Status and Future of the Caltech 40m Lab

Jan 29, 2007

the 40m team:

Rana Adhikari, Ben Abbott, Rich Abbott, Rolf Bork, Tobin Fricke, Keisuke Goda, Jay Heefner, Alexander Ivanov, Kirk McKenzie, Osamu Miyakawa, Robert Taylor, Stephen Vass, Sam Waldman, Rob Ward, Alan Weinstein

also starring:

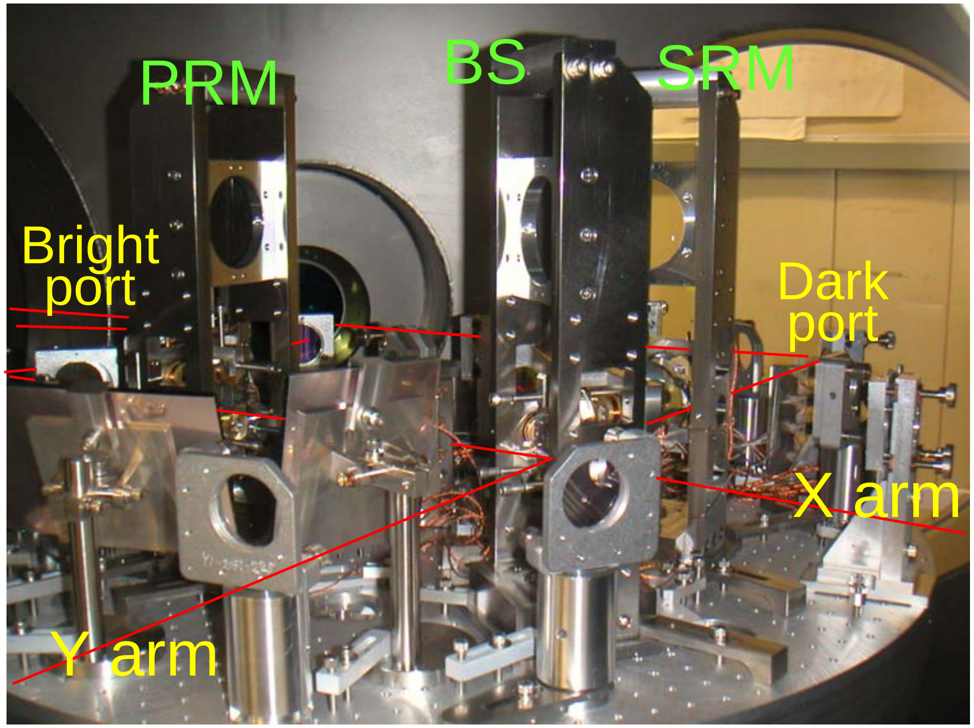
Dan Busby, Matt Evans, Valera Frolov, Justin Garifoldi, Seiji Kawamura, Shally Saraf, Bram Slagmolen, Michael Smith, Kentaro Somiya, Monica Varvella

and lots of summer SURF students

Caltech 40 meter prototype interferometer

Objectives

- Develop **lock acquisition procedure** of detuned Resonant Sideband Extraction (RSE) interferometer, as close as possible to AdvLIGO optical design
- Test/Characterize LSC scheme
- Develop DC readout schemes for eLIGO and AdvLIGO
- Characterize noise mechanisms
- Develop/test alignment sensing scheme and sensors
- Test QND techniques



Prototyping will yield crucial information about how to build and run AdLIGO (and eLIGO).

- Extrapolate to AdLIGO via simulation

Lock acquisition and control

- **Development of lock acquisition and control scheme for a detuned Resonant Sideband Extraction (RSE) interferometer, as close as possible to AdvLIGO optical design (Dual Recycled Fabry-Perot Michelson, DRFPMI)**
  - » **Characterize noise couplings and mechanisms in DRFPMI configuration.**
  - » **The 40m prototype should be used to inform the design and reduce the commissioning time for eLIGO and AdvLIGO.**

- **Also smoooooth locking procedure for Initial LIGO -> eLIGO PRFPMI.**

Lock acquisition and control

- **ISC team is reconsidering the high-frequency RF scheme for AdvLIGO sensing, and is developing schemes using frequencies well below 100 MHz.**
  - » **We will want to prototype this scheme at the 40m.**
  - » **It likely will require significant in-vacuum changes for cavity lengths, finesses, etc.**
  - » **Replace/upgrade Mach-Zehnder with better RF modulation system?**
- **Alignment sensing and control of detuned-DRFPMI with new WFS technology**

Other Interferometer technologies

The 40m lab is a facility for the development, testing, implementation, and staging of small improvements to the LIGO interferometers

- **PCIX-based front end controls and data acquisition for AdvLIGO CDS**
- **In-vac PDs, PZTs, steering mirrors, picomotors**
- **Timing, RF distribution systems**
- **DC (dither) alignment sensing**
- **Continued development of auxiliary systems: oplevs, FSS, ISS, CMservo, auto-alignment, automated scripting procedures, etc…**

Training and outreach

- **Training of new generation of GW interferometer scientists**
  - » **with deep knowledge of LSC and ASC issues, noise mechanisms, etc.**
  - » **Including many visitors from US, Japan, Perth, Canberra, Glasgow, Hannover, Orsay, …**
- **Training of SURF students, drawing them into the field**
  - » **average of 4 SURF students each year for the last 6 years.**
- **Tours / outreach**
  - » **Nothing as elaborate as at the sites.**
  - » **Given the large community in Pasadena area, we could consider a larger, more formal program.**

Some lessons learned

Full prototyping is often the best way to find problems *before* AdvLIGO commissioning

- **The effect of sidebands-on-sidebands on the LSC signals, and the use of Mach-Zehnder (or other techniques) for recovering good signals.**
- **Dynamics of optical springs in length and alignment degrees of freedom, effect on lock acquisition and development of techniques for dealing with them**
- **Effectiveness of DC and normalized signals for robust lock acquisition.**
- **Challenges of working with high RF frequencies (above 100 MHz).**
- **Effectiveness of dither-locking for length and alignment control.**

What's NEXT?

- We have a clear set of objectives for the next ~6 months or so.
  - » lock acquisition – AdvLIGO and eLIGO
  - » DC readout
  - » injection of squeezed vacuum
- What comes next?
  - » new signal matrix (lower RF sideband frequencies)
  - » Alignment sensing and control for AdvLIGO
- And maybe:
  - » new modulation scheme (non-Mach-Zehnder)
  - » Suspension Point Interferometer
  - » Thermally actuated Output Mode Cleaner
  - » …

Manpower

- We expect/hope the 40m team to continue playing essential roles in the development of AdvLIGO ISC,
  and also to continue training the next generation of GW instrument scientists.

- At present, the scientists at the 40m are either part-time (Adhikari, Miyakawa, Waldman, Weinstein),
  will graduate soon (Ward), or are temporary visitors.

- We are actively searching for Caltech grad students.

- We may want to supplement the staff with at least one new postdoc hire (or existing or new scientific staff) dedicated to 40m work associated with AdvLIGO ISC.

The remaining slides give more information on recent and current scientific activities at the 40m lab

DC readout

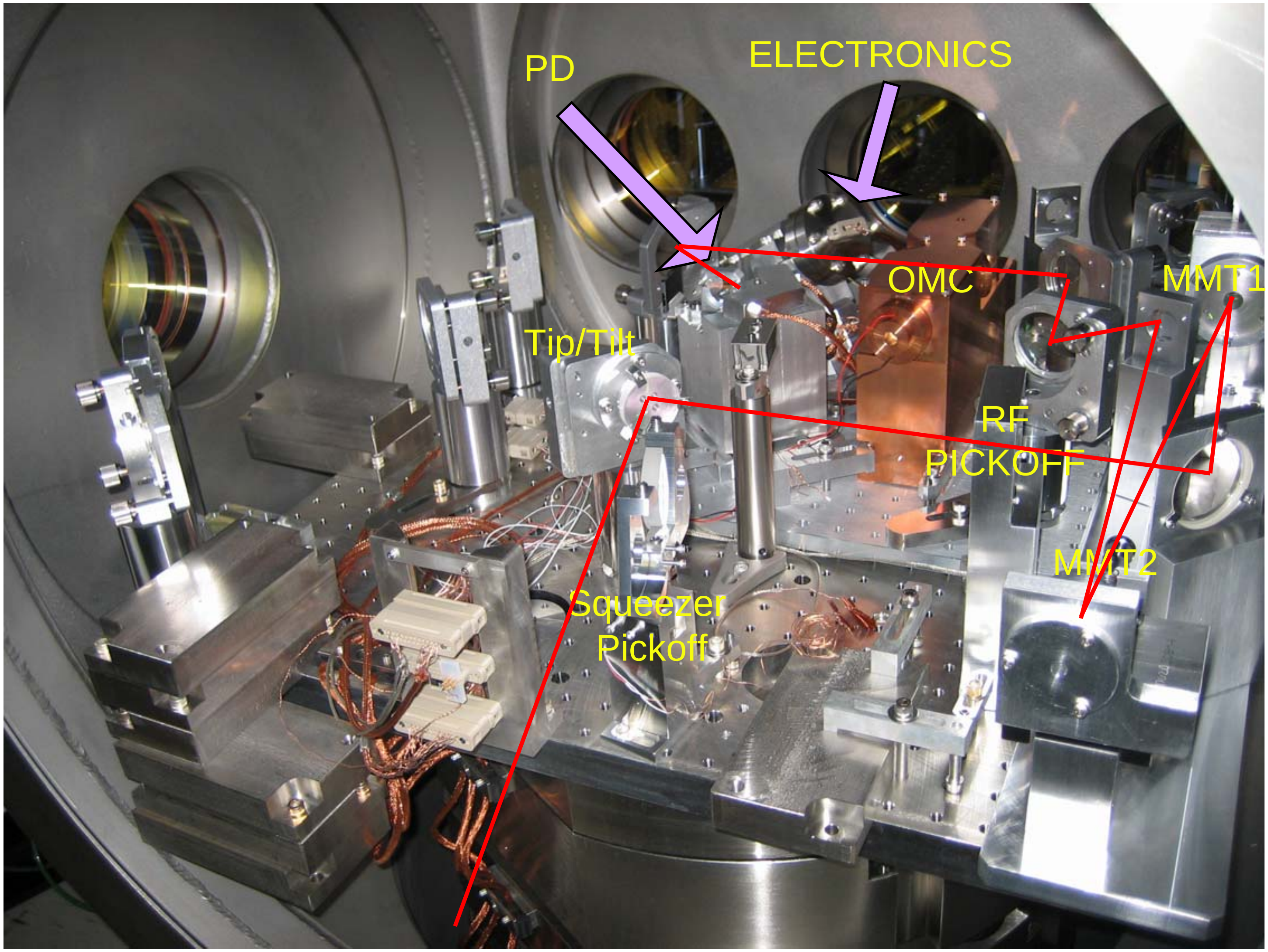
vacuum squeezing

Detuned RSE optical response

DRFPMI locking

DC readout

DC READOUT INSTALLATION



DC Readout components

- Two in-vac PZT tip-tilt steering mirrors
- Mode-matching telescope (picomotor focus control)
- Output Mode cleaner
  - » Four-mirror design, 48 cm round-trip length
  - » Finesse 190; transmission 95%; loss 0.1% rt
  - » PZT length actuation; dither-lock at ~3 kHz
- In-Vacuum Photodetector
  - » 2mm InGaAs diodes, with an amplifier/whitening circuit in a can.
  - » input-referred noise of 6nV/rtHz
- PCIX system for digital control
  - » digital lock-in software for controlling 5 DOFs
  - » “oscillator” generated digitally, all-digital dither-lock-in module
  - » Interfaces to existing RFM network
  - » 32 kHz real time control

DC READOUT COMMISIONING

- **most hardware installed, tested**
  - » **All PZTs, picos, PDs work as expected. Still QPDs to go.**
- **All software installed, tested**
  - » **PCIX controls, interfaced successfully with current VME ISC control system**
  - » **Myrinet-RFM bridge runs happily. PCIX Linux framebuilder plays nice with Solaris framebuilder. Multiple AWG/TP systems still have kinks to work out.**
- **OMC Controls version 1.0**
  - » **All digital demodulation**
  - » **OMCL dither locked (dither freq 12kHz, UGF 100Hz)**
  - » **OMC ASC dither locked (two tip/tilts, 4 DOFs)**
    - – **dither freqs ~4,5,6,7 kHz**
    - – **UGFs 2@20Hz, 2@subHz**

DC Readout first DARM noise

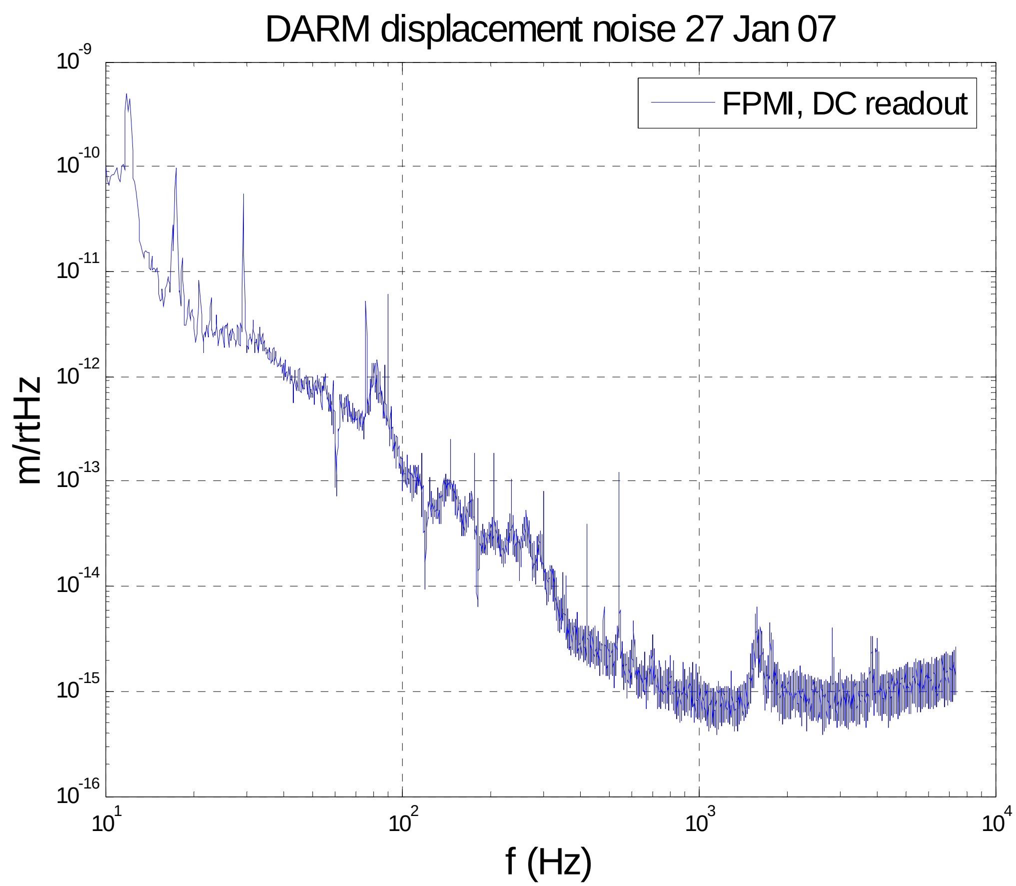
- FPMI
  - Recycling mirrors mis-aligned
- DARM offset: ~ 70 picometers
  - (not nec. optimal)

Control Scheme

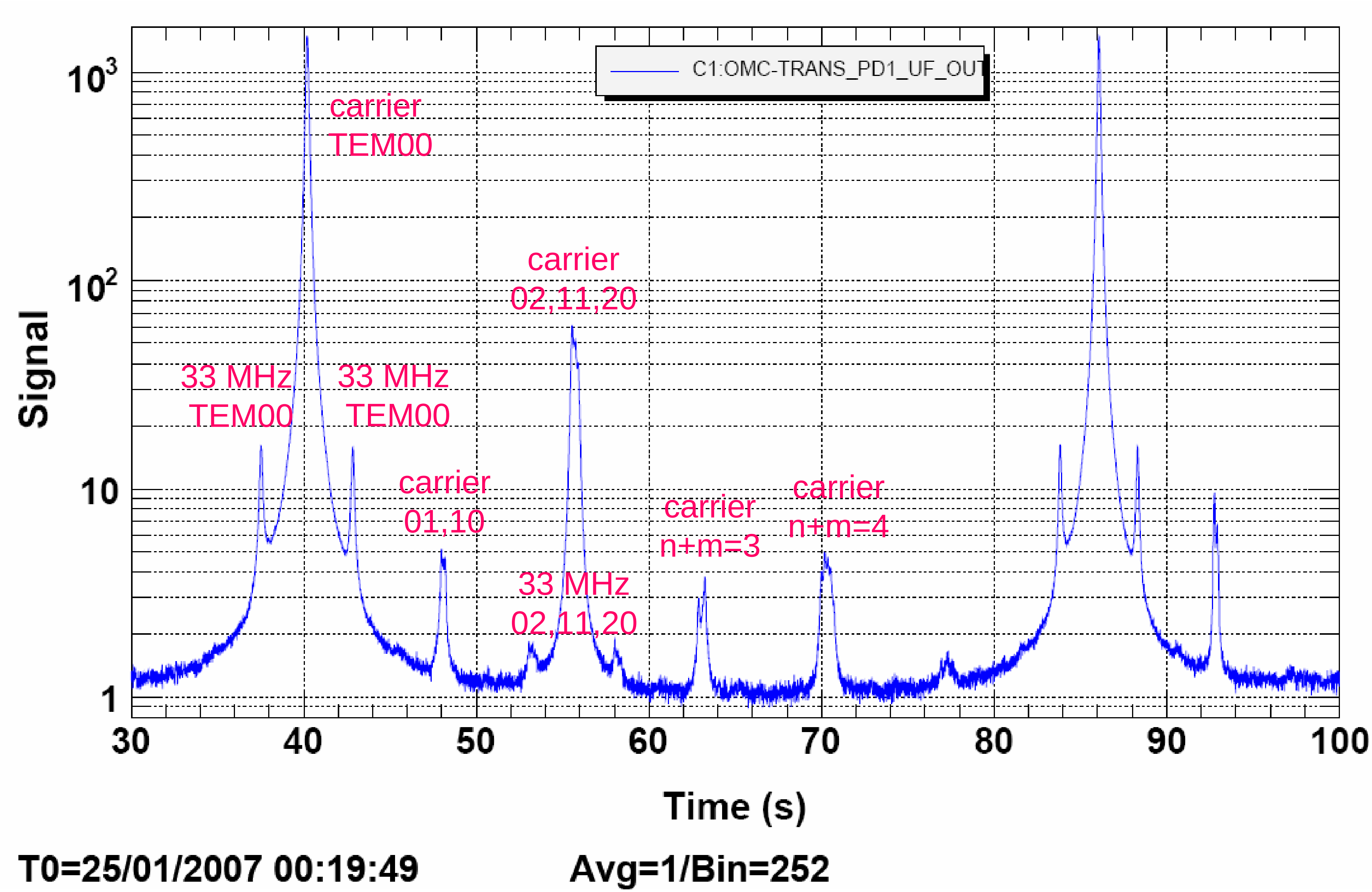
- DARM: OMC Transmission
  - MICH: REFLQ
  - CARM: REFLI
  - (common mode servo)

UP NEXT:

- More configurations
- Noise characterization & hunting



OMC mode scan
(not yet mode matched!)



Next DC readout tests

Done or in progress:

- Establish lock acquisition
  - » Control the OMC length
  - » Control steering into OMC (2x2 angular dofs with tip-tilt mirrors)
  - » Determine optimal L- offset (in progress)
  - » **Control DARM with DC signal**
- Measure HOM structure of the AS beam
  - » optimize mode matching (in progress)

NEXT:

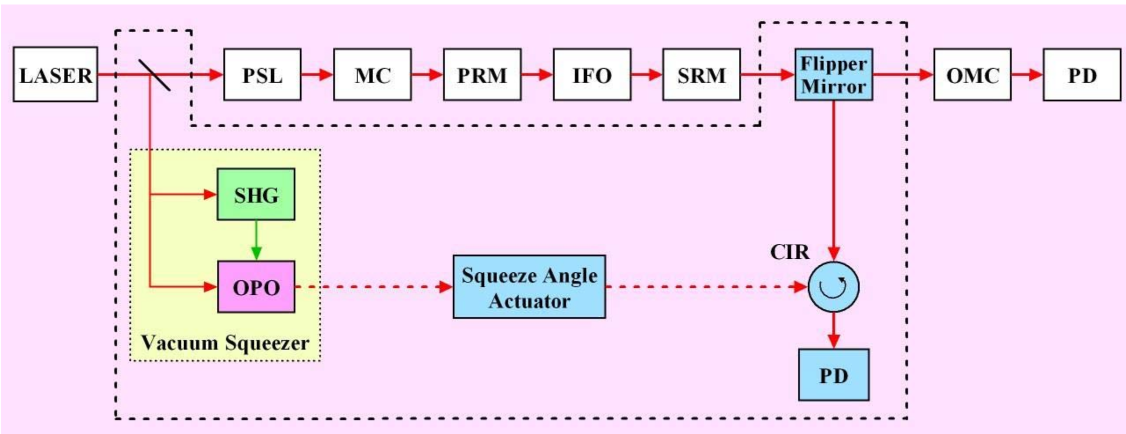
- Characterize and verify noise mechanisms
- Explore parameter space of offsets, demod phases, SR detune
- Noise budget, calibration, noise reduction

Injection of squeezed vacuum

Squeezing Project @ 40m

Keisuke Goda, Osamu Miyakawa, Eugeniy Mikhailov,
Shailendhar Saraf, Steve Vass, Alan Weinstein, Nergis Mavalvala

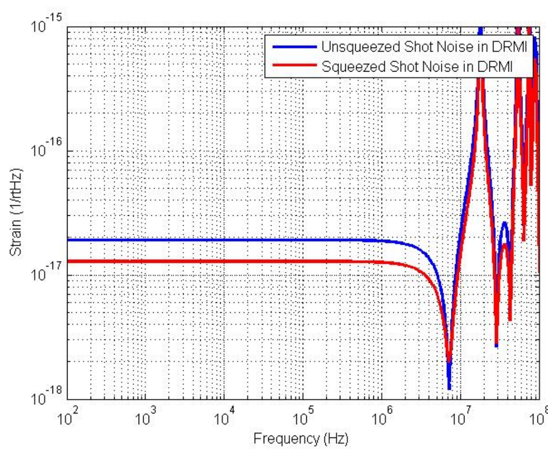
Goal: **First Experimental Demonstration of a Squeezing-Enhanced Laser-Interferometric Gravitational Wave Detector in the Advanced LIGO Configuration (or similar configurations)**

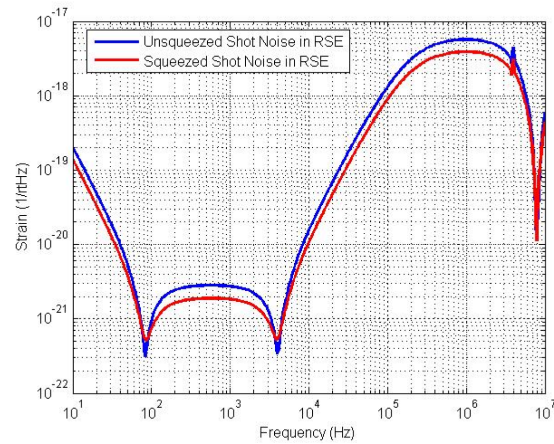


- The flipper mirror is inserted in between the SRM and OMC for squeezing measurements.
- Squeezed vacuum is generated by the optical parametric oscillator (OPO) pumped by the MOPA laser.
- The squeezed vacuum is injected into the dark port via the optical circulator (Faraday isolator and PBS).
- Noise-locking technique is used to lock the squeeze angle so that broadband reduction of the IFO shot noise can be achieved.

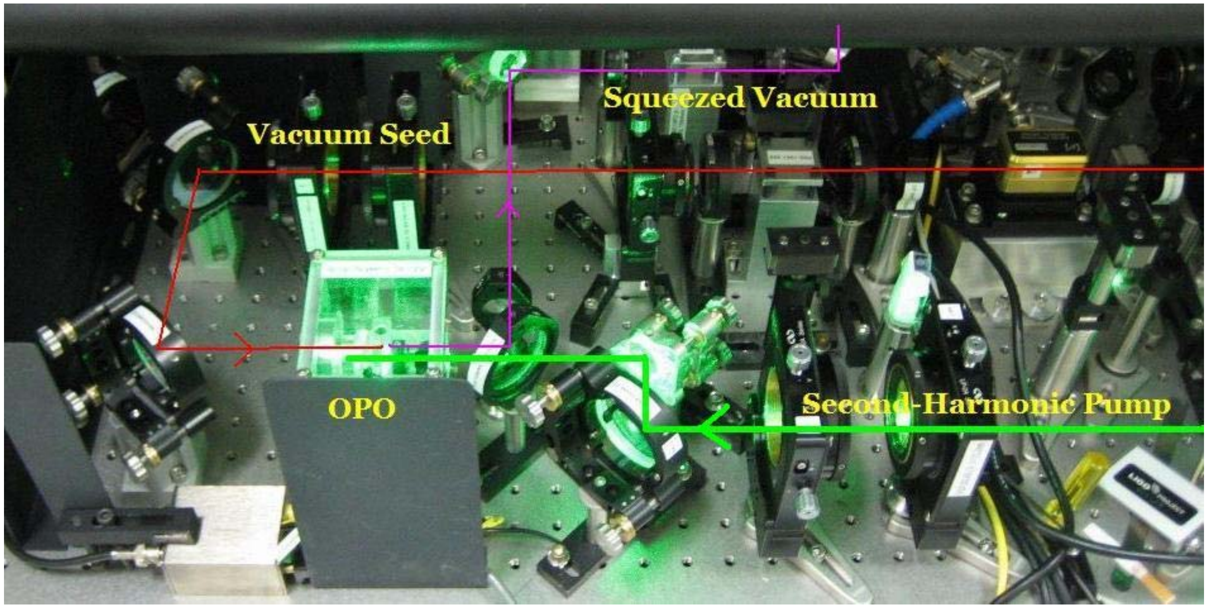
DRMI/RSE Quantum Noise Budget

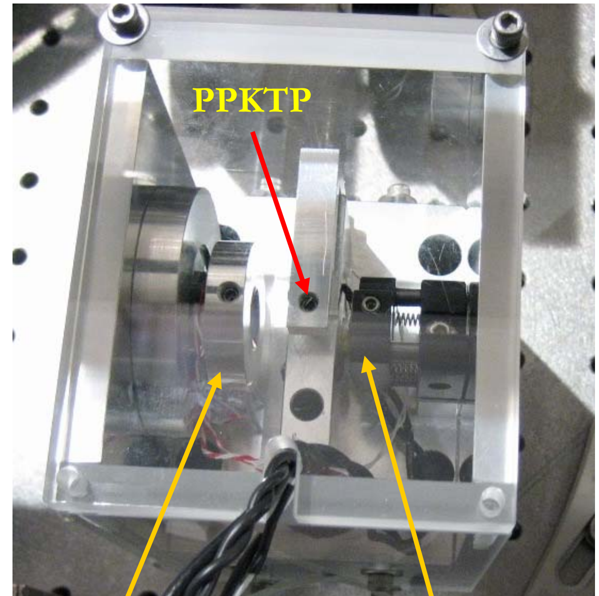
- Input Power to BS = 700mW
- Homodyne Angle = 0
- Squeeze Angle = $\pi/2$
- Initial Squeezing Level = 5dB
- Injection Loss = 10%
- Detection Loss = 10%





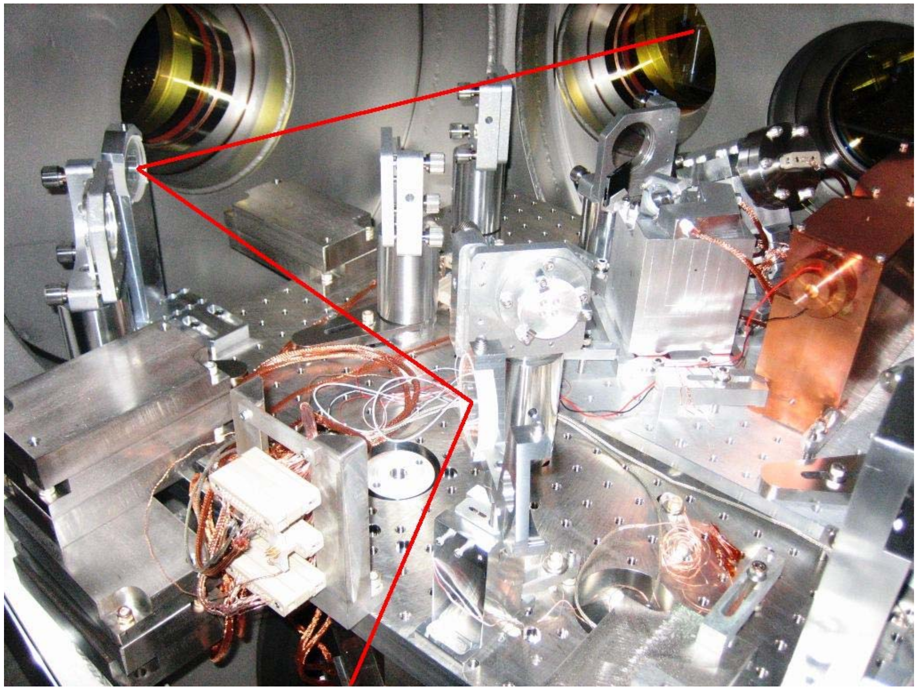
Generation of Squeezed Vacuum in Optical Parametric Oscillation with PPKTP



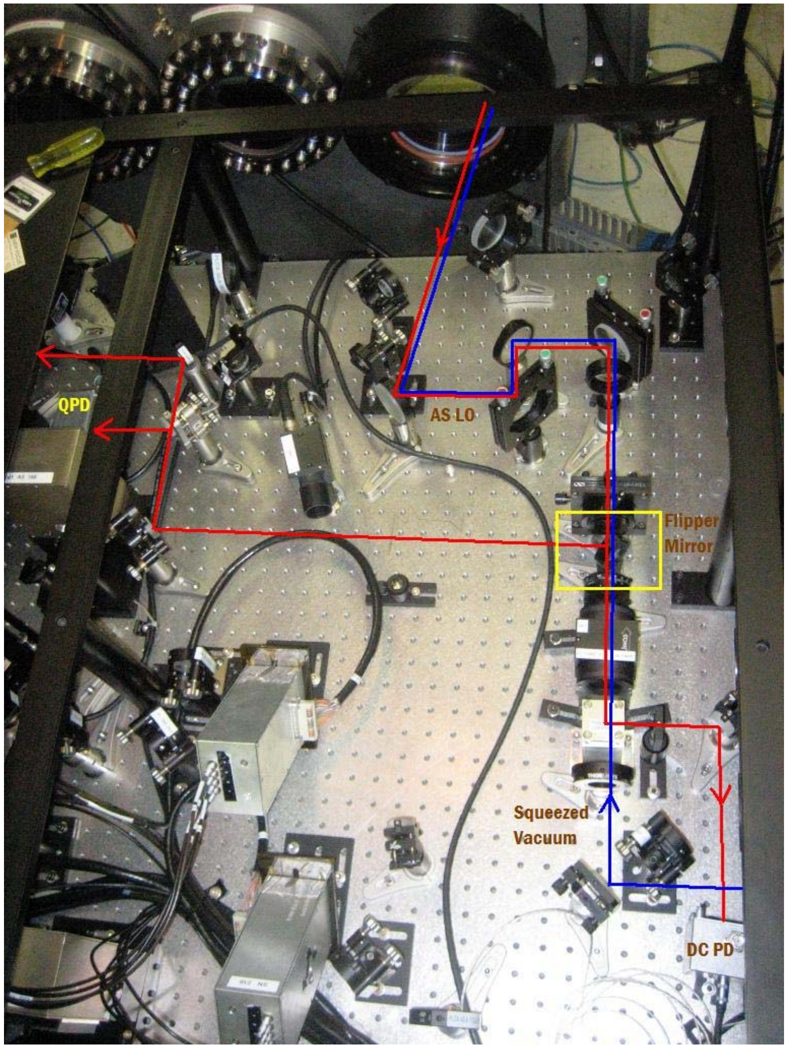


- The OPO is a 2.2cm long cavity composed of a periodically poled KTP crystal with flat/flat AR/AR surfaces and two coupling mirrors (R = 99.95% at 1064/532nm and R = 92%/4% at 1064/532nm).
- The OPO is pumped by 300 mW of second-harmonic light at 532nm.
- The PPKTP crystal is maintained at 35 deg C for maximum 1064/532 parametric down-conversion.
- Quasi-phase matching is used and both the seed and pump are polarized in the same direction.
- Frequency-shifted, orthogonally polarized light is used to lock the OPO cavity so that a vacuum field at 1064nm can couple to the cavity and get squeezed by its nonlinear interaction with the pump field in a TEM00 mode.

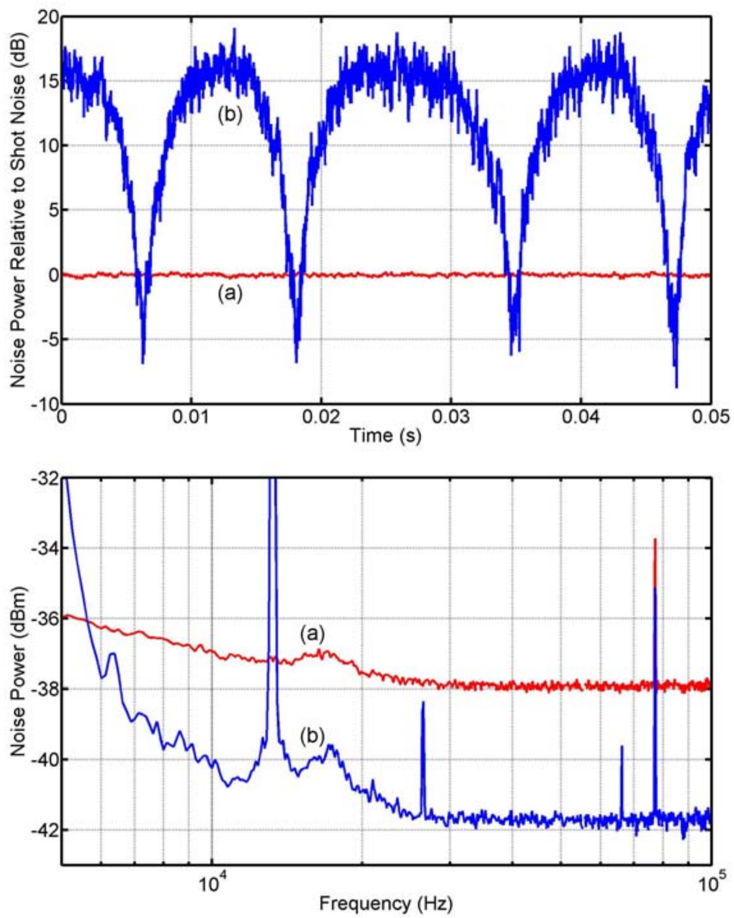
Injection of Squeezed Vacuum to IFO



- The picomotor mirror can be rotated in or out for squeezing-enhanced IFO measurements.
- Mode-matching and alignment of squeezed vacuum to the IFO are done on the AP table.
- Isolation of a squeezing-enhanced GW signal from the injection of squeezing is done by Faraday isolation.



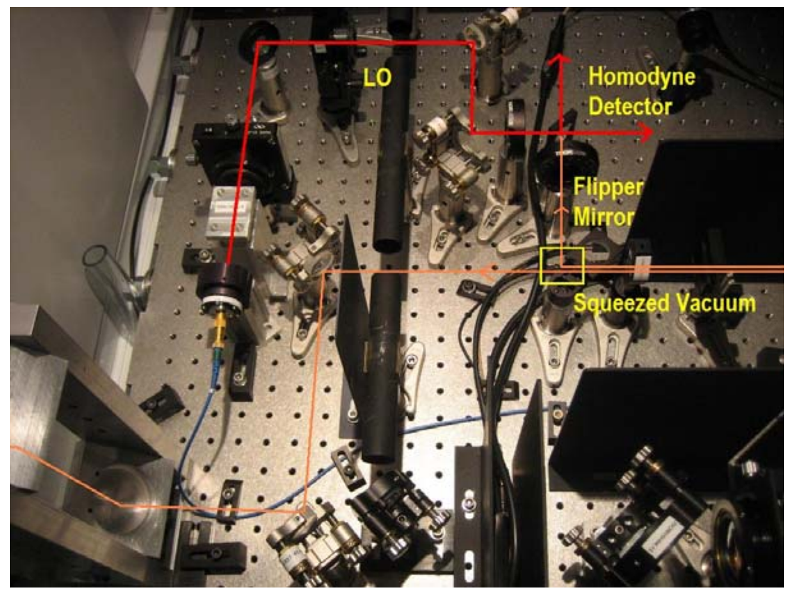
Some Results & Future Work



(a) Shot noise
(b) Squeezed shot noise

- ❖ About **6dB** of scanned squeezing
- ❖ About **4dB** of phase-locked squeezing

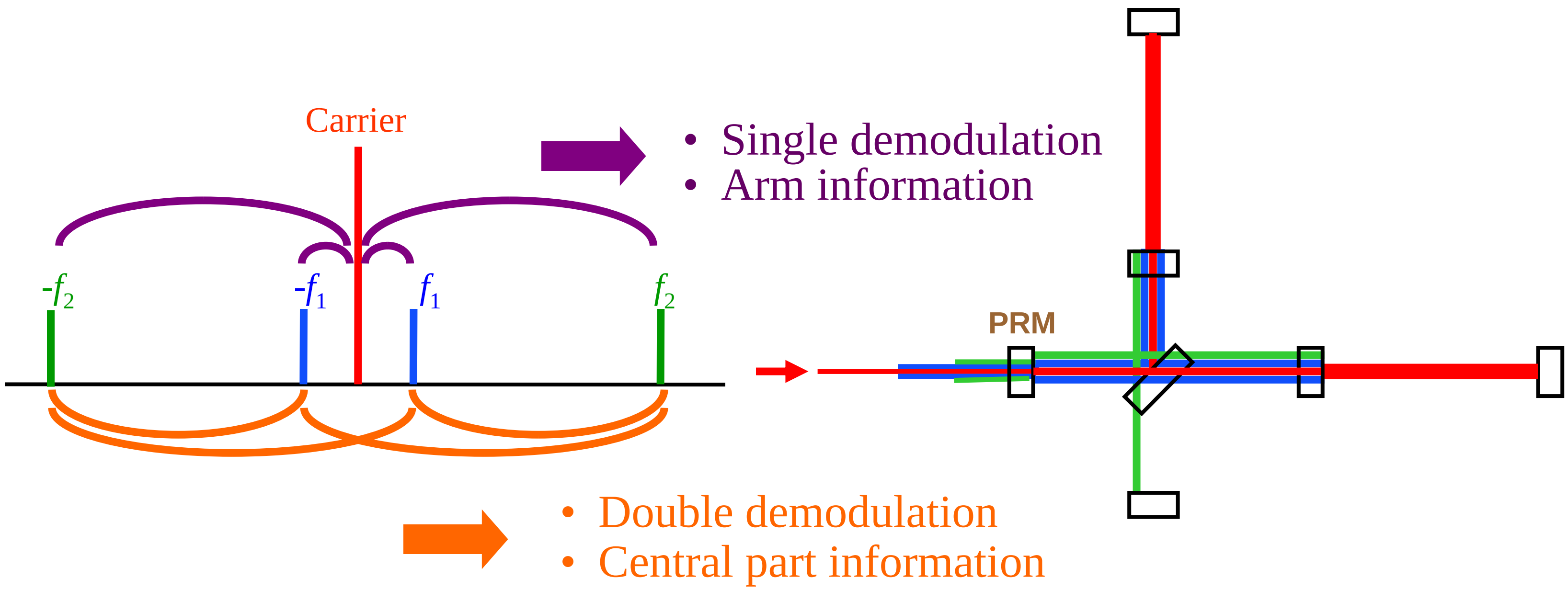
- ❖ Measured by the squeezing monitoring homodyne detector



- ❖ Ready to be injected into the IFO in the next few weeks to demonstrate squeezing-enhanced IFO

Length signal extraction and DRFPMI lock acquisition

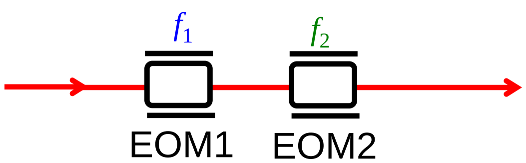
Signal Extraction Scheme



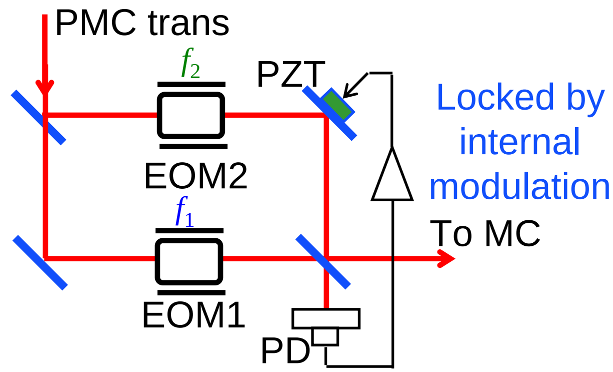
- Arm cavity signals are extracted from beat between carrier and f_1 or f_2.
- Central part (Michelson, PRC, SRC) signals are extracted from beat between f_1 and f_2, not including arm cavity information.
- Only $+f_2$ sideband resonates in combined PRC+SRC

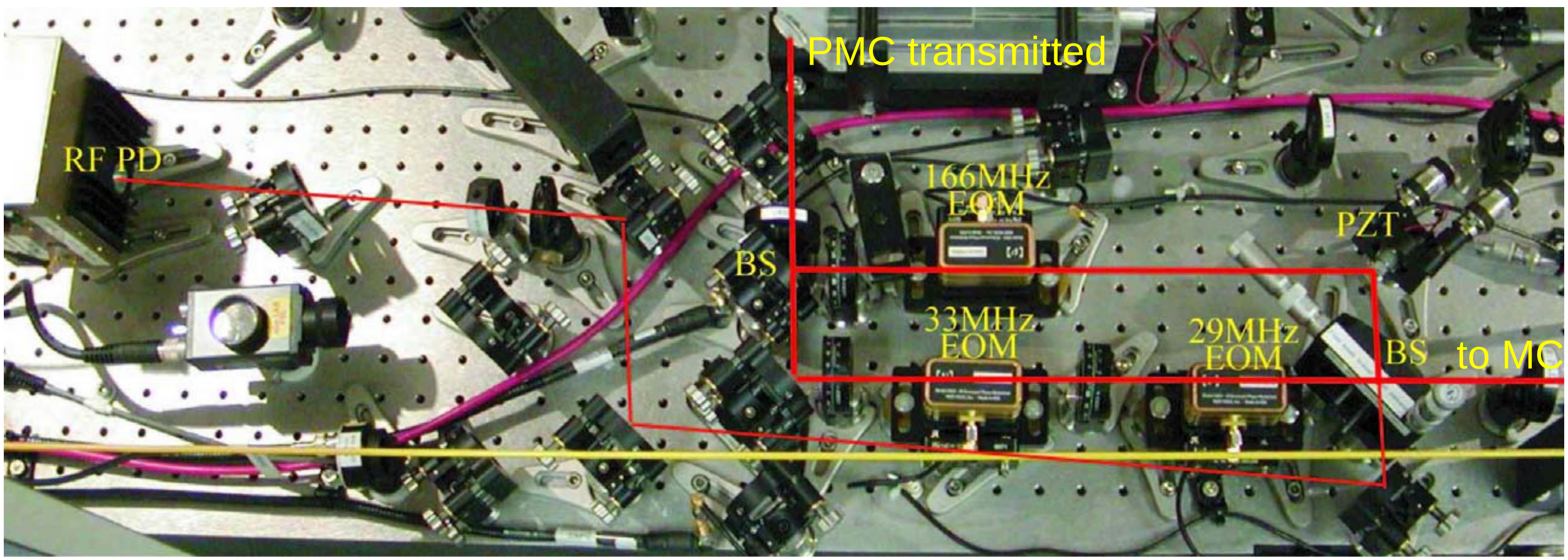
Mach-Zehnder interferometer on 40m PSL to eliminate sidebands of sidebands

Series EOMs
with sidebands of sidebands



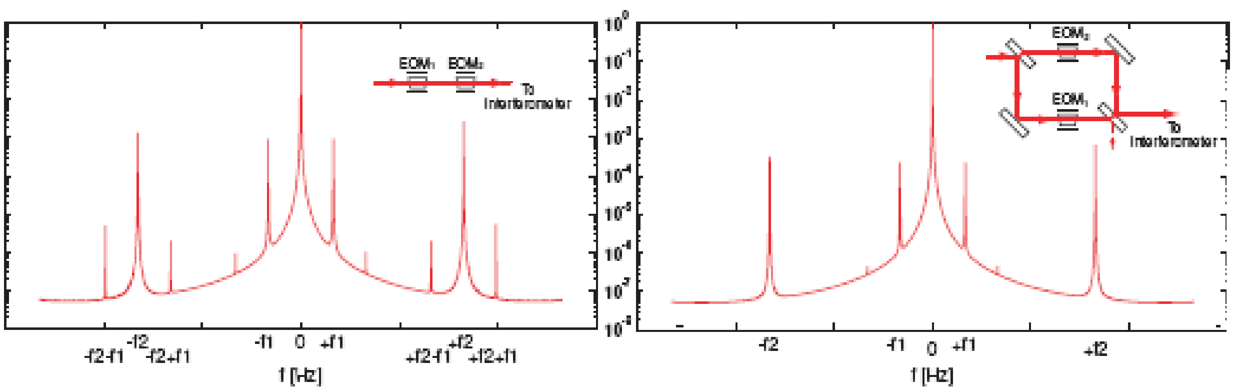
Mach-Zehnder interferometer
with no sidebands of sidebands

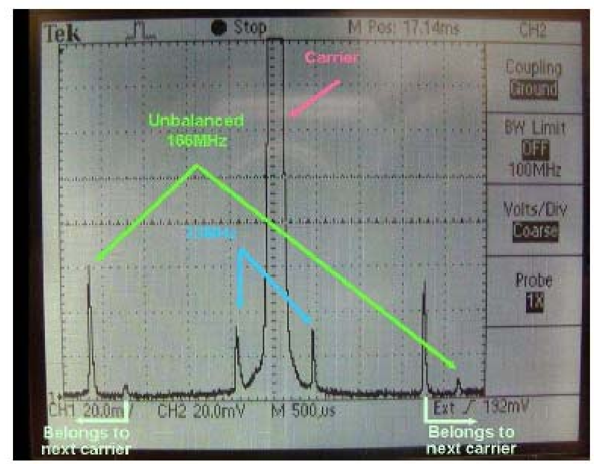




Control sidebands paper

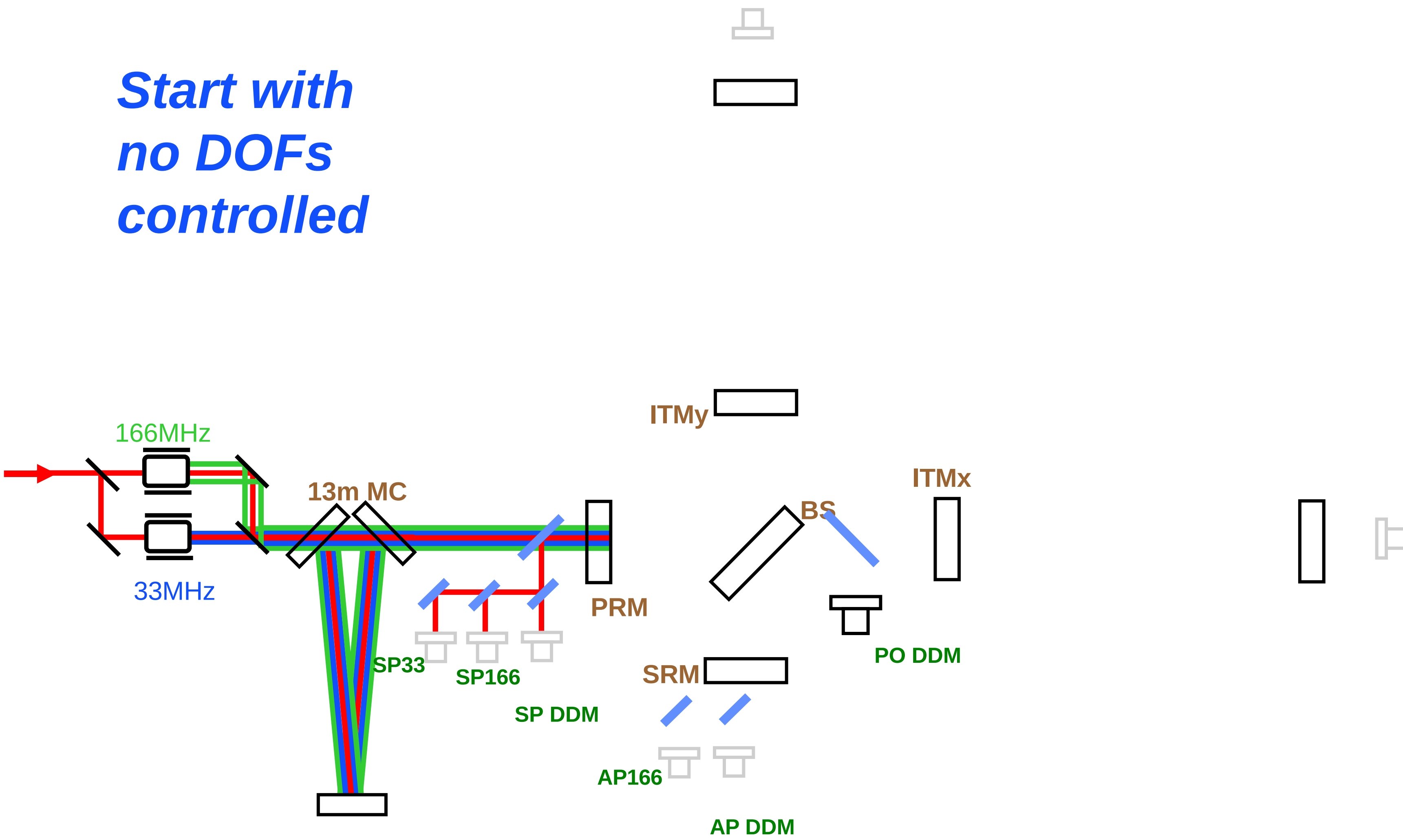
- "Control Sideband Generation for Dual-Recycled Laser Interferometric Gravitational Wave Detectors", accepted for publication in Classical and Quantum Gravity. http://www.ligo.caltech.edu/docs/P/P060022-00/
- Bryan Barr, Glasgow, lead author





40m Lock acquisition procedure (v 1.0)

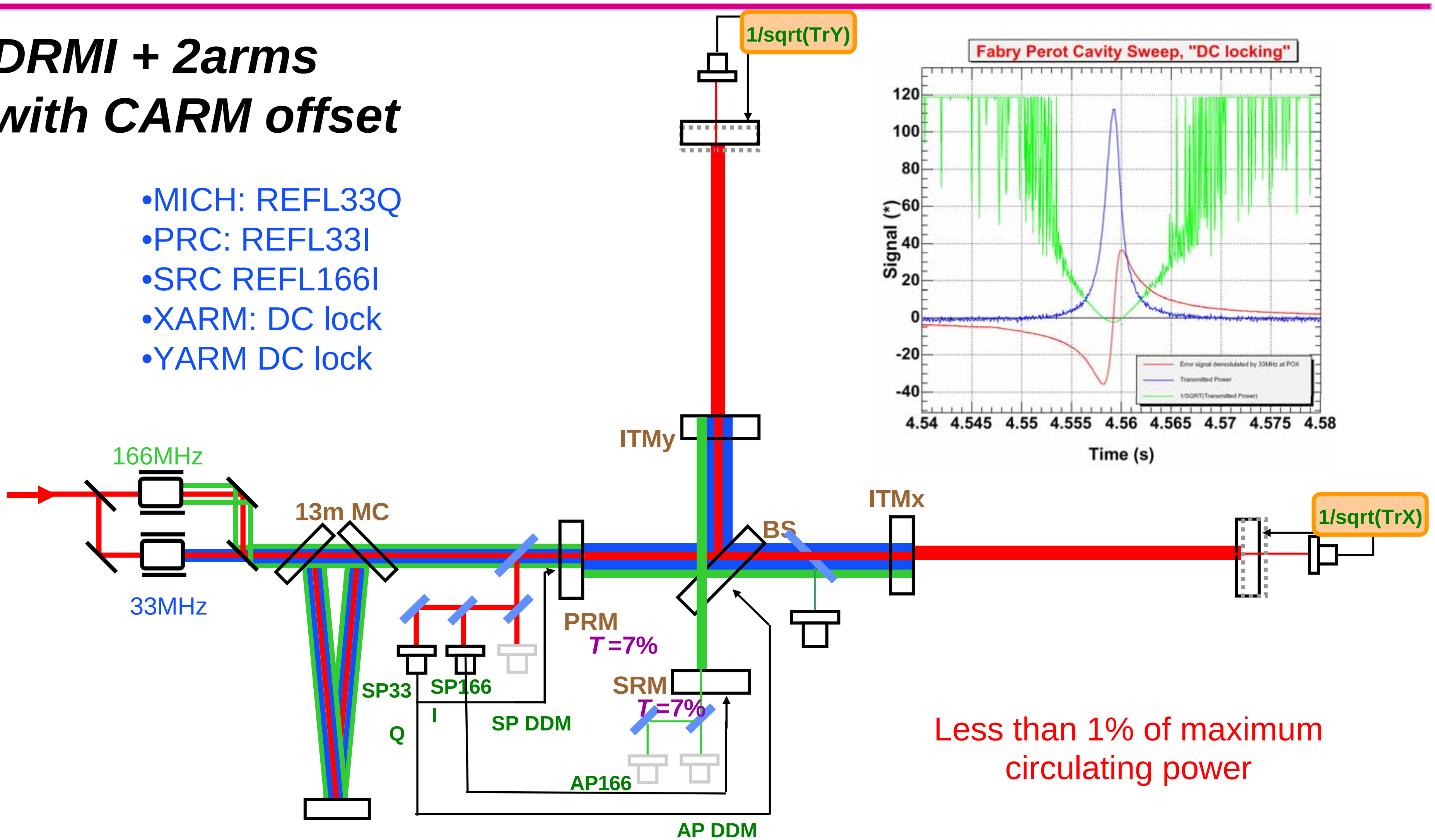
Start with no DOFs controlled



40m Lock acquisition procedure (v 1.0)

DRMI + 2arms
with CARM offset

- MICH: REFL33Q
- PRC: REFL33I
- SRC REFL166I
- XARM: DC lock
- YARM DC lock

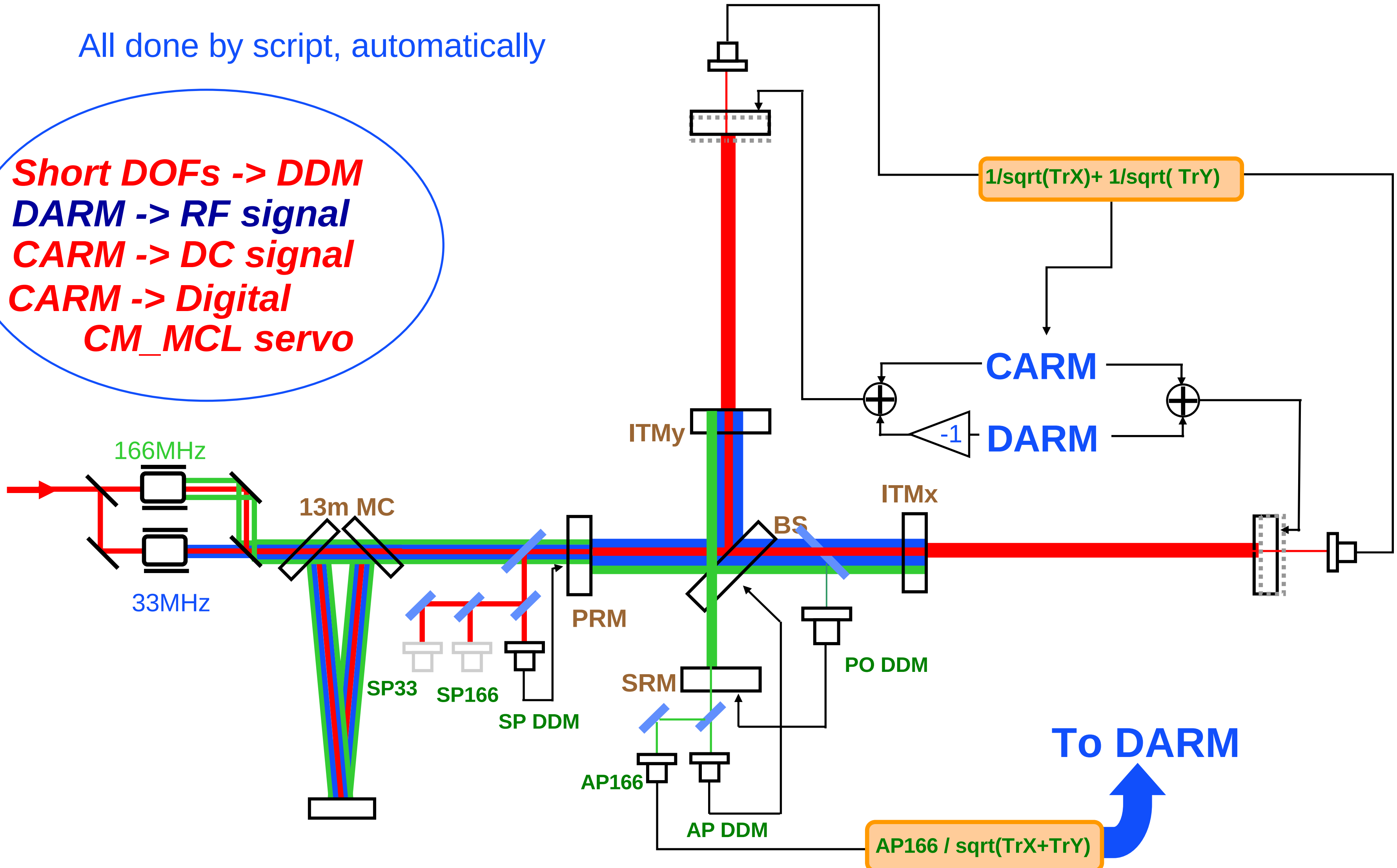


Less than 1% of maximum circulating power

40m Lock acquisition procedure (v 1.0)

All done by script, automatically

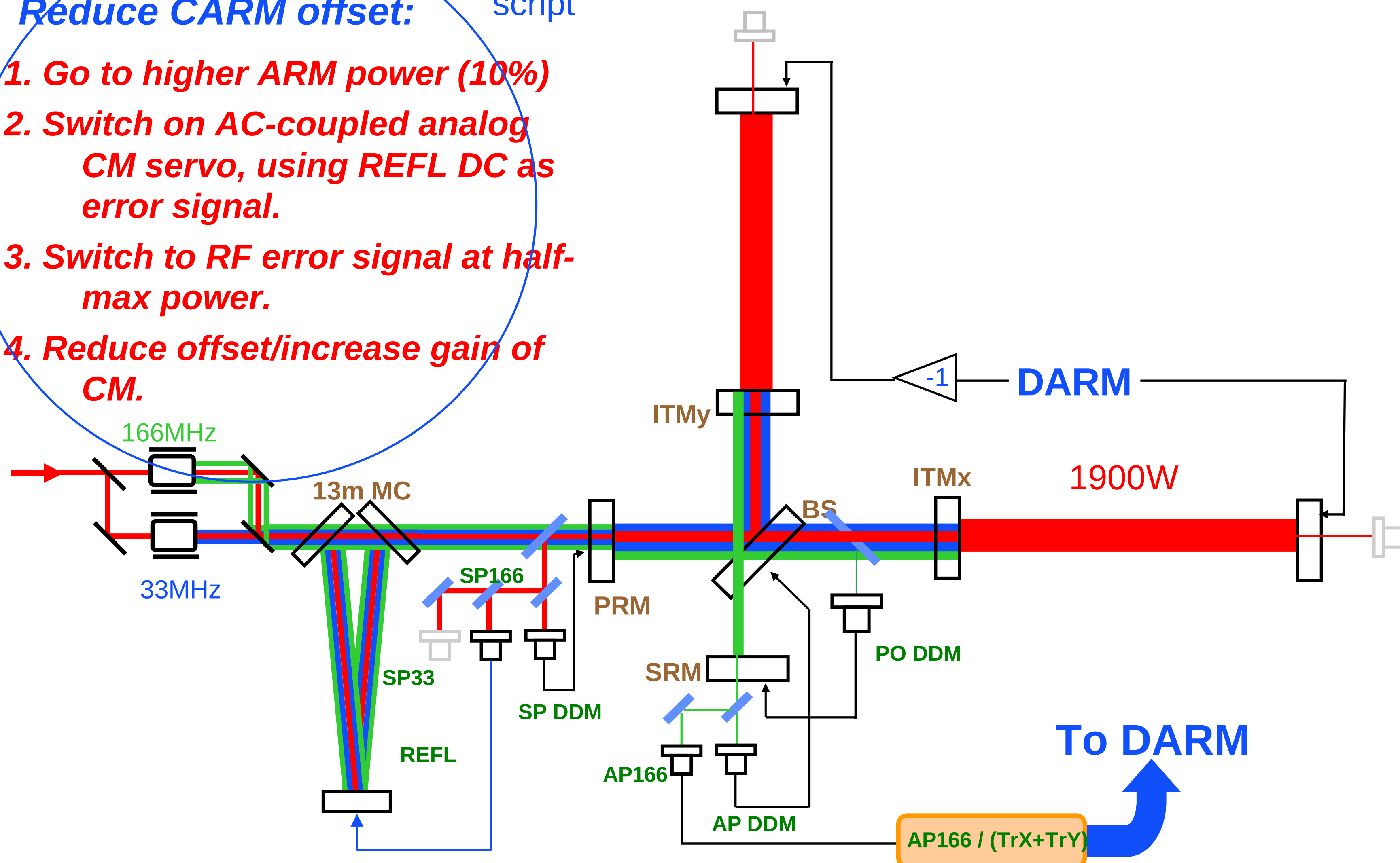
Short DOFs -> DDM
DARM -> RF signal
CARM -> DC signal
CARM -> Digital CM_MCL servo



40m Lock acquisition procedure (v 1.0)

Reduce CARM offset: script

1. ***Go to higher ARM power (10%)***
2. ***Switch on AC-coupled analog CM servo, using REFL DC as error signal.***
3. ***Switch to RF error signal at half-max power.***
4. ***Reduce offset/increase gain of CM.***

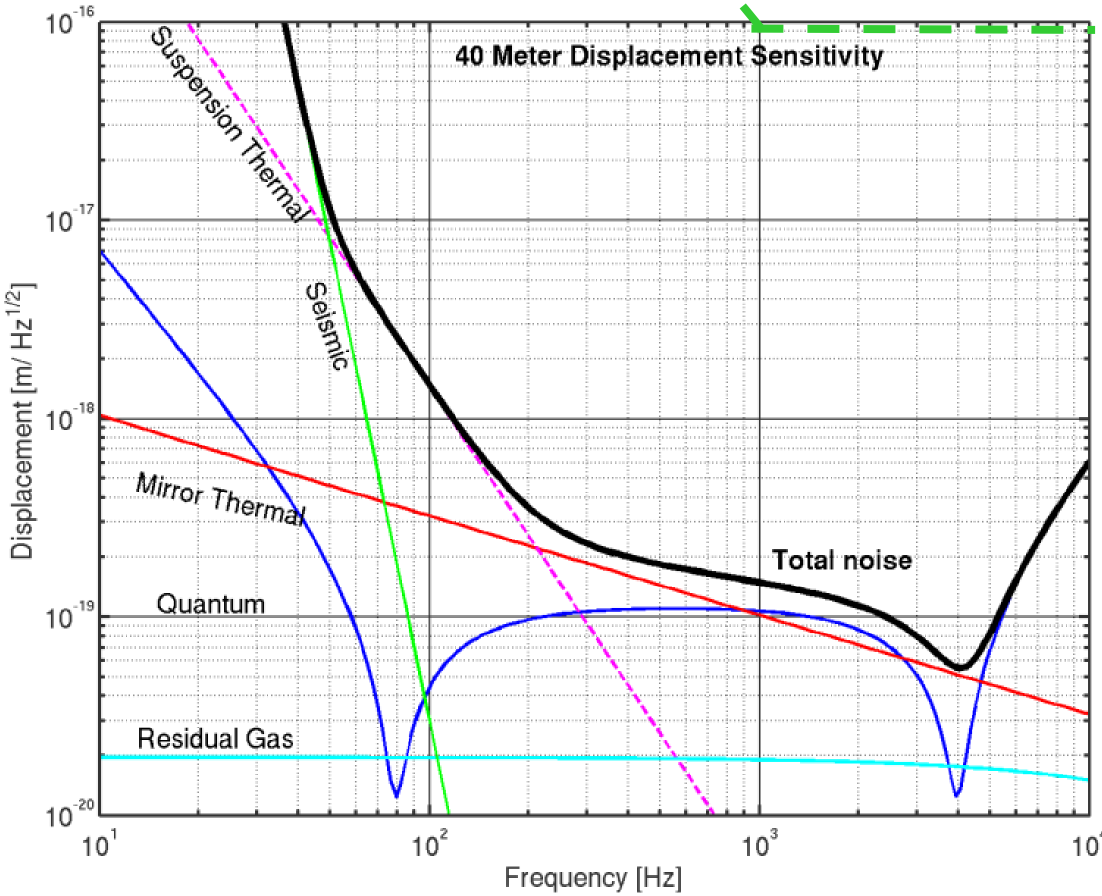


Lock acquisition development, automation

- Initial, scripted, auto-alignment works now for all DOFs
- All loops use single-demod signals (carrier+one sideband) for initial lock acquisition, to aid in tuning double-demod signals (offsets, demod phases).
- In initial stage, all loops now have useful power level triggers.
- Fast input matrix ramping: all signal handoffs are automated and smooth.
- With improved LO levels, now using real double-demod at 133 and 199 MHz.
- Work continues on Deterministic Locking.
  - » PRFPMI, DRMI, no DRFPMI
- E2E modeling of lock acquisition under development

40m TAC Update

October 2006

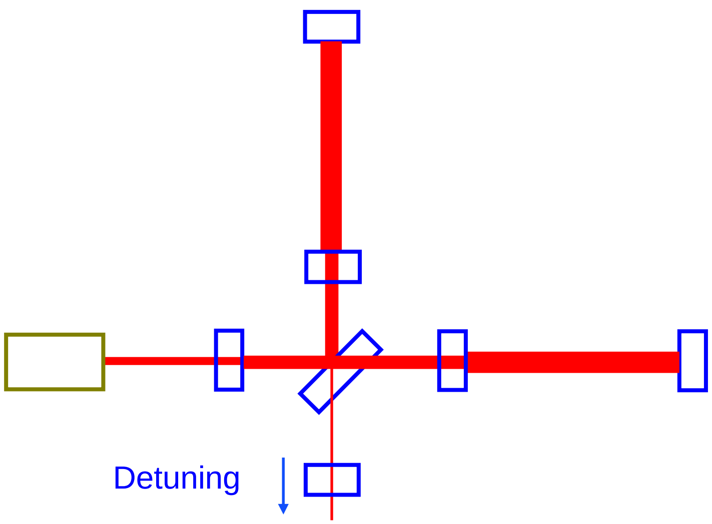


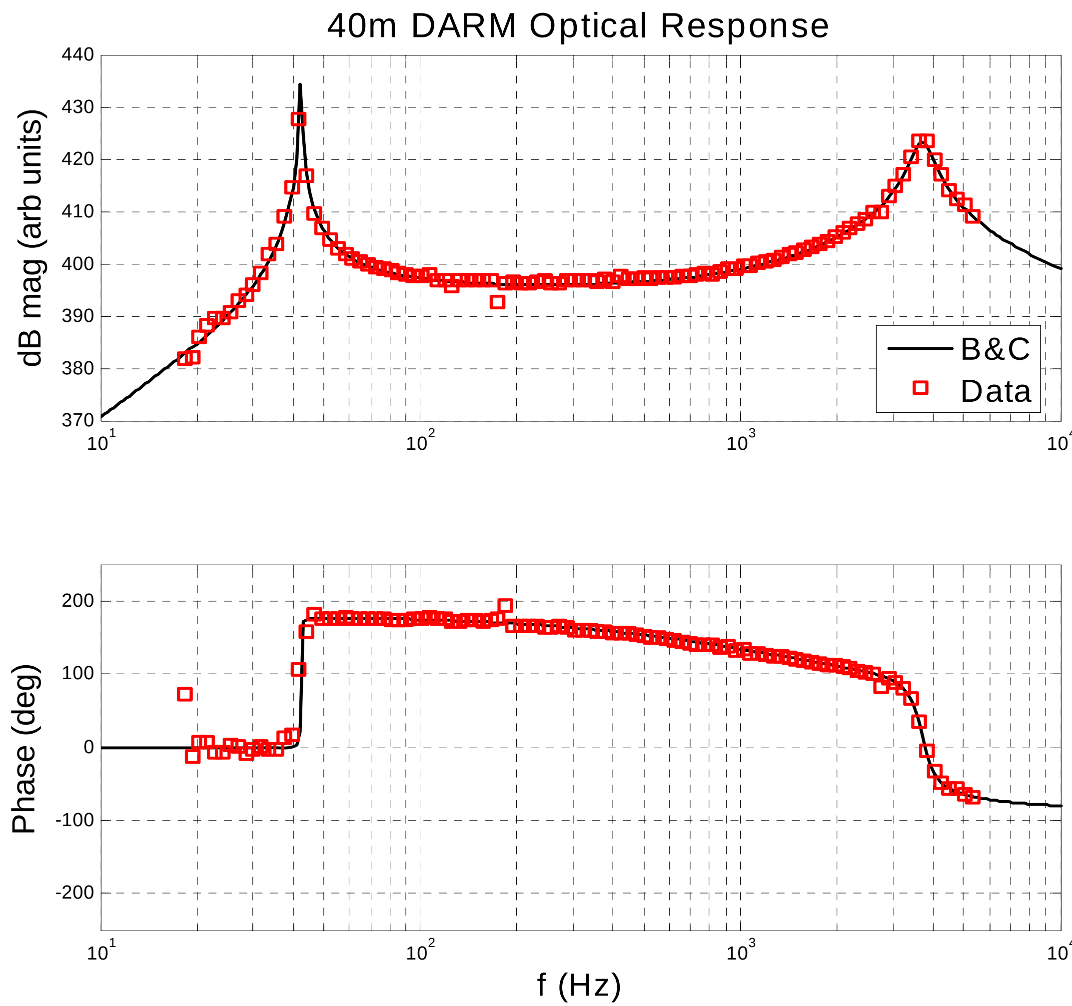
The 40m Team

Detuned RSE optical response

DARM Optical response

Optical spring and optical resonance of detuned RSE were measured and fitted to theoretical prediction from A. Buonanno and Y. Chen, PRD64, 042006.





Optical Response paper

- "Measurement of Optical Response of a Detuned Resonant Sideband Extraction Interferometer" Miyakawa *et al*, Published in Phys. Rev. D74, 022001 (2006) LIGO-P060007-00-R

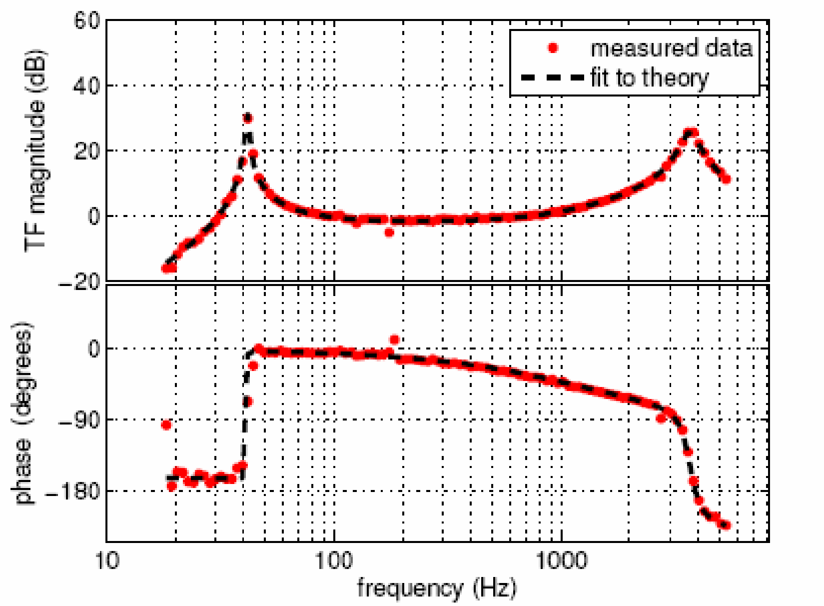


FIG. 3: The magnitude (top) and phase (bottom) response

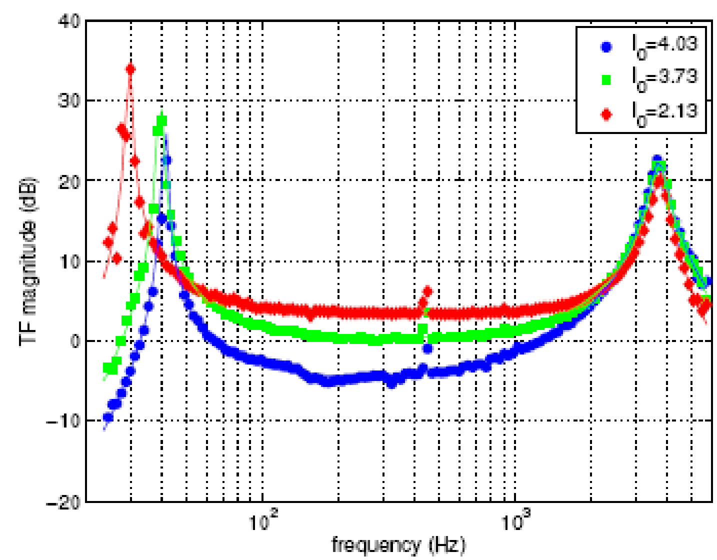


FIG. 4: The magnitude response of the 40m interferometer