Fachhochschule Dortmund
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ASIC Development - System Aspects

Power Distribution

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Terascale Detector Workshop - Heidelberg

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Power Demand of Pixel Detectors

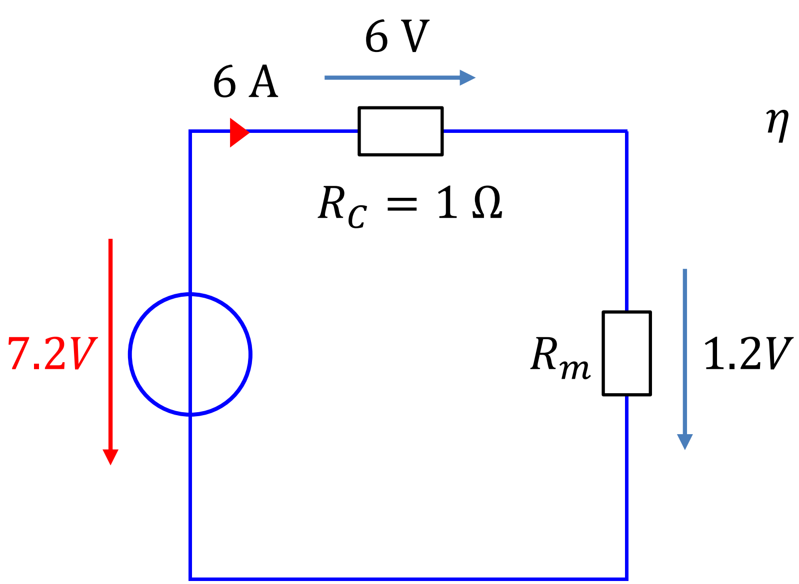
- Hybrid-Pixel detectors are power hungry devices

Chip	Pixel Area	Current per Pixel	Current Density
FE-I3	50 x 400 µm^2	47 µA	1400 A/m^2
FE-I4	50 x 250 µm^2	16 µA	1280 A/m^2
RD53	50 x 50 µm^2	7 µA	2800 A/m^2

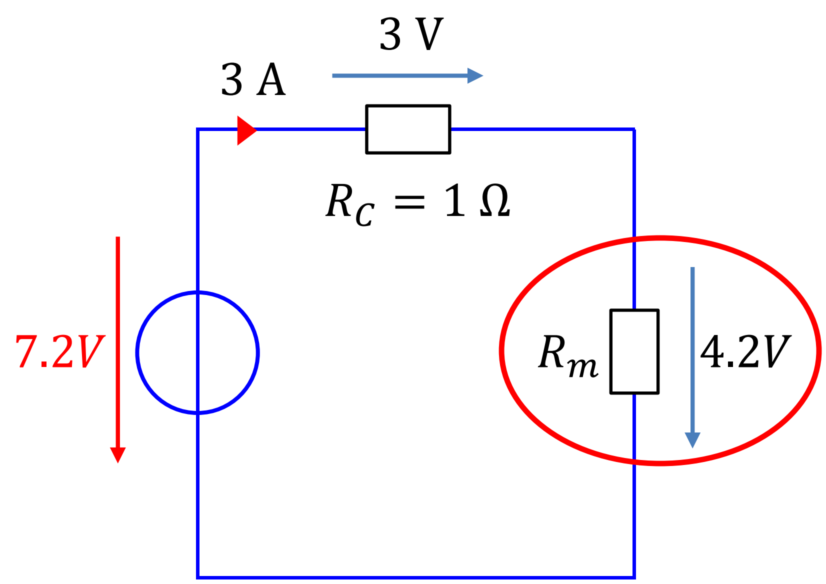
- Increased current consumption caused by
  - parasitic detector capacitances
  - additional digital functionality
- ITkPix quad-module expected to consume 4.5-7.5 A of current
  - Exact current consumption depends module position e.g. layer

Need for Low Mass

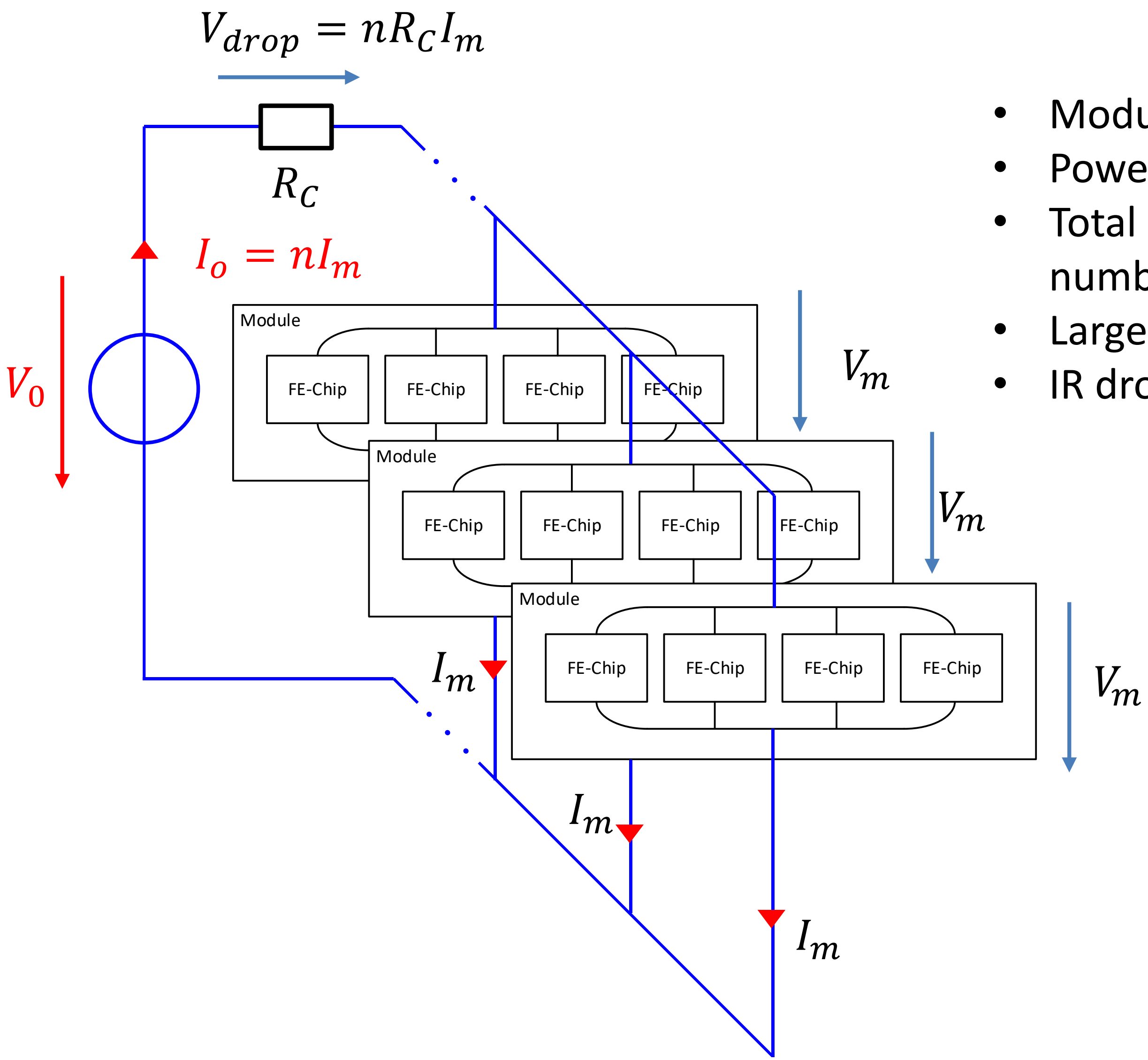
- detector mass influences the tracking and calorimeter resolution
  - multiple-scattering, Bremsstrahlung, photon conversion
- limited material budget
  - affects available number and diameter of supply lines
  - no sense lines
- long supply lines
  - power supplies are outside the active area
  - assuming c.a. 200m aluminum of 5 mm^2 diameter gives 1Ω cable resistance



$$\eta = \frac{1.2V \cdot 6A}{7{,}2V \cdot 6A} \approx 16.7\ \%$$



Power Efficiency of Conventional Power Scheme



- Modules are connected in parallel
- Powered by constant voltage source
- Total supply current scales with the number n of modules
- Large supply currents affect efficiency
- IR drops on power cables

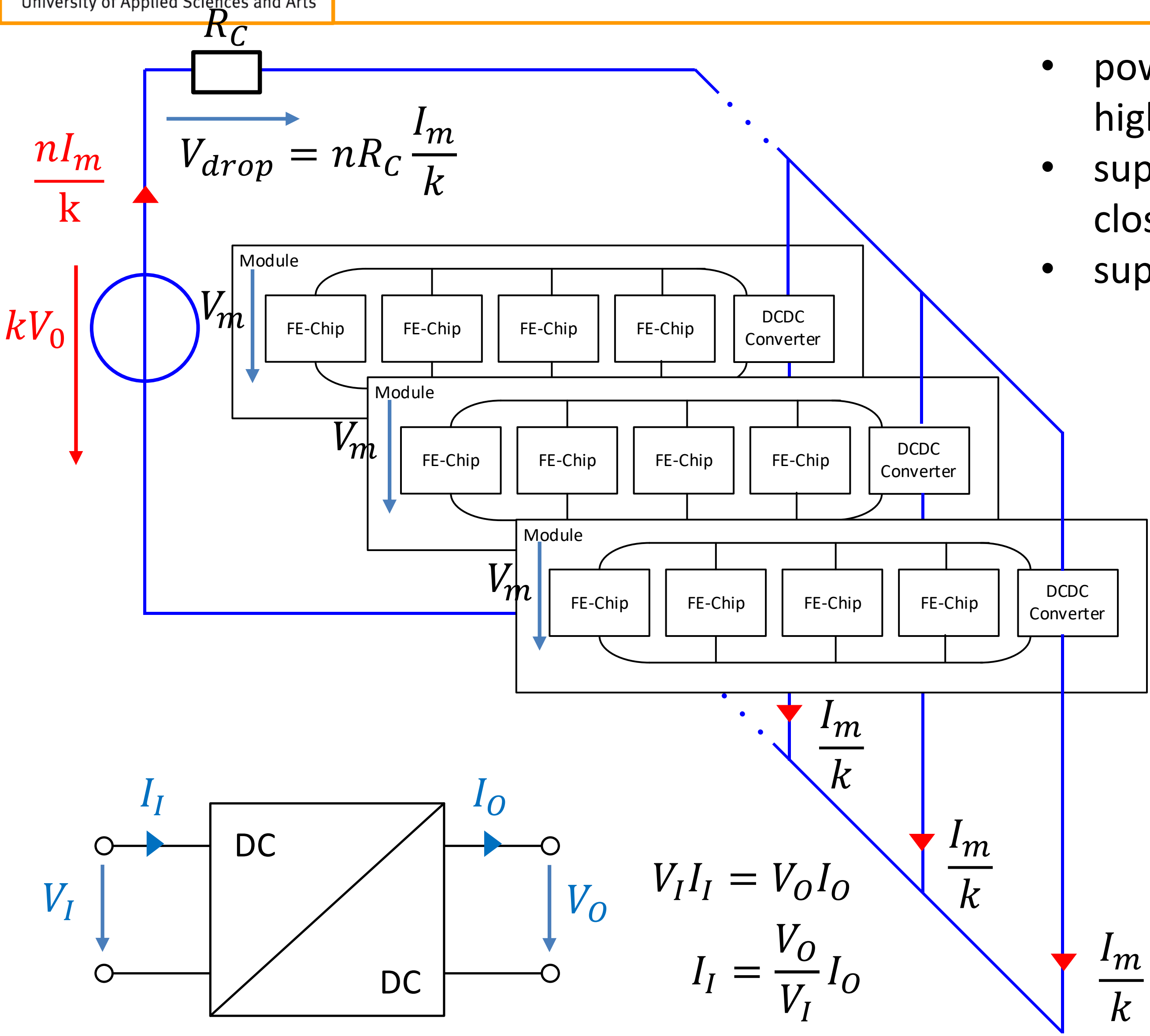
$$\eta = \frac{1}{1 + n\frac{R_C I_m}{V_m}}$$

$$\eta = \frac{1}{1 + 16\frac{1\Omega \cdot 6A}{1{,}2V}}$$

$$\approx 1.23\ \%$$

DC / DC Conversion

- power is distributed at k-times higher supply voltage
- supply voltage is converted down close to the load
- supply current is reduced by k



$$V_{drop} = nR_C \frac{I_m}{k}$$

$$\eta = \frac{1}{1 + \frac{n}{k^2}\frac{R_C I_m}{V_m}}$$

$$\eta_4 = \frac{1}{1 + \frac{16}{16}\frac{1\Omega \cdot 6A}{1.2V}}$$

$$\approx 16.7\ \%$$

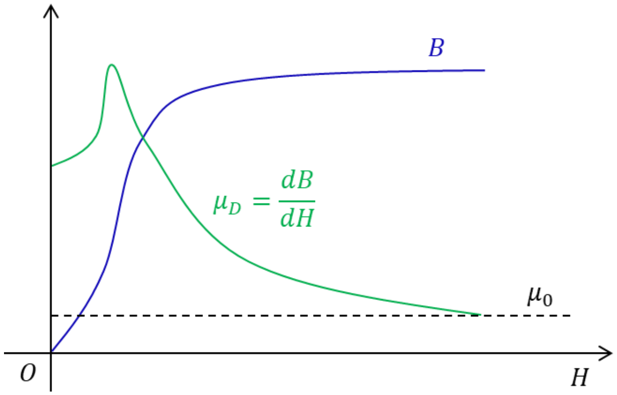
$$\eta_8 \approx 44.4\ \%$$

$$\eta_{16} \approx 76.2\ \%$$

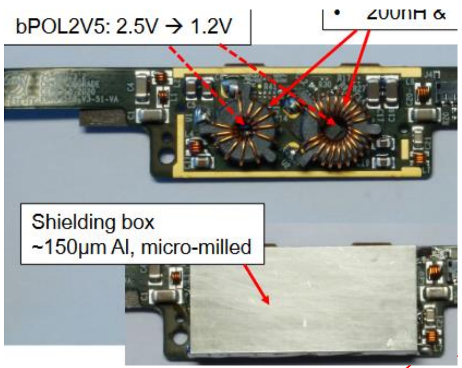
$$V_I I_I = V_O I_O$$

$$I_I = \frac{V_O}{V_I} I_O$$

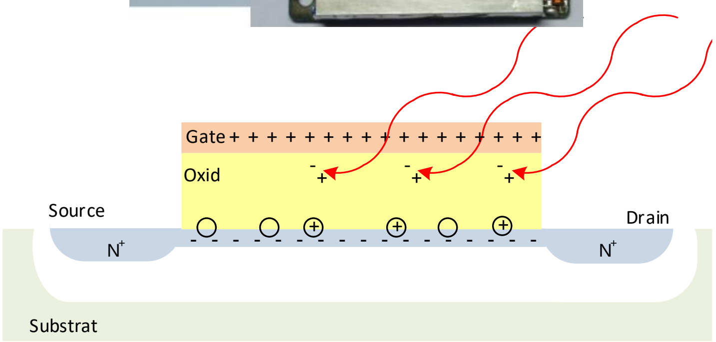
Special Conditions in HEP Experiments



- High magnetic field to measure momenta and charge
- ferromagnetic materials saturate
- only air coils applicable
- air coils have larger dimensions than coils with core

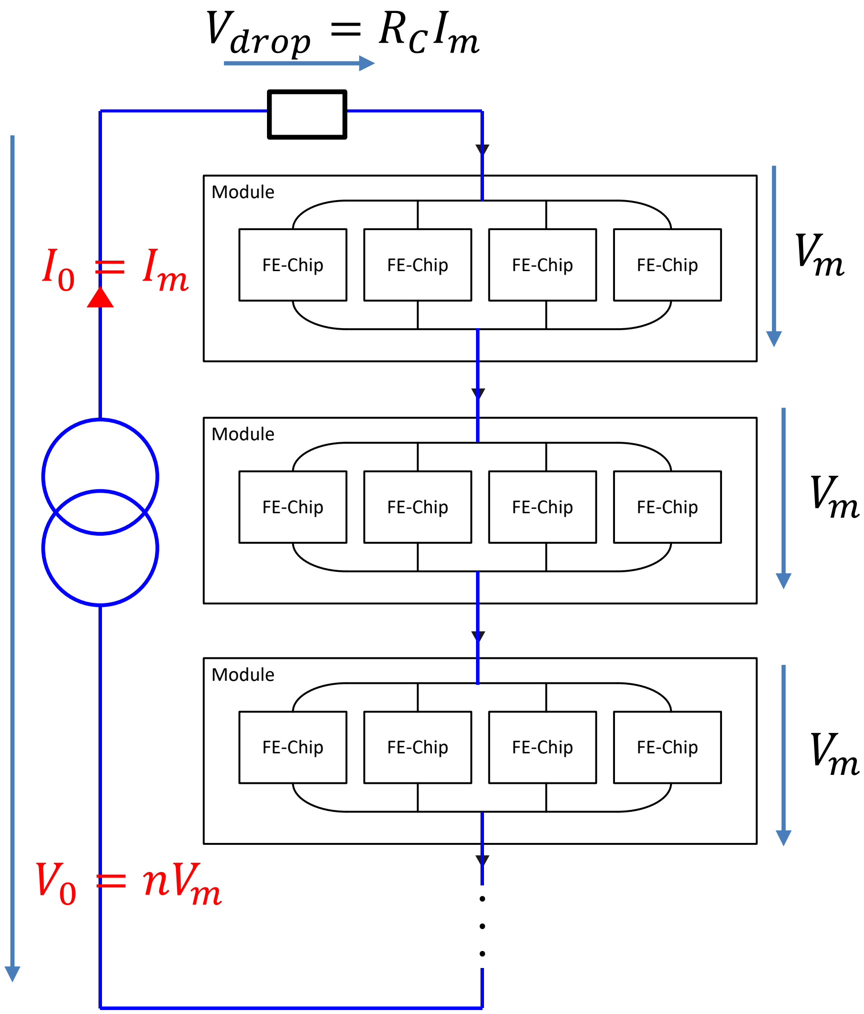


- frontend electronics very sensitive to noise coupling
- shielding of coil required
- increased material budget



- higher voltages can only be handled by thick-gate oxide transistors
- significant radiation induced threshold voltage shifts for gate-oxide thickness larger than 5nm

Serial Powering



- modules are connected in series
- powered by constant current source
- total supply current is defined by maximum load current of a single module
- total supply voltage across the chain scales with the number of powered modules

$$\eta = \frac{1}{1 + \frac{R_C I_m}{n V_m}}$$

- regulator circuitry required to generate constant supply voltage out of constant current

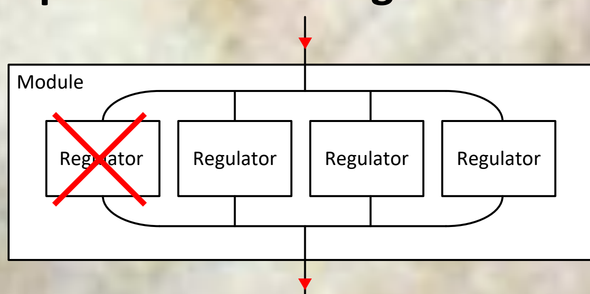
$$\eta = \frac{1}{1 + \frac{1\Omega \cdot 6A}{16 \cdot 1.2V}} \approx \frac{1}{1 + \frac{1\Omega \cdot 6A}{16 \cdot 1.2V}}$$

$$\approx 76{,}2\%$$

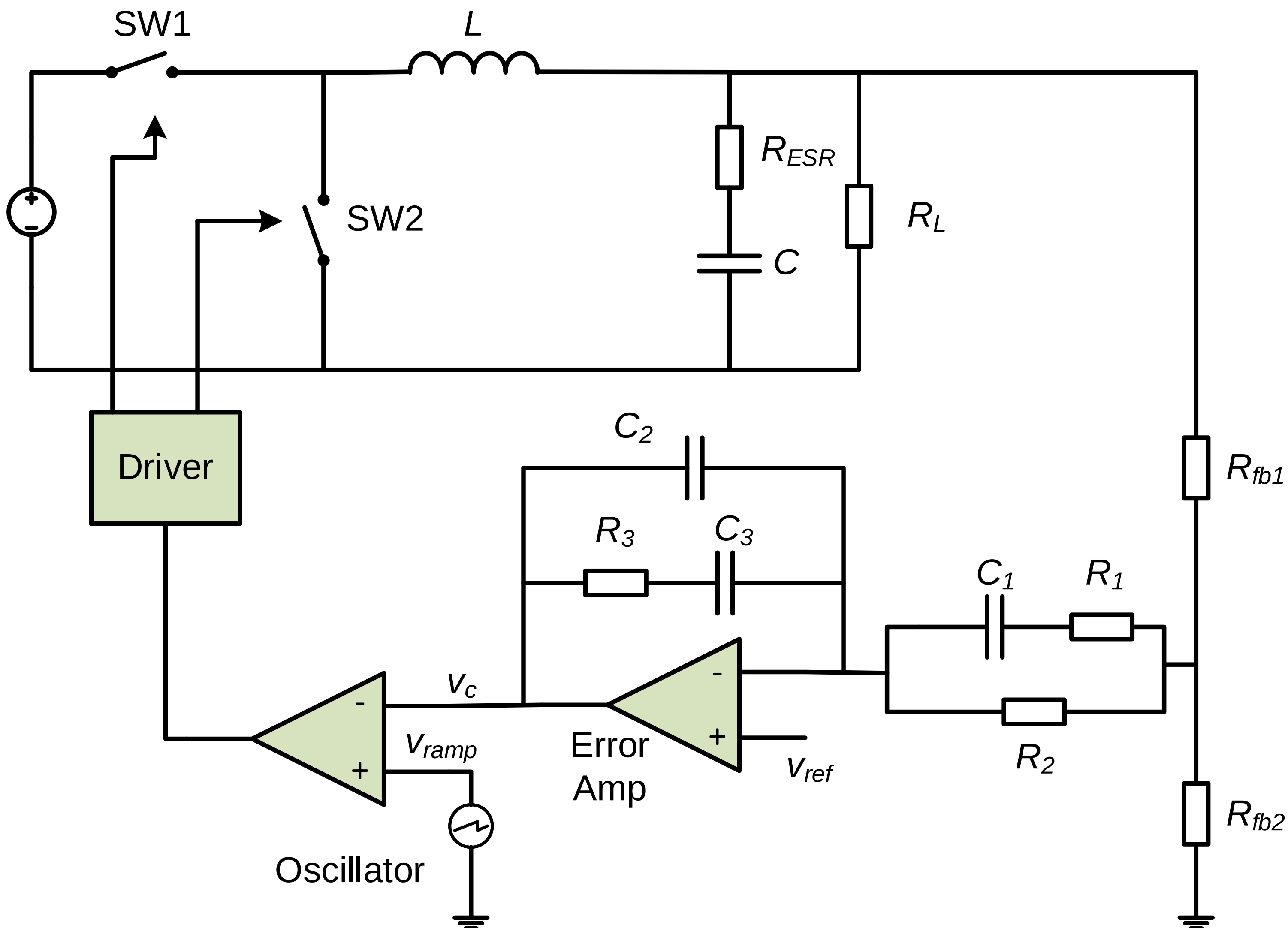
The Serial Powering Commandments

- **You shall prevent the break of the serial powering chain**
- **You shall avoid hot spots**
- **You shall distribute power equally across the chips and the module**
- **You shall avoid single point of failure**
- **You shall introduce redundancy**

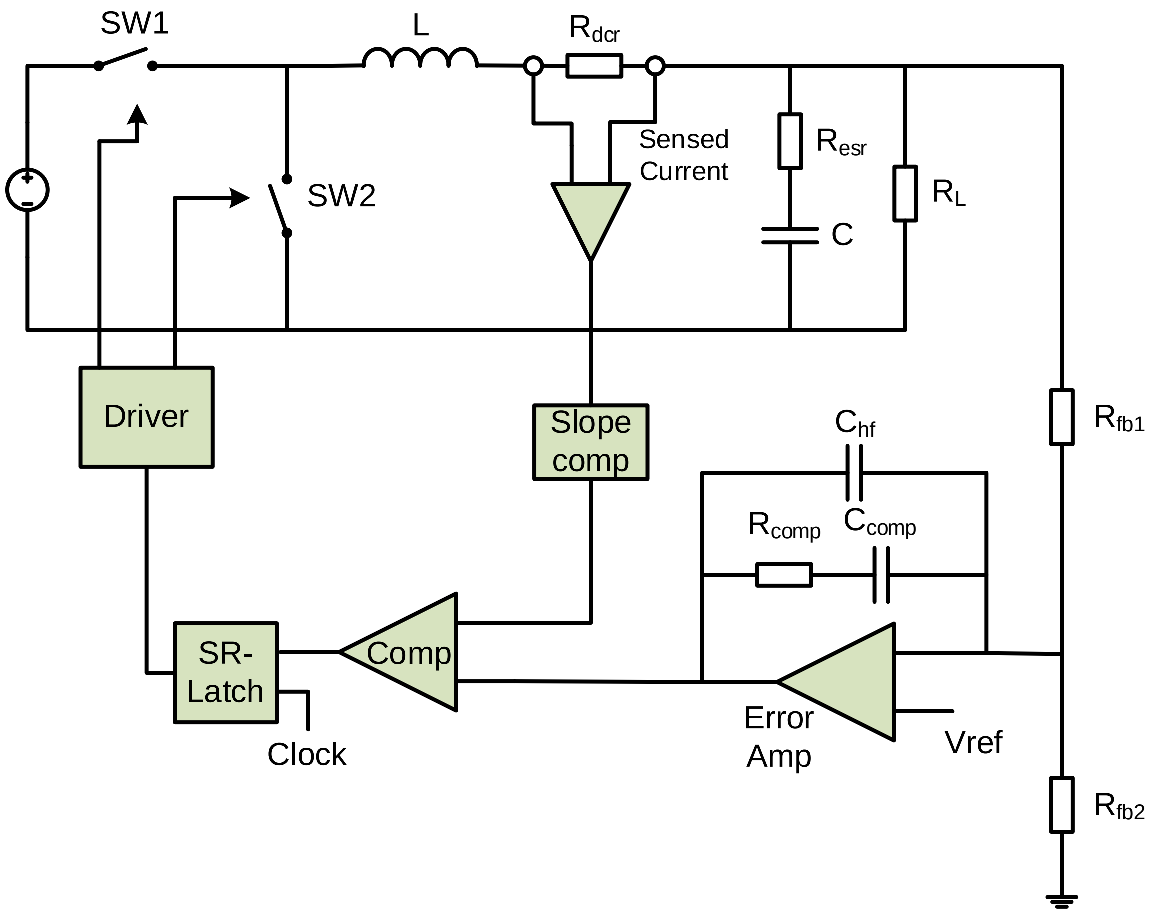
- **You shall operate several regulators in parallel on module level**



Voltage Controlled Buck Converter



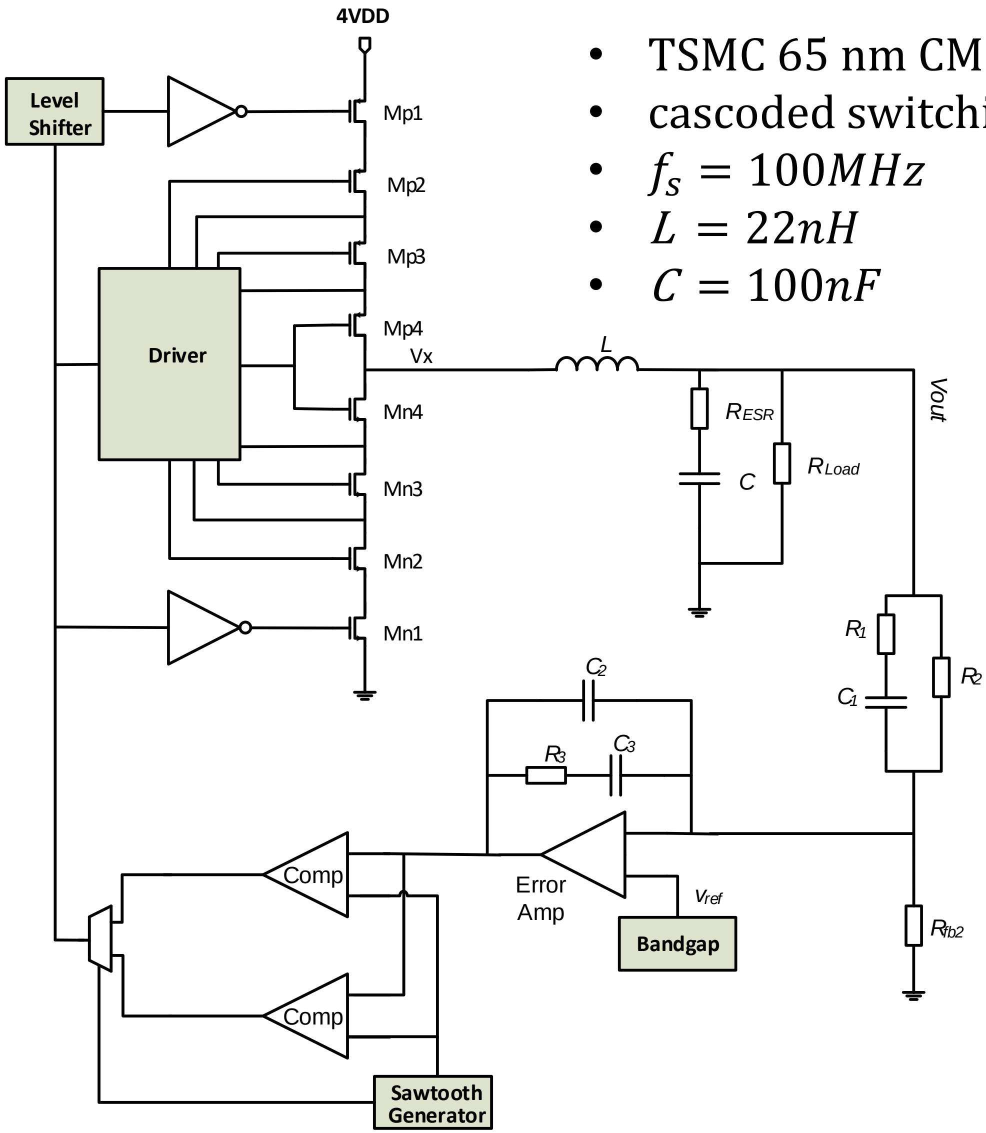
Current Controlled Buck Converter

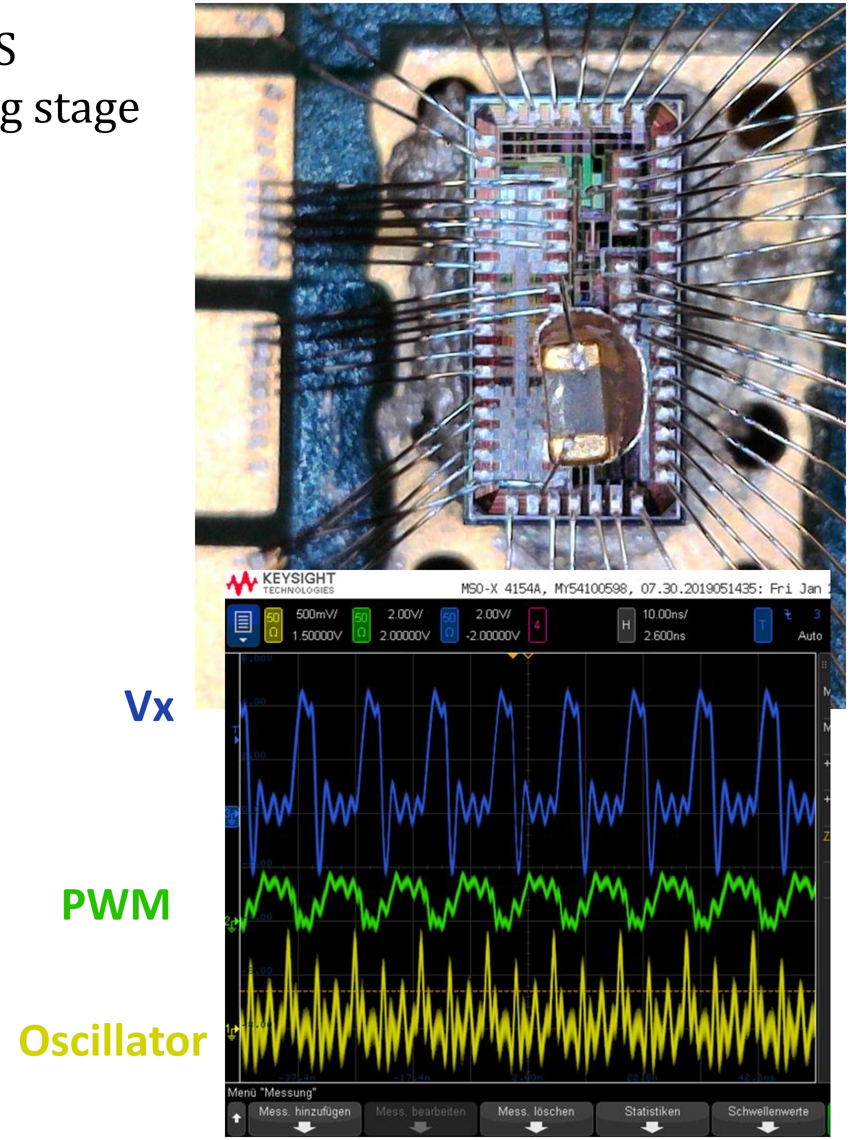


- inductance current is controlled
- If inductance current reaches peak value SW1 is opened
- output voltage determines peak value
- inductor behaves like a current source
- regulation loop becomes single pole system
- much easier to compensate

High-Frequency Buck-Converter

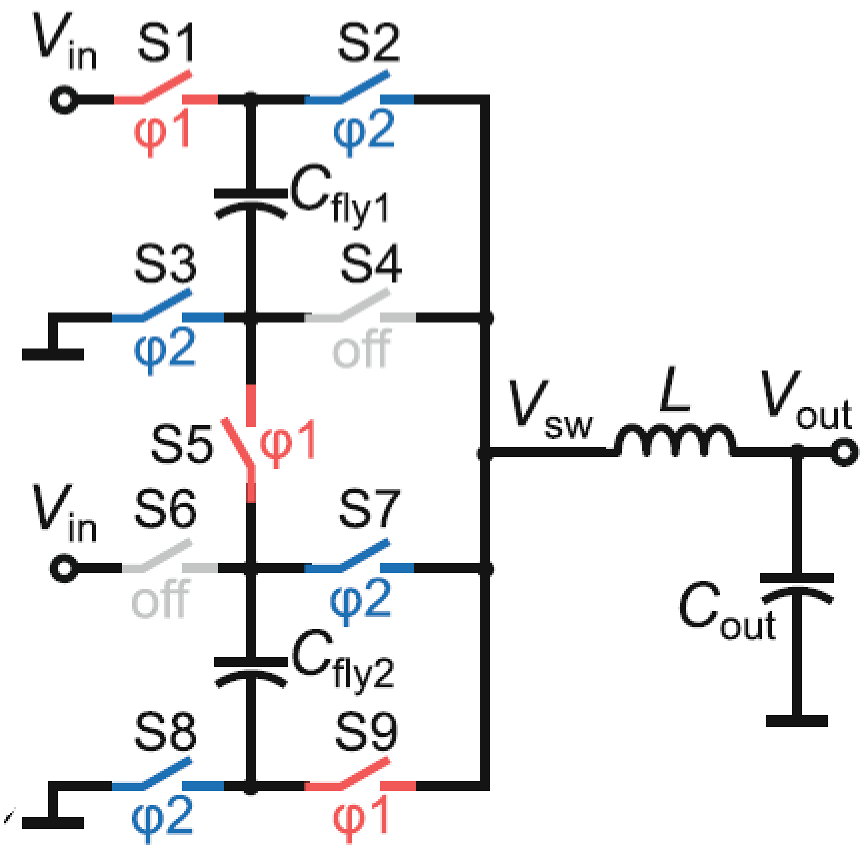
- TSMC 65 nm CMOS
- cascoded switching stage
- $f_s = 100MHz$
- $L = 22nH$
- $C = 100nF$



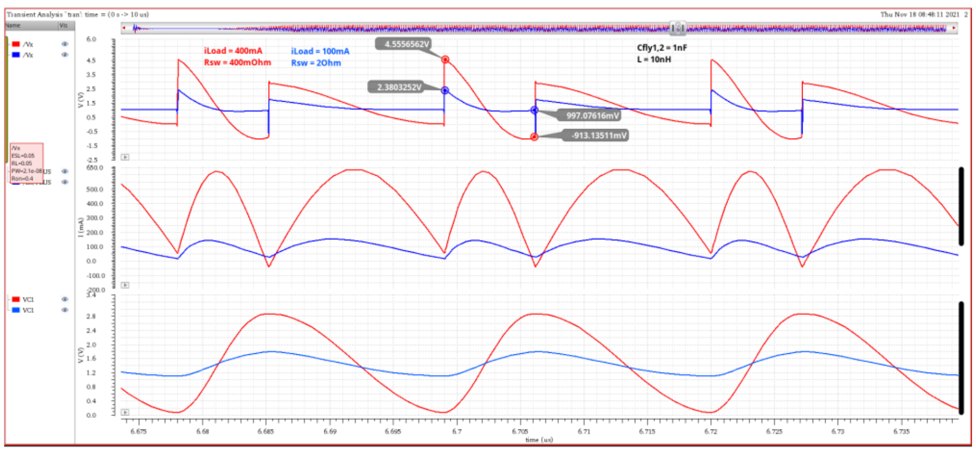


New Class of DCDC-Converter: Resonant Converter

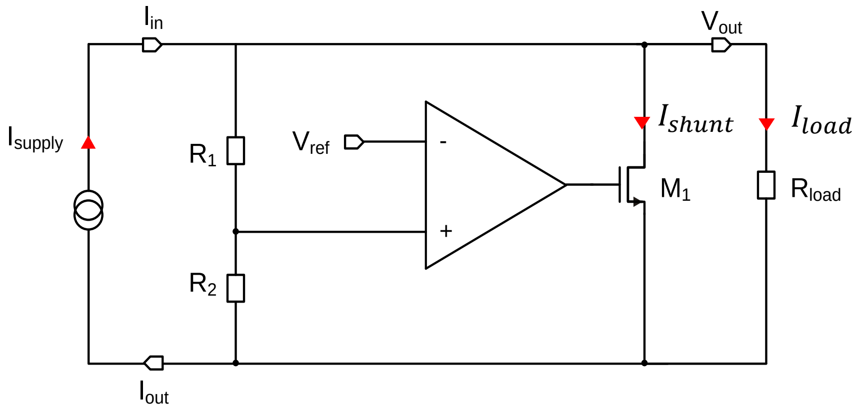
3-1 Resonant Converter



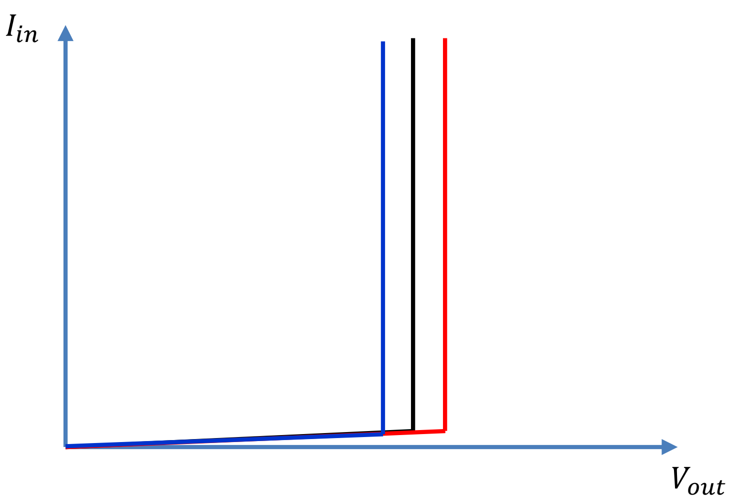
- Converter Is operated at higher frequencies close to resonant frequency
- Passive components can be reduced in size significantly
- Switching occurs when current becomes zero
    - Higherer efficiency



Shunt Regulator Operation Principle



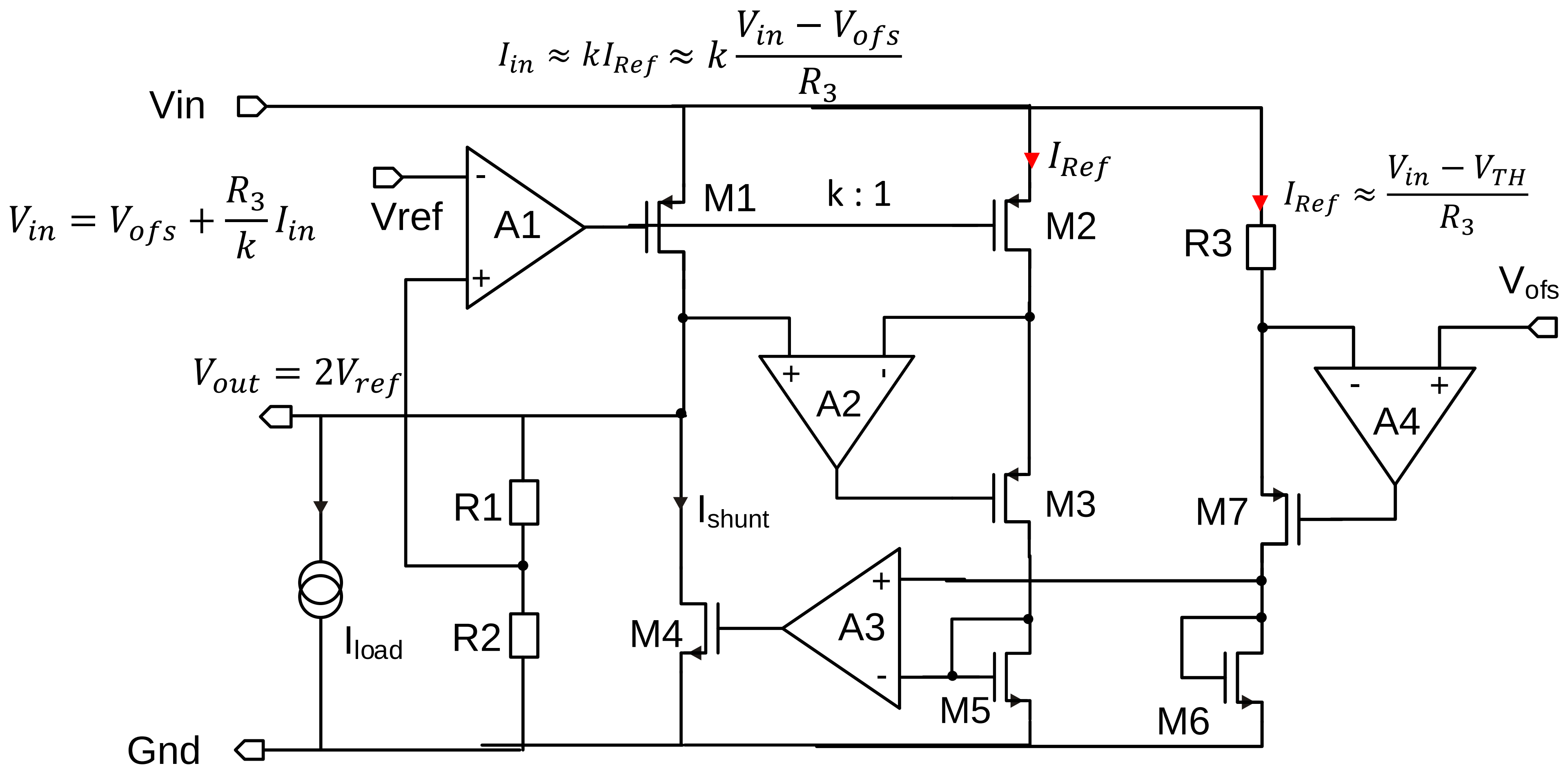
- Voltage regulation by current steering
- Current flow through load defines V_{out}
- Referenced voltage $V_{out} = \left(1 + \frac{R_1}{R_2}\right) V_{ref}$
- Excess current I_{Shunt} is shunted by M1
- $I_{in} > I_{load} \rightarrow \eta = \frac{I_{load}}{I_{in}}$



- Very steep voltage to current characteristic
- → Small voltage source output impedance ☺
- → Unbalanced current distribution across parallel placed regulators ☹
- Parallel placed regulators generate different V_{out}
  - voltage reference variations
  - error amplifier offset
  - resistor mismatch
  - ground shifts
- Current will flow through regulator with small V_{out}
- Regulator may be destroyed due to overload cond.

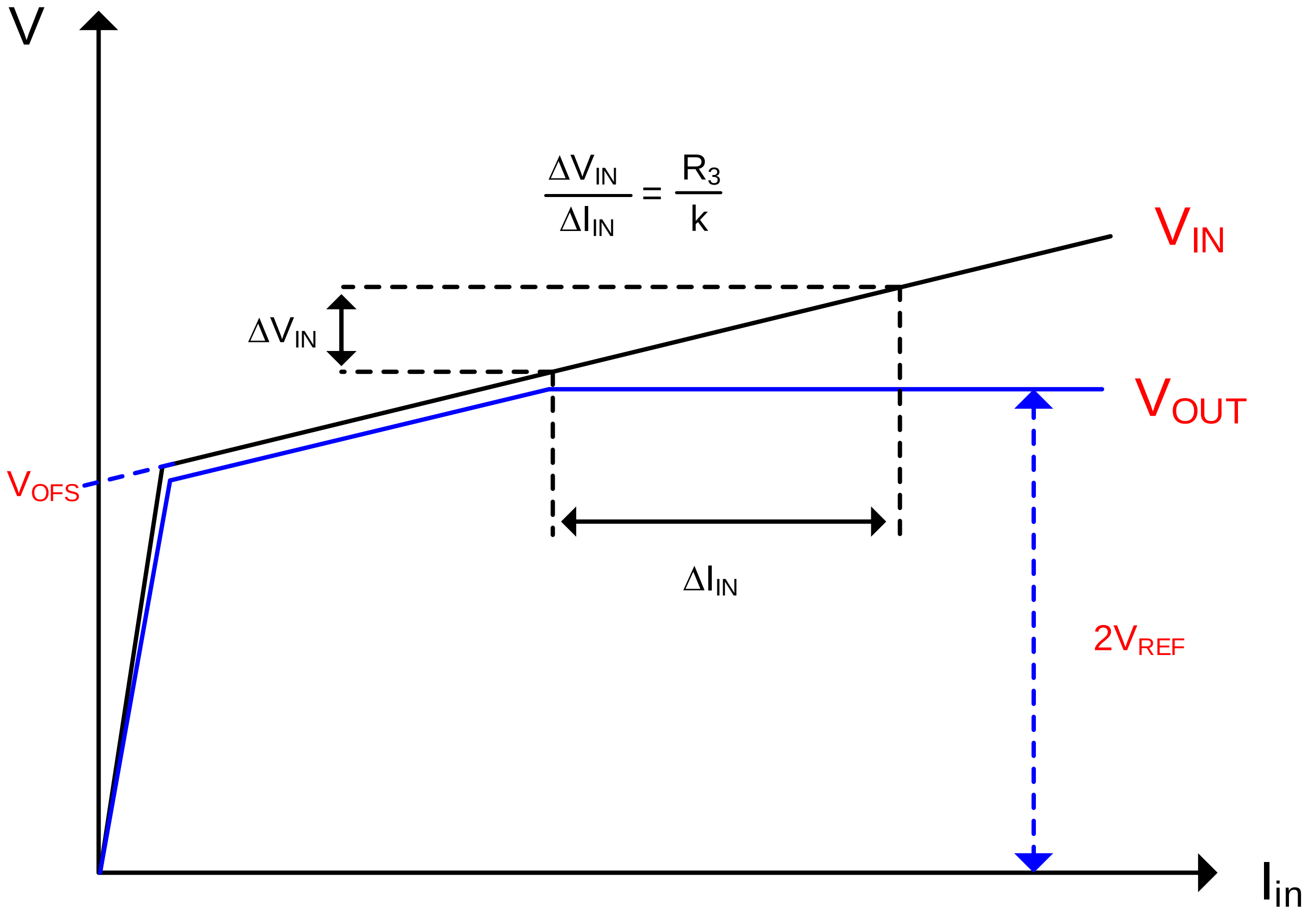
Design Concept

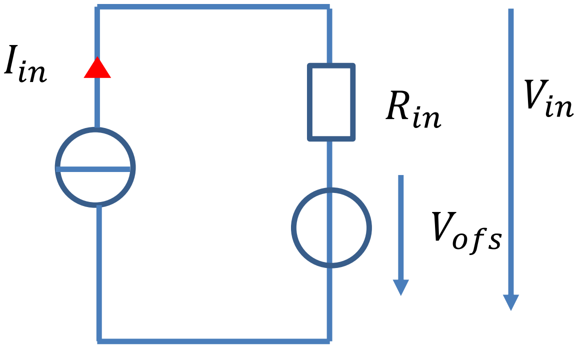
- The Shunt-LDO regulator combines the functionality of an LDO voltage regulator with the capability of a shunt regulator to drain a constant current
- Two control loops: 1) constant output voltage 2) constant current flow through the regulator

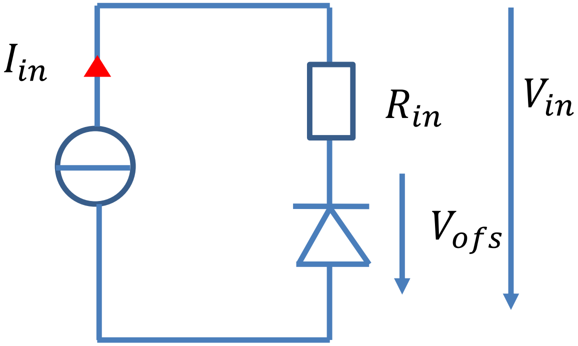


V/I Characteristic

$$V_{in} = V_{ofs} + \frac{R_3}{k} I_{in}$$







Conclusion

- Power Aspects are always relevant and challenging
  - Especially due to additional constraints in HEP experiments
- Conventional parallel/voltage based powering scheme is not viable
  - Radiation hard custom made DC/DC converters are an option for outer layers
  - Serial Powering with SLDO are used in inner layers
- Hybrid/Resonant Converters may allow DC/DC conversion in hybrid-pixel detectors
  - e.g. as an alternative to short serial chains with 3D sensors