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

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Many thanks to

✓ Suppliers:

✓ Colleagues:

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CERN: Eric Montesinos
Efficiency

\[ \eta = \frac{\text{Aimed Output}}{\text{Required Input}} \]

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

energy efficiency = \[ \frac{\text{Aimed output}}{\text{Required energy input}} \]
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

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 \( \eta \) more
Energy efficiency for Warm linac

\[ \eta \text{ of klystron} = 50\% \]

\[ P_{dc} = \frac{P_{avgRF}}{\eta} = \frac{140\,\text{kW}}{0.5} = 280\,\text{kW} \]

\[ P_{\text{collector}} = P_{dc} - P_{\text{avgRF}} = 140\,\text{kW} \quad \text{Dissipated in Collector} \]

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

Power profile along ESS linac

As Amplifier doesn’t exist at ESS specifications — Technology demonstrator

Courtesy: Sabastien Bouson (IPN Orsay)
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 cryomodules at high power (proposal submitted)
Calculation of Amplifier Power

• Maximum RF power coupled to beam = 330 kW

• Considering LLRF overhead = 15%

• RF loss in distribution system = 5%,
  \[ \text{Power of RF source} = 390 \text{ kW} \approx 400 \text{ kW} \]

• Beam pulse width = 2.86 ms, repetition rate = 14 Hz,
  Natural fill time = \( t_f = \frac{2Q_L}{\omega} \approx 135 \mu s, \quad (Q_L = 1.5 \times 10^6) \)
  RF pulse width = 3.1 ms
  **Duty factor of the amplifier \( \approx 4.28 \% \)**

• Spoke cavity band-width = 2.34 kHz
  System band-width \( \approx 100 \) 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 exist. 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

RF Loss overhead = 5%

Requirement of power is lower for tetrodes

Tetrodes are more efficient!
Running cost for 25 years of operation

Variation of Amplifier efficiency with cavity number

Tetrodes: HV efficiency 67 %

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

<table>
<thead>
<tr>
<th>Tetrode</th>
<th>Klystron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life time: 20 k hours</td>
<td>Life time: 70 k hours</td>
</tr>
<tr>
<td>Cost: x kEUR</td>
<td>Cost &gt; 15x kEUR</td>
</tr>
<tr>
<td>Replacements: 14</td>
<td>Replacements: 2</td>
</tr>
</tbody>
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Cost of replacements for tetrodes is less by few MEUR

* Maximum two replacements of klystron with refurbishment are possible.

Courtesy: Eric Montesinos (CERN)
Tetrodes & Diacrodes available from industry

- Tested for 100 kW, CW
  - A = 13 dB
  - η = 55%

- Tested for 200 kW, CW
  - A = 15 dB
  - η = 67%

- Tested for 100 kW, for 100 µs

- peak < 1 ms

Courtesy: Data for Tetrode and Diacrodes: Eric Montesinos (CERN)
Selection of Tetrode at ESS Specifications

Peak power = 400 kW
Avg power = 20 kW

TH781
High Voltage  η = 55 %
Pdc = 36.36 kW

TH595
High Voltage  η = 67 %
Pdc = 29.85 kW

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 !

First time Reported by me
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

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.

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

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

Cost effective, minimum number of spares

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

Working on power-supply specifications and cost estimation for this System.
One HV supply per one cavity ie. for 2 tetrodes

One HV supply per 8 cavities ie. for 16 tetrodes
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Thank you!