Advanced Beam Dynamics Workshop on High Intensity and High-Brightness Hadron Beams

Alternating Phase Focusing Under Influence of Space Charge Defocusing

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INTRODUCTION

What is alternating phase focusing?

Linac design without space charge

Lessons learned during APF design

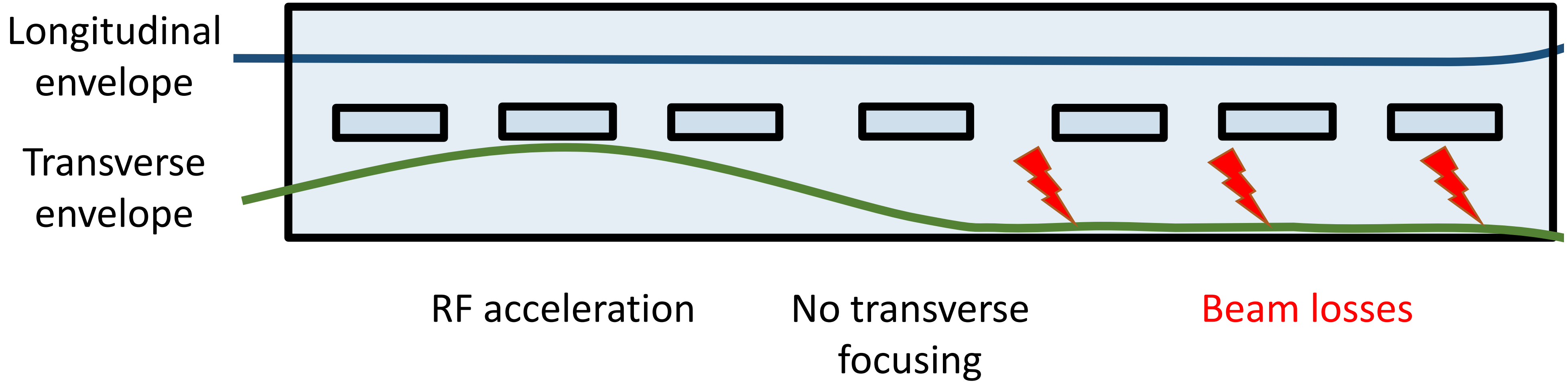
New software capabilities: Tech-demo with space charge

WHAT IST
ALTERNATING PHASE FOCUSING?

MOTIVATION

Without magnetic focusing inside the cavity, a high share of beam might be dumped to the walls.

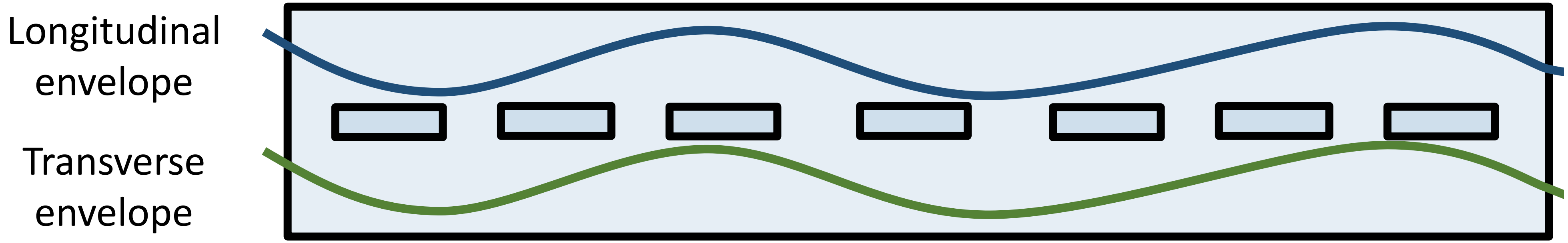
Thus, only short cavities are feasible without magnetic focusing?



MOTIVATION

Alternating Phase Focusing Cavity (proposed in 1950s)

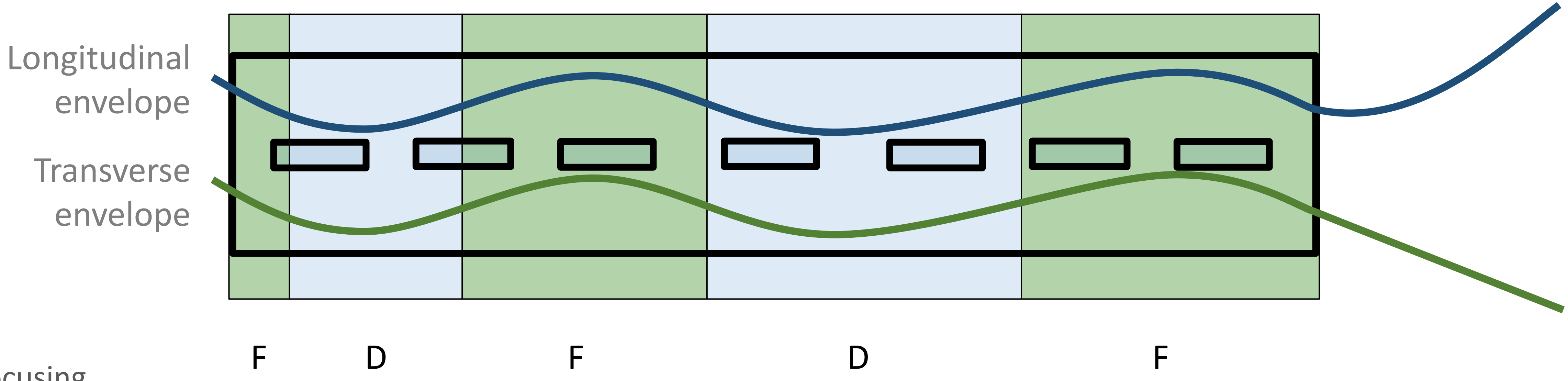
- Removes magnetic focusing lenses from the DTL
- Achieved with advanced *electric* focusing



BASICS OF ALTERNATING PHASE FOCUSING

Alternating Phase Focusing Cavity

- Removes magnetic focusing lenses from the DTL
- Achieved with advanced electric focusing
- Alternating focusing (F) and defocusing (D)
- Special timing of the bunch with respect to RF phase required

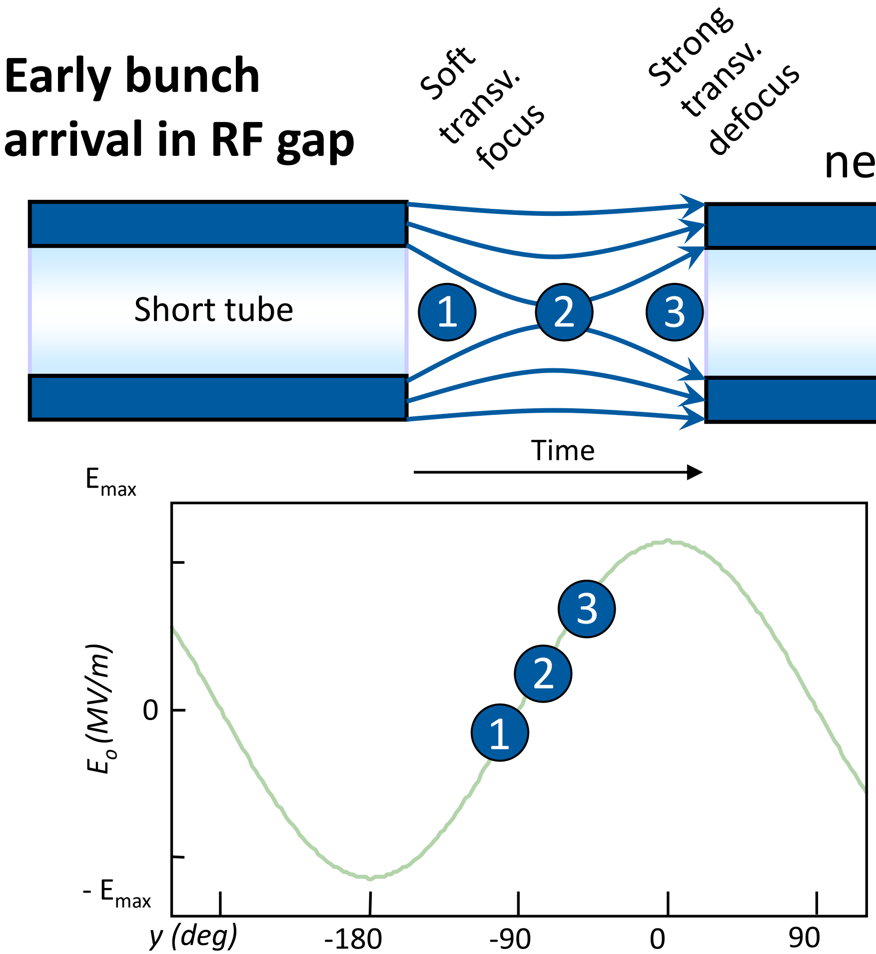


F: Focusing
D: Defocusing

BASICS OF ALTERNATING PHASE FOCUSING

Early bunch arrival in RF gap

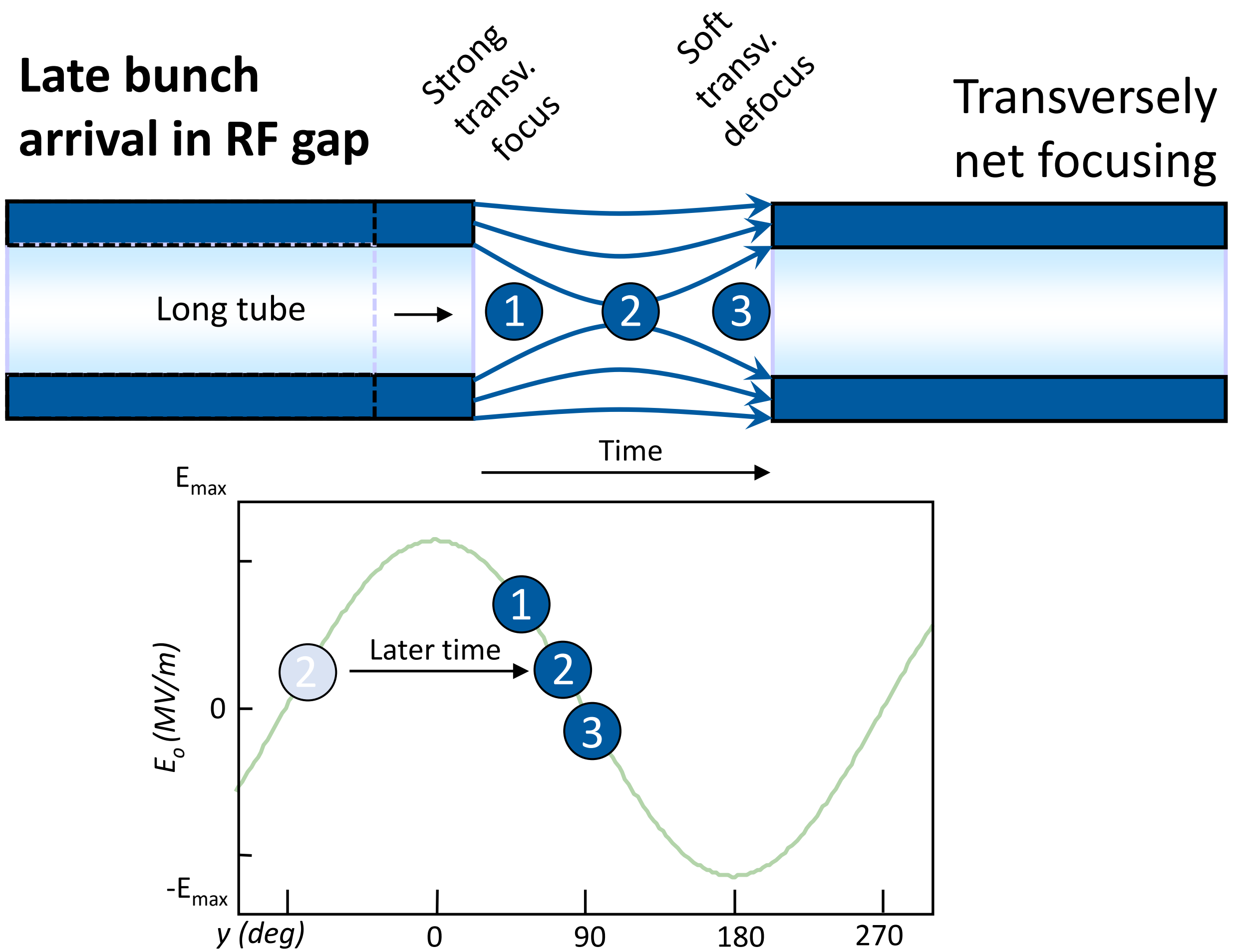
Transversely net defocusing



Longitudinal net focusing

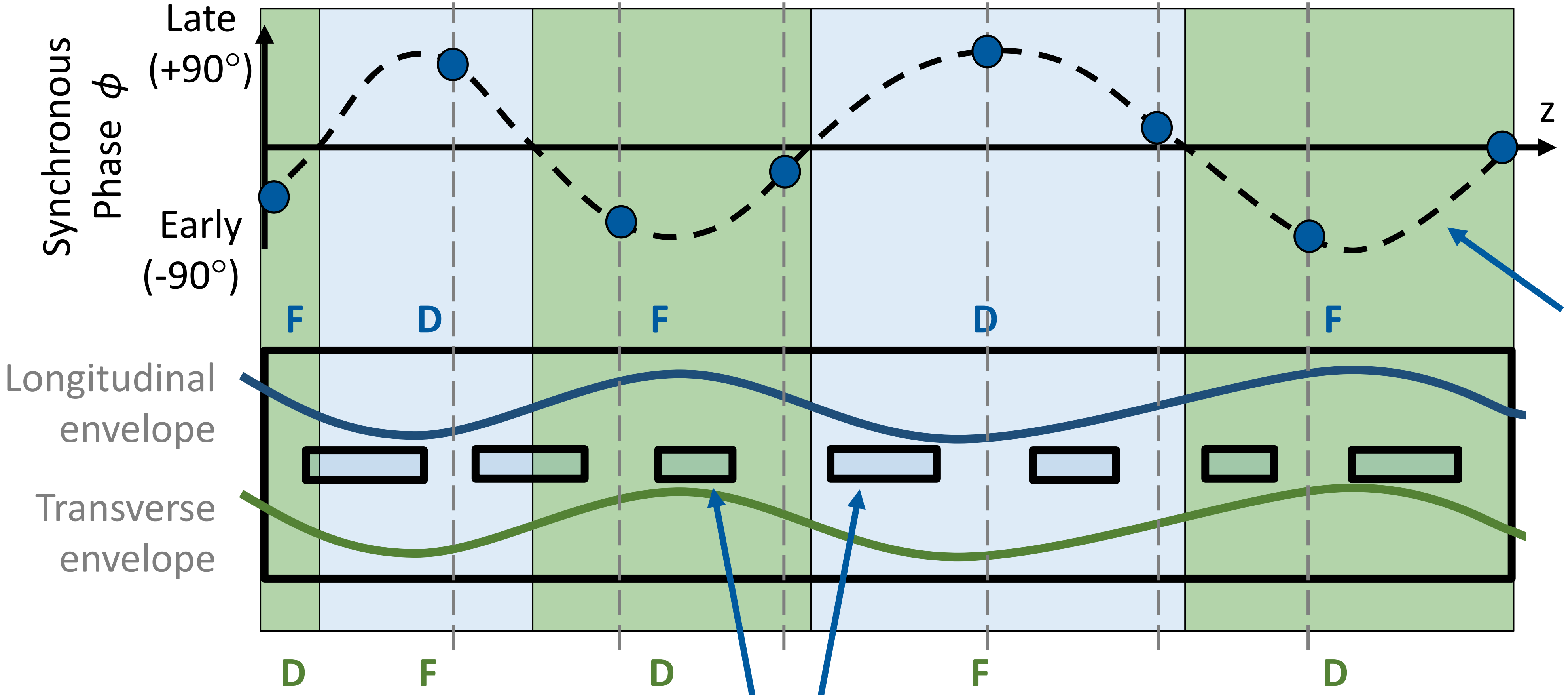
Late bunch arrival in RF gap

Transversely net focusing



Longitudinal net defocusing

BASICS OF ALTERNATING PHASE FOCUSING



What is the "optimum" phase-profile?

…adjusted tube length: $L_{\text{cell}} = \frac{\beta\lambda}{2} + \beta\lambda\frac{\Delta\phi}{360°}$

F: Focusing
D: Defocusing

Several phase-profiles were presented during the last decades:

- Sinusoidal
- Stepfunction
- Heavyside
- Sawtooth

$$\phi_i = \alpha \cos\left(\frac{\omega t}{n}\right)$$

$$n = \sqrt{\frac{\beta}{A(1-\beta^2)^{3/2}}}$$

$$A = \frac{\alpha}{\pi}\frac{e\bar{E}\eta\lambda}{mc^2}$$

[Fainberg 1956]

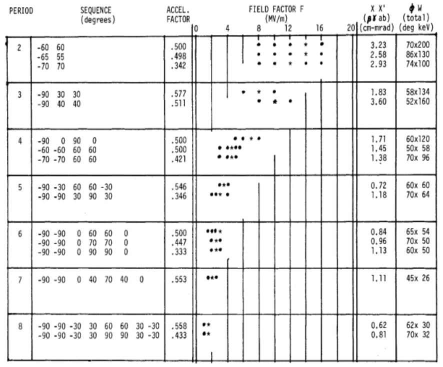


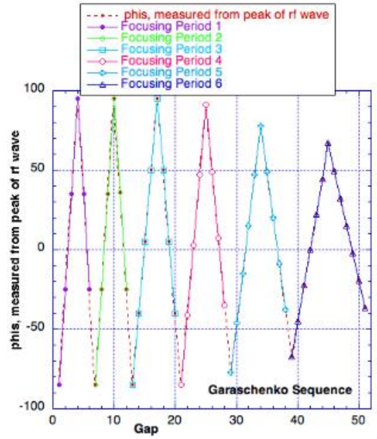
FIGURE 1 Array of basic phase sequences with excitation and performance data.

[Swenson 1975]

Table 3
Main parameters for final HSC linac design.

	RFQ	GBP+DTs
Charge to mass ratio (q/A)	6/12 (C^{6+})	
Operation frequency (MHz)	100	
Total length (mm)	1800	
Power (kW) (MWS)	93.98	
Q value (MWS)	14577	
ERT length (mm)	150	
Maximum field (Kipat.)	1.8	
Number of cells	41	1+16
Synchrotron phase	−90 → −30	0, −60, −30, 30, 30

[Lu 2012]



[Garschenko 1982, Jameson 2015]

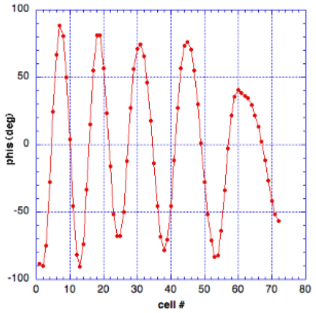
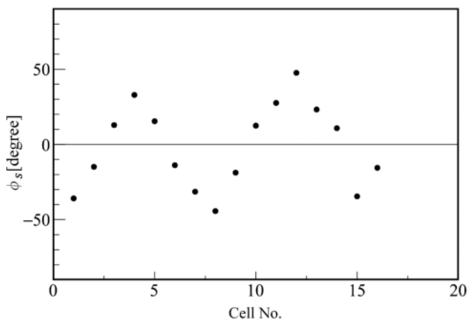
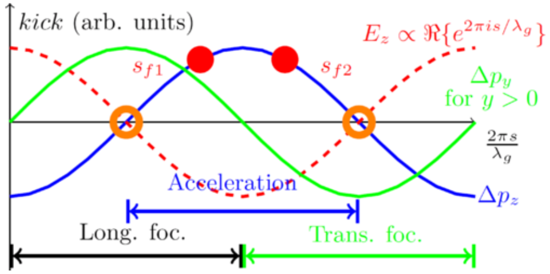


Fig. 3. The NIRS APF sequence. (Courtesy of NIRS.)

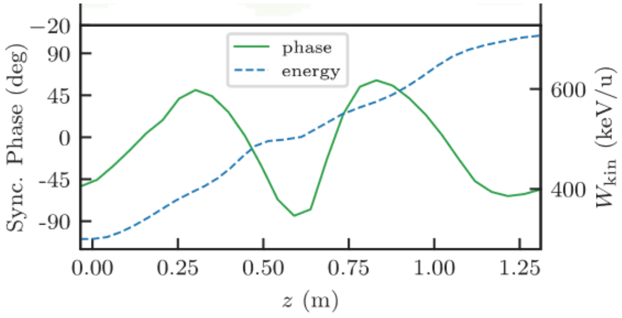
[Iwata 2006, Jameson 2015]



[Otani 2016]



[Niedermayer 2018]



[Lauber 2022]

HISTORY

First theoretic proposal of alternating phase focusing (APF) [Adlam 1953, Good 1953, Fainberg 1957]

3.4m medical $^{12}C^{4+}$ injector **operated** based on APF [Iwata 2007]

APF@J-PARC Muon Linac **operated** [Otani 2022]

First (?) APF DTL **operated** at Dubna [Jameson 2015]

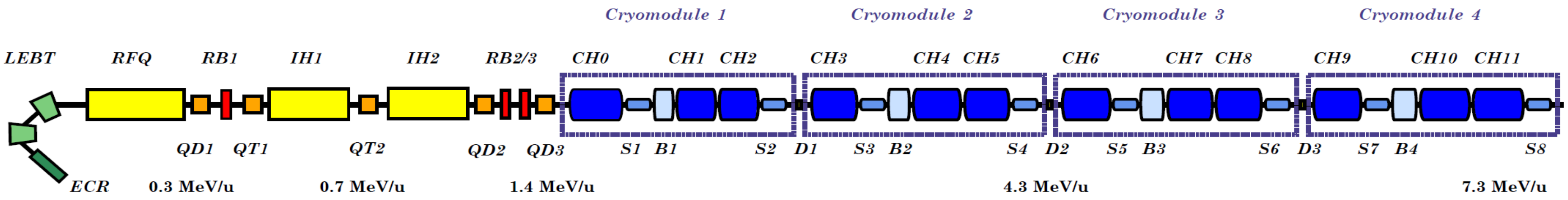
Hybrid single cavity linac (RFQ+APF-IH) **operated** [Lu 2012, Lu 2015]
Dielectric-Laser Acceleration proposed [Niedermayer 2018]

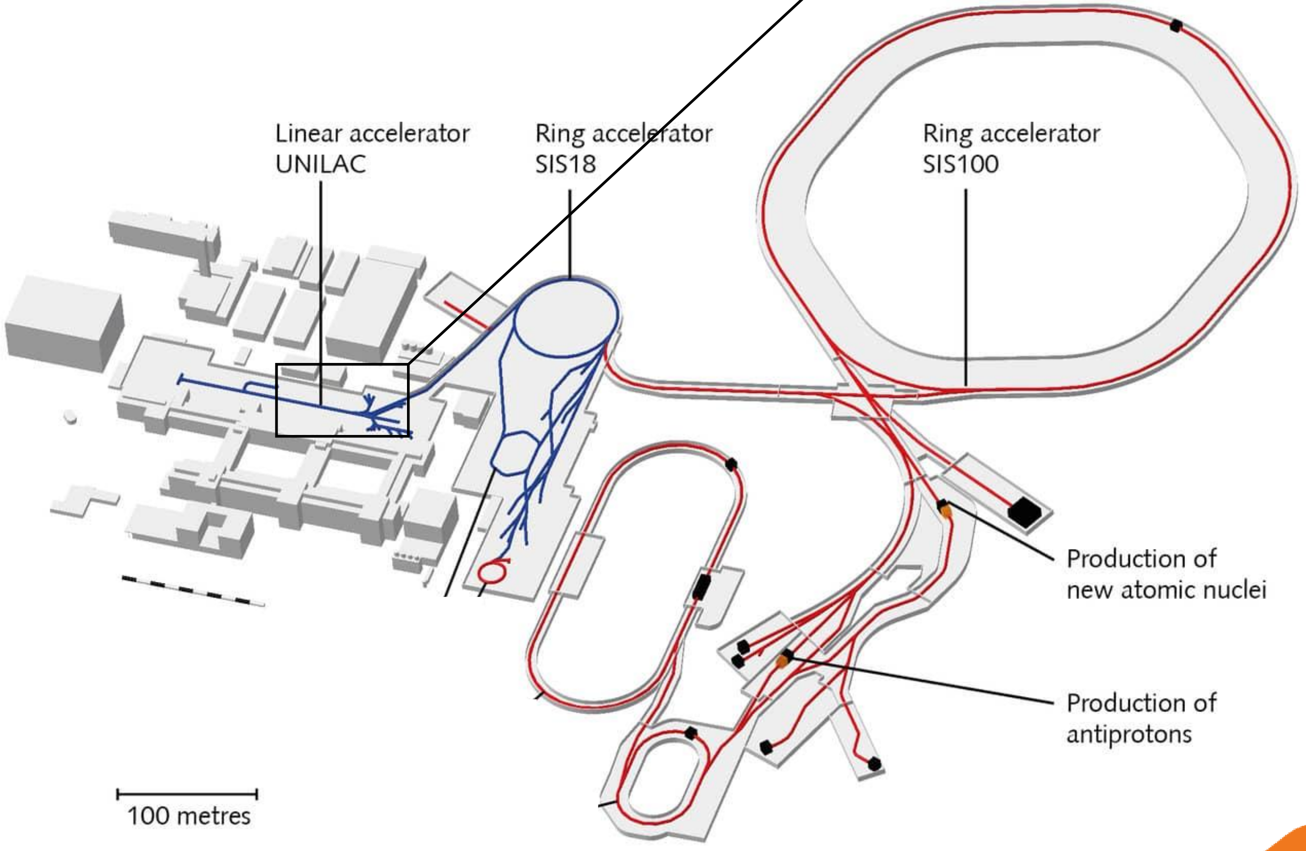
APF-IH @ Helmholtz Linear Accelerator [Lauber 2022]

LINAC DESIGN WITHOUT SPACE CHARGE

APF-IH @ Helmholtz Linear Accelerator

GSI/FAIR & HELMHOLTZ LINEAR ACCELERATOR





A new continuous wave accelerator is under construction for superheavy ion research:

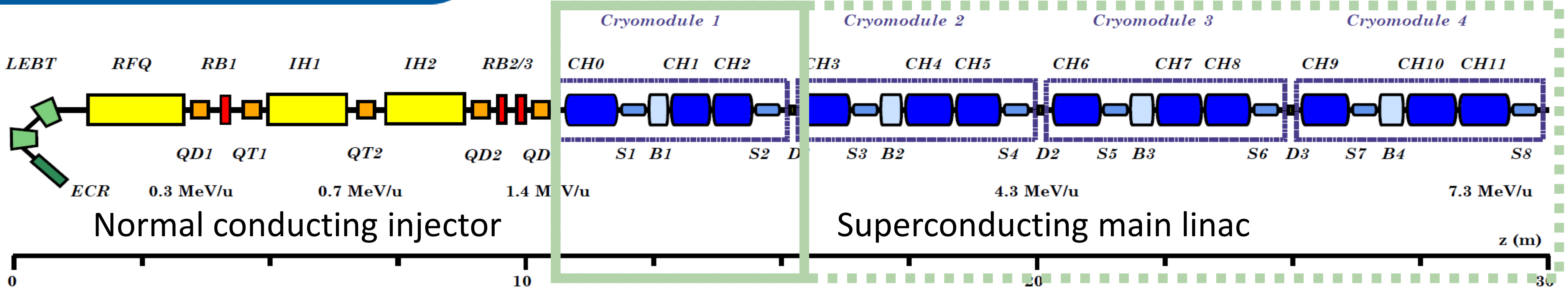
HElmholtz LInear Accelerator

Common project of HIM and GSI

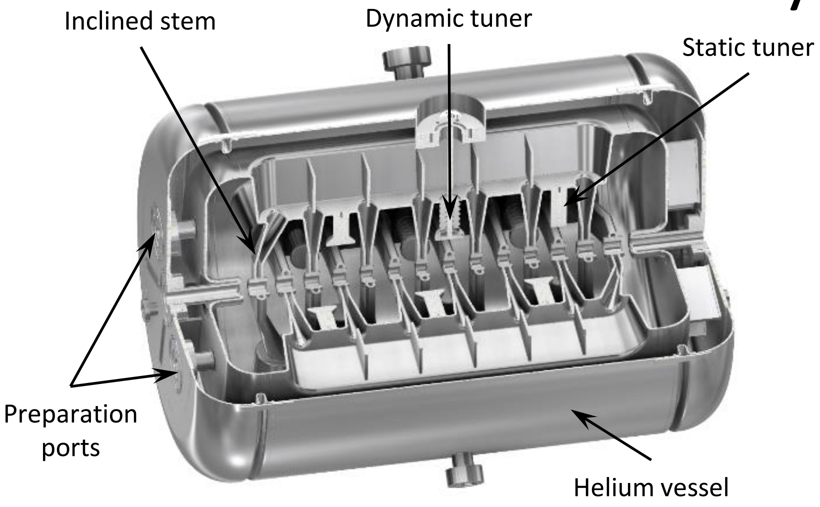
under key support of IAP

- existing facility
- planned facility
- experiments

GSI/FAIR & HELMHOLTZ LINEAR ACCELERATOR

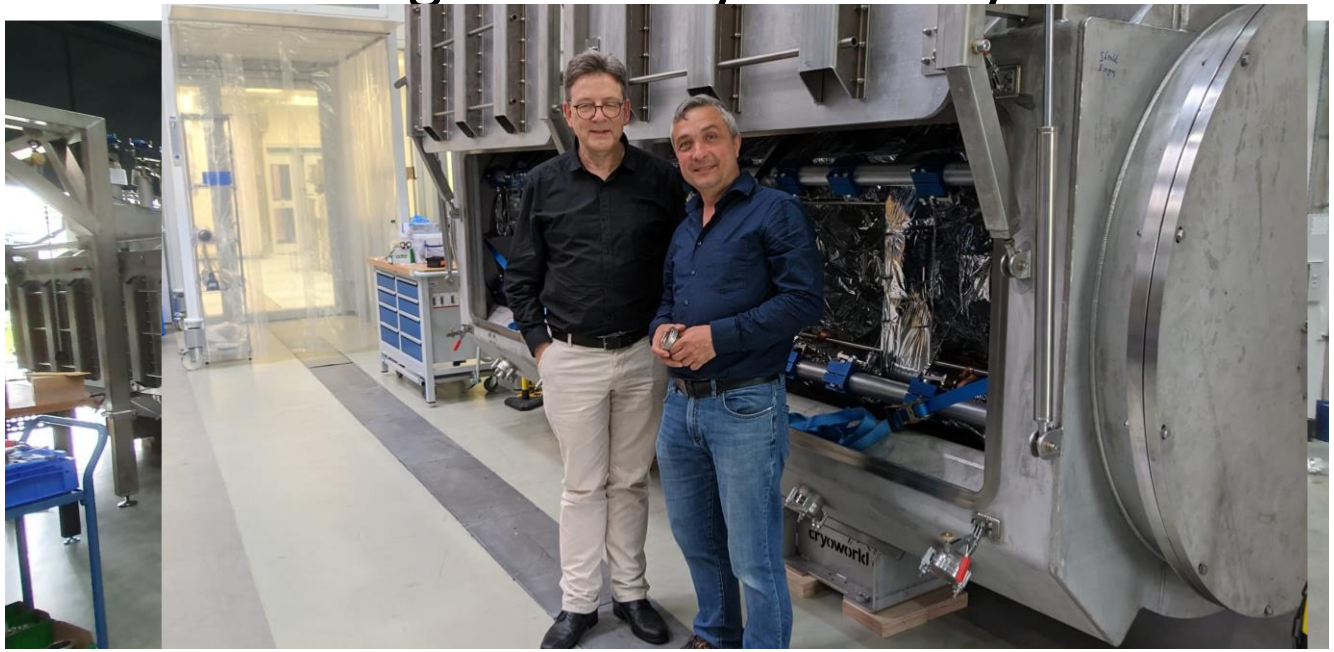


Superconducting crossbar H-mode cavity

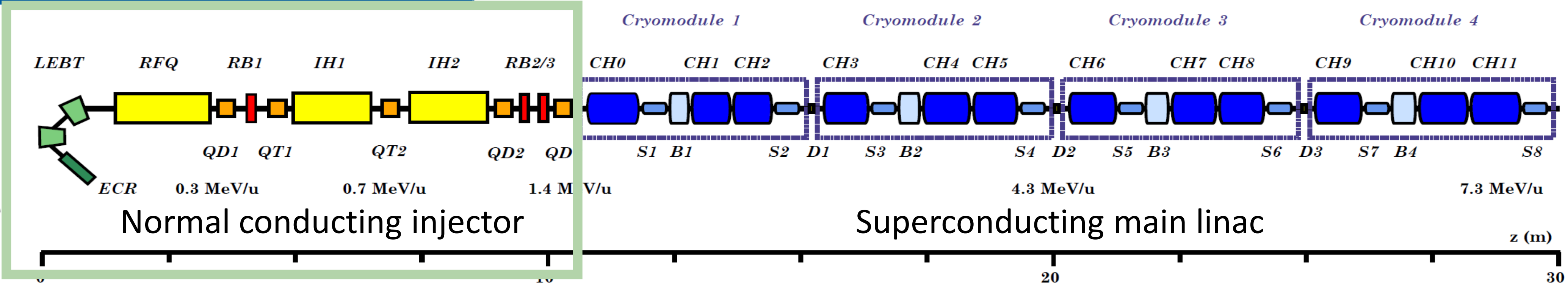


Cold string assembly

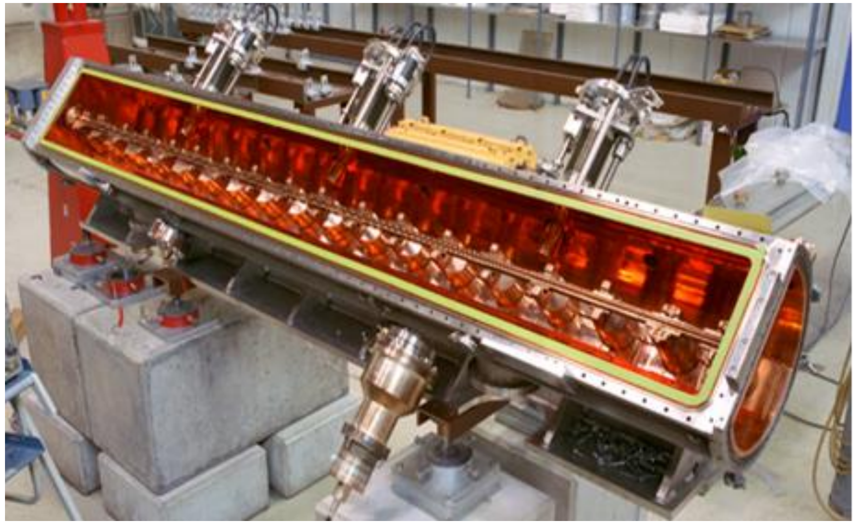
Cryomodule 1



GSI/FAIR & HELMHOLTZ LINEAR ACCELERATOR

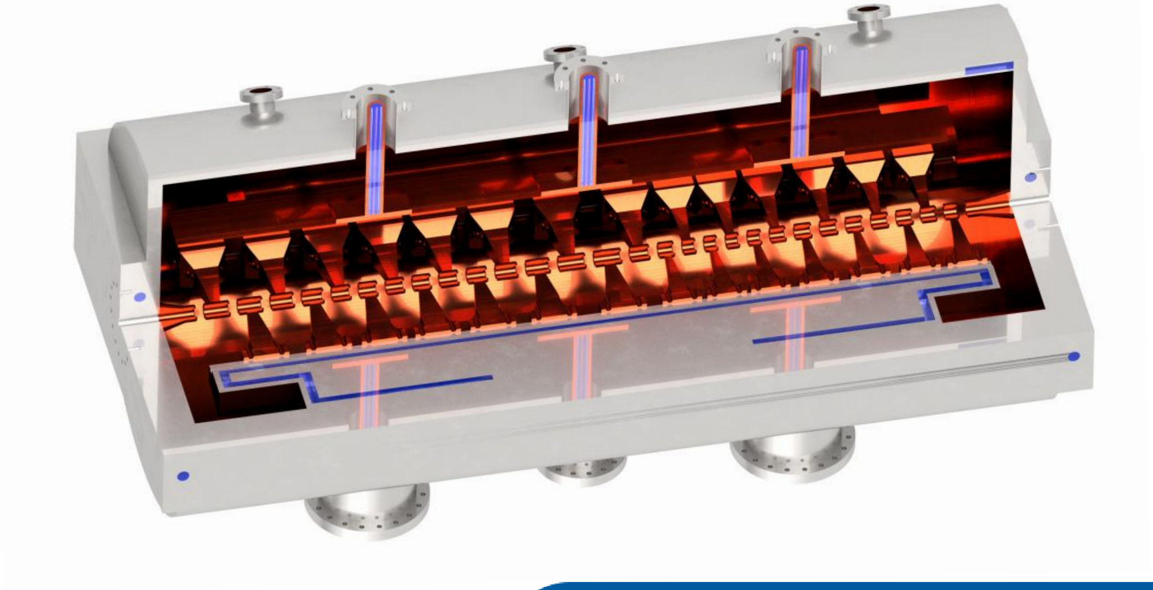


Radio frequency quadrupole



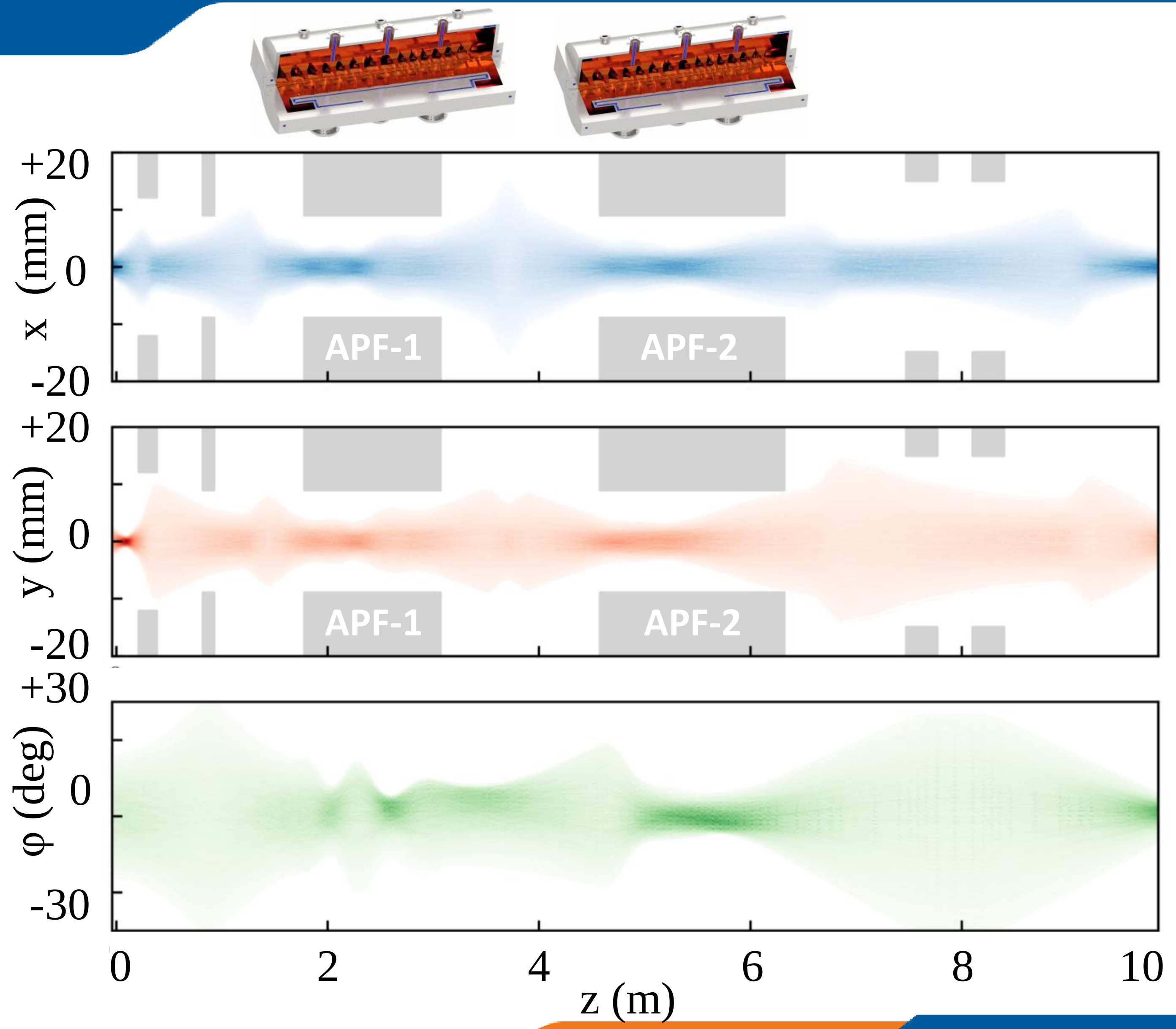
Two normal conducting APF injector cavities

(low 1mA current, under construction)



Transversal

Longitudinal

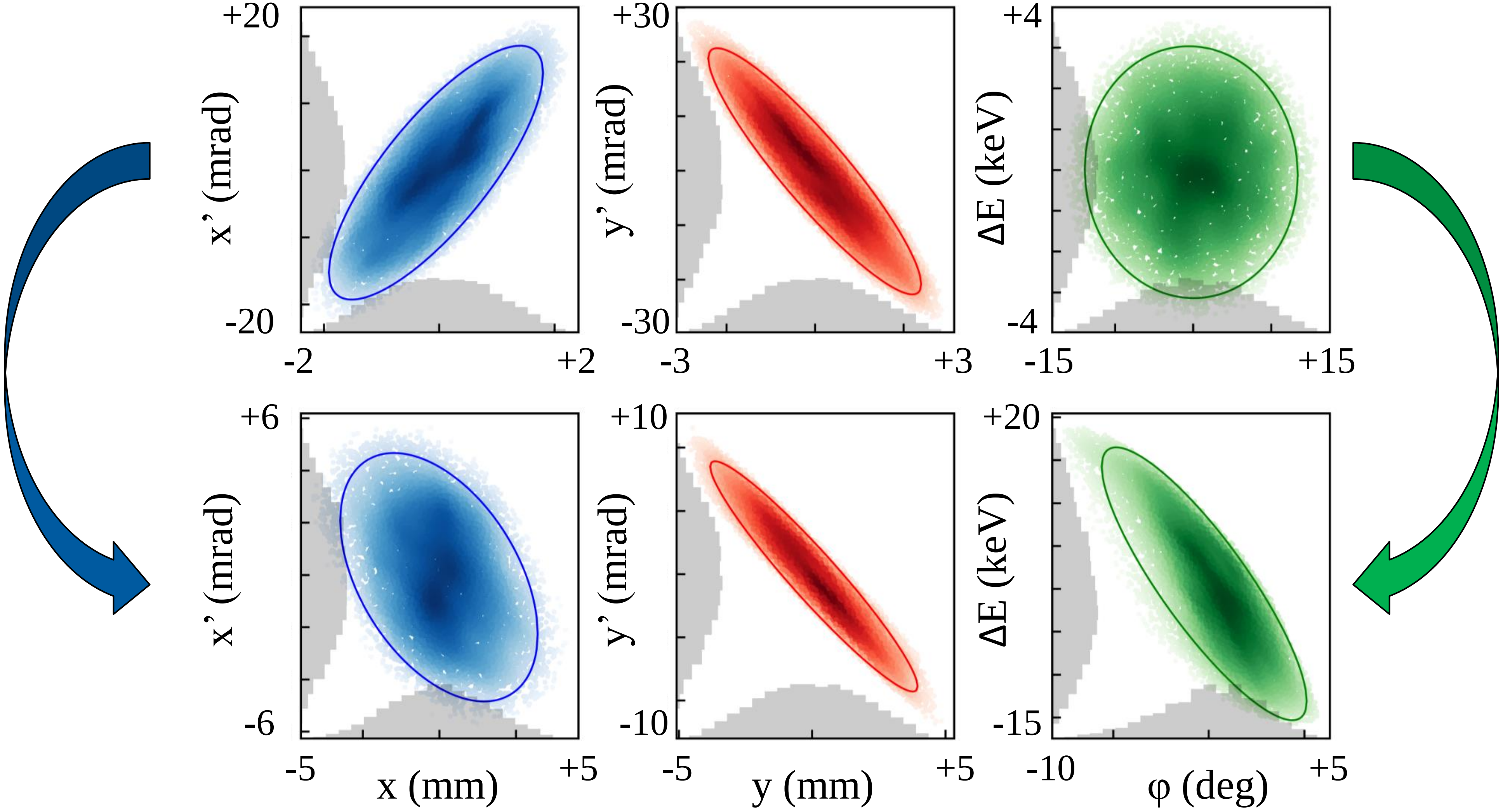


BEAM DYNAMICS DESIGN OF THE ENTIRE DTL SECTION

Beam input and output in three main phase planes

RFQ Output

~8% emittance growth without halo



3% emittance growth without halo

IH2 Output

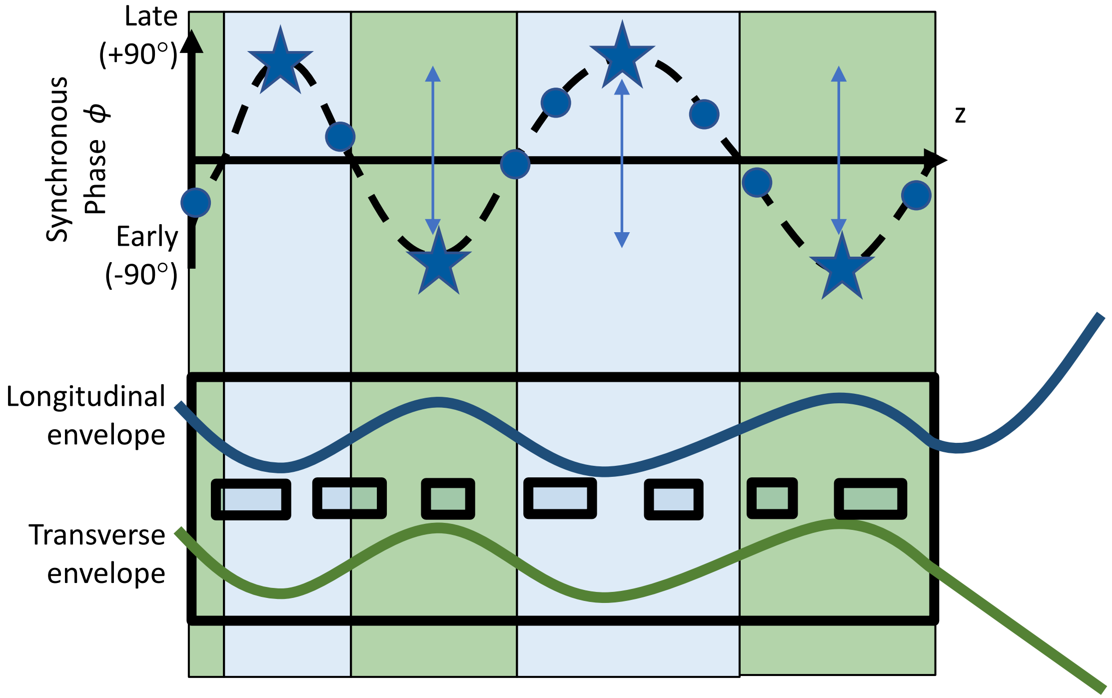
LESSONS LEARNED FROM APF DESIGN

LESSONS LEARNED FROM APF DESIGN

Learnings developing our APF cavities

- The optimum phase-profile is sinus-like
  - ➢ Use splines to optimize phase profile (instead of every single phase)
- Target a fixed energy
  - ➢ Automatic scaling of phase-profile to reach energy
- Monte Carlo is inefficient
  - ➢ Apply other global optimization strategies
- Realistic beam transport is slowly calculated
  - ➢ Use matrix-based transport-code for max. performance

A software package for APF prototyping was developed , allowing delivering beam dynamics designs within 1 day!



SciPy

LESSONS LEARNED FROM APF DESIGN

Simulation Parameters
- Particle number
- Space charge accuracy (using naïve Coulomb solver)
- Gap phases

Consider 6D coupling
High performance required

Accelerator Parameters
- Input/output energy
- Number of gaps
- Frequency
- Acceleration gradient (mean / minimum)
- Cell/gap-length ratio
- **Optional: Voltage per Gap (e.g., from CST)**

Bunch Parameters
- Input emittance
- RMS/total ratio
- Mass
- Charge

Optimization
- (Initial guess of phase-profile)
- Spline points/phases
- Twiss parameters

Global/local optimizers
⤇Yields phase-profile

Cost Function
- Losses (dominates)
- Envelope size along linac
- Emittance growth

Tricks
Spline interpolation of gap phases
Rescaling of phases to reach output energy

SOFTWARE CAPABILITIES:
Tech-demo with space charge

BOUNDARY CONDITIONS

Realistic boundary conditions are used:

- HELIAC cryomodule 1
- UNILAC tank A1

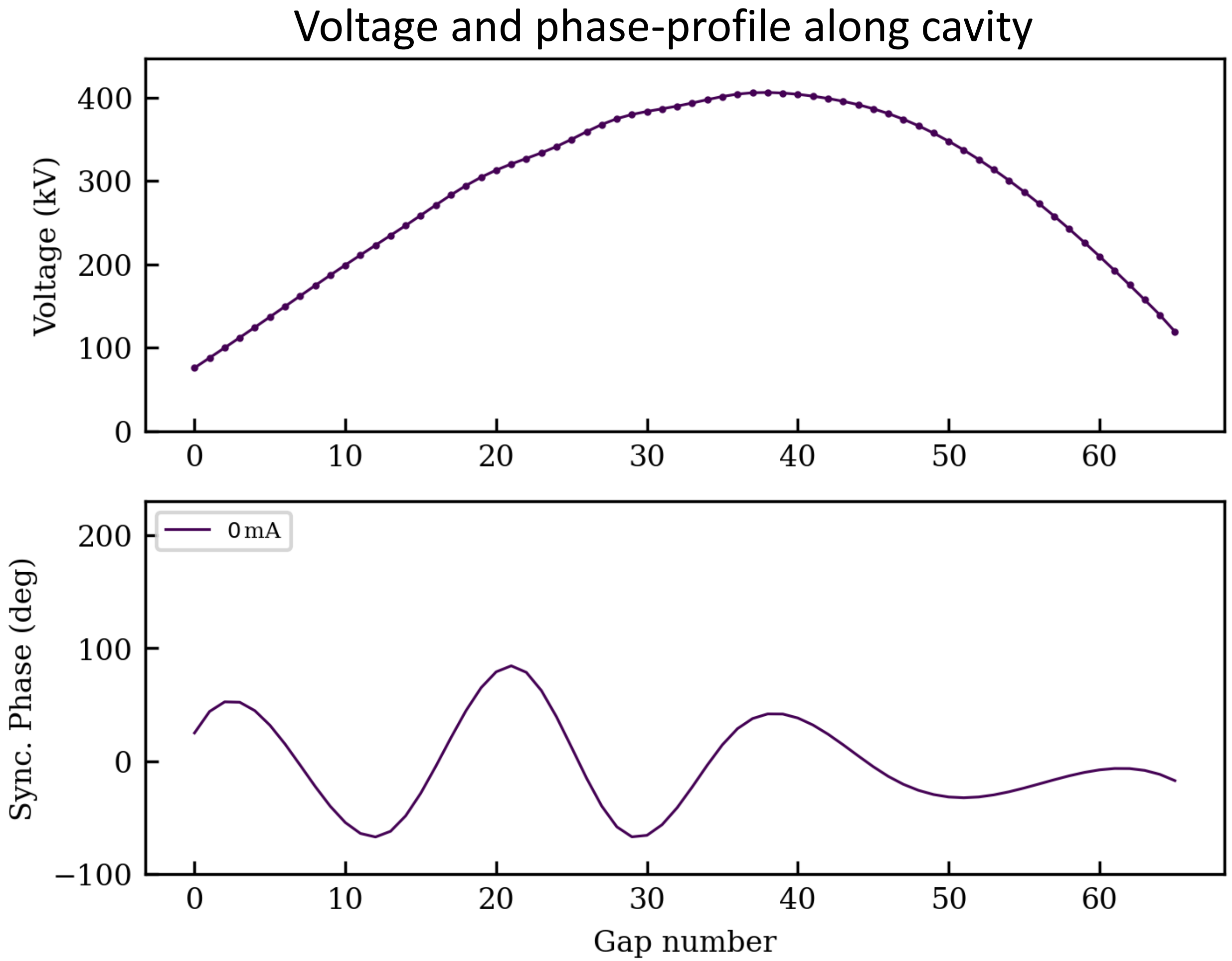
These conditions are used to investigate the capabilities of the software under influence of space charge.

Parameter	Value
Mass-to-charge ratio	6
Frequency	108.408 MHz
Injection energy	1.4 MeV/u
Output energy	3.6 MeV/u
Aperture radius	15 mm
Total emittance (longitudinal)	72 deg keV/u (1.85 keV/u ns)
Total emittance (transversal)	18 mm mrad (0.97 mm mrad *normalized*)
Electric field gradient (avg.)	3 MV/m

INCREASING SPACE CHARGE, ALTERING GEOMETRY

- Realistic voltage profile
  - Average field gradient
  - Minimum field gradient
  - Gaps longer -> higher voltage
- Calculated during beam dynamic due to APF geometry

What is the ideal *66 cell* structure for 5mA, … 15mA?



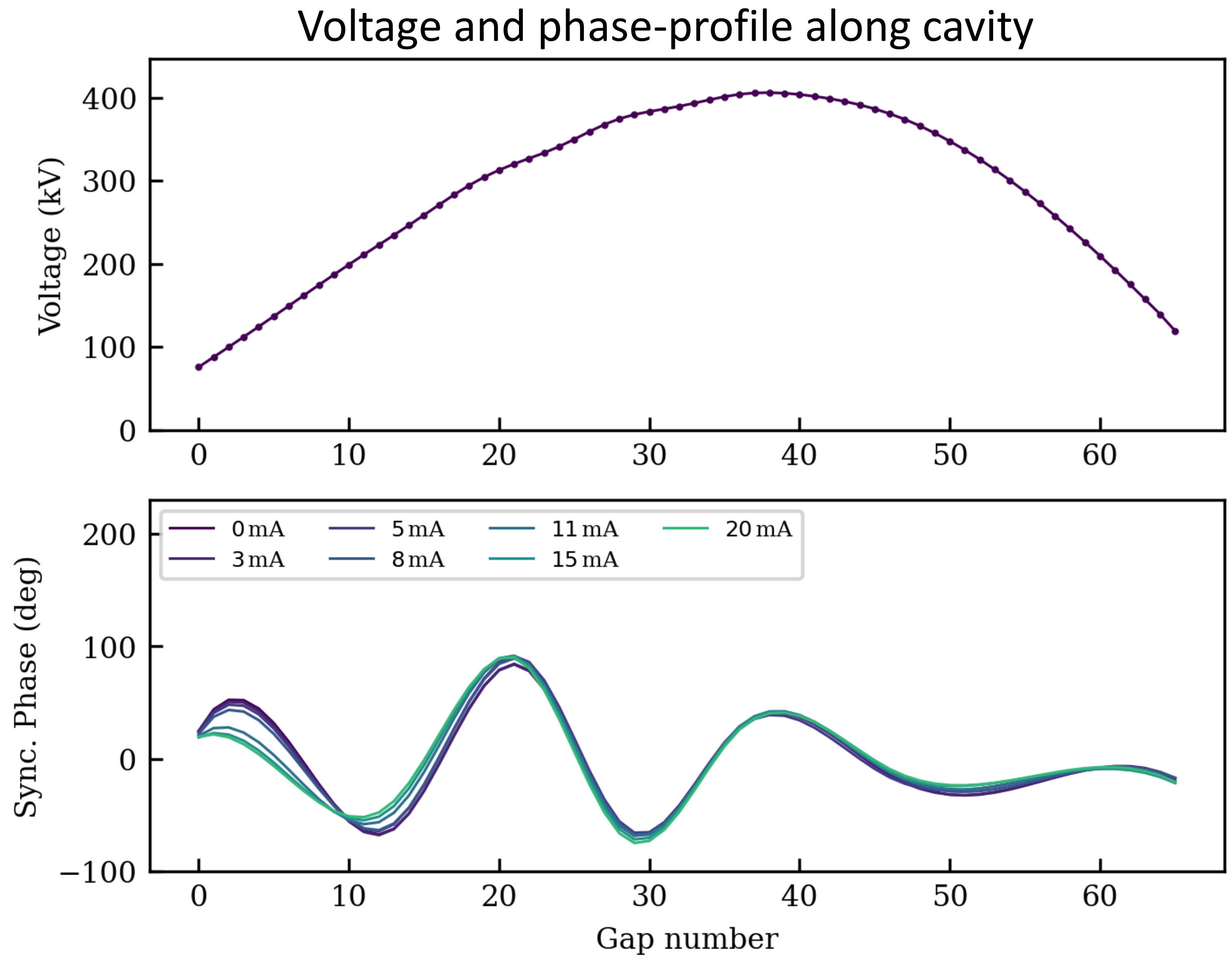
INCREASING SPACE CHARGE, ALTERING GEOMETRY

- Realistic voltage profile
  - Average field gradient
  - Minimum field gradient
  - Gaps longer -> higher voltage
- Calculated during beam dynamic due to APF geometry

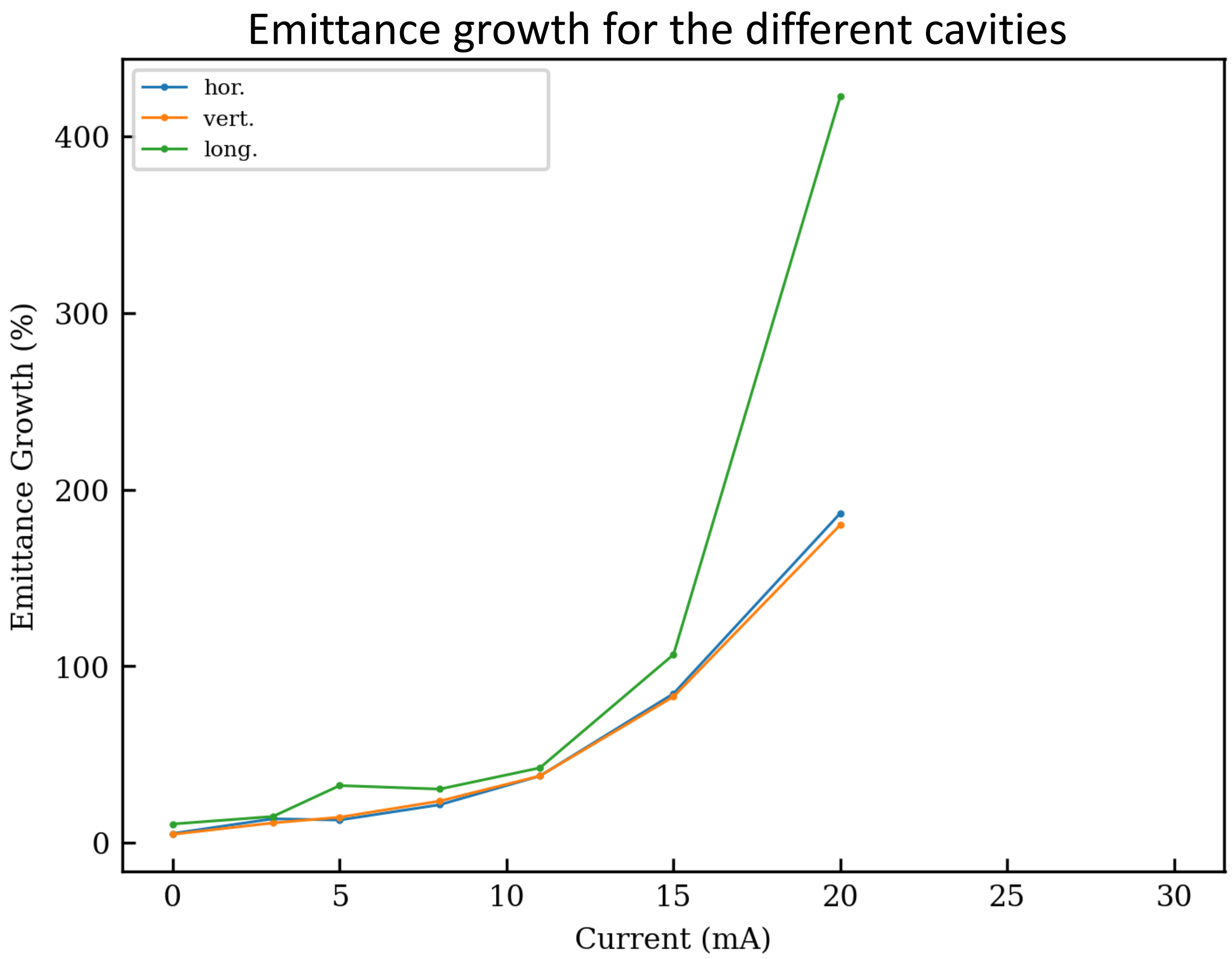
What is the ideal 66 cell structure for 5mA, … 15mA?

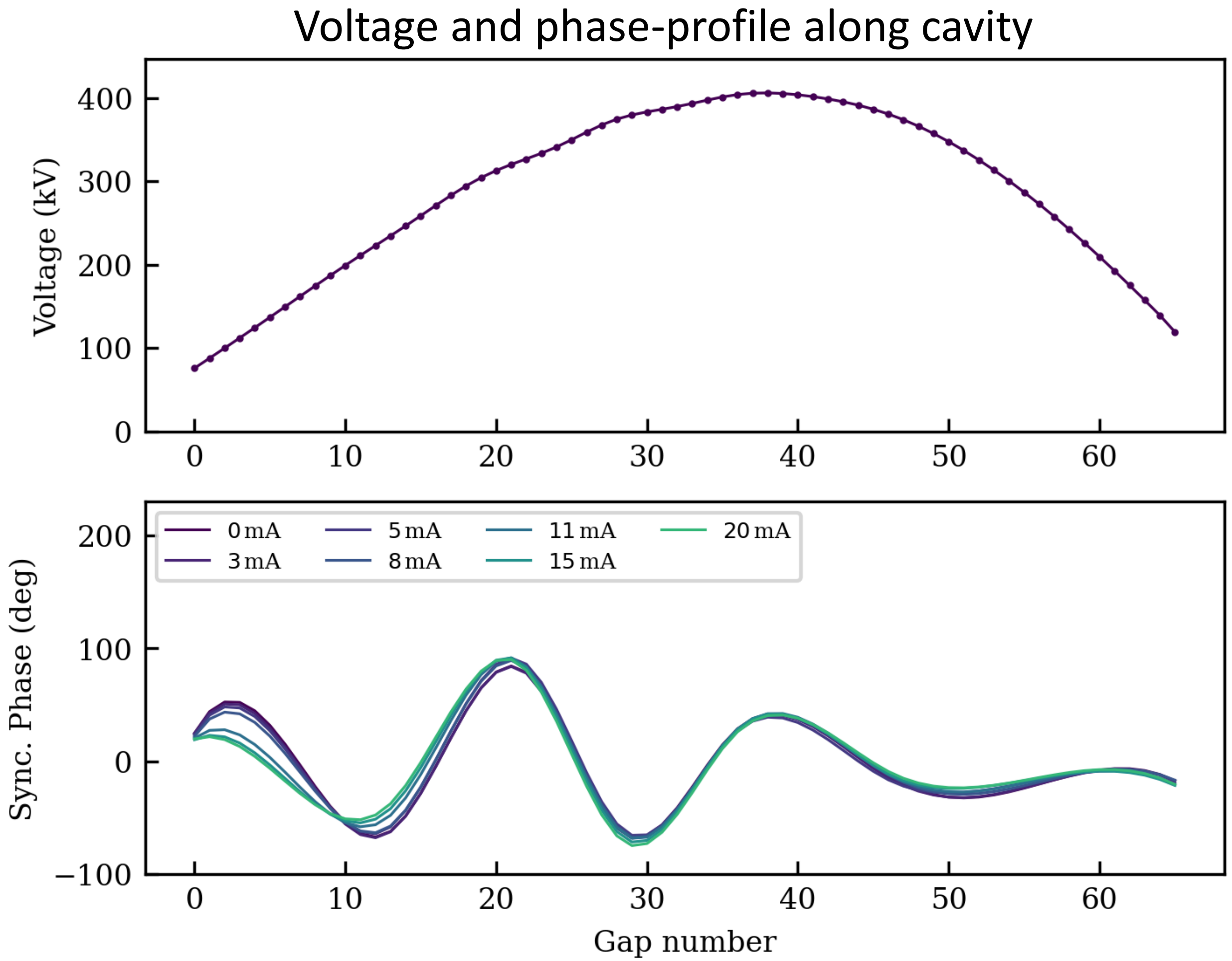
- Beam current is increased
  - Phases are adjusted
  - More focusing at the center
  - Less focusing at the start
  - Overall same output energy

7 different DTL geometries are yielded



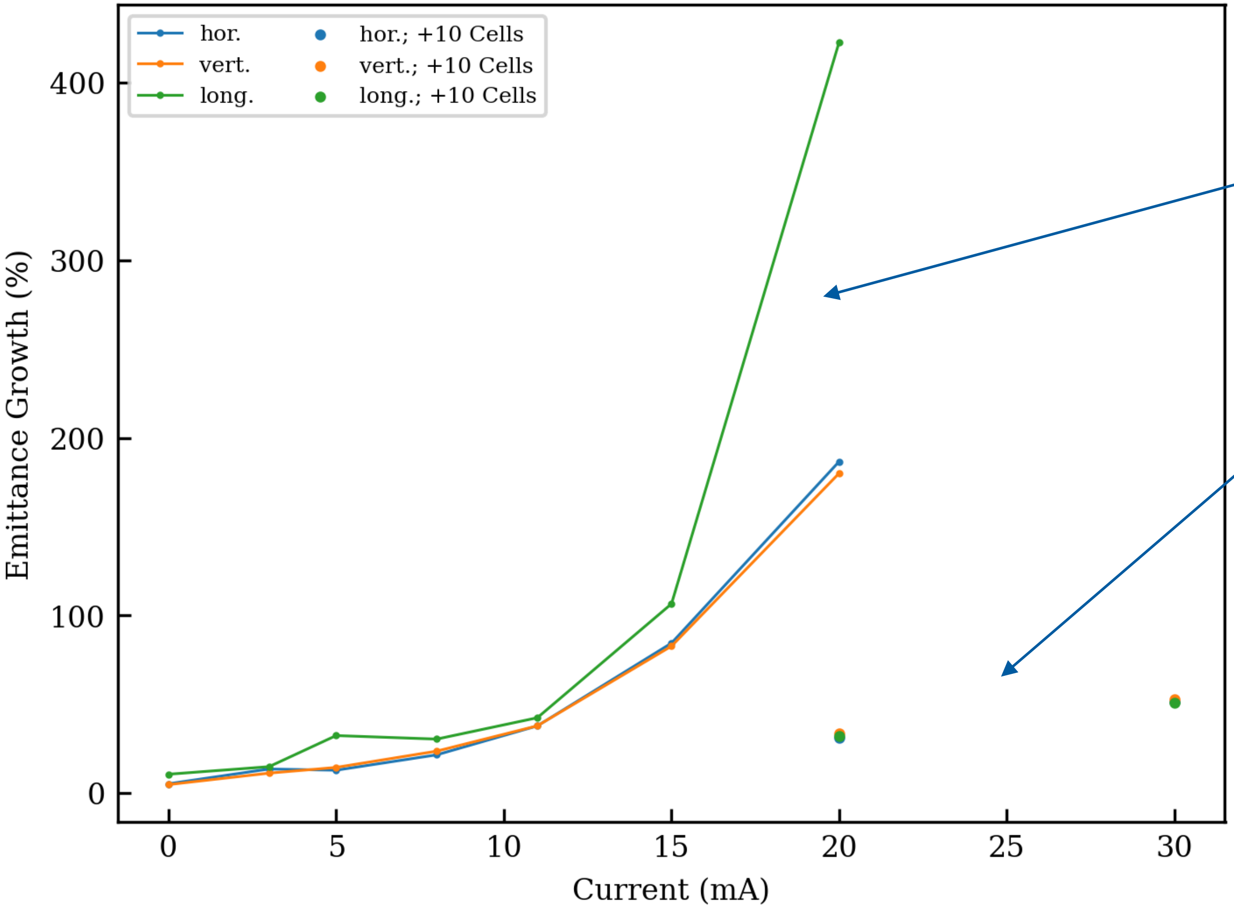
INCREASING SPACE CHARGE, ALTERING GEOMETRY



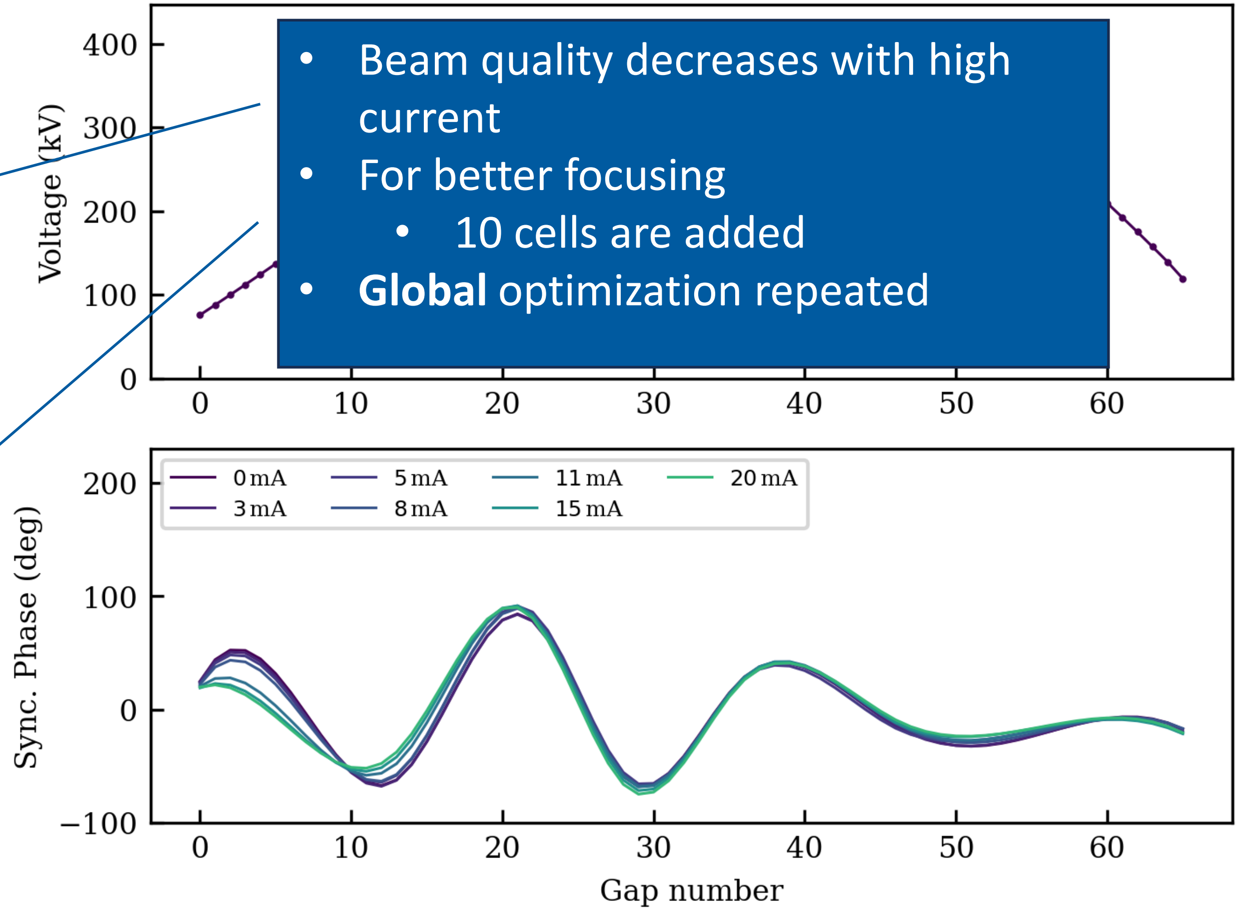


INCREASING SPACE CHARGE, ALTERING GEOMETRY

Emittance growth for the different cavities

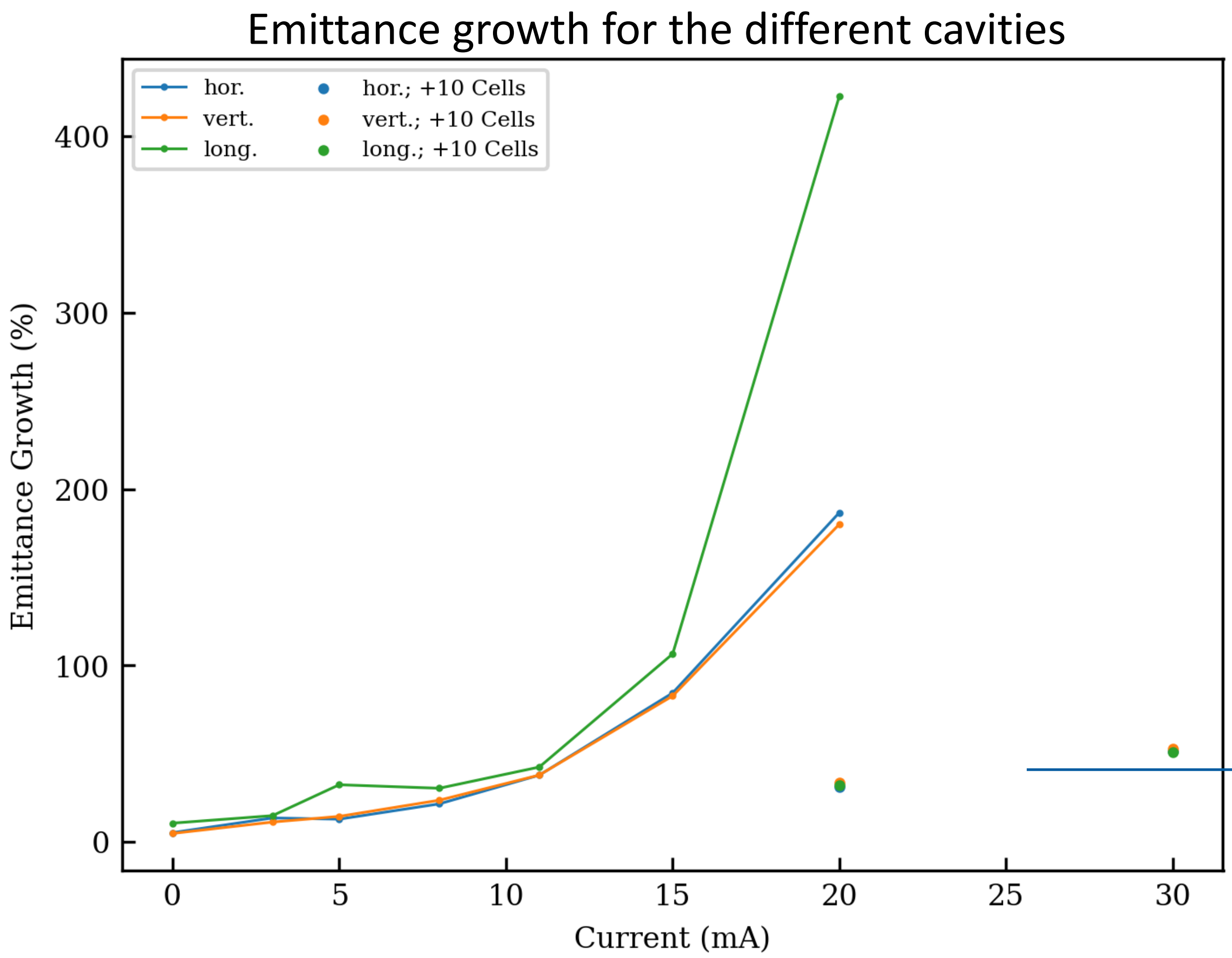


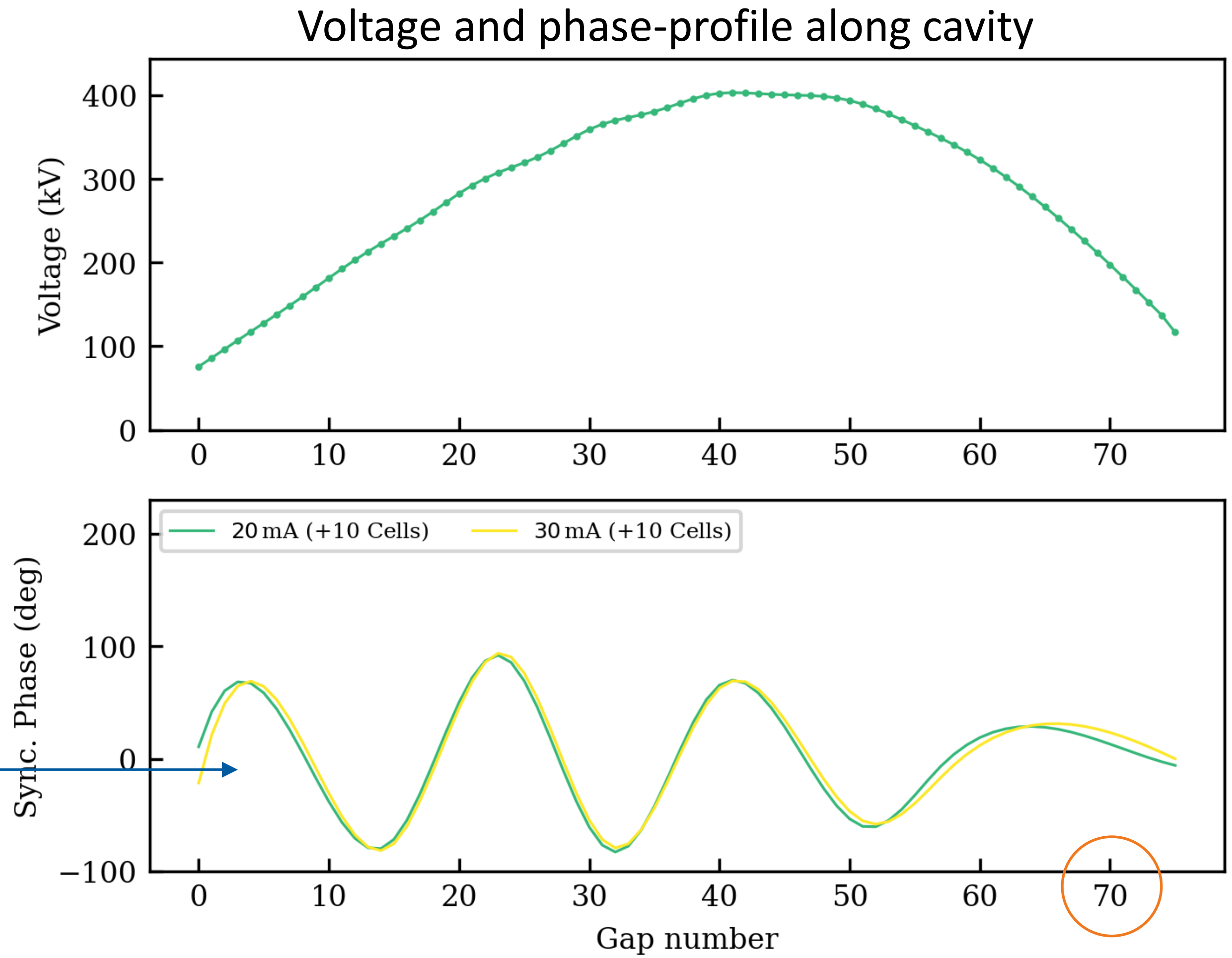
Voltage and phase-profile along cavity



- Beam quality decreases with high current
- For better focusing
  - 10 cells are added
- **Global** optimization repeated

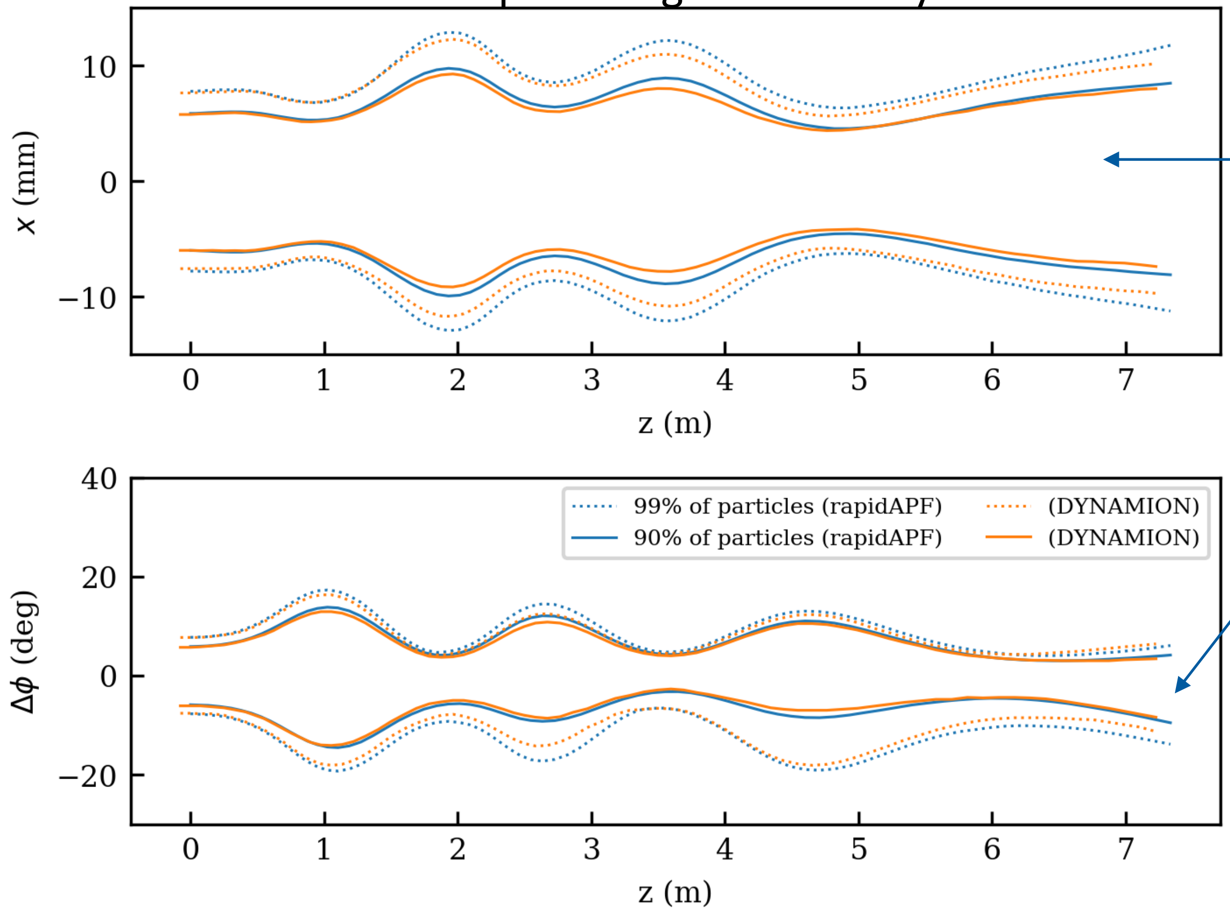
INCREASING SPACE CHARGE, ALTERING GEOMETRY



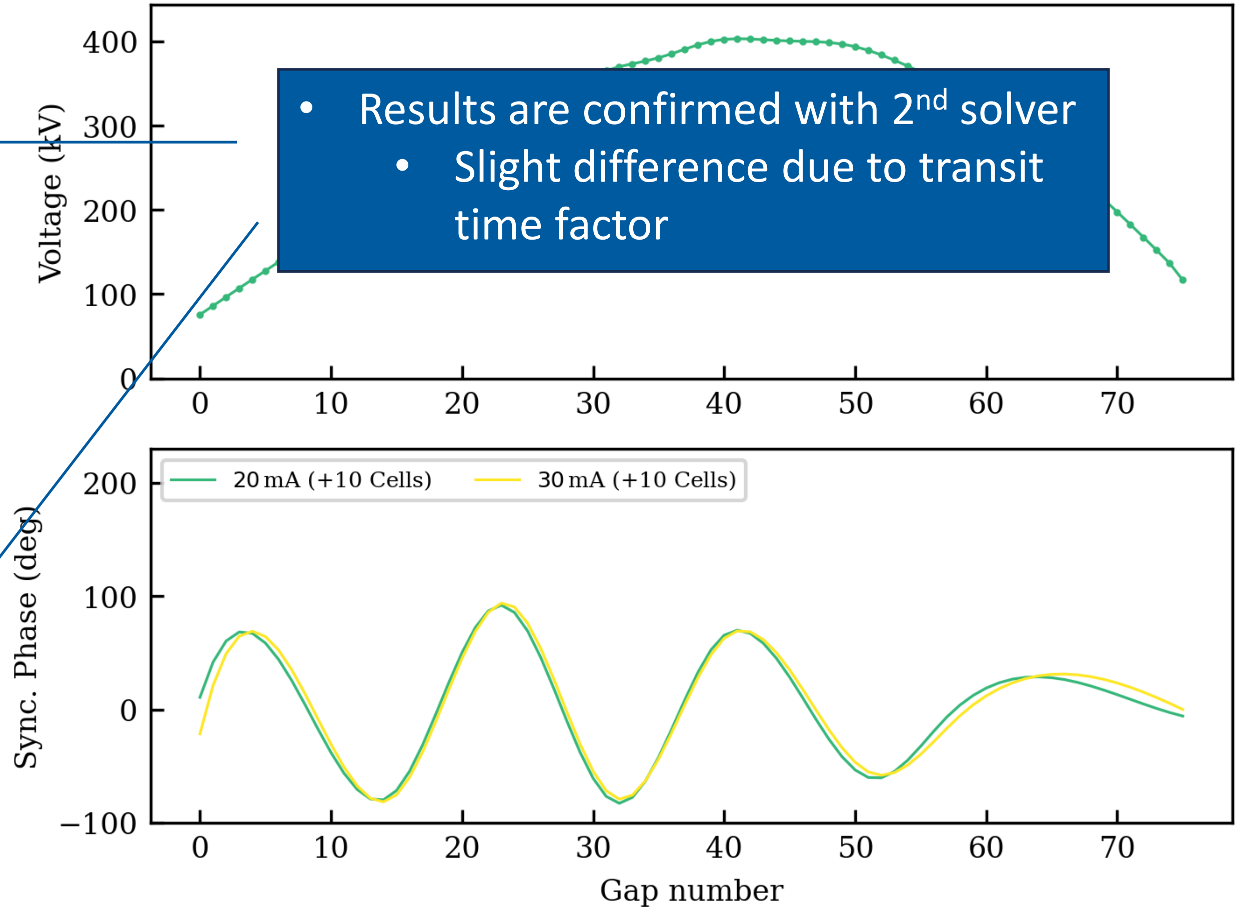


INCREASING SPACE CHARGE, ALTERING GEOMETRY

Envelopes along 30mA cavity



Voltage and phase-profile along cavity



- Results are confirmed with 2nd solver
  - Slight difference due to transit time factor

INCREASING SPACE CHARGE, ALTERING GEOMETRY

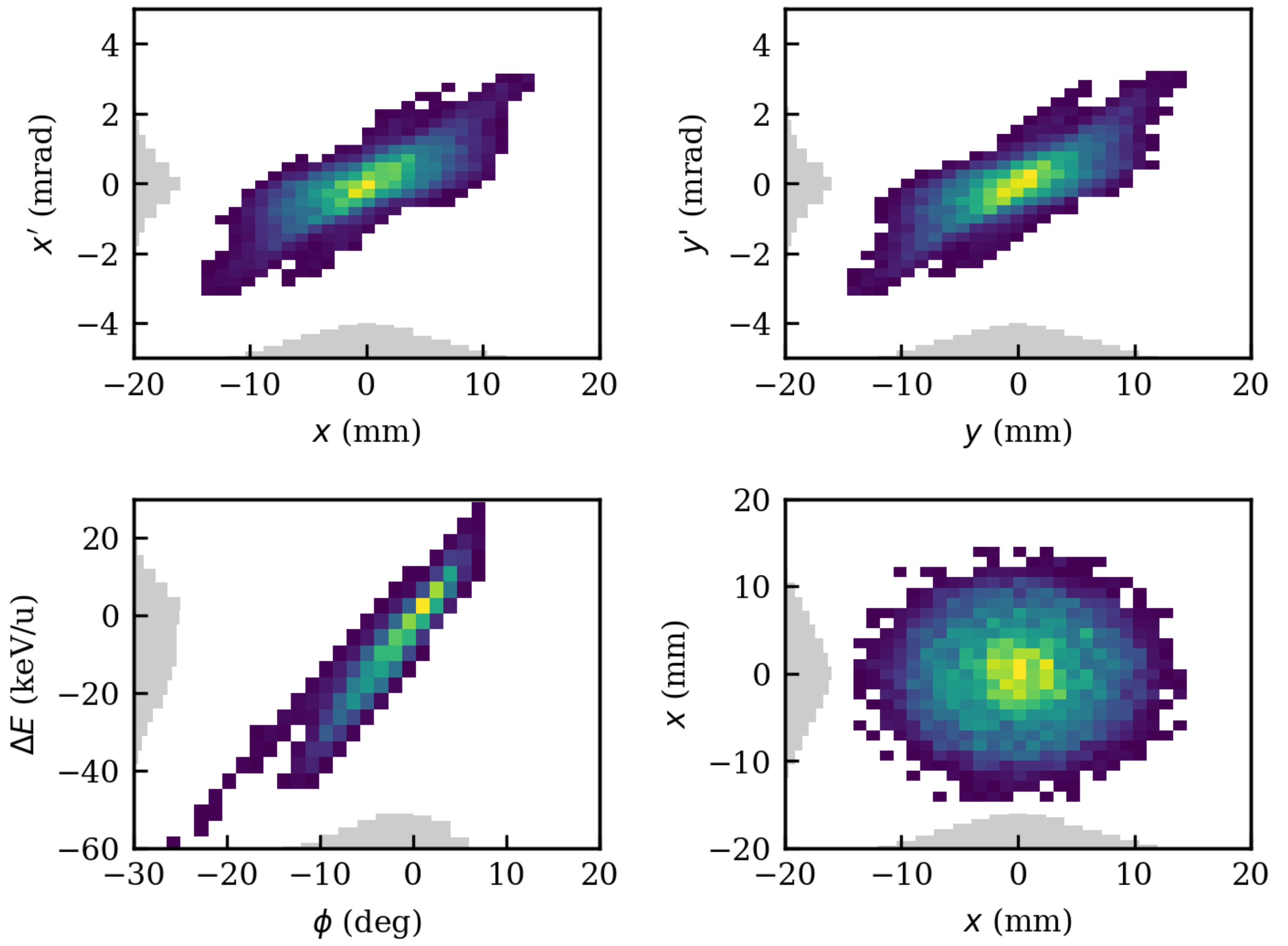
The beam quality with 30mA heavy ion beam is still high after 7.6m transport!

Full transmission!

Considering 90% of all particles:

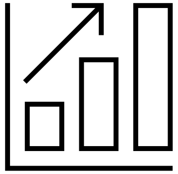
- 36% *longitudinal* emittance growth
- 50% *transverse* emittance growth

The beam quality strongly depends on the boundary conditions, that are set for each project individually.

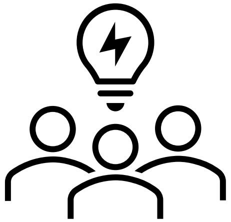


CURRENT STATUS AND FUTURE DIRECTIONS

- Has been discussed in literature since many decades
- Due to computer aided design of accelerators, construction is eased
- A high challenge is still the demand for expertise to design such linac



- APF acceleration is adopted in several fields
  - For dielectric acceleration, as magnetic focusing is impeded
  - For ion accelerators (also for medical application), where financial constraints are given



- APF theory must be further developed to make it more accessible
  - Ideal equations should depend on acceptance (long. & transv.), acceleration gradient, and input twiss parameters, considering 6D coupling
  - Recent solutions comprise numerical optimization

Design of high current APF structures is conveniently achievable using efficient approaches.

THANK YOU
FOR YOUR ATTENTION!

HB 2023

NEW SOFTWARE IMPLEMENTING BEST PRACTICES

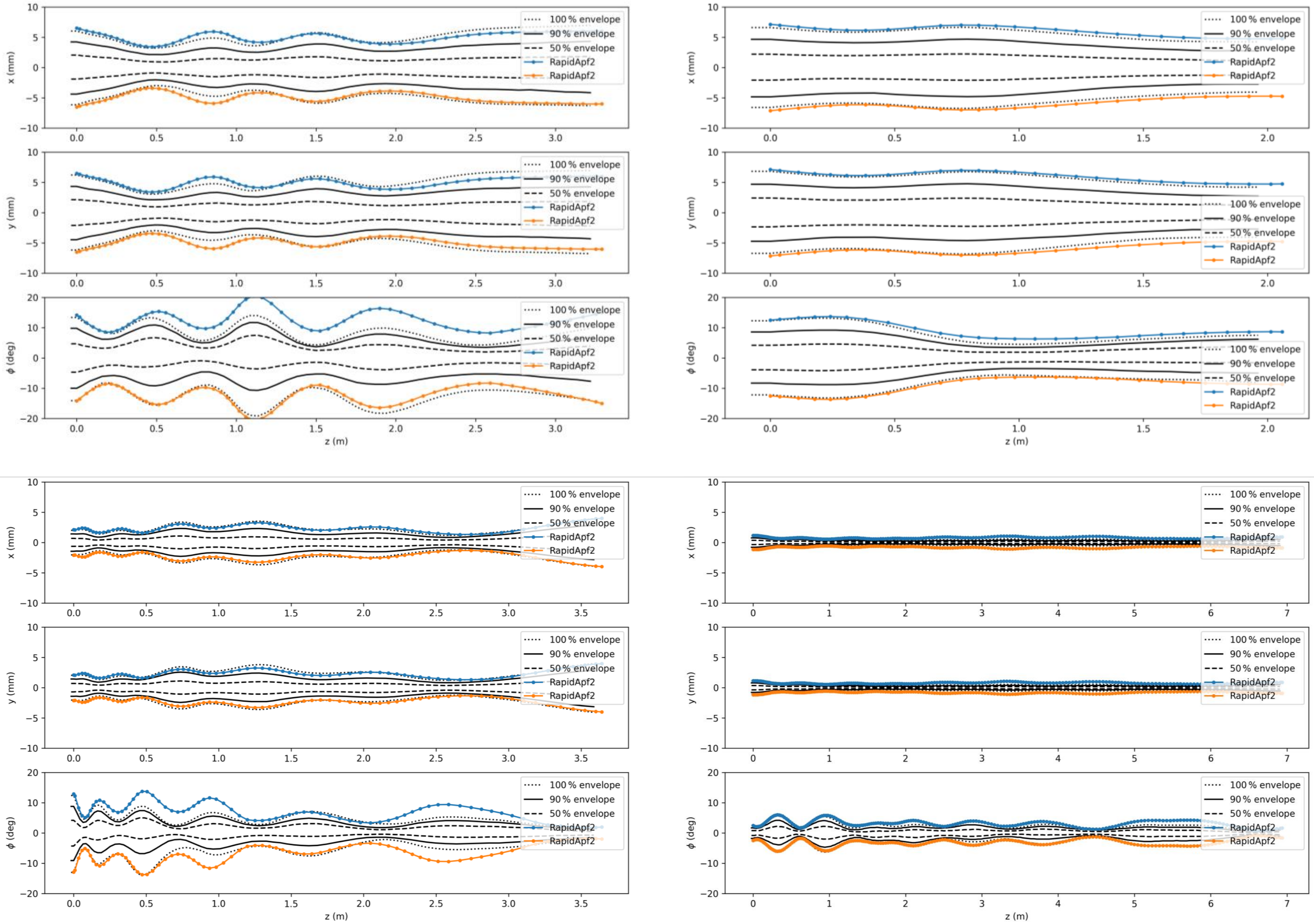
NEW SOFTWARE: COST FUNCTION

```python
import numpy as np

def total_cost(self) -> float:
    """Calculates total cost function

    :return: cost value
    """
    cost = 0
    # protect against very high losses
    xs = self.distr_out[:, 0]  # x positions array
    nonan = np.isreal(xs) & (~np.isnan(xs)) & (~np.isinf(xs))

    # if only two particles remain, emittance couldn't be calculated
    if np.sum(nonan) < 3:
        # shall return float anyway
        return np.inf

....
```

```python
....

    # emittance growth
    for axis in range(3):
        cost += self.emittance_growth_pseudo_tot(axis) ** 2
    # maximum transverse beam size
    cost += np.nanmax(self.envelope_trans_m) * 1e3
    # mean transverse beam size
    cost += np.nanmean(self.envelope_trans_m) * 1e3
    # very high cost if losses appear
    if self.losses() > 0:
        cost += 1e8 * ((1 + self.losses()) * 100) ** 4
    return cost
```

NEW SOFTWARE: ZERO CURRENT EXAMPLES

Trans. and long. Envelopes in 4 different linac examples



High performance for designing alternating phase focusing DTL…

The new software allows rapid beam dynamics design within hours

(instead of weeks with previous approach)

Example1: IH1&2 as one tank

Example2: CM1 replaced

Example3: 3.5m medical APF-tank

Example4: 7.0m medical APF-tank

and so on…

NEW SOFTWARE: PERFORMANCE

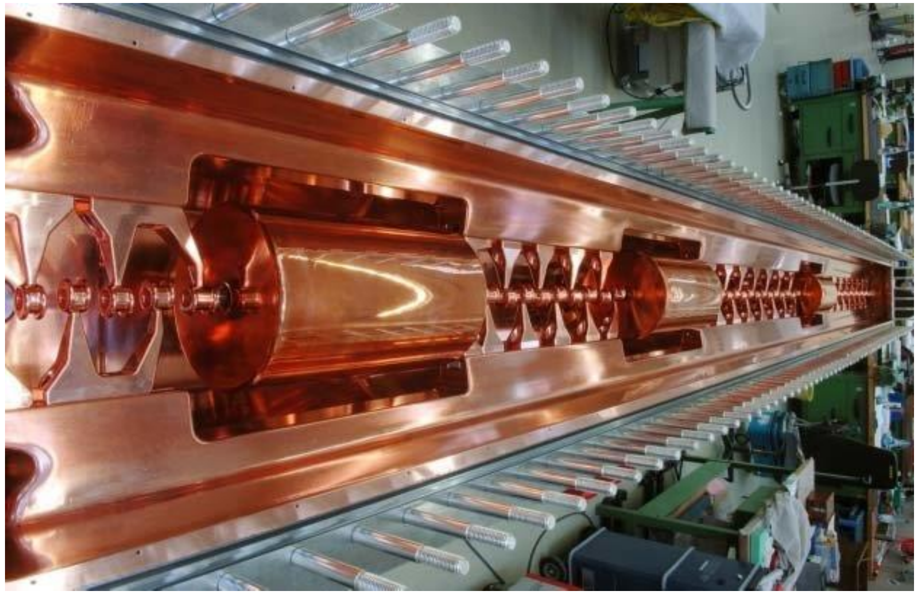
- Performance (7.6m 76 cells linac)
  - (CPU: Intel Xeon Platinum 8268 2.9GHz)
  - 10ms — w/o space charge
  - 80ms (0.8s single core) — **500** particles, 5 calculations of space charge per cell
  - 150ms (3s single core) — **1000** particles, 5 calculations of space charge per cell

- Further speed-up by FFT-Based space charge?

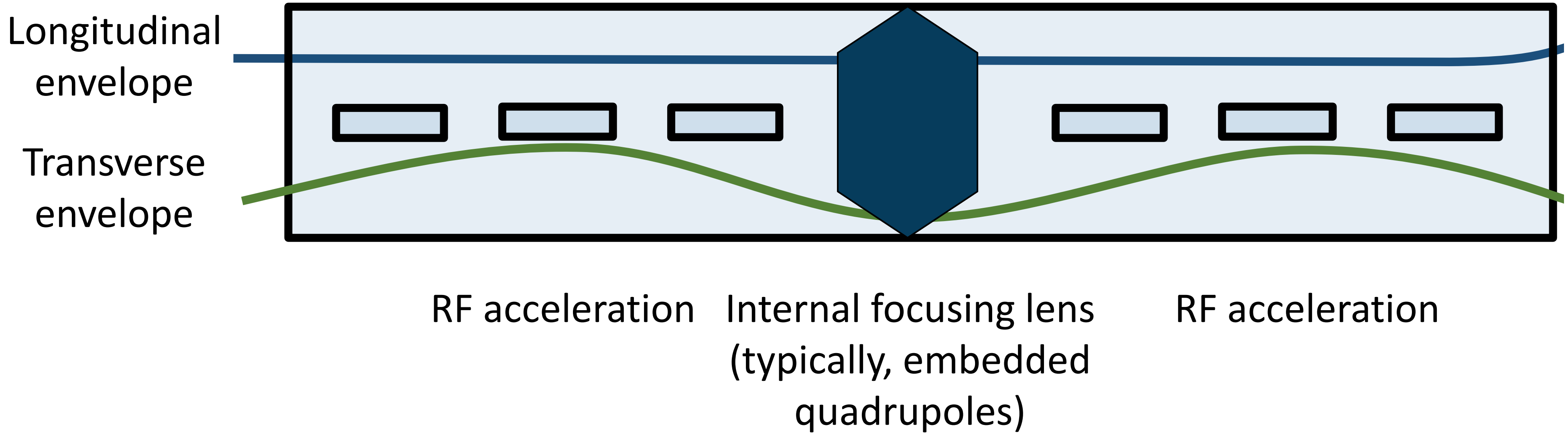
MOTIVATION

Conventional heavy ion drift tube linac (DTL) **H**-mode for ion injectors

- Costly internal lenses of conventional DTLs



[Schlitt 2006]



MOTIVATION

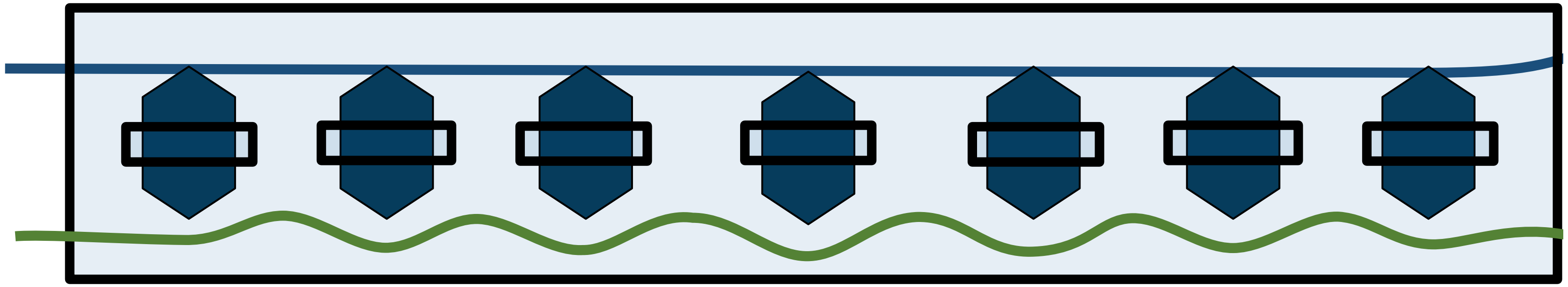
Conventional heavy ion drift tube linac (DTL) **E**-mode for ion injectors

- Costly internal lenses of conventional DTLs
- High energy consumption in E-Mode structures

[GSI 2021]

Longitudinal envelope

Transverse envelope



RF acceleration

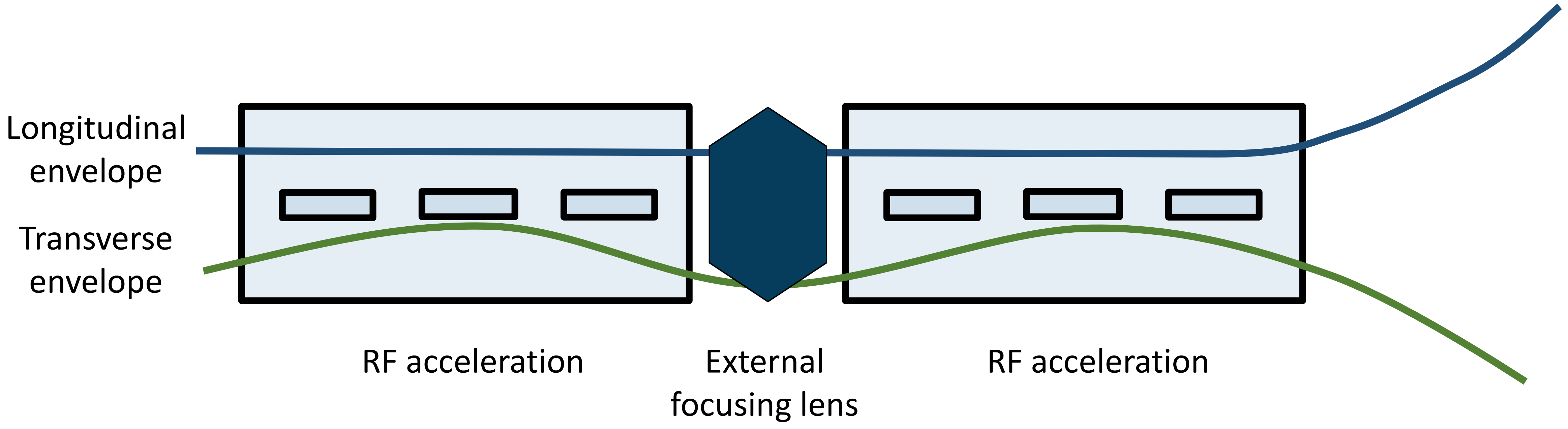
Many internal focusing lens

RF acceleration

MOTIVATION

Short cavities with external lenses

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



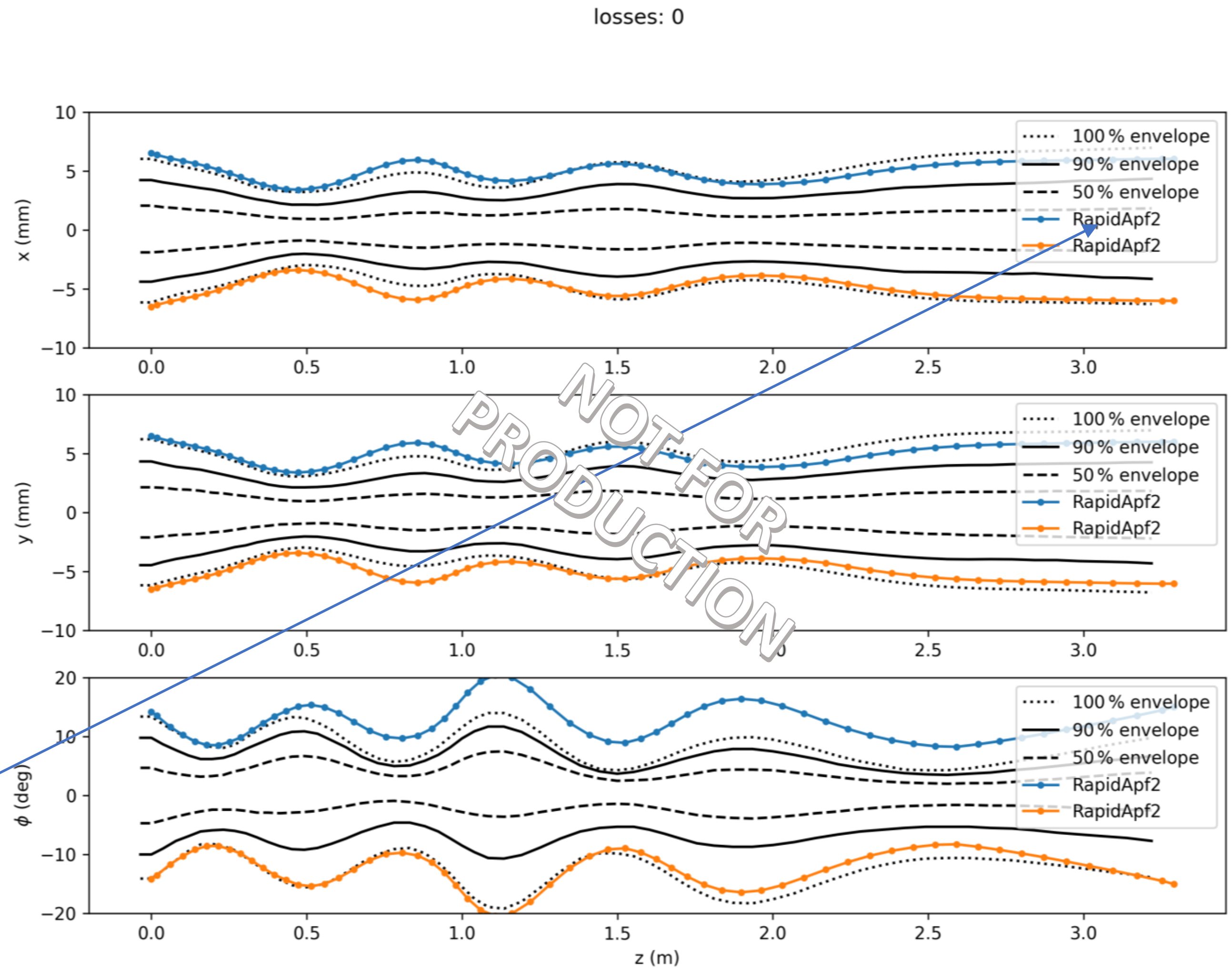
NEW SOFTWARE

High performance for designing alternating phase focusing DTL…

The new software allows rapid beam dynamics design within hours

Example1: IH1&2 as one tank

Confirmed with second solver (*DYNAMION*)



High performance for designing alternating phase focusing DTL…

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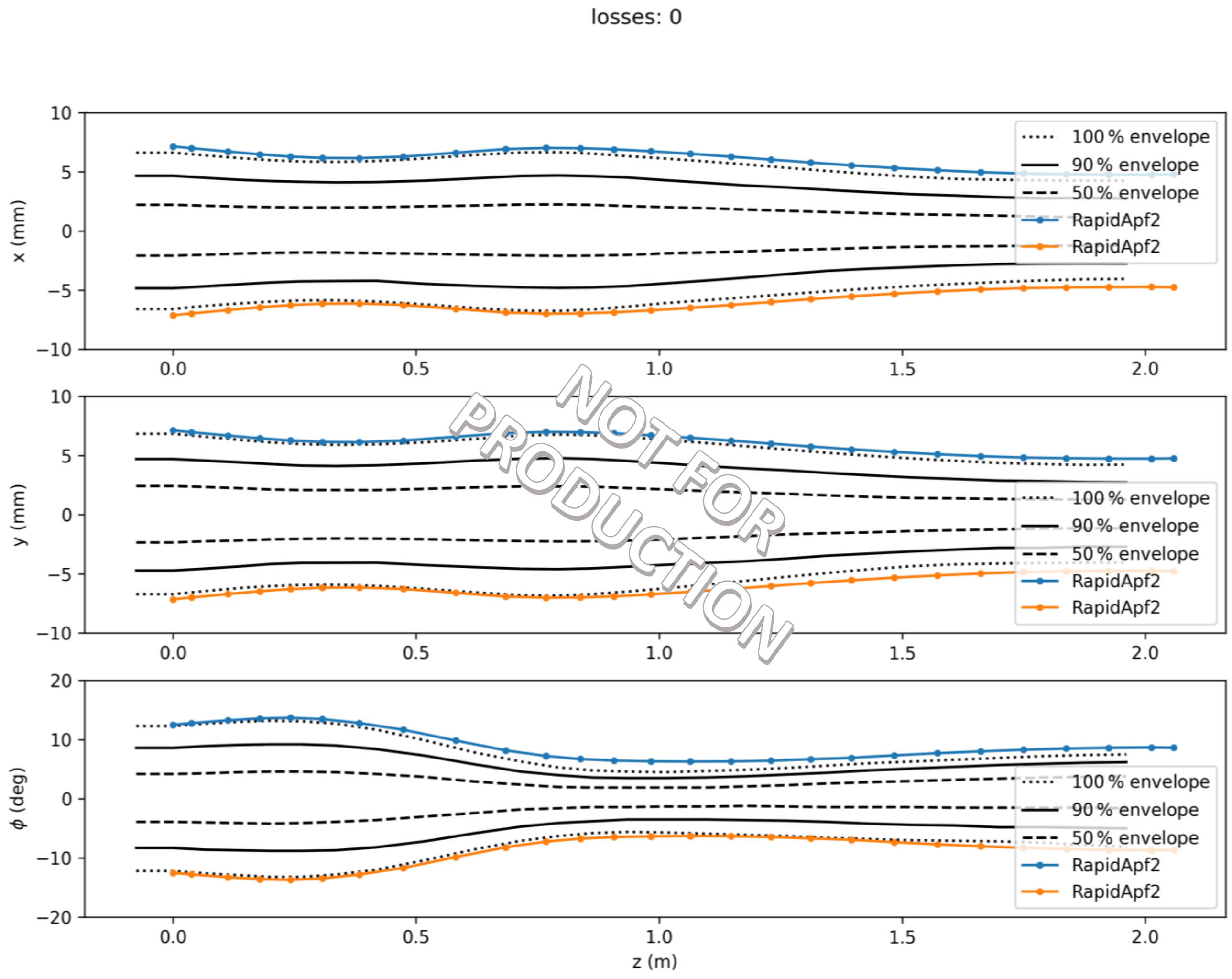
Example1: IH1&2 as one tank

Example2: CM1 replaced



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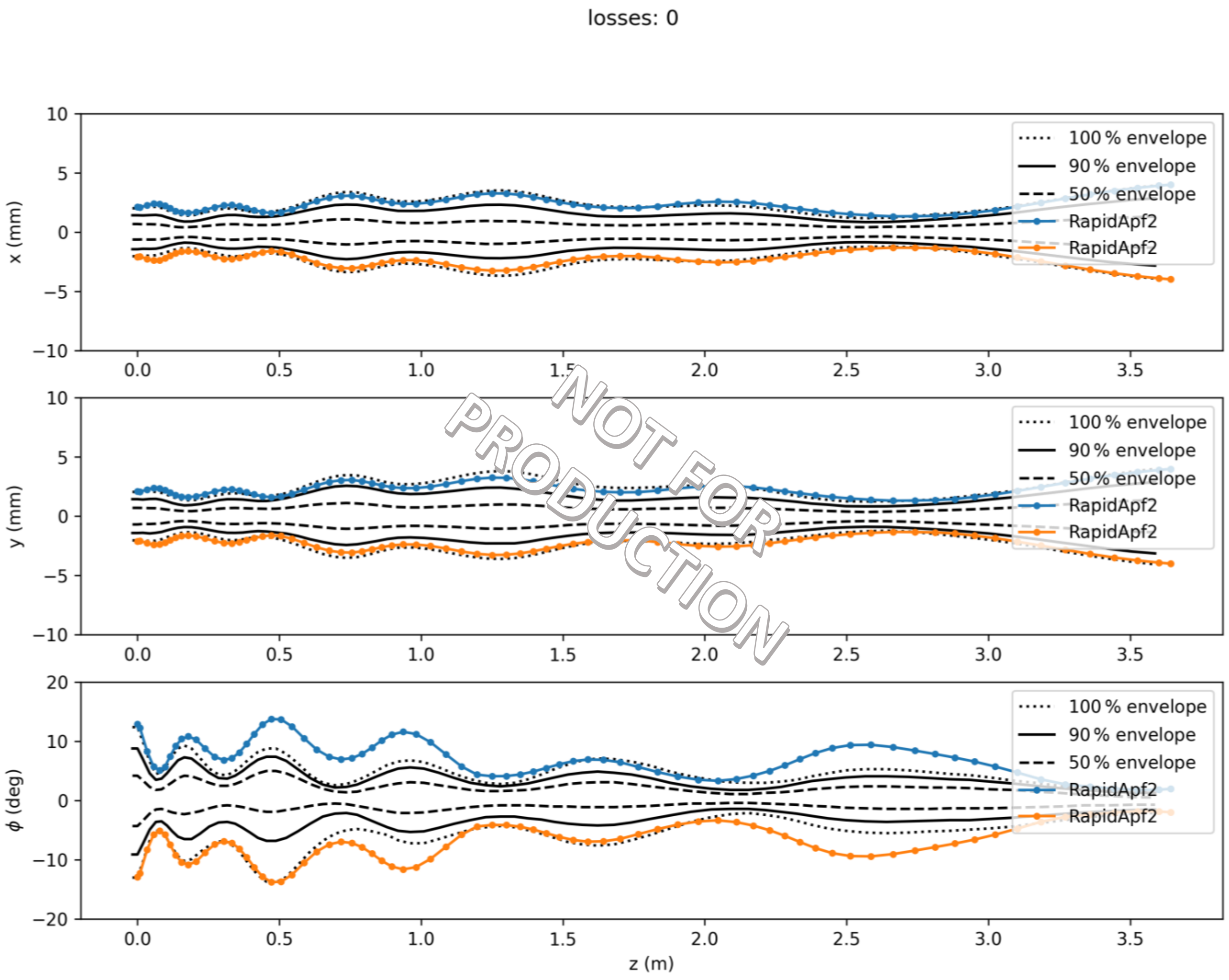

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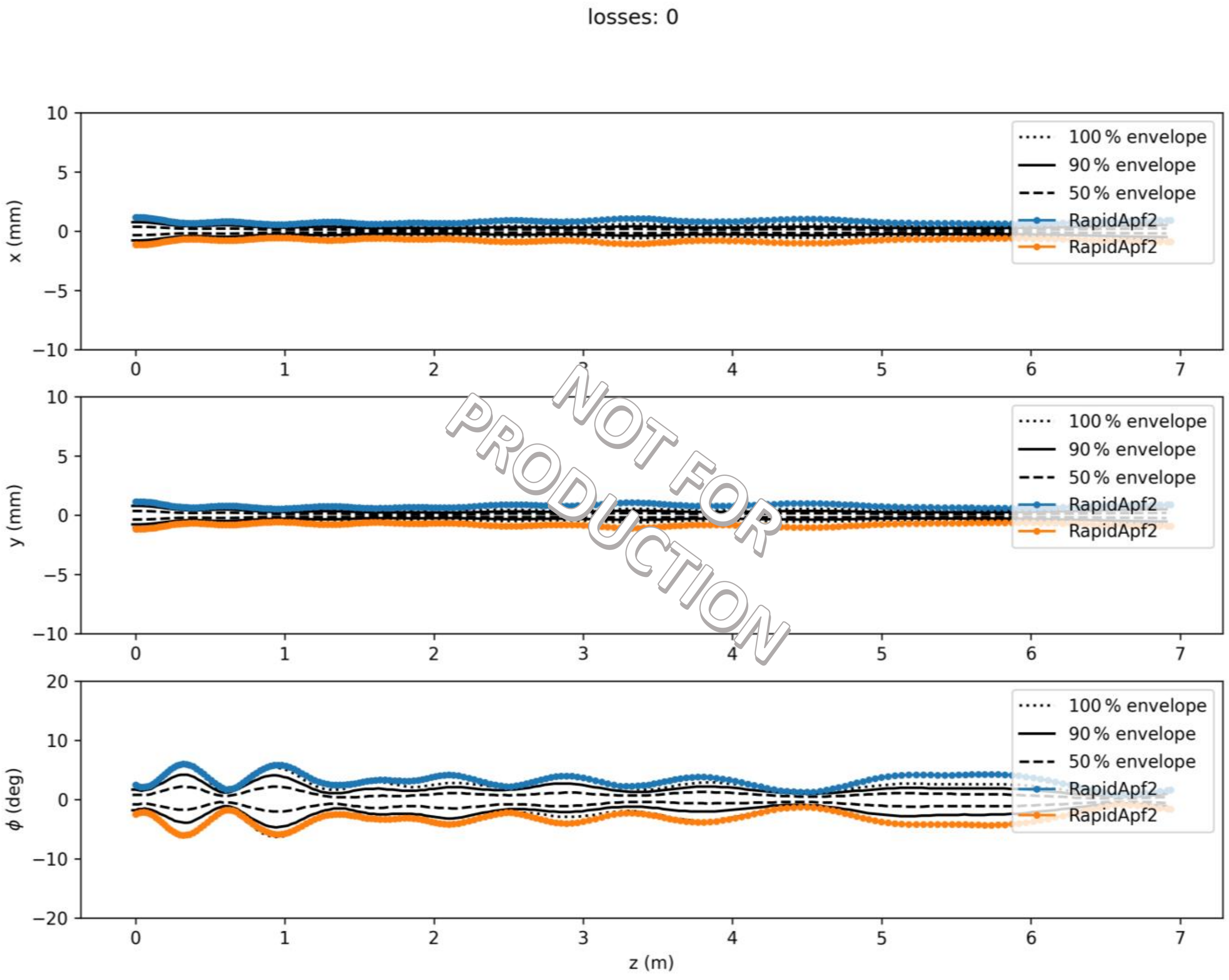
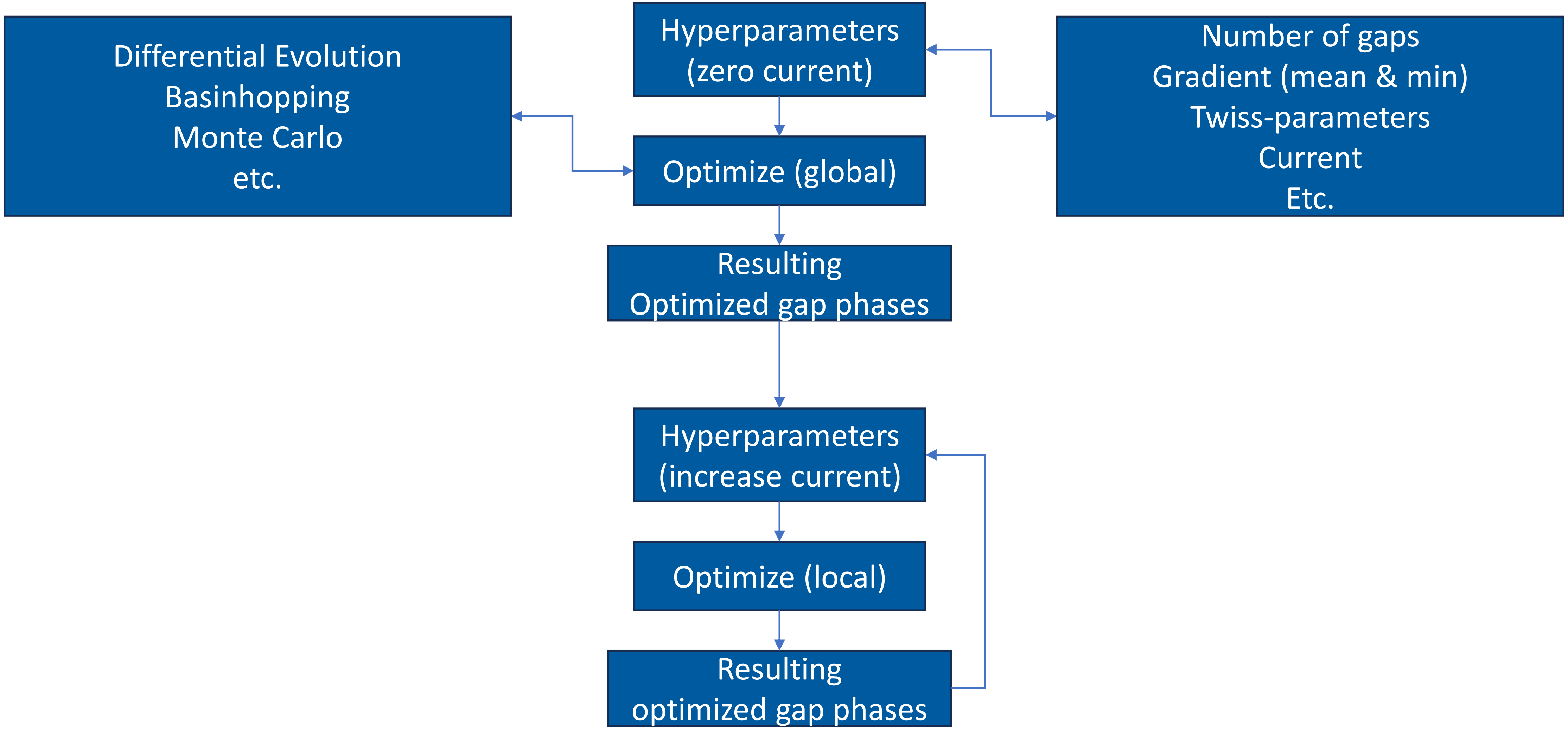
Example3: 3.5m medical APF-tank

Example4: 7.0m medical APF-tank

and so on…



INCREASING SPACE CHARGE, ALTERING GEOMETRY

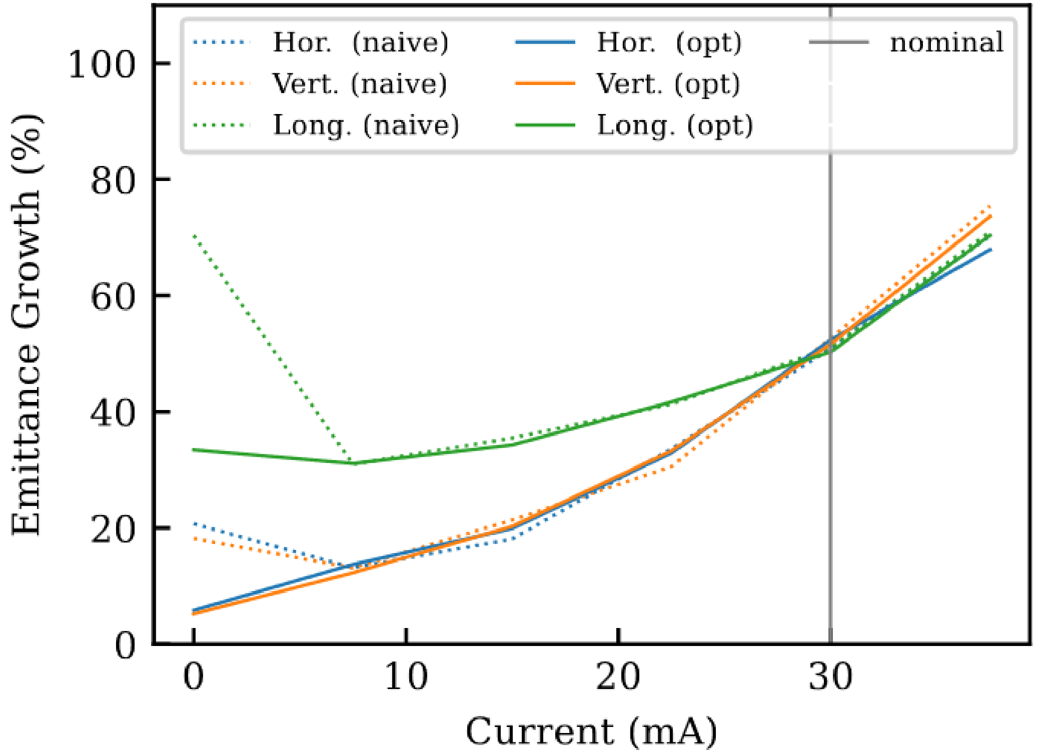


DEVIATION FROM NOMINAL CURRENT

Using the 30mA 76 cell linac design,

the influence of non-nominal current is investigated.

During commissioning with lower current, even better beam quality can be expected.



III. Historical Development

Several patterns were presented during the last decades:

- **Sinusoidal**
- Stepfunction
- Heavyside
- Sawtooth

$$\phi_i = \alpha \cos\left(\frac{\omega t}{n}\right)$$

$$n = \sqrt{\frac{\beta}{A(1-\beta^2)^{3/2}}}$$

$$A = \frac{\alpha}{\pi}\frac{e\bar{E}\eta\lambda}{mc^2}$$

[Fainberg 1956]

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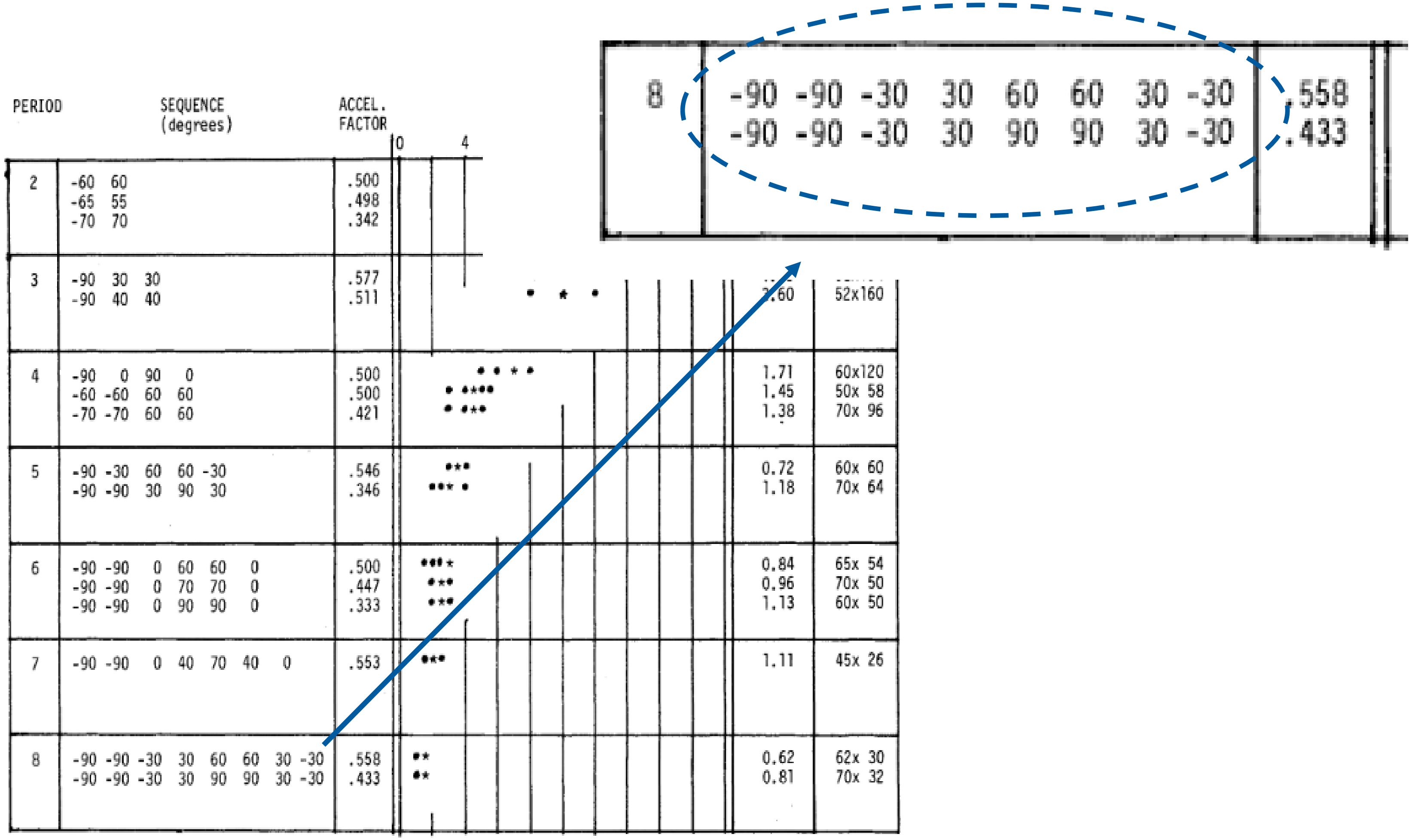

PERIOD	SEQUENCE (degrees)	ACCEL. FACTOR		
2	-60 60 -65 55 -70 70	.500 .498 .342		
3	-90 30 30 -90 40 40	.577 .511	[illegible].60	52x160
4	-90 0 90 0 -60 -60 60 60 -70 -70 60 60	.500 .500 .421	1.71 1.45 1.38	60x120 50x 58 70x 96
5	-90 -30 60 60 -30 -90 -90 30 90 30	.546 .346	0.72 1.18	60x 60 70x 64
6	-90 -90 0 60 60 0 -90 -90 0 70 70 0 -90 -90 0 90 90 0	.500 .447 .333	0.84 0.96 1.13	65x 54 70x 50 60x 50
7	-90 -90 0 40 70 40 0	.553	1.11	45x 26
8	-90 -90 -30 30 60 60 30 -30 -90 -90 -30 30 90 90 30 -30	.558 .433	0.62 0.81	62x 30 70x 32

FIGURE 1 Array of basic phase sequences with excitation and performance data.

[Swenson 1975]

III. Historical Development

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- Heavyside
- Sawtooth

Table 3
Main parameters for final HSC linac design.

	RFQ	GBP+DTs
Charge to mass ratio (q/A)	6/12 (C^{6+})	
Operation frequency (MHz)	100	
Total length (mm)	1800	
Power (kW) (MWS)	93.98	
Q value (MWS)	14577	
ERT length (mm)	150	
Maximum field (Kipat.)	1.8	
Number of cells	41	1+16
Synchrotron phase	−90 → −30	0, −60, −30, 30, 30

[Lu 2012]

III. Historical Development

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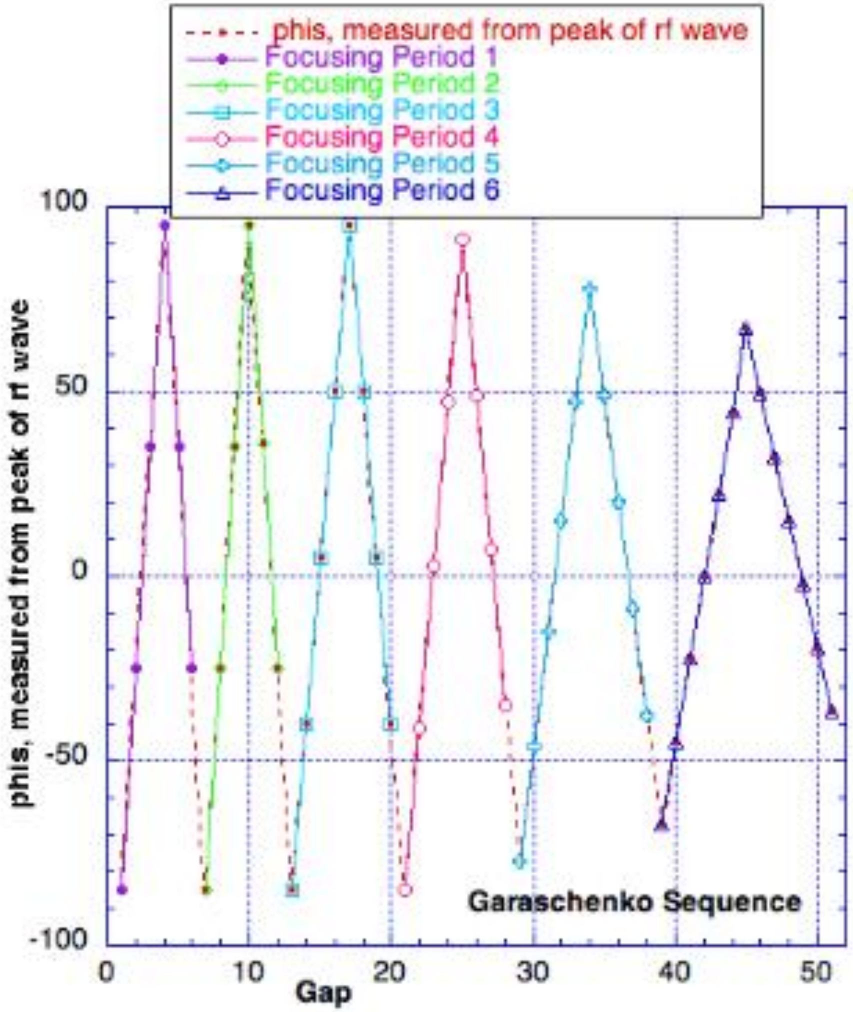
- **Sawtooth**



[Garschenko 1982, Jameson 2015]

III. Historical Development

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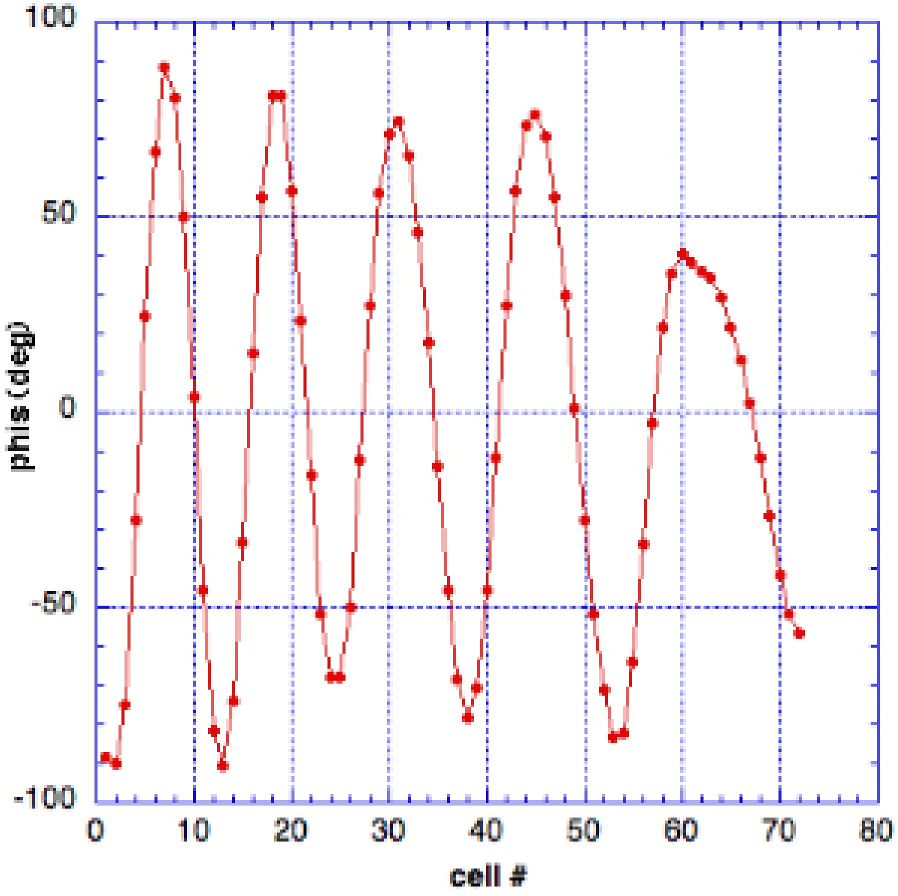

Fig. 3. The NIRS APF sequence. (Courtesy of NIRS.)

[Iwata 2006, Jameson 2015]

III. Historical Development

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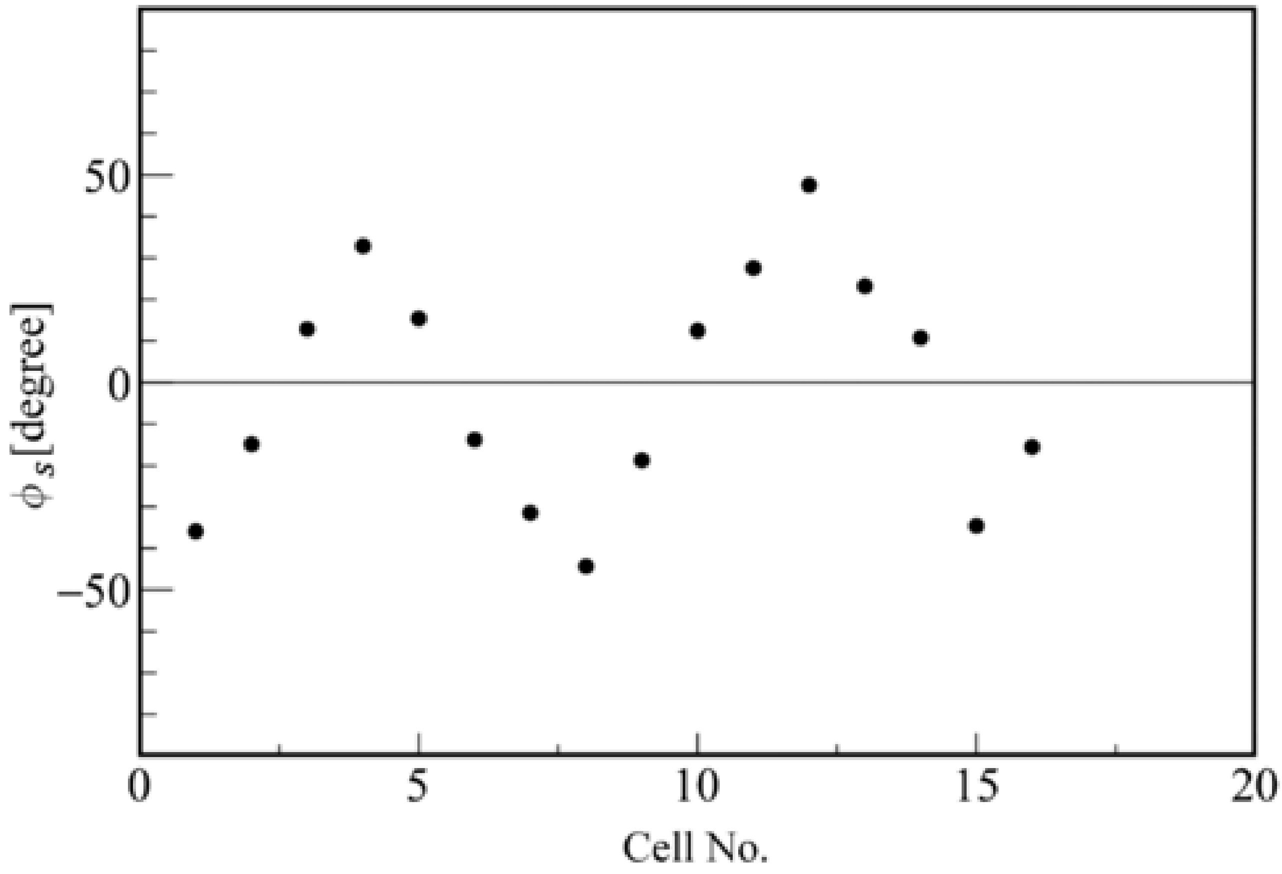
- **Sawtooth**



[Otani 2016]

III. Historical Development

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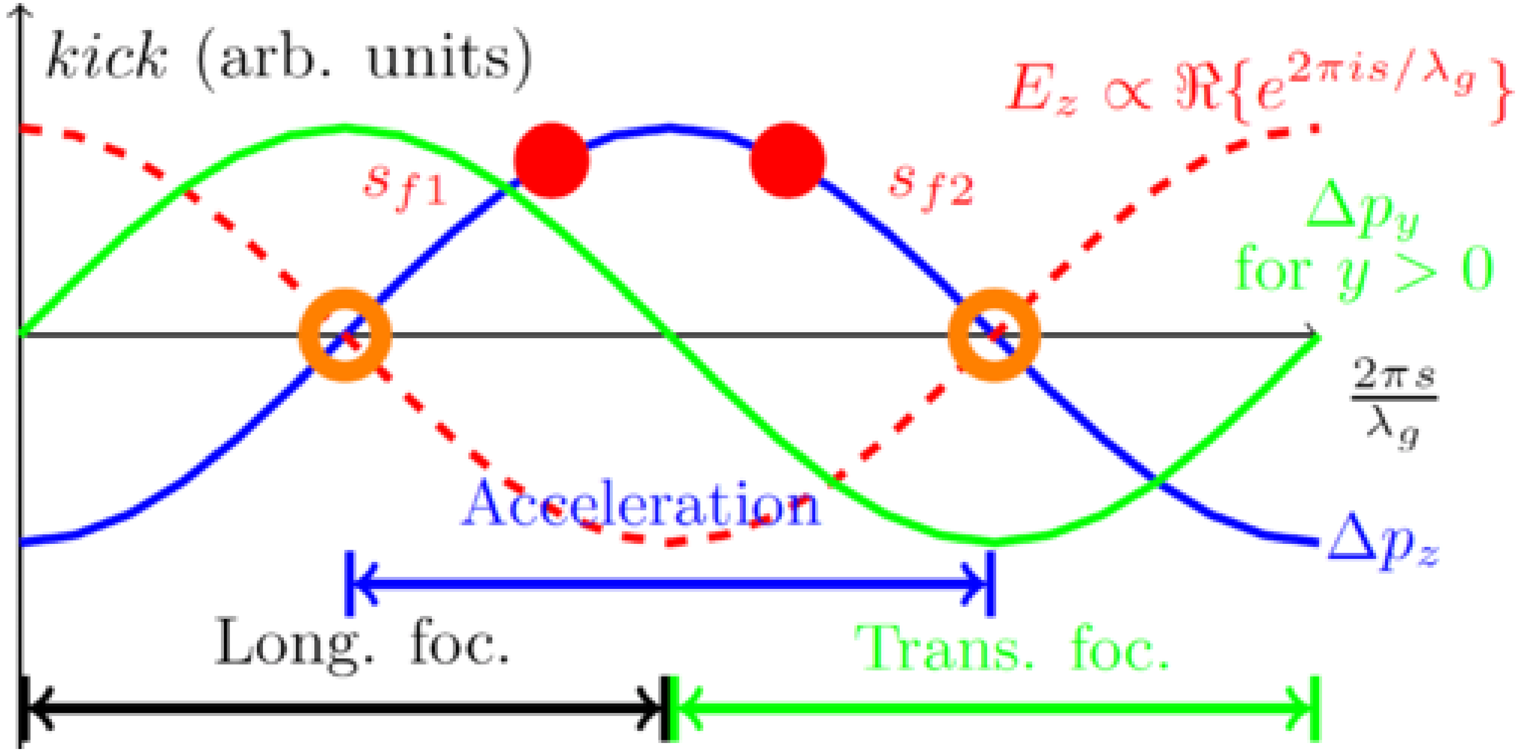

[Niedermayer 2018]

III. Historical Development

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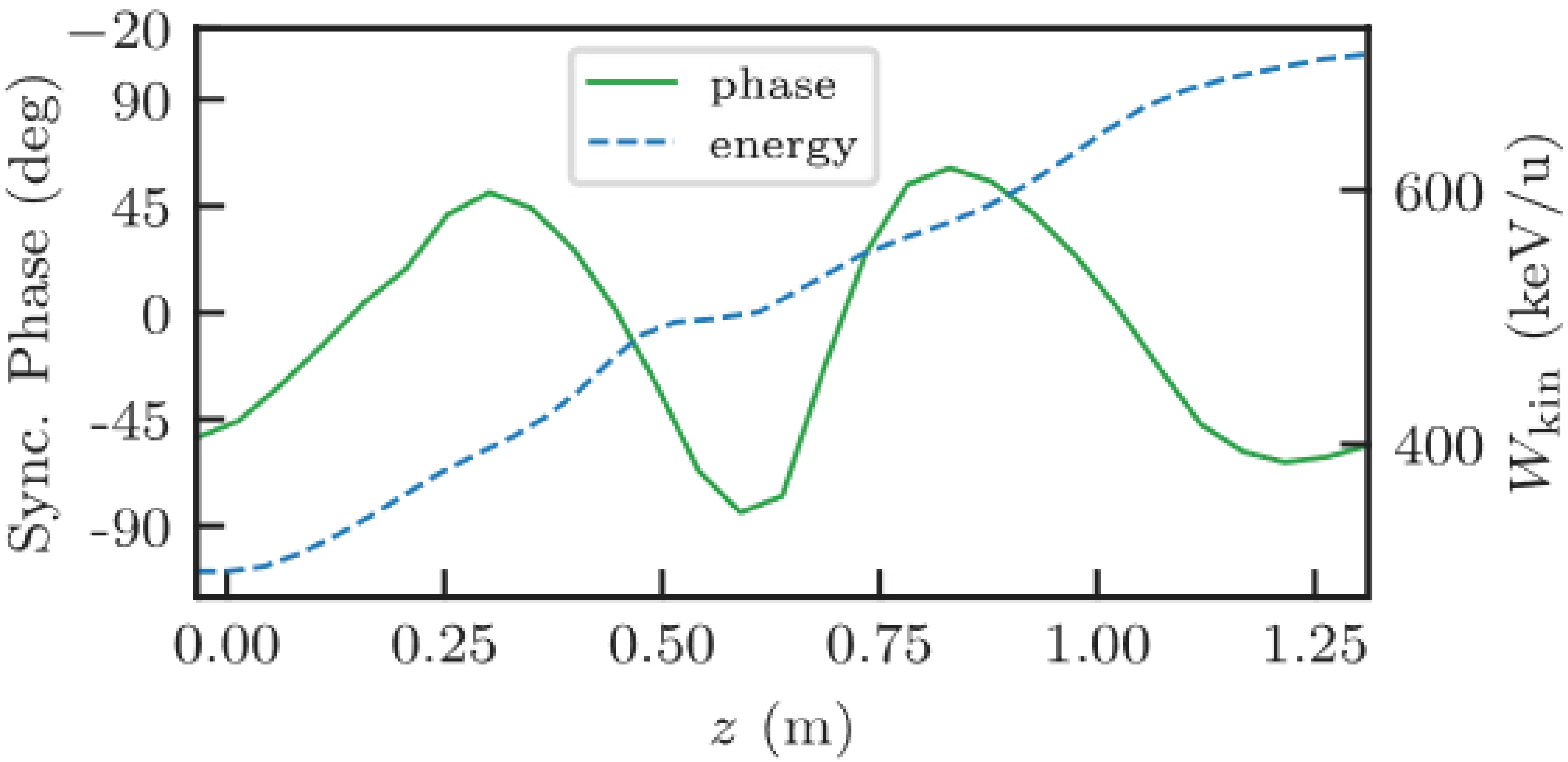

[Lauber 2022]