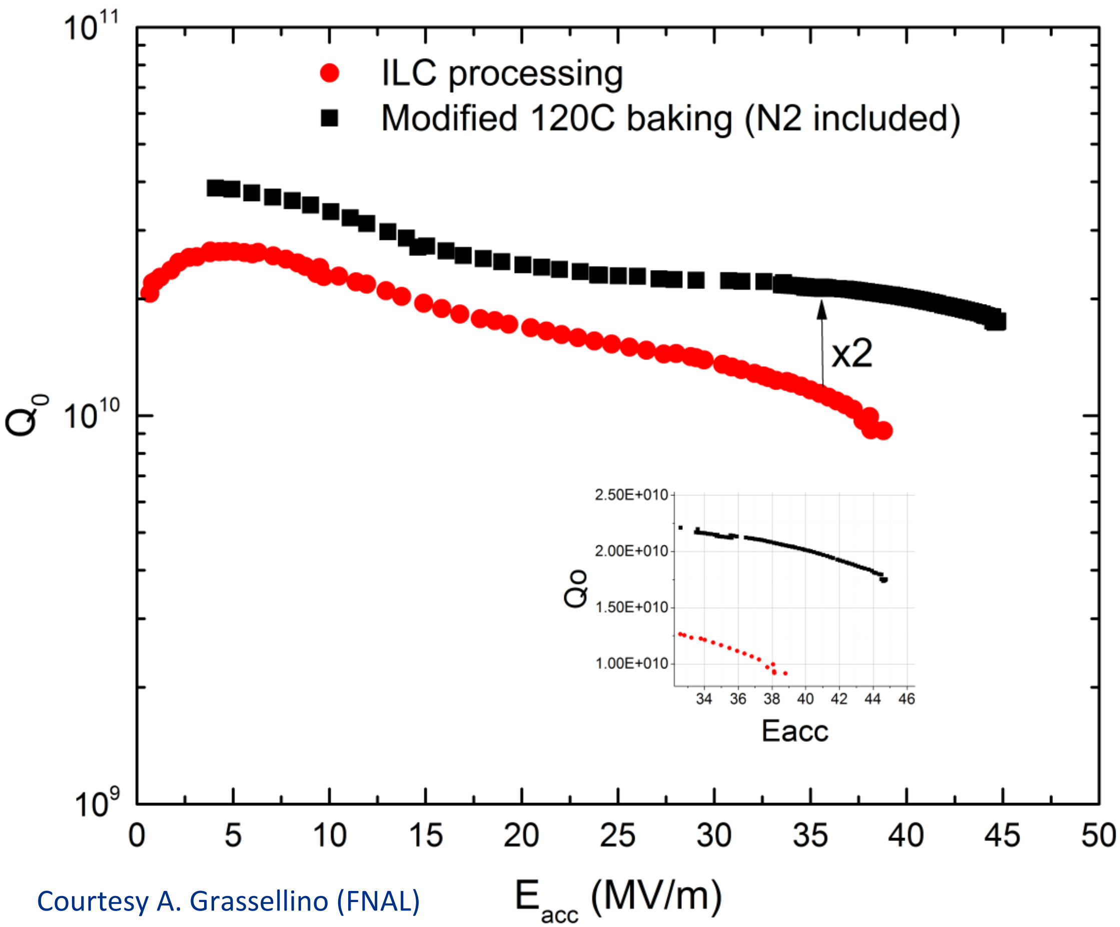
SRF technology for ILC: path to cost reduction

- 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- and mid-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.



Cost Breakdown from ILC TDR

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



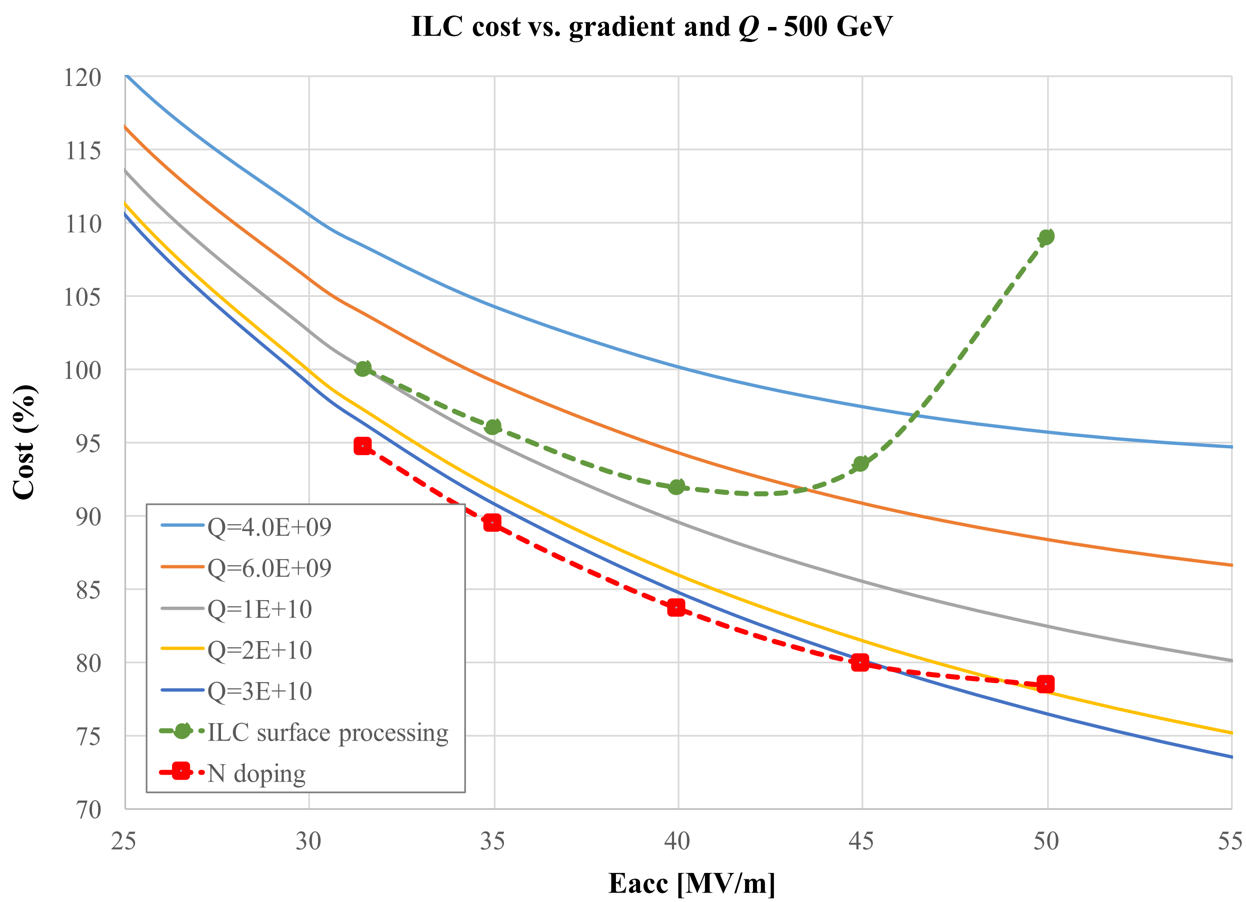
Courtesy A. Grassellino (FNAL)

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.

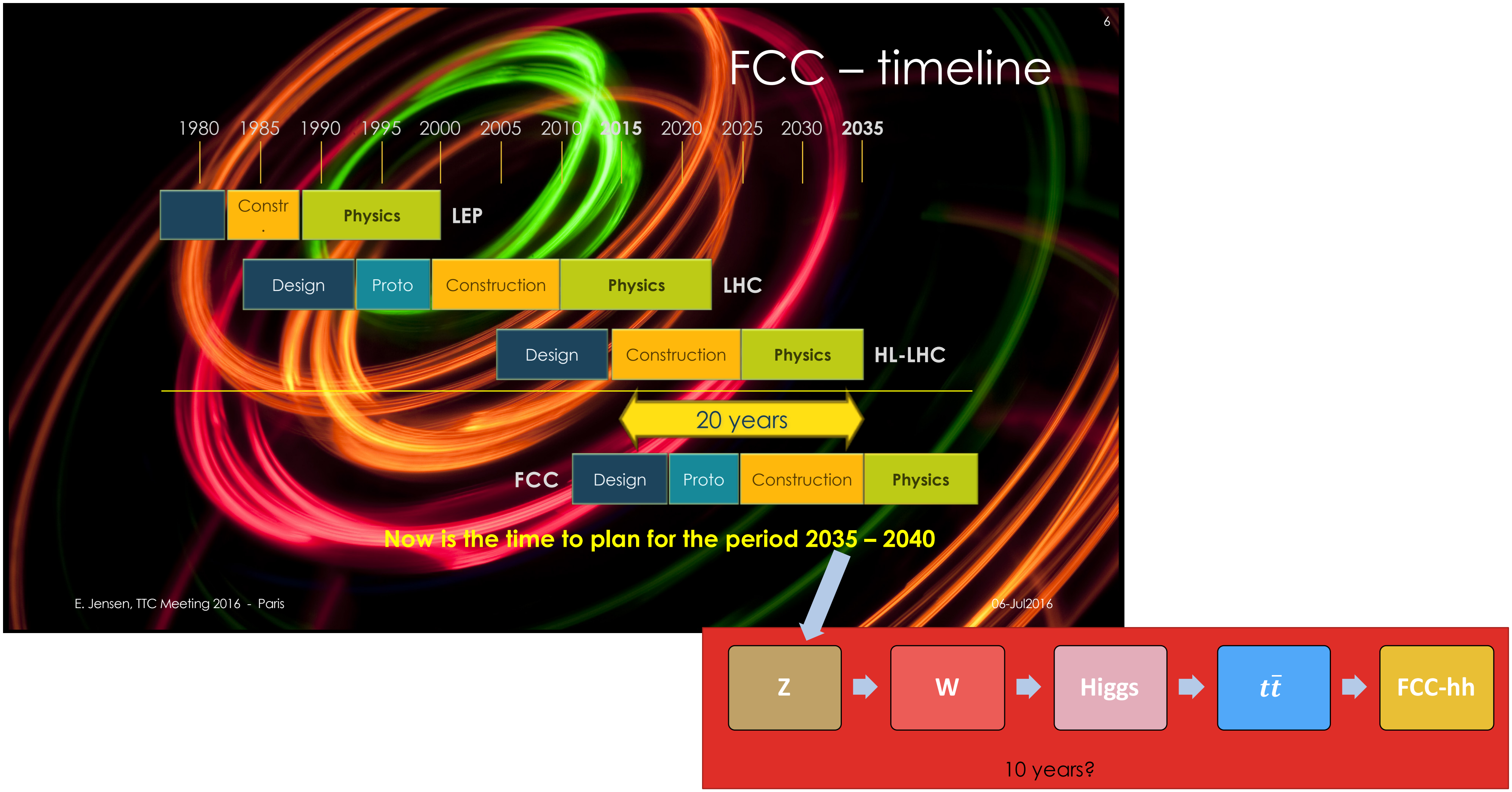
Potential ILC cost reduction

- 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

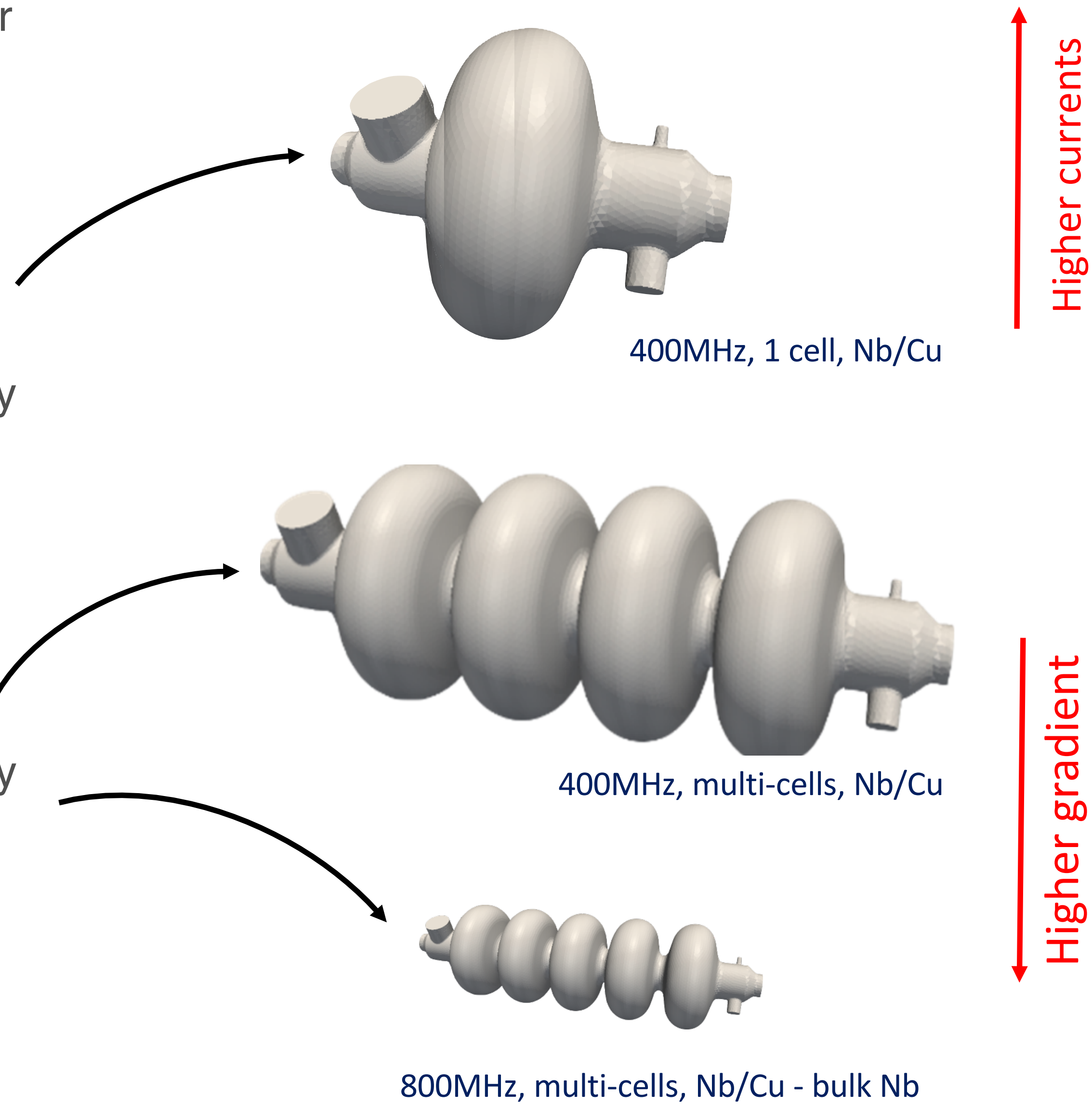
Courtesy E. Jensen (CERN)

short bunches

"high gradient" machines

SRF technology for FCC-ee

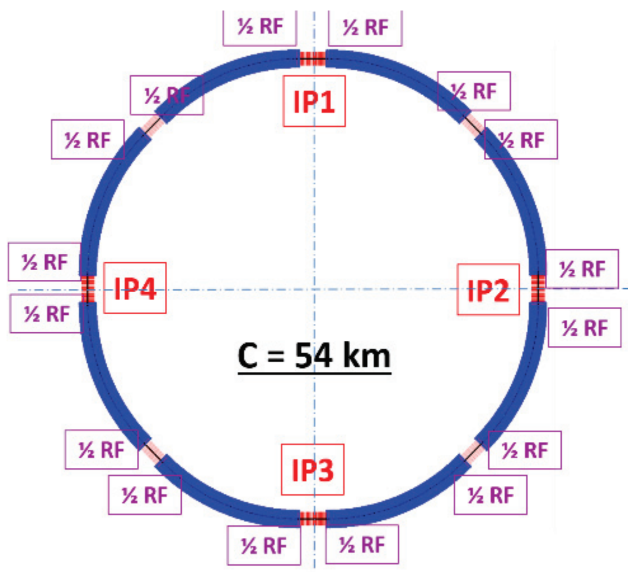
- Parameters of the FCC-ee options cover very wide range and cannot be satisfied with one SRF system design.
- At the "***high current***" end, where the total voltage is relatively small, the design will be determined by ***strong HOM damping*** requirements and RF power couplers. Hence, single-cell 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***.



Courtesy E. Jensen (CERN)

SRF technology for CEPC

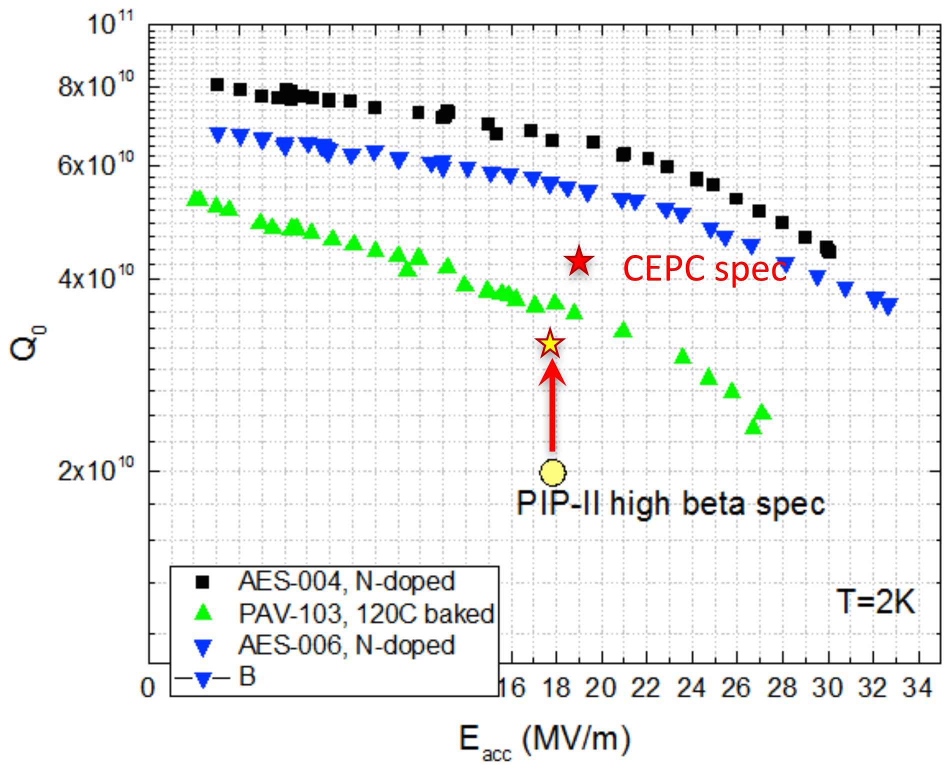
- CEPC's main physics goal is operation at 240 GeV center-mass energy as a Higgs factory.
- The collider RF system will consist of 384 650-MHz 5-cell SRF cavities operating at 19.3 MV/m with *Q* of $4 \cdot 10^{10}$.
- Nitrogen doping and magnetic flux expulsion technologies will be used to support high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

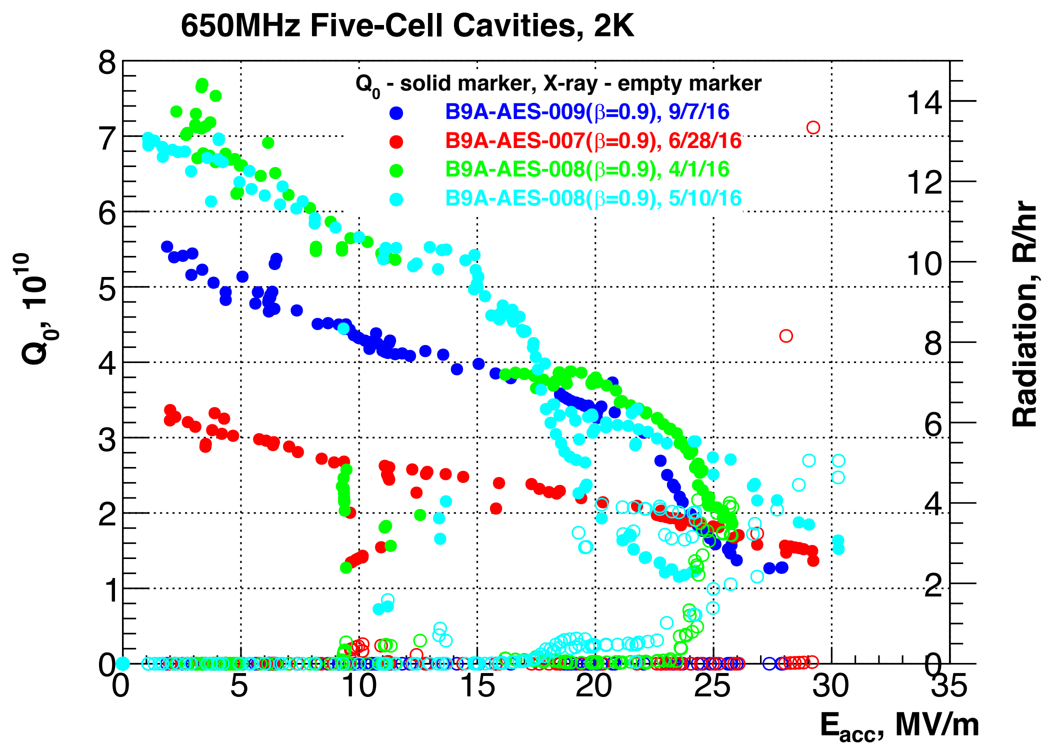


CEPC layout from J. Y. Zhai, et al., SRF2015

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.

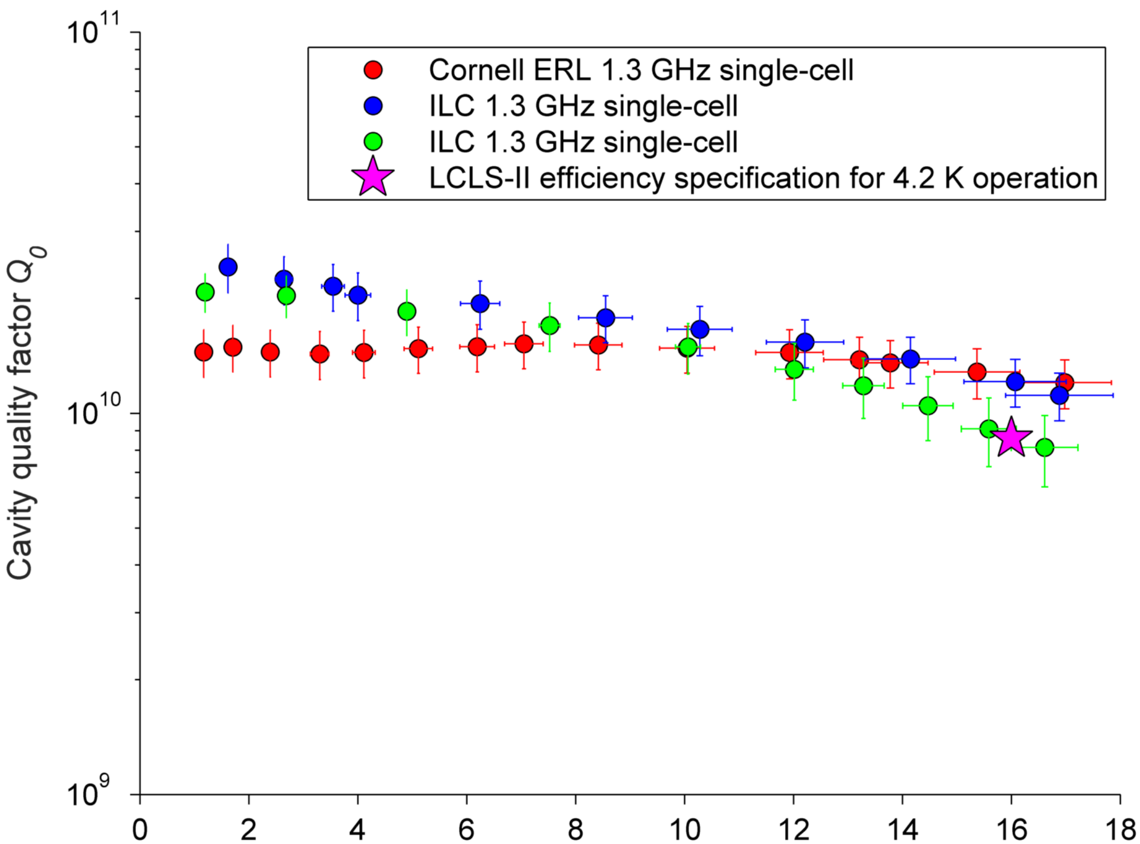




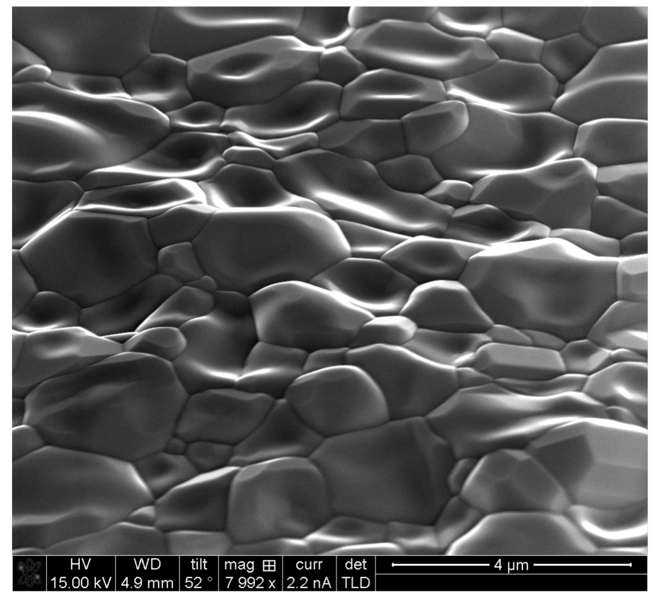
Courtesy A. Grassellino (FNAL)

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; exploring ways to improve gradient.



Courtesy D. Hall and M. Liepe (Cornell)



Nb_3Sn cavity surface
Courtesy Cornell University

Multi-purpose ILC facility?

- Can we imagine a multi-purpose facility based on ILC? Is this crazy enough?
- The SRF linac can be sectioned into several linacs. Each linac can have different energy and beam parameters, tuned to a particular user community. Then a facility for a particular purpose could be built around each linac, e.g.
  - Linac 1: CW FEL (*a la* LCLS-II)
  - Linac 2: pulsed FEL (*a la* European XFEL)
  - …
  - Linac N: MaRIE-like machine, especially if high-power proton linac happens to be nearby ☺
- Time-share concept, e.g. 50% time for HEP, 50% for other experiments working in parallel.

Synergies with NCRF

- High-power fundamental power couplers.
- Flexible RF power distribution system
- High-efficient RF sources
- New analytical and modeling tools

Summary

- Future HEP IF and EF accelerators require advances in SRF 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.