Update on HOM studies for PIP II SC Linac

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Fermilab, TD SRF T&D

PIP-II Project

- Mission: deliver intense beam of neutrinos to the international LBNF/ DUNE project

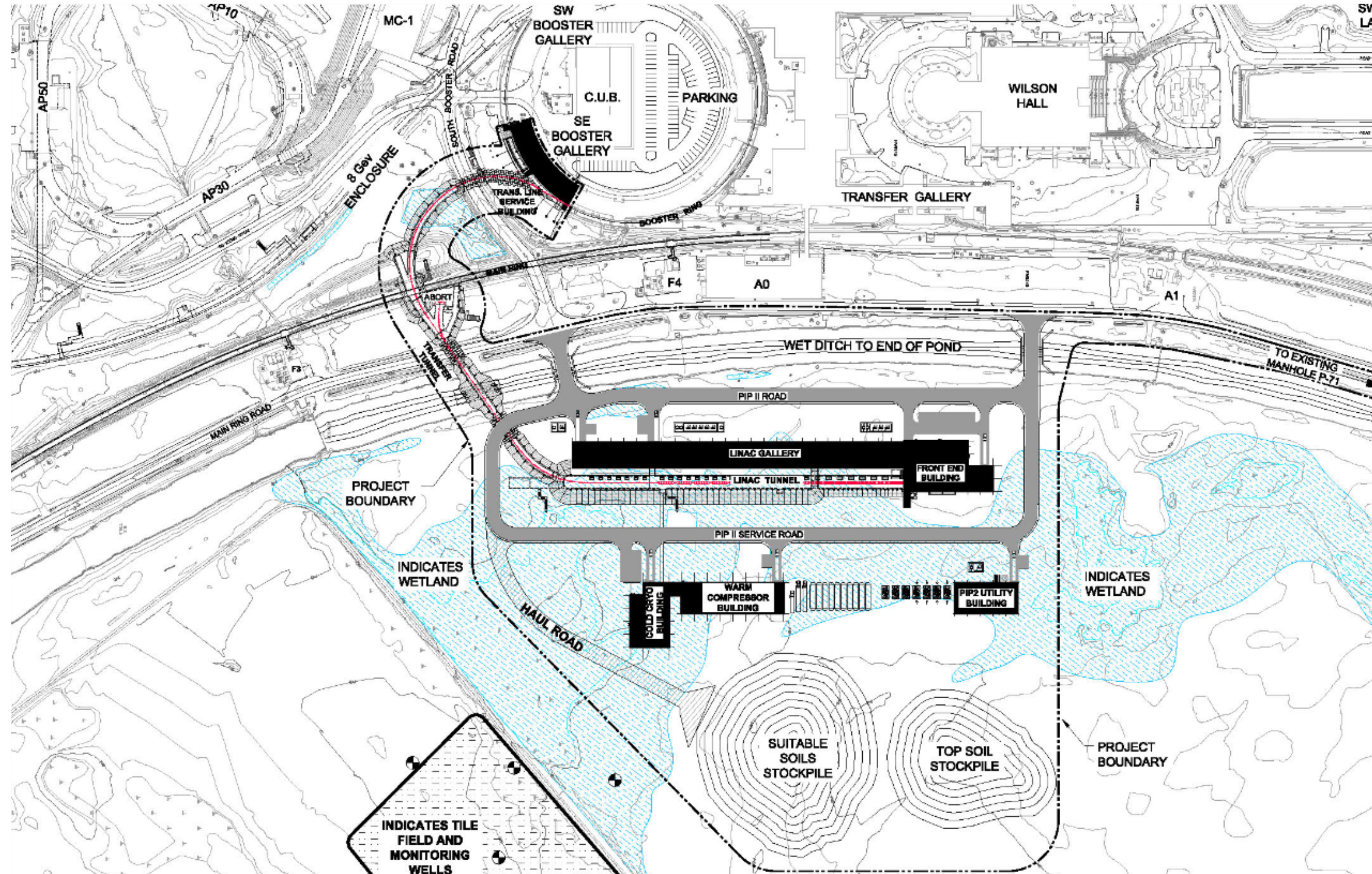
- Goals:

  - Deliver >1 MW proton beam power from the Fermilab Main Injector over the energy range 60 — 120 GeV, at the start of LBNF operation
  - Support ongoing 8 GeV program at Fermilab, including upgrade path for Mu2e
  - Possibility of extension of beam power to LBNF >2 MW
  - Possibility of extension to high duty factor/higher beam power

PIP-II Project

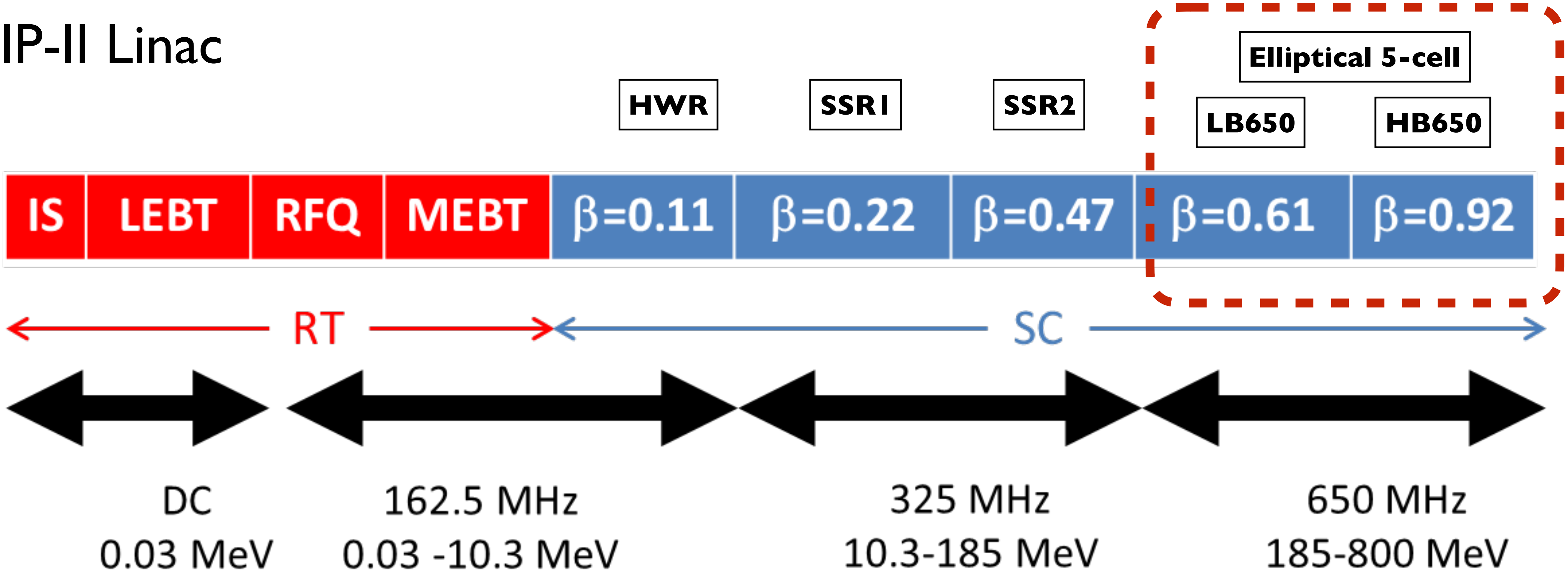
- PIP-II Linac

Parameter	
Particle species	H-
Input beam energy	2.1 MeV
Output beam energy	800 MeV
Bunch repetition rate	162.5 MHz
RF pulse length	pulsed-to-CW
Sequence of bunches	Programmable
Average beam current	2 mA
Final rms norm trans. emittance	<= 0.3 mm-mrad
Final rms norm long. emittance	<= 0.35 mm-mrad
RMS bunch length	< 4 ps



PIP-II Project

- PIP-II Linac



Cavity	Aperture, mm	Eff. length, cm	Eacc, MV/m	Epeak, MV/m	Bpeak, mT	(R/Q), Ohm	G, Ohm
LB650	88	70.3	16.9	40.3	74.6	341	193
HB650	118	106.1	18.8	38.9	73.1	610	260

CM	#cav/CM	#CM	CM config	CM length, m	Q0 x1e10, @2K	Rs, nOhm	QL, x1e6
LB650	3	11	ccc	4.32	2.15	9.0	10.36
HB650	6	4	cccccc	9.92	3	8.7	9.92

HOM in PIP II (a.k.a. Project X)

- Presented at HOMSC 2012, published in Proceedings

Higher Order Modes in the Project-X Linac

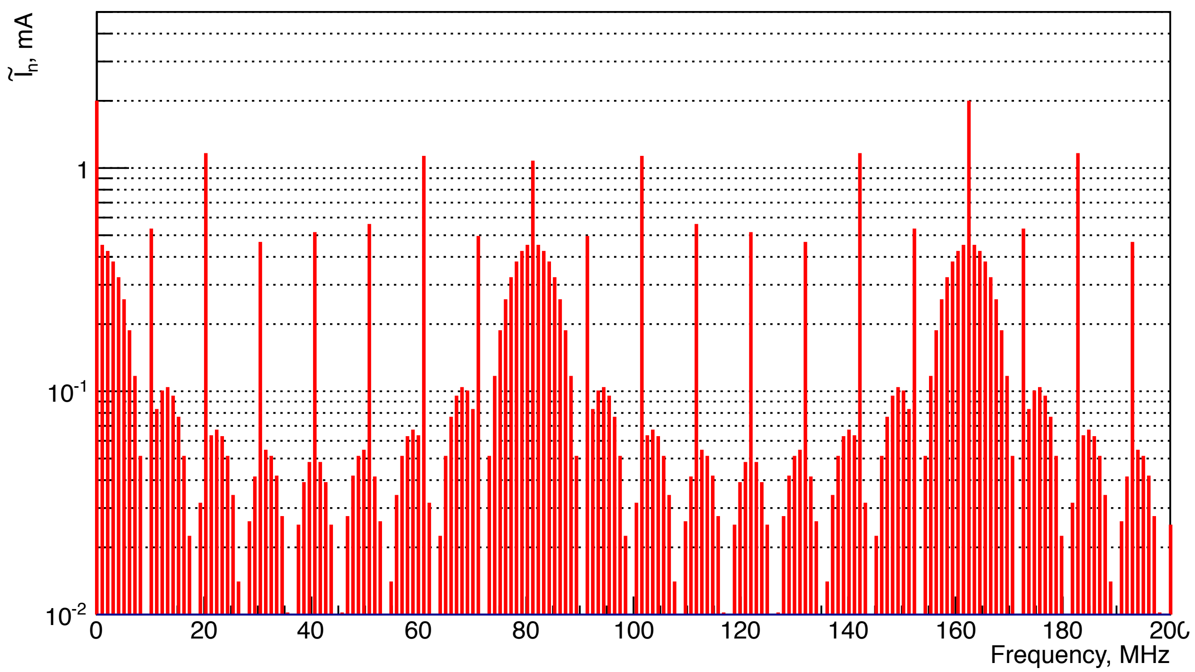
V. Yakovlev, Fermilab

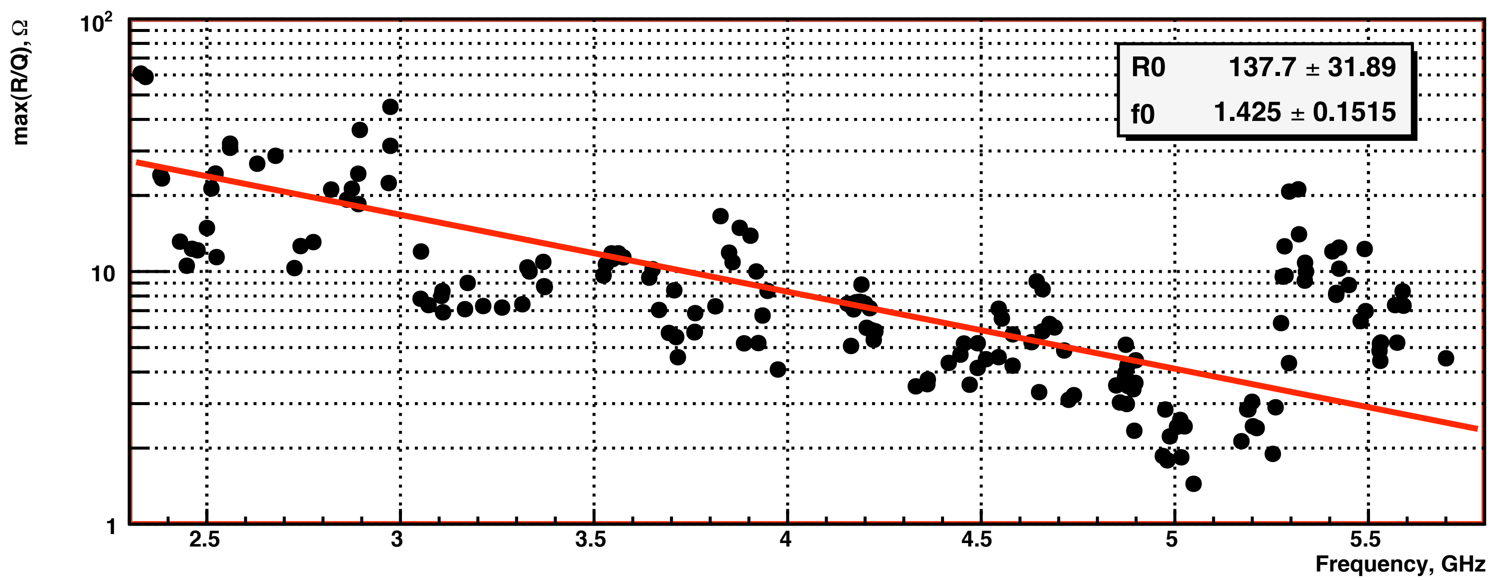
Project X

Fermilab | U.S. DEPARTMENT OF ENERGY

HOM in PIP II

- Complex beam current spectrum
- No HOM couplers and dumpers (QL up to 1e7)





- Investigation of HOM various effects in PIP II reported at HOMSC 12:
  - found no big issues

- Here we consider HOM effects in PIP II
  - new modes of linac operation (long trains of 162.5 MHz bunches, 10 mA)
    - important for accelerator-driven sub-critical system demonstration
  - modifications to LB650 cavity design
    - optimization of EM and mechanical parameters, production process

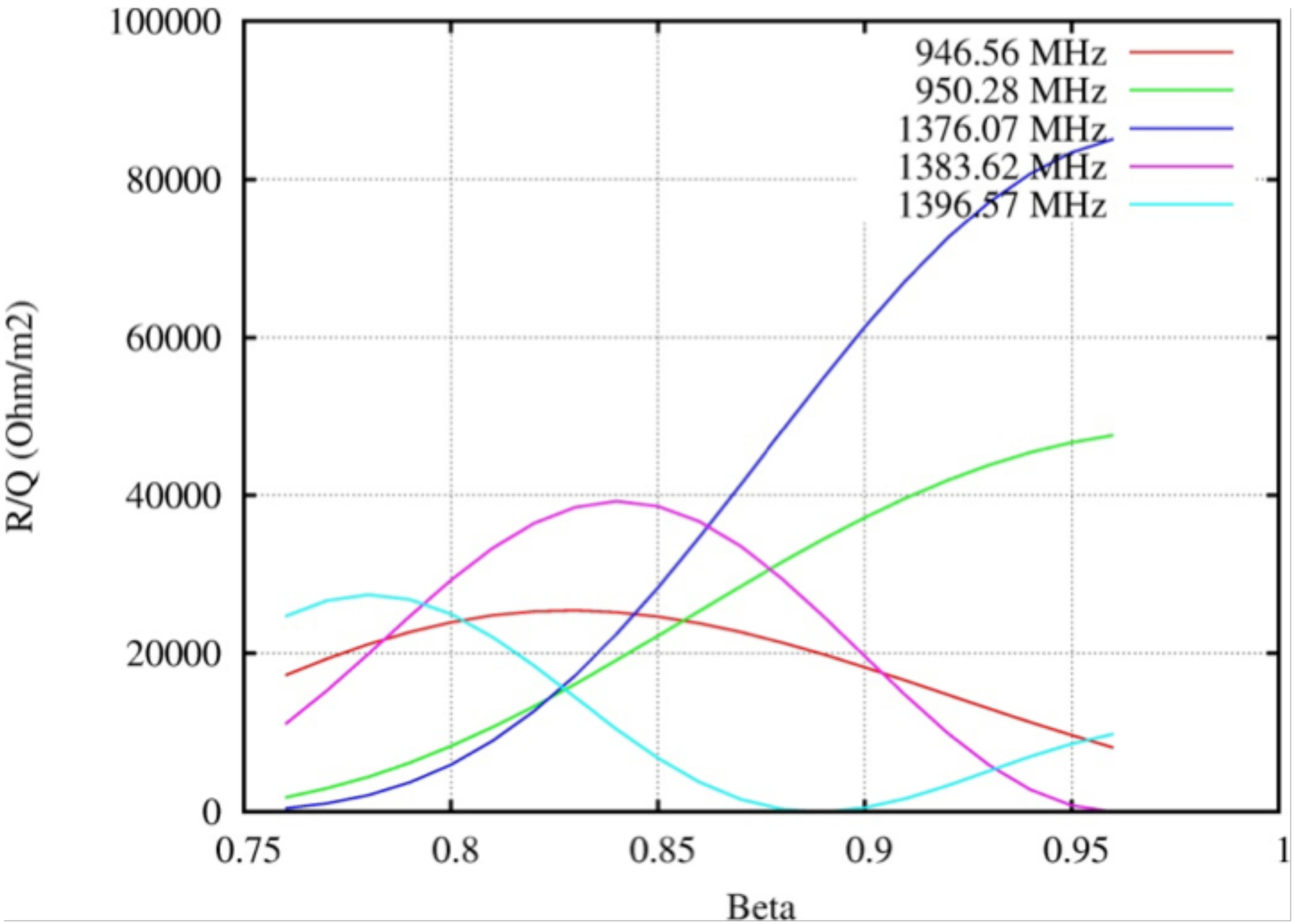
Beam Dynamics in PIP2 Linac with 10 mA

Motivation

- Transverse misalignment of SRF cavities and beam offset lead to excitation of dipole HOMs
  - depends on bunch charge, mode (R/Q), Qext
  - excited dipole HOMs introduce additional kick on beam particles
  - increase of transverse beam emittance
  - small effect in a steady state (CW beam, no variations in beam current and/or bunch timing pattern)
- Study transverse emittance variations due to transitions (beam turn on) and bunch charge variations in HB650 section of PIP2 linac
  - (R/Q) of dipole modes in LB650 are much smaller compared to HB650

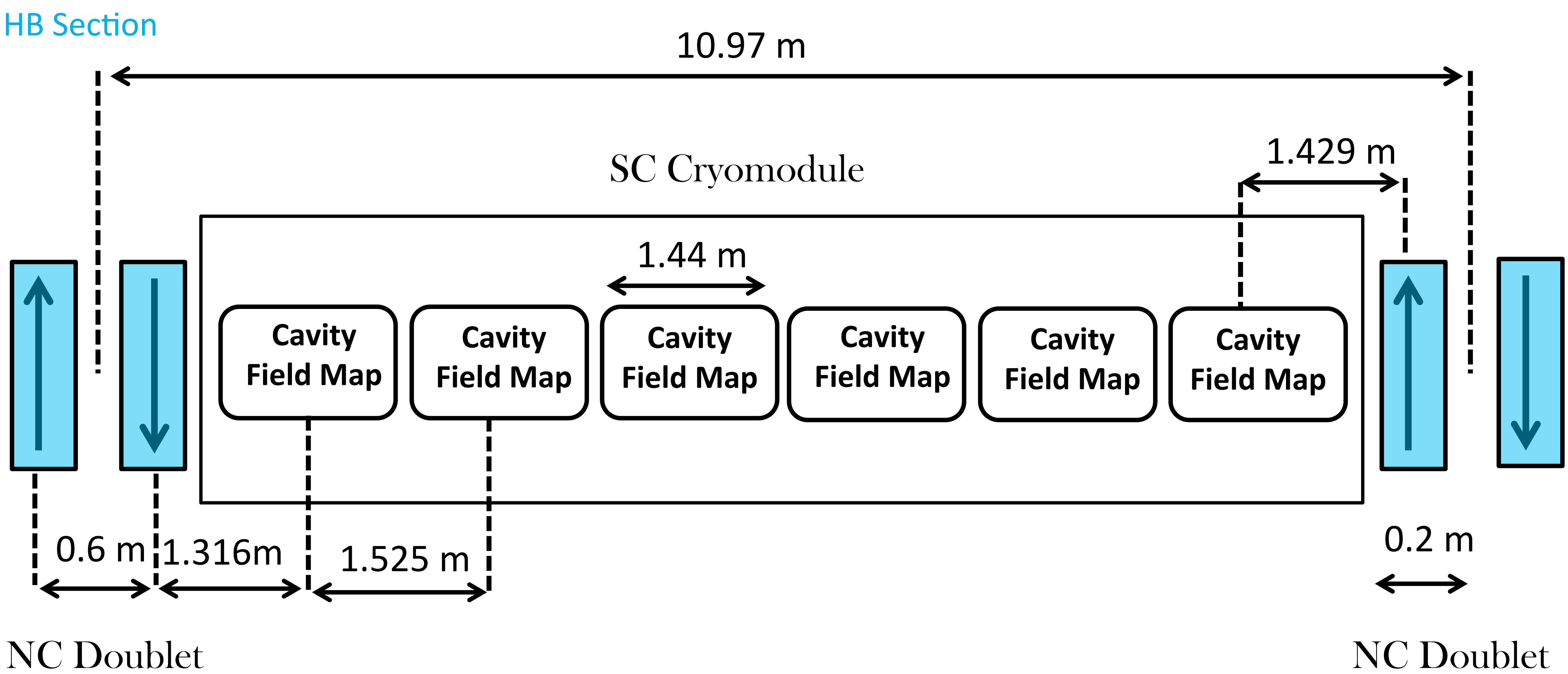
Dipole modes in HB650

- (R/Q) depends on beam velocity
- Mode 1376 MHz: (R/Q)=80kOhm/m2, Qext=1e7



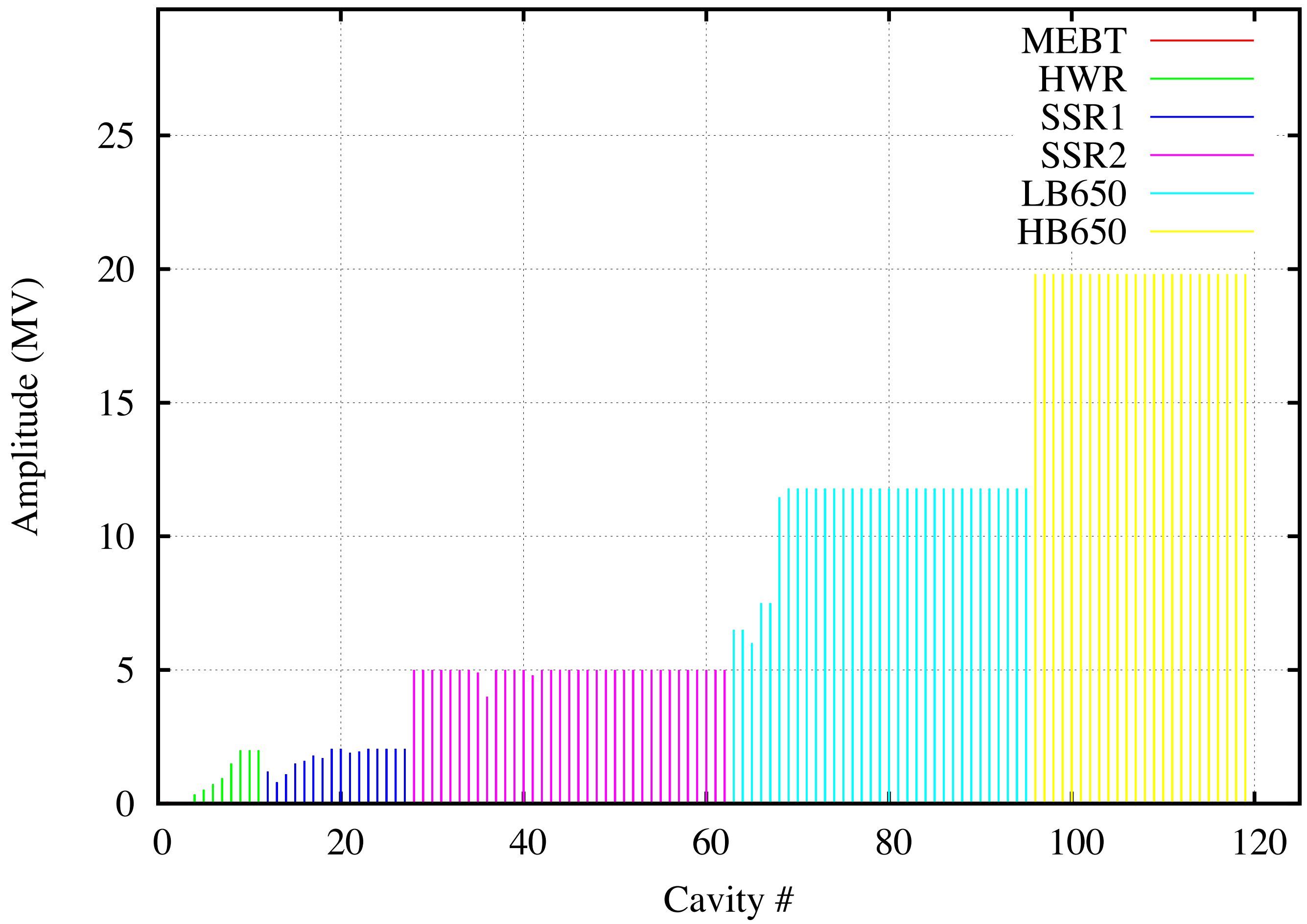
Linac layout

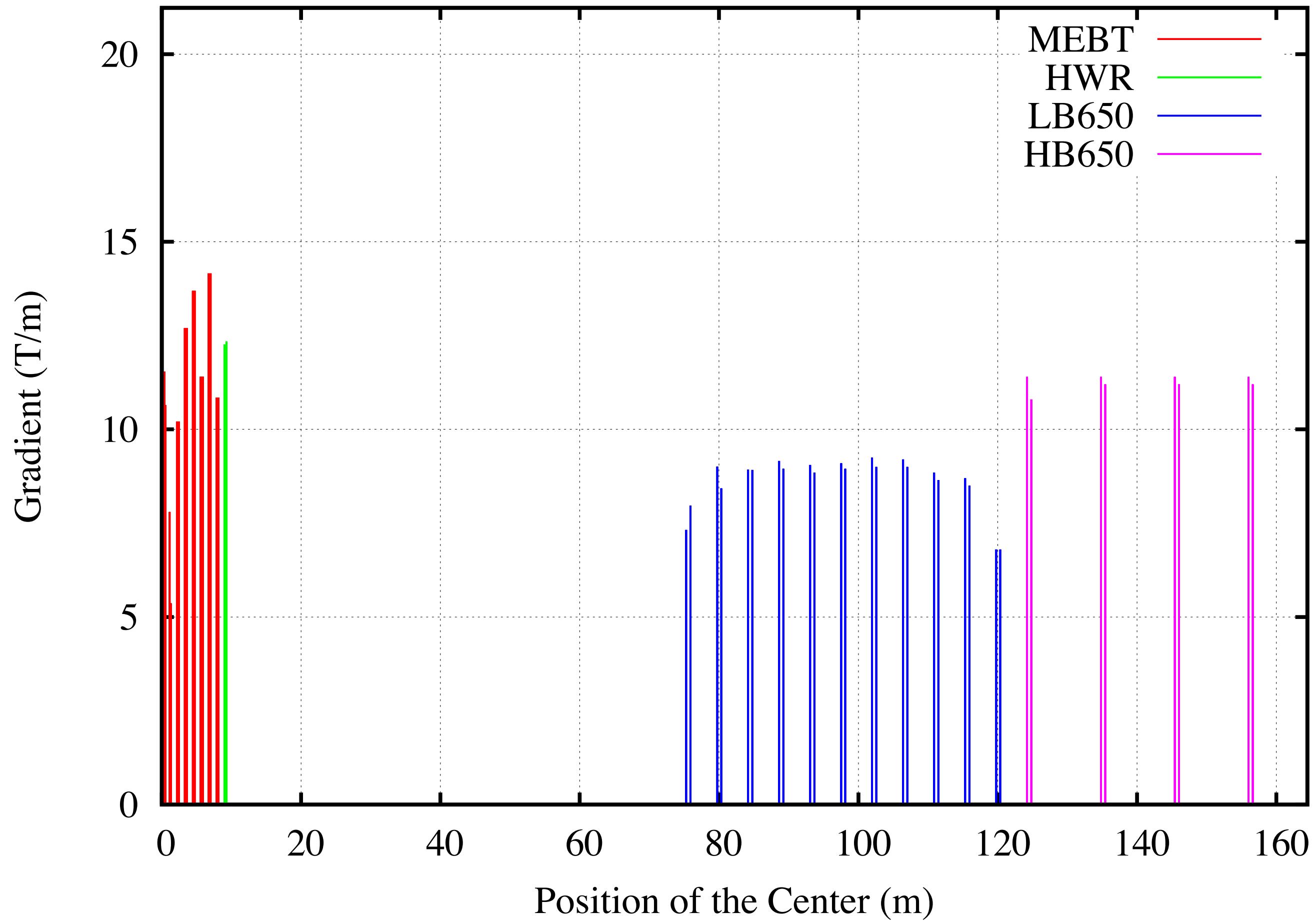
- HB650 beta=0.92 section: 4 cryo-modules, 24 cavities (6 cavities per CM)
- Matrix tracking through linac elements



Cavity Gradient and Quadrupole Fields

- HB650 Vacc(beta_G) = 20 MV
- HB650 Quad gradient 12 T/m



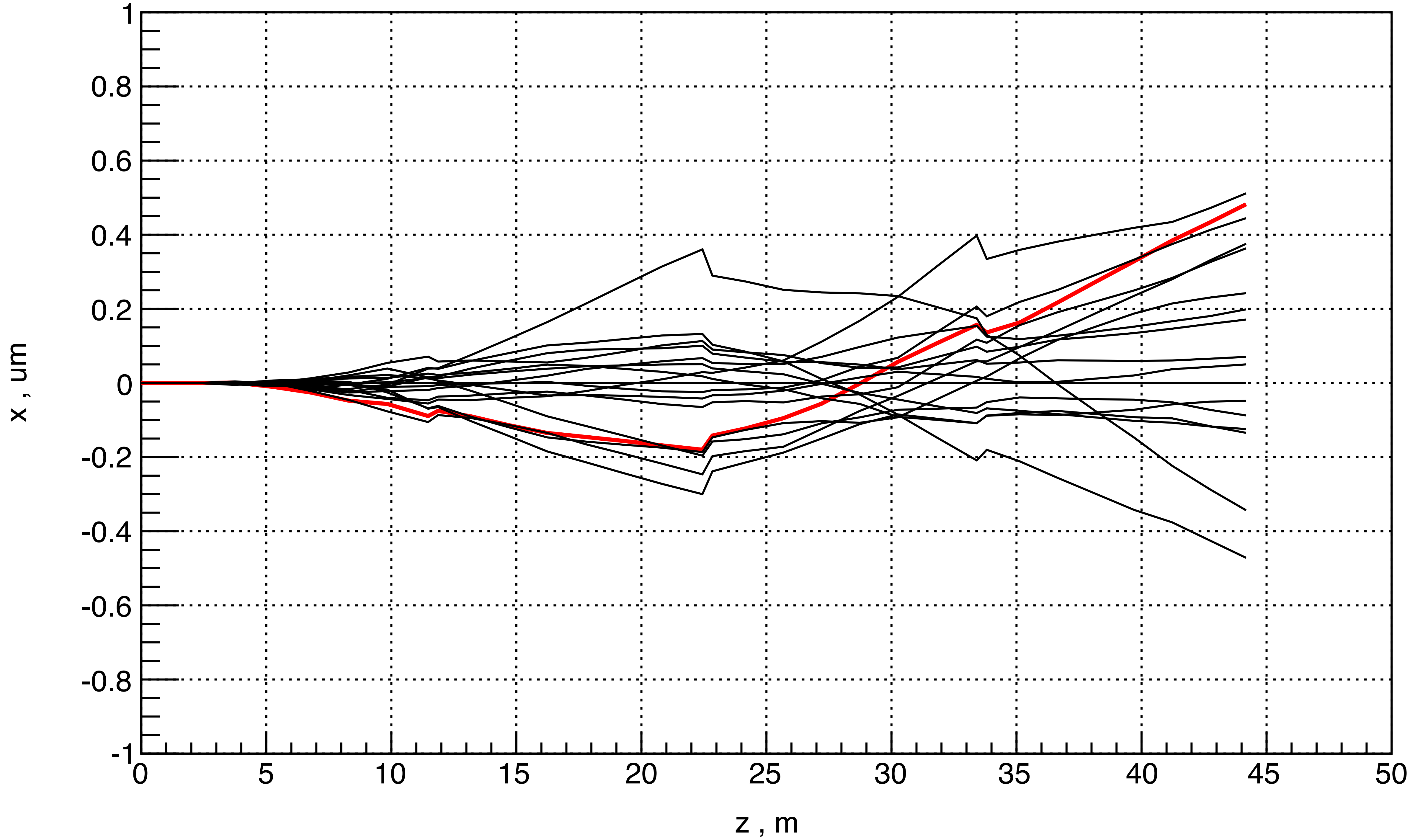


Model

- 60 pC bunches with 10% variation, 162.5 MHz bunch frequency
  - train of 5e6 bunches
- Transverse misalignment of cavities R.M.S. = 0.5 mm
- Matrix tracking through linac
- Consider one dipole mode with highest (R/Q)
- Each bunch introduces voltage V[i] = jcq(R/Q)x
  - bunch sees half of this kick voltage
- Total kick seen by bunch is sum of voltages from all previous bunches with proper time dependent factors: ~exp(jwTb)*exp(-wTb/2Q)
- Simulate 100 linac configurations (time consuming)
  - random variations of transverse displacement of cavities and HOM frequency with 1 MHz RMS
- Calculate effective RMS emittance at the end of linac from variations of (x,x') of bunches
  - compare to nominal emittance 0.3 mm*mrad (relative emittance)

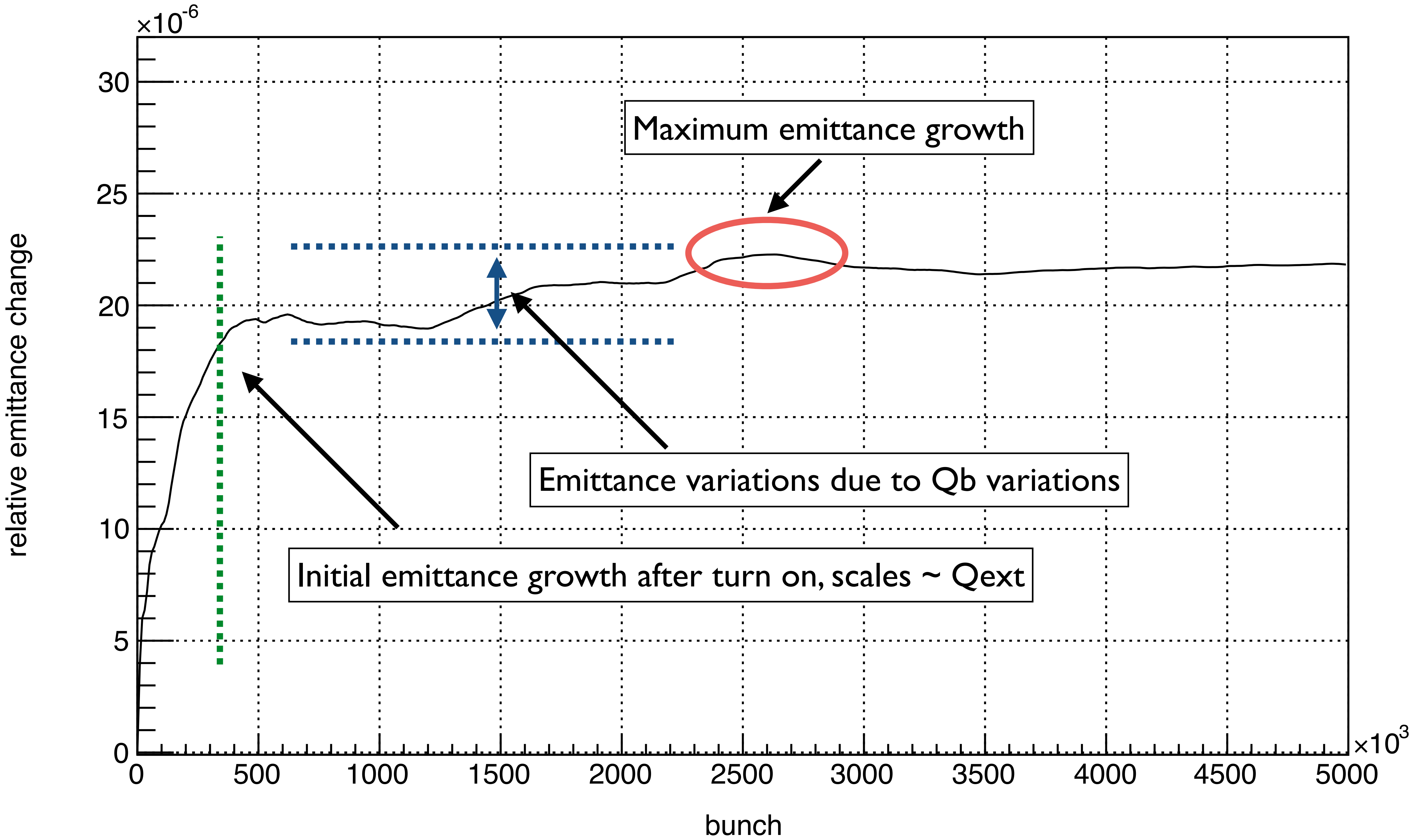
Tracking in linac

- bunch trajectories in linac



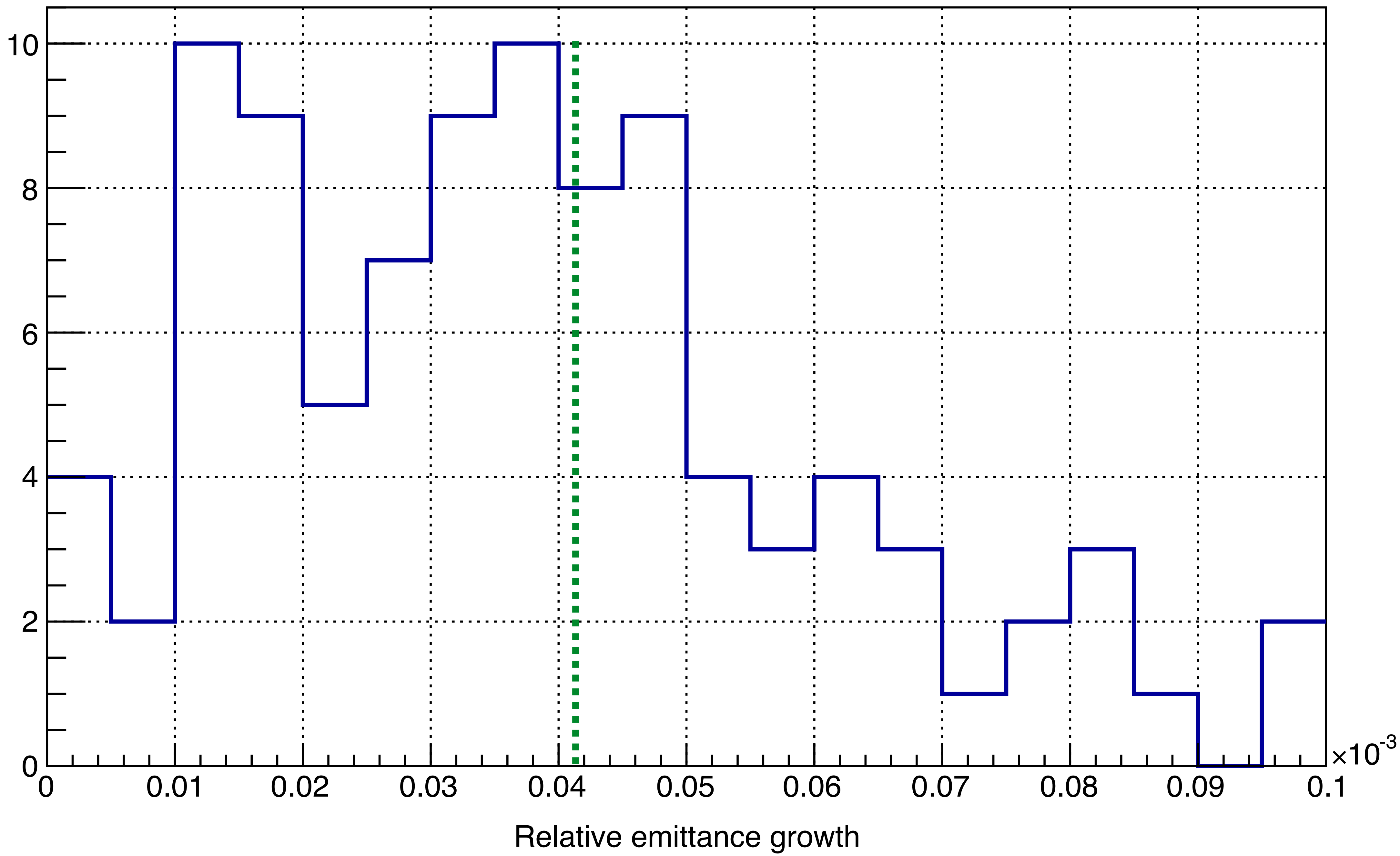
Effective emittance

- Effective emittance at the end of linac for single linac configuration as a function of bunch number



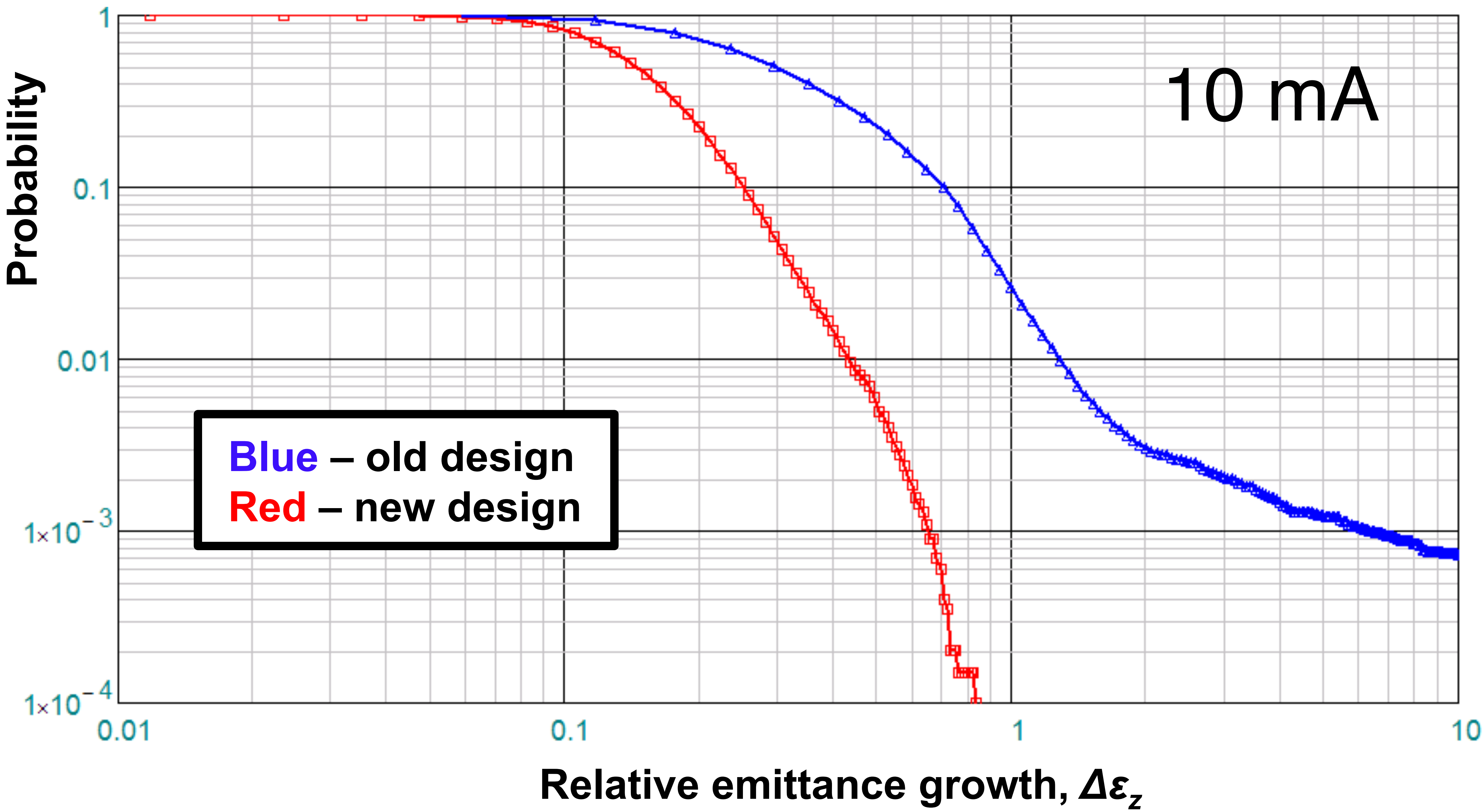
Maximum emittance growth

- 100 configurations of linac with random cavity misalignment of 0.5 mm
  - Median value of relative emittance growth is 4e-5



Longitudinal emittance

- 10 mA (presented in LINAC'12, TUPB054)



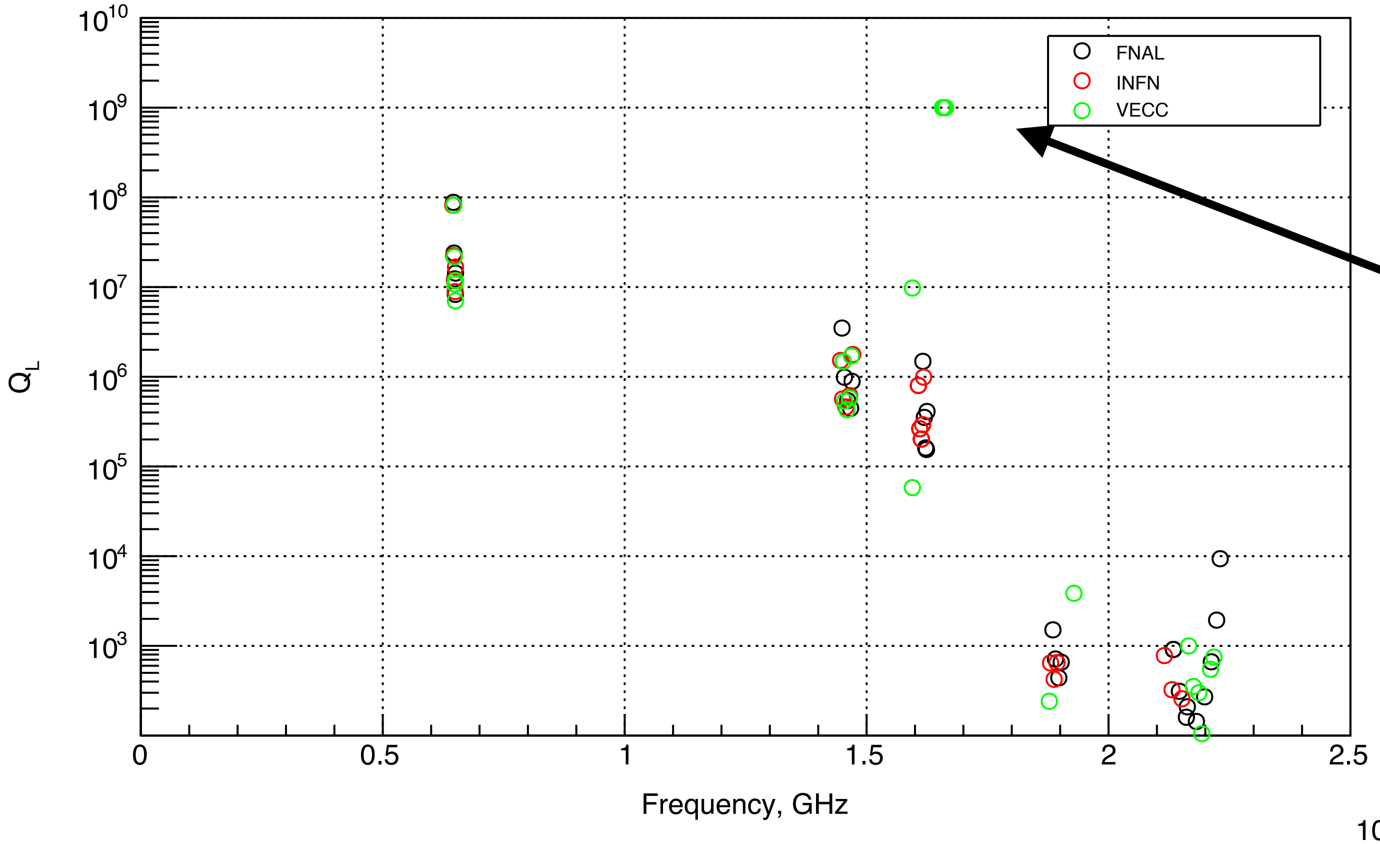
New Design of LB 650 MHz 5-cell Cavities

New Designs of LB650 5-cell Cavities

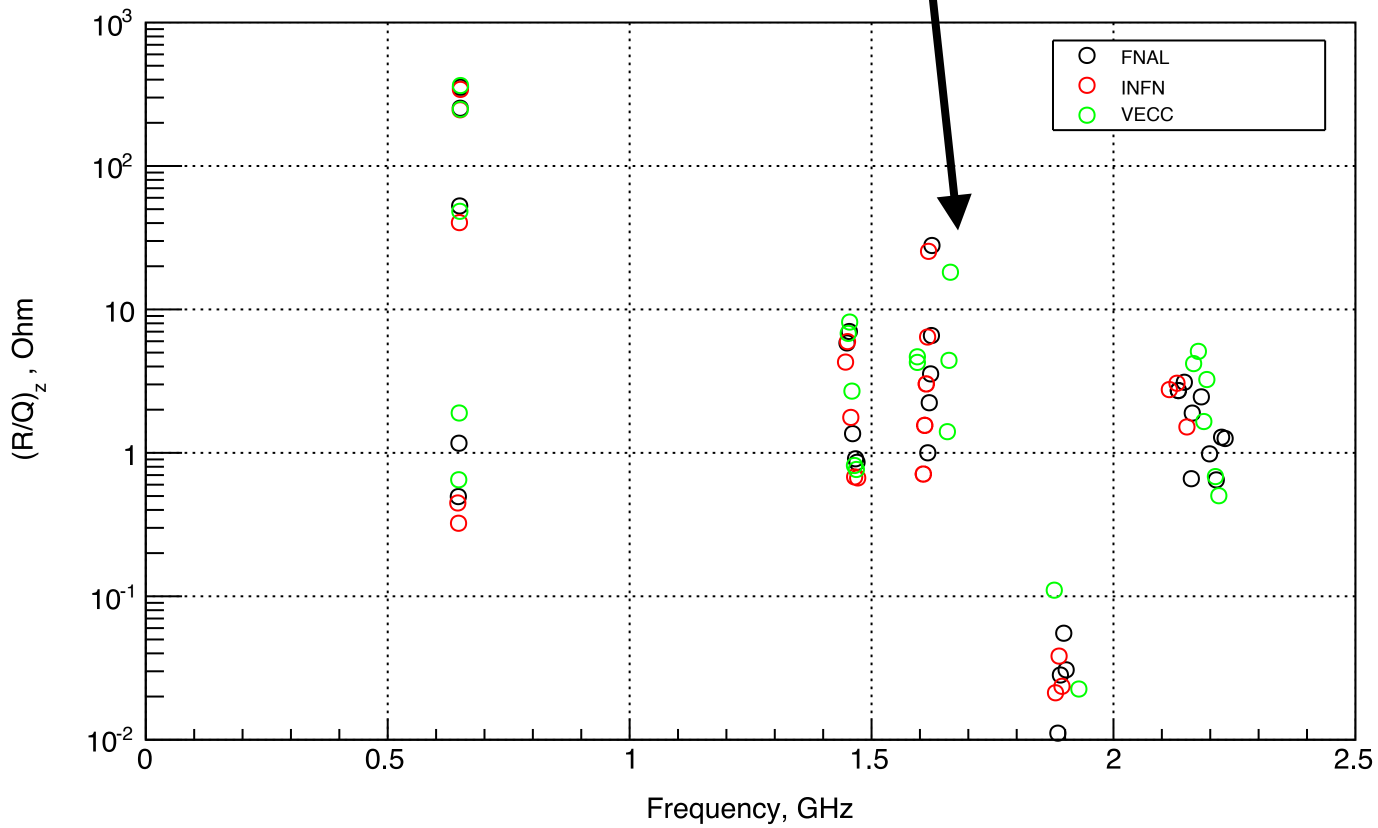
- New designs of LB650 5-cell cavities have been developed at FNAL, INFN and VECC
  - Optimization of EM and mechanical properties, production process
- 3-D RF simulation of cavities of each design (A. Lunin)
  - calculate frequency spectra, QL, (R/Q) of monopole, dipole and quadrupole modes

Monopole modes

- QL and (R/Q)

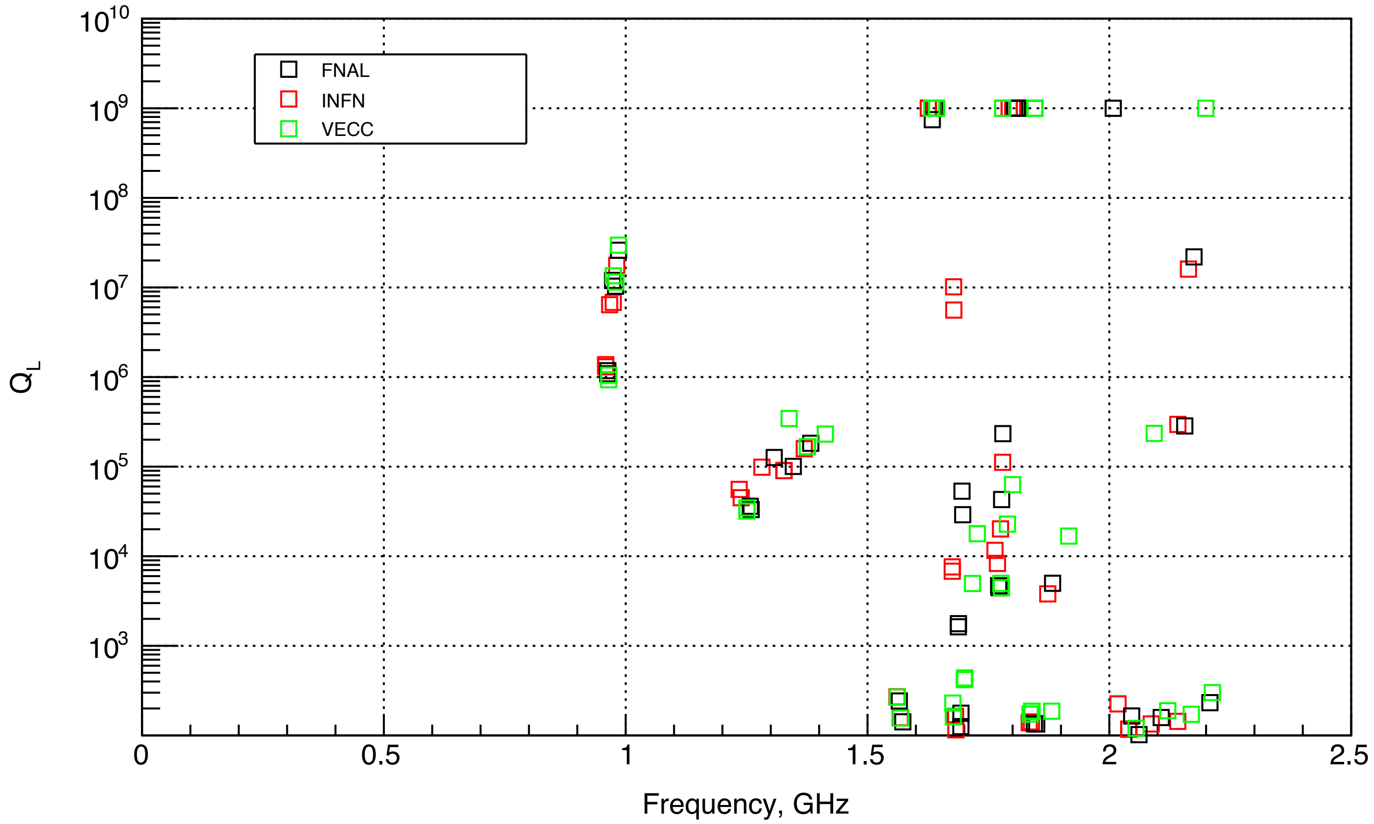


Dangerous trapped mode in VECC design: f=1.663 GHz, (R/Q)=18 Ohm
This mode is relatively far from main beam current harmonics of 162.5 MHz

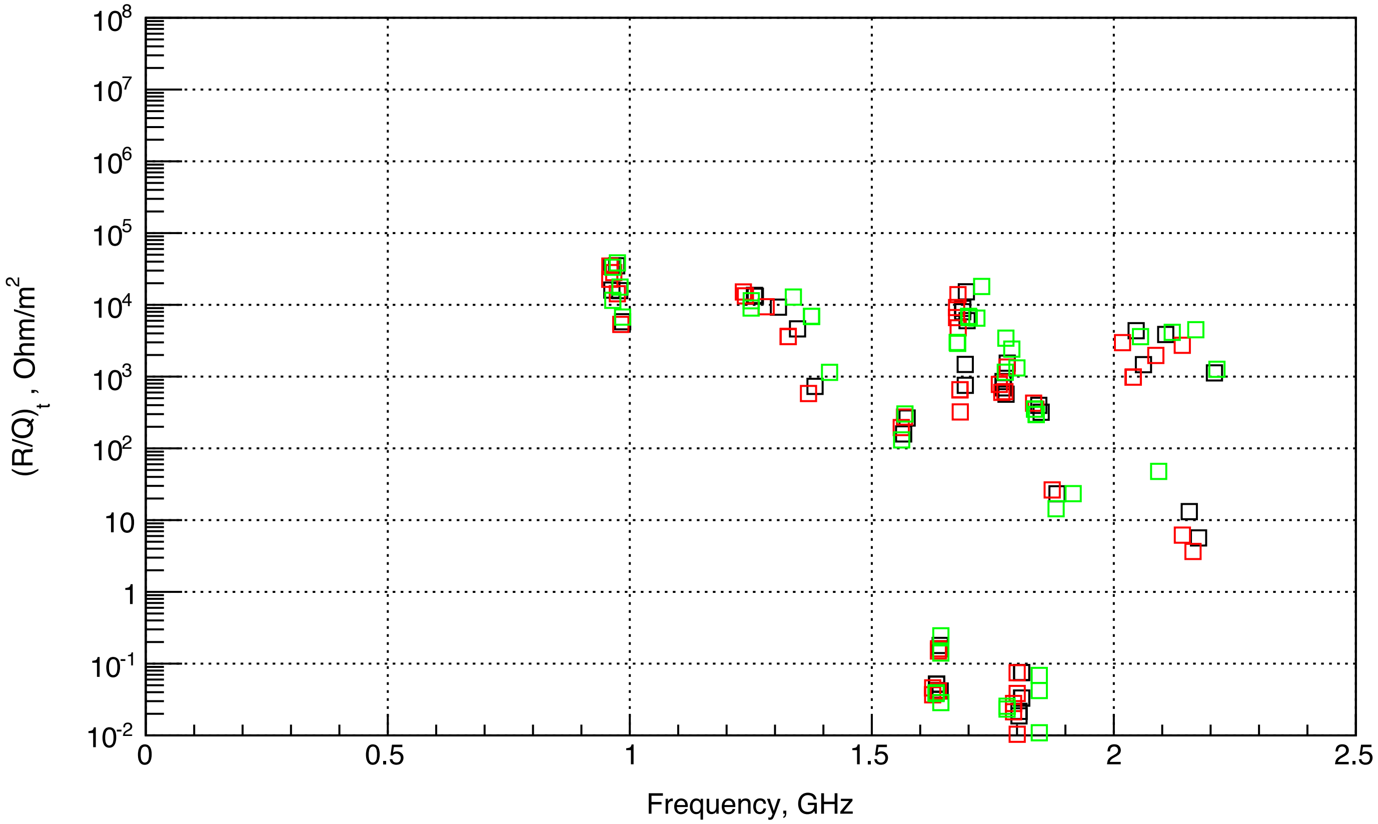


Dipole modes

- QL and (R/Q)



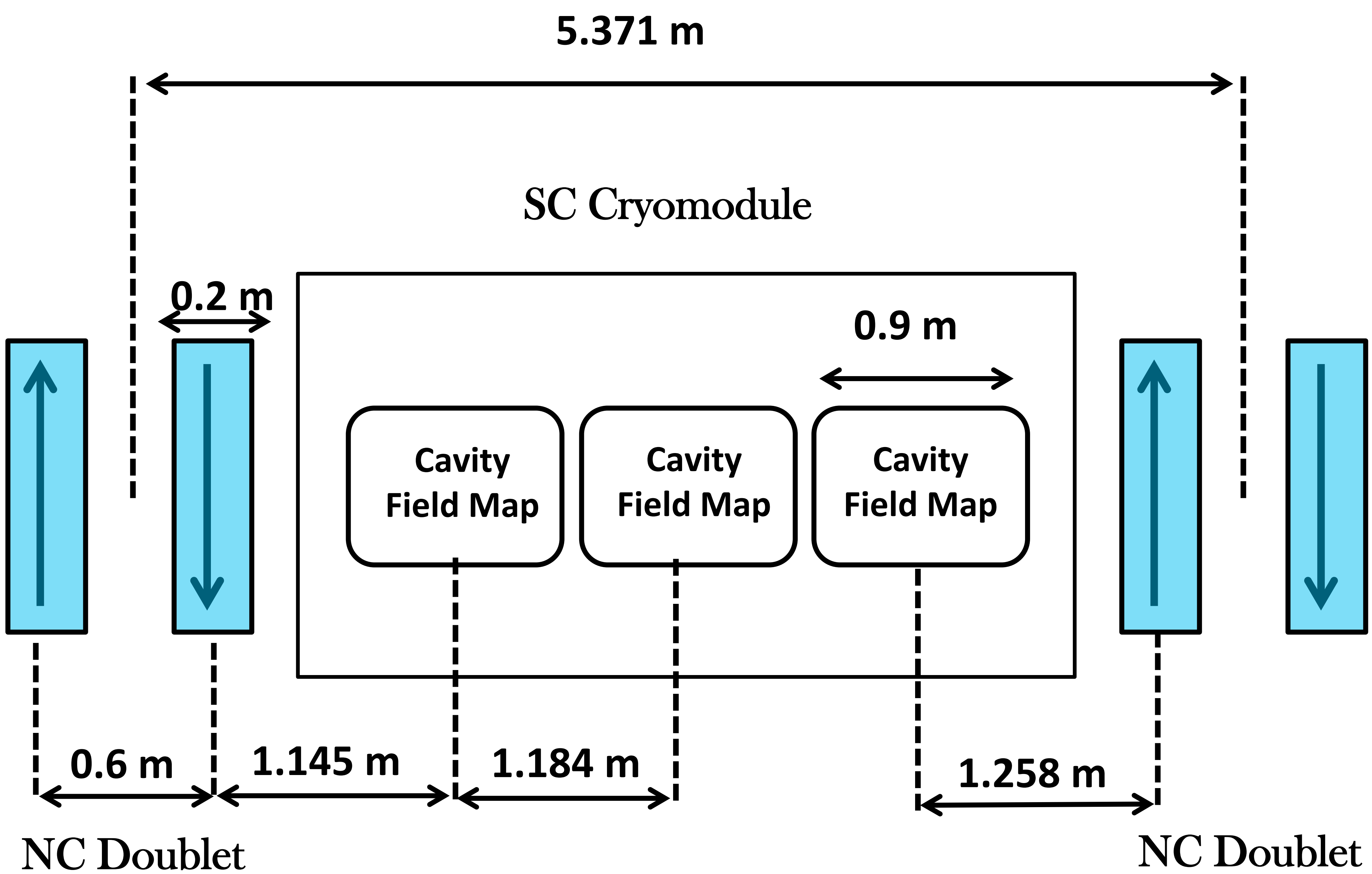
Most possibly dangerous modes are:
VECC: 0.974 GHz, (R/Q) = 38 hOhm/m**2
df = 1 MHz
FNAL: 0.973 GHz, (R/Q) = 35 kOhm/m**2
df=2 MHz



Linac Layout

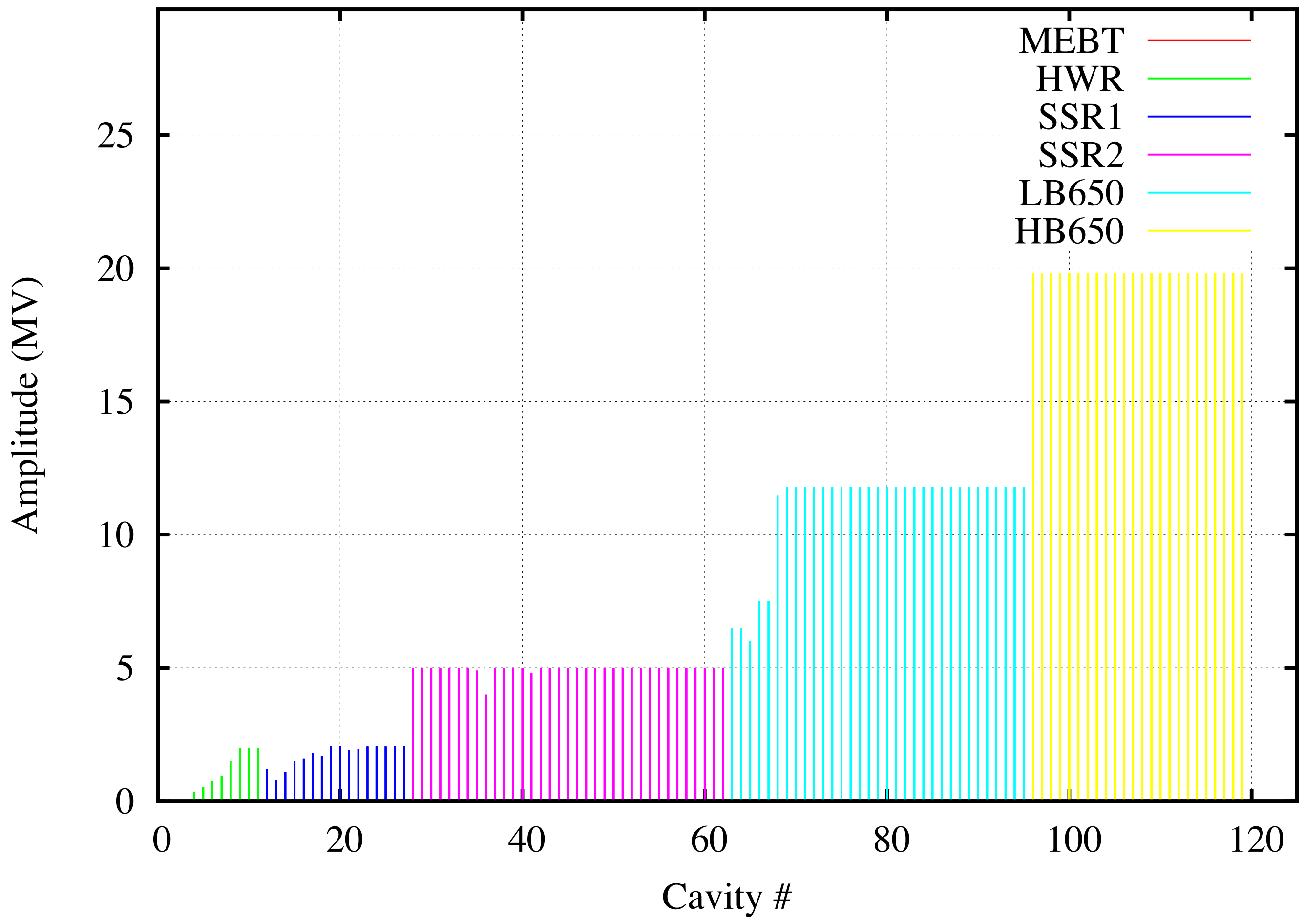
- LB650 beta=0.61 section: 11 cryo-modules, 33 cavities (3 cavities per CM)

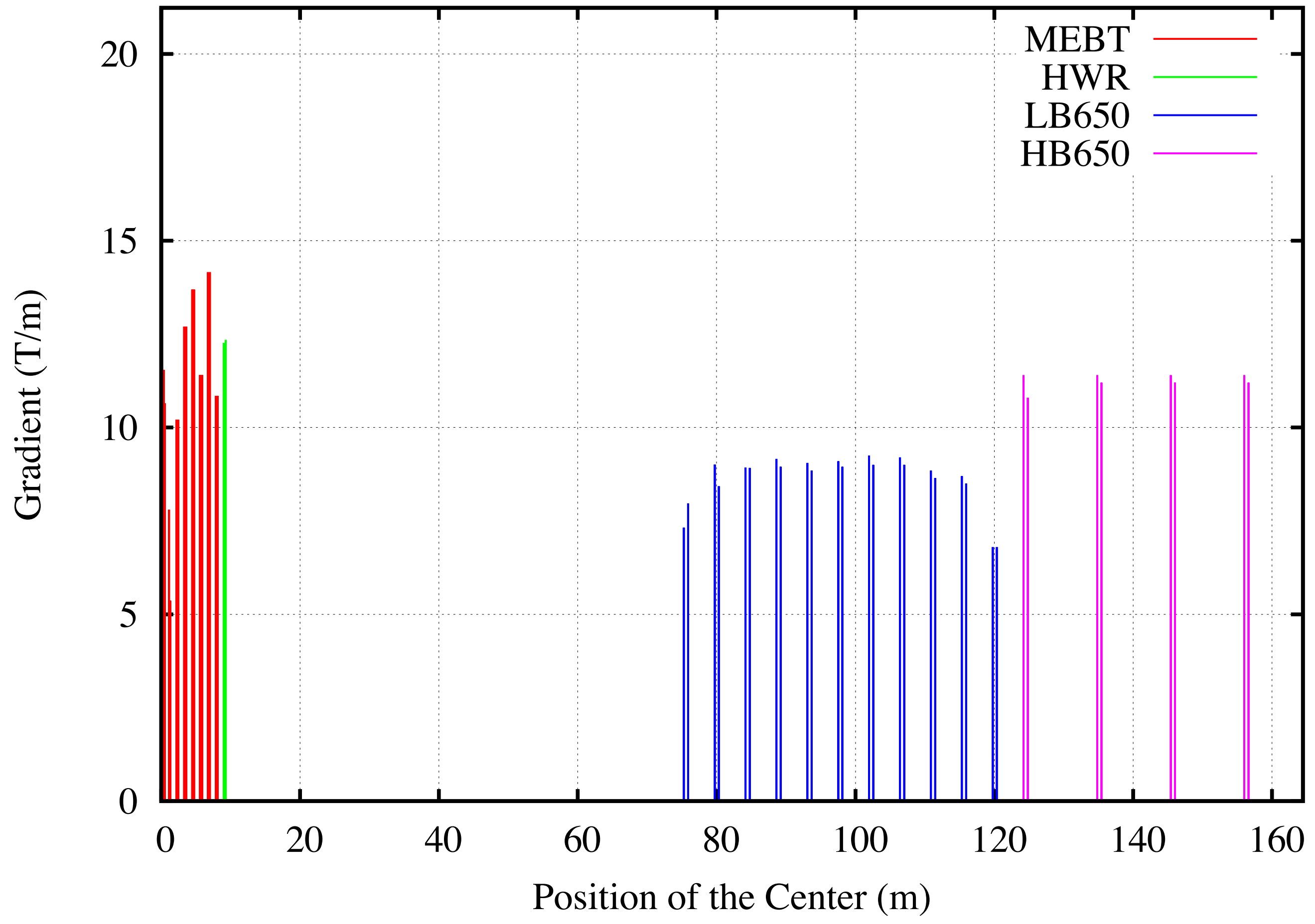
LB Section



Cavity Gradient and Quadrupole Fields

- LB650 Vacc(beta_G) = 12 MV
- LB650 Quad gradient 9 T/m



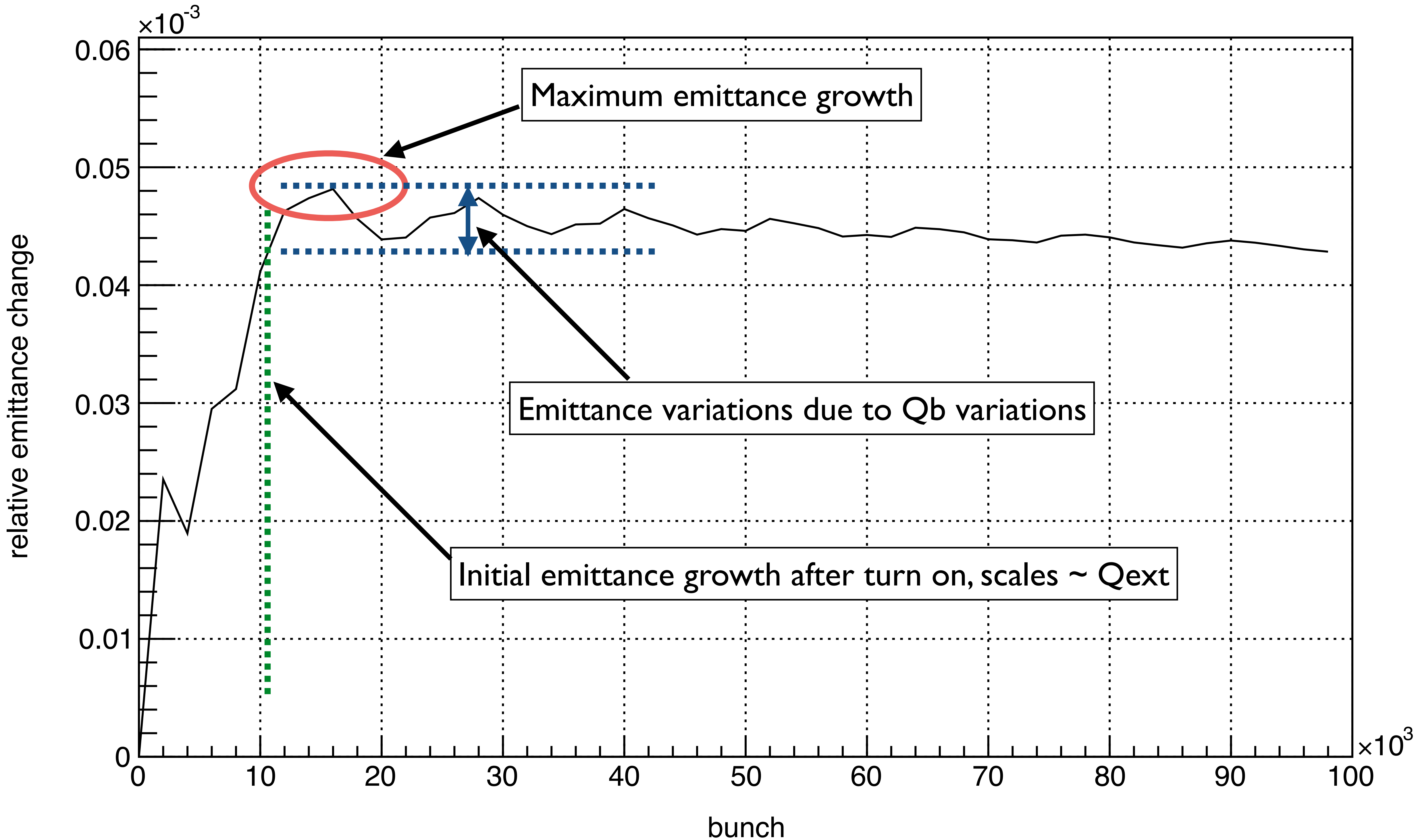


Model

- 30 pC bunches with 10% variation, 162.5 MHz bunch frequency
  - train of 1e5 bunches
  - about 50% of bunches removed for injection at 44.705 MHz
- Transverse misalignment of cavities R.M.S. = 0.5 mm
- Matrix tracking through linac
- Consider one dipole mode with highest (R/Q)
- Each bunch introduces voltage V[i] = jcq(R/Q)x
  - bunch sees half of this kick voltage
- Total kick seen by bunch is sum of voltages from all previous bunches with proper time dependent factors: ~exp(jwTb)*exp(-wTb/2Q)
- Simulate 100 linac configurations (time consuming)
  - random variations of transverse displacement of cavities and HOM frequency with 1 MHz RMS
- Calculate effective RMS emittance at the end of linac from variations of (x,x') of bunches
  - compare to nominal emittance 0.3 mm*mrad (relative emittance)

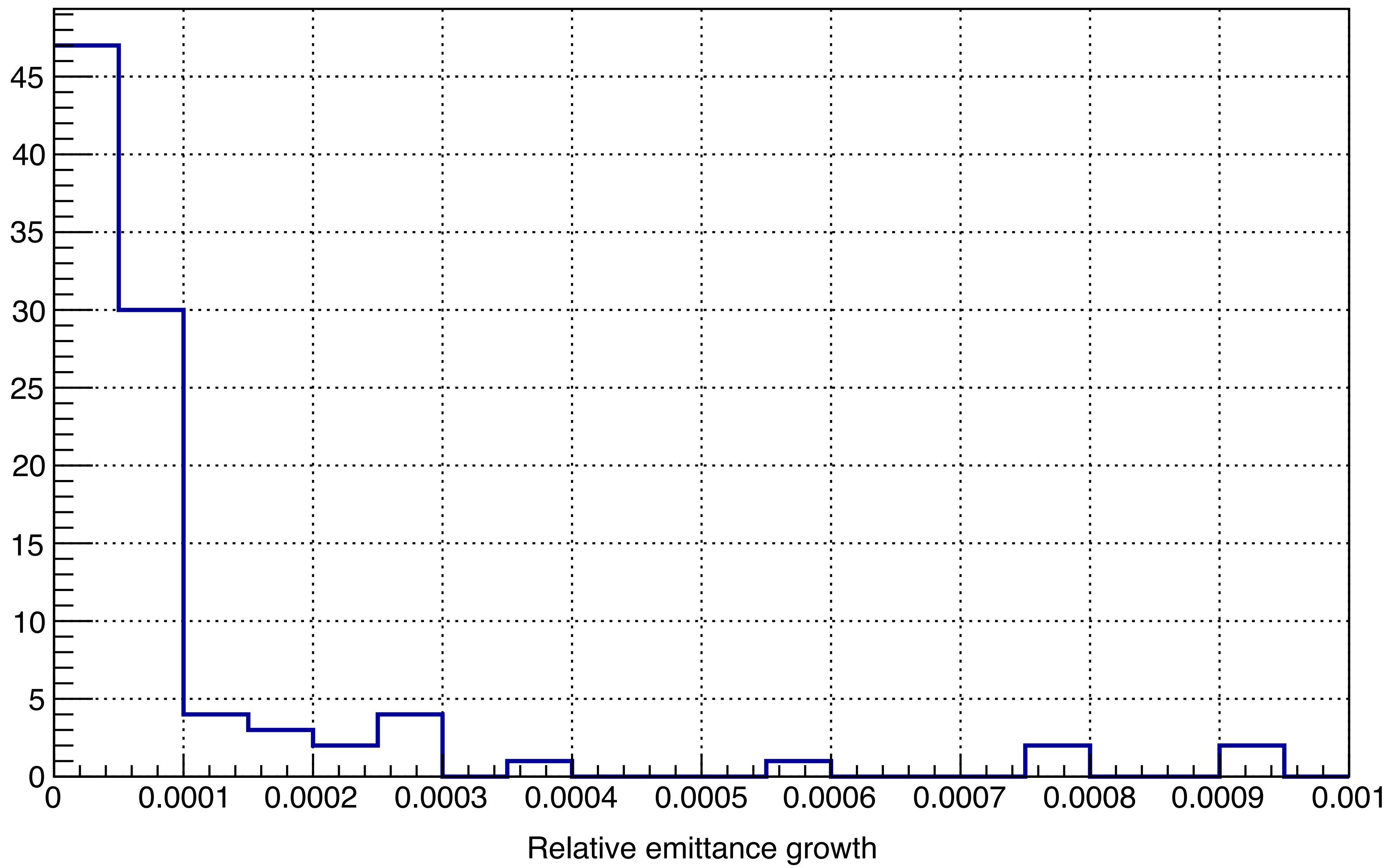
Effective emittance

- Effective emittance at the end of linac for single linac configuration as a function of bunch number



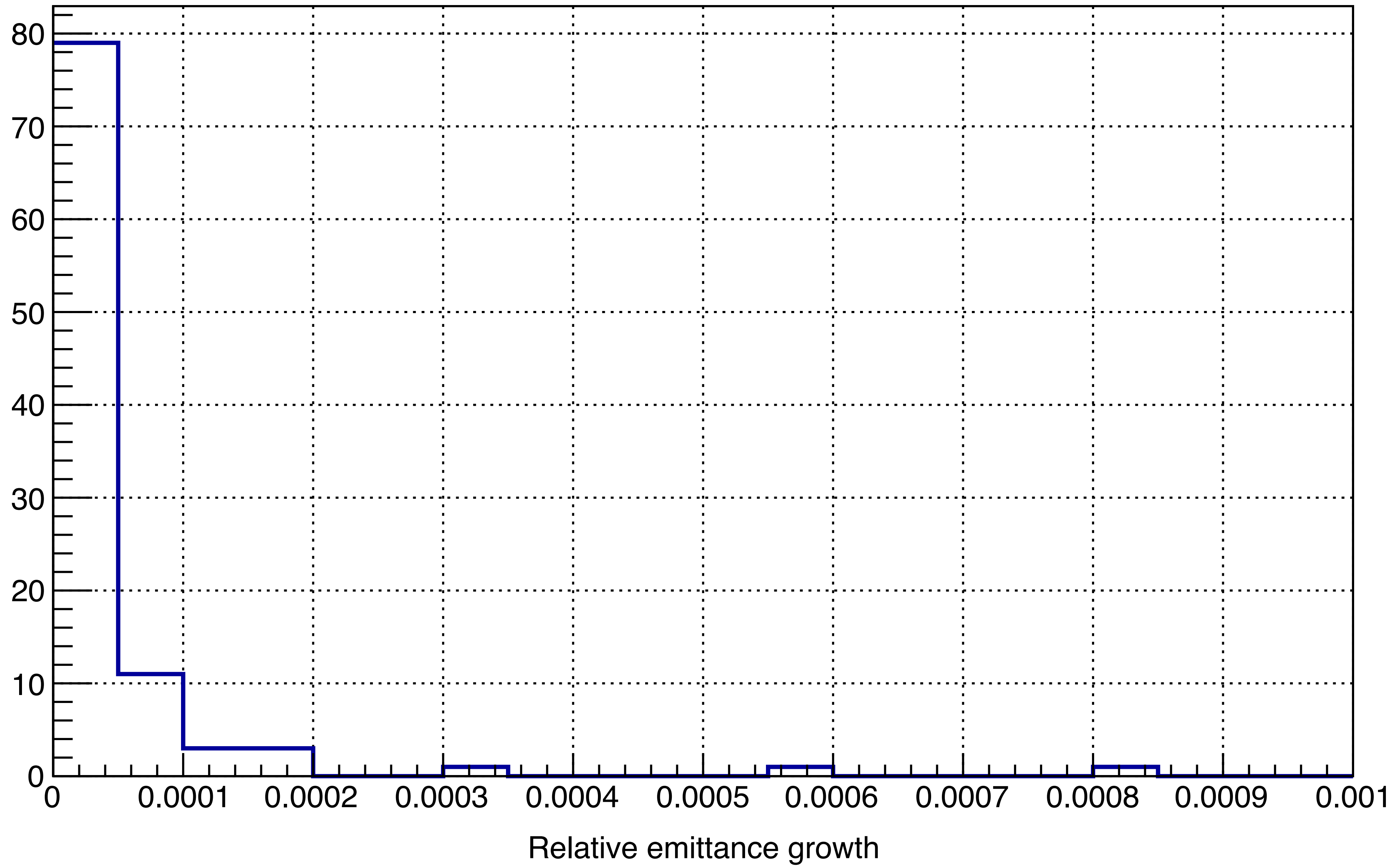
Maximum emittance growth, VECC design

- 100 configurations of linac with random cavity misalignment of 0.5 mm
  - Median value of relative emittance growth is 5e-5
  - 95% of configurations have relative emittance growth less than 1e-3



Maximum emittance growth, FNAL design

- 100 configurations of linac with random cavity misalignment of 0.5 mm
  - Median value of relative emittance growth is 2.5e-5
  - 95% of configurations have relative emittance growth less than 1.5e-4



Conclusion

- Study effects of dipole HOM excitation on transverse beam dynamics in PIP2 linac with 10 mA peak current
  - Considered mode with largest (R/Q)=80 kOhm/m2, f=1376 MHz, Qext=1e7
  - 0.5 mm random cavity misalignment
  - 10% bunch charge variations
- Relative emittance growth is 4e-5 - should not be a problem in PIP2 linac with 10 mA
- Study effects of dipole HOM excitation on transverse beam dynamics in LB650 section of PIP2 linac with different designs of LB650 cavities
  - Considered modes with largest (R/Q)
    - VECC design, mode 0.974 GHz, (R/Q)=38 Ohm/m**2, df=1MHz
    - FNAL design, mode 0.973 GHz, (R/Q)=35 Ohm/m**2, df=2 Mhz
  - 0.5 mm random cavity misalignment
  - 10% bunch charge variations
- Relative emittance growth is 5e-5 for VECC design and 2.5e-5 for FNAL design
- No considerable effects are expected for INFN design