HE-Linac: Layout and (quasi) Front-to-End Simulations

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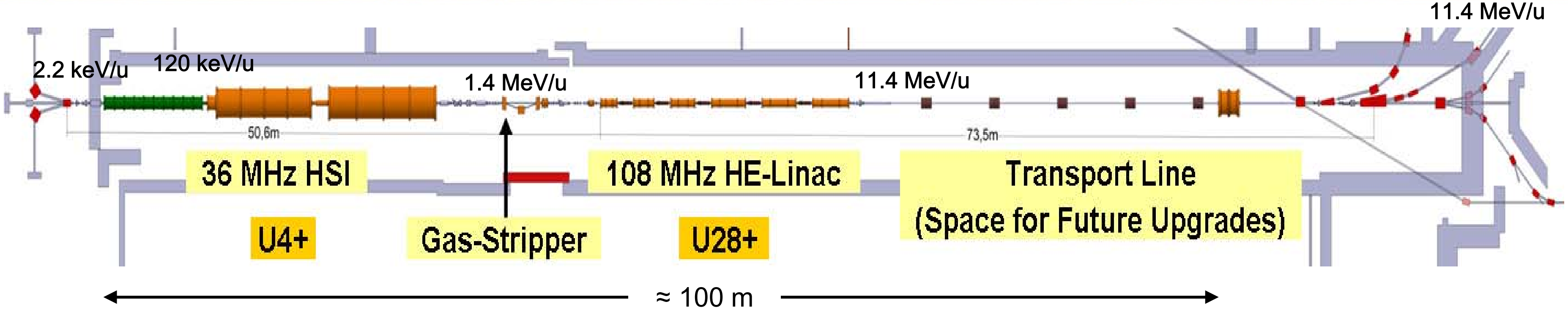
Outline

- UNILAC for FAIR
- LEBT, RFQ, matching section, pre-stripper DTL, stripper & matching section
- Todays post-stripper Alvarez DTL
- Planned post-stripper IH-DTL
- Front-to-end simulations:
- Codes & methods for beam propagation
- Beam quality development along sections

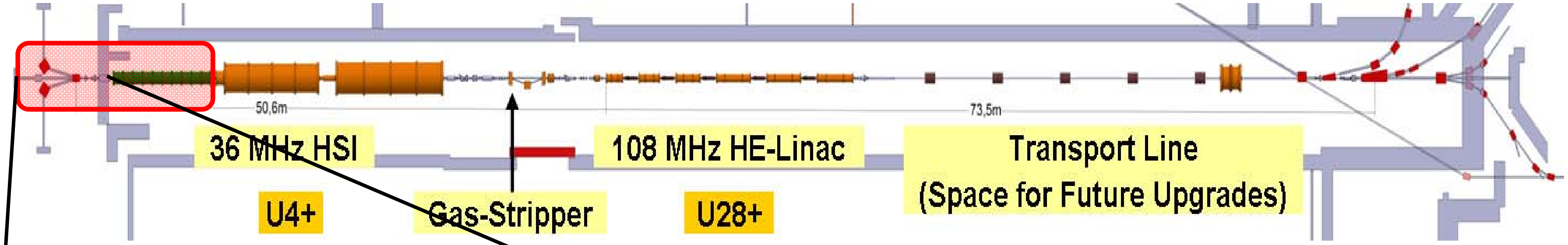
High Energy (HE) Linac Layout

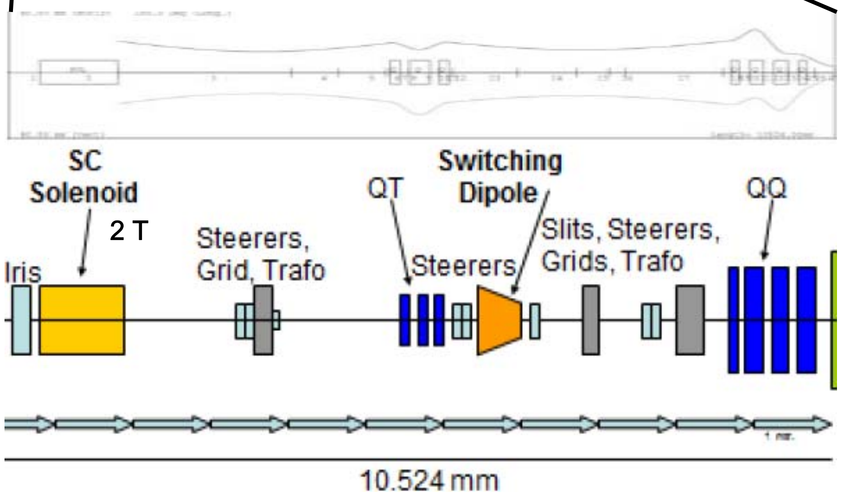


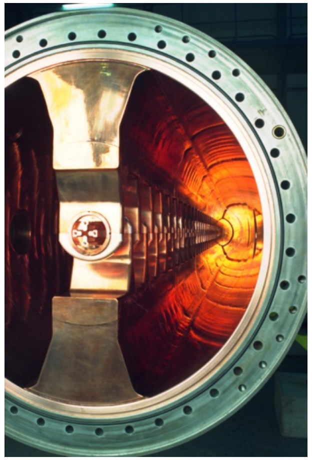
- „HE-linac“ shall replace existing Alvarez DTL, which operates since 40 years

- it refers to the DTL section providing acceleration beyond 1.4 MeV/u, i.e. post-stripper
- „high energy“ is misleading: baseline layout foresees same energy as Alvarez, i.e. 11.4 MeV/u

LEBT & RFQ



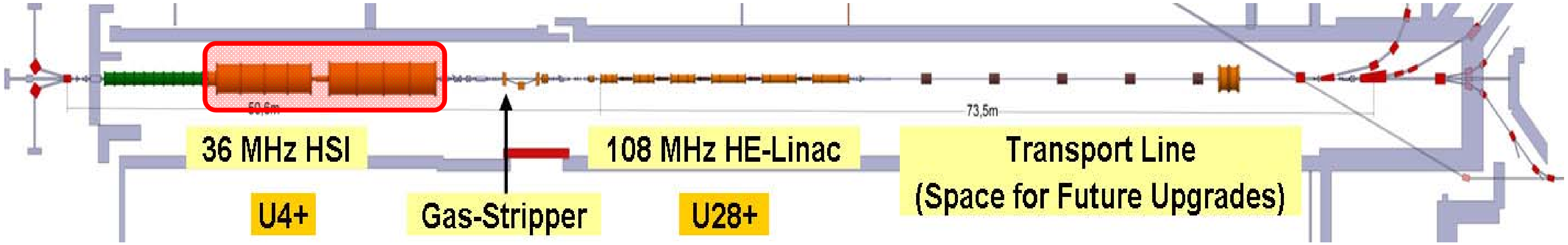




- acceleration from 2.2 to 120 keV/u
- 418 cells, i.e. 9.27 m in length
- 31 MV/m = 2.8 E_K

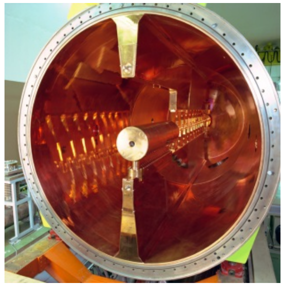
- separation of U^{4+} from U^{3+} by solenoid & iris *and RFQ*
- intensity attenuation by iris

IH-Cavities & Super-Lens



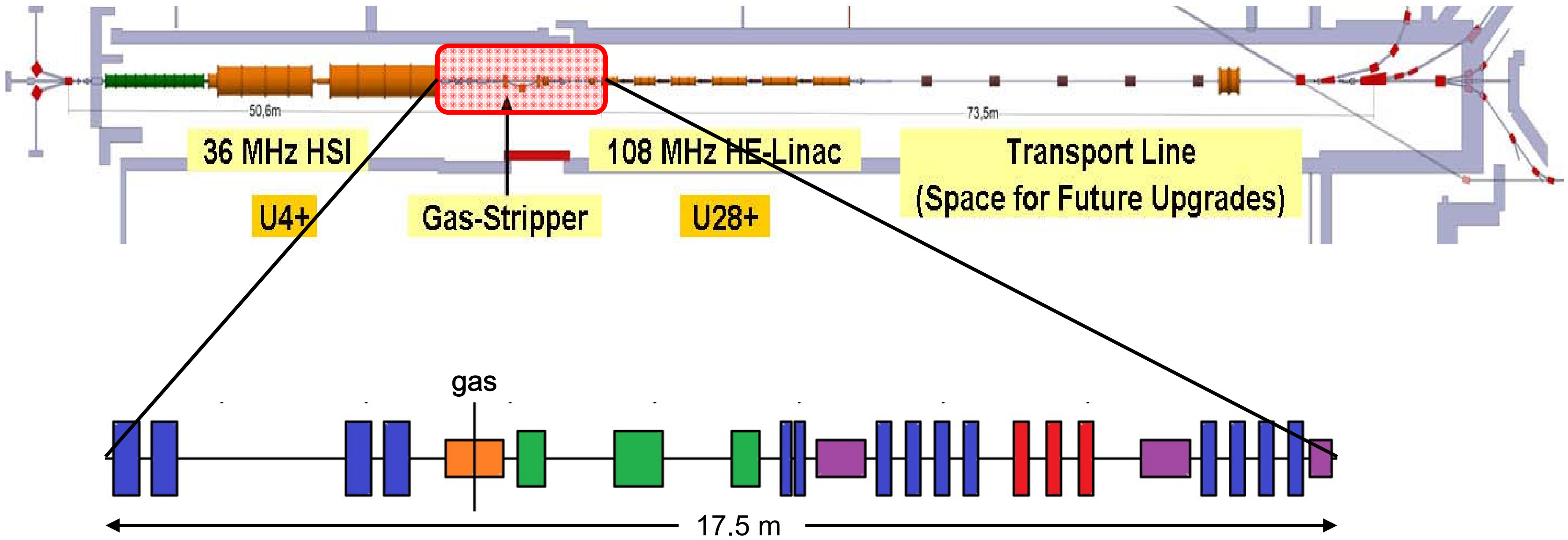
- super-lens: IH-type RFQ, no acceleration, just matching to IH-DTL

- IH-cavity I
  - KONUS-acceleration to 0.74 MeV/u
  - 53 gaps
  - 3 internal triplets
  - 1.6 MW of rf-power



- IH-cavity II
  - KONUS-acceleration to 1.4 MeV/u
  - 46 gaps
  - 3 internal triplets
  - 1.6 MW of rf-power

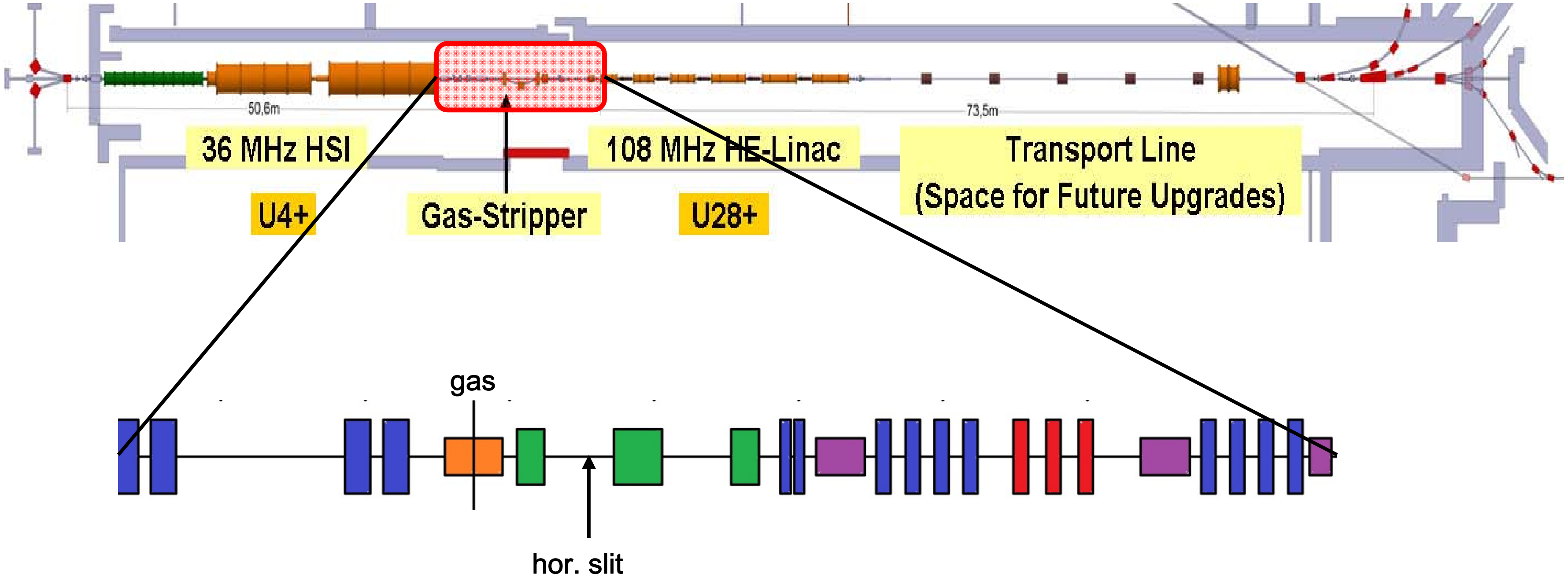
Stripper & DTL-Matching Section



<u>Tasks:</u>

- charge state stripping $U^{4+} \rightarrow U^{28+}$
- remove charge states ≠ 28+
- provide rf-frequency transition 36 → 108 MHz
- beam diagnostics
- match to periodic DTL

Stripper & DTL-Matching Section

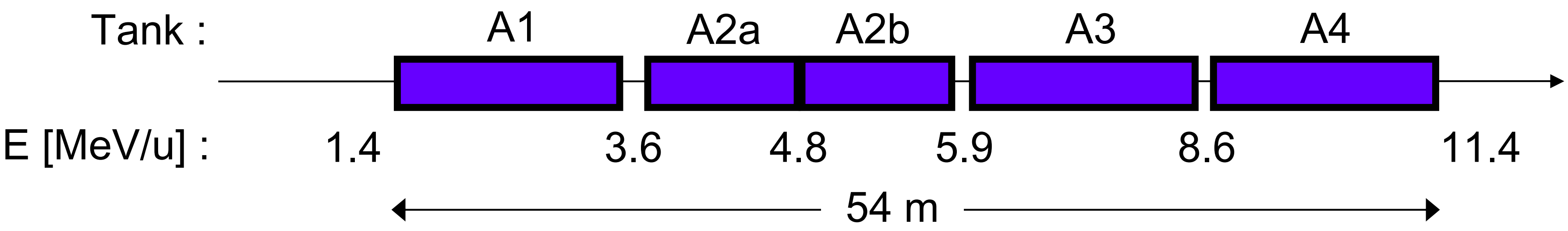


optical elements:

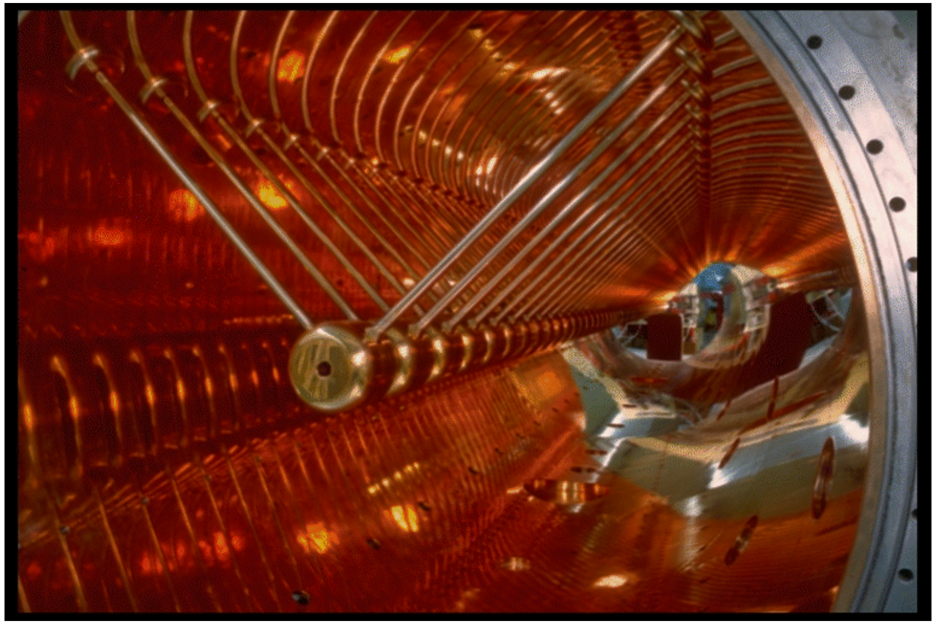
regular quads
solenoid
hor. bends (15°, -30°, 15°)
Buncher (36 MHz)
skew quads
buncher (108 MHz)

- present section may be redesigned
- new section (shown here) is prolonged incl. additional Buncher
- new section includes solenoid and skew quads
- use of these elements to be explained in „flat beam“ presentation
- for this presentation they are „switched off“

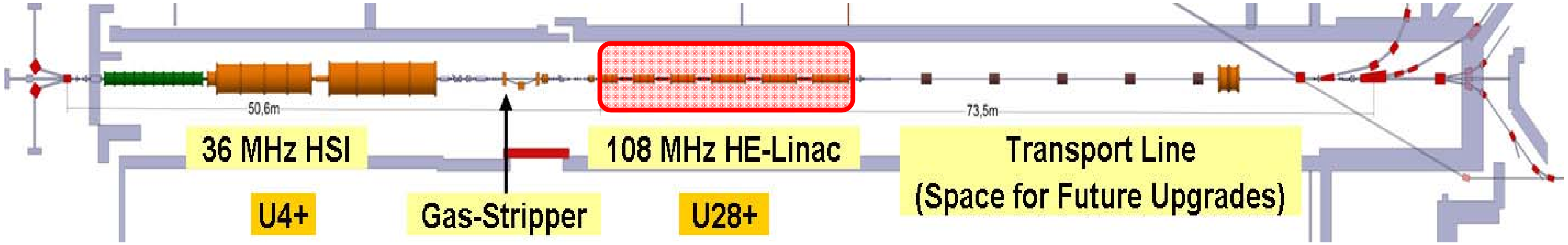
Post-Stripper Alvarez DTL



- 5 independent rf-tanks
- 108 MHz, 50 Hz, 5 ms
- transv. F-D-D-F focusing
- inter-tank focusing : F-D-F
- synchr. rf-phases -(30°,30°,30°,25°,25°)



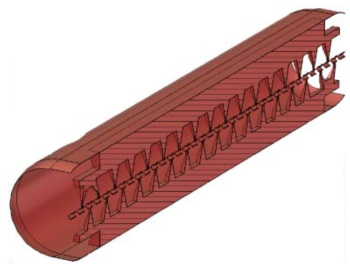
Post-Stripper IH-DTL



cavity	rf-power [MW]	# gaps	length [cm]	fin. energy [MeV/u]
1	1.3	9	66	2.08
2	1.3	15	149	3.49
3	1.3	16	200	5.31
4	1.3	17	256	7.34
5	1.3	17	294	9.34
6	1.3	17	327	11.4

same as existing Alvarez DTL but low duty factor

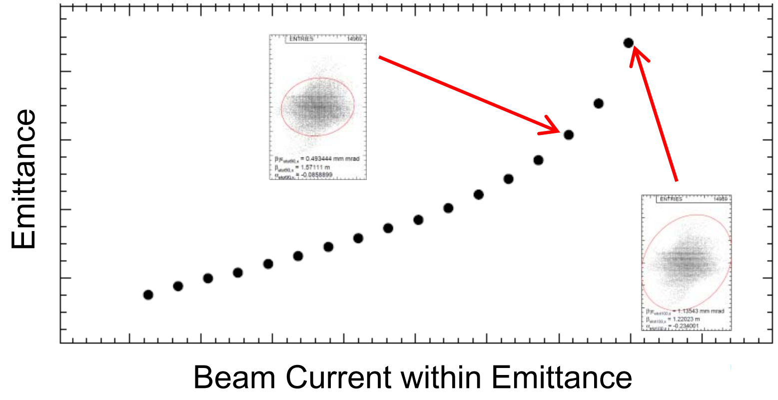
Design-Ion	$^{238}U^{28+}$	
Max. mass / charge ratio	8.5	
Design beam current (pulse)	15	mA
Input beam energy	1.4	MeV/u
Output beam energy	11.4	MeV/u
Max. norm. horizontal beam emittance at SIS18 inection	0.8	mm mrad
Max. norm. vertical beam emittance at SIS18 inection	2.5	mm mrad
Max. beam energy spread at SIS18 injection	±0.2	%
Beam pulse length	≤ 100	µs
Beam repetition rate	≤ 2.7	Hz
Operating frequency	108.408	MHz
RF duty factor	≤ 1	%
Number of IH-DTL cavities	6	
IH-DTL tank length	0.8 – 3.5	m
Max. RF power / cavity (incl. beam loading)	≤1300	kW
Linac length (new linac only)	≈ 20	m
Total acceleration voltage	85	MV
Max. on-axis electric field strength	≤19	MV/m



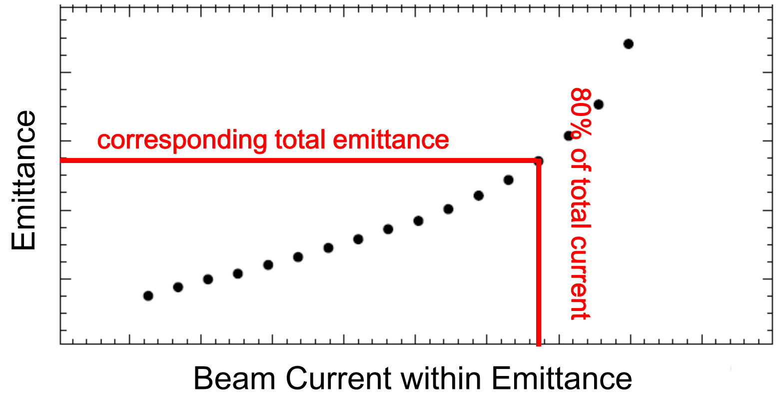
- cavities are separated by external symm. triplets
- no internal triplets

Figure of Merit: Brilliance

- in front-to-end simulations we analyze the horizontal brilliance of the beam
- brilliance = current / norm. tot. hor. emittance
- we plot size of ellipse needed to enclose a given current
- cutting in hor. & long. plane (limited acceptances)
- we do this for the <u>same(!)</u> distribution
- we apply this procedure behind each linac section



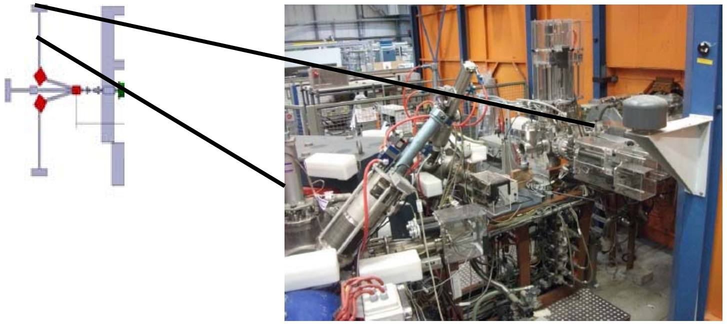
- the brilliance decreases from core to halo
- we define as „the brilliance" the ratio current/emittance at 80% of the total current
- that means: to get this „brilliance", 20% of the beam are scraped-off (in practice via):
  - hor. slits before ring injection (hor.)
  - momentum spread acceptance of ring (long.)

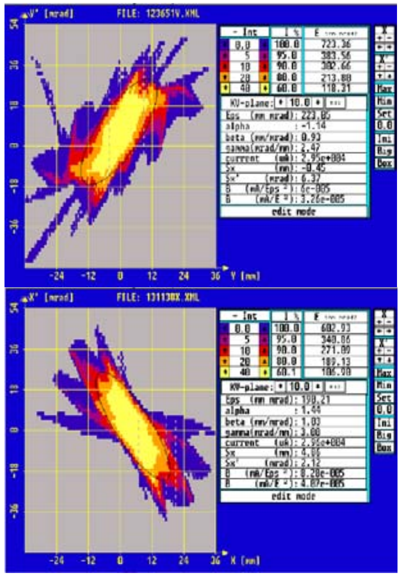


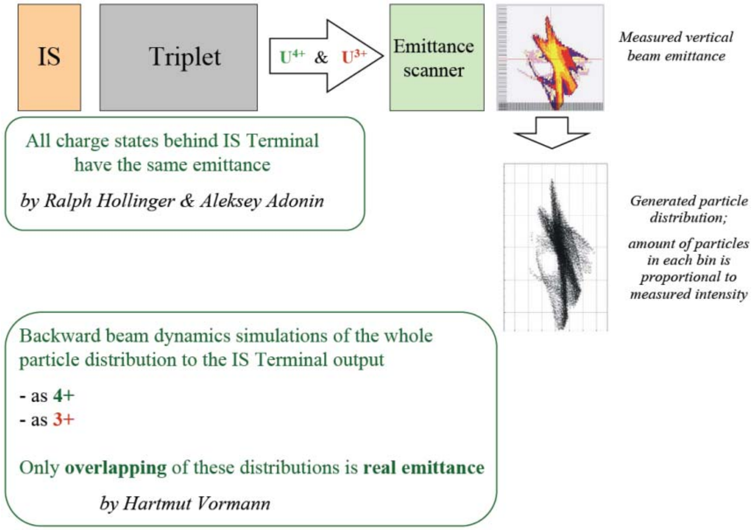
Front-to-End Simulations, Preparation

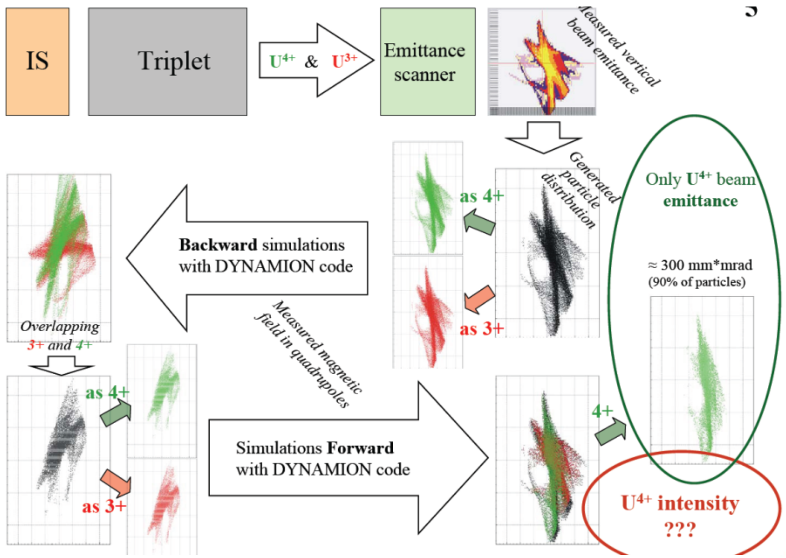
- aim: estimate maximum achievable performance wrt hor. brilliance at DTL exit
- simulations based on beam measurements, i.e. recently achieved source performance (September 2013)
- brilliance is analyzed behind each section, i.e.:
  - source
  - LEBT
  - RFQ
  - HSI (super lens, IH-cavities)
  - stripper & matching
  - DTL
- if well defined matching to section is known → go through section by tracking simulation
- if well defined matching to section is unknown → reconstruct transport from measurements, similar previous simulations, scaling laws ...

Front-to-End Simulations: Measured Beam from Source



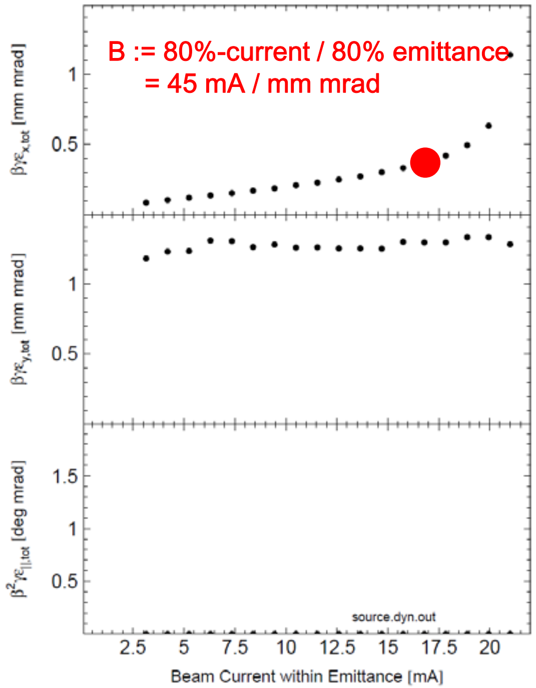


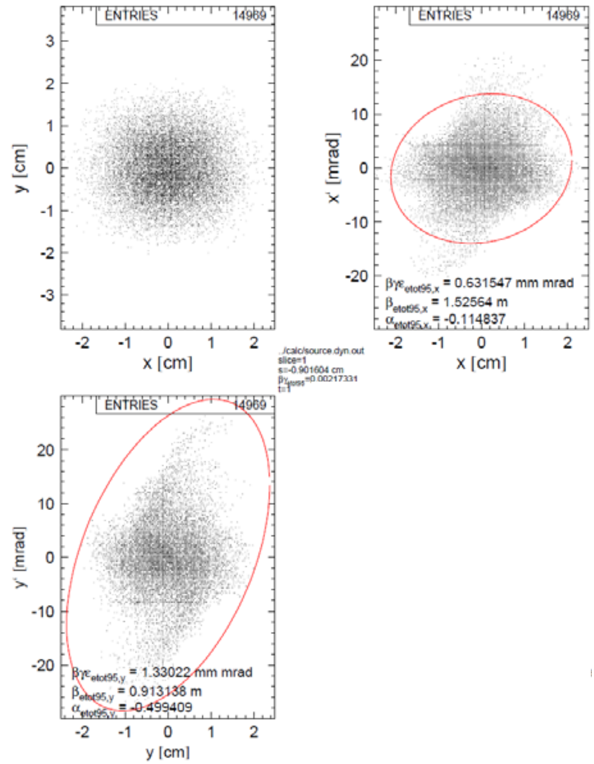




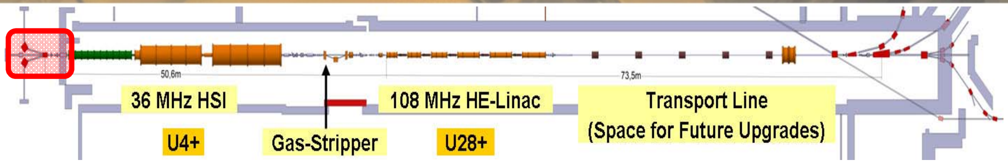
Front-to-End Simulations: Measured Beam from Source

- method of evaluation of U^{3+} & U^{4+} currents is beyond scope of this presentation (see Appendix)
- the $U^{4+/3+}$ currents were estimated to 21/13 mA
- the measured distribution was plugged into DYNAMION code
- no rms-equivalent distribution was used as KV, Gauss, Waterbag ...



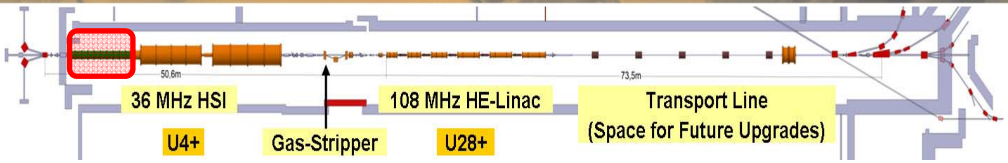


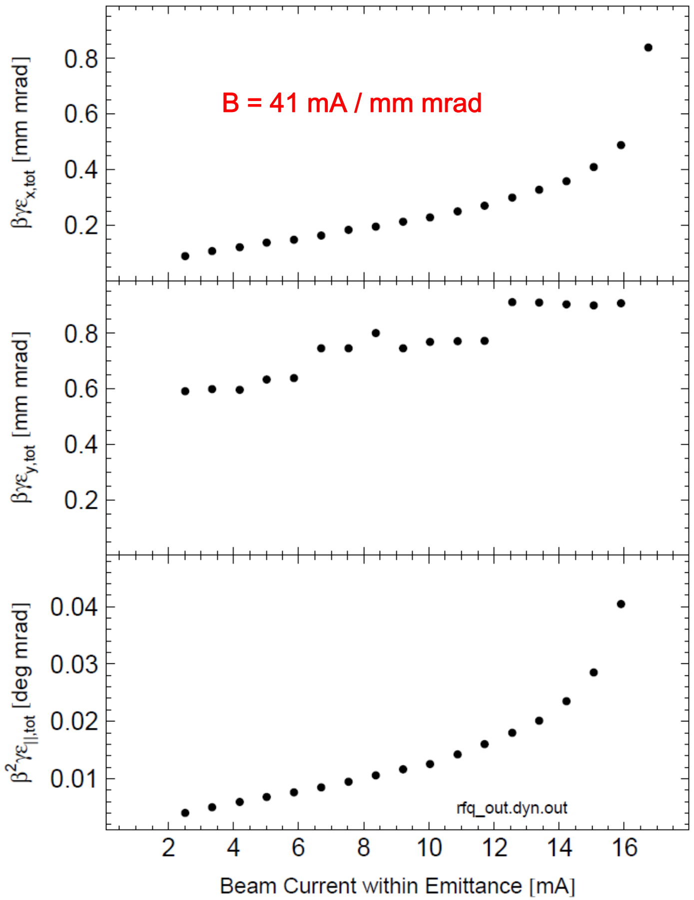
Front-to-End Simulations: Source to RFQ



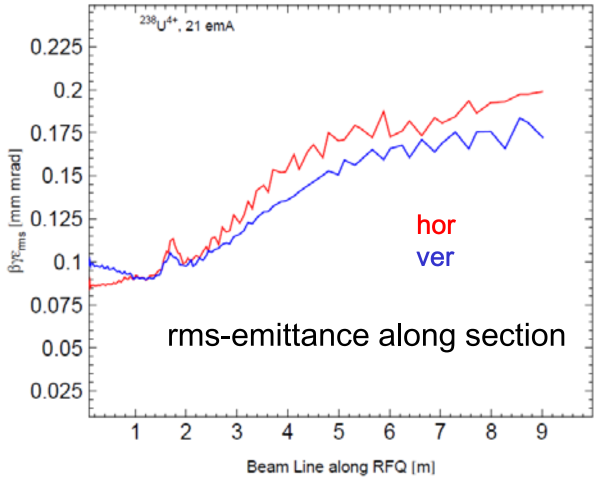
- LEBT design at preliminary stage
- alternative layouts are considered : two solenoids, solenoid + triplet, just triplets ...
- optimized layout might depend significantly on type of distribution
- for transport through LEBT we assume the optimum case:
    - transport w/o losses
    - transport w/o emittance growth
- source distribution is artificially matched to high-current RFQ acceptance
- done by re-positioning of particles in phase space to obtain matched Twiss parameters (beta & alpha)
- emittances and type of distribution is preserved
- accordingly, brilliance is fully preserved & best matching to RFQ is provided

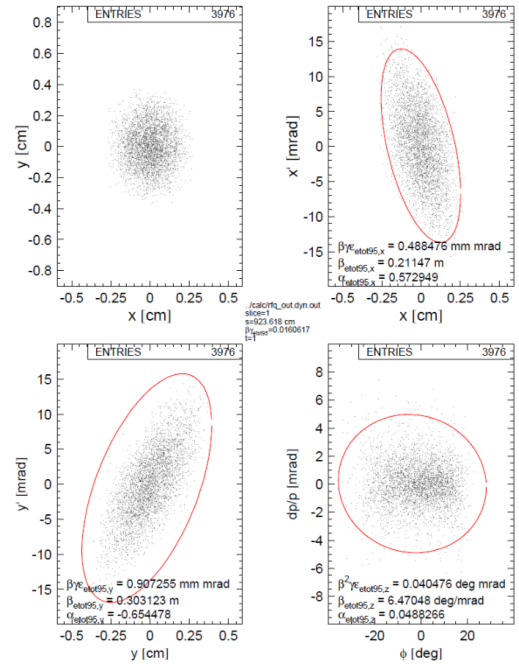
Front-to-End Simulations: through RFQ



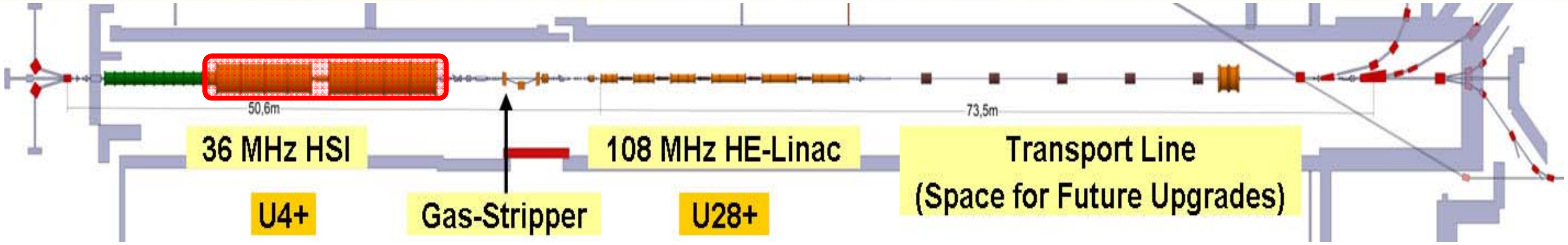


- DYNAMION code used
- existing RFQ assumed
- transmission = 80%
- brilliance change = -9%





Front-to-End Simulations: RFQ exit to HSI Exit



- we found that results of simulations through section is very sensitive to type of distribution, i.e. rms-equivalent initial distributions give quite different results

- although exit distribution types look always quite similar, transmissions & emit. growth rates depend strongly on distribution type at entrance

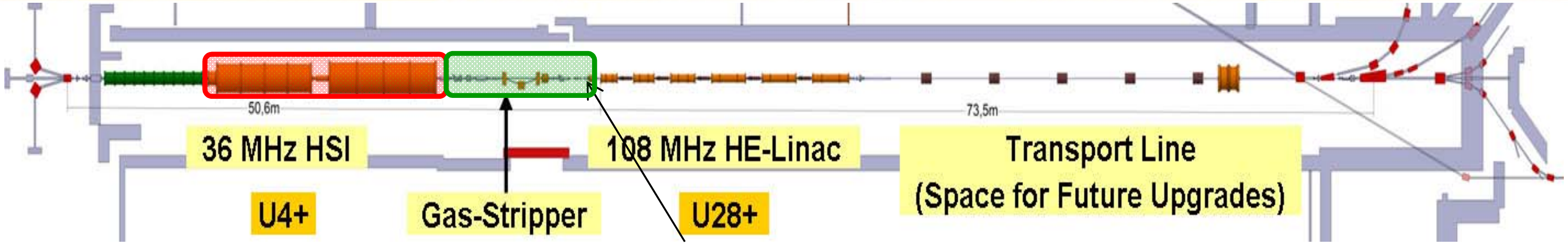
- accordingly, no straight forward simulation of RFQ-exit distribution through this section can be presented here

- we rather tried to reconstruct distribution at the section`s exit ...

any distribution is characterized by:

- type: KV, Waterbag, Gauss, Lorenz, ...ugly, ...arghhh
- 3 rms-emittances
- 3 set of Twiss parameters: beta & alpha
- total current

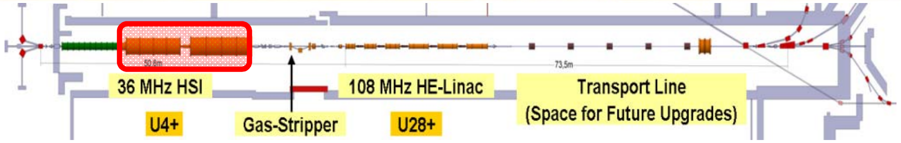
Front-to-End Simulations: RFQ exit to HSI Exit



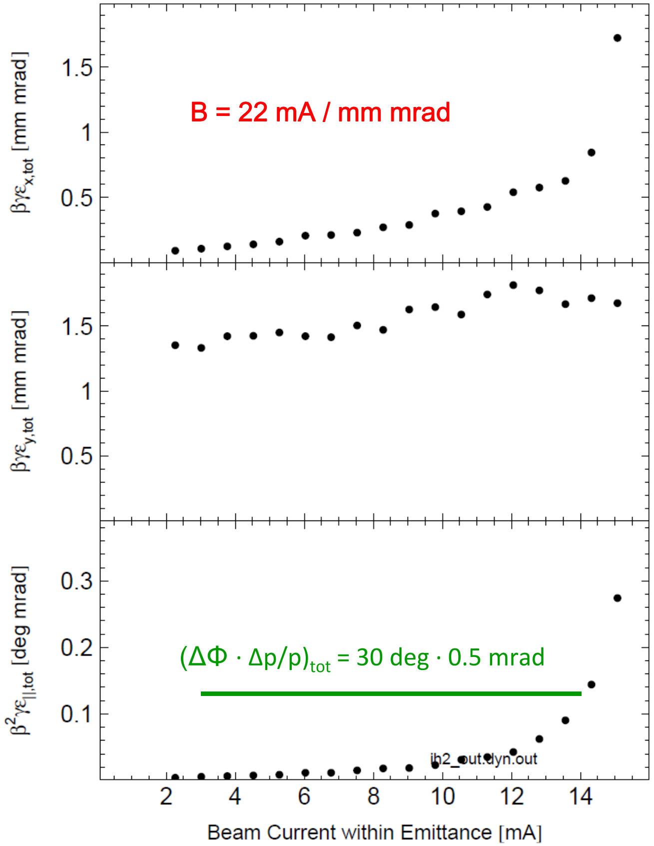
hor. & ver. slit/grid emit. +
current measurement devices

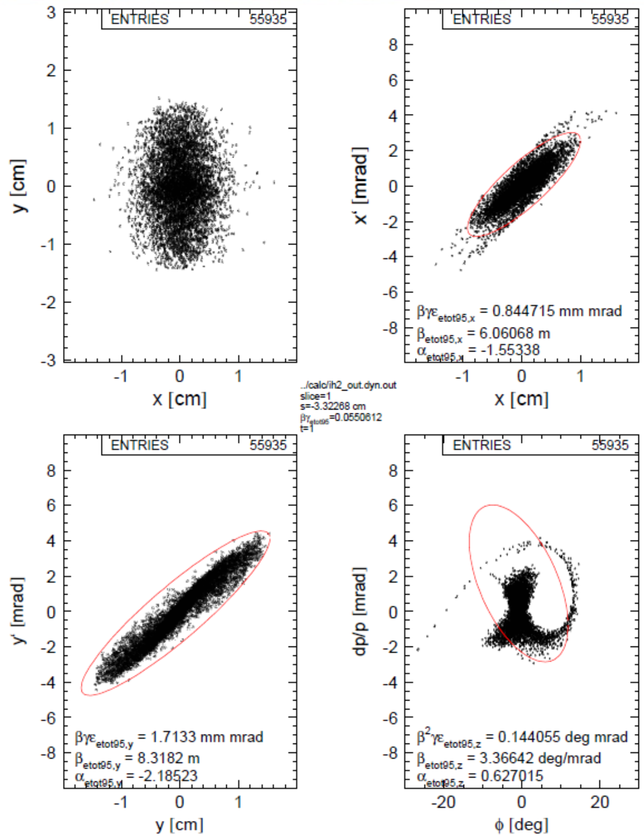
feature of distribution	method to reconstruct
type	output of preliminary DYNAMION HSI-simulations with 15 mA of U^{4+} done for design of todays RFQ, using transv. distribution measured directly at RFQ exit (2009)
rms-emittances	take rms-emittances measured at entrance to DTL. Estimate their growth along matching section from PARMILA simulations done during design phase (15 mA) of existing section (W. Barth, LINAC1998) Take measured beam current I=3.6 mA at entrance to DTL. Scale previously estimated emit. growth rate with I/15mA to obtain rms-emittances at HSI exit
Twiss params α, β	from output of HSI-simulations with 15 mA of U^{4+} done for design of todays RFQ
total current	transmission of DYNAMION HSI-simulations with 15 mA of U^{4+} was 92%. Apply these 92% to simulated output current of RFQ simulations → 15 mA

Front-to-End Simulations: RFQ exit to HSI Exit

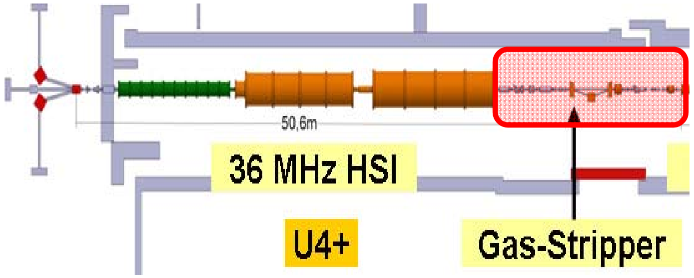


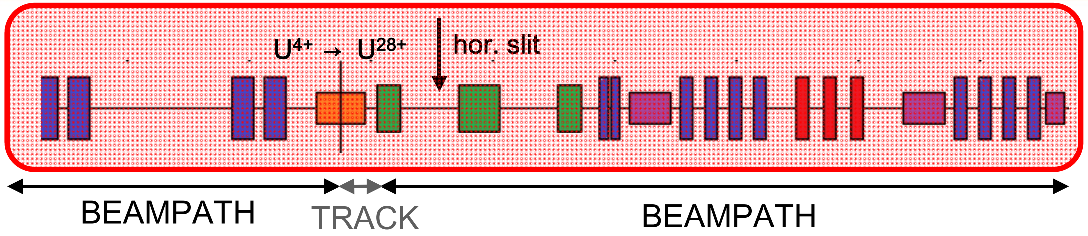
- reconstructed (see prev. slide)
- transmission = 92%
- brilliance change = -46%





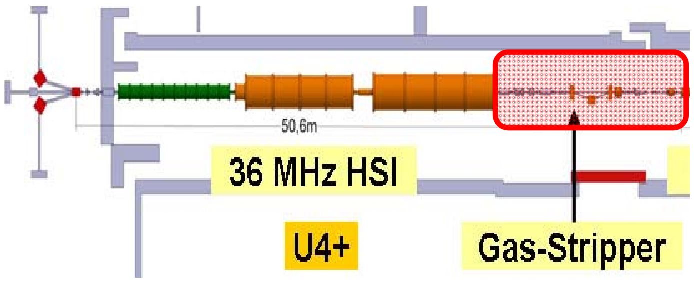
Front-to-End Simulations: HSI Exit to DTL Entrance

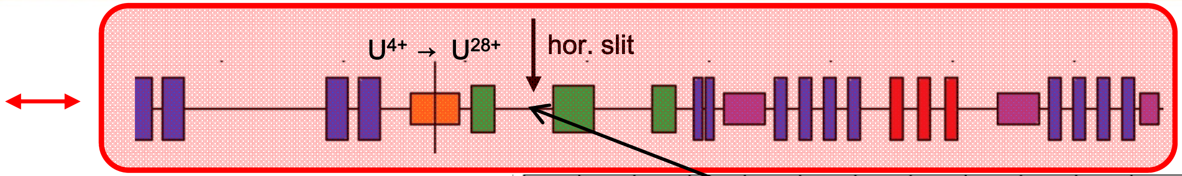




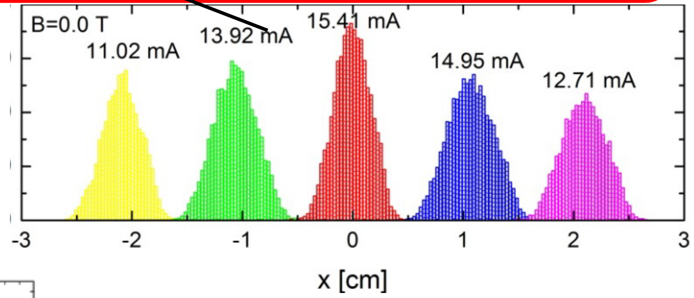
- two simulation codes used :
  - BEAMPATH: up to the stripper
  - TRACK: up to the q-separating bend
  - BEAMPATH: up to the exit
- stripper creates spectrum of charge states, scattering & straggeling occurs
- beam current is increased by factor 28/4 = 7 !
- current partially compensated by co-moving electrons from stripping medium
- up to 1st bend we assume 50% of space charge compensation to account for that
- hor. slits are included in simulations
- exit distribution artificially matched to subsequent DTL

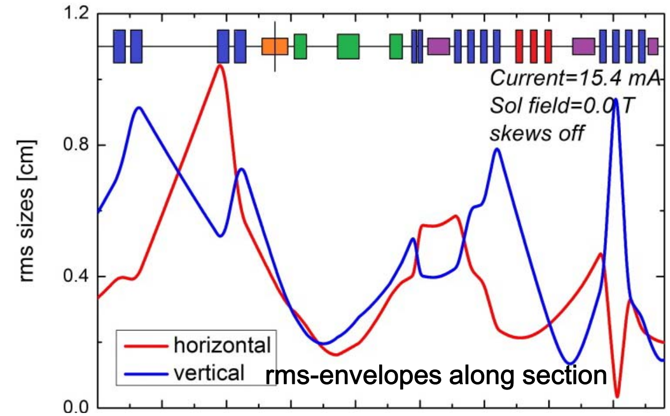
Front-to-End Simulations: HSI Exit to DTL Entrance

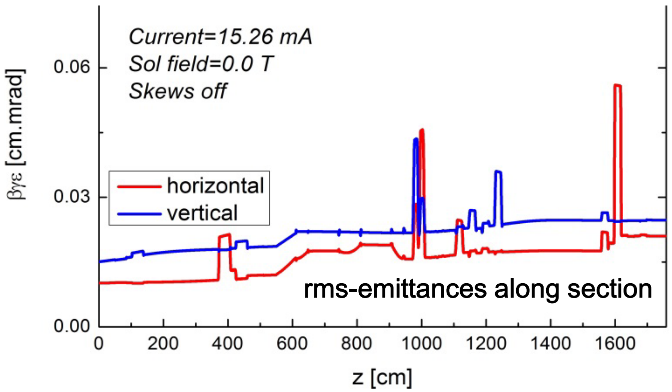


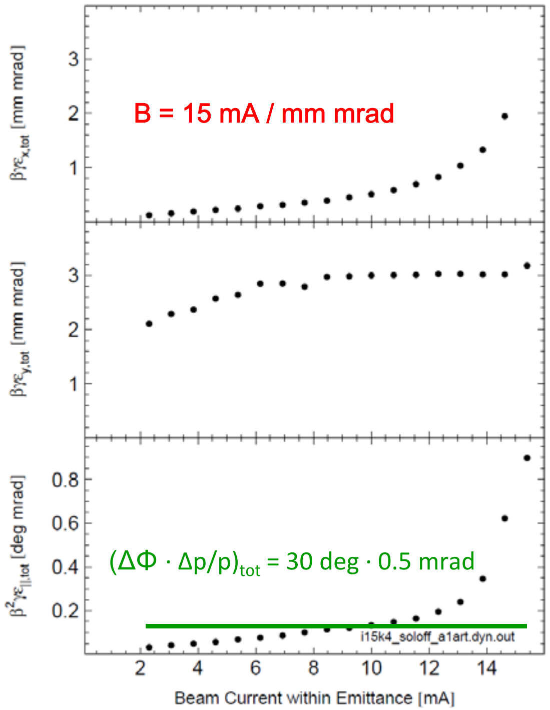


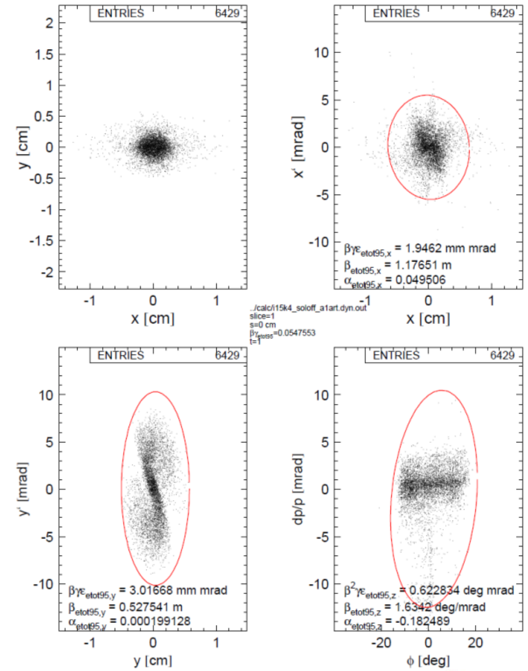
brilliance change = -33%



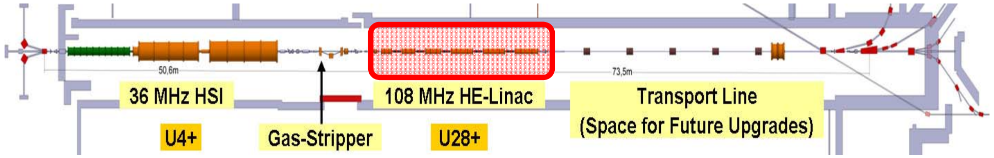






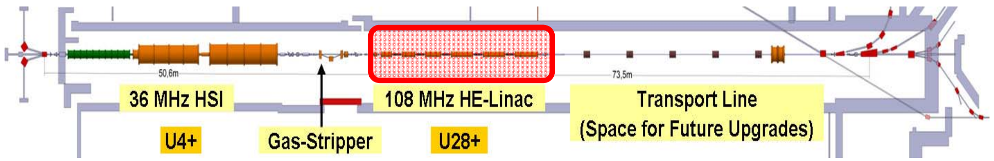


Front-to-End Simulations: Through IH DTL

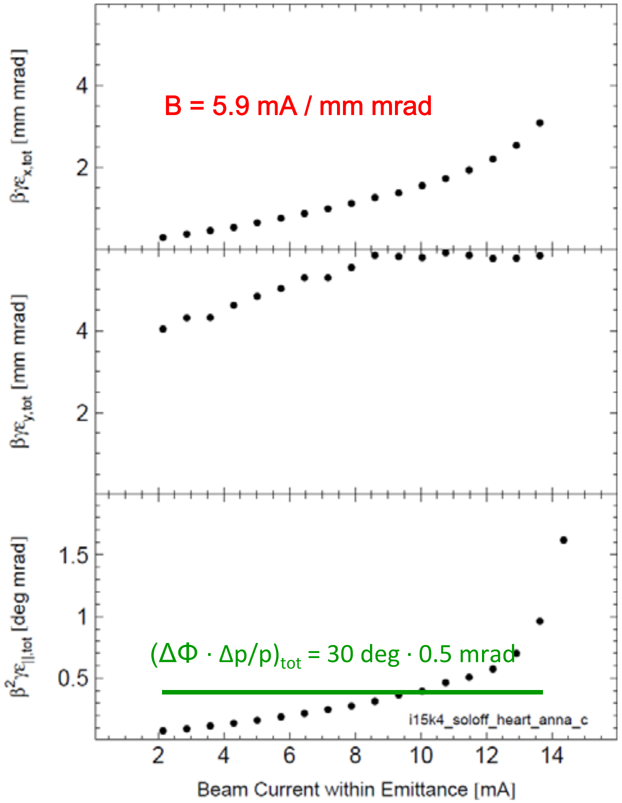


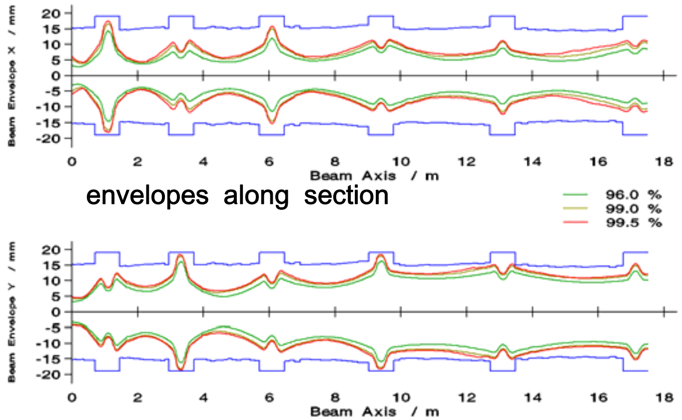
- simulation code LORASR, specialized in KONUS beam dynamics design
- GSI´s high-current beam dynamics experience with IH-DTL is less wrt Alvarez DTL
- still no straight forward recipe for provision of and matching to periodic/matched solution
- simulations revealed that rms-equivalent envelope matching is more sensitive to type of distribution
- accordingly, the results are to be considered as preliminary wrt to expected IH-DTL performance

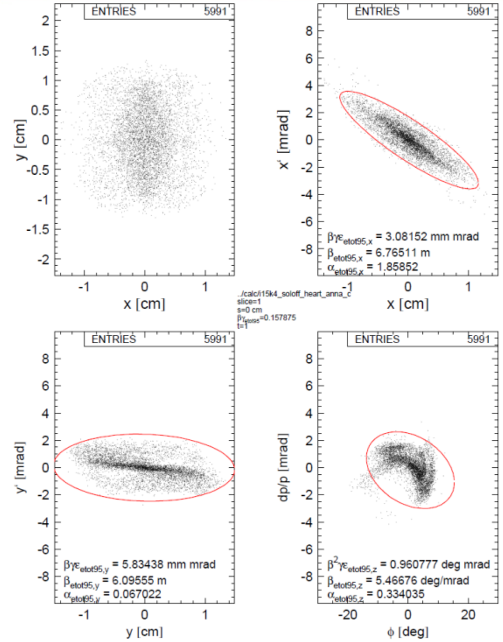
Front-to-End Simulations: Through IH-DTL

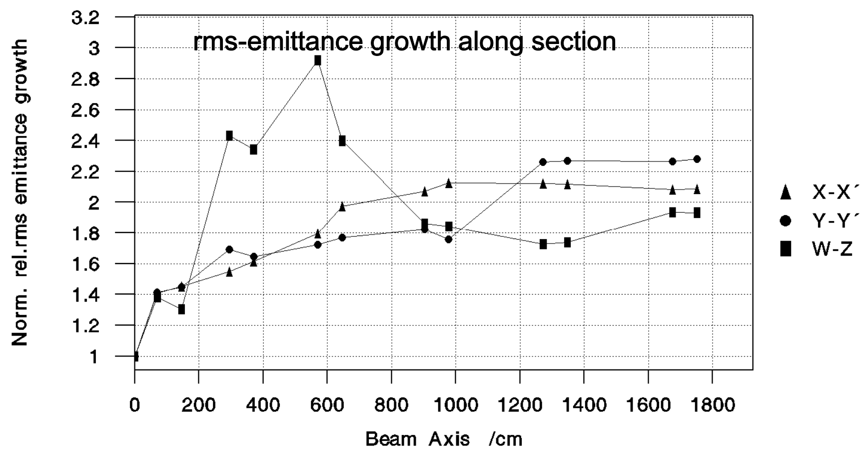


- transmission = 93%
- brilliance change = -60%

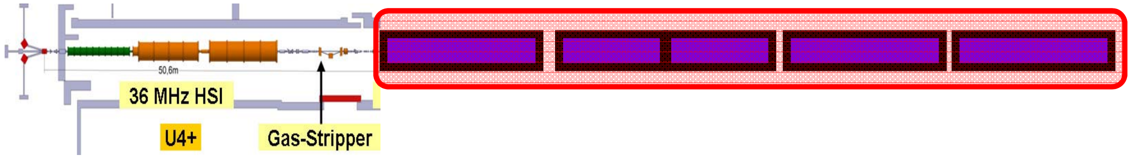




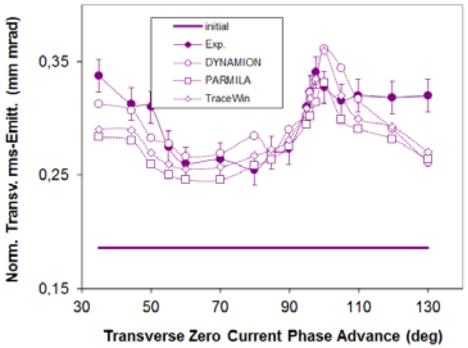




Front-to-End Simulations: Through Alvarez DTL

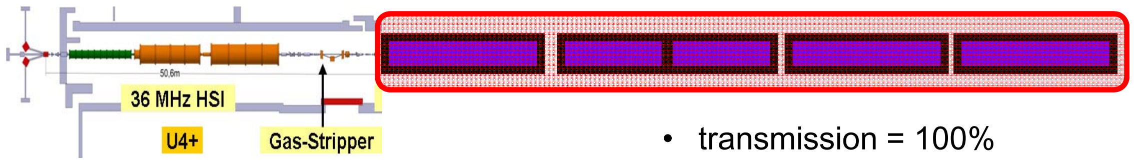


- simulation code: DYNAMION
- GSI´s has (also experimental) experience with high-current beam dynamics along Alvarez DTL
- straight forward recipe for matching to periodic solution (L. Groening, ICAP 2009)
- experience and benchmarking to exp. with DYNAMION, published (1 PRST-AB, 2 PRL)
- we chose $\sigma_{\perp 0}$ = 70° based on emittance growth measurements with space charge equivalent Ar beam

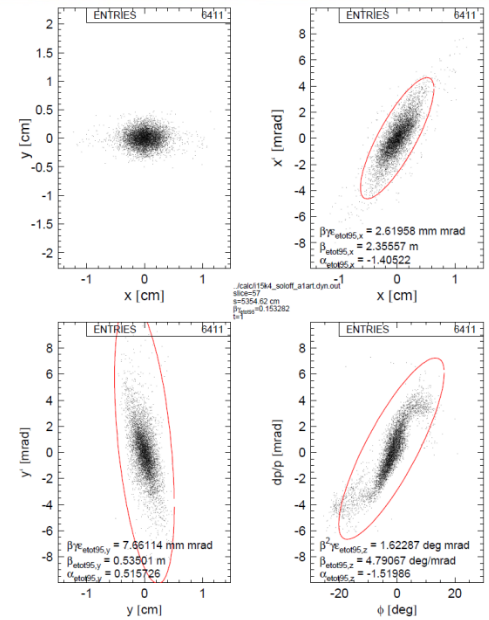


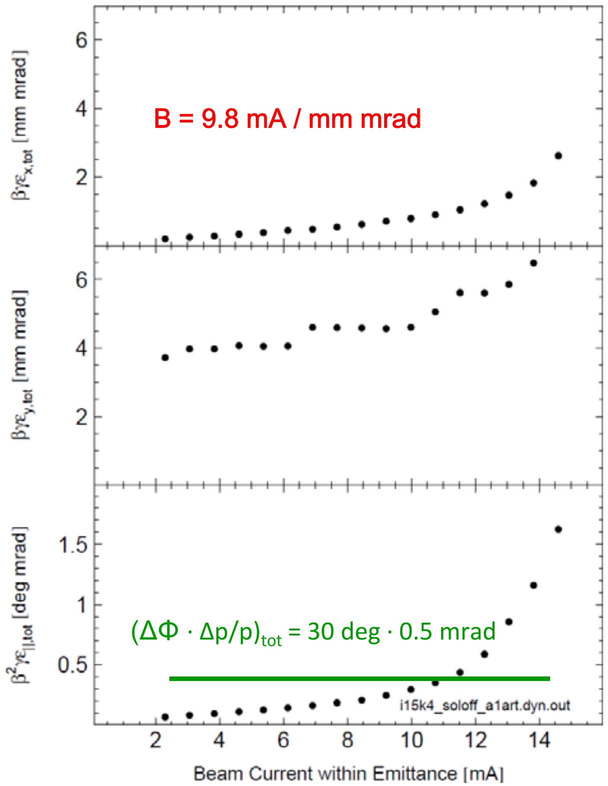
- for 70° with U, stronger quads needed wrt today

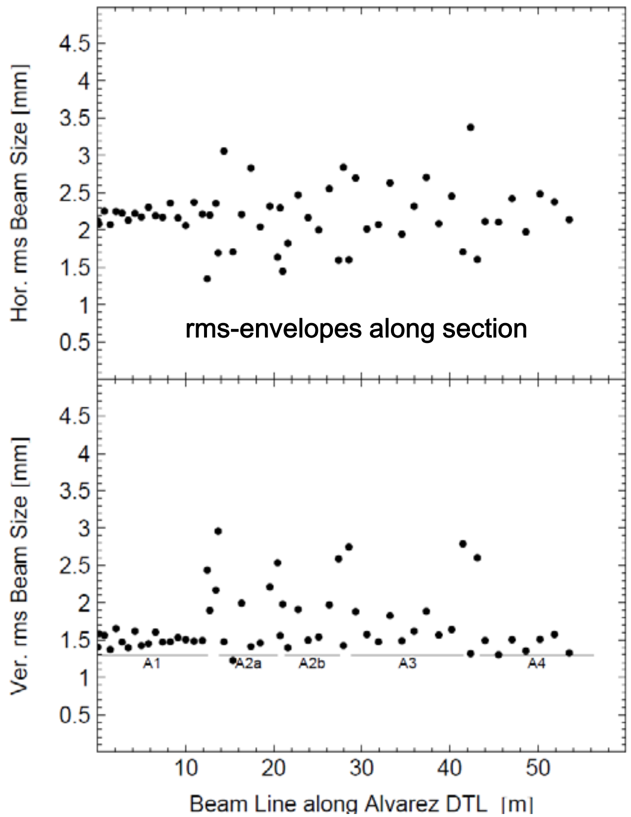
Front-to-End Simulations: Through Alvarez DTL

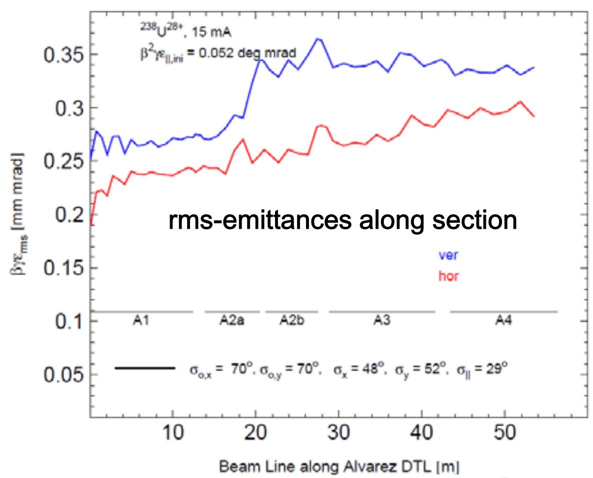


- transmission = 100%
- brilliance change = -34%



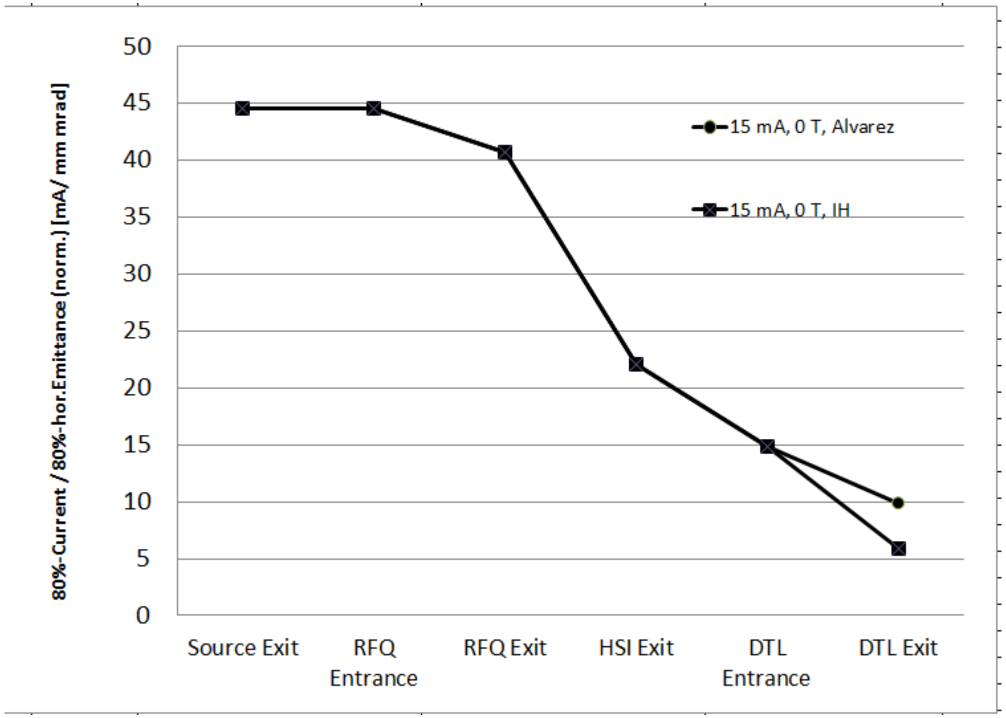






Front-to-End Simulations: Summary

development of horizontal brilliance along UNILAC



Summary

- brilliance decreases along all sections, mainly due to space charge
- less decrease along RFQ
- there is large potential to improve matching to and transport through IH-DTLs
- IH-DTL allows for energy upgrade
- simulations indicate maximum achivable hor. brilliance of about 10 mA/ mm mrad
- estimate based on simulations
- real operation will meet technological discomforts

Estimate of 3+ & 4+ currents from source

Least squares method implementation for our case

by Anna Orzhekhovskaya

Let us consider an equation

$$A(N,M)P(M) = B(N) \quad where \quad A(N,M) = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1M} \\ a_{21} & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ a_{N1} & \dots & \dots & a_{NM} \end{pmatrix}$$ - *matrix with coefficients,*

$$P(M) = (p_1 \quad p_2 \quad \dots \quad p_M)$$ - *vector of variables,*

$$B(N) = \begin{pmatrix} b_1 \\ b_2 \\ \dots \\ b_N \end{pmatrix}$$ - *vector of meanings.*

Then a *"solution"* of such over-defined linear system one can get as

$$P = (A^T A)^{-1} A^T B$$

Estimate of U^{3+} & U^{4+} currents from source

Based on an experimental experience and on the simulations results,
we limit ourself by only two charge states **3+** and **4+**

Two transverse phase planes **X-X'** and **Y-Y'** are under consideration **independently** !

Two independent *"solutions"* of such over-defined linear systems gives us
the most probable intensity ratio of U^{3+} and U^{4+} for the measured beam emittances:

Horizontal plane - 36% of U^{3+} and **64% of U^{4+}** intensity

Vertical plane - 39% of U^{3+} and **61% of U^{4+}** intensity

Estimate of 3+ & 4+ currents from source

Quadrupole Triplet +

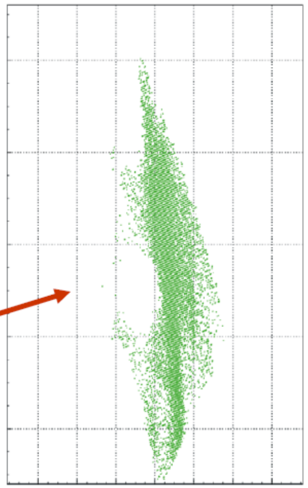
DYNAMION software =

virtual Charge State Separator

Only $\mathbf{U^{4+}}$ beam

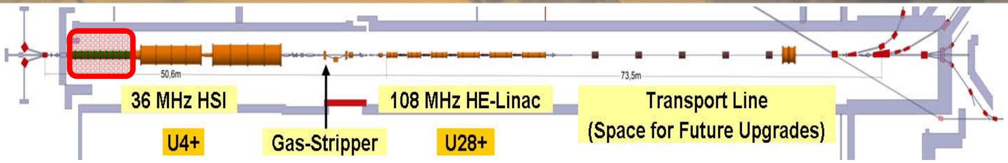
emittance & current

≈ 65 %
of total intensity is $\mathbf{U^{4+}}$

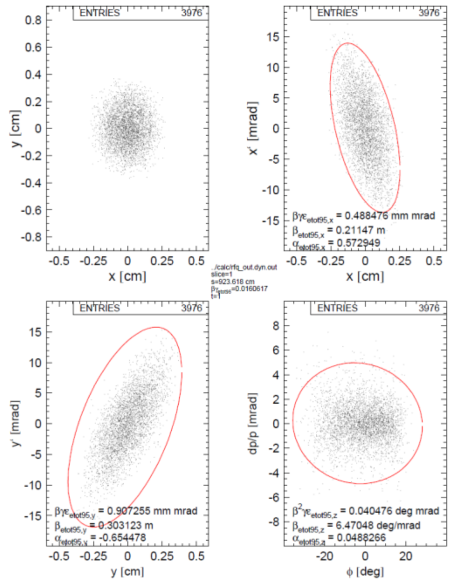


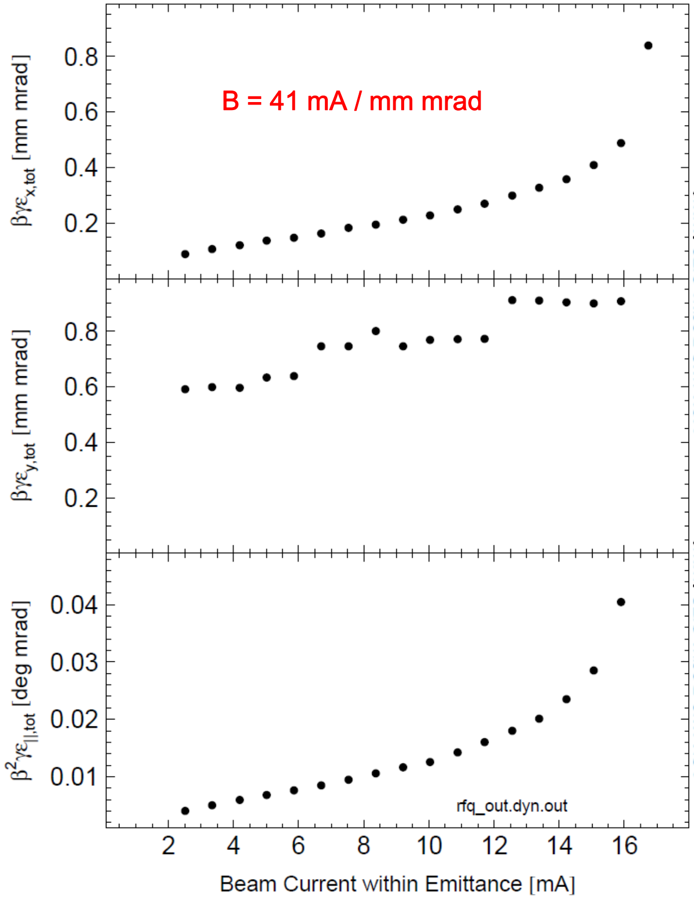
Preliminary measurements in June 2013 !

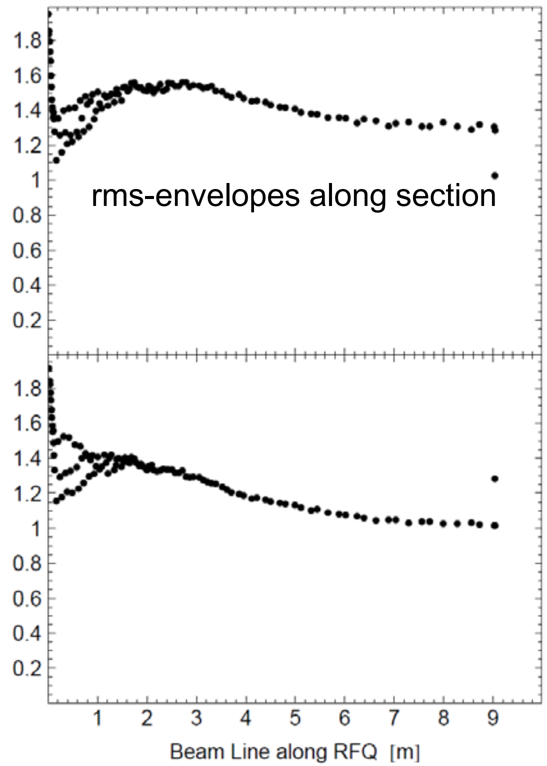
Front-to-End Simulations: through RFQ

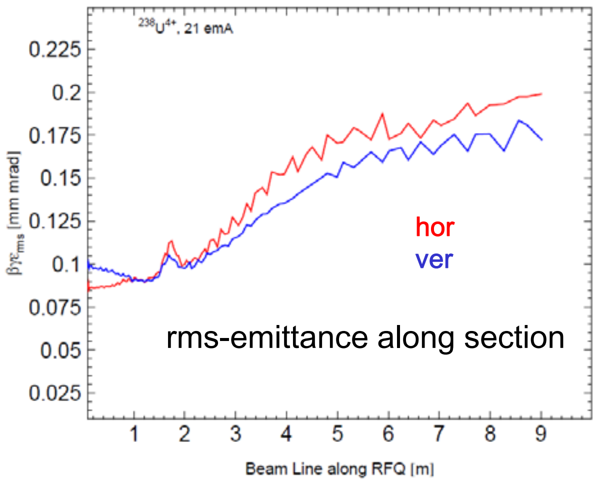


- DYNAMION code used
- existing RFQ assumed
- transmission = 80%
- brilliance change = -10%









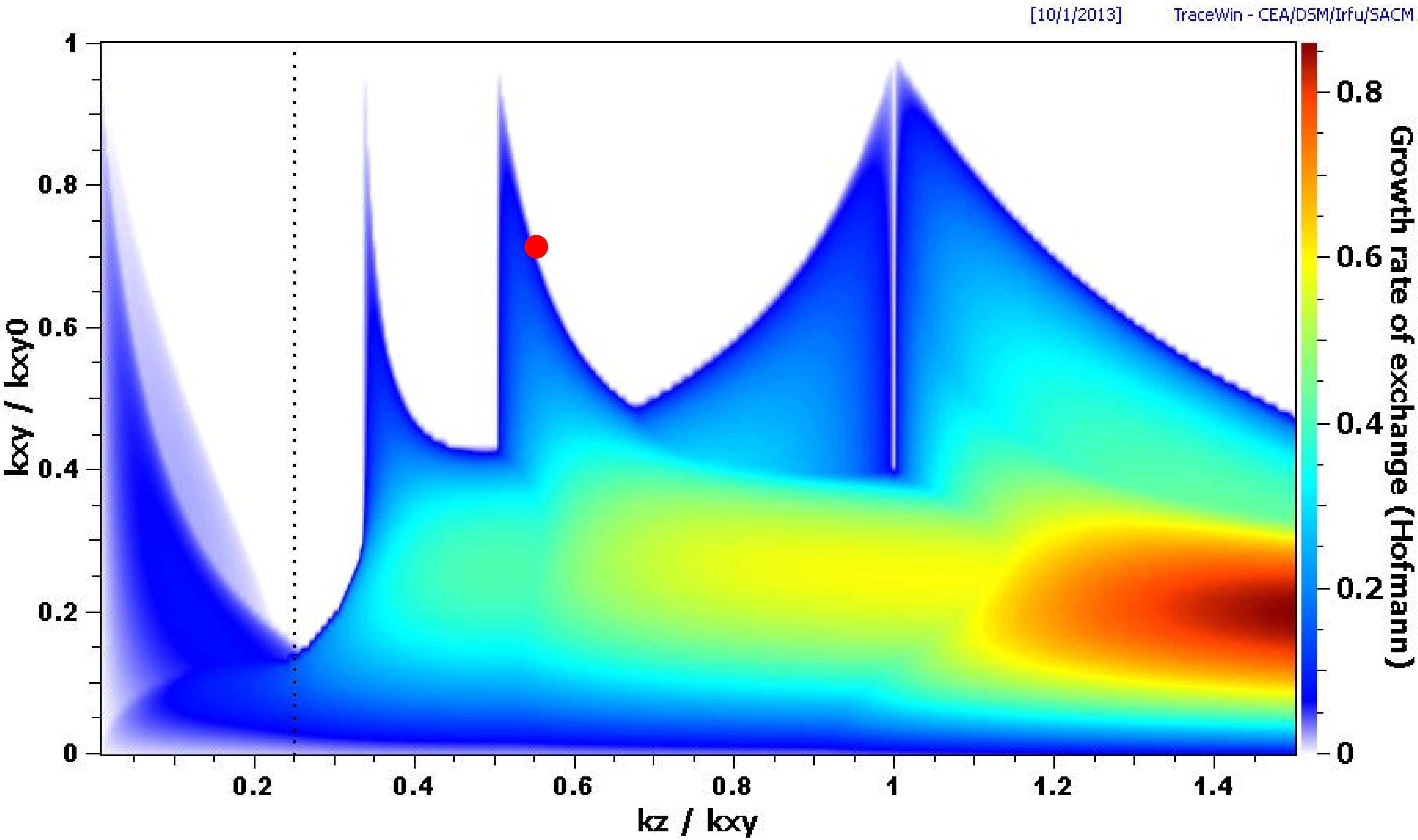
Space Charge Perveance along Linac

scales as

$$\frac{I\,q}{f_{rf}\ \gamma^3\beta^2}$$

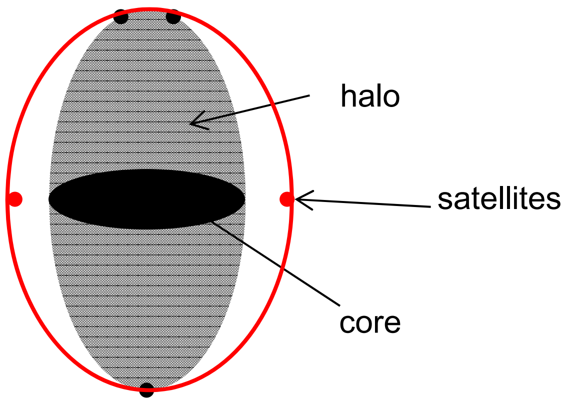
RFQ Exit	E [MeV/u]	0,12	7190
	beta	0,01605001	
	gamma	1,00012883	
	q	4	
	f [MHz]	36,136	
HSI Exit		1,4	554
		0,0547648	
		1,00150297	
		4	
		36,136	
DTL Entrance		1,4	3961
		0,0547648	
		1,00150297	
		28	
		36,136	
DTL Exit		11,4	477
		0,15503184	
		1,0122385	
		28	
		36,136	

Full Current, DTL Entrance



Why less included current gives larger ver. emittances?

- if the smallest enclosing ellipse is searched, one needs first to identify the outermost particles. If the wanted ellipse encloses them, the inner ones are enclosed automatically
- a useful definition of „outermost“ is not straight forward
- the strict definition suggests the 3 black & 2 red particles. This definition ignores the terms core, halo, and satellite
- a more practical definition defines as „outer“ those particles, which are most far away from the rms-ellipse being dominated by the core, i.e. just the 3 black particles. This definition we used, and the smallest ellipse is the grey one



- since the cutting procedure is just in hor. & long. plane, the cutting may cut particles from the vertical core instead of the 3 black particles! This core-cutting may change the rms-ellipse of the core. This in turn will change the „rms-outer“ particles of the whole distribution
- After some cutting using the rms-definition, it may happen that the „rms-outer“ particles are the 3 black & two 2 red particles. The smallest ellipse in that case is the red one
- Although the red ellipse encloses less particles it is larger than the grey one