KONUS Beam Dynamics Using H-Mode Cavities

R. Tiede

42nd ICFA Advanced Beam Dynamics Workshop
on High-Intensity, High-Brightness Hadron Beams „HB2008“

August 28’th 2008, Nashville, Tennessee, USA

Involved key persons:

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

G. Clemente (GSI Darmstadt)

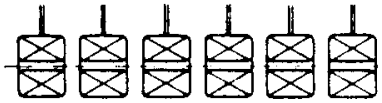
Outline

- 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

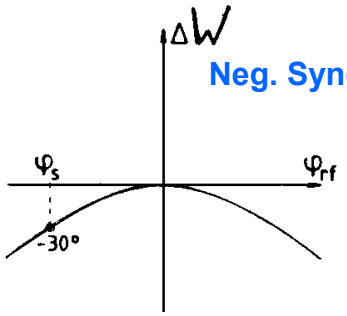
- “Standard” linac design (up to ≈ 100 MeV) : Alvarez DTL + FODO beam dynamics.

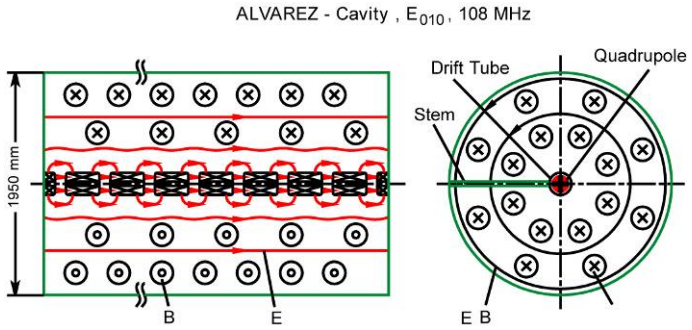
FODO



a)

Neg. Synchr. Phase

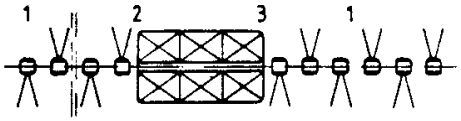




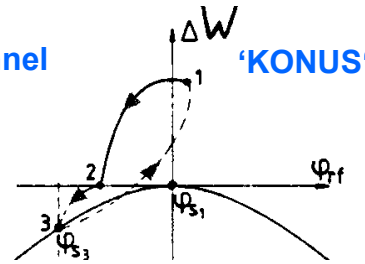
Alternative :

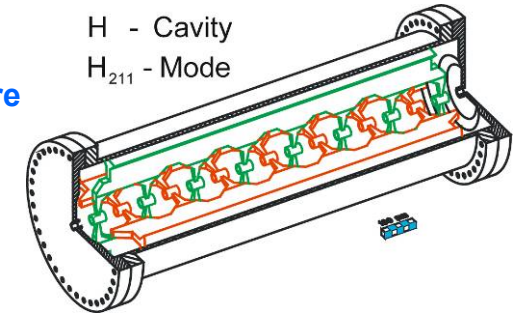
- H-Type DTL (IH or CH) and KONUS beam dynamics,
  each lattice period divided into 3 regions with separated tasks:
  - Main acceleration at $\Phi_s = 0°$, by a multi-gap structure (1).
  - Transverse focusing by a quadrupole triplet or solenoid (2).
  - Rebunching: 2 - 7 drift tubes at $\Phi_s = -35°$,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

Quadrupole Triplet Channel



‘KONUS‘ – Combined 0° Structure



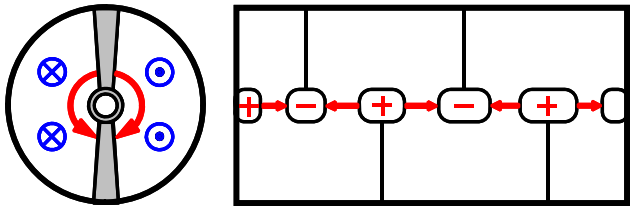


H-Mode Cavities

IH-DTL

r.t.
W < 30 MeV
30-250 MHz

Interdigital H-Type structure (IH)





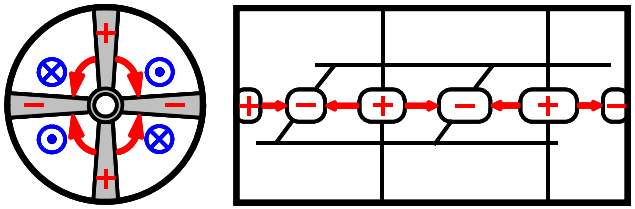
Carbon Injector for the Heidelberg Therapy Center

217 MHz, 20 MV,
0.3 – 7 MeV/u, 800 kW,
1% duty factor

CH-DTL

r.t. and s.c.
W < 150 MeV
150-700 MHz

Crossbar H -Type structure (CH)





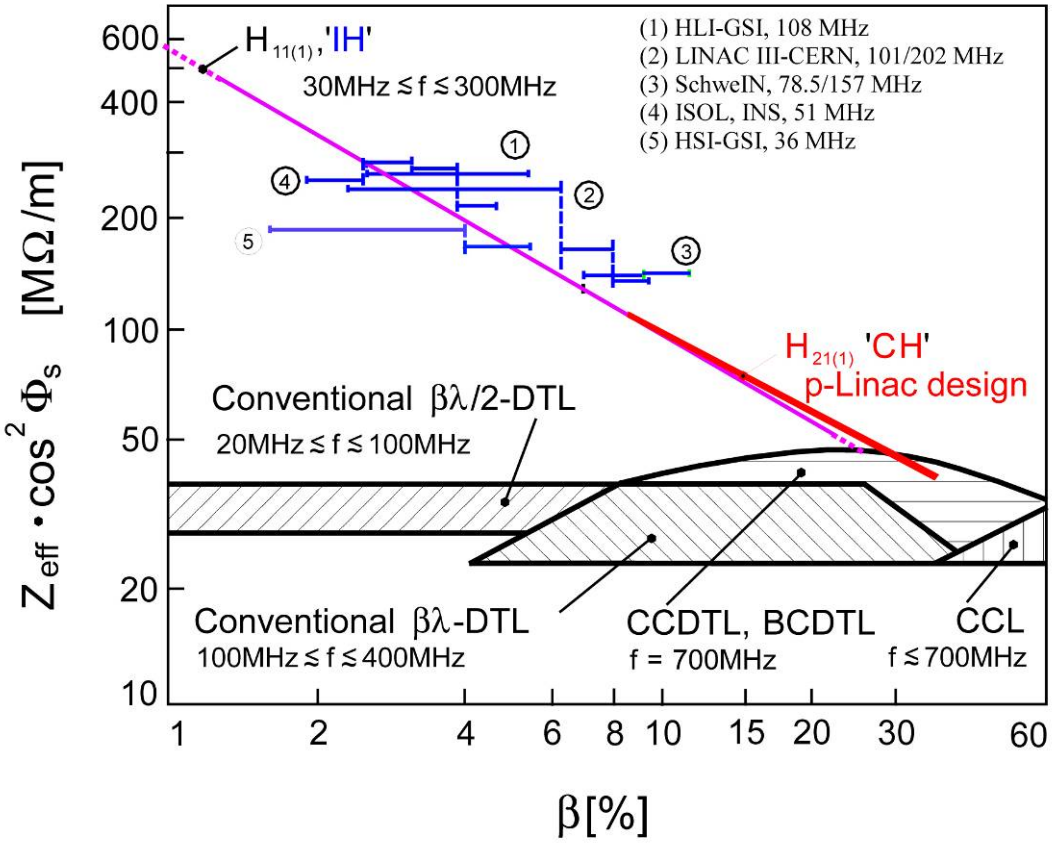
s.c. (bulk niobium)
CH-DTL prototype cavity

352 MHz,
$\beta = 0.1$,
Ø = 276 mm

Comparison of Shunt Impedances

Higher shunt impedances for $\beta \leq 0.3$ are due to:

- H-mode
  - low rf wall losses P_{loss}. (cross sectional rf current flow, all gaps fed in parallel).
- KONUS
  - multi gap structures with 'slim' drift tubes, carrying no focusing elements.

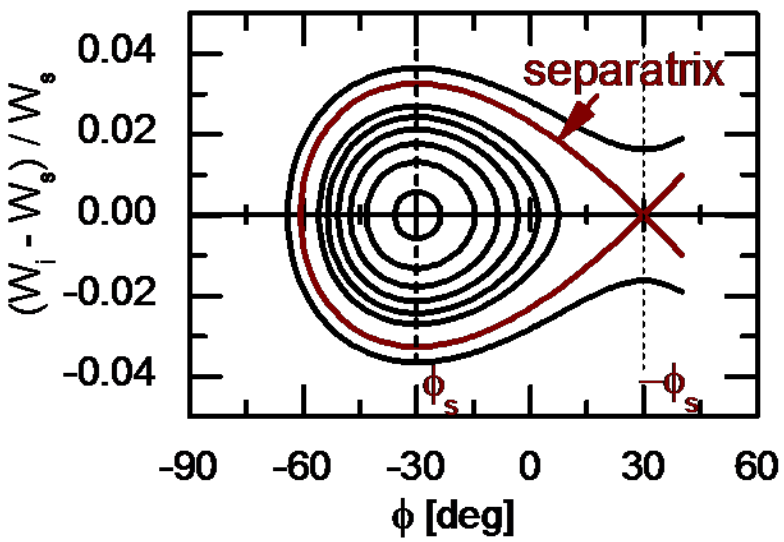


$$Z_{eff} \cdot \cos^2 \varphi_s = \frac{V_{gain}^2}{P_{loss} \cdot L_{\text{tank}}}$$

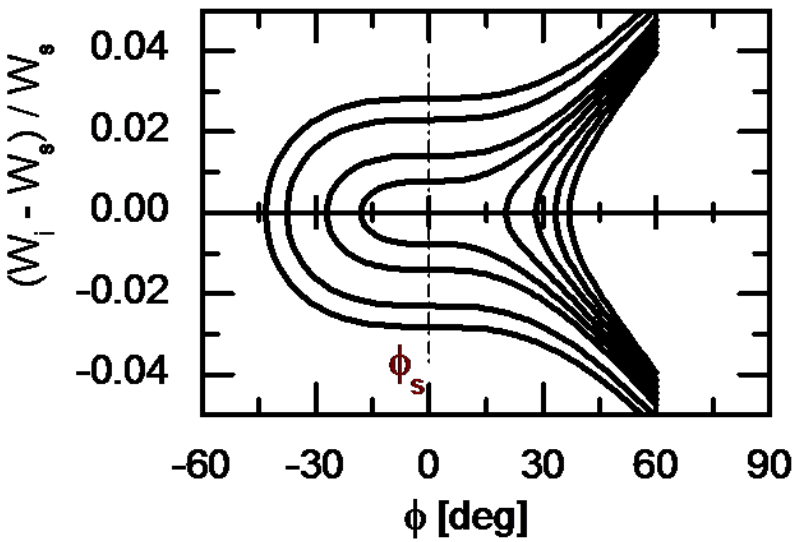
Particle Trajectories in Longitudinal Phase Space at $\phi_s = 0°$

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

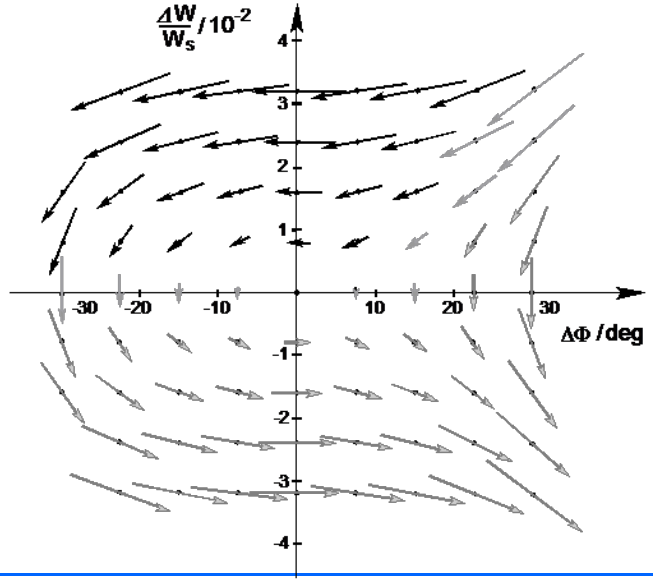
ϕ_s = -30°



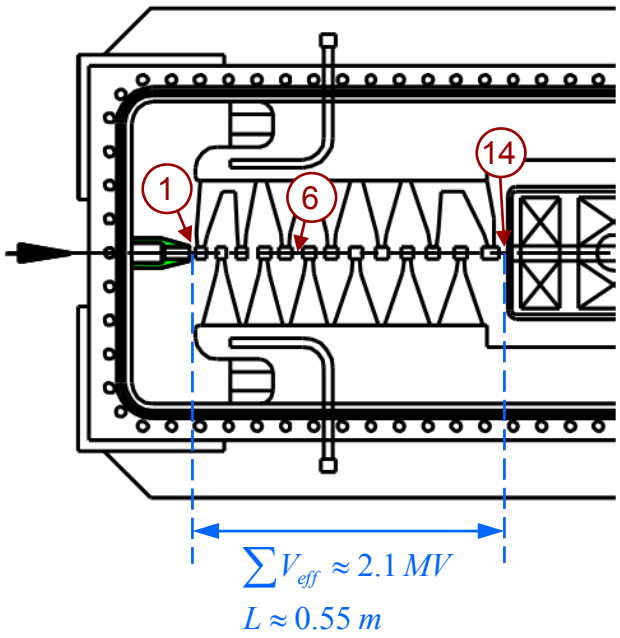
ϕ_s = 0°

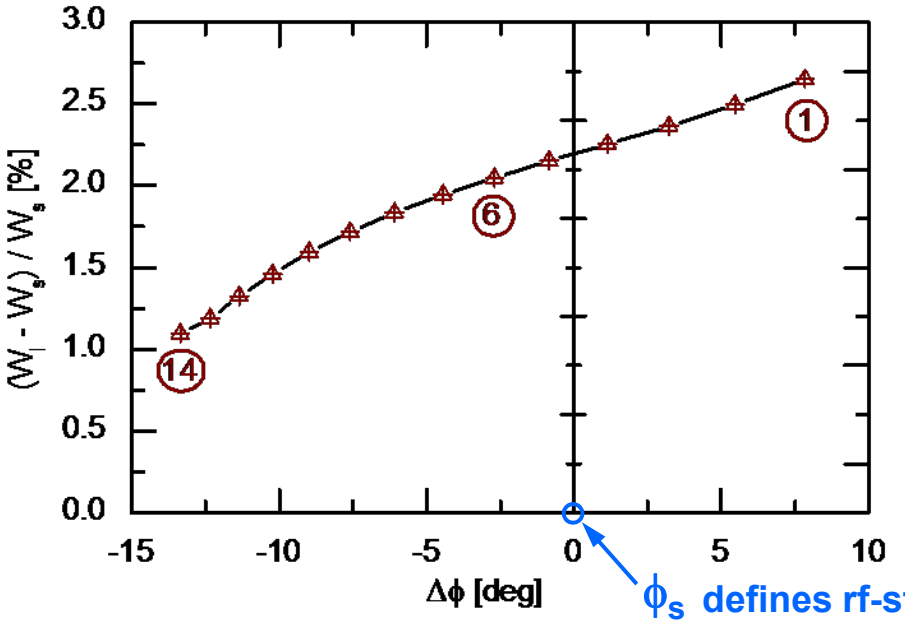


Black arrows:
area used by KONUS



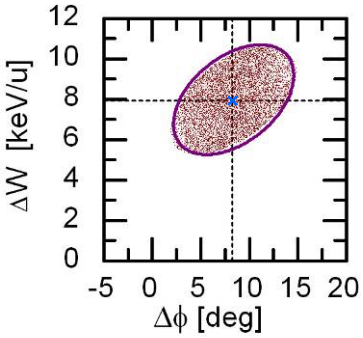
Bunch Center Motion Along 0° Synchronous Particle Sections



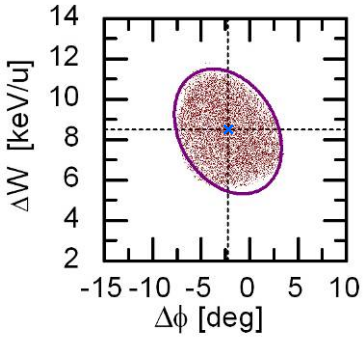


ϕ_s defines rf-structure (geom. lengths)

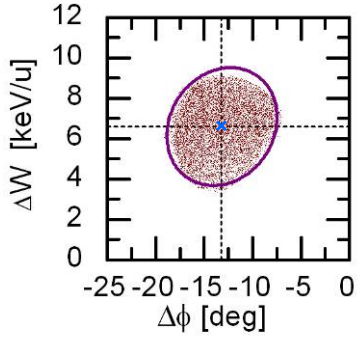
Gap 1:
W_s = 302 keV/u ; W_i = 310 keV/u



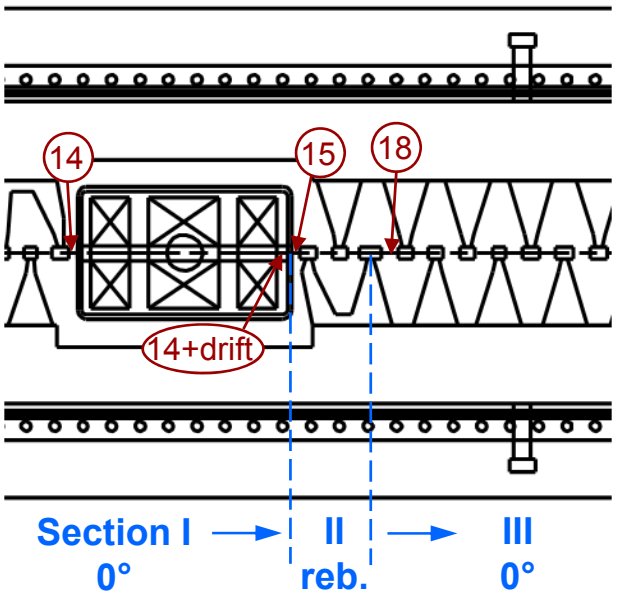
Gap 6:
W_s = 409 keV/u ; W_i = 418 keV/u

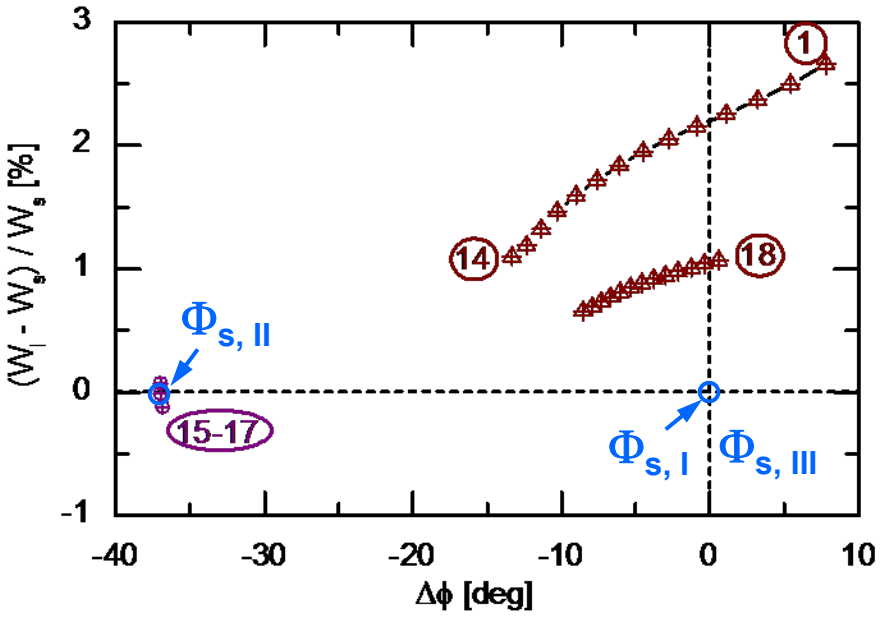


Gap 14:
W_s = 603 keV/u ; W_i = 609.5 keV/u

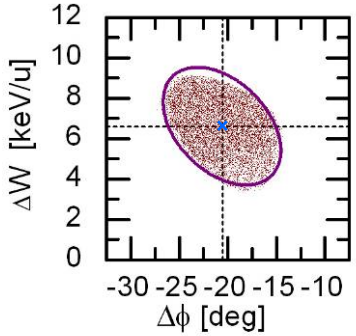


Bunch Center Motion Along Negative Synchr. Phase Rebunching Sections

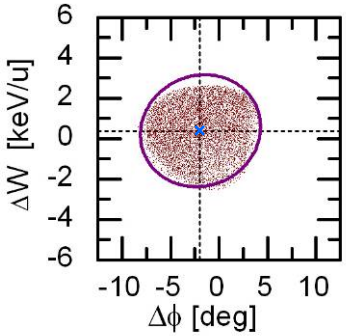




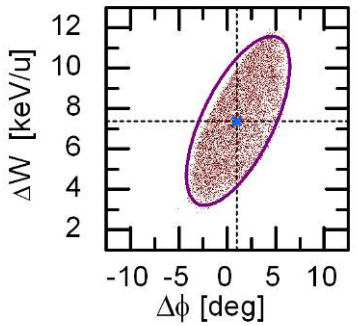
Gap 14, after quad. lens (drift):
W_s = 603 keV/u ; W_i = 609.5 keV/u



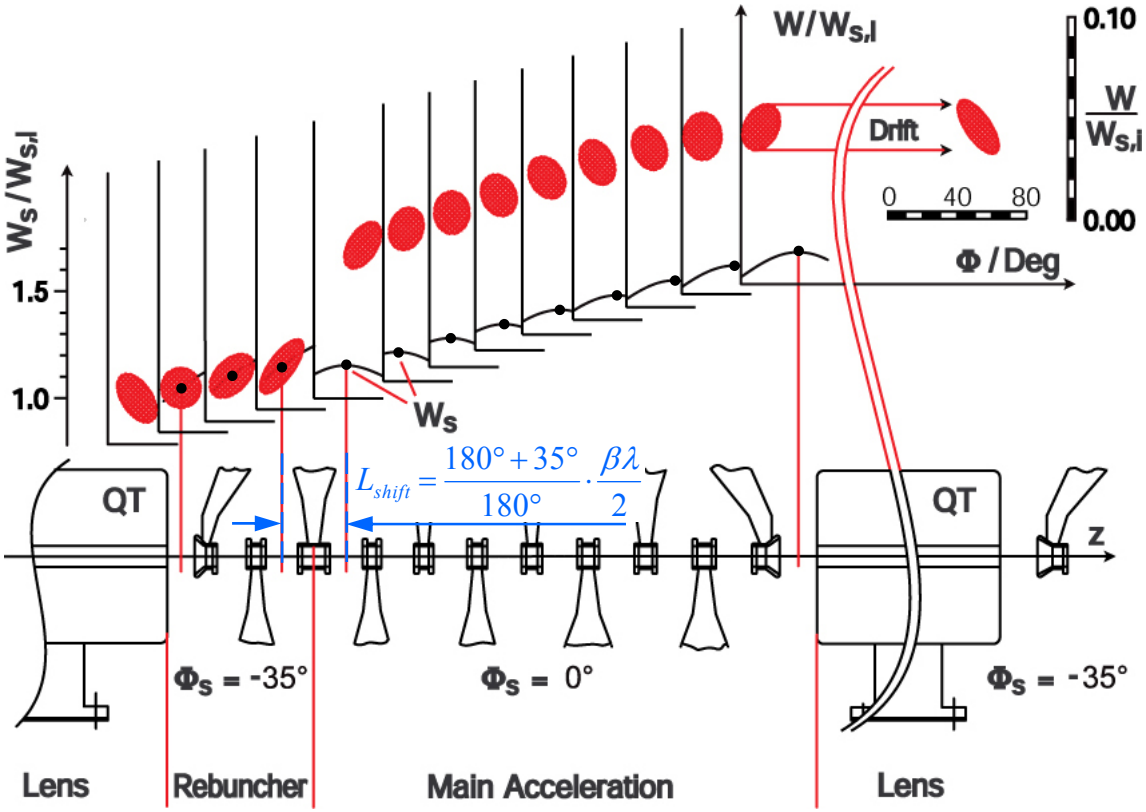
Gap 15:
W_s = 623.6 keV/u ; W_i = 624 keV/u



Gap 18:
W_s = 691 keV/u ; W_i = 698 keV/u

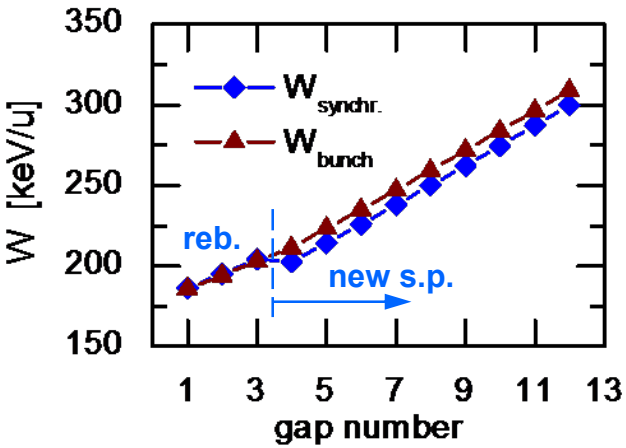


Overview of the Bunch Motion Along a Full Longitudinal KONUS Period



Energy shift

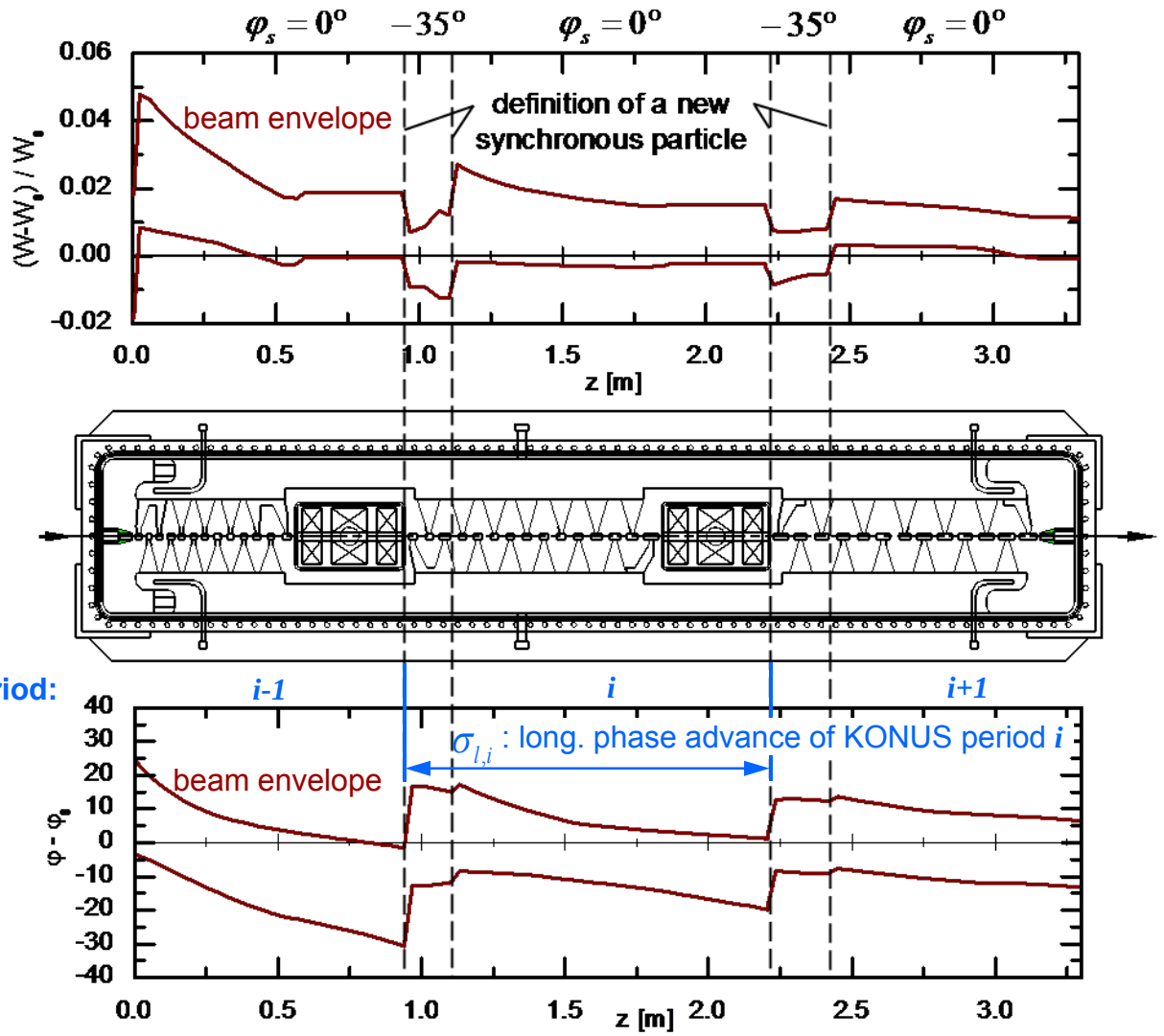
- (Geometrical) periodic lengths of 0° sections are related to the (new) synchronous particle, and not to the bunch centroid.
- Bunch energy gain is evidently smooth:



Phase shift at transition: rebunching → 0° section

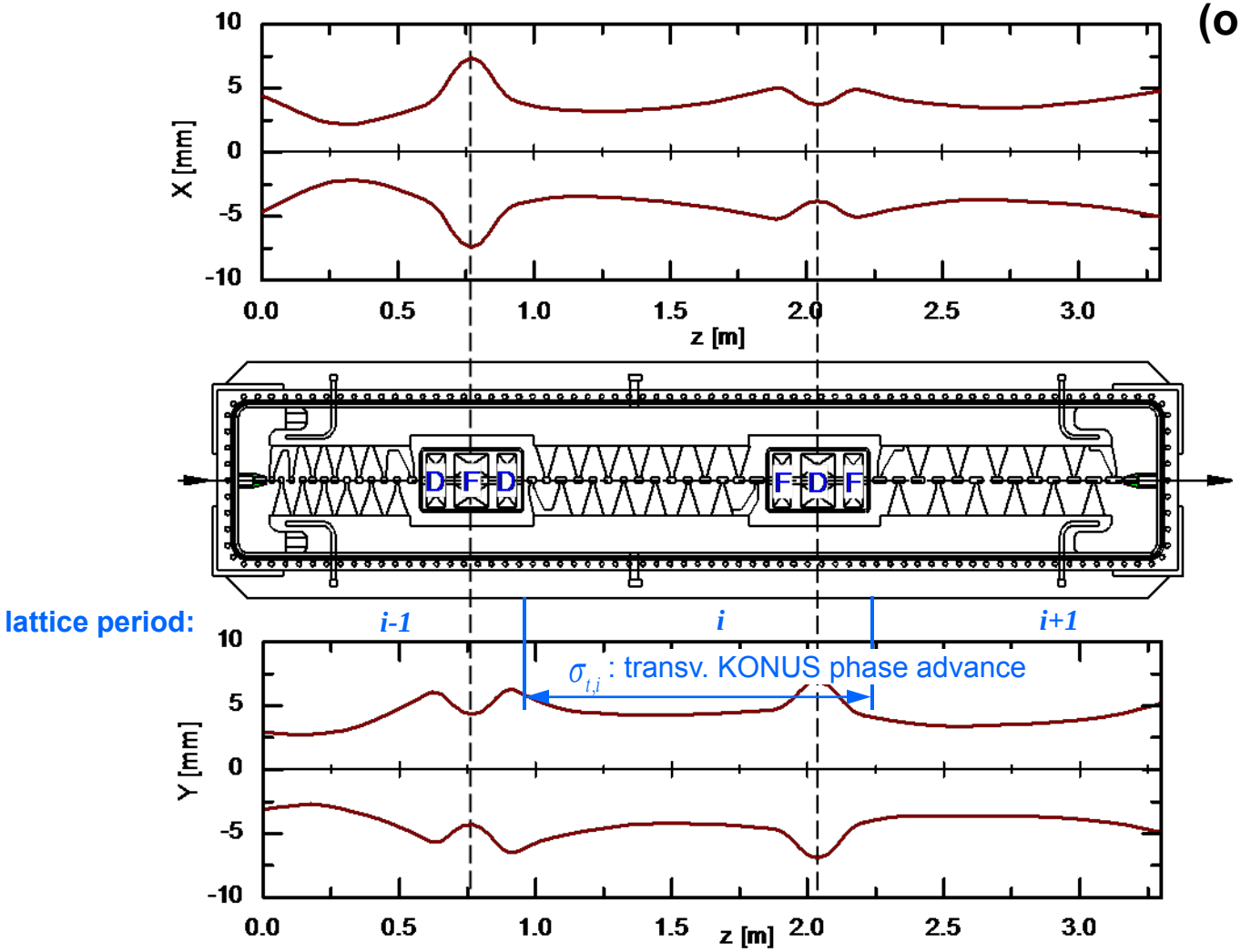
- Geometrical length adjustment (longer drift tube).
- Independent choice of tank rf phases, if transition gaps belong to separated cavities.

Combined 0° Structure Overview and Definition of the Longitudinal KONUS Lattice Period



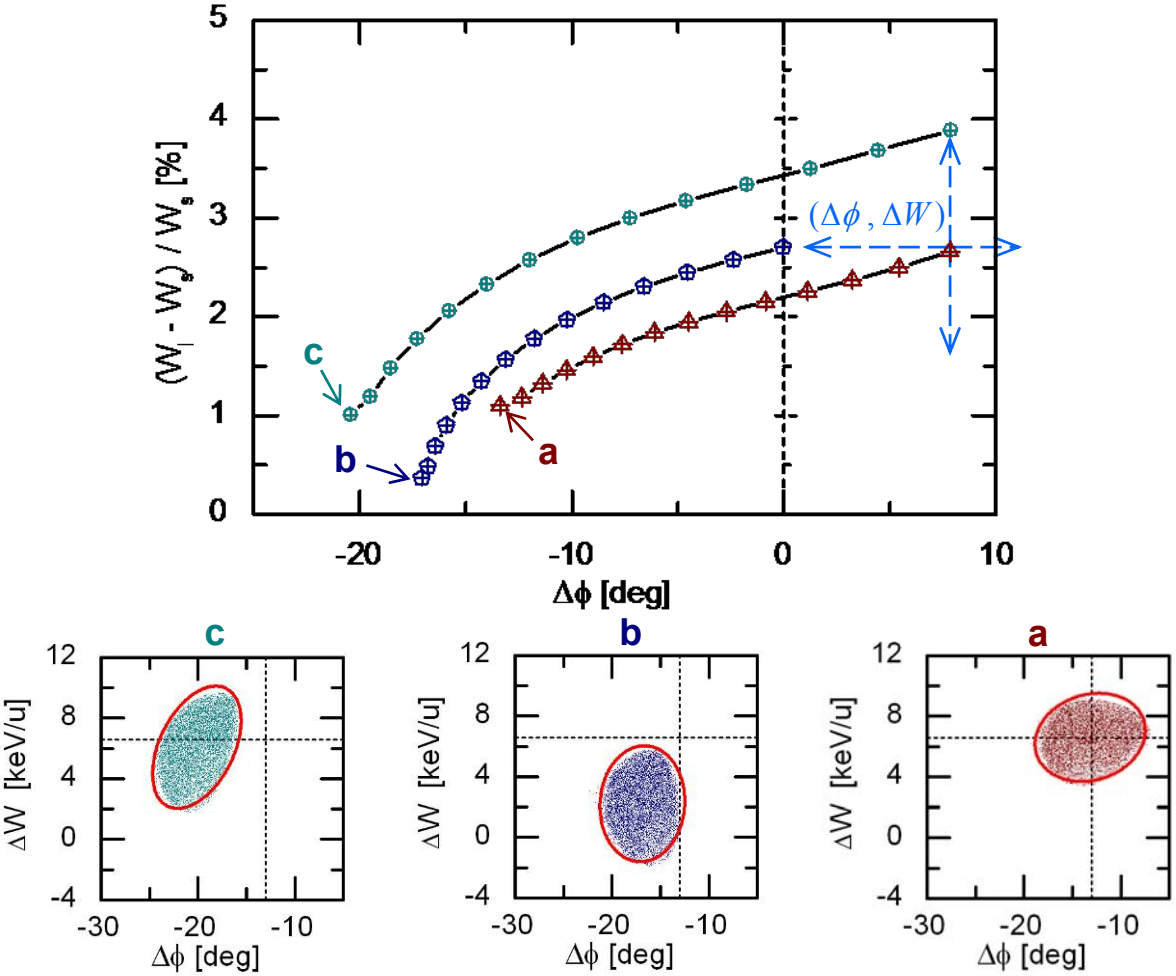
Transverse KONUS Beam Dynamics: Quadrupole Triplet Channel

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

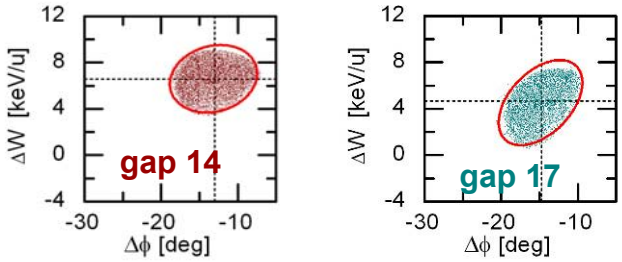
- By variation of the starting conditions $\Delta\Phi$ and ΔW of the first gap of each 0° section, the desired output parameters (distribution shape and orientation) can be matched to the needs of the following sections.

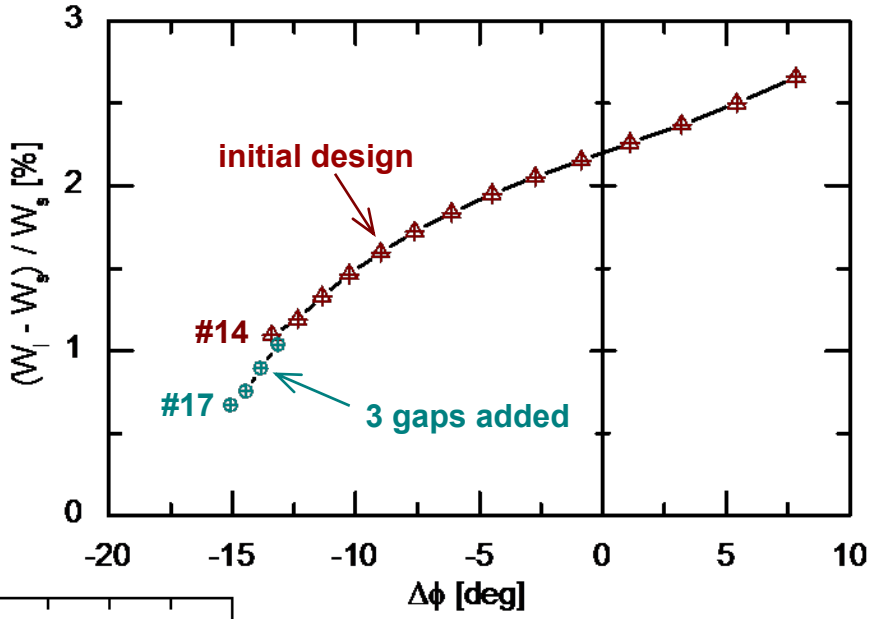


KONUS Design Margins: Number of Gaps Per 0° Section

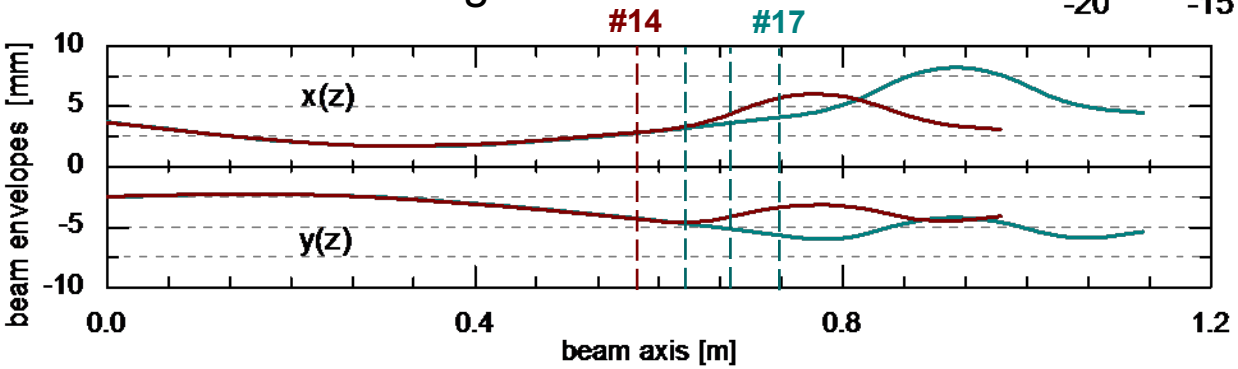
Basically the higher $N_{gap,0°}$ the better, but there are several constraints:

- Longitudinal matching:





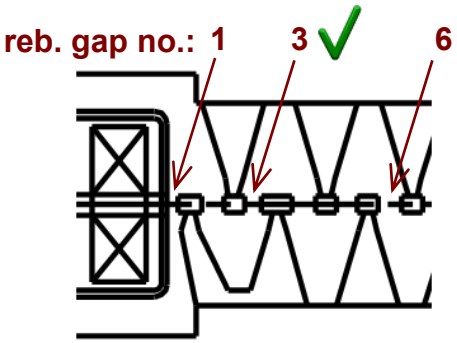
- Transversal matching:

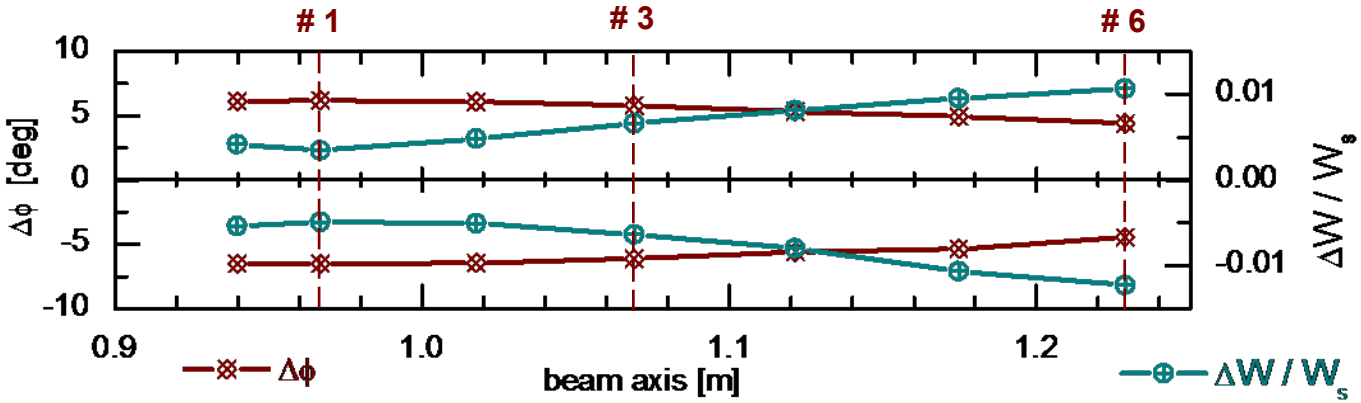


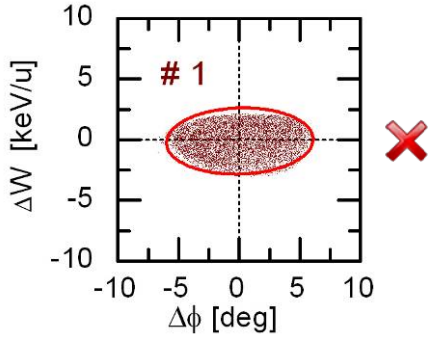
- Well-balanced ratio $N_{gap,reb}$ / $N_{gap,0°}$ (between 1:2 and 1:4, typically).
- Max. number of gaps per section (up to ≈15) and per tank (up to ≈60). This is for example limited by tank voltage flatness reasons, by the available rf power etc.

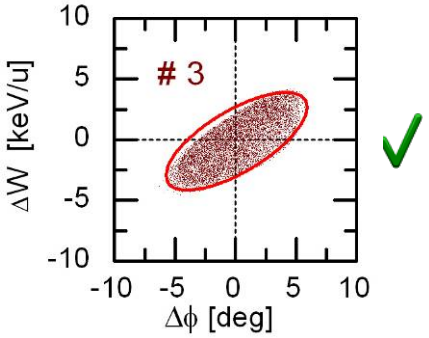
KONUS Design Margins: Number of Gaps Per Rebunching Section

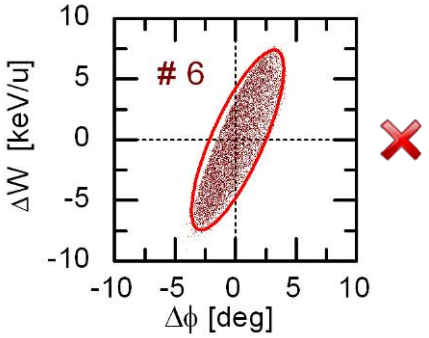
- The number of rebunching gaps $N_{gap,reb}$ for each section (at Φ_s = -35° usually) is ranging between 2 and 7, depending on the design constraints and on the beam parameters (energy, A/q, etc.).
- For each individual case, the assumed number $N_{gap,reb}$ for best matching to the subsequent 0° section must be confirmed by the beam dynamics calculations. Example:





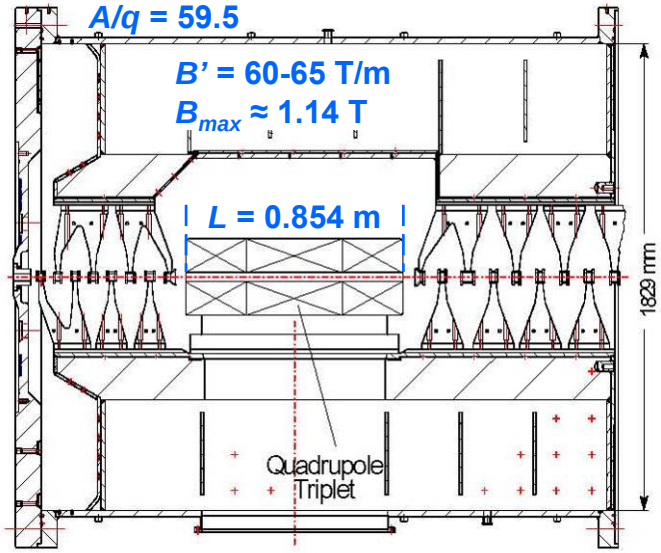


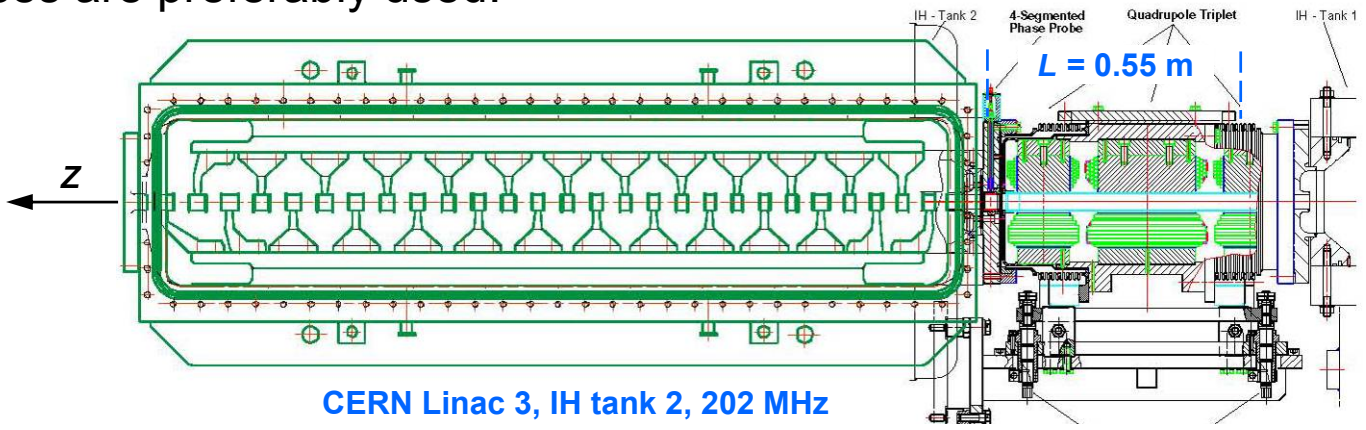




KONUS Design Margins: Transverse Focusing Elements

- 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.



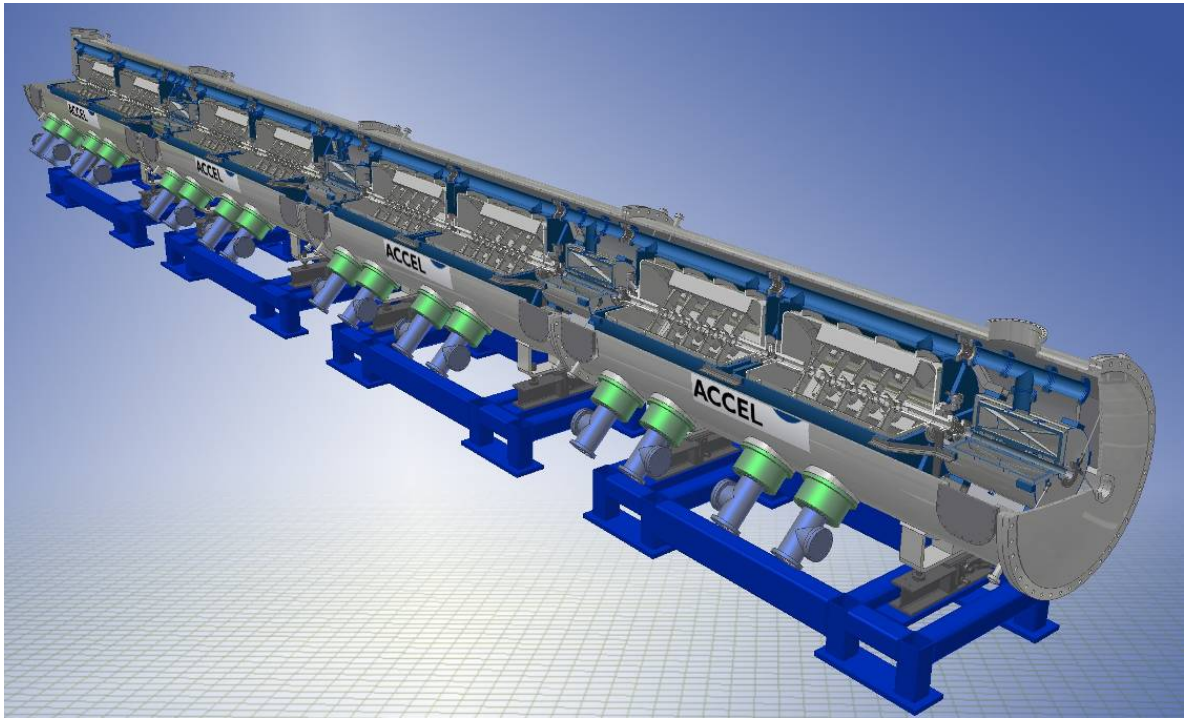


CERN Linac 3, IH tank 2, 202 MHz
A/q = 8.32 ($^{208}Pb^{25+}$)

B' = 68-70 T/m; B_{max} ≈ 0.9 T

KONUS Design Margins: Transverse Focusing Elements

- Since powerfull superconducting magnets (B = 4 – 10 T) are available, solenoid focusing becomes attractive also at higher β 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 U^{4+}, 0.12 – 1.4 MeV/u, 90 MV, 1% duty cycle, in operation since 1999.

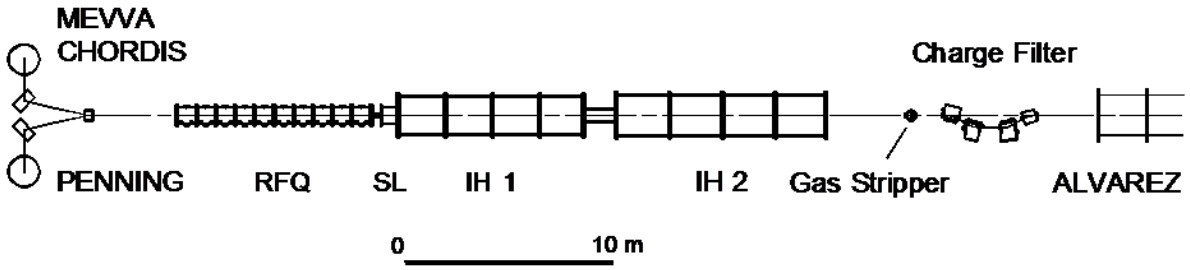
- **Superconducting CH-DTL section for IFMIF (IAP proposal)**
  175 MHz, 125 mA deuterons, 2.5 – 20 MeV/u, cw operation.

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

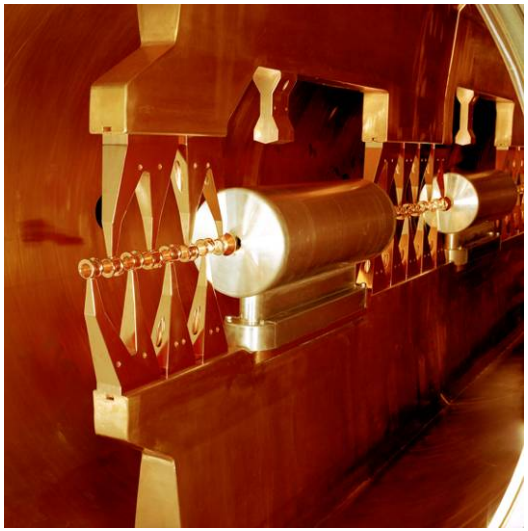
  Dedicated presentation:
  G. Clemente, 'Investigation of the Beam Dynamics Layout of the FAIR Proton Injector'

KONUS Design Examples: GSI High Current Injector ('HSI')

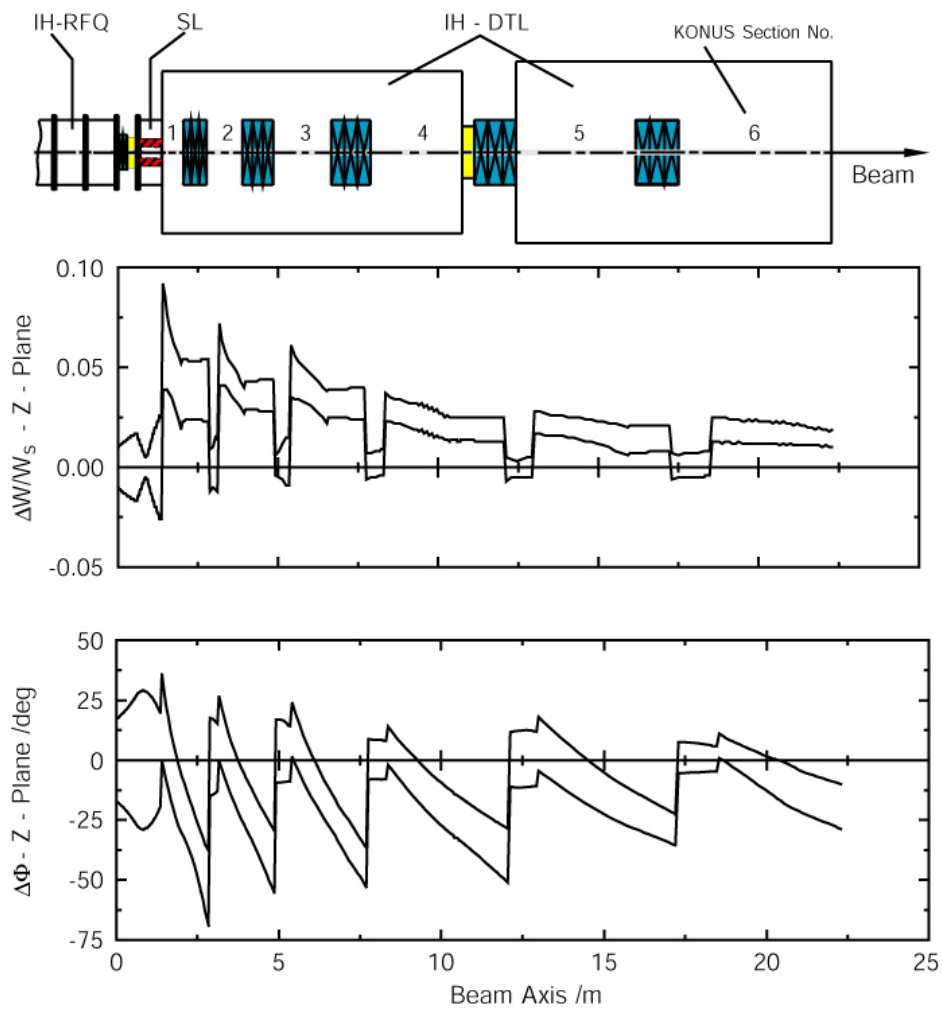
- In operation since 1999.

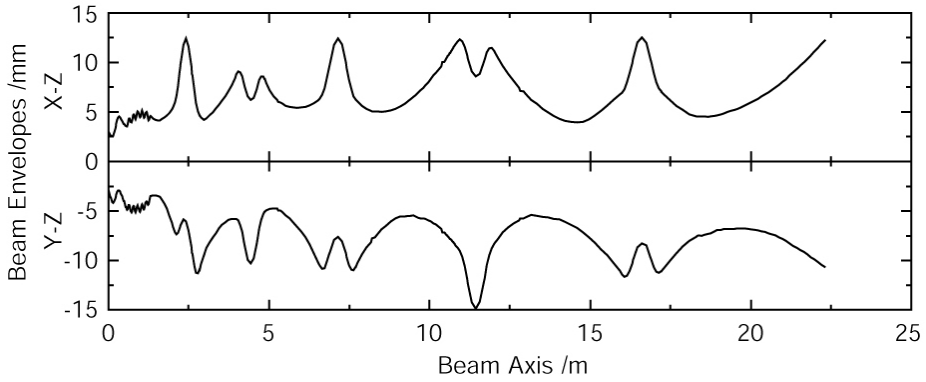


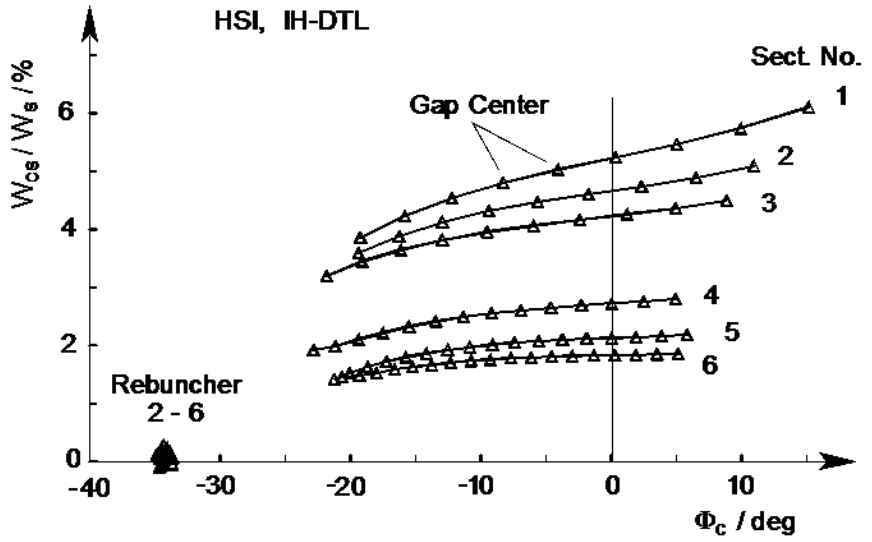
resonance frequency	36.136 MHz
design particle A / q	59.5 ($^{238}U^{4+}$)
design beam current (1996)	15 mA
duty cycle	1 % at A/q ≤ 59.5 30 % at A/q ≤ 26
energy range	0.12 – 1.4 MeV/u
number of IH-DTLs	2
total length (IH1 + IH2)	≈ 20 m
number of KONUS periods	4 (IH1) + 2 (IH2)
$\varepsilon_{tr,n,rms}$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



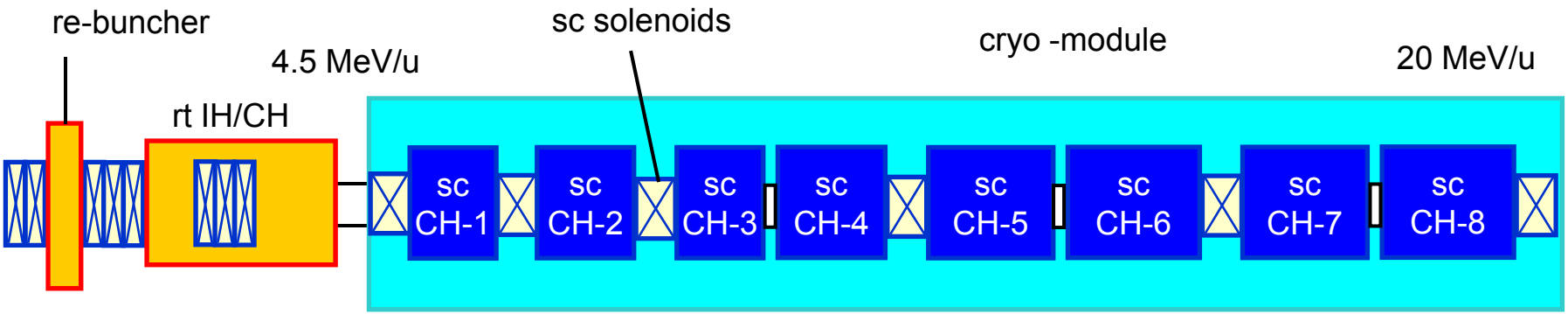
KONUS Design Examples:
GSI High Current Injector ('HSI')





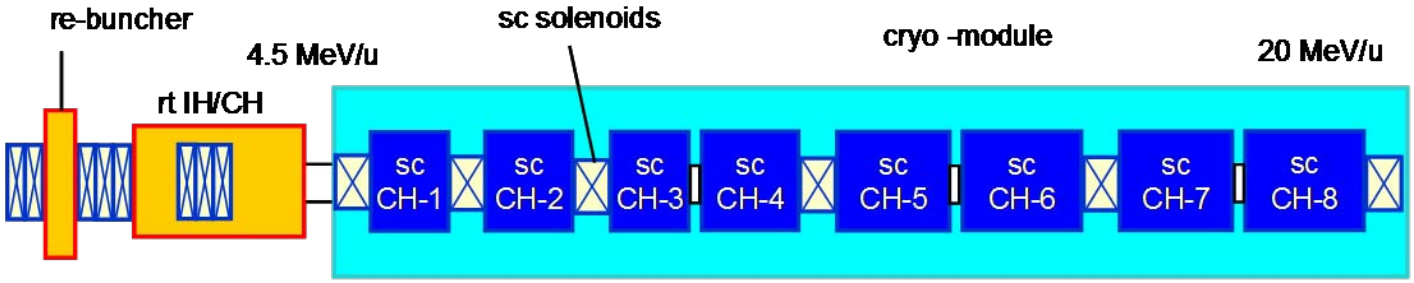


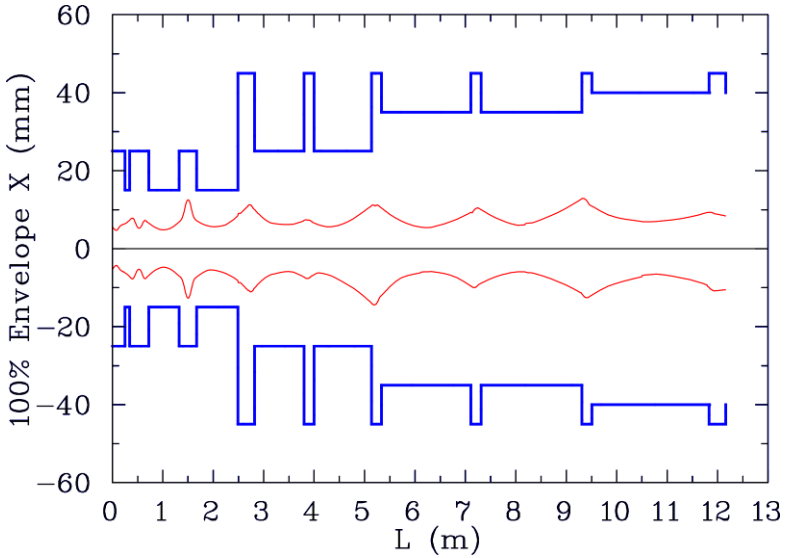
KONUS Design Examples: S.C. CH-Linac for IFMIF

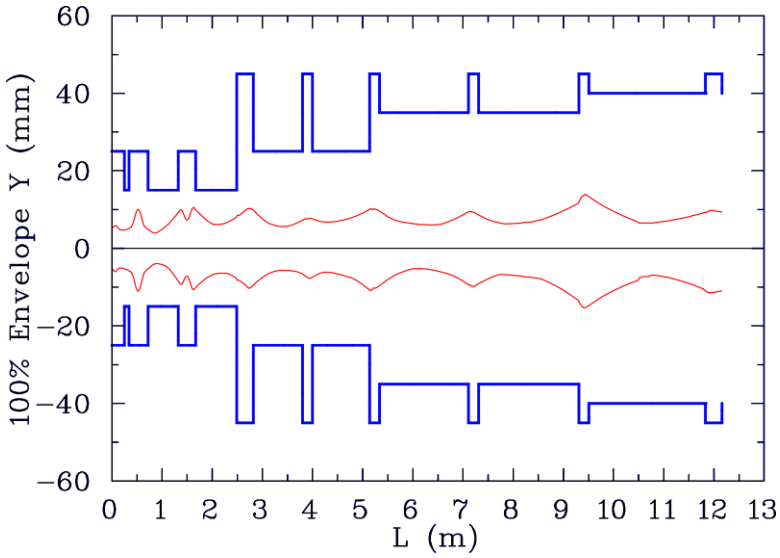


resonance frequency	175 MHz
design particle	$^2H^+$
design beam current	125 mA
duty cycle	cw
energy range	2.5 – 20 MeV/u
number of DTLs	1 r.t. IH/CH + 8 s.c. CH
total DTL length	≈ 12 m
number of KONUS periods	7
$\varepsilon_{tr,n,rms}$	0.4 mm·mrad (growth rate: 60%)
$\varepsilon_{long,n,rms}$	1.8 keV/u·ns (growth rate: 30%)

KONUS Design Examples: S.C. CH-Linac for IFMIF

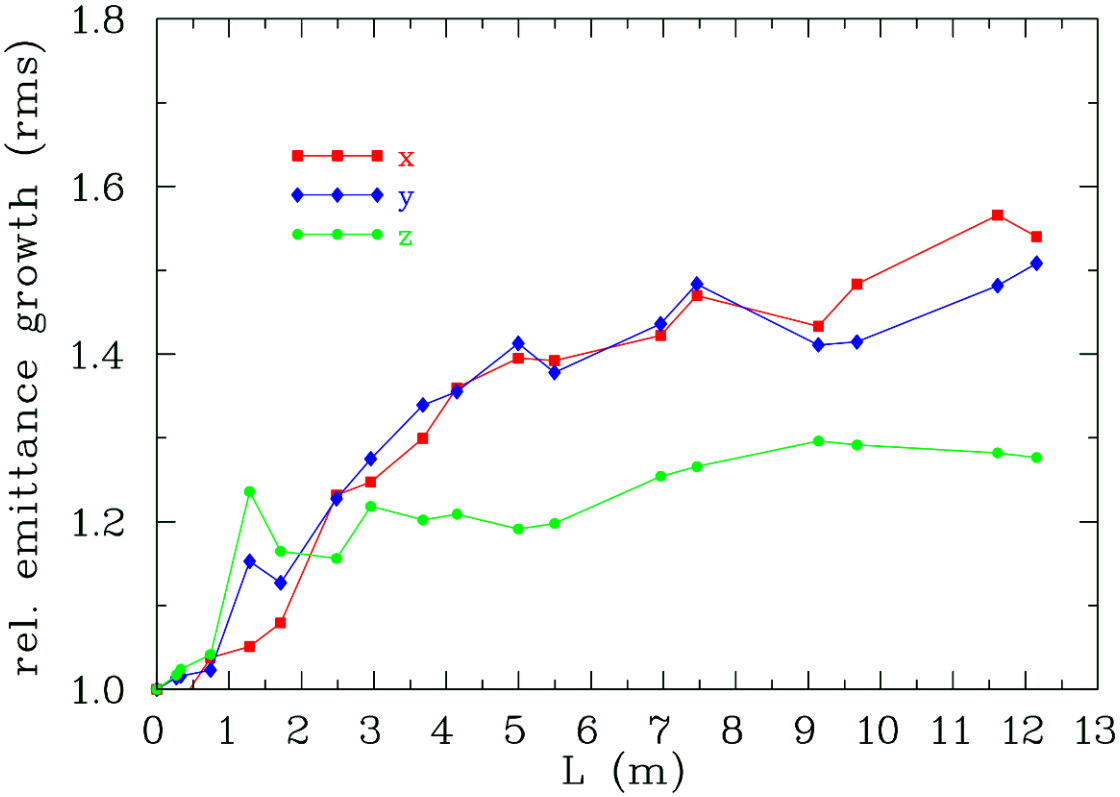






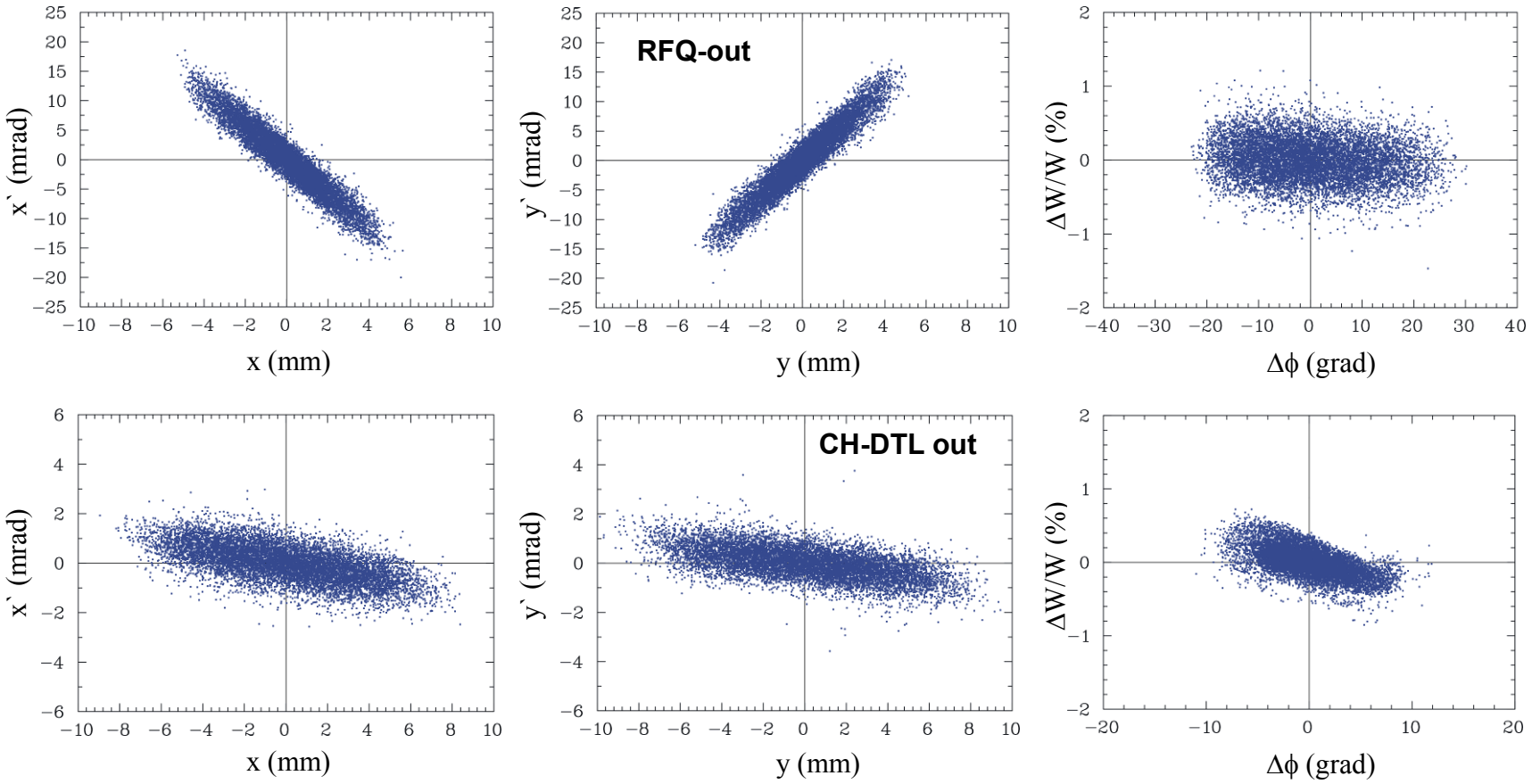
Transverse 100% beam envelopes along the H-Mode-Linac

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, $^2H^+$ - beam)

LORASR Code Features - Overview

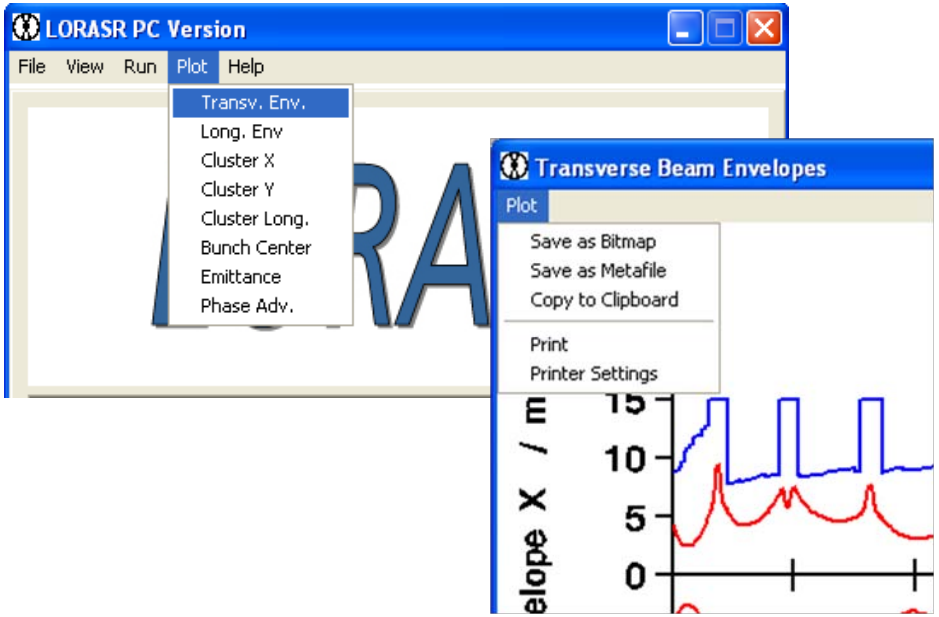
Longitudinale und **ra**diale **S**trahldynamikrechnungen mit **R**aumladung
Longitudinal And Radial Beam Dynamics Calculations including Space Charge

- 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 :



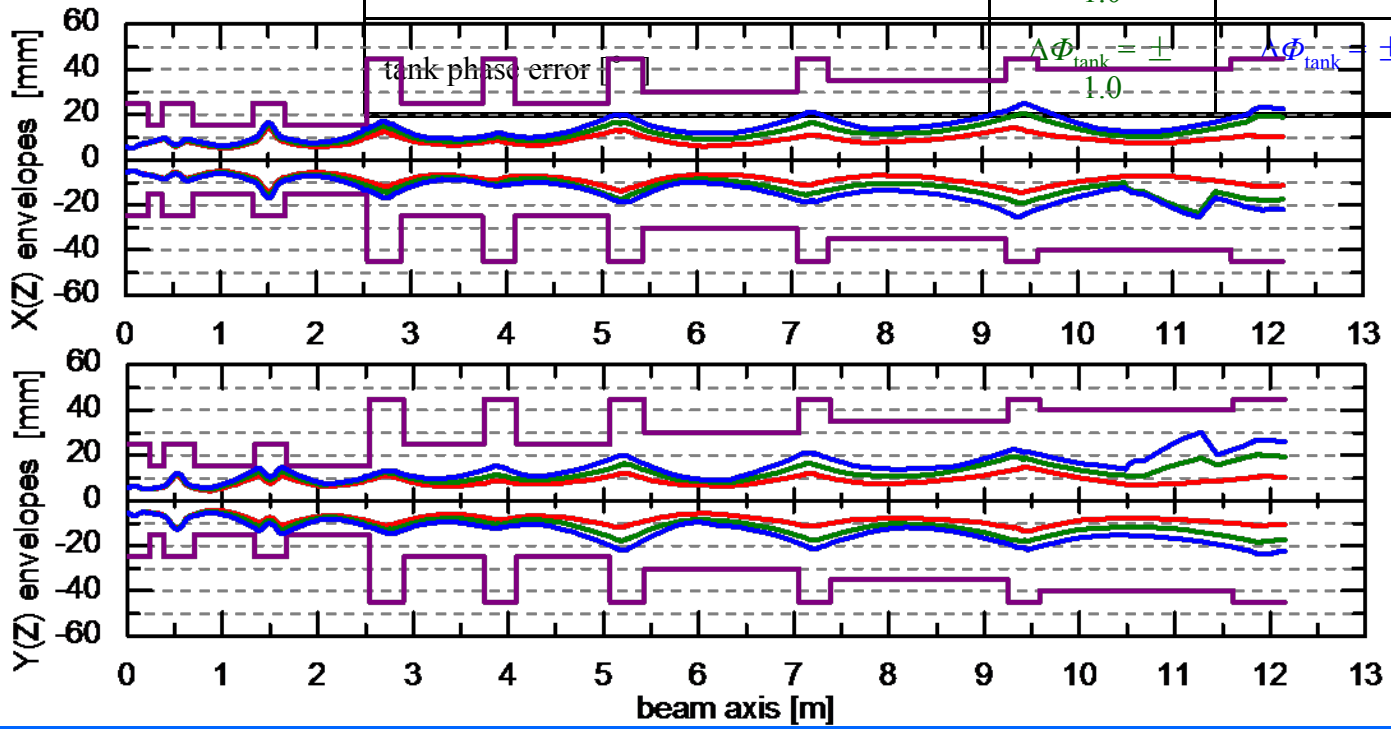
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

- **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)

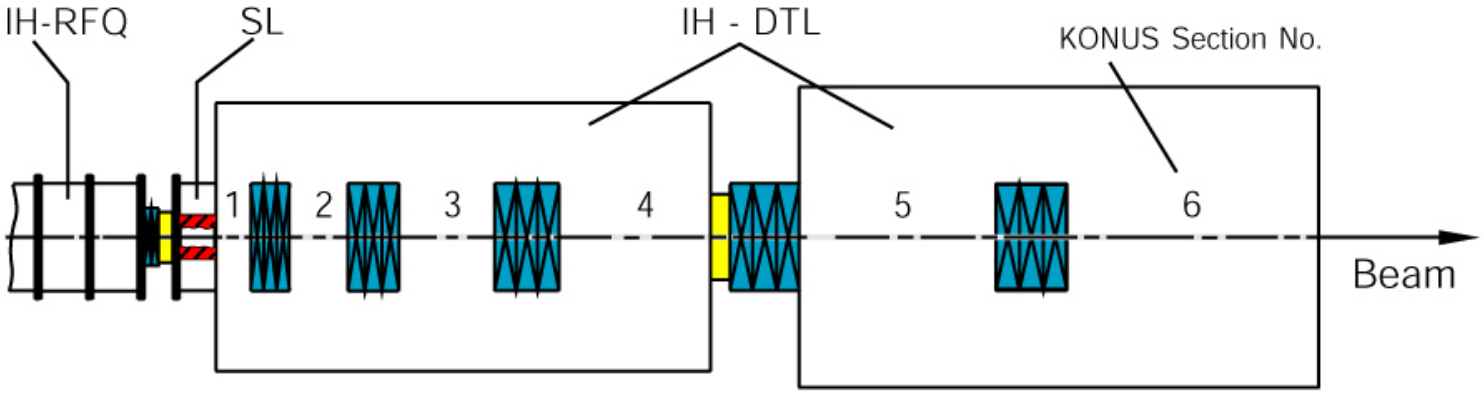
Type	Setting1	Setting2
transverse translations of focusing elements [mm]	$\Delta X_{lens} = \pm 0.1$ $\Delta Y_{lens} = \pm 0.1$	$\Delta X_{lens} = \pm 0.2$ $\Delta Y_{lens} = \pm 0.2$
rotations of focusing elements [mrad]	$\Delta\varphi_x = \pm 1.5$ $\Delta\varphi_y = \pm 1.5$ $\Delta\varphi_z = \pm 2.5$	$\Delta\varphi_x = \pm 3.0$ $\Delta\varphi_y = \pm 3.0$ $\Delta\varphi_z = \pm 5.0$
gap and tank voltage amplitude errors [%]	$\Delta U_{gap} = \pm 5.0$ $\Delta U_{tank} = \pm 1.0$	$\Delta U_{gap} = \pm 5.0$ $\Delta U_{tank} = \pm 1.0$
tank phase error [°]	$\Delta\Phi_{tank} = \pm 1.0$	$\Delta\Phi_{tank} = \pm 1.0$

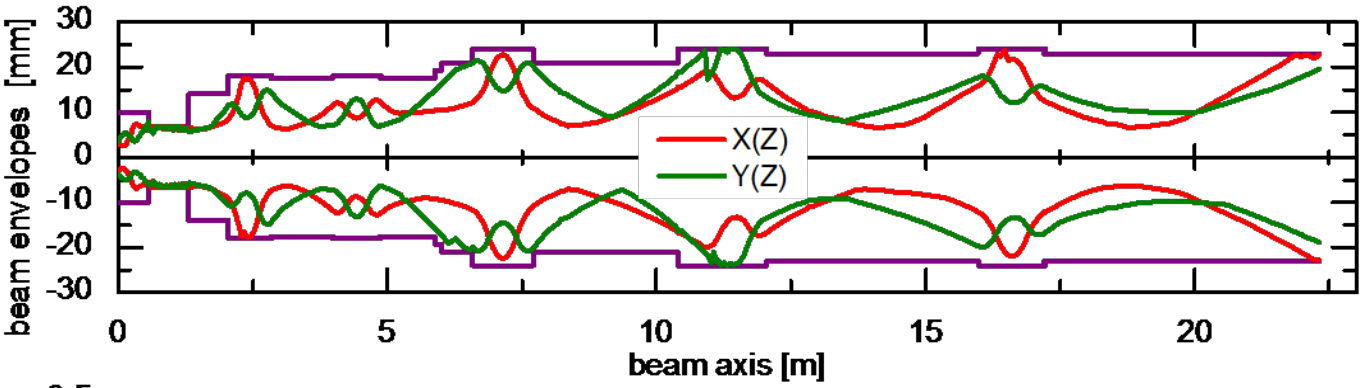


100% common beam envelopes of 100 runs, 10^6 particles each

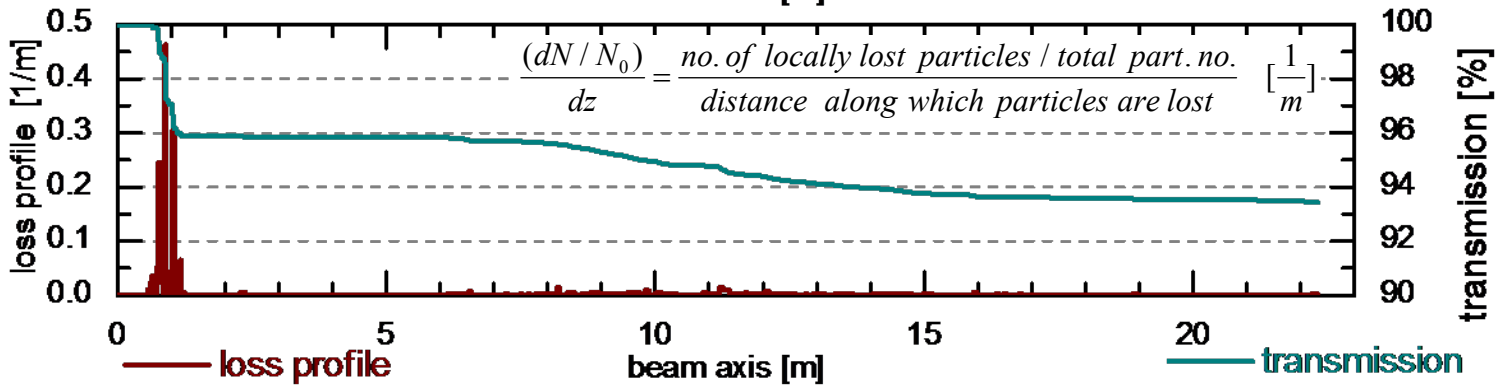
red: nominal run
green: error settings 1
blue: error settings 2

LORASR: Loss Profile Calculation Example (GSI HSI, Beam Current Upgrade Program)





100% beam envelopes



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 β 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.