Tetrodes for FREIA & ESS Spoke Linac: An Efficient Choice !

Rutambhara Yogi

Many thanks to

- ✓ Suppliers:

THALES — CPI Communications & Power Industries — TOSHIBA

SIEMENS RESEARCH CENTER — electrosys

- ✓ Colleagues:

ESS: David McGinnis, Anders Sunnesson, Morten Jensen, Carlos Martins, Rafael Montano, Anders J Johansson Rihua, Daniel Lundgreen, Carl Johan Hardh

FREIA: Rolf Wedberg, Lars Hermansson, Konrad Gajewski, Tord Ekelof, Volker Ziemann, Roger Ruber

CERN: Eric Montesinos

EUROPEAN SPALLATION SOURCE

Efficiency

$$\uparrow \eta = \frac{Aimed\ Output}{Required\ Input} \downarrow$$

Input = f (time, manpower, expenses, effort, energy resources)

$$energy\ efficinecy = \frac{Aimed\ output}{Required\ energy\ input}$$

Why energy efficiency?

Reduces energy costs (running cost)and hence result in cost saving

New developments for energy efficient technology : Growth of technology

Green facility: Reducing energy usage helps in reducing carbon dioxide emissions.

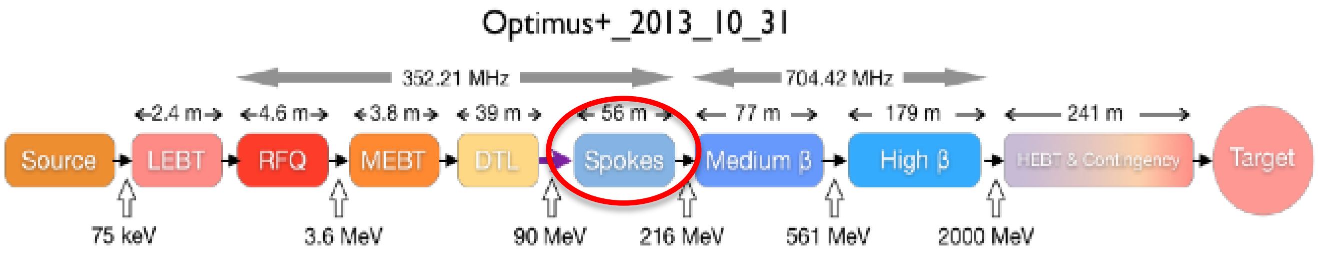
Developing facilities think about Energy Efficiency !

Europe's one of the largest infrastructure ESS (European Spallation Source)

Being constructed in Lund, Southern Sweden

← ESS group of flags:
> 26 Nationalities

ESS Superconducting Linac



Long pulsed superconducting linac

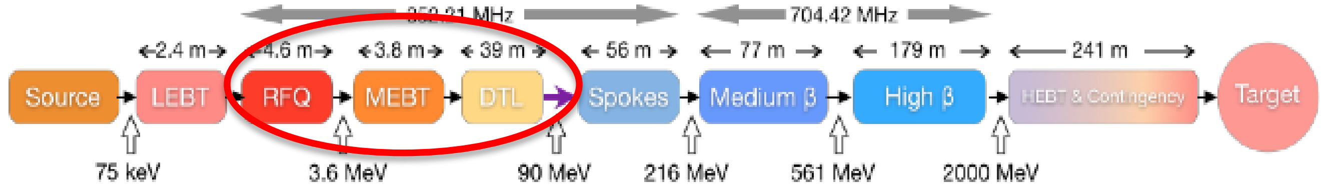
Average proton beam power to the target = 5MW

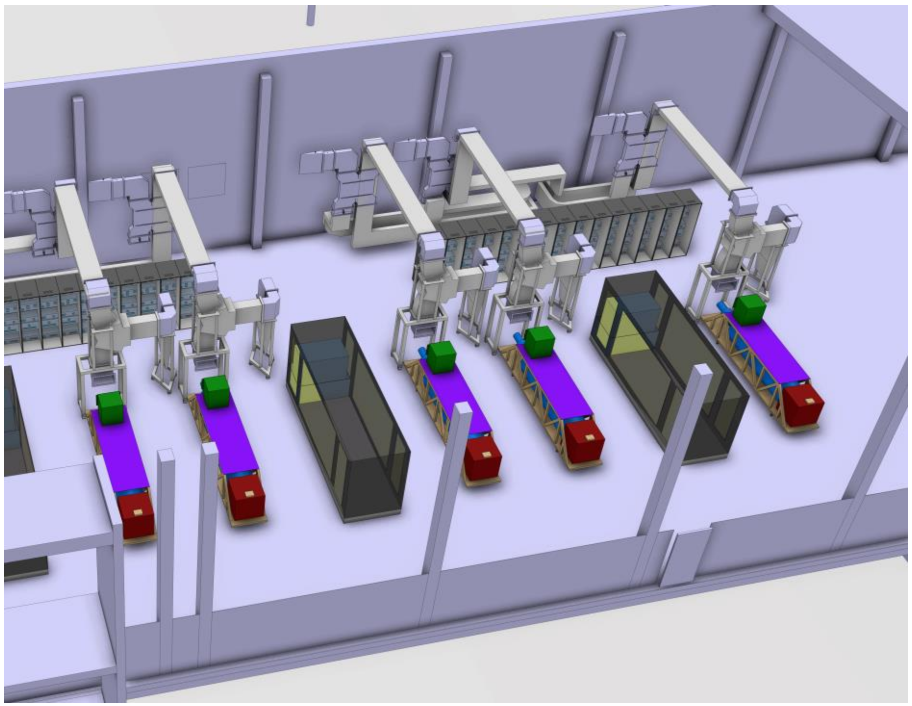
Most intense pulsed neutron source in the world : proton beam power larger by factor 5 compared to existing spallation facilities

Number of RF systems:150 !
One RF source per cavity : 150 RF sources !
Cost of RF systems > 200 MEUR

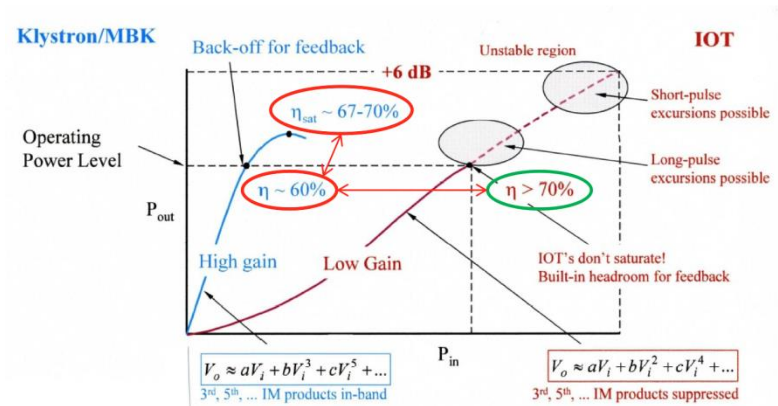
Warm linac

Optimus+_2013_10_31





Frequency = 352.21 MHz
Power = 2.8 MWp
Avg power = 150 kW
Pulse width = 3.5 ms
Pulse repetition rate = 14 Hz



Available. Proven. So Input (time, NRE expenses, effort) ↓

Hence η more

Energy efficiency for Warm linac

η of klystron = 50 %

$P_{dc} = P_{avgRF} / \eta$ = 140 kW / 0.5 =280 kW

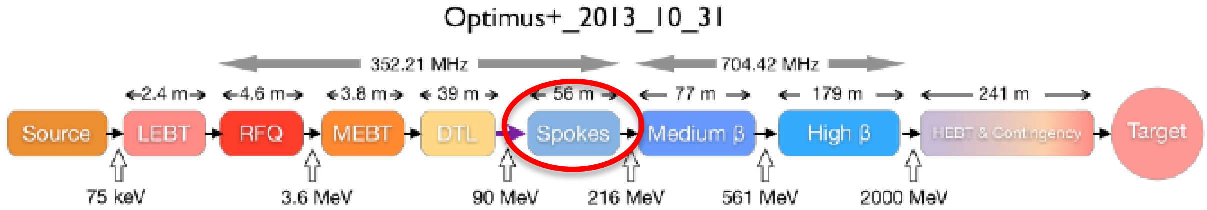
$P_{collector} = P_{dc} - P_{avgRF}$ = 140 kW   Dissipated in Collector

This energy is used to heat water for Lund city.

ESS plans to *recycle waste heat* to the Lund district heating network, supplying 20 percent of its total annual requirement.

Lund city will provide water at three temperatures 5 C, 25 C and 50 C, ESS will provide hot water at 80 C

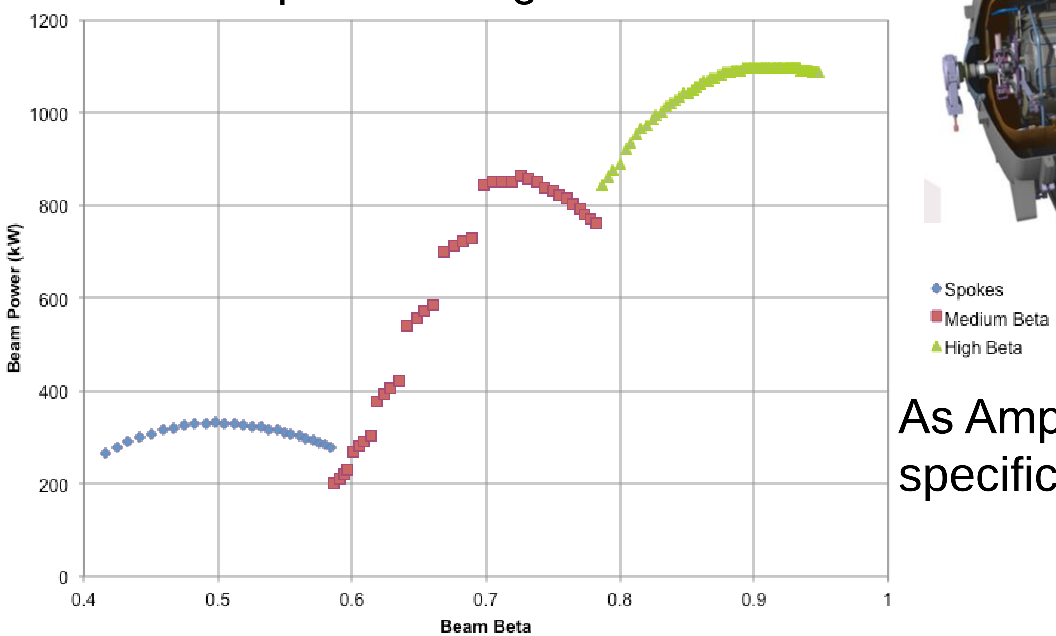
ESS Superconducting Linac

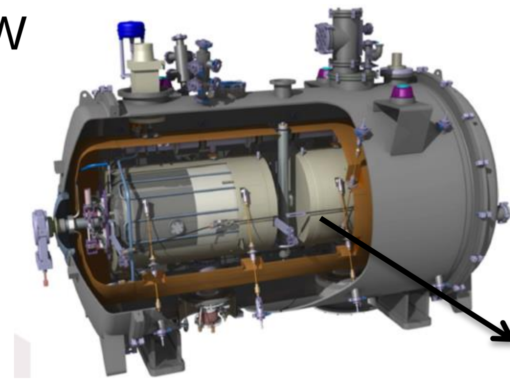


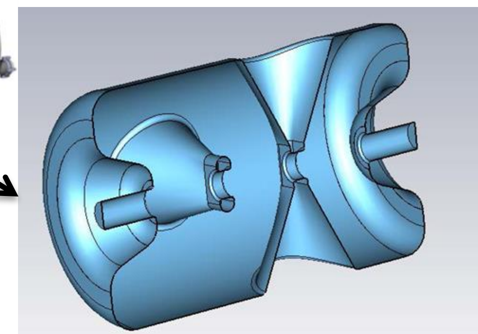
Frequency = 352.21 MHz
Number of spoke resonators = 26
Maximum power coupled to beam = 330 kW

Courtesy: Sabastien Bouson (IPN Orsay)

Power profile along ESS linac



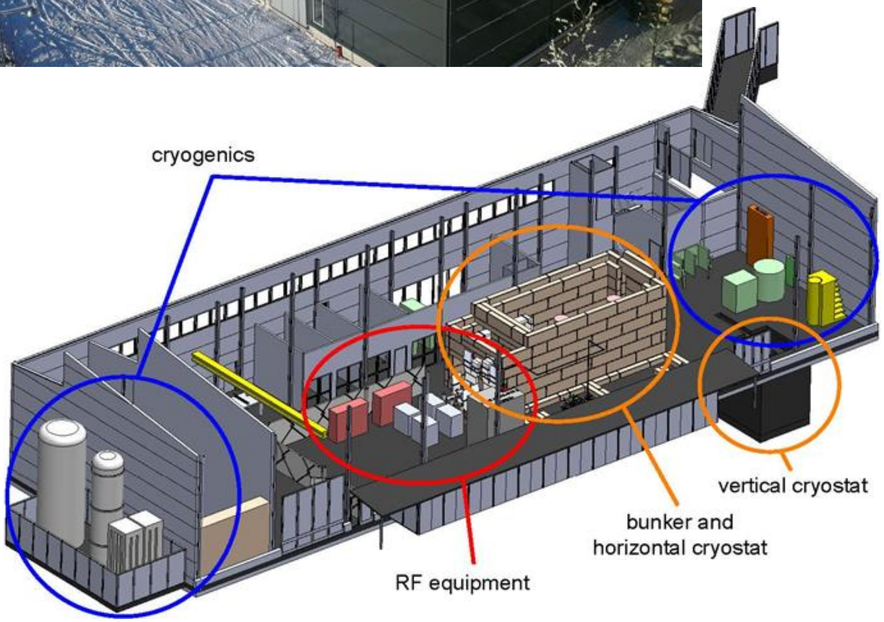




As Amplifier doesn't exist at ESS specifications ⟶ Technology demonstrator

FREIA Laboratory

Facility for Research, Instrumentation and Accelerator Development



ESS related RF Development at FREIA:

- Development of Spoke Linac Amplifier
  - Technology demonstrator: (Tetrode)
  - Testing of Solid State Amplifier
- Design of RF Distribution system for ESS Linac
  - Technology demonstrator for Circulator at 352 MHz, 400 kWp
- High power testing of spoke prototype cavity
- Acceptance test for spoke crymodules at high power (proposal submitted)

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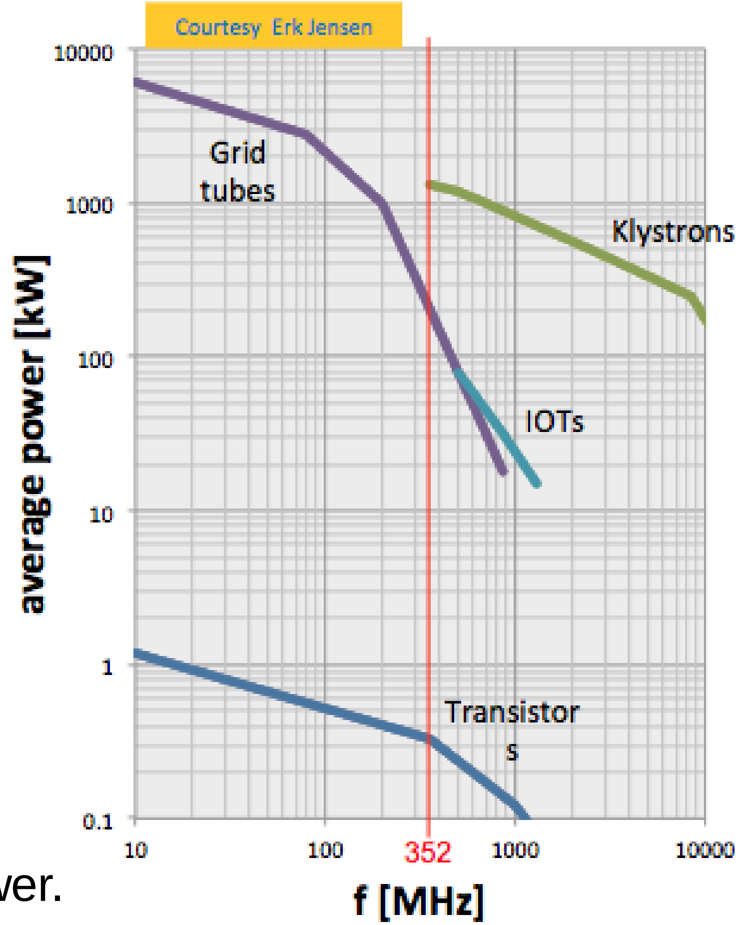
Calculation of Amplifier Power

- Maximum RF power coupled to beam = 330 kW
- Considering LLRF overhead = 15%
- RF loss in distribution system = 5%,
  Power of RF source = 390 kW ≈ 400 kW
- Beam pulse width = 2.86 ms, repetition rate = 14 Hz,
  Natural fill time = $t_f = 2Q_L / \omega$ = 135 µs, ($Q_L = 1.5 \times 10^6$)
  RF pulse width = 3.1 ms
  Duty factor of the amplifier ≈ 4.28 %
- Spoke cavity band-width = 2.34 kHz
  system band-width ≈ 100 times larger than spoke resonator
  band-width for tuning and regulation delay.
  3 dB bandwidth > 250 kHz.

Possible Amplifier Technologies

Tetrode, Klystron, solid-state, IOT

Comparison of all possible technologies and selection Tetrode for the first RF power station at FREIA



Solid state technology:

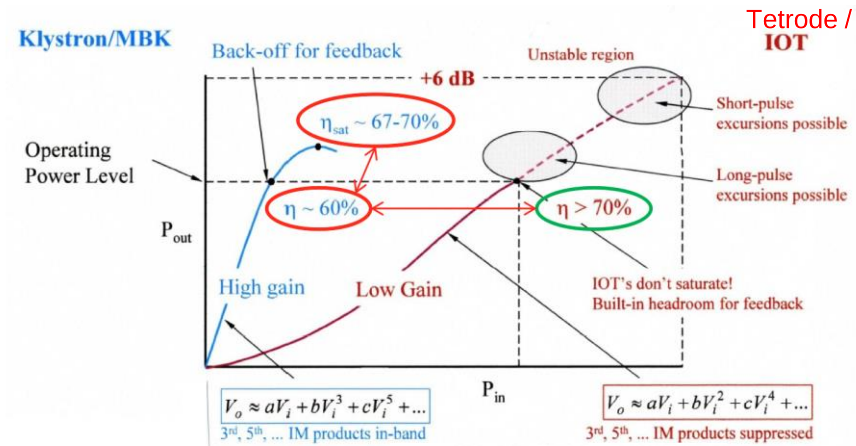
Siemens are developing 400 kW@ 352 MHz to be tested at FREIA.
According to updated schedule – delivery Q4 of 2014 (**Study from ESS point of view is ongoing**)

IOT:

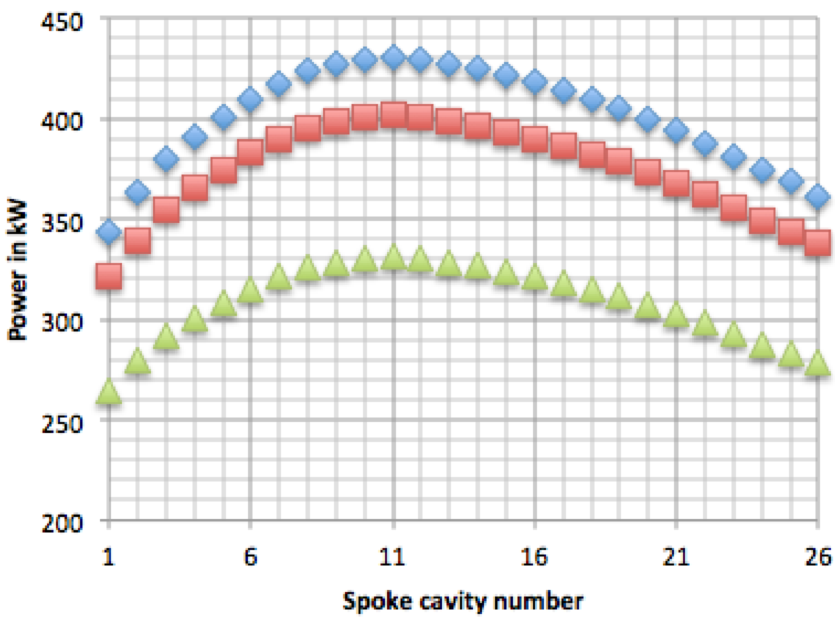
Single IOT delivering 400 kW doesn't exists.
Combine 4 IOTs of 100 kW to deliver 400 kW power.
Foot print – 3.8 m x 3.8 m Will not fit in ESS gallery

Required Tetrode Power

LLRF overhead:
Reactive beam loading, Lorentz force detuning, variation in Q_L, Beam current fluctuations, variations in cavity parameters, back-off for feed-back



Courtesy Heinz Bohlen



LLRF overhead:
For klystron: 25 %
For Tetrode: 15 %

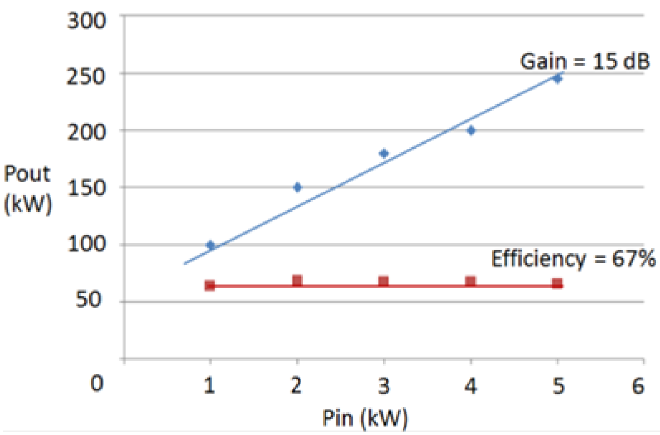
RF Loss overhead = 5%

- : Klystron amplifier power
- : Tetrode amplifier power
- : Power to beam

Requirement of power is lower for tetrodes ↗

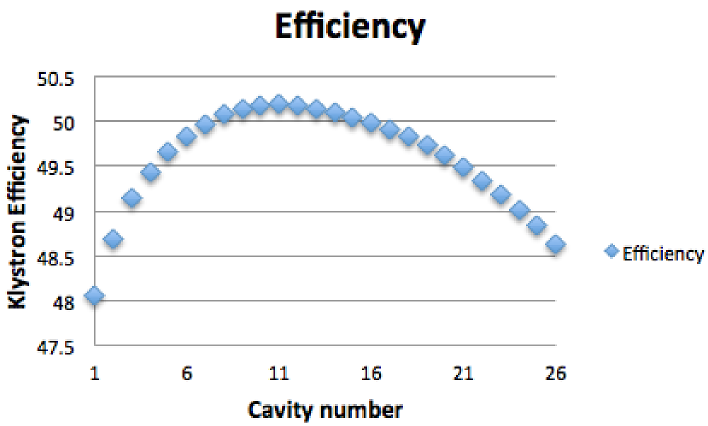
Tetrodes are more efficient !

Running cost for 25 years of operation



Tetrodes: HV efficiency 67 %

Variation of Amplifier efficiency with cavity number



Klystron: Predicted HV efficiency : 48 – 50 %

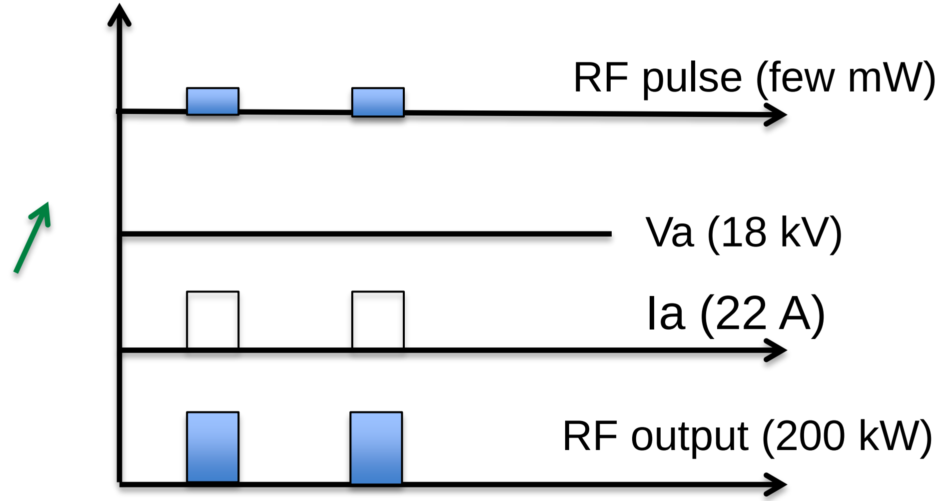
For ESS,
Cost of electricity = 0.05 EUR/kW-hr

Operational cost for Tetrodes less by few MEUR

Pulsing of Tetrode

Tetrodes:

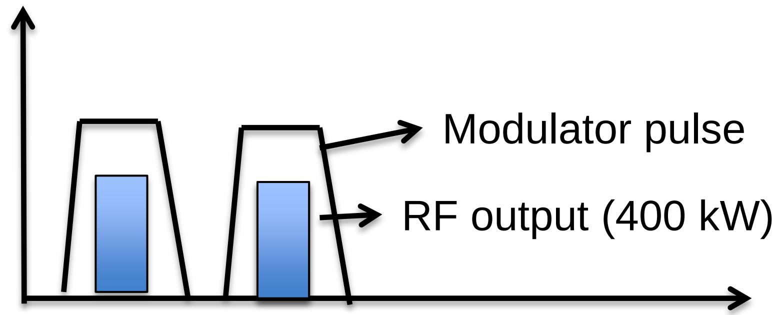
Pulse via RF drive, reduce wall plug power, improve wall plug-rf efficiency



Klystrons

HV supply (Modulator): pulsed, 70kV, 10.1 A
Pulse via Modulator, extra rise time losses

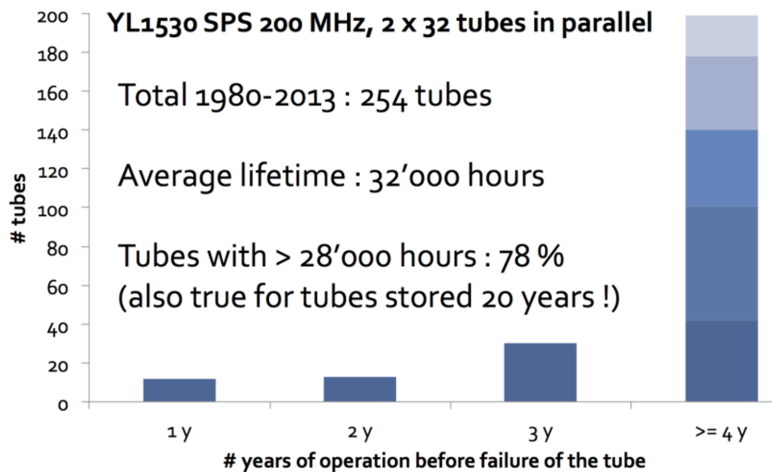
Reduce wall plug-rf efficiency



Tetrodes !

Replacement Cost for 25 years of operation (25 x 6000 =150 000 hours)

Tetrode	Klystron
Life time: 20 k hours	Life time: 70 k hours
Cost: x kEUR	Cost > 15x kEUR
Replacements: 14	Replacements: 2

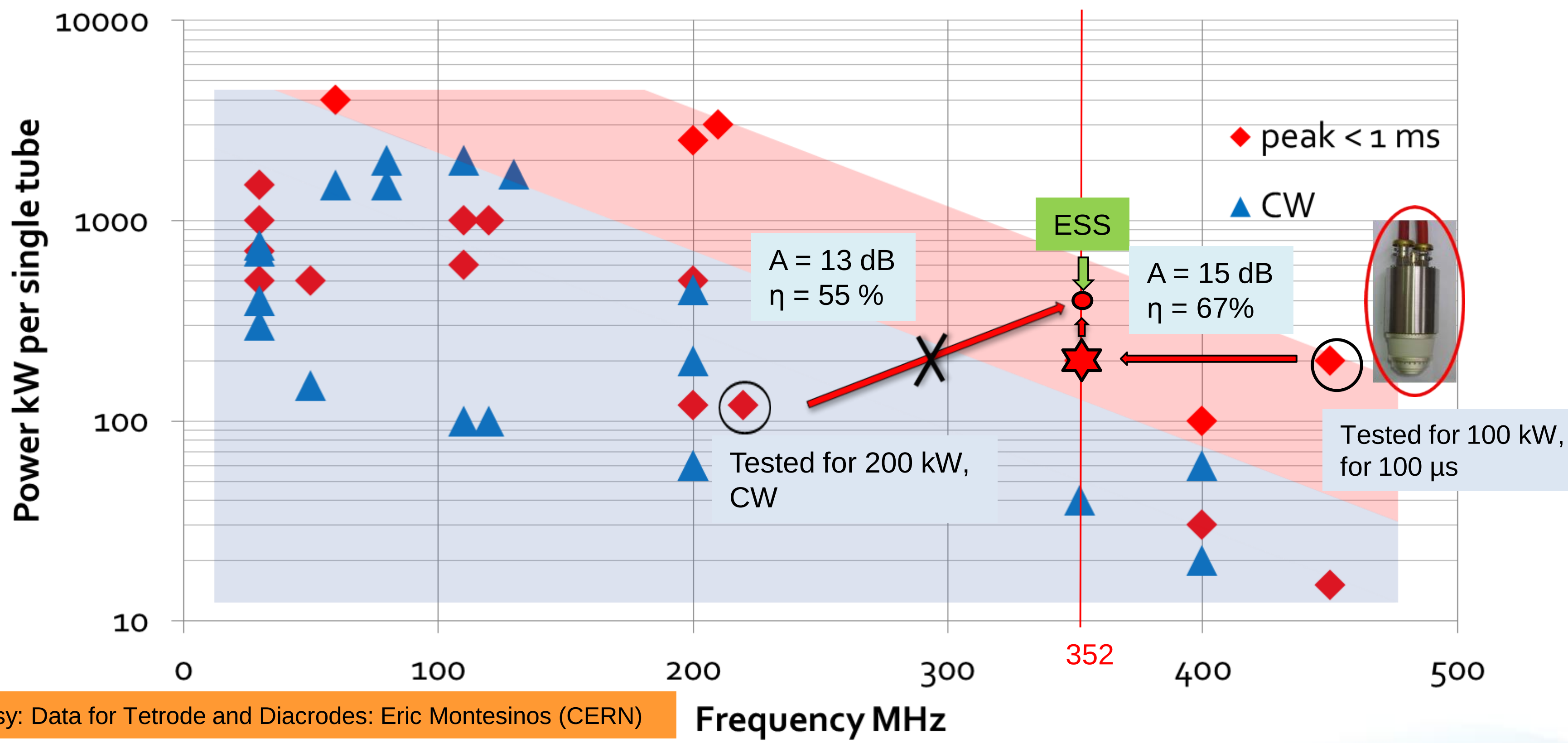


Courtesy: Eric Montesinos (CERN)

Cost of replacements for tetrodes is less by few MEUR

* Maximum two replacements of klystron with refurbishment are possible.

Tetrodes & Diacrodes available from industry



Courtesy: Data for Tetrode and Diacrodes: Eric Montesinos (CERN)

Selection of Tetrode at ESS Specifications

Peak power = 400 kW
Avg power = 20 kW

Pdc = Avg power / η

TH781	TH595
High Voltage η = 55 %	High Voltage η = 67 %
Pdc = 36.36 kW	Pdc = 29.85 kW

First time
Reported by me

Diff in DC power = 36.36 kW – 29.85 kW = approx. 6 kW

Energy diff per year for Spoke linac
= 26 x 6 kW x 6000 x 3600 sec = 3369.7 G joule
= 30% of the average RF Energy provided by spoke linac per year

Cost diff per year = Energy diff per year for Spoke linac x 0.05 EUR /kW-hr =46.8 kEUR

Cost diff for 25 years > 1 MEUR

Thus TH595 is selected !

Tetrode: Baseline design for ESS Spoke Linac

Tetrode RF power station will be tested in FREIA in 2014, klystrons at ESS
Specifications is not existent

FREIA will get second RF power station by Q4 of 2015, ESS Amplifier

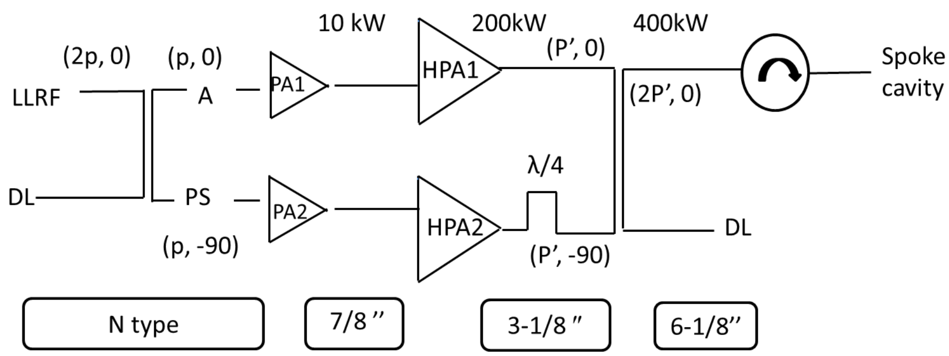
Tetrode solution has lowest technical and schedule risk

Working to lower the capital cost !

Considering all the costs (capital cost, replacement cost, operation cost), tetrode solution cheaper.

Initial cost of ESS accelerator = 1840 MEUR
Tetrode solution is cheaper by about 0.3 % of ESS accelerator initial cost.

Specifications:
Frequency = 352 MHz
Peak power = 400 kW
Average power = 20 kW
Pulse width = 3.5 ms
Pulse repetition frequency = 14 Hz



Schematic of RF Power Station Layout

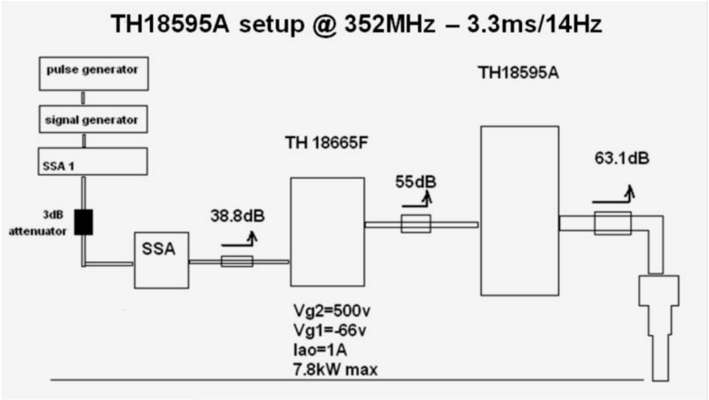
Test results of Technology Demonstrator

VA (kV)	12,0	14,0	15,3	16,0	17,8
VG2 (V)	900	900	900	900	900
VG1 (V)	-170	-200	-200	-200	-200
IA0 (A)	0,2	0,0	0,0	0,0	0,0
IA (A)	13,0	15,8	17,6	18,7	21,0
IG2 (A)	0,11	0,16	0,21	0,24	0,34
IG1 (A)	0,70	1,00	1,30	1,50	2,10
Pout (kW)	**100**	**150**	**180**	**200**	**245**
Pin (kW)	2,9	4,6	5,8	6,3	7,8
G (dB)	15,4	15,1	15,0	15,0	15,0
ηA (%)	64	68	67	67	66
pulse time (ms)	3,300	3,300	3,300	3,300	6,600
p.r.r. (Hz)	14	14	14	14	7
duty factor	4,6%	4,6%	4,6%	4,6%	4,6%

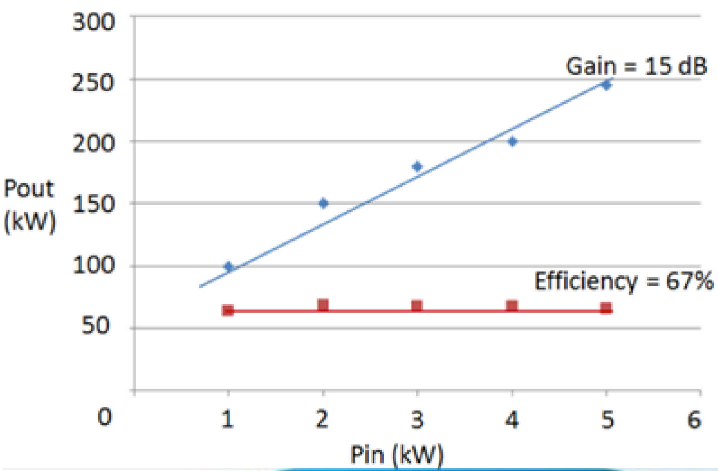
IA, IG2, IG1: during pulse

For all tests: Filament: VF = 7,7 V, IF = 175 A
Frequency: 352 MHz
Transmission bandwidth (-1 dB): 7,3 MHz

Harmonics (200 kW): H2: -35 dB
H3: -38 dB
H4: -34 dB



THALES

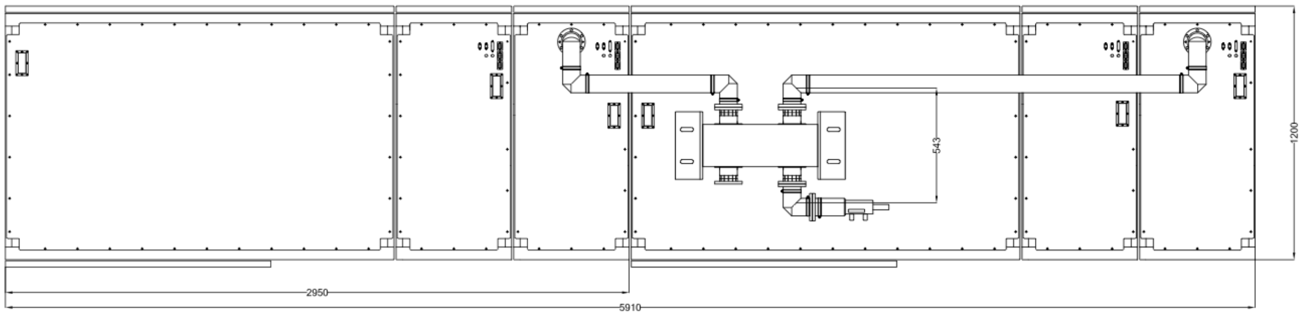


Thus TH595 is selected for first RF Power Station at FREIA !

Tetrodes : Available
Cost (Cheapest)
Energy efficient
Less efforts required

Efficient choice for FREIA and ESS Spoke Linac !

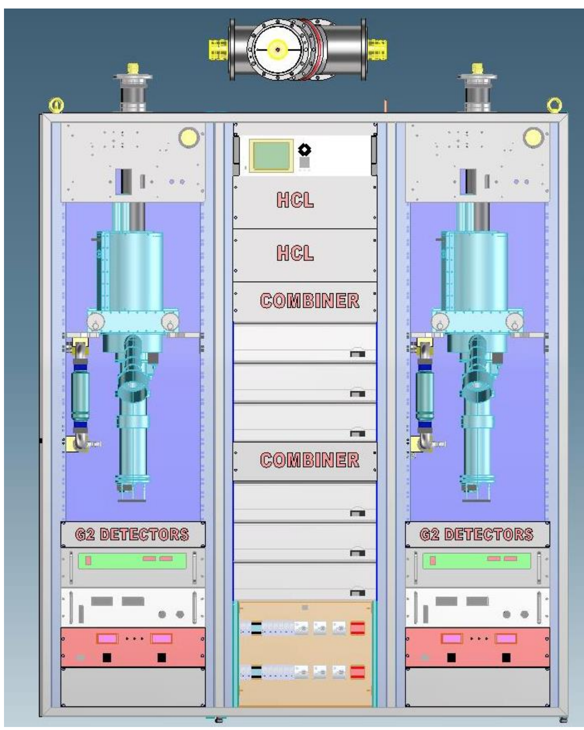
Baseline design for ESS Spoke Linac.



Earlier proposed foot-print: 5.91 m x 1.2 m

Foot print for Uppsala RF power station:
5 m x 1 m

Not able to fit in ESS gallery.

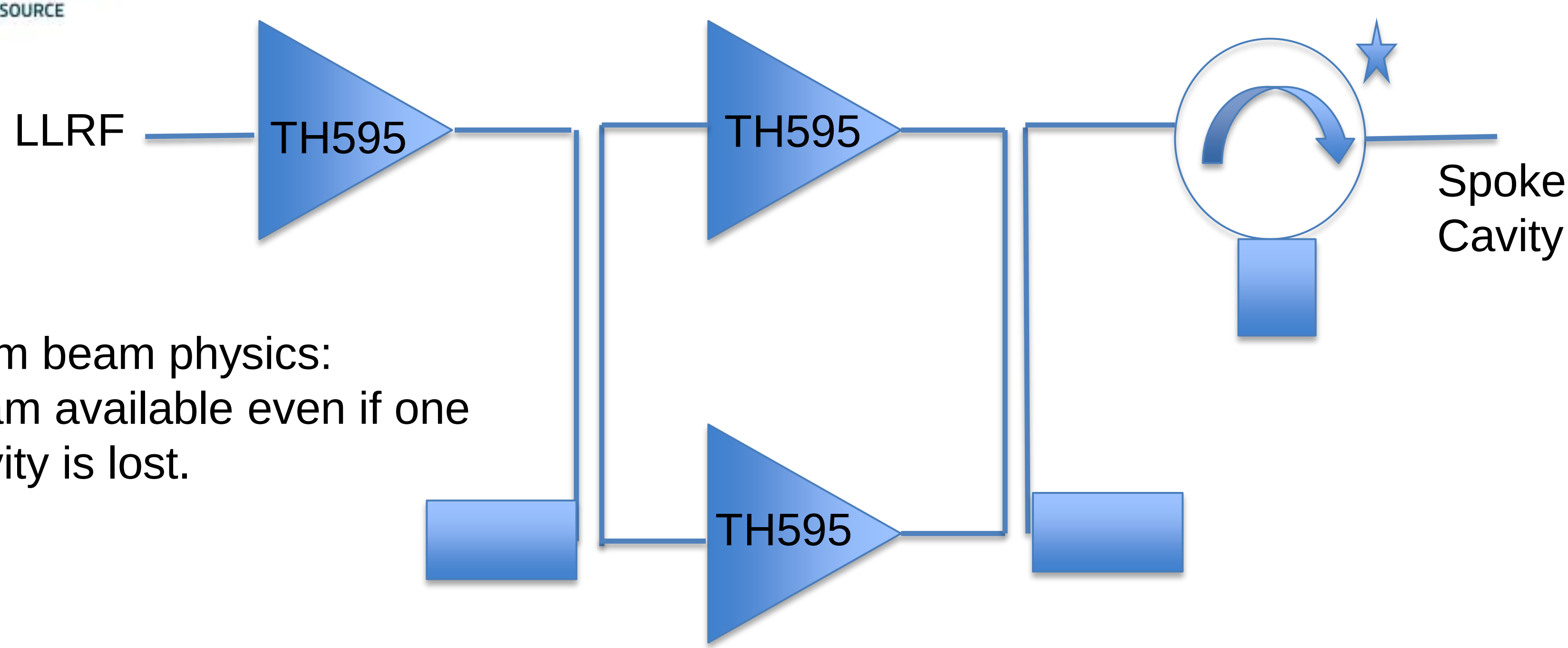


1.8 m

So worked with Electrosys
Updated layout: 1.8m x 1m for high power amplifiers, preamplifiers, G1, G2 and filament power-supplies.
Anode power supply: 2m x 1 m (trying to reduce)

Fits in ESS gallery

RF power station for Accelerator



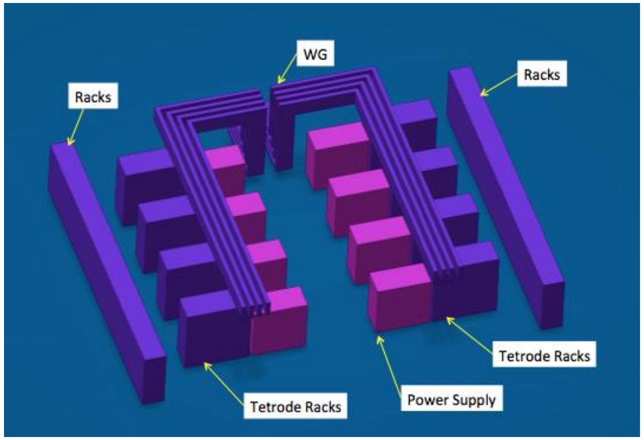
From beam physics:
Beam available even if one
Cavity is lost.

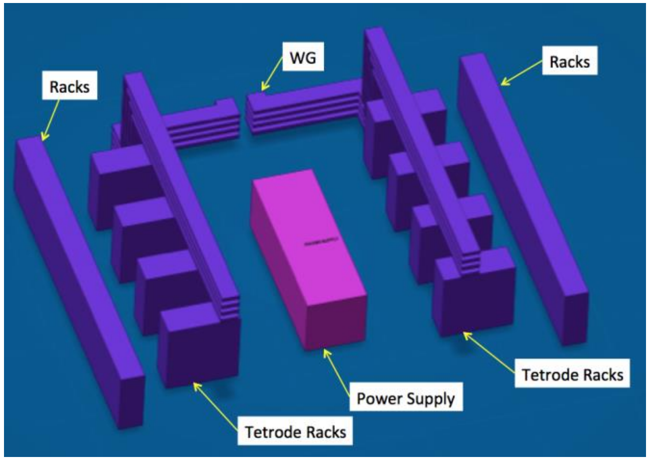
- Single anode supply with crow-bar
- Single G2 supply
- Single filament supply
- Separate G1 supply

Working on power-supply specifications
and cost estimation for this Sytem.

Cost effective, minimum number of spares

One HV supply per one cavity ie. for 2 tetrodes





One HV supply per 8 cavities ie. for 16 tetrodes

Tetrodes for FREIA & ESS Spoke Linac: Efficient Choice !

Thank you !