Power Electronics for Fusion Power Plant

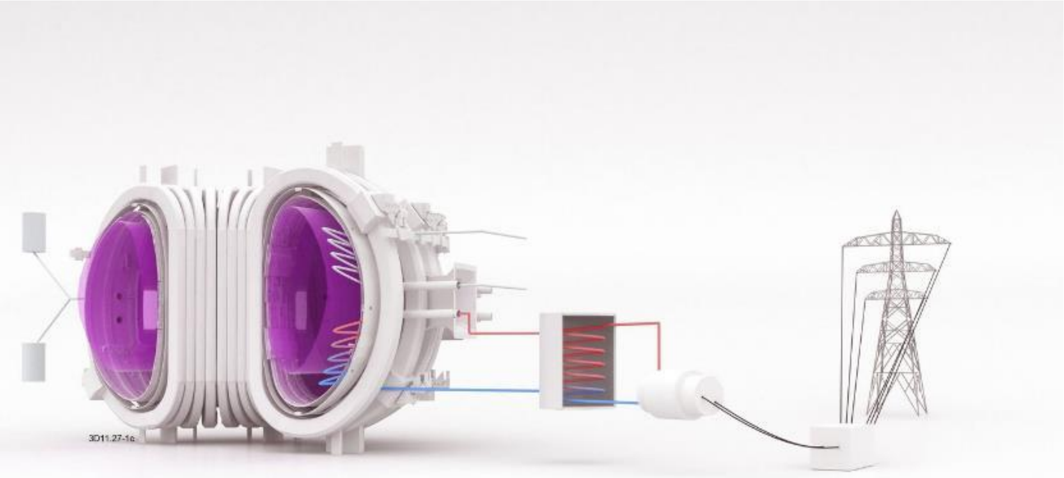

Image taken from https://www.euro-fusion.org/programme/demo/

Ugo Siravo

04.03.2025

Swiss Plasma Center

Power Electronics for Fusion Power Plant

1. Introduction
2. Comparison between ITER, TCV and Demo
3. Power Electronic basics
4. High voltage converters (additional heating)
5. High current converters (coils)
6. Exercises

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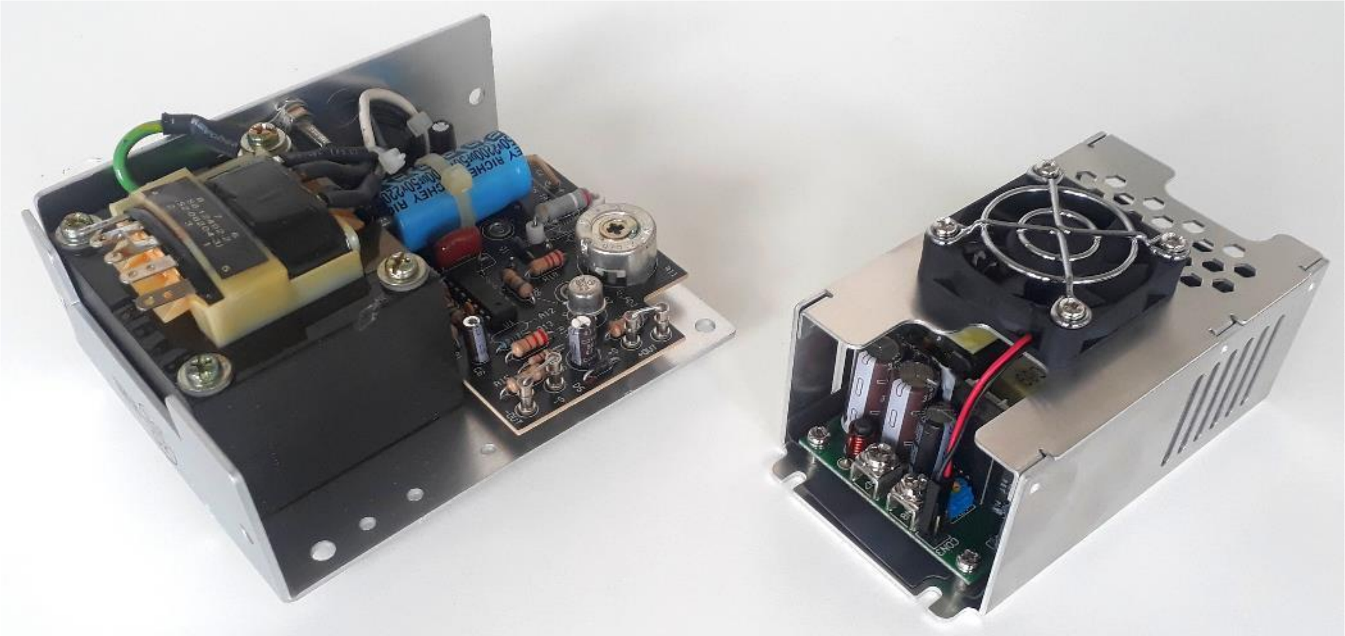
Power Electronics for Fusion Power Plant

Some definitions

- **Power Electronics**: application of solid-state electronics to the control and conversion of electric power, applying **switching** techniques
- Power Supply: an electrical device that supplies electric power to an electrical load, may be intended as a synonym for (power) converter
- Power Converter: a device that transform the voltage or/and the current between the grid and the load, e.g. AC/DC or DC/DC converter
- Power Supply (sing.): electricity delivery via electric power generation, distribution networks, and power converters
- Power grid or mains electricity, utility power, domestic power, etc: distribution network that provides electric power to customers via alternating current (AC) and voltage

1. Introduction

Benefits of switching techniques



- **Linear** AC/DC (1980s)
  - 24V/1.2A **30W**
  - 12.5x10x6cm **40W/dm³**
  - 1.2kg **25W/kg**
  - **50Hz** transformer
- **Switching** AC/DC (2020s)
  - 24V/12.5A **300W**
  - 10.5x6x6cm **800W/dm³**
  - 0.3kg **1000W/kg**
  - **150kHz** transformer

Power converter design

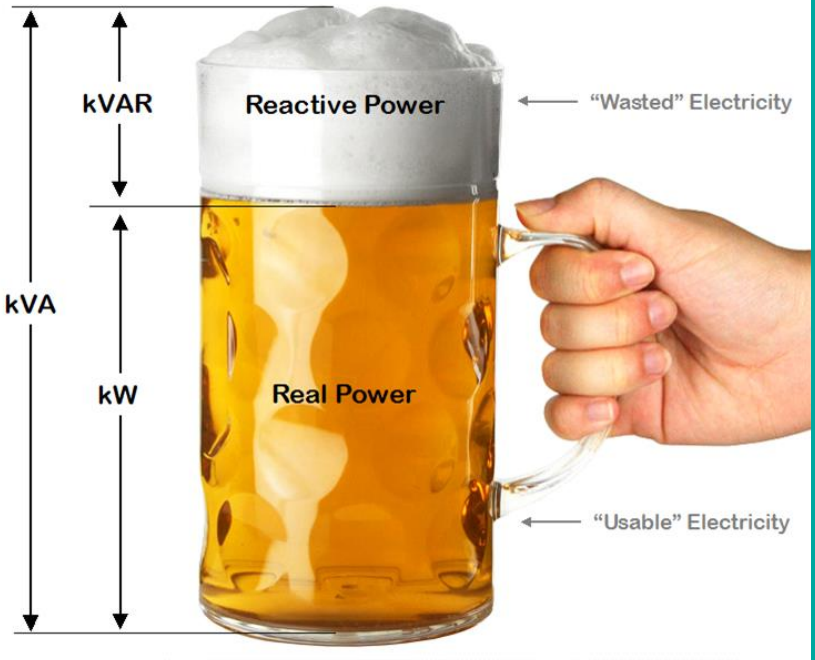
- Today, a power converter design results from an **optimization process**
- An **iterative algorithm** performs a swept of various selected parameters
- Starting from the selection of a possible topology, it takes into account
  - Design modularity and redundancy
  - Integration of storage energy, if required
  - Sourcing of power semiconductors and other devices
  - Passive components realization (inductance, transformer, DC link, etc.)
  - Efficiency constraints, power factor, EMC/EMI aspects
  - Complexity of the control system
  - Volume, surface and weight
  - Losses removal
- Usually a **figure of merit** is constructed to help selecting the best design
- The selected solution should be located on the **Pareto front**
- Nevertheless, final cost might be the only relevant factor

High current and high voltage converters for Fusion

- In fusion technology, there are two main categories of power converters
  - High Current/Low Voltage → magnet power supplies typ. 1kV/50kA
  - High Voltage/Low Current → additional heating systems typ. 50kV/100A

- **High Current** is obtained by **parallel** assembly of semiconductors
- Very inductive load (current source) → low dynamics
- Voltage margin is needed for ramp-up → low power factor

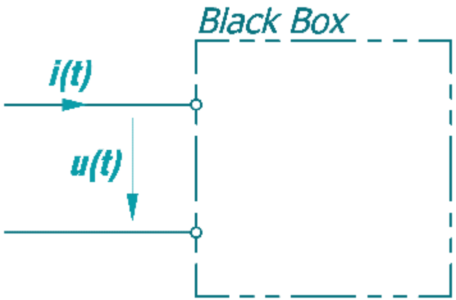
- **High Voltage** is obtained by **series** assembly of semiconductors
- Resistive or capacitive load (voltage source) → high dynamics
- No need for current margin (if resistive load) → good power factor



Active power, reactive power, apparent power & power factor

$$PF = \frac{Active\ Power \quad [kW]}{Apparent\ Power\ [kVA]}$$

Active power, apparent power, etc.: definitions



- $u(t) = {}^1U\sqrt{2}\sin(\omega t + \alpha_1) + {}^2U\sqrt{2}\sin(2\omega t + \alpha_2) + \ldots$
- $i(t) = {}^1I\sqrt{2}\sin(\omega t + \beta_1) + {}^2I\sqrt{2}\sin(2\omega t + \beta_2) + \ldots$

- $U_{RMS} = sqrt({}^1U^2 + {}^2U^2 + \cdots)$, $I_{RMS} = sqrt({}^1I^2 + {}^2I^2 + \cdots)$

- P = active power $= \frac{1}{T} \cdot \int_0^T u(t) \cdot i(t)dt$, with $T = 1/f = 2\pi/\omega$
- S = apparent power $= U_{RMS} \cdot I_{RMS}$
- Q = reactive power $= sqrt(S^2 - P^2)$
- PF = power factor = P/S

- If $u(t) = {}^1U\sqrt{2}\sin(\omega t)$, $PF = {}^1I/I_{RMS} \cdot \cos(\varphi)$, $\varphi = angle({}^1U, {}^1I)$
  - $PF = \cos(\varphi)$, only in absence of current *harmonics*

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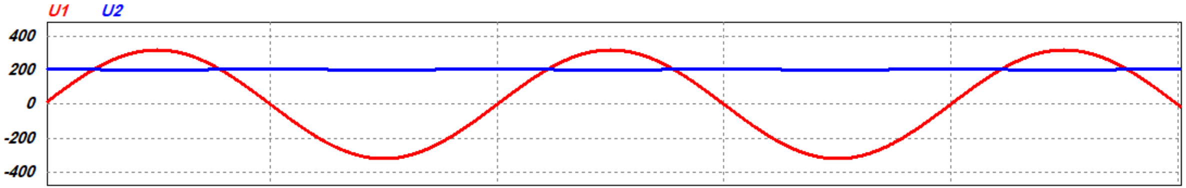
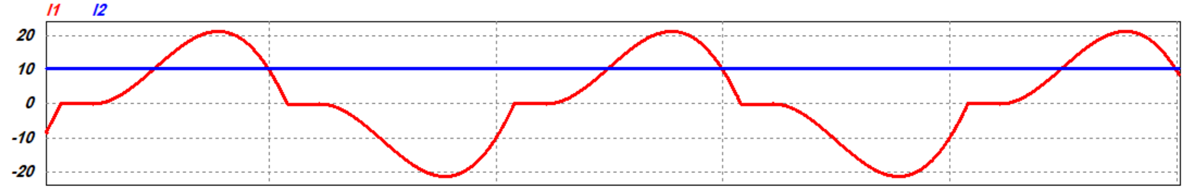
Apparent power & power factor: example

- U1: sinus AC voltage
- U2: smooth DC voltage



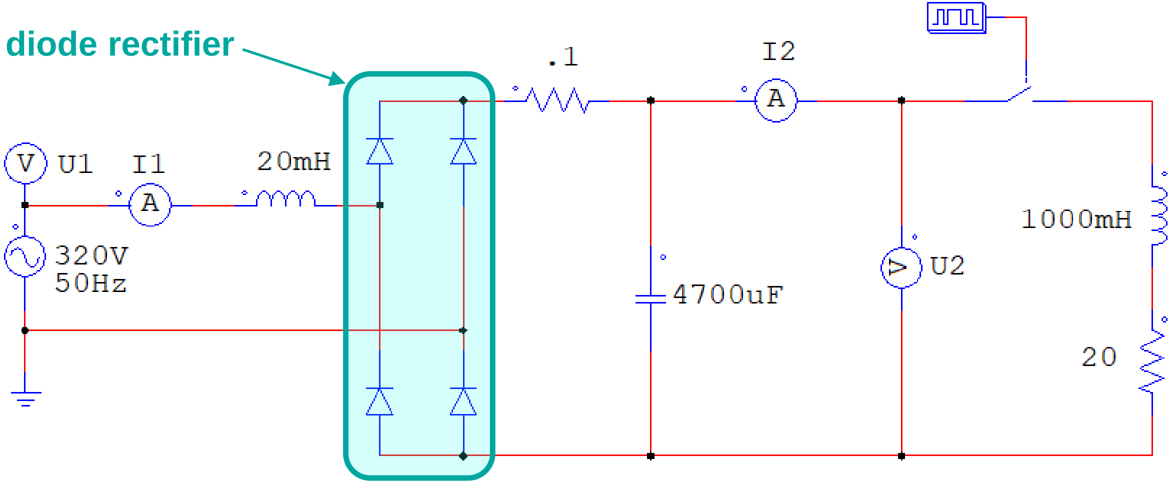
- I1 rises when U1>U2
- I1 has harmonics
- I2=U2/R



- W2=U2·I2≅2000W
- S1≅2500VA

- PF≅0.8

1-phase diode rectifier



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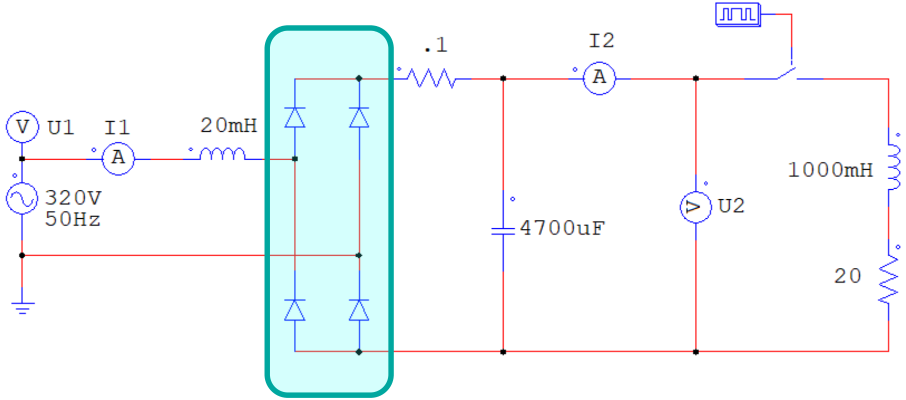
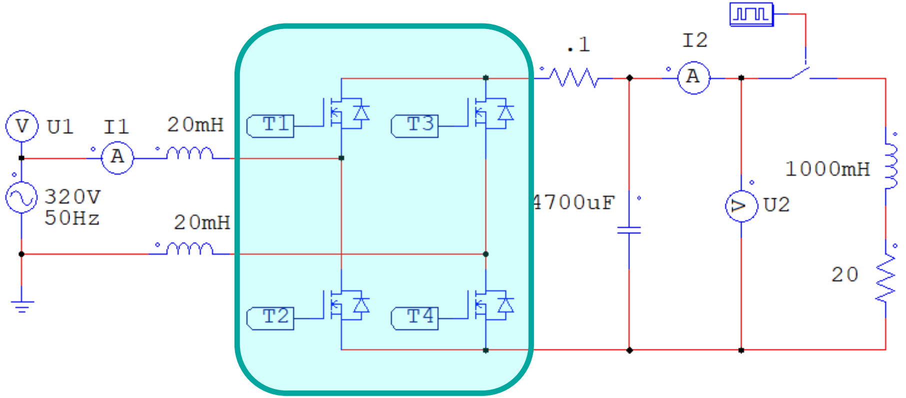
Active power & apparent power: Power Factor Control

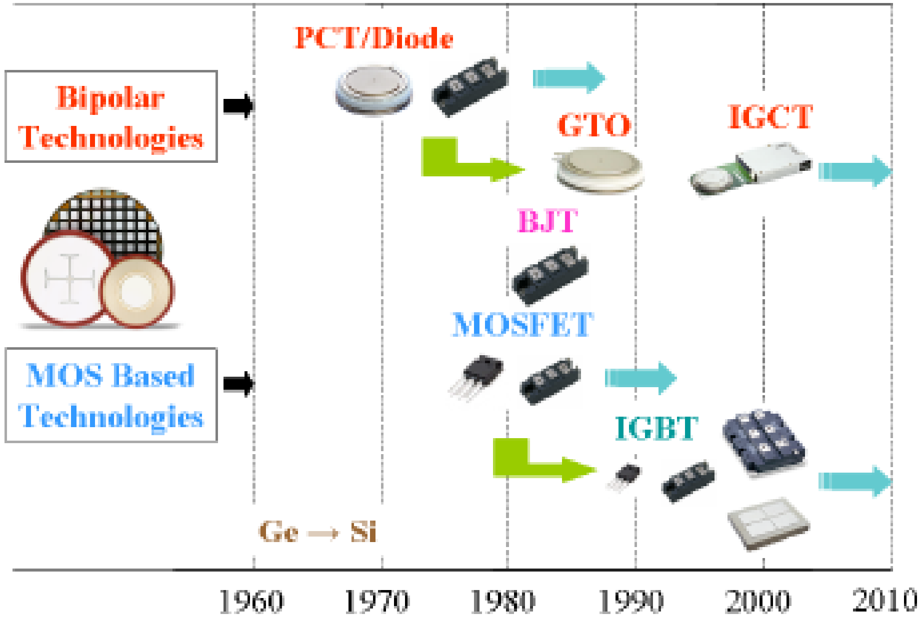


- Passive rectifier
  - no control of output voltage
  - no control of apparent power



- Active rectifier
  - Control of output voltage
  - Power Factor Control (**PFC**)
  - Can work at [1]φ=[-90°..90°]
    - Stated as *lagging* or *leading*
  - Requires U and I measurements
  - Requires control device (typ. FPGA)

Semiconductors history



- PCT: Phase Controlled Thyristor
- SCR: Silicon Controlled Rectifier
- GTO: Gate Turn-Off (thyristor)
- BJT: Bipolar Jonction Transistor
- IGCT: Integrated Gate-Commutated Thyr.
- MOS: Metal Oxide Semiconductor
- FET: Field Effect Transistor
- IGBT: Insulated-Gate Bipolar Transistor
- IEGT: Injection-Enhanced Gate Transistor

Present competition between Si-SiC-GaN

IGBT vs SiC MOSFET vs Si-MOSFET vs GaN HEMT

Silicon (Si)

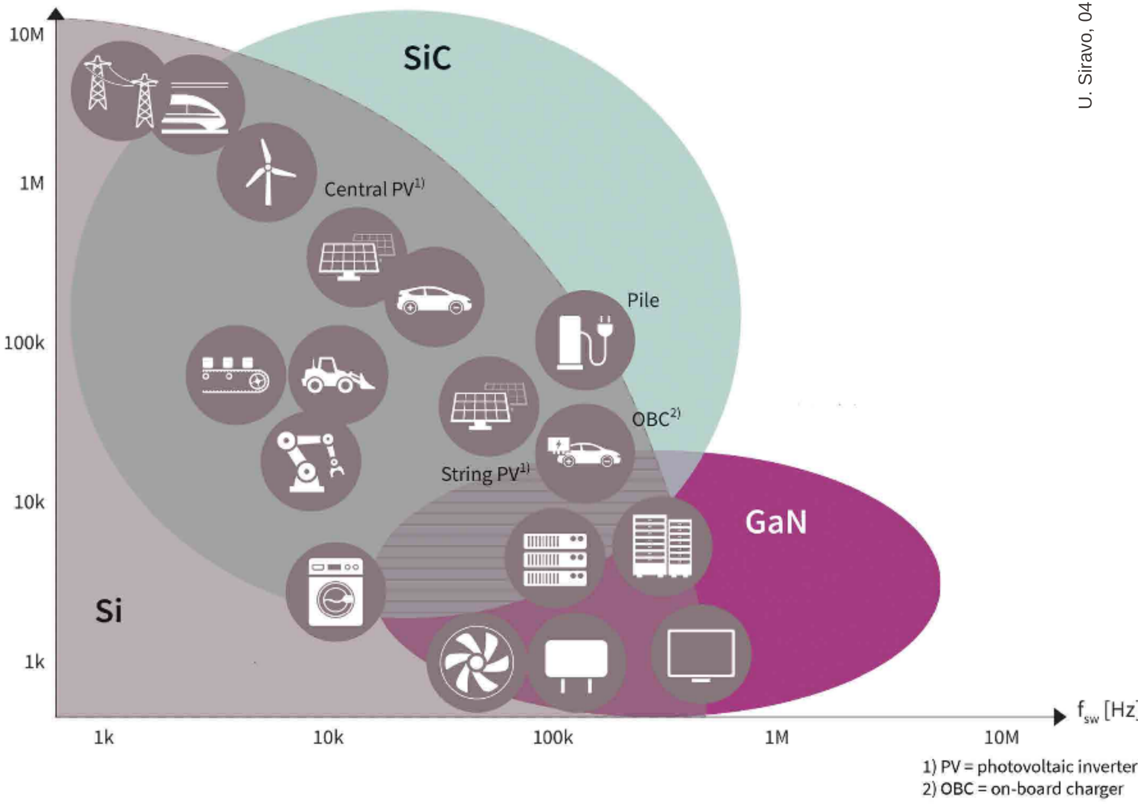
- Targeting voltages ranging from 25 V to 1.7 kV
- The mainstream technology
- Suitable from low to high power

Silicon carbide (SiC)

- Targeting voltages ranging from 650 V to 3.3 kV
- High power from moderate to high switching frequency

Gallium nitride (GaN)

- Targeting voltages ranging from 80 V to 650 V
- Medium power at highest switching frequency



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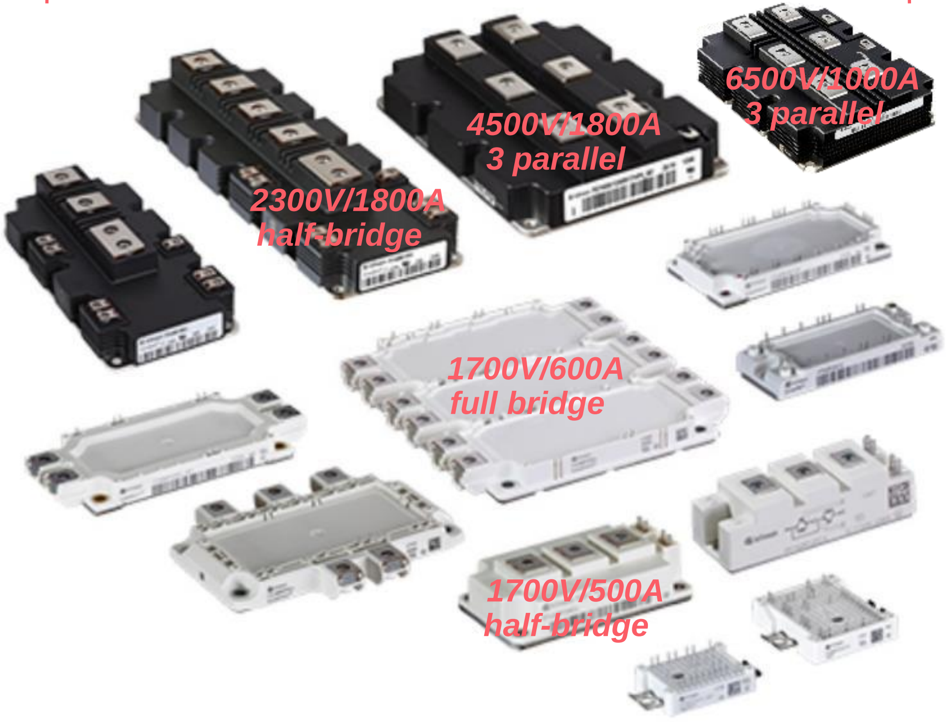
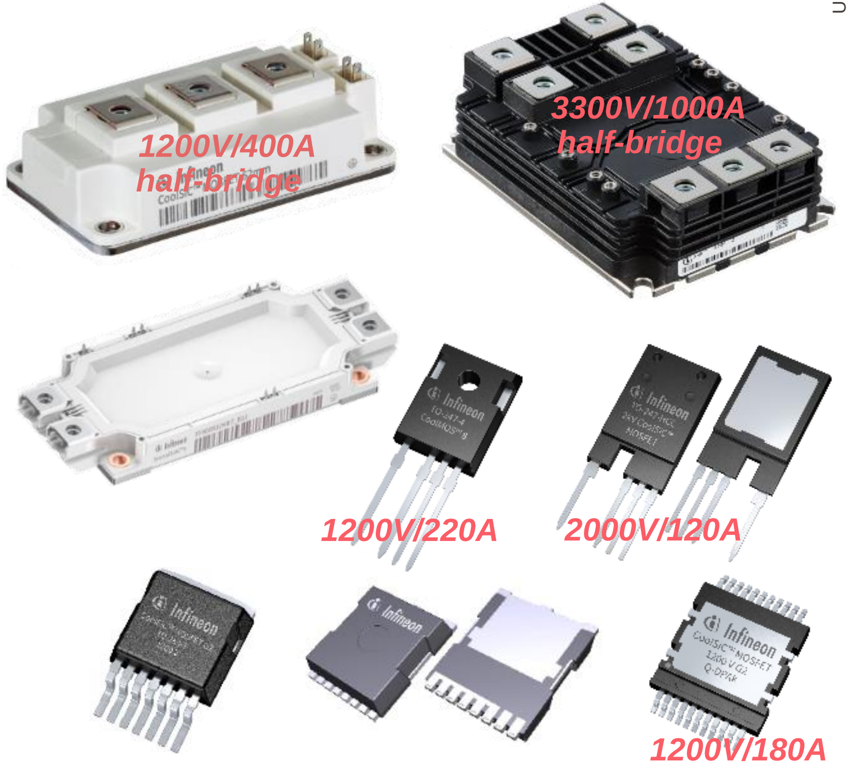
[Infineon] IGBT modules vs SiC MOSFET

(Si) IGBT



(SiC) MOSFET



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[Behlke] New design opportunity

- MOSFET (Si and SiC) integrated in series-parallel assembly to be used e.g. for
  - Auxiliary HVPS for additional heating with high-speed/low-frequency switching
  - High-voltage/low-current repetitive short pulse for plasma DBD

2. Comparison between ITER, TCV and Demo

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ITER platform (as planned 15.03.2019)

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ITER platform (16.10.2024)

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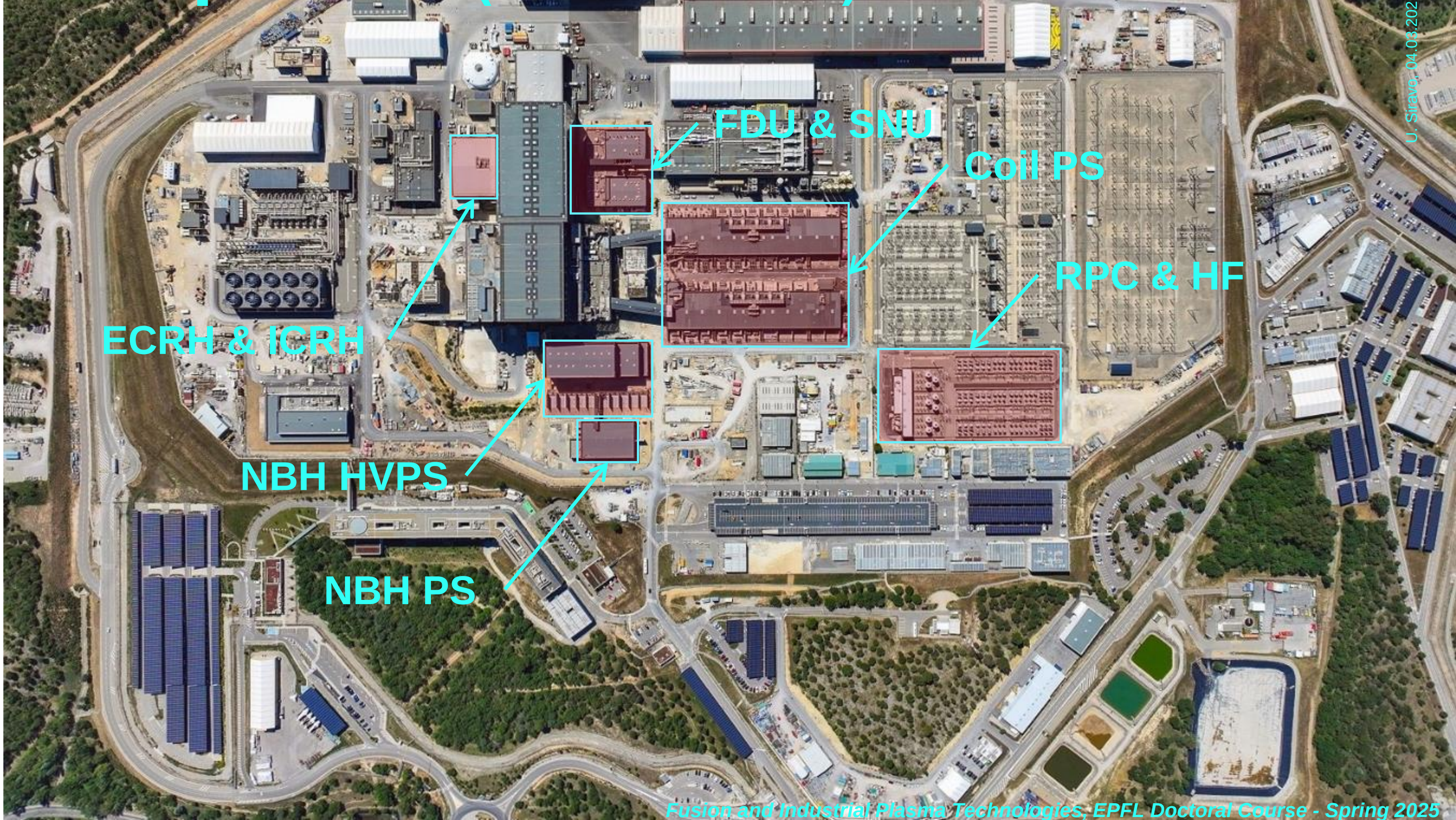
ITER platform (20.06.2024)



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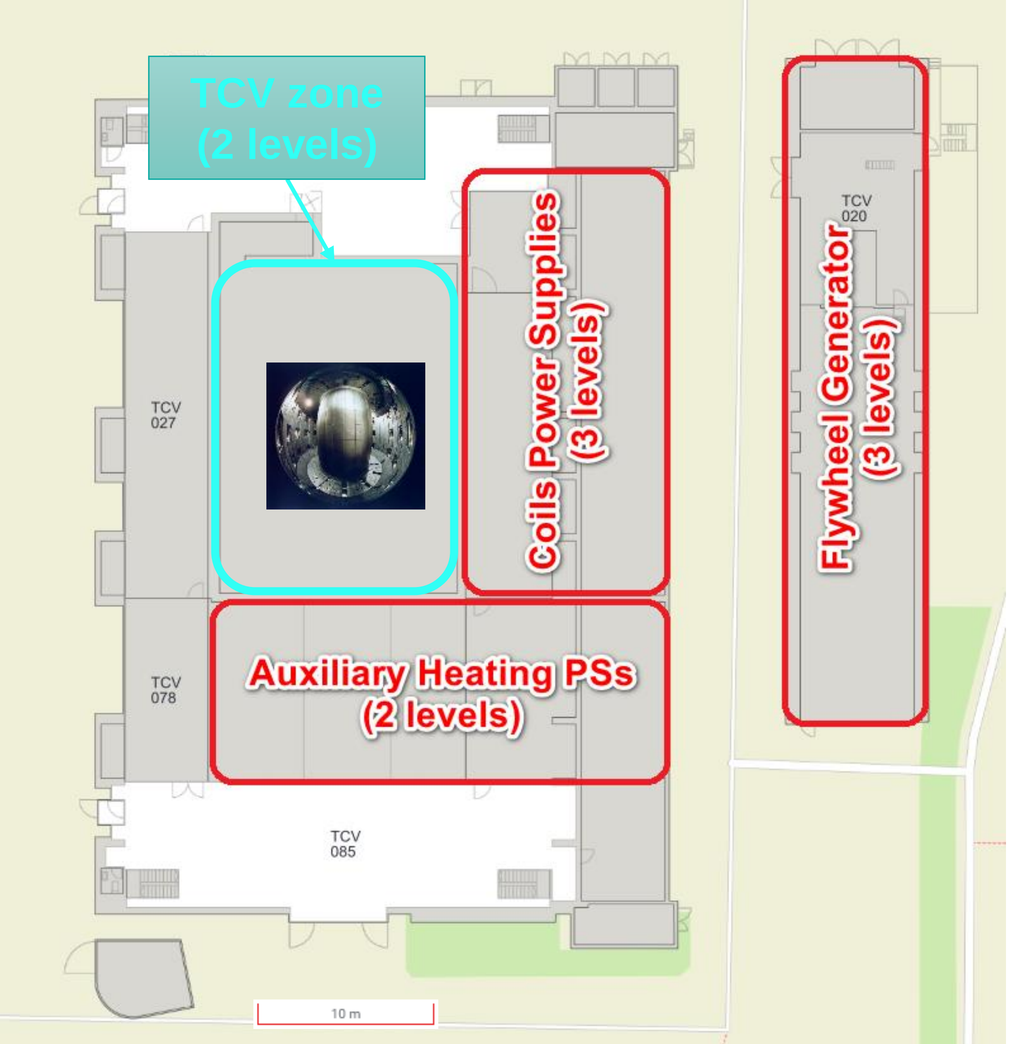
TCV PS system

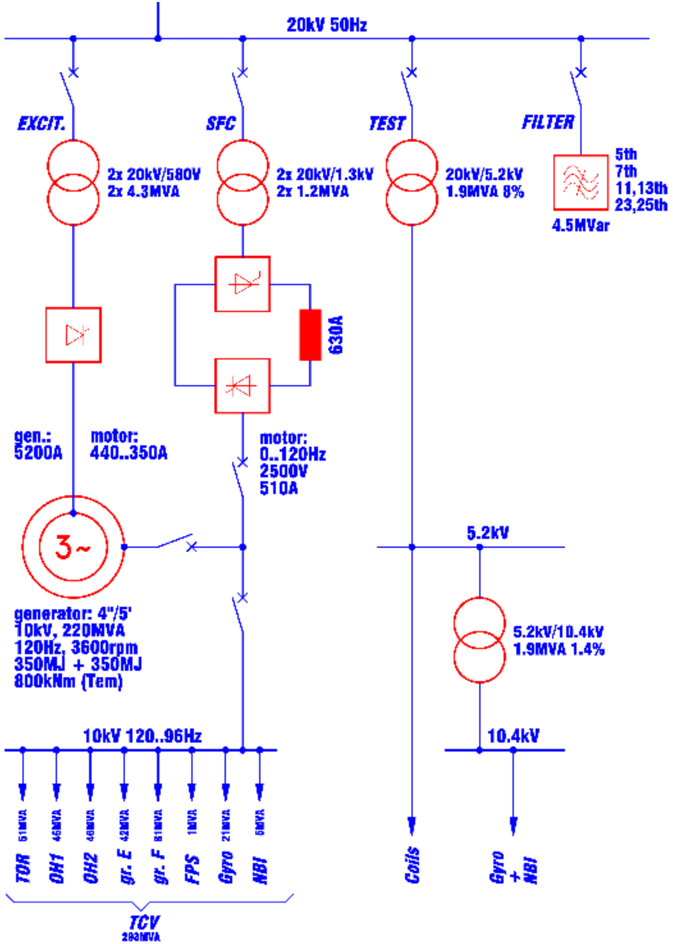
- PPEN: 1 generator (no pony motor)

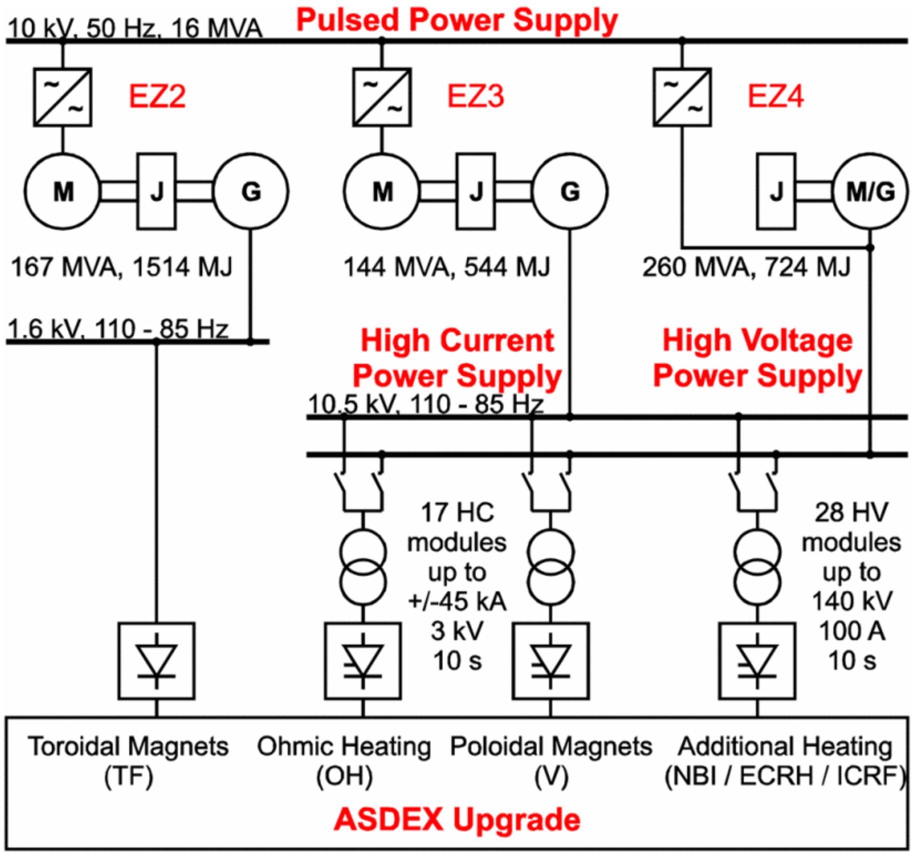
- TF: 1 PS
- OH: 2 PS
- PF: 16 PS
- VS: 1 PS

- EC: 3 MHVPS
- NBI: 2 AGPS



TCV vs ASDEX Upgrade PS system





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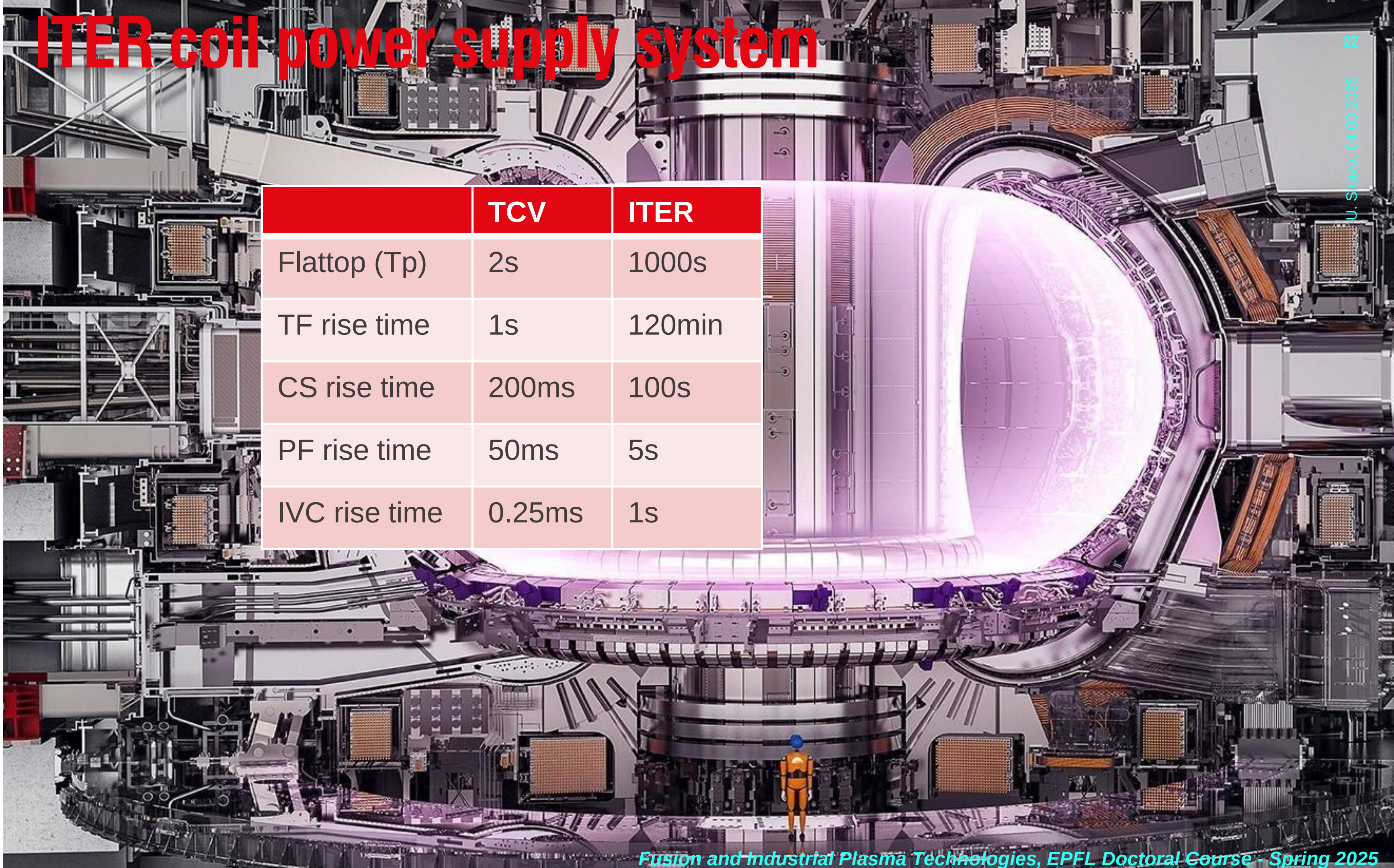
ITER coil power supply system



	TCV	ITER
Flattop (Tp)	2s	1000s
TF rise time	1s	120min
CS rise time	200ms	100s
PF rise time	50ms	5s
IVC rise time	0.25ms	1s

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Comparison between TCV, ITER and Demo

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	TCV	ITER	DEMO (EU, ITER-like)
Major radius	0.89 m	6.2m	9.0m
Plasma current	1.2MA	17MA	18MA
Toroïdal field	1.54T (copper)	5.3T (NbTi, Nb_3Sn)	5.9T (Nb_3Sn)
Energy stored in TF	19MJ (16 coils)	41GJ (18 coils)	161GJ (16 coils)
Pulse duration	2.6s (4s ECCD)	1000s	7200s (burning phase)
Fusion power	Nill	500MW	2000MW
Power generation	Nill	Nill	500MW
Power grid	20kV, 5MVA	400kV, 670MVA	400kV, 650MVA
FW generator	10kV, 220MVA, 300MJ	N/A	N/A
Power peak	150MVA	>1GVA	ITER-like: >2GVA
RPC & HF	Passive, ~30m^2	250Mvar, ~12'500m^2	ITER-like: ~40'000m^2

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Comparison between TCV, ITER and Demo

	TCV	ITER	DEMO (EU, Iter-like)
TF coils	78kA/630V (16 coils)	68kA/900V (18 coils)	75kA/~900V (16 coils)
CS coils	2x 31kA/1400V	6x 45kA/1350V	5x 45kA/8000V
PF coils	8x 7.7kA/630V 8x 7.7kA/1250V	14x 55kA/1350V	6x 55kA/10kV
VS coils	N/A	2x 22.5kA/1350V	TBD
CC	N/A	3x 10kA/450V 6x 10kA/90V	TBD
IVC	2kA/560V (IGBT)	80kA/2.3kV (TBD)	TBD
ELM coils	N/A	27x 15kA/200V (TBD)	TBD
ECRH MHVPS	3x 85kV/80A	12x 55kV/110A	TBD
NBH AGPS	1x 40kV/50A 1x 60kV/50A	3x 1MV/40A	TBD

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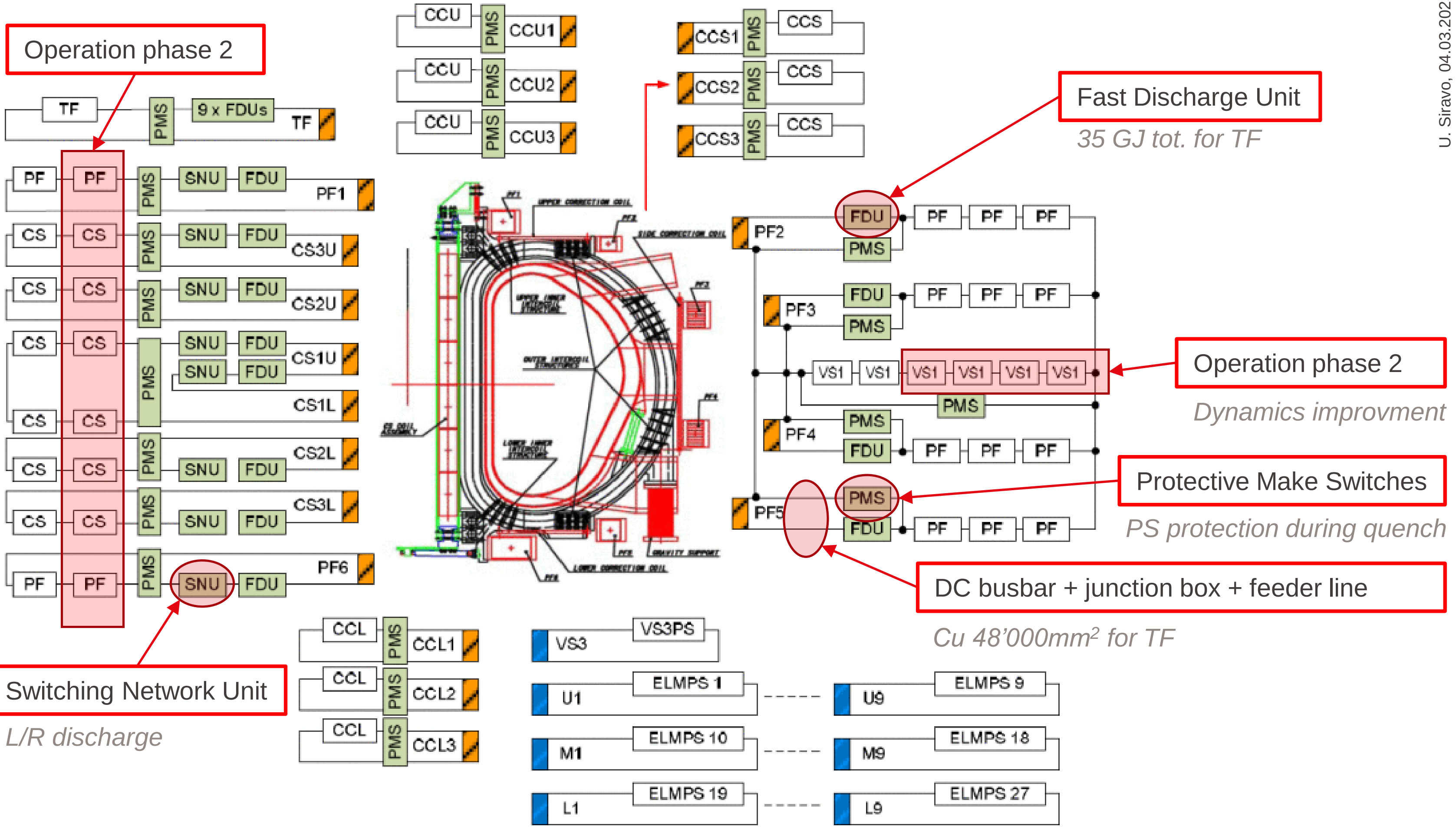
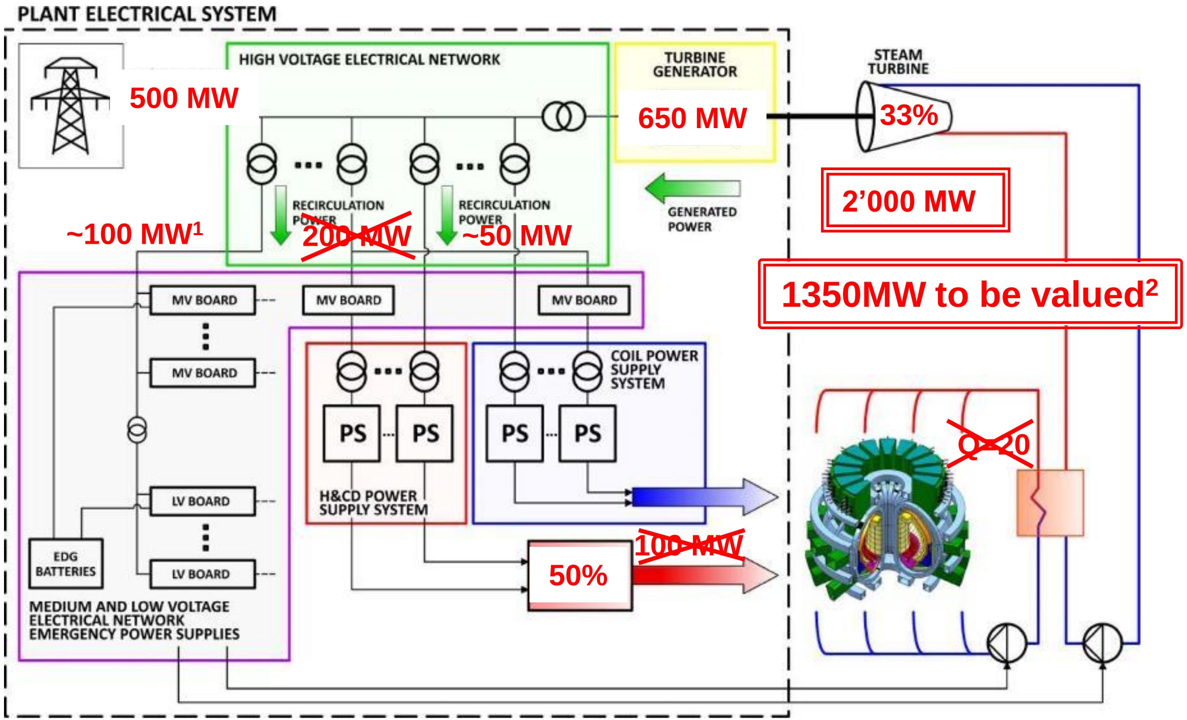
ITER coil power supply system



Power supply of a Fusion Power Plant (EU Demo)

- **Tokamak as a power plant** looks like a large electromagnetic device, composed by several magnetic coils with additional heating systems, to produce heat which shall be turned into electricity by a steam turbine



[1] Refer to *Time-dependent power requirements for pulsed fusion reactors in systems codes*, J. Morris & M. Kovari in Fusion Eng. Des. 2017, 124, 1203–1206.

[2] In Lausanne area (250’000 ppl.), 1/3 of the buildings are connected to a central heating plant of 85MW, so such FPP should be installed in a city of 3 millions ppl.

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References

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  Jun Tao (Iter.org) et al. in 2011 IEEE/NPSS 24th Symposium on Fusion Engineering
  https://doi.org/10.1109/SOFE.2011.6052201
- *ITER Power Supply Innovations and Advances*
  Charles Neumeyer (PPPL) et al. in 2013 IEEE 25th Symposium on Fusion Engineering
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- *In Vessel Coils Power Converters*
  Ivone Benfatto (Iter.org) et al. in Remote ITER Business Meeting, 7-8 avril 2021
  https://indico.iter.org/event/14/attachments/95/139/In_Vessel_Coil_Power_Converters.pdf
- *Overview of the DEMO staged design approach in Europe*
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- *Status and challenges for the concept design development of the EU DEMO Plant Electrical System*
  E. Gaio (Consorzio RFX) et al. in Fusion Engineering and Design 177 (2022) 113052
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- *Electrical Loads and Power Systems for the DEMO Nuclear Fusion Project*
  Simone Minucci (University of Tuscia) et al. in Energies 2020, 13, 2269
  https://doi.org/10.3390/en13092269

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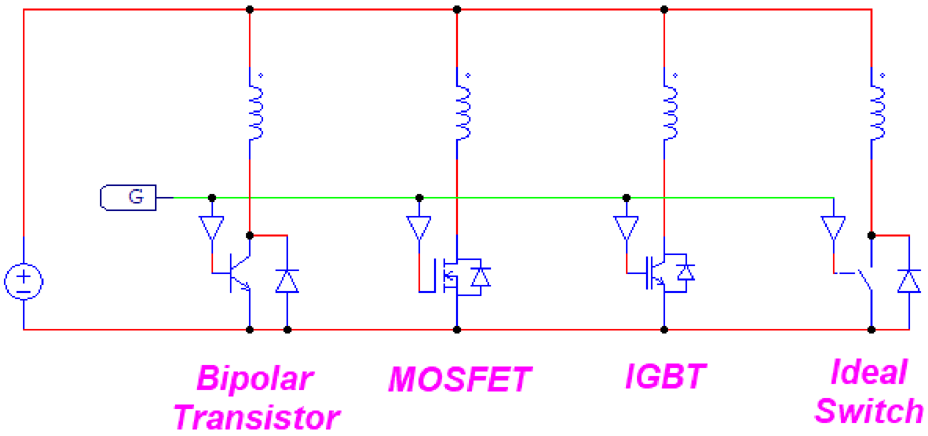
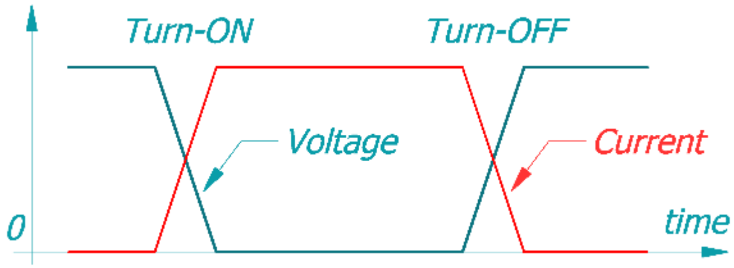
3. Power Electronics basics

Transistors for Power Electronics

- Transistors in Power Electronics are used as **switches**
- Ideally only 2 states: ON (conductive) or OFF (non-conductive)
- Device selection is primarily based on losses minimization
- Conduction losses ($I_D \cdot (V_0 + r_f \cdot I_D)$ or $R_{DSON} \cdot I_D^2$)
- Switching losses depending on switching speed
- Soft switching (zero-voltage or zero-current) to reduce switching losses





Hard switching principle

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Basic topologies and control

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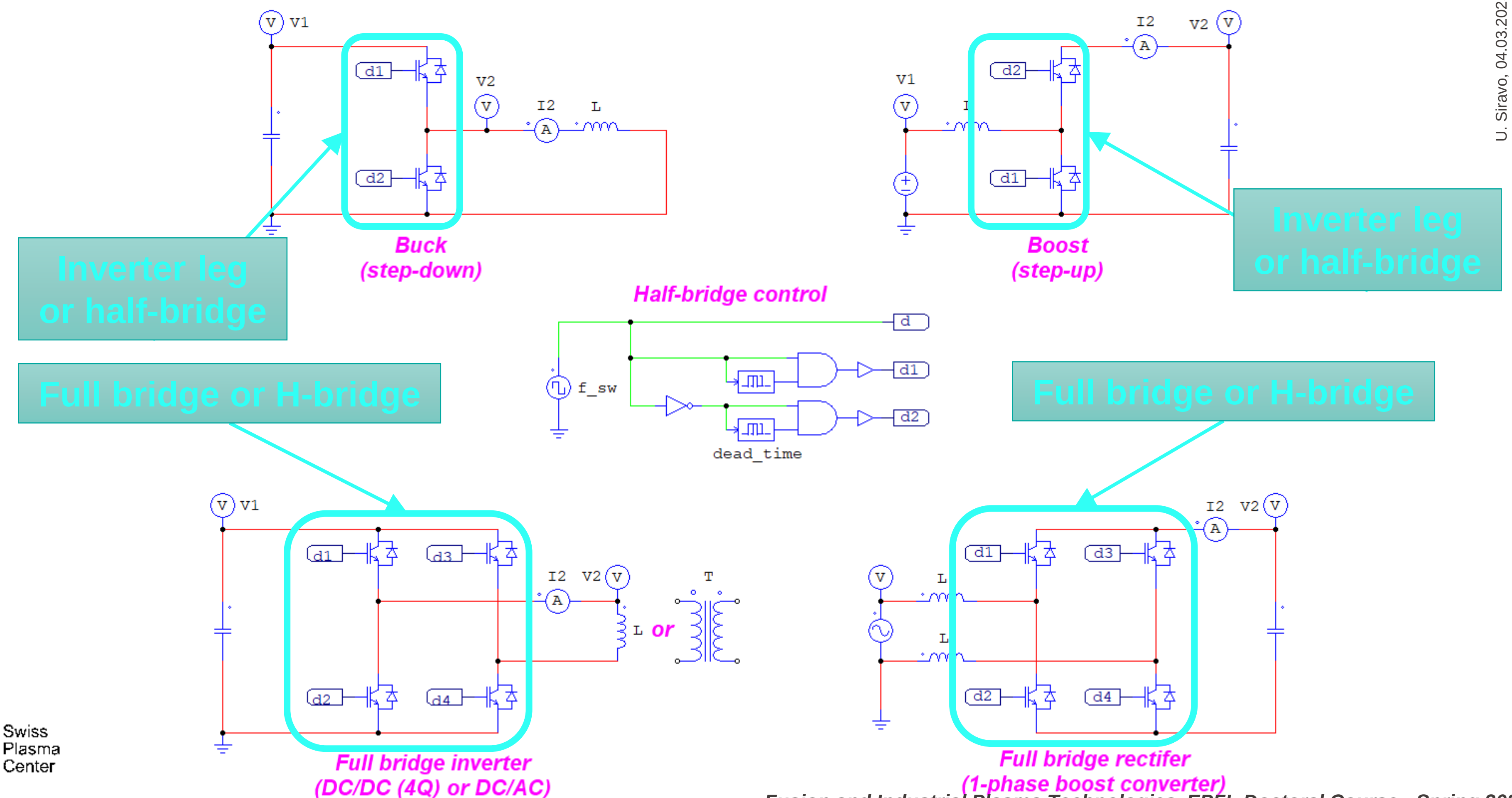

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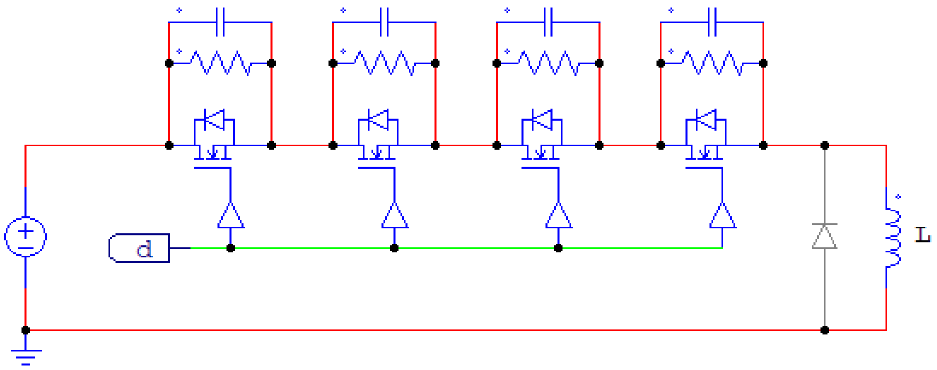
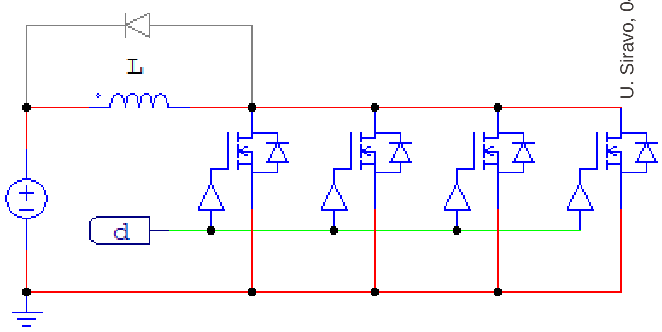
MOSFETs series and parallel connection





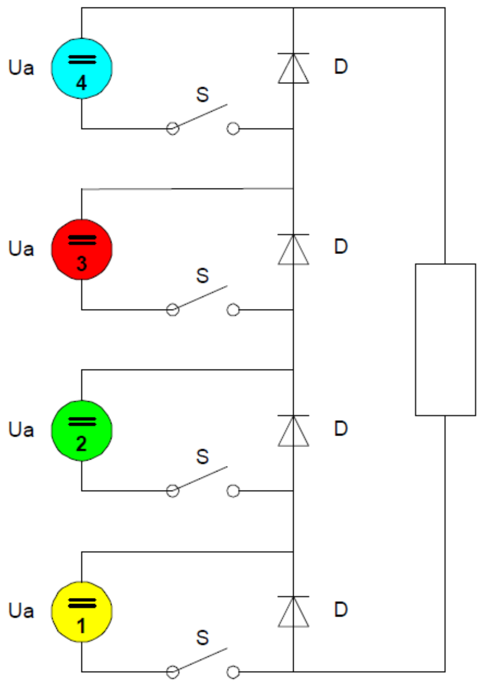
- Voltage balancing must be managed to avoid destruction due to overvoltage
- Static balancing depends on device leakage current; ensured by parallel resistor
- Dynamic balancing is influenced by many factors, including time delays of gate signal
- Simplest solution is using a RC snubber (snubber capacitor C to nullify the mismatch in device output capacitances, and resistance R such that RC time constant is low enough to discharge the snubber capacitor during ON time)

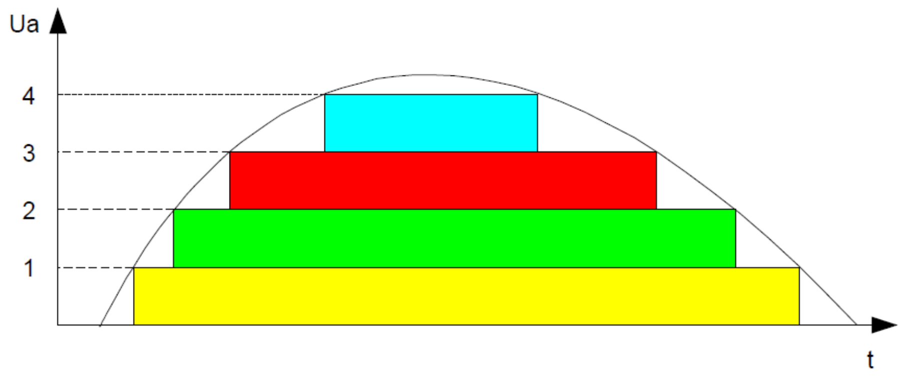
- Current balancing to manage temp.
- Static balancing depends on $1/R_{DSON}$
- For a device, deviation of R_{DSON} is low
- Dynamic balancing depends on $V_{GS(th)}$
- $V_{GS(th)}$ mismatch can be important
- More the branches worst the dynamic balancing, means higher dissipation, so limiting the switching frequency

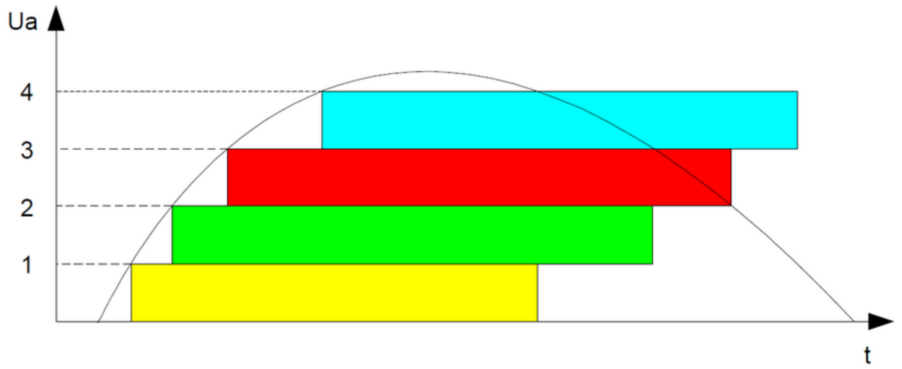
Power converter built with power modules

- Instead of connecting transistor in series and/or parallel, converter ratings can be improved by connecting sub-converter in series and/or parallel
- These sub-converters are usually called Power Modules (PMs)
- PMs series connection is possible only if they are isolated from each other that's to say they are fed through individual power transformer
- PMs parallel connection is possible only if the total output current is well balanced. This can be done by control and/or thanks to passive elements
- In both cases, sub-converters improve the output quality in terms of ripple, accuracy, slew rate, etc. so that a single converter cannot reach

HVPS built with series connected power modules







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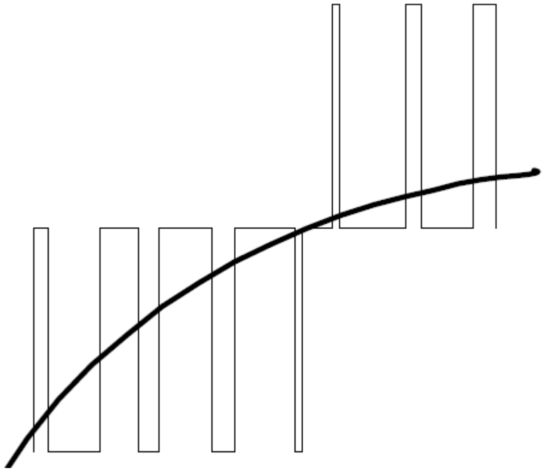
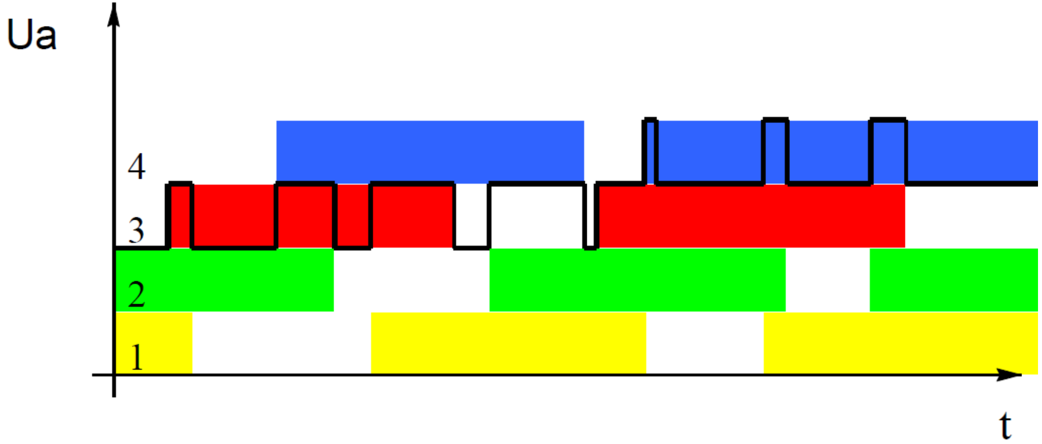
Interleaved Pulsed Width Modulation (i-PWM)

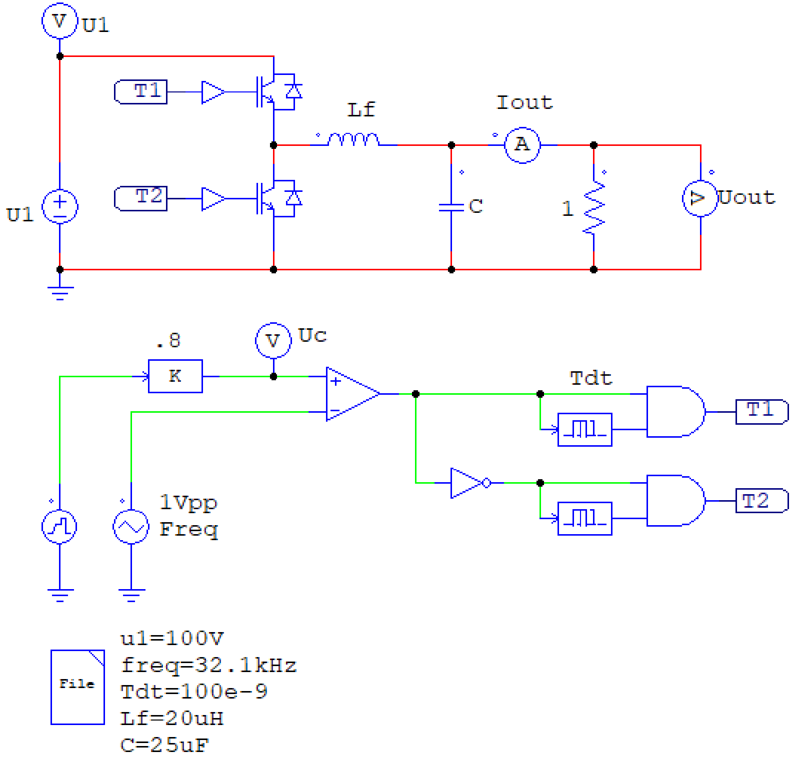
Modulation technique used in Pulse Step Modulator (PSM)

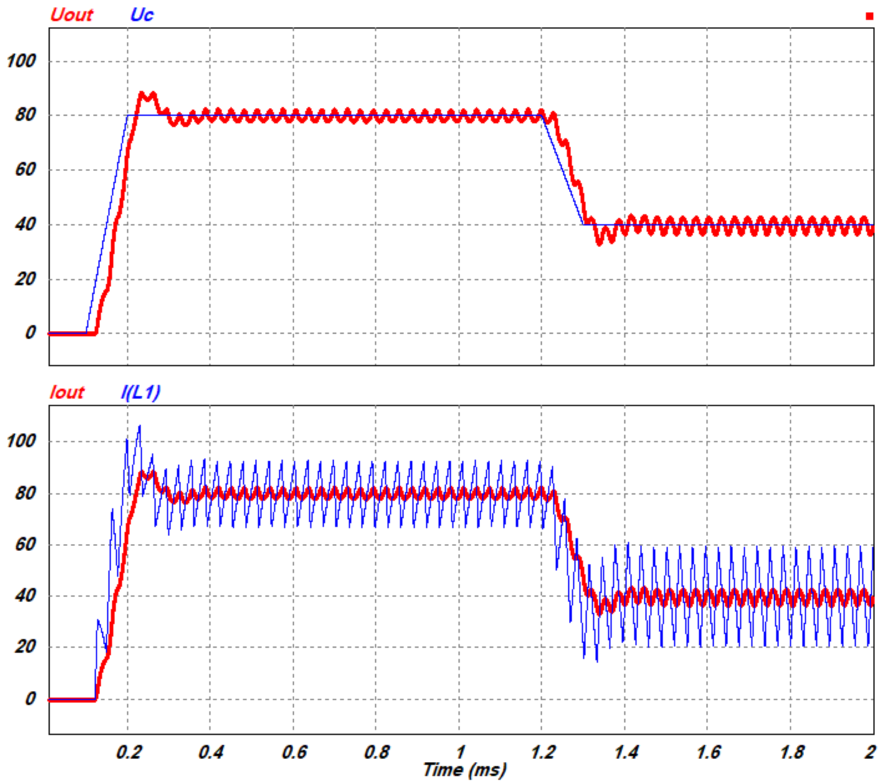




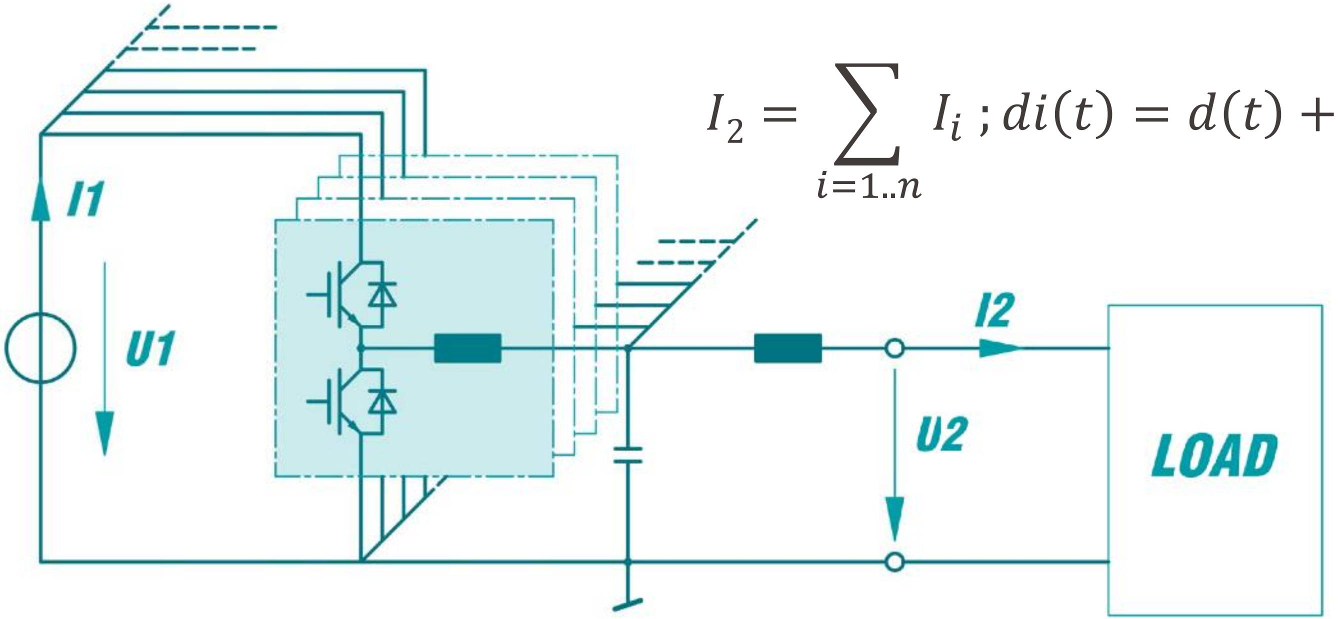
- PSM control knows continuously the value of each LVDC-voltage
- Same duty-cycle applied on each module
  - Same switching losses on each module
  - Power load is equally shared between modules

PWM control of a buck converter





Interleaved buck converter



$$I_2 = \sum_{i=1..n} I_i \; ; di(t) = d(t) + \frac{2\pi}{n} \cdot i$$

- Here: parallel input and parallel output
- But all alternative are possible

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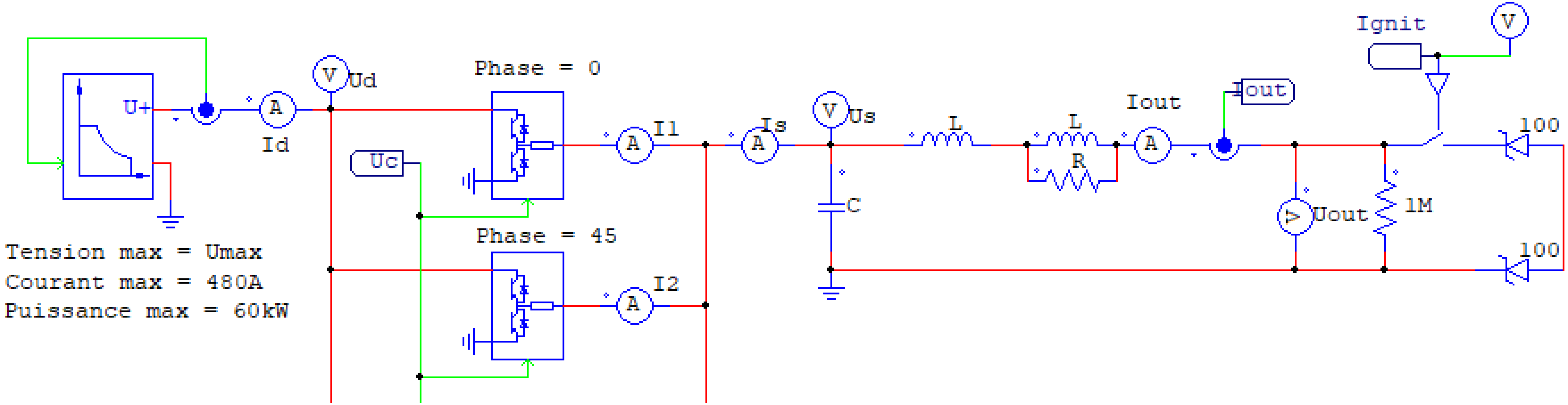
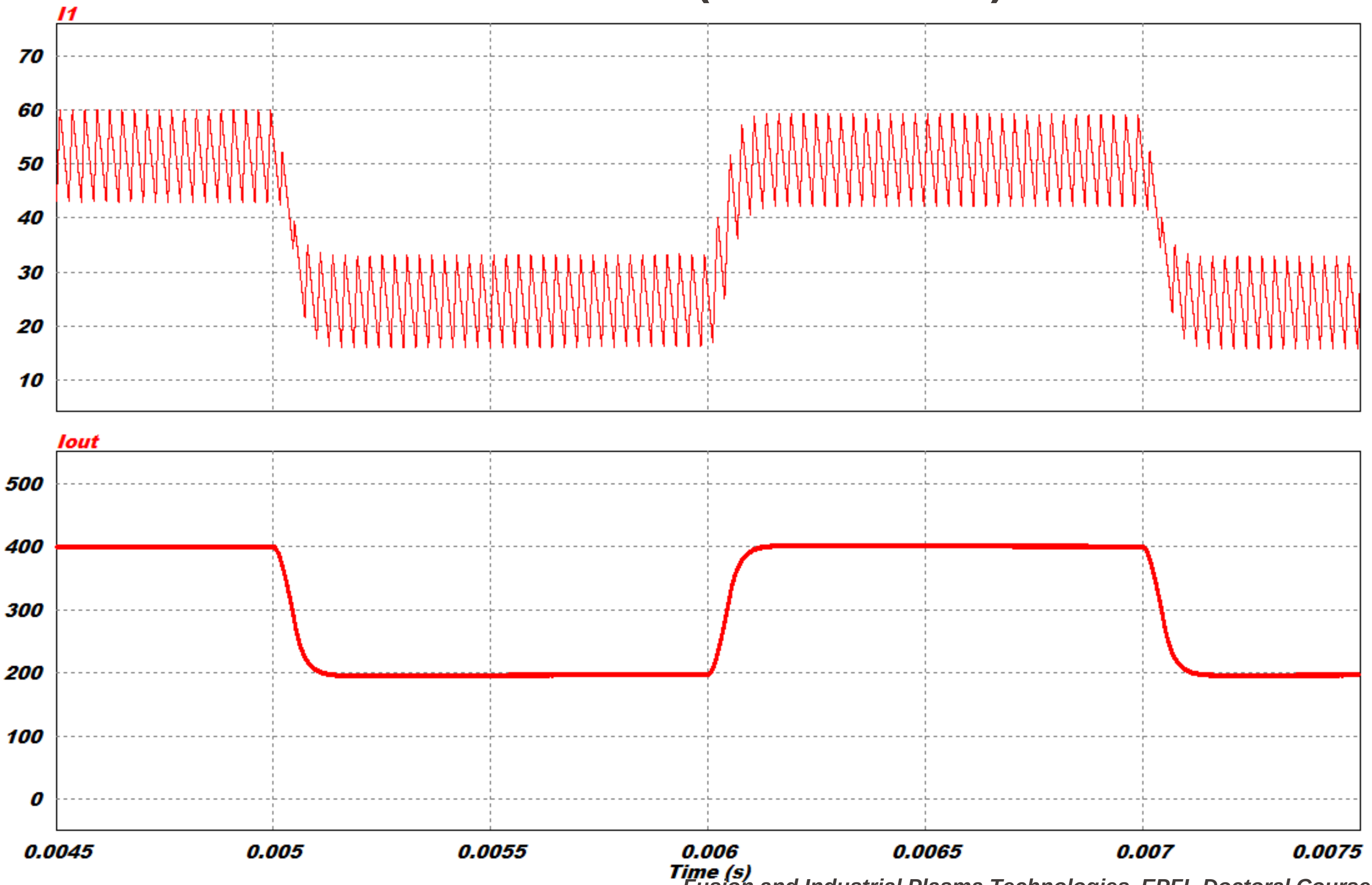
Interleaved buck converter (8 branches)

- Example of a high-speed current power supply for the TCV DNBI connected to the arc-discharge plasma source of the ion source
- Specs are 400A/100V, di/i<0.5%, ramp-up/down <100µs, no overshoot



- Control system has to manage 16 synchronized gate signals
- Current balancing is improved with 8 independent control loops

Interleaved buck converter (8 branches)



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Interleaved buck converter for DNBI on TCV

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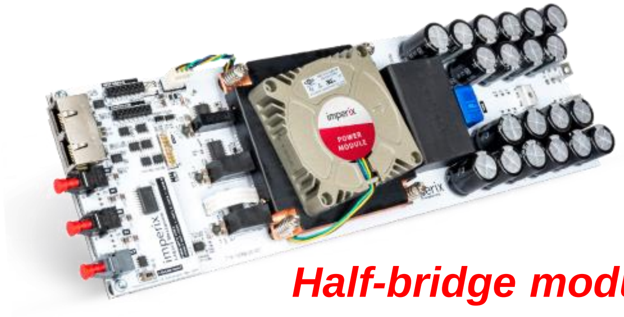
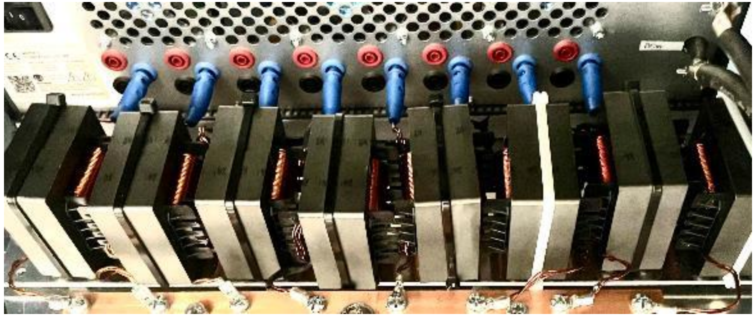
Control system



Half-bridge module

DC power supply (2 units)

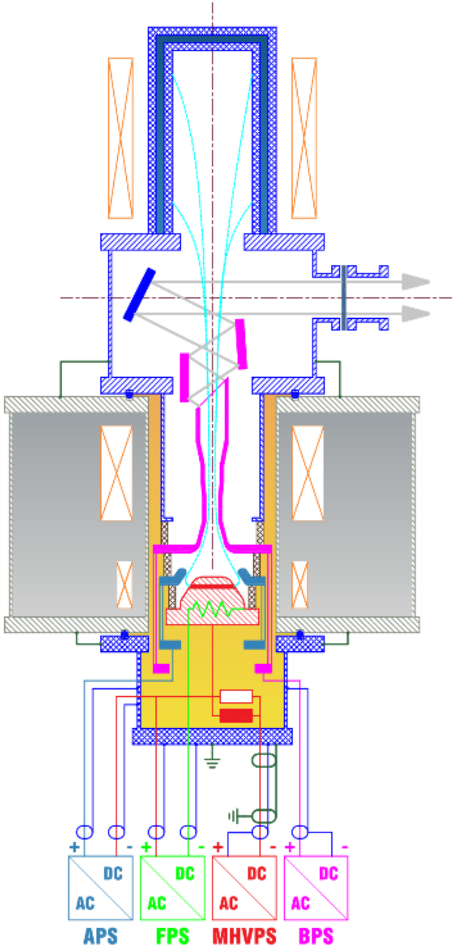
Rack for 8 half-bridge module



Home-made inductors

4. High voltage power supplies for aux. heating

Gyrotron power supply set



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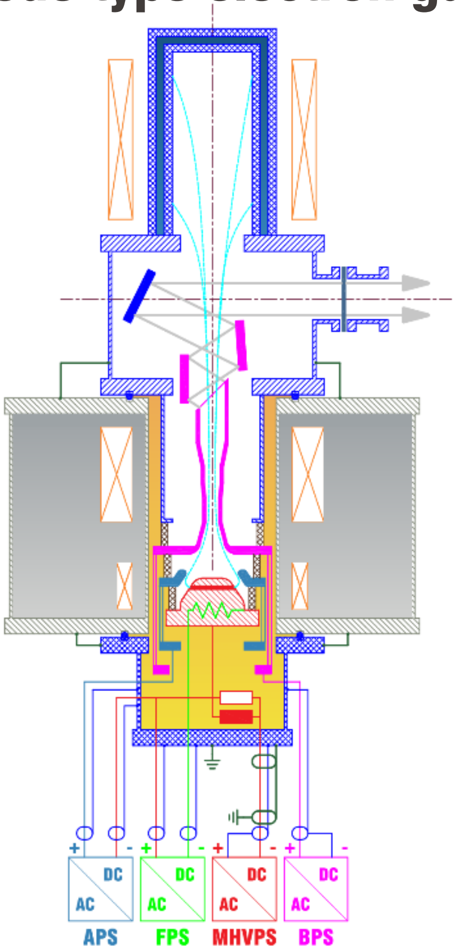
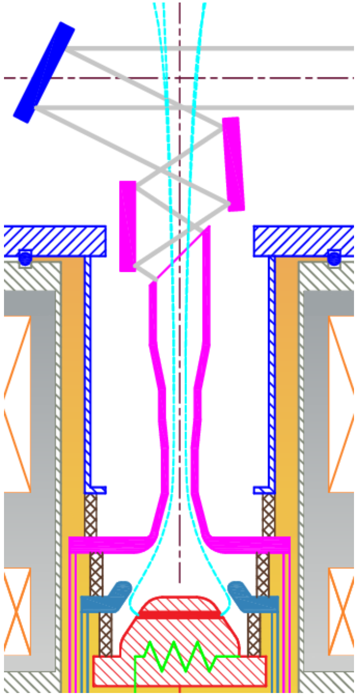
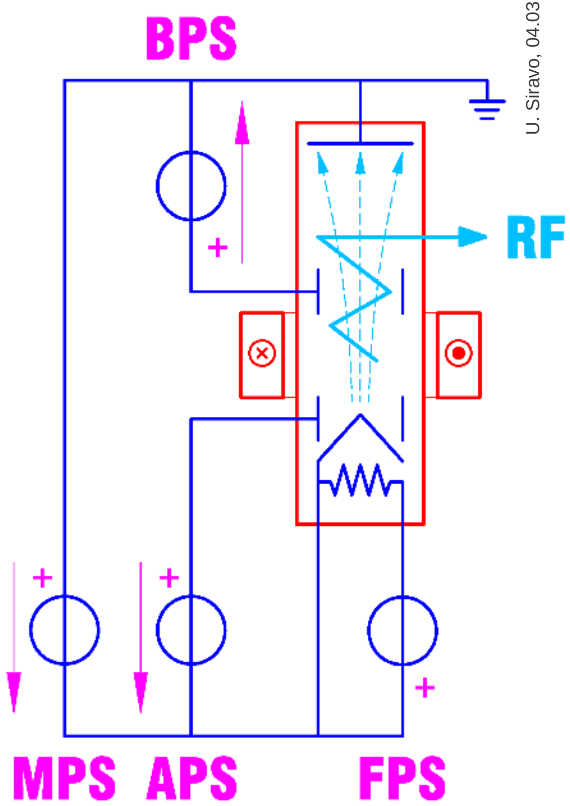
Triode type electron gun and depressed collector

U. Siravo, 04.03.2025







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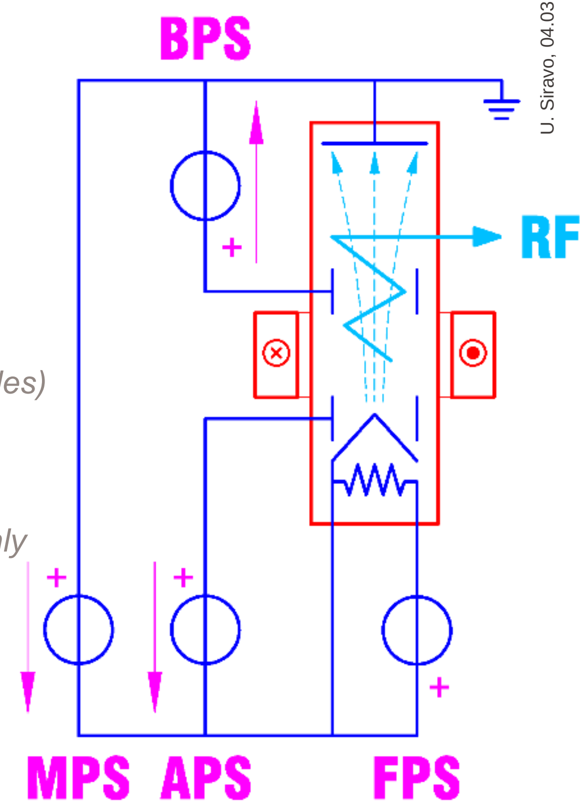
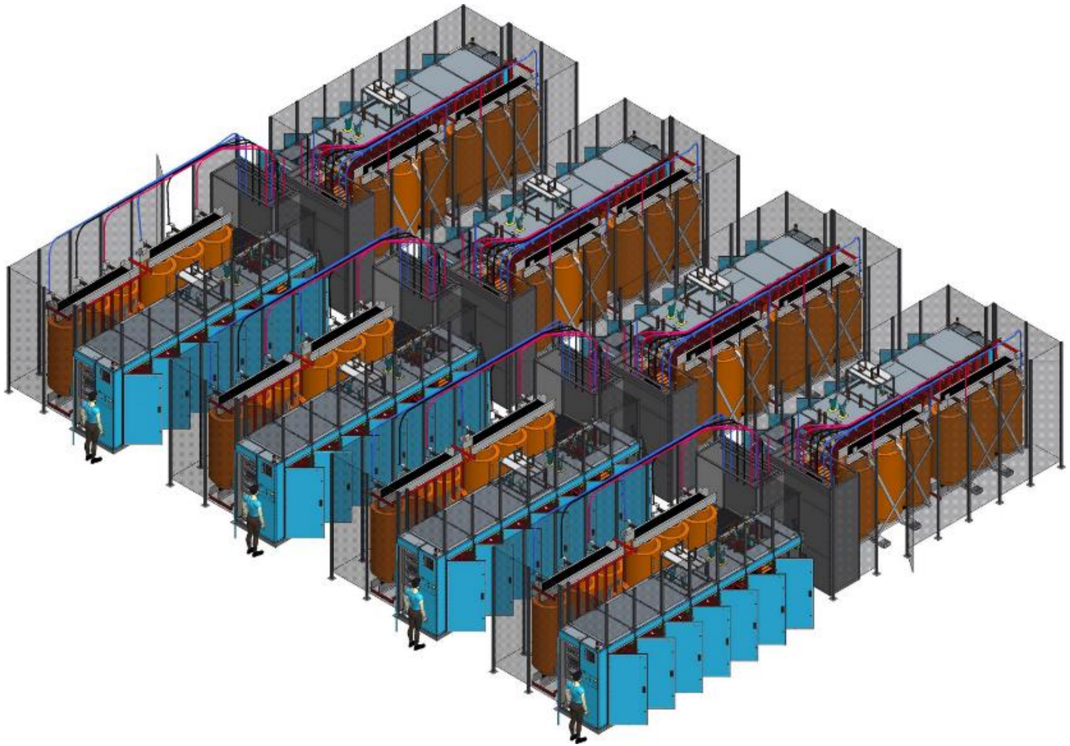
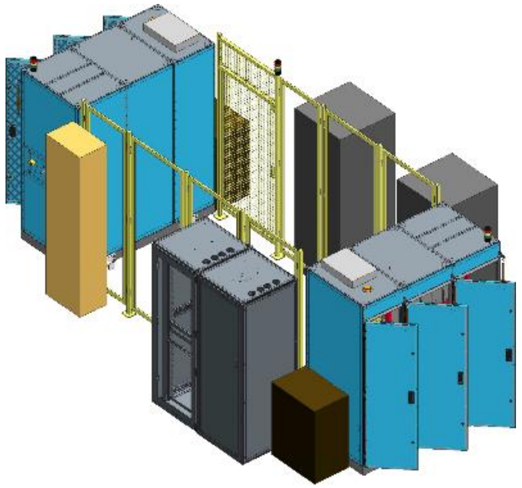
Typical gyrotron power supply set (present design)

- Gyrotron Power: ~1.2MW, $\eta_{tot} \geq 50~\%$ (ITER target)
- Main HVPS (MHVPS), typ. 50kV, 2x50A PSM
  - *Provide all the power to the gyrotron (RF power + collector losses)*
  - *Provide the whole current of the electron beam*
  - *Provide part of the acceleration voltage (or beam voltage)*
- Body Power supply (BPS), typ. 40kV/50mA
  - *Provide the second part of the beam voltage*
  - *Provide no current to the electron beam → mainly capacitive load (cables)*
  - *Allows improving the overall efficiency from typ. 30% up to 50..55% (?)*
- Anode Power Supply (APS), typ. 40kV/50mA
  - *Control of electric field on the emitting cathode → capacitive current only*
  - *At ITER: only JA-GT, HVDC source with HV series switches (!!!)*
- Filament heating PS (FPS), typ. 40V/25A (1kW)
  - *Heats up the emitting cathode; output voltage is referred to cathode*
  - *HV isolated COTS DCPS (EU) or HV isolated AC/AC converter (RU)*



ITER EU EC HVPS (Building 15, Level 1 and 2)



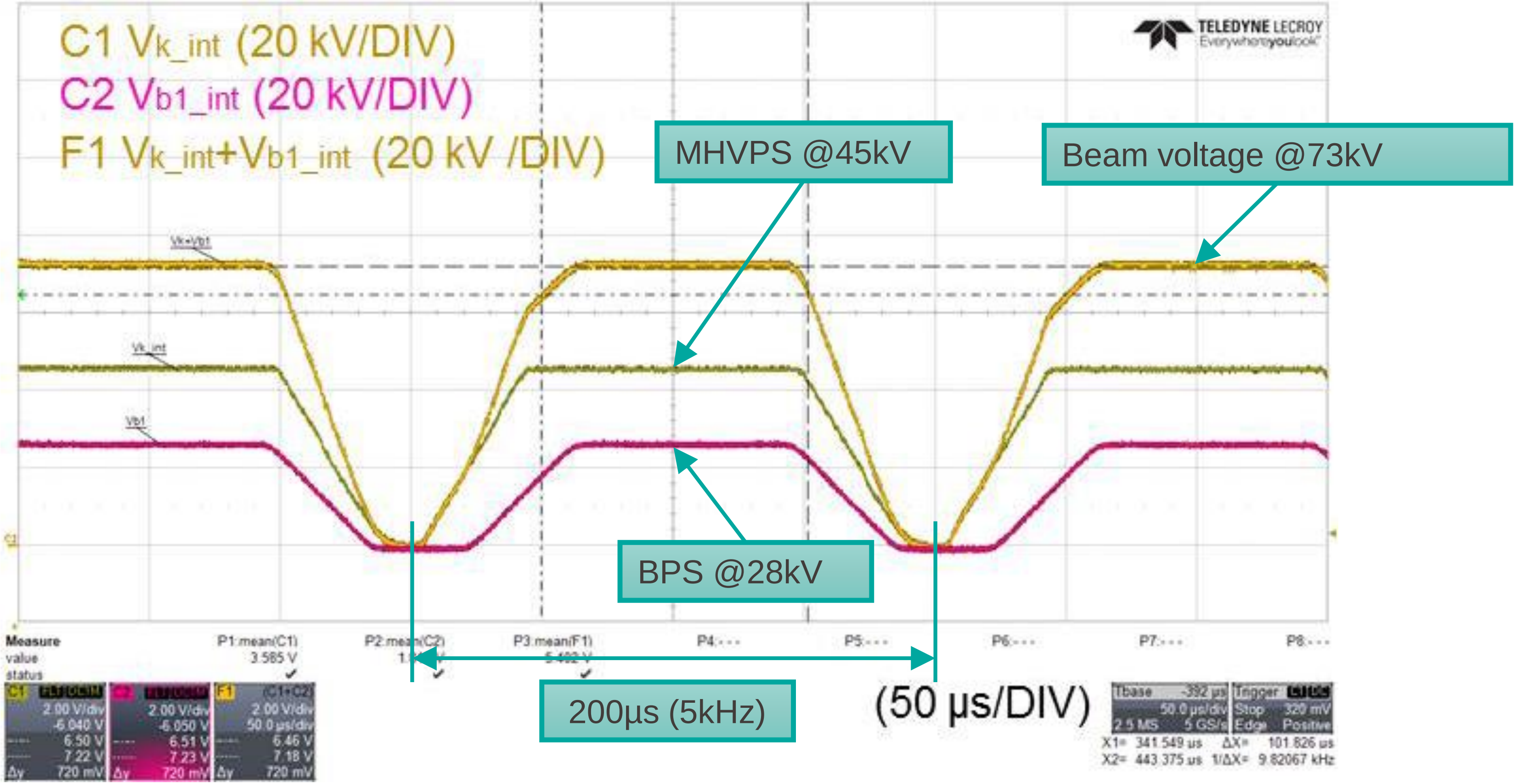


- MHVPS: 55kV/110A (8 units)
- Footprint ~15x20m (~6m^2/MW)

- BPS: 40kV/100mA (16 units)
- Footprint 6.0x3.7m (2 units)

ITER EU MHVPS+BPS on dummy loads

Synchronized operation of BPS and MHVPS with realistic gyrotron voltages (during FAT)



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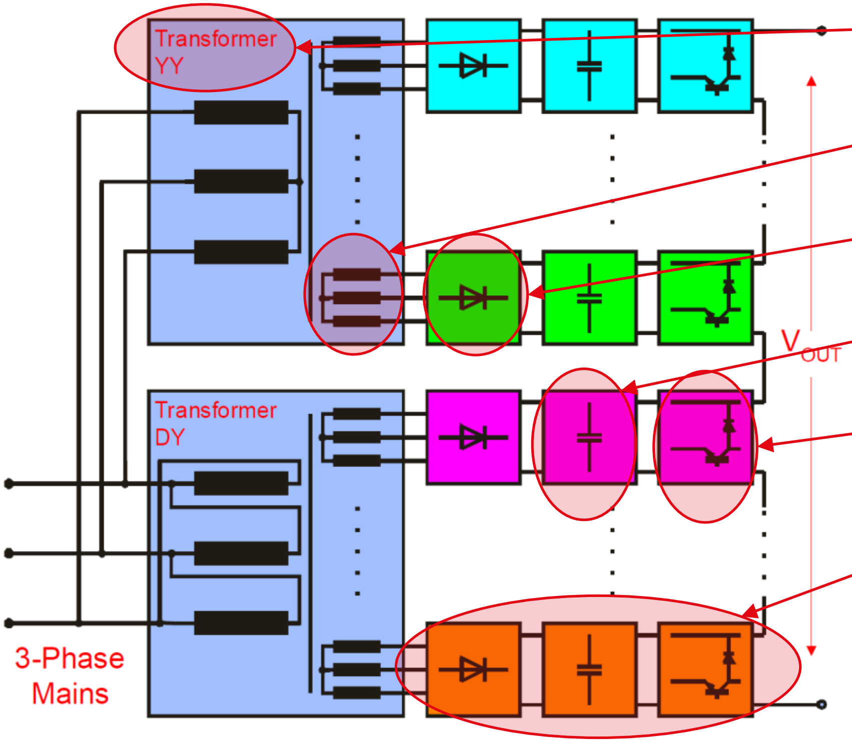
PSM: block diagram (reference design)



- 2 kinds of multi-secondary transformer
- 3 phases secondary winding
- 6 pulses diode rectifier
- LVDC capacitor bank
- IGBT output switch
- PM are sometimes described as SPS Switched Power Supply (chopper)

EC HVPS requirements for future fusion devices

EU Demo (present design)

- 130MW, 108x 2MW gyrotrons
- 54 HVPS, if ITER-like

STEP (UKAEA)

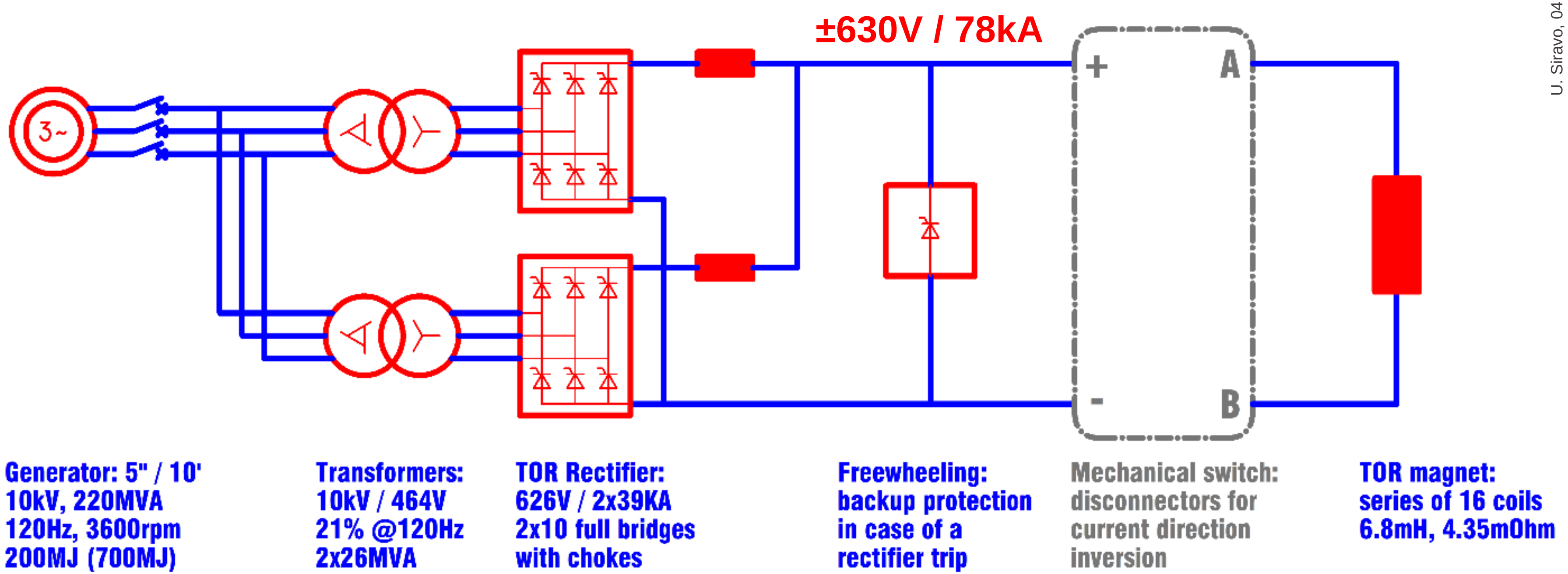
- 300MW, 320x 1MW Gyrotron
- 80 HVPS, 8MW each, $3m^2$/MW

A **specific R&D task** for gyrotron HVPS would allow to

- Improve efficiency, reduce footprint and weight
- Investigate alternative designs based on SiC MOSFET
- Accommodate the gyrotron onto the power supply cabinet, as for klystron ?
- Integer energy storage inside power supply to smooth load step on the grid ?

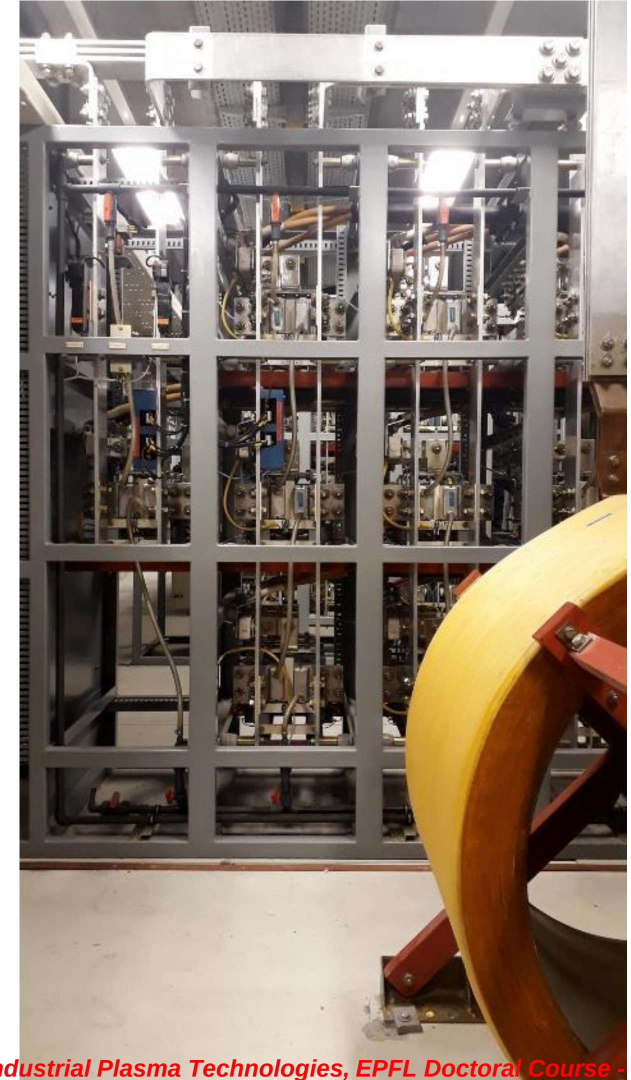
5. High current power supplies for (superconductive) coils

TCV Toroidal field converter



- 12-pulse parallel thyristor rectifier, unidirectional (2-quadrant)
- Automatic mechanical inversion of toroidal field direction (2016)

TCV Toroidal field converter



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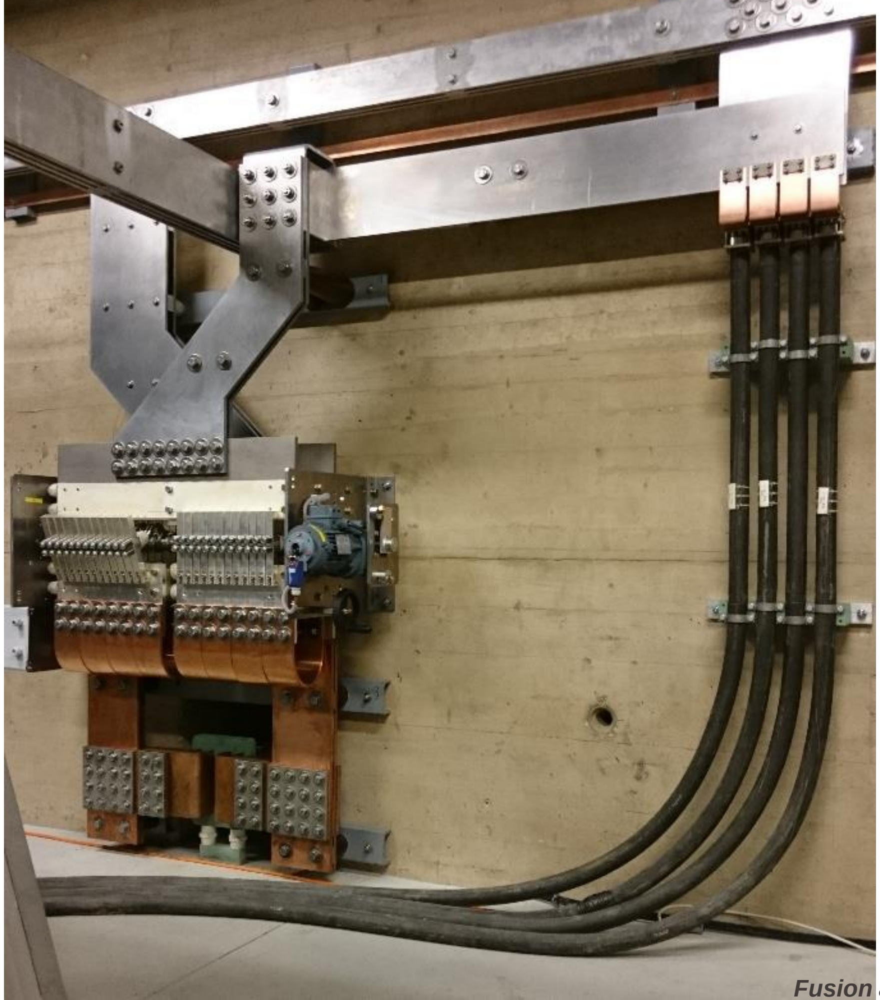
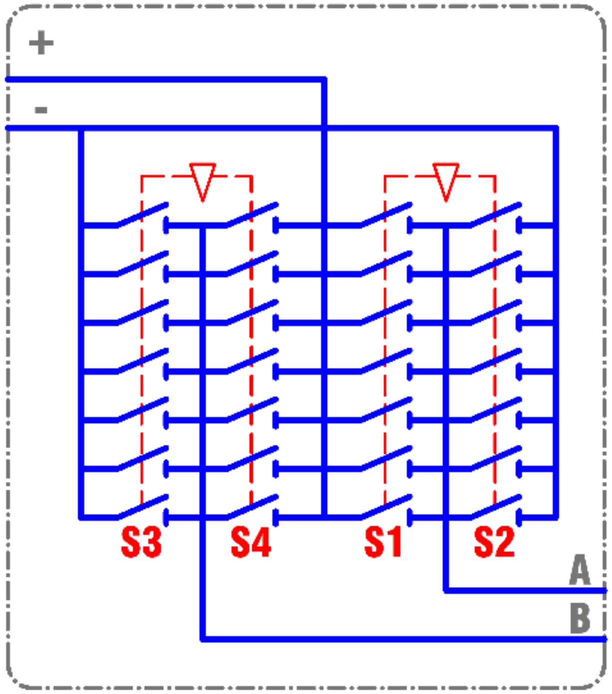
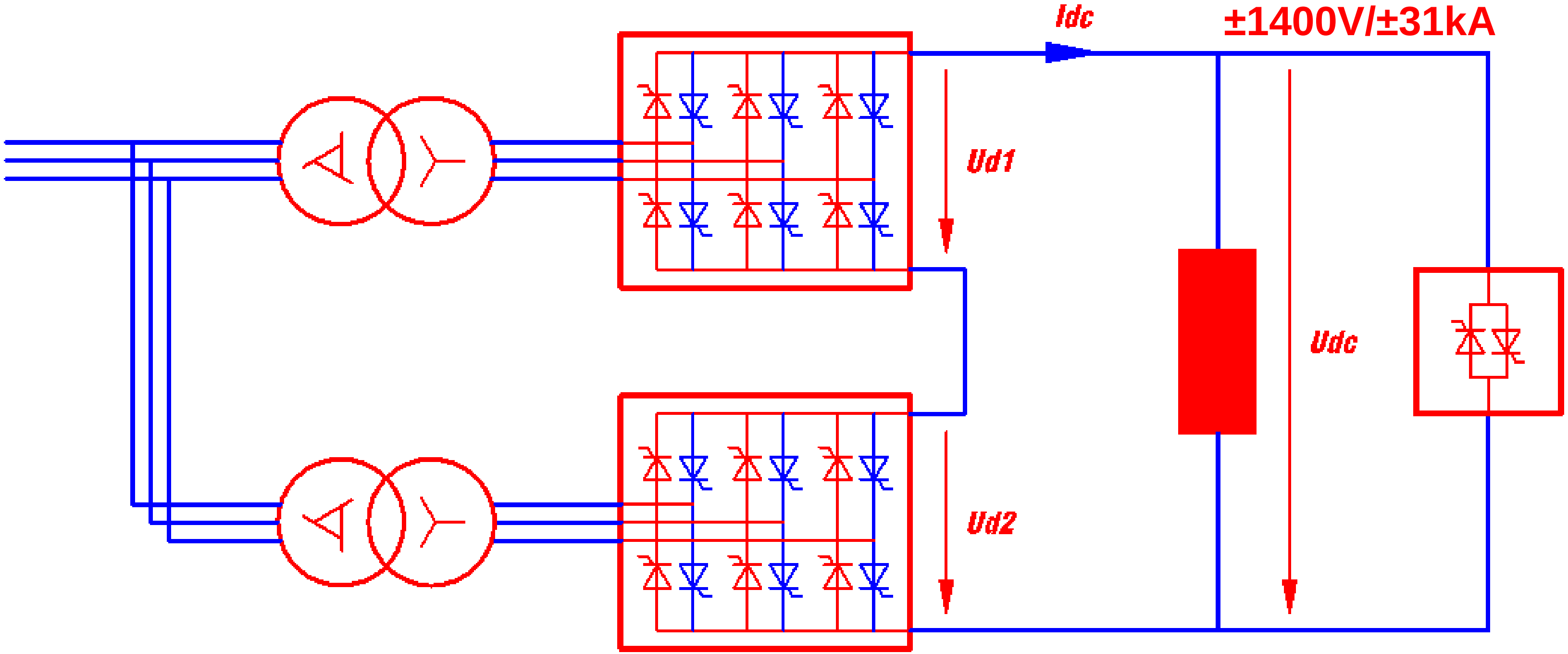
TCV Toroidal field converter



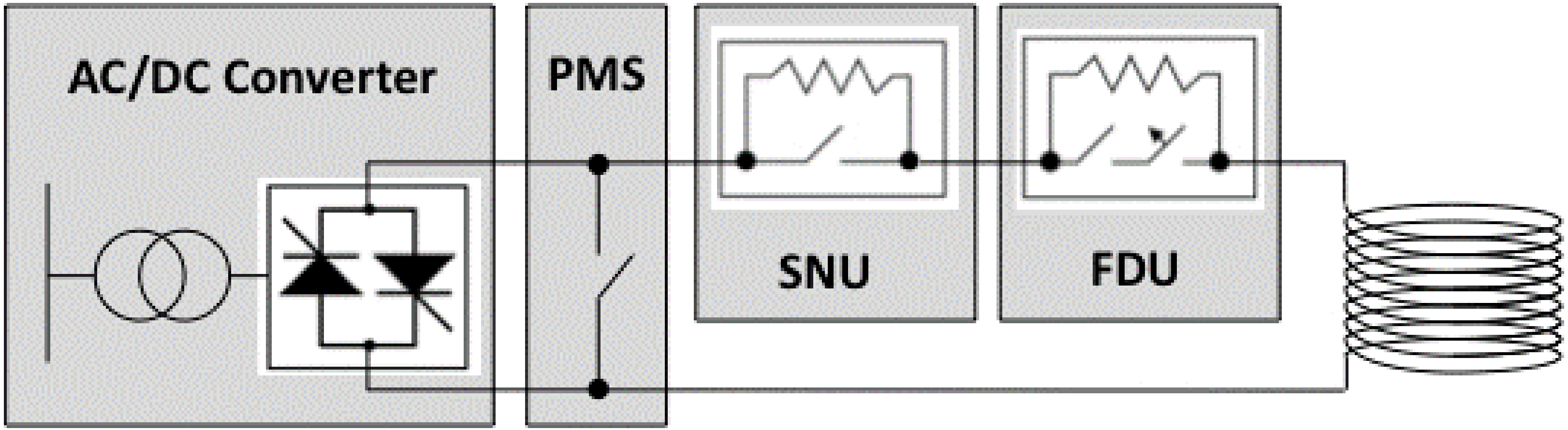


TCV Central Solenoid converter (OH1 + OH2)



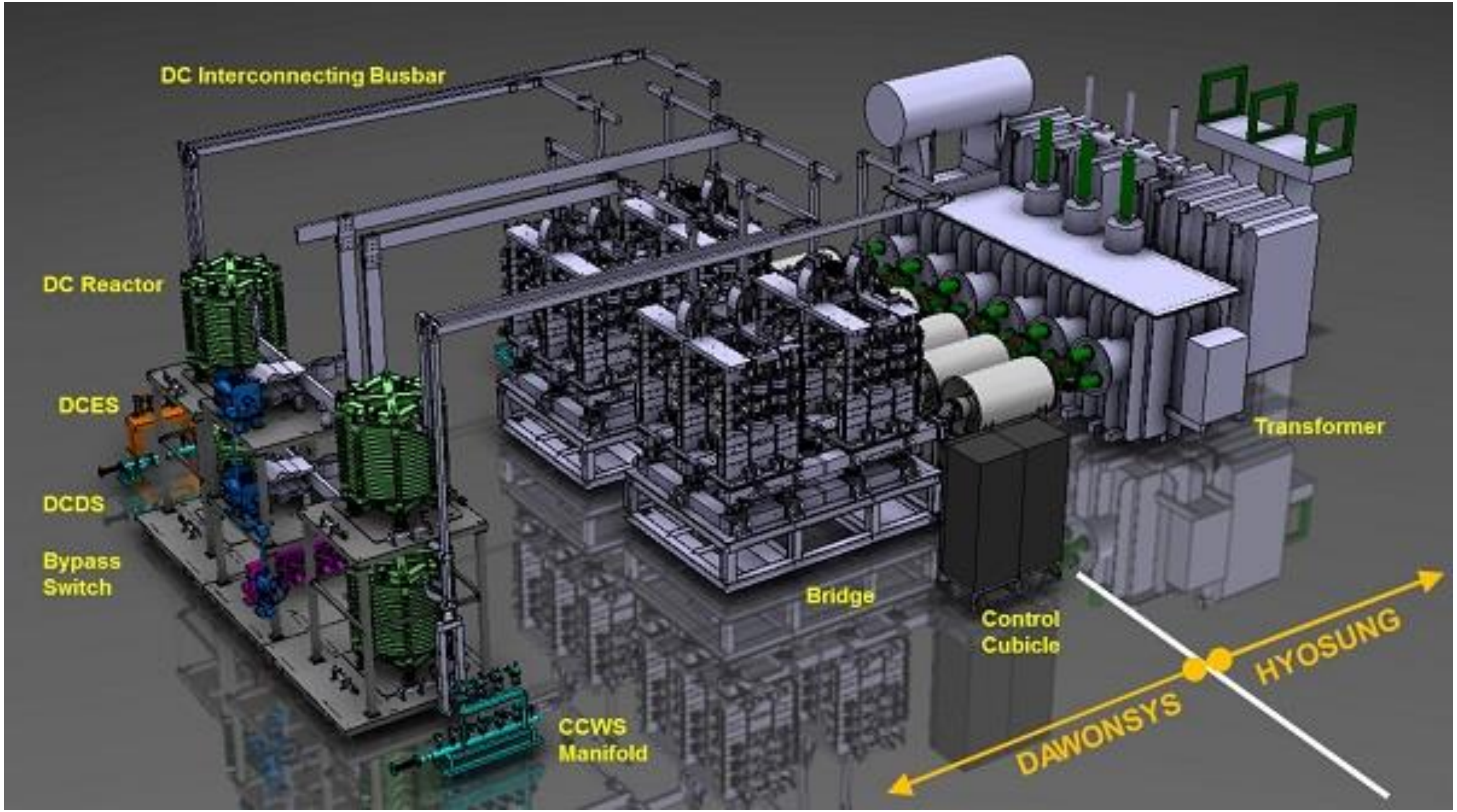
- 12-pulse series thyristor rectifier (8 parallel units), 4-quadrant
- Simultaneous control of both bridges: $Ud1=Ud2=0.5Udc$

ITER typical coil power supply arrangement



- PMS: Protective Make Switches
- SNU: Switching Network Unit (L/R discharge)
- FDU: Fast Discharge Unit (35GJ for TF)

ITER Converter typical layout



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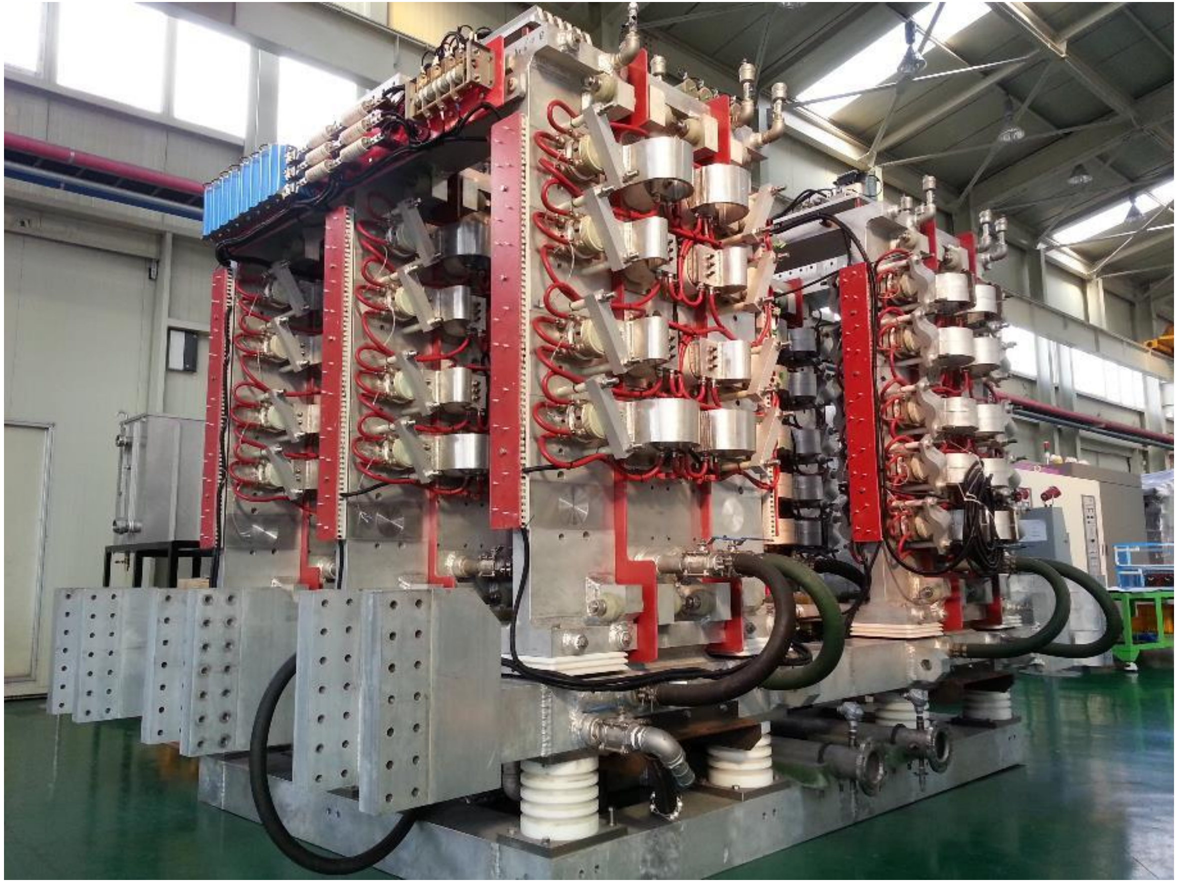
Example of ITER Converter



- VS: 22.5kA/±1350V
- 2 series bridges

References

- Bin Wu & Mehdi Narimani in *High-Power Converters and AC Drives, 2nd Edition Wiley IEEE Press, 2017 https://ieeexplore.ieee.org/servlet/opac?bknumber=7823162*

6. Exercices

Simple exercises related to a Fusion Power Plant (FPP)

- Considering that ITER is designed to produce 500MW of fusion heat (Q=10), with a repetition rate of 1h/4h, estimate the electrical energy that would be produced per year, if ITER would be equipped with a steam turbine generator.
- Compare the above result with the production of a solar field that would occupy the whole ITER platform (180 hectares), knowing that the solar potential at ITER is of 1700 kWh/m^2/year, and considering solar cells with 22% efficiency.
- For information, the Swiss Government, in the panic of war in Ukraine, as built in less than 1 year an emergency power plant of 250MW, composed by 8 mobile gas turbine generators, that occupies less 10’000m^2.
- Reminding that Lausanne has a district heating network rated 85MW to provide heat for 1/3 of the buildings in the area (250’000 habitants), in which cities a 1’000MW Fusion Power Plant would ideally be built in Europe?

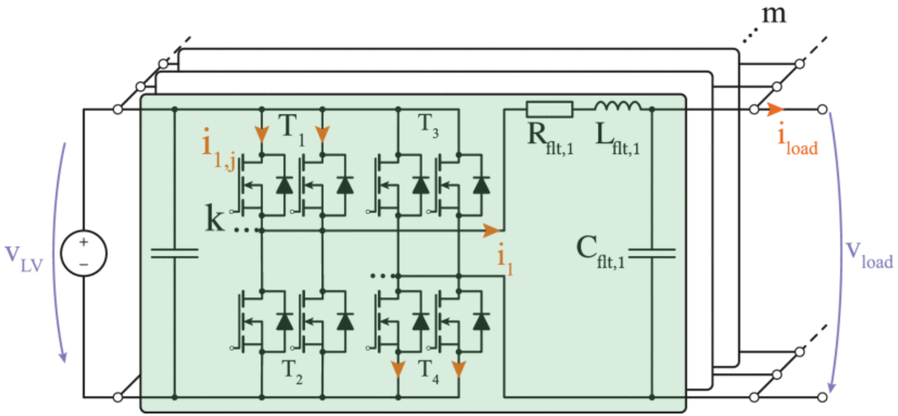
Few small calculations related to electrical power

1. Can you demonstrate that P= $^1U \cdot {}^1I \cdot \cos({}^1\varphi)$, when $u(t) = {}^1U\sqrt{2}\sin(\omega t)$?
2. For a passive and equilibrate load, with U1, U2, U3 sinus and equilibrate, what is the expression of P(t)=sum(Pi(t)) and S(t)=sum(Si(t)) ?
3. If U1,U2,U3 contain third harmonic, what does it for a Yy0 transformer ?

Renew of the TCV fast power supply (FPS)

FPS is connected to G1 and G2 internal coils, for vertical stabilization

- Specs are ±2kA on L=60µH, with di/dt > 5A/µs
- Estimate the appropriate output voltage
- Propose a block diagram using a) 1.2kV/2kA IGBT and b) 1.2kV/220A MOSFET, taking inspiration from DOI 10.1109/TPEL.2020.2988901
- Achievable current resolution and current ripple with both solutions?
- Where to implement an energy storage system? For what the benefits?
- Size of the storage system for a duty cycle of 2kA/100ms/5minutes.



DC/DC converter, split in m parallel branches

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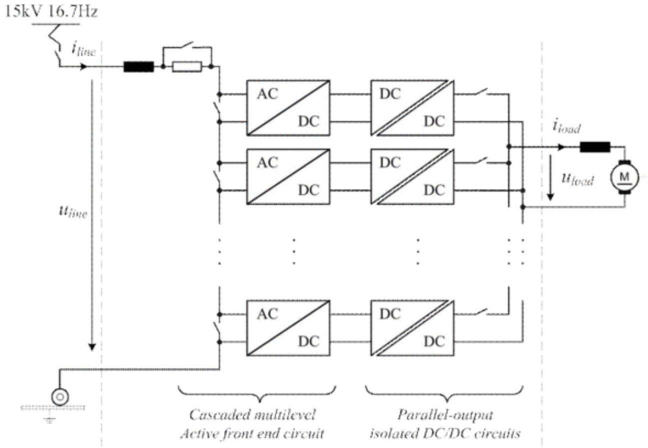
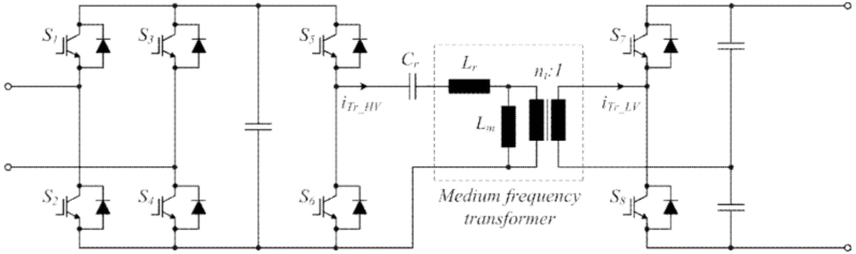
Alternative MHVPS design for a 1.2MW gyrotron

Implementing cascaded h-bridges and medium frequency transformers

- Consider a 1.2MW gyrotron with 48A beam current and 30% intrinsic efficiency. What would be the cathode and body voltages to fulfill the ITER requirement of 50% efficiency? Why is it difficult to exceed 50% efficiency?
- Propose a block diagram for an MHVPS, inspired by the EPFL Power Electronic Transformer *https://doi.org/10.1109/SPEEDAM.2012.6264496*
- Estimate the minimal number of power modules for a 24kV grid, using a) 1.7KV IGBT, b) 3.3kV SiC MOSFET, considering some redundancy
- What are the input and output ratings of the power modules ?



EPFL Power Electronic Transformer (PET)



Topology of one cell in the PET, composed of a full-bridge circuit and a half-bridge LLC isolated resonant circuit.