SPARX note n. 4

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AN L-BAND CW "COLD" LINAC TO BOOST THE BEAM FROM AN S-BAND "WARM" INJECTOR: POSSIBLE RF LAYOUTS AND BUDGETARY COST ESTIMATE

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S-Band Injector characteristics and LINAC basic specifications:

INJECTOR

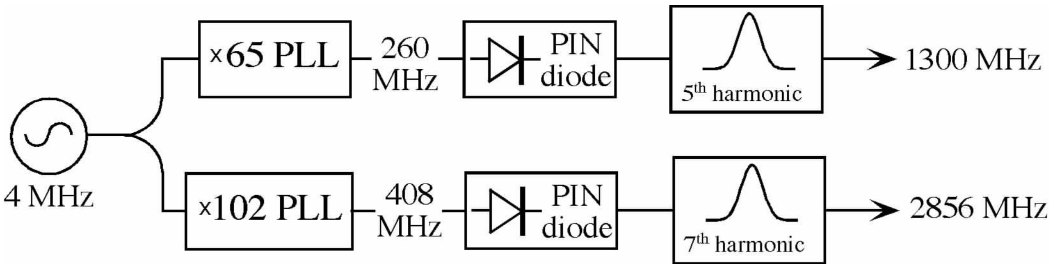
Energy	E_{inj}	150 MeV
Technology		S-band, normal conducting
Mode of operation		pulsed
Pulse length	τ_p	• 3 μs
Max charge per bunch	q_b	1 nC
Max bunch frequency	f_b	10^4/s
Max number of bunches per pulse	N_b	10
Max pulse repetition rate	f_{rep}	1 kHz
Max beam current	I_b	10 μA
Max average beam power	P_b	1.5 kW

LINAC

Energy	E_{linac}	2.0 GeV
Technology		L-band, superconducting
Mode of operation		CW
Max beam current	I_b	10 μA
Max average beam power	P_b	20 kW

THE SYNCHRONIZATION PROBLEM

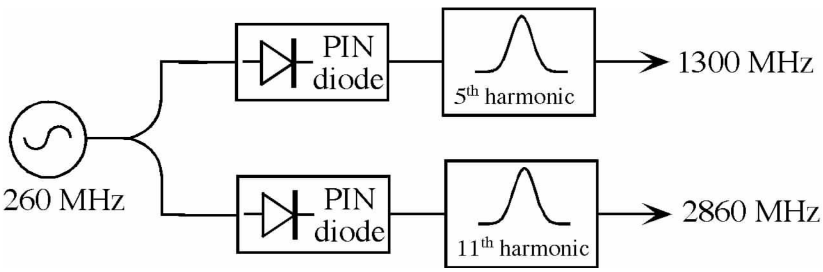
1) SLAC S-Band: 2856 MHz = 714 x 4 MHz
TESLA L-Band: 1300 MHz = 325 x 4 MHz



Advantages: use of the most widely diffused standard frequencies/technologies

Limitations: low master frequency, poor flexibility for the bunch pattern in the pulse

2) Modified SLAC S-Band: 2860 MHz = 11 x 260 MHz
TESLA L-Band: 1300 MHz = 5 x 260 MHz



Advantages: simple frequency ratio, great flexibility for the bunch pattern in the pulse

Limitations: S-band sections slightly modified (respect to the SLAC standard)

3) CERN S-Band: • 3000 MHz
CEBAF L-Band: • 1500 MHz

Advantages: integer frequency ratio, total flexibility for the bunch pattern in the pulse

Limitations: use of less widely diffused standard frequencies/technologies

TESLA SC CAVITIES BASIC SPECIFICATIONS:

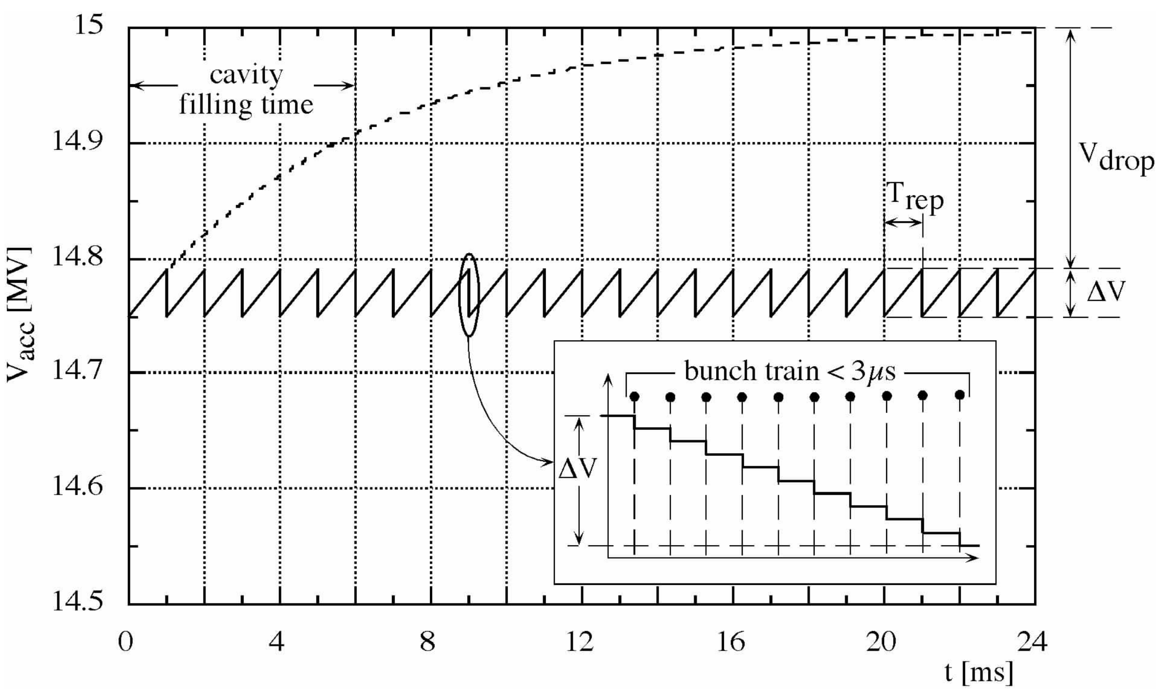
Resonant frequency	f_0	= 1.3 GHz

Number of cells	N_c	= 9
Quality factor	Q_0	• 1 10^{10} @ 15 MV/m • 7 10^{9} @ 25 MV/m
Geometrical impedance	$R/Q=V^2/\omega_0 U$	• 1 k•
Structure length	L	• 1 m
Accelerating voltage	V	• 15 MV @ 15 MV/m • 25 MV @ 25 MV/m
Wall power dissipation	P_d	• 23 W @ 15 MV/m • 90 W @ 25 MV/m
Number of cavities (@ 2.0 GeV)	N_{cav}	• 133 @ 15 MV/m • 80 @ 25 MV/m
Total wall power dissipation	P_{dTot}	• 3.1 kW @ 15 MV/m • 7.2 kW @ 25 MV/m
Max beam current	I_b	10 µA
Max average beam power per cavity	P_{bc}	• 150 W @ 15 MV/m • 250 W @ 25 MV/m
Max external quality factor	Q_{ext}	• 2.5 10^{7}
Min loaded cavity bandwidth	f_{BW} • f_0/Q_{ext}	• 50 Hz
Max cavity filling time	τ_f • $1/$•f_{BW}	• 6 ms
Min RF forward power per cavity	P_{RF} • $V^2/4(R/Q)Q_{ext}$	• 2.25 kW @ 15 MV/m • 6.25 kW @ 25 MV/m

THE BEAM LOADING PROBLEM

Since we are considering the option of using a CW, SC linac coupled to a pulsed NC injector, the beam current is fractionated in short trains confined in one pulse of the S-band RF system. In the limit case of trains made of a single bunch, beam loading effects are absent. If each train is composed by a certain number of bunches, each bunch will absorb some energy from the cavity reducing the available gradient for the following bunches. The train duration (i.e. the pulse length) is definitely too short to allow the cavity energy restoring through the input RF, and an head-tail energy spread along the train is unavoidable.

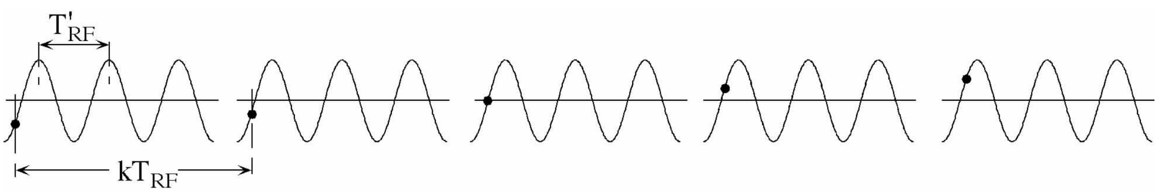
If we consider a cavity powered to V_{acc} •*15 MV/m* and a beam current I_b • *10 μA*, obtained with 10 bunches of charge q_b •*1 nC* per pulse and a rep rate $f_{rep} = 1\ kHz$ ($T_{rep} = 1\ ms$), we typically end up with the following accelerating voltage envelope:



The saw-tooth voltage parameters are given by:

$$\Delta V = \frac{1}{2} N_b \, q_b \, \omega_0 \, (R/Q); \qquad V_{drop} = \Delta V \frac{e^{-T_{rep}/\tau_f}}{1 - e^{-T_{rep}/\tau_f}}$$

The expected energy spread along the train is *•E/E • 0.28 %* in this case. If more than 10 bunches are considered, a larger energy spread is expected. Being perfectly correlated, the spread can be (eventually) cancelled by properly powering one or more off-frequency cavities.



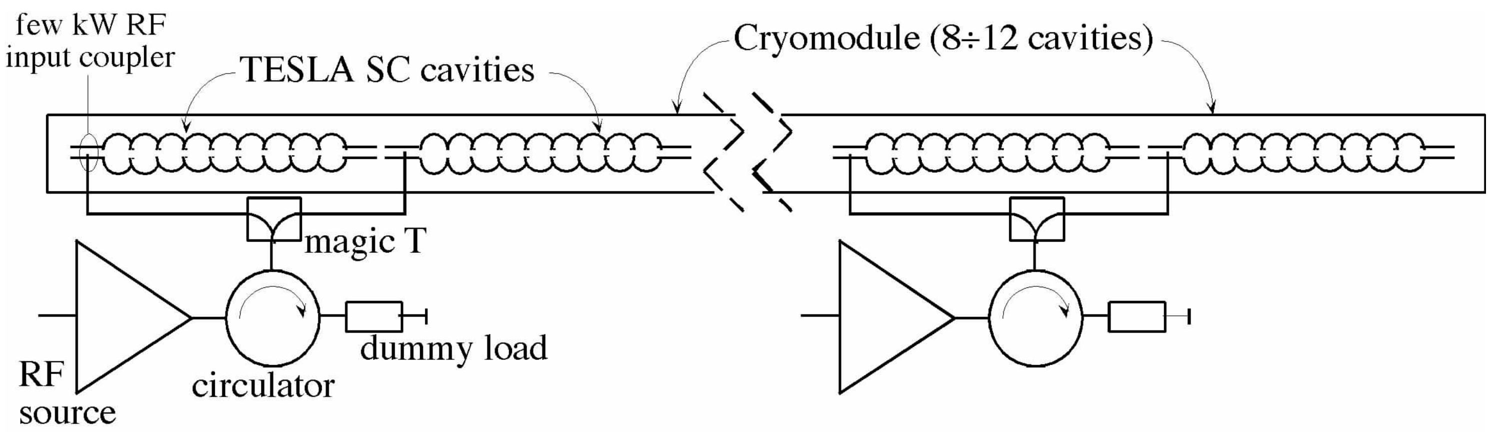
To distribute the train from -•/6 to +•/6 along the "correcting" sine wave the ratio of the frequencies should be: $\omega'_{RF}/\omega_{RF} = 1 + 1/6k\,N_b$

while the amplitude of the correcting sine wave is: $V'_{RF} = N_{cav}\,\Delta V$

The condition on the frequencies adds one extra synchronization problem, and it pose some constraints in the choice of bunch pattern inside the pulse.

The feasibility of other compensation methods (like injection of the bunch trains on the rising front of the voltage of the correcting cavities) can be studied.

BASIC LAYOUT OF A CW, L-BAND SC LINAC FOR SASE

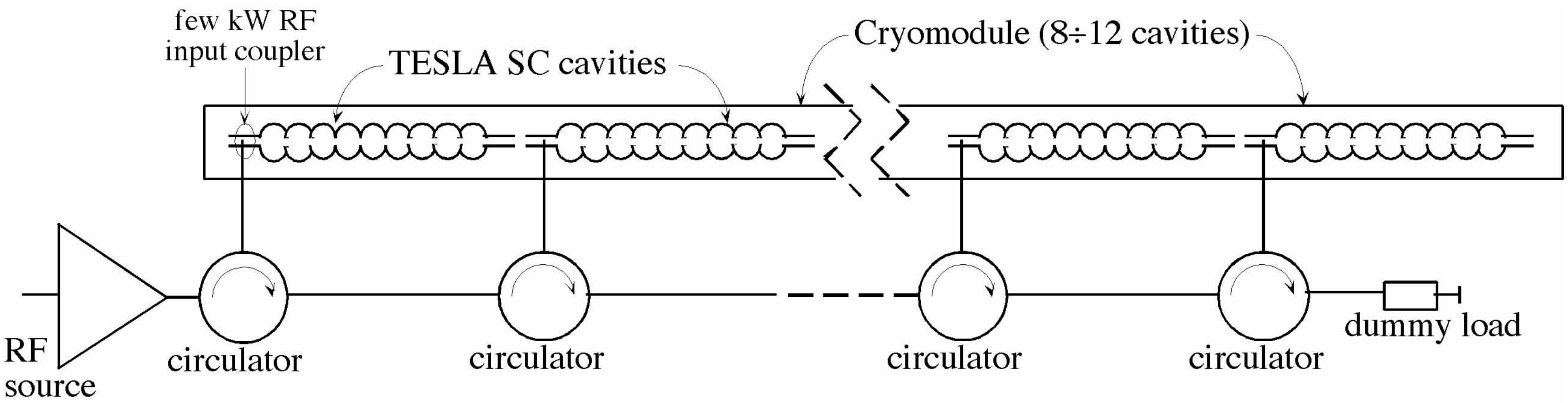


E_{linac} = 2GeV; Q_{ext} • 2.5 10^7

Cavity cost: 3 G£/12 cavities; Cryogenics cost: 10 G£ • (P_{tot} @ 2°K /1 kW)$^{0.6}$; RF cost: 30 M£ / kW

Gradient [MV]	Qo/10^9	PRF/cav [kW]	PRFtot [kW]	Pd/cav [kW]	Pdtot [kW]	Cavities [G£]	Cryo [G£]	RF [G£]	Tot [G£]
15	10	2.17	289.58	0.022	2.896	33.33	18.93	8.69	60.95
16	9.7	2.47	308.88	0.025	3.184	31.25	20.04	9.27	60.55
17	9.4	2.79	328.19	0.030	3.491	29.41	21.17	9.85	60.43
18	9.1	3.13	347.49	0.034	3.819	27.78	22.34	10.42	60.55
19	8.8	3.48	366.80	0.040	4.168	26.32	23.55	11.00	60.87
20	8.5	3.86	386.10	0.045	4.542	25.00	24.80	11.58	61.38
21	8.2	4.26	405.41	0.052	4.944	23.81	26.09	12.16	62.06
22	7.9	4.67	424.71	0.059	5.376	22.73	27.43	12.74	62.90
23	7.6	5.11	444.02	0.067	5.842	21.74	28.84	13.32	63.90
24	7.3	5.56	463.32	0.076	6.347	20.83	30.31	13.90	65.04
25	7	6.03	482.63	0.086	6.895	20.00	31.85	14.48	66.33

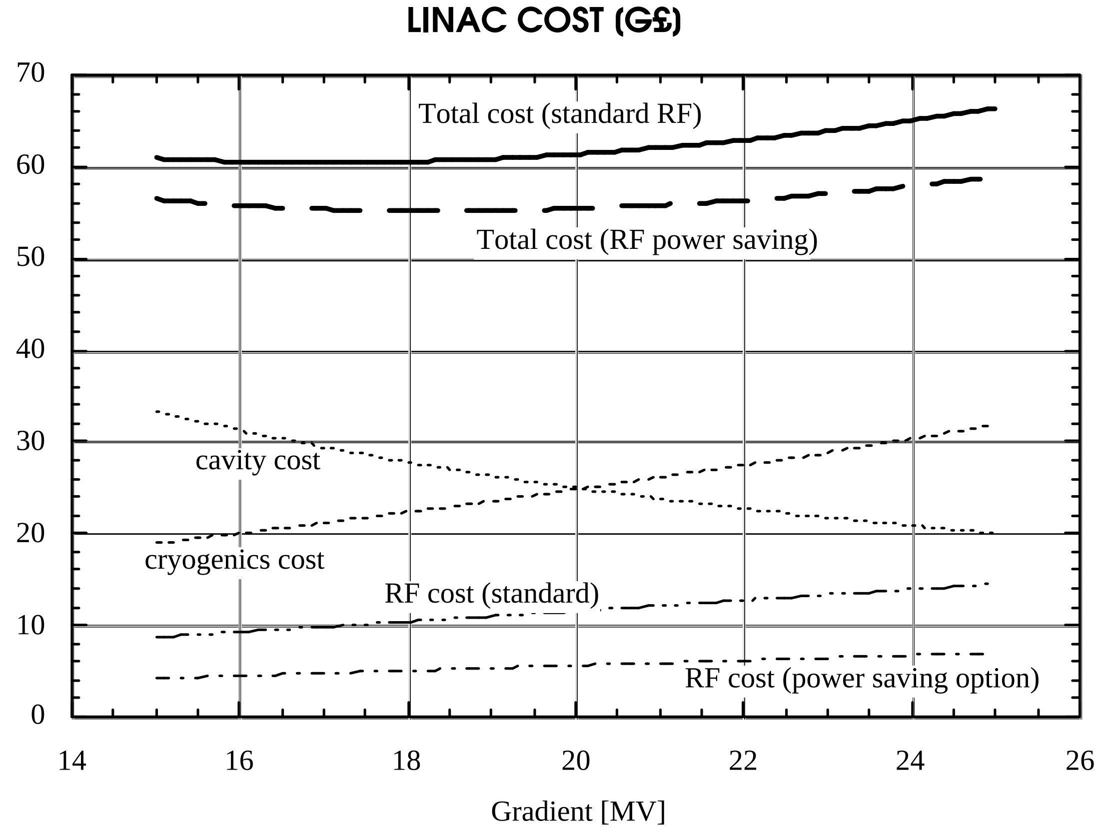
RF SAVING LAYOUT (Feasible? to be verified)

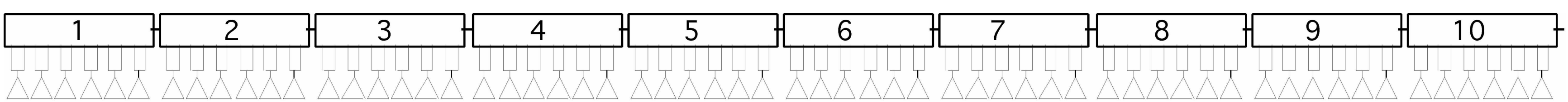


E_{linac} = 2GeV; $\mathbf{Q_{ext}}$ **• 1.2 10^7**

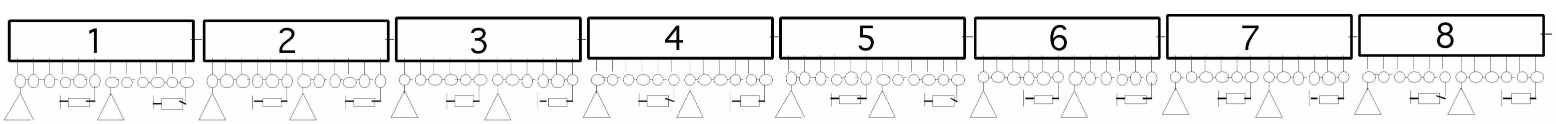
Cavity cost: 3 G£/12 cavities; Cryogenics cost: 10 G£ • (P_{tot} @ 2°K /1 kW)$^{0.6}$; **RF cost: 7 M£ / kW**

Gradient [MV]	Qo/10^9	PRF/cav [kW]	PRFtot [kW]	Pd/cav [kW]	Pdtot [kW]	Cavities [G£]	Cryo [G£]	RF [G£]	Tot [G£]
15	10	4.52	603.28	0.022	2.896	33.33	18.93	4.22	56.48
16	9.7	5.15	643.50	0.025	3.184	31.25	20.04	4.50	55.79
17	9.4	5.81	683.72	0.030	3.491	29.41	21.17	4.79	55.37
18	9.1	6.52	723.94	0.034	3.819	27.78	22.34	5.07	55.19
19	8.8	7.26	764.16	0.040	4.168	26.32	23.55	5.35	55.21
20	8.5	8.04	804.38	0.045	4.542	25.00	24.80	5.63	55.43
21	8.2	8.87	844.59	0.052	4.944	23.81	26.09	5.91	55.81
22	7.9	9.73	884.81	0.059	5.376	22.73	27.43	6.19	56.35
23	7.6	10.64	925.03	0.067	5.842	21.74	28.84	6.48	57.05
24	7.3	11.58	965.25	0.076	6.347	20.83	30.31	6.76	57.90
25	7	12.57	1005.47	0.086	6.895	20.00	31.85	7.04	58.89





"Standard" solutions: 10 cryomodules, 120 cavities, V_{acc}•17 MV/m, L_{tot}•170 m, => **60.5 G£**



"RF power saving" solution: 8 cryomodules, 96 cavities, V_{acc}•21 MV/m, L_{tot}•136 m, => **55.8 G£**