

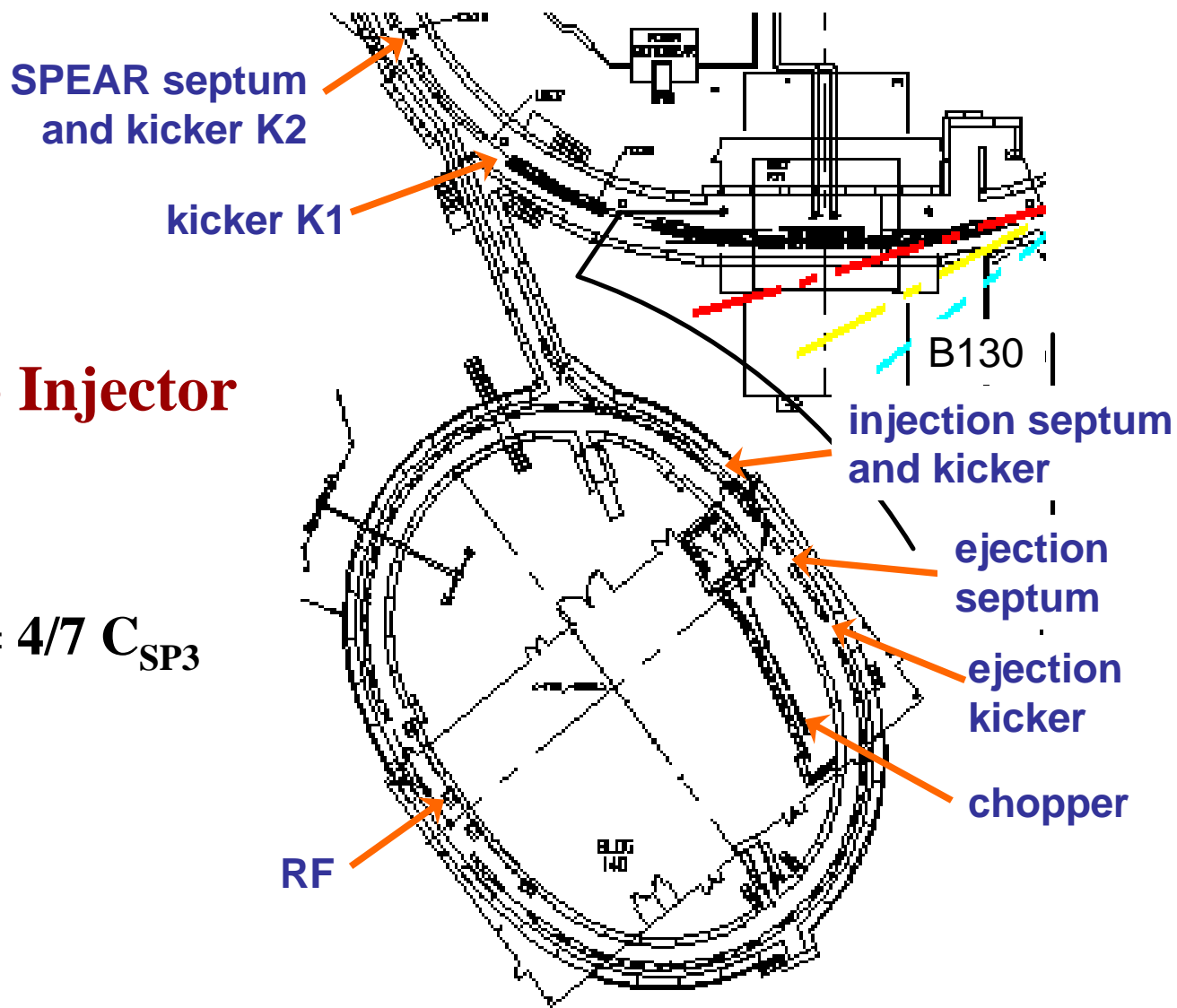
SPEAR 3 Timing System

R. Hettel

- Injection timing intervals and sequence
- Injection and ejection energy windows
- Timing system configuration
- SPEAR 3 and Booster RF frequency choices
- RF signal and clock frequencies
- RF stability and resolution requirements
- Master oscillator
- Booster RF Generator and Timing Modulator
- Bucket select using I/Q modulation of RF
- Injection rate reduction

SPEAR 3 Injector

$$C_{B00} = 4/7 C_{SP3}$$



SPEAR 3 Injection Timing Intervals

- Time interval between Chopper and Booster RF cavity is fixed:
T(Chop-BOOrf) adjusted using analog vernier input to Coincidence/Vernier
- Time interval between Booster RF cavity and 1st SPEAR RF cavity is fixed:
T(BOOrf-SPrf) adjusted using SPEAR RF phase control (LLRF)
- Time interval in Booster (measured at RF cavity) = $M \times T_{\text{BOOrf}}$, $M = \text{integer}$
Booster bucket will be aligned with SPEAR target bucket every 7 Booster revolutions = 4 SPEAR revolutions
- Time interval in Booster can be delayed or advanced by an integer number of SPEAR RF bucket periods using I/Q modulation of Booster RF
- Injection and ejection energy windows can be detected and used to gate RF-sync'd triggers

SPEAR 3 Injection Timing Sequence

Sequence of events needed to inject beam into a given SPEAR bucket:

- Detect first SPEAR revolution timing fiducial occurring within injection energy window

timing fiducial repeats at f_{SPrev} ; $T_{\text{SPrev}} = 280 T_{\text{BOOrf}}$

⊃ proper timing to hit Booster RF bucket is maintained

- Trigger Linac klystron modulator and S-band drive amplifier

~2 ms macropulse width; ~100 ns timing accuracy

- Trigger Booster Injection Kicker

~0.8 ms width; ~10 ns timing accuracy

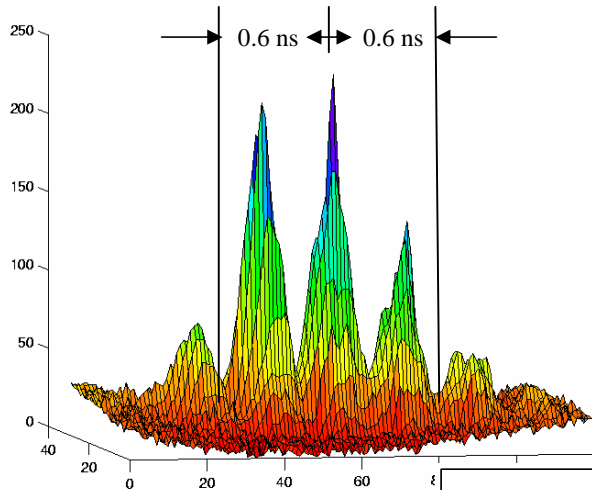
- Trigger Linac beam Chopper to permit 3-5 S-band microbunches to enter Linac and Booster

~200 ps timing accuracy with respect to Booster RF cycle

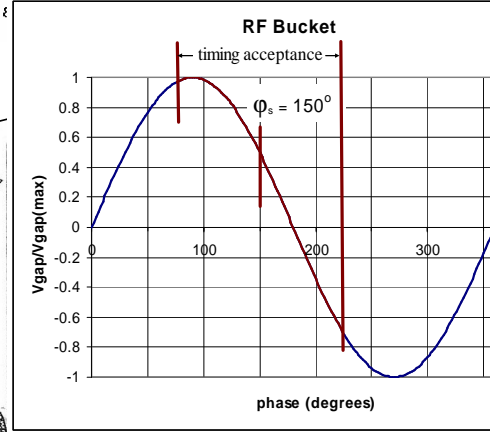
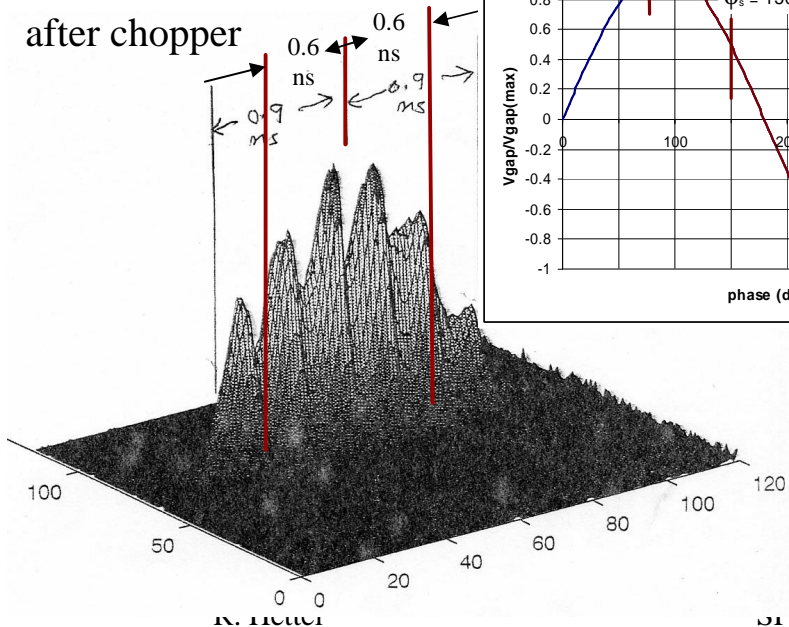
- The above three triggers must occur within a Booster injection energy window of $\pm \sim 0.1\%$ for effective beam capture

~112 MeV \pm 0.1%

Booster Injection Timing Acceptance



S-band microbunches after chopper



Time acceptance determined by momentum acceptance: bunch momentum oscillations caused by Δt_b time of arrival wrt to synchronous phase:

$$\frac{\Delta p}{p} = \frac{2\pi v_s f_{rev}}{\alpha} \Delta t_b$$

$$v_s = \text{synchrotron tune} = \left[\frac{\alpha h \cos(\phi_s) eV_{gap}}{2\pi E_b} \right]^{1/2}$$

$\phi_s = \text{synchronous phase} = \sin^{-1}(q^{-1}) = \sim 150^\circ$ at injection
 $v_s = \sim 0.016$ at injection; $v_s f_{rev} = \sim 35 \text{ kHz}$

RF momentum acceptance in ramping booster:

$$\frac{\Delta p}{p} = \pm \left[\frac{2(U_{E_b} - \Delta E_b)}{\pi \alpha h E_b} (\sqrt{q^2 - 1} - \cos^{-1}(q^{-1})) \right]^{1/2}$$

$$U_{E_b} \text{ (GeV)} = \text{radiated energy loss / turn} = \frac{C_\gamma E_b^4 \text{ (GeV}^4\text{)}}{\rho \text{ (m)}}$$

$C_\gamma = 88.6 \times 10^{-6} \text{ (m/GeV}^3\text{)}$, $\rho = \text{dipole bend radius} = 12 \text{ m}$

$$\Delta E_b = \text{energy change / turn from ramp} = \frac{dE_b}{dt} T_{rev}$$

$$q^{-1} = \frac{U_{E_b} - \Delta E_b}{eV_{gap}}$$

$\alpha = \text{momentum compaction factor} = 0.033$

$h = \text{harmonic number} = 160$

For booster, $\frac{\Delta p}{p} \cong 0.4\%$ at injection

$\Rightarrow \text{can accept } \Delta t_b \cong \pm 0.6 \text{ ns } (\Delta \phi_b \cong \pm 75^\circ)$

SPEAR 3 Injection Timing Sequence - cont.

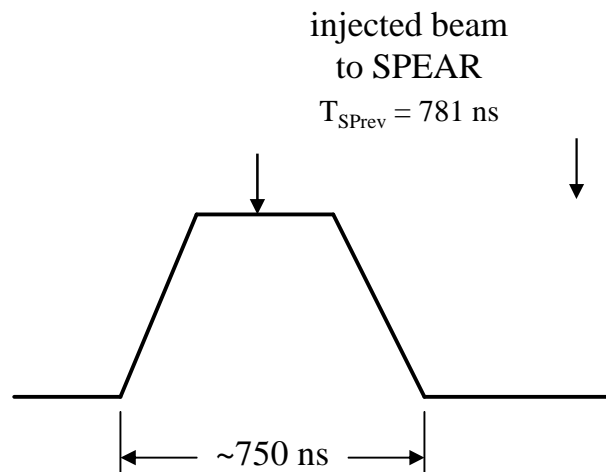
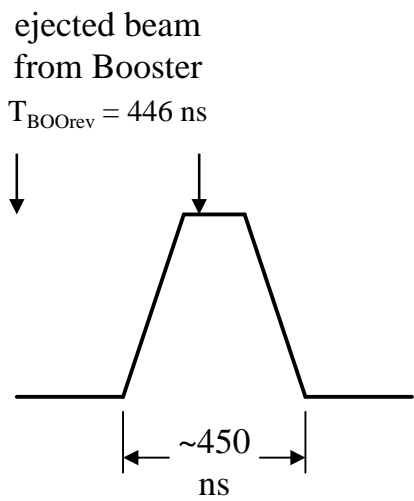
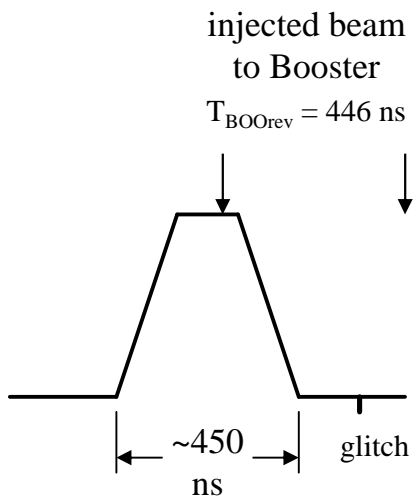
- Delay or advance the timing of bunch in Booster during acceleration so that proper SPEAR bucket will be filled
- Trigger Booster Ejection Septum supply ~ 15 ms before beam extraction
- Trigger Booster Ejection Kicker and SPEAR Injection kickers after accelerating beam in Booster for ~ 36 ms, during a Booster revolution when the bunch is temporally aligned with the target SPEAR bucket

~ 0.8 ms width; ~ 10 ns timing accuracy

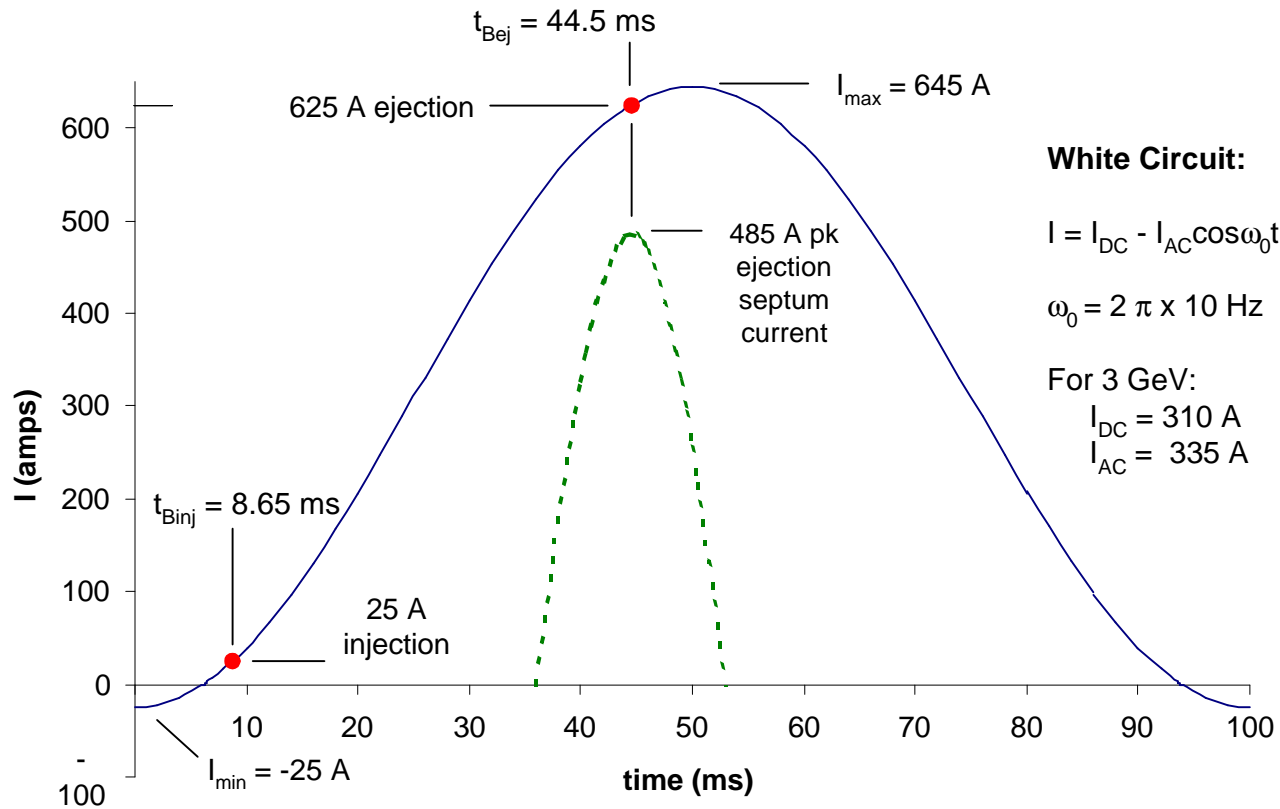
- The above kicker triggers must occur within a Booster ejection energy window of $\pm \sim 0.1\%$ for effective SPEAR beam capture

3 GeV $\pm 0.1\%$

Kicker Timing

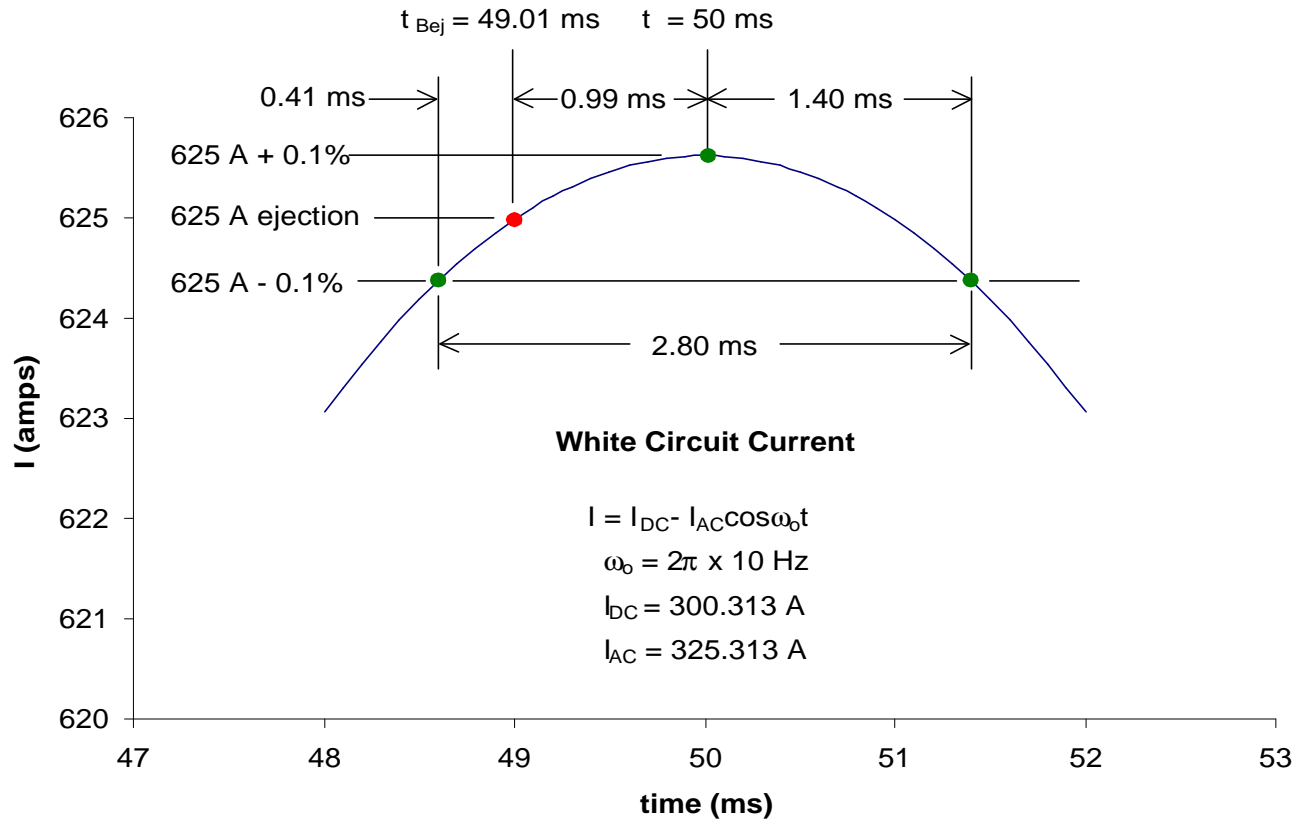


Injection/Ejection Timing and 10 Hz White Circuit



White Circuit magnet and pulsed Ejection Septum current waveforms for 112 MeV injection and 3 GeV ejection.

Maximum Ejection Timing Window



Ejection energy window is maximized when peak White Circuit current is set 0.1% higher than ejection current. Current stability must be a small fraction of 0.1%.

White Circuit Injection/Ejection Timing Windows

Injection energy window:

$$\Delta E/E = \Delta I_{WC}/I_{WC} = 0.1\%$$

$$\Rightarrow \Delta t_{\text{Binj}} = \pm 2.5 \mu\text{s} \quad (= \pm \sim 3 \text{ SPEAR revs})$$

$$\Delta I_{\text{Binj}} = \pm 0.1\% \times 25 \text{ A} = \pm 0.006\% I_{\text{max}}$$

⚠ need peaking strip to detect t_{Binj}

Ejection energy window:

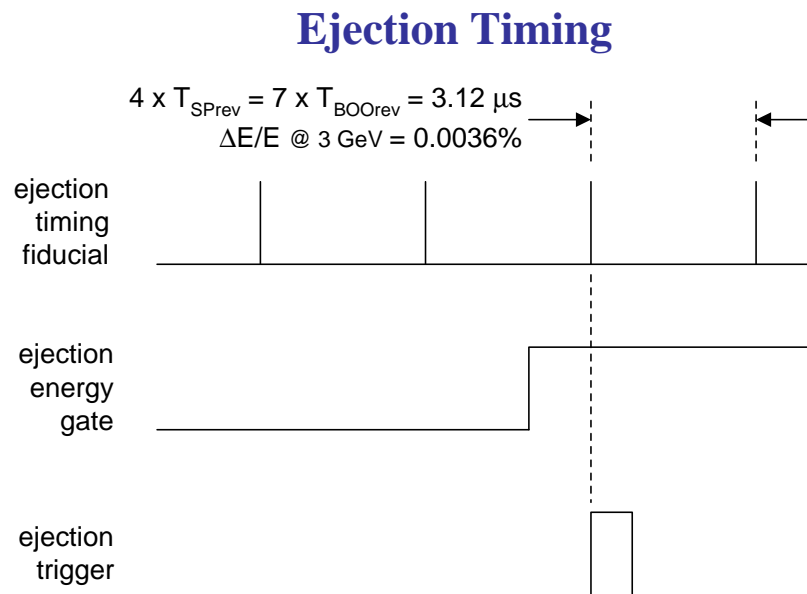
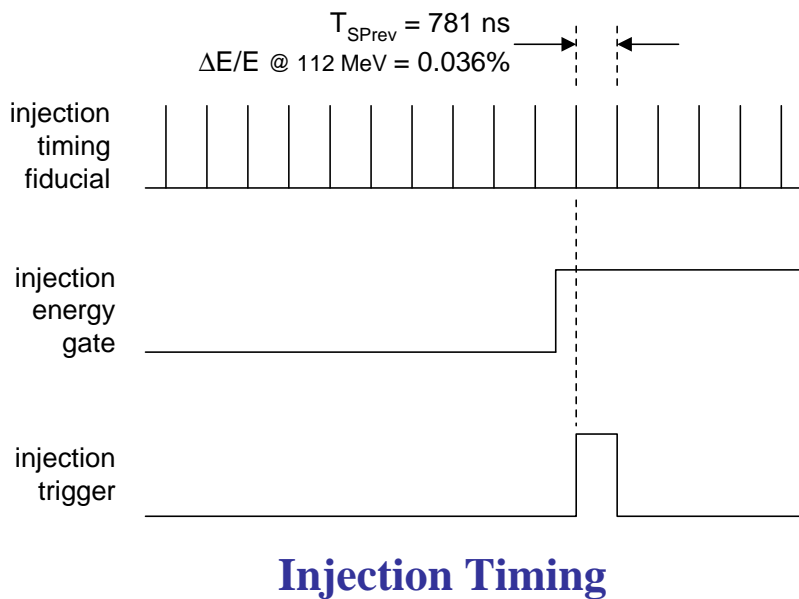
$$\Delta E/E = \Delta I_{WC}/I_{WC} = 0.1\%$$

$$\Rightarrow \Delta t_{\text{Bej}} = \pm 88 \mu\text{s} \quad (= \pm \sim 115 \text{ SPEAR revs})$$

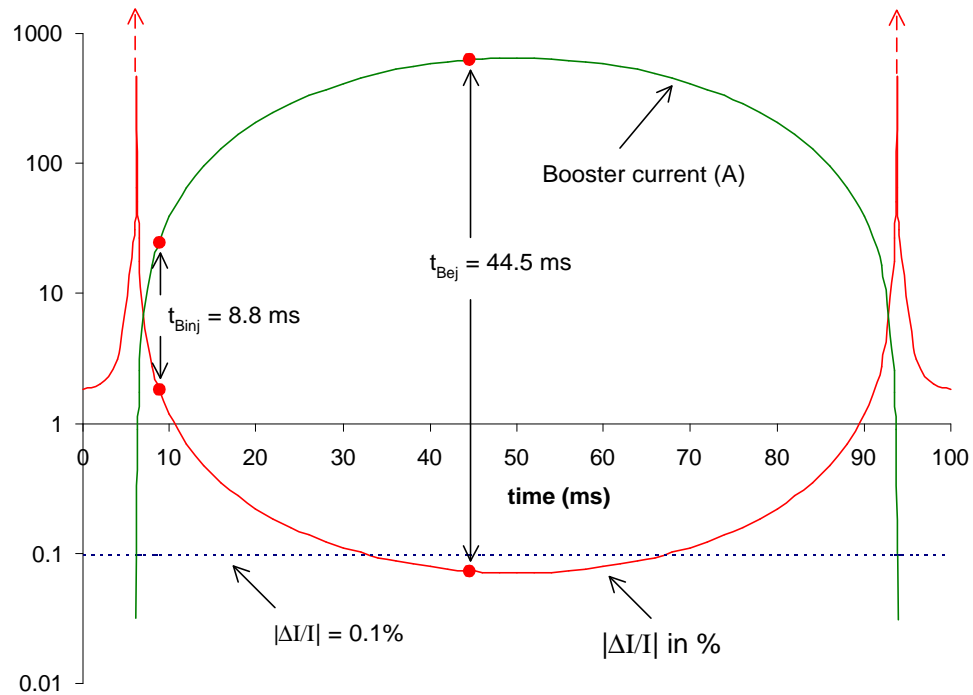
$$\Delta I_{\text{Bej}} = \pm 0.1\% \times 625 \text{ A}$$

\Rightarrow could dead-reckon to t_{Binj} if have 0.1% power supplies,
but use WC current transducer (Danfysik) to detect I_{Bej}

Injection and Ejection Timing Triggers

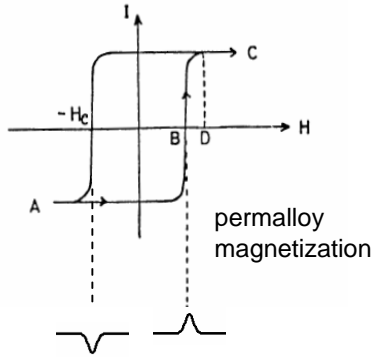


White Circuit Current Regulation and Timing



White Circuit current stability as a function of time in a 10 Hz cycle, assuming the DC and AC power supplies each have 0.1% stability. The ejection current stability is $<0.1\%$ at t_{Bej} , implying the ejection time can be dead-reckoned.

Injection Energy Gate - Peaking Strip Processor

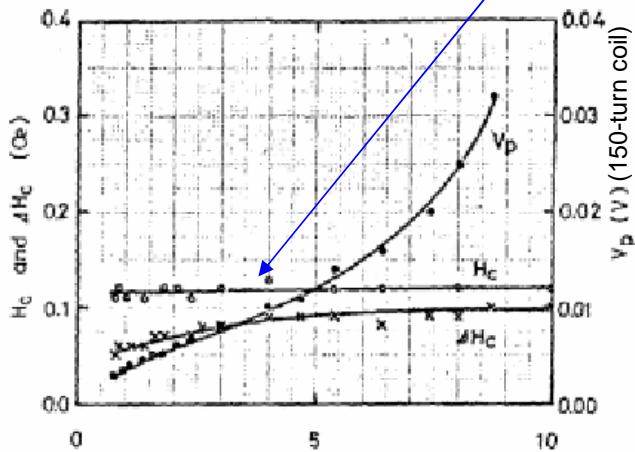


$$B(3 \text{ GeV}) = 8.35 \text{ kG}$$

$$B(112 \text{ MeV}) = 0.31 \text{ kG}$$

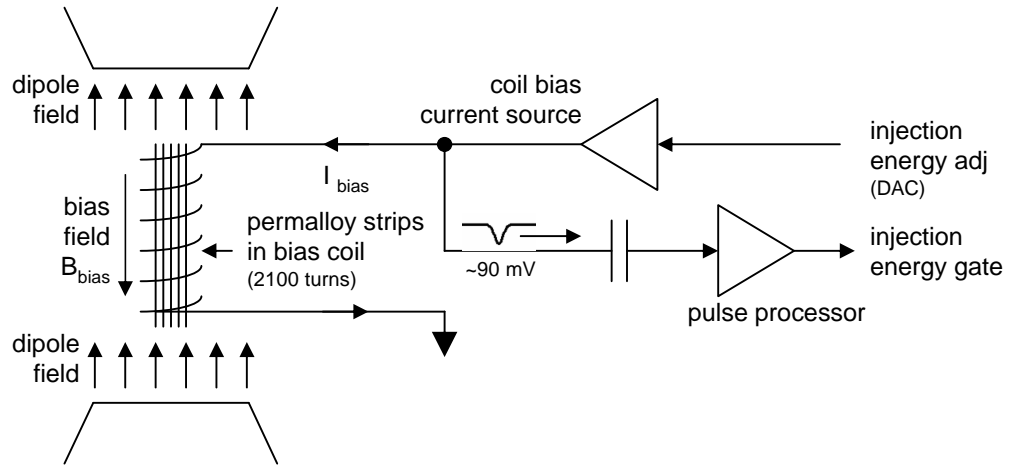
$$B_{WC} = 4.14 - 4.48 \cos(20\pi t) \text{ kG}$$

$$dB/dt (112 \text{ MeV}, t = 8.65 \text{ ms}) = 3.8 \text{ kG/s}$$

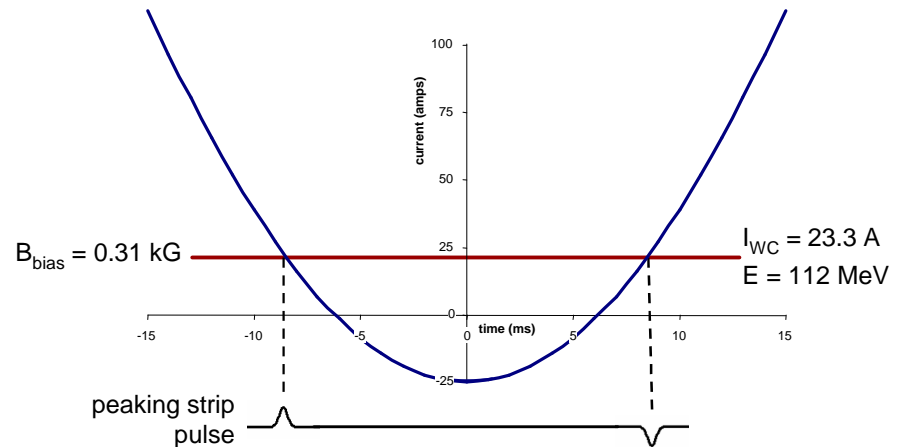


K. Endo, H. Sasaki
INS Tokyo
SJC-A-70-5, 1970

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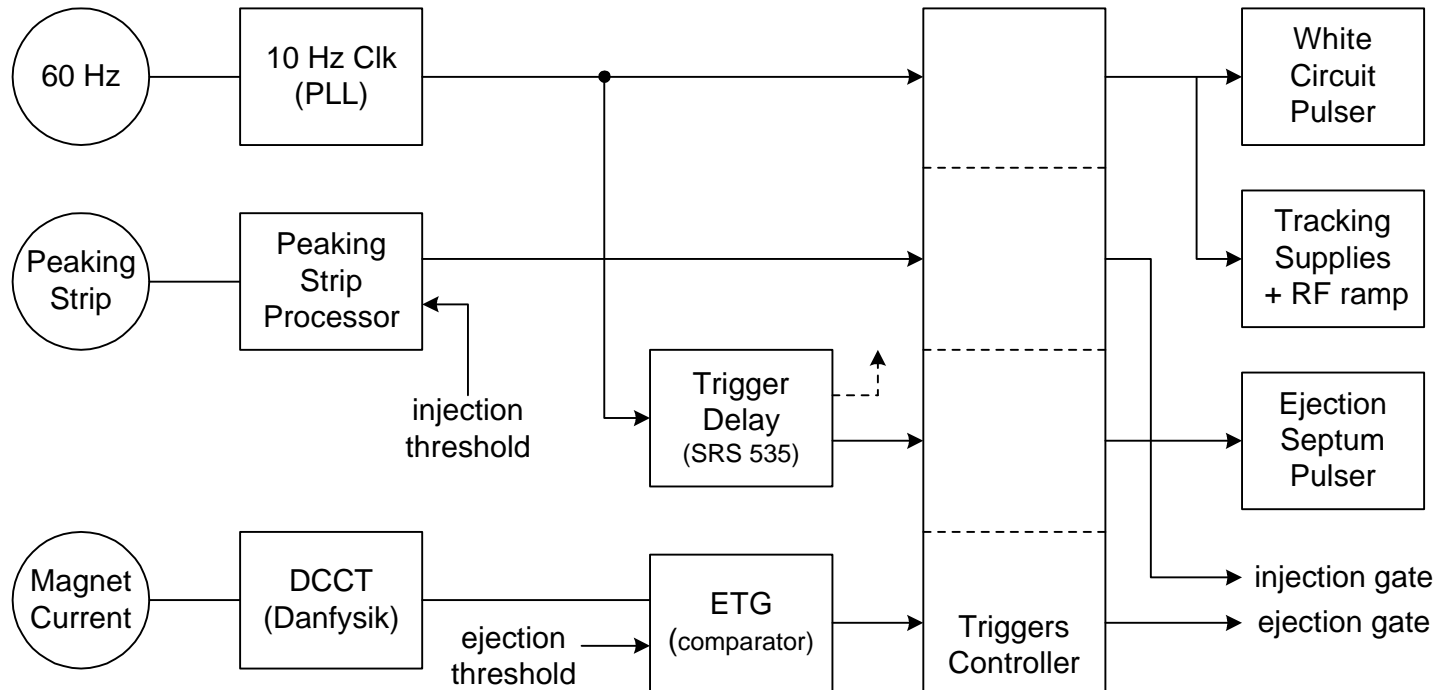
White Circuit Injection Energy Detection



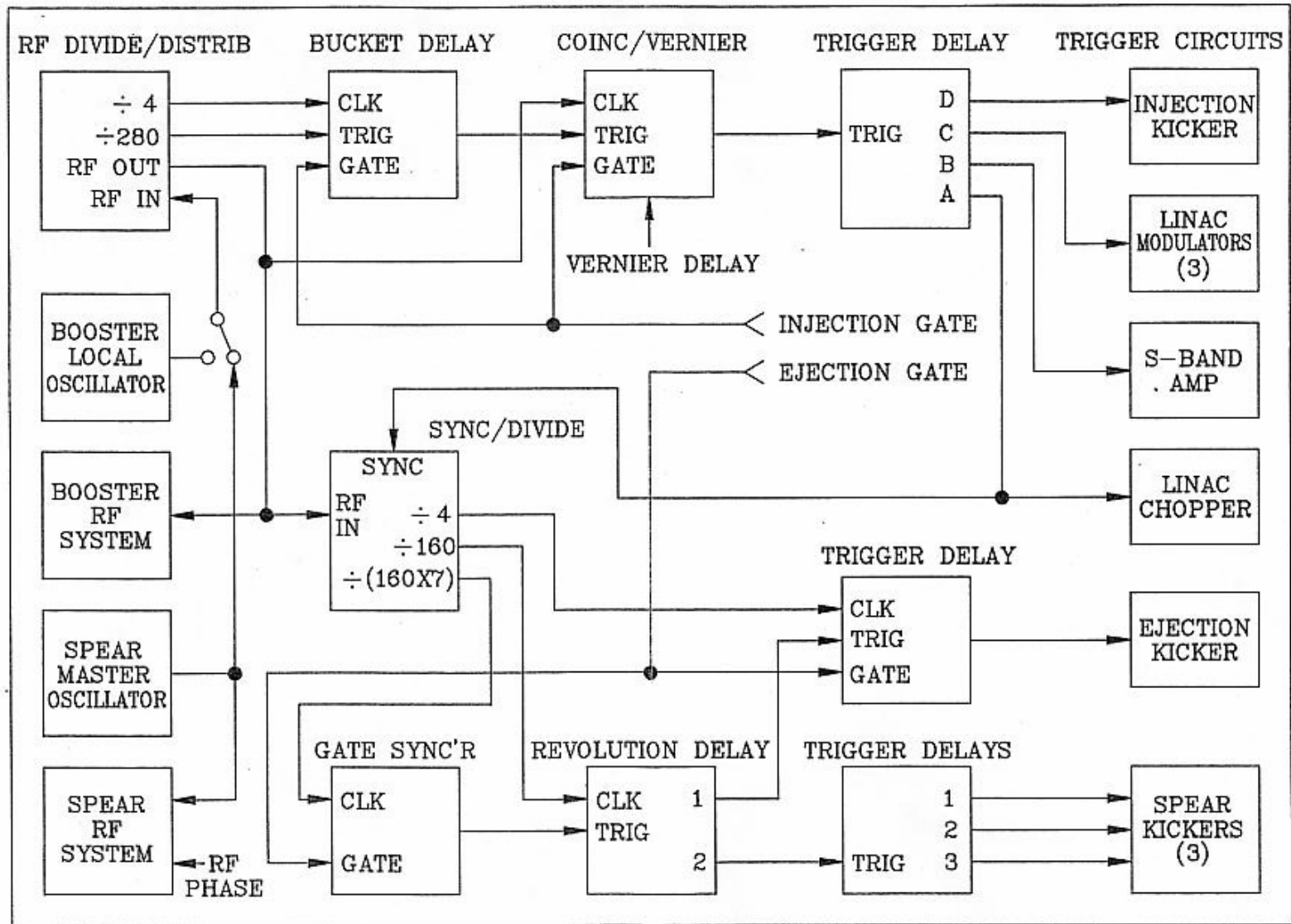
SPEAR 3 Timing System

Sept. 18, 2003

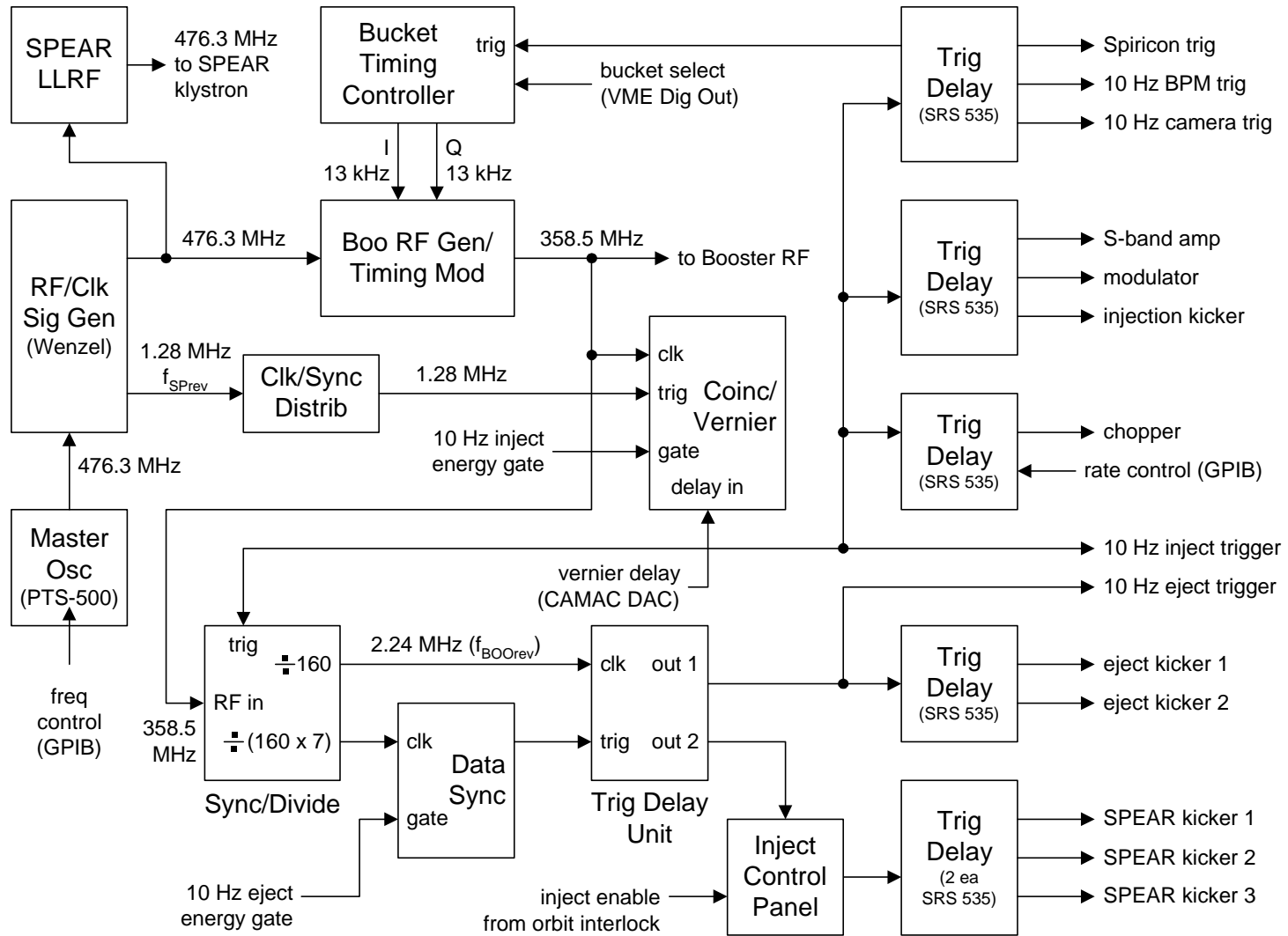
10 Hz Clock and Energy Gate Timing System



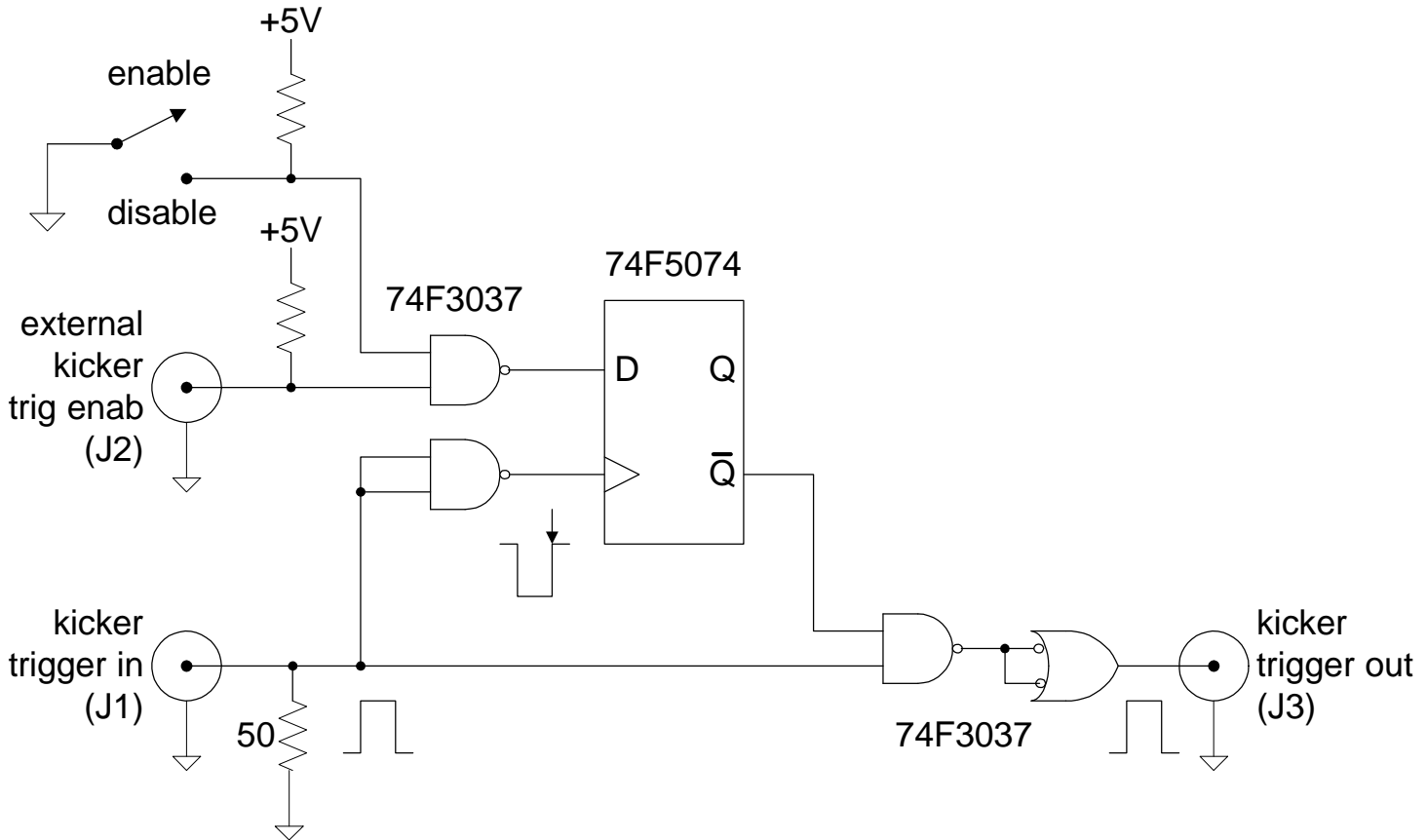
SPEAR 2 RF-Synchronized Timing System



SPEAR 3 RF-Synchronized Timing System



SPEAR 3 Kicker Trigger Enable/Disable



SPEAR 3 and Booster RF Frequency Choices

Table 1. Harmonic number, rf frequency and circumference options for SPEAR and the Booster assuming the use of either SPEAR 2 (~358.5 MHz) or PEP -II (~476 MHz) rf cavities.

	h	factors of h	f _{rf} (MHz)	C (m)	constraints
SPEAR	280	2 ³ · 5 · 7	358.53 - 358.60	234.08 - 234.15	SPEAR circumf. limit ^a
	371	7 · 53	475.00 - 475.15	234.08 - 234.15	SPEAR circumf. limit
	372	2 ² · 3 · 31	476.28 - 476.43	234.08 - 234.15	SPEAR circumf. limit
Booster	160	2 ⁵ · 5	358.48 - 358.60	133.76 - 133.80	cavity freq. limit ^b
	212	2 ² · 53	475.00 - 475.35	133.70 - 133.80	Booster circumf. limit ^c ; cavity freq. limit ^d
	212	2 ² · 53	476.33 - 476.43	133.40 - 133.43	Extended Booster circumf. limit ^e ; same freq as h = 372 SPEAR
	213	3 · 71	476.89 - 477.00	133.87 - 133.90	Booster circumf. limit; cavity freq. limit ^d
	213	3 · 71	476.33 - 476.43	134.03 - 134.06	Extended Booster circumf. limit ^e ; same freq as h = 372 SPEAR

$$h_{SP3} = 372 = 2 \cdot 2 \cdot 3 \cdot 31$$

9 symmetric fill patterns:

2-, 4-, 6-, 12-, 31-, 62-, 93-, 124- and 186-bunch

$$h_{Boo} = 372 = 2 \cdot 2 \cdot 2 \cdot 2 \cdot 2 \cdot 5$$

$$C = hc / f_{RF}$$

$$C_{SP3} = 234.1421 \text{ m} \Rightarrow f_{rfSP3} = 476.3 \text{ MHz}$$

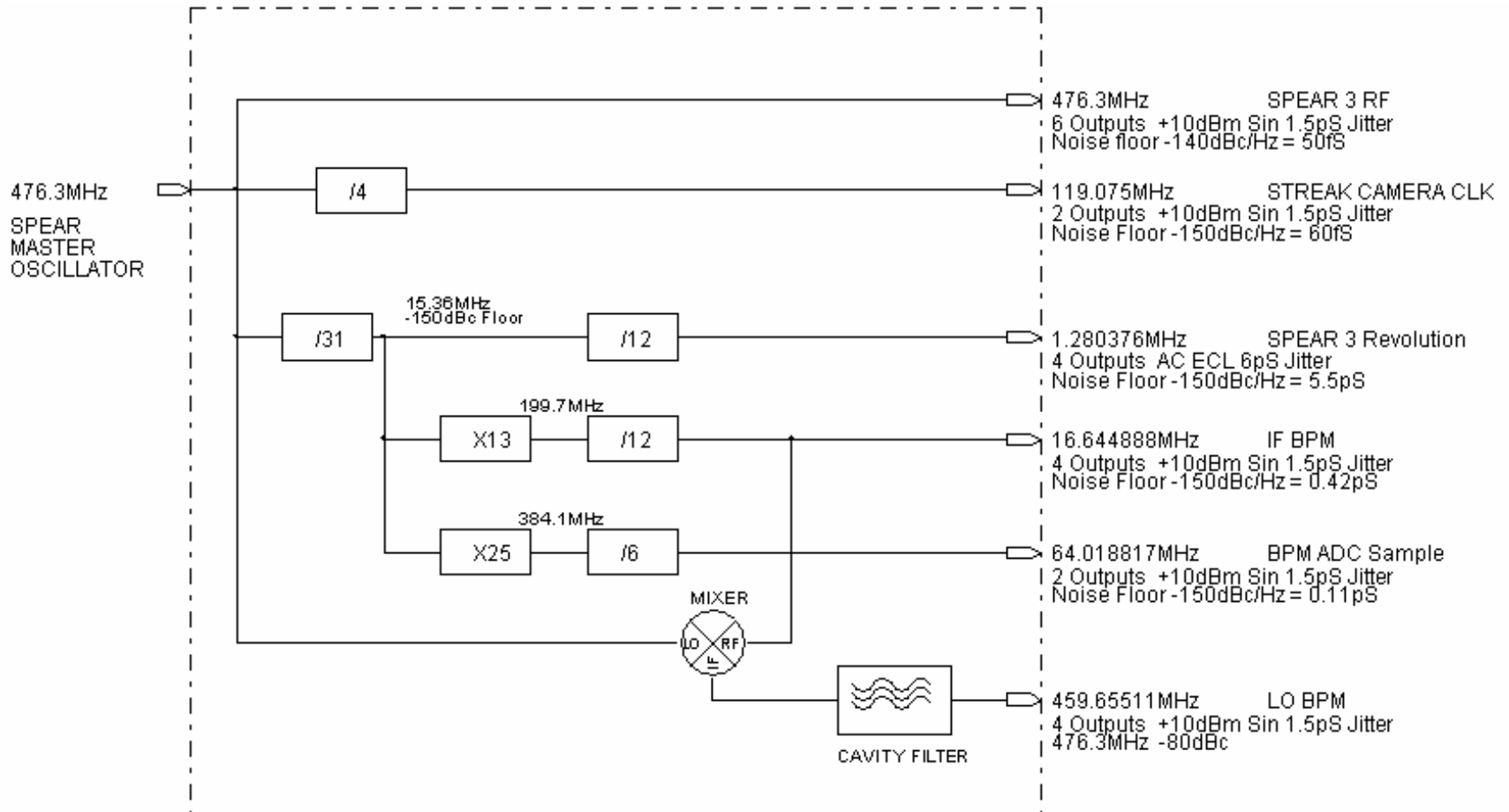
$$C_{Boo} = 4/7 C_{SP3} = 133.7955 \text{ m} \Rightarrow f_{rfBoo} = 358.505 \text{ MHz}$$

$$f_{rfBoo} / f_{rfSP3} = 70/93$$

SPEAR 3 RF Signal and Clock Frequencies

SPEAR RF:	$f_{\text{SPrf}} = 372 \times f_{\text{SPrev}} = 476.300 \text{ MHz}$
SPEAR revolution freq:	$f_{\text{SPrev}} = 1.2804 \text{ MHz}$
Booster RF:	$f_{\text{Brf}} = 160 \times f_{\text{BOOrev}} = 70/93 \times f_{\text{SPrf}} = 358.505 \text{ MHz}$
Booster revolution freq:	$f_{\text{BOOrev}} = 7/4 \times f_{\text{SPrev}} = 2.2407 \text{ MHz}$
BPM LO:	$f_{\text{LO}} = 359 \times f_{\text{SPrev}} = 459.655 \text{ MHz}$
BPM IF:	$f_{\text{IF}} = 13 \times f_{\text{SPrev}} = 16.645 \text{ MHz}$
IF digitizing clock:	$f_{\text{IFclk}} = 50 \times f_{\text{SPrev}} = 64.019 \text{ MHz}$
Streak camera clock:	$f_{\text{SC}} = f_{\text{SPrf}}/4 = 93 \times f_{\text{SPrev}} = 119.075 \text{ MHz}$

SPEAR 3 RF Clock/Signal Generator (Wenzel)



SPEAR RF: $f_{SPrf} = 372 \times f_{SPrev} = 476.300 \text{ MHz}$

BPM LO: $f_{LO} = 359 \times f_{SPrev} = 459.655 \text{ MHz}$

SPEAR revolution freq: $f_{SPrev} = 1.2804 \text{ MHz}$

BPM IF: $f_{IF} = 13 \times f_{SPrev} = 16.645 \text{ MHz}$

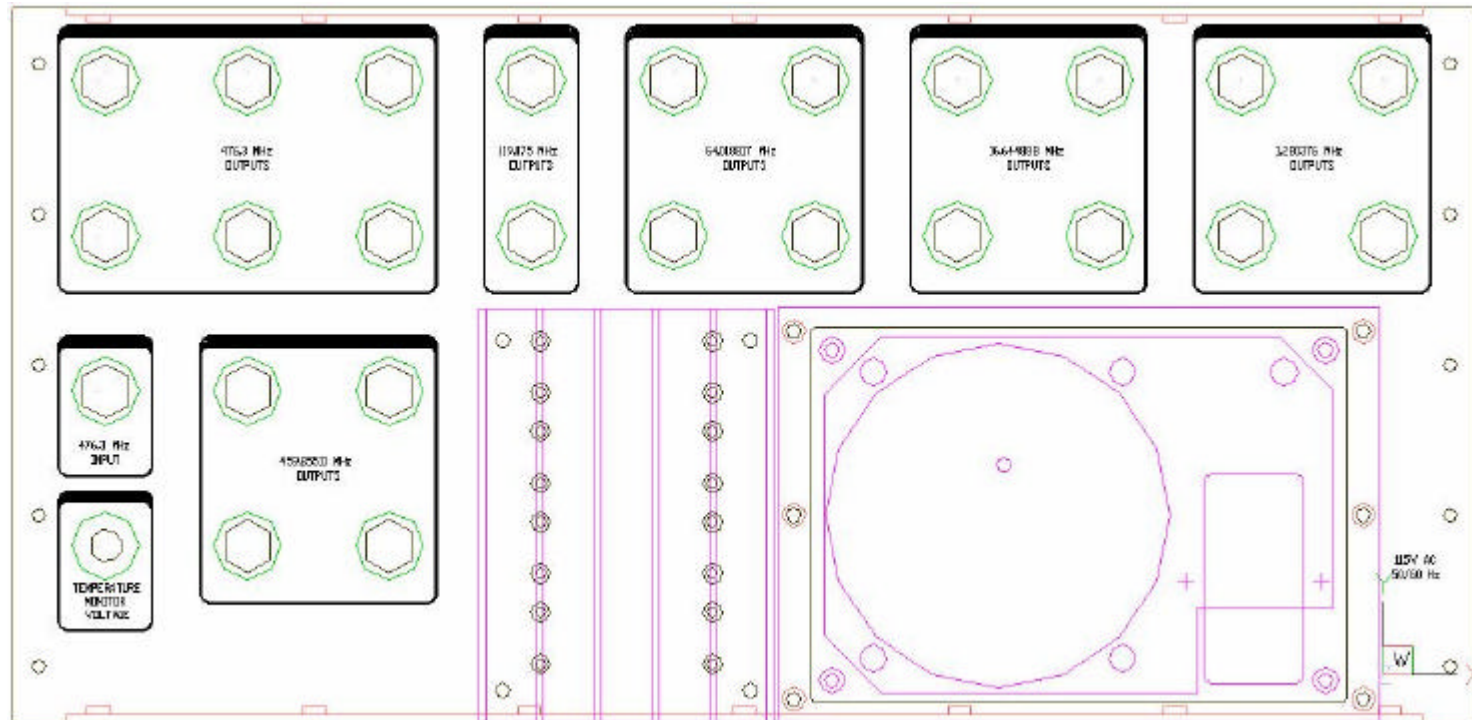
Booster RF: $f_{Brf} = 160 \times f_{BooRev} = 358.505 \text{ MHz}$

IF digitizing clock: $f_{IFclk} = 50 \times f_{SPrev} = 64.019 \text{ MHz}$

Booster rev freq: $f_{BooRev} = 7/4 \times f_{SPrev} = 2.2407 \text{ MHz}$

Streak camera clock: $f_{SC} = f_{SPrf}/4 = 93 \times f_{SPrev} = 119.075 \text{ MHz}$

SPEAR 3 RF Clock/Signal Generator (Wenzel)



rear panel

SPEAR 3 RF Stability and Resolution Requirements

- Δf_{RF} causes change in path length and **horizontal beam position** in dispersion regions (e.g. dipole source points):

$$\Delta X = -\frac{\eta_x}{\alpha} \frac{\Delta f_{\text{RF}}}{f_{\text{RF}}} < \sim 0.01 \sigma_x = 1.6 \mu\text{m} \text{ for dipole source}$$

$$\alpha = 0.00113 \quad \eta_x = \sim 0.1 \text{m}$$

$$\Rightarrow \frac{\Delta f_{\text{RF}}}{f_{\text{RF}}} < 1.8 \times 10^{-8} \quad \Rightarrow \quad \Delta f_{\text{RF}} < 9 \text{ Hz}$$

- Phase noise:

$$\phi_{\text{max}} = -\frac{h}{v_s} \frac{\Delta f_{\text{RF}}}{f_{\text{RF}}} = \sim 0.06^\circ$$

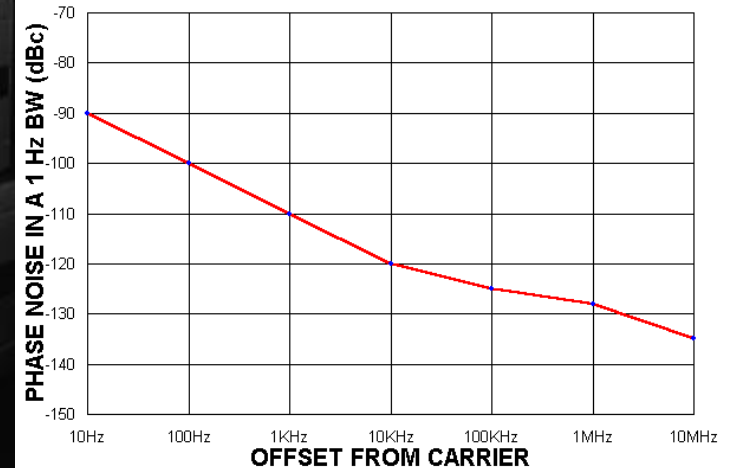
$$v_s = \text{synchrotron tune} = 0.007 \text{ for SPEAR3}$$

- Δf_{RF} causes beam **energy shift**; to maintain $< 10^{-4} - 10^{-5}$ undulator photon energy stability:

$$\frac{\Delta E}{E} = -\frac{1}{\alpha} \frac{\Delta f_{\text{RF}}}{f_{\text{RF}}} < 5 \times 10^{-5} \text{ to } 5 \times 10^{-6} \quad \Rightarrow \quad \frac{\Delta f_{\text{RF}}}{f_{\text{RF}}} < \sim 5 \times 10^{-8} \text{ to } 5 \times 10^{-9}$$

$$\Rightarrow \Delta f_{\text{RF}} < \sim 2 - 20 \text{ Hz} \quad \Delta \phi_{\text{max}} < \sim 0.01^\circ - 0.1^\circ$$

SPEAR 3 Master Oscillator

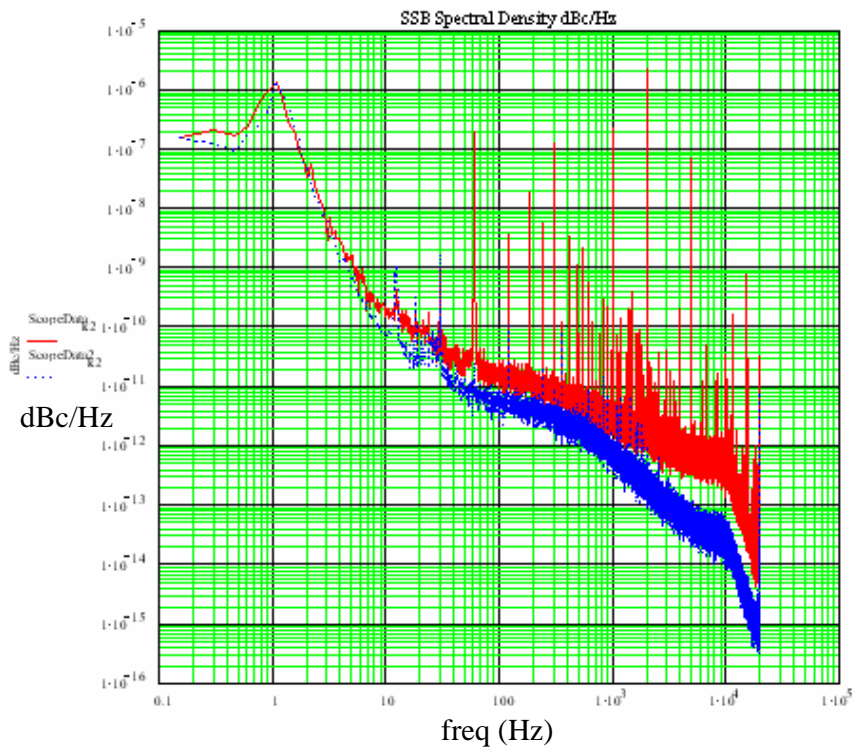


- 1-500 MHz, DDS-based
 - need 476.3 MHz \pm 50 kHz
- 0.2 Hz step resolution
- Phase-continuous frequency switching
- Stability: 3×10^{-9} /day, 10^{-6} /yr, $\pm 10^{-8}$ /0-50°C
- 0.057° integrated phase noise, 0.5 Hz-15 kHz
- GPIB control

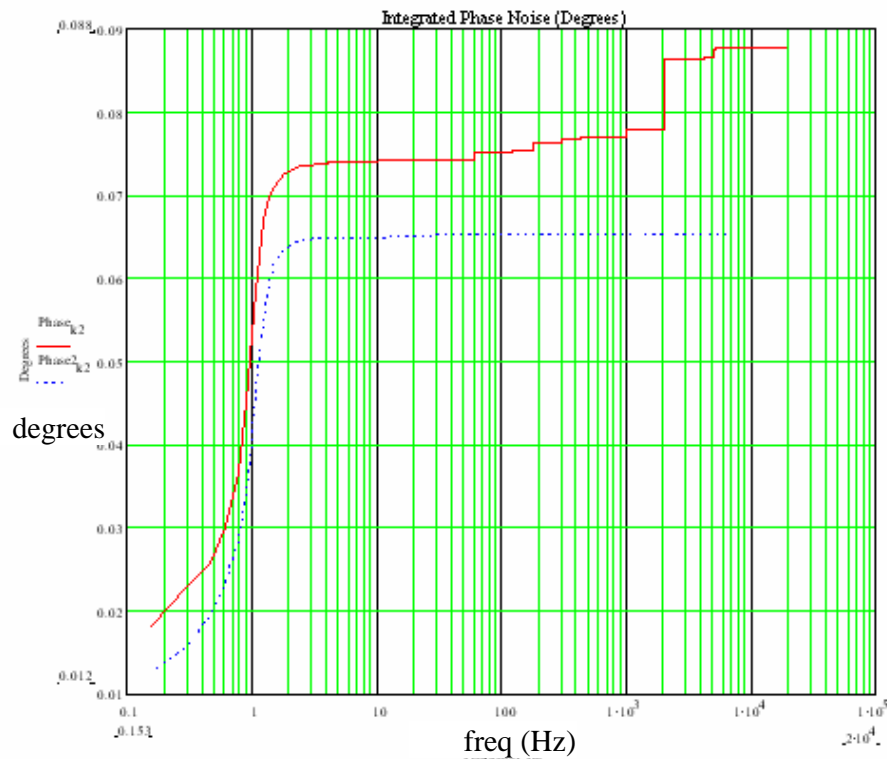
Phase Noise Measurements: PTS-500 vs Wenzel Plate - 40kHz

Resolution Bandwidth: Freq/step = 0.076

SSB spectral density (L(f))

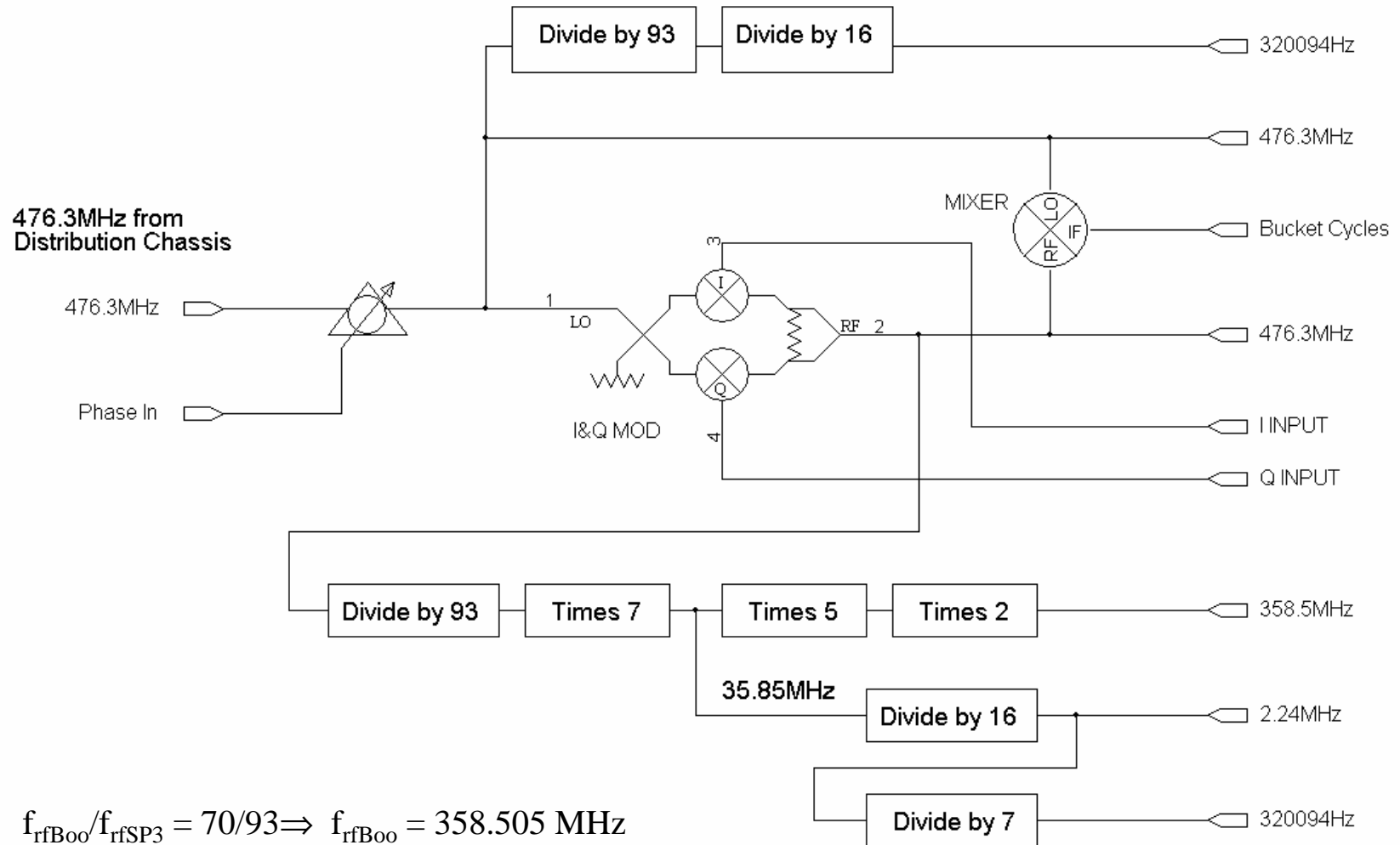


Integrated phase noise



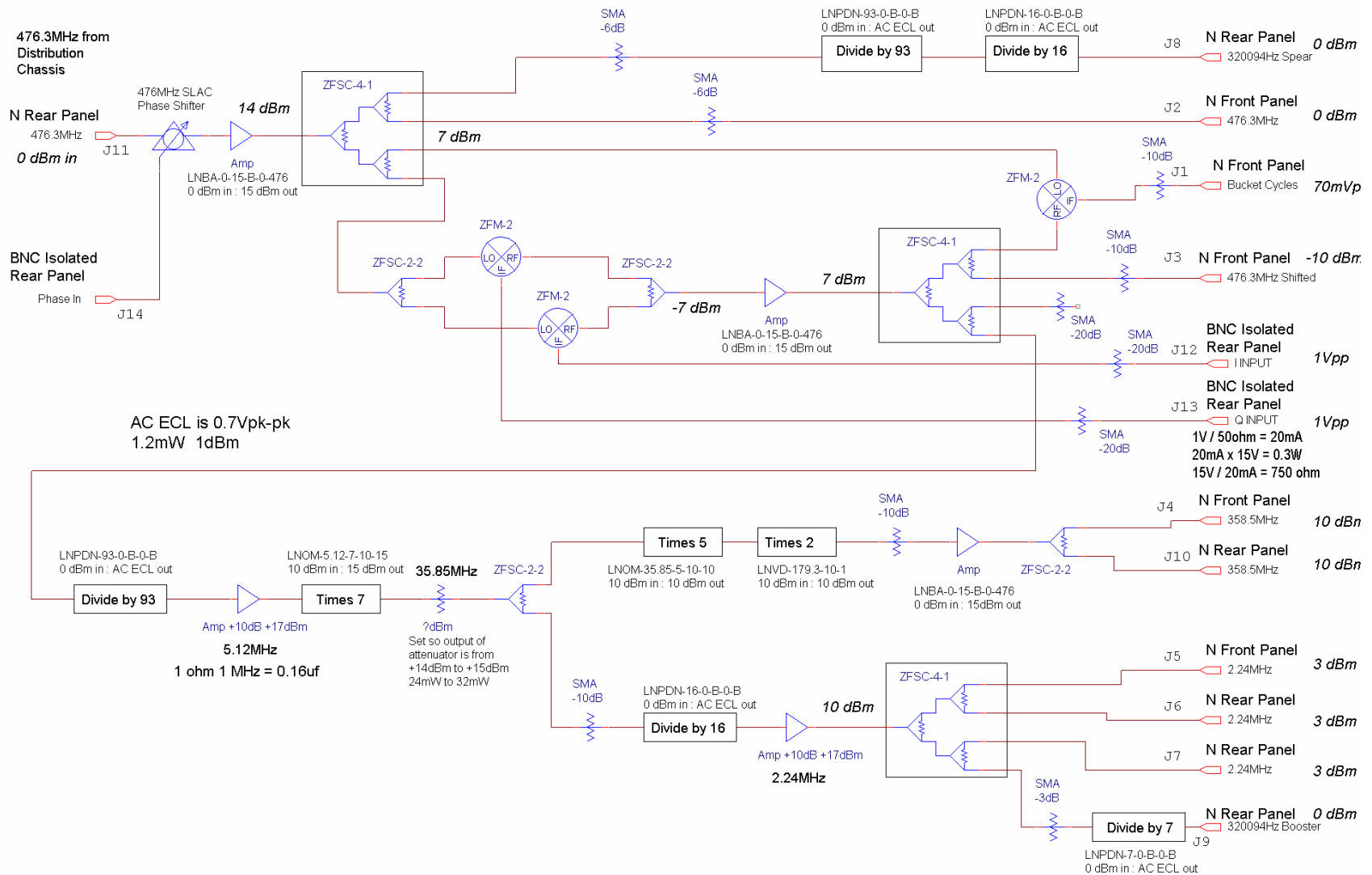
$$\phi^2 = \int 2L(f)df$$

SPEAR 3 Booster RF Generator and Timing Modulator

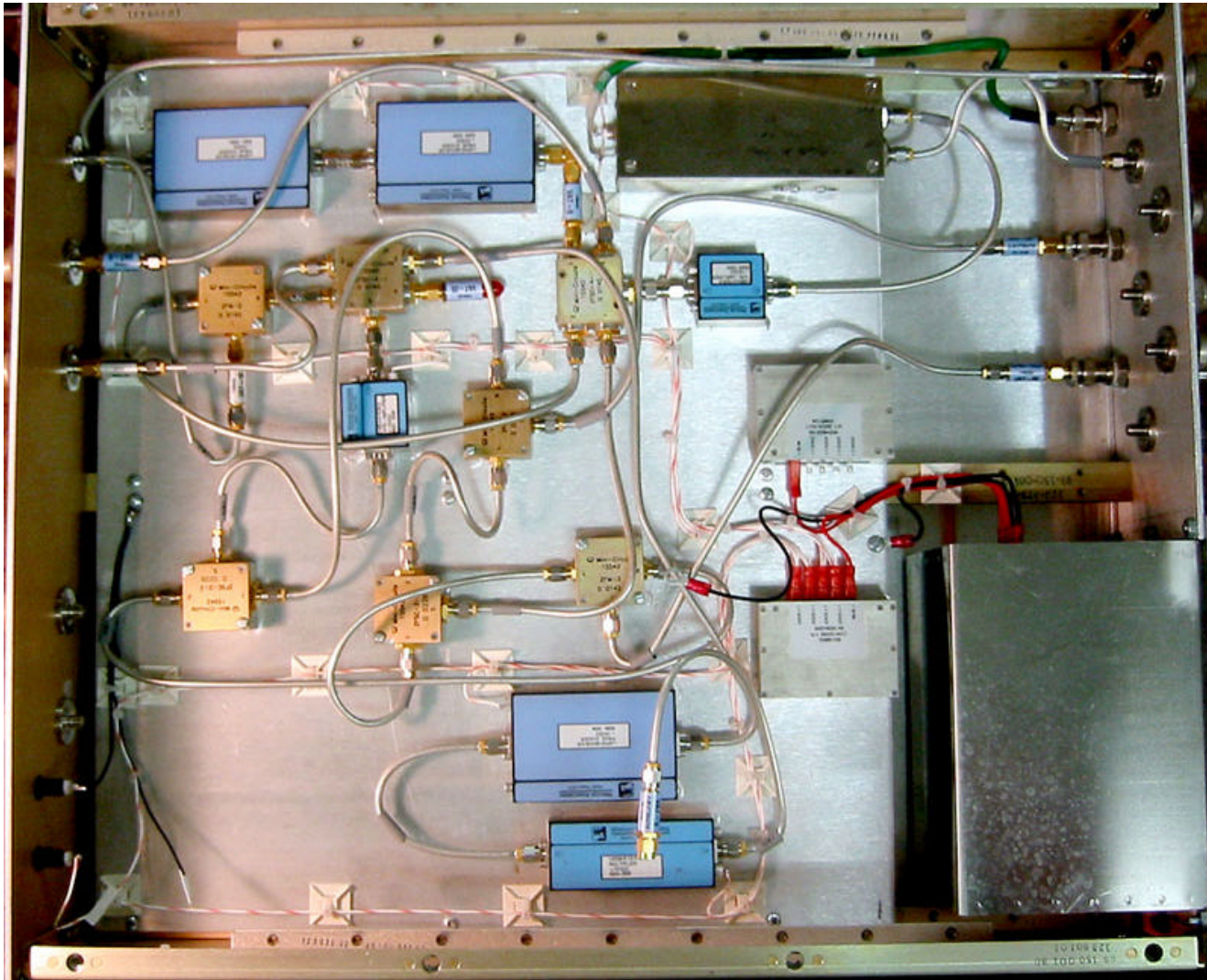


$$f_{rfBoo}/f_{rfSP3} = 70/93 \Rightarrow f_{rfBoo} = 358.505 \text{ MHz}$$

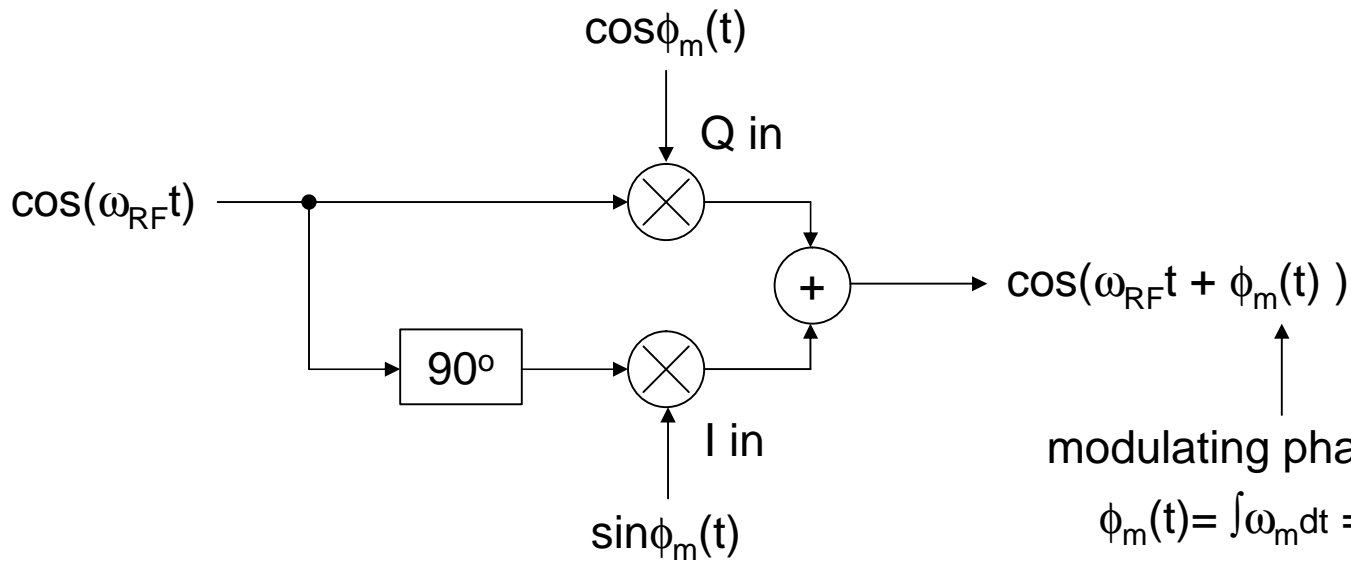
SPEAR 3 Booster RF Generator and Timing Modulator



SPEAR 3 Booster RF Generator and Timing Modulator



Injection Timing with I/Q Modulation of RF



modulating phase shift:

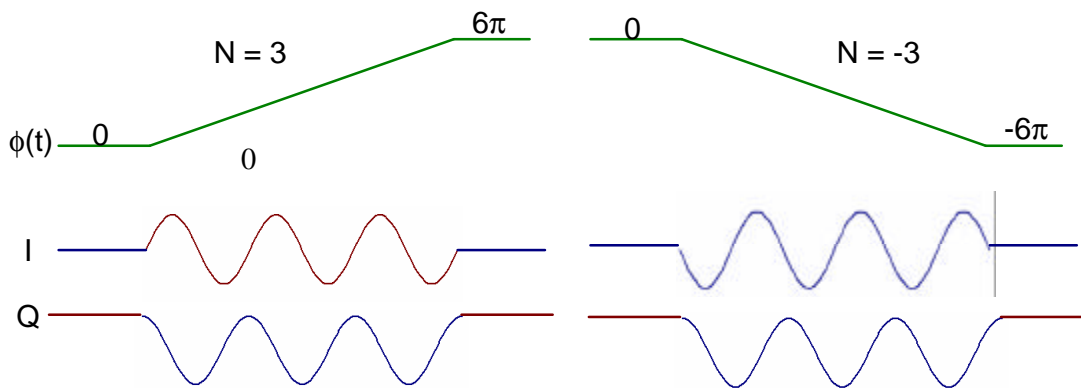
$$\phi_m(t) = \int \omega_m dt = 2\pi N$$

N = number of modulating waveform cycles

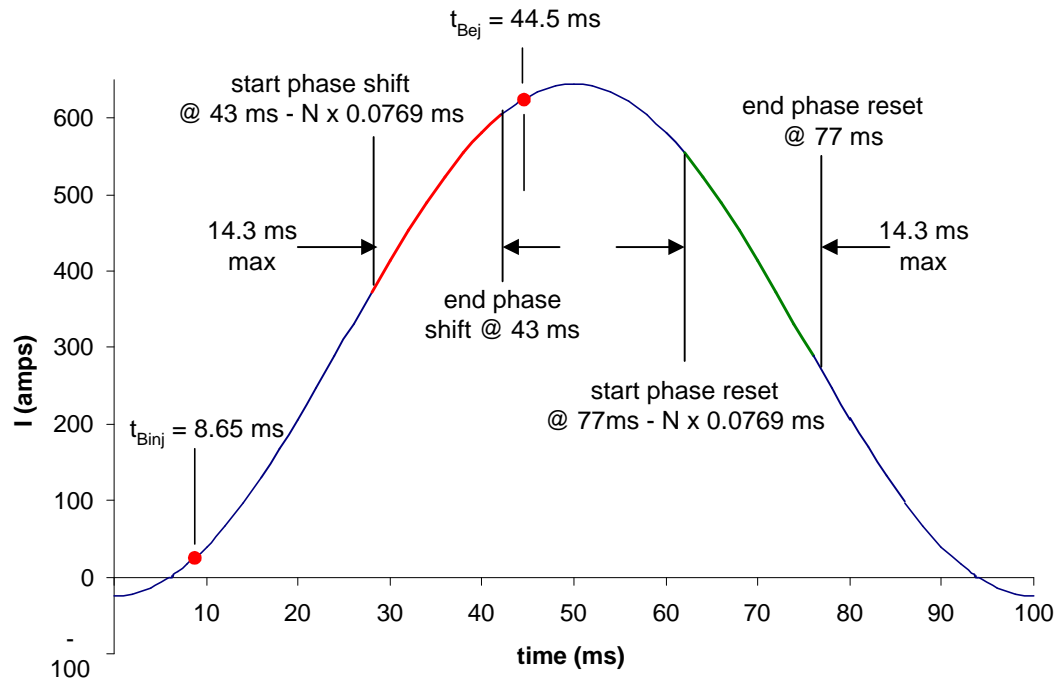
= bucket number

(N = -185 to +186)

$$f_m = \omega_m / 2\pi = 13 \text{ kHz}$$



Booster RF Phase Shift Timing



I/Q control frequency = 13 kHz

I/Q control period = 0.0769 ms

time for max phase shift of 186 buckets = 186×0.0769 ms = ~ 14.3 ms

SPEAR 3 Chopper Rate Reduction

for Booster radiation dose control

