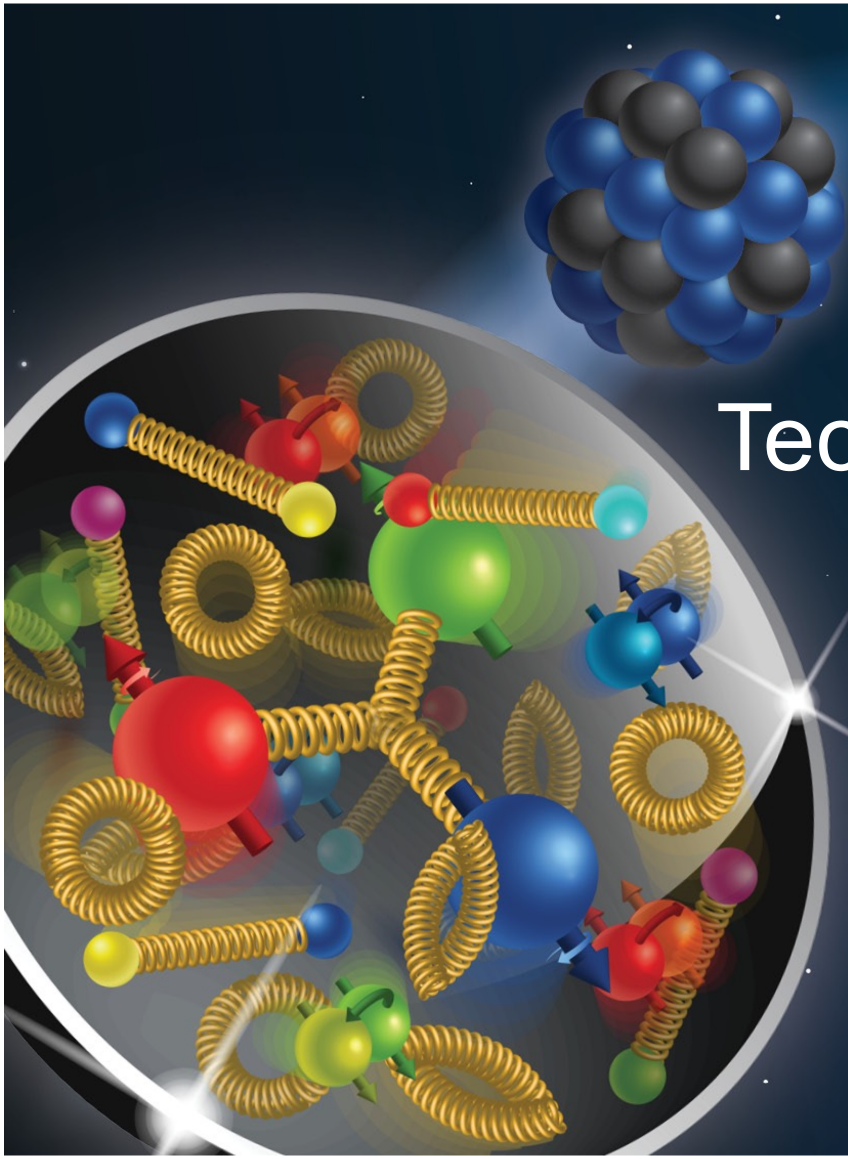


EIC Accelerator New Technologies and Challenges

Todd Satogata, Jefferson Lab

For the EIC Project and EIC Collaboration

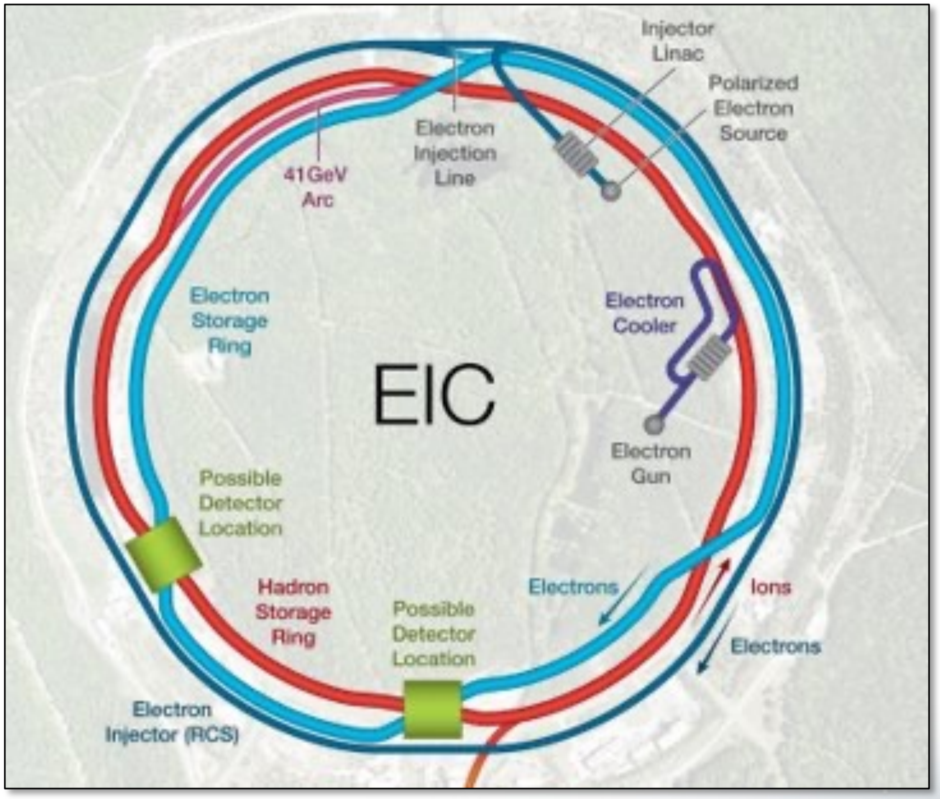
JUAS Lecture

30 January 2024

EIC: Electron-Ion Collider

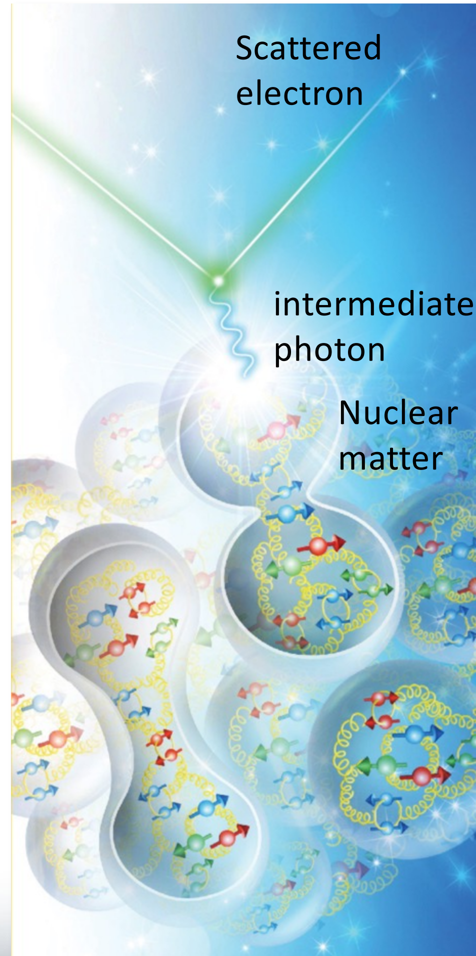
Outline

- The EIC accelerator
  - Requirements and present design
- Accelerator technology challenges
- Some project technology R&D
- Luminosity limiting factors
- Luminosity measurement
- Collider luminosity experience



“Not Like The Others” (LHC, FCC...)

- The **electron-ion collider (EIC)** is:
  - a **nuclear physics** (NP) collider
    - nuclear physics scattering experiments
    - includes “deep inelastic” scattering, or EM-intermediated scattering of electrons and partons
    - collective and single-particle effects in the strong interaction sector
  - NOT a high-energy physics collider
- Addresses **three fundamental nuclear physics questions:**
  - How does nuclear mass arise?
  - How does nuclear spin arise?
  - What are emergent properties of dense gluon systems?



Ultimately, nuclear tomography

EIC Requirements

- **EIC design goals**
  - High luminosity: **$L = (0.1\text{-}1)\cdot 10^{34}\ cm^{-2}\ s^{-1}$**
    - ➔ 10-100 fb^{-1}
  - Collisions of highly **polarized (>70%)** e and p (and light ion) beams
    - with flexible bunch by bunch spin patterns
  - Large range of CM energies:
    - **E_{cm} = 20-140 GeV**
  - Large range of ion species:
    - Protons – Uranium
  - Ensure accommodation of a second IR
  - Large detector acceptances; good background
    - Hadron particle loss
    - IR synchrotron radiation backgrounds

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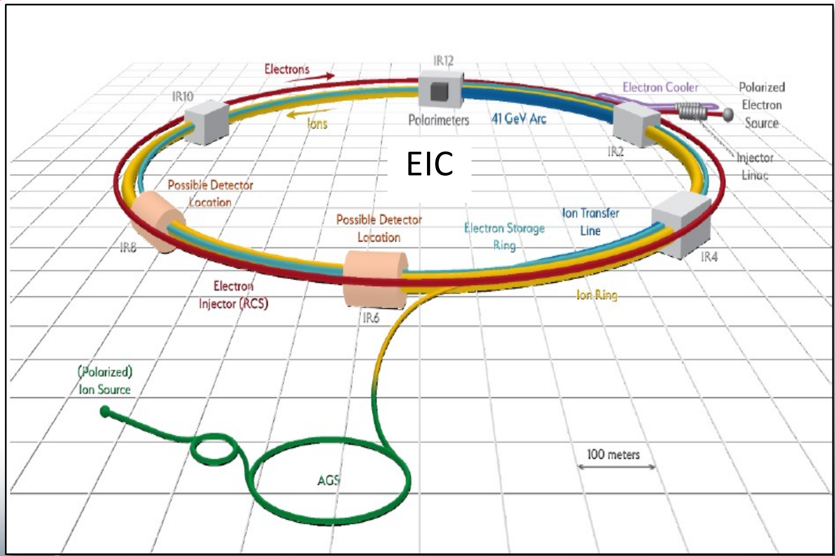
    - Hadron particle loss
    - IR synchrotron radiation backgrounds

"High" Unique "Low" Diverse → **uniquely challenging**

EIC Accelerator Design Overview

- **Hadron storage ring (HSR): 40-275 GeV** **(existing)**
  - up to 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance (1.5 nm); new vac sleeves
  - strong cooling (coherent electron cooling, ERL)
- **Electron storage ring (ESR): 2.5–18 GeV** (**new**)
  - up to 1160 polarized bunches
    - high polarization by continual reinjection from RCS
  - large beam current (2.5 A) ➔ 9 MW SR power
  - superconducting RF cavities
- **Rapid cycling synchrotron (RCS): 0.4-18 GeV** (**new**)
  - 2 bunches at 1 Hz; spin transparent due to high periodicity
- **High luminosity interaction region(s)** (**new**)
  - L = 10^{34} $cm^{-2}s^{-1}$ = 10 kHz-uba, superconducting magnets
  - 25 mrad crossing angle with crab cavities
  - spin rotators (produce longitudinal spin at IP)

Comparable to new mature B-factory, e.g. SuperKEKB



Luminosity (Lumi) Limits In One Slide™

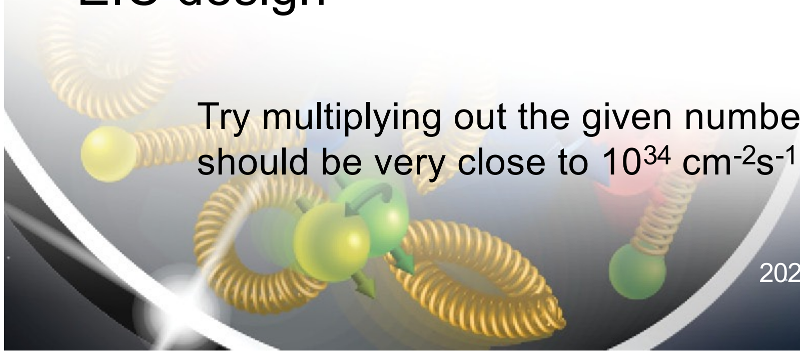
$$L \propto f_{\mathrm{coll}} N_1 N_2 / \sigma_x^\star \sigma_y^\star$$

f_{coll} : collision frequency

$N_{1,2}$: particles per bunch

$\sigma_{x,y}^\star$: (equal) beam sizes at IP

Every parameter optimized separately and collectively in the EIC design



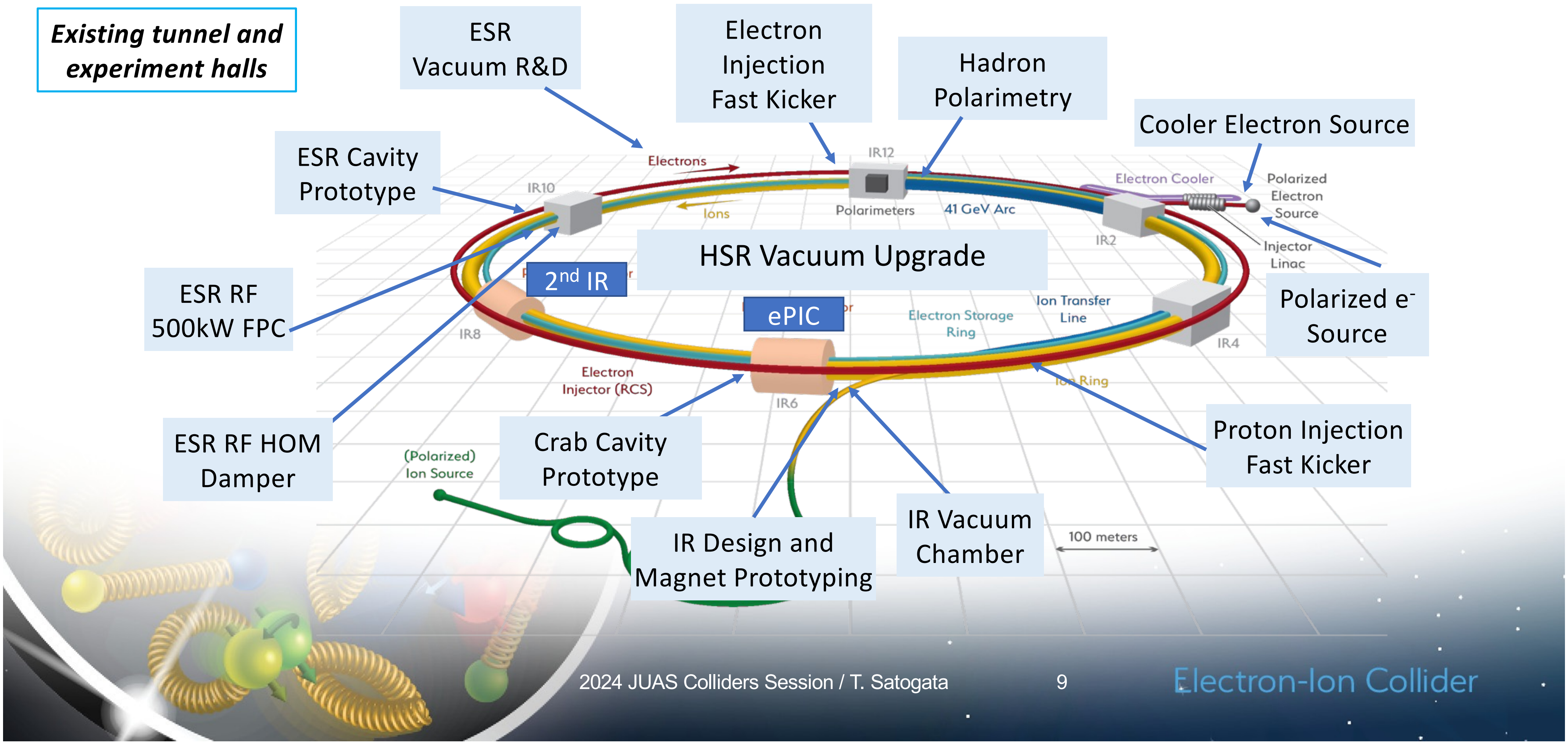
Try multiplying out the given numbers – should be very close to 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- **Maximize collision frequency (~90 MHz)**
  - Limited by kicker rise times
  - Limited by parasitic collisions (crabbing)
- **Maximize particles per bunch (~10^{11})**
  - Limited by sources, space charge
  - Limited by collective effects
    - Interaction of beam with impedances
    - Also total currents: $I_{1,2}=q_{1,2}N_{1,2}f_{\mathrm{coll}}$ ~1-3A
- **Minimize beam sizes at IP (~250/25 um)**
  - Limited by IR focusing, magnets
  - Limited by chromatic dynamic aperture
  - Limited by emittance growth (IBS)

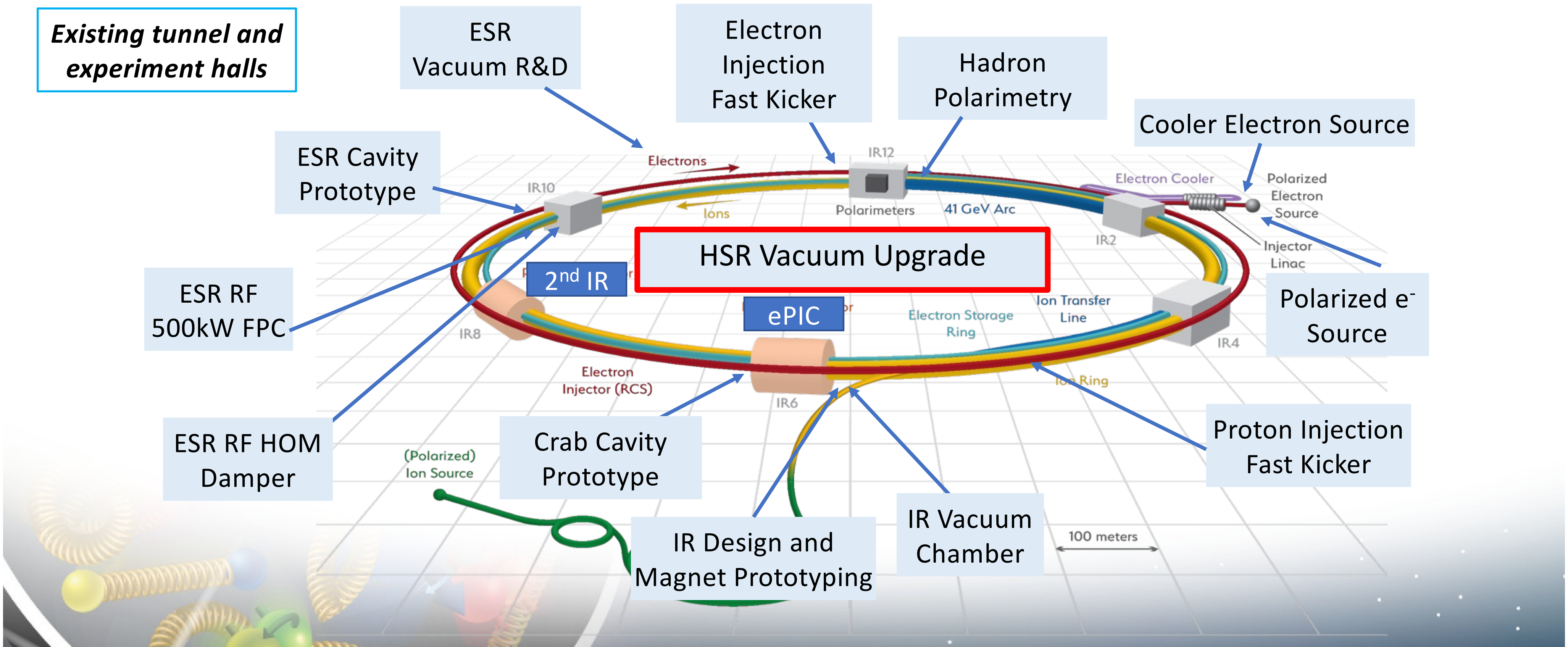
Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

EIC Accelerator Technology Challenges, R&D



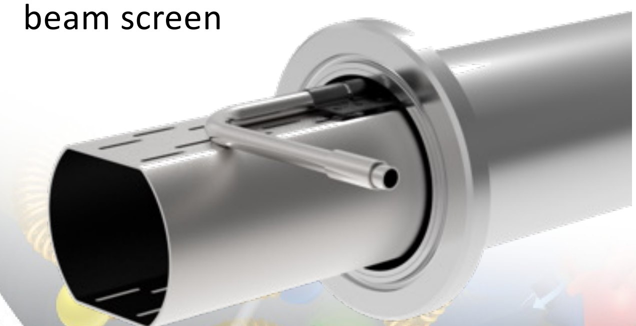
EIC Accelerator Technology Challenges, R&D



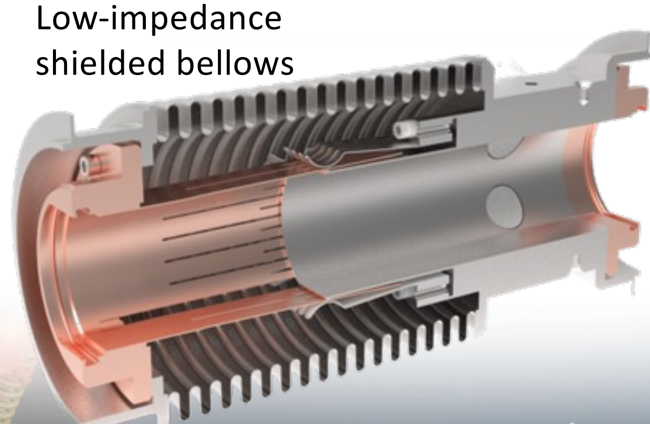
HSR Vacuum Cu/aC Coated Beam Screen

- The resistive losses of the 1A proton beam current leads to an unacceptable cryogenic load
  ➔ need a **Cu coated surface**
- Build up of electron cloud by ionization of rest gas amplified by secondary emission from stainless steel beam pipe
- Need increase conductivity of RHIC cold SS beampipe, **suppress electron cloud** with SEY ~1
  ➔ In situ insertion of a **Cu and aC (amorphous Carbon) coated screen**
- Actively **gas-cooled** screen is the only feasible solution

Insertable cooled beam screen



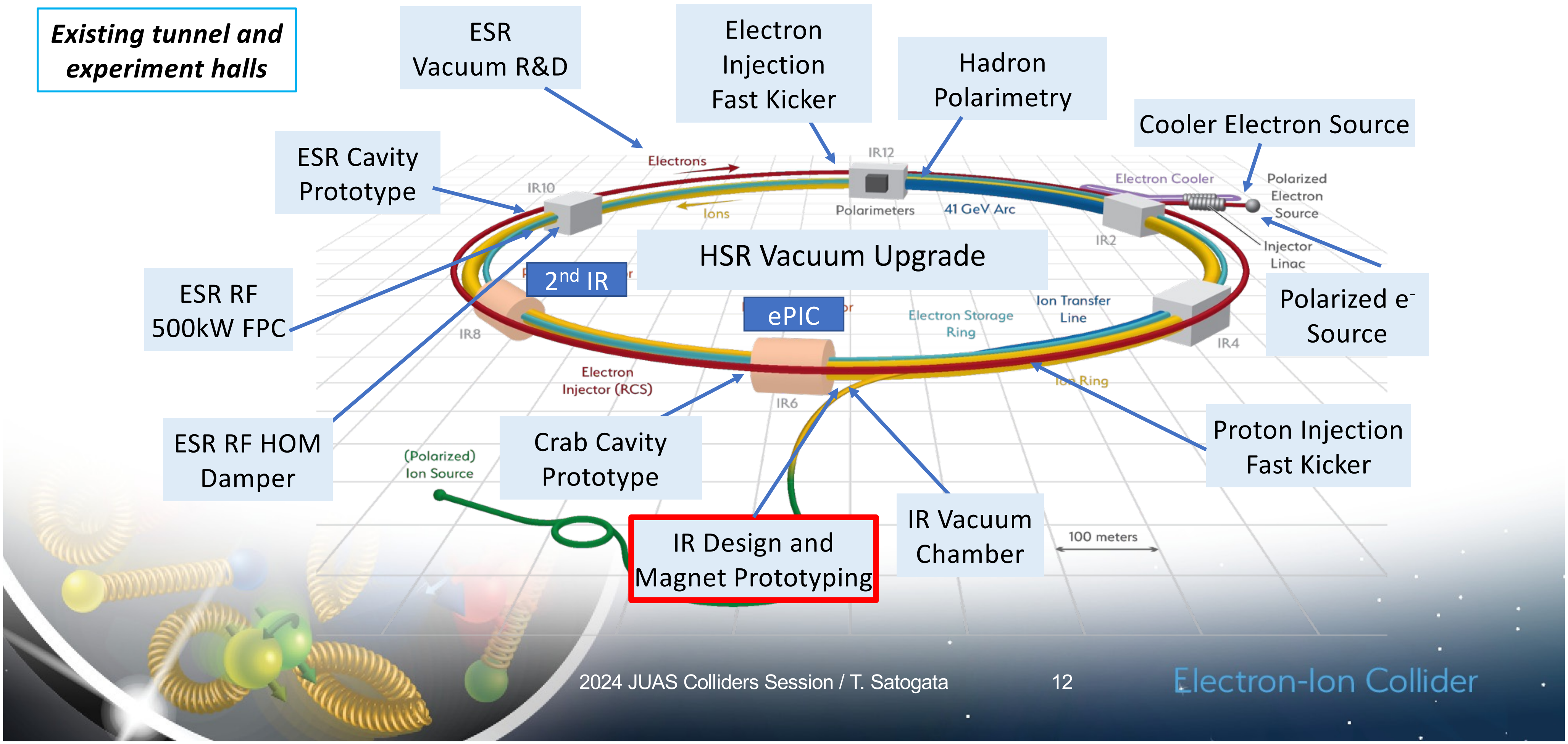
Low-impedance shielded bellows



- Beam screen (including BPM & cold-cables) is part of the early procurement program
- Systems are (almost) ready to be manufactured

- Active collaboration with INFN

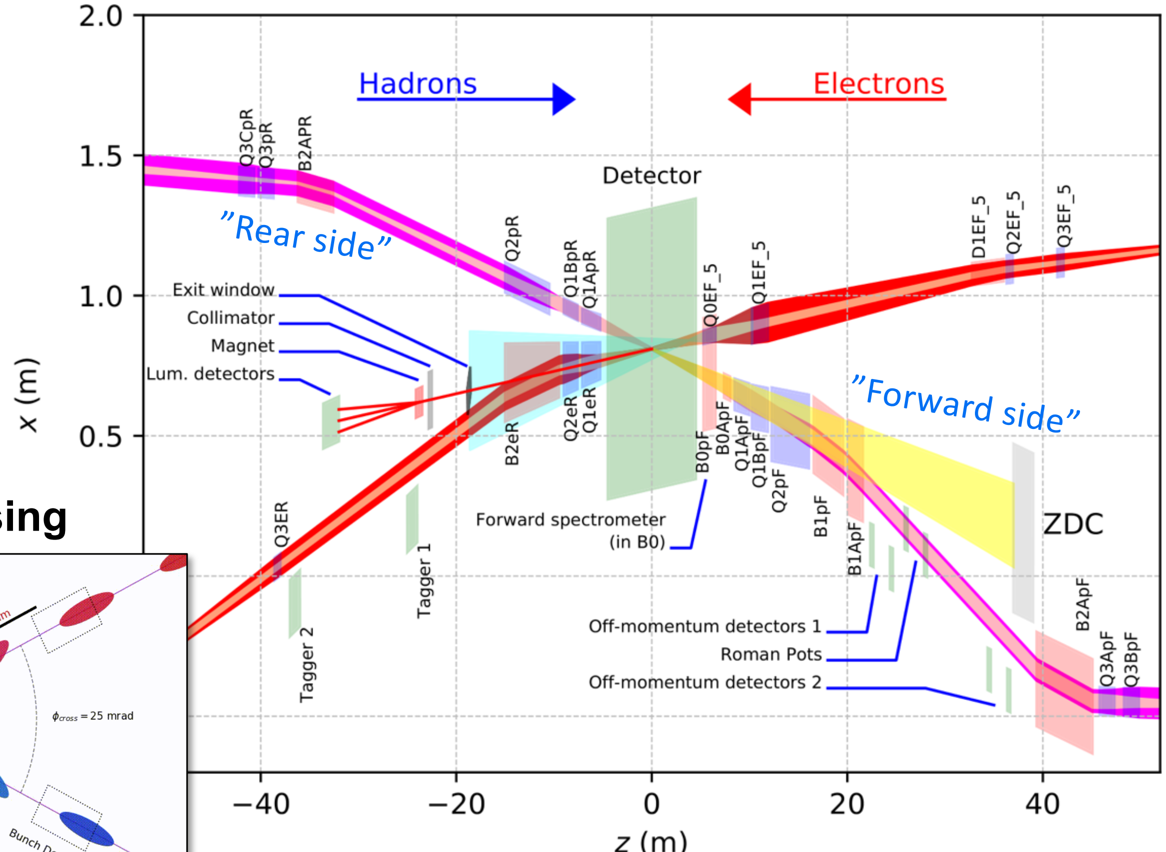
EIC Accelerator Technology Challenges, R&D

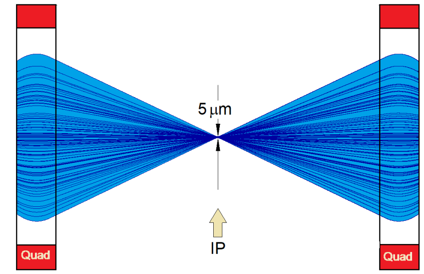


EIC Primary Interaction Region

Existing tunnel and experiment halls

Different
axis scales!





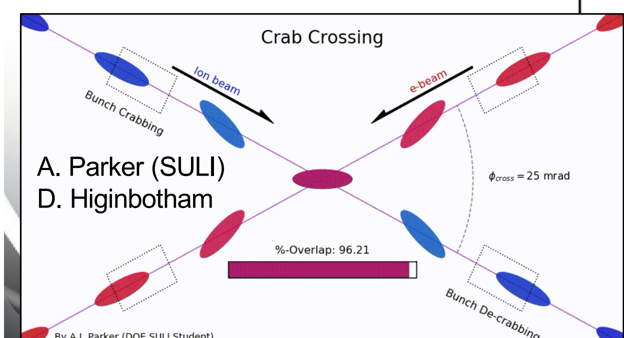
Focusing (quads) as close to IP as possible (~5m!)

Tensions in magnet requirements:

- high field
- large apertures
- e/p magnet proximity near IP

Chromaticity: focusing dependence on particle energy

25 mrad crab crossing

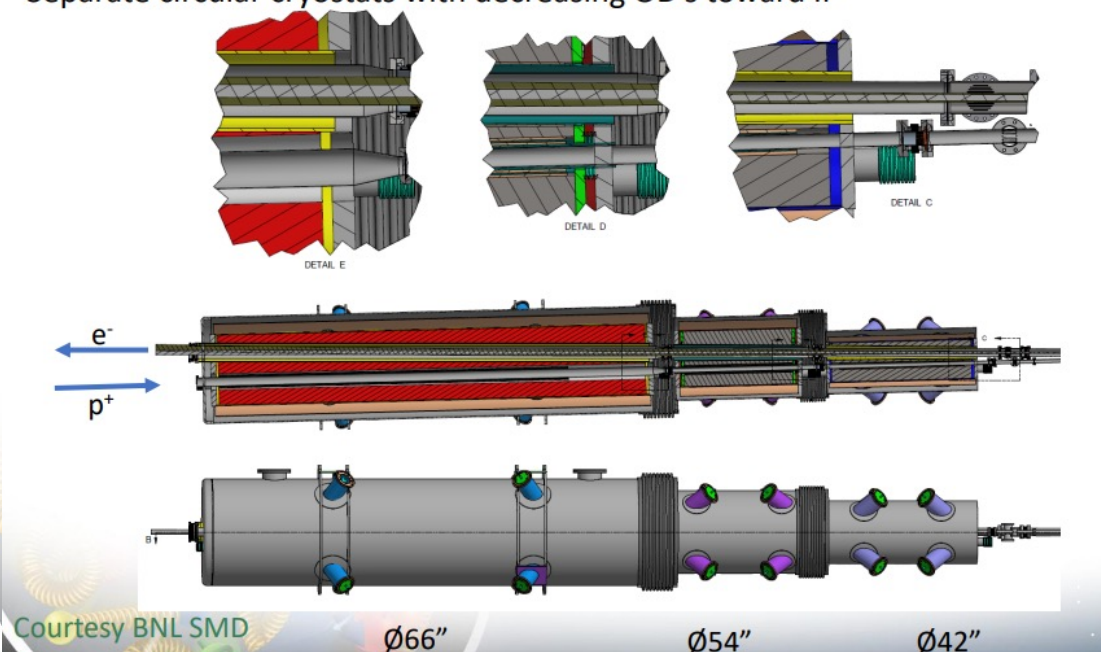


A. Parker (SULI)
D. Higinbotham

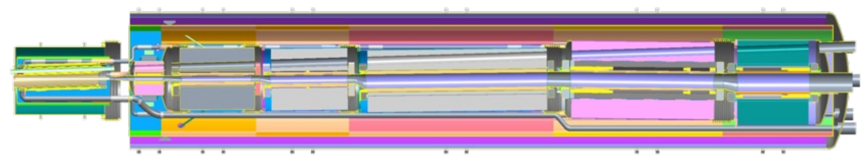
EIC R&D: IR Superconducting Magnets

Rear Side Integration / Beampipe

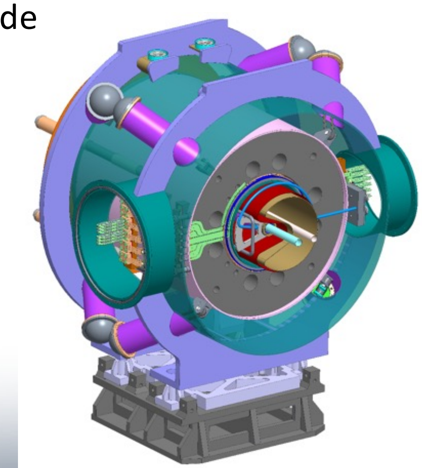
Separate cold masses - helium vessels
Separate circular cryostats with decreasing OD's toward IP



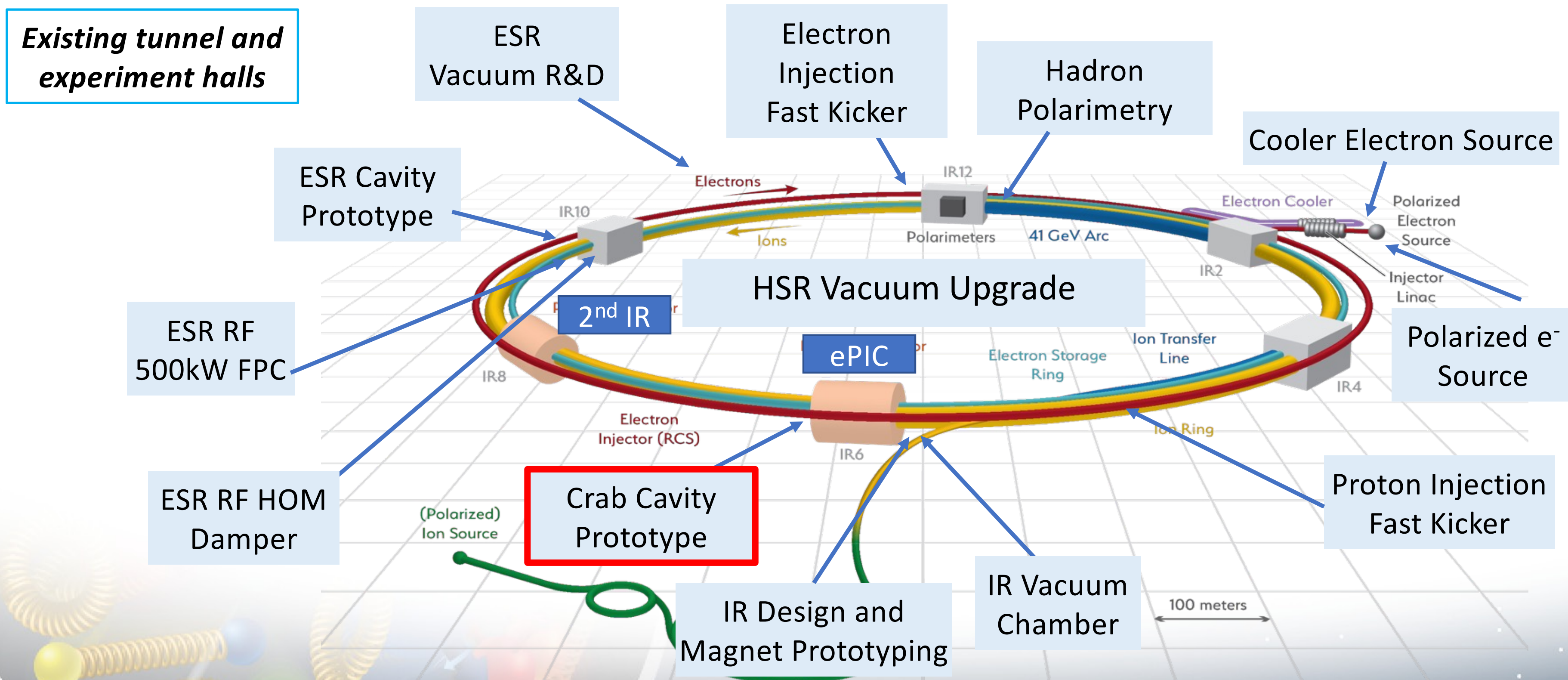
Forward superconducting magnet integration



Multiple function spectrometer magnet at the forward hadron side



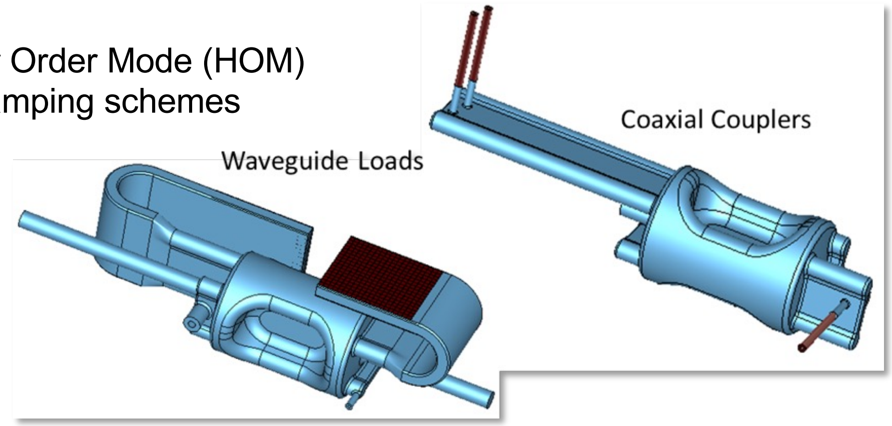
EIC Accelerator Technology Challenges, R&D

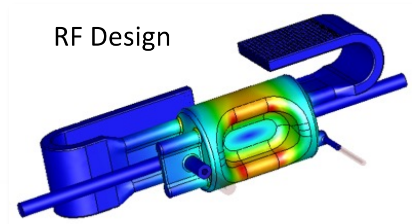


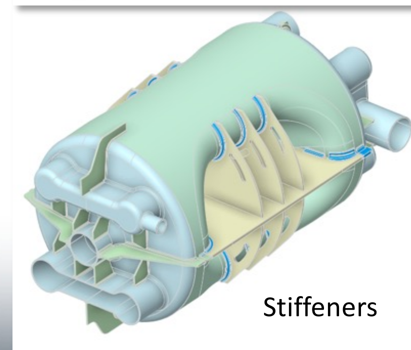
EIC R&D: Crab Cavities

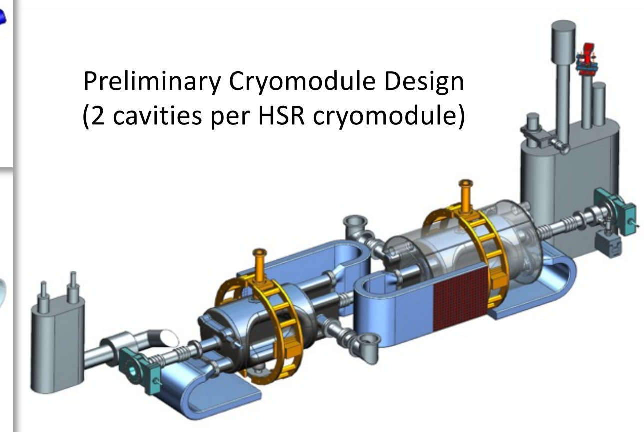
- **Hadron collider crabbing unprecedented**
  - Collaborating with HL-LHC
    - Beam dynamics, RF control stability
    - SPS tests: Phys. Rev. Accel. Beams 24, 062001 (2021)
  - **Electron crabbing** was performed at KEKB (arXiv:1410.4036)
- **Superconducting "RF dipole" cavity**
  - **ODU design**
  - High electric field and overall field quality requirements
- **197 MHz HSR crab cavity being prototyped**
  - Jefferson Lab/ODU/(BNL) collaboration
  - Two possible HOM damping schemes: Waveguide loaded and coaxial couplers
  - Stress analysis near completion, with stiffeners

Higher Order Mode (HOM) damping schemes

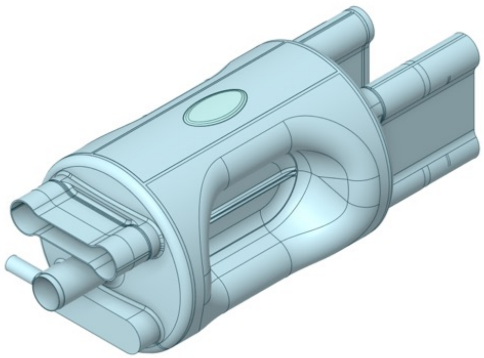




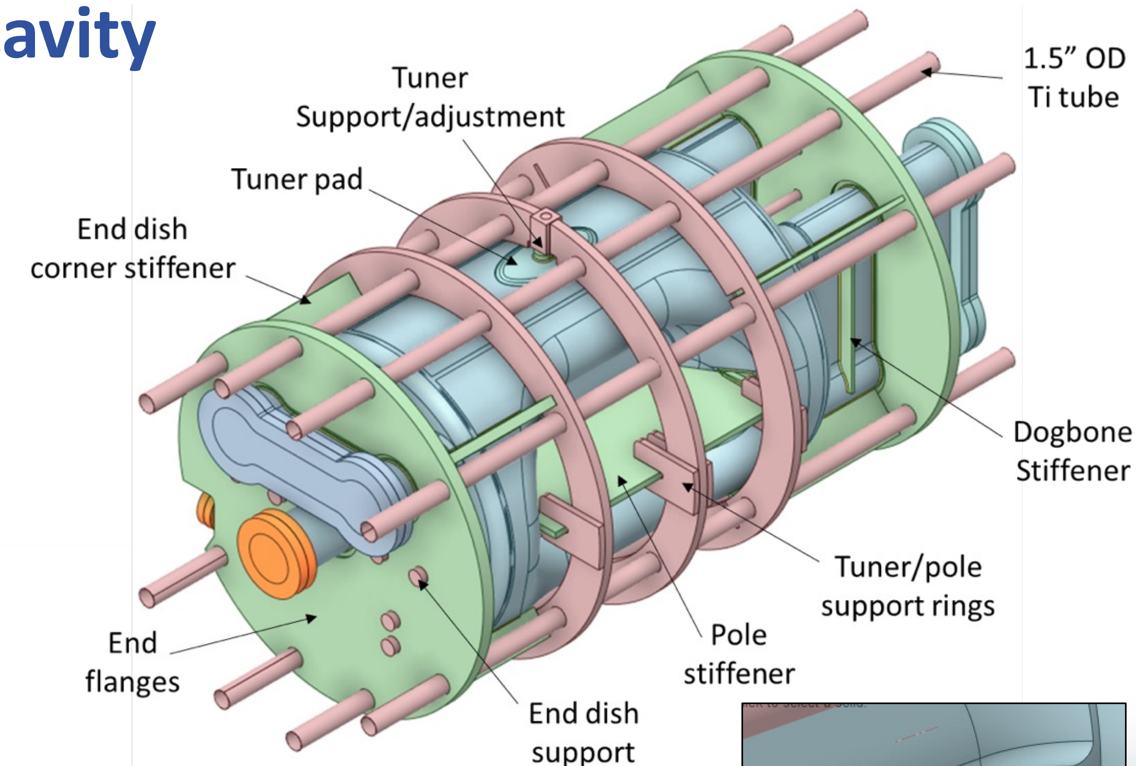


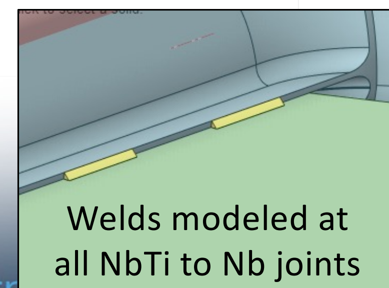


197 MHz Prototype Crab Cavity



	Nb
	NbTi
	Ti
	SS
	Weld

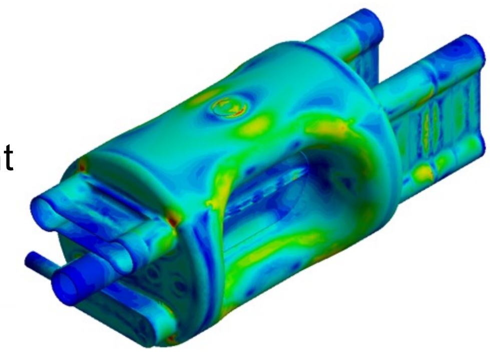


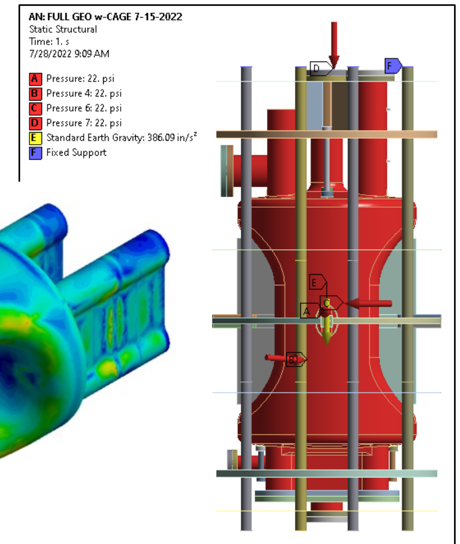


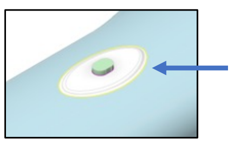
- Cavity body is comprised of 4 mm Nb with some regions thicker than 4 mm
- Stiffeners are needed to maintain stress at acceptable level

Mechanical Analysis for 197 MHz Crab Cavity

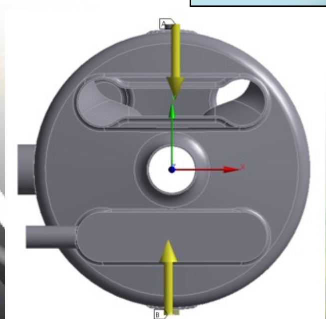
- Cavity body is comprised of 4 mm Nb with some regions thicker than 4 mm
- Stress analysis
  - For VTA test at 22 psi is within allowable stress of 6.3 ksi
- Tuning analysis - Tuning in the magnetic field region
  - Δf = ± 682.3 kHz (Requirement: ± 472 kHz)
  - Tuning sensitivity = 126.4 kHz/mm for a total 5.4 mm displacement
  - 2.7 mm push/pull tuning limit at allowable stress
  - 7400 lb force on each tuner pad (2740 lb/mm)

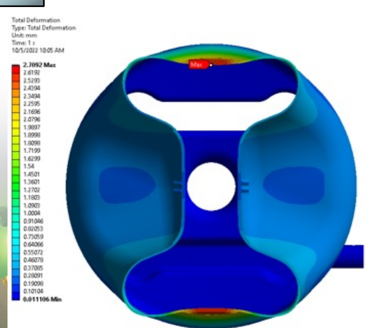




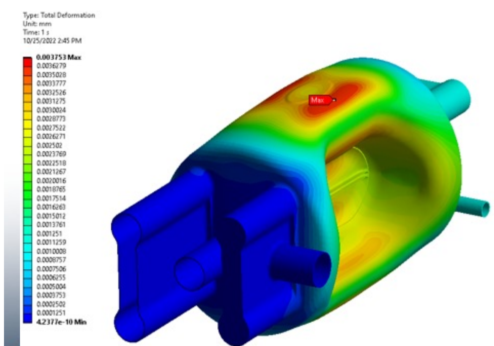


Tuner plate and adapter



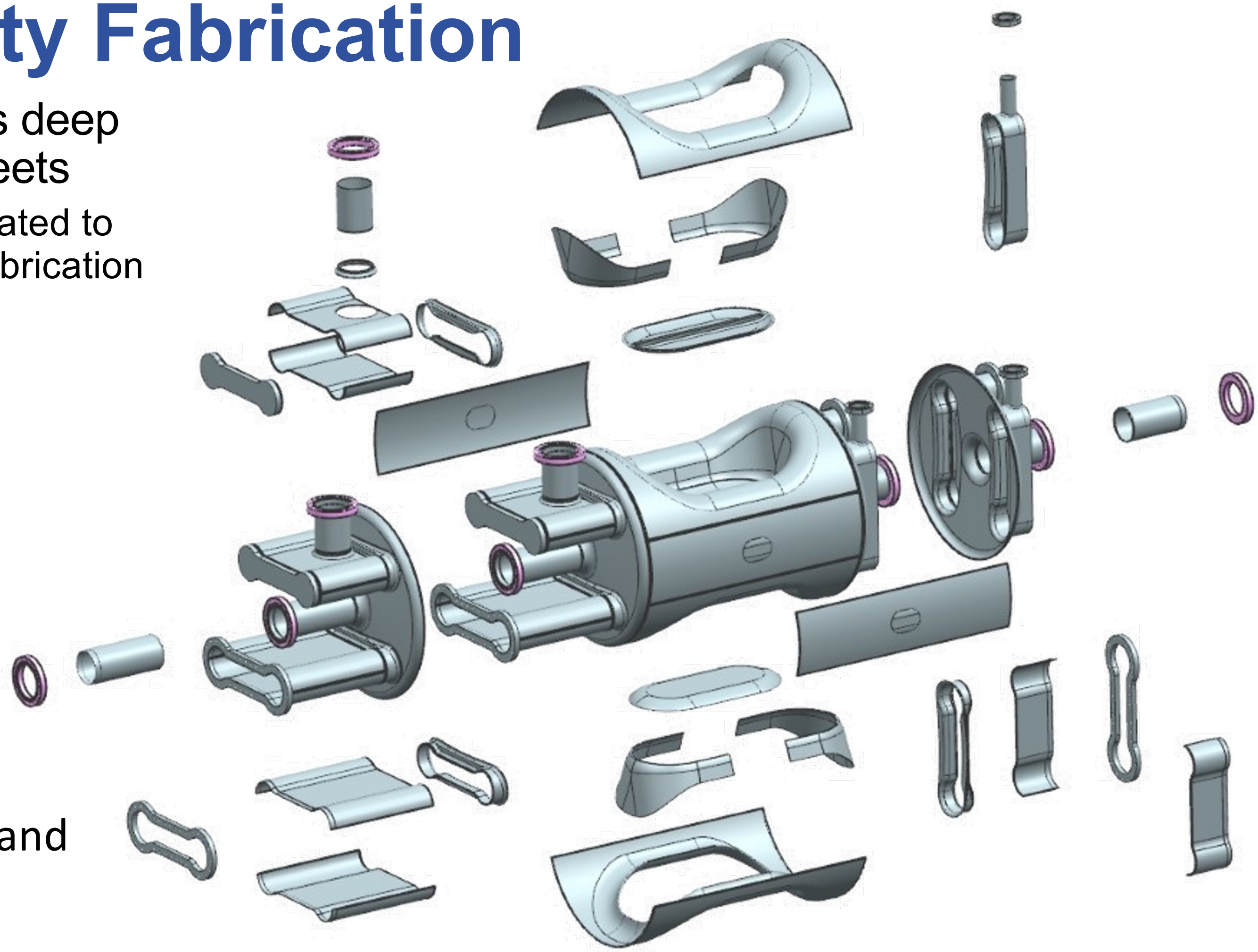


- Pressure sensitivity – 178 Hz/torr
- Lorentz detuning:
  - Beam pipes fixed → -222.7 Hz/(MV)^2
  - Tuner fixed → -108.8 Hz/(MV)^2
  - Beam pipes fixed with support cage → -42 Hz/(MV)^2



Prototype Cavity Fabrication

- Majority of the cavity body is deep drawn from 4.17 mm Nb sheets
  - A full Cu cavity will be fabricated to understand and verify the fabrication process
  - Also, to perform room temp measurements
- Flanges:
  - Dogbone flanges – Nb with Indium seals
  - All other flanges – 316 LN SS CF flanges with Cu gaskets
- All Nb purchased
- JLab actively pressing parts and testing welding approaches



Electrons and Hadrons in Synchrotrons (EIC)

- **Electrons**
  - **Larger charge/mass ratio**
    - Smaller B to bend/focus (E, crab)
    - Normal conducting magnets
    - Polarization time dependence
  - **Synchrotron radiation**
    - Photonic backgrounds
    - Damping
    - Dynamic aperture: Touschek
    - Large RF power needs
    - **Flat beam aspect ratio**
  - Harder collimation (multi-stage)

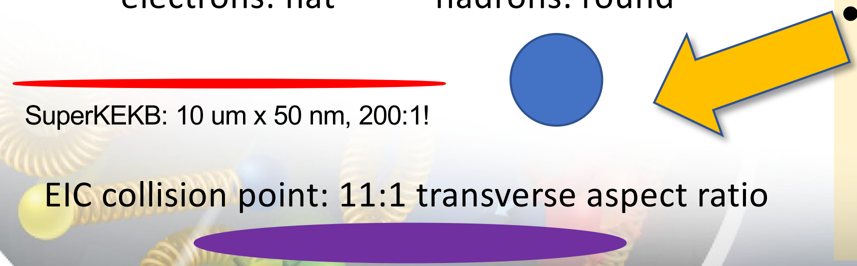
- **Hadrons**
  - **Smaller charge/mass ratio**
    - Larger B to bend/focus (E, crab)
    - Superconducting magnets
    - No depolarization (in principle)
  - **No synchrotron radiation**
    - Hadronic backgrounds
    - Negligible damping (EIC energies)
    - Dynamic aperture: “Diffusion”
    - Modest RF power needs
    - **Round beam aspect ratio**
  - Easier collimation (single-stage)

Lumi Limits In (more than) One Slide[NoTM]

$$L \propto f_{\text{coll}} N_1 N_2 / \sigma_x^\star \sigma_y^\star$$

- f_{coll} : collision frequency
- $N_{1,2}$: particles per bunch
- $\sigma_{x,y}^\star$: (equal) beam sizes at IP

Challenge: colliding asymmetric beams

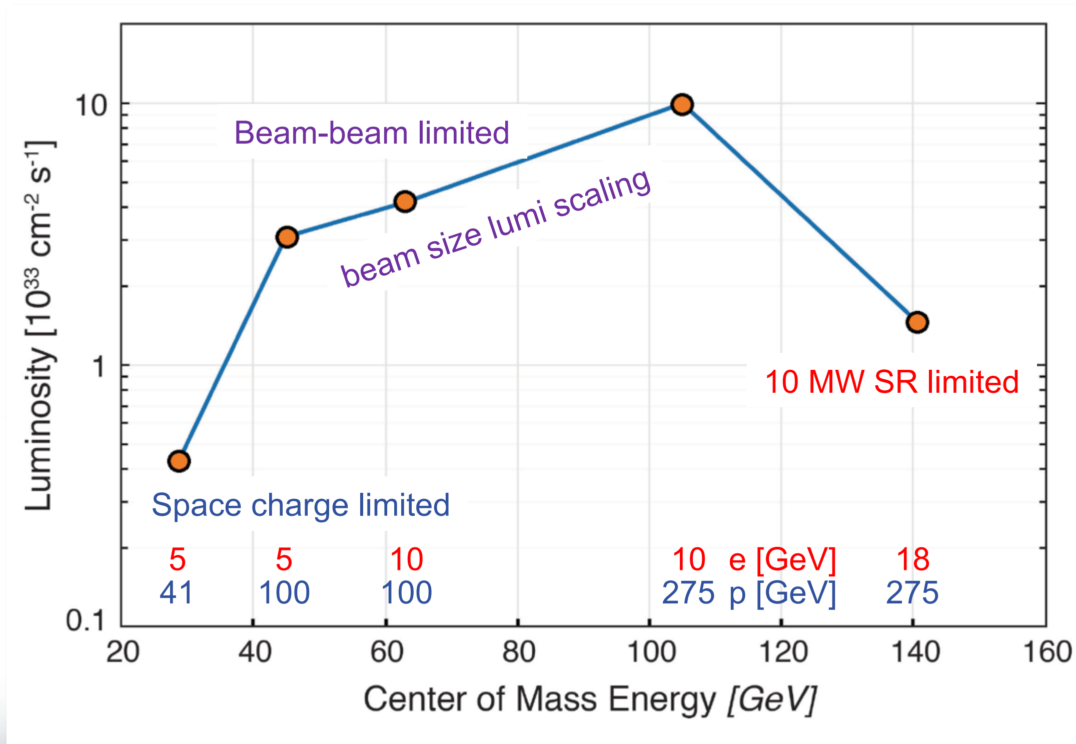


- **Maximize collision frequency (~90 MHz)**
  - Limited by kicker rise times
  - Limited by parasitic collisions (crabbing)
- **Maximize particles per bunch (~10^{11})**
  - Limited by sources, space charge
  - Limited by collective effects
    - Interaction of beam with impedances
    - Also total currents: $I_{1,2}=q_{1,2}N_{1,2}f_{\text{coll}}$ ~1-3A
- **Minimize beam sizes at IP (~250/25 um)**
  - Limited by IR focusing, magnets
  - Limited by chromatic dynamic aperture
  - Limited by emittance growth (IBS)

EIC CDR (CD-1) Parameters for E_{cm} and Luminosity

	Electrons	Protons
Beam energies	2.5 - 18 GeV	41- 275 GeV
Center of mass energy range	E_{cm} = 20-140 GeV	

	Electrons	Protons
Beam energies	10 GeV	275 GeV
Center of mass energy	E_{cm} = 105 GeV	
number of bunches	nb =1160	
crossing angle	25 mrad	
Bunch Charge	$1.7\cdot10^{11}$e	$0.7\cdot10^{11}$e
Total beam current	2.5 A	1 A
Beam emittance, horizontal	20 nm	9.5 nm
Beam emittance, vertical	1.2 nm	1.5 nm
β- function at IP, horizontal	43 cm	90 cm
β- function at IP, vertical	5 cm	4 cm
Beam-beam tuneshift, horizontal	0.073	0.014
Beam-beam tuneshift, vertical	0.1	0.007
Luminosity at E_{cm} = 105 Gev	**$1\cdot10^{34}$cm^{-2}s^{-1}**	

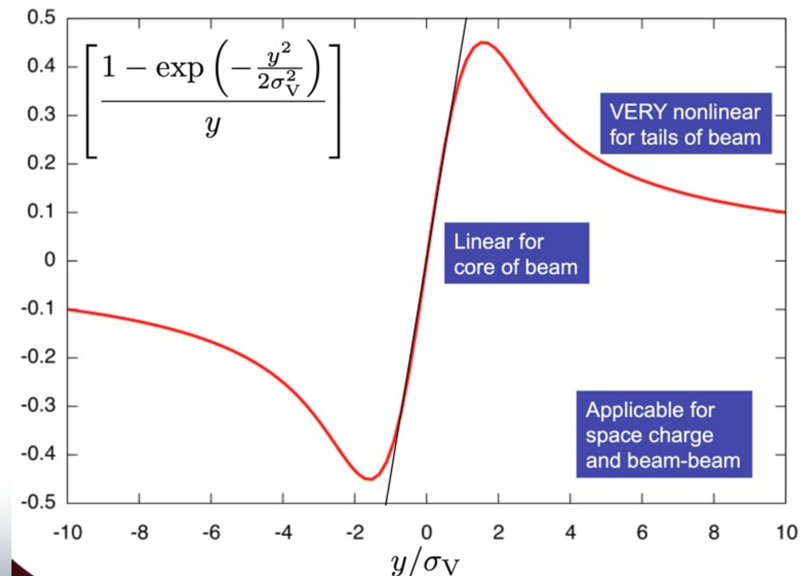


$L = 10^{34}$ cm^{-2}s^{-1} = 10 kHz-uba

Lumi Limitations: Space-Charge (low E_{cm})

- Dense charged particle bunches **electrostatically repel** in rest frame
- Creates **nonlinear** space charge force and equation of motion in lab frame
- Fortunately scales with $1/\gamma^3$ so worst at low energies
  - Great example of time dilation
  - Limits high-intensity injector emittances
  - Force applies continuously within beam
- Tolerable linear "space charge tune spread" of 0.05 limits total current of 41 GeV proton beam to ~0.4A.
- (IBS: intra-beam hard scattering also contributes)

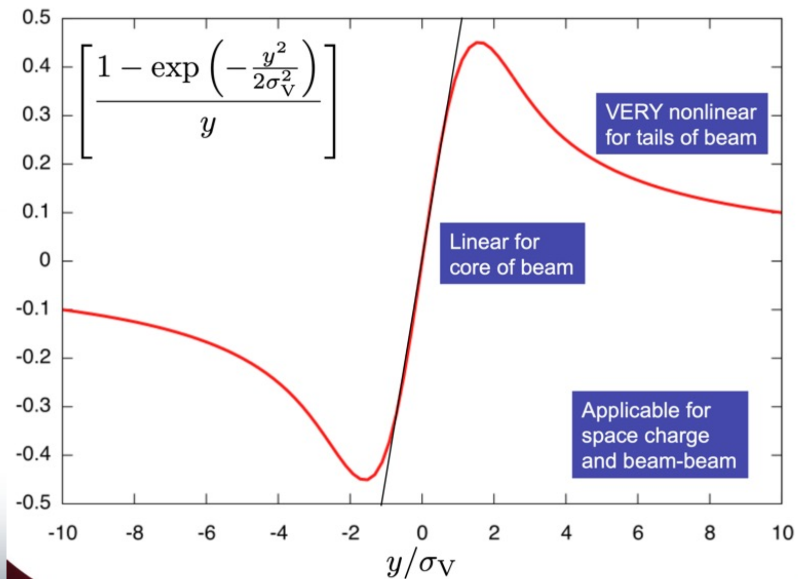
$$\frac{d^2y}{d\theta^2} + Q_V^2 y = \frac{2Nr_0R^2}{l\beta^2\gamma^3}\left[\frac{1-\exp\left(-\frac{y^2}{2\sigma_V^2}\right)}{y}\right]$$



Lumi Limitations: Beam-Beam (mid E_{cm})

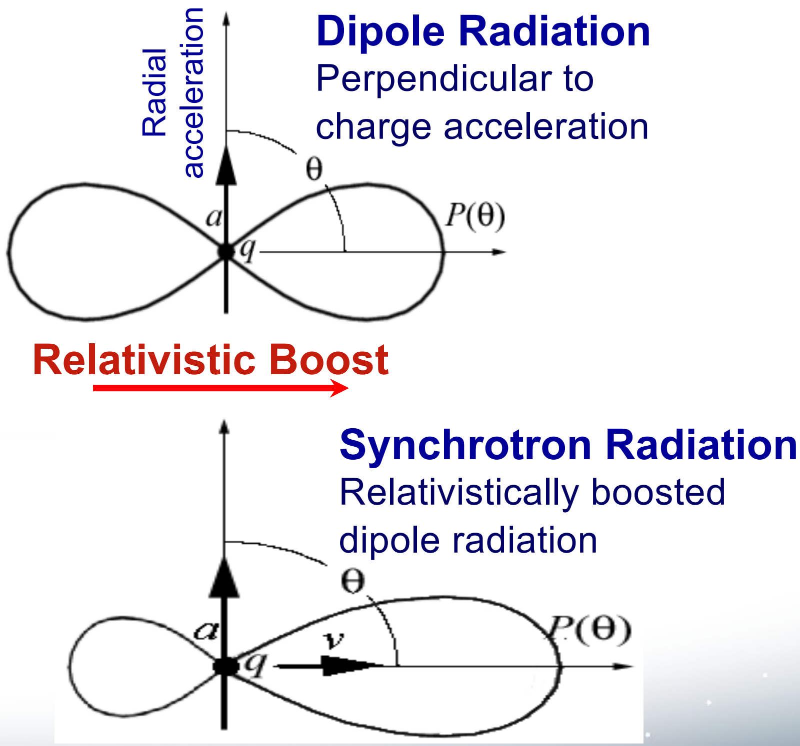
- Colliding beams see each other's collective charge distributions
- Creates **nonlinear** beam-beam force and equation of motion similar to space charge
  - **BUT** now the fields and force are in the lab frame already
  - **NO** benefit of relativistic scaling
  - **Force applies only once per turn**
- Tolerable "beam-beam tune spead" of 0.015 limits highest EIC luminosity

$$F(r) = \frac{Nq^2}{2\pi\epsilon_0 l}\frac{1+\beta^2}{r}\left[1-\exp\left(-\frac{r^2}{2\sigma^2}\right)\right]$$



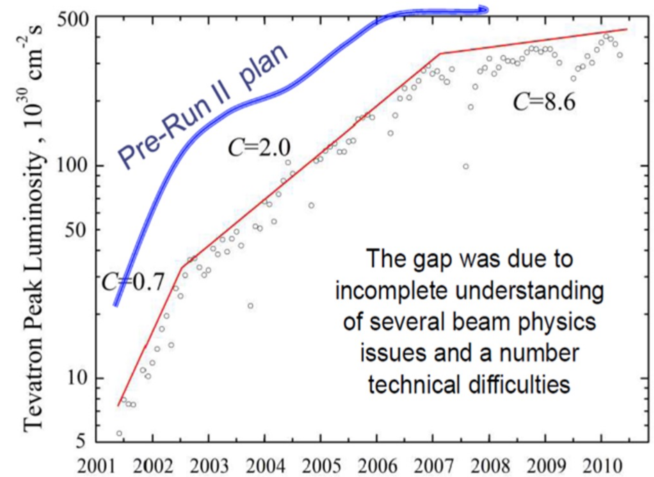
Lumi Limitations: Electron SR Power (high E_{CM})

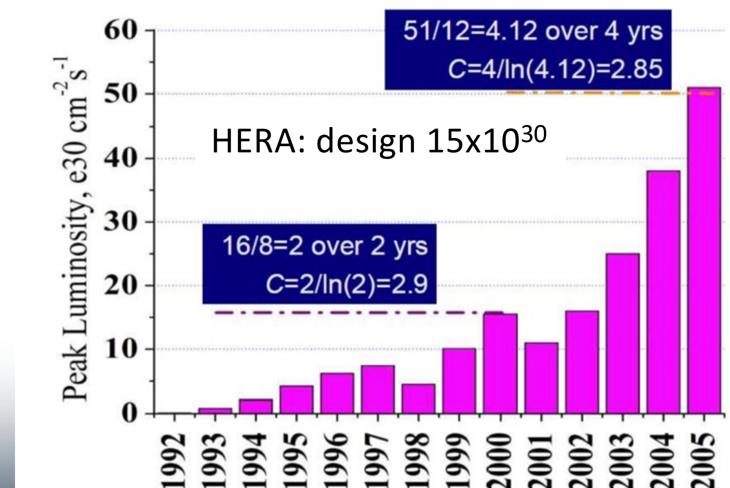
- Accelerated charged particles emit photons
  - Electrons in synchrotron: radially accelerated
  - **Synchrotron radiation** emitted in forward cone
    - Cone opening angle $\propto 1/\gamma$
    - Radiated power $P_\gamma = \frac{2}{3} \frac{e^2 c}{4\pi\epsilon_0} \frac{(\gamma\beta)^4}{\rho^2}$
  - γ scaling **much** worse for electrons
    - 18 GeV e: γ=3.5x10^4 vs 255 GeV p: γ=3x10^2
- **Design: 9 MW** @ 18 GeV (facility limit 10 MW)
- **Expensive:** Power must be provided by SRF
- Raise electron energy last (e current limit)



Collider Luminosity Ramp-Up

- Luminosity ramp-up to design takes **years**
  - Useful paper: arxiv 1202.3950 (V. Shiltsev)
  - Contextualizes Tevatron Run-II and early LHC
  - Luminosity ramp-up parameter C: **complexity**
    - **C: time (years) to increase lumi by e**
    - C=2: factor of e luminosity increase in 2 years
  - Early commissioning can make quick strides
    - C<1 (or <<1) but do not get too exuberant
  - Long-term commissioning usually C~2-3
- **EIC will very likely take years to reach design luminosities**
  - **But we will get there!**





K. Piotrzkowski, https://arxiv.org/pdf/2106.08993.pdf 2021 *JINST* **16** P09023

EIC Luminosity Measurement

- Bethe-Heitler bremsstrahlung
  - Induced e- radiation
  - Proportional to luminosity
    - With correction terms
  - Very ”e-forward” electrons
    - Similar to synchrotron radiation

- **Challenges**
  - Bremsstrahlung rate suppression due to the so-called beam size effect (observed at HERA)
  - Huge synchrotron radiation fluxes should be mitigated (split dipole)
  - Enormous bremsstrahlung event rates, up to 10 GHz

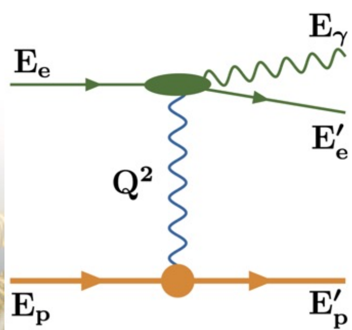


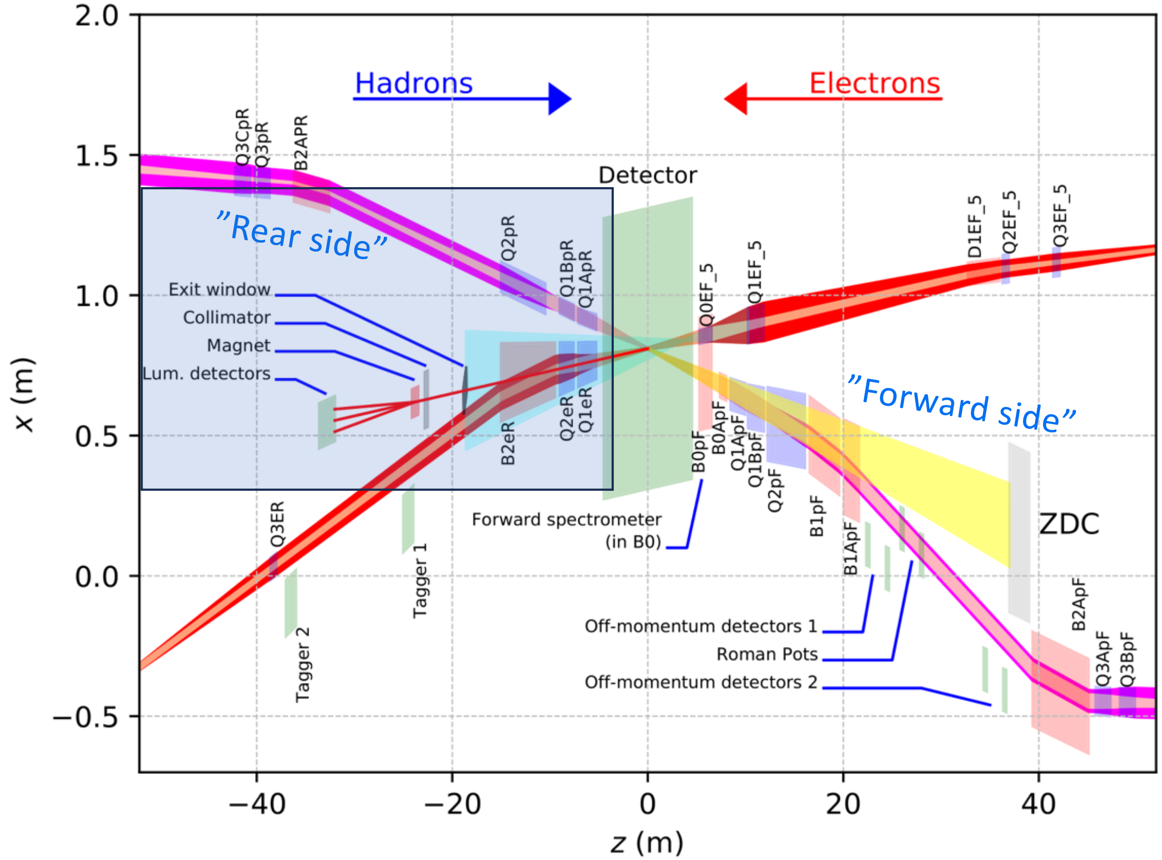
Table 1. Bethe-Heitler *ep* bremsstrahlung cross sections in mb (and the corresponding event rates in GHz, for the nominal EIC luminosities), for various beam energies in GeV and three selection criteria.

E_e	E_p	$E_\gamma/E_e > 0.01$	$1 > E_\gamma/E_e > 0.7$	$0.4 > E_\gamma/E_e > 0.1$
18	275	237 (0.36)	11.6 (0.018)	65.2 (0.10)
10	275	230 (2.3)	11.1 (0.11)	63.2 (0.63)
5	100	209 (0.77)	9.81 (0.036)	57.1 (0.21)

EIC Primary Interaction Region: Lumi Monitor

Existing tunnel and experiment halls

Different axis scales!



Summary

- EIC design meets all design requirements
- EIC luminosity is **highly optimized**
  - Balances several individual parameter optimizations
- EIC R&D progressing
  - Focus: challenging technical components
- e/p beam differences drive EIC choices
  - e.g. luminosity vs E_{cm}, IP aspect ratio
- Luminosity ramp-up will take time
  - will last substantially beyond project end
  - project provides excellent basis to get there!