SUPERCONDUCTING HARMONIC CAVITY SYSTEMS FOR ELECTRON STORAGE RING APPLICATIONS

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OUTLINE

- Introduction
  - Harmonic RF in Electron Storage Rings
  - Superconducting Harmonic Cavities

- Advanced Photon Source (APS) Upgrade Superconducting Harmonic Cavity for Bunch Lengthening
  - Technical Subsystems: Cavity, Pneumatic Slow Frequency Tuner, Coaxial RF Couplers, Beamline HOM Absorbers
  - Interactions with Beam

- Concluding Remarks
HARMONIC RF IN STORAGE RINGS
Higher Harmonic RF Combined with Main RF

- Potential well broadening and, as a result, bunch lengthening
  - Reduces beam loss rate due to large-angle intrabeam (Touschek) scattering
  - Increase single bunch charge limited by collective effects
  - Also Landau damping enhanced by synchrotron frequency spreads

- Purely beam induced voltage
  - In the decelerating phase with high beam current
  - Detuning angle close to 90°

APS-U Bunch Lengthening with the 4th Harmonic RF

RF Voltages and Potentials

Longitudinal Bunch Distribution
SUPERCONDUCTING HARMONIC CAVITIES

- **SUPER-3HC**: installed and operating in ELETTRA and SLS
  - Total 0.8 MV @ 1.5 GHz with 2 cavities: Nb/Cu cavity scaled from the 500 MHz SOLEIL cavity
  - NO fundamental-mode RF couplers: the detuning angle is 89.9°
  - Successfully commissioned and operating

  [SUPER-3HC developed at CEA-Saclay [P. Bosland et al., SRF03]](image1)

- **Superconducting 3rd Harmonic Cavity for SSRF**: under development
  - Harmonic voltage: 1.8 MV @ 1.5 GHz
  - Two-cell cavity with no fundamental-mode RF coupler, Fluted beam pipes

  (Courtesy of H. Hou @ SSRF)
BUCK LENGTHENING HARMONIC RF CAVITY FOR APS UPGRADE

- APS Upgrade replaces the storage ring with a new Multi-Bend Achromat (MBA) lattice
  - X-ray brightness improves by ~2 orders of magnitude
  - 6 GeV, average 200 mA beam with the maximum single bunch charge of 15 nC
  - Re-use the exiting main RF, normal conducting 352 MHz

- Bunch lengthening harmonic RF cavity
  - To improve Touschek lifetime and increase single bunch charge limit
  - Necessary to operate at the design beam current and single bunch charge, 200 mA and 15 nC

- Superconducting cavity option
  - Best technology to generate the required harmonic voltage, 1.25 MV, in the physical space, 2.5 m, allowed

Lattice
(Repeats in the 40 periodic sectors)

Transverse Beam Profile

Current

Upgrade
The 4th harmonic with fundamental-mode RF couplers
- Ideal harmonic phase: relatively far away from 0° due to relatively high energy loss per turn/main RF voltage
- Loading with the RF coupler to achieve this ideal harmonic phase
- The 4th harmonic, 1.4 GHz, was chosen for a moderate level of the beam loss power to be extracted

Harmonic cavity
- Harmonic voltage: 1.25 MV nominal
- Scaled the TESLA shape with an enlarged beam pipe

Two RF couplers
- 1.4 GHz 20 kW (traveling wave, per coupler) adjustable couplers

HOM Damping
- Strong damping: Q of ~1000 or less
- SiC Beamline HOM absorbers optimized using ‘dielectric resonator’ effect
- Wedge antenna to extract coupler modes

With the adjustable coupler and pneumatic frequency tuner, it is possible to run at the ideal harmonic voltage and phase for different beam currents
CAVITY FABRICATION/ SURFACE PROCESSING

Based on ANL’s past fabrication/surface processing experience for the coaxial cavities as well as elliptical cavities, e.g. the ILC single-cell cavity

- Hydroforming and electron beam welding at AES with Nb/SS braze assemblies made by ANL
- Stainless steel helium jacketing at Meyer Tool
- Electropolishing for 120 \( \mu m \) removal at ANL: ANL-FNAL SRF Cavity Surface Processing Facility
- 600°C baking at FRIB/MSU and then additional 20 \( \mu m \) EP, high pressure rinsing, clean assembly at ANL
Achieved design goals at both temperatures, 2 K and 4.5 K
- Chose 2 K since the up-to-date requirement from beam dynamics studies is 1.25 MV
- Further conditioning efforts to extend the maximum gradient were not necessary

No multipacting or conditioning effects were observed up to the maximum achieved gradient

Residual resistance is 8 nΩ with $B_{ext}$ of approximately 10 mG
MICROPHONICS

- Microphonics
  - The stainless steel helium jacketed niobium cavity was designed such that:
    - the first mechanical mode is higher than 300 Hz and
    - the measured df/dP was -13 Hz/Torr
  - Measured in the test cryostat: Gaussian distribution with $1\sigma=5$ Hz

- Impact on the beam
  - Particle tracking simulations show no measurable impact on the beam at this level of microphonics

Measured frequency fluctuations in Cold Test at 2.0 K, V=1.8 MV

Particle tracking simulation with ~40 Hz pk-pk microphonics
**PNEUMATIC SLOW FREQUENCY TUNER**

- Cold test with slow tuner
  - No hysteresis or dead bands in the full tuning range, 0 to -600 kHz
  - Measured maximum slew rate was 190 kHz/sec
- Estimated resolution: <10 Hz
- Support cavity ‘parking’
  - At cryogenic and room temperatures

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![Diagram of Pneumatic Slow Frequency Tuner](image.png)
RF POWER COUPLER

- OD 8 cm – 50 Ohm coax, warm and cold RF windows
- Adjustable external Q: $2 \times 10^5 - 2 \times 10^7$ using a 4 cm variable bellows
- Design power: 20 kW (traveling wave) per coupler at 1.4 GHz
- Tested up to 18 kW at 1.3 GHz in a LN2 cooled transmission line setup

M.P. Kelly
FRXBA03 (Fri 10 am)
“Coaxial Power Coupler Development at ANL”
HOM DAMPING

Animation: Wake Induced by Single Bunch

SiC HOM Absorber

Beam: 1 nC, RMS 15 mm long

SiC HOM Absorber

Wedge Antenna

- Optimized SiC for efficient damping using ‘Dielectric Resonator’ effect

Monopole and Dipole Impedances Compared to Instability Thresholds

E-field strength

Dipole X/ Dipole Y Coupled-bunch Instability Thresholds

Monopole mode Coupled-bunch Instability Threshold
**SIC HOM ABSORBER**

- Similar to Cornell’s design but used at room temperature
  - Simulated dissipation power = 1 kW per absorber
- Graphite-direct-sintered SiC, Coorstek SC-35
- Shrink fit with 0.1 mm interference, chosen based on mechanical analysis
- Thermal tests with a radiative heat source
  - Temperature rise on the SiC inner surface = 2°C at 1 kW
  - Capable of dissipating at least 10 kW heat load
- HOM damping tests at room temperature
  - Damped Qs are 700 or less and they are dominated by the SiC so almost the same damping is expected in the real cryomodule

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![Graph showing HOM resonance curves with and without damper.](image)

**Setup for High-frequency Monopole HOMs**

- Drive Probe
- Small HOM Absorber
- He-jacketed Niobium Cavity
- Large HOM Absorber
- Pickup Probe

**Without absorbers**

**With absorbers**

S.H. Kim, Superconducting Harmonic Cavity Systems, SRF2017
COUPLER WEDGE ANTENNA FOR HOM DAMPING

- A trapped HOM induced with a symmetric antenna is problematic
  - Has high $r/Q$, about 10 Ohm
  - Below the cutoffs both in the beam pipe and in the coupler (TE11)

- ‘Wedge’ antenna
  - Convert this mode to the TEM mode to extract it along the coupler

- Demonstrated in room temperature tests
CONCLUDING REMARKS

- The cavity and subsystems for the APS Upgrade Bunch Lengthening harmonic RF system have been developed since last SRF conference
  - Demonstrated their functionality and performance meet design criteria
  - Conceived and implemented several unique features

- Project status: building the cryomodule
  - Plan: finish the cryomodule and carry out the offline test in 2019

- Technologies developed in this project are also applicable for future high-intensity accelerators
  - >10 kW room temperature beamline SiC HOM absorber
  - 1.4(1.3) GHz CW high power variable RF power coupler
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