Pulse modulators for science

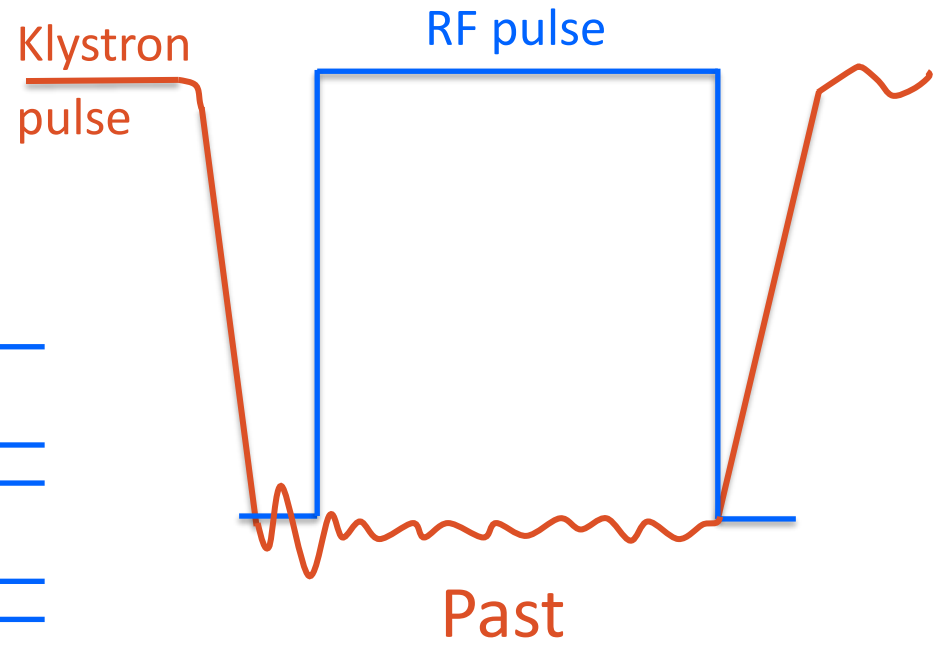
Kevin Pepitone, PhD, RF Application specialist

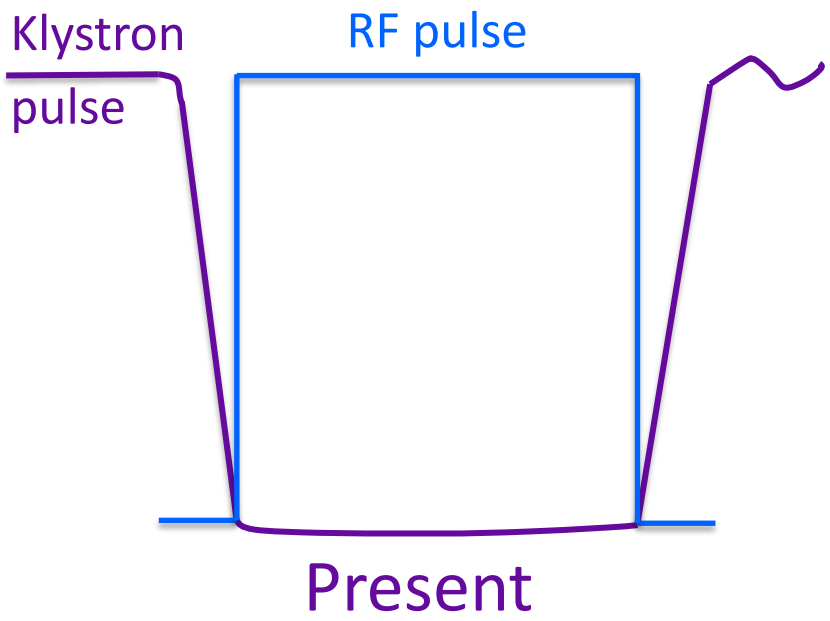
Workshop on efficient RF Source, Toledo, 23-25 Sept. 2024

ScandiNova

Outline

- ScandiNova
  - Products
  - Deliveries
- Modulators technologies
  - PFN
  - ScandiNova modulators
- Studie of pulse signals
  - Experimental data
  - Power lost in the beam
  - Cost
- Efficiency
  - ScandiNova K300
  - CERN case
  - Publication PFN modulator
  - Cost
- Future
  - Rise/Fall time
  - Pulse droop
  - Matching impedance
- Conclusions
  - Conclusions
  - Future development





ScandiNova

ScandiNova

A full product range for a variety of applications

K-SERIES

Klystron RF Units
Up to 100 MW RF Peak Power

M-SERIES

Magnetron Modulators
Up to 5 MW RF Peak Power

PG-SERIES

Pulse Generators
Up to 36 MW Peak Power

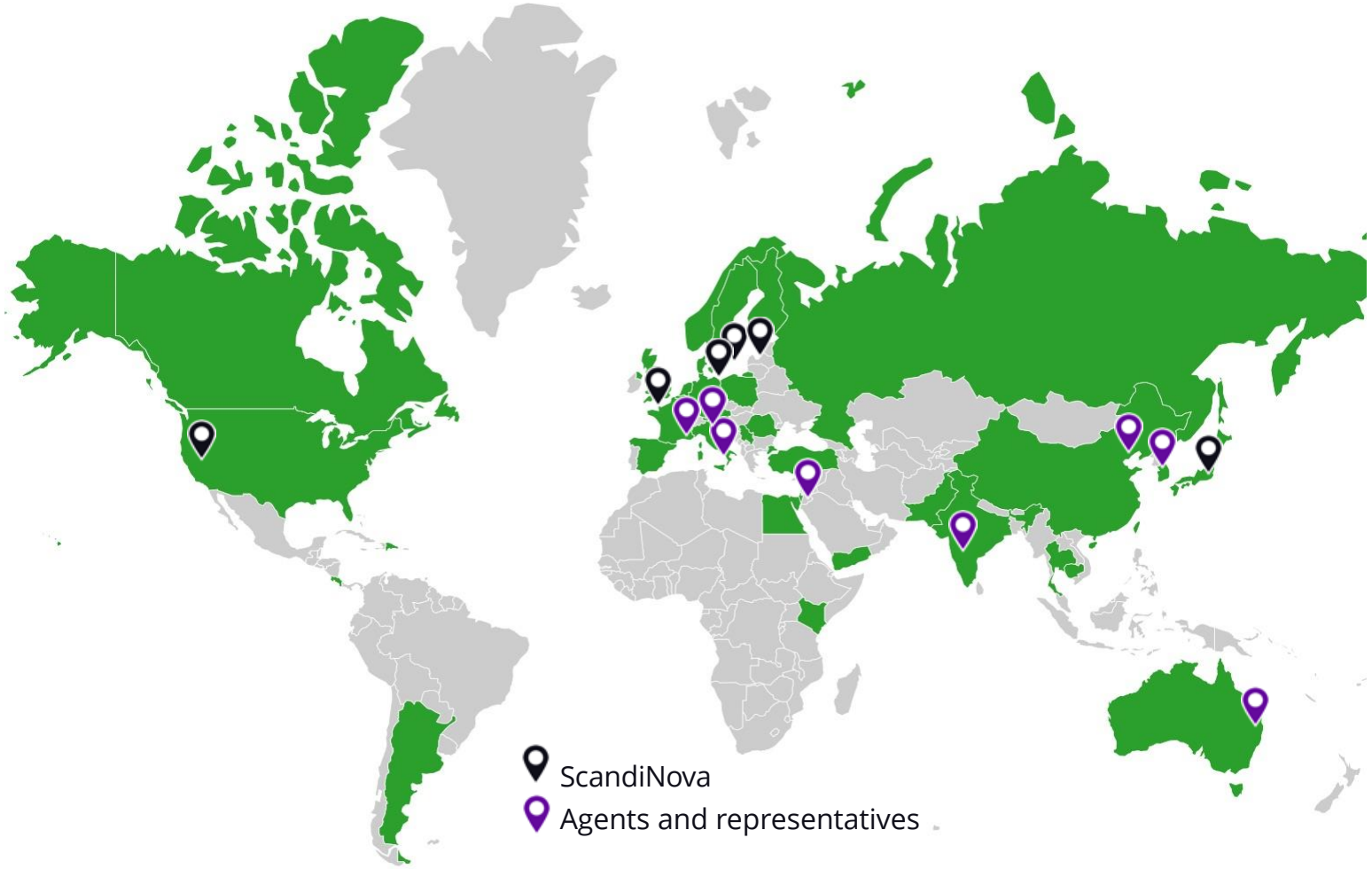
E-SERIES

E-gun Modulators
Up to 30 kV

A standardized modular concept, adaptable for specific needs

ScandiNova

Deliveries



2024
April

Installations:

320

(3220 modulators delivered)

Countries:

50

Operation Hours:

4 071 047

ScandiNova goup

A wide range of high-end critical sub systems

High-voltage pulse modulators and RF-systems

ScandiNova
Excellence in pulsed power

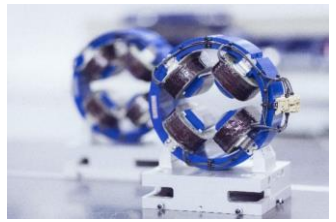
RF and microwave amplifiers

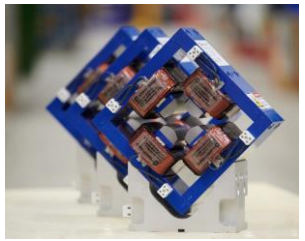
microwave amps
A ScandiNova Company

Power amplifiers and precision power supplies

IECO A ScandiNova Company

Magnets and coils

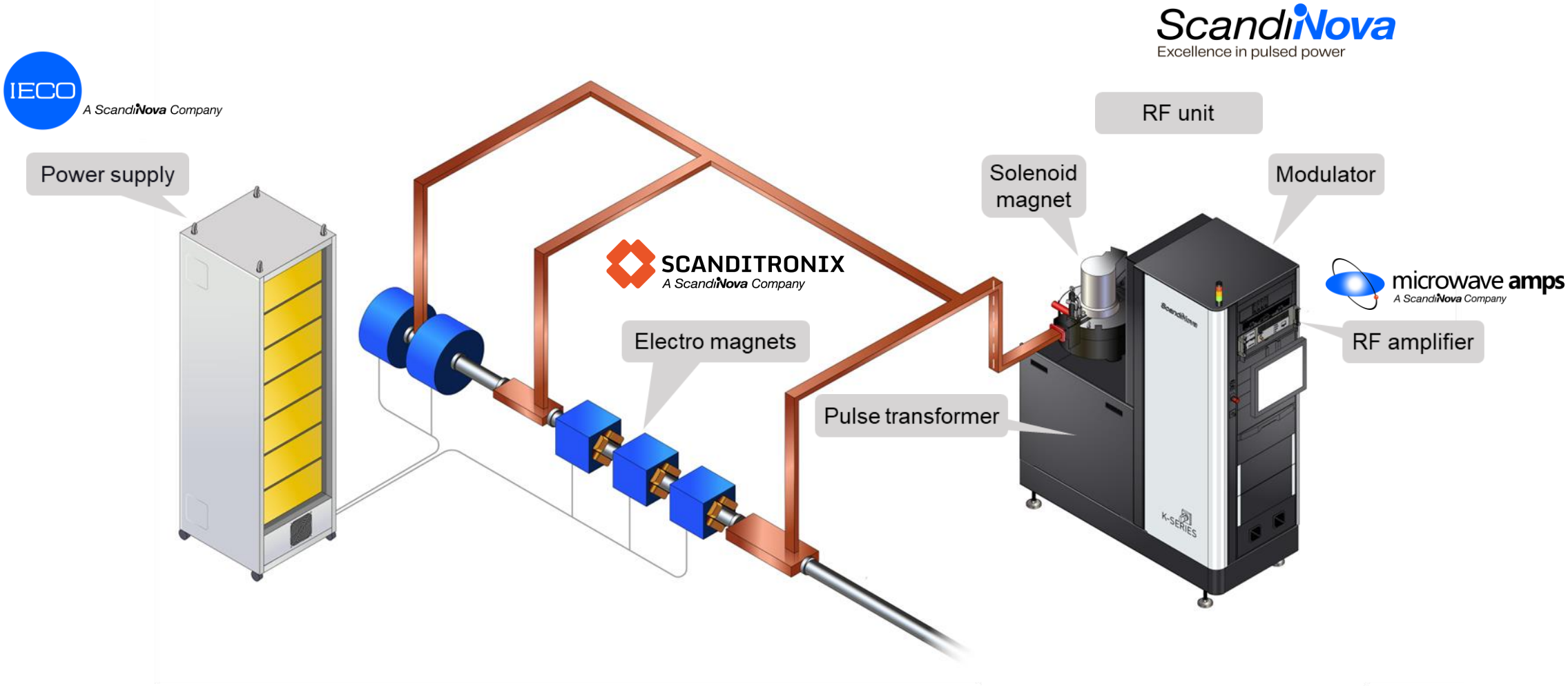




SCANDITRONIX
A ScandiNova Company

ScandiNova group

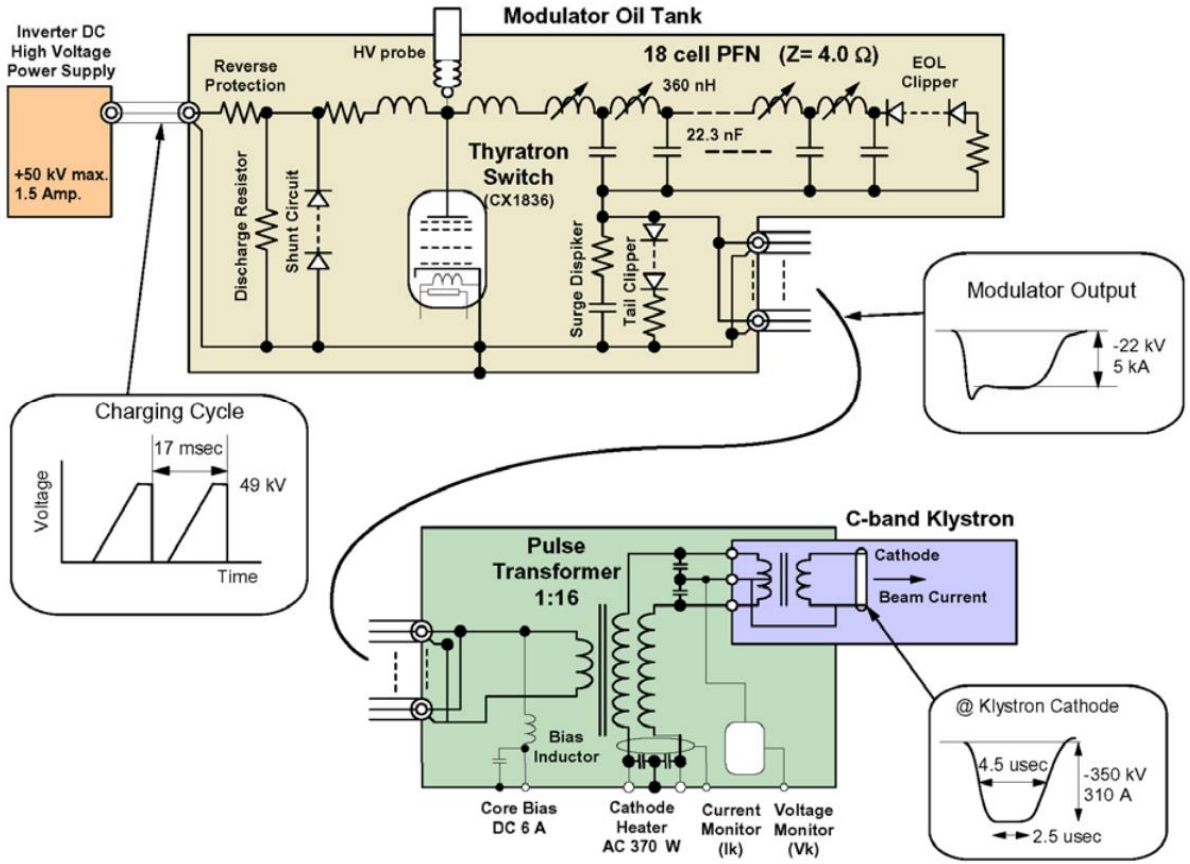
Increase offering



Modulator technologies

Modulator technologies

PFN



- **Approved technology**
- **Very robust**

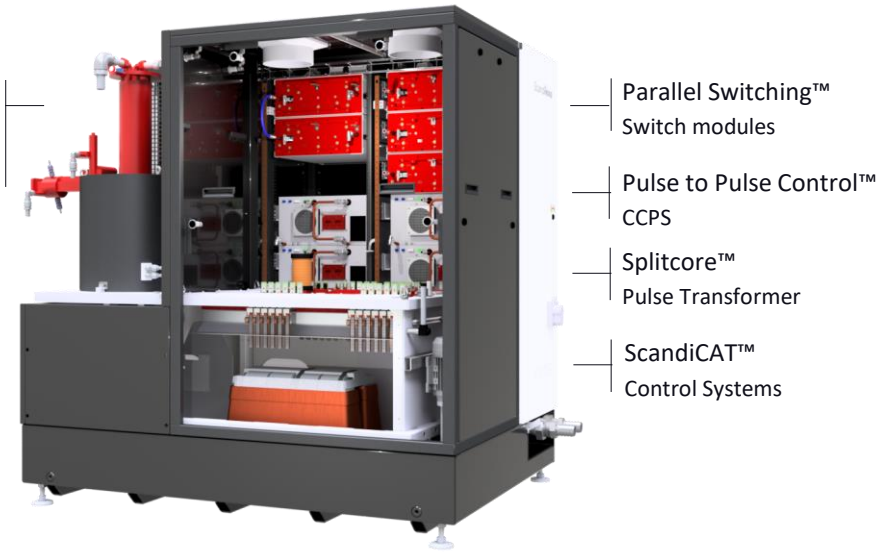
- High voltage
- Bulky
- AC cooling
- Flatness
- Fixed pulse duration
- Need impedance matching

Modulator technologies

ScandiNova

Solid-state pulsed power technology

K300 RF Unit



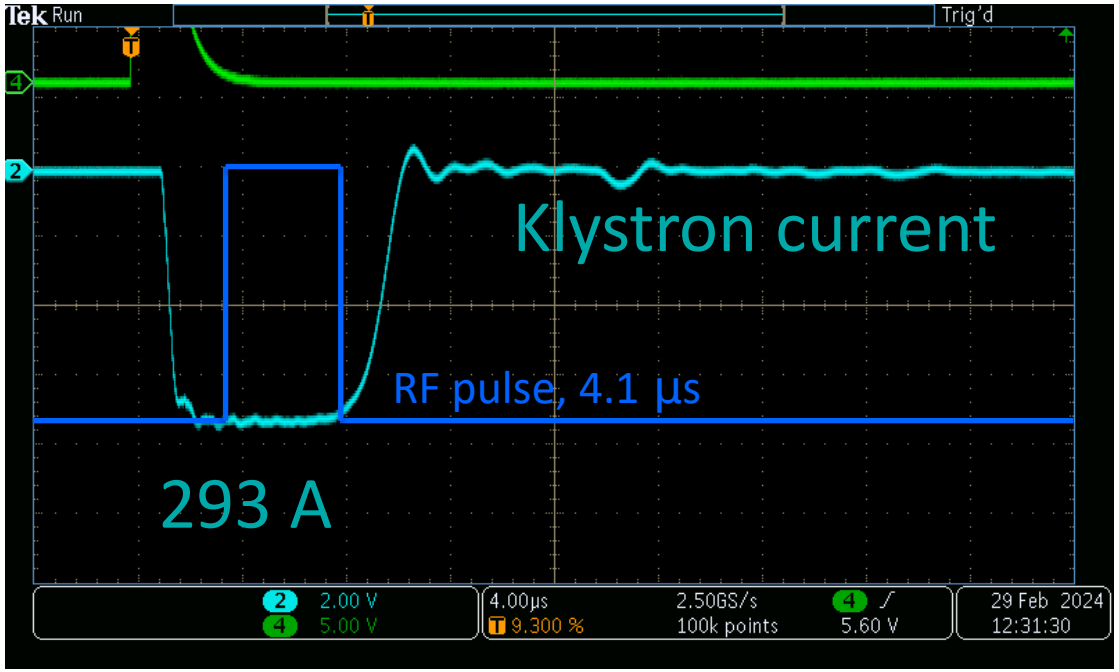
- **Approved technology**
- **Robust**
- **Compact and fully integrated**
- **Water cooling**
- **Flexibility (pps, pulse duration)**
- **Low insertion loss**
- **Low voltage**

- Many parts
- Need expert to install and maintain

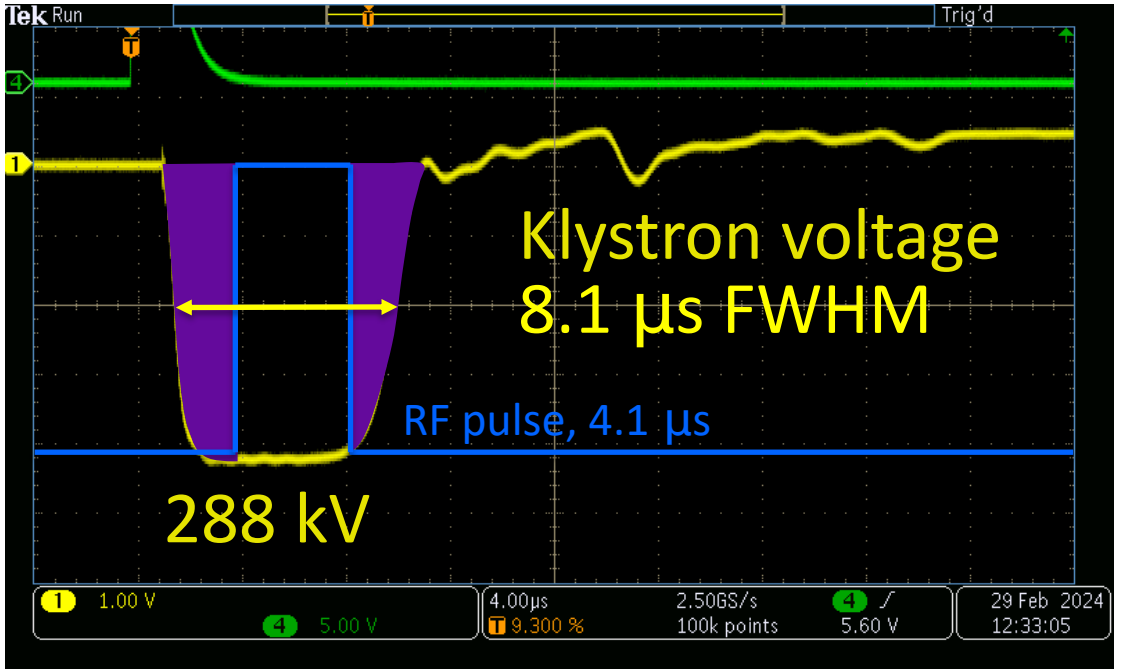
Pulse signals

Studie of pulse signals

Pulse PFN modulator



PFN modulator

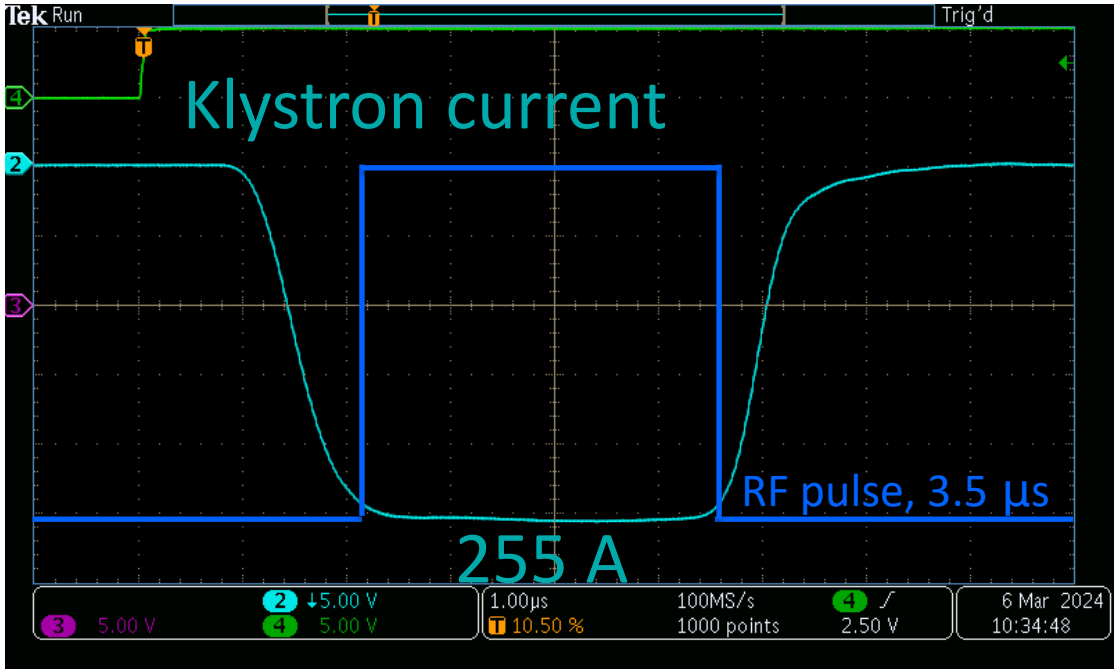


PFN modulator

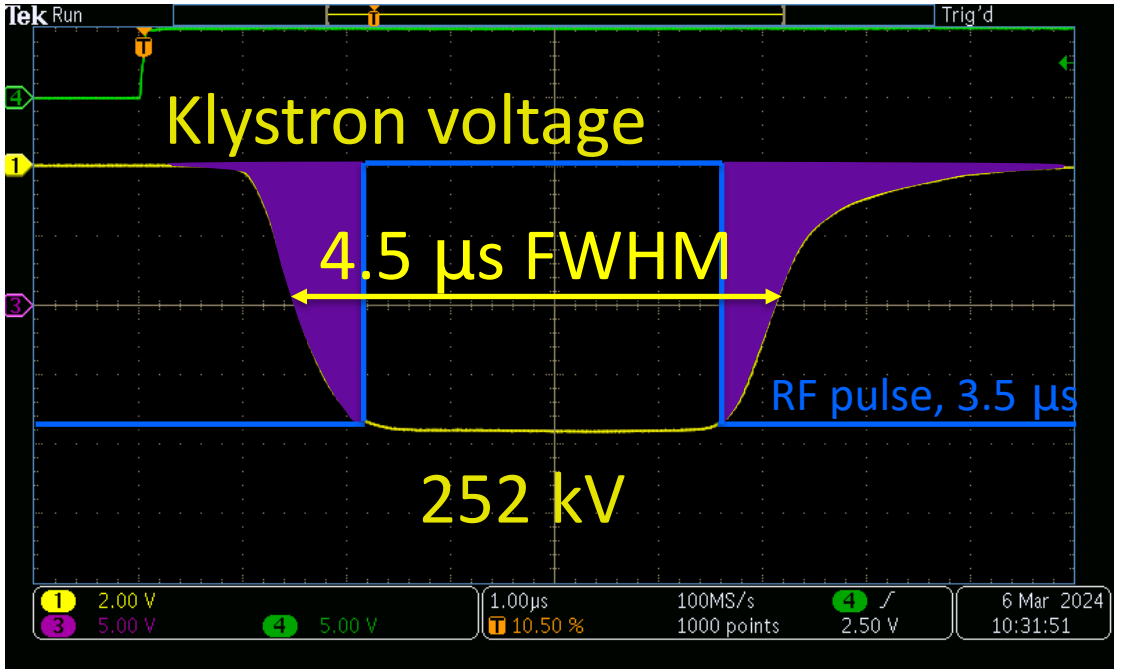
Courtesy A. Chauchet, S. Curt

Studie of pulse signals

Pulse ScandiNova modulator



ScandiNova modulator

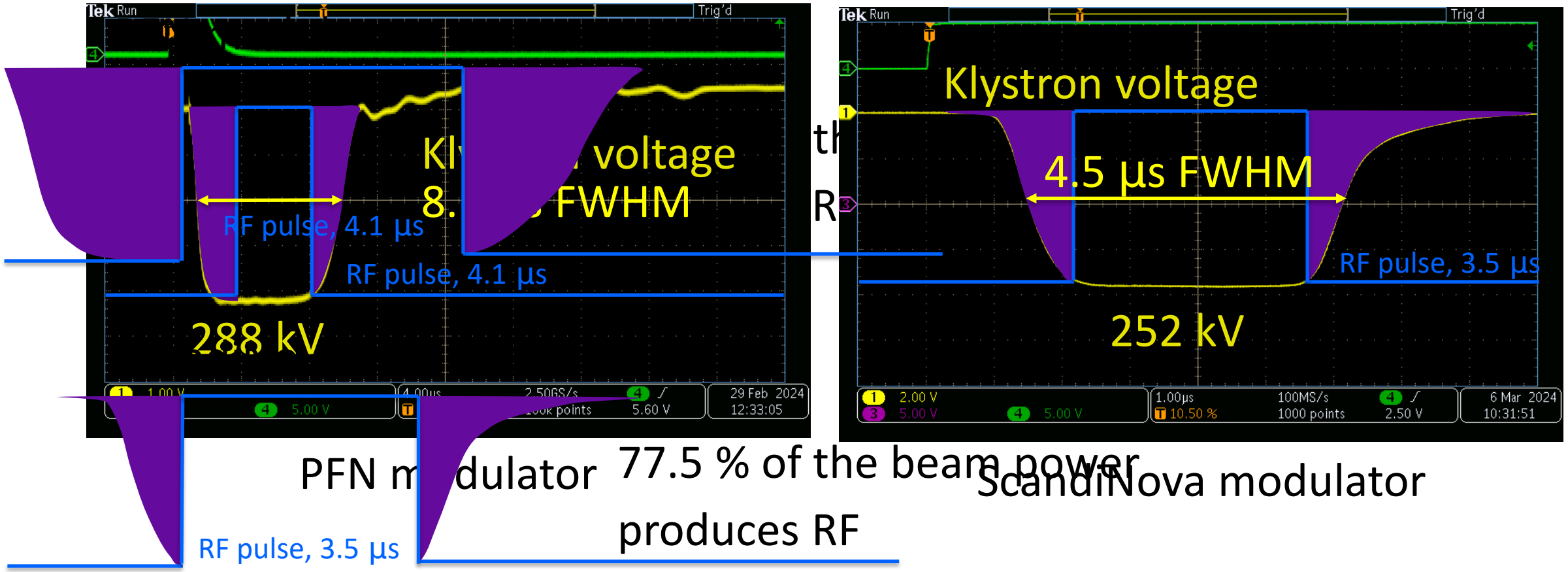


ScandiNova modulator

Courtesy A. Chauchet, S. Curt

Studie of pulse signals

Beam power losses



PFN modulator

77.5 % of the beam power produces RF

ScandiNova modulator

Efficiency

Efficiency

CERN case #1

Equipment	ScandiNova modulator: TH2100 – 10 Hz	PFN modulator: TH2100 – 10 Hz
Ion pump	0.1 nA – 3-5 kV	0.1 nA – 3-5 kV
Klystron heater	DC: 23.1 A - 26.5 V **Total = 0.6 kW**	AC (primary): 3.1A – 258 V **Total = 0.8 kW**
Solenoids	Ibucking: 18.3 A – 4 V IfocalA: 183 A – 25.6 V IfocalB: 133 A – 17.2 V IfocalC: 165 A – 21.3 V **Total = 10.5 kW**	Ibucking: 18.3 A – 4 V IfocalA: 166 A – 21.6 V IfocalB: 148 A – 19.2 V IfocalC: 160 A – 19.9 V **Total = 10.0 kW**
Thyratron heater	-	4 A – 147 V (86.4 A – 6.3 V) **Total = 0.6 kW**
Thyratron	-	200 mA – 39 kV **Total = 7.8 kW peak**
Water flow	Body: 13.7 L/min Solenoid: 11.4 L/min Collector: 108.4 L/min CCPS (1-4) and SU: 8.3 L/min	Body: 13.7 L/min Solenoid: 11.4 L/min Collector: 108.4 L/min -
RF amplifier	200 W RF peak	200 W RF peak
Air cooling	-	**Needed**
Modulator	**255** A – **252 kV** -> **Electric power= 24.6 MW** **RF 4 us, 10 Hz -> RF power= 35%** **(+ cooling)**	**293** A – **288 kV**-> **Electric power= 37.6 MW** **RF 4.5 us, 10 Hz -> RF power= 22%** **(+ cooling)**

Extracted from CERN data

Courtesy A. Chauchet, S. Curt

Studie of pulse signals

Energy saving for the RF pulse

Let’s consider a klystron producing 40 MW, 4 µs RF and operating at 100 Hz.

- The RF average power is 16 kW.

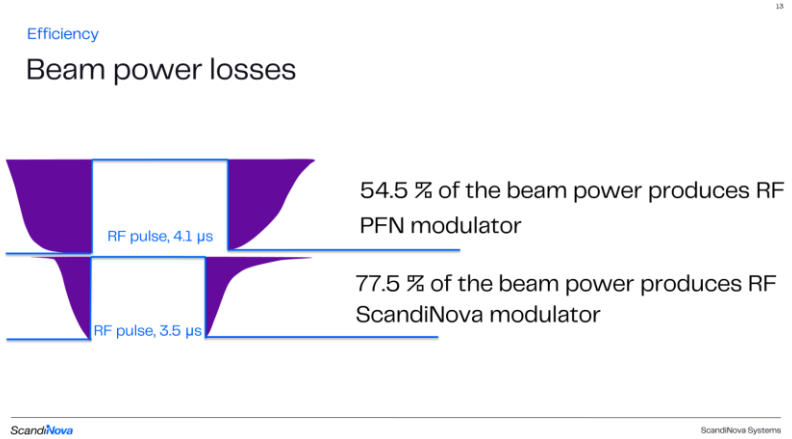
Let’s consider that the klystron has an efficiency of 45%

If it operates 10 hours/day and 5 days a week

After 1 year the consumption is 64 500 kWh/year

A PFN modulator will consume 93 500 kWh/year

A ScandiNova modulator will consume 79 000 kWh/year



Studie of pulse signals

Energy saving for the cooling

Let’s consider a klystron producing 40 MW, 4 µs RF and operating at 100 Hz.

It operates 10 hours/day and 5 days a week

- PFN modulator is air cooled
- A ScandiNova modulator is water cooled

	ScandiNova modulator	PFN modulator
Average modulator heat	6.1 kW	24.8 kW
Air conditioning*	0.3 tons	9 tons
Water cooling*	1.7 tons	0

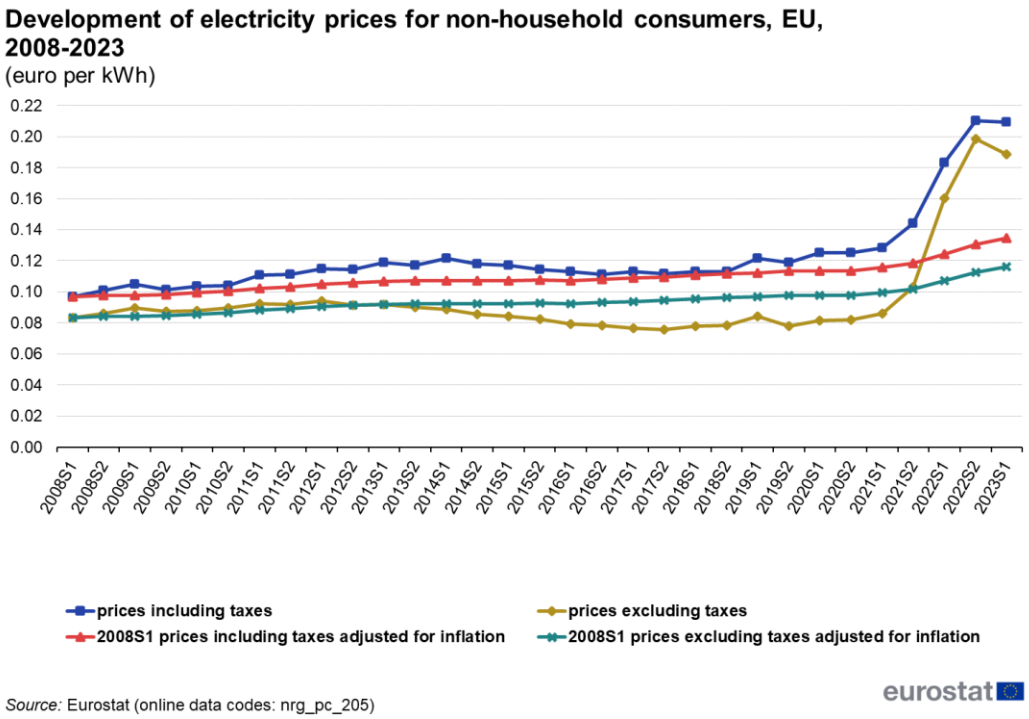
*A ton refers to the amount of heat it takes to completely melt a ton of ice

A PFN modulator will consume 90 500 kWh/year
A ScandiNova modulator will consume 22 300 kWh/year

https://energyusecalculator.com/electricity_airconditioner.htm

Studie of pulse signals

Cost



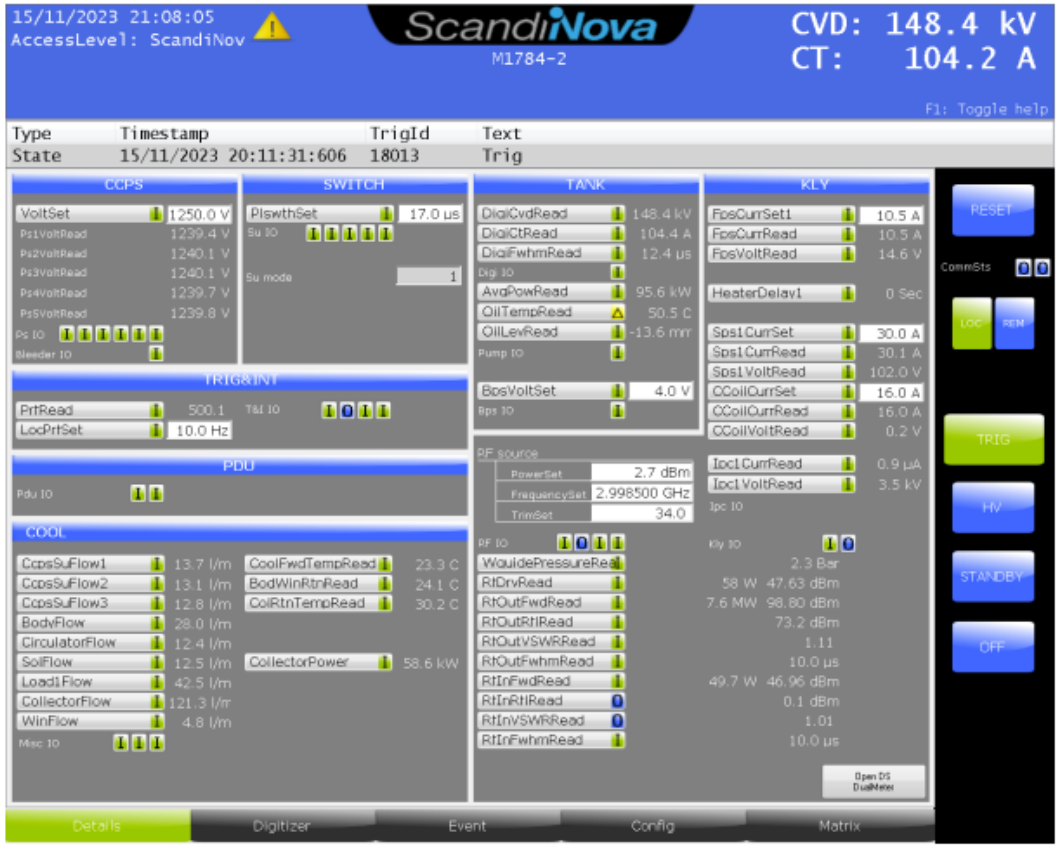
Source: Eurostat (online data codes: nrg_pc_205)

	ScandiNova modulator	PFN modulator
Energy consumption to produce the RF pulse	79 000 kWh/year	93 500 kWh/year
Energy consumption to cool down the system	22 300 kWh/year	90 500 kWh/year
Total consumption	101 300 kWh/year	184 000 kWh/year
Price	21 300 €/year	39 000 €/year
Saving	46 %	

Efficiency

Klystron modulator – K300 and S-band klystron

Total Power	Detail	Total	Percentage
	400 Vac, 178 A, cosϕ=0.92	113.4 kW	
RF power	7.5 MW, 10 µs, 500 Hz	38.0 kW	33.5 %
Wasted beam power Power dumped in the collector	Klystron efficiency is 44.7 %	47.0 kW	41.4 %
Wasted pulse power Power which doesn't contribute to the RF pulse	Magnetization : 900 W Rise/Fall Time : 15300 W	16.2 kW	14.3 %
Charging losses Losses in the transformer and tuning elements	1250 V x 2 cores x 64 turns – RF power – Wasted beam	7.6 kW	6.7 %
Auxiliary power supplies	Klystron heater: 150 W Oil pump: 750 W Solenoid: 3060 W Counter coil: 3.2 W Controllers: 600 W	4.6 kW	4.1 %



S-band

Calculation inspired by DOI: 10.1109/PAC.1997.749775

Efficiency

Wasted beam power

Total Power	Detail	Total	Percentage
	400 Vac, 178 A, cosϕ=0.92	113.4 kW	
RF power	7.5 MW, 10 µs, 500 Hz	38.0 kW	33.5 %
Wasted beam power Power dumped in the collector	Klystron efficiency is 44.7 %	47.0 kW	41.4 %
Wasted pulse power Power which doesn't contribute to the RF pulse	Magnetization : 900 W Rise/Fall Time : 15300 W	16.2 kW	14.3 %
Charging losses Losses in the transformer and tuning elements	1250 V x 2 cores x 64 turns – RF power – Wasted beam	7.6 kW	6.7 %
Auxiliary power supplies	Klystron heater: 150 W Oil pump: 750 W Solenoid: 3060 W Counter coil: 3.2 W Controllers: 600 W	4.6 kW	4.1 %

Retrofit design

Canon

8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	94	94
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	48
Efficiency, %	42	56.4
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.42
RF circuit length, m	**0.127**	**0.127**

THALES
Building a future we can all trust

	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	59
Efficiency, %	36.2	66
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.37
RF circuit length, m	**0.316**	**0.316**

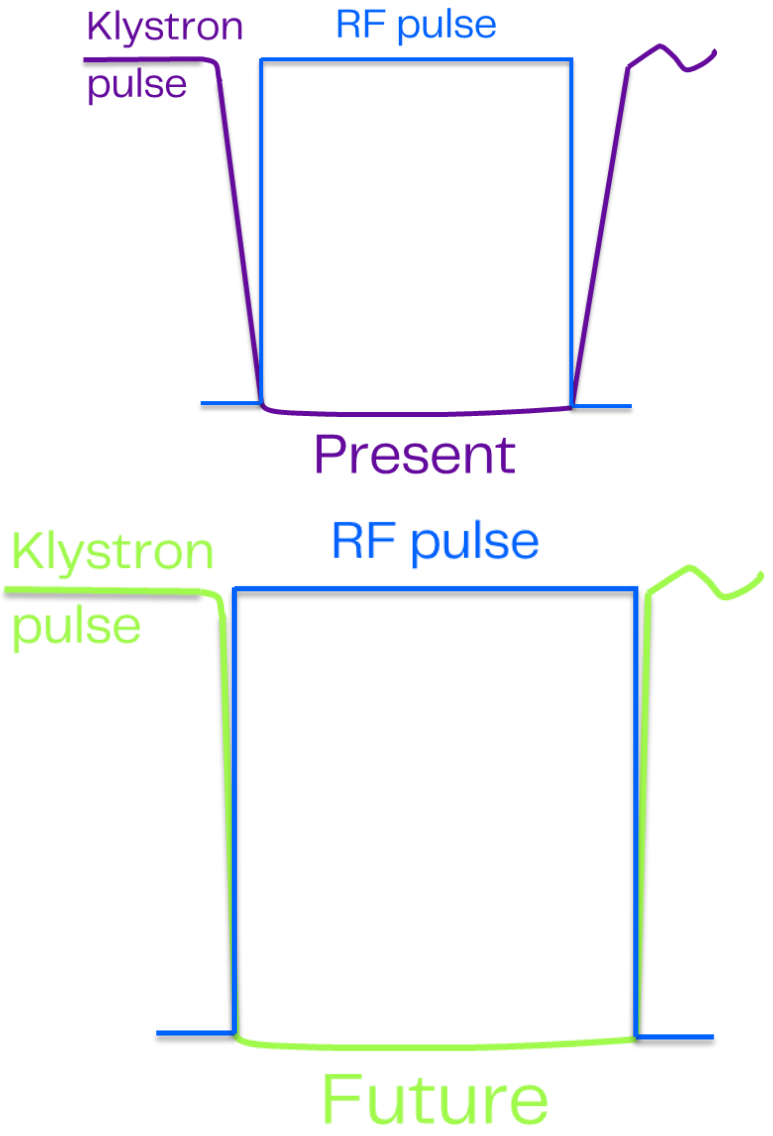
LCWS2023 International Workshop on Future Linear Colliders
15-19 May 2023

High Efficiency Klystrons project at CERN: Status and updates.
I. Syratchev for HE project team at CERN & Lancaster

Efficiency

Wasted pulse power

Total Power	Detail	Total	Percentage
	400 Vac, 178 A, cosϕ=0.92	113.4 kW	
RF power	7.5 MW, 10 µs, 500 Hz	38.0 kW	33.5 %
Wasted beam power Power dumped in the collector	Klystron efficiency is 44.7 %	47.0 kW	41.4 %
Wasted pulse power Power which doesn't contribute to the RF pulse	Magnetization : 900 W Rise/Fall Time : 15300 W	16.2 kW	14.3 %
Charging losses Losses in the transformer and tuning elements	1250 V x 2 cores x 64 turns – RF power – Wasted beam	7.6 kW	6.7 %
Auxiliary power supplies	Klystron heater: 150 W Oil pump: 750 W Solenoid: 3060 W Counter coil: 3.2 W Controllers: 600 W	4.6 kW	4.1 %



Efficiency

Charging losses

Total Power	Detail	Total	Percentage
	400 Vac, 178 A, cosϕ=0.92	113.4 kW	
RF power	7.5 MW, 10 µs, 506 Hz	38.0 kW	33.5 %
Wasted beam power Power dumped in the collector	Klystron efficiency is 44.7 %	47.0 kW	41.4 %
Wasted pulse power Power which doesn't contribute to the RF pulse	Magnetization : 900 W Rise/Fall Time : 15300 W	16.2 kW	14.3 %
Charging losses Losses in the transformer and tuning elements	1250 V x 2 cores x 64 turns – RF power – Wasted beam	7.6 kW	6.7 %
Auxiliary power supplies	Klystron heater: 150 W Oil pump: 750 W Solenoid: 3060 W Counter coil: 3.2 W Controllers: 600 W	4.6 kW	4.1 %

Use of DMPS (Digitally Modulated Pulse Shaping, also known as Softgating) **on all the modulators**

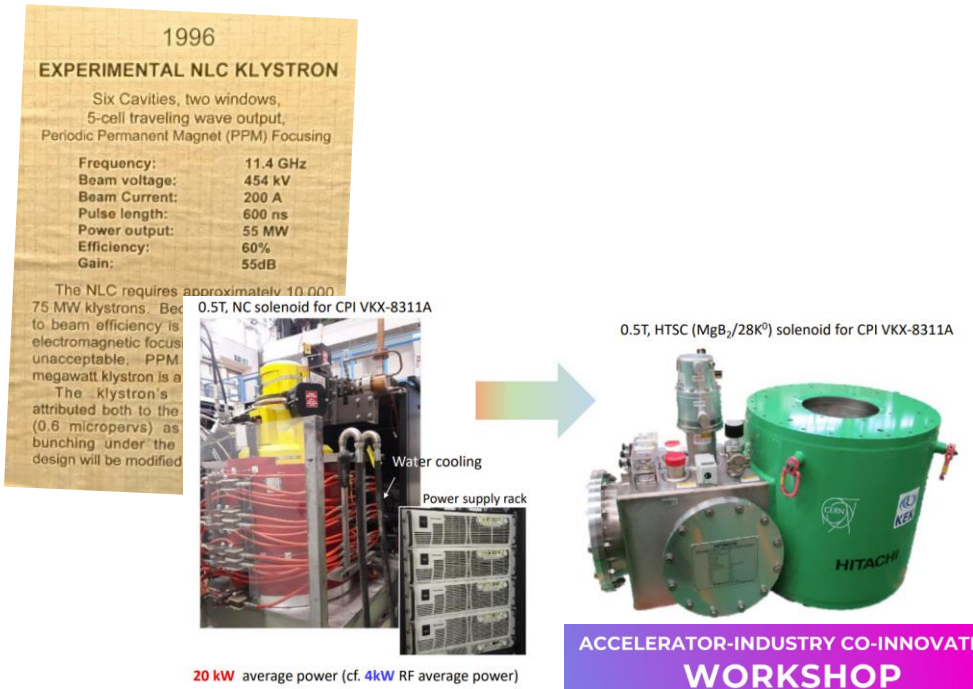
Efficiency

Auxiliary power supplies

Total Power	Detail	Total	Percentage
	400 Vac, 178 A, cosϕ=0.92	113.4 kW	
RF power	7.5 MW, 10 µs, 500 Hz	38.0 kW	33.5 %
Wasted beam power Power dumped in the collector	Klystron efficiency is 44.7 %	47.0 kW	41.4 %
Wasted pulse power Power which doesn't contribute to the RF pulse	Magnetization : 900 W Rise/Fall Time : 15300 W	16.2 kW	14.3 %
Charging losses Losses in the transformer and tuning elements	1250 V x 2 cores x 64 turns – RF power – Wasted beam	7.6 kW	6.7 %
Auxiliary power supplies	Klystron heater: 150 W Oil pump: 750 W Solenoid: 3060 W Counter coil: 3.2 W Controllers: 600 W	4.6 kW	4.1 %

SCANDITRONIX
A ScandiNova Company

Use permanent magnets or superconducting magnets



High efficiency klystrons.
I. Syratchev CERN

Efficiency

Optimized model

Total Power	Detail	Total	Percentage
	400 Vac, 178 A, cosϕ=0.92	113.4 kW	
RF power	7.5 MW, 10 µs, 500 Hz	38.0 kW	33.5 %
Wasted beam power Power dumped in the collector	Klystron efficiency is 44.7 %	47.0 kW	41.4 %
Wasted pulse power Power which doesn't contribute to the RF pulse	Magnetization : 900 W Rise/Fall Time : 15300 W	16.2 kW	14.3 %
Charging losses Losses in the transformer and tuning elements	1250 V x 2 cores x 64 turns – RF power – Wasted beam	7.6 kW	6.7 %
Auxiliary power supplies	Klystron heater: 150 W Oil pump: 750 W Solenoid: 3060 W Counter coil: 3.2 W Controllers: 600 W	4.6 kW	4.1 %

Efficiency issue in C-band klystron-modulator system for linear collider

J.S. Oh; M.H. Cho; W. Namkung; T. Shintake; H. Matsumoto; K. Watanabe; H. Baba

Proceedings of the 1997 Particle Accelerator Conference

Table 4: Power distribution of a C-band system.

Total Power = 51,371 W		
1. RF Power	12,488	(24.3%)
2. Wasted Beam Power	15,263	(29.7%)
3. Wasted Pulse Power	12,071	(23.5%)
4. Charging Loss	7,072	(13.8%)
5. Aux. Power	4,477	(8.7%)
Wasted Pulse Power		
a. Rise/Fall Time Loss	9,991	(19.45%)
b. Magnetizing Loss	929	(1.81%)
c. Thyratron Loss	416	(0.81%)
d. Eddy Current Loss	463	(0.90%)
e. RC Snubber Loss	272	(0.53%)
Aux. Power		
a. Klystron Magnet	3,000	(5.84%)
b. Thyratron Heater	567	(1.10%)
c. Cooling Fan	450	(0.88%)
d. Klystron Heater	316	(0.62%)
e. Core Bias	100	(0.19%)
f. Thyratron Reservoir	44	(0.09%)

DOI: 10.1109/PAC.1997.749775

Efficiency

Optimized model

Total Power	Detail	Total	Percentage
	400 Vac, 178 A, cosϕ=0.92	113.4 kW	
RF power	7.5 MW, 10 µs, 500 Hz	38.0 kW	33.5 %
Wasted beam power Power dumped in the collector	Klystron efficiency is 44.7 %	47.0 kW	41.4 %
Wasted pulse power Power which doesn't contribute to the RF pulse	Magnetization : 900 W Rise/Fall Time : 15300 W	16.2 kW	14.3 %
Charging losses Losses in the transformer and tuning elements	1250 V x 2 cores x 64 turns – RF power – Wasted beam	7.6 kW	6.7 %
Auxiliary power supplies	Klystron heater: 150 W Oil pump: 750 W Solenoid: 3060 W Counter coil: 3.2 W Controllers: 600 W	4.6 kW	4.1 %

Detail	Total	Percentage
	72.8 kW	
7.5 MW, 10 µs, 500 Hz	38.0 kW	52.1 %
Klystron efficiency is 60 %	25.3 kW	34.8 %
Magnetization : 900 W Rise/Fall Time : 5000 W	5.9 kW	8.1 %
1250 V x 2 cores x 64 turns – RF power – Wasted beam	2.0 kW	2.7 %
Klystron heater: 150 W Oil pump: 750 W Solenoid: 0 W Counter coil: 3.2 W Controllers: 600 W	1.6 kW	2.2 %

DOI: 10.1109/PAC.1997.749775

Efficiency

Impact on the bill

Total Power	Detail	Total	Percentage
	400 Vac, 178 A, cosφ=0.92	113.4 kW	
RF power	7.5 MW, 10 µs, 500 Hz	38.0 kW	33.5 %
Wasted beam power Power dumped in the collector	Klystron efficiency is 44.7 %	47.0 kW	41.4 %
Wasted pulse power Power which doesn't contribute to the RF pulse	Magnetization : 900 W Rise/Fall Time : 15300 W	16.2 kW	14.3 %
Charging losses Losses in the transformer and tuning elements	1250 V x 2 cores x 64 turns – RF power – Wasted beam	7.6 kW	6.7 %
Auxiliary power supplies	Klystron heater: 150 W Oil pump: 750 W Solenoid: 3060 W Counter coil: 3.2 W Controllers: 600 W	4.6 kW	4.1 %

Detail	Total	Percentage
	72.8 kW	
7.5 MW, 10 µs, 500 Hz	38.0 kW	52.1 %
Klystron efficiency is 60 %	25.3 kW	34.8 %
Magnetization : 900 W Rise/Fall Time : 5000 W	5.9 kW	8.1 %
1250 V x 2 cores x 64 turns – RF power – Wasted beam	2.0 kW	2.7 %
Klystron heater: 150 W Oil pump: 750 W Solenoid: 0 W Counter coil: 3.2 W Controllers: 600 W	1.6 kW	2.2 %

Klystron

See High efficiency klystrons

Pulse shape

Tunings

Solenoid

See High efficiency klystrons

Electricity price 0.21€/kWh

It operates 10 hours/day and 5 days a week

Total price to produce 38 kW average of RF power: 61 900 €/year

Each kW saved on the modulator will help to save 550 €/year

Future

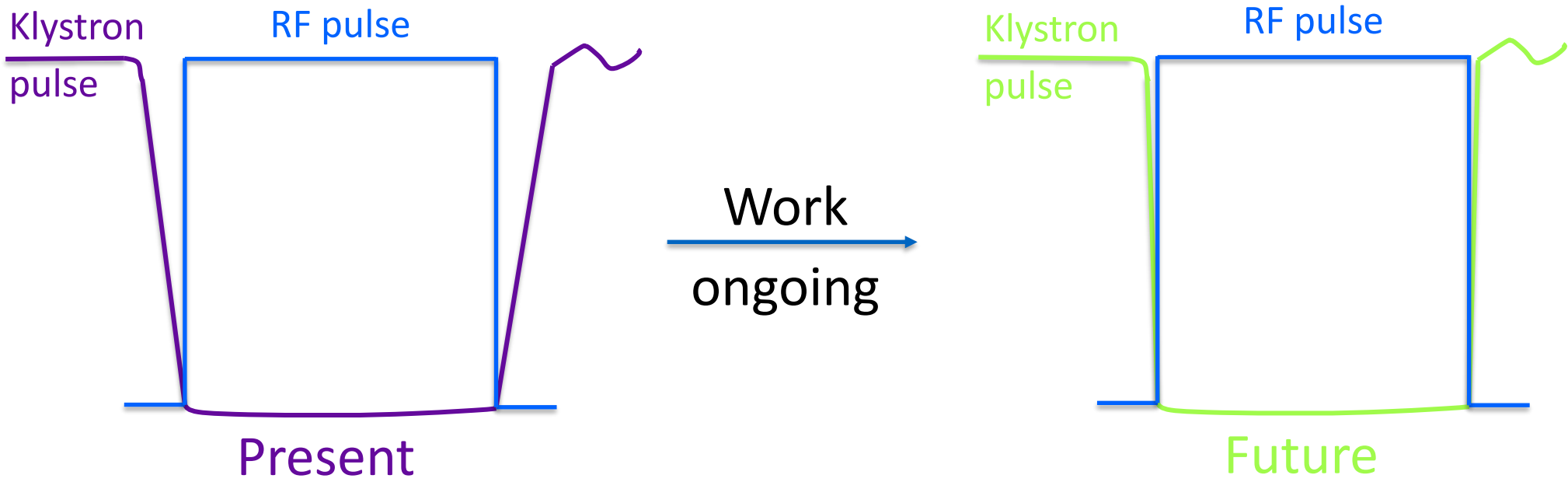
Future – work ongoing

Rise/Fall time improvement

Implemented on the M060

We are working on improving transformer size to **reduce leakage inductance**

Also looking into **improvements** on the **inductance of the primary side of the transformer**



Future – work ongoing

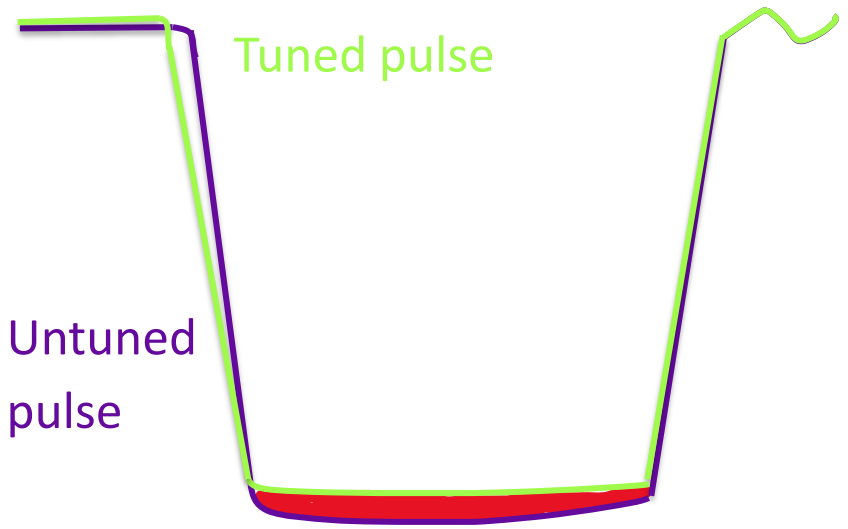
Pulse droop losses

Implemented on the M060

To compensate for the droop of capacitor bank an amount of **energy is burned to ”flatten” the pulse**

This is something we are looking into to improve

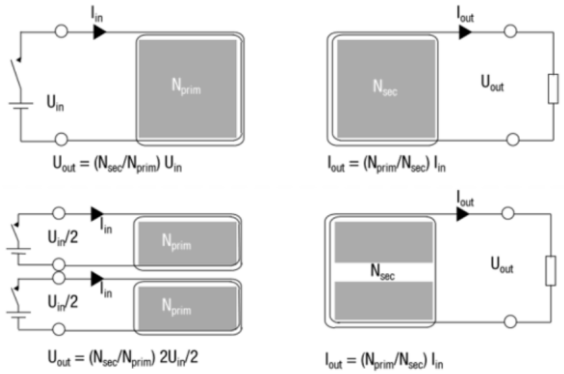
Big capacitor bench



Future – work ongoing

Easier impedance matching with klystrons

Split Core™ – the secret of ScandiNova



Parallel Switching™

Implemented on the M060

Work ongoing →

Asynchronus parallel switching

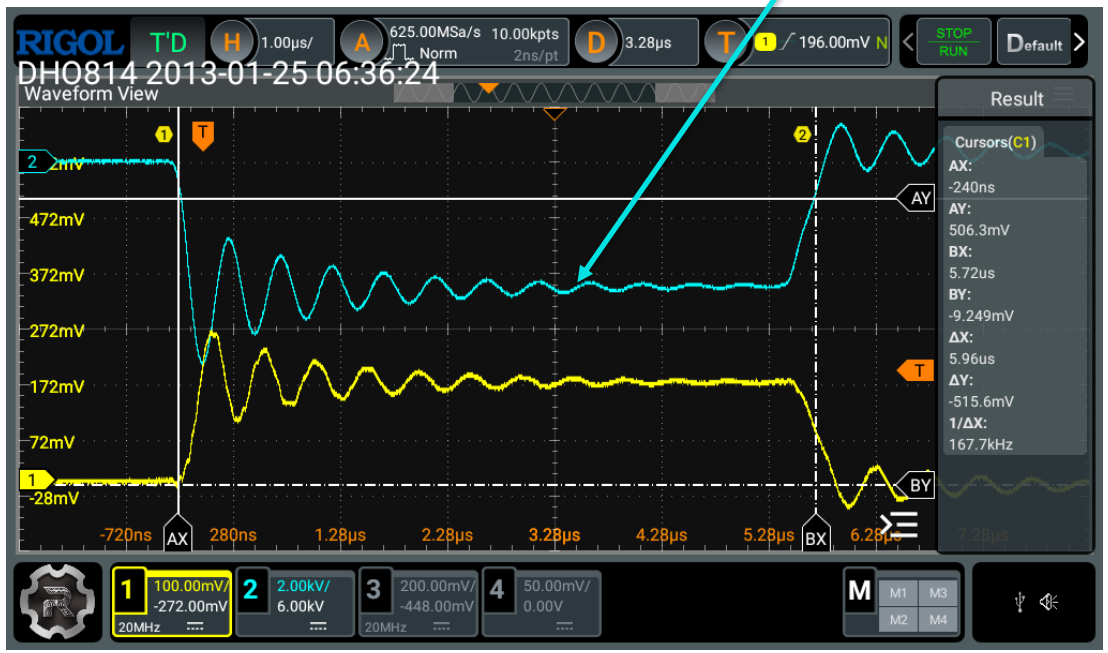
By sequentially triggering the split cores the overshoot that is otherwise tuned by other means can be reduced

Covered by a split core patent

Future – work ongoing

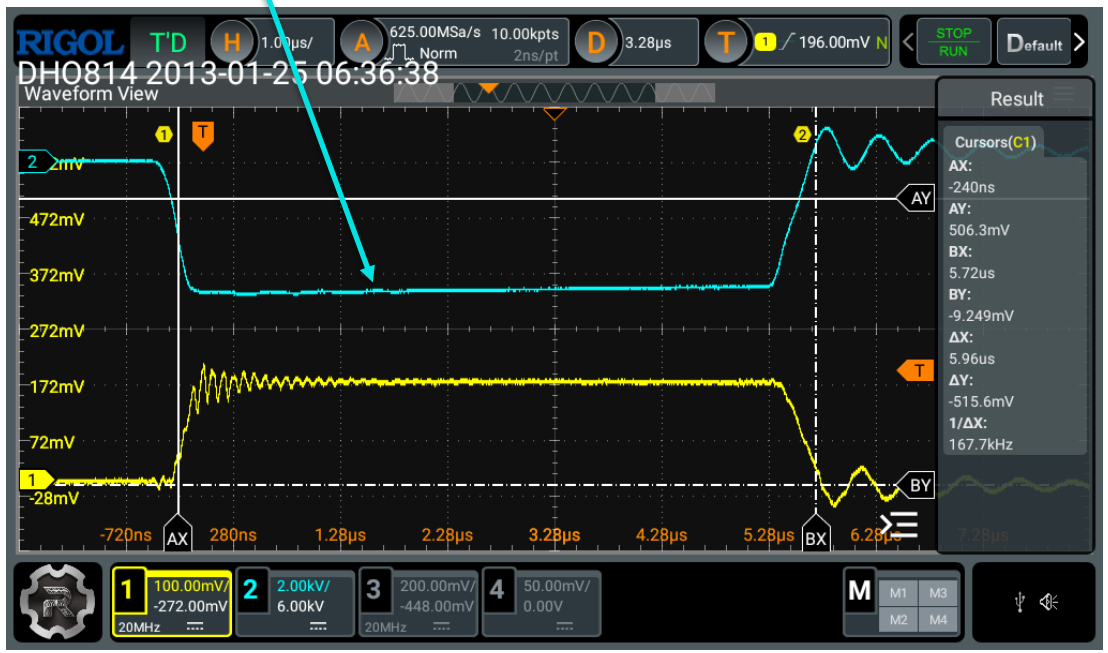
Experimental results

Voltage



Rise/Fall time improvement

Voltage

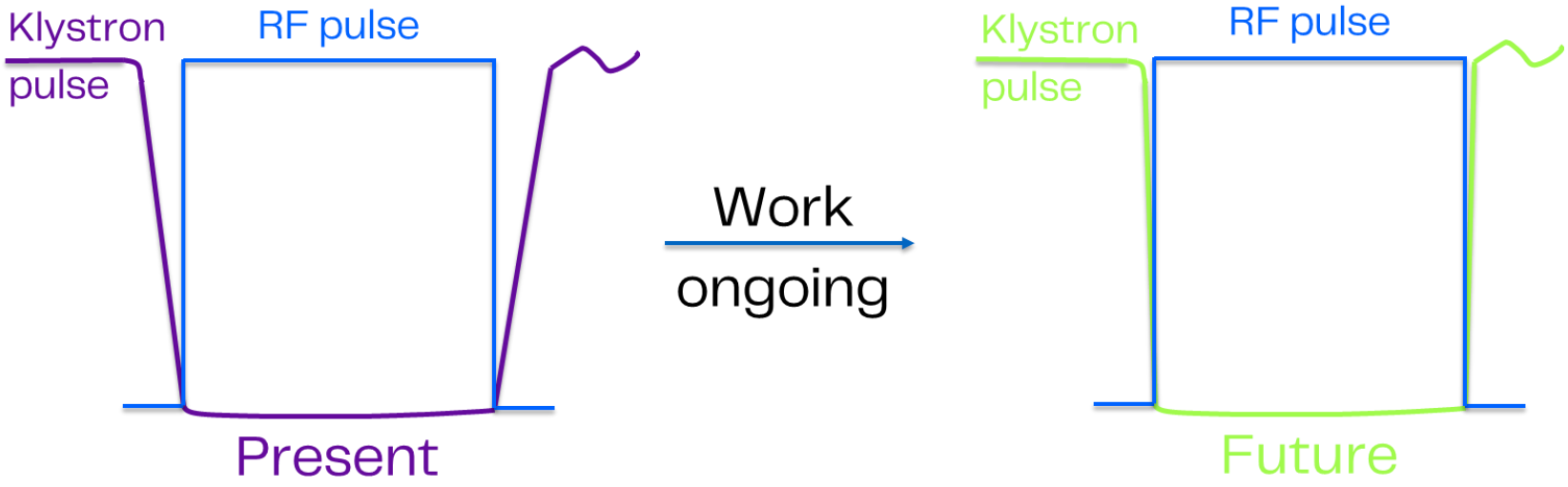


All the improvements

Conclusions and future developments

To achieve future state, we are looking into **3 main parameters**

- Rise/Fall time improvement
- Pulse droop losses
- Easier impedance matching with klystrons



Good wall plug efficiency

Amazing wall plug efficiency

Thanks for your attention!

info@scandinovasystems.com
+46 18 480 59 00
Typsnittsgatan 15
754 54 Uppsala
Sweden

ScandiNova