Report to 40 Meter TAC

Alan Weinstein, Caltech

- **Caltech 40 Meter Prototype**
  - **Objectives and scope**
  - **Trade-offs and compromises**
  - **Recent progress in infrastructure, procurement, modeling**
  - **plans and milestones**
  - **Conceptual design review:**

    October 18, 2001, 8:30 AM PDT

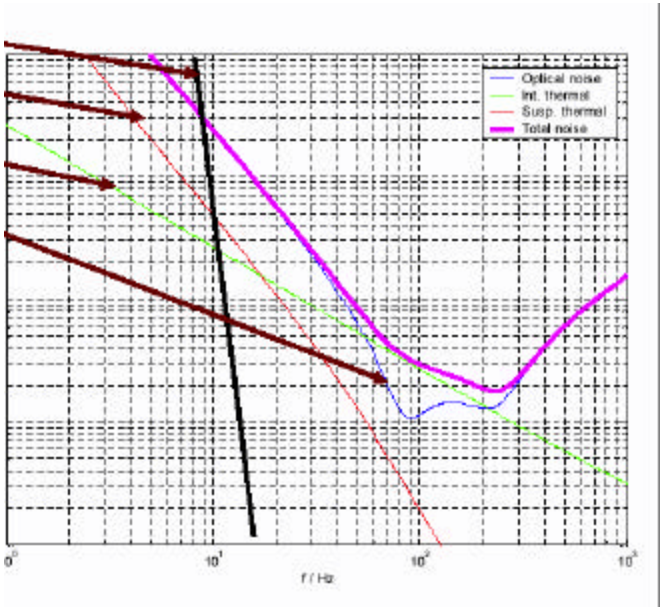
People

- Live & breathe 40m: Alan Weinstein, Dennis Ugolini, Steve Vass, Ben Abbott
- LIGO lab engineers playing major roles: Garilynn Billingsley, Lisa Bogue, Rolf Bork, Lee Cardenas, Dennis Coyne, Jay Heefner, Larry Jones, Rick Karwoski, Peter King, Janeen Romie, Paul Russel, Mike Smith, Larry Wallace
- 6month visiting grad student Guillaume Michel
- Lots of SURF students (this summer – 6).
- We'll need lots of add'l help in coming years!

40m Laboratory Upgrade - Objectives

- Primary objective: full engineering prototype of optics control scheme for a dual recycling suspended mass IFO
  - » Table-top IFOs at Caltech, Florida, Australia, Japan (~ complete!)
  - » These lead to decision on control scheme by LSC/AIC (August 2000 LSC)
  - » Glasgow 10m DR prototype with multiple pendulum suspensions
  - » Then, full LIGO engineering prototype of ISC, CDS at 40m
  - » First look at DR shot noise response (*high-f*)

- Other key elements of AdvLIGO are prototyped elsewhere:
  - »**LASTI, MIT**: full-scale prototyping of Adv.LIGO SEI, SUS (*low-f*)
  - »**TNI, Caltech** : measure thermal noise in Adv.LIGO test masses (*mid-f*)
  - » **AIGO, Gingin** : high powered laser, thermal effects, control stability
  - »**ETF, Stanford:** advanced IFO configs (Sagnac), lasers, etc



Advanced LIGO technical innovations tested at 40m

- **a seventh mirror for signal recycling**
  - » **(length control goes from 4x4 to 5x5 MIMO)**
- **detuned signal cavity (carrier off resonance)**
- **pair of phase-modulated RF sidebands**
  - » **frequencies made as low and as high as is practically possible**
  - » **unbalanced: only one sideband in a pair is used**
  - » **double demodulation to produce error signals**
- **short output mode cleaner**
  - » **filter out all RF sidebands and higher-order transverse modes**
- **offset-locked arms**
  - » **controlled amount of arm-filtered carrier light exits asym port of BS**
- **DC readout of the gravitational wave signal**

Much effort to ensure high fidelity between 40m and Adv.LIGO!

Differences between AdvLIGO and 40m prototype

- **Initially, LIGO-I single pendulum suspensions will be used**
  - » Full-scale AdvLIGO multiple pendulums will not fit in vacuum chambers
  - » to be tested at LASTI
  - » Scaled-down versions can fit, to test controls hierarchy – in 2004?
- **Only commercial active seismic isolation**
  - » STACIS isolators already in use on all 4 test chambers
  - » providing ~30 dB of isolation in 1-100 Hz range
  - » No room for anything like full AdvLIGO design – to be tested at LASTI
- **LIGO-I 10-watt laser, negligible thermal effects**
  - » Other facilities will test high-power laser: LASTI, Gingin, …
  - » Thermal compensation also tested elsewhere
- **Small (5 mm) beam spot at TM's; stable arm cavities**
  - » AdvLIGO will have 6 cm beam spots, using less stable cavities
  - » 40m can move to less stable arm cavities if deemed useful
- **Arm cavity finesse at 40m chosen to be = to AdvLIGO**
  - » Storage time is x100 shorter
  - » significant differences in lock acquisition dynamics, in predictable ways
- **Due to shorter PRC length, control RF sidebands are 36/180 MHz instead of 9/180 MHz; less contrast between PRC and SRC signals**

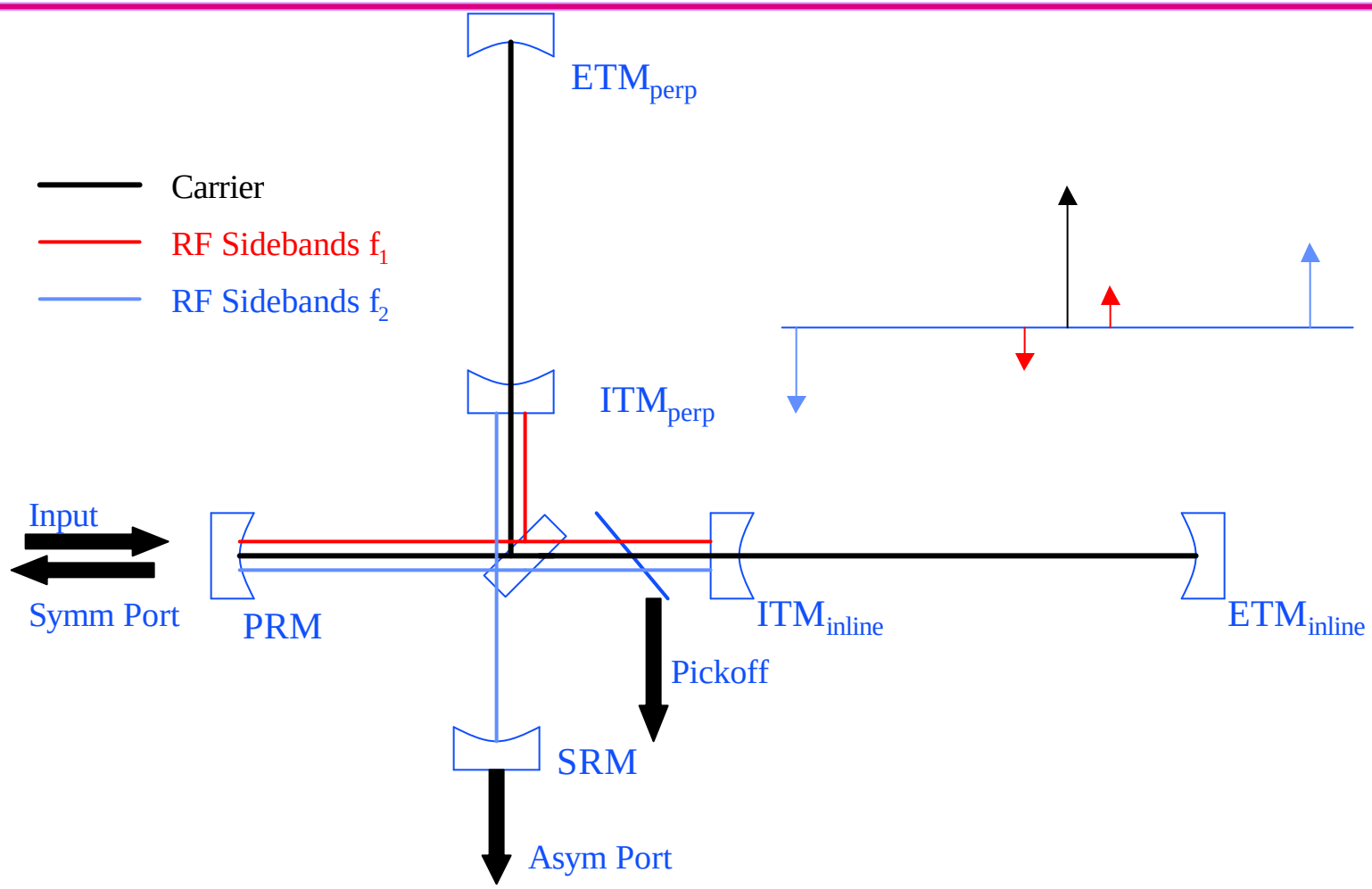
40m Laboratory Upgrade – More Objectives

- Expose shot noise curve, dip at tuned frequency
- Multiple pendulum suspensions
  - » this may be necessary, to extrapolate experience gained at 40m on control of optics, to LIGO-II
  - » For testing of mult-suspension controllers, mult-suspension mechanical prototypes, interaction with control system
  - » Not full scale. Insufficient head room in chambers.
  - » Won't replace full-scale LASTI tests.
- thermal noise measurements
  - » Mirror Brownian noise will dominate above 100 Hz.
- Facility for testing/staging small LIGO innovations
- Hands-on training of new IFO physicists!
- Public tours (SURF/REU students, DNC media, princes, etc)

Optical configuration design

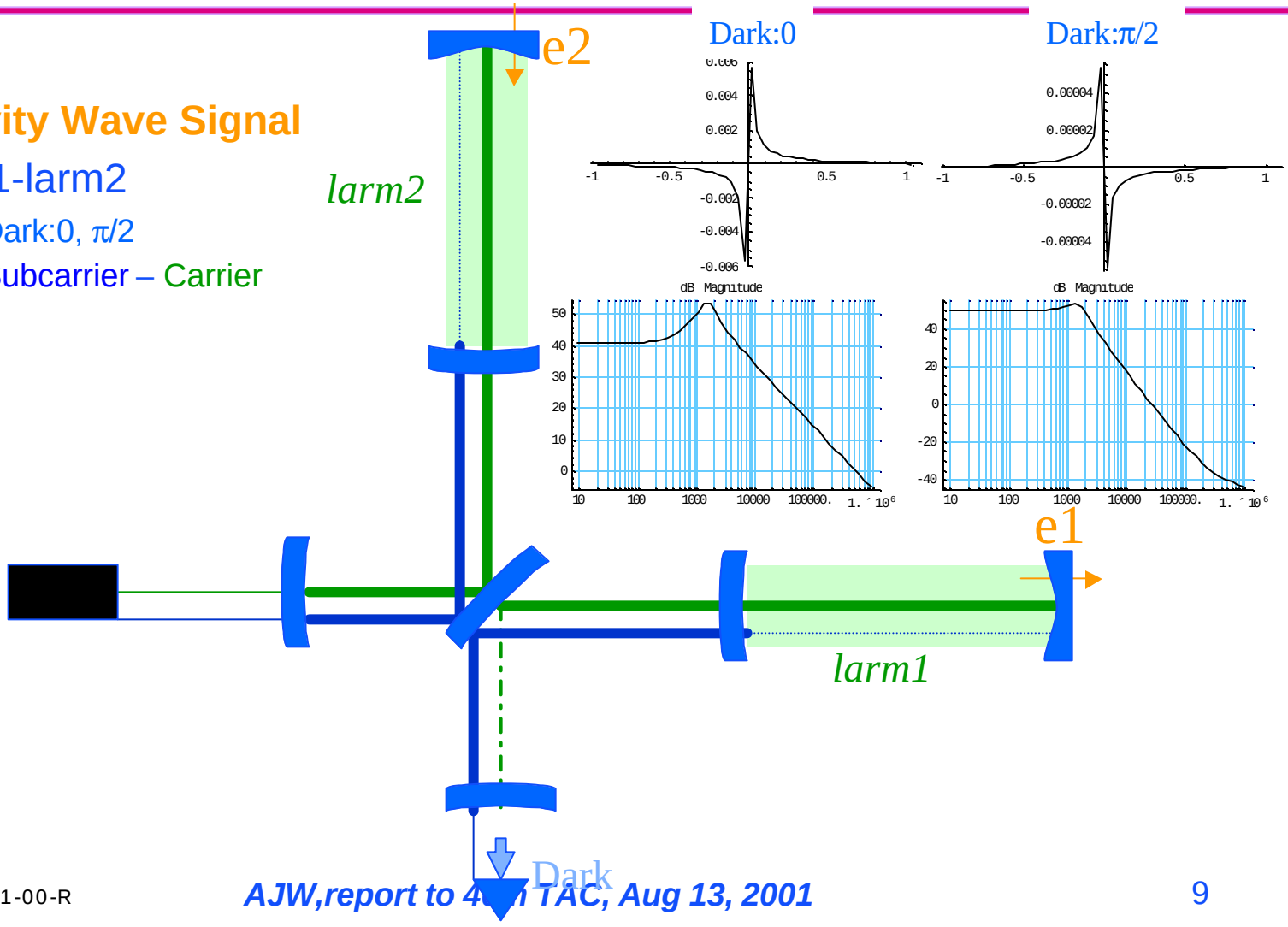
- **A working draft of the 40m upgrade conceptual design report (T010029, link on 40m web page) is substantially complete, and an update will follow this meeting**
- **Requires careful review, prior to and at the Conceptual Design Review (10/18/01)**
  - » **Infrastructure upgrade**
  - » **Optical topology (Dual recycled Michelson with F-P arms)**
  - » **Mirror dimensions, transmissivities, cavity finesses, etc**
  - » **Cavity lengths, RF frequencies, resonance conditions**
  - » **SRC tune specified, transfer function determined**
  - » **Mirror ROC, beam dimensions everywhere**
  - » **12m Input Mode Cleaner design, expected performance**
  - » **DC detection scheme**
  - » **Twiddle modeling, DC fields, length sensing matrix**
  - » **ModalModel, alignment sensing matrix, WFS parameters**
  - » **Expected noise (BENCH)**
  - » **Thermal effects – estimated to be negligible (Kells, AJW)**
- **Mike Smith preparing a detailed optical design requirements document.**

Control topology for Advanced LIGO



Control signals from Twiddle Differential Arm (L-)

- **Gravity Wave Signal**
- larm1-larm2
  - » Dark:0, π/2
  - » Subcarrier – Carrier



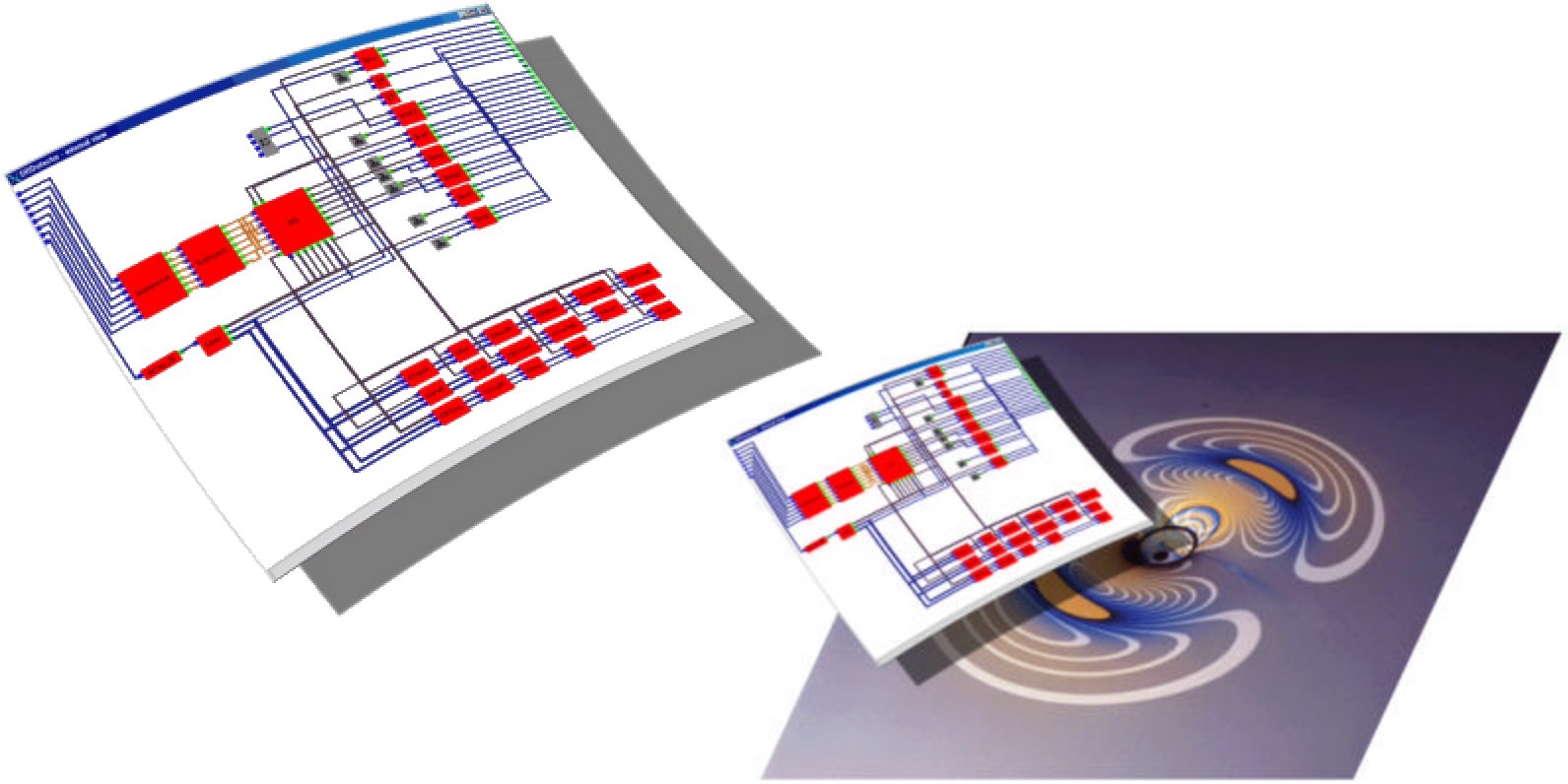
Length sensing signals from Twiddle

Table 4: LSC signals. ⊗ means double demodulation.

Signal	L_+	L_-	l_+	l_-	l_s
SP, f_1	**18.4**	0.01	-0.03	0.12	0.006
AP, f_2	0	**-42.8**	0	-0.05	0
SP, $f_2 - f_1$	0.004	0.002	**-0.155**	0.045	0.088
AP, $f_2 \otimes f_1$	0.0001	0.0002	0.0002	**0.0036**	-0.0019
PO, $f_2 - f_1$	-0.041	0.012	-0.363	0.225	**1.22**

- **Twiddle is a Mathematica program to numerically calculate response of RF demodulation of IFO signals in response to motion of mirrors away from locked configuration.**
- **Can construct MIMO length sensing and control matrix.**
- **AdvLIGO control matrix much more diagonal than LIGO I!**
- **Mainly due to the availability of 2 pairs of RF sidebands**
- **Use double demodulation at asym port for the Michelson (l_-) signal**

Modeling: E2E/DRLIGO



Comparing Twiddle and E2E: DC Fields

Richard George 9th August 2001 Hanford

Fields agree between E2E and Twiddle well at DC.

Power Recycling Fields	Power Twiddle (W)	Power E2E (W)	Error (%)
-2 Sideband	0.0452101	0.042669	1.45%
-1 Sideband	0.10813	0.107517	0.14%
Carrier	13.9928	13.013907	1.81%
+1 Sideband	0.10813	0.107517	0.14%
+2 Sideband	0.0452101	0.042669	1.45%

Input	Power Twiddle (W)	Power E2E (W)	Error (%)
-2 Sideband	0.00249371	0.002481	0.13%
-1 Sideband	0.00249371	0.002481	0.13%
Carrier	0.990025	0.990044	0.00%
+1 Sideband	0.00249371	0.002481	0.13%
+2 Sideband	0.00249371	0.002481	0.13%

Signal Recycling Fields	Power Twiddle (W)	Power E2E (W)	Error (%)
-2 Sideband	0.0429205	0.044945	-1.15%
-1 Sideband	0.000162607	0.00017	-1.11%
Carrier	0	0	0.00%
+1 Sideband	0.000162607	0.00017	-1.11%
+2 Sideband	0.0429205	0.044945	-1.15%

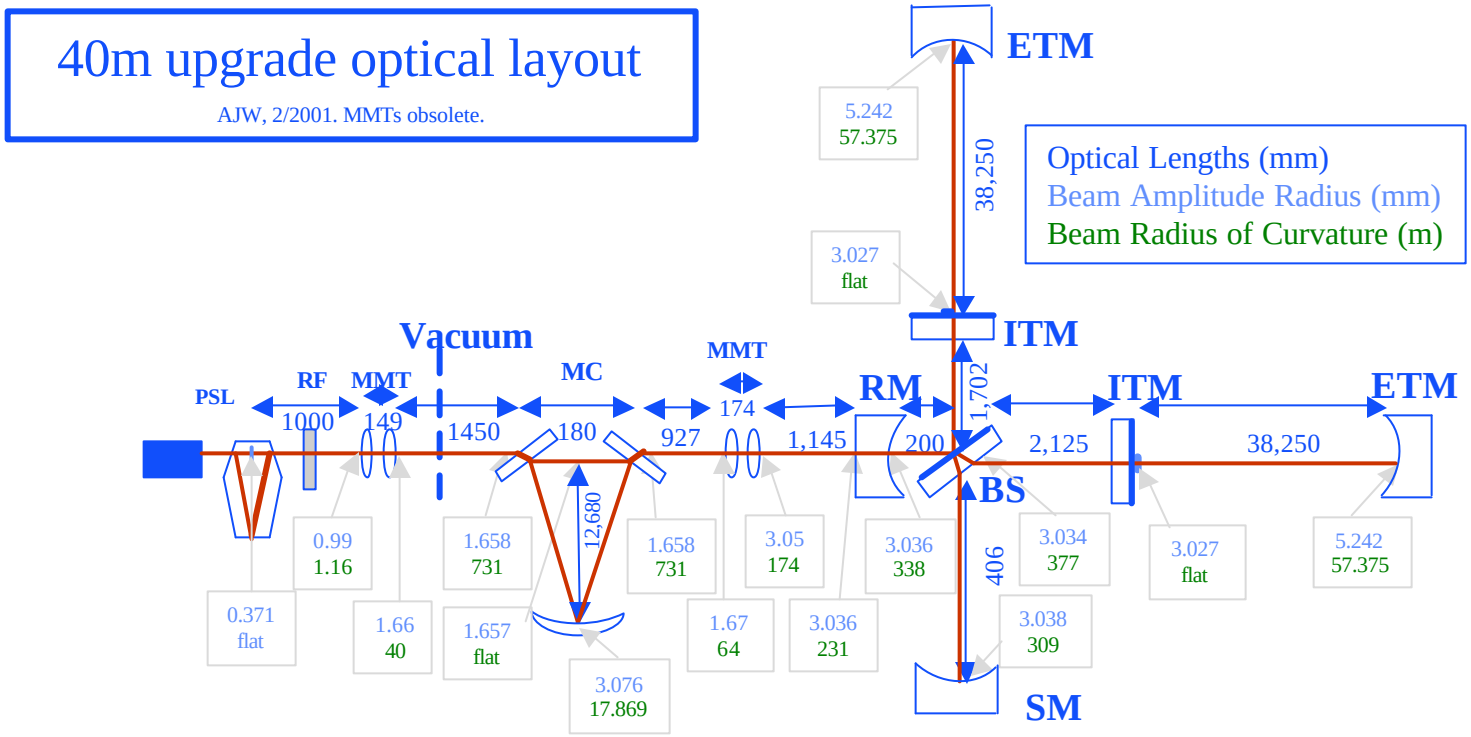
Reflected Fields	Power Twiddle (W)	Power E2E (W)	Error (%)
-2 Sideband	0.000175061	0.000175	0.01%
-1 Sideband	0.00241193	0.0024	0.12%
Carrier	0.011389	0.01138	0.02%
+1 Sideband	0.00241193	0.0024	0.12%
+2 Sideband	0.000175061	0.000175	0.01%

Transmission Arm	Power Twiddle (W)	Power E2E (W)	Error (%)
-2 Sideband	7.75625E-05	0.000078	-0.14%
-1 Sideband	0.000273275	0.000272	0.12%
Carrier	5386.13	5385.819498	0.00%
+1 Sideband	0.000273275	0.000272	0.12%
+2 Sideband	7.75625E-05	0.000078	-0.14%

Dark Port	Power Twiddle (W)	Power E2E (W)	Error (%)
-2 Sideband	0.00225907	0.002247	0.13%
-1 Sideband	8.56E-06	0.000009	-1.26%
Carrier	0	0	0.00%
+1 Sideband	8.56E-06	0.000009	-1.26%
+2 Sideband	0.00225907	0.002247	0.13%

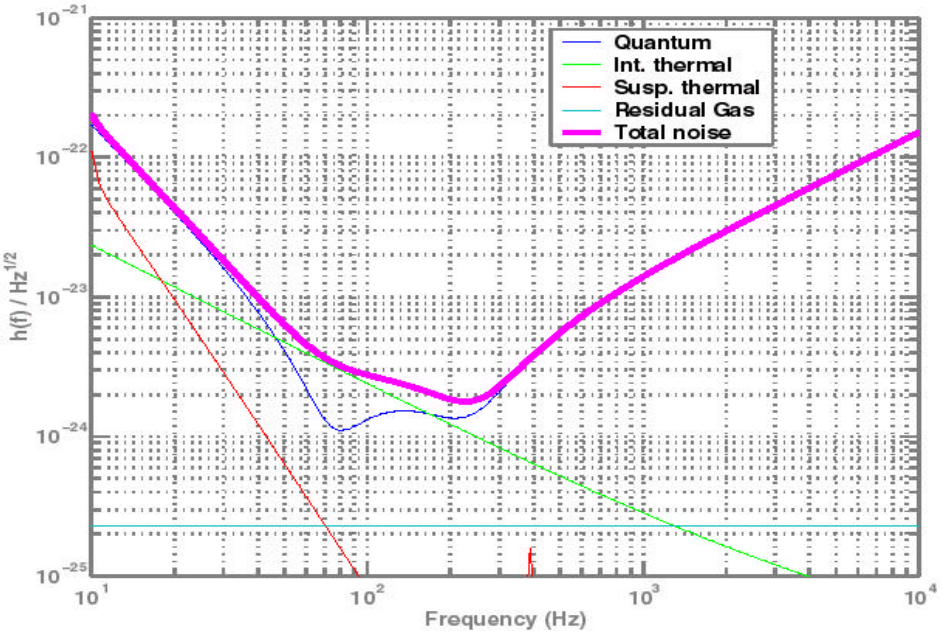
Reflected Arm	Power Twiddle (W)	Power E2E (W)	Error (%)
-2 Sideband	7.73162E-05	0.000078	-0.22%
-1 Sideband	0.000273368	0.000272	0.13%
Carrier	5386.13	5385.819498	0.00%
+1 Sideband	0.000273368	0.000272	0.13%
+2 Sideband	7.73162E-05	0.000078	-0.22%

Optics Parameters

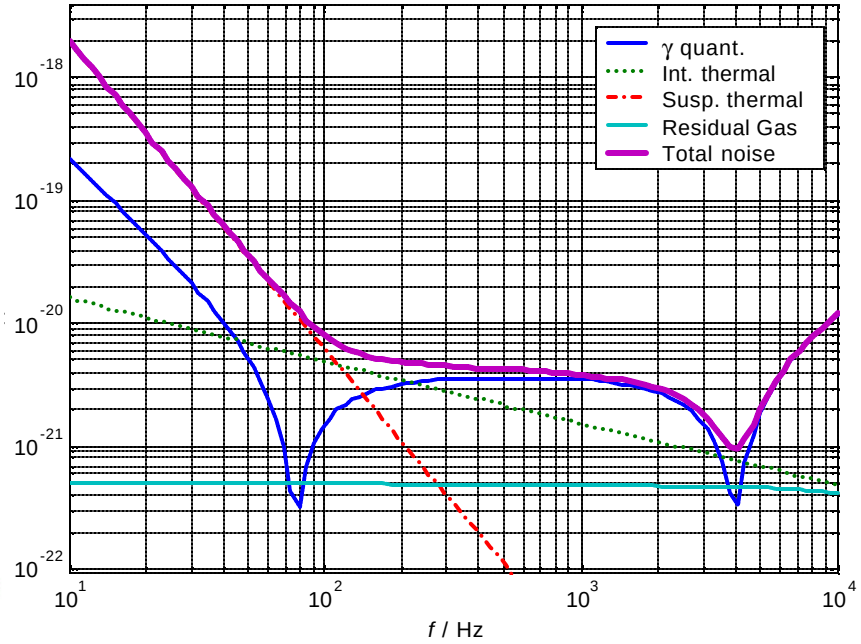


AdvLIGO and 40m noise curves

AdvLIGO (PF, 7/01)



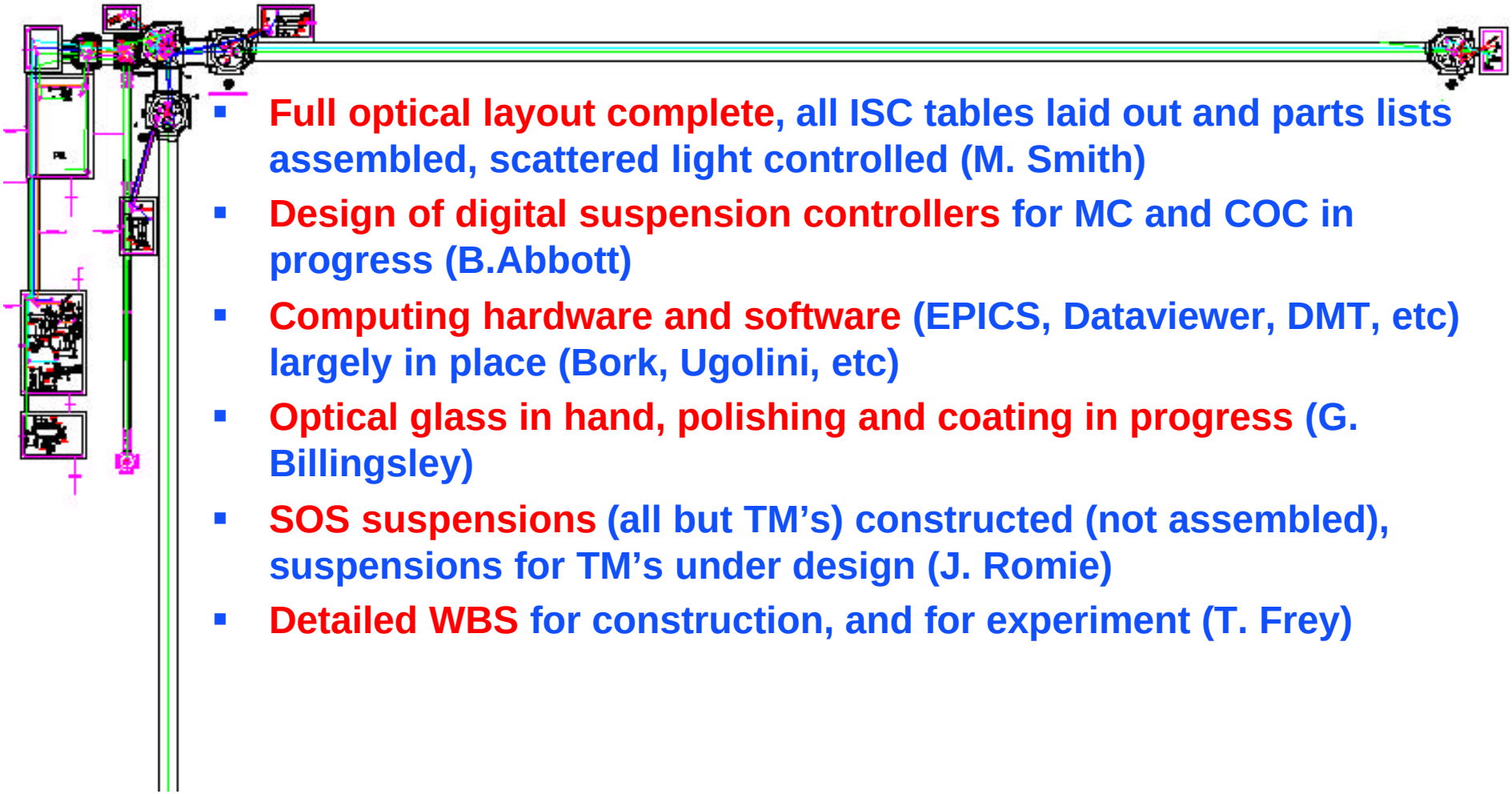
40m



Milestones Achieved so far

- **Lab infrastructure substantially complete, incl new conditioned power and new 12” cable trays**
- **Active seismic isolation system installed, commissioned (Vass, Jones, etc)**
- **Vacuum control system complete (D. Ugolini)**
- **Vacuum envelope for 12m MC and output optic chamber installed (Vass, Jones)**
- **All but one optical table in place (Vass, Jones)**
- **Remaining on infrastructure: install seismic stacks for 12m MC and OOC; all in-vacuum cabling; and one more (big) optical table.**
- **DAQ system installed, logs frames continuously (R. Bork)**
- **PSL installed, commissioned; full tuning and characterization in progress (P. King, L. Cardenas, R. Karwoski, P. Russell, D. Ugolini, B. Abbott, SURFs)**
- **Many PEM devices installed, in EPICS and DAQS, and in routine use (vacuum gauges, weather station, dust monitor, STACIS, accelerometer, mics, …) (Ugolini, SURF Tsai).**

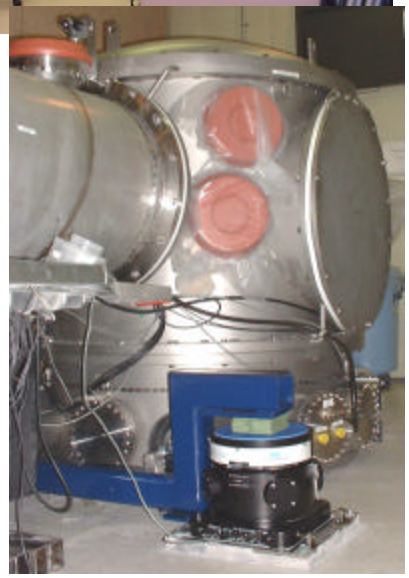
More milestones achieved



- **Full optical layout complete, all ISC tables laid out and parts lists assembled, scattered light controlled (M. Smith)**
- **Design of digital suspension controllers for MC and COC in progress (B.Abbott)**
- **Computing hardware and software (EPICS, Dataviewer, DMT, etc) largely in place (Bork, Ugolini, etc)**
- **Optical glass in hand, polishing and coating in progress (G. Billingsley)**
- **SOS suspensions (all but TM's) constructed (not assembled), suspensions for TM's under design (J. Romie)**
- **Detailed WBS for construction, and for experiment (T. Frey)**

40m Infrastructure – substantially complete

- **Dismantling of old IFO, distribution of surplus equipment to LIGO and LSC colleagues**
- **Major building rehab:**
  - » **IFO hall enlarged for optics tables and electronics racks**
  - » **roof repaired, leaks sealed**
  - » **new electrical feeds and conditioners, 12" cable trays, etc**
  - » **new control room and physicist work/lab space**
  - » **New entrance room/changing area**
  - » **rehab of cranes, safety equipment, etc**
- **Active seismic isolation system (STACIS) procured, installed, and commissioned on all four test mass chambers**



STACIS Active seismic isolation

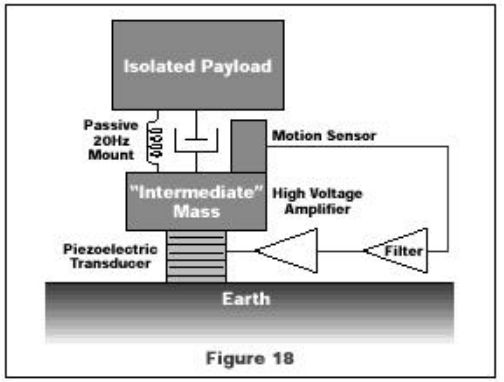
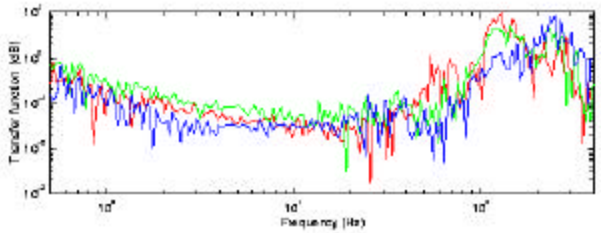
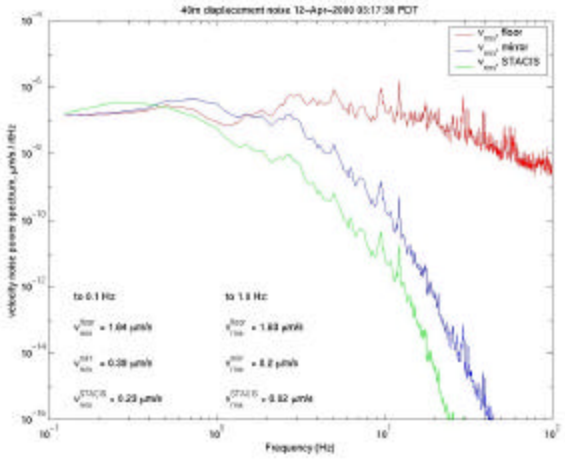


Figure 18

- One set of 3 for each of 4 test chambers
- 6-dof stiff PZT stack
- Active bandwidth of 0.3-100 Hz,
- 20-30dB of isolation
- passive isolation above 15 Hz.

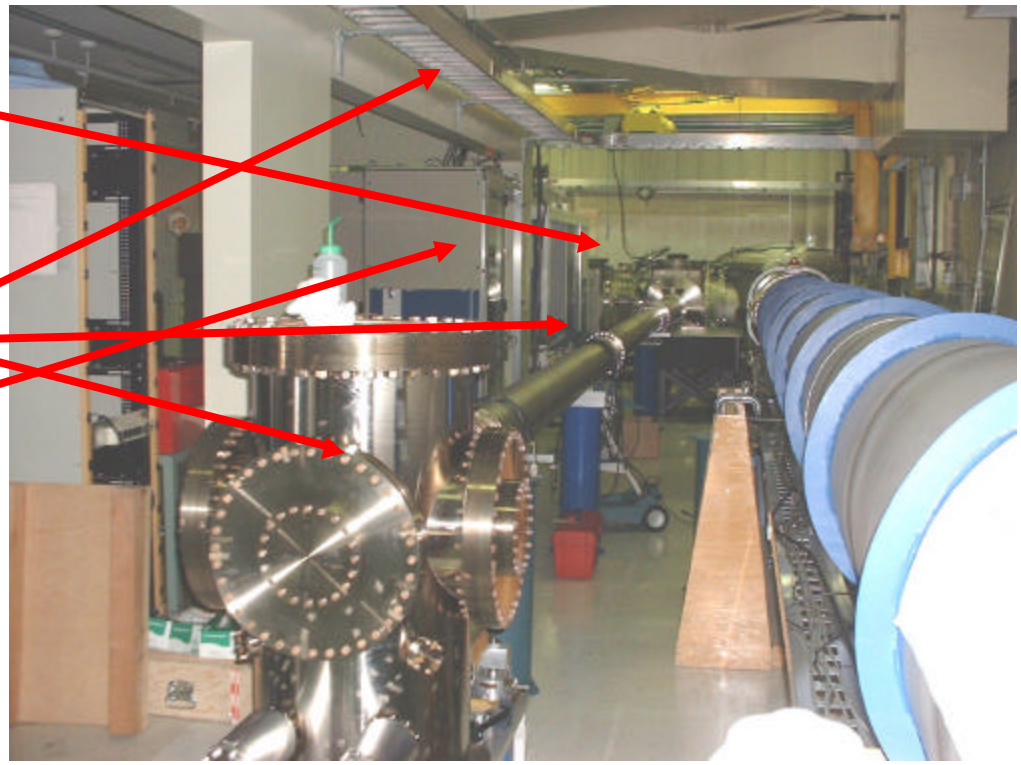




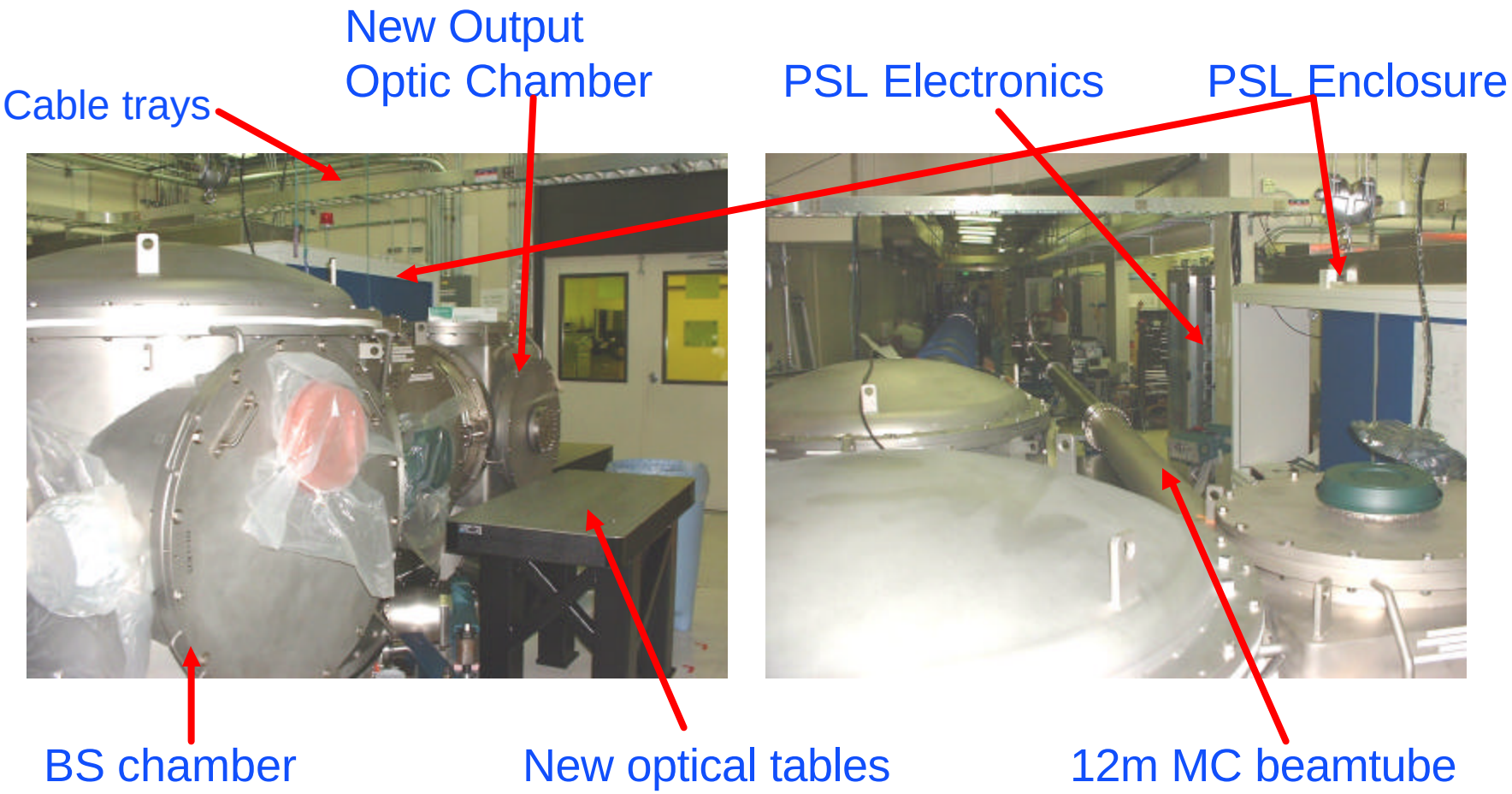
AJW,report to 40m TAC, Aug 13, 2001

40m Infrastructure, continued

- **New vacuum control system and vacuum equipment**
  - » **Installed and commissioned**
- **New output optic chamber, seismic stack fabricated**
  - » **Chamber installed in July, stack to be installed in fall 2001**
- **Vacuum envelope for 12 m input mode cleaner fabricated**
  - » **Chamber installed in July, stack to be installed in fall 2001**
- **All electronics racks, crates, cable trays, computers, network… procured and installed**

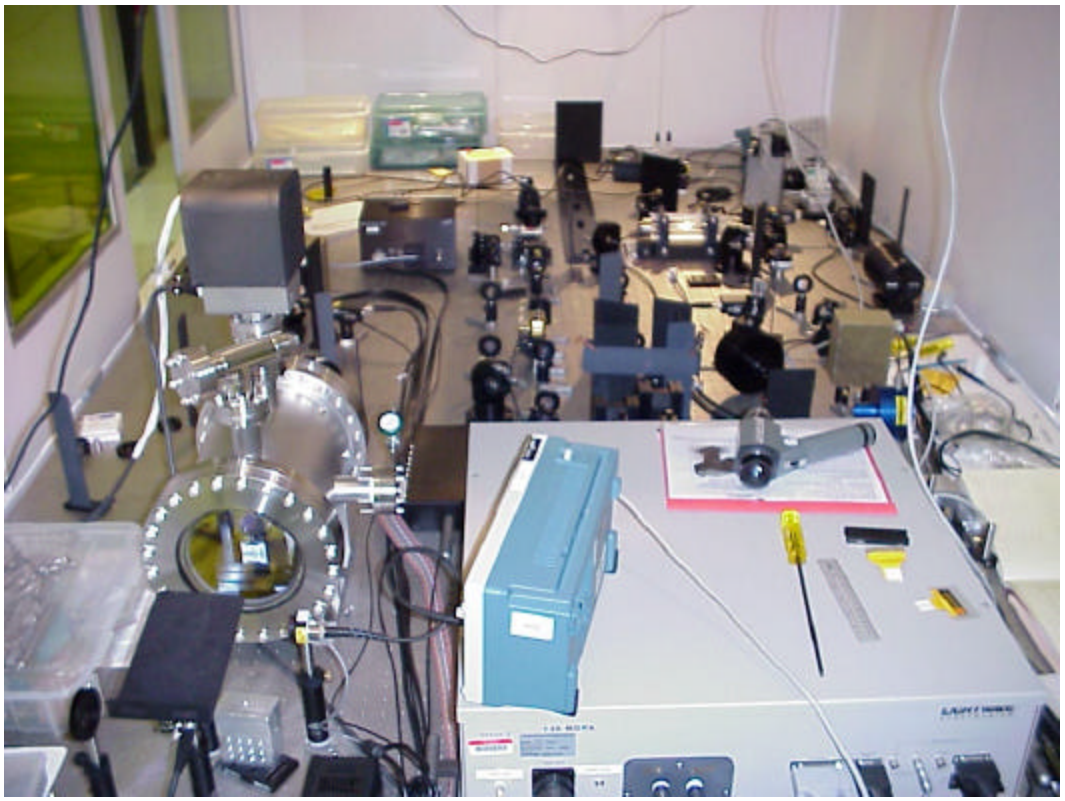


New vacuum envelope at 40m

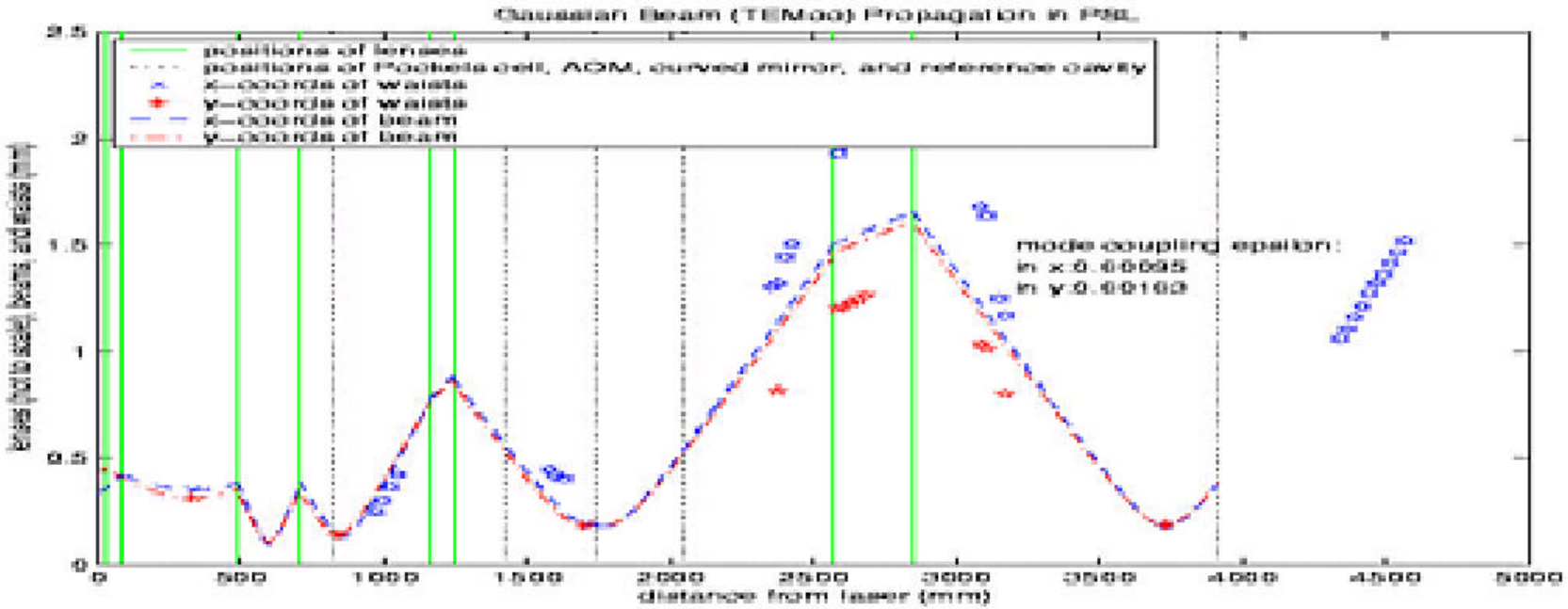


40m PSL

- LIGO-I PSL installed in June by Peter King, Lee Cardenas, Rick Karwoski, Paul Russell
- Spent the last month fixing birthing problems, tuning up (Ugolini, Ben Abbott, SURF students)
- All optical paths have had one round of mode matching tune-up, comparing BeamScan with model; round 2 coming up.
- Frequency stability servo (FSS) and PMC servo (PMCS) have been debugged
- Both servos now lock easily, reliably, stably
- DAQ birthing problems have been fixed; full DAQ readout of fast channels (and slow EPICS channels) logged to frames routinely
- Frequency reference cavity has visibility > 94%; PMC has visibility ~80% and transmission > 50%. More tuning required, and Peter will install less lossy curved mirror sometime soon.
- No temp stability on Freq reference cavity; Peter should have heating jacket on order.
- Full characterization of PSL in progress, first draft available within a month:
  - Frequency noise
  - Intensity noise
  - Pointing and angle jitter
  - Long-term stability of frequency, intensity, pos/angle
  - Beam size and mode matching everywhere on table.

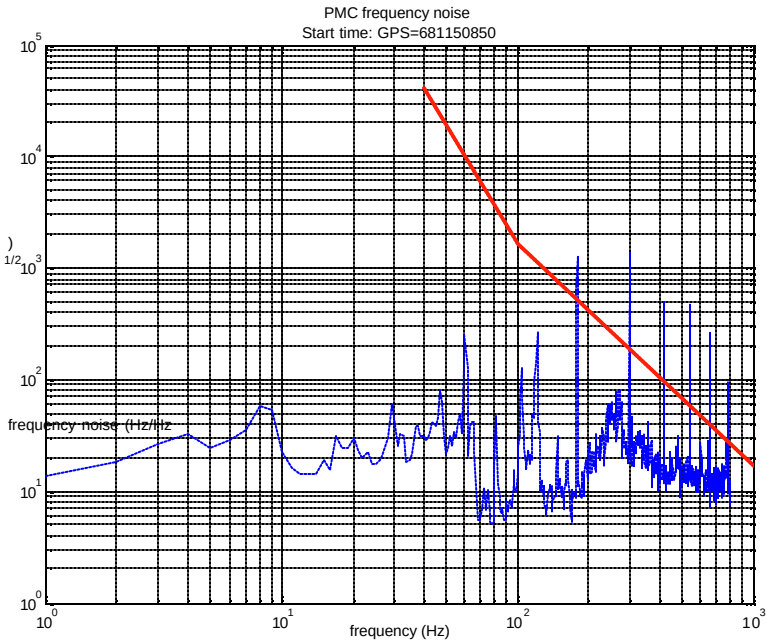


PSL Mode Matching (SURF Tim Piatenko)

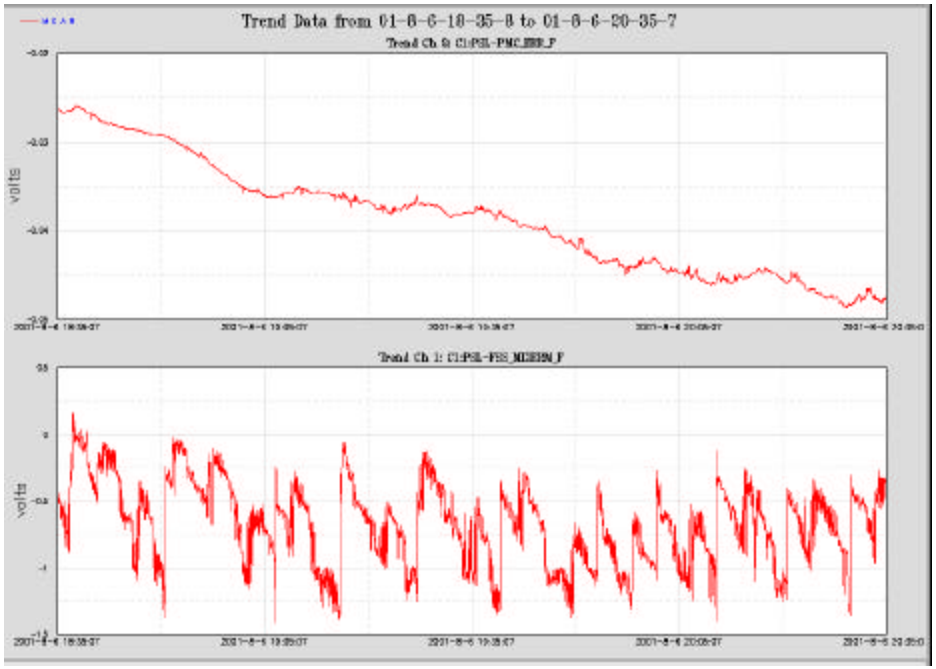


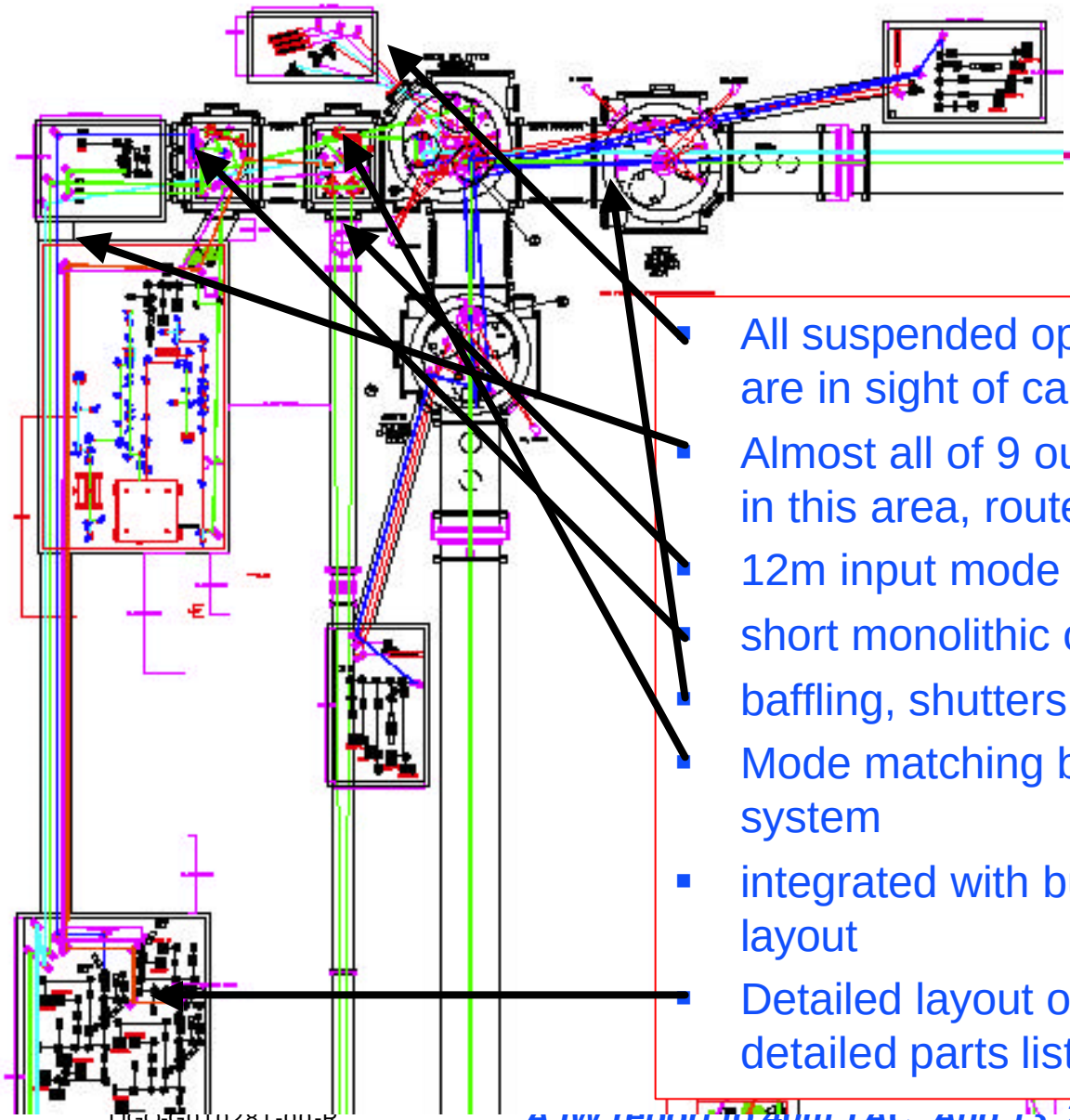
Preliminary PSL performance results (SURF A. DeMichele)

PMC servo noise



PMC and FSS stability

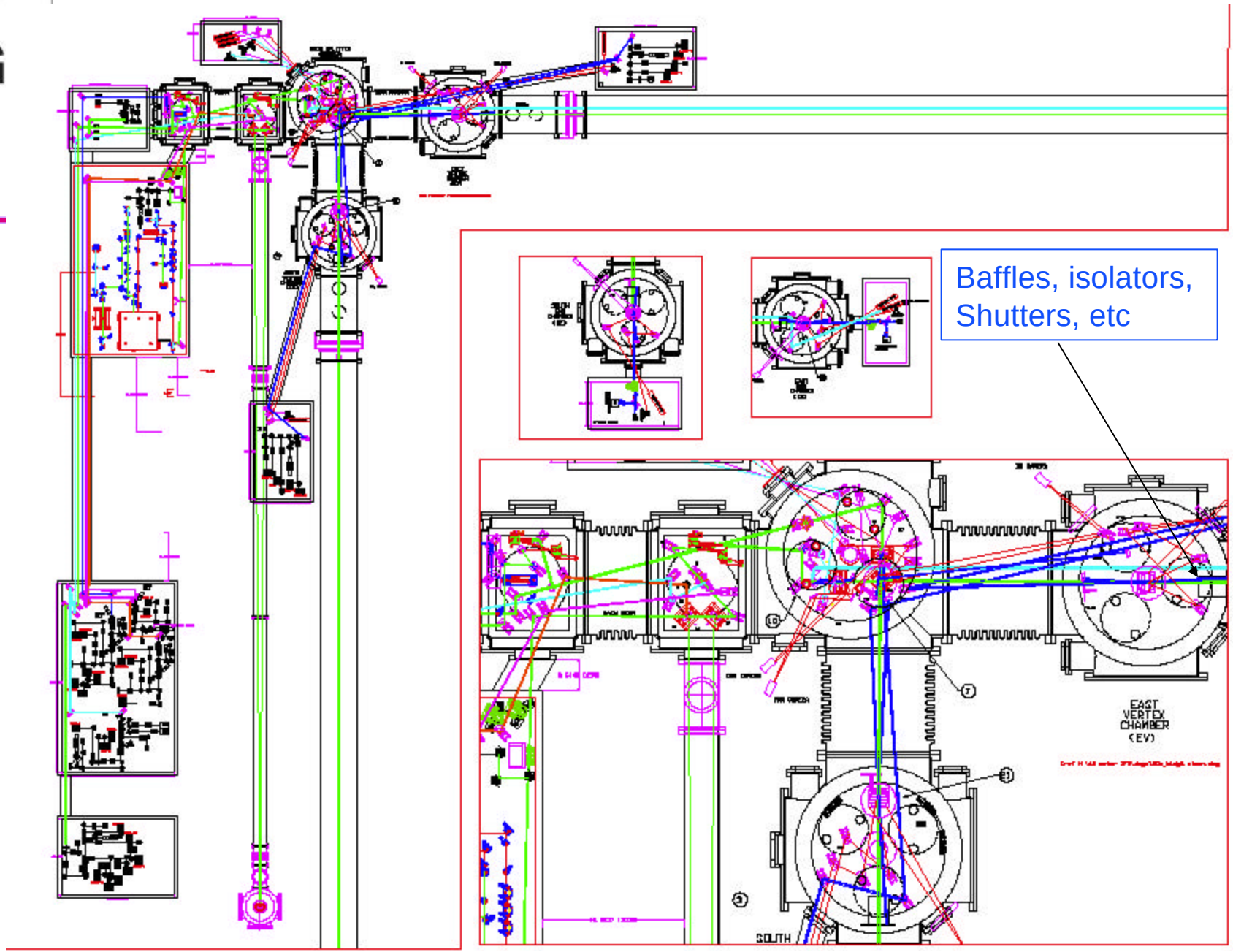




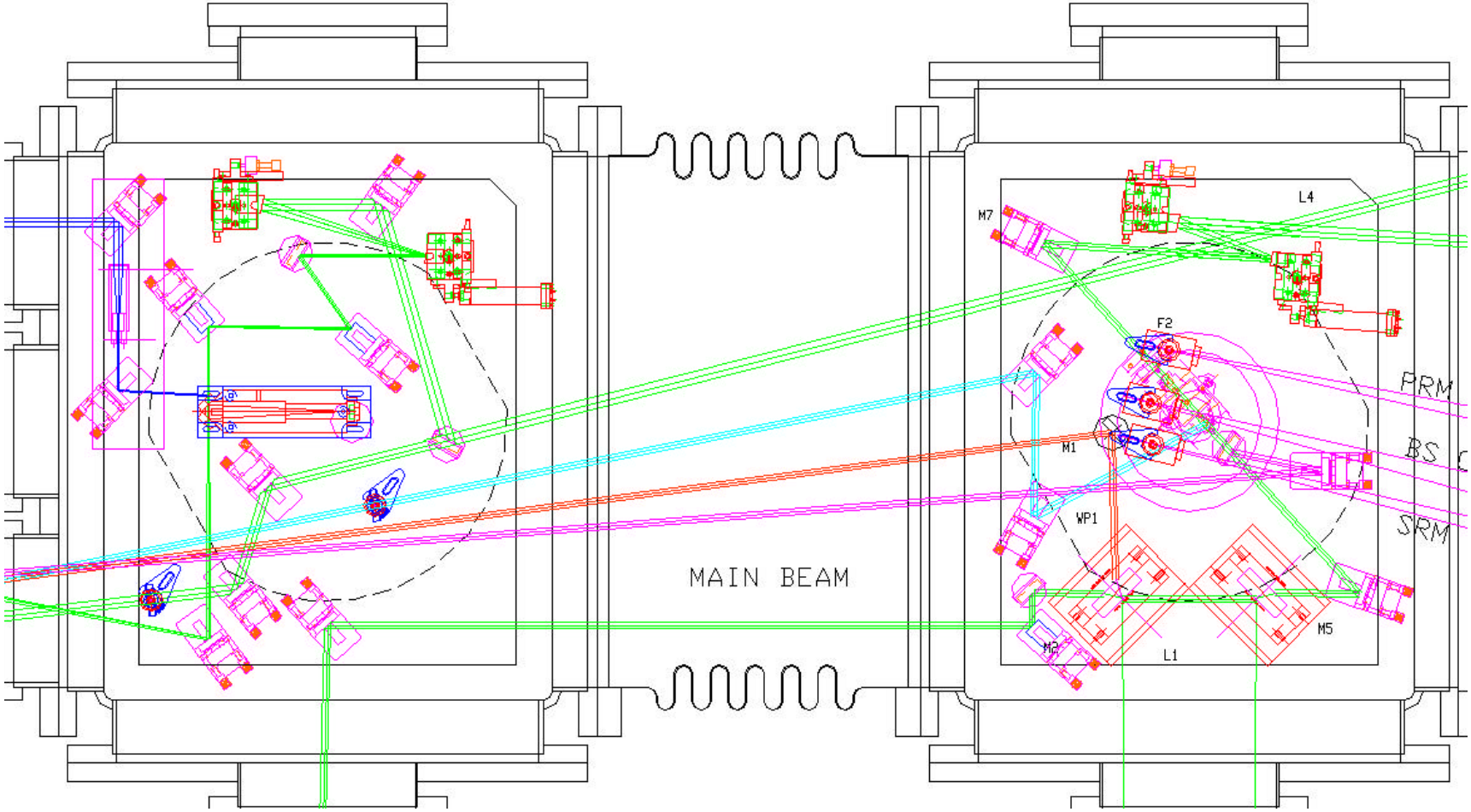
Optical Layout

Mike Smith

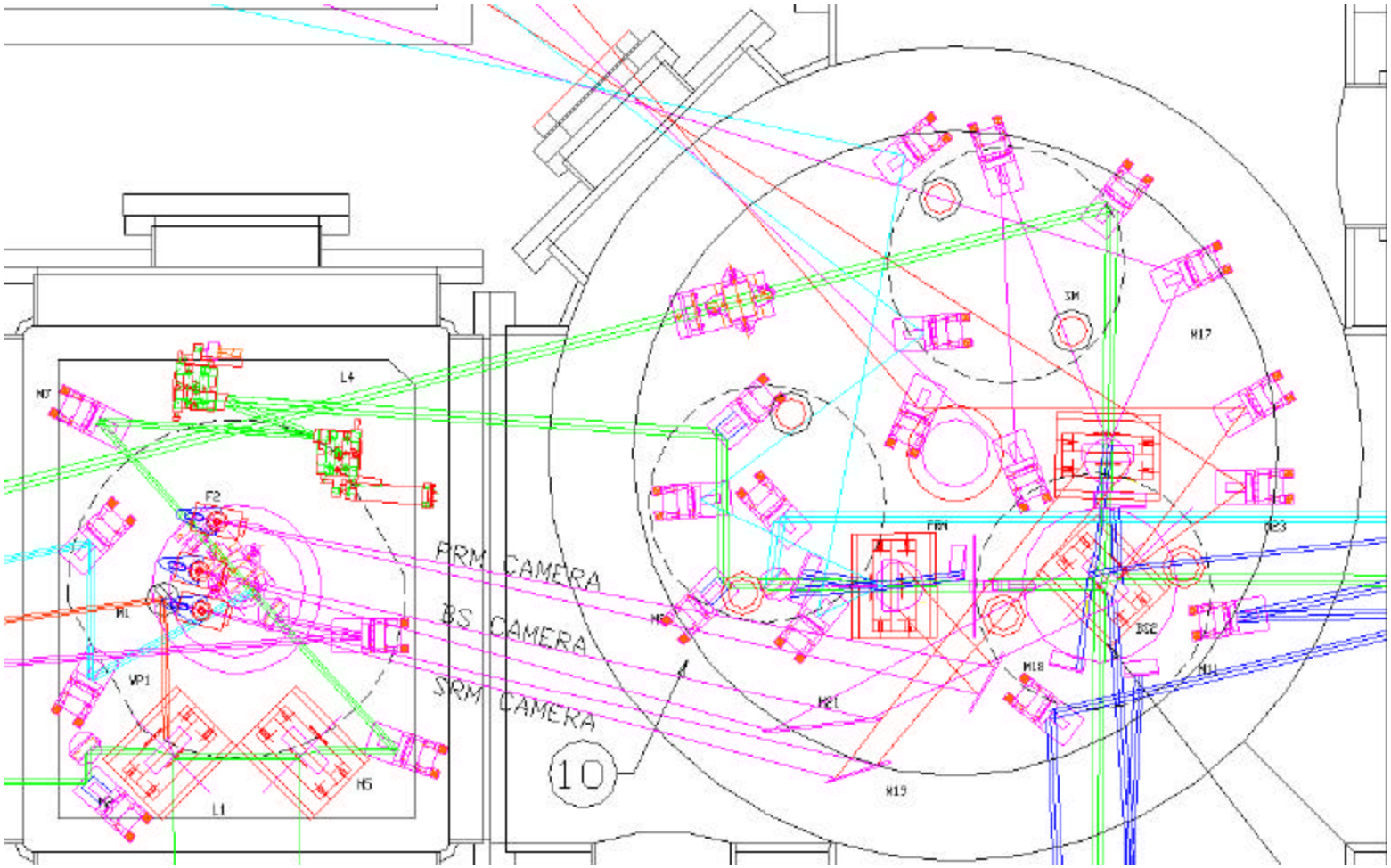
- All suspended optics have OpLevs and are in sight of cameras
- Almost all of 9 output beams come out in this area, routed to ISC tables
- 12m input mode cleaner
- short monolithic output MC
- baffling, shutters, scattered light control
- Mode matching between each optical system
- integrated with building, electrical, CDS layout
- Detailed layout of all ISC tables, with detailed parts lists


Baffles, isolators,
Shutters, etc
EAST
VERTEX
CHAMBER
(EV)
SOUTH

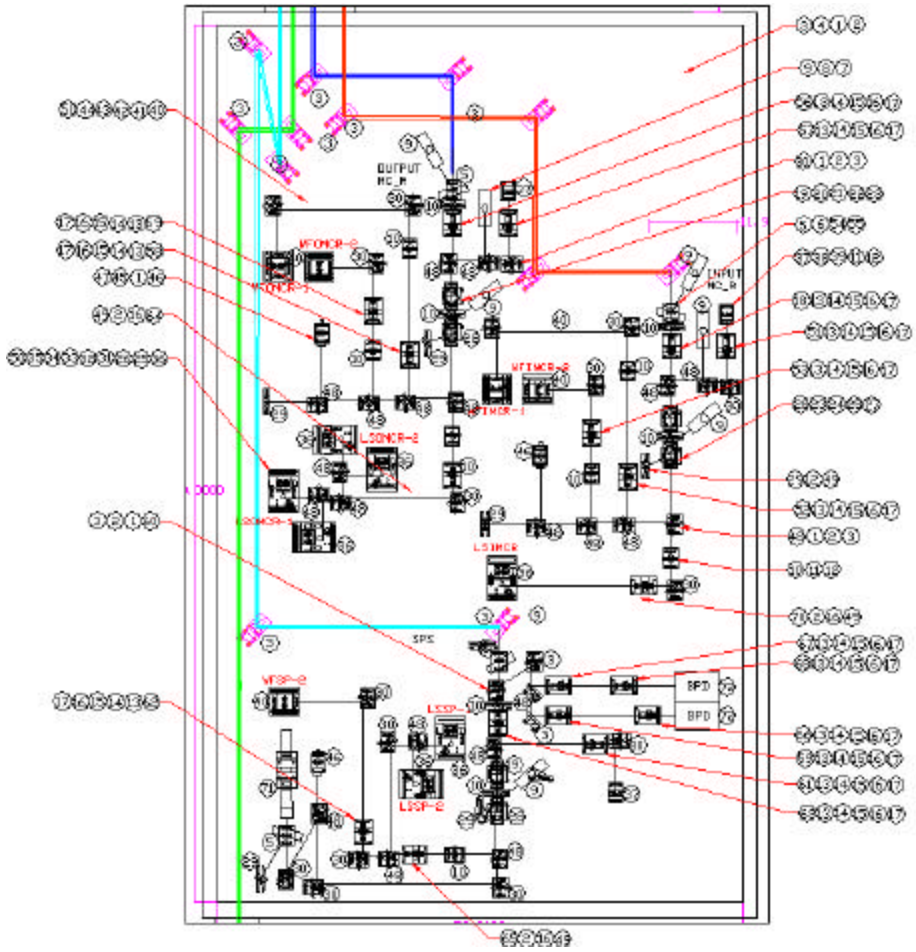
Output and Input Optic Chambers

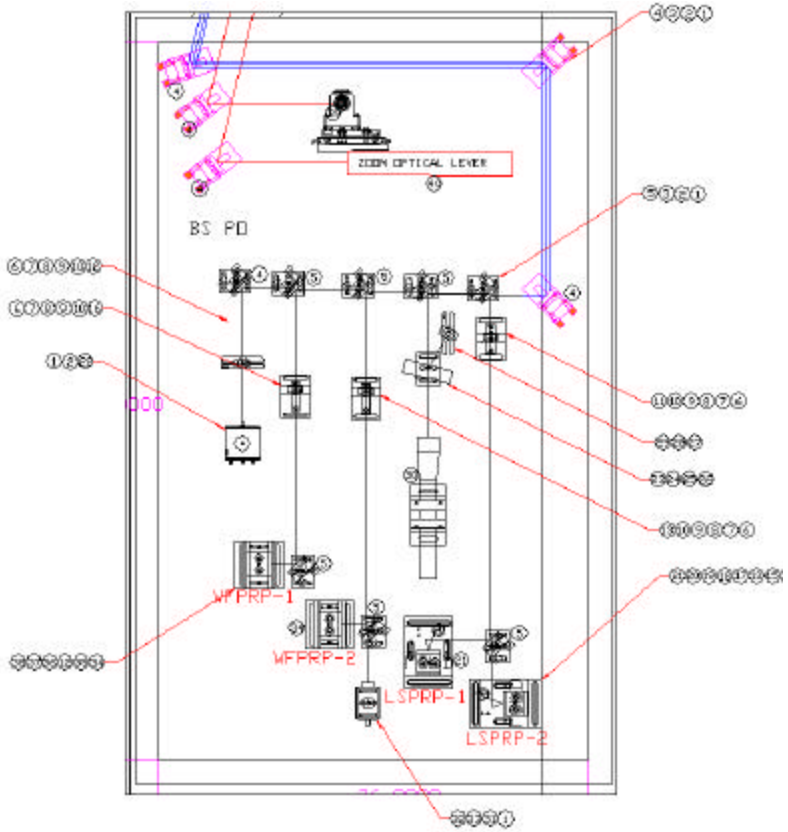


Input Optic and BS chambers



Detailed layouts of ISC tables, parts lists





Optics, suspensions

- All glass blanks received (3 MC, 2 RM, BS, ITMs, ETMs, + spares) received from Corning and Heraeus.
- 3 MC mirrors + spares are at WP for coating (they broke 2 blanks already).
- Hope to have 3 MC mirrors polished, coated, and ready for hanging by beginning of 2002.
- Specs near readiness for polishing and coating core optics; hope to have them ready for hanging by fall 2002.
- Parts for SOS suspensions (all but the 4 TM's) are in hand (first set went to Hanford; now have 2nd set).
- Janeen hopes to finish design for TM suspensions by end of summer; constructed by beginning of 2002.
- Ben Abbott (with Jay Heefner) designing and assembling digital suspension controllers for all 10 suspended optics.

Milestones through 2004

- **4Q 2001: Infrastructure complete**
  - » PSL, 12m MC envelope, vacuum controls, DAQS, PEM
  - » Conceptual design review. Begin procurement of CDS, ISC, etc
- **2Q 2002:**
  - » 12m input MC optics and suspensions, and suspension controllers.
  - » Begin installation and commissioning of 12m input mode cleaner
- **4Q 2002:**
  - » Core optics (early) and suspensions ready. Suspension controllers. Some ISC.
  - » Glasgow 10m experiment informs 40m program
  - » Control system finalized
- **2Q 2003:**
  - » Core optics (late) and suspensions ready. Suspension controllers.
  - » auxiliary optics, IFO sensing and control systems assembled
- **3Q 2003: Core subsystems commissioned, begin experiments**
  - » Lock acquisition with all 5 length dof's, 2x6 angular dof's
  - » measure transfer functions, noise
  - » Inform CDS of required modifications
- **3Q 2004: Next round of experiments.**
  - » DC readout. Multiple pendulum suspensions?
  - » Final report to LIGO Lab.

(Some) outstanding issues and action items

- IFO design (optics, sensing, control, etc) needs careful review by experts – before, during, and after October 18, 2001 CDR.
- Any significant changes in people's thinking re: optical configuration, controls, CDS architecture??
- Output mode cleaner – will PSL-PMC-like device be adequate? (For 40m, for AdvLIGO). Suspended?
- 180 MHz – too fast for WFS, LSC PD's?
- Detailed noise model (RSENOISE, Jim Mason)
- Triple-check LSC, ASC calculations (Twiddle, ModalModel)
- Design servo filters!
- Lock acquisition studies with E2E/DRLIGO
- Triple-check thermal effects (Melody) – negligible?
- DC GW PD – in vacuum?

SURF 2001 at the 40m

- Richard George, U. Cambridge
  - » E2E DRLIGO vs Twiddle
- Andrea DeMichele, Pisa
  - » 40m PSL servos characterization
- Mihail Amarie, Caltech/Romania
  - » burst waveforms, database events, coincidence analysis
- Tim Piatenko, Cornell/Moscow
  - » 40m PSL Optics characterization
- Victor Tsai, Caltech
  - » 40m PEM
- Irena Zivkovic, U. Nis, Serbia
  - » t/f characterization of SN burst waveforms