RF systems for CW SRF linacs

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Outline

- Introduction: CW SRF linac types, requirements and challenges
- High power RF system architecture
- RF power generation options: klystron vs IOT vs solid state amplifier
- Specific projects, operating or under construction:
  - JLab FEL & CEBAF
  - ELBE
  - ALICE
  - Cornell ERL injector
  - ERL prototype for electron cooling and eRHIC at BNL
  - SPIRAL-2
- Future projects and requirements
- Summary
One can distinguish four types of CW SRF linacs:

- Low-current high-\( \beta \) linacs: typically L band, low to medium RF power
- ERLs: L or UHF band, low to medium RF power
- High-current high-\( \beta \) injectors/drivers: L or UHF band, medium to high RF power
- Low-\( \beta \) linacs: VHF band, low to medium RF power

Requirements/challenges:

- Provide stable, reliable source of RF power
- Maintain stable cavity field (amplitude and phase) - LLRF
- High efficiency of converting AC power to RF and transferring it to SRF cavities
- High availability of the RF system
- Easy maintainability
- Cost-effective design
- Compactness, especially for large installations (e.g. CEBAF)

In this talk we will consider only medium and high RF power systems.
RF POWER SOURCES FOR CW SRF LINACS

**VHF to UHF frequencies:**
Coaxial transmission lines, losses increase as $\sqrt{f}$

**UHF and higher:**
Waveguides, losses increase as $\sim f^{3/2}$ as in addition to skin depth decrease one has to use smaller and smaller size waveguides.
All CW SRF linacs use a simple architecture with one RF high power amplifier per cavity. Reasons: flexibility, available RF power sources, requirements to fields stability, efficiency of RF system, ...

Key
- Waveguide System
- Power Supplies
- Utilities
- Instrumentation
- RF High Power
- RF Low Power

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How RF power spec is set?

1. Calculate beam loading
2. Add margin for regulation
3. Set requirement for RF power available at the cryomodule for each family of cavities
4. Set requirement for power available at the high power amplifier taking into account losses in the transmission line elements

SPIRAL-2

Linac amplifier power budget

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RF power generation at higher frequencies is still dominated by vacuum tubes: klystrons and, with the success in broadcast applications, IOTs.

At lower frequencies tetrodes were traditionally used, but recent progress in solid state technology will make it the technology of choice in VHF and UHF bands, except when very high power is required.
### Choice of RF power source: klystron vs. IOT

<table>
<thead>
<tr>
<th><strong>Injector</strong></th>
<th><strong>Main linac</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Klystron</strong></td>
<td><strong>IOT</strong></td>
</tr>
</tbody>
</table>

- **Electron bunches are formed by velocity modulation from the cavities translated into density modulation in the drift spaces**
- **Density modulation directly from cathode**  
- **Several bunching cavities, optional mod anode**  
- **Control grid**  
- **High gain (> 40 dB): low power drive amplifier**  
- **Low gain (~22 dB): high power drive amplifier (expensive)**  
- **High efficiency in saturation, which drops rapidly at reduced power**  
- **Higher efficiency, which does not drop quickly at reduced power: highly linear device**  
- **Longer, expensive device**  
- **Shorter, less expensive tube**  
- **Can be designed for very high power operation**  
- **Output power is limited though R&D for high power tubes are underway**

**Normalized characteristics of output power (vertical axis) vs. drive power (horizontal axis) for klystrons (blue, saturating) and IOTs (green, not saturating).**

**Efficiency of Klystron and IOT**

- IOT Prototyp
- Klystron VKL7811
- Optimized Klystron

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JLab SRF linacs

JLab FEL Upgrade
- THz User Labs
- Attosecond Beam
- UV User Labs
- IR User Labs

Machine Configuration
CEBAF

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• 3 control racks
• 5 racks for klystrons: VKL6811W (CPI) or L491 (L3)
• Single shared HV power supply
• 42 systems in CEBAF
• 3 more in FEL
• FEL Injector 2 stand-alone 100 kW klystrons: VKL7966A (CPI)
Klystron configuration

- 8 klystrons per zone
- Powered from single HV power supply
- Circulators, couplers, etc.
- 4 waveguides per penetration to tunnel
- After addressing initial failure modes, present average lifetime of the klystrons is 165,000 hours
JLab klystrons

**VLK7811W**
- Purchased through competitive bid
- Order of 350 units
- 3 year delivery period
- Specifications
  - 5 kW CW
  - 11.6 kV @ 1.33 A
  - 32.4% efficiency (min)
  - 38 dB gain
  - 4 cavity design
  - Coaxial output
  - Permanent magnet focusing
  - Potted gun
- Size limitations

**L491**
- Replacement from competitive bid
- Multi-year order
- Purchase in lots of 10 or 20 units
- 119 received

**VKL7966A**
- 110 kWatts
- 33.5 kV @ 6.5 A
- 1497 MHz
- -1dB Bandwidth 14 MHz
- Saturated Gain 55.5 dB
- Efficiency 51 %
## CEBAF 12-GeV Upgrade

<table>
<thead>
<tr>
<th></th>
<th>6 GeV</th>
<th>12 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy to Halls A,B,C / D</td>
<td>6 GeV</td>
<td>11 GeV / 12 GeV</td>
</tr>
<tr>
<td>Number of passes for Halls</td>
<td>5</td>
<td>5 / 5.5 (add a tenth arc)</td>
</tr>
<tr>
<td>A,B,C / D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duty Factor</td>
<td>CW</td>
<td>CW</td>
</tr>
<tr>
<td>Max. Current to Halls A+C / B</td>
<td>200 μA / 5 μA</td>
<td></td>
</tr>
<tr>
<td>Max. Current to Halls A+C / B+D</td>
<td></td>
<td>85 μA / 5 μA</td>
</tr>
<tr>
<td>Max. Beam Power</td>
<td>1 MW</td>
<td>1 MW</td>
</tr>
<tr>
<td>Emittance at max. energy (unnormalized, rms)</td>
<td>1 nm-rad</td>
<td>10 nm-rad</td>
</tr>
<tr>
<td>Energy spread at max. energy (rms)</td>
<td>$2.5 \times 10^{-5}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

### 12 GeV CEBAF

- Add 5 cryomodules
- 20 cryomodules
- Add arc
- 20 cryomodules
- New cryomodules get new RF zones
  - Two 1.1 GeV linacs

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10 new zones of RF power for new accelerating structures:

- 80 new tubes, 10 HVPS
- WG network for 80 cavities
- Operating freq. 1497 MHz
- Operating gradients required >17.5 MV/m
- Operating RF power per cavity 13 kW saturated power

<table>
<thead>
<tr>
<th></th>
<th>Fast (&lt;1sec)</th>
<th>Slow (&gt;1sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Stability (rms)</td>
<td>correlated</td>
<td>0.24°</td>
</tr>
<tr>
<td></td>
<td>un-correlated</td>
<td>0.5°</td>
</tr>
<tr>
<td>Amplitude (rms)</td>
<td>correlated</td>
<td>2.2x10^{-5}</td>
</tr>
<tr>
<td></td>
<td>un-correlated</td>
<td>4.5x10^{-4}</td>
</tr>
</tbody>
</table>
Waveguide layout

Penetrations to Service Bldg.

Tunnel Ceiling Level

Cryomodule

Tunnel Waveguide
ELBE is a multi-purpose facility based on a CW Superconducting RF linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Thermionic Gun</th>
<th>SRF Photo Gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Energy</td>
<td>40 MeV (CW)</td>
<td>40 MeV (CW)</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>77 pC</td>
<td>77 pC / 2.5 nC</td>
</tr>
<tr>
<td>Beam Current</td>
<td>1 mA CW</td>
<td>1 mA</td>
</tr>
<tr>
<td>Bunch Length (rms)</td>
<td>1 – 10 ps</td>
<td>4 / 20 ps</td>
</tr>
<tr>
<td>Transv. Emittance (rms)</td>
<td>2/10 mm mrad</td>
<td>0.5 / 2.5 mm mrad</td>
</tr>
<tr>
<td>Max. Rep.Rate</td>
<td>260 MHz@0.77 pC</td>
<td>13 MHz</td>
</tr>
<tr>
<td></td>
<td>13 MHz@77 pC</td>
<td></td>
</tr>
<tr>
<td>Energy Spread</td>
<td>35 keV / 55 keV</td>
<td>40 keV</td>
</tr>
</tbody>
</table>

- Two Cryomodules, equipped with two TESLA (DESY) 1.3 GHz cavities
- Individually driven systems, one cavity – one klystron
- Injector: Thermionic Gun (250 kV) + two Bunchers (260 MHz, 1.3 GHz)
**Thermionic**
- DC Gun
- 250 kV
- \(\leq 260\text{ MHz}\)
- \(<80\text{ pC}\)
- \(\sim 500\text{ ps}\)
- \(\sim 10\text{ mm mrad}\)

**RF Bunchers**
- 260 MHz
- +1.36 GHz
- compr. \(\sim 100:1\)

**Linac**
- 1.3 GHz
- \(\sim 20\text{ MeV} @ 10\text{ MeV/m}\)
- CW

**Linac**
- 1.3 GHz
- \(\sim 20\text{ MeV} @ 10\text{ MV/m}\)
- CW

**SRF photo gun**
- 9.5 MeV
- \(\leq 13\text{ MHz}\)
- \(80\text{ pC} / 1\text{nC} / 2.5 \text{nC}\)
- \(\sim 5\text{-}20\text{ ps}\)
- \(\sim 1.5\text{-}3\text{ mm mrad}\)

**Helium**
- Liquifier
- LINDE
- 200 W @ 1.8 K

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**Notes:**
- FWKZ: Dr. Ing. H. Bölli
- www.kzi.de • Mitglied der Leibniz-Gemeinschaft

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**Reference:**
- S. Belomestnykh: RF systems for CW SRF linacs
Recently installed a new 30 kW CW system built by Bruker, based on the CHK51320W IOT (CPI)

**Klystron**

VKL7811St (CPI)

6-klystrons running

PS: SMPS 15 kV; 2.5A

(FuG Rosenheim, Germany)

Water: 46 l/min, 6 Bar
Accelerators and Lasers in Combined Experiments (ALICE) is an R&D facility for the development of advanced accelerator systems; from high-intensity electron sources, CW SRF linac cryomodules, short pulse FEL undulators and associated optical diagnostics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Gun Energy</td>
<td>350 keV</td>
</tr>
<tr>
<td>Injector Energy</td>
<td>8.35 MeV</td>
</tr>
<tr>
<td>Circulating Beam Energy</td>
<td>35 MeV</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Bunch Repetition Rate</td>
<td>81.25 MHz</td>
</tr>
<tr>
<td>Nominal Bunch Charge</td>
<td>80 pC</td>
</tr>
<tr>
<td>Maximum Train Length</td>
<td>100 µs</td>
</tr>
<tr>
<td>Maximum Train Repetition Rate</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Maximum Average Current</td>
<td>13 µA</td>
</tr>
</tbody>
</table>
ALICE RF system

<table>
<thead>
<tr>
<th></th>
<th>Booster</th>
<th>ERL Linac</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cav1</td>
<td>Cav2</td>
</tr>
<tr>
<td>$E_{acc}$ (MV/m)</td>
<td>4.8</td>
<td>2.9</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>$5 \times 10^9$</td>
<td>$5 \times 10^9$</td>
</tr>
<tr>
<td>$Q_e$</td>
<td>$3 \times 10^6$</td>
<td>$3 \times 10^6$</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>32</td>
<td>20</td>
</tr>
<tr>
<td>Power Source</td>
<td>2 x e2v</td>
<td>CPI</td>
</tr>
</tbody>
</table>

0.1ms bunch trains @ 20 Hz repetition rate

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### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>max beam current at q = 77 pC</td>
<td>100 – 33 mA</td>
</tr>
<tr>
<td>beam energy gain</td>
<td>5 – 15 MeV</td>
</tr>
<tr>
<td>bunch repetition rate</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>transverse emittance</td>
<td>&lt; 1 mm-mrad</td>
</tr>
<tr>
<td>max. emittance growth</td>
<td>&lt;0.1 mm-mrad</td>
</tr>
<tr>
<td>bunch length</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Number of 2-cell SRF cavities</td>
<td>5</td>
</tr>
</tbody>
</table>

**Diagram:**
- **klystron xmtrs**
- **beam dump**
- **beam lines**
- **cryomodule**
- **buncher IOT xmtr**
- **WG distribution network**
- **buncher**
- **DC gun**
- **beam lines**
INJECTOR CRYOMODULE RF SYSTEM

- Five 2-cell SC cavities, each delivering up to 100 kW of RF power to beam
- Five identical RF channels
- RF power is delivered to cavities via twin 50 kWCW input couplers
- RF power delivery system includes an adjustable short slot hybrid and a motorized 2-stub WG phase tuner
- 170 kWCW circulators manufactured by the Ferrite Co.
- Two production input couplers reached maximum RF power level of 61 kW on a coupler test stand
- Six klystrons K3415LS manufactured by e2v, all tested at the factory and at Cornell

**Specifications of the ICM RF system**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cavities</td>
<td>5</td>
</tr>
<tr>
<td>Accelerating voltage per cavity</td>
<td>1 – 3 MV</td>
</tr>
<tr>
<td>2-cell cavity length</td>
<td>0.218 m</td>
</tr>
<tr>
<td>R/Q (linac definition)</td>
<td>222 Ohm</td>
</tr>
<tr>
<td>Q_{ext}</td>
<td>4.6×10^4 – 4.1×10^5</td>
</tr>
<tr>
<td>RF power per cavity</td>
<td>100 kW</td>
</tr>
<tr>
<td>Maximum useful klystron power</td>
<td>≥ 120 kW</td>
</tr>
<tr>
<td>Amplitude stability</td>
<td>9.5×10^{-4} (rms)</td>
</tr>
<tr>
<td>Phase stability</td>
<td>0.1° (rms)</td>
</tr>
</tbody>
</table>
Parameters of the 7-cavity K3415LS klystron (e2v):

- beam voltage 45 kV @ 5.87 A
- full power collector
- max. output power 135 kW
- efficiency >50%
- gain >45 dB
- bandwidth >±2 MHz @ 1 dB and >±3 MHz @ 3 dB
Prototype ERL

Electron cooling is a key component in RHIC II. Cooling gold beams at 100 GeV/nucleon require an electron beam energy of 54 MeV and a very high average current of about 200 mA. Future projects such as eRHIC (electron-ion collider) push the operational current to ~500 mA at 20 nC bunch charge or higher.

A prototype ERL is a first step towards an ampere class electron cooler. The ERL will consist of a 703.75 MHz, 2 MeV SRF gun as an injector to the five-cell linac cavity which will accelerate the beam to about 20 MeV.
Electron cooler for RHIC

**SRF gun**

- Assembly Support Fittings
- Helium Vessel
- Helium Main Line
- Tuner Bellows
- Opposing Pickup Ports
- Cathode location
- FPC Port Stiffener
- Double Quarter Wave Choke (cavity portion)
- 10 cm Beam Pipe
- Opposing FPC Ports

**ERL cryomodule**

- 4" RF shielded gate valve
- HOM ferrite assembly
- Tuner location
- 2K main line
- Space frame support structure
- Cavity assembly
- Vacuum vessel
- 2K fill line
- Outer magnetic shield
- Thermal shield
- Inner magnetic shield
- Heater
- He vessel
- Fundamental Power Coupler assembly
1 MW RF for SRF gun

Parameters of VKP-7952B klystron (CPI):
- beam voltage 92 kV @ 17.1 A
- full power collector
- max. output power 1000 kW
- efficiency 65%
- gain >40 dB
- bandwidth ±0.7 MHz @ 1 dB
- WR1500 waveguide output
IGBT based system that uses a Fast Shut Down Mode (FSDM) instead of a crowbar. Transmitter was manufactured by Continental Electronics.
50 kW RF for ERL cavity

- broadcast transmitter manufactured by Thomson-BM (former Thales-BM)
- modified version TH793 Thales broadcast IOT
• Radioactive beam facility
• Protons: 33 MeV, 5 mA; deuterons: 40 MeV, 5 mA; heavy ions: 14.5 MeV/u, 1 mA
• $12 \beta = 0.07$ QWR cavities
• $14 \beta = 0.12$ QWR cavities
• Independently phased cavities for wide velocity acceptance and output energy optimization for each ion species

• Utilized power equipment developed for FM market
• 3, 5.5, 10 & 20 kW amplifiers are available
• 3 1/8” 50-Ohm transmission line, air cooled
• Test bench was designed and operated up to 20 kW
• The 10 kW prototype has been used at IPN-Orsay for $\beta = 0.12$ cryomodule test
• Class C amplifiers
10 kW amplifier architecture. Circulators and dummy load are outside the amplifier cabinet, at high power level. Green elements are water cooled.

Two 10 kW amplifiers.
Could not resist to mention:

- 180 kW CW solid state amplifier for SOLEIL storage ring based light source (France)
- 352 MHz
- Very reliable and stable operation
- Efficiency ~50%
More and more future projects are based on CW superconducting RF technology.

Here is a sample list of such projects that utilize L band SRF linacs and will require medium to high power CW RF systems:

- STARS (BESSY)
- ERL@CESR (Cornell)
- KEK ERL
- 0.5 MW drive linac (TRIUMF)
- WiFEL (Wisconsin)
- CW SRF linacs are used for a wide variety of scientific applications from nuclear physics to light source facilities to radio isotopes production.

- In all machines presented in this talk a simple architecture with one RF high power amplifier per cavity is used. Reasons: flexibility, available RF power sources, requirements to fields stability, efficiency of RF system, ...

- Most of high-β linacs operate in L band. UHF band is left for ampere-class machines. IOTs successfully compete with klystrons at medium power levels due to their better efficiency and linearity.

- Solid state amplifiers are rapidly becoming the technology of choice in VHF band at medium power levels and making way into UHF and L bands (though they are still pricey and not very efficient there.)

- There are more CW SRF linac based projects under consideration at different laboratories.
I would like to thank people who provided information, slides and pictures for this talk:

C. Hovater (Jlab)
T. Powers (JLab)
H. Buettig (Rossendorf)
P. McIntosh (Daresbury)
A. Zaltsman (BNL)
M. Di Giacomo (GANIL)
R. Laxdal (TRIUMF)
End of talk
Additional slides
LAMBDA developed a precision 75 kW, 25 kV switching HVPS for a klystron amplifier (reported at PAC’07)

Output Voltage Range: -10 to -25kV
Output Current: 0 to 4A max
Average Power: 75kW
Ripple and noise: <0.015% p-p
Efficiency: 90%
Power factor: 0.92
Stability: 10ppm/°C
Load regulation: 0.0001%
Line regulation: 0.0001%
Stored energy: 7.5J
Features:

- Compact design
- CW or pulse operation
- 35kW CW or 80 kW pulse
- Easy installation
- Fast tube replacement
  (down time less than 1 hour)
- VSWR 1.3:1
## Operating specifications

<table>
<thead>
<tr>
<th></th>
<th>CW</th>
<th>Pulsed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous wave output power</td>
<td>16</td>
<td>30</td>
</tr>
<tr>
<td>Frequency range</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Bandwidth at -1 dB</td>
<td>≥ 3</td>
<td>≥ 3</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>-100</td>
<td>-90</td>
</tr>
<tr>
<td>Cathode current</td>
<td>0.30</td>
<td>1.47</td>
</tr>
<tr>
<td>Cathode voltage</td>
<td>28.5</td>
<td>33</td>
</tr>
<tr>
<td>Gain</td>
<td>20.9</td>
<td>22.1</td>
</tr>
<tr>
<td>Efficiency</td>
<td>60.4</td>
<td>61</td>
</tr>
<tr>
<td>CW input power</td>
<td>146</td>
<td>190.1</td>
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<tr>
<td>Filament voltage</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Filament current</td>
<td>16.5</td>
<td>16.5</td>
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## Maximum ratings

<table>
<thead>
<tr>
<th></th>
<th>CW</th>
<th>Pulsed</th>
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</thead>
<tbody>
<tr>
<td>Continuous wave output power</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Input power</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Anode dissipation</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Anode voltage</td>
<td>24</td>
<td>34</td>
</tr>
</tbody>
</table>

## Gain variation

- Delta gain: 3 dB
- From 1 to 16 kW
- Sweep time = 2 seconds

## Phase variation

- Delta phase: 7°
IOT manufacturers: e2v

- Standard warranty period is 10,000 hrs
- Average life of 1213 broadcast IOTs is 31,700 hrs (for all e2v tubes that have recorded installation and removal date, tubes still in service are not included)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>1.3GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Power</td>
<td>16kW</td>
</tr>
<tr>
<td>Beam Voltage</td>
<td>&lt;28kV</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;60%</td>
</tr>
<tr>
<td>Gain</td>
<td>&gt;20dB</td>
</tr>
<tr>
<td>Class of operation</td>
<td>B or AB</td>
</tr>
</tbody>
</table>

Figure 3: Efficiency versus output power at a beam voltage of 25kV.