Physics design of front ends for superconducting ion linacs

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Content

- RF ion linear accelerators (Normal Conducting and Superconducting)
  - CW (100% duty factor)
  - Pulsed
- Available SC accelerating structures for low energy hadron beams
- Focusing Lattice
- HINS PD - Example of axial-symmetric focusing SC Front End
- RFQ design to form axial-symmetric beams
- Properties of focusing lattice for HINS PD – 40 mA peak current
- Front End for a SC Linac with 100 mA beam current
- Conclusion

RF linacs

- **RF Linacs**
  - **CW**
    - **NC**
      - Low-energy
      - <several MeV/u
      - Heavy-ions
      - **ISAC-I**
      - **RIKEN inj.**
      - IFMIF- ?
      - …..
    - **SC**
      - **ATLAS**
      - **ISAC-II**
      - **INFN**
      - SPIRAL-2
      - SARAF
      - FRIB
      - EURISOL
      - Several "waste transmutation" projects
  - **Pulsed**
    - **NC**
      - **LANSCE**
      - **Synchrotron Injectors (FNAL,KEK CERN….)**
      - **MMF (Moscow)**
      - **SNS**
    - **SC**
      - **SNS**
      - HINS (Project X)
      - Several other projects

CW Linacs: NC or SC ?

- Required RF power to create accelerating field

$$P = \frac{V_{eff}^2}{L \cdot R_{sh}}, \; R_{sh} = function(f, \beta, a)$$

- Typical example: FRIB driver linac

$$V_{eff} = 800\ MV = 8 \cdot 10^8\ V, \quad R_{sh} \approx 40 \cdot 10^6\ Ohm/m, \quad E = 2\ MV/m$$

$$L = 400\ m, \quad P = \frac{64 \cdot 10^{16}}{400 \cdot 40 \cdot 10^6} = 40\ MW$$

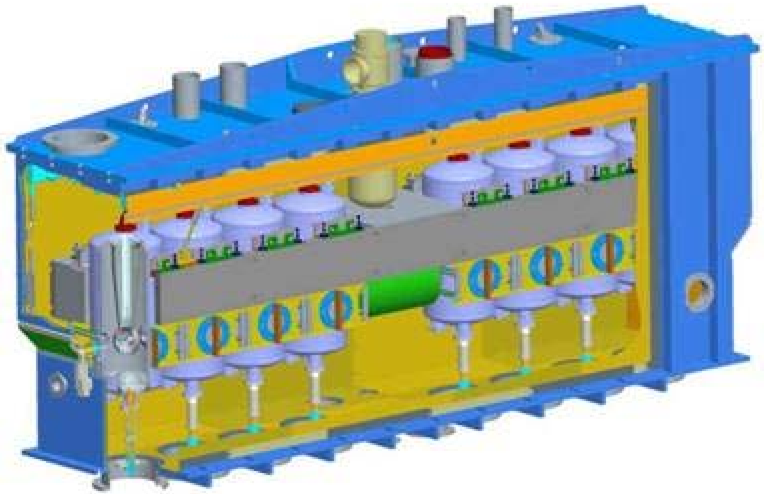
Efficiency of RF amplifiers is ~(40-60)%

Required AC power is ~100 MW just for RF

- Superconducting CW linac is much more economic than NC
- Both pulsed or CW SC linacs require NC front end for ~0.1 to 200 MeV/u depending on q/A and duty factor

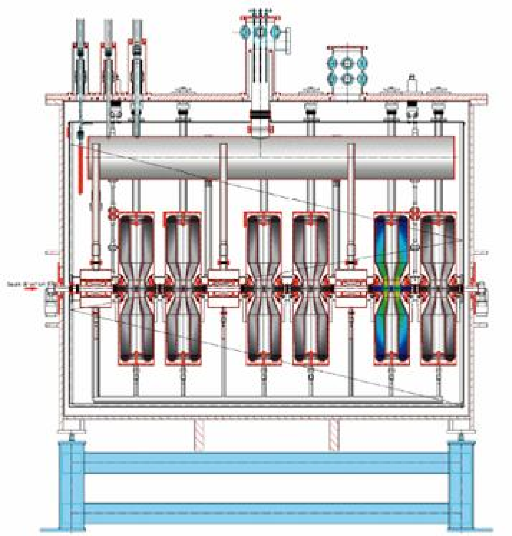
Examples of CW SC linacs

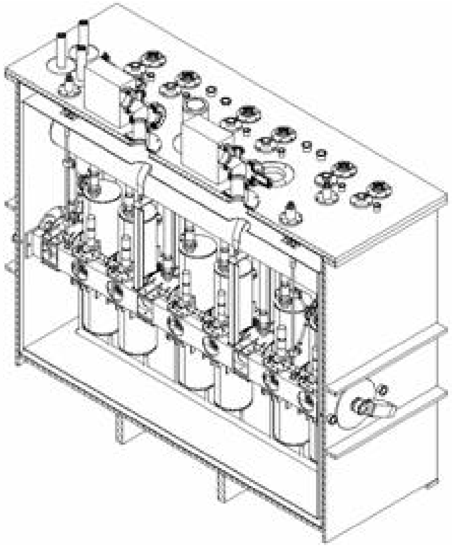
- ATLAS



TRIUMF

ACCEL for SARAF





Pulsed Superconducting Linacs

- SC structures offer higher accelerating gradients then NC structures
  - SNS NC Front End – 128.5 m, 185.6 MeV
  - HINS (Project X) SC Front End– 137 m, 420 MeV
- Comparable cost for the duty factor ~7% - SNS high-energy section

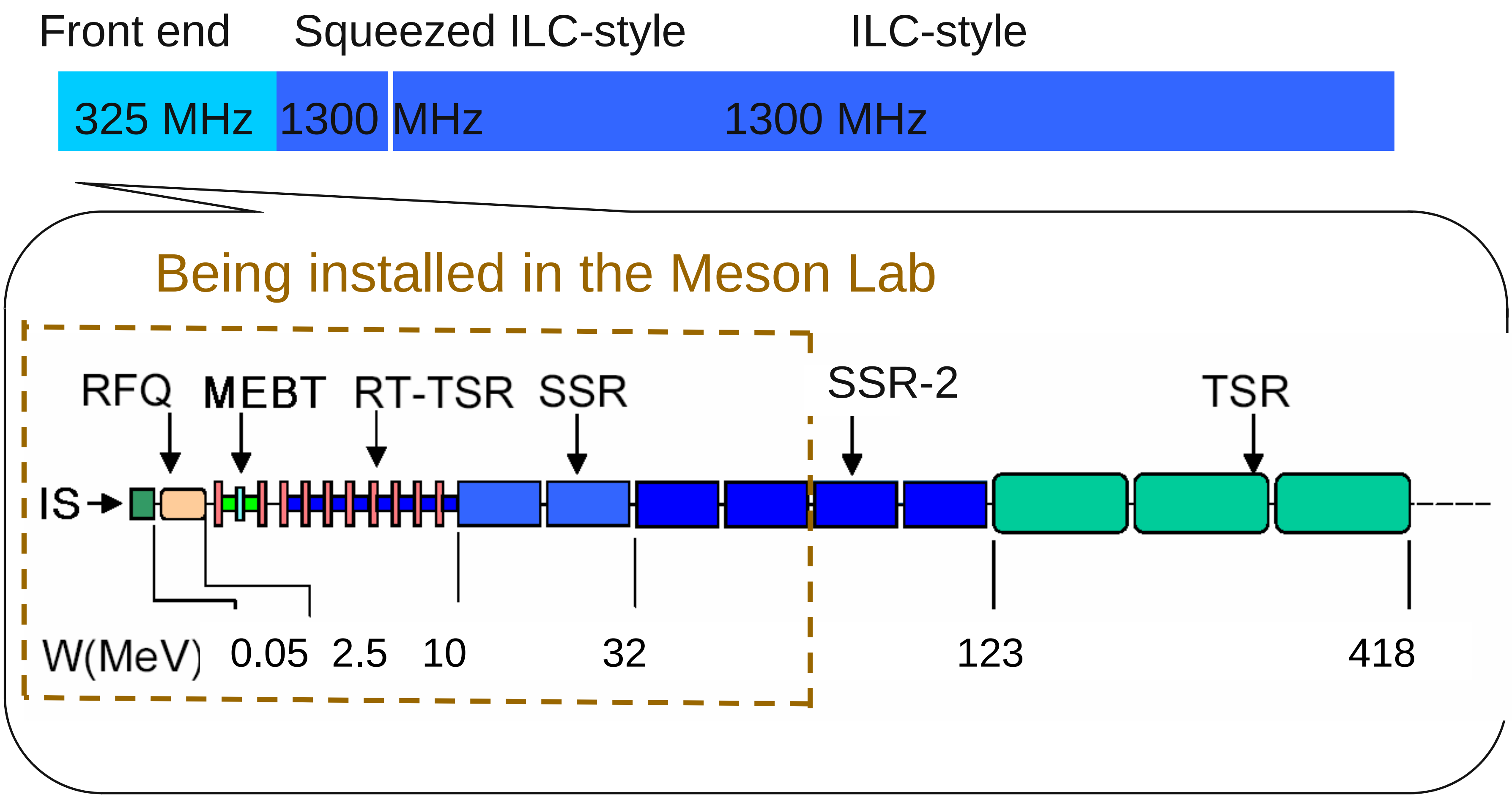
- 8 GeV p & H-minus Linac with low duty factor <1% (FNAL: HINS or Project X)
  - Cost-effective above ~0.4 GeV thanks to the ILC developments
  - Innovative technology: one klystron feeds multiple cavities
    - *One J-PARC klystron is required to obtain 100 MeV*
    - *5 klystrons for Front End 420 MeV*
  - Below 400 MeV the costs of NC and SC linacs are comparable. In the presence of cryoplant, a SC front end is favorable

HINS SC Linac design

- 8-GeV based on ILC 1300 MHz 9-cell cavities
  - H-minus linac
  - 45 mA peak current from the Ion Source
- Requires Front End above ~420 MeV.
- Superconducting linac 325 MHz,
  - 2 types of Single Spoke Resonators and Triple SR from 10 MeV to ~420 MeV
- NC front end: RFQ, MEBT and 16 short CH-type cavities
- Apply SC solenoid focusing to obtain compact lattice in the front end including MEBT
- RFQ delivers axial-symmetric 2.5 MeV H-minus beam
- MEBT consists of 2 re-bunchers and a chopper. Smooth axial-symmetric focusing mitigates beam halo formation
- ILC section: 1 klystron feeds ~20-26 cavities
- Apply similar approach for the Front End
- Five klystrons are sufficient to accelerate up to ~420 MeV

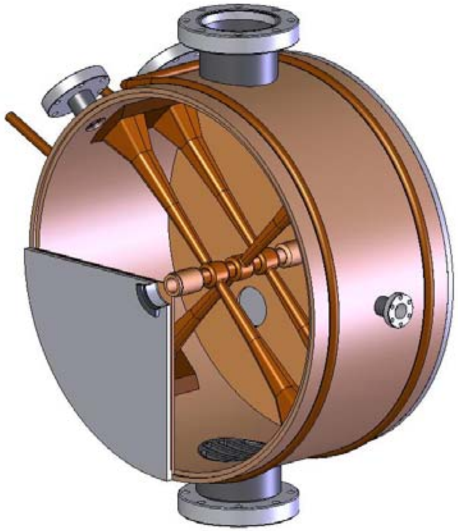
Linac Structure

Major Linac Sections

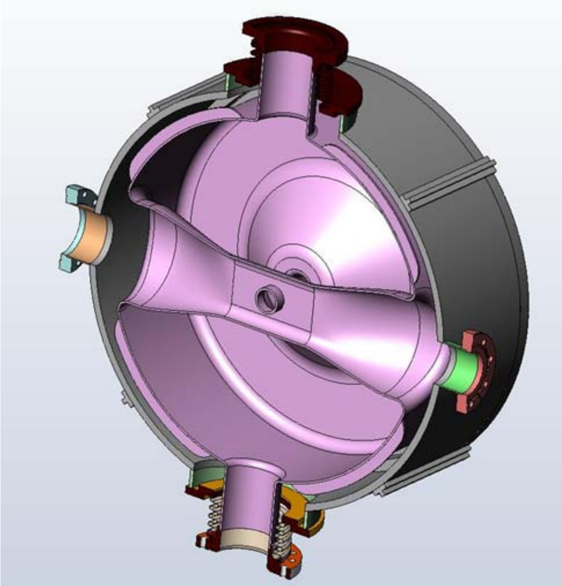


Accelerating cavities (not to scale)

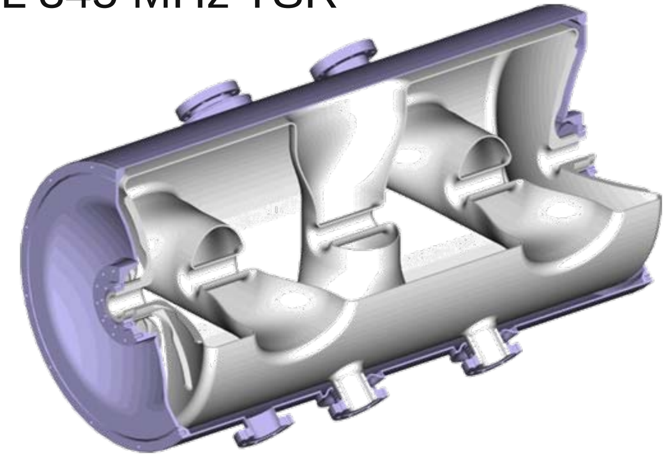
NC spoke



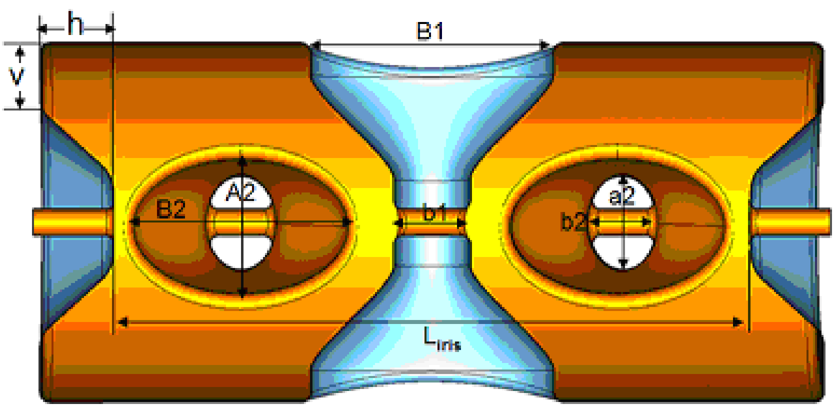
SC single spoke



ANL 345 MHz TSR

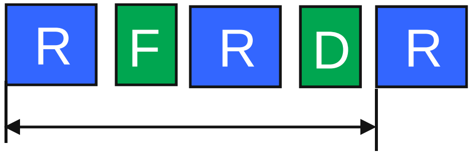


FNAL 325 MHz TSR

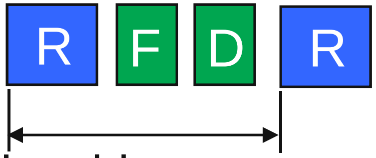


Focusing structure in the SC Linac

- In low energy section SC cavities can provide high accelerating gradients
  - CW linac: ~12 MV/m (real estate ~4-5 MV/m)
  - Pulsed: ~18 MV/m (real estate ~6-8 MV/m), (SNS = 1.5 MV/m)
- Real estate gradient is higher than in NC by factor of 4-6
  - To fully use available gradients, apply strong focusing
- Available options for the focusing structure
  - FODO

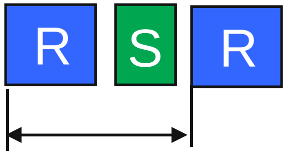


  - FDO



Beam modulation is high
Long drift space for longitudinal dynamics

  - SC Solenoids



Focusing by SC solenoids

- To provide stability for all particles inside the separatrix the defocusing factor

$$\Delta_s = \frac{\pi}{2} \frac{1}{(\beta\gamma)^3} \frac{S_f^2}{\lambda} \frac{eE_m \sin\varphi_s}{m_0 c^2}$$

  should be below ~0.7
- Solenoids decrease the length of the focusing period S_f by factor of 2 compared to FODO. It means factor of 4 in tolerable accelerating fields for the same S_f.
- This argument works even better for 600 MeV>W>~100 MeV proton linac, the acceleration can be done with low frequency structures (triple spoke cavities)
- Other advantageous of solenoids compared to typical FODO
  - Acceptance is large for the same phase advance μ. Important for NC structures, aperture can be small
  - Less sensitive to misalignments and errors. The most critical error – rotation about the longitudinal axis – does not exist
  - Beam quality is less sensitive to beam mismatches

Focusing by SC solenoids (cont'd)

- Long term experience at ATLAS (ANL)
- Now operational at TRIUMF
- New projects: SARAF
- Perfectly suitable for SC environment together with SRF
  - Beam quality is less sensitive to inter-cryostat transitions
  - Easily re-tunable to adjust to the accelerating gradient variation from cavity to cavity. This is critical in low energy SC linac due to the beam space charge.
  - Can be supplemented with dipole coils for corrective steering
- MEBT: long drift space for chopper does not cause dramatic emittance growth for high current beams

- Not suitable for H-minus above ~100 MeV due to stripping at solenoid edge field

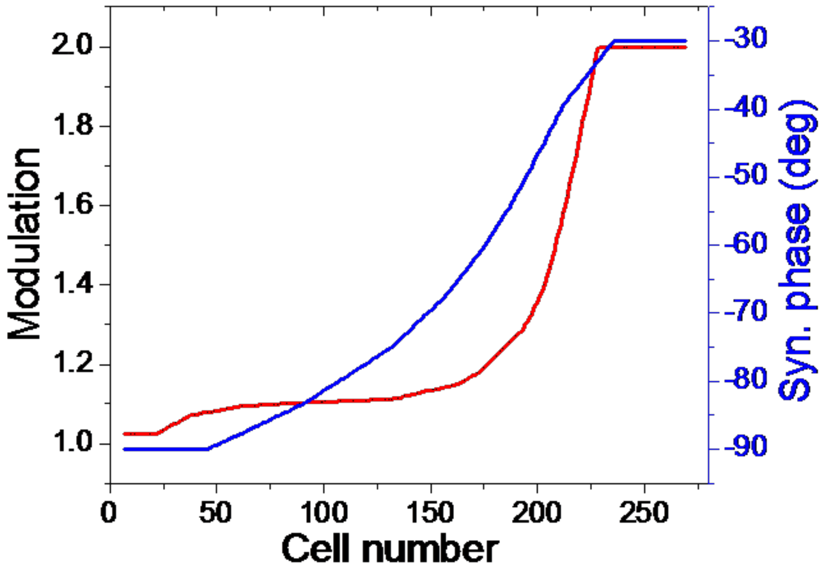
Why SC solenoids in the HINS proton driver (or Project X) ?

- Cryogenics facility is available, major part of the linac is SC
- The Front End (up to 420 MeV) is based on SC cavities: 325 MHz SSR, TSR
  - Long cryostats house up to ~10 SC cavities and solenoids
- Short focusing periods in the low energy region, 75 cm
- Axially-symmetric beam is less sensitive to space charge effects in the MEBT where the long drift space is necessary to accommodate the chopper and following beam dump
- Using SC solenoids in the NC section from 2.5 MeV to 10 MeV
  - Small beam size, aperture of the cavities is 18 mm in diameter
  - Short focusing periods from 50 cm to 75 cm
- RFQ can provide axial-symmetric beam

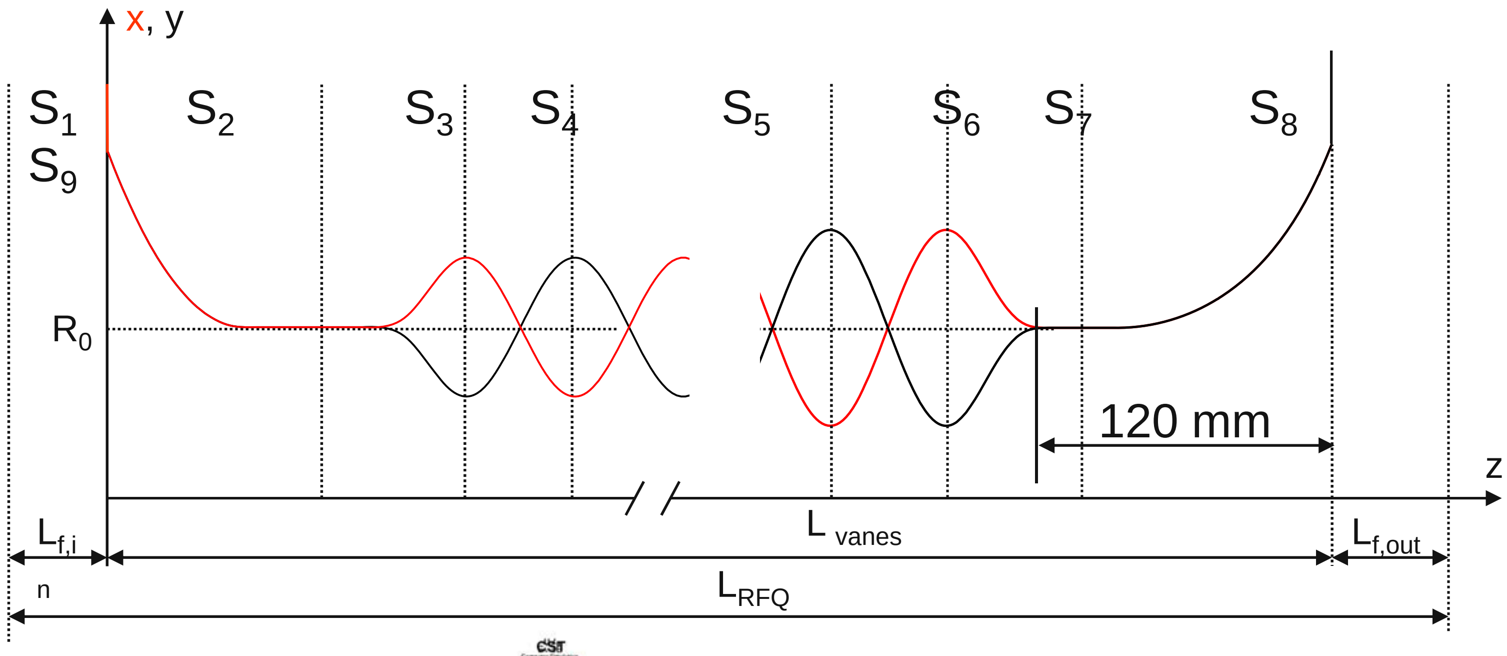
Radio Frequency Quadrupole

- Basic PD requirements:
  - Cost-effective
  - Produce axially-symmetric beam
  - Small longitudinal emittance

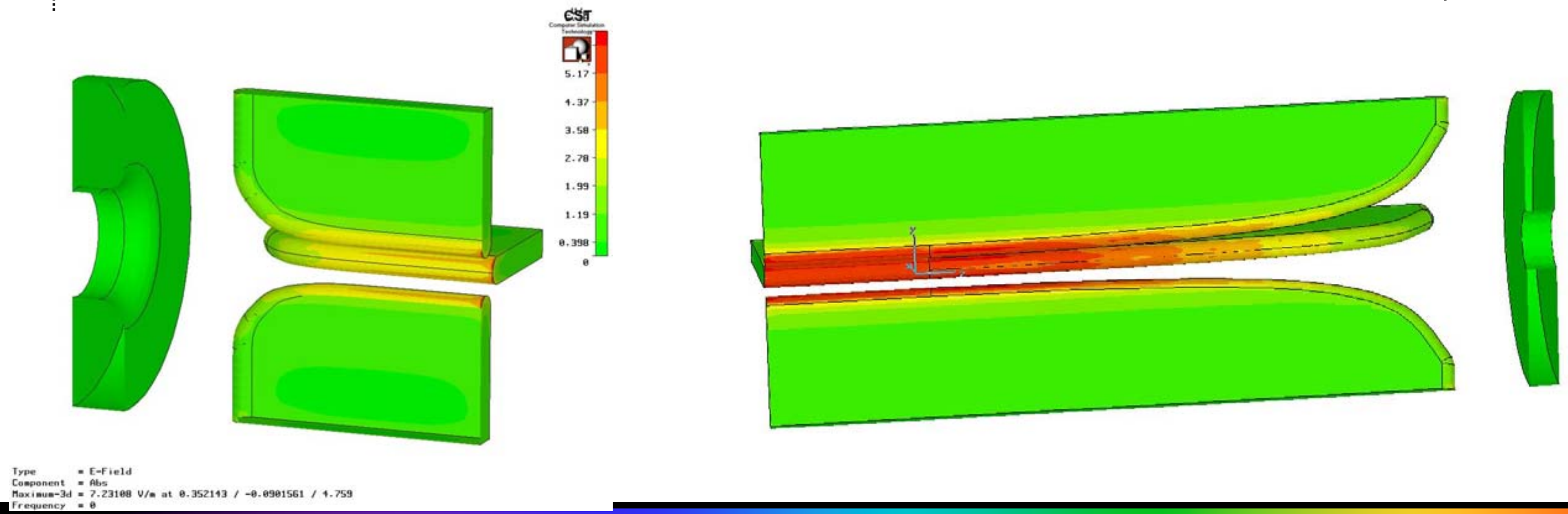
Average radius R_0, cm	0.340
Inter-vane voltage U_0, kV	90.45
Vane length, cm	302.428
Peak surface field, kV/cm	330
Output energy, MeV/u	2.498
Transverse emittance, rms, in/out, π mm mrad	0.10/0.10
Transverse emittance, 99.5%, in/out, π mm mrad	0.14/0.17
Long. emittance, rms, keV/u deg	133
Long. emittance, 99.5%, keV/u deg	1870
Transmission efficiency, %	97.8
Acceleration efficiency, %	95.9



RFQ vanes

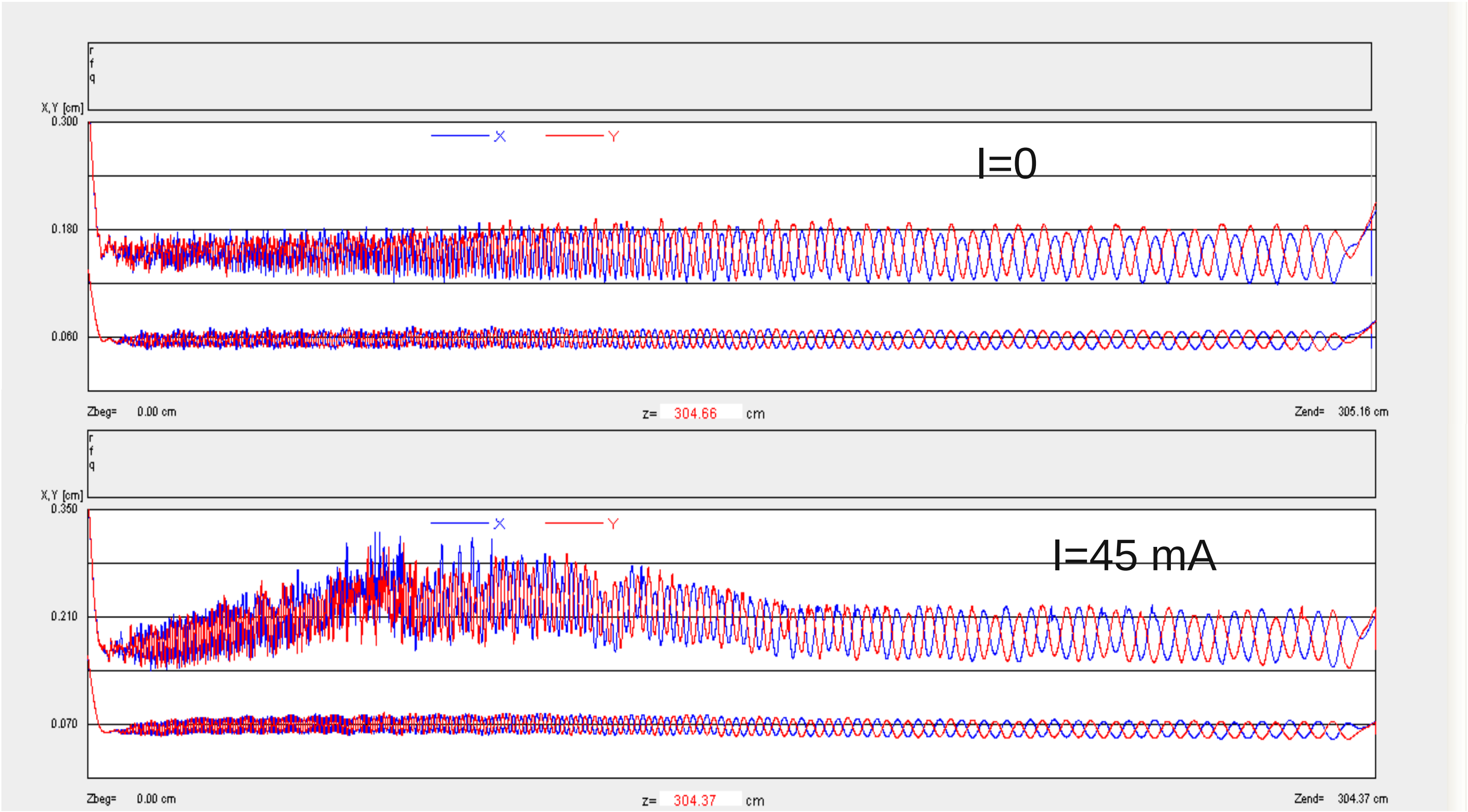


x, y
S1
S9
S2
S3
S4
S5
S6
S7
S8
R0
120 mm
z
Lf,i
n
L vanes
Lf,out
LRFQ



CST
5.17
4.37
3.58
2.78
1.99
1.19
0.398
0
Type = E-Field
Component = Abs
Maximum-3d = 7.23108 V/m at 0.352143 / -0.0901561 / 4.759
Frequency = 0

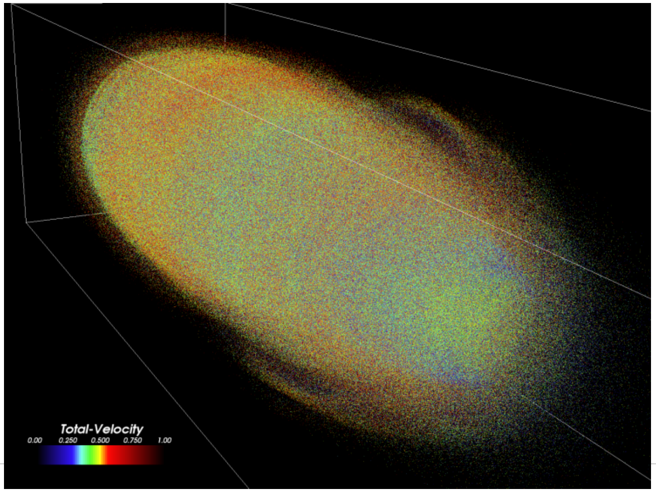
Beam envelopes along the RFQ

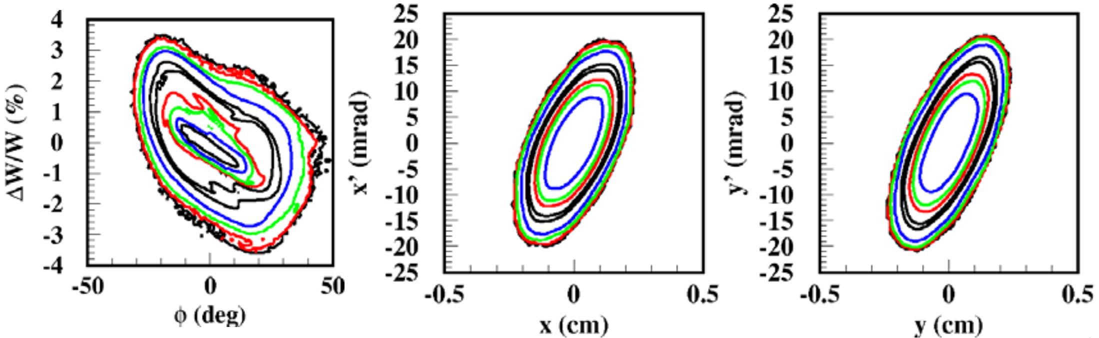


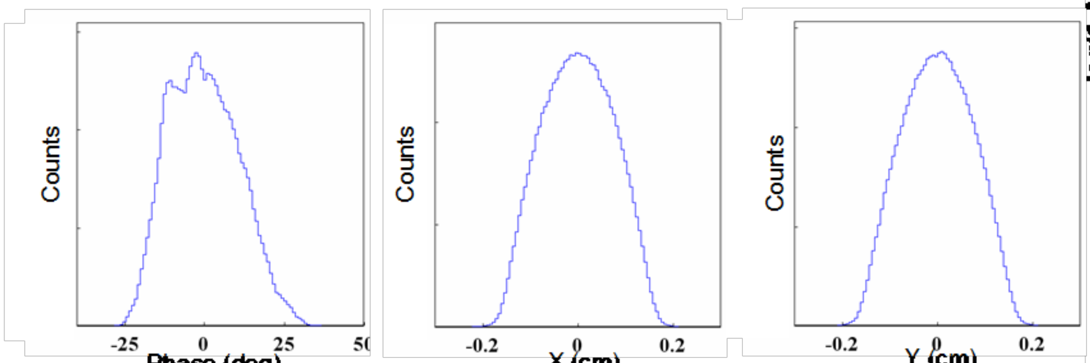
RFQ Beam Parameters (2.5 MeV, 43 mA)

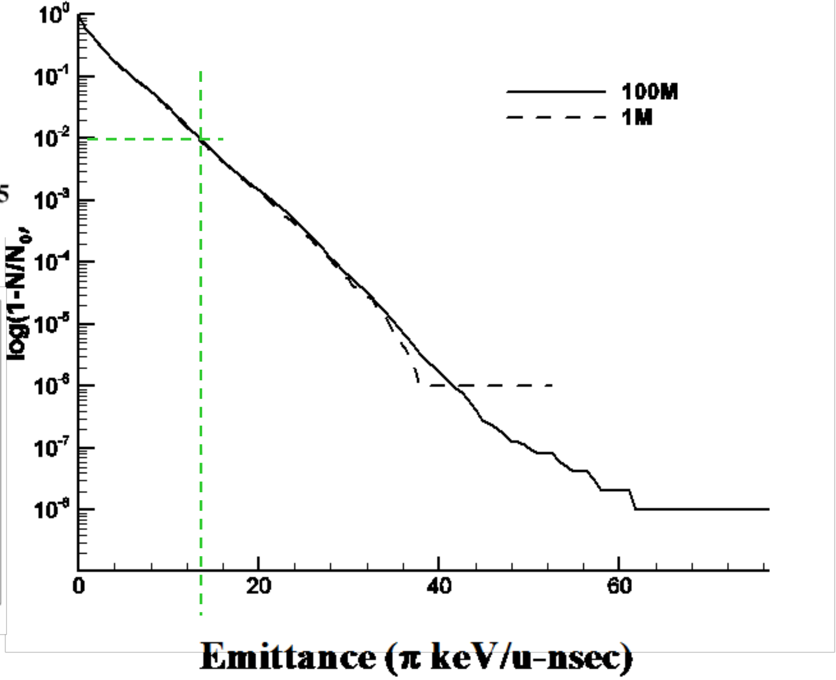
Image of 100 million particles

Δφ-ΔW/W XX′ YY′ Δφ-ΔW/W

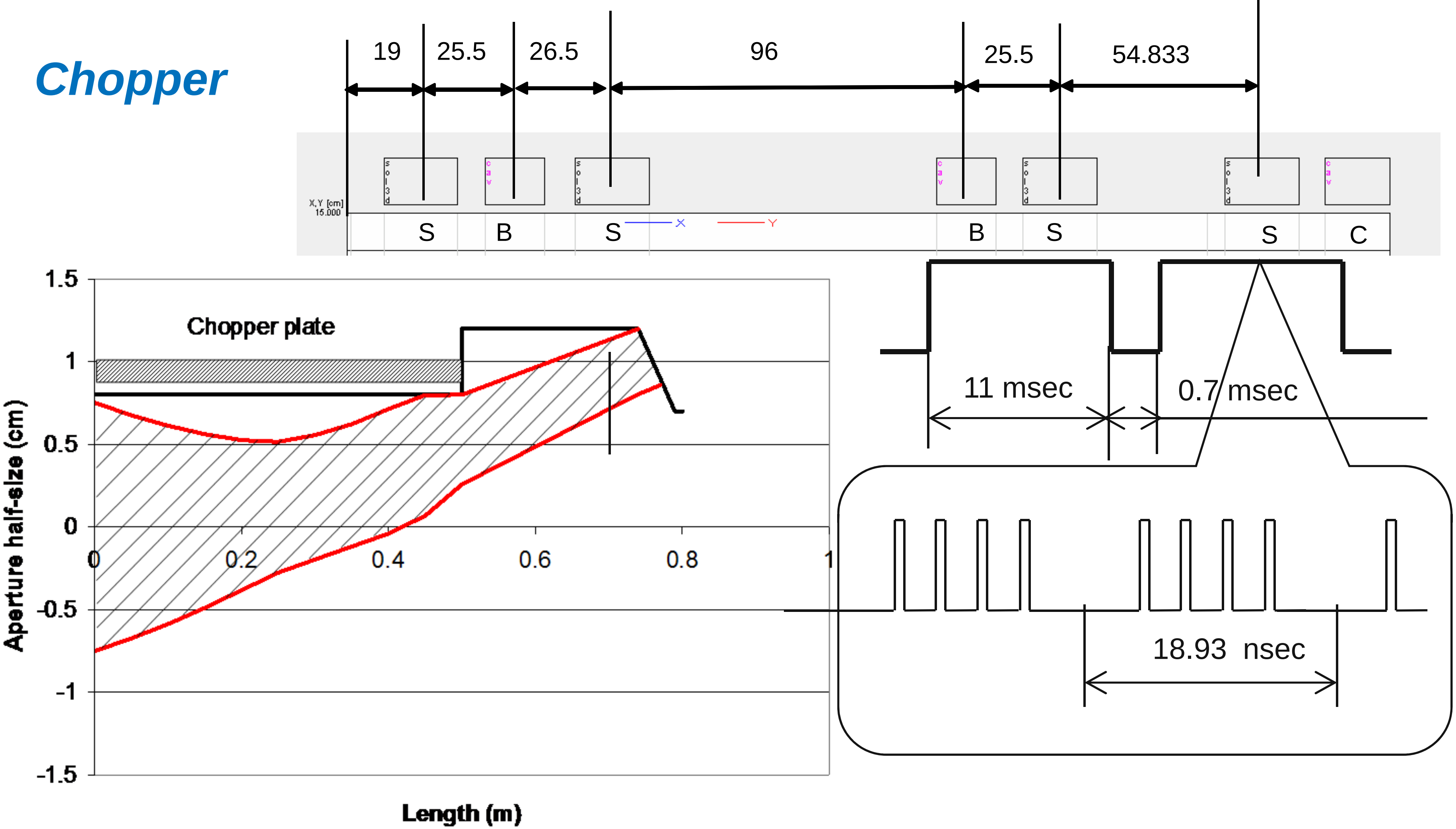








Chopper



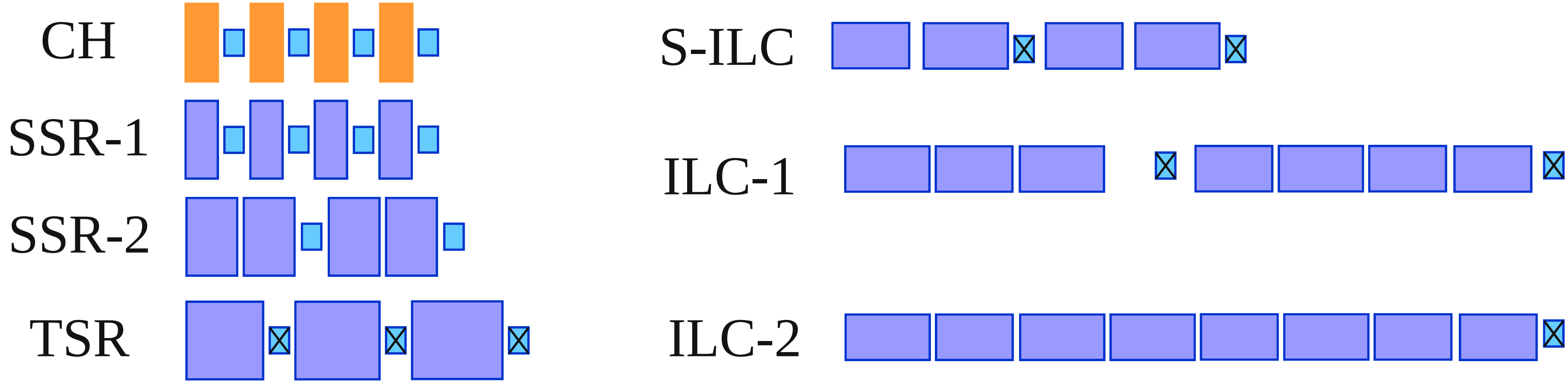
Pulser voltage ± 1.9 kV
Rep. rate 53 MHz
Rise/fall time ≤ 2 nsec (at 10% of the voltage level)
Beam target power: 37 kW pulsed, 370 W average

Properties of an ion SC linac and lattice design

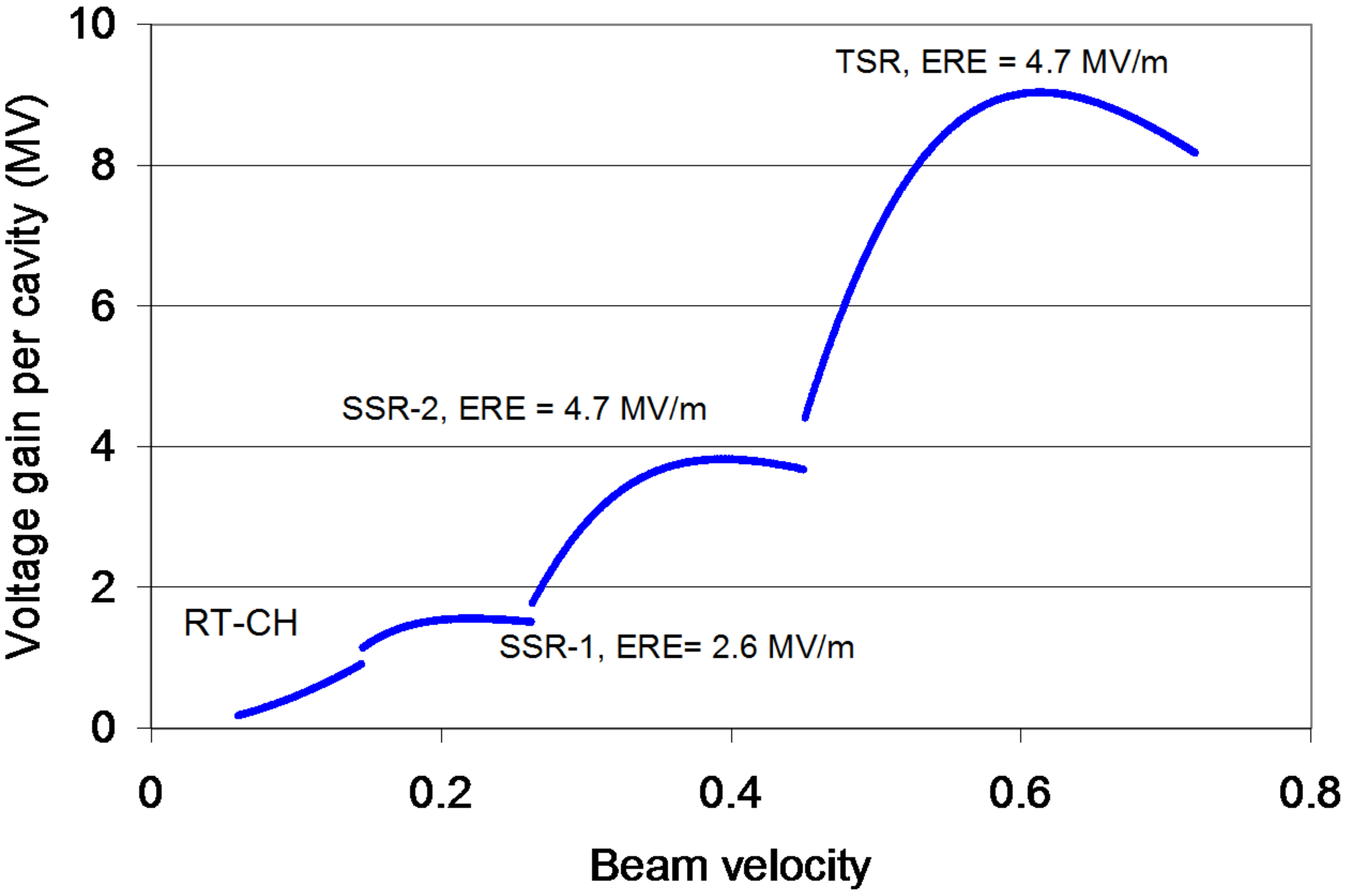
- The acceleration is provided with several types of cavities designed for fixed beam velocity. For the same SC cavity voltage performance there is a significant variation of real-estate accelerating gradient as a function of the beam velocity.
- The length of the focusing period for a given type of cavity is fixed.
- There is a sharp change in the focusing period length in the transitions between the linac sections with different types of cavities
- The cavities and focusing elements are combined into relatively long cryostats with an inevitable drift space between them. There are several focusing periods within a cryostat.
- Apply an iterative procedure of the lattice design
  - Choice of parameters
  - Tune for “zero” beam current
  - Tune for design beam current
  - Multiparticle simulations
  - Iterate to improve beam quality and satisfy engineering requirements

Cavity parameters and focusing lattice (Proton driver, 43.25 mA peak current)

Section	CH	SSR-1	SSR-2	TSR	S-ILC	ILC-1	ILC-2
β_G	-	0.2	0.4	0.6	0.83	1	
# of res.	16	18	33	42	56	63	224
# of cryost.	-	2	3	7	7	9	28
E_{peak} (MV/m)	-	30	28	30	52	52	
Focusing	SR	SR	SRR	FRDR	FR^2DR^2	FR^4DR^3	FR^8DR^8
$L_{Focusing}$ m	0.515-0.75	0.75	1.6	3.81	6.1	12.2	24.4

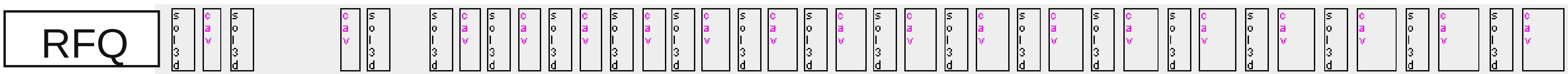


Cavity effective voltage (HINS PD and Project X)

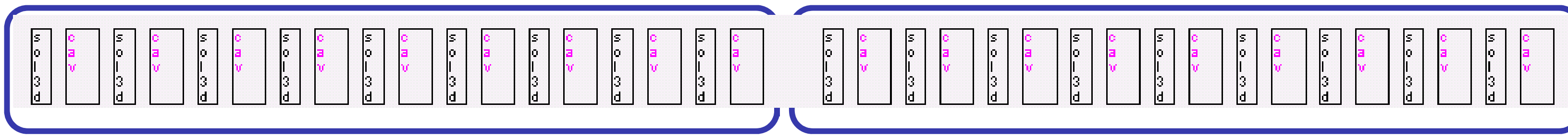


HINS PD lattice, mitigation of the effect of the lattice transitions

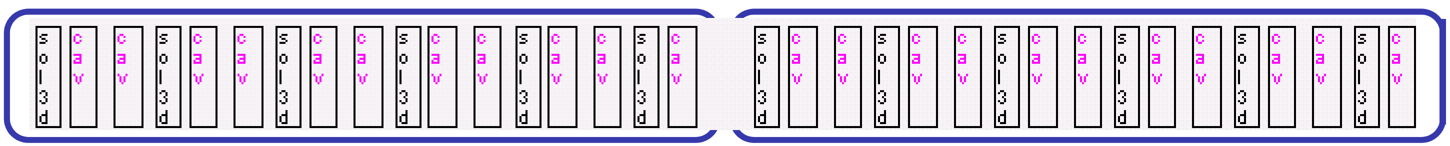
- MEBT and NC section, short focusing periods, adiabatic change from 50 cm to 75 cm



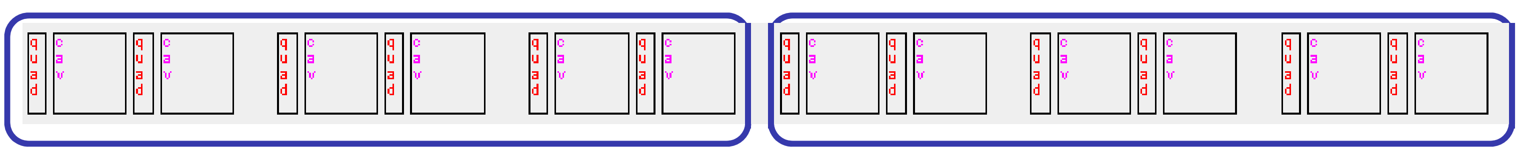
- 2 cryomodules of SSR-1: Minimize the inter-cryostat drift space



- 3 cryomodules of SSR-2: Provide a drift space by missing the cavity



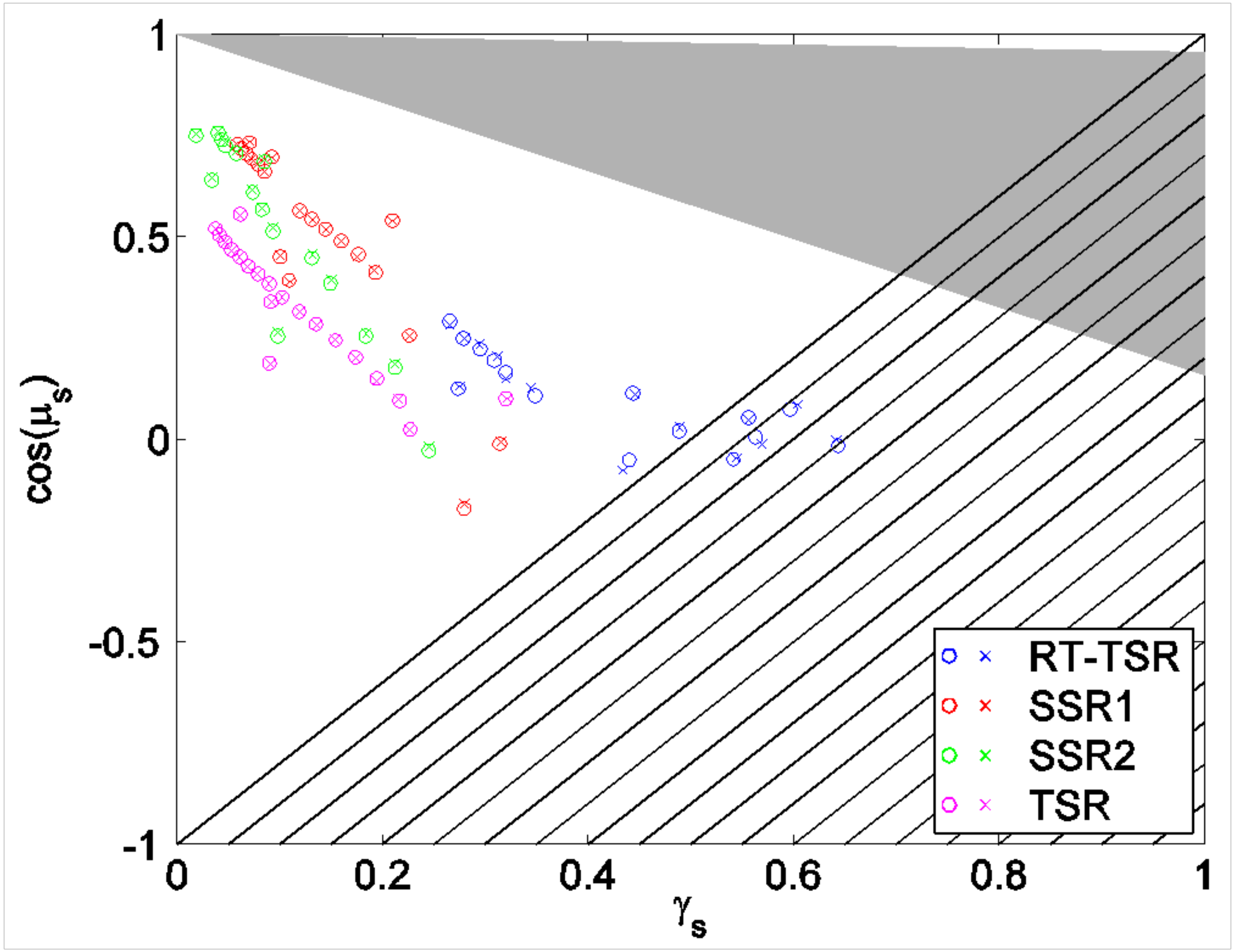
- 7 cryomodules of TSR: Provide an extra drift space inside the cryostat



Beam Dynamics Simulations

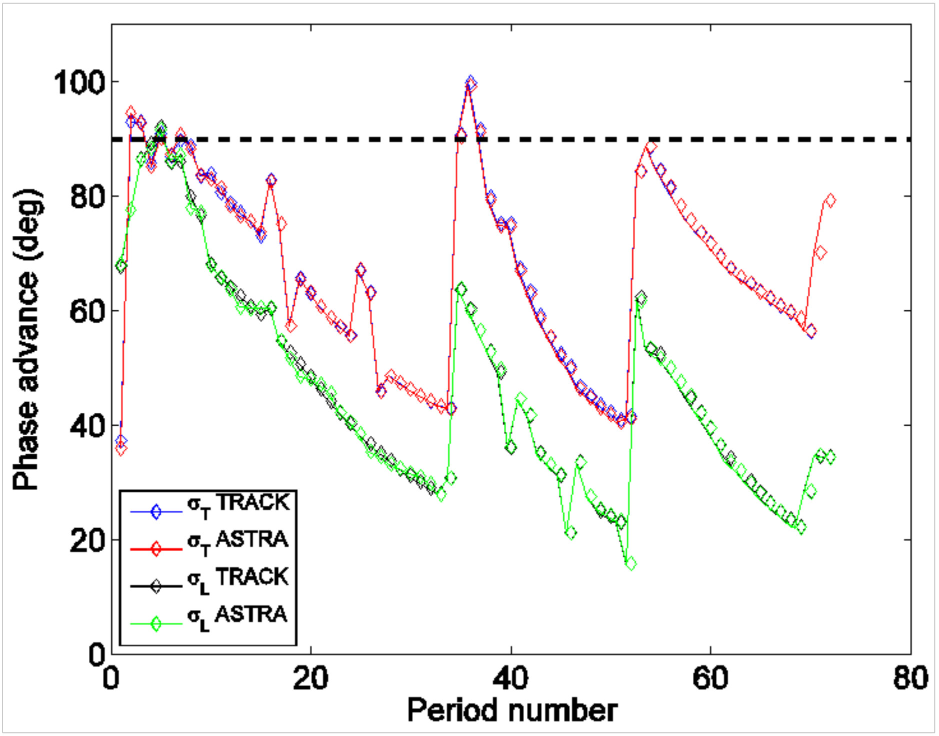
- The major workhorse is TRACK, recently P-TRACK
- “Zero-current” tune were created using TRACK routines in 3D-fields
- The tuned lattice was simulated with ASTRA for detailed comparison
- Tune depression with space charge:
  - rms beam dimensions are from TRACK or ASTRA
  - Use formula from T. Wangler’s book

Stability chart for zero current, betatron oscillation

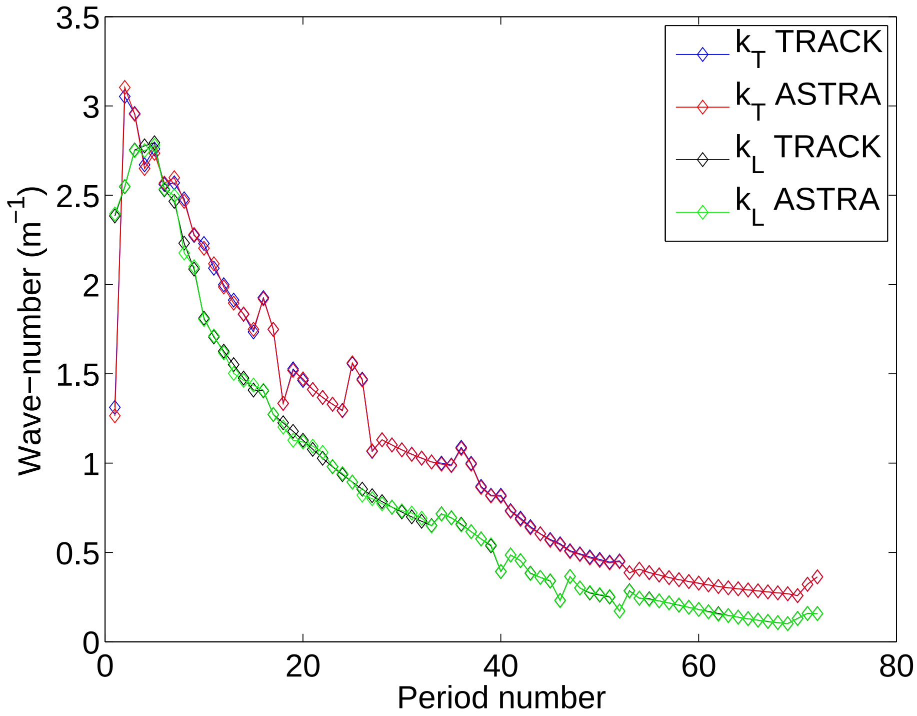


Variation of lattice parameters along the linac (preliminary design)

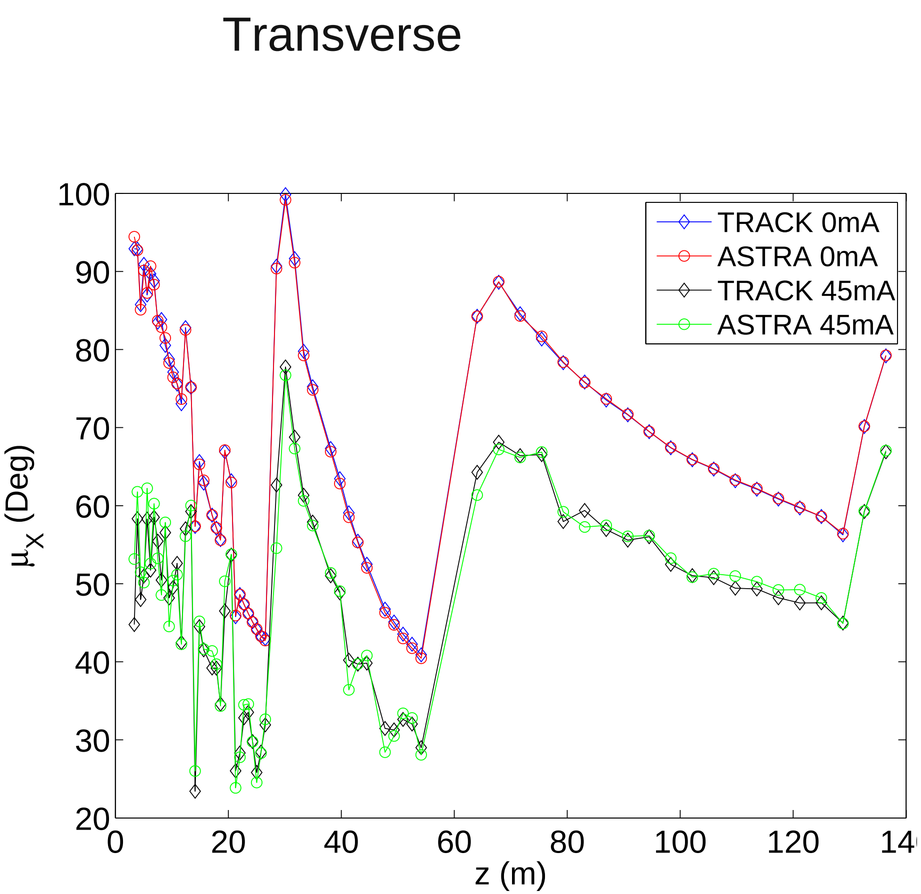
Phase advance

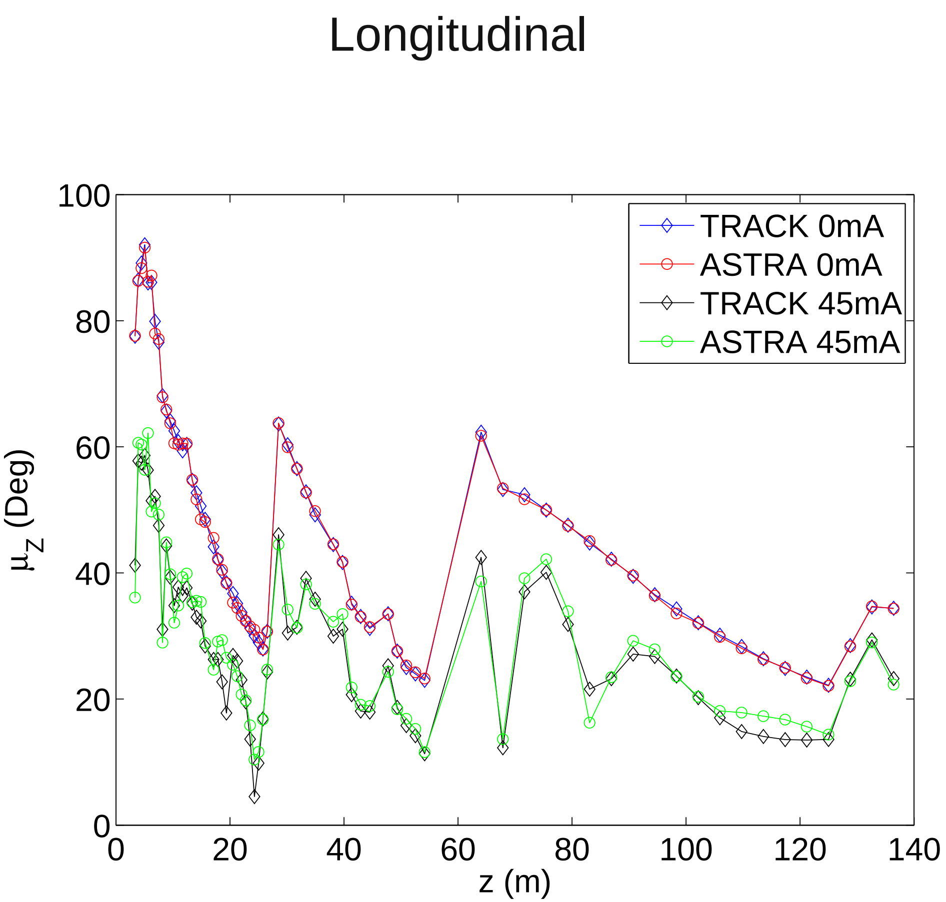


Wave numbers of transverse and longitudinal oscillations

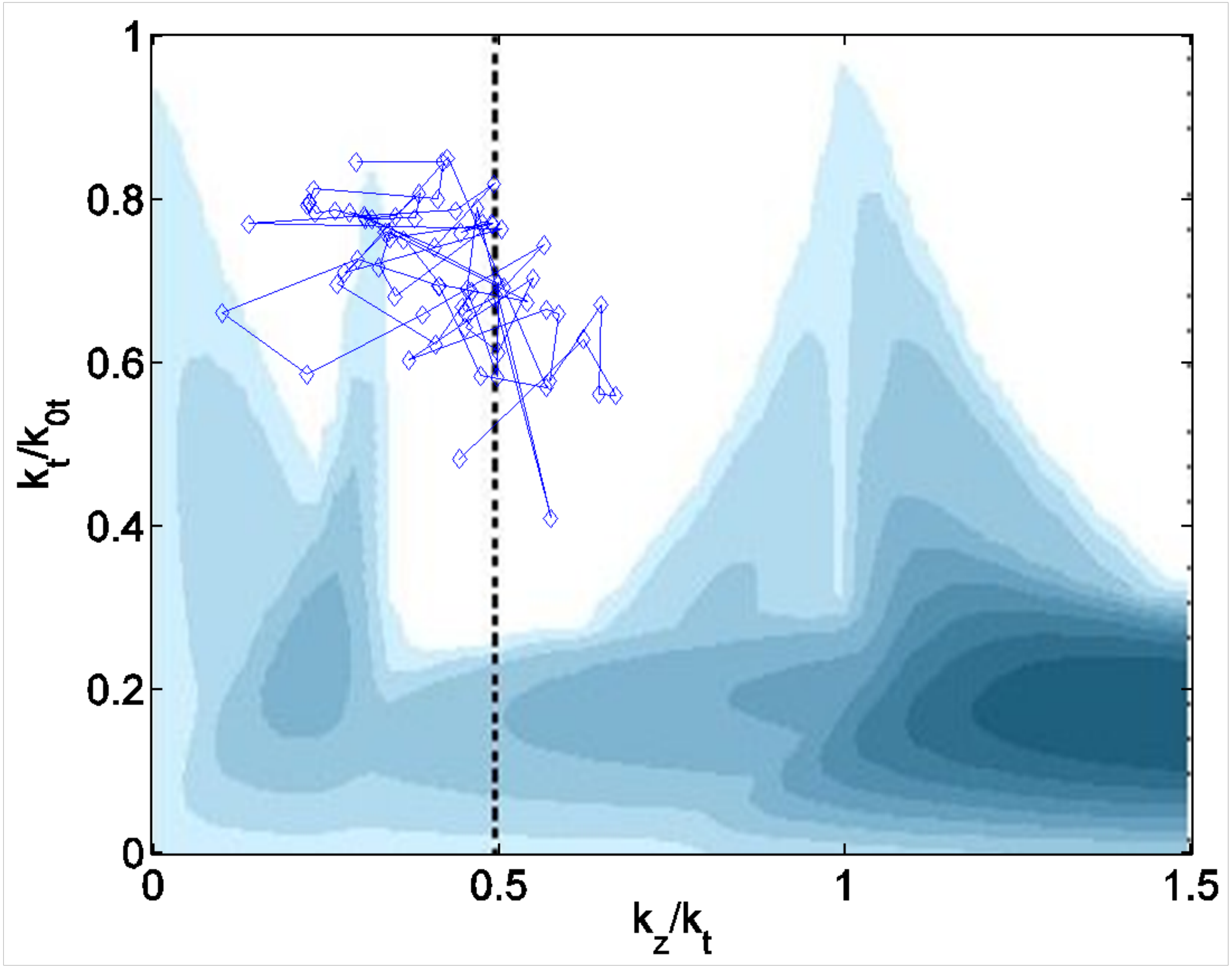


Tune depression due to the space charge





Hofmann's chart for the PD Front End

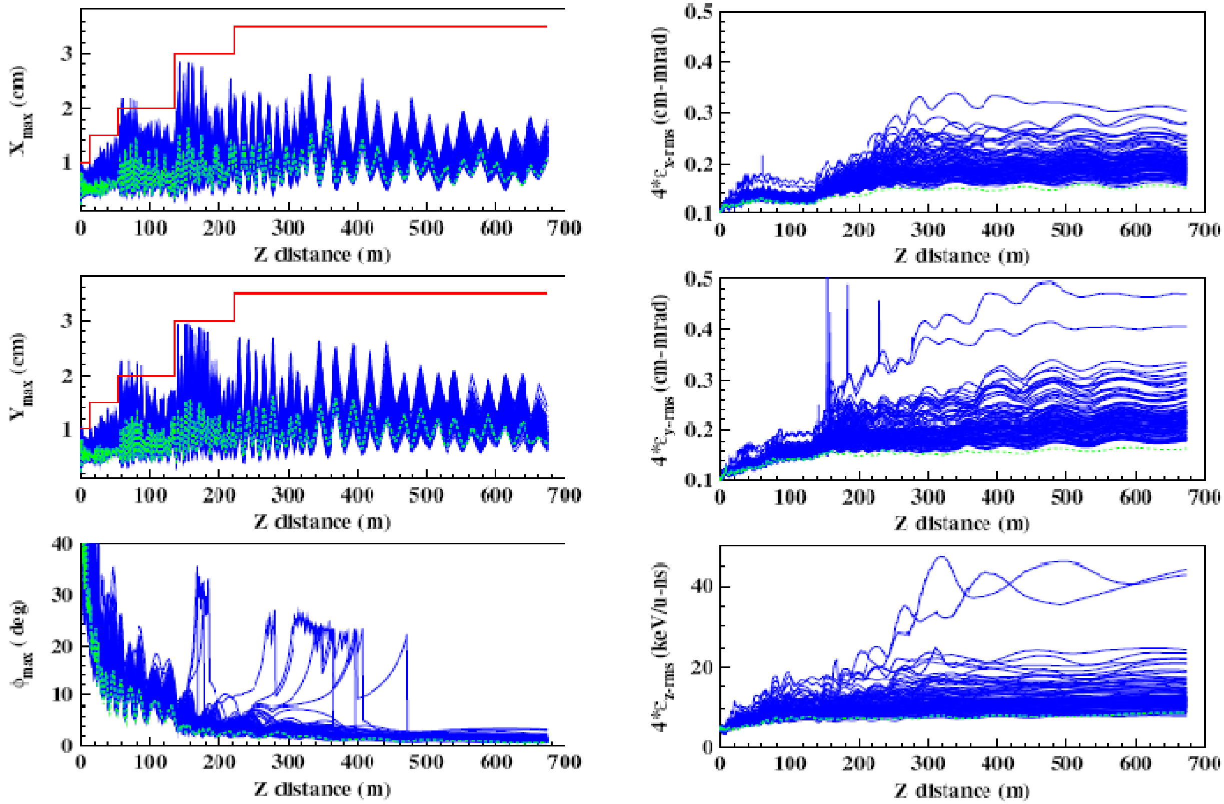


High statists for 8-GeV, 100 seeds with all errors

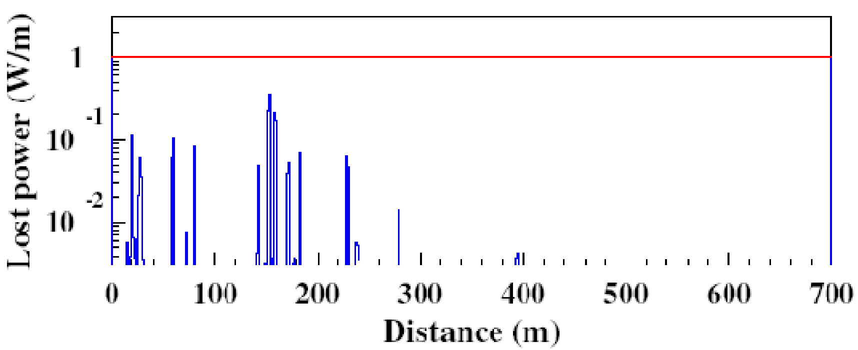
Envelopes

RMS emittances

Beam Losses (W/m)



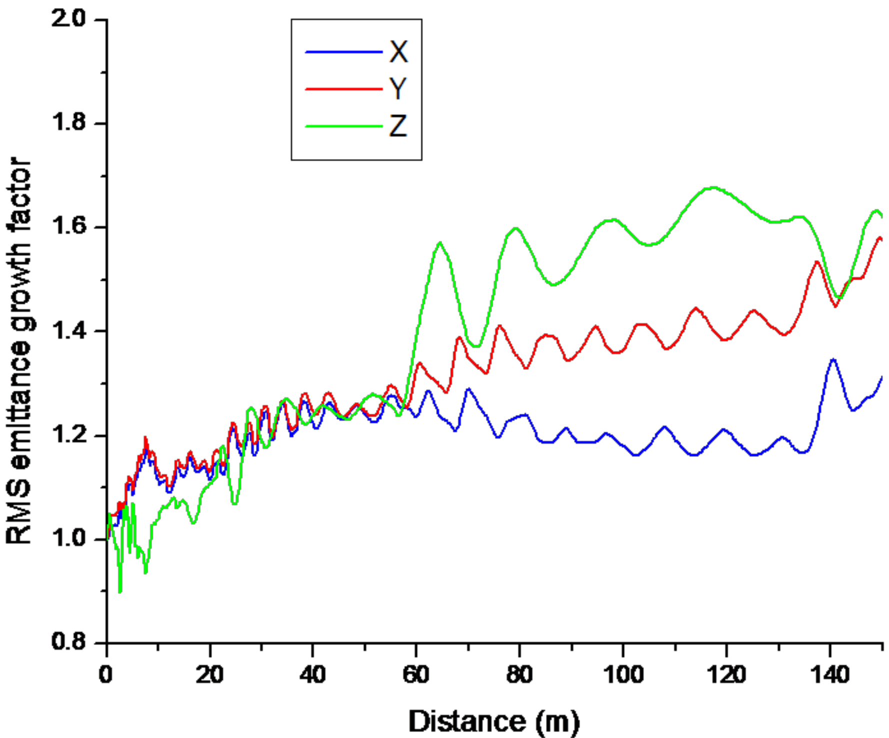
RF errors: 1 deg and 1% RMS



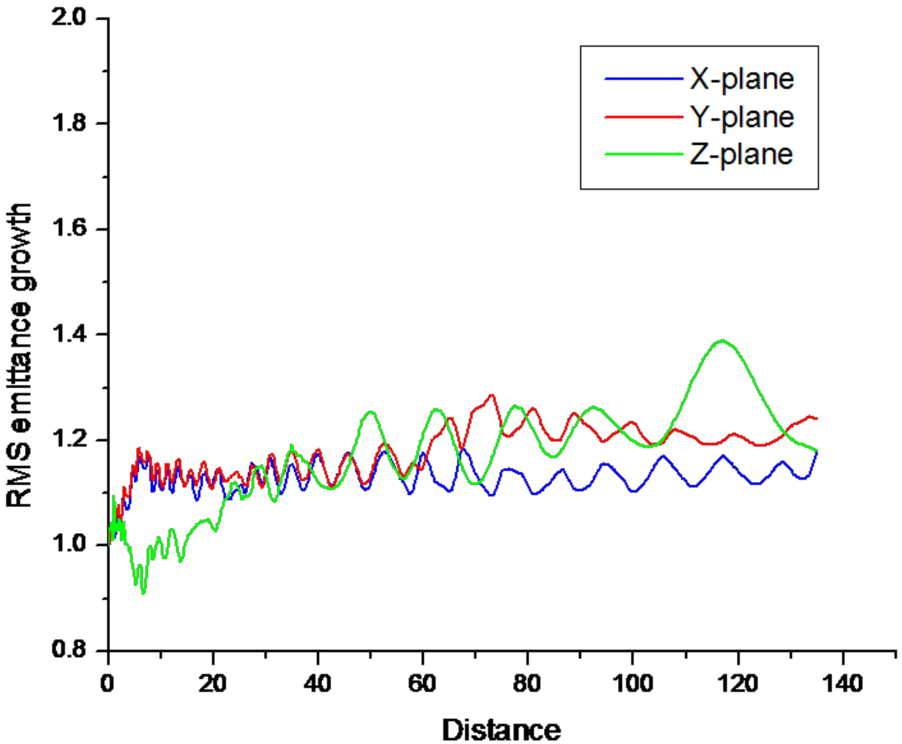
Effect of drift space in the MEBT and inter-cryostat drift (ICD) spaces for SSR-1

- Effect of drift spaces in low energy section (below 30 MeV)
- RMS emittance growth, I = 43.25 mA

With MEBT and ICD

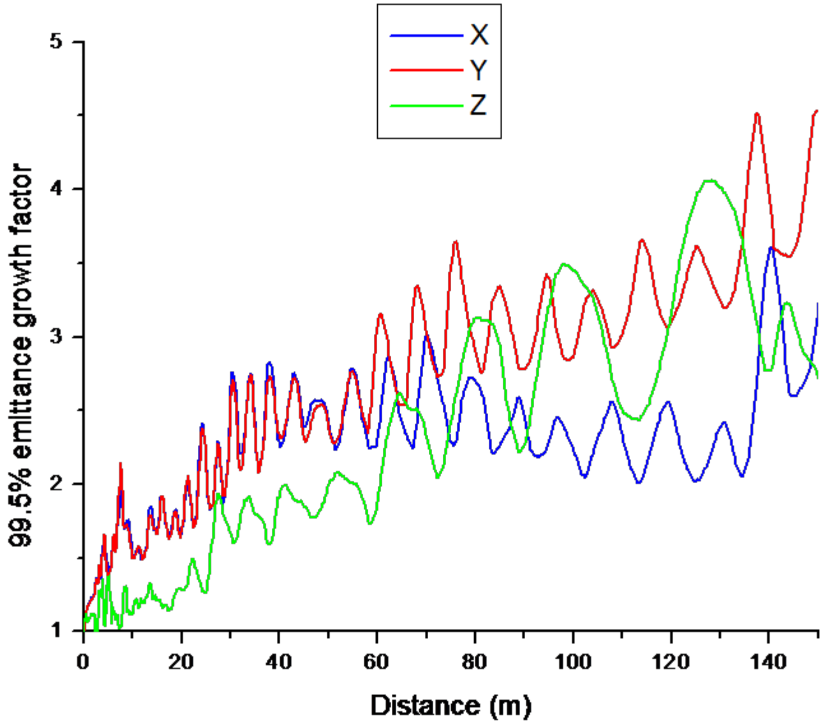


Without MEBT and ICD

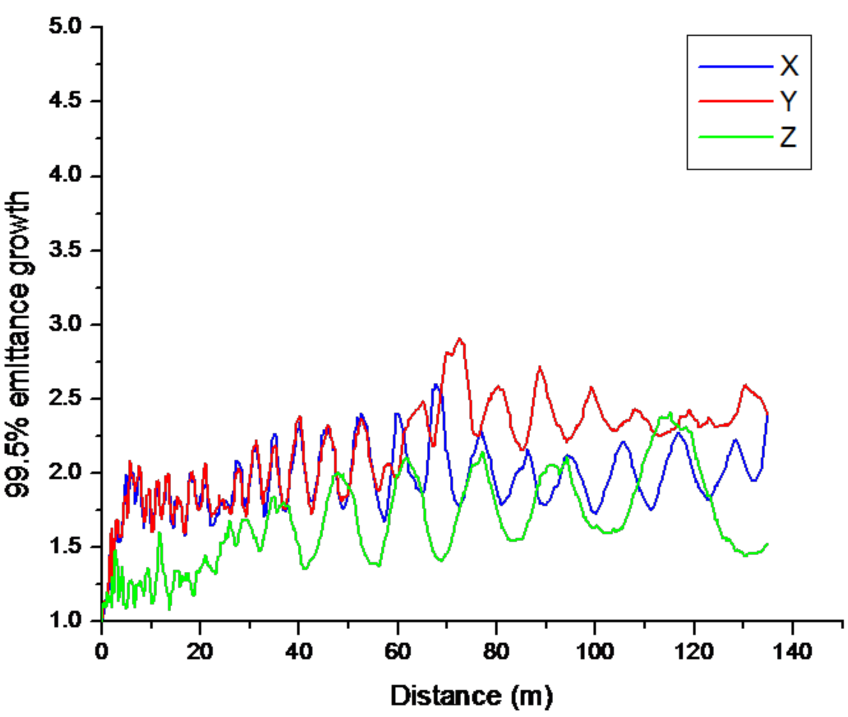


The same as previous slide, 99.5% emittance growth

With MEBT and ICD

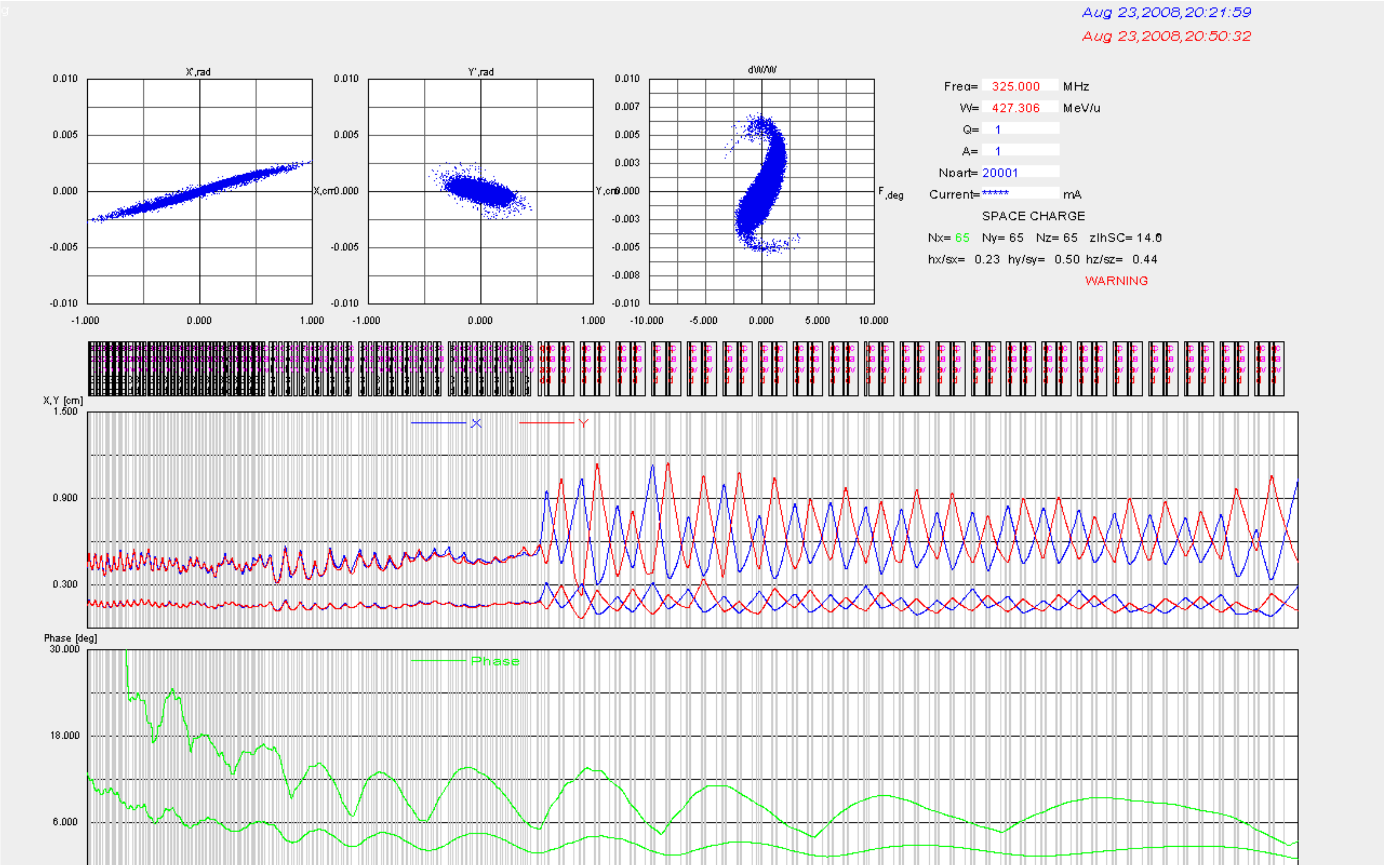


Without MEBT and ICD



An example of 100 mA linac with SC Front End

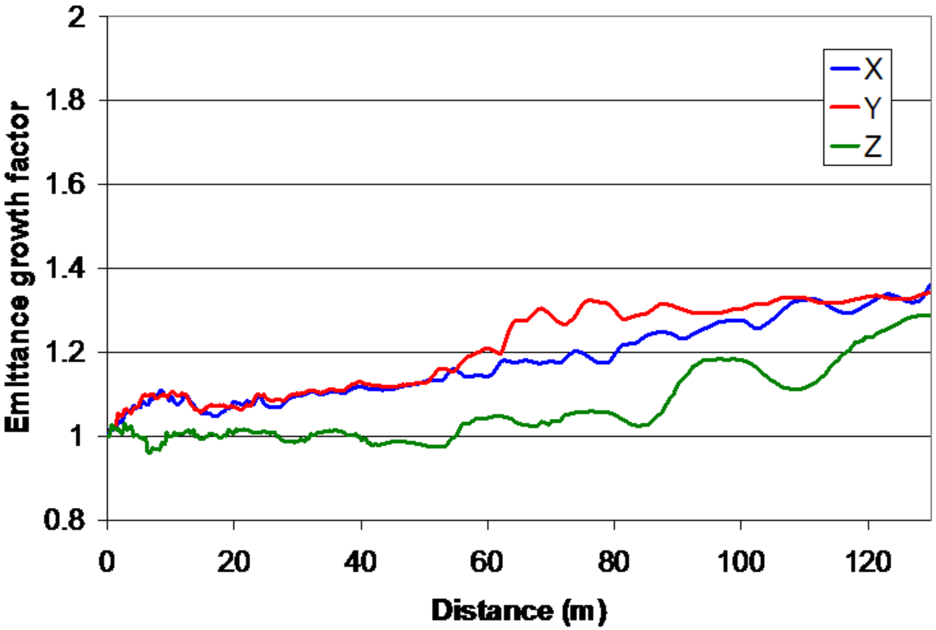
- Initial beam is “6D waterbag”, acceleration from 7 to 430 MeV, E_{RE}= 3.2 MV/m



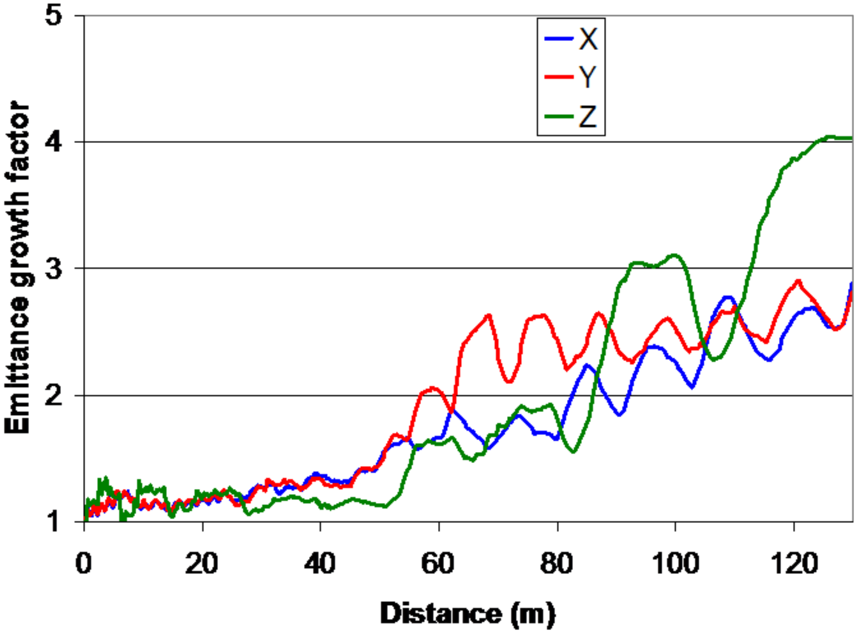
Emittance growth of 100 mA beam

- The matching is not perfect due to the transitions between solenoids and FODO

RMS



99.5%



Conclusion

- New approach in hadron linacs – “Pulsed SC Front End” provides high-quality beams
  - High-statistics BD simulations with all machine errors show negligible beam losses even for CW mode (below 0.1 W/m)
- SC cavities offer higher real-estate accelerating gradients than NC structures
  - HINS PD, conservative design $E_{RE} \cong$ from 2.6 to 4.7 MV/m
- RFQ can produce axial-symmetric beam with no emittance growth
- Focusing of high-intensity beams with SC solenoids provide several advantages compared to quadrupole focusing
- Using solenoids in the MEBT provides sufficient space for the chopper with minimal effect on beam halo formation
- The Front End based on SC cavities and solenoids can be easily applied for acceleration of beam with the intensity higher than 100 mA