R&D towards an 800 MHz cryomodule

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Overview

• High $Q_0$ for FCC-ee
• 800 MHz Cavity Studies
• Fermilab Cryomodule Design & Production
• Summary
1. High $Q_0$ for FCC-ee
2. 800 MHz Cavity Studies
3. Fermilab Cryomodule Design & Production
4. Summary
Impact of $Q_0$ -> Cryogenic Infrastructure, Operating Cost

- Quality factor of cavities determines heat deposited at cryogenic temperatures
  - Especially important for high duty factor RF (particularly CW)
- Heat deposition at cryogenic temperatures determines the size of cryoplant needed
  - **Cost** → up-front infrastructure cost and longer term operating costs
  - **Sustainability** → Optimization of ~100 nm of cavity inner surface can have a big impact on footprint of cryogenic systems
- 2 K inverse coefficient of performance is ~800 W/W
Focusing on 800 MHz systems (bulk niobium)

Bulk niobium high $Q_0$ treatments include nitrogen doping, mid-T bake, Nb$_3$Sn

Flux expulsion also important to consider

High $Q_0$ for FCC-ee 800 MHz Systems

Slide from B. Naydenov, CERN
Nitrogen Doping

• Cavity is heat treated in vacuum at ~800 C
• Small nitrogen pressure injected into furnace for a few minutes
• Creates nitrogen interstitials as well as surface layer of niobium nitride (poorly superconducting)
• NbN removed via electropolishing of a few micrometers
• Now industrialized and used for LCLS-II production cavities
• Previous state of the art was $Q_0 \sim 1.5 \times 10^{10}$; N-doping made it possible to have LCLS-II $Q_0$ specification of $2.7 \times 10^{10}$
Medium Temperature (mid-T) Bake

- Cavity is heat treated typically in the range ~300-400 C: above low temperature bake, and below high temperature degas
- Best understood mechanism is that oxide dissociates and oxygen impurities diffuse into RF layer, creating interstitials
- Similar to nitrogen doping, but without additional electropolishing step – simpler, and less prone to non-uniform EP, can be important for larger cavity geometries
Mid-T Bake for PIP-II LB650 Cryomodule

- High Q recipe using Mid-T furnace baking was endorsed by a review committee and adopted for LB650 cryomodules.
Magnetic Flux Expulsion

Animation by S. Posen and M. Hassan

- Meissner Effect – niobium tends to expel applied magnetic flux well below $T_c$
- However, flux can become trapped in superconductor during cooldown, and trapped flux degrades $Q_0$
- Large impact on LCLS-II CM $Q_0$. In-situ demag of cryomodules to reduce ambient field also results in improvement.

Ambient magnetic field during cooldown

R&D in Vertical Test

Implementation in LCLS-II Cryodmodule
Flux Expulsion and LCLS-II

• High $Q_0$ depends on:
  – High massflow cooldown to create spatial thermal gradient to expel flux (each CM has its own JT valve)
  – Careful heat treatment of cavities (typically ~900°C) to achieve high expulsion
• $3 \times 10^{10}$ is achieved in the linac

Operational experience from LCLS-II cryomodule testing

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Fermilab Nb$_3$Sn Coating System

First and only Nb$_3$Sn coating chamber capable of coating 1.3 GHz 9-cell cavities or 5-cell 650 MHz cavities
Nb$_3$Sn Coating – Possibility for 4 K Operation

- Inverse coefficient of performance substantially (~3x) better at 4 K than at 2 K
- Advantages for efficiency, avoids subatmospheric helium and cold compressors
- Still under development, but promising results for bare multicells

Includes correction for stainless steel flanges 2x0.8 nΩ

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![Graph showing performance comparison between 4 K and 2 K temperatures for Nb$_3$Sn-coated cavities.](image-url)

**Nb$_3$Sn-coated 9-cell cavities**

**TB9ACC014 and TB9AES005**
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Prototype 800 MHz Cavity R&D

- 1-cell and 5-cell 800 MHz cavities were fabricated, treated, and tested by JLab
- Copper cavities were also fabricated (not discussed here)
- 5-cell cavity does not have additional ports (e.g. coupler, HOM, pickup)
Both cavities had quite good performance in initial testing, reaching ~30 MV/m with $Q_0$ in the range of 2-3x10^{10} at 2.0 K.

Continued processing of single cell (including electropolishing) led to degradation – cavity limited by multipacting.

From Frank Marhauser, FCC Week 2018
1-Cell 800 MHz Cavity Testing at Fermilab

- Cavity was sent to Fermilab – testing in March 2023 confirmed multipacting limit, unable to process or ‘jump’ over – similar to JLab post-EP result
1-Cell 800 MHz Cavity Inspection

- Boroscope inspection revealed substantial defect at equator weld, likely worsened by EP
- Defect visible by eye on interior
- Replica shows ~1 mm ridge, indicating a trench on cavity
- Expected to be cause for strong multipacting
- Currently discussing if fix is possible
  - Deep mechanical polishing
  - Reweld may be possible but risk of blowout
- Meanwhile working on 5-cell
• 5-cell cavity recently arrived at Fermilab
• Optical inspection shows some signs of incomplete welds, but not as bad as 1-cell
• Possibly some etching in previous EP based on inspection – plan to use lessons from FNAL 650 MHz experience to try to improve further
5-Cell 800 MHz Cavity Testing at Fermilab

- Working now on preparation of 5-cell for baseline testing
- If successful, possible next steps include studies with mid-T bake, EP using 650 MHz lessons learned, additional mid-T bake temperatures
- Nb$_3$Sn coating may also be tried, but lack of stiffening rings on 5-cell cavity may be a challenge – Nb$_3$Sn is brittle, and 1100 C heat treatment makes Nb substrate soft (1-cell would be preferable for Nb$_3$Sn if it can be recovered)
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LCLS-II and LCLS-II-HE

- ILC-like CMs, but operating in CW mode, nitrogen-doped cavities
- FNAL high Q SRF R&D is critical: N-doping, flux expulsion
- LCLS-II was the first large-scale SRF CM production for Fermilab
- Designed, built, tested, and delivered 1.3 GHz & 3.9 GHz CMs

Fermilab cryomodule results exceed specifications
- (17) 1.3 GHz cryomodules: average energy gain/CM = 158 MV (spec 128 MV), average $Q_0 = 3 \times 10^{10}$ (spec $2.7 \times 10^{10}$)
- (3) 3.9 GHz cryomodules: average energy gain/CM = 46.5 MV (spec 41 MV), average $Q_0 = 3.45 \times 10^9$ (spec $1.5 \times 10^9$)

- LCLS-II commissioning now underway, with Fermilab experts participating – performance is very promising so far
- LCLS-II-HE: ~20 more CMs from FNAL, R&D was critical to achieve high-Q at higher gradients ~21 MV/m

**In summary**: substantial 1.3 GHz CM production experience, excellent performance, FNAL R&D advances were critical
**PIP-II superconducting CW linac**

- PIP-II linac is technically complex, state of the art superconducting RF accelerator

![Diagram of PIP-II superconducting CW linac](image)

- **RFQ**
  - 2.1 MeV
  - 10 MeV
  - 32 MeV
  - 177 MeV
  - 516 MeV
  - 833 MeV

- **Cryoplant**
  - Half Wave
  - Single Spoke
    - SSR1
    - SSR2

- **Elliptical**
  - LB650
  - HB650

**Room Temperature**
The “Strongback” serves as the coldmass foundation for PIP-II cryomodules.

It will support all the elements of the beamline, shielding, and piping from below. This will enable the entire coldmass to be assembled and aligned as a unit which is then inserted into the vacuum vessel during final assembly.

Maintaining the strongback at room temperature will help to minimize axial movement of the cold elements during cooldown, which will reduce the displacement of couplers, current leads, and many of the internal piping components.
PIP-II style cryomodule

- HB650 cryomodule

- SSR2 cryomodule
Cryomodule String Assembly

- New cleanroom was commissioned last year to allow PIP-II CM assembly in parallel to LCLS-II
- Designed to be compatible with both PIP-II cryomodules and 1.3 GHz ILC-like cryomodules
- Crucial for PIP-II, but new infrastructure will be available after PIP-II
New SRF String Assembly Cleanroom with PIP-II HB650 String
Cryomodule Testing

- Cryomodule test stands at the Fermilab Cryomodule Test Facility (CMTF) characterize cryomodule performance prior to installation in the tunnel
- Cryogenics, pumps, RF power, shielding, instrumentation, DAQ
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Summary

- High $Q_0$ is impactful for power consumption and infrastructure cost of FCCee cryogenic system, particularly at highest energy configurations.
- State-of-the-art SRF cavity treatments such as mid-T bake and Nb$_3$Sn can help enable high Q at gradients relevant to FCCee.
- Fermilab SRF team has substantial experience at frequencies near (above and below) 800 MHz, now working on 800 MHz cavities built by JLab.
- Fermilab SRF team has key experience from PIP-II and LCLS-II including cryomodule design and production; facilities are capable for FCCee 800 MHz CMs.