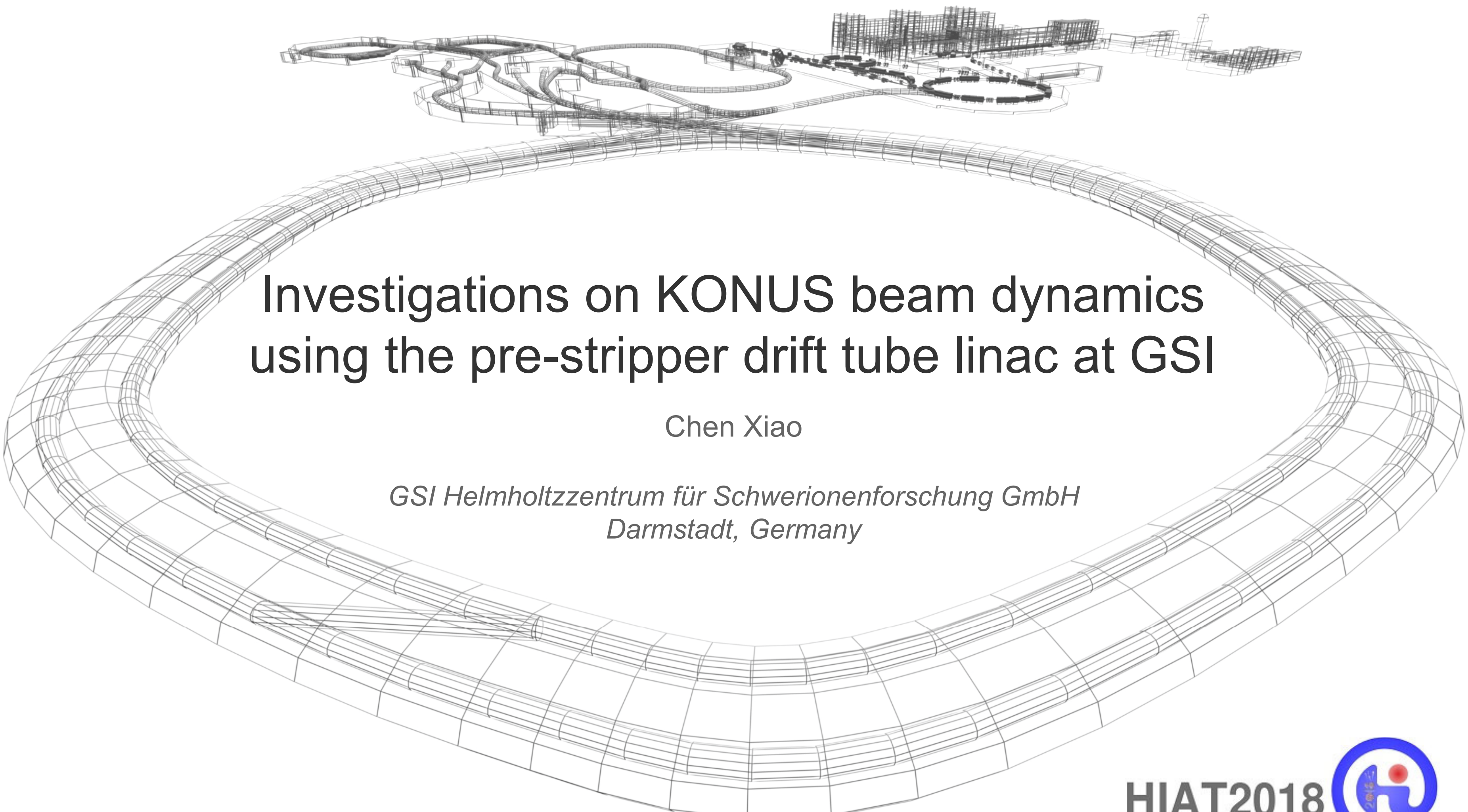

Investigations on KONUS beam dynamics using the pre-stripper drift tube linac at GSI

Chen Xiao

GSI Helmholtzzentrum für Schwerionenforschung GmbH
Darmstadt, Germany

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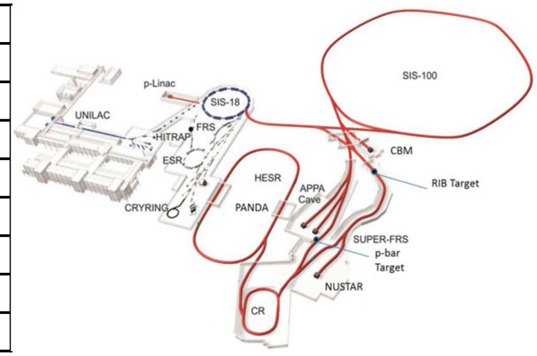
Outline

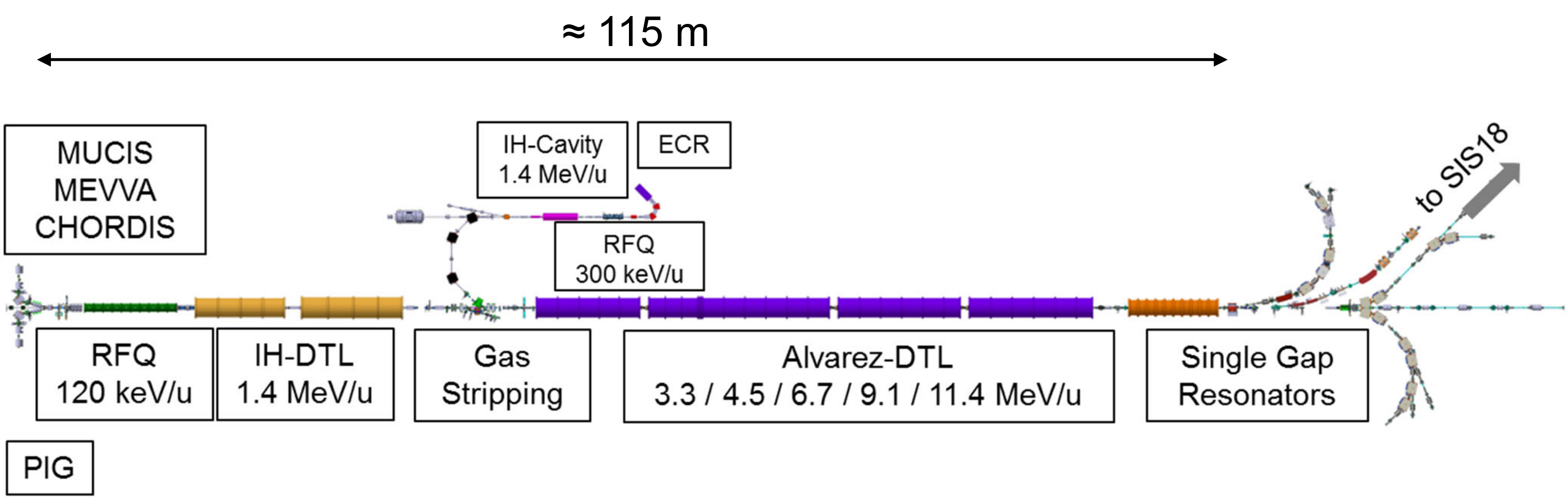
- Overview
- UNILAC introduction
- KONUS beam dynamics design
- Single-particle tracking through the IH-DTL
- TTF parameter calculation using tracking method
- Multi-particle tracking through the IH-DTL
- Conclusion

UNIversal Linear ACcelerator

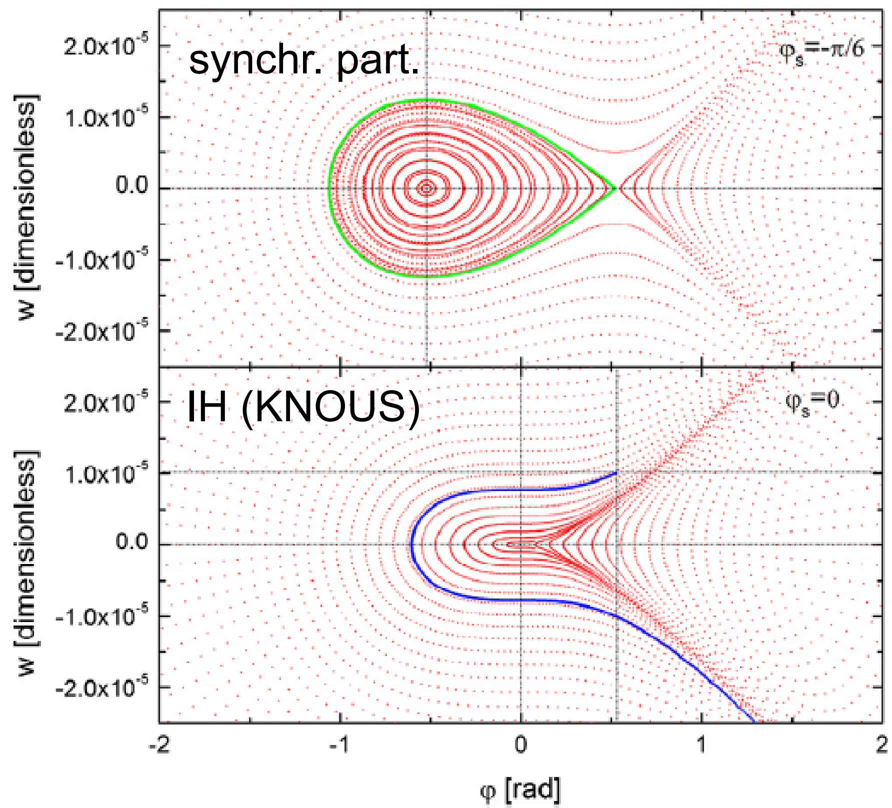
Design parameters after upgrade

ion A/q	≤ 8.5, i.e. $^{238}U^{28+}$	
beam current (pulse) * A/q	1.76 (0.5% duty cycle)	emA
input beam energy	2.2	keV/u
output beam energy	3.0 - 11.7	MeV/u
normalized total output emittance, horizontal / vertical	0.8 / 2.5	mm mrad
beam pulse duration	≤ 1000	μs
beam repetition rate	≤ 10	Hz
operating frequency	36.136 / 108.408	MHz
length	≈ 115	m





KONUS beam dynamics design



A Hamiltonian can be constructed describing the particle motion in phase space as

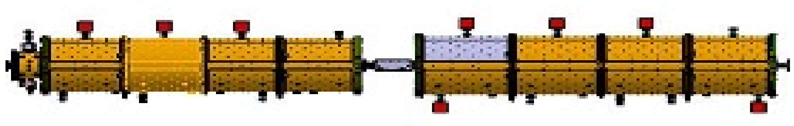
$$H = -\frac{\pi w^2}{\beta_s^3 \gamma_s^3 \lambda} - \frac{q E_0 T_n(\beta)}{mc^2}(\sin\psi - \psi\cos\psi_s)\,,$$

since ψ and w are variables canonically dependent on s

$$\frac{d\psi}{ds} = -\frac{2\pi w}{\beta_s^3 \gamma_s^3 \lambda}, \qquad \frac{dw}{ds} = \frac{q E_0 T_n(\beta)}{mc^2}(\cos\psi - \cos\psi_s)\,,$$

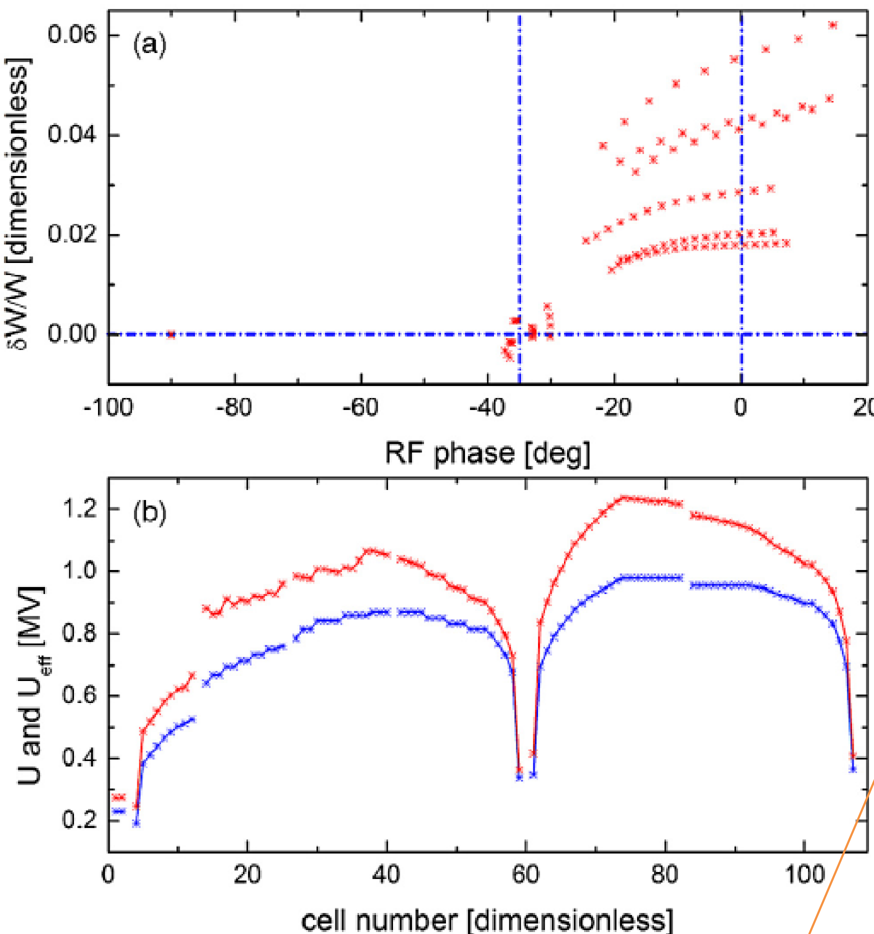
For simplicity this term is normalized to the rest energy of the particle under study

$$w = \frac{W_n - W_{n,s}}{mc^2}\,.$$



IH-cavities with KONUS
(combined 0-degrees structure)

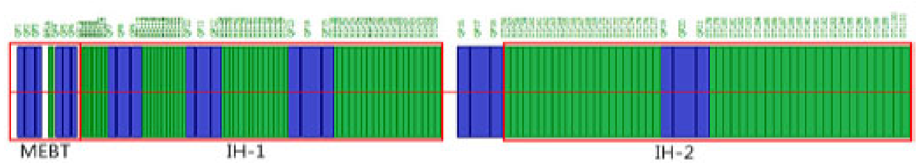
IH-DTL design at UNILAC



New MEBT design by H. Hähnel (IAP)

Table 1
GSI pre-stripper IH-DTL parameter list.

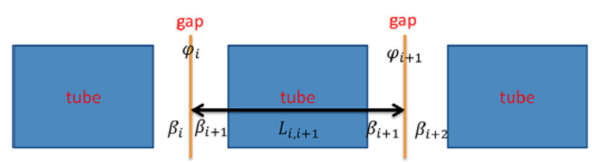
Parameter	Value
Frequency	36.136 MHz
Design particle	$^{238}U^{4+}$
Design intensity	15 emA (electric)
Energy range	0.12 to 1.4 MeV/u
Number of cavities	2
Total length	20 m
Number of sections	4(IH-1) + 2(IH-2)
Norm. exit rms-emittances	0.1 mm mrad, 0.45 keV/u ns



$$W_{n+1} - W_n = qU_{eff,n} \cos \psi_n \,,$$

energy gains

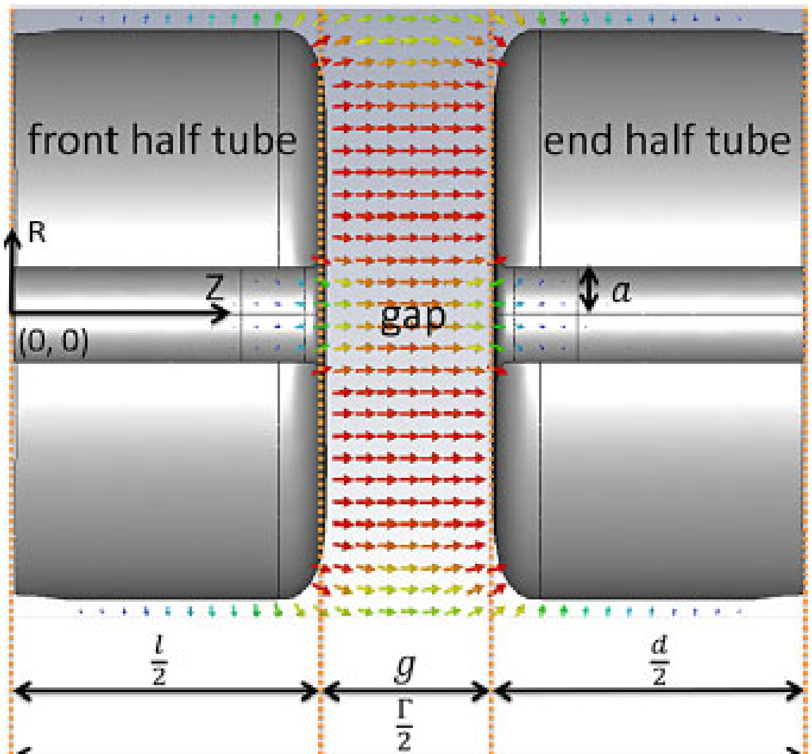
$$U_{eff,n} = U_n T_n \,,$$



$$\psi_{n+1} - \psi_n = \frac{2\pi L_{n,n+1}}{\beta_{n+1}\lambda} - \pi \,,$$

rf-phase shift calculation

Electric field expansion



$$E_m = \frac{4E_0}{I_0(\mu_m a)} \frac{\pi m(l+g)}{\Gamma} \frac{g}{\Gamma} \frac{\sin\left[\frac{\pi m(l+g)}{\Gamma}\right]}{\frac{\pi m(l+g)}{\Gamma}} \frac{\sin\left(\frac{\pi m g}{\Gamma}\right)}{\frac{\pi m g}{\Gamma}},$$

$\psi_r = 2\pi T + \psi_0.$ *rf-phase shift calculation*

Field map inside a gap is described by Fourier–Bessel series

$$E_z(z,r,t) = -\cos(\omega t + \psi_0) \sum_{m=1}^{M} E_m I_0(\mu_m r) \sin\left(\frac{2\pi m z}{\Gamma}\right),$$

$$E_r(z,r,t) = \cos(\omega t + \psi_0) \sum_{m=1}^{M} \frac{2\pi m E_m}{\mu_m \Gamma} I_1(\mu_m r) \cos\left(\frac{2\pi m z}{\Gamma}\right),$$

$$B_\theta(z,r,t) = \sin(\omega t + \psi_0) \sum_{m=1}^{M} \frac{2\pi E_m}{\mu_m \lambda c} I_1(\mu_m r) \sin\left(\frac{2\pi m z}{\Gamma}\right),$$

and

$$\mu_m = \frac{2\pi}{\lambda}\sqrt{\left(\frac{m\lambda}{\Gamma}\right)^2 - 1}, \quad \Gamma = l + 2g + d, \quad E_0 = \frac{U}{g},$$

First section of IH-1, five rf-gaps

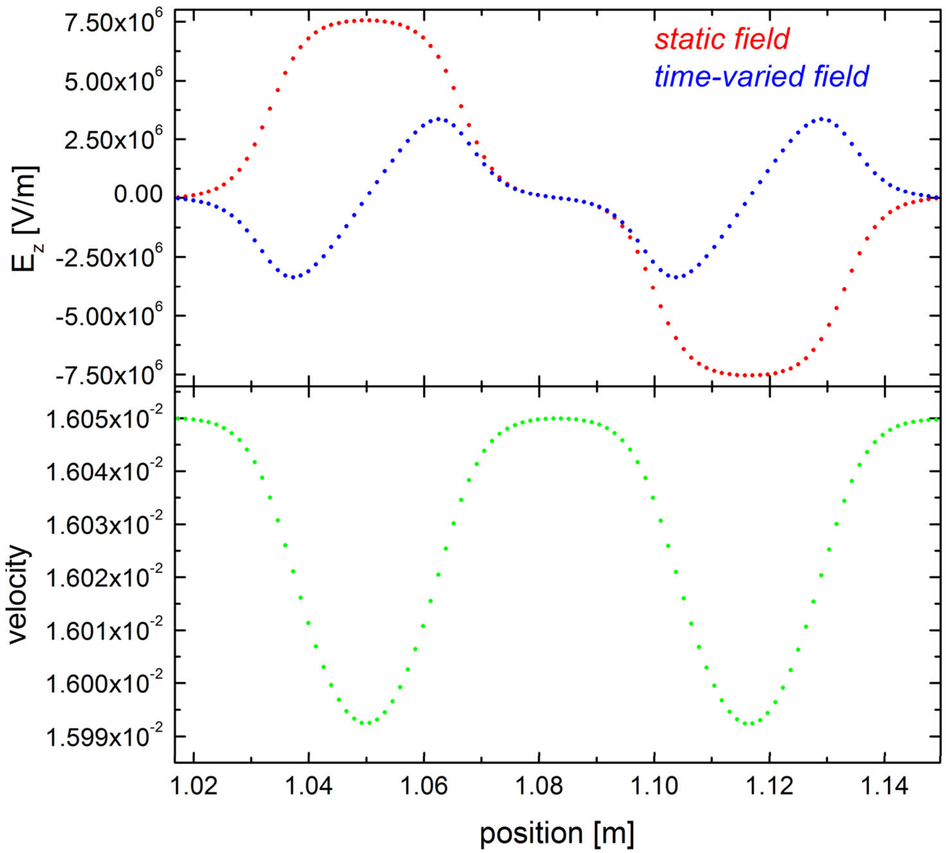
$$(\psi_1, \psi_2, \dots \psi_5)_{Analytical} = 14.5°, 9.4°, 4.5°, -0.2°, -4.6°.$$

$$(\psi_1, \psi_2, \dots \psi_5)_{Lorasr} = 14.5°, 9.1°, 3.9°, -1.0°, -5.7°.$$

$$(\psi_1, \psi_2, \dots \psi_5)_{Beampath} = 14.5°, 9.1°, 4.0°, -0.9°, -5.6°.$$

Single-particle tracking basing on MATHCAD

beam at 0.12 MeV/u is the injected



In MATHCAD, the reference particle vector function is defined as

initial time/position

$$Z(t,z) := \begin{bmatrix} z \\ \frac{dz}{dt} \end{bmatrix} = \begin{bmatrix} z \\ \beta c \end{bmatrix}, \qquad Z(0,0) := \begin{bmatrix} 0 \\ \beta_0 c \end{bmatrix}.$$

The derivative DZ is

$$DZ(t,z) := \frac{dZ(t,z)}{dt} = \begin{bmatrix} \beta c \\ \frac{q}{\frac{m_0}{\sqrt{1-\beta^2}}} E_z(z)\cos(\omega t + \psi_0) \end{bmatrix}.$$

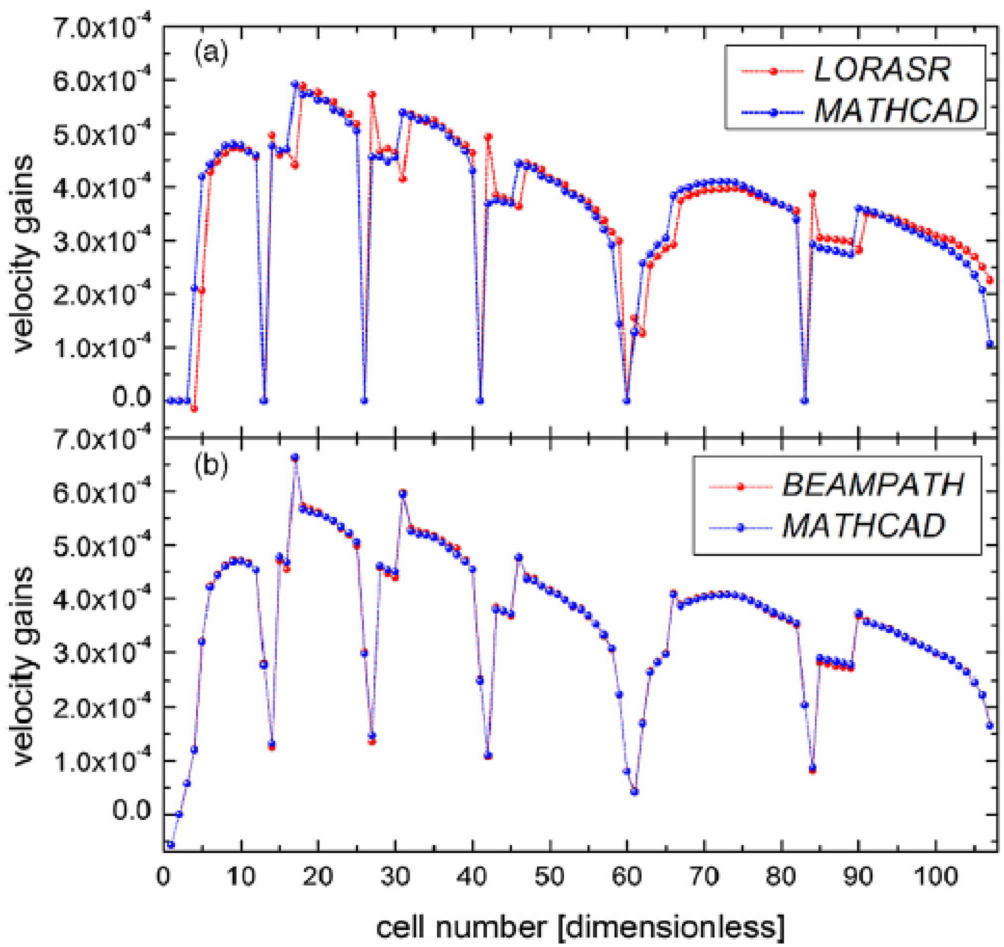
The Bulirsch–Stoer method is adopted and the results are written as matrix F

$$F = Bulstoer[Z(0,0), t_i, t_f, s, DZ(t,z)],$$

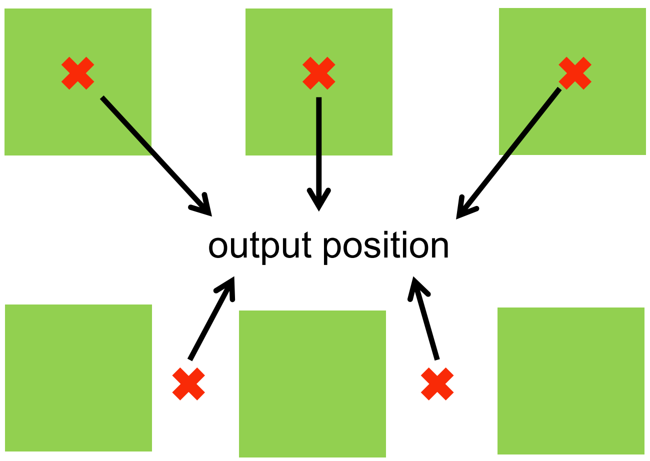
at each step

$$F^1 = t_n,\ F^2 = z_n,\ F^3 = \beta_n c, \quad n = 1, 2 \cdots s.$$

Comparison of simulation results

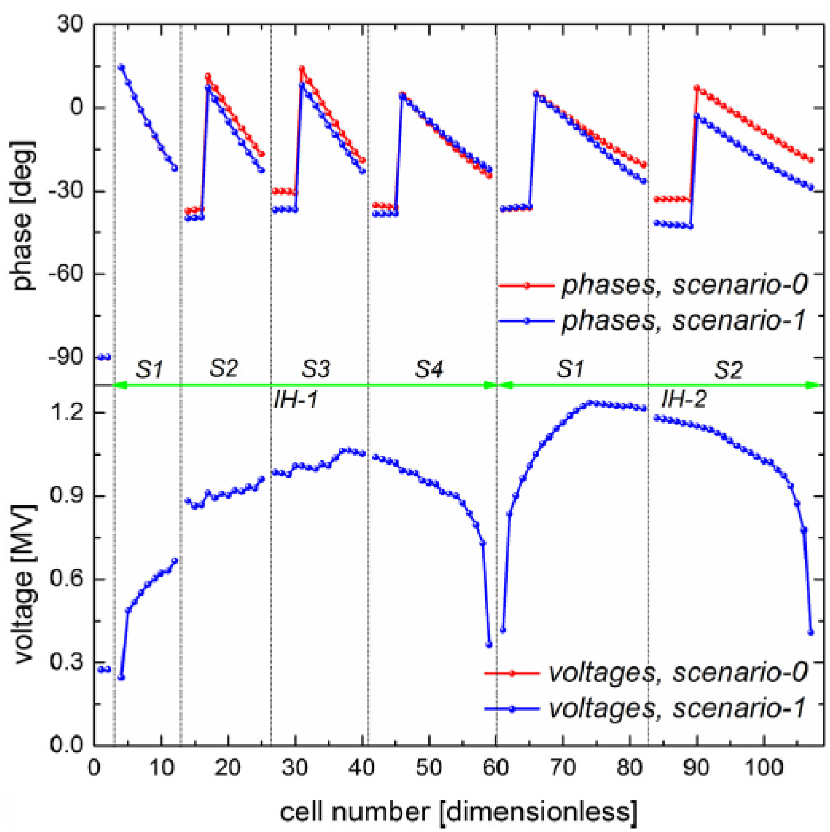


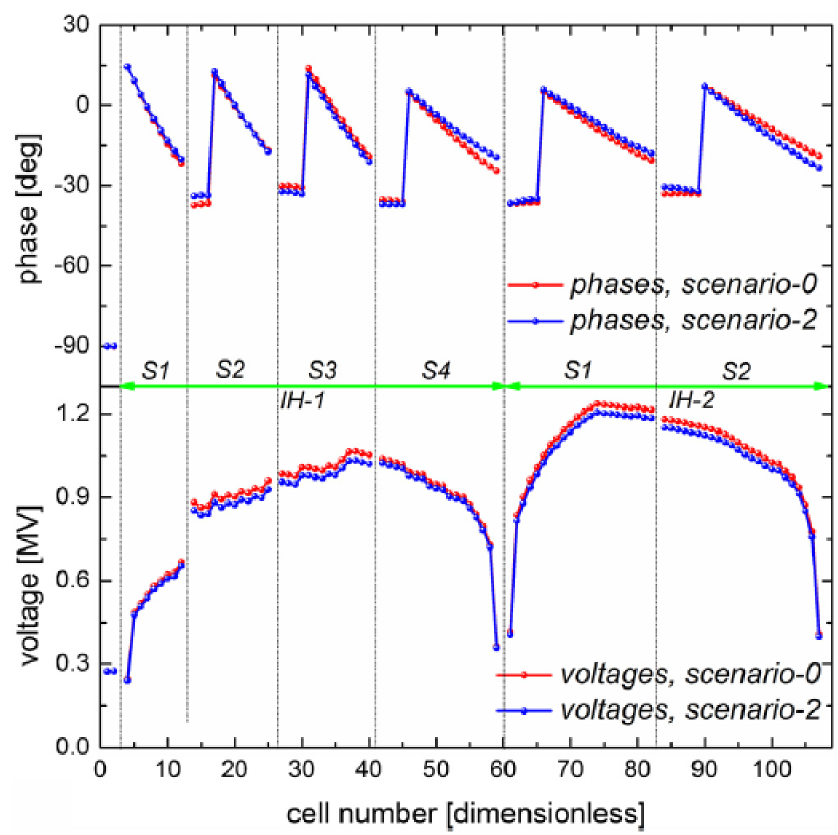
energy gains comparing



Compared with results from LORASR, simulations with BEAMPATH deliver more reliable results.

Single-particle tracking using specified voltages

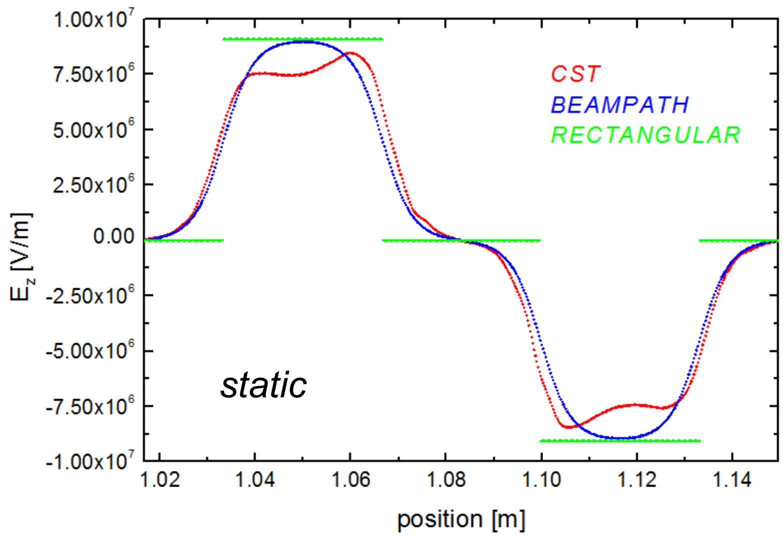


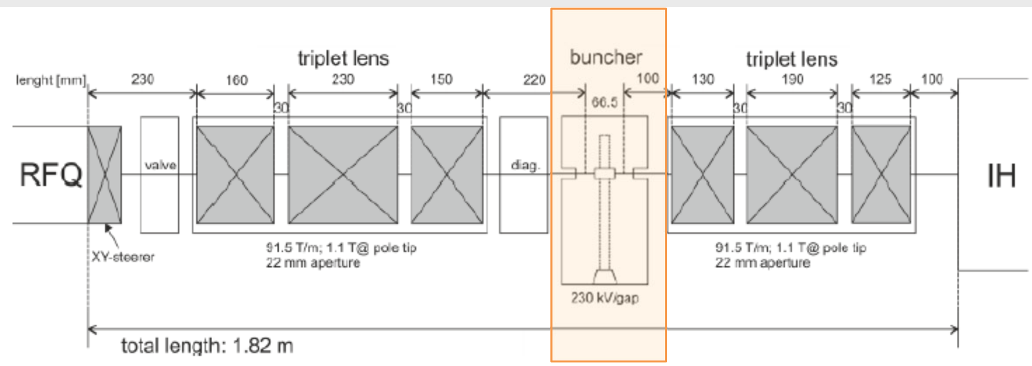


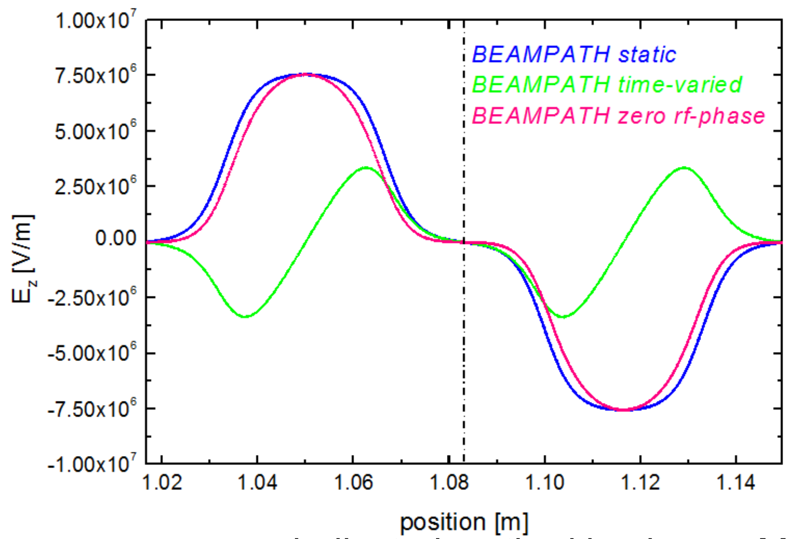
output energies: 1.3837 MeV/u and 1.3992 MeV/u

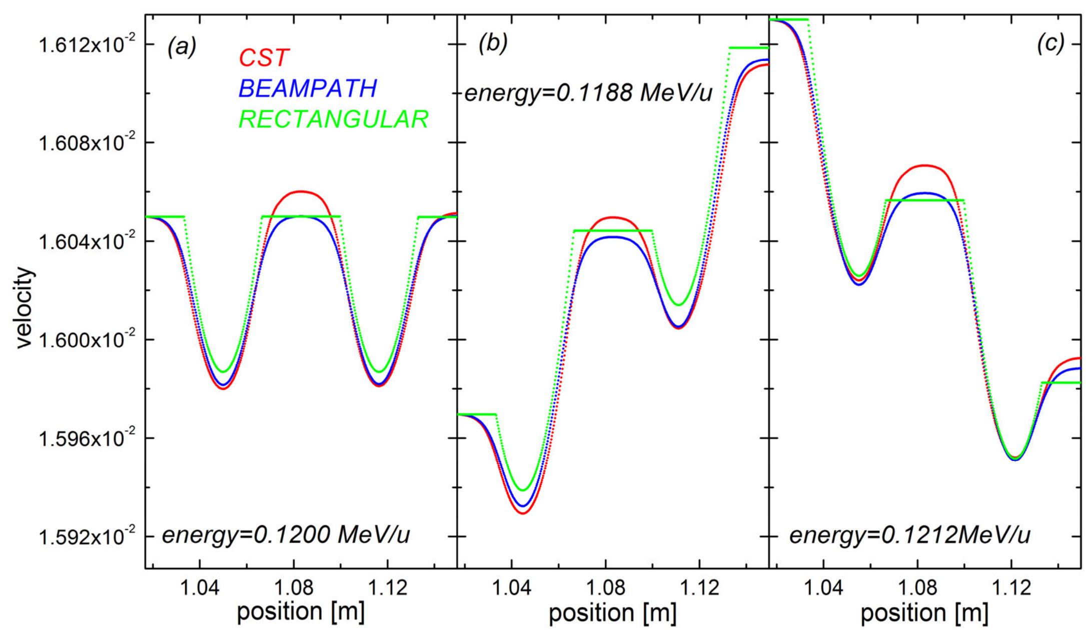
output energies: 1.3837 MeV/u and 1.4010 MeV/u

TTF calculation using filed-map tracking









a dedicated method basing on MATHCAD is adopted to calculate TTF parameters.

Different energy injections through MEBT

correct energy injection

Gap	RF-phase	Effective voltage	TTF	Field map
1/2	-89.96/-90.01	0.2571/0.2551	0.849/0.845	CST
1/2	-89.98/-89.98	0.2630/0.2609	0.871/0.861	BEAMPATH
1/2	-90.01/-90.08	0.2734/0.2709	0.902/0.899	Rectangular

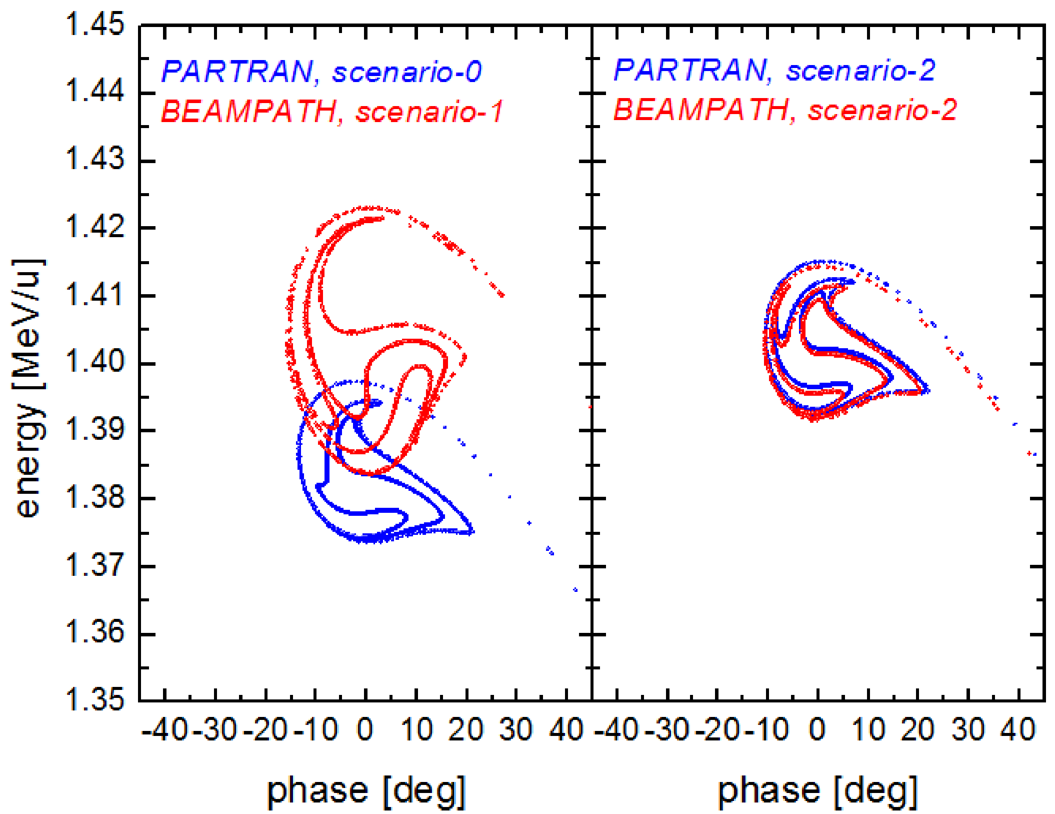
lower energy injection (1% lower)

Gap	RF-phase	Effective voltage	TTF	Field map
1/2	-75.72/-75.66	0.2566/0.2551	0.848/0.845	CST
1/2	-75.73/-75.65	0.2627/0.2608	0.870/0.867	BEAMPATH
1/2	-75.76/-75.78	0.2738/0.2707	0.900/0.899	Rectangular

higher energy injection (1% higher)

Gap	RF-phase	Effective voltage	TTF	Field map
1/2	-104.01/-104.18	0.2575/0.2552	0.850/0.846	CST
1/2	-104.02/-104.14	0.2634/0.2609	0.872/0.867	BEAMPATH
1/2	-104.05/-104.21	0.2747/0.2711	0.902/0.899	Rectangular

Multi-particle tracking through IH-DTL



More detail information can be found in Nuclear Inst. and Methods in Physics Research, A 887 (2018) 40–49

Conclusion

- As part of the pre-stripper injector HSI, the IH-DTL has been designed in the 1990s applying KONUS beam dynamics. KONUS allowed for the desired high accelerating gradients compared to conventional $\beta\lambda$-DTLs with constant rf-phases. Particle motion along KONUS DTLs is very sensitive to the actual rf-phase and effective voltage at each cell.

- For cavities comprising many gaps small rf-phase errors being neglected may harm further stable acceleration along subsequent cavities and lower the precision of the predicted DTL output energy. The mentioned inconsistencies cannot be modeled by z-codes as PARTRAN for instance.

- Self-consistent beam dynamics of this IH-DTL optimized with the t-code BEAMPATH (scenario-2) can be reproduced very well with PARTRAN using realistic TTF parameters, measured gap voltages, and upgraded rf-phases taking into account unequal lengths of front and end half tubes.

Thank you !