Power Distribution, Cables, and Reliability

Vertex 2007

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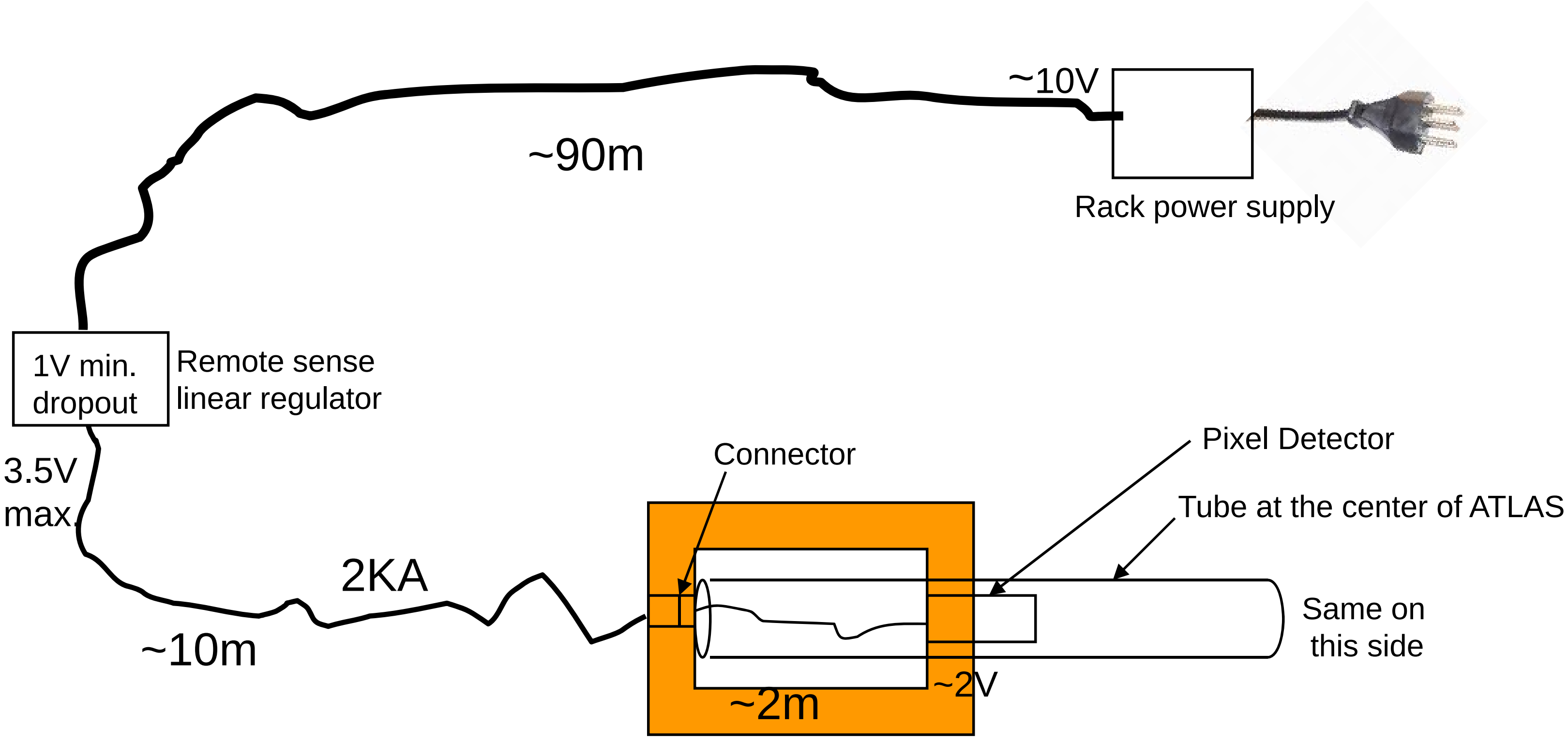
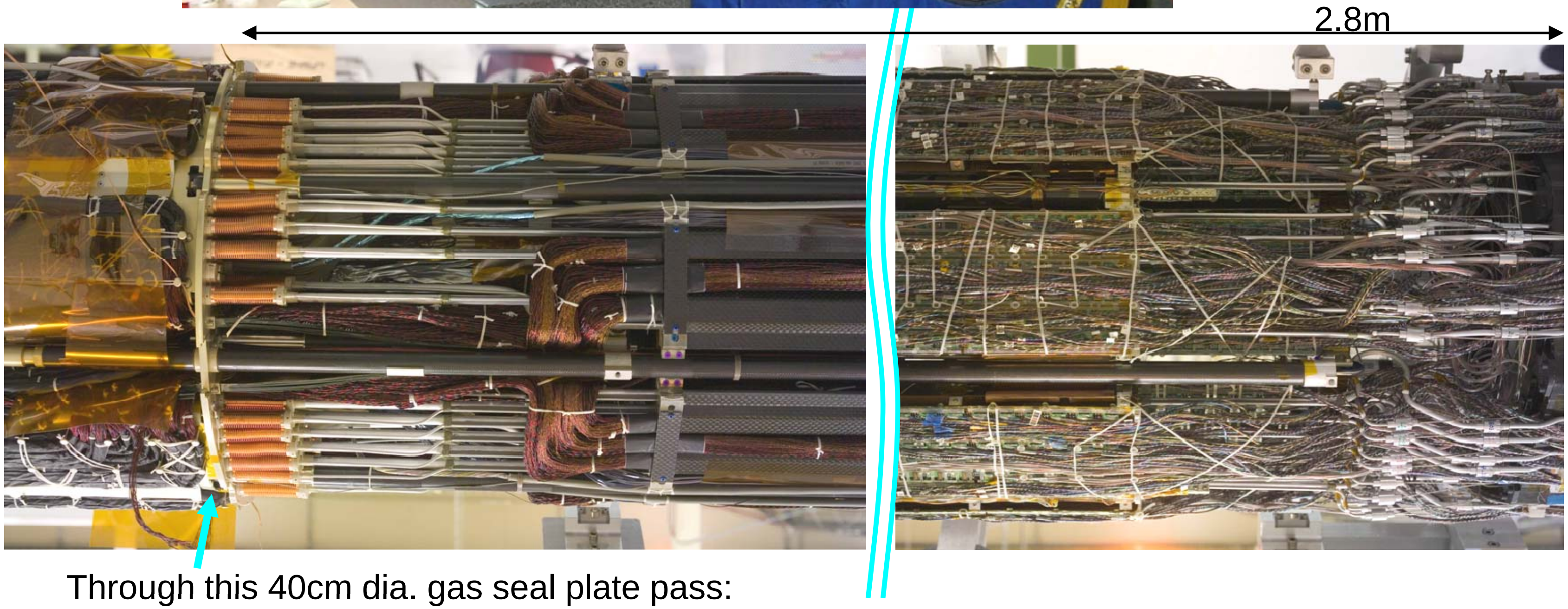
Background: powering the ATLAS pixel detector

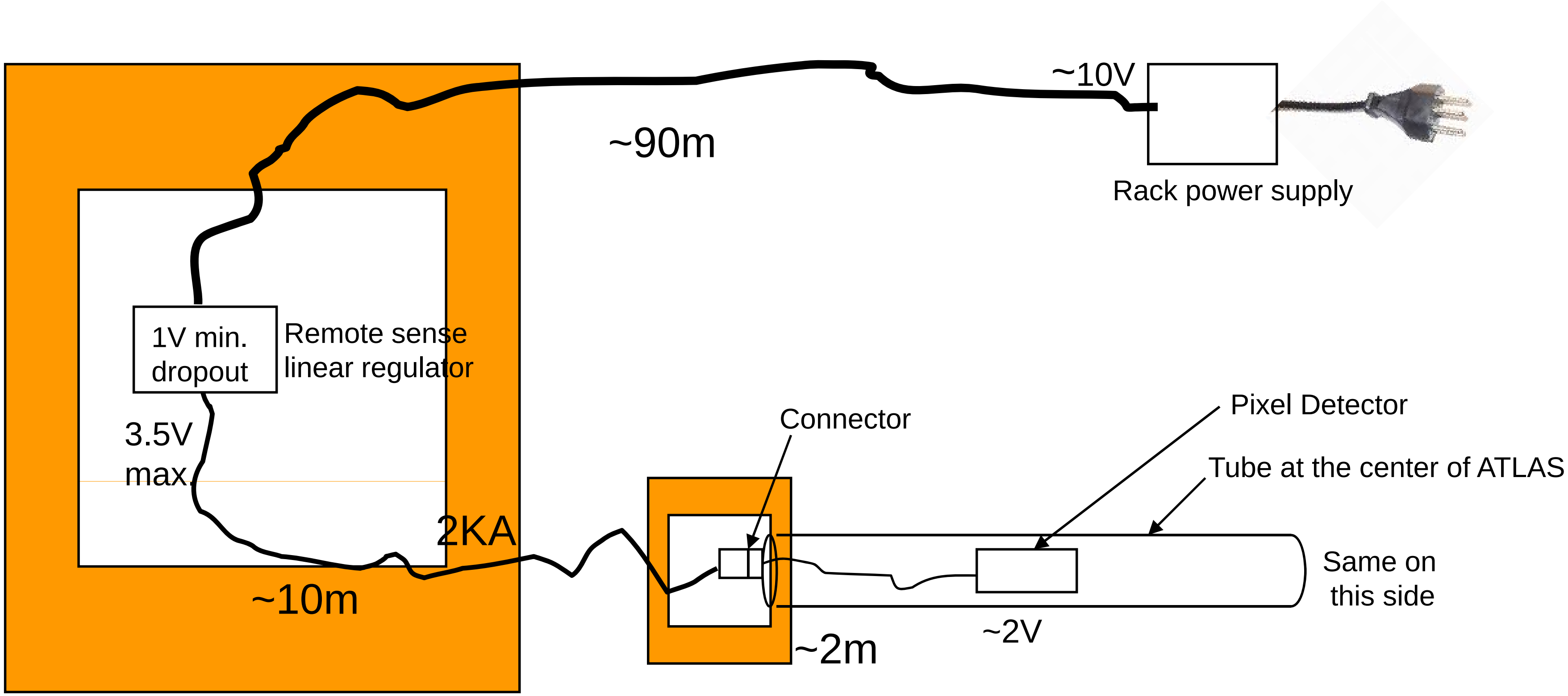


Support tube and internal services



Through this 40cm dia. gas seal plate pass:
2KA supply and 2KA return current, 1 beam pipe, 140Gb/s data, 5KW of cooling, +HV and sensing

Background: powering ATLAS pixel detector



Transition to conventional cables

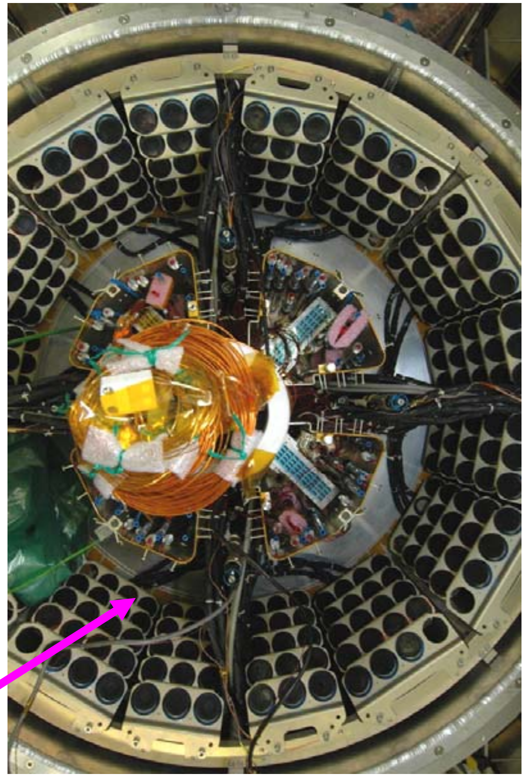
90m cables to racks

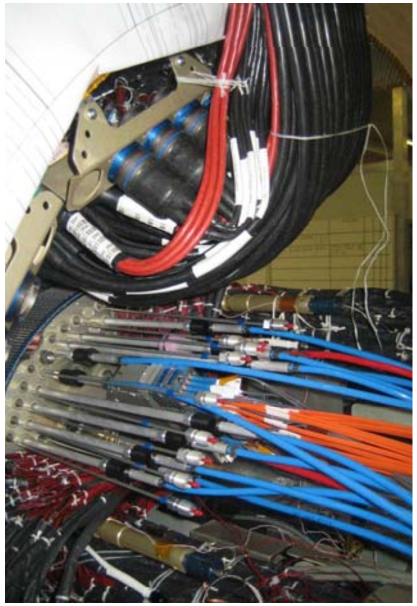
Voltage regulators

10m cables to support tube

10% of detector

5x this connects in here

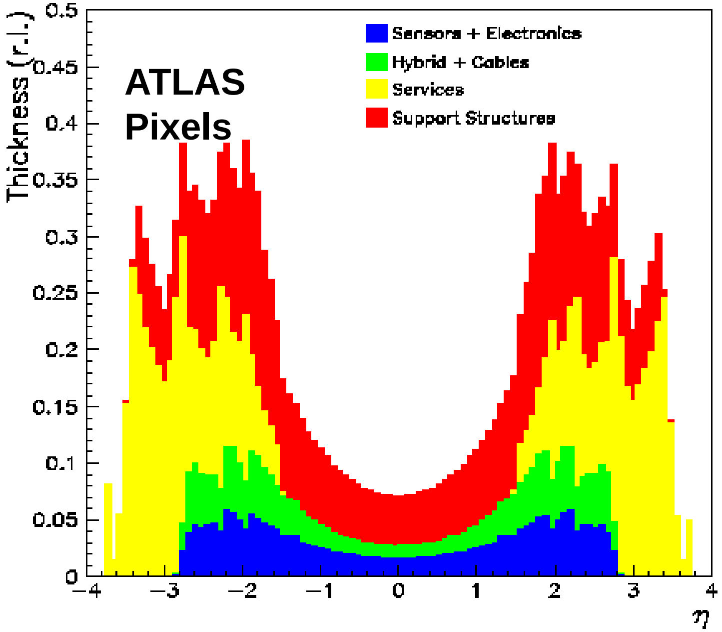




Mockup with 1/8 of the stuff

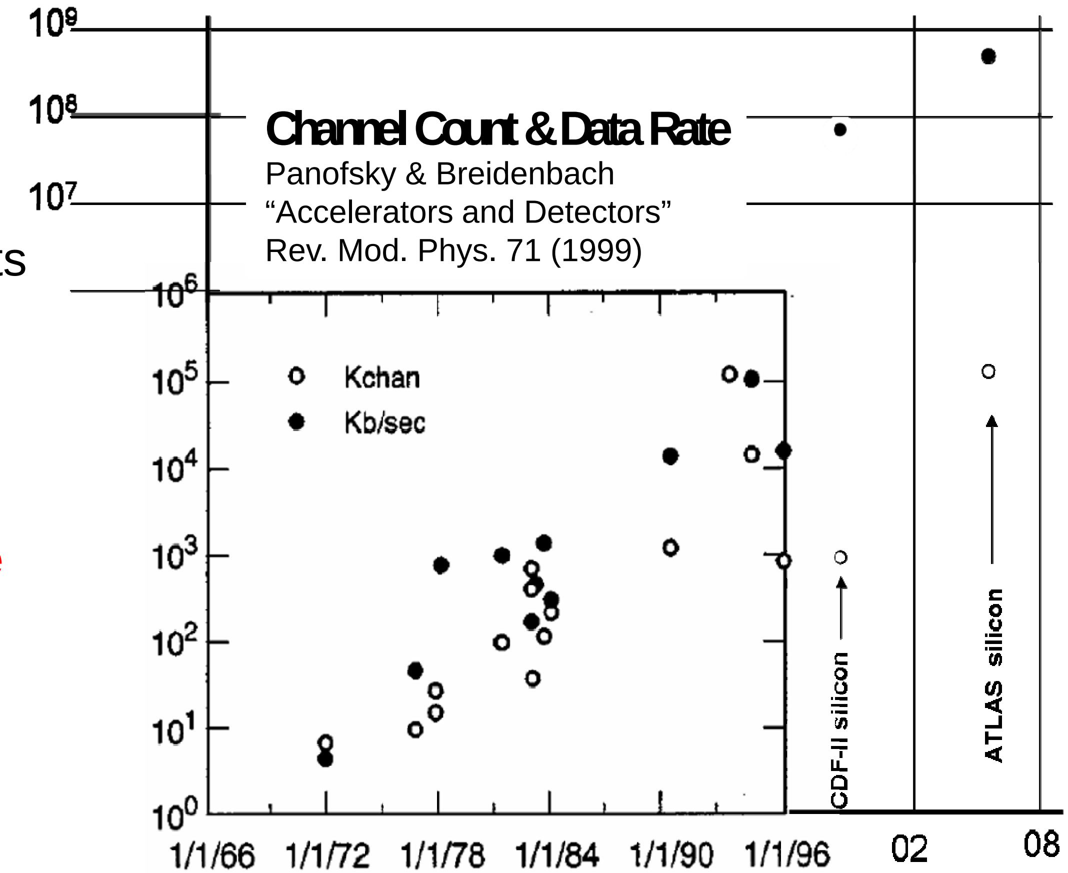
What is the general problem?

- Density of connections is pushed to the limit, resulting in highly complex assemblies whose cost starts to compete with active elements in order to maintain reliability.
- The services (electrical cables and cooling pipes) dominate the radiation length



Why do we have this problem?

- **Speed**: higher luminosity needs higher data output rate **=> more power**.
- **Channel count**: Denser events (higher energy and pile-up of interactions) need higher granularity **=> more power**.
- **Physical size**: Bigger detectors **=> power has to be delivered further**.
- **Moore's Law**: **=> power has to be delivered effectively further**



Really two problems

- Power
- Distance

Effective distance scale

- Efficiency of power delivery is given by

  $\varepsilon = V_{load} / V_{supply}$. (For typical case $I_{load} = I_{supply}$)
- For pure cables,

  $V_{supply} = V_{load} + I \,.\, R_{cable} = V_{load} + I \,.\, \alpha L_{cable}$,

  $1/\varepsilon = 1 + I\alpha \,.\, L_{cable} / V_{load}$
- If load is an integrated circuit, the operating voltage is proportional to the oxide thickness,

  $V_{load} = I \,.\, \beta T_{ox}$, therefore,

  $\mathbf{1/\varepsilon = 1 + I\alpha/\beta \,.\, L_{cable} / T_{ox}}$
- <u>IC Feature size sets an effective distance scale for power delivery</u>
- For example, when comparing CDF and ATLAS vertex detectors, cables runs are ~twice as long, but the IC feature size ratio is 0.25/0.8, so the effective cable runs are 6 times worse in ATLAS.

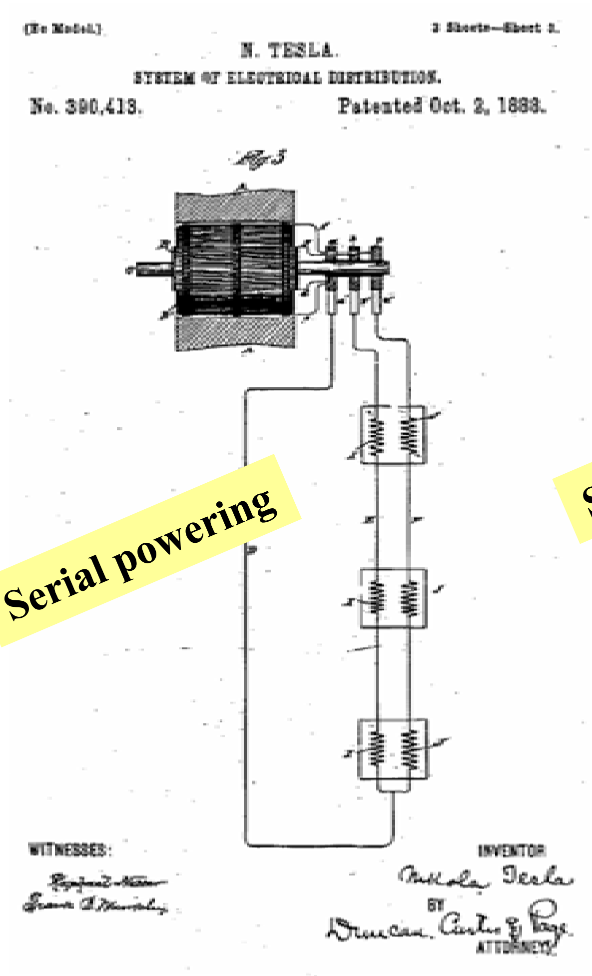
Power consumption & Power delivery efficiency

- A large operating power requirement makes the power delivery efficiency problem worse
- But power delivery efficiency is a problem independently of power consumption.
- With low power delivery efficiency, small load current changes lead to large voltage swings.
- This is an issue for DSM IC's even in a low power case such as ILC
- The detector radiation thickness is given by the operating power, while the cable plant mass & complexity are given by the power delivery efficiency

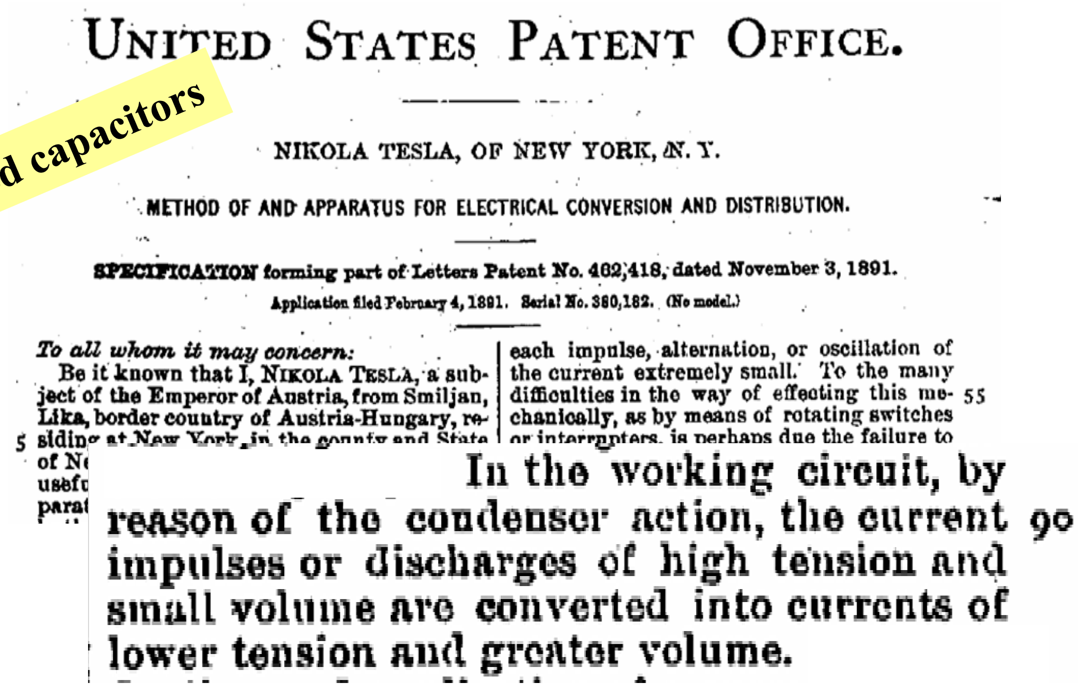
How do we solve the problem?

- Reduction of IC power
  - Big industrial R&D area for digital circuits
  - Important point for HEP- analog power tied to sensor choice
  - Not covered further in this talk
- Increase power delivery efficiency
  - Significant interest in this area over past ~2 years.
  - Basic principle: deliver power at higher voltage
    - Serial connection, or
    - DC-DC conversion
  - Covered in next few slides
- More system-oriented design approach
  - What seems conservative in a narrow view may be quite the opposite for the system.
  - Must consider full system- including cable plant- early in the design process.

Tesla



- Delivering power at higher voltage is not new
  - Most ideas for how to do this can be found in patents filed by Tesla well before 1900.



UNITED STATES PATENT OFFICE.

NIKOLA TESLA, OF NEW YORK, N. Y.

METHOD OF AND APPARATUS FOR ELECTRICAL CONVERSION AND DISTRIBUTION.

SPECIFICATION forming part of Letters Patent No. 462,418, dated November 3, 1891.

Application filed February 4, 1891. Serial No. 380,182. (No model.)

To all whom it may concern:

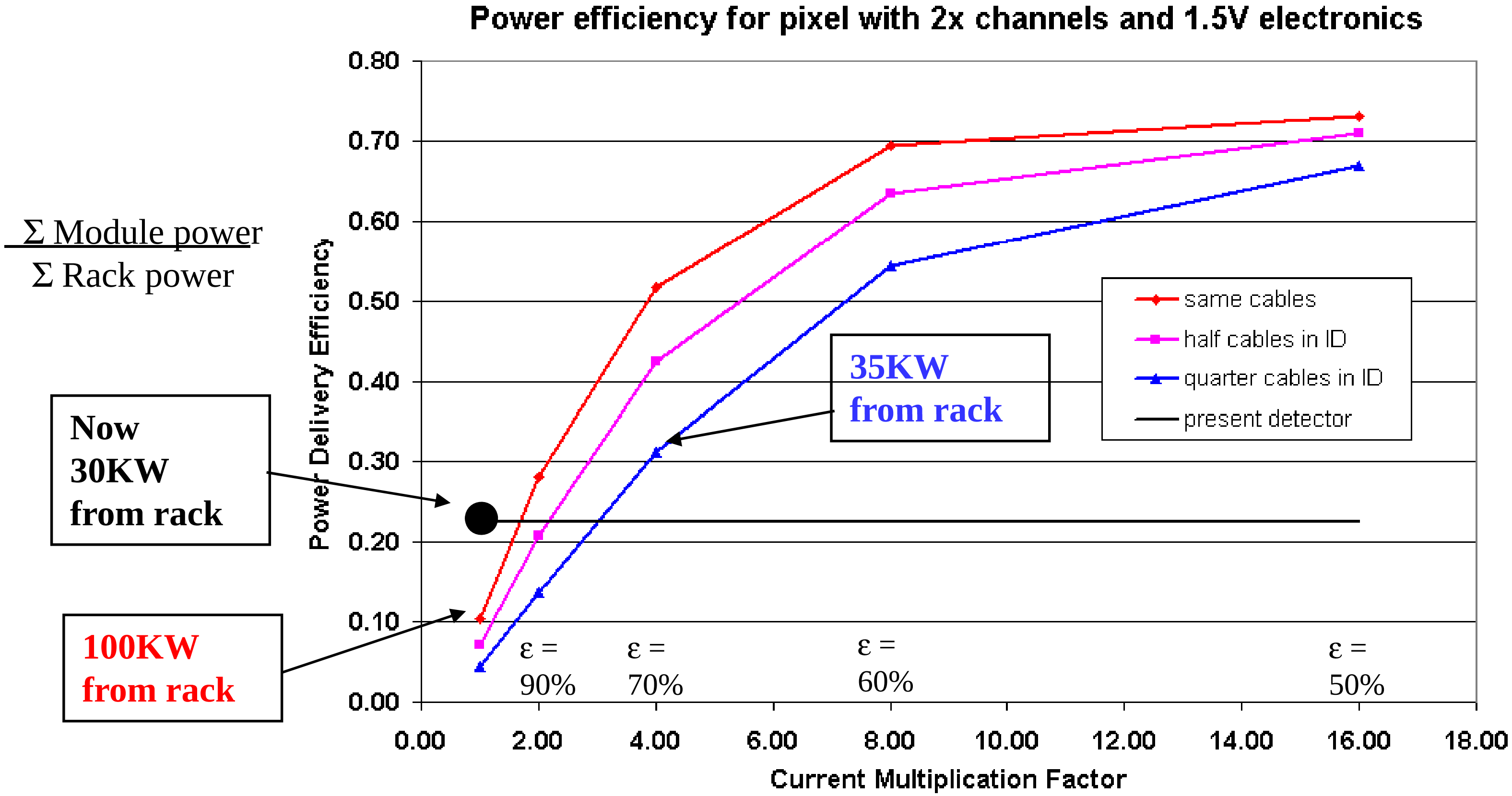
Be it known that I, NIKOLA TESLA, a subject of the Emperor of Austria, from Smiljan, Lika, border country of Austria-Hungary, residing at New York, in the county and State of N…

each impulse, alternation, or oscillation of the current extremely small. To the many difficulties in the way of effecting this mechanically, as by means of rotating switches or interrupters, is perhaps due the failure to …

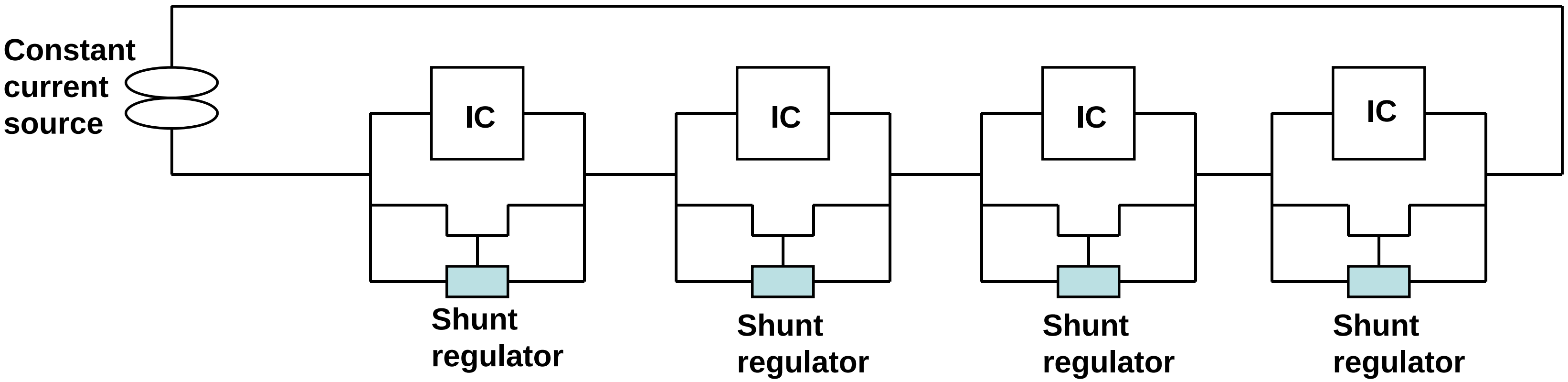
In the working circuit, by reason of the condenser action, the current impulses or discharges of high tension and small volume are converted into currents of lower tension and greater volume.

Power efficiency vs. conversion factor

- Consider a next generation pixel detector for ATLAS, keeping much of the installed cable plant



Multiplication by serial connection (current recycling)



- Regulator can be inside IC. In fact present ATLAS pixel IC has such a regulator in it- not being used.
- I/O must use level shifters, and sensor bias is referenced to local regulated voltage
- Noise coupling between stages is to first order absent because current is conserved (one stage cannot affect the current in the next stage)

Serial power references

Pixels

T. Stockmanns, P. Fischer, F. Hugging, I. Peric, O. Runolfsson, N. Wermes, "Serial powering of pixel modules", Nucl. Instr. & Meth. A511 (2003) 174–179;

D. B. Ta, T. Stockmanns, F. Hügging, P. Fischer, J. Grosse-Knetter, Ö. Runolfsson, N. Wermes, "Serial Powering: Proof of Principle demonstration of a scheme for the operation of a large pixel detector at the LHC", Nucl. Instr. Meth. A557 (2006) 445-459

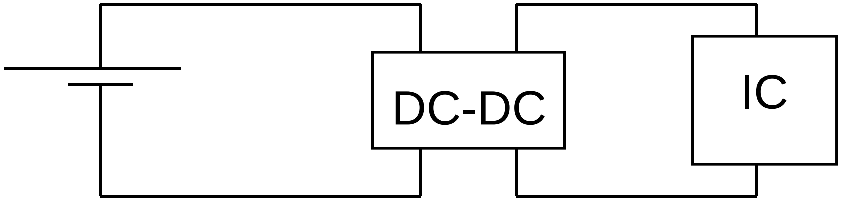
Strips

Marc Weber, Giulio Villani, Mika Lammentausta, Proceedings of the 11th workshop on electronics for LHC and future experiments, CERN-LHCC-2005-038, (2005) pp. 214-217;

Marc Weber, Giulio Villani, "Serial Powering of Silicon Strip Detectors at SLHC", Proceedings of the 6th "Hiroshima" conference on Silicon detectors (2006);

Carl Haber, "A Study of Large Area Integrated Silicon Tracking Elements for the LHC Luminosity Upgrade", Proceedings of the 6th "Hiroshima" conference on Silicon detectors (2006).

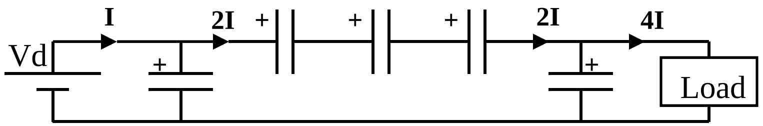
DC-DC conversion



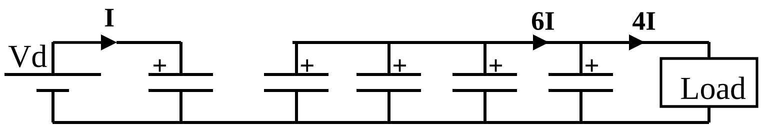
- Ubiquitous
- Not much explanation needed
- Commercial parts are inductive using ferrites
- High efficiency because ferrites enhance stored energy per unit volume by ~2 orders of magnitude

A switched capacitor x4 DC-DC converter

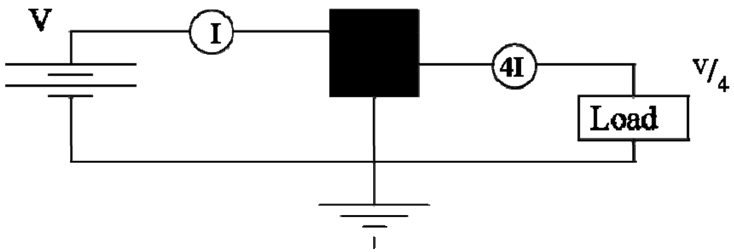
- **Phase 1 - Charge**

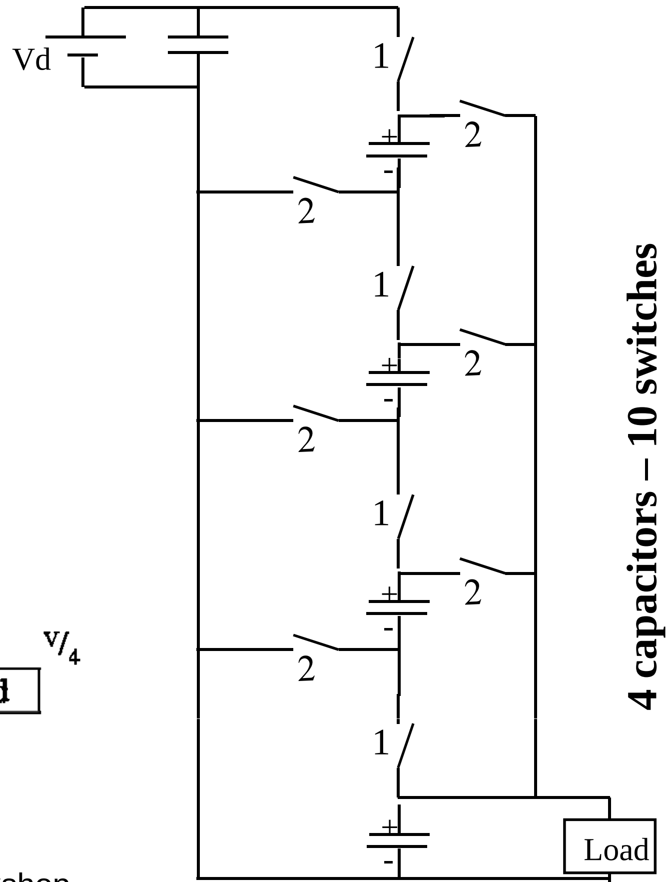


- **Phase 2 - Discharge**



- **Ideal device operation:**



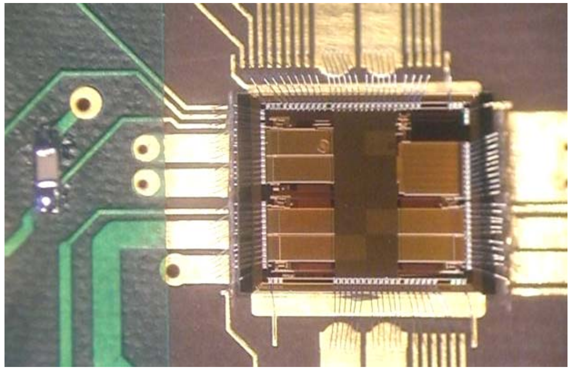


4 capacitors – 10 switches

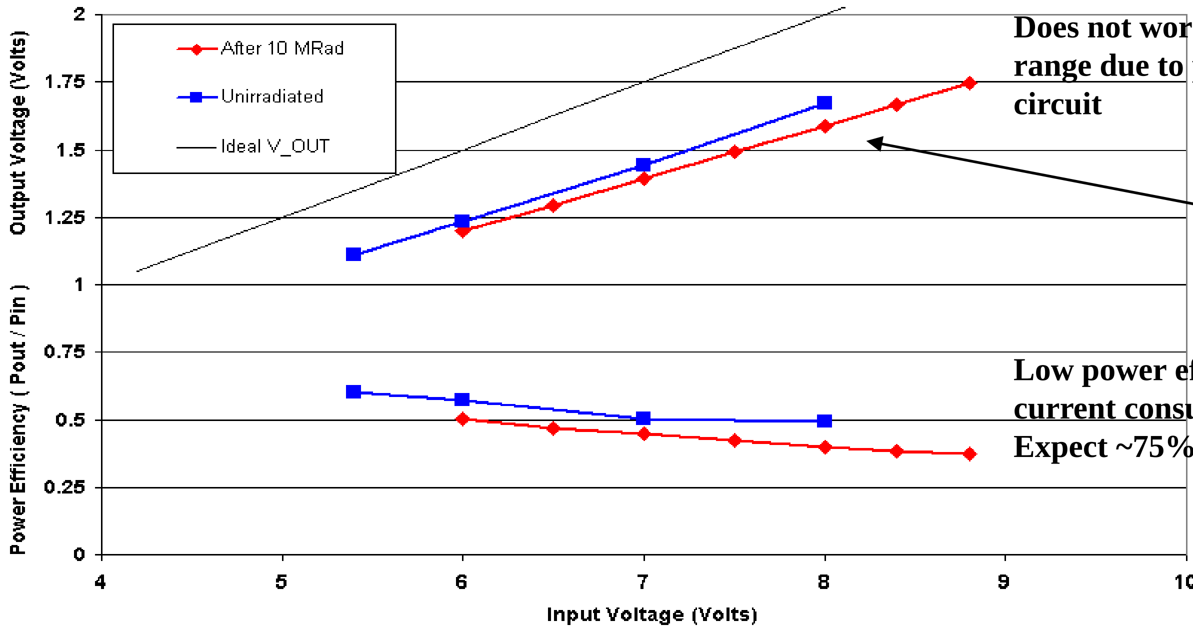
Ref: "DC-DC Power Conversion", R. Ely & M. Garcia-Sciveres, 12 Workshop on Electronics for LHC and Future Experiments, CERN-2007-001 p. 89 (2007)

Prototype IC

P. Denes, R. Ely, M. Garcia-Sciveres, LBNL



- Received May 2007
- 50V (source to drain) 0.35mm HV CMOS process
- 10 power switches in 4.3 x 4.9 mm footprint
- All capacitors external, all clocks external
- Chip re-submitted Aug. 14, 2007 with bias circuit fix AND external override



Does not work outside shown voltage range due to problems with bias circuit

Can be used as a "passive" voltage divider.
Full control of output voltage without any control signals

Low power efficiency is due to large current consumption in bad bias circuit.
Expect ~75% after fix.

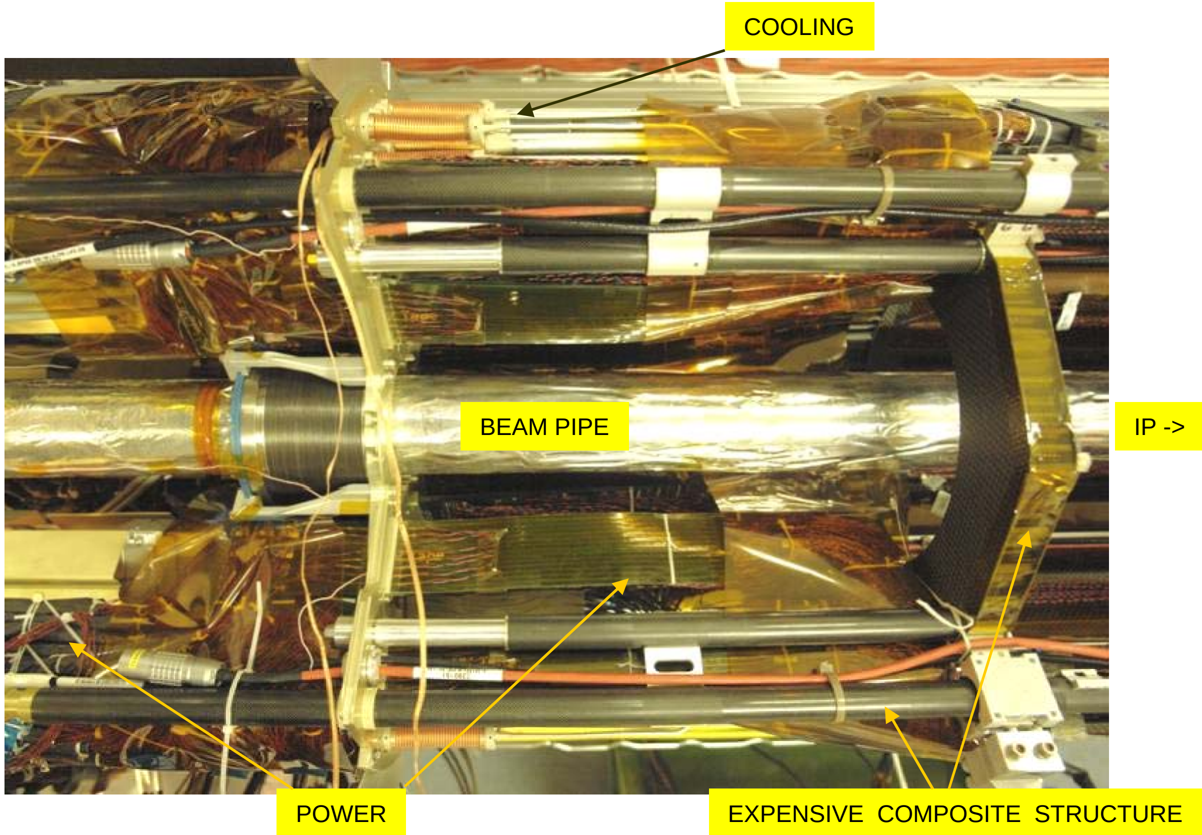
Reliability and number of connections

- Increasing the number of connections typically DECREASES reliability.
- “Conservative choice” of independent connections for every circuit element may not be at all conservative from a system perspective
  – Need to consider full system before choosing number of I/O and slow control lines needed per element
- **A simple calculation for a large system of N.n elements:**
  – **Case A:**
    - make N.n connections
    - Single connection failure probability is α
    - => Expected number of element failures is N.n.α (binomial mean)
  – **Case B:**
    - Gang n elements together
    - Make N connections
    - Single connection failure probability is β
    - => Expected number of element failures is n.N.β
  – B is more reliable because $\beta \ll \alpha$
    - bigger contacts and bigger wires are more reliable. Alternatively consider B has n redundant connections. If current capacity is not an issue then $\beta \sim \alpha^n$
  – Analysis not as simple if internal failure of one element disables all of its ganged neighbors.

Conclusion

- Silicon detectors have become very large systems
- “Boring stuff” like power delivery efficiency and electrical contact reliability are critical design elements
- System consideration must be a top priority in the design process
- An example of system thinking: the choice of sensor parameters may have more to do with reduction of IC power than with radiation thickness of the sensor itself. Might choose a bulky sensor over a light-weight sensor because it leads to a lower mass full system.
- DC/DC conversion and/or serial powering will inevitably be a part of the next generation of LHC detectors

Backup 1: Section through pixel services



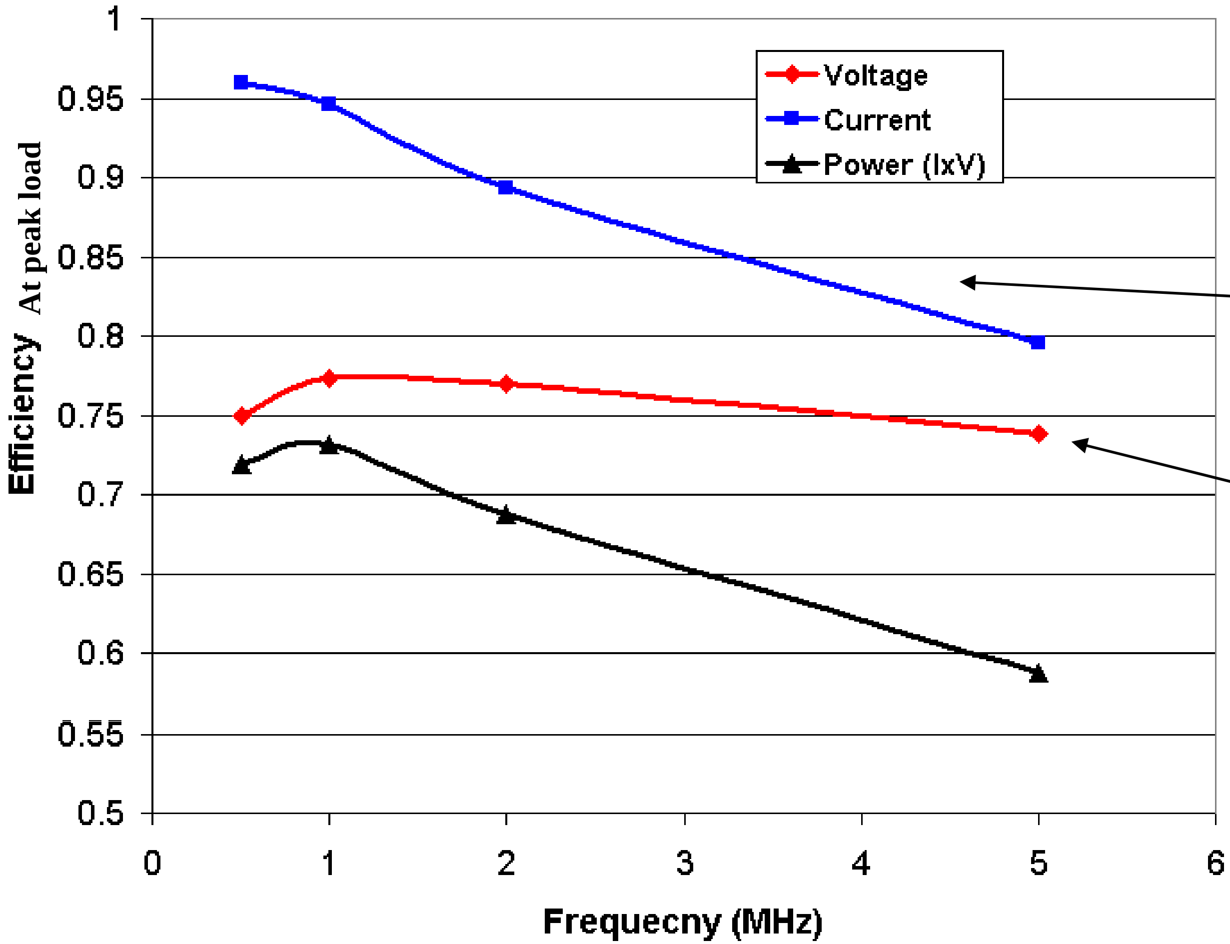
Backup 2: DC-DC vs. Serial

- DC-DC
  - Single module is electrical unit.
  - 1 common logic- no external components.
  - Independent control possible
  - Can produce “off the shelf” universal components
  - Requires external component (DC-DC converter)
  - Rad-hardness of DC-DC must be proven
- Serial
  - Multi-module electrical unit
  - Multiple logic levels (requires level shifting external components)
  - Individual control difficult (requires voltage shifted slow control)
  - Has to be engineered for every new application
  - Can be built into IC
  - Naturally as rad-hard as IC if built-in

Backup 3: Why switched capacitors?

- Commercial DC-DC down-converters for power applications are all inductive.
  - (Switched capacitors used to step-up voltage at low power to drive displays, etc.)
- Why then study switched capacitors for power?
  - Cannot use ferrites in magnetic field => performance penalty for magnetic converters
  - With magnetic converters fringe AC magnetic fields may produce pickup in detectors (must study case-by-case)
  - Ceramic capacitor miniaturization makes great advances year after year (but air-core inductors cannot be improved).
  - Over-voltage safety considerations

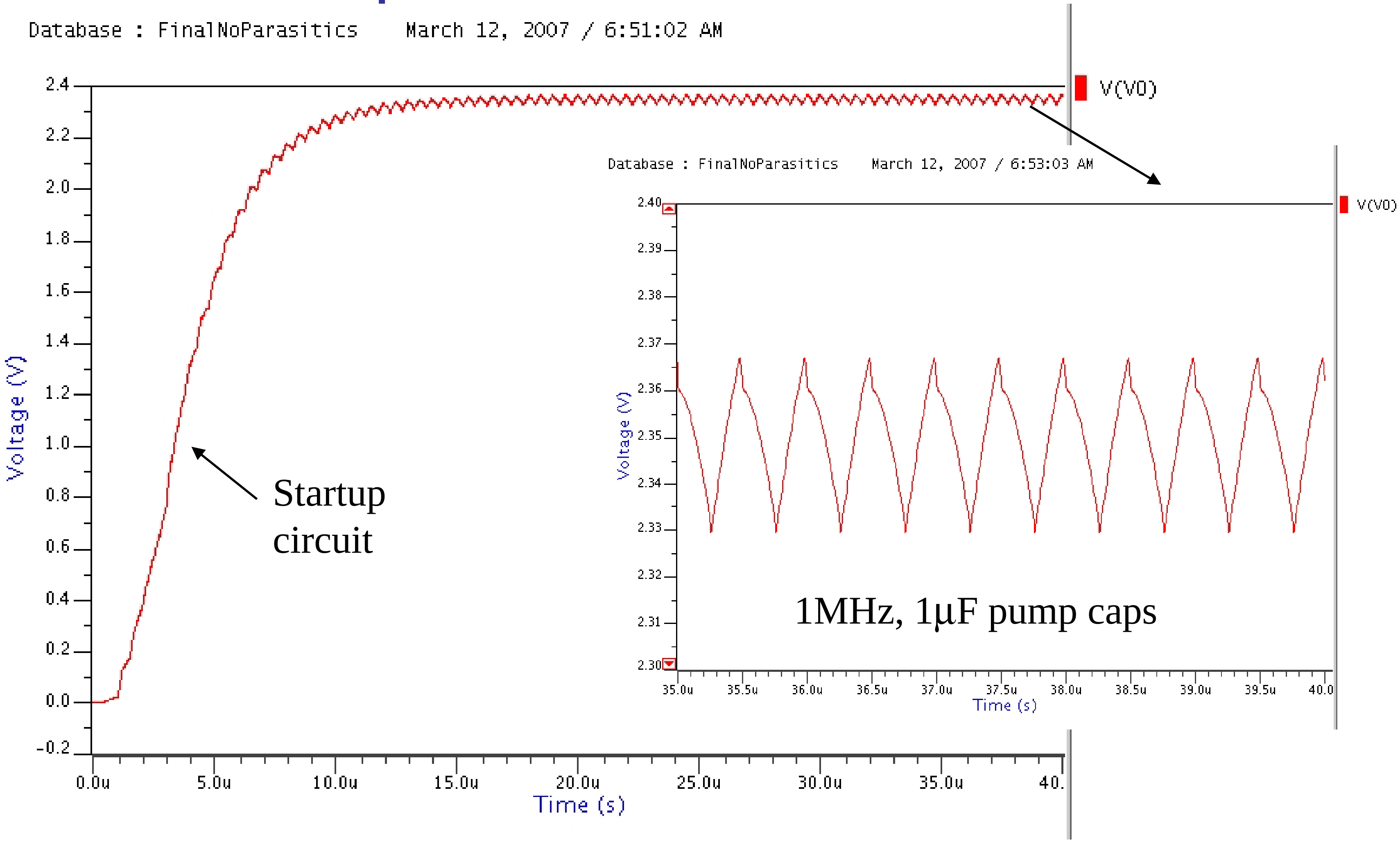
Backup 4: Simulation efficiencies



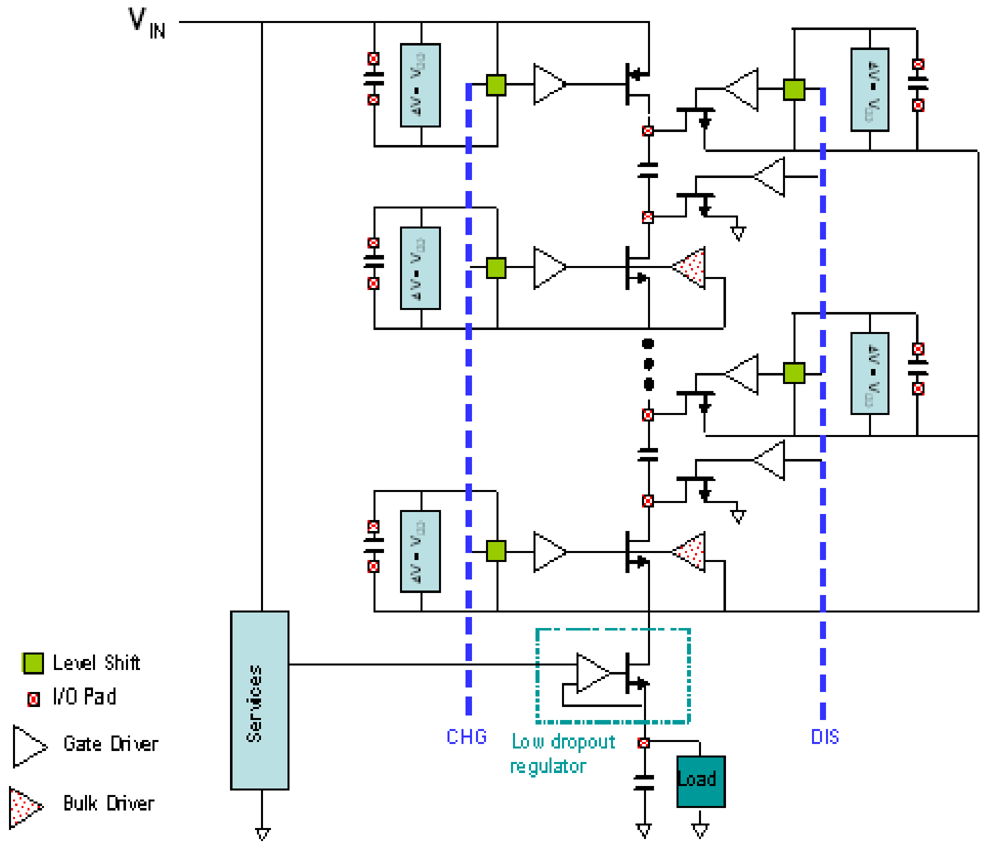
Load-independent charge lost in switch parasitics

Load-dependent. Dominated by switch resistance

Backup 5: Simulation Transient

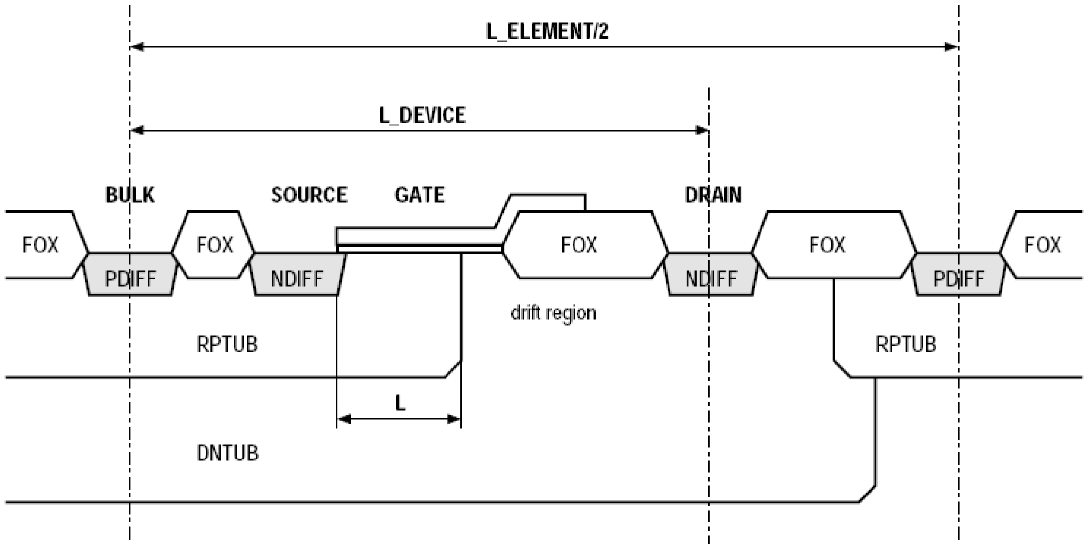


Backup 6: Switched cap chip schematic



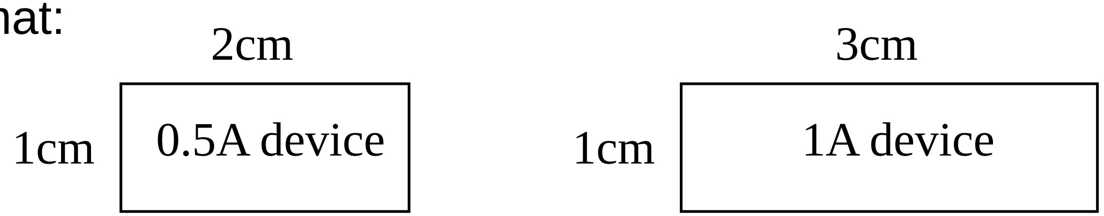
Backup 7: LDMOSFET

6.2.7 NMOSI50T, NMOSI50M, NMOSI50H



Backup 8: plans for next switched cap.

- Expected delivery date Nov. 5
- Concentrate on building “plug and play” prototypes that can be used to power existing and new detector assemblies.
- Target format:



- Inputs: Power (I_out/4), +4V (~20mA), Clock (optional).
- Miniaturization challenging because several external components needed.
- In eventual production size could be further reduced (ultimate goal is 1cm2/Amp of output) by absorbing more functionality into ASIC.