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Accelerator Department Lecture Series: Some Beam Related rf Topics

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AGS Division Technical Note <u>No. 206</u>

Some Beam Related rf Topics

Accelerator Department Lecture Series

September 8-14, 1984

Daniel Boussard CERN, SPS RF Group

October 1, 1984

* ACCELERATOR DEPARTMENT LECTURES *

Some Beam Related RF Topics

by

Dr. Daniel Boussard

CERN, SPS RF Group

Time: 11:00 a.m., September 8-14, 1983

Place: Snyder Seminar Room, First Floor, Bldg. 911

1. Longitudinal Phase Space for Beginners (Thursday)

2. Phase Space Manipulations (Friday)

3. Beam Control Systems (Monday)

4. Instabilities (Tuesday)

5. Two Examples of Beam Loading Compensation at CERN (Wednesday)

1. Longitudinal Phase Space for Beginners

Stable and unstable points, trajectories in phase space.
 Stationary and accelerating buckets. Conservation of phase space area, adiabaticity, filamentation.

Longitudinal phase space RF OFF Cavity particle with energy & moc2 ß. p, Maguetic field Bo - $R_{\circ} = \frac{L}{2\pi}$ fo 2nd particle with energy 80+08, Bo+AB, po+Apo of? AR? Simple and mrealistic cases. a) Uniform field - circular trajectories $f = \frac{\beta c}{2\pi \rho}$ $f = \frac{e^{B}}{2\pi} \frac{1}{\sqrt{\frac{Eo^{2}}{c^{2}} + b^{2}}}$ P=eBP 4 f

N						
In terms of Wanted	β	¢p	T	E	٣	
β≖.	ß	$[(E_{o}/cp)^{2} + 1]^{-\frac{1}{2}}$	$\int s = (1 + \pi/\pi)^{-2} \frac{1}{2}$	$[1 - (E_0/E)^2]^{\gamma_2}$	$(1 - \gamma^{-2})^{\frac{1}{2}}$	
		cp/E	[[= ([+ 1/2s)]	cp/E		
CP =	$E_0(\beta^{-2}-1)^{-\gamma_2}$	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	$[T(2E_0 + T)]^{\frac{1}{2}}$	$(E^2 - E_o^2)^{\gamma_2}$		
	Ēβ		$T[(T + 1)/(T - 1)]^{\frac{1}{2}}$	Eβ	$E_a(\gamma^2 - 1)^{\prime a}$	
Ε, Ξ΄	cp/By	$cn(x^2 - 1)^{-1/2}$		(E/Y	
	$E(1-\beta^2)^{\frac{1}{2}}$		V(Y = 1)	(E ⁻ - c ⁻ p ⁻)/ ⁻		
Τ=	$[(1 - \beta^2)^{-\frac{1}{2}} - 1]E_{2}$	$[E_0^2 + c^2 p^2]^{y_2} - E_{\phi}$	_		$E_0(\gamma = 1)$	
		$cp[(\gamma - 1)/(\gamma + 1)]^{1/2}$	I .	$E = E_{q}$		
¥ =	$(1 - \beta^2)^{-\gamma_2}$	cp/E₀β		,		
		$[1 + (ep/E_0)^2]^{1/2}$	$i + T/E_{\bullet}$	E/E.	. T	

1.2 First Derivatives

-. .

In terms of Wanted	dβ	d(cp)	$d\gamma = dE/E_{\bullet} = dT/E_{\bullet}$	
dβ _	dβ 🚡	$[1 + (ep/E_0)^2]^{-\frac{1}{2}} d(ep)/E_0$	$\gamma^{-2}(\gamma^2-1)^{-\gamma_2} d\gamma$	
		$\gamma^{-3} d(cp)/E_{\sigma}$	$\beta^{-1} \tau^{-3} d\gamma$	
d(cp) =	$\frac{E_0(1-\beta^2)^{-\dot{\gamma}_2}}{E_0\gamma^3}d\beta$		$E_{0\gamma}(\gamma^2-1)^{-\gamma_2}d\gamma$	
		αίσρι	$E_{\bullet} \beta^{-1} d\gamma$	
dy =	$\beta(1-\beta^2)^{-\gamma_2} d\beta$	$[1 + (E_o/cp)^2]^{-1/2} d(cp)/E_o$		
$= dT/E_{e} =$	₽√³ 4₿	$\beta d(cp)/E_{o}$	ď۲	

1.3 Logarithmic first derivatives

In terms of Wanted	<i>4β/β</i>	dp/p	at/t	$dE/E = d\gamma/\gamma$
dβ/β. =	dβ/β	$\frac{\tau^{-2} dp/p}{dp/p - d\gamma/\gamma}$	$[\gamma(\gamma + E)]^{-1} dT/T$	$\frac{(\gamma^2 - 1)^{-1}}{(\beta\gamma)^{-2}} \frac{d\gamma}{\gamma}$
dp∕p =	ϫ _ͻ ͻϥϩʹ	dp/p.	[Y/(Y + I)] dT/T	β ⁻² ἀγ/Υ
- T/Τb	т(т + 1) <i>ар/р</i>	(1 +	dT/T	$\gamma(\gamma = 1)^{-1} d\gamma/\gamma$
dE/E = dy/y =	$(\beta\gamma)^2 d\beta/\beta$ $(\gamma^2 - 1) d\beta/\beta$	β ² dp/p dp/p - dβ/β	(1 – y ^{-*}) dī/T	dy/y

 $\begin{aligned} \mathcal{Y}_{n}^{2} \frac{dR}{R} &= \frac{dP}{P} - \frac{dB}{B} \\ \frac{dP}{f} &= \frac{\vartheta_{n}^{2} - \vartheta^{2}}{\vartheta_{n}^{2}} \frac{dP}{P} + \frac{1}{\vartheta_{n}^{2}} \frac{dB}{B} \\ \frac{\eta}{\eta} \end{aligned}$

. !(`

 $\frac{dp}{p} = \frac{\chi^2 df}{f} + \frac{\chi^2 dR}{R}$ $\frac{dB}{B} = \frac{\chi^2 df}{f} + \frac{\chi^2 dR}{R}$



alucys hegatist

b) Uniform magnetic field + straight sections



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straight sections : L avec : $2\pi\rho$ There = $\frac{L+2\pi\rho}{\beta c}$









 $\frac{d T_{em}}{d Y} = \frac{2\pi E_0}{eBc^2} - \frac{L}{c\beta^2} \frac{d\beta}{dY}$ $\frac{d^{\beta}}{dr} = \frac{1}{\beta \delta^3}$ Sto determined by <u>LTree</u> =0 $(\beta \delta)^3 = \frac{LeBc}{2\pi E_0}$ With { p=eBeo $(\beta \gamma)_{t}^{2} = \frac{L}{2\pi\rho_{0}}$ Va depends on lattice geometry For a smooth machine The ~ Vx Let's turn RFONT at fr= h fo intega; harmonic number Synchronom particle : we know its notion for ever \$ =0° \$=180° fo=fre/h Non synchronous particle 2) 2 effets : gap + duft space

in ΔE sap $\Delta \phi$ ΔE $\Delta E + eV \sin \Delta \phi$ ith turn A\$\$\$ k(AE+eVsmA\$) drift Space » AE+eVsinA¢ it the treasure drift X=X+K+Y $\int_{a}^{a} \left[\begin{array}{c} x \\ y \end{array} \right] \frac{gap}{y=y+V\sin x}$ Thase space plot of, DE (DR, Df). X , Y : phase oscillation Projections ou axes reduces forcallation 2 regions of phase space closed Open SEPARATRIX trajectories trajectories stable point : elliptical trajecturies unstable point : hyperbolic trajectories.



Bucket parameters

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10) <u>Synchrotron frequency</u>. fs «fr energy gain / turn = eVsin ¢ (unit time = eVsin ¢ fr = <u>d D</u>E

$$\Delta E \longrightarrow \Delta f = \frac{1}{2\pi} \frac{d\phi}{dE}$$

$$\begin{cases} \frac{d\Delta E}{dt} = a \sin \phi \\ \frac{d\Phi}{dt} = b \Delta E \end{cases}$$

- Small oscillations sin & ~ +

$$\frac{d^{2}\varphi}{dc^{2}} - ab \varphi = 0$$

$$\frac{d^{2}\varphi}{dc^{2}} = \frac{d^{2}\varphi}{dc^{2}}$$

$$\frac{d^{2}\varphi}{dc^{2}} = \frac{d^{2}\varphi}{dc^{2}}$$

$$\frac{d^{2}\varphi}{dc^{2}} = \frac{d^{2}\varphi}{dc^{2}}$$

$$\frac{d^{2}\varphi}{dc^{2}} = \frac{d^{2}\varphi}{dc^{2}}$$

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2°) Bucket height, area Verify that $\Delta E = \Delta E_m \cos \frac{\phi}{2}$ satisfy the equations for a particular value of DEmay : bucket height. DEmax - Dfmax 2 fs. of firsts F5) 1 2 1/ ₽▲∲ bucket area = $\frac{2}{TL} \times 2TL \times 2$ bucketheight Area inside a given trajectory -> use tables 30) Non sinvsoidal buckets. flat - toped bunches - 2nd harmonic linearized - 3rd harmonic missing bucket



$$\frac{1}{3}$$

$$\frac{1}{2} \frac{1}{2} \frac{$$

	¢1 -	\$ 2	y		Ta	fπ	
0	180.	-188.3	1.414214	1.4008-1-	*** [*] *****	-0000000	
₹ <u>3</u>	175.	-175.0	1.412868	.795225	25:57024	,0391080	
•	170.	-170.0	1.408532	.983557	21:67561	,0461348	
•	165.	165.0	1.402115	.966537	19:41534	0514951	
	160.	-160.0	1.392728	.945128	17:83824	+0560593	
	155.	-155.0	1,380691	.719668	16-62970	,0601334	
	150.	-150.0	1.306025	.390980	15:65253	.0638630	
	145.	-145.5	1,348759	.859421	14:85237	,0673293	
	148.	-140.0	1.328926	.325401	14:16787	.0705822	
	-37.	-135.0	1.306263	.789298	13:57698	.0736541	
	13U.	-138-0	1.201/13	•/51464	13+06947	-0/62669	
	122.	-125.0	1.224723	•/12235	12:00457	• 0/93363	
	+20+		4 499777	•0/192/	12:19505	-0014/03	-
•	140		-1+174/30 4 4Ka4e/	•030045	11.83628	10544800	
÷	145	-105.0	1 424974	*7872/9	11 21005	10000000	
• •	100.	=100.0	1.083360	*34/349	10 94630	-0913300	
• .	- 05.	-95.0	1.042648	.444420	-10-7-768	10710000	
	93.	-50.0	1.000000	.423607	10+48823	.0953450	
	85.	-25.0	955429	-383598	10.28272	.0971932	
	80.	-80.0	,909030	.344621	10+10749	0989365	
•	75.	-75.0	.860919	.306890	9 94281	-1005752	
'	70.	-70.0	.811160	.270608	· 9:79340	.1021096	
. • . •	65.	-65.0	759856	.235968	9.05814	1035396	
	60.	-60.0	1707107	.203149	1 9. 53604	1048653	1
	55.	-55.0	+653011	,172322	9.42028	1069864	
•	50.	-50.0	.597672	.143640	9:32813	,1072027	
:	. 45.	-45.0	.541196	.117.250	9124395	+1082139	
•	.40.	-40.0	.483000	.093280	9.16425	1091197	
	. 32.	-32.0	.445462	.071850	9:09754	1099198	
•	38.	-30.0	.306025	.153064	9:04046	:1100139	
	27.	-23.4	.340492	.43/012	8.9926/	,111201/	
	204	-45 0	+8/500	.023773	8 95391	+1110830	
	12.	-12.0	+272=7	.110410	8.92398	11243/0	•
i	10.	-10.0	******	•UUD9/2	0.902/1	+174460	1
	2.	-4-7	403EE		0109000 3-895/7	********	
	3	-7+4	+U-7922	10005797	8 + 89726	*********	
	2.		. 124684		E.88444	1125310	
•	· · · · ·	=1.0	.017344		- 8.88504	1125374	
	- 1		10				
		• • • • •		•	•	•	I

Accelerating bucket. B≠0 f≠0 R = comt. ¢≠0 $\dot{R} \neq 0$ B=0 R=0 (electrons) f =0 B=0 in all cases energy gaine /turn +0 for Eynchronous purticle (countant phase) $\frac{dp}{dt} = e \oint \frac{dB}{dt}$ $\int \Delta E = 2\pi R \oint B$ $\int turn = \frac{2\pi R}{Bc}$ - B+0 R=0 $\Delta E / turn = \frac{1}{3\epsilon_0} \frac{e^2}{R} \left(\frac{E}{m_0 c^2}\right)^4$ - electrons A E/turn différence in energy / my synchronous particle $\Delta E = eV sin \phi = eV sin \phi_s \simeq eV cos \phi_s. \Delta \phi$ J synchronaus particle particle fs=fs ×vcosds

12	· · · · · · · · · · · · · · · · · · ·
	5 GCLEAR 19 SCALE -3.5,3.5,-25,25 15 XAXIS 0,.5 20 YAXIS 0,5 20 YAXIS 0,5 25 V0=1 30 INPUT X 35 INPUT Y 38 MOVE X,Y 46 K=01 45 V=V0%(SIN(X)-SIN(.523)) 50 Y=Y+V 52 PLOT X,Y 65 GOTO 45 70 END
	<pre>5 GCLEAR 10 SCALE -3.5,3.5,-25,25 15 XAXIS 0,.5 20 YAXIS 0,5 20 YAXIS 0,5 20 YAXIS 0,5 25 V0=1 30 INPUT X 35 INPUT Y 33 MOVE X,Y 40 K=01 45 V=V0*(SIN(X)-SIN(PI/2)) 50 Y=Y+V 52 PLOT X,Y 55 X=X+K*Y 65 GOTO 45 70 END</pre>

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Many ponticles (protom) No damping at all -> complete memory conservation of phase space area (Liouville Hecorem) S, - to t $S_1 = S_2$ Conservation of phase space deusity But: - proper choice of raiables : $(\phi, \Delta \beta^{\gamma}(\Delta \mu))$: mrad alt, DE : cV.s - possible exchange between transvase & longitudinal phase planes - Ways to cheat Liowille theorem - H⁻injection - stochastic cooling

1+ Matched beam. (uniform deuxity case) frontie of beam 1 porticular trajectory =macroscopic steady situation. inner Ver a transfer from machine Ato B after 1/4 Ts Filamentation on Dilution 52 >51 because fs = fso

2. Phase Space Manipulations

re

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Debunching, capture, transition, controlled blow-up. Normal modes of oscillation. Beam signals, beam transfer functions. 0

Conclusion : beam area (beam emiltance) can only grow (like entropy)

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5 GCLEAR 10 SCALE -3.5,3.5,-25,25. 15 XAXIS 0.5 20 YAXIS 0.5 20 YAXIS 0.5 25 V0=1 30 INPUT X 35 INPUT Y 38 MOVE X,Y 40 K=-.01 42 V0=V0-.001 \leftarrow slow decrease of V 45 V=V0*SIN(X) 50 Y=Y+V 52 PLOT X,Y 55 X=X+K*Y 65 GOTO 42 70 END

Phase space manifordations.

1º/ Debunching (RF cut off)



Debruching time

T-Ab 2TT far 2 AP P





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$$\frac{AP}{Noc} = A/2\pi$$

but of academic interest fs -> 0 T -> 0







xe < 0.5

As $f_s = kA$ $\frac{dA}{dt} = \gamma_c k A^2$

$$A(t) = \frac{A_{i}}{1 - \frac{b-b_{i}}{b_{2}-b_{1}}} \left(\frac{A_{2}-A_{1}}{A_{2}}\right)$$

A, Az initial, final bombet areas

<u>See</u>: 1983 US conf p2220. few Ts2 , A2/A = 4 Capture efficiencies > 30% , time ~ for synchrotrous. For storage rings A2/A, much larger : perfectly reversible operation Example : unstacking , stacking - unstacking -> - stacking May need very low voltages (fen Volto in AA) _o une missing bucket scheme to carry smaller emiltances. - AGS at injection \$\$ \$0 efficiency ~ 75 to 80% more complicated simulation.



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2.11

from CERN. MPS/BR 73-17

 v_1

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5"

Final bunch shapes



Lincor rise

150 Adiabatic rise



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Example of an exotic RF manipulation þ unioun ched scam -11 empty bucket r Kr small bucket out ide (empty) Ib (AC component) =-Ib (full bucket) allin with same density × DE Energy given to full bucket = 5 × D Surfree density energy displacement = Evergy lost by full beam = Average energy loss x um be of particles en x de x D δE × $\delta E = \frac{S}{2\pi}$ -> phase displacement acceleration
Another example of sophisticated manipulation : marging of 2×5 bunches in the CPS

How to produce 5 bunches with energy E_1 and 5 bunches with energy E_2 ? Synthesize a missing bucket waveform (amplitude modulated RF wave) by combining h=20 (carrier) h=19 fidebands h=21 fidebands

= AA circumference.

S

Steady state beam currents.



projection on time axis

Ib = dr

Monitored directly by a wall monitor I wall = - Ib

With an electrostatic monitor : charge instead of current.

Note the difference with B change (acceleration)





No losses during acceleration.

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With AC coupled detectors, the base line height is a measure of the beam current (or charge) in the bunch

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Si=Se (AC compliang) S1+53 = bean charge . = h x period

- Measure of capture efficiency.



Amplitudes depends on distribution inside the bunch -> bunch shape

 $A_{DC} = \frac{2}{T_{C}} A_{m} \frac{C_{0}}{T}$ cosine shaped bunches examples : lugth to, $A_{n=2}A_{n}\left(\frac{\cos(n\pi \frac{p}{r})}{1-(2n\frac{p}{r})^{2}}\right)$ Ant-2



b) h identical bunches : line

lives spaced by h x fo= fac



Steady state components of beam current will develop steady state voltages in the ring impedances. - in the cavities (beam loading effect) - in the vacuum chamber (space change, inductive well)

Consequences : - distorsion of bucket trajectories - energy exchange between RF system and beam.

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Evergy exchange with RF cantice. Ino extreme cases: - Narrow band carity of 348 < fo Beam induced voltage = simsoid Power received by beam V sinds Ib Power delivered by RF L V I_{bga} cosφ \$ = phase of know current RF harmonic: $cn\phi = sin \phi_s \frac{2I_h}{I_h}$. Wide band cavity \$ f318 >> fo or frep , shat bunch transient has decayed to zero at the next bunch fassage Is _______ >t Vinen = $\frac{q}{c}$ $W cav = \frac{1}{2} C V_{m}^{2} = \frac{1}{2} q V_{max}$ W lost by beam = q V teen by beam V = 1 Vmax

Fundamental theorem of beam loading (P. Wilson)



If: $\lambda_1 \neq \lambda_2$ = Perfectly smooth, conducting vall: Ez=0 on well





Reduction of bucket area (below tramition)

important at low energy

3.2.2 Reduction of bucket area due to space charge effects (below transition) This reduction can be obtained from Fig. III.J.2.2, whore

A Asped. = 4 = h g Le r H/(Det 72)

[15,3]

with

Consequences:

maber of accolorated perticies

1 + 2 Im (vacuum chamber dismeter/beam diameter) £. =

classical proton radius

and L and are in the same units (as are r and R).



Fig. III.3.2.2 $(A - A_{sp.c})/A = f(A A_{sp.c.})$ (for constant density in phase space)

For $\phi_{\pm} = 0^6$ (and a cos² distribution in real space) one has

 $A_{space}/A = [1 - g_s + h R/(4\pi c_0 \gamma^2 R \tau)]^{\frac{1}{2}}$

[18, Appendix IV]

where T is in wolts.

If the vacuum chamber well is not perfectly smooth: - cross section discontiunities boxn - high order moder of RF carrilies represent it by a reactance, usually and inductance at low prequestion Additional Ez field on the wall: Ez = L d Ib ~ L dz inductioner (meter Finally. for a parahelic bunch: $V_{2_{max}} = \frac{3IR}{2\pi^2 MR} \left(\frac{2\pi R}{R}\right)^3 \left(\frac{9020}{2\beta r^2} - W_0L\right)$ strong bunch langth dependance ordinary space change

change bucket area Consequences : synchron frequency of individual particles 4 power losses (important for et e machines)

3. Beam Control Systems

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- Damping of dipole oscillations: description of various schemes (multibunch, single bunch).
- Low frequency corrections: radial loop, frequency loop, synchronization loop.
- o Quadrupole mode damping.

Few words on Schottky signals.







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Perturbed beam currents Displified affranch : constant dansity distribution Represent the beam boundary by its Fourier components: IJ. Numerology: steady state M = 0dipole m = 1quadrupole m = 2m = 3sextupole 2) Study the evolution of each mode separately For example: Dipole mode Described by the motion of the Cuto of granity of bouch





to = brunch length

Perturbation cuerent spectra for various modes

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Dipole mode beam transfer function. Those (frequency) perturbation on RF (fogunay) + Phase perturbation on beam Test with stop function on RF frequency : +

From synchrotron $\phi = \frac{j\omega}{\omega_{1}^{2} - \omega^{2}} \quad \delta \omega_{RF}$ oscillation equations $\delta \omega_{b} = \frac{\omega_{1}^{2}}{\omega_{1}^{2} - \omega^{2}} \quad \delta \omega_{RF}$

 $\phi = \phi_b - \phi_{RF}$

No damping unless you wait for filamentation (blow-up).

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LOW LEVEL RF SYSTEMS



VCO = voltage controlled oscillator FP = frequency program

6



Damping of <u>dipole mode</u> (not individual particles)

Loop equations: $5\omega - 5\omega' - B - \phi$ $B = \frac{j\omega}{w_s^2 - \omega^2}$

$$\varphi = B \delta \omega \times \frac{1}{1+kB}$$

$$\varphi = \frac{j\omega \delta \omega}{\omega_{s}^{2} - \omega^{2} + j\omega k}$$

$$\int damping term$$

Usually the system is strongly over damped (k large)

$$\delta \omega' = \frac{\delta \omega}{1 + k \frac{j\omega}{\omega_s^2 - \omega^2}} \simeq \frac{\delta \omega}{1 + j \omega \frac{k}{\omega_s - \omega_s}} \qquad for \ \omega < \omega_s$$



The effect of the loop is to make beam perturbations adiabatic

Bandwidth considerations

$$f_{rev} > mitj gan figuring > fs$$

present in surrect
 $For w > w_{5} = \frac{jw}{w_{5}w_{5}} = \frac{j}{jw}$
ben equivalent to an extravel oscillater \rightarrow classical phone lock incuit
 $\frac{\sqrt{co}}{42}$ Ref
 $- Delay \sim 1$ two limits bandwidth to $f_{1} < \frac{1}{42}$
 $f_{2} < \int_{1}^{1} e_{1}$
 $delay z = \int_{1}^{1} e_{2}$
 $- Cavity bandwith: $\delta f_{328} > f_{5}$ (limitation for electron mechanics)$

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- Filtering of TU signals:
tunable filters (self-tacking amphifin)
heterodyne filters (self-tacking amphifin)
heterodyne filters (single bunches)
La equivalent low frass filter
- Phan advance networks to optimise loop suppose

$$fle A q S$$
 low level system $k \rightarrow \infty$
 $\varphi = \varphi_b - \varphi_{RF} = \frac{j\omega \delta \omega}{\omega_s^{1-\omega^2} + j\omega k} \rightarrow o$ if $k \rightarrow \infty$
 $\varphi = \varphi_b - \varphi_{RF} = \frac{j\omega \delta \omega}{\omega_s^{1-\omega^2} + j\omega k} \rightarrow o$ if $k \rightarrow \infty$
Take beam RP component and field RF carries directly
 $\frac{\sqrt{\alpha_{eqn}(n)}}{-(c_1+2)}$
 z
 $q_{eqn} = \frac{\beta \omega}{\beta \omega}$
Required circuit characteristic:
 $q_{out} - Q_{in} = -\omega (z_2+z_1) + constant$
 $only for simusoidal signal \rightarrow nes negative delay!
- one possible technique:
 $w = \frac{\beta}{z_1+z_2}$$

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The AGS solution:



- -Filtue to select the proper side bands -Phase shifter works at fixed frequency - If fif >> frequency no trunable filters are needed.
- Like the Phase Lacked Loop it is a non linear system. Oterall delay: 2(2:+72)_____ In the phase loop technique equal lengths of cable from Ple and cavities (\$\Phimed meaning technique (\$\Phimed m

But limited to small k (limited range of Gshiffer + inkgester) Useful to damp I bunch separately (unelliplesur) ISR, SPS.

Low frequency corrections





$$\delta \omega_{b} = \frac{-kz\omega^{2}}{\omega_{s}^{2} - \omega^{2} + jk\omega} \simeq \frac{1}{j\omega}\omega^{2} z$$







slope ~ independent of loop parameters

need corrections

1st solution AC coupling of phase loop F.Pr. ф П 60 vco OK if F. Program precise enough never the at transition example. PS Booster 2nd Solution Radial coovertion Phase loop type AGS type phase Loop $\frac{\delta R}{R} = \frac{\gamma^2}{\delta_{R}^2 - \gamma^2} \frac{\delta_{f}^2}{f}$ JR Sw, X 9

 $SR = g \frac{\omega r^2}{j\omega} (z - G_p SR)$ $SR = \frac{1}{G_r} - \frac{2}{1 + \frac{j\omega}{g \omega^2 G_r}}$



- SR limited - single pole 2011 off for Gr real

Frequency loop.
If a presice frequency program is available, measure

$$\delta f = f_{RF} - f_{prog} = f_6 - f_{prog}$$

and use instead of SR

Instabilities 4.

- 0
- Coasting beam, microwave, negative mass. Robinson instability, coupled bunch instabilities. Coupled loop instabilities. Landau damping. 0
- 0

of measurement not affected by beam internity like SR · low internity beaus (pilot pp, heavy ions). SPS Xtal f. discri, soire problems t transition of R - 0 00 for $\delta f \neq 0$ need fast crowing (PS) presie program No change of sign Synchronization loop locks the beane (and RF) on an external frequency transfors from one machine to the next. Free Ad fre ς_{z} $\frac{1}{j\omega}$ °s√_∗∕∽ freq to plane contesion freq - > phase phase loop $\frac{1}{\sqrt{16}} \omega_s^2 = \frac{1}{\sqrt{16}} \frac{1}{\sqrt{16}}$ x _____; If Gs real : system un table (2 integrators) Need a phase advance metricite:

#2 -! . Phose advance network Corrected loop QUADRUPULE MODE DAMPING. dipete mode _ phase seillation at fre quedrupole mode for amplitude oscillation at for / bruch length - ocultation of peak bunch currich. Similei malysis trainfer frischim amplitude wodulation peak current of Alahing of VRF $\sigma, f \phi_{i} \neq o$ place modulation of line $\frac{\alpha}{\left(-2\omega_{2}\right)^{2}-\omega^{2}}$ Damping if peak outfulion is unifected in presidence Piel quadrahue differ and Drawn h quadrature and DCreject

格了 The perturbation affresach to beam damping. Leave the RF waveform unchanged, but synthesize the required perturbution .. Damping of dipole mode is obtained if: $\delta \omega_{RF} = \delta \omega \Phi_{RF} = k \Phi = k (t_0 - t_{RF})$ $\varphi_{RF} = \frac{k}{k+j\omega} \varphi_{L} \simeq \frac{k}{j\omega} \varphi_{b}$ (svill damping) - \$ \$ RF must have a quadrature component 1 \$6 Represent to and the (phase modulations at w) with carrier + sidebands -+ W side band -- To The - w side band Beam side bands + w, w, should be transformed by an <u>equivalent</u> impedance with RF sick brady such that quadrature of in official. Carrier transminin unimportant

An 4 A possible solution ; Zequivalut Real and changes sign at for Ver I des + w ride kand ride band (changes sign) $\varphi_b = 0 \longrightarrow \varphi_{RF} = c$ } quadr. <u>Circuit synthesis</u> I, ____> Zequis $V_{\rm r,f}$ fr.F Gr Gr Pul RF+90° T 19!4 Trainfer impedance: 4 <u>fr</u> >E







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INFTACはITE Robinson instability, Futerangle. RLIZ) NF carity infederies f τ +ω. fre Detrone the country : - 2 unque signal. 40 £ an change of Ws (real) damping or antidamfring 10.5774 11.17

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$$Aw = \mathbf{P} - w \simeq \frac{\mathbf{P}}{2\mathbf{P}} \left(\cos v \frac{\mathbf{P} \mathbf{P}}{\mathbf{P}} + \mathbf{j} \sin v \frac{\mathbf{2}\mathbf{n}}{\mathbf{e}^2} \right)$$

$$\frac{1}{\mathbf{P}} \frac{1}{\mathbf{P}} \frac{1}$$

$$\frac{G_{1}}{2} = \frac{1}{\Delta \omega} = \frac{\varepsilon_{1}}{\beta_{1}} = \frac{\varepsilon_{1}}{\beta_{1}}$$

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5. Two examples of beam loading compensation at CERN

Narrow band (CPS) against coupled loop instabilities.
Broad band (SPS) against coupled bunch instabilities.

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The RF loops including compensation



Fig. 2 Vector diagram of the compensated case

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<u>Fig. 3</u>: Small signal model showing transmissions between generator current, gap voltage, beam current and tuning control.

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2) New transfer functions between If and terming phing

Transient response of the system (RF voltage at the gap)

Top trace $I_p = 2 \times 10^{12}$ Bottom trace $I_p = 1.1 \times 10^{13}$ Sweep 50 µs/div



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<u>Photo 1</u>

No compensation

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<u>Photo 2</u>

With compensation



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Fig. 3 Small signal model with compensation. Compared to the normal case, compensation modifies the G_{pp} , G_{pa} , G_{ap} , G_{aa} and H_{pp} transfer functions and introduces an extra connection (H_{ap}).

10.

For frequencies & conty bondwidth, the Gap, 970 == compressation remains arose contributions the functions - Suppression of the isstation . - Tube works in the same condition (no entry for one weeded) - Synthesizes a zero impedance cauty (at free) Implementation in the PS - exact compensation at all figureis defficient (phase and complitude control) - Few fixed points: 800 Met injection I gell with flat tops (blow-up) (actounding) 10 Gel flat top outile : coase correction. Realistive wall BU : setter them electrostatic (I's directly) Satting up : RF drive off - minimize beau loading veltage on cavity to be adjusted. 2 durand by 22023

COMPENSATION PERMANENTE - RESULTATS DU 28.3.79 TENSION RELEVEE SUR LE "GAP" DE LA CAVITE 96

 $I_p = 1.1 \cdot 10^{13} ppp$



1.1

Sans compensation

X : Trigger C235 - 20 ms/div

Y : 50 mV/div



Avec compensations	fixes
(Injection - 1 GeV	- 10 GeV)
X : Trigger C235 -	50 ms/div
Y : 10 mV/div	

Avec compensations fixes									
+ compensation permanente									
X		Trigger	C235	-	50	ms/div			

Y : 10 mV/div

Avec compensation fixe à l'injection + compensation permanente

X : Trigger C235 - 20 ms/div Y : 10 mV/div THE RE FEEDBACK SYSTEM IN THE SPS

Accelerating cavities = travelling wore structures los FIH2.

5 1 Lead A Pur Roundelt (Surface bruilding)

- No tuning - EF amplifier sees a matched load transfer function Iz -> VRF Z, real v(sin 7/2)/(Z/2)
- Beau sees on RIC circuit Ib- WRF Z2 complex

 $V = Z_1 I_{q_1} + Z_2 I_{t_{q_1}}$

Z2 (12) extends even many for Erice transent beau boaching (not corrected by ACC - a complet bunch instabilities at virjection (Re Z2 (Wrs+4.00) + Re Z2 (Wrs-4.00)



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Due to the dulay helpseen any life and centry the bandwidth of the system would be very small. Shape the transfer function C.f. <u>f</u> Loops gain is high, phase is night near nx freu ust night a $\left(u + \frac{1}{2} \right) f = u$ Stability can be achieved, but the factback is efficient only in free, where the beau contributions at the - transient (ean leading at m fur ± mfs -> makehatities. Synderic et the filter Cit









 $G_{\text{max}} = \frac{1}{1-K}$ $G \min = \frac{1}{HK} - shakility$ limitK defines the bandwidth

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Test of the RF feedback system without beam (cavity 3)

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Fig. 3 - Perturbed RF wave at the revolution frequency (no feedback)

THE REAL PROPERTY AND A DESCRIPTION OF A DE



- Corrected RF wave by the RF feedback system



Fig. 5 - Correcting signal (input power to cavity 3)





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