KCS Development and Consideration of KCS/RDR Operation with Reduced Bunch Number

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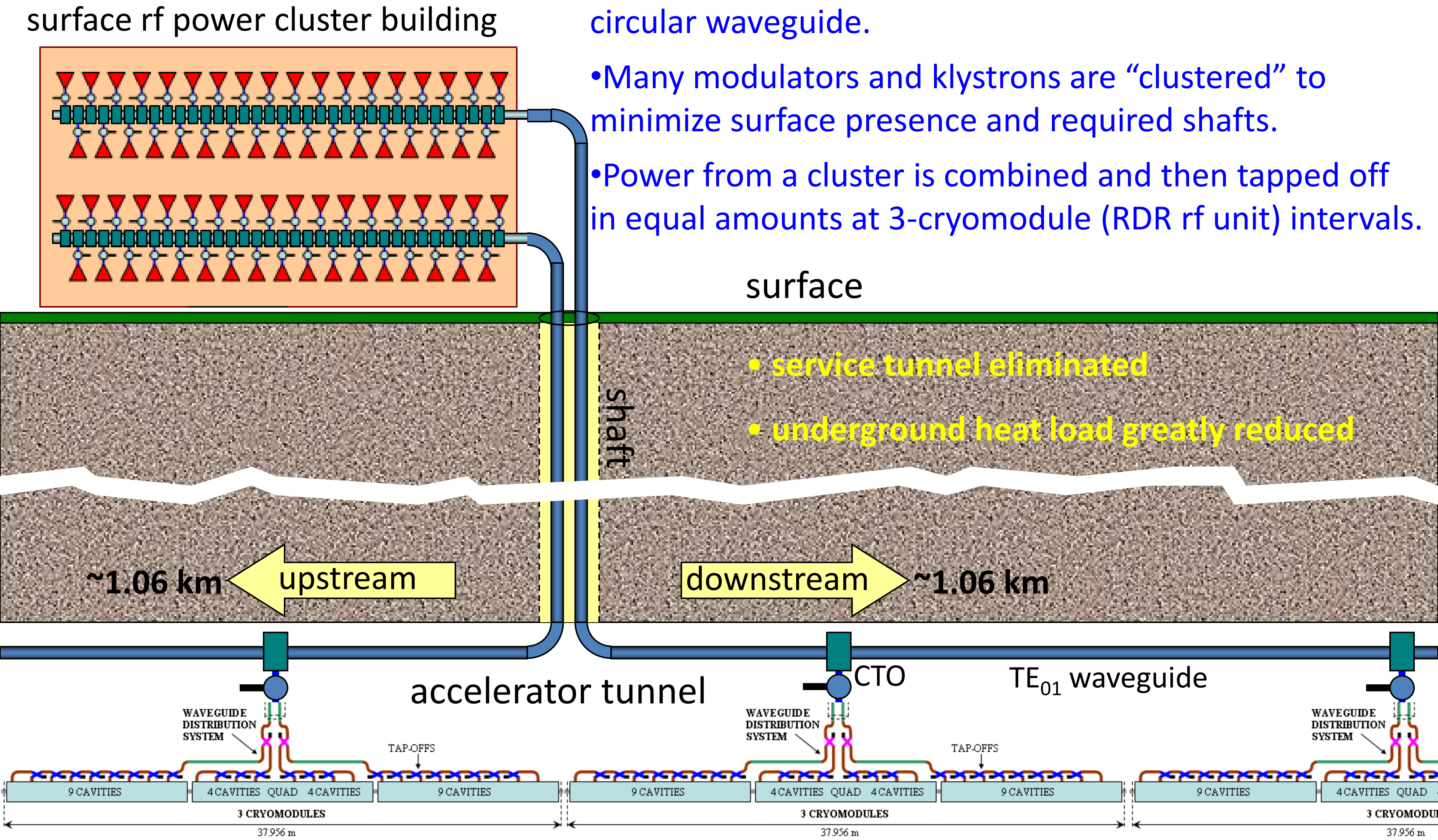
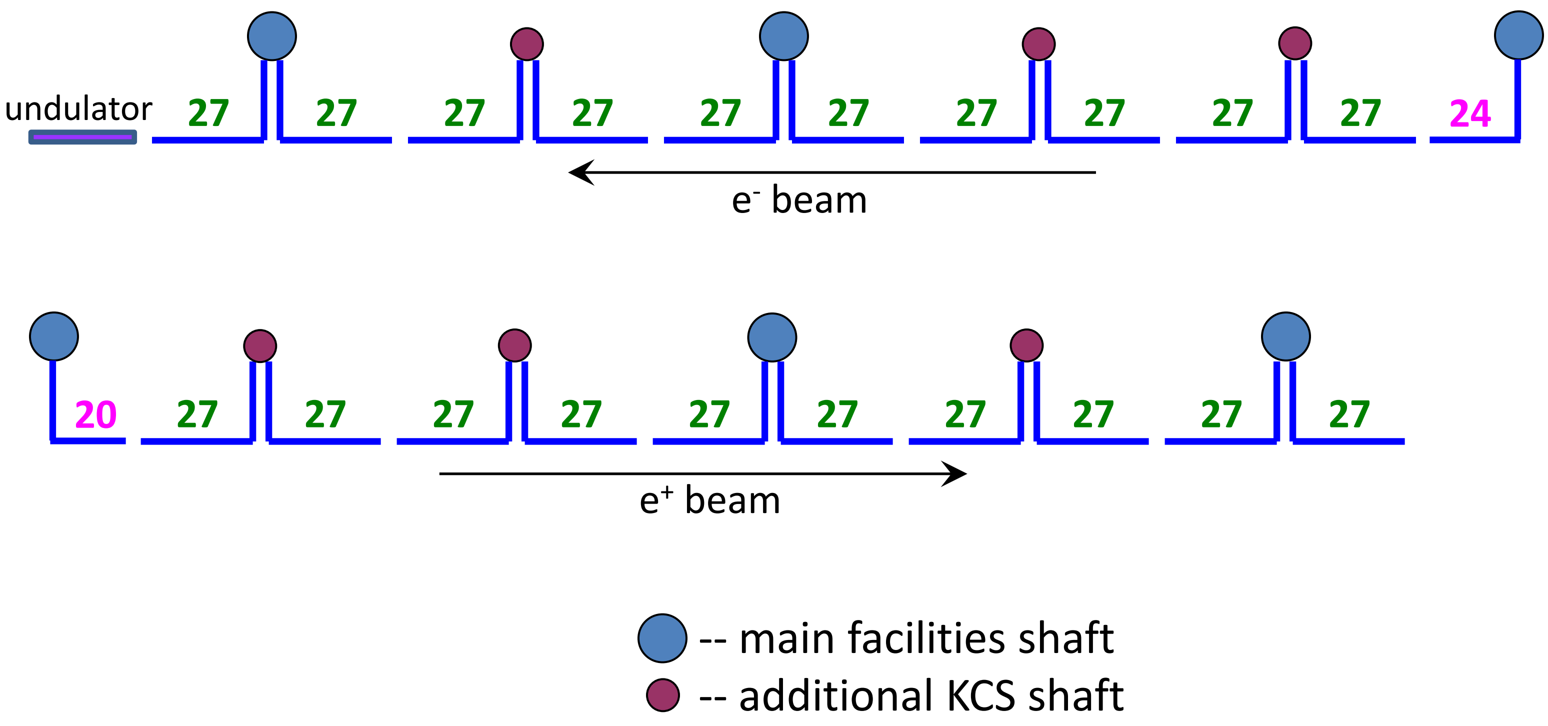
Klystron Cluster System Basic Layout

- Main linac rf power is produced in surface buildings and brought down to and along the tunnel in low-loss circular waveguide.
- Many modulators and klystrons are “clustered” to minimize surface presence and required shafts.
- Power from a cluster is combined and then tapped off in equal amounts at 3-cryomodule (RDR rf unit) intervals.



KCS Shafts and RF Units per KCS

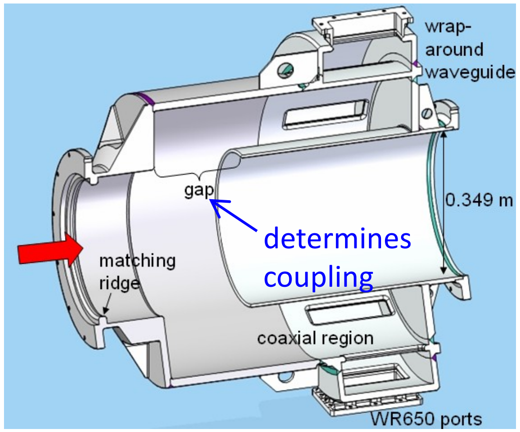
With 12 rf units from the RTML added to each of the main linacs and 4 more in the e^- linac than the e^+ linac for undulator losses, they have **294** and **290** rf units, respectively. The following would seem to be a reasonable modified KCS layout.

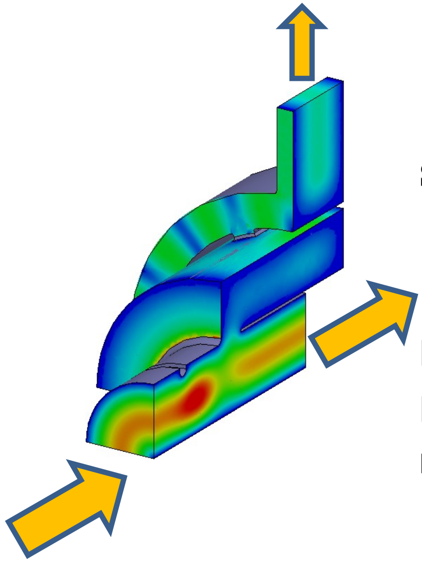


Combining and Distributing Power

Couplings ranging from ~1 to 1/33 to the TE_{01} (low loss, no surface E-field) mode are required.

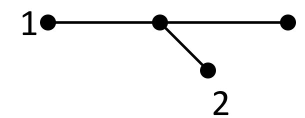
CTO (Coaxial Tap-Off)





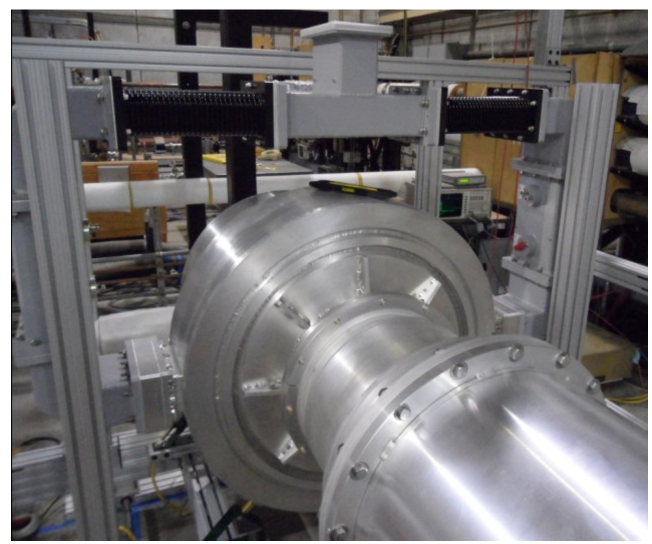
"3-port" coupler

$$\mathbf{S} = \begin{pmatrix} 0 & \sqrt{C} & \sqrt{1-C} \\ \sqrt{C} & (1-C) & -\sqrt{C(1-C)} \\ \sqrt{1-C} & -\sqrt{C(1-C)} & C \end{pmatrix}$$



For combining, the tap-offs are installed backwards. Proper phase and relative amplitude needed for match (mismatched power goes to circulators).

A pair of 3-dB CTO's.



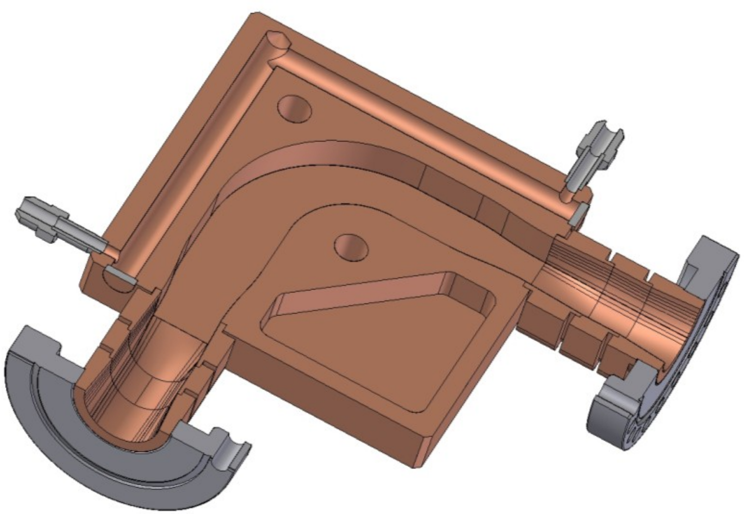
A CTO connecting WR650 waveguide to 48cm-diameter circular waveguide.

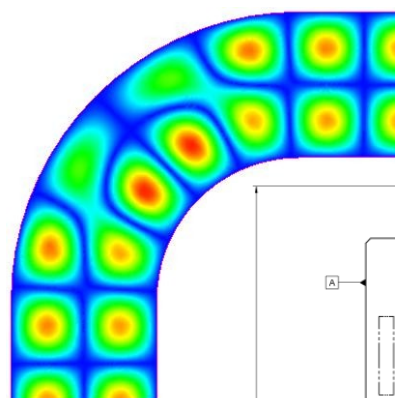
Main Waveguide Bends

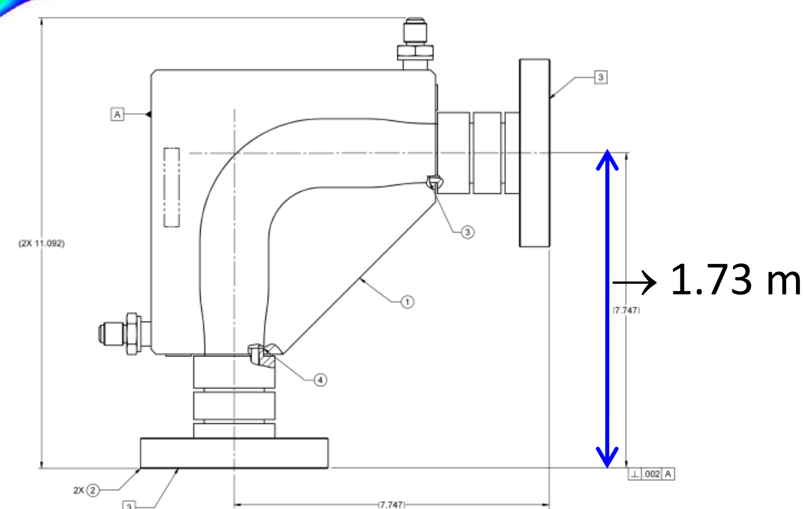
For KCS, we need to bend the main rf waveguide *at full power* through multiple 90˚ bends to bring it down to and along the linac tunnel. Demonstration of such a bend is crucial to establishing the feasibility of KCS.

Though we've considered other options, including a more compact design with significantly higher surface fields, the leading contender is a scaled modification of the following X-band SLAC design*.

Smooth, properly spaced circular-elliptical and elliptical-rectangular tapers convert the circular TE_{01} mode into the rectangular TE_{20} mode, which is preserved around a swept bend.



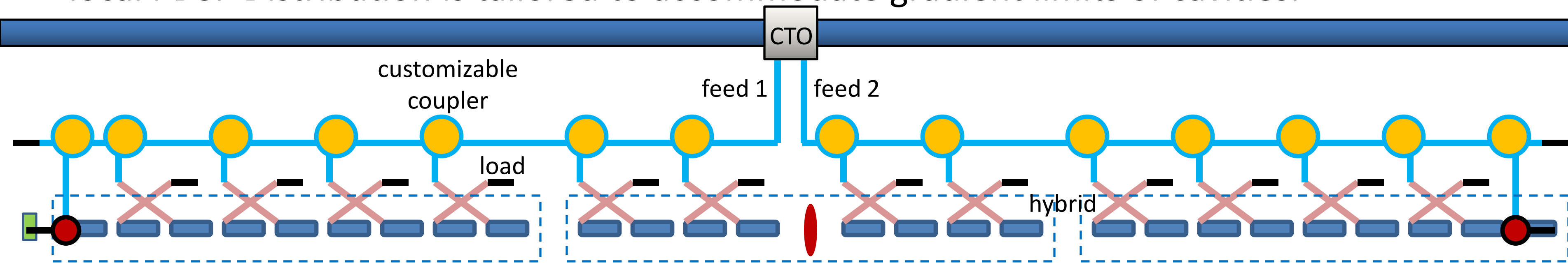




* S. Tantawi, V. Dolgashev, C. Nantista

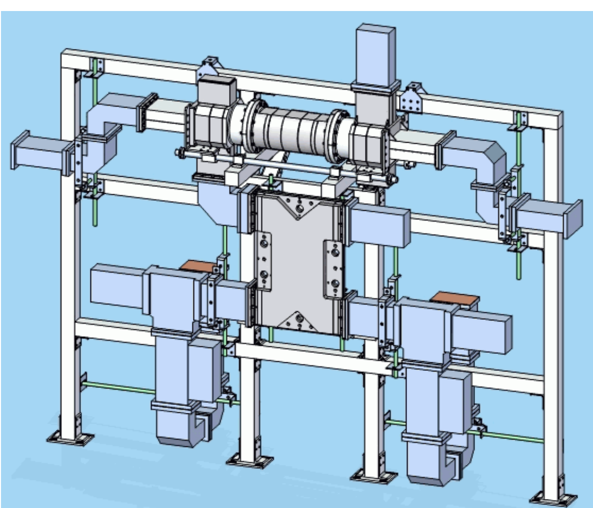
Local RF Power Distribution Scheme

Power from each CTO is distributed along a 3-CM rf unit containing 26 cavities through a local PDS. Distribution is tailored to accommodate gradient limits of cavities.



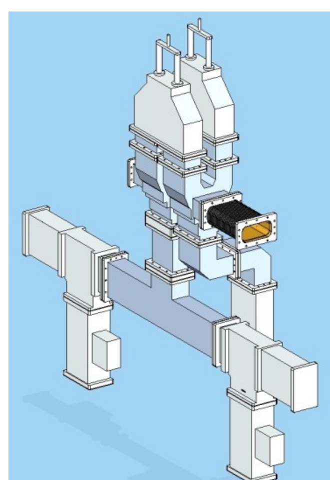
Original VTO (Variable Tap-Off) Pair-Feeding Concept

- manually adjustable by pairs
- requires pair sorting
- circulators can be eliminated



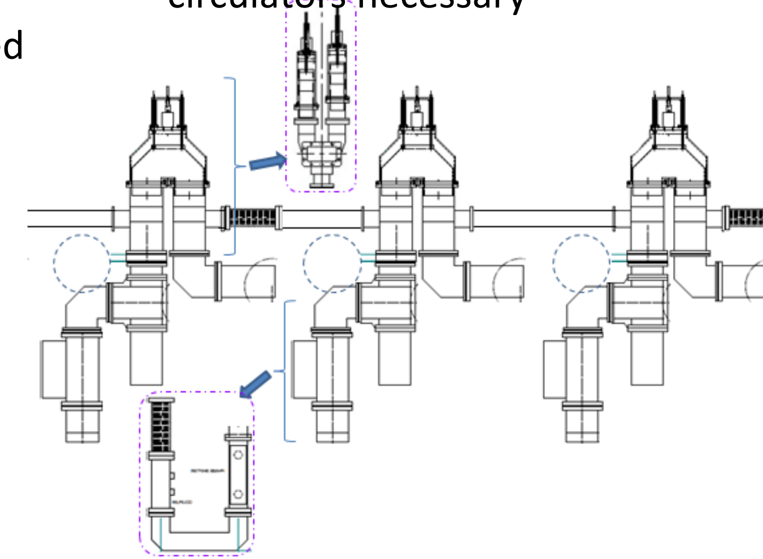
Alternate Scheme w/ Folded Magic-T's and Motorized U-Bend Phase Shifters

- *remotely* adjustable by pairs
- requires pair sorting
- circulators can be eliminated



Folded Magic-T's and Motorized U-Bend s for Each Cavity

- *remotely* adjustable by pairs
- *no* pair sorting required
- circulators necessary



Peak RF Power Required from Klystrons per 27 RF Unit KCS (full current)

294.3 kW	(nominal to beam per cavity = 31.5 MV/m $\times$1.038m $\times$ 9 mA)
× 1.059	(for flat gradient w/ cavity gradient spread and common timing)
× 1.062	(for statistical spread in feed/rf unit requirements w/ fixed couplings)
× 26	(cavities/rf unit)
÷ 0.95	(~5% local distribution losses) = 9.06 MW/rf unit @ CTO
× 27	(rf units)
÷ 0.935	(6.5% main waveguide losses) = 271.3 MW @ beginning of linac run
÷ 0.983	(shaft and bends)
÷ 0.993	(combining CTO circular waveguide losses)
÷ 0.965	(input circulator and WR650 losses)
÷ 0.977	(CTO coupling/klystron amplitude mismatches)
284.2 MW	from klystrons

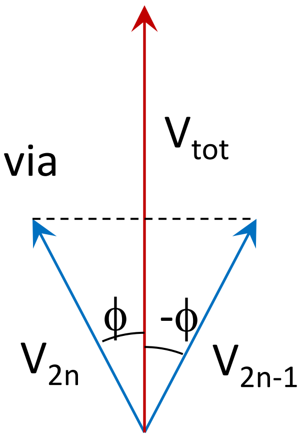
~8% klystron-to-tunnel

Klystrons Needed per 27 Unit KCS (full current)

The calculation/estimate suggests we need 284.2 MW worth of klystron power.
At 10 MW each, 29 klystrons would give us 290 MW (2.0% to spare).

However, we want to be robust against a single klystron failure per system. With N sources combined in a passive network, failure of one source leaves combined the equivalent of $(N-1)^2/N$ sources.

With 31 klystrons and 30 on, we have 290.3 MW available (2.2% to spare).



However, we also need 7% (5% usable) overhead for LLRF to be harnessed via phase control of the rf drives, oppositely dephased in pairs, such that the combined power is reduced as $P = P_{max} \cos^2 \phi$, with ϕ nominally 15˚.

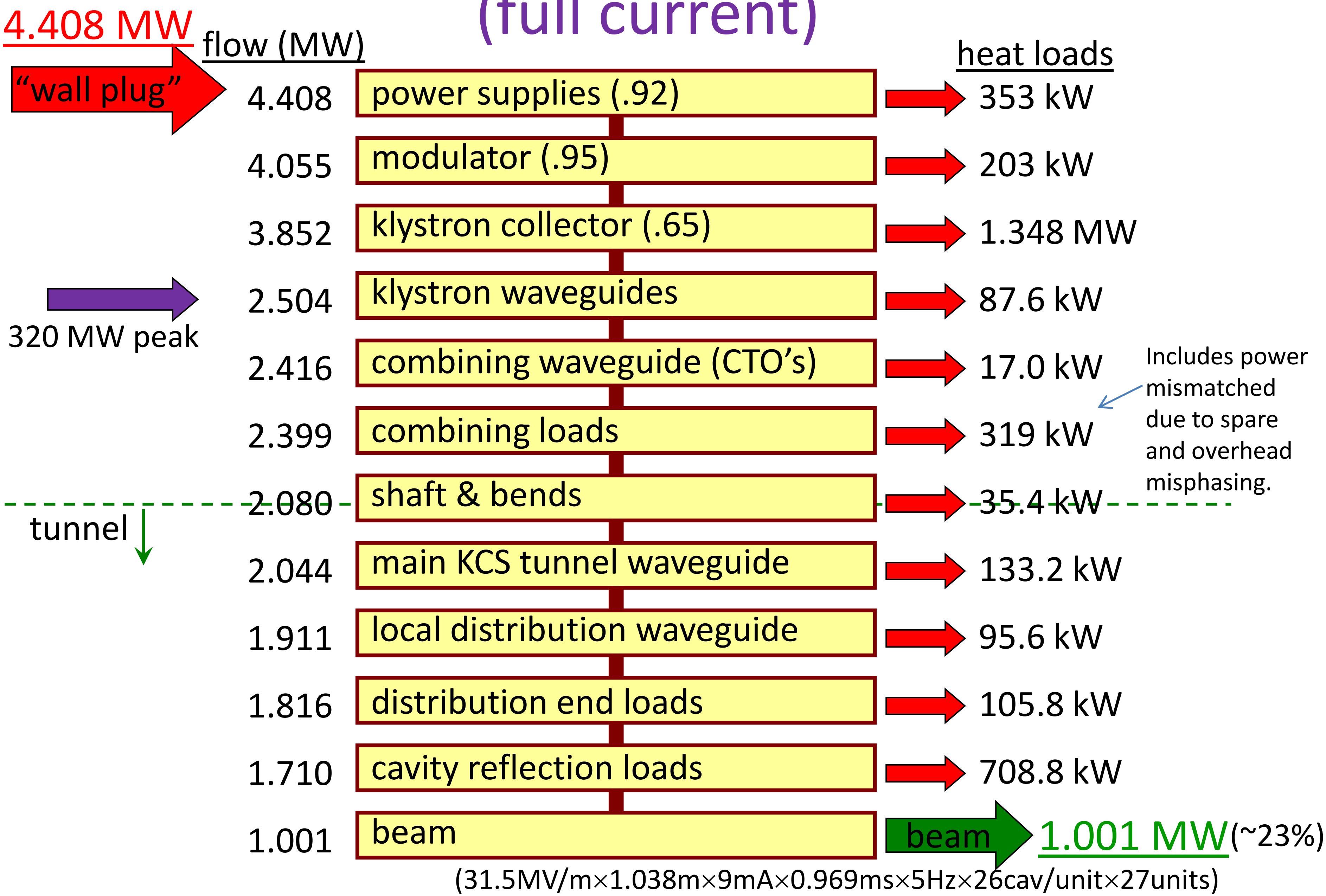
The maximum power requirement rises to 284.2 MW ÷ 0.933 = 304.6 MW,

With **33 klystrons** and one off, we have 310.3 MW (1.9% to spare).

(30 klystrons for the 24 unit KCS and
25 klystrons for the 20 unit KCS)

TOTAL: 20×33 + 30 + 25 = 715 klystrons installed (693 on)

27 Unit KCS Average Power Diagram (full current)



Reduced Beam Current

Halving the number of bunches in the ILC beam pulse is considered as a way to reduce the (initial) cost of the machine. The direct impact on the luminosity might be ameliorated by introduction of a traveling focus scheme. In this reduced beam current "low power" scenario, **site power** is reduced, along with **water cooling** requirements.

Additionally, for the high-power rf system, the amount of **installed rf** production equipment can be significantly **reduced**.

The impact depends on the bunch frequency, f_B, which affects:

beam pulse current: $I_b = N_e e f_B$

beam pulse duration: $t_b = (n_B - 1) f_B^{-1}$

and thus

rf power per cavity: $P_{rf} = I_b V_c = N_e e V_c f_B$

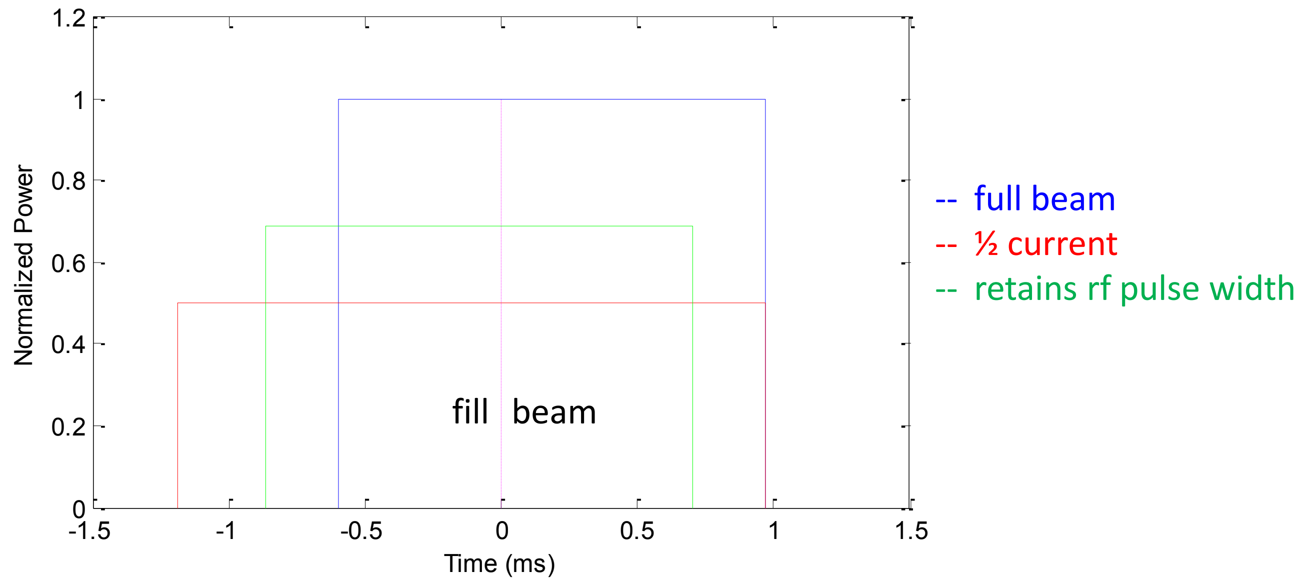
rf pulse duration: $t_{rf} = t_i + t_b = \left[\frac{2 \ln 2}{\omega N_e eR / Q} V_c + (n_B - 1) \right] f_B^{-1}$

KCS Low Power

KCS is very *flexible*. Combining tens of klystrons allows us to adjust installed power with relatively fine granularity.

Fixed t_b: Simply eliminating every other bunch (**halving f_B**) maintains the beam duration and halves the *current*, cutting in **half** the required ***peak power***. *<u>However</u>*, it also *doubles* the cavity *fill time*. , thereby **increasing** the required **rf pulse width** at full gradient by **38%**. ($P_{rf} \rightarrow ½ P_{rf0}$, $t_{rf} \rightarrow 1.38\ t_{rf0}$)

Fixed t_{rf}: It's preferable to adopt parameters which allow use of the modulators and klystrons developed for full RDR beam specifications, i.e. to stay within the ~1.6 ms pulse width. This can be achieved by reducing the bunch spacing to increase the current to **0.69 I_0**. The rf peak power required at the cavities is reduced from that for the full beam by this factor. ($P_{rf} \rightarrow 0.69\ P_{rf0}$, $t_{rf} \rightarrow t_{rf0}$)



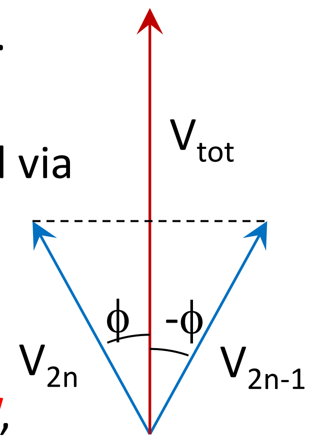
Klystrons Needed per 27 Unit KCS (1/2 bunches)

Scaling from the full current case, we need (0.69×284.2=) 196.1 MW worth of klystron power. At 10 MW each, 20 klystrons would give us 200 MW (2.0% to spare).

However, we want to be robust against a single klystron failure per system. With N sources combined in a passive network, failure of one source leaves combined the equivalent of $(N-1)^2/N$ sources.

With 22 klystrons and 21 on, we have 200.5 MW available (2.2% to spare).

However, we also need 7% (5% usable) overhead for LLRF to be harnessed via phase control of the rf drives, oppositely dephased in pairs, such that the combined power is reduced as $P = P_{max} \cos^2 \phi$, with ϕ nominally 15˚.



The maximum power requirement rises to 196.1 MW ÷ 0.933 = 210.2 MW,

With **23 klystrons** and one off, we have 210.4 MW (0.12% to spare).

(21 klystrons for the 24 unit KCS and
18 klystrons for the 20 unit KCS)

TOTAL: 20×23 + 21 + 18 = 499 klystrons installed (477 on)

30.2% reduced from full current

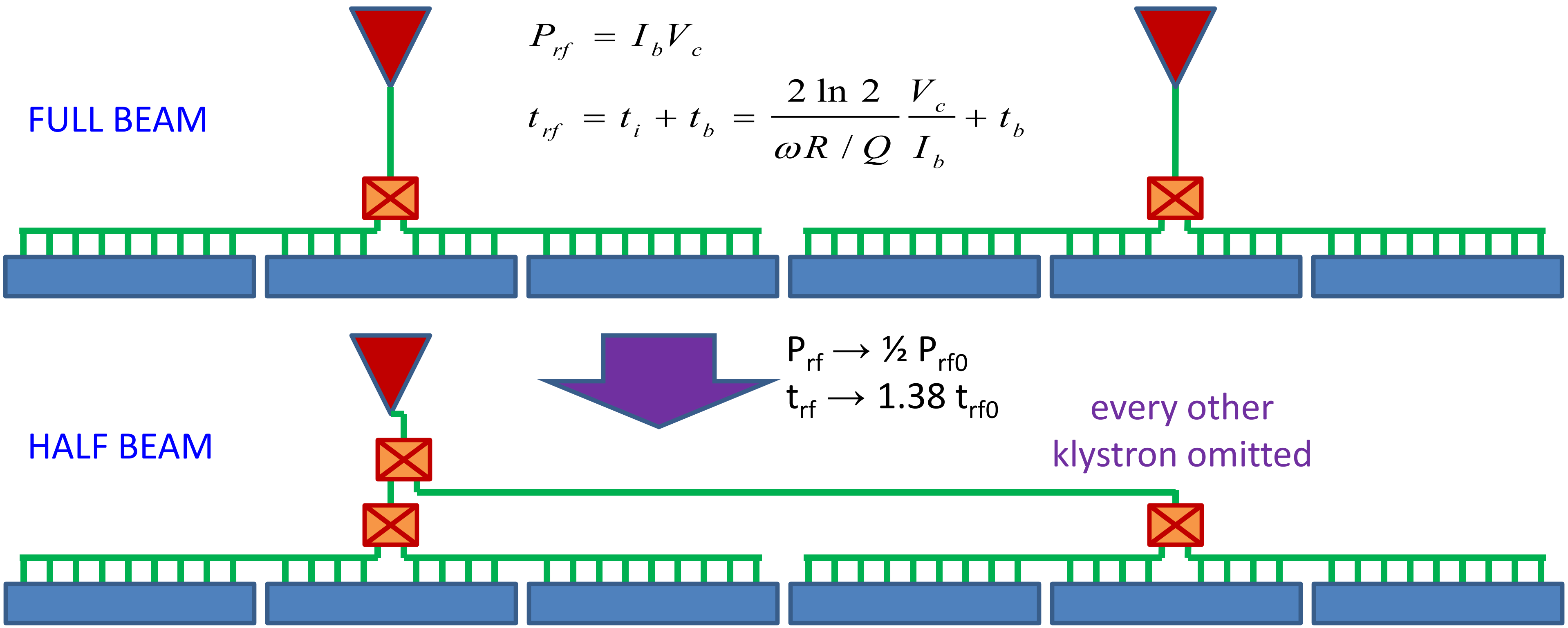
RDR-Like Fallback Low Power

With the KCS and DRFS schemes in development, an RDR-like layout w/ **10 MW klystrons, modulators, etc. in the (enlarged) single tunnel** is considered the fallback plan.

For half bunches operation, one could double the bunch spacing and install half the modulators and klystrons, each feeding 6 CM's, rather than 3.

$$P_{rf} = I_b V_c$$

$$t_{rf} = t_i + t_b = \frac{2\ln 2}{\omega R/Q}\frac{V_c}{I_b} + t_b$$



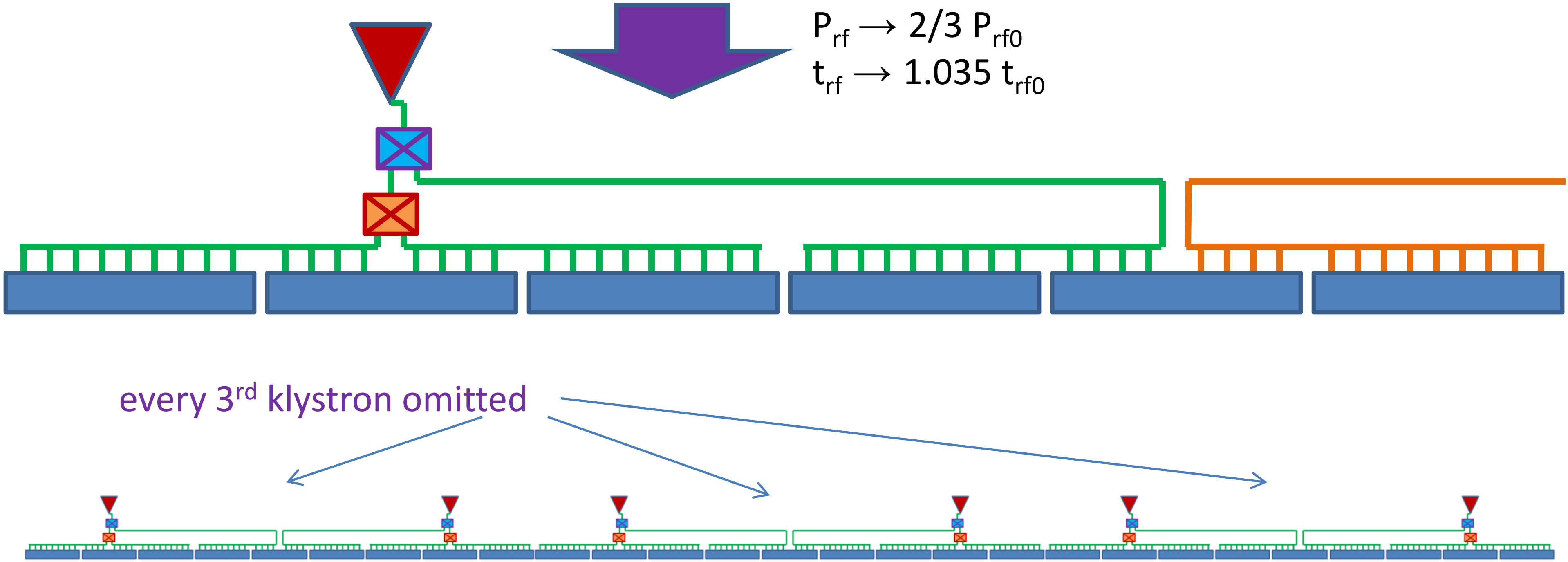
$P_{rf} \rightarrow \frac{1}{2} P_{rf0}$

$t_{rf} \rightarrow 1.38\, t_{rf0}$

This would double the fill time, **increasing** the required **rf pulse** width by 38%.
The installed modulators and klystrons would then be overspec.ed for the upgrade.

Alternatively, one could install 2/3 of the rf production equipment, with each klystron feeding 4 ½ CM's.

This would reduce the available power per cavity, and thus the acceleratable beam current or bunch frequency, by a factor of ~2/3 vs. RDR.

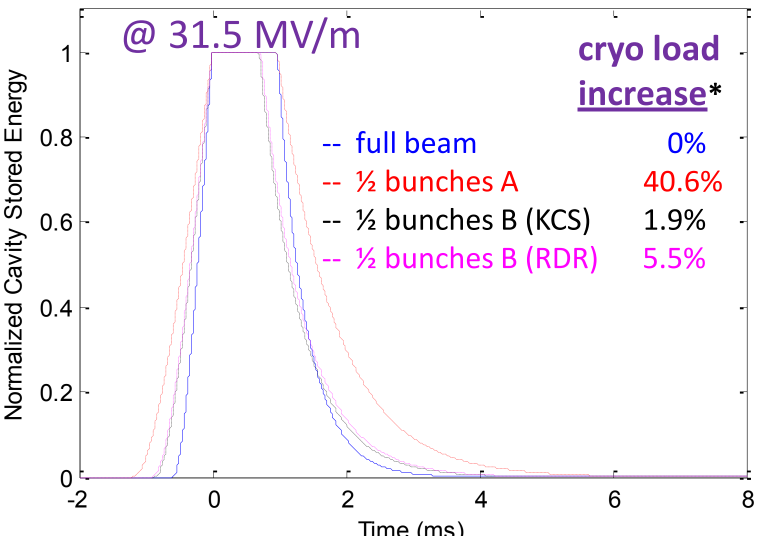


The beam pulse duration ($\propto n_B/I_b \rightarrow$ ½ / 2/3) is then shortened by a factor of ¾, and the fill time increased by a factor of 3/2, yielding an rf pulse width increase of only ~3.5%.

Parameter Summary

250 GeV/beam	# of bunches	bunch spacing	beam current	beam duration	rf peak power	fill time, t_i	rf pulse duration
full beam	2625	369.2 ns	9 mA	0.969 ms	294.2 kW	0.595 ms	1.564 ms
½ bunches A	1313	738.5 ns	4.5 mA	0.969 ms	147.1 kW	1.190 ms	2.159 ms (up 38%)
½ bunches B KCS	1313	535.1 ns	6.21 mA	0.702 ms	203.0 kW	0.862 ms	1.564 ms
½ bunches B RDR	1313	553.8 ns	6 mA	0.727 ms	196.1 kW	0.893 ms	1.619 ms (up 3.5%)

Parameter choice also impacts cryogenic load.

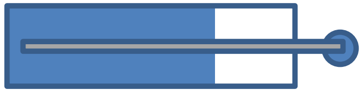


* Only includes dynamic load of fundamental rf in cavity. Additional contributions come from coupler (linear w/ power and time) and HOM (current dependent).

Installation for Reduced Bunches

KCS:

- Everything in the tunnel is installed.
- 69.8 % (499/715) of high power rf production equipment (klystrons, modulators, power supplies, etc.) in KCS surface buildings, *upstream* from shaft, with main waveguide runs traversing the region where the rest will go.



- 68.8% (477/693) of "wall plug" power for main linac high power rf.
- 75%* of water cooling capacity for heat load from high power rf.

RDR-Like Fallback:

- 66.7 % of high power rf production equipment in the linac tunnels, with *additional* power dividers and waveguide.
- 69% (1.035 × 2/3) of "wall plug" power for main linac high power rf.
- ~ 75%* of water cooling capacity for high power rf heat load.

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* <u>full current</u>

rf power: P_{rf0}

beam power: $P_{b0} = 0.23P_{rf0}$ (see slide 9)

heat load: $P_{h0} = P_{rf0} - P_{b0} = 0.77P_{rf0}$

<u>1/2 bunches</u>

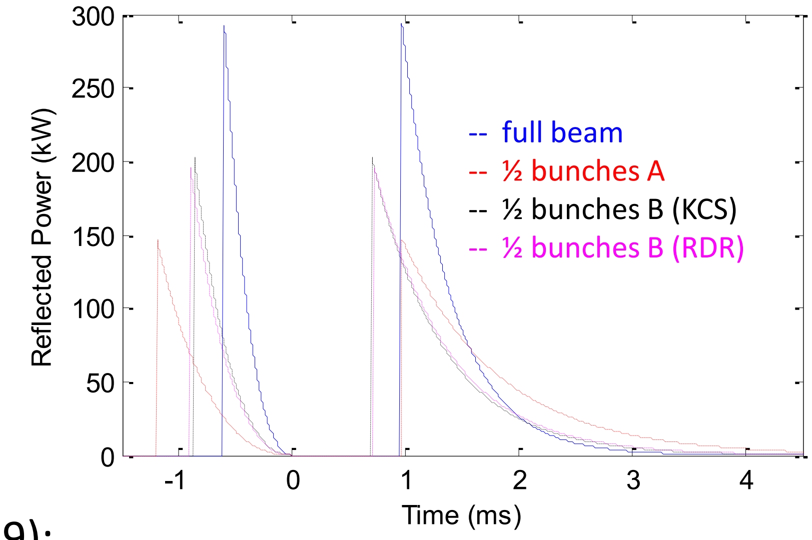
rf power: $P_{rf} = 0.69P_{rf0}$

beam power: $P_b = 0.5P_{b0} = 0.115P_{rf0}$

heat load: $P_h = P_{rf} - P_b = 0.575P_{rf0} = \underline{0.747}P_{h0}$

Heat Load Breakdown for KCS

The rf energy deposited per pulse into the cavity reflection loads (circulator loads), being the product of P_{rf} ($\propto I_b$) and t_i ($\propto I_b^{-1}$), is, for a given gradient, constant across the parameter sets.



<u>HPRF heat load distribution</u> (from slide 9):
above ground – 68.3%
below ground – 31.2% (65.7% fixed, 34.3% power dependent)

<u>HPRF heat load reduction factor:</u>
above ground – 0.69
below ground – (0.657 + 0.343×0.69) = 0.894
Total – (0.683×0.69 + 0.312×0.894) = <u>0.750</u>

For the RDR-like layout the total reduction is the same, 0.75, all below ground.

Transition to Full Beam Current

KCS:

- Upgrade is all above ground.
- Install remaining 31% of “wall plug” power capacity.
- Install remaining 25% of cooling capacity.
- Install remaining 30.2% of high-power rf hardware in the *KCS buildings*.

Most, up to the point of connecting the sources into the main waveguide, can be done while *running*.

RDR-Like Fallback:

- Install remaining 31% of “wall plug” power capacity.
- Install remaining 25% of cooling capacity.
- Install remaining 33.3 % of high-power rf hardware in the *linac tunnels*.

ILC is *shut down* during installation.