

Alternating Phase Focusing Beam Dynamics for Drift Tube Linacs

**HIM****HELMHOLTZ**

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JGU



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International Conference on
**Accelerators for Research
and Sustainable Development:**
From Good Practices Towards Socioeconomic Impact



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**GSI Facility Overview
and New Accelerators at GSI**

Theory of Alternating Phase Focusing

**Applied Beam Dynamics Employing
Alternating Phase Focusing**

INTRODUCTION

- GSI is one of the worldwide leading centers for heavy ion research
- The GSI Super Heavy Element (SHE) program led to the discovery of six elements for the periodic table

$^{262}_{107}\text{Bh}$

$^{265}_{108}\text{Hs}$

$^{268}_{109}\text{Mt}$

$^{281}_{110}\text{Da}$

$^{280}_{111}\text{Rg}$

$^{277}_{112}\text{Cn}$

- GSI Helmholtzzentrum at Darmstadt pushes limits of accelerator technology:
 - Heidelberger Ion Therapy Center
 - Facility for Antiproton and Ion Research (FAIR)
- In the last 50 years the heavy ion Universal Linear Accelerator (UNILAC) was the main injector linac facility at GSI
- But UNILAC is going to be upgraded as a heavy ion injector Linac for the FAIR-facility

REQUIREMENTS FOR FAIR, THE “SHE”-PROGRAM, AND MATERIAL SCIENCE AT GSI

Facility for Antiproton and Ion Research (FAIR) requirements:

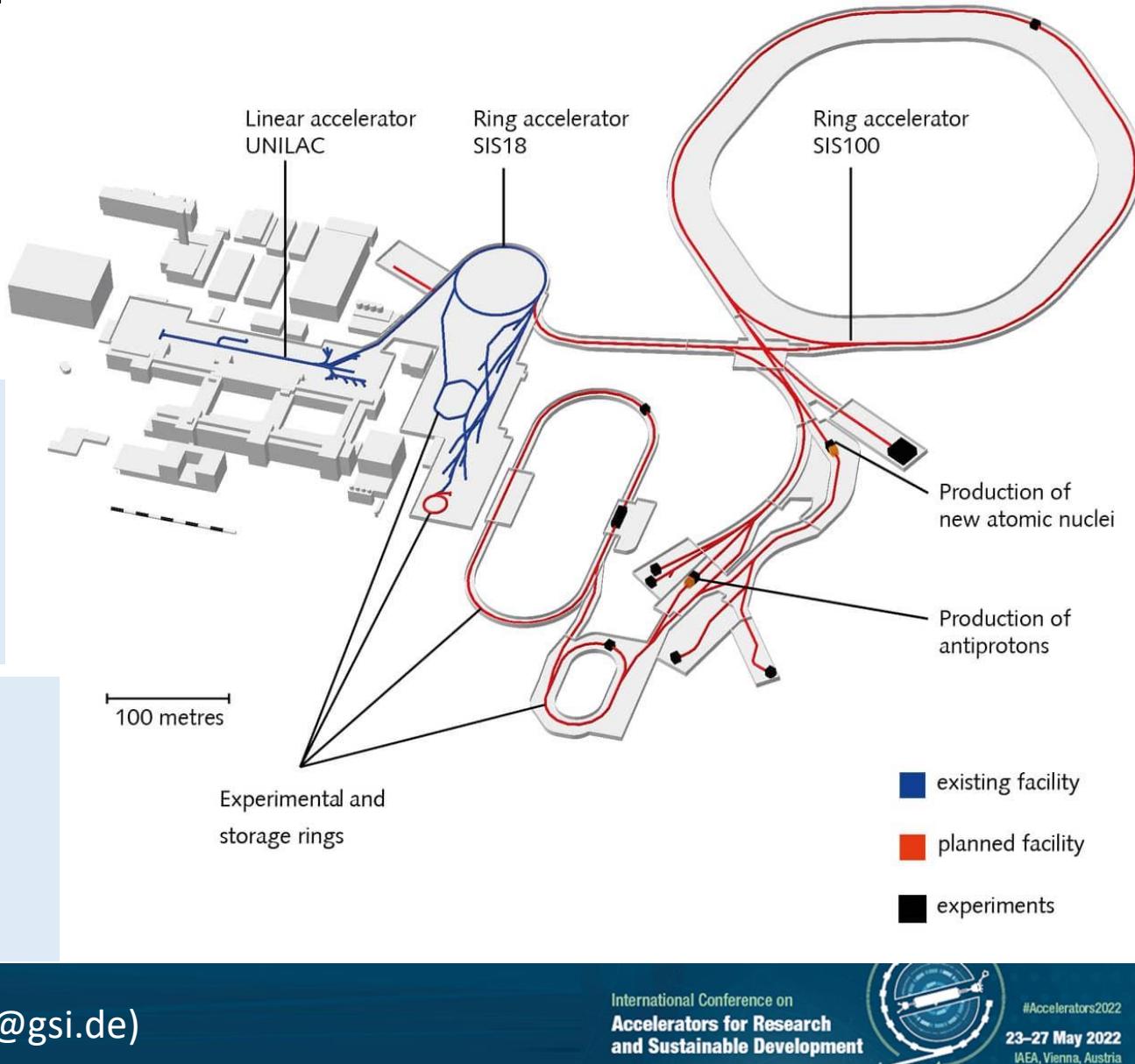
- High beam currents
- Low repetition rate (max. 3 Hz)
- Low duty factor

Super Heavy Element (SHE) requirements:

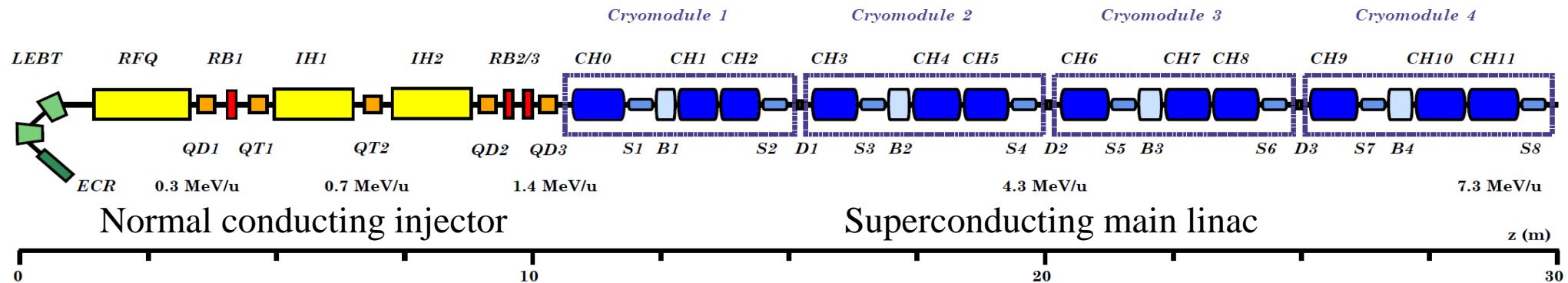
- Relatively low beam currents
- High repetition rate (50 Hz)
- High duty factor (100 %, pulse length up to 20 ms)

Material Science at GSI requirements

- Heavy ions ($m > 200$)
- Beam energy (up to 10 MeV/u)
- Smoothly variable beam energy (1.5 – 10 MeV/u)



A NEW ACCELERATOR FOR SHE RESEARCH



A new dedicated CW capable accelerator is under construction:

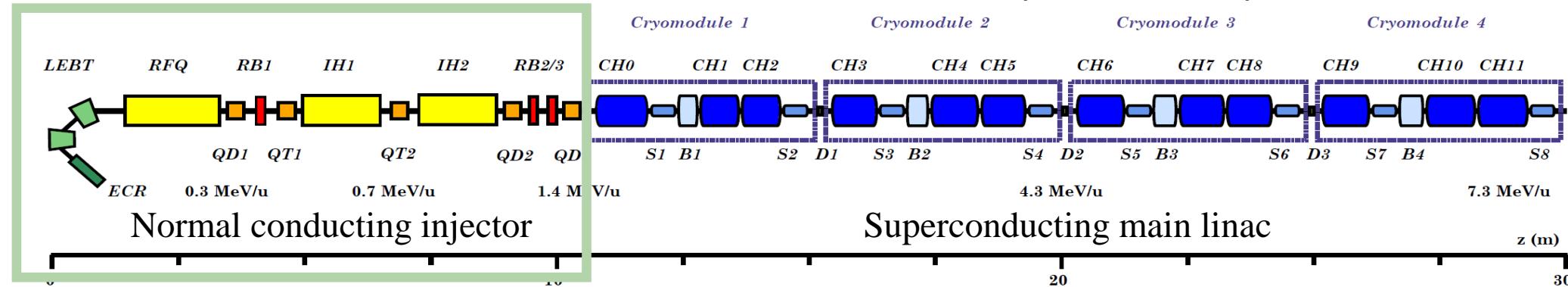
HElmholtz LInear Accelerator



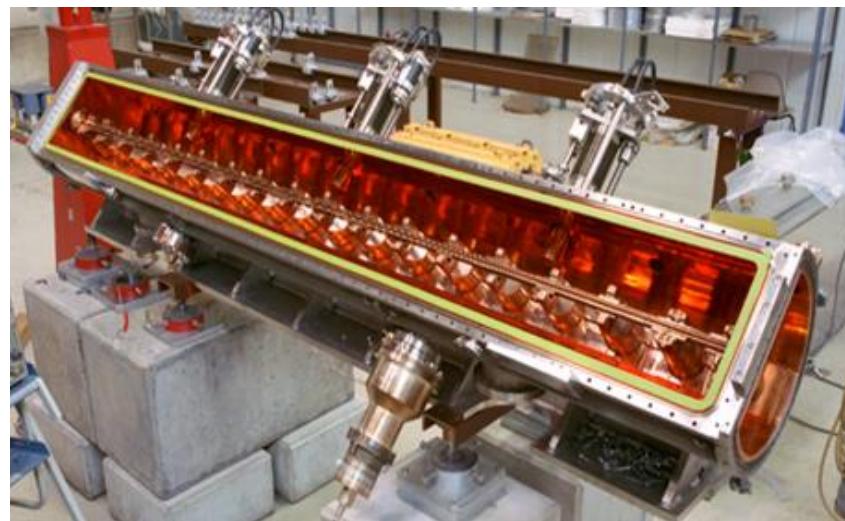
Common project of HIM and GSI
under key support of IAP

	Design Value
Mass-to-charge ratio	≤ 6
Frequency	108.408 (216.816) MHz
Injection energy	1.4 MeV/u
Output energy	3.5–7.3 MeV/u
Output energy spread	± 3 keV/u
Max beam current	≤ 1 mA
Operation mode	continuous wave (CW)

HELMHOLTZ LINEAR ACCELERATOR (HELIAC)

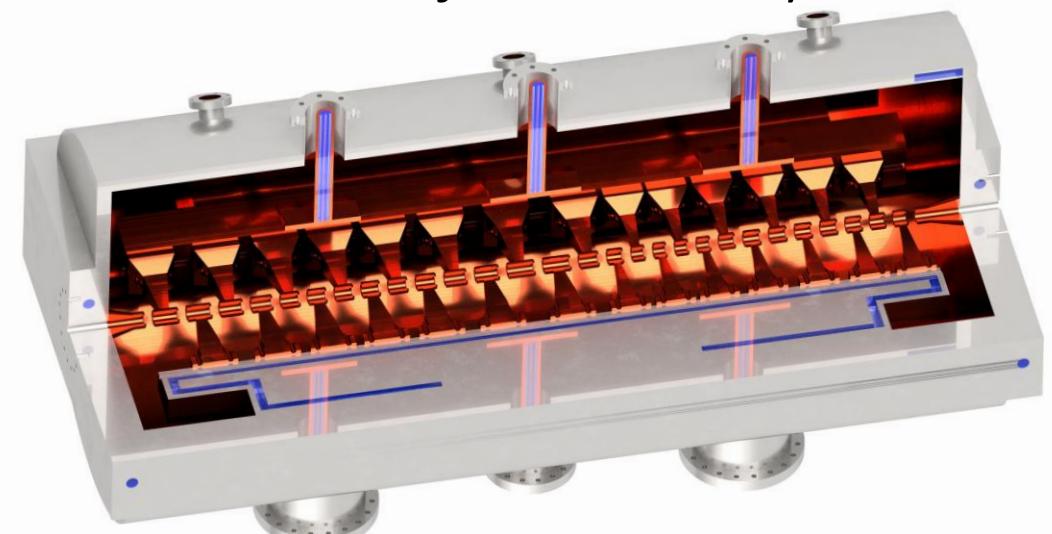


Radio Frequency
Quadrupole

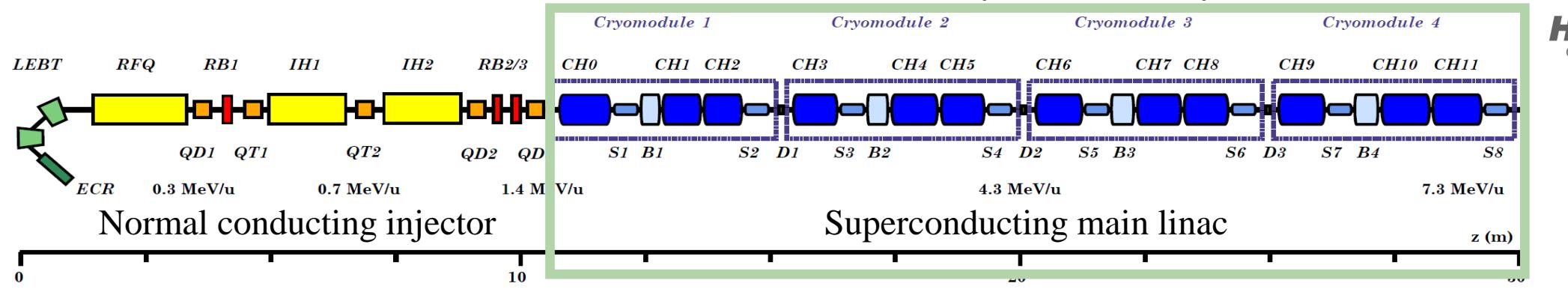


Superconducting main linac

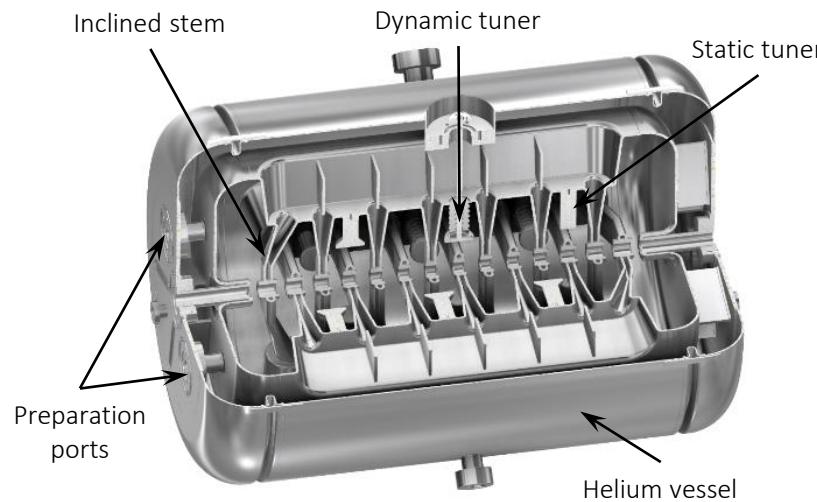
Normal Conducting
APF Injector Cavity



HELMHOLTZ LINEAR ACCELERATOR (HELIAC)



Cavity CH0



Cold string assembly



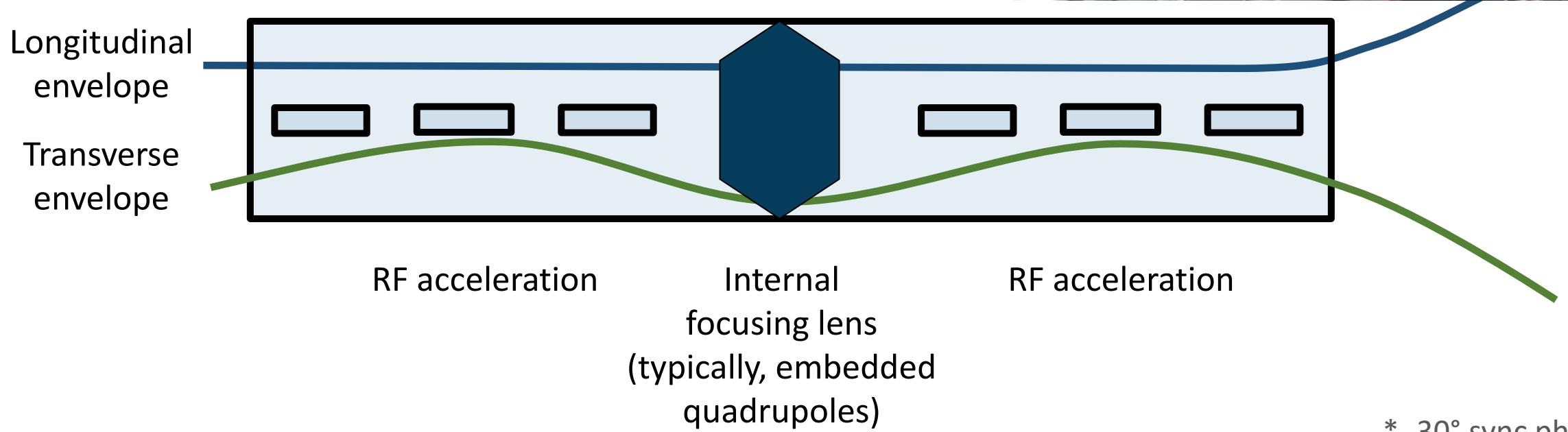
Cryomodule 1

THEORY OF ALTERNATING PHASE FOCUSING

DRIFT TUBE LINAC CONCEPTS

Conventional* Heavy Ion Drift Tube Linac (DTL)

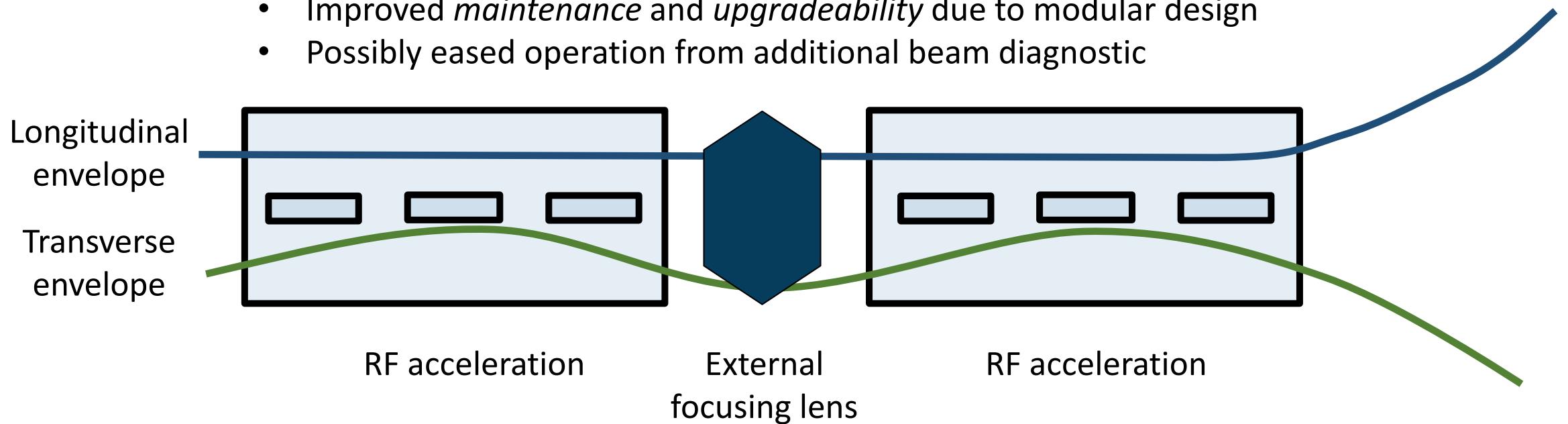
- Costly internal lenses of conventional DTLs



DRIFT TUBE LINAC CONCEPTS

Short Cavities with external lenses

- Improved *maintenance* and *upgradeability* due to modular design
- Possibly eased operation from additional beam diagnostic

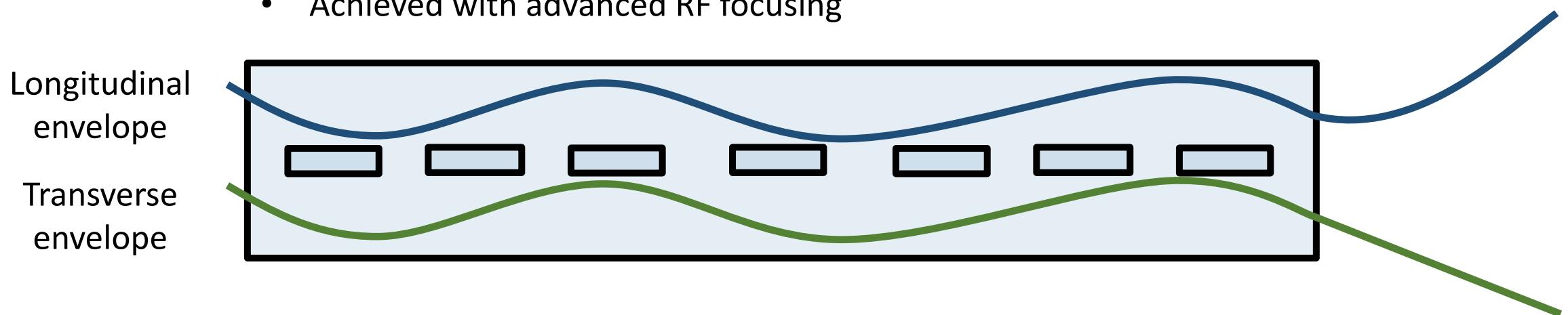


DRIFT TUBE LINAC CONCEPTS

Alternating Phase Focusing Cavity

(J. H. Adlam, 1953; M. Good, 1953, Y. Fainberg 1957)

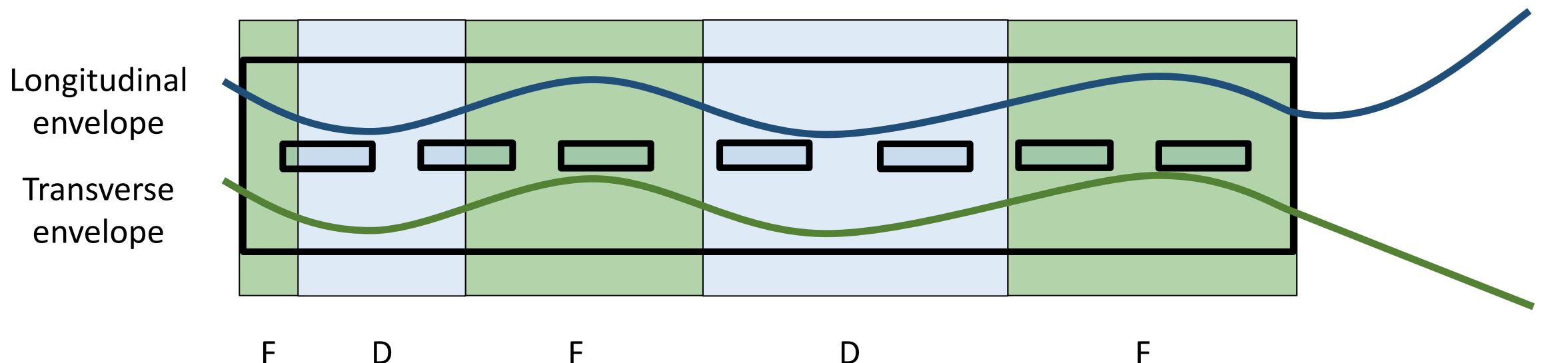
- ..Or even one RF cavity without additional focusing
- Achieved with advanced RF focusing



ALTERNATING PHASE FOCUSING

Alternating Phase Focusing Cavity

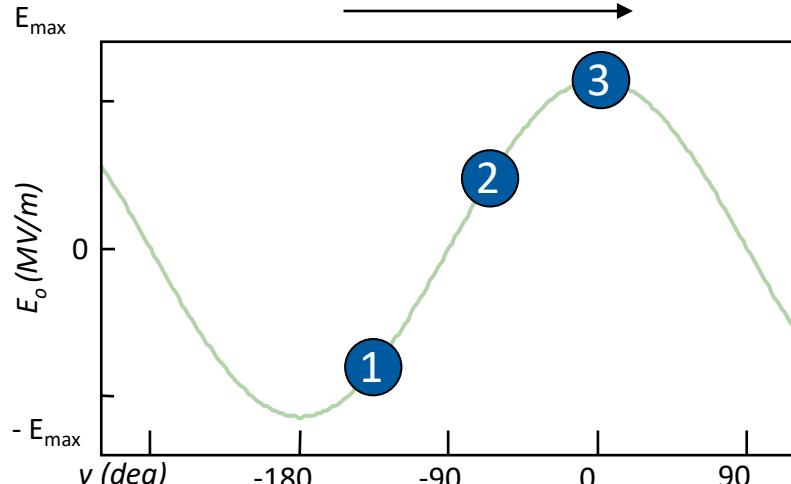
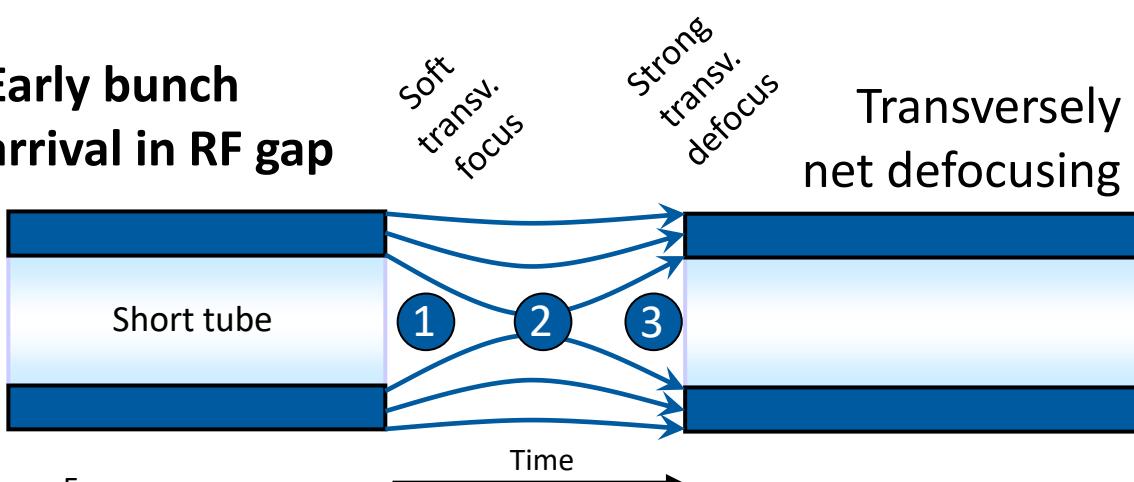
- Alternating focusing (F) and defocusing (D)
- Special timing of the bunch with respect to RF phase necessary



F: Focusing
D: Defocusing

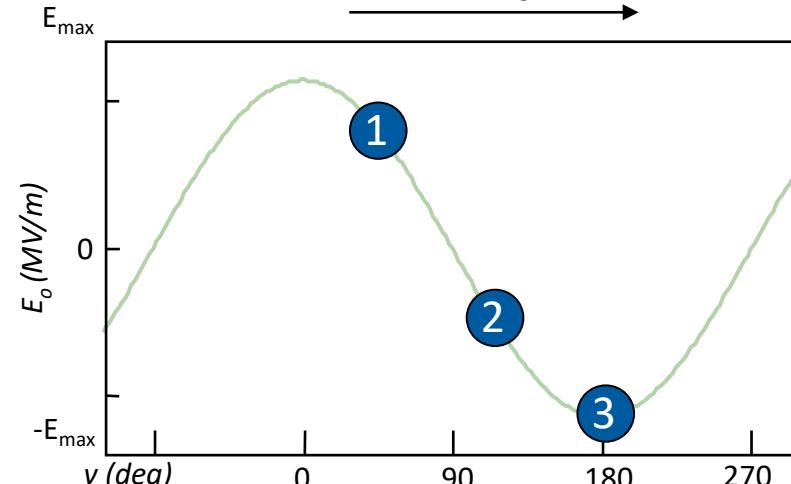
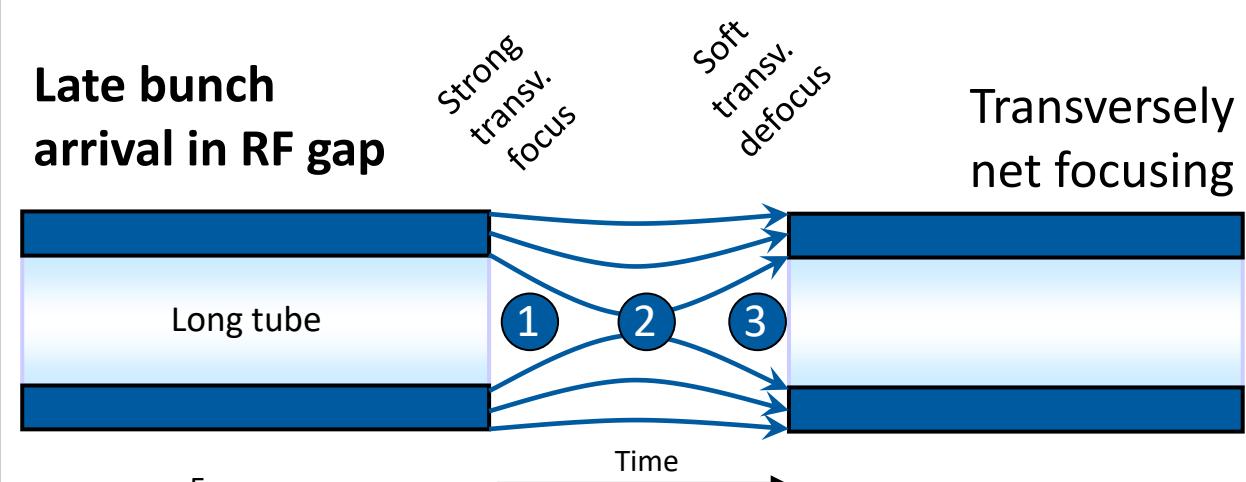
ALTERNATING PHASE FOCUSING

Early bunch arrival in RF gap



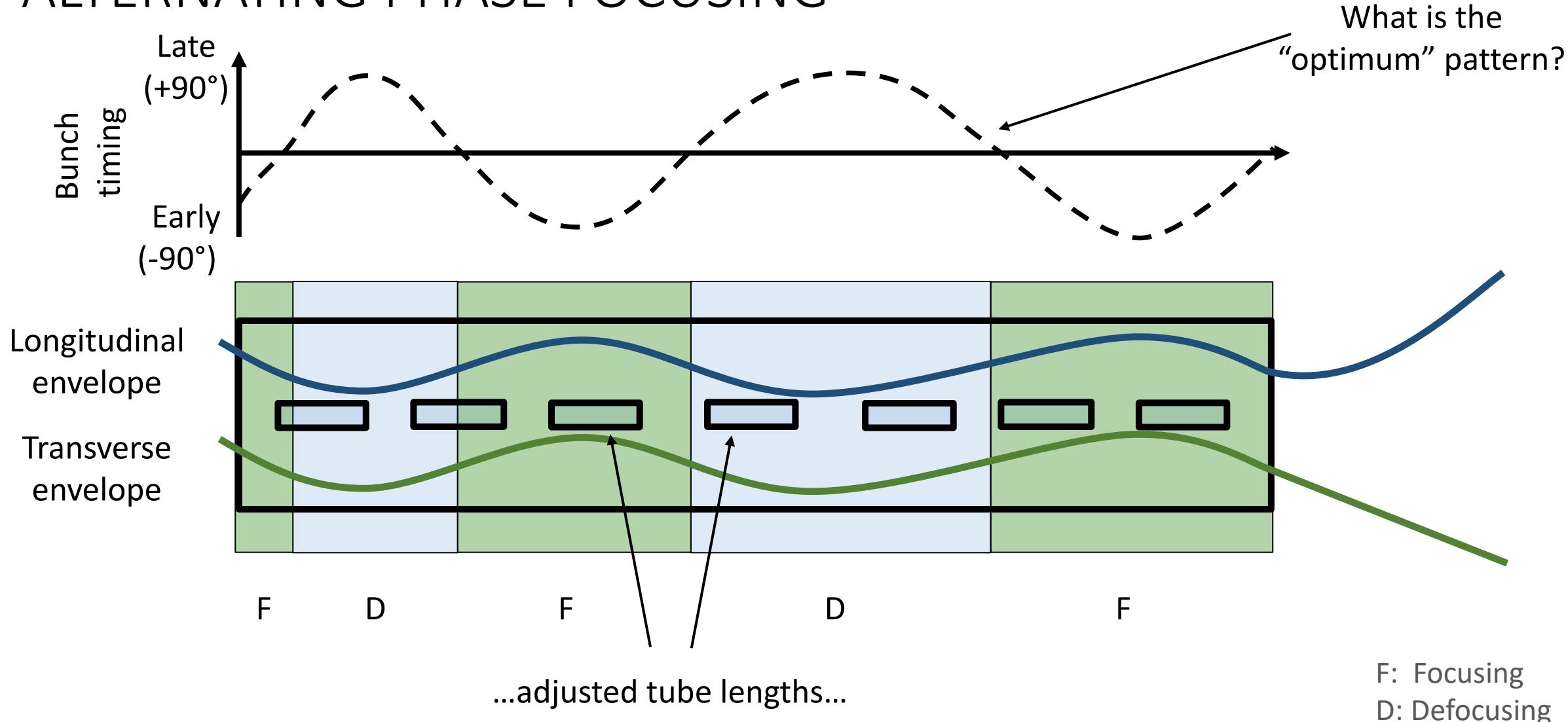
Longitudinal net focusing

Late bunch arrival in RF gap



Longitudinal net defocusing

ALTERNATING PHASE FOCUSING



ALTERNATING PHASE FOCUSING

PROS

- Embedded transverse focusing
 - Highly reduced number of control parameter (retaining tank phase & voltage)
- No additional lenses necessary
- Reduced construction and operation costs
(U. Ratzinger, 1999)
- Applicable for superconducting (SC) accelerators
 - Absence of internal focusing lenses required due to SC breakdown limits
- Applicable to other resonance accelerator systems, e.g., dielectric laser acceleration
(U. Niedermayer, 2018)

CONS

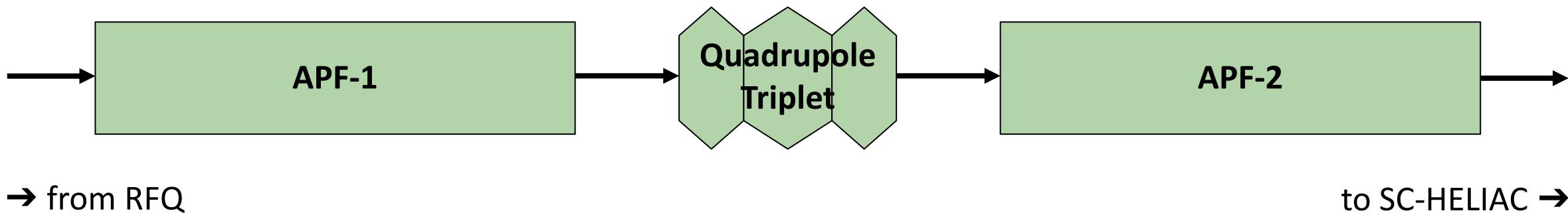
- High demand for expertise
- Modern beam dynamics solver is mandatory
- Increased R&D efforts
 - No consensus on optimum design
- Tight tolerance specifications
(V. Kapin, 2004)
- Low experience in operating such linacs beyond HIMAC for medical treatment
(Y. Iwata, 2006)



A NEW APF DTL FOR THE HELIAC INJECTOR LINAC

Advanced APF DTL design
as dedicated heavy ion injector linac





Hybrid approach incorporating APF focusing has been designed (S. Lauber, 2022)

- Two energy-efficient Interdigital H-Mode (IH) cavities
 - For increased adaptability when operation with different ions (A/Q 1 to 6)
 - Additional quadrupole triplet is installed

This solution with longer tanks is not available from conventional* beam dynamics

- Transverse RF defocusing demands more (quadrupole) lenses

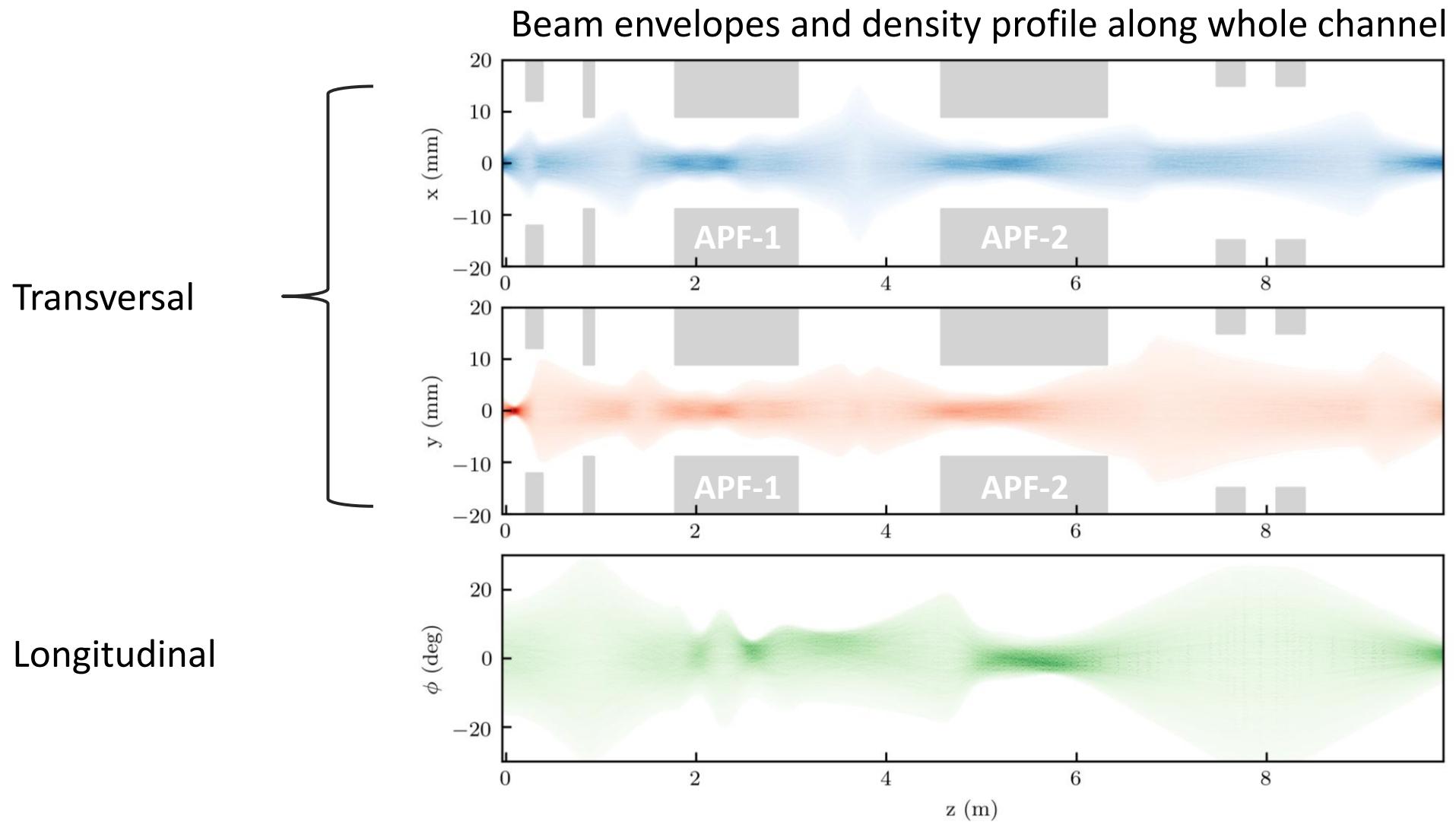
Design with two separate cavities offers:

- Low emittance growth
 - Reduced number of control parameters, yet flexible operation
 - Cooling concept for continuous wave operation
 - Additional beam diagnostics installed to the intertank

* -30° sync phase



BEAM DYNAMICS DESIGN OF THE ENTIRE DTL SECTION



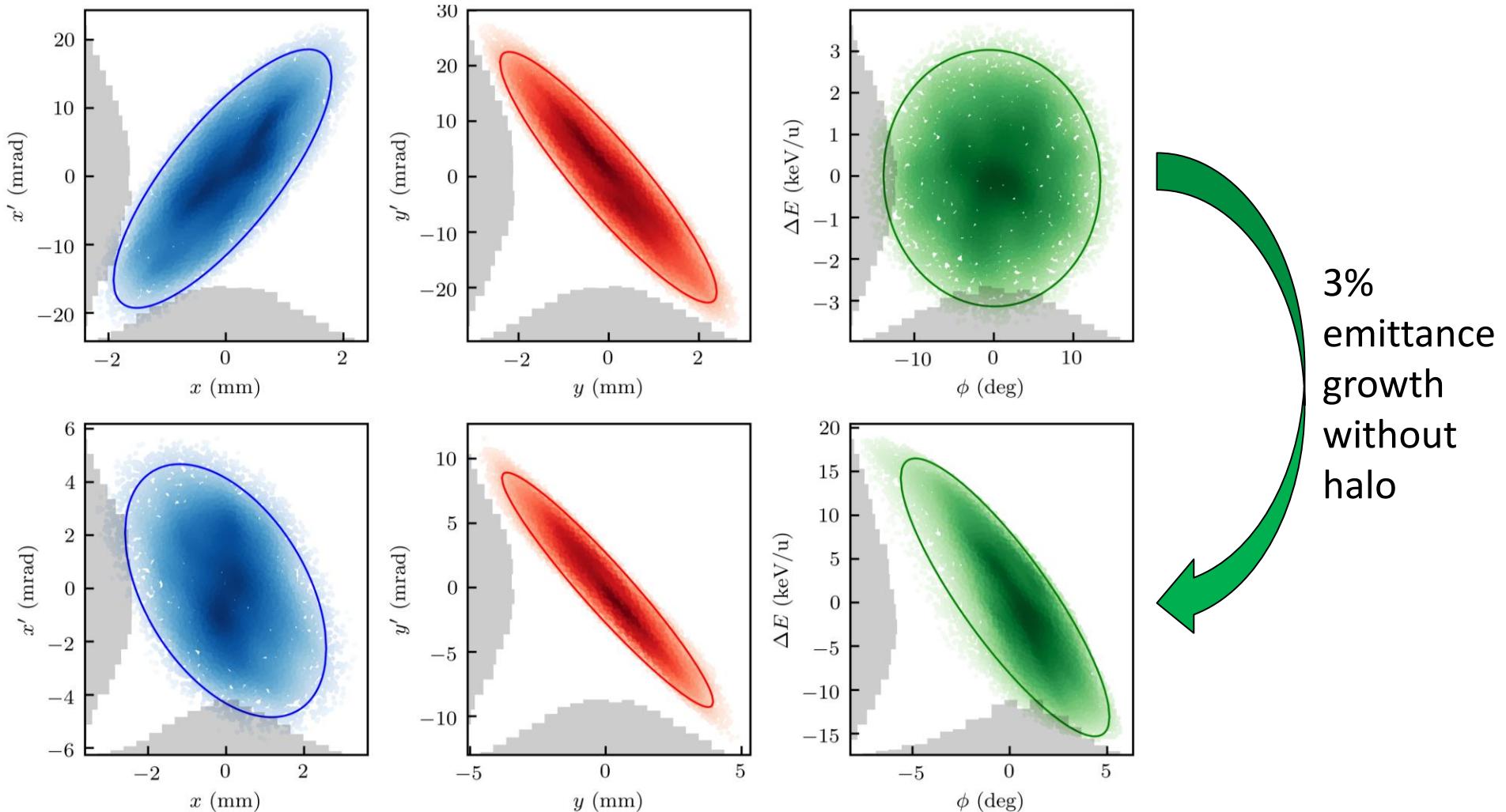
BEAM DYNAMICS DESIGN OF THE ENTIRE DTL SECTION

RFQ Output

~8%
emittance
growth
without
halo

IH2 Output

Beam input and output in three main phase planes



CONCLUSION 1/2

APF DTLs are an attractive approach to deliver high beam quality

- Effective acceleration → compact
- Low number of control parameters
- Time-efficient commissioning
- Reliable operation
- Reduced construction costs

CONCLUSION 2/2

- Reliable operation at the medical accelerator HIMAC
- Continuous wave operation with various ion species at HELIAC
 - An IH Cavity with embedded APF beam dynamics designed
 - High beam quality
 - Full transmission
- Discovery of new superheavy elements with assistance of this new linac HELIAC
 - Fundamental physis research
 - Improving quantum-chemical model of atoms
 - Promoting for advanced chemical applications and material research

Thank you
for your attention!

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23–27 May 2022

IAEA Headquarters, Vienna, Austria