Waveguide Heat Loads

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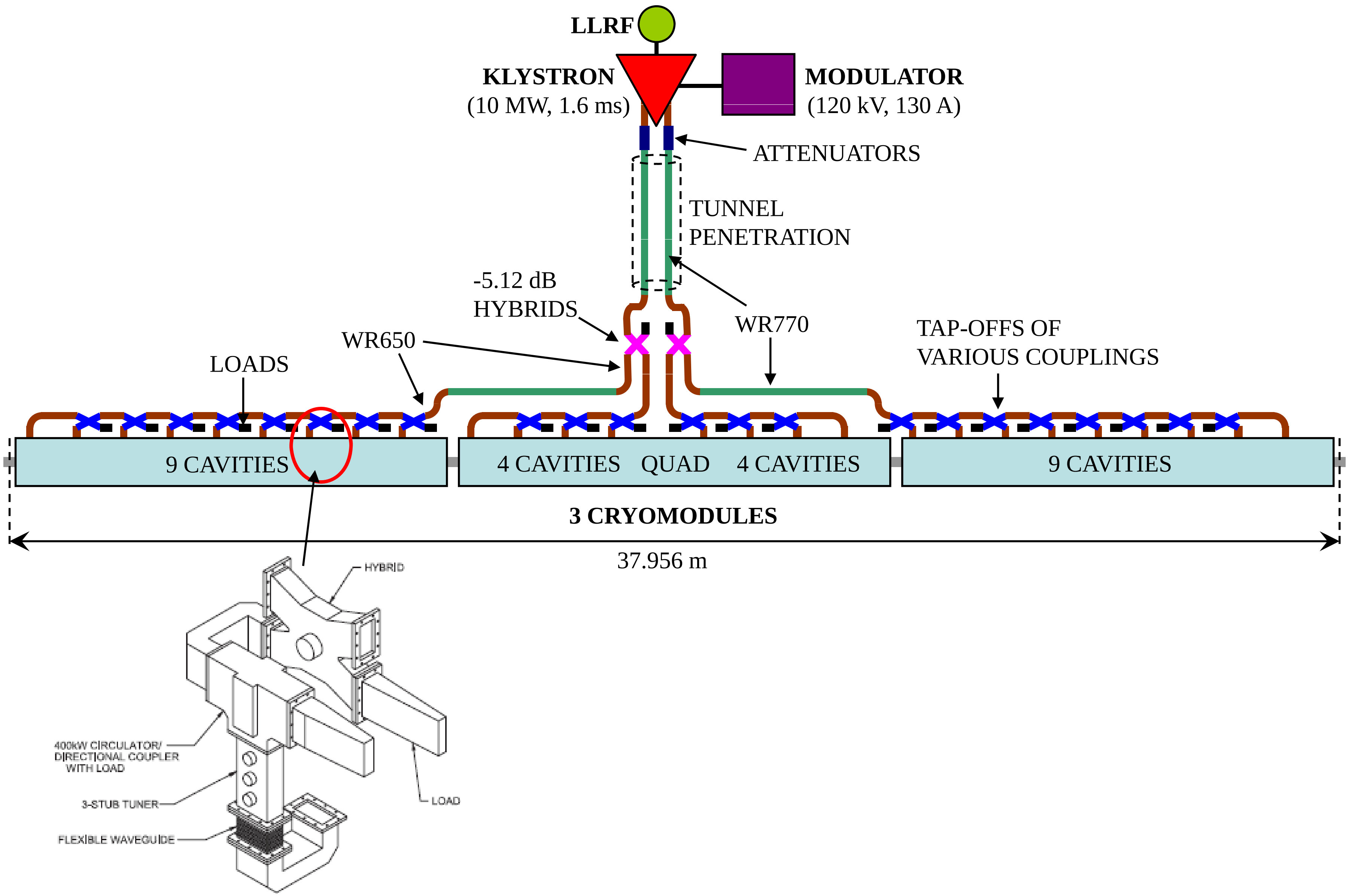
Outline

- High Power RF Distribution System
- Waveguide Attenuation
- Power Calculation
- Heat Loads
- Removing the Heat
- Waveguide Temperature Rise
- Thermal Phase Shifts
- Conclusions

High Power RF Distribution System



LLRF

KLYSTRON
(10 MW, 1.6 ms)

MODULATOR
(120 kV, 130 A)

ATTENUATORS

TUNNEL
PENETRATION

WR770

-5.12 dB
HYBRIDS

WR650

LOADS

WR770

TAP-OFFS OF
VARIOUS COUPLINGS

9 CAVITIES

4 CAVITIES QUAD 4 CAVITIES

9 CAVITIES

3 CRYOMODULES

37.956 m

Waveguide Attenuation

Take: .0078 dB/m for WR650 and .0053 dB/m for WR770 (11.6% above theoretical)*.

Horizontal run through penetration (~1.5m+6.75m+~3m = 11.25m WR770):	.0596 dB	(1.36%)
Up & down/back & forth, both tunnels (~9m WR650):	.0702 dB	(1.60%)
Average tunnel run to cryomodule (6.0m×9/13 = 4.15m WR770):	.0220 dB	(0.505%)
Average longitudinal run along cryomodule (1.376m**×3.23 = 4.44m WR650):	.0347 dB	(0.795%)
Circulators:	.10 dB	(2.28%)
Other feed components (bends, phase shifter, directional coupler):	.020 dB	(0.459%)
Flex waveguides (3×0.027dB):	.081 dB	(1.85%)
TOTAL Waveguide Loss:	.3875 dB	(**8.54%**)

* Consistent with DESY measurements (Katalev, EPAC06).

** Enhanced from 1.326m coupler spacing to account for jogs through hybrids.

Power Calculation

9 mA	beam pulse current
× 31.5 MV/m	accelerating gradient
× 1.038 m	effective cavity length
294.2 kW/cav	pk. power per cavity
× 26 cav	cavities per RF unit
7.649 MW	pk. power into cavities
÷ 0.9146	transmission efficiency (η_T)
8.363 MW	min. needed kly. power
× 1.565 ms	RF pulse length
× 5 Hz	rep. rate

7.649 MW	pk. power into cavities
× 0.970 ms	beam pulse length
× 5 Hz	rep.rate
37.10 kW	avg. power into beam (P_B)

10 MW*	max. avail. kly. power
× 1.565 ms	RF pulse length
× 5 Hz	rep. rate

min.		max.
65.44 kW	avg. RF power (P_{RF})	78.25 kW
× 0.0854	$1 - \eta_T$	× 0.0854
5.589 kW	transmission loss (P_L)	6.683 kW
22.75 kW	power to loads(/attenuators?) ($P_{RF} - P_L - P_B$)	34.47 kW

*19.6% overhead available to compensate for imperfect power division and to maximize and flatten gradient through a set of non-perfect, non-identical cavities with a scatter of gradient limits. Gradient has priority over power efficiency.

Heat Loads

For the minimum – full power case (8.36 MW – 10 MW pk.), we have heat loads of:

22.75 kW – 34.47 kW in water-cooled loads(/attenuators)
5.59 kW – 6.68 kW in transmission waveguide and components

Circulators (1.409 kW – 1.685 kW of transmission loss) are water-cooled, so:

→ 24.16 kW – 36.16 kW in water-cooled loads(/attenuators) and circulators
4.18 kW – 5.00 kW in transmission waveguide & other comp.

If we further subtract the load from half the inter-tunnel transmission system and one flex waveguide (in service tunnel), we get accelerator tunnel only heat loads of:

→ 24.16kW – 36.16 kW in water-cooled loads(/attenuators) and circulators
2.81 kW – 3.37 kW in accel. tunnel transmission waveguide & other comp.
(with an additional 1.37 kW – 1.64 kW in the support tunnel)

Note that if 10% of the heat in water-cooled components leaks to adjacent parts of the system and into air, the uncooled load approximately doubles, giving:

→ 21.74 kW – 32.54 kW into water
5.23 kW – 6.99 kW into tunnel air
(with an additional 1.37 kW – 1.638 kW into support tunnel air)

Removing the Heat

AIR CONDITIONING

Assume running at an intermediate power level, using some but not all of the overhead, with ~90% efficient water-cooling (maybe we can do better) on the loads/attenuators & circulators.

There might then be ~6.2 kW of air heating.

Removing this would require

6.2 kW × 3,412 BTU/h/kW = 21,154 BTU/h of air conditioning.

One can buy a 10,000 BTU/h portable air conditioner for $380.

→ 21,154BTU/h / 10,000 BTU/h × $380 = ~$804

Assume a typical heat pump efficiency:

COP* = heat removal rate / AC power used ~= 3

→ 6.2 kW of cooling @ COP of 3 = 2.07 kW AC power

× 8,766 h/yr. × $.087/kW-h = $1,576/yr

1BTU = 1.055 kJ

*coefficient of performance

ADDITIONAL WATER-COOLING

Alternatively, one could deal with some or all of this remaining heat load by adding additional water cooling to parts of the distribution system.

Allowing a water temperature rise of two degrees Celsius, removing 6.2 kW would require an additional water flow per RF unit of

$$3.788\ °\mathrm{C/kW\ gal./min} \div 2°\mathrm{C} \times 6.2\ \mathrm{kW} = \sim 11.74\ \mathrm{gal./min}$$

This example assumes some heat leak from already cooled parts. For a perfectly insulated system, complete water-cooling would require only about 3.1 kW more (5.9 gal./min), or about a 10% increase in the water already required for loads, etc.

THOUGHTS

Cooling the long waveguide runs (through the penetration, to the cryomodules), is straight-forward.

Trying to water-cool the whole system would be complicated and costly.

It would increase risk of leaks.

The lossy flex guides, in particular, do not lend themselves to water-cooling.

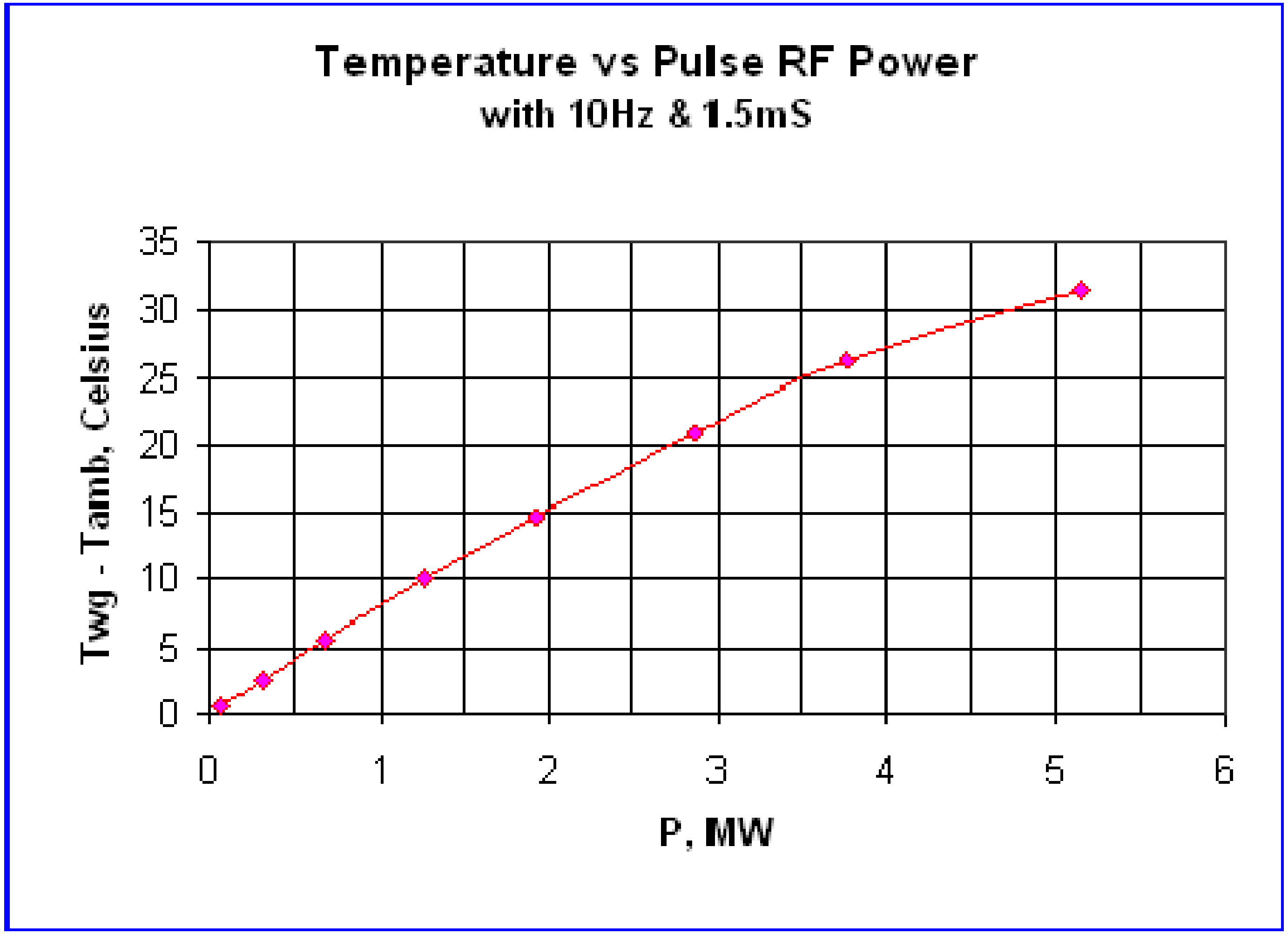
The gradual power decrease along the main distribution lines would call for different water circuits for similar components.

Hoses and bulky insulation would take up more precious volume in the tunnel.

A combination of additional water cooling (long runs, hot parts) and air conditioning would seem to be the best approach.

Waveguide Temperature Rise

Valery Katalev’s Measurements:



For 1.565 ms, 5 Hz → reduce peak power to account for factor of 0.522 in duty factor.

Faya Wang's Measurements:

Temperature Measurement During Hybrid Test Jul-31-2007

	T_i	T_f	P/m	ΔT
Keith Jobe setup (heat tape inside guide)	78°F	94°F	34 W/m	8.9°C
Straight waveguide (high-power RF)	78°F	93°F	34.6 W/m*	8.3°C
Flex waveguide (high-power RF)	77°F	103°F	34.6 W/m	14.4°C

Waveguide Temperature Measurement Aug-17-2007

	Ti	Tf	P/m	DT
Straight waveguide (heat tape)	82°F	135±5°F	143 W/m	29.4±1.8°C

From Valery Katalev's curve

143 W/m equivalent of 5.3 MW 1.5 ms 10 Hz → ΔT~=31°C

*Assuming: ~.0078 dB/m for Al WR650 → 72 W/m @ 5 MW, 1.6 ms, 5 Hz
~.0053 dB/m for Al WR770 → 49 W/m @ 5 MW, 1.6 ms, 5 Hz

Thermal Phase Shifts

almost 2

WR650: 0.0504°/m/°C
WR770: 0.0446°/m/°C

	max. available, no atten. power flow	approx. length	from Katalev's plot ΔT	$\Delta\phi$
penetration	5 MW (770)	11.25 m	11°C*	5.52°
up & down	5 MW (650)	9 m	19°C	8.62°
to cryomodule	3.46 MW (770)	6 m	8°C*	2.14°
to 2nd & 3rd feeds	2.88 MW (650) avg.	2.75 m	12°C	1.66°
to 4th & 5th feeds	2.11 MW avg.	2.75 m	9°C	1.25°
to 6th & 7th feeds	1.35 MW avg.	2.75 m	6°C	0.83°
to 8th & 9th feeds	577 kW avg.	2.75 m	3°C	0.42°
feed	384 kW	3 m	2°C	0.30°

14.44° common shift

6.3° max. diff structure to structure

20.7° max. total klystron to structure

*Scaled with power dissipation and inversely with perimeter for WR770
(may get much hotter in penetration without cooling)

COMMENTS

Flex waveguide sections might absorb some longitudinal expansion, cutting phase shifts in particular runs by up to half.

Water-cooling the penetration waveguide can reduce the total common phase shift by ~38% to 8.92°C. Without water-cooling this contribution to phase shift could be much higher than given unless there is sufficient ventilation through the penetration.

This common phase shift can be tracked by LLRF drive, anyway.

Water-cooling the runs to adjacent cryomodules can reduce the maximum differential phase shift by ~34% to 4.16°C. This is more important for LLRF, particularly without motorized phase shifters.

Copper plating waveguide and/or waveguide components can reduce transmission losses by 22% and thus reduce thermal phase shifts.

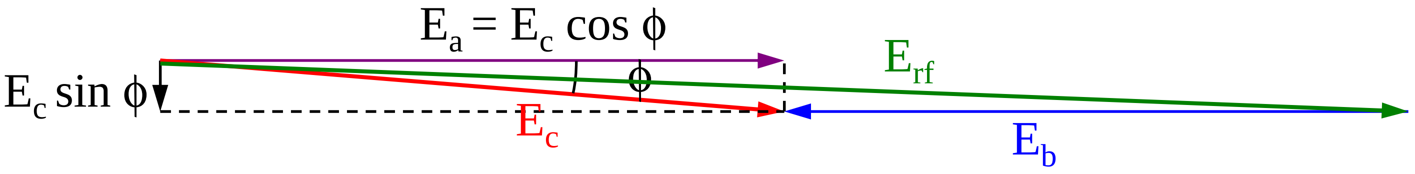
Effect of Phase Shifts

To maintain accelerating gradient, the power required for a cavity off phase by $\Delta\phi$ normalized to that needed at the nominal 5° is

$$\frac{P(5^o + \Delta\phi)}{P_0(5^o)} = \frac{\cos^2 5^o}{\cos^2(5^o + \Delta\phi)}$$

For a 6° differential phase shift, the LLRF phase can be set so that the cavities run with $\Delta\phi = \pm 3°$. At these limits, the above factor is 1.012 and 0.9936. Without adjustment, the $\Delta\phi = 6°$ shift would give a factor of 1.032.

From the below phasor diagram, one can see that if a cavity is run at its *gradient limit*, an increase in ϕ lowers the accelerating gradient, and thus the required power ($\approx I_b V_a$) as cos ϕ. Thus with an anticipated phase shift of 3°, one would have to drive a cavity with 0.988 times the nominal power.



Actually, it's more complicated. The point is that to avoid exceeding cavity gradient limits, one must operate sufficiently below those limits to allow for any change in cavity gradients due to thermal phase shifts. These changes will likely be smaller than the margin within which we'll be able to approach those limits anyway. The effect on flatness optimization should probably be more of a concern.

Conclusions

- We have ballpark estimates for the RF distribution system heat loads based on the RDR configuration.
- Numbers for the ACD would be similar, except for the possible elimination of circulators.
- Most of this by far is “discarded” power, rather than “dissipated” power, and will depend on how gradient and gradient flatness are optimized.
- Of the dissipated power, some can be water cooled (as the discarded power mst be) to minimize the heat load to air in the tunnel, as well as phase shifts.
- Estimates have also been presented of thermal phase shifts, which can be minimized by steps such as the above.
- Common phase shifts to all cavities in an RF unit can be canceled through the drive phase.
- Differential phase shifts cannot (short of including motorized phase shifters). Their impact on the beam acceleration and the LLRF’s ability to deal with them needs to be further studied.