High Power RF Sources for the ESS
RF Systems

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Co Authors:

www.europeanspallationsource.se
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Agenda

• Introduction to ESS
• Power profile and Technology Choices
• IOTs
Linac Design Choices

- User facilities demand high availability (>95%)
- The linac will be mostly (>97%) superconducting
- Front end frequency is **352 MHz** (CERN Standard)
- High energy section is at **704 MHz**
- ESS will limit the peak beam current below **62.5 mA** (was 50 mA)
- Linac Energy of 2 GeV - **125 MW** peak power.
The ESS Superconducting Power Profile

> 150 cavities/couplers

1 RFQ and 5 DTL tanks
352 MHz 2.8 MW Klystrons
Total Power: 13 MW

26 Cavities
352 MHz
2*200 kW
Tetrodes
Total: 8 MW

36 Medium Beta
704 MHz (6 cell)
1.5 MW Klystrons
Total: 22 MW

84 High Beta
704 MHz (5 cell)
1.2 MW IOT
MB Klystron as backup
Total: 90 MW

Total High Power RF: 133 MW peak (4% duty) plus overhead
RF distribution for the RFQ and 5 DTLs Layout being finalised

One 2.8 MW for RFQ
Five 2.8 MW klystrons for DLT

Power split to two couplers per DTL tank
CPI – VKP-8352B
Thales – TH2179

2 Klystrons per modulator
Possible RFQ and DTL Power Source

Investigating option to operate at lower voltage for lower power operation

DTL:
- Saturation efficiency = 55%
- Beam efficiency = 46%
- Full voltage efficiency = 41%

RFQ:
- Saturation efficiency = 52%
- Beam efficiency = 43%
- Full voltage efficiency = 31%

2.8 MW
108 kV, 46.5 A
3.4 ms, 14 Hz

Courtesy of Thales
Spoke linac (352 MHz) RF System Layout

Conceptual Only

26 Double Spoke cavities
Considering: 1 PSU per
1 / 8 / more RF stations
Spoke linac RF System

Individual or common (tetrode) driver
Circulator under consideration

High efficiency at point of operation
Margin for overhead

Anode efficiency > 65% at all power levels

Output Power and Efficiency

- Output Power (kW)
- Efficiency (%)

Input Power (kW)

0 5 10

Co-Dr. Anode efficiency > 65% at all power levels.

RF In

Load

DA

10 kW 200 kW

Tetrode

λ/4

3 dB Combiner

400 kW

Cavity

Load

TH595 Tetrode

Courtesy of R. Yogi
Elliptical (704 MHz) RF System Layout

- One cavity per klystron
- 4 klystrons per modulator
- 16 klystrons per tunnel penetration
Elliptical (704 MHz) RF System Layout

Limited space available

4.5 Cells of 8 klystrons for Medium Beta
10.5 Cells of 8 klystrons (IOTs) for High Beta
Elliptical (704 MHz) RF System Layout

(but last week it may have changed)

Racks moved to allow the cables to follow the route of the waveguide
704 MHz Klystron (Thales) factory tests

![Graph showing power transfer curve](image)

Courtesy of Thales and CERN
TH2182 001 Peak Power and Efficiency versus Cathode Voltage

<table>
<thead>
<tr>
<th>Cathode Voltage (kV)</th>
<th>Saturated Peak Power (MW)</th>
<th>Saturated Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>80</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>90</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>100</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>110</td>
<td>1.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

704 MHz Klystron (Thales) factory tests

Courtesy of Thales and CERN

Operating Range
- Efficiency (predicted)
- Efficiency (measured)
- Peak power (predicted)
- Peak power (measured)
An RF Source for a Proton Linac

- NC cavities with electrons
  - Operation at full power
  - ‘Easy’ to manufacture
  - Long cavity strings, no Lorentz detuning
  - Flat power profile – large source feeding many cavities

Very high power klystron is a good match

- Compared to copper cavities, superconducting cavities offer:
  - over three times the gradient
  - over 10 times the aperture
  - with virtually no power dissipated in the cavities

- SC cavities are difficult to manufacture
- Cell structure designed for one beam velocity
- Power profile shaped by transit time effects
- Strong individual Lorentz detuning
  - Short Cavity strings – lower power
  - One amplifier per cavity

SRF supported by R&D and investment
An RF Source for a Proton Linac

Investment in SRF has not been matched with investment in high efficiency RF sources

In a klystron operation below saturation is inefficient and reduces ‘actual’ efficiency

Power-to-beam efficiency \( \leq 43\% \)

Each cavity operated at peak field (45 MV/m)

No Flat Power Profile
Where next?
The ESS Requirement

Carbon Neutral
Innovative
Green

Opportunity to develop Super Power IOT

<table>
<thead>
<tr>
<th>Accelerating Structure</th>
<th>Freq. (MHz)</th>
<th>Quantity</th>
<th>Max Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ, DTL</td>
<td>352</td>
<td>5</td>
<td>2200**</td>
</tr>
<tr>
<td>Spoke</td>
<td>352</td>
<td>30</td>
<td>330**</td>
</tr>
<tr>
<td>Elliptical Medium Beta</td>
<td>704</td>
<td>34</td>
<td>860**</td>
</tr>
<tr>
<td>Elliptical High Beta</td>
<td>704</td>
<td>86</td>
<td>1100**</td>
</tr>
</tbody>
</table>

** Plus overhead for control
Klystron and IOT Principles

Klystron (Velocity Modulated)

RF input

RF output

Cathode (DC Beam)

Collector
Klystron and IOT Principles

**Klystron (Velocity Modulated)**
- RF input
- Collector
- Cathode (DC Beam)

**IOT (Density modulated)**
- RF input
- Biased Control Grid
- RF output
Tube History:
Invented in 1938 by Andrew V. Haeff as a source for radar.
Used first in 1939 to transmit television images from the Empire State Building to the New York World Fair.
Difficult to manufacture.

Reduced velocity spread
Higher efficiency
No pulsed high voltage
No classical saturation

Typical Example of 80 kW IOT
Tuned for 80 kW @ 36 kV

Courtesy of e2v
An RF Source for a Proton Linac

Each marker is an RF Source

Assume 25% overhead
Modulator $\eta = 93$
Klystron saturation $\eta = 64$
IOT $\eta = 65$

Actual Power-to-Beam Profile
An RF Source for a Proton Linac

Estimated Electrical consumption using Klystrons

Estimated Electrical consumption using IOTs

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Assume 25% overhead
Modulator $\eta = 93$
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An RF Source for a Proton Linac

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IOT $\eta = 65$

Power which can be saved

Actual Power-to-Beam Profile
## An IOT for ESS

Work is being carried out in collaboration with CERN
- ESS to procure prototypes
- CERN to make space and utilities available for testing

**Target: Approval for ESS series production in 2017/18**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td><strong>704.42 MHz</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Bandwidth &gt; +/- 0.5 MHz</strong></td>
</tr>
<tr>
<td><strong>Maximum Power</strong></td>
<td><strong>1.2 MW</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Average power during the pulse</strong></td>
</tr>
<tr>
<td><strong>RF Pulse length</strong></td>
<td>Up to 3.5 ms</td>
</tr>
<tr>
<td></td>
<td><strong>Beam pulse 2.86 ms</strong></td>
</tr>
<tr>
<td><strong>Duty factor</strong></td>
<td>Up to 5%</td>
</tr>
<tr>
<td></td>
<td><strong>Pulse rep. frequency fixed to 14 Hz</strong></td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td><strong>Target &gt; 65%</strong></td>
</tr>
<tr>
<td><strong>High Voltage</strong></td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td><strong>Expected &lt; 50 kV</strong></td>
</tr>
<tr>
<td><strong>Design Lifetime</strong></td>
<td>&gt; 50,000 hrs</td>
</tr>
</tbody>
</table>
A 3rd Generation Light Source Storage Ring

Three 500 MHz 300 kW amplifier for SR
- 4 x 80 kW IOT combined
One 80 kW for the Booster

Other examples of IOTs exist throughout Europe
... but not at MW power levels
1.2 MW Multi-Beam IOT

- ESS launched tender for IOT prototypes
- Tender replies received and contracts about to be signed for two IOTs
- Delivery in 24 months
- Site acceptance at CERN followed by long term soak test
- ESS > 3 MW saved from high beta linac = 20 GWh per year

Pre-tender CPI Cartoon
## Summary of Key Parameters for the ESS High Power Devices

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Klystron 352 MHz</th>
<th>Tetrode* 352 MHz</th>
<th>Klystron 704 MHz</th>
<th>IOT 704 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak output power (MW)</td>
<td>2.8</td>
<td>400</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>352.21</td>
<td>352.21</td>
<td>704.42</td>
<td>704.42</td>
</tr>
<tr>
<td>Gun</td>
<td>Diode gun</td>
<td>Filament</td>
<td>Diode gun</td>
<td>Gridded Gun</td>
</tr>
<tr>
<td>Pulse length (ms)</td>
<td>4</td>
<td>3.5</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>Rep. rate (Hz)</td>
<td>Up to 14</td>
<td>Up to 14</td>
<td>Up to 14</td>
<td>Up to 14</td>
</tr>
<tr>
<td>Maximum Beam Voltage (kV)</td>
<td>115</td>
<td>18</td>
<td>115</td>
<td>50</td>
</tr>
<tr>
<td>Efficiency at nominal output power</td>
<td>≥ 55%</td>
<td>&gt; 65%</td>
<td>&gt; 60%</td>
<td>&gt; 65%</td>
</tr>
<tr>
<td>- 1dB Bandwidth (MHz)</td>
<td>≥ +/- 1</td>
<td>≥ +/- 3</td>
<td>≥ +/- 1</td>
<td>≥ +/- 1</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>≥ 40</td>
<td>&gt;15</td>
<td>≥ 40</td>
<td>≥ 20</td>
</tr>
</tbody>
</table>
Acknowledgements

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