Measuring Spatial Plasma Profiles on JT-60SA Using Soft X-Ray Tomography

Integrated Systems and Project Management for Fusion Applications

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Chapter 1

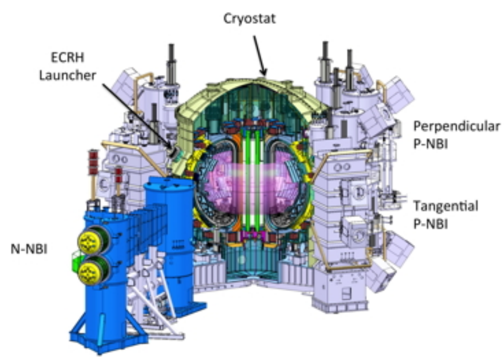
Introduction

We propose a diagnostic system that allows for the measurement of spatial plasma profiles for JT-60SA using soft x-ray (SXR) tomography. We look at the current aims and capabilities of the JT-60SA tokamak in Japan and the relevancy of the proposed diagnostic.

1.1 Goals of JT-60SA

Construction and exploitation of the JT-60 Super Advanced (JT-60SA) tokamak are being implemented by JT-60SA Research Unit collaborating with Japanese and European fusion research communities from June 2007. The research objectives and strategy cover all major research fields of:

- Development of the operation regime.
- MHD stability and control.
- Transport, confinement and high energy particle behavior.
- Exhaust physics, including divertor and scrape off layer (SOL).
- Pedestal and edge physics.



The project mission of JT-60SA is to complement ITER in resolving key physics and engineering issues for DEMO reactors. In particular, the most important goal of JT-60SA is to decide the practically acceptable plasma design for DEMO, including reliable plasma control schemes suitable for a power plant. By superconducting toroidal and poloidal coils, the JT-60SA device is capable of confining break-even equivalent class high-temperature deuterium plasmas at a plasma current I_p of 5.5 MA, a major radius of $\sim$ 3 m and a toroidal field of 2.25 T lasting for a duration of $\sim$ 100 s at high heating power [1].

In such long-pulse discharges, significant heat and particle load onto plasma-facing components is expected, in particular onto the carbon mono-block divertor is utilized in JT60-SA, with cooling capabilities compared in Table 1. In support of ITER and DEMO, low heat flux regimes will be explored with the plasma-facing components fully covered with metal, after achieving the integrated long-pulse high-β operation with the carbon mono-block divertor. Carbon has the advantage of high heat flux resistance and thermal conductivity although the high fuel retention and short lifetime is not acceptable in ITER and DEMO. Metal plasma-facing components have the advantage of low fuel retention resulting in low out-gassing, alleviating difficulties of steady-state particle control, as well as low radiative power and long lifetimes.

Tokamak	**Divertor Cooling Capability (MWm^{-2})**
JT60-SA	15
ITER	10
DEMO	$\sim$5

Table 1.1: Divertor cooling capability of JT60-SA in comparison to ITER and DEMO.

The SXR diagnostic proposed is relevant for measuring the spatial profile of these impurities. Once the metal ions penetrate into the core plasma, they tend to accumulate and radiate significantly, lowering the core plasma temperature. Impurities from plasma-facing components are generated by physical sputtering process or anomalous transport, such as edge localized modes (ELMs). The generated impurity could penetrate and cool the core plasma by causing power to be radiated away via bremsstrahlung, radiative recombination and line emission. Impurities increase plasma resistivity and can change the radial plasma-current distribution, affecting stability. They should be traced with high temporal and spatial resolution.

In chapter 2, the scope of X-rays diagnostics design and its suitability on JT60-SA are discuss. X-ray emissions theories are also shortly introduced and reviewed in this chapter. Chapter 3 outlines the the engineering requirements for the X-ray diagnostics system. Project management aspect such as WBS, timetable, cost and risk assessment are covered in chapter 4.

Chapter 2

Physics Case for SXR Diagnostic

2.1 Scope of Diagnostic

X-rays offer unparalleled versatility when it comes to diagnosing fusion plasmas. The soft x-ray regime at roughly 1-20KeV (the upper bound being more loosely defined) is especially convenient as, between hydrogenic bremsstrahlung and impurity line radiation, it is characteristic emission at baseline tokamak operating parameters and so requires minimal filtering or manipulation to get data. The range of plasma properties we can understand from the intensity and spectrum of the signal include: electron temperature, electron (plasma) density and the plasma composition. Added to convenience and versatility is the virtue of reliability since signals are easily measured - typical tokamak plasma densities are optically thin to soft x-rays. The first absorption of emitted light is highly likely to be at either a filter or detector of the diagnostic; affording us confidence that we are measuring a true signal that has not interfered with other plasma particles or phenomena.

There are typically two diagnostic routes to studying x-ray emission. Pulse-height studies are optimized to look at emission spectra and so emphasize a wide spectral range with moderate resolution enabling detailed information on impurities. Imaging systems preferentially look at the behaviour of plasmas and so optimize (in particular temporal) resolution in order to capture changes over a broad spectral range, but give a coarse understanding incoming x-ray energy. While both types will be included in the JT60-SA diagnostic suite, we have taken the view that a significant improvement in the capability of soft x-ray plasma imaging (tomography) should be prioritized. This position is intended to complement the research goals of the upgraded tokamak as indicated below from the JT60-SA website and research plan respectively:

> It is designed to allow the optimization of configurations for ITER and DEMO by operating with a wide range of plasma shapes (elongations and triangulari-

> ties) and aspect ratios (A=R/a down to 2.5) including that of ITER, with the capability to operate in both single and double null divertor configurations.
>
> In particular, the most important goal of JT-60SA is to decide the practically acceptable DEMO plasma design including practical and reliable plasma control schemes suitable for a power plant.

With the introduction of superconducting magnets alongside the stabilising coils, the JT60 programme makes a technological leap toward highly controlled plasmas. Research into these shapes is in principle transferable to fusion machines on any scale and so a thorough understanding of their physics is vital to fusion. Taken together, the shaping aims and capabilities provide a compelling case for mapping the plasma behaviour.

Given this focus, we note that the primary parameter of concern will be the electron temperature in the plasma core as indicated by the intensity of energetic brehmsstrahlung radiation. Isotropy of temperature parallel to magnetic field lines (as a result of rapid transport) allows for accurate recording of the signal at varying positions in the plasma. This gives a map of flux surfaces that is invaluable to understanding magnetohydrodynamic (MHD) flows.

We argue that the principal heavy ion concentration will come from the first wall in this case initially a carbon design. The intention is to swap to a metallic ITER-like wall in future. Such a material choice is widely acknowledged to be not a reactor-relevant one and is replicated in few existing and future experimental machine designs. Consequently, a detailed knowledge of impurity concentrations, even spatio-temporally resolved over a shot, has limited further application. A generic understanding of the effects that impurity concentration have (on cross-field transport and instability and flow behaviour for example) can inform a number of modeling and experimental efforts. Finally, we note that there remain some significant opportunities to develop and interpret impurity data with the proposed tomography design route often by working in conjunction with the results of other diagnostics, especially Thomson Scattering - to examine the time evolution of ionisation stages in heavy impurities.

Optimising such a measurement in the proposed magnetic geometry imposes several constraints (in conjunction with those implied by vacuum vessel design) on the diagnostic design. While well known detector technology can be utilised to record soft x-ray signals, to achieve a robust understanding requires measuring in as many places as possible simultaneously. Ideally, tomography relies on homogeneous coverage of the poloidal cross section of the plasma.

Attempts to deploy 2D tomography in a purely tangential (to field line) orientation have sought to overcome this need as they rely only on one camera array often in the visible or sxr (DIII-D) range. We reject such a design as it limits the plasma coverage and is more suited to regions of specific interest such as x-points or the divertor. It further requires significant a priori information; being highly sensitive to misalignment and making assumptions about toroidal symmetry. Both of these make a tangential setup an unsuitable design as (re)shaping the plasma will involve changing the field lines in the tokamak and so positions of plasma edge and x-point(s).

We propose to mimic successful attempts on tokamaks such as TCV, AUG, C-MOD and JET (emphasizing plasma shape) to achieve robust coverage of the full cross-section. Rather than assuming toroidal symmetry that may not be robust, these designs position detectors around the same poloidal cross-section. Actual coverage is limited by: available viewing directions, number of lines of sight, cost of installing multiple arrays and electronics, finite beam width as well as noisy or otherwise irregular measurements.

Achieving a 2D image of the plasmas requires line integration of the incoming signals and then the inversion of those results to reproduce the physical picture. This is done by the series expansion of emissivity data onto basis functions. The precision of the resulting emissivity pattern is strongly proportional to the number of cameras looking at chords of the cross-section (i.e. the sample rate of data acquisition). Reiterating well understood methods for tomography is outside the scope of our proposal but it is important to note that this type of physical environment of interest necessitates the series-expansion approach and that means digitizing the raw signal prior to inversion.

Baseline operation of tokamak plasmas usually exhibits a pedestal in temperature and density at the centre of the radial profile which falls off towards the plasma edge. This means the temperature will be orders of magnitude lower beyond the pedestal and the diagnostic is likely to have severely limited performance in that region of the plasma.

Finally, we discuss the suitability of JT60-SA to make use of such a diagnostic. JT60-SA is a non-spherical tokamak with the only plasma facing components being a solid first wall (i.e. no test breeder blankets). This mean we anticipate that there is sufficient wall area available to implement the number of detector arrays necessary for a robust measurement. Crucially, the machine is presently being upgraded to run a campaign complementary to ITER operation and so a window already exists to upgrade the in-vessel diagnostic suite.

2.2 Theory

Measurement of X-ray spectra offer some of the most information dense diagnostic tools available to us for studying the development of a fusion plasma. The X-ray emission from an energetic plasma can be accounted for by a continuum of radiation emitted in three phenomena:

- Free-Free (ff) bremsstrahlung radiation between electrons and ions
- Free-Bound (fb) recombination of electrons with impurity ions
- Bound-Bound (bb) line emission from impurity ions

Continuum radiation arises from electron-ion bremsstrahlung (ff) and recombination (fb). The continuum spectrum contains information on the atomic number, ionization state and plasma electron temperature. Line radiation is emitted by electronic transitions in ions (typically impurities) in the plasma. The intensity and position of line radiation contains information about the type and temperature of ions in the plasma.
In this section, we will provide a brief introduction to the phenomena on which the physics case for our diagnostic is based. We will first discuss the use of broad background spectra (ff and fb) in determining the electron temperature and magnitude of plasma current, before looking at the finer details of the x-ray spectrum (bb).

2.2.1 Electron Temperature

The X-ray power per unit volume (δW) in a wavenumber interval $k \rightarrow k + \delta k$ from bremsstrahlung radiation is:

$$\frac{\delta W}{\delta k} = 3 \times 10^{11} \frac{n_e \Sigma_i n_i z_i^2}{10^{26} cm^{-3}} \left(\frac{T_e}{keV} \right)^{-1/2} \times \bar{g}(T_e, k) \exp(-k/T_e) \mathrm{sec}^{-1} \tag{2.2.1}$$

where $n_{e,i}$ are the electron/ion number densities, T_e is the electron temperature, z_i is the ion charge and $\bar{g}$ is the temperature averaged Gaunt factor (of order unity). Measurement of this continuum radiation can therefore be used to identify the electron temperature.

2.2.2 Plasma Current

The energy released by bremsstrahlung radiation (1.2.1) is calculated assuming the plasma is purely isotropic and has no bulk motion. In the case of a (non-relativistic) current-carrying tokamak plasma, we must also consider the bulk motion of electrons:

$$\mathbf{k}_{elec} = \mathbf{k}_{th} + \mathbf{k}_{cur}$$

The addition of a constant current term to the velocity of electrons in the plasma can be treated as a change in reference frame away from the inertial frame. Thus the spectrum observed in the lab frame will differ from a pure bremsstrahlung spectrum by a doppler shift, pushing the observed x-rays towards the high energy region. The phenomenological result is the formation of a long 'tail' at the high end of the x-ray energy spectrum which can be used to find the magnitude of the plasma current ($I_P \approx n_e q v_{cur}$).

2.2.3 Plasma Impurities and Ion Temperature

Transitions between internal atomic energy levels in the plasma ions release x-rays at well-known, specific wavelengths. These characteristic x-rays occur at well-defined energies and can be used as an atomic 'fingerprint'. Line spectra from these events can be used to identify the atomic impurities in the plasma. The gaussian profile of the line intensity is determined by doppler broadening and is given by:

$$I(k)dk \propto n_i \sqrt{\frac{2\pi m_i}{k_B T_i k_0^2}} \exp\left(-\frac{m_i c^2 (k-k_0)^2}{2 k_B T_i k_0^2}\right) dk \tag{2.2.2}$$

Where m_i, n_i are the mass and number density of the impurity species, k_0 is the centre of the spectral line, T_i is the ion temperature and k is the wavenumber of the observed x-ray. The line profiles can be used to determine the number density and temperature of impurity ions in the plasma, as well as the species involved.

Chapter 3

Technical Specification

Engineering requirements must be considered for the diagnostic, for example: understanding the position of dust and coatings on critical surfaces, radiation damage induced in any collection optics, any line of sight and access restrictions and the lifetime between component replacements. Many of these issues are commonplace for diagnostics commissioned in nuclear environments. Here we discuss line of sight requirements for the diagnostic and complete a breakdown of diagnostic components and their protections.

3.1 Line of Sight

In spite of a complex operating environment, computerized tomographic methods have been applied to diagnose plasmas in most fusion machines. A challenge to acquiring optimal data from these hostile environments has been poor spatial resolution compared to those where a complete field of view is possible. The technique developed to overcome this is sparse data tomography with, instead of a field of data, typically between 2 and 10 viewpoints of between 10 and 30 channels each. Tomography strictly relies on having at least two lines to compare but that is insufficient to deliver useful information from around the plasma. Positioning these detectors around the plasma edge facilitates 100 to 200 chordal measurements.

Tokamak tomography entails determining the distribution of the emissivity in the soft x-ray spectrum of plasma over a poloidal cross-section. A set of pinhole style cameras, each with an array of x-ray detectors around the vacuum vessel, makes the measurements. A viewing cone is defined by the relative position of each detector and an aperture subject to the condition that the field of view needs to be sufficiently narrow to justify approximating the cone by a line of sight. This is satisfied by a focal length (minimum separation of aperture and detector) of 14cm. To achieve multiple lines of sight in one of the available dimensions our aperture is usually a slit rather than a dot. The center of this slit pinhole corresponds to the middle position of the array. In real terms a line of sight will be established by a viewing point in the vacuum vessel and the detectors angle to it.

Another important factor in the resolution achievable with this technique is the beam width with which the plasma is viewed in each channel. We would like these to be consistent and collimated on every detector. However, in reality they will have some finite width, set by the distance of the detector from the viewing slit. Wider beams can be beneficial for improving the signal to noise ratio and avoid aliasing smaller structures though at the cost of spatial resolution.

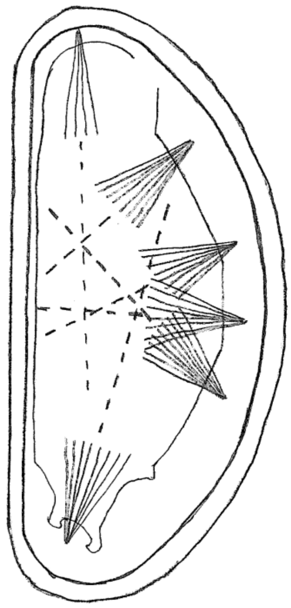


Figure 3.1: A sketch of JT60SA PFCs and toroidal field magnet with the proposed 6 detector positions and indication of the 32 chords from each (half at the top to capture double null operation.) These positions combine those used previously for maximally homogeneous coverage at AUG.

The exact positioning of detector units will be specified by reference to major radius and the mid plane i.e. (r,z) coordinates. An angle will indicate the direction of the tangent to the array and the central line of sight. These will only be specified to a high degree of intended accuracy once the diagnostic is in a position to be installed accounting for changes to the plan, the positions of other hardware etc. We can set out rough estimates for these three parameters per figure 3.1, to indicate the extent of coverage we propose with this system. We intend to take advantage of the higher aspect ratio of JT-60SA to install detectors above the inboard, high-field side of the plasma to study a region not usually accessible (especially to the modern fleet of spherical tokamaks) as well as to expand coverage of the low-field side as part of the upgrade. Though not part of our design proposal, it is worth commenting that by having identical lines of sight (i.e. duplicating one or more detector positions) for a different poloidal cross section would give researchers the opportunity to determine toroidal mode number with this technique.

3.2 Breakdown of Diagnostic Components

3.2.1 Detector

For detection of soft X-rays we have chosen a silicon photodiode array coupled with a scintillator. This is mostly for cost reasons; photodiode arrays are cheap and can be replaced fairly easily, whereas high speed, high resolution CCD cameras can be particularly expensive. In harsh environments, it would be prudent to use a system which is cheap to replace as this could decide the critical path for the diagnostic project. The upper limit of the spectral range at higher energies is determined by the thickness of the active layer of the silicon diode. Since the diodes are not operated fully depleted, this can be smaller than the diode thickness, but it is also not identical with the depleted layer thickness.

Silicon Photodiode Arrays

Silicon (Si) photodiode arrays are routinely used as detectors, given their sensitivity to a broad range of X-rays up to around 20keV. They are normally coupled to a scintillator; an Si photomultiplier with various scintillator-mounting options.

The Si photodiode array chosen is a back-illuminated photodiode array for X-ray non-destructive inspection manufactured by Hamatsu (S12362 series) [5]. Back illumination photodiode array assist in coupling to a scintillator. Two 16 element arrays will be used in the set up. This configuration allows for improved spatial measurements at each pinhole. A GOS ceramic is the best scintillator to use with this specific detector for monitoring fast moving objects. Two options include Caesium Iodide (CsI), which is a high energy absorber and ensures the device is resistant to thermal stress and mechanical shock, both of which could be issues associated with use in a tokamak. Ceramic scintillators have a much higher sensitivity to X-rays as well as low afterglow. The scintillator chosen is a Toshiba Gd_2O_2S:Pr multi-crystal scintillator, due to the low cost proportional to it's performance.

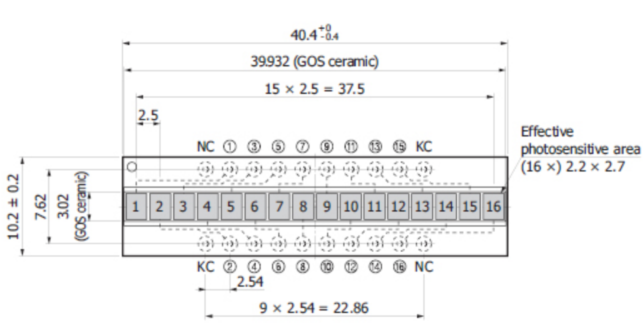


Figure 3.2: Dimensional Outline of 16 element Si photodiode array including GOS ceramic.

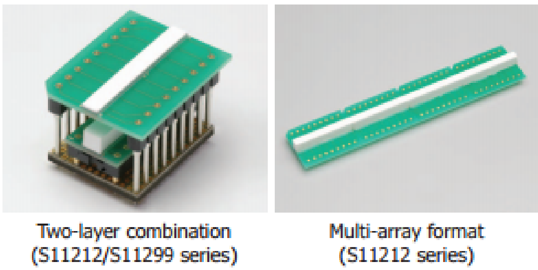


Figure 3.3: **Left:** Two layer setup of 16 element photodiodes. Each layer must have its own scintillator attached. **Right:** Multi-array format for spatial measurement.

3.2.2 Filters and Shielding

Each detector unit must be protected both from plasma and radiation. The former entails windowing the camera pinhole and the latter encasing our units. Radiation protection is also required to preserve the integrity of the vacuum vessel and machine radiation shield.

In most tomographic systems the first filter is also the vacuum seal/window. The separation of the torus vacuum and camera vacuum is provided by, for example beryllium, foils. Using a thickness of around 50 microns allows this window material to act as a filter that blocks photons with an energy of less than about 1 keV. This high pass filtering is important as it limits the number of incident photons coming from background radiation in the tokamak plasma, as opposed to soft x-ray emission from the sources that are of interest to us as set out in the physics case. Without filtering, the diagnostic also sees low energy photon radiation and the soft x ray signal would be swamped by visible light. Although not resolved by this technique, the spectrum of energy detected has a lower bound defined by this filter (where the upper is set by the detector choice.)

Installing the beryllium foil as a spherical or at least curved surface means equal absorber thickness for all detectors lines of sight. This is essential for a precise calibration. The filter is mounted directly behind the pinhole. Behind the plasma facing wall the unit will have to be protected from radiation to preserve its components as well as to ensure that the detectors do not represent a gap in the protection of tokamak users. We intend that, given the pinhole is covered, the detector vacuum may be broken for access (principally for maintenance) without breaking the vacuum vessel vacuum and therefore needing to be pumped down. Otherwise the shielding can straightforwardly be incorporated as the housing for the detector units. Since JT-60SA will not use tritium we are not operating in a high energy neutron environment which limits the damage that will be done. A steel case design should be sufficient to guarantee the lifetime of components. It will be important to establish a means of electronics access without breaching this shielding; RF shielding for the circuitry between the photodiode and DAQs such as RC filters is also necessary and should be adequately dealt with by a steel cage.

It should be possible to shutter the pinhole to prevent damage to detectors when the machine is not being used or used in unfavourable parameter space. However, the cost of adding in such a mechanism compares poorly with the limited additional protection in the absence of collection optics to protect. It also requires substantially altering the mounting (and shielding) to allow the additional functionality.

3.3 Data Acquisition

The data acquisition for this system is composed of three stages. Firstly the signal from the photodiode array is amplified. It is then passed to a multichannel data acquisition board (DAQ) where it is further amplified and digitized. The data from each channel of each DAQ is then collected and sent as over Ethernet to a central computer which collates the data and interfaces with the central data system of JT-60SA. The system is shown schematically in fig. 3.4.

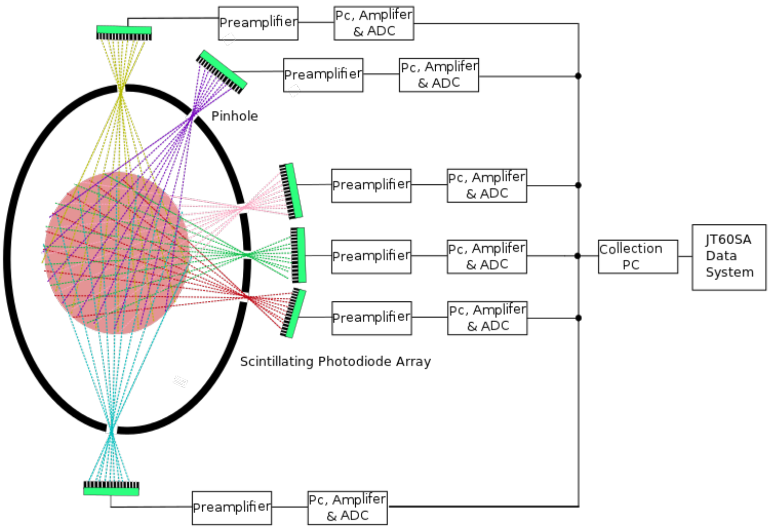


Figure 3.4: Overview of the data acquisition system connected to the lines of sight. This feeds back to the central JT-60SA data system.

Pre-amplification

PIN diode arrays require a charge collection pre-amplification circuit, which will convert the current pulses from the diode array to a voltage signal that can be passed to data acquisition boards and will be tailored to the electrical characteristics of the chosen diode array. There will be one pre-amplification circuit per diode array. The pre-amplification circuits will be an on-board solution. The pre-amplifier circuit will interface directly with the diode arrays and will be on the same circuit board. This ensures that the stray capacitance in the circuit is minimized and helps to maximize noise-resilience.

A prototype for the acquisition and pre-amplification board has been developed to a stage suitable for manufacture and testing. Schematics and 3d models of the circuit are shown in the appendix. The prototype takes a $12V$ and ground input from the tokamak from which it generates a low noise $\pm 15V$ supply which is used to bias the photodiodes and as a voltage reference for the op-amps which amplify the diode signal.

Data Acquisition Boards

Multichannel simultaneous sampling DAQs will be employed. Off the shelf DAQs (such as advantech PCI-1714UL) are chosen to ensure stable operation at high frequencies. These DAQs will further amplify the pre-amplified signal and convert it to a digital signal. This digital signal will be passed to an acquisition computer via PCI. The acquisition computer will contain multiple DAQs so that each chord can be simultaneously sampled at high frequency. The digital data will be sent over gigabit ethernet as it is acquired from the acquisition boards. There will be one acquisition computer per pinhole.

Central Data Collection

The data from each acquisition computer is sent over ethernet to a central computer remote to the acquisition systems. The acquisition computers will connect through a gigabit ethernet switch to the central collection computer. This computer buffers and collates the data. The data will be buffered so that excessive bandwidth during the pulse is not required between the collation computer and the central data system. After the each pulse the data can then be sent to the central data system. It will also carry out the tomography procedure to convert the line integrated chord signals to a 2d intensity map, which is transferred to central data systems along with the raw line integrated data.

Interfaces

The various acquisition components will interface as follows.

- The diodes and pre-amplifier will interface over high speed, short copper traces.
- The pre-amplifier output will connect to the DAQs via shielded coaxial cable.
- The DAQs will connect to the acquisition PCs via a PCIe bus.
- The acquisition PCs will connect to the collation PC via gigabit ethernet.
- The collation PC to central data system connection will also be gigabit ethernet.

Bandwidth

The bandwidth of required per viewing port is calculated:

$$12\text{bits} \times 500\text{kHz} \times 32\text{chords} = 192\text{Mbs}^{-1} \tag{3.3.1}$$

A bandwidth of ≈ 200 megabits per second is required for each viewing port, this is easily achievable with PCIe and gigabit ethernet. The collation PC will require a bandwidth approximately 200 megabits per second per viewing port so up to 10 ports can be supported with two gigabit ethernet cards and gigabit switches. Two gigabit ethernet cards on the collection pc will therefore suffice to acquire data from 6 ports.

Chapter 4

Management Plan

4.1 Work Breakdown Structure

4.1.1 Planning & Project Management

The initial stages of diagnostic development are very heavily skewed toward planning. The physics and technical cases for the diagnostic need to be put forward as well as a reasonable completion plan. The project must appear to an impartial observer to not only be of value, but feasible within a reasonable timescale and represent value for money. It must be reasonably costed and present little risk for a worthy reward. This phase of the diagnostic will be used to secure funding and space on the JT-60SA vessel.

Physics Case

The starting point for any diagnostic tool is to identify the Physics which is to be measured and assess the value of the accessible data. The diagnostic should be as information dense as possible and offer insight into as-yet-un-researched processes and phenomena. In our case, not only do X-rays offer a wide range of information about the nature of a fusion plasma, but the tomographic capability of our device will give insight into the spatial profile of impurities in the reactor core. Given the ability of the JT-60SA upgrade to control the shape of the plasma, a tomographic analysis of impurity distribution for different plasma shapes will allow us to determine how the severity of impurity cooling in the plasma core depends on the shape and size of the plasma itself. Chapter 2 gives a detailed overview of the Physics which can be studied by our diagnostic and the benefits offered by a tomographic x-ray system, so we will elaborate no further here.

Technical Case

Where the Physics case outlines the potential reward from our diagnostic, the technical case assesses the cost (both financial and otherwise) of completion and provides a specifi-

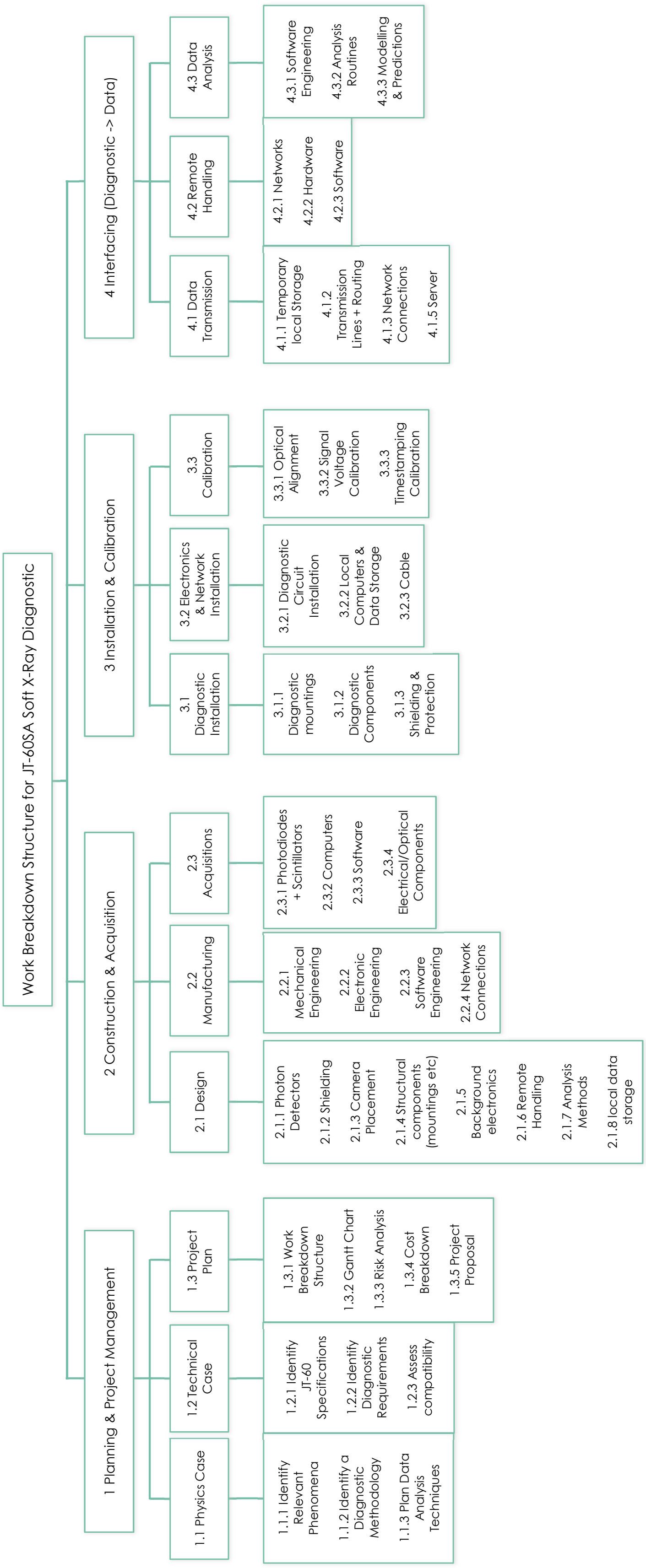


Figure 4.1: The Work Breakdown Structure for our JT-60SA Diagnostic

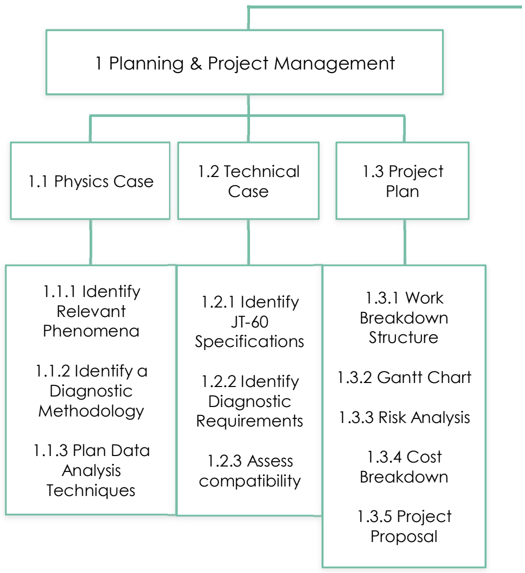


Figure 4.2: The Planning and Project Management Phase of the WBS

cation for the system. The equipment required to run the diagnostic must be financially achievable and well-valued. We must argue that the data which can be acquired by our diagnostic tool is both ground-breaking and world-class. The technical case exists to make these arguments in a concise and easily understood manner.

Project Plan

To ensure efficient and successful completion of this project, a detailed plan is needed. This includes identifying the time frames, costs and relative importance of all tasks which must be completed before the project can be deemed a success. This chapter is devoted to the completion plan for this diagnostic and will outline the tasks which need to be performed, as well as providing timeframes, assessment of risk and estimated costs for completion.

4.1.2 Construction & Acquisition

A significant portion of the time taken to complete the project will be in the construction and acquisition phase. The diagnostic must be designed to the specifications of JT60-SA, this will include the design of hardpoints to secure the cameras to the bulk of the tokamak, shielding and protection for the delicate instrumentation. These areas in turn will require the exact specifications of the experimental equipment (cameras, photodiodes, lenses etc). The components will then need to be commissioned (if they are going to be bespoke to the diagnostic) or purchased accordingly. The electronics which will be used to remotely control the diagnostic and transport data will also need to be designed in line with the existing networks in JT-60SA, and any software required for remote handling/analysis will need to be purchased/commissioned.

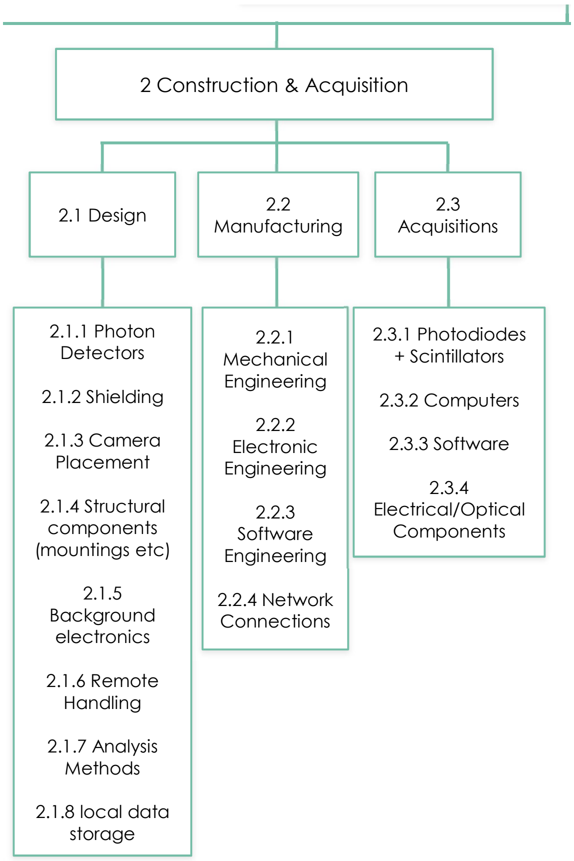


Figure 4.3: The Construction and Acquisition Phase of the WBS

Design

Real estate around a tokamak is highly competetive. Any diagnostic proposal must be absolutely sure that it is making the most efficient use of the space available. To that end, the mechanical fittings and data pathways will need to be designed to an exact specification far in advance of the actual construction process. This stage will involve:

- Identifying the fittings on the inboard and outboard side of JT-60SA to which the pinhole cameras will be mounted.
- Designing the radiation shielding for the pinhole cameras to ensure the diagnostic components are properly protected.

- Identifying an appropriate optical path for the diagnostic x-rays and designing the mountings for any optical equipment (lenses, mirrors etc).
- designing the mountings for the silicon photodiodes and scintillators which are to be used to perform the measurements.
- Organising the data pathways and electronic networks which are needed on the back end of the detector to transfer information to the data storage drives.

With this task completed, the manufacturing stage can begin without the worry of discovering an incompatibility further down the line.

Manufacturing

Once the design phase has been completed, any parts which need to be specifically created will need to be commissioned either by a mechanical engineering team in the case of physical structures which need to be manufactured or by an electronic engineering team in the case of any circuitry which will be necessary in the production of the data signal. This process will be a significant fraction of the cost of the diagnostic, both in time and financially. There are four central aspects of this section which must be completed:

- Hardpoints and mountings to fix the diagnostic to the outboard side of the tokamak
- Shielding and protection from the hostile plasma environment
- Electronic circuitry and data transmission networks
- New analysis routines in existing software or new pieces of code for data analysis

The major cost associated with this stage is in materials procurement and staffing. Staff are going to need to be employed to perform these tasks, or independent contractors are going to be required. Raw materials for any bespoke aspects of the diagnostic are going to need to be identified and ordered to measure. Software alterations which are needed to accommodate the data output of the diagnostic should also be considered here, although they will not be able to reach full completion until the later stages of the project. Electronic and optical components which will be needed should also be purchased at this stage.

Acquisitions

If done correctly, this stage should present no issues in terms of the project timeline. The silicon photodiodes and scintillators are likely to be the most important acquisition, and they should be ordered well in advance to account for any possible delays. Aside from this, the acquisitions which are required merely include:

- Optical Components for Optical Path Engineering.
- Electronic Components for any Bespoke Circuitry.
- Computers which may be needed in addition to the existing hardware
- Software for Data Analysis, if it has not already been purchased.

4.1.3 Installation & Calibration

This is the stage where all the hard work and effort comes together. By this point, the diagnostic should be laid out in full component form and be ready for installation. The installation process will have considerable staffing costs associated with it, as it will need to be professionally and expertly crafted to ensure proper operation. It will also be required to time this stage with a period of shutdown for JT-60SA, as installation cannot take place while the tokamak is operational. Once the installation has been performed, the system will need to be calibrated. While extra care will be taken to ensure full compatibility, it is highly likely that some unforseen issue will have presented itself during the installation process. The calibration stage is there to ”iron out” any issues which have presented themselves and ready the diagnostic for its first data collection run.

Electronics & Network Installation

The backend of the diagnostic will probably be the first aspect to be installed, since this can be done without the need to shut down the tokamak for an extended period of time. This involves laying the transmission lines which will take the scintillator output away from the reactor vessel and into the analysis electronics/digitisers which will save the data as a digital, accessible file in the JT-60 newtork. It may also involve some of the mountings being fastened to the outside of the vessel if an appropriate time can be found. This stage can largely be performed without any major inconvenience to the running of the tokamak.

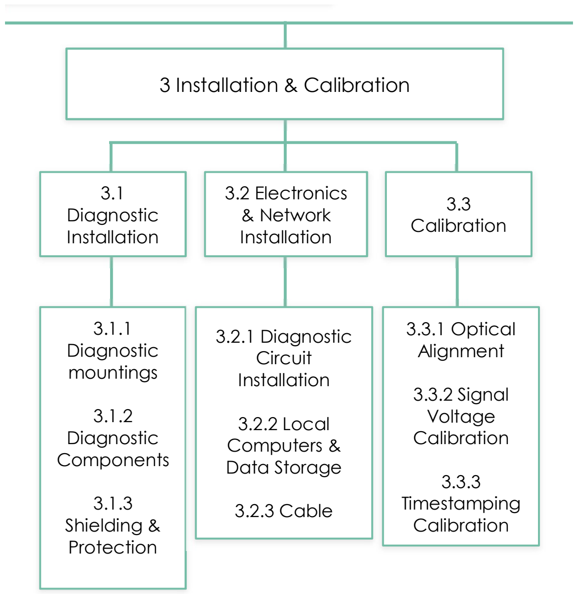


Figure 4.4: The Installation and Calibration Phase of the WBS

Diagnostic Installation

The installation phase of the diagnostic will need to be performed at a time when JT-60SA is non-operational, as such we will need to optimise the efficiency of this stage in order to minimise the shut-down time required for our installation. Once the backend has been laid down successfully, the task of installing mountings for the photodiodes/scintillators, radiation shielding and the photodiodes themselves can be performed with minimal inconvenience to the running of the tokamak. Our diagnostic has the added benefit of not requiring any cameras on the inboard side of the reactor vessel, which will significantly reduce overall installation time. This phase of construction is absolutely vital and extreme care must be taken to ensure it is performed expertly and with minimal inconvenience caused.

Calibration

Once all the installations have been completed, the final calibration of the diagnostic can take place. The most time consuming part of this process will involve the alignment of the pinhole cameras to create the correct tomographic map of the tokamak interior. This will most likely need to be done while the tokamak is not operational and can be combined with the installation process to minimise down-time. Further to this, the electrical output from the scintillators will need to be digitised and calibrated to remove background noise and ensure the voltage levels are balanced between the different cameras. The signals will also need to be timestamped for accurate tomagraphic reconstruction; the diagnostic is useless if the cameras do not record and timestap their outputs simultaneously.

4.1.4 Interfaces & Analysis

Some of the core interfaces to be considered in the diagnostic are outlined in an N^2 diagram in fig. 4.5.

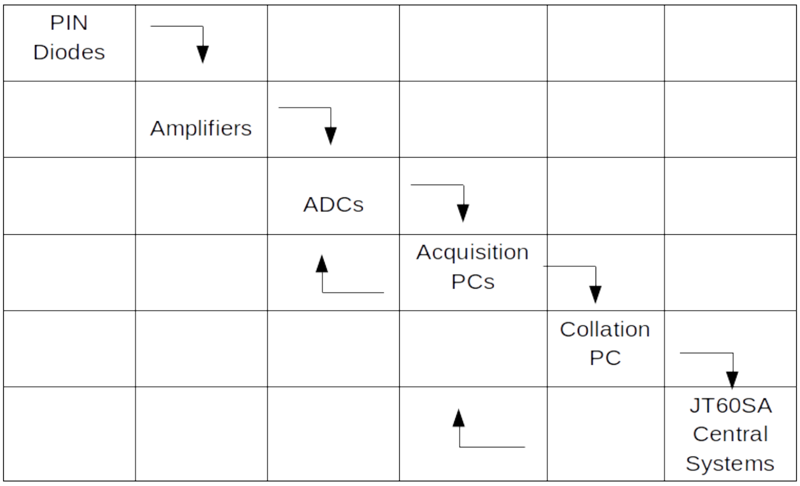


Figure 4.5: N^2 Diagram for the data acquisition system

The output from the first acquisition stage of the diagnostic will be a relatively low voltage analogue signal. There is a great deal of work which needs to be done to turn this input signal into a digital dataset which can be analysed and turned into useful science. Much of this can be entirely automated and does not need human input, and the electronics/code required to do this should be done in advance.

There are also many peripheries which can be implemented to optimise the use of the diagnostic. This aspect of the diagnostic is vital to efficient operation, but is not so restricted by cost and timescales as the rest of the system. Examples of jobs which need to be completed in this final stage of diagnostic installation are:

- data transmission and routing
- analysis routines
- remote handling architecture

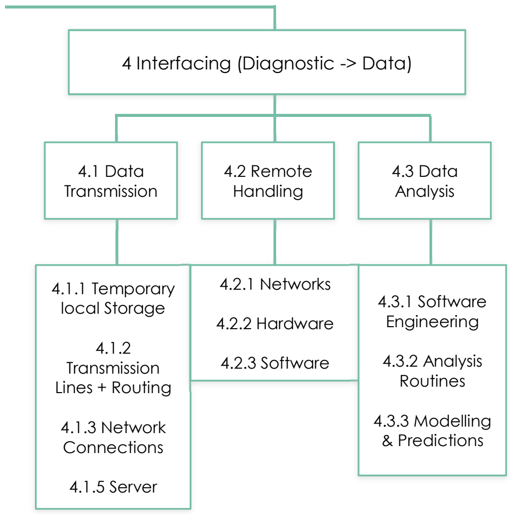


Figure 4.6: The Interfaces and Analysis Phase of the WBS

Data Transmission

The electronic signals produced by the photodiodes will need to be converted into digital data files and stored on the local network. This will involve digitising the signals and developing an automated routine which creates and saves a data file to a prescribed hard drive. As the data is being collected it will be stored in an intermediary buffer hard drive. At the end of the experiment, this data will be saved and transmitted to a long term storage hard drive. Each of these stages will need to be completed automatically and reliably. This will involve writing the subroutines to handle the data as it comes in from the diagnostic as well as automating the transfer of data without any loss. It is likely that it will be possible to extend the existing data handling routines at JT-60 to include our diagnostic without requiring too many alterations, and this can be done separately to the installation of the diagnostic with no need for the tokamak to go through a period of shut-down. It would even be possible to set up a mock diagnostic to simulate the creation of data. This would allow for the development of this system to be performed entirely separately from the physical installation of the diagnostic itself. In this respect, the data handling routines should not be a limiting factor in the completion timeframe of this proposal.

Remote Handling

To optimise the data available from this diagnostic it will (among other things) be necessary to have deployable radiation shields and orientable pinhole cameras. In the radioactive environment of a tokamak reactor, this cannot be done by human intervention. As such, the diagnostic must be equipped with remote handling capabilities. This will involve installing motors and actuators on the diagnostic, which must be done in-line with the rest of the diagnostic installation. The software used in the control room will need to be updated to include these systems, which will involve calibration of the motors and the creation of new electronic pathways between the control room and the tokamak. As with the data transmission lines, these are pre-existing connections which need only be modified to include our diagnostic, but they will have to be modified nonetheless.

Data Analysis

Once the data transmission lines are in place and the diagnostic is in full working order, the only task left to complete is the conversion of raw data into publishable science. This is a somewhat open-ended section of the work breakdown structure since it is likely to never be completed. There are, however, some aspects which can be finished in advance. Turning the input data from the pinhole cameras into a tomographic map is something which can be done by a dedicated piece of software. This can be written as soon as the input data format is known. There is also a level of modelling which must be done to explain/predict the observations. While this is going to be a continually evolving process, the starting point for the model should at least be established and some preliminary predictions made before the first set of results comes in. With a solid foundation, both in terms of analysis software and physical models, the diagnostic will not only provide useful science from day one but will also have the freedom to grow and adapt as the data comes in, unveiling new areas of physics which have been unobserved to date.

4.2 Timetable

Our plan to install this diagnostic system upgrade on JT60SA must fit the timetable of the upgrade itself. To this end it is helpful that the design is relatively well understood as well as simple. A proposed schedule of deadlines to be met in order to achieve all elements of the work breakdown structure within this time limit can be found in the Gantt chart at figure 4.7. This has been designed to superficially highlight stages of the project for resource allocation and not as an exhaustive guide to tasks to complete per the WBS.

As can be seen, two features supervene on the whole project. The first is the current upgrade schedule and its milestones. The second is the need to maintain coherent management and ancillary functions throughout our project. Since the overall upgrade involves many systems we do not propose to do anything other than the management ourselves and will use the teams in place for the larger project for finance function etc.

The upgrade schedule affords us significant opportunities to test and calibrate the device once installed. We can take advantage of additional slack in our project timeline by working on the IT systems in tandem with developing the detector hardware, so long as both are installed by the time of tokamak assembly. We have given a generous time allocation (given the installation deadline) for the project to initialise and the design/ prototype of soft x-ray detectors to be adapted for JT-60SA. If this can be achieved quickly then we can move to procurement sooner. This would free up more time for the tightest part of this schedule the construction of detector units. To limit the fte hours needed for this we are not building all of them simultaneously. It may prove more reasonable to assume later units will require less time to build and test than the first.

Milestones and Critical Path

To summarise the essential order of tasks and non-negotiable deadlines: We cannot purchase components until a design of detectors is finalised. We must have taken delivery of the bulk of components (not computer hardware) before constructing units can begin. Construction of all hardware must be final and installed by the time the tokamak is sealed at the end of 2018. First plasma in 2019 is a critical project milestone that will allow us to test the hardware and data and control systems. The project will close at the end of 2019 as the tokamak begins its research programme.

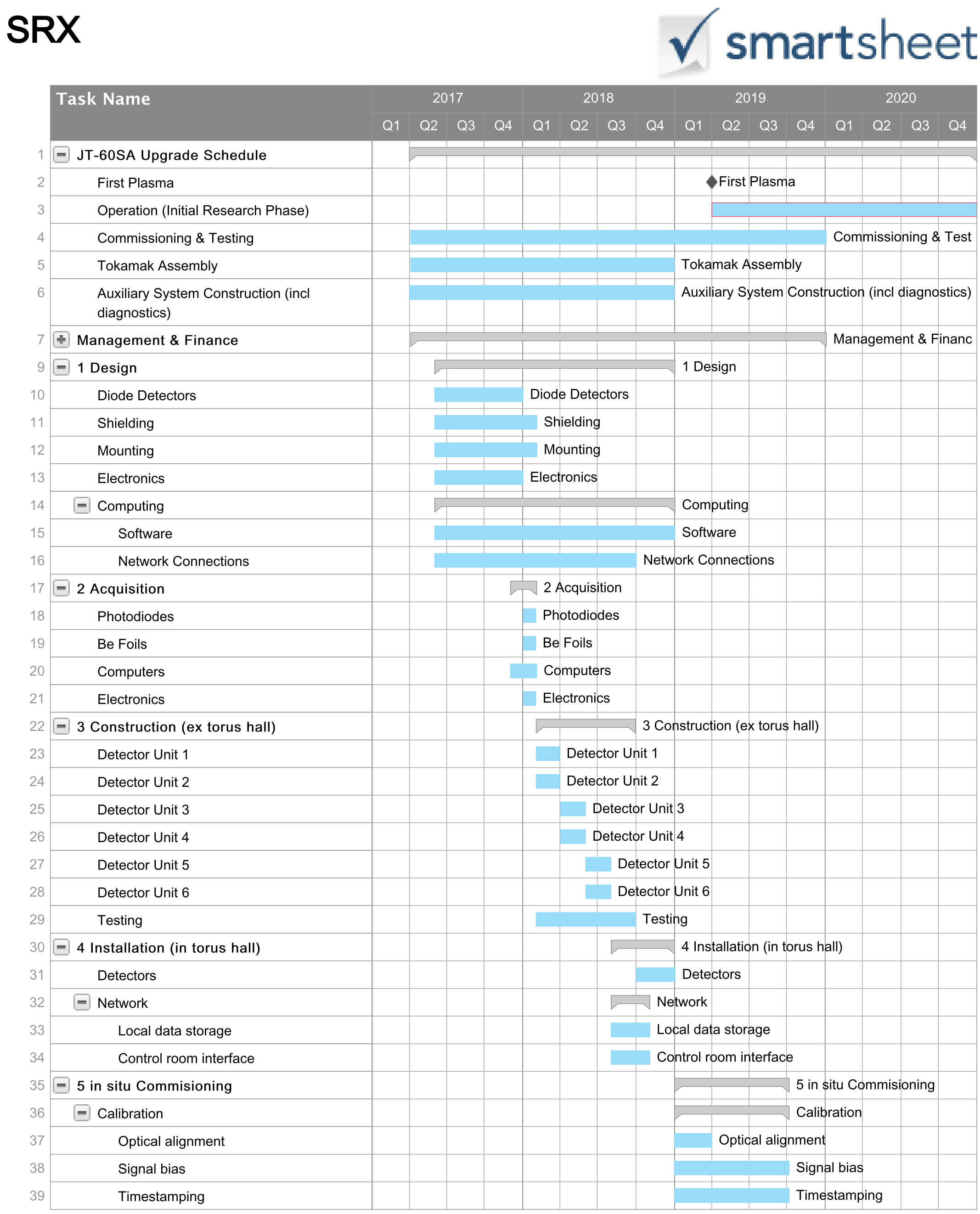


Figure 4.7: The proposed project timeline for JT-60SA SXR Diagnostic

4.2.1 Tracking and Closure

By continuing to manage the project through to the completion of commissioning and handing over control to the research teams we can ensure that all issues are addressed in a timely fashion. The project management team will need to make sure tracking takes account of personnel changes at the various stages of the project as designers hand over to engineers. Stages such as acquisition, with a thorough paper trail, will be straightforward to track. Albeit to a lesser extent, progress during construction will be manifestly obvious and requires only strong upwards communication. The design stage will require regular contact and setting of sub-deadlines to ensure completion on time. Management should be mindful of future pinch points and so aware when monitoring progress of any scope to advance the timetable (as described above.) Distant deadlines cannot be a reason to slow the pace. Tracking will also have to report upwards when working in the torus hall to satisfy the demands of the JT-60SA management team.

Closure will come at the end of the commissioning phase (after first plasma) when the control system is handed over to researchers. It will be important to have calibration data and detector handling training available for this stage. We will then conclude with a register of changes to the design/ timetable evaluated against the risks set out in this report to ensure that the project is accountable and can provide insight to future diagnostic upgrade efforts.

Change Management

To achieve this schedule we will have to manage material (by scale or type) impacts to the proposed timetable either delays or changes of project scope effectively as they arise. If it appears that any of the milestones will be missed or that we will have to adapt the functionality set out in the technical specification of this report, because of difficulties encountered by either this project or the tokamak upgrade, we will convene a (minuted) meeting of the project management team. This meeting will include designers and/or engineers as appropriate to that stage of the project. The purpose of the meeting in the first instance will be to discover any potential fixes to the problem that can be effected by adding the leverage of senior management (for example additional resourcing or pressure on external agents.) Failing that, we will produce a revised schedule reflecting necessary changes. Any changes to the delivery of the diagnostic will be recorded in a project log as well as immediately communicated to the tokamak upgrade team.

4.3 Cost Analysis

4.3.1 Top Down from WBS

Here we consider a top-down estimate of costs - primarily looking at the top levels from the work breakdown structure. Consideration is required of both direct and indirect costs incurred by the diagnostic. This then provides a groundwork for the full cost analysis below.

Area from WBS			
Planning and Project Management	Construction and Acquisition	Installation and Calibration	Interfacing Diagnostics to Data
Health and Safety Contractor to ensure project meets H&S requirements.	Engineers for construction of diagnostic	Engineers for installation	Data storage facility
Hiring an R/O for the diagnostic	Optical Equipment	Engineers for calibration	Server storage space
Project Manager	Data acquisition components	Risk assessment officer	Software required for data analysis
Insurance for specific components	Software for data acquisiton		Systems engineer for interfacing
Electrical design of pre-amplification circuit /electrical circuits	Detector (photodiodes), scintillator and external casing		
Finance Team	Specialist window for port		
Drawing office time (for CAD modelling etc.)	Quality assurance that parts meet specification		

Table 4.1: Top down approach to costing, using the top level headings of WBS. Direct costs are shown in blue and indirect costs in green.

4.3.2 Total Cost Breakdown

Staff Costs

Table 4.3 shows the costing analysis for staff required to run the diagnostic, which is the most costly part of the project. It would be useful if some technical staff and engineers could be from JT-60SA, as this would reduce staffing costs. The salaries are calculated pro-rata, as some staff will not spend all of their time on this specific diagnostic. Other staff such as the project manager would be required for the entirety of the project.

Diagnostic Equipment Costs

A substantial fraction of the budget is to be spent on the data acquisition system. This is due to savings made by choosing the photodioide set up which is significantly cheaper than the alternative CCD camera approach. Quotes for both the photodiodes and CCD camera are in the appendix.

4.3.3 Unforeseen Expenditure

Unforeseen expenditure can occur within any of the areas within the work breakdown structure. Of particular note, changes in the JT60-SA scheduling or plans for the upgrade could cause unforeseen expenditure for the diagnostic. Alterations such as an increase

WBS Overhead	Required Staff	Job/Purpose	Time (years)	Salary (Annual)	Total Cost
Project Management	Project Manager	Oversee Project	1.5	£42,000.00	£63,000.00
	Liason to JT-60SA	Technicalities of JT-60SA and diagnostic	1.5	£24,000.00	£36,000.00
	Finance Manager	Oversee budget/wages etc.	0.33	£38,000.00	£12,540.00
	Risk Management Officer	Oversee risk assessment and assurance project meets safety standards	0.08	£29,000.00	£2,320.00
Planning (Physics Case)	Physicist (Simulation)	Map diagnostic to theory	1.5	£34,000.00	£51,000.00
	Physicist (Experiment)	Understands how to build and put the diagnostic together	1.5	£34,000.00	£51,000.00
					£0.00
Acquisition	Sales Co-ordinator	Liases with companies for acquiring diagnostic equipment and items for technical staff	0.16	£20,000.00	£3,200.00
	Courier	Transporting goods (Possibly external to reduce costs)	0.08	£18,000.00	£1,440.00
Construction, Installation & Calibration	Mechanical Engineer	Diagnostic assembly	1	£25,000.00	£25,000.00
	Electrical Engineer	Diagnostic assembly	1	£25,000.00	£25,000.00
	Physicist (Simulation)	Diagnostic assembly	1	£34,000.00	£34,000.00
	Physicist (Experiment)	Diagnostic assembly	1	£34,000.00	£34,000.00
	JT-60 Technicians	Diagnostic assembly	1		
Interfacing	Data Acquisition Specialist	DAQ assembly and maintenance	0.5	£23,000.00	£11,500.00
	Quality Assurance Specialist	within technical specifications and the diagnostic meets it's requirements		£27,000.00	£0.00
Close off	Project Manager	Required just after diagnostic is built to discuss the project as a whole		N/A	
				TOTAL	£350,000.00

Figure 4.8: The table includes the required staff and their duties for the entire project.

Diagnostic Component	Cost	VAT (per item)	Quantity	Total Cost
Hamamatsu Photodiode	£67.10	£13.42	12	£966.24
Beryllium foils (0.05mm)	£497.46	£99.49	6	£3,581.71
Be foil (corrosive/toxic materials handling fee)	£120.00	N/A	12	£1,440.00
Photodiode mounting	£40	N/A	12	£480
Data acquisition board	£800	£160.0	12	£11,520.0
DAQ PC - advantech PCI-1714UL	£3,000	Inclusive	6	£18,000
BNC Connectors	£6.99	Inclusive	80	£559.20
Ethernet Cables (Cat6/7)	£8.00	Inclusive	6	£48.00
Gigabit ethernet switches	£139	Inclusive	6	£834
3TB Hard Drive (12Gb/s)	£209.95	(Inclusive)	6	£1,259.70
Import duty (US to UK)	£203.70	N/A	1	£203.70
Import duty (Japan to UK)	£33.82	N/A	1	£33.82
			TOTAL	£38,926.37

Figure 4.9: Total costs, including VAT and import duty for each individual diagnostic component.

in neutral beam heating power, running a deuterium-tritium campaign could affect the lifetime of the diagnostic. Unforeseen replacement of parts could be an issue due to radiation damage, though with quality assurance and risk assessment the probability of this occurring should be low. Any late deliveries for diagnostic parts could delay the schedule and incur indirect costs via extension of staffing hours to be paid. Import tax, VAT and delivery must be paid on all items, which can increase costs particularly when shipping and importing electrical goods from abroad. Finally, one particular unforeseen cost which arose whilst estimating component cost was an additional corrosive/toxic material handling fee imposed upon the beryllium foils, coming in at around half the cost of the foil itself. The width of the foil also scaled the cost considerably, therefore 0.5mm was chosen as the best cost to efficacy ratio.

4.4 Risk Assessment

A risk assessment is developed by the likelihood (L), impact (I) and likelihood-impact product (L $\times$ I). The level numbers in table 4.2 measure how easily the risk will occur and how dangerous the risk will be. Colours given by likelihood-impact product in table 4.4 highlight the level of the potential hazard. Some risks are given along with their likelihood, impact, effects and mitigation methods in table 4.5.

Table 4.2: Likelihood of risk description

Level	Destination	Definition
Low (Grade 1)	Rare (10%)	Occur in exceptional circumstances
Medium (Grade 2)	Possible (20%)	Might occur
High (Grade 3)	Likely (50%)	Quite likely to occur
Very High (Grade 4)	Highly likely (75%)	Will almost certainly occur

Table 4.3: Impact of risk description

Level	Destination	Definition
Low (Grade 1)	Insignificant/Minor	Minor change to functionality requiring remedial action.
Medium (Grade 2)	Moderate	Some functionality is compromised requiring review and possible change to meet requirements.
High (Grade 3)	Major problem	Major risk of failure to meet requirements.
Very High (Grade 4)	Catastrophic problem	Instrument will not meet any of the requirements and is effectively of no use.

Table 4.4: Likelihood-Impact product L ×I

Impact → Likelihood ↓	Low 1	Medium 2	High 3	Very High 5
Low 1	1	2	3	5
Medium 2	2	4	6	10
High 3	3	6	9	15
Very high 4	4	8	12	20
	Cat L	Cat M	Cat H	

Table 4.5: A list of potential risks along with the mitigation methods

Risk Description	L	I	L× I	Quality effect of risk	Mitigation	L	I	L× I
Finding enough spaces above the inboard, high-field side for all detectors	3	5	15	Lack of comparing data as they are not installed completely.	Negotiate with other diagnostic groups.	1	5	5
Fail to position the detectors to achieve the cross-section coverage	3	5	15	The measurement is invalid as it will not perform the designed diagnostics.	Give extra time on detector positioning and test before DT experiment start.	1	5	5
Detector unit and pinhole damages from the neutron radiation and high magnetic field.	3	4	12	Repairing or repurchase the damaged unit will increase the cost and hinder the progress on the project.	Steel case design is used for each detector unit to guarantee the lifetime of components.	1	4	4
High temperature effects on photodiode characteristics	3	3	9	This might give the unreliable data and misunderstanding in physics analysis.	Have back-up components ready.	2	3	6
Delay of JT-60SA upgrading programme	1	3	3	The project will not complete as it is planned.	Keep up to date with the upgrading programme and adjust the schedule accordingly.	1	3	3
Late delivery of equipment	2	3	6	The diagnostics cannot be tested and the entire project will be postponed.	Give more time for delivery.	1	3	3

4.5 Quality Assurance

In order to assure that our product is built according to its specifications and relevant regulations a quality control system will be implemented. This quality control system will be in accordance with ISO 9001:2015. A key component of the quality control system will be regular design reviews. All work will be reviewed and monitored so that key deliverables will meet deadlines and that any delays or issues can be identified early in the design process. This review process will ensure that not only progress towards deliverables can be monitored but so too can the budget and resource allocation. It will also allow the scope of the project to be tracked and controlled.

Bibliography

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[3] S. Von Goeler et al, *Thermal X-Ray Spectra and Impurities in the ST Tokamak*, Nuclear Fusion, **15**.2, (1975) 301.

[4] J. Clementson et al, *Atomic Data of Tungsten for Current and Future Uses in Fusion and Plasma Science*, AIP Conference Proceedings, **1525**.1 (2013) 78-83.

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Chapter 5

Individual Contributions

5.1 Adam Dempsey

Specified data acquisition and handling systems. Carried out in-depth design of detection circuitry for use in the diagnostic in the form of the detector/pre-amplifier board. Quality assurance and collaboration on interfaces.

5.2 Sam Gibson

Project manager role, divided up tasks and collaborative editing of document with Andrew Malcolm-Neale/referencing. Wrote section on the detector for the diagnostic/RF shielding. Contacted companies for quotes to ensure the detector would realistically meet our requirements. In management plan wrote cost analysis for the diagnostic.

5.3 Andrew Malcolm-Neale

Wrote scope section of physics case in line with push for a tomographic detector. Noted JT60 could be upgraded and looked at port access. Worked on optics throughout in particular wrote the Line of Sight and Filters/shielding sections of the tech specification (with input from cost and detector/data authors on number of units.) Wrote project schedule per timetabling in management plan and associated management/change sections. Editing, some proofreading, minimal Latex skill.

5.4 Andrew Smith

Researched and wrote the Physics Case & Work Breakdown Structure/management plan for the diagnostic. Worked with Andrew Malcolm-Neale & Sam Gibson to identify items from the WBS to be used in the cost analysis and Gantt chart.

5.5 Tiantian Sun

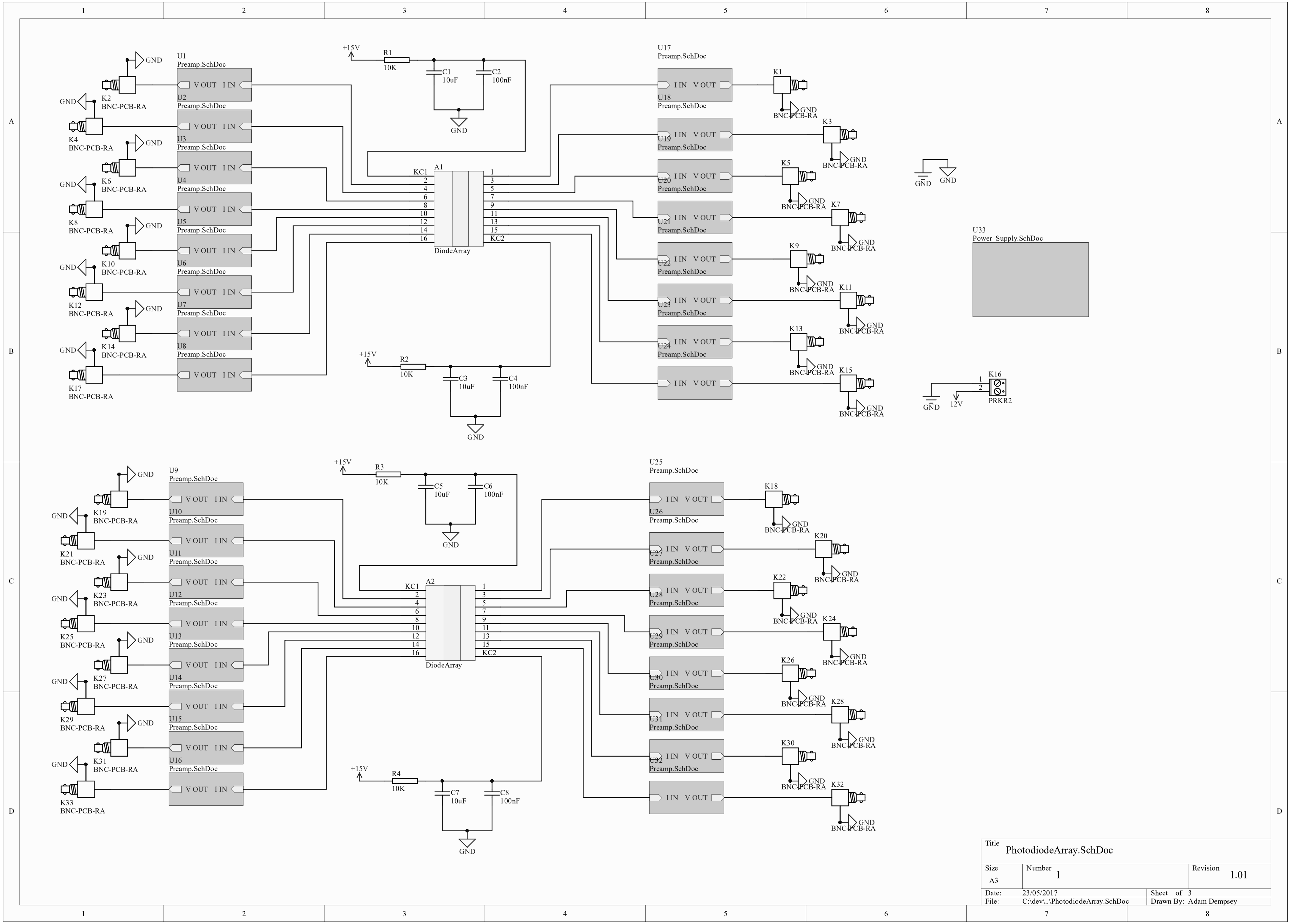
Responsible for the introduction of JT-60SA, the motivation, the scope, and the risk assessment.

Chapter 6

Appendix

6.1 Electrical Design

The following design documents describe the first revision of the detector/pre-amplifier board. This board has been designed as per the design-documents associated with the constituent components. The board is currently in a state suitable for manufacture, assembly and testing. The board should output a 0 to 1V signal on each BNC connection for each photodiode segment.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Revision 1.01
Date: 23/05/2017
Sheet 3 of 3
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A2 DiodeArray
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R3 10K
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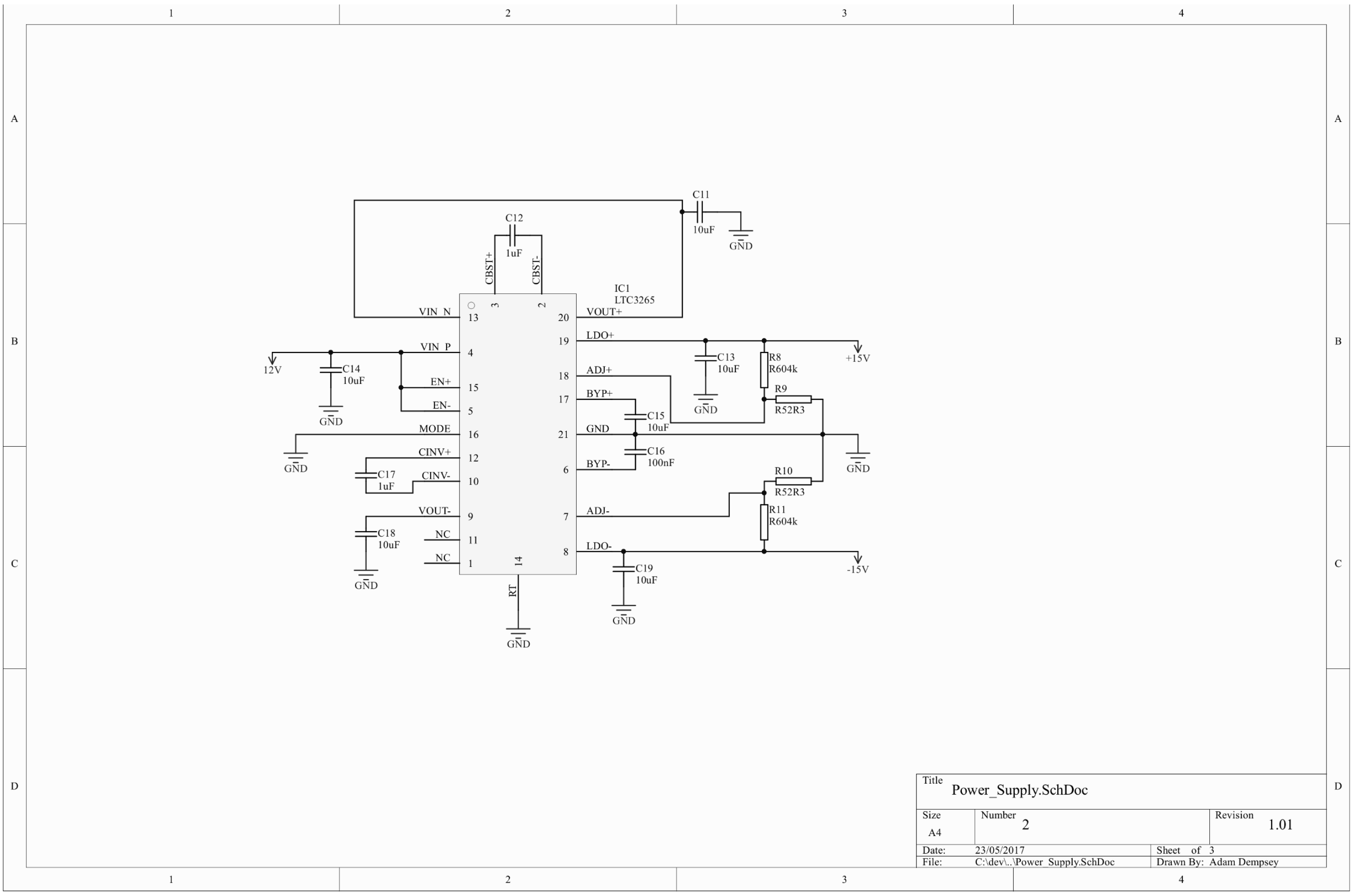
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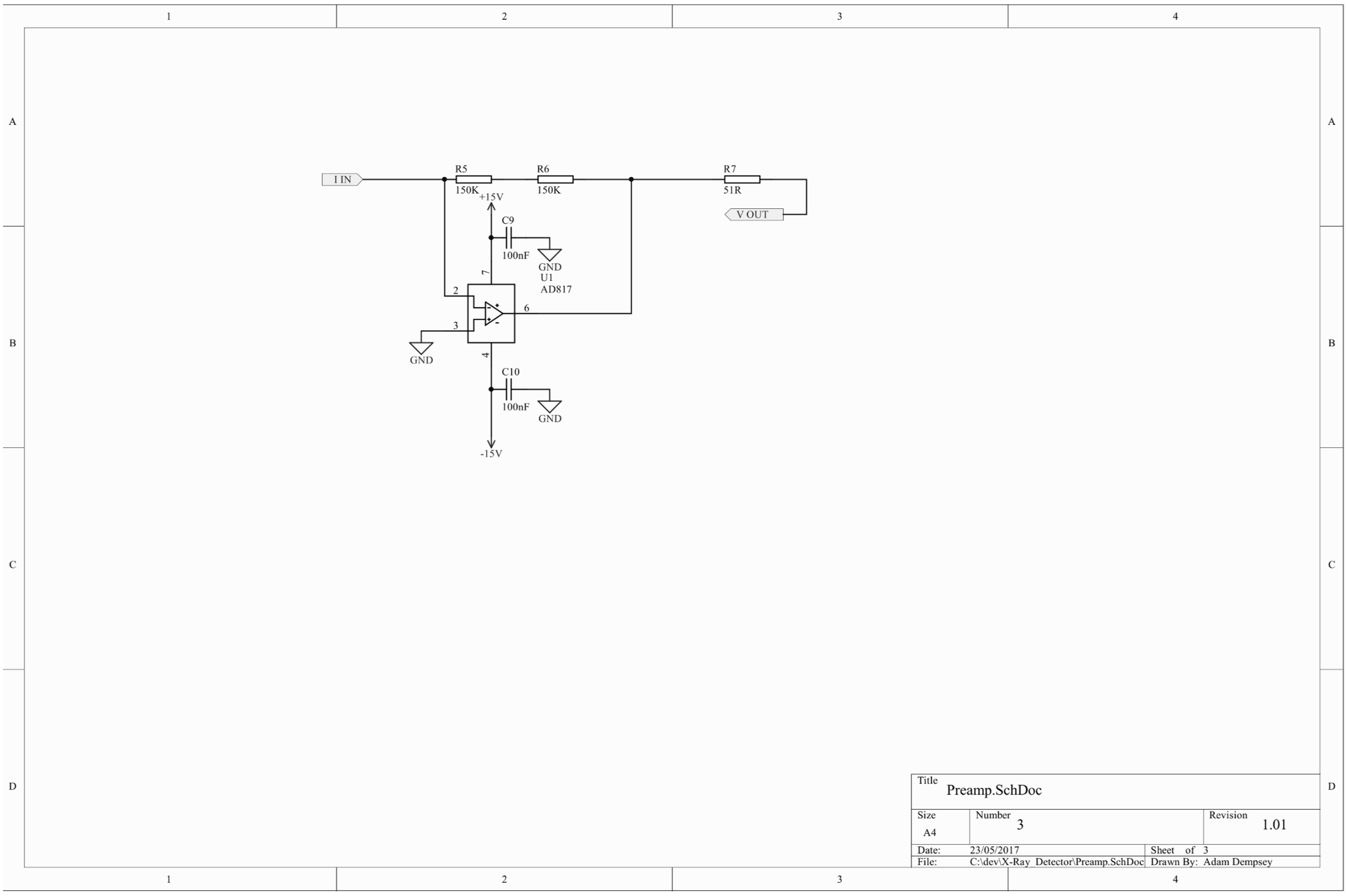
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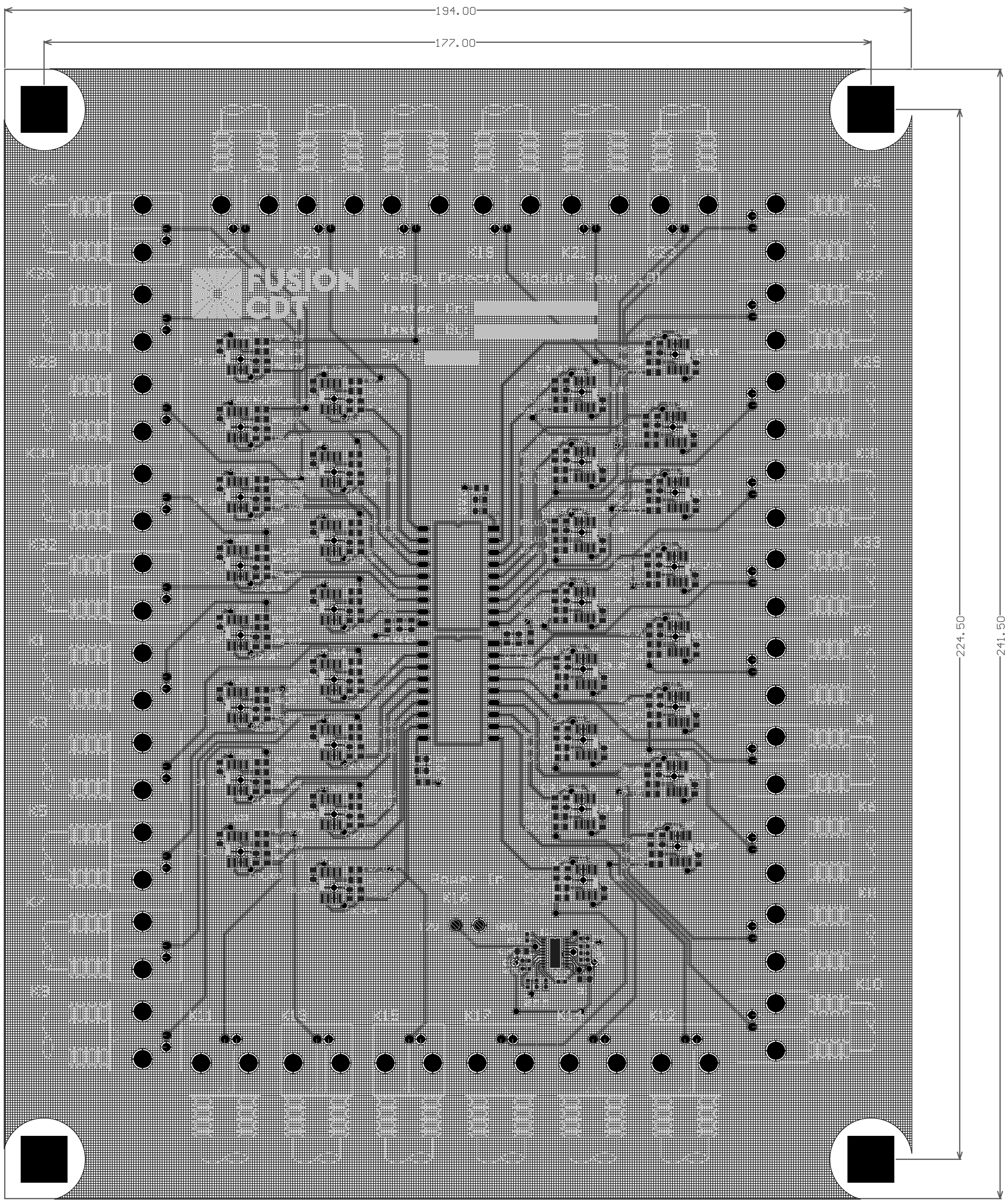
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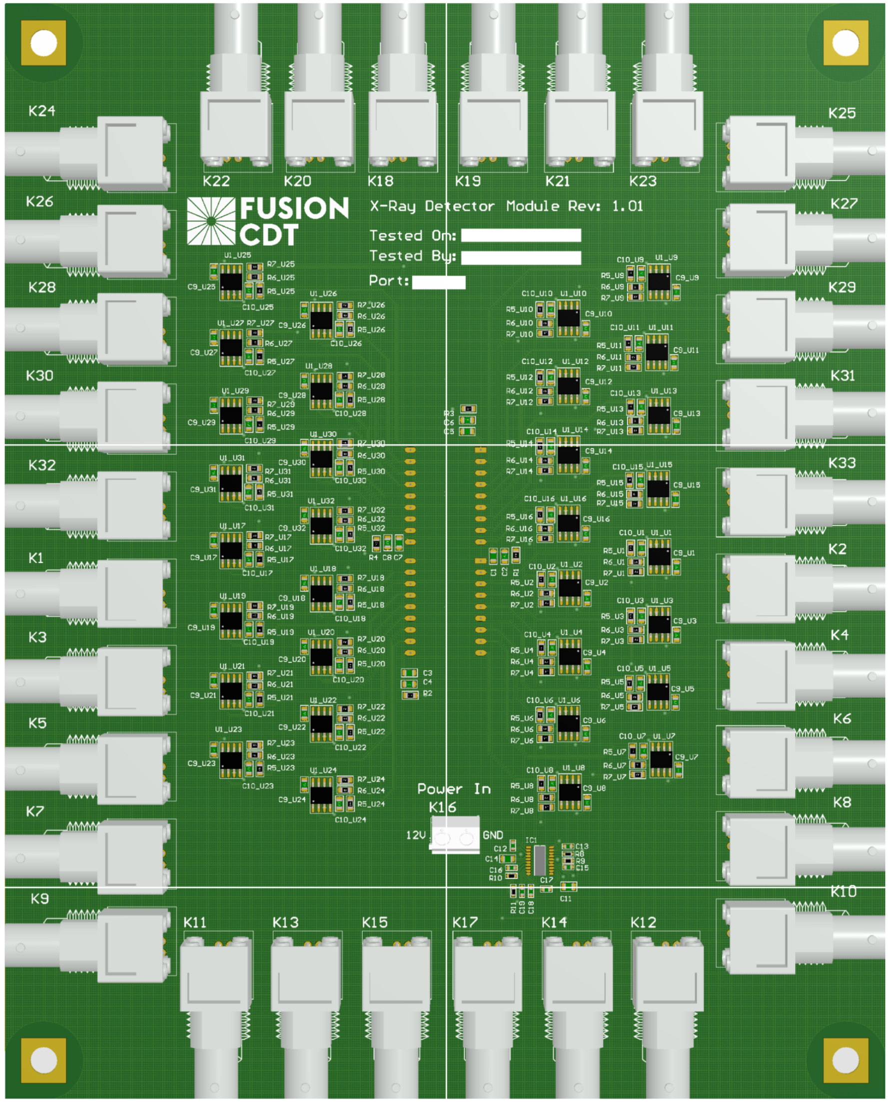
Tested By:
Port: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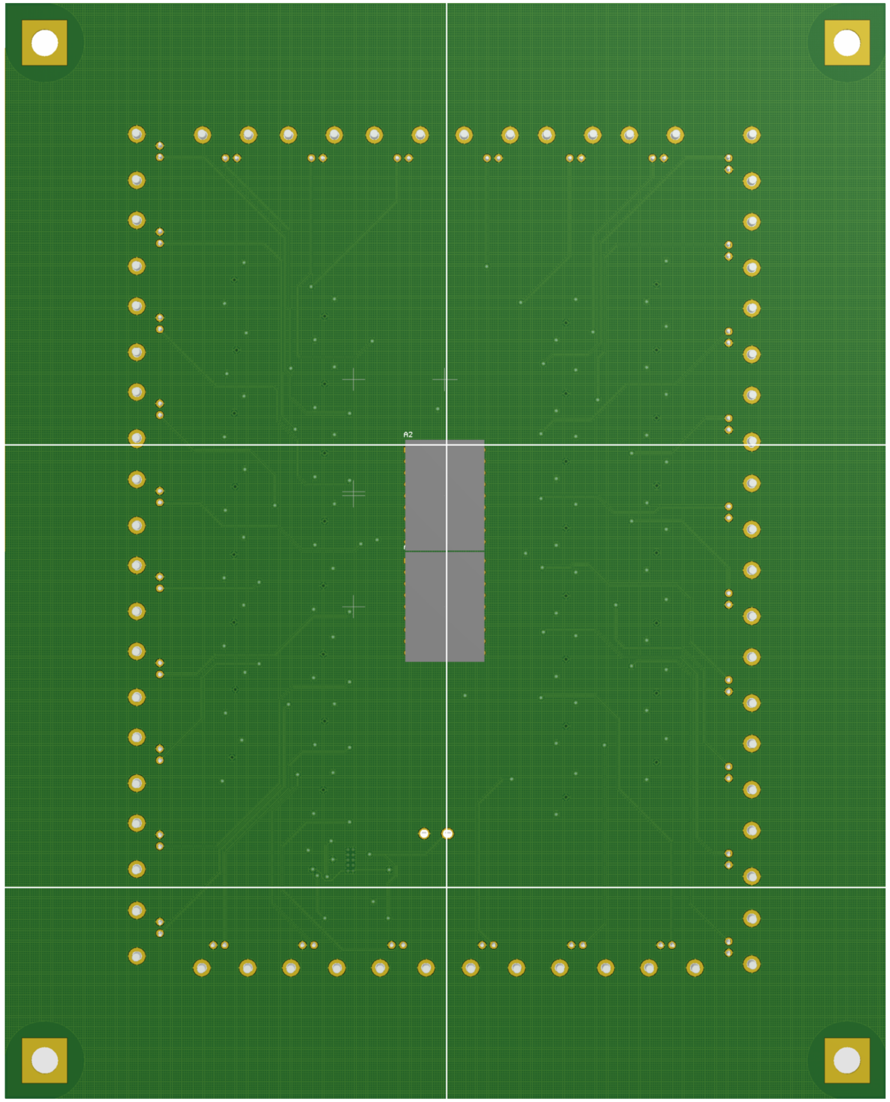
A2

6.2 Costing and Quotes

Prices quoted for photodiodes compared to a CCD camera.

Princeton Instruments

25 Nuffield Way
Abingdon
Oxfordshire
OX14 1RL

Customer Details:

Contact Name Sam Gibson
Account Name Durham University
Bill To
Durham,
United Kingdom
Phone 07397227666
Email sam.gibson@durham.ac.uk

Princeton Instruments Details:

Created Date 5/2/2017
Expiration Date 5/31/2017
Sales Inquiries Harish Sinha
hsinha@princetoninstruments.net
+44 07810835719

Quote Number 19559

Line Number	Product	Product Description	Price	Quantity	Total Price
1	PXO-100B	Princeton Instruments PIXIS-XO:100B Digital CCD Camera System • Exclusive CCD36-00 scientific grade 1, back-illuminated, NoAR, AIMO CCD • 1340 x 100, 20 x 20 um pixels (26.8mm x 2mm image area) • Thermoelectric Peltier cooled with forced air • Dual speed read out, 16-bit, 2 MHz and 100 kHz • USB 2.0 interface with 5 meter USB cable	£ 33,766.00	1.00	£ 33,766.00
2	LF	LightField Acquisition software with built-in Math Engine • Full acquisition support for Princeton Instruments cameras and spectrometers • Built-in math engine for real time and post-acquisition analysis • Improved user experience • Integrated LabView and Matlab support - samples provided • Supports IntelliCal - accurate and easy intensity and wavelength spectral calibration (light sources sold separately) • Free 1-yr maintenance upgrades	£ 3,730.00	1.00	£ 3,730.00
3	Delivery		£ 240.00	1.00	£ 240.00
4	VAT (20%)		£ 7,547.20	1.00	£ 7,547.20
Grand Total					£ 45,283.20

All prices in GBP
Sales tax and shipping charges will be added where appropriate
Payment Terms: Net 30

Please complete the End User Statement and
include it with your signed purchase order.

REGISTERED IN ENGLAND # 2509935 A DIVISION OF ROPER INDUSTRIES LIMITED (Registered Office) Fifth Floor, 9/10 Market Place, London, W1W 8AQ Local Office: 25, Nuffield Way, Abingdon, Oxfordshire, OX14 1RL http://www.princetoninstruments.com VAT Reg. No. GB 571 0884 35

Re: [Hamamatsu WEB] Inquiry (Receipt Number: 161348)

K ktalbot@hamamatsu.co.uk
Mon 08/05, 09:00
GIBSON, SAM

Reply all

Inbox

Action Items

Dear Sam,

Thanks again for getting in touch. For this photodiode array costs £67.10 per pc (before VAT and delivery), but does decrease in cost at certain quantities. If this pricing works for you, could you let me know how many arrays you would require and I will send you a full quotation through.

Best regards

Kane Talbot
Internal Sales Engineer

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We received the following inquiry on our HAMAMATSU web site.
Please follow up on your side.

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[Inquiry Information]
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Receipt number:161348
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