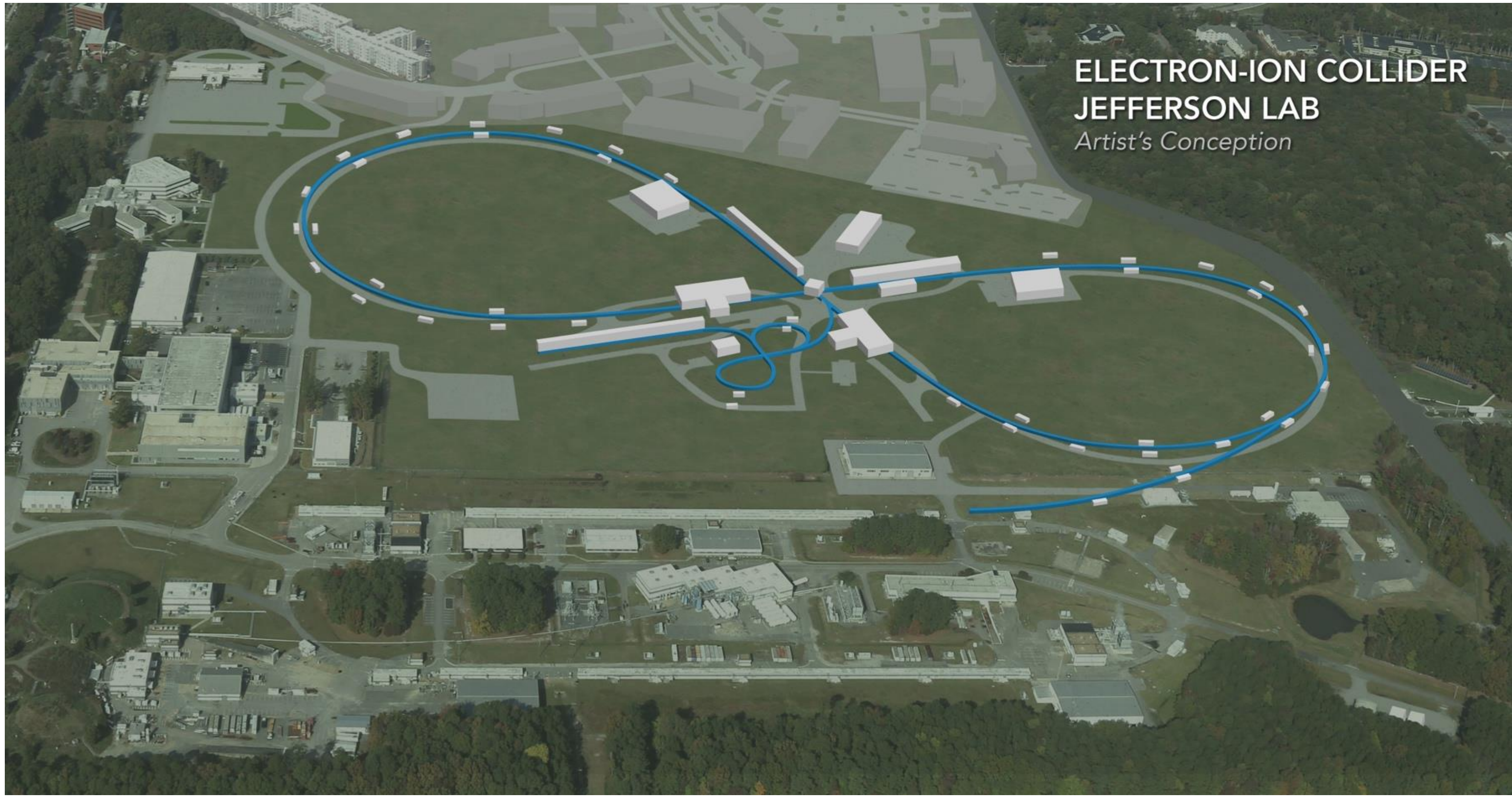
Crab Crossing Design and Simulations

PI: Vasiliy Morozov



FY'17 DoE Accelerator R&D Additional Funding Award

2018 NP Accelerator R&D PI Exchange Meeting

November 13-14, 2018

Outline

- Crab crossing design and simulation project
- Motivation
- Crab crossing parameters and simulation setup
  - Optical parameters
  - Crabbing system setup
  - Cavity turn on time
  - Cavity multipoles
  - Amplitude and phase noise
- Higher-order modes and coupled bunch instabilities
- Beam-beam effect

Crab Crossing Design and Simulation Project

- Description
  - Investigate higher-order mode and impedance requirements for the engineering design of a crab cavity
- Status
  - Completed
- Main goal
  - Specify higher-order mode and impedance requirements for ion crab cavities
- Supported by JLab's Additional DoE NP Accelerator R&D funding
- The project's funding is not continued by the FY'18 NP Accelerator R&D FOA. However, two funded FY'18 projects benefit from this project's results
  - Crab Cavity Operation in a Hadron Ring
  - Development and test of simulation tools for EIC beam-beam interaction

Crab Crossing Design and Simulation Project

- Budget

	FY'16-FY'17	Totals
a) Funds allocated	$58,000	$58,000
b) Actual costs to date	$57,379	$57,379

- Deliverables and schedule

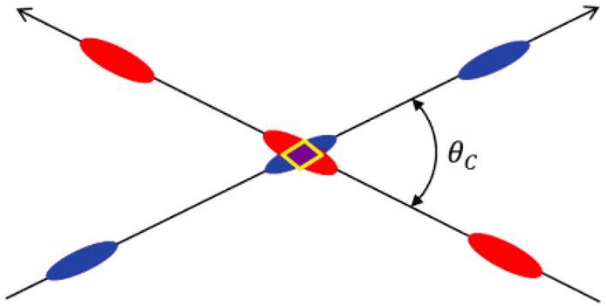
Task	FY'17 Q1	FY'17 Q2	FY'17 Q3	FY'17 Q4
Higher-order mode and impedance specifications	×	×	×	×

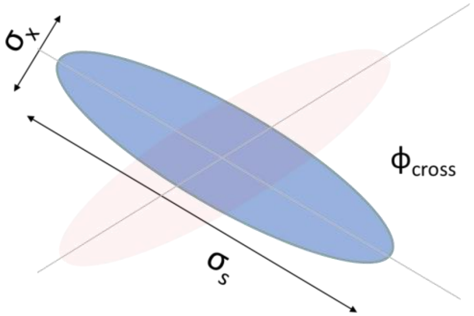
- The project corresponds to Line 1, "Crab cavity operation in a hadron ring", Priority High-A of the Jones' Panel report

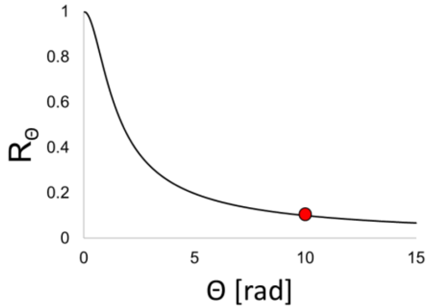
Crossing Angle

- The beams in an EIC must collide at a crossing angle to
  - Allow forward ion detection
  - Improve momentum resolution for hadrons within a few degrees of the ion beam direction
  - Eliminate parasitic collisions of closely-spaced bunches
  - Provide beam separation in the IR to place independent electron and ion magnets
  - Reduce detector background by shortening the common section of the detector beam pipe
- Geometric luminosity reduction factor and Piwinski angle:

$$R_\Theta = \frac{1}{\sqrt{1+\Theta^2}}, \qquad \Theta = \frac{\varphi_{cross}}{2}\frac{\sigma_s}{\sigma_x^*}$$







- In case of JLEIC with a 50 mrad crossing angle, the reduction factor $R_\Theta \approx 0.12$

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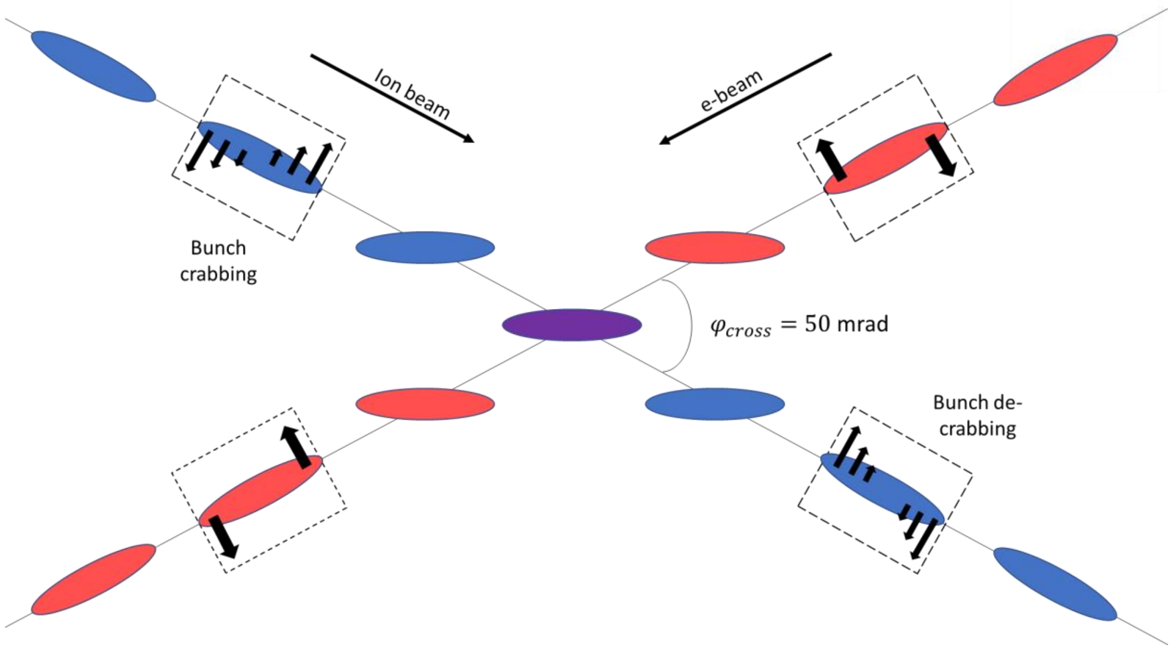
Crab Crossing

- Restores effective head-on collisions and prevents luminosity loss

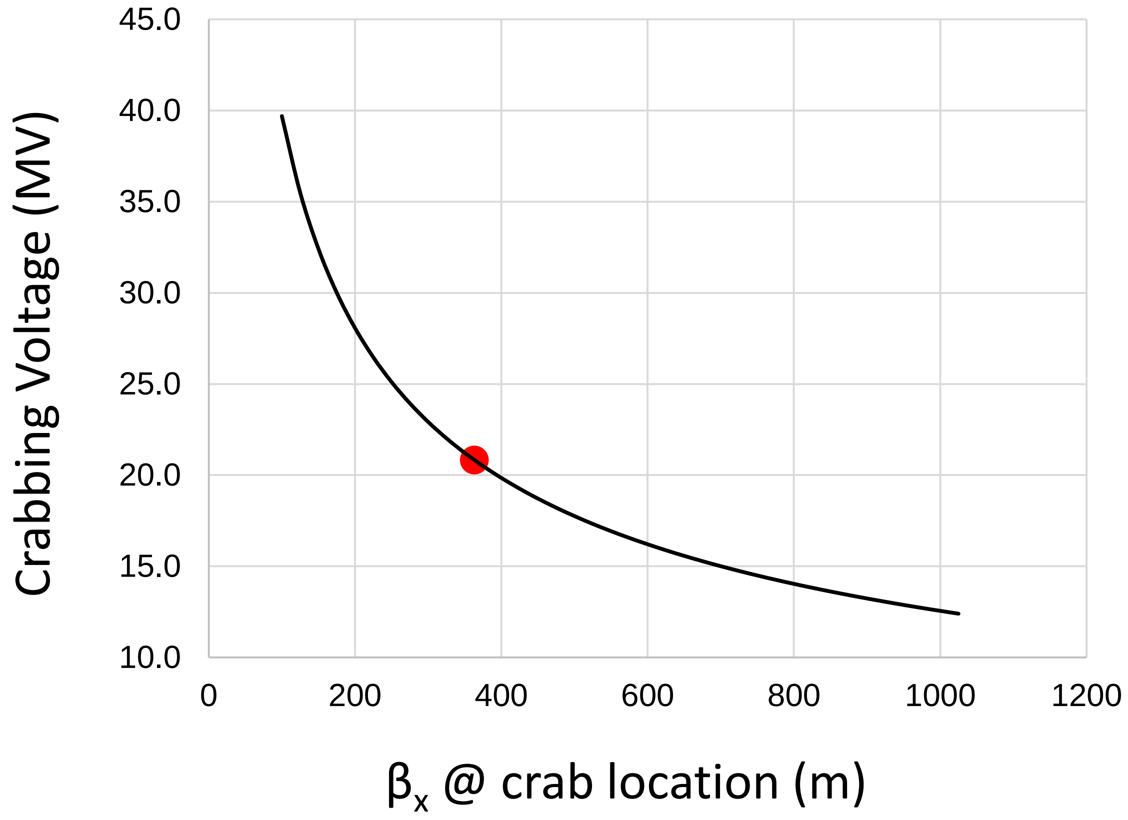


- Required crab kick

$$V_{crab} = \frac{cE_b \tan(\varphi_{cross}/2)}{e\omega\sqrt{\beta_{crab}\beta^*}\sin(\Psi_{CC\to IP})}$$

JLEIC Crab Crossing Parameters

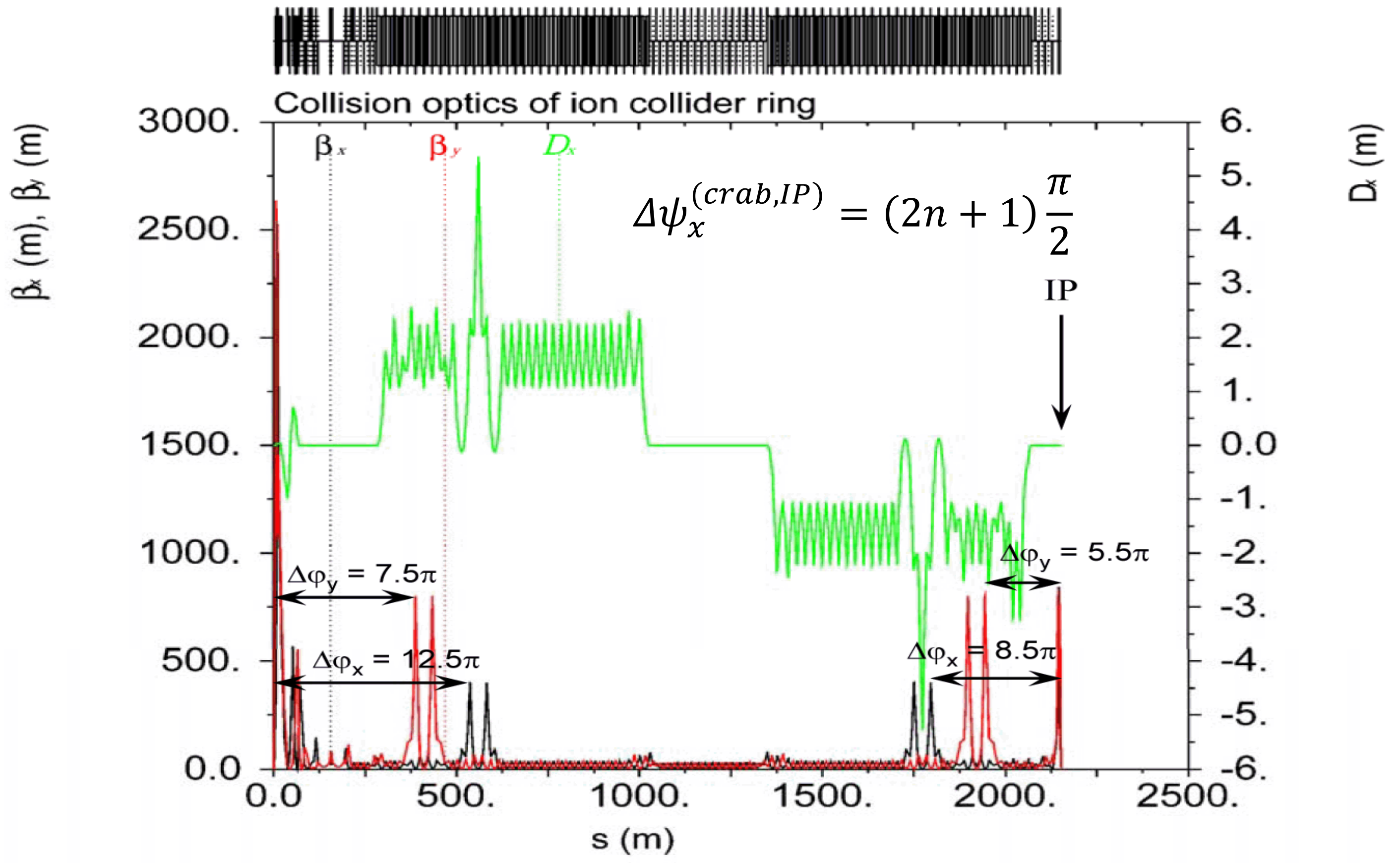
- Required voltage may be reduced by optimizing the ring optics

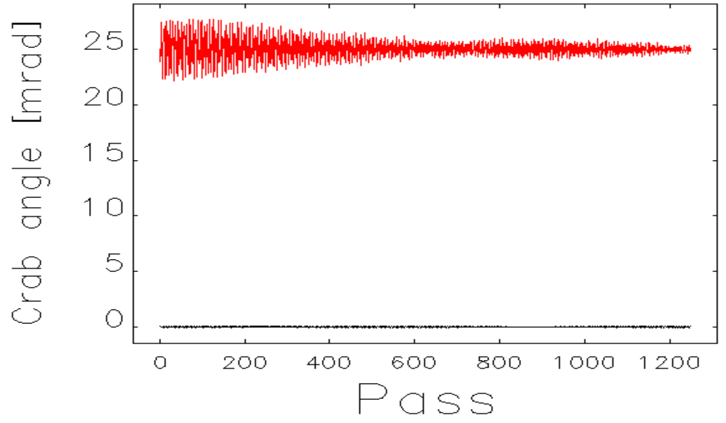


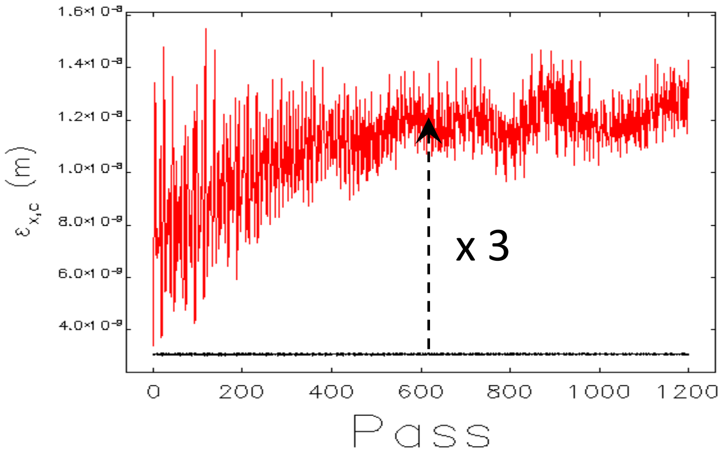
Parameter	Electron ring		Ion ring			Units
Energy	5	10	20	60	100	GeV
Frequency	952.6					MHz
Crossing angle	50					mrad
β_x^*	0.1					m
β_x^{crab}	200		363			m
Crab voltage	1.4	2.8	4.2	12.5	20.8	MV

Initial Ion Colldier Optics Setup

- Crab cavities located near horizontal chromatic sextupoles
- Observe emittance growth due to crabbed beam going through vertical chromatic sextupoles

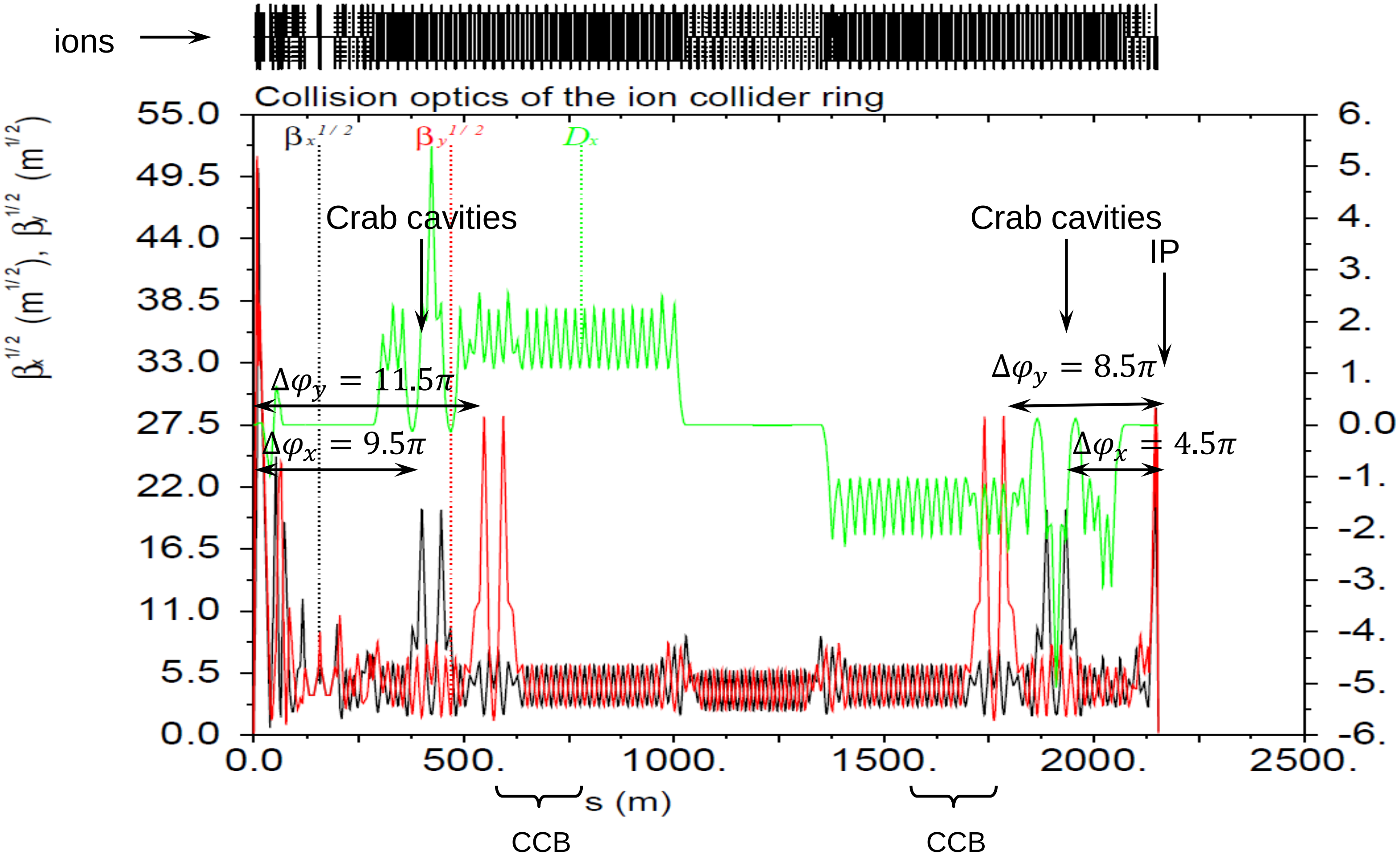


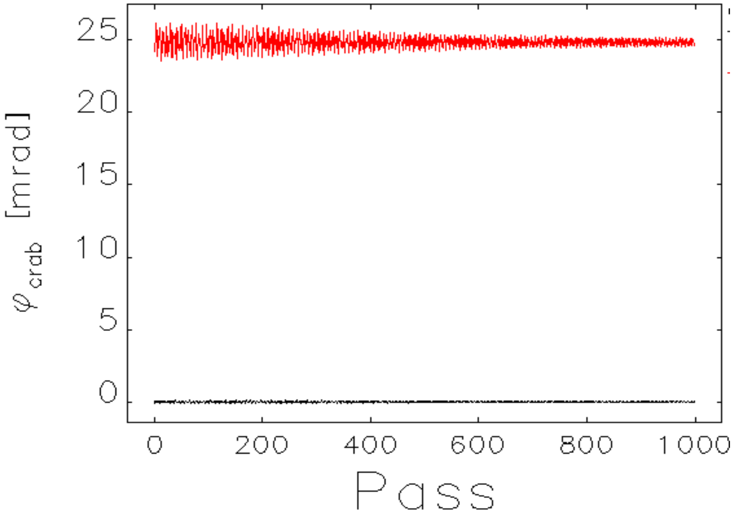


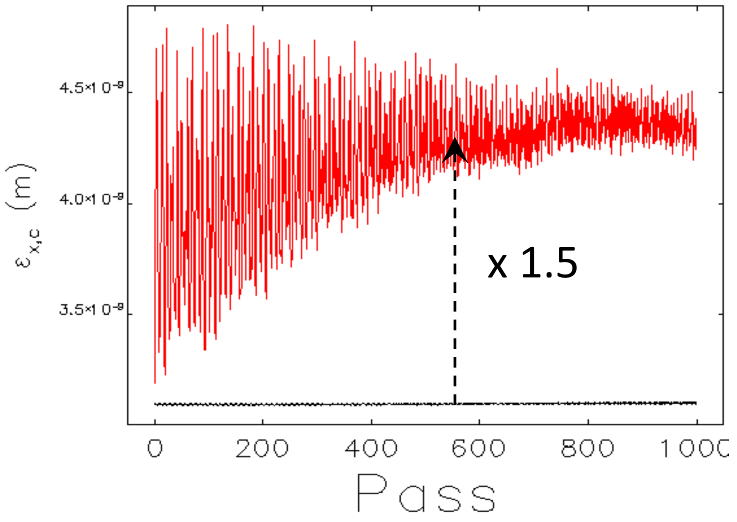


Optimized Ion Collider Optics

- Horizontal and vertical sextupole pairs switched

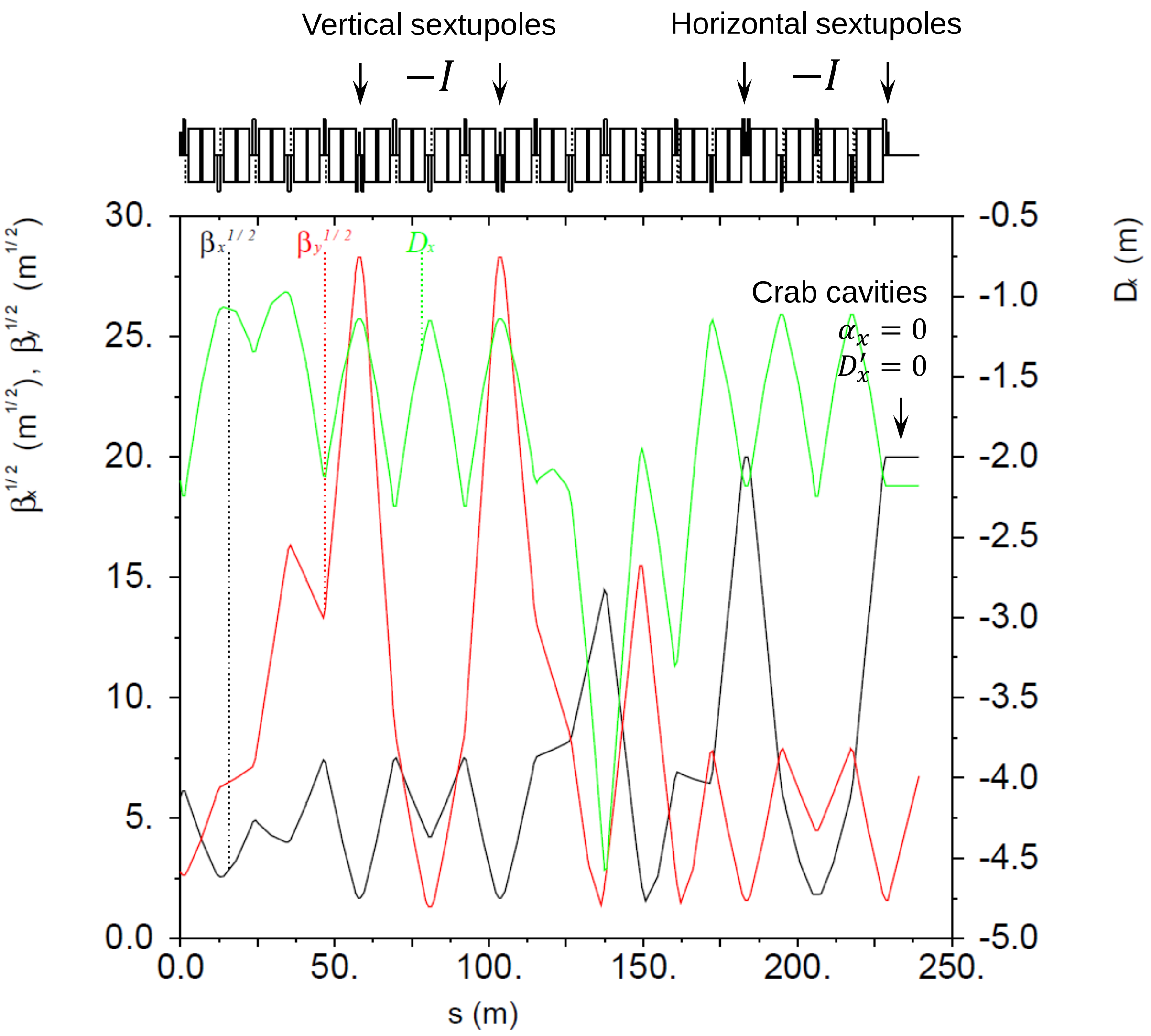






Chromaticity Compensation Block with Space for Crab Cavities

- Initial simulations assumed thin crab cavities
- Design of realistic crab sections in progress
- 10 m reserved for crab cavities
- Optics and space can be optimized for crab crossing



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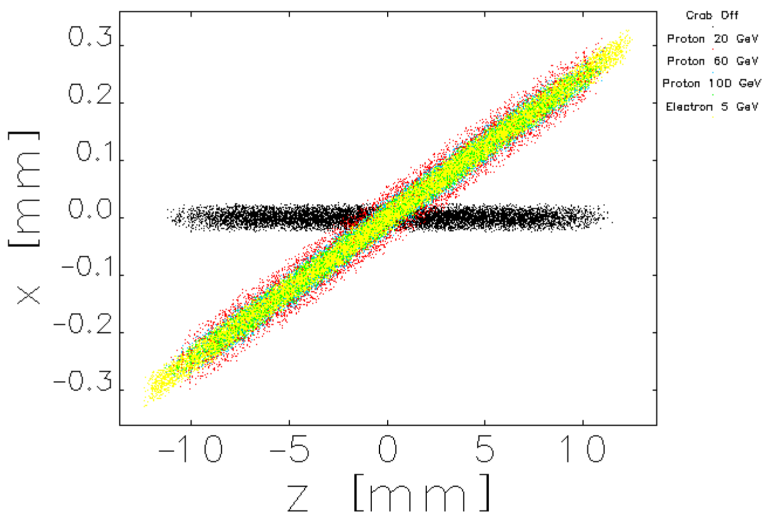
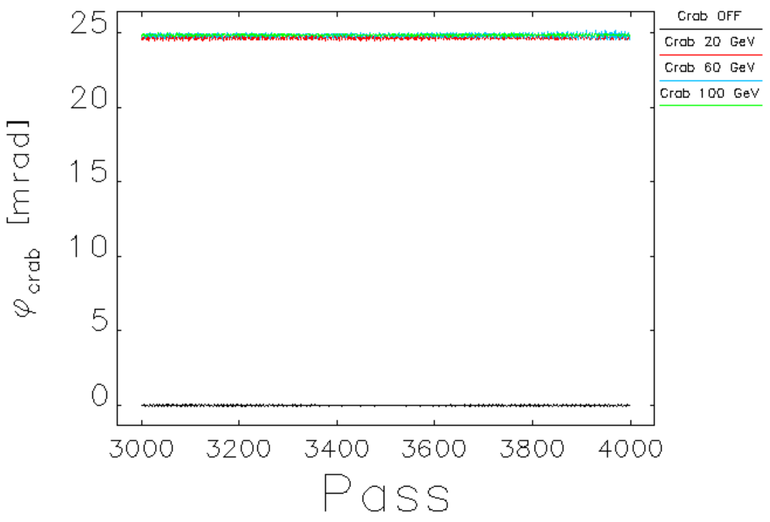
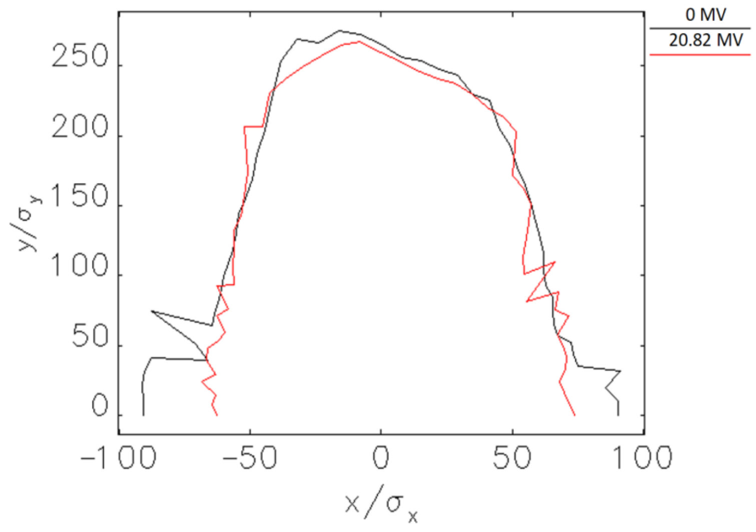
Crab Tilt Simulation

- Observe expected bunch tilt
- No significant impact on the dynamic aperture

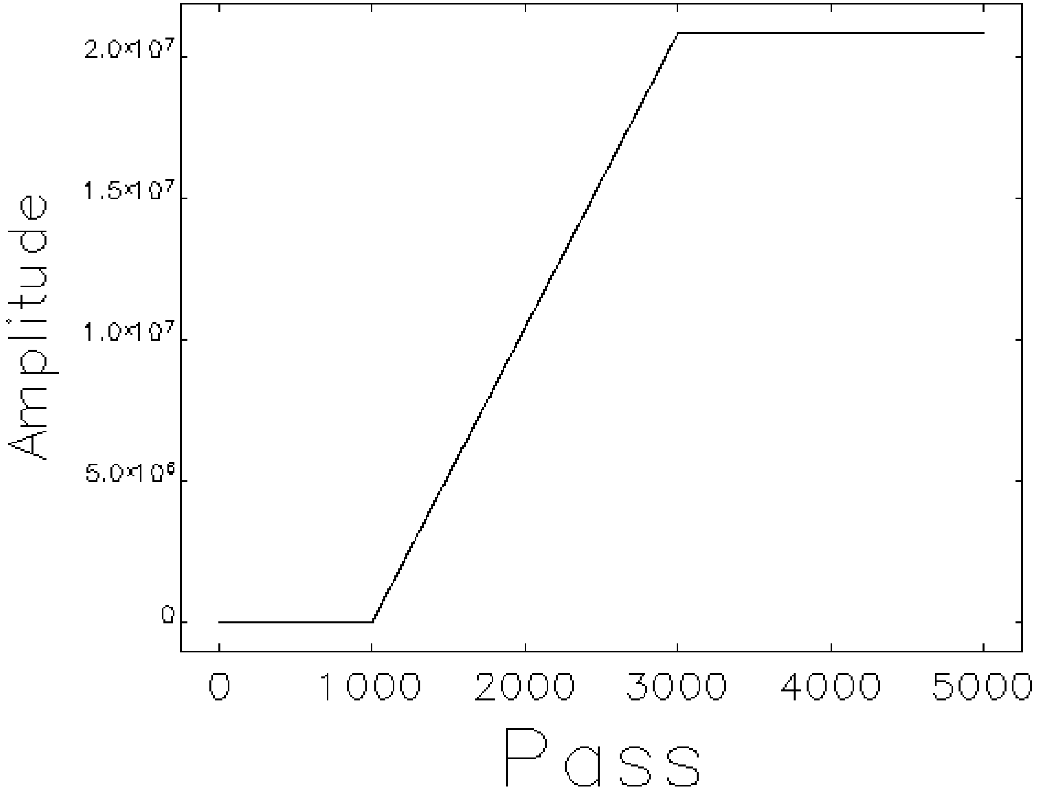


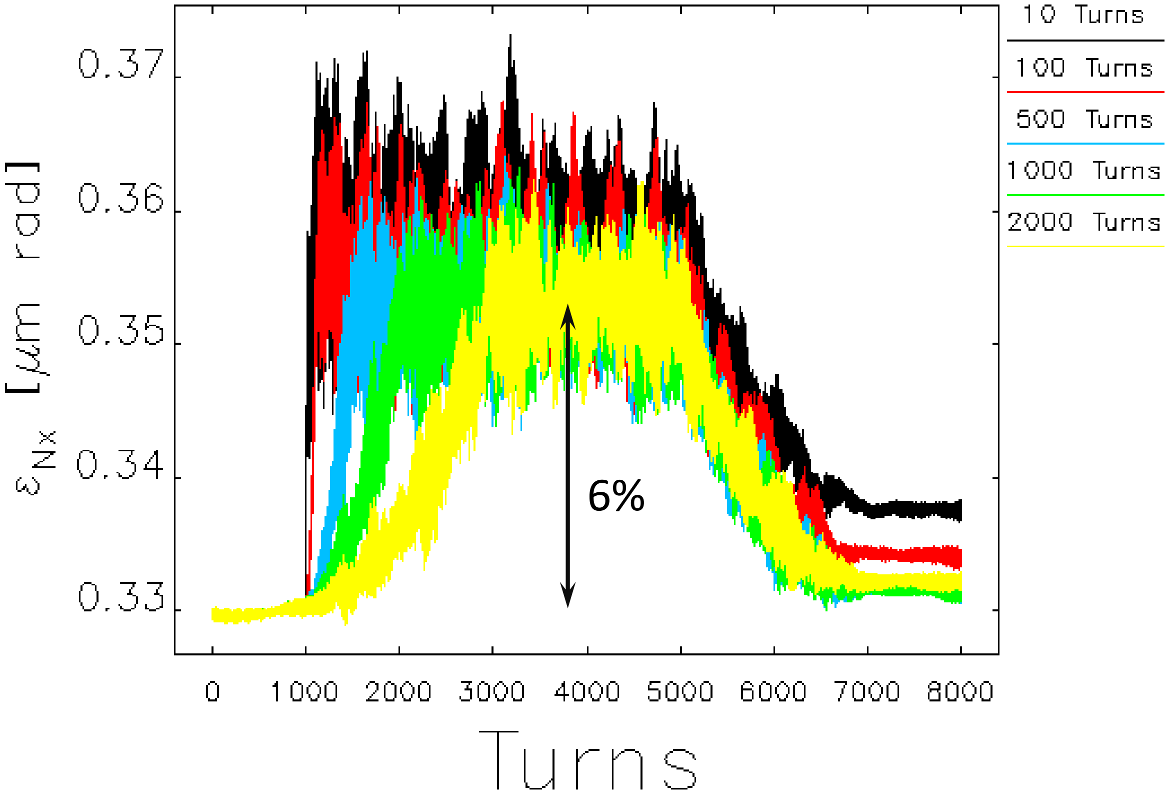




Optimization of Crab Cavity Turn On Time

- Imperfect compensation of the crabbing kick seems to cause transverse-longitudinal coupling leading to correlated increase in the projected emittance
- Fast crab cavity turn-on excites betatron oscillations increasing uncorrelated beam emittance.
- A sufficiently slow turn-on (>500 turns) prevents uncorrelated emittance growth.





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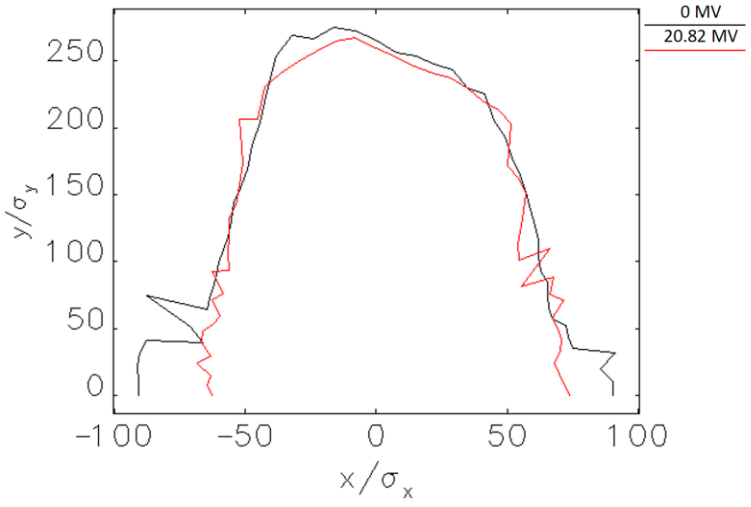
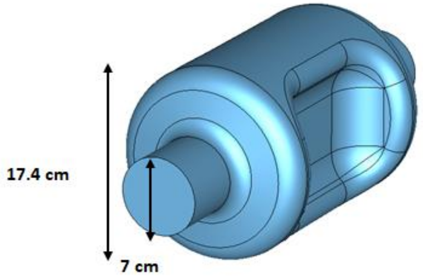
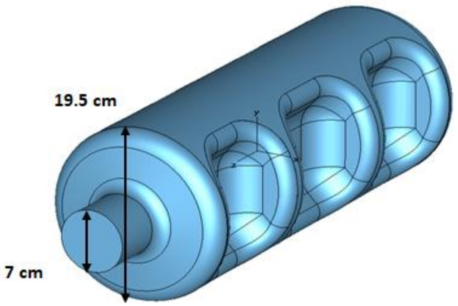
Impact of Crab Cavity Multipoles

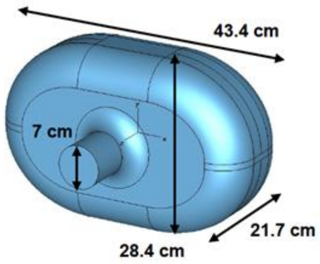
- Transversely uniform crabbing kick
- No impact on the DA

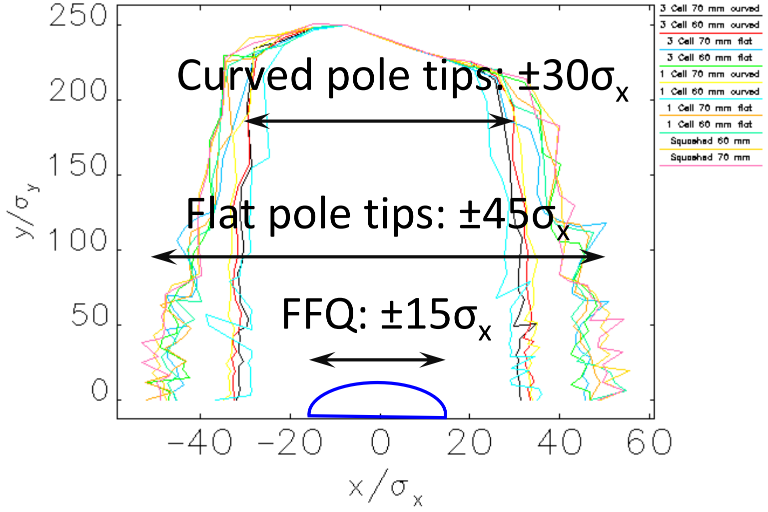
- 1-cell, 3-cell, and squashed crab cavities
- Multipoles are simulated in CST Microwave Studio
- Multipoles do not impose a constraint on the DA

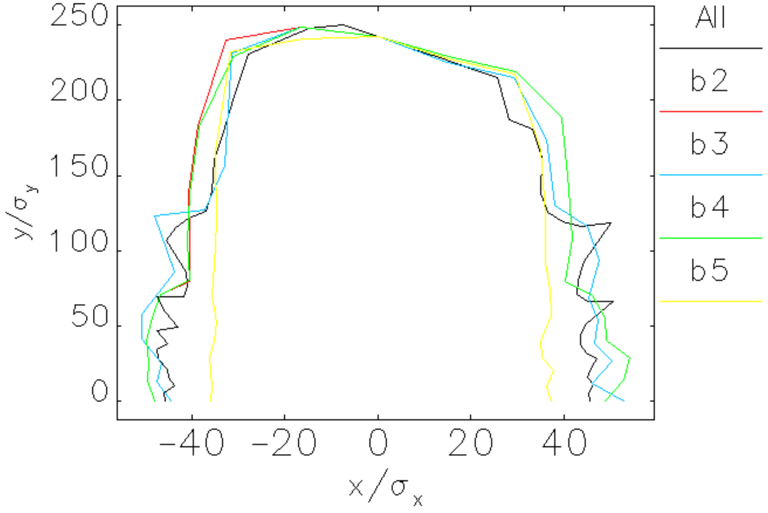








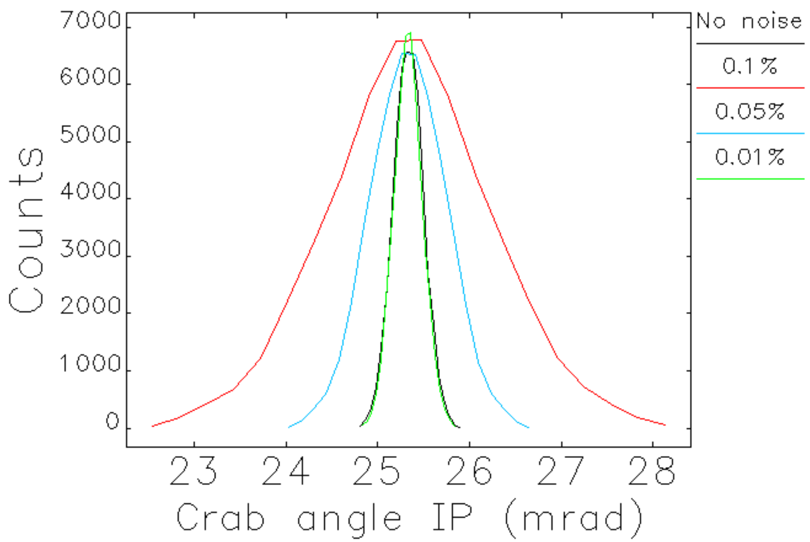


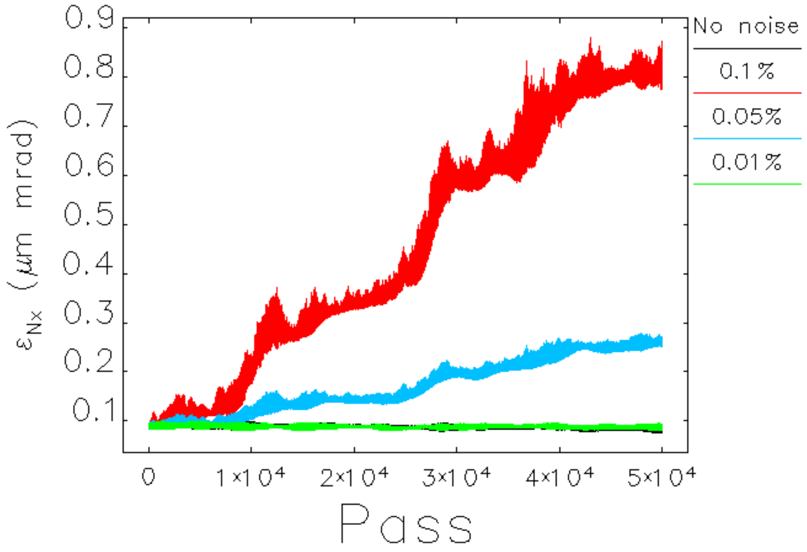


3 Cell 70 mm flat

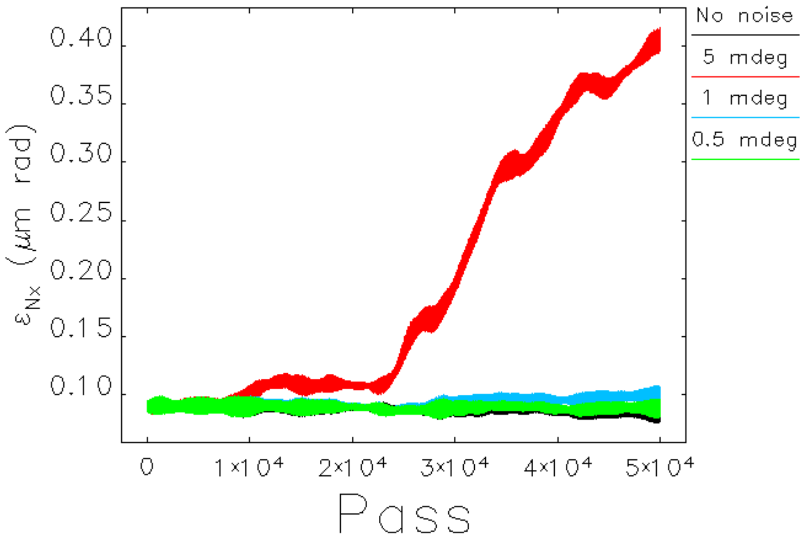
Sensitivity to Amplitude and Phase Noise

- Gaussian amplitude noise



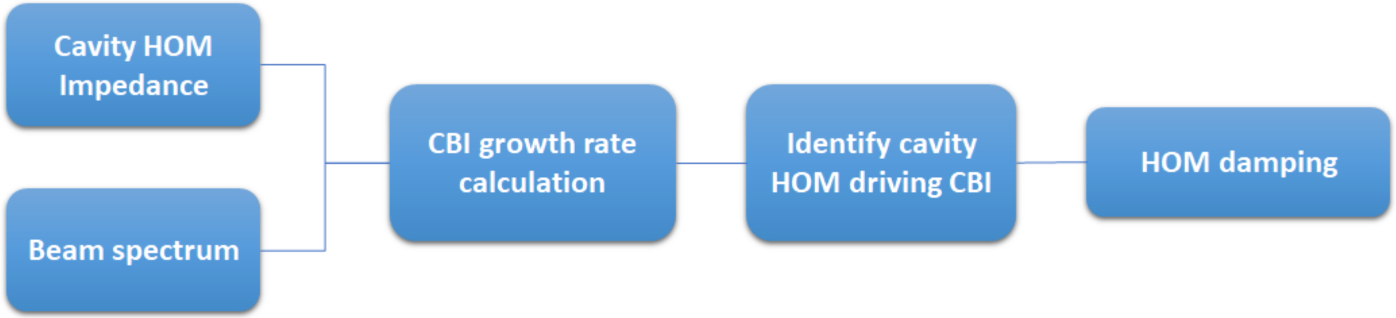


- Gaussian phase noise



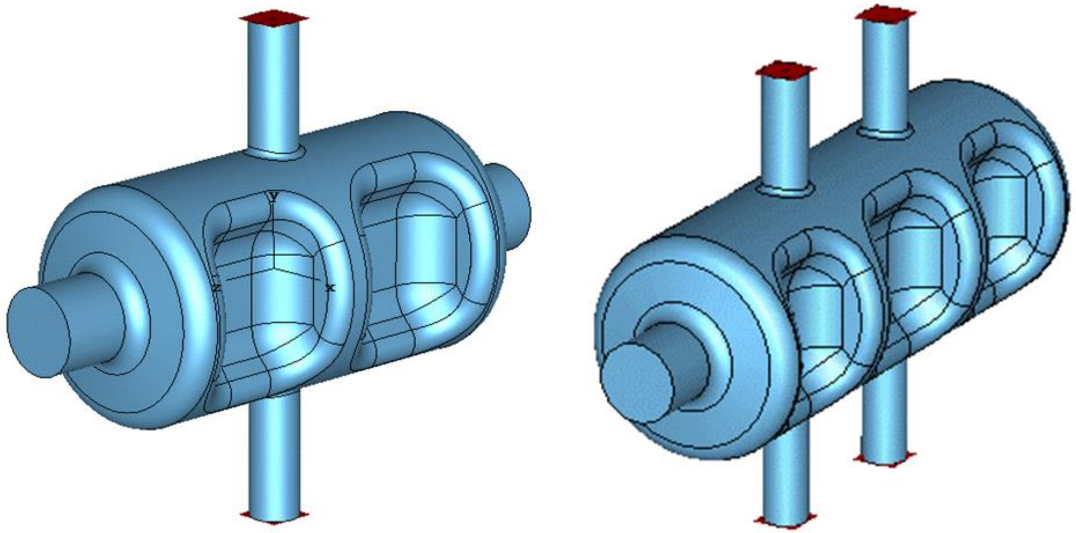
Higher-Order Modes and Coupled Bunch Instability

- An SRF cavity contains a number of resonant higher-order modes which may be excited by a passing beam
- 1 cm long bunches can potentially excite HOMs of up to ~3 GHz
- Oscillations at frequencies below the beam pipe cutoff frequency may get trapped and resonate long enough to interact with subsequent bunches driving bunch oscillations
- A beam consisting of M equally-spaced bunches can have a coupled-bunch oscillation mode μ where $0 \leq \mu < M$ and $2\pi\mu/M$ is the oscillation phase shift between adjacent bunches
- A resonant build-up of coupled bunch oscillations may lead to a coupled bunch instability
- We evaluate the growth time of different coupled bunched modes based on the beam spectrum and the cavity HOM impedance

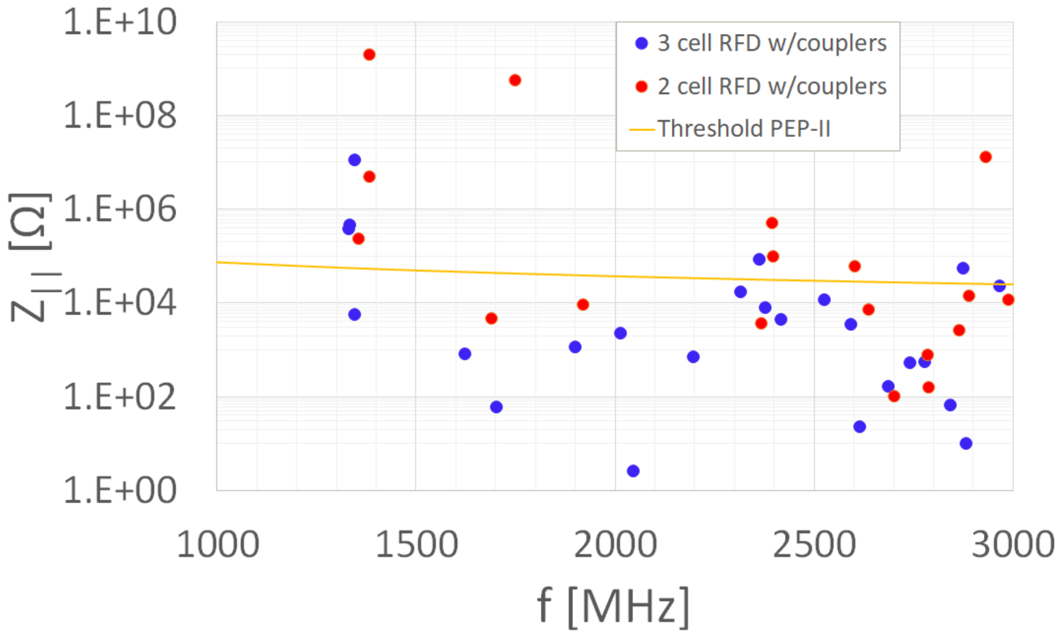


Impedance of Longitudinal HOMs

- 2- and 3-cell crab cavities with coaxial couplers



- Impedance of longitudinal HOMs



Coupled Bunch Instability Growth Times

- Narrow-band impedance

$$Z_{\parallel}(\omega) = \sum_k \frac{R_k}{1 + iQ_k\left(\frac{\omega_k}{\omega} - \frac{\omega}{\omega_k}\right)}$$

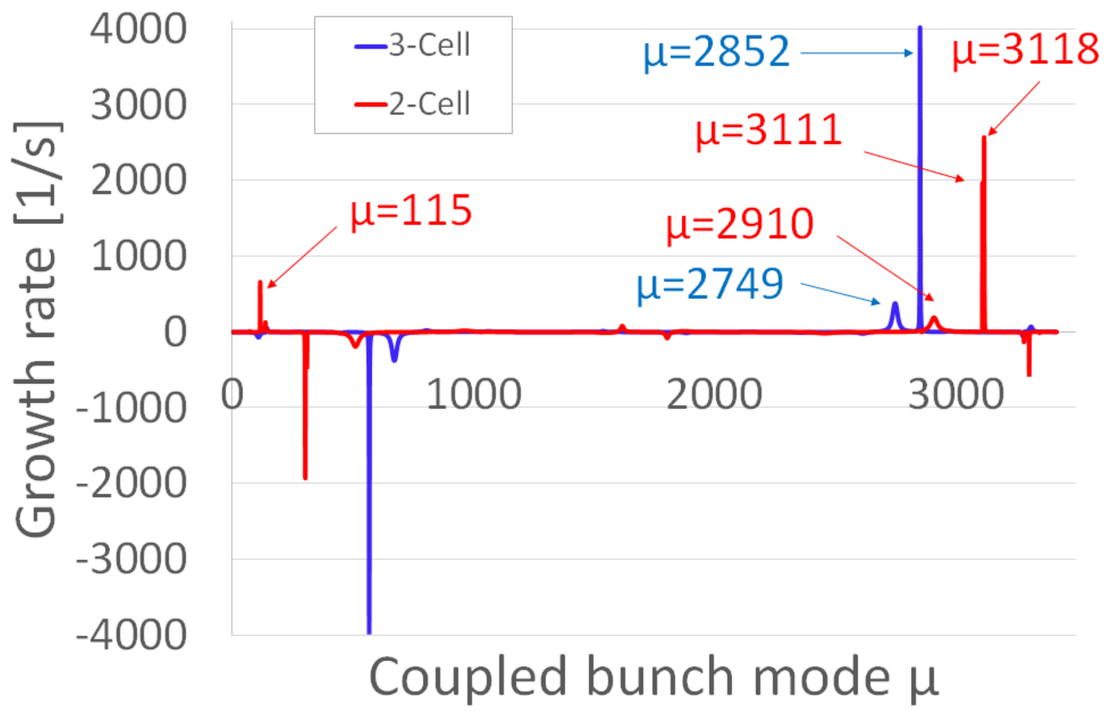
R_k, Q_k, and ω_k are obtained from a cavity simulation

- The beam frequency spectrum given by $\omega_{p,\mu} = (pM + \mu)\omega_0 + \omega_s$ is folded with the real part of the longitudinal impedance to evaluate the coupled bunch instability growth times

$$\tau_{\parallel}^{-1} = \frac{I_b \omega_0^2 \eta}{6(L/2\pi R)^3 2\pi\beta^2 (E/e)\omega_s} \sum_p \frac{Re\{Z_{\parallel}(\omega_p)\}}{\omega_p/\omega_0} \frac{h_a(\omega_p)}{S_a}$$

Coupled Bunch Instability Growth Rate

- Determined modes requiring HOM damping down to the level where they can be handled the Landau damping and/or a feedback system



Mode	μ	p	Beam $f_{\mu,p}$ (MHz)	HOM f (MHz)
2-cell cavity				
1	3118	2	1384.17	1385
2	3111	2	1383.2	1385
3	115	6	2868.27	2866
4	2910	2	1355.26	1357
3-cell cavity				
1	2852	2	1347.2	1349
2	2749	2	1332.89	1334
3	2749	5	2759.02	2743

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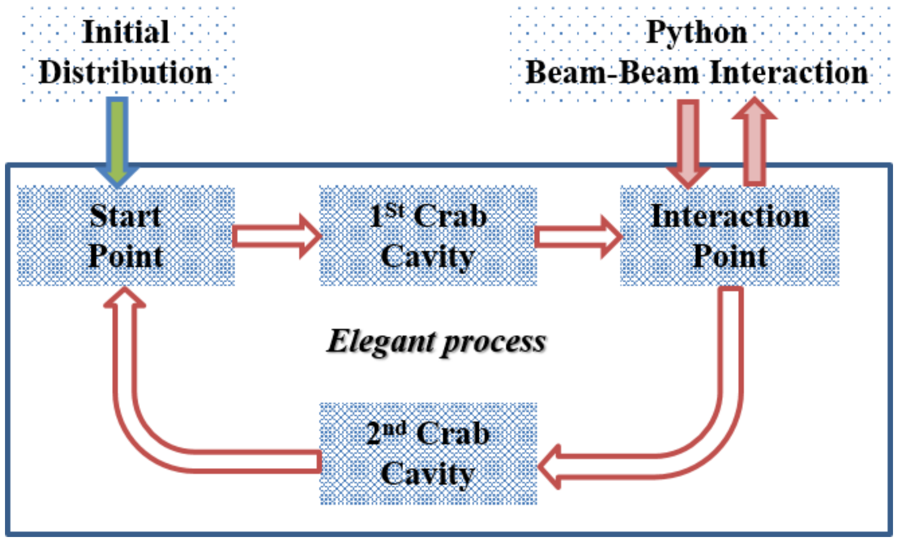
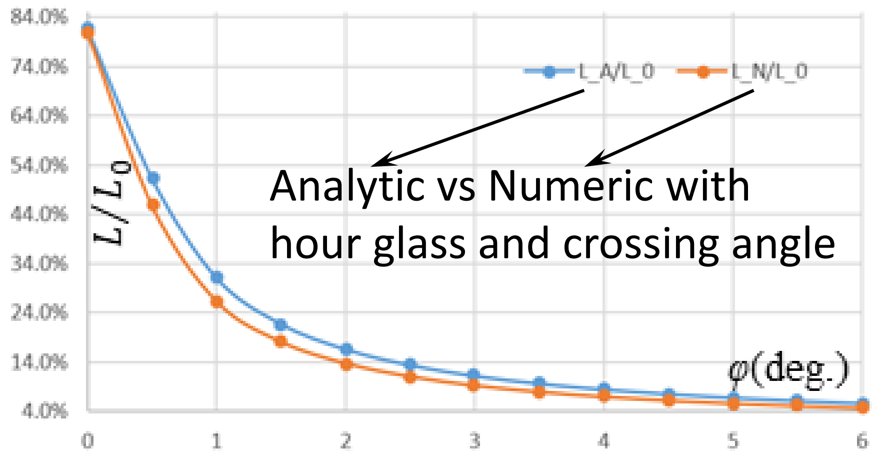
Beam-Beam Effect

- Beam-beam may speed-up damping or cause additional resonances and needs to be studied
- Beam-beam model: multiple longitudinal slices interacting pair-wise according to Bassetti-Erskine
- Code implemented in Python and accounts for
  - Bunch tilt
  - Bunch offset
  - Bunch length
- Reads and outputs SDDS files
- Easy interface to Elegant
  - Accurate beam dynamics around the ring
  - Access to all features of Elegant
- Has recently been benchmarked against analytic calculations





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Summary

- JLEIC crabbing system has been setup
- Crabbing dynamics has been studied in simulations
- One must avoid strong non-linear fields in the crabbed region
- Considered the effects of
  - Cavity turn on time
  - Cavity multipoles
  - Amplitude and phase noise
- Developed specifications for HOM damping
- A small number of HOMs requires development of dedicated dampers
- Introduced the beam-beam effect into simulations
- The results and developed tools will be used in
  - Crab Cavity Operation in a Hadron Ring
  - Development and test of simulation tools for EIC beam-beam interaction