FEASIBILITY OF A PHASE-DISPLACEMENT ACCELERATION SYSTEM AND A MICRO-BUCKET TRANSFER SYSTEM FOR 'FEEDING' THE RESONANCE

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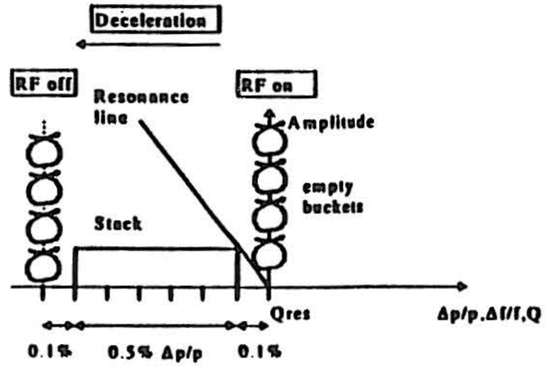
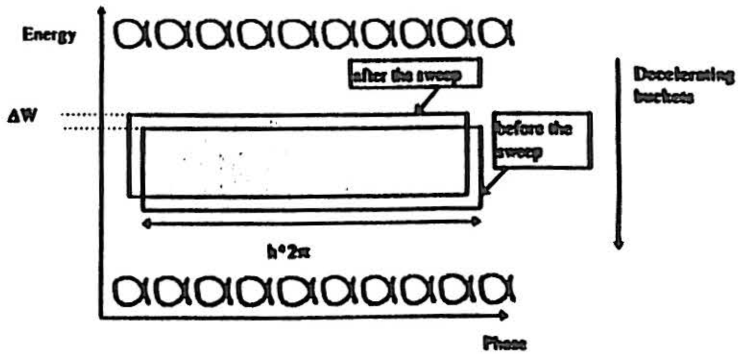
PHASE DISPLACEMENT ACCELERATION





Small empty buckets are created at the resonance energy.

The buckets are decelerated through the stack, that is swept to higher energy ($\Delta W = A_{bucket}/2\pi$). During the sweep, a $\Delta P/P$ increase occurs (stack dilution).

The particles are extracted in small micropulses (not continuous process) with a $\Delta P/P = 0.1$ %.

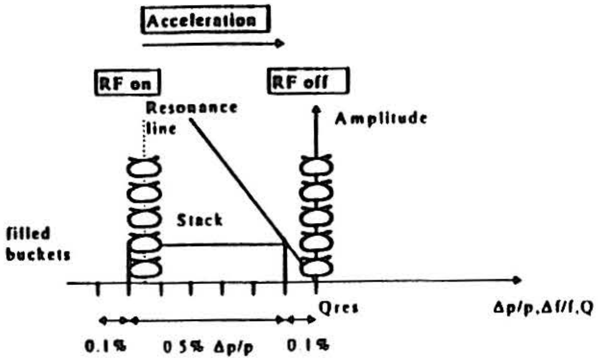
The speed of the sweep (i.e. of the acceleration) is limited by the synchrotron frequency.

The bucket dimensions are kept small in comparison with the stack to limit disturbancies to a small portion of the stack.

The extraction stops if the RF power is switched off.

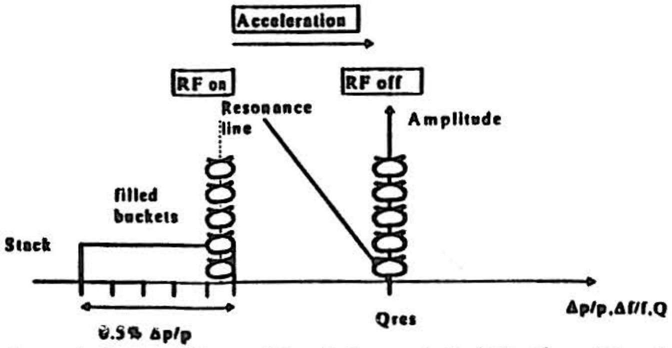
FEEDING THE RESONANCE BY UNSTACKING

ACCELERATION STARTING FROM THE BOTTOM OF THE STACK.



The beam is trapped in small buckets created at the bottom of the stack.
The buckets are accelerated through the stack until the particles are extracted.
The number of particles extracted at each sweep is proportional to the bucket area.
The stack is swept down by $\Delta W = A_{bucket}/2\pi$, stack dilution is not avoided.
The frequency swing is constant.

ACCELERATION STARTING FROM THE TOP OF THE STACK.



The beam is trapped in small buckets created at the top of the stack.
The buckets do not traverse the stack, thus avoiding stack dilution.
The frequency swing is variable.

BUCKET CALCULATIONS

stationary bucket area[eV x s]:

$$A_{bs} = A_b(0) = 16 \times \frac{\beta}{2\times\pi\times f_{rf}\times h} \times \sqrt{\frac{h\times e\times V_{rf}\times W}{2\times\pi\times|\eta|}}$$

stationary bucket height [eV]:

$$H_{bs} = \frac{(2\times\sqrt{2}\times\beta)}{h} \times \sqrt{\frac{h\times e\times V_{rf}\times W}{\pi\times|\eta|}}$$

stable phase and related parameters:

$$\phi_s, \Gamma = \sin\phi_s, \alpha(\Gamma) = \frac{A_b(\Gamma)}{A_b(0)}, \Upsilon(\Gamma)$$

bucket area [eV x s]:

$$A_b = \alpha(\Gamma)\times A_{bs}$$

bucket height [eV]:

$$H_b = \Upsilon(\Gamma)\times\frac{H_{bs}}{\sqrt{2}}$$

synchrotron frequency [Hz]:

$$\Omega_s = \frac{\sqrt{\dfrac{e\times V_{rf}\times 2\times\pi\times f_{rev}^2\times h\times\eta\times\cos(\phi_s)}{W\times\beta^2}}}{2\times\pi}$$

ACCELERATION

frequency sweep [Hz]:

$$\Delta f_{sweep} = \frac{\Delta P}{P} \times \eta \times f_{rev} \times h$$

kinetic energy increase per sweep [eV]:

$$\Delta W_{sweep} = \frac{A_b}{2 \times \pi}$$

number of sweeps (theoretically):

$$N = \frac{\Delta W_{tot}}{\Delta W_{sweep}}$$

maximum speed of the sweep [Hz/s]:

$$\dot{f}_{rf} = \frac{\eta \times f_{rf}^{2}}{\beta^{2} \times W \times h} \times e \times V_{rf} \times \Gamma$$

TENTATIVE PARAMETERS

- $\Delta P/P_{beam} = 0.5$ %

limited by the dimensions of the vacuum chamber.

- h = 10/100

tentative to provide an as much as possible uniform "feeding" of the resonance.

- $\phi_s = 15$ deg

usually chosen between 10/20 to keep constant bucket area during the frequency swing.

- V_{rf} less than 3 kV

need to keep it as small as possible to reduce the RF system requests.

- number of sweeps < 100

need to limit stack dilution to a max $\Delta P/P_{tot} = 0.7$ %.

- spill time = 250 ms

need to limit the treatment time.

- nr of particles per micropulse ~ 1E9 protons, ~ 1E7 ions.
- nr of particles per pulse ~ 1E11 protons, ~ 1E9 ions.

tenta[illegible] to cope with voxel scanning specifications.

TENTATIVE CHOICES FOR A PHASE DISPLACEMENT ACCELERATION INTO THE RESONANCE (h=10)

kinetic energy per nucleon	60MeV p+	300MeV p+	120MeV/u $^{12}C^{+6}$	400MeV/u $^{12}C^{+6}$
γ	1.064	1.32	1.128	1.426
β	0.342	0.653	0.463	0.713
η (γ_t=3)	0.772	0.463	0.675	0.38
f_{rev} [MHz]	1.348	2.576	1.826	2.815
Δp/p total (Δp/p beam=0.5%) [%]	0.7	0.7	0.7	0.7
Δf_{sweep}=Δp/p x f_{rev} x η x h [KHz]	73	83.5	86.3	74.9
h	10	10	10	10
BUCKETS				
ϕ_s [deg]	15	15	15	15
Γ=senφ$_s$	0.259	0.259	0.259	0.259
V_{rf} [V]	25	170	700	2700
F_{rf}[Hz]	1.35E+07	2.58E+07	1.83E+07	2.82E+07
Abucket [eV*rad]	1.24E+04	1.78E+05	4.65E+05	3.42E+06
Hbucket [eV]	4.96E+03	7.14E+04	1.86E+05	1.37E+06
Synchrotron Frequency [Hz]	7.00E+03	6.32E+03	2.48E+04	1.98E+04
Δp/p increase per sweep [%]	3.67E-06	2.23E-05	8.60E-06	3.02E-05
PHASE DISPLACEMENT				
mean current [nA]	3.2	3.2	3.86	3.86
totalnparticles	1.00E+11	1.00E+11	1.00E+09	1.00E+09
ΔWtotal [eV]	7.30E+04	7.90E+05	2.47E+06	1.41E+07
ΔWsweep [eV]	1971	2.84E+04	7.40E+04	5.45E+05
nsweeps	38	28	34	26
PULSED FASHION				
Tsweep [μs]	5316	7891	3260	8686
Tmicropulse [μs]	702	986	407	103
nparticlespersweep	>1e9	>1e9	>1e7	>1e7
Tspill [s]	0.21	0.217	0.243	0.224
maxspeedofsweep [Hz/sec]	1.30E+08	1.06E+08	2.65E+08	8.63E+06
Δp/p of extracted beam [%]	0.1	0.1	0.1	0.1

TENTATIVE CHOICES FOR A PHASE DISPLACEMENT ACCELERATION INTO THE RESONANCE (h=100)

kinetic energy per nucleon	60MeV p+	300MeV p+	120MeV/u $^{12}C^{+6}$	400MeV/u $^{12}C^{+6}$
γ	1.064	1.32	1.128	1.426
β	0.342	0.653	0.463	0.713
η (γ_t=3)	0.772	0.463	0.675	0.38
f_{rev} [MHz]	1.348	2.576	1.826	2.815
Δp/p total (Δp/p beam=0.5%) [%]	0.7	0.7	0.7	0.7
Δf_{sweep}=Δp/p x f_{rev} x η x h [KHz]	730	835	863	749
h	100	100	100	100
BUCKETS				
ϕ_s [deg]	15	15	15	15
Γ=senφ$_s$	0.259	0.259	0.259	0.259
V_{rf} [V]	50	350	1400	5500
F_{rf}[Hz]	1.35E+08	2.58E+08	1.83E+08	2.82E+08
Abucket [eV*rad]	5.54E+03	8.09E+04	2.08E+05	1.55E+06
Hbucket [eV]	2.22E+03	3.24E+04	8.34E+04	6.19E+05
Synchrotron Frequency [Hz]	3.13E+04	2.87E+04	1.10E+05	8.93E+04
Δp/p increase per sweep [%]	4.34E-06	1.00E-05	3.58E-06	1.36E-05
PHASE DISPLACEMENT				
mean current [nA]	3.2	3.2	3.86	3.86
totalnparticles	1.00E+11	1.00E+11	1.00E+09	1.00E+09
ΔWtotal [eV]	7.30E+04	7.86E+05	2.47E+06	1.41E+07
ΔWsweep [eV]	881	1.29E+04	3.31E+04	2.46E+05
nsweeps	84	61	75	57
PULSED FASHION				
Tsweep [μs]	2800	3832	3260	4264
Tmicropulse [μs]	350	480	407	533
nparticlespersweep	>1e9	>1e9	>1e7	>1e7
Tspill [s]	0.235	0.232	0.243	0.244
maxspeedofsweep [Hz/sec]	2.60E+08	2.18E+08	2.65E+08	1.76E+08
Δp/p of extracted beam [%]	0.1	0.1	0.1	0.1

TENTATIVE CHOICES FOR A MICROBUCKETS ACCELERATION TO FEED THE RESONANCE (h=10, proton case considered)

ACCELERATION FROM THE BOTTOM OF THE STACK					ACCELERATION FROM THE TOP OF THE STACK			
kinetic energy	60MeV p⁺		300MeV p⁺		60MeV p⁺		300MeV p⁺	
totalnparticles	1.00E+11		1.00E+11		1.00E+11		1.00E+11	
nparticlespersweep	>1e9		>1e9		>1e9		>1e9	
h	10		10		10		10	
ϕ_s [deg]	15		15		15		15	
V_{rf} [V]	20		140		20		140	
F_{rf}[Hz]	1.35E+07		2.58E+07		1.35E+07		2.58E+07	
Δp/p incr. due to trav. bucket[%]	1.47E-06		9.05E-06		/		/	
Synchrotron Frequency [Hz]	6.26E+03		5.74E+03		6.26E+03		5.74E+03	
maxspeedofsweep[Hz/s]	1.04E+07		8.70E+06		/		/	
					MIN fsweep	MAX fsweep	MIN fsweep	MAX fsweep
$\Delta f_{sweep}=\Delta p/p \times f_{rev} \times \eta \times h$ [Hz]	6.25E+04		7.16E+04		1.04E+04	6.25E+04	1.19E+04	7.16E+04
ΔWtotal [eV]	6.34E+04		6.69E+05		6.34E+04		6.69E+05	
ΔWsweep [eV]	1763		2.57E+04		1763		25741	
numberofsweeps	36		26		36		26	
Tsweep [μs]	6017		8213		1002	6017	1369	8213
Tmicropulse [μs]	752		1026		752		1026	
Tspill [ms]	216		213		216		213	
Δp/p of extracted beam[%]	0.1		0.1		0.1		0.1	

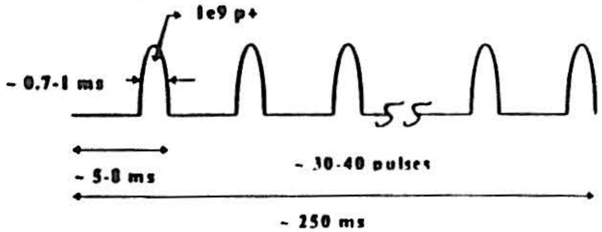
TENTATIVE CHOICES FOR A MICROBUCKETS ACCELERATION TO FEED THE RESONANCE (h=100, proton case considered)

ACCELERATION FROM THE BOTTOM OF THE STACK					ACCELERATION FROM THE TOP OF THE STACK			
kinetic energy	60MeV p⁺		300MeV p⁺		60MeV p⁺		300MeV p⁺	
totalnparticles	1.00E+11		1.00E+11		1.00E+11		1.00E+11	
nparticlespersweep	>1e9		>1e9		>1e9		>1e9	
h	100		100		100		100	
ϕ_s [deg]	15		15		15		15	
V_{rf} [V]	40		280		40		280	
F_{rf}[Hz]	1.35E+08		2.58E+08		1.35E+08		2.58E+08	
Δp/p incr. due to trav. bucket[%]	1.47E-06		9.05E-06		/		/	
Synchrotron Frequency [Hz]	2.80E+04		2.57E+04		2.80E+04		2.57E+04	
maxspeedofsweep[Hz/s]	2.08E+08		1.74E+08		/		/	
					MIN fsweep	MAX fsweep	MIN fsweep	MAX fsweep
$\Delta f_{sweep}=\Delta p/p \times f_{rev} \times \eta \times h$ [Hz]	6.25E+05		7.16E+05		1.04E+05	6.25E+05	1.19E+05	7.16E+05
ΔWtotal [eV]	6.34E+04		6.69E+05		6.34E+04		6.69E+05	
ΔWsweep [eV]	788		1.15E+04		788		11511	
numberofsweeps	80		58		80		58	
Tsweep [μs]	3008		4106		501	3008	684	4106
Tmicropulse [μs]	376		513		376		513	
Tspill [ms]	242		238		242		238	
Δp/p of extracted beam[%]	0.1		0.1		0.1		0.1	

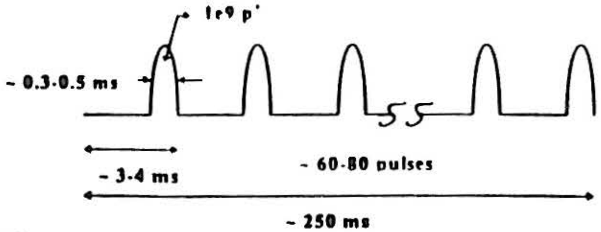
BEAM PULSE STRUCTURE (PROTONS W=60-300 MeV)

Phase Displacement and Unstacking from Bottom.

- $h = 10$ $V_{rf} = 25\text{-}170$ V

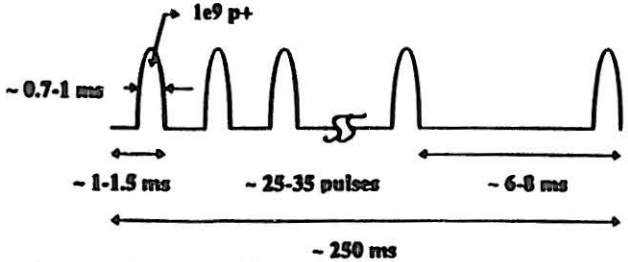


- $h = 100$ $V_{rf} = 50\text{-}350$ V

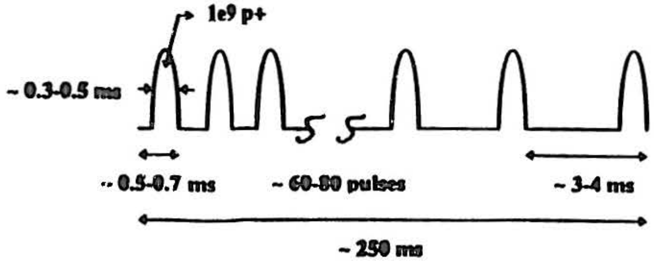


Unstacking from Top.

- $h = 10$ $V_{rf} = 20\text{-}140$ V

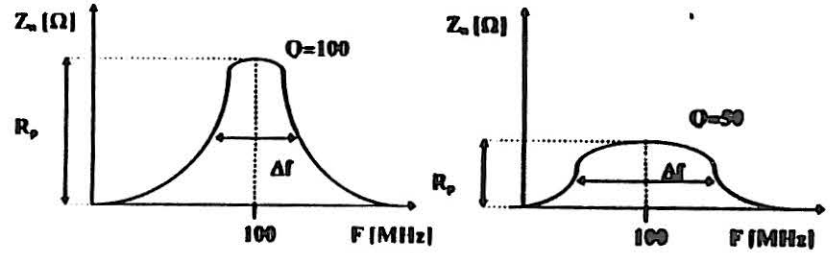


- $h = 100$ $V_{rf} = 40\text{-}280$ V



RF SYSTEM (h = 100)

$F_{rf} = 100$ Mhz $\Delta f \sim 1$ Mhz $\Rightarrow Q = F_{rf}/\Delta f = 100$



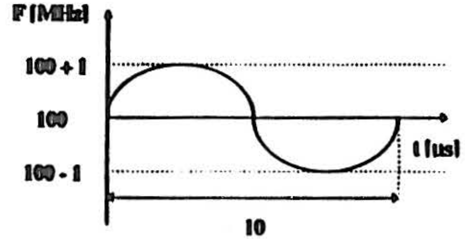
If we decrease the Q factor we can do the Δf swing without tuner.

$Q \sim 50$ $Z_s = R_p/Q \sim 100\ \Omega$ $\Rightarrow R_p = 5\ k\Omega$

$V_{rf} \sim 1000$ V

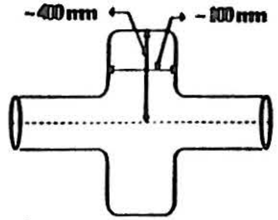
$P = V_{rf}^2/(2 x R_p) = 100$ W $\Rightarrow$ small power to handle.

$\tau = Q/\pi \times 1/f \sim 160$ ns $\Rightarrow$ the cavity will rapidly follow the swing.



$\lambda = c/F_{rf} = 3$ m

Example: a pill-box cavity.



Small beam pipe dimensions.
Low dispersion region needed.

CONCLUSION

POINTS IN FAVOUR

- very few parameters to vary: RF voltage, frequency swing.
- unstacking from the top good estimation of the number of particles extracted per micropulse (+ A_h).
- pulsed extraction (possible treatment with voxel scanning?)
- easy and quick to stop: RF power off.

POINTS NOT IN FAVOUR

- **slow micropulse extraction (hundreds of microseconds).**
- **not continuous beam pulse extraction (not possible treatment with raster scanning?).**
- **if high harmonic number a "small" dedicated RF system is needed.**
- **lattice constraints: additional ~ 0.2/0.3 m needed for the additional cavity in a low dispersion region.**

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2) E. Ciapala, Stacking and Phase Displacement Acceleration, CERN 85/19 CAS.

3) C. Bovet et al., A Selection of Formulae and Data Useful for the Design of Alternating Gradient Synchrotrons, CERN MPS-SI, Int. DL/70/4.

4) P. Bryant, E. Ciapala, W. Pirkl, private communications.