Investigation of Plasma Processing for Coaxial Resonators

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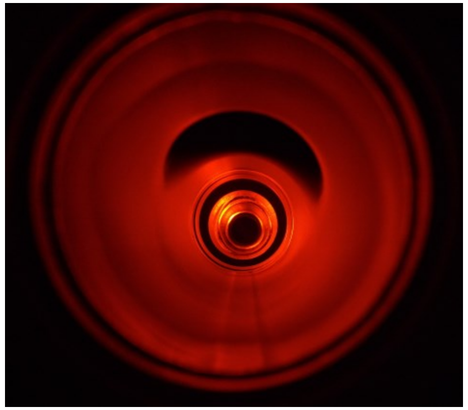

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Topics

- Introduction
- Plasma processing development
- Plasma observations
- Cold test results
- Fundamental Power Coupler (FPC) integrity
- Conclusion

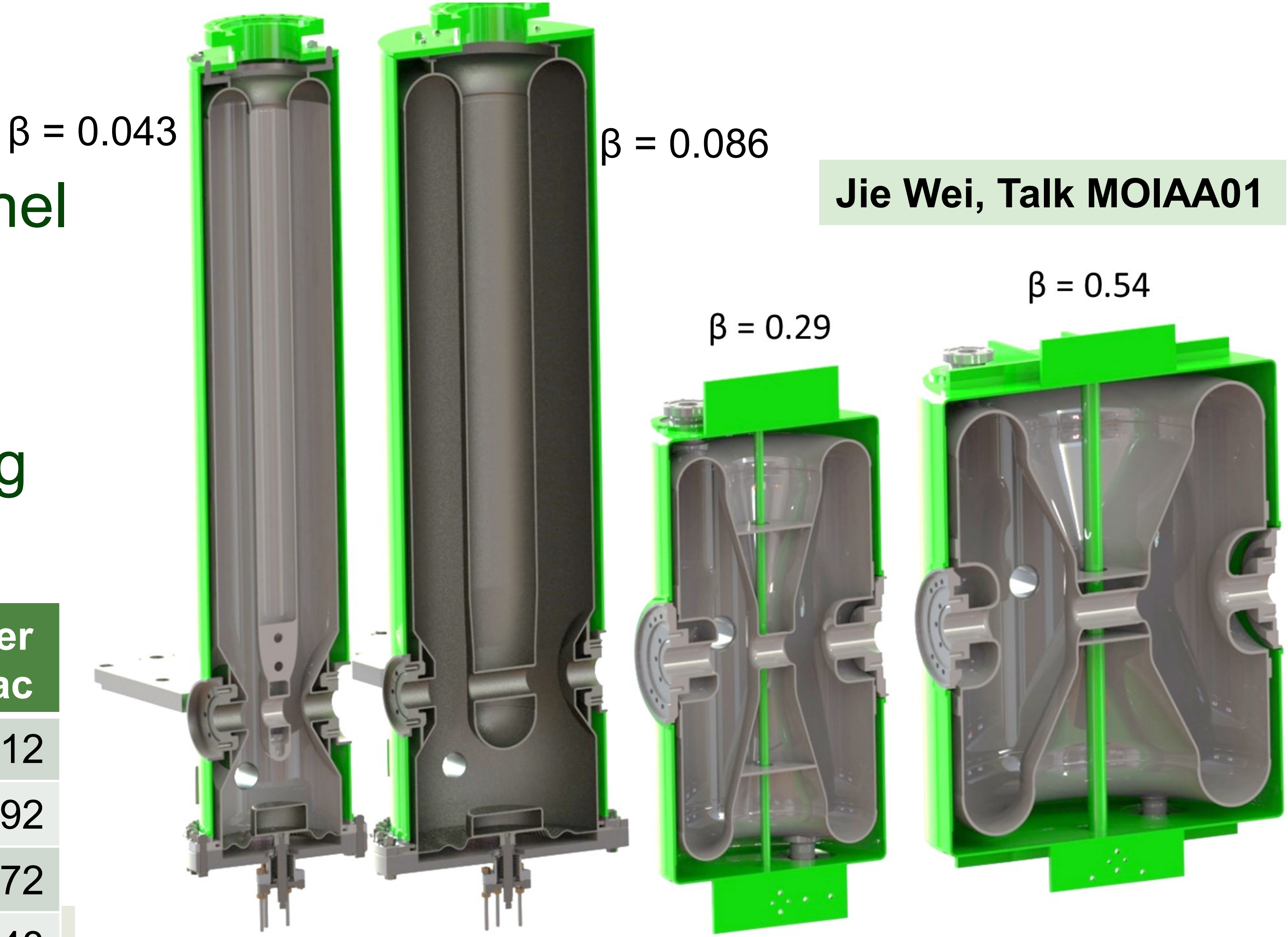
Introduction: Plasma Processing

- Degradation of SRF cavity performance over time: a concern for long-term accelerator operation
- Traditional refurbishment of a cryomodule: labor-intensive, costly, and time-consuming
- In-situ plasma processing: developed by several Labs over the past few years, with promising results; first demonstrated in an accelerator tunnel at SNS

Introduction: FRIB

- Quarter- and Half-wave resonators (QWR, HWR)
- Total: 324 cavities in the tunnel
- In operation for users since May 2023
- Pro-active plasma processing program in progress

Jie Wei, Talk MOIAA01



Beta / Type	Number in Linac
0.043 / QWR	12
0.086 / QWR	92
0.29 / HWR	72
0.54 / HWR	148

Plasma processing development for FRIB: Challenges and Steps

Challenges

- Weak input coupling: a lot of fundamental power coupler (FPC) mismatch at room temperature
- Difficult to see cavity interior through viewports

Development Steps

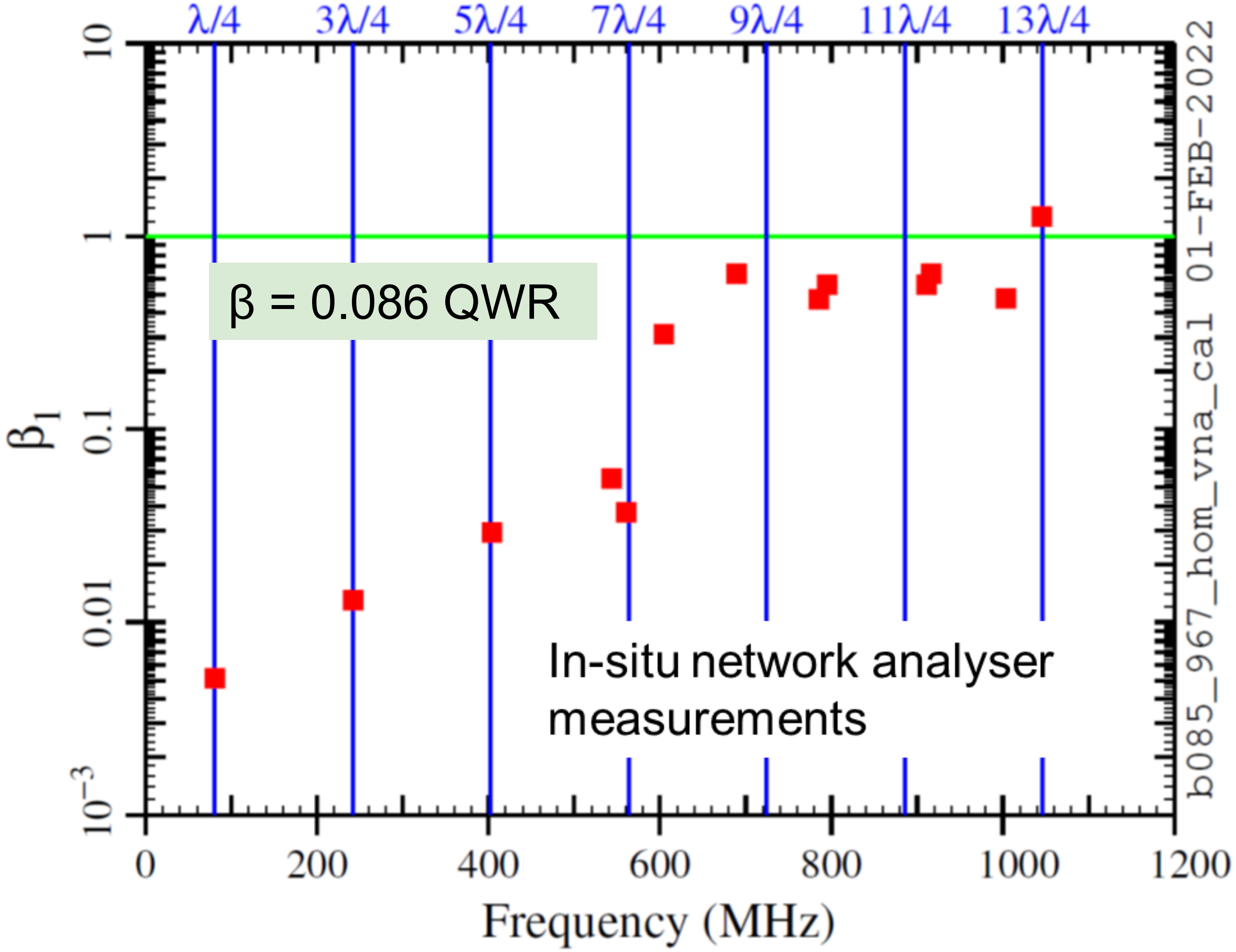
Cavity β	0.043	0.086	0.29	0.54
Step	**Started?**			
1 Feasibility study	yes	yes	yes	yes
2 Plasma with custom input coupler		yes		yes
3 Cavity cold test before and after		yes		yes
4 Plasma with FPC		yes		yes
5 Cavity cold test before and after		yes		yes
6 Repeat 4 & 5 without venting in between				
7 Repeat 4 & 5 for offline **cryomodule**				

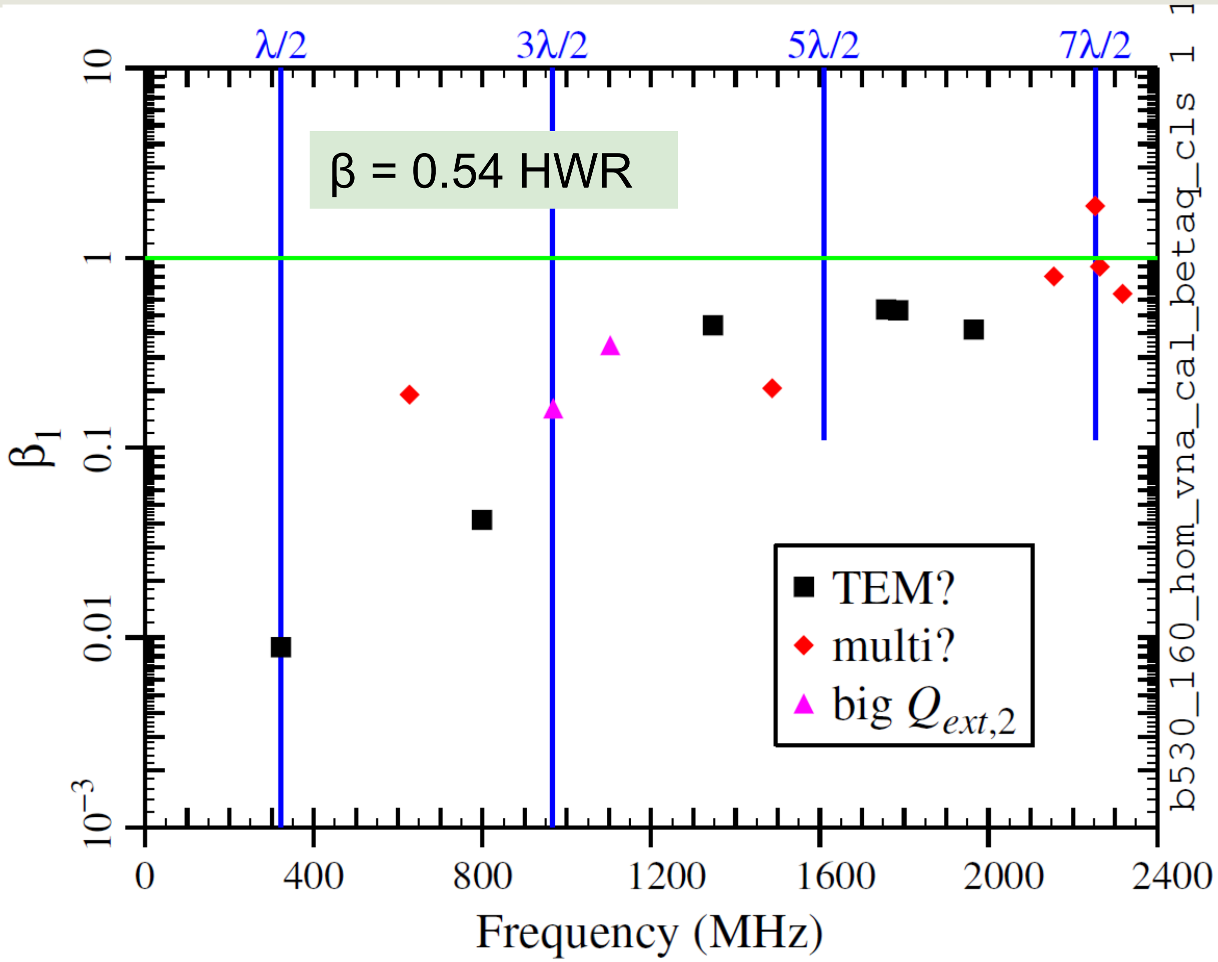
Warm Cavity: FPC is mismatched for fundamental mode

Cavity β	0.043	0.086	0.29	0.54
Cavity Q_0	$2\cdot10^3$	$3\cdot10^3$	$6\cdot10^3$	$9\cdot10^3$
Min $Q_{ext,1}$	$1\cdot10^6$	$1\cdot10^6$	$3\cdot10^5$	$8\cdot10^5$
$\beta_1 = Q_0/Q_{ext,1}$	$2\cdot10^{-3}$	$3\cdot10^{-3}$	$2\cdot10^{-2}$	$1\cdot10^{-2}$

- Concern: plasma in FPC rather than the cavity, risk to damage the FPC
- Alternative approach: drive plasma with a higher-order mode (HOM) using FPC, as developed by Fermilab for spoke cavities

FPC mismatch for fundamental vs HOM





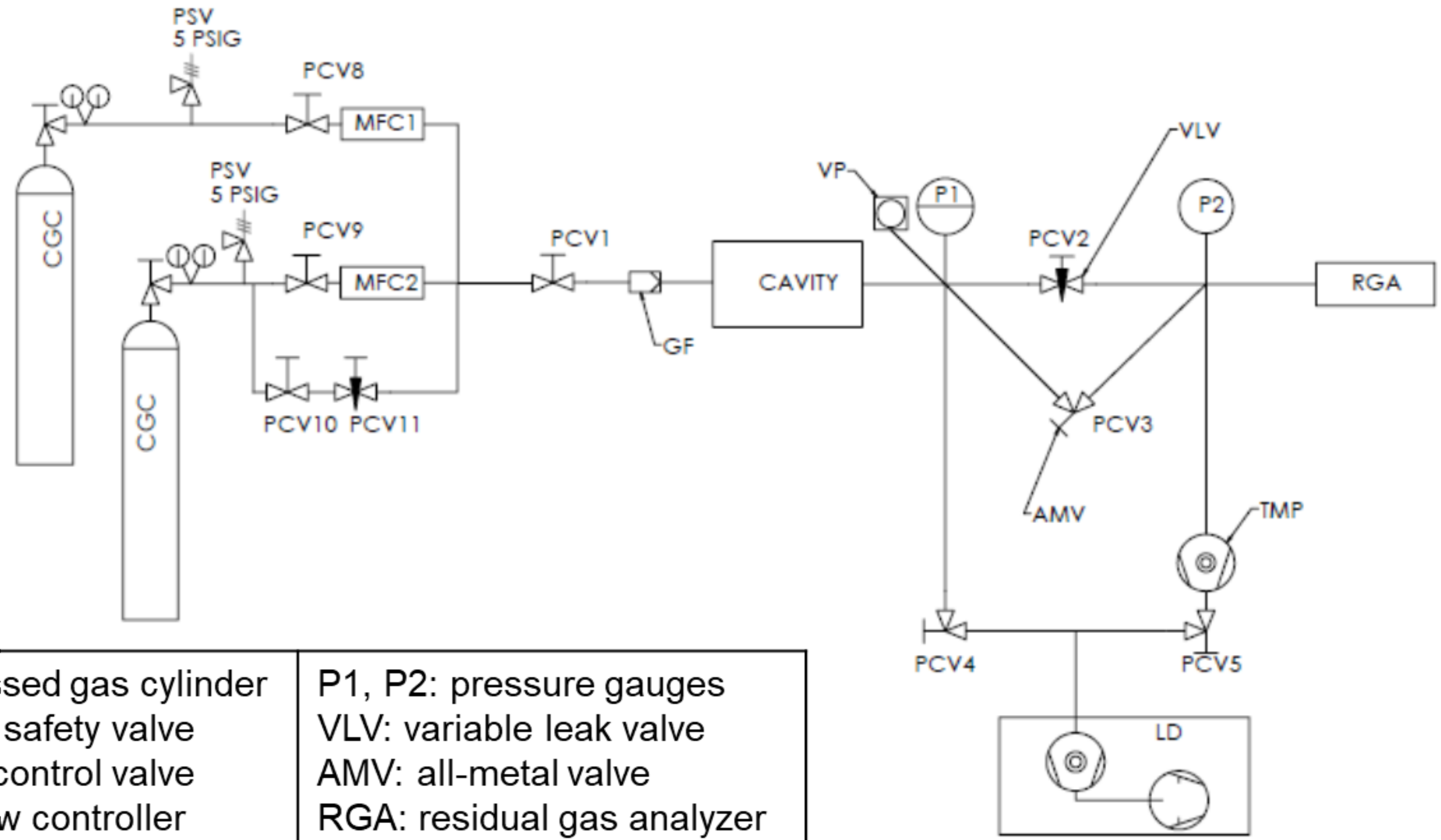
Less FPC mismatch as *f* increases

Plasma Processing Development

- Using FRIB cavities (leftover from production or being produced for spares)
- Clean room assembly, but must vent between plasma processing and cold tests
- Custom input antenna or spare FPC to drive plasma

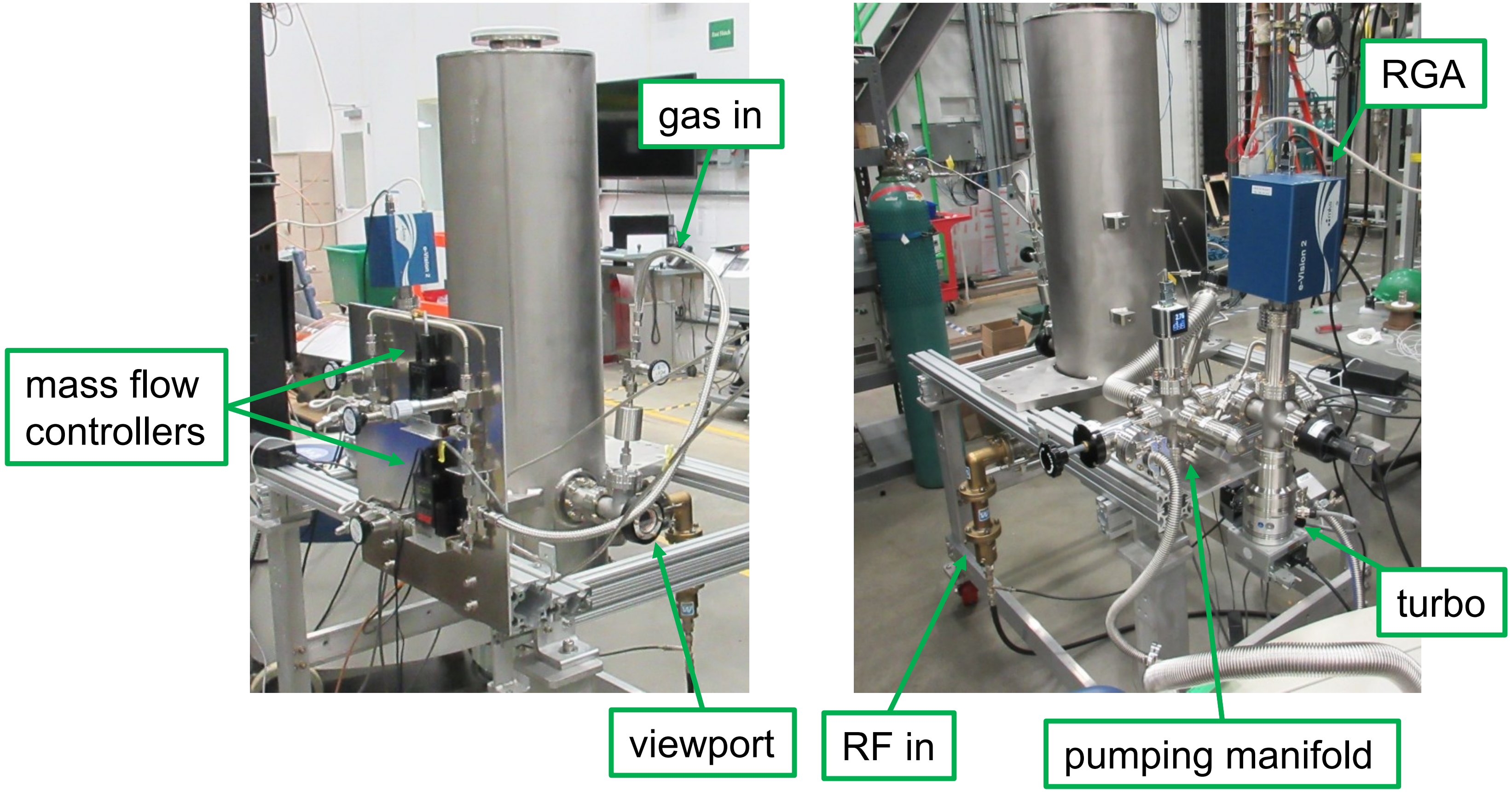
Gas system

- Plasma: neon with a few % oxygen, ~100 mtorr



CGC: compressed gas cylinder	P1, P2: pressure gauges
PSV: pressure safety valve	VLV: variable leak valve
PCV: process control valve	AMV: all-metal valve
MFC: mass flow controller	RGA: residual gas analyzer
GF: gas filter	TMP: turbo-molecular pump
VP: viewport	LD: leak detector cart

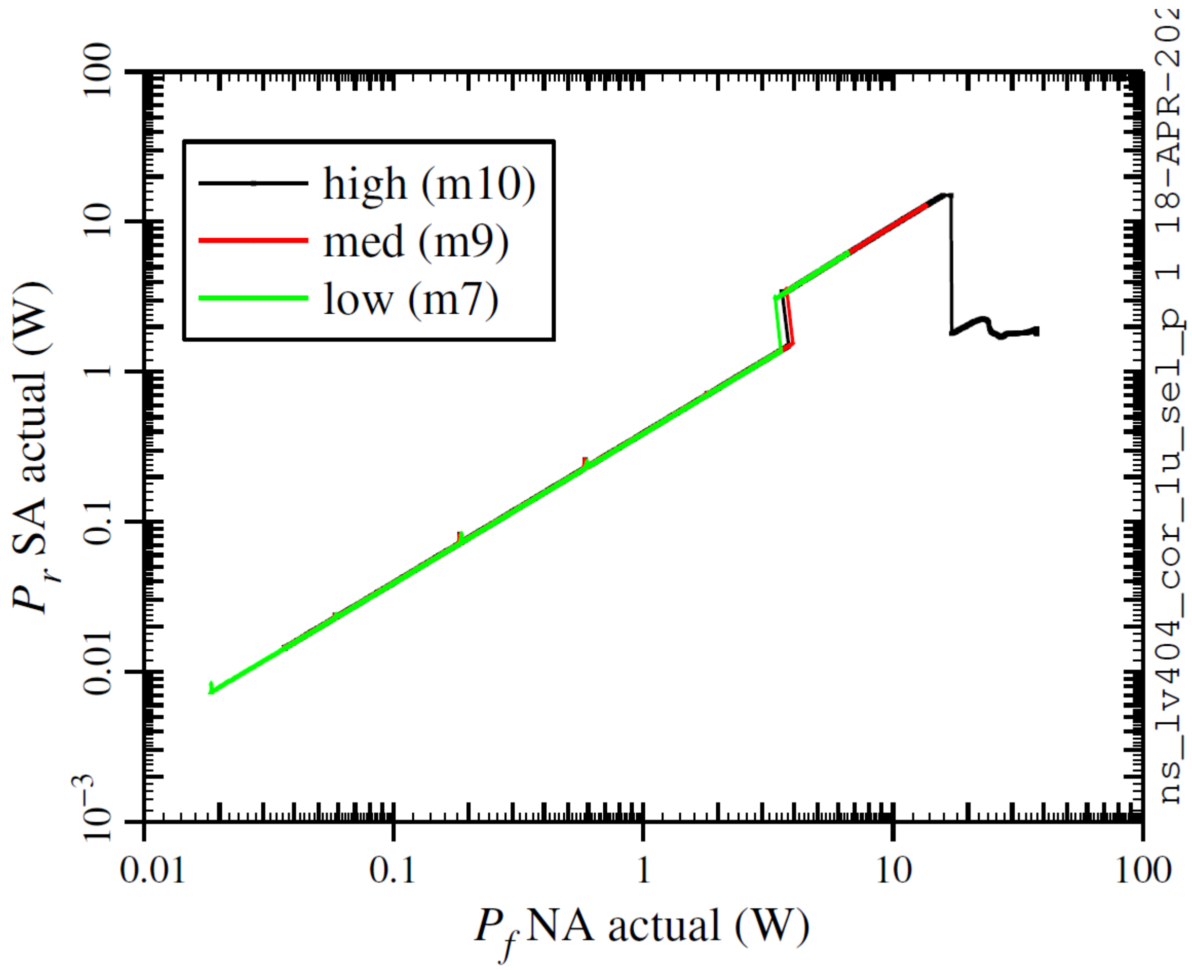
QWR with FPC

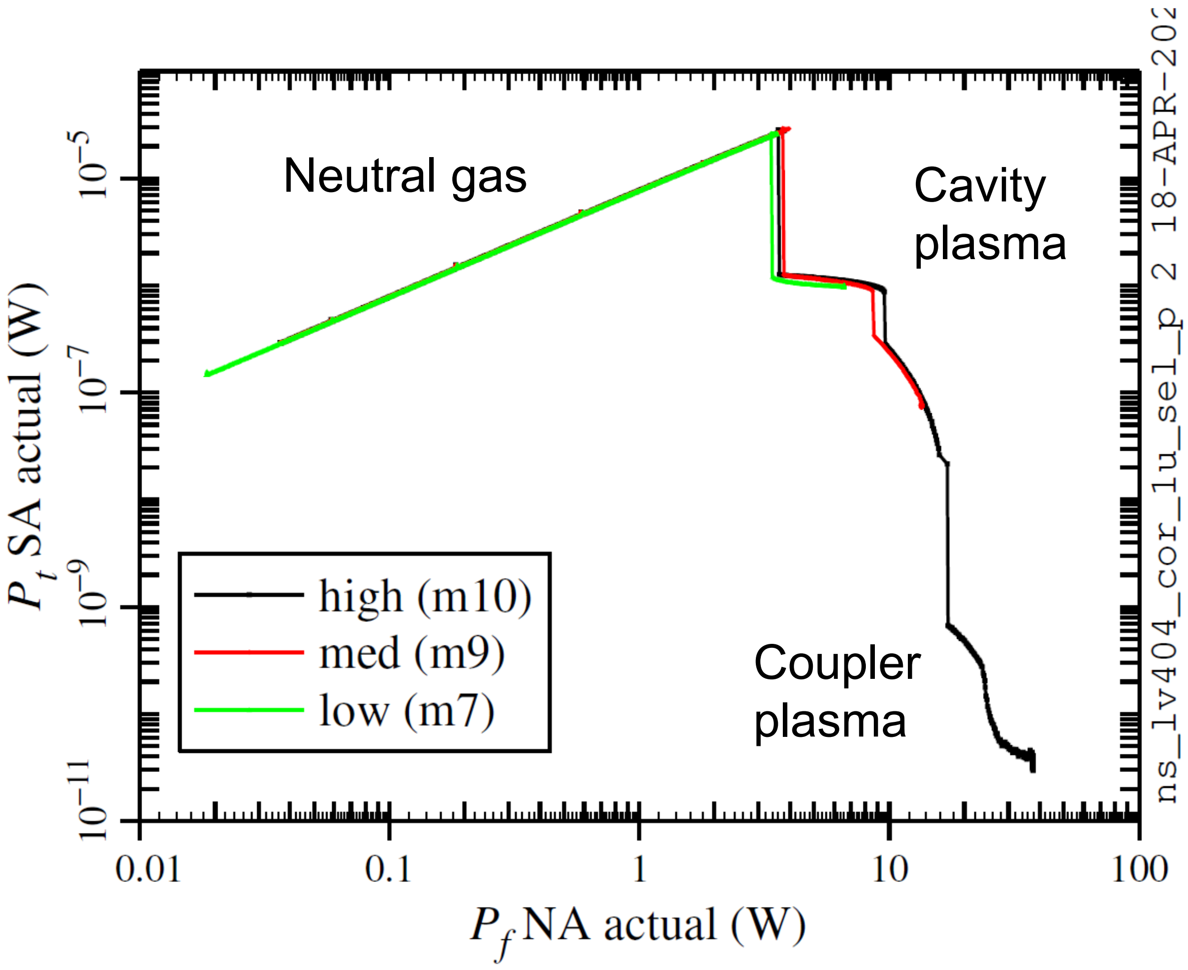

gas in
mass flow controllers
viewport
RGA
turbo
RF in
pumping manifold

Plasma Excitation and Monitoring

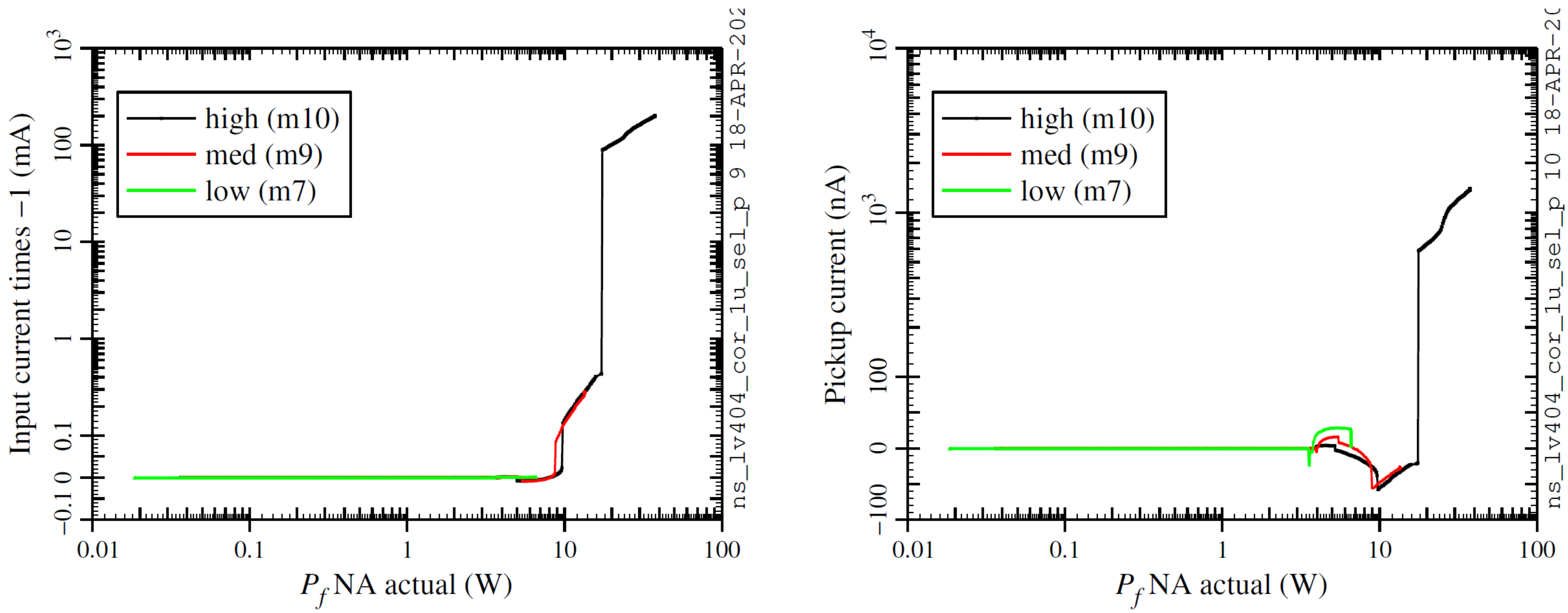
- "Multi-mode" monitoring: network analyzer to look for upward shift in resonant frequency due to plasma; raise drive frequency, and iterate; similar to methods used at Fermilab and JLab
- Monitor light and DC current from RF antennae

RF Measurements Example: QWR with custom antenna, TEM 5λ/4, fixed drive frequency



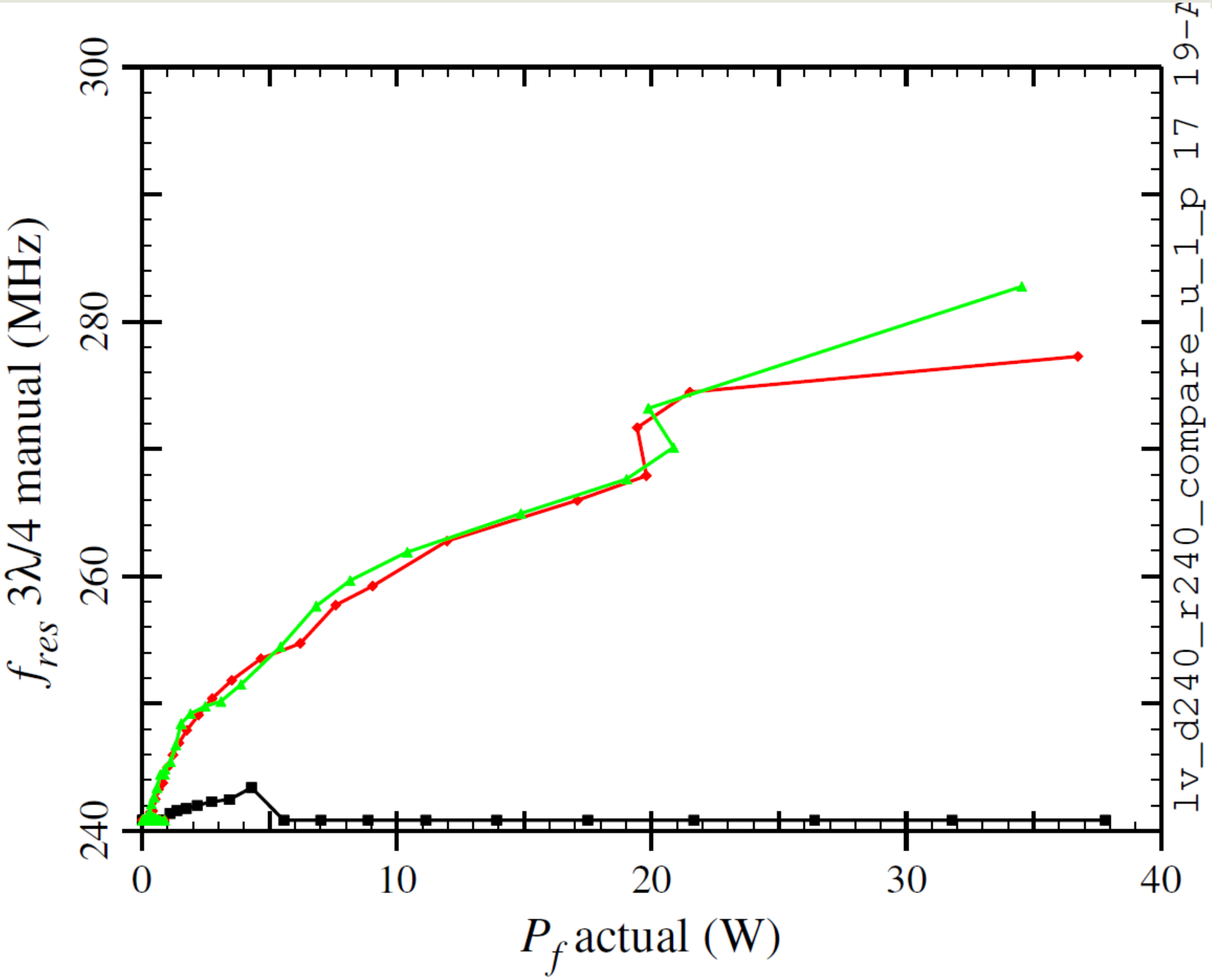


Current Monitoring Example: QWR with custom antenna, TEM 5λ/4, fixed drive frequency



QWR + custom antenna example: Const drive *f* vs shifted drive *f*

- Drive: TEM 3λ/4
- Monitor with network analyzer: same mode
- See very large shift for this mode; less extreme for other modes



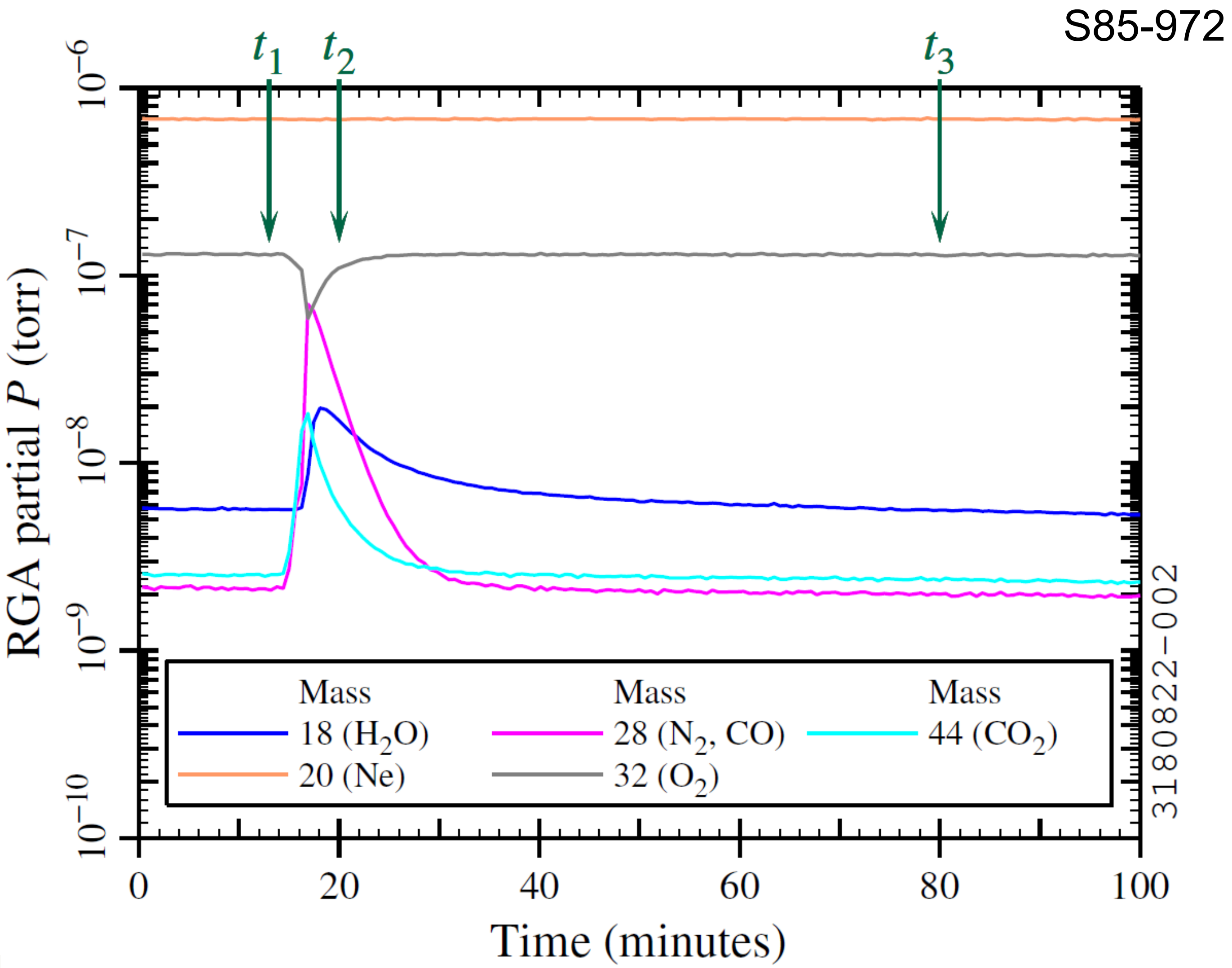
RGA measurements: QWR with FPC Example: Day 1 of Plasma

t_1 = start RF power ramp-up

t_2 = reduce power after plasma ignition

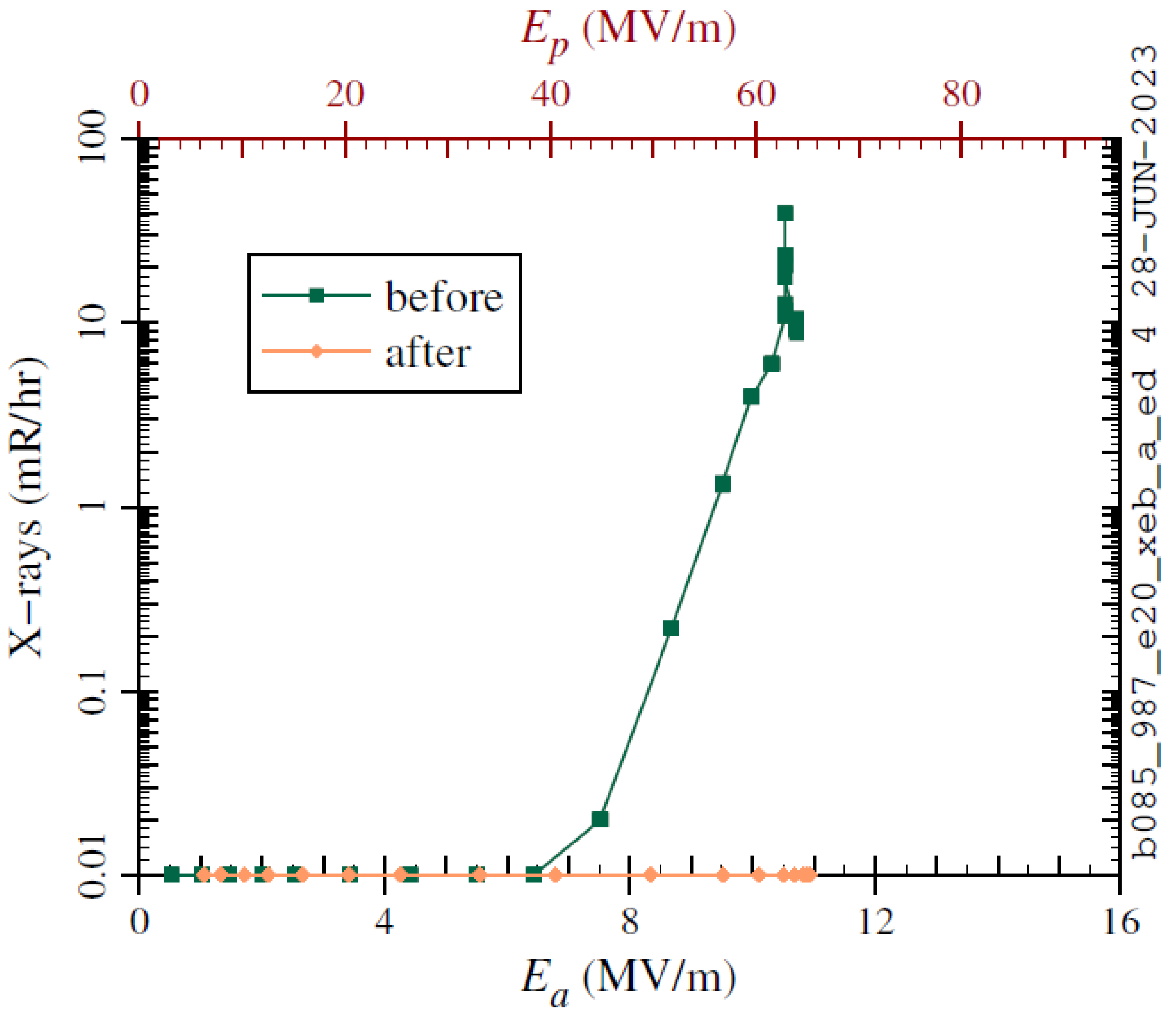
t_3 = RF ramp-down and turn-off

- When plasma ignited:
  - Increase in CO_2, CO, H_2O
  - Decrease in O_2
- Signals are short-lived
- Peaks return when plasma is re-ignited the next day, as reported by SNS
- RGA signals decrease with repeated iterations



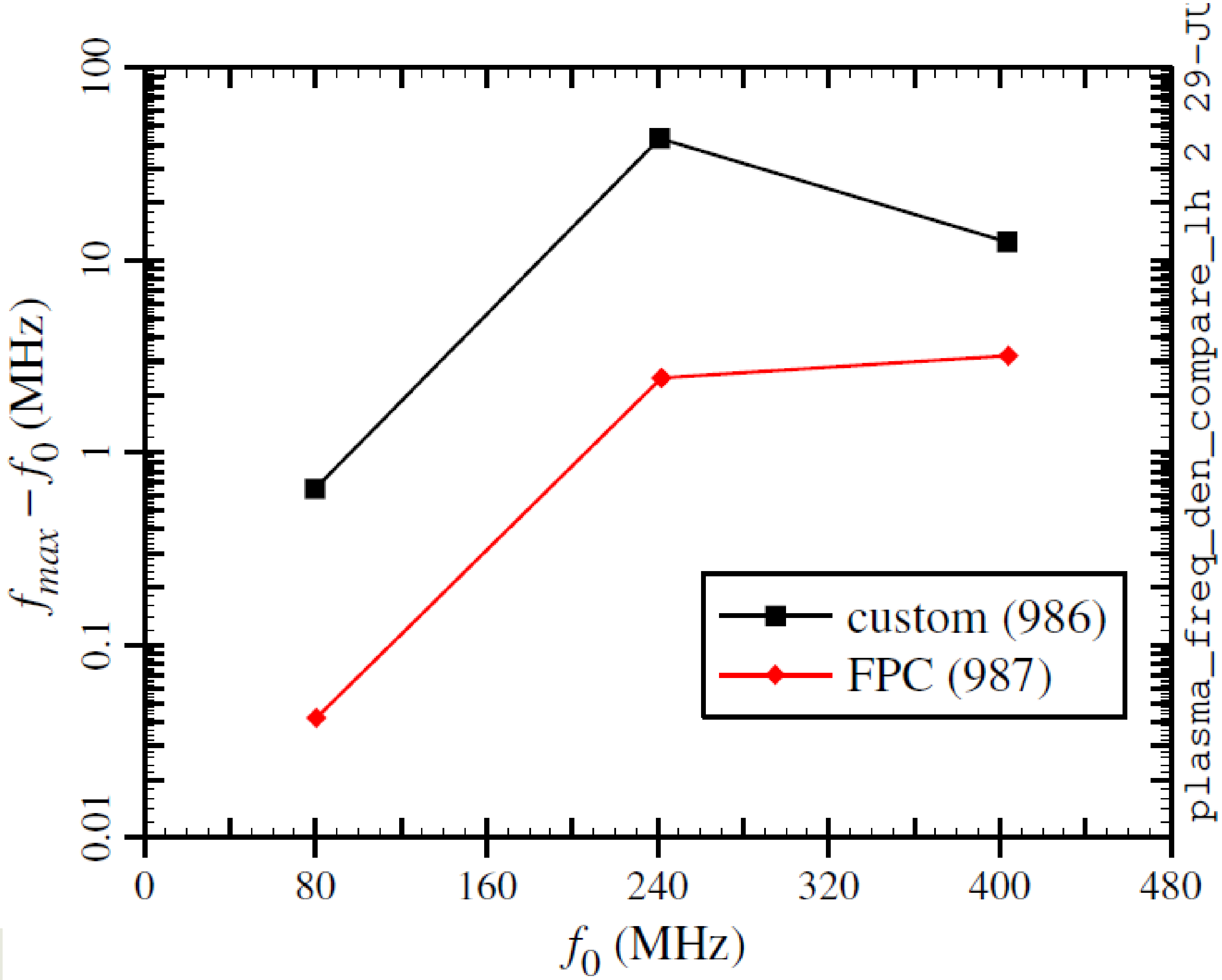
Before-and-after cold tests example: QWR with FPC

- 2 K measurements show significant reduction in field emission X-rays after plasma processing (S85-987)
- Little change in Q_0 after plasma processing



Choice of Drive Mode

- Frequency shift due to plasma is limited by coupler ignition threshold
- Simple-minded approach: pick the mode with the highest plasma density as inferred from frequency shift



Plasma processing tests

	Date	S/N	Input coupler	Harmonic number	Before & after cold tests?	Notes
β = 0.086 QWR	May 2021	986	custom	1	Yes: better	
	May-Jun 2021	986	custom	1	Yes: worse	Possible leak in gas sys
	Jul 2021	986	custom	1	Yes: better	(after cold test: FE worse after low-*T* bake)
	Oct 2021-Jan 2022	967	FPC	1, 3, 5	Yes: better	Devel: n = 1, 3, 5; f sweeps; process: n = 5
	Feb-Mar 2022	979	FPC	5	Yes: better	
	May-Jun 2022	972	FPC	5	Yes: similar	
	Jul 2022-Jan 2023	986	custom	1, 3, 5	Yes: better	Devel: n = 1, 3, 5; f sweeps; MMM; process: n = 1
	May-Jun 2023	987	FPC	1, 3, 5	Yes: better	Devel: n = 1, 3, 5; f sweeps; MMM; process: n = 1
β = 0.54 HWR	May 2020-Mar 2021	150	custom	1	No	Devel; vary pressure, gas types (Cu sputtering)
	Feb-Mar 2023	155	custom	1, 3	Yes: worse	Devel: n = 1, 3 (& 5); MMM; process: n = 1 new recipe
	Apr 2023	096	custom	1	Yes: similar	n = 1 new recipe
	Jun 2023-	096	FPC	1, 3, …	In progress	Devel

MMM: Multi-mode monitoring of resonant frequencies

Plasma processing tests

	Date	S/N	Input coupler	Harmonic number	Before & after cold tests?	FE onset before (MV/m)	FE onset after (MV/m)	
β = 0.086 QWR	May 2021	986	custom	1	Yes: better	5	8	
	May-Jun 2021	986	custom	1	Yes: worse	8	6	
	Jul 2021	986	custom	1	Yes: better	6	8	
	Oct 2021-Jan 2022	967	FPC	1, 3, 5	Yes: better	6.4	10	
	Feb-Mar 2022	979	FPC	5	Yes: better	7	>10	
	May-Jun 2022	972	FPC	5	Yes: similar	6.6	7	
	Jul 2022-Jan 2023	986	custom	1, 3, 5	Yes: better	6	9	
	May-Jun 2023	987	FPC	1, 3, 5	Yes: better	7	≥11	
β = 0.54 HWR	May 2020-Mar 2021	150	custom	1	No			
	Feb-Mar 2023	155	custom	1, 3	Yes: worse	4.7	3	
	Apr 2023	096	custom	1	Yes: similar	8.2	≥8.4	
	Jun 2023-	096	FPC	1, 3, …	In progress			

FE: field emission

Plasma processing tests

	Date	S/N	Input coupler	Harmonic number	Before & after cold tests?	FE onset before (MV/m)	FE onset after (MV/m)	Plasma Location
β = 0.086 QWR	May 2021	986	custom	1	Yes: better	5	8	Coupler
	May-Jun 2021	986	custom	1	Yes: worse	8	6	Coupler
	Jul 2021	986	custom	1	Yes: better	6	8	Coupler
	Oct 2021-Jan 2022	967	FPC	1, 3, 5	Yes: better	6.4	10	Coupler
	Feb-Mar 2022	979	FPC	5	Yes: better	7	>10	Coupler
	May-Jun 2022	972	FPC	5	Yes: similar	6.6	7	Coupler
	Jul 2022-Jan 2023	986	custom	1, 3, 5	Yes: better	6	9	Coupler
	May-Jun 2023	987	FPC	1, 3, 5	Yes: better	7	≥11	Cavity
β = 0.54 HWR	May 2020-Mar 2021	150	custom	1	No			Coupler
	Feb-Mar 2023	155	custom	1, 3	Yes: worse	4.7	3	Cavity & Coupler
	Apr 2023	096	custom	1	Yes: similar	8.2	≥8.4	Cavity
	Jun 2023-	096	FPC	1, 3, …	In progress			Cavity & Coupler

MMM: Multi-mode monitoring of resonant frequencies

FPC plasma ignition, plasma sputtering

- Plasma ignition field increases ~ linearly with frequency
- At low frequency, cavity plasma ignition happens at low field with dim light and weak RGA response
- Some time and effort for us to distinguish cavity plasma vs coupler plasma
- Have seen sputtering from Cu antenna onto Nb beam port for 2 HWRs; not seen for QWRs
- Did not see sputtering (so far) if only cavity plasma at P ~ 100 mtorr; more experience needed

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RF port of HWR after coupler plasma (with custom Cu antenna)

Conclusion

- Results so far suggest that **plasma processing has good potential for improving FRIB resonators**; effectiveness may depend on the nature of the contaminants
- More work needed on plasma development for FRIB HWRs
- Method optimization is a work in progress
  - Would like to process with cavity plasma rather than coupler plasma
  - Best mode to drive plasma: HOMs look promising; still under study
  - Optimum processing time?
  - Different groups have explored different variations in methods
- Need to **test plasma processing with a cryomodule**
- Need to **try in the FRIB tunnel**
- Parallel efforts
  - 3D RF model for cavity and coupler fields
  - Apply existing models to predict ignition thresholds
  - Additional diagnostics

Patrick Tutt, Poster WEPWB127

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