Study and Optimization of RF and Beam dynamics for Project-X CW SC linac.

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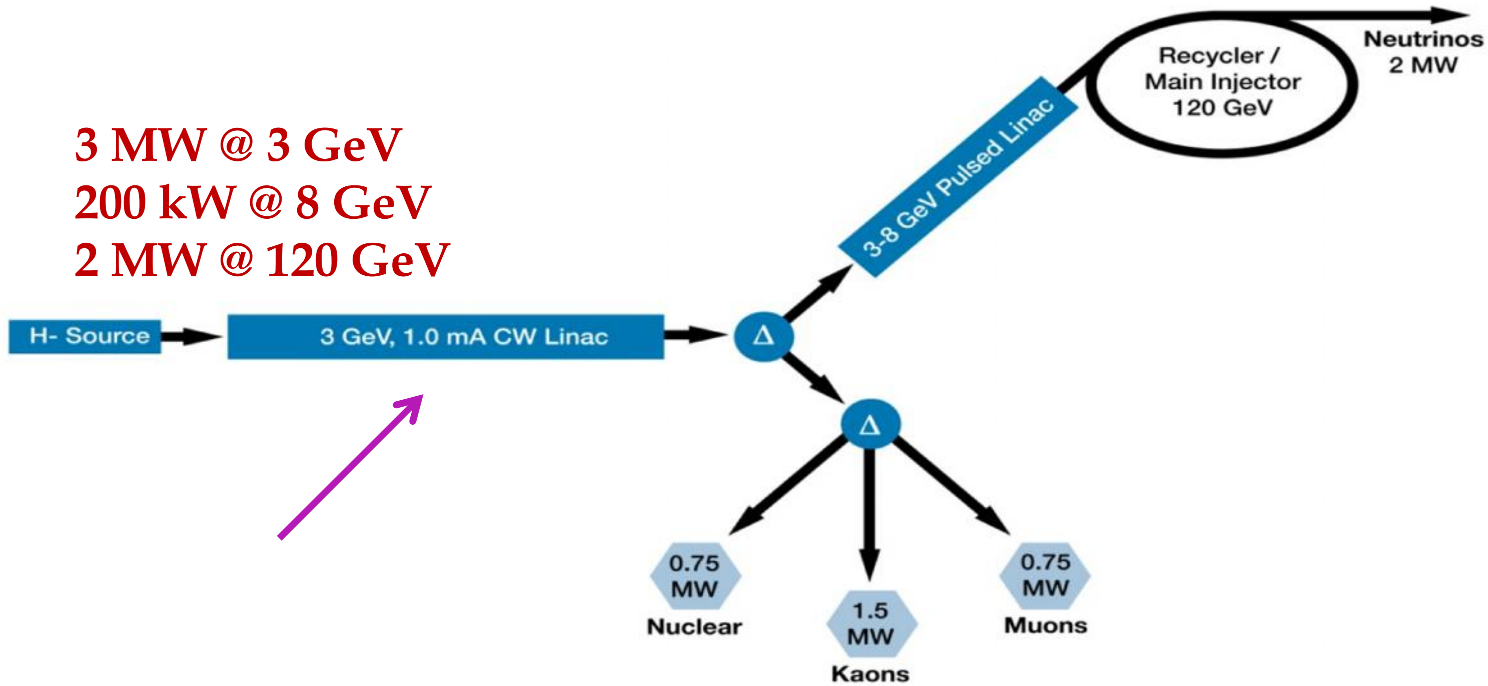
Outline

- Project-X facility
- Layout of CW linac
- General Concept
- RF Cavities and Magnets
- Lattice Design
- Beam dynamics studies
- Reliability of Linac.
- Summary

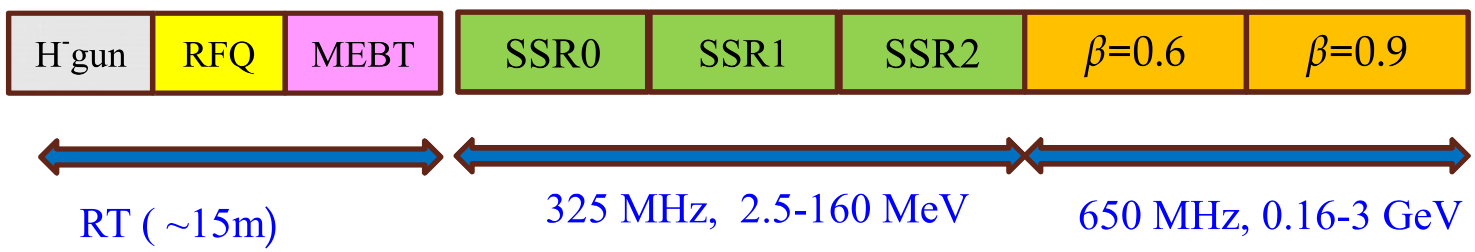
Project-X facility: Reference Design

3 MW @ 3 GeV
200 kW @ 8 GeV
2 MW @ 120 GeV



- Reference Design supports all mission elements
- Stable for more than a year

Layout of CW linac



- H^- -source: 10 mA peak current
- RFQ (RT): 325 MHz, ~ 2.5 MeV, 1/10mA avg/peak
- MEBT (room temperature):
  - *Chopper*
  - *RT bunching cavities, P < 5kW each*
  - *Triplet (RT) optics*
- Low-energy SC 325 MHZ linac (2.5-160 MeV)
  - *3 families of single-spoke cavities*
  - *Solenoidal focusing (SC)*
  - *Separate cryomodules with warm inter-connection*
- Two families of 650 MHz cavities to cover 160 MeV -3 GeV range
  - *Low-β (LB) β=0.61 and high-β (HB): β=0.9 cavities*
  - *Focusing: Doublets.*

Choice of Magnets

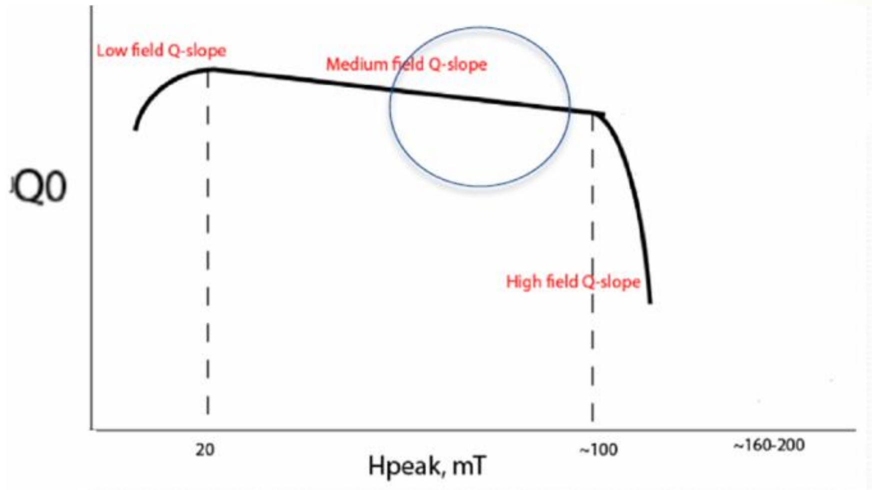
- All magnets are superconducting
  - Compact in size
  - Provide intense magnetic field with low power consumption.
- Dipole correctors are built in each magnets.
- Solenoidal focussing is used to keep the beam round for 325 MHz section.
- Quadrupole focusing is used for 650 MHz section.
- Focusing period for each section is shown below

Section	SSR0	SSR1	SSR2	LE650	HE650
Focusing	SR	SR	SR^2	FDR^3	FDR^8

Elements: S – solenoid, R resonator, FD – doublet (F and D – quads).

Cavity : Choice of Gradient

- Gradient in cavities are limited by peak surface magnetic fields.
- $$Q_0 = \frac{\omega U}{P_{diss}}$$
- Higher the Q_0 lower the dynamics heat losses.
- Medium field Q slope region is chosen for cavity operation to reduce the cryogenic losses.

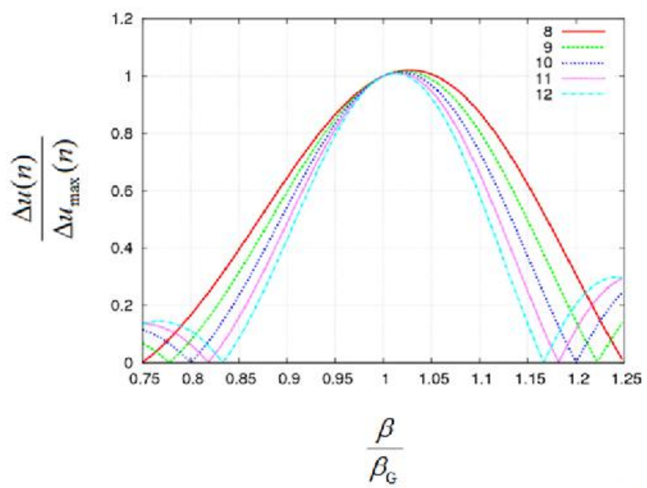


CW Project X assumptions:

- 325 MHz: $H_{pk} < 60$mT
- 650 MHz: $H_{pk} < 70$mT
- $E_{pk} < 40$ MV/m.

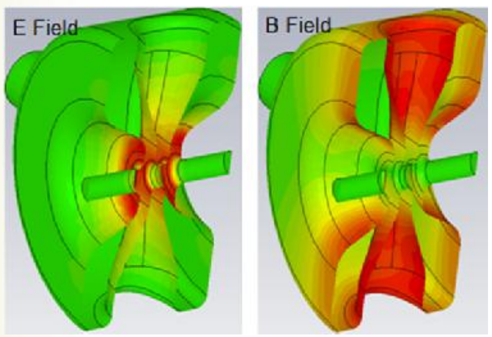
Cavity Design

- Fundamental aspects
  - Velocity acceptance
  - Field enhancement factors (H_p/E_{acc}, E_p/E_{acc}) should be as small as possible.
  - Optimization of effective impedance (R/Q)
  - No trapped modes.
  - Field Flatness in multi-cell cavity
- Practical aspects
  - Industrial yield.
  - Mechanical design stability.



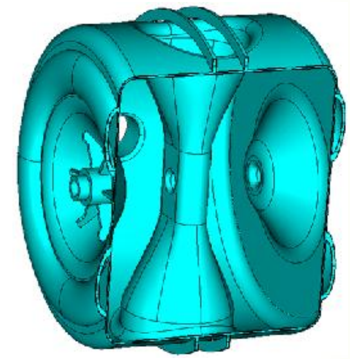
$$\Delta u_{max}(n) = n.G.\frac{\beta_G \lambda}{2}$$

325 MHz spoke cavities family



SSR0 design

SSR1 – prototyping, testing



SSR2 -design

Parameters of the single-spoke cavities

cavity type	β_G	Freq MHz	E_{max} MV/m	B_{max} mT	R/Q, Ω	G, Ω	$^*Q_{0,2K}$ $\times 10^9$
SSR0	β=0.114	325	32	39	108	50	6.5
SSR1	β=0.215	325	28	43	242	84	11.0
SSR2	β=0.42	325	32	60	292	109	13.0

Frequency jump in linac

- Frequency jumps in ion linac use to be made in order to provide large transverse acceptance in the low energy part and higher accelerating gradient in high energy part.
- Higher frequency also reduces cavity size hence cost of machine.
- Frequency jump is made at sufficiently high energy to avoid beam dynamics problem.
- Beam phase amplitude is strong function of energy and roughly decreases as

$$\phi_a \propto (\beta_s \gamma_s)^{-3/4}$$

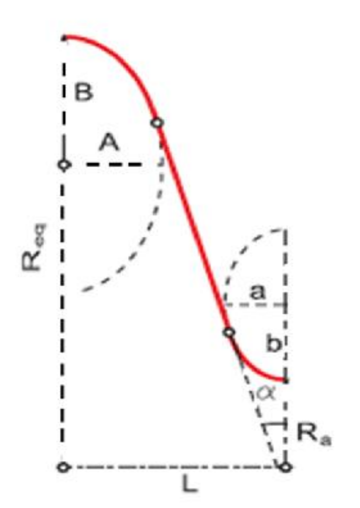
- where β_s and γ_s are relative velocity and Lorentz factor for synchronous particle respectively.
- Frequency jump (325 MHz to 650 MHz) is made at 160 MeV in Project-X CW linac.

Why 650 MHz instead of 1.3 GHz?

- 2-fold frequency jump instead of 4-fold ➔ easier transition & higher longitudinal acceptance.
- Wider aperture and thus, higher transverse acceptance which results in smaller beam losses.
- Less effect of cavity focusing (~1/ λ). (λ is rf wavelength)
- Smaller losses caused by intra-beam stripping (~1/ λ).
- $Q_0 \propto \omega^{-2}$ thus operation at low frequency improves quality factor hence reduces cryogenic losses.
- β=0.90 , 5-cell 650 MHz cavity has same length as for ILC-type thus about the same maximal energy gain & same power requirements per cavity.

Designing constraints of 650 MHz elliptical cavities: Iris aperture

- **Smaller aperture** → smaller field enhancement factors which leads to improve the interaction between beam and cavity.
- **Coupling Coefficient :** Larger aperture leads to large cell to cell coupling (k) which results in good field flatness ($\delta E/E$).
- $\delta E/E \sim \Delta f / f \cdot N^{3/2} \cdot k^{-1}$
- where N is no. of cell in multi-cell cavity and k is coupling coefficient.
- ILC, N=9: **$\delta f / f_\pi$ = 6e-4** (*k*=1.87%) & We use, N=5: (*k*=0.75%).
- **Beam Losses :** Large aperture provides large transverse dynamics aperture which reduces losses.
- **Surface processing :** Larger aperture reduces the possibility of chemical residual.



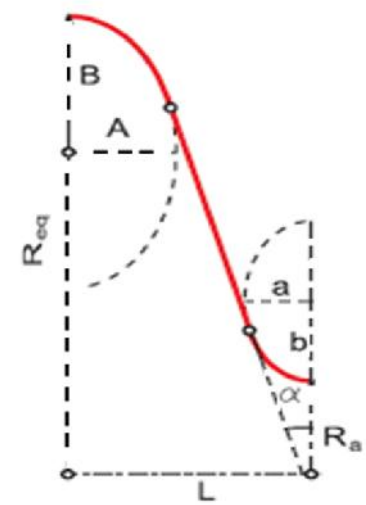
Design constraint of 650 MHz elliptical cavities: wall slope

- **Wall slope:-** Smaller slope leads smaller electric & magnetic field enhancement factors.

Limitation

➢Surface processing :- Smaller slope may lead to chemical residual during chemical treatments of cavity.

➢Mechanical stability

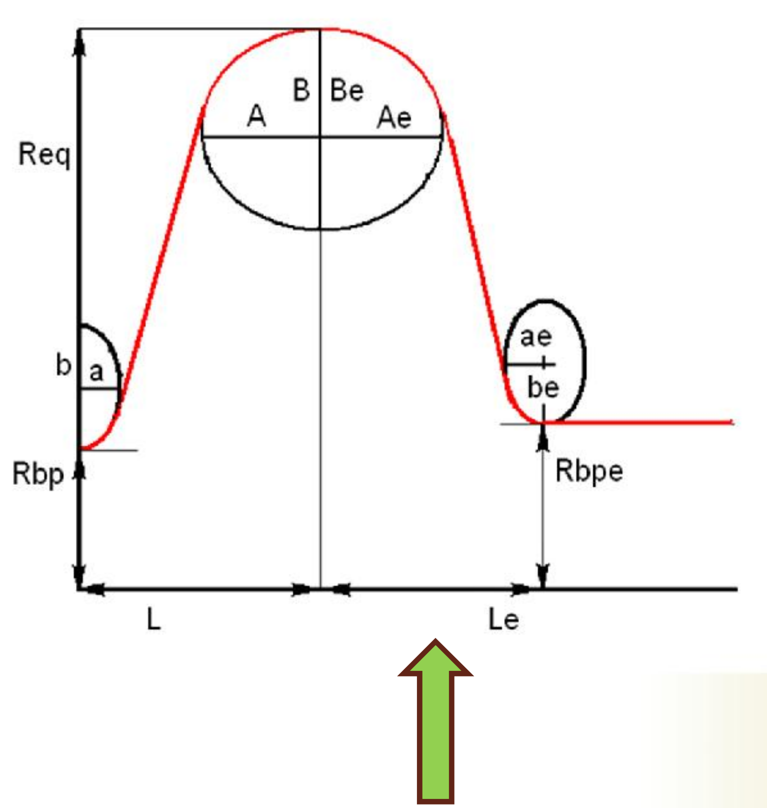


- 5 deg for β=0.9 cavity
- 2 deg for β=0.61 cavity

❖**(Low Loss has zero slope, Re-entrant has negative).**

Design of cavity:- End Cell

- End cell is used to connect both ends of cavity with beam pipe so to maintain the same operating frequency, shape of half end cell is different than inner cell.
- Shape of end cell is optimized
  - To maintain field flatness along cavity.
  - To get rid of trapped modes.
- Asymmetrical cavity (different end cell at both ends) can be considered if HOMs are found to be trapped inside the cavity.
- End cells are symmetric for both 650 MHz cavities for Project-X linac.

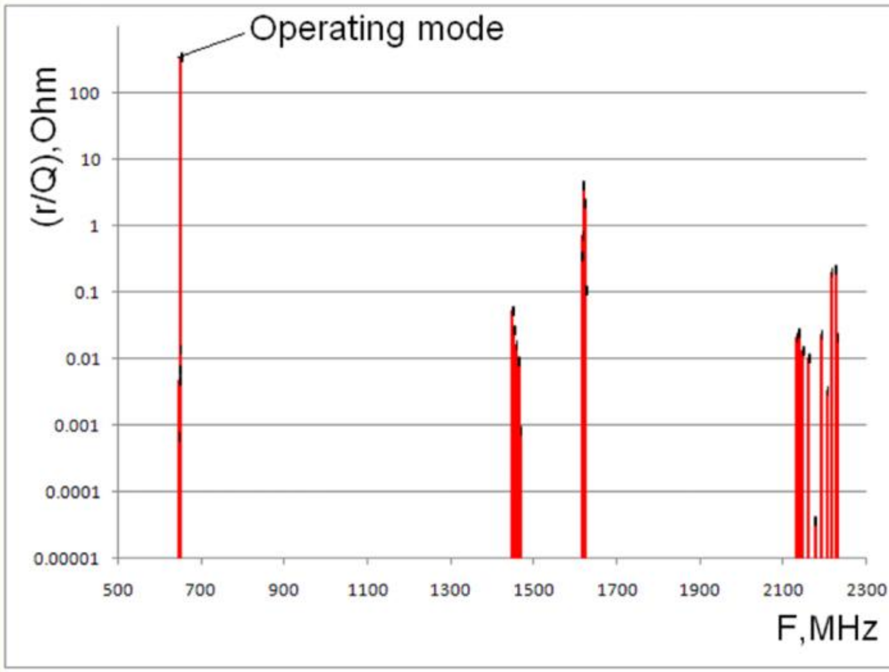


Half end cell

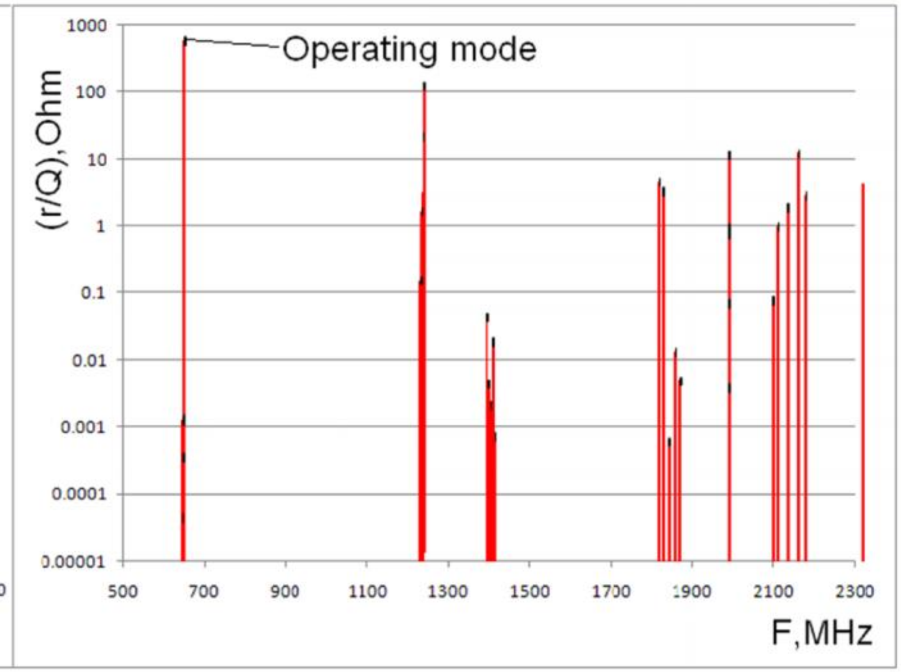
RF Parameters for 650 MHz cavities

β_G	0.61	0.9	
Length (from iris to iris)	705	1038	mm
Aperture	83	100	mm
Cavity diameter	389.9	400.6	mm
R/Q, Ohm	378	638	Ω
G - factor	191	255	Ω
Max. gain per cavity (φ-0)	11.7	19.3	MeV
Gradient	16.6	18.6	MV/m
Max surface electric field	37.5	37.3	MV/m
E_{pk}/E_{acc}	2.26	2.0	
Max surf magnetic field	70	70	mT
B_{pk}/E_{acc}	4.21	3.75	mT/(MeV/m)

Monopole mode spectrum in 650 MHz cavities



$\beta = 0.61$

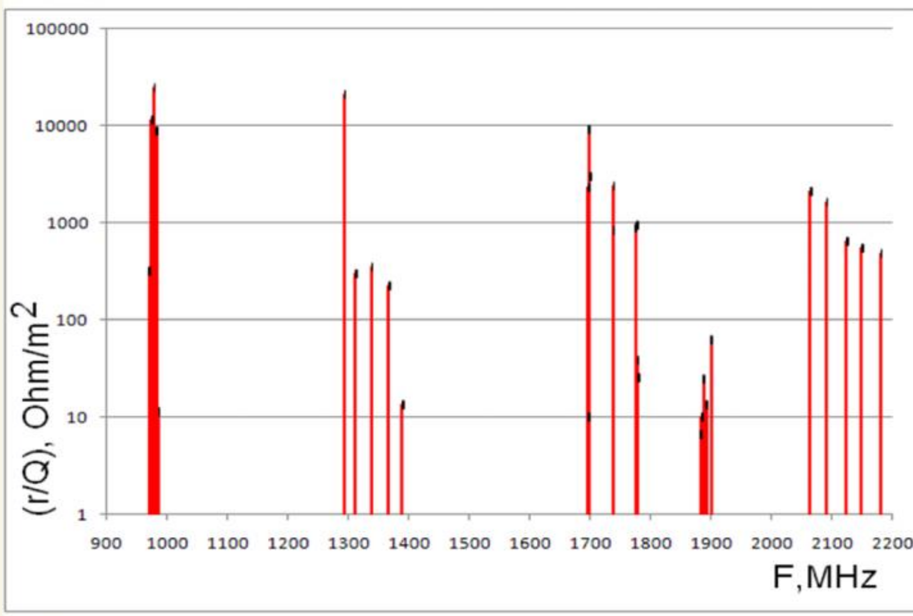


$\beta = 0.9$

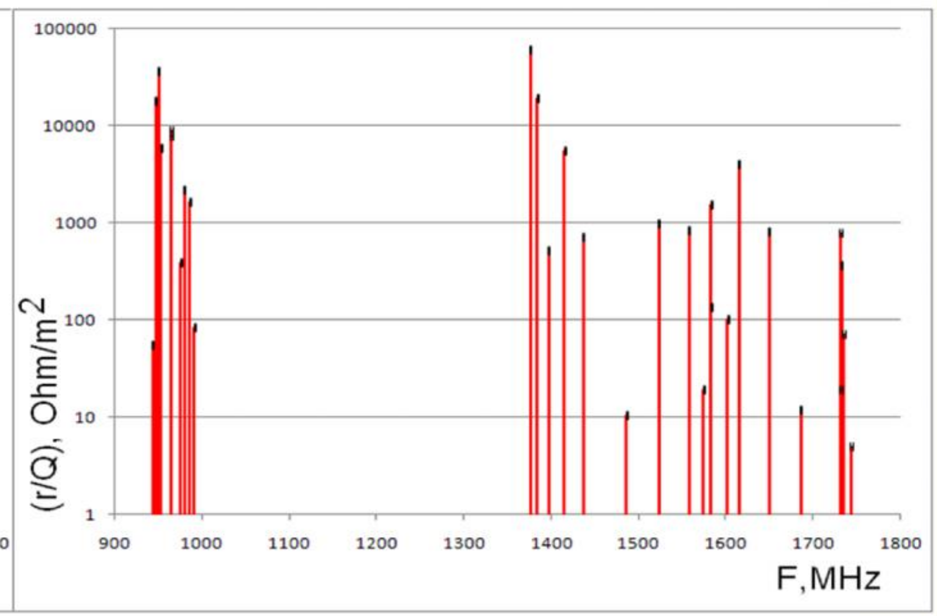
- **For $\beta = 0.61$: all the modes have (r/Q) below 10 Ohms;**
- **For $\beta = 0.90$:**

-two modes have (r/Q) ~10 Ohm: F=1988MHz and 2159 MHz.
-one mode has (r/Q) = 22 Ohm: F=1238.6 MHz
-one mode has (r/Q) = 130 Ohm: F=1241 MHz

Dipole mode spectrum



β = 0.61



β = 0.9

- **For β = 0.61 three modes have (r/Q) above 10^4 Ohm/m^2 (F=974, 978.6 and 1293 MHz);**
- **For β = 0.90 four modes have (r/Q) above 10^4 Ohm/m^2 (F=946.6, 950.3, 1376 and 1383 MHz).**

Requirements of HOM damper for 650 MHz cavity

- Due to operation of linac at low current (1 mA), there is no problems related with
  - Beam Break up effects (BBU).
  - Resonance excitation of dipole modes.
  - No trapped modes
- Accidental resonance excitation may be mitigated by
  - Properly tuning of the cavities in order to remove the "dangerous" HOMs from the beam spectrum line.
  - Tuning-detuning of the operating mode that leads to HOM frequency change caused by residual deformation (needs further tests).
- Studies performed and SNS experience suggests that we can survive without HOM damper.

* V. Yakovlev et al , Longitudinal and Transverse effects of HOMs in the Project -X linac (http://epaper.kek.jp/IPAC10/papers/tupea020.pdf)

Lattice design & Beam physics studies

- Beam dynamics codes
  - GENLINWIN : Optimization of longitudinal dynamics.
    - Optimization : Number of cavities, smooth phase advance and constance acceptance regime for acceleration.
  - TRACEWIN : Optimization of transverse dynamics.
    - Optimization : Matching between two cryomodules, beam matching
  - PARTRAN : Multiparticle simulation.
  - TRACK : Benchmarking with TRACEWIN results and error analysis.

Lattice Design: Principles and constraints

- Lattice design should be robust to allow for spread in designed parameters like spread in cavity gradient, operation of linac with failed elements, misalignments etc.
- Length of the focusing period is kept short, especially in the low energy section where space charge dominates.
- Transverse and Longitudinal phase advance must change adiabatically along the linac. This feature minimizes the potential for mismatches and helps to assure a current-independent lattice.
- Beam matching between the cryostats: Smooth beam matching is achieved by adjusting the gradients and phases of outermost elements (solenoids, rf cavities) of each side of transition.
- Minimize halo formation.

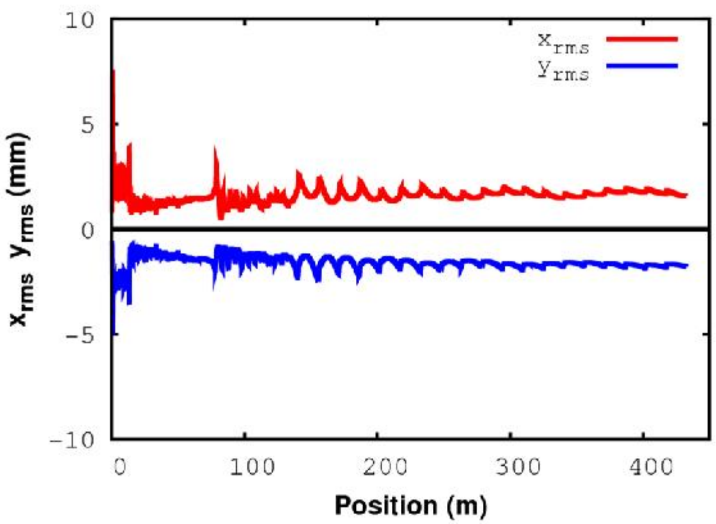
No. of elements & break points

	SSR0	SSR1	SSR2	b=0.6	b=0.9
Cavities	18	20	40	36	152
Solenoids	18	20	20	0	0
Quads	0	0	0	24	38
CM	1	2	4	6	19
Period length (m)	0.61	0.8	1.6	5.0	15.4
Section length (m)	10.98	16.40	33.20	60.00	292.6
Transition energy (MeV)	10.2	42.6	160.5	515.4	3028.3

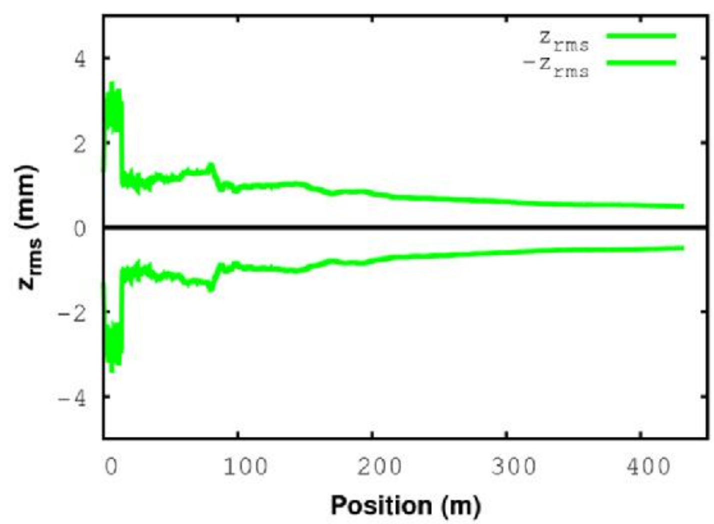
v 3.8.3

Baseline Lattice :Beam trajectories

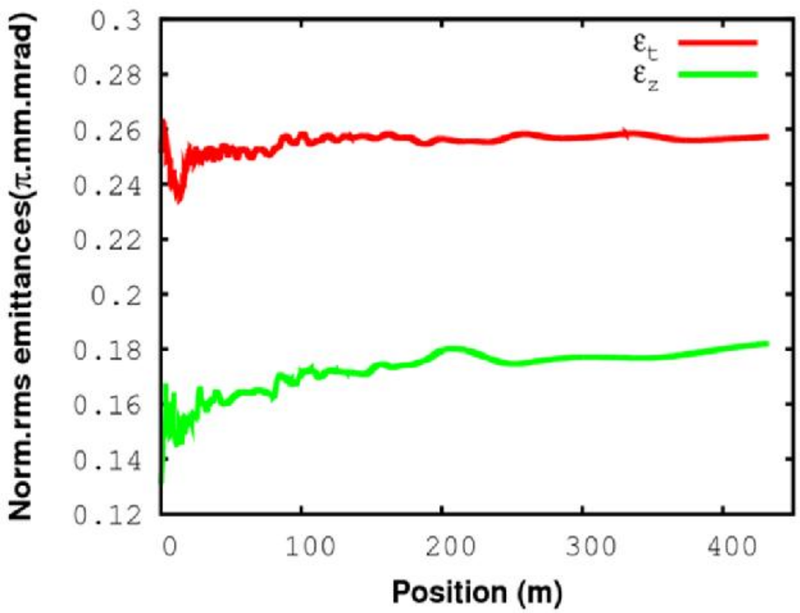
Transverse beam size



Longitudinal Beam size



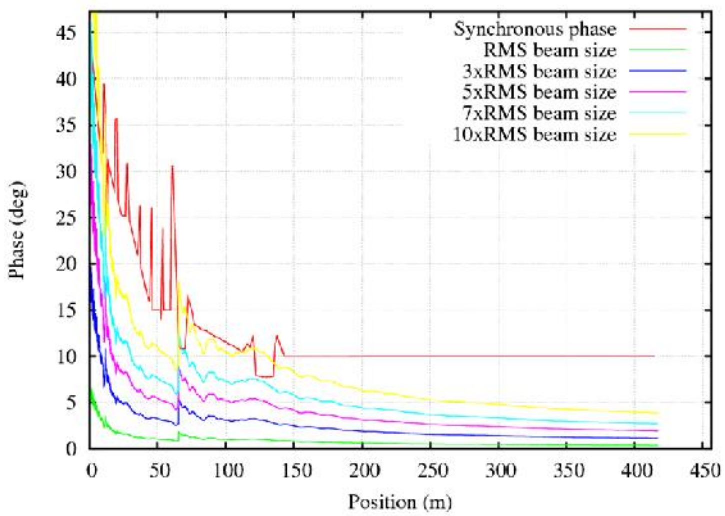
Baseline lattice :Beam emittances



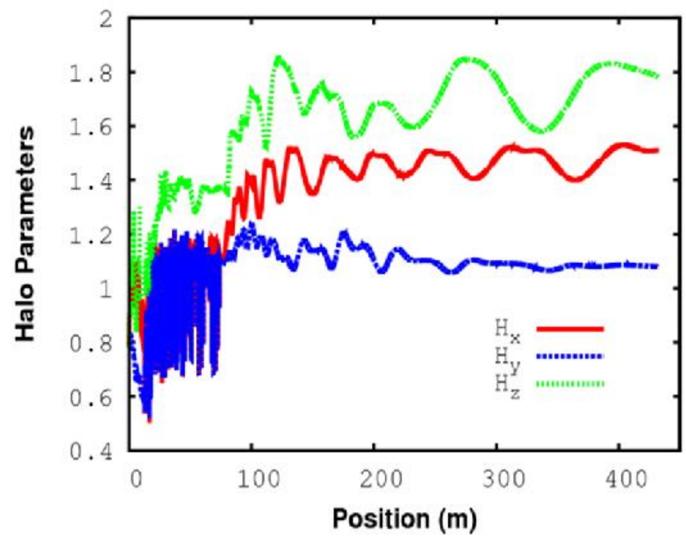
Parameters	Units	Start	End
ε_z	π· mm rad	0.127	0.18
ε_t	π· mm mrad	0.250	0.258
Energy	MeV	2.5	3028.3

Baseline Lattice

Synchronous & Beam phase

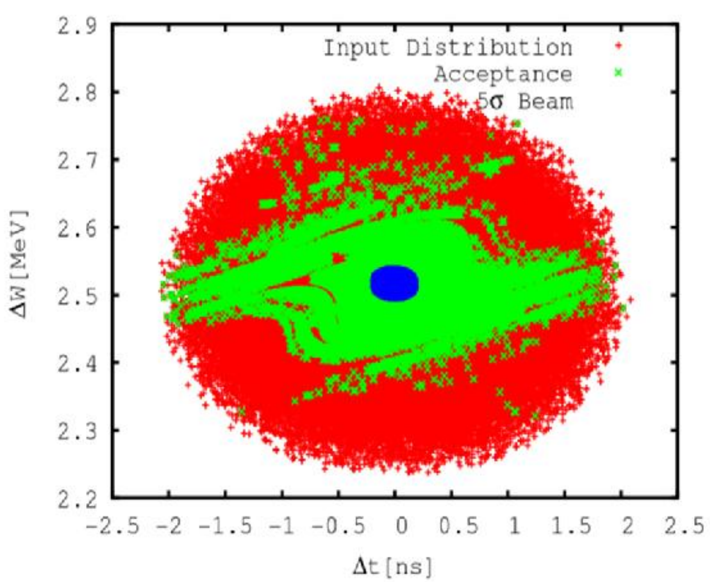


Beam Halo

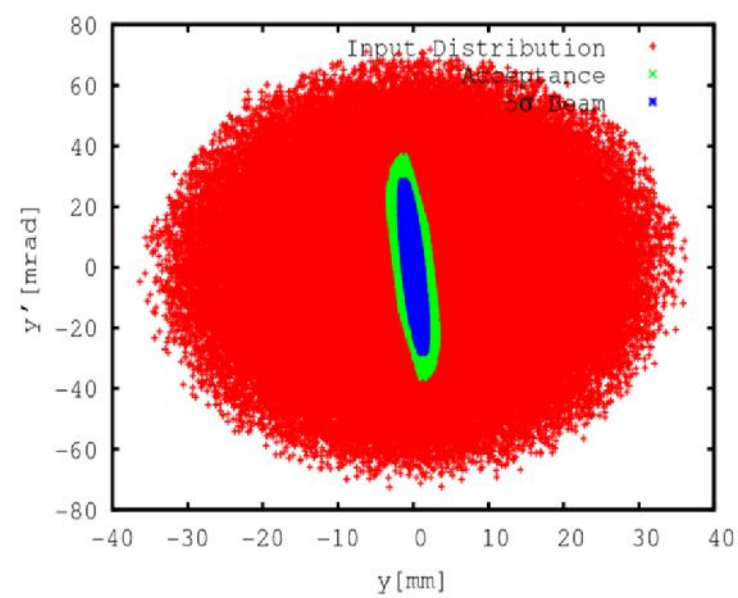


Baseline lattice : Acceptances

Longitudinal Acceptance

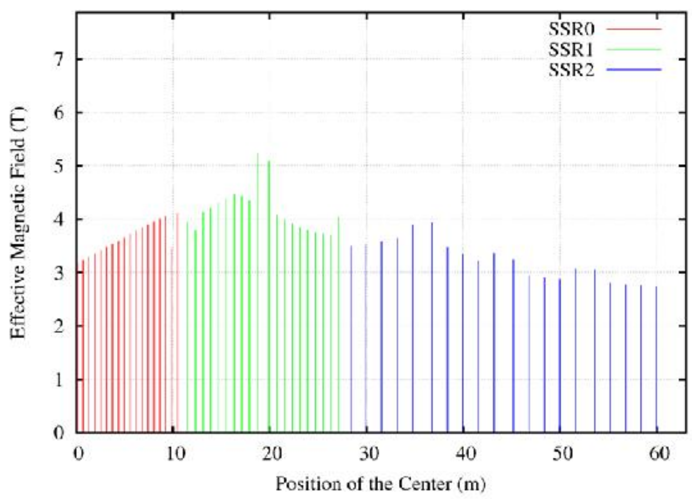


Transverse Acceptance

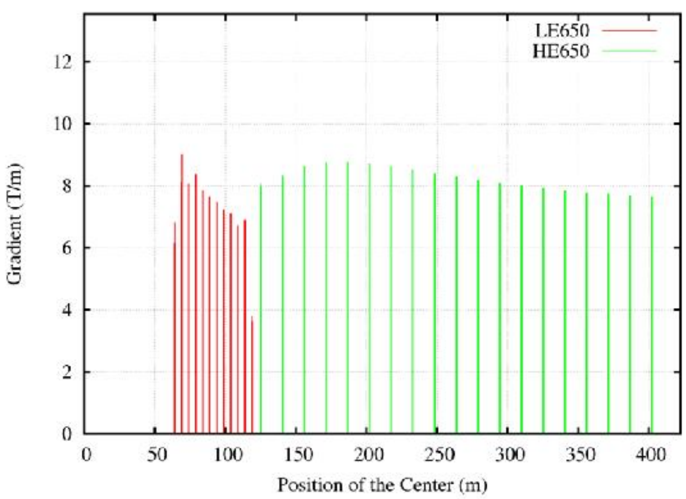


Baseline Lattice : Magnetic strength

Solenoids

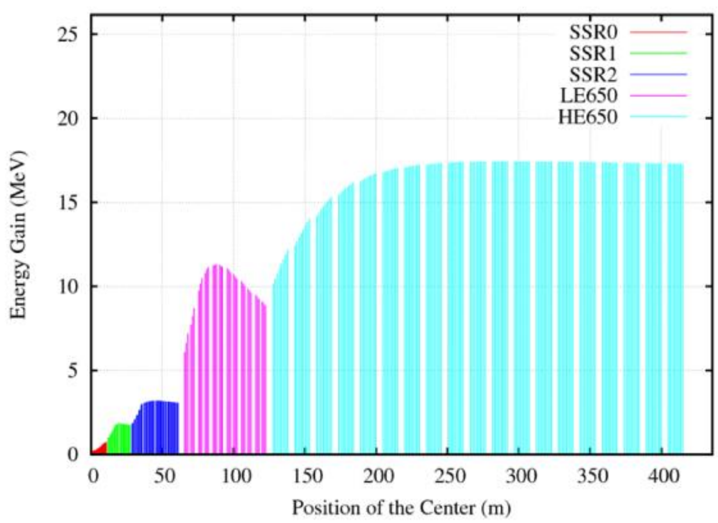


Quadrupoles

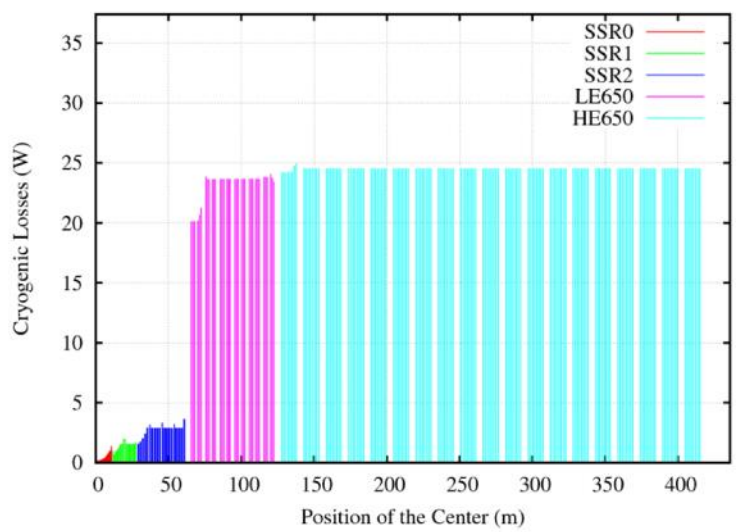


Baseline lattice

Energy Gain



Cryogenic Power



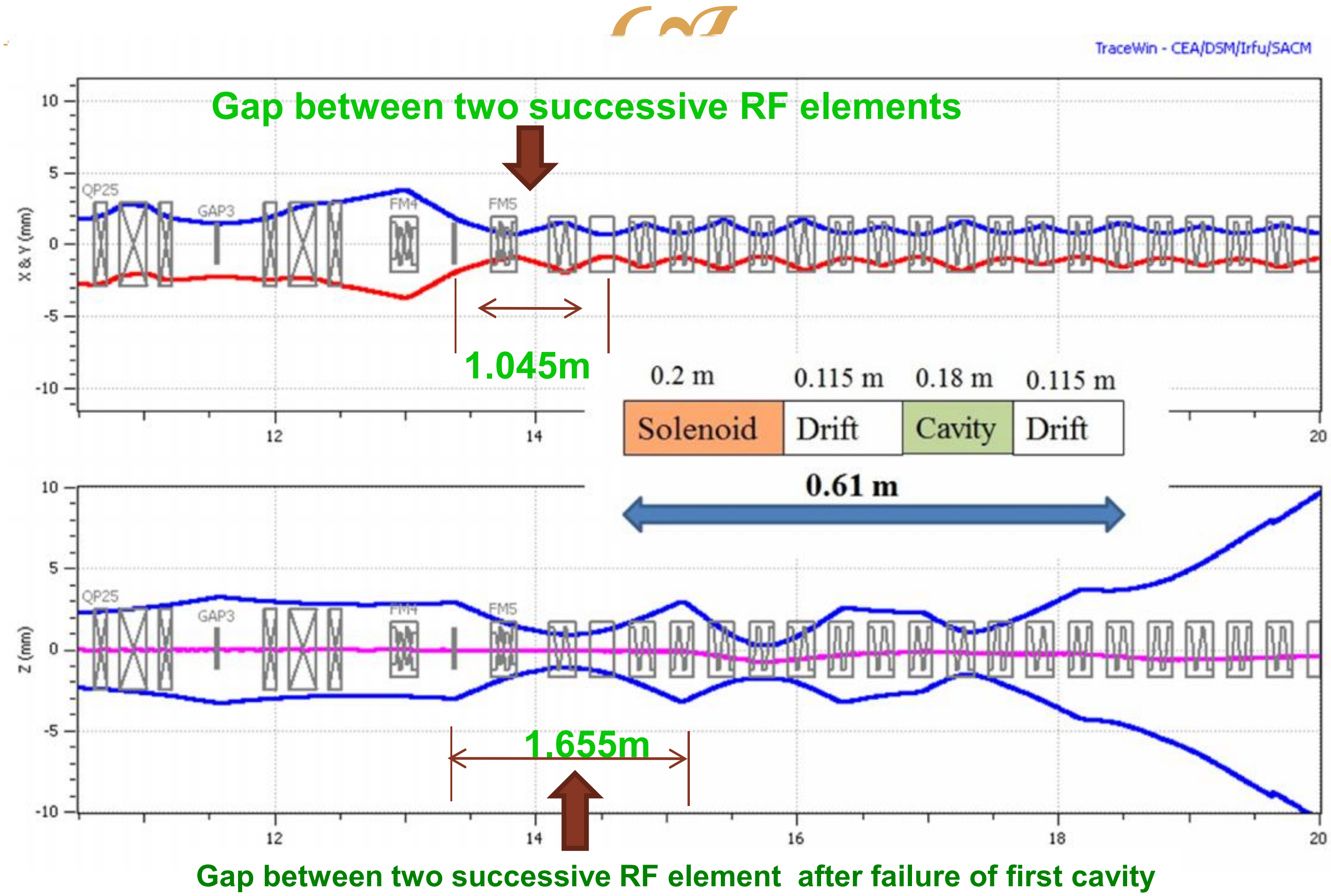
Reliability of linac

- Operation of linac at cw mode puts stringent tolerances on beam transport elements especially at low energy section which increases the possibility of Failure of RF cavity and focusing magnets.
- Failure of the beam transport elements alters the focusing period of the beam, resulting in a mismatch of the beam with the subsequent sections.
- Sensitivity of the linac performance towards failure's effects also depends on the location of failed elements.
- Failure at critical location could result in huge beam losses hence radio activation.

Failure of RF cavity in lattice

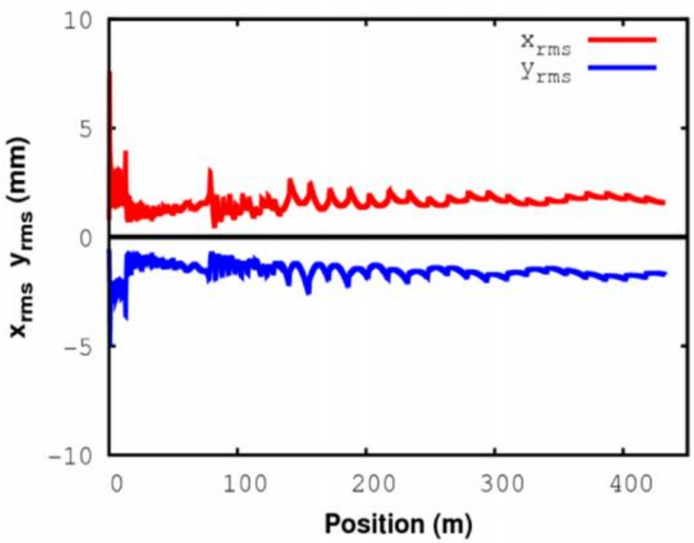
- Failure of cavity tuner. In absence of tuner, cavity will be out of resonance regime, thus unavailable for beam acceleration.
- Failure of power coupler due to window problem, multipacting, cooling, high power dissipation etc.
- Failure of RF power supply. Failure of elements like klystron, circulator, divider etc. in power distribution line results in interruption of RF power supply to cavity.
- Degradation in inner surface of RF cavity during operation.

Failure of first cavity in SSR0 section

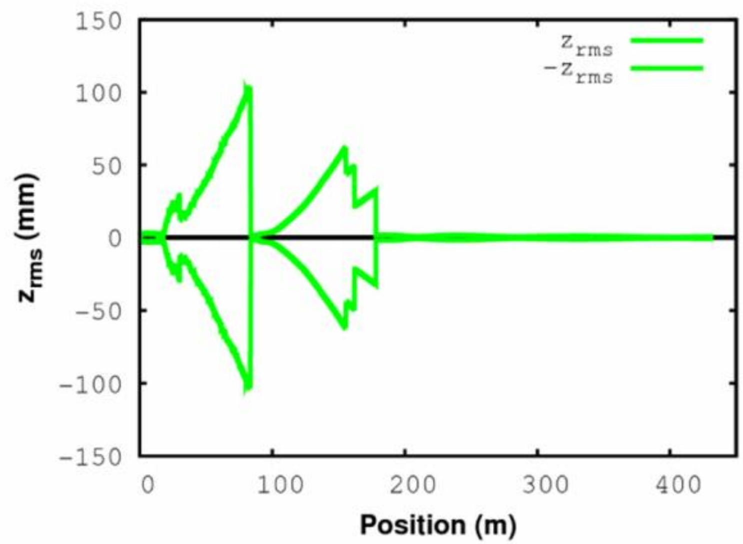


Failure of SSR0 cavity: Beam trajectories

Transverse beam size

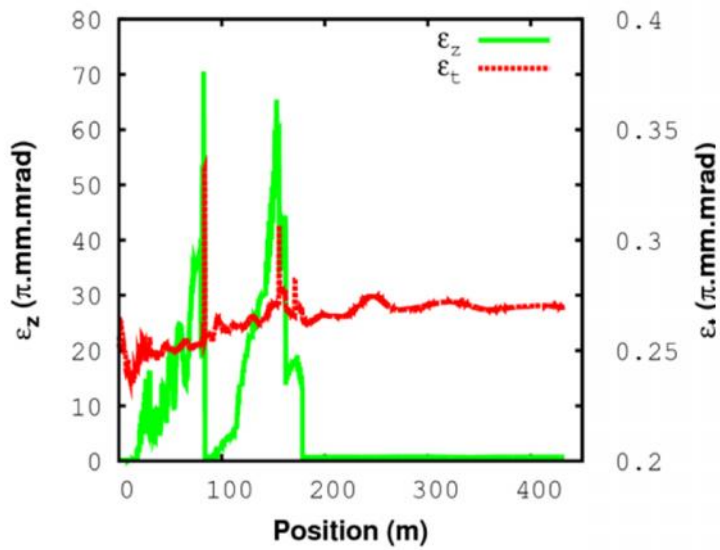


Longitudinal beam size

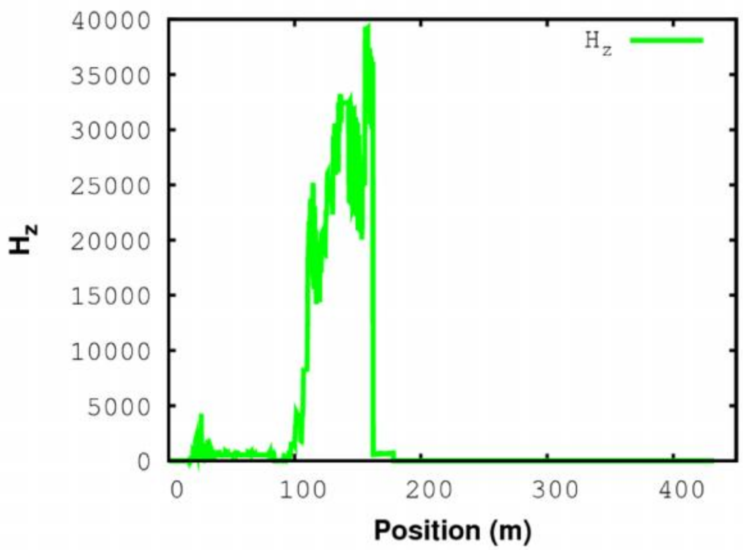


Failure of first SSR0 cavity

Emittances



Beam Halo



Local Compensation scheme

- Neighboring elements in the vicinity of failed cavity are retuned in order to achieve designed beam energy.
- RF phase and field amplitude of RF cavities are varied to recover beam energy and to achieve smooth longitudinal profile of beam.
- Gradient of the solenoid and quad are varied to tune transverse dynamics.
- 100 % transmission i.e. no beam loss is obtained after applying local compensation.

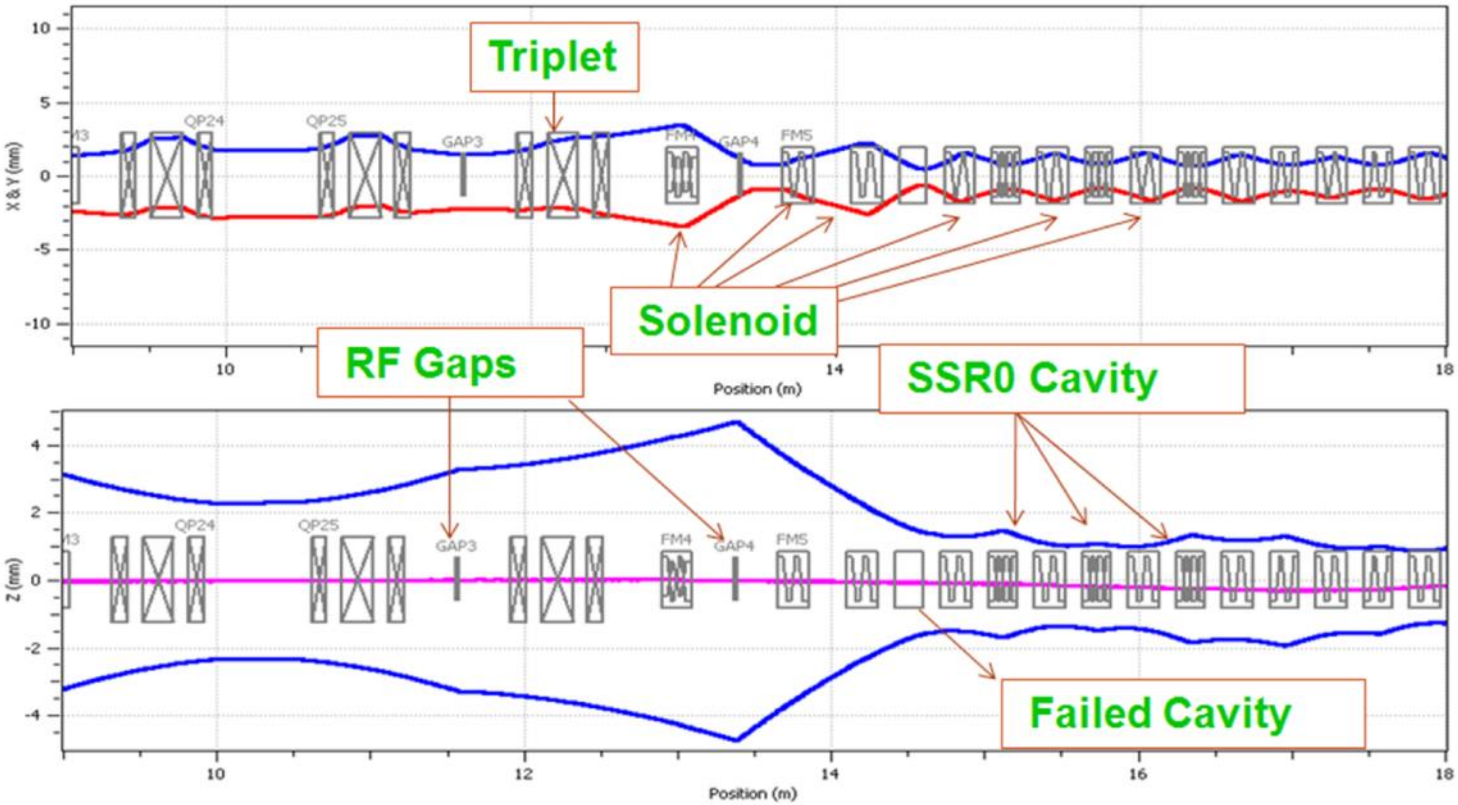
Local Compensation scheme: Limitation & constraints

- Accelerating field in cavity: Accelerating field are increased to recover the beam energy but it is ensured that corresponding surface peak magnetic field in SSR0 cavity should not be exceed above 60 mT.
- Ratio of synchronous phases (ϕ_{synch}) to longitudinal beam size (ϕ_{beam}) should not be less than 3.

$$\frac{\phi_{synch}}{\phi_{beam}} > 3$$

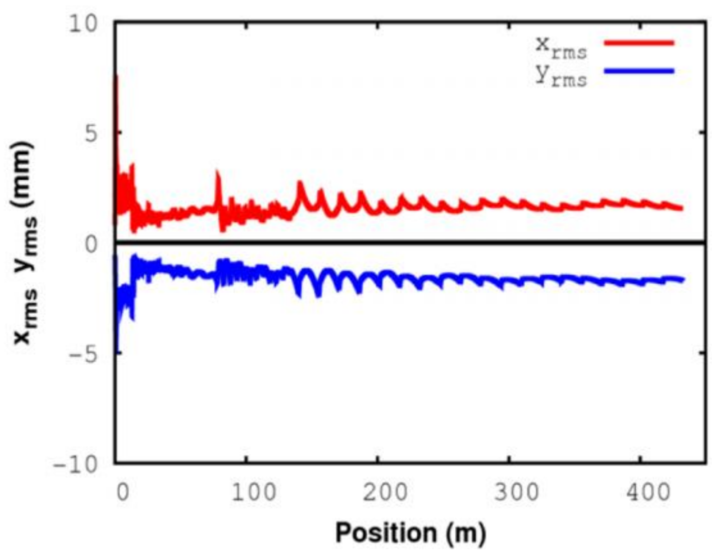
- Magnetic field gradient in solenoid and quadrupole should not exceed above 10 T/m.
- Minimum user disruption.

Local Compensation of first cavity in SSR0

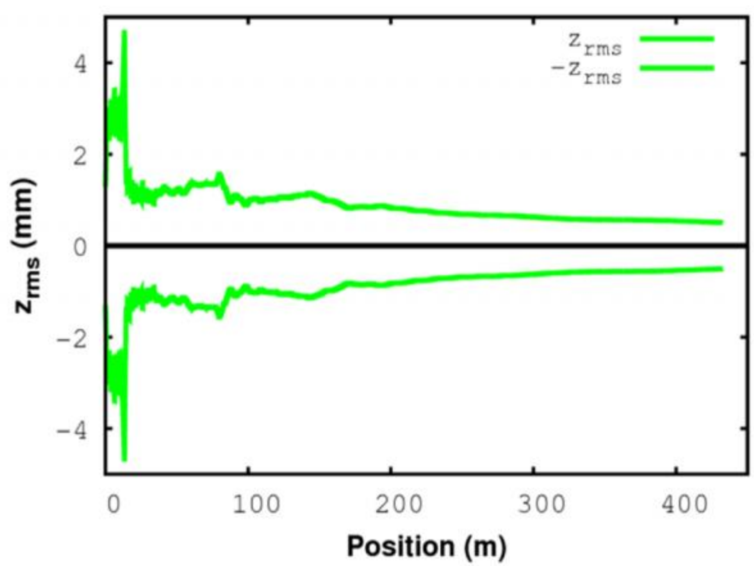


Beam trajectories after compensation

Transverse Beam size

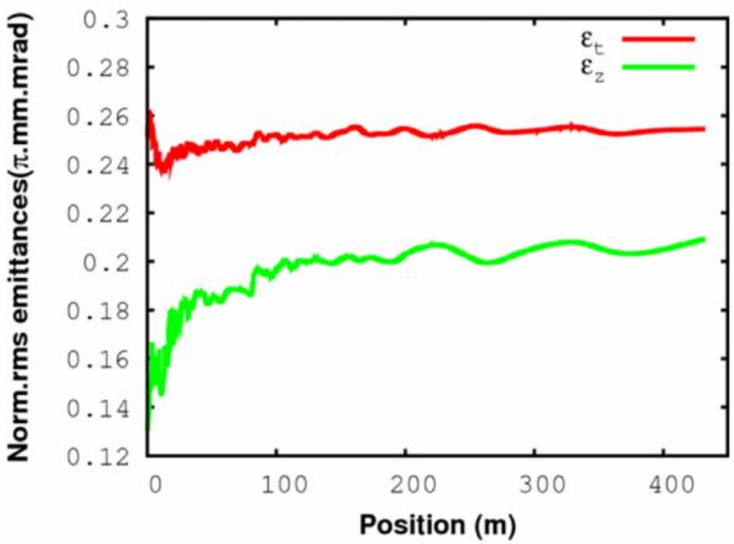


Longitudinal Beam size

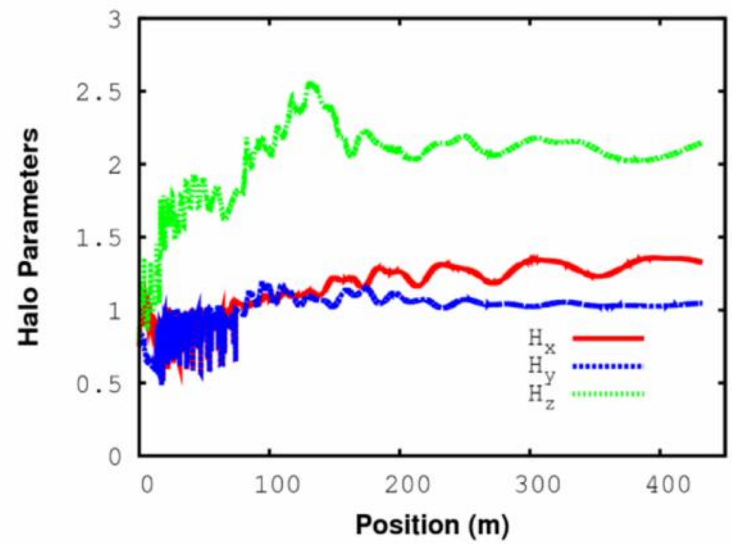


Beam Emittances & Halo

Emittances



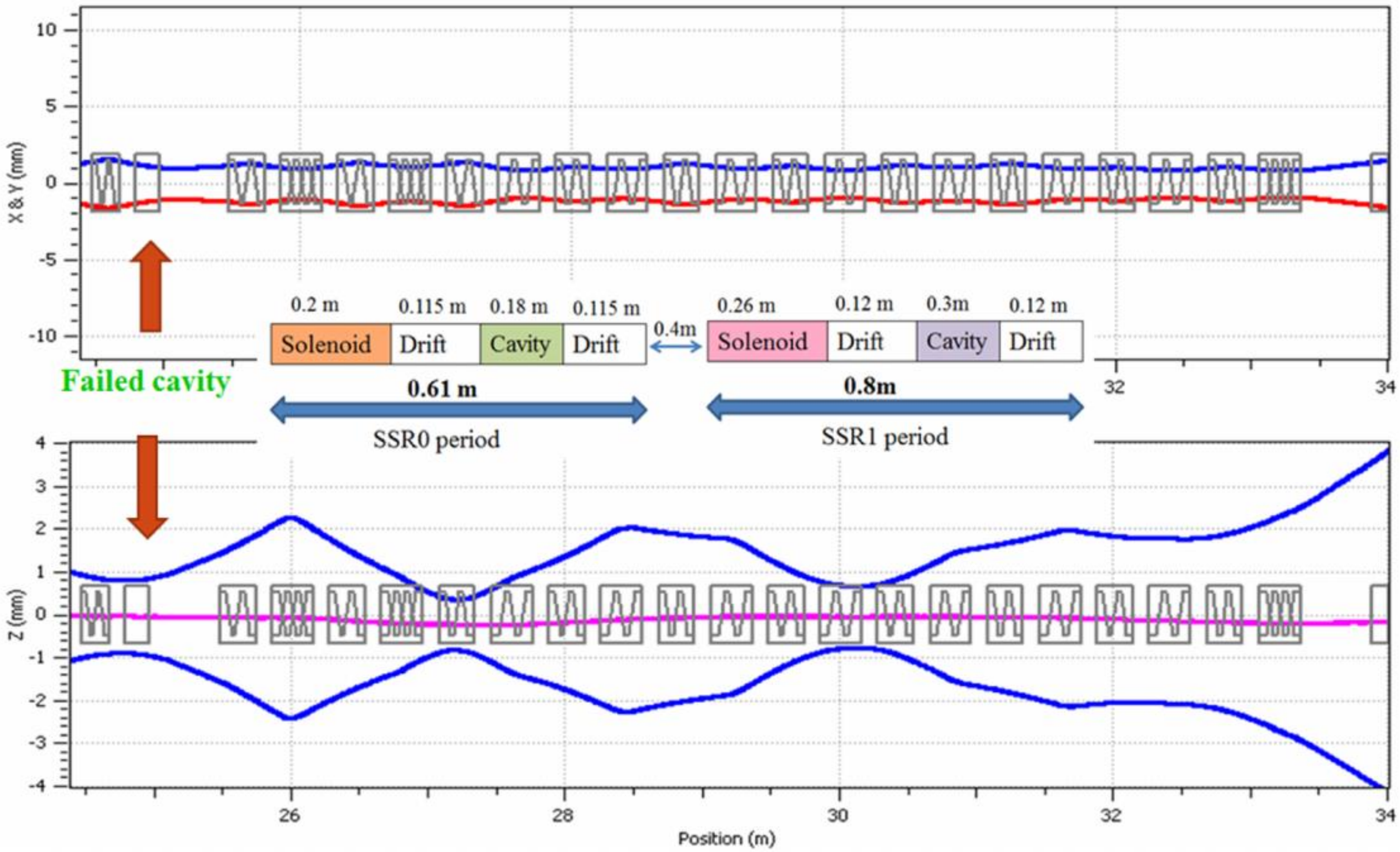
Beam Halo



Compensation of first cavity in SSR0 section

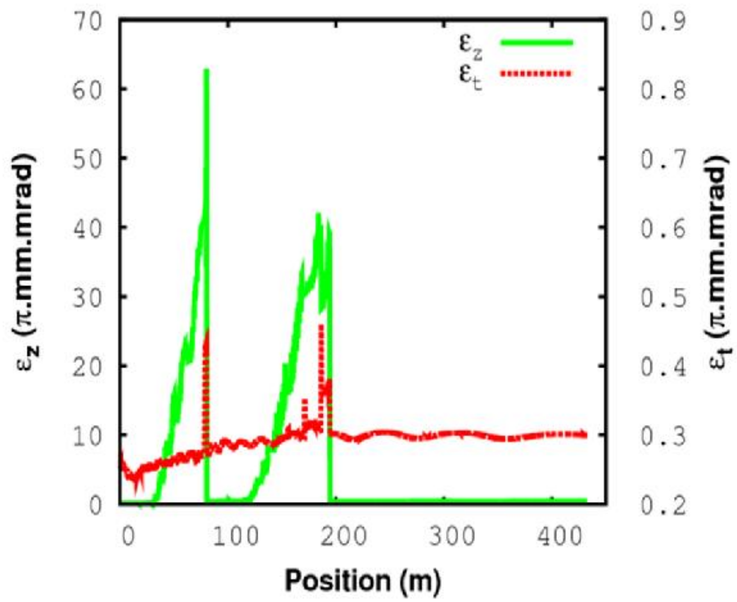
Parameters	Units	No Failure	With failure of first SSR0 cavity	
			Before compensation	After compensation
ε_z	$\pi\cdot$ mm mrad	0.18	0.74	0.21
ε_t	$\pi\cdot$ mm mrad	0.258	0.27	0.255
Energy	MeV	3028.32	3027.5	3028.4

Failure of last cavity in SSR0 section

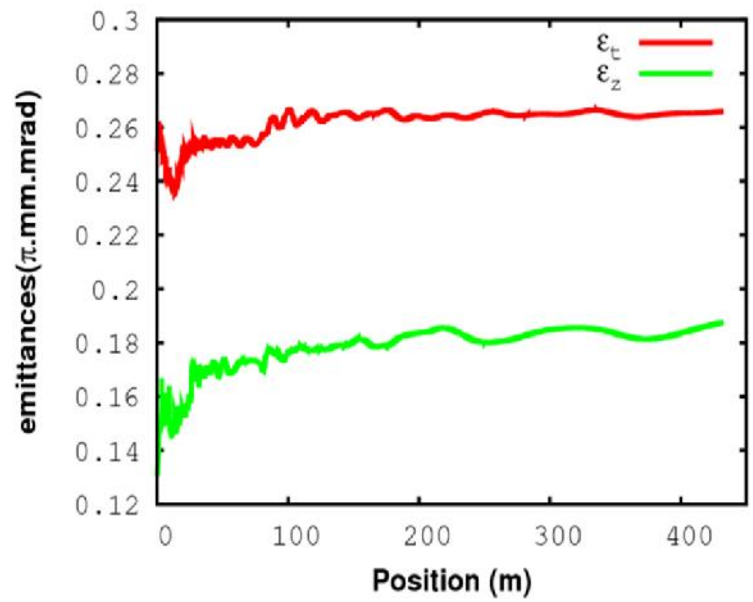


Beam emittance

Before Compensation



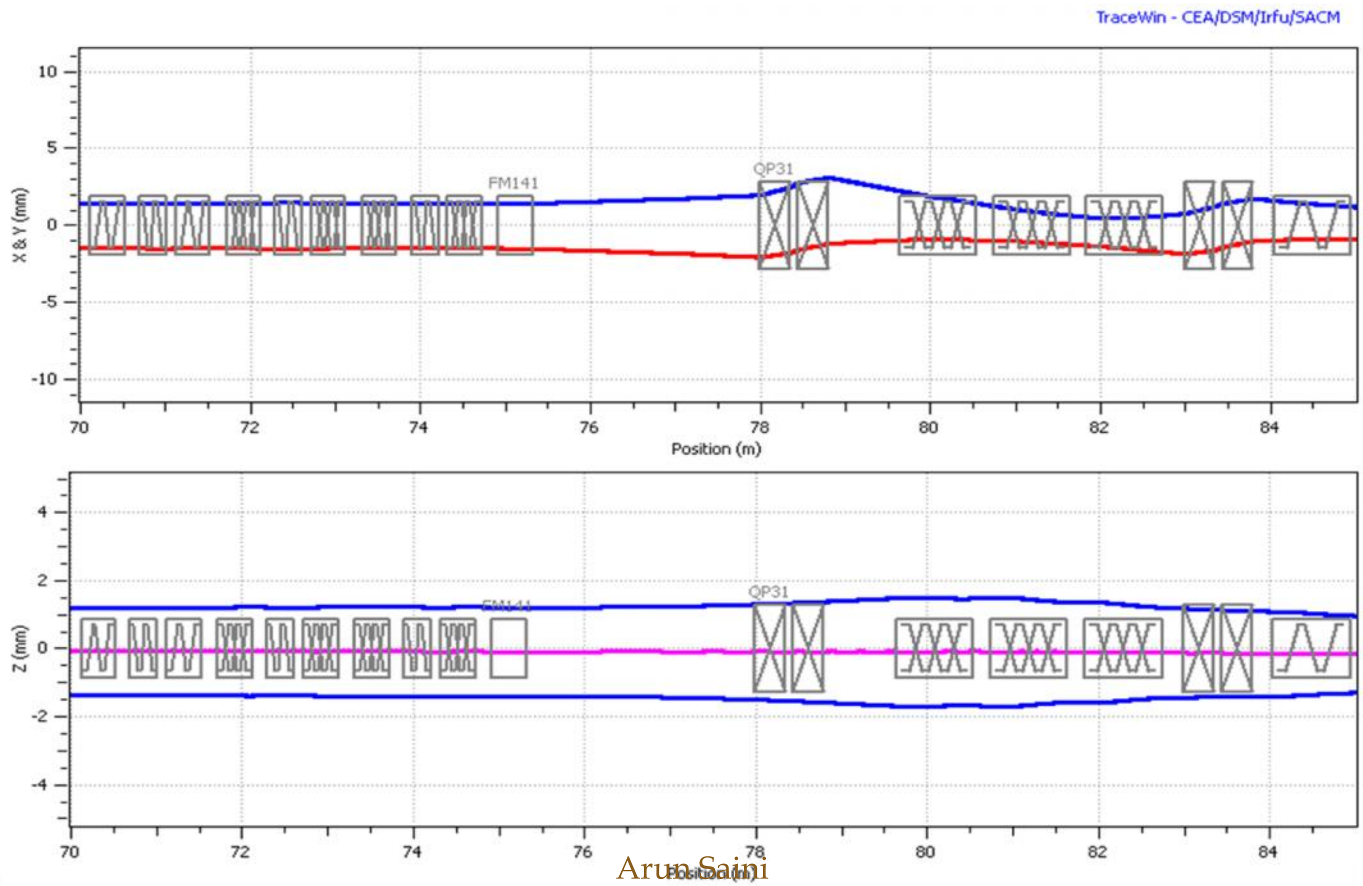
After Compensation



Compensation of SSR0 last cavity

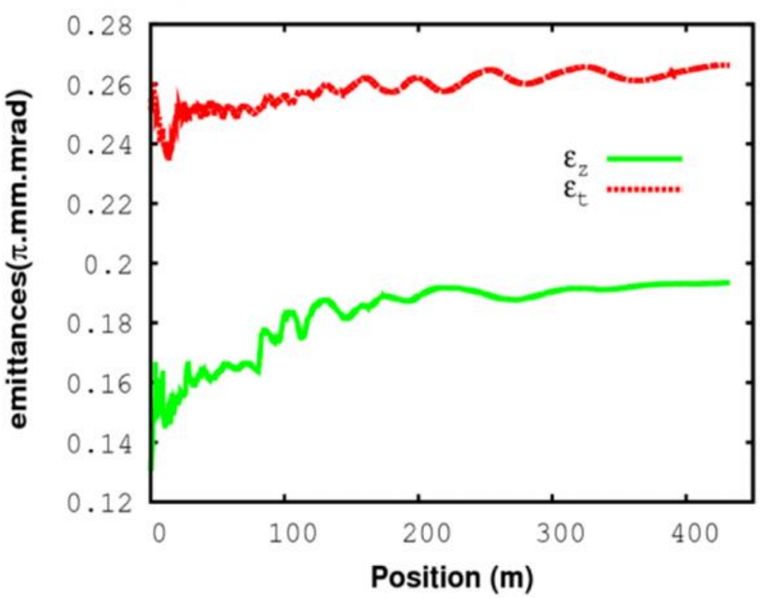
Parameters	Units	No Failure	With failure of last rf cavity in SSR0	
			Before compensation	After compensation
ε_z	$\pi \cdot$ mm mrad	0.18	0.48	0.19
ε_t	$\pi \cdot$ mm mrad	0.258	0.30	0.265
Energy	MeV	3028.3	3025.1	3028.4

Failure of last cavity in SSR2 section

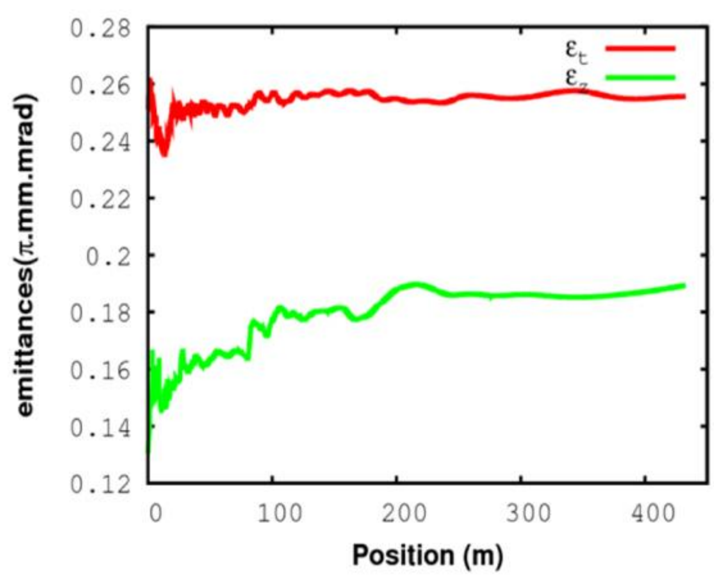


Beam emiitance

Before compensation



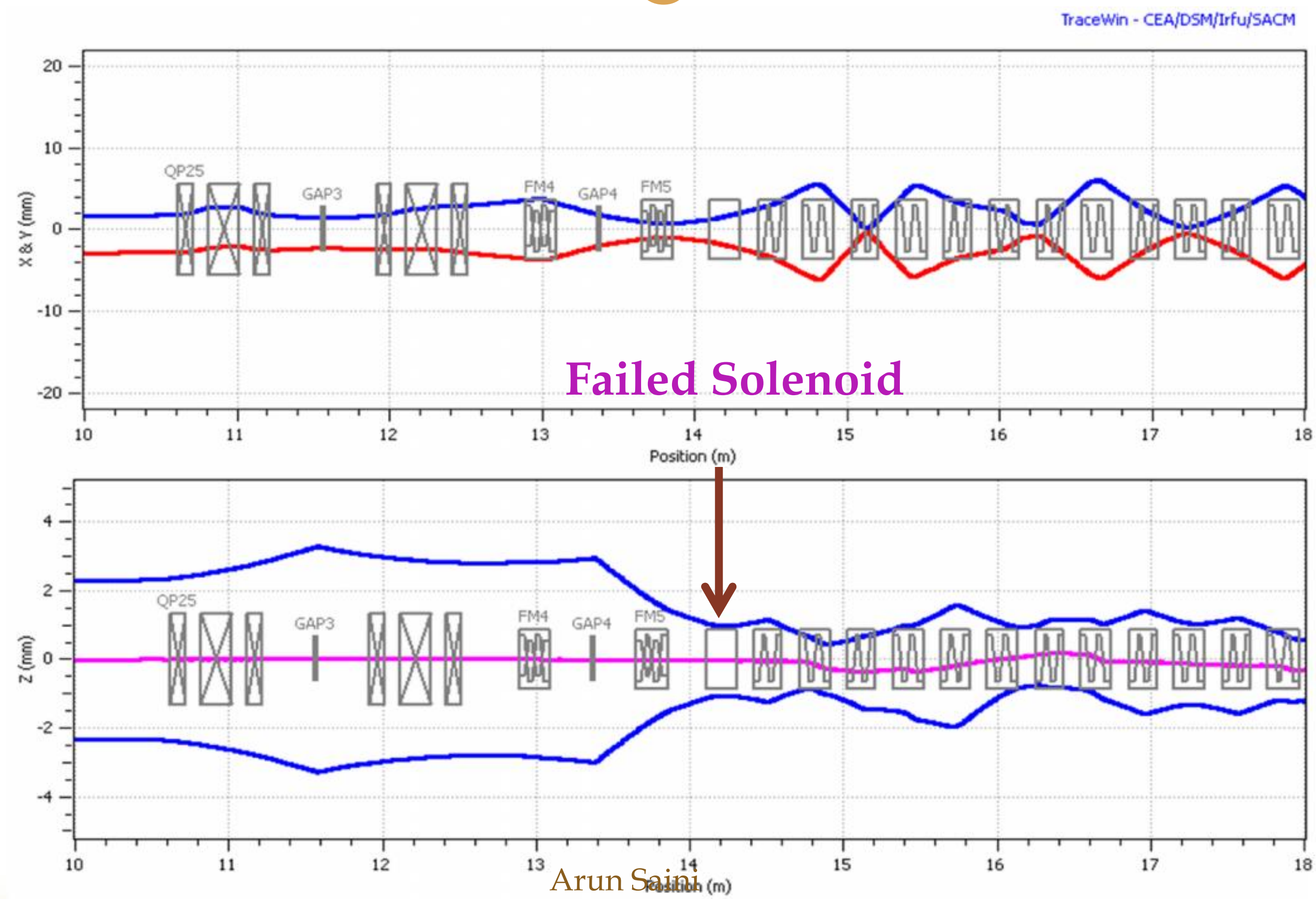
After compensation



Compensation of last cavity in SSR2 section

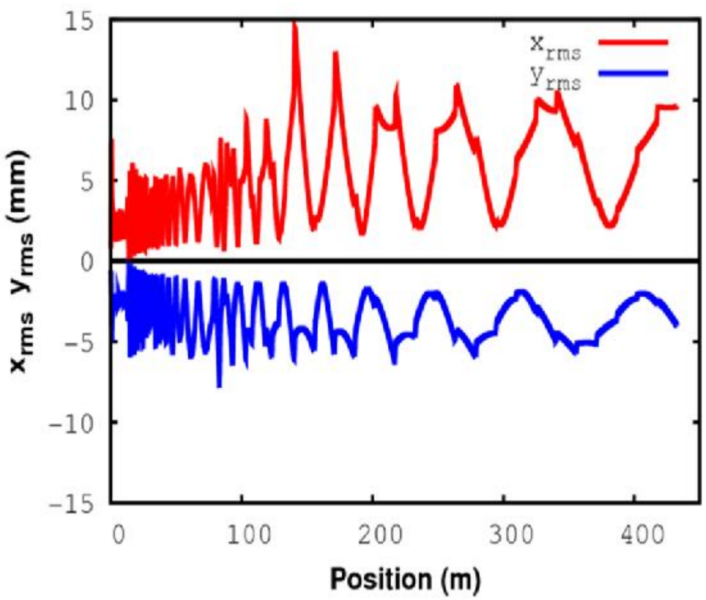
Parameters	Units	No Failure	With failure of last rf cavity in SSR2	
			Before compensation	After compensation
ε_z	$\pi\cdot$ mm mrad	0.18	0.194	0.19
ε_t	$\pi\cdot$ mm mrad	0.258	0.267	0.255
Energy	MeV	3028.3	3020.0	3029.6

Failure of First solenoid in SSR0 section

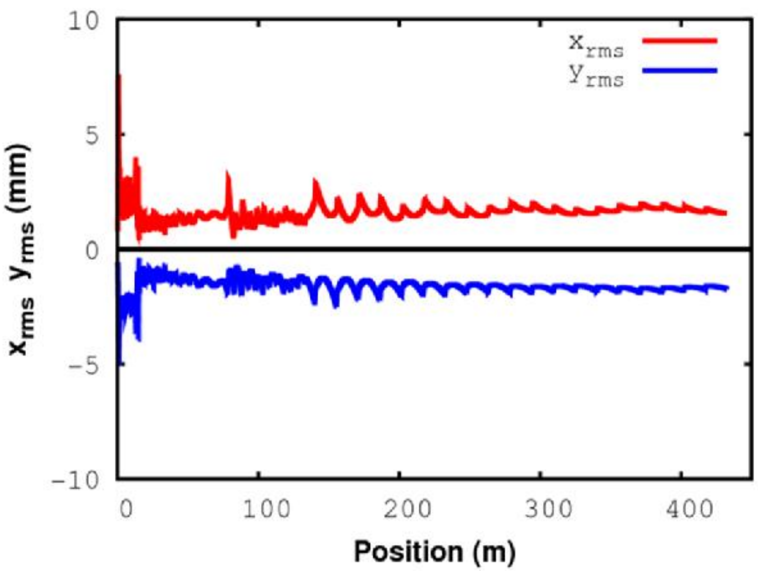


Beam transverse trajectories

Before compensation

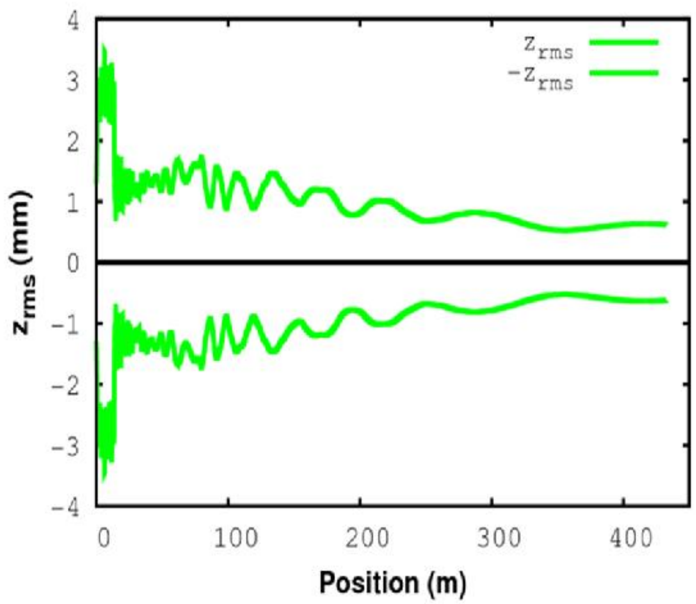


After compensation

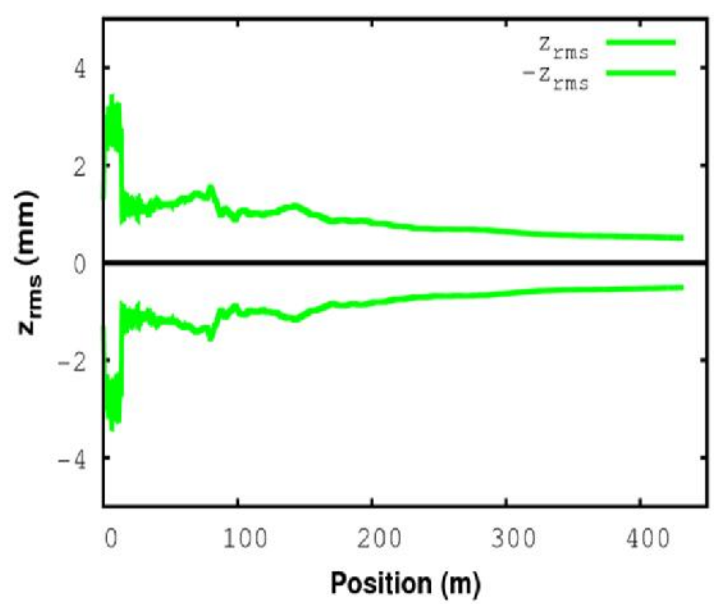


Beam trajectory : Longitudinal plane

Before Compensation

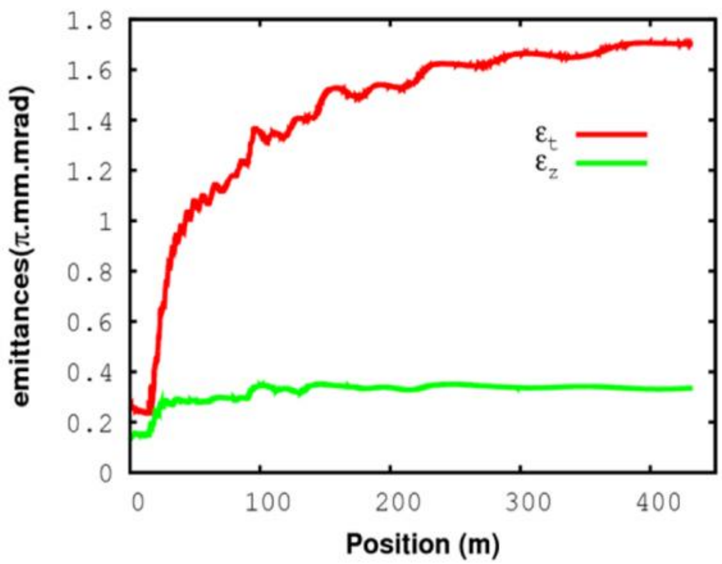


After Compensation

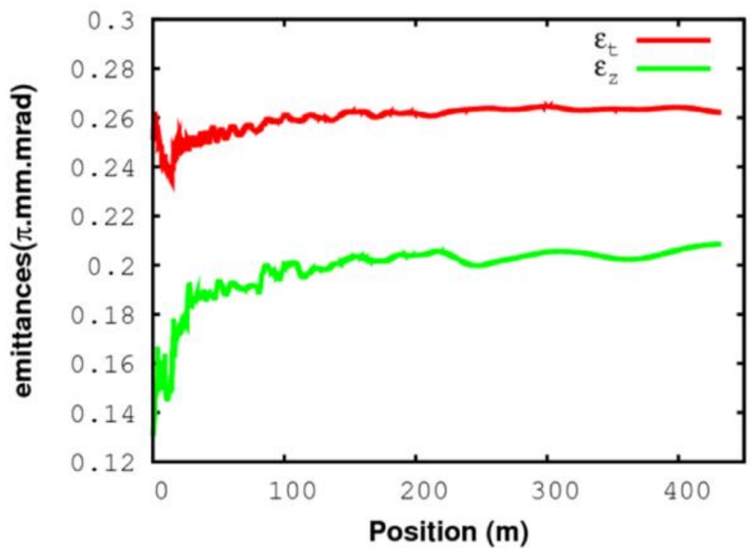


Emittances

Before Compensation



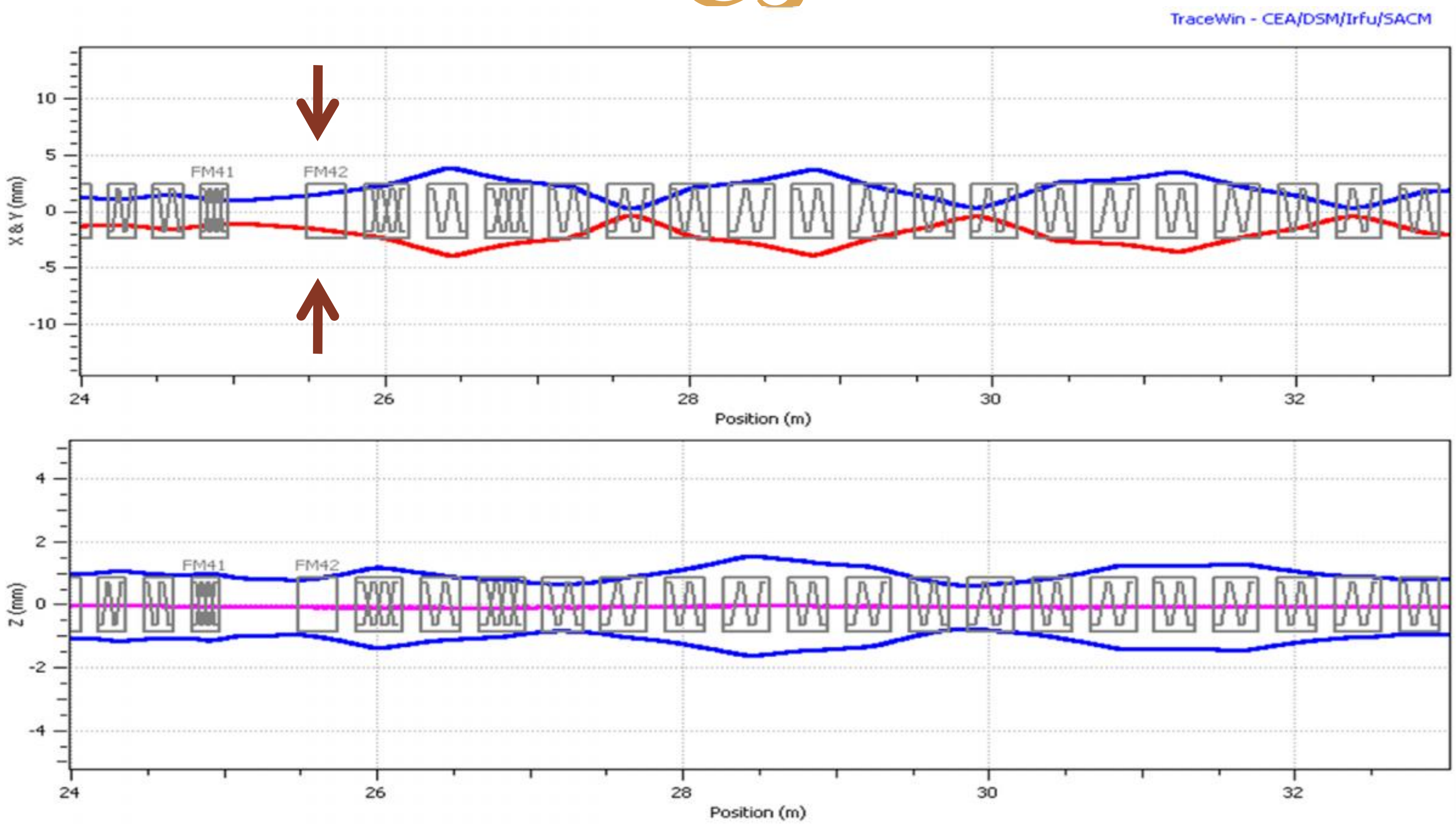
After compensation



Compensation of first solenoid in SSR0

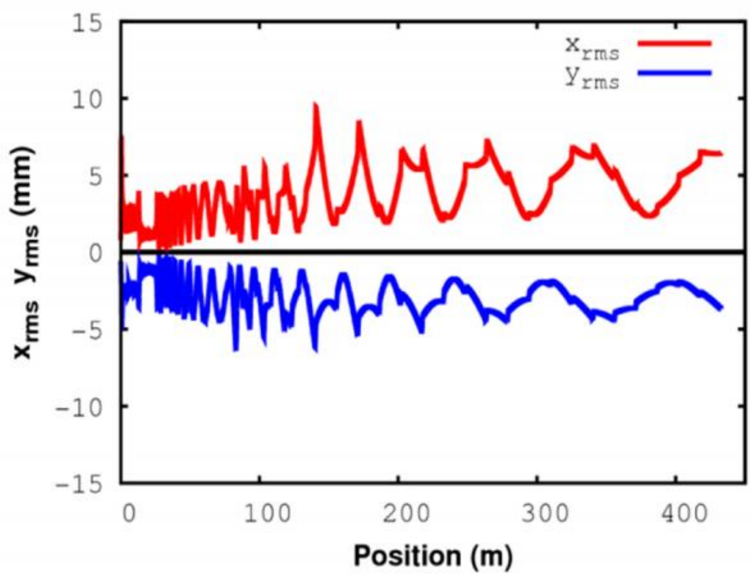
Parameters	Units	No Failure	With failure of first solenoid in SSR0	
			Before compensation	After compensation
ε_z	$\pi\cdot$ mm mrad	0.18	0.34	0.208
ε_t	$\pi\cdot$ mm mrad	0.258	1.7	0.262
Energy	MeV	3028.3	3028.3	3028.4

Failure of first solenoid in SSR1 section

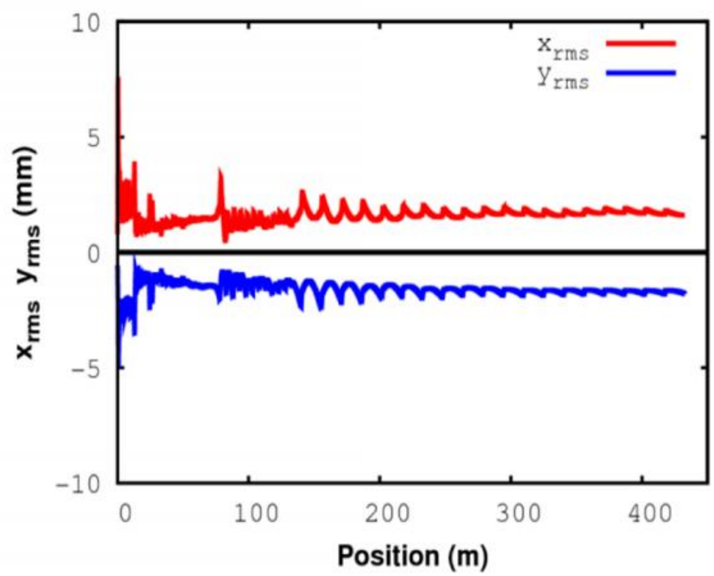


Beam transverse trajectory

Before compensation

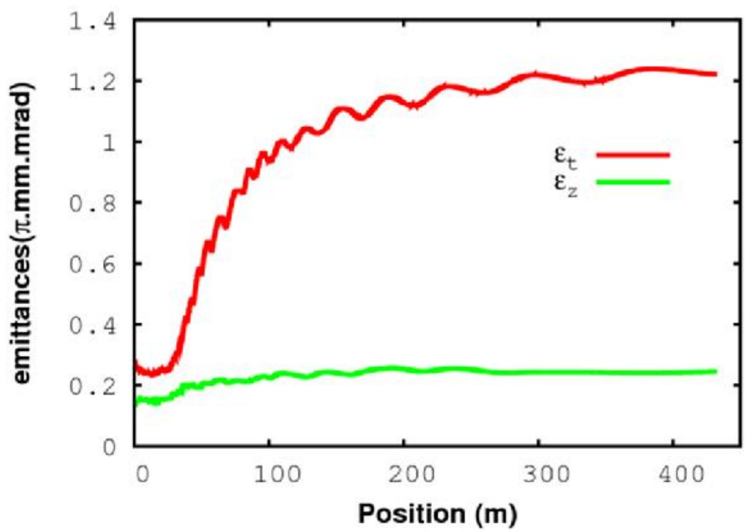


After compensation

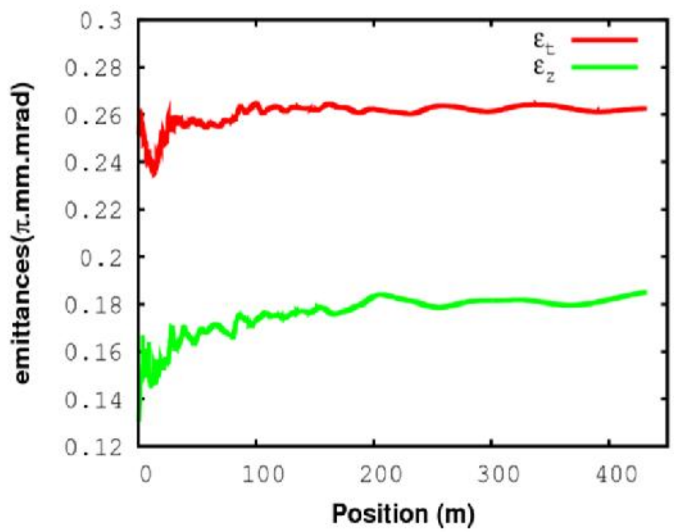


Emittances

Before compensation



After compensation



Compensation of failure of first solenoid in SSR1

Parameters	Units	No Failure	With failure of first solenoid in SSR1	
			Before compensation	After compensation
ε_z	$\pi\cdot$ mm mrad	0.18	0.25	0.185
ε_t	$\pi\cdot$ mm mrad	0.258	1.23	0.263
Energy	MeV	3028.3	3028.3	3028.4

Summary

- RF cavities and magnets have been designed and optimized.
  - Beta =0.90, 650 MHz single cell cavity has been ordered.
- Lattice design for cw linac is studied extensively.
- Study has been performed to understand reliability of linac and including this scenario in lattice design to improve linac performance.
  - Low energy section is very sensitive to failure of elements
  - Local compensation is possible with this variant of linac.

Acknowledgement

My sincere thanks to all my supervisors: Dr. Kirti Ranajn, Dr. Nikolay Solyak, Dr. Shekhar Mishra, Dr. Vyacheslav Yakovlev.

Many thanks to my RF group
(I. Gonin, A. Lunin, A. Sukhanov, ……….)

&

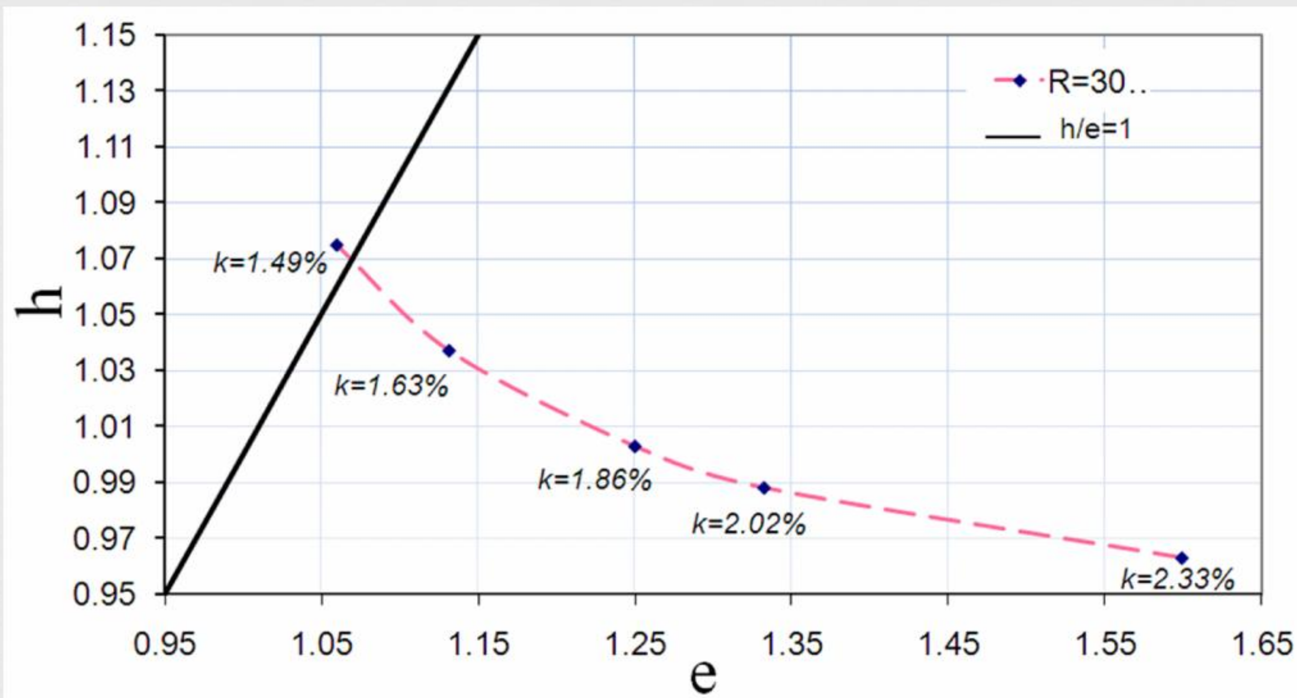
Many thanks to my Linac beam dynamics group
(F. Ostiguy, J.P. Carneiro, B. Shteynas, A. Vostrikov……….)

THANKS

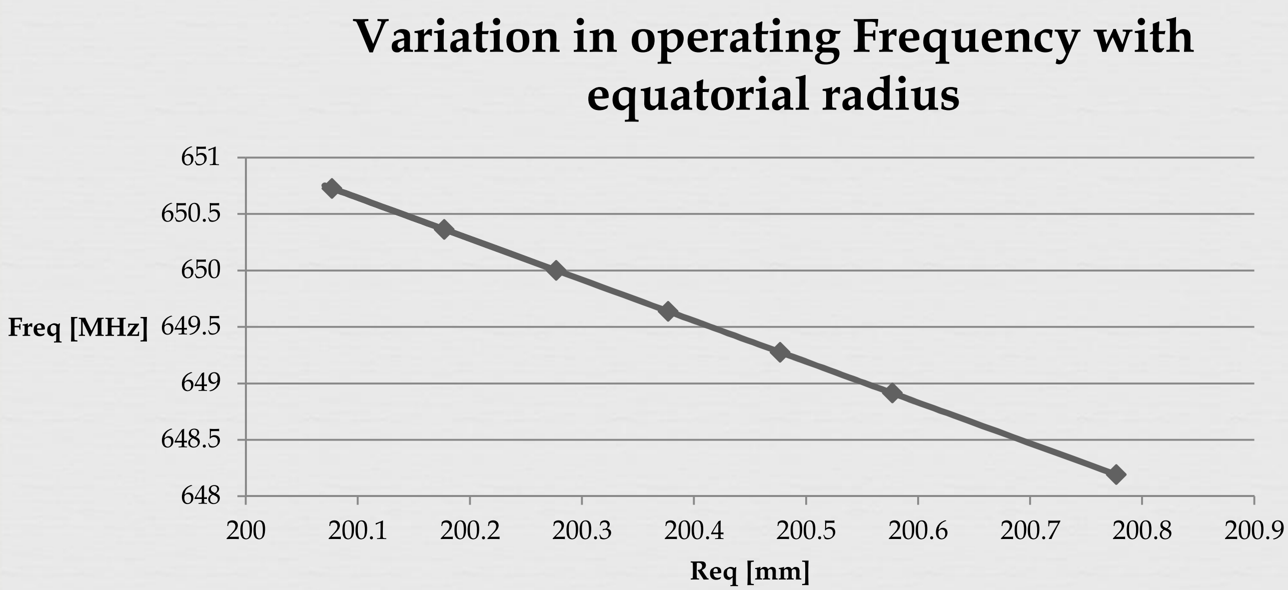
Back-up slides

Optimization Process

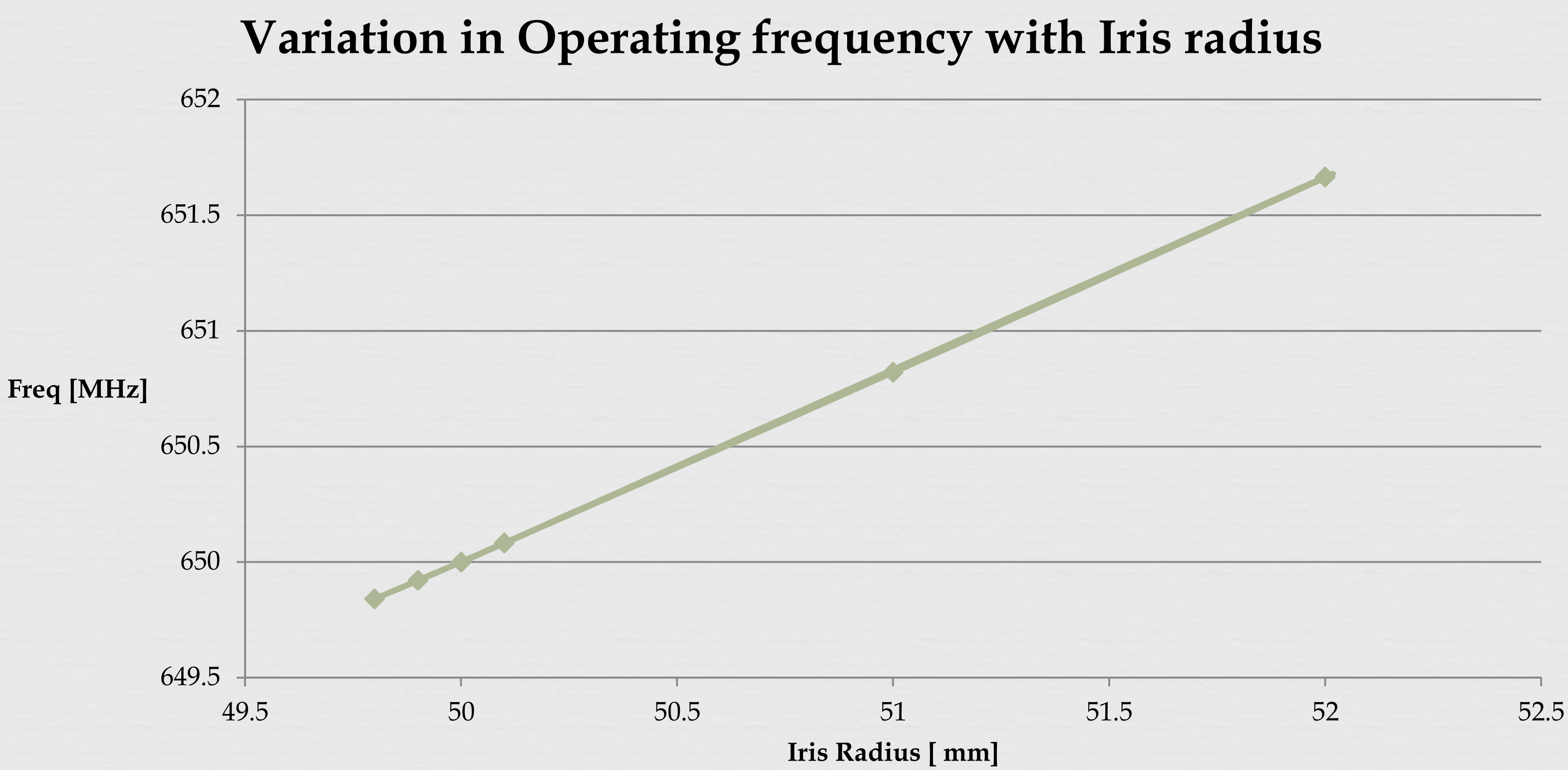
➤Process of optimization means searching the cell shape which has minimum field enhancement factor s with required coupling.



Fabrication errors

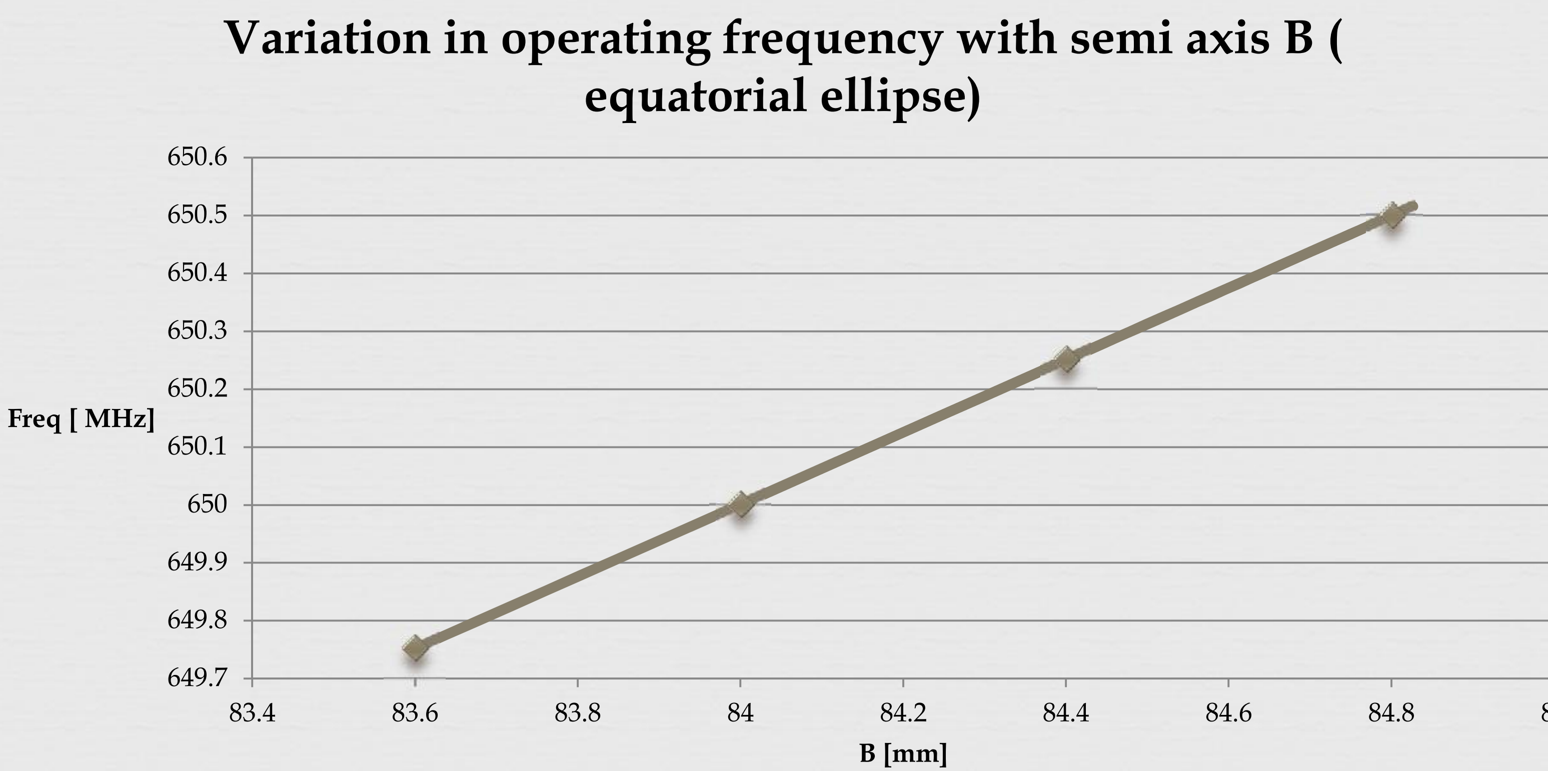


Fabrication errors

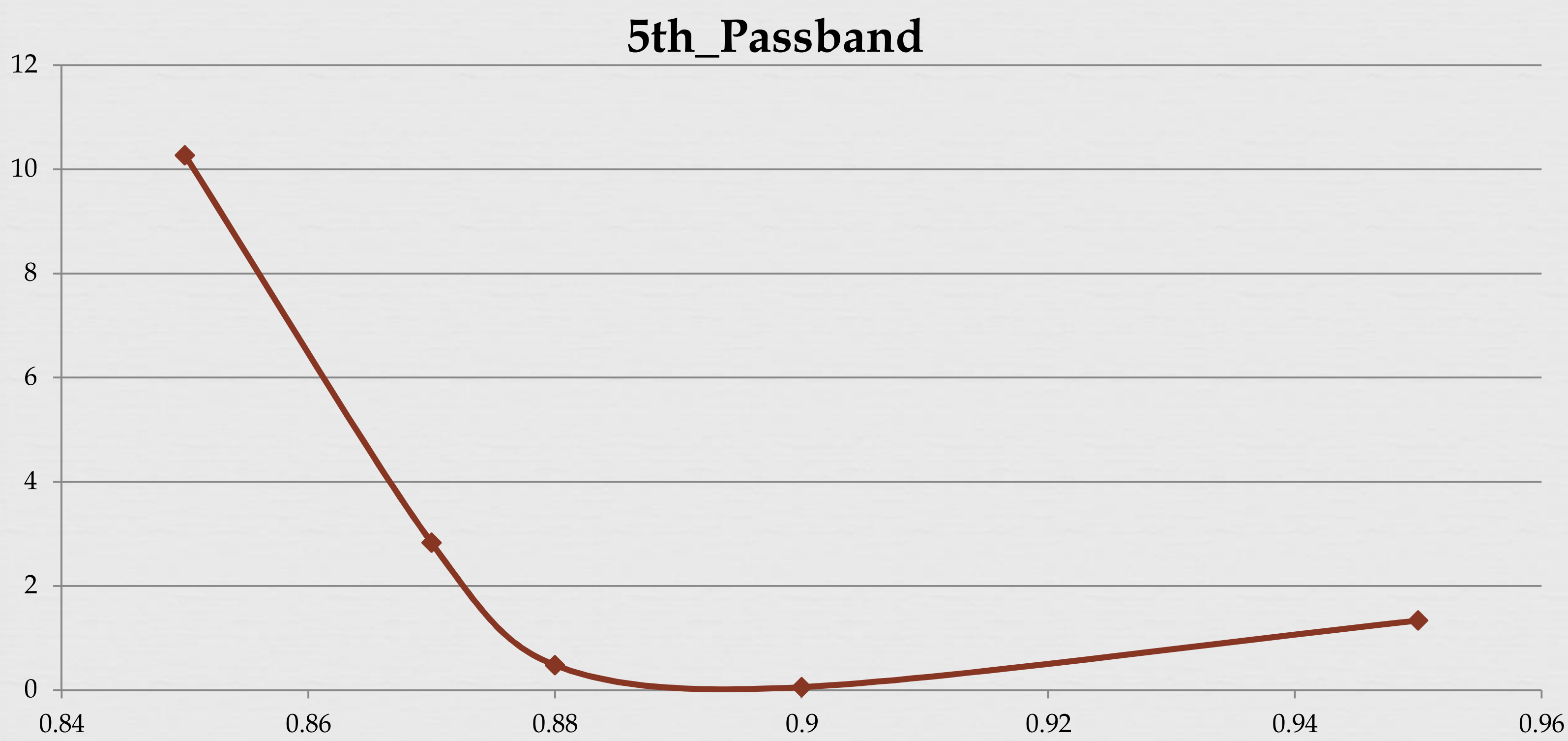


Fabrication errors

Fabrication errors



Variation in bandwidth of 5th pass bands with beta



Microphonics

Section	Freq MHz	Microphonic amplitude Hz	Minimal bandwidth Hz	Maximal loaded Q	Max power per cavity kW
SSR0	325	30	72	4.5e6	0.65
SSR1	325	30	68	5e6	1.7
SSR2	325	20	44	7.5e6	4.3
LE 650	650	15	33	2e7	16
HE 650	650	15	35	2e7	27
ILC	1300	30	85	1.5e7	20

Acitive microphonics compensation is necessary!

what is spoke cavity?

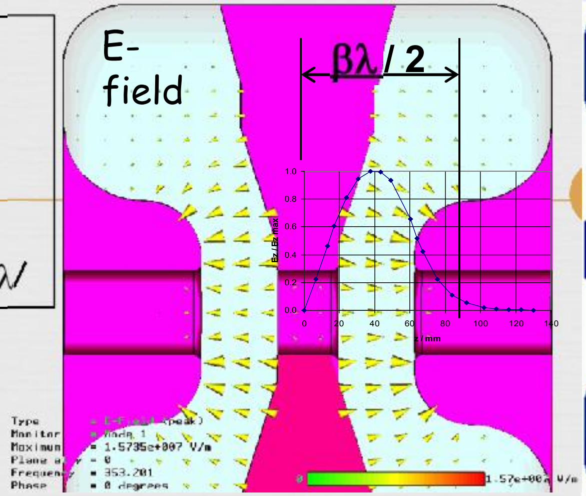
352 MHz

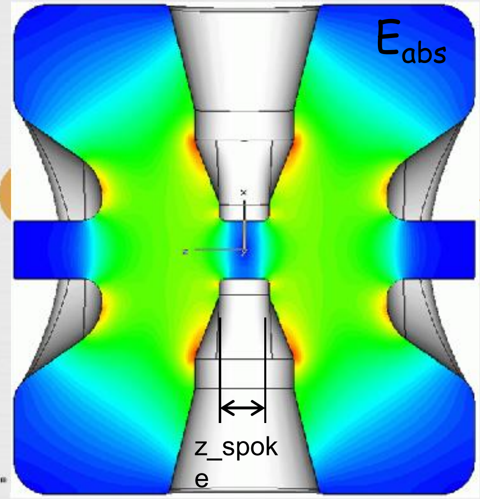
β= 0.35

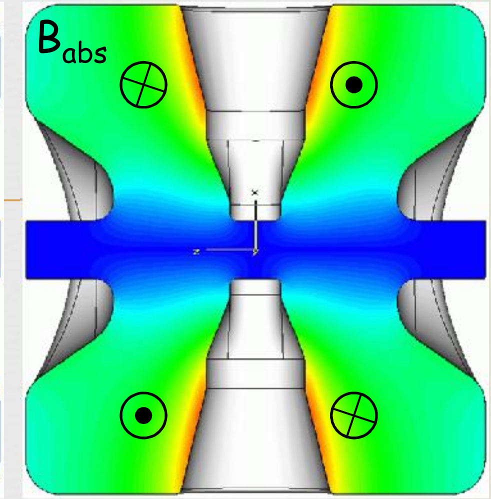
R_{app} = 25 mm

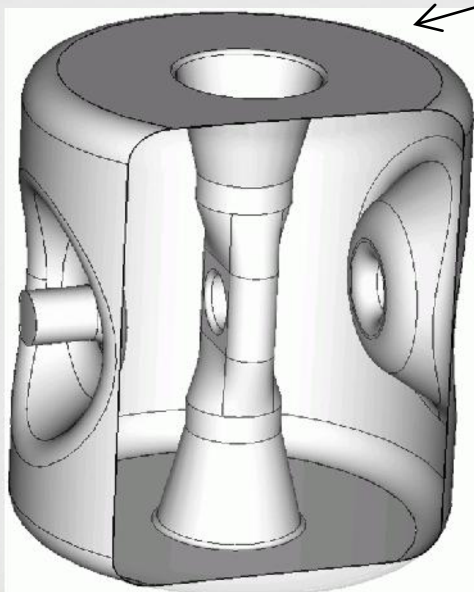
$\beta\lambda/2$ = 149 mm

z_spoke=0.3*$\beta\lambda/2$

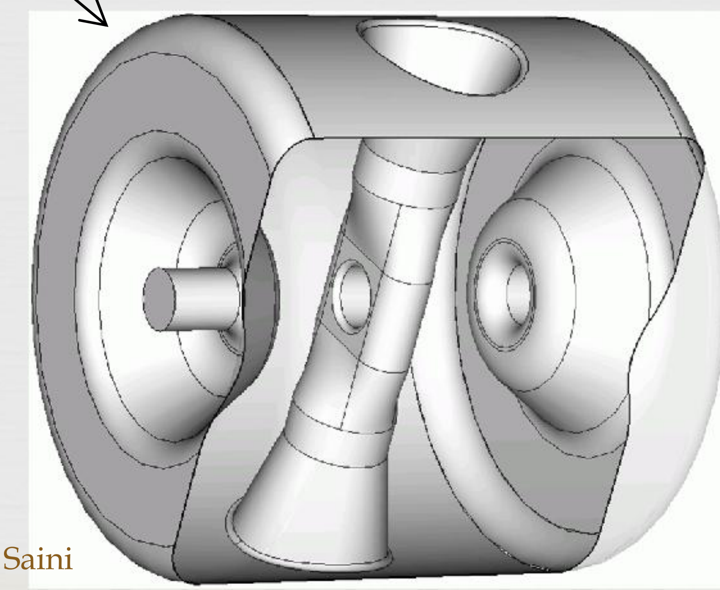








half-
wave
resonator
(HWR)



single-
spoke
resonator
(SSR)

3. Acceleration from 2.5 to 160 MeV:
three families of 325 MHz SC single-spoke resonators (SSR).

Why SSR?

QWR:

- Compact
- Modular
- Low cost
- Easy access

But: dipole steering;
mechanical stability
Field asymmetry needs to be compensated :
beam offset, dipole steering or shaping the gap.

HWR:

- No dipole steering
- High performance
- Lower surface electric field
- Wider beta range

But not easy access
more difficult to tune


MSU 322 MHz β=0.28


The first 355 MHz SC HWR ANL - β=0.12

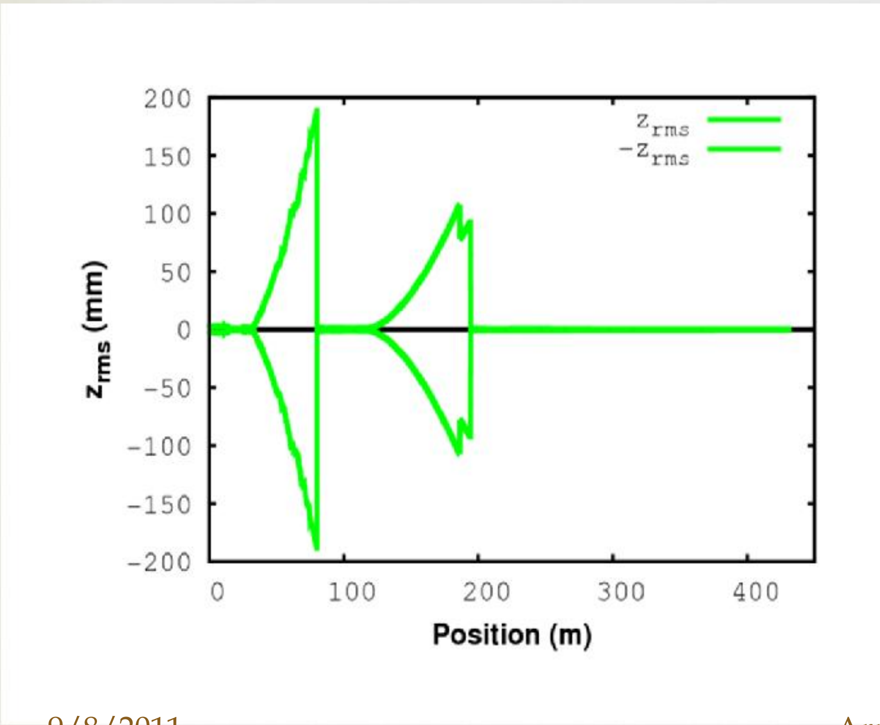
Concept of Cryo-Segmentation

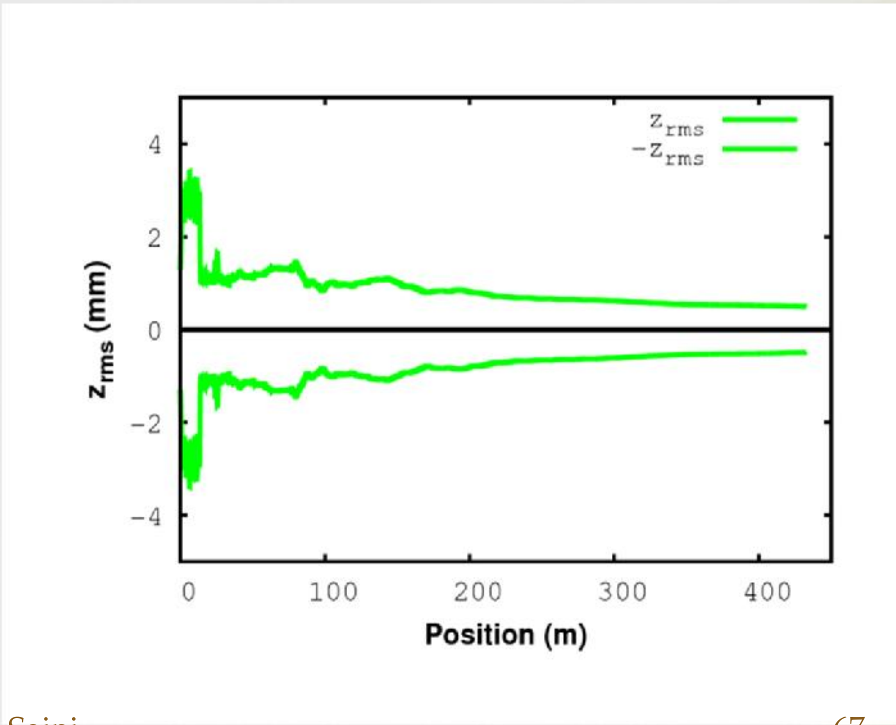
- All crymodules in LE (325 MHz) part of the linac are separated by short RT sections
  - *Maintenance, reliability*
  - *Beam profile diagnostics*
  - *Possible dump (reduction of diameter) for halo cleaning*

- HE sections (Low-β and high-β 650 MHz) are assembled in Cryo-strings with warm inter-connections between sections:
  - *Each string ~6-8 CM's*
  - *Extra-length warm drift between sections:*
    - *SSR2-LE650 - 2 m*
    - *LE650-HE650 - (2-12) m*
    - *HE650 –HE650 – (2-12) m*

Beam trajectory: Longitudinal

Before Compensation	After compensation





Halo definition

If the motion is uncoupled between phase planes, the following quantities are kinematic invariants of motion:

$$I_2^i \equiv \langle q_i^2 \rangle \langle p_i^2 \rangle - \langle q_i \, p_i \rangle^2$$

$$I_4^i \equiv \langle q_i^4 \rangle \langle p_i^4 \rangle + 3\langle q_i^2 p_i^2 \rangle^2 - 4\langle q_i p_i^3 \rangle \langle q_i^3 p_i \rangle$$

Then we define the halo intensity parameter, *Hi*, in the *i*th phase plane, as

$$H_i \equiv \frac{\sqrt{3I_4^i}}{2I_2^i} - 2 = \frac{\sqrt{3\langle q_i^4 \rangle \langle p_i^4 \rangle \ + 9\langle q_i^2 p_i^2 \rangle^2 - 12\langle q_i \, p_i^3 \rangle \langle q_i^3 p_i \rangle}}{2\langle q_i^2 \rangle \langle p_i^2 \rangle - 2\langle q_i \, p_i \rangle^2}$$

From ref: "PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS,VOLUME 5, 124202 (2002)", "Beam halo definitions based upon moments of the particle distribution (C. K. Allen and T. P.Wangler) "