System and Subsystem Engineering of Long Baseline Detectors

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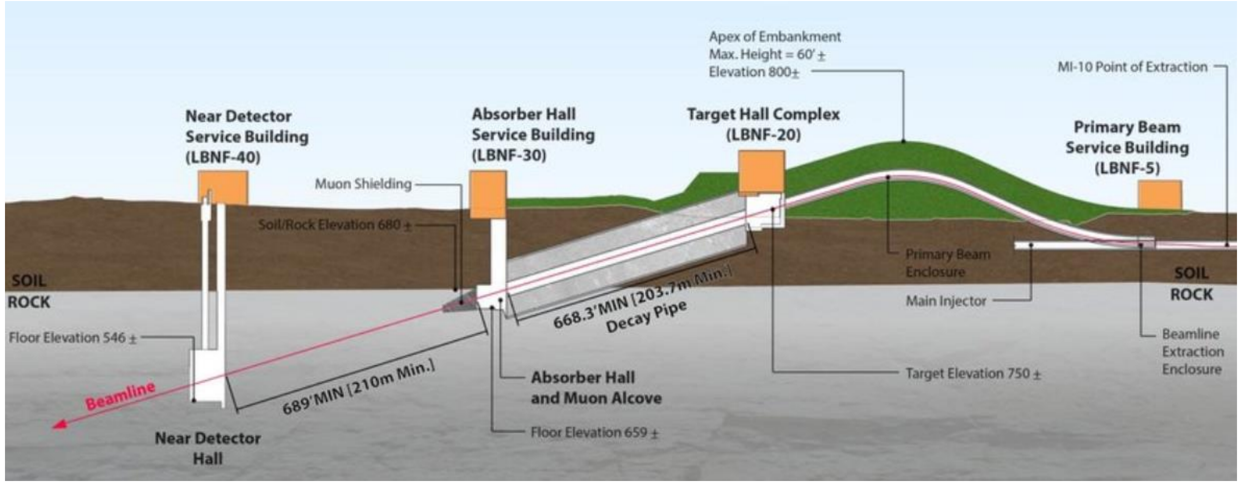
27 July 2021

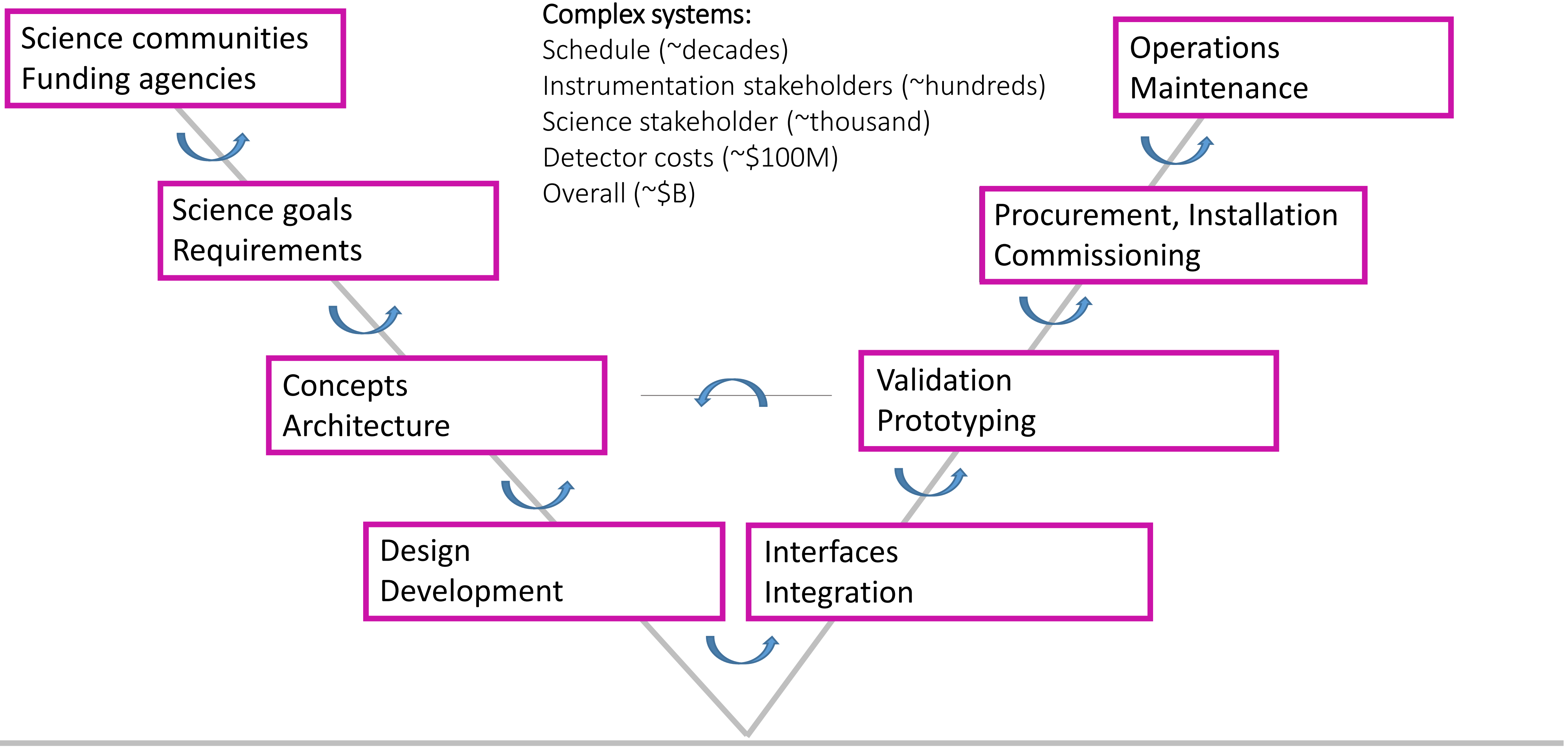
An overview of system engineering of large physics experiments

Gravitational wave detectors

Neutrino experiments

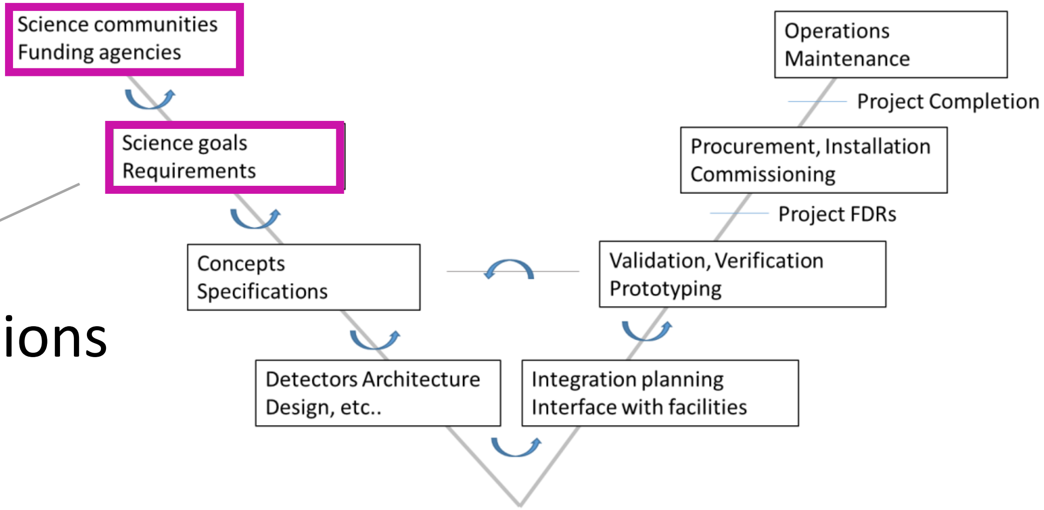


V-model of system engineering for large physics experiments

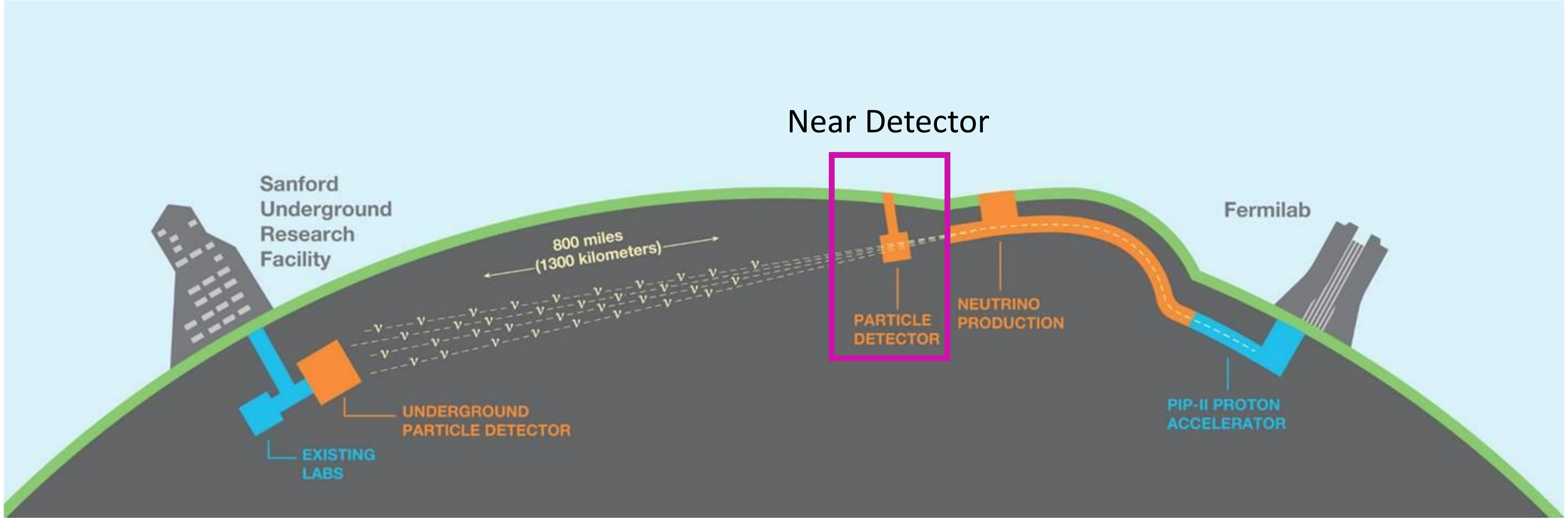


Complex systems:
Schedule (~decades)
Instrumentation stakeholders (~hundreds)
Science stakeholder (~thousand)
Detector costs (~$100M)
Overall (~$B)

Neutrino experiments

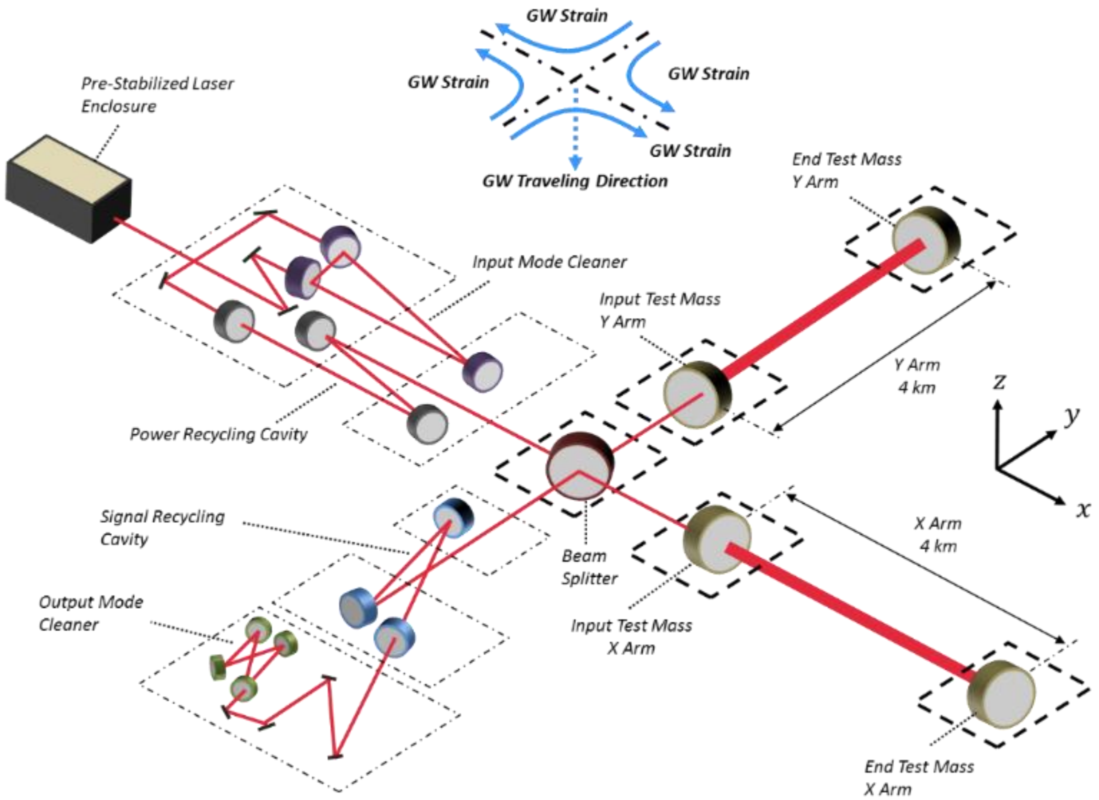


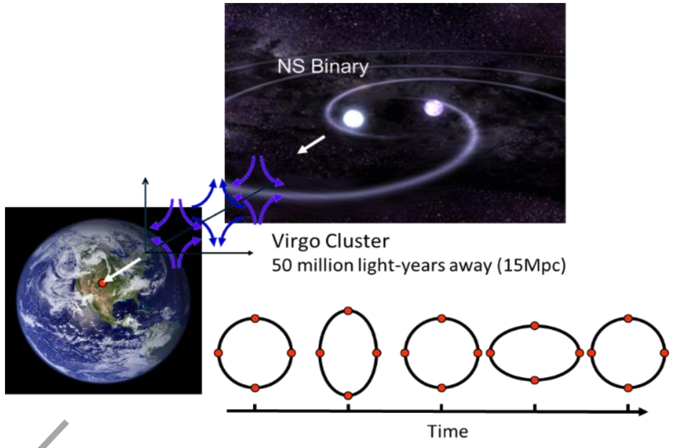
Long baseline to study neutrino oscillations

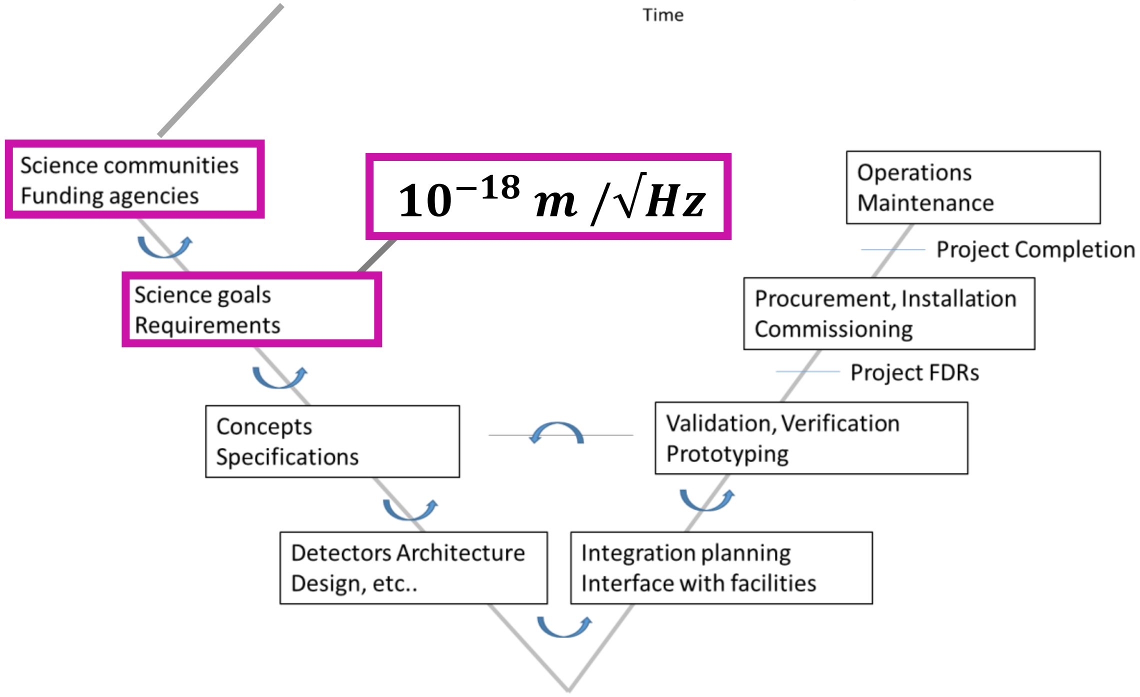


Gravitational wave detectors

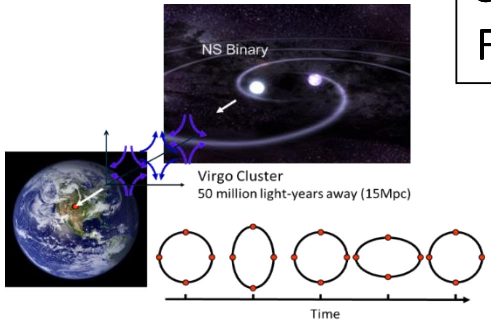
Long baseline to imprint the strain from gravitational waves





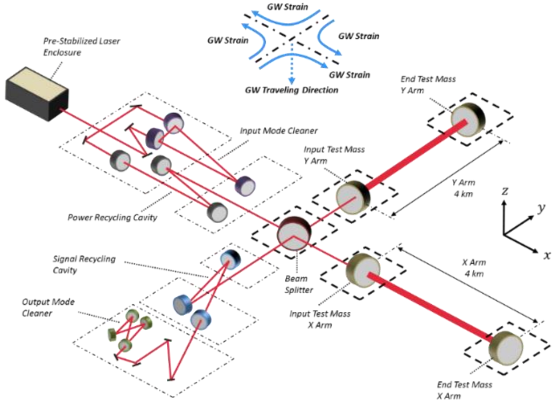


Left image source: Matichard, Classical and Quantum Gravity 32.18 (2015): 185003
Right image credit: image assembly by Beverly Berger, using NASA pictures



Science communities,
Funding agencies

Science goals,
Specifications

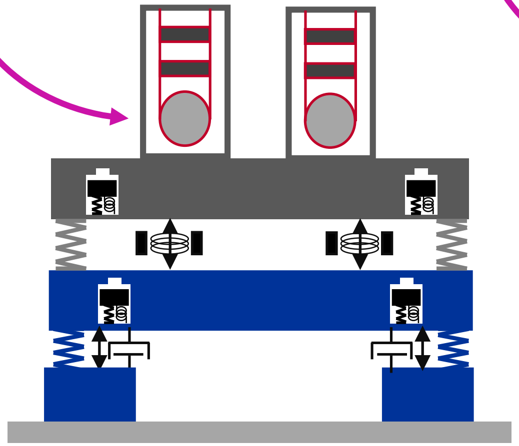


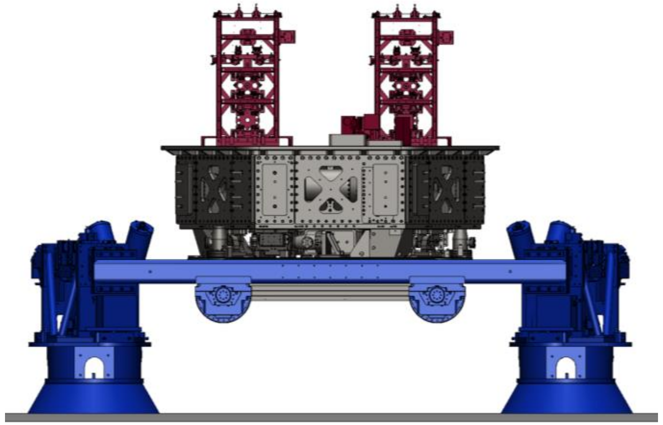
$$10^{-18}\ m\ /\sqrt{Hz}$$

Requirements

Architecture

Design



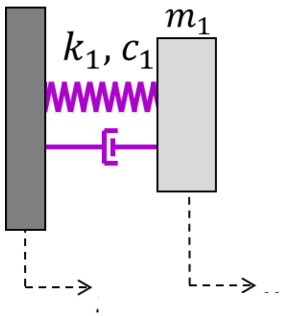


Top left: image assembly by Beverly Berger, using NASA pictures
Others: Matichard, Classical and Quantum Gravity 32.18 (2015): 185003

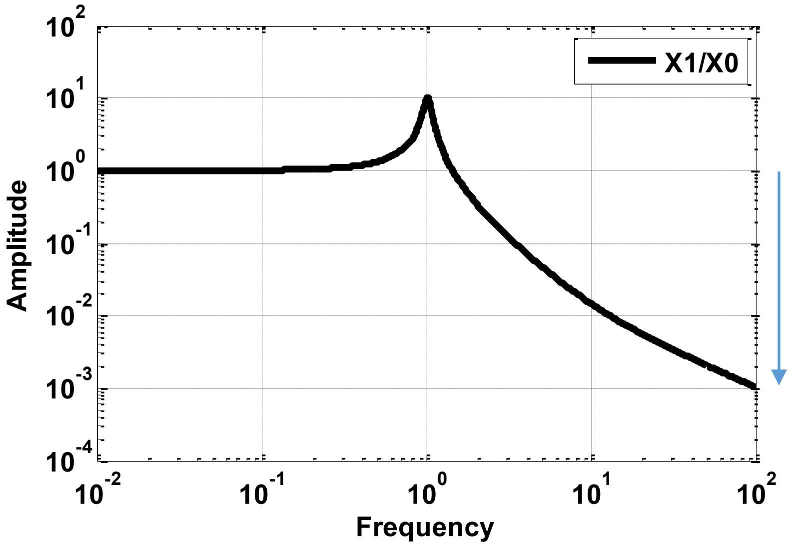
Requirements

Concepts

Inertial Decoupling

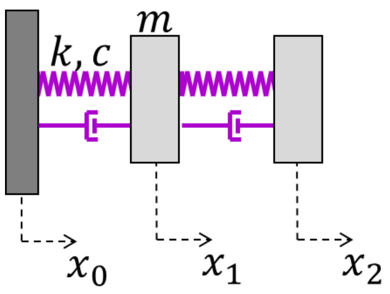


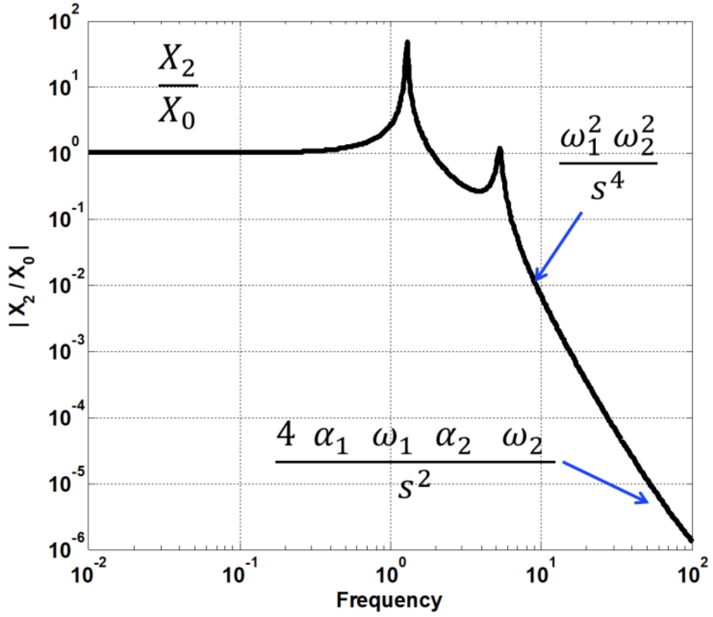
$$\frac{X_1}{X_0} = \frac{2\,\alpha\,\omega\,s + \omega^2}{s^2 + 2\,\alpha\,\omega\,s + \omega^2}$$



3 orders at 100Hz

Multi-Staging





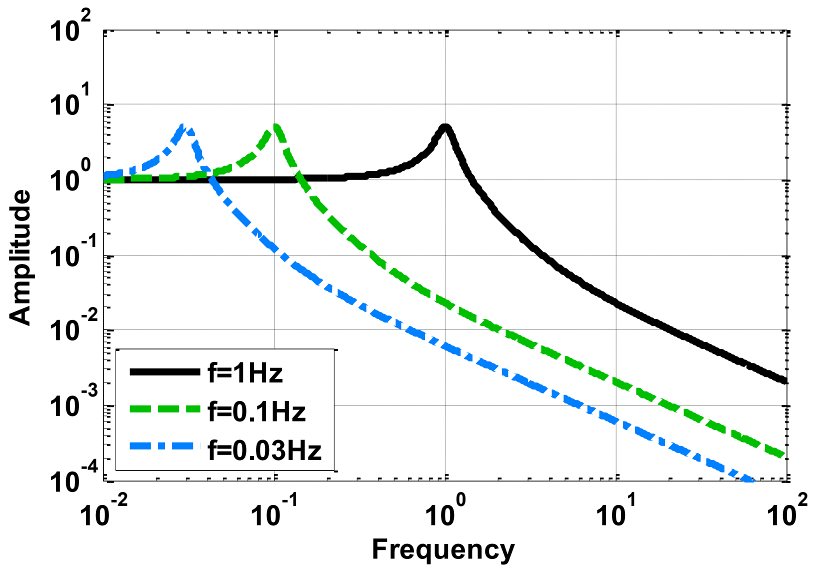
6 orders at 100Hz

Matichard, ASPE tutorials and active vibration isolation (2013, 2014, 2015)

Concepts

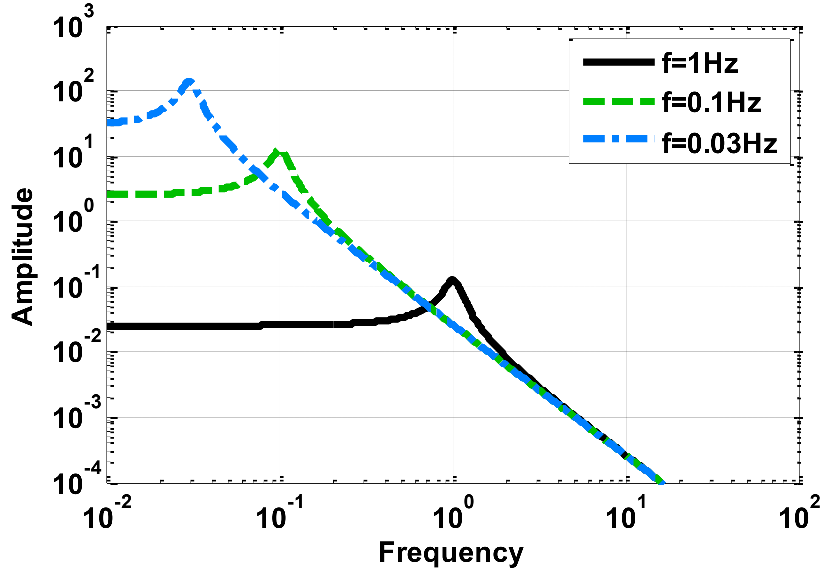
Trade offs

Transmissibility



$$\frac{X_1}{X_0} = \frac{2\,\alpha\,\omega\,s + \,\omega^2}{s^2 + 2\,\alpha\,\omega\,s + \,\omega^2}$$

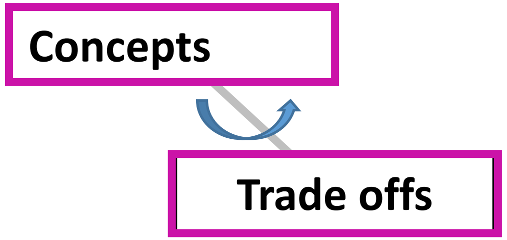
Compliance



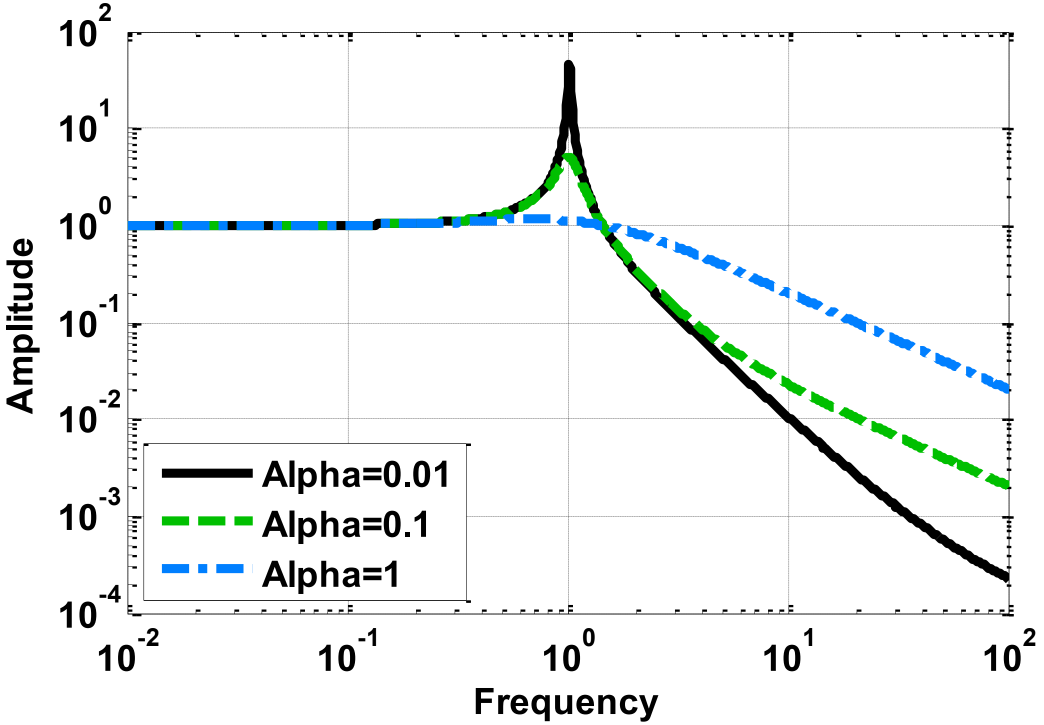
$$\frac{X_1}{F} = \frac{1}{ms^2 + c\,s + k}$$

- *Static deflection*
- *Internal disturbance*
- *Temperature Changes*
- *Mechanical Shortcuts*

Matichard, ASPE tutorials and active vibration isolation (2013, 2014, 2015)

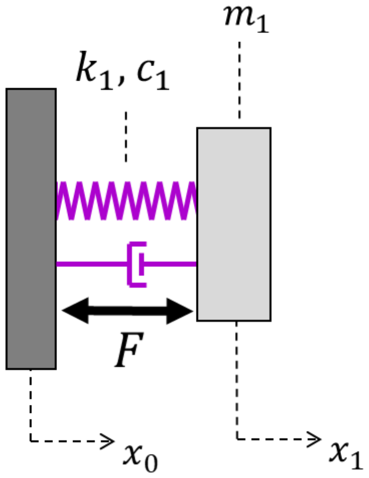


Damping trade offs



$$\lim_{s\to\infty}\left(\frac{X_1}{X_0}\right) = \frac{2\,\alpha\,\omega}{s}$$

Passive/Active trade offs



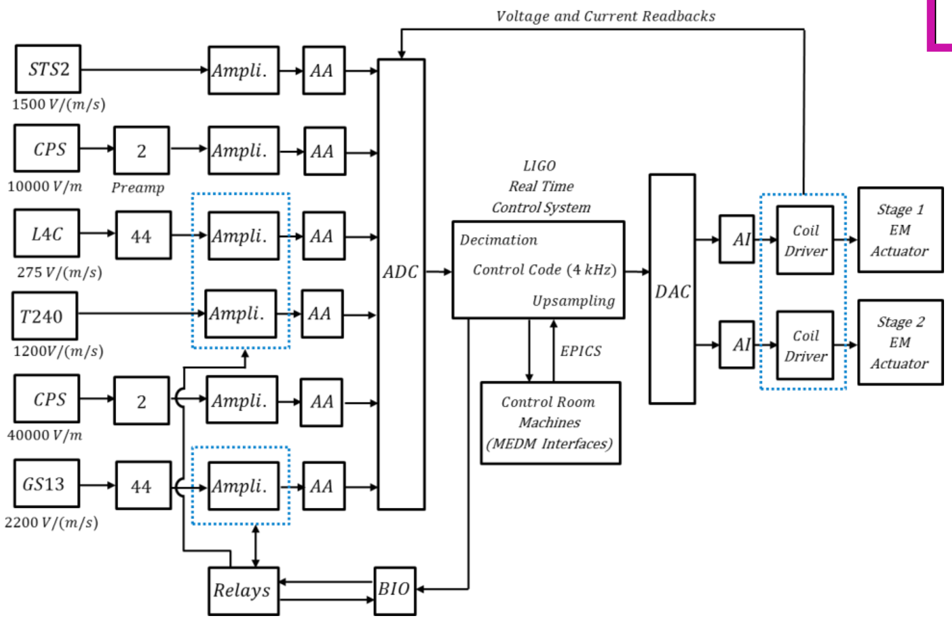
Complexity, cost

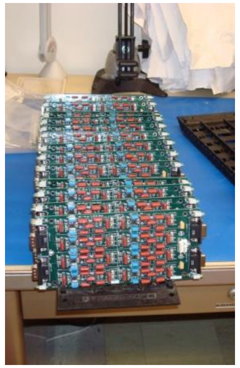
Matichard, ASPE tutorials and active vibration isolation (2013, 2014, 2015)

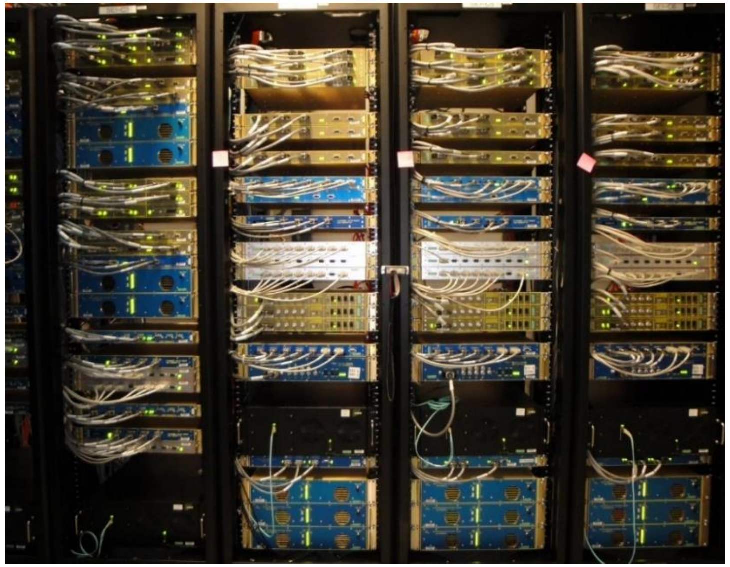
Instrumentation cost

Concepts

Trade offs







Two-stage Vibration Isolation And Alignment System, F. Matichard, ASPE 2014

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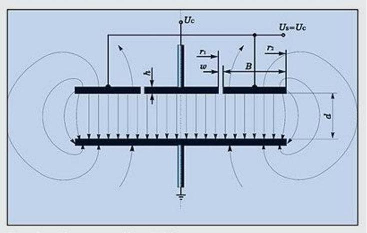
Concepts

Cost Performance

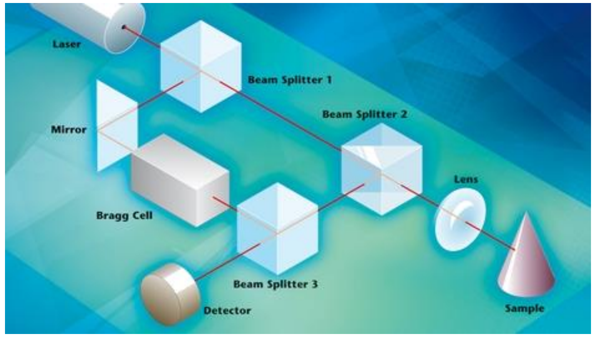
Trade offs

Capacitive



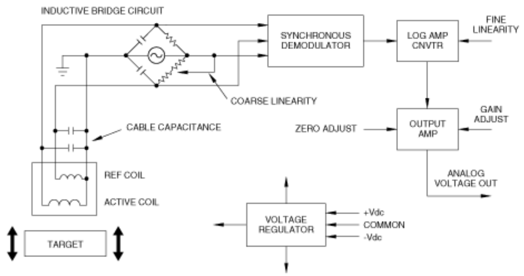
http://www.microsense.net/

Laser Doppler Vibrometer



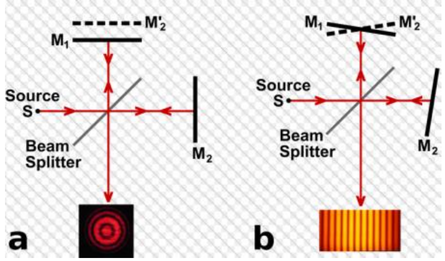
http://www.polytec.com

Inductive

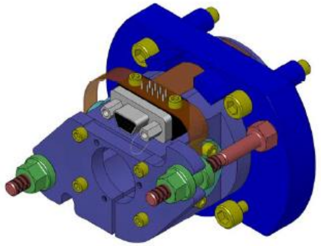


http://www.kamansensors.com/

Interferometric Sensors



Optical Shadow Sensors



LIGO OSEM

http://www.attocube.com/attosensorics/

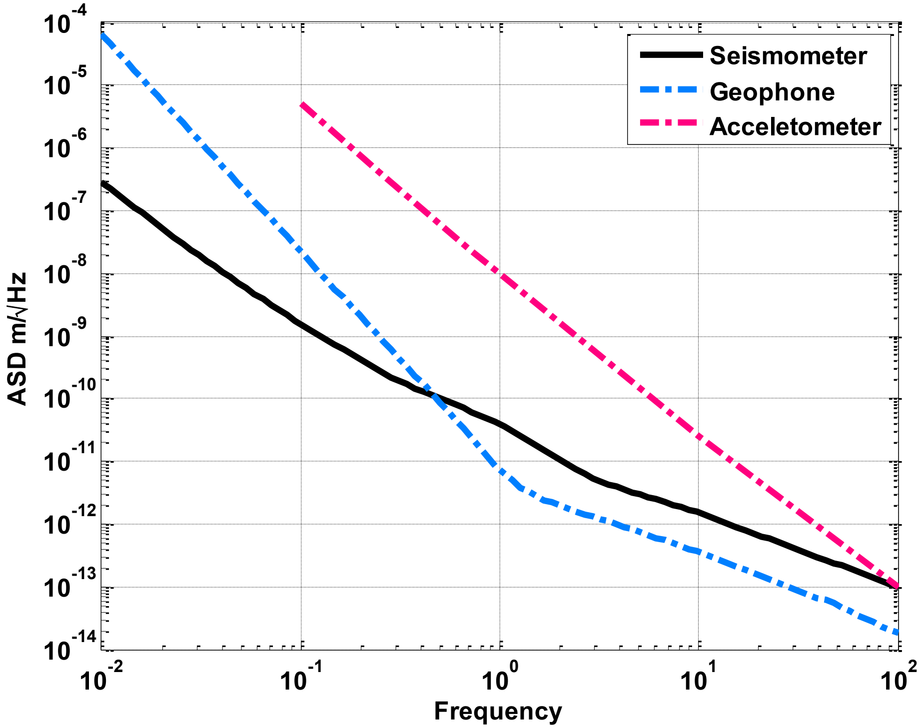
Performance

Sensitivity

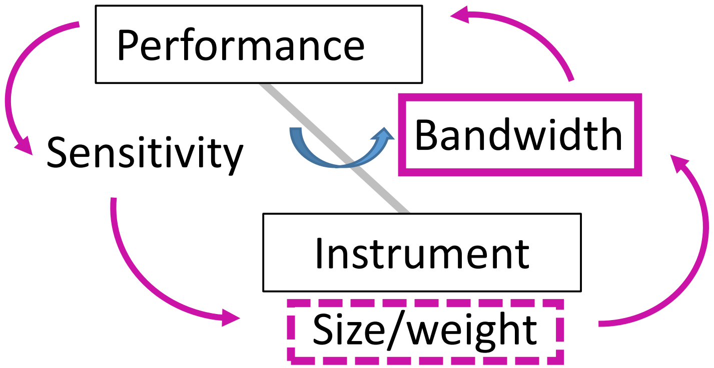
Bandwidth

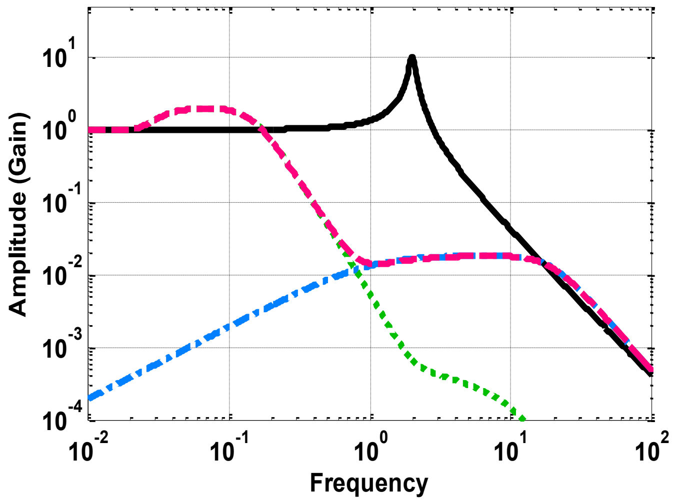
Instrument

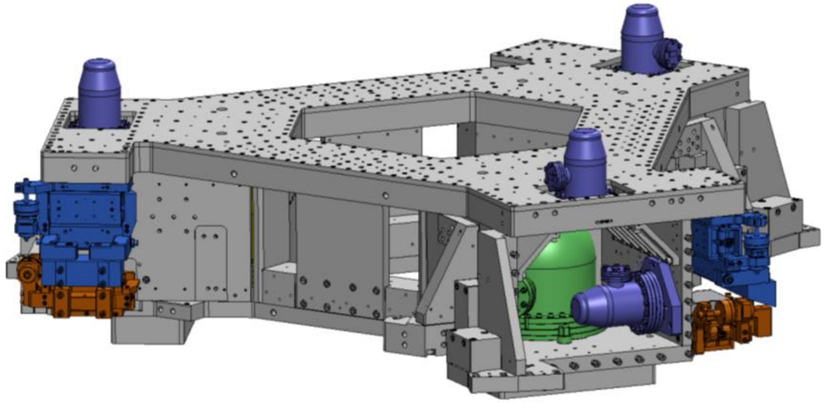
Size/weight

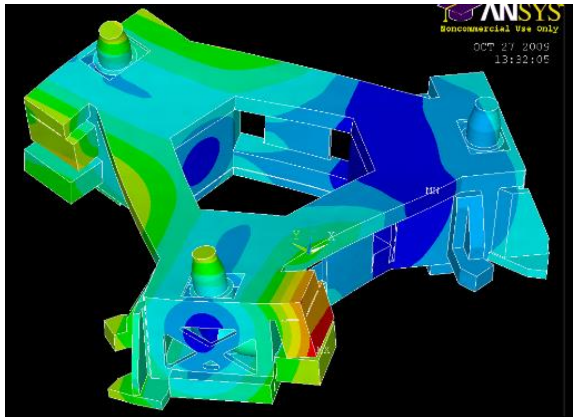


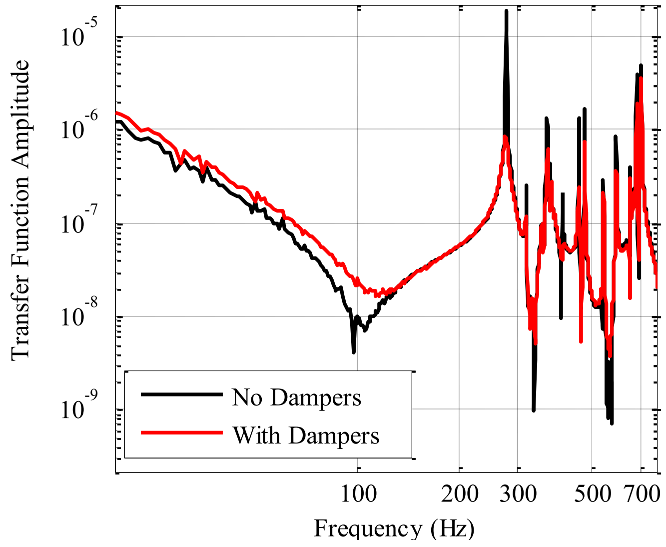
Matichard, Fabrice, and Matthew Evans. "Tilt-free low-noise seismometry."
Bulletin of the seismological society of America 105.2A (2015): 497-510











Vibration Isolation and Control of Sensitive Systems, F. Matichard, ASPE 2015

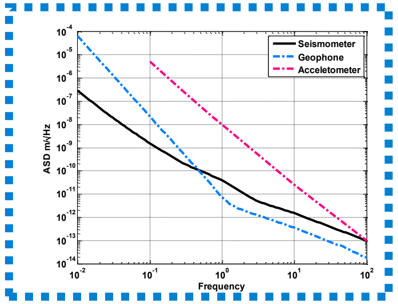
Error Budgeting

Concepts

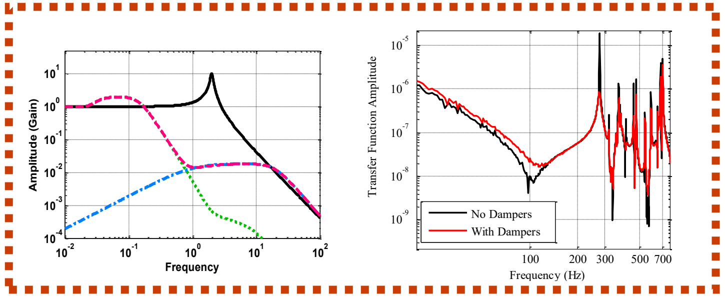
Error Budgeting

Trade offs

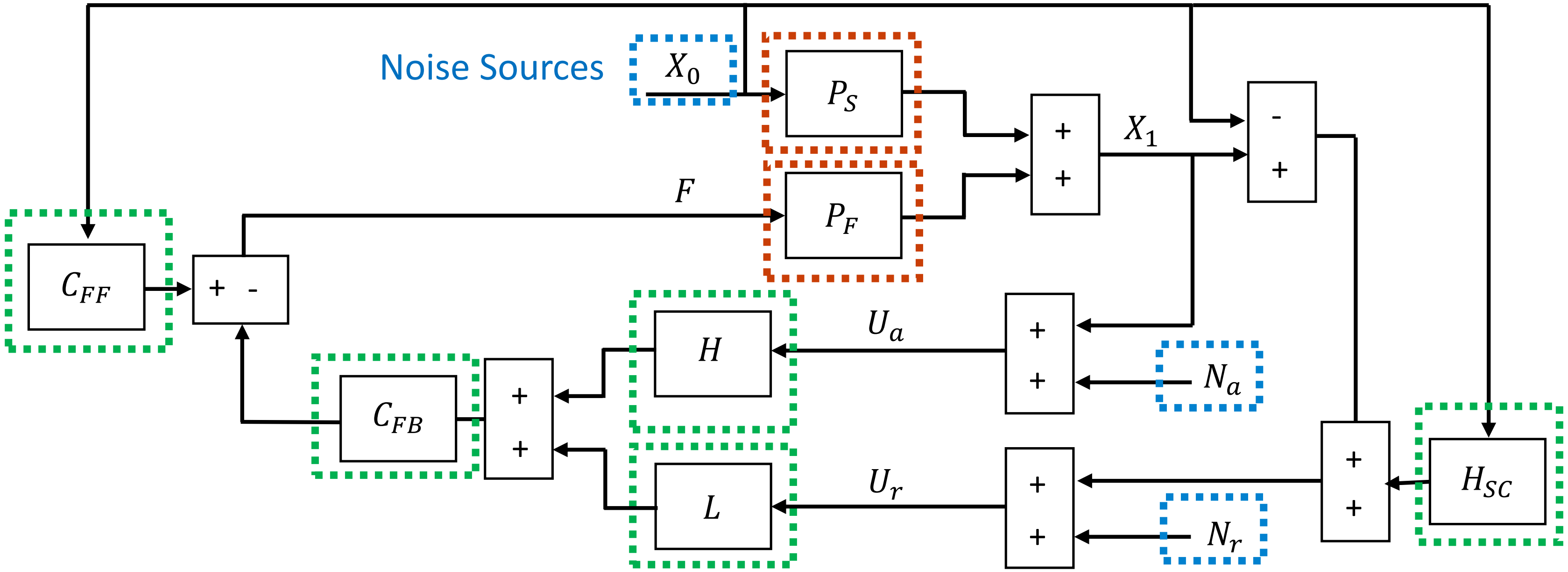
Noise Sources Characterization



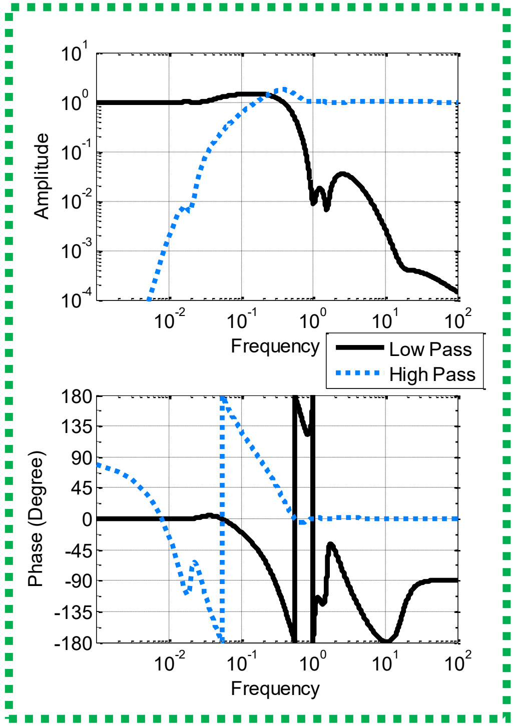
System Modeling and Identification



Noise Sources



Filtering and Control



Optimization

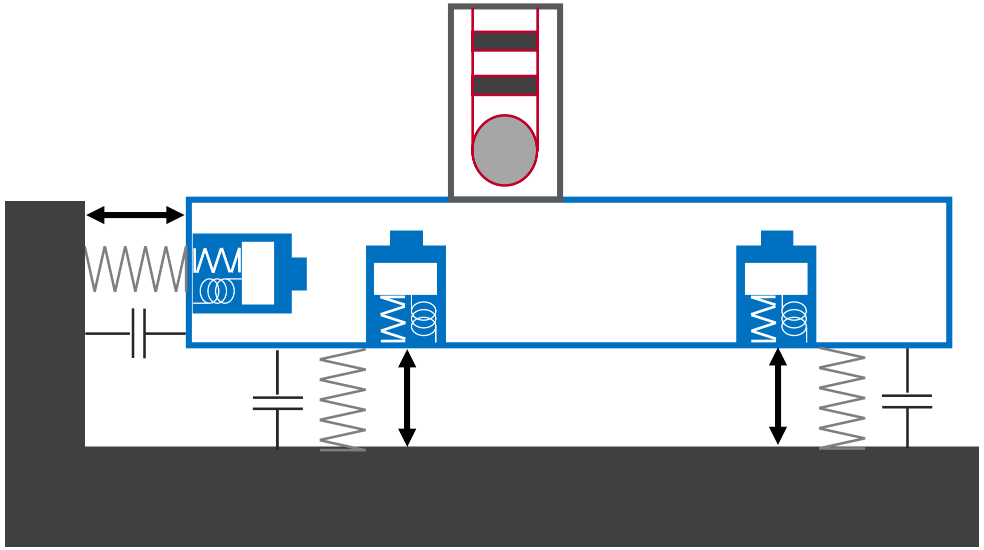
$$\boxed{\langle {X_1}^2\rangle} = \left|\frac{P_s + L\ C\ P_F}{1 + C\ P_F}\right|^2 \boxed{\langle {X_0}^2\rangle} + \left|\frac{H\ C\ P_F}{1 + C\ P_F}\right|^2 \boxed{\langle {N_a}^2\rangle} + \left|\frac{L\ C\ P_F}{1 + C\ P_F}\right|^2 \boxed{\langle {N_r}^2\rangle}$$

Requirements

Concepts

Trade offs

Architecture

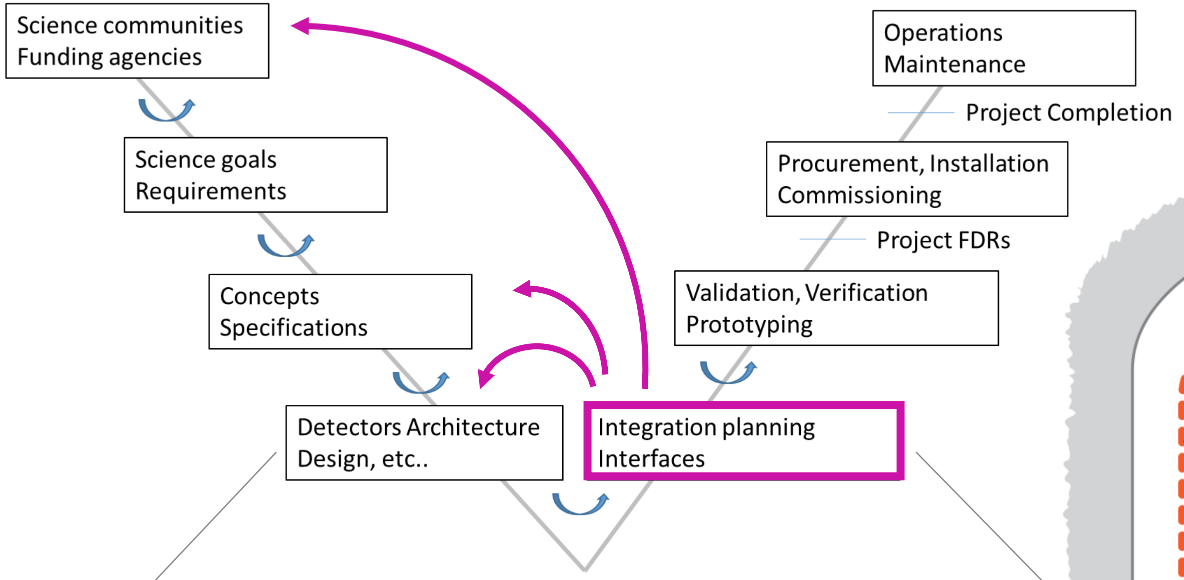


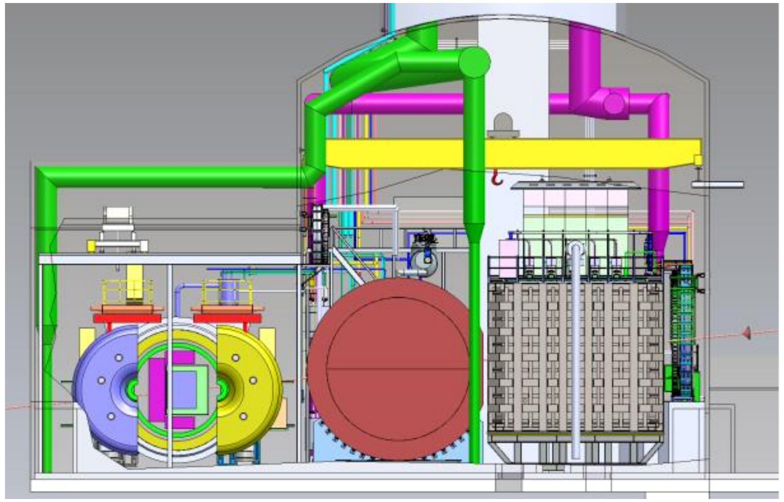
Stiff - Active Inertial - Low Noise platform

Multi-stage passive – Top stage relative active damping

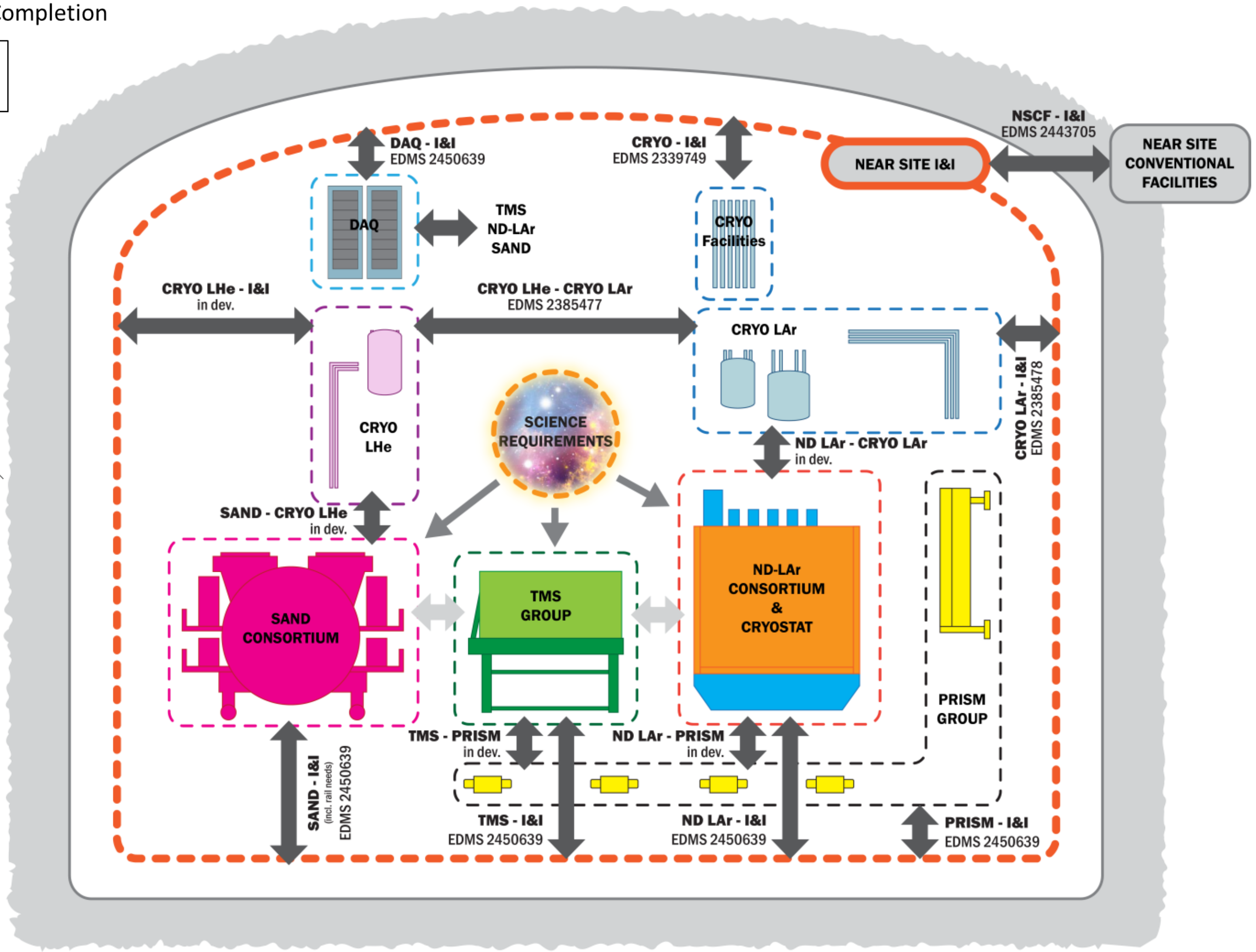
Slide source: Overview Of Advanced LIGO Combination of Passive And Active Vibration Isolation, F. Matichard, ASPE 2015

Interfaces





Interface definition
Sub-system boundaries



Credits: picture on the right, Matthaeus Leitner, LBNL/DUNE

Interface Control Documentation – Detectors

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5 SAND DETECTOR I&I REQUIREMENTS AND IN

This section describes SAND Detector requirements and interface
integration activities at the DUNE Near Detector facility.

5.1 SAND Detector I&I Requirements

Following table summarizes all SAND detector requirements applic

Table 2. SAND Detector I&I Requirements

REQ-#	Item	Requirement
PRM-SND 1-01	Rail Dimensions for SAND Detector Interface	SAND wheelbase shall conform to PRISM rail spacing as provided in EDMS 2450637.
I&I-SND 1-02	SAND Available Space Within Cavern	The SAND team shall verify that the clearances available to the detector in the alcove are adequate (per EDMS 2450637).

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Table 2 SAND Detector I&I Requirements List (continued)

I&I-ALL 1-03	Detector transportation requirements	Detector components shall be shipped su that they comply with weight and outsize dimension limitations according to US DO transportation and logistics requirements t ensure they can be received at FERMILAB
I&I-ALL 1-04	List of Detector Components	Each detector team shall provide I&I with a of all detector components and sub-assemblies, including weights, any hazard associated with them, and any storage or preservation requirements associated with each component.
SND-I&I 1-05	Storage & Assembly	Storage and assembly space shall be pro to SAND to assemble the cryostat and inn tracker components and storage of equip in a climate controlled assembly hall. - Temperature: 20 +/- 3 deg C - Dry
I&I-SND 1-06	Detector Component Maximum Weights	Individual components for the detector (or assemblies not installed while on the PRIS rails) shall be limited so they remain, with rigging and lifting fixtures, within the plann crane capacities: - Cavern crane capacity: US ton - Surface Building crane capacity: US ton - Annex freestanding bridge crane tons - Temporary surface crane capacity: ton [shaft lift capacity]
I&I-SND 1-07	Detector Sub-Assembly Weight Exceptions	ANY exceptions to the weight limitation described in I&I-SND-1-06 shall be discus with I&I for additional lifting/move plan

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Table 2 SAND Detector I&I Requirements List (continued)

		development. Exceptions to the weight limits cannot be allowed without detailed cost/benefit analysis and approval.	case 08.
SND-I&I 1-08	SAND Cryostat and Inner Detector Oversized Lift	I&I shall make provisions to lift the SAND Cryostat and inner detector, which are estimated to have a lift weight of ~180 US tons. SAND shall provide a skidding system for the cavern to move the detector onto the yoke insertion fixture.	
I&I-SND 1-09	Shaft Size Limitations	Individual components for the detectors (or any assemblies completed on the surface) shall be sized such that they fit within the shaft clearance area. The shaft clearance is provided in EDMS 2443706.	Magn maxi whic calor mour with (prec (prec are c show m x 9
I&I-SND 1-10	Detector Assembly Tooling Requirements	Detector teams shall supply I&I with the anticipated tooling requirements of their detector. In particular, if there are any specialized tooling requirements that are unique to their detector. E.G. - Forms, Jigs, lifting attachments, resins, adhesives, solvents, etc.	Magn EXTE BUIL mour calor for c 7 US m^2 ND S with CAVE hook prese hand reass
SND-I&I 1-11	SAND Assembly Fixtures	SAND shall provide a jig for mounting the modules of the calorimeter, a cradle for the coil vessel.	
SND-I&I 1-12	SAND Assembly Fixtures	I&I shall provide lifting capabilities to level the SAND components, either with a dual crane hook configuration or with appropriate spreader bar configurations.	Curre lift sc hook
SND-I&I 1-13	SAND Assembly Fixtures	I&I shall provide two (2) lifting platforms for detector assembly.	ECAL of no capa
I&I-SND 1-14	SAND Detector Maintenance	SAND team shall define maintenance items and intervals for detector operation.	Magn norm pmt c
I&I-SND 1-15	Maintenance Access Requirement for SAND	Regular SAND maintenance shall be performed within the alcove. Alcove space accommodates opening of the SAND Yoke endplates, but not rotation of the endplates. Available access space is defined in EDMS 2450637.	Movi alcov and s repai PMT alcov

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Safety

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Table 2 SAND Detector I&I Requirements List (continued)

I&I-SND 1-16	SAND Detector Safety Requirements	SAND detector shall comply with safety regulations for the FERMILAB site - FESHM	Magnet: Protection for magnet quenching comply the safety regulation, electric hazard: the power line will comply the safety regulations, ODH hazard to be evaluated considering the amount of 150 l of LHe, all mezzanine are comply with all the regulations (rails, floor, safety access..) ECAL: no high impact safety issue TPC: - High-Voltage (50 kV) - Gas mixture (Ar, CO2, Isobutane) / ODH LAr: LAr 1500 lt LN2 for cooling/argon purification 10 lt/hr
SND-I&I 1-17	ODH Safety Requirement	DUNE ND Cavern shall provide sufficient ODH ventilation for 150l of LHe volume in the SAND cryostat.	
I&I-SND 1-18	SAND Magnetic Fringe Field Requirement	The SAND Detector shall not exceed a magnetic field of 2 Gauss measured at a radial distance of 2 m from the outside surface of the yoke. Field should be verified by simulation, including adjacent detectors.	Magnet: SAND magnetic field: 1-2 Gauss at radial distance of 2 m from the yoke MPD magnetic field: in the SAND yoke 0.3T, to be completed with the magnetic field in the iron by SAND ECAL: maximum magnetic field for pmt: up to 0.2 T for theta<30° the MPD magnetic field in the pmt region is smaller than 50 Gauss
SND-GAR 1-19	SAND Magnetic Fringe Field Requirement	ND-GAr detector shall not increase the magnetic field inside the SAND iron yoke by more than 0.3T.	maximum magnetic field for SAND pmt: up to 0.2 T for theta<30° the ND-Gar magnetic field in the SAND pmt region shall be smaller than 50 Gauss
I&I-SND 1-20	Surface Equipment & Facilities Requirements	Detector teams shall define a general list of equipment needs and facility support needs required to assemble the detector.	Magnet: ND DETECTOR ASSEMBLY HALL: with opening roof
I&I-SND 1-21	Delivery Schedule to FermiLab	Detector teams shall define a general delivery schedule.	Magnet: we deliver the components accordingly to the proposed timeline
I&I-SND 1-22	Surface Delivery Lift Plan	Detector teams shall provide the document number of the approved delivery lift plan and supporting analysis document numbers.	All lift plans and documentation after delivery will be in the scope of I&I to develop.
I&I-SND 1-23	Surface Delivery Uncrating & Handling	Detector teams shall provide general uncrating and handling instructions for the components being delivered.	If known, this may need to be developed in the future.
I&I-SND 1-24	Surface Assembly Instructions	Detector teams shall define general surface assembly instructions and shall indicate any	Magnet: no assembly in the ND Surface Assembly Hall, the detector will be assembled in the

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Dimensions
Locations

Weight
Transportation

Assembly, Installation

Credits: Gordon Cline, Matthaeus Leitner, LBNL/DUNE

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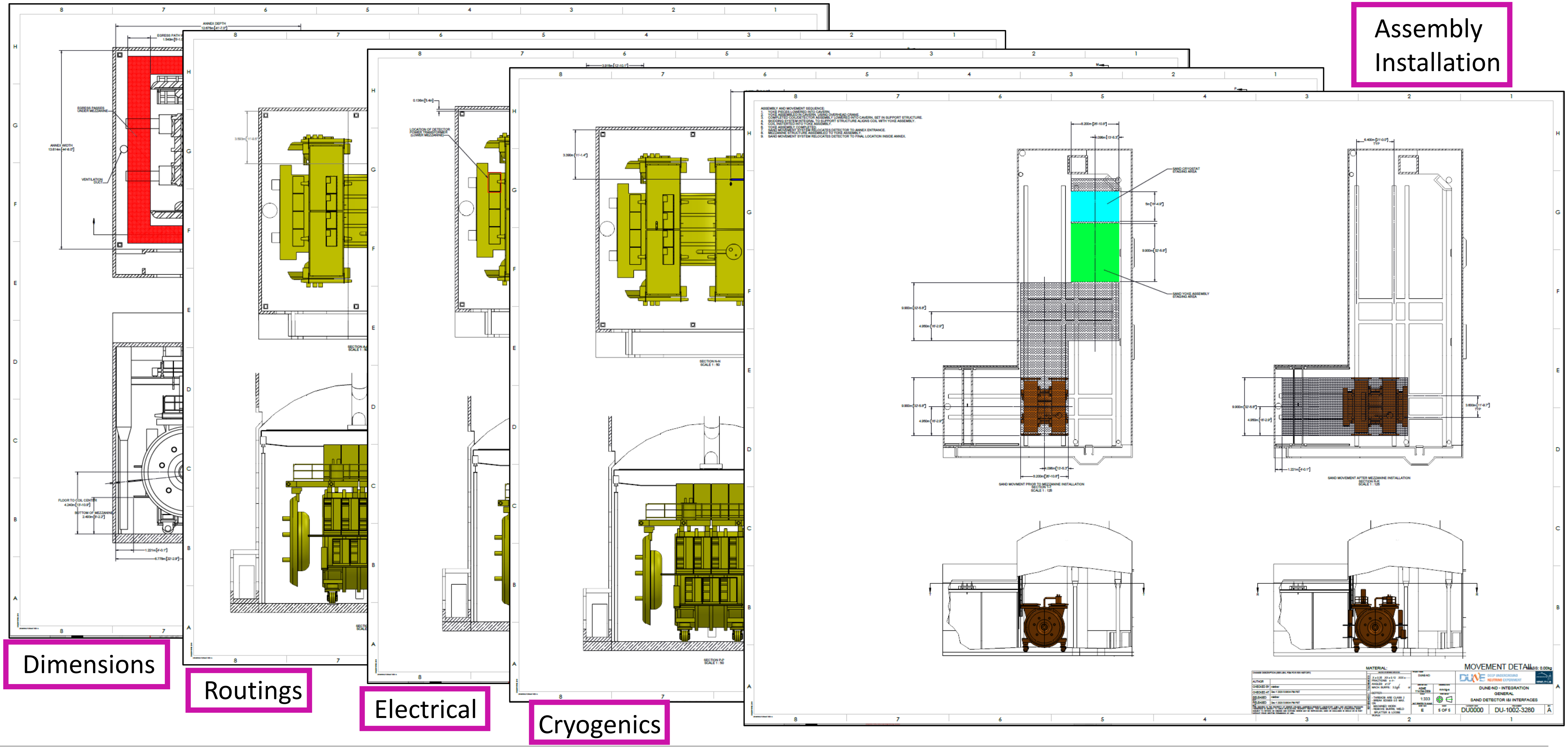
Interface Control Drawings - Detectors



Credits: Gordon Cline, Matthaeus Leitner, LBNL/DUNE

Interface Control Documentation - Facilities

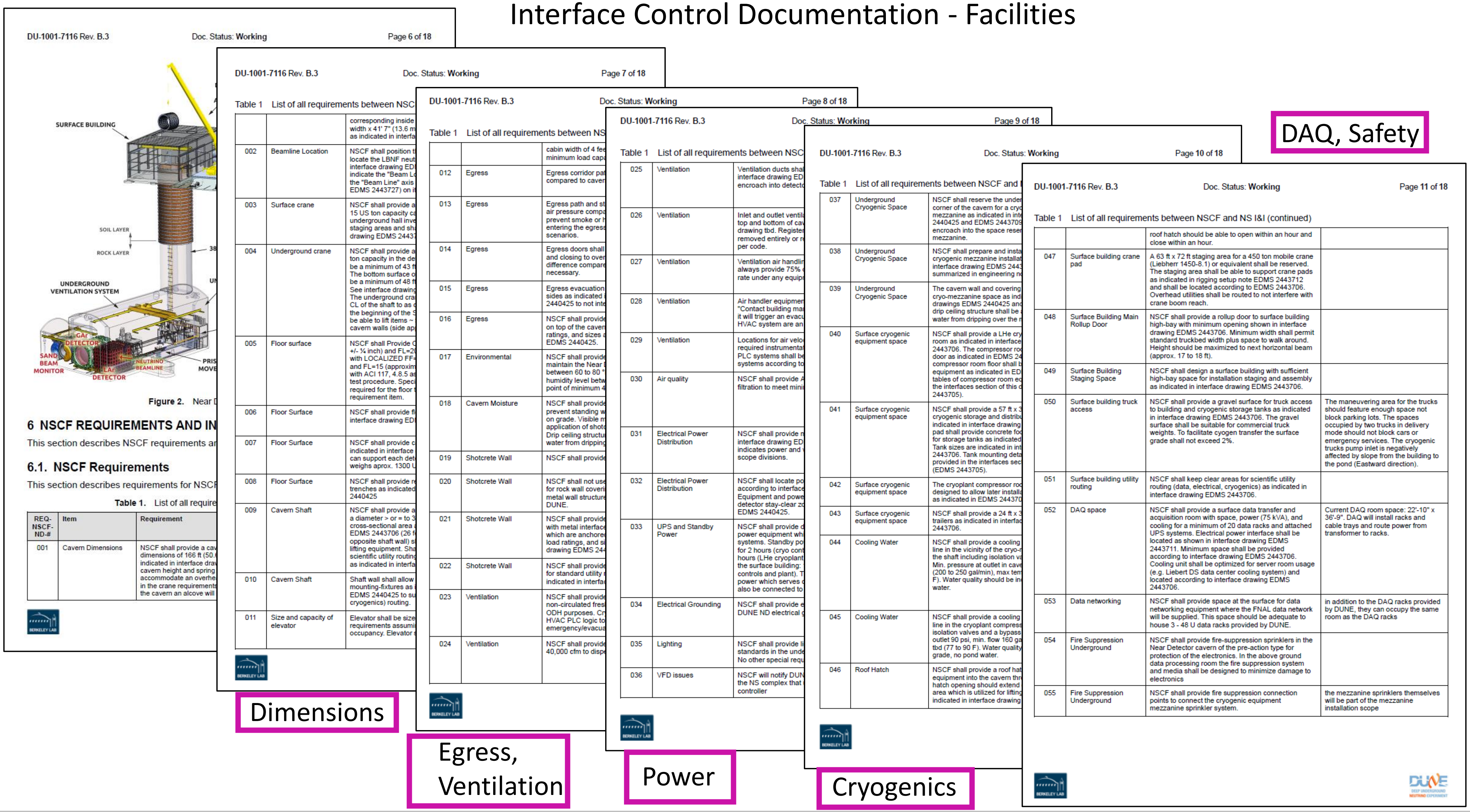


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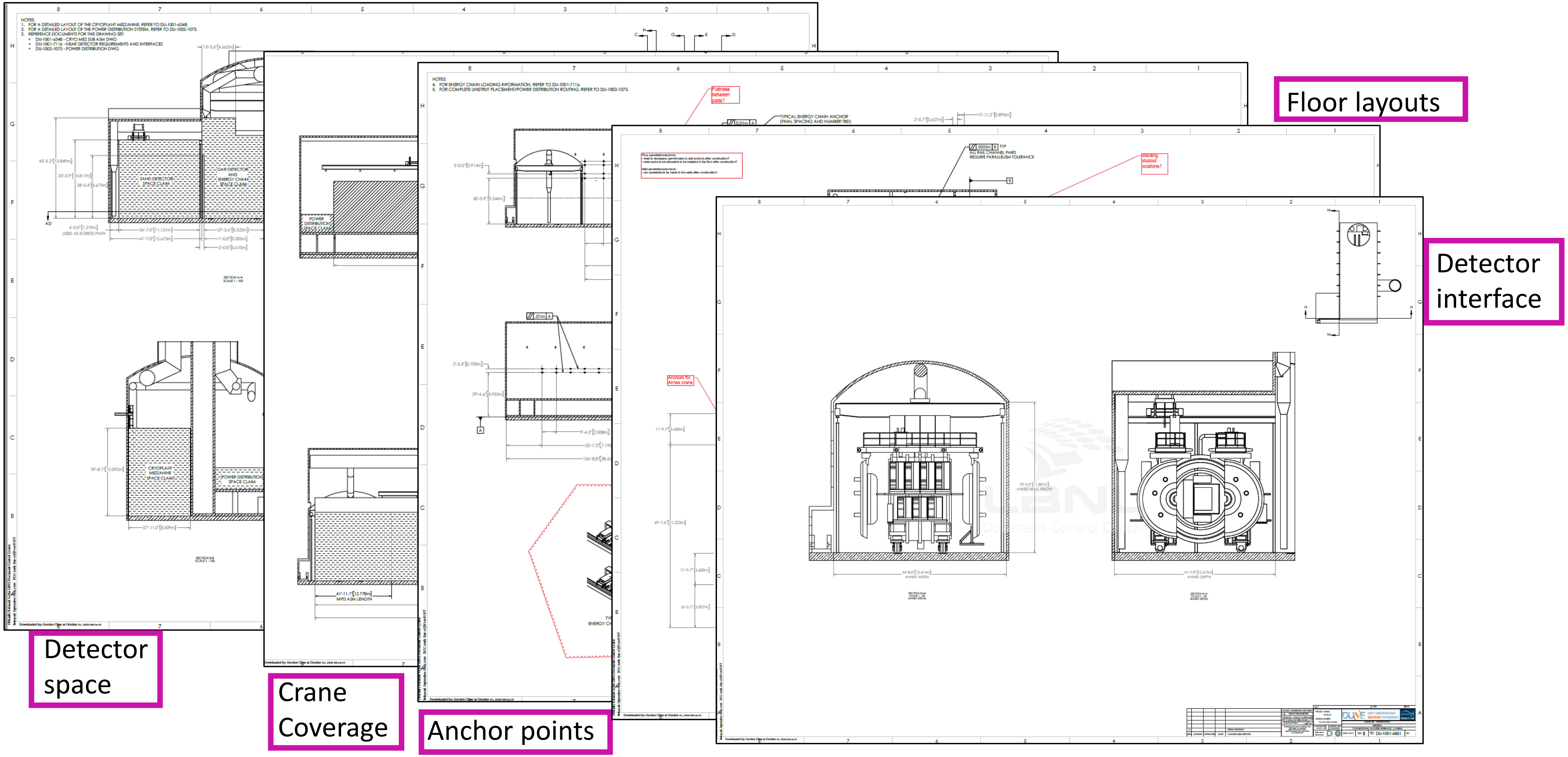
Table 1 List of all requirements between NSCF and NS I&I (continued)

		roof hatch should be able to open within an hour and close within an hour.	
047	Surface building crane pad	A 63 ft x 72 ft staging area for a 450 ton mobile crane (Liebherr 1450-8.1) or equivalent shall be reserved. The staging area shall be able to support crane pads as indicated in rigging setup note EDMS 2443712 and shall be located according to EDMS 2443706. Overhead utilities shall be routed to not interfere with crane boom reach.	
048	Surface Building Main Rollup Door	NSCF shall provide a rollup door to surface building high-bay with minimum opening shown in interface drawing EDMS 2443706. Minimum width shall permit standard truckbed width plus space to walk around. Height should be maximized to next horizontal beam (approx. 17 to 18 ft).	
049	Surface Building Staging Space	NSCF shall design a surface building with sufficient high-bay space for installation staging and assembly as indicated in interface drawing EDMS 2443706.	
050	Surface building truck access	NSCF shall provide a gravel surface for truck access to building and cryogenic storage tanks as indicated in interface drawing EDMS 2443706. The gravel surface shall be suitable for commercial truck weights. To facilitate cyogen transfer the surface grade shall not exceed 2%.	The maneuvering area for the trucks should feature enough space not block parking lots. The spaces occupied by two trucks in delivery mode should not block cars or emergency services. The cryogenic trucks pump inlet is negatively affected by slope from the building to the pond (Eastward direction).
051	Surface building utility routing	NSCF shall keep clear areas for scientific utility routing (data, electrical, cryogenics) as indicated in interface drawing EDMS 2443706.	
052	DAQ space	NSCF shall provide a surface data transfer and acquisition room with space, power (75 kVA), and cooling for a minimum of 20 data racks and attached UPS systems. Electrical power interface shall be located as shown in interface drawing EDMS 2443711. Minimum space shall be provided according to interface drawing EDMS 2443706. Cooling unit shall be optimized for server room usage (e.g. Liebert DS data center cooling system) and located according to interface drawing EDMS 2443706.	Current DAQ room space: 22'-10" x 36'-9". DAQ will install racks and cable trays and route power from transformer to racks.
053	Data networking	NSCF shall provide space at the surface for data networking equipment where the FNAL data network will be supplied. This space should be adequate to house 3 - 48 U data racks provided by DUNE.	in addition to the DAQ racks provided by DUNE, they can occupy the same room as the DAQ racks
054	Fire Suppression Underground	NSCF shall provide fire-suppression sprinklers in the Near Detector cavern of the pre-action type for protection of the electronics. In the above ground data processing room the fire suppression system and media shall be designed to minimize damage to electronics	
055	Fire Suppression Underground	NSCF shall provide fire suppression connection points to connect the cryogenic equipment mezzanine sprinkler system.	the mezzanine sprinklers themselves will be part of the mezzanine installation scope

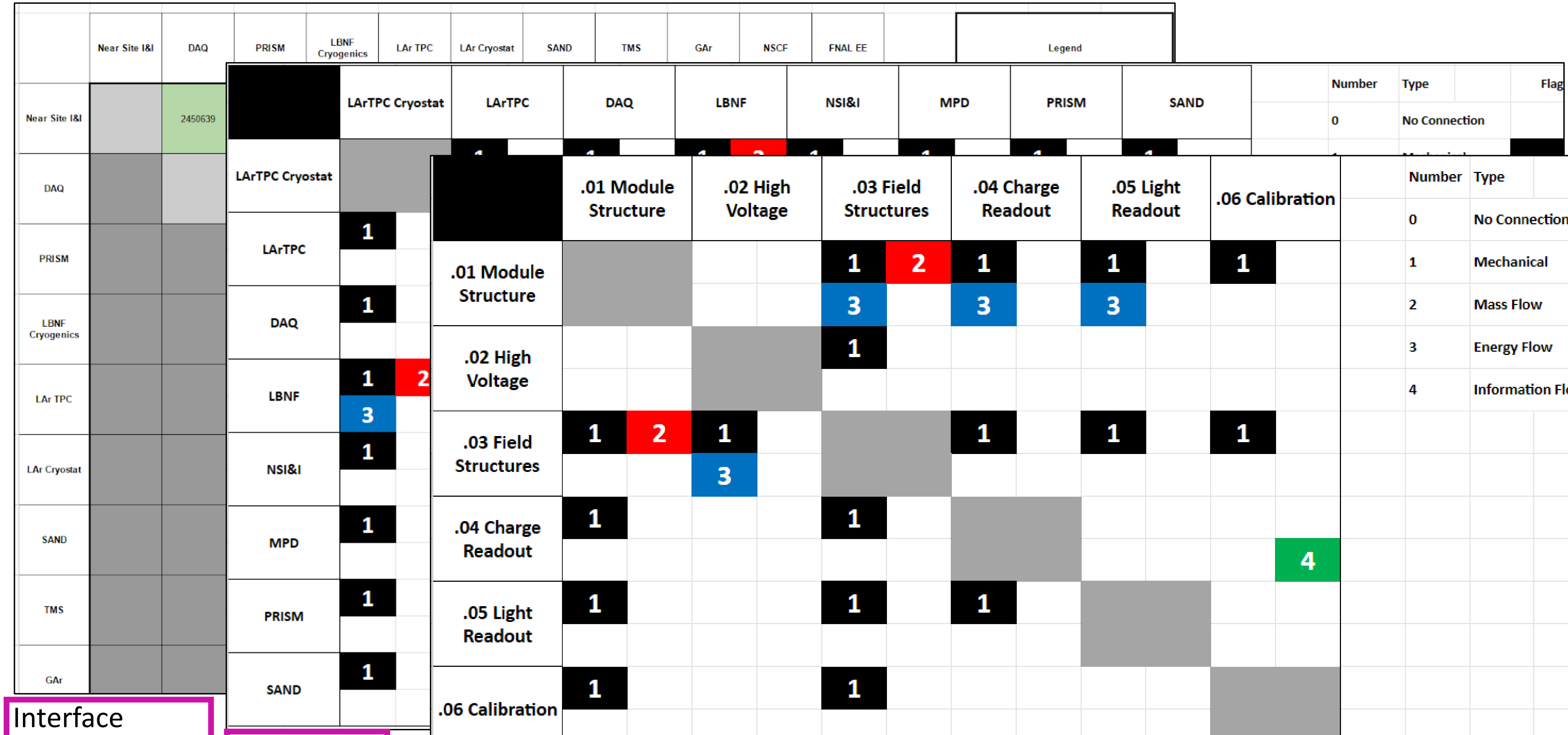
Credits: Gordon Cline, Matthaeus Leitner, LBNL/DUNE

Interface Control Drawings with Facilities



Credits: Gordon Cline, Matthaeus Leitner, LBNL/DUNE

N² matrices



	.01 Module Structure	.02 High Voltage	.03 Field Structures	.04 Charge Readout	.05 Light Readout	.06 Calibration
.01 Module Structure			1 2 3	1 3	1 3	1
.02 High Voltage			1			
.03 Field Structures	1 2	1 3		1	1	1
.04 Charge Readout	1		1			4
.05 Light Readout	1		1	1		
.06 Calibration	1		1			

Number	Type	Flag
0	No Connection	
1	Mechanical	
2	Mass Flow	
3	Energy Flow	
4	Information Flow	

Interface Documentation

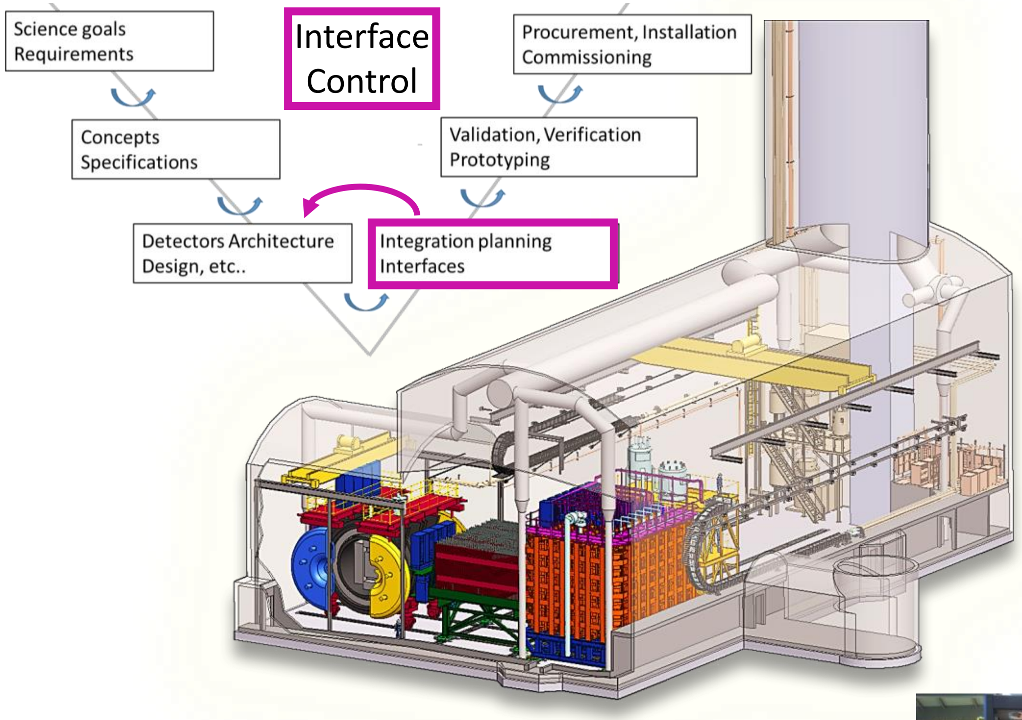
System Interfaces

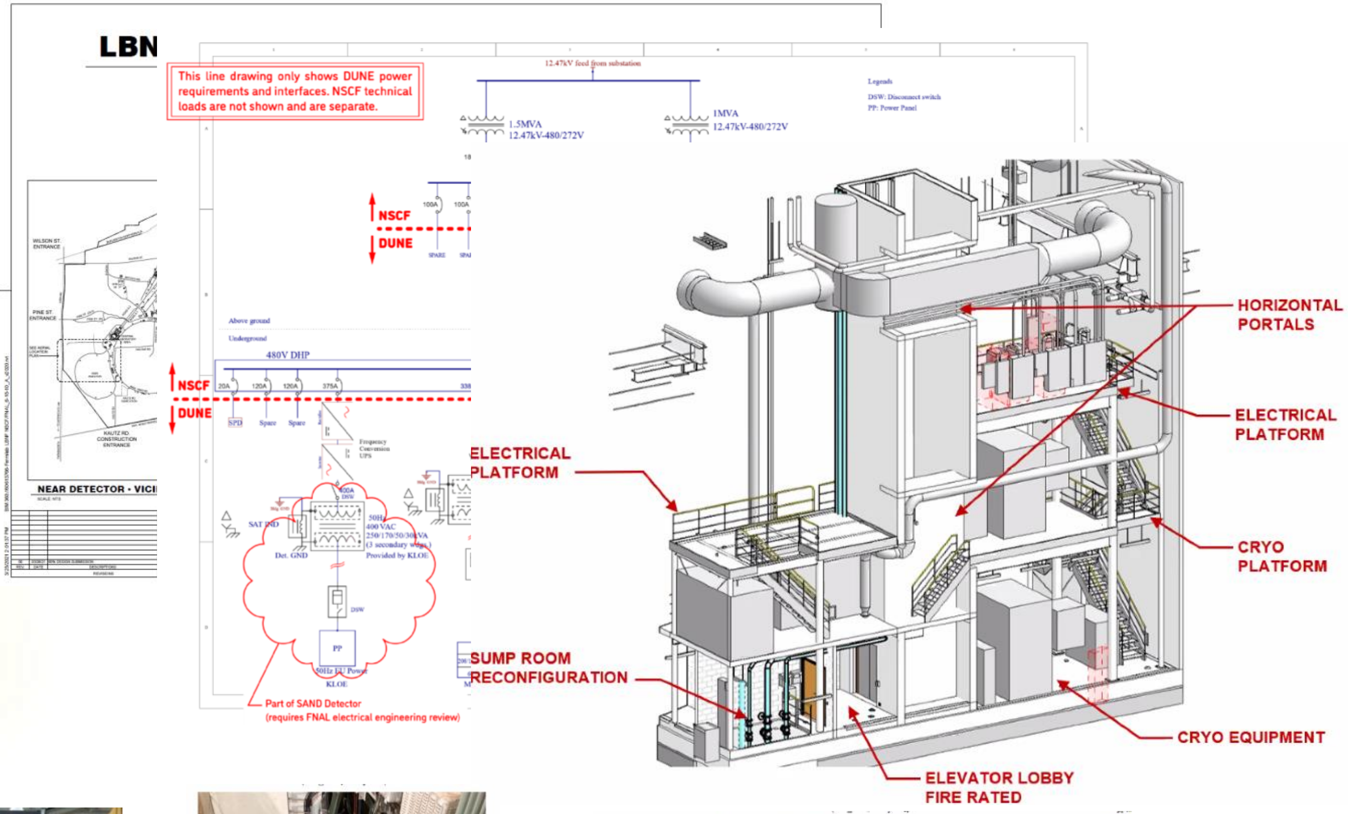
Sub-System Interfaces

Credits: Peter Tennessen, Andrew Lambert, LBNL/DUNE

MEDSI CHICAGO 2020

Integration






Disconnects, panels


Transformers

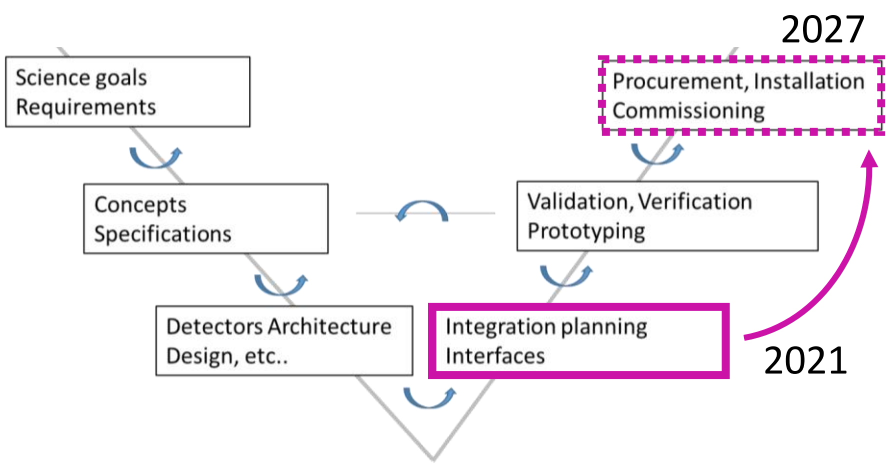

Monitoring

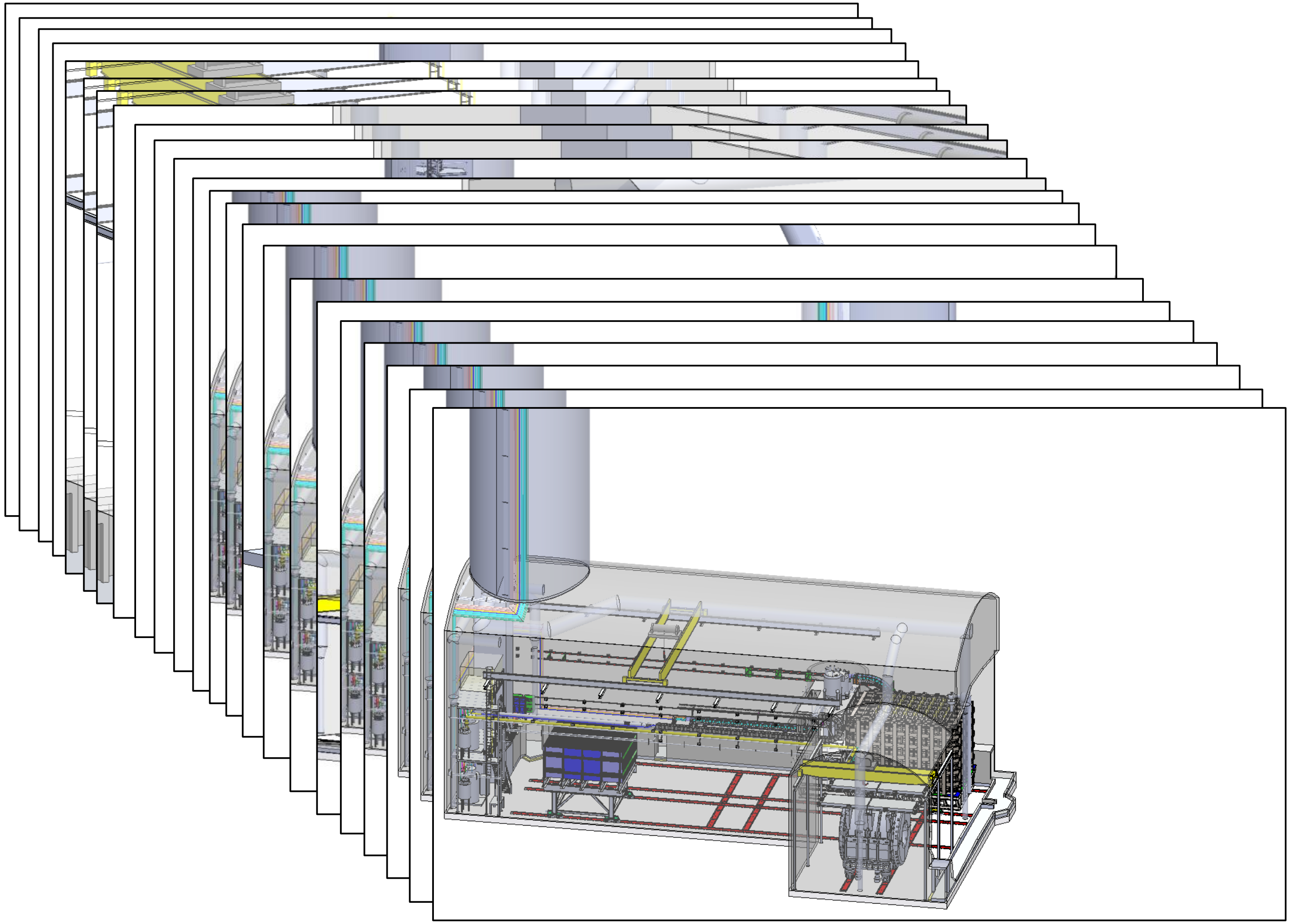

Routing


Cryogenics

Credits/Sources - Top left: DUNE I&I – Matthaeus Leitner, Top right: DUNE EE (Shaw and team), NSCF- AECOM (architecture), Bottom: FERMI/CERN/Proto-DUNE

Installation planning





Installation sequence

Resources: labor, equipment, rental

Needed to baseline the project

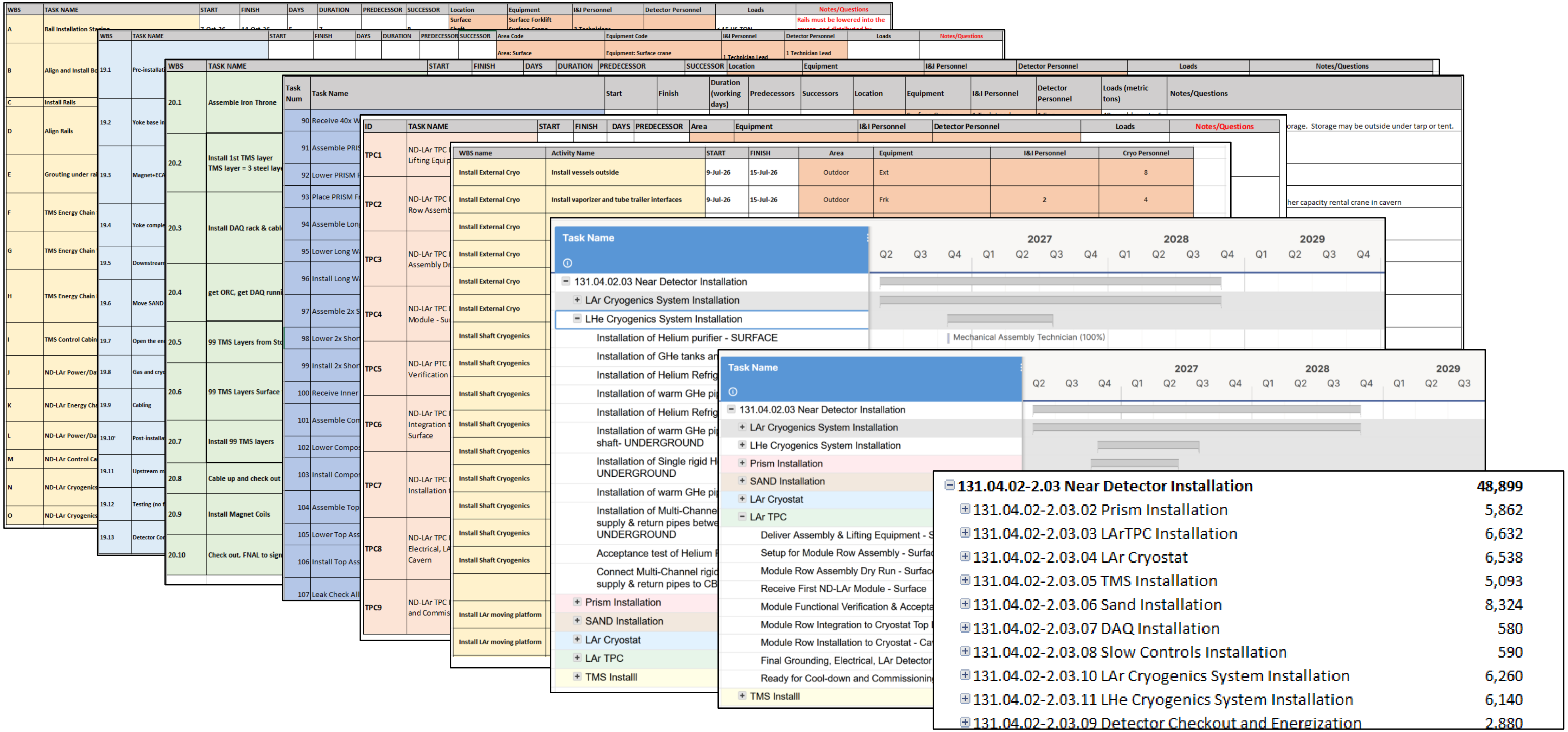
Assembly & Installation tooling

Integrated to the sub-system development

Integrated safety considerations

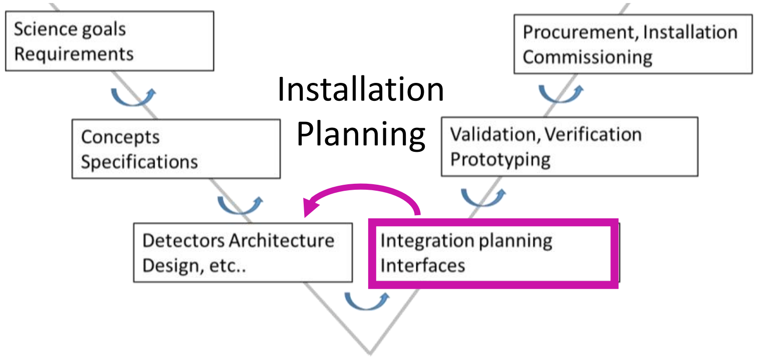
Power needs (outlets, currents…)

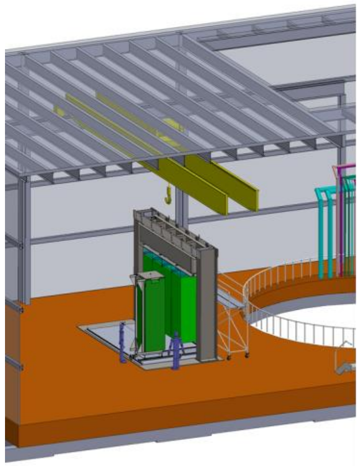
Installation planning: resources, schedules

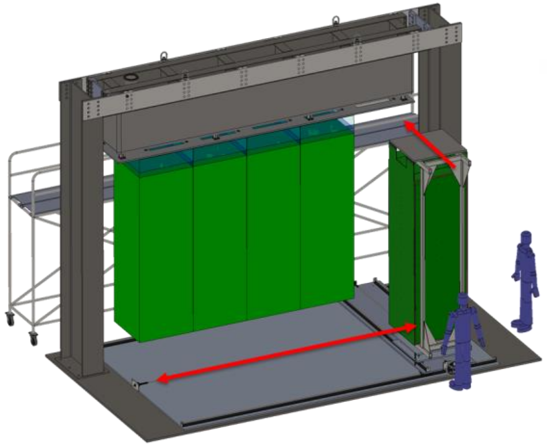


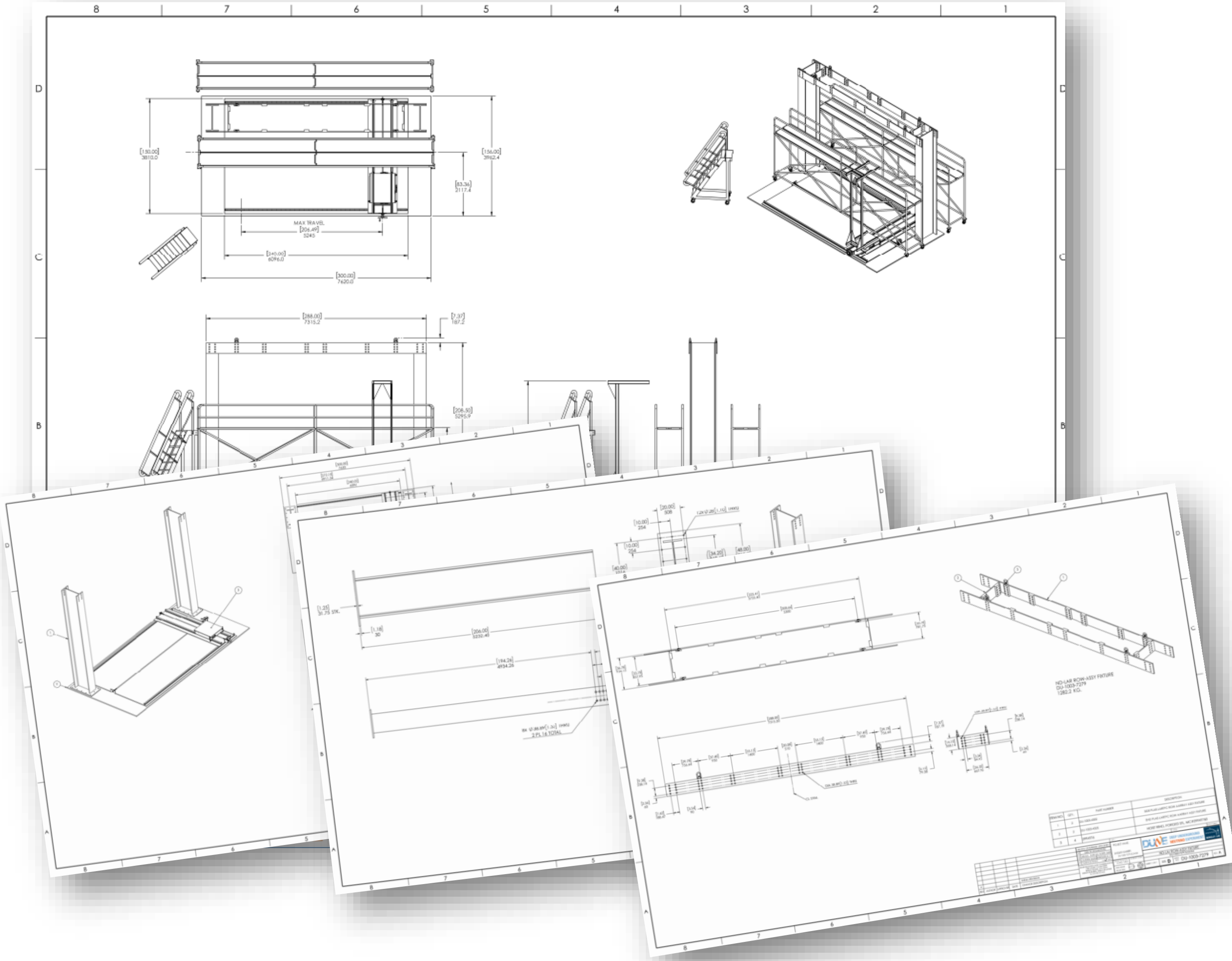
Credits/Source: Installation planning, LBNL/DUNE

Installation planning: workflows, procedures

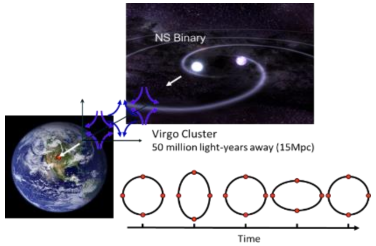








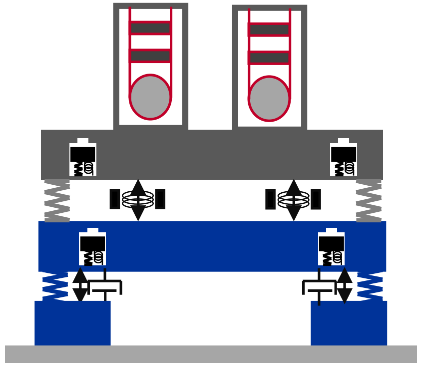
Science goals, Specifications



Requirements

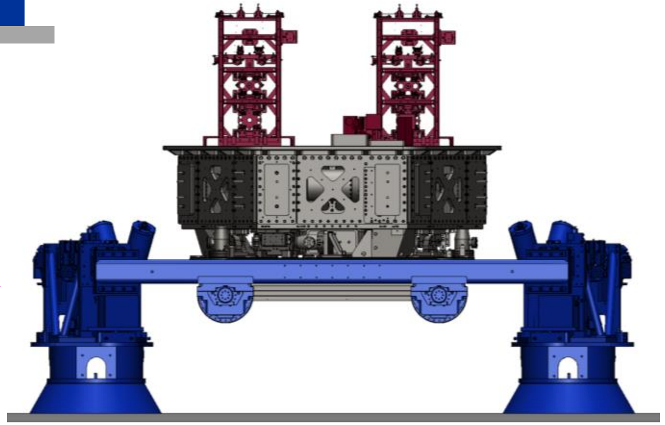
$10^{-18}\ m/\sqrt{Hz}$

Architecture



Conceptual design

Technological tradeoffs

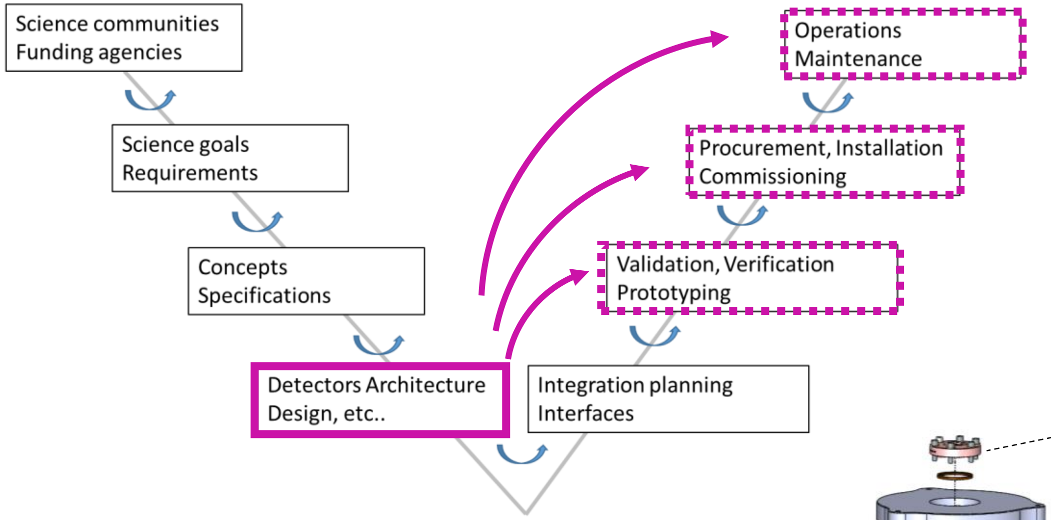


Preliminary design

Design

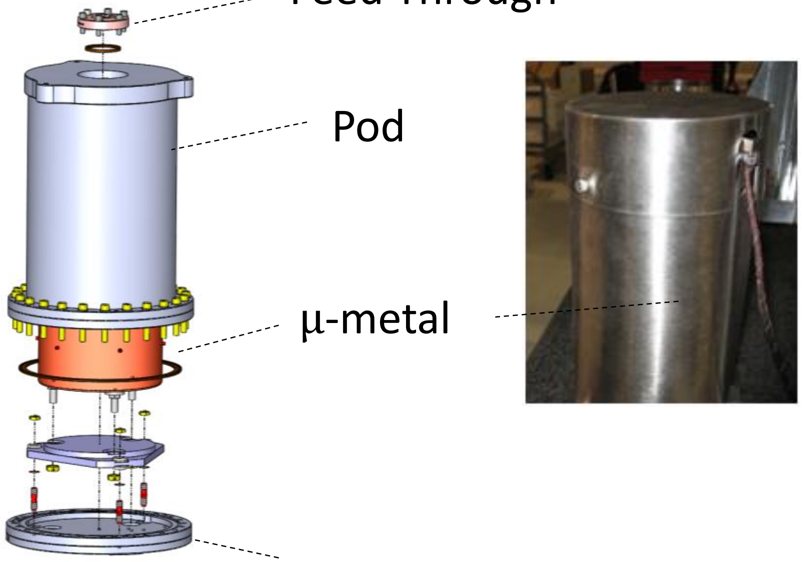
Integration

Example 1: Geophones



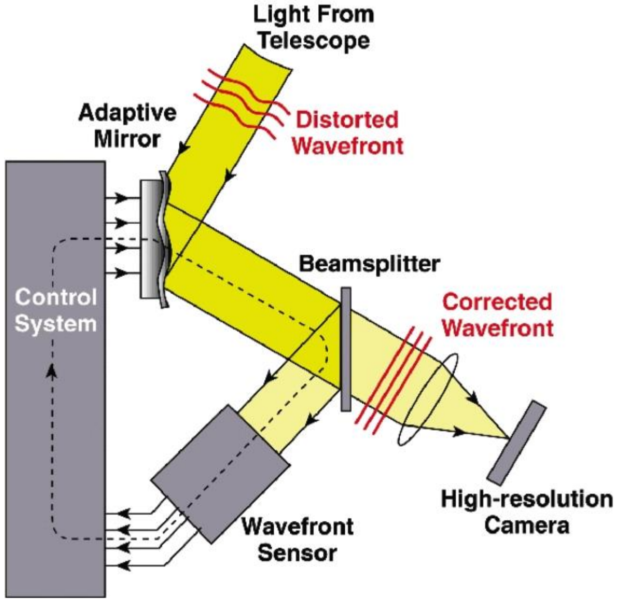
GS13 geophone

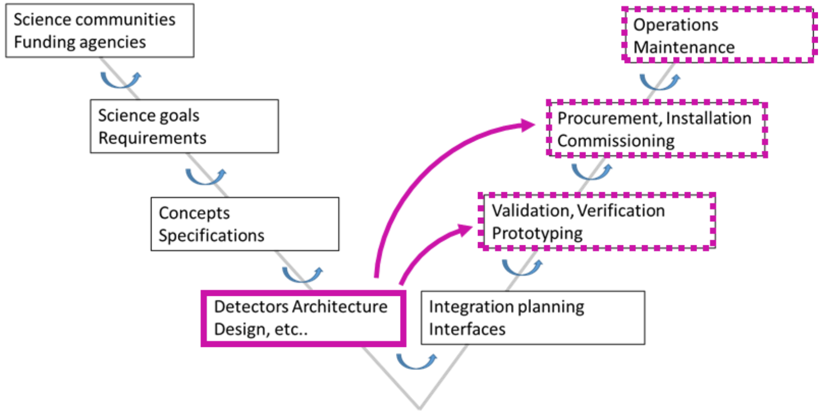
Retrofitted, Shielded, Podded

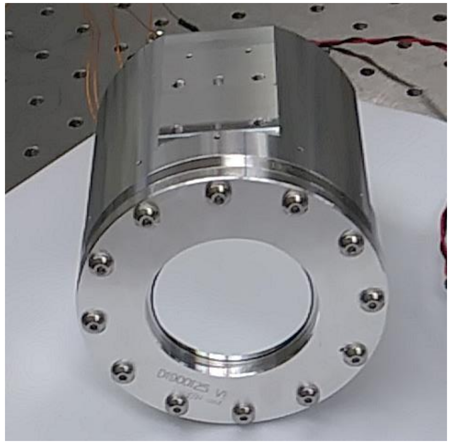


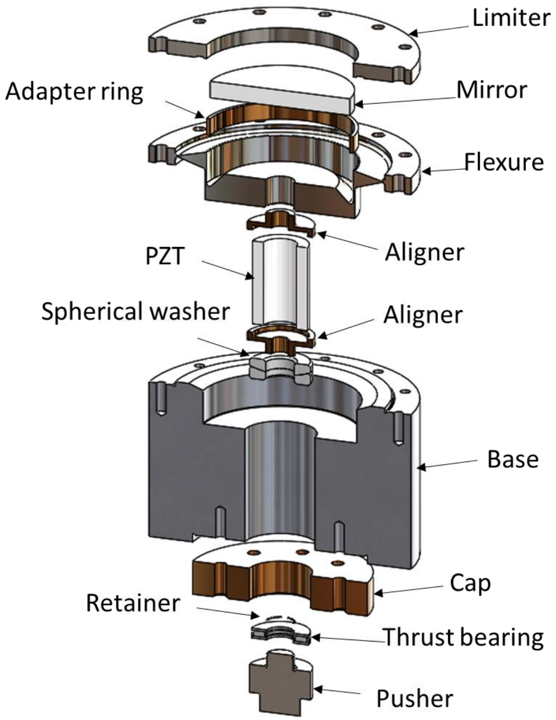
Source-Credit: Brian Lantz, Stanford

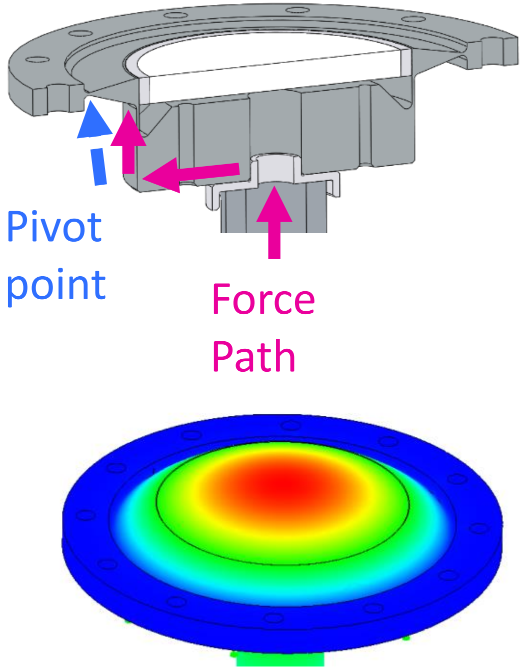
Example 2: Adaptive optics





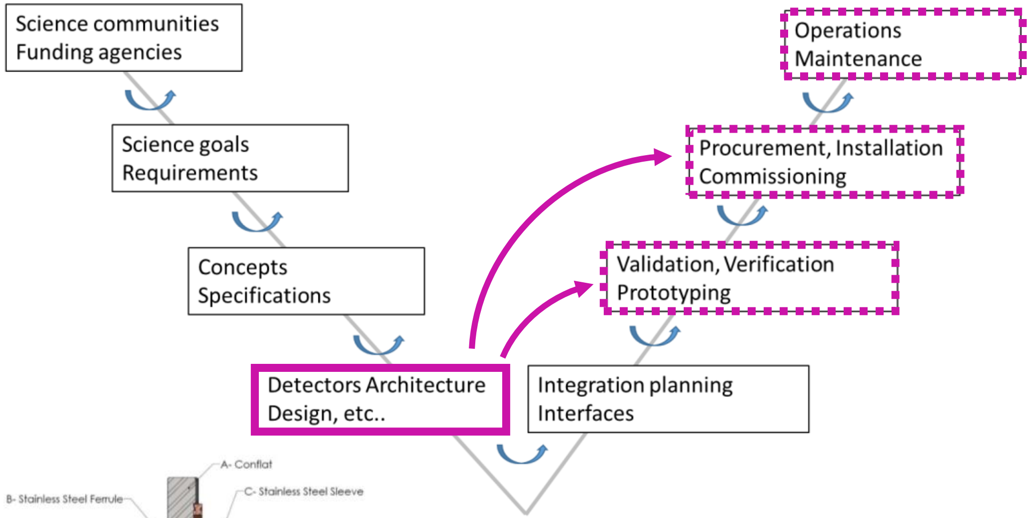


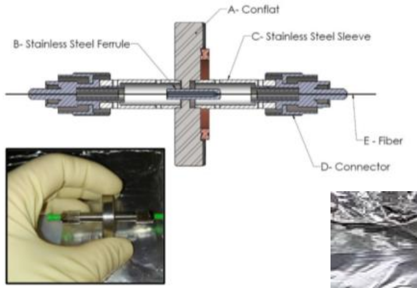




Source-Credit: Matichard, *Active Optical Mode Matching for* the Quantum Squeezing Cavities and Upcoming LIGO Upgrades, ASPE 2020

Example 3: Fiber Feedthrough



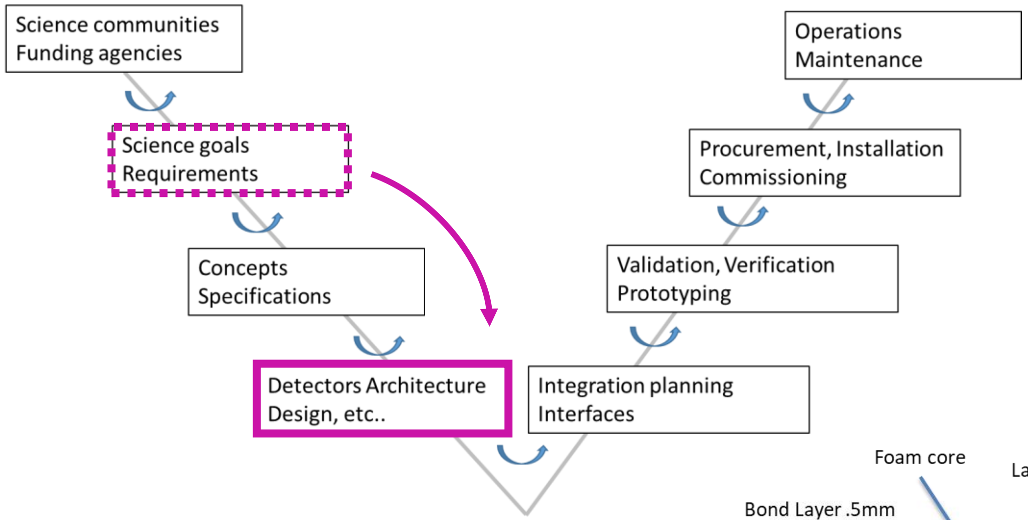


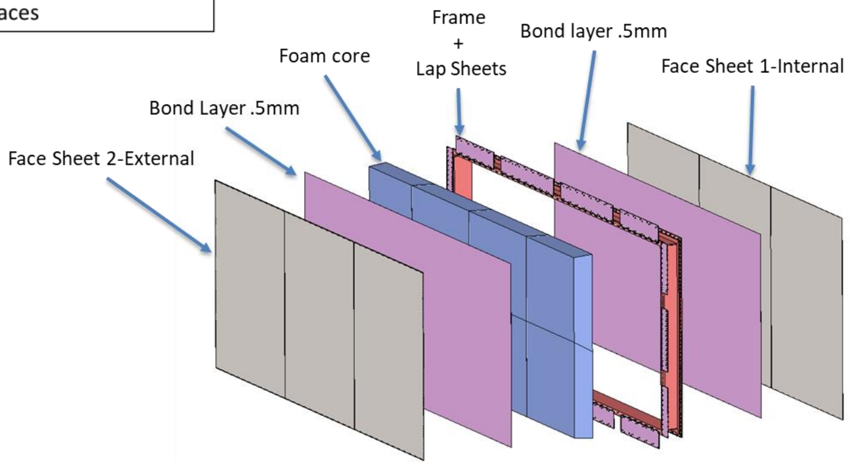
	Option #	Description	Benefits (problem solving): Avoid damage related to polyimide removal	Solve buckling in the fiber	Suppress physical contact at the connector	Better clean-ability / inspectability	Reduce glue degradation at the ferule	Reduce stress at the sealing point	Solve connector alignment concentricity issues	Reduce photo-darkening effect	Cost and Risk: Development time	Development cost	Risk of introuducing other problems
General	G0	Current solution (reference)	No	No	No	Yes	No	No	No	No	na	na	na
	G1	Replace fibers by free-space and tip-tilts	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	High	High	Moderate
	G2	Increase OPO cavity finesse	na	na	na	na	Maybe	Maybe	na	Maybe	Moderate	Low	Low
Feedthru	FF1	Feedthru - D1800102-v2 - long on air side	na	Yes	na	Yes	na	na	na	Maybe	Low	Low	Moderate
	FF2	Feedthru - D1800102 improved curing process	na	na	na	Yes	Maybe	Maybe	na	Maybe	Low	Low	Moderate
	FF3	Feedthru - Vacom (MPF) hardware	Maybe	Yes	No	No	No	Yes	No	Maybe	Moderate	High	Moderate
	FF4	Feedthru -Soft sealing	na	Yes	na	na	na	Yes	na	Maybe	High	Moderate	High
	FF5	Feedthru - Fiber design	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	FF6	Feedthru - Other vendors? LSC/LVC users?	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	FF7	Feedthru - AEI - Diamond optics	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Moderate	Moderate	Moderate
	FF8	Feedthru - OZ Optics receptacle style	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	FF9	Feedthru - Apogee spectrometer style	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Patch-cord	PC1	Fujikara mechnical polyimide removal (LL)	Yes	na	na	na	na	na	na	Maybe	Low	Low	Low
	PC2	3SAE Plasma workstation polyimide removal	Yes	na	na	na	na	na	na	Maybe	Moderate	Moderate	Low
	PC3	Furnace polyimide removal	Maybe	na	na	na	na	na	na	Maybe	Low	Low	Moderate
	PC4	Acrylate coating qualification	Yes	na	na	na	na	na	na	Maybe	Moderate	Moderate	High
	PC5	Photonics Crystaline Fiber (Acrylate)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	PC6	Vacom Pathcord adapted to 532nm	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	PC7	OZ Optics Pathcord adapted to 532nm	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	PC8	Chemical polyimide removal	Yes	na	na	na	na	na	na	Maybe	High	High	High
Coupler	CPL1	U-Bench coupler	na	na	Yes	Yes	Maybe	na	Maybe	Maybe	Low	Low	Moderate
	CPL2	PFP High Power Connectors (145um)	Yes	na	Yes	Yes	Yes	na	Maybe	Maybe	Moderate	Moderate	Moderate
	CPL3	PFP High Power Connectors (125um)	na	na	Yes	Yes	Yes	na	Maybe	Maybe	Moderate	Moderate	Moderate
	CPL4	PFP low concentricy connectors (125um)	na	na	na	Yes	Maybe	na	Maybe	Maybe	Low	Low	Moderate
	CPL5	Mechanical Cleaver (0 or 8 degree)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	CPL6	Short End cap	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	CPL7	Long end cap (Peter)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	CPL8	Lincoln lab end cap	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	CPL9	Light path Fiber collimator	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
	CPL10	OZ Optics - High power connectors / couplers	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
		Feedthru #3 & Patch-Cord #1 & Coupler #1	Yes	Yes	Yes	Yes	Maybe	No	Maybe	Maybe	Low	Low	Moderate
		Feedthru #3 & Patch-Cord #1 & Coupler #2	Yes	Yes	Yes	Yes	Yes	No	Maybe	Maybe	Moderate	Moderate	Moderate
		Feedthru # 5	Maybe	Yes	No	No	No	Yes	No	Maybe	Moderate	High	Moderate
		Feedthru #6 & Patch-Cord #1 & Coupler #2	Yes	Yes	Yes	Yes	Maybe	Yes	Maybe	Maybe	High	Moderate	High

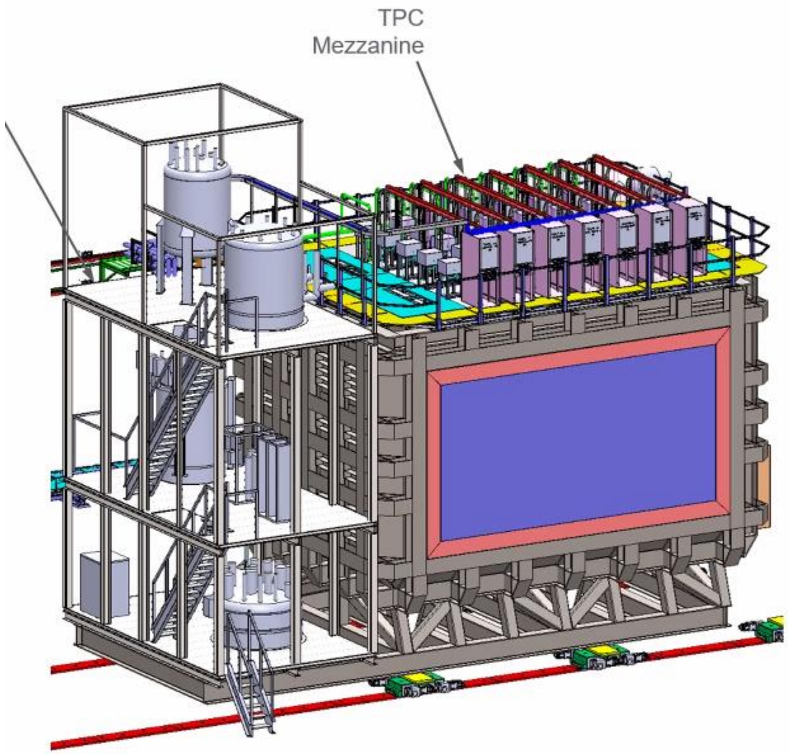
Tradeoffs methodologies

Ranking criteria

Example 4: Cryostat wall

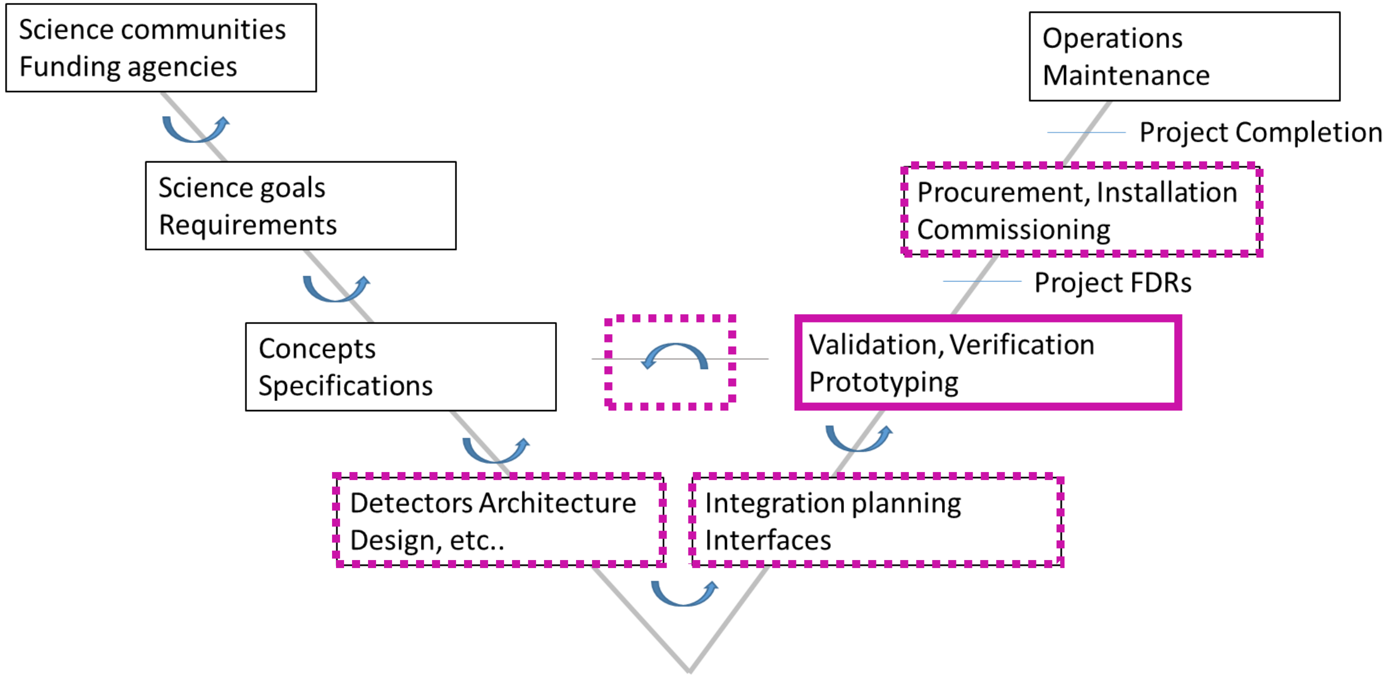




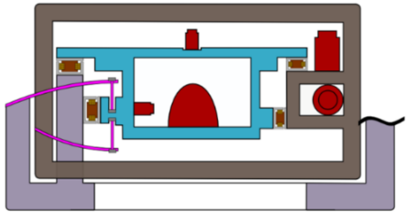


Source-Credit: Joseph Silber, Andrew Lawrence, Peter Tennessen – LBNL/DUNE Near Detector Cryostat

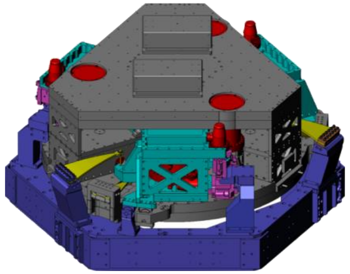
Validation and verification



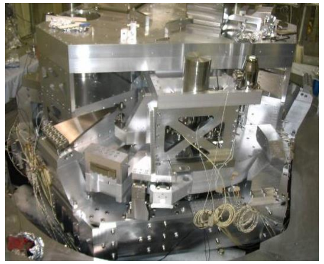
Technology readiness



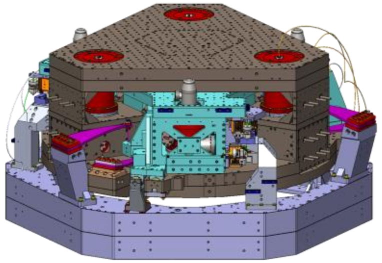
Concepts, R&D



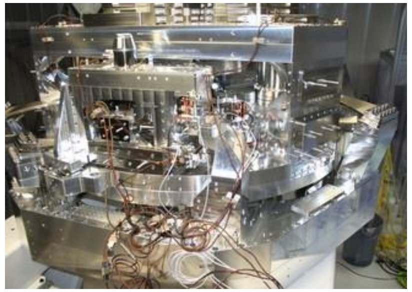
Demonstrators



Prototypes



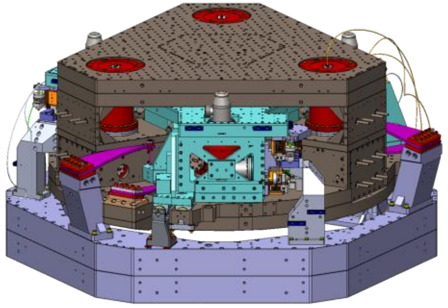
Final design validated

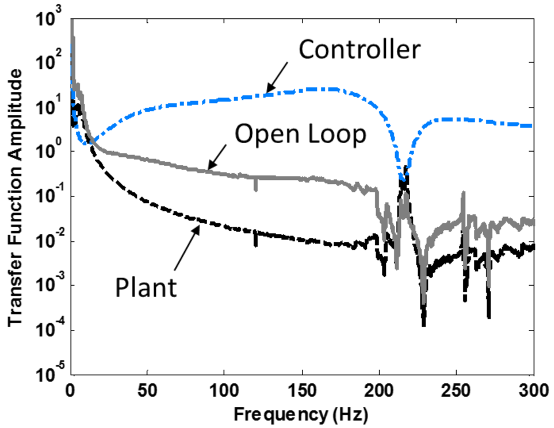


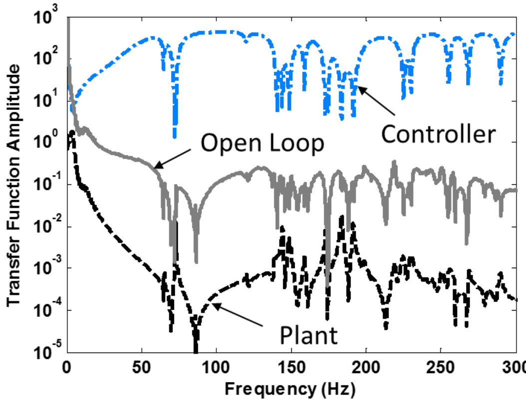
Operations

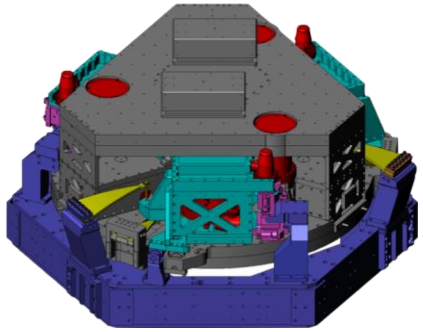
Matichard, Fabrice, et al. "Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. Part 1: Design and production overview." *Precision Engineering* 40 (2015): 273-286

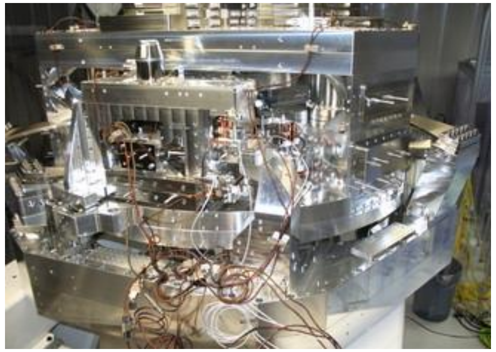
From prototyping to production



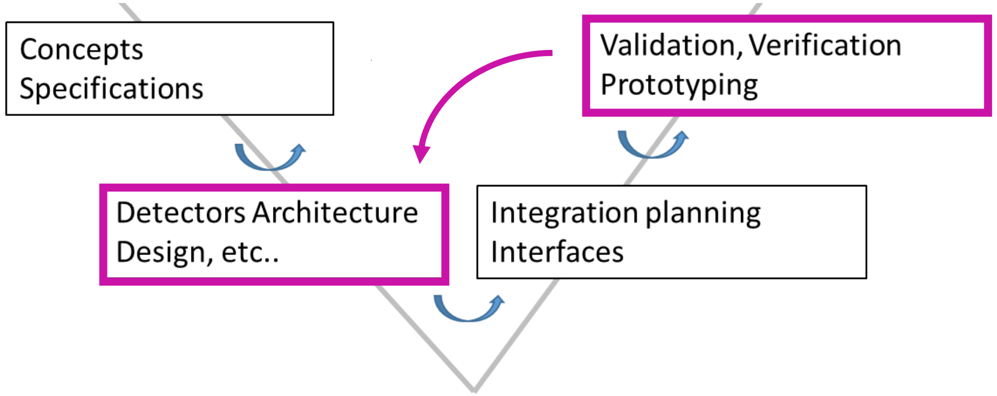


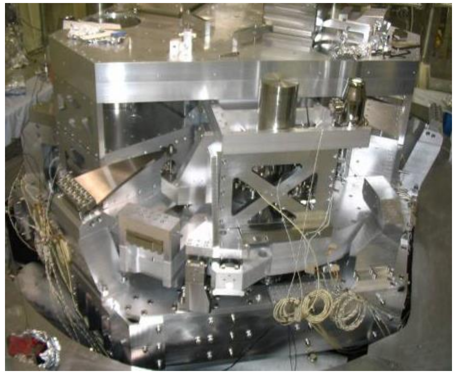






- Assembly ~ 4 weeks

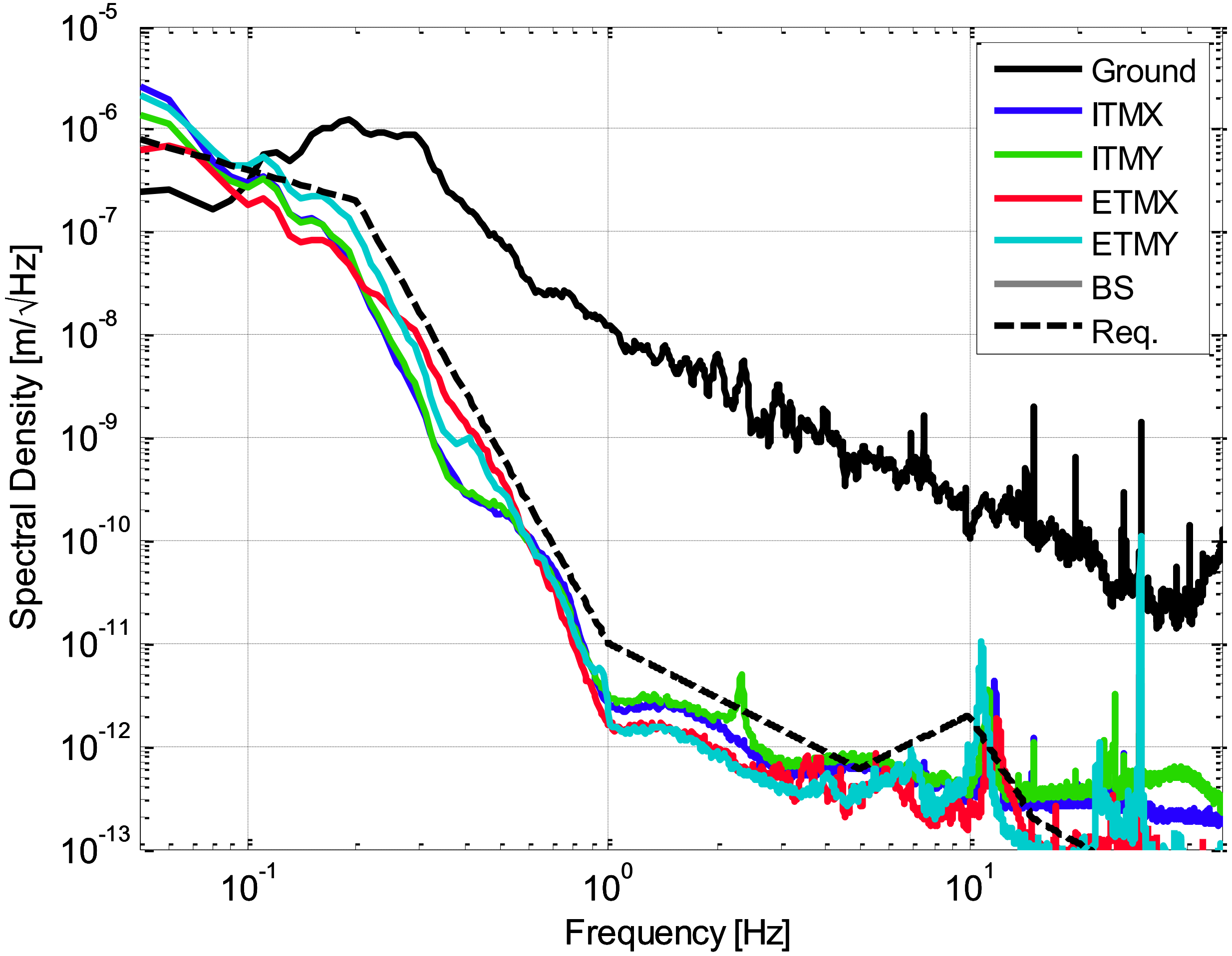


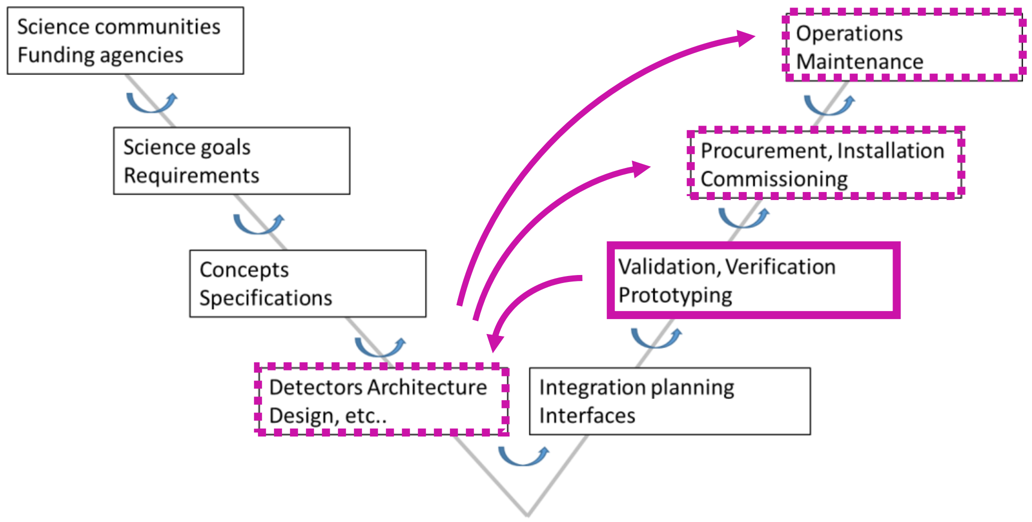


- Assembly ~ 4 Months

Matichard, Fabrice, et al. "Advanced LIGO two-stage twelve-axis vibration isolation and positioning platform. Part 2: Experimental investigation and tests results." *Precision engineering* 40 (2015): 287-297

Operational performance





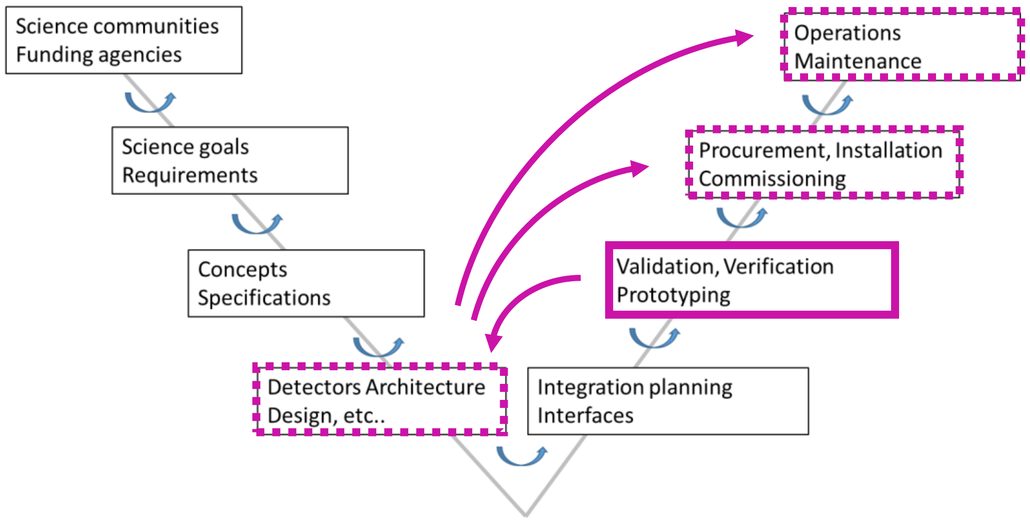
Matichard, Fabrice, et al. "Seismic isolation of Advanced LIGO: Review of strategy, instrumentation and performance." *Classical and Quantum Gravity* 32.18 (2015): 185003.

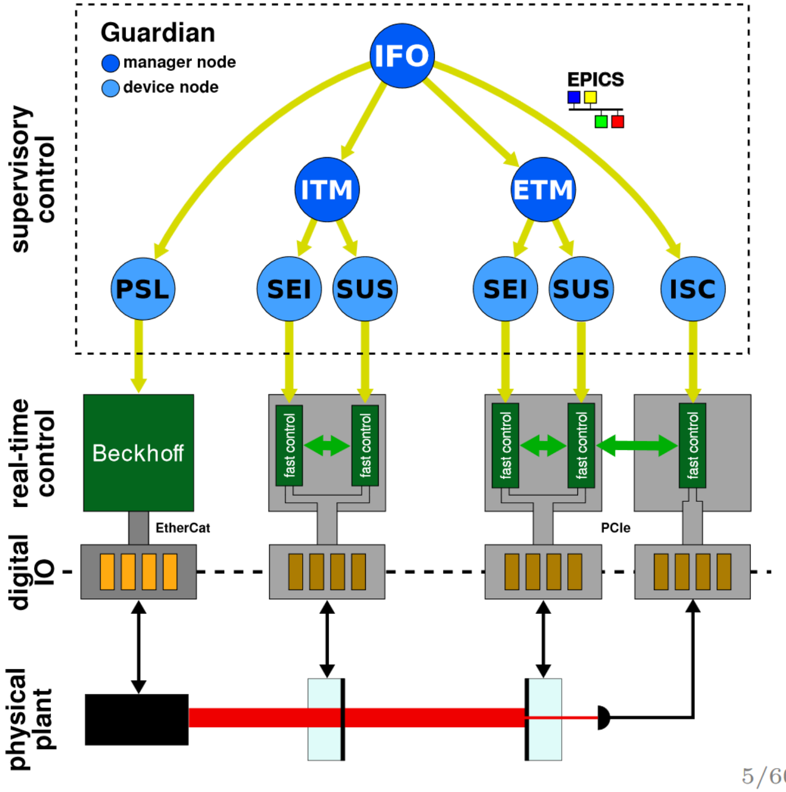
Testing the controls system

Fast controls

Slow controls

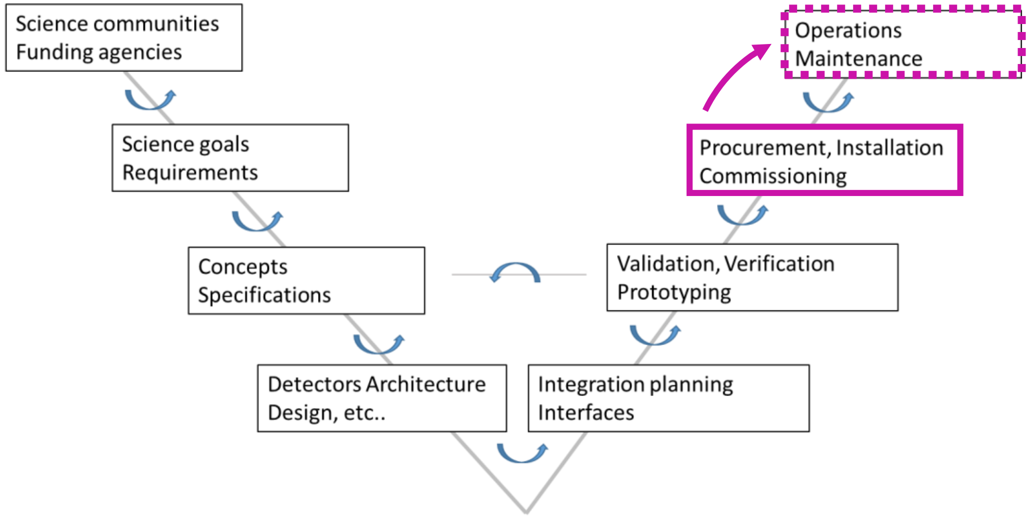
Supervisory





Source/Credits - Top right LIGO supervisory system (Jamie Rollins)

Procurement – QA/QC



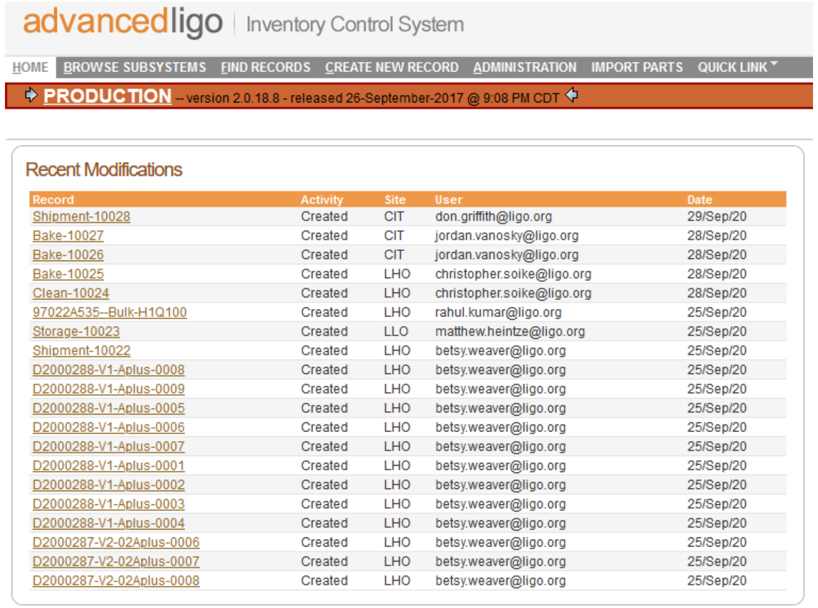
QA/QC

Inspections

Records

Inventory

Traceability



advancedligo | Inventory Control System

HOME BROWSE SUBSYSTEMS FIND RECORDS CREATE NEW RECORD ADMINISTRATION IMPORT PARTS QUICK LINK

PRODUCTION -- version 2.0.18.8 - released 26-September-2017 @ 9:08 PM CDT

Recent Modifications

Record	Activity	Site	User	Date
Shipment-10028	Created	CIT	don.griffith@ligo.org	29/Sep/20
Bake-10027	Created	CIT	jordan.vanosky@ligo.org	28/Sep/20
Bake-10026	Created	CIT	jordan.vanosky@ligo.org	28/Sep/20
Bake-10025	Created	LHO	christopher.soike@ligo.org	28/Sep/20
Clean-10024	Created	LHO	christopher.soike@ligo.org	28/Sep/20
97022A535--Bulk-H1Q100	Created	LHO	rahul.kumar@ligo.org	25/Sep/20
Storage-10023	Created	LLO	matthew.heintze@ligo.org	25/Sep/20
Shipment-10022	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000288-V1-Aplus-0008	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000288-V1-Aplus-0009	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000288-V1-Aplus-0005	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000288-V1-Aplus-0006	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000288-V1-Aplus-0007	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000288-V1-Aplus-0001	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000288-V1-Aplus-0002	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000288-V1-Aplus-0003	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000288-V1-Aplus-0004	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000287-V2-02Aplus-0006	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000287-V2-02Aplus-0007	Created	LHO	betsy.weaver@ligo.org	25/Sep/20
D2000287-V2-02Aplus-0008	Created	LHO	betsy.weaver@ligo.org	25/Sep/20

Fabrication

Statement of work

Request for information

Request for quotation

Purchase orders

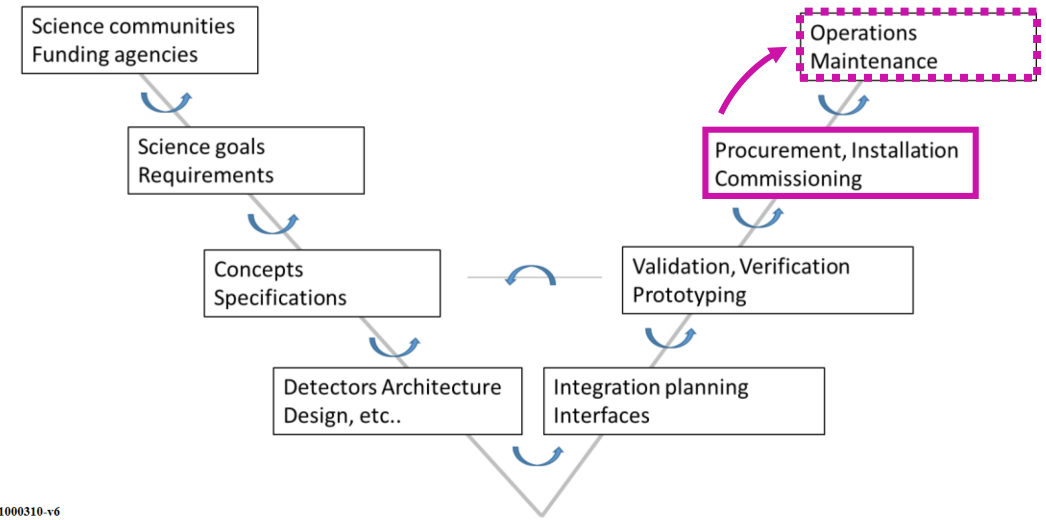
Source Credits – Top: LIGO DCC and PDM, Right: LIGO ICS, Bottom: LIGO suspension by Don Griffith

Testing

Test stands

Test Procedures

Tests reports



LIGO LIGO-E1000310-v6

Table of contents:

- *Step 14 - Linearity test*

	Slope	Offset	Average slope	Variation from average(%)
H1	2.1099	-293.75		1.93
H2	2.0571	-274.49	2.07	-0.62
H3	2.0426	-136.64		-1.32
V1	1.4892	278.92		0.97
V2	1.4757	284.92	1.47	0.06
V3	1.4597	289.52		-1.03

Table - Slopes and offset of the triplet 'Actuators - HAM-ISI – Sensors'

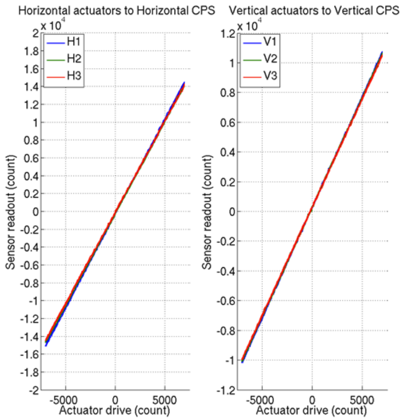
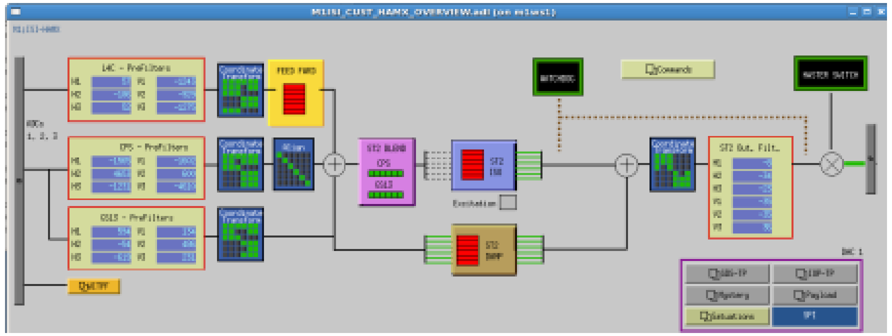
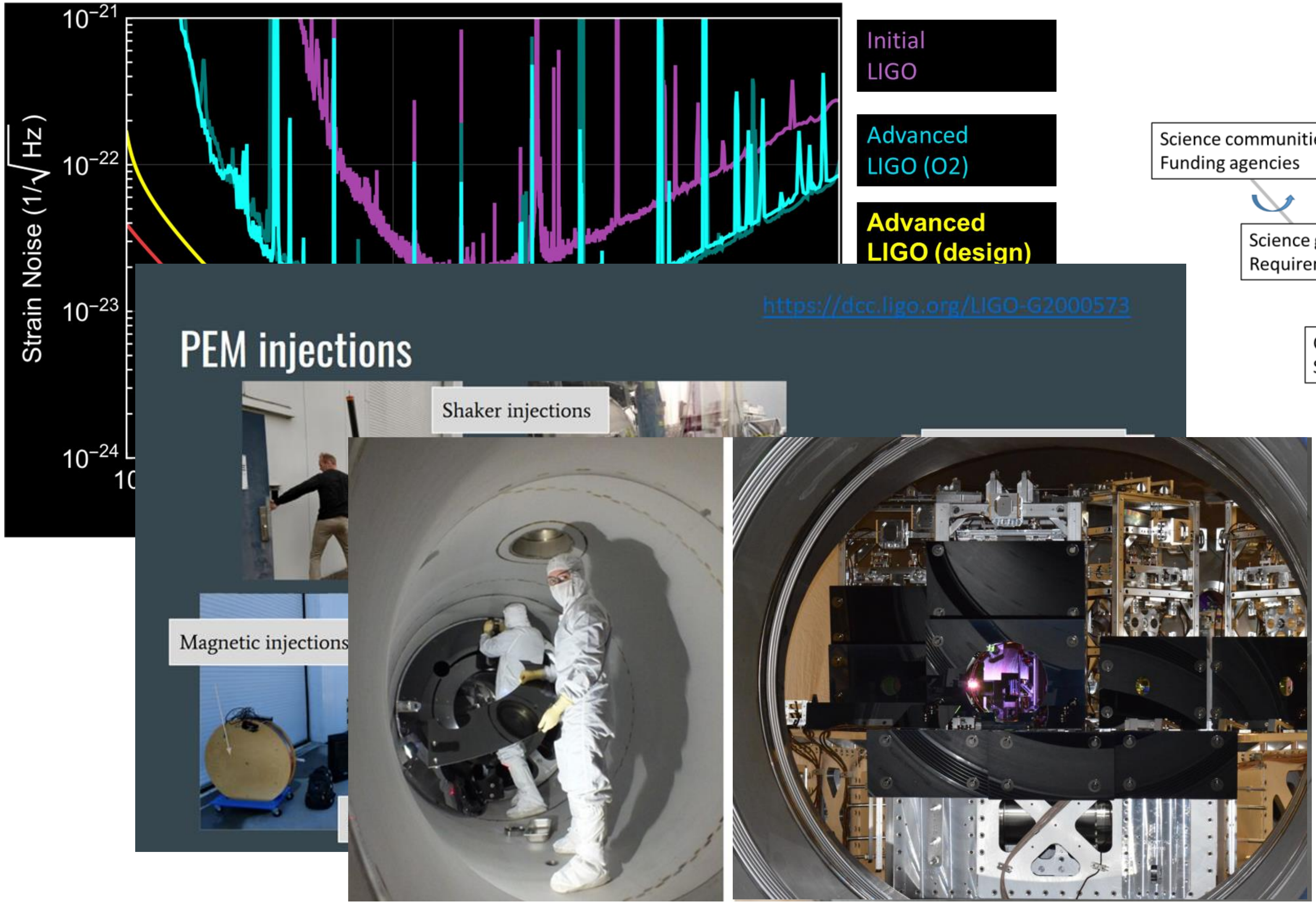


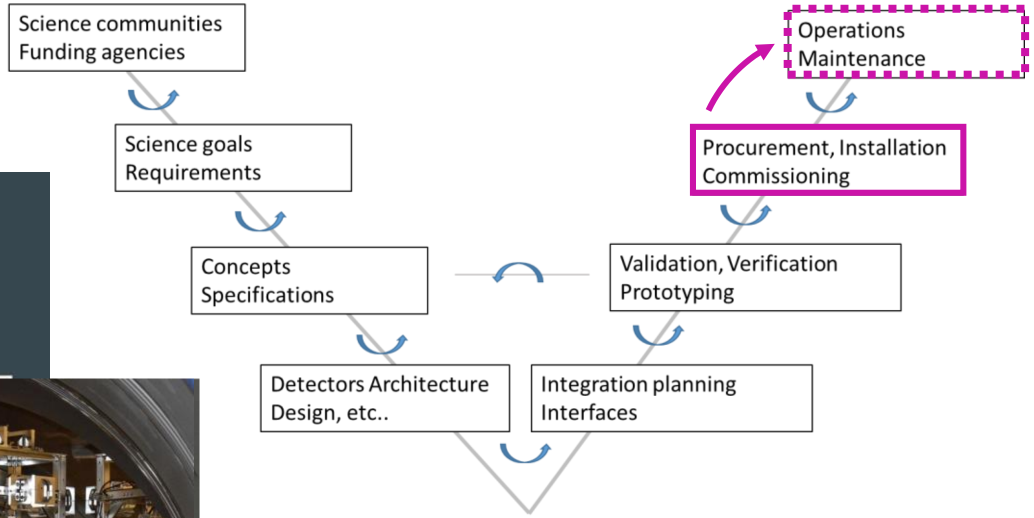
Figure - Linearity test on the triplet 'actuators - HAM-ISI – sensors' in both Horizontal and vertical directions



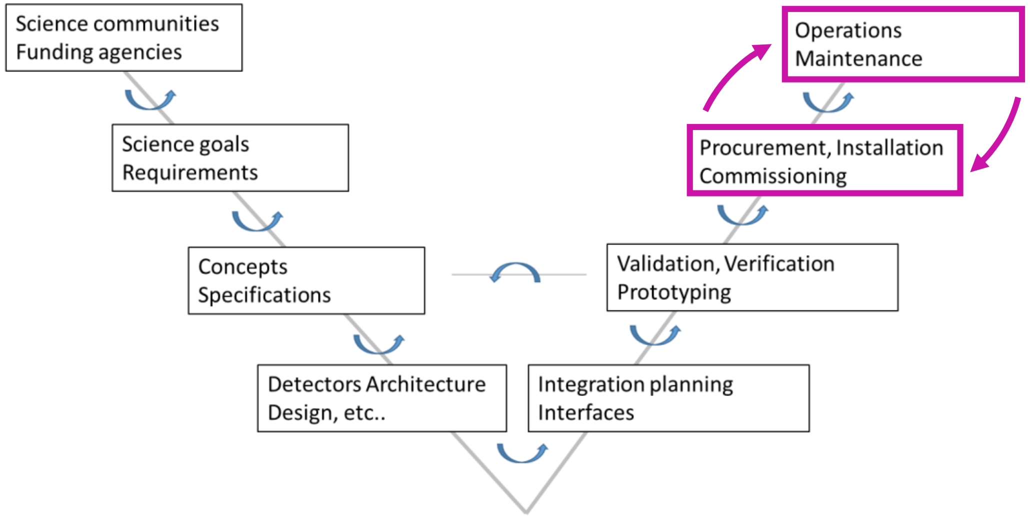
Source Credits – LIGO testing procedures. Lhuillier, Matichard

Commissioning

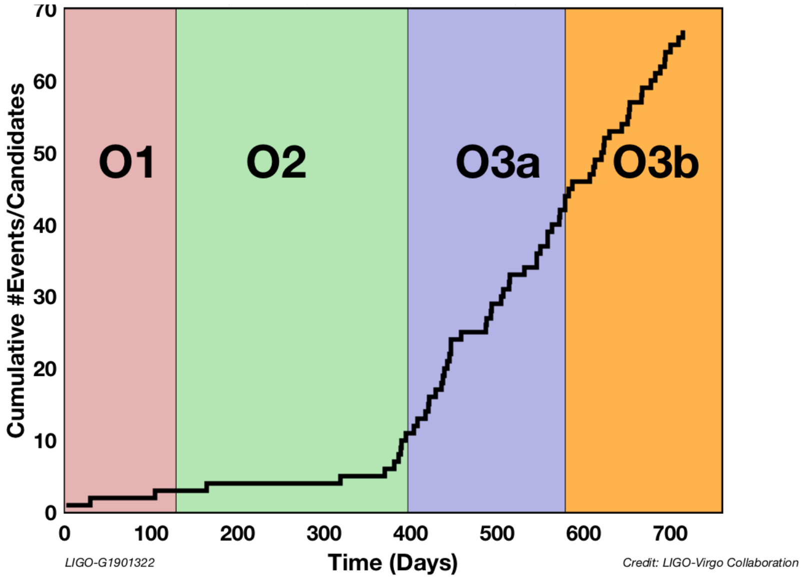




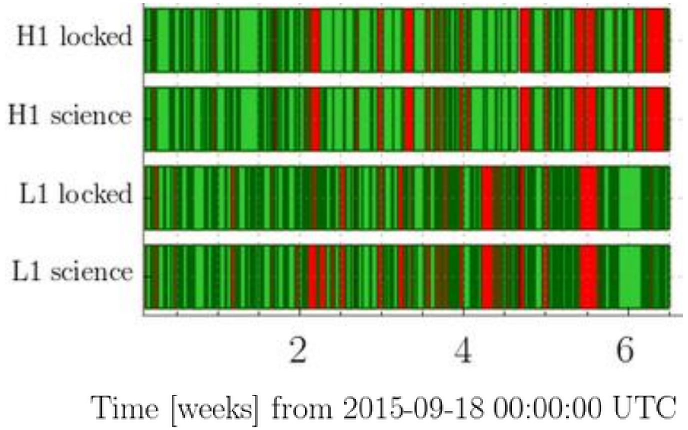
Operations



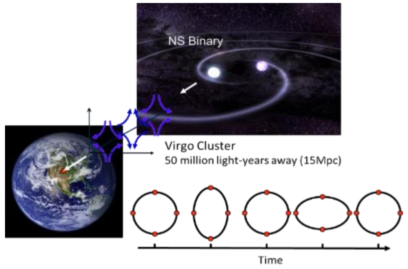
Maintenance

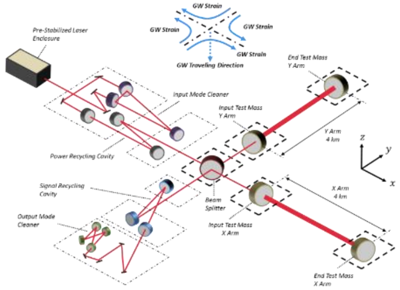


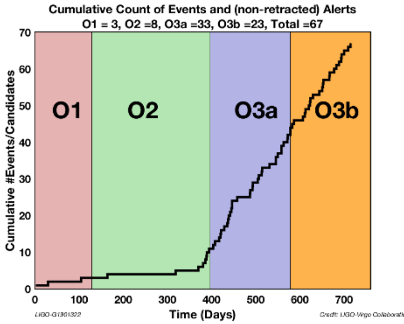
Duty-Cycle



Maintenance







Science communities
Funding agencies

Science goals
Requirements

Concepts
Specifications

Detectors Architecture
Design, etc..

Integration planning
Interfaces

Validation, Verification
Prototyping

Project FDRs

Procurement, Installation
Commissioning

Project Completion

Operations
Maintenance