Validation of EIC IR Magnet Parameters and Requirements Using Existing Magnet Results

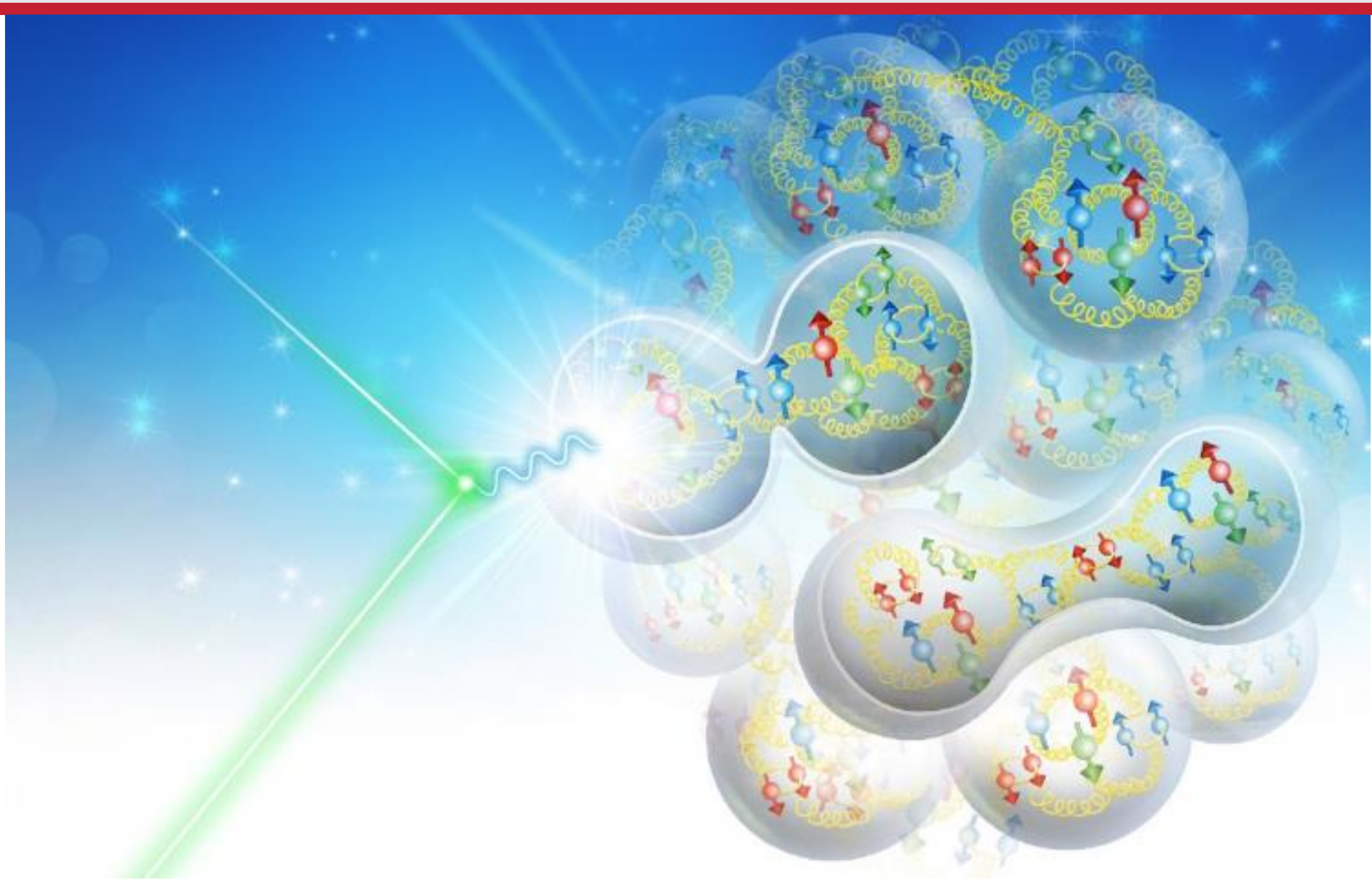
Tim Michalski (PI)

With contributions from:

Chuck Hutton, Fanglei Lin, Vasiliy Morozov, Renuka Rajput-Ghoshal, Mark Wiseman (JLAB)

GianLuca Sabbi (Co-PI) – (LBNL)

Michael Sullivan (Co-PI), Yuri Nosochkov (SLAC)



Nuclear Physics Accelerator R&D PI Meeting

December 2, 2020

Description of the project

- The main goal of the project:
  - It is very important to understand the alignment and multipole requirements of the FFQs and to design an orbit correction scheme and a multipole compensation system, as proposed in this project.

- Jones Report Priority Alignment:

Row No.	Proponent	Concept / Proponent Identifier	Title of R&D Element	Panel Priority	Panel Sub-Priority
4	PANEL	ALL	Benchmarking of realistic EIC simulation tools against available data	High	A
5	PANEL	ALL	Validation of magnet designs associated with high-acceptance interaction points by prototyping	High	A

  - The main alignment is Row 5.
  - Since we propose to compare our simulation results to existing data, our proposal also meets the High-A priority item in row 4 of the panel's priority table: Benchmarking of realistic EIC simulation tools against available data.

Annual Budget and the Total Received to Date

	BASELINE Total Cost (AY - $k)	Costed & Committed (AY - $k)	Estimate to Complete as of January, 2020 (AY - $k)	Remaining Funds	Total (AY - $k)
JLab	$684	$489	*$195* *	$0	$489
SLAC	$278	$219	*$59* **	$0	$278
LBNL	$258	$163	*$95* ***	$95	$258
TOTAL	$1,220	$871	*$349*	$95	$1,025

* - The award for the JLab (TJNAF) portion was part of the Lab Base R&D (redirect). This amount was not spent on the FOA. Remaining FY'20 activities were focused on EIC Task Forces.

** - SLAC performed similar tasks on the EIC and these remaining funds were spent on EIC Task Forces.

*** - LBNL has remaining funds to be spent towards EIC activities.

Major Deliverables and Schedule

- **Milestones reached by**
  - **6 months after the start of funding**
    - Interaction Region (IR) orbit correction and alignment tolerances
    - Synchrotron Radiation (SR) heat loads and shielding
  - **12 months after the start of funding**
    - Performance with existing magnet data
    - SR heat loads and shielding
  - **18 months after the start of funding**
    - Design and simulation of multipole correction
    - SR heat loads and shielding
  - **24 months after the start of funding**
    - Multipole tolerances and corrector specifications
    - SR heat loads and shielding
    - Layout of JLEIC IR

Task	YR 1 Q1	YR 1 Q2	YR 1 Q3	YR 1 Q4	YR 2 Q1	YR 2 Q2	YR 2 Q3	YR 2 Q4
IR orbit correction ✓	X	X						
IR with existing magnet data ✓			X	X				
IR multipole correction				X	X ✓	X	X	X
SR heat loads and shielding	X	X	X	X	X ✓	X	X	X
Feedback on magnet requirements from the accelerator physics team ✓	X	X						
Assess magnet space requirements to ensure a realistic IR layout ✓		X	X					
Formulate field error tables based on LARP experience ✓			X	X				
Explore and select from alternative magnet and structure options ✓	X	X	X	X				
Mechanical and magnetic analysis of proposed design					X ✓	X	X	X
Incorporate experience from BNL model design, fabrication, and test					X ✓	X	X	X
Update IR layouts based on results of project						X	X	X

Jefferson Lab

Current Status

- This project was on track to complete all activities when the EIC site selection was announced in January, 2020.

- The JLab contribution was stopped upon site selection.
- JLab funding was redirect of operations funding – further spending was discontinued.
- JLab has engaged on various fronts with BNL on EIC.

- The SLAC contribution was redirected towards the EIC development at BNL.
- Remaining SLAC funds for this FOA were used on the redirected effort at BNL.

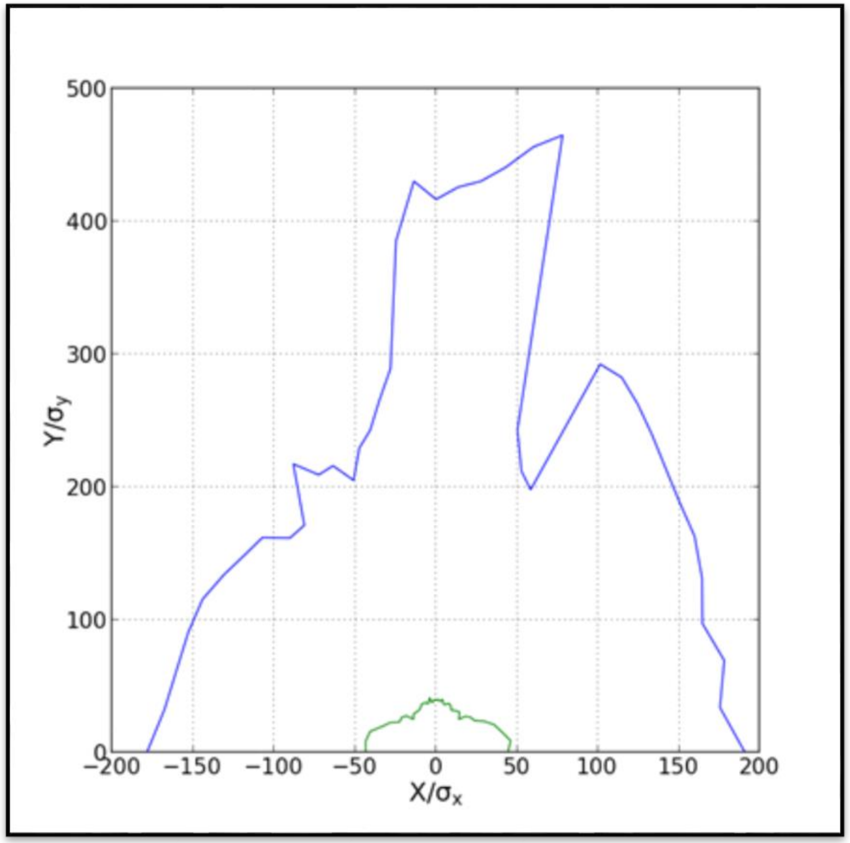
- The LBNL contribution was stopped upon site selection.
- Remaining LBNL funds for this FOA are awaiting direction on how to apply them.
- LBNL and BNL staff have been in discussions regarding potential contributions. This will be presented later.

Closed Orbit Correction

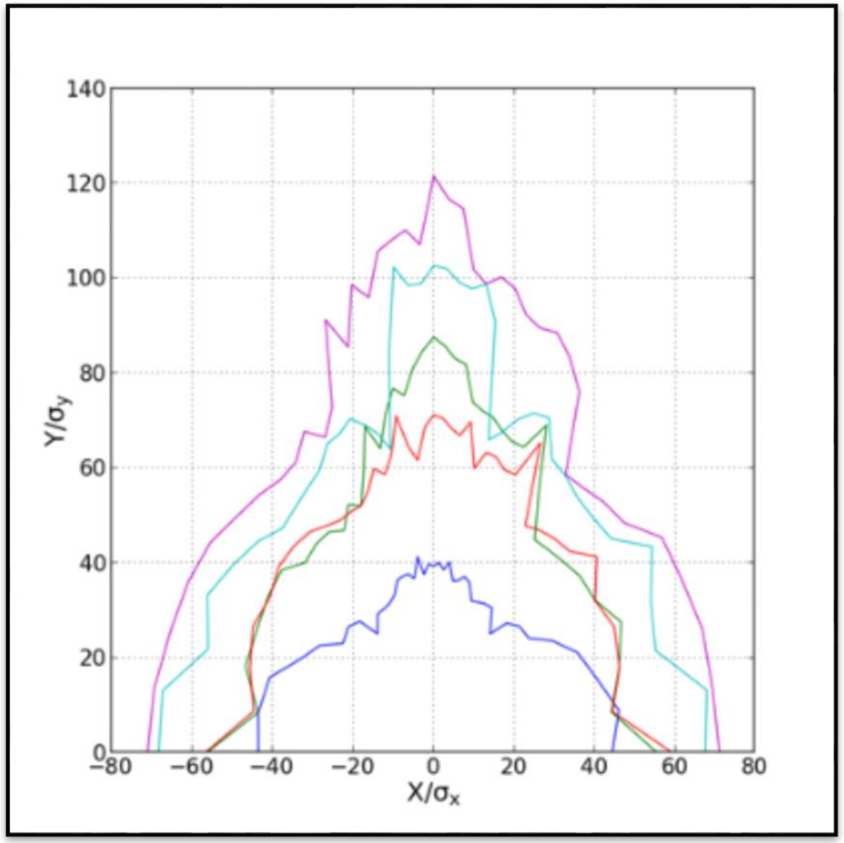
- Corrector placement options were considered to optimize the dynamic aperture (DA) of the JLEIC ion collider ring (ICR).
- A single systematic multipole (b6 component) was introduced in the first upstream quadrupole next to the IP.
- Several corrector placements were assessed.

Case		0	1	2	3	4
Comments		No orbit excursion in the FFQs but high corrector strengths and invasion of the detector space.	Lowest corrector strengths but orbit excursion inside the FFQs.	Orbit excursion in the two FFQs adjacent to the IP but none in the rest of the FFQs.	No orbit excursion downstream and minimum invasion into the downstream IR. Upstream correctors are high.	No orbit excursion upstream and minimum invasion into the upstream IR. Downstream correctors are high.
Upstream correctors [Tm]	X1	$-4.43 \cdot 10^{-3}$	$1.82 \cdot 10^{-3}$	$-5.81 \cdot 10^{-3}$	$-4.86 \cdot 10^{-4}$	$2.33 \cdot 10^{-3}$
	Y1	-1.21	$8.53 \cdot 10^{-3}$	$-1.68 \cdot 10^{-1}$	$1.71 \cdot 10^{-2}$	N/A
	X2	$6.34 \cdot 10^{-3}$	$7.28 \cdot 10^{-4}$	$4.11 \cdot 10^{-3}$	$7.42 \cdot 10^{-4}$	N/A
	Y2	1.14	$-4.89 \cdot 10^{-3}$	$1.54 \cdot 10^{-1}$	$-9.79 \cdot 10^{-3}$	N/A
Downstream correctors [Tm]	X1	$-1.91 \cdot 10^{-3}$	$-4.21 \cdot 10^{-4}$	$5.97 \cdot 10^{-3}$	$-1.91 \cdot 10^{-3}$	$-2.42 \cdot 10^{-3}$
	Y1	$-2.22 \cdot 10^{-1}$	$2.15 \cdot 10^{-5}$	$-2.22 \cdot 10^{-1}$	N/A	$2.85 \cdot 10^{-5}$
	X2	N/A	N/A	$-5.73 \cdot 10^{-3}$	N/A	$1.54 \cdot 10^{-4}$
	Y2	$1.47 \cdot 10^{-1}$	$2.24 \cdot 10^{-2}$	$1.47 \cdot 10^{-1}$	N/A	$4.48 \cdot 10^{-2}$

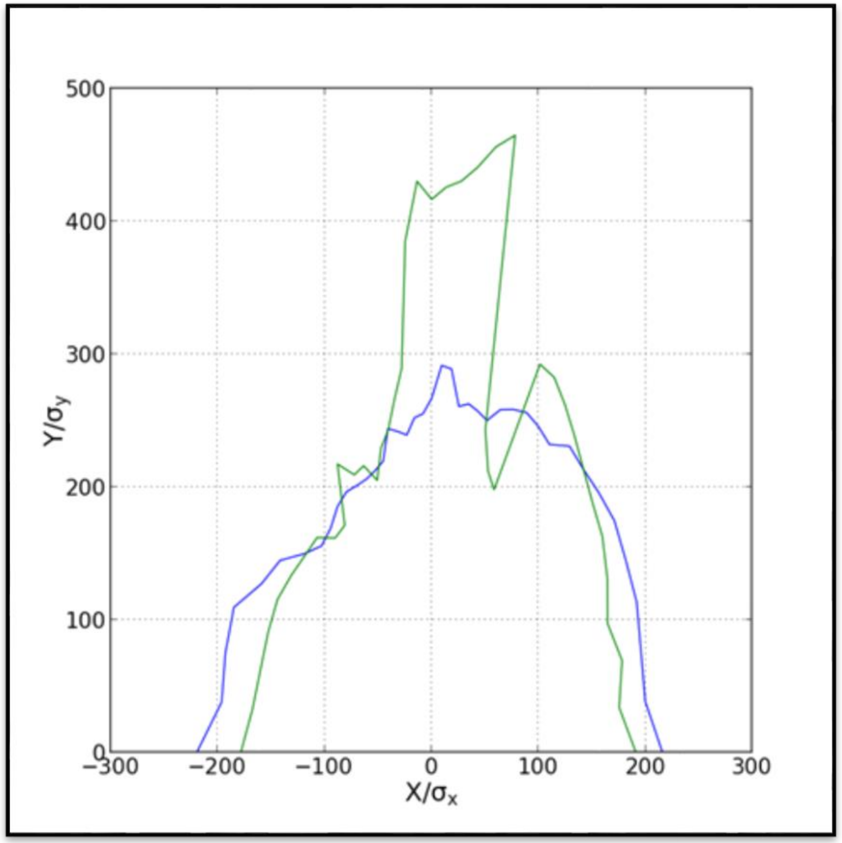
Closed Orbit Correction



Dynamic aperture for the bare lattice (blue) and with one b6 systematic multipole in the first upstream FFQ (green) [8]



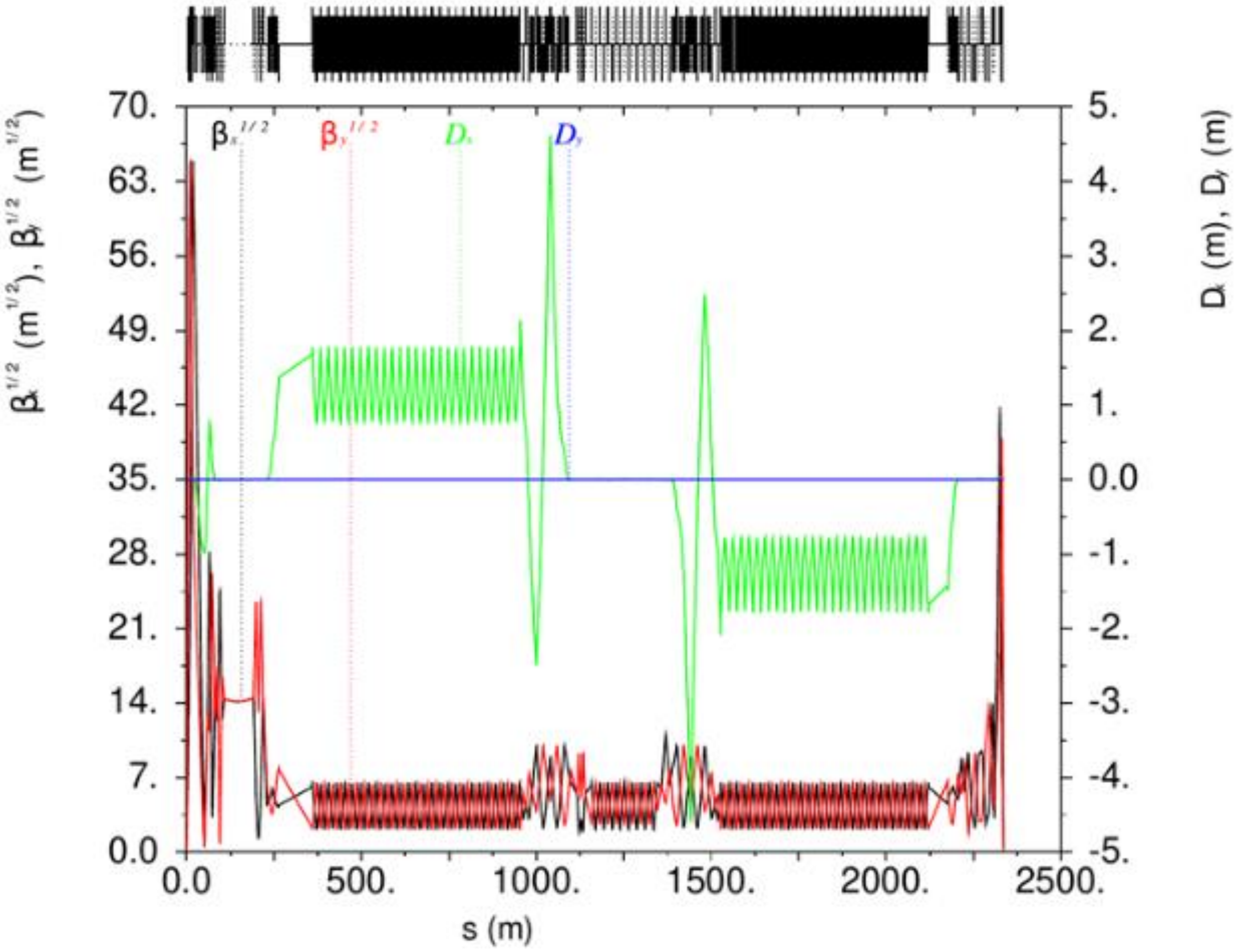
Dynamic aperture with no corrector (blue), case 1 (red), case 1 with 0.2m corrector length (green), case 2 (cyan), case 3 (magenta) [8]



Dynamic aperture for case 4 (blue) and for bare lattice (green) [8]

Closed Orbit Correction

- The ICR lattice was optimized to minimize the IBS rate which in turn would relax the cooling requirements and improve the luminosity lifetime. [6]
- Areas in the lattice that contributed to high IBS growth rate were identified.
- The two chromaticity compensation blocks were removed and the phase advance per arc FODO cell was increased from 90º to 108º.
- Two möbius insertions were added to locally couple the beam in one arc.



- We considered several chromaticity compensation schemes and found globally compensating chromaticity using all arc (26 FODO cells per arc) sextupoles gives reasonable momentum aperture and a dynamic aperture.

Jefferson Lab

Beam Dynamics

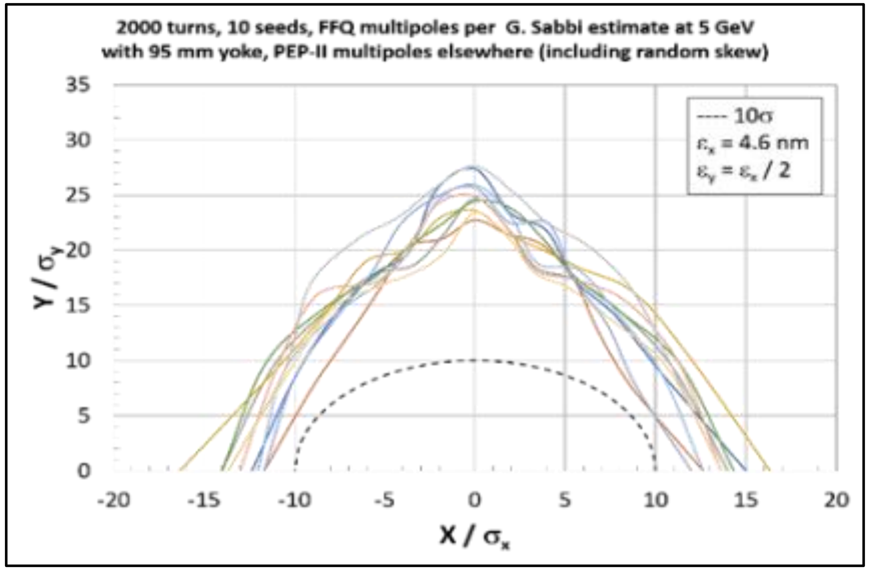
- Random and systematic errors have been introduced in order to assess the impact on dynamic apertures (DA) of the electron collider ring (ECR) and ion collider ring (ICR).
- The FFQ rms offset tolerance = 0.1 mm. The FFQ rms roll angle error = 0.5 mrad.

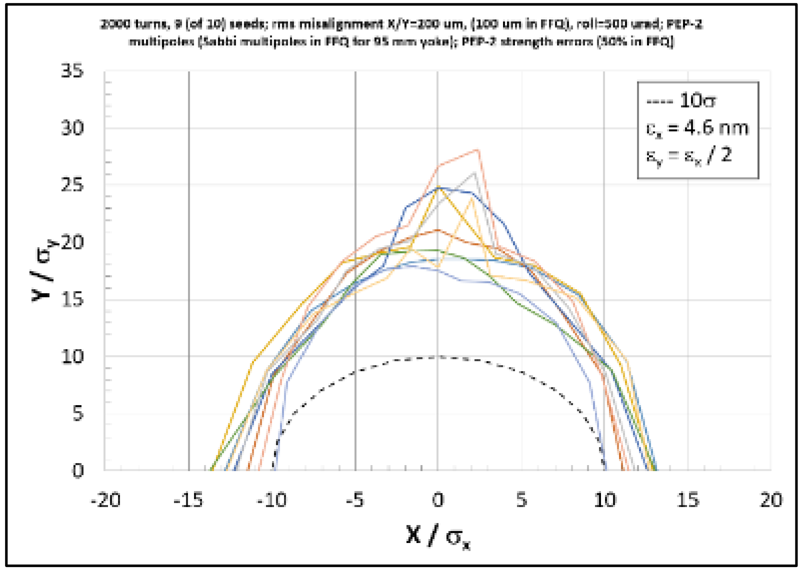
Estimated random multipoles for JLEIC FFQ at 5 GeV

Rcoil = 53 mm, Rref = 35 mm

n	bn	an
3	4.39	4.79
4	8.06	3.68
5	2.73	2.73
6	2.23	2.02
7	1.73	1.49
8	1.15	1.17
9	0.69	0.68
10	0.45	0.48

Estimated random multipoles (rms) in the FFQ based on the magnet design by G. Sabbi (in 10-4 units) for 5 GeV, 95 mm yoke size, 53 mm coil radius, and reference radius of 35 mm [2].





Electron ring DA at 5 GeV with the PEP-II multipoles in all magnets except the FFQ where multipoles are based on G. Sabbi design for 95 mm yoke: 1) without (left) and 2) with the random misalignment and magnet strength errors and corrections (right).

- The main conclusion - with the studied FFQ multipoles and all other errors, the electron ring DA at 5 GeV is sufficiently large, as long as the error tolerances are optimized and the orbit and other optics perturbations are reasonably corrected.

IR FFQ Magnet Design

- Work on the large aperture downstream ion quadrupoles for JLEIC.
- The main goal is to optimize the end geometry, in order to improve the field quality while decreasing the peak field.
  - As a first step, a modified end configuration was developed that allows cancelation of the integrated dodecapole (b6 component) over the end region (Figure 1).
  - The peak field is also lower with this configuration, but still higher than in the straight section (Figure 2).

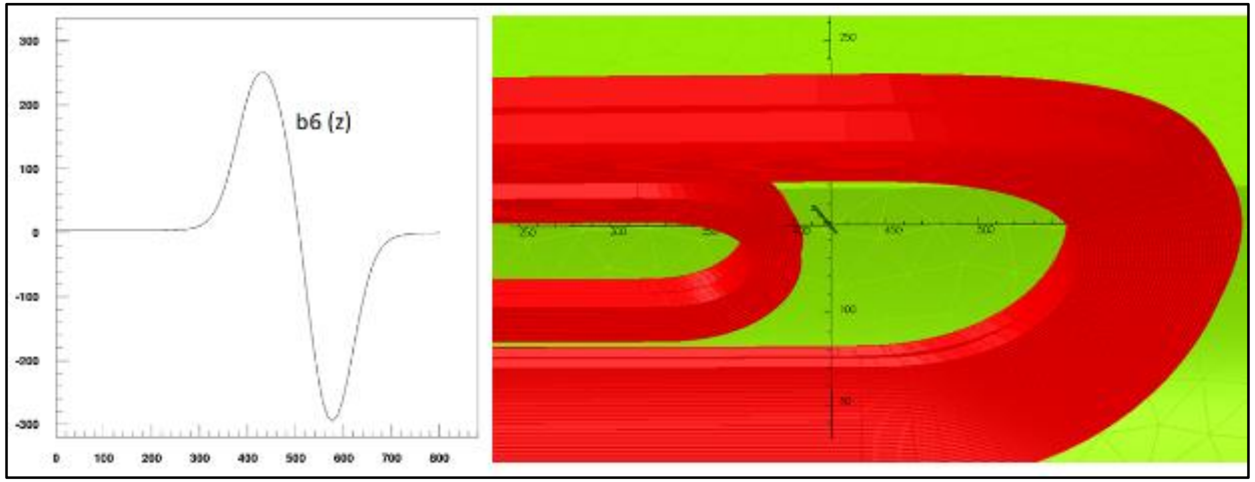


Fig. 1: Modified end configuration for canceling the b6 integral [5].

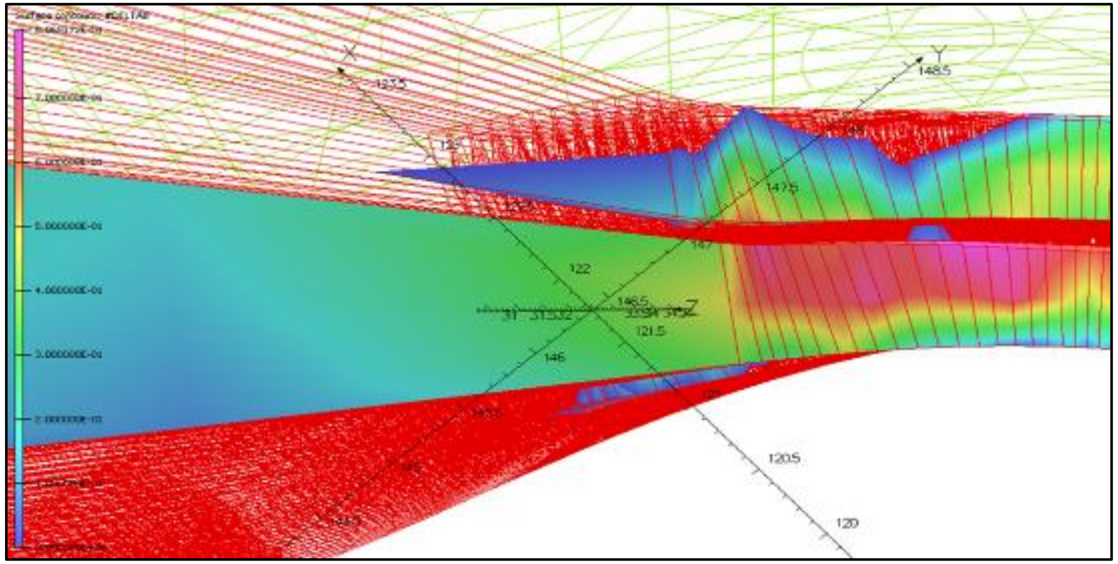


Fig. 2: Peak field in the magnet ends vs. straight section with the modified geometry [5].

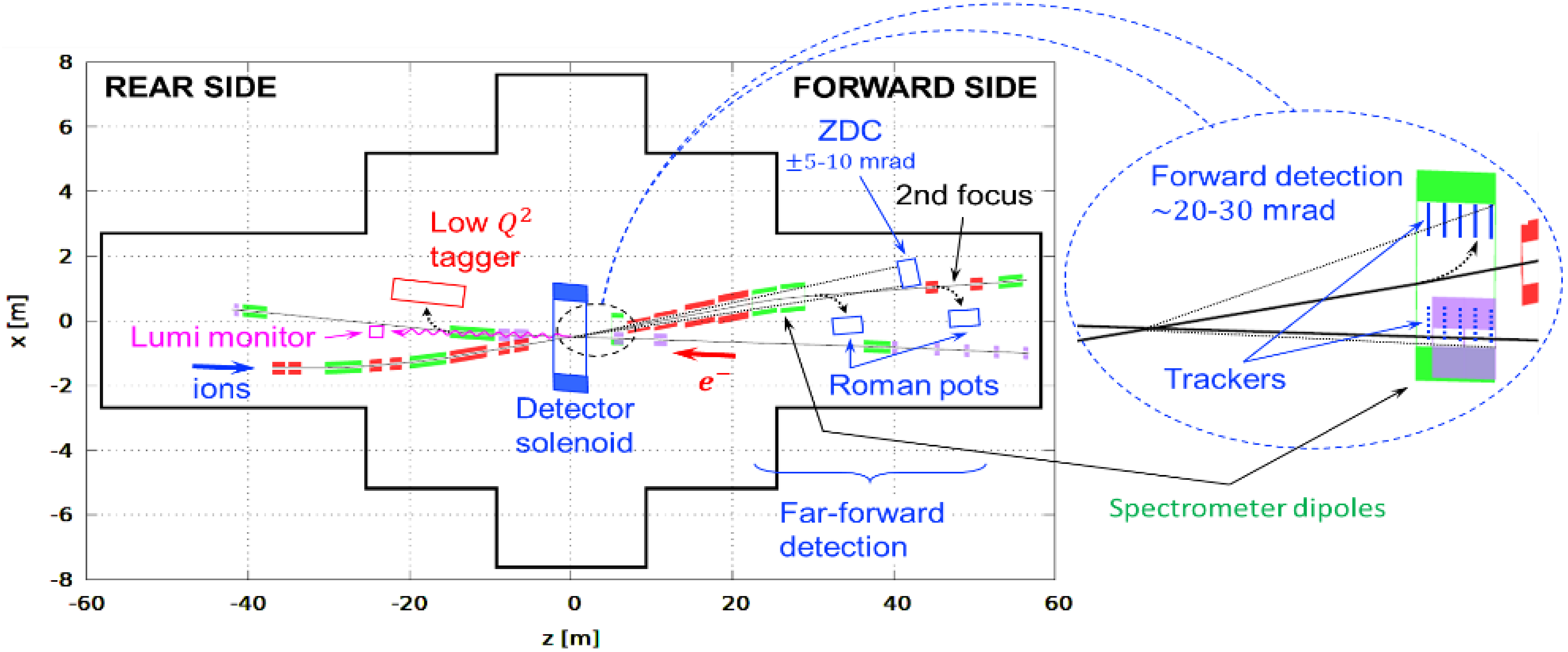
Synchrotron Radiation (SR) Assessment

- Continuous injection technology has enabled new accelerator designs (i.e. JLEIC and eRHIC) to employ this technique into the design in order to have a polarized electron beam.
- The injected beam is polarized and if the stored beam lifetime is short (e.g. 10 min.) then the stored beam has a reasonable polarization fraction.
- The JLEIC design called out this procedure in order to have a polarized electron beam. The low beam lifetime means the beam tail particle density can be significantly higher than previous estimates.
- Preliminary results indicate the upstream masking scheme looks alright and now the study needs to move to the downstream side of the interaction region to see if the cold bore sections of the downstream cryostats are properly protected from the increased SR from these new beam tail distributions.
- In the JLEIC design the downstream crab cavity is close to the last bend magnet from the electron polarimeter chicane. In the EIC (eRHIC) design, both crab cavities (upstream and downstream electron) are near bend magnets of considerable strength. The SR power from these bend magnets must be masked away from the cryogenic beam pipe of the crab cavity structure.
- The SR from nearby quadrupoles is also a concern, especially with the enhanced non-gaussian beam tails. Like the cold bores of the final focus magnets for the JLEIC design, the cold bore pipes around the crab cavities must be shielded from SR.

Redirected Work on the EIC

2nd IR Layout

- Consistent with existing infrastructure: experimental hall and tunnel size
- Necessary components integrated: ZDC, luminosity monitor, Roman pots, crab cavities, etc.
- Geometric and optical match to the rest of the collider rings even with 50 mrad crossing angle
- All beams transport over full energy range
- Magnet aperture-edge fields < 4.6 T even with ± 10 mrad far-forward acceptance



Jefferson Lab

Dynamic Aperture

Minimum dynamic aperture requirements:

- 10 sigma transverse on-momentum aperture
- 10 sigma momentum acceptance

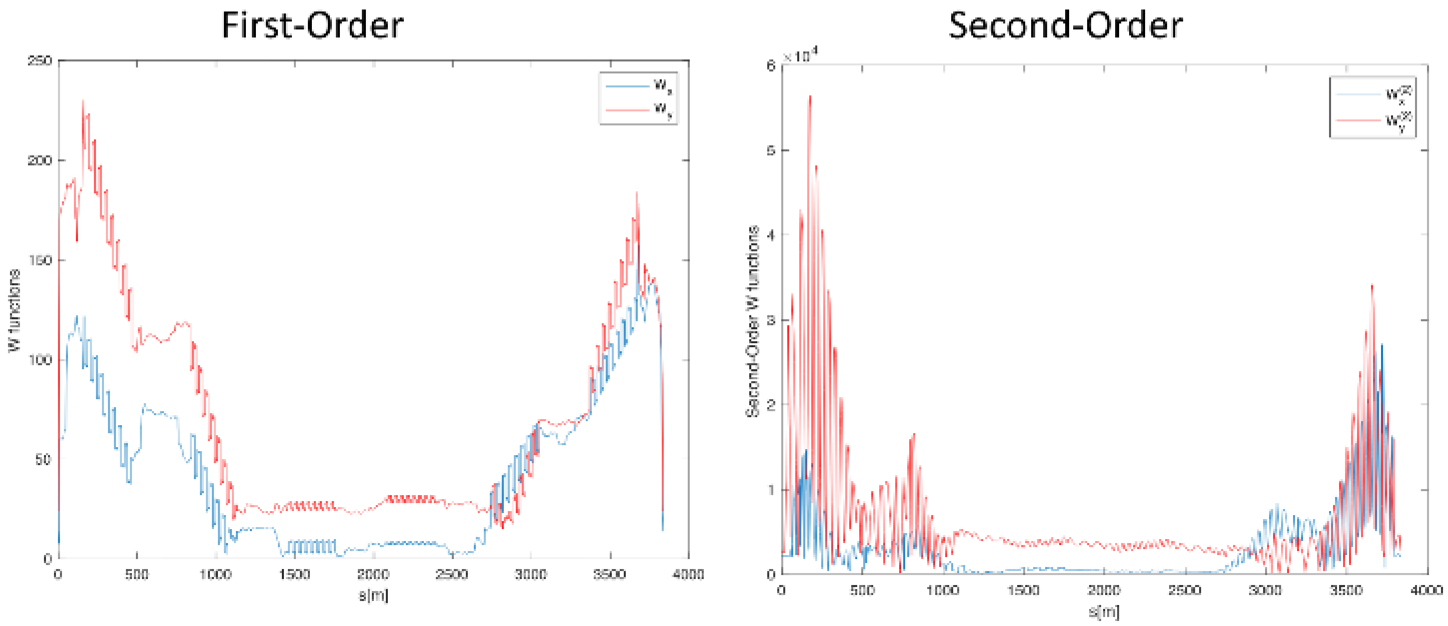
18 GeV, 90 degree lattice is most challenging:

- Additional constraints on phase advance to first sextupoles in the arc
- Large RMS momentum spread, nearly 1e-3

Strategy:

- Compensate chromatic β-beat over two arcs on each side of the IP
- Correct nonlinear chromaticity

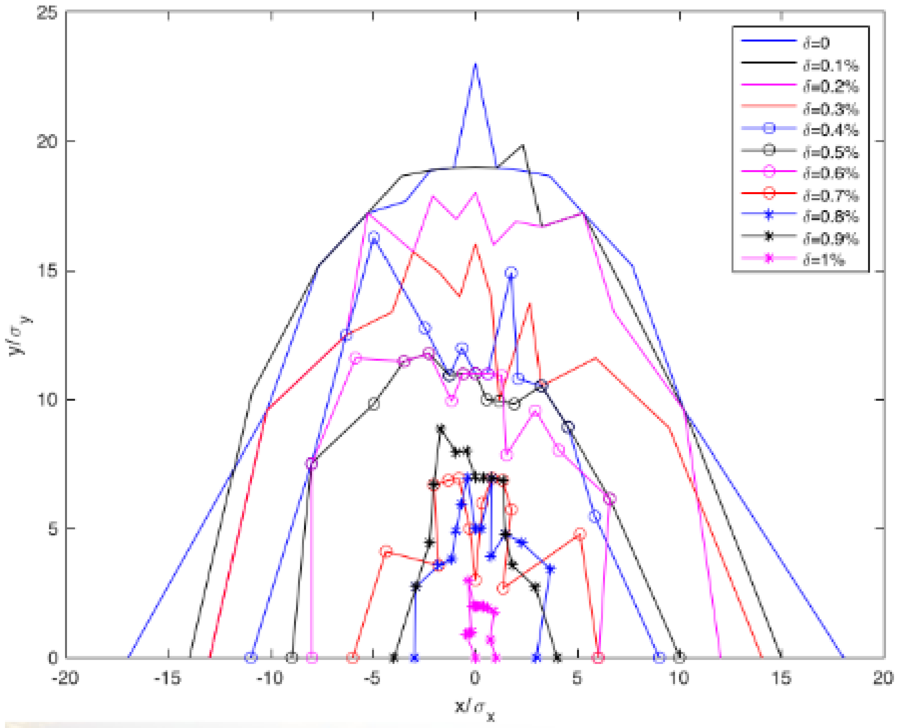
Off-Momentum β-Beat



First and second-order chromatic β corrected over two arcs on each side of the IR

Courtesy Y. Cai

Dynamic Aperture at 18 GeV, 90 degree lattice



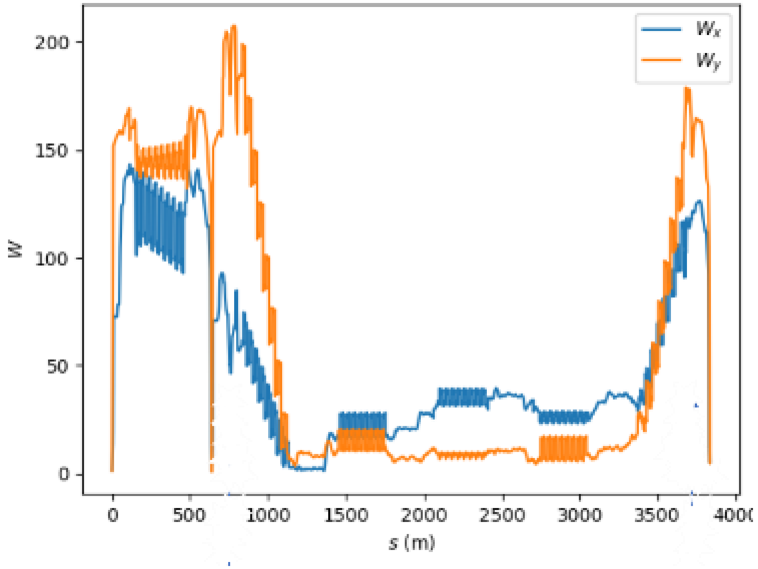
- 17 sigma transverse dynamic aperture
- 1% momentum acceptance (10 sigma)
- Results obtained with 10 GeV, 60 degree lattice indicate sufficient margin for misalignments and magnet multipole errors (Y. Nosochkov)

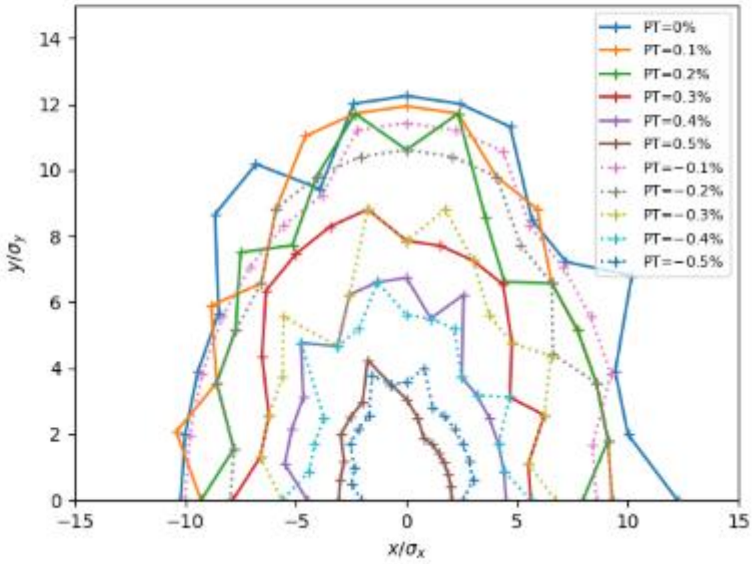
Courtesy Y. Cai

Dynamic Aperture with two IRs

- Each IR is a large source of off-momentum β-beat
- If the two IRs (sources) are 90 degrees betatron phase apart, the off-momentum β-beat forms a closed "β-bump"
- Remainder of the ring has very little off-momentum β-beat
- Concept was successfully applied at HERA

Closed “β-bump” and dynamic aperture with two IRs

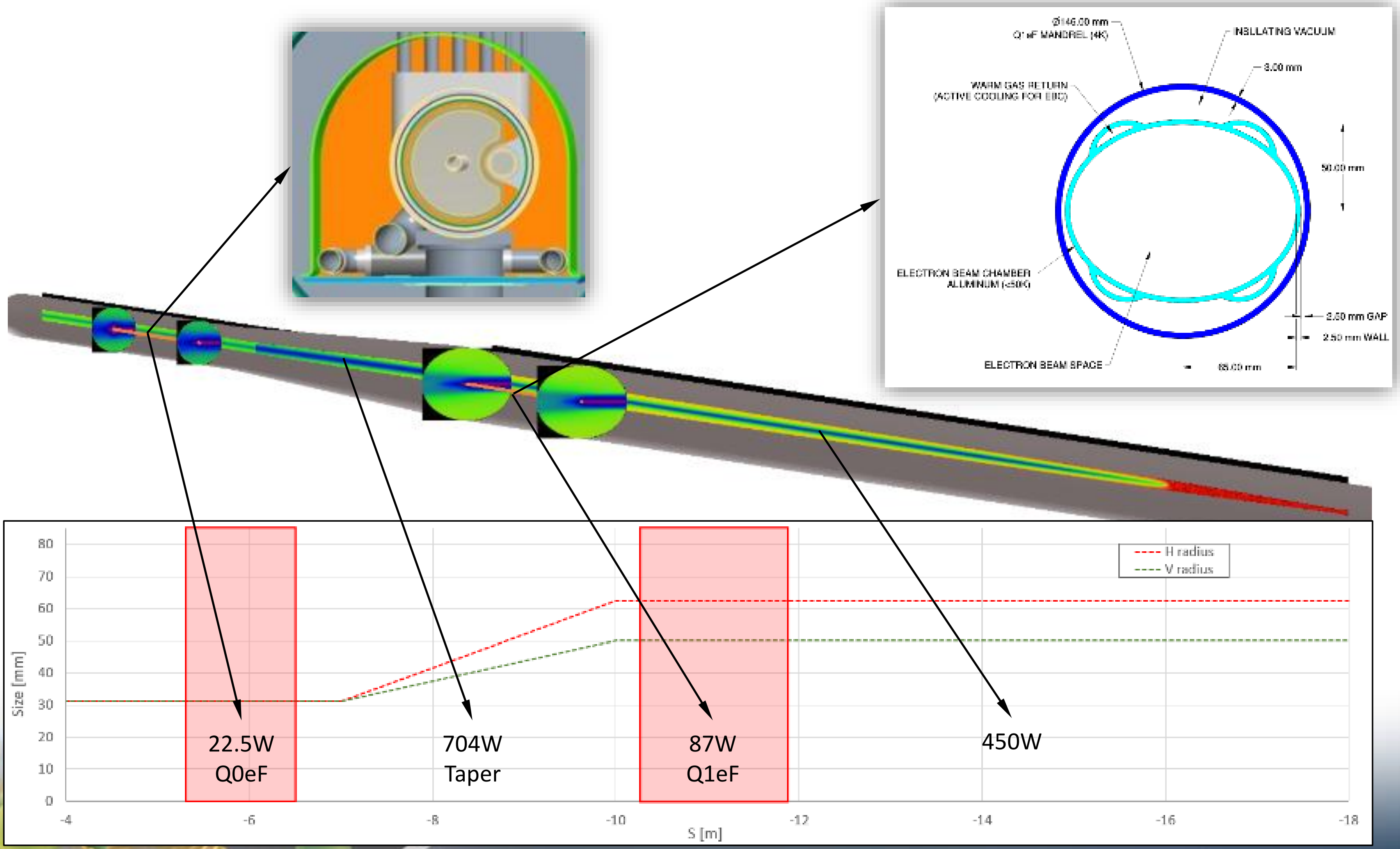




- 10 sigma on-momentum dynamic aperture, 0.5% momentum acceptance with relatively simple sextupole scheme
- Further optimization of sextupole families underway

Courtesy Y. Cai, D. Marx

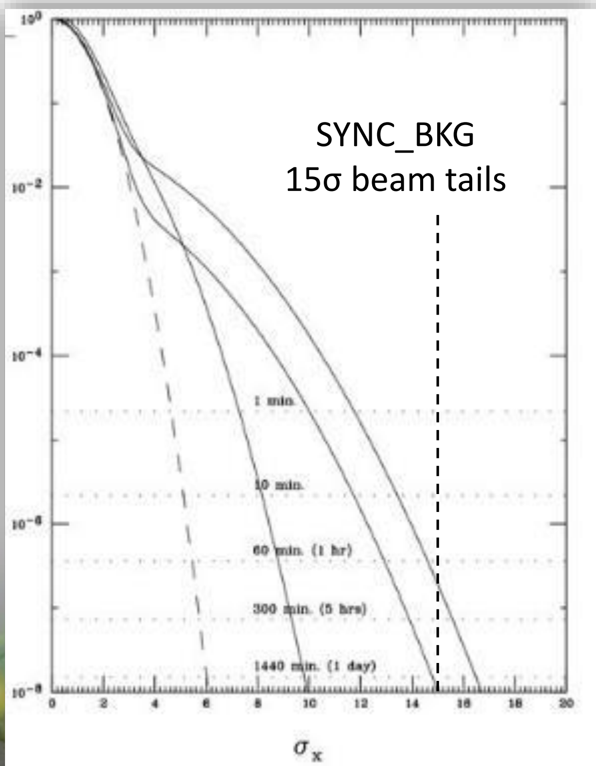
Heat Load in Cold Magnets



SR Studies – 10GeV High Divergence

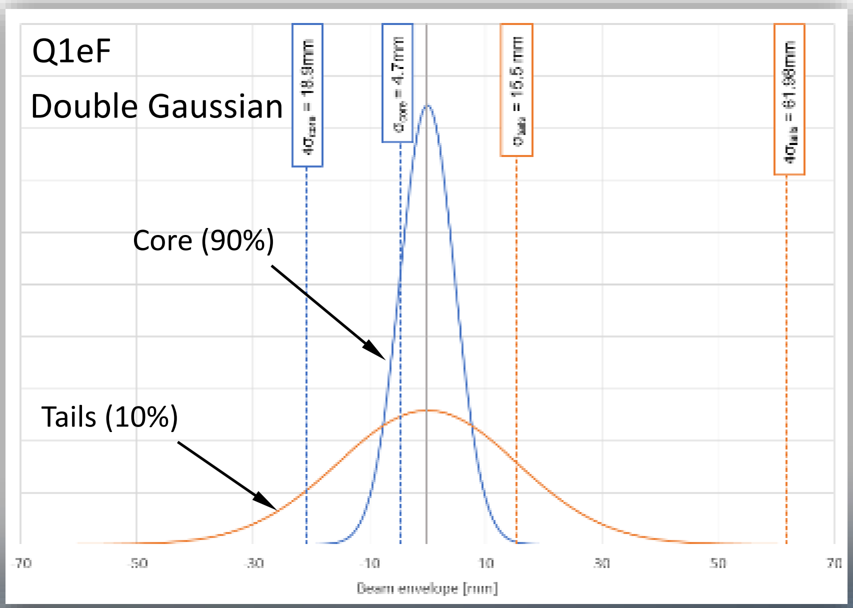
SYNC-BKG (M. Sullivan)
10keV photons hitting beryllium

1.93e^5 ph/crossing ~ 1.75x10^{13} ph/sec



SynRad (C. Hetzel)
10keV photons hitting beryllium

2.64x10^{13} ph/sec



Electron-Ion Collider

Priorities Moving Forward

- RF shielding for vacuum components
  - Bellows optimization
  - Flange joint interconnects
  - Prototypes and testing
- Chamber profiles and tooling development

R&D planned
6.2.3.9.1
Complete Aug 2022

- Movable electron beam collimators
- Central detector chamber
  - Minimize forward scattering
  - Shadowing central detector beam pipe
  - Impedance optimization
  - Fabrication techniques and prototypes

R&D planned
6.2.3.9.2
Complete Oct 2022

- Global impedance budget and instability thresholds
- Detector background studies
- Special chambers with integrated detectors (lumi monitor, e-tagger)

Downstream Hadron Quadrupole Features

Both JLEIC and eRHIC:

- Very large aperture, high field, forces, stored energy
- Cos (2θ) coil layout, strong (collar-based) mechanical structure, high pre-load
- Challenging space constraints, both transverse and longitudinal

JLEIC:

- Aperture range 184-354 mm, pole tip field range 3.4-4.6 T
- Larger transverse envelope available (larger crossing angle): independent hadron/electron magnet cold masses

eRHIC:

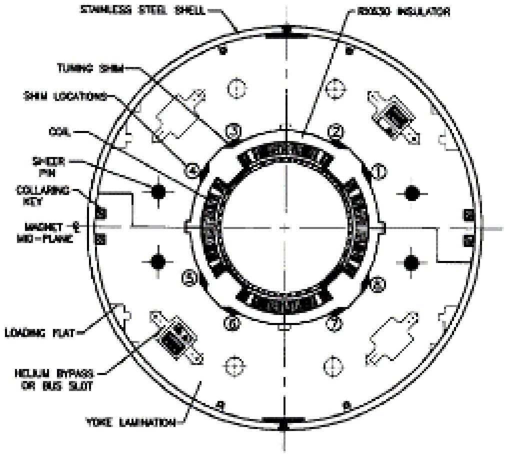
- Aperture range 112-262 mm, pole tip field range 4.1-5.3 T
- Quads are tilted and shifted relative to the beam axis: minimize aperture, maximize iron on the electron beam side avoiding a tapered coil geometry
- No longitudinal gap and bam proximity → Q1BpF/Q2eF in common yoke

Very Large Aperture NbTi Quadrupoles

Magnet	Gradient (T/m)	Bore ID (m)	FoD* – G^2R^3 $(T/m)^2m^3$
RHIC IRQ	48	0.13	5.1
eRHIC Q1ApF	72.6	0.112	7.4
JLEIC iQDS1a	37.2	0.184	8.6
CERN ISR	40	0.20	12.8
JLAB Hall C, Q3	7.9	0.6	13.5
AHF Case II	10.3	0.51	14.1
eRHIC Q1BpF	66.2	0.156	16.6
JLEIC iQDS1b	37.2	0.246	20.6
eRHIC Q2pF	40.7	0.262	29.8
JLEIC iQDS2	26	0.354	30
JLAB Hall C, Q2	11.8	0.6	30.1
HIF RPD FFQ	24.2	0.51	77.7

(*) Ref: J. Waynert et al, IEEE Trans. Appl. Supercond. Vol. 11, March 2001, pp. 1522

BNL RHIC IRQ



JLAB Hall C
SHMS Q2

LBNL Plans

- LBNL activities in 2018-19 were focused on magnetic design and field quality assessment for both electron and ion quadrupoles
- Following the EIC site selection announcement, LBNL has been in discussion with the EIC management to redirect the remaining FOA funds to maximize the benefits to the project.
- The revised plan is centered on the design of the large aperture IR quadrupoles and dipoles: Q1ApF, Q1BpF, Q2pF + B1pF, B1ApF
  - Direct extension of the work performed in the earlier part of the FOA.
  - Latest design parameters and magnetic models were provided by BNL
- Goal: provide feedback to the project on current designs and opportunities for improvement
  - Review SC cable parameters based on LBNL cabling experience and previous large aperture quadrupoles such as the SHMS Q2 at JLAB and the AHF at LANL
    - Critical to all aspects of the design (magnetic, mechanical and quench protection)
  - Preliminary mechanical and protection analysis and feedback on magnetic performance

Publications/Presentations

1. G. Sabbi, “**Recent Advances in IR Magnets**”, EIC Accelerator Collaboration Meeting 2019, Argonne National Laboratory, October 9-11, 2019, https://indico.fnal.gov/event/21416/session/7/contribution/31/material/slides/1.pdf
2. G. Sabbi, B.R. Gamage, T.J. Michalski, V.S. Morozov, R. Rajput-Ghoshal, M. Wiseman, “**Field quality analysis of interaction region quadrupoles for JLEIC**”, NAPAC 2019, https://napac2019.vrws.de/papers/moplo13.pdf
3. R. Rajput-Ghoshal, R. Fair, P. K. Ghoshal, G. Sabbi, “**Optimization of an Interaction Region Quadrupole Magnet for a Future Electron-Ion Collider at JLab”,** 26th International Conference on Magnet Technology (MT-26), in press.
4. G. Sabbi, “**The IR Magnets for EIC**”, EIC User Meeting, Paris, July 2019, https://indico.in2p3.fr/event/18281/contributions/71973/
5. R. Rajput-Ghoshal, C. Hutton, F. Lin, T. Michalski, V.S. Morozov, M. Wiseman, “**Optimization of an Interaction Region Quadrupole Magnet for a Future Electron-Ion Collider at JLab”,** paper TUZBA4, NAPAC2019, Lansing, MI, September, 2019. https://napac2019.vrws.de/papers/tuzba4.pdf
6. V.S. Morozov, et.al., “**Full Acceptance Interaction Region Design of JLEIC**”, IPAC 2019, Melbourne, Australia, doi:10.18429/JACoW-IPAC2019-WEPGW123.
7. Contribution to: B. Parker, et.al., “**Electron Ion Collider Machine Detector Interface**”, paper TUZBA2, NAPAC2019, Lansing, MI, September, 2019. https://napac2019.vrws.de/papers/tuzba2.pdf
8. B.R. Gamage, et.al., “**Multipole Effects on Dynamic Aperture in JLEIC Ion Collider Ring**”, paper TUPLO15, NAPAC2019, Lansing, MI, September, 2019. https://napac2019.vrws.de/papers/tuplo15.pdf
9. R. Rajput-Ghoshal, R. Fair, P. Ghoshal, C. Hutton, E. Sun, M. Wiseman, “**Conceptual Design of the Interaction Region Magnets for Future Electron-Ion Collider at Jefferson Lab**”, IEEE Transactions On Applied Superconductivity, Vol. 29, No. 5, August, 2019, DOI: 10.1109/TASC.2019.2901590.

Summary

- Significant progress was made towards the goals of the R&D project.
- The site selection of the EIC in January, 2020 terminated the specific activities on this R&D project.
- The objectives of this R&D project were well aligned with work required on the EIC at BNL.
- Resources from this R&D project were redirected to Task Forces on EIC during FY’20.
- A small amount of funds remain from this R&D project at LBNL. Plans are under way for LBNL to engage with BNL on EIC tasks.

Thank you for your attention.

Questions?