EUROPEAN SPALLATION SOURCE

Efficiency, Power Quality and Performance of ESS Klystron Modulators

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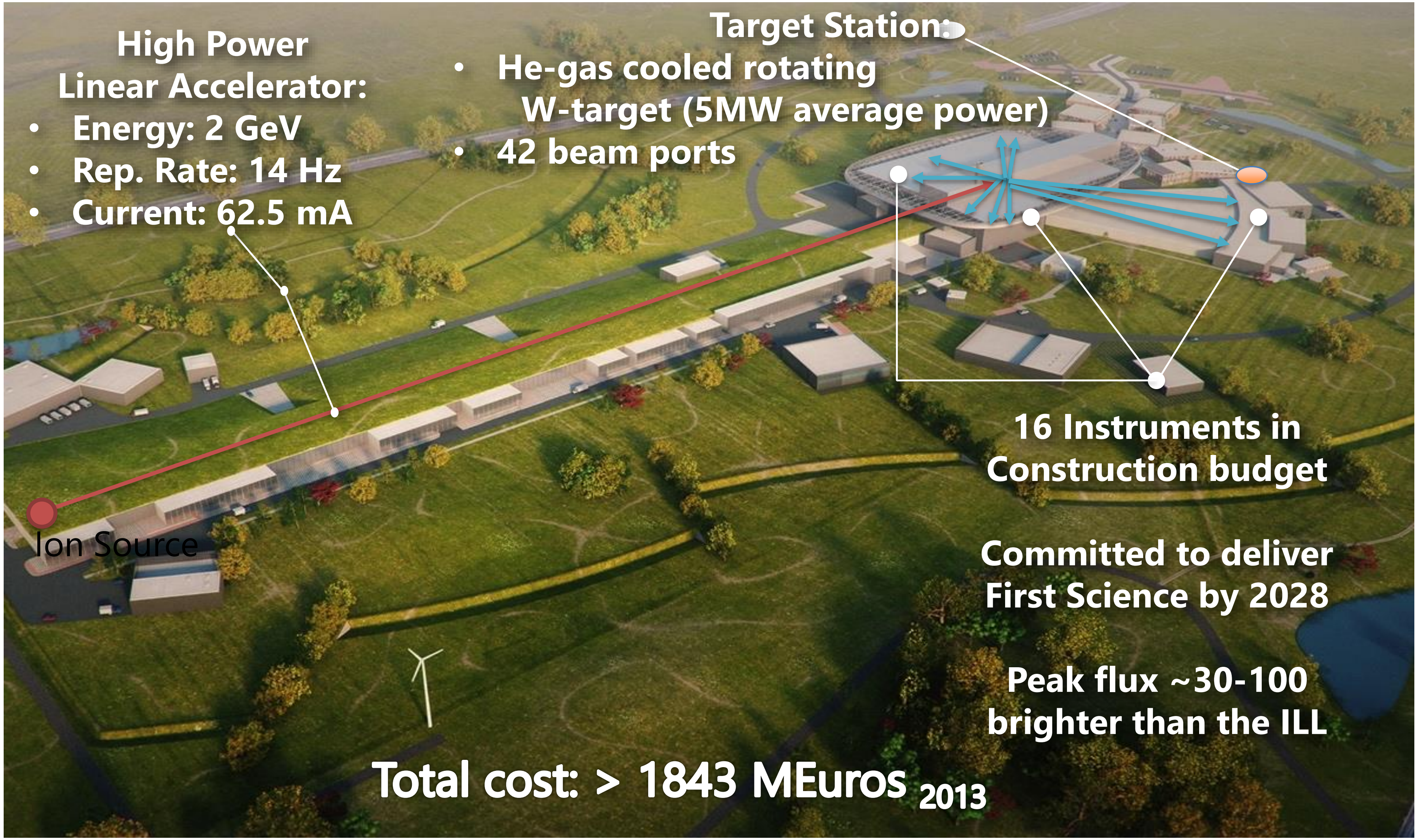
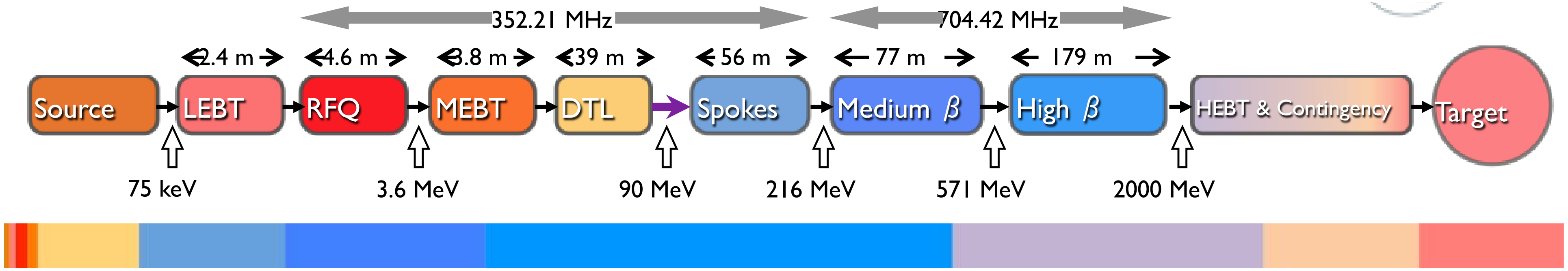
www.europeanspallationsource.se
Workshop on Efficient RF sources, 4th – 6th July 2022

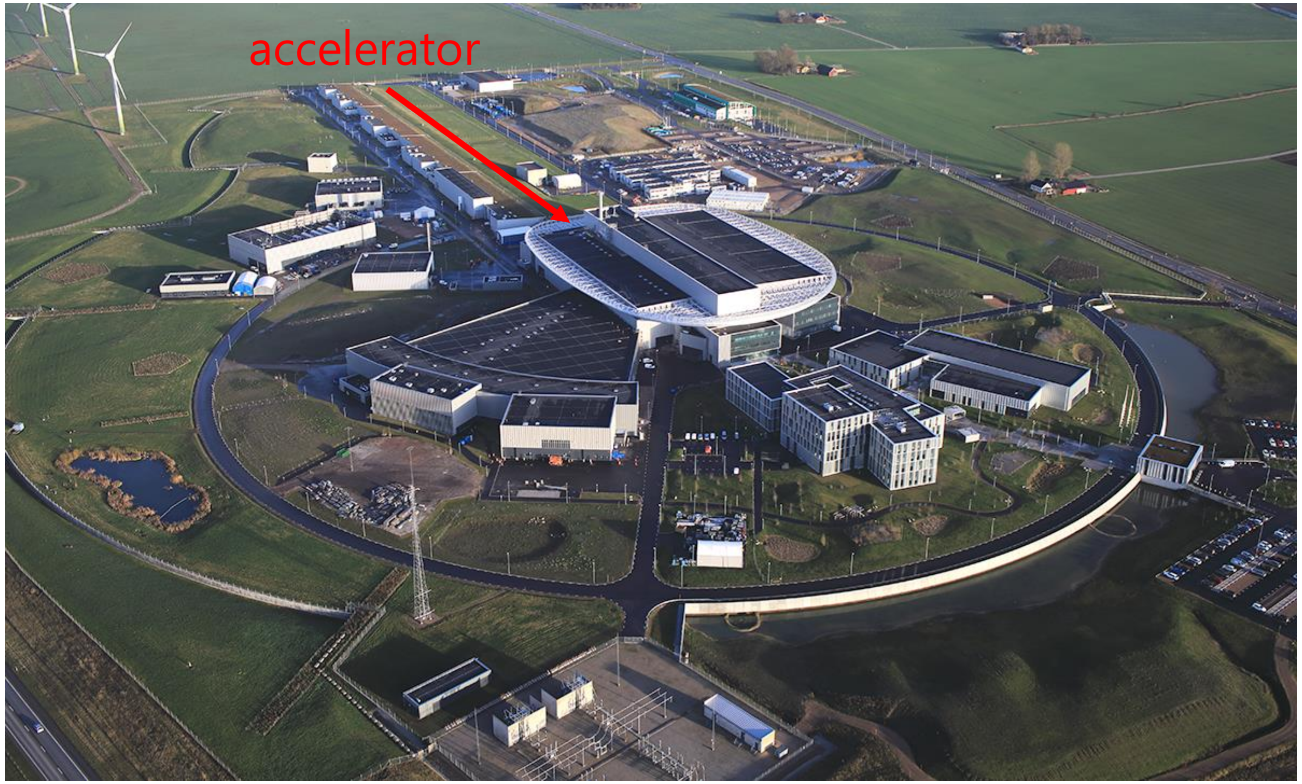
Synopsis – ESS facility



Synopsis – ESS accelerator

Beam power on target: 125MW$_{pk}$, 5MW$_{av}$; Beam pulse length = 2.86ms; PRR = 14Hz





Baseline (end 2027):

- 1 RFQ;
- 5 DTL tanks;
- 36 Medium Beta SCRF cavities (1MW$_{RF}$ each);
- 20 High Beta SCRF cavities
- (1MW$_{RF}$ each)

Upgrade:

- + 64 High Beta SCRF cavities (1MW$_{RF}$ each) (upgrade to 5MW average beam power)

ESS modulator development strategy #1

July 2011

ESS has launched an Invitation To Tender for the design and construction of one 180kVA modulator (turn-key, functional specification):

- Contract awarded in Dec. 2011; Delivery May 2014 (30 months delivery time);

➢ **1st ESS modulator (monolithic topology, pulse transformer based):**

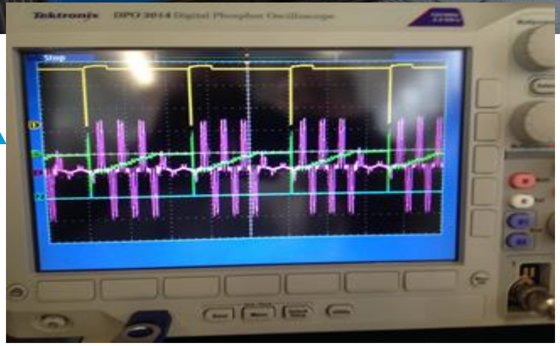
Rated @ 115kV/25A; 2.8ms/20Hz; 160kVA -> **enough to power one 1.4MWpk klystron**;

Limited performance:

- **Rise time$_{(10\text{-}99\%)}$ = 350µs;**
- **Flat-top droop = 3%;**
- **Efficiency = 88%;**
- **Power density = 22kVA/m^2 (no space in RF Gallery)**
- **AC power quality issues (flicker, current harmonic distortion)**

High capital cost:

- ~130 modulators needed

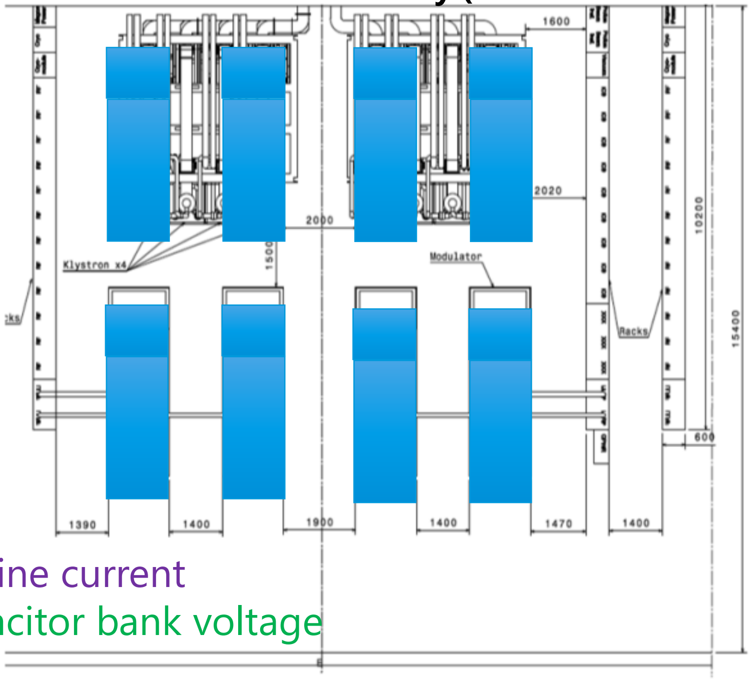


Purple: AC line current

Green: Capacitor bank voltage

8 modulators per RF cell needed (Med-Beta, High-Beta)

One section of the RF Gallery (8x 704 MHz RF sources)



ESS modulator development strategy #2

Jan. 2014 **ESS has launched an Invitation To Tender for the design and construction of one 330kVA modulator (turn-key, functional specification):**

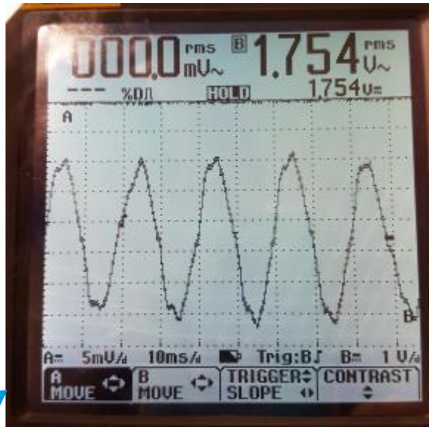
- Contract awarded in June 2014; Delivery June 2017 (36 months delivery time);

➢ **2st ESS modulator (modular topology, HF transformers based):**

Rated 115kV/50A; 3.5ms/14Hz; 330kVA -> **enough to power two 1.4MWpk klystrons**;

Better but still limited performance:

- **Rise time$_{(10\text{-}99\%)}$ = ~120μs;**
- **Flat-top droop < 1%;**
- **Efficiency = 87%;**
- **Power density = 66kVA/m^2**
- **Better AC power quality: still high current distortion;**
- **Reliability concerns due to huge number of components and limited design margins**



Still high capital cost:

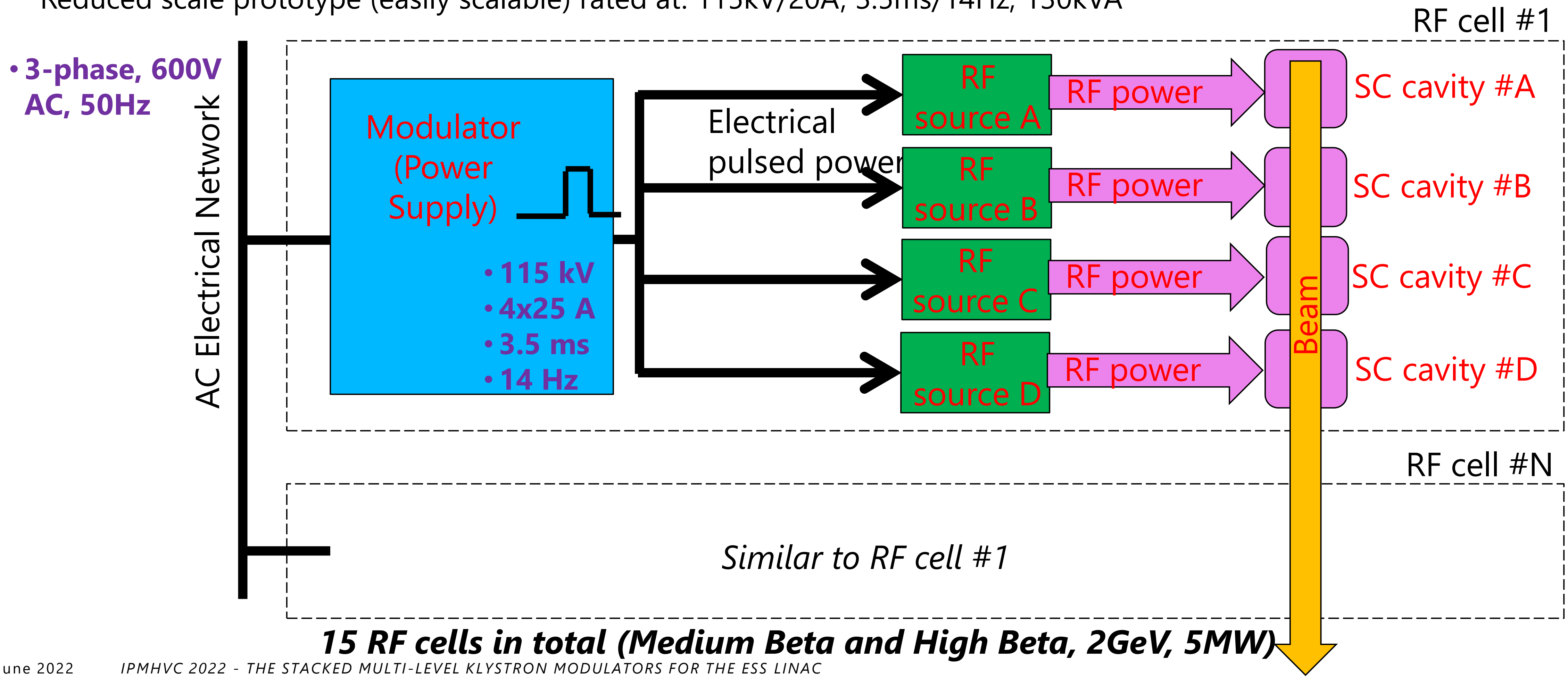
- ~65 modulators needed

ESS modulator development strategy #3 – SML modulator

June 2013 **ESS has decided to launch a collaboration with LTH / IEA Department, in view of designing and building a modulator prototype for ESS, following a novel topology:**

- **3rd ESS modulator (Stacked Multi-Level topology)**

Aimed at final ratings: 115kV/100A; 3.5ms/14Hz; 660kVA -> **enough to power four 1.4MWpk klystrons**;
Reduced scale prototype (easily scalable) rated at: 115kV/20A; 3.5ms/14Hz; 130kVA



15 RF cells in total (Medium Beta and High Beta, 2GeV, 5MW)

SML Modulator main parameters

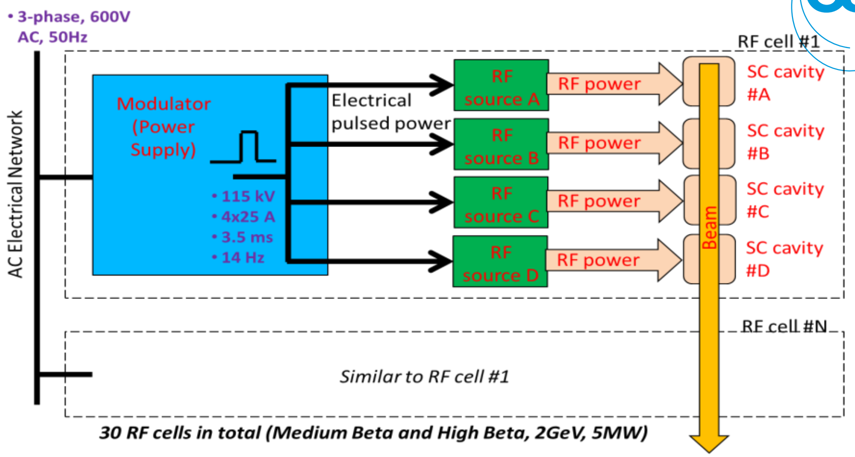
- Main parameters of SML klystron modulators (as from SoW)

Nominal pulse voltage amplitude	U_K	-115 kV
Nominal pulse current amplitude (sum of four outputs)	I_K	4x25 A =100 A
Nominal pulse power amplitude (sum of four outputs)	P_K	11.5 MW
Nominal pulse repetition rate	PRR	14 Hz
Nominal pulse width (at 50% of magnitude)	T_P	3.5 ms
Maximum pulse rise/fall times (10..99% / 100..10%)	T_R, T_F	120 µs
Minimum flat-top duration	T_T	3.35 ms
Maximum droop or slow oscillation at flat-top (frequency range: < 0.3kHz)	ΔU_K	1% of U_K
Maximum voltage ripple in the flat-top, rms - 0.3kHz > freq. range > 1kHz: - 1kHz > freq. range > 100kHz: - 100kHz > freq. range > 300kHz: - 300kHz > freq. range:	$\tilde{u}_K$	 0.3% of U_K 0.2% of U_K 0.15% of U_K 0.3% of U_K
Maximum pulse overshoot	$U_{K\,OVS}$	2% of U_K
Pulse to pulse reproducibility (Average voltage over flat-top)	PP_{REP}	0.15% of U_K
Pulse stability (average voltage over flat-top): - Over 1 hour, without warm-up: - Over 24 hours, after 1 hour warm-up: - Over 1 year, after 1 hour warm-up:	$\bar{u}_K$	 0.3% of U_K 0.3% of U_K 1% of U_K
Maximum energy in case of arc (arc voltage: 50V; with 4 HV output cables <4m length per cable; with R=5Ω in series with output, before arc)	E_{ARC}	10 J
Minimum efficiency at nominal conditions		90%
Maximum total power losses in air		4% of total power losses
Mains supply, AC power port (R, S, T)		3 x 600V, 50 Hz
Mains supply, AC control port (ext. UPS)		3 x 400V, 50 Hz
Cooling		Water cooled
High voltage insulation type, at the oil tank level		Mineral oil
Maximum audible noise, at 1m from any point of cabinet	An	75 dBA
AC line power quality - Total Harmonic Distortion (THDi) - Flicker of current amplitude	 % %	 3 5

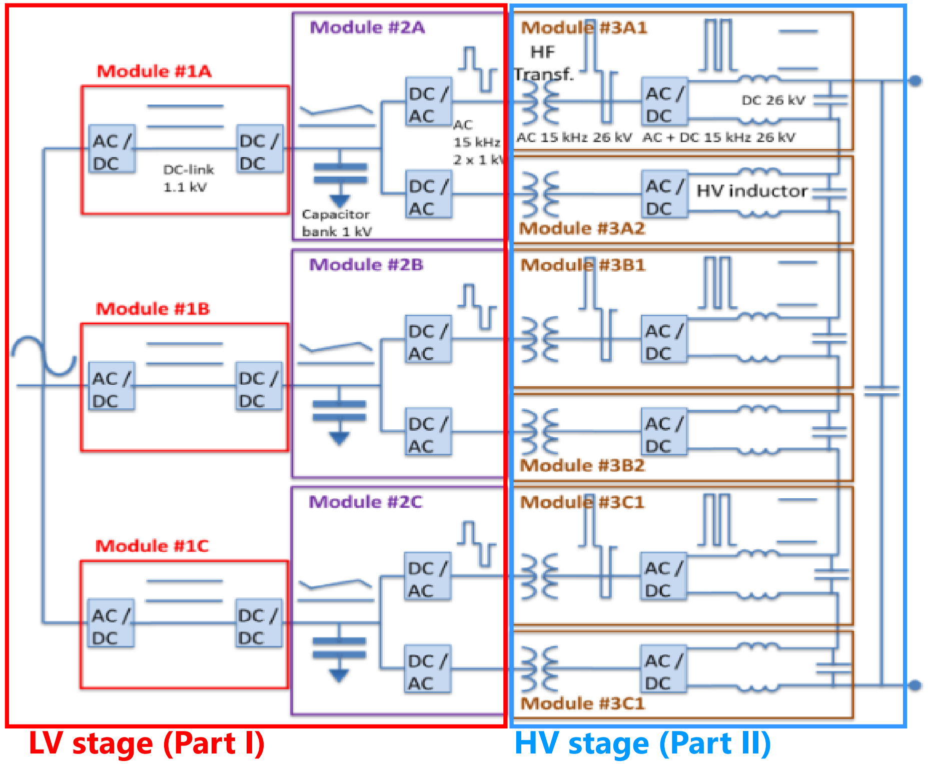
exceeded

met

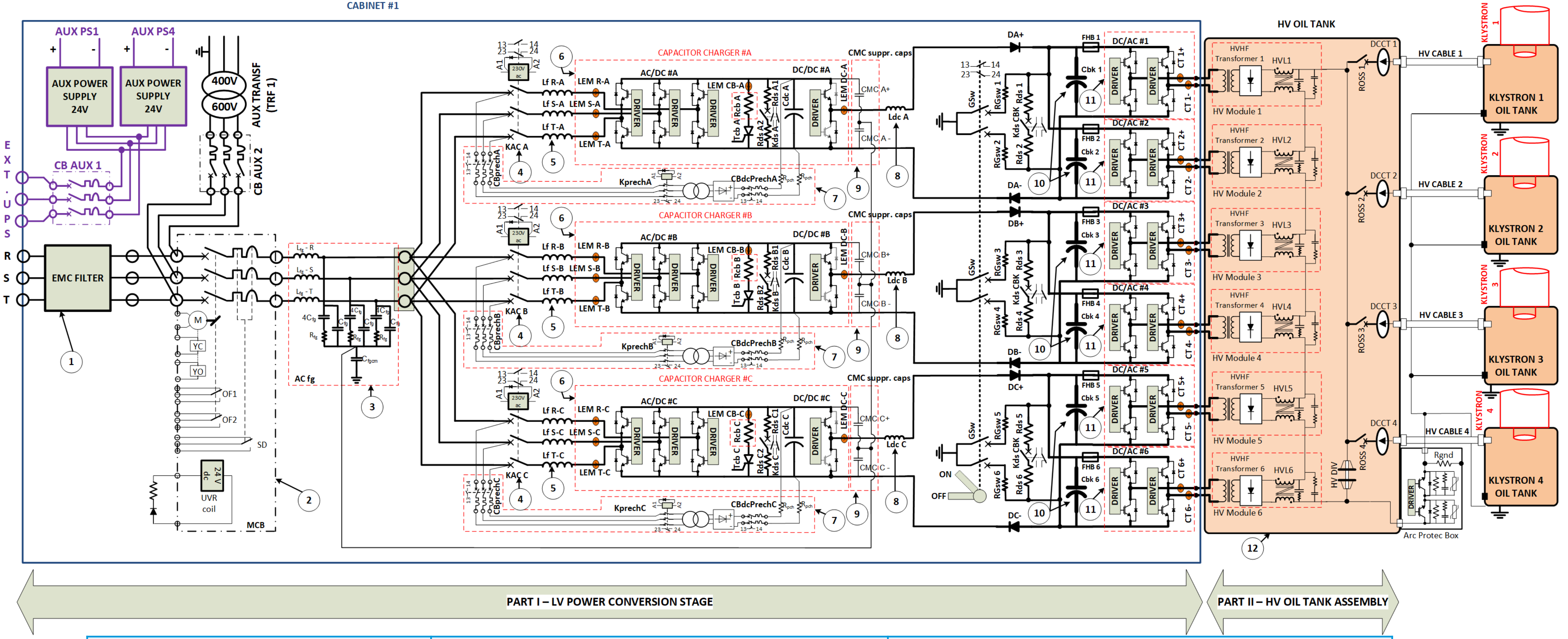
not met, but non-critical



- Topology simplified schematic



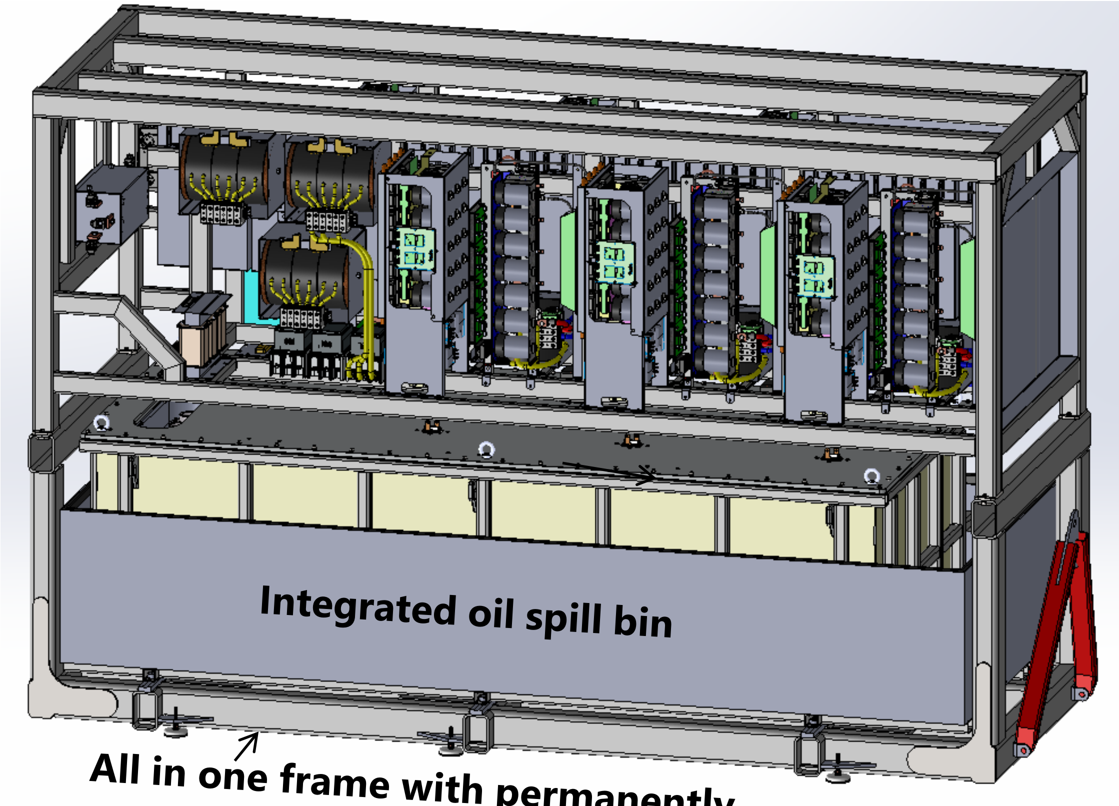
SML modulator schematics

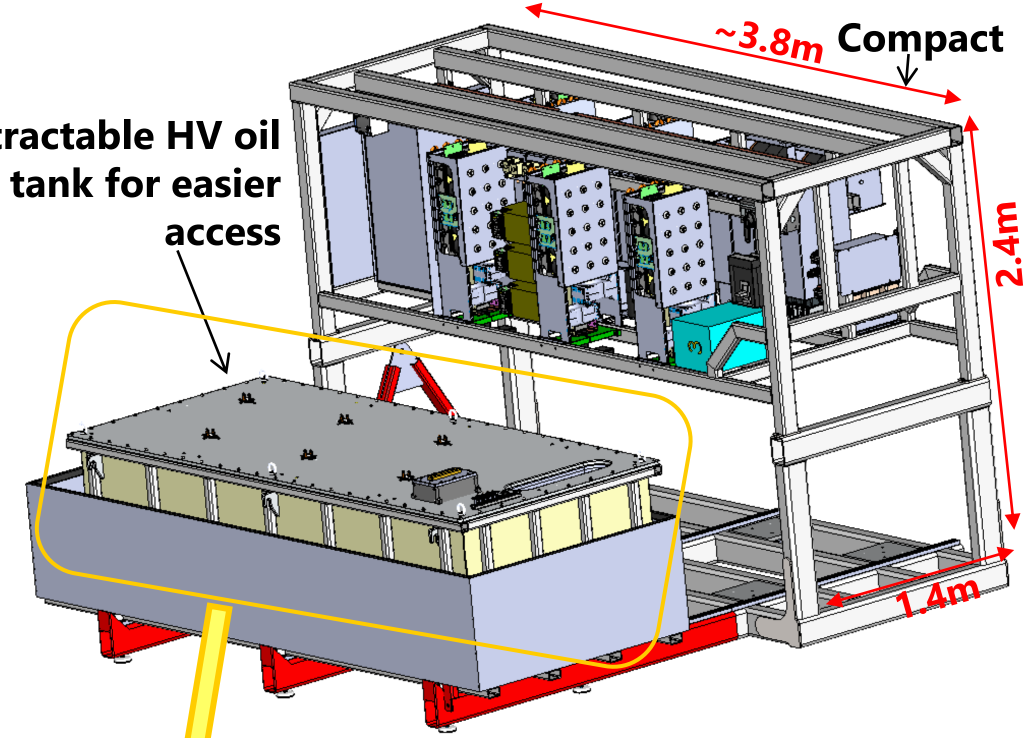


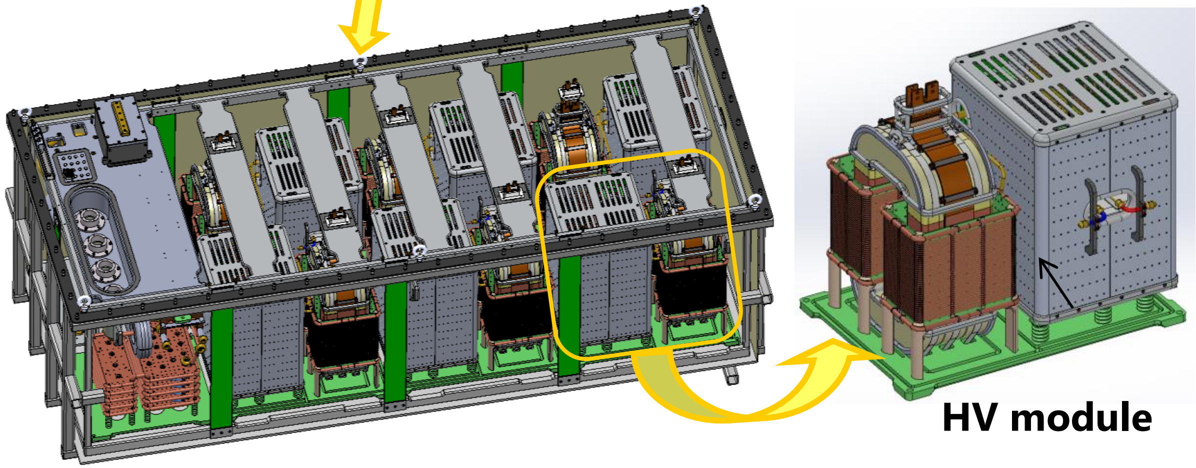
(1)- EMC filter	(5) - AC line filter (L_2 branch)	(9) - Common mode suppression capacitors
(2) - Main Circuit Breaker	(6) - AFE (AC/DC) + DC/DC power stacks	(10) - Main capacitor banks
(3) - AC line filter (L_1C branch)	(7) - DC-link busses pre-charge circuits	(11) – H-bridge (DC/AC) power stacks
(4) - AC contactors	(8) - DC filter inductors	(12) – Oil tank assembly

Full Scale Units, rated at 115kV/100A ; 3.5ms/14Hz

Calendar **Sept. 2016** **Design of full scale modulator completed, ready for call for tender**

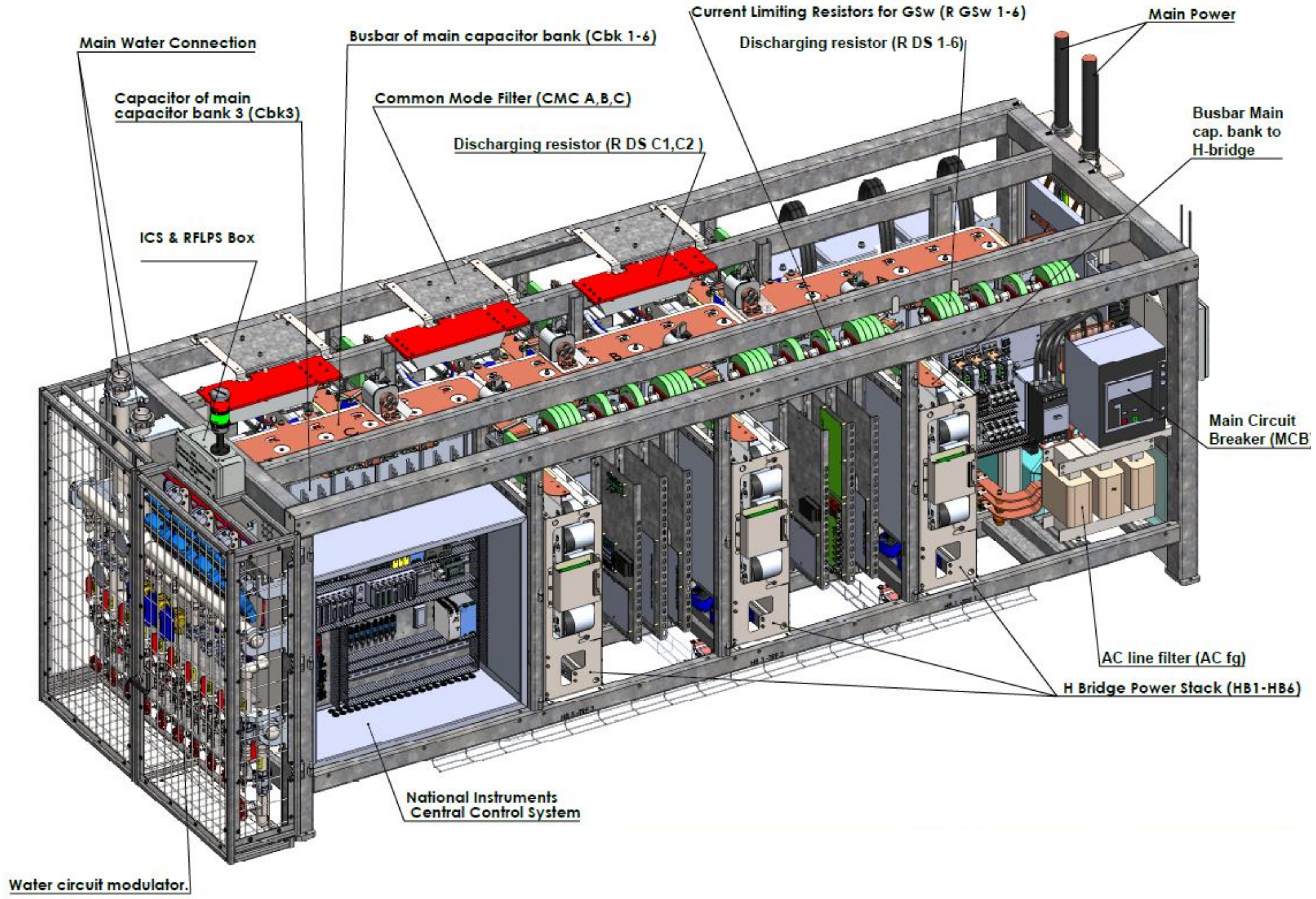






- **Total footprint:** 4.2m x 1.4m
- **Total weight:** < 12 tons (with oil);
- **Total volume of oil:** ~ 2000 litters;

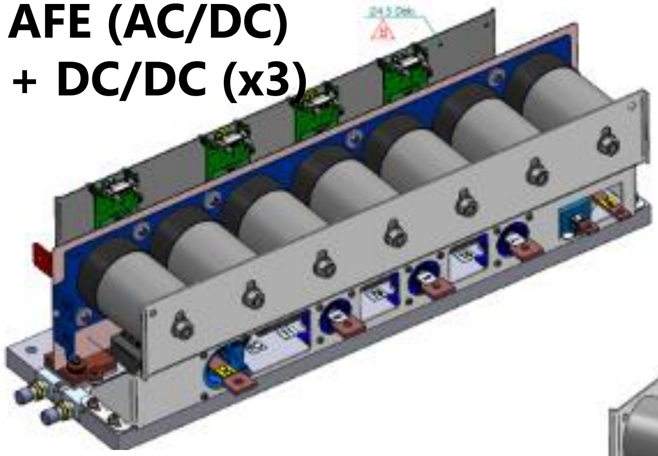
Part I – Low Voltage power conversion cabinet

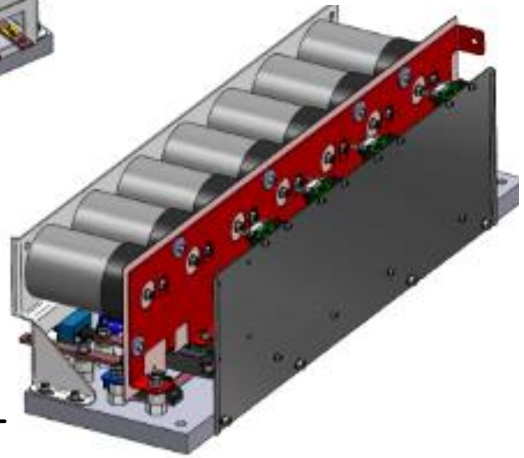


Part I – Low Voltage power conversion cabinet

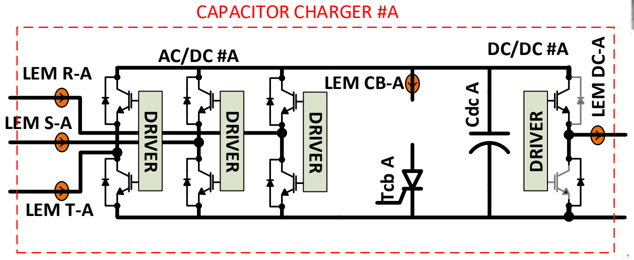
Power Stacks

AFE (AC/DC) + DC/DC (x3)

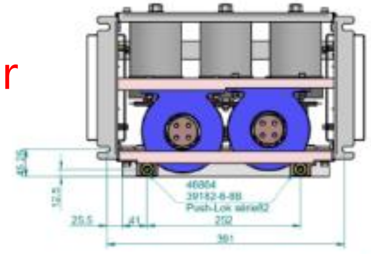


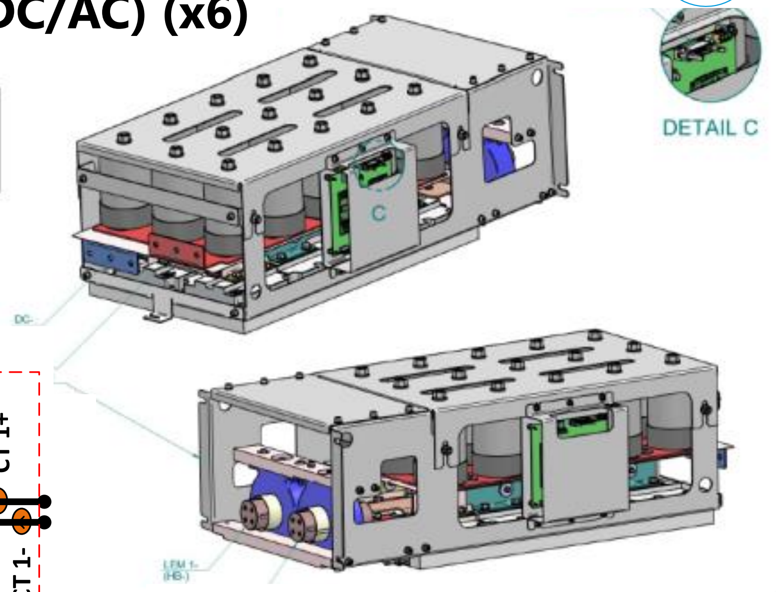


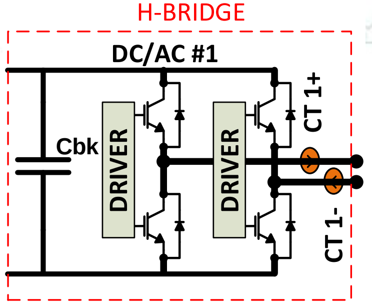
Designed, manufactured and tested in factory by a specialized sub-contractor



H-BRIDGES (DC/AC) (x6)

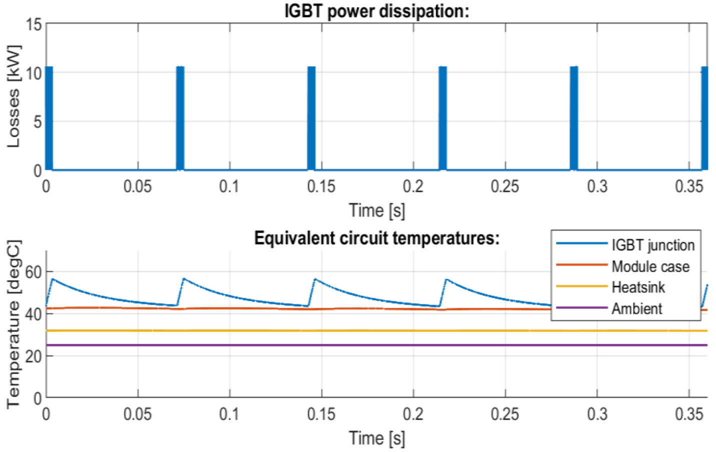


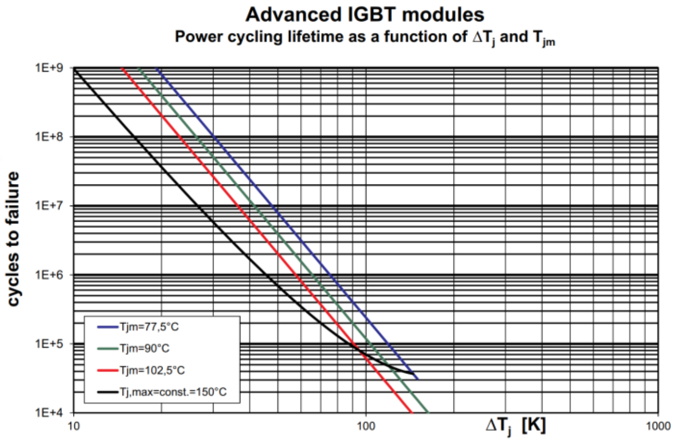


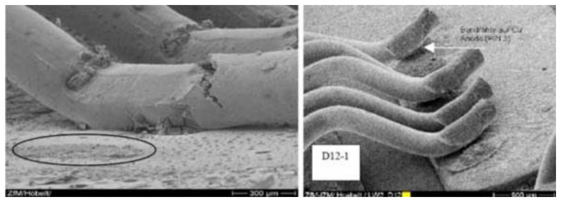


- Water cooled heatsinks;
- IGBT modules with Al-Sic baseplates in H-bridges (higher power cycling capabilities);
- Standard / well proven IGBT drivers with embedded protections:
  - Short circuit, by Vcesat;
  - Dead time generation;
  - +15V aux. supply undervoltage protection;
  - Active Vce clamping at turn-off;

Power cycling and IGBT lifetime



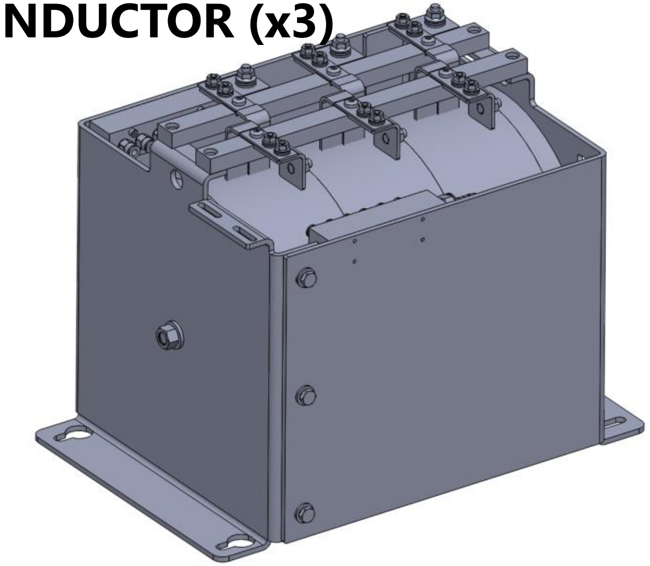




AC line and DC filter inductors

New technology (Casted Iron Powder Inductors)

AC LINE INDUCTOR (x3)



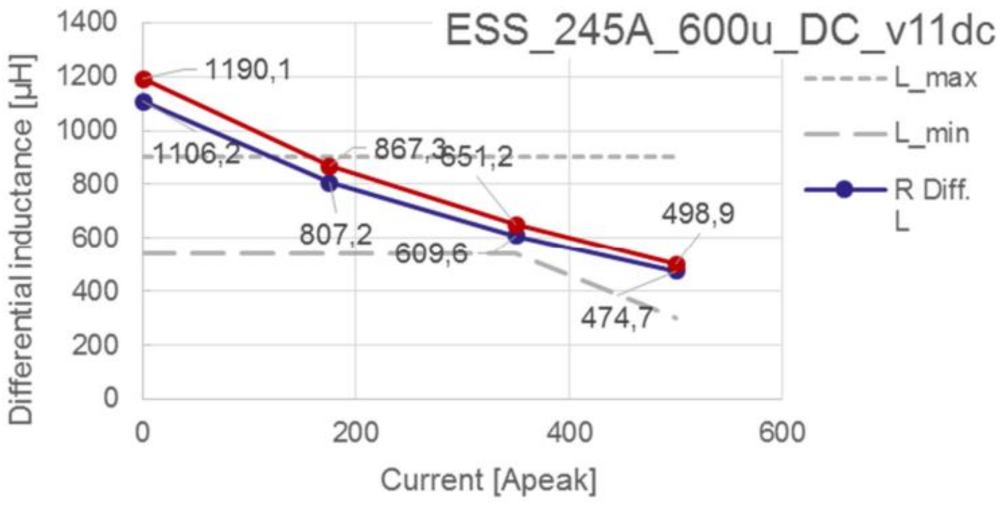


Figure 2: Inductance vs. current. Three inductors, incremental inductance.

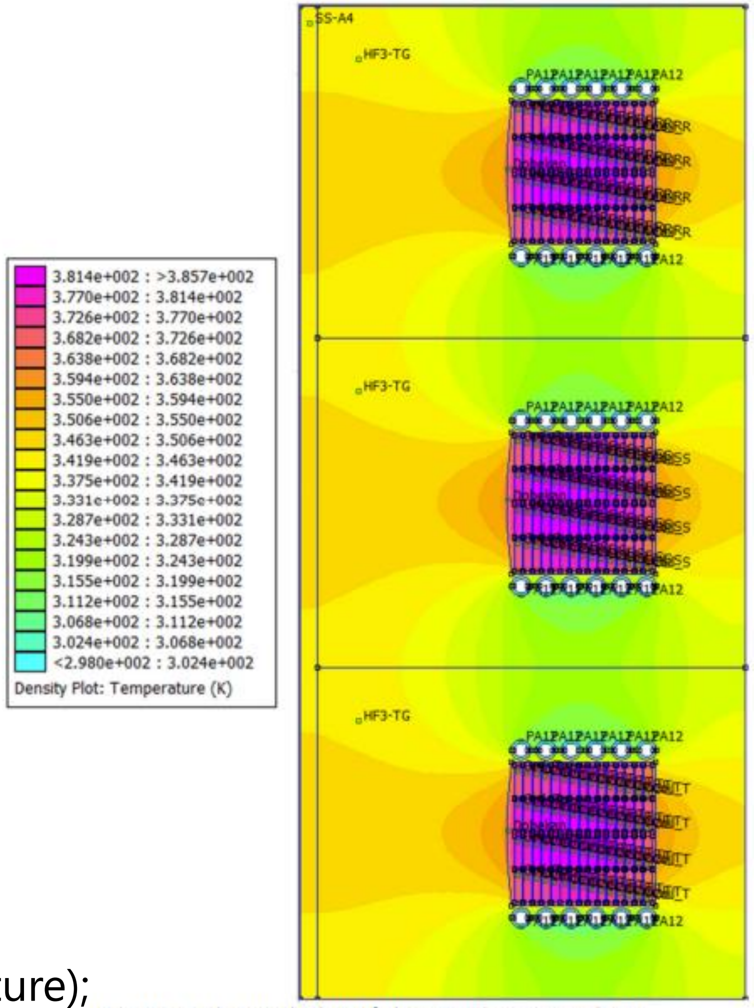
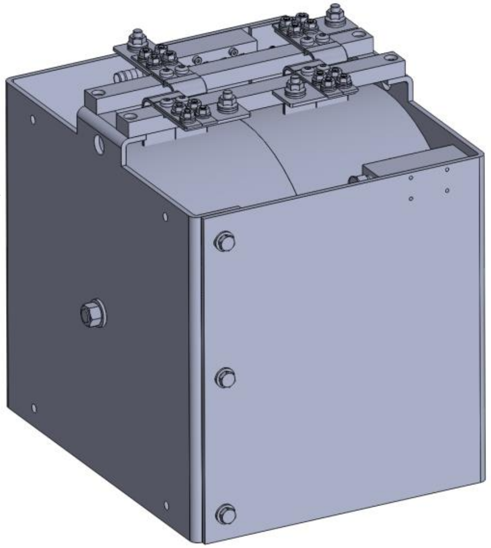


Figure 3: Thermal plot of three inductor package

DC FILTER INDUCTOR (x3)



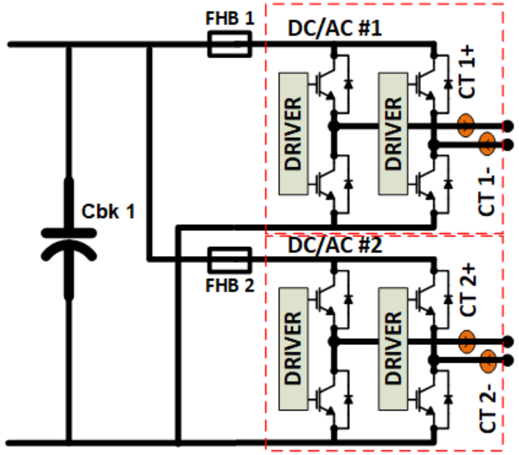
- Water cooled;
- Casted core (iron powder / epoxy resin mixture);
- Compact;
- Higher efficiency;
- No saturation “knee”;
- Higher inductances (for free) at lower currents, where current ripples are higher);
- Very low acoustic noise

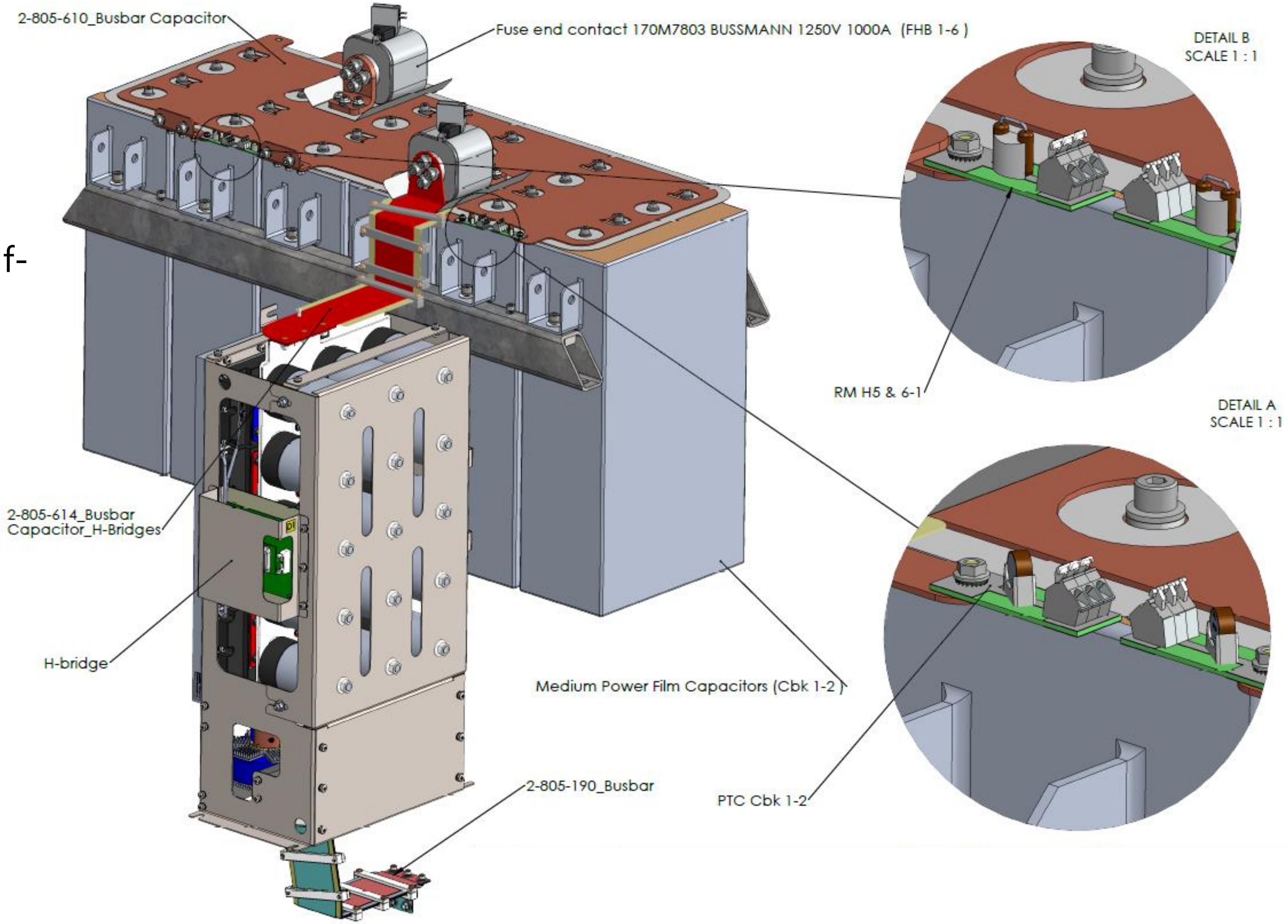
Main Capacitor Banks

Capacitors:

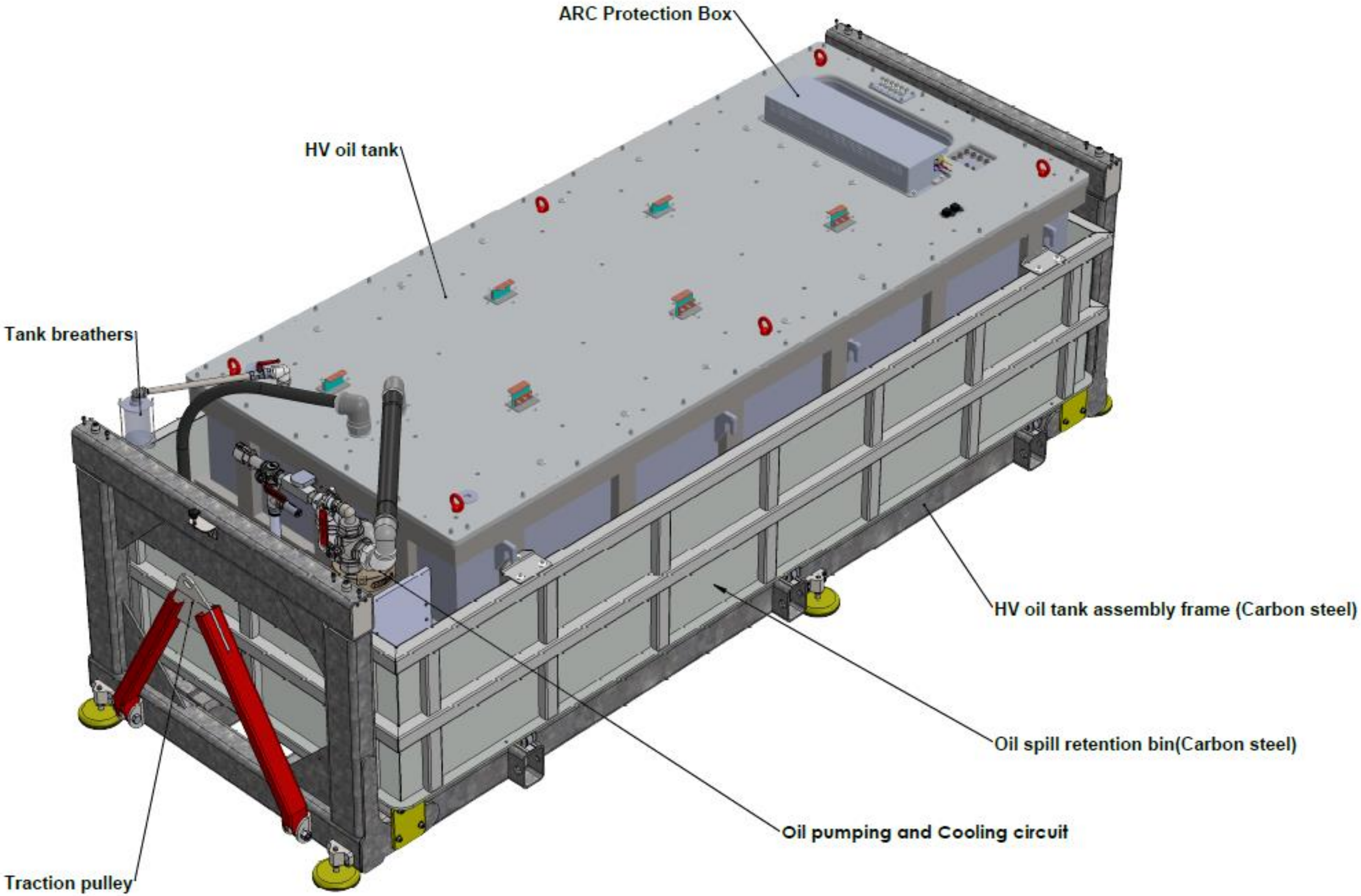
- Polypropylene, dry, self-healing type;

- 1.1kV / 3x(6x18mF)





Part II – High Voltage oil tank assembly



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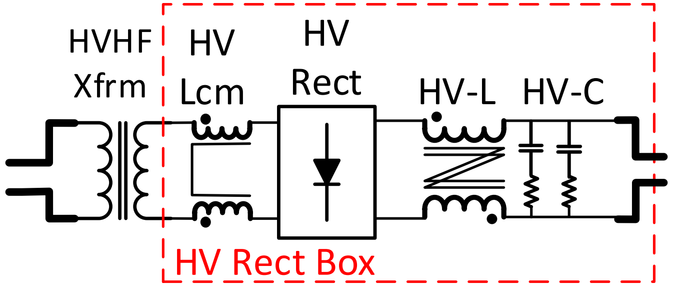
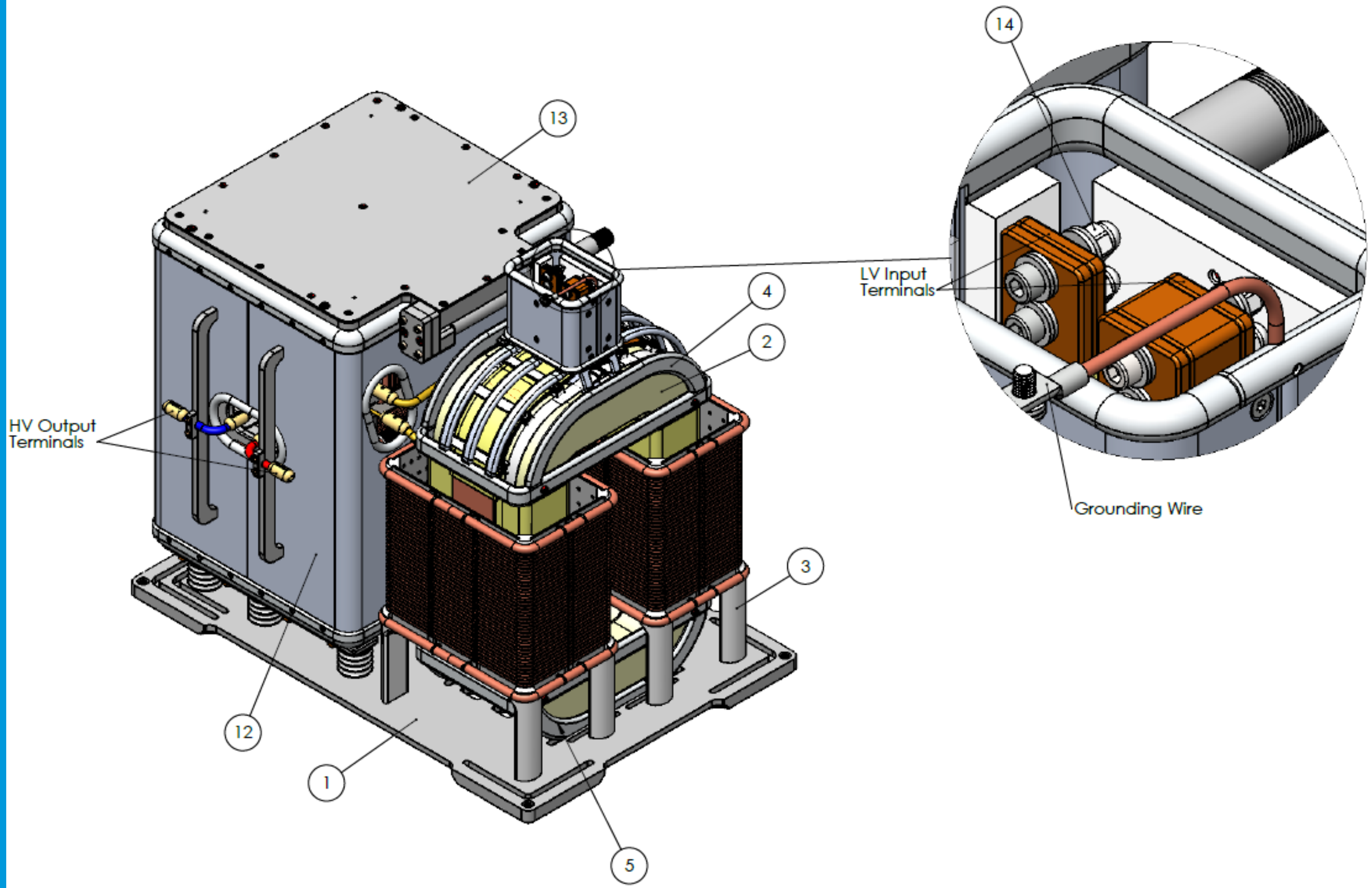
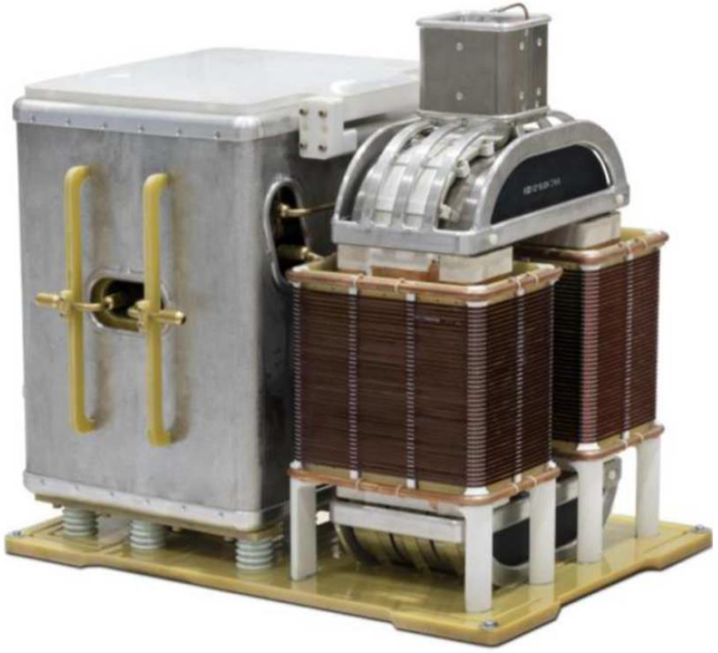


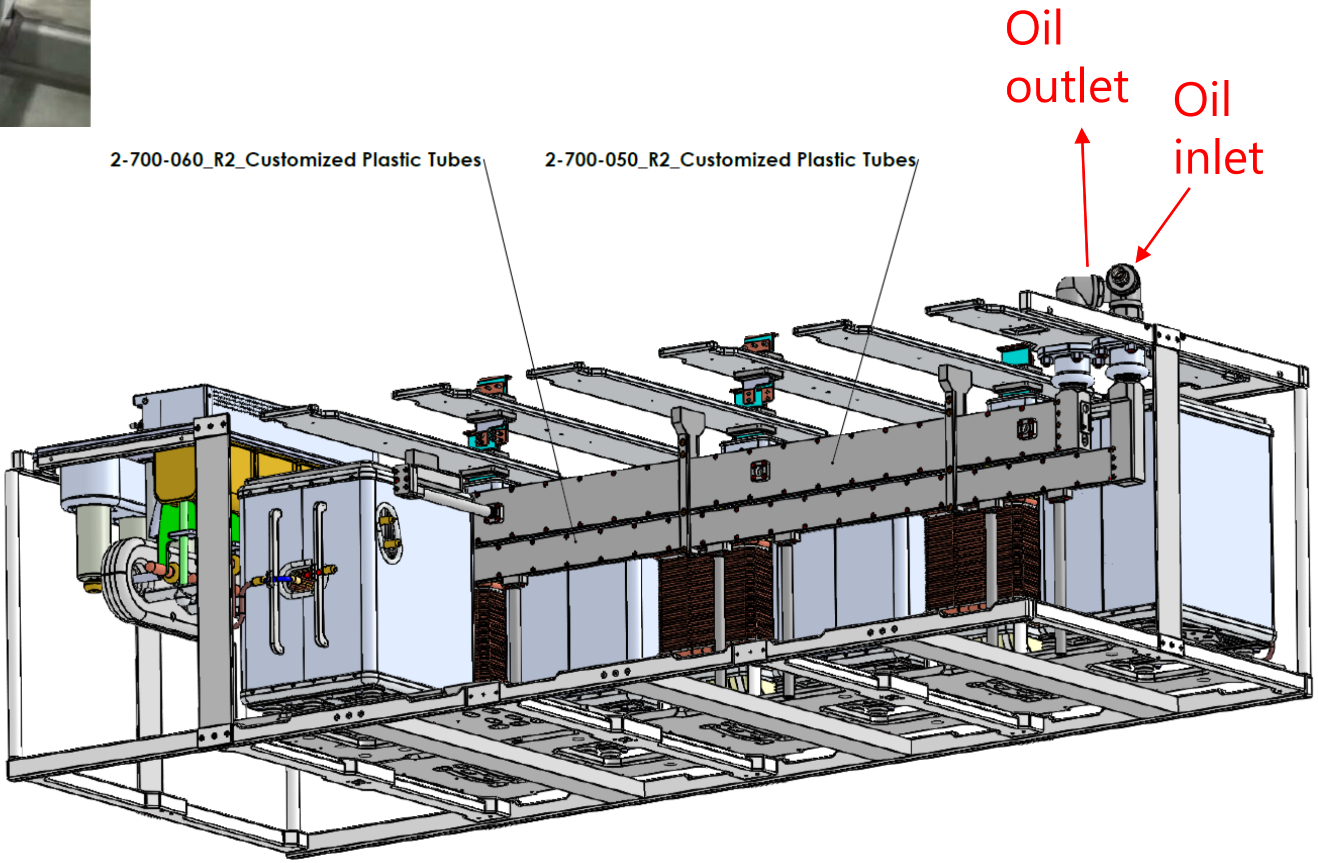




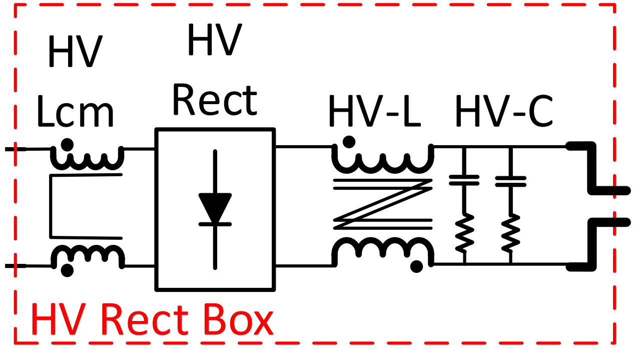
Part II – High Voltage Oil Tank Assembly

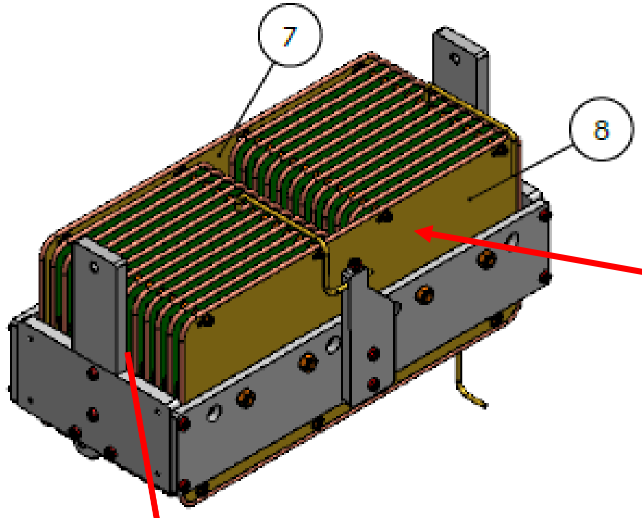
Oil cooling unit

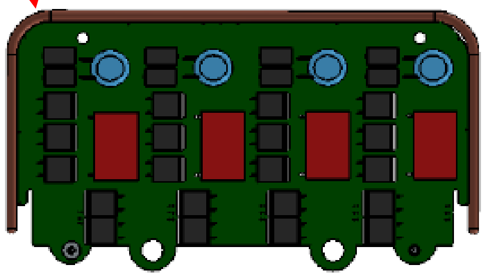
(oil pump, filter, flow sensor, oil/water heat exchanger

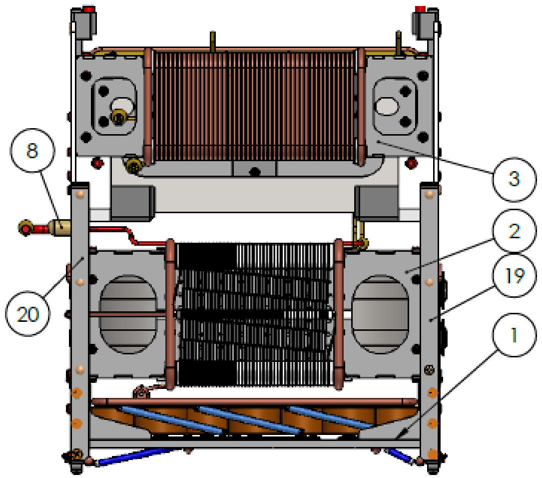


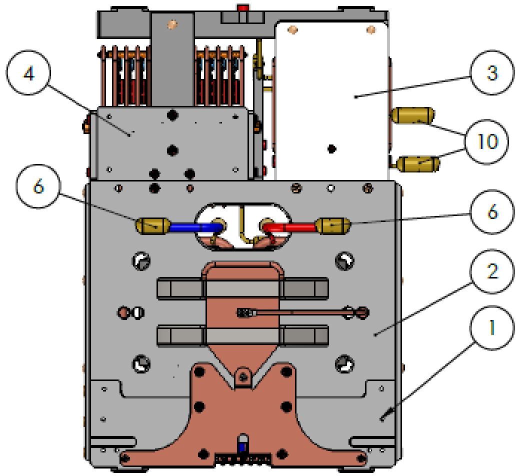
HV rectifier box

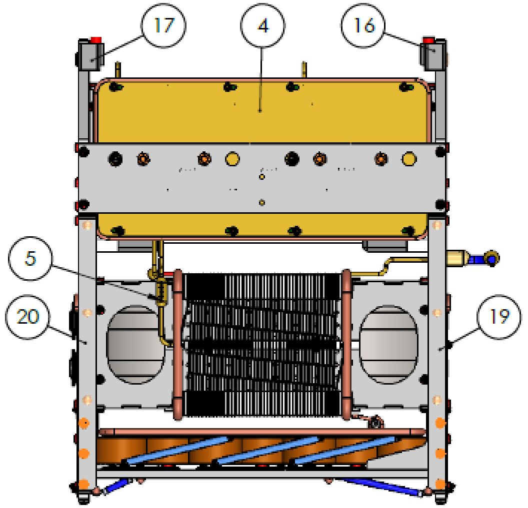


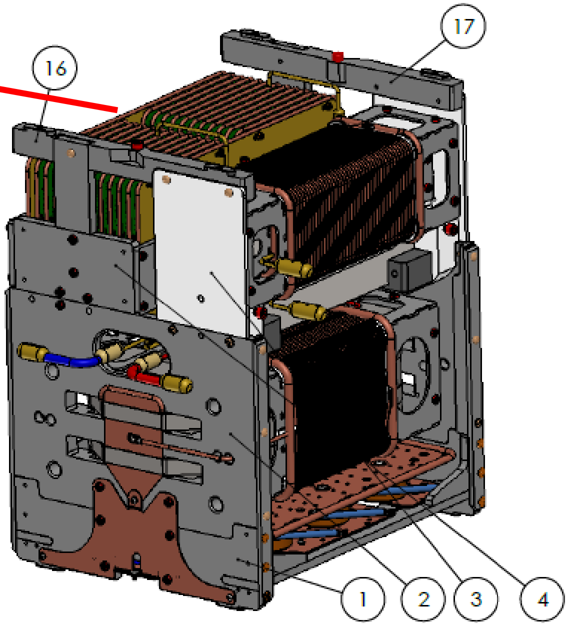


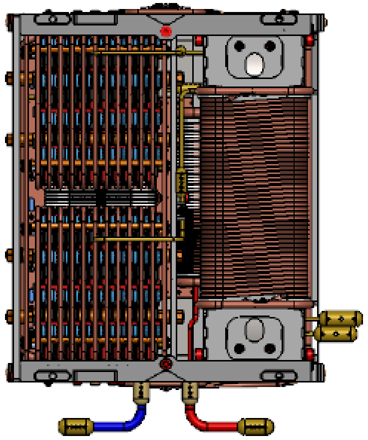


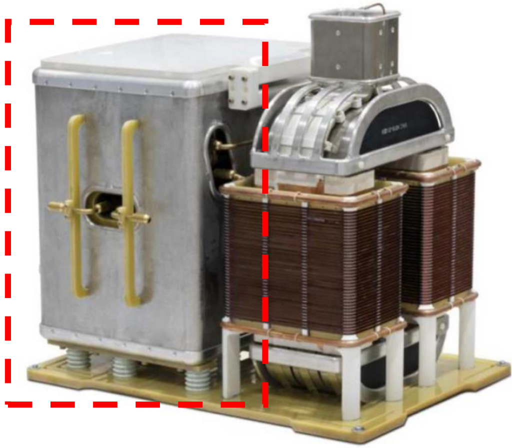




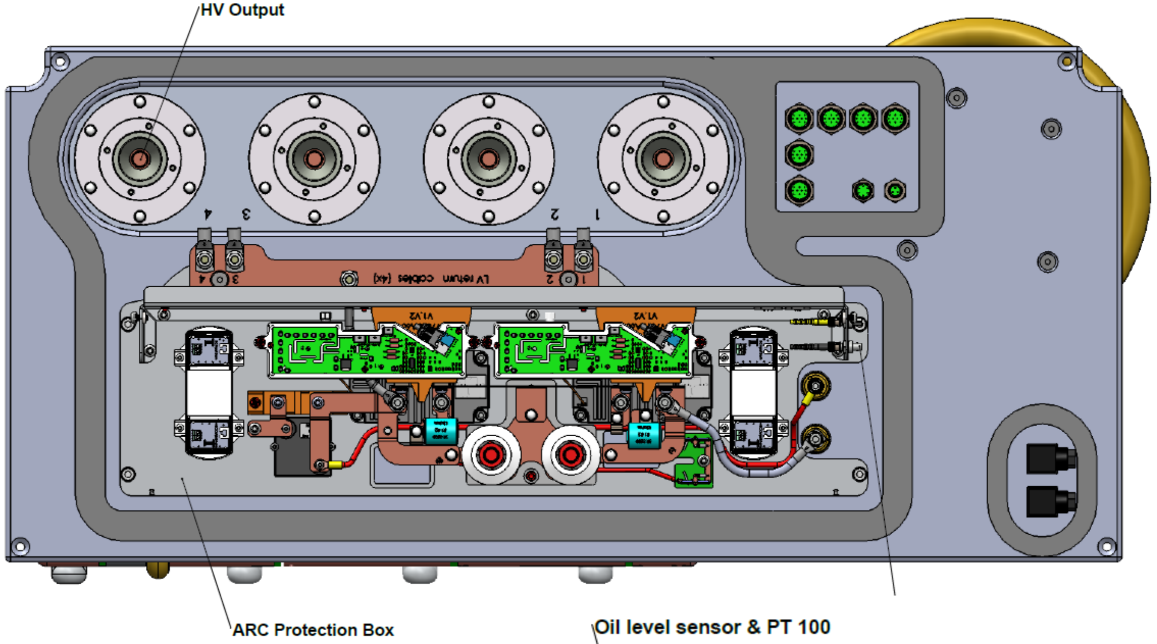


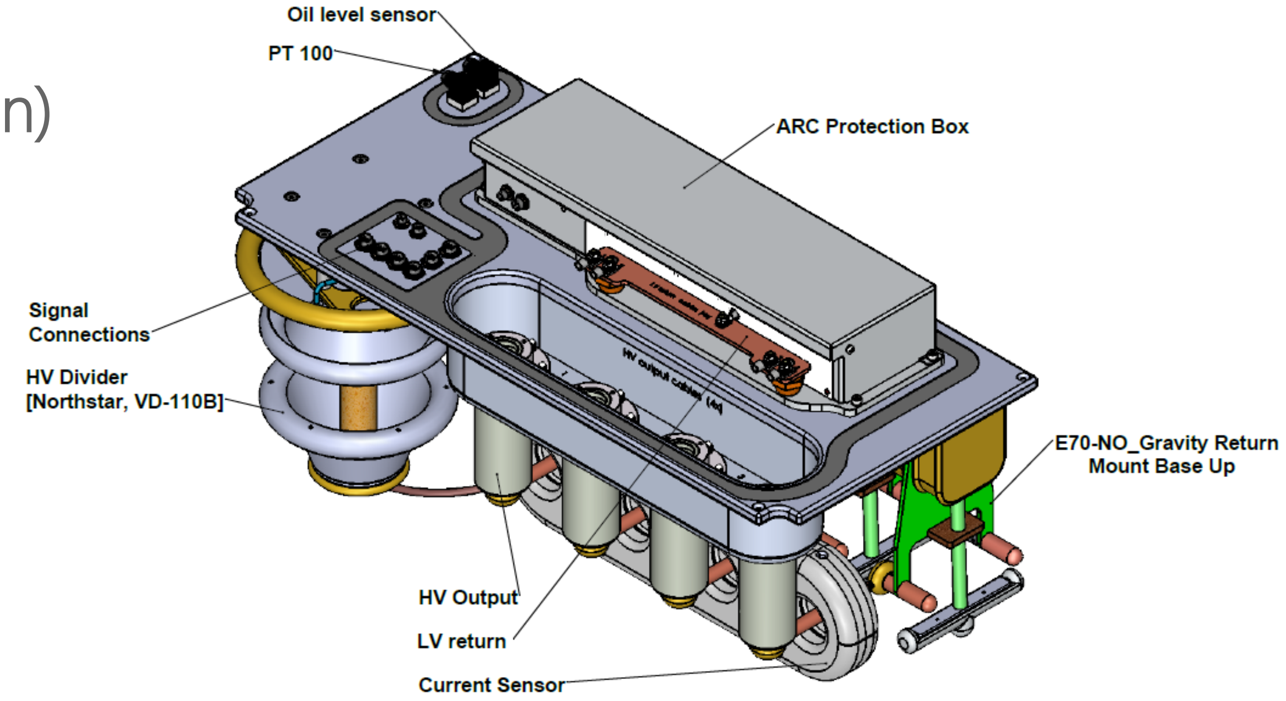


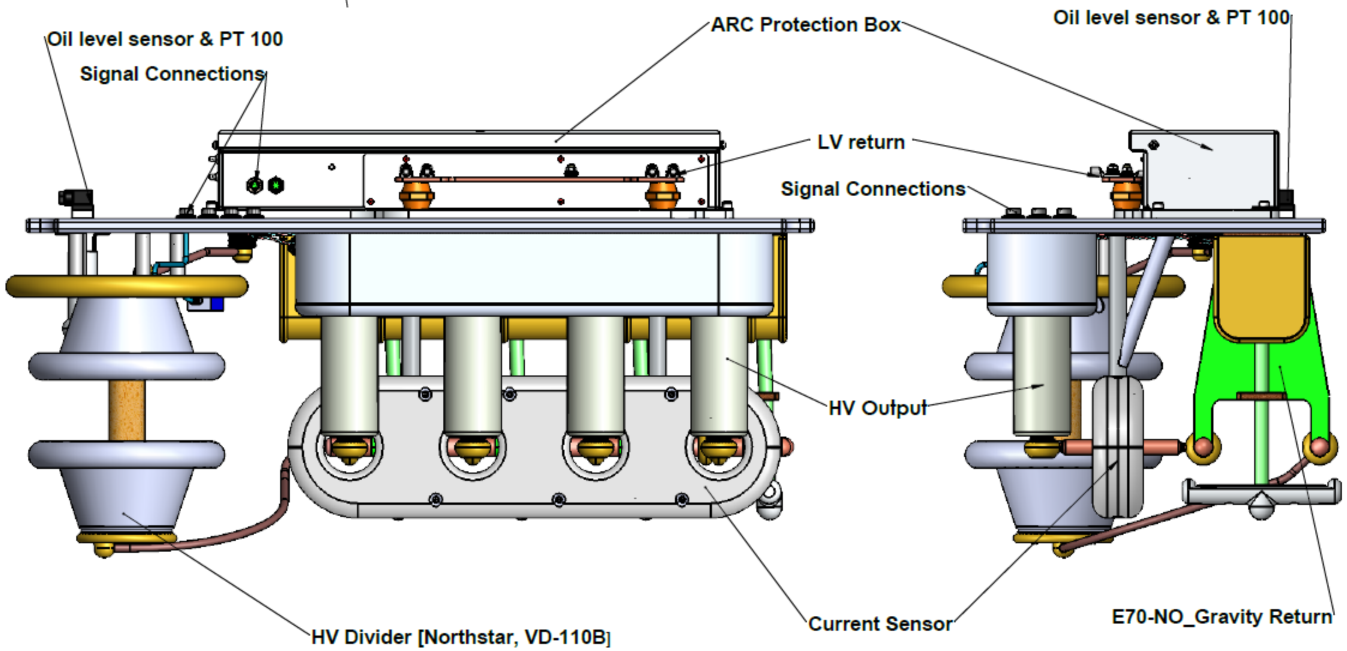




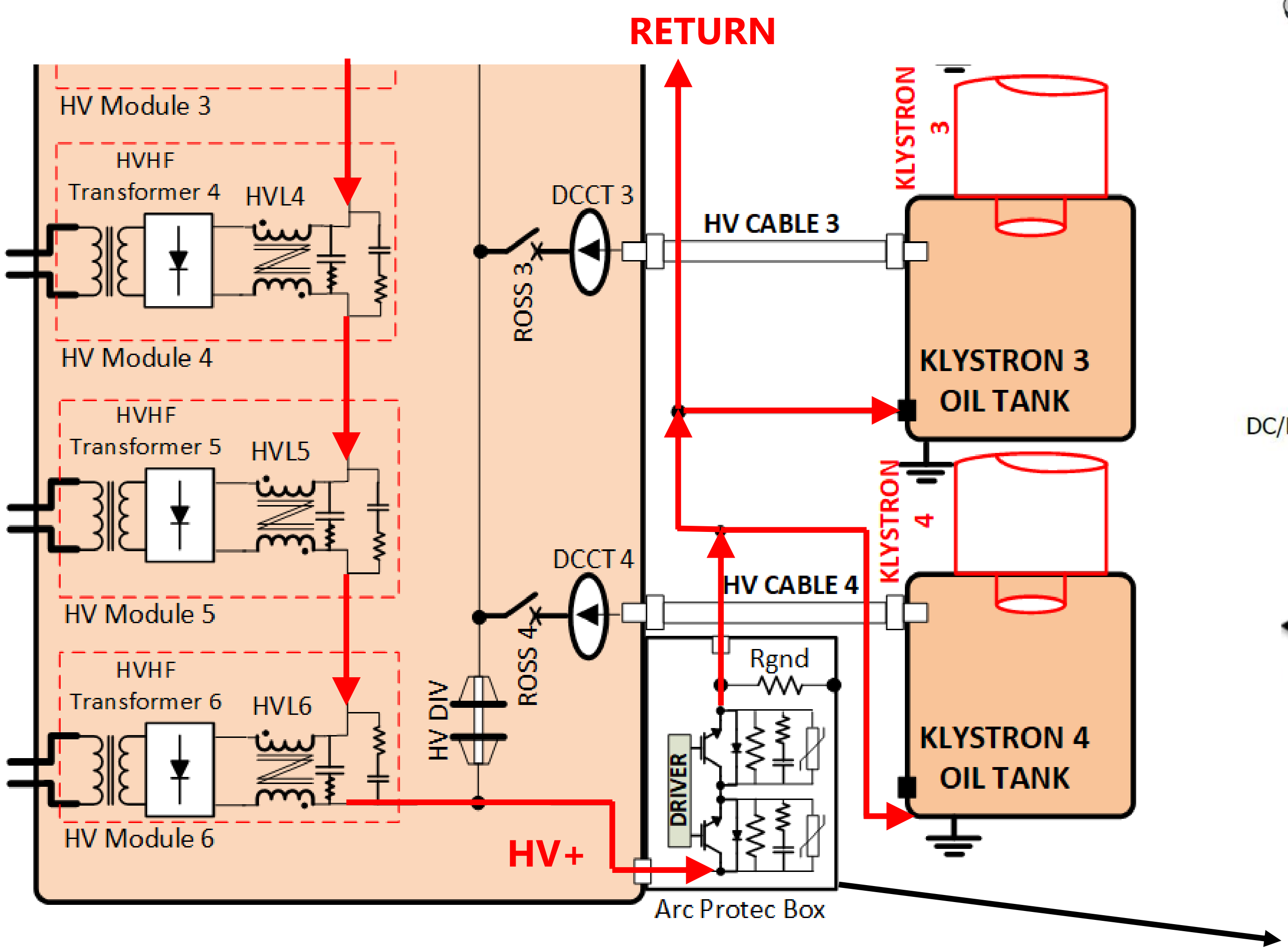
HV output stage
(Connectors, instrumentation, arc protection)

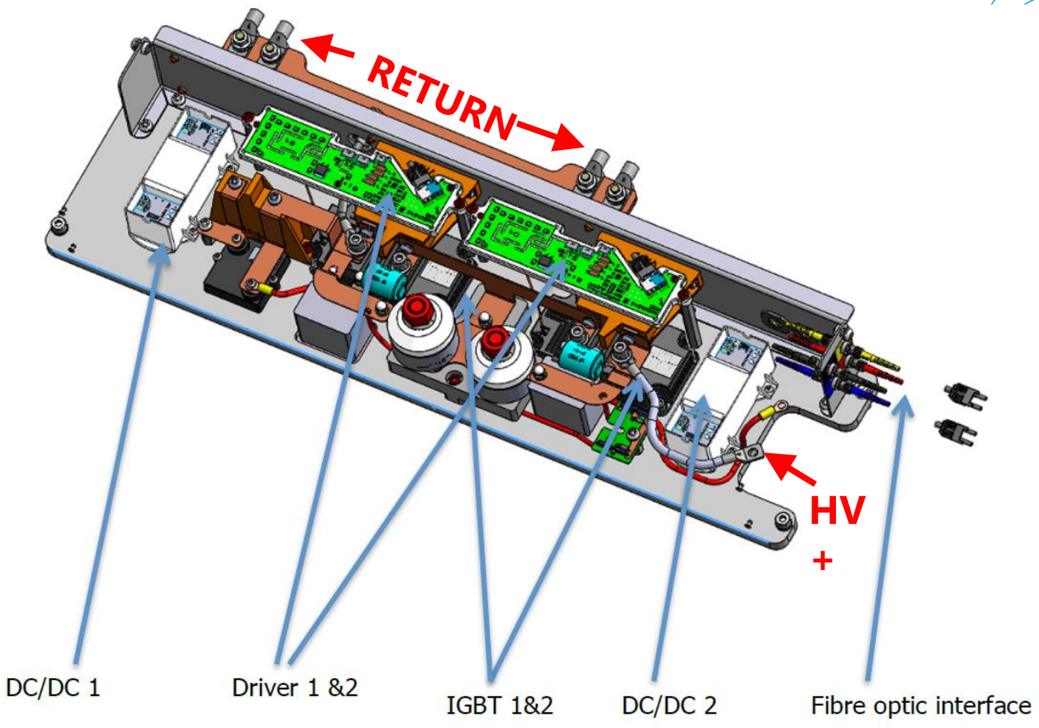


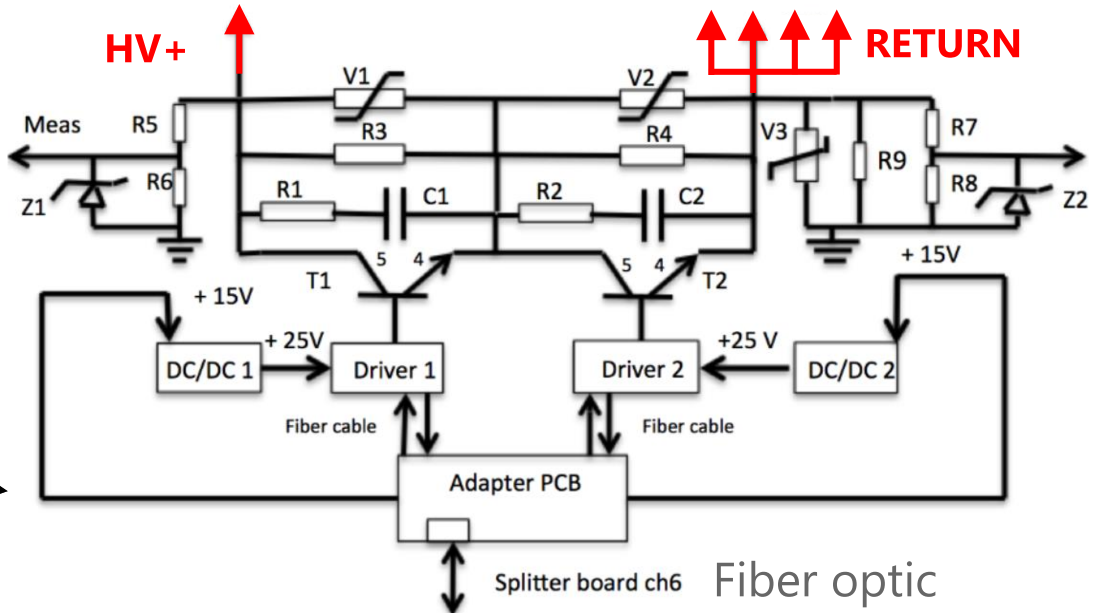




Arc Protection Box

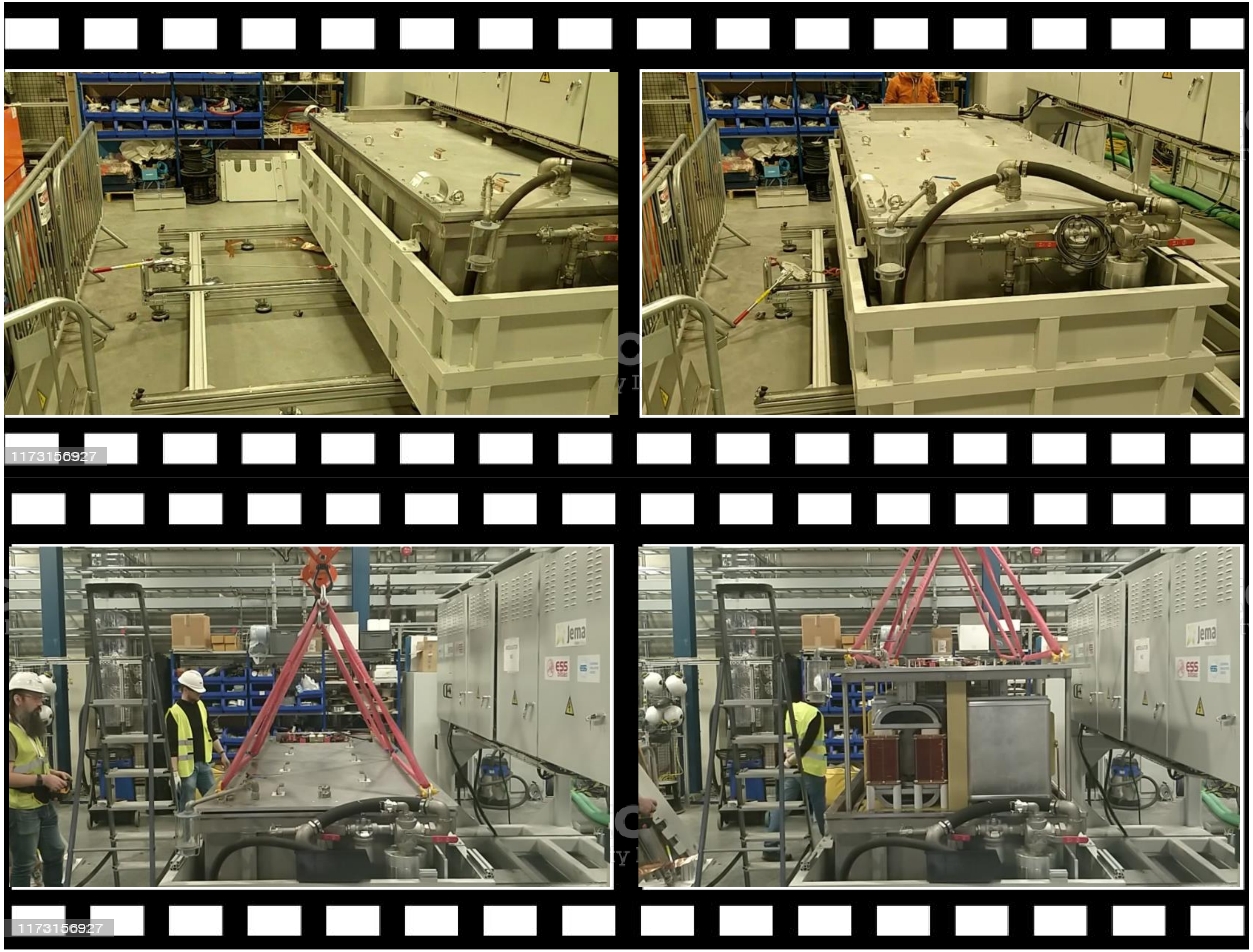




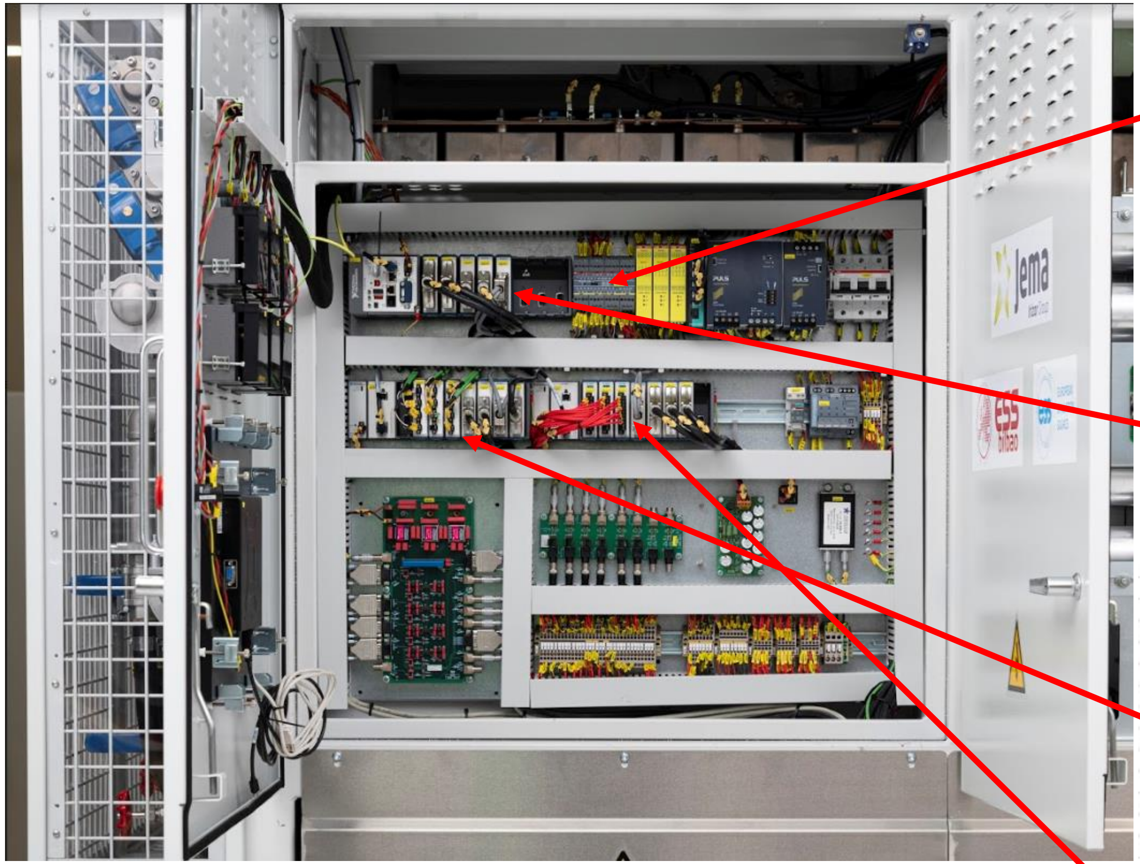


Fiber optic

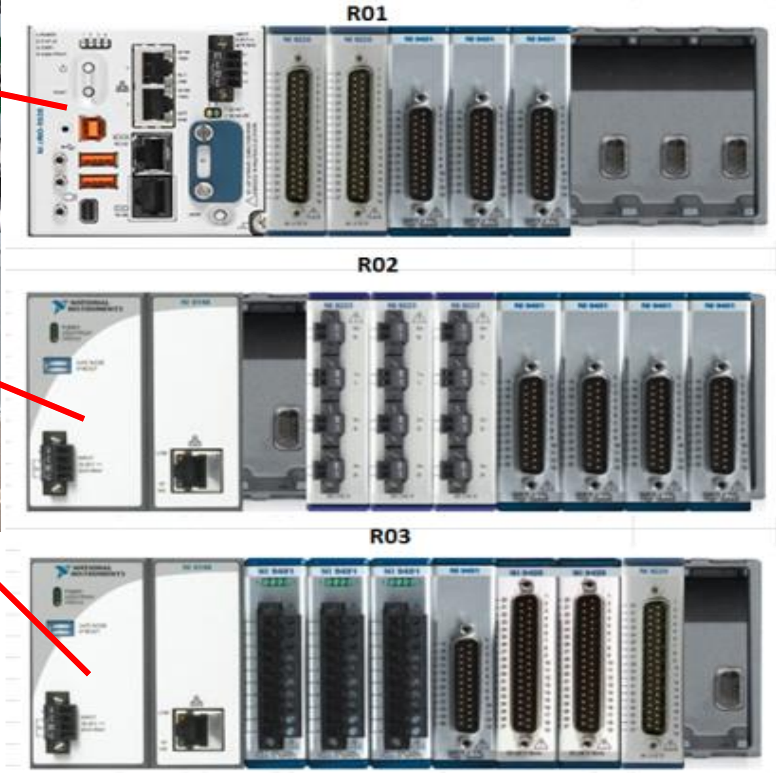
Extraction and opening of oil tank assembly



Control system



Safety PLC, PLUTO - ABB®
- Personnel safety:
(Emergency stops, door switches)



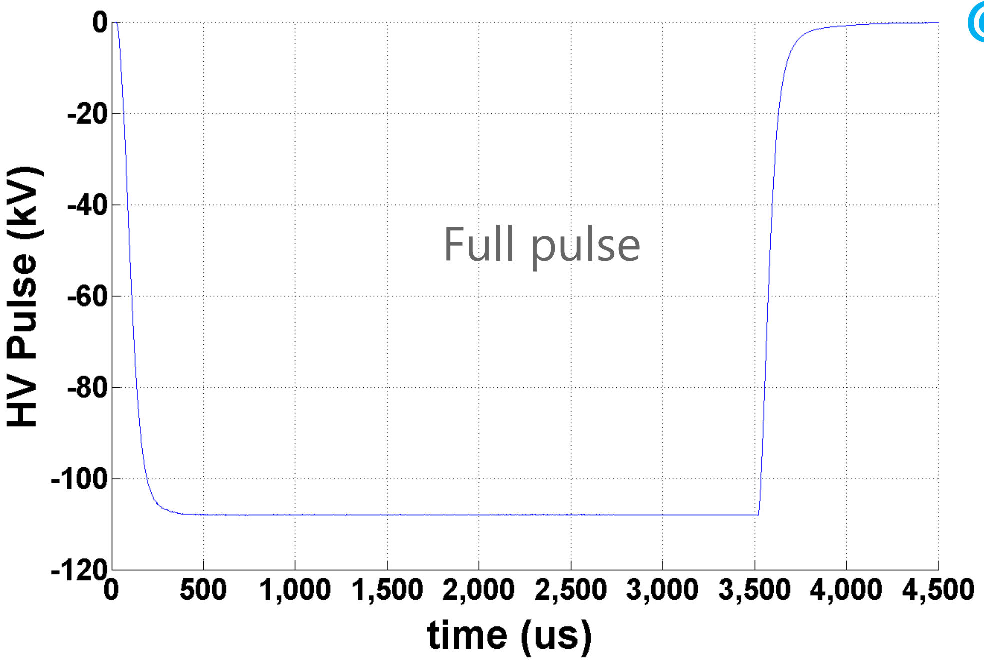
CompactRIO, NI®
- General state machine controls (CPU);

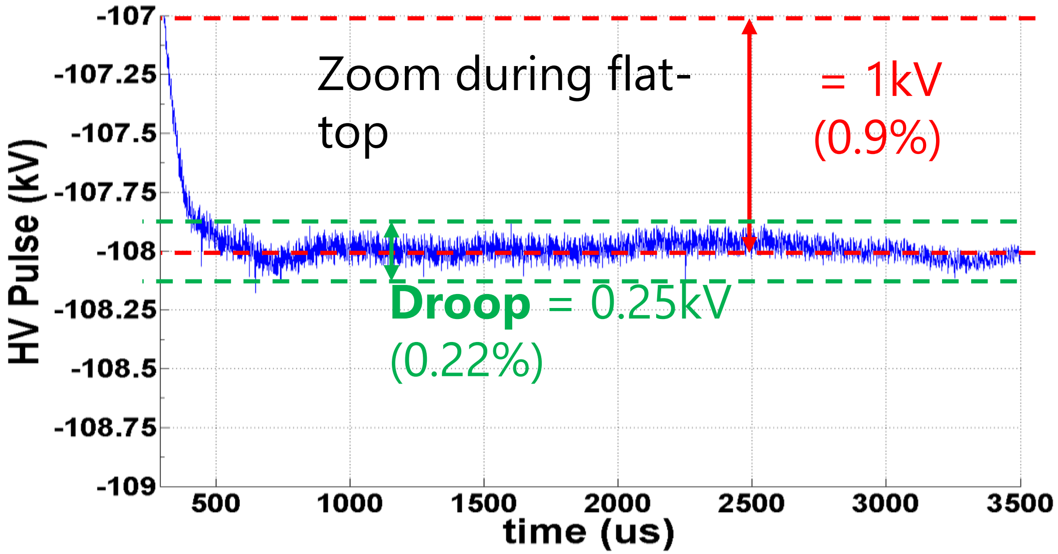
- Fast regulation loops & fast interlocks (FPGA);
(voltage/current/power regulations;

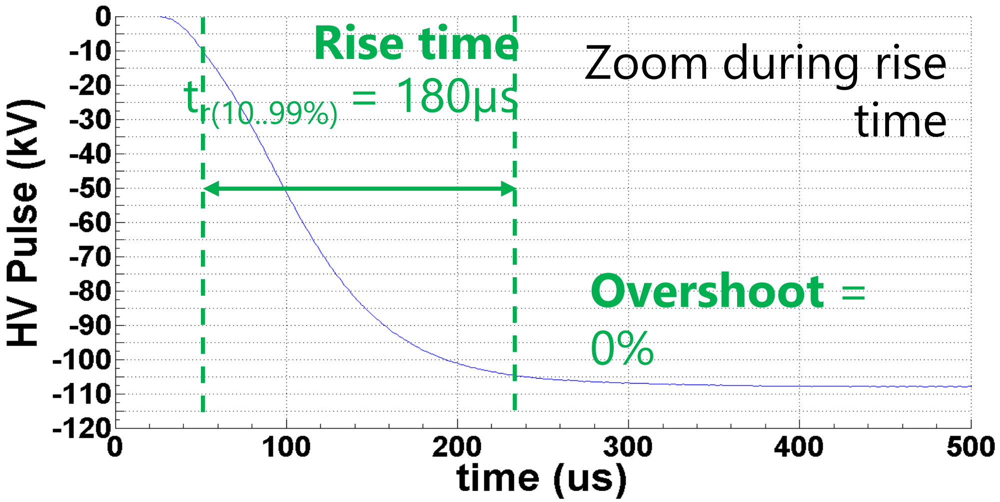
overcurrent, overvoltages, dry contact switches, oil / water flows, contactors, etc.)

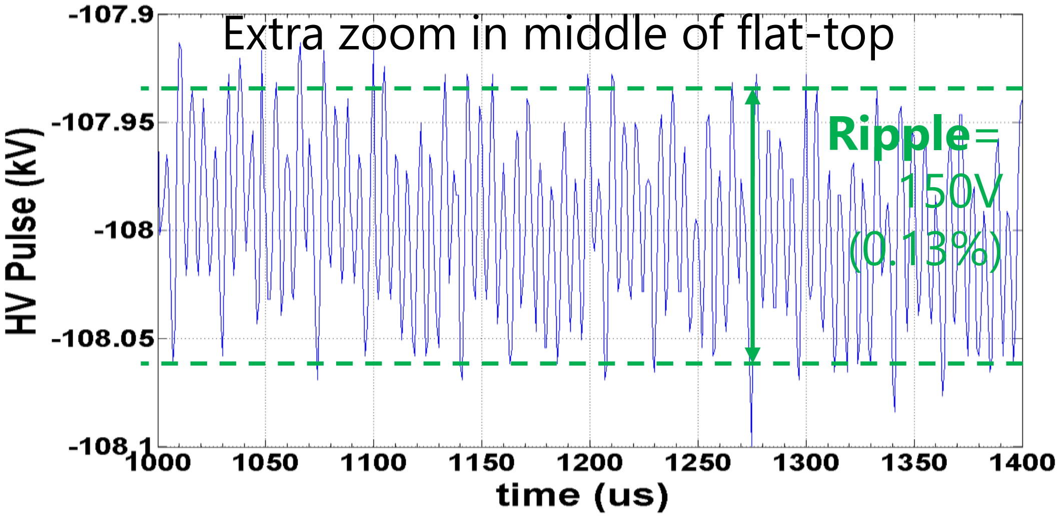
Experimental results on resistive dummy load – HV Pulse Quality: Rise time, Overshoot, Flat-top Droop, Flat-top Ripple

@ 108kV/96A ; 3.5ms/14Hz



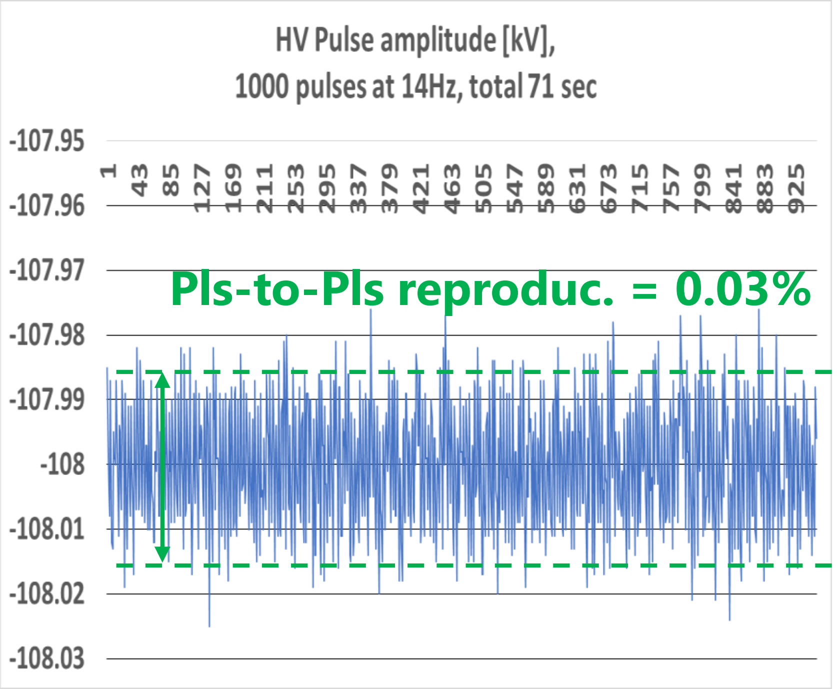




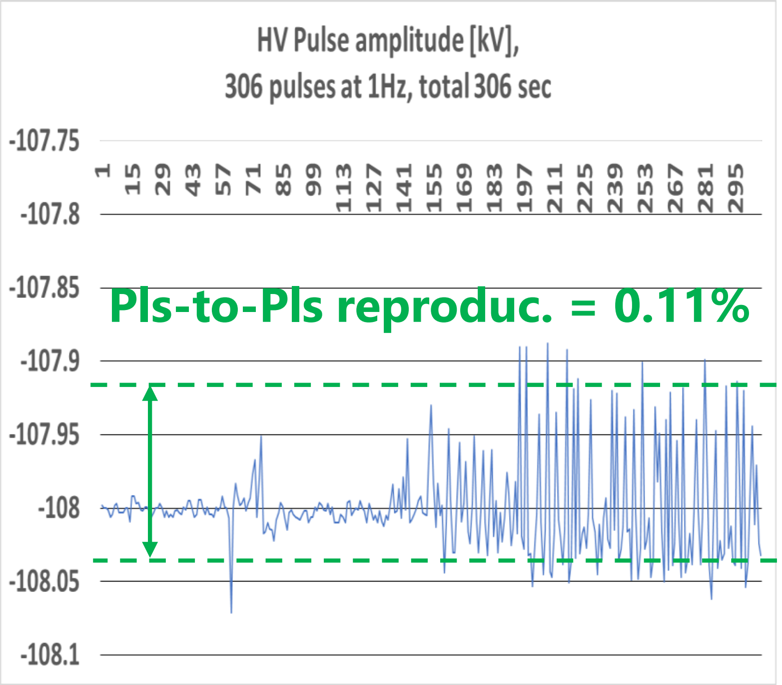


Experimental results on resistive dummy load
– HV Pulse Quality: Pulse-to-pulse reproducibility

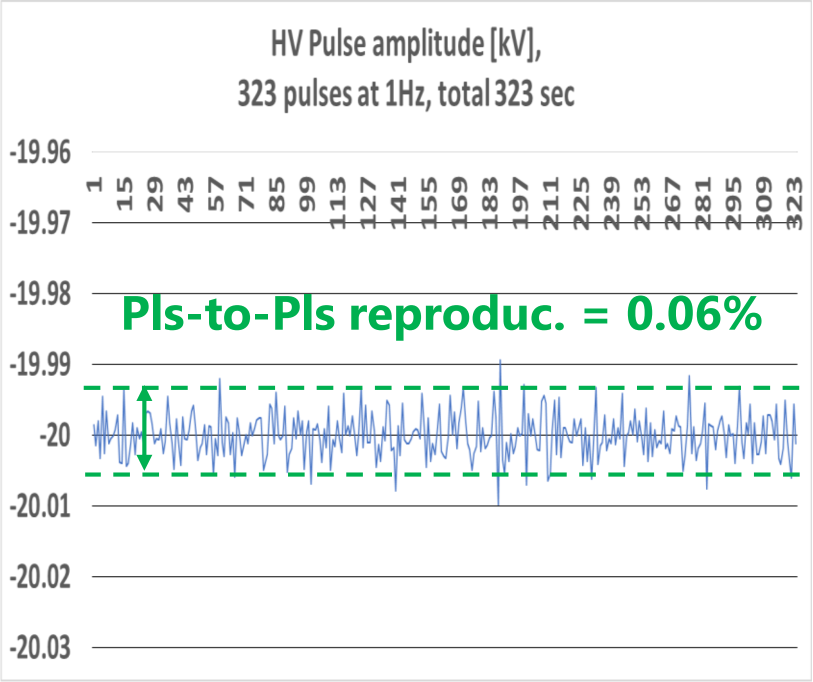
@ 108kV/96A ; 3.5ms/14Hz
(Pav = 508kW ; 90%)



@ 108kV/96A ; 0.5ms/1Hz
(Pav = 5.2kW ; 0.9%)

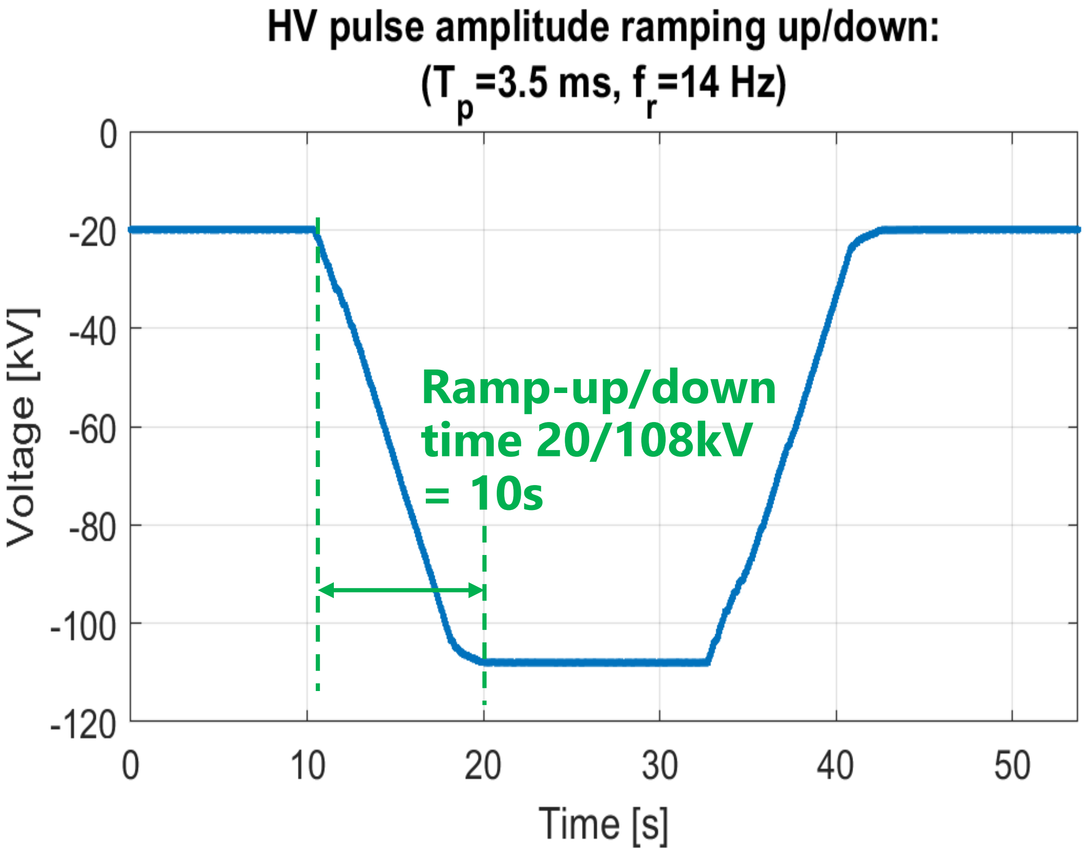


@ 20kV/17A ; 0.5ms/1Hz
(Pav = 170W ; 0.03%)

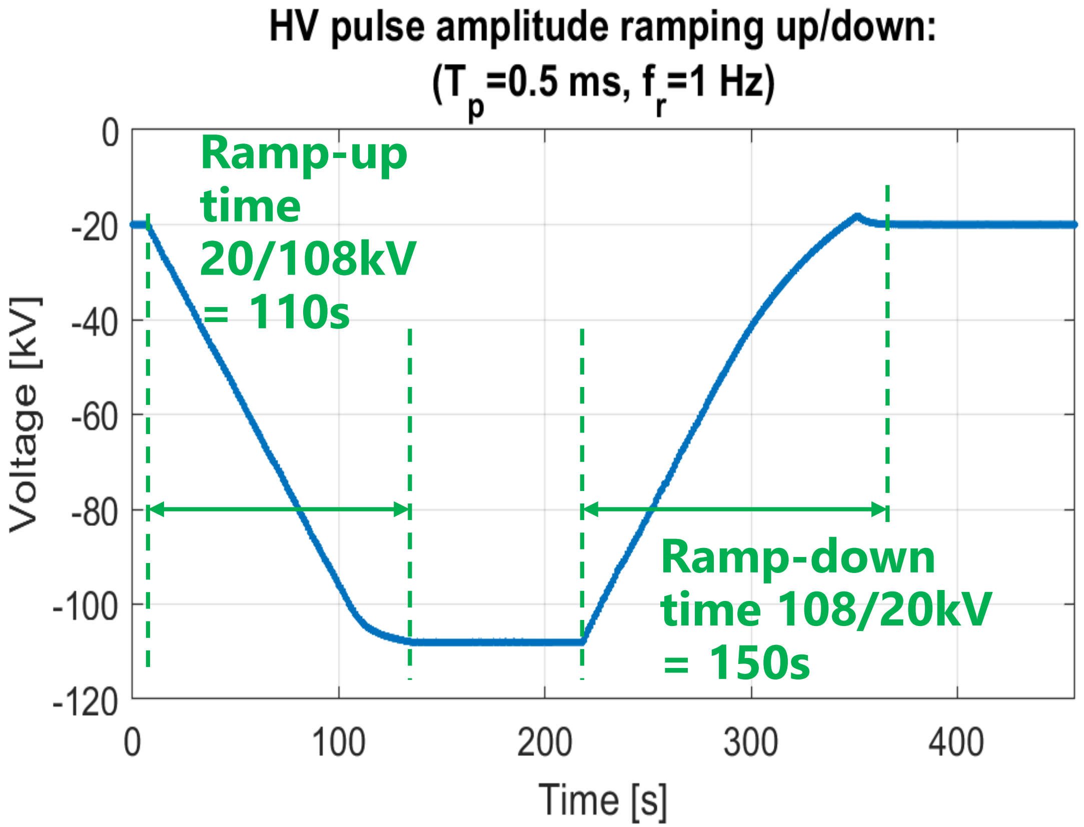


Experimental results on resistive dummy load – HV Pulse Quality: Power ramping up/down

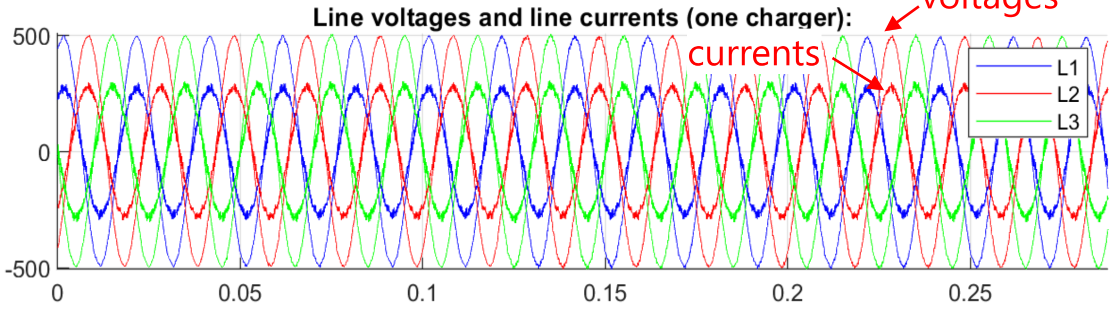
Ramp-up/down 20-108kV; 3.5ms/14Hz

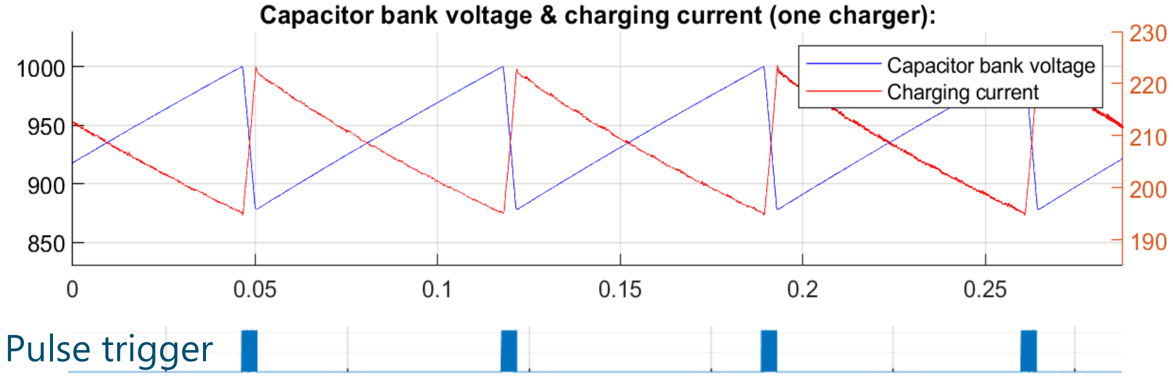


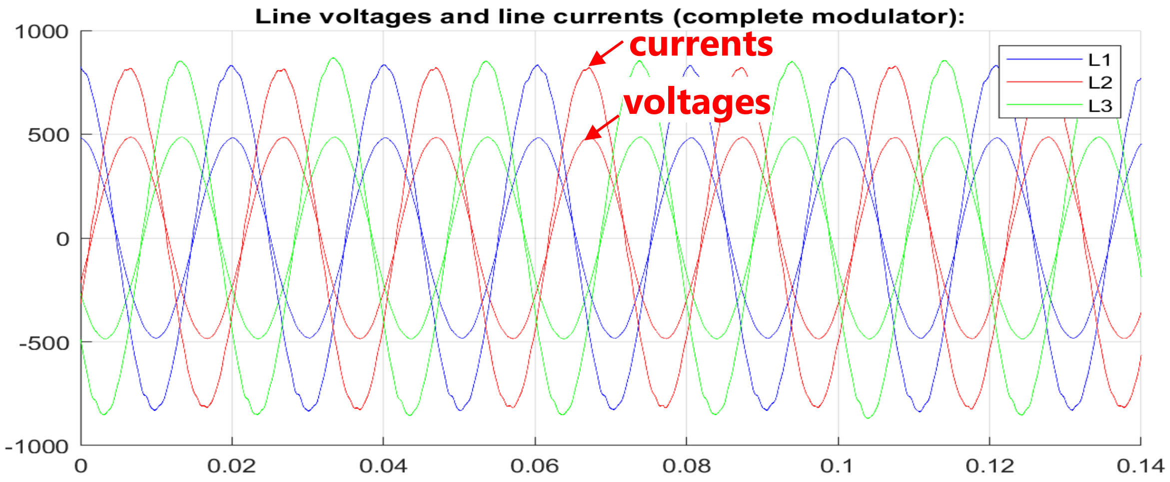
Ramp-up/down 20-108kV; 0.5ms/1Hz

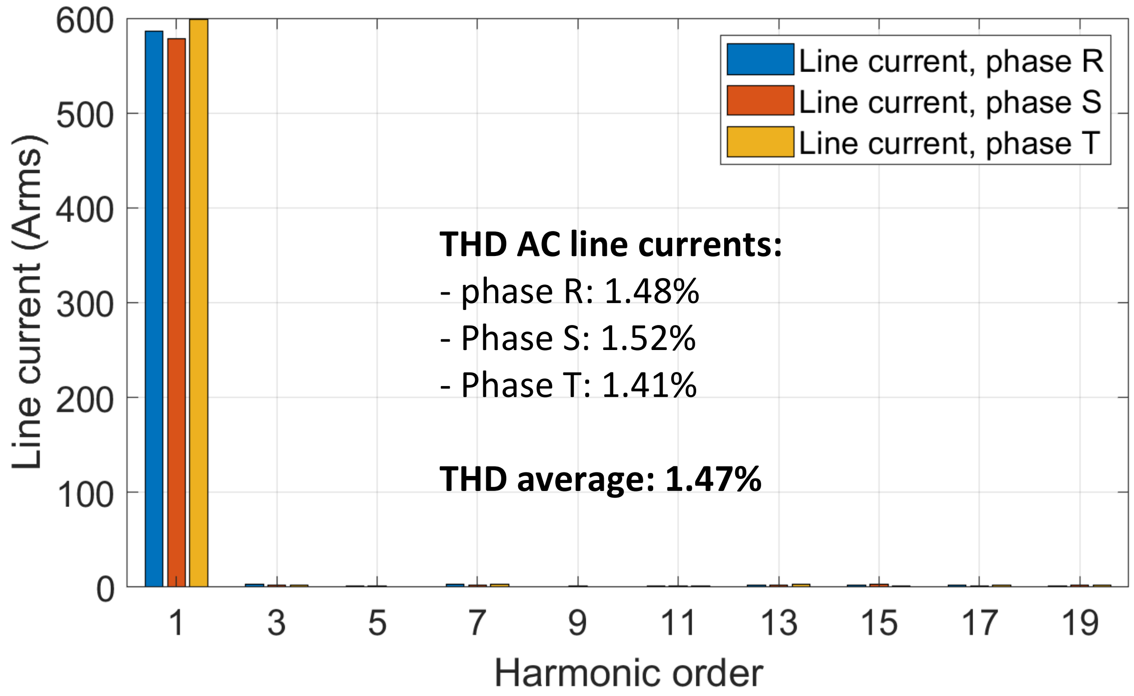


Experimental results on resistive dummy load – AC power quality





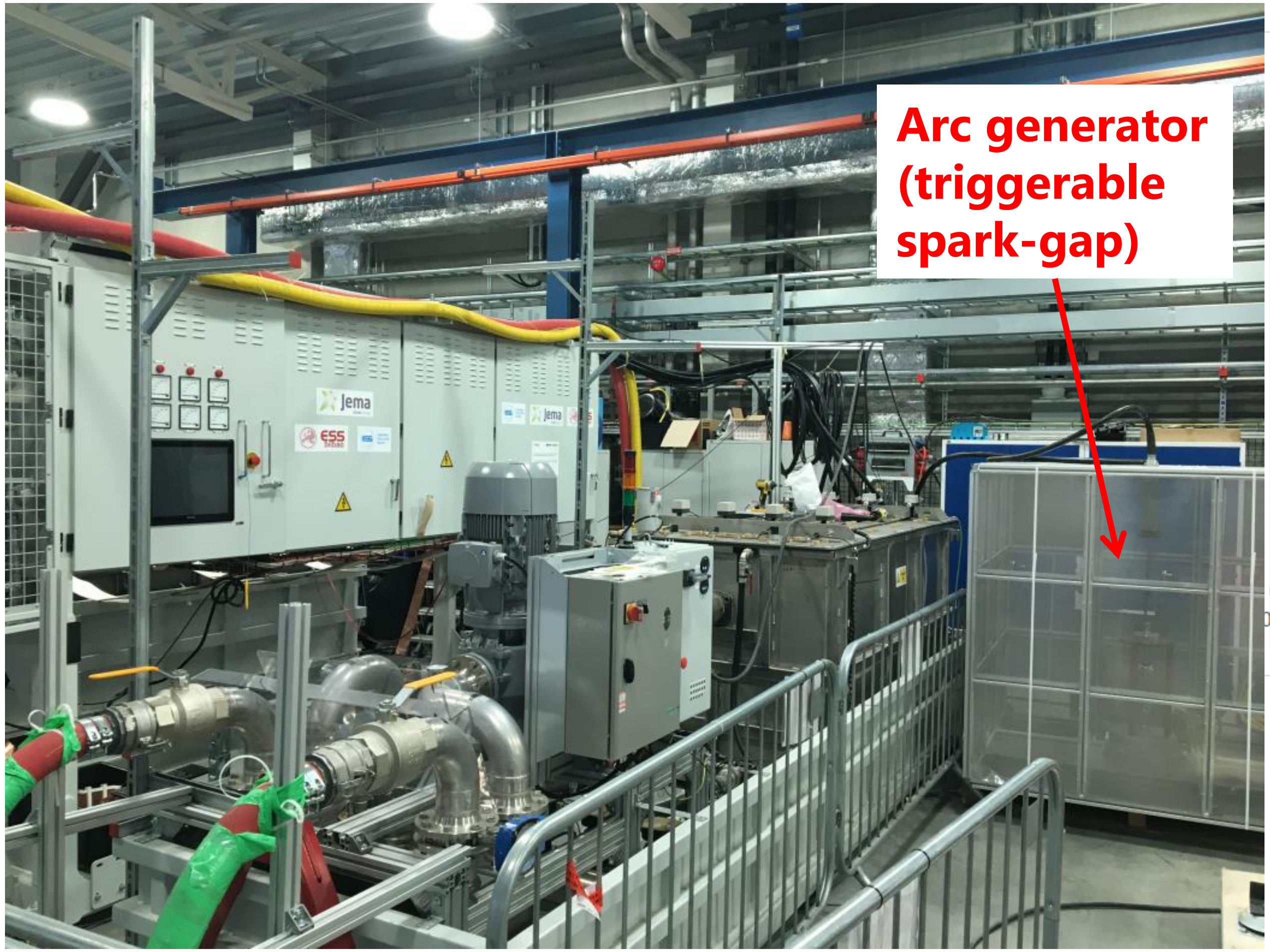


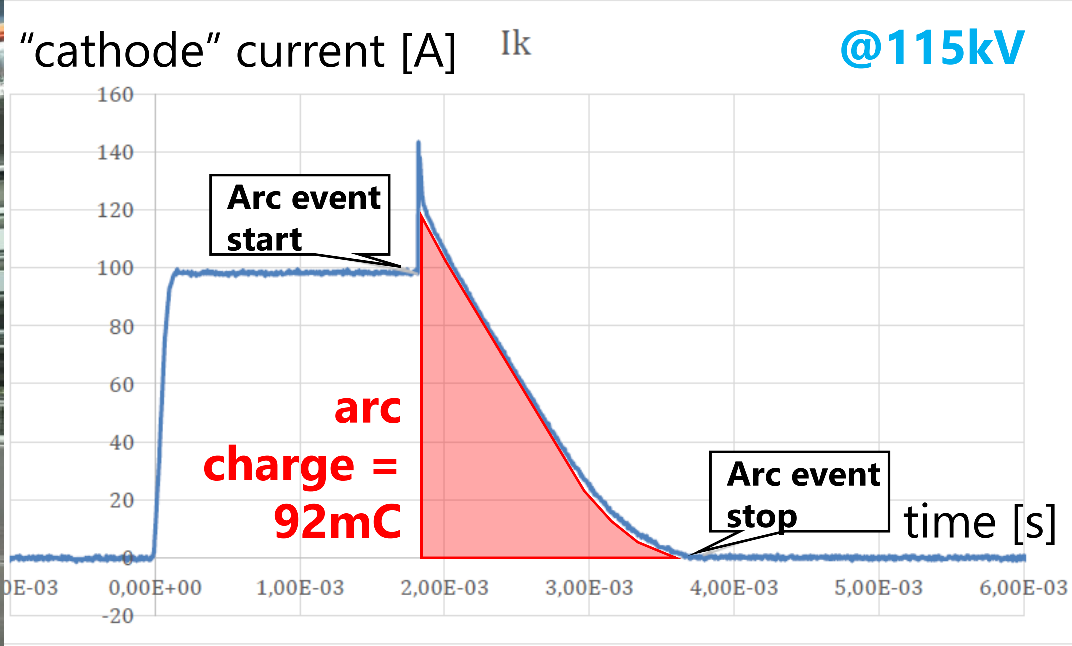


- ➢ Unitary power factor;
- ➢ Flicker free operation (constant line currents)
- ➢ Pure sinusoidal current absorption

- ❖ **Minimal line RMS current consumption;**
- ❖ **No extra power losses on AC power line (cables, transformers, filters & compensators)**

Arc simulation tests

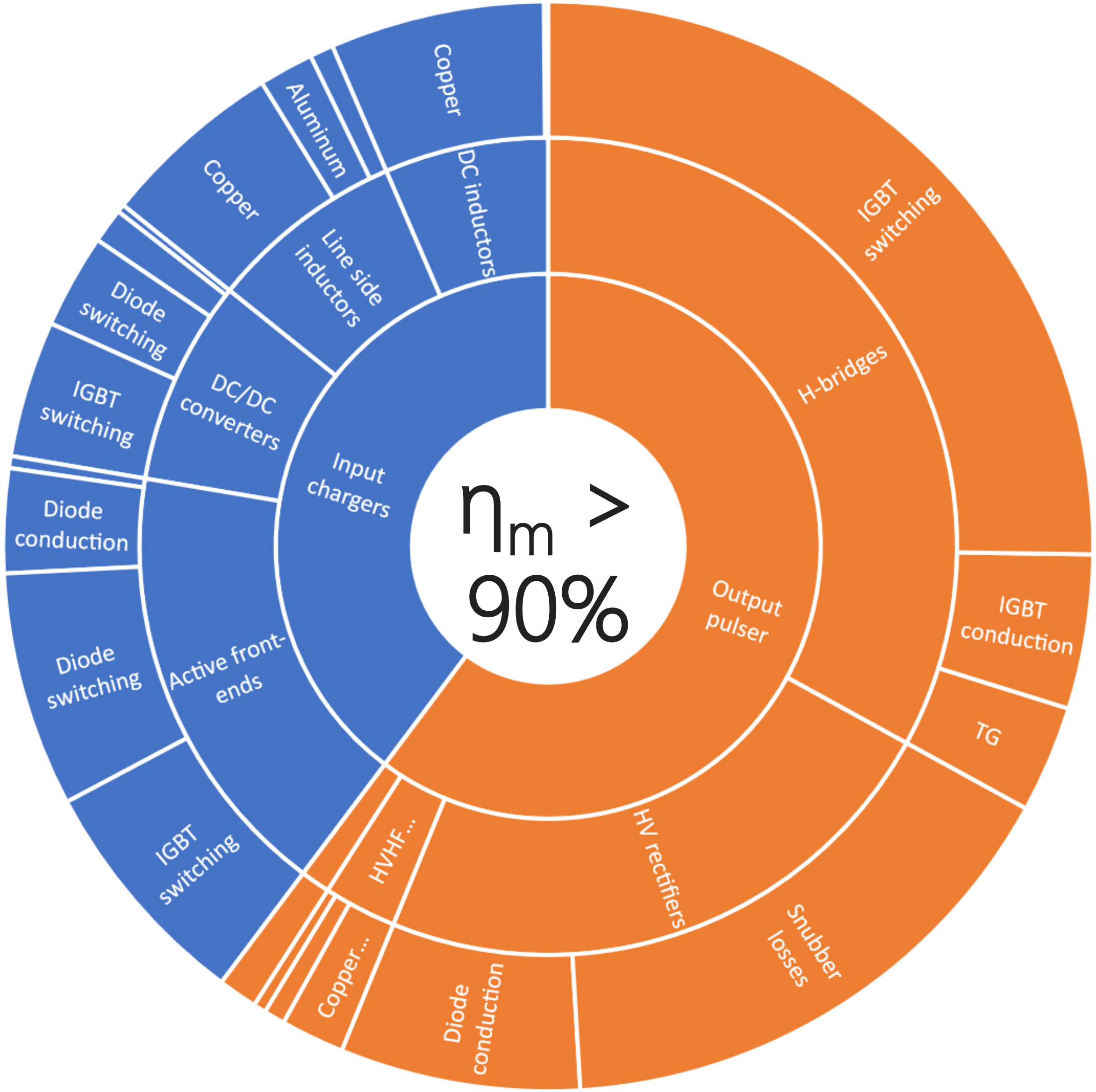


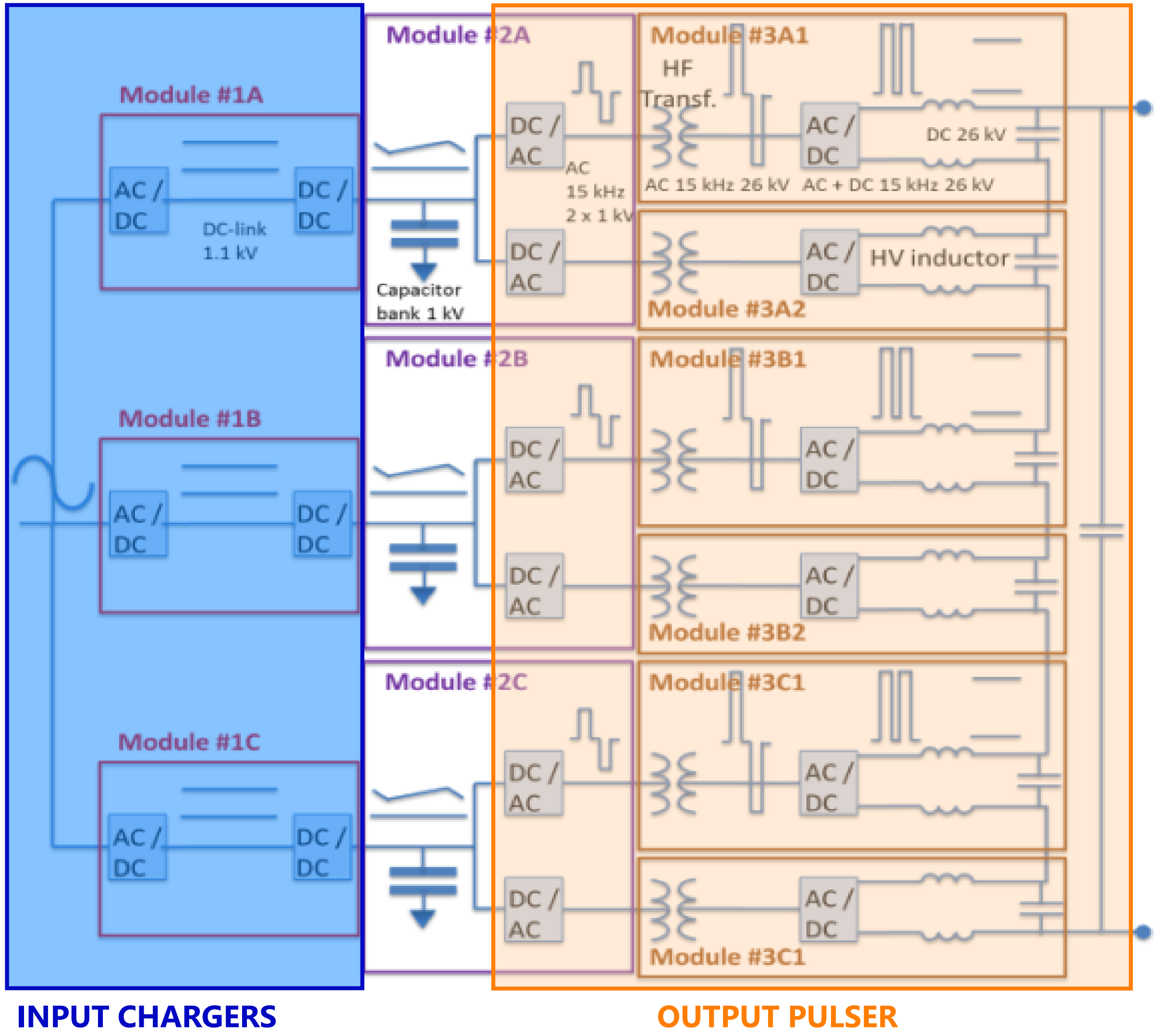


Arc voltage: 50V ➡ **"arc energy" = 4.6J**

Note: Energy stored in the HV cables not included

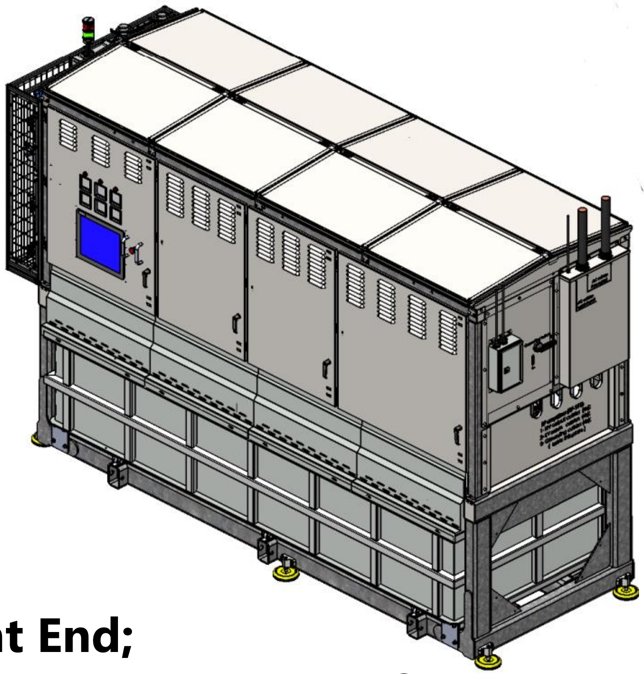
Experimental results on resistive dummy load
– Power Losses and Efficiency





SML Modulator main features and performance

Rated 115kV/100A; 3.5ms/14Hz; 660kVA -> enough to power four 1.4MWpk klystron in //;

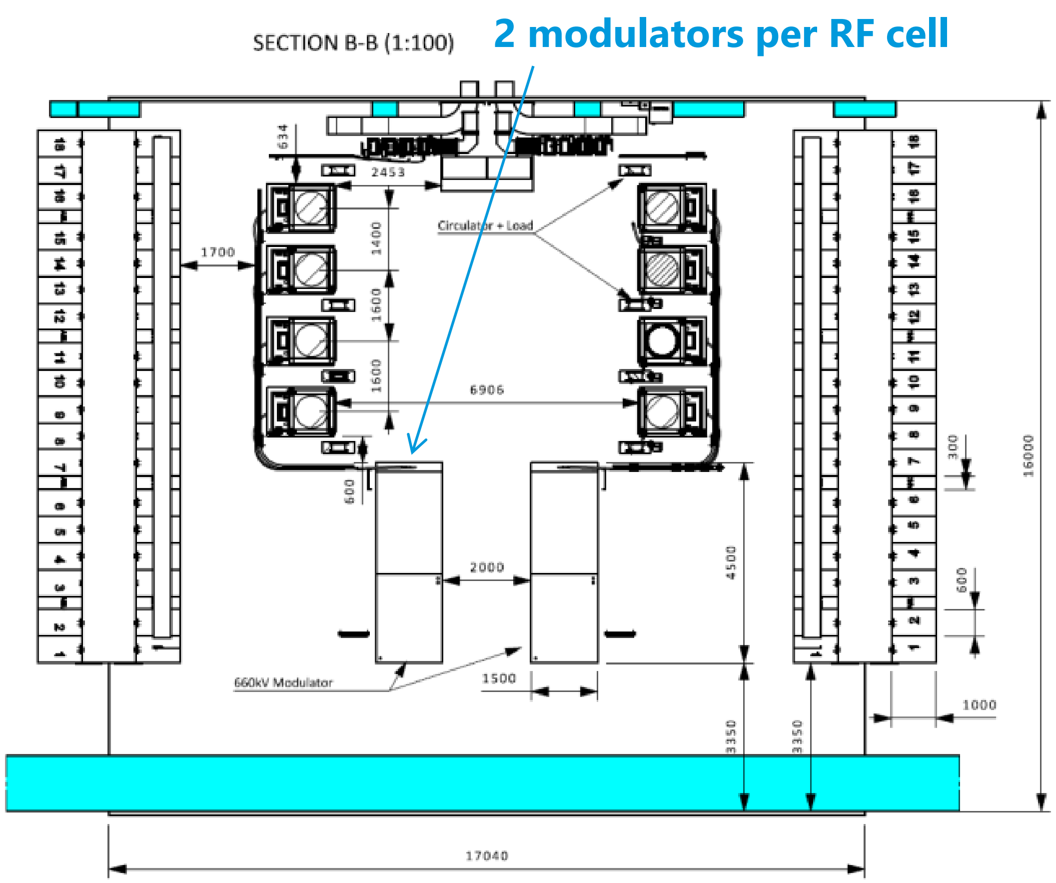


Demonstrated Performance:

- **Rise time = ~180µs;**
- **Flat-top droop < 1%;**
- **Flat-top ripple < 0.2%$_{pk\text{-}pk}$**
- **Efficiency = ~90%;**
- **Power density = 124kVA/m^2**
- **AC power quality: Active Front End;**
  (flicker free, sinusoidal current, unitary power factor)
- **Improved reliability; minimal number of components (most are standard)**

Effective capital cost (Mβ+Hβ):

- **33 modulators**



I-FAST WU#1 – Powering accelerators from local PV renewable energy

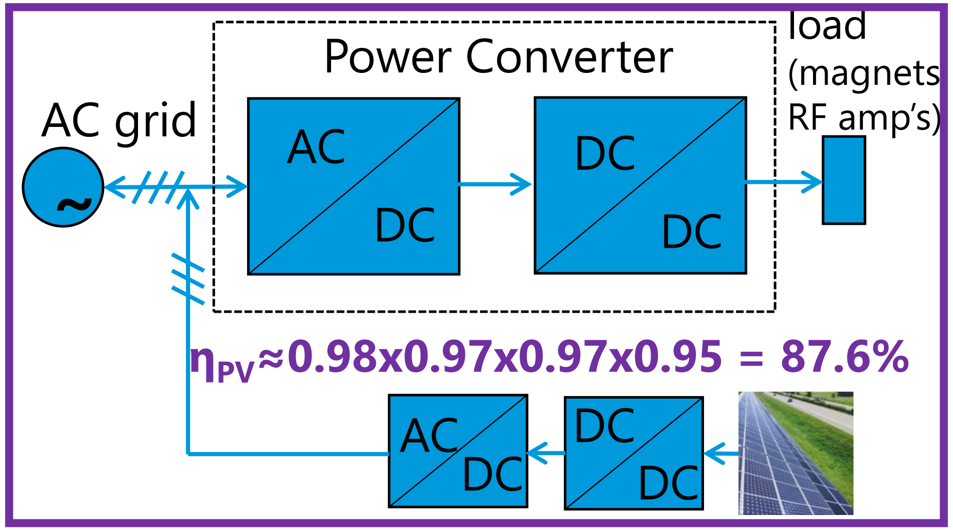
Concept:

- Install PV panels near accelerators' "wasted land";
- Connect them to the main power converters supplying accelerator magnets or RF amplifiers, using high efficiency DC/DC converters;
- AFE's can redirect the PV energy back to the AC grid when accelerator not running;
- Up to 15-20% renewable energy utilization possible with no transmission losses and high conversion efficiency;
- Lower capital cost & lower payback time;

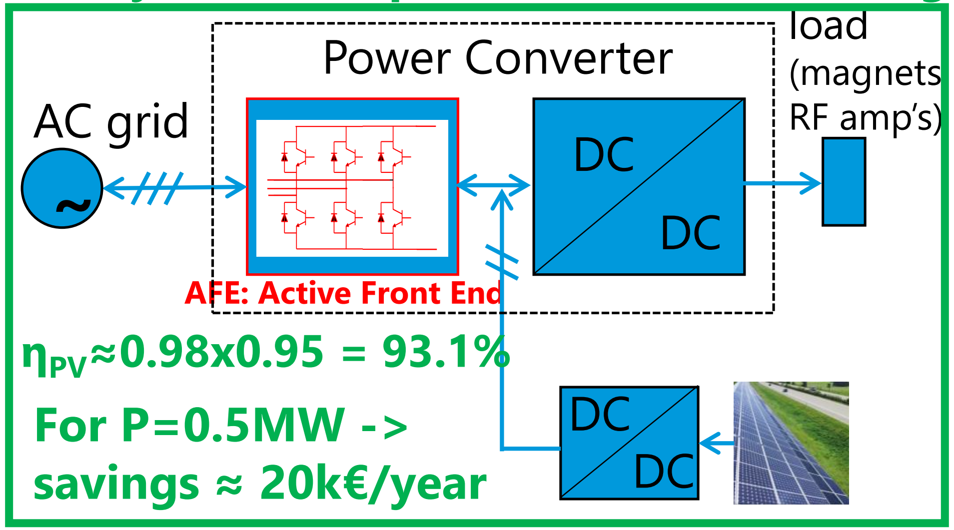
Objectives:

- Feasibility study for ESS case: up-to 2MW installed PV injected into the Linac RF klystron modulators;
- MSc thesis with Lund University (starting Feb. 2022);

Conventional scheme:
PV injected into the AC grid (4 stages)



New scheme:
PV injected into power converters (2 stages)



PV energy potential wrt ESS accelerator annual consumption?

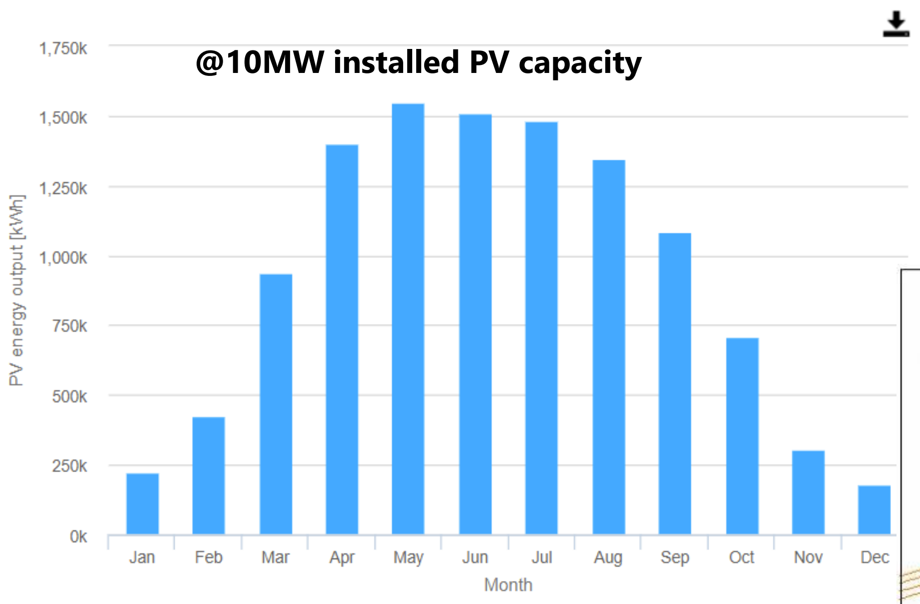
PERFORMANCE OF GRID-CONNECTED PV: RESULTS — PV output

Summary

Provided inputs:	
Location [Lat/Lon]:	55.735,13.253
Horizon:	Calculated
Database used:	PVGIS-SARAH2
PV technology:	Crystalline silicon
PV installed [kWp]:	10000
System loss [%]:	5

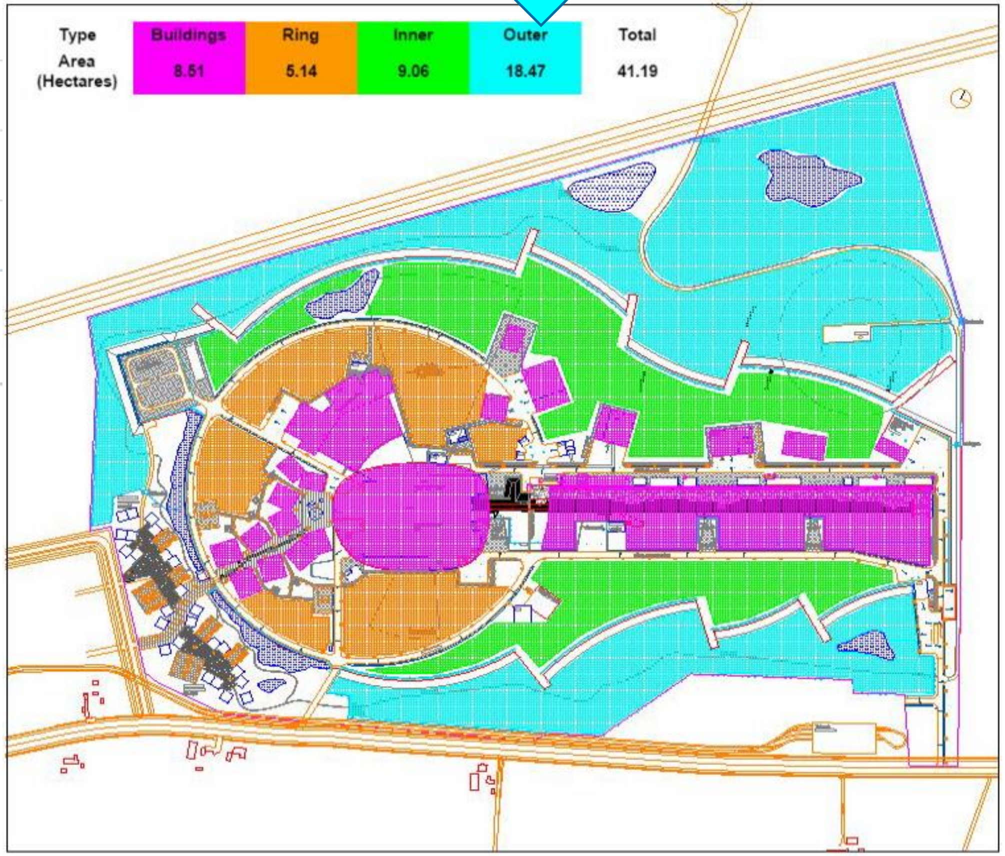
Simulation outputs:	
Slope angle [°]:	40 (opt)
Azimuth angle [°]:	2 (opt)
Yearly PV energy production [kWh]:	11162309.12
Yearly in-plane irradiation [kWh/m²]:	1251.02
Year-to-year variability [kWh]:	488195.41
Changes in output due to:	
Angle of incidence [%]:	-3.02
Spectral effects [%]:	1.51
Temperature and low irradiance [%]:	-4.59
Total loss [%]:	-10.77

Monthly energy output from fix-angle PV system



10MW installed PV capacity
- Land area: ~18 hectares

Areas in **"blue"**
(i.e. outer area of ESS site):
~ 18.5 hectares



Yearly electrical PV power yield Lund: 11.2 GWh
(@10MWpk installed PV capacity)

~ 17% of ESS accelerator annual consumption

Acknowledgements