Controlling Fusion Yield in Tokamaks with Spin Polarized Fuel, and Feasibility Studies on the DIII-D Tokamak

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Abstract The march towards electricity production through tokamaks requires the construction of new facilities and the inevitable replacement of the previous generation. There are, however, research topics that are better suited to the existing tokamaks, areas of great potential that are not sufficiently mature for implementation in high power machines, and these provide strong support for a balanced policy that includes the redirection of existing programs. Spin polarized fusion, in which the nuclei of tokamak fuel particles are spin-aligned and favorably change both the fusion cross-section and the distribution of initial velocity vectors of charged fusion products, is described here as an example of a technological and physics topic that is ripe for development in a machine such as the DIII-D tokamak. Such research and development experiments may not be efficient at the ITER-scale, while the plasma performance, diagnostic access, and collaborative personnel available within the United States' magnetic fusion research program, and at the DIII-D facility in particular, provide a unique opportunity to further fusion progress.

Keywords spin polarized fusion · magnetic confinement fusion · tokamak · high temperature plasma diagnostics · fusion research policy

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1 Introduction

The concept of spin polarized thermonuclear fusion, wherein the deuterium and tritium nuclei in a reactor have their nuclear spins aligned to allow additional

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control over the fusion reaction, provides a suitable backdrop for shaping a fusion research policy by retooling existing facilities to advance largely unexplored physics and technology. Considering the tokamak approach [1] to magnetic confinement fusion, it is argued that, whereas present facility development rightfully leads to larger and more expensive tokamaks, it is nonetheless in the best interests of the fusion research program to maintain the devices of the previous generation and purpose them toward issues that are not yet ready for testing on the scale of the newer devices. The argument proceeds thusly, Sec. 2 provides a primer on spin polarized fuel in tokamaks, Sec. 3 lays out the implications for research program and policy direction, Sec. 4 provides a case study for conducting spin polarized fuel research in the DIII-D tokamak [2], and then Sec. 5 presents the summary, conclusions, and discussion.

2 Spin Polarized Fuel for Tokamaks

The present reaction of interest for producing electricity from nuclear fusion is,

where the attractive qualities of this method include the large energy release, the easily available deuterium, the ability to use the neutron to breed tritium, and the charged nature of the helium that allows it to remain confined by the tokamak's magnetic field so that it heats the thermal plasma and maintains fusion temperatures. The fusion cross-section for the DT reaction, $\langle\sigma v\rangle_{DT}$, is more than two orders of magnitude larger than that of other reactions (e.g., DD) at temperatures near 10 keV. In all previous measurements, the nuclear spins of the components have been isotropically distributed. The realized value of $\langle\sigma v\rangle_{DT}$ varies according to the actual spin distribution, however, as does the initial (i.e., birth) distribution or velocity of the fusion products, $\mathbf{v}_i$. Optimizing $\langle\sigma v\rangle_{DT}$ and $\mathbf{v}_i$ provides a host of benefits related to energy production.

The first theoretical treatment of the application of spin polarized fuel came from Kulsrud, et al., [3] and was later refined and expanded [4]. DT fusion may benefit from two effects of spin polarized fuel: (1) increased fusion yield at given plasma parameters through an increase in $\langle\sigma v\rangle_{DT}$, and (2) improved confinement of fusion alphas through a biased angular or velocity distribution, $\mathbf{v}_i$. Benefit (1) is achieved by polarizing all of the DT fuel such that the nuclear spins are non-isotropic, specifically, parallel to the background magnetic field. Compared to a non-polarized case, this can increase the fusion cross section by a factor of 1.5 with the resulting fusion products distributed with initial pitch angles, θ (with respect to the magnetic field, and using θ as a simplified way of discussing $\mathbf{v}_i$), following a $\sin^2(\theta)$ dependence. Figure 1(a) schematically shows the geometries that determine θ .

An example of scenario (2) would use deuterium fuel spin polarized perpendicular to the magnetic field (tritium polarization is not needed). This results in the same $\langle\sigma v\rangle_{DT}$ as obtained with completely unpolarized fuel, but the fusion products are distributed with a θ -dependence proportional to $1 + 3\cos^2(\theta)$. The benefit in this scenario is that the fusion alphas are born with pitch angles predominantly

Fig. 1 (a) Diagram showing the definition of the pitch angle, θ , with respect to the background magnetic field, B . (b) Relative probability of the initial pitch angle for fusion products born through $DT \parallel B$ (solid black trace) or $D \perp B$ (dashed blue trace) polarizations.

close to parallel or anti-parallel to the magnetic field and this results in a reduction in the loss of trapped orbits and increased alpha heating. A comparison of the fusion product initial pitch angles is shown in Fig. 1(b).

These considerations demonstrate the potential value of spin polarized fusion (SPF) to an electricity producing DT reactor, while the additional possibilities for $D + D$ and $D + {}^3\text{He}$ reactions provide a practical mechanism for study in present research tokamaks. The following reactions are accessible to existing tokamaks (noting that tritium reactions are limited due to nuclear regulations, rather than to plasma parameters),

where reactions are written in the standard nuclear convention where convenient, e.g., Eq. 2 can be written as $D(D,n){}^3\text{He}$. The $D + {}^3\text{He}$ reaction is the focus of this treatment. This process is an isospin-mirror reaction to DT and the results from $D + {}^3\text{He}$ studies would be directly applicable to polarized $D + T$ (as discussed further in Section 4.1). Polarized D and ${}^3\text{He}$ spins produce significantly different fusion yields based on whether they are aligned parallel or anti-parallel to the magnetic field, just as in the DT case. The DD reaction is a focus of research for nuclear physics community [5], and the ability to apply polarization to suppress the neutron-producing branch of the reaction would prove technically useful for

achieving nearly aneutronic fusion. For proof-of-principle experiments in present day tokamaks, however, a large deuterium background from previous plasma discharges, as well as uncertain interference effects in $D + D$, require experiments utilizing $D + {}^3\text{He}$ reactions, as discussed later.

Thirty years ago, in the wake of the series of papers by Kulsrud and others [3,4 (and references therein)], a cost analysis was carried out by an Argonne group in an attempt to project the impact of using polarized fuel in a future commercial DT fusion reactor [6]. The increase in reactivity was assumed to be a simple factor of 1.5 (corresponding to fully polarized fuel, but ignoring the additional gains from increased alpha heating). General assumptions were made regarding the costs of polarizing fuel by optical pumping. Although it remains to be seen if this would actually be the preferred polarization method, we note that the subsequent advent of diode lasers has decreased the cost of such an approach. The costs of the magnets and the power plant as a whole were based on variations of the STARFIRE design, and it is worth noting that these assumed baseline costs are about an order of magnitude lower than that of ITER. Although the fractional changes found in that study were modest, a number of gains were noted in several key areas. Polarized fuel would decrease the cost of the current driver needed to establish ignition, would increase the lifetime of the first wall, would potentially allow for a lower field and a reduced plant size for the same power output, and would lower the operating cost per kW. While the cost balance has likely improved in the years since this initial analysis, their final assessment is undoubtedly valid - polarized fuel is an option that can be applied if design conditions become difficult to achieve. Given the challenges ahead, and a cost estimate for polarizing fuel that is an insignificant fraction of the total plant investment, the development of such a reserve is prudent to say the least. Such a technological development program will require a comprehensive exploration of many techniques and, as discussed below, is most efficiently conducted with an existing well-established and well-characterized facility.

3 Program and Policy Direction

The fundamental tenet of the fusion research direction suggested here is that it is more productive, including fiscal considerations, to retool the facilities of the previous generation (e.g., Alcator C-Mod [7], DIII-D [8], and NSTX-U [9]) for physics and technology development instead of shutting them down as new facilities approach an operational phase (e.g., ITER [10]). In fact, a vigorous and focused complementary program of development on specialized problems using existing well characterized machines is essential to maximize the impact of the next generation devices. World-class research facilities do not lose their relevance as a simple function of age; rather, they become uninteresting as their available parameter space reaches full exploration. Extensions to this parameter space come about either through physical upgrades (e.g., new plasma facing materials), or through the application of new technologies to an existing and well characterized system (e.g., adding SPF).

There are many relevant experiments necessary for the development of commercial electricity producing fusion facilities that may be difficult to perform in ITER either due to higher risk or timeliness (e.g. if SPF is incorporated into post-

ITER facilities, it's efficacy must be demonstrated well before ITER experiments could be performed). The early spin polarized fuel experiments may belong in the former category due to its risky nature when applied to ITER. Safe plasma ramp-down in ITER is a distinct issue that has been experimentally studied to provide demonstration of the planned procedure [11]. A polarized fuel experiment, in the case of full polarization, would cause the fusion power in ITER to increase by at least the theoretical factor of 1.5 (and more from the accompanying increase in alpha heating), leading to an achieved maximum fusion- α power of at least 150 MW instead of 100 MW. A sudden failure of that total power may be beyond the level that can be replaced by the auxiliary heating systems. While it would certainly be possible to design ITER experiments using reduced polarization fraction pellets, or even fewer of them, such a design leads to increased difficulty in documenting the effect and further risk in case of an unexpected output.

4 Case Study: Utilizing DIII-D to Advance Polarized Fuel Research

A modest resource allocation will provide for a comprehensive research portfolio concerning spin polarized fusion, which has the potential to significantly advance the control and economic viability aspects of fusion energy. Recent efforts investigating the possibility of conducting polarized fuel experiments in a tokamak led to a cooperative effort involving researchers from the Thomas Jefferson National Accelerator Facility and the DIII-D National Fusion facility and associated collaborators [12]. In the following, we present a case study detailing the setup for a polarized fuel experiment at DIII-D and include the benefits and role of this effort within the greater fusion research program.

One particularly attractive aspect of this proposed research plan is that it leverages many different partnerships to achieve its goals. Recent statements from the US Department of Energy's Office of Fusion Energy Science (FES) [13] describe the need for "community engagement & participation" to solve fusion energy challenges while praising partnerships with additional research agencies [14]. Spin polarized fusion research opens an additional partnership with the Office of Nuclear Physics [15], which is an opportunity not presently discussed within the FES expected plans. This effort truly represents expansion of the fusion energy program and interaction with an entirely new research community. Purposely applying interdisciplinary studies to solve challenging problems is highly suggested by the National Academies [16], and it has been shown to be a part of many fundamental discoveries (e.g., high-temperature superconductivity [17]).

In the following sections we discuss key elements that have been, or need to be considered for a successful SPF proof-of-principle experiment. A more detailed analysis, including modeling is treated in [12, 18].

4.1 Fuel: Polarization and Delivery

The ^5He and ^5Li compound states in the $D + T \rightarrow \alpha + n$ and $D + ^3\text{He} \rightarrow \alpha + p$ reactions are isospin-mirror nuclei and have a nearly identical low-energy structure. Both have a spin 3/2 capture resonance just above their particle decay thresholds and a large gap to the next excited level. This all but eliminates interference effects

and makes the consequences of polarization straight forward to calculate. Thus, polarization experiments at DIII-D can be conducted using the $D + {}^3\text{He} \rightarrow \alpha + p$ process, and the lessons learned are directly applicable to planning for polarized $D + T \rightarrow \alpha + n$.

In the last 25 years there have been key advances in the production of pure highly-polarized H and D, driven by nuclear and particle physics experiments, as well as in the production of highly-polarized ${}^3\text{He}$ gas for use both as a contrast agent in medical imaging and in high-energy spin physics. During the same period, inertial confinement fusion polymer shell technology has been extensively developed and can now be adapted to contain polarized fuel. Furthermore, cryogenic injection guns have been demonstrated to convey pellets into the core of tokamak plasmas with high efficiencies, and will be used for primary fueling in ITER. The combining of these technologies that have matured since the original Kulsrud, et al. paper [3] can be used to test the long-standing prediction of polarization survival, using the $D + {}^3\text{He} \rightarrow \alpha + p$ reaction.

Polarization survival is the first key question. The goals of the research that has led to the advances in polarized materials during the last decades, few mole samples with 10^6 to 10^8 sec lifetimes, are very mismatched to the requirements of fusion energy where ultimately kilo-moles would be needed, but with merely few second polarization lifetimes. Thus, in planning reactor fueling schemes, it would not be appropriate to simply scale existing methods from such a different starting point. To feed a power reactor with polarized fuel will ultimately require significant research. Nonetheless, current technologies and existing facilities can be exploited in a cost effective way for tests of polarization survival, as well as studies of enhanced confinement from non-uniform decay angular distributions.

In a collaborative effort with the Office of Nuclear Physics, deuterium (in the form of solid HD pellets) can be polarized at the Thomas Jefferson National Accelerator Facility in Virginia using existing (and costly) low-temperature equipment, and subsequently transported to DIII-D (capitalizing on the very long life-times of this nuclear physics grade material). Likewise, ${}^3\text{He}$ can be polarized with spin-exchange optical pumping, using what are now standard methods, either in Virginia and shipped to DIII-D, or on site at DIII-D, since the required equipment is not cost prohibitive to duplicate. The latter is likely to be more appropriate for an extended research effort that would be committed to a series of experiments.

Technological development will be necessary to adapt cryogenic pellet injector designs for handling polarized fuel. Given the recent success in using pellets to reduce the energy deposition at the divertor by Edge Localized Modes (ELMs) [19], injector designs will continue to evolve and provisions for magnetic holding fields to maintain the polarization of pellets before entering the tokamak are expected to be straight-forward.

A DIII-D experiment would require less than 1 milli-mole per pellet so that, even in the exaggerated case of 10 pellets per shot and 40 plasma shots per day, less than 1 mole of polarized material would suffice. This is readily achievable with existing technology. In contrast, about 2000 moles of D and T per day would be needed to fuel ITER at 500 MW total output power, which would require significant development. Thus, an initial investigation of the potential of polarized fuel for fusion energy is much better matched to existing machines, such as DIII-D.

4.2 Plasma Repeatability

The creation and injection of polarized fuel is a development task in addition to the actual experiment concerning the behavior of the polarized pellet as it passes through a hot plasma. It is reasonable to imagine a scenario in which the quality of the pellet (e.g., polarization fraction or pellet solidity) is itself a focus of the measurements. Reproducibility of the target plasma is important in this context, and this is another area in which DIII-D and similar tokamaks are much more fit than the ITER-grade machines. As the operational parameter space of a tokamak becomes well traveled, a large collection of easily reproducible¹ plasma shots is documented. Reproducible plasma parameters are already a stalwart of experimental design and an example of this is shown in Fig. 2, which plots four plasma parameters as a comparison in two repeat shots. The experiment [20] concerned the effects of large magnetic perturbations caused by the DIII-D test blanket module (TBM), which is a mockup coil (in terms of the plasma perturbation) intended to form expectations for the ITER TBM [21]. To systematically determine the effects of the TBM, it is necessary to isolate that input.

Figures 2(a) and 2(b) show that the plasma current and the central electron temperature are highly repeatable, respectively. Each panel of Fig. 2 displays the linear coefficient of the best-fit resulting from regression analysis (Coeff.) and the correlation coefficient (Corr.). This case is presented as a general example, it remains necessary to develop an ideal plasma shot for any specific polarized fuel experiment, and then to determine the reproducibility of that scenario (or to adjust the scenario taking reproducibility into account). Figure 2(c) plots the amplitude of the magnetic fluctuations observed to have a toroidal mode number of $n = 1$. This should be one of the more difficult characteristics to reproduce since it can be very sensitive to changes in magnetic equilibrium, impurity concentration, and assorted combinations of many other plasma properties. The production of the $n = 1$ fluctuations is similar in the two shots. The final panel, Fig. 2(d), shows the line-averaged electron density and another acceptable level of reproducibility.

A spin polarized fuel experiment will benefit from a dedicated shot development to improve plasma reproducibility beyond what is shown in this example. The important profile to reproduce is the product of ion density and temperature, specifically, $\langle n_i(r) \rangle^2 T_i(r)$, where the density is integrated over space and the entire term is integrated over the confinement time. Density profiles may end up being the most important feature to reproduce since they will also affect the assimilation of the injected fuel. (Ion temperature is important as a determining parameter for the number of fusion reactions that occur.) Monte Carlo modeling of a spin polarized fuel experiment shows that with a 15% variation in this profile term, it would require 25 tokamak shots with fixed setup to produce a measurement result with a 5σ confidence level. While the realized reproducibility would be determined based on the DIII-D parameters at the time of the spin polarized experiments (i.e., implementation of heating and control upgrades), a review of past experiments suggests that a neutron rate (proxy for the profile term) variability of better than 10% is achievable for plasmas featuring central ion temperatures of $T_i(0) \approx 8$ keV.

¹ A tokamak engineering operator may note that no full power shot is ever “easily” reproducible. This is addressed by explicitly stating that all of the experiments proposed here require a complete operations group to perform.

Fig. 2 Comparison between measured plasma parameters for two repeat shots, 157399 and 157400, including the resulting linear fit and correlation coefficients. Red dashed lines represent a perfect linear relationship. (a) Plasma current, (b) central electron temperature, (c) root-mean-square amplitude of magnetic fluctuations corresponding to a toroidal mode number of $n = 1$, and (d) line-averaged electron density. Each point represents the same time in these companion discharges.

The sheer number of plasma shots available is another factor that makes a current generation tokamak such as DIII-D the natural development environment for fuel polarization. Figure 3 shows the number of DIII-D plasma shots with $I_p > 0.3$ MA over the most recent four calendar years. The threshold of 0.3 MA is somewhat arbitrarily chosen to represent the type of plasma shot for which a high temperature situation could have been achieved if desired. In the data shown here, the number of shots taken is more strongly limited by funding and upgrade-related vent periods than by any other cause. Existing tokamaks are naturally poised for use in new development experiments, whereas new machines such as ITER are expected to have many years between their first plasmas and the peak performance plasmas advertised as part of their ultimate experimental goals.

4.3 Modeling Support

Research aimed at harnessing favorable aspects of spin polarized fusion is expedited through the use of detailed plasma equilibrium and transport modeling of existing plasma experiments. Rapid progress is possible by enhancing mature plasma models and analysis workflows, which are hallmarks of well-established scientific laboratories such as the DIII-D facility. The feasibility of spin polarized fusion experiments in DIII-D is confirmed in a recent study, which uses the EFIT equilibrium reconstruction code [22] and the plasma transport code ONETWO [23] as part of a larger workflow developed to identify suitable target plasma conditions, and assess the capability of proposed plasma diagnostics.

Fig. 3 Number of DIII-D shots featuring plasma currents that surpassed 0.3 MA over the past four calendar years.

Modeling results indicate that high-temperature Quiescent H-mode plasma discharges are a likely scenario for initial spin polarized fusion experiments in DIII-D. Figure 4 shows a sample calculation of the unpolarized $D + {}^3\text{He} \rightarrow \alpha + p$ reaction rate density, calculated within ONETWO using the cross-sections of Bosch and Hale [24]. Spin polarized effects are coupled to the initial velocity vector of the charged fusion products, and are accounted for in subsequent analyses. The impurity densities assumed for the D and ${}^3\text{He}$ fuels, shown in Figure 5, are based on densities achieved in previous deuterium pellet experiments using injection from inside the magnetic axis [25]. It is reasonable to assume that the spin polarized fuel delivery system can achieve similar efficiencies. The assumed thermal ion temperature, which reaches 15 keV in the core, is routinely achieved for long durations in DIII-D in QH-mode discharges [26]. At these temperatures, the volume-averaged reaction rate for $D({}^3\text{He}, p)\alpha$ is $2.4 \times 10^{14} \text{ s}^{-1}$, which is comparable to detectable neutron rates for the $D(D, n){}^3\text{He}$ reaction under achievable H-mode conditions.

4.4 Diagnostic Capability

Diagnostic access can only reduce as tokamaks evolve from research-driven facilities with many ports to electricity producing reactors with full blankets for tritium breeding. Spin polarized fuel experiments at DIII-D may be some of the most thoroughly measured plasmas ever produced. Confirmation of the quality of the polarized fuel immediately prior to injection is necessary, and may require the installation of a superconducting quantum interference device (SQUID) at the interface between the pellet injector and the tokamak [12]. Such an installation is feasible in DIII-D where the access between the existing pellet injectors and the vacuum chamber involves only a short distance of a few meters.

Once injected into the plasma, the polarized fuel will change the number of $D + {}^3\text{He}$ fusion products produced. Those α -particles (3.7 MeV) and protons (14.7 MeV) are highly energetic and largely unconfined in DIII-D plasmas with minor radius $a \sim 0.6 \text{ m}$ and magnetic field $B = 2.15 \text{ T}$. Modeling the fusion birth profile from the $D + {}^3\text{He}$ reaction (Fig. 4), calculations have been carried out to track the trajectories of 14.7 MeV protons. Many of these proton orbits intersect the plasma facing wall, but with a particular wall strike profile. The wall strike profile is shown in Fig. 6. With a poloidal angle of 0° corresponding to the outer midplane, this

Fig. 4 Spatial distribution of the predicted rate density for the $D(^3\text{He}, p)\alpha$ reaction assuming unpolarized fuels.

Fig. 5 Flux-surface averaged profiles of impurity density and thermal ion temperature used to model $D(^3\text{He}, p)\alpha$ reaction rate density in ONETWO.

histogram suggests that there are desirable locations to install a detector. The result is symmetric, meaning that a plasma with the toroidal magnetic field in the opposite direction would cause the results of Fig. 6 to display a peak in the negative poloidal angle region.

Specific sample orbits for these charged fusion products are shown in Fig. 7 using a plasma shape that has been previously applied to measurements of lost energetic ions injected by neutral beams [27]. The orbit example displays the strongest loss case of ions born with zero velocity parallel to the background magnetic field ($v_{\parallel} = 0$ or $\theta = 90^\circ$). This initial velocity vector results in the largest possible gyroradius and a very short transit time to the outer wall. Measurements of the

Fig. 6 Histogram of the number of 14.7 MeV proton birth trajectories reaching specific poloidal angles of the wall in DIII-D. The poloidal angle of 0° corresponds to the outer mid-plane, with the angle 90° (-90°) corresponding the upper (lower) vertical position.

lost fusion products would be made possible through either modifications to the existing fast ion loss detectors (FILDs) [28, 29] or the installation of a single-hit detector as has already been developed for the MAST facility [30].

Fig. 7 Example orbits from a $D(^3\text{He})$ fusion born α -particle at 3.7 MeV and a proton at 14.7 MeV using DIII-D equilibrium from shot 142111 at 525 ms.

4.5 Tokamak Wall Interactions

Most of the ions in a tokamak core will leave the plasma before undergoing a nuclear interaction. Once these particles reach the walls, there are several potential mechanisms that can, depending upon the conditions of the wall, lead to depolarization. However, the consequences of wall depolarization are significantly different between a high power reactor such as ITER and the current generation of lower-power machines. ITER must be fueled by pellets injected through the edge pedestal, since the scrape-off layer is expected to be almost opaque to neutrals from the walls [31, 32]. In ITER, particles leaving the plasma will be swept to the diverter by convection so that the recycling of fuel from the walls, and hence the dilution of the polarization in the core, is expected to be essentially insignificant.

This is not the case in a lower-power machine such as DIII-D. Potential wall-depolarization mechanisms have been discussed extensively in [33], where low-Z, non-metallic materials were expected to be optimal. Fortunately, the graphite walls of DIII-D are well suited. Carbon has no conduction band, so that hyperfine interactions with polarized material are eliminated. However, the material is porous and excessive dwell times at the wall could compound the chance of encountering paramagnetic impurities. But this can be mitigated by the deposition of a thin (100 nm) layer of boron on the walls, which has been shown to dramatically increase confinement times [34, 35]. The reduced dwell-time on a boronized wall, coupled with modest energy confinement times in machines such as DIII-D (~ 0.2 s), is expected to be effective in keeping wall depolarization at a minimal level for a program of spin-polarized fusion studies.

5 Conclusion and Discussion

Spin polarized fuel research is the type of topic that crosses the fundamental divide between fusion science and fusion energy. As the Director-General of ITER noted [36],

ITER is the last chance we have to demonstrate that tokamak fusion is manageable - there will be no other.

Here the key word is *manageable*. While fusion science research has shown that the principle of plasma confinement with magnetic fields is sound, it remains to demonstrate that a magnetic confinement device can produce net electricity. The challenge of producing net electricity involves a level of fusion power output control well beyond that of a research device. Spin polarized fuel has the potential to provide a control knob for power output that is far simpler to manage (changing pellet material) than almost all other options (e.g., externally applied three-dimensional magnetic field perturbations). It also has the potential of lowering the auxiliary power required to obtain ignition, thus reducing plant costs. This research is applicable to the next-generation of fusion devices, yet it lends itself to being performed cost-effectively using present facilities.

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