HLRF
Power Distribution System
(PDS)

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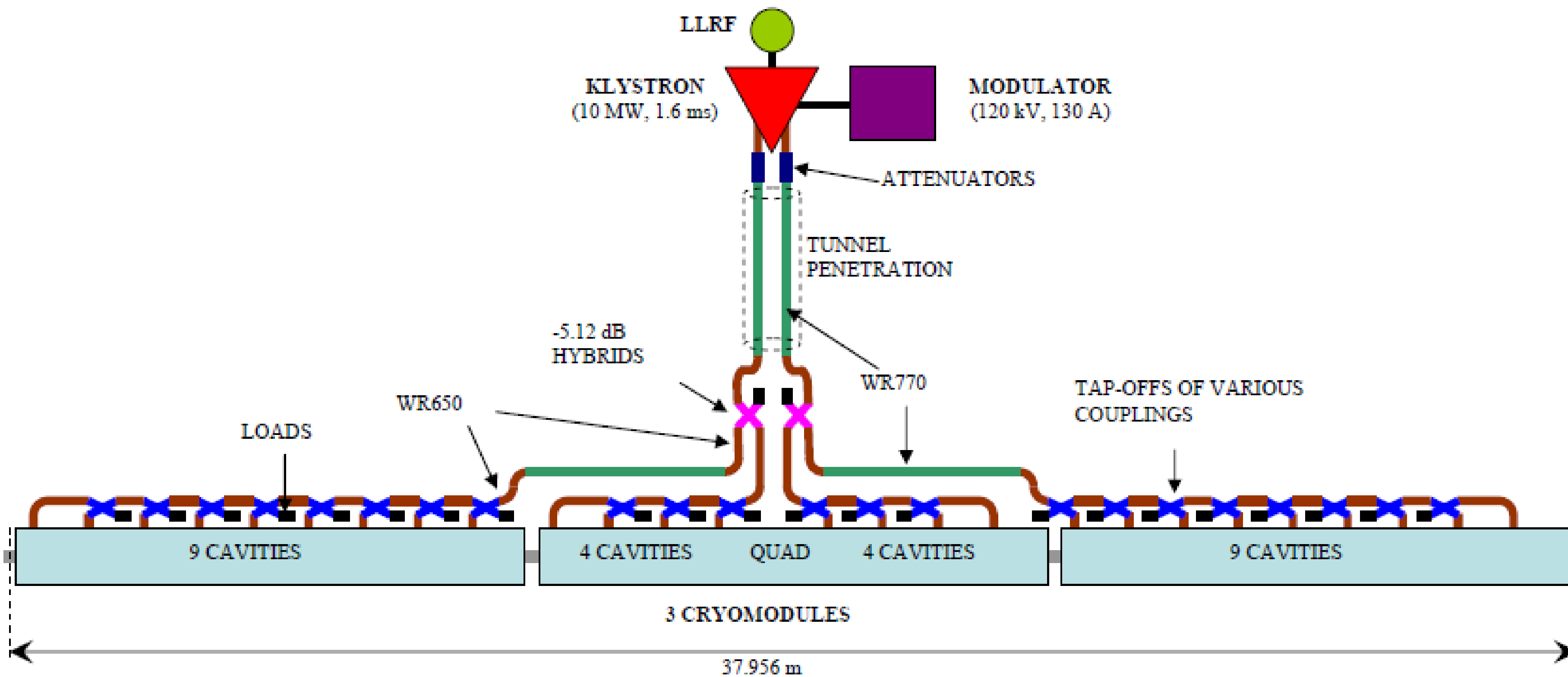
SLAC

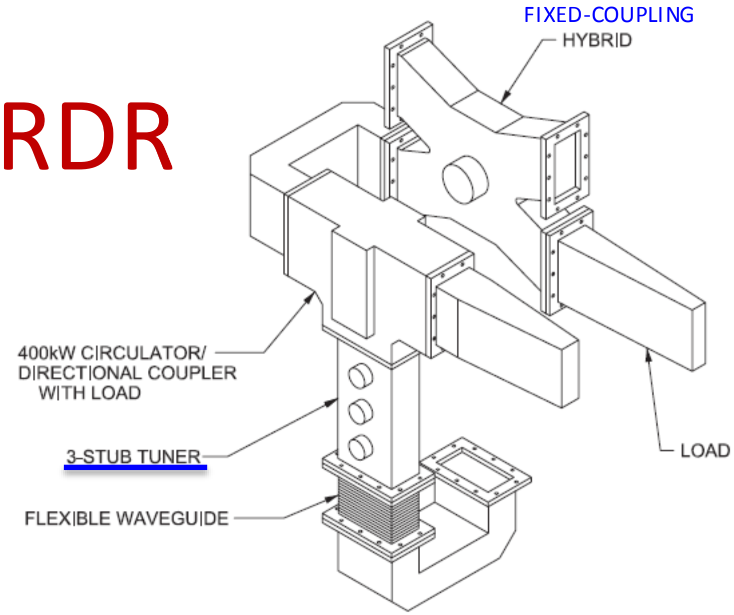
KILC, Daegu, Korea
April 23-27, 2012

Old RDR Power Distribution System

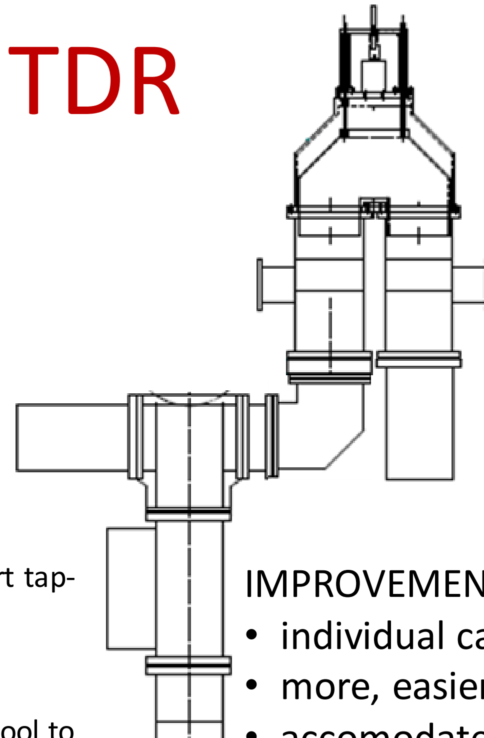


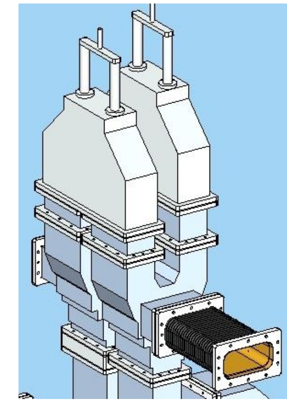
Main Changes to Local Power Distribution System (LPDS)

RDR



TDR





"RF power is equally distributed among the cavities… hybrid-style 4-port tap-offs… couple the appropriate sequential fraction…
The three-stub tuner allows fine adjustment of both cavity phase and external coupling. …
With three degrees of freedom, the three-stub tuner is a complicated tool to use. It is, however, compact and well tested in TTF. It may be desirable to replace it with an alternate phase shifter, with the movable coupler antenna providing Q_{ext} adjustment. …
The entire waveguide system, from the klystron window to the outer coupler window, is pressurized with dry nitrogen to a pressure of 3 bar absolute."

IMPROVEMENTS:

- individual cavity power adjustability
- more, easier cavity phase control
- accomodates unpressurizable couplers

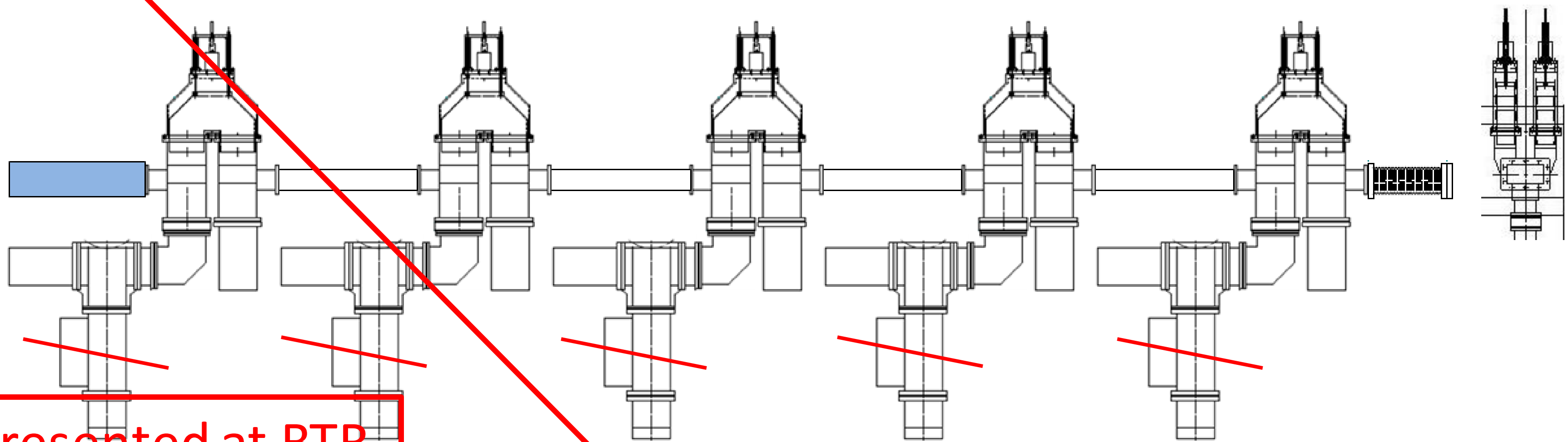
<u>base cost</u> <u>quantity reduction</u>

2×(folded magic-T + U-bend ϕ-shifter) + window + ϕ-shifter:

fixed "slot" or ferrite-based hybrid + 3-stub tuner:

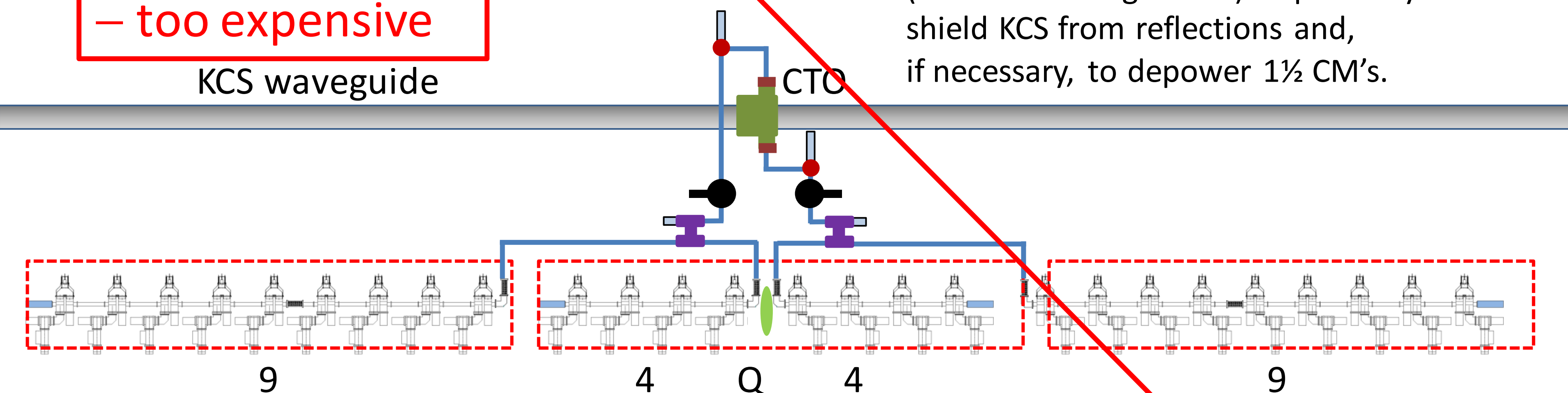
Also, the 5 MW variable attenuators shown in RDR for 13-cavity power tweeking may not have been costed (or even exist).

Local PDS Circuit



presented at BTR
in January 2012
– too expensive

Use ~~circulators~~ and r.c. ~~switches~~ (as in combining circuit) respectively to shield KCS from reflections and, if necessary, to depower 1½ CM's.



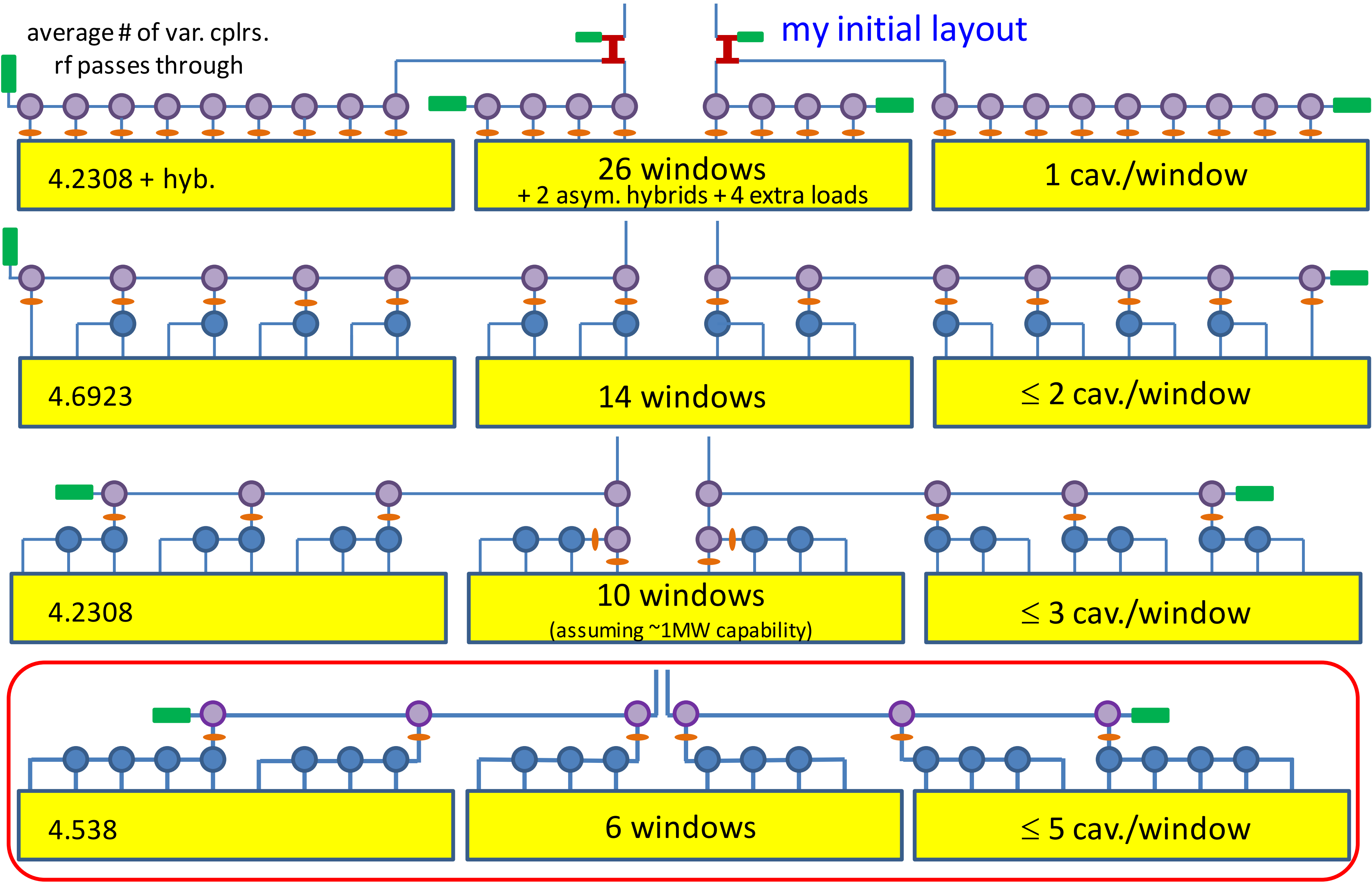
By splitting CTO outputs through ~~asymmetric (-5.12 dB) "hybrids"~~, as in the RDR, we can physically decouple cryomodules and limit variable coupler cascading.

PDS Cost Reduction

After the costing exercise performed for the BTR meeting, the cost estimate for the PDS was considered too high, requiring efforts to find a more economical solution. Options considered have included:

- ~~Returning to cavity pairing~~
- Removing remote control of relative power couplings to cavities ?
- branching distribution to minimize number of windows ✔
- substituting limited range for unnecessary full range power dividers ?

Branched PDS Layouts



Window Power Handling

Maximum Power Needed per Cavity Fed:

	287.2 kW	(nominal for ***high power***)
×	1.06	(timing)
×	1.04	(local losses)
×	1.20	(max gradient - all unlikely)
	380 kW	

→	1 cav.:	380 kW
	2 cav.:	760 kW
	3 cav.:	1.14 MW
	4 cav.:	1.52 MW
	5 cav.:	**1.90 MW**
	9 cav.:	3.42 MW
	13 cav.:	4.94 MW

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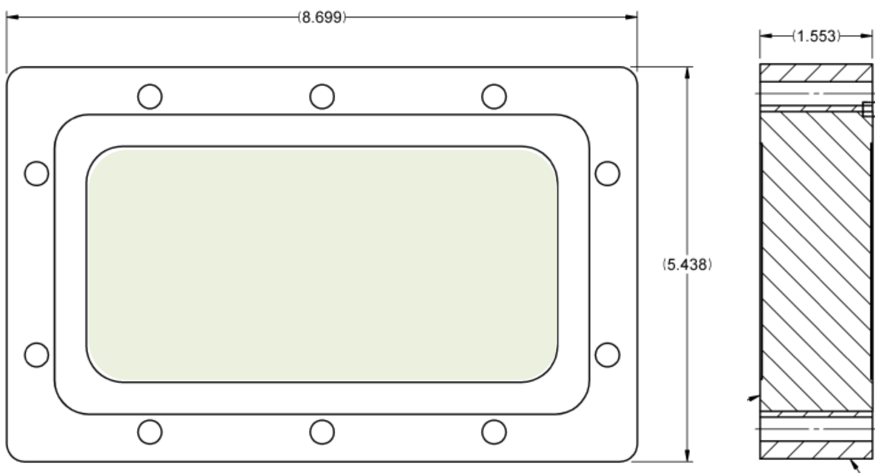
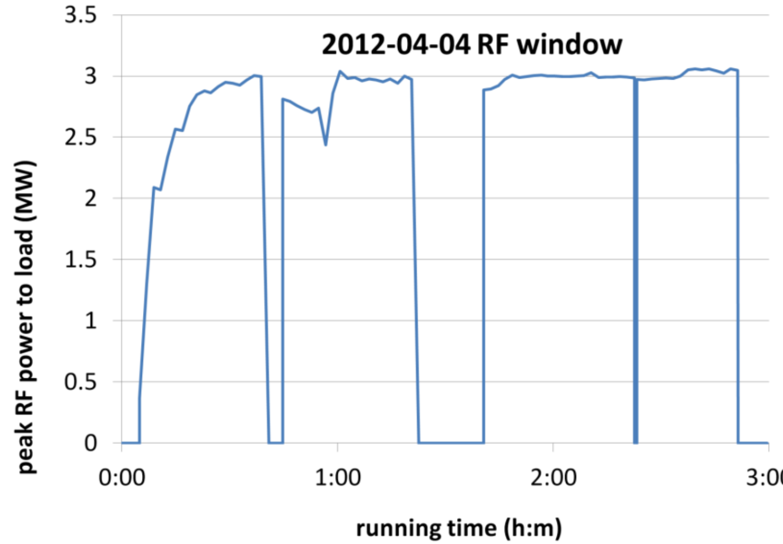
Nantista & Neubauer



Ceramic Plug
Pressure Window

High power tested up to **3 MW, 1 ms**.



U-bend Phase Shifter

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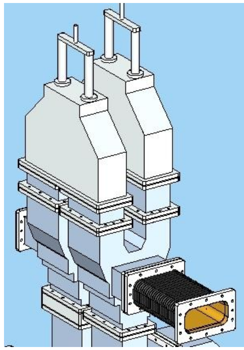
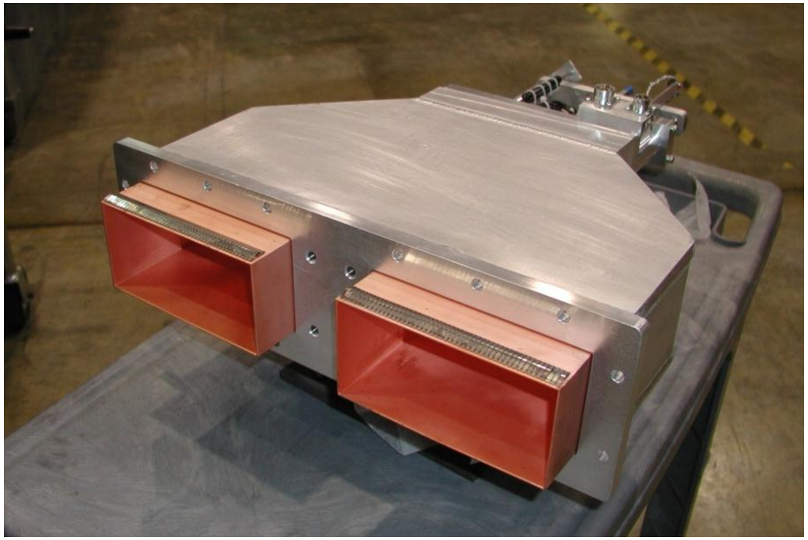
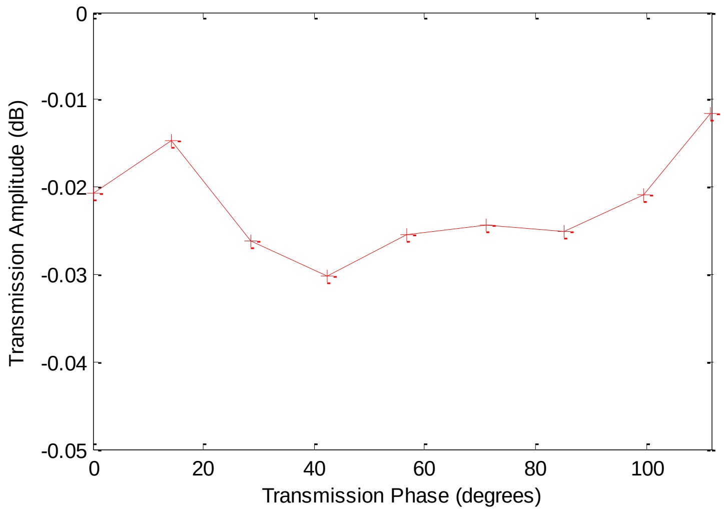
Nantista



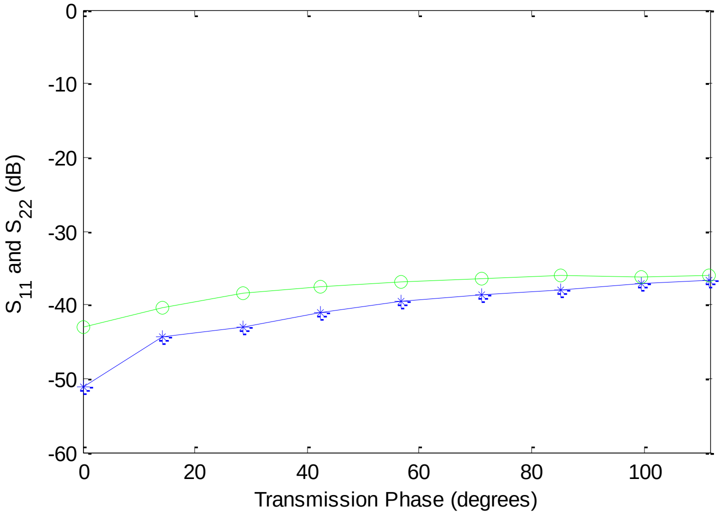


Tested to **2 MW**

- No significant field enhancement or mismatch.
- Rate of phase change with mechanical position independent of position

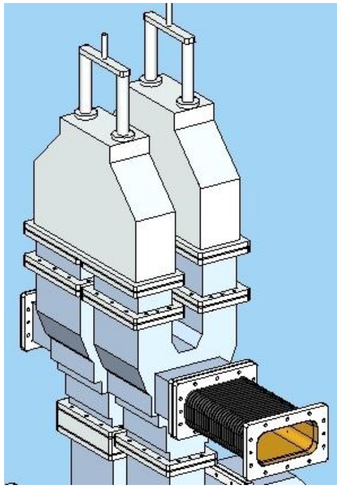


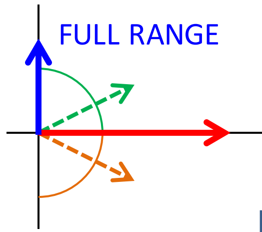
mean loss: ~0.51% (-.0221 dB)

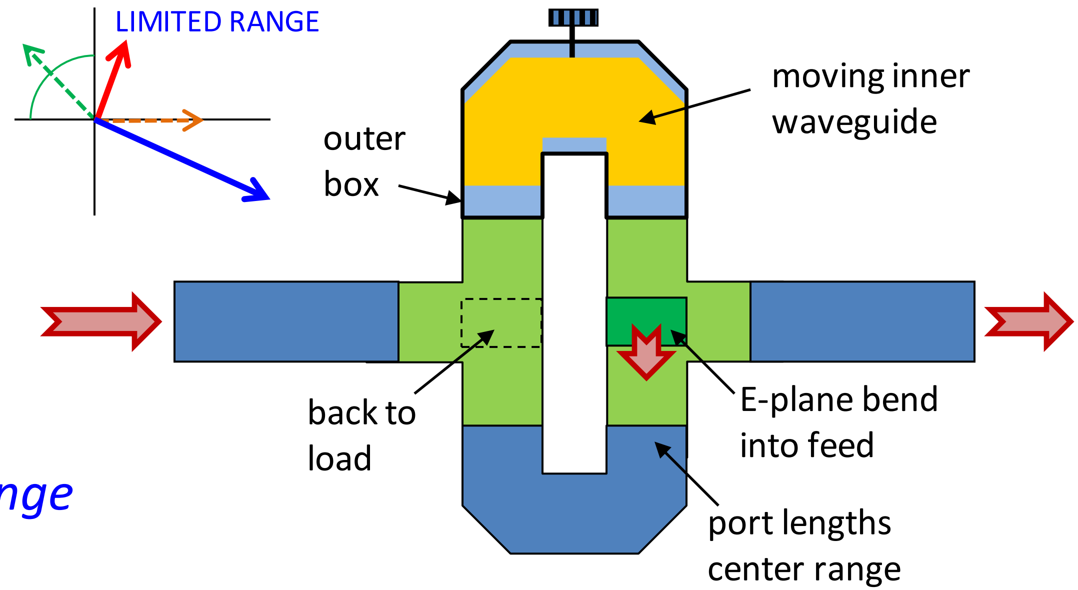


max reflection: ~0.025% (-36 dB)

Simplify Most Power Dividers







For *unpressurized*, *limited range* variable power dividers, use:

- *non-pressurizable* waveguide (after windows)
- *ordinary* (not folded) magic-T's
- a *single* trombone + a U-bend (need phase shifters)

nominal coupling	Δϕ range	coupling range ($\cos^2\Delta\phi/2$)
20%	81.9°–171.9°	0.5–57.0%
25%	75°–165°	1.7–62.9%
33%	64.5°–154.5°	4.9–71.5%
50%	45°–135°	14.6–85.4%

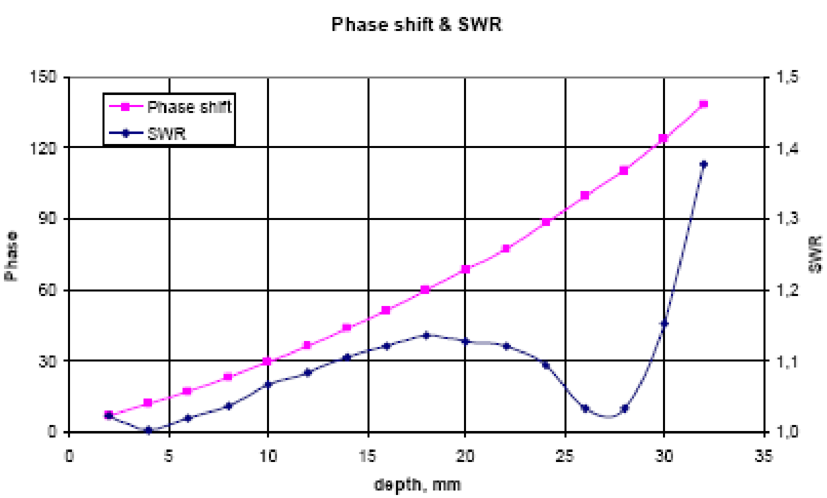
Set cavity phases right for nominal couplings by input waveguide length (spacers on E-plane U-bend).

Each divider can introduce a phase change of up to ±22.5°.

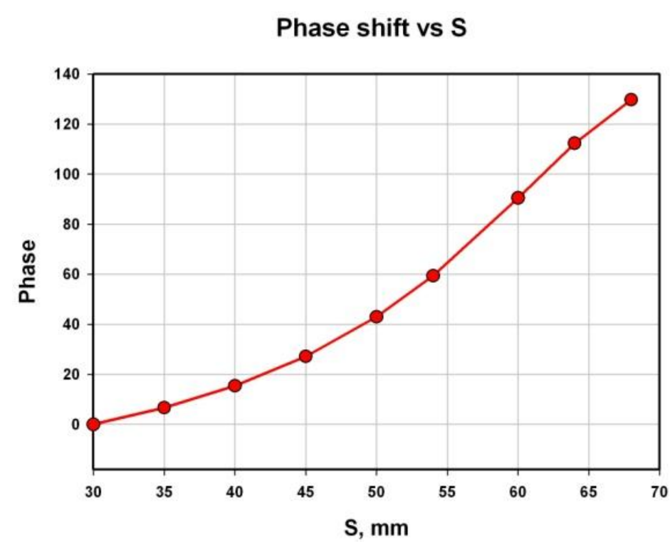
Phase shifters have a range of ~130° (± 65°), so it's possible, but unlikely to get out of range by the 5th cavity in a group of 5.

Phase Shifters

DESY/SPA Ferrite
Katalev & Choroba



KEK/Toshiba
Kazakov



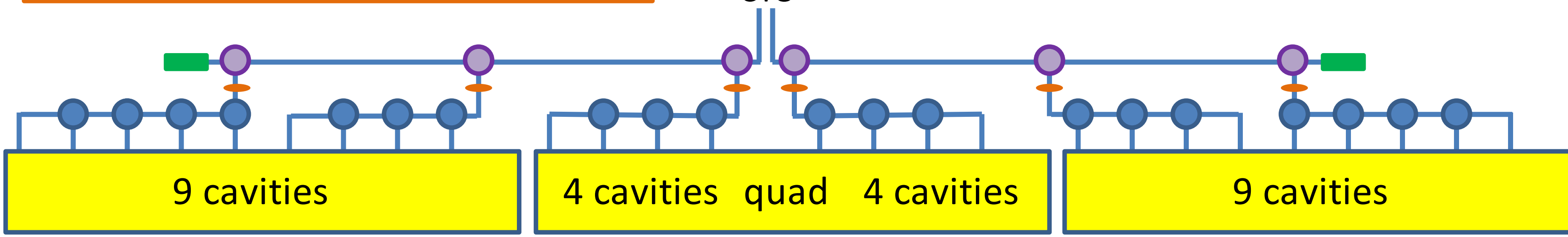
Streamlined PDS

- – pressurizable, 0-100%, phase stable
- – non-press., limited range
- – pressure window
- – 5 MW load

Unused power can be dumped to the loads

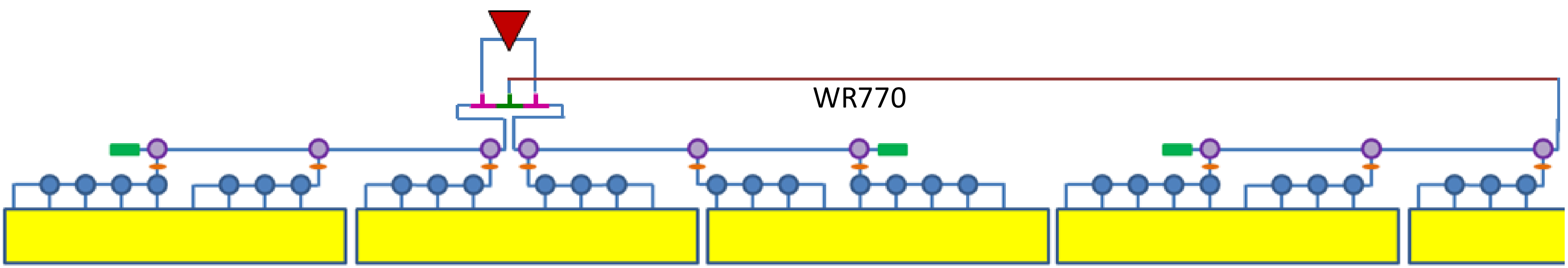
Power to ½ CM's fully adjustable without affecting phases.

from CTO



phase shifter on each feed, as well as isolator, bi-directional coupler, and flex guide.

RF UNIT: 3 cryomodules (26 cavities)



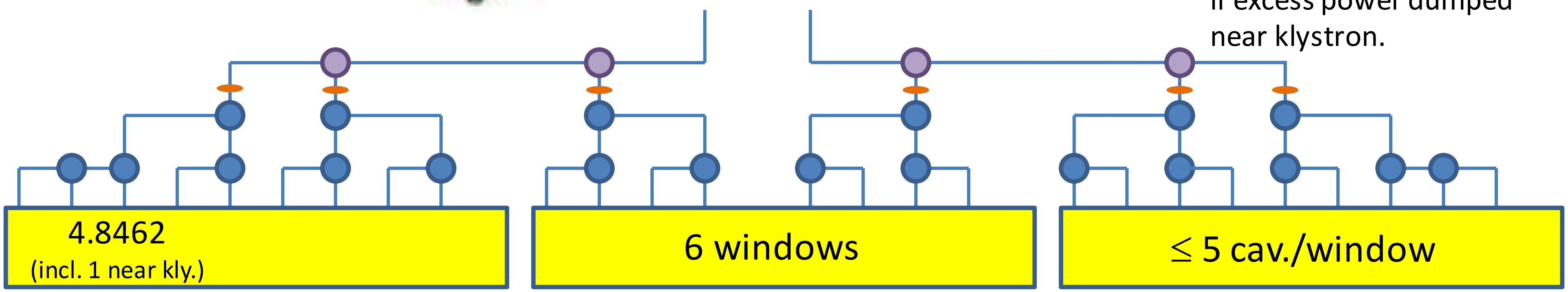
For low power **Kamaboko** Tunnel option, one klystron powers 1 ½ rf units or 4 ½ cryomodules (39 cavities).

Shigeki’s Tree-Like Layout

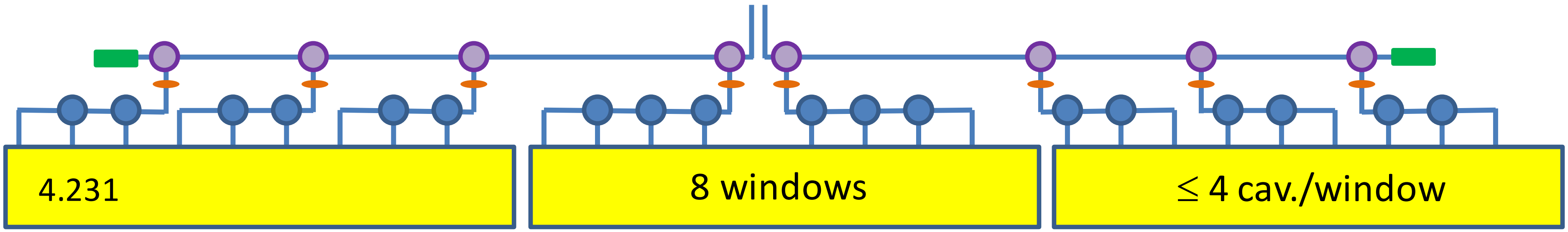
w/ Kazakov hybrids
+ phase shifters

to neighboring ½ rf unit for low power

plus 2 var. cplr’s & 2 loads if excess power dumped near klystron.

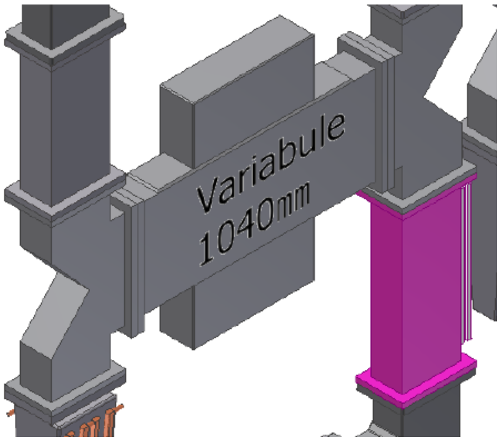


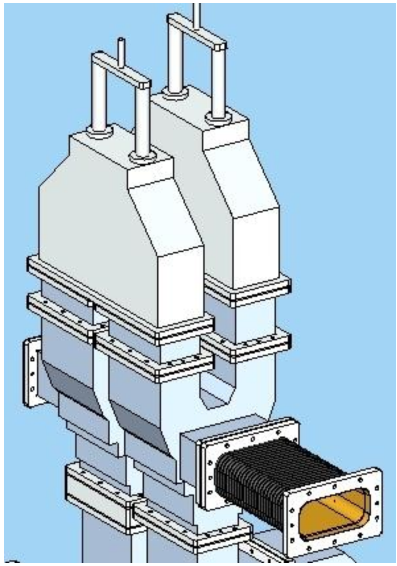
Double branching used to avoid small coupling ratios, where Kazakov variable hybrid becomes highly sensitive.

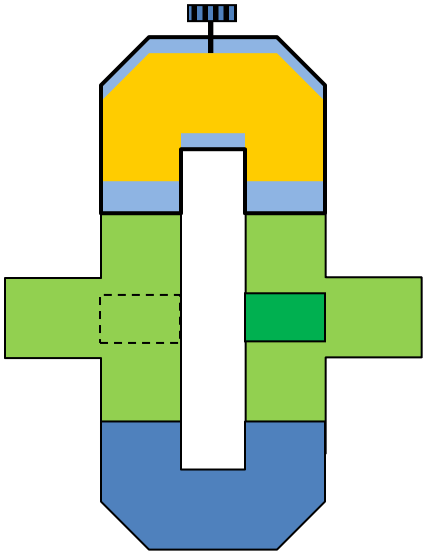

4.231
8 windows
≤ 4 cav./window

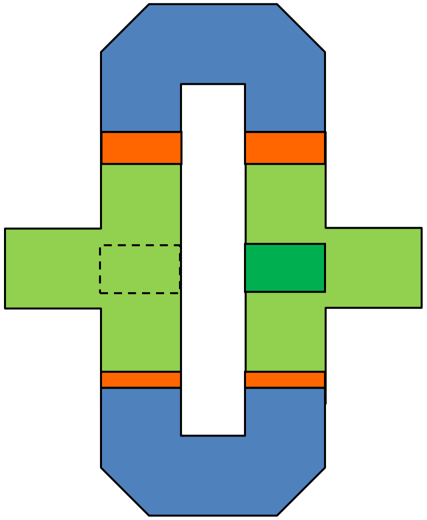
Options for PDS Power Splitting

VTO (mode rotator) – too long w/out pairing, not motorizable.









Variable H-hybrid

motorizable

needs phase shifters

small coupling limited

folded magic-T's and U-bend phase shifters

motorizable

magic-T's, U-bend phase shifter, and U-bend

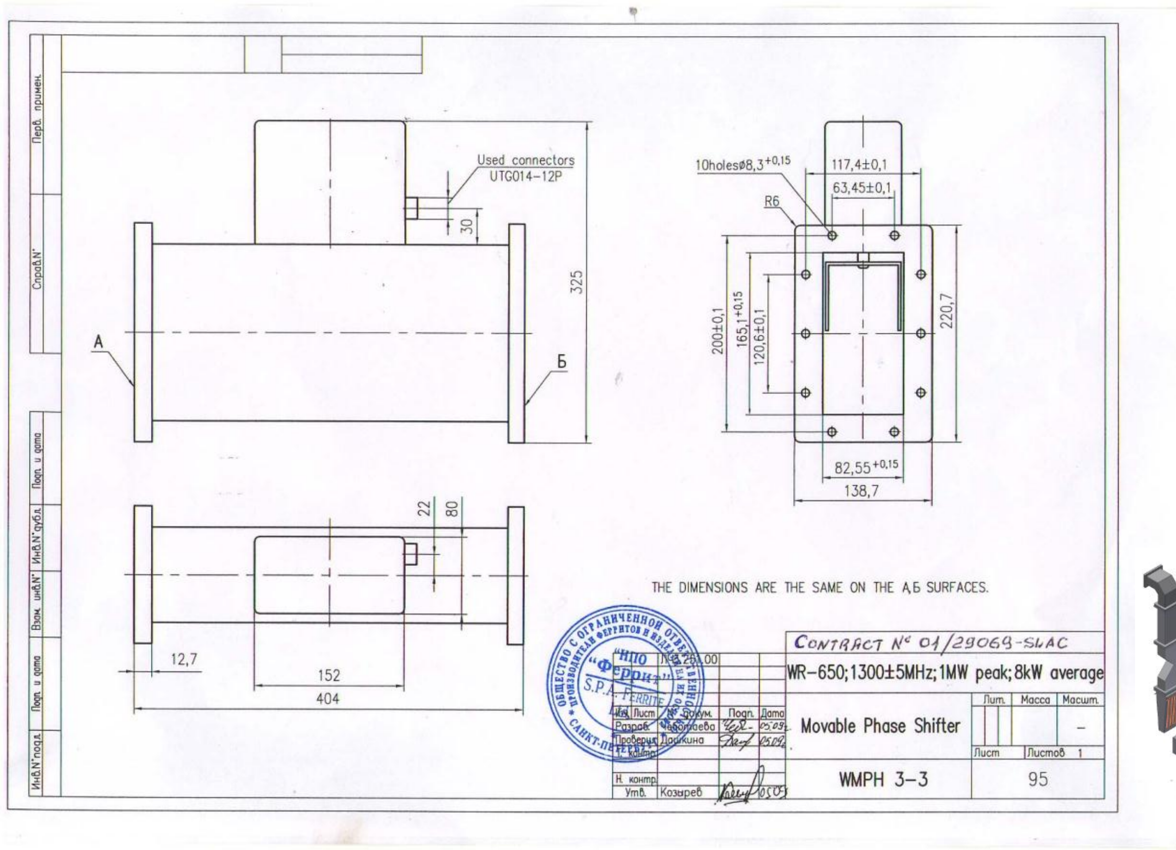
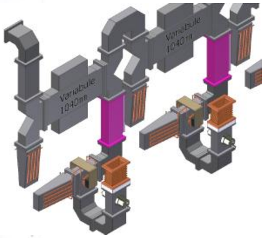
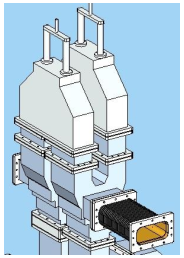
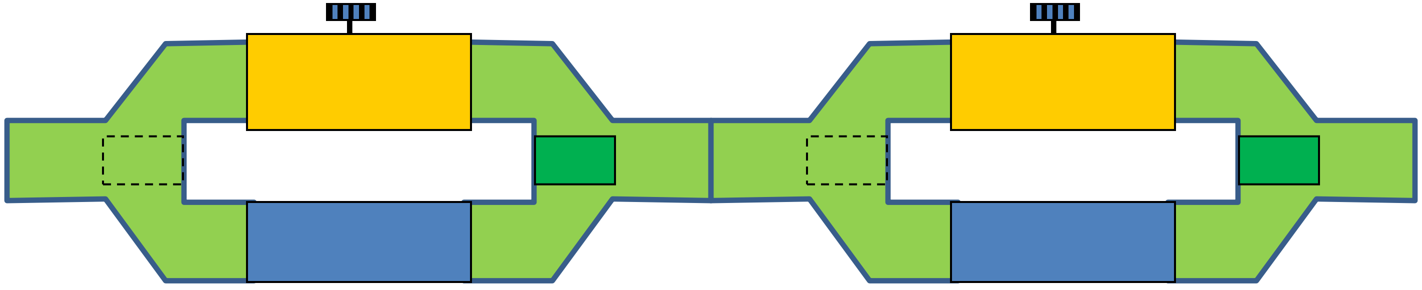
motorizable

needs phase shifters

magic-T's, U-bends, and customized spacers

custom machining?*

*stacked shims?


Used connectors
UTG014-12P
10holesø8,3+0,15
117,4±0,1
63,45±0,1
R6
30
325
200±0,1
165,1+0,15
120,6±0,1
220,7
82,55+0,15
138,7
A
Б
22
80
12,7
152
404
THE DIMENSIONS ARE THE SAME ON THE A,Б SURFACES.
CONTRACT № 01/29069-SLAC
WR-650; 1300±5MHz; 1MW peak; 8kW average
Movable Phase Shifter
WMPH 3-3
95
Лит.
Масса
Масшт.
Лист
Листов 1
Разраб.
Провер.
Н. контр.
Утв.
Козырев
Подп.
Дата
Перв. примен.
Справ. N°
Подп. и дата
Инв. N° дубл.
Взам. инв. N°
Инв. N° подл.




Klystron Cluster System (KCS) Layout

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Power Needed per Cavity
(low power)

$$V(t) = V_{rf}(t) - V_b(t) = \sqrt{4P\frac{R}{Q_0}Q_L}\left(1 - e^{-\frac{\omega t}{2Q_L}}\right) - I_b\frac{R}{Q_0}Q_L\left(1 - e^{-\frac{\omega(t-t_i)}{2Q_L}}\right)$$

For optimal coupling of power to beam:

$$\text{Given}: E_{acc},\ L,\ I_b,\ R/Q_0$$

$$V = E_{acc}L, \quad P = I_b V$$

$$Q_L = \frac{P}{I_b^2 R/Q_0}, \quad t_i = \tau_c \ln 2 = \frac{2Q_L}{\omega}\ln 2$$

<u>Main Linacs are run at ϕ = 5° off-crest.</u>

E_{acc} = 31.5 MV/m, L = 1.038 m, I_b = 5.7857 mA, R/Q_0 = 1,036 Ω
$V_{eff} = E_{acc} \cos\phi\, L$ = 32.5726 MV
In-phase power: $P_{0,i} = I_b V_{eff}$ = 188.4546 kW into beam
$Q_L = 5.434 \times 10^6$, t_i = 922.3 μs

Out-of-phase power: $P_{0,o}(t<t_i) = P_{0,i} \tan^2 5°$ = 1.4425 kW

→ <u>$P_0(t<t_i)$ = 189.897 kW</u>

$$P_{0,o}(t > t_i) = \frac{V_{eff}^2 \tan^2\phi}{4(R/Q_0)Q_L} = \frac{1}{4}P_{0,i}\tan^2\phi = 360.6\ \text{W}$$

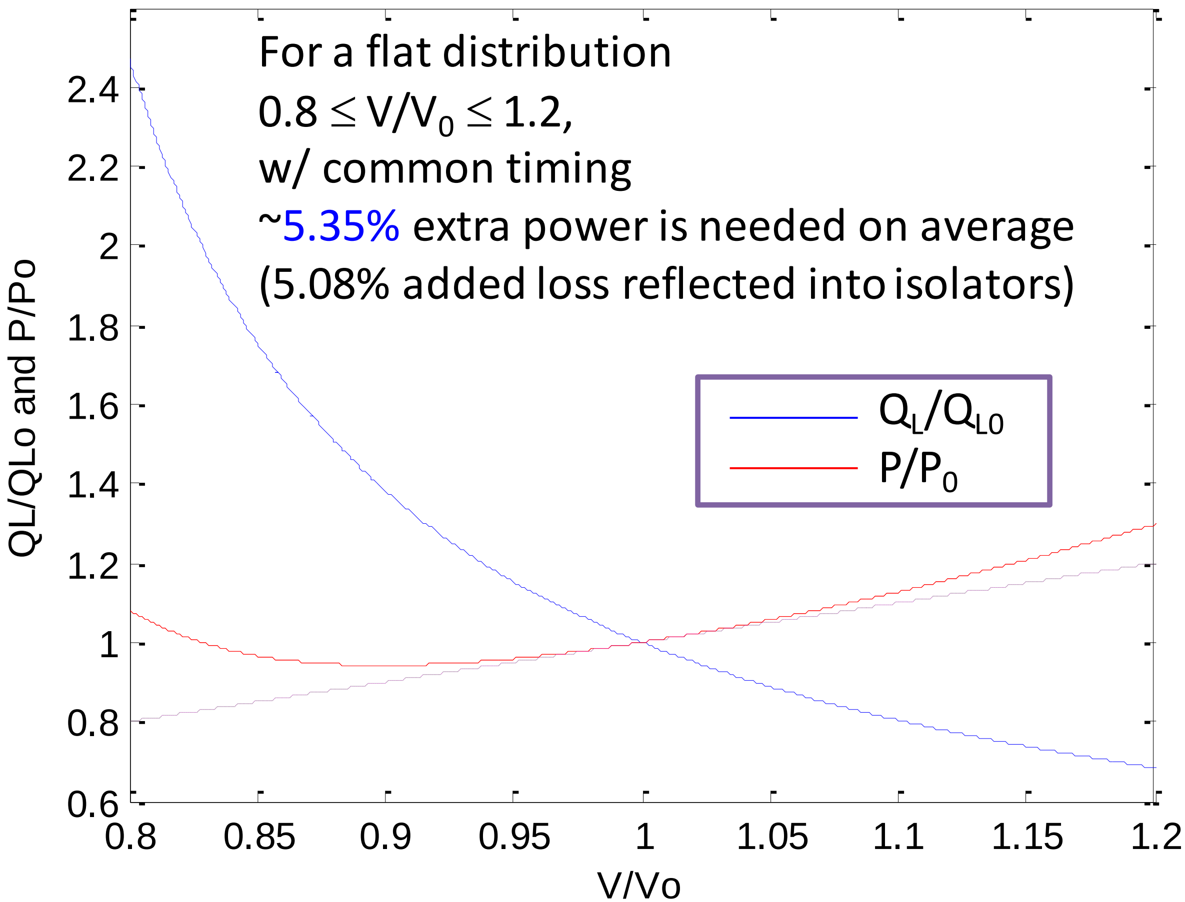
Drop out-of-phase component to steady state value at beam injection.

→ <u>$P_0(t<t_i)$ = 188.815 kW</u>

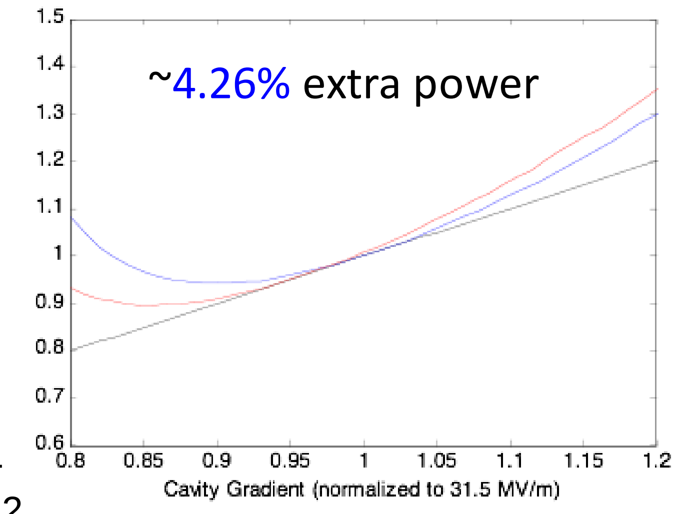
Achieving Flat Gradient w/ Common Timing

With control of P_k, Q_e, and t_i, can achieve flat acceleration at desired cavity gradient, with no power reflected during the beam pulse.

With 39—676 cavities locked to a common source timing,* flat acceleration over a range of gradients is still achievable by adjusting P_k and Q_e, albeit with some level of power reflected into isolator loads.



For a given distribution of gradients, the timing can be set so as to minimize the average reflected power.



* For upstream(downstream) KCS feeding, the effective spread in fill time is ~7.64(0.40) μs, roughly 1.28%(.07%) of the nominal fill time and has little effect on efficiency.

Peak RF Power Required from Klystron for RDR-Like feeding of 1.5 26-Cavity RF Units (Low Current)

189.9 kW	(nominal to beam per cavity)
× 39	(cavities fed) ~7.406 MW
÷ 0.965	(big circulator and WR650 losses)
÷ 0.94	(6% local distribution losses) ~8.164 MW
÷ 0.983	(WR770 run to other ½ rf unit)
× 1.054	(for flat gradient w/ cavity gradient spread and common timing)
× 1.062	(for statistical spread in feed/rf unit requirements)
÷ 0.933	($\cos^2 15^\circ$, counter-phasing to give 7% (5% usable) overhead for LLRF
9.965 MW	from klystron

Eliminate KCS Backup Klystrons

Power needed per 26(25) rf unit KCS KCS: ~193.26 MW (~185.19 MW)

With backups for a single failure per KCS:

$(21/22)^2 \times 22 \times 10$ MW = 200.45 MW → 22 klystrons (21 on) for 26 rf units 3.7% extra

$(20/21)^2 \times 21 \times 10$ MW = 190.48 MW → 21 klystrons (20 on) for 25 rf units 2.9% extra

If we eliminate backup spares, we can drop to:
→ 20 klystrons for 26 rf units 3.5% extra
→ 19 klystrons for 25 rf units 2.6% extra

Then **if one** klystron **fails** in a KCS:

$(19/20)^2 \times 20 \times 10$ MW = 180.5 MW 9.75% drop 6.6% low

$(18/19)^2 \times 19 \times 10$ MW = 170.53 MW 10.25% drop 7.9% low

- Squeeze overhead power out of remaining klystrons (~3%).
- Detune one cavity in each set of 13 (7.7%) fed by a CTO port.
- Adjust PDS power division to reestablish operating conditions in other cavities.
- Regain energy by bringing into play 2 of 4.5 available overhead rf units.

Then one loses 26 rf units × 2 cavities/rf unit = 52 cavities
→ 52 cav. × ~32.58 MeV/cav. = ~1.69 GeV (0.68%)

For Kamaboko option, one klystron loss costs 39 cavities
→ 39 cav. × ~32.58 MeV/cav. = ~1.27 GeV (0.51%)

TOTAL ML KLYSTRONS

RDR-Like (Kamaboko): 188 + 190 = **378** (374 on)

KCS (no backup): 17×20 + 5×19 = **435** (15% more)

KCS (backup): 17×20 + 5×19 = **479** (457 on) (27% more)

→ Overhead allows for **3** failed klystrons per main linac for Kamaboko and **2** for KCS (as long as not in the same KCS).

Copper Plate KCS Circular Waveguide?

σ = 2.459 $\times 10^7\ \Omega^{-1}\text{m}^{-1}$ (6061-T6 Al)
f = 1.3 GHz (k_0 = 27.246 m^{-1})
$\delta_s = (\mu_0 \pi f \sigma)^{-1/2}$
$R_s = 1/(\sigma\delta_s) = \sqrt{\mu_0 \pi f/\sigma}$ = 0.0144

k_0 = 27.246 m^{-1}
R_s = 0.0144
$\chi_{0,1}$ = 3.8317

TE°_{01}: $$\alpha = \frac{R_s}{Z_0}\frac{1}{\sqrt{k_0^2-(\chi_{01}/a)^2}}\frac{\chi_{01}^2}{k_0 a^3}$$

= **6.771×10^{-5} m^{-1}** , a = 0.24 m
= **2.404×10^{-4} m^{-1}** , a = 0.1746 m

$\rightarrow$ σ = 5.8 $\times 10^7\ \Omega^{-1}\text{m}^{-1}$ (Cu)
$R_s = 1/(\sigma\delta_s) = \sqrt{\mu_0 \pi f/\sigma}$ = 0.00941

TE°_{01}: **α = 4.41×10^{-5} m^{-1}** , a = 0.24 m
α = 1.57×10^{-4} m^{-1} , a = 0.1746 m

a=0.24m: L_1=37.039m
a=0.1746m: L_2=1.75m

Power attenuation per rf unit (6061 Al): $e^{-2\alpha L} \rightarrow \exp(-2\alpha_1 L_1)\ \exp(-2\alpha_2 L_2)$=.9967385× *.9994507*= 0.996191
=.9967385× *.9991590*= 0.995900

Tunnel pipe loss goes from 7.15% to 4.70% (or ~5.05% if WC13.75 not plated). Gain 2.6%.
Combining, bends, & shaft loss ~2.77% $\rightarrow$ ~1.82%. Gain 0.98%.
Overall, copper plating gains **~3.64%**.

9.72% loss $\rightarrow$ 6.43% loss

Peak RF Power Required from Klystrons per KCS feeding 26(25) 26-Cavity RF Units (Low Power)

Sort CM's for installation to accommodate power requirements to measured relative installed CTO power couplings.

189.9 kW	(nominal to cavity)	
× 26	(cavities/rf unit) 4.937 MW	
× 26 (25)	(rf units) 128.37 MW	
÷ 0.933	($\cos^2 15^\circ$, counter-phasing for 7% LLRF overhead, 5% usable)	
÷ 0.950	(input circulator and WR650 loss)	
÷ 0.990 (0.9904)	(1.00%(0.96%) combining CTO circular waveguide ohmic losses)	~0.8539
÷ 0.982	(klystron combining CTO ±0.2dB errors)	
÷ 0.9821	(1.79% shaft and big bends loss)	
÷ 0.953 (.9548)	(4.70%(4.52%) main KCS waveguide loss)	
÷ ~~0.96~~	(tunnel CTO ±0.2dB errors)	
× ~~1.062~~ ×~1.05?	(for statistical spread in feed/rf unit requirements)	~0.7984
× 1.059	(for flat gradient w/ cav. gradient spread and common timing)	
÷ 0.94	(6% local distribution losses)	
188.3 MW (180.6 MW)	from klystrons	

19 (20?) klystrons for 26 rf units

18 (19?) klystrons for 25 rf units

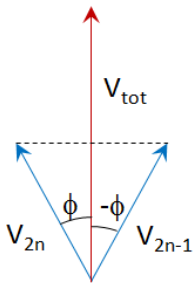
TOTAL KLYSTRONS: 17×19 + 5×18 = **413**

RDR-Like (Kamaboko): 188 + 190 = **378**

Klystrons Needed per KCS (Low Current)

The calculation/estimate suggests we need generate ~185 MW worth of klystron power for a **<u>26 rf unit</u>** KCS at I_b = 5.79 mA.

However, we need 7% (5% usable) <u>overhead for LLRF</u> 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 185 MW/0.933 = ~198.3 MW.

~~We also want to be robust against a <u>single klystron failure</u> 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 21 klystrons and 20 on, we have 190.5 MW available (~4% short).

With **<u>22 klystrons</u>** and one off, we have 200.45 MW (~1% to spare).

<u>21 klystrons</u> for the 25 unit KCS (need ~190.7 MW)

<u>13 klystrons</u> for the 16 unit KCS @ 27.6° (need ~108.6 MW)

TOTAL: 17×22 + 5×21 + 2×13 = **<u>505</u>** klystrons installed (481 on)

KCS Shafts and RF Units per KCS

Latest Changes:

- Back to 9-8-9 (26 cavity) rf units.
- 2nd stage bunch compression at 15 GeV → 10 GeV accel. moved from each main linac to RTML2. Since the latter are in-line w/ the main linacs, we can power them with upstream KCS's running past the BC's from the first shaft at the start of each main linac.
- Add 3 rf units (~1%) to each linac for overhead.

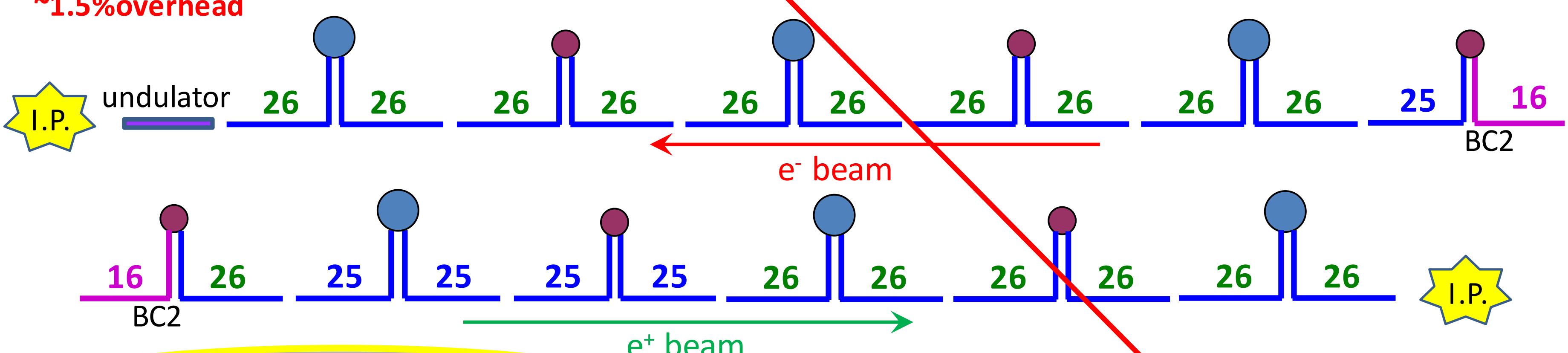
presented at BTR in January 2012

RTML2's: 10 GeV ÷ (27.1 MeV/m*×cos27.6°×1.038 m/cav.) = ~401 cav.
401 cav. ÷ 26 cav./rf unit = 15.42 rf units → RTML2: 16 rf units

Main Linacs: (250 GeV–15 GeV) ÷ (31.5 MeV/m(avg.)×cos5°×1.038 m/cav.) = 7,215 cav.'s
7,215 cav. ÷ 26 cav./rf unit = 277.5 rf units + 1.5 = 279 rf units (186 RDR-like units)

Add 3 rf units per ML for ~1.5%overhead → e^+ ML: 282 rf units (4×25 + 7×26)
e^- ML: 285 rf units** (1×25 + 10×26)

-- main facilities shaft
-- additional KCS shaft



NOTE: Feasibility of feeding RTML w/ KCS must be confirmed.

total:
599 rf units (567 ML + 32 RTML)
1,797 cryomodules
15,574 cavities

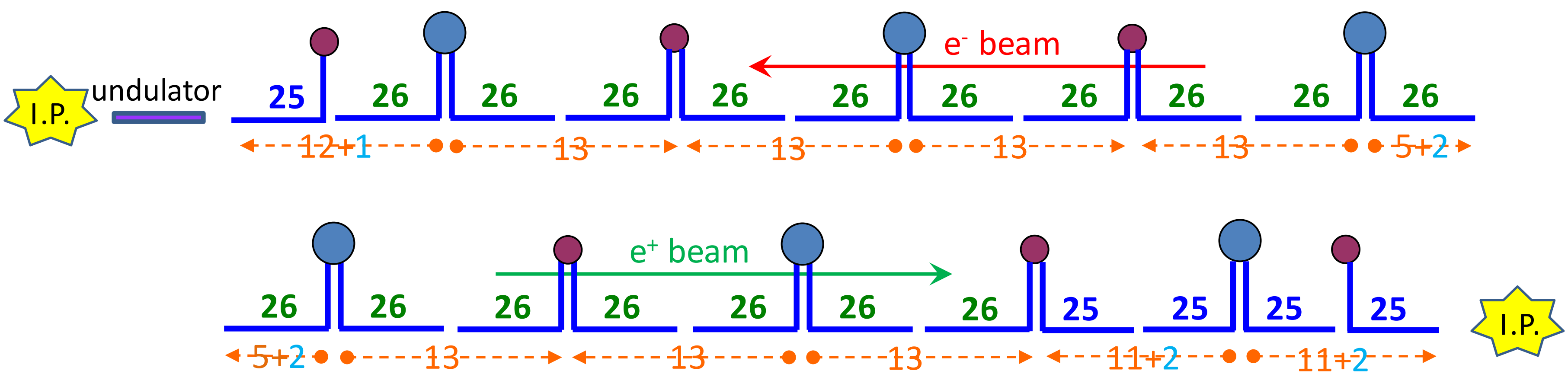
* all cavities same gradient for off-crest common rf control.
** 3 more to restore up to 2.54 GeV loss in undulator.

3/20/12

KCS Final Layout

- -- main facilities shaft
- -- additional KCS shaft
- -- cryogenic systems

- ## -- 3-CM rf units
- # -- 4-rf unit cryostrings
- # -- 3-rf unit cryostrings



main linac totals:

12 shafts
22 KCS's
567 rf units (285+282)
1,701 cryomodules
14,742 cavities

Evolving KCS Parameters

rf units added from RTML (9/2010 → 3/2011)

9-8-9→8-8-8 (3/2011 → 9/2011)

half bunches (9/2011 → TDR)

10 GeV → RTML but *included*, 8-8-8→9-8-9 (TDR → 1/2012)

separate RTML
add 1.5% overhead
eliminate spare klys.
Cu plate main wg (1/2012 → 4/2012)

	9/2010 BAW1	3/2011 ALCPG11	9/2011 LCWS11	TDR LCWS11	1/2012 BTR	4/2012 KILC
# of shafts / main linac	5	6	6	6	6	6
# KCS systems /ML	10	11	11	12	11 + 1(RTML)	11
# of rf units /ML (e^+/e^-)	280/284	290/294	314/319	314/319	278+15 / 282+15	282/285
# of rf units (CTO's) / KCS	28	27	29	27 (22)	25–26, 15	25–26
linac length fed / KCS (km)	1.064	1.026	1.024	0.994	0.965–1.003, 0.58	0.965–1.003
# of cryomodules / KCS	84	81	87	81	75–78, 45	75–78
# of cavities / KCS	728	702	696	648	650–676, 390	650–676
# of klystrons&mod.'s / KCS	34	33	33	22 (18)	21–22, 14	18–19
peak rf power /system (MW)	340 inst. 330 gen. 320 into	330 inst. 320 gen. 310 in	330 inst. 320 gen. 310 in	220 inst. 210 gen. 200.5 in	220 installed 210 generated 200.5 into syst.	190 inst. 190 gen. 190 in

AC Power and Heat Loads (KCS)

(Low Power)

For **both main linacs**, **ex**cluding second RTML stage

Average **rf power**: **413** klystrons × 10 MW × 1.65 ms × 5Hz = 34.1 MW
Average **beam power**: 5.79 mA × 472.54 GV × 727μs × 5Hz = 9.945 MW (26.4%)
wall plug–modulator pulse efficiency: ~87%
modulator pulse–HPRF efficiency: ~65% ➔ wall plug – HPRF: ~57%
34.1 MW / 0.57 = **59.8 MW AC**
59.8 MW(AC) – 9.95 MW(beam) = 49.9 MW ML cooling

.57	AC to rf	0.487 → 51.3% lost *above ground*:	**~30.7 MW**
.854	comb. into shaft		
.798	shaft to cav.	0.349 → 31.7% lost *below ground*	**~19.0 MW**
.437	cav. to beam		
.1698			

~16.6% efficient

~17% into beam/beam dumps **~10.1 MW**