Status of JLEIC R&D at SLAC

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Introduction
- Project tasks and goals
- Budget
- Milestones and schedule
- Interaction Region design and optimization
  - Masking and beam pipe design
  - Synchrotron radiation assessment
- Non-linear beam dynamics for the electron collider ring
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Introduction

JLEIC collider design specifications include

- High-current electron beam (0.7 – 3 A) over a wide energy range (3 – 10 GeV)
- Interaction Region (IR) with extreme forward detectors and polarimetry
- Low-beta IR and low emittance electron ring lattice for high luminosity (10^{33} – 10^{34} $cm^{-2}s^{-1}$)

The challenges are the IR design satisfying multiple beam conditions, synchrotron radiation (SR) background in the detector, compensation of non-linear optics effects, and design of low emittance lattice with sufficient dynamic aperture

SLAC has an expertise in the design and operation of high-current e^+e^- colliders (PEP-II), as well as experience with other collider designs (ILC, MAP, FCC), applicable to the JLEIC design. Specific to the above challenges, SLAC team can provide support in these areas:

- **IR design**, including machine-detector interface, masking and beam pipe design, synchrotron radiation (SR) background and power issues
- **Beam dynamics**, including IR low-beta optics, low emittance lattice, compensation of non-linear effects, dynamic aperture optimization, error analysis, and tolerance specifications

Project tasks and goals

Tasks

- Lattice design and non-linear beam dynamics (Y. Cai, Y. Nosochkov)
- Interaction region design and optimization (M. Sullivan)

Goals

- Baseline design of the electron collider ring lattice with non-linear chromaticity correction satisfying a low beam emittance and sufficient dynamic aperture
- IR design with acceptable SR background in the detector over the JLEIC range of electron beam energies and optics conditions

Budget

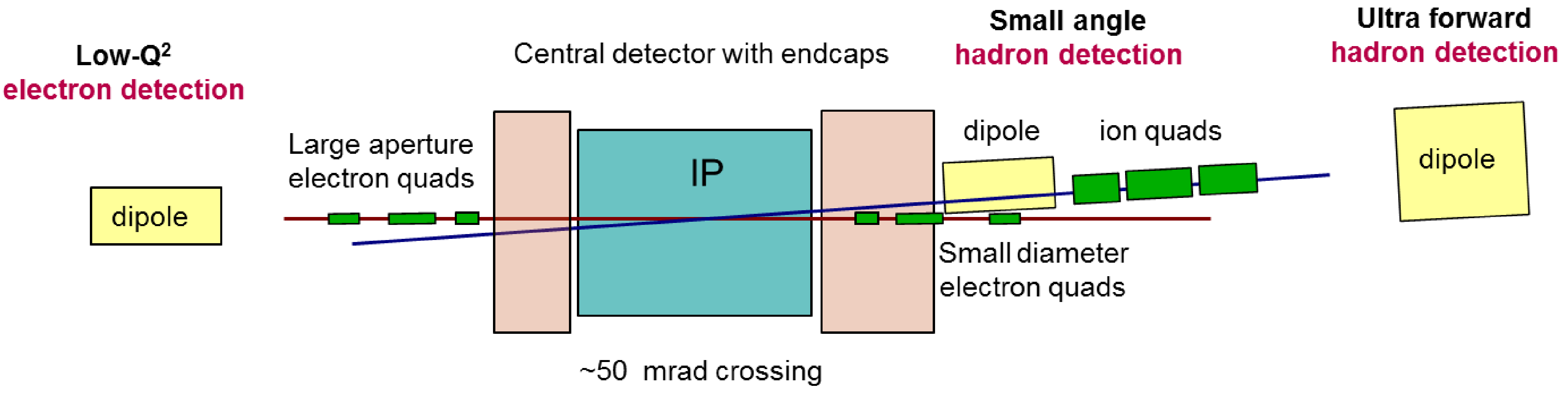
Summary of expenditures by fiscal year for SLAC

	FY12+FY13	FY14+FY15	FY16+FY17	Totals
Funds allocated	**158.5k** (75.5k+83k)	**268k** (134k+134k)	**80k** (80k+0)	**506.5k**
Actual costs	**79k** (0+79k)	**183k** (59k+124k)	**244k** (185k+59k)	**506k**

FY17 milestones and schedule

Milestones	**Schedule**	**Priority designation from 2017 Jones report**			
		Row	**Title**	**Priority**	**Sub-Priority**
Non-linear chromaticity compensation for the low emittance electron collider ring	Q1-Q2	53	Nonlinear beam dynamics in ion and electron rings	Medium	
IR design and optimization	Q1-Q2	44	IR design and detector integration	High	
Dynamic aperture and field quality tolerances for the electron collider ring	Q1-Q3	53	Nonlinear beam dynamics in ion and electron rings	Medium	
Documentation of the studies	Q3-Q4	53	Nonlinear beam dynamics in ion and electron rings	Medium	

Status of IR design optimization

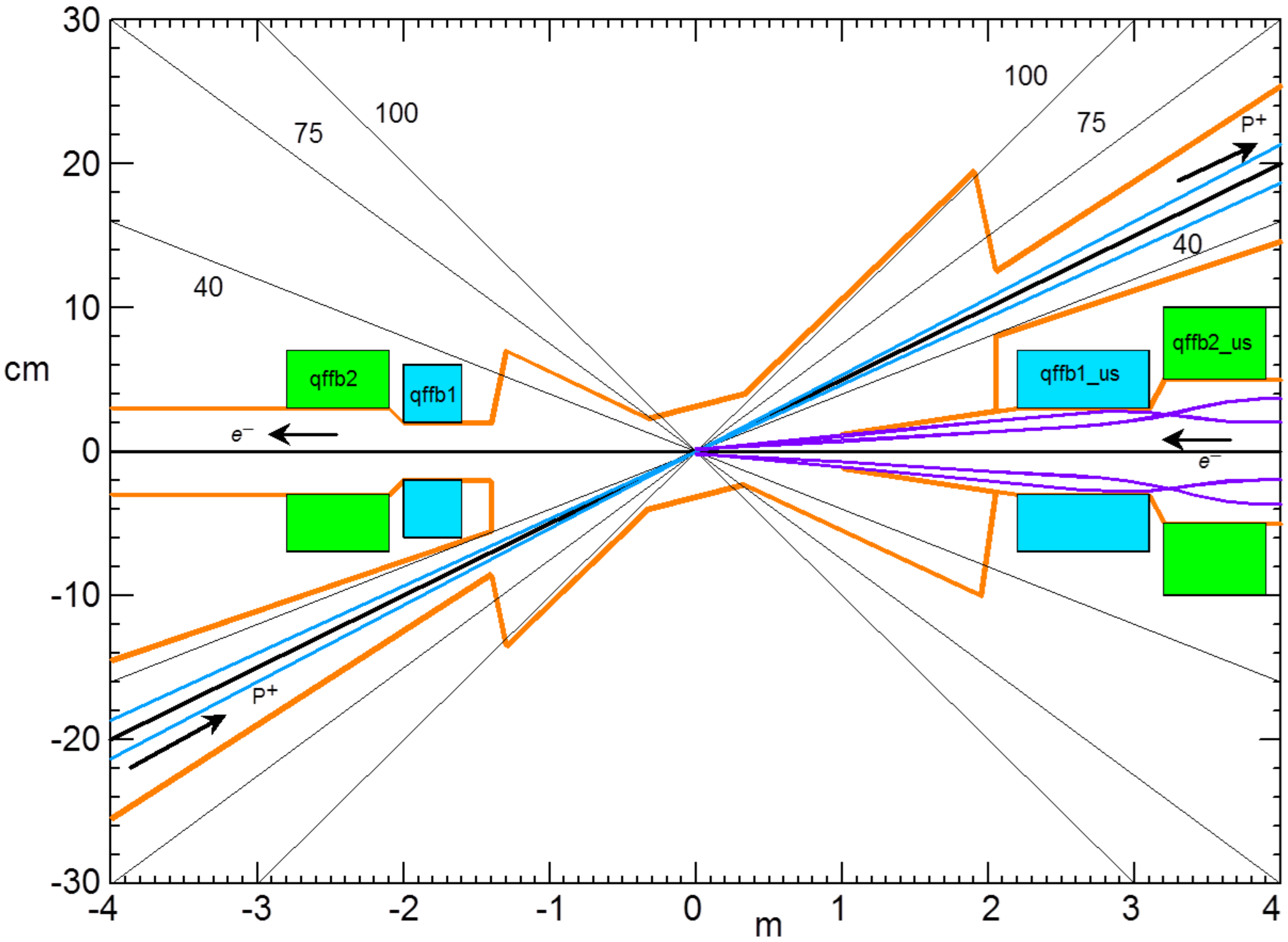


Detector layout

The JLEIC design calls for a high-current (0.7 – 3 A) electron beam over a wide energy range (3 – 10 GeV)

- **This is unique and makes designing a single IR challenging**
  - **The B-factories were fixed energy machines**
- **SR masking and beam pipe design has to be compatible with different beam conditions (current, energy , β*)**

Initial IR beam pipe design with SR masking



- Mask is 1 m upstream of the IP on the electron beam line with a radius of **12 mm**
- Detector central beam pipe with **+/-33 cm length** and **3cm radius**
- The central pipe axis is between the two beams, at **±25 mrad angle relative to the beams**
- The central pipe at the downstream end is 22 mm from the electron beam
- **The mask taper on the upstream side is too shallow** – the surface can scatter incident photons directly to the central chamber

Courtesy of C. Hyde (ODU)

SR calculations

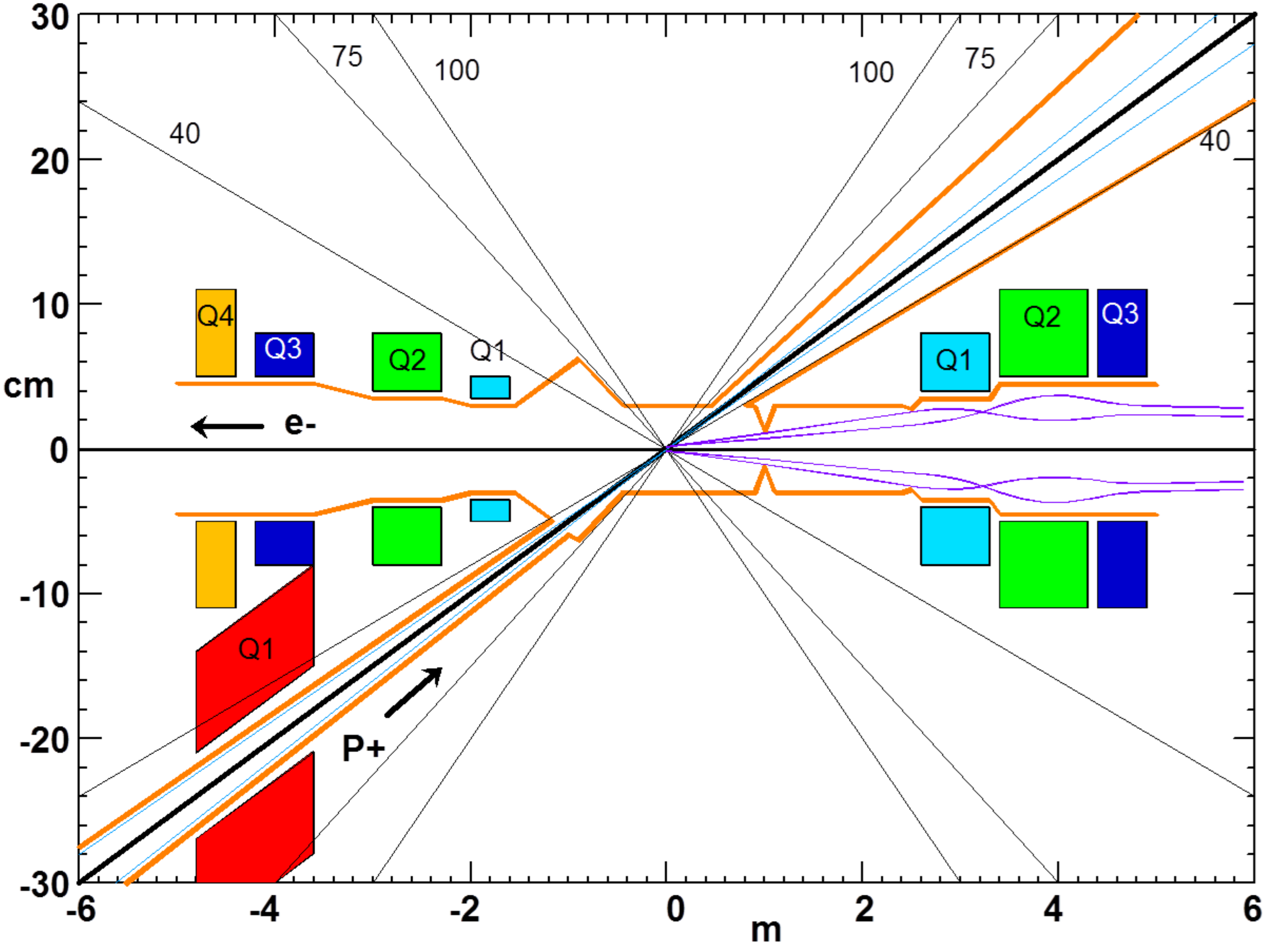
In all studies

- Mask is 1 m upstream of the IP on the e- beam line with a radius of **12 mm**
  - This aperture is ≈50σ in X and Y
  - **The mask picks up significant power and must be cooled**
- Particles are traced out to 15σ / 25σ in X / Y for the 5 GeV beam, fewer for the 10 GeV case
- Beam model includes **non-gaussian beam tail** distribution
- Central beam pipe with **3 cm** radius

Conclusions for the initial pipe design

- **SR rates on the central beam pipe for the 5 GeV beam**
  - Total of 4200 x-rays per bunch incident on the central chamber
  - Only 64 of these photons per crossing are >10 keV – **acceptable**
- **For the 10 GeV beam**
  - Total incident is $1.1\text{x}10^5$ photons/crossing
  - 3300 photons/crossing are >10 keV – **probably not acceptable**

New beam pipe proposal



- As minimal adjustments to the initial C. Hyde design as possible
- Central chamber is **longer (+/-45 cm)** and **on axis with the electron beam**
- **Steeper angle in upstream part of the mask** at Z = 1 m
- Adjustments to **reduce HOM issues**
- Mask and beam pipe need **cooling**
- Central chamber is **easier to shield**
- **No hits on the central chamber at 5 GeV**
- 3400 hits / crossing on the central beam pipe at 10 GeV, with 1200 hits at >10 keV
- **SR rates at 10 GeV may be not low enough (?)**
- Feedback from the detector team is needed to iterate on the design

SR rates at lower β*

Lattice set-up

- Previous studies used β* = 10 / 2 cm in X / Y
- **Lower β* = 5 / 1.0 cm at 5 GeV**
  - Max BSC ($17\sigma_x$ / $44\sigma_y$) = 33.3 / 39.7 mm
- **Lower β* = 4 / 0.8 cm at 10 GeV**
  - Max BSC ($11\sigma_x$ / $18\sigma_y$) = 50.1 / 36.0 mm
- Matched lattice was not yet ready → used **local lattice optimizer for first order check**
- **Large BSC** even with reduced number of sigmas

Preliminary SR background results

- **5 GeV** → **OK** on central chamber with hits just starting at Z = 45 cm (<0.01 hits/xing)
- **10 GeV** → Hits on the central chamber starting at the IP (Z=0), with $3.9\text{x}10^4$ hits/xing on downstream half of the chamber → Most likely **unacceptable**
- The 10 GeV rate decreases to **7474 hits / crossing** if mask aperture is reduced from R = 12 to 10 mm
- A shorter ±30 cm central chamber with a 10 mm radius mask drops the rate to **1299 hits / crossing**

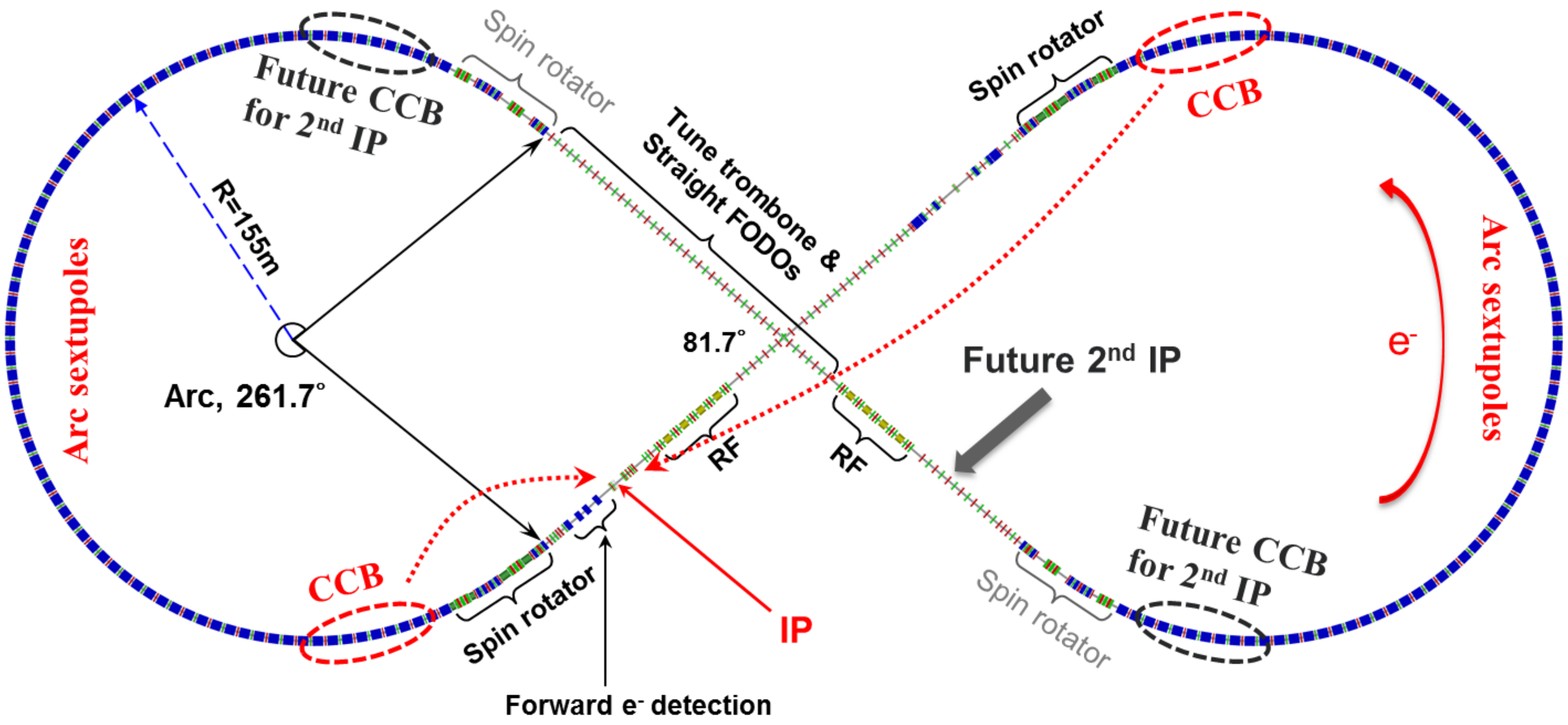
Discussion

- **Non-gaussian beam tail is the main source of the SR background**
- The SR model uses a **conservative distribution** corresponding to a **beam lifetime of ~1 hour** and **$15\sigma_x$ mask aperture**
- **The tail distribution is not precisely known** → Changes of the tail profile and/or mask aperture can significantly affect the SR rates

Beam dynamics in the electron collider ring

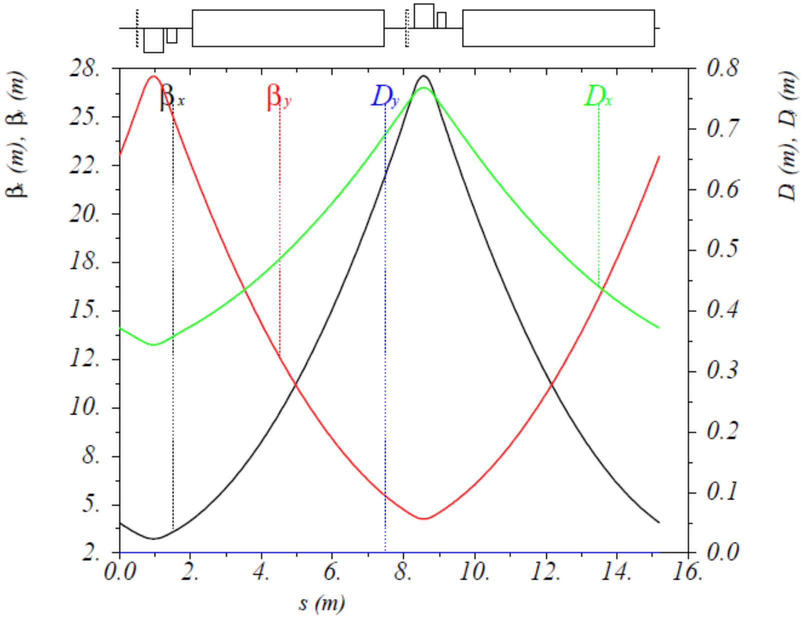
Study topics

- **Low emittance lattice**
  - Arcs
  - Non-linear chromaticity correction blocks (CCB)
- **Non-linear chromaticity correction**
  - Chromatic tune shift
  - Chromatic β*
- **Dynamic aperture**
  - Energy dependence
  - Betatron tune
  - Non-linear effects
  - Field quality



Selection of low emittance arc lattice

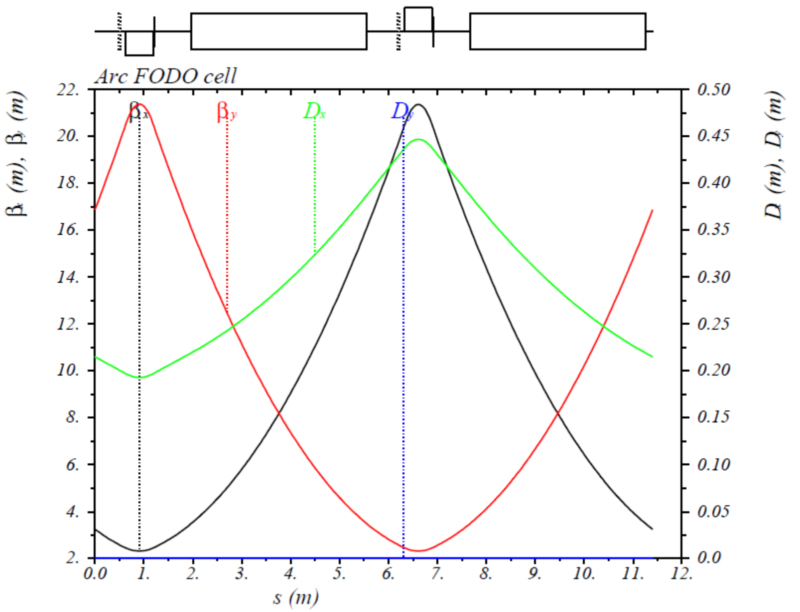
FODO cell with PEP-II magnets
L = 15.2 m, ε = 9 nm at 5 GeV



Pros: good dynamic aperture, existing magnets

Cons: large emittance ε, momentum compaction α_p, sagitta

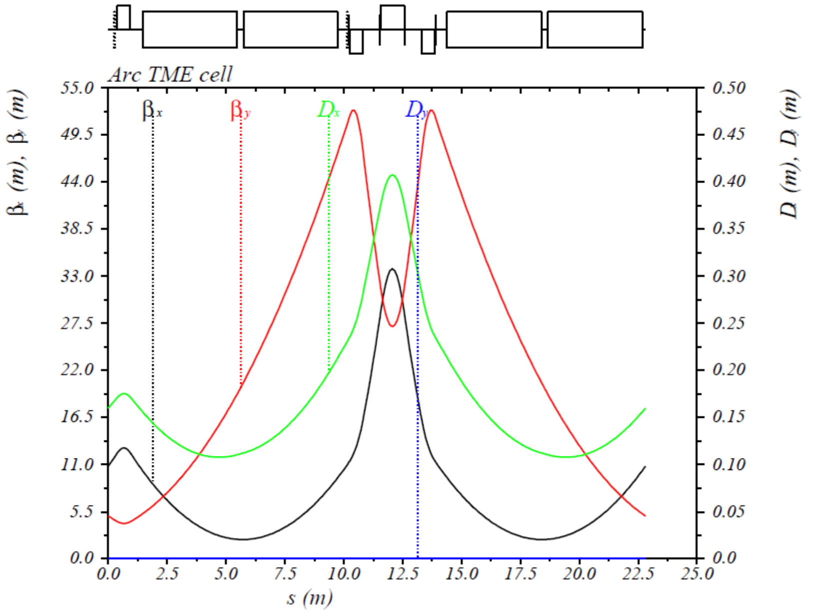
FODO cell with new magnets
L = 11.4 m, ε = 5.5 nm at 5 GeV



Pros: small enough ε, α_p, sagitta, good DA, reasonable strengths quads

Cons: new magnets

TME cell with new magnets
L = 22.8 m, ε = 3.2 nm at 5 GeV



Pros: smallest ε, α_p, sagitta

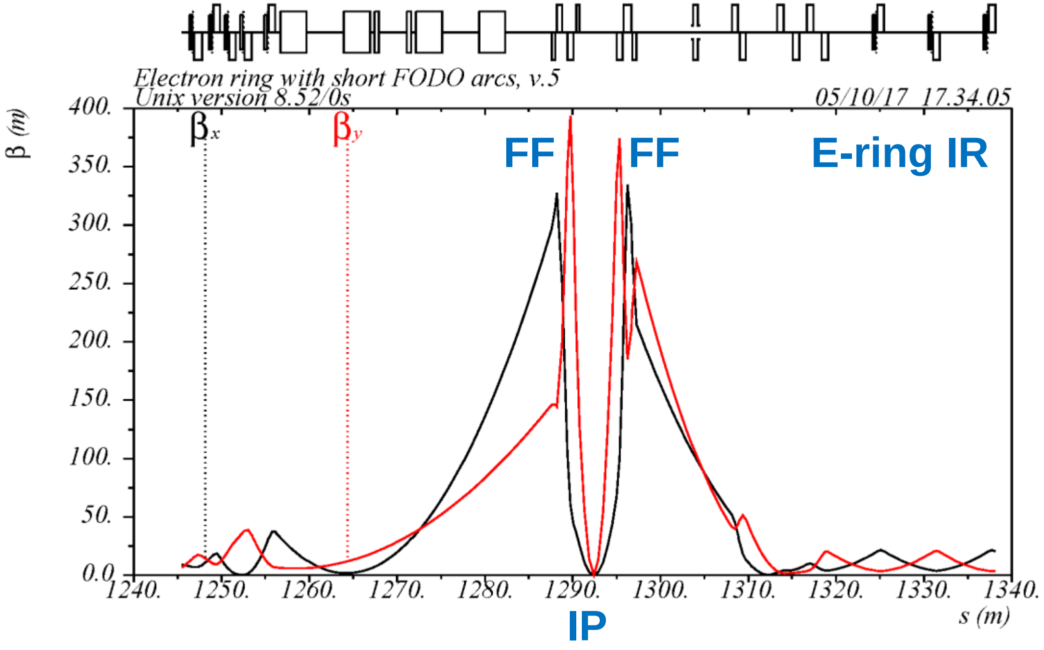
Cons: DA may not be large enough, strong quads, new magnets

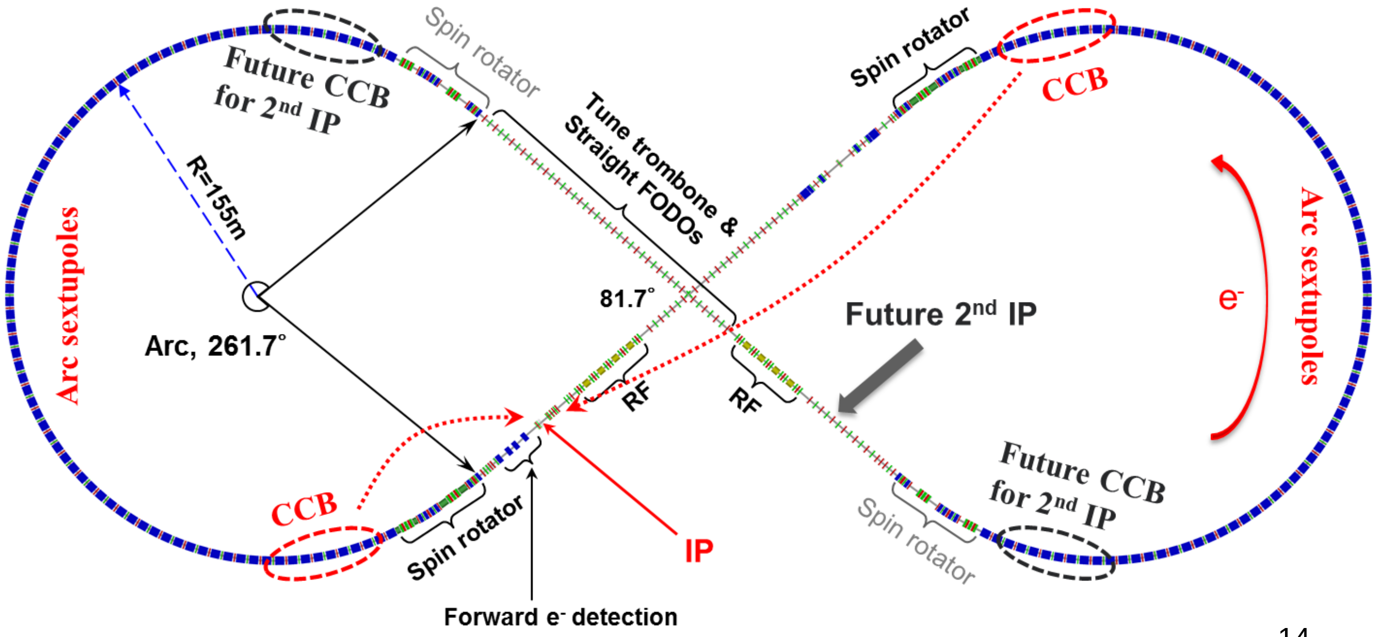
Electron ring lattice designs with arc cells based on long FODO, short FODO, and TME optics are studied in detail.

The short FODO 108° cells provide the best overall performance → This lattice is now the Baseline.

Non-linear chromaticity correction blocks (CCB)

- CCBs contain **dedicated sextupoles to locally correct large chromatic effects created by the final focus (FF) quads**, where β functions are high → **FF linear chromaticity, chromatic beta perturbation, non-linear chromatic tune shift** which can limit dynamic aperture, beam lifetime and luminosity
- **Two CCBs are required** to cancel the non-linear chromatic perturbation at IP and in the rest of the ring
- CCB sextupoles require non-zero dispersion and should be as close as possible to the FF → **nearest suitable locations are at the arc ends**
- Two additional CCBs are reserved at the other arc ends for a future 2nd IP

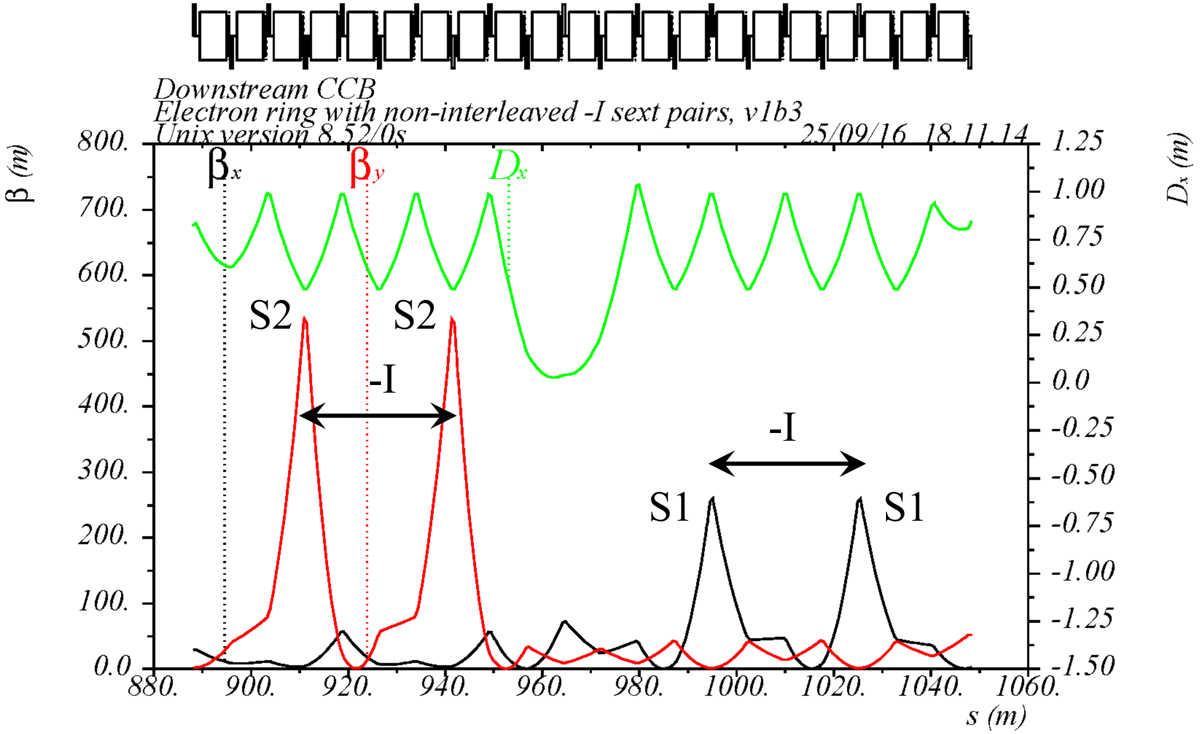




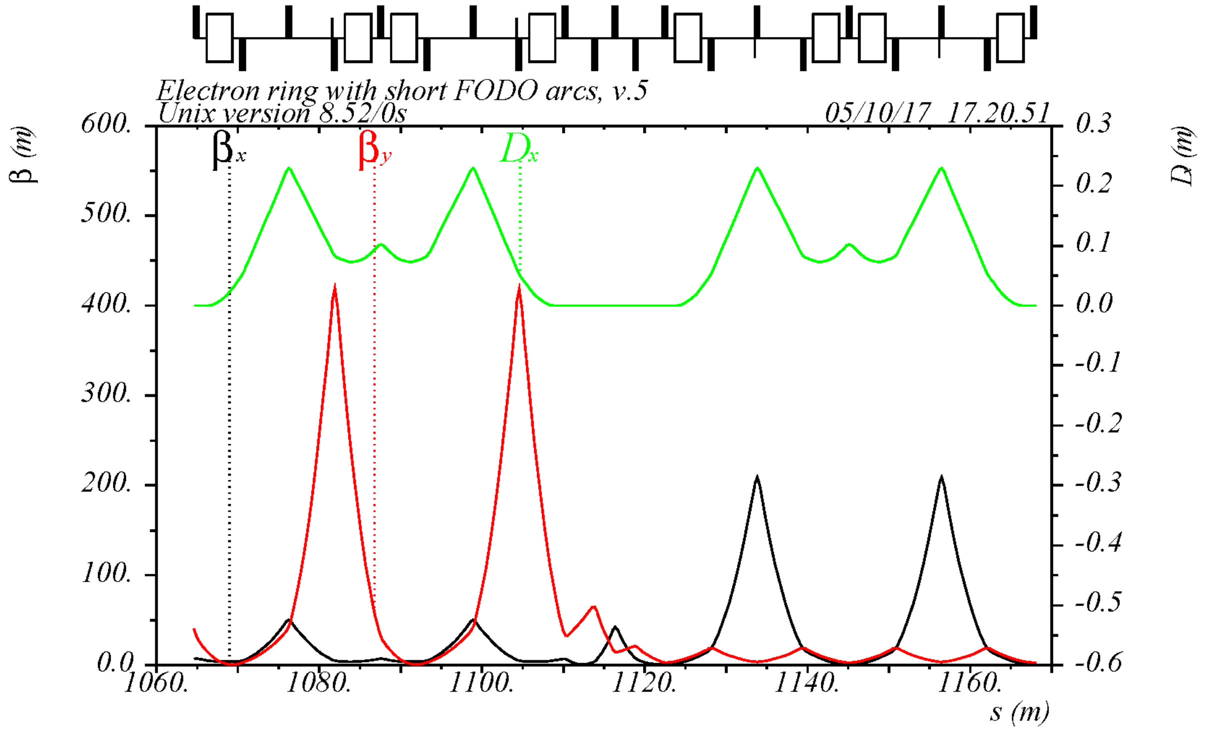
CCB optics for electron collider ring

- Two **non-interleaved –I sextupole pairs** per CCB, where **beta functions and $\beta_{x,y}/\beta_{y,x}$ ratios are increased** → **Efficient orthogonal (X/Y) chromaticity correction, reasonable sextupole strengths, cancellation of sextupole 3rd order resonance effects**
- Initial design is based on **regular arc cells**, however it leads to a **large emittance** (factor of 2 increase) due to dipoles located near high peaks of horizontal beta
- **Solution → Super-B type chromaticity correction (SBCC) scheme with dipoles removed from high β_x locations**

CCB based on regular arc cells

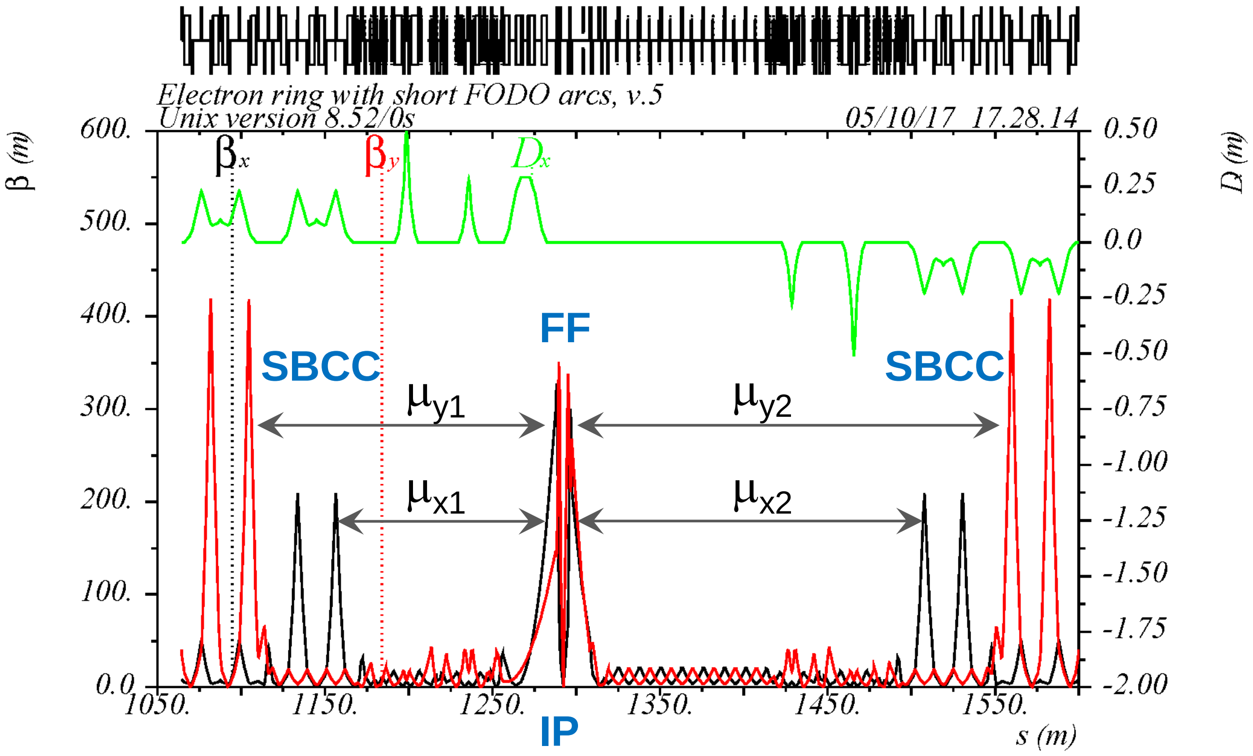


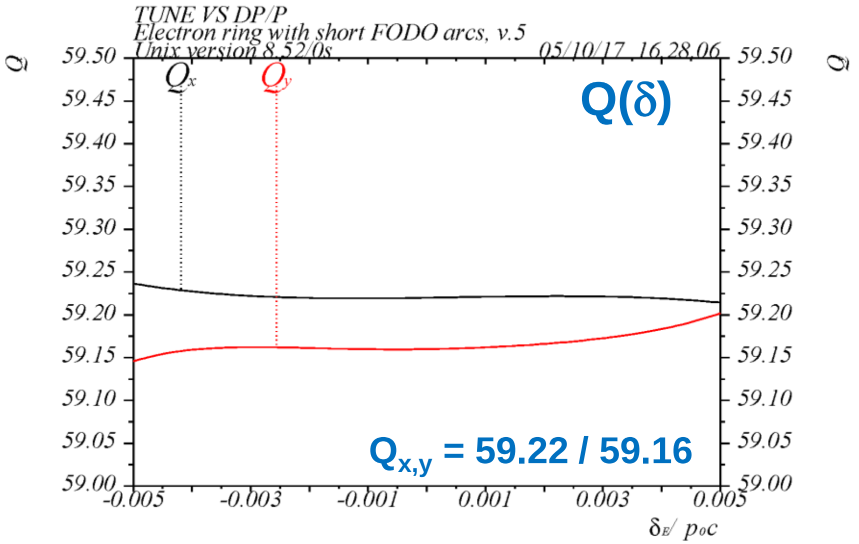
Low emittance SBCC with missing bends



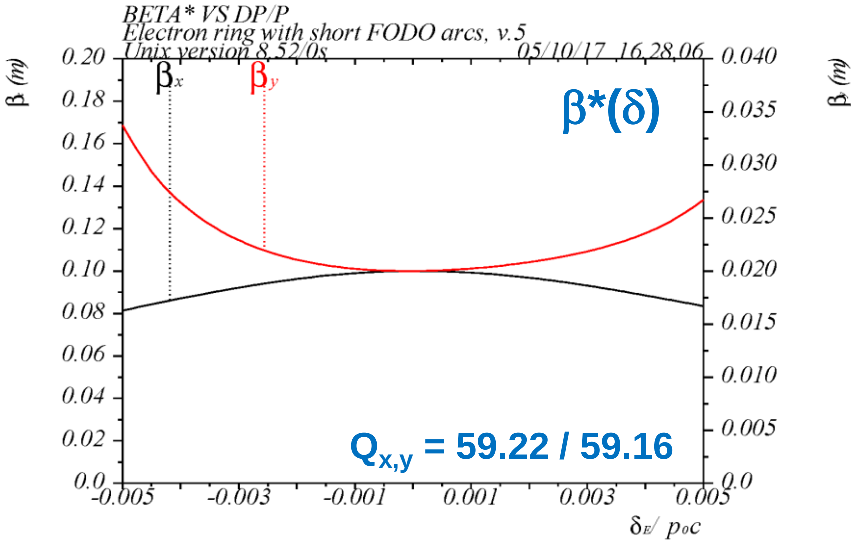
Non-linear chromaticity correction

- Optimized phase advance from SBCC sextupoles to IP for **minimum chromatic tune shift and cancellation of chromatic β variation at IP**
- Adequate energy range → **over ±11σ_p at 5 GeV**





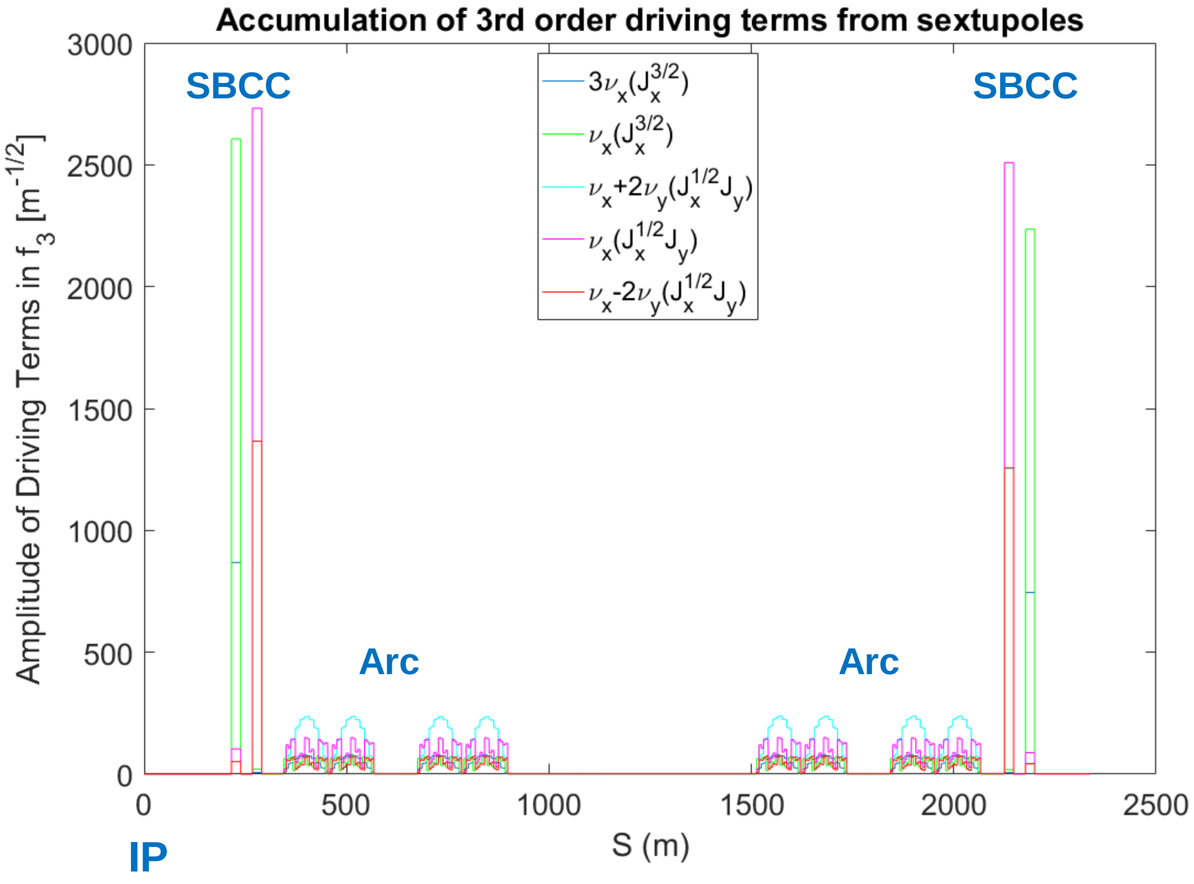
±11σ



Compensation of sextupole non-linear resonance effects

- Complete JLEIC chromaticity correction system consists of
  - **Linear correction** using periodic arc sextupoles
  - **Non-linear correction** using SBCC
- **Both systems are designed to compensate the sextupole non-linear geometric effects (resonances)**
  - **Non-interleaved –I sextupole pairs in SBCC**
  - **Arc sextupoles arranged in N_c periodic cells, where total phase advance is made to be $N_c\mu_c = 2\pi$*integer**
- This compensation cancels some of the resonances driven by sextupoles → **Larger dynamic aperture**

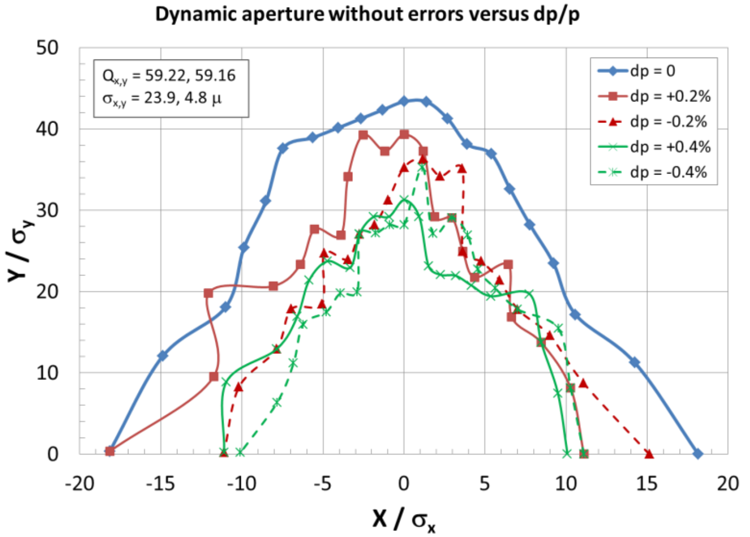
Cancellation of 3rd order resonance driving terms in electron ring



Dynamic aperture vs energy and tune

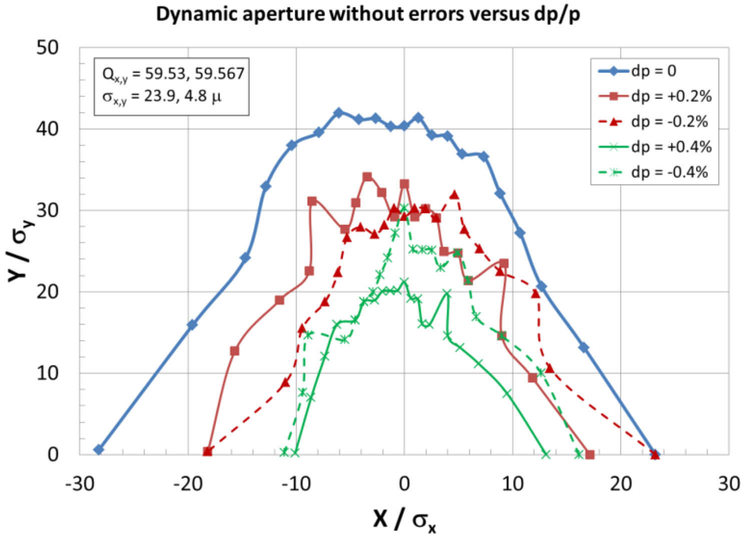
- Tracking with LEGO, 1024 turns, 21 x-y angles, $\xi = +1$, $\varepsilon_x = 5.7$ nm at 5 GeV
- **Adequate DA** (without magnet errors)
- On-energy minimum DA ≈ **18σ** at Q = 59.22, 59.16;   ≈ **23σ** at Q = 59.53, 59.567
- Energy range exceeds **$\pm 11\sigma_p$** (±0.5%) at Q = 59.22, 59.16 at 5 GeV
- No significant sensitivity to integer part of tune (without errors)
- Limited number of studied tune options → detailed tune scan is needed to select an optimal working point for maximum DA

Q = 59.22, 59.16



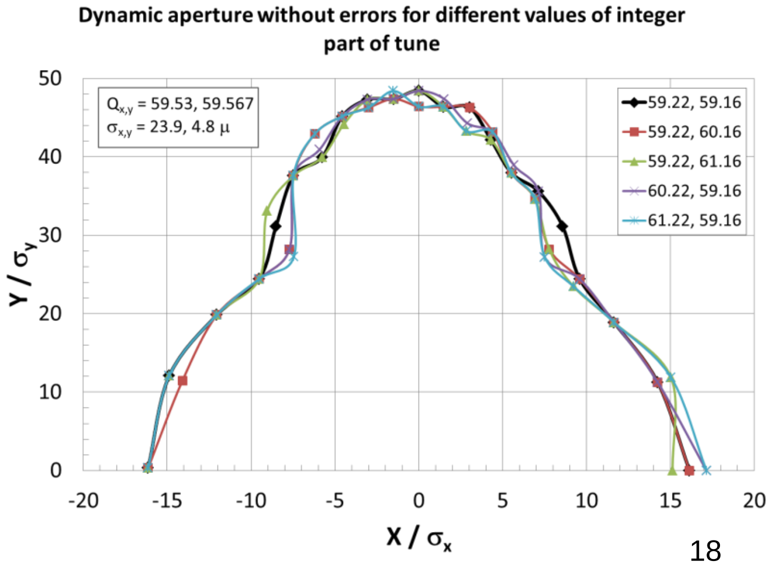
Dynamic aperture without errors versus dp/p

Q = 59.53, 59.567



Dynamic aperture without errors versus dp/p

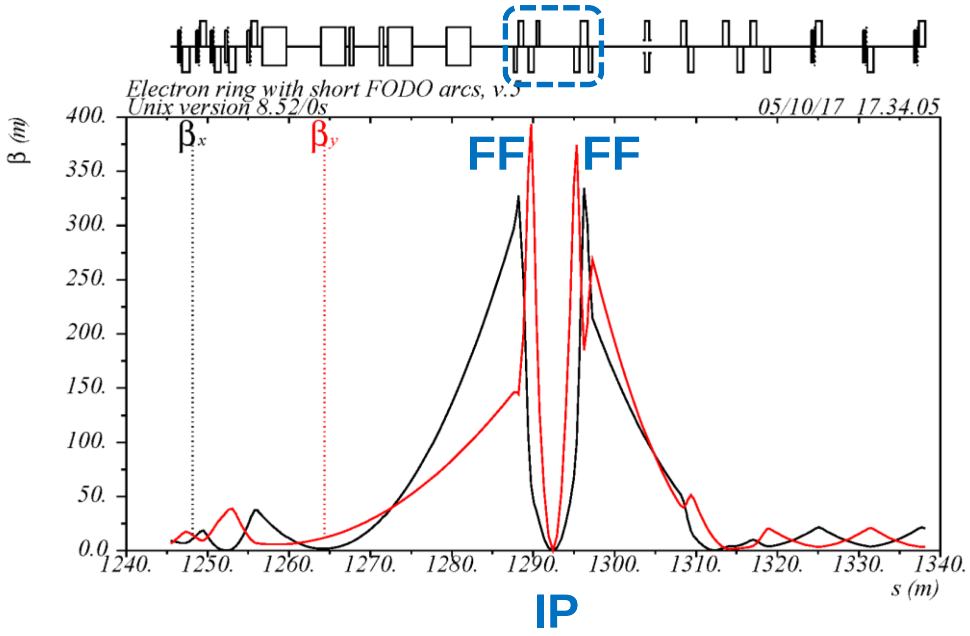
DA vs integer part of tune (59/59, 59/60, 59/61, 60/59, 61/59)

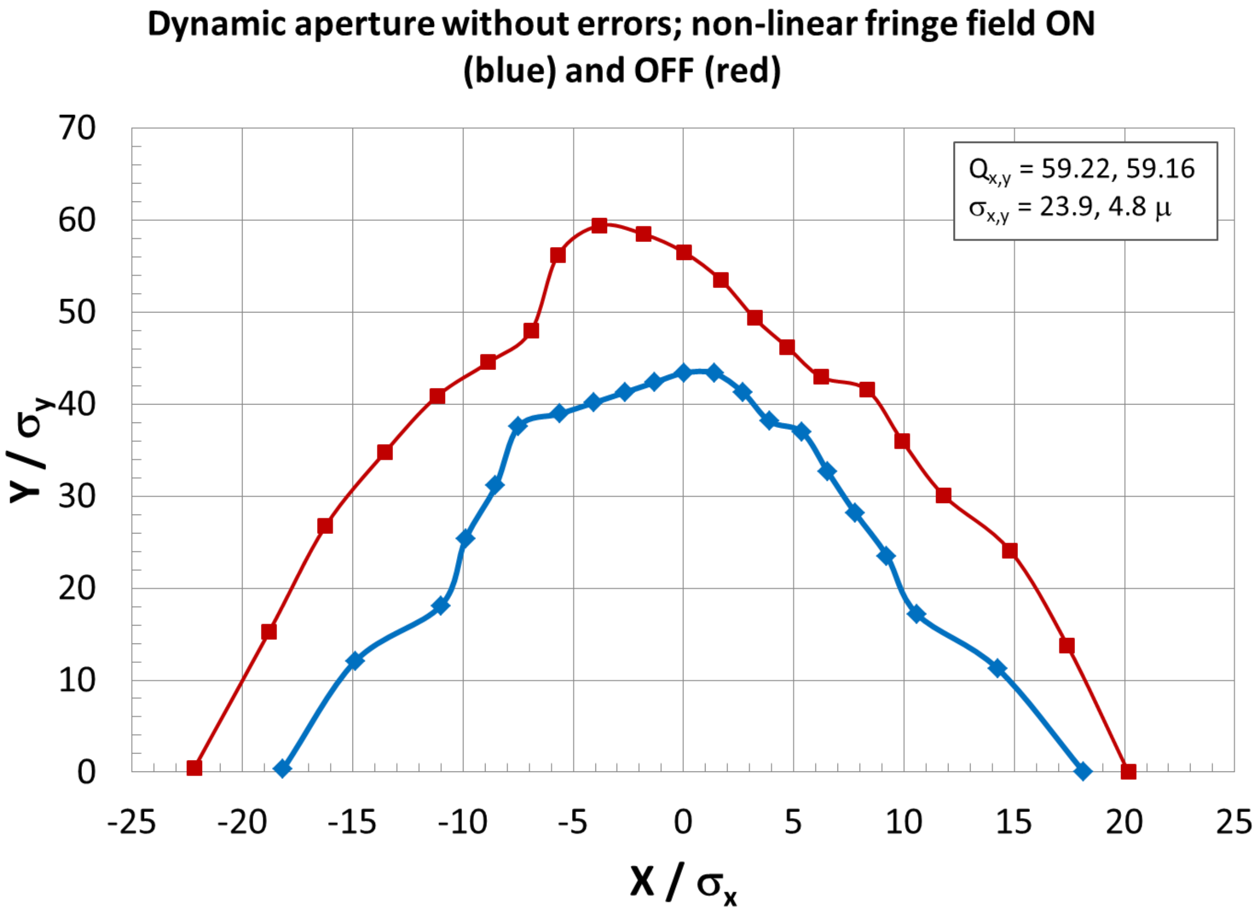


Dynamic aperture without errors for different values of integer part of tune

Dynamic aperture and non-linear fringe field

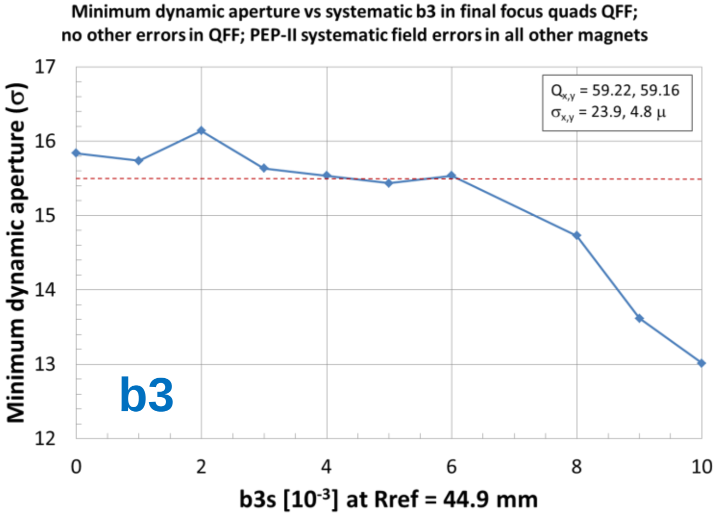
- Effects of non-linear fringe field are implemented in the LEGO tracking code (Y. Cai)
- The fringe field in quads creates non-linear **octupole-like effects** which are enhanced by high beta functions → FF quads
- Impact of the non-linear fringe on the electron ring DA is **a few σ reduction**

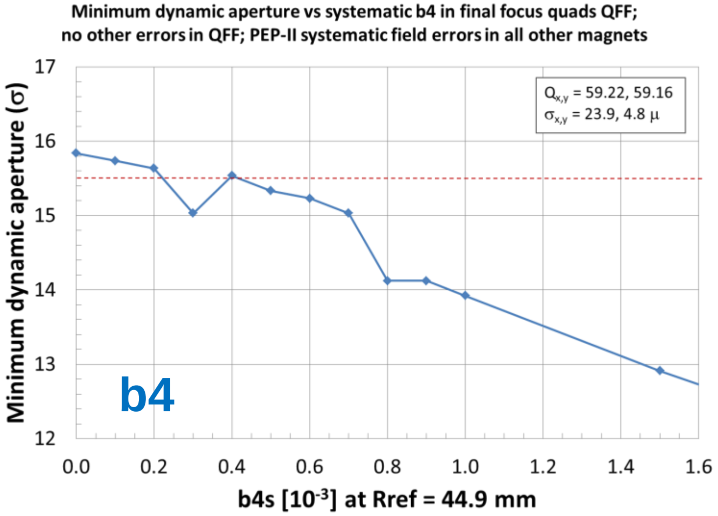




Tolerances for non-linear field errors in FF quads

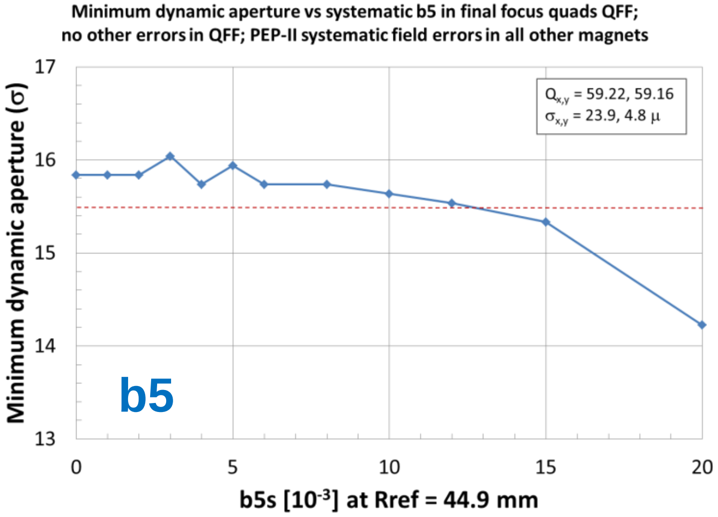
- **Systematic non-linear field errors (b_n) in FF quads** are scanned, one at a time, while other QFF terms are off
- PEP-II measured systematic field errors in other ring magnets
- **A set of FF b_n “tolerances” is obtained** (“**Table-1**”) based on the same DA reduction (red line in plots) for each b_n

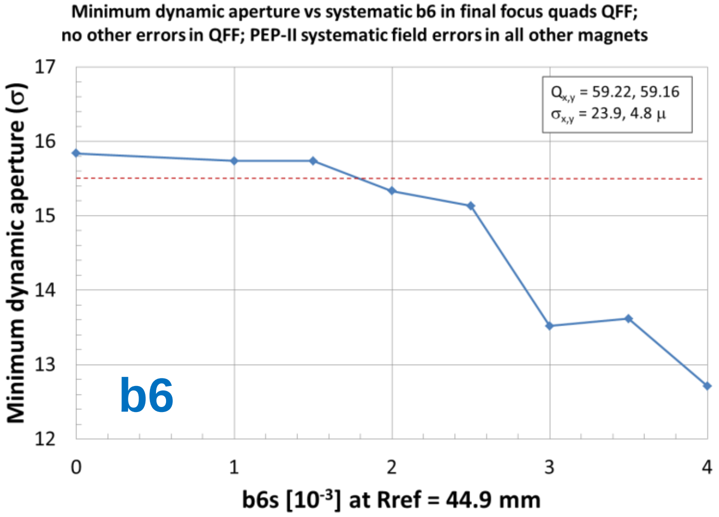

Minimum dynamic aperture vs systematic b3 in final focus quads QFF; no other errors in QFF; PEP-II systematic field errors in all other magnets

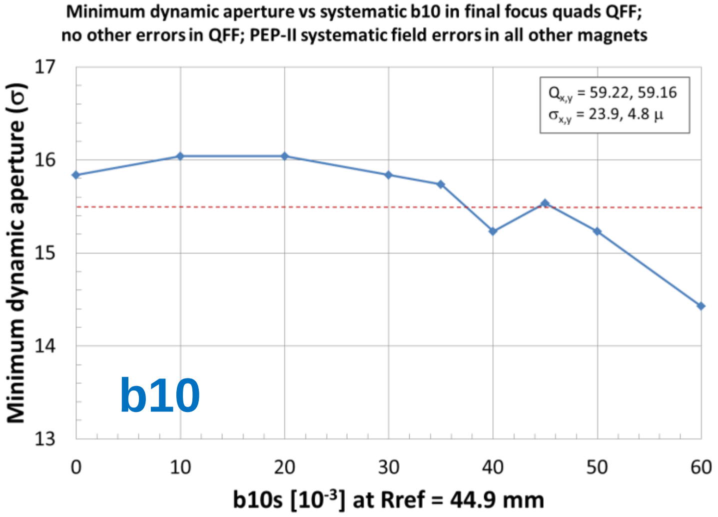

Minimum dynamic aperture vs systematic b4 in final focus quads QFF; no other errors in QFF; PEP-II systematic field errors in all other magnets

FF “Table-1”
R = 44.9 mm

n	b_n [10^{-3}]
3	4
4	0.2
5	10
6	1.5
10	35


Minimum dynamic aperture vs systematic b5 in final focus quads QFF; no other errors in QFF; PEP-II systematic field errors in all other magnets


Minimum dynamic aperture vs systematic b6 in final focus quads QFF; no other errors in QFF; PEP-II systematic field errors in all other magnets

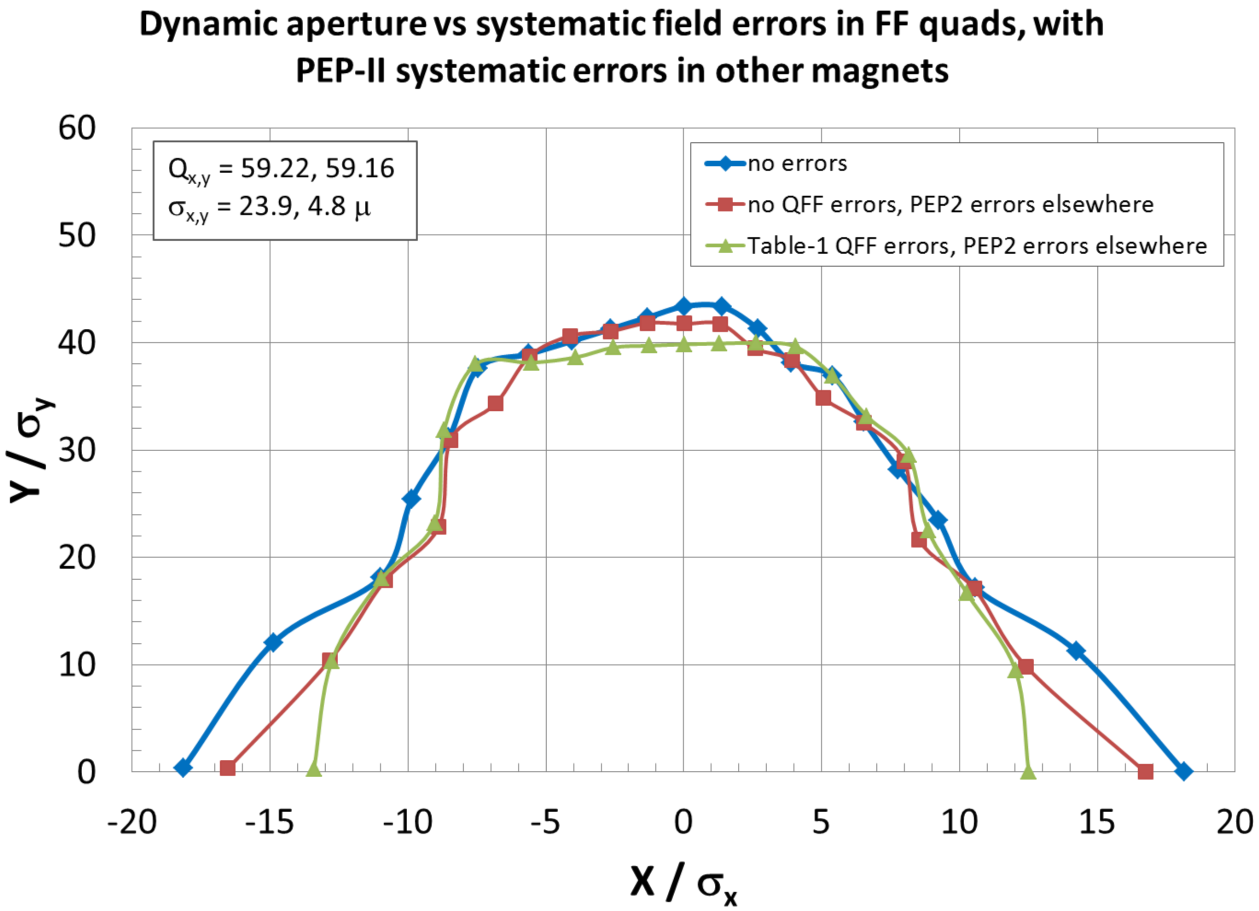

Minimum dynamic aperture vs systematic b10 in final focus quads QFF; no other errors in QFF; PEP-II systematic field errors in all other magnets

DA with FF systematic field tolerances from Table-1

Effects of systematic field errors are compared for three cases

1. **Without any errors (blue line in the plot)**
2. **Without errors in the FF quads, and with PEP-II systematic field errors in all other magnets (red)**
3. **With “Table-1” field errors in FF quads, and with PEP-II systematic errors in all other magnets (green)**

- ➢ **Adequate DA**, even with reduction by a few σ_x due to the Table-1 errors
- ➢ b3, b5, b10 tolerances in Table-1 are quite loose → **further optimization may be needed** to maximize the DA → to be studied



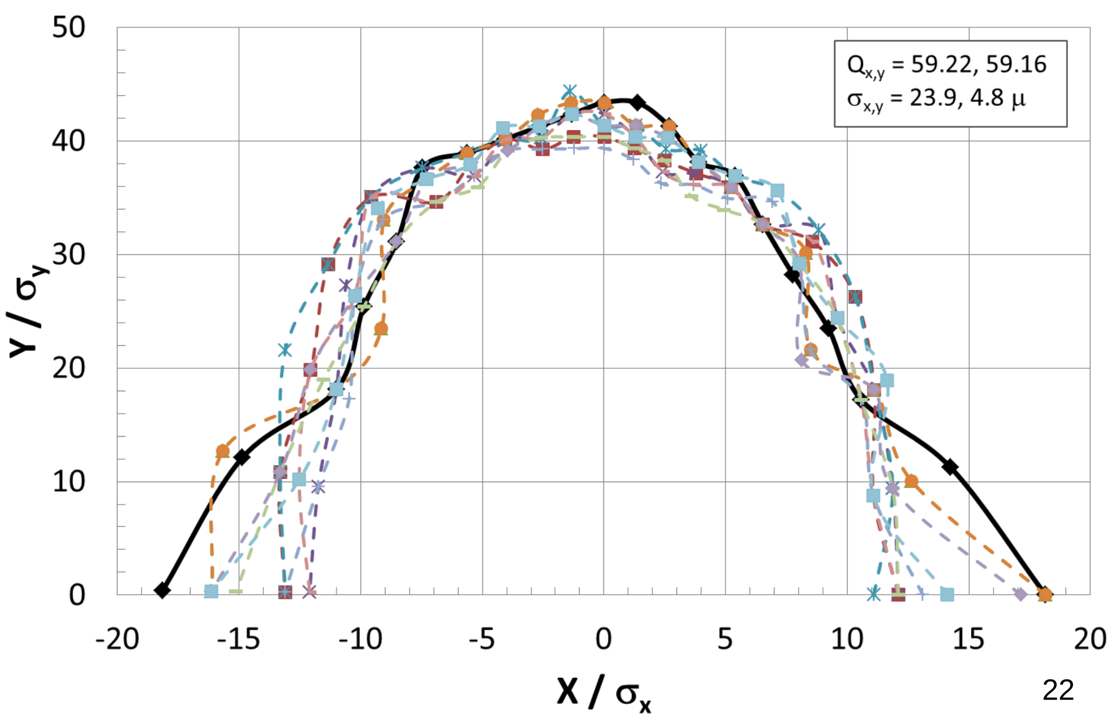
DA with PEP-II measured field errors in all magnets

- **PEP-II HER measured systematic and random field errors in all magnets (including FF)**
- 10 random seeds, 1024 turns
- Absolute minimum DA for all seeds is ~11σ with the **average minimum DA of about 13σ**
- **Sufficient DA** → should improve with further tolerance optimization
- Other errors (alignment, main field) and corrections are not yet included

PEP-II systematic and random b_n

Systematic			Random (rms)	
Dipole	R = 30 mm		Dipole	R = 30 mm
n	Bn/B1 (R)		n	Bn/B1 (R)
3	1.00E-05		3	3.20E-05
			4	3.20E-05
			5	6.40E-05
			6	8.20E-05
Quadrupole	R = 44.9 mm		Quadrupole	R = 44.9 mm
n	Bn/B2 (R)		n	Bn/B2 (R)
3	1.03E-03		3	5.60E-04
4	5.60E-04		4	4.50E-04
5	4.80E-04		5	1.90E-04
6	2.37E-03		6	1.70E-04
10	-3.10E-03		10	1.80E-04
14	-2.63E-03		14	7.00E-05
Sextupole	R = 56.52 mm		Sextupole	R = 56.52 mm
n	Bn/B3 (R)		n	Bn/B3 (R)
9	-1.45E-02		5	2.20E-03
15	-1.30E-02		7	1.05E-03

Electron ring dynamic aperture with PEP-II non-linear field errors; solid -- no errors; dash -- 10 seeds of random errors



Documentation

Conference publications

Update on the JLEIC Electron Collider Ring Design

Y. Nosochkov, Y. Cai, M. Sullivan (SLAC), Ya. Derbenev, F. Lin, V. Morozov, F. Pilat, G. Wei, Y. Zhang (JLab), M.-H. Wang
IPAC 2017, WEPIK041, May 2017

Integration of the Full-Acceptance Detector Into the JLEIC

G. Wei, F. Lin, V. Morozov, F. Pilat, Y. Zhang (JLab), Y. Nosochkov (SLAC), M.-H. Wang
IPAC 2017, THPAB084, May 2017

Compensation of Chromaticity in the JLEIC Electron Collider Ring

Y. M. Nosochkov, Y. Cai, M. Sullivan (SLAC), Ya. S. Derbenev, F. Lin, V. S. Morozov, F. Pilat, G. H. Wei, Y. Zhang (JLab)
NAPAC 2016, TUPOB31, Oct 2016

Simulations of Nonlinear Beam Dynamics in the JLEIC Electron Collider Ring

F. Lin, Ya. S. Derbenev, V. S. Morozov, F. Pilat, G. H. Wei, Y. Zhang (JLab), Y. Cai, Y. M. Nosochkov, M. Sullivan (SLAC), M.-H. Wang
NAPAC 2016, TUPOB29, Oct 2016

Summary

- The FY17 tasks are completed
- Optimization of the IR design is performed
- Design of the IR masking and beam pipe is significantly improved
- Low emittance options for the electron collider ring lattice are studied, and the baseline lattice is selected
- Low emittance non-linear chromaticity correction, providing large energy bandwidth, is designed
- Dynamic aperture of the baseline lattice is sufficiently large for the required energy range, as well as for the studied tune options
- Tolerances for the systematic non-linear field in the FF quads are evaluated
- Dynamic aperture is sufficient with realistic PEP-II HER measured field errors
- The studies are documented in conference publications

Outlook

- The SLAC team looks forward to future collaboration with the JLEIC design team
- **Further IR design studies**
  - Design iterations based on detector team feedback
  - Scattered photon rates from the tip of the mask
  - HOM power calculations
  - Beam pipe thickness tolerated by the detector
  - Radiation loads on FF quads
- **Electron ring beam dynamics studies**
  - Tune scan to optimize the working point and the DA
  - Complete diagnostic and correction system
  - Alignment and main field error tolerances
  - Further iteration on FF field quality
  - Detector solenoid and compensation
  - Lower β^* lattice → corrections, DA, tolerances
- **Ion ring studies**
  - Alignment and field quality for the SC FF quads
  - Local correctors for the FF non-linear field errors and specifications

Thank you for your attention!

Acknowledgements:

Fanglei Lin, Vasiliy Morozov, Guohui Wei, Yuhong Zhang (JLab)

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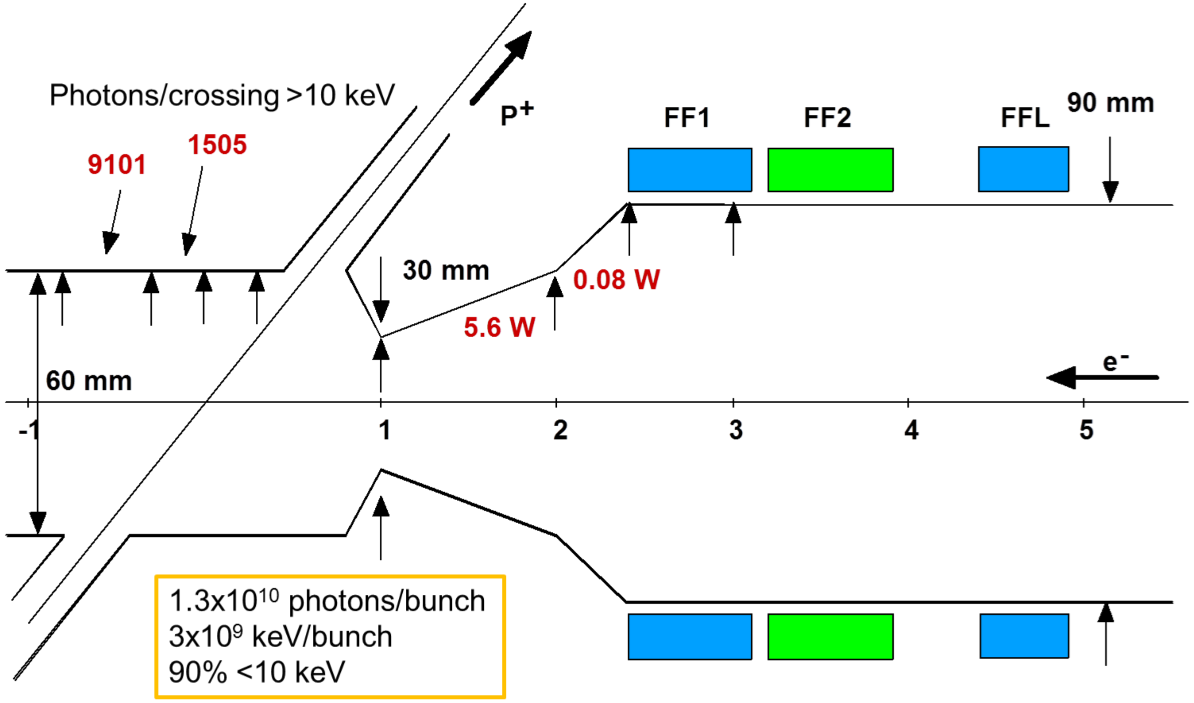
Back-up slides

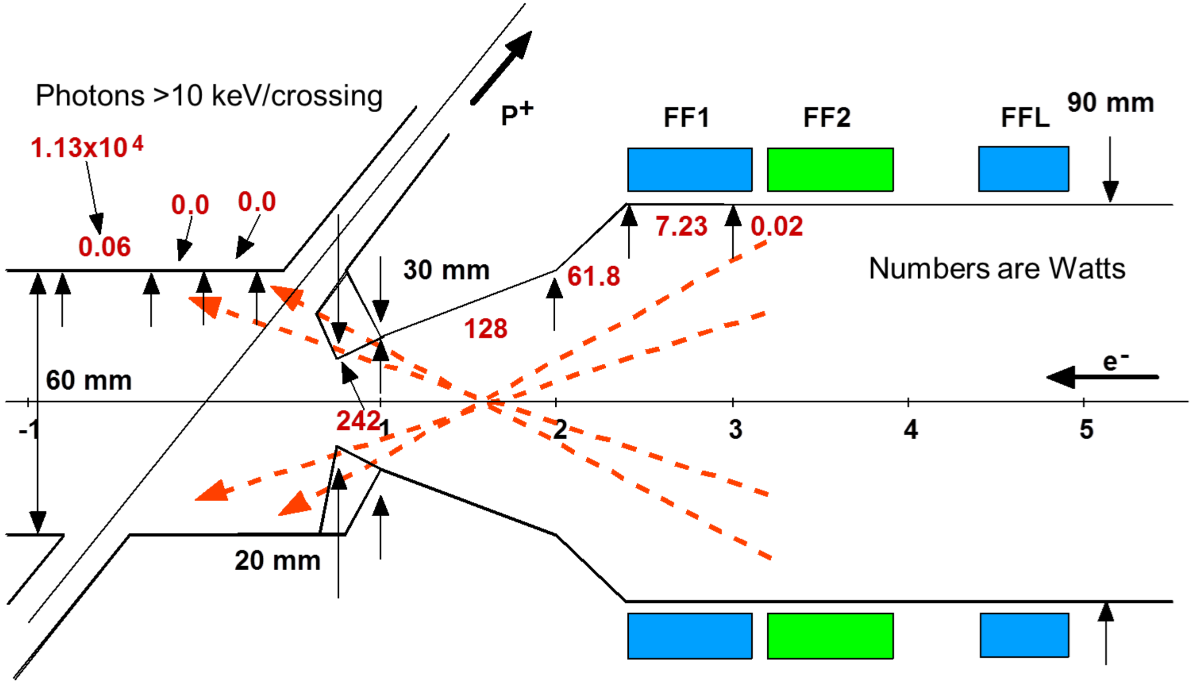
Initial SR masking design

Masking design for 5 GeV (2.8 A)



$1.3\text{x}10^{10}$ photons/bunch
$3\text{x}10^{9}$ keV/bunch
90% <10 keV

10 GeV (0.7 A) needs a tighter mask



5 GeV, 2.8 A beam

- β_x/β_y = **10/2** cm, $\varepsilon_x/\varepsilon_y$ = **5.5/1.1** nm-rad,
- BSC = $17\sigma_x$ and $45\sigma_y$
- Maximum X BSC = ±22.3 mm at 4.075 m
- Maximum Y BSC = ±28.5 mm at 2.95 m

10 GeV, 0.71 A beam

- β_x/β_y = **10/2** cm, $\varepsilon_x/\varepsilon_y$ = **22/4.4** nm-rad,
- BSC = $14\sigma_x$ and $22\sigma_y$
- Maximum X BSC = ±36.9 mm at 4.075 m
- Maximum Y BSC = ±27.8 mm at 2.95 m