KONUS Beam Dynamics Using H-Mode Cavities

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Involved key persons:

H. Klein, H. Podlech, U. Ratzinger, C. Zhang (IAP Frankfurt),

G. Clemente (GSI Darmstadt)
Outline

- Description of the ‘Combined Zero-Degree Structure’ (‘Kombinierte Null Grad Struktur – KONUS’) concept
- KONUS lattices parameters + design criteria
- Application examples
- LORASR beam dynamics code status
- Summary and outlook
KONUS Versus FODO Lattice

- “Standard” linac design (up to ≈ 100 MeV): Alvarez DTL + FODO beam dynamics.

Alternative:
- H-Type DTL (IH or CH) and KONUS beam dynamics, each lattice period divided into 3 regions with separated tasks:
  - Main acceleration at $\Phi_s = 0^\circ$, by a multi-gap structure (1).
  - Transverse focusing by a quadrupole triplet or solenoid (2).
  - Rebunching: 2 - 7 drift tubes at $\Phi_s = -35^\circ$, typically (3).
H-Mode Cavities

**IH-DTL**
- r.t.
- \( W < 30 \text{ MeV} \)
- 30-250 MHz

**Crossbar H-Type structure (CH)**

**CH-DTL**
- r.t. and s.c.
- \( W < 150 \text{ MeV} \)
- 150-700 MHz

**Interdigital H-Type structure (IH)**

Carbon Injector for the Heidelberg Therapy Center
- 217 MHz, 20 MV,
- 0.3 – 7 MeV/u, 800 kW,
- 1% duty factor

s.c. (bulk niobium)
- CH-DTL prototype cavity
- 352 MHz,
- \( \beta = 0.1 \),
- \( \varnothing = 276 \text{ mm} \)
Higher shunt impedances for $\beta \leq 0.3$ are due to:

- **H-mode**
  - low rf wall losses $P_{\text{loss}}$.
  (cross sectional rf current flow, all gaps fed in parallel).

- **KONUS**
  - multi gap structures with ‘slim’ drift tubes, carrying no focusing elements.
Particle Trajectories in Longitudinal Phase Space

at $\phi_s = 0^\circ$

$\phi_s = -30^\circ$

$\phi_s = 0^\circ$

Black arrows: area used by KONUS
Bunch Center Motion Along 
0° Synchronous Particle Sections

Gap 1: 
\( W_s = 302 \text{ keV/u} \); \( W_i = 310 \text{ keV/u} \)

Gap 6: 
\( W_s = 409 \text{ keV/u} \); \( W_i = 418 \text{ keV/u} \)

Gap 14: 
\( W_s = 603 \text{ keV/u} \); \( W_i = 609.5 \text{ keV/u} \)

\[ \sum V_{eff} \approx 2.1 \text{ MV} \]
\[ L \approx 0.55 \text{ m} \]

\( \phi_s \) defines rf-structure 
(geom. lengths)
Bunch Center Motion Along Negative Synchr. Phase Rebunching Sections

Gap 14, after quad. lens (drift):
\( W_s = 603 \text{ keV/u} \); \( W_i = 609.5 \text{ keV/u} \)

Gap 15:
\( W_s = 623.6 \text{ keV/u} \); \( W_i = 624 \text{ keV/u} \)

Gap 18:
\( W_s = 691 \text{ keV/u} \); \( W_i = 698 \text{ keV/u} \)
Overview of the Bunch Motion Along a Full Longitudinal KONUS Period

Phase shift at transition: rebunching → 0° section

- Geometrical length adjustment (longer drift tube).
- Independent choice of tank rf phases, if transition gaps belong to separated cavities.

Energy shift

- (Geometrical) periodic lengths of 0° sections are related to the (new) synchronous particle, and not to the bunch centroid.
- Bunch energy gain is evidently smooth:
Combined 0° Structure Overview
and Definition of the Longitudinal KONUS Lattice Period

IH cavity of the GSI HLI injector

lattice period:

beam envelope

$\varphi_s = 0^\circ$ $-35^\circ$ $\varphi_s = 0^\circ$ $-35^\circ$ $\varphi_s = 0^\circ$

$\sigma_{li}$: long. phase advance of KONUS period $i$
Transverse KONUS Beam Dynamics: Quadrupole Triplet Channel

IH cavity of GSI HLI injector: first built cavity containing several KONUS periods (op. since 1991)
KONUS Design Margins:
Starting Phase and Energy of 0° Sections

- By variation of the starting conditions $\Delta \Phi$ and $\Delta W$ of the first gap of each 0° section, the desired output parameters (distribution shape and orientation) can be matched to the needs of the following sections.
KONUS Design Margins: Number of Gaps Per 0° Section

Basically the higher $N_{\text{gap,0°}}$ the better, but there are several constraints:

- **Longitudinal matching:**

  ![Graphs showing transverse matching for gaps 14 and 17.]

  - Well-balanced ratio $N_{\text{gap,reb}} / N_{\text{gap,0°}}$ (between 1:2 and 1:4, typically).

- **Transverse matching:**

  ![Graph showing beam envelopes for x(z) and y(z) for gaps 14 and 17.]

  - Max. number of gaps per section (up to $\approx 15$) and per tank (up to $\approx 60$). This is for example limited by tank voltage flatness reasons, by the available rf power etc.
The number of rebunching gaps $N_{\text{gap,reb}}$ for each section (at $\Phi_s = -35^\circ$ usually) is ranging between 2 and 7, depending on the design constraints and on the beam parameters (energy, $A/q$, etc.).

For each individual case, the assumed number $N_{\text{gap,reb}}$ for best matching to the subsequent $0^\circ$ section must be confirmed by the beam dynamics calculations. Example:
KONUS Design Margins: Transverse Focusing Elements

- Powerful, long 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 resonators, 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 ($B = 4 - 10$ T) are available, solenoid focusing becomes attractive also at 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):

Design study for IFMIF based on s.c. CH-cavities (125 mA, 20 MeV/u $^2$H$^+$ - beam)
KONUS Design Examples
(High Intensity Linacs)

- **GSI High Current Injector (HSI)**
  36 MHz, 15 mA U⁴⁺, 0.12 – 1.4 MeV/u, 90 MV, 1% duty cycle, in operation since 1999.

- **Superconducting CH-DTL section for IFMIF (IAP proposal)**
  175 MHz, 125 mA deuterons, 2.5 – 20 MeV/u, cw operation.

- **Proton Injector for the GSI FAIR Facility**
  325 MHz, 70 mA protons, 3-70 MeV, 0.1% duty cycle

  Dedicated presentation:
  G. Clemente, ‘Investigation of the Beam Dynamics Layout of the FAIR Proton Injector’
KONUS Design Examples:
GSI High Current Injector (‘HSI’)  

- In operation since 1999.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>resonance frequency</td>
<td>36.136 MHz</td>
</tr>
<tr>
<td>design particle A / q</td>
<td>59.5 (^{238}\text{U}^{4+})</td>
</tr>
<tr>
<td>design beam current (1996)</td>
<td>15 mA</td>
</tr>
<tr>
<td>duty cycle</td>
<td>1 % at A/q ≤ 59.5</td>
</tr>
<tr>
<td></td>
<td>30 % at A/q ≤ 26</td>
</tr>
<tr>
<td>energy range</td>
<td>0.12 – 1.4 MeV/u</td>
</tr>
<tr>
<td>number of IH-DTLs</td>
<td>2</td>
</tr>
<tr>
<td>total length (IH1 + IH2)</td>
<td>≈ 20 m</td>
</tr>
<tr>
<td>number of KONUS periods</td>
<td>4 (IH1) + 2 (IH2)</td>
</tr>
<tr>
<td>(\varepsilon_{tr,n,rms})</td>
<td>0.10 mm·mrad</td>
</tr>
<tr>
<td>(\varepsilon_{long,n,rms})</td>
<td>0.45 keV/u·ns</td>
</tr>
</tbody>
</table>

![KONUS Design Example Diagram](image)
KONUS Design Examples:
GSI High Current Injector (‘HSI’)

R. Tiede, Institute for Applied Physics (IAP), Goethe-University Frankfurt
KONUS Design Examples:
S.C. CH-Linac for IFMIF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>resonance frequency</td>
<td>175 MHz</td>
</tr>
<tr>
<td>design particle</td>
<td>$^{2}\text{H}^+$</td>
</tr>
<tr>
<td>design beam current</td>
<td>125 mA</td>
</tr>
<tr>
<td>duty cycle</td>
<td>cw</td>
</tr>
<tr>
<td>energy range</td>
<td>2.5 – 20 MeV/u</td>
</tr>
<tr>
<td>number of DTLs</td>
<td>1 r.t. IH/CH + 8 s.c. CH</td>
</tr>
<tr>
<td>total DTL length</td>
<td>$\approx$ 12 m</td>
</tr>
<tr>
<td>number of KONUS periods</td>
<td>7</td>
</tr>
<tr>
<td>$\varepsilon_{\text{tr,n,rms}}$</td>
<td>0.4 mm·mrad (growth rate: 60%)</td>
</tr>
<tr>
<td>$\varepsilon_{\text{long,n,rms}}$</td>
<td>1.8 keV/u·ns (growth rate: 30%)</td>
</tr>
</tbody>
</table>
KONUS Design Examples:
S.C. CH-Linac for IFMIF

Transverse 100% beam envelopes along the H-Mode-Linac
KONUS Design Examples:
S.C. CH-Linac for IFMIF

Emittance growth along the H-Mode-DTL
(for a 125 mA, $^2$H$^+$ - beam)
KONUS Design Examples: S.C. CH-Linac for IFMIF

Phase space distribution after the RFQ and after the CH-DTL (for a 125 mA, $^2\text{H}^+$ - beam)
LORASR Code Features - Overview

Longitudinale und radialen Strahldynamikrechnungen mit Raumladung
Longitudinal And Radial Beam Dynamics Calculations including Space Charge

• General:
  - Multi particle tracking along drift tube sections, quadrupole lenses, short RFQ sections including fringe fields and dipole magnets.
  - Running on PC-Windows platforms (Lahey-Fujitsu Fortran 95).

• Available 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

• GUI:

![GUI Image]

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LORASR: Recent Code Development and Applications

- Implementation of a new space charge routine based on a PIC 3D FFT algorithm.
  - Benchmarking with other codes within the framework of the ‘High Intensity Pulsed Proton Injector’ (HIPPI) European Network Activity (CARE-Note-2006-011-HIPPI, see also talk by L. Groening).

- Implementation of machine error setting and analysis routines.
  - Error study on the FAIR Proton injector (talk by G. Clemente).
  - Error study on the IAP designs for IFMIF and EUROTRANS based on solenoid focusing (C. Zhang, EPAC08, THPC112, pp. 3239-3241).
LORASR: Error Study Example
(IAP IFMIF-Design)

<table>
<thead>
<tr>
<th>Type</th>
<th>Setting 1</th>
<th>Setting 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>transverse translations of focusing elements [mm]</td>
<td>$\Delta X_{\text{lens}} = \pm 0.1$ \hspace{1em} $\Delta Y_{\text{lens}} = \pm 0.1$</td>
<td>$\Delta X_{\text{lens}} = \pm 0.2$ \hspace{1em} $\Delta Y_{\text{lens}} = \pm 0.2$</td>
</tr>
<tr>
<td>rotations of focusing elements [mrad]</td>
<td>$\Delta \phi_x = \pm 1.5$ \hspace{1em} $\Delta \phi_y = \pm 1.5$ \hspace{1em} $\Delta \phi_z = \pm 2.5$</td>
<td>$\Delta \phi_x = \pm 3.0$ \hspace{1em} $\Delta \phi_y = \pm 3.0$ \hspace{1em} $\Delta \phi_z = \pm 5.0$</td>
</tr>
<tr>
<td>gap and tank voltage amplitude errors [%]</td>
<td>$\Delta U_{\text{gap}} = \pm 5.0$ \hspace{1em} $\Delta U_{\text{tank}} = \pm 1.0$</td>
<td>$\Delta U_{\text{gap}} = \pm 5.0$ \hspace{1em} $\Delta U_{\text{tank}} = \pm 1.0$</td>
</tr>
</tbody>
</table>

100% common beam envelopes of 100 runs, $10^6$ particles each

red: nominal run
green: error settings 1
blue: error settings 2
LORASR: Loss Profile Calculation Example
(GSI HSI, Beam Current Upgrade Program)

\[
\frac{dN}{dz} = \frac{\text{no. of locally lost particles}}{\text{total part. no.}} \frac{1}{\text{distance along which particles are lost}} \quad \left[ \text{m}^{-1} \right]
\]

100% beam envelopes

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Conclusions / Outlook

• The ‘Combined Zero Degree Structure‘ (KONUS) beam dynamics concept has been developed during the past 3 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 (GSI-HLI, GSI-HSI, CERN Linac 3, TRIUMF ISAC-I, Heidelberg Therapy Injector, etc.).

• 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 D$^+$, 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.

• A theoretical framework for the description and parametrization of the KONUS beam dynamics concept is still under development.