Development of Higher Harmonic Superconducting Cavity for Light Sources
WEB2IO01

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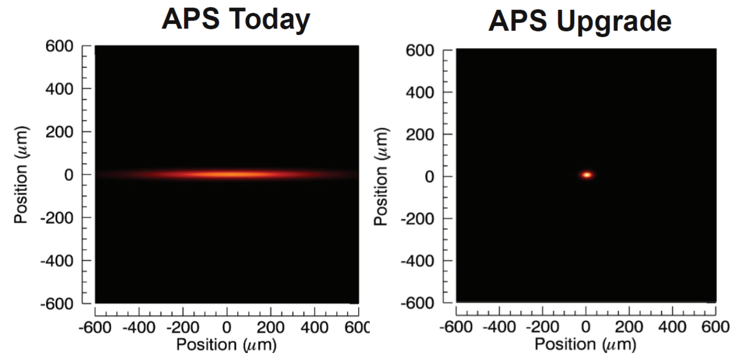
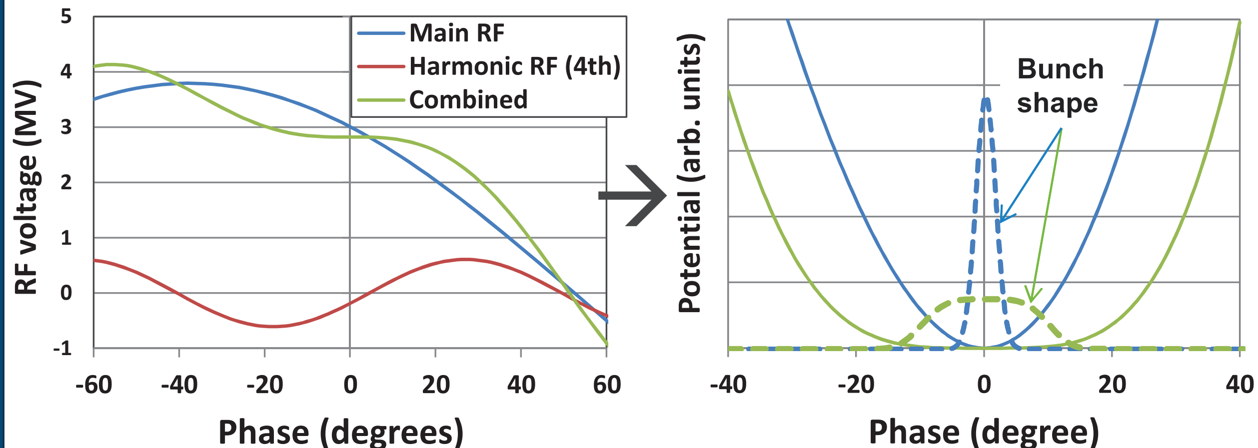
A Harmonic Cavity for the APS-U: Why?

- High-current, low-emittance beams have high charge particle density → particle loss from Touschek scattering
- Practically, a 4th harmonic system can reduce Touschek scattering and increase the beam lifetime by ~70% to ~300% (for 48- and 324-bunch modes respectively)





Examples of harmonic cavities in light sources

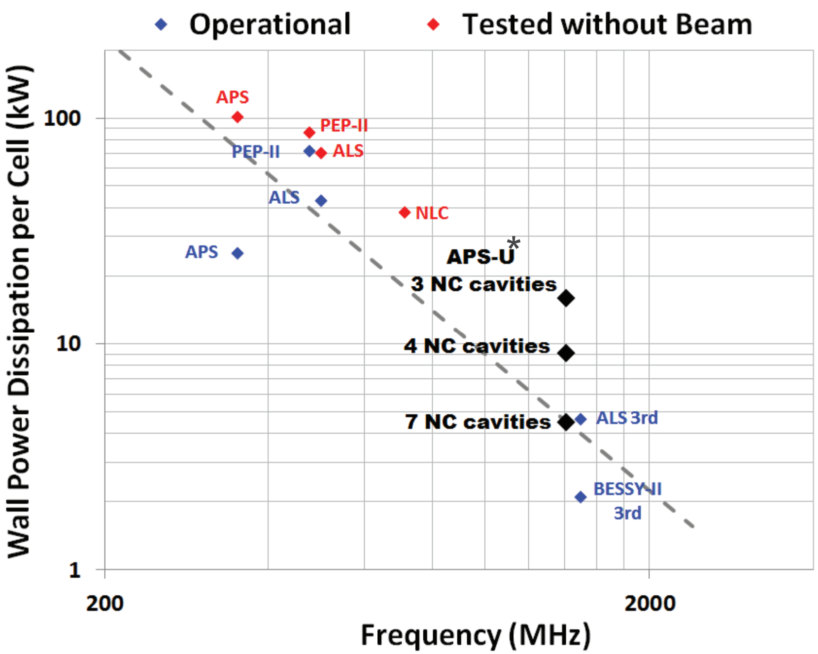
J.M. Byrd, et al., Nucl. Inst. Meth. A, **(455)** 2(2000) pp. 273-284.

P. Bosland, et al., SRF2003

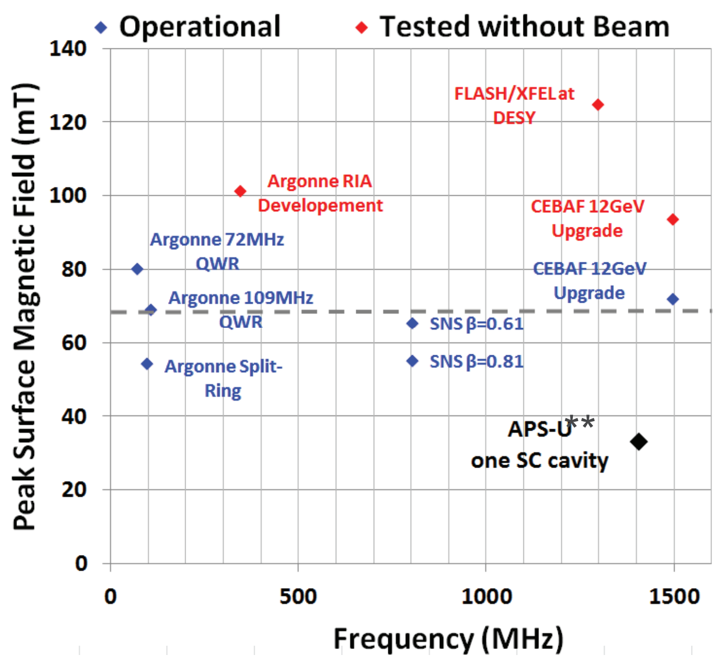
Why Use a Superconducting Cavity for APS-U?

Required harmonic cavity voltage ~1 MV

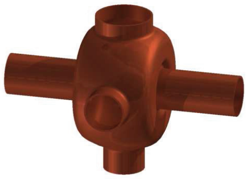
Normal Conducting Cavities

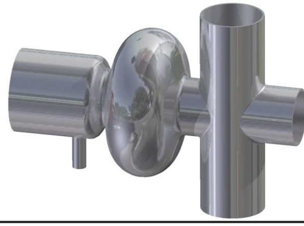


Superconducting Cavities



Assumed cavity shapes taken from ALS and 'TESLA' for normal and superconducting structures





Why Use a Superconducting Cavity for APS-U? Answer:

- Requires a single small cavity
- Meets APS-U requirements with ample margin on performance
- Extremely stable when operated away from performance limits
- Straightforward handling of HOMs
- Lower impedance presented to beam
- Flexibility to adjust loaded quality factor

These are unique to the superconducting cavity and derive from fundamental physical properties

Outline

✓Technical options

- System requirements
- The hardware
  - Cavity
  - Cryomodule
  - Coupler
  - Higher order modes dampers
- Summary

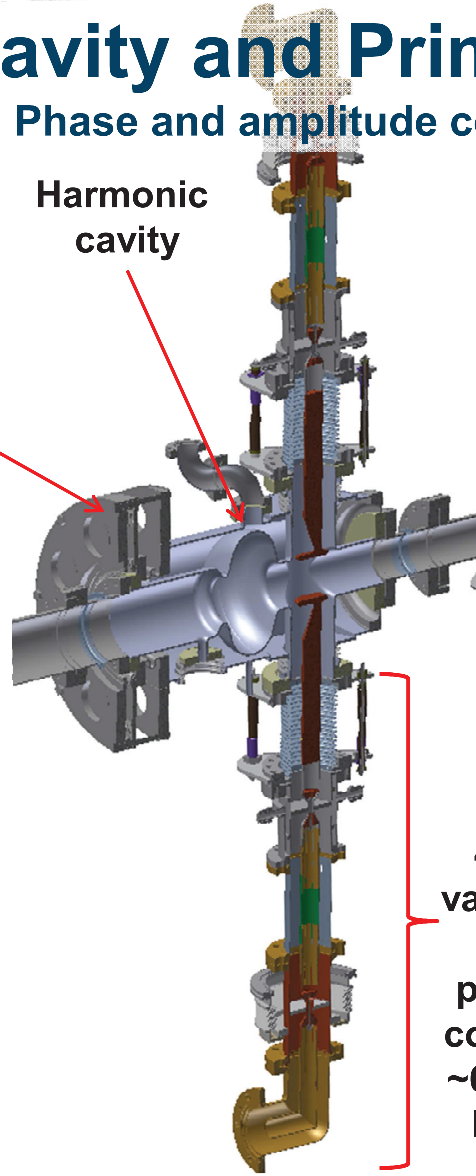
APS-U Bunch Lengthening System

Scope and high-level requirements

- Developed the concept starting spring 2014 for one module with one harmonic cavity in the APS-U storage ring
  - To increase the beam lifetime, providing a tremendous practical benefit to the majority of APS users
- Key constraint: should be compact, preferably fitting within ½ of an APS-U 5-meter straight section
- A superconducting cavity-based bunch lengthening system:
  - **1 superconducting cavity with mechanical tuner**
  - **2 adjustable RF power couplers**
  - **2 beamline higher-order mode dampers**
- An RF system for *extracting* up to 40 kW of beam power
- A liquid helium refrigerator, 100 W @ 4.5 K

SRF Cavity and Primary Subsystems

Phase and amplitude control of the cavity



- A mechanical tuner sets the proper ‘offset’ frequency
- The external RF couplers provide variable coupling strength for
  - Improved bunch lengthening
  - A means of conditioning the cavity

System Requirements and Parameters for a 4th Harmonic (CW) SC Cavity

Question for the R&D program: 2 Kelvin or 4 Kelvin operation?

	Parameter	Symbol	Unit	Value
	Operating Temperature	T	K	2.1 (4.5)
	R/Q	r/Q	Ohm	104
	Cavity Quality Factor	Q_0		1×10^{10} (2×10^{8})
	External Q range	Q_{ext}		2×10^{5}-2×10^{7}
	Detuning Frequency	Δf_r	kHz	13.5
Green – high-level requirements	Q_L nominal	Q_L		6×10^{5}
	Cavity Resonant Frequency	f_r	MHz	1407.8
	Beam-Induced Voltage	V_b	MV	1
	Detuning angle	ψ_h	degrees	85.0
	Cavity Loaded Bandwidth	Δf_{BW}	kHz	2.35
	Beam Loss Power (nominal $Q_L=6 \times 10^{5}$)	P_b	kW	12.8
	Cavity Wall Loss Power	P_{wall}	W	1 (58)
	Peak Surface Electric Field	E_{peak}	MV/m	21
	Peak Surface Magnetic Field	B_{peak}	mT	43

Fabrication for ANL-produced cavities

All steps performed either in house or side-by-side with vendors

ANL-brazed stainless-to-niobium ports

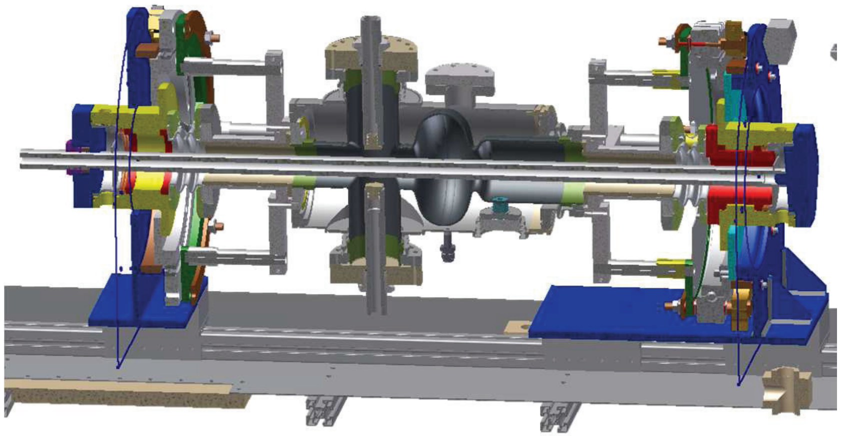
Half-cell assemblies at Advanced Energy Systems

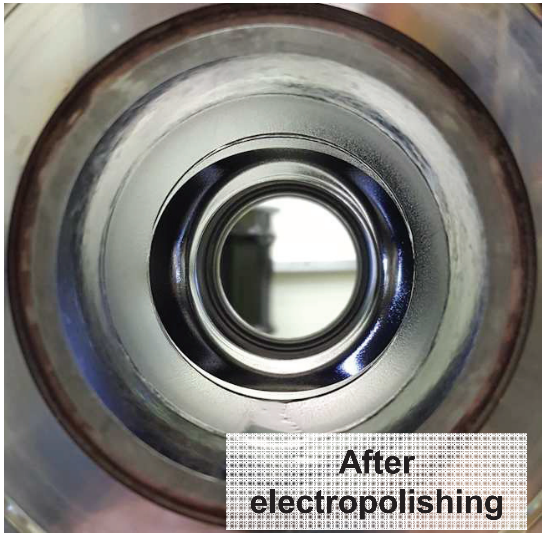
Two complete niobium cavities

Helium-jacketed cavity with 'cold' power coupler

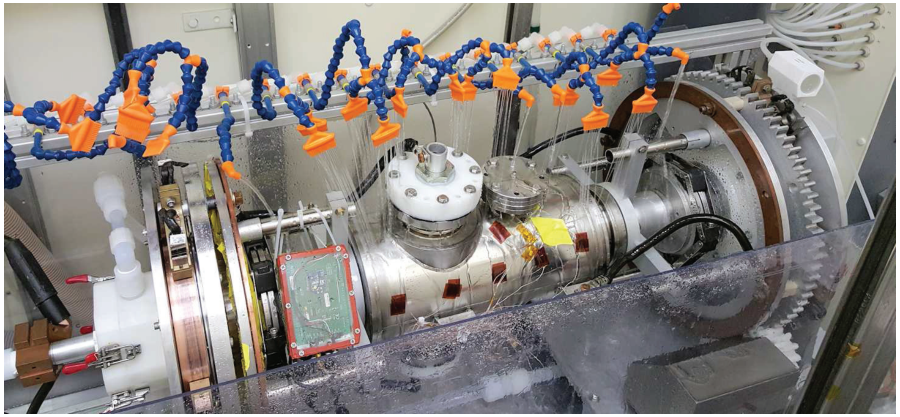
Harmonic Cavity Processing

Electropolishing is the final step of surface preparation at joint ANL/FNAL processing facility





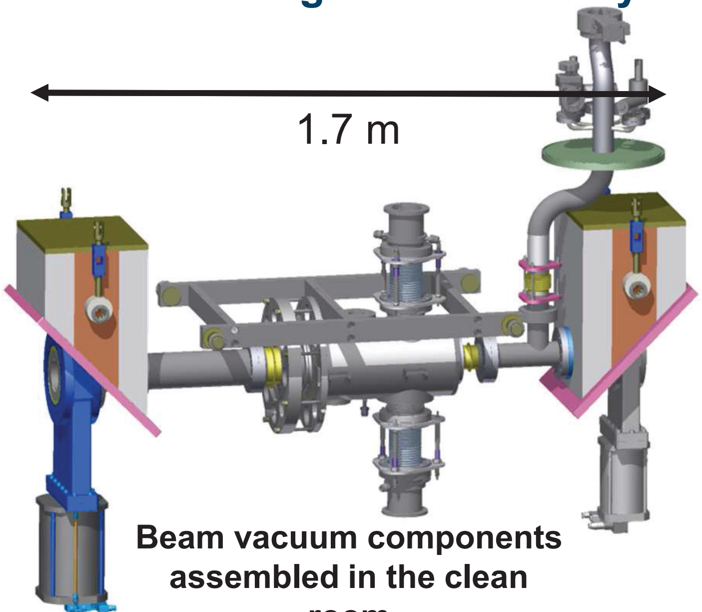
ANL electropolishing system for ILC-style cavities adapted for the 4th harmonic cavity



work performed by B. Guilfoyle, T. Reid (ANL-HEP/PHY)

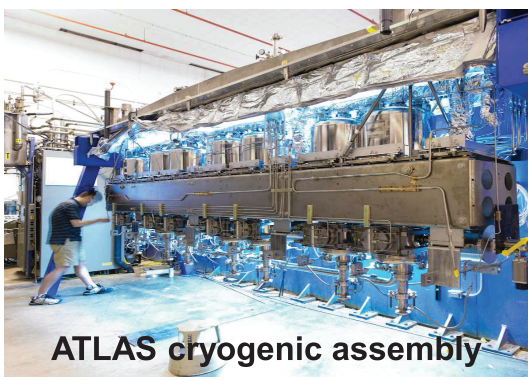
Bunch Lengthening System Cryomodule

Design based heavily on recent *existing* cryomodules

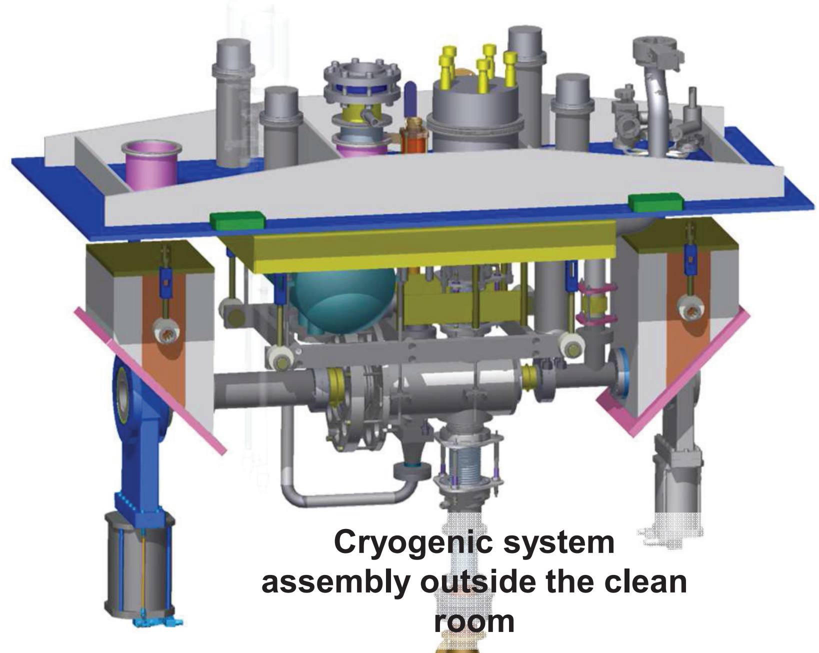


Beam vacuum components assembled in the clean room

ATLAS clean assembly (2014)



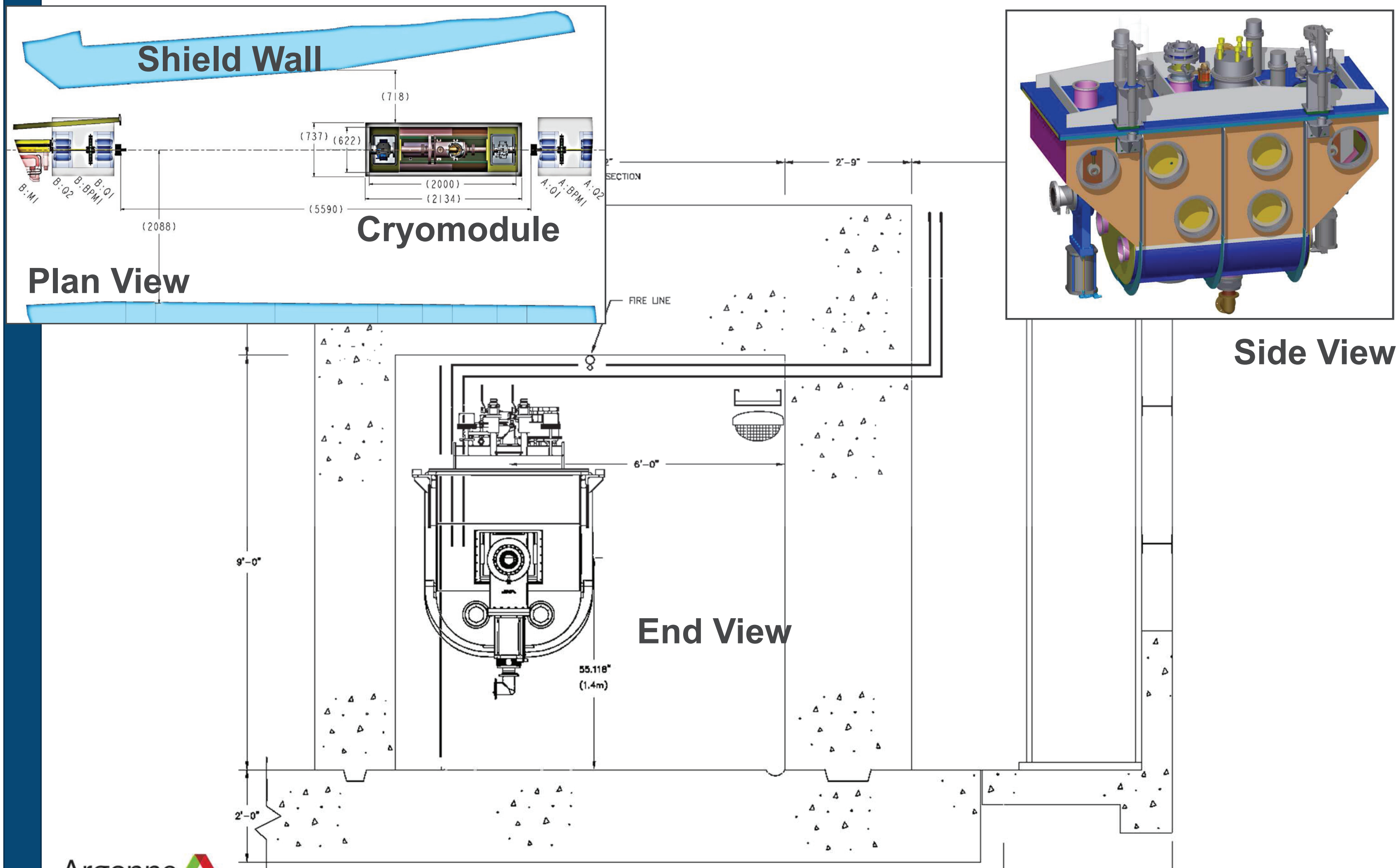
ATLAS cryogenic assembly



Cryogenic system assembly outside the clean room

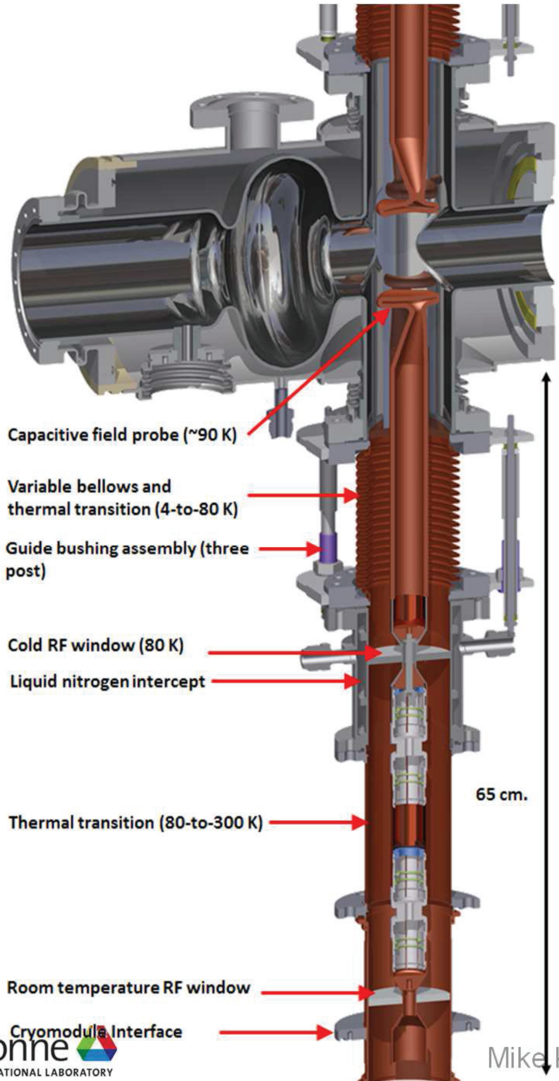
Bunch Lengthening System Cryomodule

Footprint in the tightest section of the existing APS tunnel

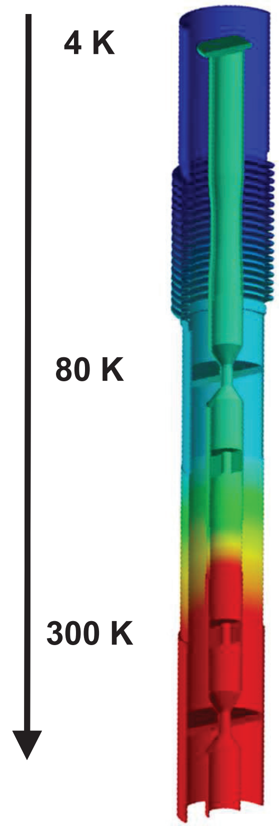


High-power 1.4 GHz 20 kW CW Power Coupler

The coupler shown as mounted on the cavity



Temperature profile in operation



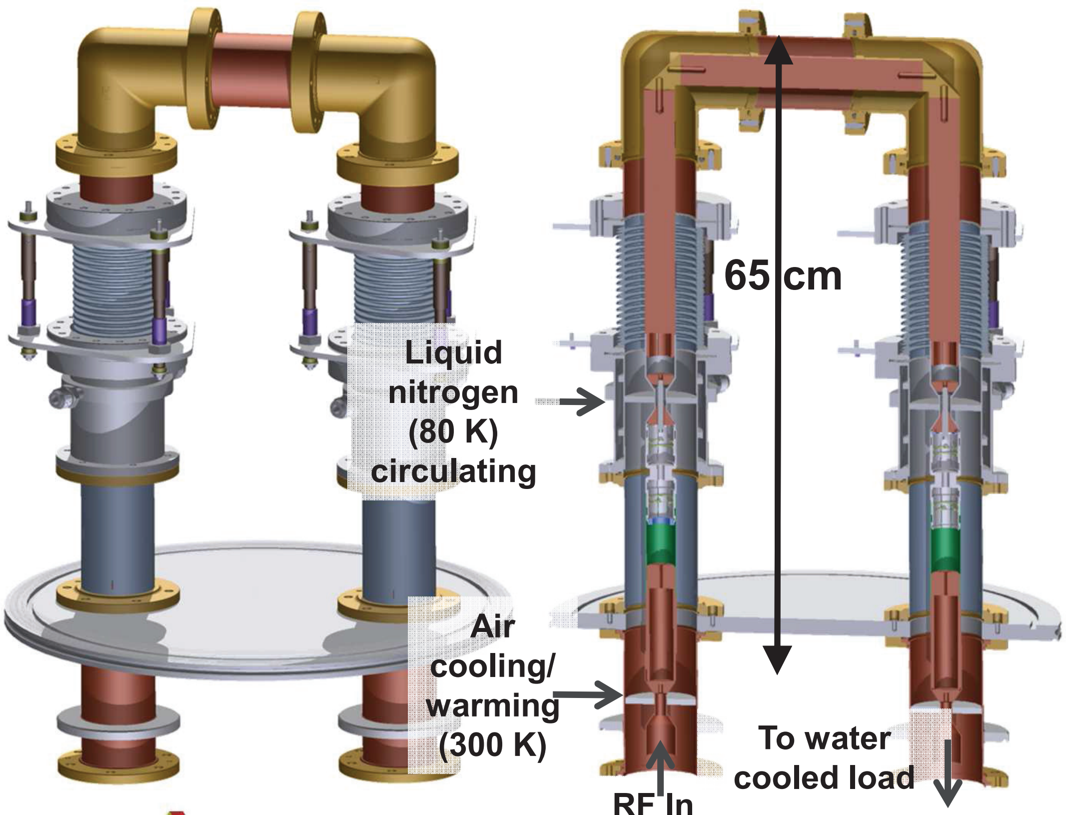
courtesy S. Kutsaev (presently Radiabeam)

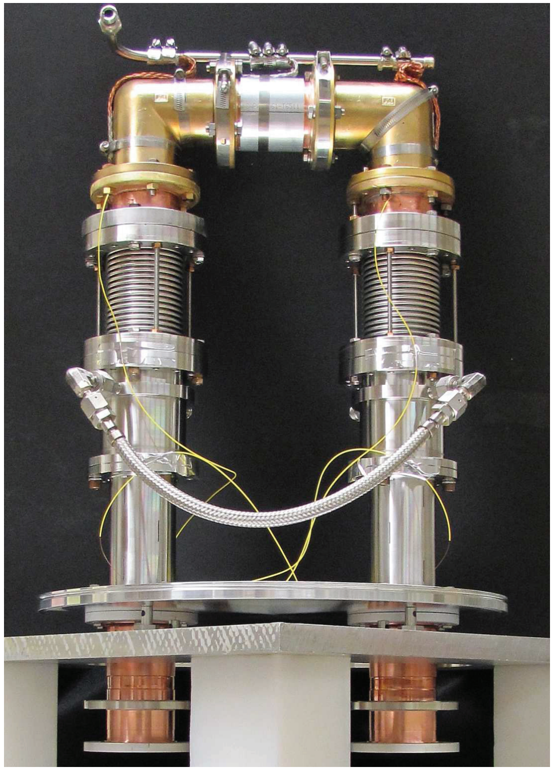
ANSYS 14.0

High-power 1.4 GHz CW Power Coupler

A 'cryostat-based test stand' with a realistic temperature profile

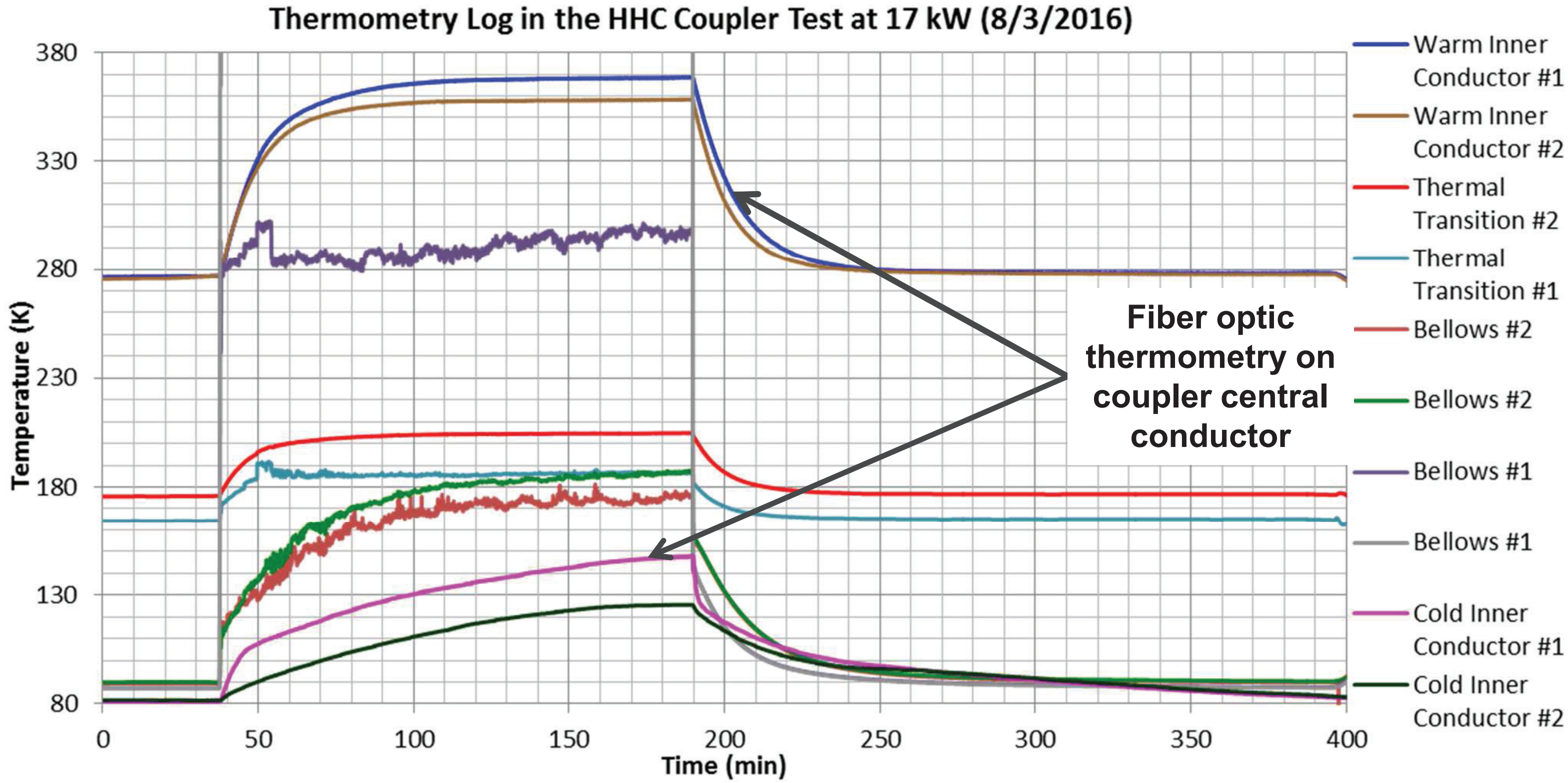
- Two production 'prototypes' are complete
- ~2 weeks of testing complete with up to 18 kW Watts at 1.3 GHz
- Results indicate stable operation up to at least 20 kW CW





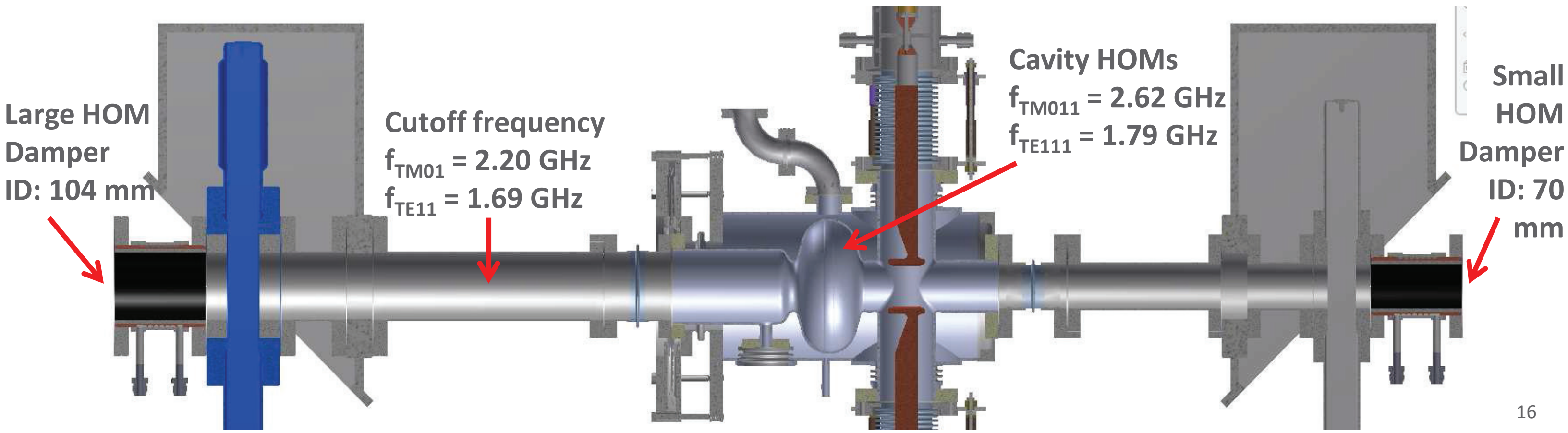
High-power 1.4 GHz CW Power Coupler

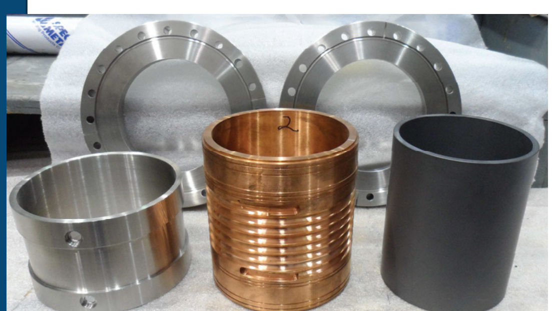
Example of test data at 17 kW forward power

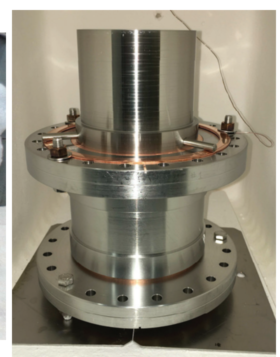


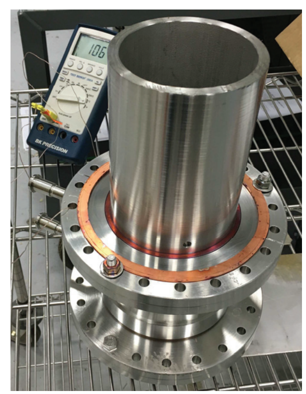
Higher Order Mode Damping in the Harmonic Cavity

All cavity (monopole and dipole) HOMs propagate out of the cavity



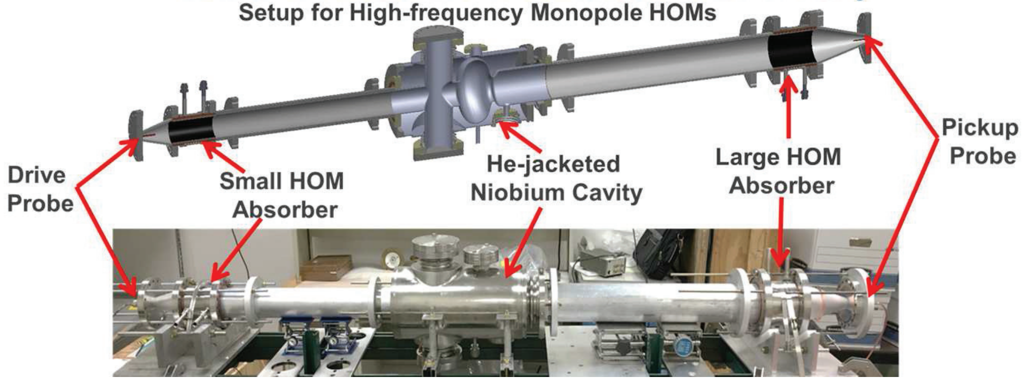


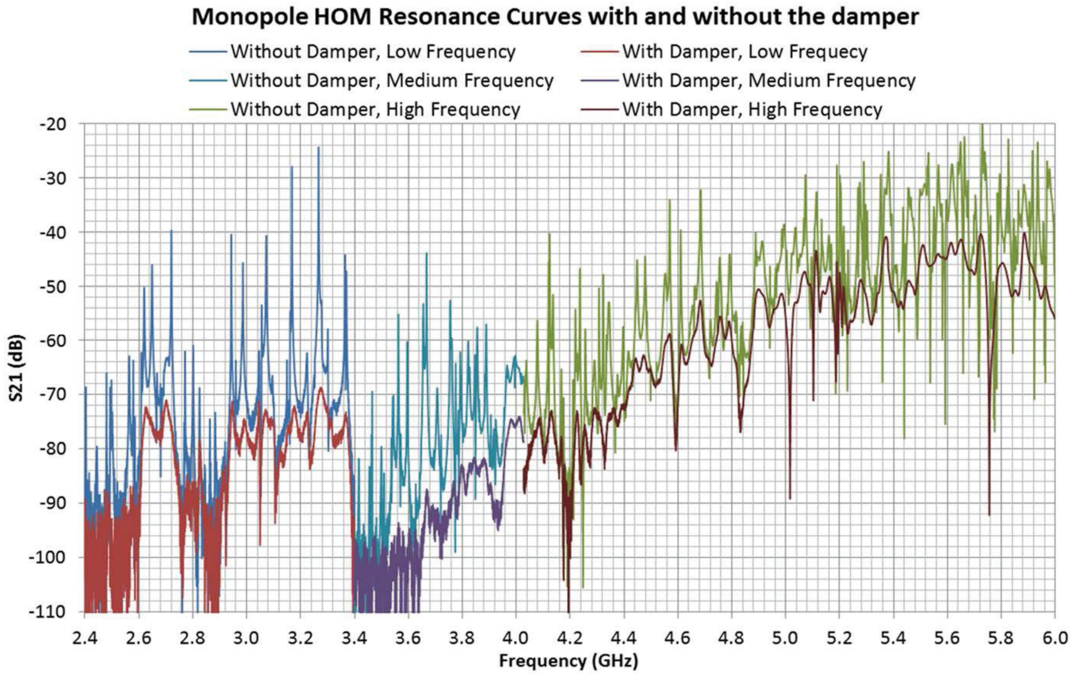




Benchtop Test of HOM Damping

With a realistic beamline assembly





S.H. Kim
MOPOB09

Cavity Ready for Cold Testing

Friday Oct. 7, 2016

Mid- and Long-term Plan

- Major procurements
  - Cryomodule vacuum vessel – 2017
  - Cryomodule internal hardware – 2018
  - Cryoplant and distribution - 2019
- Installation
  - Presently planned in 2022
  - There is ample time for an in-ring beam test of the cryomodule before the shutdown of the present APS

Summary

- Superconducting is the technology of choice for a bunch lengthening system for the APS-U and similar high-energy, high-current light source storage rings
  - Compact, stable, flexible, easy HOM handling, lower impedance presented to the beam
- Does not require an advance in the ‘state-of-the-art’
- Rather, we have a rapidly progressing R&D program building on four decades of SRF experience at ANL to demonstrate simple, robust, reliable operation of
  - A superconducting cavity
  - 20 kW 1.4 GHz CW power couplers
  - Room temperature beamline higher order mode dampers

Thank you to the Team

Advanced Energy Systems, Roark

Niobium tooling and forming
Finite Element Analysis
Electron beam welding

Meyer Tool

Helium and vacuum ASME vessel fabrication

MPF Inc

Saporito, AJ Tuck

RF couplers fabrication
Copper plating

Advance Photon Source

RF Systems – Doug Horan
Tim Berenc
Interfaces – John Carwardine
EM Design – Geoff Waldschmidt

PHY Accelerator Development Group

Sang-hoon Kim

Coordination
QA, Nb procurement,
Mechanical & EM design
Chemistry
Clean processing & assembly
Testing

Argonne Central Shops

& Nuclear Engineering

Brazing – Bill Toter
Engineering/Mechanical design – Al Barcikowski, Glenn Cherry

Fermilab

Vacuum furnace baking
Clean room support

Summary of Hardware Engineering Specifications

	Parameter	Symbol	Unit	Value
Cavity	Operating temperature	T	K	2.1 or 4.3
	Frequency (tuner released)	f_0	GHz	1.4078
	Peak Surface Electric Field	E_{peak}	MV/m	21
	Peak Surface Magnetic Field	B_{peak}	mT	43
	Pressure sensitivity	$\Delta f/\Delta p$	Hz/Torr	<20
	Microphonic bandwidth	Δf	Hz p-p	<300
	Cavity tuning sensitivity	$\Delta f/\Delta x$	MHz/mm	-1.8
	Cavity transverse alignment	δx, δy	mm	+/- 0.5
Coupler	Stroke	Δl	cm	4
	External Q range (both couplers)	Q_{ext}		$2x10^5$-$2x10^7$
	Power rating per coupler (CW TW)	P	kW	20
Tuner	Range	Δf_{tun}	kHz	600
	Force	F	kN	20
	Pressure	P	bar	0-3
	Resolution	Δf_{res}	Hz	<10
	Slew rate	$\Delta f/\Delta t$	KHz/s	100
HOM damper	Simulated power loss per damper	P_{HOM}	kW	1
	Design power handling per damper	P_{HOM}	kW	10
Module	Length (flange-to-flange)	L_{mod}	m	1.73

Backup Slide: 'Parking' with the Slow Tuner

Three viable alternatives

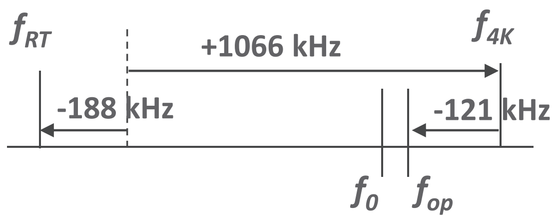
f_0: beam harmonic frequency = 1407.76 MHz

f_{op}: HHC cavity operational frequency = f_0+15 kHz

f_{4K}: HHC cavity frequency parked at 4 K

f_{RT}: HHC cavity frequency parked at room temperature

i) Case I: $f_{4K} = f_0 + 136\ kHz$

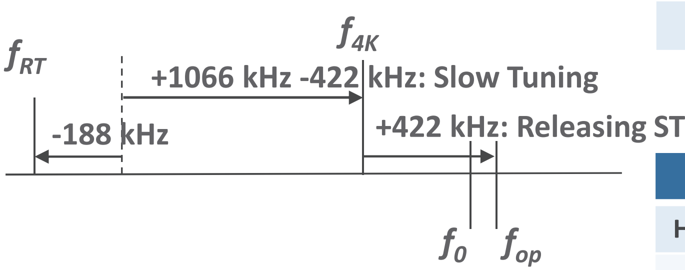


Case I	4 K parking	RT parking
Harmonic voltage	110 kV	14 kV
Beam loss power	500 W	188 W
Cavity wall loss	0.6 W	181 W

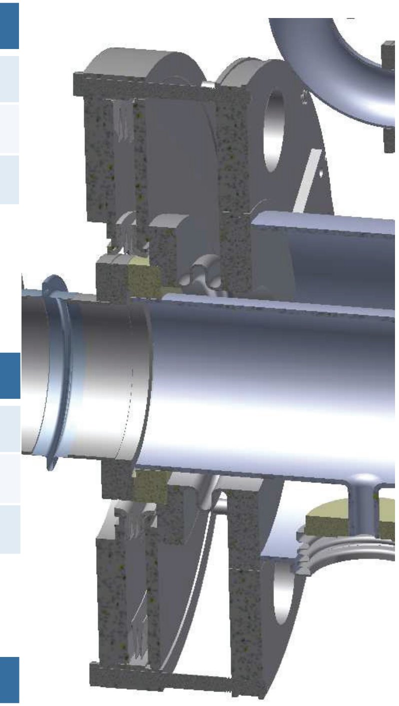
ii) Case II: $f_{4K} = f_0 + 407\ kHz$

Case II	4 K parking	RT parking
Harmonic voltage	38 kV	18 kV
Beam loss power	54 W	327 W
Cavity wall loss	0.1 W	314 W

iii) Case III: $f_{4K} = f_0 - 407\ kHz$



Case III*	4 K parking	RT parking
Harmonic voltage	38 kV	9 kV
Beam loss power	54 W	85 W
Cavity wall loss	0.1 W	82 W



Argonne NATIONAL LABORATORY

Selection of the harmonic number

Category	Parameter	Symbol	Unit	Value			
				Without HHC	APS-3rd	APS-4th	APS-5th
Cavity	Cavity Resonant Frequency	f_r	MHz	-	1056	1408	1760
Beam	Optimum Harmonic Voltage	V_h	MV	-	1.2	0.90	0.73
	Optimum Detuning Angle	ψ_h	degree	-	74.1	78.9	81.4
	Beam Loss Power at 200 mA	P_{beam}	kW	-	60	32	20
Performance	RF Acceptance	ε_{RF}	%	4.0	3.9	3.9	3.7
	RMS Bunch Length	σ_t	ps	12	58	49	44
	Touschek Lifetime	τ	arb.	1.0	5.0	4.1	3.4

- The 4th harmonic: power handling is moderate
- Infrastructure for 1.3 GHz ILC cavities at Argonne can be utilized
- Available RF power at a nearby frequency (1.3 GHz)