NUMERICAL DESIGN STUDY OF STOCHASTIC STACKING OF 3 GEV ANTI-PROTON BEAM IN THE RESR FOR THE FAIR PROJECT

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Abstract

The accumulation of anti-proton beam up to the 1e11 particles with high density in longitudinal phase space is planned at the FAIR project. Following the experiences at CERN and FNAL, the accumulation with stochastic stacking method will be employed at the accumulator ring RESR. In the present paper, firstly the characteristics of incoming anti-proton beams are given as well as the basic design parameters obtained from the analytical method. Then the stochastic stacking process is numerically investigated with use of Fokker-Planck approach. The key elements for the stacking process are explained and then some results of simulation of stacking are described.

INTRODUCTION

At the FAIR project, the sequence of anti-proton production, cooling and stacking is as follows. Proton beam is accelerated at the SIS100 up to 29 GeV with the intensity of 2e13 per 10 sec. After passing through the production target of nickel, the anti-proton flux of 4e8 is produced within the transverse emittance of 240 π mm.mrad and the momentum spread of +/- 3% (uniform). The bunch length from the SIS100 is +/- 25 n sec. Thus produced anti-proton beam is injected into the Collector Ring (CR) with the circumference of 216.25 m and the ring slipping factor of 0.0107. In the CR the injected bunch is rotated to reduce the momentum spread from +/- 3 % (uniform) to 2.45e-3 (rms) with use of harmonic=1 RF of 100 kV. Subsequently the stochastic cooling is applied to further reduce the momentum spread to 5.0e-4 (rms) with the notch filter cooling system of band width 1-2 GHz and the microwave power 1.2 kW. The transverse cooling system is also envisaged to reduce the emittance from 240 π mm.mrad to 5 π mm.mrad.

The stacking ring, RESR, has a little bit larger circumference 239.9 m comparing with that of CR, and the ring slipping factor is adjustable from 0.03 to 0.11. The stochastic stacking system is in principle similar to those at CERN AAC and FNAL AS. The anti-proton beam is injected on the injection orbit of the RESR, and is accelerated to the deposit orbit which aparts from the injection orbit by around Δp/p=1.0 %. There prepared a stochastic stacking system, being composed of radial aligned two tails and core cooling system.

The goal of the RESR stacking system is to stack the 1e11 particles in the core region with the deposited particle number 1e8 from the CR Ring. While the cycle time is planned at 10 sec at the 1st phase of the project, it will be shortened to 5 sec at the goal. Then all the stacking system have to be designed to accommodate this final goal.

SIMPLIFIED ANALYTICAL APPROACH

A simplified theoretical model of the stacking process was developed by van der Meer [1]. It is based upon the assumptions that the voltage on the kicker is exactly in phase with the particles, and the diffusion terms by electronic noise, and intra-beam scattering effects are neglected. In addition the beam feedback effects and the difficulty of achieving the designed coherent term is not taken into account. While these assumptions are not fulfilled in the real stacking system, the simplified approach could give some basic parameters of the stacking system.

The stacked beam profile and the required voltage gain/turn to attain this profile are given as

$$\Psi(E)=\Psi_1 \exp(E-E_1)/E_d]$$

$$V(E)=2\phi_0 T/\Psi_1 \exp[(E_1-E)/E_d] \qquad (1)$$

where E_1 and Ψ_1 are the deposit energy and particle density. At the numerical calculation, Ψ_1 is given by $N/\Delta E_1$ where N is the deposited particle number and ΔE_1 is energy width (4 sigma) of the newly deposited batch. Ed is the characteristic energy defining the exponential profile of density and voltage gain.

$$E_d=4A\phi_0 T^2=\beta pc\Lambda\phi_0/TW^2\eta \qquad (2)$$

with the particle flux which can be transported

$$\phi_0=TW^2\eta E_d/\beta pc\Lambda \qquad (3)$$

where

$$A=\beta pc\Lambda/4T^3W^2\eta$$
$$\beta=v/c,\ W=Bandwidth\ (f_{min}\text{-}f_{max}),\ \Lambda=ln(f_{max}/f_{min})$$
$$T=Revolution\ period,\ \eta=1/\gamma^2-1/\gamma^2_t$$

The required total width of the stack region is given by

$$\Delta E_{stack}=E_d \ln(\Psi_2/\Psi_1) \qquad (4)$$

where Ψ_2 is a particle density at the core region. Thus obtained exponential profile of density and gain determines the minimum width for the stack region, namely the sharpest particle density. However many important effects increase the required width, and then the analytic approach is just the simple estimation while it gives the basic feeling of the stacking parameters.

The other important factor which should be taken into account for the determination of voltage gain is the minimum voltage at the deposit position. Suppose that the energy width of deposited beam σ_I and its distribution is Gaussian. The deposited beam should be cleared off the deposited position by the next deposit time to clear up the space for the next batch. Then the minimum voltage is given as

$$V_{deposit} > 6\sigma_I/f_0T_{cycle} \quad (5)$$

.

In Table 1, the obtained parameters from the analytical method are tabulated for the cycle time 5 sec. The momentum spreads of deposited beam are 2.5e-4 and 5.0e-4. Following values are used in the calculation.

Beam energy E=3 GeV, N(deposited)=1e8, η=0.032, f_0=1.19e6, N(core)=1e11, $\Delta p/p$(core)=+/-2.5e-4, W=1-2 GHz.

Table 1: Parameter List from the Analytical Solution

Cycle Time	5 sec	
Deposit Δp/p (rms)	2.5e-4	5.0e-4
4 Δp/p (rms)	1.0e-3	2.0e-3
4 ΔE (rms) [eV]	3.71e6	7.42e6
Psi(1)=N_1/4ΔE [/eV]	26.9	13.45
ΔE(core) [eV]	1.86e6	1.86e6
Psi(core)=Ncore/ΔE(core) [/eV]	5.38e4	5.38e4
Psi(core)/Psi(1)	2.0e3	4.0e3
Flux [/sec]	2.0e7	2.0e7
Ed [eV]	1.9e6	1.9e6
Tail Width (ΔE) [eV]	14.4e6	15.7e6
Tail Width (Δp/p)	3.88e-3	4.23e-3
V(1) [Volt]	1.25	2.50
V(core) [Volt]	6.26e-4	6.26e-4
V(1)/V(core)	2.0e3	4.0e3
Min V(1) [Volt]	0.94	1.87

The last column shows the minimum voltage at the deposit position to clear up the space for the next batch.

From the results it is found that the required width of stacked region is around 16 MeV.

In Fig. 1 the schematic layout of tails and core system are illustrated as well as the typical calculated beam density (/eV) after 1000 stacking and the coherent term (eV/sec) in log scale. The beam is deposited in the middle of Tail1 plates, and is shifted towards the stacking area due to the coherent term, around 3e6 [eV/sec] generated by Tail1, Tail2 system. At the core center, 3 GeV energy, beam is sharply populated due to the core cooling system and the notch filter characteristics. In the following chapter, simulation parameters and main factors which determines the required coherent term, are described.

STACKING SIMULATION PARAMETERS

Considering the beam size at the deposit region, and partly from the numerically calculated results, for example the core PU positioning, the parameters for the simulation for Fokker-Planck approach are as follows.

Table 2: Simulation Parameters

	Tail1	Tail2	Core
Frequency band (GHz)	1-2	1-2	2-4
PU and Kicker Type	Loop	Loop	Loop
Positioning (MeV)	-22.9	-16.9	+/- 8.6
PU gap (mm)		20 or 30	
Number of PU units	64	64	64
PU Coupling Impedance/unit (Ohm)	25	25	25
Kicker gap (mm)		40	
Number of Kicker unit		16	
Kicker Impedance/unit (Ohm)		100	

Note that we define that the middle of two core plates is 0 MeV.

Key factors for the design of stacking system are as follows.

1) Construct the exponential type gain shape.
2) Optimal shape of coherent term in the concerned energy range.
3) Suppression of the Schottky noise and thermal noise as large extent as possible.

To attain the goal of these purposes, the positioning of Tail and Core PUs, the PU heights, the notch depth, the system delay and amplifier gain are adjusted.

System Structure of the Stacking System

To achieve the required coherent term, we plan to compose the system as given in Fig. 2. Two Tail systems are prepared to form the desired coherent term. Output signal from each Tail PU is pre-amplified and is followed by Delay, Notch filter and Main-Amplifier. Finally it is powered into the kicker as well as the amplified signal from the core system. The transfer function $TF(E,T_d)$ of the chain of Tail system is given as

$$TF(E, T_d)=Z_{pu}\, G_{pu}(E)\, F(T_d)\, H(E)\, G_{amp}\, G_k(E)\, Z_k \quad (6)$$

where Z_{pu}, and Z_k are the coupling impedances of pickup and kicker, G_{pu} and G_k are the geometric factors as a function of beam position or the beam energy as the PU are located at the position of large dispersion 13 m. $F(Td)$ and $H(E)$ are the function of system delay and the transfer function of notch filter.

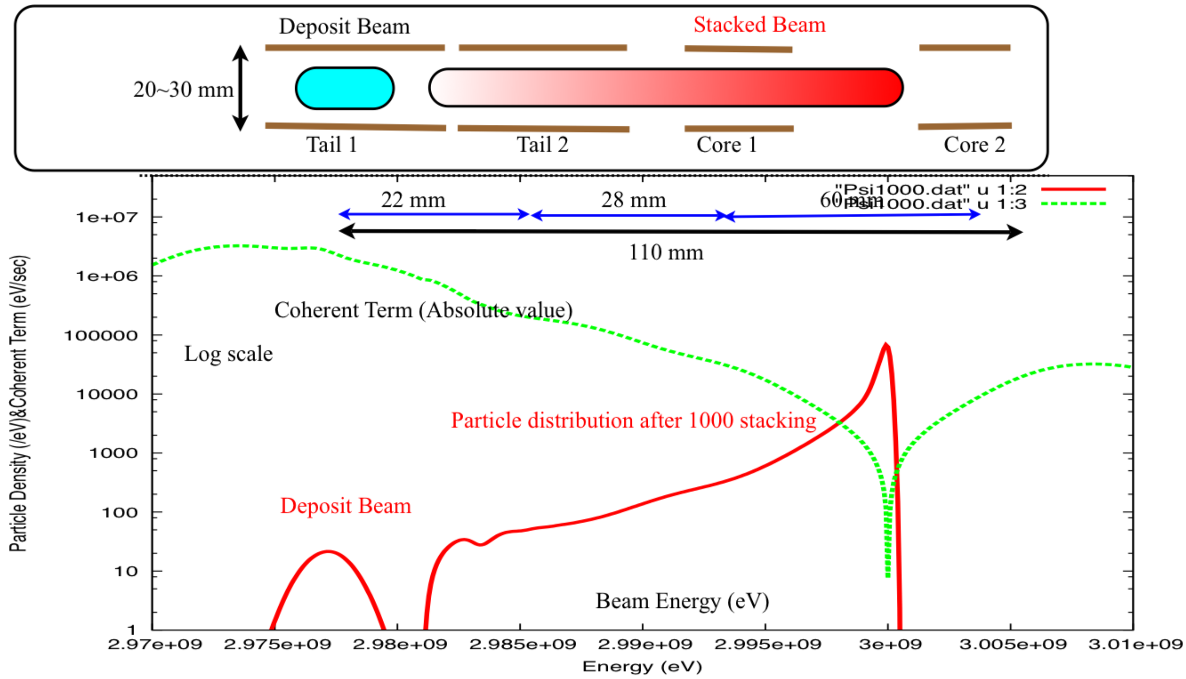

Figure 1: Schematic layout of the stochastic stacking system. The injection orbit (not illustrated in the figure) is around 1 % (Δp/p) left from the deposit position.

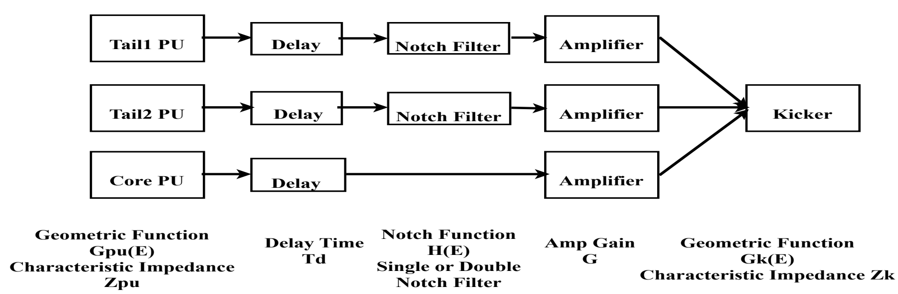

Figure 2: System structure of stacking system.

Geometric Factor

The sensitivity of each PU plate is given by

$$g(x,h,w)=2/\pi \arctan[\sinh(\pi w/2h)/\cosh(\pi x/h)] \quad (7)$$

where w is a width of plate (40 mm), h the gap height (20 or 30 mm) and x the horizontal beam position relative to the center of plate. For the large x, this sensitivity function has an asymptotic form $\exp(-x/h)$ which is required exponential shape as a function of energy E.

Notch Filter

The transfer function of correlator single notch filter with depth a is given as a function of frequency f by

$$H(f)=[1.0-a \exp(-j2\pi\Delta f/f_0)]/(1+a) \quad (8)$$

where f_0 is a notch frequency and Δf the frequency difference from the notch frequency. The double notch filter is a series of single notch filter. The typical shapes of amplitude of single and double notch filters are illustrated in Figure 3.

The horizontal scale is a frequency, vertical scale is an amplitude. The upper curve is corresponding to the single notch and the lower line the double notch case. It is apparently shown that the double notch reduces the central part signal, the Schottky and thermal noise. But it is noted that the signal between the notch frequency and the edge frequency is also reduced, namely the required coherent signal is also reduced.

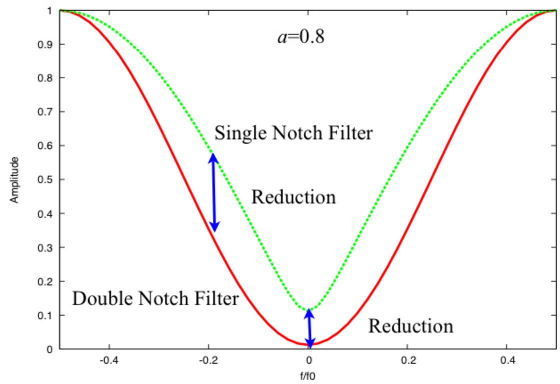

Figure 3: The amplitude shape of the single and double notch filters. Depth parameter *a* is 0.8.

Coherent Function

The coherent function plays a key role of the design of coherent term which is a function of ring slipping factor η, the band width *W*, the notch depth *a*, and the system delay T_d. Typical example of the calculated coherent function is given in Fig. 4 where each line corresponds to the delay time difference of 20 psec. The horizontal scale is the energy in MeV. Note that the position of Tail1 PU is -22.9 MeV and Tail2 PU is -16.6 MeV and the Core PUs are +/- 8.6 MeV. The system delay has to be chosen to give the required value of coherent function.

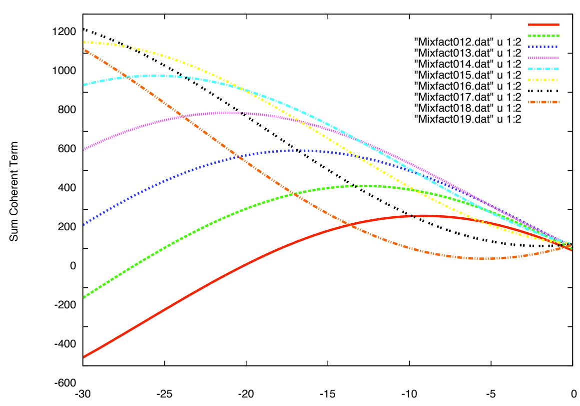

Figure 4: The coherent function as a parameter of system delay. Horizontal scale is energy in MeV. Each line corresponds to the delay time of 20 psec difference. η=0.03 and *W*=1-2 GHz and the notch depth=30 dB.

Coherent Term

Including the above described elements, the coherent term is calculated as a function of energy. The typical result is given in Fig. 5. The horizontal scale is beam energy and the vertical scale is absolute value of coherent term. The top curve is a sum of the coherent terms. The second line is the produced by Tail1, and the 3 rd line is due to the Tail2 and the bottom line is due to the Core system. The sharp dip at 3 GeV is mainly due to the notch filter.

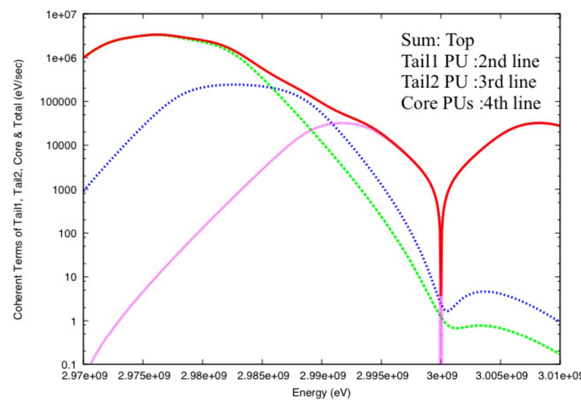

Figure 5: Typical coherent term as a function of energy.

INTRA BEAM SCATTERING EFFECTS

Main source of the diffusion of the stacked particle is an Intra-Beam Scattering, IBS effect. There were several formalism of the growth rate calculation. Among them we use the Matini formula [2] to obtain a numerical results. The lattice structure of RESR is included to calculate the growth rate at each accelerator segment and they are averaged over the ring. In the present estimation, the transverse emittance is assumed as constant of 2π mm.mrad for both the horizontal and vertical betatron freedom. At each computing cycle the rms value of Δp/p of the stacked beam is calculated which is varied around 3e-4 to 9e-4 during the stacking number up to 1000.

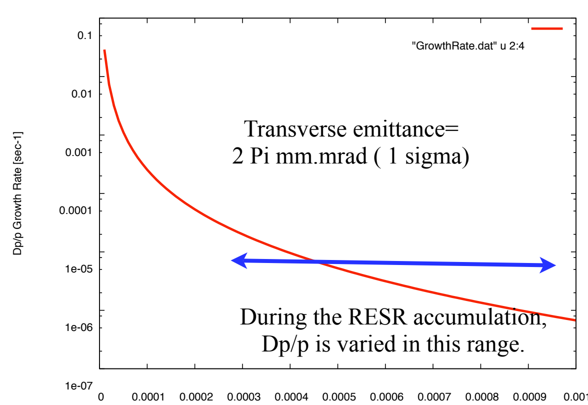

Figure 6: IBS growth rate during the stacking up to 1000 times. Transverse emittances are kept at 2 π mm.mrad.

The calculated growth rate is given in Fig. 6. The stacked particles are populated almost 90 % in the core region within Δp/p value of +/- 2.5e-4. Then in the simulation, the IBS heating term is approximated as 10 times larger than the calculated growth rate.

RESULTS OF STACKING SIMULATION

We have investigated many cases of stacking parameters including beam feedback effects and intra-beam scattering. Typical example of the stacked beam profile is given in Fig. 7.

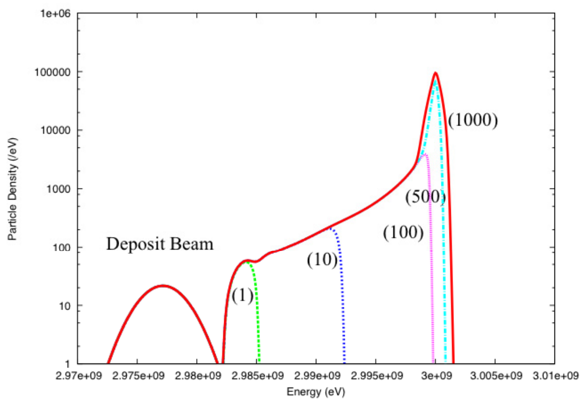

Figure 7: Beam profile during the stacking.

In the Fig. 7, the horizontal scale is the beam energy, the vertical scale is a particle density per unit energy. The figures in the bracket represent the number of stacking. Other parameters in this simulation are as follows.

Cycle time=10 sec, *N*(deposit)=1e8, Ring slipping factor=0.03, Deposited Beam $\Delta p/p$=5e-4 (rms), Tail1 Gain=130dB, Tail2 Gain=106dB, Core Gain=90dB, Notch Depth=20dB, IBS factor=10.0, Tail & Core Gap Height=30 mm, Tail1 Delay Time = -0.500 ns, Tail2 Delay Time = -0.320 ns, Core Delay Time = -0.167 ns

The required microwave power are calculated at 210 Watt for Tail1, 0.9 Watt for Tail2 and 0.1 Watt for Core system.

As is clear in the figure the stacked particles are populated mainly in the core region. The number of particles in the whole stacked area and the one in the window momentum spread (+/-2.5e-4) around the core center, and their ratio are given in the Figure 8. The top line is a ratio (right scale) and the 2nd and the 3rd lines show the particle number in the whole stacked region and in the window momentum spread around the core center of the energy 3.0 GeV. Almost 90 % particles are stacked in the window energy.

In the stacking simulation, we have assumed the momentum spread of the deposited beam as 2.5e-4 or 5.0e-4 (rms). The cycle time is 5 or 10 sec. In most cases the beam feedback effects do not seriously deteriorate the stacking performance except for extreme parameters when say η=0.03 and cycle time 5 sec, Nyquist plot of Tail1 can dangerously approach the unstable territory just after the deposit for the large Tail1 gain.

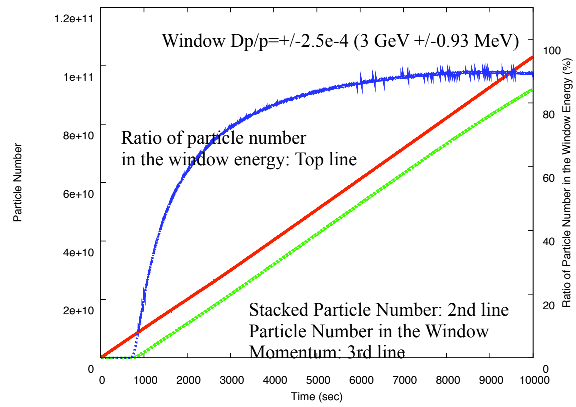

Figure 8: The stacked particle number in the whole stacked area and in the window energy at the core center.

PRE-COOLING AT RESR

The pre-cooling at the RESR injection orbit with the band system 2-4 GHz could cool the momentum spread of the beam from Collector Ring 5.0e-4 to 1.0 e-4 within 5 sec with moderate cooling system of room temperature. Thus pre-cooled beam of the momentum spread Δp/p=1e-4 (rms) can be stacked in the stacked region with Tail1 gain of 120 dB, which results in the reduction of microwave power order of magnitude smaller (Tail1: 32 Watt) than the case without pre-cooling. On the other hand the small momentum spread gives the large signal suppression via a beam feedback effect. The real and imaginary parts of Open Loop Gain reach to around +/-0.5. The careful choice of ring slipping factor and the gain of Tail1 are required.

SUMMARY AND OUTLOOK

1). We have numerically designed a stochastic stacking system of RESR with a Fokker Planck approach where IBS effects and beam feedback effects are included.

2). Two tails and a core cooling/stacking system allow us the stacking of the deposited beam, *N*=1e8 up to the 1000 stacking, *N*=1e11. The deposited momentum spread, 2.5e-4 or 5e-4 (rms), both are acceptable for the stacking of cycle time 5 sec and 10 sec.

3). Ring slipping factor, η is a key parameter of the design of the system. In the present design it is assumed as 0.03 or 0.05 which is optimal for the Tail1 system of band width 1-2 GHz.

4). Transverse cooling system for the core region is a forthcoming subject.

REFERENCES

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[2] M. Martini, “Intrabeam Scattering in the ACOL-AA Machines”, CERN PS/84-9, 1984