Overview of recent SRF developments for ERLs

S. Belomestnykh

Brookhaven National Laboratory and Stony Brook University

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- I also grateful to **H. Sakai (KEK) and E. Jensen (CERN)** for their efforts on organizing a working group on SRF at the ERL'2015 Workshop and writing an excellent summary report.

State of the ERL field

- Energy Recovery Linacs still generate a lot of interest: recent **ERL'2015 Workshop** attracted more than 100 participants.
- Along with "traditional" **applications of ERLs** for *X-ray light sources* and *FELs*, *electron-ion colliders* and *electron coolers*, several new proposals and ideas were presented at the workshop.
- Among those are: a compact *ultra-high flux X-ray and THz source* at John Adams Institute, ERLs for *nuclear physics research* MESA at Mainz University *and particle physics experiments* at the jointly proposed BNL/Cornell demonstration multi-pass FFAG machine, *γ-ray sources*, an *ERL facility at CERN for applications* and even a concept of *lepton ERL scalable to TeV energies*. However, only a handful of big proposals are actually funded.
- The field is very active, but is still in the development/demonstration stage, which means **a lot of need and opportunities for R&D!** – M. Tigner's talk "Energy Recovery Linacs: Past… Present… Future…"

Superconducting RF for ERLs

- As SRF linacs are essential to realize full benefits of the ERL approach, a significant portion of the *ERL'2015* was devoted to the SRF technology, which was discussed in several working groups.
- **ERL R&D needs related to SRF**:
  - *CW operation of large-scale SRF installations: high Q_0 at 15-20 MV/m is essential.*
  - *Unprecedented beam currents and unprecedented number of spatially superimposed high charge bunches in the SRF linacs: BBU, halo, other beam dynamics issues.*
  - *Photoinjectors producing high-brightness beams.*
  - *Very precise phase and amplitude control of narrow-bandwidth SRF cavities required over large spatial extent with varying ground vibration conditions.*

This talk

- As it is impossible to cover all these topics in a short talk, I will concentrate on a few. In particular, I will not discuss high Q_0 research. This very important "hot topic" is of a general interest and will be extensively covered during the conference.
- **In this talk I will review**:
  - *Recent results from SRF photoinjectors for ERLs (briefly, as they will be covered in two talks:* **THAA02** *and* **THAA03***).*
  - *New SRF cavities for ERLs.*
  - *Development of ERL linacs including precise field control.*

Recent results from SRF photoinjectors for ERLs

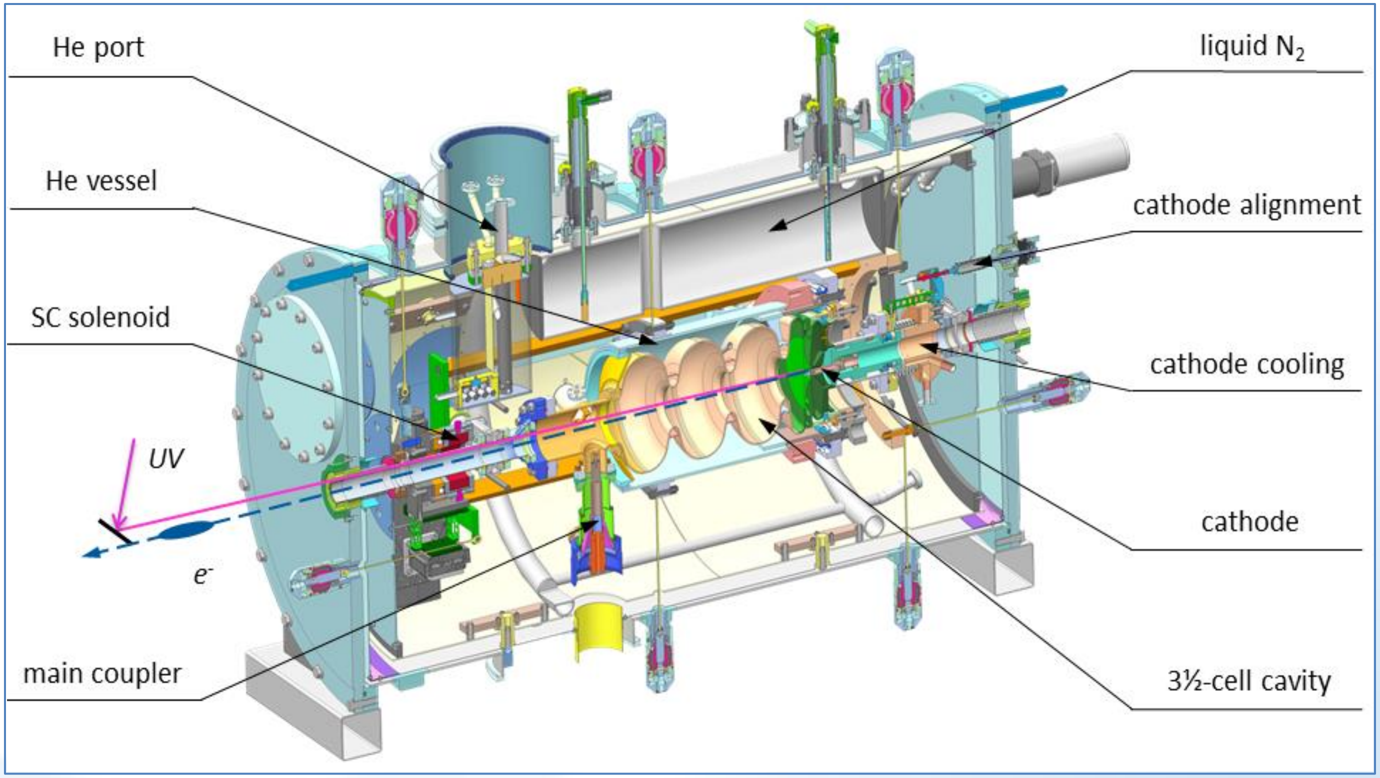
- SRF Gun II at ELBE
- Recent results on SRF gun for b*ERL*inPro
- First beams from SRF guns at BNL

Issues

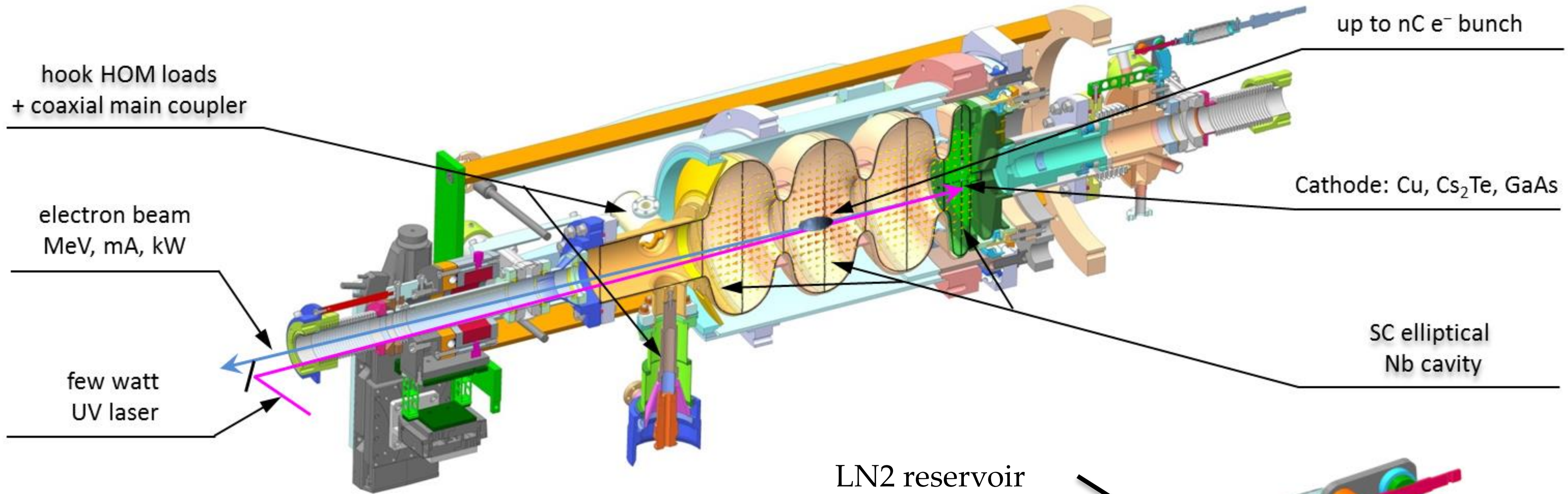
- Operation with high QE photocathode materials: MP and FE, cavity contamination

SRF Gun II at ELBE

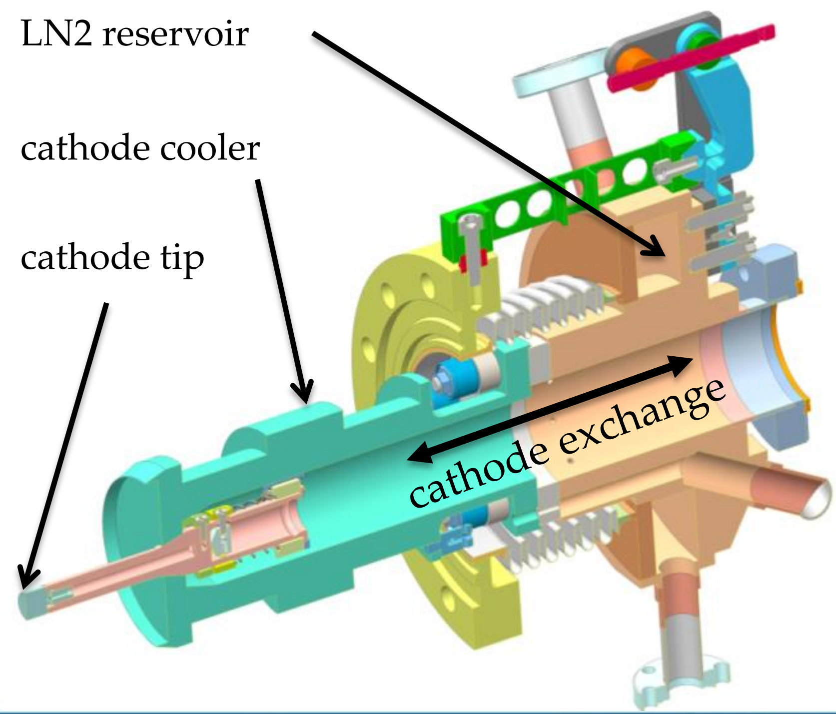
- This gun has an improved 3.5-cell niobium cavity with a better accelerating filed distribution: peak field ratio of 0.8:1 between the half-cell and TESLA cells.
- A superconducting solenoid is integrated into the gun cryomodule. There were also several smaller modifications.



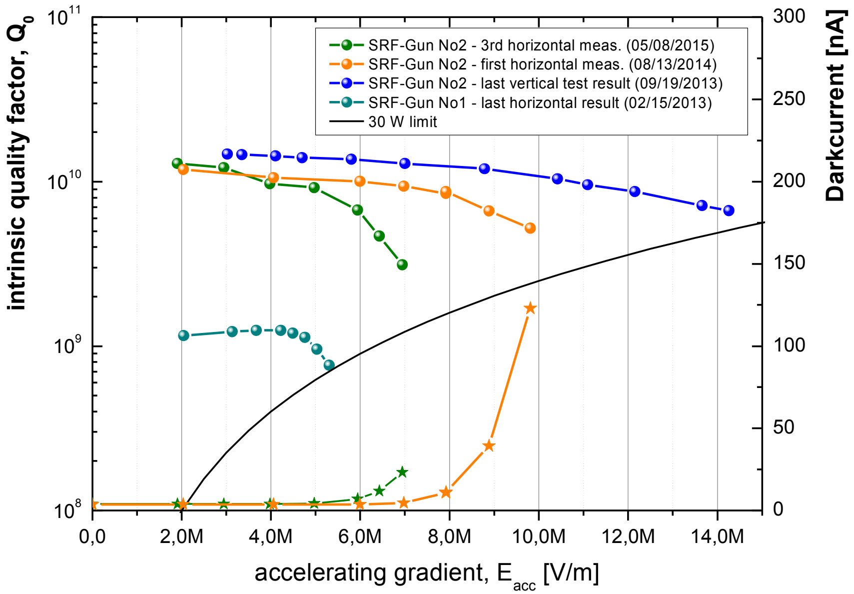
Design of the ELBE SRF gun II



- Cs_2Te, Cu, GaAs, Mg cathode
- Cooled by LN2 to 77 K
- Therm. and electr. isolated from cavity
- Up to 7 kV DC bias for MP suppression
- Moveable and tiltable by remote stepper



SRF Gun II test results



- An accelerating gradient of 10 MV/m was achieved in the first RF test of the gun without a cathode, which is a significant improvement as compared with SRF Gun I.
- Beam dynamics simulations showed that higher gradient should result in reduced emittance and bunch length.
- The first beam test has been carried out with a copper photocathode with gradients up to 9 MV/m. Installation of a Cs_2Te photocathode was not successful as it resulted in very low quantum efficiency (QE) and contamination of the gun cavity.
- Thus in the following the accelerating gradient was restricted to 7 MV/m, it should still potentially allow generating a bunch charge up to 500 pC, improving user operation.
- Transverse emittance and longitudinal phase space measurements were performed, and agreed well with expectations from Astra simulations.
- The critical issue at present is the quality and cleanliness of photocathodes.

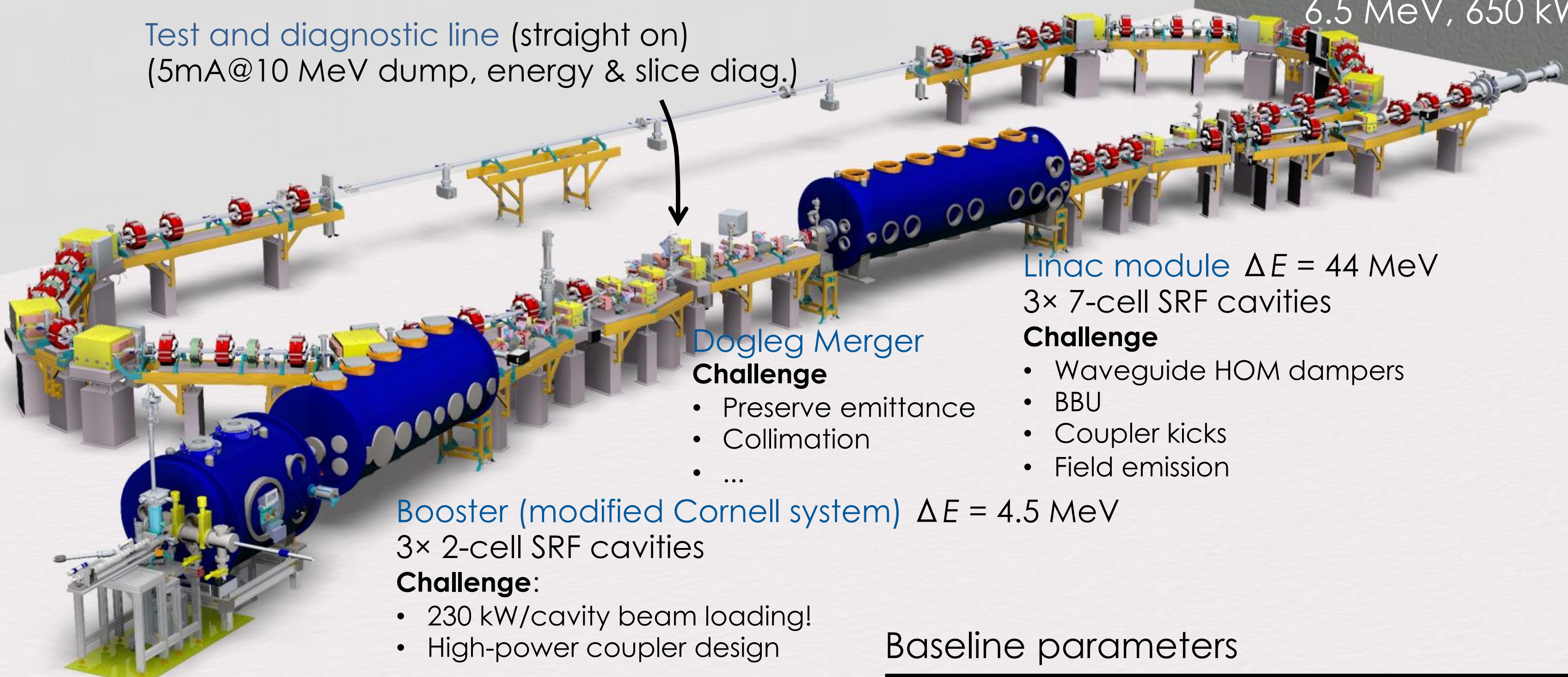
Posters: TUPB055, THPB10, THPB057

b*ERL*inPro – A demonstration Energy Recovery LINAC

bERLinPro layout

J. Knobloch, 2015-06-08
HZB Helmholtz Zentrum Berlin

– M. Abo-Bakr et al., "Status of the HZB ERL project bERLinPro", *Proc. IPAC2014*
– J. Knobloch et al., "bERLinPro – addressing the challenges of modern ERLs (a status report), *ICFA Beam Dynamics Newsletter* **58**, Aug. 2012, (http://www-bd.fnal.gov/icfabd/Newsletter58.pdf)



Beam dump
6.5 MeV, 650 kW

Test and diagnostic line (straight on)
(5mA@10 MeV dump, energy & slice diag.)

Linac module ΔE = 44 MeV
3× 7-cell SRF cavities

Challenge
- Waveguide HOM dampers
- BBU
- Coupler kicks
- Field emission

Dogleg Merger

Challenge
- Preserve emittance
- Collimation
- …

Booster (modified Cornell system) ΔE = 4.5 MeV
3× 2-cell SRF cavities

Challenge:
- 230 kW/cavity beam loading!
- High-power coupler design

SRF photoinjector, with SC solenoid, 1.5 – 2.3 MeV

Challenge:
- 30 MV/m CW operation with CsK_2Sb cathode
- Cathode performance @ 100 mA
- Dark current/halo control
- Emittance compensation
- …

Facility is fully funded (Helmholtz Assoc., HZB and State of Berlin)

Baseline parameters

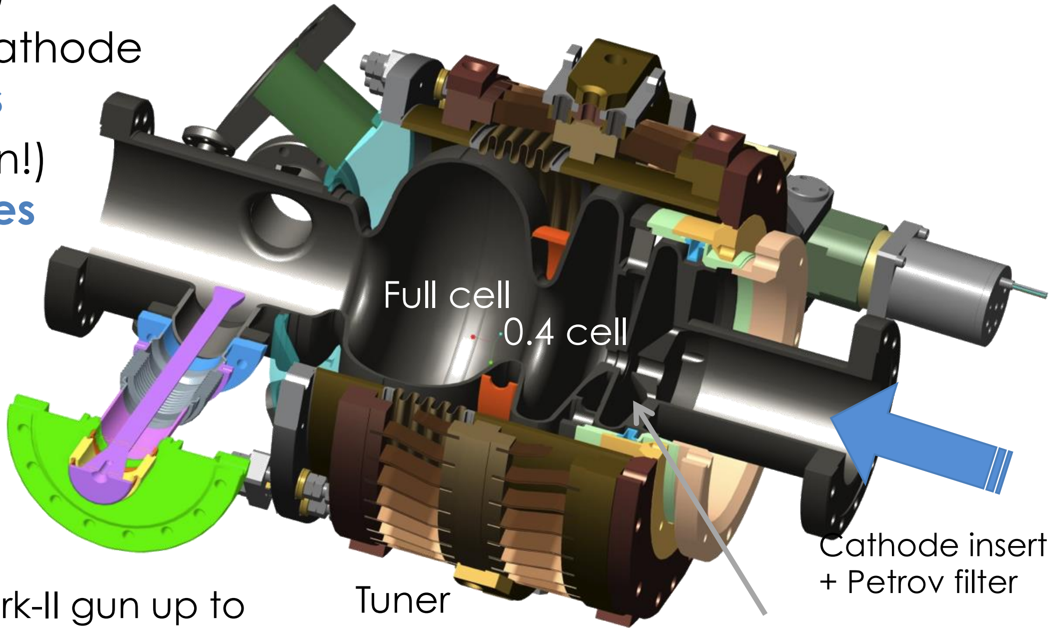
Parameter	Design goal
max. beam energy	50 MeV
max. current	100 mA (77 pC/bunch)
frequency	1.3 GHz
normalized emittance	1 mm (ca. 0.5 mm sim.)
bunch length (straight)	2 ps or smaller (100 fs)
losses	< 10^{-5}

Status: RF photoinjector

– Neumann et al., “Towards a 100 mA superconducting RF photoinjector for bERLinPro”, *Proc. SRF2013*
– T. Kamps et al., “Beam dynamics studies for SRF photoinjectors”, *Proc. LINAC2012.*

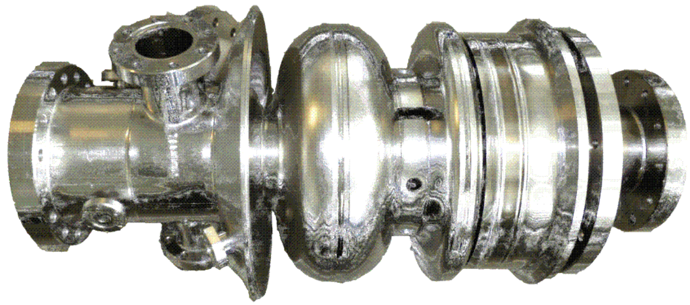
New SRF gun, based in part on HZDR’s design

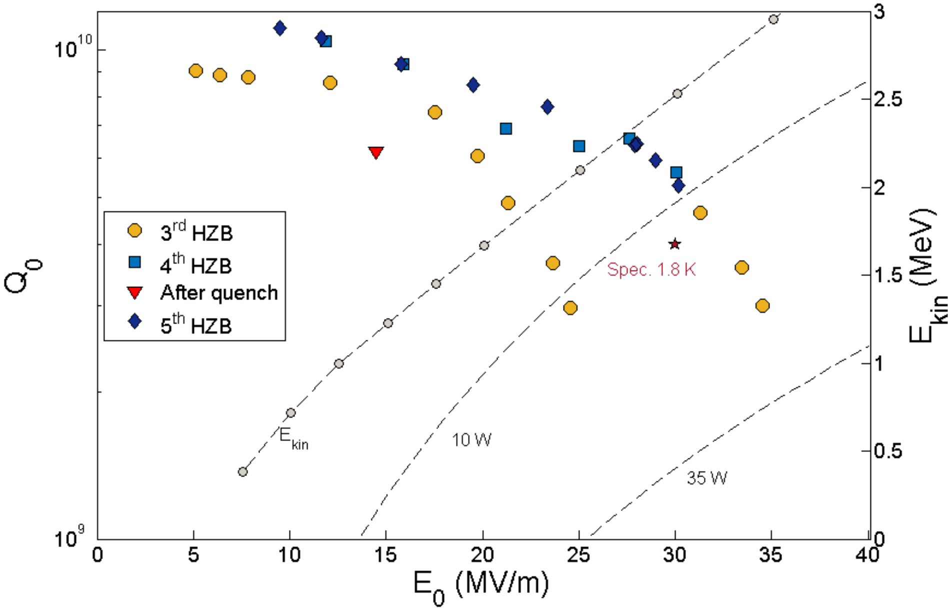
- Potentially very powerful injector (CW operation + high field + high voltage + UHV simultaneously), but not demonstrated to date.
- 1.3 GHz, 1.4-cell SRF cavity
  - Compromise between RF voltage, RF field and beam loading (≤ 230 kW)
- CsK_2Sb Photocathode
  - Reasonable longevity, vacuum requirements, QE and laser wavelength (green)
  - Challenge: normal conducting cathode in the SRF cavity ✎ **cooling issues**
  - Operating a cathode (low work-fn!) at high field ✎ **field emission issues**



Twin CW RF couplers (Mark-II gun up to 115 kW. Shown here: Mark-I gun with CW modified TTF-III couplers for 10 kW CW)

Status of the SRF gun for b*ERL*inPro

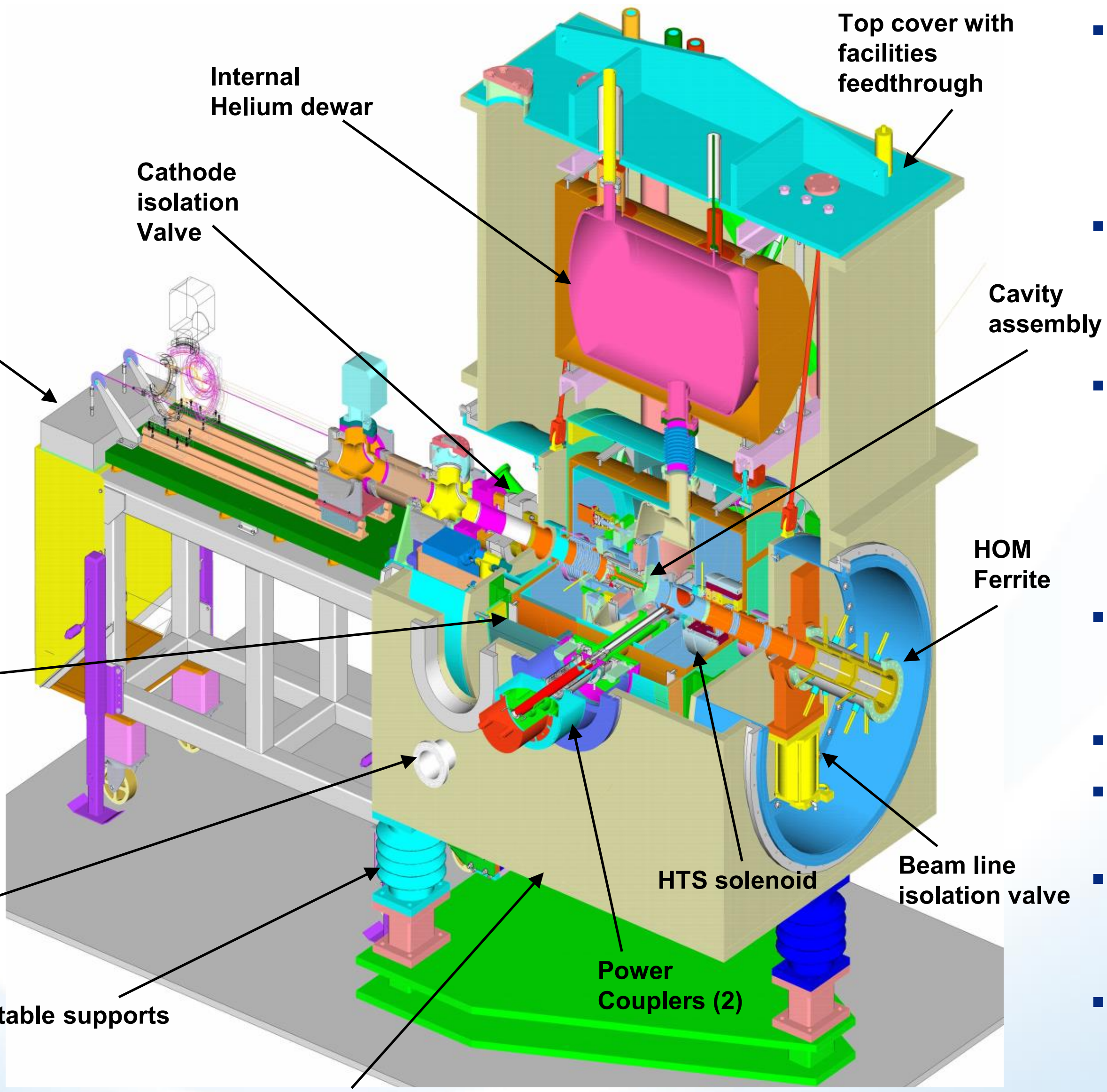




Poster: TUPB026

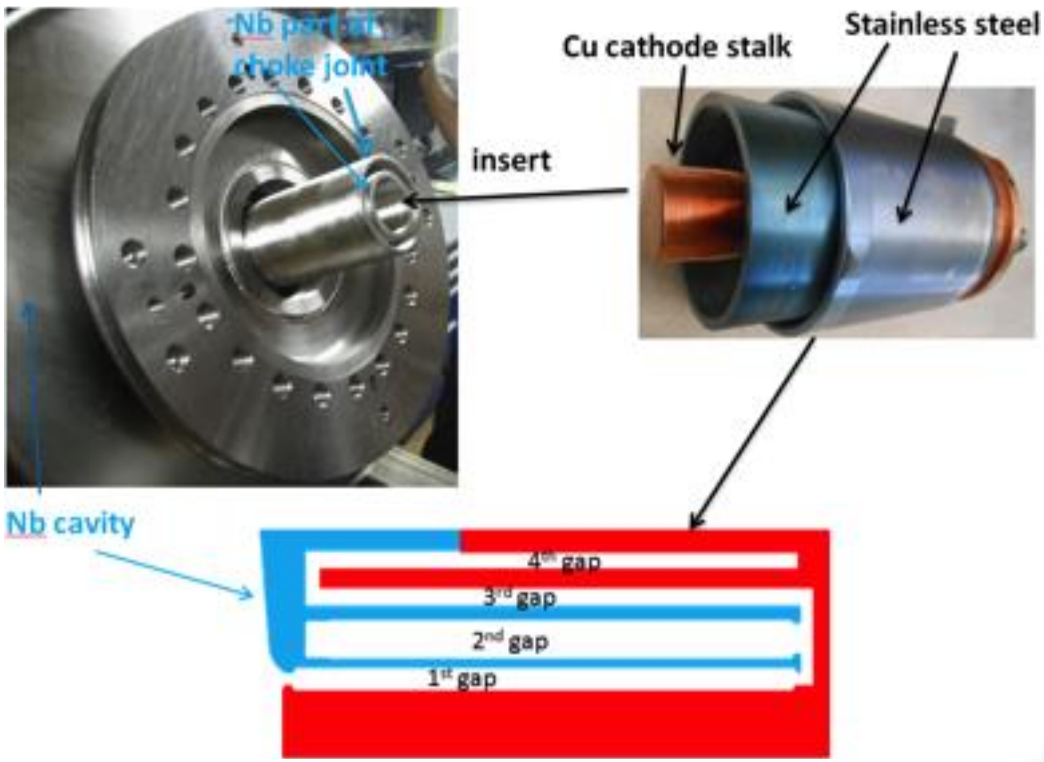
- Cavity after welding without helium vessel, before first VTA tests (Sep. 2013).
- First prototype manufactured at Jlab, complicated design, hard to manufacture. The produced cavity deviated from the design geometry (first half-cell is 5 mm shorter). This caused MP.
- First horizontal test of the prototype gun in HoBiCaT at HZB with the same critically coupled antennas as used in the VTA at Jlab.
- Second horizontal test series after modifications of helium vessel: the same measurement configuration as in the first horizontal test. Both without inner magnetic shielding, but also without tuner, all at 1.8 K.
- The cavity has reached 34.5 MV/m, where it quenched. Its performance was recovered after thermal cycling and it now routinely achieves design field with the *Q* factor above design specification.
- The plan is to use this cavity in the first gun cryomodule.

SRF gun for R&D ERL at BNL



- The 703.75 MHz ½-cell SRF gun with an independently cooled (by LN_2) demountable cathode stalk will use a multi-alkali (CsK_2Sb) photocathode.
- A quarter wave RF choke-joint supports the photocathode stalk and has triangular grooves for suppression of multipacting.
- Two Fundamental input Power Couplers (FPCs) will allow delivery of 1 MW of RF power to a 0.5 A electron beam at an energy gain of 2 MeV. The couplers were conditioned off line in 2012.
- A high-temperature superconducting solenoid is located inside the cryomodule.
- The cavity active length is 8.5 cm.
- Frequency tuning range is 1.2 MHz (1 mm of cavity deformation).
- HOM damping is provided by an external beamline ferrite load with a ceramic break.
- The cryomodule was built by AES, Inc.

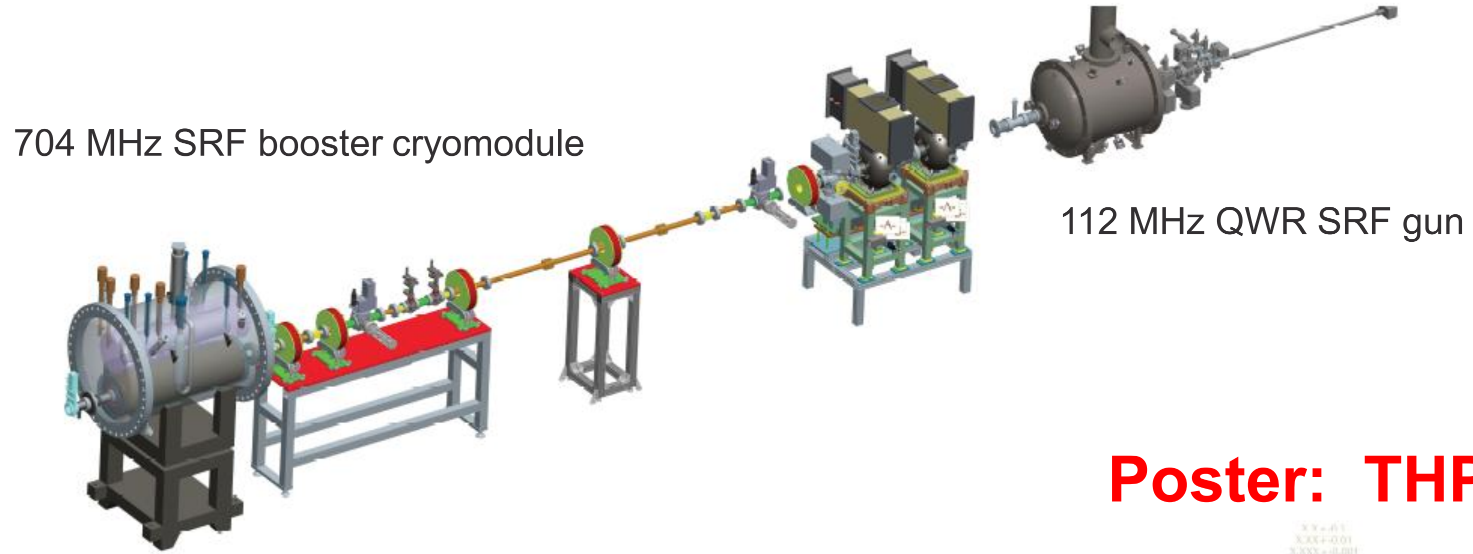
SRF gun for R&D ERL at BNL



- The gun cavity performs well without the cathode stalk, reaching an accelerating voltage of 2 MV in CW mode.
- When the original cathode stalk was inserted, MP zones in the 3rd and 4th gaps (unexpected) prevented the gun from operating in CW mode in the desired voltage range. Also, the copper tip of the stalk was not suitable for high QE photocathodes.
- The cathode stalk was redesigned: i) the RF choke geometry was improved to eliminated MP; ii) the tip of the stalk was coated with tantalum to increase QE of the photoemission layer. With the new stalk the gun cavity could be quickly conditioned for CW operation.
- However, after deposition of CsK_2Sb, the gun can still operate only in pulsed mode due to contamination of the sides of the tip with the photoemission layer.
- To date, the 704 MHz SRF gun generated electron bunches with a charge up to 0.55 nC

Talk: THAA03

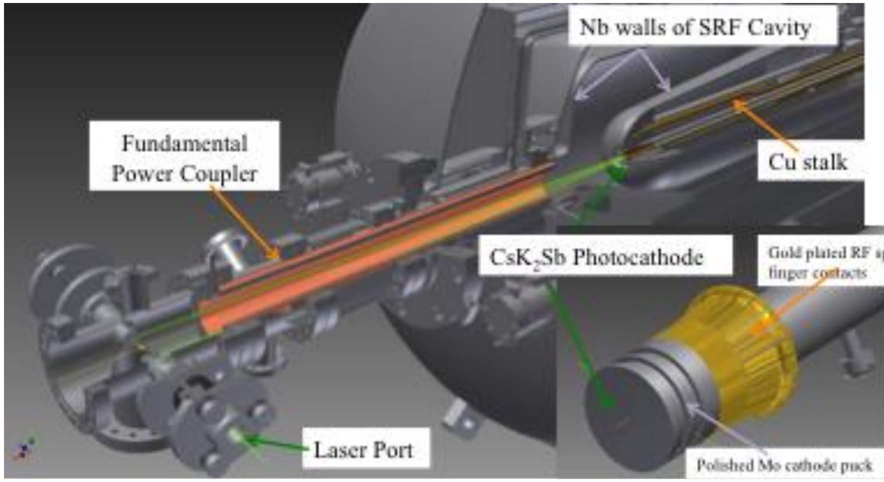
Coherent electron Cooling Proof-of-Principle experiment

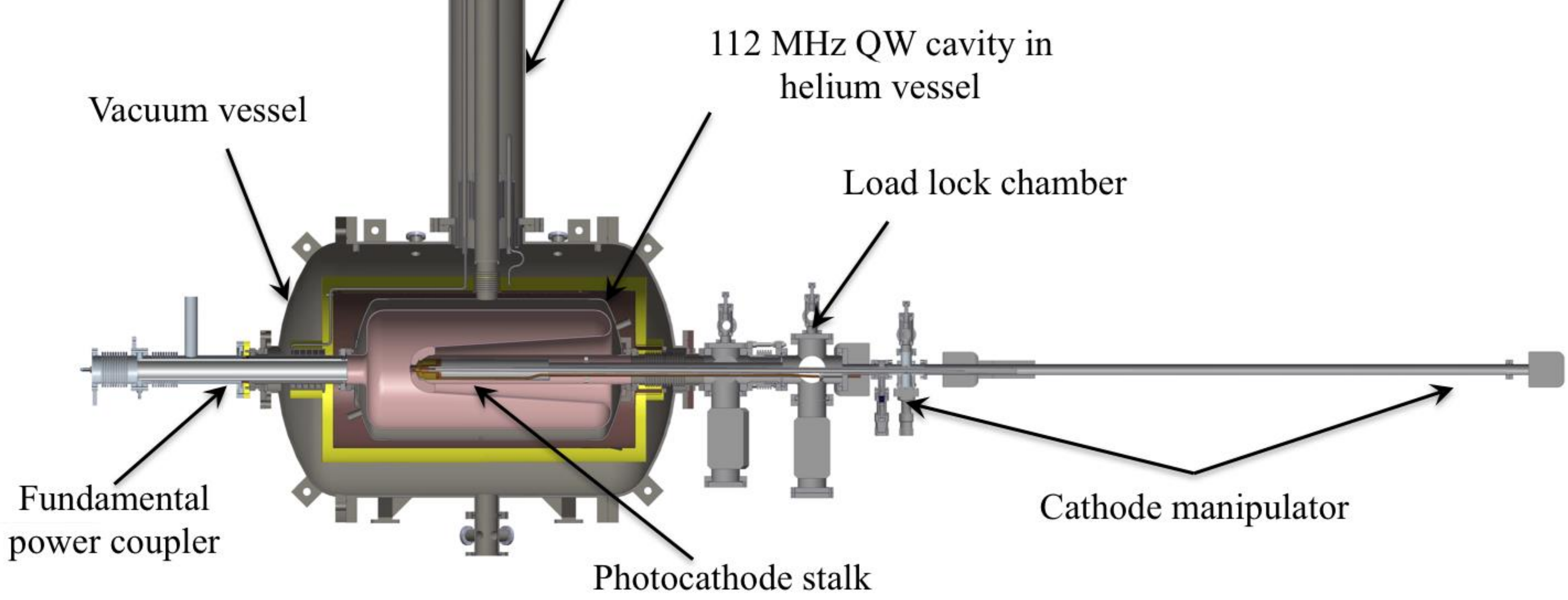


Poster: THPB058

- A Proof-of-Principle (PoP) experiment is under preparation at BNL to demonstrate feasibility of CeC for future improvements of luminosity in high-energy hadron-hadron and electron-hadron colliders.
- Only one RHIC ion bunch will be cooled. To generate a high-bunch-charge, low-repetition-rate beam, we are building a short 22-MeV superconducting linac.
- The linac includes two SRF systems: a 112-MHz Quarter Wave Resonator (QWR) photoemission electron gun and a 704-MHz booster cavity cryomodule.

112 MHz SRF gun cryomodule

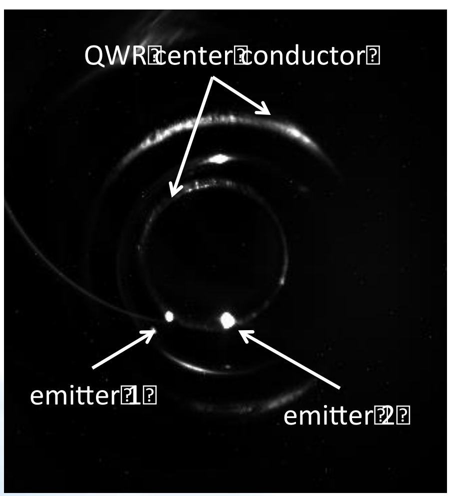


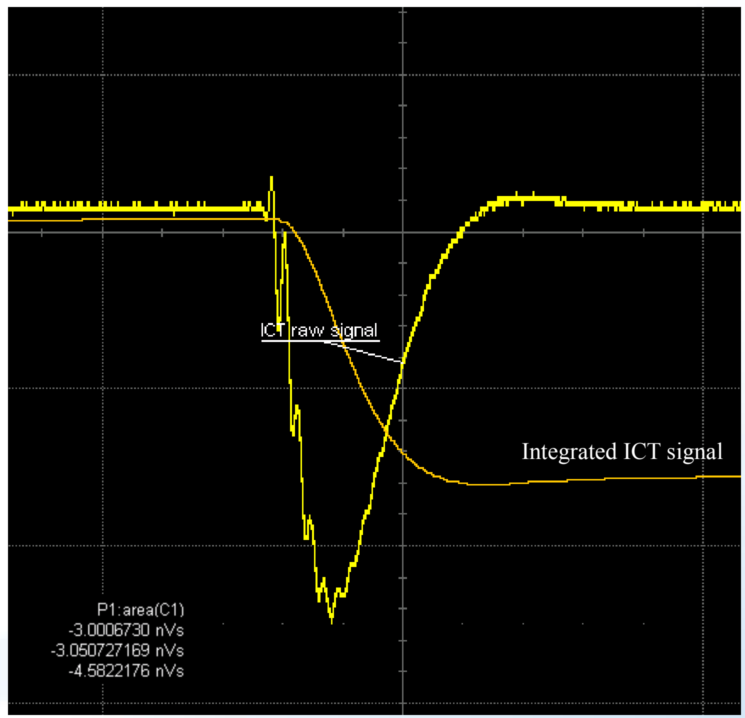


112 MHz SRF commissioning

- The 112 MHz quarter-wave SRF gun was successfully installed and commissioned in the RHIC tunnel.
- After initial RF conditioning the gun cavity was limited to 1.3 MV CW. After helium processing was applied, the voltage went up to 1.7 MV.
- While still limited by field emission at its highest voltage (1.7 MV in CW, 2 MV in pulsed mode), the gun was able to generate a record-high bunch charge of 3 nC from a CsK_2Sb photocathode.
- At a repetition rate of 5 kHz, the beam current was about 15 μA.
- After the RHIC operation resumes in January of 2016, the SRF gun beam testing will continue.

Two active field emitters inside the QWR center conductor.





Oscilloscope trace of a raw signal from ICT and its integral. The integrated signal corresponds to bunch charge of 2.4 nC.

New SRF cavities under development for ERLs

- Development of the high current superconducting cavity at IHEP
- SRF cavities for b*ERL*inPro
- 422 MHz cavity for eRHIC at BNL
- UH-FLUX: Asymmetric ERL

Issues

- HOM damping: high average power handling, wide frequency range

Development of high current SRF cavity at IHEP

Talk by Zhenchao Liu at ERL'2015

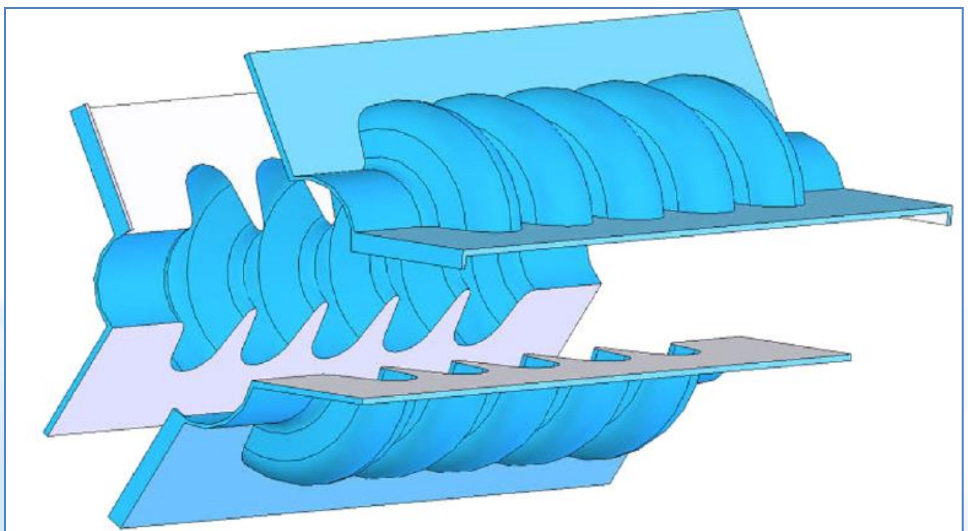
- A slotted SRF cavity was proposed in 2010 by Z. Liu and A. Nassiri.
- In 2012 development of this cavity was funded by NSFC.
- The cavity was fabricated in 2014 and first tests began this year.

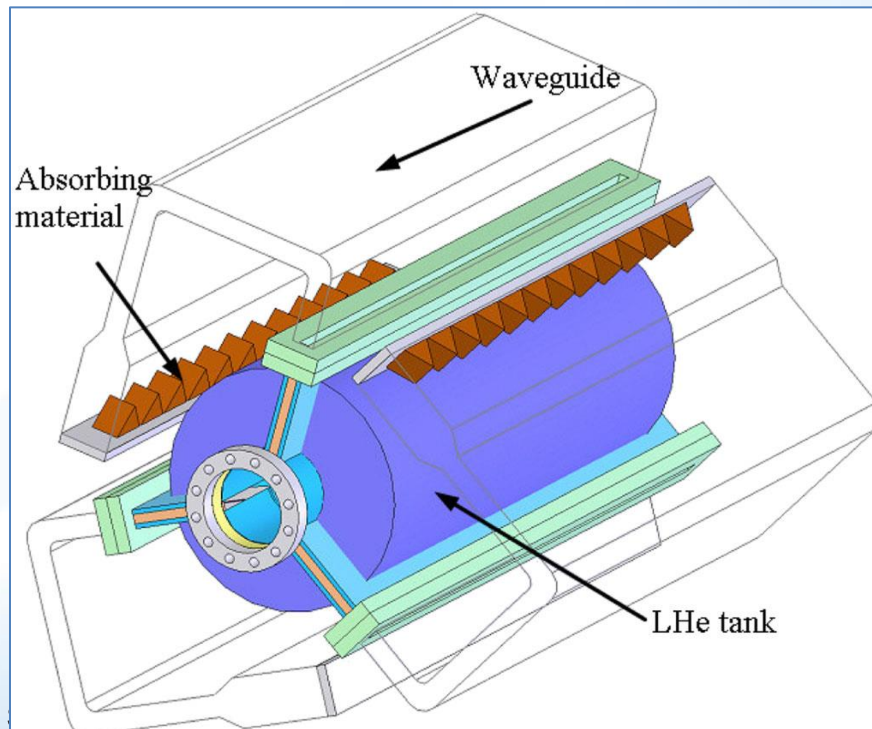
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 012001 (2010)

Novel superconducting rf structure for ampere-class beam current for multi-GeV energy recovery linacs

Z. Liu[1,2] and A. Nassiri[2]
[1]*Institute of Heavy Ion Physics, Peking University, Beijing, China*
[2]*Advanced Photon Source, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois 60439, USA*
(Received 12 August 2009; published 6 January 2010)

Future ampere-class energy recovery linacs (ERLs) based on superconducting technology demand efficient damping of the higher-order modes in the superconducting radio-frequency (SRF) accelerating structures to achieve stable beam operation in multipass, multibeam ERLs. We propose a new and novel SRF structure that is extremely efficient in damping the higher-order modes of SRF structures for ERLs. Initial simulation results indicate extremely good and efficient damping of the dipole and the quadrupole modes that determine the beam breakup threshold of the superconducting structures. The proposed new structure has the added benefit of having simpler fabrication steps with potential fabrication cost savings.



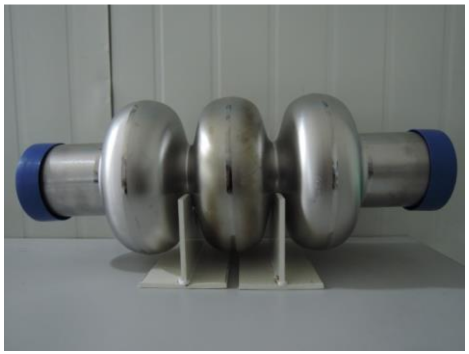


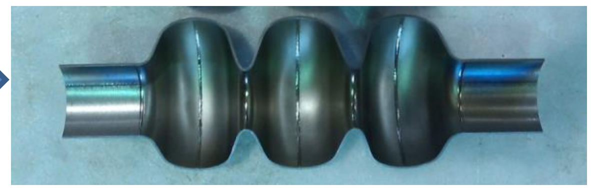
Cavity parameters

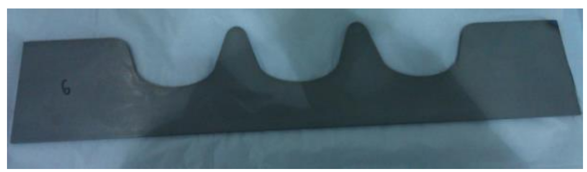
- Proper cell numbers. For the test cavity, we chose a 3-cell cavity to simplify the fabrication and lower the cost.
- Minimized E_{pk}/E_{acc} and B_{pk}/E_{acc}.
- No hard multipacting barrier caused by cavity shape and the slotted structure.
- Frequency can be easily tuned. Easy to fabricate.
- The cavity was fabricated. Its HOM properties were studied confirming strong damping.

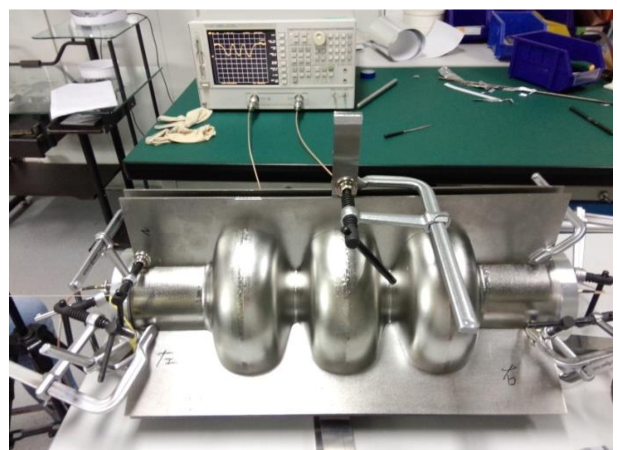
	Center cell	End cell
L (mm)	57.7	57.7
Riris (cm)	41.152	48.733
Requator(mm)	103.899	103.899
A(mm)	37.904	35.434
B(mm)	23.825	23.55
a(mm)	10.83	16.786
b(mm)	16.244	16.244
Frequency(GHz)	1.30108	
E_p/E_{acc}	3.57	
H_p/E_{acc}mT/(MV/m)	5.72	
r/Q [Ω]	268.9	
k [%]	2.7%	
Field flatness [%]	>97%	

Fabrication and Welding







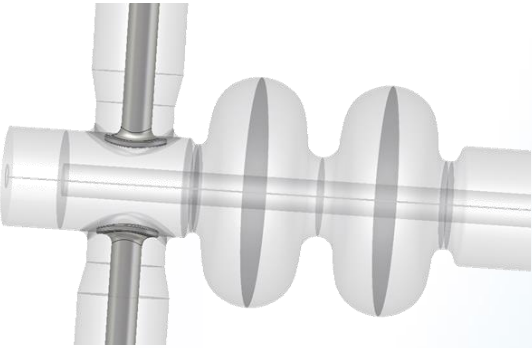


Vertical test

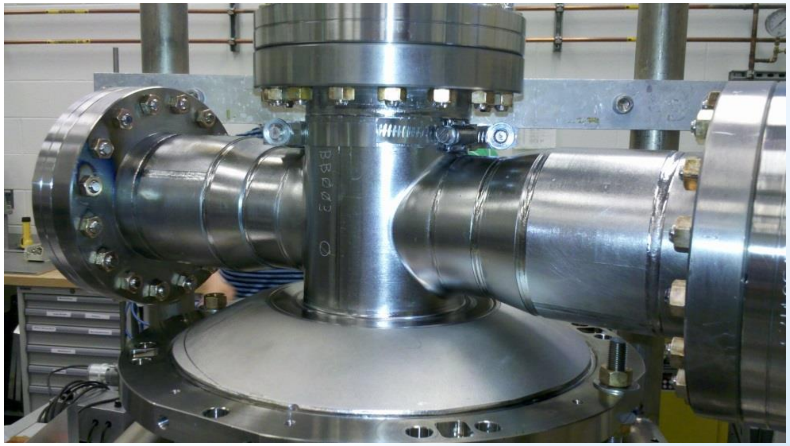
- Established 1.3 GHz vertical test system
- Calibrated the coupler probe and pick-up probe
- 4.2 K vertical test, limited by power, the accelerating gradient of the cavity reached 2.4 MV/m (Q_0 = 1.4x10^8)
- Verified the probability of the slotted cavity working at 4.2 K
- The cavity will be tested at 2 K in future.

Booster SRF cavities for b*ERL*inPro

The Booster cavities are of Cornell type with modified FPC section to accommodate modified KEK c-ERL coupler (golf tee antenna tip)



Poster: TUPB026

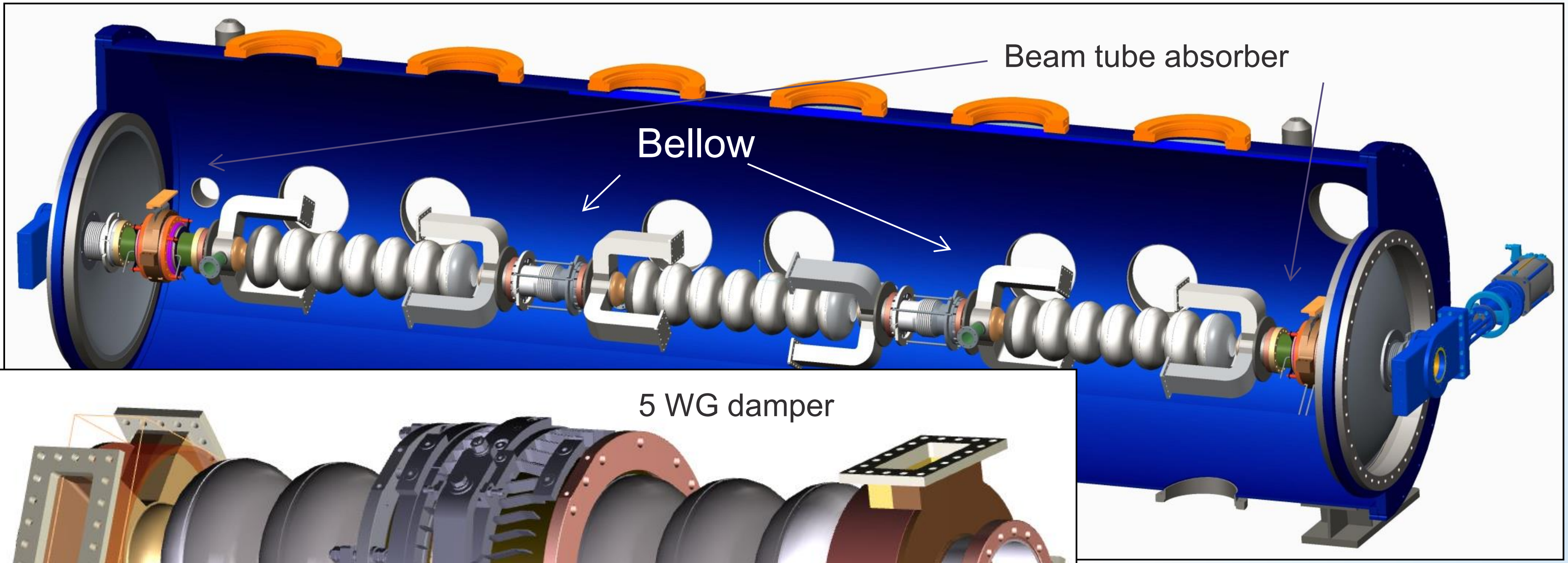


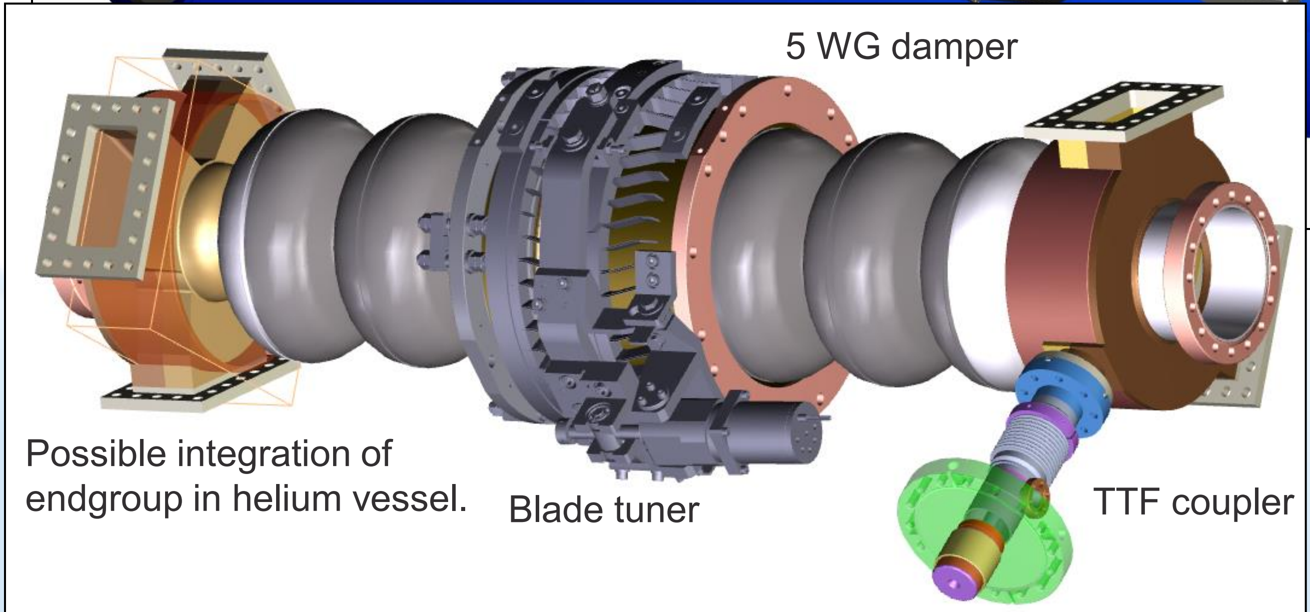
- 4 cavities were manufactured at JLab, all of them met the specs. and far beyond already after first vertical test, with only one treatment (bulk 120 µm BCP, 600° C bake, light 25 µm BCP).
- 3 cavities got helium vessels welded and tested very good again, the 4th will remain as spare with helium vessel separate (all cavities are at HZB).

Linac SRF cavity for b*ERL*inPro

Poster: TUPB026

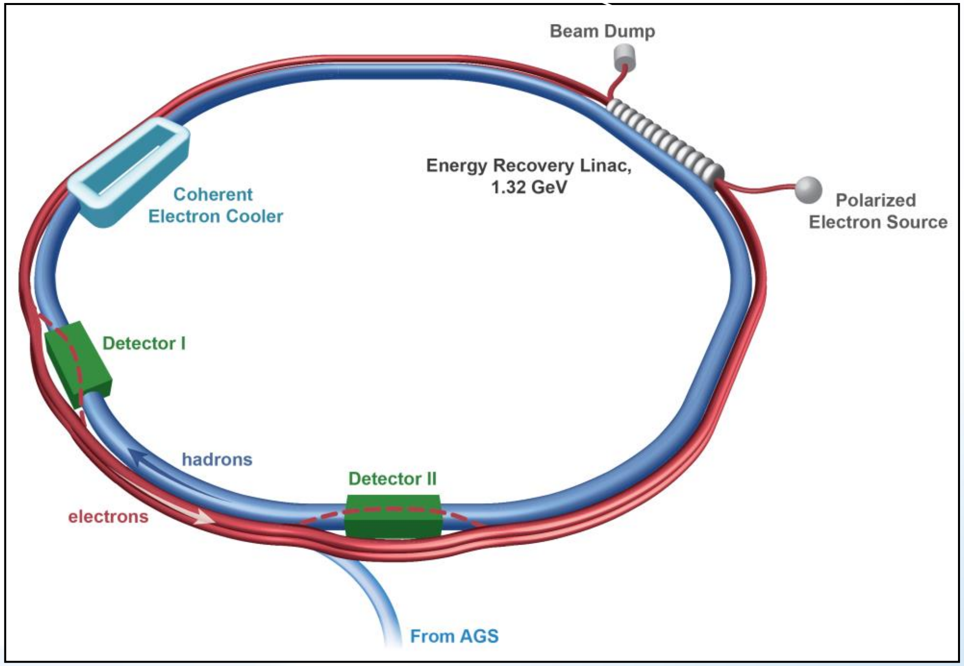
Linac cavity: 7 cell, mid-cell of Cornell geometry, end-cell optimized for WG based HOM damping (Jlab) and one TTF coupler. RF design done, WG tapering helped to reducie coupler kicks. At the moment module and helium vessel are under design, integrating the WG, cooling concept. Optimization of module with respect to lowest coupler kick effect and best orientation of all HOM damping ports → Rostock university concatenation studies.





422 MHz cavity for eRHIC at BNL

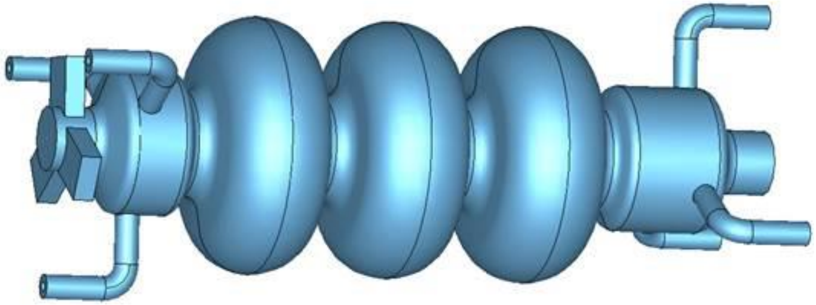
- An electron-ion collider eRHIC will collide high-intensity hadron beams from RHIC with an electron beam delivered by a multi-pass ERL. An FFAG-based ERL will accelerate an electron beam to 15.9 GeV (50 mA) after 12 passes through an SRF linac or to 21.2 GeV (18.5 mA) after 16 passes. In both cases, the linac energy is 1.322 GeV.
- With up to 16 passes in the FFAG version of eRHIC the requirements to the HOM impedance becomes more stringent. To mitigate various beam dynamics effects, it was proposed to lower the RF frequency to 422 MHz.
- The new cavity, BNL4, is designed to operate at 18.5 MV/m at $Q_0 = 5 \times 10^{10}$. It is a 5-cell cavity.

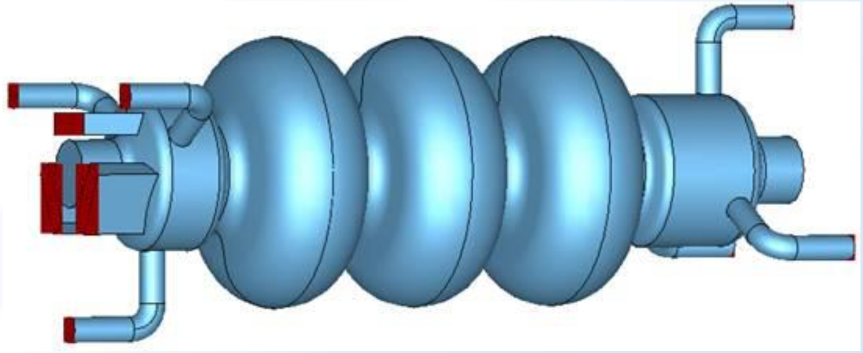


HOM damping for the BNL4 cavity

Poster: TUPB074

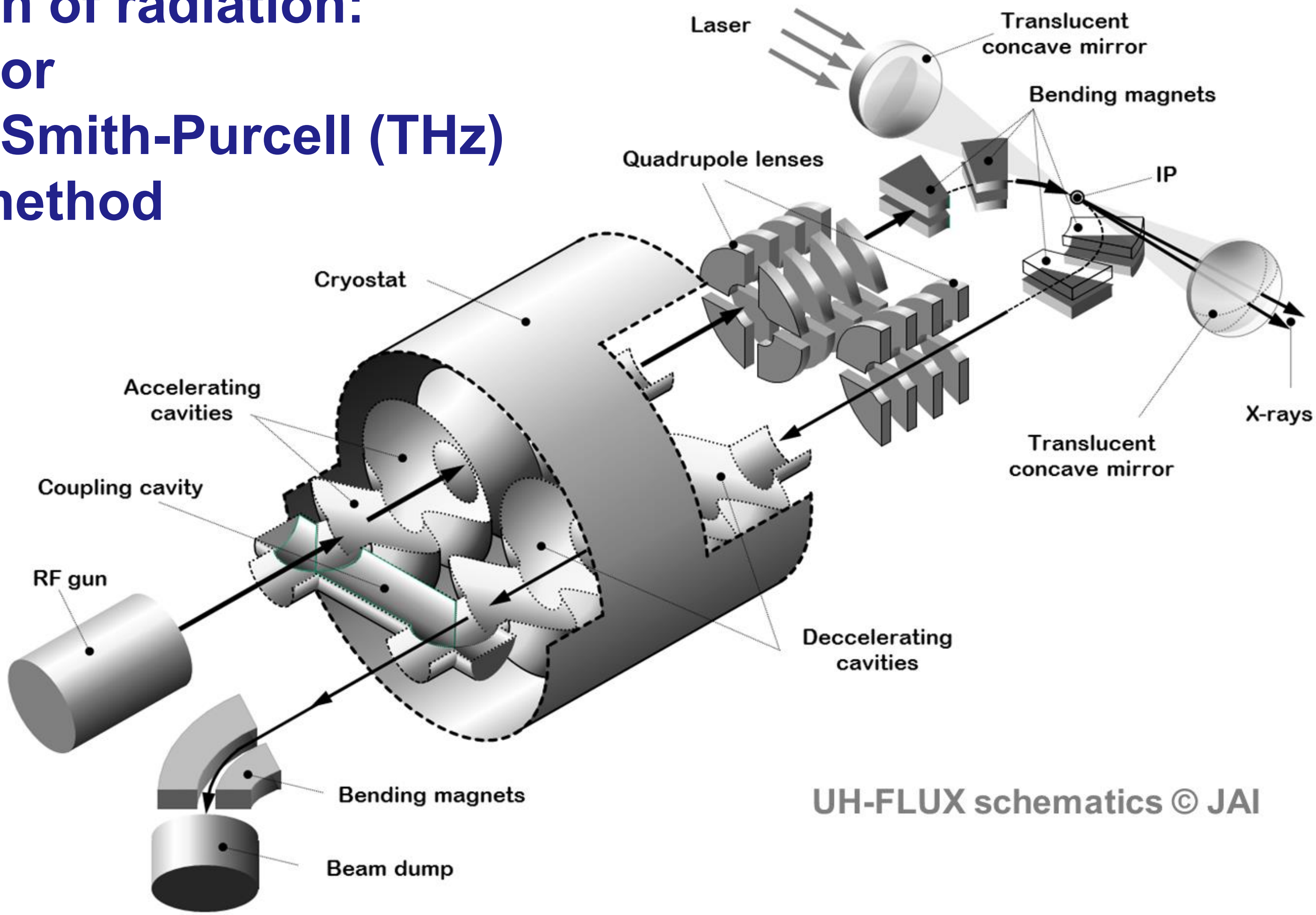
- HOM damping is challenging with power reaching up to 7 kW in a very broad frequency range to ~30 GHz.
- A 3-cell prototype is on order to demonstrate the cavity performance and study HOM damping schemes.
- Two potential damping schemes include six coaxial couplers to cover lower frequency part of the HOM spectrum (72% of HOM power below 5 GHz) and three waveguide couplers for the high end of HOM spectrum.





UH-FLUX – conceptual layout

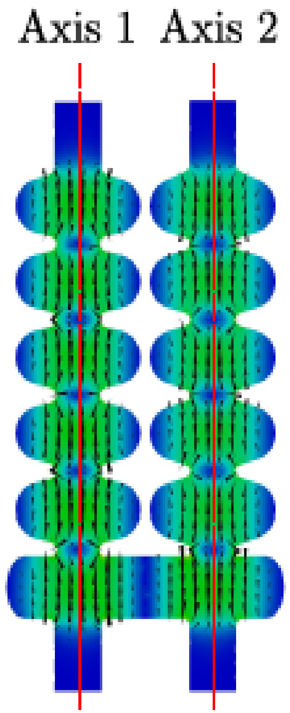
Generation of radiation:
Compton or
Coherent Smith-Purcell (THz)
or other method



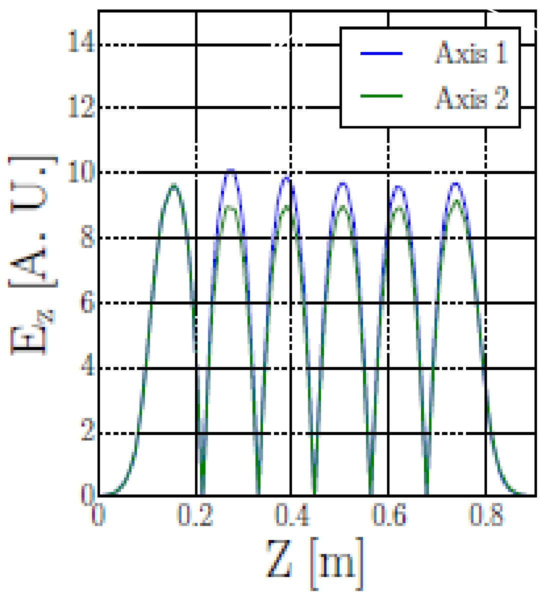
UH-FLUX cavity

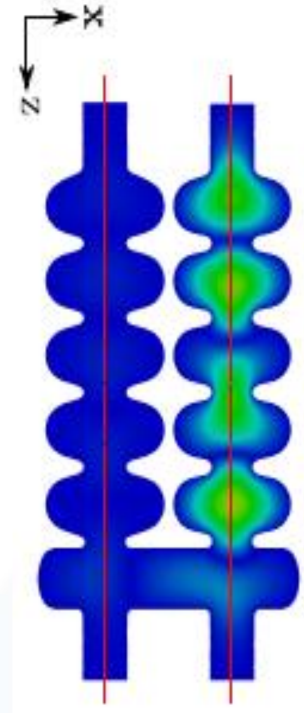
Decoupling all modes except the accelerating mode to maximize the beam current

Electric field contour plot of operating eigenmode at 1.3GHz



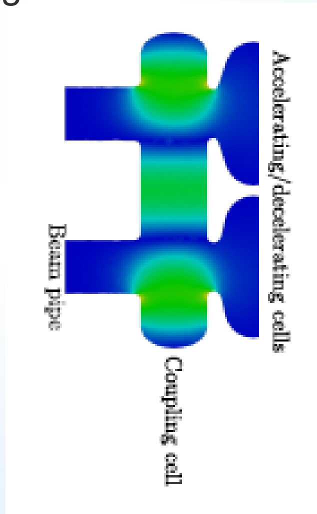
Operating field flatness @1.3GHz





Electric field contour plot of dipole eigenmode at 1.73GHz

Electric field contour plot of resonant coupler eigenmode at 1.48GHz



Development of ERL linacs including precise field control

- Operational experience of CW SRF injector and main linac cryomodules at the compact ERL (cERL) at KEK
- Completion of the Cornell's ERL Main Linac Cryomodule
- Cryomodule for SETF at Peking University
- ARIEL e-Linac cryomodules
- Resonance control for narrow-band SRF cavities (Fermilab and Cornell University)

Issues

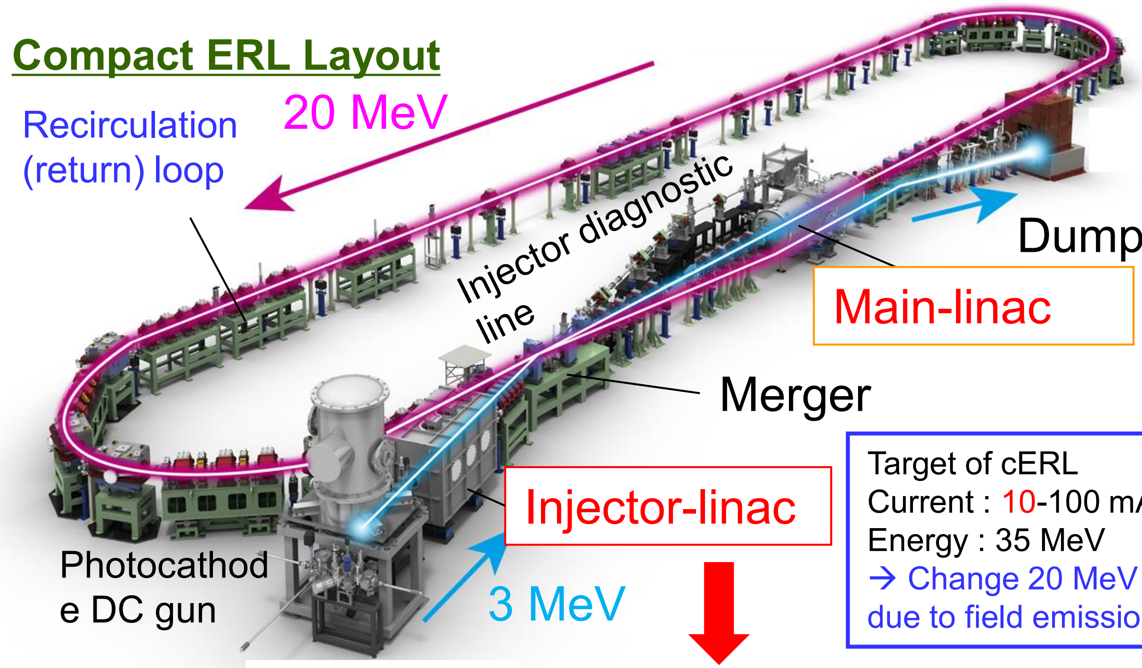
- Maintaining high Q_0 during cryomodule assembly and long-term
- Resonance control of narrow-band cavities, robustness of control algorithms

OPERATIONAL EXPERIENCE OF CW SRF INJECTOR AND MAIN LINAC CRYOMODULES AT THE COMPACT ERL (cERL)

H. Sakai and K. Kako et al.

"Operational Progress in Compact-ERL"
H. Kawata Tuesday 8:00-8:20 talk in SRF15

Compact ERL Layout

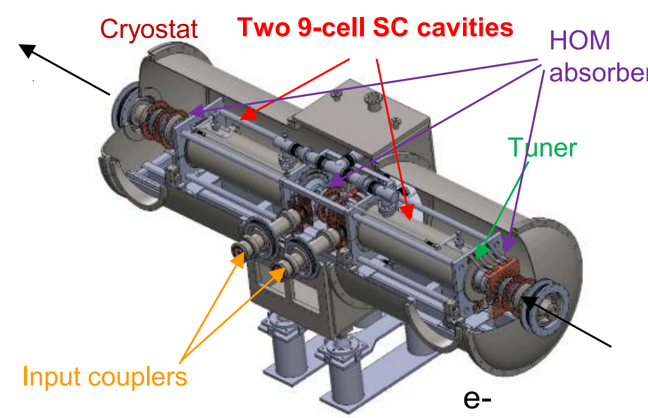


Target of cERL
Current : 10-100 mA
Energy : 35 MeV
→ Change 20 MeV
due to field emission

Main linac module

HOM damped (for 100 mA circulation to suppress HOM-BBU in design)

RF frequency: 1.3 GHz
Input power : 20 kW CW (SW)
E_{acc}: 15 MV/m (design)
Unloaded-Q: $Q_0 > 1\times10^{10}$

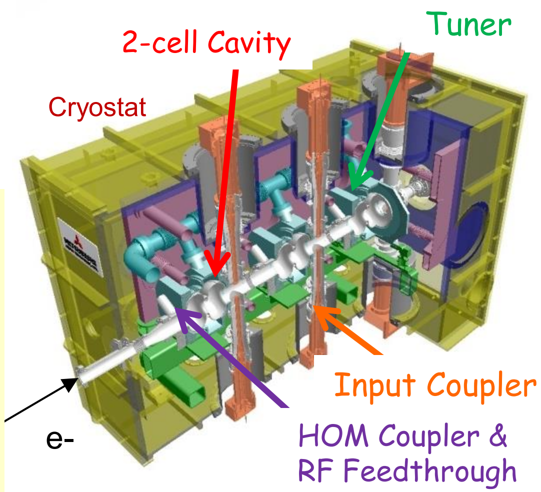


Requirement was satisfied at V.T. Heavy F.E was met @9-10 MV/m after string assembly.

Injector module

2-cell cavity × 3
Double coupler

RF frequency: 1.3 GHz
Input power :
10 kW/coupler (10 mA, 5 MeV)
180 kW/coupler (100 mA, 10 MeV)
E_{acc}: 7.6 MV/m (5 MeV)
15 MV/m (10 MeV)
Unloaded-Q: $Q_0 > 1\times10^{10}$



Requirement was satisfied at V.T and for initial 10 mA requirement .

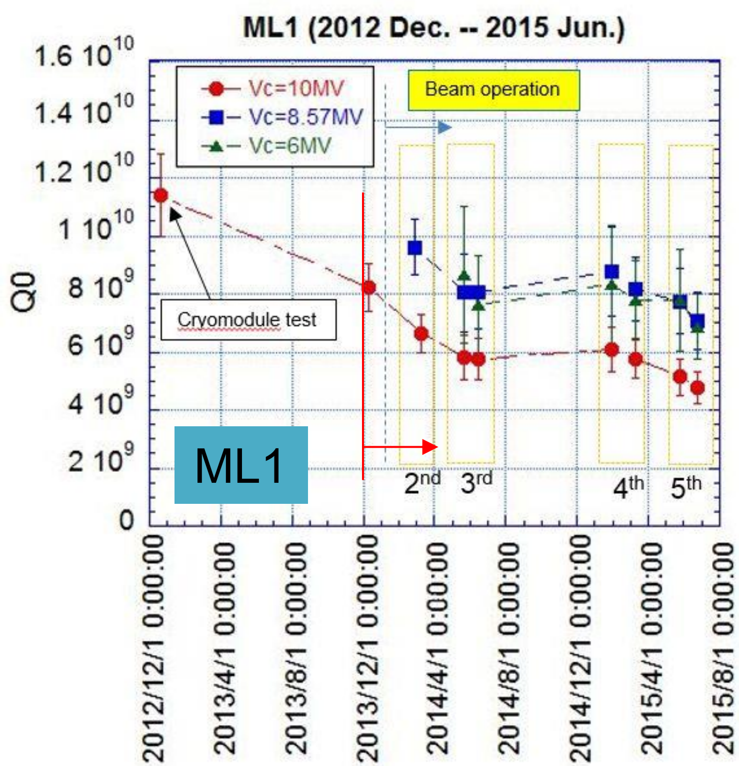
*) Progress since SRF2013

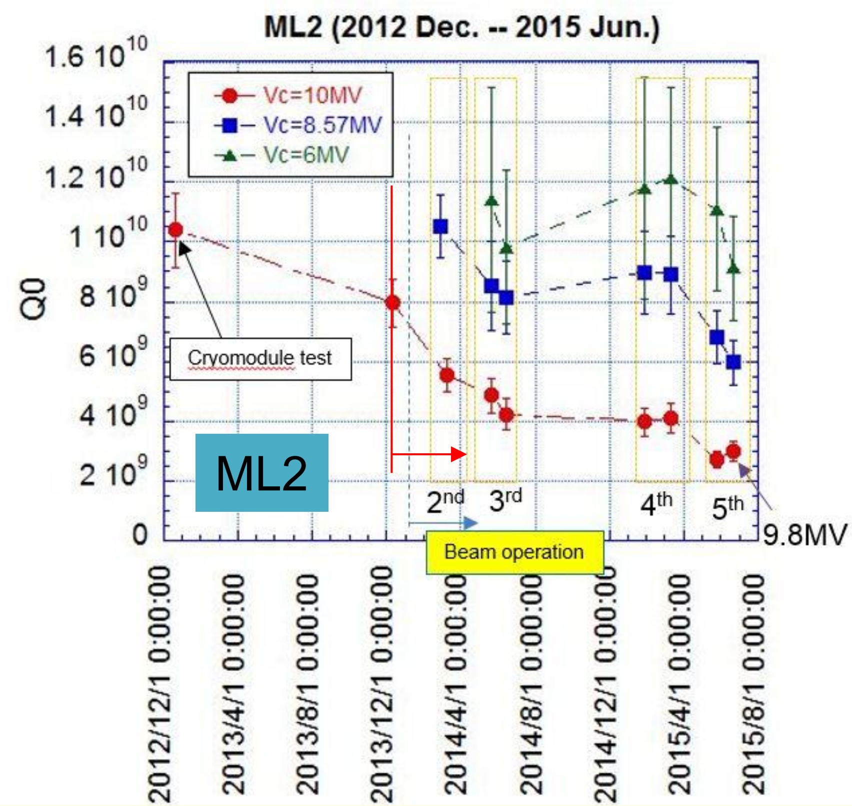
Start beam operation with ERL return loop.

- Completed construction in Dec. 2013.
- Commissioned started in Dec. 2013.
  20 MeV 10 uA (Dec.2013 – Jun.2014)
  20 MeV 100 uA (Jan.2015 – Jun.2015)

Q-value history of Main linac (ML) (from high power test to beam operation for 2.5 years)

<u>See details in H.Sakai et al "Measurement of the cavity performances of compact ERL main linac cryomodule during beam operation", TUPB021 poster</u>

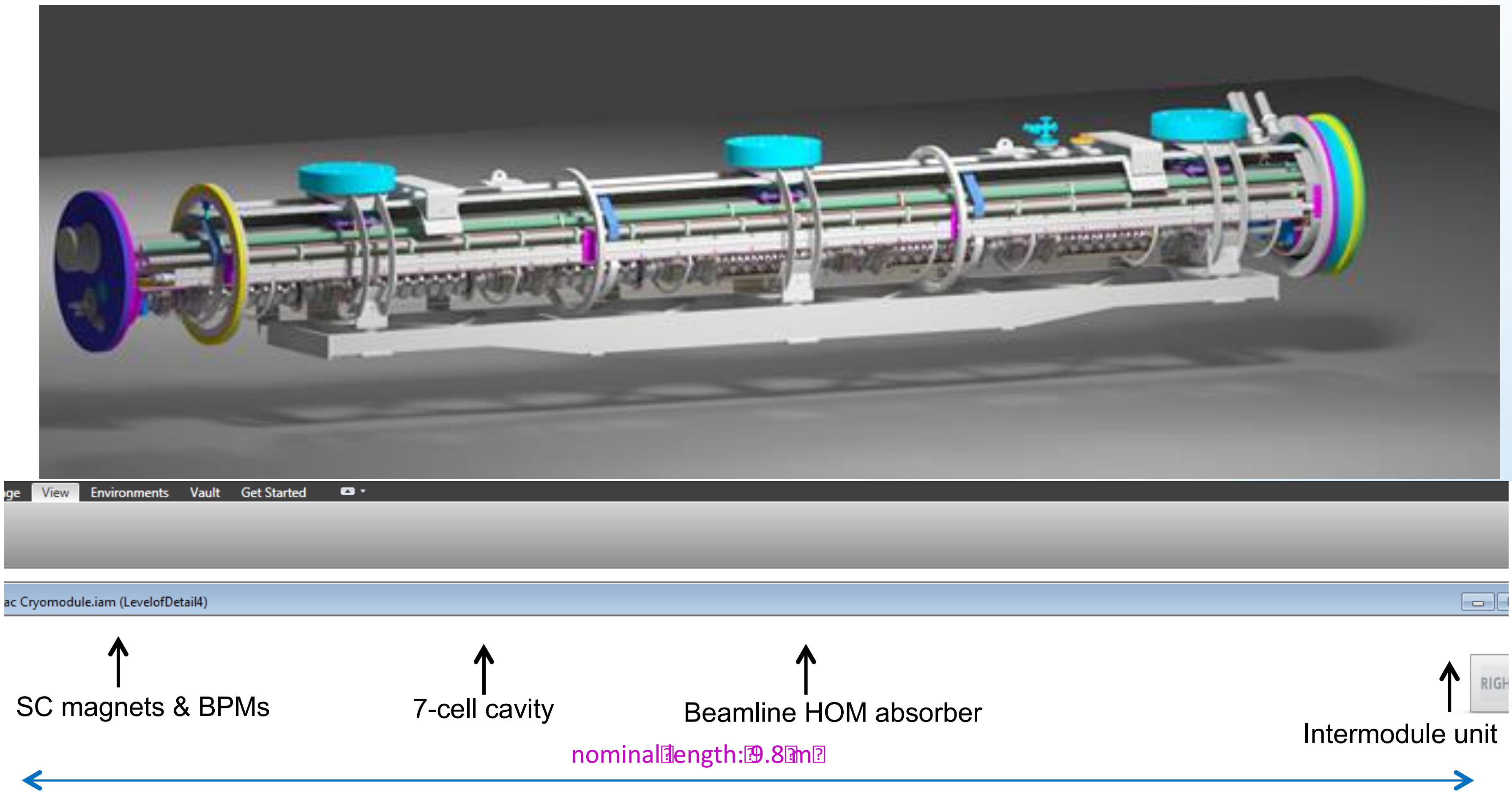




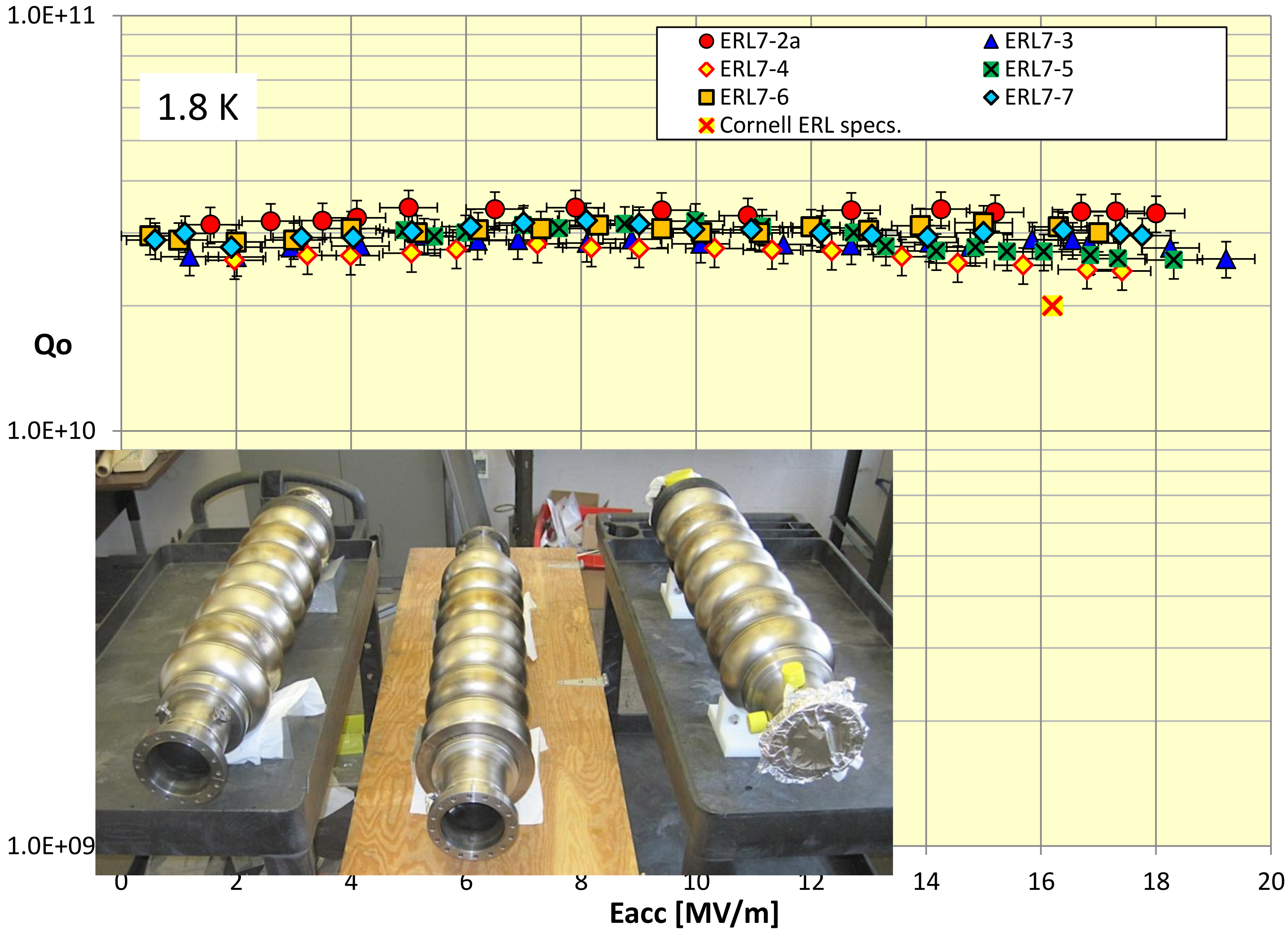
- We kept stable beam operation of 20 MeV by digital LLR Fsystem (ΔA/A < 0.01% , Δθ < 0.01 deg) and suppressed the microphonics on both injector and main linac cryomodules.
- Several trips were observed on a year. No crucial hardware trouble ,for example, come from miss operation of CW beam & or quench was met by fast & sophisticated ITL system to beam and RF.
- We met the Q degradation & radiation increase during beam operation on ML. We apply pulse processing pragmatically. Now we could suppress cavity degradation. (ML1:200mSv/h, ML2 80mSv/h)
- Finally we met no trip for 1.5 months on both ML 2 cavities in 4th phase.
- We plan to make the new cryomodule with four 9cell cavities to overcome field emission problem.

Completion of the Cornell’s ERL Main Linac Cryomodule (MLC)

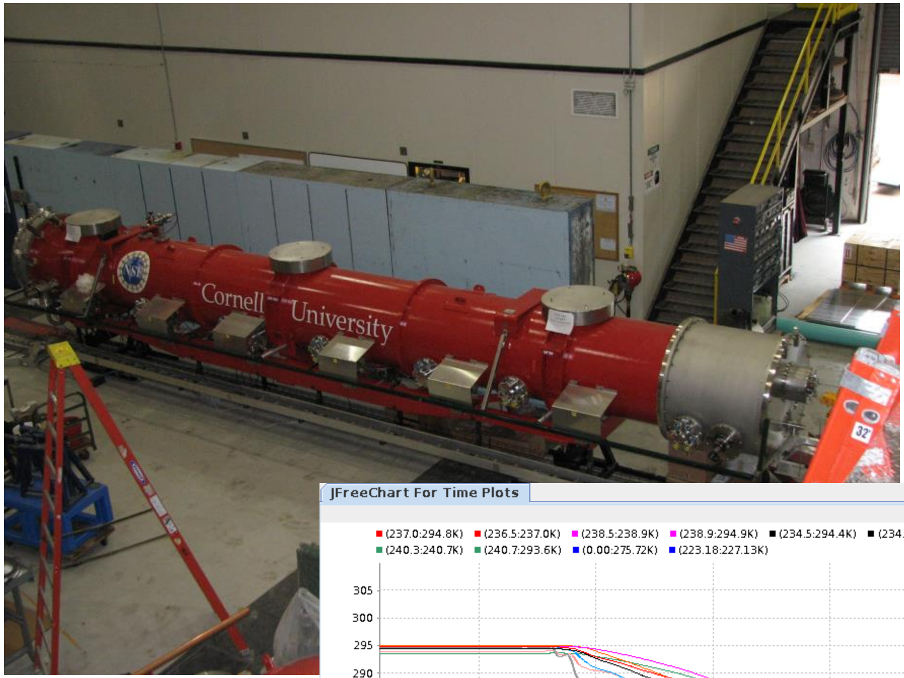
- The cryomodule hoses six 7-cell cavities equipped with beamline HOM absorbers
- The cavities should operate at 16 MV/m with $Q_0 > 2 \times 10^{10}$ at 1.8 K



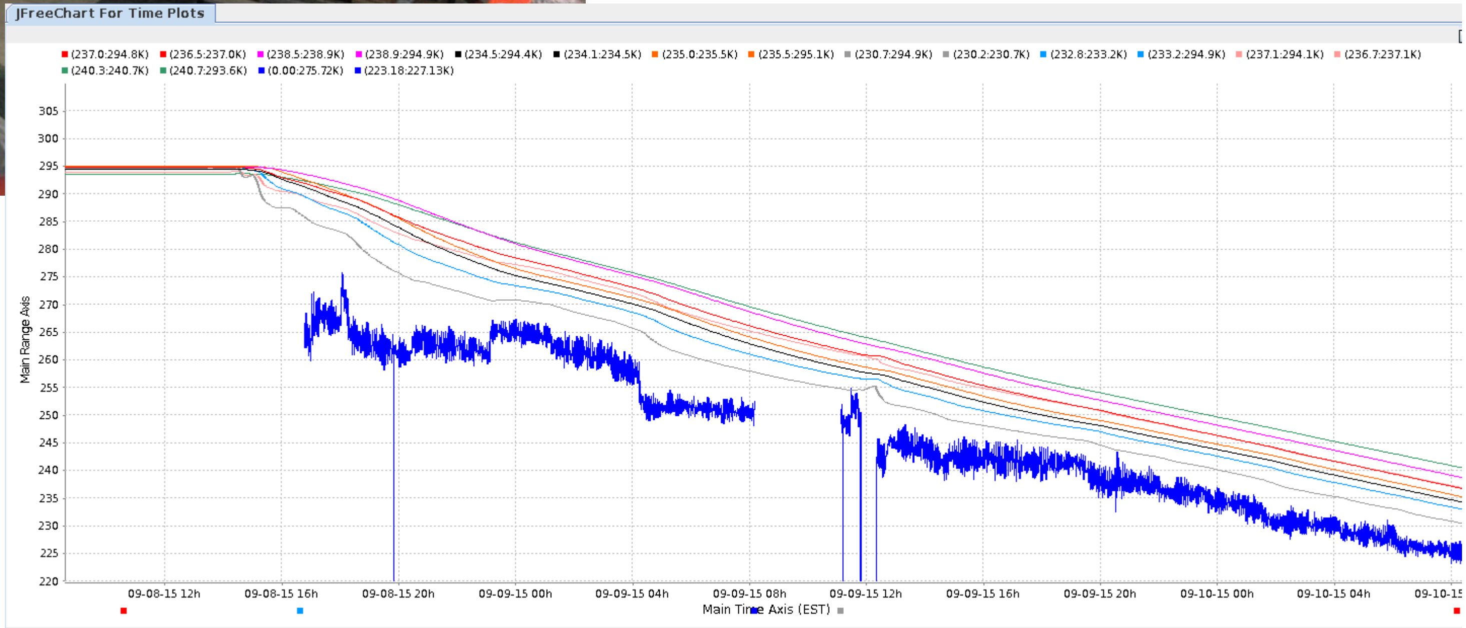
Vertical Cavity Test Results



Cool-Down and Testing at Wilson Lab



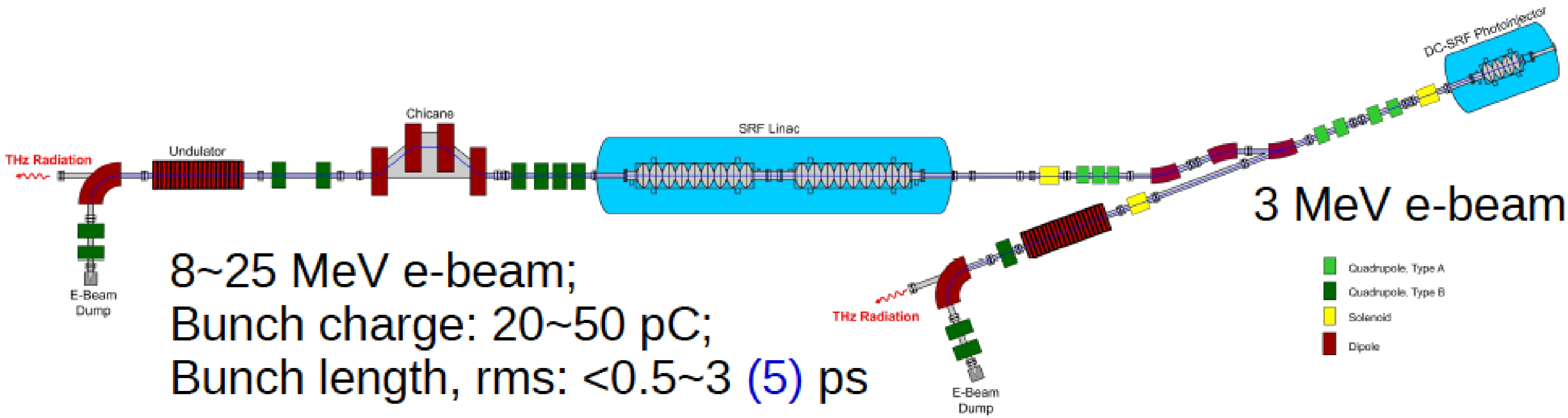
- Vertical test results were confirmed in the HTC tests
- The cryomodule assembly was finished in Nov. 2014
- Cool-down has commenced 09/08/15
- The cool-down rate (80 K shield) is 2 K/hr



Talk: FRAA04

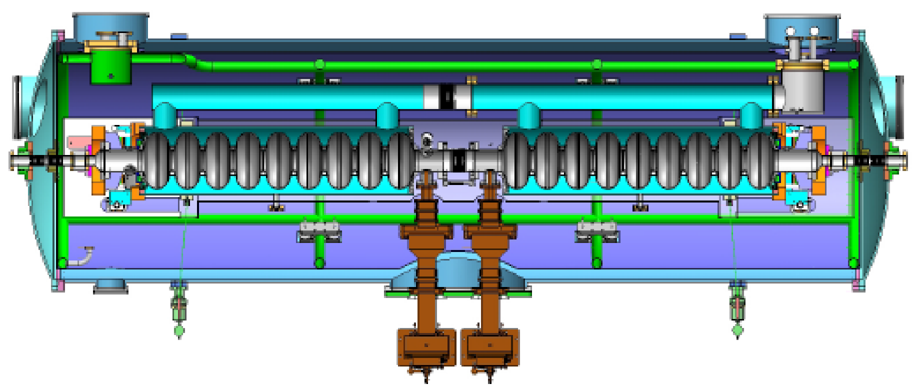
Superconducting ERL Test Facility at Peking University

25 MeV Beam Line

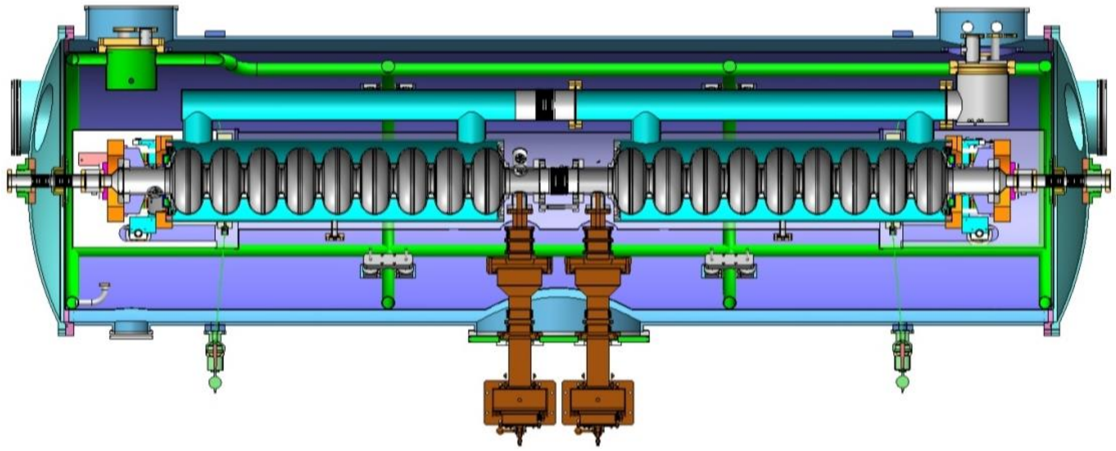


8~25 MeV e-beam;
Bunch charge: 20~50 pC;
Bunch length, rms: <0.5~3 (5) ps

- 2x9-cell cryomodule



Cryomodule for SETF

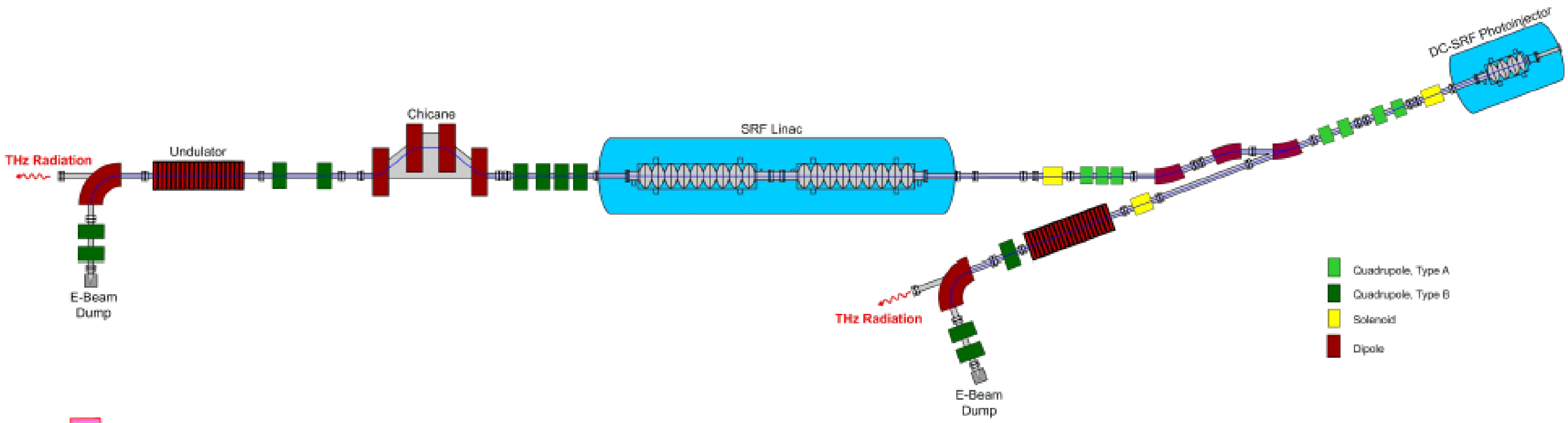


- The assembling of a 2×9-cell cryomodule for the Superconducting ERL Test Fcility (SETF) at Peking University (PKU) has been finished.
- It is cooling down and waiting for RF and beam test.
- It is expected to accelerate the electron beam to 25 MeV together with the injector.

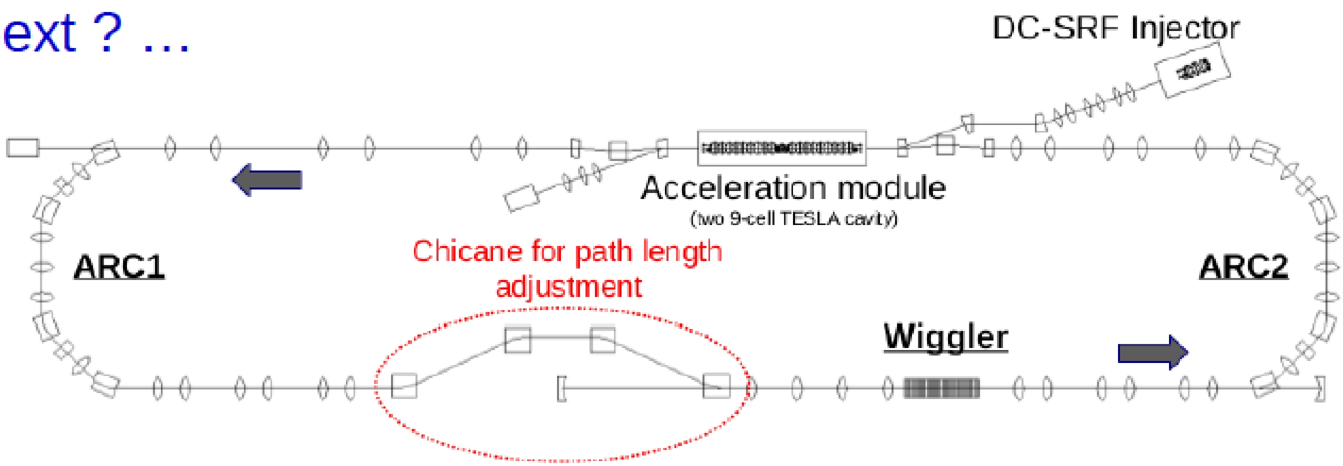
Talk: FRAA05

Poster: THPB079

Outlook

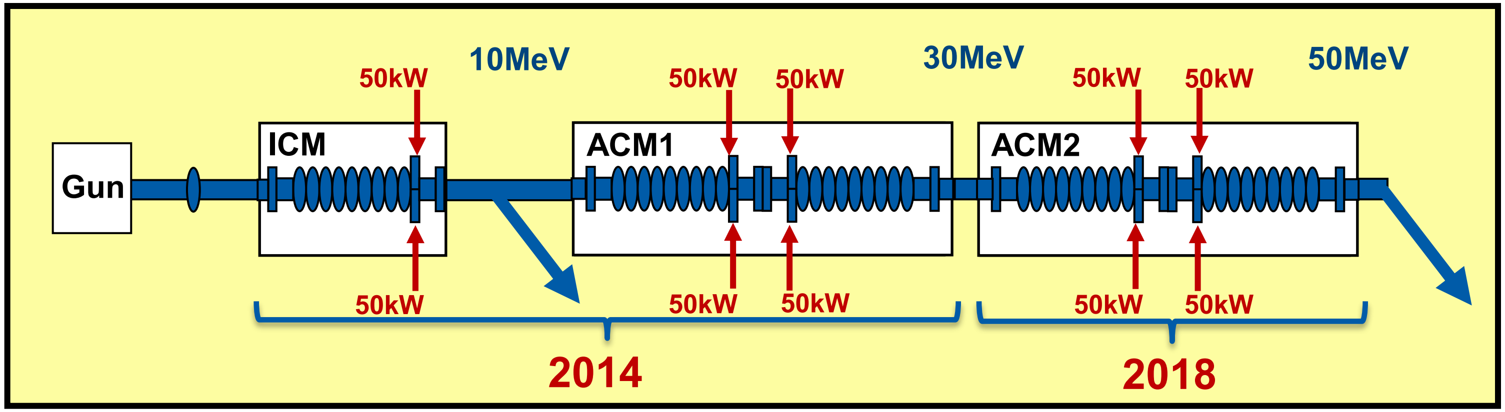


Next ? …

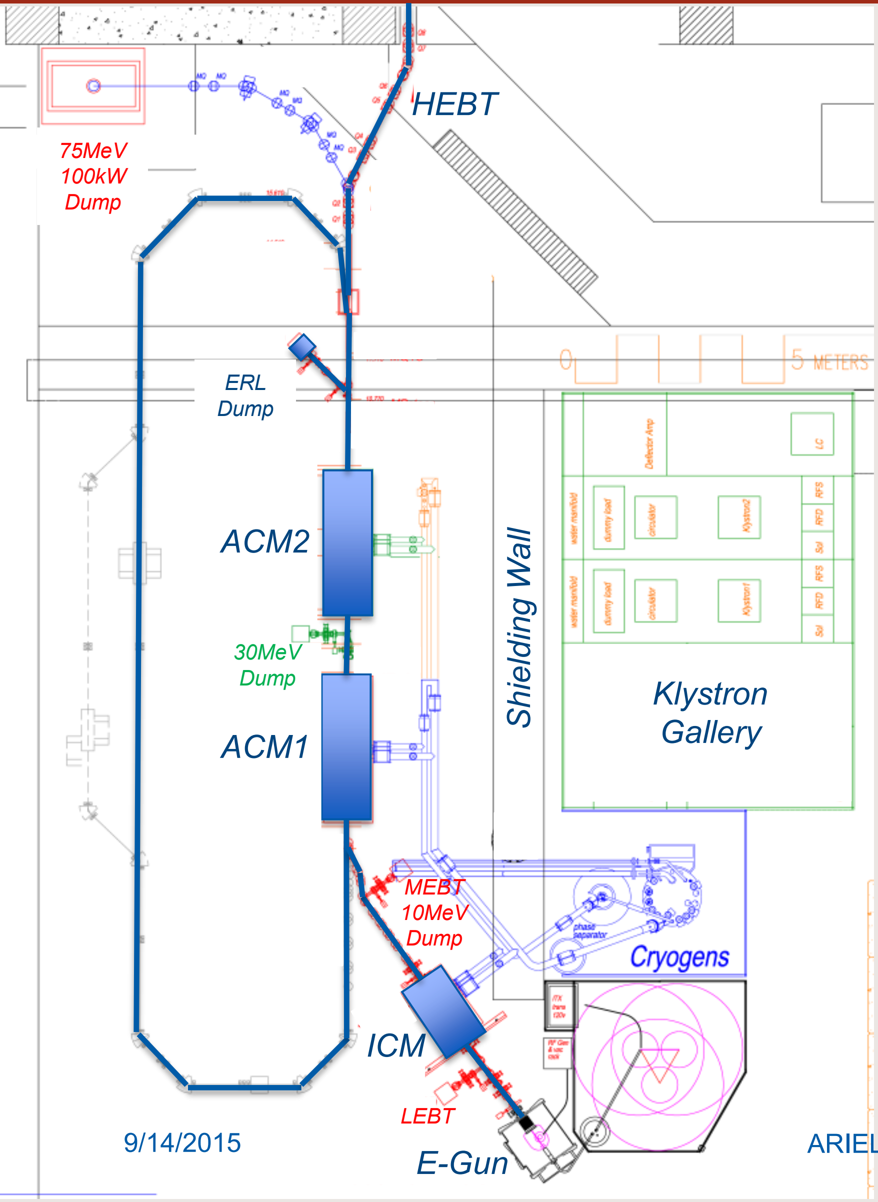


E-Linac Specifications

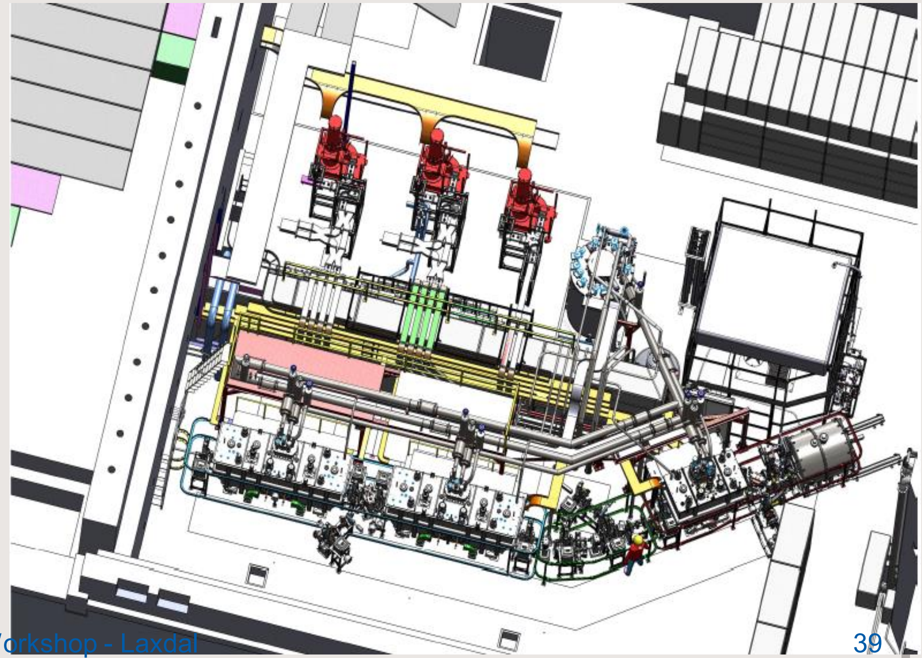
- The ARIEL E-Linac specification – dominated by RF beam loading
  - 10 mA CW at 50 MeV - 0.5 MW of beam power
  - Choose five cavities 100 kW of beam loaded RF power per cavity
  - two couplers per cavity each rated for 50 kW operation
  - Means 10 MV energy gain per cavity
- Linac divided into three cryomodules
  - one Injector cryomodule (ICM) with one cavity
  - two Accelerator crymodules (ACM1, ACM2) with two cavities each
  - Installation is staged - Phase I – includes ICM and ACM1 for a required 25 MeV/100 kW demonstration by end of 2014



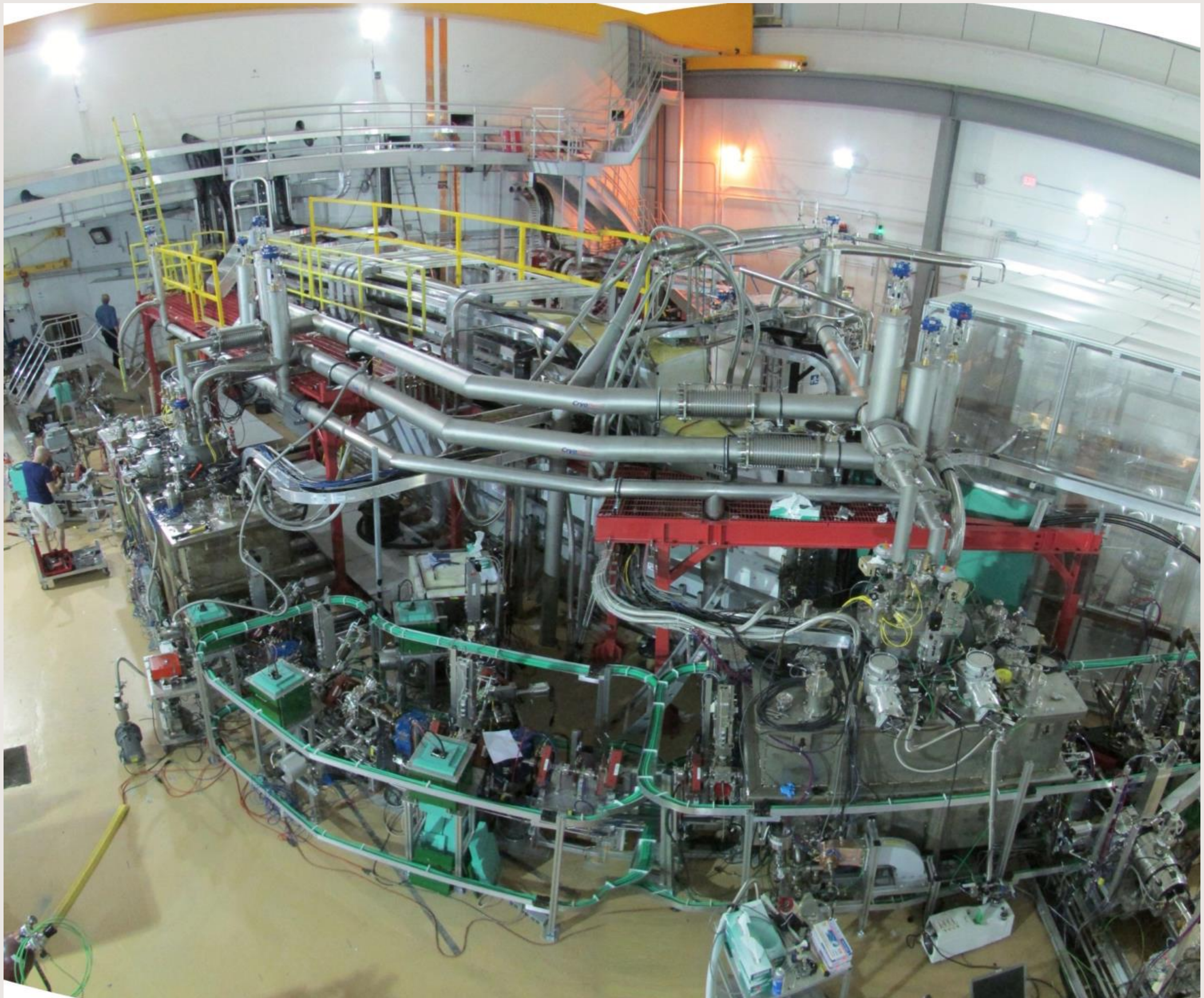
The ARIEL e-Linac as a recirculator



- The linac is configured to eventually allow a recirculating ring for a multi-pass `energy doubler' mode or to operate as an energy recovery linac for accelerator studies and applications



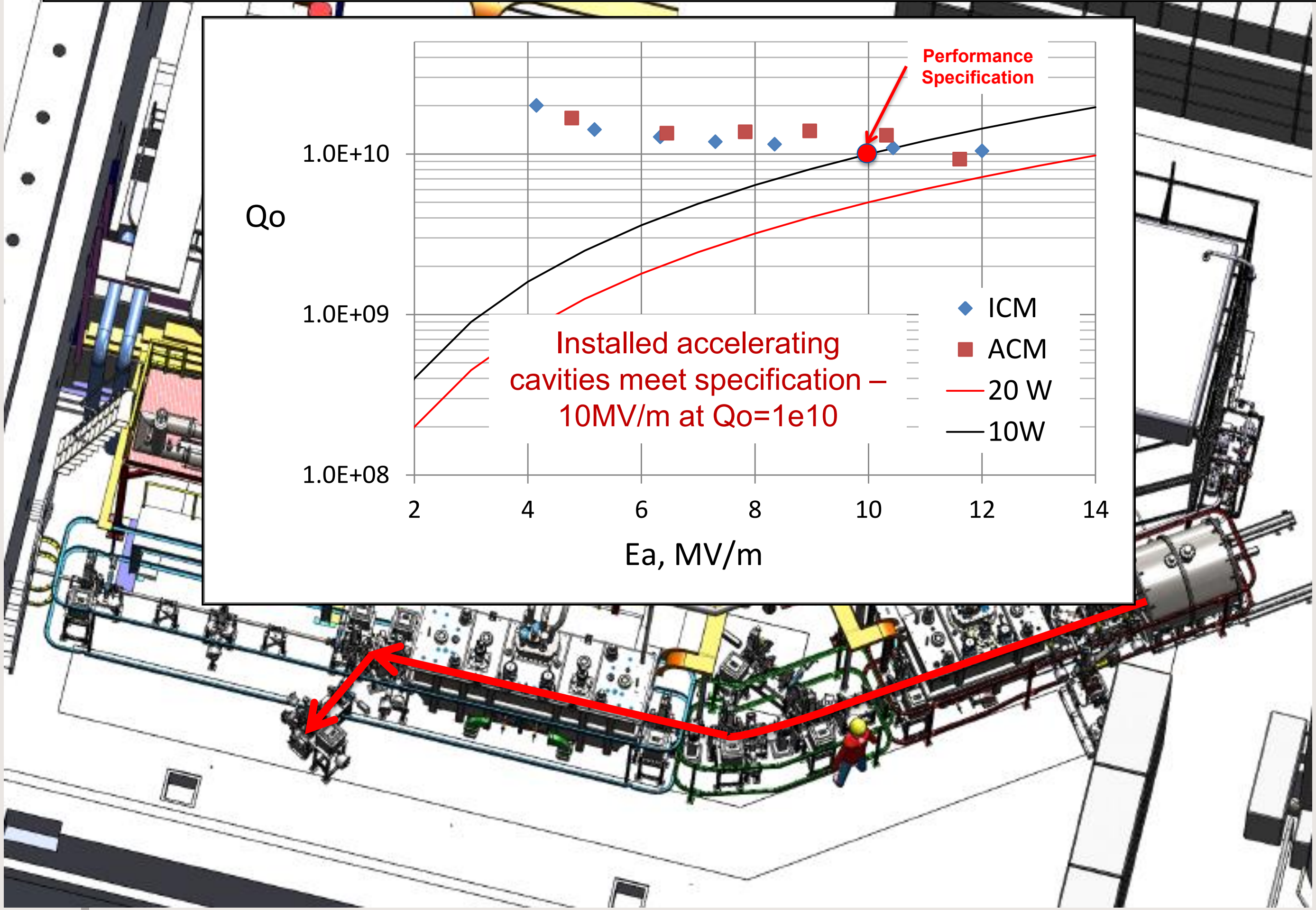
Hardware Installed – Sept. 26



- 1 E-gun
- 2 CMs
- 2 RF systems
- 60 beam diagnostics
- 1400 cables
- 2000 control GUI pages

ICM / ACM Beam test

Culmination of five years of development, design, fabrication, assembly, testing, installation



TRIUMF

Status

- Two cryomodules intsalled and commissioned each with one nine-cell cavity
- Each cavity reaches on-line performance as demonstrated by electron acceleration – Q > 1e10, E_{acc} > 10 MV/m
- After initial commissioning we halted pending license approval to proceed with high intensity commissioning
- Approval received Sept. 3, 2015 – we are not turning systems on for intensity ramp up through 2015

Talk: TUAA02

TRIUMF

e-Linac at SRF2015

MOPB088 HOM Measurements on the ARIEL eLINAC Cryomodules	Philipp Kolb	poster	student
MOPB089 1.3 GHz Cavity Test Program for ARIEL	Philipp Kolb	poster	student
MOPB096 Vertical Electropolishing at TRIUMF	James Keir	poster	
TUAA02 Commissioning of the SRF Linac for ARIEL	**Vladimir Zvyagintsev**	**oral**	
TUPB011 HPRF Transmission Componenets Study and Distribution in TRIUMF Electron Linac	Zhengting Ang	poster	
TUPB103 Cryomodule Protection for ARIEL e-Linac	Zhongyuan Yao	poster	
TUPB114 Transient Study of Beam Loading and Feedforward LLRF Control of ARIEL Superconducting RF e-LINAC	Edward Thoeng	poster	student
TUPB120 The Cryogenic Infrastructure for SRF Testing at TRIUMF	Ruslan Nagimov	poster	student
THPB043 Alternative Fabrication Methods for the ARIEL e-Linac SRF Separator Cavity	Douglas W Storey	poster	student
THPB044 A Superconducting RF Deflecting Cavity for the ARIEL e-Linac Separator	Douglas W Storey	poster	student
THPB103 High Power Coupler Test for Ariel SC Cavities	Yanyun Ma	poster	
THPB115 ARIEL e-Linac Cryomodule - Design and Performance	Norman Muller	poster	

Resonance control of narrow-band SRF cavities

- LCLS II (CW)
  - Feedforward LFD compensation (piezo driven with stimulus pulse proportional to E_{acc}^2) & feedback to detuning & 45 Hz external noise compensation.
  - Results close to LCLS II requirements (peak detuning 10 Hz).
- PIP II (325 MHz in CW and pulse mode)
  - Feedforward for LFD compensation (proportional to E_{acc}^2) & feedback to detuning.
  - Results: RMS ~ 10 Hz in pulsed mode… there is a prediction that with filter on some frequency one can achieve 4 Hz (already just 2 times worse that PIP II target of 1.5 Hz).
- Conducted study of transfer functions for 1) piezo-to-RF and 2) field modulation-to-mechanical vibration of the cavity. This information will lead to construction of "full electromechanical model of the cavity”.

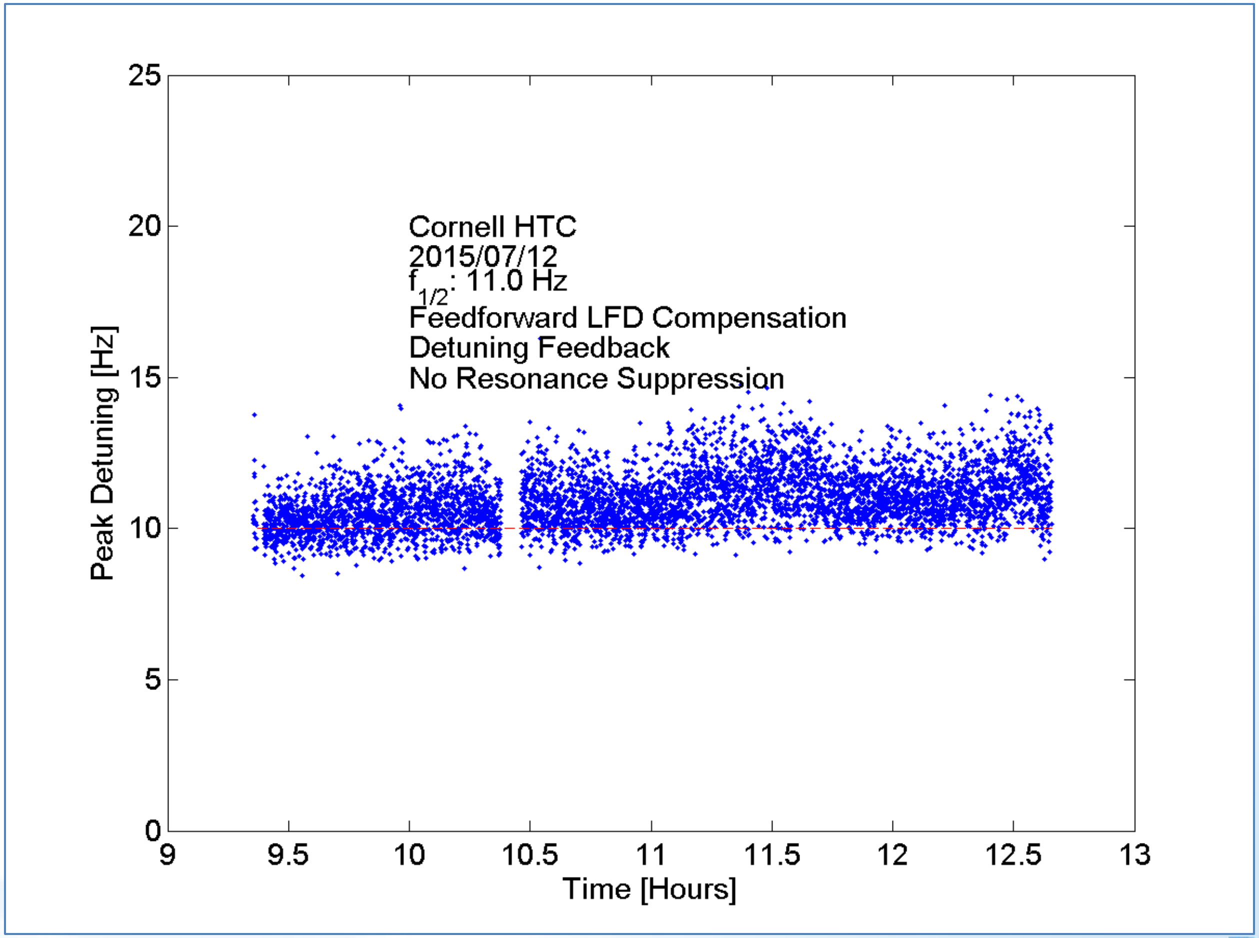
Poster: TUPB095

LCLS-II results

LCLS II 1.3 GHz 9-cell elliptical cavity CW-mode operation

$f_{1/2}$ = 12 Hz ; E_{acc} = 7.5 MV/m; T = 2 K

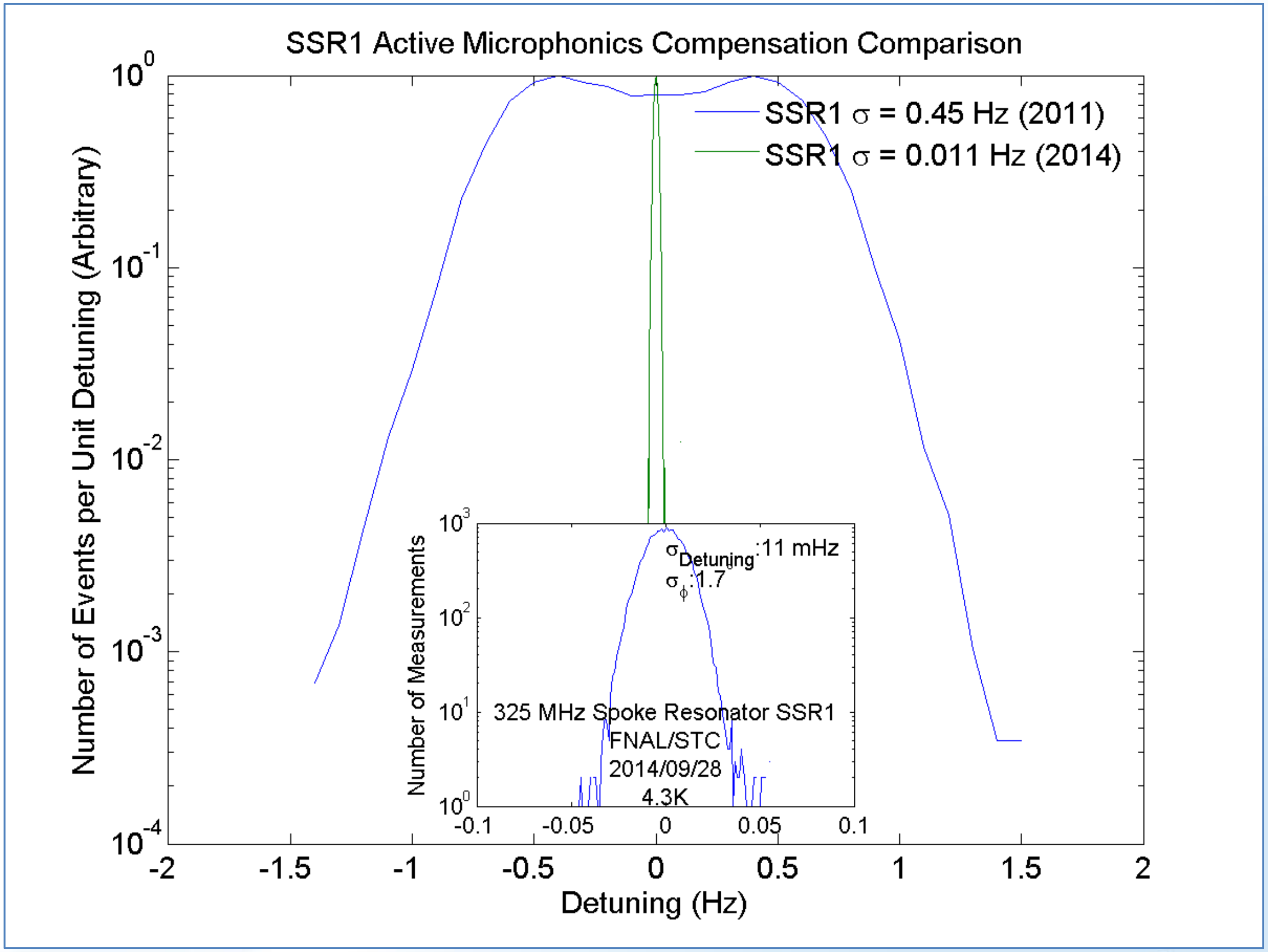
LFD Feedforward Compensation and Detuning feedback



PIP-II results

Active Resonance Stabilization PIP II (SSR1) SRF cavity at CW-mode

- **Full stabilized cavity**
  - Feed-forward LFD compensation
  - Fast Feed-back on forward/probe phase
  - Slow feedback on detuning
  - Synchronous down-conversion
- $\sigma_{Detuning}$ **= 11 mHz**



Summary

- The ERL field is very active, but is still in the development/demonstration stage: a lot of need and opportunities for R&D.
- ERL R&D needs related to SRF:
  - *CW operation of large-scale SRF installations: high Q_0 at 15-20 MV/m is essential.*
  - *Unprecedented beam currents and unprecedented number of spatially superimposed high charge bunches in the SRF linacs: BBU, halo, other beam dynamics issues.*
  - *Photoinjectors producing high-brightness beams.*
  - *Very precise phase and amplitude control of narrow-bandwidth SRF cavities required over large spatial extent with varying ground vibration conditions.*
- In this talk I reviewed:
  - *Recent results from SRF photoinjectors for ERLs (briefly, as they will be covered in two talks:* **THAA02** *and* **THAA03***).* First beams were obtained from several SRF guns. **Issues**: Operation with high QE photocathode materials: MP and FE, cavity contamination.
  - *New SRF cavities for ERLs*. Still opportunities for new cavity designs. **Issues**: HOM damping: high average power handling, wide frequency range.
  - *Development of ERL linacs including precise field control.* **Issues**: Maintaining high Q0 during cryomodule assembly and long-term. Resonance control of narrow-band cavities, robustness of control algorithms.

Thank you!