High frequency stepdown DC-DC converter with switched capacitors

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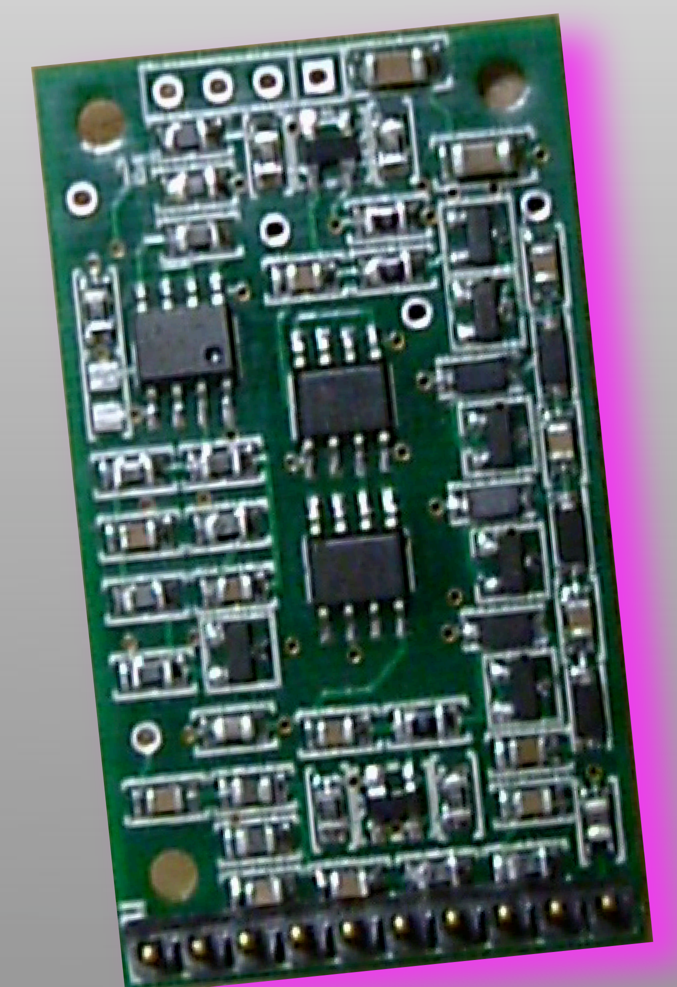


This work is part of the INFN DACEL program (BA-BO-FI-PD-TO)

Overview

- Why is it necessary ?
- The realized DC-DC converter(s)
- The power transfer efficiency
- The model of $\eta_{voltage}$ and the prototype efficiency measurements
- Conclusions

About power distribution at sLHC

Presently long cables are used to bring the low voltages (2.5V and 1.5 V) to the detectors. The voltages are remotely regulated with long sense wires.
The total current flows inside the long cables and a lot of power get dissipated there (30%).
This will be worse at sLHC because of the expected higher number of detectors channels (total current higher) and lower Vdd. We propose the introduction of "new" techniques to limit the use of Cu cables with their power loss (cooling) and high cost.

The choice is mainly among common techniques but to be used in a not standard environment: high magnetic field (B> 1T), high radiation, high density of electronics.

The DC-DC conversion from "high" voltages and low currents, to lower voltages and higher currents, implies the reduction of cables material and related power loss. The efficiency of the regulators is an important issue because the all "unconverted" power will be dissipated close to the detector. Others issues are the services required by the DC-DC regulators and their frequency of operation.

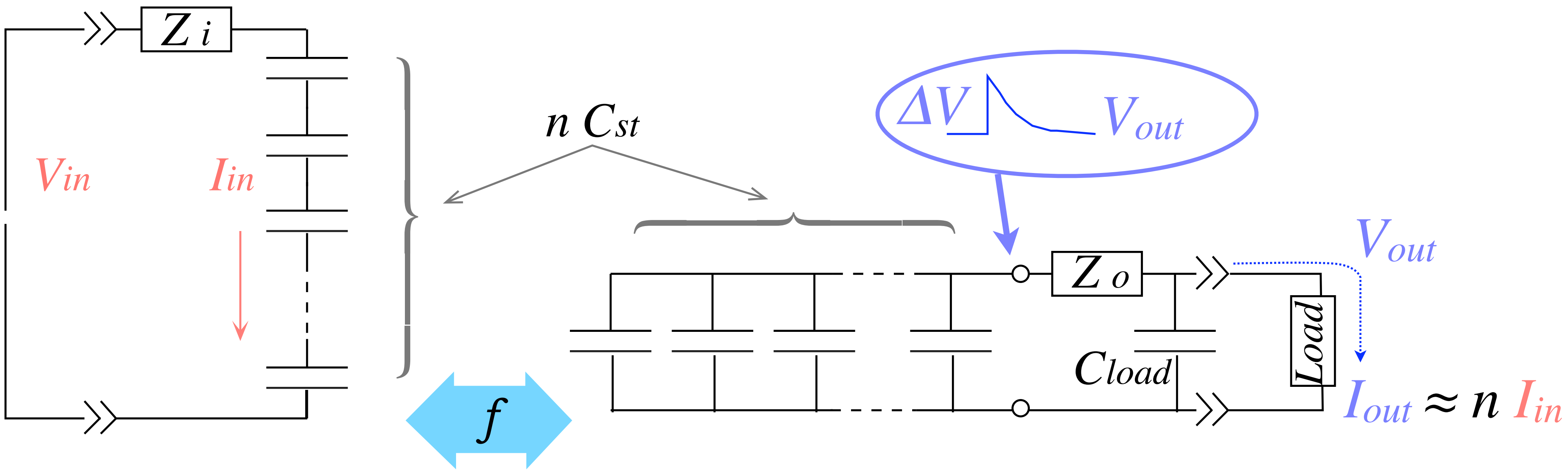
The present DC-DC converter(s)

The present work is the experimental study of two prototypes of switched capacitors converter : 1.25 V, 2.5 V both with current up to 1.5 A.

The two prototypes (same architecture) have been assembled on small PCBs with commercial SMDs. The absence of commercial power Mosfet with floating body has imposed to use diodes in place of few transistors with an additional loss of efficiency (due to the Vγ), especially at 1.25 V. This, however, does not limit the understanding of the general behavior of the converter.

Our aim is to investigate the dependance of the conversion efficiency with the frequency. We strongly believe that the DC-DC regulators must be operated at frequencies higher than the bandwidth of the signal electronics (few MHz) to preserve the quality of the signals.

"charge pump" regulator: general scheme



phase 1:
series capacitors charge

phase 2:
parallel capacitors discharge

$$V_{in} \approx n \times V_{out} + \frac{I_{out}}{f \times C_{st}}$$

minimum

overvoltage ≈ $nx\Delta V$

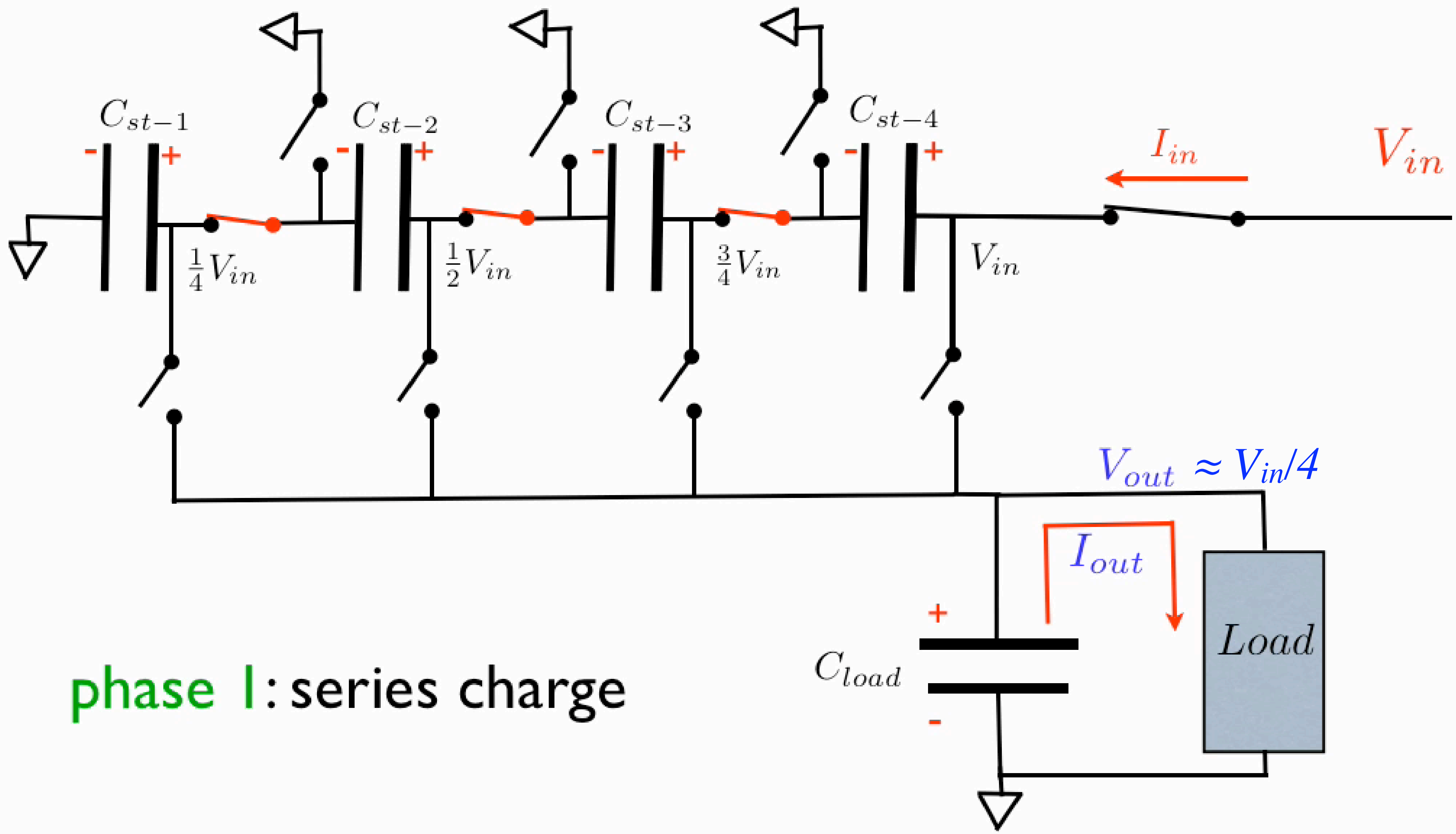
$$V_{out}\left(n, I_{out}, V_{in}, f\right)$$

present prototypes :

n = 4 , C_{st} ≈ 470 nF, C_{load} ≈ 220 μF (>> C_{st})

switches and capacitors network

$$N_{switches} = (3 \times n) - 1 \;, \; N_{switches} = 11 \;\; for\; n = 4$$

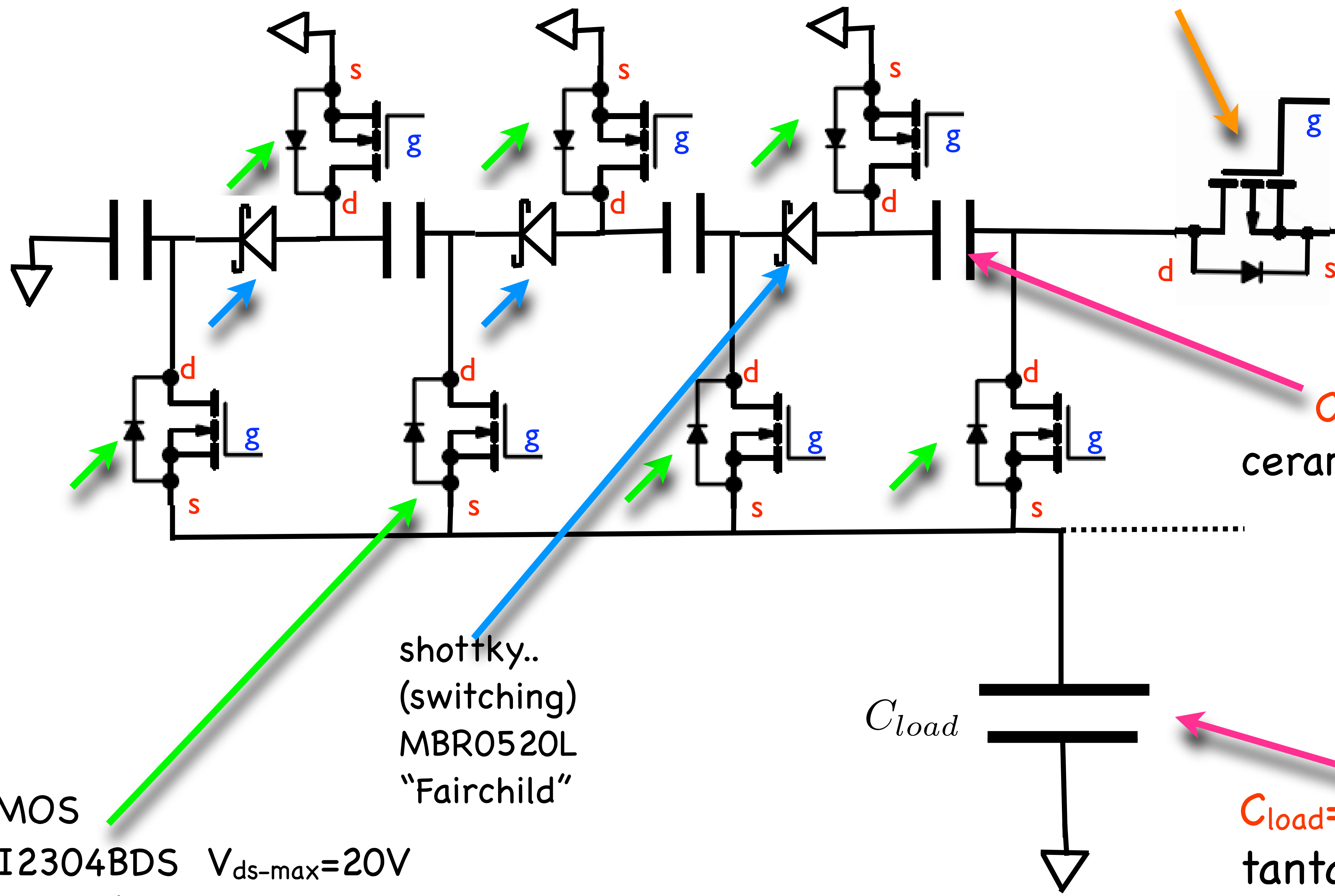


C_{st}=470nF (ceramic "Kemet")

C_{load}=220μF (tantalum "Kemet")

used components.....

pMOS
SI2303BDS V_{ds-max}=30V
"Vishay"
R_{on}~0.2Ω@Vgs≈-5V



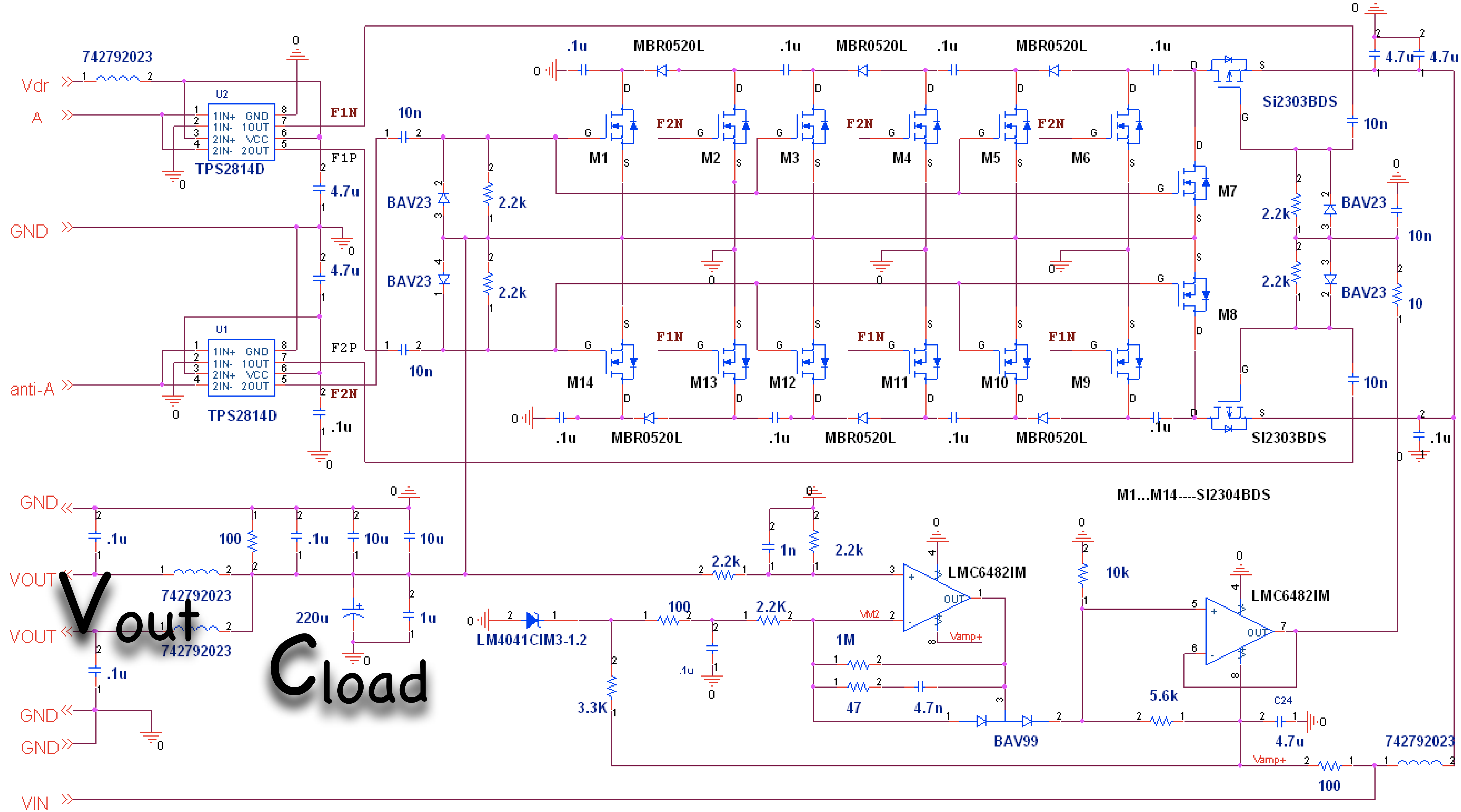
C_{st}=470nF
ceramic "KEMET"

shottky..
(switching)
MBR0520L
"Fairchild"

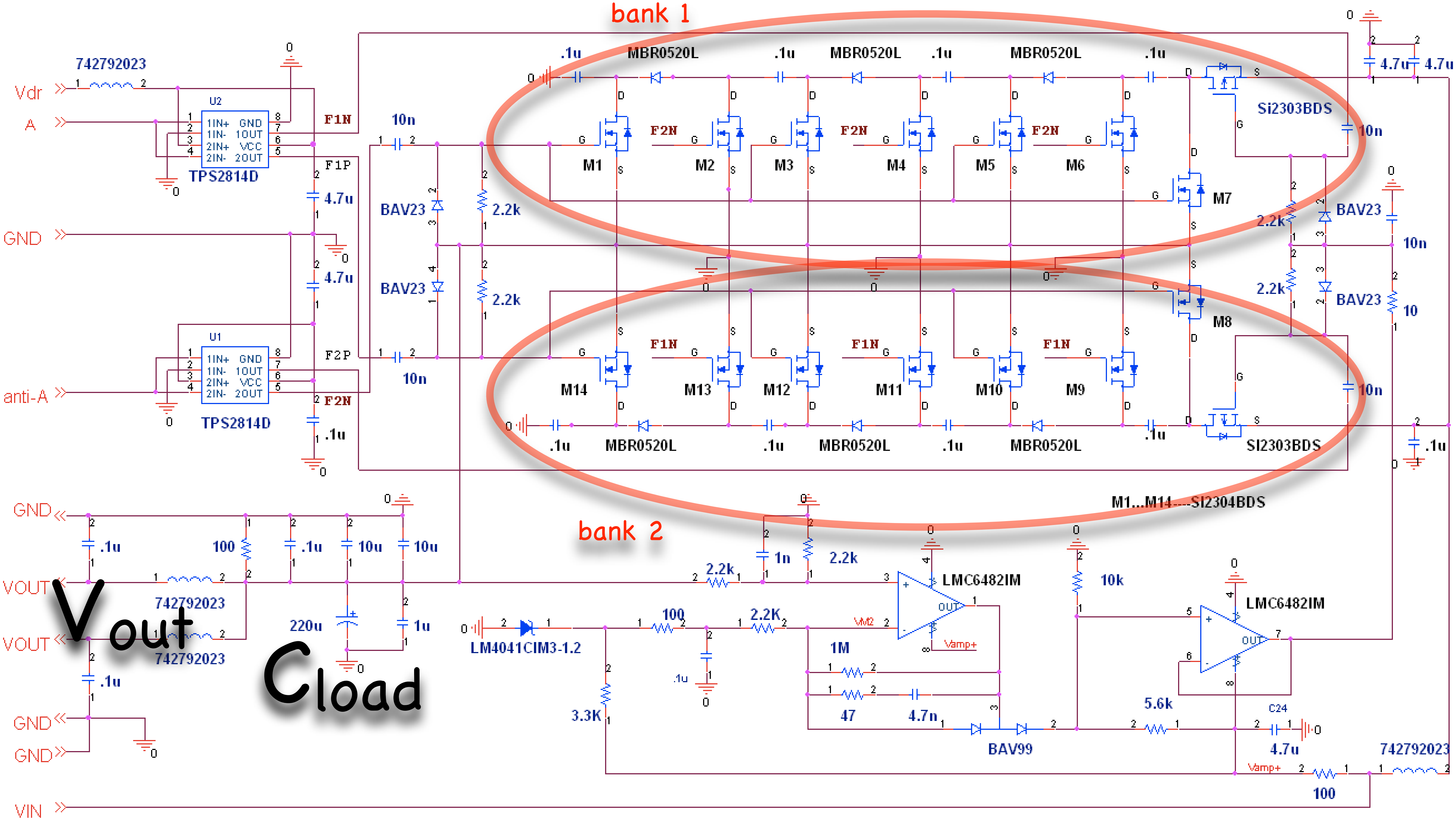
C_{load}=220μF
tantalum "KEMET"

nMOS
SI2304BDS V_{ds-max}=20V
"Vishay" R_{on}~0.06Ω@ Vgs≈5V

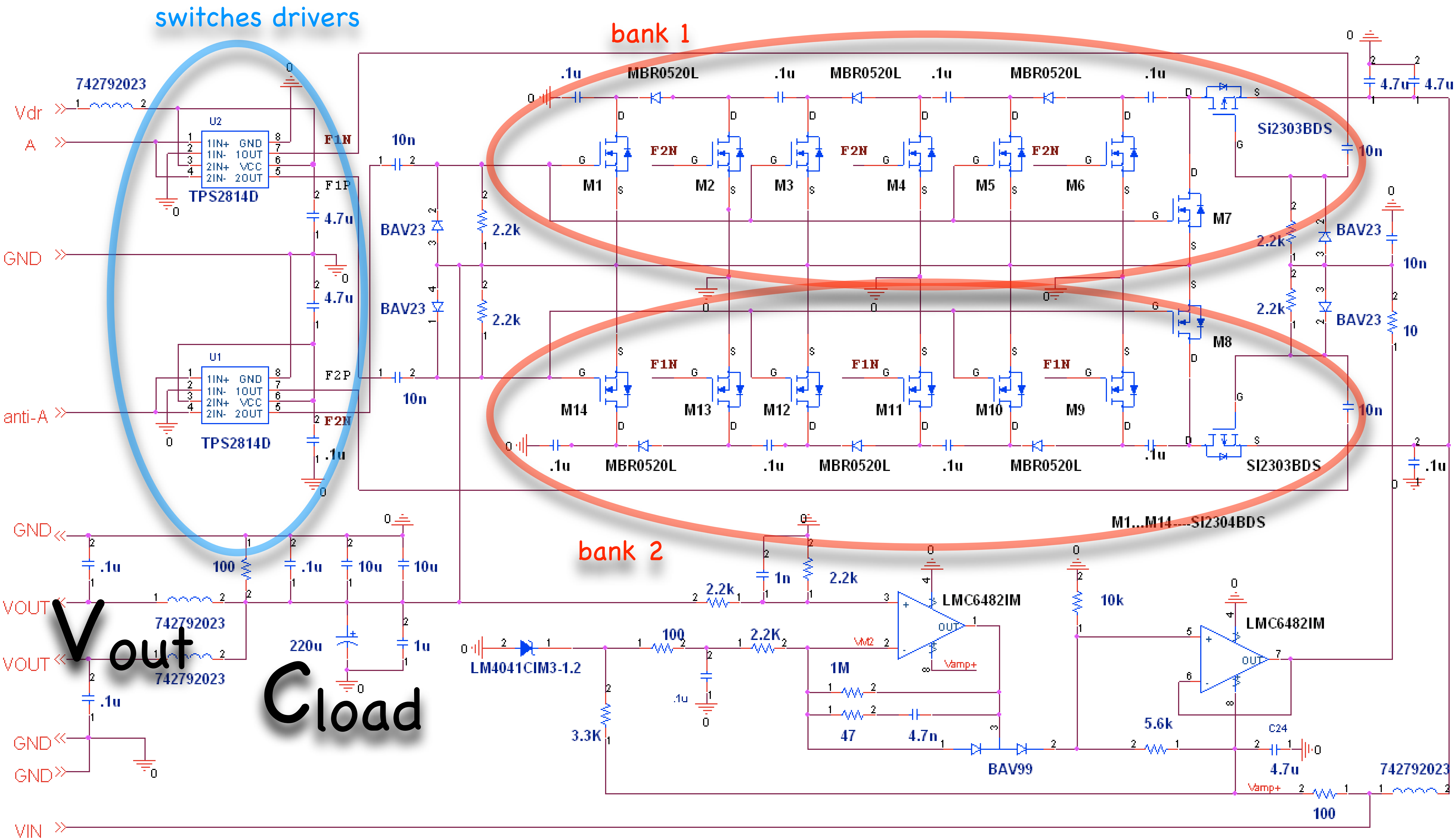
prototype schematic



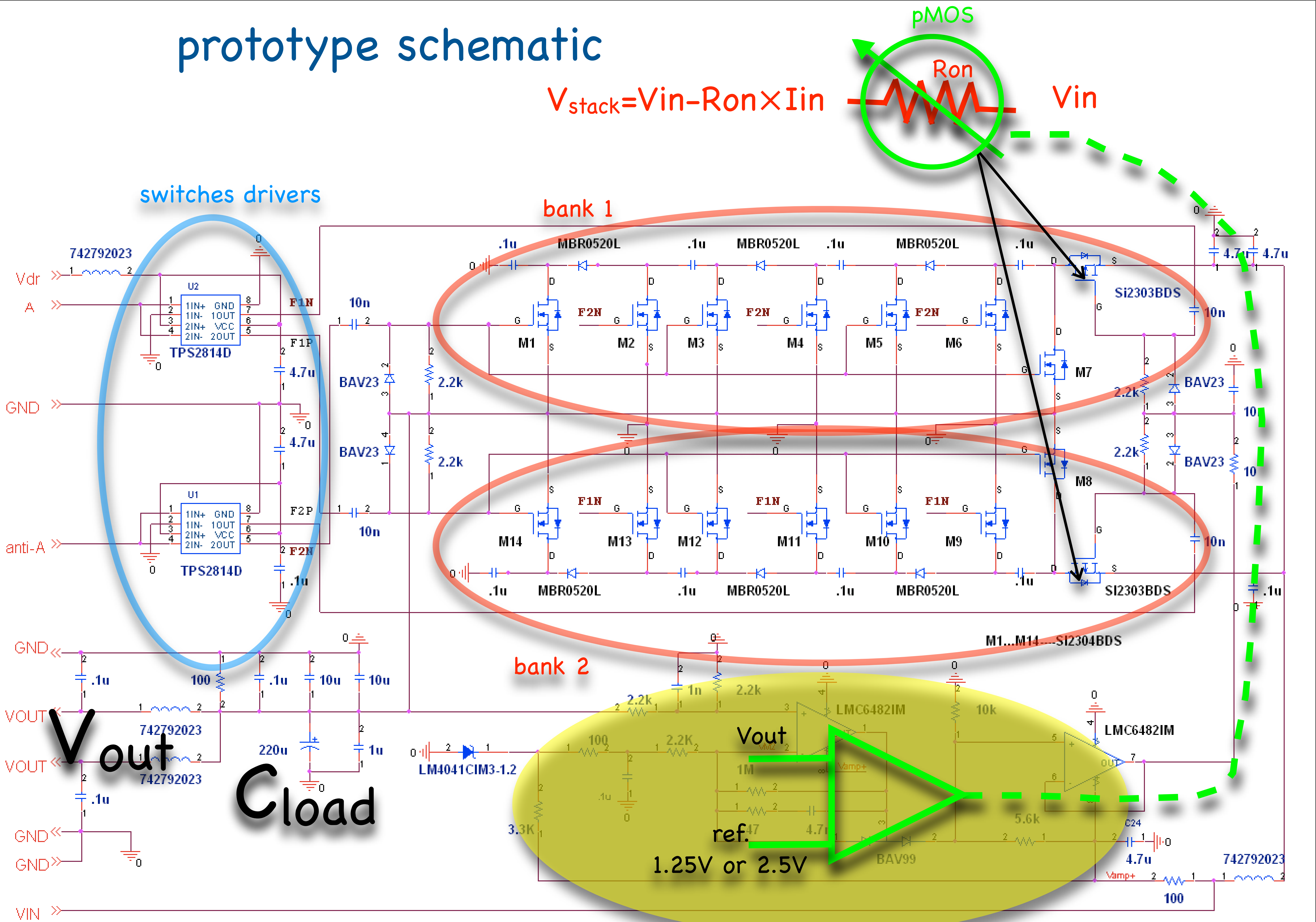
prototype schematic



prototype schematic



prototype schematic



Power efficiency : definition

PWR_{in}	input power
PWR_{out}	output power
PWR_{dr}	power to operate the switches

$$\eta = \frac{PWR_{out}}{PWR_{in} + PWD_{dr}} = \frac{PWR_{out}}{PWR_{in}} \times \frac{PWR_{in}}{PWR_{in} + PWR_{dr}}$$

η_c can be written as : $$\eta_c = \frac{PWR_{out}}{PWR_{in}} = \frac{V_{out}}{V_{in}} \times \frac{I_{out}}{I_{in}}$$

... or even better $$\eta_c = \left(\frac{n \times V_{out}}{V_{in}}\right) \times \left(\frac{I_{out}}{n \times I_{in}}\right) = \eta_{voltage} \times \eta_{current}$$

$\eta_{voltage}$ ≤ 1 (1 is a limit case)

$\eta_{current}$ ≤ 1 (1 is the theoretical case)

n is the conversion factor : 4, in our regulator

Power efficiency : definition

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η_c
efficiency due to the conversion process

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$\eta_{voltage}$ ≤ 1 (1 is a limit case)

$\eta_{current}$ ≤ 1 (1 is the theoretical case)

n is the conversion factor : 4, in our regulator

Power efficiency : definition

η_d

efficiency due to switches drivers

$$\eta = \frac{PWR_{out}}{PWR_{in} + PWD_{dr}} = \frac{PWR_{out}}{PWR_{in}} \times \frac{PWR_{in}}{PWR_{in} + PWR_{dr}}$$

η_c

efficiency due to the conversion process

PWR_{in}	input power
PWR_{out}	output power
PWR_{dr}	power to operate the switches

η_c can be written as :

$$\eta_c = \frac{PWR_{out}}{PWR_{in}} = \frac{V_{out}}{V_{in}} \times \frac{I_{out}}{I_{in}}$$

… or even better

$$\eta_c = \left(\frac{n \times V_{out}}{V_{in}}\right) \times \left(\frac{I_{out}}{n \times I_{in}}\right) = \eta_{voltage} \times \eta_{current}$$

$\eta_{voltage} \leq 1$ (1 is a limit case)

$\eta_{current} \leq 1$ (1 is the theoretical case)

n is the conversion factor : 4, in our regulator

$\eta_{voltage}$: voltage efficiency

From slide 5 the input voltage necessary for provide the I_{out} current at the voltage V_{out} must be at least

$$V_{in} = n \times V_{out} + \frac{I_{out}}{f \times C_{st}}$$

charge to supply in one period

$f = 2 \times f_{bank}$

so a very "basic" expression for the voltage efficiency is:

$$\eta_{voltage} = \frac{n\,V_{out}}{V_{in}} = \frac{1}{1 + \frac{I_{out}}{V_{out}} \times \frac{1}{n \times f \times C_{st}}} < 1$$

1 is the ideal value to aim.

Large values for n and f should be chosen but they have also implications on the other terms of the global efficiency: hence the best choice must be a compromise.

Also C_{st} should be taken large, but it too has some implications in the efficiency.

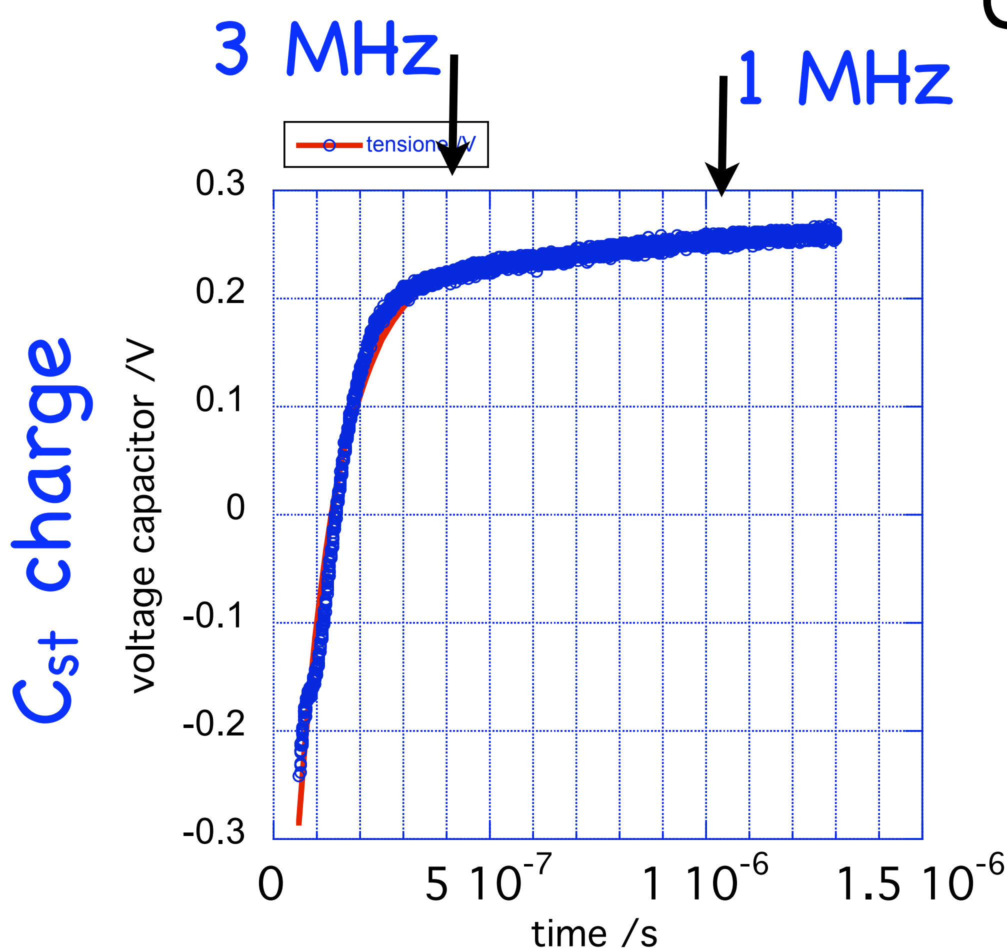
The actual dependence of $\eta_{voltage}$ require a more complex model.

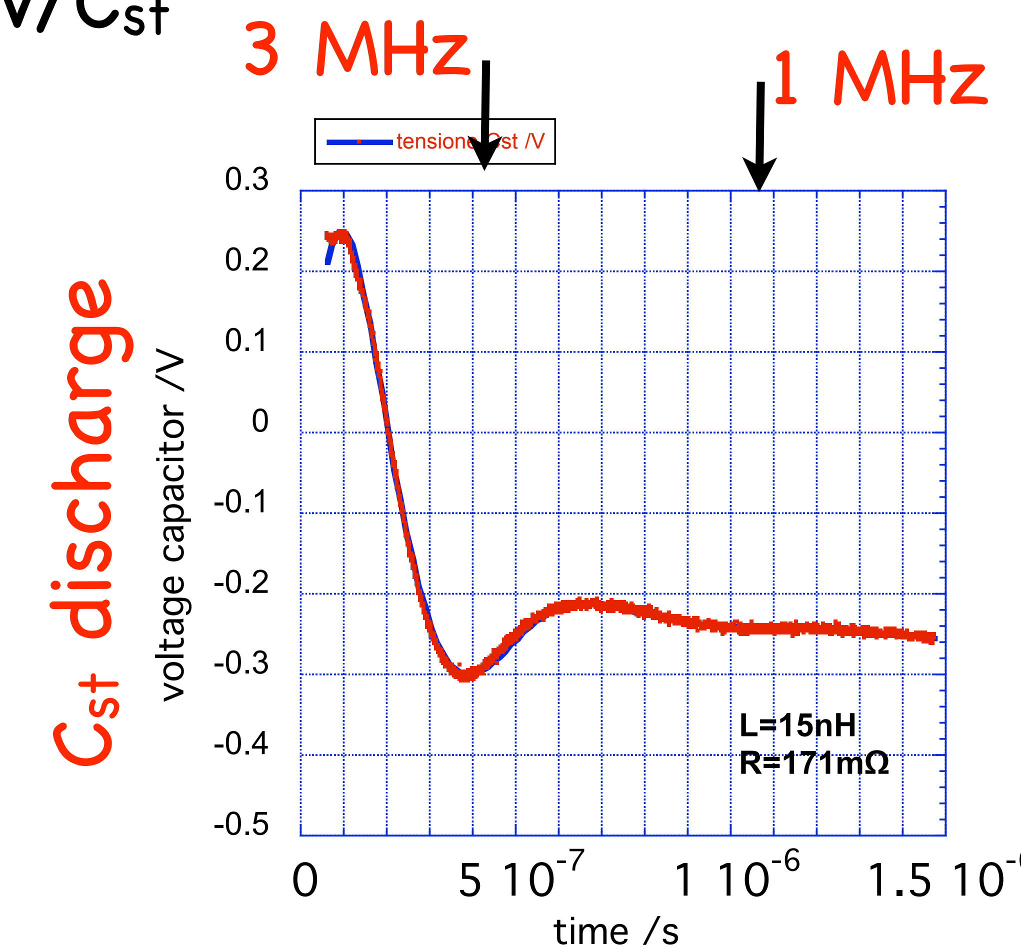
Charge / Discharge of the capacitors

$\eta_{voltage}$ depends also on the time evolution both of the charge and discharge of the C_{st} capacitors.

In the time available for the charges transfers (frequency period) the involved charge is given by

$$Q_{transfer} = \Delta V / C_{st}$$





$$\Delta V_C = \frac{V_{in} - 3 \times V_\gamma}{4} \times \left(1 - e^{-\frac{t - t_0}{\tau}}\right) + \frac{3}{4} V_\gamma \times \frac{t - t_0}{\tau_D}$$

$$\Delta V_D = \frac{\Delta V_C}{\cos(\delta)} e^{-\beta (t - t_0)} \cos[\omega_1 (t - t_0) - \delta]$$

$\eta_{voltage}$: voltage efficiency formula

Starting from the charge/discharge shapes we derive the final expression for the $\eta_{voltage}$ of the regulator

$$\eta_{voltage} = \frac{1}{1 + \frac{3}{4}\times\frac{V_\gamma}{V_{out}} + \frac{I_{out}}{V_{out}}\times\frac{1}{4\times f\times C_{st}}\times\left[\left(1-\frac{12\times V_\gamma\times f\times C_{st}}{\tau_S\times I_{out}}\times T\right)\frac{1}{h(T)}+\frac{g(T)}{1-g(T)}\right]}$$

$$h(T) = (1 - e^{-\frac{(T-\tau_{mc})}{\tau_c}})$$ (exponential of the charging shape)

$$g(T) = \frac{1}{\cos(\delta)} e^{-\beta\,(T-\tau_{ms})} \cos\left[\,\omega_1 (T-\tau_{ms}) - \delta\,\right]$$ (discharging shape)

T is the time at disposition for the transfer: T= 1/f = 1/2xf_{bank}.

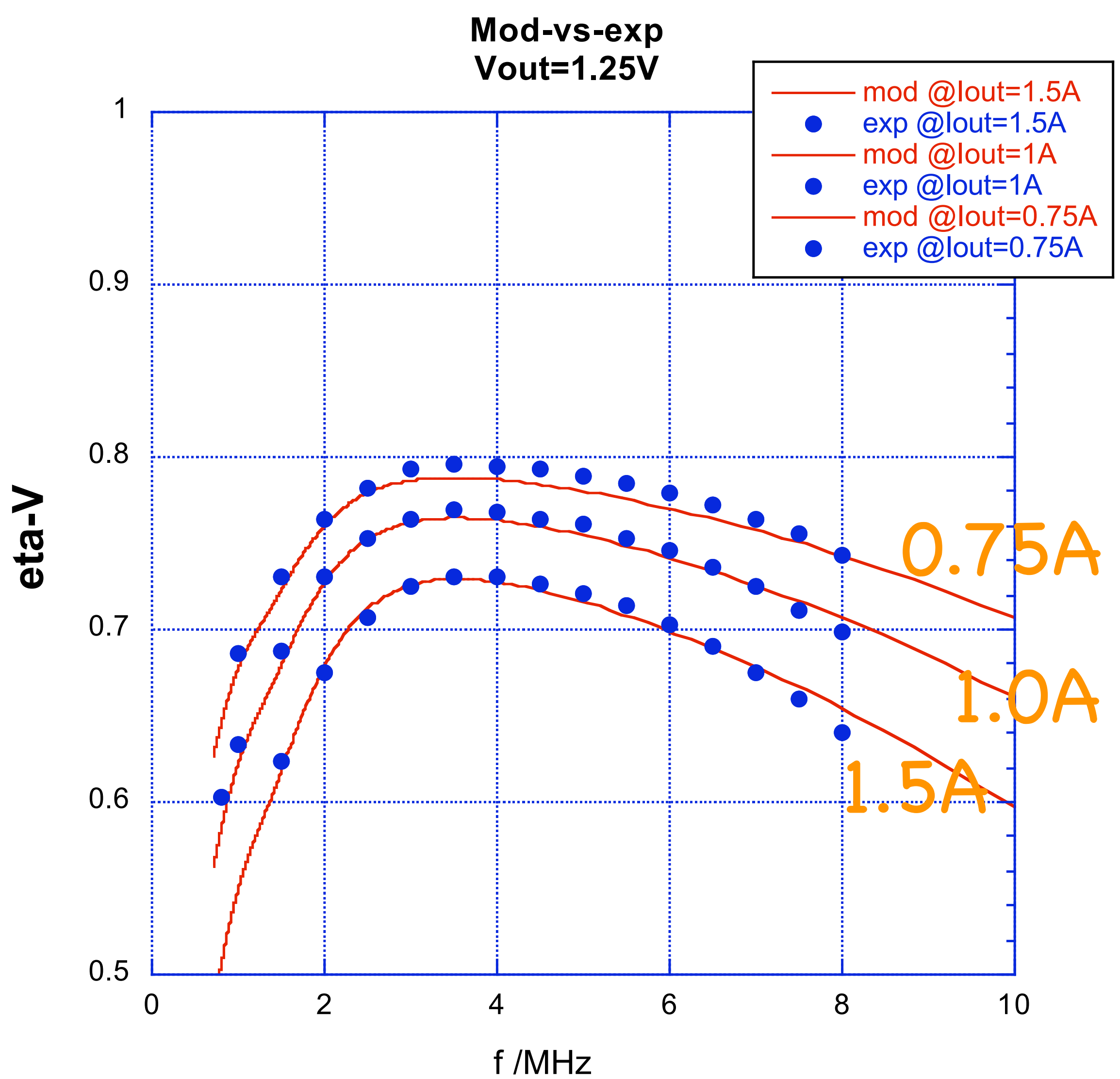
τ_{mc} and τ_{ms} are dead times due to the project (can be changed)

τ_s is a suitable time scale (≈ 7.5μs)

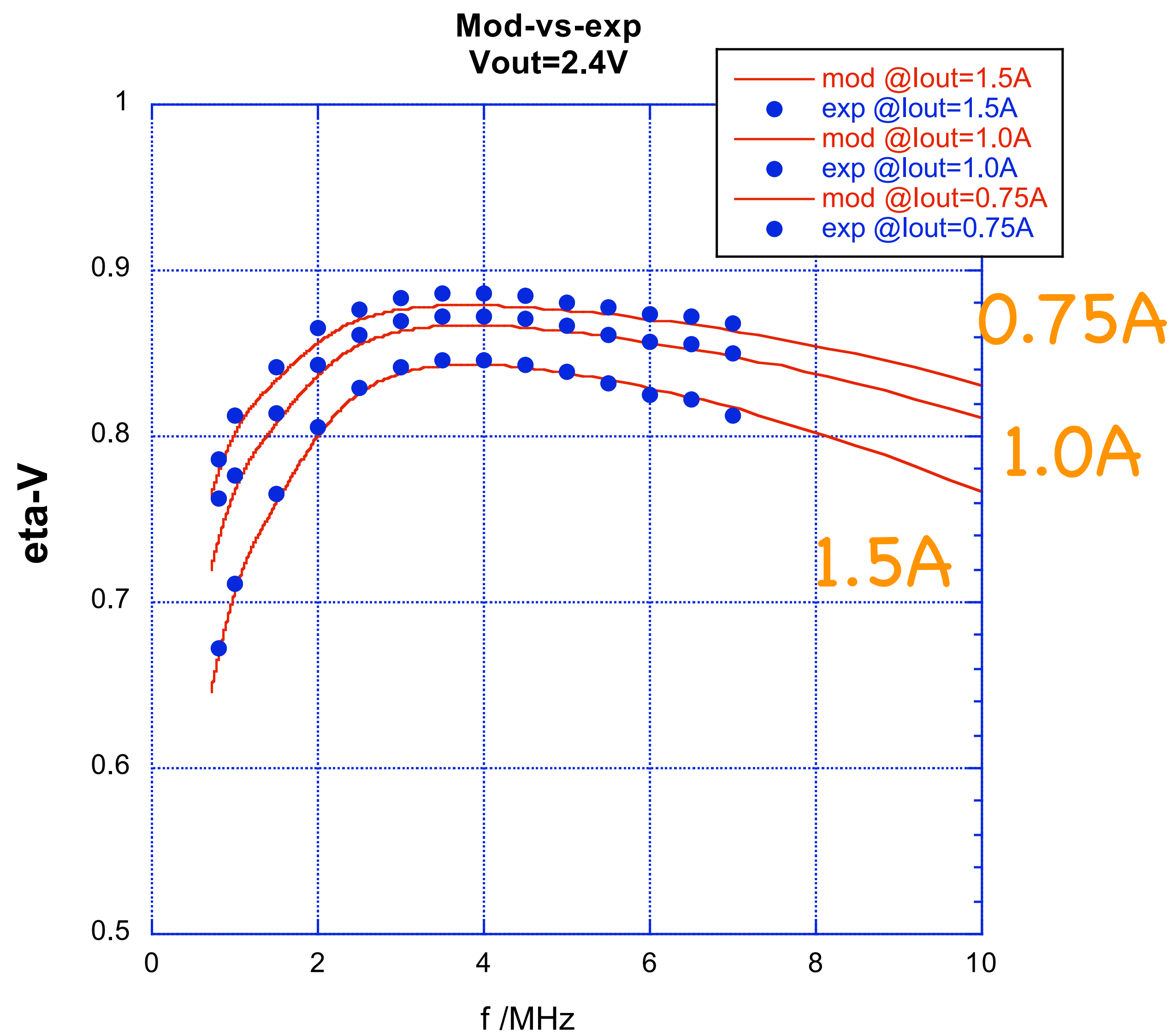
V_Υ ≈ 0.3 V is due to the diodes

$\eta_{voltage}$ vs frequency : formula versus experimental data

1.25V



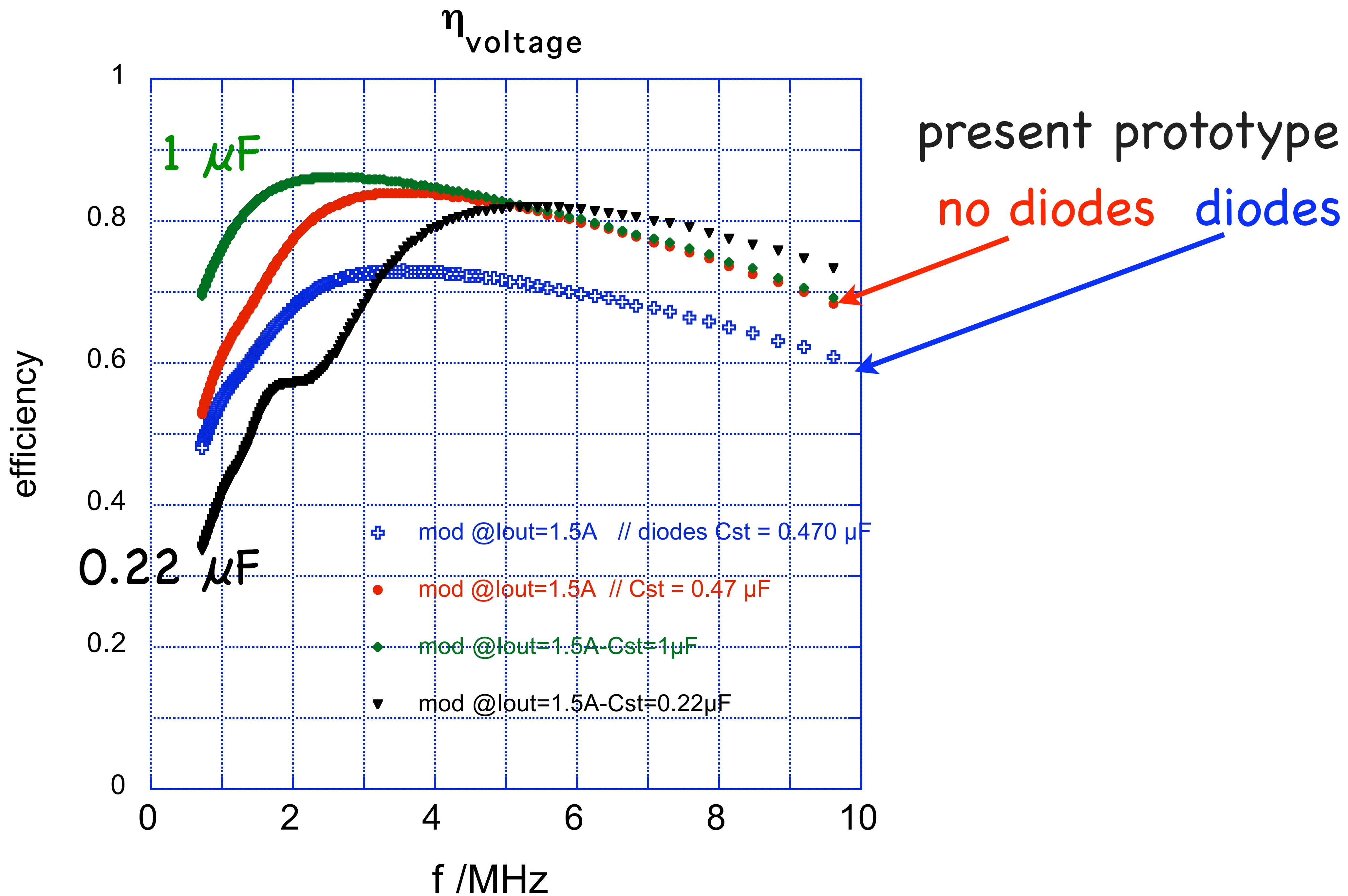
2.5V



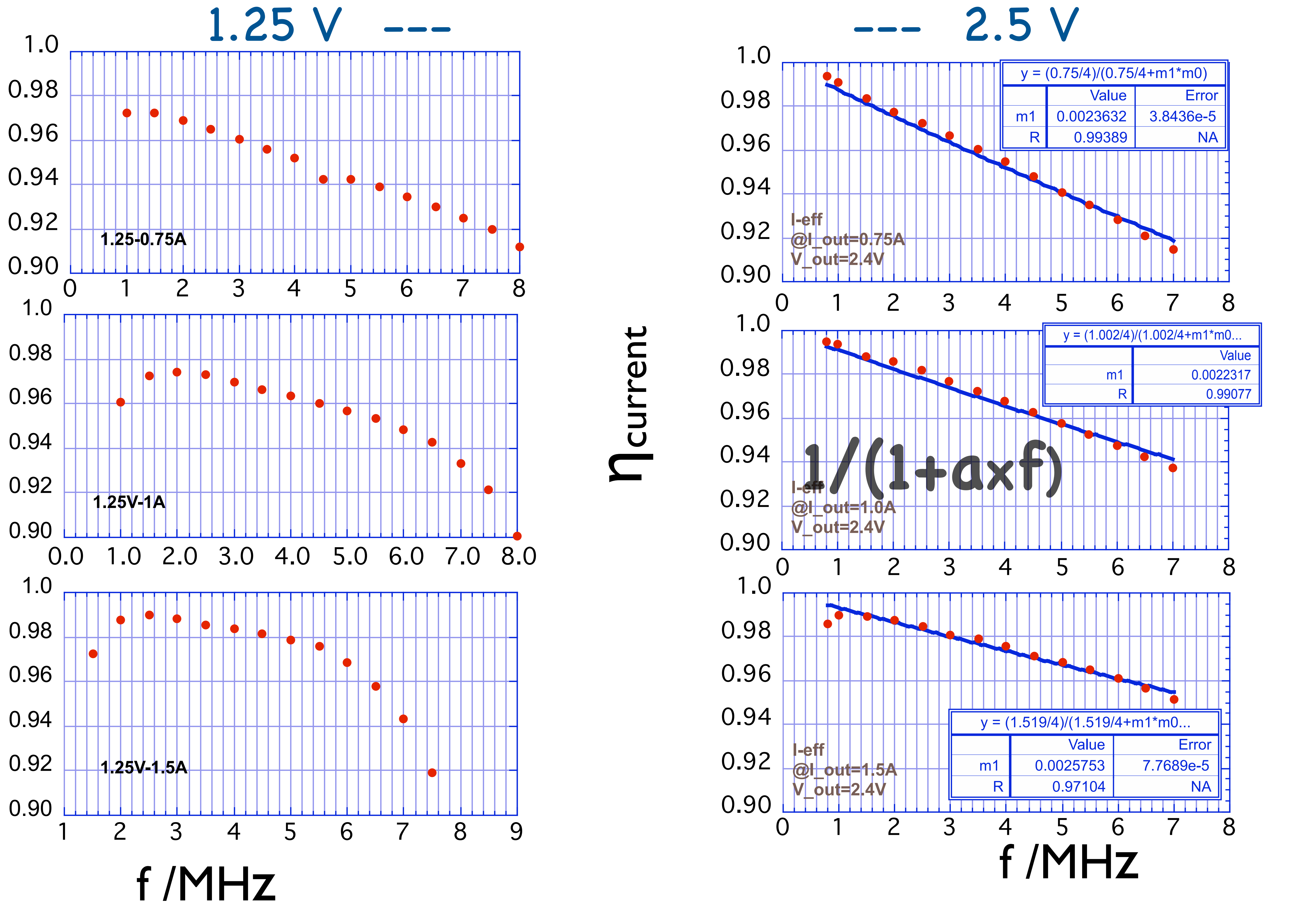
max. variation ≤2%

predictions of the model for 1.25V prototype

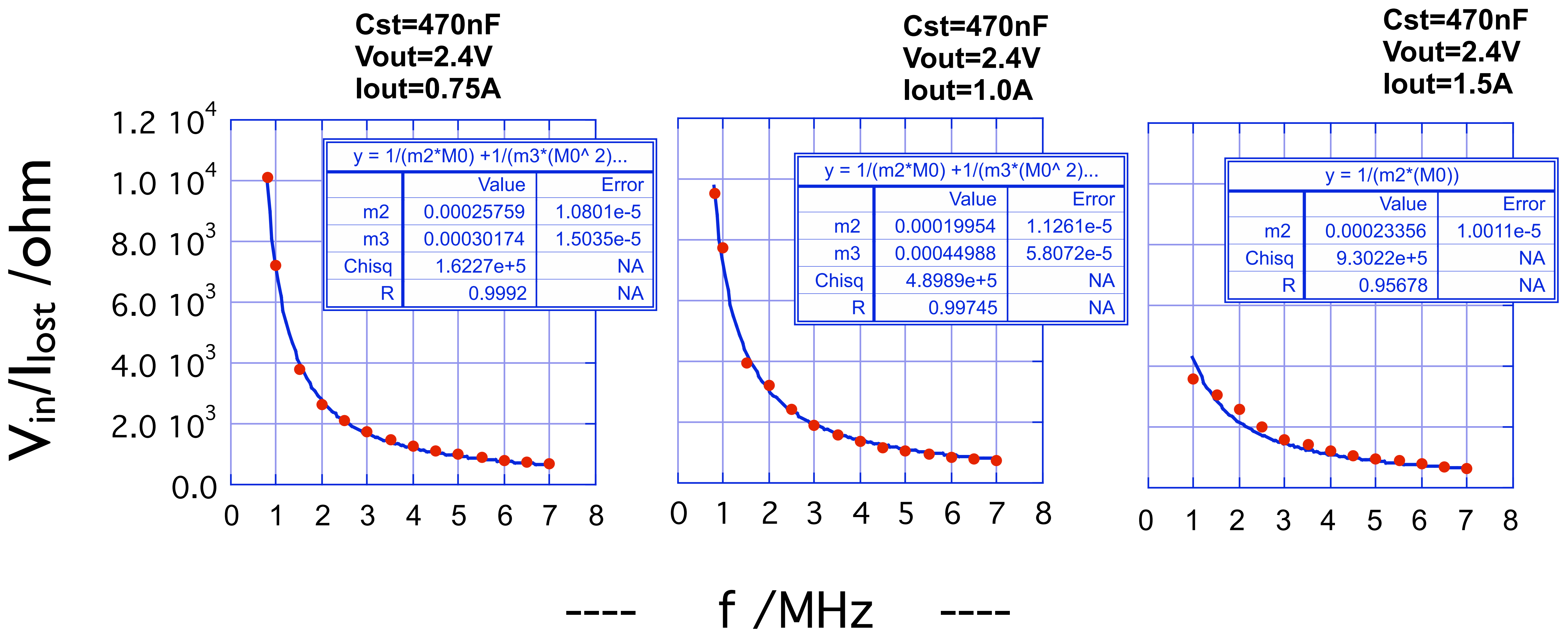
Using the voltage efficiency formula we evaluate the behavior of the present prototypes without diodes and for different values of C_{st}.



$\eta_{current}$ efficiency: well above the 90%



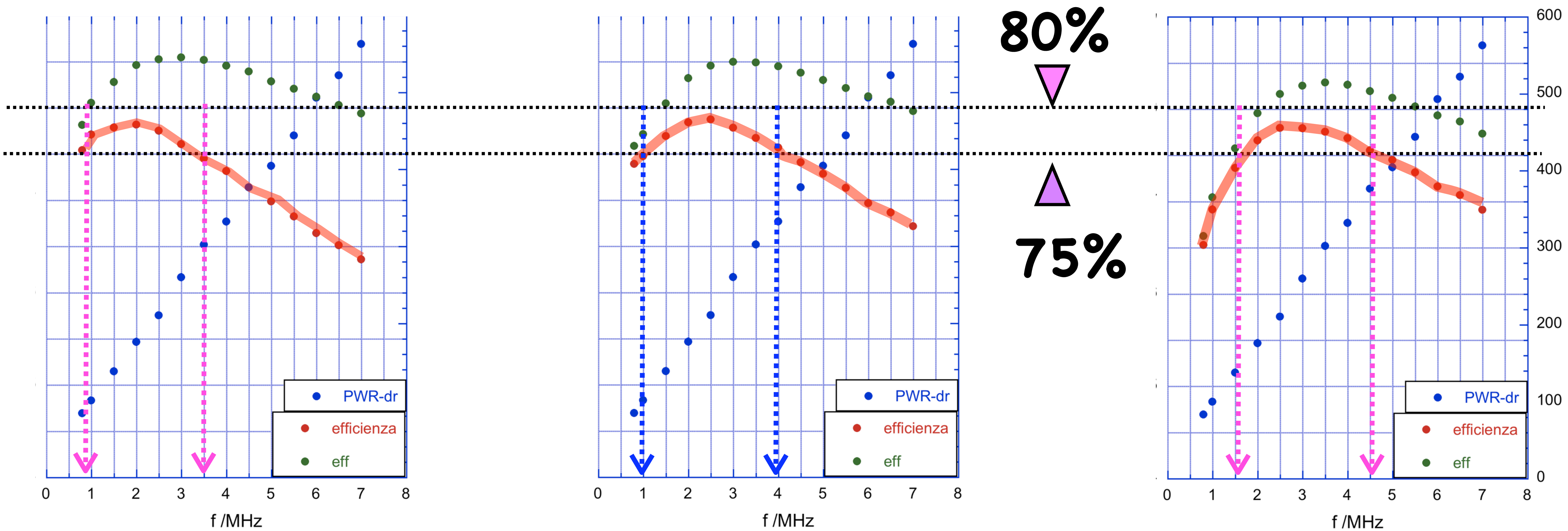
leaking impedance:



$I_{lost} = I_{in} - I_{out} /4$

$$V_{in}/I_{lost} \approx a/f + b/f^2$$

Prototype efficiency (all included)



0.75A 1.0A 1.5A

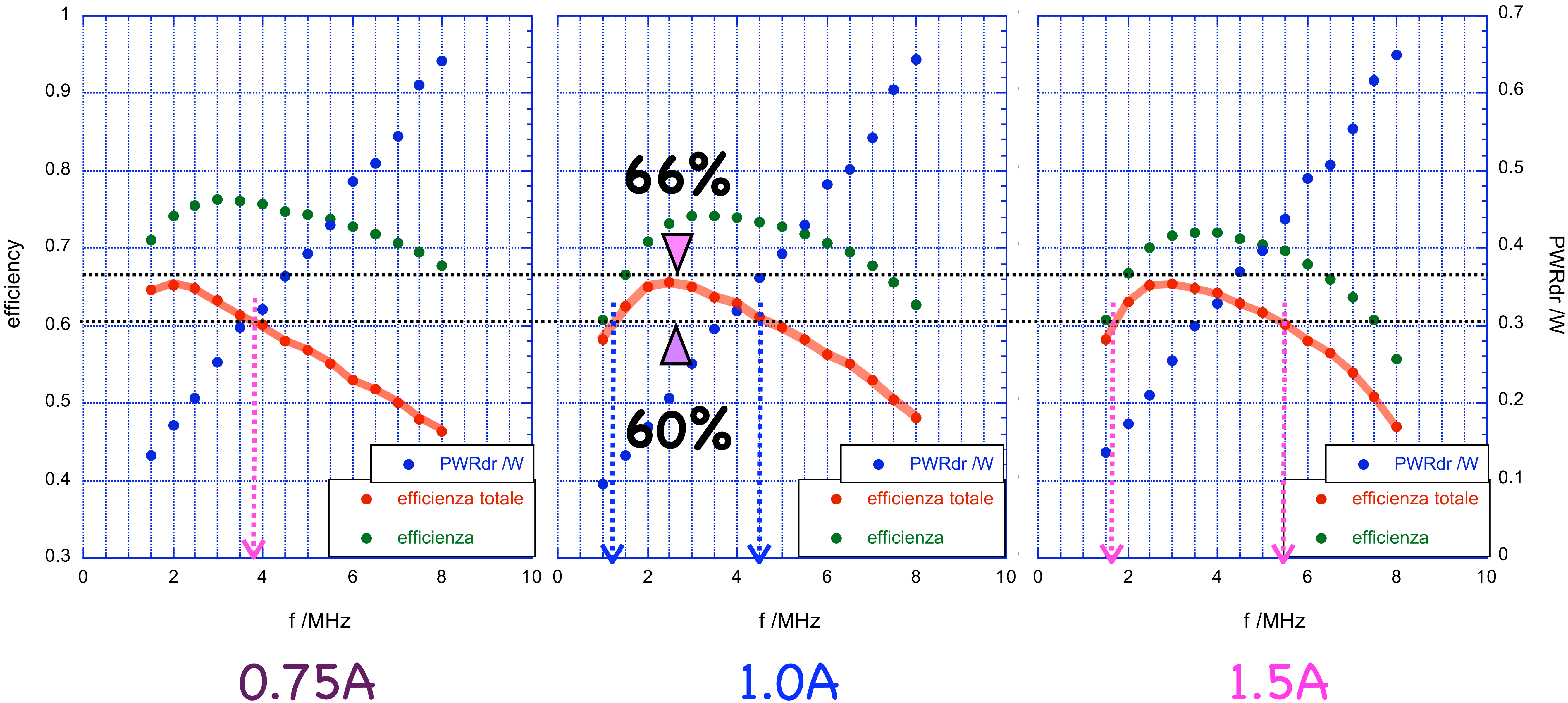
Drivers power: 5 mW/ (MHz x gate)

-7%

-1MHz **...frequency position of the maximum efficiency**

Vout=2.4V

Prototype efficiency (all included)



Vout=1.25V

Conclusions:

Two prototypes of charge pump voltage regulator have been realized with outputs of 2.5 V (≤1.5A) and 1.25 V (≤1.5A) with the aim of defining an integrated circuit project to be deployed in an hostile (high B and high radiation) environment .

The actual efficiency values obtained at operating frequencies up to 4-5 MHz are (75-80)% @ 2.5V and (60-65)% @ 1.25V

The possibility of improving the 1.25 V efficiency of about 10%, by replacing the diodes with floating body mosfets, has been shown .

The optimization of the switches drivers is still an open question.

Operation frequencies up to 5 MHz have been demonstrated and improvements are possible by carefully optimizing the layout.

Thanks for your attention