CW RF systems at Cornell University:
status and operational experience

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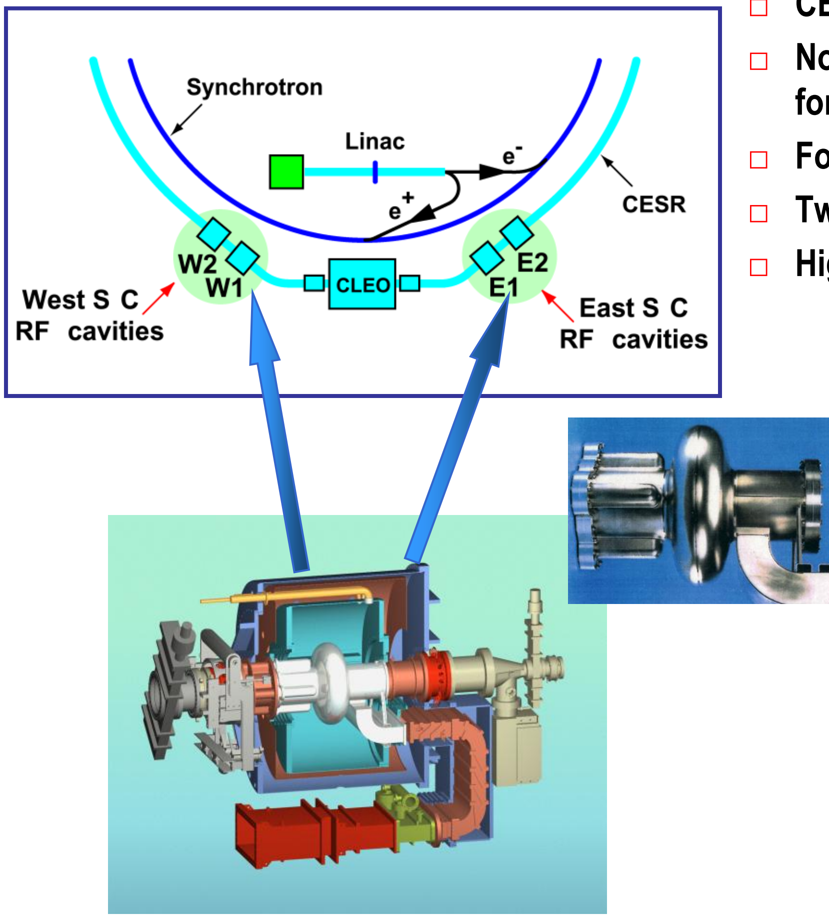
Outline

- Introduction
- CESR 500 MHz RF system
- ERL injector 1300 MHz RF systems
- Medium power: IOT-based HPA
- High power: klystron transmitters
- Future plans
- Summary

Introduction

- There are two CW RF systems at Cornell: 500 MHz RF for CESR and 1300 MHz RF for ERL.
- The CESR RF is in operation for more than 30 years, had several upgrades during this period. About 13 years ago it underwent transformation from normal conducting to superconducting RF.
- ERL is a new project: a prototype of the ERL injector was commissioned about 2 years ago.
- RF for the 5 GeV ERL is under development.

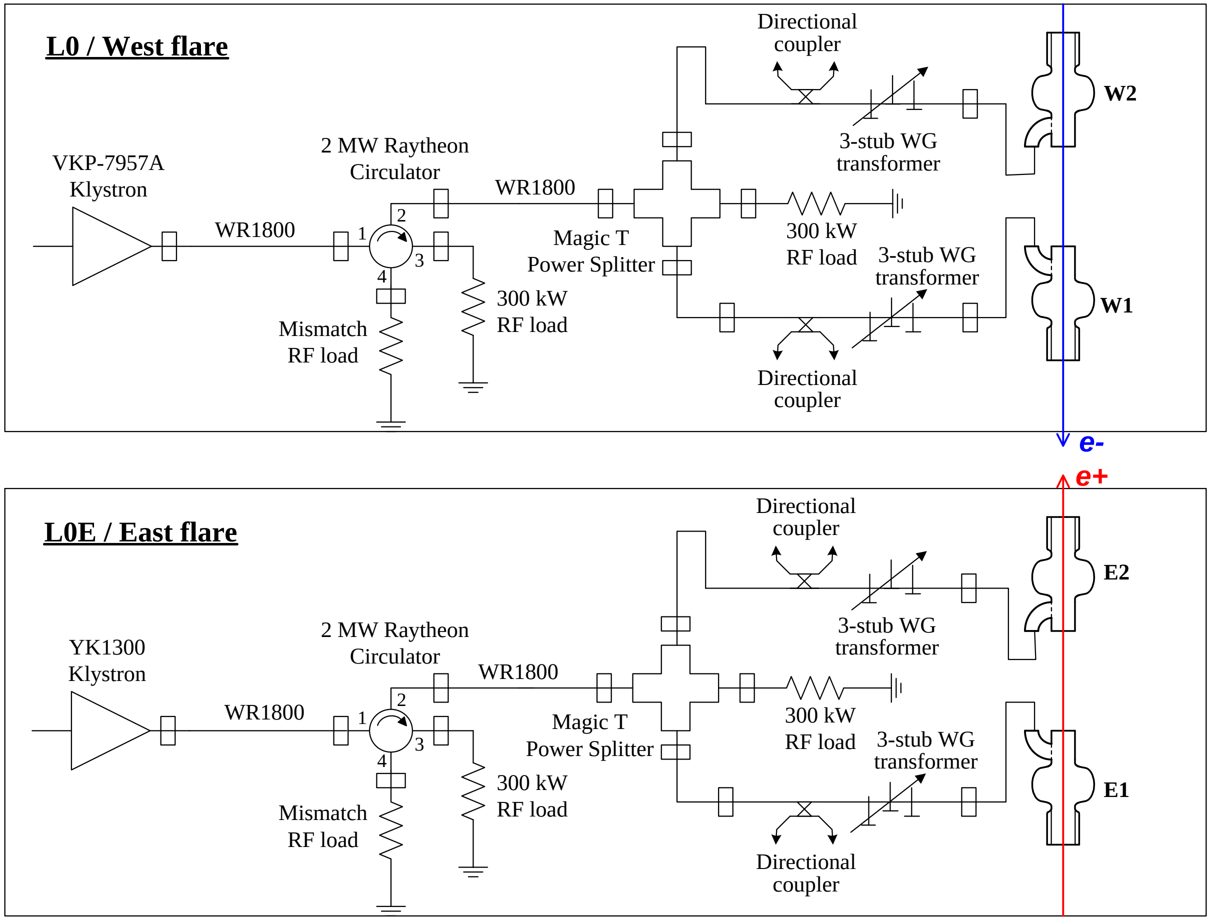
CESR RF system



- CESR is an e+e- storage ring originally built as a collider for HEP
- Nowadays it operates as a light source CESR-CHESS and provides beams for ILC damping ring experiments as CESR-TA
- Four superconducting single-cell RF cavities
- Two cavities are driven by one klystron in parallel
- High beam loading → low loaded *Q* factor

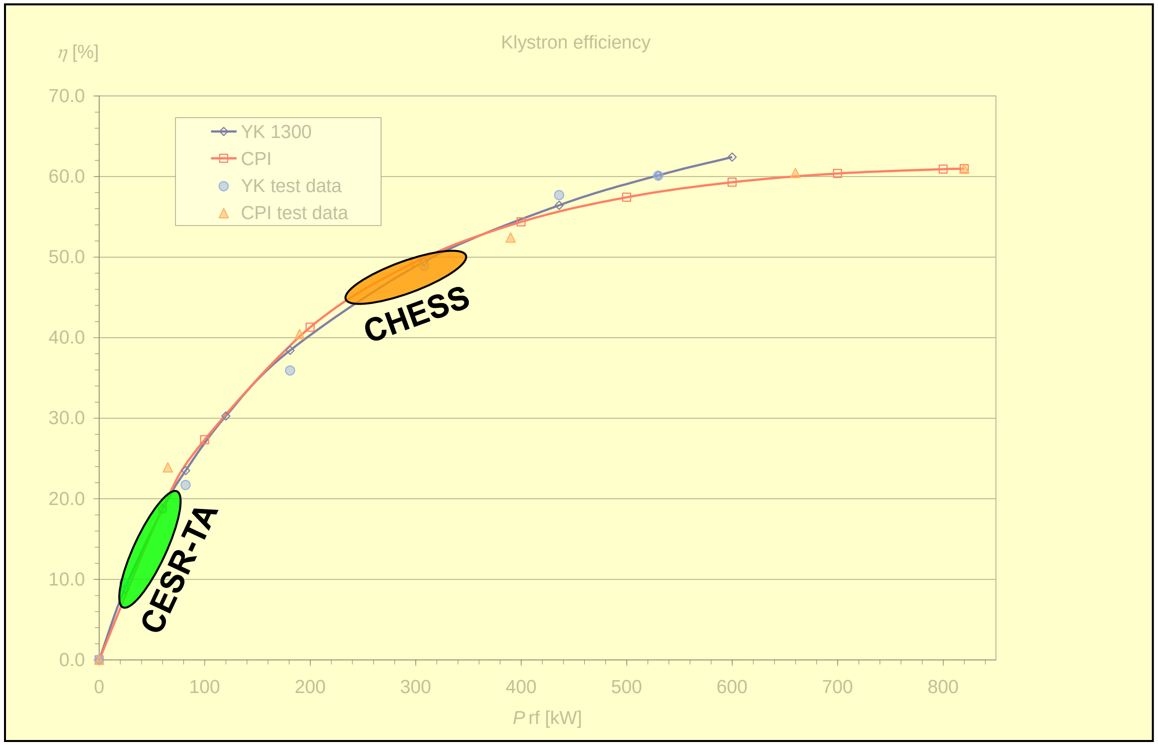
Beam energy	1.5 to 5.6 GeV
Beam current	0 to 500 mA
Frequency	500 MHz
Number of cavities	4
R/Q per single-cell cavity	89 Ohm
Q_{loaded}	1.5×10^5 to 4×10^5
Accelerating voltage per cavity	1.2 to 2.4 MV
Klystron power per cavity	up to 175 kW
Number of klystrons	2
Required ampl. stability	< 1%
Required phase stability	< 0.5°

CESR RF block diagram



CESR klystrons

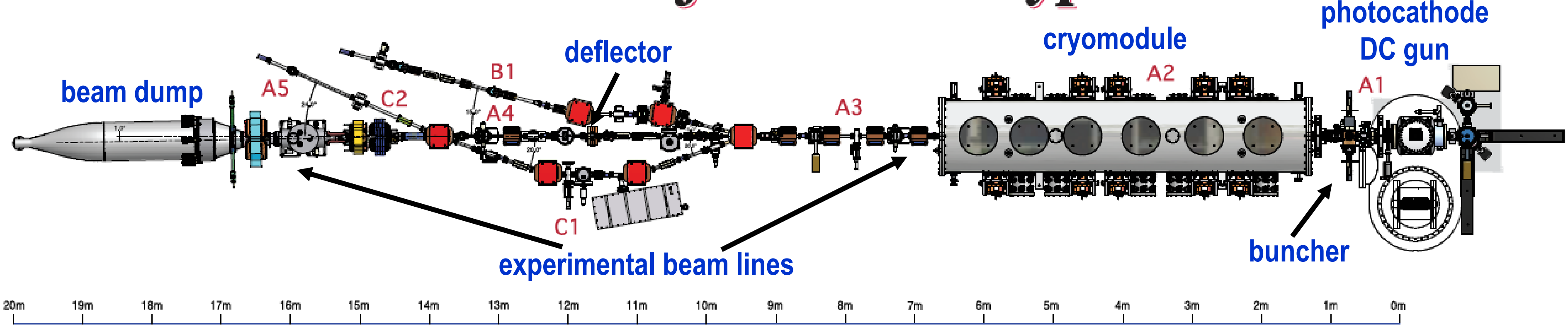
- 600 kW YK 1300 (Valvo/Philips) : 1 in operation plus 5 spares with a range of 6,000 to 65,000 hrs
- One 800 kW VKP-7957A (CPI) in operation, has 54,000 hrs
- At one point we had four klystrons in service



- The klystrons have very similar efficiency
- All tubes have mod anode
- As nowadays we operate very far from maximum power, the tubes are not stressed and expected to have very long life time
- Occasionally tubes require high-potting
- Digital LLRF system is used since 2004 (the 1st generation, developed in house), excellent performance

ERL injector RF systems

ERL – Injector Prototype

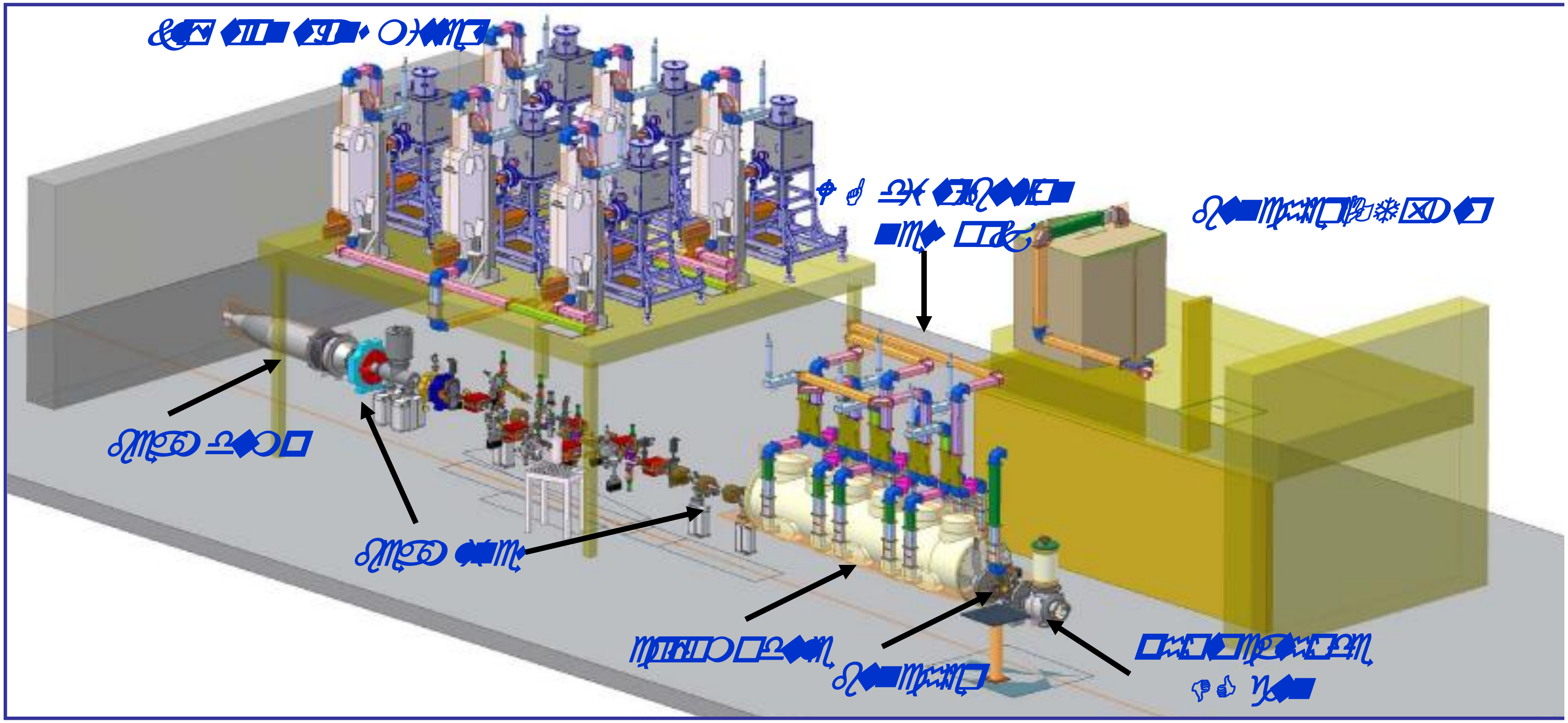


Nominal bunch charge	77 pC
Bunch repetition rate	1300 MHz
Beam power	550 kW
Nominal gun voltage	500 kV
SC linac beam energy gain	5 to 15 MeV
Beam current	100 mA at 5 MeV
	33 mA at 15 MeV
Bunch length	0.6 mm rms
Transverse emittance	< 1mm·mrad

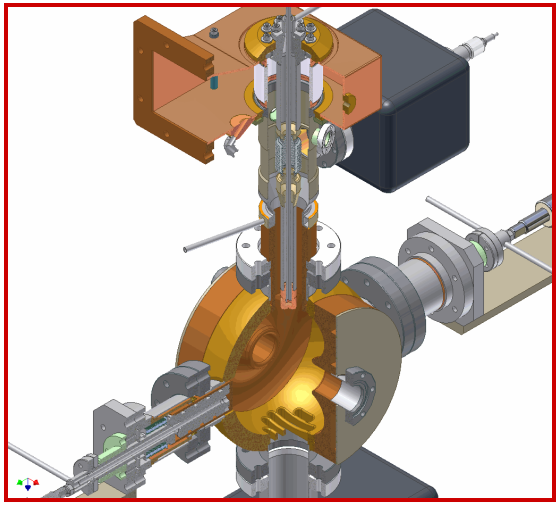
There are three distinct 1300-MHz RF systems:

- Buncher RF → single-cell normal conducting cavity powered by a 16 kW CW IOT xmtr;
- Injector Cryomodule (ICM) RF → five 2-cell SC cavities with two input couplers per cavity, powered by 120 kW CW klystrons;
- Deflecting cavity RF → single-cell normal conducting cavity operating at TM110-like mode in pulsed regime.

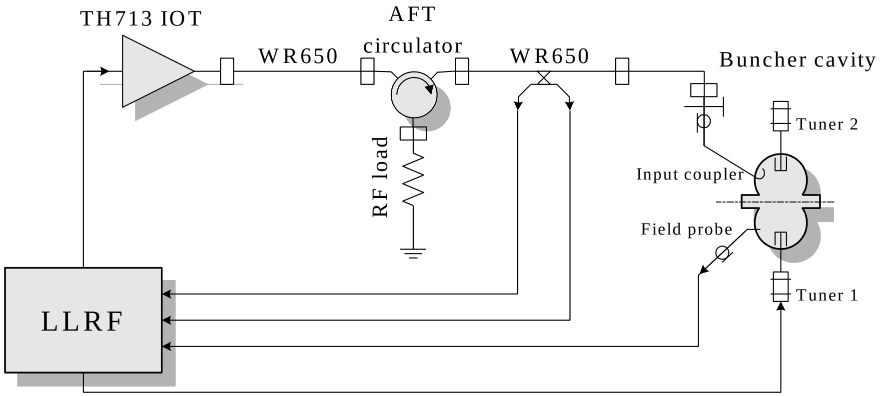
ERL injector RF layout



Buncher RF



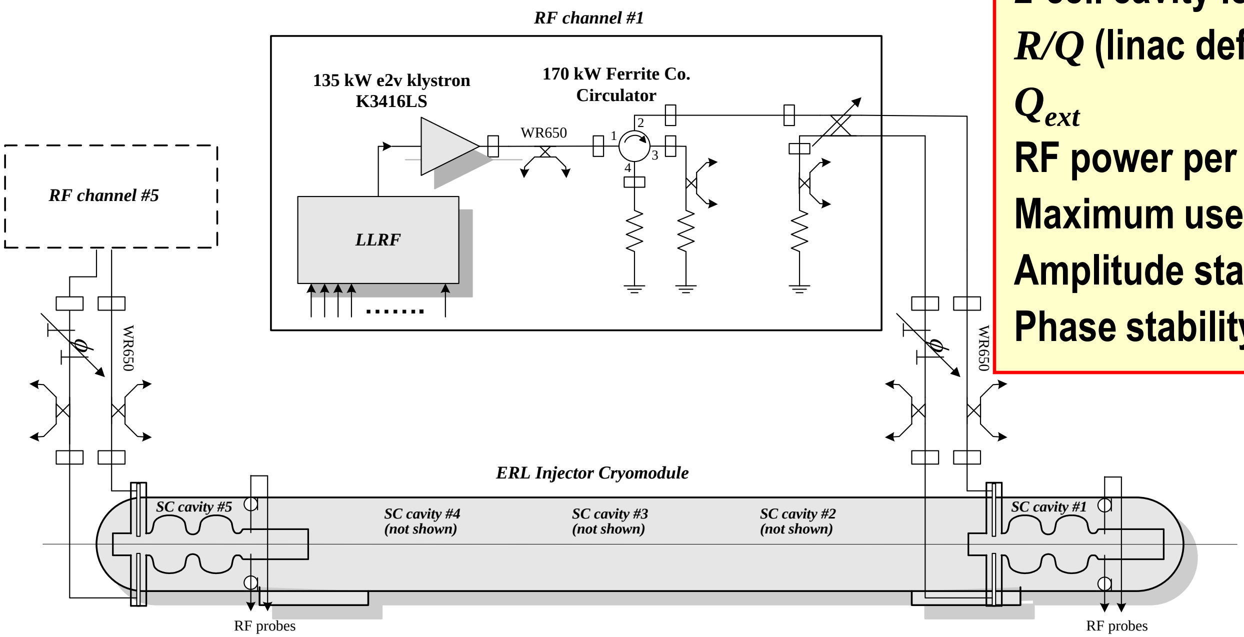
Number of cavities	1
Nominal accelerating voltage	120 kV
Maximum accelerating voltage	200 kV
Shunt impedance, $R_{sh} = V^2/2P$	1.7 MOhm
Maximum dissipating power	11.8 kW
Maximum transmitter output power	16 kW
Amplitude stability	8×10^{-3} (rms)
Phase stability	0.1° (rms)



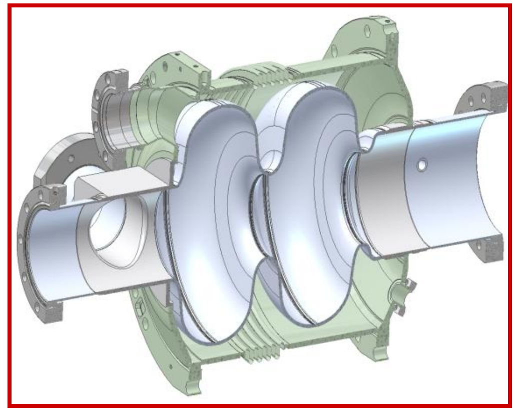
Buncher IOT High-Power Amplifier

- Medium power requirements → IOT-based HPA
- Manufactured by Thomson-BM
- Modified version of the DCX SIIA broadcast transmitter system
- 16 kWCW tube TH713 by Thales-ED
- HVPS is manufactured by NWL

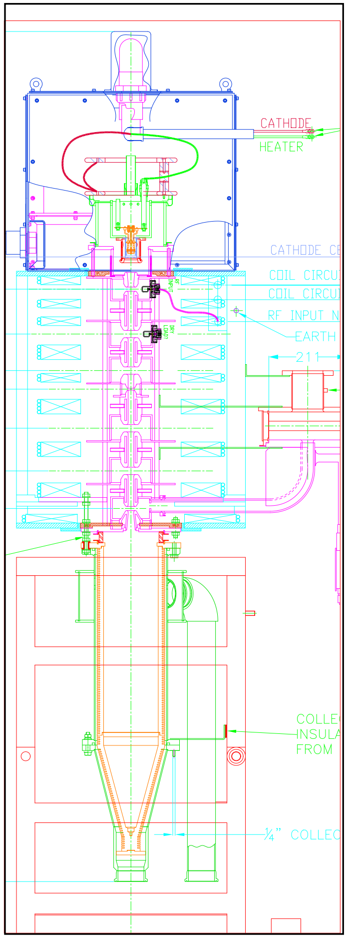
Injector Cryomodule RF



Number of cavities	5
Accelerating voltage per cavity	1 – 3 MV
2-cell cavity length	0.218 m
R/Q (linac definition)	222 Ohm
Q_{ext}	$4.6\times10^4 – 4.1\times10^5$
RF power per cavity	100 kW
Maximum useful klystron power	≥ 120 kW
Amplitude stability	9.5×10^{-4} (rms)
Phase stability	0.1° (rms)

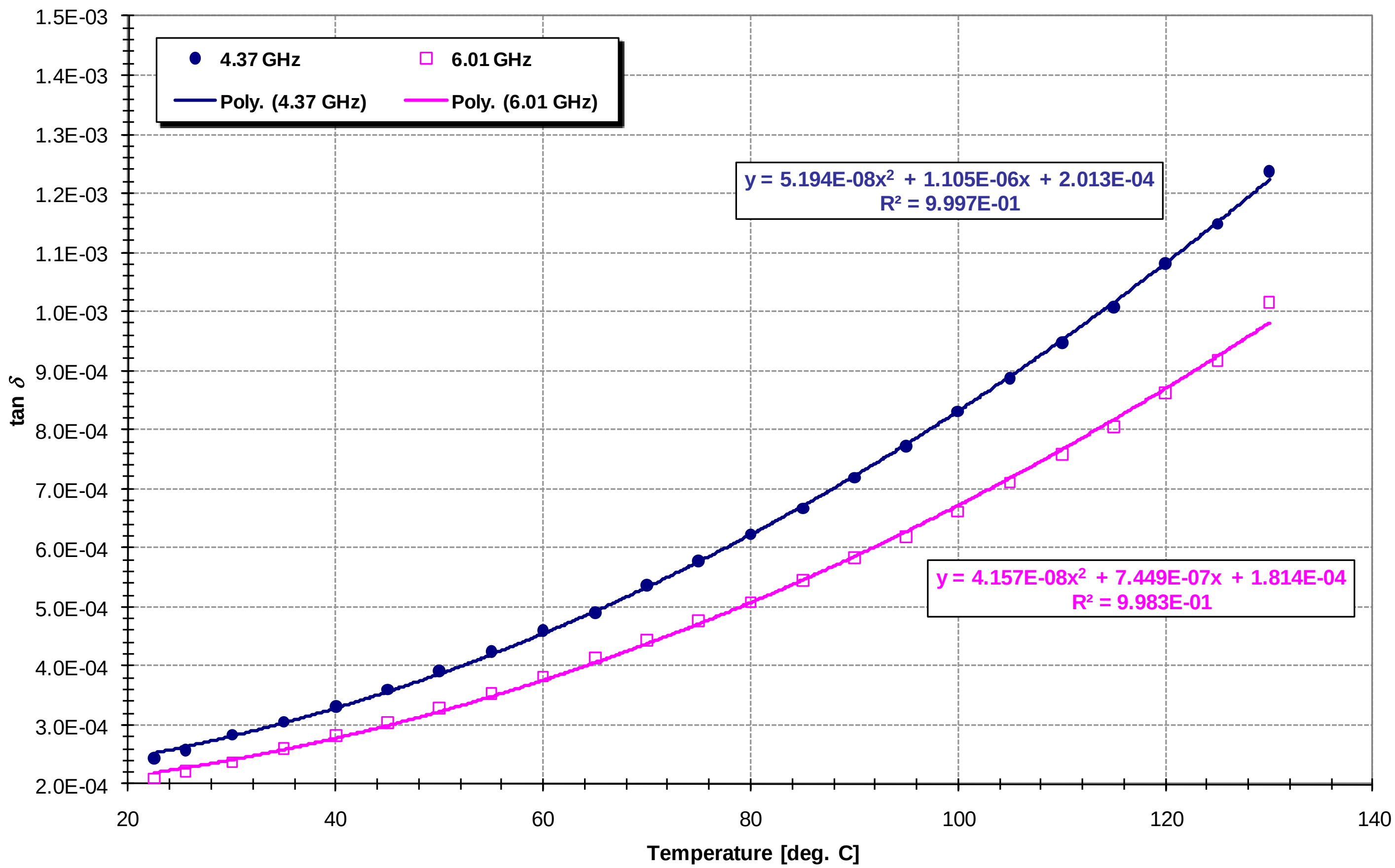


Injector klystron development

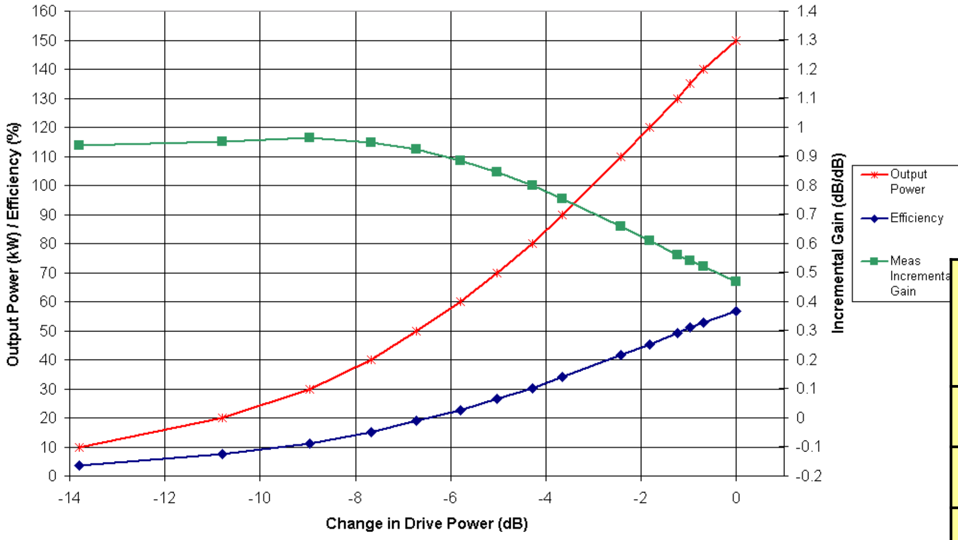


- The tube was developed at e2v
- Six K3415LS klystrons were manufactured
- 7-cavity tube, can be used in either vertical or horizontal orientation
- Full dissipation collector, no mod anode
- As the tube specifications were deemed very challenging, Cornell closely followed tube development and fabrication via design reviews, conference calls, helping with solving problems, acceptance tests at the factory and at Cornell, etc.
- Example: output ceramic window failure. To determine the cause, we developed a simple set up to measure ceramics loss tangent and found abnormal temperature dependence. The ceramics manufacturer had to deliver new batch of ceramics, which exhibited normal temperature dependence of loss tangent.
- So far we have ~2,000 hours per klystron.

Abnormal losses of the window ceramics

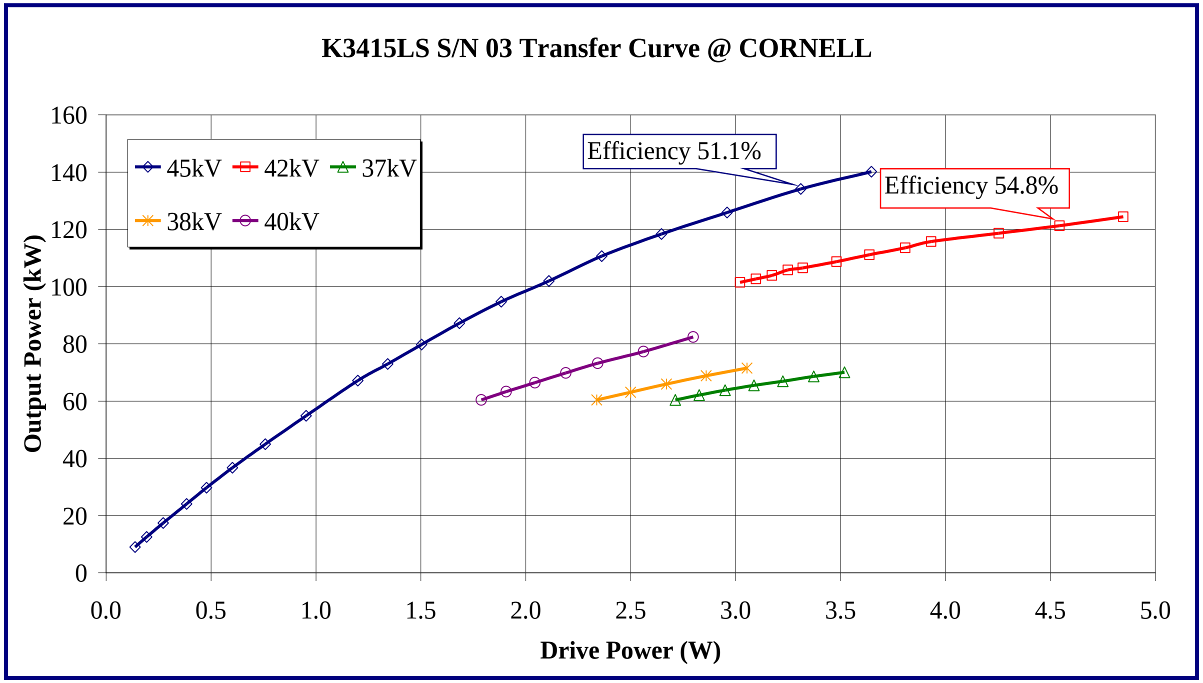


Injecto klystron parameters

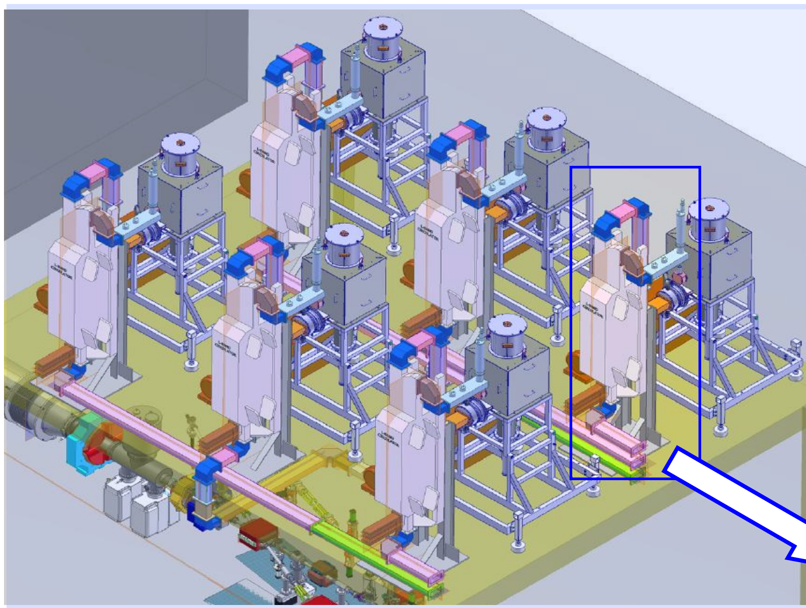


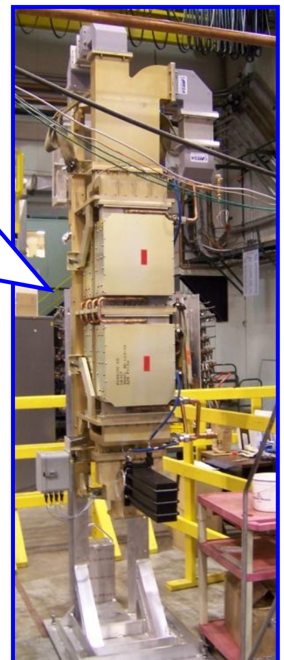
Maximum useful klystron output power (with an incremental gain of 0.5 dB/dB)	≥ 120 kW
Klystron efficiency at maximum useful power	> 50%
Tube bandwidth at -1 dB	± 2 MHz
Tube bandwidth at -3 dB	± 3 MHz
Klystron gain at nominal operating conditions	> 45 dB
Klystron beam high voltage	45 kV
Typical klystron current	5.87 A
Maximum klystron CW output power	135 kW
Klystron saturated output power (pulsed)	165 kW
Tube efficiency at saturated power	> 60%

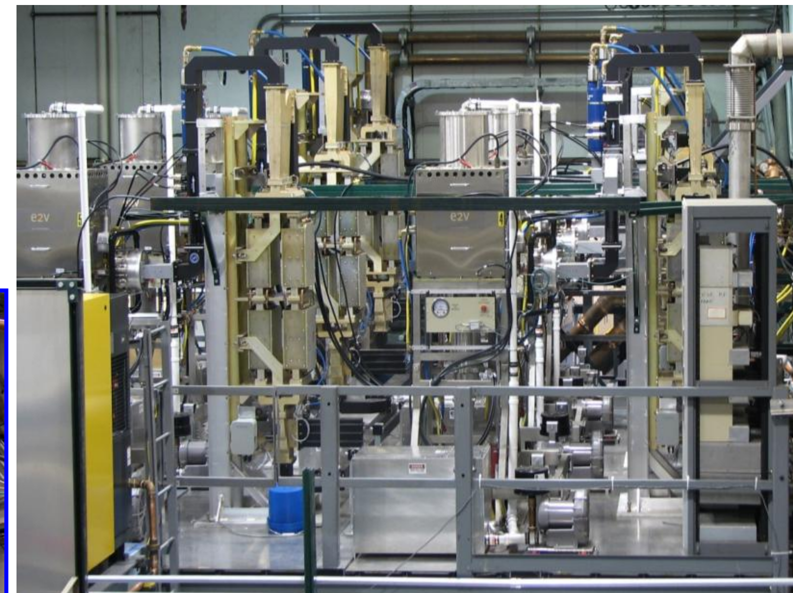
Injector klystron transfer curve



ERL injector klystron mezzanine

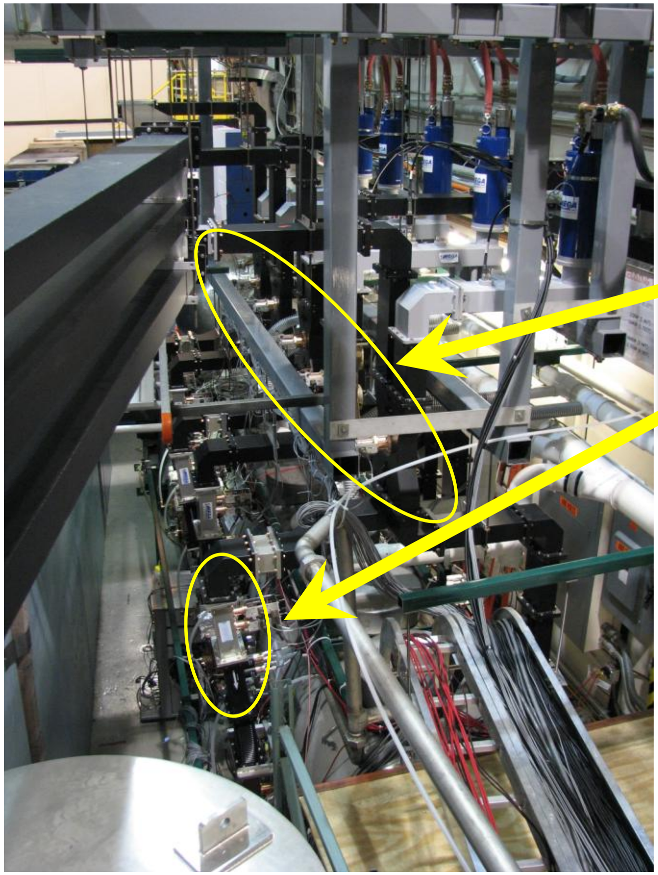




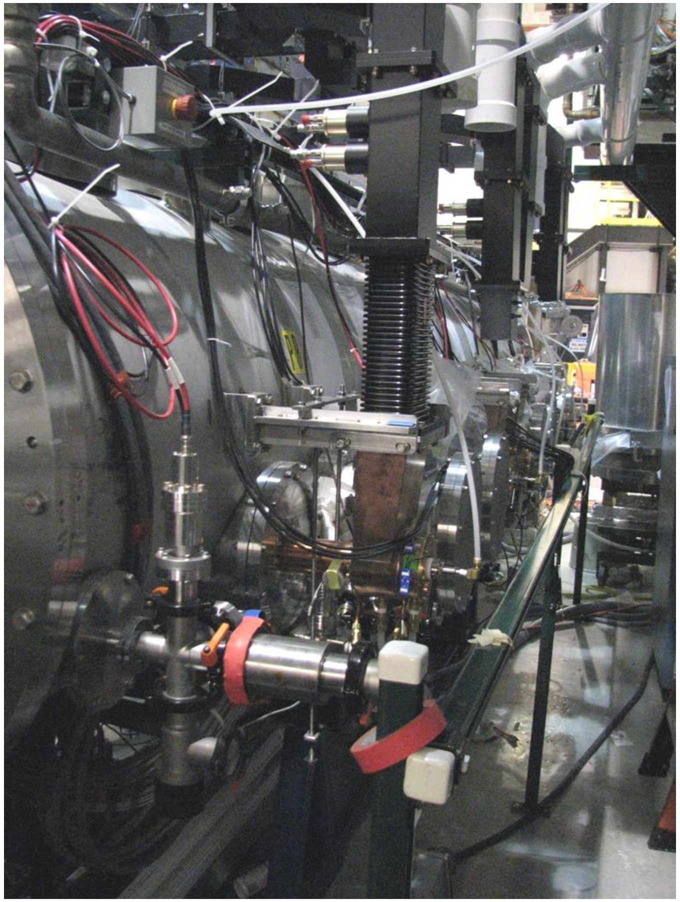


- 170 kW CW 4-port ferrite circulator
- Manufactured by Ferrite Co.

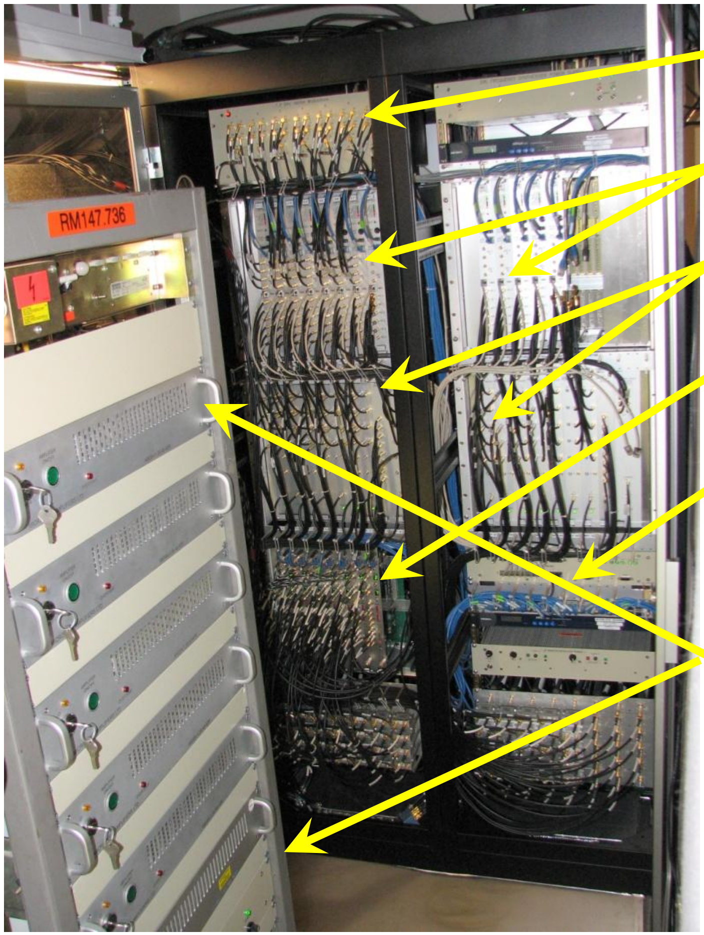
Waveguide distribution network



- Adjustable 3-dB hybrids
- Two-stub waveguide phase shifters

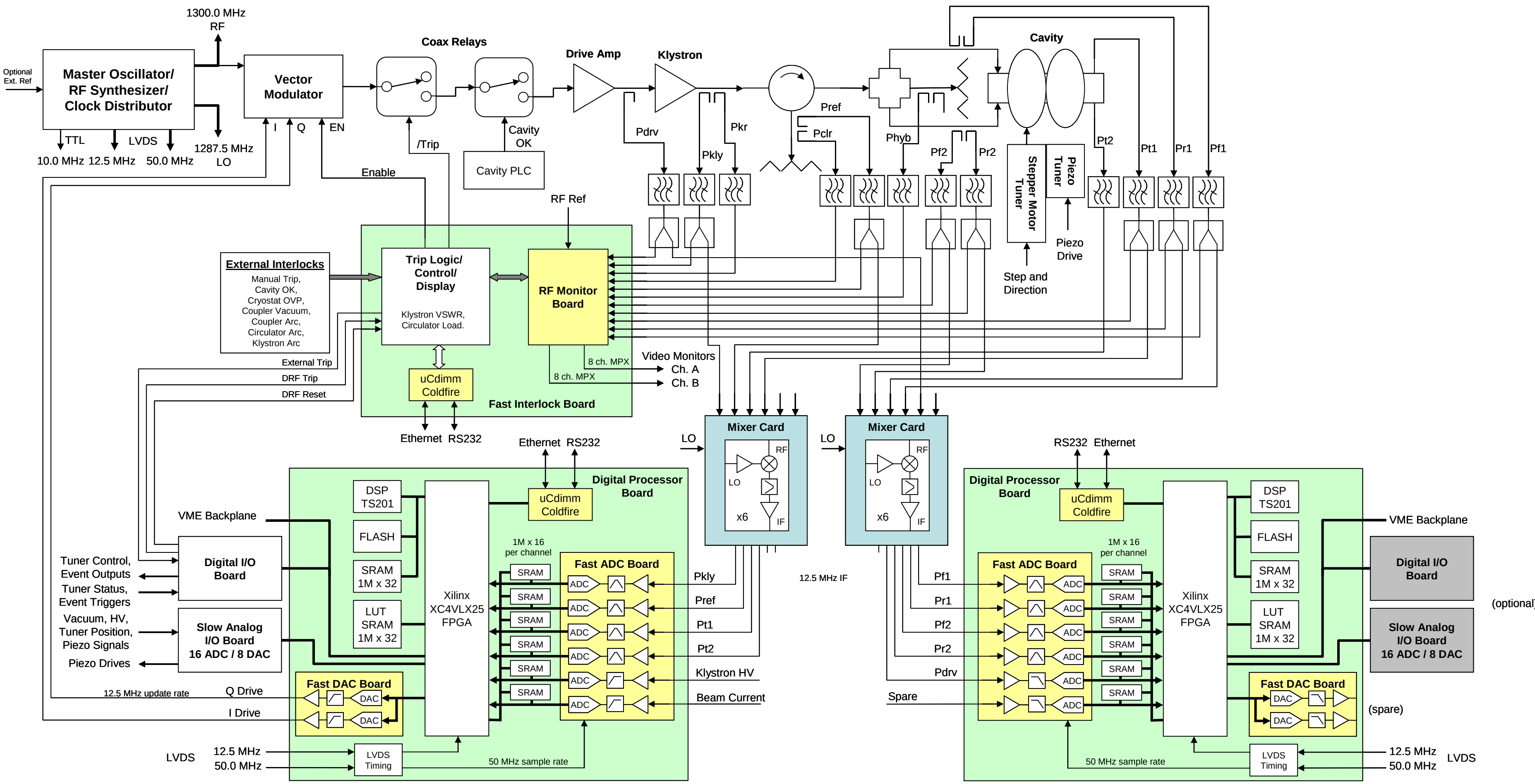


ERL injector LLRF

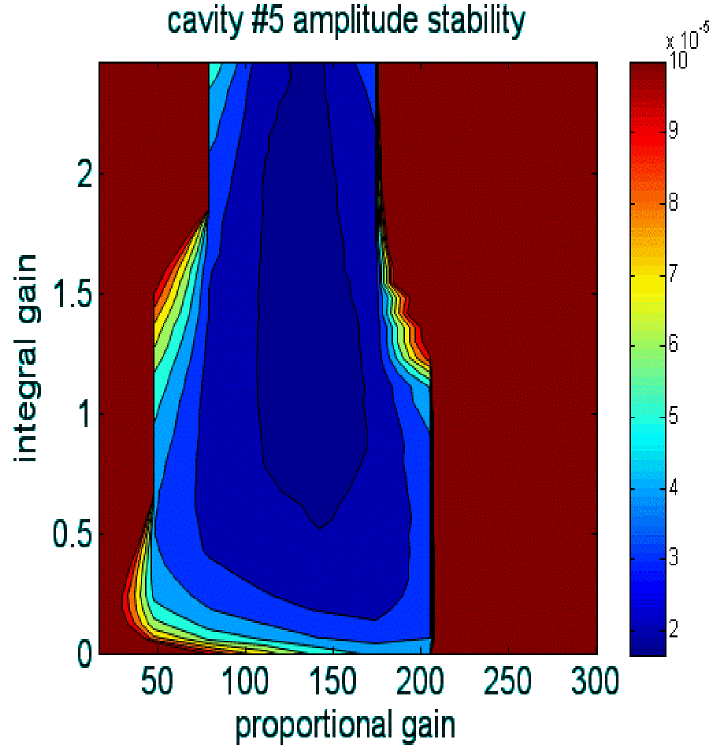


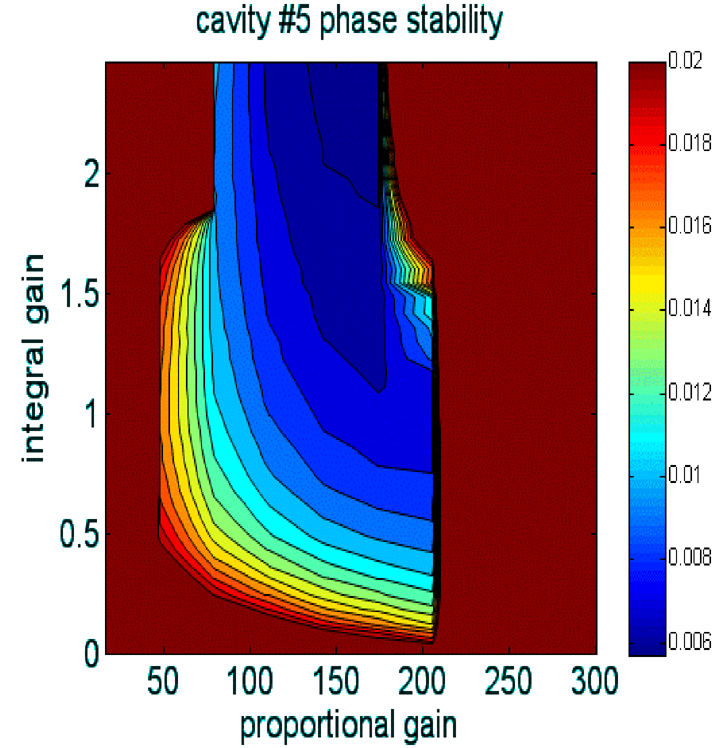
- The LLRF electronics for ERL injector is a new, improved generation of digital LLRF previously developed for CESR
- The new electronics, like the CESR LLRF, uses VME form-factor.
- The crates are housed in two temperature-controlled racks.
- Performs well with excellent field stability.
- All critical signals are transferred from the cavities via FSJ2-50 Heliax cables enclosed in a temperature-controlled conduit.

ICM LLRF block diagram



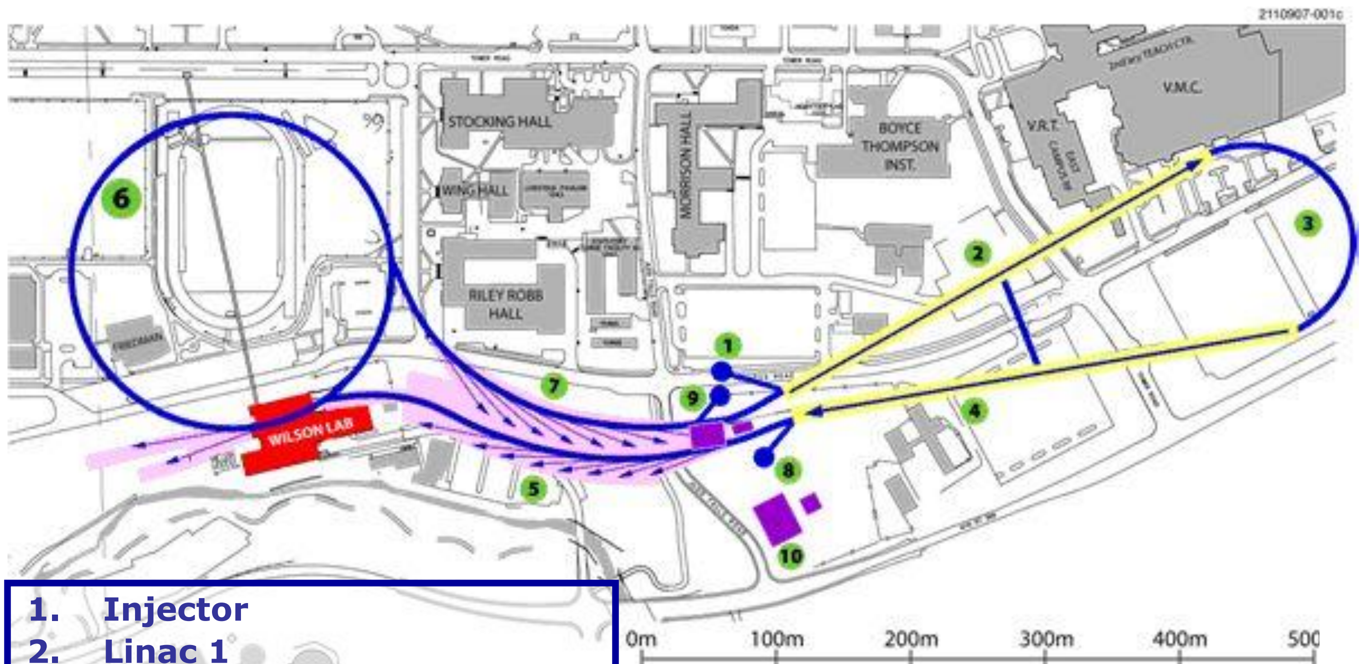
PI gain optimization study



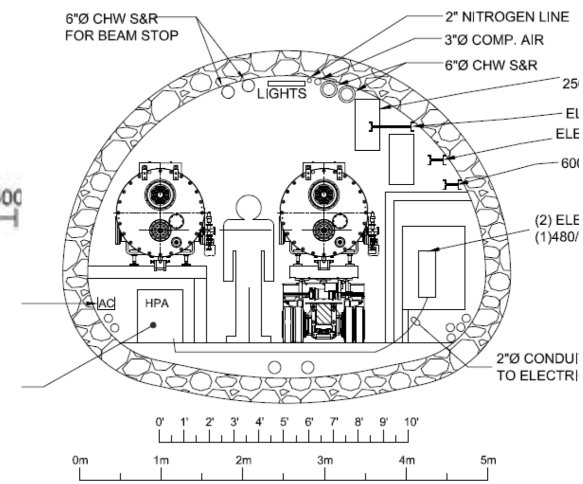


- During the first test of the new LLRF the amplitude stability of 10^{-4} rms and the phase stability of 0.05° rms were easily achieved, exceeding the ERL injector requirements.
- After that more systematic studies were performed to find the optimal P and I gain settings.
- The achieved amplitude stability is $< 2\times10^{-5}$ rms and the phase stability is $< 0.01°$ rms.

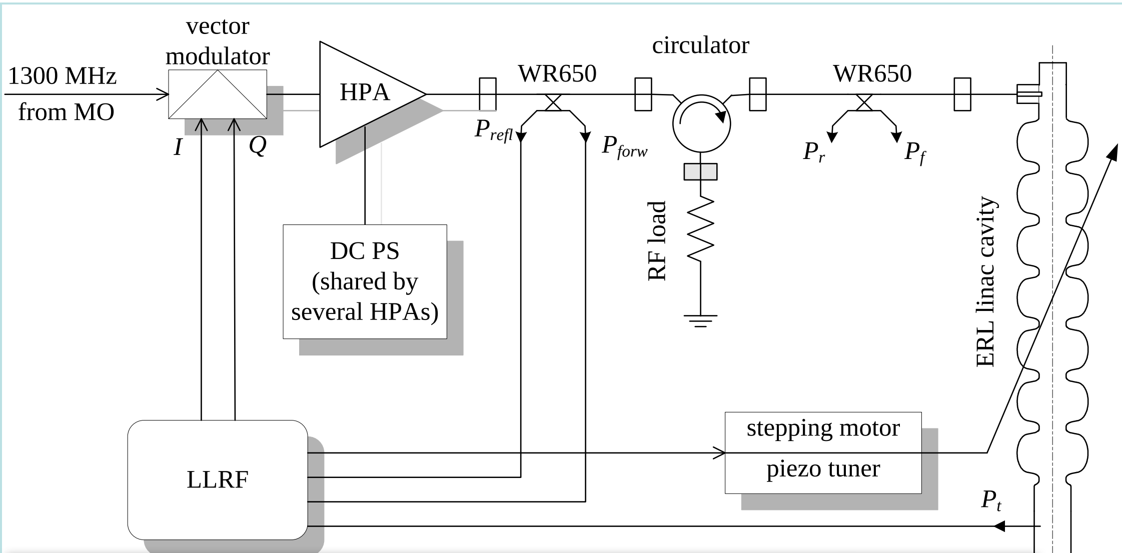
Future Plans: 5-GeV, 100-mA ERL



1. Injector
2. Linac 1
3. 2.5 GeV turn-around
4. Linac 2
5. 5 GeV transfer line
6. 5 GeV turn-around (CESR)
7. 5 GeV transfer line
8. Beam dump



ERL linac RF system



Operating frequency	1300 MHz
Number of 7-cell cavities	384
Accelerating gradient	16.2 MV/m
Accelerating voltage per cavity	13.1 MV
R/Q (circuit definition)	400 Ohm
Qext	6.5×10^7
Peak detuning due to microphonics	20 Hz
Typical detuning due to microphonics	10 Hz
Peak RF power per cavity	5 kW
Average RF power per cavity	< 2 kW
Amplitude stability	1×10^{-4} rms
Phase stability	0.05° rms

Frequency	1300 MHz
Peak output RF power	≥ 5 kW
Average output RF power	≥ 2 kW
Bandwidth at 1 dB points (min.)	± 1.5 MHz
Bandwidth at 3 dB points (min.)	± 2.5 MHz
RF phase pushing (0.03 kW to 5 kW output power)	< 7°
Gain change (0.03 kW to 5 kW output power)	< 3 dB
RF output amplitude ripple (0.03 kW to 5 kW output power)	< 0.2% rms
RF output phase ripple (0.03 kW to 5 kW output power)	< 0.5° rms
Efficiency at 5 kW	≥ 50%
Efficiency at 2 kW	≥ 40%

Summary

- The 500-MHz CESR RF system is operating reliably and doesn't require much attention.
- The new 1300-MHz RF systems have been recently designed and built for the ERL injector prototype.
- One system, to power normal conducting buncher cavity, is based on a 16-kW IOT.
- The other system, for the 5-cavity superconducting injector cryomodule, uses 120-kW klystrons.
- The ERL RF systems have been commissioned in 2008 and operate reliably.
- Both CESR and ERL injector employ digital LLRF designed and built at Cornell.
- Future plans include 1300-MHz RF system for 5-GeV ERL at Cornell, consisting of 384 HPAs with peak power of 5 kW.