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ISG-5
24 Feb. 2000

SWIRL* Pulse Compression Concept

1. Component configuration uses two active (and non-reciprocal) phase shifters in between two 3-db couplers. Same s-matrix as a SLED-II system with circulator and variable reflection coefficient.

2. Example given for double switching of phase shifters (at end of 1st time bin and at beginning of last time bin) with a compression ratio of 8. Compression efficiency depends strongly on round trip loss in delay-line/switch system.

3. Application to NLC parameters.

4. Propose a conventional SLED-II for 500 GeV NLC with upgrade to SWIRL for 1.0 – 1.5 TeV.

***SWI**tched **R**esonant **L**ine

Component configuration for a SLED-II System with Circulator

Phasor conventions

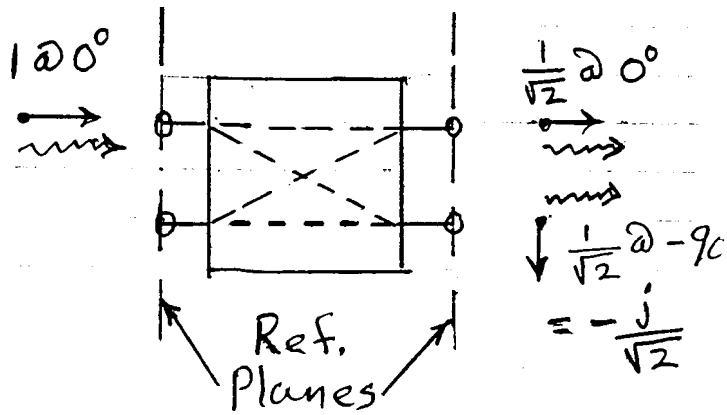
$$\tilde{E} = E_0 e^{j\phi}$$

$$\phi = \omega t - kz$$

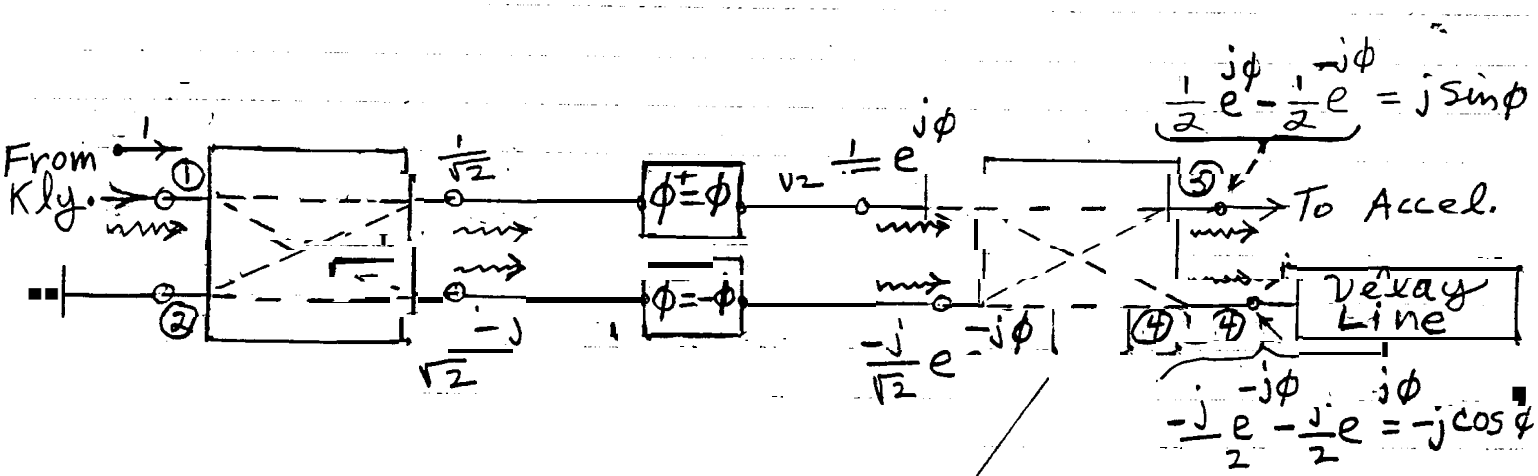
Phasor wave direction

$e^{j\omega t}$ ↻ e^{-jkz} ↺

3-db Coupler



Forward wave – 1st time bin

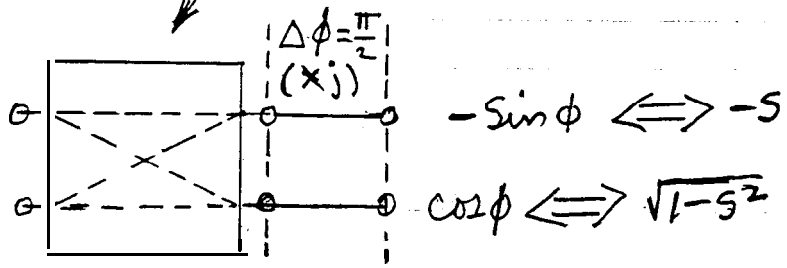


Extend Reference planes at ports 3 + 4 by $k\Delta z = \frac{3\pi}{2}$

output at 3 $= -s$

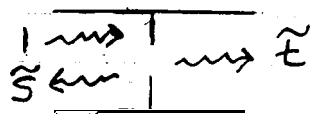
output at 4 $= \sqrt{1-s^2}$

$\phi = \sin^{-1} s$



Comparison with conventional SLED-II configuration with circulator

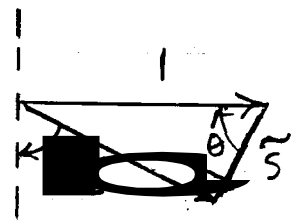
Phasor relationship at a capacitive iris



At iris $1+\tilde{s}=\tilde{t}$

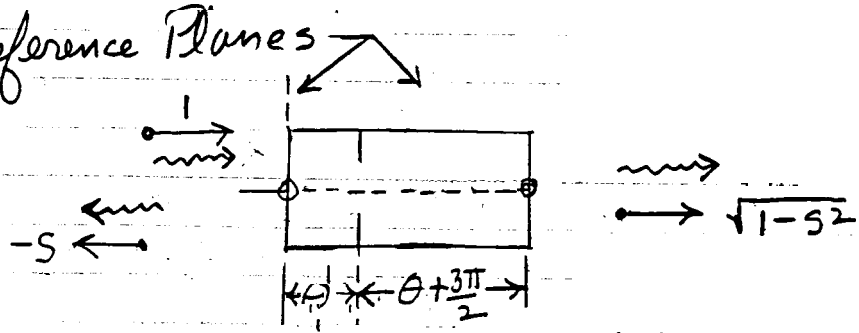
conservation of energy: $t^2+s^2=1$

$|t| = \sqrt{1-s^2}$



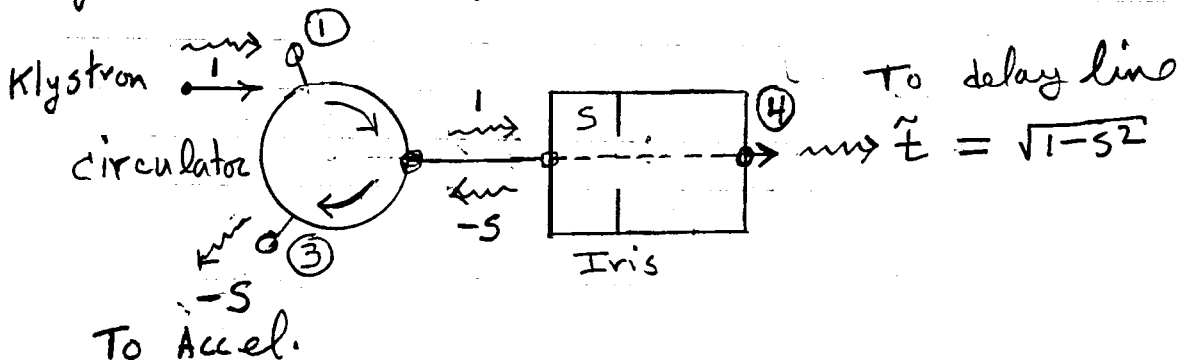
$|s| = \cos\theta$

Define Reference Planes

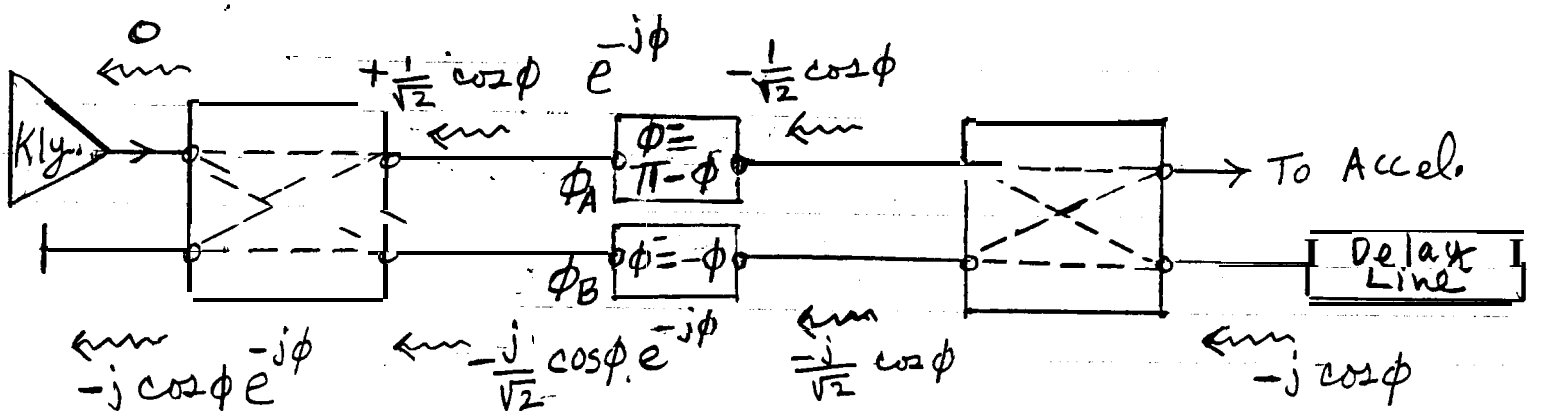


Plane of iris

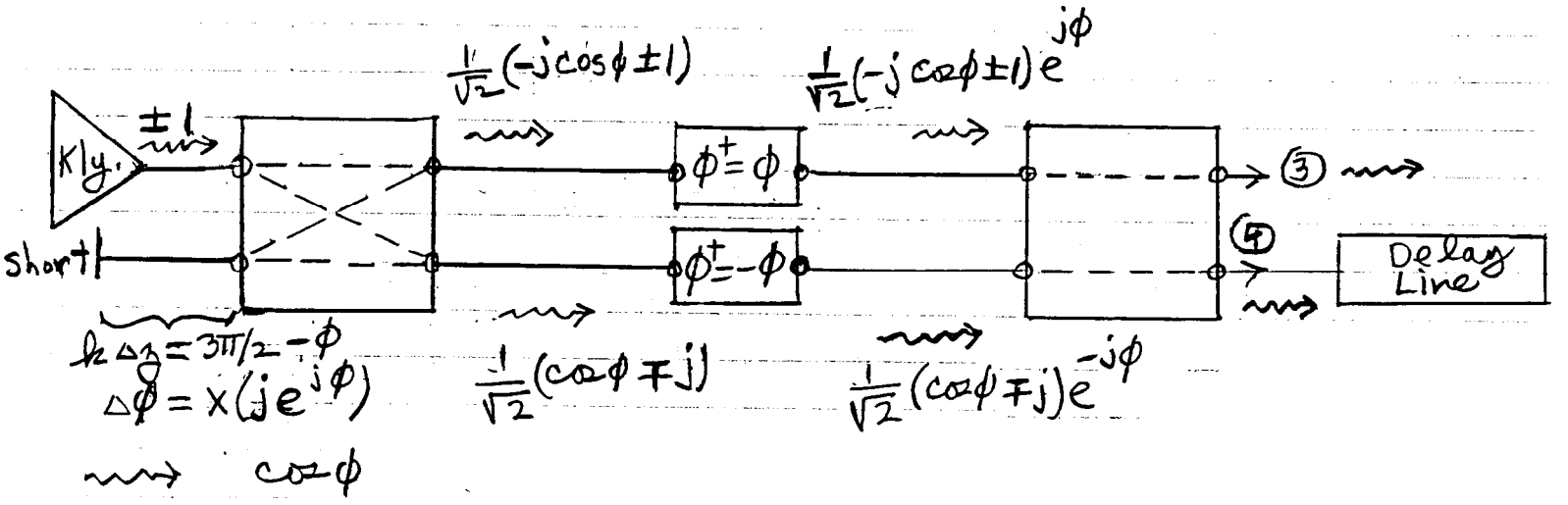
Equivalent configuration to previous page



Reverse Wave — 2nd time bin (without switching)



Forward Wave — 2nd time bin (without switching)



Port ③: $\frac{1}{2}(-j\cos\phi \pm 1)e^{j\phi} - \frac{j}{2}(\cos\phi \mp j)e^{-j\phi} = -j\cos^2\phi \pm j\sin\phi$

$\times j \Rightarrow -(1-S^2) \mp S$

Port ④ $\frac{1}{2}(-\cos\phi \mp j)e^{+j\phi} + \frac{1}{2}(\cos\phi \mp j e^{-j\phi}) = -j\cos\phi(\sin\phi \pm 1)$

$\times j \Rightarrow \sqrt{1-S^2}(S \pm 1)$

Note: $\phi_B^- = \phi_B^+ = \phi$

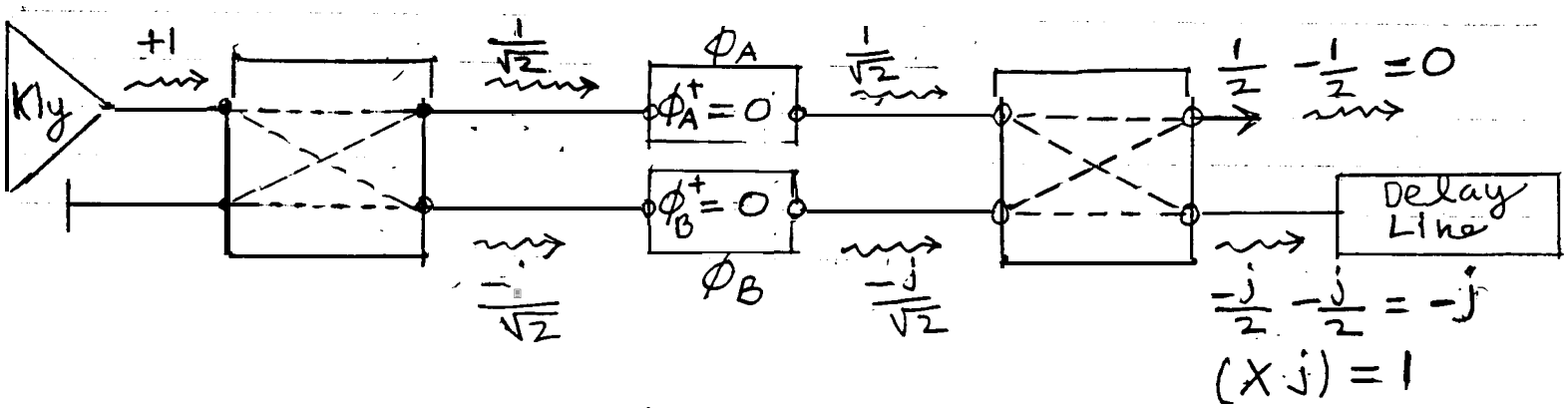
$\phi_A^- = \phi_A^+ + (\pi - 2\phi)$

Again, same result as for equivalent configuration with circulator on p. 3.

Active S switching at end of 1st time bin

During time bin #1, set $\phi_A^+ = 0$, $\phi_B^+ = 0$

Forward wave - time bin #1

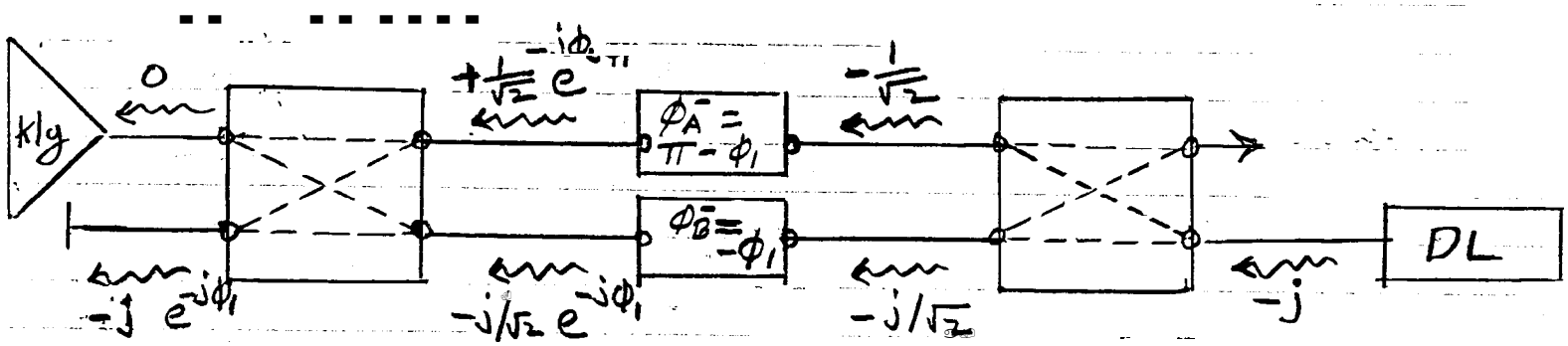


At end of time bin #1 switch ϕ_A and ϕ_B to:

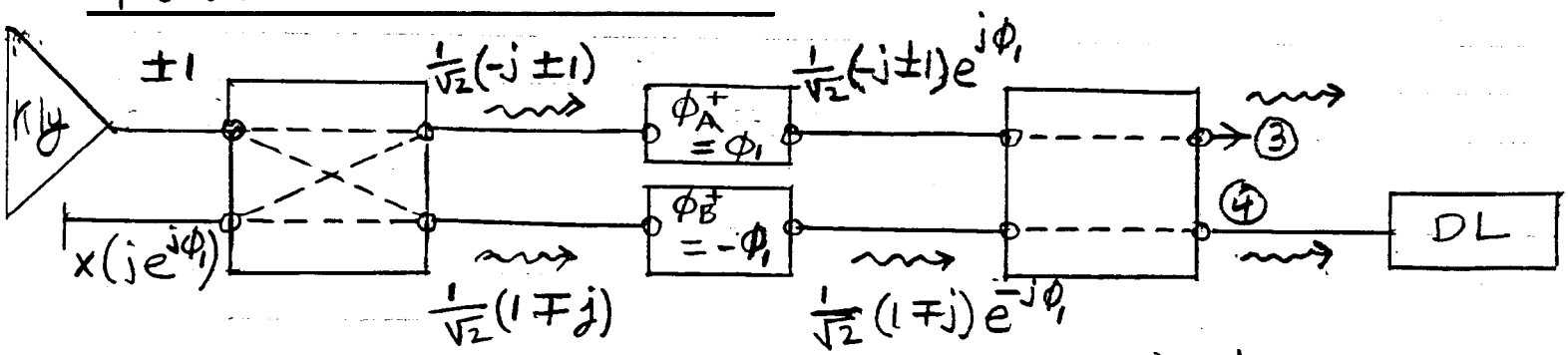
$$\phi_A^+ = \phi_1, \quad \phi_A^- = \pi - \phi_1$$

$$\phi_B^+ = -\phi_1, \quad \phi_B^- = -\phi_1$$

Reverse wave - time bin #2



Forward wave - time bin #2



Port 3 $\quad -j[\cos\phi_1 \mp \sin\phi_1]$

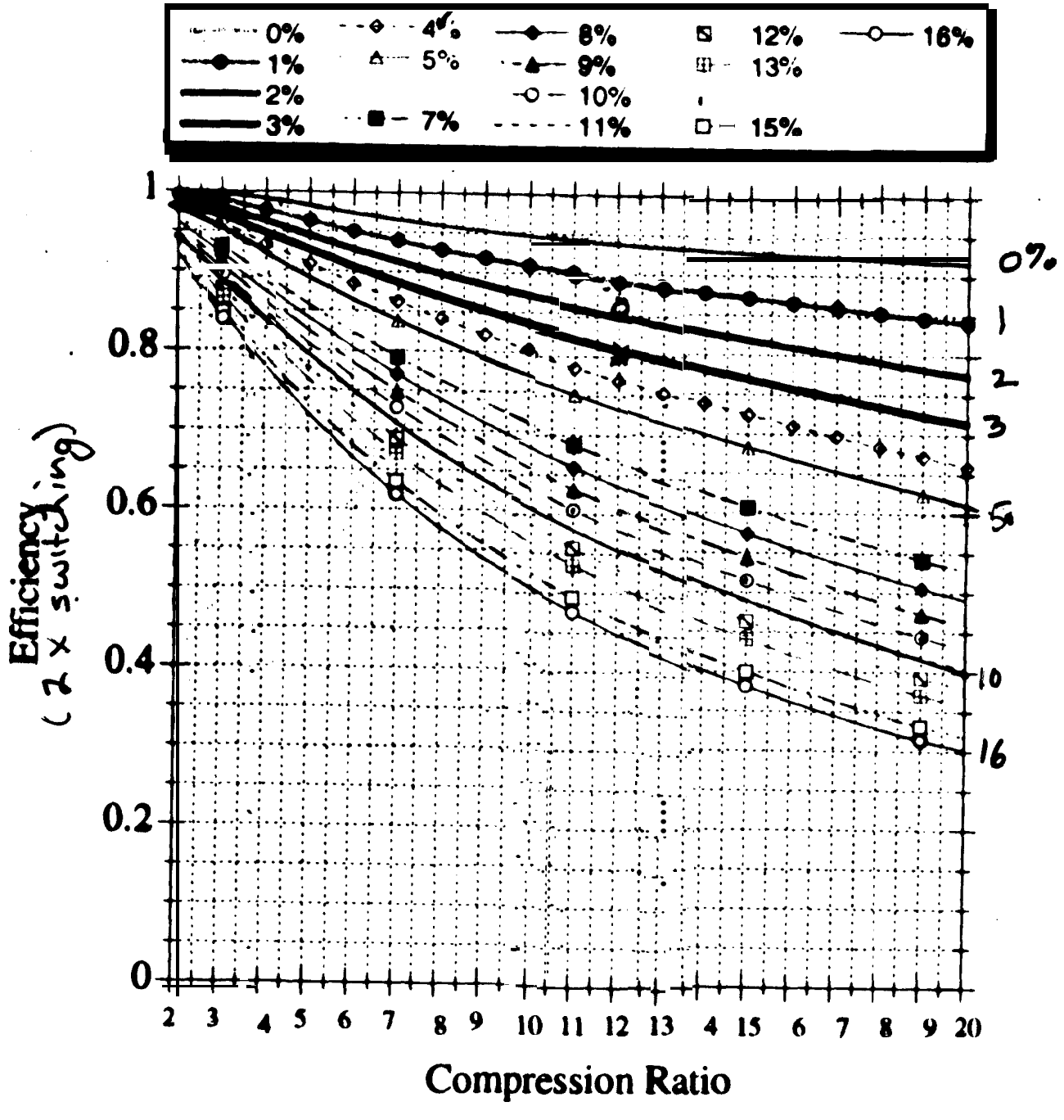
Port 4 $\quad -j[\sin\phi_1 \pm \cos\phi_1]$

If phase is flipped:

$$\left.\begin{aligned} E_3 &= \cos\phi_1 + \sin\phi_1 = \sqrt{2} \\ E_4 &= \sin\phi_1 - \cos\phi_1 = 0 \end{aligned}\right\} \text{at } \phi_1 = 45^\circ, \; S = \sqrt{2}/2$$

SWIRL efficiency depends strongly on round trip loss in delay line and switch components

Tantawi



Phase Shifter Status for Double Switching (Example for N = 8 in parentheses)*

Time Bin	ϕ_A^+	ϕ_A^-	ϕ_B^+	ϕ_B^-	Phase Changes
n=1	0	Arb	0	Arb	
First Switching					$\Delta\phi_A^+ = \phi_1$ (+63°) $\Delta\phi_B^+ = -\phi_1$ (−63°)
n = 2 to n = N−1)	ϕ_1 (63°)	$\pi-\phi_1$ (117°)	$-\phi_1$ (−63°)	$-\phi_1$ (−63°)	
Second switching					$\Delta\phi_A^+ = \phi_2-\phi_1$ (−41°) $\Delta\phi_A^- = \phi_1-\phi_2$ (+41°) $\Delta\phi_B^+ = \phi_1-\phi_2$ (+41°) $\Delta\phi_B^+ = \phi_1-\phi_2$ (+41°)
n = N	ϕ_2 (22°)	$\pi-\phi_2$ (158°)	$-\phi_2$ (−22°)	$-\phi_2$ (−22°)	

* Reflection coefficients (depend on RT loss)

$s_0 = 0$

$s_1 = 0.89$ at end of time bin 1

$s_2 = 0.37$ at end of time bin N−1

} Those values optimize voltage gain G_V

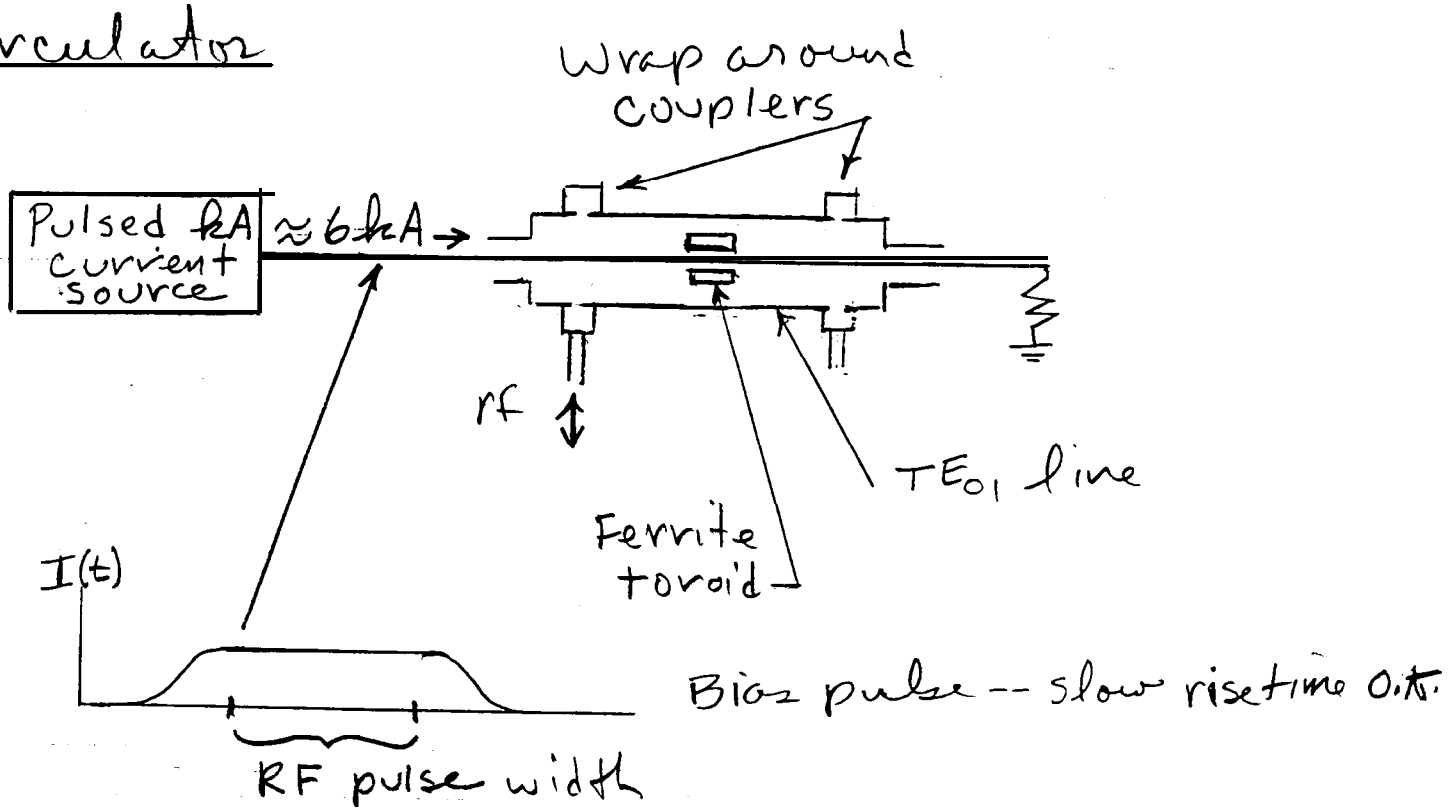
$$G_V = s_2 + T(1-s_2^2)^{1/2}\left\{(s_1T)^{N-2} + (1-s_1^2)^{1/2}\left[\frac{1-(s_1T)^{N-2}}{1-s_1T}\right]\right\}$$

$$\eta_{comp} = \frac{G_V^2}{N} = 0.814 \text{ for } N=8,\ T=\sqrt{0.95} \text{ (5\% RT loss)}$$

Compare $\eta = 0.62$ for conventional SLEO-II

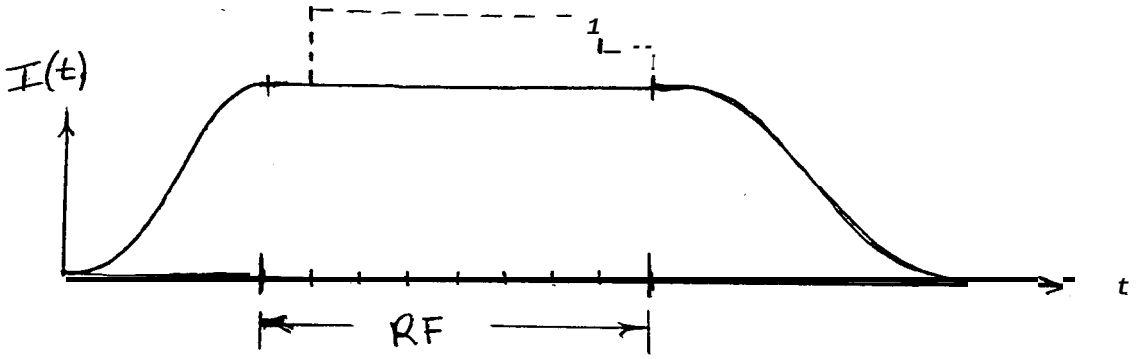
Realization of Circulator and Switch
(Sami Tantawi)

Circulator



Switch

Add fast switching pulse (few hundred amps) on top of bias pulse



PBW
10/14/99

Updated Parameters for NLC with a SWIRL Pulse Compression System

Comp. Ratio	T_{kly} (μsec)	Pulse Energy (J)	Peak Power (MW)	Comp. Efficiency	Power/structure (MW)	Unloaded Gradient (MV/m)	Effective Gradient (MV/m)	Energy (GeV)	P_{AC} (MW) @ Rep. Rate (Hz)
Notes	(1)	(2)	(3)	(4)		(5)	(6)	(7)	(8)
DLDS 4	1.50	SM 225 MM 900	600	0.85	170	73.0	55.4	1012	199 @ 120
SWIRL									
4	1.50	112	300	0.87	130	63.8	47.1	863	149 @ 120
5	1.875	141	375	0.84	157	70.2	52.9	967	186 @ 120
1.0 TeV } 6	2.25	169	450	0.81	183	75.7	57.8	1055	224 @ 120
8	3.00	225	600	0.77	230	84.8	66.1	1203	149 @ 60
10	3.75	281	750	0.73	272	92.3	72.9	1325	186 @ 60
12	4.50	338	900	0.69	310	98.6	78.5	1425	224 @ 60
1.5 TeV } 14	5.25	394	1050	0.66	344	103.9	83.3	1511	260 @ 60
16	6.00	450	1200	0.63	376	108.6	87.6	1588	149 @ 30

(1) Assumes 375 ns output pulse.
(2) Maximum energy per delay line (no losses); SM = single mode, MM = Multi mode.
(3) Maximum peak power seen by rf components (no losses).
(4) Assuming 5% delay line & switch loss per round trip and 6% kly to accel loss.
(5) See Farkas/Wilson 8/2/91 memo for details of gradient calculation.
(6) Effective gradient: 0.903 G(unloaded) − 10.5 MV/m { 0.903 = 0.92 cos 11° ; 10.5 MV/m = beam loading at 0.95×10^{10}
(7) Energy = 17.90 km (9936 structures) + 20 GeV.
(8) P_{AC} = (U_{pulse} × 4968 klystrons × rep. rate)/0.45 ; 0.45 = η_{KLY}(60%) × η_{MOD}(75%).

Table II

Comparison of DLDS, SLED-II and SWIRL Pulse Compression Systems for NLC

System	R	T_K (μsec)	Delay Line Modes/Dia.	Peak Power (MW)	Pulse Energy (J)	Comp. Efficiency		P_s (MW)	G_0 (MV/M)	E (GEV/TEV)	Relative N_K/L_A
Notes	(1)		(2)	(3)	(4)	(5)	(6)	(7)	(8)		(9)
DLDS (8/98)	4	1.5	1 M/4.75	600	225	0.85	170	73.0	515/1.01		0.97/0.97
DLDS (2/00)	8	3.0	2 M/7.125	600	450	0.83	166	72.1	490/0.96		0.51/1.02
SLED-II	8	3.0	1 M/4.75	600	225	0.57	171	73.2	520/1.02		0.72/0.97
	12	4.5	1 M/4.75	900	338	0.43	194	78.0	555/1.09		0.67/0.90
SWIRL	8	3.0	1 M/7.125	600	225	0.77	230	84.8	610/1.20		0.61/0.82
	12	4.5	1 M/7.125	900	338	0.69	310	98.6	720/1.43		0.52/0.69
	16	6.0	1 M/7.125	1200	450	0.63	376	108.6	805/1.59		0.47/0.62

Notes

(1) Compression ratio = klystron pulse length T_k/375 ns.

(2) 1 M = TE_{01} mode only; 2 M = TE,, and one polarization of TE,, in delay line.

(3) Peak power $\hat{P}$ in delay lines or in any rf component, ignoring losses; klystron power = 75 MW.

(4) Pulse energy = maximum peak power in (3) times longest pulse length in a delay line or t-f component.

(5) Compression efficiency η_{comp} assumes a 3% loss from klystron to compression system input, and 3% loss from delay line tap-offs or SLED output to accelerator structure inputs.

(6) P_s = input power at each accelerator structure; $P_s = \hat{P}\,\eta_{comp}/n_s$, where n_s is the number of structures per output spigot. n_s = 3 for DLDS systems; n_s = 2 for SLED-II/SWIRL systems.

(7) G_0 = unloaded gradient = $(P_s/170)^{1/2}$ x 73.0 MV/m.

(8) Effective gradient is G_L (MV/m) = 0.903 G_0–10.5 at 0.95 x 10^{10} particles/bunch. Energy is E = 8.95 km (4968 structures) x G_L + 20 GeV. Energy following slash is for 17.90 km machine.

(9) N_k = no. of klystrons normalized to 1656; L_A = active length for 500 GeV where 1 .O = 8.95 km.

Table I

Comparison of Delay Line Lengths

System	Max. No. of Modes in Delay Line	Delay Line Length* per 6 Structures
1. DLDS 4	1	1.5 T
2. DLDS 4	2	1 T
3. DLDS 4	3	0.75 T
4. DLDS 8	2	2 T
5. DLDS 8	3	1.5 T
6. SLED-II	1	3 T
7. SLED-II	2	1.5 T
8. SWIRL	1	1.5 T

* T = output pulse length = 375 ns ≈ 110 m of delay line.
6 structures = 10.8 m of active length
Delay line length/structure length ≈ 10 x where number in column is xT.