# KONUS BEAM DYNAMICS DESIGNS USING H-MODE CAVITIES

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## *Abstract*

The 'Combined Zero-Degree Structure' ('Kombinierte Null Grad Struktur - KONUS') beam dynamics concept is described in detail. A KONUS period consists of a quadrupole triplet or a solenoid lens, a rebuncher section at negative synchronous phase and a multi cell zero degree synchronous particle main acceleration section. This concept is especially effective when applied for accelerator designs using H-mode resonators with 'slim' drift tubes which carry no focusing elements. The definition and typical ranges of KONUS lattice parameters are discussed on a general level, as well as on the basis of examples for realized or planned high current accelerators, like the GSI High Current Injector (HSI), the 70 mA, 3-70 MeV Proton Injector for the FAIR Facility and the IAP proposal of a 125 mA $D^+$, 5-40 MeV superconducting CH-DTL section for the International Fusion Materials Irradiation Facility (IFMIF).

## INTRODUCTION

Conventional room temperature linear accelerator designs for low and medium beam energies ($\beta$ up to 0.3 - 0.4) use the Alvarez-type $\beta\lambda$-DTL with constant negative synchronous phase operation, together with a FODO focusing lattice for transverse stability. This requires the installation of quadrupole singlet lenses inside the drift tubes.

The alternative beam dynamics concept described in this paper makes use of $\beta\lambda/2$ - H-mode DTLs and is called 'Combined 0 Degree Structure' – 'KONUS' [1], [2], [3]. The main characteristic of KONUS is to divide each lattice period into regions with separated tasks. These are:

- Main acceleration along a 0° synchronous particle structure with asynchronous beam injection and a surplus in bunch energy compared to the synchronous particle.
- Transverse focusing by a quadrupole triplet or a solenoid lens.
- Longitudinal focusing by a few rebunching gaps operated at $\phi_s$ = -35°, typically.

By this means the overall gap rf defocusing effect is reduced, allowing to build relatively long multi-cell structures with 'slim' drift tubes without any focusing element, and thus taking advantage of the high efficiency of H-mode cavities at low capacitive load.

H-mode cavities are based on the corresponding $H_{n10}$-modes of empty cylindrical resonators. The 'Interdigital H-Type Structure (IH)' based on the $H_{110}$-mode achieves highest acceleration efficiencies compared to conventional $\beta\lambda$ and $\beta\lambda/2$-DTLs at low and medium energies, i.e. $\beta$ = 0.01 - 0.2. It is operated at resonance frequencies ranging from 30 to 250 MHz.

At higher resonance frequencies the cavity diameter of the IH structure becomes too small. This is why the 'Crossbar H-Type Structure (CH)' based on the $H_{210}$-mode is usually the right candidate for KONUS designs in the velocity range $\beta$ = 0.1 - 0.5 and for resonance frequencies between 150 and 700 MHz typically. Moreover, CH-cavities have an excellent mechanical rigidity due to the crossed stems and can be easily cooled. This opens the possibility of high duty cycle or superconducting multi-cell cavity applications of the CH structure.

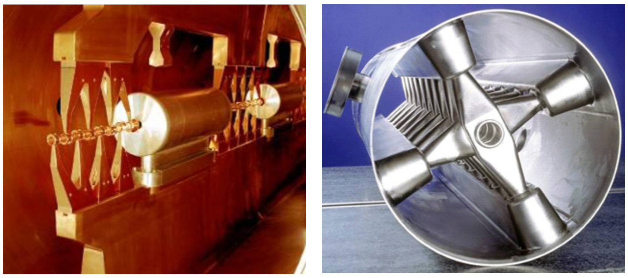

Figure 1: Examples of realized H-mode cavities. Left: IH-DTL for the GSI High Current Injector (room temperature, 36 MHz); slim drift tubes combined with quadrupole triplets. Right: CH-DTL prototype cavity (super-conducting – bulk niobium, 352 MHz).

The high efficiency (shunt impedance) of H-mode resonators for $\beta \leq 0.3$ can be explained by the low rf wall losses due to the cross sectional rf current flow and the low capacity load per length resulting from the slim drift tube geometry. The latter is a direct consequence of KONUS. Slim drift tubes are also very resistant against voltage break down, which can be explained by the inhomogeneous field distribution and the very concentrated high field zones at the tube edges.

Meanwhile a large number of low $\beta$ accelerators based on the KONUS concept are in routine operation in several laboratories (the GSI injectors HLI and HSI, CERN Linac 3, TRIUMF ISAC-I, Heidelberg Therapy Injector, etc.).

This paper is focused on high intensity KONUS designs. The following application examples were selected: the IAP proposal of a 125 mA $D^+$, 5-40 MeV superconducting CH-DTL section for the International Fusion Materials Irradiation Facility (IFMIF) [4], the 15 mA $U^{4+}$, 0.12 – 1.4 MeV/u GSI High Current Injector (HSI) [5] in operation since 1999, as well as the scheduled 70 mA, 3-70 MeV Proton Injector for the GSI FAIR Facility [6].

## LONGITUDINAL KONUS BEAM DYNAMICS

The key part of a longitudinal KONUS period is the 0° synchronous particle section.

It is well known that stable motion in the longitudinal phase space is only provided at negative synchronous phases. For $\phi_s$ = 0° the separatrix shrinks to zero. As illustrated by Figure 2, the single particle orbits are not closed any more and the bunch particles would all be lost after several accelerating cells, except for the synchronous particle. This general view implies that the bunch centroid (index 'cp') is identically equal to the synchronous particle (index 's').

For KONUS this restriction is cancelled. The beam is injected asynchronously, it means with a surplus in bunch energy and with a matched phase slip against the synchronous particle:

$$\Delta W = (W_{cp} - W_s) > 0 \quad ; \quad \Delta\phi = \phi_{cp} - \phi_s = \phi_{cp} \overset{gen.}{\neq} 0 \qquad (1)$$

### Preliminary KONUS Lattice

Under these conditions a stable beam motion can be provided for a limited cell number only (10 to 20 gaps typically, depending on the input beam energy). The bunch centroid performs up to one quarter phase oscillation around the 'fictional' 0° synchronous particle, which defines only the drift tube structure (see marked area in Figure 2). The 0° section is then ended and the bunch enters the transverse focusing lens. Afterwards the next drift tube section begins.

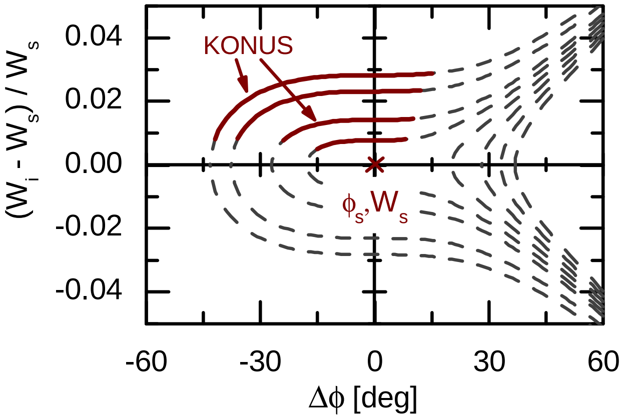

Figure 2: Single particle orbits in $\Delta W/W_s$ – $\Delta\phi$ phase space at $\phi_s$ = 0° with color marking of the area used by KONUS.

The main advantages of the 0° synchronous particle section compared to the conventional negative synchronous phase approach are as follows:

- Higher energy gain according to maximum accelerating fields at $\phi_s$ = 0°.
- Smaller radial rf defocusing effect, allowing for longer accelerator units without radial focusing elements.
- Towards the end of each 0° section, the bunch passes the gap centers at increasing negative rf phase values and thus experiences longitudinal focusing forces like in a conventional negative synchronous phase lattice.

This concept has been developed and first applied in combination with an IH structure for the heavy ion postaccelerator at the Munich tandem laboratory [7]. It was demonstrated multi-cell IH structures with quadrupole doublet lenses placed only in between the tanks can provide stable motion in all phase space planes.

However, for longer linacs, lower injection energies and under the influence of space charge the longitudinal focusing along the 0° section is not adequate. It was realized that additional rebunching elements (several gaps operated at $\phi_s$ = -35°, typically) are needed after each lens to complete each longitudinal KONUS period.

### Improved KONUS Lattice

The IH cavity of the GSI 'High Charge State Injector (HLI)', in operation since 1991, is the first cavity containing several extended KONUS periods [1]. In this chapter it is used for an exemplary description of the longitudinal motion along a KONUS period consisting of a 0° and a rebunching section:

- At the entrance of each 0° synchronous particle section the bunch must be longitudinally focused (position 'a' and 'd' in Figure 3 and Figure 4).

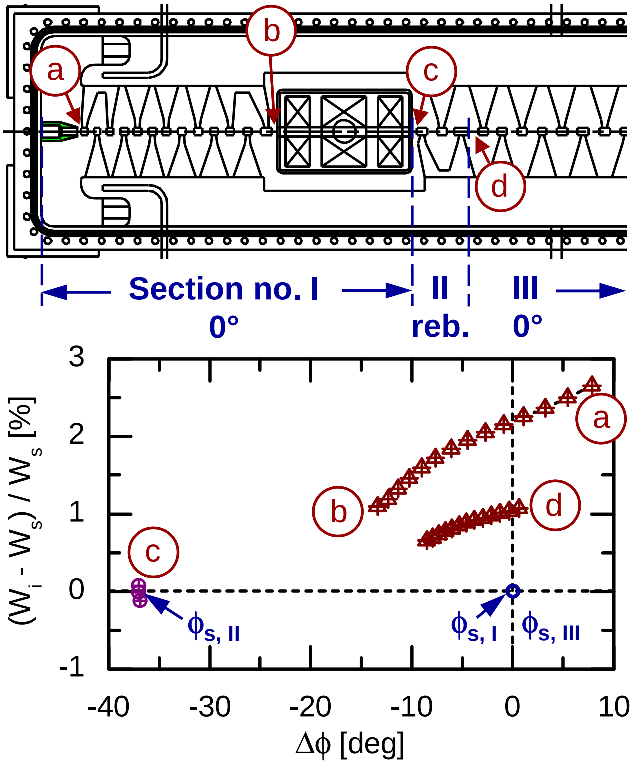

Figure 3: Example of the bunch center motion along a longitudinal KONUS period (from 'a' to 'd').

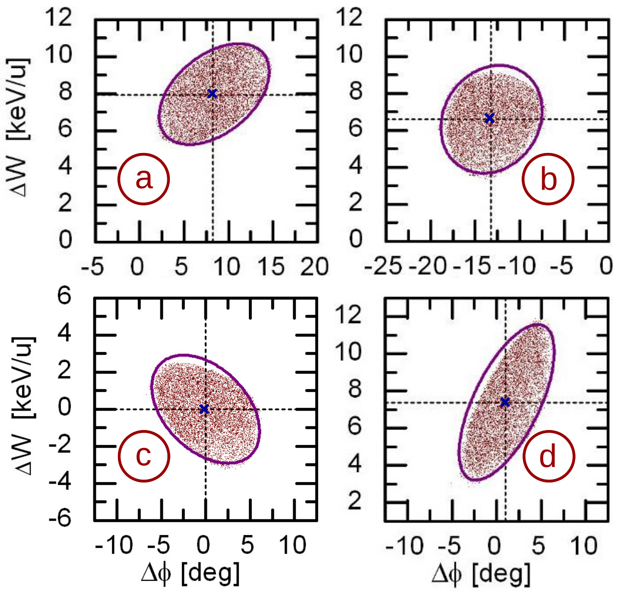

Figure 4: Longitudinal particle distributions corresponding to the positions ‘a’ to ‘d’ of Figure 3.

- When passing the first gaps of the 0° section the bunch is close to 0° rf phase and becomes longitudinally defocused. This effect is partly compensated in the last gaps of the 0° section, when approaching negative rf phases. At the exit (Figure 4, position ‘b’) the bunch can even be slightly focused.
- Each accelerating section is followed by a transversal focusing element (here a quadrupole triplet), to compensate the rf defocusing effect of the gaps and refocus the beam. For the longitudinal motion the lens acts like a drift space and must be as short as possible, in order to keep the phase spread of the bunch small.
- However the bunch is defocused at the lens exit (Figure 4, position ‘c’). This is why a rebunching section, typically consisting of 2-7 gaps at $\phi_s$ = -35° must follow. Note that by the redefinition of $\phi_s$ and $W_s$ for the new synchronous particle, the bunch centroid and the synchronous particle are now identical (Figure 4, position ‘c’), like in conventional designs. This is the case for all KONUS rebunching sections.
- At the exit of the rebunching section the beam is longitudinally focused (Figure 4, position ‘d’) and ready to be injected to the next 0° section. For this purpose adequate starting parameters for generating the next 0° synchronous particle section have to be defined.

  One longitudinal KONUS period is now completed.

The question might arise how the successive definition of new synchronous particles and the corresponding shifts in phase and energy are feasible.

Concerning the $W_s$ setting, the synchronous particle defines the geometrical lengths (velocity profile) of the drift tube array as it is built. Along rebunching sections $W_s = W_{cp}$ and at transition to the 0° section $W_s < W_{cp}$ is chosen, which makes an apparent surplus energy of the bunch.

Concerning the phase shifts (for example at the transition -35° → 0°) there are some options: if the transition gaps belong to different cavities, the tank rf phases can be chosen independently (operating knob); if the transition gaps belong to the same resonator, the geometrical length of the transition cell can be adjusted, for example by mounting a longer drift tube:

$$L_{shift} = (180^\circ + 35^\circ)/180^\circ \cdot \beta\lambda/2 \tag{2}$$

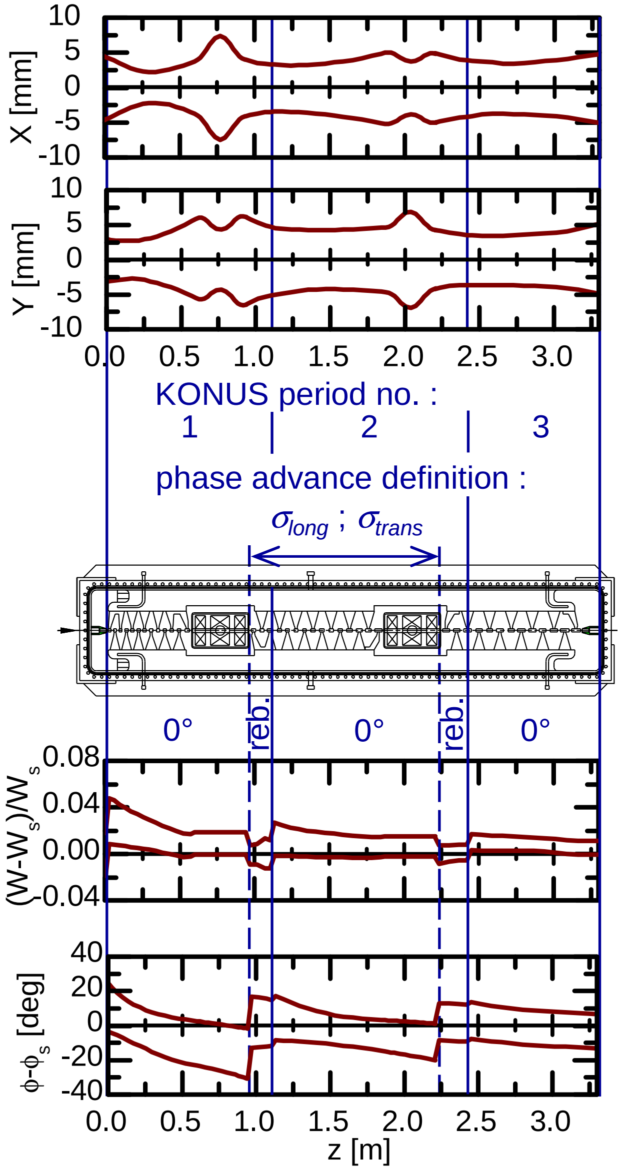

Figure 5: Example of beam envelopes along a KONUS lattice, together with the lattice period and phase advance definitions.

## TRANSVERSE KONUS BEAM DYNAMICS

The transverse focusing elements used for KONUS are magnetic quadrupole lenses (usually triplets) or solenoids.

If quadrupole triplets are used, the polarity is alternating, i.e. the basic lattice unit is DFD O FDF O (see Figure 5). This sequence is preferable compared to DFD O DFD O or FDF O FDF O for various reasons:

- In the latter case the beam envelopes have different sizes in the x(z) and y(z)-plane, which requires larger drift tube apertures.
- Asymmetric beams are unfavourable with respect to space charge.
- Not least the focusing strengths are different ($\kappa_{DFD} \neq \kappa_{FDF}$), leading to different phase advances in x and y ($\sigma_x \neq \sigma_y$) [2].

Even with alternating lens polarity as used for KONUS, the effect caused by $\kappa_{DFD} \neq \kappa_{FDF}$ for successive triplets in the same plane is of concern. Unlike FODO lattices, a quadrupole triplet lattice is an array of solely focusing lenses $F_1OF_2O$ with $F_1$=DFD and $F_2$=FDF.

When the KONUS lattice period $L_P$ is including one triplet lens and one multi gap section, as defined in Figure 5, lattice resonances occur at $\sigma_{t,L_P} = 90°$. The bandwidth of the unstable region around $\sigma_t$ = 90° can be minimized by the proper choice of the ratio $L_1/L_2$, where $L_1$ is the length of the inner singlet and $L_2$ the sum length of the outer singlets. For equal lens gradients an optimum ratio

$$L_1/L_2 \in [0.9-1.0]$$

has been found from design experience and by systematic investigations [2]. However, in practice the $\sigma_t$ = 90° resonance will usually not develop, as in KONUS designs the lattice parameters do not evolve stringently periodic.

As already mentioned, the transverse KONUS lattice periodicity is $2 \cdot L_P$ when using triplet focusing. However, for the calculation of the transverse and longitudinal phase advances $\sigma_x$, $\sigma_y$, $\sigma_{long}$ the positions between the exits of two consecutive focusing elements was chosen (see Figure 5), it means each KONUS period is made up of a 0°, a rebunching drift tube section and a focusing element. This definition has the advantage of using the same geometrical positions for the transverse and longitudinal phase advance calculation. When applying solenoid focusing, the KONUS lattice periodicity is exactly $L_P$, namely the space between two solenoids.

It should be pointed out that the resulting phase advances are sum effects of all elements of a KONUS period with different impacts on the particle motion. For example the transverse phase advance is the sum of the rf defocusing of several gaps together with the effect of the focusing lens.

Unlike in FODO lattices, it makes no sense to define the phase advance related to a constant multiple of the unit cell (e.g. $2\beta\lambda$ for an Alvarez structure). Nevertheless the resulting design values are comparable to those applied in conventional designs: for low current applications $\sigma_t$ > 90° (typically around 120°) is sometimes necessary, especially at low energies, because of the relatively small focusing element density. With increasing beam energy $\sigma_t$ 'drops' below 90°. For high current designs $\sigma_t$ < 90° is usually kept throughout.

## KONUS DESIGN CRITERIA AND OPTIONS

So far it was shown that the KONUS beam dynamics concept is suited for building long linacs, providing stable particle motion along a quasi-periodic lattice made up of components with dedicated tasks.

However, it is up to the beam dynamics designer to find the optimum parameter settings for a specific application. So far the parametrization of KONUS lattices is rather based on the experience of the beam dynamics designer than on a theoretical framework.

In this chapter the major 'degrees of freedom' available to KONUS designers are presented.

### *Starting Phase and Energy of 0° Sections*

By variation of the starting conditions $\Delta\phi$ and $\Delta W$ of the bunch at the first gap of each 0° section (see eq. (1), the desired output parameters (distribution shape and orientation) can be matched to the needs of the following sections.

On the one hand, the trajectories in the longitudinal phase space are very sensitive to the starting conditions, but on the other hand this property can be used as a powerful design tool, as can be seen from the different resulting trajectories and bunch shapes in Figure 6.

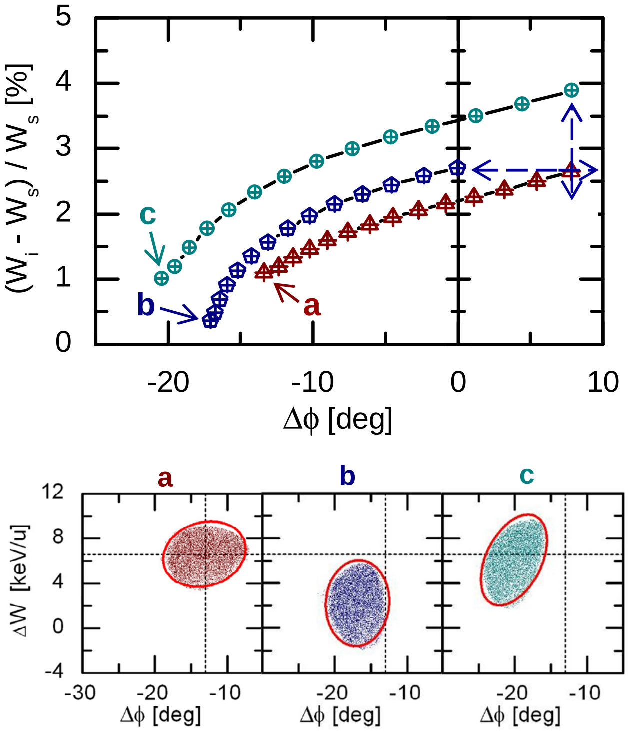

Figure 6: Top: Variation of the starting phase and energy of 0° sections. Bottom: Corresponding emittances at exit.

### *Number of Gaps per 0° Section*

Basically the higher $N_{gap,0^\circ}$ the better for rf efficiency, but there are several constraints:

- The longitudinal and the transverse matching. If the gap number is too high, the bunch center performs more than a quarter oscillation in phase space with rather negative rf phases and finally leaves the applicable phase space area. Moreover the bunch shape and orientation at exit must be suited for matching to the following section. With respect to the transverse KONUS dynamics, the total gap number defines the distance between the focusing elements. The optimum distance is usually predetermined by factors like beam energy and emittance, space charge defocusing etc. and thus the gap number is not a free parameter.
- Well-balanced ratio $N_{gap,reb}$ / $N_{gap,0^\circ}$ (between 1:2 and 1:4, typically). The number of rebunching gaps $N_{gap,reb}$ (with $\phi_s$ = -35°, typically) is ranging between 2 and 7 per section, depending on the design constraints and on the beam parameters (energy, $A/q$, etc.)
- Max. number of gaps per section (up to ≈ 20) and per tank (up to ≈ 60). This is for example limited by tank voltage flatness reasons, by the available rf power etc.

### *Options for the Transverse Focusing Elements*

Powerful quadrupole triplet lenses are needed for sufficient transverse focusing.
Pole tip fields up to $B_{max}$ = 1.3 T are available with conventional technology (room temperature, laminated cobalt steel alloys).

At lower beam energies, the lenses must be installed within the resonator while providing the shortest possible drifts between the accelerating sections, which makes the mechanical design and the rf tuning more complicated. With increasing beam energies, external (inter-tank) lenses are preferably used.

Since powerful superconducting magnets ($B$ = 4 – 12 T) are available, solenoid focusing becomes attractive also for higher $\beta$ values, especially in combination with s.c. cavities (no iron yokes!). Several KONUS lattices based on solenoid focusing were investigated (e.g. for IFMIF – see next section).

## KONUS DESIGN EXAMPLES

Among the plenty KONUS-based accelerator designs which came in routine operation or were proposed during the past decades and up to now, three significant examples of high intensity linacs will be presented, namely:

- The superconducting CH-DTL section for IFMIF [4].
- The GSI High Current Injector (HSI) [5].
- The Proton Injector for the GSI FAIR Facility [6].

This introduction covers only KONUS-specific aspects of the above-mentioned accelerator examples.

### *The Superconducting CH-DTL for IFMIF*

The International Fusion Material Irradiation Facility (IFMIF) is an accelerator-based $d$ on $Li$ neutron source, which will deliver a high flux of 14 MeV neutrons on a massive target for testing of materials to be used in fusion reactors like ITER.

The linac has to provide 250 mA of $d$ coming from two parallel accelerators in cw mode operation.

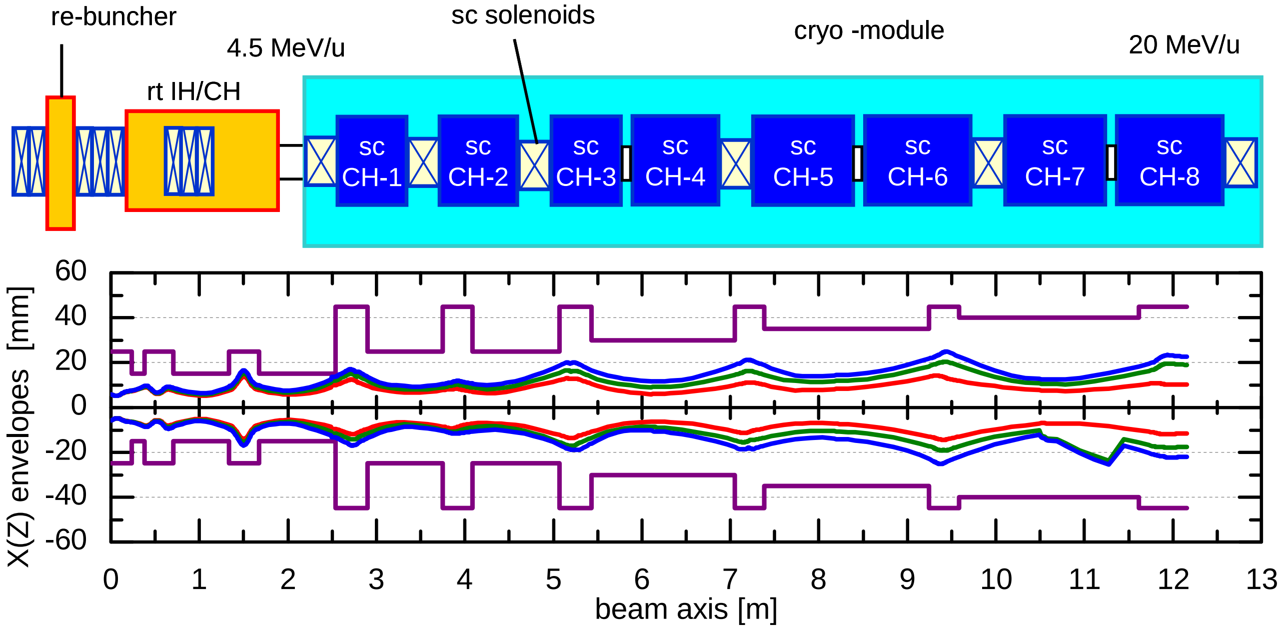

Figure 7: Schematic layout and transverse 100% beam envelopes along the H-mode linac for IFMIF (red: nominal run; green and blue: common beam envelopes from 100 runs with different machine error settings, $10^5$ particles for each run).

Table 1: CH-DTL for IFMIF Parameter List

| | |
|---|---|
| resonance frequency | 175 MHz |
| design particle | *d* |
| design beam current | 125 mA |
| duty cycle | cw |
| energy range | 2.5 – 20 MeV/u |
| number of DTLs | 1 r.t. IH or CH + 8 s.c. CH |
| total DTL length | ≈ 12 m |
| number of KONUS periods | 7 |
| $\varepsilon_{tr,n,rms}$ , at linac output | 0.4 mm·mrad |
| $\varepsilon_{long,n,rms}$ , at linac output | 1.8 keV/u·ns |

The IAP Frankfurt proposal consists of a 2.5 – 4.5 MeV/u room temperature IH- or CH-cavity and a chain of eight superconducting CH-cavities for the energy range 4.5 – 20 MeV/u, all operated at 175 MHz.

The focusing scheme in the CH-linac is based on superconducting solenoids, which turned out to be of great advantage with respect to beam dynamics as well as for mechanical design and system integration issues:

- The high gradients of the superconducting solenoids helped reducing the lens lengths, i.e. the drifts between cavities, which improved the longitudinal KONUS dynamics a lot. At the same time the transverse envelope oscillations were significantly reduced (see Figure 7) as compared with previous quadrupole triplet based designs.

  Finally the improvements achieved for the beam dynamics design can be counted in terms of emittance growth, which was reduced to about 60% for the transverse and 30% for the longitudinal phase space. These are acceptable growth rates for a 125 mA deuteron beam.
- Both the CH-cavities and the s.c. solenoids can be integrated to a common cryo-module, which further reduces the drifts between components and the number of cold-warm junctions. A design study has been performed together with an industrial manufacturer, showing the technical feasibility of this concept.

The IFMIF project has one of the most stringent particle loss prevention requirements: the 1 W/m limit means in this case losses below 25 nA/m or $2\cdot10^{-7}$ /m.

This is why one major beam dynamics design criterion was to avoid particle losses. Superconducting components have the advantage to allow for large aperture radii. As a result, large safety margins between the 100% beam envelopes and the drift tube apertures could be achieved (see Figure 7).

A detailed error analysis has been performed [4]. No transverse losses occurred in 100 runs with $10^5$ particles each and randomly distributed errors. The maximum error settings were lens displacements ≤ 0.2 mm, lens rotations ≤ 3 mrad in x and y and ≤ 5 mrad in z, tank voltage amplitude errors (from rf) ≤ 1%, single gap voltage errors (from cavity tuning) ≤ 5% and tank phase errors (from rf) ≤ 1°. The error tolerances would be in reality even higher, as no steering corrections were included in the beam dynamics simulations.

## *The GSI High Current Injector*

A particular reason for mentioning the GSI High Current Injector as a KONUS application example is the fact that it was the first realized and routinely operated high intensity and low $\beta$ linac based on this beam dynamics concept.

At GSI higher beam currents were required in order to fill the synchrotron SIS up to the space charge limit for the heaviest ion species. This was only possible by re-defining the design particle from $U^{10+}$ to $U^{4+}$, because only low charge states out of MEVVA-type ion sources are available with sufficient beam current for uranium beams.

This is why a new pre-stripper section, now in operation since 1999, had to be designed, replacing the 34 MV Wideröe section of the UNILAC by an RFQ and two IH-DTLs with 91 MV accelerating voltage in total. One design constraint was to keep within the total length occupied by the Wideröe linac within the UNILAC tunnel. Thus a linac concept providing high acceleration efficiency was needed. Enabled by KONUS, averaged effective voltage gains of 4.3 MV/m were reached inside the IH-DTLs.

In addition, the new linac had to be suited for two major operation modes: the traditional 30% duty factor low intensity operation and the short high intensity beam pulses with 1% duty factor.

The frequency of 36.136 MHz is one third of the UNILAC Alvarez section frequency. It was the lowest frequency which allowed building IH-DTLs with tank diameters not larger than 2 m, the tank sizes being limited by the installation into the UNILAC tunnel and for copper plating reasons.

Table 2: GSI High Current Injector Parameter List

| | |
|---|---|
| resonance frequency | 36.136 MHz |
| design particle | $^{238}U^{4+}$ |
| design beam current | 15 mA |
| duty cycle | 1% for A/q ≤ 59.5<br>30% for A/q ≤ 26 |
| energy range | 0.12 – 1.4 MeV/u |
| number of IH-DTLs | 2 |
| total DTL length | ≈ 20 m |
| number of KONUS periods | 4 (IH1) + 2 (IH2) |
| $\varepsilon_{tr,n,rms}$ , at linac output | 0.1 mm·mrad |
| $\varepsilon_{long,n,rms}$ , at linac output | 0.45 keV/u·ns |

As an outcome of all above-mentioned constraints, a KONUS based IH-DTL setup consisting of two main accelerating units (IH1 with a maximum voltage gain of 40.5 MV, IH2 with 42.7 MV) and two inter tank MEBT sections was designed.

The transverse focusing is provided by up to 1 m long, powerful quadrupole triplet lenses partly integrated into the rf structures (see Figure 1 and Figure 8).

The beam dynamics design as illustrated by Figure 8 shows the periodicity of the KONUS lattice with only small beam envelope oscillations in the longitudinal plane. The larger envelope oscillation in the transverse planes is typical for the quadrupole triplet focusing. The largest beam size is attained inside the quadrupole lenses. Lens aperture diameters are between 35 and 47 mm. Along the drift tube sections with aperture diameters of 28-46 mm the beam envelopes are much slimmer, which gives enough safety with respect to beam losses.

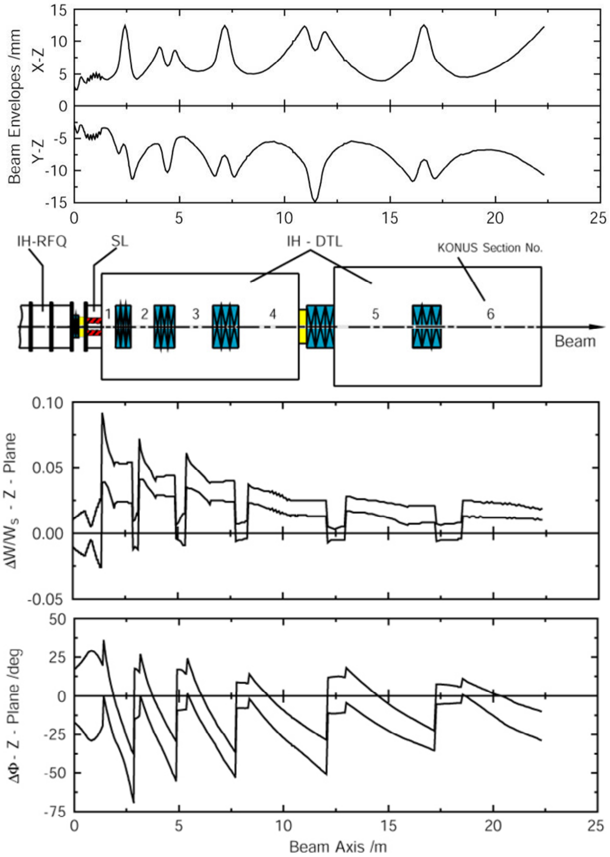

Figure 8: Schematic layout of the GSI High Current Injector with beam envelopes for the 15 mA $^{238}U^{4+}$ design current.

Emittance measurement results from the running in of the High Current Injector were published in ref. [5] and show very good agreement with the predictions from simulations.

Meanwhile the IH-DTL part of the GSI High Current Injector is in routine operation since almost ten years without major difficulties and providing high transmission rates for many different machine settings needed for the different ion species. This operation experience demonstrates that KONUS designs in combination with H-mode cavities are robust and well suited for high current applications.

### *The Proton Injector for the GSI FAIR Facility*

The needed intensities for the FAIR facility antiproton research program can be provided only by a dedicated high current proton linac directly injecting the beam into the existing synchrotron SIS 18.

A design proton current of 70 mA will be accelerated to 70 MeV with 0.02% duty cycle. The KONUS layout of this linac consists of three coupled CH resonators from 3 – 35 MeV followed by another setup of three coupled CH cavities up to 70 MeV. A design alternative using three standard CH cavities without integrated quadrupole lenses is under investigation.

In this paper the proposed Proton Injector for the GSI FAIR Facility is only mentioned as an important high intensity KONUS design example presently under development. More details on the present status of the project, especially with regard to beam dynamics issues, can be found in ref. [6], which is a dedicated ‘HB2008’ Workshop contribution on the FAIR Proton Linac

## THE LORASR BEAM DYNAMICS CODE

LORASR (‘Longitudinale und radiale Strahldynamikrechnungen mit Raumladung’ – ‘Longitudinal and Radial Beam Dynamics Calculations Including Space Charge’) is the dedicated multi particle tracking code for the design of KONUS lattices.

The LORASR code can treat all kind of drift tube structures, but the code architecture and handling as well as the input file structure are optimized for the definition of KONUS lattices. One example is the distinction between the synchronous particle and the real bunch.

Table 3: Available LORASR Elements

| |
|---|
| magnetic quadrupole lens |
| solenoid lens |
| dipole bending magnet |
| accelerating gap |
| RFQ section (constant rf phase, ‘Superlens’) |
| 3D FFT space charge routine |
| error study routines |

A first version of LORASR was developed for the Munich heavy ion postaccelerator [7]. At GSI a code version operated on UNIX workstation platforms was developed for the beam dynamics design of the GSI High Charge State Injector as well as of the CERN Lead Injector. Substantial changes and improvements of the code were necessary: the gap field representation was improved; various graphical output features were added, as well as routines to investigate the beam quality quantitatively. Finally a PIC space charge routine was added. Another step in the development of the code was initiated by the design of the GSI High Current Injector [5]. The calculation of short RFQ-sections was implemented. An 11-cell RFQ operated at $\phi_s$ = -90° and installed between the main RFQ and the DTL, the so called 'Superlens', was designed by LORASR and realized successfully.

During the last decade, a PC-Windows version of the code using the Lahey-Fujitsu© Fortran 95 compiler was created and is under permanent development at IAP, Frankfurt University.

An overview on the recent code development can be found in ref. [8]. The focus was on the following items:

- Implementation of a new space charge routine based on a PIC 3D FFT algorithm.
- Implementation of tools for error study and loss profile investigations.

The new space charge routine was successfully benchmarked with other codes within the framework of the 'High Intensity Pulsed Proton Injector' (HIPPI) European Network Activity [9].

First applications of the machine error setting and analysis routines are the error study investigations on the FAIR Proton Injector and on the IAP designs for IFMIF and EUROTRANS, as mentioned in the previous chapter.

In Figure 9 an example of the LORASR loss profile calculation and illustration options is given.

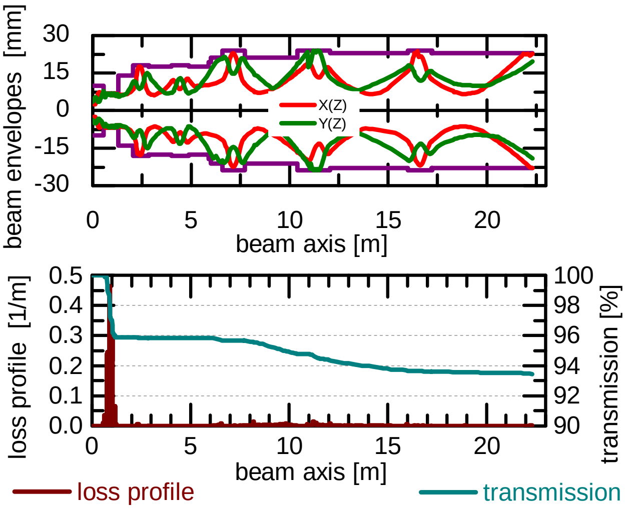

Figure 9: LORASR loss profile calculation example: GSI HSI, cross check simulations for the UNILAC beam current upgrade program (20 mA U$^{4+}$ input current).

## CONCLUSIONS

The 'Combined Zero Degree Structure' (KONUS) beam dynamics concept has been developed during the past three decades together with H-Mode DTL linear accelerators (IH, CH). Meanwhile a large number of low $\beta$ accelerators based on this concept are in routine operation in several laboratories all over the world.

Scheduled high intensity accelerators like the 70 mA, 3-70 MeV Proton Injector for the GSI FAIR Facility and the IAP proposal of a 125 mA $^2H^+$, 5-40 MeV superconducting CH-DTL section for IFMIF are based on KONUS beam dynamics designs.

LORASR, a dedicated tool for the design of KONUS lattices, has been upgraded in order to meet modern design criteria of high intensity linacs: a new, fast space charge routine enables validation runs with up to 1 million macro particles within a reasonable computation time, including machine error studies.

However, a theoretical framework for the description and parametrization of the KONUS beam dynamics concept is still under development.

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