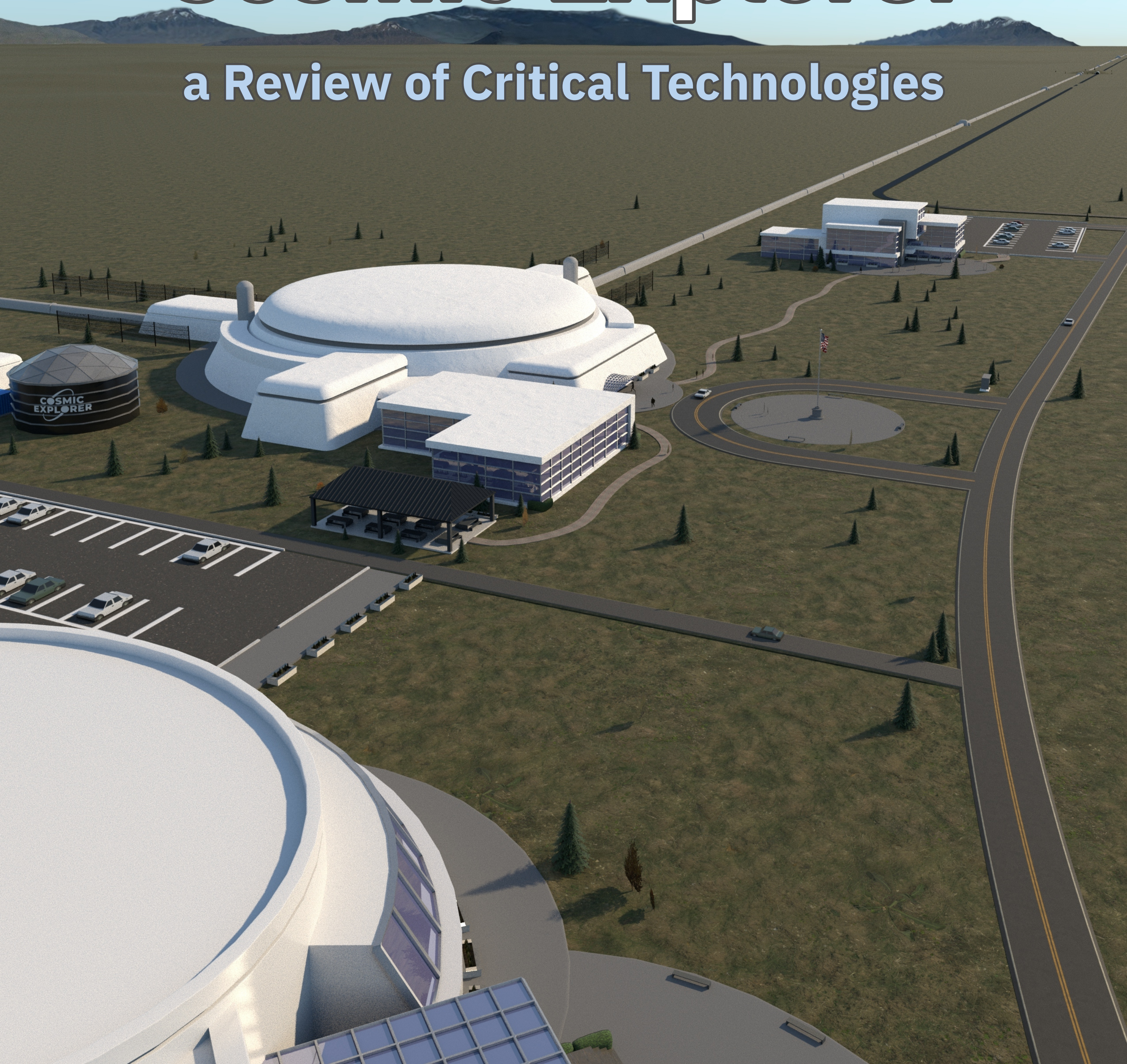
COSMIC EXPLORER

Design Stage R&D for

Cosmic Explorer

a Review of Critical Technologies



Cosmic Explorer Technical Report CE–P2100xxx–vN
September 2021

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Cover Image

Artistic visualization of a Cosmic Explorer facility by Cal State Fullerton undergraduate Edward Anaya.

Work on Cosmic Explorer is funded by the National Science Foundation.

Contents

1 Purpose and Scope

With the completion of the Cosmic Explorer Horizon Study,[1] Cosmic Explorer will soon be ready to enter the formal project design stage. Following the National Science Foundation (NSF) process for "major facilities",[2] the design stage consists of 3 phases (conceptual, preliminary, and final) and will last approximately 7 years.[1] This review outlines the research and development (R&D) that will be required for completion of the design stage of the Cosmic Explorer project. As such, the scope of this work is explicitly limited, and is not intended to replace the broader R&D documents that have been produced by the Gravitational Wave International Committee (GWIC),[3] and the LIGO Scientific Collaboration.[4]

In order for R&D products to be useful in the Cosmic Explorer design stage, they must feed into the Preliminary Design Review, which is expected to occur 5 years into the design process. Longer term research products will be of use if they inform the design and feed into the operations stage of Cosmic Explorer (e.g., data-analysis techniques); explore planned upgrades of the Cosmic Explorer detectors (e.g., improved inertial sensors); or study alternative detector technologies (e.g., 2 μm laser technology). These longer-term research topics are not covered in this review, but rather in the Cosmic Explorer Horizon Study[1] the GWIC R&D report,[3] and the LIGO Voyager report.[5]

This review is organized by impact area, with topics in each area identified as either targeting technologies that are critical for the conceptual design phase (i.e., most pressing), or the preliminary design phase. The research areas and activities covered are:

- Science Goals
  - Scientific Objectives: Engage the community to develop and prioritize Cosmic Explorer's science objectives. Explore partnerships with international and U.S. agencies. Develop a plan for research community engagement, and data management plans.
  - Science Goals and Traceability Matrix: Deliver a comprehansive statement of the requirements placed by the research objectives on observatory parameters, analysis and computational requirements, requirements on community infrastructure, and human resources.
- Detectors
  - Interferometer Configuration: add detail to the interferometer configuration and define facility interfaces (e.g., recycling cavity configurations, mode cleaner lengths, filter cavities)
  - Large Optics: investigate the production of large optics (substrates, polishing, coating, etc.)
  - Suspensions and Seismic Isolation: scale up current suspension and isolation technology, and develop potential upgrade routes

  - Lasers and Squeezed Light: investigate the production of lasers and squeezed light sources
  - Detector Control, Calibration and Computing: identify new technologies required for control and calibration, and elaborate detector computing requirements

- Facilities
  - Site Identification: determine site requirements and characterization techniques, and find candidate sites
  - Civil Engineering and Vacuum System: identify technologies to be used in the civil engineering design of the facility and in the vacuum system, including Newtonian noise and scattered light mitigation

It should be noted that there are several areas of important design-stage effort that are not covered herein because they are not R&D topics: community building and outreach, project organization, civil engineering, etc.

2 Cosmic Explorer Science

Cosmic Explorer's observations will drive discovery across a wide range of domains in physics and astronomy, including nuclear physics, high-energy and relativistic astrophysics, stellar evolution, large-scale structure formation, particle physics, cosmology, and gravitational physics. Achieving Cosmic Explorer's science goals will require advances in computational physics, large-scale computing, and machine learning. Reflecting the breadth of third-generation observatories, the Gravitational Wave International Committee (GWIC) has organized community studies[3,6–10] of the gravitational-wave network's scientific potential, and its synergy with ground- and space-based gravitational-wave, electromagnetic, and astro-particle observatories. The Cosmic Explorer Horizon Study focuses on three central scientific themes that Cosmic Explorer will address and the discovery potential of an observatory that will see gravitational waves out to the edge of the universe.

A significant, community-wide research and development effort is necessary to refine and fully develop the science goals mapped out in the Horizon Study. The Horizon Study argues that the scale of the analysis and simulation campaign needed to realize the science of Cosmic Explorer is not intractable, but significant work lies ahead to realize Cosmic Explorer's science. Cosmic Explorer will continue to rely on an engaged community of scientists supported by grants from U.S. federal funding agencies to develop its scientific program. Individual and collaborative grants funded through the merit-based review process will ensure a diversity of approaches to the key problems including—among many other tasks—defining and refining the science goals of the network, development of new data-analysis algorithms that tackle the complexities of third-generation networks, and new methods of modeling the gravitational and electromagnetic waves that the third-generation network will detect.

In this section, we do not attempt to describe all of the techniques and approaches that the community will pursue over the coming decade. We expect that a large amount of innovative science will be performed by the community using real-time calibrated data streams or archival observations from Cosmic Explorer and we do not attempt to proscribe this research, nor do we attempt to describe other enabling research in physics and astrophysics. However, effort will be required to ensure that the design of Cosmic Explorer can achieve the goals that are identified as highest priority by the community, and that Cosmic Explorer can do so effectively and cost-efficiently. As technology risks are quantified, the impact of these risks on the science goals must be studied. Research and development are required for infrastructure planning to ensure that Cosmic Explorer's data and observations can be delivered to the scientific community promptly, reliably, and in the most broadly usable form. Accurate costing will be required for the human, computational, and other external resources needed to realize Cosmic Explorer's science. For computing, this includes hardware that will need to be dedicated to Cosmic Explorer and the impact of Cosmic Explorer's science on national cyberinfrastructure platforms. A careful study of the demands of multi-messenger astronomy will be required to assess the impact and demands of third-generation observatories on the nation's astronomical observing portfolio.

Below, we enumerate the tasks that must be accomplished in the conceptual design and preliminary design phases of the Cosmic Explorer major facility project. Section 2.1 describes the work needed to define the project requirements based on the science goals, §2.2 describes the work needed to develop science-driven instrument and observatory requirements and costing.

2.1 Scientific Objectives

The key science questions presented the Cosmic Explorer Horizon Study[1] are as follows:

1. **How have the populations of black holes and neutron stars evolved over the history of the universe?** Cosmic Explorer will detect gravitational waves from black holes and neutron stars in binaries to redshifts of ~ 10 and above, allowing us to shed light on Population III stars through the black holes they might have left behind, measure the properties of the first black holes and their role in forming supermassive black holes and galaxies, and characterize the populations of compact objects and their evolution.

2. **How does matter behave under the most extreme conditions in the universe** Cosmic Explorer will measure gravitational radiation from binary neutron star coalescences and provide the precise source localizations required for multimessenger astronomy, allowing us to determine the internal structure and composition of neutron stars, explore new regions in the phase diagram of quantum chromodynamics and the nuclear equation of state, map heavy element nucleosynthesis in the universe through counterpart kilonovae and distant mergers, and reveal the nature of the central engine of highly relativistic jets and how they power short gamma-ray bursts.

3. **What is the nature of the strongest gravity in the universe, and what does that nature reveal about the laws of physics?**. Cosmic Explorer's observations of loud and rare gravitational waves will reveal the (potentially new) physics of the most extreme gravity in the universe, allowing us to probe the nature of strong gravity with unprecedented fidelity, discover unusual and (if they exist) novel compact objects impossible to detect today, and probe the nature of dark matter and dark energy.

As the community continues to define and prioritize these requirements though the conceptual design phase, new discoveries will be made by existing facilities and new ideas will emerge. The following work will be required during the conceptual design and preliminary design phase to deliver the tasks required in the NSF Major Facilities Guide:

Conceptual Design

1. Convening community planning exercises to prioritize and review Cosmic Explorer's scientific objectives. These exercises must deliver a set of compelling and achievable science goals that have broad support in the scientific community.
2. Deliver a description of Cosmic Explorer's scientific objectives that motivate the facility in the project execution plan.
3. Explore partnerships with international agencies and organizations or agencies in the United States, evaluate the role of potential partners and impact on the NSF, and perform risk assessment of possible partnerships.
4. Develop a plan for community outreach activities to engage and maintain the broader research community in Cosmic Explorer science. Develop data management and publication policies appropriate for the project and that ensure the broadest possible community engagement in Cosmic Explorer's science.

Preliminary Design

1. Continue to refine and update Cosmic Explorer's scientific objectives in the Project Execution Plan as new knowledge is developed in the community.
2. The Project Execution Plan refined to clearly clearly delineate the tasks that will be delegated to the community, performed in partnership with the community, and performed by operations personnel and assess the risk and benefit of such demarcation.

2.2 Science Flow Down to Design

A statement of Cosmic Explorer's scientific requirements and their impact on instrument requirements will be a critical deliverable of the conceptual design phase. The Cosmic Explorer Horizon Study presented an initial science tracability matrix based on the preliminary trade study. However, this needs significant refinement to deliver the comprehensive statement of the requirements matrix required in the Project Execution Plan. During the conceptual design and preliminary design phases, the following tasks must be completed:

Conceptual Design

1. Clearly establish the connection between the key science goals and Cosmic Explorer's design. Identify the minimum essential requirements to achieve the science goals as well as the desirable quantitative requirements for both the detector hardware (e.g. interferometer configuration) and the observatory parameters (e.g. network, location, and orientation).

2. Explore demarcations of data production, calibration, and analysis that are internal to the Cosmic Explorer project, that require partnership with other facilities, or that require on community-driven effort to deliver. Assess the risks to project science goals of different demarcations of tasks between the project and the community.

3. Identify the areas where project science goals rely on algorithms and methods that are currently available and those that are not yet fully developed. Assess the risks to the project of the current state-of-the art of algorithm development and the computational and analytic understanding of sources and their properties.

4. Clearly describe the computational requirements of the project, and the costs of the internal computing needed to deliver the science goals and the impact of Cosmic Explorer's science on external computational resources provided by the national cyberinfrastructure.

5. Determine the scope of the external infrastructure requirements (if any) needed to deliver Cosmic Explorer's science goals, particularly with respect to multi-messenger astrophysics. Determine the requirements that Cosmic Explorer's science objectives will place on the U.S. ground- and space-based observational astronomy portfolio. Assess the benefits and risk to Cosmic Explorer's science objectives resulting from reliance on external partners for multi-messenger observations. Explore possible paths for coordination of multi-messenger science to ensure that Cosmic Explorer's science goals are met.

6. Determine how the project goals impact the human resources needed to perform tasks related to data preparation, alert generation, data curation, and user community support during the operations phase of the project.

Preliminary Design

1. The Project Execution Plan must be refined to provide a bottom-up cost estimate of the data, computing, and analysis tasks that must be delivered during the operations phase.

2. An implementation plan and risk analysis for the management, calibration, analysis, dissemination, and archival of Cosmic Explorer data in the operations phase must be developed.

3 Detectors

The reference detector concept for Cosmic Explorer is largely based on the evolution of technology currently deployed in LIGO and other gravitational-wave detectors. Dedicated funding is needed for this evolution to happen during the design phase. This section identifies the areas where research and development are required during the conceptual design and preliminary design phase in order to realize the Cosmic Explorer observatory at its target sensitivity.

We start with a top-level overview of the detector work required during the conceptual design and preliminary design phase to deliver the tasks required in the NSF Major Facilities Guide:

Conceptual Design

1. Poof-of-concept for critical items: Pathfinder projects for any project-critical items need to be initiated early on. They need to be capable of addressing manufacturability questions. In particular, a test mass pathfinder and a vacuum system pathfinder are essential. Vacuum requirements are discussed in next section under infrastructure. The ability to manufacture Cosmic Explorer test masses that meet the size, mechanical and optical specification is critical for the project to move forward. Coating options for the test masses also need to be understood, and the test masses need to meet the thermal lens constraints imposed by the wavefront control requirements.

2. Integrated detector design: The detector conceptual design needs to be specific on seismic isolation and suspension design choices, the main detector layout including input and output chain, mode cleaners and laser stabilization. Functional requirements of all systems need to be defined. In particular, choices that affect the facility layout need to be addressed. For potential alternative technologies the impact on facility design also needs to be understood.

3. Risk analysis: All risk items present in the detector conceptual design need to be identified and mitigation plans needs to be developed. Integrating key new technologies in to the existing LIGO observatories can potentially significantly reduce the technical risk for Cosmic Explorer while at the same time boosting the scientific output of the existing observatories.

4. Cost analysis: Early in the CD phase, updated estimates of the R&D costs for the CD and PD phase will be needed in order to enable this research to proceed smoothly.

		Initial CE	CE
Core Optics	Substrates (§3.2)	Production of 70 cm ∅ fused silica optics, 320 kg Polishing at spatial scales $\gtrsim$ 20 cm	
	Coatings (§3.2)	A+ coatings at 70 cm scale	Best effort for improved coatings
Test mass isolation	Suspensions (§3.3)	2 m fibers 1.2 GPa fiber stress	2 m fibers 1.6 GPa fiber stress
	Active vibration isolation (§3.4)	$0.1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 10 Hz $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 1 Hz	$0.03\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 10 Hz $0.1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 1 Hz
	Newtonian noise mitigation (§3.5)	6 dB Rayleigh-wave suppression No body-wave suppression No infrasound suppression	20 dB Rayleigh-wave suppression 10 dB body-wave suppression No infrasound suppression
Lasers & squeezing	Lasers (§3.6)	140 W into interferometer Frequency noise $< 0.7\,\mu\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 10 Hz	
	Squeezing (§3.7)	6 dB frequency-dependent squeezing	10 dB frequency-dependent squeezing
Controls & data	Control systems (§3.8)	Fully deterministic lock acquisition Environmental robustness	
	Calibration (§3.9)	$< 0.1\,\%$ absolute calibration Investigation into • photon calibration, • Newtonian calibration, • frequency calibration, • astrophysical calibration	
	Computing (§3.10)	2 TB/day	

Table 3.1: Summary of Cosmic Explorer detector R&D activities.

Preliminary Design

1. System interconnections: All interferometer and facility system interconnections need to be understood and documented. Among others this includes the seismic, suspension, core optic, laser, squeezed light, vacuum, auxiliary, environmental, control, computing and data acquisition systems.

2. Complete noise budget: The preliminary detector design needs to be at the level where a reliable and complete noise budget for all technical and fundamental noise sources specific to the design choices can be given.

3. Updated risk analysis: Identify any remaining risk present in the preliminary detector design, and identify mitigation plan.

4. Technology readiness: Demonstrate that key technologies are feasible and can be industrialized. This requires successful conclusion of the pathfinder projects initiated at the beginning of the conceptual design phase.

The remainder of this chapter lays out the development areas for each of the subsystems in more detail. The current timeline for Cosmic Explorer is constructed to make the best possible use of the anticipated technology development over the next two decades. Where applicable, such technology choices are also highlighted in the following subsections. The research laid out here will take place in collaboration with other projects such as Einstein Telescope and existing interferometer prototype facilities.

3.1 Interferometer Configuration

The Cosmic Explorer reference detector concept is a dual-recycled Fabry–Pérot Michelson interferometer (DRFPMI) scaled up to use 40 km or 20 km long arms. Though this technology concept is well developed and tested, there are a wide range of possible variations which may be necessary in order to optimize the scientific output of Cosmic Explorer. It is important to identify design variants that impact the Cosmic Explorer facility design as early as possible (i.e., during the conceptual design phase), while other optimizations may be incorporated in later design phases. Design areas and R&D topics that will be required to establish the detailed Cosmic Explorer detector configuration, and thus its vacuum system requirements and interface to the facility, are described in the following paragraphs.

Input Chain The laser source for Cosmic Explorer is similar to that of LIGO and begins with a 1 µm, 1–2 W seed laser. This is amplified by a multi-stage amplifier to produce the full input power of up to 200 W. Together with some laser intensity and frequency stabilization and some cleaning of the spatial mode of the laser, this comprises the pre-stabilized laser.[11] The light from the pre-stabilized laser is then sent through two triangular cavities known as input mode cleaners to provide further laser frequency stabilization and cleaning of the spatial mode. The frequency stabilization scheme used in LIGO relies on a single mode cleaner, but the longer arms of Cosmic Explorer require a new control scheme which, while possible to implement with a single mode cleaner, greatly benefits from two.[12] The light exiting these mode cleaners, required to be ~140 W to reach the goal of 1.5 MW arm power with the expected optical loss, is

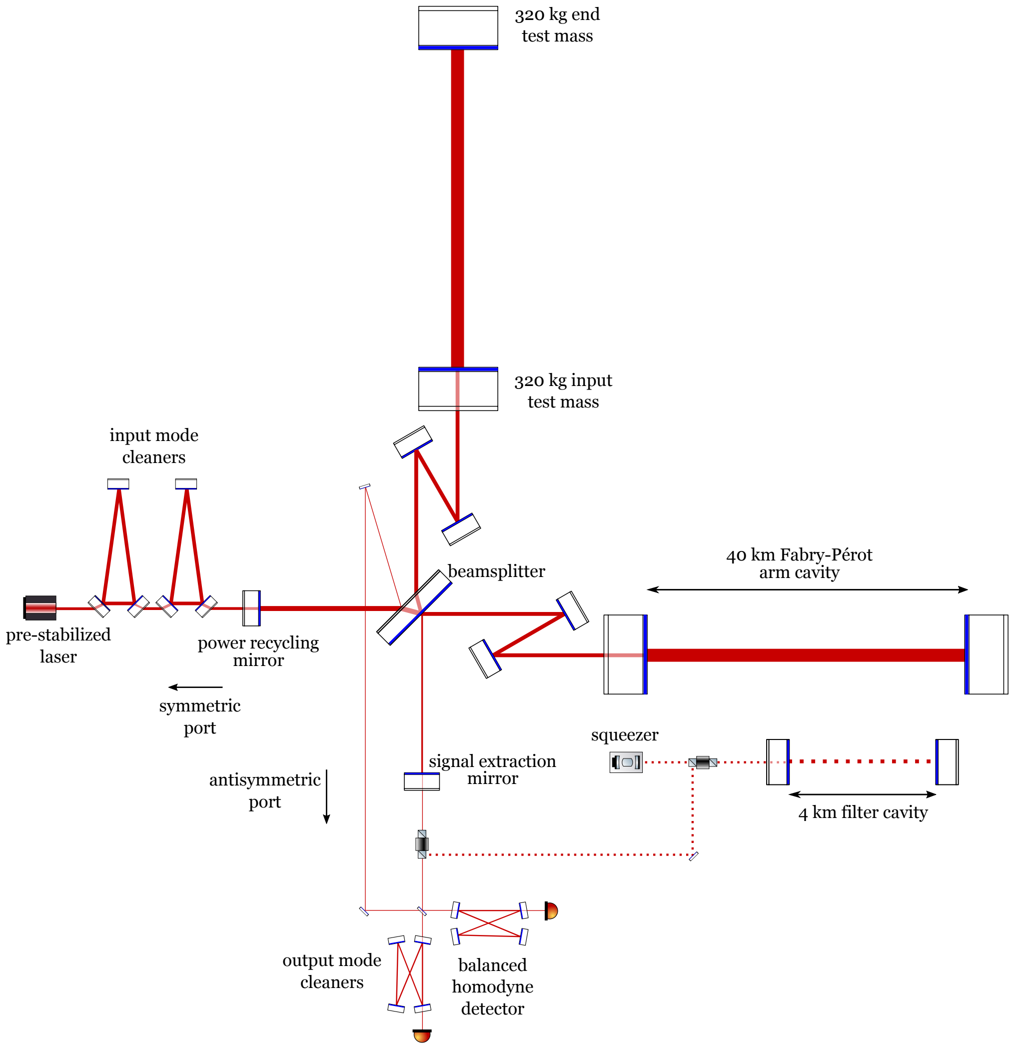

Figure 3.1: Simplified optical layout of the Cosmic Explorer reference detector concept for the 40 km implementation. The input and end test masses form the two arm cavities which, together with the beamsplitter, power recycling mirror, and signal extraction mirror, comprise the core of the dual-recycled Fabry–Pérot Michelson interferometer. The light carrying the gravitational wave signal is spatially filtered and read out from the antisymmetric port by a balanced homodyne detector comprised of two photodiodes and output mode cleaners. A high power laser is injected into the symmetric port of the interferometer after passing through two input mode cleaners which assist in producing a frequency and intensity stabilized beam with a spatially clean mode. The squeezer generates squeezed vacuum states which are reflected off of a filter cavity and injected into the antisymmetric port to provide broadband quantum noise reduction. The beamsplitter is shown with the high-reflective surface facing the antisymmetric port rather than the laser, unlike current detectors, to minimize loss in the signal extraction cavity, but careful analysis of thermal effects is needed before finalizing the design.

	Quantity	Units	LIGO A+	CE
	Arm length	km	4	40
	Laser wavelength	µm	1	1
	Arm power	MW	0.8	1.5
	Squeezed light	dB	6	10
	Susp. point at 1 Hz	$\mathrm{pm}/\sqrt{\mathrm{Hz}}$	10	0.1
Test masses	Material		Silica	Silica
	Mass	kg	40	320
	Temperature	K	293	293
Suspensions	Total length	m	1.6	4
	Total mass	kg	120	1500
	Fiber stress	GPa	0.8	1.6
Newtonian noise	Rayleigh wave suppr.	dB	0	20
	Body wave suppr.	dB	0	10
Optical loss	Arm cavity (round trip)	ppm	75	40
	SEC (round trip)	ppm	5000	500
	BNS horizon redshift		0.19	8.3
	BBH horizon redshift		2.7	41
	BNS SNR, $z = 0.01$		75	1260
	BNS warning, $z = 0.01$	min	4	103

Table 3.2: Key design parameters and astrophysical performance measures for the LIGO A+ and 40 km Cosmic Explorer detectors. The astrophysical performance measures assume a 1.4–1.4$M_\odot$ binary-neutron-star (BNS) system and a 30–30$M_\odot$ binary-black-hole (BBH) system, both optimally oriented. "BNS warning" is the time before merger at which the event has accumulated a signal-to-noise ratio (SNR) of 8.

then injected into the main interferometer at the back of the power recycling mirror.

Output Chain The gravitational wave signal is imprinted on the light exiting the interferometer from the signal extraction mirror. This signal is measured using a balanced homodyne detector with a local oscillator derived from a few hundred milliwatts of light extracted from the beamsplitter. The spatial mode and frequency content of the signal and local oscillator are cleaned by two bow-tie cavities known as output mode cleaners before being detected with high quantum-efficiency photodiodes.

Filter cavity Low-frequency design and high-mass mirrors give Cosmic Explorer a very low "standard quantum limit" (SQL) crossover frequency where the quantum noise has equal contributions from photon shot noise and quantum radiation pressure noise. It is necessary for the squeezed state to rotate from amplitude squeezing to phase squeezing at this frequency in order to achieve broadband quantum noise reduction, and this will be accomplished with a 4 km filter cavity with a finesse of ~4000, based on the 60–70 ppm losses achieved in the Advanced LIGO arm cavities. A 4 km filter cavity length is necessary to prevent the loss-induced dephasing of the cavity from limiting the allowable injected squeezing.[13]

The additional design constraints for controlling squeezing with a 40 km interferometer can be alleviated given more research into the scheme proposed in Ref. [14], which uses the filter cavity itself as a low-noise phase reference for the squeezed light.

Core Optics Optical losses in an interferometer limit the enhancement due to squeezing, independent of other aspects of the system.[15] In Cosmic Explorer, the loss in the signal extraction cavity directly limits the high-frequency sensitivity of the detector and thus the postmerger science it can perform. Thus, minimizing loss is especially important for the 20 km instrument which targets postmerger signals in the 2–4 kHz range.

Mode Matching and Optical Wavefront Control The squeezed states will interact with a sequence of optical cavities: the squeezer's optical parametric amplifier, the filter cavity, the interferometer, then finally the output mode cleaner. The overall curvature mismatch can be corrected using active wavefront control,[16,17] as is planned for LIGO. However, research is needed into control and mitigation of astigmatism in the telescope designs, and the ability to measure and quantify wavefront errors in-situ using auxiliary beams and detectors should also be improved. The need for higher-order aberration correction may prove necessary to match the squeezer beam to the interferometer, given that the interferometer has contrast defect and distortion from heating. More modeling is necessary to establish those needs.

Even at the sub-part-per-million level of optical absorption achieved in the current Advanced LIGO mirror coatings, thermal lensing and thermal expansion induced by the high laser power circulating in the arm cavities (1.5–3 MW for Cosmic Explorer) will lead to significant changes of the optical mode in the interferometer. In addition, any anomalous absorption from small defects will make the problem significantly worse. If not corrected, the resulting wavefront distortions lead to excess scattering in the arm cavities, limit the power build-up, degrade the interferometer contrast at the readout port, and limit mode matching the output mode cleaner cavity and injected squeezed vacuum.

Constraints due to the Integration of Subsystems In Advanced LIGO, some of the interferometer alignment signals are sensed at the antisymmetric port using a 1 % transmissive mirror. Additionally, the filter cavity also samples 1 % of the power for alignment control. For Cosmic Explorer, these transmissivities should ideally be avoided or reduced, which will impact the overall controls design of the instrument. This will require research given that the alignment sensing and controls need to achieve the low frequency sensitivity goals of Cosmic Explorer. Additionally, there are integrative constraints for the squeezer and filter cavity involving the total optical isolation, the length and alignment noises which must be suppressed, and the sensing noise injected by the control systems. Improved seismic isolation will reduce the required control bandwidth and offset the requirements imposed by the lower frequency sensitivity of the CE detectors. A more detailed design study is required.

3.2 Production and Acquisition of Large Optics

Cosmic Explorer requires large and high-quality optical substrates for the main interferometer mirrors (a.k.a. test masses). The Cosmic Explorer test masses will be much heavier than the current Advanced LIGO mirrors (320 kg instead of 40 kg) in order to reduce quantum radiation pressure noise, suspension thermal noise, and all technical force noises. Furthermore, due to the larger diffraction-limited beam size, the Cosmic Explorer mirrors must have a diameter of more than 50 cm in order to hold round-trip optical losses from aperture effects to the parts-per-million level.[18]

Large silica optics The fused silica test masses used for Cosmic Explorer will be roughly twice the diameter of those in Advanced LIGO (70 cm instead of 34 cm), again to reduce diffraction loss from the large beams. Such large volume masses are thought to be achievable with excellent optical properties. However, a careful engineering design, specification, and characterization of the optics will need to be carried out as with Advanced LIGO.[19] The GWIC 3G R&D report[3] calls out the importance of the homogeneity of the index of refraction for silica optics, which may be a significant challenge for the Cosmic Explorer beamsplitters and input test masses due to their large diameter.

Polishing and surface figure Scattered light continues to be a significant source of noise for the current generation of gravitational-wave detectors. Continued improvements in surface polishing of large optics would help to reduce the level of scattered light from the optical surfaces. Estimates of the noise from scattered light for Cosmic Explorer suggest that the required surface polish is comparable to that already achieved in Advanced LIGO for spatial scales below a few cm.[20] However, due to the larger Cosmic Explorer beam size, it is necessary to ensure that this level of surface uniformity can be achieved up to spatial scales of several tens of cm. See §4.3.2 for a broader discussion of the scattered light mitigation research required for Cosmic Explorer.

Low-Loss Mirror Coatings Current Advanced LIGO coatings are alternating layers of SiO_2 and $Ti{:}Ta_2O_5$ (nearly quarter wavelength) Bragg stacks, deposited via ion-beam sputtering. Research is underway to improve upon the mechanical loss and optical properties of these for A+. The Cosmic Explorer 1 μm technology will require A+-like low-mechanical-loss coatings, scaled to larger substrates, and with excellent purity to minimize scattering and absorption. Cosmic Explorer will benefit from current research aimed at improving the A+ coatings. Because the room-temperature mechanical loss of the current low-index material (SiO_2) is quite low, significant effort is focused on identifying a high-index material with lower mechanical loss. Doped germanium is a promising coating for A+, potentially offering a factor of 2 reduction in coating thermal noise.[21] Crystalline GaAs/AlGaAs coatings[22] could provide even lower coating thermal noise if they can be scaled to the size of Cosmic Explorer optics. Scaling the technology for crystalline coatings is more challenging than for amorphous coatings due to the different manufacturing process (crystal growth instead of ion beam sputtering).

Anomalous absorption from small defects in the Advanced LIGO test mass coatings has proven to be a major challenge and limits the sensitivity of the instruments via degradation of the cavity buildup.[23] Research to solve this problem is currently a major focus for LIGO coatings, and clearly it must be solved for Cosmic Explorer as well.

Conductive Coatings Silica is an insulator, and hence charge can build up on its surface. This has been an issue in Advanced LIGO, so it will be important to limit the amount of charge that is able to build up on the Cosmic Explorer optics.[24] With R&D underway on slightly conductive overcoatings and with the experience of charge control in LIGO to capitalize on, charge is not expected to be a major issue for Cosmic Explorer.

3.3 Suspensions

As described in §3.4, each of the four test masses will be suspended by quadruple pendulum suspensions similar to those currently employed by LIGO. The reference concept is a 4 m long suspension chain of total mass 1500 kg. Such suspensions can be achieved and supported by scaling up current Advanced LIGO systems.

Increasing the mechanical compliance of the suspensions — in all six degrees of freedom — is key to reduce seismic and thermal noises. More compliant suspensions produce lower frequency mechanical resonances, and displacement noises are passively filtered above these frequencies. The mechanical loss of the suspension material determines the magnitude of the suspension thermal noise.

Developing highly stressed suspensions is critical for two reasons. First, this provides the opportunity to increase the suspension compliance. Second, it increases the fundamental and harmonic frequencies of the high-Q transverse vibrational ("violin") modes of the suspensions, which degrade the sensitivity in a narrow ($\sim 1/Q$) band around the mode frequencies, thus reducing the number of modes in the detection band. The development status of highly stressed materials for the two technologies is discussed below.

The gravitational-wave community has much experience with manufacturing highly stressed fused silica suspension fibers using a fiber pulling technique.[25] Tapered fibers are used in order to reduce thermoelastic noise at the ends of the fiber where the most bending, and therefore the most loss, occurs. The end radius is chosen to cancel the two contributions to thermoelastic loss — one from thermal expansion and one from the temperature dependence of the Young modulus. A smaller radius is chosen to maximize the stress along the length of the fiber. The maximum stress in the Advanced LIGO silica fibers is 800 MPa,[26] which provides a safety factor of about six for the breaking stress of fibers realized at the time the LIGO suspensions were designed.[27] Recent advances in these fabrication techniques allow for fibers to be manufactured with working stresses of 1.2 GPa, which provides a safety factor of about three.[28] It is assumed that with additional R&D, the working stress can eventually be increased to 1.6 GPa in order to reach Cosmic Explorer's low-frequency sensitivity goals. As a fallback option, the suspensions could be fitted with fused silica blade springs with 800 MPa stress, which would require R&D since no fused silica blade springs have been manufactured to date.[20]

3.4 Seismic Isolation

Cosmic Explorer will benefit greatly from research and development into low-noise inertial and position sensors. Such sensors will enable improvements in seismic isolation and suspension control, both of which enhance the low-frequency sensitivity of Cosmic Explorer, and thereby improve its localization, early warning, and/or high-redshift detection capabilities for compact binaries.

The seismic isolation for the initial Cosmic Explorer target assumes a moderate improvement over current technology: 0.1 $\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 10 Hz, which is threefold better isolation than Advanced LIGO, and 1 $\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 1 Hz, which is tenfold better than Advanced LIGO.[20] Promising technologies to achieve this include combining the mechanics of a conventional geophone (GS13) with an interferometric proof mass readout.[29] The noise below 1 Hz is residual ground motion that comes from the inclusion of a position sensor signal to lock the suspension point to the ground on long timescales (a technique known as "blending"). Additionally, the horizontal inertial sensing is susceptible to contamination from ground tilt, and should therefore be paired with low-noise tiltmeters.[30] This is motivated by studies at LIGO Hanford that have shown that ground tilt couples significantly to the strain readout of the interferometer even after active seismic isolation.[31] Lowering the tilt coupling, along with mitigating Newtonian noise fluctuations from the atmosphere, is an important motivator for carefully designed buildings.[32] Further research in all of these areas is warranted.

Subsequent upgrades are planned to achieve a more significant isolation improvement: an additional threefold improvement at 10 Hz and tenfold improvement at 1 Hz. A number of efforts are underway to meet this challenge worldwide.[33–36] Moreover, improved low-frequency noise of the inertial sensors leads to less reliance on the low-frequency position sensor signals, thereby lessening the contamination from residual ground motion.

3.5 Newtonian noise

Newtonian noise refers to test mass acceleration caused by local fluctuations in the Earth's gravity. For Cosmic Explorer, the dominant contributions to these fluctuations are expected to be ambient seismic waves in the ground, along with ambient infrasound in the atmosphere. Much of the Newtonian noise work in the design phase will focus on understanding how the facility can be located and designed to avoid excessive local gravity fluctuations in the vicinity of the test masses (§§4.1 and 4.2). In the case of the seismic wave contribution, it is assumed that seismometer arrays can be used to estimate the local gravity fluctuation and subtract it from the detector's data stream.

The Cosmic Explorer design currently assumes the seismic field of the site is $1\,(\mu\text{m/s}^2)/\sqrt{\text{Hz}}$ in Rayleigh waves and $0.3\,(\mu\text{m/s}^2)/\sqrt{\text{Hz}}$ in body waves, and that a combination of facility design and seismometer array subtraction can reduce these noises by 20 dB and 10 dB, respectively. The design also assumes the infrasonic background at the site is $1\,\text{mPa}/\sqrt{\text{Hz}}$; no reduction factor is assumed, but structural mitigation is a focus area of research (§4.2).

3.6 Laser

Cosmic Explorer will use a similar laser source as that of LIGO. The laser source, including a seed laser, laser amplifier, up-front frequency and intensity stabilization, and reduction of higher order mode content,[11] is known as the pre-stabilized laser. The Cosmic Explorer requirements on laser frequency noise incident on the interferometer are estimated to be $7 \times 10^{-7}\,\text{Hz}/\sqrt{\text{Hz}}$. The frequency stabilization scheme currently employed by LIGO relies on the two arm cavity as the ultimate frequency reference. However, due to the extra signal delay from the ten times longer arms, this scheme cannot achieve the frequency noise requirements for Cosmic Explorer across the entire detection band.

A new scheme using two suspended modecleaners can achieve these requirements without relying on the arms as a reference[12] and is used as the reference concept for Cosmic Explorer. While the second mode cleaner is not strictly necessary to meet the frequency stabilization requirements, it simplifies the intensity stabilization, can reduce the complexity of the pre-stabilized laser, and reduces other technical noises.

After passing through the mode cleaners, Cosmic Explorer will require ~140 W to be injected into the interferometer to reach the nominal 1.5 MW arm power given the expected optical loss. This level of output power has already been demonstrated in stabilized continuous-wave lasers.[37] If the alternative 2 μm technology were employed, a significantly higher power of ~280 W would be needed to reach the nominal 3 MW of arm power. The technology available at 2 μm is much less advanced than 1 μm technology, and considerable research and development toward ultrastable 2 μm laser sources[38] and their high power amplification is needed.

3.7 Squeezed Light

Squeezed states of light are used to reduce quantum noise in current gravitational-wave detectors . This technology will also be used in Cosmic Explorer, initially at modest levels of noise reduction with planned upgrades expected to bring Cosmic Explorer to its target sensitivity. Frequency-independent squeezing is employed in the current Advanced LIGO[39] and Advanced Virgo[40] detectors, and has reached 6 dB of noise reduction in GEO600.[41] Frequency-dependent squeezing has been achieved by reflecting squeezed light off of filter cavities as described above,[42,43] and a 300 m filter cavity is now being installed at the LIGO sites for the A+ upgrade. These two demonstrated technologies set the baseline 6 dB of frequency-dependent squeezing for the initial Cosmic Explorer target. Research and development is needed to reach the required 10 dB of frequency-dependent squeezing, down to about 10 Hz, for the final Cosmic Explorer design.

Squeezer design The existing design of in-vacuum squeezers used by Advanced LIGO,[44,45] which yields 2 % internal cavity losses, is nearly sufficient for the Cosmic Explorer requirements, and only incremental improvements are needed to achieve the Cosmic Explorer loss target of 1 %.

Low-loss Faraday isolators Low-loss Faraday isolators are now used in Advanced Virgo[46] and Advanced LIGO. These demonstrate 0.5–1 % loss per pass of the squeezed light. The current design of a filter cavity requires a minimum of four total passes through Faraday isolators. An additional fifth pass is used in Advanced LIGO to add optical isolation, but can be avoided with improved isolation and scattered light mitigation. Minor improvement is required to bring the isolator losses down to a total of 2 % given the four required isolator passes.

Signal Recycling Cavity Design A significant fraction of the allowable optical loss budget is used up the imperfections in the signal recycling cavity of the interferometer. While that cavity is technically not part of the squeezer, care must be taken to minimize any optical losses or mode mismatch in that cavity to achieve the full benefit from squeezed light. As an example, figure Fig. 3.1 shows the beam splitter mounted with the high-reflectivity surface facing the signal recycling mirror to avoid the optical loss of double-passing the beam splitter. However, this also increases the total laser power traversing the beam splitter optic, so any detrimental thermal effects need to be managed.

3.8 Control Systems

Holding the detector at its stable, astrophysically sensitive operating point requires feedback control on a large number of degrees of freedom, such as the relative distances and angles between the suspended optics. Additionally, bringing the detector to its operating point requires a multi-step locking scheme. Similar to LIGO,[47] Cosmic Explorer will use a hybrid digital and analog real-time data acquisition and controls system, along with automated supervision of the detector locking. The digital system will also provide near real time calibration and astronomical alerts.

Because of their susceptibility to environmental conditions and the time required for the locking process, current gravitational-wave interferometers have roughly 75 % availability; the Cosmic Explorer designs will strive to improve upon this. The greatest improvement in observing time will likely come from reducing the time required to achieve lock, e.g., with a fully deterministic locking scheme and feed-forward thermal compensation, and from improving the instrument's robustness to environmental disturbances, particularly from high seismicity and wind.

3.9 Calibration Techniques

Like current gravitational-wave detectors, Cosmic Explorer will need a calibration apparatus to turn the raw detector data into an estimated strain time series. The greater sensitivity of Cosmic Explorer compared to today's detectors, coupled with the expected improvement in theoretical waveform accuracy, will result in calibration requirements more stringent that those of Advanced LIGO and Virgo. The calibration requirements for Cosmic Explorer are likely to be significantly below 1 % accuracy so as to not limit the astrophysical output of Cosmic Explorer.

The primary calibration standards for the current detectors are so-called photon calibrators, which use power-modulated laser light from auxiliary lasers to drive the test masses with radiation pressure.[48,49] Improving the photon calibrator systems to the accuracy level required for Cosmic Explorer (perhaps $< 0.1\,\%$) should be possible with anticipated improvements in laser power standards from the global network of national metrology institutes (including NIST)[50,51] and the reduction of other practical limiting systematics to the systems.[52]

In addition to photon calibrators, other supplemental calibration standards are being considered. Options include using existing subsystems of the detectors themselves, such as frequency modulation of the primary laser[53] or the use of auxiliary lasers,[54] or measurements based on the laser wavelength with the detector temporarily configured as a simple Michelson interferometer.[54–56] The use of gravitational-wave sources themselves as calibration standards (sometimes referred to as astrophysical calibration) has been studied and demonstrated; however, the accuracy of these methods will not be competitive with photon calibrators, even for 3G detectors.[57,58] Other direct force options such as spinning gravitational calibrators (Newtonian calibrators) have demonstrated promising accuracy in early prototypes[59,60] and recent work suggests that a combination of photon and gravitational calibrators could achieve an absolute accuracy of 0.17 %.[61]

3.10 Detector Computing

The bandwidth of the control systems required to operate Cosmic Explorer does not differ significantly from that of Advanced LIGO. As in Advanced LIGO, the cost of the digital detector control systems is not expected to be a significant fraction of the cost of the instrument. Since the number of Cosmic Explorer control and data channels will be similar to that of Advanced LIGO, we expect data rates of 2 Tb per day of detector operation. Storage and dissemination of data of this scale is a solved problem with current technology.

4 Facilities

Developing a solid conceptual design for the Cosmic Explorer facilities, driven by the science goals as they flow down through the detector, is a central part of the conceptual design effort. The facility, including all civil works and large vacuum components, will be the primary cost and schedule driver for the CE Project.

Since the facility design will need to be integrated with the local community and environment, it is important that a number of candidate sites be identified and characterized as early as possible in the conceptual design phase. Site selection will take place early in the preliminary design phase to enable detailed facility designs. It bears repeating (from the CE Horizon Study[1]) that building and maintaining a synergistic relationship with potential host communities, including Indigenous Peoples, will be both time consuming and fundamental to project success.

4.1 Site Identification and Characterization

Selection of a major facility's site(s) is called for in the Preliminary Design phase. Thus a major focus of the Conceptual Design phase must be on searching for and evaluating candidate sites. The conceptual design phase also calls for "Potential environmental and safety impacts to be considered in site selection." The outcomes of the following site research will inform the CE Project Execution Plan, particularly Section 11, "Site and Environment," which will detail "Site selection criteria and description of selected site(s)" and "List need for any Environmental Impact Statements, permitting, site assessments, etc."

A wide variety of factors must be considered when looking for sites suitable for hosting a Cosmic Explorer observatory. Important aspects range from community and history (which impact viability), to topology and geology (which impact cost), to environmental noises and ambient seismicity (which impact scientific suitability). As part of the Cosmic Explorer Horizon Study, many potential CE candidate sites that are topologically favorable were identified. Furthermore, the software used for this algorithmic search can be improved and augmented to better identify candidate sites in the US and elsewhere. However, the Horizon Study effort revealed that each candidate presents it own set of challenges and contact must be made with the local community in order to understand the viability of any potential CE site. The following outlines work that will need to be done for the CE CD and PD phases to determine the viability, construction cost, and scientific suitability of candidate sites and ultimately to select sites.

1. **Define and Apply Site Selection Criteria**
   A set of criteria for site selection must be defined and then applied and refined. Site selection criteria for LIGO and other large projects, particularly the Einstein Telescope will provide some guidance, however some aspects of Cosmic Explorer will require special consideration. A first outline of criteria and work required to assess the sites based on them is given below.

2. **Initial Site Identification**
   Near the start of the CD phase, 10 to 20 potential sites (half each of 40 km and 20 km) should be identified as suitable following the preliminary site selection criteria. Each of these sites will need to be assessed for potential no-go issues, including initial NEPA and NHPA impact assessments.

3. **Site Down-Selection**
   Before the end of the CD phase, sites which remain viable after the initial assessment should undergo more thorough assessment so as to identify several viable 40 km and 20 km sites (e.g., 5 total, with 3 that could host 40 km or 20 km observatories, and 2 that are appropriate only for a 20 km facility). This list of viable candidate sites will need to be ready for presentation to the NSF before the CDR to allow time for further down-selection based on non-technical criteria.

Preliminary Design

1. **Site Identification**
   The CE observatory sites will need to be selected well before the PDR in order to allow for accurate cost estimates to be made.

The following is a brief summary of the site selection criteria which are discussed in the CEHS. The topics listed here are intended only as a starting point, and there may be important areas which are missing from this list.

Environmental Impact When searching for potential CE sites one should expect that many topographically favorable locations will be eliminated by environmental constraints (e.g., sage grouse leks in Idaho), and that some construction costs will be expended to accommodate animal populations (e.g., wildlife bridges). Preliminary impact assessments (both environmental via NEPA and cultural via NHPA) should be conducted as quickly as possible to eliminate sites where hosting a Cosmic Explorer observatory would be damaging to the environment or community. All candidate sites that remain in consideration after this and other preliminary constraints are considered will require thorough impact assessments. It is likely that this will be both time consuming and expensive, and as such it should be taken into account both in the project budget and schedule.

Land Acquisition Sites which are favorable for CE are vast open spaces with relatively flat terrain, and as such they tend to be either very remote, already in use (as national parks, military facilities, etc.), or both. In some cases, this can facilitate land acquisition for CE (e.g., if the land is federally owned), or make it unfeasible (e.g., if the space is a national monument). Land acquisition may also be difficult in areas that are mostly private land due to the length of the CE arms, which may cross many individual plots. A potential site could be unsuitable if the land cannot be acquired or its acquisition would greatly increase the cost of the project. Preliminary assessments of land acquisition issues must be carried out for identified sites.

Geotechnical Issues Any potential site will require a geotechnical investigation to assess its suitability and to arrive at a precise cost estimate for the construction of a CE observatory. In addition to standard civil-engineering aspects, this assessment will need to evaluate the potential for seismic engineering for Newtonian Noise mitigation.

Natural Hazards Certain potential sites could be disqualified due to unacceptably high probability of catastrophic natural disaster (flood, fire, earthquake, etc.). In addition to consulting the historical record (e.g., the 100-year flood level), the potential impact of climate change on the suitability of a location must also be considered.

Surrounding Infrastructure Some otherwise promising sites may be disqualified if they are hard to access or frequently rendered inaccessible (e.g., due to inclement weather). Access roads will be needed, and access to rail would be advantageous, especially for delivery of the vacuum pipe. The absence of anthropogenic noise sources (e.g., industry, wind farms) must be assured for the lifetime of CE. Not all potential sites will be located close enough to critical infrastructure (e.g., roads, utilities) required to construct and operate the facility, and building such infrastructure may be prohibitively expensive. In addition, candidate sites must be sufficiently close to social infrastructure (hospitals, schools, airports, etc.) to sustain an effective workforce and allow for visiting experts.

Ambient Seismicity Ground motion directly impacts the sensitivity of Cosmic Explorer, including from seismically induced fluctuations in the local gravitational field. A dedicated seismic survey for Cosmic Explorer must be done to establish both the overall ground motion amplitude from 10 mHz to 20 Hz. Above 5 Hz, the partitioning of the seismic field into its bulk and surface wave components should also be measured. Attention must also be paid to existing and potential nearby human activity that would negatively impact observatory performance: logging, mining, underground pipelines, railways and highways, military tests, etc. While the presence of these activities may not rule out a site, the impact on observatory performance and duty cycle must be considered.

Ambient Infrasound Because Newtonian noise (§3.5) will place more stringent requirements on the acoustics of CE sites, a careful measurement of site acoustics and particularly infrasound (sound at frequency less than 20 Hz)[20]) is needed. The infrasound survey for Cosmic Explorer must be careful to disentangle the effect of wind confusion noise.

Ambient Environment Long-term measurements of the environment are required to determine the variation in noise arising from the weather (for example, wind and thunderstorms) or from anthropogenic origins (such as cars and trains). Other potential noise sources from the environment, such as magnetic and radio frequency disturbances, should also be characterized. Approximate requirements for these noise sources will need to be developed, with the existing LIGO observatories as a basis for the estimated couplings.[62]

4.2 Civil Engineering

The Cosmic Explorer building design and construction can be based upon those used for LIGO. Many aspects of the design and construction will require research, especially considerations such as aerodynamic building shapes, wind fences, and other vibration reduction engineering. This is driven in large part by the desire to reduce seismicity and infrasound, particularly as these lead to Newtonian noise.

Conceptual Design

1. **Define Requirements**
   Requirements for seismicity, infrasound, and other environmental effects on the detector will be defined.

2. **System Option Identification and Costing**
   Techniques for reducing the effects of environmental noise via civil engineering will be identified, and cost estimates developed.

Preliminary Design

1. **Building design**
   The locations and broad designs of the Cosmic Explorer buildings will be determined, with associated cost estimates.

2. **Newtonian noise mitigation**
   Any pieces of infrastructure (such as low-density materials or metamaterials) with the specific purpose of mitigating Newtonian noise will be selected, and cost estimates will be provided.

4.2.1 Research areas

Monitoring of non-gravitational-wave disturbances from the environment, using an array of instruments located at the sites as well as information from global monitoring, has been critical for ground-based gravitational-wave observatories to date. The main purposes of environmental monitoring are localizing and mitigating sources of noise, assuring that the contribution of ambient environmental noise is kept below the background noise of the detectors or subtracted from the detector strain data, and validating candidate gravitational-wave signals by ruling out potential sources of terrestrial origin.[63]

Operating the existing LIGO observatories has taught us the importance of designing facilities that have more immunity to environmental noise. As much as possible, equipment and personnel that cause vibration, acoustic, infrasound, and electromagnetic disturbances should be located far from the most sensitive equipment, for example in out-buildings near to the corner and end stations. In addition to the buildings housing the CE detector infrastructure, CE will require laboratories, warehouses, mechanical and electrical workshops, and offices, as well as meeting spaces for users and visitors. These buildings should be close enough to allow access to the CE site, but far enough away that they do not significantly couple anthropogenic noise into the detector. This leads to an important component of the civil engineering research:

1. **Modeling of seismic, atmospheric, magnetic, and other noises at the observatory.** This should take into account not only noise generated in the ambient environment, but also noises generated by observatory infrastructure and human activity.

In addition to a model of observatory noise, Cosmic Explorer will almost certainly need a facility in which immunity to these noises is specifically engineered. In part this will involve paying attention to the basic design of the buildings, rather than adding specialized features. Areas of focus are:

2. **Structural mitigation of atmospheric infrasound**
   Facility structures can to some extent mitigate ambient infrasonic noise in the atmosphere.

3. **Mitigation of facility-induced infrasound**
   This could include minimizing infrasound-producing sources like HVAC systems.

4. **Mitigation of seismicity induced by structural interaction with the atmosphere**
   Usually encountered in LIGO literature as "wind-induced tilt", these effects can be mitigated by wind fences or aerodynamic building design, which likely need numerical simulation and in-field testing.

5. **Mitigation of structure-induced turbulence**
   Turbulent atmospheric flow across the building will produce density fluctuations, and hence Newtonian noise. Analytical approximations of turbulent density fluctuations due to detector buildings are also given in the literature,[64] but they need to be compared against numerical simulations.

In addition to general building design considerations, specific pieces of infrastructure or detector components can be installed for Newtonian noise mitigation. For seismic Newtonian noise, these include

6. **Low-density materials**
   Newtonian noise may be reduced by lowering the overall material density near the test mass.[65] This is achieved in the facility design by having recesses (e.g., a basement) or low-density building materials (e.g., Geofoam) near/under the test masses, and/or by locating the test masses well above the ground level (e.g., on the second floor).

7. **Seismic metamaterials and architected structures**
   Seismic waves can be deflected or dissipated before they reach the test masses with intentionally designed structures. Seismic metamaterials are architected structures that can reduce surface wave propagation, using above-ground resonators, buried resonators, inclusions, and/or exclusions.[66–71] While more detailed studies will be needed on the feasibility of employing this technology, the CE facility is expected to incorporate at least the simplest of these techniques into its design.

The above techniques largely rely on modeling wave propagation through homogeneous media; thus, another research component is

8. **Newtonian noise from inhomogeneous ground**
   Future studies on wave propagation through inhomogeneous media, such as stratified soil, natural topological structures, etc., will need to be conducted to ensure that these techniques are capable of reaching design sensitivity in a given seismic noise environment.

4.3 Vacuum System

The vacuum system parameters and requirements for Cosmic Explorer are similar to those of LIGO and other gravitational-wave detectors (see Table 4.1 and Table 4.2). While the vacuum techniques developed for the LIGO detectors are adequate for Cosmic Explorer, there is room for improvement and value engineering (§4.3.1).

The vacuum tubing for Cosmic Explorer will be separated into 10 km sections, which are independently pumped. Each section is further divided into 2 km subsections for outgassing and leak hunting as shown in Fig. 4.1. The ends of the 10 km sections will require fully capable gate valves but the 2 km subsections need only the equivalent of light weight shutters to aid in the initial commissioning and operational leak checking. These shutters can be allowed to leak between subsections by as much as 10^{-3} L/s and do not have to bear atmospheric loads. We call this a “soft” close valve which should be significantly lower in cost than the “hard” close valves used at the ends of the 10 km sections. The soft close valves could be magnetically actuated and will not require penetrations in the vacuum envelope.

Beamtube diameter	48 in (122 cm)
Beamtube thickness	$\frac{1}{2}$ in (13 mm)
Beamtube material	mild steel
Beamtube BRDF	10^{-3} sr^{-1}
Hard close gate valves	10, partitioning into 10 km sections
Soft close gate valves	32, partitioning into 2 km subsections
2000 L/s ion pumps	40, one for each subsection
Roughing pumps	40, one for each subsection
non-evaporable getters	distributed throughout
6 in pumping ports	one every 250 m
Baffle aperture	100 cm
Baffle BRDF	10^{-3} sr^{-1}

Table 4.1: Reference parameters for the Cosmic Explorer vacuum system for a 40 km facility. Fig. 4.1 shows a schematic of how the vacuum system is broken up into 10 km subsections.

Ideally, the vacuum practices used with the test mass chambers of Cosmic Explorer will be improved relative to those for current LIGO chambers to reduce pumpdown times and to minimize cleanliness requirements. One option is to separate the vacuum volume for the bottom two stages of the suspension (consisting of the test mass and penultimate mass) from that of the upper stages (similar to what is done in Virgo). This will enable the stages to be separately accessed, and can shield the test masses from materials with high outgassing (e.g., cables in the seismic isolation system). The feasibility of doing this in a manner that both withstands atmospheric loads and maintains the necessary vibration isolation needs to be investigated. In addition to Increasing pumping capacity (e.g., by adding titanium sublimation or non-evaporable getter pumps), it may be necessary to heat the test mass chambers post-access to increase the evaporation rate.

The following R&D will be required in order to support the CD and PD phases of the Cosmic Explorer design process:

Conceptual Design

1. **Define Requirements**
   The vacuum requirements given in the CEHS and Table 4.2 should be verified. Scattered light calculations (see §4.3.2) should also be finished and turned into beamtube diameter and baffling requirements.

2. **System Option Identification and Costing**
   Based on the requirements, implementation options should be evaluated (e.g., as in LIGO, mild steel, nested system: see §4.3.1) and a cost estimate produced for each.

3. **System Down-Selection Path**
   Early in the CD phase, a path for vacuum system design down-selection should be defined,

	Beamtubes			Chambers	
Species	Req / torr	Goal / torr	LIGO Achvd / torr	Req / torr	Goal / torr
He	1.3×10^{-9}	3.4×10^{-10}		8.8×10^{-10}	7.9×10^{-11}
H_2	3.3×10^{-10}	8.3×10^{-11}	3.4×10^{-9}	3.1×10^{-9}	2.8×10^{-10}
Ne	1.8×10^{-10}	4.5×10^{-11}		3.9×10^{-10}	3.5×10^{-11}
H_2O	3.0×10^{-11}	7.6×10^{-12}	2.3×10^{-12}	1.0×10^{-9}	9.4×10^{-11}
O_2	2.1×10^{-11}	5.3×10^{-12}	2.0×10^{-13}	7.8×10^{-10}	7.0×10^{-11}
N_2	1.9×10^{-11}	4.7×10^{-12}	1.0×10^{-13}	8.3×10^{-10}	7.5×10^{-11}
Ar	6.7×10^{-12}	1.7×10^{-12}	9.0×10^{-14}	2.8×10^{-10}	2.5×10^{-11}
CO	5.8×10^{-12}	1.4×10^{-12}	2.0×10^{-12}	3.3×10^{-10}	3.0×10^{-11}
CH_4	4.8×10^{-12}	1.2×10^{-12}	2.2×10^{-11}	4.4×10^{-10}	4.0×10^{-11}
CO_2	2.8×10^{-12}	6.9×10^{-13}	4.0×10^{-13}	2.7×10^{-10}	2.4×10^{-11}
Xe	6.3×10^{-13}	1.6×10^{-13}		1.5×10^{-10}	1.4×10^{-11}
100 u H_nC_m	8.9×10^{-14}	2.2×10^{-14}		1.8×10^{-10}	1.6×10^{-11}
200 u H_nC_m	1.7×10^{-14}	4.2×10^{-15}		1.2×10^{-10}	1.1×10^{-11}
300 u H_nC_m	6.2×10^{-15}	1.5×10^{-15}		1.0×10^{-10}	9.2×10^{-12}
400 u H_nC_m	3.1×10^{-15}	7.6×10^{-16}		8.8×10^{-11}	7.9×10^{-12}
500 u H_nC_m	1.7×10^{-15}	4.3×10^{-16}		7.9×10^{-11}	7.1×10^{-12}
600 u H_nC_m	1.1×10^{-15}	2.8×10^{-16}		7.2×10^{-11}	6.5×10^{-12}

Table 4.2: Cosmic Explorer residual gas requirements and goals. The requirements are that the total gas scattering noise is a factor of five below the design sensitivity and that the total gas damping noises are a factor of three below the design sensitivity. The goals are that the total residual gas noise is a factor of ten below the design sensitivity everywhere. The pressures achieved in the Advanced LIGO beamtube are also shown for comparison.[72] The H_2 pumping speed can easily be augmented by titanium sublimation or non-evaporable getter pumps to reach the required pressures in both the chambers and beamtubes.

along with any remaining open questions. The project risk register should reflect the potential outcomes of down-selection, and their impact on project cost.

4. **System R&D**
   R&D on the vacuum system options in support of down-selection should be happening throughout the PD phase. This may be as part of the CE project, or as separately funded efforts working in coordination with the project.

Preliminary Design

1. **System Down-Selection**
   Early in the PD phase the vacuum system design down-selection will need to occur such that the selected design can be incorporated into the facility design and costing effort.

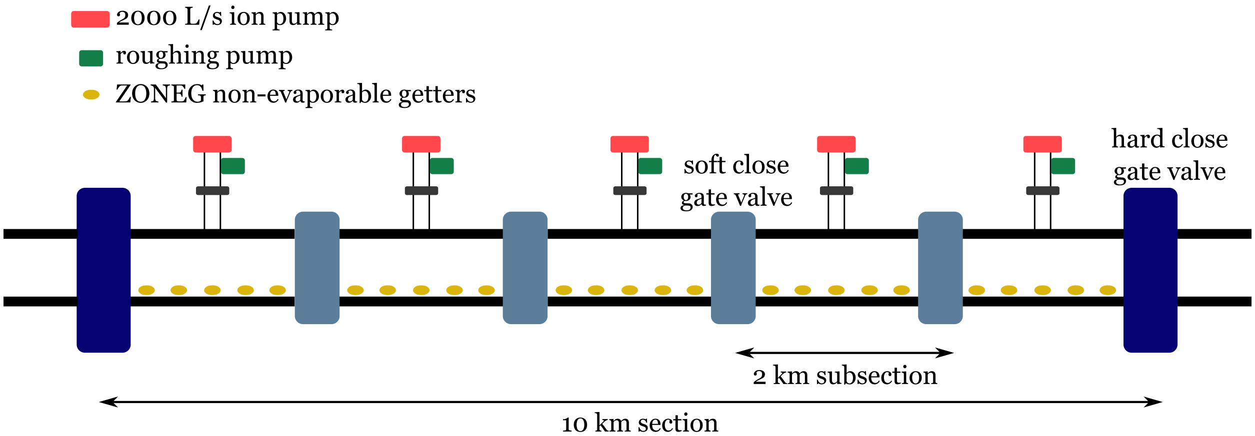

Figure 4.1: Schematic of a 10 km beamtube section. Each 10 km section can be pumped and serviced independently. The ends of the section are determined by commercial 48 in (122 cm) gate valves with elastomer O-rings that can withstand an atmospheric pressure from either side. The 2 km subsections are separated by soft-close gate valves used for separating regions with small pressure differences during some bake operations and for diagnostics. 6 in pumping ports (not shown) are located every 250 m and can be used for leak hunting and diagnostics or while pumping down.

4.3.1 Reducing System Cost

Roughly 34% of the cost of CE resides in the ultrahigh vacuum (UHV) system needed for the beamtubes and vacuum chambers. While the vacuum technology used in LIGO could be used to meet the goals for CE, ongoing research indicates that significant cost savings may be available, and as such LIGO vacuum technology serves as a backup strategy should new techniques not be realized. In particular, the research described below aims to develop technology that could meet the CE requirements and reduce the cost of UHV systems from the estimate of around $520 million for duplication of the LIGO approach to less than $340 million.

1. **Techniques to eliminate high temperature bakes**
   The LIGO bakeout consisted of pumping the water out of the system while the beamtubes were heated to 150 °C for three weeks. While it is possible for CE to meet its residual gas requirements in the beamtubes by simply replicating this approach, doing so would conservatively cost nearly $100M for the 2-observatory reference concept. This cost is dominated by the electricity needed for the bake which motivates developing more economical methods such as:

   a) Using lower temperature bakes with modest pumping capacity for longer durations. Modeling suggests that this could reduce the water outgassing to levels that meet the CE requirements in the beamtubes.

   b) Using a moving external heater with dry flush gas to remove water from a tube. The process would take place before the tube is evacuated and involves passing the dry gas through the tube while heating the tube to between 145 to 200 °C with a movable external ring oven about a meter long. The gas density and flow rate are adjusted to keep the water entrapped in the gas from diffusing back as the oven is slowly moved from one end of the tube to the other in the direction of the gas flow. The temperature of the tube in the short region under the ring heater can be significantly higher than in a full bake which reduces the emission time of the tightly bound water and allows shorter dwell time for the ring heater at each point along the tube. It would take about 14 days to complete the bake for one 2 km subsystem. CERN is investigating a system which uses inductive rather than radiative heating.

2. **Mild steel instead of stainless steel beamtubes**
Low carbon steel is a quarter to a third the cost of stainless steel with comparable mechanical properties. Standard production techniques now produce carbon steel with 0.1–0.3 % of the entrapped hydrogen and comparable water outgassing than most stainless steels.[73] Recent preliminary measurements at CERN and NIST have provided additional evidence for the low hydrogen outgassing but more research is needed to verify these findings and to develop the practical techniques necessary to use mild steel in UHV.

3. **Beamtube coatings**
Coating the interior of the beamtubes with a material that has a low binding energy for water would reduce the time needed to bake the beamtubes. Ongoing research by metallurgists indicates that the dark oxide that forms on carbon steel (magnetite, Fe_3O_4) may have a lower binding energy for water, but this needs to be tested. This naturally forming oxide, similar to "gun bluing", could be generated on both the internal and external surfaces of the beamtubes to both lower binding energies and prevent oxidation (rust). It may also be worth looking into using hydrophobic silicon coatings for the internal surface, and considering the oil-industry standard epoxy coating for the external surface.

4. **Soft-close gate valves for leak hunting** As shown in Fig. 4.1, each beamtube is broken up into 10 km long sections separated by hard close gate valves, and each of these is further broken up into five 2 km subsections separated by soft close gate valves. Development of these soft close valves to separate the 2 km subsections could result in a significant cost savings compared to the use of the commercially available hard close valves everywhere.

5. **Nested system** In the event that the water outgassing cannot be reduced sufficiently to meet the CE requirements, it becomes useful to investigate another option. There are engineering and operational advantages to separating the functions of maintaining a space against the atmospheric pressure load from that of reducing the residual gas to the levels of UHV. One promising concept uses a nested vacuum system with an outer shell of carbon steel tubing and an inner tube of thin wall aluminum.[74] If the research shows the nested system is favored, it will be useful to develop an annular soft close valve that separates the inner and outer systems for outgassing and UHV operations and opens quickly in the event of a pressure increase in the outer system.

4.3.2 Scattered Light Mitigation

Noise from light that is scattered out of the main laser beams has been a persistent issue for current gravitational-wave detectors.[75,76] While scattered light reduction was included in the design of the advanced detectors, much effort has been devoted to diagnosing and fixing light scattering issues after installation.[63,77,78] Scattered light effects, which are often driven by seismic motion, will be particularly important to address in order to ensure the excellent low-frequency performance of Cosmic Explorer.

An evolution and front-loading of the stray light control work done for the LIGO detectors will be needed for Cosmic Explorer. In Advanced LIGO, for example, it was necessary to incorporate dozens of baffles and beam dumps specifically designed, using ray-tracing software, to intercept significant stray light.[79] Some baffles also required better seismic isolation and damping of resonant motion.[63] Significant design work is called for to identify and eliminate scatter and stray beams associated with the many optical and mechanical components of CE, along with continued R&D into low-scatter materials and coatings that could reduce the levels of stray light.

Abbreviations

2G Second generation of gravitational-wave detectors
3G Third generation of gravitational-wave detectors
A+ LIGO A+ upgrade
AAS American Astronomical Society
AISES American Indian Science and Engineering Society
APS American Physical Society
BBH Binary black hole
BNS Binary neutron star
BRDF Bidirectional reflectance distribution function
CBO Compact-binary-optimized detector configuration
CE Cosmic Explorer
CERN European Organization for Nuclear Research
DECIGO Decihertz Gravitational-Wave Observatory
DOE Department of Energy
ET Einstein Telescope
EOS Equation of state
GWAC Gravitational-Wave Agencies Correspondents
GWADW Gravitational-Wave Advanced Detector Workshop
GWIC Gravitational-Wave International Committee
GWPAW Gravitational-Wave Physics and Astronomy Workshop
IMBH Intermediate-mass black hole
KAGRA Kamioka Gravitational-Wave Detector
LIGO Laser Interferometer Gravitational-Wave Observatory
LISA Laser Interferometer Space Antenna
LSC LIGO Scientific Collaboration
LVK LIGO–Virgo–KAGRA Collaboration
MREFC NSF's Major Research Equipment and Facilities Construction
NASA National Aeronautics and Space Administration
NEMO Neutron-Star Extreme Matter Observatory
NIST National Institute of Standards and Technology
NSF National Science Foundation
PMO Postmerger-optimized detector configuration
QCD Quantum chromodynamics
SACNAS Society for Advancement of Chicanos/Hispanics and Native Americans in Science

SMBH Supermassive black hole
SNR Signal-to-noise ratio
UHV Ultrahigh vacuum
USD US dollars

References

1. M. Evans et al., *A Horizon Study for Cosmic Explorer: Science, Observatories, and Community*, tech. rep. CE–P2100003–v6 (Cosmic Explorer, 2021) (cit. on pp. 1, 4, 19).
2. NSF Large Facilities Office, *Major Facilities Guide*, NSF 19–68 (National Science Foundation, Sept. 2019) (cit. on p. 1).
3. *GWIC-3G Subcommittee Reports on Next Generation Ground-based Observatories*, Gravitational Wave International Committee, https://gwic.ligo.org/3Gsubcomm/documents.html (visited on 5 July 2021) (cit. on pp. 1, 3, 13).
4. LIGO Scientific Collaboration, *Instrument Science Whitepaper 2020*, tech. rep. LIGO–T2000407–v3 (LIGO, Aug. 2020) (cit. on p. 1).
5. R. X. Adhikari et al., *LIGO Voyager Upgrade: Design Concept*, tech. rep. LIGO–T1400226–v9 (LIGO, Dec. 2020) (cit. on p. 1).
6. B. S. Sathyaprakash et al., "Multimessenger Universe with Gravitational Waves from Binaries", (2019), arXiv:1903.09277 [astro-ph.HE] (cit. on p. 3).
7. V. Kalogera et al., "The Yet-Unobserved Multi-Messenger Gravitational-Wave Universe", (2019), arXiv:1903.09224 [astro-ph.HE] (cit. on p. 3).
8. V. Kalogera et al., "Deeper, Wider, Sharper: Next-Generation Ground-Based Gravitational-Wave Observations of Binary Black Holes", (2019), arXiv:1903.09220 [astro-ph.HE] (cit. on p. 3).
9. B. S. Sathyaprakash et al., "Cosmology and the Early Universe", (2019), arXiv:1903.09260 [astro-ph.HE] (cit. on p. 3).
10. B. S. Sathyaprakash et al., "Extreme Gravity and Fundamental Physics", (2019), arXiv:1903.09221 [astro-ph.HE] (cit. on p. 3).
11. P. Kwee et al., "Stabilized high-power laser system for the gravitational wave detector advanced LIGO", Optics Express **20**, 10617 (2012) (cit. on pp. 9, 16).
12. C. Cahillane, G. Mansell and D. Sigg, "Laser Frequency Noise in Next Generation Gravitational-Wave Detectors", (2021), arXiv:2107.14349 [physics.ins-det] (cit. on pp. 10, 16).
13. L. McCuller et al., "LIGOs Quantum Response to Squeezed States", arXiv:2105.12052 (cit. on p. 12).
14. N. Kijbunchoo et al., "Low phase noise squeezed vacuum for future generation gravitational wave detectors", Classical and Quantum Gravity **37**, 185014 (2020) (cit. on p. 12).
15. H. Miao, N. D. Smith and M. Evans, "Quantum Limit for Laser Interferometric Gravitational-Wave Detectors from Optical Dissipation", Physical Review X **9**, 011053 (2019) (cit. on p. 12).
16. H. T. Cao et al., "Enhancing the dynamic range of deformable mirrors with compression bias", Optics Express **28**, 38480 (2020) (cit. on p. 12).

17. H. T. Cao et al., "High dynamic range thermally actuated bimorph mirror for gravitational wave detectors", Appl. Opt. **59**, 2784 (2020) (cit. on p. 12).

18. B. P. Abbott et al., "Exploring the sensitivity of next generation gravitational wave detectors", Classical and Quantum Gravity **34**, 044001 (2017) (cit. on p. 13).

19. G. Billingsley, H. Yamamoto and L. Zhang, "Characterization of Advanced LIGO core optics", American Society for Precision Engineering (ASPE) **66**, 78–83 (2017) (cit. on p. 13).

20. E. D. Hall et al., "Gravitational-wave physics with Cosmic Explorer: Limits to low-frequency sensitivity", Phys. Rev. D **103**, 122004 (2021) (cit. on pp. 13, 15, 22).

21. G. Vajente et al., "Low Mechanical Loss TiO2:GeO2 Coatings for Reduced Thermal Noise in Gravitational Wave Interferometers", Phys. Rev. Lett. **127**, 071101 (2021) (cit. on p. 14).

22. P. Koch et al., "Thickness uniformity measurements and damage threshold tests of large-area GaAs/AlGaAs crystalline coatings for precision interferometry", Optics Express **27**, 36731 (2019) (cit. on p. 14).

23. A. F. Brooks et al. (LIGO Scientific), "Point absorbers in Advanced LIGO", Appl. Opt. **60**, 4047 (2021) (cit. on p. 14).

24. A. Buikema et al., "Sensitivity and performance of the Advanced LIGO detectors in the third observing run", Phys. Rev. D **102**, 062003 (2020) (cit. on p. 14).

25. A. Heptonstall et al., "Invited Article: CO_2 laser production of fused silica fibers for use in interferometric gravitational wave detector mirror suspensions", Review of Scientific Instruments **82**, 011301-011301–9 (2011) (cit. on p. 14).

26. S. M. Aston et al., "Update on quadruple suspension design for Advanced LIGO", Classical and Quantum Gravity **29**, 235004 (2012) (cit. on p. 14).

27. K. V. Tokmakov et al., "A study of the fracture mechanisms in pristine silica fibres utilising high speed imaging techniques", Journal of Non Crystalline Solids **358**, 1699–1709 (2012) (cit. on p. 15).

28. K.-H. Lee et al., "Improved fused silica fibres for the advanced LIGO monolithic suspensions", Classical and Quantum Gravity **36**, 185018 (2019) (cit. on p. 15).

29. S. J. Cooper et al., "A compact, large-range interferometer for precision measurement and inertial sensing", Classical and Quantum Gravity **35**, 095007 (2018) (cit. on p. 15).

30. K. Venkateswara et al., "A high-precision mechanical absolute-rotation sensor", Review of Scientific Instruments **85**, 015005 (2014) (cit. on p. 15).

31. M. W. Coughlin et al., "Implications of Dedicated Seismometer Measurements on Newtonian-Noise Cancellation for Advanced LIGO", Phys. Rev. Lett. **121**, 221104 (2018) (cit. on p. 15).

32. M. P. Ross et al., "Towards windproofing LIGO: reducing the effect of wind-driven floor tilt by using rotation sensors in active seismic isolation", Classical and Quantum Gravity **37**, 185018 (2020) (cit. on p. 15).

33. J. V. van Heijningen, A. Bertolini and J. F. J. van den Brand, "A novel interferometrically read out inertial sensor for future gravitational wave detectors", in 2018 IEEE Sensors Applications Symposium (SAS) (2018), pp. 1–5 (cit. on p. 15).

34. J. V. van Heijningen, "A fifty-fold improvement of thermal noise limited inertial sensitivity by operating at cryogenic temperatures", Journal of Instrumentation **15**, P06034 (2020) (cit. on p. 15).

35. C. M. Mow-Lowry and D. Martynov, "A 6D interferometric inertial isolation system", Classical and Quantum Gravity **36**, 245006 (2019) (cit. on p. 15).

36. H. Yu et al., "Prospects for Detecting Gravitational Waves at 5 Hz with Ground-Based Detectors", Phys. Rev. Lett. **120**, 141102 (2018) (cit. on p. 15).

37. B. Willke et al., "Stabilized High Power Laser for Advanced Gravitational Wave Detectors", in Journal of Physics Conference Series, Vol. 32, Journal of Physics Conference Series (Mar. 2006), pp. 270–275 (cit. on p. 16).

38. D. P. Kapasi et al., "Tunable narrow-linewidth laser at 2 μm wavelength for gravitational wave detector research", Optics Express **28**, 3280 (2020) (cit. on p. 16).

39. M. Tse et al., "Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy", Phys. Rev. Lett. **123**, 231107 (2019) (cit. on p. 16).

40. F. Acernese et al., "Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light", Phys. Rev. Lett. **123**, 231108 (2019) (cit. on p. 16).

41. H. Grote et al., "First Long-Term Application of Squeezed States of Light in a Gravitational-Wave Observatory", Phys. Rev. Lett. **110**, 181101 (2013) (cit. on p. 16).

42. E. Oelker et al., "Audio-Band Frequency-Dependent Squeezing for Gravitational-Wave Detectors", Phys. Rev. Lett. **116**, 041102 (2016) (cit. on p. 17).

43. L. McCuller et al., "Frequency-Dependent Squeezing for Advanced LIGO", Phys. Rev. Lett. **124**, 171102 (2020) (cit. on p. 17).

44. A. R. Wade et al., "A squeezed light source operated under high vacuum", Scientific Reports **5**, 18052 (2015) (cit. on p. 17).

45. E. Oelker et al., "Ultra-low phase noise squeezed vacuum source for gravitational wave detectors", Optica **3**, 682 (2016) (cit. on p. 17).

46. E. Genin et al., "Vacuum-compatible low-loss Faraday isolator for efficient squeezed-light injection in laser-interferometer-based gravitational-wave detectors", Appl. Opt. **57**, 9705 (2018) (cit. on p. 17).

47. R. Bork et al., "advligorts: The Advanced LIGO real-time digital control and data acquisition system", SoftwareX **13**, 100619 (2021) (cit. on p. 17).

48. S. Karki et al., "The Advanced LIGO photon calibrators", Review of Scientific Instruments **87**, 114503 (2016) (cit. on p. 18).

49. D. Estevez et al., "The Advanced Virgo photon calibrators", Classical and Quantum Gravity **38**, 075007 (2021) (cit. on p. 18).

50. M. Spidell et al., "A Bilateral Comparison of NIST And PTB Laser Power Standards for Increased Calibration Confidence at LIGO", in, Vol. OR (14th International Conference on New Developments and Applications in Optical Radiometry, 2021), p. 017 (cit. on p. 18).

51. A. Vaskuri et al., "Microfabricated bolometer based on a vertically aligned carbon nanotube absorber", in Synthesis and Photonics of Nanoscale Materials XVII, Vol. 11269, edited by J. J. Dubowski, D. B. Geohegan and A. V. Kabashin (International Society for Optics and Photonics, 2020), pp. 41–52 (cit. on p. 18).

52. D. Bhattacharjee et al., "Fiducial displacements with improved accuracy for the global network of gravitational wave detectors", Class. Quant. Grav. **38**, 015009 (2021) (cit. on p. 18).

53. E. Goetz and R. L. Savage Jr, "Calibration of the LIGO displacement actuators via laser frequency modulation", Class. Quant. Grav. **27**, 215001 (2010) (cit. on p. 18).

54. B. P. Abbott et al., "Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914", Phys. Rev. D **95**, 062003 (2017) (cit. on p. 18).

55. J. Abadie et al. (LIGO Scientific), "Calibration of the LIGO Gravitational Wave Detectors in the Fifth Science Run", Nucl. Instrum. Meth. A **624**, 223–240 (2010) (cit. on p. 18).

56. T. Accadia et al., "Calibration and sensitivity of the Virgo detector during its second science run", Classical and Quantum Gravity **28**, 025005 (2011) (cit. on p. 18).

57. R. Essick and D. E. Holz, "Calibrating gravitational-wave detectors with GW170817", Classical and Quantum Gravity **36**, 125002 (2019) (cit. on p. 18).

58. B. F. Schutz and B. S. Sathyaprakash, "Self-calibration of Networks of Gravitational Wave Detectors", (2020), arXiv:`2009.10212 [gr-qc]` (cit. on p. 18).

59. M. P. Ross et al., "Initial Results from the LIGO Newtonian Calibrator", arXiv:`2107.00141` (cit. on p. 18).

60. D. Estevez, B. Mours and T. Pradier, "Newtonian calibrator tests during the Virgo O3 data taking", Class. Quant. Grav. **38**, 075012 (2021) (cit. on p. 18).

61. Y. Inoue et al., "Improving the absolute accuracy of the gravitational wave detectors by combining the photon pressure and gravity field calibrators", Phys. Rev. D **98**, 022005 (2018) (cit. on p. 18).

62. M. W. Coughlin et al., "Measurement and subtraction of Schumann resonances at gravitational-wave interferometers", Phys. Rev. D **97**, 102007 (2018) (cit. on p. 22).

63. P. Nguyen et al. (AdvLIGO), "Environmental noise in advanced LIGO detectors", Class. Quant. Grav. **38**, 145001 (2021) (cit. on pp. 23, 29).

64. T. Creighton, "Tumbleweeds and airborne gravitational noise sources for LIGO", Class. Quant. Grav. **25**, 125011 (2008) (cit. on p. 23).

65. J. Harms and S. Hild, "Passive Newtonian noise suppression for gravitational-wave observatories based on shaping of the local topography", Classical and Quantum Gravity **31**, 185011 (2014) (cit. on p. 24).

66. S. Brûlé et al., "Experiments on Seismic Metamaterials: Molding Surface Waves", Phys. Rev. Lett. **112**, 133901 (2014) (cit. on p. 24).

67. A. Palermo et al., "Engineered metabarrier as shield from seismic surface waves", Scientific Reports **6**, 39356 (2016) (cit. on p. 24).

68. A. Colombi et al., “A seismic metamaterial: The resonant metawedge”, Scientific Reports **6**, 27717 (2016) (cit. on p. 24).

69. P. Roux et al., “Toward seismic metamaterials: The METAFORET project”, Seismological Research Letters **89**, 582–593 (2018) (cit. on p. 24).

70. B. Kamai and LIGO Team, “Can we cloak LIGO from Seismic Waves?”, in APS April Meeting Abstracts, Vol. 2019, APS Meeting Abstracts (Jan. 2019), R11.006 (cit. on p. 24).

71. R. Zaccherini et al., “Locally Resonant Metasurfaces for Shear Waves in Granular Media”, Physical Review Applied **13**, 034055 (2020) (cit. on p. 24).

72. R. Weiss, *Postbake Measurements of Module Y2 at Hanford*, tech. rep. LIGO–C982529 (LIGO, Sept. 1998) (cit. on p. 26).

73. C. Park, T. Ha and B. Cho, “Thermal outgassing rates of low-carbon steels”, Journal of Vacuum Science Technology A: Vacuum Surfaces and Films **34**, 021601 (2016) (cit. on p. 28).

74. R. Weiss, *Third generation beamtube vacuum system study*, tech. rep. LIGO–T1900023 (LIGO Laboratory, 2019) (cit. on p. 28).

75. G. Vajente and J. Marque, “Stray light issues in advanced interferometers and the search for gravitational waves”, Astrophys. Space Sci. Libr. **404**, 275–290 (2014) (cit. on p. 29).

76. D. J. Ottaway, P. Fritschel and S. J. Waldman, “Impact of upconverted scattered light on advanced interferometric gravitational wave detectors”, Optics Express **20**, 8329 (2012) (cit. on p. 29).

77. S. Soni et al. (LIGO), “Reducing scattered light in LIGO’s third observing run”, Class. Quant. Grav. **38**, 025016 (2020) (cit. on p. 29).

78. M. Wąs, R. Gouaty and R. Bonnand, “End benches scattered light modelling and subtraction in advanced Virgo”, Classical and Quantum Gravity **38**, 075020 (2021) (cit. on p. 29).

79. A. Ananyeva, Stray light control upgrades for LIGO 4th Observation run, GWADW, 2021 (cit. on p. 29).

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