Overview of Beam Optics For Project-X CW Linac

J.-F. Ostiguy
(on behalf of the Lattice design Team)
APC/Fermilab

ostiguy@fnal.gov

Acknowledgments

The Team:

APC SC Linac Group:
*N. Solyak
J.F. Ostiguy
A. Vostrikov
A. Saini
J.P. Carneiro
(E. Giannfelice-Wendt)
(D. Johnson)

and
S. Nagaitsev
V. Lebedev
V. Yakovlev

Project-X in a Nutshell

Centerpiece of the future US HEP program, focused on the intensity frontier.

<u>Broad Objectives</u>:

* Provide a high power proton source with energies between 50-120 GeV to produce intense neutrino beams at a distant underground laboratory.
* Provide flexible beam of a few GeV to run,
  Kaon, muon, precision experiments **<u>simultaneously</u>** with the neutrino program
* Provide a path to a future neutrino factory and a muon collider

Some History …

Proton Driver: (2002, Foster)

Pulsed 8 GeV SC Linac 0.5-2 MW

use MI as accumulation ring

Project-X ICD-1: Pulsed 8 GeV Linac, 0.5 MW

+ slow extraction for mu2e, rare kaons/muons experiments

Project-X ICD2.1 (2008) CW SC Linac, 1 mA x 2 GeV

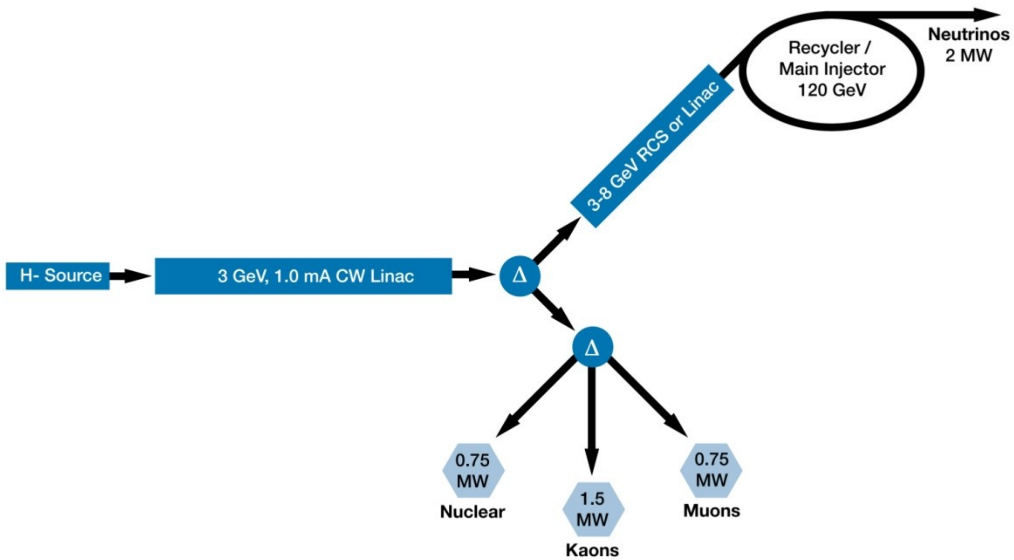
kaon/muon precision experiments

RCS to 8 GeV for neutrino program

Project-X ICD-2.2: (Nov 2009) CW SC Linac 1mA x 3 GeV

pulsed linac or RCS to ~8 GeV for neutrino program

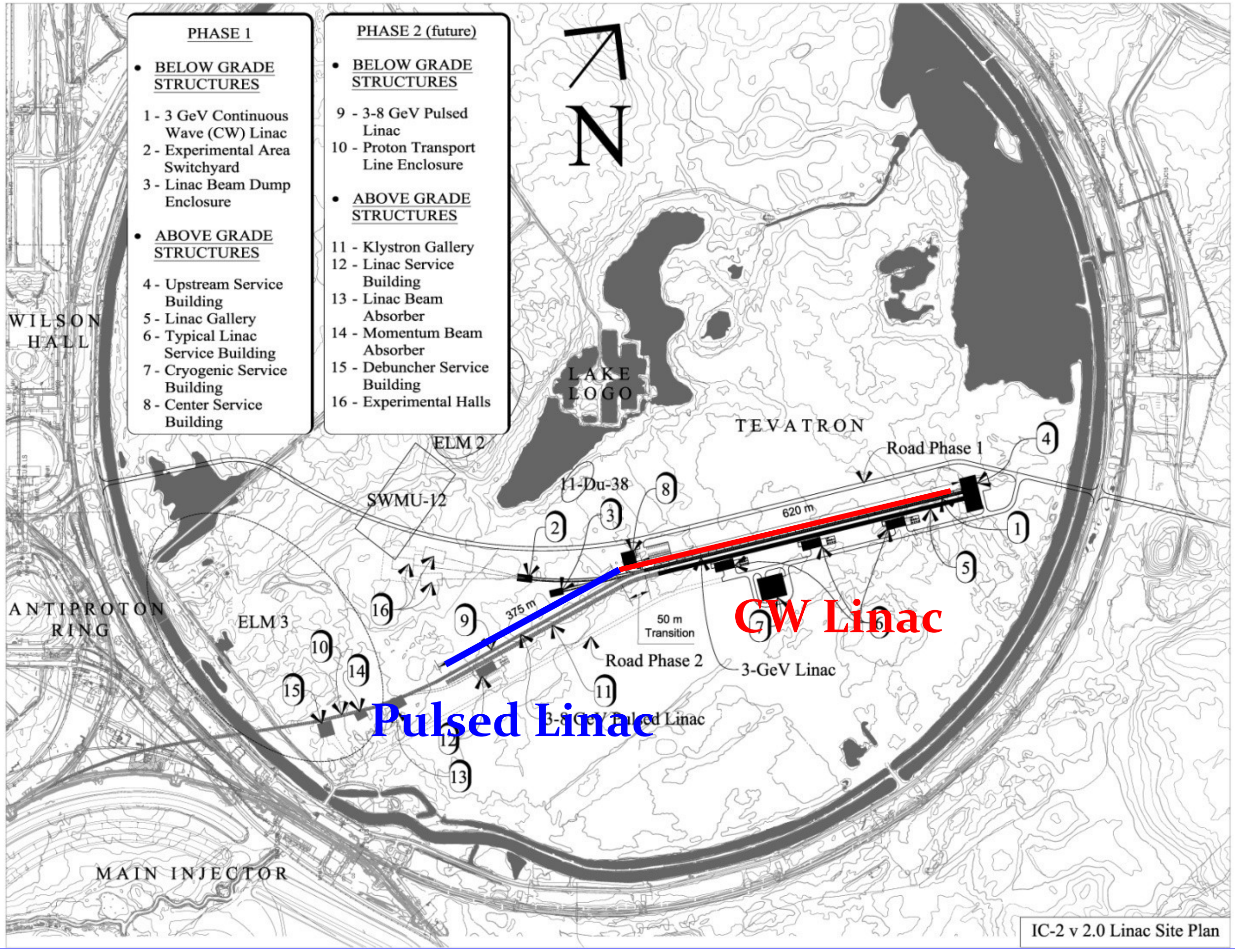
Initial Configuration Version 2



3 GeV, 1 mA ***CW*** linac for rare processes program
~ 3MW, flexible beam structure to support multiple users
< 5% beam sent to MI

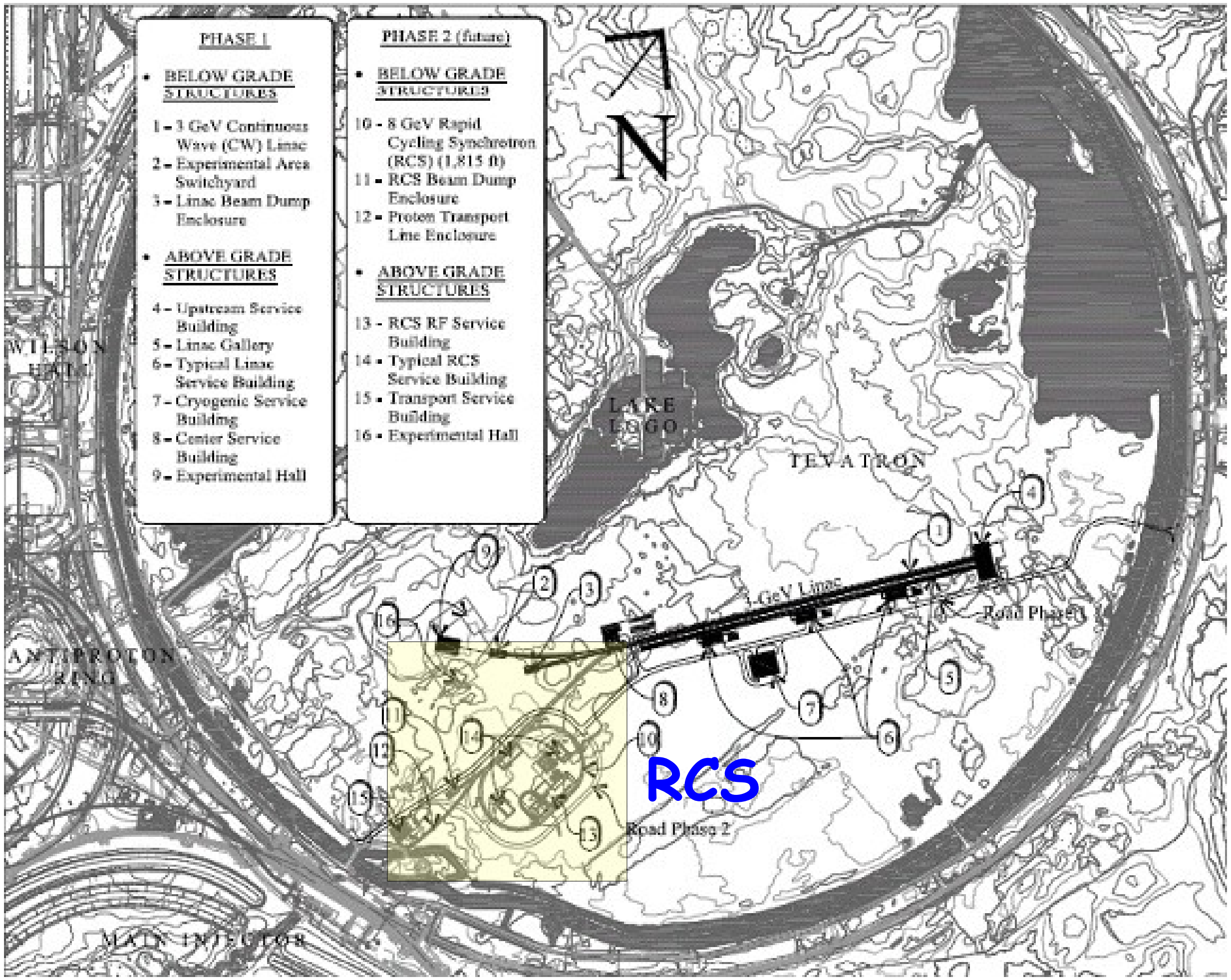
Options for 3-8 GeV acceleration RCS or pulsed linac
Linac would be 1.3 GHz with < 5% duty cycle

Project X IC-2 Siting with pulsed 3-8 GeV Linac



Pulsed 3-8 GeV Linac based on ILC / XFEL technology

IC-2 Siting with RCS

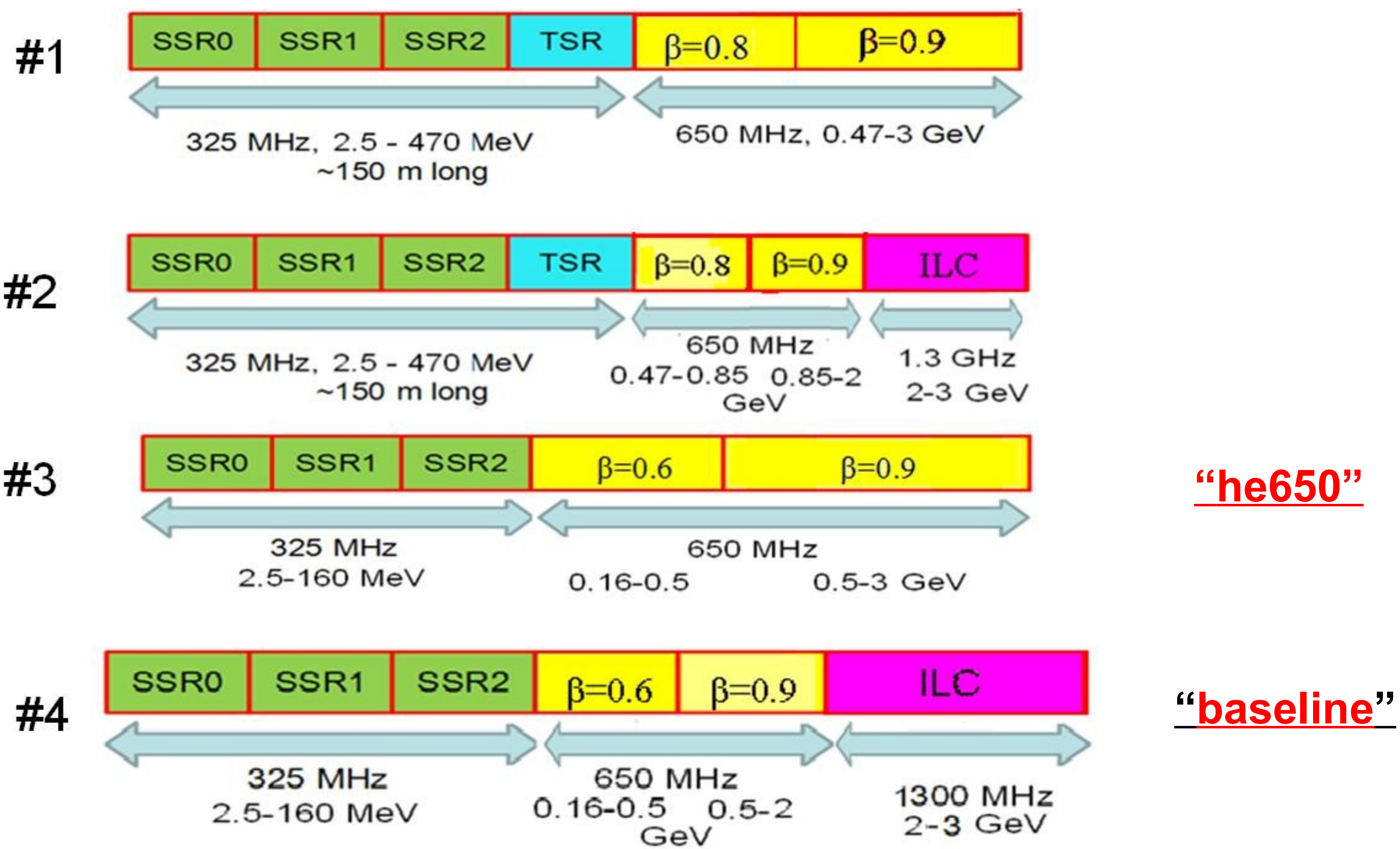


Accelerator Parameters Summary

CW Linac		
Particle Type	H-	
Beam Kinetic Energy	3.0	GeV
Average / Peak Beam Current	1/10	mA
Linac pulse rate	CW	
Beam Power	3000	kW
Beam Power to 3 GeV program	2870	kW
RCS/Pulsed Linac		
Particle Type	protons/H-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	0.002/2	msec
Cycles to MI	6/20	
Particles per cycle to Recycler	2.6E13	
Beam Power to 8 GeV program	200	kW
Main Injector		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.4	sec
Particles per cycle	1.6E14	
Beam Power at 120 GeV	2200	kW

See tomorrow:
"ProjectX as
A driver for
NF/Muon Collider"
WEO2B05

Project X 2.5 – 3 GeV CW Linac Lattice Studies

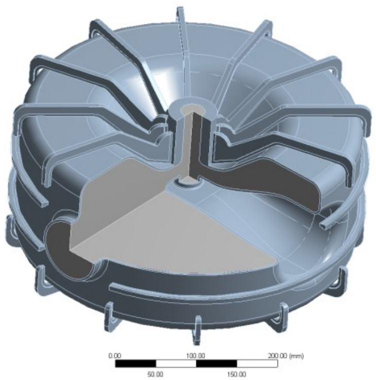


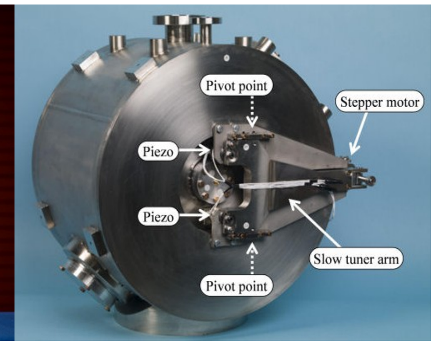
Many alternatives considered. We concentrated on #3 and #4

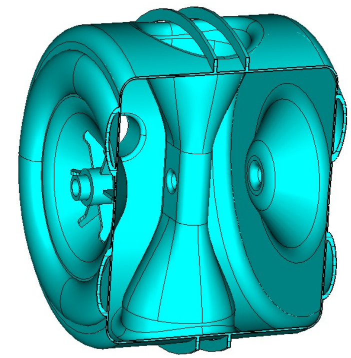
3 GeV CW Linac Baseline

Section	Freq, (MHz)	Energy (MeV)	Cav/mag/CM	Type
SSR0 (β_G=0.11)	325	2.5-10	26 /26/1	SSR, solenoid
SSR1 (β_G=0.22)	325	10-32	18 /18/ 2	SSR, solenoid
SSR2 (β_G=0.42)	325	32-160	44 /24/ 4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-520	42 /21/ 7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	520-2000	96 / 12/ 12	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	2000-3000	64 / 8/ 8	9-cell elliptical, quad

325 MHz Spoke Cavities







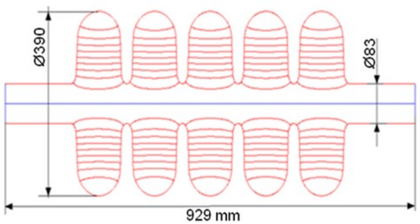
SSR0: design

SSR-1: Prototyping, testing

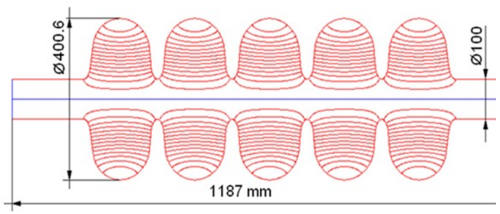
SSR2: design

cavity type	β_G	Freq MHz	Uacc, max MeV	Emax MV/m	Bmax mT	R/Q, Ω	G, Ω	*Q0, 2K 10E9	Pmax,K W
SSR0	β=0.114	325	0.6	32	39	108	50	6.5	0.5
SSR1	β=0.215	325	1.47	28	43	242	84	11.0	0.8
SSR2	β=0.42	325	3.34	32	60	292	109	13.0	2.9

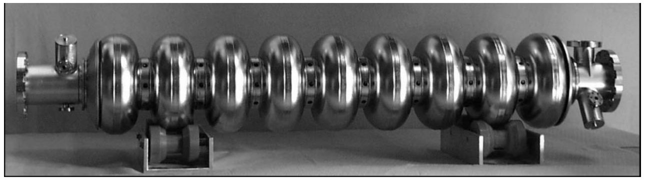
650 MHz + ILC Elliptical Cavities



650 MHz: β=0.61



650 MHz: β=0.9



1.3 GHz ILC

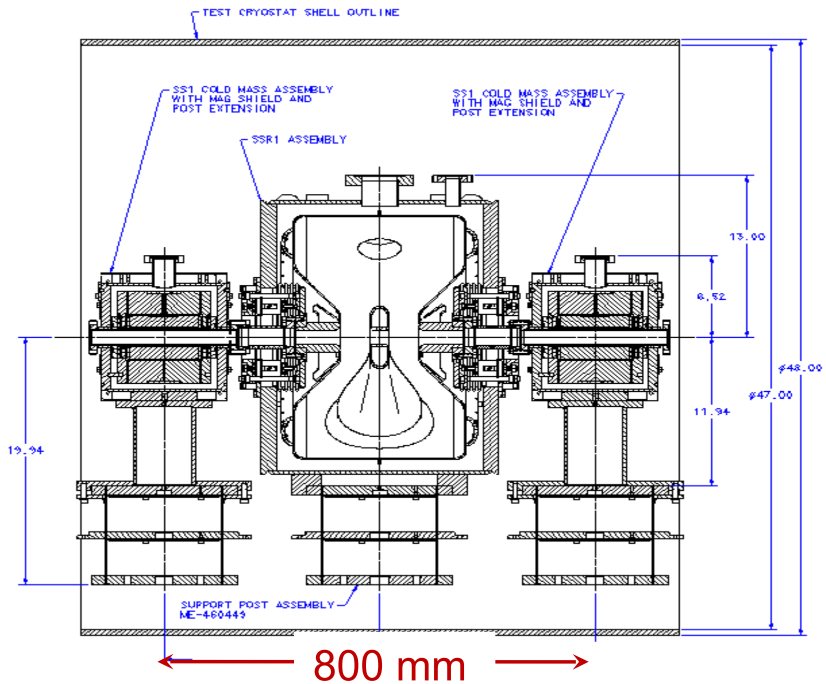
Parameter		LE650	HE650	ILC
β_geom		0.61	0.9	1
R/Q	Ohm	378	638	1036
G-factor, Ohm		191	255	270
Max. Gain/cavity	MeV	11.7	19.3	17.2
Acc. Gradient	MV/m	16.6	18.7	16.9
Max surf. E field	MV/m	37.5	37.3	34
Max surf B field	mT	70	70	72
Q0 @ 2°K	E10	1.5	2.0	1.5
P@2K max	W	24	29	20

Magnetic Focusing

- In the initial part of the low-energy linac, focusing is provided by solenoids.
- Starting with the 650 MHz section, a standard FD-doublet lattice is used.
- In the 1.3 GHz ILC section, FODO focusing is used.
- All magnets are superconducting with built-in dipole correctors for beam steering.
- Cavities and focusing elements are grouped in cryomodules. For the high energy linac, ILC Type-4 cryomodules can be used (with minor modifications).

Section	SSR0	SSR1	SSR2	LE650	HE650	ILC
Focusing	SR	SR	SR2	FDR2	FDR8	FR8DR8

Solenoids for SSR-x Sections



<u>Solenoid status</u>

- SSR0 – conceptual design
- SSR1 – prototype tested
- SSR2 –prototype is ready for tests

<u>Features</u>: Built-in correction coil to correct ~5 mm offset; BPM is attached or built-in.

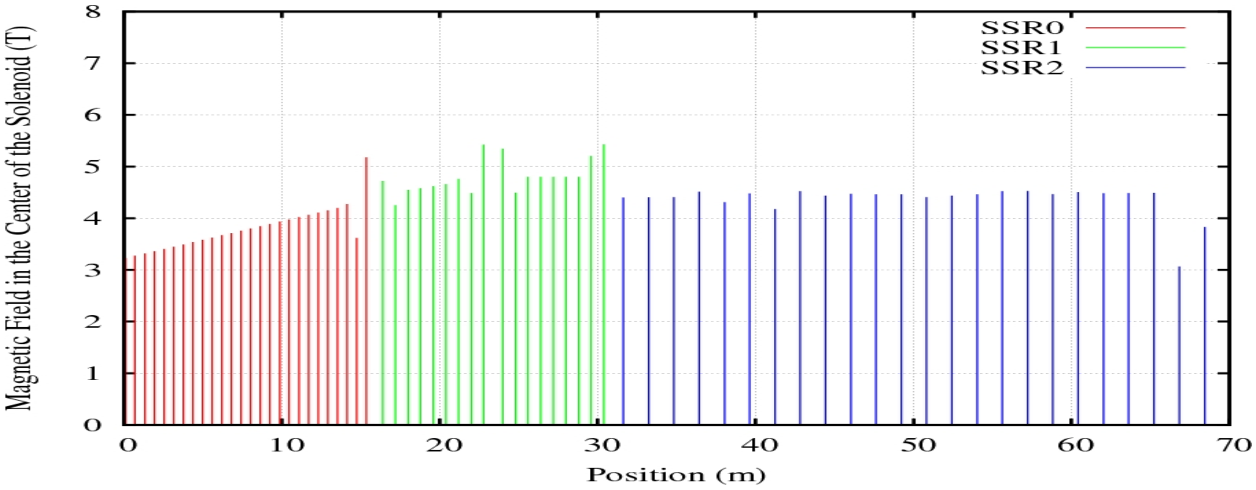
<u>Cryomodule design status</u>

- Design of SSR type of cryomodule has started. Conceptually, all SSR cryomodules are similar.

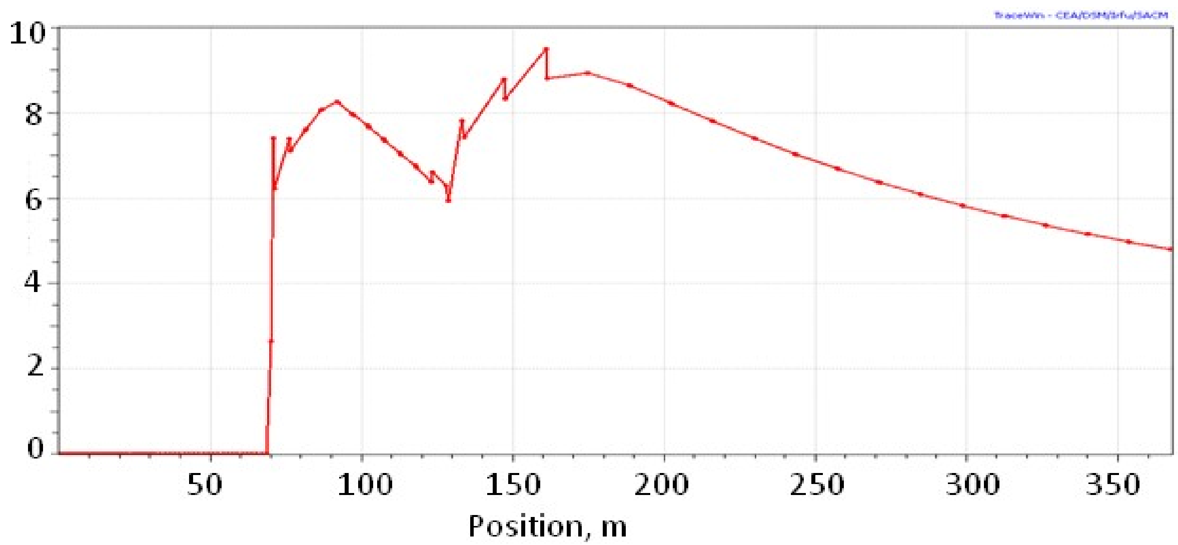
<u>Focusing Period:</u>

SSR0: (sol+cav) = 610 mm
SSR1: (sol+cav) = 800 mm
SSR2: (sol+cav+cav+60 mm) = 1300 mm

Solenoid/Quad Strengths



Solenoid axial field
T



Quad Gradients
T/m

Cryo-Segmentation Concept

- All cryomodules in the LE (325 MHz) part of the linac are separated by short room temperature sections
  - Maintenance, reliability
  - Beam profile diagnostics
  - Possible collimation for halo cleaning
- HE sections (Low-β and high-β 650 MHz and ILC 1.3 GHz) are assembled in cryo-strings with warm inter-connections between sections:
  - One string = ~6-8 CM's
  - Individual CMs, separated by warm drifts is optional (ver.3)
  - Extra-length warm drift between sections:
  - SSR2-LE650 - 2 m
  - LE650-HE650 - (2-12) m
  - HE650 -HE650 - (2-12) m
  - He650 – ILC – (2-12) m

Optics Design

Overall Objective:

Minimize emittance growth and potential for beam loss by supporting a beam envelope that is as smooth and regular as possible.

Codes:

TraceWin (CEA/Saclay)
TRACK (Argonne)
ASTRA (DESY)
TRACE3D,PARMILA (LANL)

Envelope Stability

In a periodically focusing system, single particle trajectories are known to be stable for $\sigma_0 < 180$ deg. This is the Courant-Snyder result.

In the presence of space charge, it has been shown (.e.g. see M. Reiser's book) that envelope instabilities can develop when $\sigma > 90$. This is more restrictive.

phase advance/period should a be less than 90 deg

Parametric Resonances

The longitudinal and transverse oscillations are parametrically coupled through the dependence of the rf defocusing on the phase.
A simplified model based on Mathieu equation shows that parametric resonances occur when

$$\sigma_{0\perp} = \frac{n}{2}\sigma_{0||}$$

n=1 is usually the most (and only) important resonance

Ensure that $$0.6 < \frac{\sigma_{0\perp}}{\sigma_{0||}} < 0.8$$

Uniform Transverse Envelope Amplitude

$$x'' + k^2(z)x - \frac{\epsilon_x^2}{x^3} - \frac{< xF_{\rm SC} >}{x} = 0$$

Envelope equation

The EE admits a constant amplitude solution when $x'' = x' = 0$

Within a section with regular periods, if the field strength of the focusing element is kept constant, the wave number k, ε and decrease inversely as βγ so the envelope amplitude will remain constant provided Fsc is small (Fsc scales as $1/\gamma^3$).

start a section by adjusting the focusing to achieve σ=90. Do not vary the focusing element field strength and let σ decrease adiabatically down to ~20 deg. Start a new section with a new period and repeat the process.

Equipartitioning

Mitigate the potential for both thermal and resonant emittance exchange by starting with a beam that is already equipartitioned.

Rule: try to pick the beam parameters so that

$$\frac{k_x \epsilon_{nx}}{k_z \epsilon_{nz}} = \frac{\sigma_x \epsilon_{nx}}{\sigma_z \epsilon_{nz}} \simeq 1$$

Aperture vs Bunch size

To avoid losses, keep the aperture radius R to rms bunch transverse size to 10 or more

Similarly, longitudinally, keep the ratio [φs/rms size] to ~5

Matching between Sections

The quality of matching between sections is important. Simulations show that losses are more likely to occur when the transitions are not smooth enough.

To ensure smooth transitions, it is better to involve more elements than strictly necessary, preferably on both sides of the transition.

Phase Smoothing

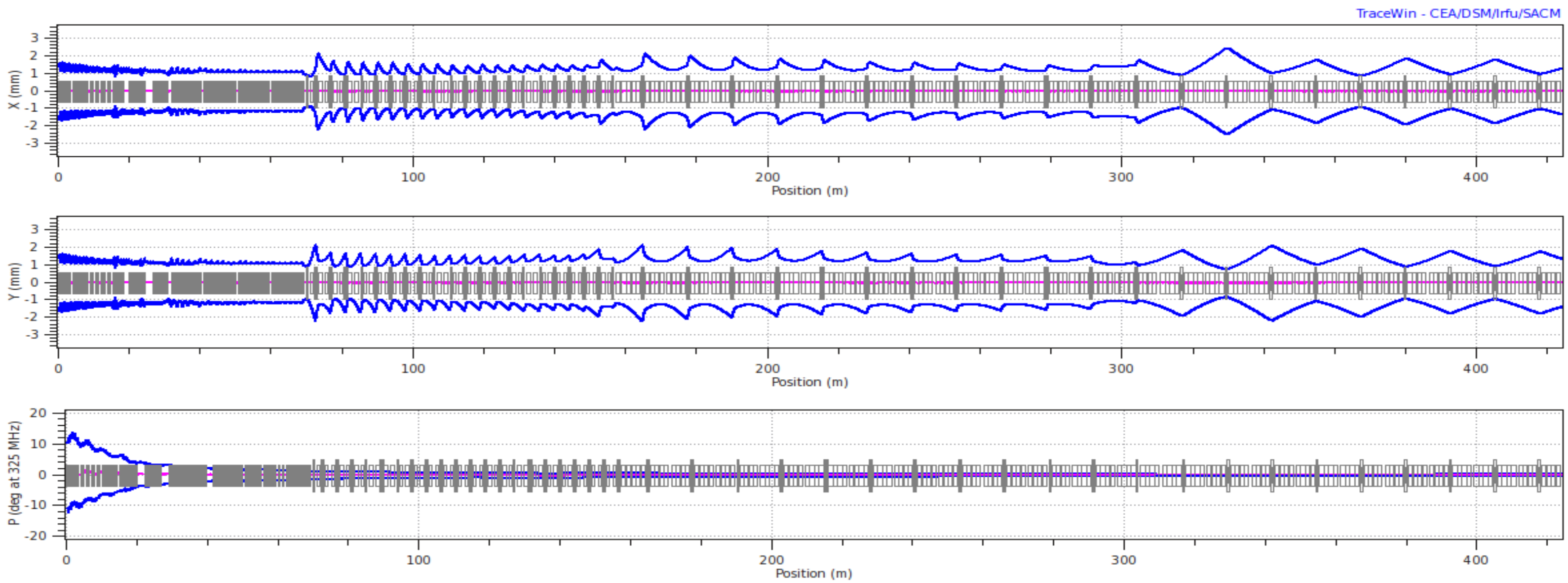
The variation in the rate of change of the phase advance is a sensitive measure of envelope regularity (WKB theory).

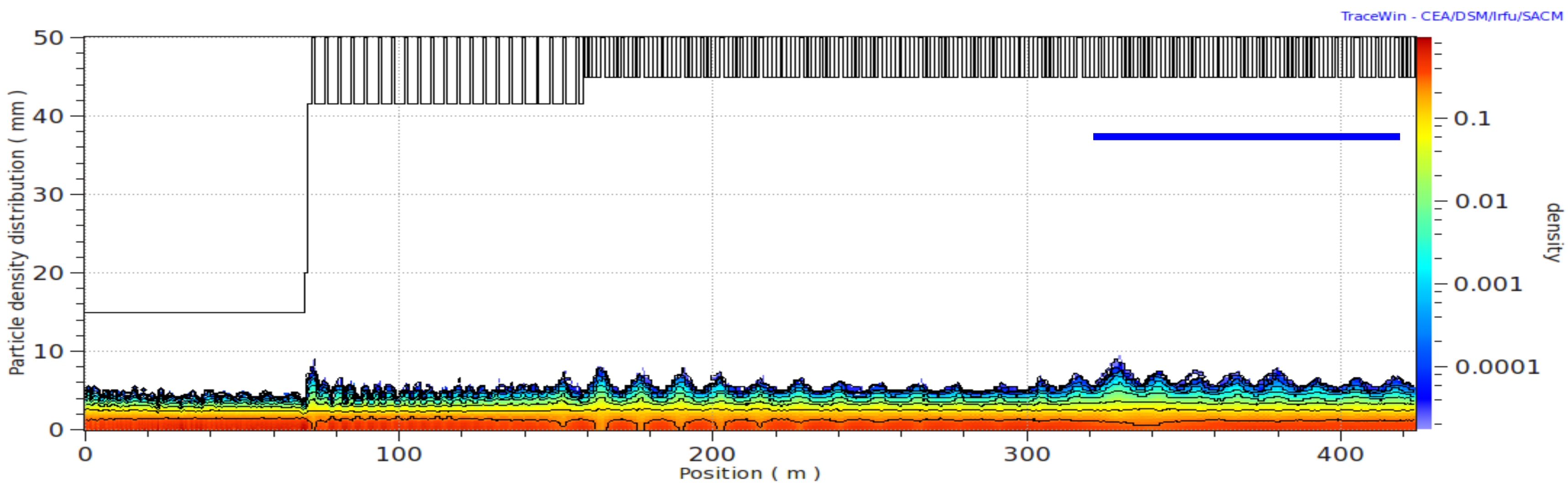
Conversely, minimizing k'',or more specifically, a discrete approximation of it results in a more regular envelope.

$$\Delta^2 k \simeq (k_{i+1} - k_i) - (k_i - k_{i-1})$$

Phase smoothing is performed after conventional matching.

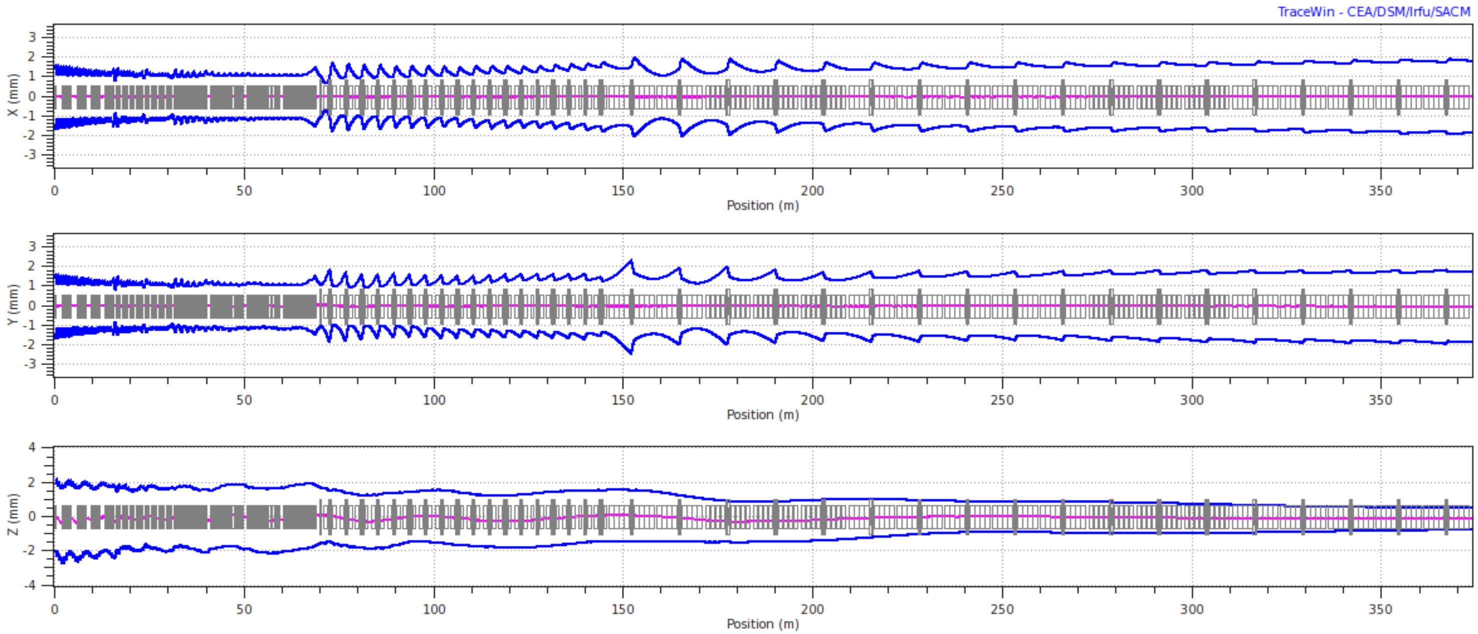
Baseline Lattice: Envelopes

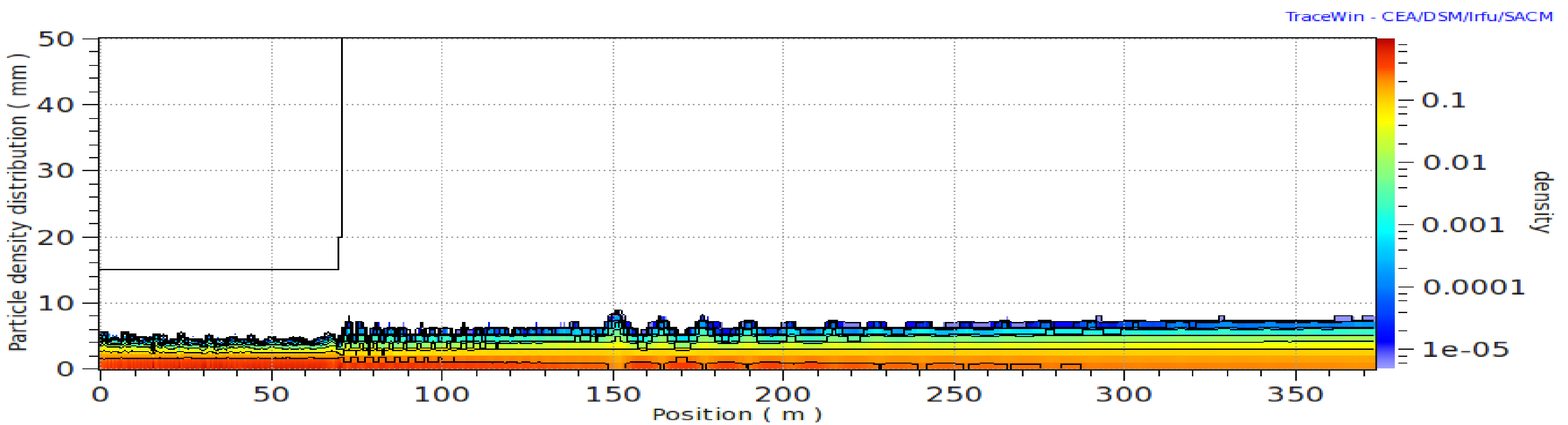




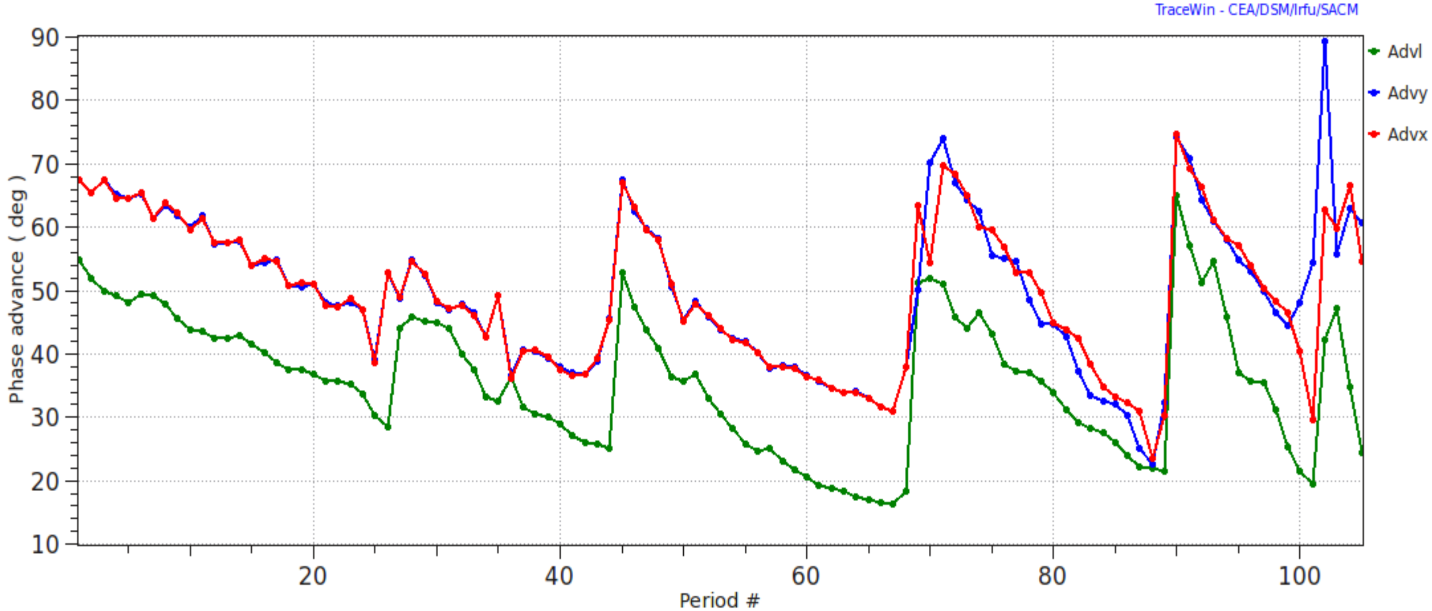
Ostiguy – TUO1B4- HB2010

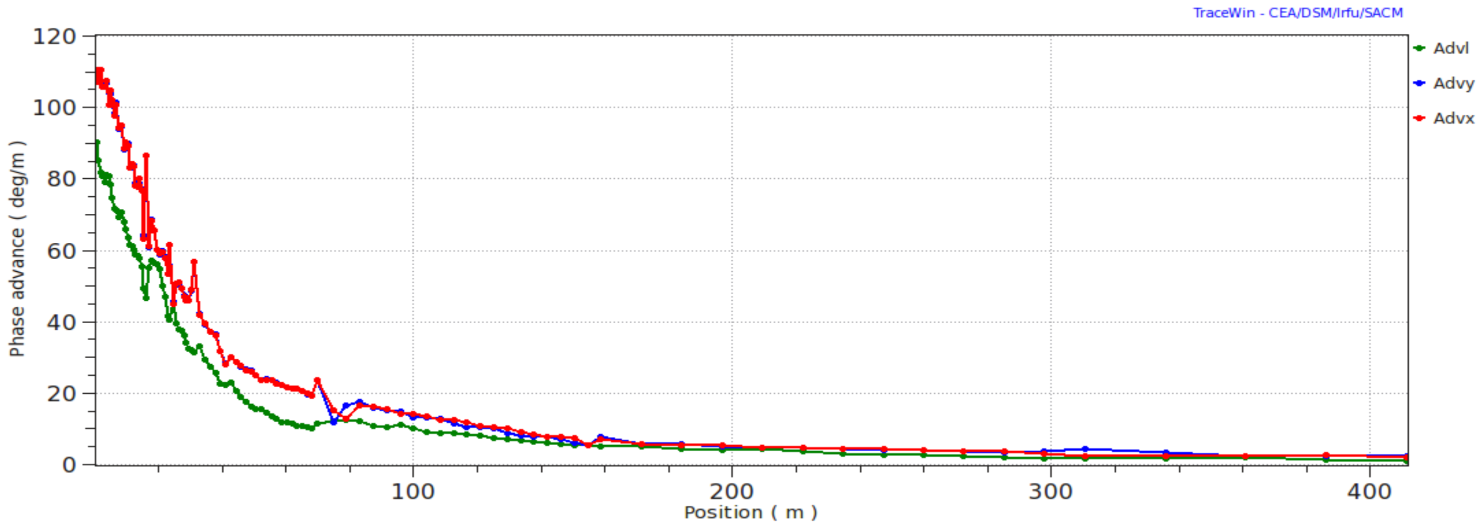
He650 lattice: envelopes



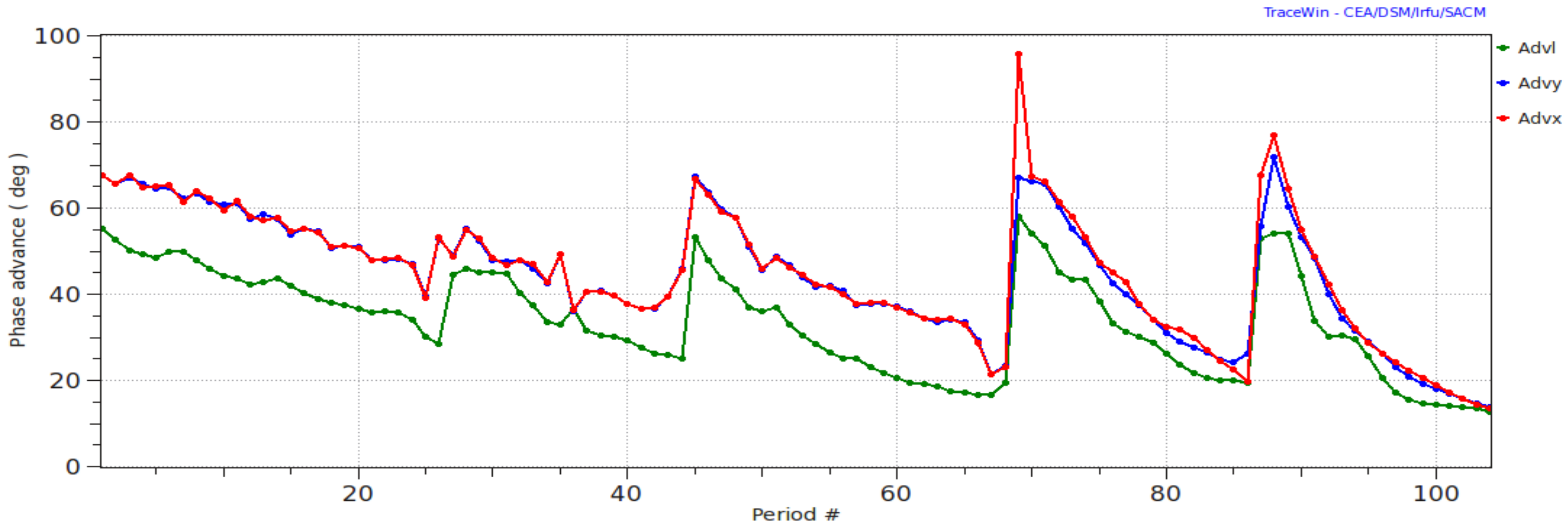


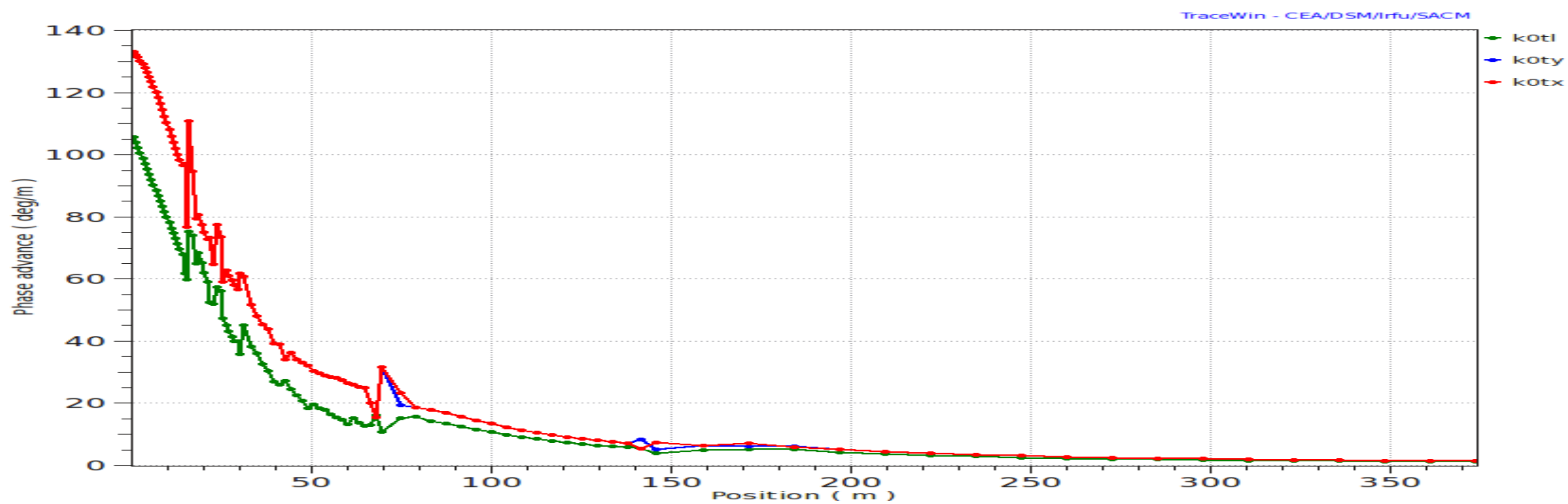
Baseline Lattice:phase advances



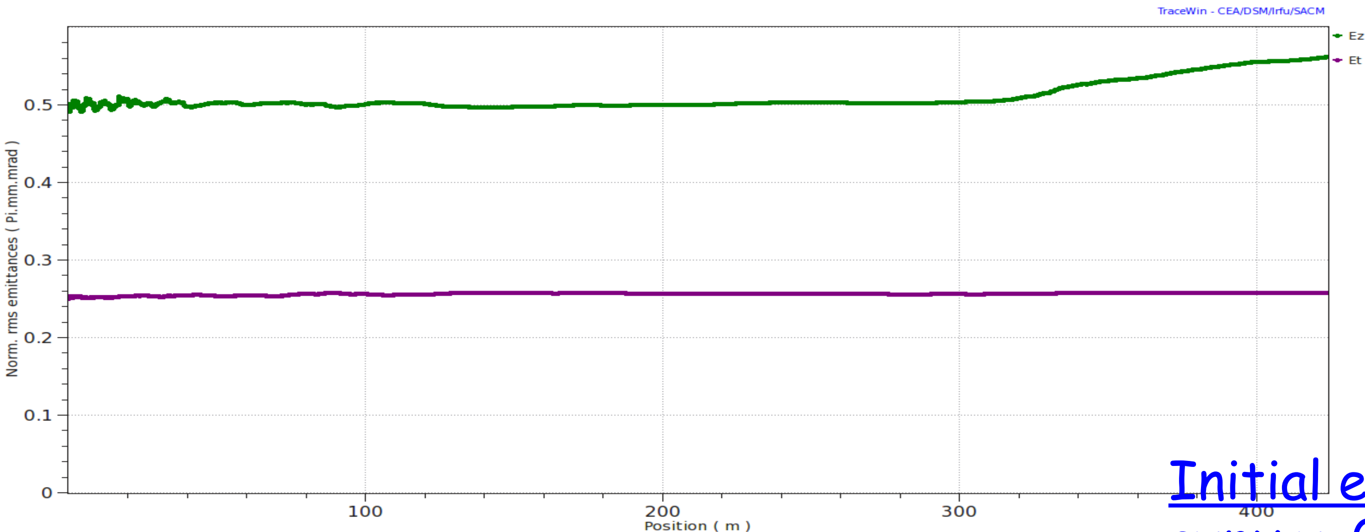


He650 lattice: phase advances



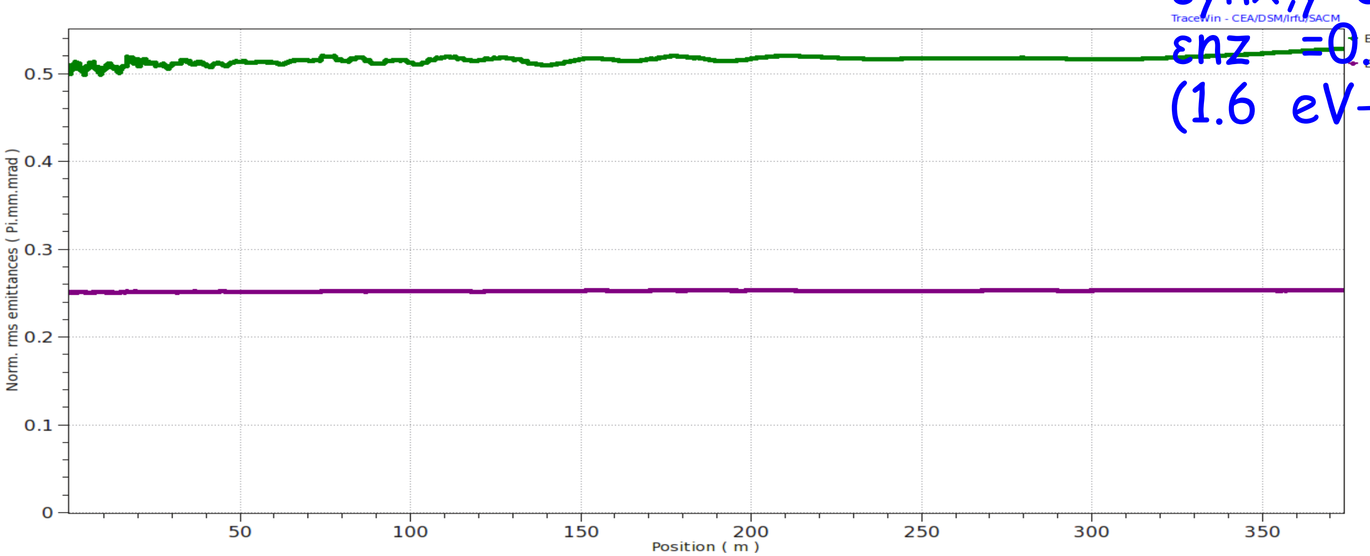


Emittances (computed from tracking)



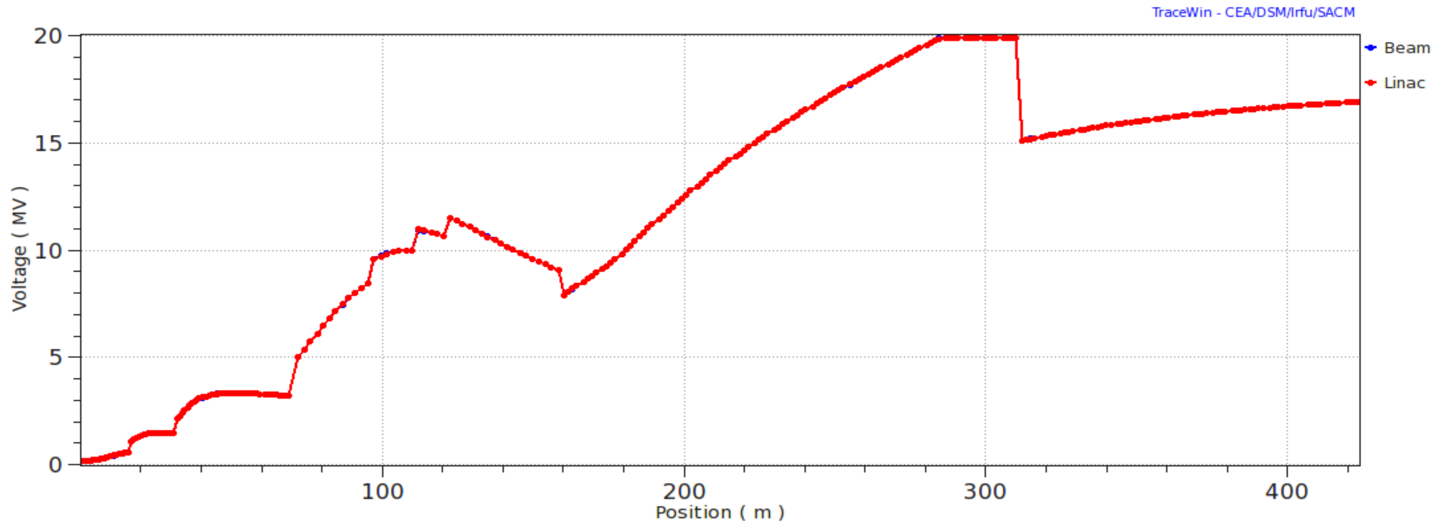
baseline

Initial emittances:
$\varepsilon_{nx,y}$=0.25 mm·mrad;
ε_{nz} =0.5 m·mrad
(1.6 eV-μsec);

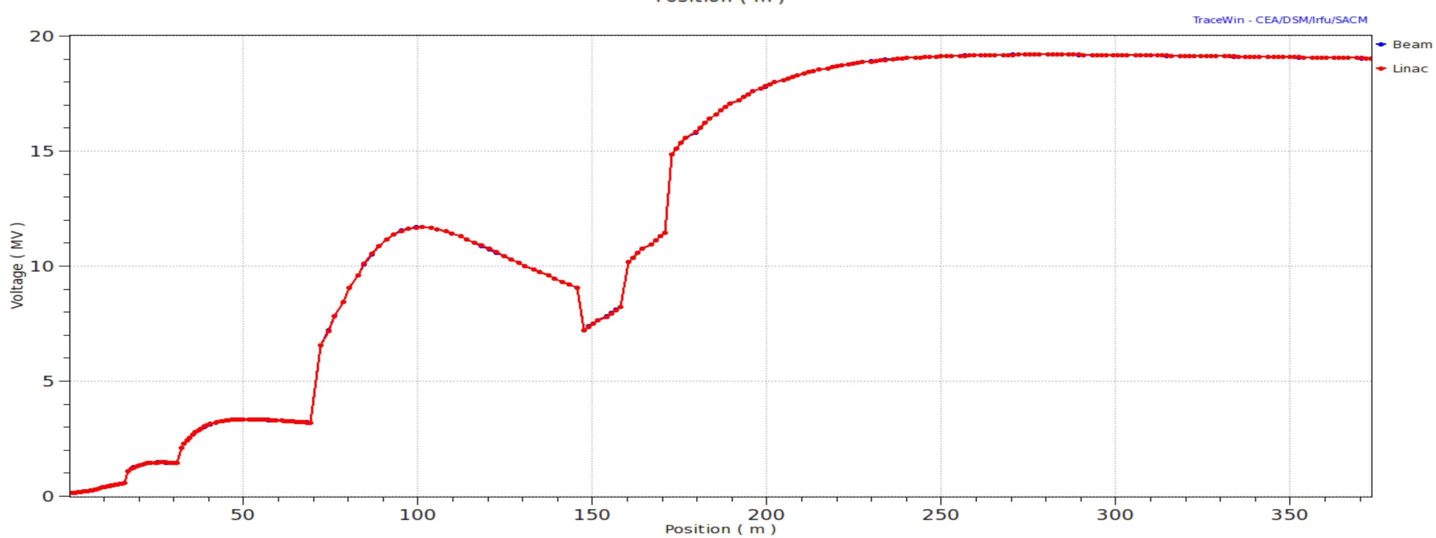


he650

Voltage/sync phase

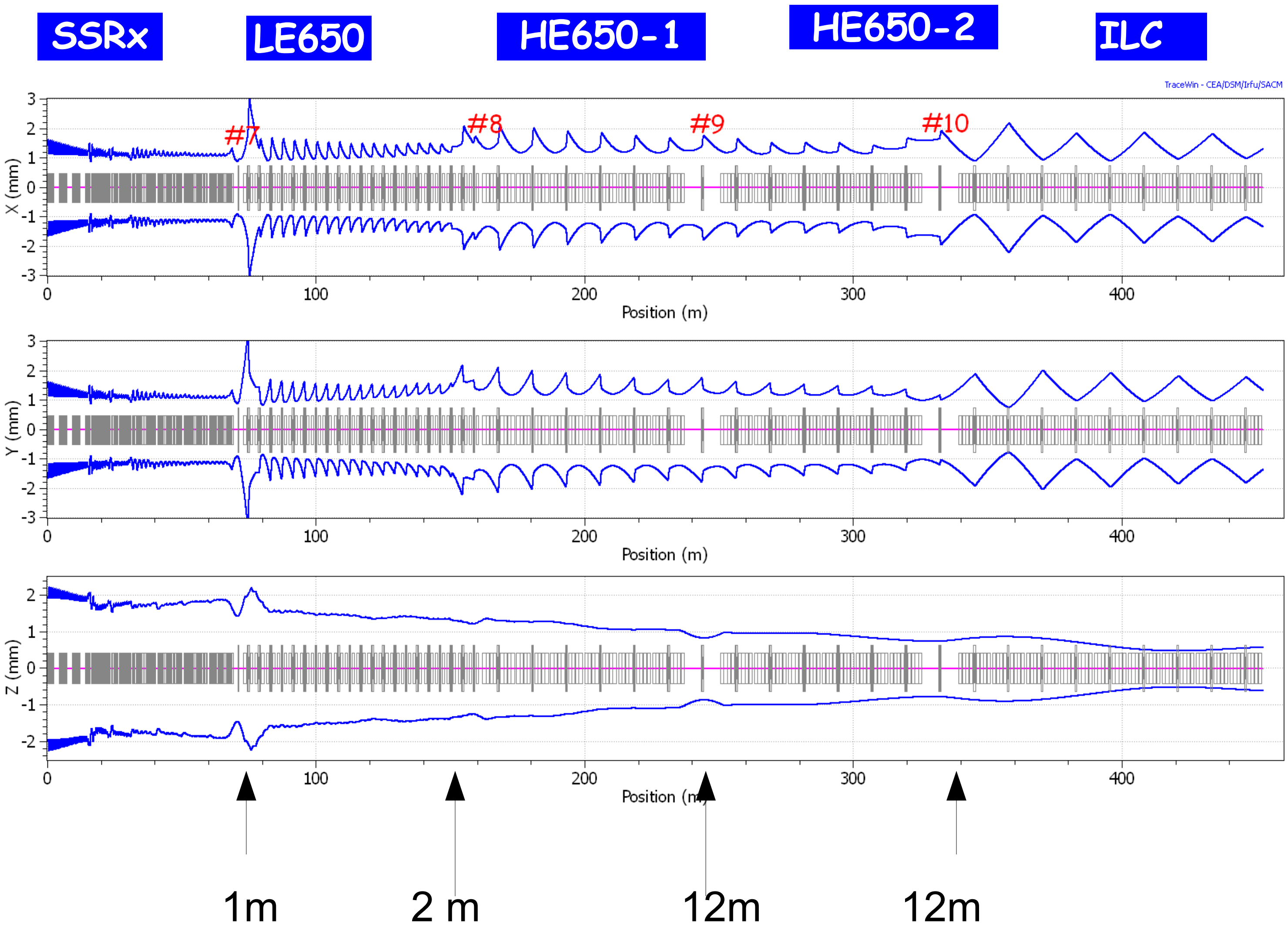


baseline



he650

Segmentation/RT Sections Study



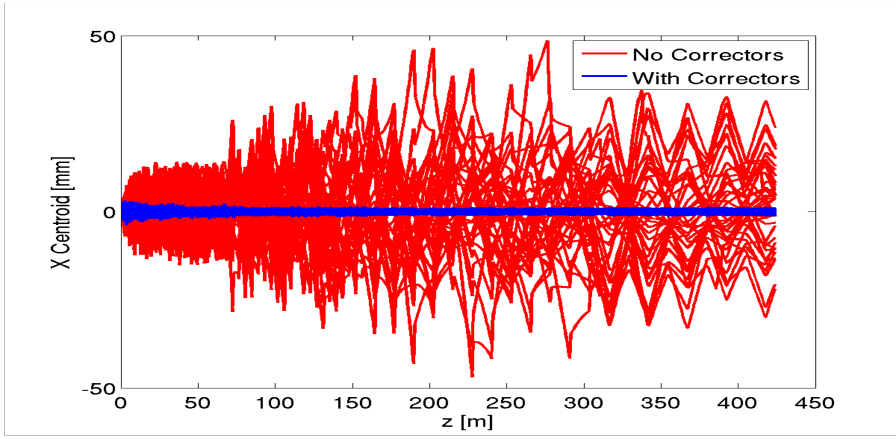
Summary of error thresholds for observable losses

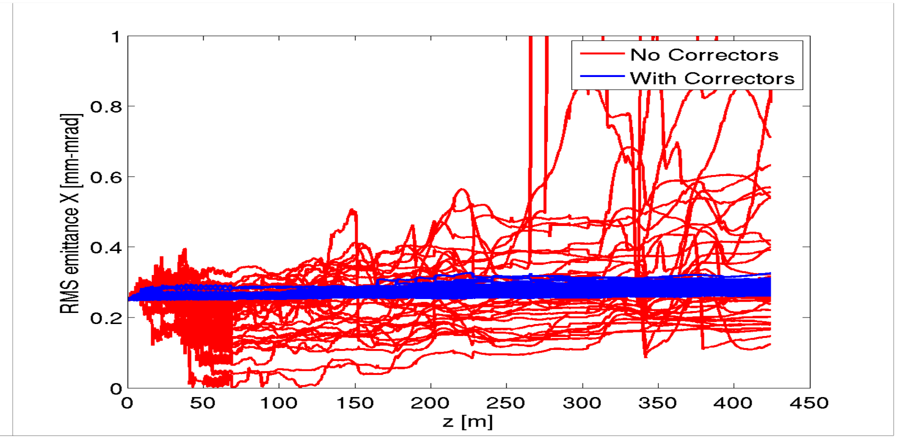
Errors Type	Limit	Lossy runs/400
Solenoid dx & dy	300 μm	3
Solenoid pitch	2 mrad	2
Quad dx & dy	300 μm	3
Quad pitch	>10 mrad	0
Cavity dx & dy	> 1 mm	0
Cavity pitch	10 mrad	6
RF phase jitter	1 deg	20
RF field jitter	1 %	3
RF phase + field	1deg + 1%	56

Study performed using TRACKv39, 50K particles/run
Using 400 Machines on the FermiGrid

Losses observed when beam is allowed to wanders ~ 10 mm off-axis.

Static Error Correction





Misalignments ±1 mm for all elements (specification ±0.5 mm)
RF jitter of 0.5 ° x 0.5 % in the front-end & 1 ° x 1% RF jitter in the high-energy part

100 seeds and 1 million macro-particles per seed.
1 corrector+ 1 BPM per solenoid/doublet/quad; BPM resolution=30 μm
Beam centroid is corrected to ±1mm;

Emittance increase < 20%.
Without orbit correction: losses above 100 W/m
With corrections: no losses

H- Stripping Summary

Losses due to residual gas is < 0.1 W/m if pressure is better than 10e-8 Torr at 300 °K (50% H_2, 25% O_2, 25% N_2)

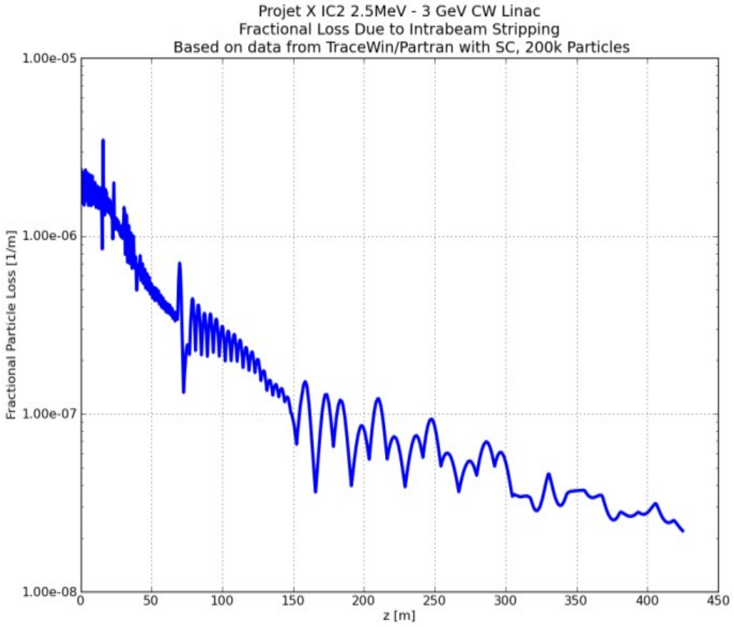
Magnetic stripping is well below 0.1 W/m even for unrealistic 5 mm beam offset.

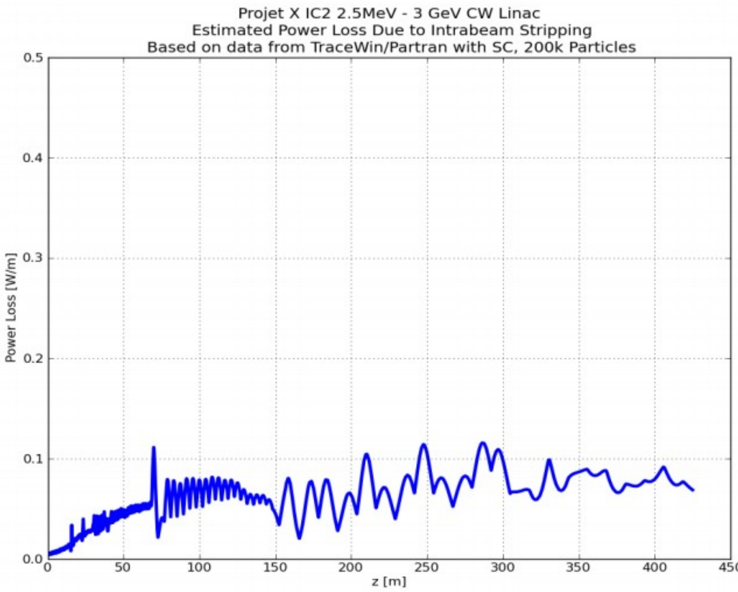
Stripping due to blackbody radiation is not an issue for the SC linac.

Intra-beam stripping is <0.1 W/m for baseline design
a little bit lower for alternative designs

IntraBeam Stripping Losses

650 MHz + 1.3 GHz (2-3 GeV)





0.1 W/m

Average power loss assumes 1 mA average beam current

Project X

Conclusions

* The CW linac concept now provides the needed flexibility to support multiple experiments with different beam requirements.

* Lattice design is maturing. Energy breakpoints are set. Design and/or prototypes exist for most components.

*Final decision about using 1.3GHz or not in CW linac is still pending.

*Much work remains to be done to finalize and optimize cry-segmentation, understand impact of various failure modes, impact of possible cavity gradient variability etc ...

*Need to finalize instrumentation & diagnostic needs and possibly optimize the optics to accommodate them.

*Need to finalize strategy to correct static errors.

* Comprehensive large scale errors studies are needed.