Summary SRF

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Erk Jensen
FCC Week Berlin 2017 – RF Sessions/presentations

**Tue morning:**

J. Zhai: RF system design for the CEPC main ring
S. Belomestnykh: Update on the US decadal roadmap on SRF technology for HEP accelerators
S. Zadeh: Cavity design approaches and HOM damping for FCC-ee
R. Calaga: Crab cavities for FCC
S. Posen: Potential performance of N doping and Nb3Sn
A-M. Valente-Feliciano: ECR: from samples to cavities
K. Ilyina: Alternative materials and coating techniques for cavities
L. Marques Antunes Ferreira: Copper electropolishing studies for the FCC-ee SC-RF cavities
R. Valizadeh: Surface characterization of Nb/Cu 6 GHz seamless cavities

**Tue afternoon:**

N. Schwerg: RF scenarios and parameters layout for FCC
A. Butterworth: Cavity design and beam-cavity interaction
I. Karpov: Beam Dynamics studies for FCC-ee
W. Hofle: RF feedback design and performance
S. Aull: Nb/Cu perspectives for FCC
R. A. Rimmer: Innovative cryomodule designs
E. Montesinos: FPC challenges and perspectives for FCC
I. Syratchev: High efficiency klystron technology

... and some RF related presentations in other sessions
J Zhai: CEPC concept (here compared to FCC-ee)

**CEPC**
- 100 km circumference
- Z, W, Higgs
- Staging not foreseen

**FCC-ee**
- 100 km circumference
- Z, W, Higgs & $t\bar{t}$
- Staging

They are very similar: The issues and possibly solutions are similar! We should work together!
### Parameters FCC-ee vs. CEPC (moving targets!)

<table>
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<tr>
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<th>FCC-ee</th>
<th>CEPC</th>
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<tr>
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<tr>
<td><strong>Luminosity</strong></td>
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<td>$1.2 \cdot 10^{35}$</td>
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<td>$1.8 \cdot 10^{35}$</td>
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<td><strong>RF Power</strong></td>
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<tr>
<td><strong>CEPC</strong></td>
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S Belomestnykh: SRF Roadmap – “evolution”

The path to the future
S Belomestnykh: High-Q roadmap

2018
- Understand the field dependence of BCS surface resistance and effect of different impurities

2020
- Understand trapped magnetic flux losses and flux trapping
- Probing the ultimate limits of Nb RF surface resistance by doping with different impurities
- Study Nb doping at different frequencies and temperatures

2022
- Pursue current promising path forward for material in bulk form (Nb₃Sn) – explore and optimize coating techniques and treatments for single cell / multi-cell cavities
- Evaluate alternative materials, bulk or film (NbN, NbTiN, MgB₂) first on samples, then on cavities
- Drastically reduce sensitivity to magnetic flux for Nb and new materials
- In situ removal of trapped magnetic field (in cryomodule)
- Develop Materials Specs to ensure maximum flux detrapping

2024
- Apply gained knowledge and develop new understanding for alternative materials

2026
- Nb₃Sn studies for cryomodule operation
- Explore SIS for Nb₃Sn

2028
- Potential of Nb material: $Q(2\,\text{K}) = 1 \times 10^{11}$ at 1.3 GHz
- Potential of Nb₃Sn material: $Q(4\,\text{K}) = 1 \times 10^{11}$ at 1.3 GHz
- Impact:
  - Retain $1 \times 10^{11}$
  - Sustain very high gradients

Goals
- $Q > 4 \times 10^{10}$ at 2 K, 1.3 GHz and $E_{\text{acc}} > 35$ MV/m
- $Nb₃Sn$: $E_{\text{acc}} > 20$ MV/m with $Q_0 > 1 \times 10^{10}$ at 1.3 GHz, 4.2 K
- Residual resistance < 1 nΩ in cryomodule
- Nb₃Sn cryomodule ready technology
S Belomestnykh: High-gradient roadmap

- **Fundamental Limits**
  - **Niobium**
    - Produce dirty surface layer on clean bulk to enhance superheating field
    - Probing and altering by doping the ultimate limiting cavity field
  - **Nb₃Sn**
    - Pursue current promising paths forward for material in bulk form
    - Evaluate superconductor-superconductor structure to delay flux entry
    - Evaluate superconductor-insulator-superconductor structure to delay flux entry
  - **Other superconductors**
    - Use theoretical and experimental expertise to evaluate promising options for SRF materials (bulk and films), develop sample coating and test tools

- **Goals**
  - Development of techniques to prevent and mitigate field emission
  - $H_{th} > H_{th}$ of bulk niobium
  - $E_{acc} = 70$ MV/m
  - Measure and outpace time scales of vortex dissipation $E_{acc} > > 120$ MV/m

- **Potential of Nb material**
  - $H_{th}$ limit: 70 MV/m
  - Above $DCH_{th}$: $> 70$ MV/m

- **Potential of Nb₃Sn material**
  - $H_{th}$ limit: 90 MV/m
  - Above $DCH_{th}$: $> 120$ MV/m

- For materials that show $B_{sat} > 50$ mT with $R_s < 300$ nΩ, develop cavity coating tools

- Evaluate feasibility of $> DCH_{th}$ fields for up to $\sim$GV/m scale gradients

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Probing the fields above $H_{th}$ on samples
Probing the limits of accelerating field on sub-nanosecond time scales
O Brunner, N Schwerg, S Gorgi Zadeh: RF scenarios

- FCC-ee has **baseline plan, fallback options** and a **believable staging scenario:**
  - 5 y @ Z-pole with $36 \times 4$ single-cell cavities at 400 MHz, Nb/Cu @ 4.5 K,
  - 2 y $W$ with $28 \times 4$ four-cell cavities at 400 MHz, Nb/Cu @ 4.5 K,
  - 6 y Higgs with $102 \times 4$ of these same cavities, but run with larger $Q_{ext}$ ($P$ distribution)
  - 6 y $t\bar{t}$ rearranging these cavities, and adding about $150 \times 4$ four-cell (5-cell?) cavities at 800 MHz, bulk Nb @ 2 K.
Where does the R&D lead us? What is the most cost effective?
L Ferreira: EP (Electro-chemical polishing)

- The coating techniques require good substrate surfaces
- EP reaches the best surface preparation $R_a = 40 \text{ nm}$!
- CERN is acquiring/installing a new EP facility compatible with FCC cavities

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<th>Task</th>
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<tr>
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<td>Preliminary tests</td>
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Chemically polished Cu, $R_a = 0.2 \mu m$, pinholes
Electropolished Cu, $R_a = 0.02 \mu m$
A.-M. Valente Feliciano, S Aull: ECR from samples to cavities

ECR compatible with non-flat surface

Nb/Cu: flux penetration proves very good quality SC layer

Surface resistance ECR on LG Cu has same $R_s$ and $Q$-slope as Bulk Nb
Cavity technology R&D: Progress clearly visible – but many things are still in the air!

New EP facility

Conformal ECR

Fighting Q-slope

Need more tests!

Optimizing recipe
A Butterworth: beam-cavity interaction challenges

- Macro-particle simulation code BLonD helps predict/solve issues for both FCC-hh and FCC-ee.
- Most challenging: Z machine \( (I_b = 1.45 \text{ A}) \)
  - similar to high current super B-factories
- Cavity fundamental-driven coupled-bunch instabilities (CBI)
  - Large number of cavities, large detuning \( (> 3 \times f_{rev}) \)
  - CBI growth rates much larger than synchrotron radiation damping \( (~1 \text{ ms cf. SR damping time of } 440 \text{ ms}) \)

→ active damping required:
  - Woofer for low order modes
  - Strong bunch-by-bunch longitudinal feedback for higher modes

- Implement beam loading compensation to avoid CBI!
  - full compensation requires very high (peak) power
  - phase modulated RF voltage reduces power transients ("full detuning" now baseline in LHC)
- Many LLRF and long. BD issues already addressed/solved in LHC
I Karpov, A Butterworth, S Gorgi Zadeh: HOM damping

FCC-ee Z: single-cell 400 MHz cavity meets criteria
HOM’s to be damped below 10 kΩ!

FCC-ee (H, $\ddot{t}$): 800 MHz 4-cell (5-cell) cavity OK
W Höfle: Transverse feedback

- FCC-hh needs a coupled bunch feedback with options for 5 ns and 25 ns bunch spacing (driven by resistive wall instability → fast instability rise times at low frequency)
- **LHC type transverse feedback system proposed** as baseline for 25 ns option, 22 kickers per plane and beam with adaptation of power bandwidth to FCC needs
- 5 ns option requires additional kickers to cover higher frequencies
- GHz feedback can be an option to mitigate slow intra-bunch instabilities, kicker designs being proposed
- Impact of feedback noise, suppression of emittance growth by ground motion and due to crab cavity noise needs consideration
- FCC-ee requires system with distributed kickers to be considered due to very short rise times (< 10 turns)
- Simulation environment developed, integrated with head-tail code to refine in simulation the specifications and evaluate the performance for the CDR treating coupled bunch and intra-bunch instabilities as well as injection errors and filamentation.
R Calaga: Crab cavities

- Crab cavities needed for FCC-hh and HE-LHC
- Large $\beta$ functions at CC location require low impedance
- A new, low-impedance CC is being prototyped.

$$R_\Phi = \frac{1}{\sqrt{1 + \Phi^2}}$$

![Graph showing the relationship between $R_\Phi$ and $\Phi$, with annotations for LHC, HE-LHC, FCC-hh (30 cm), HL-LHC, and FCC-hh (10 cm).]
R A Rimmer: JLAB Modular CM fits FCC needs

String of eight 400 MHz single-cell cavities

String of four 400 MHz 2-cell cavities
R A Rimmer: A proposed solution for 800 MHz

Large He-vessel could fit also 800 MHz cavities and the same, modular CM
E Montesinos: FPC challenges

Present LHC FPC, starting point to develop FPC for 400 MHz, up to 500 kW CW

Present high-gradient FPC (704 MHz), starting point to develop FPC for 800 MHz, up to 100 kW CW
E Montesinos: FPC R&D topics

Some of the sub-topics that will have to be addressed as well (non exhaustive list)

- Ceramic material
- Multipacting
- Brazing
- Coating
- Cryomodule integration
- Assembly in clean room
- Specific tooling
- RF power source for FPC
- Resonant rings
- Test boxes
- Diagnostics
- Conditioning processes
- Transportation
- Constraints for operation
- Statistics

High Power FPC
Variable and Adjustable FPC
Cleanliness
Large series production

Cost of FPC, and cost impact to the others

Evaluate robots!
I Syratchev: High Efficiency klystrons

- R&D that “pays for itself”
- Important societal impact!
- Fantastic progress – we firmly believe that we can reach 85% efficiency.
- Example on the right: FCC 800 MHz, 1.4 MW CW
Summary of the summary

• The RF R&D subjects are fascinating – the large international collaboration I see at work now is very motivating and vibrant! The spirit is great!
• The progress is clearly visible, even if the hard experimental evidence is still not complete.
• Concerning FCC-ee, we today have a believable concept for a baseline, fall-back options and a staging scenario
• We have identified R&D topics and are making tremendous progress on them

Thank you very much!