UPDATE ON 6D COOLING STUDIES

Muon Collider Design Workshop
Brookhaven National Laboratory
December 1-3, 2009

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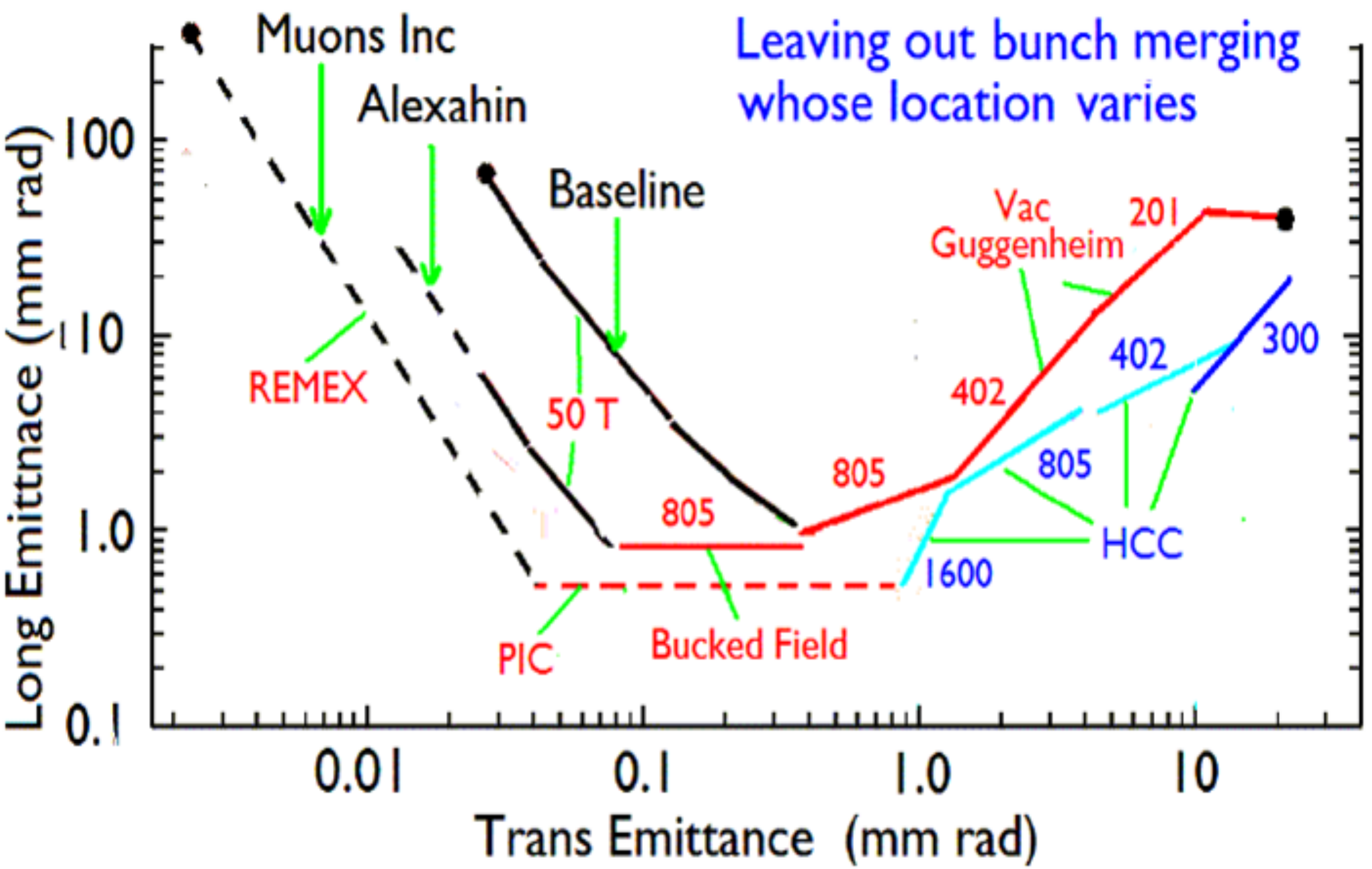
OUTLINE

- Introduction
- RFOFO Ring and Guggenheim Lattice
- Open Cavity Lattice
- Comparison of Various Open Cavity Lattice Designs Aimed at Reducing RF Gradient

INTRODUCTION

- 6D Cooling Schemes for Muon Collider:



INTRODUCTION

Combining Cooling and Heating:

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_N + \frac{\beta\gamma\,\beta_\perp}{2}\frac{d\langle\theta_{rms}{}^2\rangle}{ds}$$

- Low-Z absorbers (H_2, Li, Be, …) to reduce multiple scattering
- High Gradient RF
  - To cool before μ-decay (2.2γ μs)
  - To keep beam bunched
- Strong-Focusing at absorbers
  - To keep multiple scattering
  - less than beam divergence …

⇒ Quad focusing ?

⇒ Li lens focusing ?

⇒ Solenoid focusing?

$$\frac{d\langle\theta_{rms}^2\rangle}{ds} = \frac{z^2 E_s^2}{\beta^2 c^2 p_\mu^2 L_R}$$

INTRODUCTION

- Cooling Proposals:

  RFOFO ring/Guggenheim helix

  Modification – Open cavity lattice

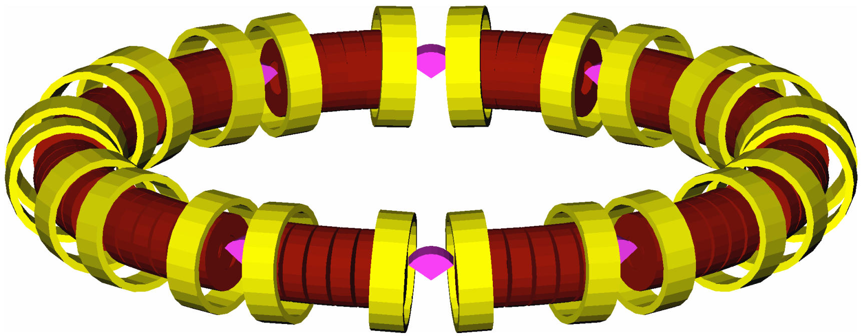
  Helical cooling channel (Muons, Inc.)

  FOFO snake (Y. Alexahin)

  Quadrupole & dipole rings

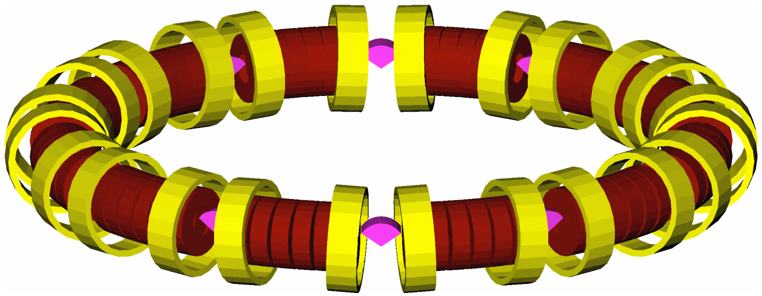
Note: All simulations done in G4Beamline by Pavel Snopok

RFOFO RING



- Yellow – tilted magnetic coils generate bending & dispersion
- Purple – wedge absorbers for cooling & emittance exchange
- Red/brown – RF cavities restore energy lost in absorber in longitudinal direction

RFOFO RING AND GUGGENHEIM HELIX



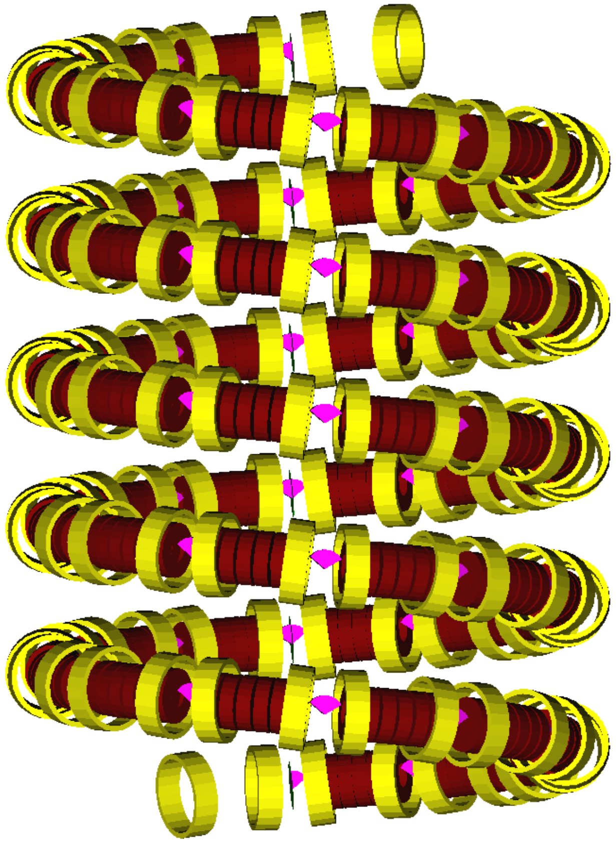
RFOFO ring

Advantages:

- Fast cooling
- Compact
- Reuse RF

Challenges:

- Injection/extraction
- Absorber overheating
- Continuous operation

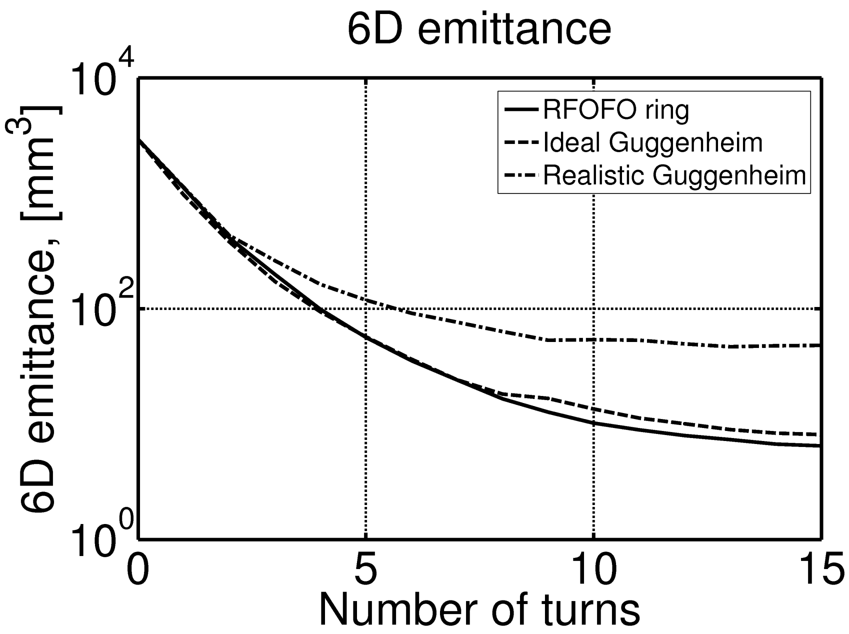


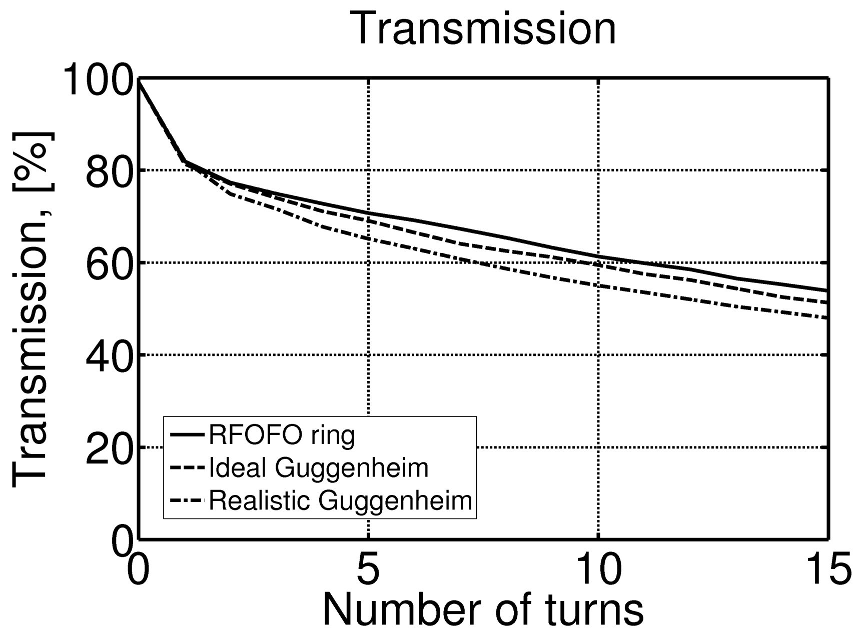
RFOFO-based Guggenheim helix

COMPARISON OF RFOFO AND GUGGENHEIM PARAMETERS

	RFOFO	Guggenheim
Circumference, [m]	33.00	33.00
RF frequency, [MHz]	201.25	201.25
RF gradient, [MV/m]	12.835	12.621
Maximum axial field, [T]	2.77	2.80
Pitch, [m]	0.00	3.00
Pitch angle, [deg]	0.00	5.22
Radius, [mm]	5252.113	5230.365
Coil tilt (wrt orbit), [deg]	3.04	3.04
Average momentum, [MeV/c]	220	220
Reference momentum, [MeV/c]	201	201
Absorber angle, [deg]	110	110
Absorber thickness on beam axis, [cm]	27.13	27.13

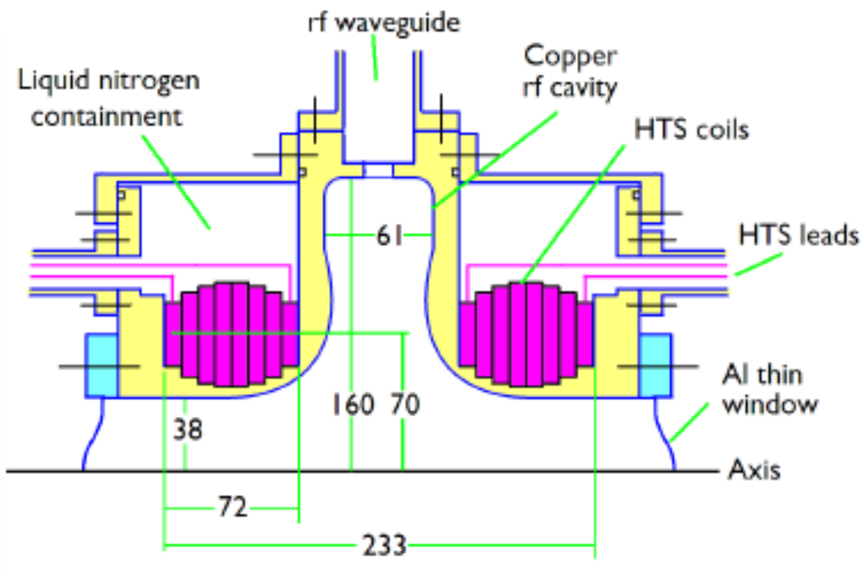
COMPARISON OF GUGGENHEIM AND RFOFO PERFORMANCE

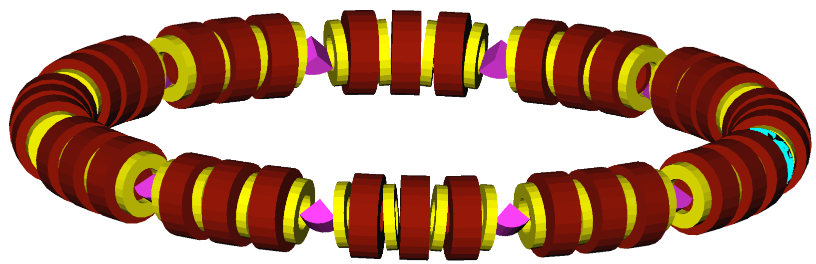


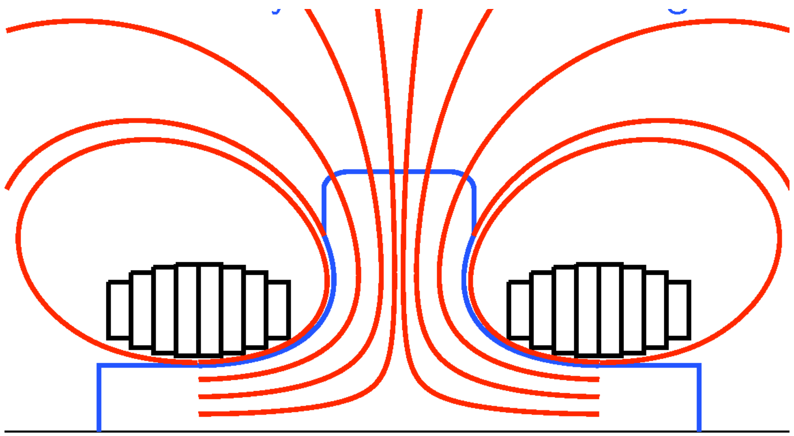


- 6D emittance reduced by factor of 448 in RFOFO ring or by factor of 360 in the Guggenheim helix (495m) with NO WINDOWS.
- Reduced by factor of 60 WITH WINDOWS in RF cavities and absorbers.

OPEN CAVITY LATTICE







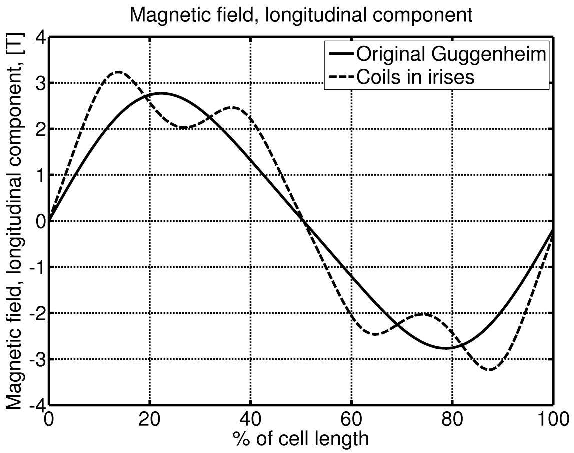
- Open cavity lattice
- Coils in the irises
- Coils tilted to generate bending field

COMPARISON OF OPEN CAVITY AND RFOFO PARAMETERS

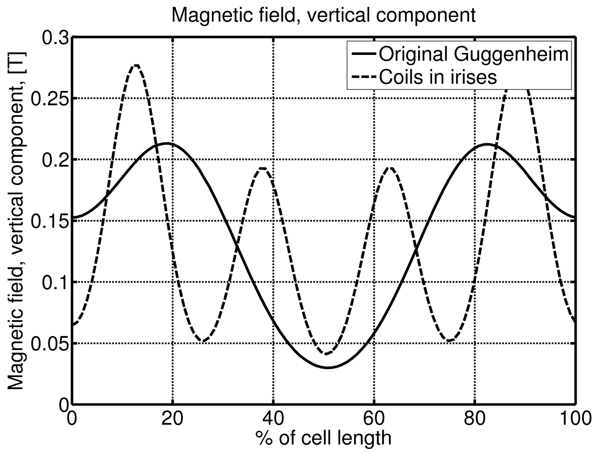
Parameter	Unit	Open cavity	RFOFO
Number of cells		12	12
Circumference	[m]	30.72	33.00
Radius	[m]	4.889	5.252
RF frequency	[MHz]	201.25	201.25
RF gradient	[MV/m]	16.075	12.835
Maximum axial field	[T]	3.23	2.80
Reference momentum	[MeV/c]	214	201
Coil tilt	[deg]	4.90	3.04
Number of coils per cell		4	2
Current densities	[A/mm^2]	[63,45,-45,-63]	[95,-95]
Number of RF cavities		3	6
Length of each RF cavity	[mm]	385	282.5
Absorber angle	[deg]	90	110
Absorber vertical offset	[cm]	12.0	9.5
Absorber axial length	[cm]	24.00	27.13
RF phase	[deg]	30.00	30.00

COMPARISON OF OPEN CAVITY LATTICE AND RFOFO MAGNETIC FIELDS

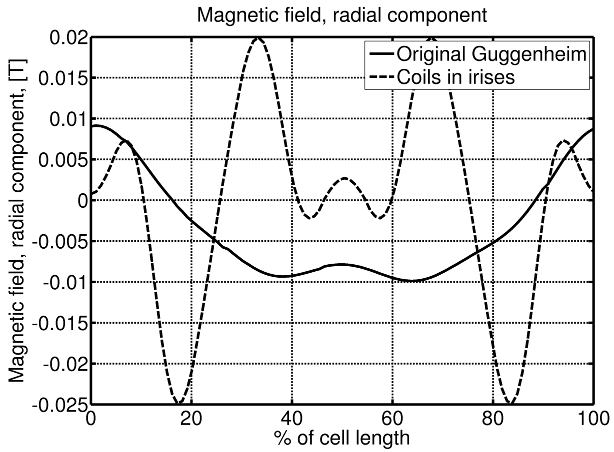
Longitudinal



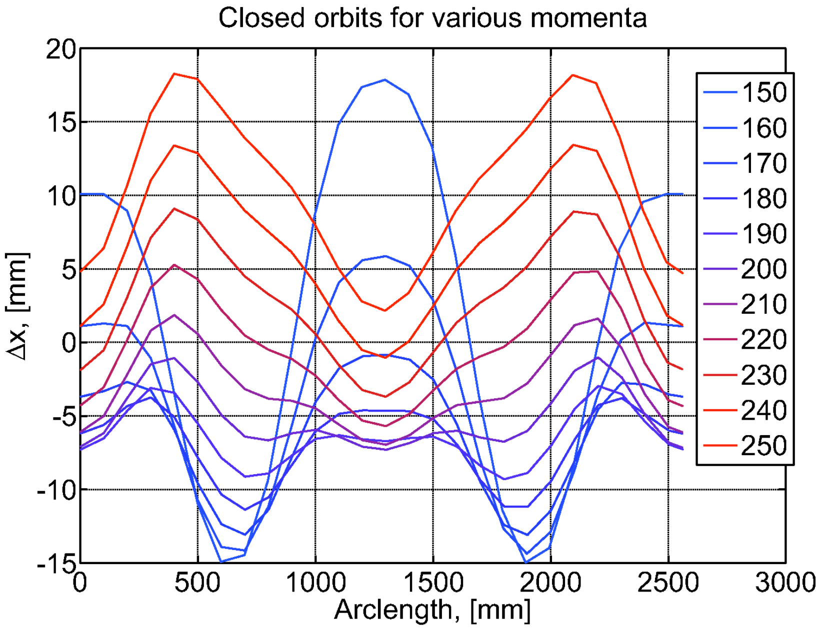
Vertical

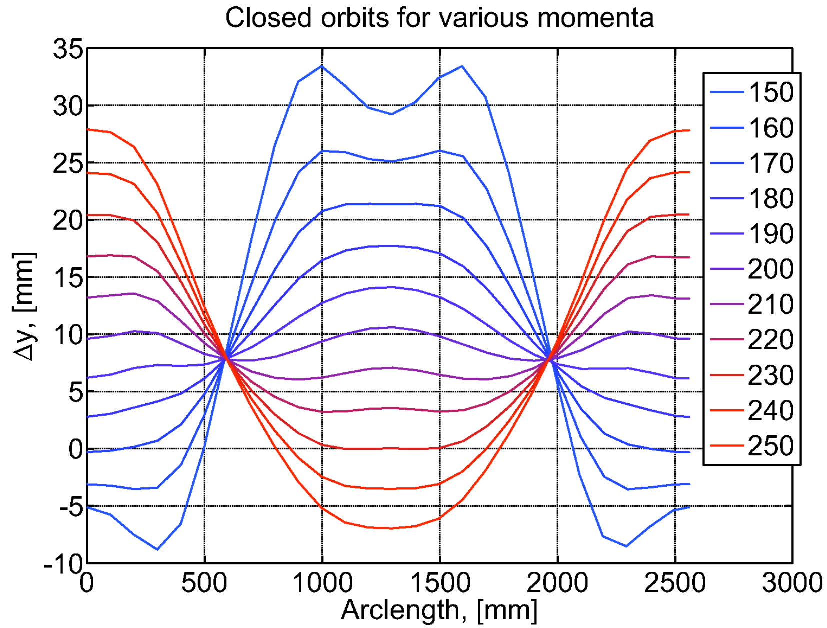


Radial



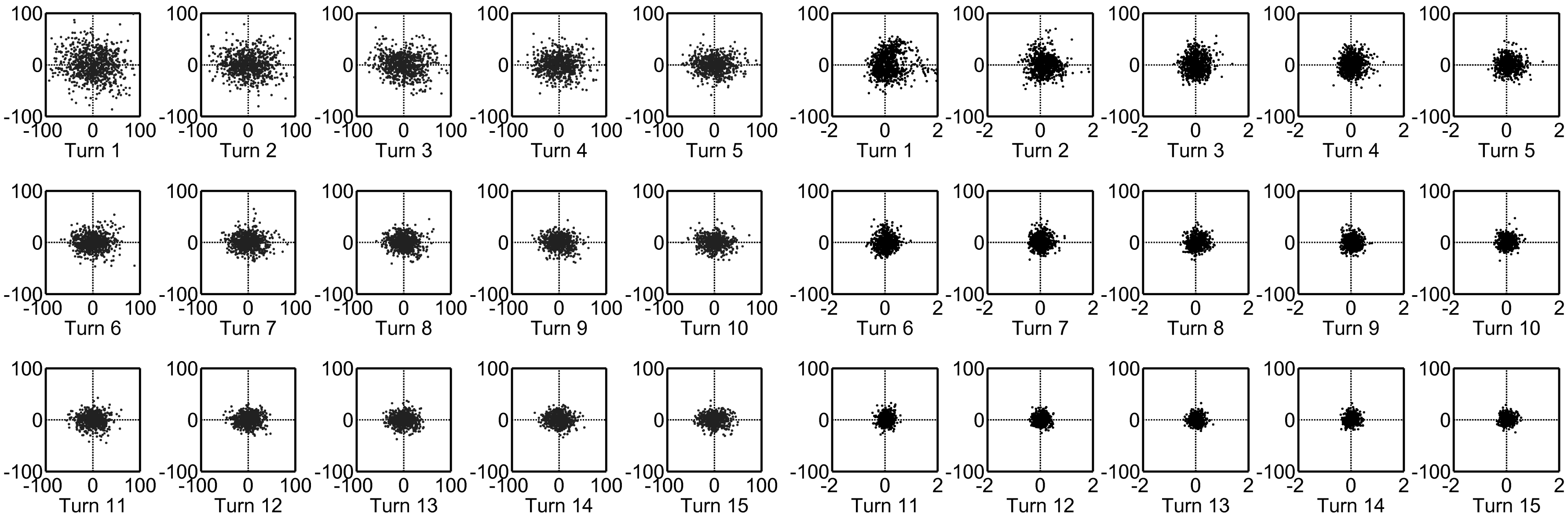
OPEN CAVITY LATTICE – OFFSETS FOR CLOSED ORBITS





OPEN CAVITY LATTICE – PHASE PORTRAITS

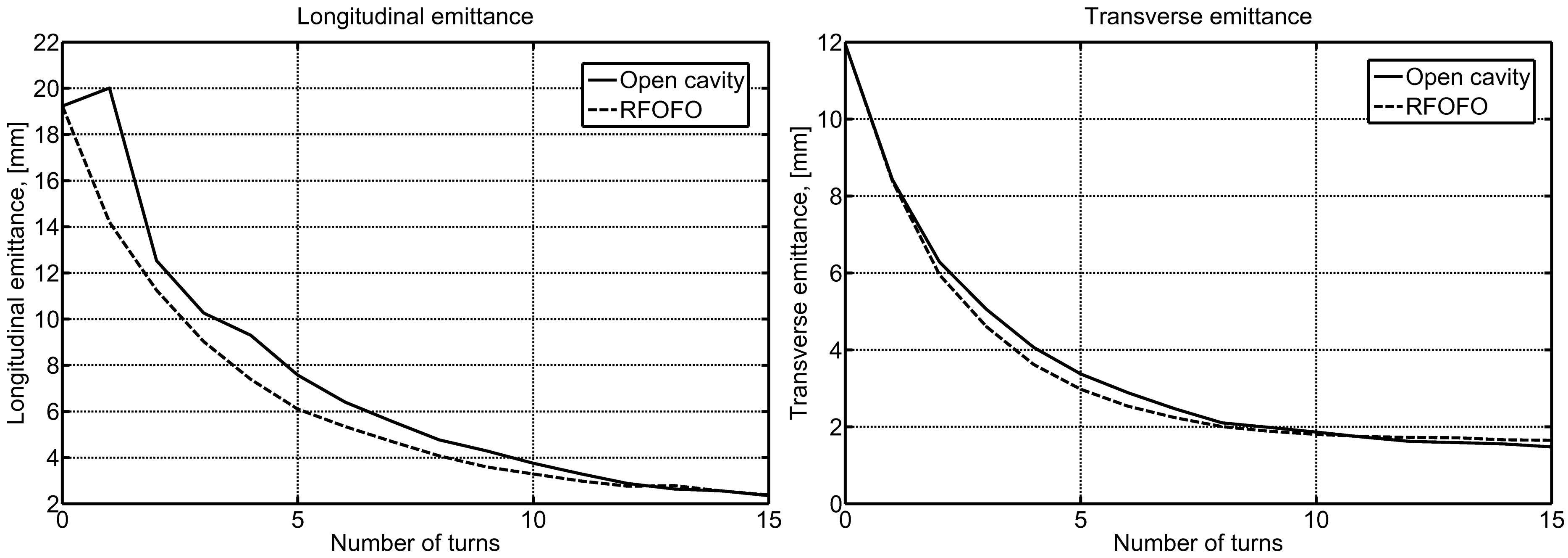
Emittance reduced until equilibrium emittance reached



x - p_x t - p_z

COMPARISON OF OPEN CAVITY AND RFOFO PERFORMANCE

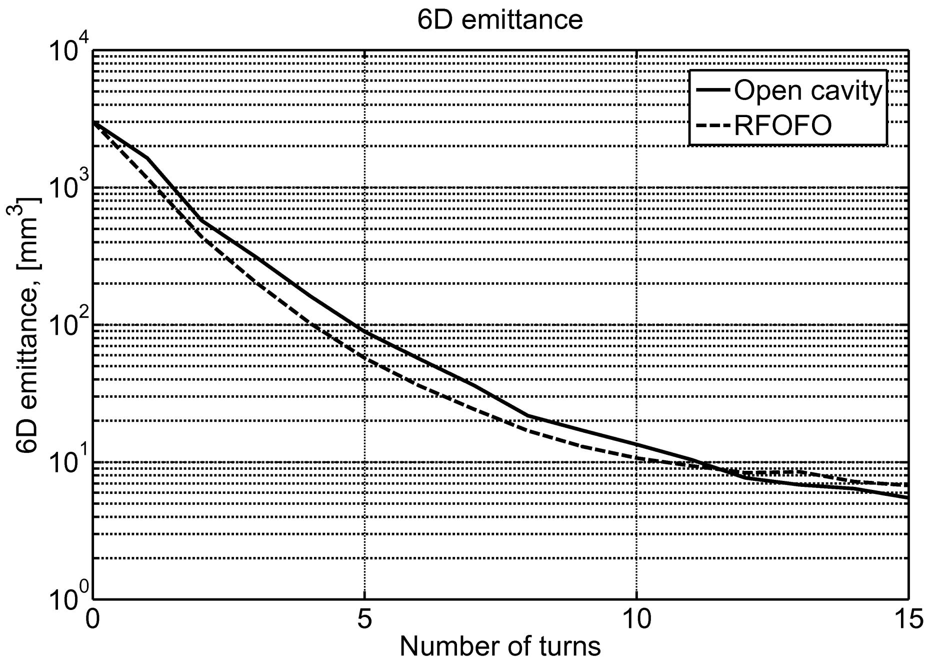
Longitudinal emittance　　Transverse emittance



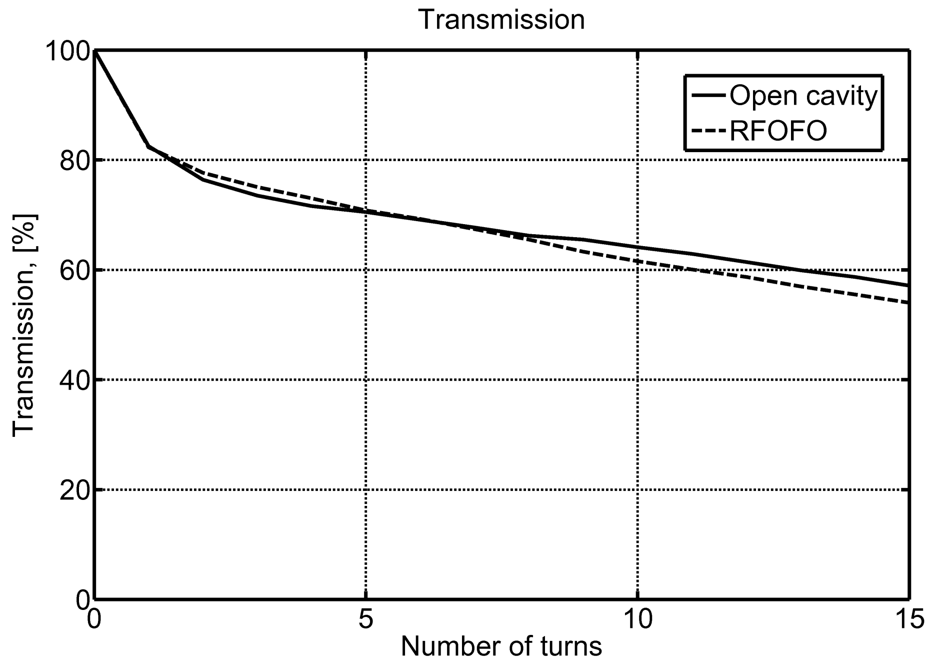
WITH decay and stochastic processes

COMPARISON OF OPEN CAVITY AND RFOFO PERFORMANCE

6D emittance



Transmission

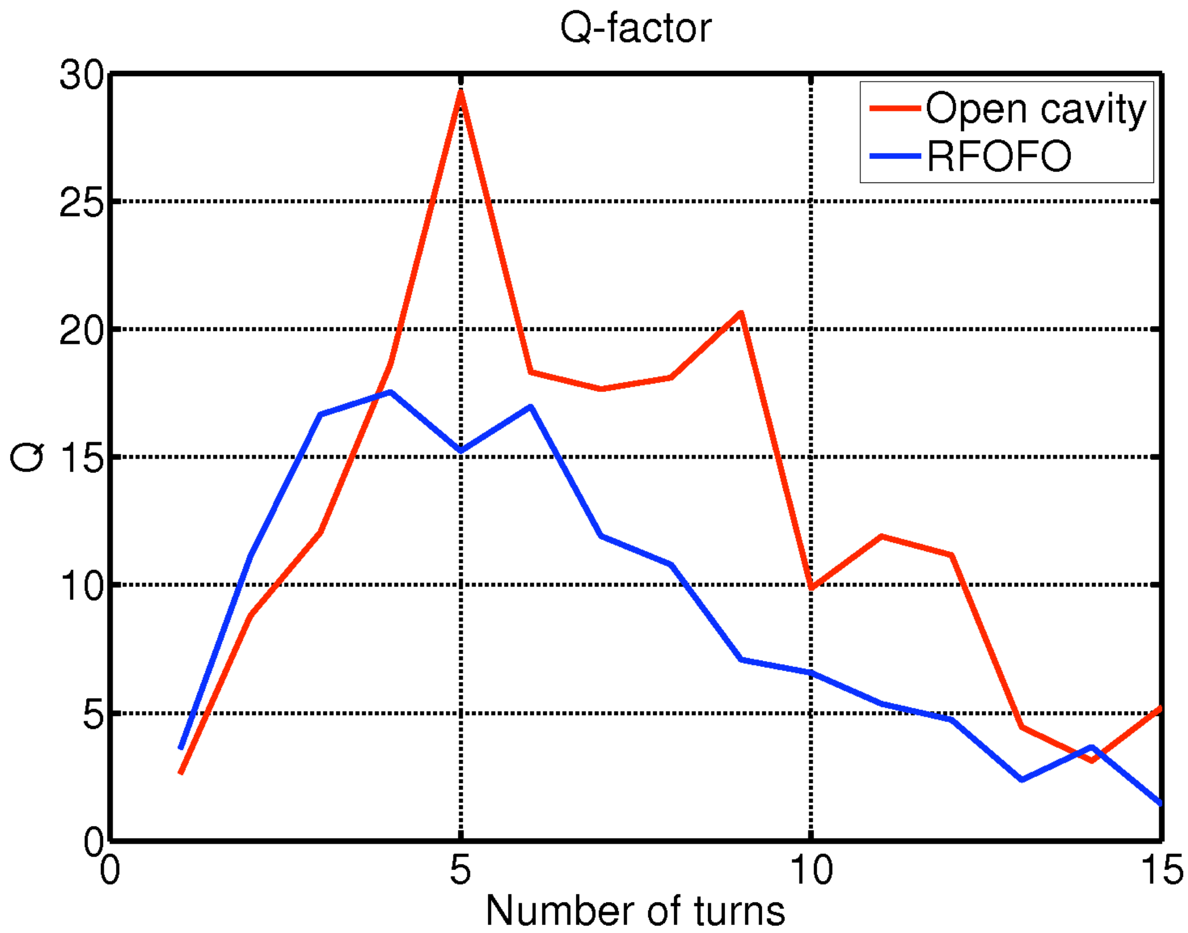


WITH decay and stochastic processes

COMPARISON OF OPEN CAVITY AND RFOFO PERFORMANCE – Q-FACTOR

New!

$$Q = \frac{d\varepsilon_{6D}^{N}/ds}{dN/ds}\,\frac{N(s)}{\varepsilon_{6D}^{N}(s)}$$

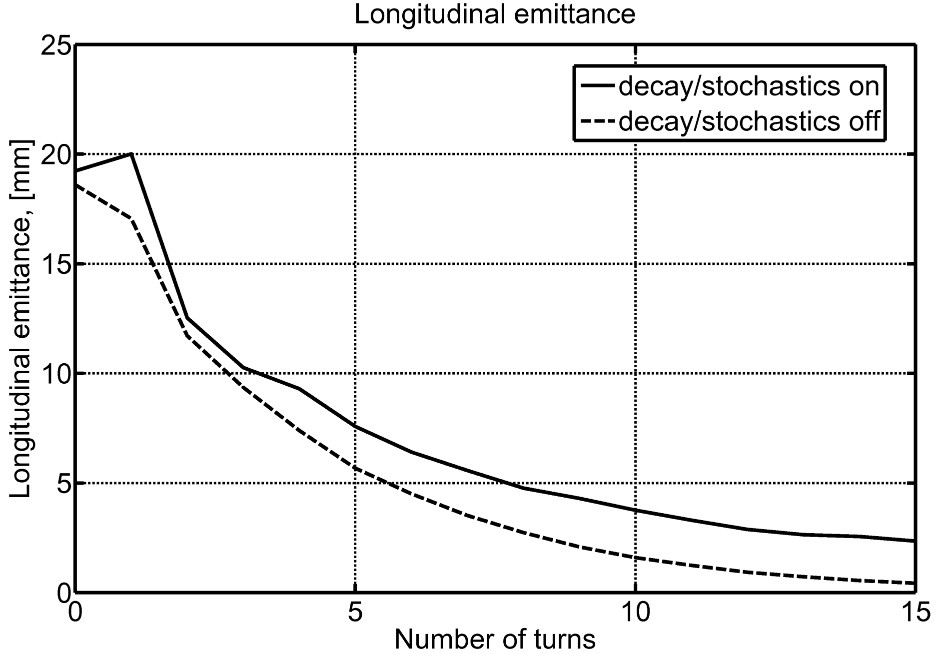


COMPARISON OF OPEN CAVITY AND RFOFO PERFORMANCE – QUANTITATIVE

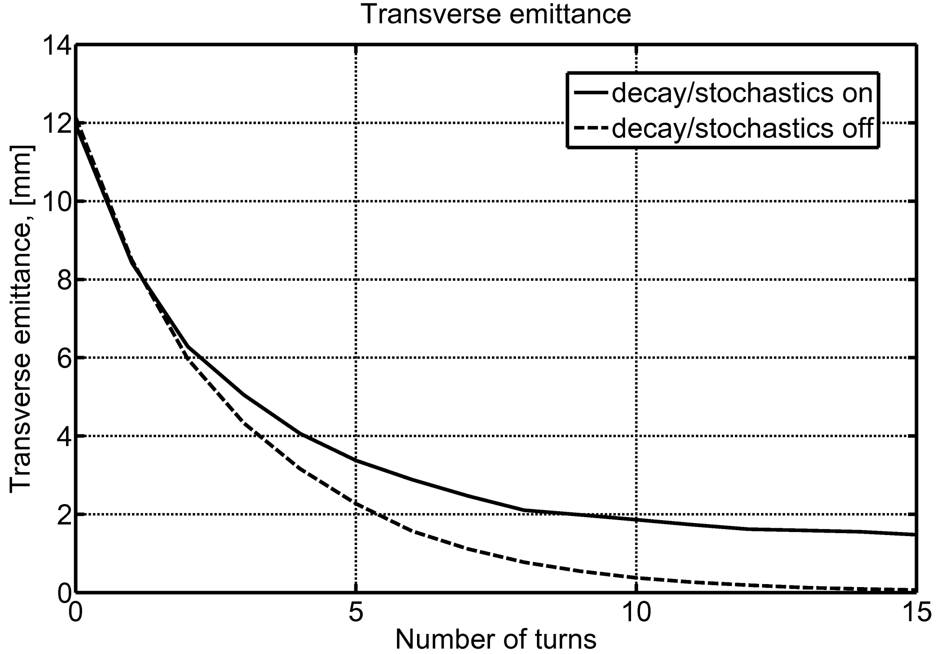
Structure	$\varepsilon_\perp$ [mm]	$\varepsilon_{\|\|}$ [mm]	ε_{6D} [mm^3]	Transmission [%]
Initial	12	19	3000	100
Open cavity (15 turns)	1.5	2.3	5.5	57
RFOFO (14 turns)	1.7	2.5	7.2	56
RFOFO (15 turns)	1.6	2.4	6.7	54

PERFORMANCE OF OPEN CAVITY LATTICE – DECAY/STOCHASTICS ON AND OFF

Longitudinal emittance



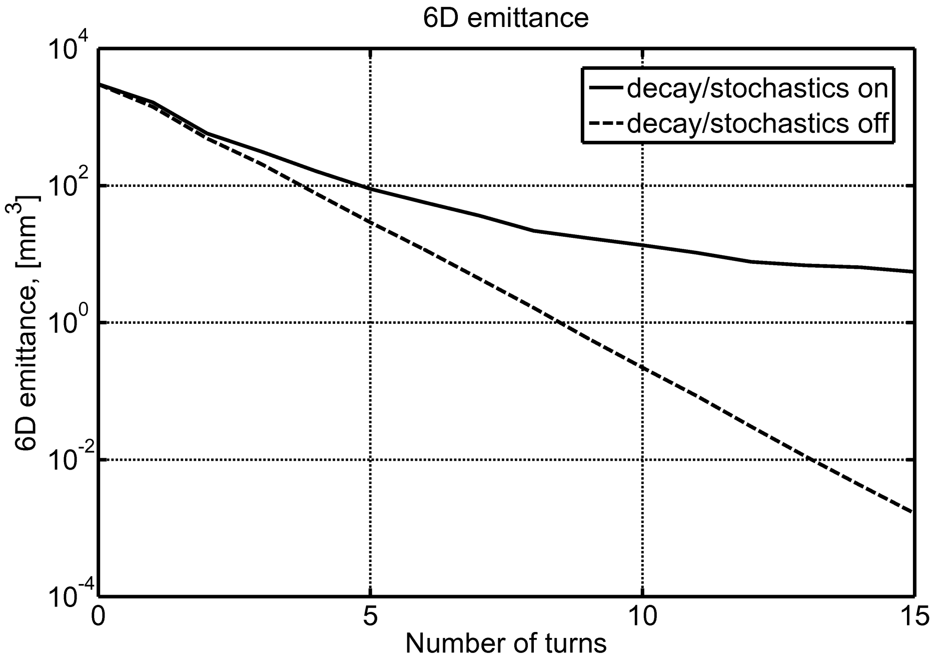
Transverse emittance



No decay/stochastics – no equilibrium emittance – both longitudinal and transverse emittances shrink to zero

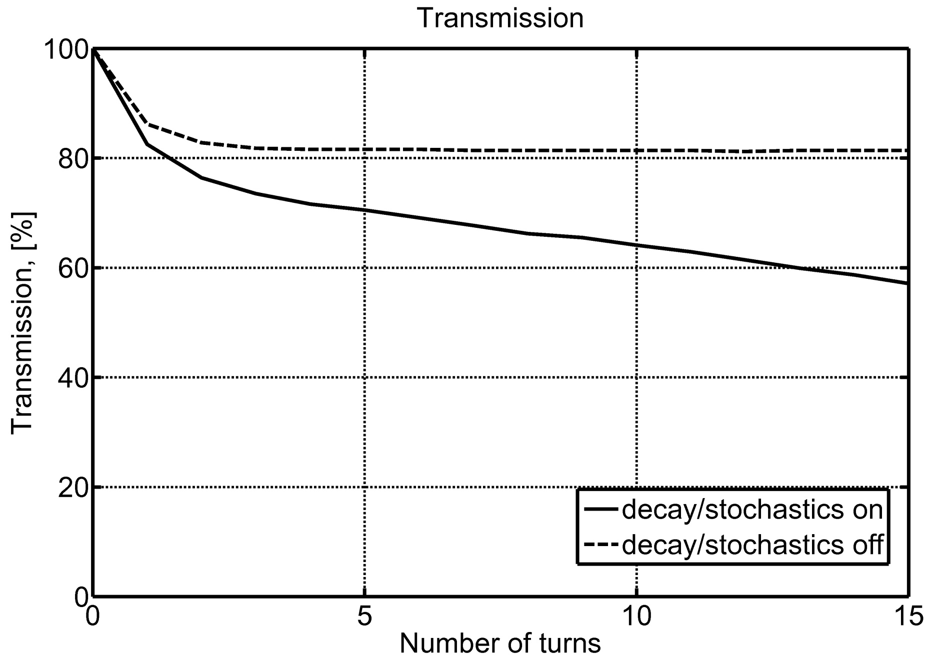
PERFORMANCE OF OPEN CAVITY LATTICE – DECAY/STOCHASTICS ON AND OFF

6D emittance



No decay/stochastics – 6D emittance shrinks exponentially

Transmission



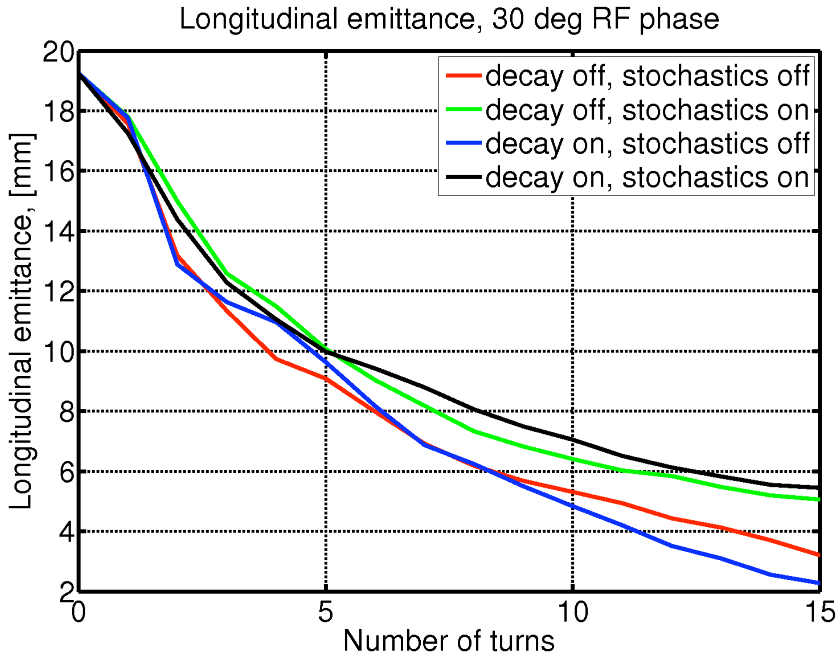
No decay/stochastics – transmission stabilizes after 3 turns to 81%

COMPARISON OF VARIOUS OPEN CAVITY RING DESIGNS AIMED AT REDUCING RF GRADIENT

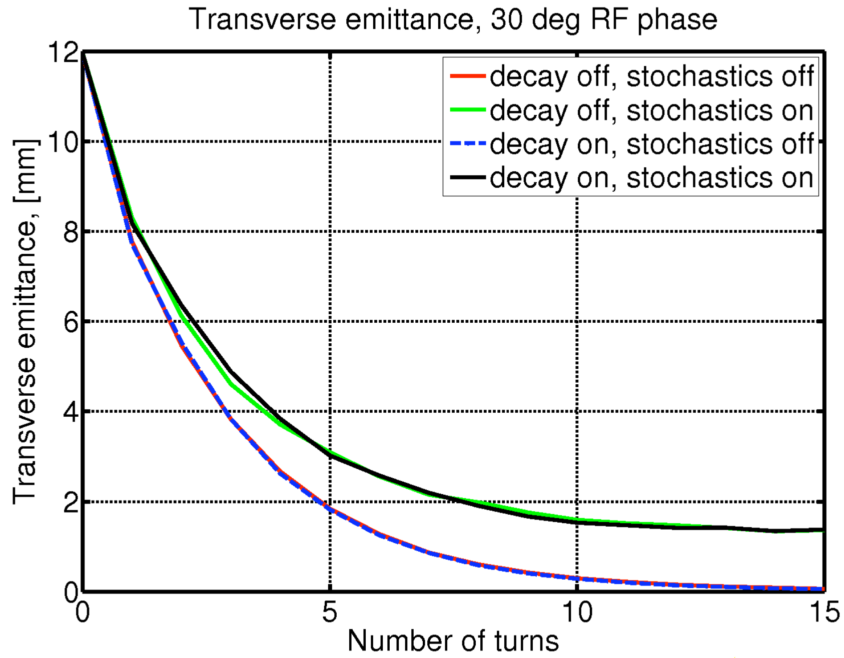
	Open cavity, 30°	Open cavity, 35°	Scaled open cavity, 30°	Scaled open cavity, 35°
R, [m]	4.89	4.89	5.25	5.25
Circumference, [m]	30.72	30.72	33.00	33.00
RF phase, [deg]	30	35	30	35
RF gradient, [MV/m]	16.0	14.0	14.8	12.9
ε_{6D} initial/ final, [mm^3]	3000/5.5	3000/5.6	3000/10	3000/9.1
Transmission, 15 turns [%]	57	47	52	50

PERFORMANCE OF OPEN CAVITY LATTICE SCALED WITH 30° RF PHASE

Longitudinal emittance



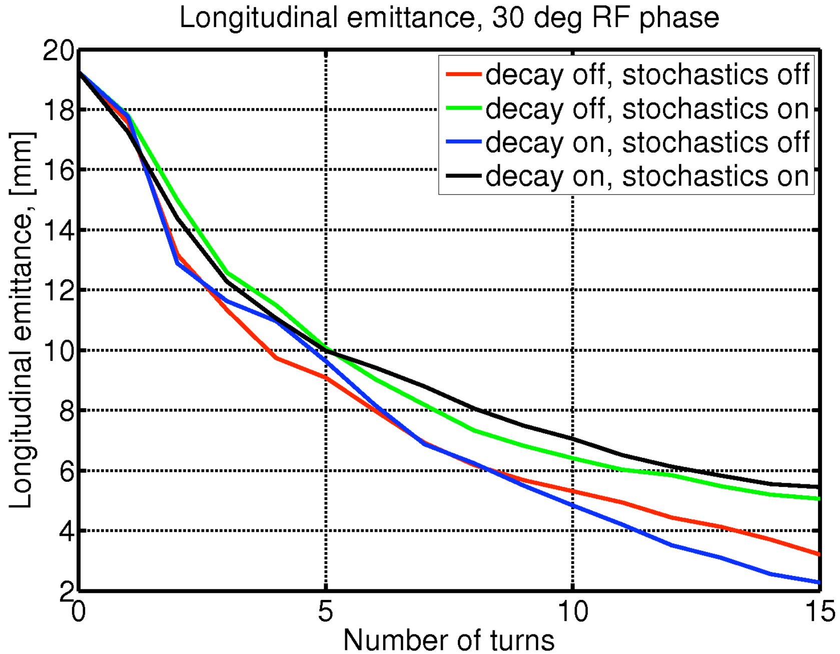
Transverse emittance



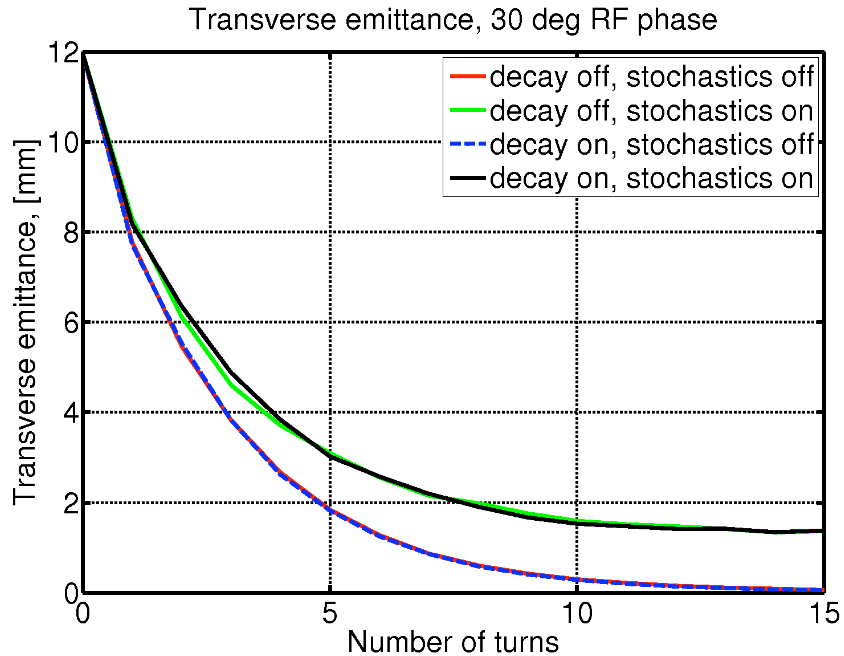
New!

PERFORMANCE OF OPEN CAVITY LATTICE SCALED WITH 30° RF PHASE

6D emittance



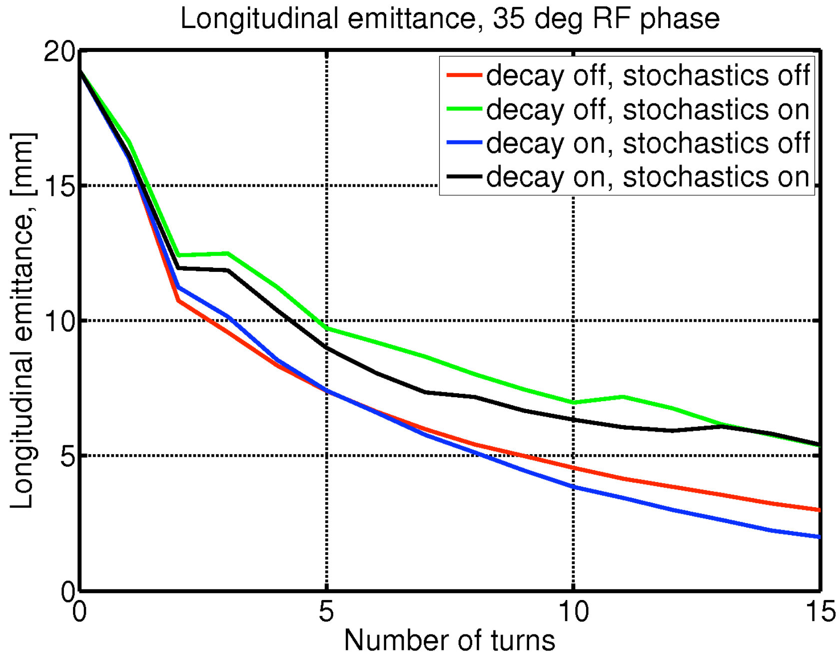
Transmission



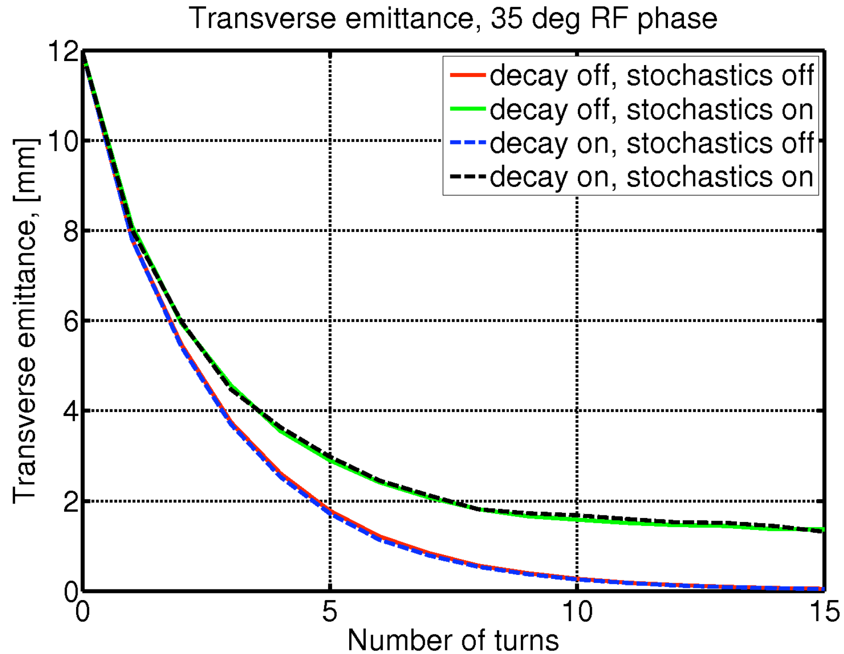
New!

PERFORMANCE OF OPEN CAVITY LATTICE SCALED WITH 35° RF PHASE

Longitudinal emittance



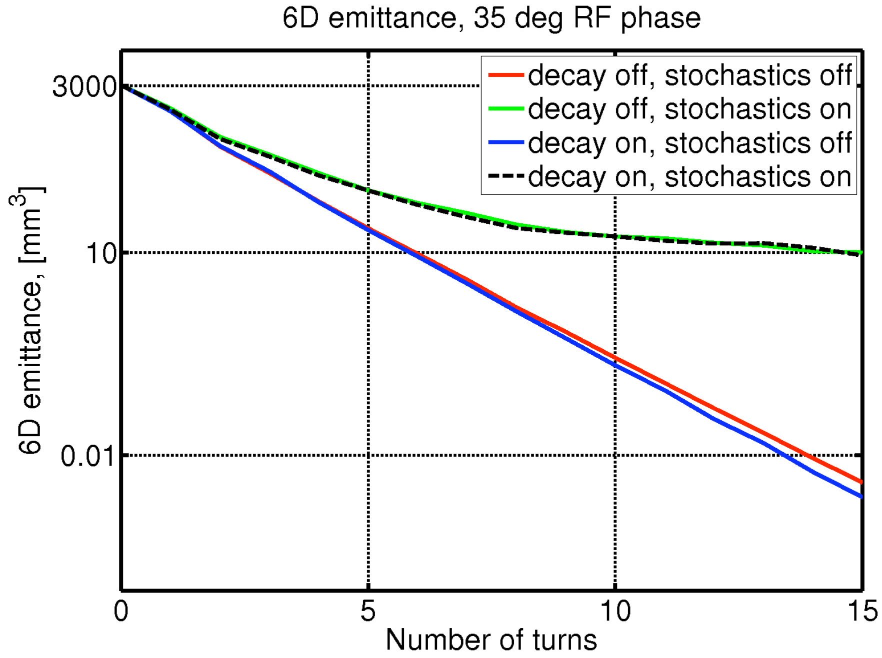
Transverse emittance



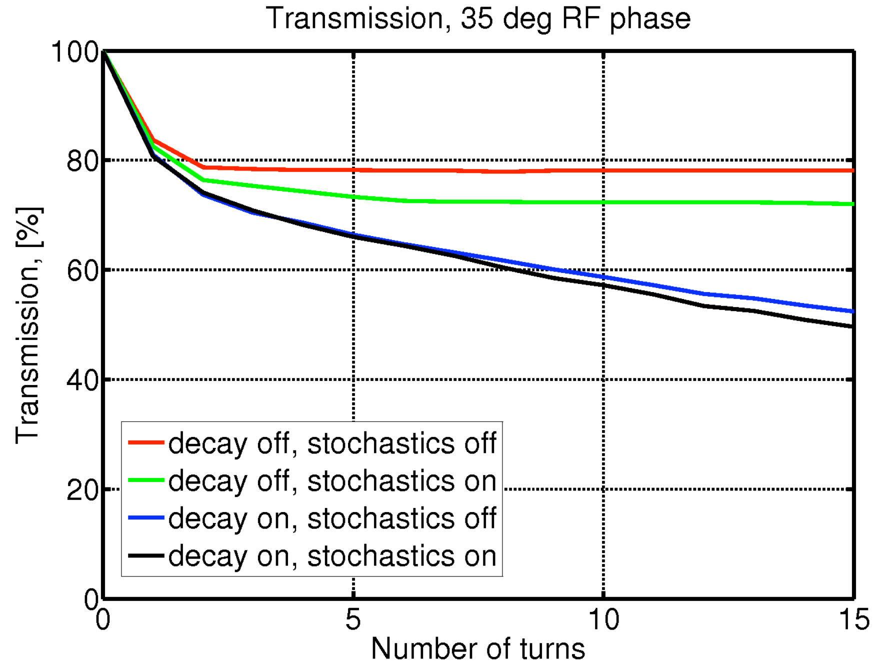
New!

PERFORMANCE OF OPEN CAVITY LATTICE SCALED WITH 35° RF PHASE

6D emittance



Transmission

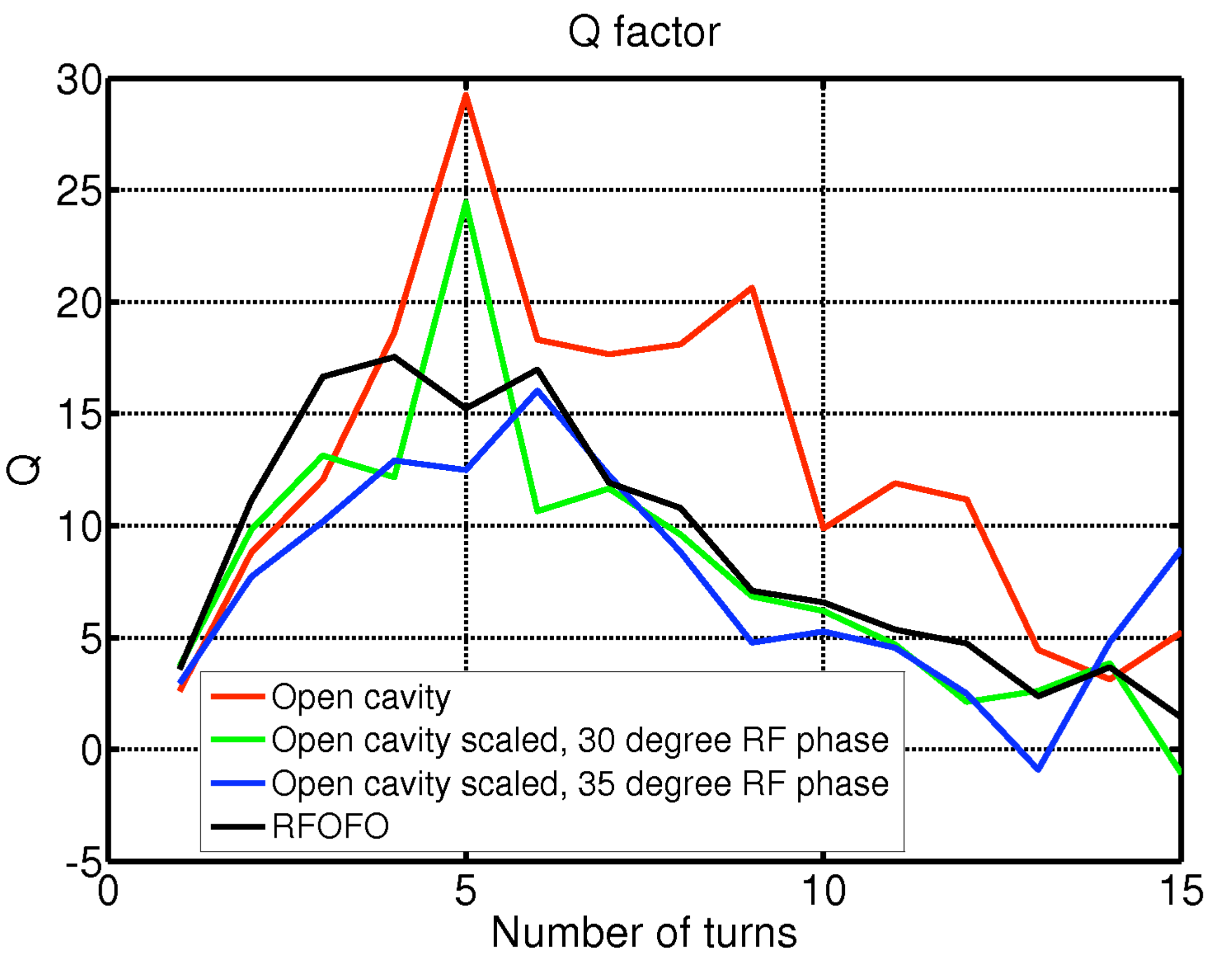


New!

COMPARISON OF OPEN CAVITY AND RFOFO PERFORMANCE – Q-FACTOR

New!

$$Q = \frac{d\varepsilon_{6D}^{N}/ds}{dN/ds}\,\frac{N(s)}{\varepsilon_{6D}^{N}(s)}$$



PLANS

- Working on 805 MHz channel simulation in G4Beamline
  - Tipped solenoids vs. constant dipole field (with Rick Fernow)
- Categorize reasons for present transmission losses
- Plus longer term items

SUMMARY

- ROFO and Guggenheim results presented
- Open cavity lattice simulation results summarized and compared with RFOFO
- Open cavity lattice scaled and RF phase changed in effort to reduce RF gradient