REVIEW OF HIGH POWER CW COUPLERS FOR SC CAVITIES

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Introduction

Many aspects of the high-power coupler design, fabrication, preparation, conditioning, integration in cryomodules, etc. will be discussed in presentations at this workshop.

Also, there were excellent overview talks by I. Campisi at the SRF’01 workshop and at the EPAC’02

- Highlights of design challenges
- Design options
- Testing setups and results
- Operating experience
- Future projects
Primary functions

Two primary functions of RF power couplers:

1. Efficiently couple RF power to a load (ideally, provide matching conditions)

2. Serve as a RF-transparent vacuum barrier (RF window)
Primary functions (2)

- High power CW klystron output couplers exist for power levels up to 1.3 MW, they efficiently couple RF power to a matched or nearly matched (VSWR better than 1:1.2) transmission line.

**BUT**

- Input couplers for SC cavities are more demanding because they must operate at a much wider range of the load impedance: from a matched condition when the cavity is beam loaded to a full reflection at an arbitrary phase w/o beam.
# Accelerator cavity specific challenges

**Additional challenges for the SC cavity couplers:**

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<td>3.</td>
<td>Must be a low heat loss thermal transition between the room temperature environment and the cryogenic temperature (2 to 4.5 K) environment</td>
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<td>4.</td>
<td>Should support clean cryomodule assembly procedures to minimize the risk of contaminating the superconducting cavity</td>
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<td>5.</td>
<td>Should minimize cavity field perturbations that can effect beam (usually not a problem for a high-energy particles) or cavity performance</td>
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<td>6.</td>
<td>Provide (in some cases, machine dependent) an adjustable coupling for different operating modes</td>
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<td>7.</td>
<td>Should be designed taking into account multipacting phenomenon: that is to be multipactor-free or provide cures such as bias voltage</td>
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**Definition of a high average power coupler for this review:**

\[ P \geq 100 \times (500/f_{\text{MHz}})^2 \text{ kW} \]
# High CW power fundamental input couplers

<table>
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<tr>
<th>Facility</th>
<th>Frequency</th>
<th>Coupler type</th>
<th>RF window</th>
<th>$Q_{ext}$</th>
<th>Max. power</th>
<th>Comments</th>
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</table>
| LEP2         | 352 MHz   | Coax fixed   | Cylindrical | $2\times10^6$ | Test: 565 kW  
Oper: 100 kW | Traveling wave  
@ $\Gamma=0.6$  
288 couplers |
| LHC          | 400 MHz   | Coax variable (60 mm stroke) | Cylindrical | $2\times10^4$ to $3.5\times10^5$ | Test: 500 kW  
Oper: 300 kW | Traveling wave  
Standing wave |
| HERA         | 500 MHz   | Coax fixed   | Cylindrical | $1.3\times10^5$ | Test: 300 kW  
Oper: 65 kW | Traveling wave  
16 couplers |
| CESR (Beam test) | 500 MHz | WG fixed     | WG, 3 disks | $2\times10^5$ | Test: 250 kW  
Oper: 155 kW | Traveling wave  
Standing wave  
Beam test |
| CESR         | 500 MHz   | WG fixed     | WG disk    | $2\times10^5$ | Test: 450 kW  
Oper: 360 kW | Traveling wave  
4 couplers  
Forward power |
| TRISTAN      | 509 MHz   | Coax fixed   | Disk, coax | $1\times10^6$ | Test: 200 kW  
Oper: 70 kW | 32 couplers |
| KEKB         | 509 MHz   | Coax fixed   | Disk, coax | $7\times10^4$ | Test: 800 kW  
Oper: 380 kW | Traveling wave  
Standing wave  
8 couplers |
| APT          | 700 MHz   | Coax variable ($\pm5$mm stroke) | Disk, coax | $2\times10^5$ to $6\times10^5$ | Test: 1 MW  
850 kW | Traveling wave  
Standing wave |
| JLAB FEL     | 1500 MHz  | WG fixed     | WG planar  | $2\times10^6$ | Test: 50 kW  
Oper: 35 kW | Very low $\Delta T$  
2 couplers |
# Fundamental RF power couplers: Design options

<table>
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<th>Pros</th>
<th>Cons</th>
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| **Waveguide** | • Simpler design  
              • Better power handling  
              • Easier to cool  
              • Higher pumping speed | • Larger size  
              • Bigger heat leak  
              • More difficult to make variable |
| **Coaxial**  | • More compact  
              • Smaller heat leak  
              • Easier to make variable  
              • Easy to modify multipacting power levels | • More complicated design  
              • Worse power handling  
              • More difficult to cool  
              • Smaller pumping speed |
Multipacting cures

- RF processing (APT, CESR, JLAB FEL)
- Bias aging (KEKB)
- Electrostatic bias (LEP2, LHC)
- Magnetic DC bias (CESR)
Multipacting in rectangular waveguides

Traveling wave

Scaling low: \[ P = (f \cdot d)^4 \]

Example:
CESR: 17"×4" 500 MHz
CEBAF: 5"×1" 1500 MHz

\[
\frac{P_{CEBAF}}{P_{CESR}} = \left(\frac{1.5}{2.0}\right)^4 = 0.316
\]
Multipacting in coaxial lines

Multipacting bands # 2...8 in a coaxial line. Power in kW, traveling wave. Z is impedance in Ohms.

(after E. Somersalo et al., Part. Acc., 1998)

\[ f = 1.3 \text{ GHz} \]

\[ d = 40 \text{ (outer diameter, mm)} \]

from 40 to 60 mm
Windows

• Waveguide windows (CESR, JLAB FEL):
  planar inserts with on or more ceramics of different shapes
  and (sometimes) variable thickness

• Coaxial windows:
  coaxial disk (APT, KEKB, TRISTAN)
  cylindrical (HERA, LEP2, LHC) as part of the waveguide
to coaxial transition

• Practically all couplers have alumina windows.
The only exception is the CESR WG window used during beam test,
which had a 3-disk berillia window.
Are other materials (aluminum nitride) worth considering?
Waveguide coupler example: CESR B-cell

- Fixed coupling $Q_{\text{ext}} = 2 \times 10^5$
- Magnetic bias of the WG to suppress multipacting
- Adjustability is provided via a 3-stub WG transformer

WR1800
Kapton window
Warm RF window
Coupling slot
Cold He gas cooled WG
Liquid nitrogen cooled WG
Pumping section
Waveguide coupler example: JLab FEL Injector

- The coupler is the same as the CEBAF cavity coupler with an adjusted coupling for higher beam loading and a new warm window
- A λ/2 stub-on-stub design
- Asymmetric fields → beam kick
- The CEBAF upgrade cryomodule has a λ/4 stub coupler design, which produces zero kick to beam
- Fixed coupling @ $Q_{ext} = 2 \times 10^6$
- The alumina ceramic window replaced the polyethylene warm window used in CEBAF
- It was tested up to 53 kW with very low $\Delta T = 7.2^\circ$
Coaxial coupler example: KEKB

- Based on the long-term operation of 32 SC cavity couplers in TRISTAN
- 50 Ohm coaxial line
- Fixed coupling \( Q_{\text{ext}} = 7 \times 10^4 \)
- Improved monitoring, cooling, choke structure around window

- Biased doorknob (±2 kV)
- Alumina (99.5%) coaxial disk window, coated with 100 Å of TiN_xO_{1-x}, air cooled outside
- Copper plated SS, 4 K He gas cooling at 8 l/min
- Water cooled inner conductor, electropolished copper
Coaxial coupler example: LHC

- Based on the LEP2 coupler design (there were 288 couplers in operation)
- Cylindrical window, Ti coated, forced air cooled
- Increased dimensions of the coaxial line
- Variable coupling @ $Q_{\text{ext}} = 2 \times 10^4 \ldots 3.5 \times 10^5$
- Waveguide to coaxial transition w/o a doorknob
- 3 kV anti-multipacting bias; multipacting in the low impedance line additional bias
- 4.5 K He gas cooled outer-conductor
Coaxial coupler example: APT

- Separated functions: vacuum break and power coupling
- Double RF window, coaxial disk, air-cooled
- 50 Ohm coaxial line
- Variable coupling @ $Q_{\text{ext}} = 2 \times 10^5 \ldots 6 \times 10^5$
- Tip bellows failure, complex and costly unit
Testing couplers (1)

Waveguide couplers:
only RF window are usually tested and processed before the final cryomodule assembly

Coaxial couplers:
more portable and can be tested and processed as a complete unit before the final assembly

Two windows/couplers are required

Directly connected to an RF power generator if one is available: more flexible scheme, allows both TW and SW tests
OR a resonant ring can be utilized: only TW

Final processing after cryomodule assembly
Testing couplers (2)

Resonant ring test setup

Coupler #1

Coupler #2

Coupling cavity

Hybrid coupler

RF power from the test transmitter

RF water load

Typical instrumentation:

- Vacuum gauges
- RGA
- Arc detectors
- View ports for IR and/or video
- e⁻ pick-up
- e⁻ energy analyzer
- RF instrumentation
- Temperature monitoring
Testing Thomson waveguide windows at CESR

**Processing:**

- initial processing in TW mode
- then SW mode at different positions of reflection plane
- both CW and pulsed regime during power ramp
- tickle processing for hard multipacting barriers
- may take from several hours to several days to reach max P
- final processing after cryomodule assembly
- *in situ* processing
Test results

Highest power reached on a test stand

- APT coupler (700 MHz) 1 MW in TW
- KEKB coupler (509 MHz) 800 kW in TW

850 kW in SW

SC cavity test setup for LEP2 couplers  
Test stand for APT couplers
Operating experience

• Highest beam power
  KEKB coupler (509 MHz)  380 kW beam power
  CESR coupler  (500 MHz)  300 kW beam power, 360 kW forward power

• Number of couplers in operation
  LEP2:  288 (decommissioned)
  TRISTAN:  32 (decommissioned)
  HERA:  16
  KEKB:  8
  CESR:  4
  JLAB FEL:  2 (decommissioned)
Future projects: LANL spoke cavity

- DoE AAA project
- 350 MHz, 212 kW
- Cylindrical window, 95% pure alumina
- 75 Ohm coaxial line
Future projects: Saclay

- A high intensity proton linac
- 704 MHz, 300 kW
- WG window
- WG vacuum valve
- Vacuum WG to coaxial transition
- Multipactor simulations: not a problem in the coaxial line
Transverse kick calculations

Field at the cavity axis

$E_1 = A \cdot \sin ky$

Electric wall at the end of coaxial, standing wave

$E_2 = B \cdot \cos ky$

Magnetic wall, standing wave

$E = \Re((E_1 + i(A/B)E_2) \exp(i\omega t)) = A \sin(ky - \omega t)$

Complex sum, traveling wave

$V_{\text{kick}} = \frac{V_t}{V_{\text{acc}}} = \frac{\int (E_y + cB_x) \, dz}{\int E_z \, dz}$

Here $E_y, B_x, E_z$ are also functions of $t, z = c0 + c\cdot t$
Emittance growth

The kick received by the center of passing bunch

\[
\alpha = \frac{p_t}{p} = \frac{eV_{\text{acc}}}{p_c} \Re \left( \frac{V_t}{V_{\text{acc}}} e^{i\phi_0} \right)
\]

can be easily compensated and do not cause emittance growth.

The kick change along the bunch, from head to tail, on the other hand, generates emittance growth:

\[
\frac{d\varepsilon_{n,t}}{\varepsilon_{n,t}} = \frac{\sigma_t}{\varepsilon_{n,t}} \frac{2\pi\sigma_z}{\lambda_{RF}} eV_{\text{acc}} \left| \Re \left( \frac{V_t}{V_{\text{acc}}} \right) \cdot \sin \phi_0 + \Im \left( \frac{V_t}{V_{\text{acc}}} \right) \cdot \cos \phi_0 \right|
\]
Possible coupler kick cures

- Symmetric input power coupler (WG-coaxial)
- Two couplers opposite each other (APT)
- Symmetrizing stub (CEBAF upgrade)
  - Larger beam pipe size
- Antenna flush with the beam pipe surface
  - Alternating couplers (CEBAF)
Future projects: Cornell ERL

- Energy Recovery Linac, injector cavity
- 1300 MHz, 100 kW
- Twin-coaxial coupler: zero transverse kick
- 60 Ohm, 60 mm line
- Multipactor-free
- Variable coupling @ $Q_{ext} = 4.6 \times 10^4 \ldots 4.1 \times 10^5$
Cornell ERL: Waveguide - coaxial coupler

- No transverse kick
- No wakes
- HOMs?

Waveguide-coaxial coupler for a two-cell cavity of the ERL.

S-parameter Magnitude in dB

A = 63.2 mm
C = 55.0 mm
1300 MHz
S11: -59.63 dB

$S_{11}$ (in dB) of the coaxial-waveguide transition, dependence on dimensions A and C. $f = 1300$ MHz.
Summary

• Great progress in achieving high power levels in operating conditions (380 kW, KEKB) and in tests (1 MW, APT).

• New emphasis: robust, reliable couplers with simplified design and manufacturing methods, reduced overall cost.

• Inter-laboratory cooperation will benefit successful development of the next-generation high average power couplers!