Re-evaluating the choice of the Advanced Virgo arm cavity finesse

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History

- Historical choice of high finesse arm cavities (in comparison to initial detectors) was motivated by sapphire as a test mass substrate → not as relevant with choice of fused silica, and new affordability of ultra-low absorption fused silica (Heraeus 3001/3002, less than .3ppm/cm).
- A trade-off study was done ~1 year ago in OSD, with a decision to keep the arm cavity finesse at ~ 900. aLIGO lowered arm cavity finesse from 1250 to 450 in LIGO-T070303-01-D.

Reminder

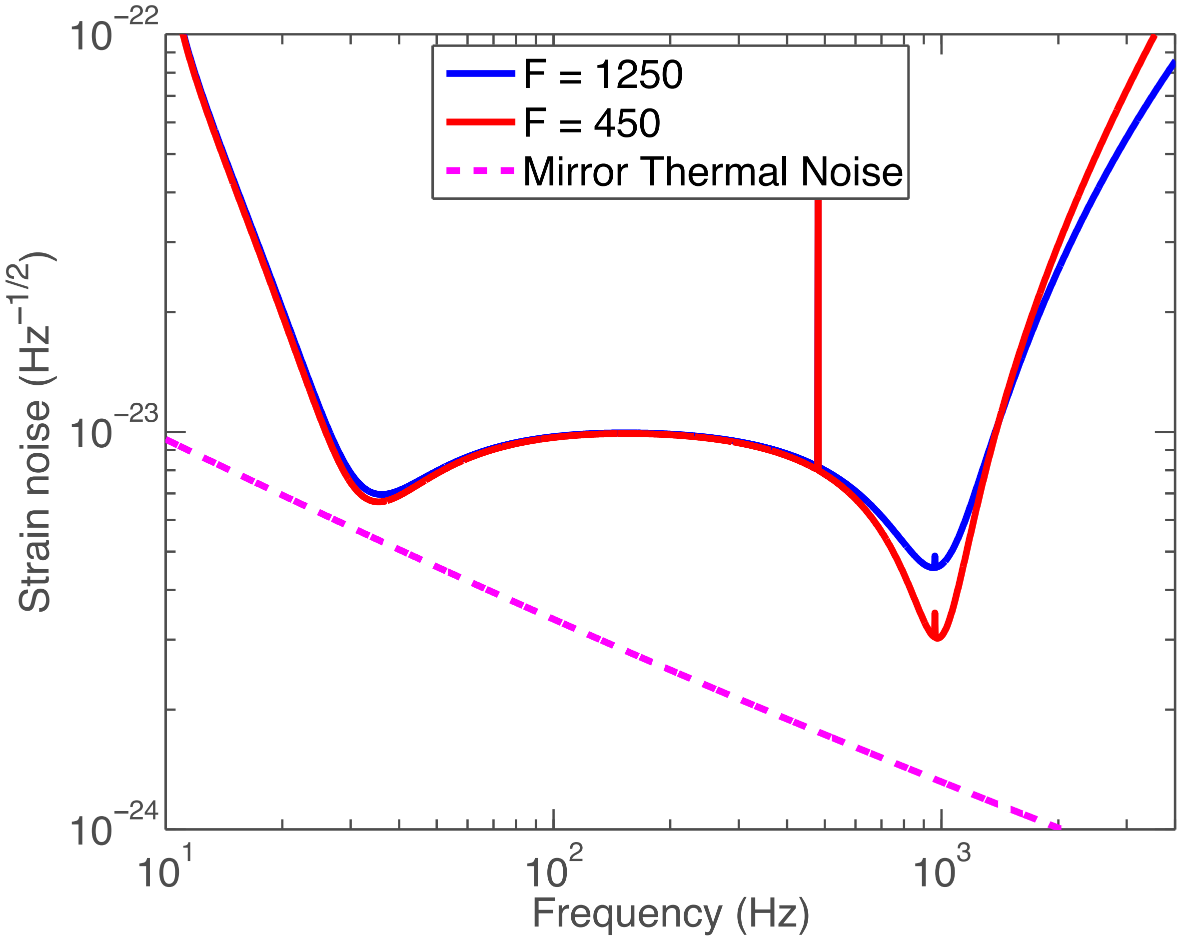
conclusions from the previous trade-off study

factor	***HI/LO finesse favored?***
quantum noise	x
MICH noise	HI
Thermal Load in CITF	HI
PRC losses	HI
SRC losses	LO
coating thermal noise	x
arm cavity losses	x
lock acquisition	x

Quantum Noise (Sensitivity)

- For the most likely quantum noise scenarios (broadband RSE, some detuning), there is not much difference between low and high finesse arm cavities.

- In the event we want a narrowband, high-frequency interferometer, lower-finesse arm cavities will be better, as this will reduce the impact of losses both in the arm cavities and the signal recycling cavity.



plot from LIGO-T070303

Thermal loading in CITF substrates

- Ultra-low absorption fused silica will be used.
- TCS concludes that a recycling gain of G_{rec}=46 is probably not a problem, but it is worth doing a real simulation of BS thermal load to be sure.
- Impact of G_{rec} = 46 on PRM curvature (HR coating absorbtion) should also be neglible (.00004% RoC change for G_{rec} = 23, VIR-0740A-09).

Lock Acquisition

- As a fall-back, "normal" lock acquisition will definitely be easier with lower finesse.
- threshold velocity scales as $v_{max} < \sqrt{\frac{F_{max}\lambda}{2\mathcal{F}m}}$

for a $F_{max} = 40mN, m = 40kg,$
we have $1\mu m/s$ for $\mathcal{F} \sim 450,$
and $0.7\mu m/s$ for $\mathcal{F} \sim 900$

this is still possibly workable

force available in Virgo

Lower finesse is favored for "digital interferometry" schemes.

For "auxilliary laser" schemes with dichroic coatings, finesse should not matter.

Recycling cavity losses

- Excess loss in the PRC favors higher arm finesse. This can be compensated with more laser power or more recycling gain.
- Excess loss in the SRC favors lower arm finesse. This cannot be compensated.

Reminder

conclusions from the previous trade-off study

factor	***HI/LO finesse favored?***
quantum noise	x →LO
MICH noise	HI
Thermal Load in CITF	HI → x
PRC losses	HI
SRC losses	LO
coating thermal noise	x
arm cavity losses	x
lock acquisition	x

Arguments missing from the previous trade-off study

- Signal recycling cavity length noise coupling.
- Sensitivity to arm cavity losses.
- Impact of losses in arm cavities on signal matrix (need input from ISC).
- Laser noise couplings.
- Possible non-signal recycled mode (early run).
- Asymmetric Michelson calibration technique.

Simulation Parameters

- I think the HI finesse is the "reference design"
- Simulations done with looptickle (Optickle)

HI finesse

T_{itm}	.007	
T_{prm}	.046	
T_{srm}	.11	
L_{arm}	3000	m
PRCL	36.439	m
SRCL	35.090	m
f_1	6.17	MHz
f_2	55.5	MHz

LO finesse

T_{itm}	.014	
T_{prm}	.027	
T_{srm}	.20	
L_{arm}	3000	m
PRCL	36.439	m
SRCL	35.090	m
f_1	6.17	MHz
f_2	55.5	MHz

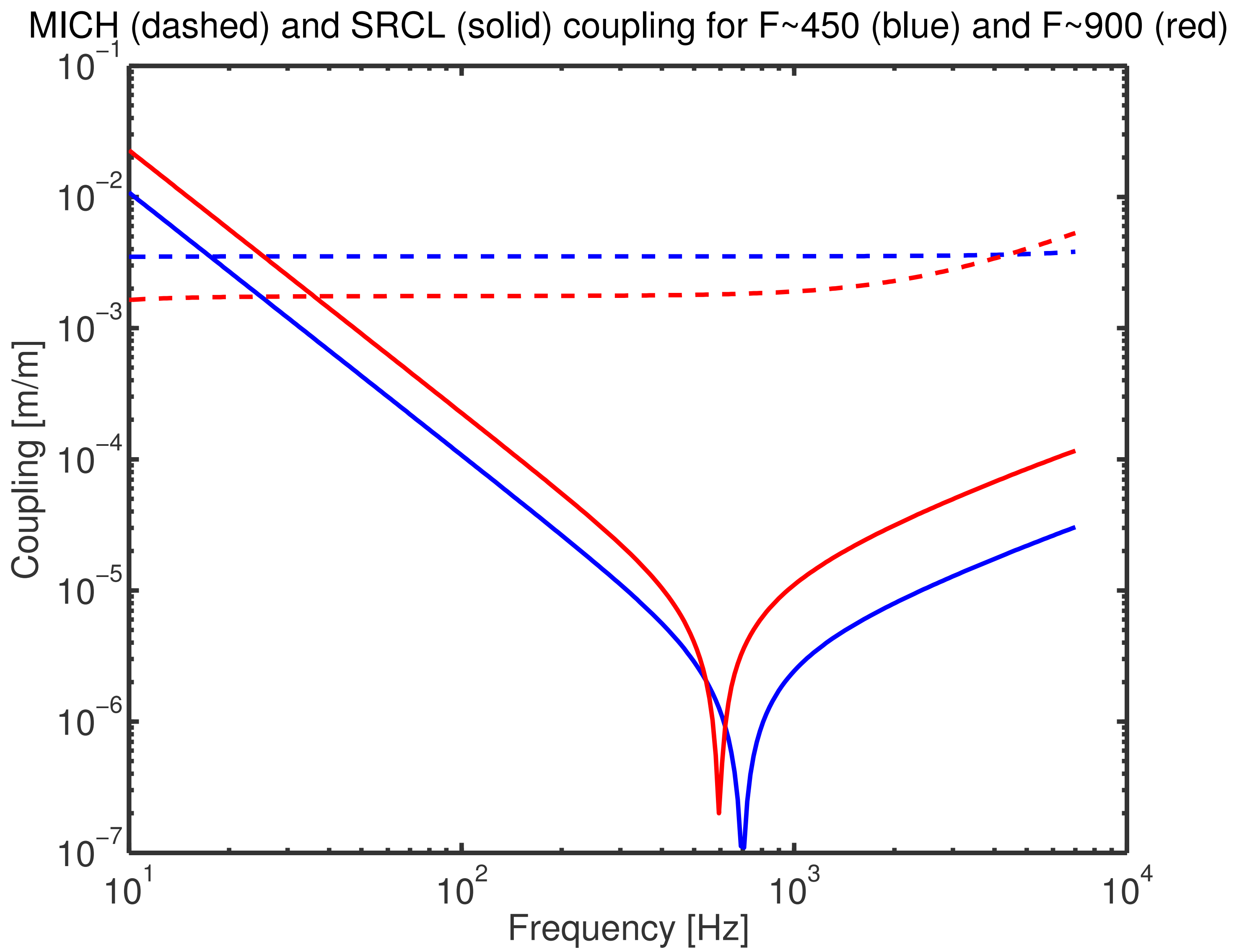
DC readout, DARM offset = 10 picometers

SRCL vs. MICH noise

- SRCL noise coupling and MICH noise coupling behave inversely with arm finesse.

$$MICH \propto \frac{1}{\mathcal{F}}$$

$$SRCL \propto \mathcal{F}$$



broadband RSE

SRCL vs. MICH

- For a proper decision, we need the SRCL and MICH noise budgets → suspension thermal noise, sensing noise, and control noise.
- Sensing noise (from ISC) can be subtracted but not thermal or control noise.
- It is likely that the SRCL will be noisier than MICH (due to 3 separate mirrors contributing to the noise) → lower finesse.

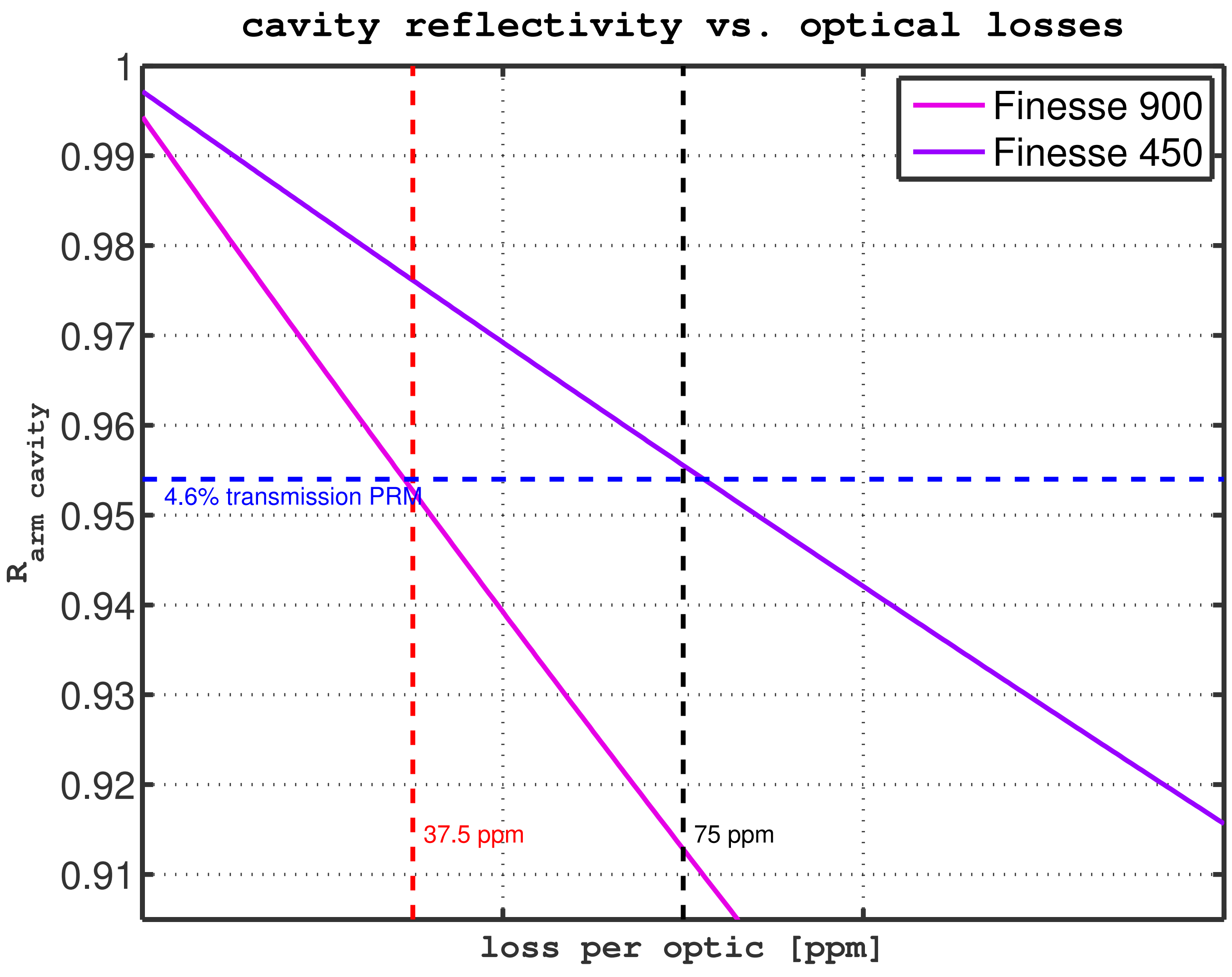
Optical losses in arm cavities

- Design spec for loss is 37.5 ppm per bounce in the arm cavities.
- This means a surface flatness better than 0.5 nm RMS and ZERO point defects.
- Corrective coatings achieved so far correspond to 0.7 nm RMS flatness → 70 ppm per bounce.
- Point defects are still not well understood, but the aLIGO test mass at LASTI appears to not have any -- but don't know if this has been examined in a high finesse cavity.

Losses and cavity reflectivity

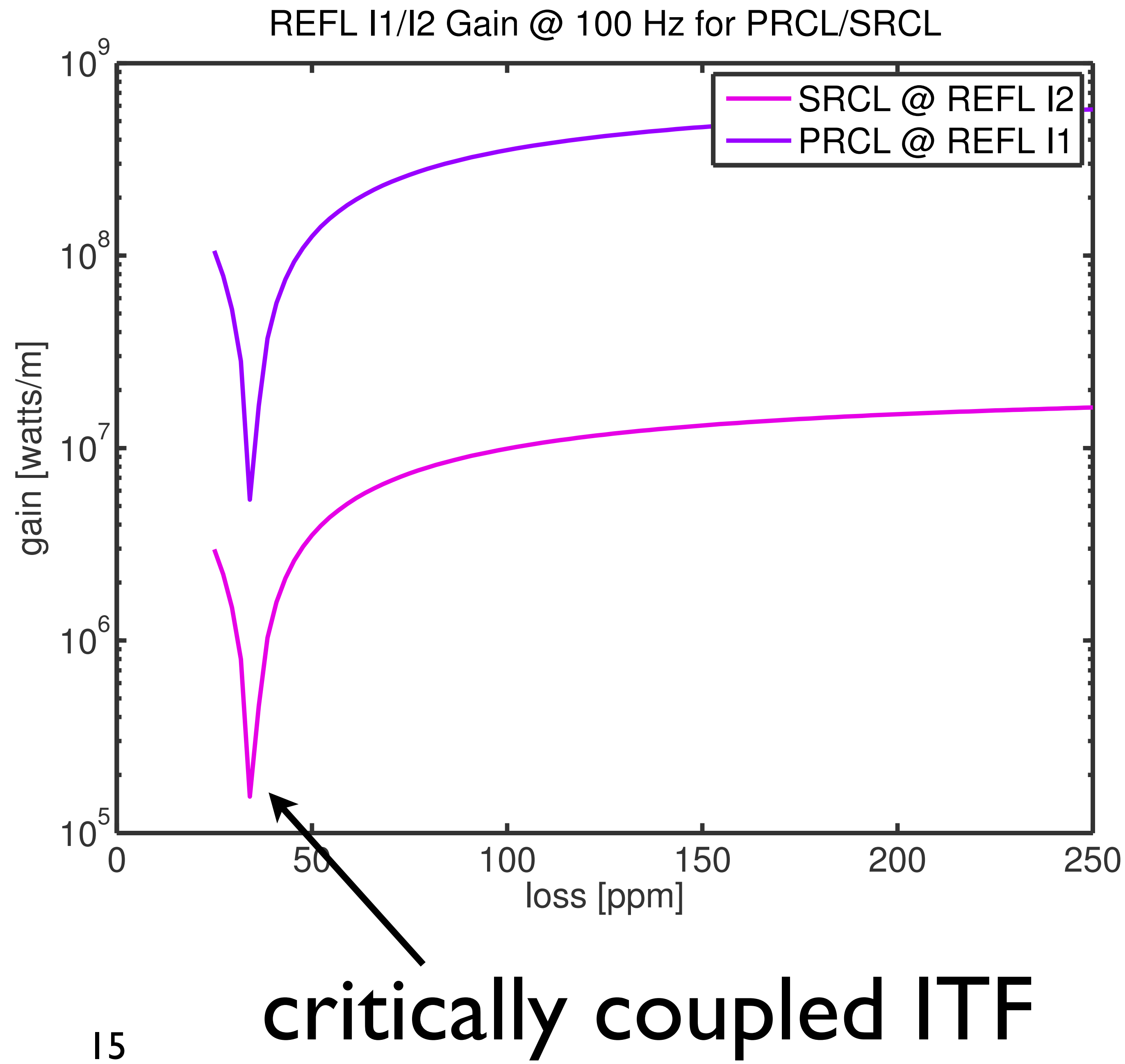
$\frac{dR_{cav}}{dLoss}$ is larger for a higher finesse cavity

In the event of higher than hoped for losses, lower finesse will be an advantage.



Interferometer Power Coupling

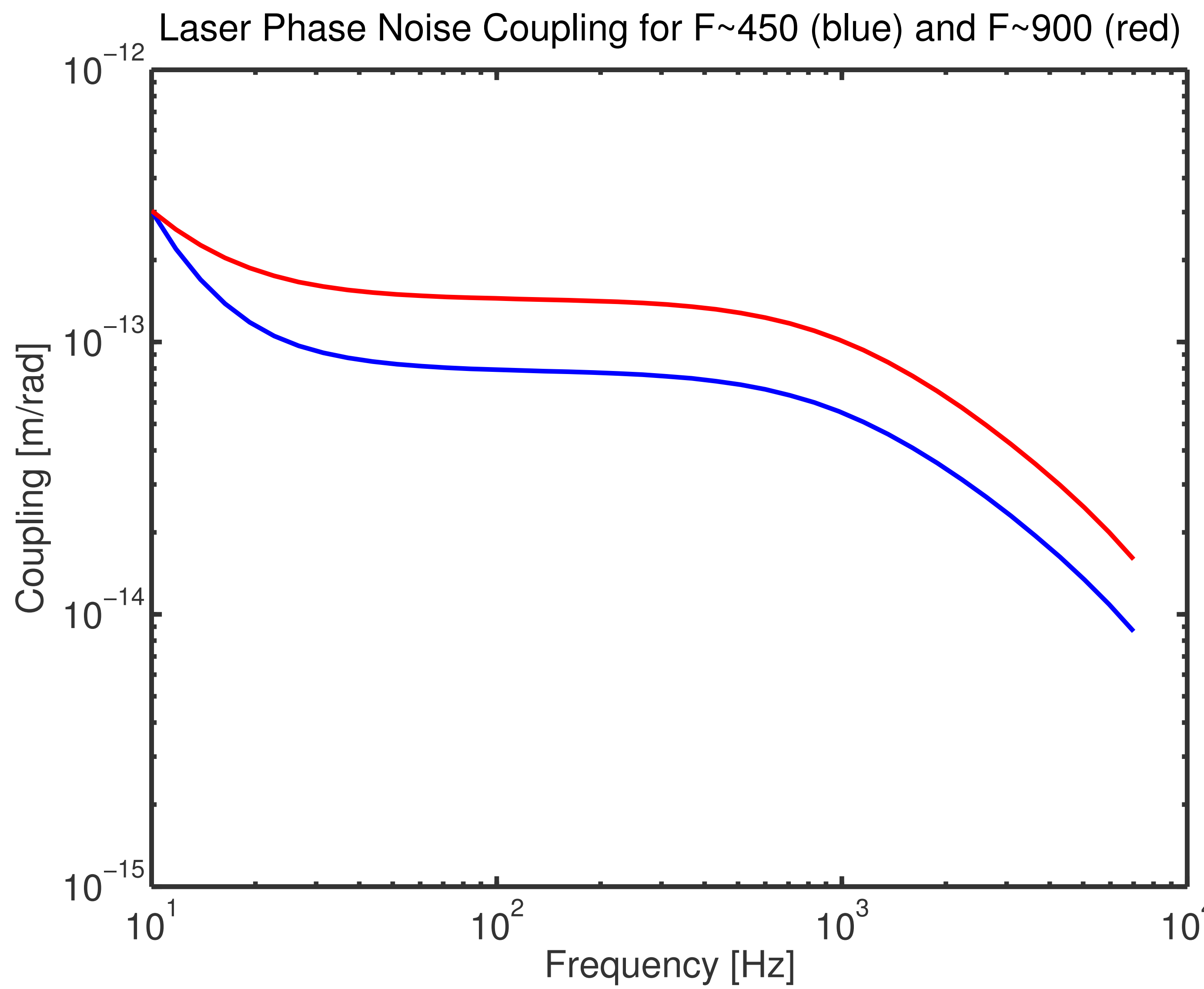
Critically coupling the ITF makes the best use of laser power, but it means we lose single demod signals in reflection for the short DOFs (PRCL, MICH, SRCL), for both length and alignment. Need input from ISC.



Laser noise

- Laser noise couplings always scale with asymmetries between the two arms. They are thus basically independent of choice of arm cavity finesse, assuming manufacturing tolerances are always "relative".

- However, it can depend on finesse, if the differential losses in the arms arise from number of point defects and we are in a low-number of defects regime.



broadband RSE

No SRM mode & Calibration

- An early run (or two-stage commissioning process) without a SRM will be more sensitive if the arm finesse is lower, especially for NS-NS inspirals.
- The asymmetric Michelson technique needs the beam to be transmitted through the ITM twice. Lower finesse allows better SNR for the test mass actuator calibration.

summary

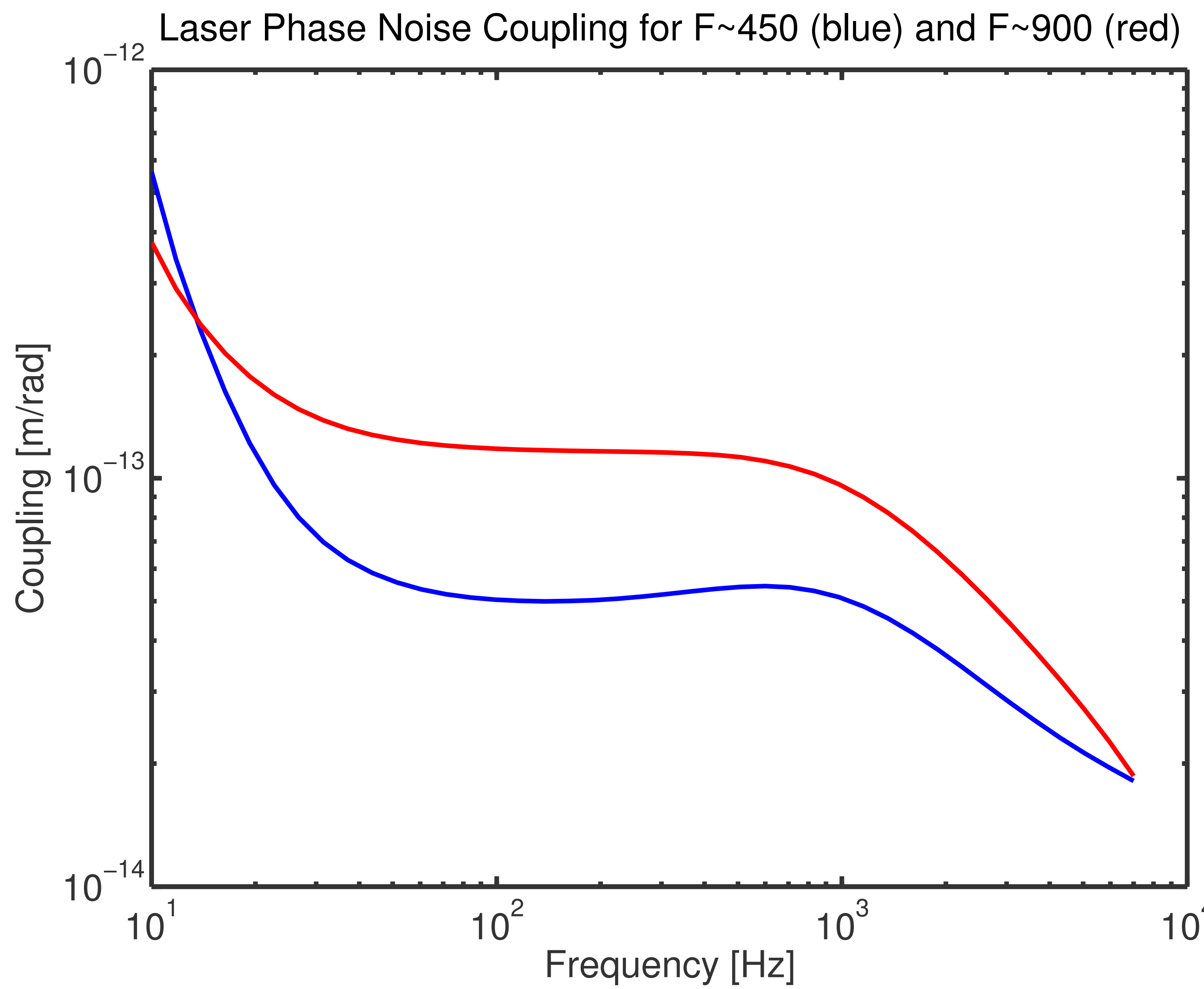
factor	***HI/LO finesse ?***
quantum noise	LO
MICH noise	HI
Thermal Load in CITF	x
PRC losses	HI
SRC losses	LO
coating thermal noise	x
losses on stored power	x
lock acquisition	LO
SRCL noise	LO
Laser noise	x
No SRM mode	LO
losses on signal matrix	LO
calibration	LO

Conclusion

- No powerful arguments in either direction
- General feeling: lower finesse is easier/simpler. If there is no compelling reason to choose high finesse, why do it?
- On balance, go for lower finesse.
- In the absence of hard numbers for MICH and SRCL suspension thermal noise, we can simply start by halving the finesse → 450. This is the same number aLIGO will use.

Laser Phase (frequency) Noise

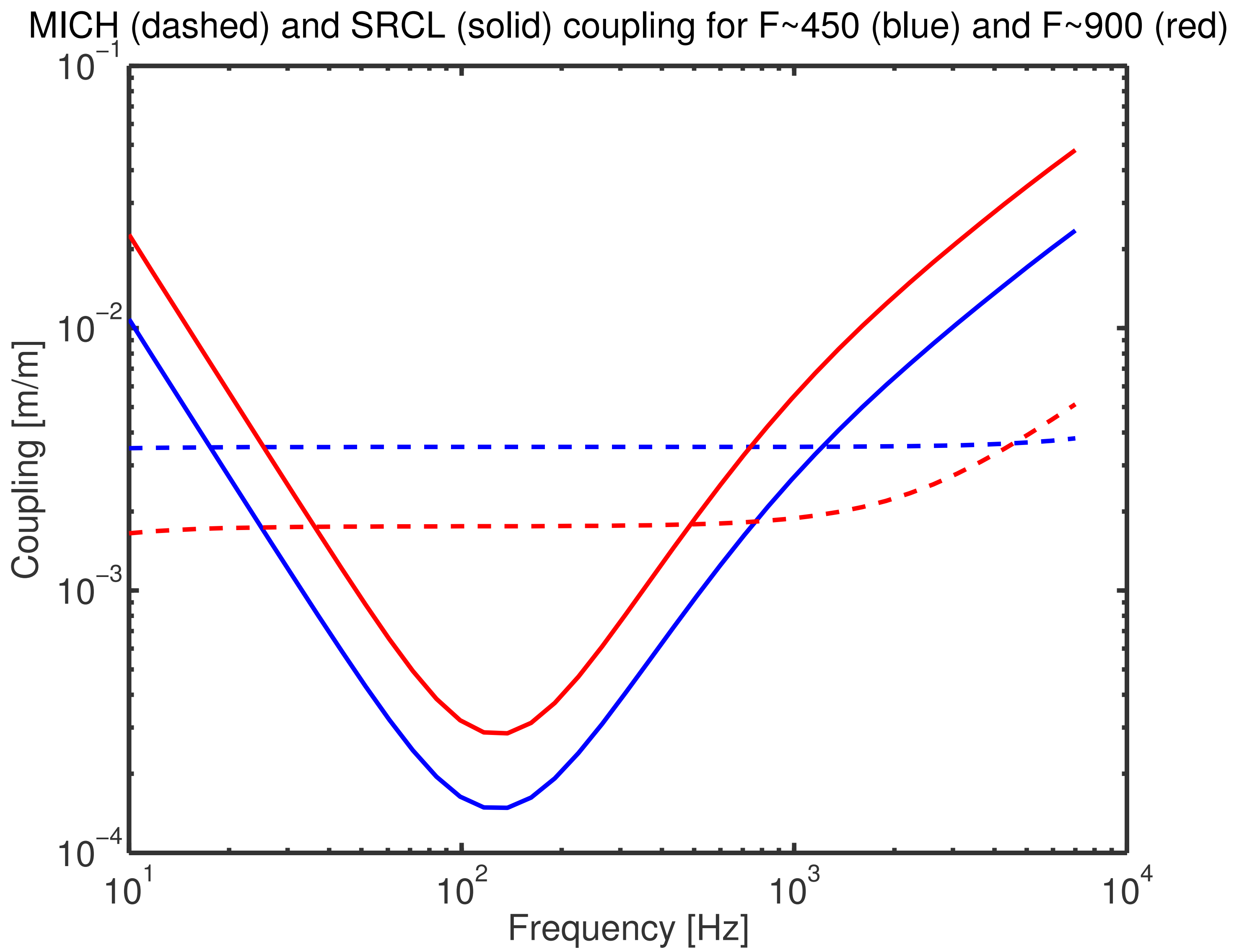
- Can depend on finesse, if the differential losses in the arms arise from number of point defects.



detuned RSE

SRCL vs. MICH

- SRCL noise coupling and MICH noise coupling behave inversely with arm finesse.



detuned RSE