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Power distribution for silicon detectors

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Power distribution has become a critical design issue for the next generation of silicon detectors being planned. The reasons for this are examined, giving examples of power distribution problems in the present Large Hadron Collider. Options are discussed for implementing power distribution at higher voltage in future detectors.

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1. Introduction

The silicon detectors of ATLAS [1] and CMS [2] at the Large Hadron Collider (LHC) make extensive use of low voltage integrated circuits in the sensitive volume, which requires a large amount of power to be distributed in a region where mass must be minimized. The pixel detector of ATLAS, for example, has a combined low voltage current of 4kA in 0.2 m^3 volume. This current is supplied from nearly 100m away due to large size of the full detector. The allowable voltage drop in the directly connected supply cables is limited by the combination of power supply technology and the maximum voltage rating of the 0.25µm feature size IC electronics, such that transients are not capable of causing damage. Linear voltage regulators are used in the distribution chain to "break" the cable plant into two segments: a ~90m run with large allowed voltage drop, and a ~10 m run connecting to the detector where the voltage drop must be limited.

The implementation of "direct" power distribution in such a situation requires pushing to the achievable limit the interconnection density, using complex cable assemblies whose cost begins to rival active components. Fig. 1 shows a composite picture of one end of the ATLAS pixel detector service connections. Most of what can be seen consists of power supply cables and cooling pipes, with a 40cm diameter aluminum endplate visible near the left end. The pixel detector itself begins just off the picture to the right. The distance between the endplate on the left and the detector to the right is ~2.5m. The aluminum endplate is an environmental gas seal through which must pass 2KA supply and 2KA return current, the accelerator vacuum beam pipe, 140Gb/s data, 5KW of cooling, and independent high voltage and temperature sensing for ~900 elements.

Figure 1: Composite image of service connections for one of the ATLAS pixel detector.

The costs of direct power distribution in such systems (beyond a high price tag) are an increase in mass and a decrease in reliability. The reason reliability is affected is that the available space for services other than power is necessarily reduced, which forces the use of higher density interconnects with minimal or no redundancy. The mass penalty is illustrated in

Fig. 2, which shows a calculation of the radiation thickness seen by particles traversing the ATLAS pixel detector. The contribution due to the active components is clearly dwarfed by “Services” and “hybrid + cables”. In this figure the “hybrid + cables” category includes only the innermost ~1m run of cables, while cables further out are included in “services”. The “support structures” category does not directly include cables, but it is affected by the need to route and support cables.

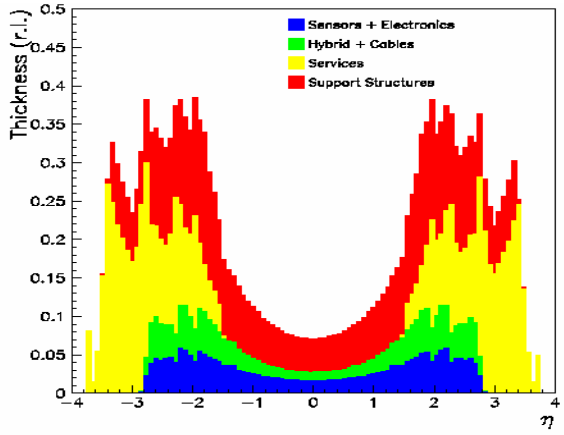

Figure 2: Calculation of radiation thickness of the ATLAS pixel detector vs. pseudo-rapidity (η). Only the blue area is due to active components.

The ATLAS pixel example is representative of the present generation of both pixel and strip silicon detectors at the LHC, where the impact of power distribution has been more serious than anticipated in the original designs. The cause of this general problem has been a confluence of several factors. The growth trend in channel count and data rate of collider detectors is exponential with time for data rate and somewhat slower for channel count [3]. The data rate growth follows Moore’s Law, which at the same time brings a decrease in operating voltage of the integrated circuit electronics. Finally, the physical size of detectors also increases, making cable runs longer. In a direct delivery system the power efficiency is given by the ratio of the load resistance to the sum of load plus cable resistances. The latter quantity scales like the cable run length, while the former scales roughly like the integrated circuit operating voltage (this applies to analog applications where the specific transconductance does not improve with decreasing feature size, as is the case for deep sub-micron CMOS). Since both voltage decrease [4] and detector size increase are roughly linear with time, the direct delivery power efficiency must drop quadratically. Direct power delivery was not an issue for the previous generation of silicon detectors, gives rise to an important material penalty for the LHC detectors, and will no longer be viable for the next generation.

2. Power consumption and delivery efficiency

A large operating power compounds the power delivery efficiency problem, but the two are problems independently of one another. With low power delivery efficiency, fast load current changes lead to voltage swings that can be large, depending on the compensation and/or crow-bar capabilities of the power supplies used. This is an issue for deep sub-micron IC's even in a low power case. The problem of transients would be especially important in a pulsed system where the average power is kept low by operating with high peak power but for short periods of time, as is proposed for International Linear Collider applications [5]. While reduction of IC power and therefore cooling load remains a critical problem (beyond the scope of this paper), it is an independent problem from power delivery, and strategies to address one do not necessarily help the other.

The problem of electrical power delivery over long distances is as old as the electric power industry, yet the only practical solution remains to transport the power at higher voltage, transforming it to a lower voltage at the point of use. Fig. 3 shows the projected power efficiency for a next generation ATLAS pixel detector as a function of power conversion ratio, including an estimated power conversion efficiency. The new detector under consideration would have twice the number of channels and lower voltage IC electronics (1.5V), but the space available for power conductors is the same. The red (top) curve shows the calculated efficiency keeping exactly the same cables as presently used, while the other two curves show the effect of decreasing the conductor mass in the last 10m of the cable run, which is desirable to improve performance. It can be seen from the figure that even a power conversion of 4 with modest 70% efficiency permits significant gains.

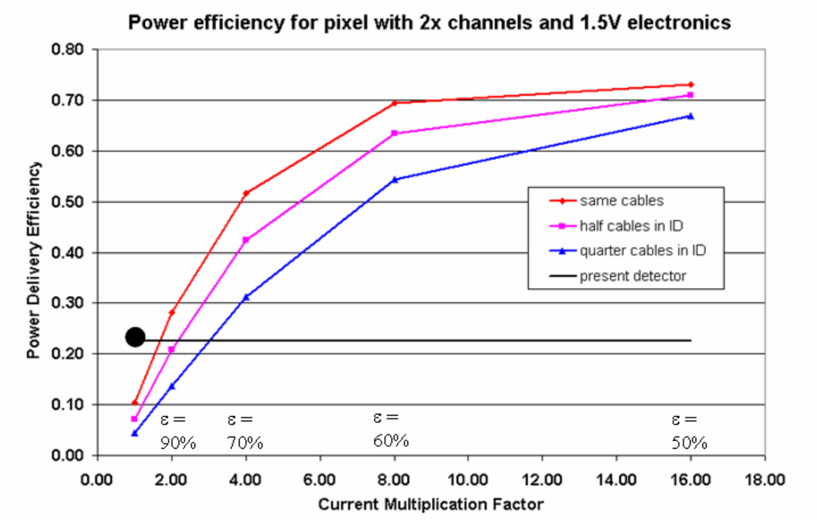

Figure 3: Projected power delivery efficiency for a next generation ATLAS pixel detector, compared to presently installed detector. The solid circle marks the efficiency of the latter, which uses direct power delivery (conversion factor is exactly 1). An efficiency has been assumed for each conversion ration as indicated.

There are several options for implementing power conversion. Magnetic DC-DC converters are widely used in commercial products, but need to be adapted to operate in a strong magnetic field and with high radiation dose [6]. Once adapted the efficiency of such converters will necessarily be reduced because ferromagnetic materials cannot be used, severely limiting inductor values. This reduced efficiency allows consideration of other possibilities that are not competitive in industry. Connection of multiple devices in series [7] and power conversion using switched capacitors [8] are not new concepts, but offer interesting advantages for detector applications.

Connection of devices in series or "serial powering" [9-12] is a natural way to achieve power conversion with a purely DC arrangement, without any switching. By chaining together N devices one increases the load resistance by a factor of N, while the cable resistance stays constant, thereby increasing the power delivery efficiency. In practice devices do not draw a perfectly constant current, and a voltage regulation scheme is therefore required for each serial stage to keep the current at the peak single device value (Fig. 4). This gives rise to an inefficiency which in prototype implementations is comparable to what can be achieved with DC-DC converters (see references). Nevertheless, serial powering is attractive because the required shunt regulators can be included in the readout integrated circuits themselves [13], making for a low mass and naturally radiation tolerant implementation. There are drawbacks, however, which include the need for shifting the logic levels of I/O signals, the management of floating sensor potentials, the lack of generality (serial power must be engineered into all components for every new system), and the complexity of control and fault tolerance for single devices within a chain.

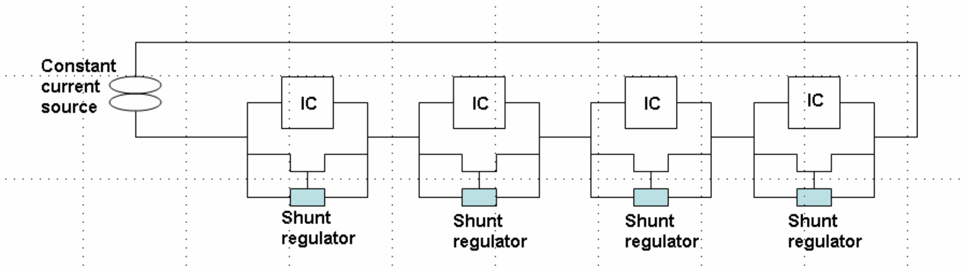

Figure 4: Diagram of serial powering setup with 4 devices.

Switched capacitor "charge pumps" are widely used commercially for low current voltage conversion- typically to increase or invert voltage- and are commonly used to drive display screens. However, they are not used for power delivery because magnetic converters are more efficient as long as high permeability materials can be used. On the other hand, capacitors are naturally compatible with the high magnetic field of particle detectors, and steady advances in miniaturization provide for low mass. Fig. 5 shows a switched capacitor arrangement with conversion factor of 4 that is simple to analyze [14]. The device can be operated at constant frequency and duty cycle for power conversion over a wide input range. The ideal device multiplies the load seen by the power source by the conversion factor, N, so that when placed near the real load the system power delivery efficiency is increased as a function of N in the same way as for serial power. In a real device the resistance of the switches used to alternate between phases A and B introduces an inefficiency. An additional inefficiency comes from current that is shunted to ground by the circuitry driving the switches, but this can be kept small by the choice of operating frequency (0.5MHz in ref. 14). At operating frequencies such that shunt current is not significant, the efficiency is limited simply by the switch resistance as long as the capacitors used are large enough that they charge and discharge linearly, which is easily achieved with present day surface mount components. Such converters have the advantages of being universal (can be easily incorporated in to new detectors) and of not spoiling the simple system architecture, with common grounds, common logic levels, and fine control granularity that has been historically used. The main disadvantage is that they depend on development of radiation tolerant, "high voltage" capable switching IC's. They may also not provide clean enough DC power unless followed by linear regulators.

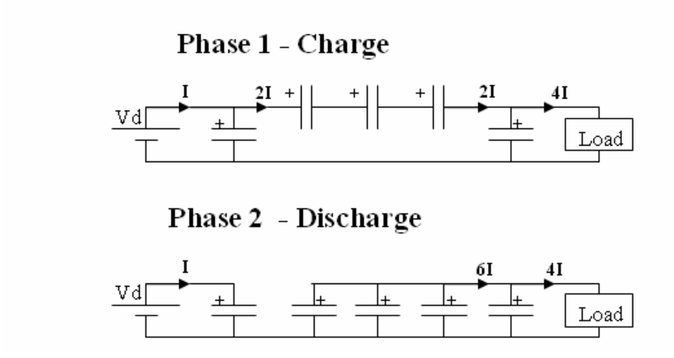

Figure 5: Diagram of x4 switched capacitor DC-DC converter topology from ref. 14.

3. Conclusion

Power distribution and power consumption have a major impact on reliability, cost and physics performance through the service plant mass and complexity. Therefore, full system design from an early stage must become a priority. For example, a lower mass sensor that may require slightly more power for readout may actually result in a higher mass system than a more massive sensor, when the full system is considered, including cables and power conversion.

While minimizing on-detector power consumption has always been a goal of silicon detector design, the independent issue of power delivery efficiency has proven more significant than anticipated in the present generation of detectors, and will be critical for the next generation. Methods for delivering power at higher voltage are presently being prototyped, including magnetic DC-DC converters, which is the industry standard, as well as capacitor charge pump DC-DC converters and series connection of devices, which, while well-known, are not found in commercial power applications. While the chosen method may vary, DC/DC conversion and/or serial powering will inevitably be a part of the next generation of LHC and other collider detectors.

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