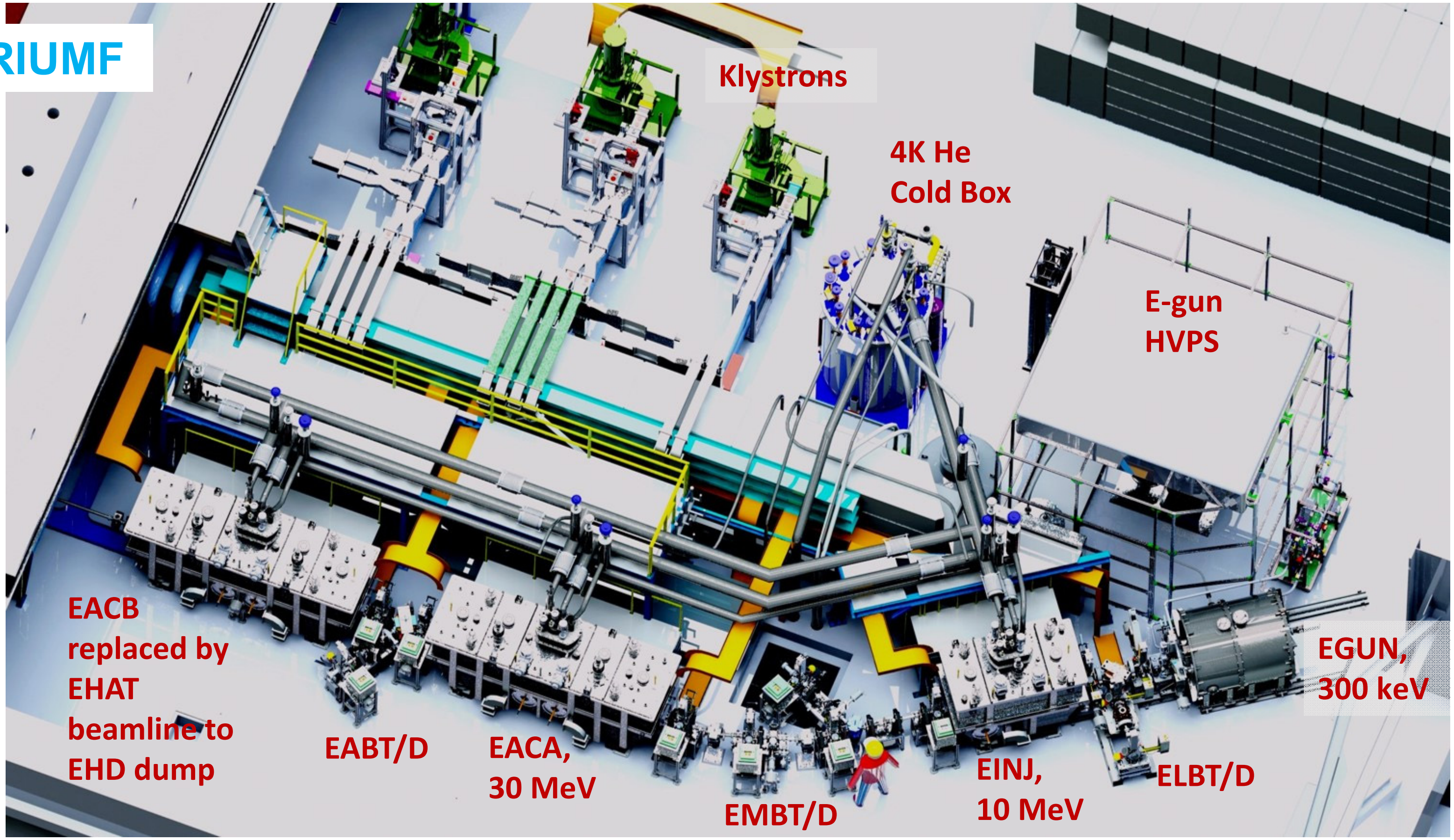


STATUS AND ISSUES (MICROPHONICS, LFD, MPS) WITH TRIUMF ARIEL E-LINAC COMMISSIONING

Shane Koscielniak , 2018 September 18

TRIUMF

Contents

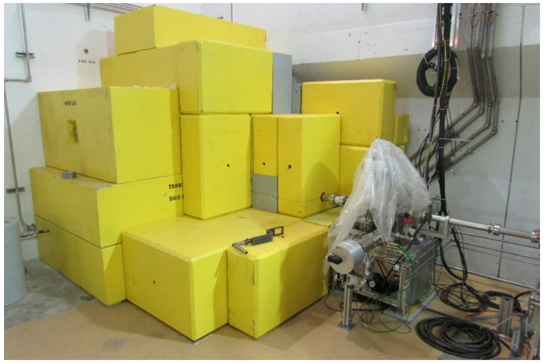
E-linac will provide high peak & average power electron beam for Rare Isotope Beam production via photo-fission from actinide targets

2017 status:

- Injector Cryomodule EINJ gradient limited to 7 MV/m by field emission.
- EINJ & EMBT commissioning compromised by beam energy instability ~ 0.5%
- EACA:CAV1 gradient limited to 5MV/m – returned to ISAC for repair
- Accelerator Cryomodule EACA:CAV2 gradient achieved 10 MV/m.

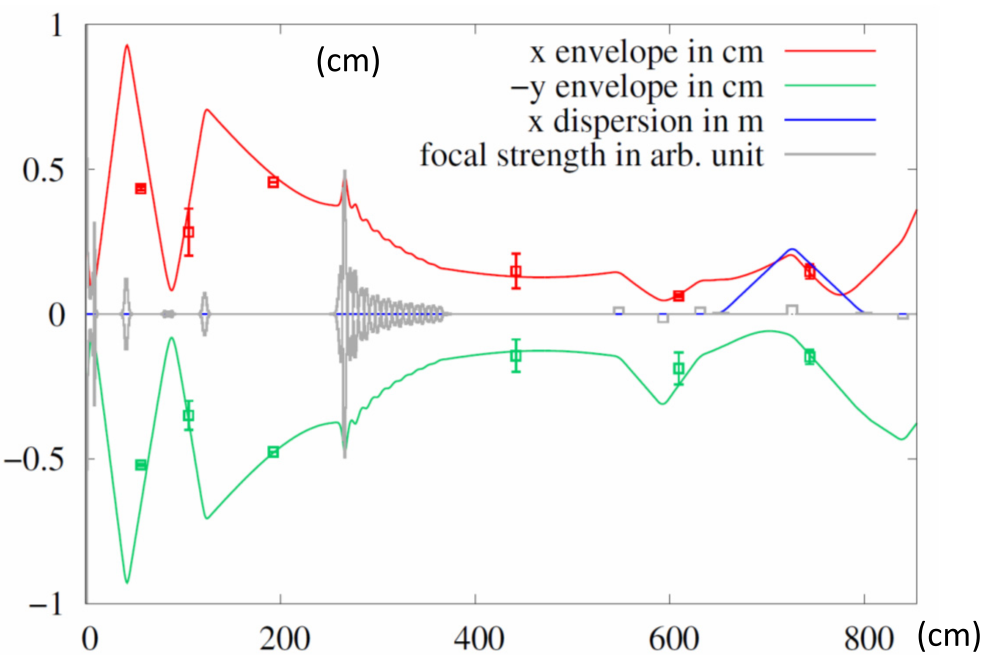
2018 Objectives:

- Improve RF stability
- Beam Energy > 25 MeV
- Commission Beam Optics (bends & quads) to EHDT dump
- Commission Machine Protection System (MPS) to EHAT
  - E-linac parameters 10 mA (c.w.) at 30 MeV → 300 kW beam power
  - Mutual agreement with regulatory authority not to operate > 100 W until MPS is fully functional



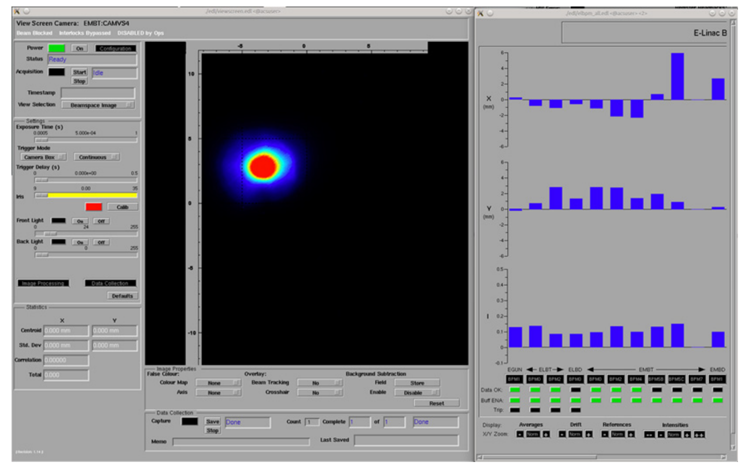
E-hall 10kW beam tuning dump (EHD)

E-linac Beamlines Commissioning: Transport from EGUN to EINJ to EMBD



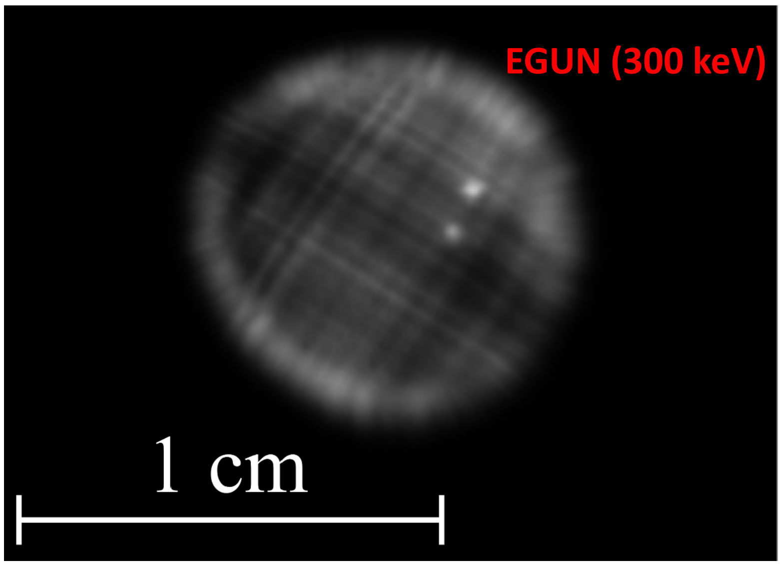
2019 May 18: For the first time, we have a stable accelerated beam at E-linac Medium Energy Beam Dump (EMBD). Energy ≈ 9 MeV.

No discernible transverse or longitudinal halo.



- Measured 2*r.m.s beam sizes (square dots) compared with calculated beam envelope (solid lines). Measurements were taken using fluorescent screens. Error bars reflect the sensitivity of the r.m.s. calculation to the background cut threshold.
- Quadrupole settings within 0.5% of calculated values
- Beam envelope is calculated using TRANSOPTR, starting practically from rest (20 eV).

Transport from EGUN to EHDT dump



- Beam image on a fluorescent screen at 300 keV (left) after the ELBT last solenoid, and at 22 MeV (right) before the EHDT dump. In both cases, the phase advance from the cathode to screen is close to a multiple of π in both planes, causing the formation of an image.
- Note the low aberration transport between object and image.

TRIUMF

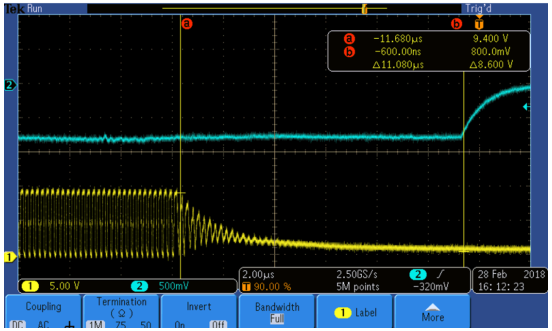
E-linac Machine Protection System (MPS)

Layered:

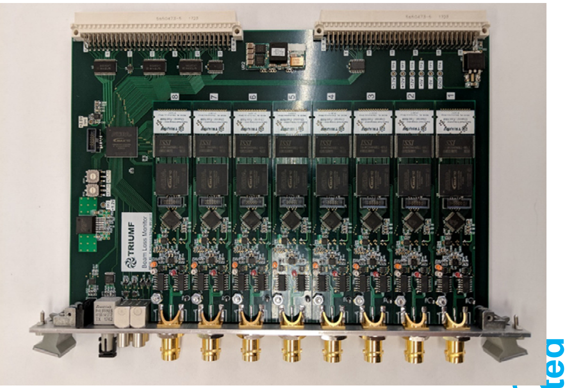
- **Equipment interlocks**
- **Beam Modes** (permitted combinations of beam properties & beam path)
  - Prescribes beam power limits according to beam terminus (dump rating) and presence/absence of intercepting beam diagnostics
  - Reduce human error
- **Beam Position Monitors (BPMs)**
  - Anticipatory/Predictive
  - Trip on beam position exceeds specified limits
  - Piggy back on existing BPM system; optical fibre links to FSD
  - Rolled out from EMBT to EHDT in 2018
- **Beam Loss Monitors (BLMs)**
  - Last resort
  - Trip on beam loss exceeds specified limits
- **Fast Shutdown (FSD)**
  - Receives all trip requests/signals
  - Remove RF from EGUN (gridded thermionic gun) → electron beam OFF

MPS Beam Loss Monitors System Specification

- **Trip rapidity < 10 µ s**
  - Respond to catastrophic beam loss
- **Dynamic range > 10^5**
  - Respond to fast and slow loss. Monitor chronic loss
- **Trip on integrated 100 nC beam loss during 100 ms sliding window**
  - 10 mA × 10µs = 100 nC
  - 1 µA × 100 ms = 100 nC
- **Post mortem capability**
  - Synchronously freeze all buffers on 1st trip
  - Deep memory ~ 1 second for every loss monitor
  - Easily calibrate and set thresholds for individual beam loss monitors
  - External trigger for testing
- **BLMs (ionizing radiation detectors)**
  - Full and redundant geographic coverage; Two types
  - Long Ionization Chambers (LICs) ~ 1 metre Heliax; Argon filled for rapidity
  - Scintillators = BGO crystal & photomultiplier tube (small)



Time from Fast Shut Down trip (yellow) to beam off (blue) ~ 11.0+/- 0.5 µs

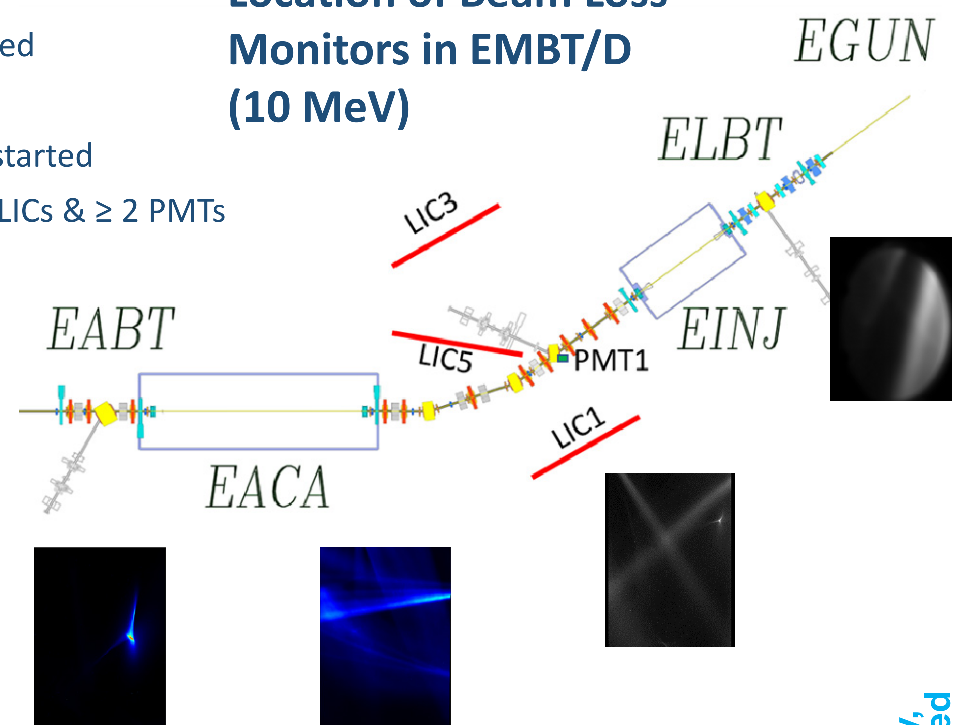


MPS BLM electronics & firmware ready for 2018 May beam start

MPS BLM system Status & Progress

- 2016: ELBT/D MPS (300 keV) commissioned
- 2017: more versatile electronics board (TBLM) developed
- 2018: EMBT/D MPS (10 MeV) commissioned
- 2018: EABT/D & EHAT BLMs deployed; commissioning started
  - BLM number and type not finalized, likely to be 6 LICs & ≥ 2 PMTs

Location of Beam Loss Monitors in EMBT/D (10 MeV)

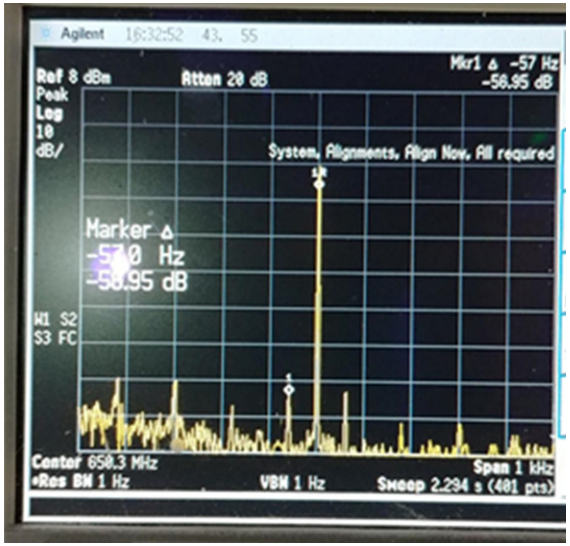


- **EMBT/D: Three LICs** are positioned to include redundancy in most areas of the beamline
- **One PMT is placed at the dipole magnet** leading to EMBD to detect spills inside the magnet.
- Commissioning consisted of performing beam spills to determine optimal numbers of BLMs and location
- Full spills were performed at low duty factors using quadrupoles and steerers to mimic point losses in H & V planes of the beamline.
- **Final step: purposeful beam spills above threshold to ensure a trip takes place within the specifications.**

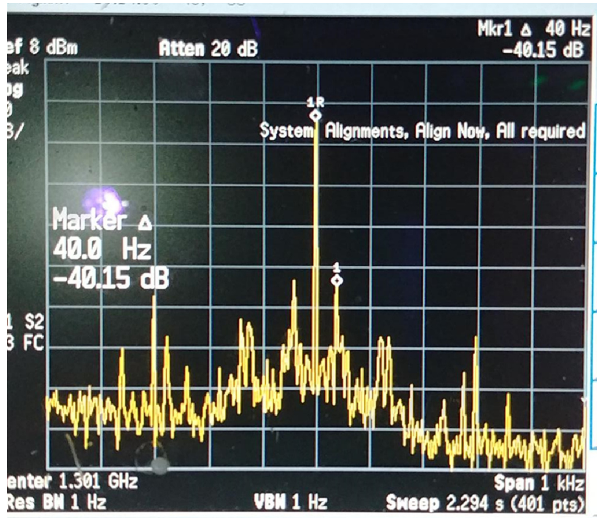
- Note, dark currents from EINJ & EACA at 5 & 3 MeV, & few keV have been found to cause false trips.

TRIUMF

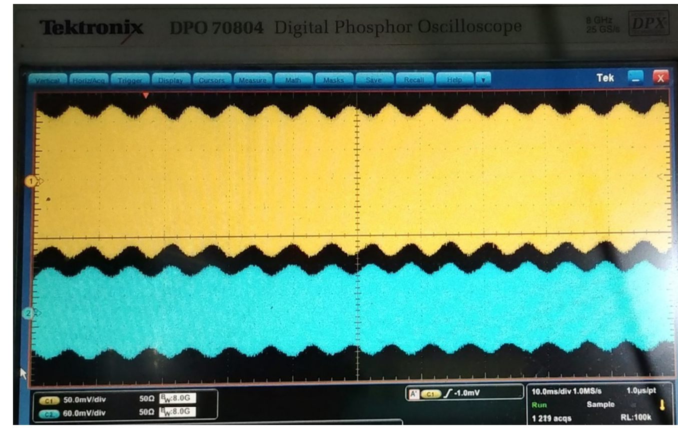
E-LINAC RF Spectra & Time Domain: 2018 June 19-21



EGUN: beam signal: 60 Hz sidebands
Other sidebands at 180, 300, 420 Hz



EINJ cavity pickup: 40Hz main sidebands
Other sidebands: 120, 300 Hz, etc



Spontaneous Amplitude Modulation of the two EACA cavities in anti-phase, above a 12 MV/m (total gradient) threshold.

These 3 measurements launched a variety of investigations:

- **Microphonics:** cavity mechanical modes, acoustic/vibrational noise sources, other disturbances (LN2 supply, switch-mode HVPS)
- **Ponderomotive Effects:** Static Lorentz Force Detuning, Dynamic LFD, Simulations, Routh-Hurwitz analysis, Experimentation.

E-linac RF Regulation and Stability

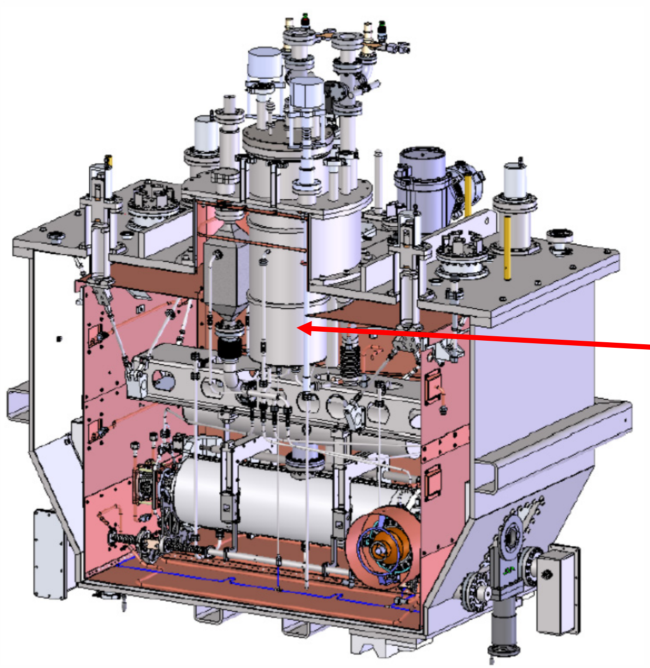
TAKE HOME Message:
After two months of investigations,
We can make almost a one-to-one correspondence between source, frequency, location, and effect of microphonic noise below the ponderomotive threshold.

The main tools have been RF phase noise spectra
and acoustic vibration spectra
Turn on/off and throttle equipment to eliminate/discriminate sources

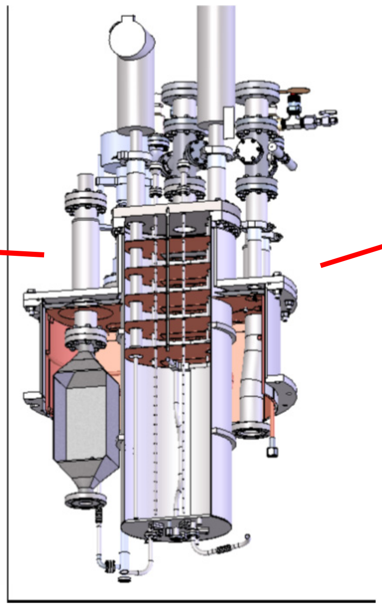
However, behavior above ponderomotive threshold still under investigation.

But first, I have to tell you about a couple of e-linac cryomodule/RF peculiarities.

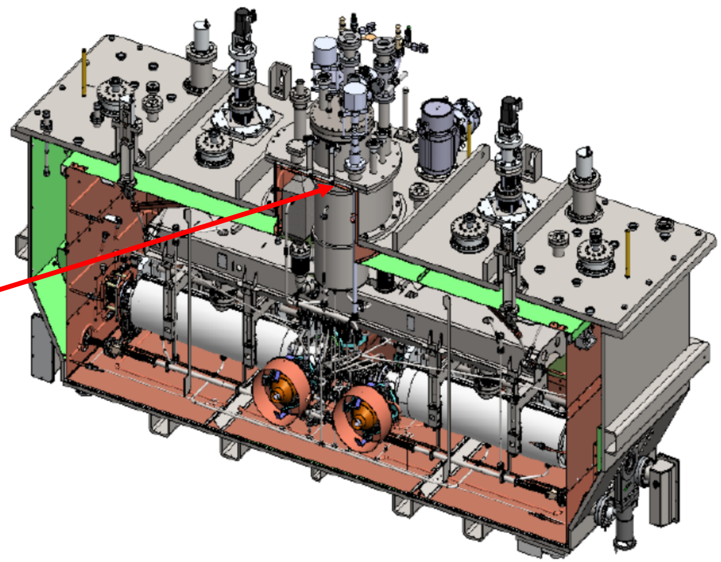
2 Kelvin LHe is made on-board with a Joule-Thomson expansion valve and 4K phase separator, 4K/2K HX, etc.



Injector Cryomodule (EINJ)

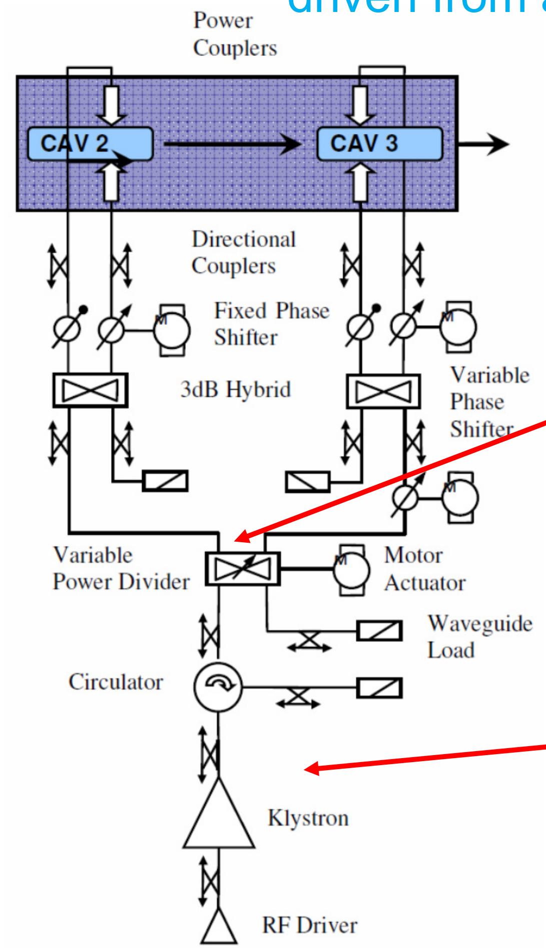


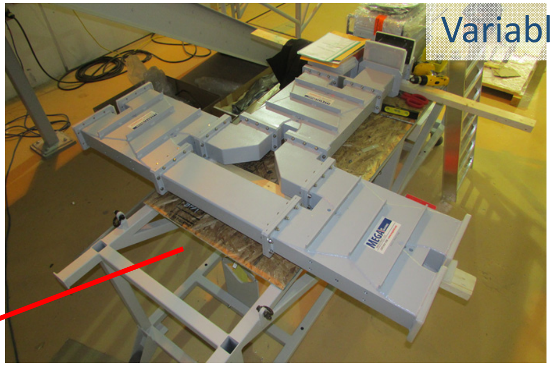
4K/2K cryo insert



Accelerator Cryomodule (EACA)

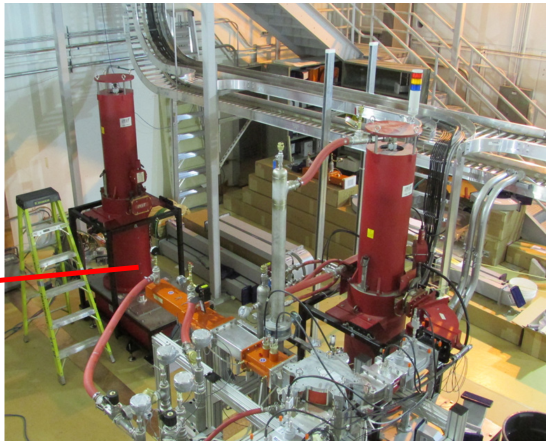
Accelerator Cryomodule has vector-sum control of two cavities driven from a single 250 kW CW klystron





Variable Power Divider

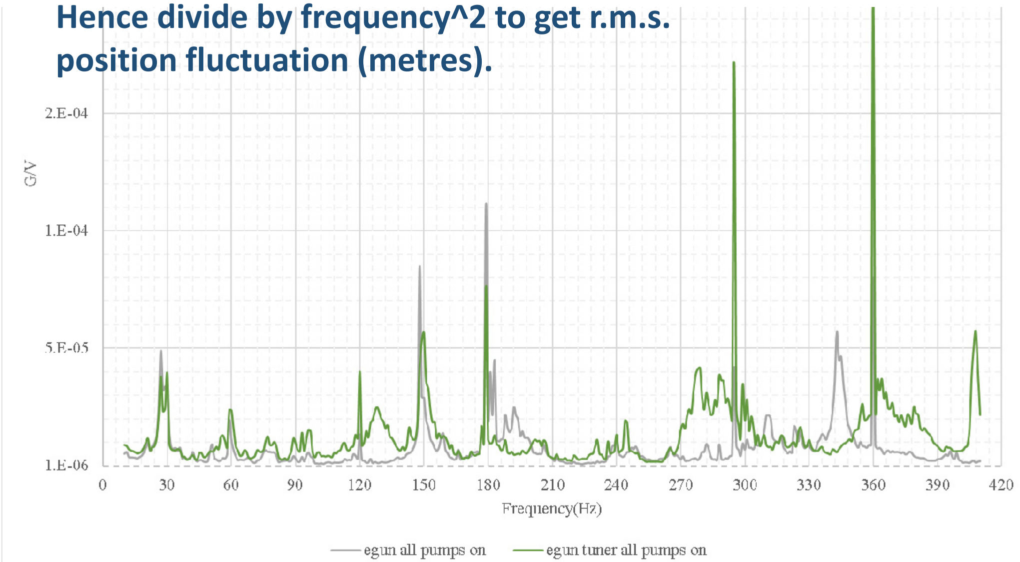
Switch-mode DC High-Voltage Power Supply



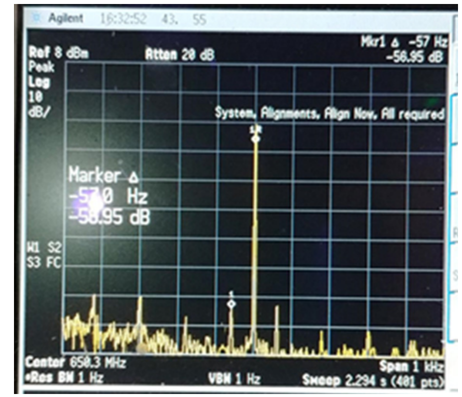
Klystron cooling pumps are in vault with e-linac

EGUN Vibrational “noise” as measured by an accelerometer

Scale is G/Volt.
G = acceleration in units of g=9.8m/s^2 .
Hence divide by frequency^2 to get r.m.s. position fluctuation (metres).



- **Most peaks are 60 Hz (&30 Hz) harmonics from raw water pumps and booster pumps.**
- E-gun impedance tuner (because of long lever arm) is about 10 times more noisy than massive SF6 tank



- 650 MHz Master Oscillator: clean as a whistle
- EGUN amp: +/- 60 Hz sidebands down to -55 dB
- EGUN beam signal: +/- 60 Hz sidebands down to –40 dB (1%*). Additional lines at 180, 300, 420 Hz
- But beam energy measurements show dp/p ~ 10^{-4} , so it is phase error

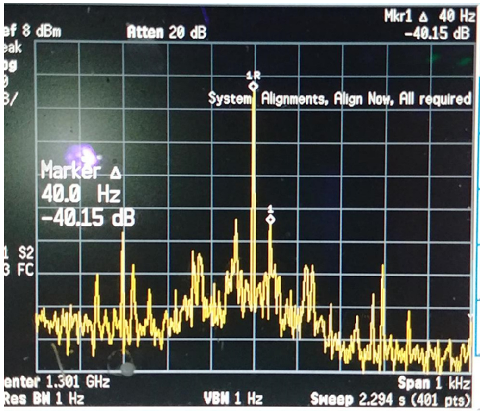
*if it is an amplitude error

E.g. 5×10^{-5} G/V @ 30 Hz → 0.54 μm @ 30 Hz
Moving impedance tuner → 0.2 deg phase jitter; carrier is 650 MHz

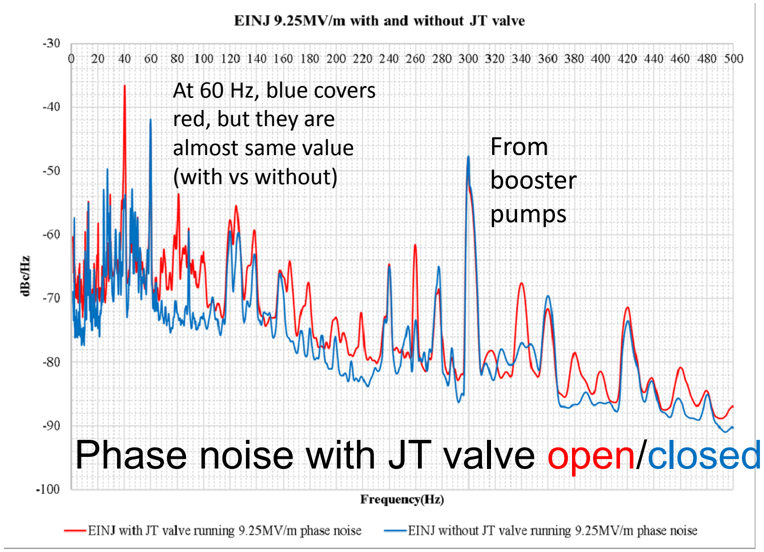
TRIUMF Injector Cryomodule RF Spectra 2018-06-21

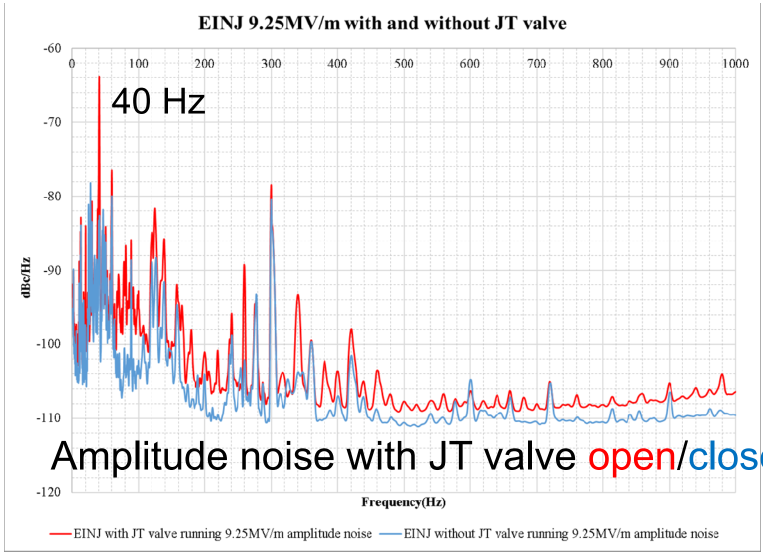
- 1.30 GHz Master Oscillator: clean as a whistle - 67 dB (0.04%)
- Signal from RF buncher: very clean down to -65 dB (0.05%)
- Signal from EINJ: +/- 40 Hz sidebands down to -40 dB (1.0%*)
- Other sidebands: 120, 300 Hz, etc

* if it is an amplitude error



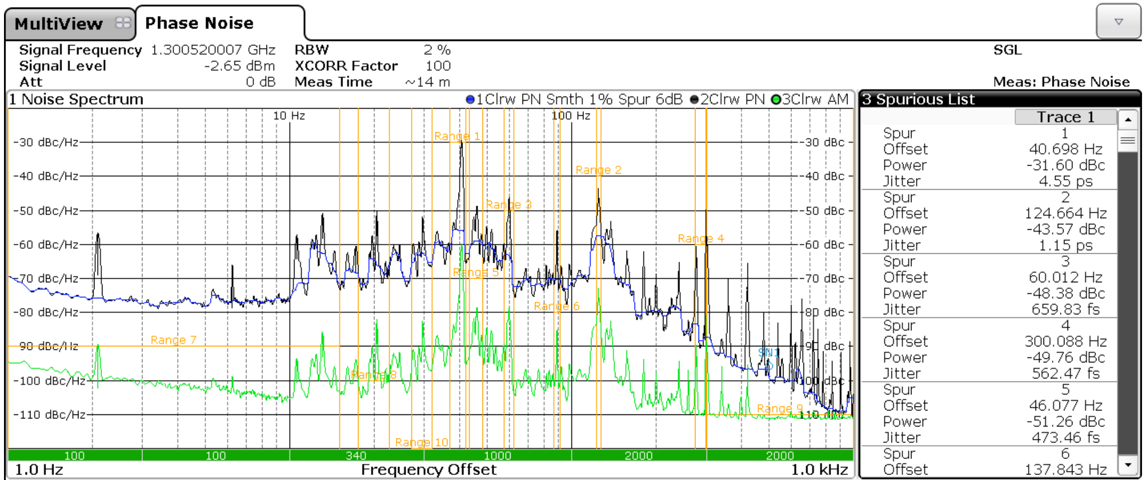
Hypothesis: components in 4K/2K insert (e.g. JT valve) behaves like blown pipe (gas/liquid mixture)





EINJ cavity pick-up results 2018-07-24: phase analyzer on loan from Rhode & Schwarz

BUT There is much, much more going on than just 40 Hz



Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM / AM	Jitter
1	2	37.000 Hz	42.000 Hz		-31.25 dBc	2.22 °/38.74 mrad	1.575 Hz	4.741 ps
2	2	122.200 Hz	127.200 Hz		-42.31 dBc	621.21 m°/10.84 mrad	1.352 Hz	1.327 ps
3	2	57.500 Hz	62.500 Hz		-46.62 dBc	378.10 m°/6.60 mrad	395 mHz	807.586 fs
4	2	274.000 Hz	302.500 Hz		-49.97 dBc	257.13 m°/4.49 mrad	1.333 Hz	549.198 fs
5	2	43.500 Hz	48.500 Hz		-47.61 dBc	337.26 m°/5.89 mrad	270 mHz	720.346 fs
6	2	86.200 Hz	91.200 Hz		-57.15 dBc	112.49 m°/1.96 mrad	174 mHz	240.262 fs
7	2	1.000 Hz	15.000 Hz		-53.58 dBc	169.[illegible]4 m°/2.96 mrad	36 mHz	362.540 fs
8	2	17.500 Hz	22.500 Hz		-54.95 dBc	144.94 m°/2.53 mrad	51 mHz	309.570 fs
9	2	300.000 Hz	1.000 kHz		-53.15 dBc	178.20 m°/3.11 mrad	1.014 Hz	380.626 fs
10	2	27.000 Hz	32.000 Hz		-53.84 dBc	164.62 m°/2.87 mrad	84 mHz	351.603 fs

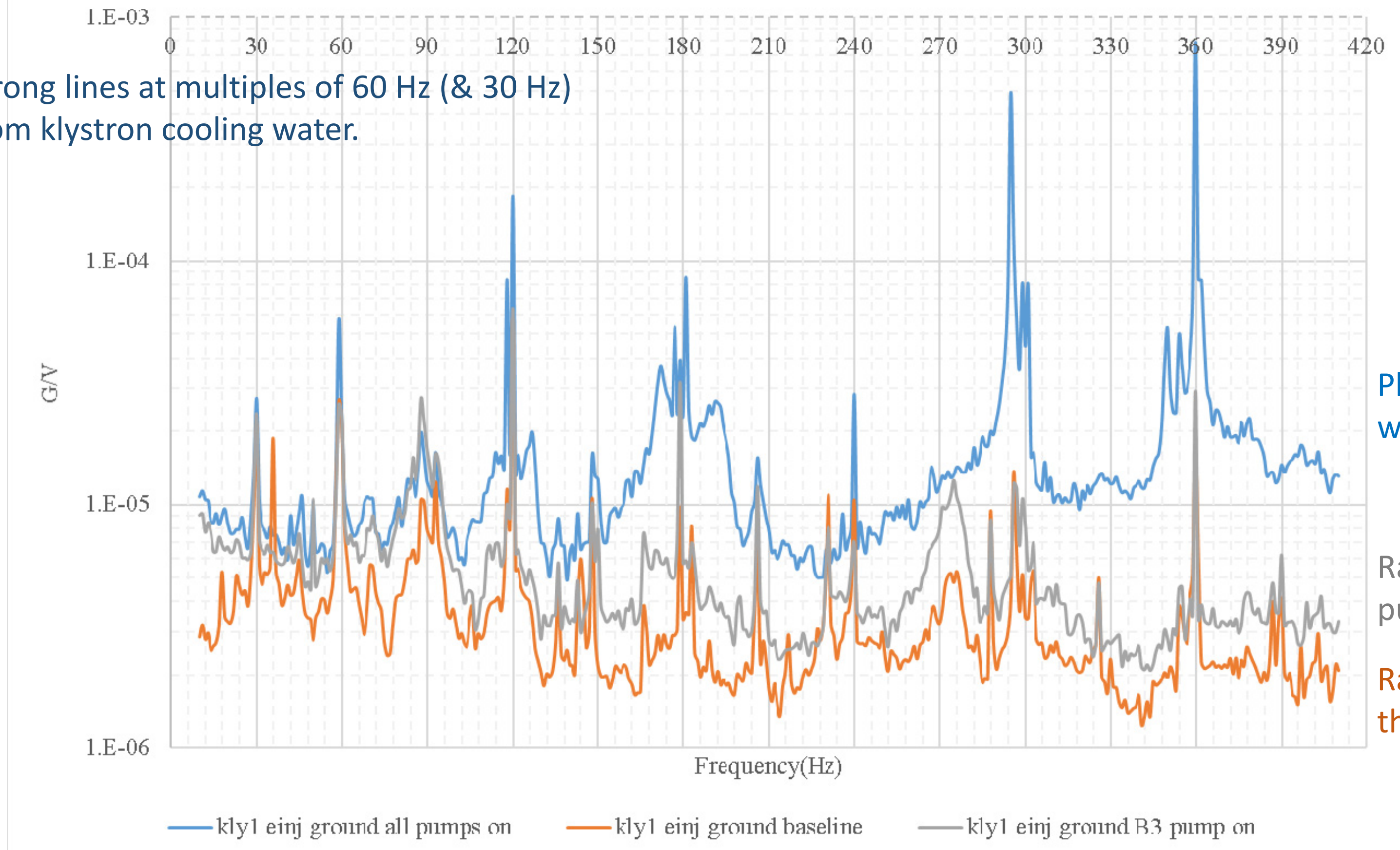
00:11:26 24.07.2018

Normal operation with beam

The first 5 peaks contribute about 3.7 degrees r.m.s --- which is similar with vector voltage meter results

Vibration (acceleration) spectrum of ground at location of EINJ klystron

Strong lines at multiples of 60 Hz (& 30 Hz) from klystron cooling water.

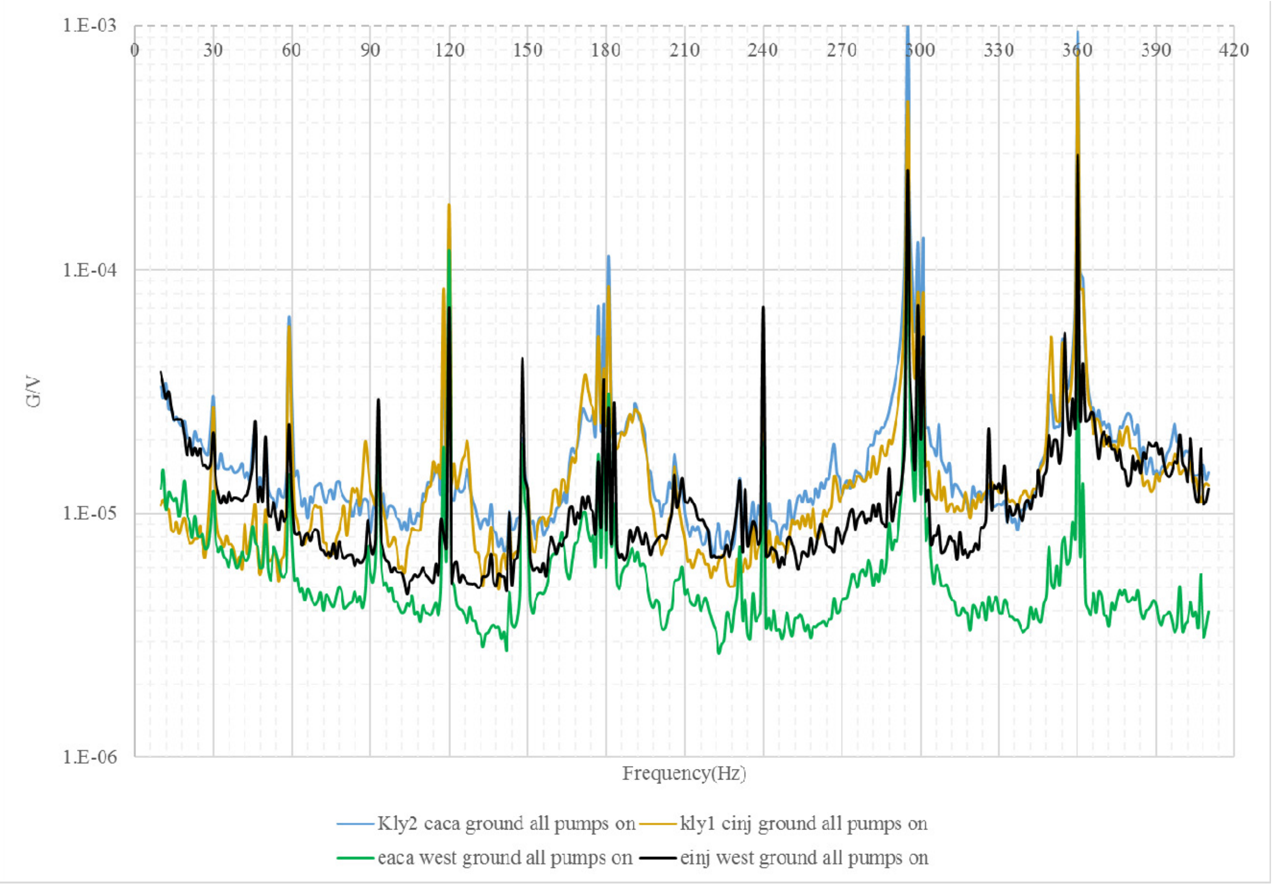


Plus Booster pumps water for klystron

Raw cooling water pumps, normal

Raw water pumps, throttled back

Water system vibrations transmitted through ground & waveguides & input couplers to the cryomodules & cold mass



Ground Motion

At EINJ klystron

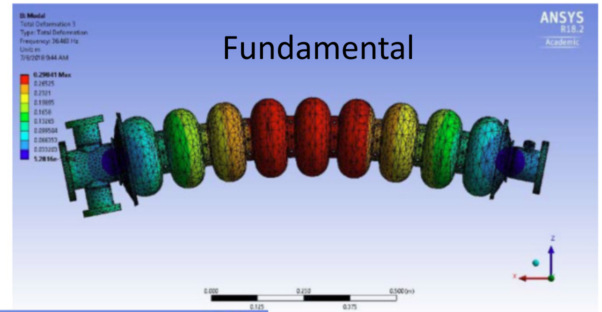
At EINJ cryomodule

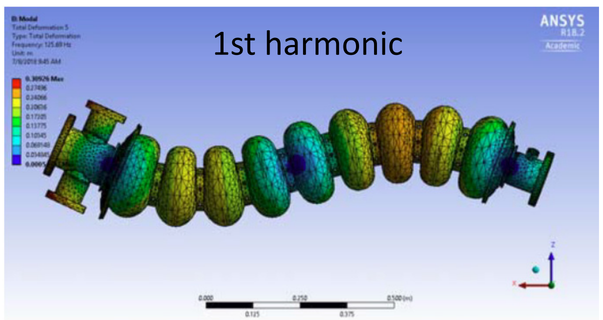
At EACA klystron

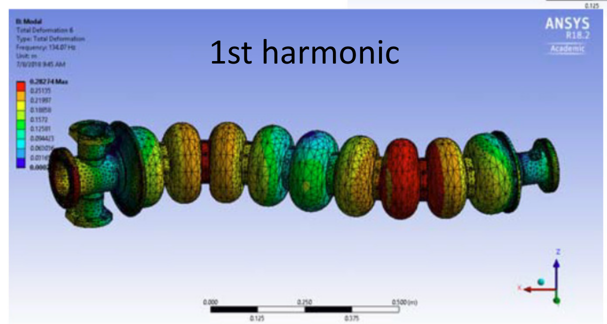
At EACA cryomodule

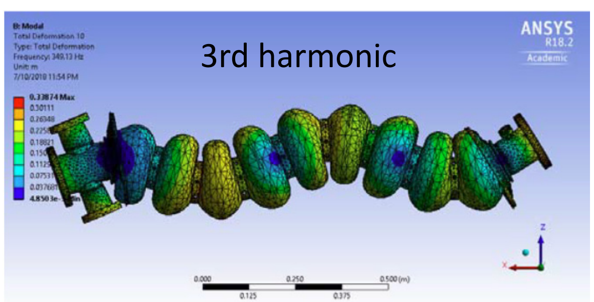
RF Cavity Calculated Mechanical Modes

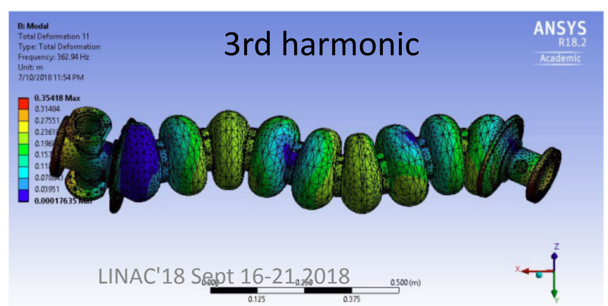
Fundamental (Hz)	36.5	37.3
1st harmonic (Hz)	125	134
2nd harmonic (Hz)	226	245
3rd harmonic (Hz)	349	363











Also longitudinal mechanical modes

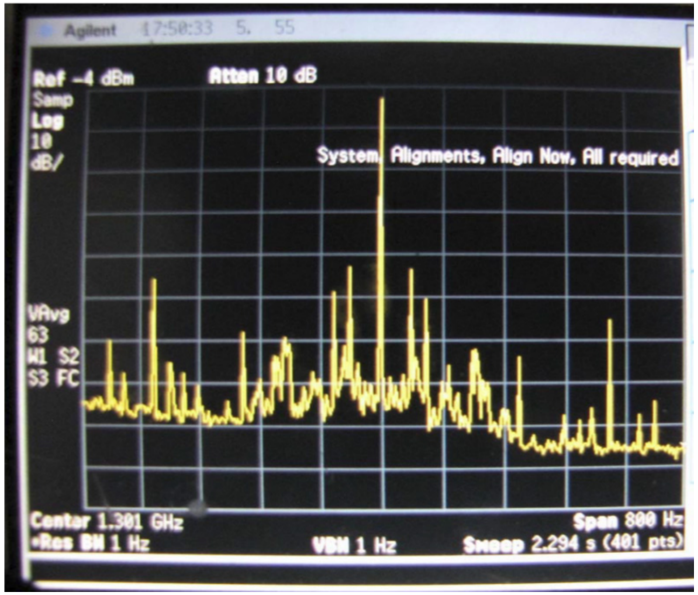
(Hz)
178
577
595

EINJ phase stability measurements 2018-07-10

- Cavity pickup signal (measured with spectrum analyzer) and phase-loop-error signal (measured with dynamic analyzer) are consistent
- All show similar disturbances at 40-50, 60, 90, 120, 180, 275, 300, 360 Hz
  - 40 Hz & 300 Hz disturbances particularly strong
- These disturbances coincide with frequencies in the cooling water acoustic spectra
- And fall within the bandwidth of several of the calculated cavity mechanical oscillation modes

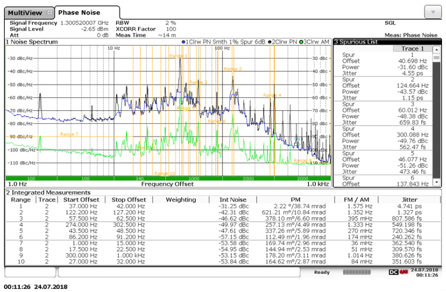
Fundamental (Hz)	36.5	37.3
1st harmonic (Hz)	125	134
2nd harmonic (Hz)	226	245
3rd harmonic (Hz)	349	363

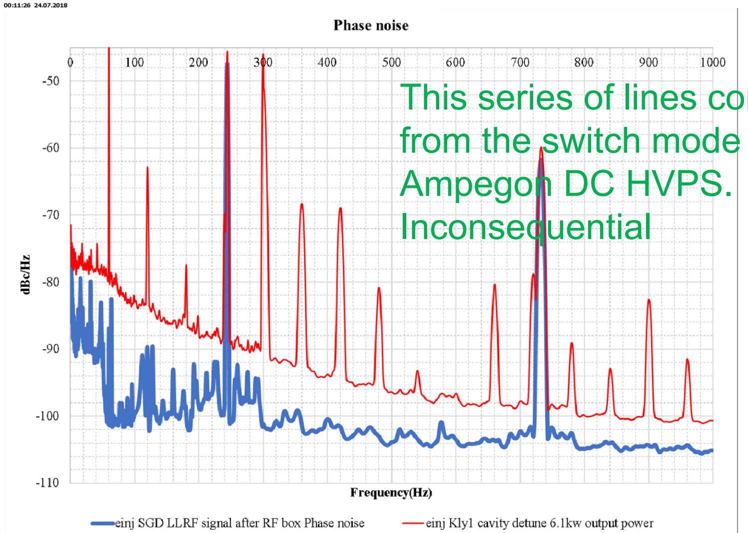
Transverse modes are split by the RF input coupler loads



- It is unfortunate that several mechanical modes lie close to multiples of 60 Hz: (37), 126, (178), 245, 363 <=> 60, 120, 180, 240, 360.
- Some of the calculated modes have been verified in shaker measurements: deliberate excitation with an acoustic oscillator.

Analysis of EINJ phase “noise” spectra





Separate measurement:
EINJ cavity detuned, generator driven

Rhode & Schwarz Strength Order

Frequency	BW	Q	Strength Order	AC harmonic
2.086215	0.0575	36.282	19	
6.258862	0.057	109.8046	23	
10.5786	0.2194	48.21603	14	
13.06756	0.2328	56.13212	9	
17.16979	0.7925	21.66535	17	
20.35614	0.2015	101.023	7	
29.59192	0.2191	135.0612	10	
40.69847	0.5927	68.66623	1	
46.07744	1.2617	36.52012	5	
60.01178	0.7		3	1
88.74512	0.5552	159.8435	8	
124.6643	2.322	53.68834	2	
137.8433	3.813	36.15087	6	
157.2808	3.1911	49.28734	12	
180.0612	1.8939		13	3
199.313	2.4667	80.80149	18	
240.0322	2.2119		15	4
277.4457	2.682	103.4473	11	
300.0875	1.242		4	5
360.0725	5.7778		20	6
420.0966	5.6337		16	7
480.0641	5.8381		25	8
540.5819	6.5857		26	9
600.1349	6.1022		22	10
655.8779	6.8381	95.91522	21	
720.1504	5.767		24	12
748.5502	6.2745	119.3004	27	
780.1735	5.8915		29	13
840.1926	7.2086		31	14
900.1993	6.4469		30	15
974.6442	8.0471	121.1174	28	

Mechanical fundamental

Mechanical 1st harmonic

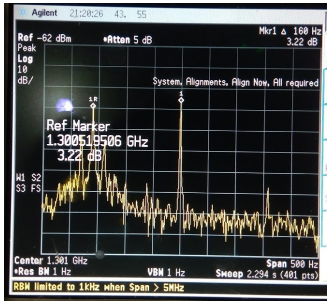
Water cooling spectrum

Klystron DC HVPS spectrum

Ponderomotive Instability in EACA limits gradient; two cavities with vector sum feedback

Pickup 1 and 2 signals; counter phase amplitude oscillations at 160 Hz

RF spectrum from 1st pick up shows 160Hz sidebands (same for 2nd cavity)



EACA presently operated under (almost) full reflection

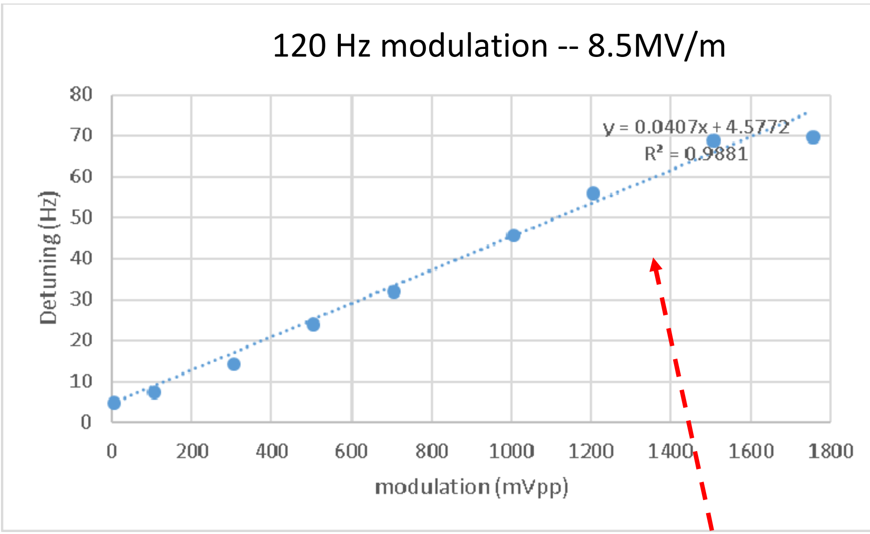
- Few Watts beam power
- 100 kW forward RF power
- Very far from RF design parameters
- Power Divider does not sufficiently isolate one cavity from reverse power of the other
- Controls cross-talk & un-intended feedback

Properties of the instability include the following:

- Thresholding
- Modulation of cavity amplitudes in-antiphase
- Frequency around 160 Hz, but varies with parameters
- Slow growth: over minutes at 12 MeV, secs at 17 MeV
- Final amplitude limited by klystron forward power
- Growth rate rises with accelerating gradient
- Sensitive to individual cavity detunings.
- In-phase AM if the cavities are grossly mis-phased.

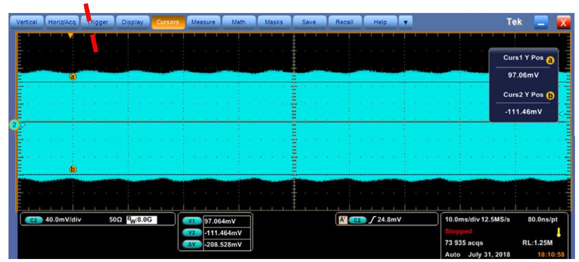
EACA 2nd Cavity Dynamic Lorentz Force Detuning

Make amplitude modulation at definite frequency.
Infer depth of detuning from synchronous phase oscillation



frequency (Hz)	Noise (dBc) without modulation	Bandwidth (Hz)	Modulation coefficient (Hz/mVpp)*
120.0		0.8869	0.0407
35.3	-44.49	0.3765	0.0405
19.3	-47.89	0.1914	0.0182
60.0	-40.26	0.3003	0.0708
21.1	-42.16	0.2	0.0192
300.1	-49.55	0.6022	0.0358
180.1	-54.21	0.9692	0.0208
49.9		0.4	0.055
29.6	-47.24	0.5	0.0279
47.9	-44.86	0.3	0.0508

- Deliberate AM excitation at 120 Hz.
- Response is detuning depth.
- Repeat at various modulation frequencies of significance (Rhode & Schwarz strength ordering)



Modulation depth = 5.25% of gradient

Way Forward – microphonics

- Vibration damping – water pumps & pipes, waveguides, flex vacuum lines, etc.
- Investigate 4K/2K cryo insert

Way Forward - ponderomotive

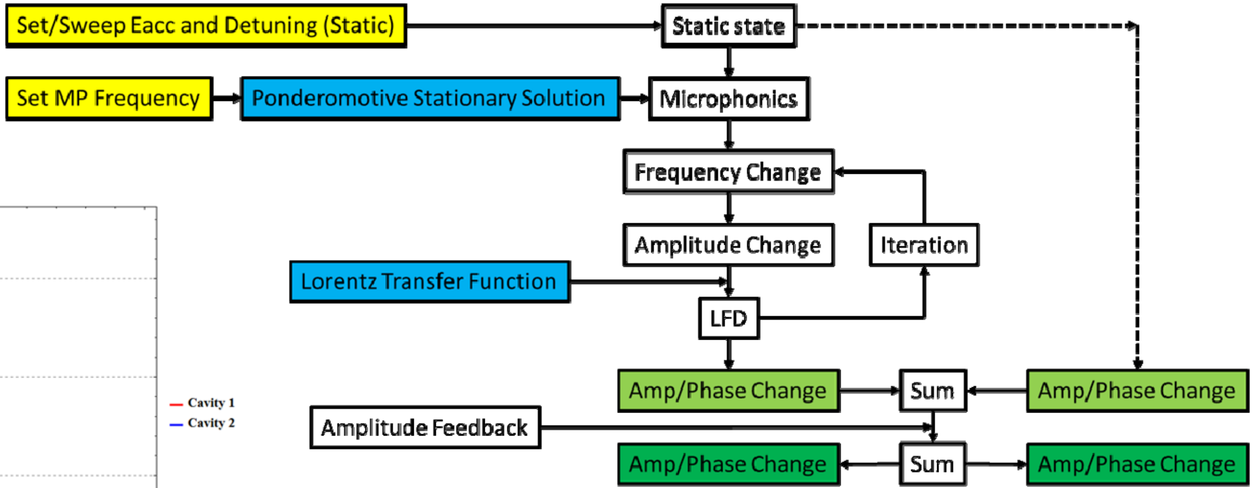
- Improved diagnostics, increase EPICS data rates from 10’s to 100’s Hz
- Conceivable that problem resolves itself – operate closer to zero reflected power
- Dynamic LFD measurements below threshold for dual cavity operation should help us understand the ponderomotive instability.
- Single cavity (1 alone) not likely to give us insight.
- However, they do provide quantitative parameter inputs for simulations

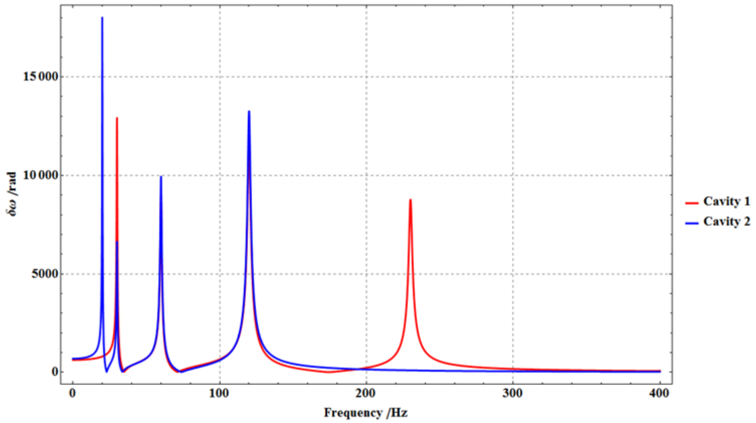
Acknowledgement

Majority of RF measurements made by Yanyun Ma (TRIUMF)

See TUPO020

Computer Simulations of Ponderomotive Instability with Vector Sum Control (Zhongyuan Yao)

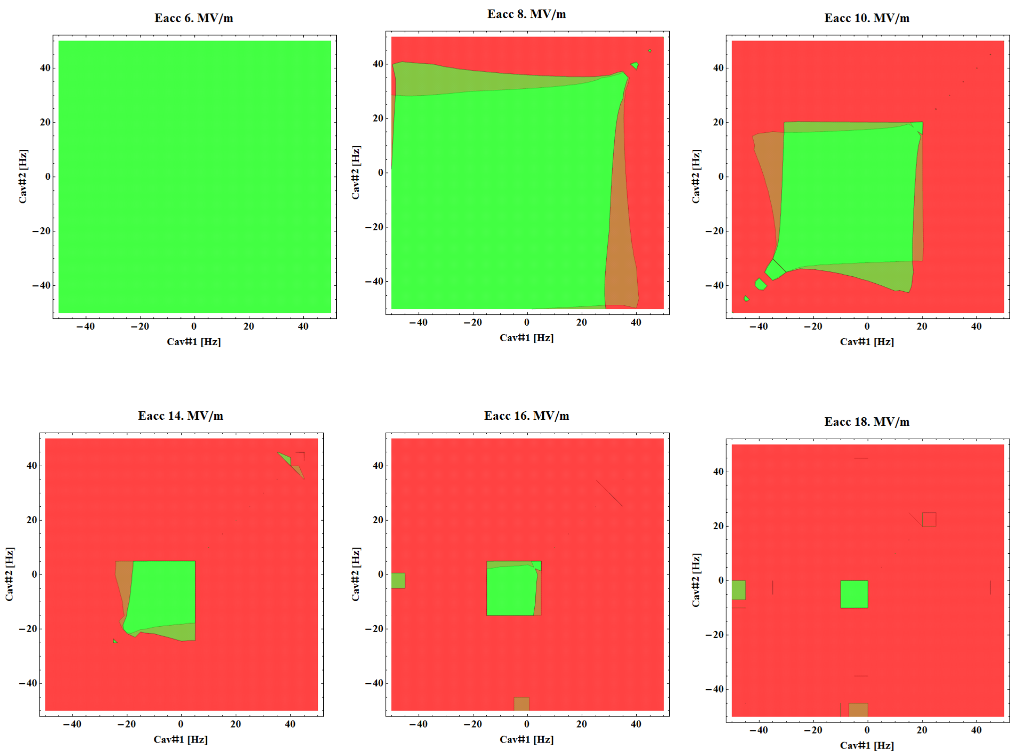


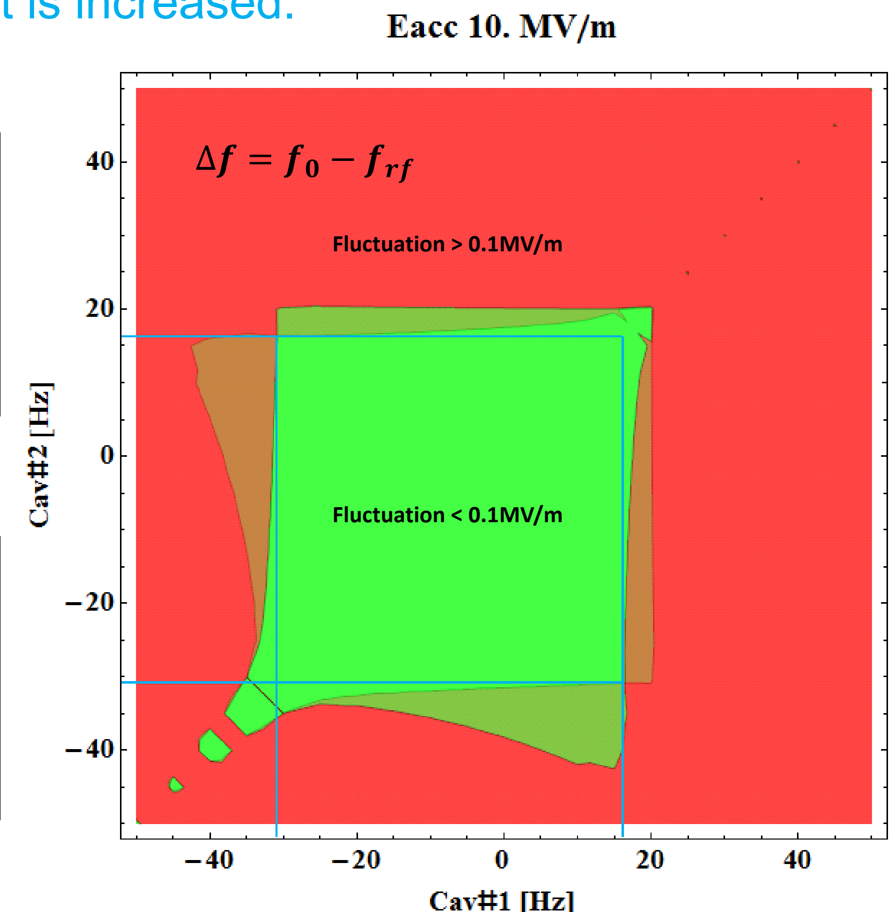


Example mechanical mode spectra of the two cryomodules

- Time domain simulation for given microphonic resonance frequencies
- Sweep the static detuning conditions
- See what happens.
- Power Divider F/B not included

Looking for a threshold. Operating area (in detuning space) shrinks to zero as the gradient is increased.



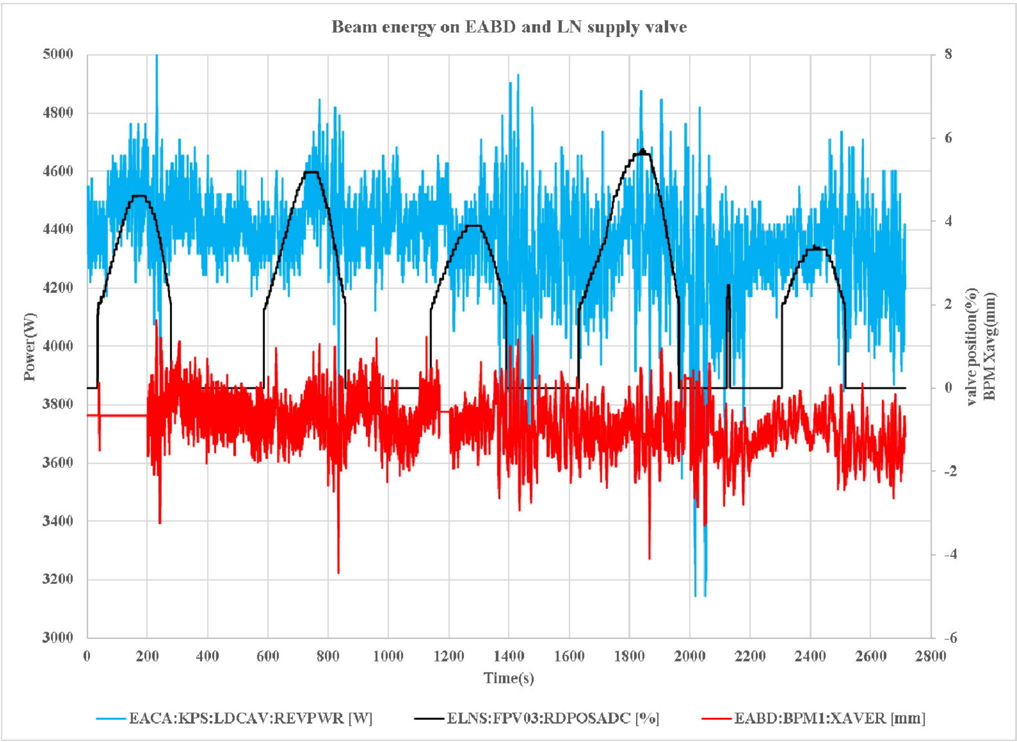


TRIUMF

High lights of the 2018 E-linac commissioning include:

- Stable operation of EGUN and entire cryogenic system for several months
- Beamline equipment and EPICS controls well behaved and supportive of rapid advancement from EINJ to EHDT beam dump
- EINJ operation with relative stability of 0.1%
- No discernible transverse or longitudinal halo in EMBT
- EMBT/D beamline equipment commissioned
- EMBD/T MPS commissioned
- 2-cavity operation of EACA
- 25.2 MeV beam at EABD momentum analysis station
- EHAT beamline equipment commissioned
- EHDT beam dump functional and interlocks in place
- Electron beam threaded to EHDT dump
- Introduced concept of controls "Optics Lock" to facilitate transition from tuning to commissioning
- Confirmation of EINJ entrance mis-steering
- Identification of microphonic noise sources in e-hall
- Identification of LN2 disturbances to EACA & EINJ
- Discovery of ponderomotive instability in EACA SRF

EACA Liquid Nitrogen Supply Valve and Beam Stability

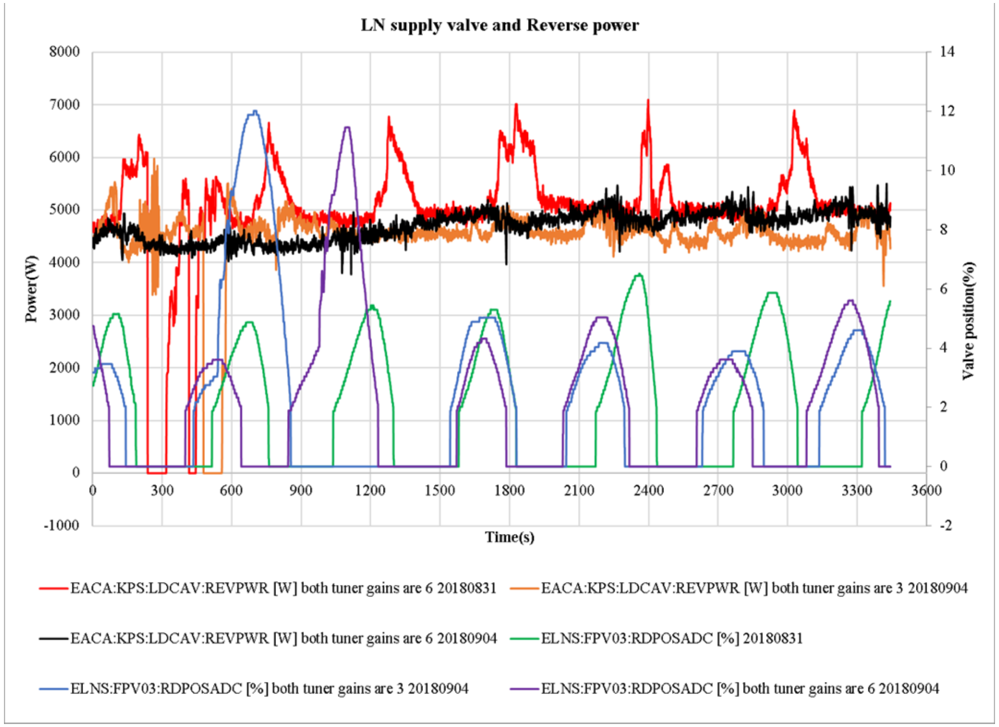


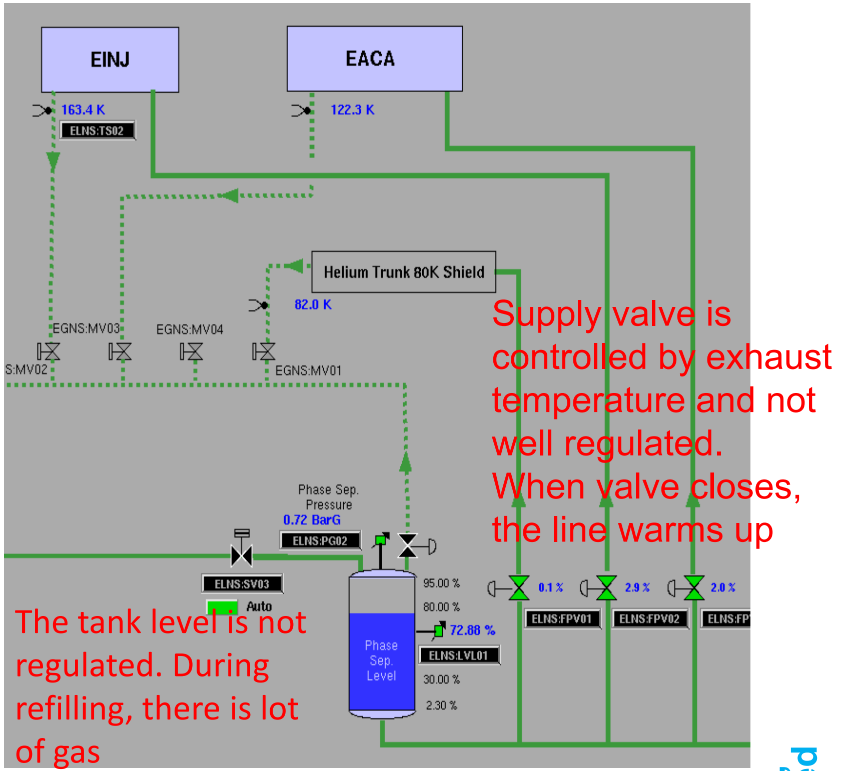
- Long term disturbances do not appear in the noise spectra – because these data are acquired over relatively short time scales.
- As it transpires, long-term quasi-periodic disturbances can be even more serious to RF regulation than the microphonics.

Xavg: 1mm means 0.133%
Hence LN2 valve bursts can change beam energy by few 0.1%

Discovery, accelerated

E-linac LN2 Supply Valve & Beam Stability

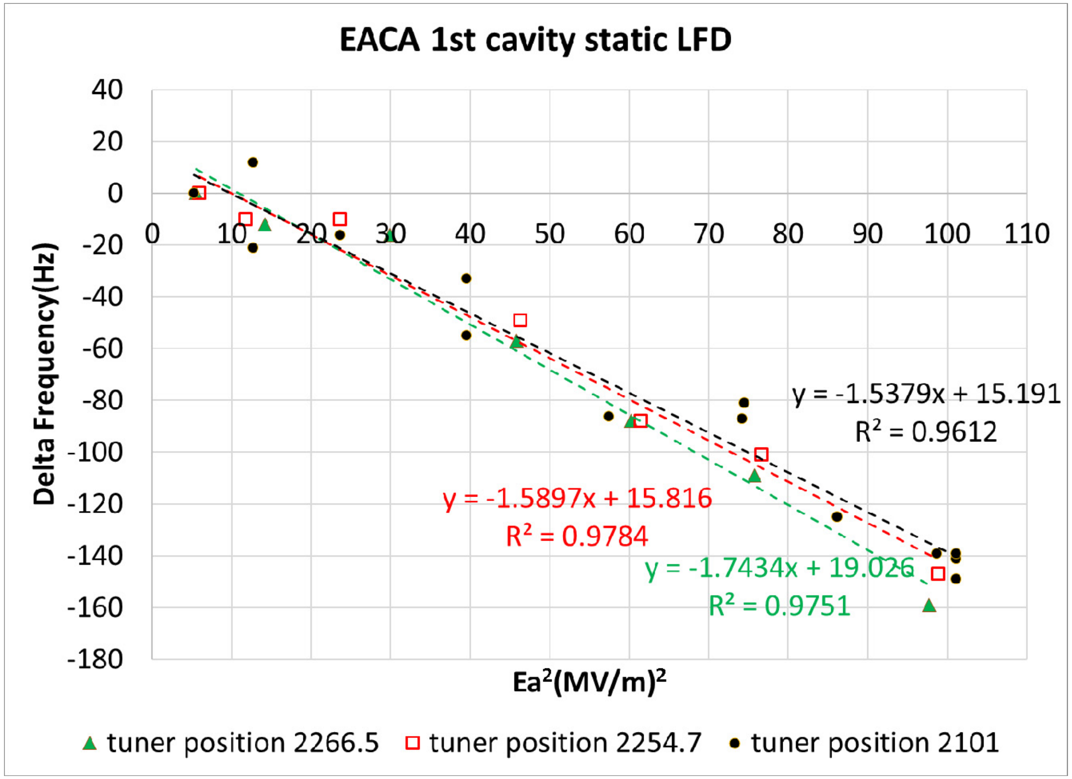




We decreased LN exhaust temperature from 130 to 120K.
The reverse power becomes more stable than before.
But running cooler also means a deeper LN2 filling cycle.
So this is a "teaser" rather than a "cure".

Note, there may be some correlation of the ponderomotive instability parameters with the LN2 disturbances

EACA 1st cavity static Lorentz Force Detuning vs different tuner positions – 2018-08-28



This is with tuner stressed. When tuner is released, value becomes ~ -2.59Hz/(MV/m)^2