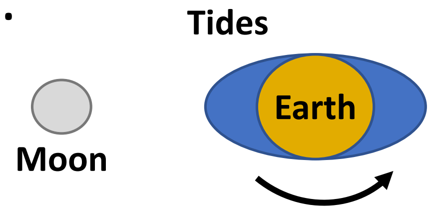
Efficient RF Systems 2022
Attempt of a Summary

Mike Seidel, PSI/EPFL

Chateau de Bossey, July 14-16

Energy Consumption - Motivation

The world energy consumption has been continuously rising, reaching **19 TW** today, **= 5× power dissipated in the tides (3.8 TW)**.



As a science community we rather want to contribute to solutions and not be part of the problem.

- climate change
- recently: pandemic, Ukraine conflict

$\rightarrow$ inflation of energy prices, scarcity of ressources

School Strike for Climate
Wikipedia

Community Activities on Sustainability

2014-17: EUCARD-2, WP Energy Efficient Accelerator Technologies

https://www.psi.ch/enefficient

2017–21: ARIES, Work Package Efficient Energy Management

https://www.psi.ch/aries-eem

2021–25: I.FAST, Work Package Sustainable Concepts

https://www.psi.ch/scat

EuCARD² Enhanced European Coordination for Accelerator Research & Development

ARIES ACCELERATOR RESEARCH AND INNOVATION FOR EUROPEAN SCIENCE AND SOCIETY

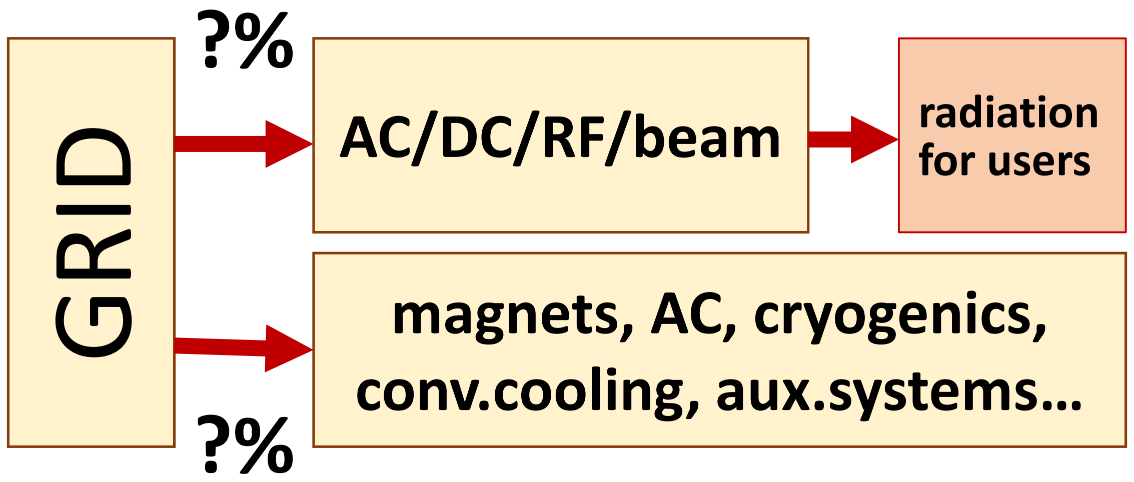
iFAST Innovation Fostering in Accelerator Science and Technology

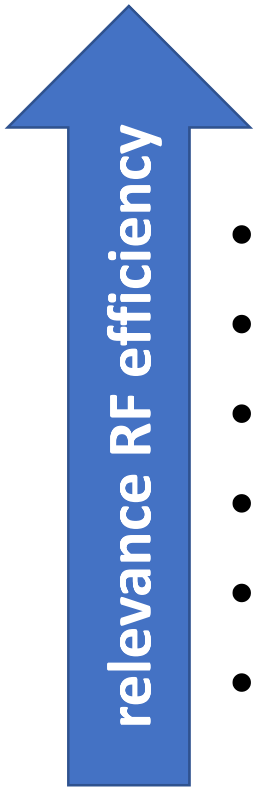
→ consult websites for link collection to workshops and documentation

ICFA

- ICFA panel on sustainable accelerators, chair: Thomas Roser (BNL)
- https://icfa.hep.net/icfa-panel-on-sustainable-accelerators-and-colliders/

Power flow in various accelerator concepts





- proton drivers (ESS, HIPA)
- linear colliders (CLIC)
- lepton ring colliders (FCC-ee)
- ring light sources (Soleil, SLS)
- hadron ring collider (LHC)
- free electron laser (SwissFEL)

RF Sources: Multi Objective Optimization

Requirements: frequency, pulse structure, RF power, # of devices, …

Technology Selection Criteria:
- market availability, long term support
- minimize overall investment cost, and operating cost
- maximize reliability in operation, serviceability
- **energy efficiency**

rich field of development activities presented at the workshop, many innovative ideas

36 registered participants

the spectrum of activities includes:

labs & universities

- concept studies: klystrons, SSA, magnetrons …
- basic investments in simulation codes with demonstrated predictive strength
- incremental and modular improvements of existing systems with moderate effort
- pragmatic and goal oriented developments for large research infrastructures like ESS, incl. transfer to industry

concrete ← abstract

A.Grudiev, on CLIC optimizations Comparison of wall plug to beam efficiencies

$\rightarrow$ impressive example of efficiency optimization of a complex collider system
main measures: new low (R/Q) damping ring resonators, drive beam klystron & modulator improvement

	PIP baseline	**New DR**	**New TS MBK**
DB klystron efficiency [%]	70	70	82
DB modulator pulse efficiency [%]	86	86	94
DB complex Wall plug to DB efficiency [%]	**31.8**	**31.8**	**37.6**
DR wall plug to MB efficiency [%]	7.9	56.7	56.7
CLIC Wall plug to MB efficiency [%]	**3.3**	**4.8**	**5.2**

PAUL SCHERRER INSTITUT

PSI, M.Pedrozzi, M.Schär, multiple e/p facilities

here: SSA upgrade in synchrotron is a result of many considerations, not just efficiency

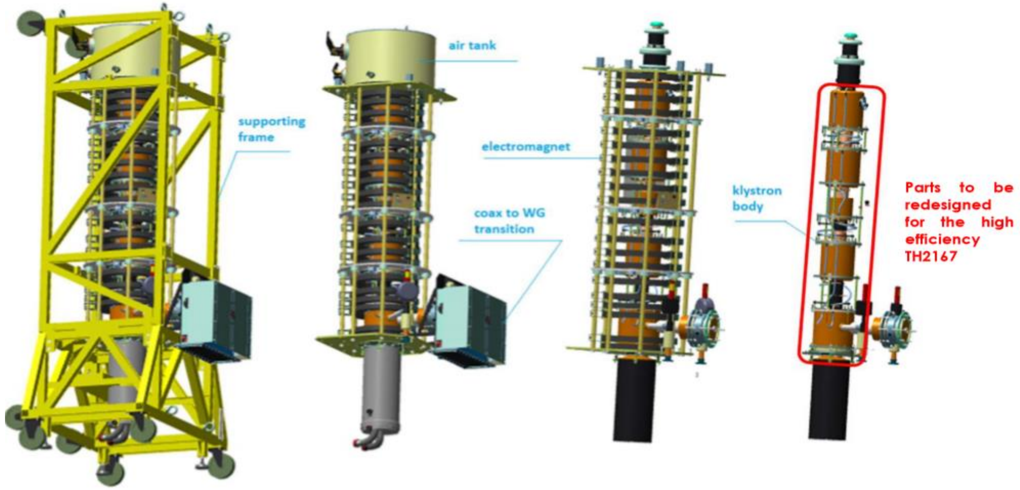
2.

Motivations	
RELIABILITY	Cope with the risk of aging and discontinued components Built-in redundancy
Phase noise	Old Station not fulfilling the SLS2 requirements (keep energy fluctuations below ID BW)
Maintenance	Modular system allows for fast maintenance / In house expertise on SSA (no HV)
Klystron availability	Only few klystron suppliers and growing costs
Grid to RF efficiency	Wasn't the driving argument, but an improvement is expected
Operational costs	Beside better efficiency, expected low maintenance costs (klystrons)

High efficiency klystron for LHC. IFAST WP11.2

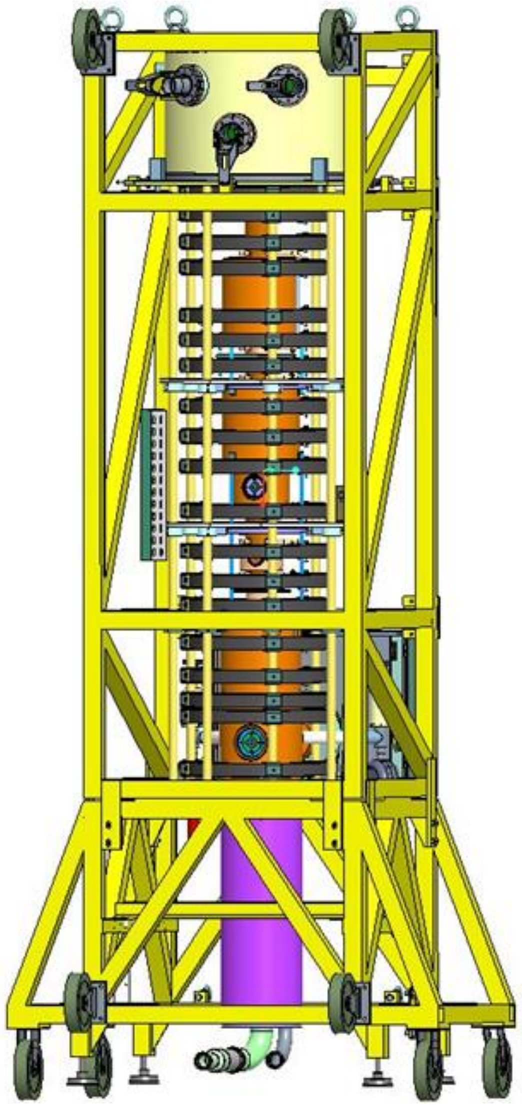
N.Catalan-Lasheras

- Design and build an industrial prototype of the LHC klystron reaching 70% efficiency, in collaboration with THALES.
- In order to control the costs, the choice was made to retrofit the existing LHC klystrons, TH2167, with the aim of reusing some components (e.g. solenoid).
- Expected gain in DC to RF conversion efficiency: **+ 10 - 15 %**



Armel Beunas (Thales) et al, Replacement Klystron for LHC

- New 6 cavities CSM structure designed by CERN with predicted efficiency > 68-70% (KLYC and CST3D).
- Still some reflected electrons predicted by KLYS2D PIC code below saturation. Additional CST3D simulations to be performed to confirm or not.
- Electrons backstreaming can be mitigated by adjusting focussing coils current; likely to use a second power supply to optimize magnetic field at the output cavity.
- Larger collector implemented to increase safety margin.
- Mechanical design of the pumped tube nearly completed.
- High efficiency TH2167 version will be a CSM proof of concept device



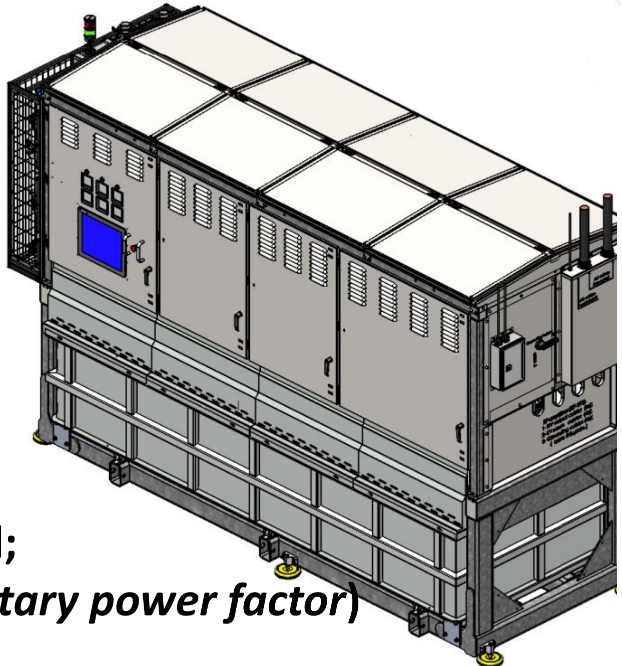
C.Martins, Result of modulator optimization process: larger, more economic units

SML Modulator main features and performance

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

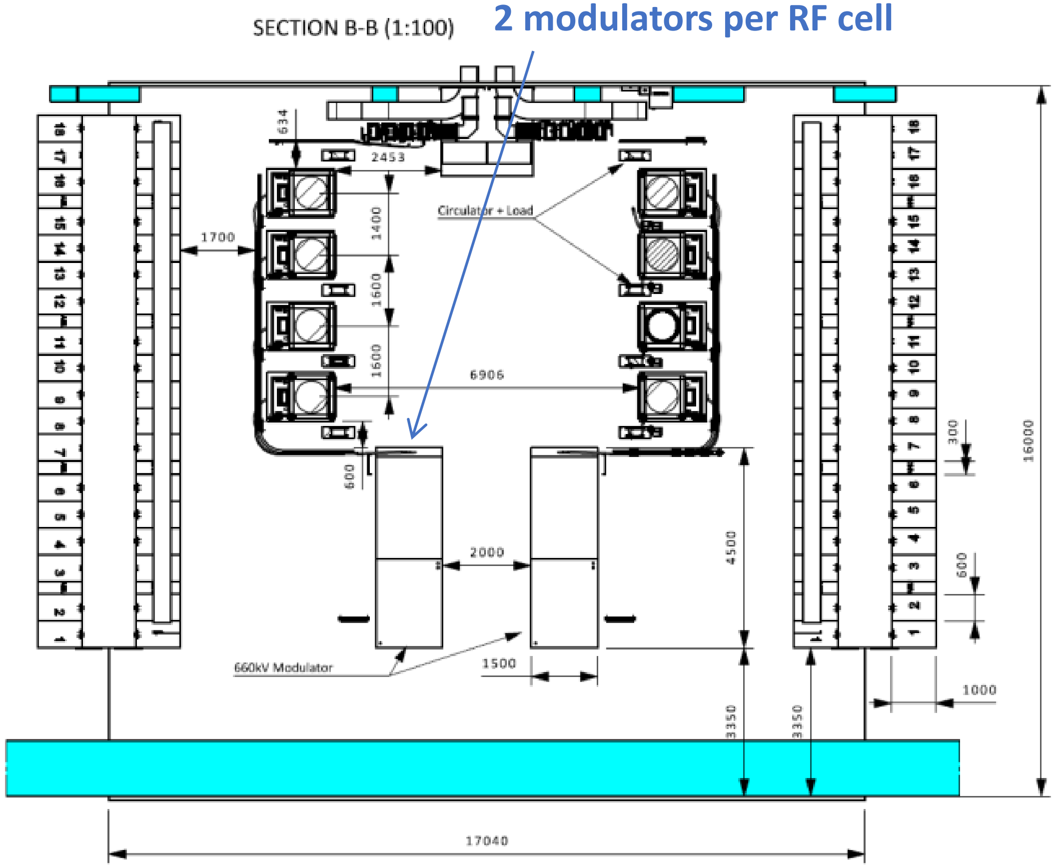
Demonstrated Performance:

- **Rise time = ~180µs;**
- **Flat-top droop < 1%;**
- **Flat-top ripple < 0.2%$_{pk-pk}$**
- **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**



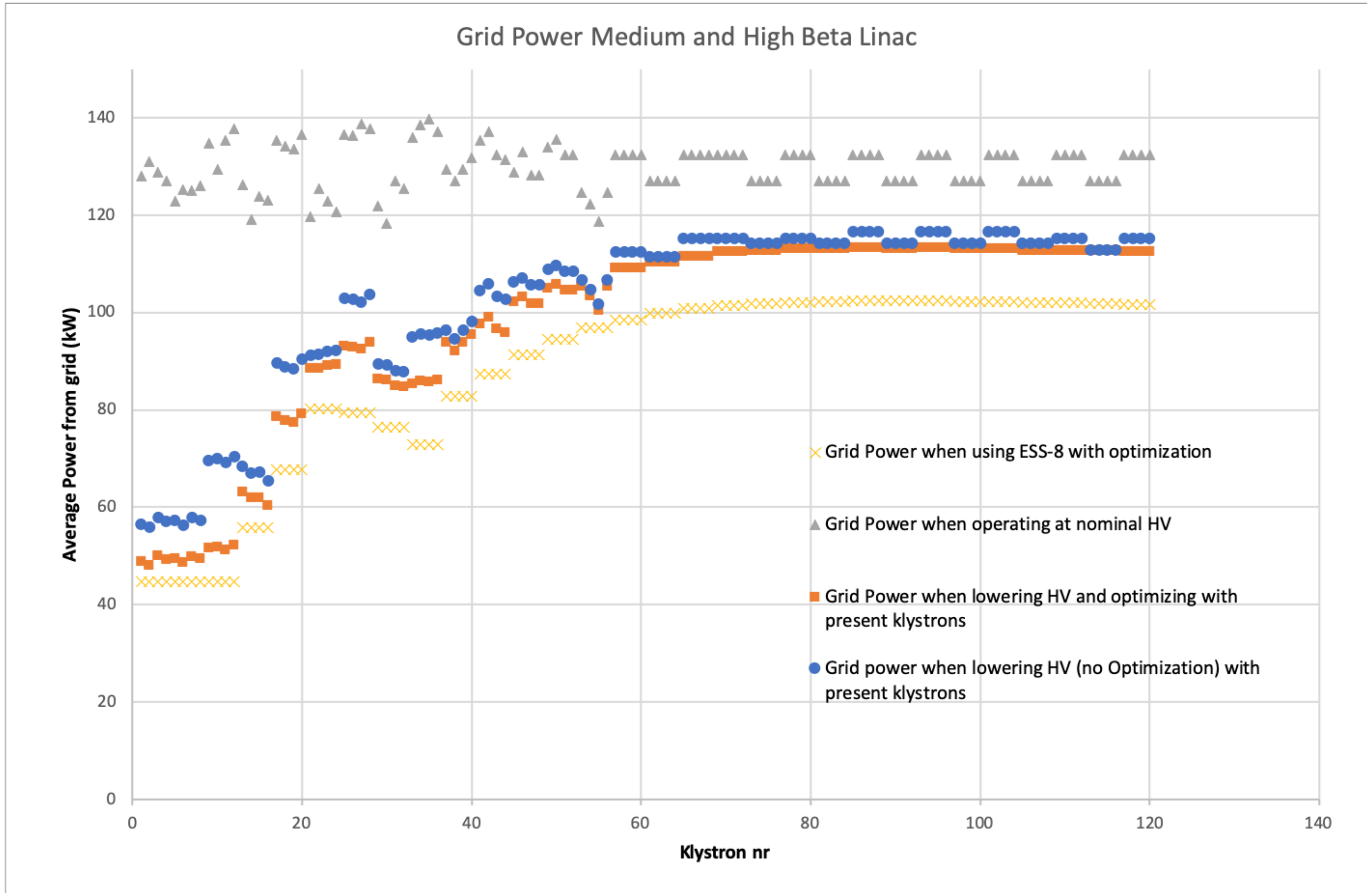
C.Marrelli, possible high efficiency klystron scenario for ESS

Medium and High Beta klystrons

Savings going to HEK

Savings/year going to ESS-8 HEK:
594 k€/year
(compared to current klystron optimized for low power)
…probably more if the price of electricity goes up….

Savings/year compared to operation with current klystrons at nominal HV: 2475 k€/year

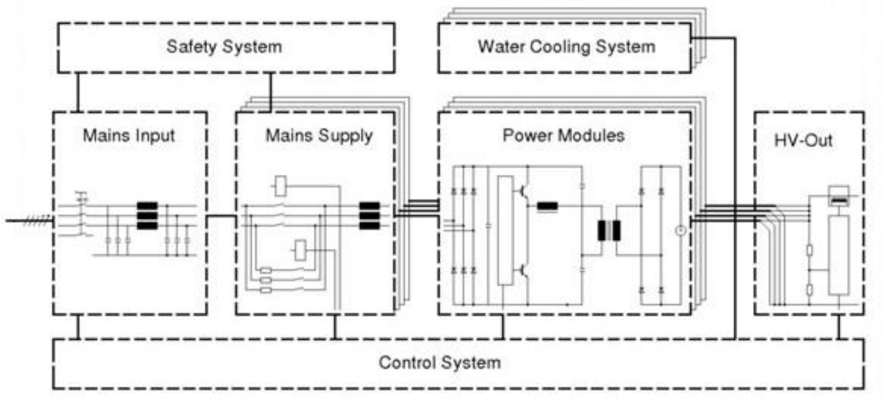


Max Collins, ESS Modulator Efficiency

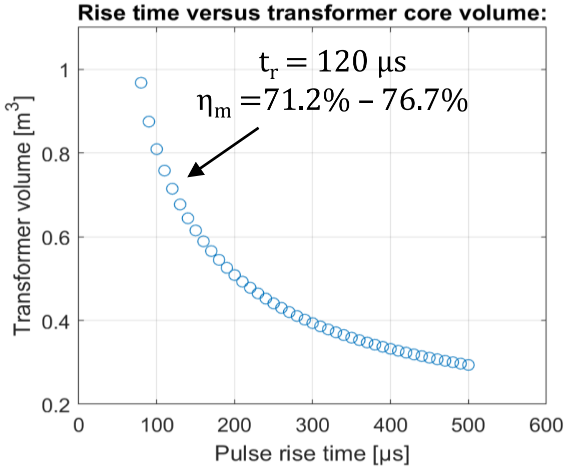
- Modulator efficiency for pulse transformer-based modulators in long pulse high power applications:
  $\eta_m = f(\eta_e, t_r) = \{ t_r = 120\ \mu s \} = 71.2\% - 76.7\%$

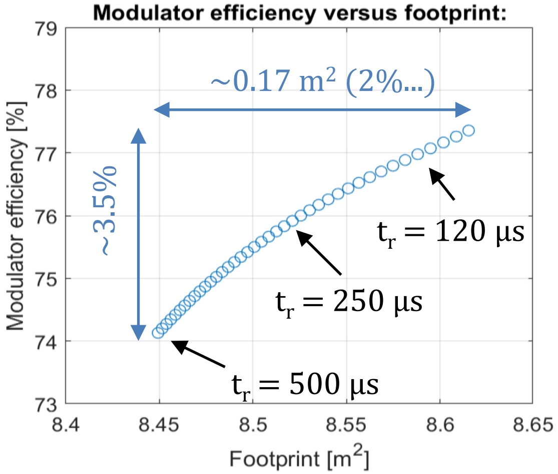
capacitor chargers are a strong driver of both modulator size and efficiency

- Improve electrical efficiency?
  - Chargers- consider <u>customized charger design</u>? Impact on size? Reliability? Still- medium voltage capacitor chargers require at least 4 conversion stages… ?
  - Switch? ✗
  - Bouncer? … +0.5% at the expense of doubling the size of the capacitor bank
  - Pulse transformer? ✗



- Improve (shorter) rise time?
  - The existing rise time already severely limits the number of turns, requiring a very large transformer magnetic cross-sectional area.. ✗

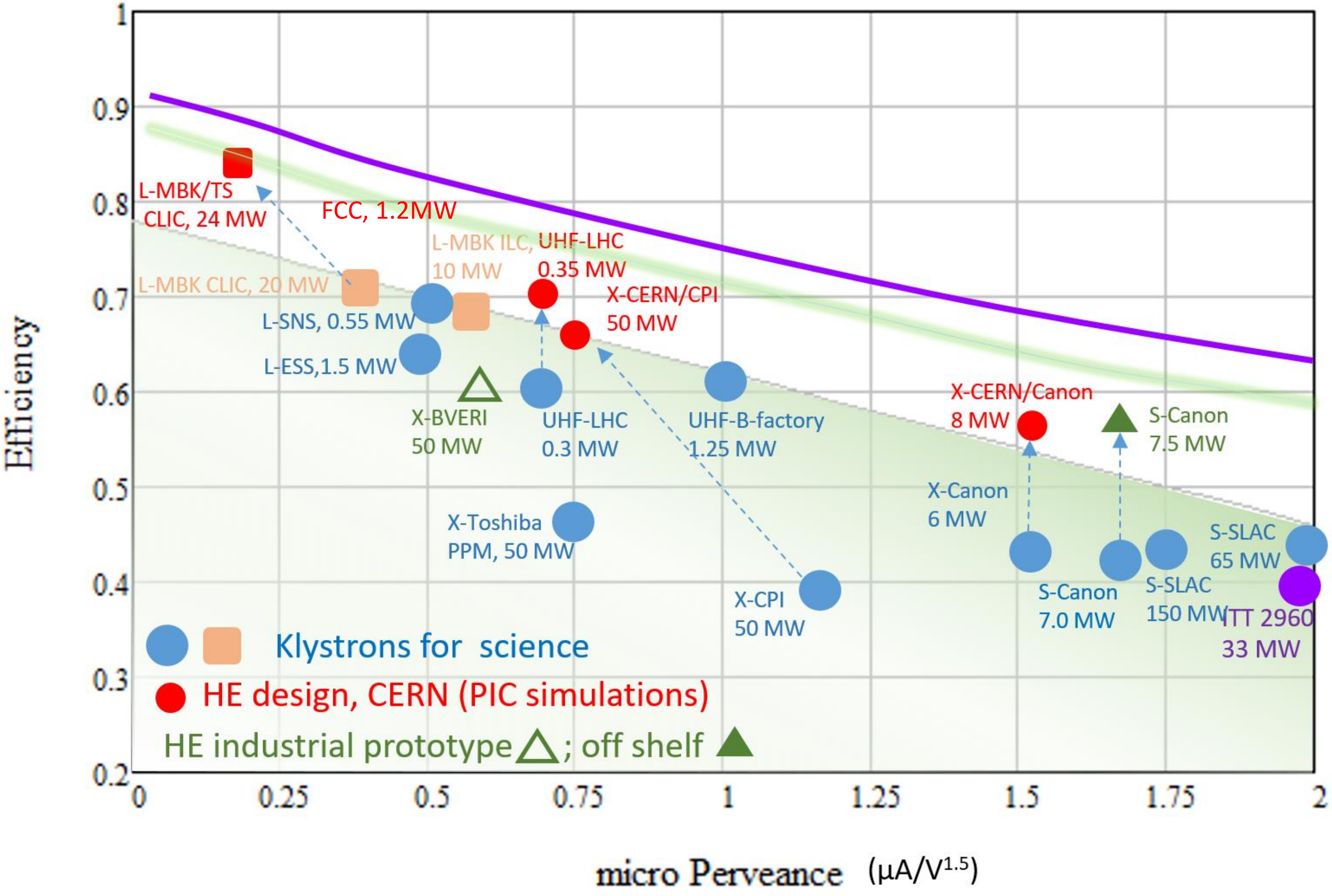




allowing a longer rise time simplies transformer design, but represents a modest reduction in footprint and at a severe reduction in modulator efficiency..

I.Syratchev, High efficiency klystron technologies

Efficiency performance of the selected commercial klystrons and the new HE klystrons.



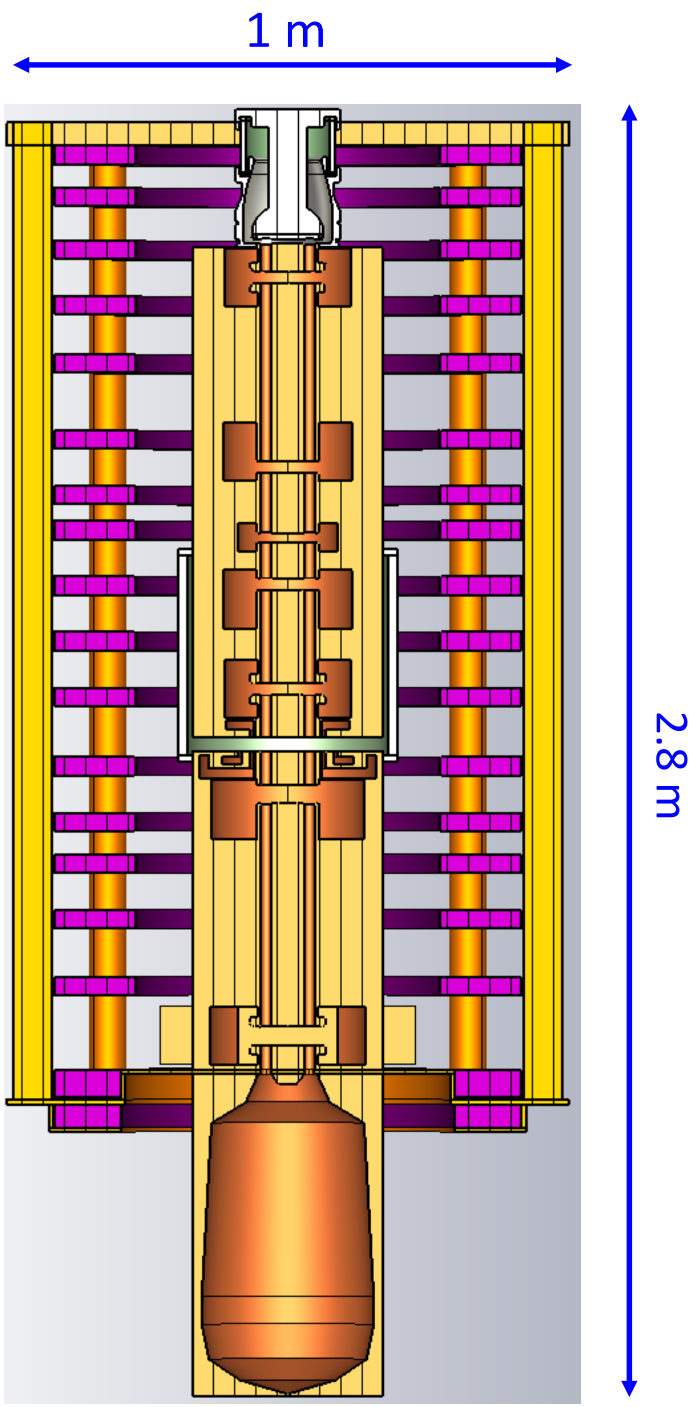
klystron talks, Tu

09:00	**HE klystrons technologies**	*Chateau de Bossey*
	Review of computer codes for the klystrons design	*Chateau de Bossey*
10:00	**FCC HE TS klystron development**	*Chateau de Bossey*
	Coffee Break	*Chateau de Bossey*
11:00	**CSM HE LHC klystron. THALES**	*Chateau de Bossey*
	50 MW Xband HE klystron program. CPI	*Chateau de Bossey*
12:00	**CEPC high efficiency klystron status**	*Chateau de Bossey*
	X-band HE klystron development. Canon Electron Tubes & Devices	*Chateau de Bossey*

Zaib Un Nisa et al, Innovative two stage CW klystron

Design Parameters for TS MBK for FCCee

Parameters	Design Target	KlyC	CST
Frequency (GHz)	0.4	0.4	0.4
Voltage (kV)	58	58	58
First stage (kV)	10-20	11.5	11.5
N beams	10	10	10
Total Current (A)	27	27	27
Output Power (MW)	1.2	1.28	1.2
Efficiency (%)	80	80.6	79
Tube length (m)	<3	--	2.8



E.Montesinos on CERN experience with Tetrodes

Regarding the frequency range & regarding the power range

If **AVAILABILITY** of the machine is the key criteria

Tetrodes are a good choice

- Multi tubes solution for redundancy operated at a lower power, lower efficiency with nevertheless a very correct final overall cost

If EFFICIENCY is the key criteria

- Regarding the arrangement choices, Tetrodes can be operated 60-70 % overall efficiency in operation

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C.Marrelli on ESS experience with IOTs

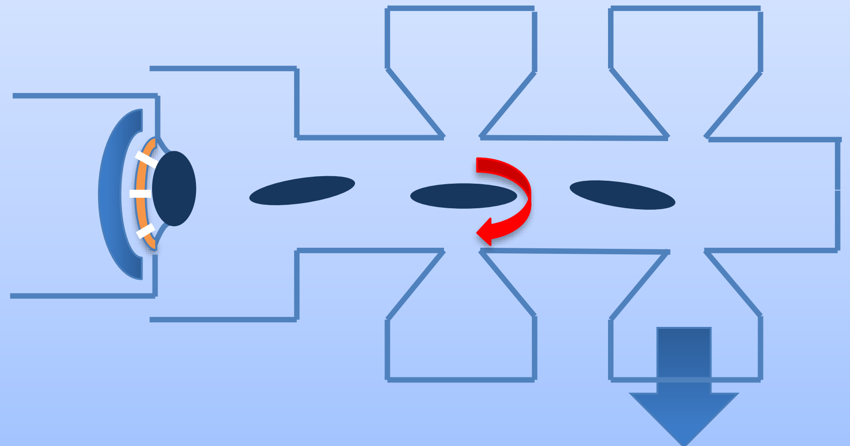
- IOT is an efficient power source, especially when considering the operational efficiency
- High power limitation can be somehow overcome by the use of MB IOT
- The MBIOT development for ESS was **successful but not mature enough for the ESS timeline**
- The technology is however now available for other users!
- Further improvements are possible: High efficiency klystron research can be applied to IOTs as well to increase the efficiency even more.

What else could we achieve?

- More power
- Higher efficiency
- Better reliability
- Smaller footprint, etc.

- High voltage, 1 MW, single cathode
- 10 MW MBIOT by combination of 1 MW tubes

Grid controlled emission with bunch forming cavities
HE-IOT (from 75% to…. 90%)
Grid controlled emission + "rotating" cavity + output cavity

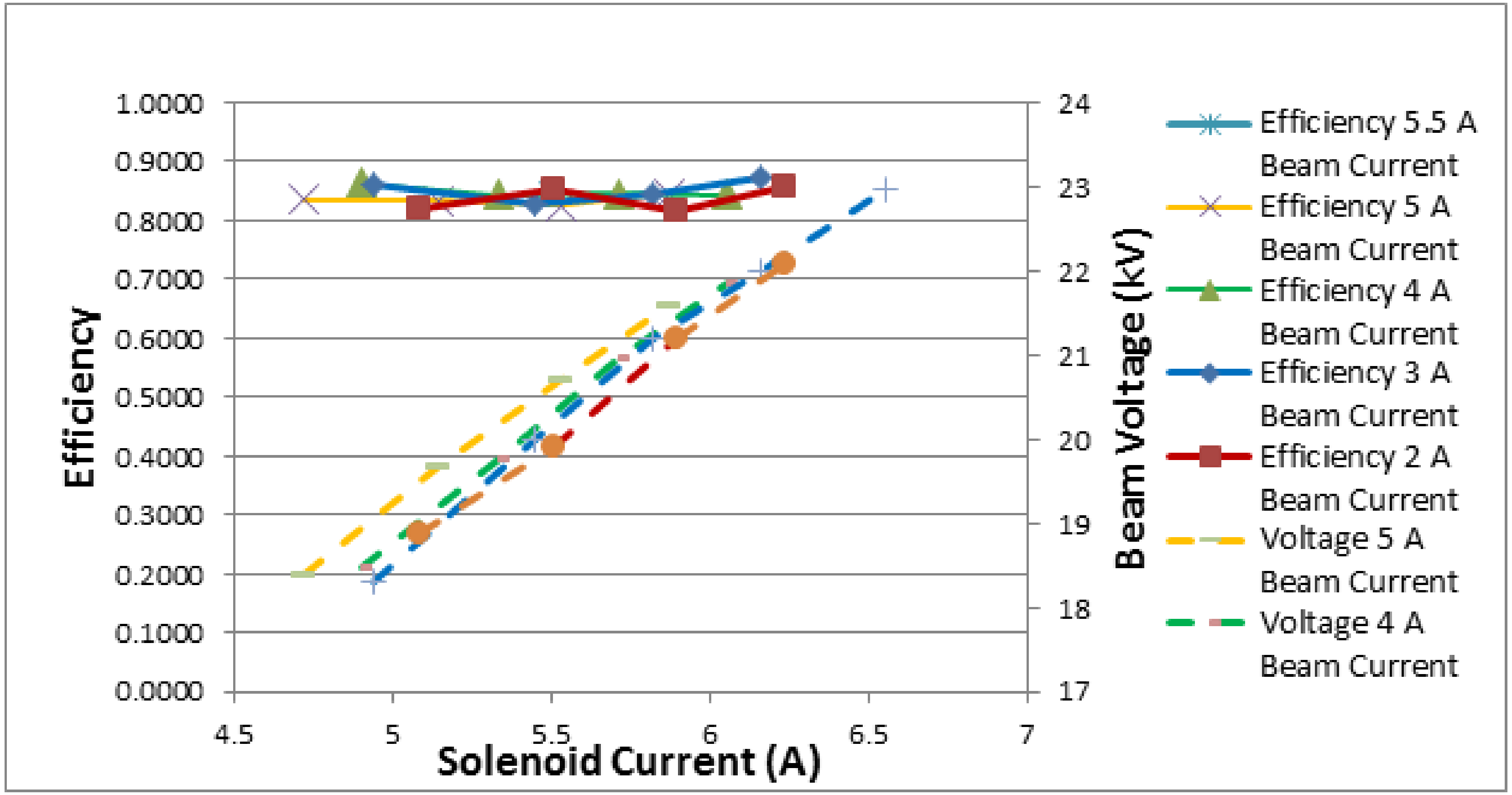


Lawrence Ives, Calabazas Creek Research, High Efficiency RF Source Development

A 100 kW 1300 MHz **magnetron** with 10% duty

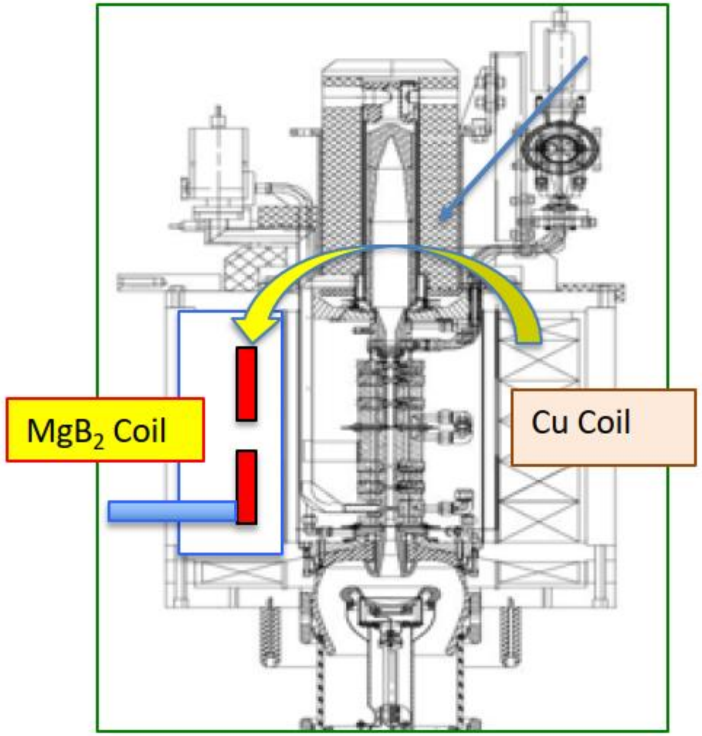
collaboration with Fermilab

Efficiency varied between 81% and 87%, depending on parameters



Marçà Boronat, s.c. solenoid for Klystron

- Proposal from A. Yamamoto (KEK) to build a superconducting solenoid that could be tested and operational on the CERN X-band facility
- The required magnetic field is well below 1T so we can use MgB_2 working below 30 K to improve the cryocooler efficiency ad minimize costs



Coil technology	Unit	Cu	MgB_2
Central field	T	0.6	0.8
Current	A	2x300	57
Voltage	V	35	0
Cooling method		Water	Cryo-cooler
Temp	K	300	~25
Wall plug power	kW	20	<3

A. Yamamoto et al., "Applying Superconducting Magnet Technology for High-Efficiency Klystrons in Particle Accelerator RF Systems", IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-4, Jun. 2020.doi:10.1109/TASC.2020.2978471

M.Diop, SOLEIL, SR SSPA's Operational Results

4 x 200 kW SSPA's
- Investment cost = 3 M€ + 350 k€ for refurbishment
- Operational cost = 400 k€ per year → 6 M€ from installation
- Maintenance annual cost = 5 k€

MTBF & beam downtime, cumulated by the 4 SR SSPA's over ~ 95 000 running hours in ~ 15 years

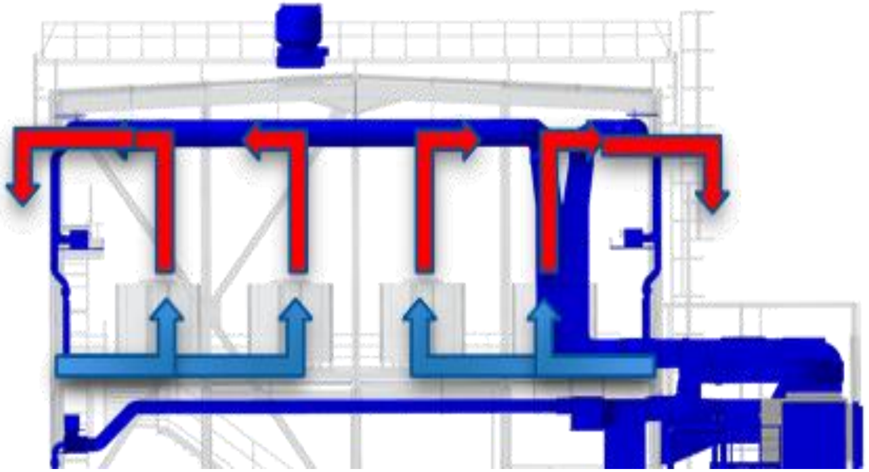
Equipment	MTBF	Downtime	Comments
a) 4 x RF amplifiers	~ 13 500 h	~ 8.10^{-5}	Failures from preamplifiers and 1st stage combiners (solved) + supervision issues
b) 4 x Power supply 500 kVA thyristor-based with 680 DC/DC converters	~ 6 300 h	~ 3.10^{-4}	Single rectifier per amplifier + aging DC/DC converters
a) + b) 4 x RF transmitters	~ 4 300 h	~ 4.10^{-4}	

Already excellent MTBF and operational avaibility, but still perfectible by :

1) Providing some **more redundancy in the ac-dc power conversion**, which originally consists in a single 500 kW rectifier per SSPA and DC/DC converters
2) **Upgrading the amplifier supervision system**

→ **Cures for these "weaknesses" in our new design**

E.Montesinos,
CERN SPS SSPA
high efficiency in reach



Cavity = 1 MW

20 m coaxial line = + 1 % = 1.010 MW

NO Circulator = 1.010 MW

VHPCC 16:1 = + 0.1 dB = + 2,5 % = 1.035 MW

DC to RF (efficiency ~ 66 %) = 1.590 MW

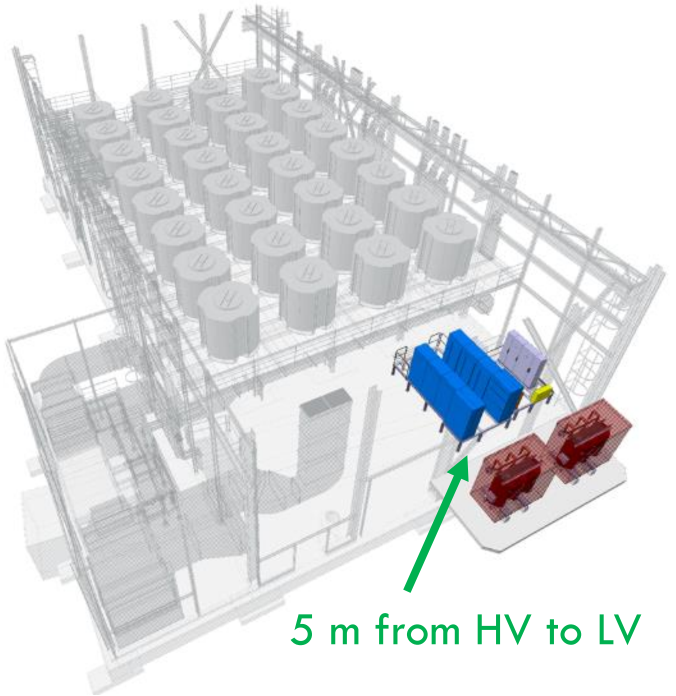
AC to DC (efficiency ~ 95 %) = 1,625 MW (590 kW to be dissipated)

Air cooling station (10 % of ~~615 kW~~ 590 kW ~ 60 kW) ~ + 27 kW = 1,652 MW

Water cooling station (90 % of ~~615 kW~~ 590 kW ~ 530 kW) ~ + 24 kW = 1,676 MW

El. distribution (~~5 % of 1,709 MW~~ 3 % 1,676 MW) ~ + 50 kW =
1,7 MW taken from the grid

Overall efficiency **58,8 %** 41,9 %



Taking advantage of the natural chimney effect of the tower, having a well defined water station (variable speed), and shortening the LV cables will help reducing the remaining losses

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Dragos Dancila, Ongoing SSPA projects at FREIA*

- 352 MHz
  - 400 kW 10% DC – prototype fabrication – VR project
- 704 MHz
  - 1 kW CW – conceptual level - MYRRHA
- 750 MHz
  - 1 kW CW – 200 W module in GaN technology for EU I.FAST project
- 3 GHz
  - 400 W pulsed – AWAKE project (plasma wake field accelerator) – klystron driver
- 12 GHz
  - 1000 W pulsed – AWAKE project (plasma wake field accelerator) – klystron driver

* in yellow, new GaN based developments

Take advantage of the ideas presented and the contacts made.

Thank you for participating and presenting your work.

Many thanks to our hosts Nuria and Igor for selecting the Chateau de Bossey and for organizing this

Workshop on Efficient RF Sources.