Research and Development in the United States towards the FCC RF/SRF systems

26 March 2024

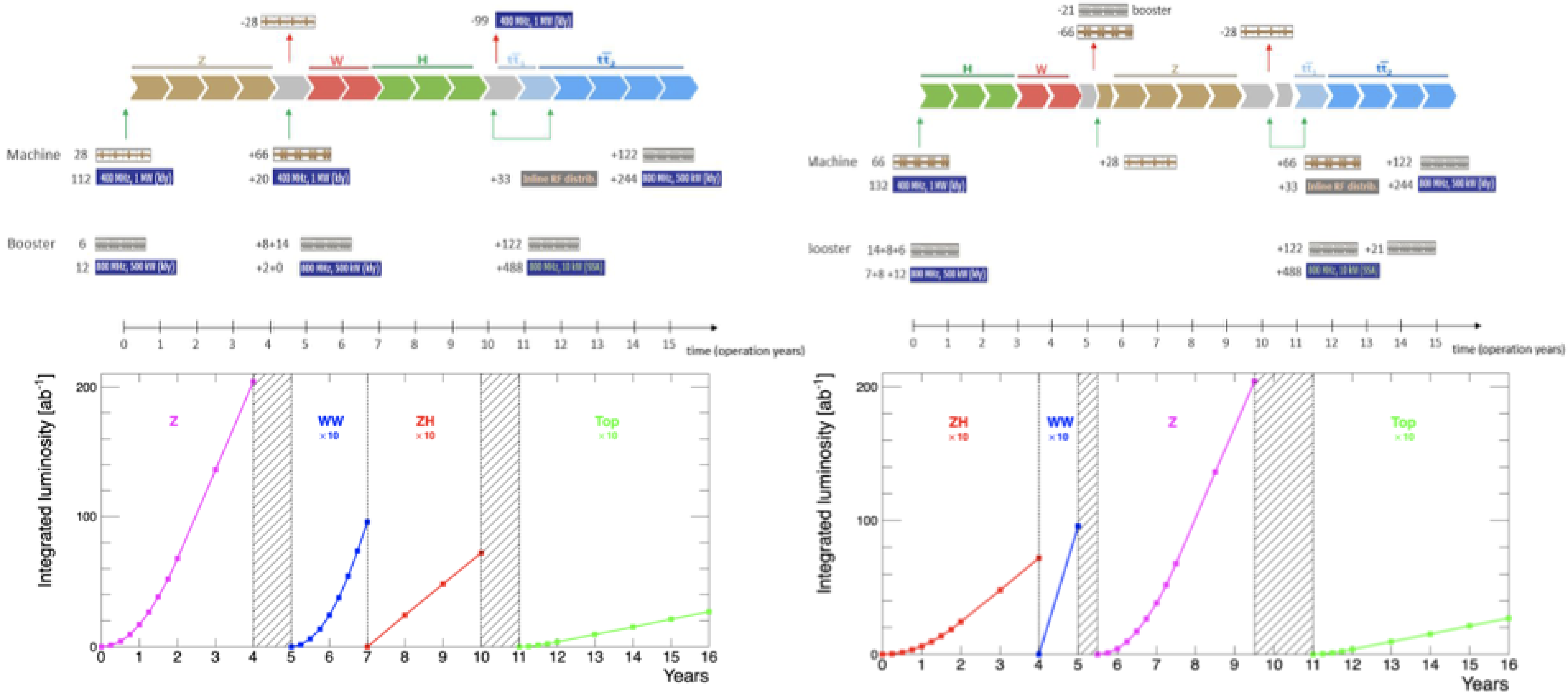
Kellen McGee, Ph.D., *FNAL*

Outline

- Introduction of Goals/Overview
- SRF development
  – Bulk Nb: Current and ongoing High Q cavity studies, tuner/design concepts, cryomodule design concepts
  – Nb/Cu energetic deposition, SIS multilayer studies
- RF sources/modulators development
  – Models for electron-positron source/injector linac
  – High-efficiency klystron development

SLAC Fermilab Jefferson Lab

Operation sequences for FCC-ee and RF configuration



- Evolution of RF configuration of collider and booster with beam energies and physics operation points
- Long-term R&D for SRF, in particular for the 800 MHz system

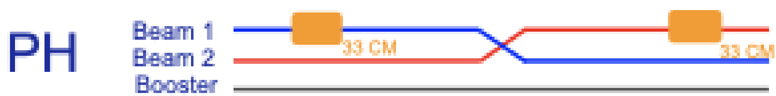
**from Michael Benedikt, Status of the FCC plenary, 3/25/2024*

RF parameters

Limiting parameters
Cavities qualified in VT with 20% margin on Q0 and Eacc

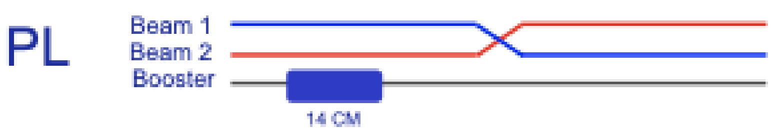
	Z		W		H		ttb		
	collider	booster	collider	booster	collider	booster	collider	collider	booster
RF Frequency [MHz]	400	800	400	800	400	800	400	800	800
Cavity type	1-cell	5-cell	2-cell	5-cell	2-cell	5-cell	2-cell	5-cell	5-cell
Eacc [MV/m]	3.8	6.2	10.6	20.1	10.6	20.1	10.6	20.1	20.1
Q0	2.7E+09	3.0E+10	2.7E+09	3.0E+10	2.7E+09	3.0E+10	2.7E+09	3.0E+10	3.0E+10
Epeak [MV/m]	8.4	12.8	21.2	41.2	21.2	41.2	21.2	41.2	41.2
Bpeak [mT]	20.4	27	56.6	87.2	56.6	87.2	56.6	87.2	87.2
Beam current [mA]	1280	128	135	13.5	53.4	2.7	10	10	0.5
RF power [kW]	900	210	378	89	382	45	78	163	8
Optimum Qext	2.6E+04	3.1E+05	9.2E+05	7.6E+06	9.1E+05	1.5E+07	4.5E+06	4.2E+06	8.1E+07
Optimum detuning [kHz]	13.662	4.385	0.575	0.140	0.106	0.013	0.009	0.056	0.002
Operating temp. [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav * [W]	9	0.3	129	3	129	3	129	23	3
stat losses/cav * [W]	8	8	8	8	8	8	8	8	8
# CM (with 4 cav/CM)	14 per beam	6	33 per beam	14	66	28	66	122	150

* Heat loads from power coupler and HOM couplers not included



one RF system per beam

common RF system for both beams
beam current is multiplied by two



Total of ~370 cryomodules and 1500 cavities with 75% in bulk niobium technology

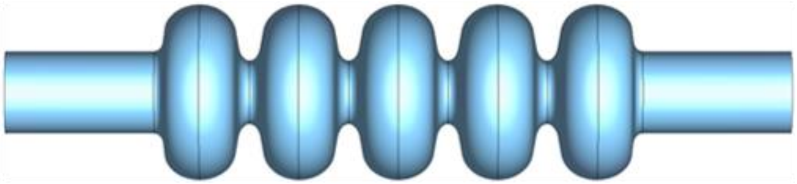
**from Franck Peauger, and CERN SRF Team*

800 MHz bulk Nb SRF Development

FCC Goals overview

- High-efficiency 800 MHz RF power sources and modulators
- FCC-ee SRF R&D
  - Phase 1: R&D on cavities to reach $Q_0 = 3 \times 10^{10}$ at $E_{acc} = 25$ MV/m for Booster up to Higgs operation (120 GeV per beam)
  - Phase 2: R&D on cavities to reach $Q_0 = 6 \times 10^{10}$ at $E_{acc} = 25$ for Booster and Main Ring for $\mathrm{t}\bar{t}$ operation
  - In parallel: Cryomodule (CM) design optimization for 800 MHz cavities, possibly with integrated focusing
    - 28 CMs for the booster up to the *H* energy
    - 244 CMs for the $\mathrm{t}\bar{t}$ energy

5-cell 800 MHz FCC SRF cavity goals



- Bulk Nb, High Q
- Desired performance
  - **Eacc = 20 MV/m, Q0 = 3e10 in operation**
  - **Eacc = 24.5 MV/m, Q0 = 3.8e10 in vertical test**

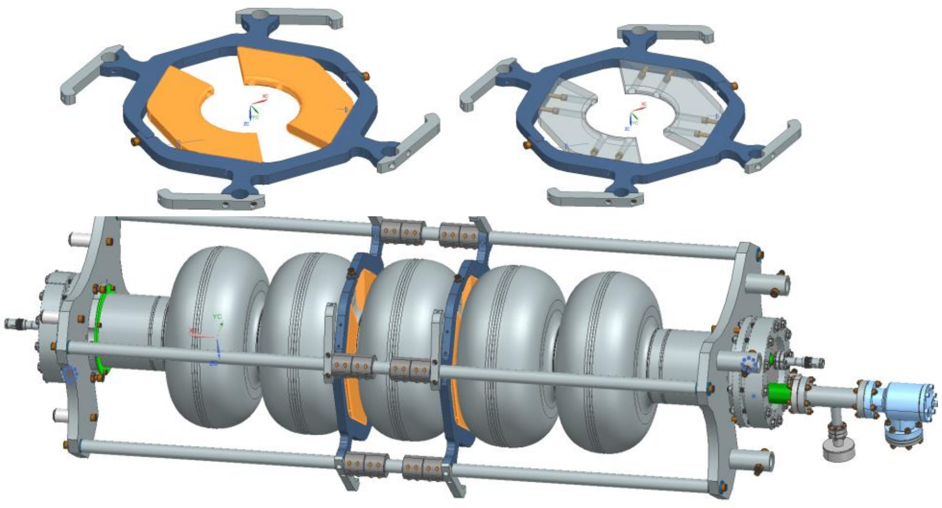
	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1280	0.080
W	80	135	1.05
H	120	26.7	2.1
ttb	182.5	5	11.3

High current machine

High gradient machine

800 MHz 5-cell prototype cavity

- Fabricated at Jlab, currently at FNAL
- High-power RF cold-test plan (Spring 2024):
  1. Baseline cold-test (EP, last tested 2018, see Figure 4.)
  2. First mid-T (300-350C) baking treatment (Spring 2024)



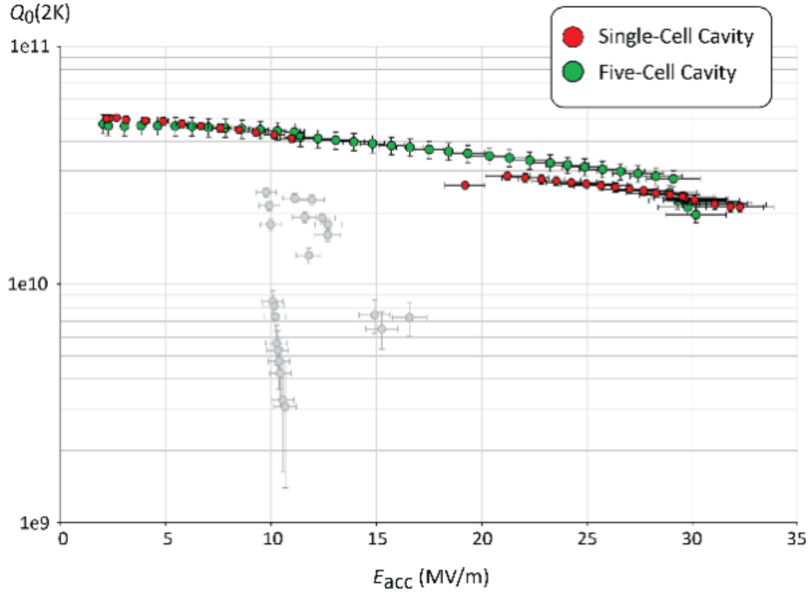
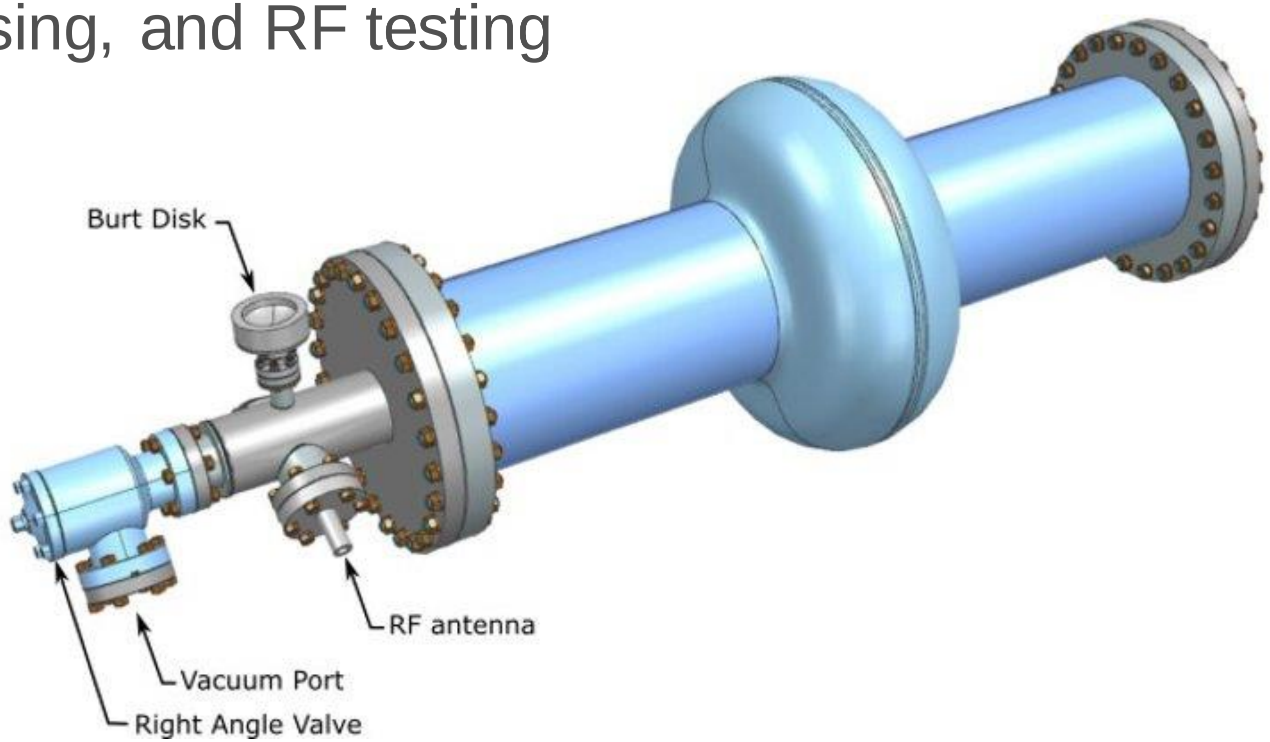


Figure 4: Combined VTA results for the five-cell and single-cell cavity as measured at 2 Kelvin.

F. Marhauser et al. [802 MHz ERL Cavity Design and Development (cern.ch)](#) *IPAC 2018* THPAL146

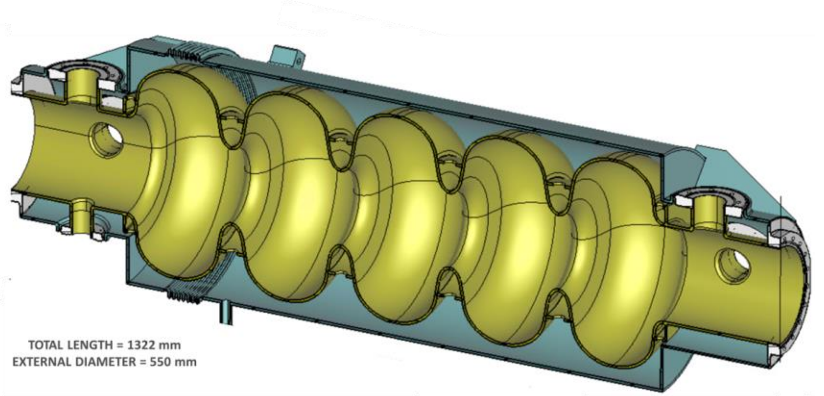
1-cell 800 MHz design

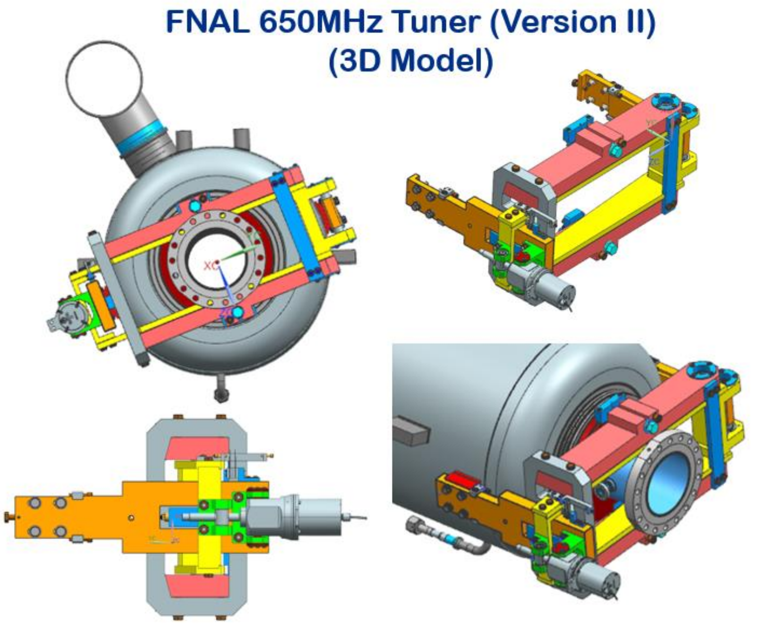
- FNAL mechanical design based on CERN RF design (end-cells)
- Compatible with high-temp; Nb3Sn cavity R&D
- CERN to fabricate 3 in-house, send to FNAL for bulk surface processing, and RF testing



Integrated jacketed cavity + tuner design

- Initial design proposed by CERN
- FNAL contributing changes based on PIP-II,LCLS-II, e.g:
  - Redesign with smaller bellows
  - Integrated He jacket and tuner design so loads/stiffness managed efficiently
- Tuner design to be based on modified FNAL 650 MHz double-lever tuner
  - FNAL has unique experience manufacturing/QA testing these in production quantities

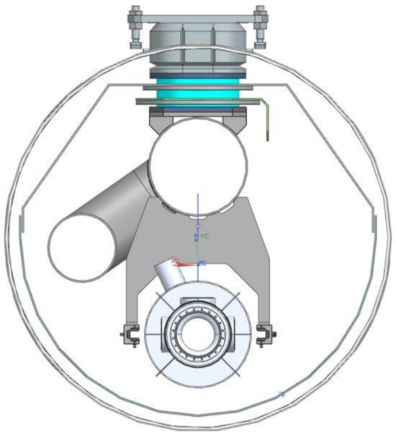




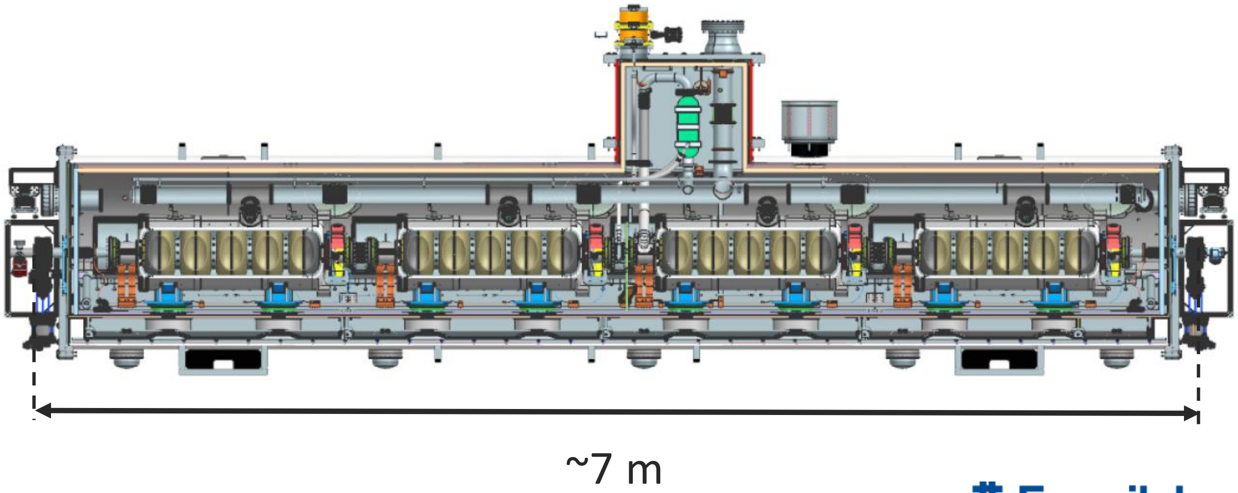
Cryomodule design

- FNAL has undertaken preliminary design work for segmented, continuous, and hybrid cryomodule concepts
  - Fine-segmented design draws heavily on PIP-II design, which also benefits from PIP-II international shipping studies, etc.
  - Continuous design concept in early stages, based on LCLS-II CM design

Continuous design:



Segmented design, with 800 MHz cavities:

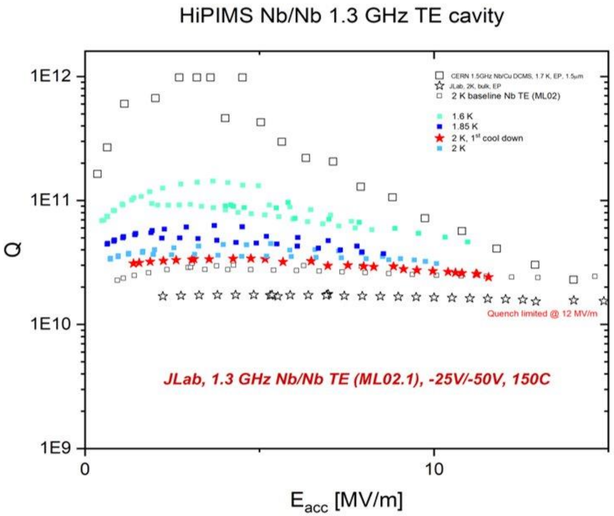


Developing contributions

Nb/Cu cavity development

Courtesy A-M. Valente-Feliciano

- Aim: Enable 4 K operation
- HiPIMS & ECR @ JLAB
  - 1.3 GHz Nb/Nb demonstration
  - lower frequency cavity deposition: 952.6 & 800 MHz, substrates on hand
  - Ideal substrates development
    - Machining (CERN), hydroforming (KEK)



Courtesy: G. Rosaz, K. Scibor - CERN

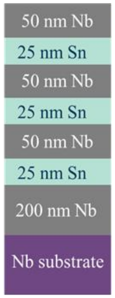
Machined cell

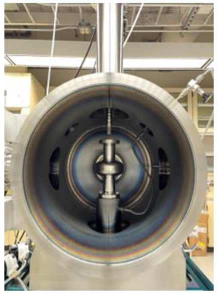
E-beam welded to cut-offs

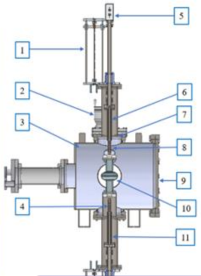
Advanced SRF development

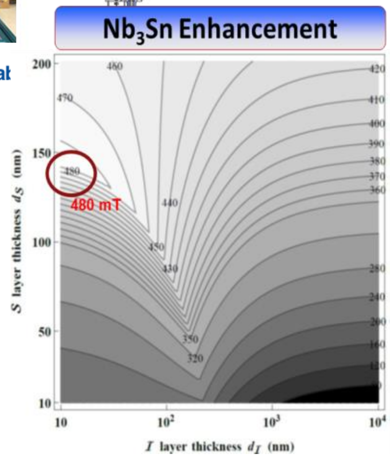
Jefferson Lab
Courtesy A-M. Valente-Feliciano

- Above 20 MV/m demonstrated in 1-cell, 15 MV/m demonstrated in multicell Nb3Sn at FNAL
- Material studies and development of Nb3Sn cavities @ JLab
  - Alternative deposition methods, SIS multilayer materials
- Process developments towards Nb3Sn cavities in operation
  - 1e10 @10 MV/m
  - Cavities coated @JLab & FNAL
  - ¼ cryomodule assembly complete!
  - Test scheduled April 2024

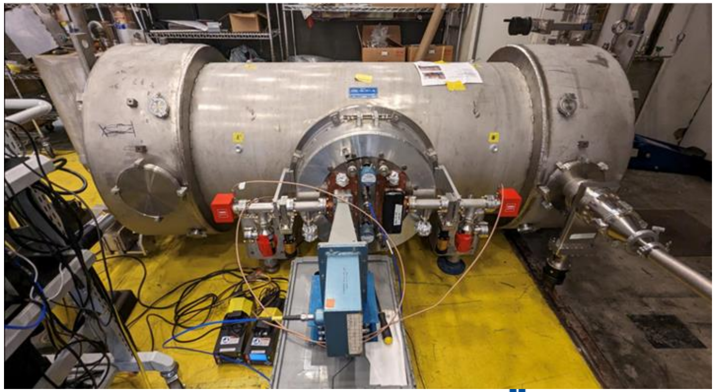








Based on G. Eremeev's ECA, Jlab cavity work supported by R&D fund.

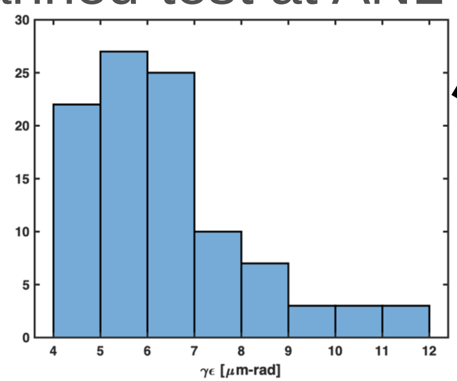


RF Accelerator Technologies for FCC-ee

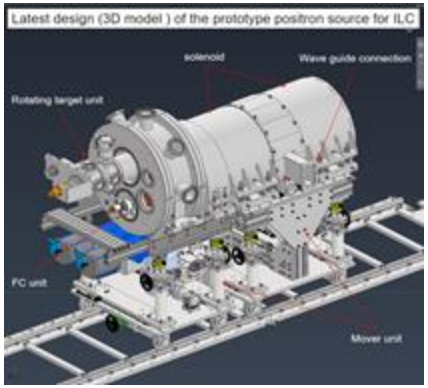
Courtesy E. Nanni

- FCC injector complex (up to 20 GeV) linac
  - Compact and high-gradient RF accelerator for injection
  - Design studies for versatile bunch format (multi-bunch and full range in charge)
  - US-Japan program on positron sources – expand to FCC-ee
    - FCC-ee common electron and positron injector linac from 6 to 20 GeV based on cold-copper: reduce length by 3.5x or reduce RF power by 3.5x
  - Planned test at ANL

Lucretia simulation 90% of seeds < 8 um-rad

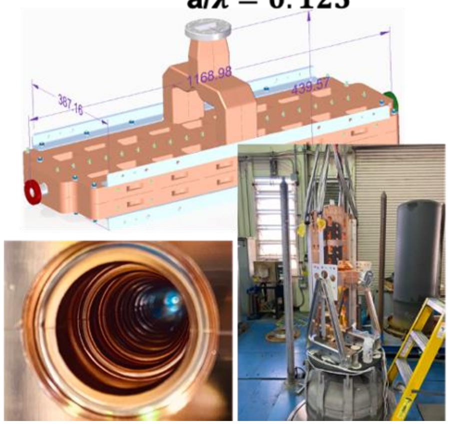


Electron Driven Positron Source



Courtesy of Y. Enomoto

Wide Aperture S-band Injector Linac
$a/\lambda = 0.125$



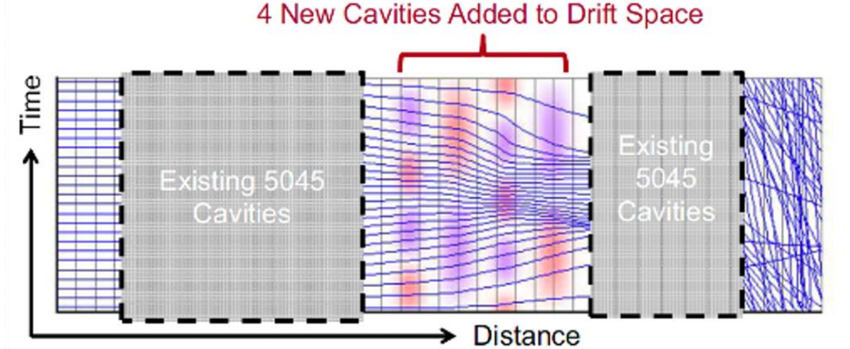
RF sources for FCC-ee

Courtesy E. Nanni

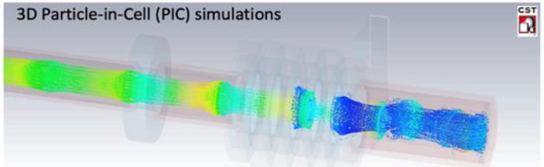
- High-efficiency RF sources needed for Injector, Booster, and collider ring

- SLAC is a participant of the CERN lead HEIKA collaboration on RF Sources
- Active development of permanent magnet klystrons
- Demonstration of high-efficiency and energy recover concepts

SLAC BAC Prototype
S-band Retrofit +10% efficiency, 73 MW



N, 12 GHz klystron (CERN/CPI).



	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	59
Efficiency, %	36.2	69
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.37
RF circuit length, m	0.316	0.316

SLAC Green-RF Energy Recovery

Summary

- Multiple strong avenues for US-FCC involvement on RF/SRF systems
  - Ongoing High Q cavity studies
    - 1-cell and 5-cell prototypes available for advanced surface processing development
    - Integrated jacket/tuner design underway
    - CM design studies undeway
  - Nb/Cu, Nb3Sn, SIS fundamental R&D ongoing
  - RF injector linac/RF power source improvement ongoing
- Multiple projects poised to make meaningful progress with dedicated FCC support

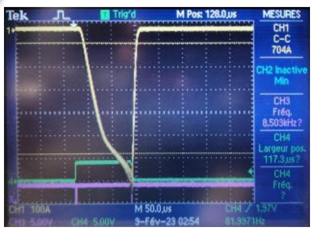
SLAC Fermilab Jefferson Lab

Development of Nb/Cu Cavities by Energetic Condensation

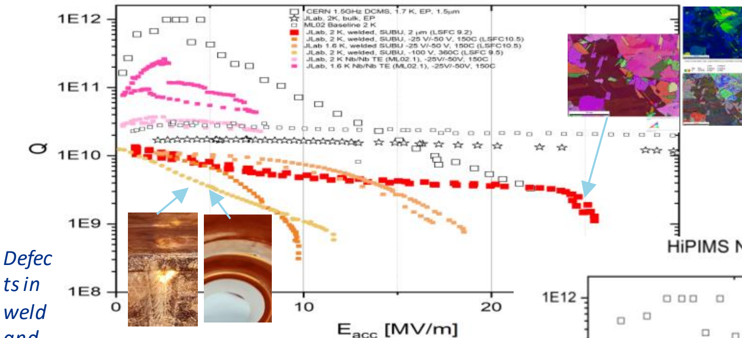
A.-M. Valente-Feliciano et al.

HiPIMS & ECR

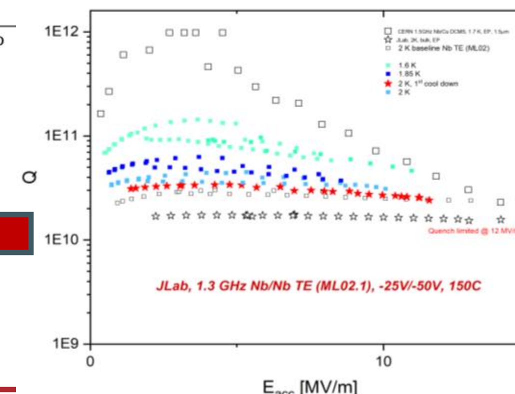
- ❑ HiPIMS cavity coating @ 1.3 GHz
  Deposition ramped up to 1 cavity/week if substrate available
- ❑ lower frequency cavity deposition
  (952.6 & 800 MHz, substrates on hand)



Defects in weld and from SUBU process



HiPIMS Nb/Nb 1.3 GHz TE cavity



HiPIMS Nb film on bulk Nb at 1.3 GHz, no significant Q-slope
No intrinsic limitation from the film itself

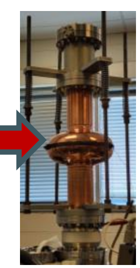
Courtesy: G. Rosaz, K. Scibor - CERN

Quality Substrates Development

- ❑ Cu cavities machined in the bulk as "ideal" substrates (CERN)
- ❑ Cu hydroformed cavities (KEK, Texas

Machined cell

E-beam welded to cut-offs

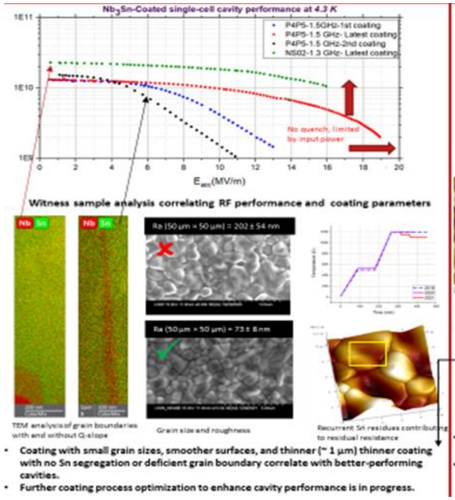


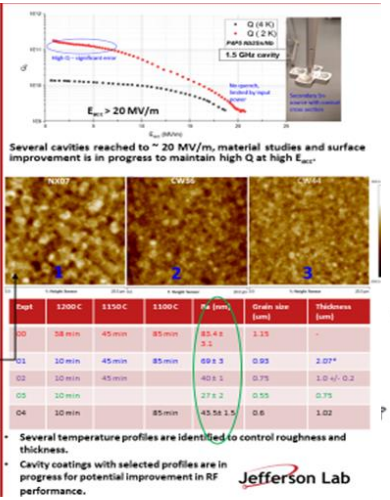
Fermilab
Jefferson Lab

SRF Developments around Nb_3Sn

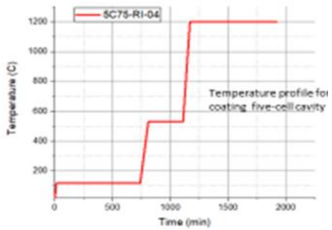
U. Pudasaini et al.

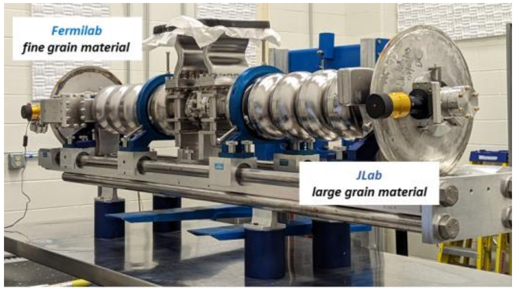
Material studies and development of Nb_3Sn-coated cavities





Process Developments towards Nb_3Sn cavities in operation





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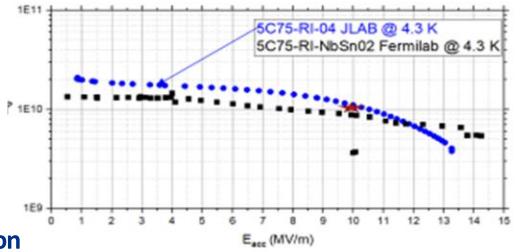
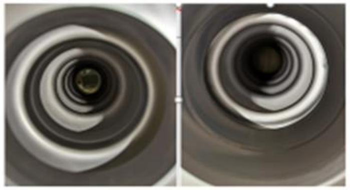
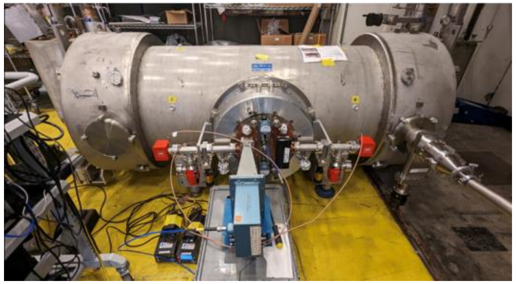


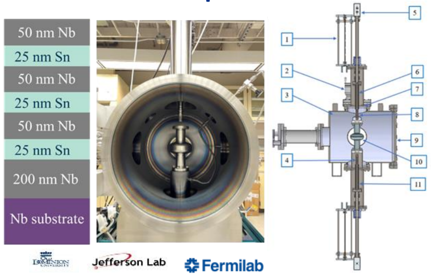
- Original C75 cavity made of ***large grain material***
- Limited by multipacting (no quench)





- Specs: 1 e10 @10 MV/m
- One cavity was coated at Fermilab and another at Jlab..
- Quarter cryomodule assembly is complete.
- Test scheduled for April 2024.

Alternate Techniques Development for Nb3Sn Deposition



Compact Accelerators based on Nb_3Sn

SIS Multilayered Structures

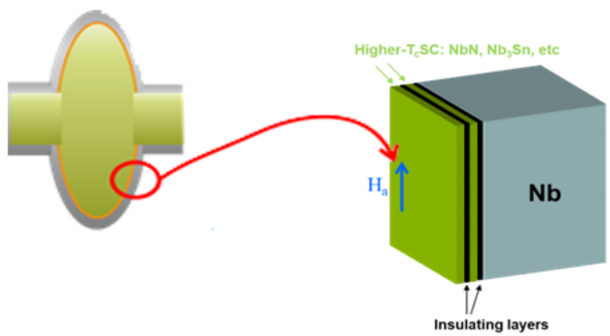
A.-M. Valente-Feliciano et al.

Taking advantage of the high –Tc superconductors with much higher H_c without being penalized by their lower Hc1…

Multilayer coating of SC cavities: alternating SC and insulating layers with $d_{SC} < \lambda$

Higher T_c thin layers provide magnetic screening of the Nb SC cavity (bulk or thick film) without vortex penetration

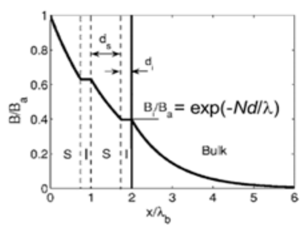
Alex Gurevich, Appl. Phys. Lett. 88, 012511 (2006)



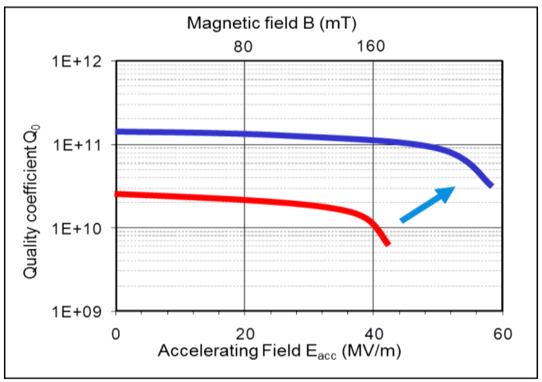
Suppression of vortex penetration due to the enhancement of H_{c1} in a thin film with $d < \lambda$

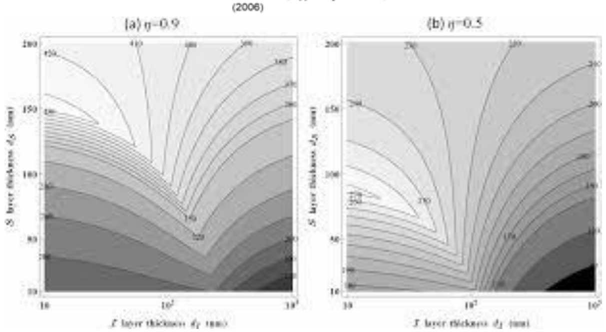
[Abrikosov, (1964)]

$$H_{c1} = \frac{2\phi_0}{\pi d^2}\left(\ln\frac{d}{\xi} - 0.07\right)$$

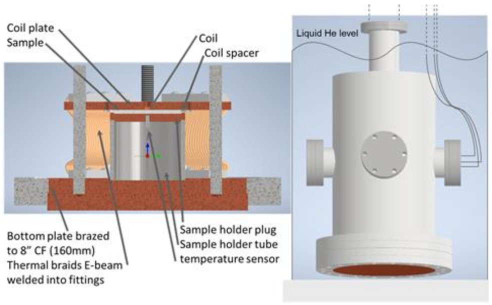


A. Gurevich, Appl. Phys. Lett. 88, 012511 (2006)





A. Gurevich, AIP Advances, 5, 017112 (2015)
T. Kubo, Y. Iwashita, T. Saeki, APL 104, 032603 (2014)
T. Kubo, SUST 30, 023001 (2017)



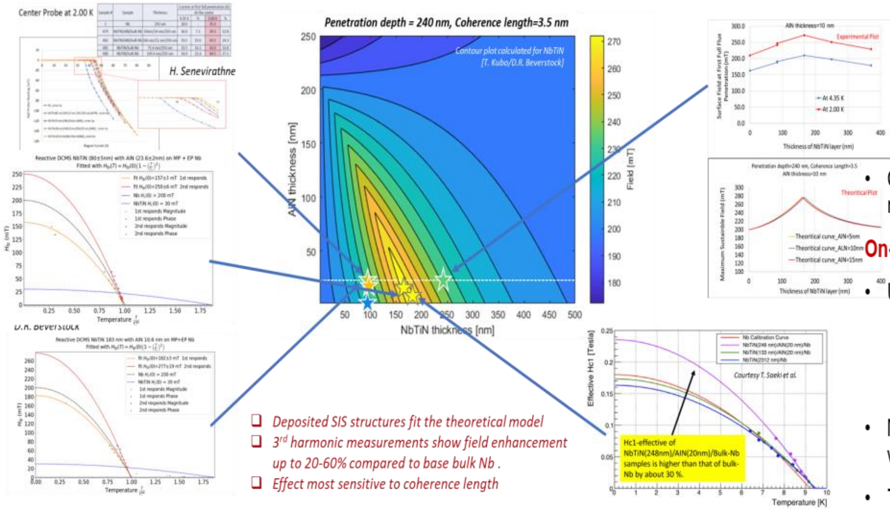
3rd Harmonic Setup for H_{FP} measurement

SIS Multilayered Structures

A.-M. Valente-Feliciano et al.

Based on NbTiN

Measurement on NbTiN SIS structures on 1" & 2" Nb substrates



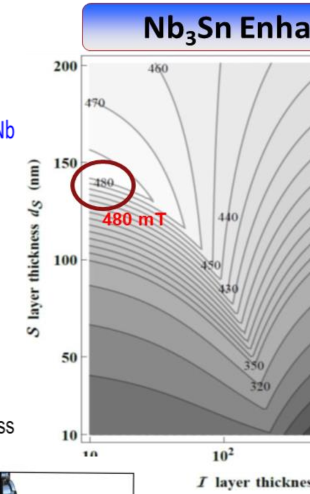
Based on Nb_3Sn

Nb_3Sn based multilayers foreseen to bring the highest enhancement of H_{max} for SIS structures

Nb_3Sn on Nb: $H_s = 0.84H_c = 454$ mT and $\lambda = 120$ nm (moderately dirty):

$H_m = 507$ mT, $E_{acc} = 120$ MV/m, $d_m = 1.1\lambda = 132$ nm

doubles the superheating field of clean Nb

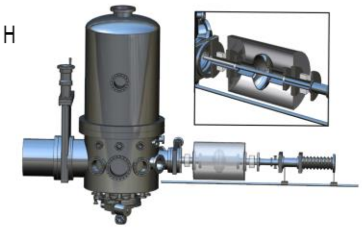


- Current deposition techniques incompatible with integration with many dielectric materials, relying only on thermal energy to achieve the desired A15 phase

On-going Developments

- Use HiPIMS/ECR to create dense Nb_3Sn films with high Nb incident ion energy
  - Explore the coating parameter space (ion energy, temperature) for Nb_3Sn with 18-25% stoichiometry
  - Effect of ion energy/temperature on A15 phase formation, differential strain between substrate and film
- Measure H_{C2} for nominal (~ 2µm) coated Nb_3Sn and establish the contour plot S layer thickness versus I layer thickness for the produced Nb_3Sn.
- Thickness series to determine/verify optimum layer thicknesses with H

- *Magnetic screening measurements with SQUID/3rd harmonic local magnetometry*
- *Implementation on QPR samples and elliptical cavities for RF evaluation*



Synergistic Developments

Application of NbTiN to superconducting digital logic and metamaterials

Application of thick Nb_3Sn on Cu films for conduction cooled cavities, industrial & environmental accelerators

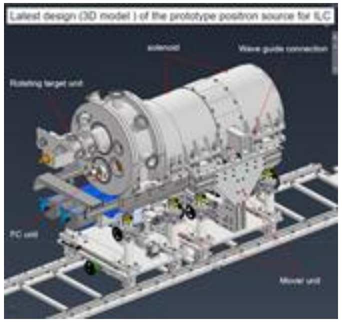
RF Accelerator Technologies for FCC-ee - Accelerator

FCC-ee injector complex include (up to 20 GeV) linac

Possible Contributions:

- Compact and high gradient RF accelerator for injection
- Design studies for versatile bunch format (multi-bunch and full range in charge
- US-Japan program on positron sources – expand to FCC-ee
- Example: FCC-ee - common electron and positron injector linac from 6 to 20 GeV based on **cold-copper**
    - **reduce length 3.5X <u>OR</u> reduce rf power 3.5X**

Electron Driven Positron Source



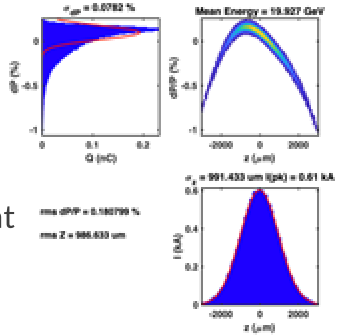
Courtesy of Y. Enomoto

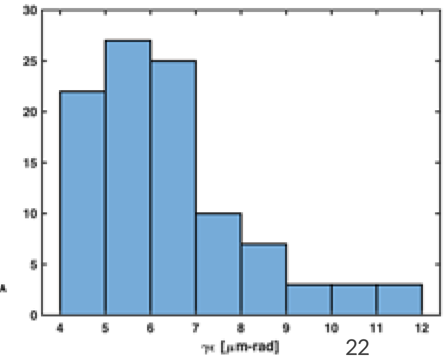
Wide Aperture S-band Injector Linac

$a/\lambda = 0.125$

- Planned test at Argonne
- Tracking with Lucretia includes longitudinal and transverse wakes, chromatic effects etc
- Error study is 100 seeds, 100 µm element offsets, 300 µrad element rolls (rms)
    - No corrections applied

90% seeds < 8 um-rad with lattice errors





SLAC

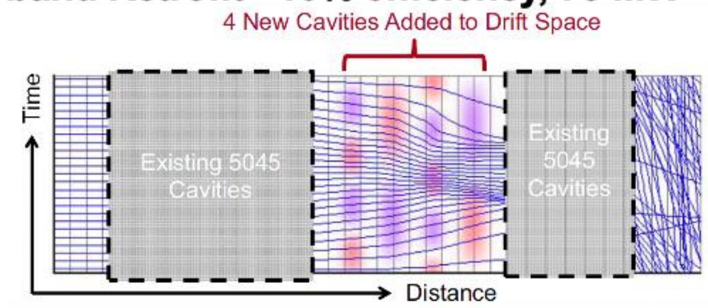
RF Accelerator Technologies for FCC-ee – RF Sources

RF Sources Needed for Injector, Booster and Collider Ring

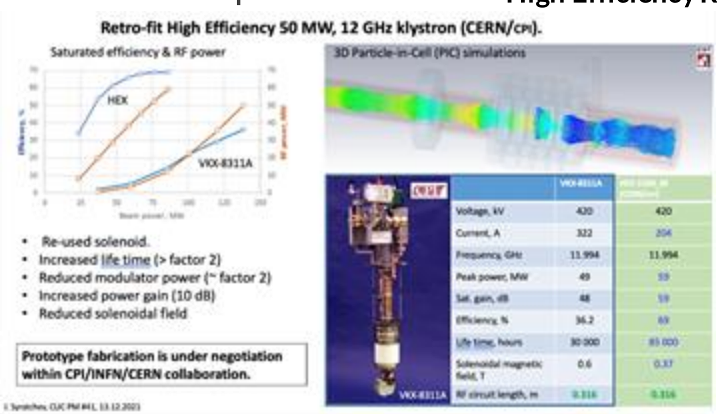
Possible Contributions:

- SLAC is a participant of the CERN lead HEIKA collaboration on RF Sources
- Active development of permanent magnet klystrons
- Demonstration of high-efficiency and energy recover concepts

SLAC BAC Prototype
S-band Retrofit +10% efficiency, 73 MW



High Efficiency RF Sources (CLIC)



	VKX-8311A	[illegible]
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	59
Efficiency, %	36.2	69
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.37
RF circuit length, m	0.316	0.316

SLAC Green-RF
Energy Recovery

US FCC Workshop 2024

[I. Sarchev, CERN]

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