# Compensation of Longitudinal Beam Dynamics Distortions due to Irregularities in Linear Accelerating Channel Periodicity in Superconducting Linac

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*DRAFT*

*Abstract*
A superconducting (SC) linac with independently phased cavities (IPC) has less uniformly distributed RF field along the accelerating channel as compared to traditional linac. This makes the beam dynamics significantly different from that of a traditional linac. Special measures must be taken in a SC linac to support the adiabatically matched periodic structure of the accelerating channel. Significant deviations from the adiabatic periodicity in a SC linac are present, in particular, from the inevitable connection gaps between separate cryostats. A new approach for the compensation of such irregularities in a SC IPC linac is considered in this paper. Simulation results using the LANA code [1] are presented and compared to several previous design studies for the RIA Driver Linac done at NSCL/MSU [2,3].

## *1. Adiabatic periodicity in an IPC linac*

Linear accelerator designs are increasingly making use of superconducting (SC) RF cavities. This is motivated by the rapid advances in the technology and engineering for SC cavities and by the improvements in performance and fault-tolerance of SCRF structures. Some of the advantages of a SC linear accelerator relevant for our study are the compactness of the accelerating structures and the increased operational flexibility. This compactness and flexibility, however, is gained at the cost of greater complexity in the assembly and tuning of SC structures.

At present, SCRF cavities are significantly smaller then its room-temperature (RT) counterparts. On one hand, this makes the linac more flexible in a sense of the changeable beam velocity profile along the accelerator, but, on the other hand, it significantly increases the frequency of the longitudinal oscillations. This is due to both: the increase in the accelerating gradient in the cavities and due to the increase of the drifts between these relatively short cavities.

This local concentration of the higher electromagnetic fields in the SC cavities with fewer accelerating gaps and with longer drift spaces between the cavities compared to the traditional machines allows us to use the smooth approximation (SA) description for the longitudinal dynamics in similar manner as it is used for the transverse dynamics [4].

The increase of the longitudinal oscillation frequency is especially problematic at the beginning of the SC linac, where the beam velocity is the smallest. The situation is worsened by the drift spaces between cryostats. These drift spaces are also needed for RT beam diagnostics and transverse focusing in some cases.

One way to avoid the negative effect of such irregularities is to use smaller size cryostats, which in this case define the longitudinal and/or transverse periodicity of the accelerating channel [7,8]. Such shortening of the cryomodules is leading to increase of the overall length of the linac and reduction of the real estate accelerating gradient, and as consequence, it leads to the reduction of the maximal achievable longitudinal acceptance of the accelerating channel. This approach is useful for radioactive ion beam (RIB) facilities due to the relaxed requirements for the beam losses (small beam currents) and the relatively small final beam energy.

The newly proposed SC ion accelerators [2,9,10] are of significantly larger scale with much more strict loss requirements due to the high beam currents. Longer cryostats seem be more appropriate in these cases [2,3,6]. The longitudinal oscillation phase advance (denoted as $\mu$ here) for a long cryostat can be several hundred degrees (for the first cryostat of the RIA Driver linac at NSCL/MSU it is ~650°!). Such a high frequency makes the longitudinal dynamics intrinsically unstable ($\mu > 180°$) if no additional measures are taken. One example is shown schematically in Fig. 1.

It is known from the transverse beam optics that the periodic configuration has the largest possible acceptance for the focusing channel with given maximum aperture and strength of the elements. Any disruption of the periodicity, respectively, always leads to degradation of the channel acceptance.

In the case of the long cryomodules one way to compensate for the adiabatic periodicity disruption caused by the inter-cryostat drifts is to use the flexibility of the SC independently phased cavities for changing the longitudinal periods properties to “match” the beam between cryomodules. In spite of this approach attractiveness due to it simplicity, it has the disadvantage of leaving the accelerating channel aperiodic most everywhere for extended section of the accelerating channel.

The other way to address this problem is to shorten the length of the elementary period of the accelerating channel to sub-cryostat elements and have a dedicated matching between the cryostats only. For the low energy part of the considered linac, as is shown in [4], the adequate length of such a period can include only one or two accelerating cavities and the additional space for a transverse focusing element (a solenoid in the case as shown in the Fig. 1). This approach would allow us to have the periodicity disruption localized in small matching regions only.

We return to the comparison of the different period configuration layouts later in this paper.

*1.1. Effect of the inter-cryostat drift on the longitudinal beam dynamics*

The obvious effect of the inter-cryostat drift on the beam dynamics in the longitudinal phase space plane can be understood from the eigenellipses shown in Fig. 1. This information was obtained using the LANA code [1]. The most recent version of LANA has the capacity not only to simulate the 6-D beam dynamics, but also to calculate the corresponding machine functions of the simulated accelerator.

For the consistent description of the beam dynamics we can use matrix formalism [5]. The matrix of a single period of the periodic accelerating channel for the particle motion in a one-dimensional phase space can be presented in a form:

$$R_{period} = \begin{pmatrix} \cos\mu + \alpha_0 \cdot \sin\mu & \beta_0 \cdot \sin\mu \\ -\gamma_0 \cdot \sin\mu & \cos\mu - \alpha_0 \cdot \sin\mu \end{pmatrix} \quad (1),$$

where: $\mu = \Delta\varphi$ is the oscillation phase advance per period, and $\alpha_0, \beta_0, \gamma_0$ are the machine function values of the present period of accelerating channel.

The mismatch of the beam to the accelerating channel (or just “mismatch”) is called the situation when the twiss parameters of the beam particle distribution deviate from the corresponding machine function values at a given location. The mismatch factor can be computed as [5]:

$$M = \sqrt{\left(1 + \frac{\Delta + \sqrt{\Delta \cdot (\Delta + 4)}}{2}\right)} - 1 \quad (2),$$

where:

$$\Delta = (\Delta\alpha)^2 - \Delta\beta \cdot \Delta\gamma \quad (3),$$

and:

$$\begin{aligned} \Delta\alpha &= \alpha - \alpha_0 \\ \Delta\beta &= \beta - \beta_0 \\ \Delta\gamma &= \gamma - \gamma_0 \end{aligned} \quad (4),$$

where: $\alpha_0, \beta_0, \gamma_0$ are the channel machine functions defined by (1), and $\alpha, \beta, \gamma$ – the corresponding beam twiss parameters at the entrance of the respective accelerating channel period.

Fig. 1 shows the significant difference in the machine functions in the 5$^{th}$ period compared to the machine functions of the previous and following periods, which breaks the adiabatic periodicity of the channel and consequently degrades the beam quality due to the large mismatch of the beam in longitudinal phase space that takes place at this location if no additional special measures are taken.

This mismatch is serious enough so that it can not be mitigated locally by changing the accelerating field parameters only in the neighboring RF cavities. Fig. 2 shows the change in the periodic system oscillation frequency (phase advance per period $\mu$) in the transverse and the longitudinal planes as a function of the relative change in the respective main focusing strength parameter (magnetic field in the solenoid for the transverse oscillations, and the amplitude or phase of the accelerating field for the longitudinal oscillations).

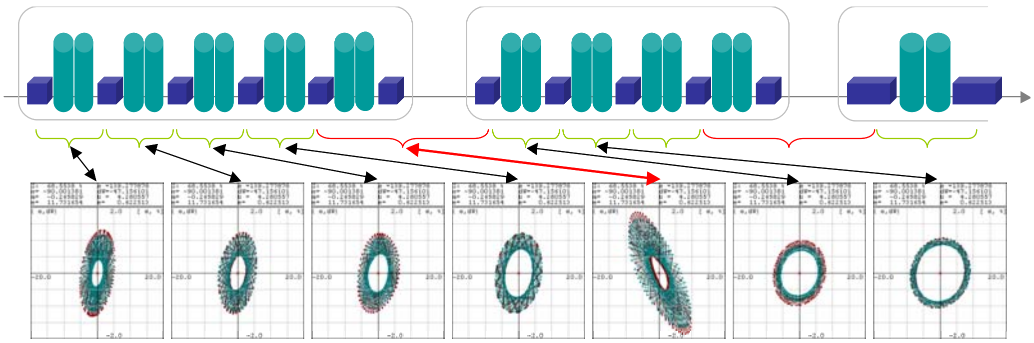


Fig. 1: The top portion of the figure shows schematic view of the first, second and the beginning of the third cryostats of the baseline layout of the NSCL/MSU RIA Driver linac design. The consecutive accelerating channel periods are shown with the curled brackets below the schematic view. Green brackets represent regular periods and red – irregular periods respectfully. The bottom portion shows the corresponding eigenellipse plots for the consecutive periods as per LANA simulation.

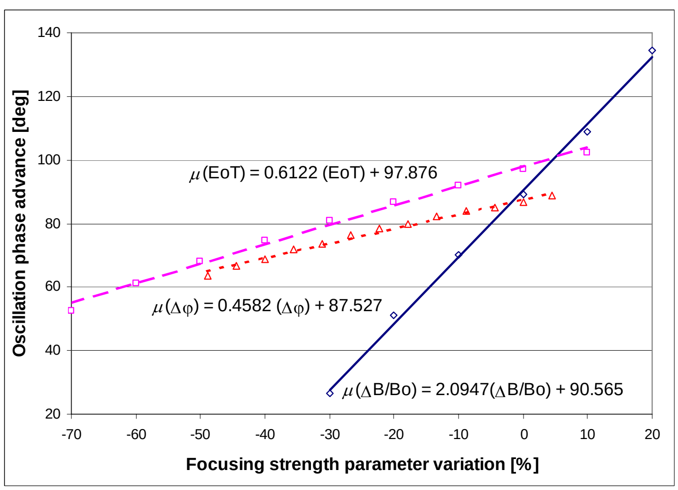



Fig. 2. Comparison of the sensitivity of the transverse and the longitudinal oscillations phase advance [degrees] per period in the first cryostat of the initial segment of the RIA Driver linac as a function of the relative change of the main parameter [%]: the magnetic field in the solenoid for the transverse plane (solid dark blue) and the accelerating field amplitude (dashed magenta) and phase (dotted red) for the longitudinal. The amplitude was varied with the phase set at the nominal value, and the phase was varied with the amplitude set at 80% (-20% on the graph).

It can be seen from the linear least-mean-square fit shown in the Fig. 2 that the change of the longitudinal oscillation phase advance per period is ~4 smaller than the change of the transverse tune with the same relative change of the corresponding focusing strength parameter: RF field amplitude/phase or the focusing field in the solenoid respectively. This situation is further complicated by the limited range in the parameters; the increase in the nonlinear dependence of the oscillation frequency on the its amplitude for the small equivalent synchronous phases and large field amplitudes; bigger setting errors; interdependence of the field parameters, dictated by the need to meet the required acceleration rate; etc.

However, as shown previously [2,3,6] this mismatch can be partially compensated via fine adjustment of the accelerating cavity amplitude and phase in the considered segment. Unfortunately, this path of abandoning the adiabatic periodicity in the accelerating channel, though it gives us the desired result, has several drawbacks:

1. The performance of the aperiodic channel in terms of the beam quality depends on properly balanced asymmetric adjustment of the cavity settings for the adequate cancellation of the non-linear effects in the part of the channel where the adiabatic periodicity is disturbed;
2. The best preservation of the beam quality in the simulations of the accelerating channel without adiabatic periodicity was achieved when the information about the propagated beam envelopes of upto second order (using forth order particle distribution moments) was used for the setting of the cavity parameters along the critical segments of this channel;
3. The number of cavities with adjusted setting in such channel is relatively high (up to a hundred in some cases).

The present paper proposes a method to reduce significantly the above requirements by localizing the adiabatic periodicity disruption zones, where the listed disadvantages will still be present.  Such separation of the SC cavities functionality can make the commissioning and operation of such a linac more tractable.

### *1.2. Spatial parameters of the accelerator channel*

The general idea proposed in this paper is doubling of the inter-cryostat matching cell. Fig. 3 shows the different layouts used in the LANA simulation for the RIA Driver linac. The newly proposed layout – case 3, has the matching cell doubled.  This allows us to tune those two matching cells so, that the beam will see this doubled cell as a minus-unit transformation.  This can be achieved by setting the corresponding cavity parameters to have $\mu = 90°$ on the corresponding accelerating channel period.  This setting can be done from the RF cavity parameters readings only without the detailed knowledge of beam distribution.  Of course, the matching of the beam at the entrance into the channel has to be done in this case as well as in the previous cases.  The channel it self, however, becomes adiabatically continuous and do not need additional measures to be taken for the re-matching outside of the dedicated matching cells in the proposed case.

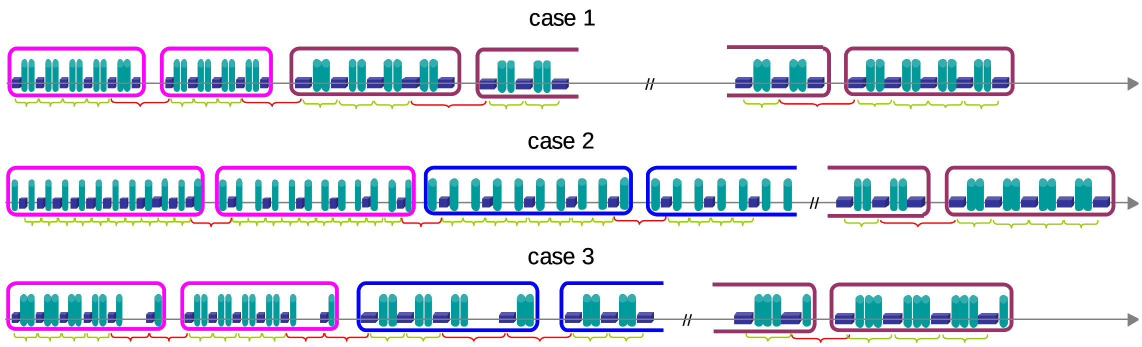



Fig. 3. A schematic view of the 3 different linac layout cases considered. Different cryostat types, listed in Table 1, are outlined by different color. Case 2 uses the same geometry for cryostats type 3 as in case 1, type 2.

Similar approach was used in the RIA Driver linac studies [6] with the special cavity at the end of the cryomodule used for "re-bunching". In the present case, the cryostat ending period together with the previous period are made geometrically identical and used not as re-bunchers, but in the "minus-unit transformation" mode.

Table 1. Number of required accelerating cavities, focusing elements and cryomodules as well as the total length of the linac segment layout for 3 different cases shown in Fig. 3.

| | Cavity | | Solenoid | | Cryomodules | | Total Length [m] |
|---|---|---|---|---|---|---|---|
| | Types | Qty | Types | Qty | Types | Qty | |
| Case 1 | 2 | 18+104 =122 | 2 | 11+65 =76 | 2 | 2+13 =15 | 83.6 |
| Case 2 | 2 | 24+108 =132 | 2 | 18+65 =83 | 3 | 2+2+11 =15 | 95.2 |
| Case 3 | 2 | 20+104 =124 | 3 | 12+15+32 =59 | 3 | 2+3+8 =13 | 83.0 |

The geometric periodicity in the first four cryomodules of the accelerating channel in case 2 is reduced to a single SCRF cavity per period. This significantly reduces the longitudinal phase advance per period (as is shown in Fig. 7) and significantly improves the beam quality in those cryomodules when compared to case 1. This improvement, however, comes for the expense of the increased number of cavities (~30%) and focusing elements (~60%) in this section of the accelerating channel. Case 2 3$^{rd}$ and 4$^{th}$ cryomodules layout is similar to that of the first and second cryomodules, as shown in Fig. 3, but utilize a different cavity type. The rest of the cryomodules for case 2 are identical to the second type cryomodule of case 1. The number of cryomodules is also the same as case 1, but the overall length is somewhat bigger because of the increased length of the first four cryostats.

The case 3 illustrates an alternative approach when the number of cavities per period and the overall number of periods in the accelerating channel are kept unchanged when compared to case 1. The cryostats in this case shown in Fig. 3 are about 15% longer then the corresponding ones from the case 1 and similar in length or shorter then the first four cryomodules of case 2. But, because of the possibility to increase the packing factor starting from the cryomodule #6, the number of cryostats and the number of the focusing elements in case 3 are smaller for the same number of cavities, so the overall length of the linac is the same as in case 1.

The simulations done with LANA code confirmed that the adiabatically smooth matching over the inter-cryomodule drift (between the periods #4 and #6 as per Fig. 1) can be easily achieved. The beam travels through the inter-cryostat region seamlessly without significant impact on the beam quality. The matching cells settings were found only approximately and can be optimized to improve the beam quality further.

Another possible solution is to use triple matching cells, which would perhaps better preserve the beam quality, but would require extra drift spaces and extra RF cavities.

### *1.3. RF cavity settings*

The main gain of the approach considered here is to eliminate the need for elaborate RF cavity parameter settings, as illustrated in Fig. 4.

Special algorithm was developed for the optimized setting of the amplitudes and phases in the accelerating cavities for cases 1 and 2 [3]. The same algorithm can be employed for the proposed layout, case 3, as well, however the partial improvement of the beam quality expected to be smaller for this case because of the better preservation of the adiabatic matching in the major part of the linac.

Special setting of the matching cells for the case 3 still has to be done with good precision in order to preserve the beam quality. And the sensitivity of the beam quality on the setting of those matching cells is expected to be comparable to the cases 1 and 2.

A new study of the setting errors impact on the beam dynamics has to be done in order to quantify the regular and matching cells setting adequate tolerances.

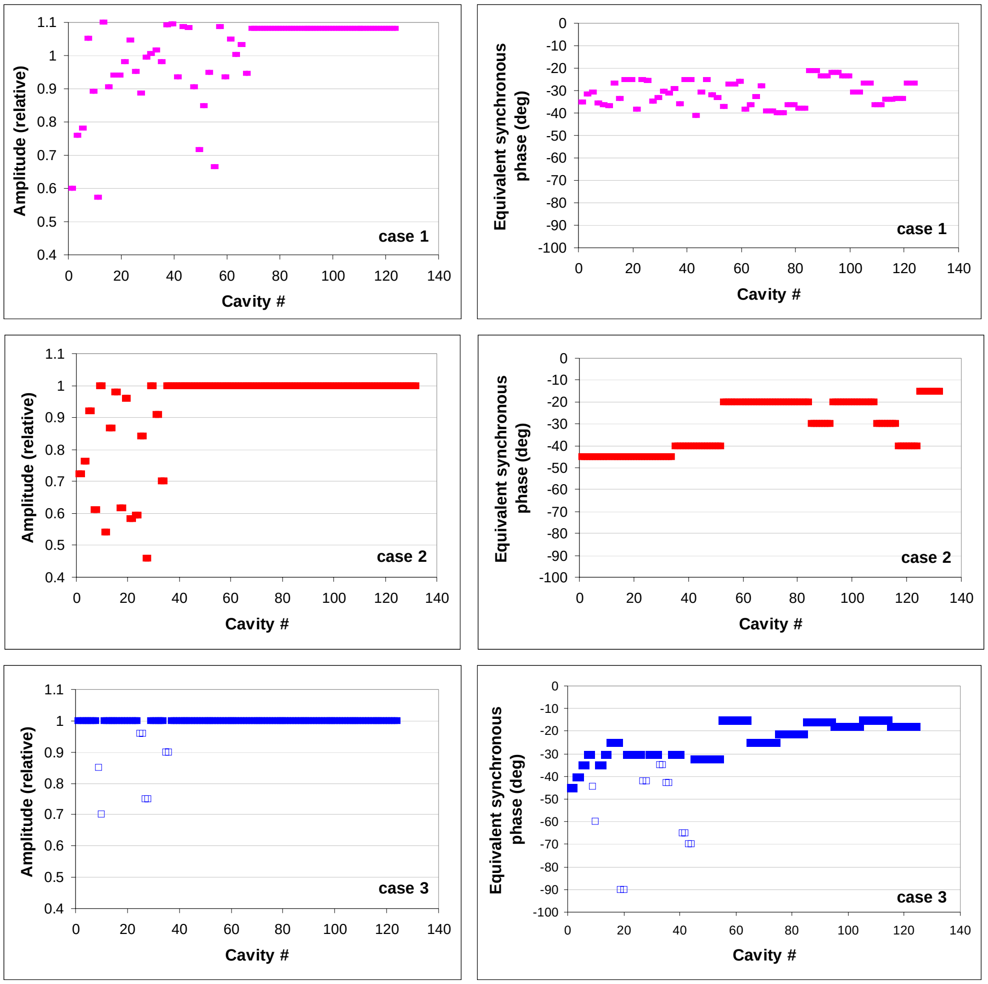
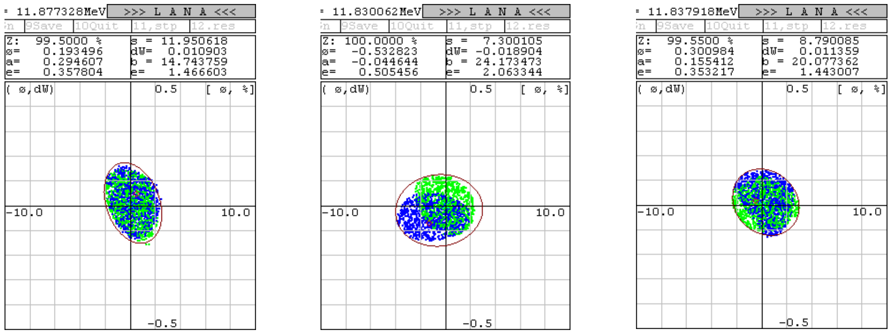



Fig. 4. Comparison of the "design" settings for the 3 cases from Fig. 3.

## *2. Longitudinal beam dynamics simulation*

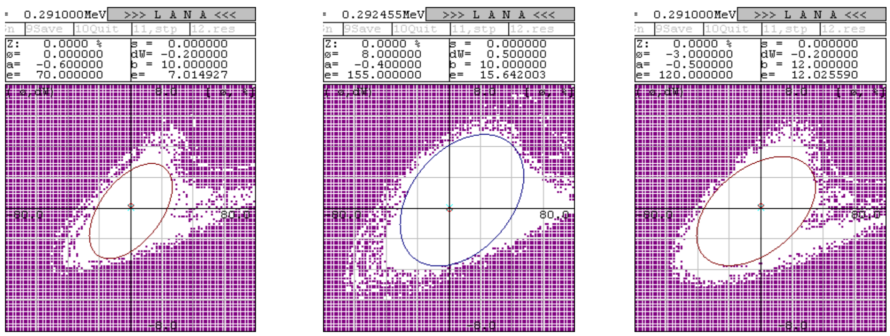
The longitudinal emittances from the simulations of different cases are compared in Fig. 5. Fig. 6 shows the corresponding estimated longitudinal acceptances. Fig. 7 presents the LANA-calculated phase advance per accelerating channel period $\mu$ for all considered cases. The significant variation of this parameter in case 3 takes place only at the locations of the inter-cryostat transitions as expected.

After the first 5 cryomodules, where the "minus-unit-transformation" technique was used to preserve the adiabatic matching of the channel, the adequate inter-cryostat matching was done by changing the cryomodule layout as shown in Fig. 3. This becomes possible due to increased beam energy resulting in reduced longitudinal oscillation frequency.



case 1 case 2 case 3

Fig. 5. Longitudinal emittance at the end of the initial segment of the RIA Driver Linac for different cryomodule layouts.



case 1 case 2 case 3

Fig. 6. Longitudinal acceptance of the initial segment of the RIA Driver Linac for different cryomodule layouts.

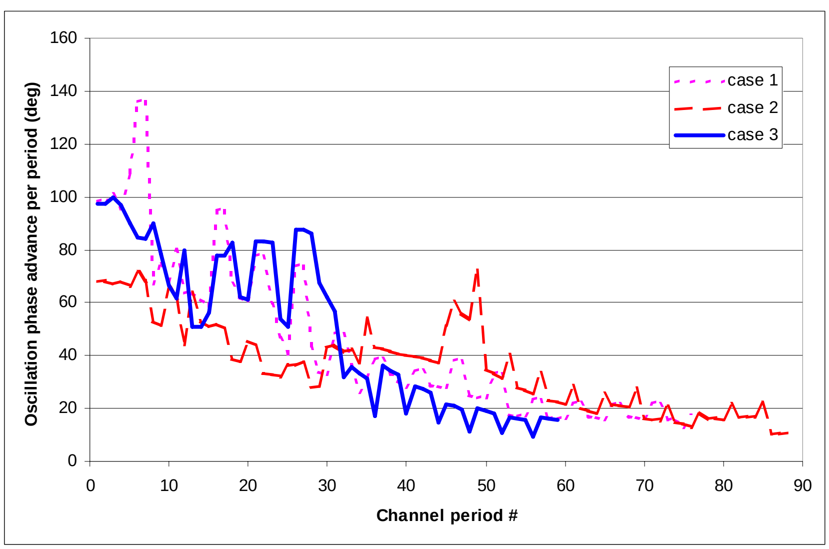



Fig. 7. Longitudinal oscillation phase advance per period in the accelerating channel for all considered cases.

## *3. Conclusion*

It has been demonstrated that the longitudinal beam dynamics can actually be improved and the longitudinal acceptance of the linac can be expanded significantly using the approach taken in the case 2 [3]. However, according to the Table 1, the proposed layout, case 3, in contrast to case 2, does not require additional cavities, reduces the overall length, and reduces the number of accelerator channel elements (cryomodules and solenoids) without significant deterioration of the beam quality and the accelerating channel longitudinal acceptance.

This approach also limits the number of cavities per cryomodule which are responsible for the sustained adiabatic beam matching along the accelerating channel and which can be set in the simulation without using the information about the propagated beam envelope parameters yielding similar beam quality as in the other cases considered.

The most beneficial approach probably would be in the appropriate combination of the both alternative approaches used in cases 2 and 3. The additional studies are needed to optimize the beam dynamics in the SC IPC linacs further.

The results of this study are applicable to the accelerator design and beam dynamics research for various SC linacs utilizing the independently phased cavities periodic accelerator channel approach.

More studies are needed to optimize the benefits of the method proposed. However, we can state now that a more clear understanding of the complicated case of the longitudinal heavy ion beam dynamics in a new type of the SC IPC linacs is achieved and the optimization of the beam quality and minimization of the beam losses in such a linac can be successfully done.

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