# CLIC Drive Beam Klystron Modulators

# R&D status & prospects

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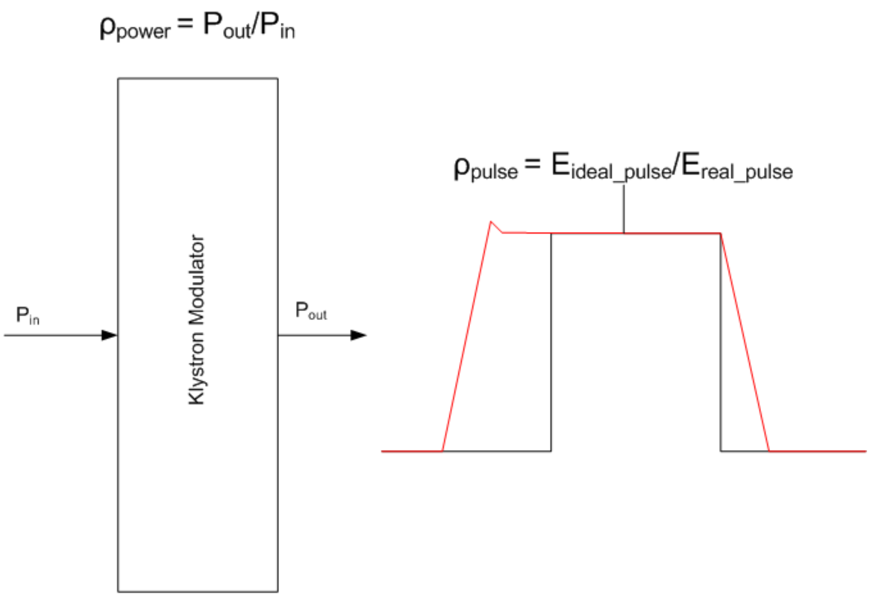
# Objectives

Everything (for the modulator) starts here…

| | |
|---|---|
| Peak power/klystron | 15 MW |
| Train length after injection | 140 μs |
| Repetition rate | 50 Hz |
| Klystrons efficiency | 65% (70% target) |
| Overall modulator efficiency | 89% |
| Phase precision | 0.05° @ 1 GHz (first 10% of the DB linac)<br>0.2° @ 1 GHz (next 90% of the DB linac) |
| Nb of klystrons (DB linac) | 2x 797 = 1594 |

# Modulator Efficiency

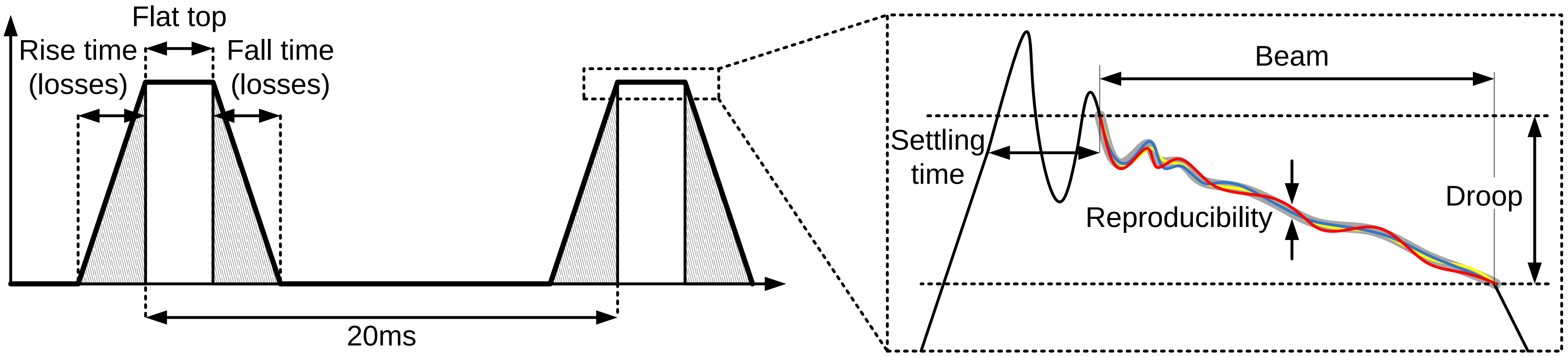



$$\rho_{modulator} = \rho_{power} * \rho_{pulse}$$

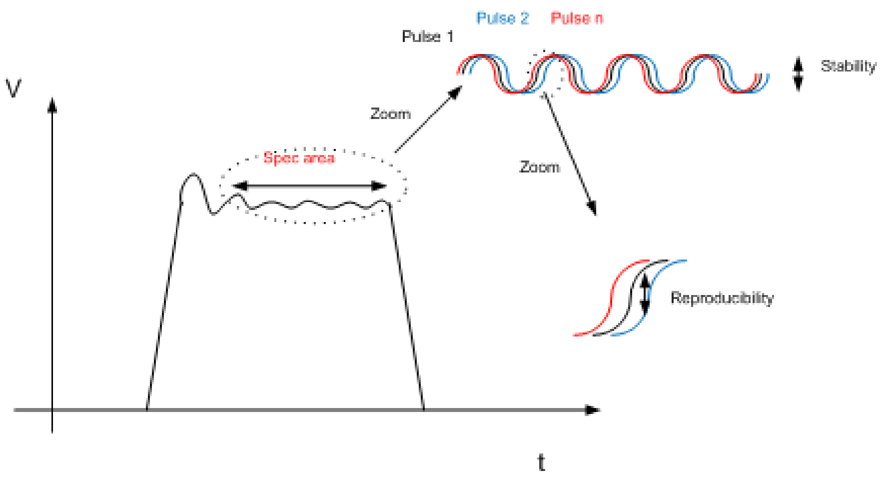
| | |
|---|---|
| Useful flat-top Energy | 22MW*140µs = 3.08kJ |
| Rise/fall time energy | 22MW*5µs*2/3= 0.07kJ |
| Set-up time energy | 22MW*5µs = 0.09kJ |
| **Pulse efficiency** | **0.95** |
| Pulse forming system efficiency | 0.98 |
| Charger efficiency | 0.96 |
| **Power efficiency** | **0.94** |
| **Overall Modulator efficiency** | **89%** |

# Pulse requirements

- Rise time: needed to reach the requested voltage.
- Settling time: needed to damp oscillations within the droop window.
- Droop: window in which remaining reproducible oscillations can be cancelled by RF feed-forward.
- Reproducibility: maximum difference allowed between two consecutive pulses.
- Fall time: time for voltage to return to zero.



# Converters reproducibility




10^-5 → Reproducibility not even close to the some ever reached on pulse applications

Not a common topic, no defined theory on the issue so far → We propose new theory

Pulse-to-pulse reproducibility of a switching power converter mainly depends on : switches jitter, switching frequency, measurement reproducibility.

What is the influence of the switches jitter? What is a typical jitter of an IGBT? We are trying to answer these questions….

Some numbers (example):

Out of Spec!

- Buck; Vin=3000 V; D=50%; Vout=1500V; Stab Spec=10^-3 → 1.5V

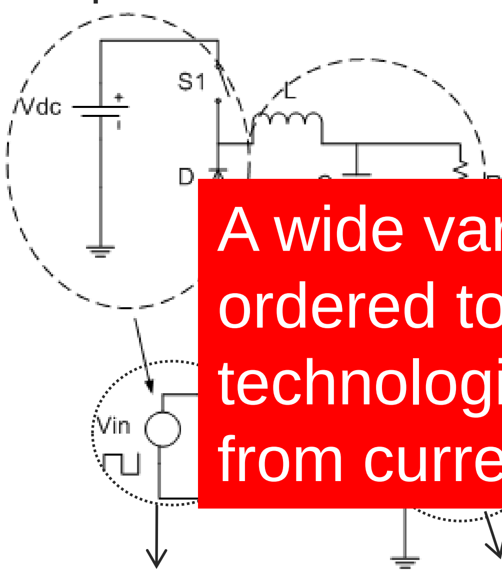
L=25mH; f=25kHz; C=4uF; ΔVR Spec=10^-5→ 15mV → Maximal jitter **50ns**

- Semikron 1203GB172-2DW (IGBT with Driver) → jitter = 150ns → Expected **47mV** of ΔVR

# Converters reproducibility

**Study approach**

Example: Buck converter




Passive
Part model
(frequency)

Active
Part model
(frequency)

$$H(s) = \frac{\frac{R}{1+sRC}}{\frac{R}{1+sRC}+sL} = \frac{R}{s^2RLC+sL+R}$$

$$(S_N f)(x) = \frac{a_0}{2} + \sum_{n=1}^{N}[a_n\cos(nx) + b_n\sin(nx)], \qquad N \geq 0$$

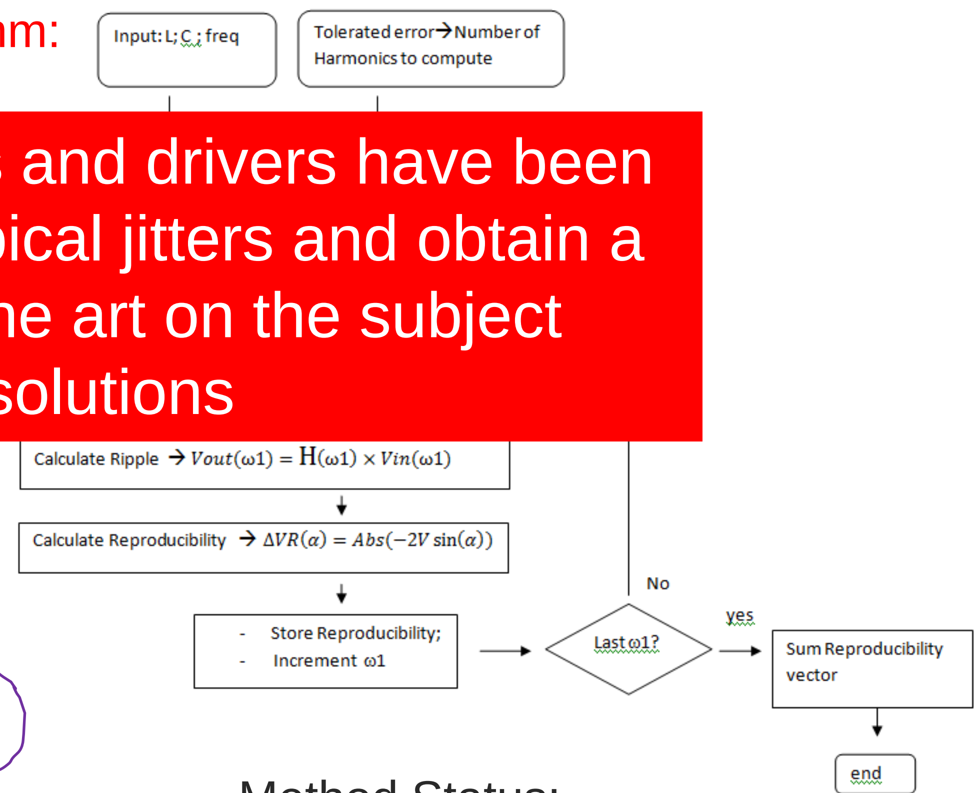
For each harmonic Reproducibility can be define as:

$$\begin{cases} \Delta Vout_1(t,\alpha) = V_1 \times \sin(\omega_1 t \pm \alpha_1) \\ \Delta Vout_2(t,\alpha) = V_2 \times \sin(\omega_2 t \pm \alpha_2) \\ \Delta VR(t,\alpha) = \Delta Vout_1(t,\alpha_1) - \Delta Vout_2(t,\alpha_2) \end{cases}$$

Some trigonometry

$$\Delta VR(\alpha) = Abs(-2V\sin(\alpha))$$

Algorithm:

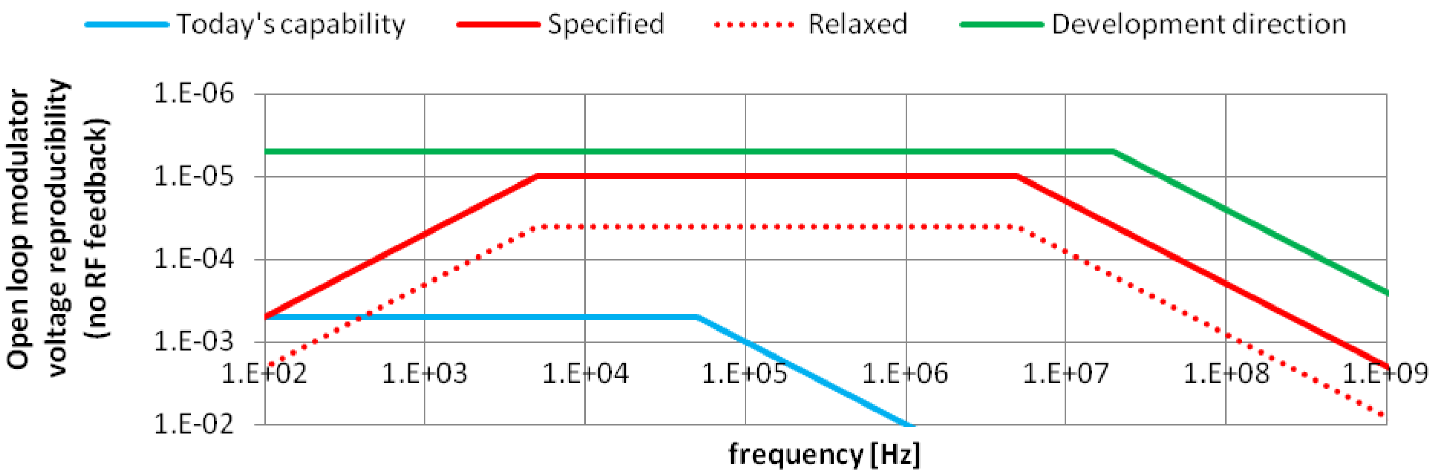



A wide variety of IGBTs and drivers have been ordered to measure typical jitters and obtain a technological state of the art on the subject from current industrial solutions

Method Status:

Validated (analytical vs. numerical methods)

# Pulsed HV measurements




If measurement performance does not exceed the red line, performance cannot be demonstrated

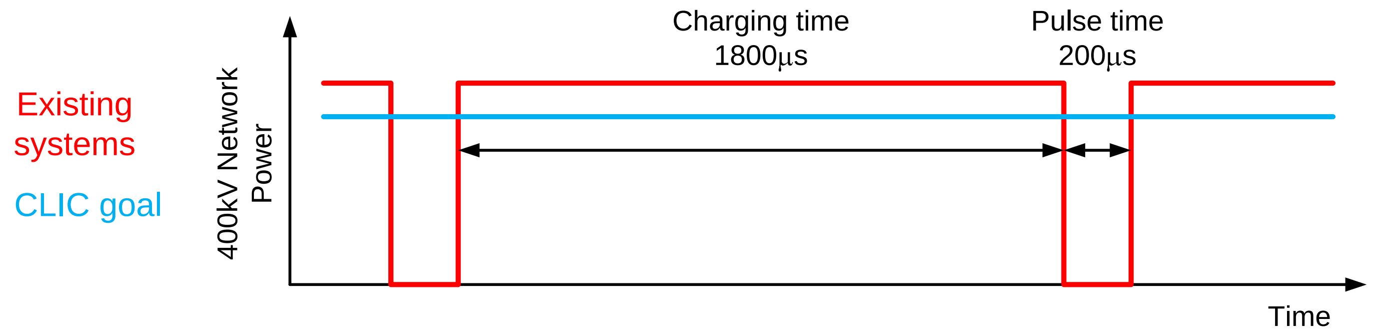
Between the red and green lines, performance can be measured and sorted to meet requirements

If measurement performance exceeds the green line, feedback on the output voltage may be implemented to fulfill the specification (provided that a 300A/5MHz active voltage compensation can be implemented!)

- **The use of indirect high bandwidth measurement on RF phase to implement a feedback on the modulator voltage and/or on the klystron RF_input modulation must be studied in parallel.**
- Strongly recommend that phase reproducibility must not rely ONLY on modulator performance

# Power from network

- Modulator charging is usually stopped before the output pulse generation.
  - Induces large power transients on the 400kV network and can affect grid stability and quality.
- Studies of methods to assure a constant power load to the grid have begun.

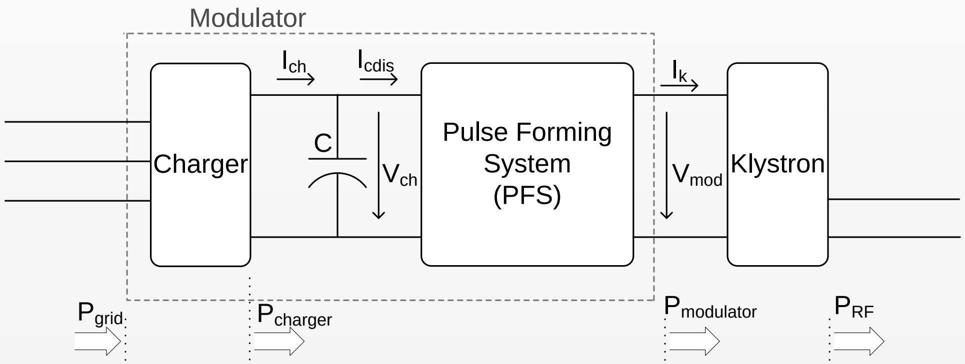



- Other issues will also to be considered (eg how to manage modulator power shutdown, finding optimal charger efficiency, etc).

- **R&D started in 2011 (1 fellow).**

# POWER FROM NETWORK: R&D OBJECTIVES

- Propose design solution for the modulators charging sub-system minimizing the grid power fluctuation.




- Design the control strategy of capacitor chargers for minimum power fluctuation.
  - Problematic:

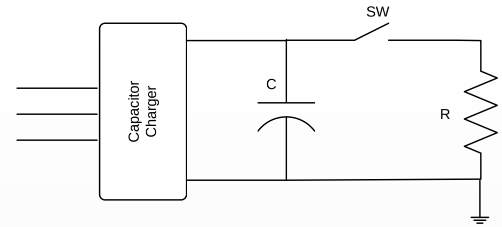
Grid power fluctuation

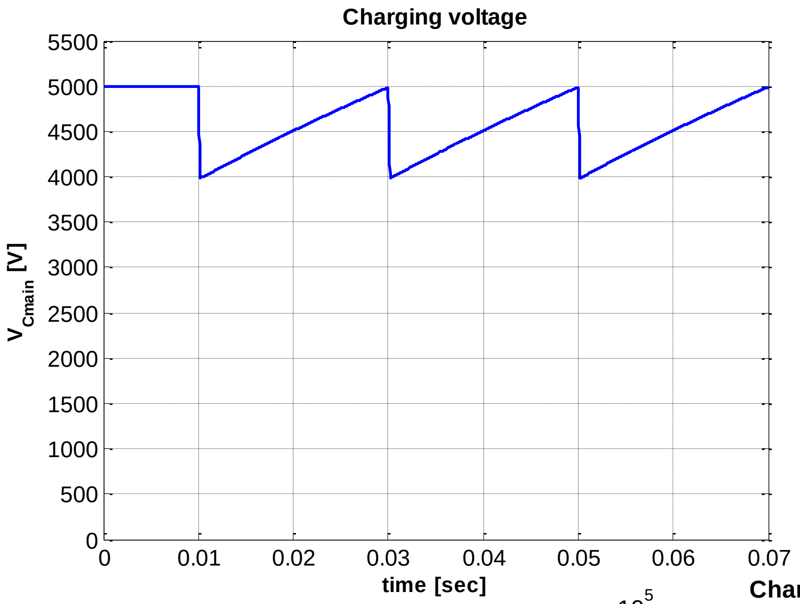
VS

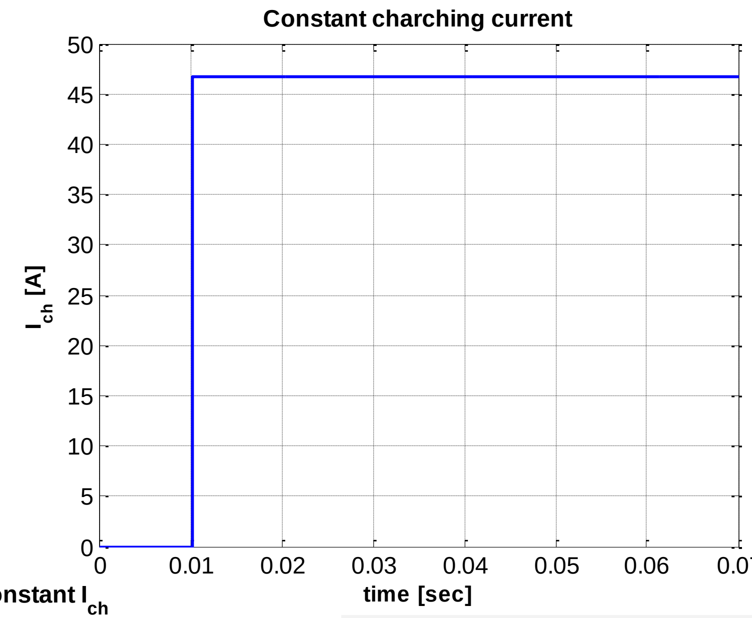
capacitors voltage droop + current and voltage regulation capabilities of the charger + cost + size

# Example:

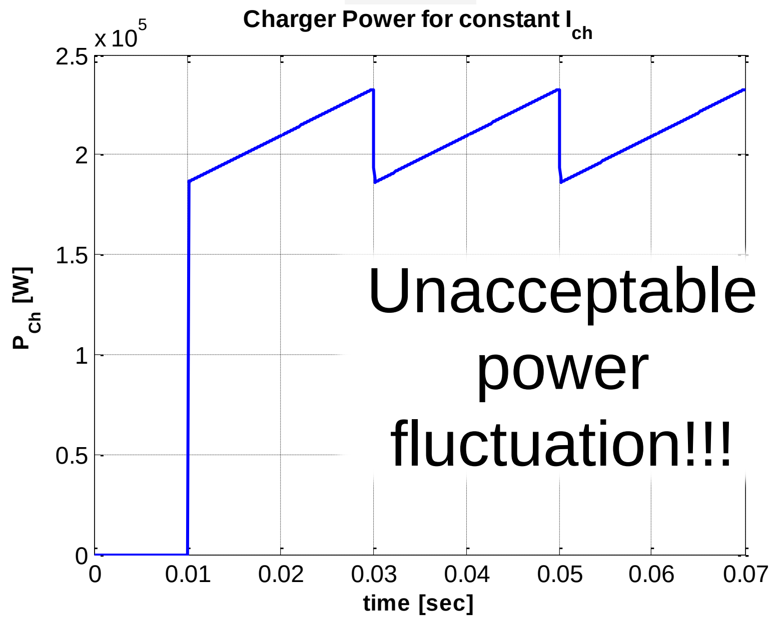
If we consider a constant charging current:



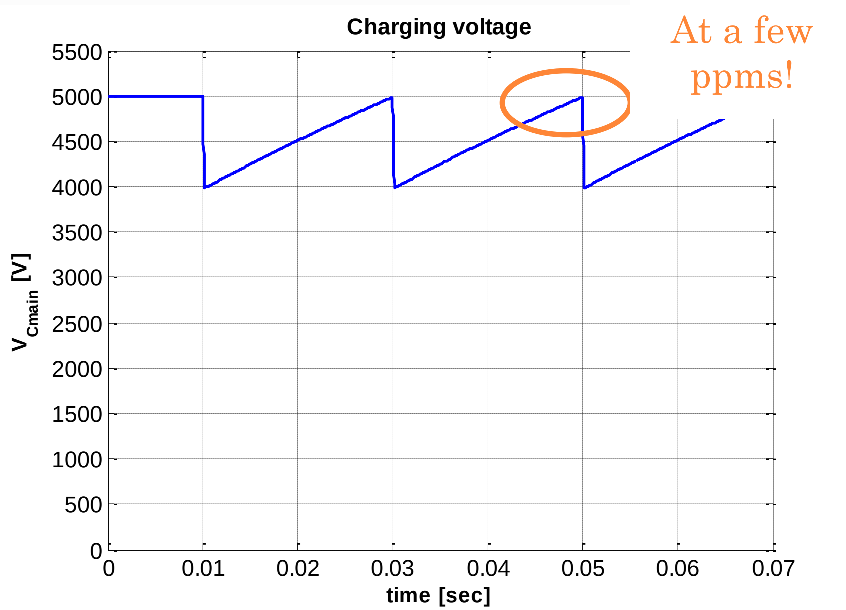




Charger Power

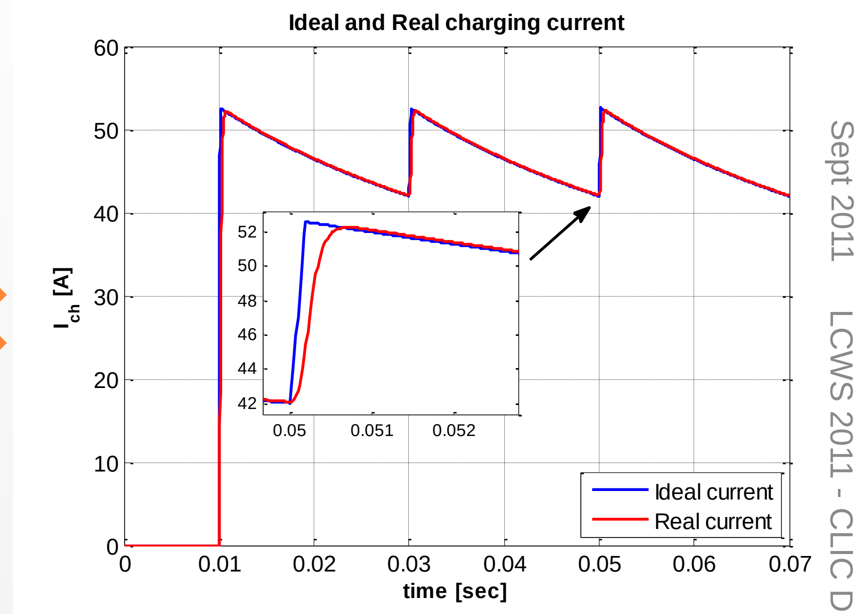



Unacceptable power fluctuation!!!

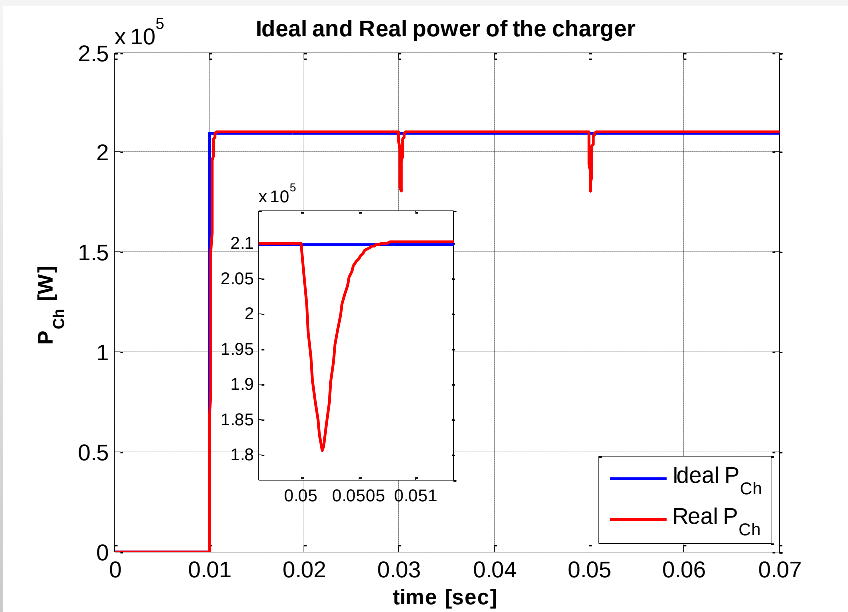
But if we want a constant charger power:
(we model the capacitor charger as a 2nd order transfer function)




At a few ppms!




**Power Consumption**



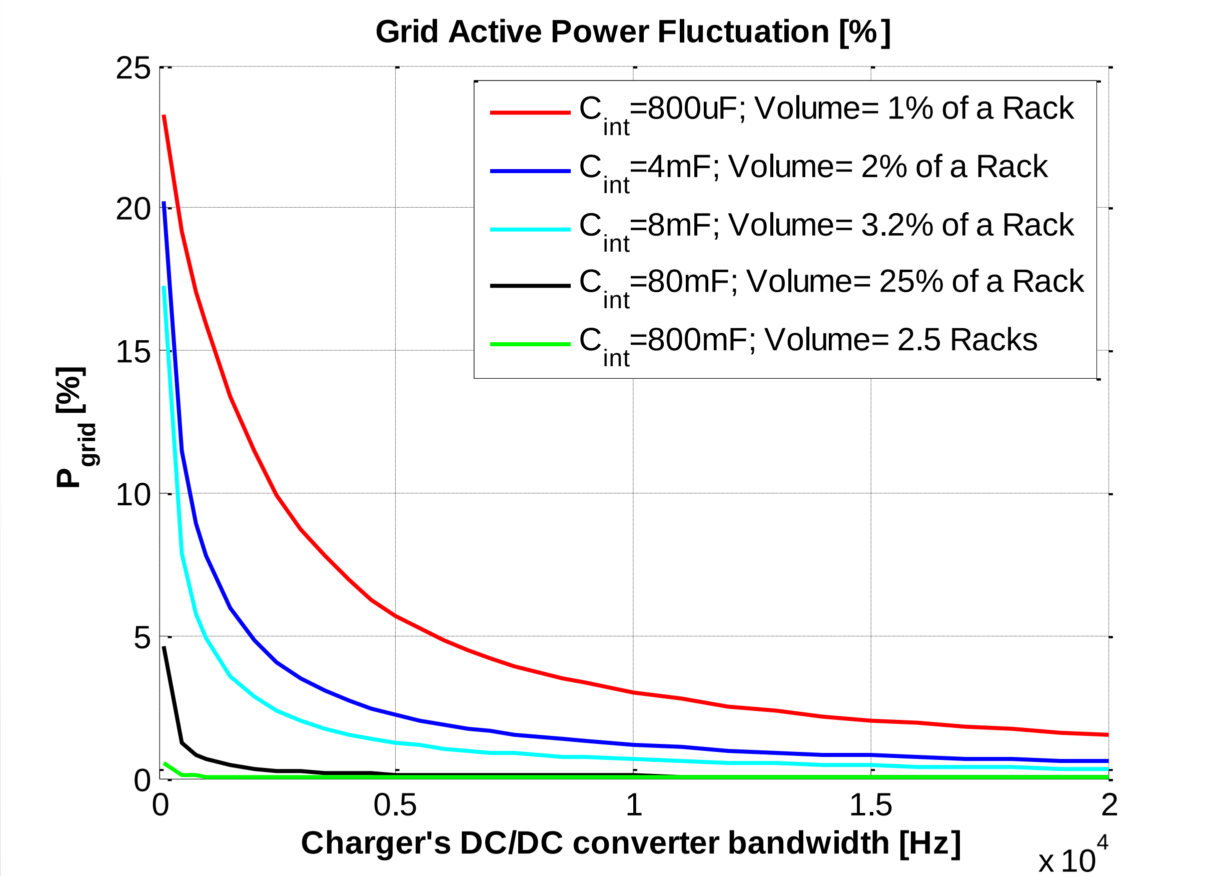

*Ideal case: infinite current bandwidth

*Real case: 2kHz current bandwidth

Very high bandwidth charger needed

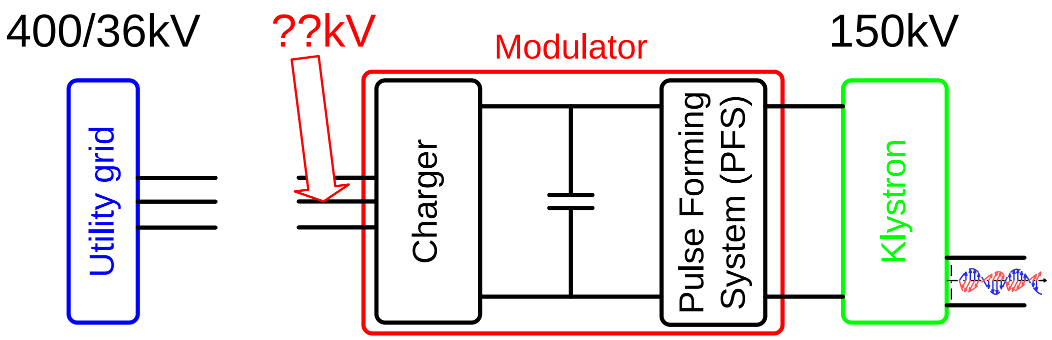
# $1^{ST}$ RESULTS FOR THE GRID ACTIVE POWER

- For different $C_{int}$ and Bandwidth of the charger



| Present | Future |
| --- | --- |
| Current research: Describe the closed loop system as a transfer function and put this transfer function in the simplified transfer function model in order to obtain faster models to simulate several systems in parallel. | What's next? Power Fluctuation VS Charging Voltage: <br><br> How can I slow down/speed up the charging of $C_{main}$ in order to reach always the same $V_{ch}$ at the end of each pulse for all the 1638 chargers? |

# AC voltage level selection




For high efficiency switching power converters are required. Switches that can be used: **IGBT**s or IGCTs (6.5kV max)

- IGBTs up to 1.7kV (1kV DC-Bus) easily operate at high switching frequencies (20kHz) thus high converter bandwidth (low power fluctuations)
- IGBTs higher than 1.7kV are operating at lower switching frequencies
- 6.5kV IGBTs are for the drive industry, meaning high current…we don't need high currents!
- What is certain: The higher the AC voltage, the more expensive the charger (compared to a step down transformer) and the lower the bandwidth (leading to more cost on an external active power compensator/storage system).

AC voltage selection has a direct impact on charger topology, cost and performances. A deep study of this subject is required. External collaborations are starting on this subject as well!

# R&D objectives and planning

- Maximise charger efficiency and power quality
  - **Objective**: better than 90% efficiency with constant power consumption
- Minimise rise, fall and settling time
  - **Objective** for 140us pulse: less than 10us total for rise, fall and setup time
- Maximise operational reliability and availability
  - **Objective**: design for 100% availability assuming interventions every 14 days
- Guarantee exceptional pulse-to-pulse voltage reproducibility
  - **Objective**: $10^{-5}$ (10ppm) from $\text{pulse}_{n-1}$ to $\text{pulse}_{n}$ (RF feedforward gives long term performance)
- Optimise volume
  - **Objective**: mechanical implementation compatible with one system every 3m

| Tentative Milestones | Year |
|---|---|
| **Invite proposals and select partners** | **2011** |
| From submitted studies, select at least one topology for prototyping | 2012 |
| Begin construction of full scale prototypes | 2014 |
| Deliver 2 validated full scale modulator prototypes | 2016 |

# R&D strategy

- CERN to develop a fundamental understanding of the issues
  - Fellows working under the supervision of Davide Aguglia are studying key topics
  - Charger technologies and issues for interfacing to the AC grid: Eleni Sklavounou
  - Reliability issues – continuing from Main Beam work : Daniel Siemaszko (end of fellowship)
  - Reproducibility issues – understanding sources of non-reproducibility: Rudi Soares

  - Still to be investigated further: measurement technologies

- Collaborations to be established to investigate and propose suitable topologies meeting the demanding criteria
  - Guidance and evaluation by core team at CERN (see fundamental knowledge above)
  - Prototyping of key technologies through collaboration, and also with assistance of CERN resources
  - Collaborations are encouraged to seek industrial partners

- Decision on whether to pursue two separate designs, or to merge designs, will be taken before construction phase
- Construction of full scale prototypes will be made using CERN and Industrial Partner facilities

# Invite proposals

- Paper written and presented to Pulsed Power community in June 2011 summarizing the challenges
    - Klystron Modulator Technology Challenges for the Compact Linear Collider (CLIC)

- Collaboration agreed with University of LAVAL, Quebec, Canada
    - To study resonant topologies and their suitability for the CLIC project
        - In particular, demonstrate that a sufficiently fast rise time can be achieved
    - Demonstrate the magnetic technologies that are required (fast rise time pulse transformers, high frequency resonant transformers)
    - Design appropriate prototype assemblies

# Invite proposals

- A number of other collaborations are under discussion
- ETH Zurich, CH
  - Has already developed a short pulse modulator for PSI.
  - Currently engaged in work for pulsed precision measurements.
  - The high voltage group has all the qualities we need from a research partner.
  - Discussions in progress – hope to conclude collaboration agreement in the coming months with emphasis on topologies and global optimization.
- SLAC, USA
  - Power research group has worked extensively on Marx topologies for ILC.
  - End of ILC research project this year.
  - modulator and klystron development team interested in being involved.
  - SLAC will prepare a white paper to summarize the contribution that can be made.
- Los Alamos National Laboratories, USA
  - Has already built (with difficulty) a high power, resonant modulator for SNS.
  - They have worked with Nottingham University on some studies.
  - Studies into a split-core transformer topology to be investigated; manpower contribution offered; cost to be evaluated.

# EPC internal organisation

- CLIC Project
  - EPC CLIC Linkman — *Serge PITTET*
    - Klystron Modulators — *David NISBET*
      - *External R&D* — *David NISBET*
        - *External Collaboration 1 LAVAL, Canada*
        - *External Collaboration 2*
        - *External Collaboration 3*
      - *CERN R&D* — *Davide AGUGLIA*
        - *Rudi Henrique CAVALEIRO SOARES*
        - *Eleni SKLAVOUNOU*
        - *Fellow - Measurement*
    - Magnet Powering — *Serge PITTET*
      - *Fellow*

http://te-epc-lpc.web.cern.ch/te-epc-lpc/machines/clic/general.stm

# Conclusion

- Promising progress on collaboration agreements for modulator topology studies

- More effort needed on measurement technologies
  - How to measure HV pulses with ppm precision?

- Relaxation of reproducibility requirements are welcome.

- Modulator testbeds need to be planned
  - Test area on passive load for power development
  - Test area on klystron load for pulse measurement and feedback studies (CLIC 0?)