Brookhaven National Laboratory

Jefferson Lab

U.S. DEPARTMENT OF ENERGY

# EIC Electron Injector Systems Overview

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ICHEP, Prague

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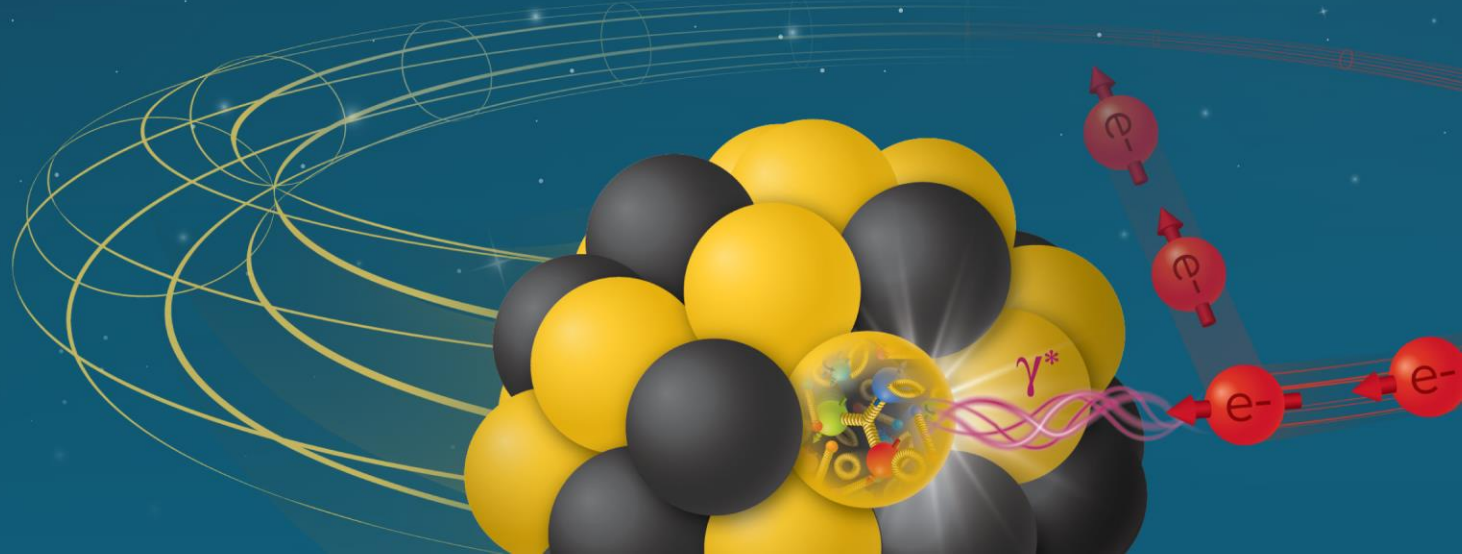


Electron-Ion Collider

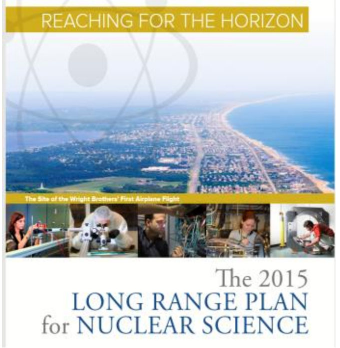
# Outline

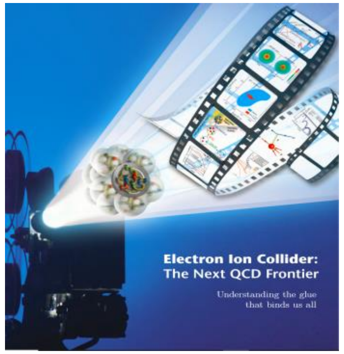
- EIC Overview
- EIC Electron Injector Systems (EIS) Performance Goals
- Pre-Injector Systems
  - Polarized Source
  - 3 GeV Injector
- Review of RCS Concept and Layout
  - Lattice Geometry
  - Charge Accumulation Strategy
  - Matching to Storage Ring Emittance

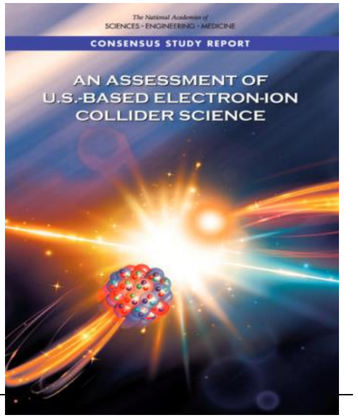
# EIC Requirements

- High luminosity: L = $10^{33}$ to $10^{34}$ $cm^{-2}sec^{-1}$ - factor 100 to 1000 beyond HERA
- Large range of center-of-mass energies $E_{cm}$= 29 to 140 GeV
- Polarized beams with flexible spin patterns in both rings
- Favorable condition for detector acceptance such as $p_T$ =200 MeV/c
- Large range of hadron species: protons ….Uranium
- Collisions of electrons with polarized protons and light ions ($^3$He, d,…)

➔EIC meets or exceeds the requirements formulated in the Long Range Plan and the EIC White Paper endorsed by NAS





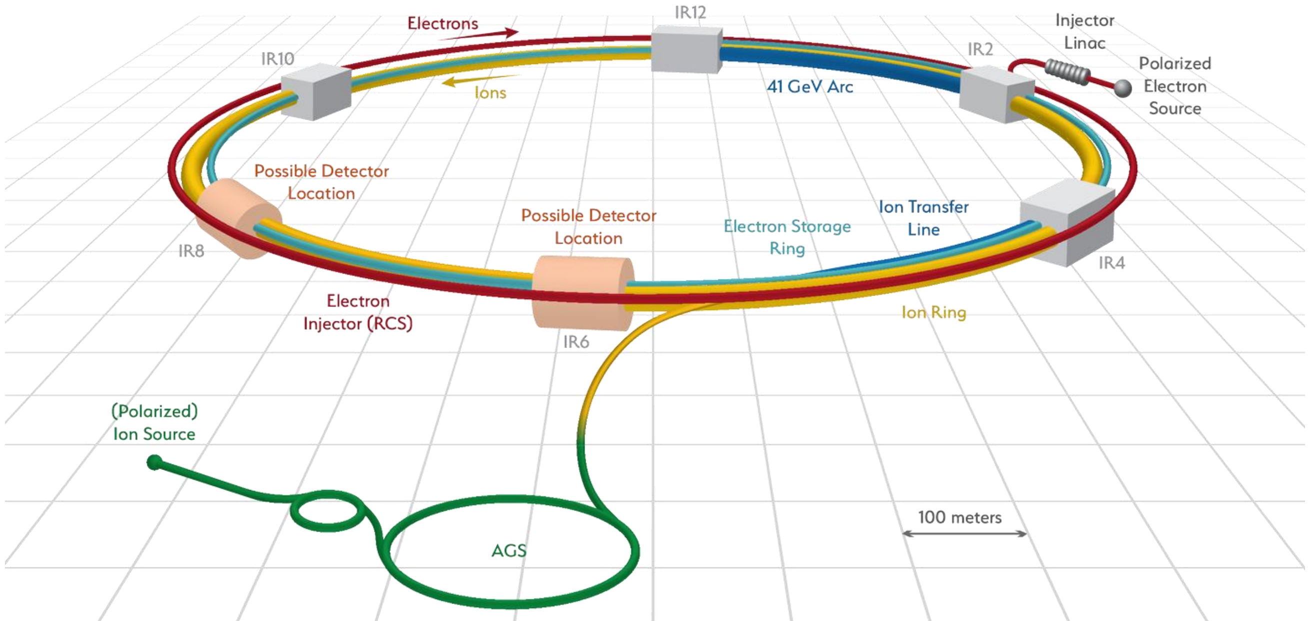


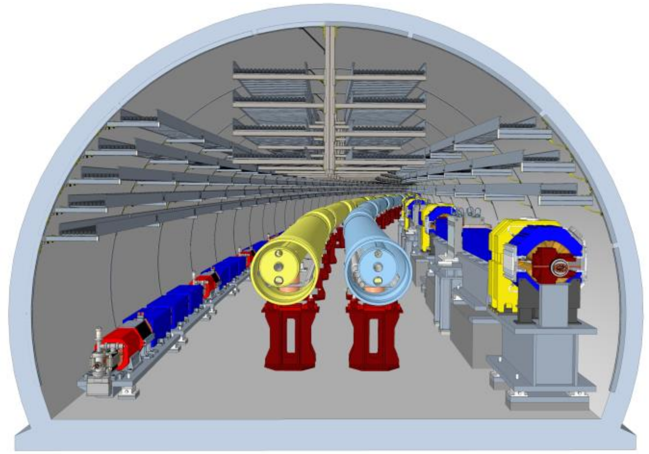
# EIC Design Concept

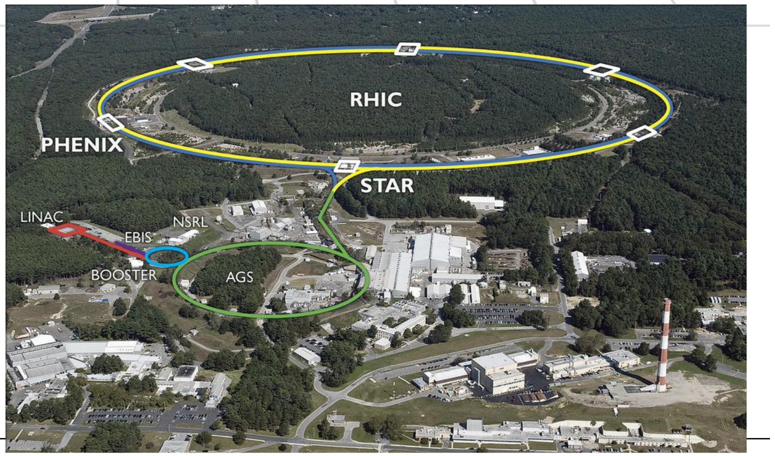
- EIC is based on the RHIC complex: Hadron Storage Ring (HSR), injectors, ion sources, infrastructure; needs modifications and upgrades
- Today’s RHIC beam parameters are close to what is required for EIC (except number of bunches, 3 times higher beam current, and vertical emittance)
- Strong Hadron Cooling to maintain beam emittances during stores
- Add a 5 to18 GeV electron storage ring & its injector complex to the RHIC facility ➔ $E_{cm}$ = 29-141 GeV
- Injector Complex needs to deliver electron bunches with high polarization and charge to the Electron Storage Ring.
- Design and built a suitable Interaction Region

# Facility layout

- Hadron Storage Ring based on “Yellow” RHIC ring
- Retaining RHIC injector chain
- Strong Hadron Cooling in IR2
- Pre-Injector at **IR4 now**
- Electron complex to be installed in existing RHIC tunnel – cost effective







# Electron Injector System Performance Goals

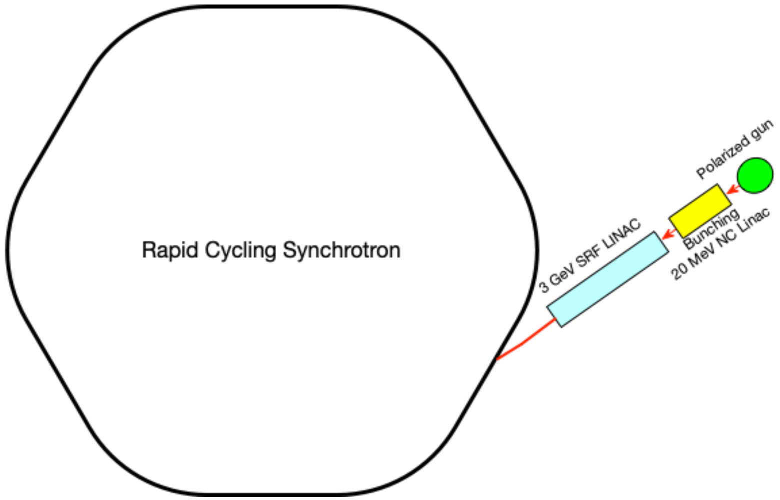
To achieve average polarization of 70% and intensity requirements of the ESR. The EIS will need to achieve the following capabilities:

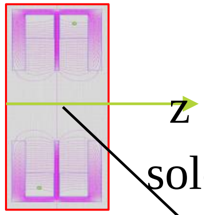
- Accelerate polarized electrons to 5, 10 and 18 GeV
- Maintain 95% polarization transmission
- Deliver 28 nC bunches at 5 and 10 GeV ( every 2.2 sec)
- Deliver 11nC at 18 GeV ( every 1 sec)
- Accumulate 28 nC in RCS from 4-7 nC charge from LINAC.

# Pre-Injector System Overview

Thanks. Erdong Wang

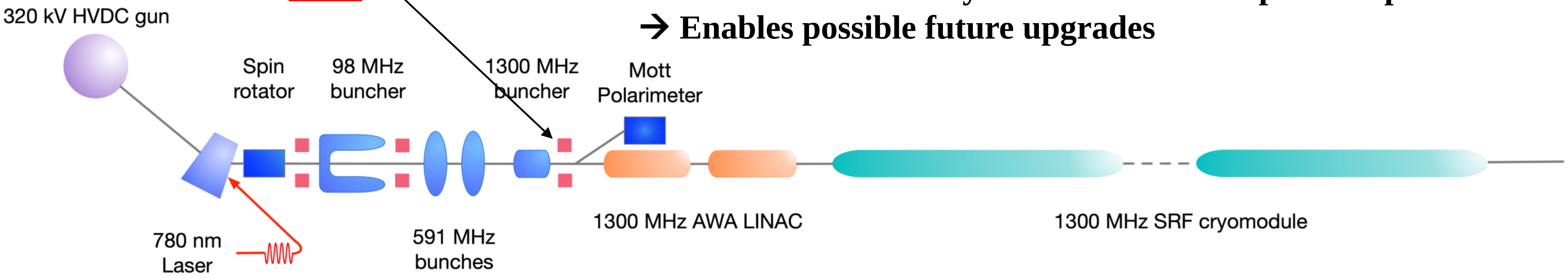
- Located at IP4 of the RCS
  1. Source → **peak charge 11nC so far (7 nC required)**
  2. Wien Filter for Spin Rotation
  3. Bunching  cavities and 1.3 GHz NCRF LINAC
  4. 1.3 GHZ SCRF LINAC to 3 GeV





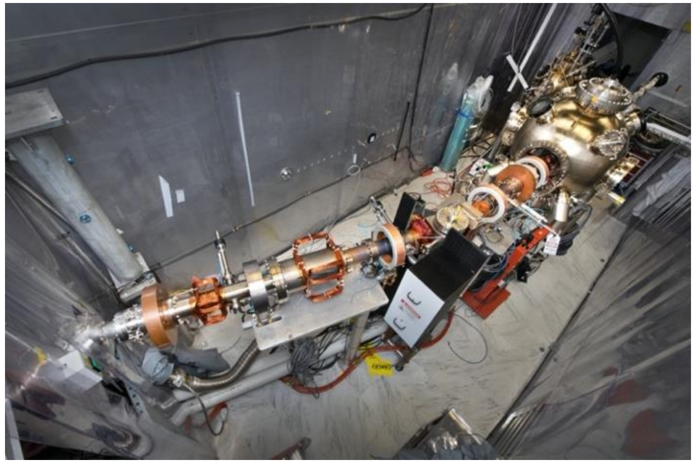
solenoid: $\int_{-\infty}^{\infty} B_z dz = 0$

**Buncher and LINAC system Permits Transport of up to 14 nC → Enables possible future upgrades**



# EIC Polarized Electron Source Requirement

| | EIC R&D goal | Achieved in stable operation | R&D delivered |
|---|---|---|---|
| Bunch charge [nC] | 7 | 7.5 (12) | Y |
| Peak current [A] | 3.8 | 4.8 (No SCL) | Y |
| Frequency [Hz] | 1 (4 bunches) | 1 (9000 bunches) | Y |
| Voltage [kV] | 300 | 320 | Y |
| Average Current | 28 nA | 67.5 uA | Y |
| Polarization [%] | > 85% | 88% | Y |



EIC polarized gun at
Stony Brook Univ.

Achieved EIC lifetime requirement: 24x7x3600x4= 2.4 e6 bunches /week for 2 weeks

- Source has achieved 11 nC
- EIC requires 7 nC
- Hope to reach 14 nC

**High voltage dc gun for high intensity polarized electron source**
Erdong Wang, Omer Rahman, John Skaritka, Wei Liu, Jyoti Biswas, Christopher Degen, Patrick Inacker, Robert Lambiase, and Matthew Paniccia
Phys. Rev. Accel. Beams **25**, 033401 – Published 24 March 2022

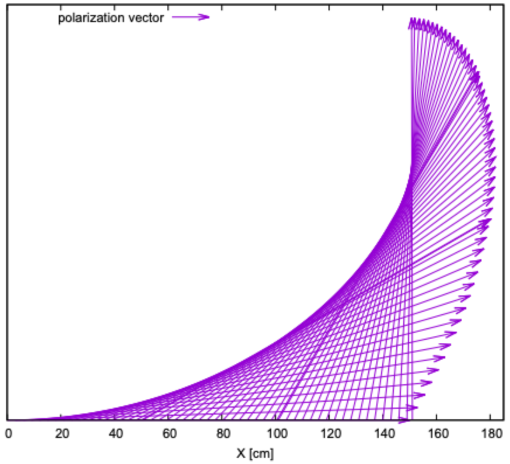
**High-intensity polarized electron gun featuring distributed Bragg reflector GaAs photocathode.** Erdong Wang,et. al; Appl. Phys. Lett. 17 June 2024; 124 (25): 254101. https://doi.org/10.1063/5.0216694

Thanks. Erdong Wang

# EIC Wien Filter design

Thanks. Erdong Wang

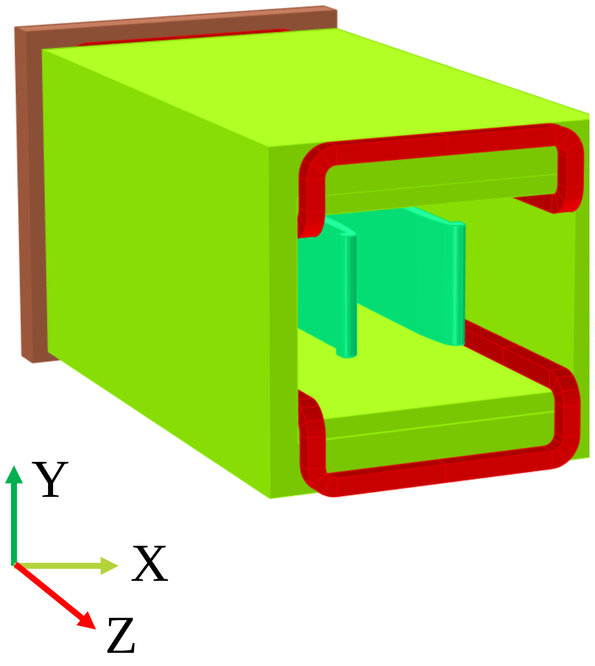
Limited by the high voltage design, higher beam energy needs a longer length. High space charge requires to put the focusing element very close. We determined the Wien filter length about 0.5 meter based on beam dynamics simulation.

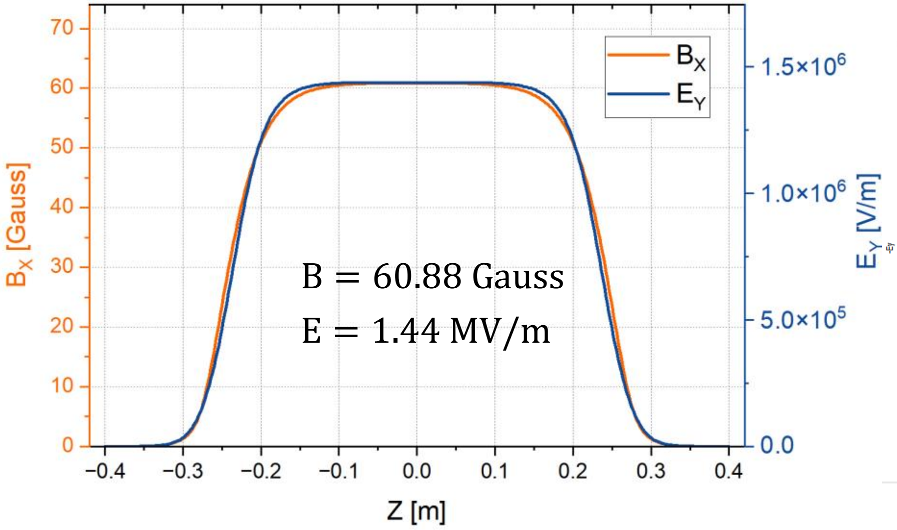


$$-\frac{E_y}{B_x} = v_z$$

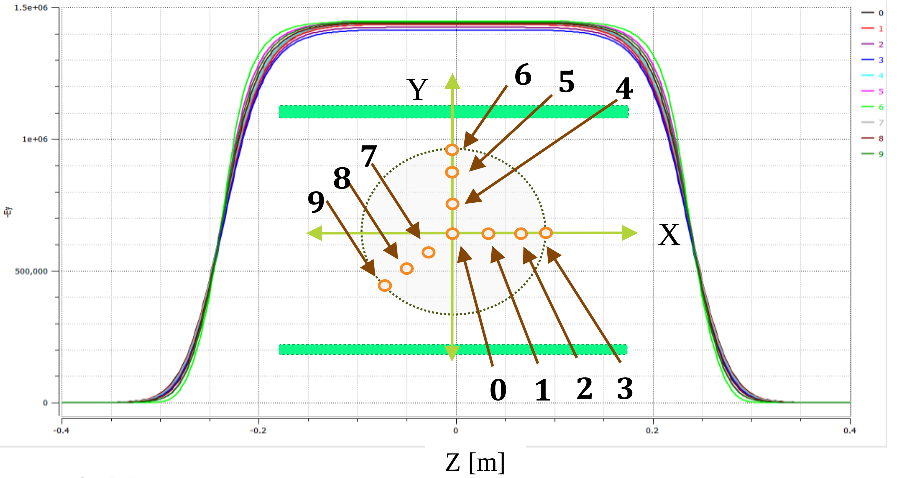
$$\theta = \frac{eL}{m_0 c\beta\gamma^2} B_x;$$

Our proposed approach:
Two Wien filters, each one rotates spin by 45 deg.





B = 60.88 Gauss
E = 1.44 MV/m



E field variations: 0.69 %
B field variations: 0.40 %

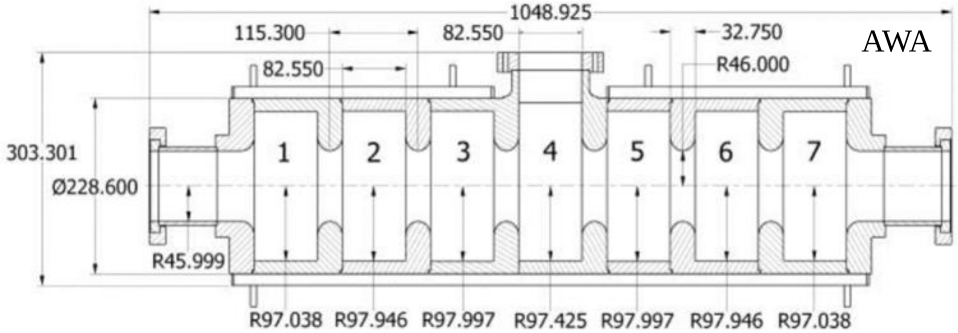
# Conceptual Layout and Geometry

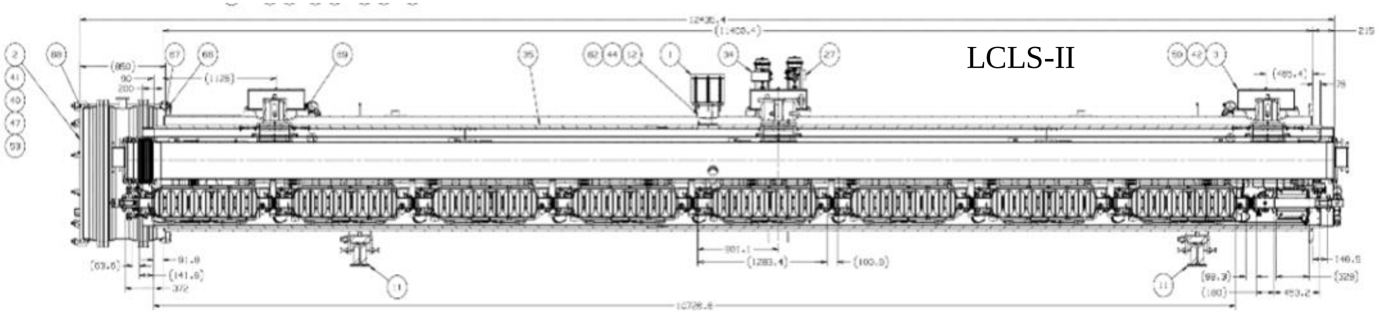
Thanks Todd Satogata

CM1 CM2 CM3 CM4 CM5 CM6 CM7 CM8 CM9 CM10 CM11 CM12 CM13 CM14 CM15 CM16

- ~200m of preinjector/linac at IR4
  - Preinjector: ~15m (4-5m gun/laser, 10m LEBT inc AWA NCRF)
  - Linac: 12x(12.8m) 1.3 GHz LCLS-II-style cryomodule slots
  - Linearizer: 4x(7.5m) 3.9 GHz LCLS-II-style cryomodule slots
    - **Possible upgrade**
- Symmetric dogleg for HEBT transport
  - Achromatic, spin transparent, match to RCS injection requirements
- Straight-ahead linac diagnostic/dump line

J. Mondillo presentation



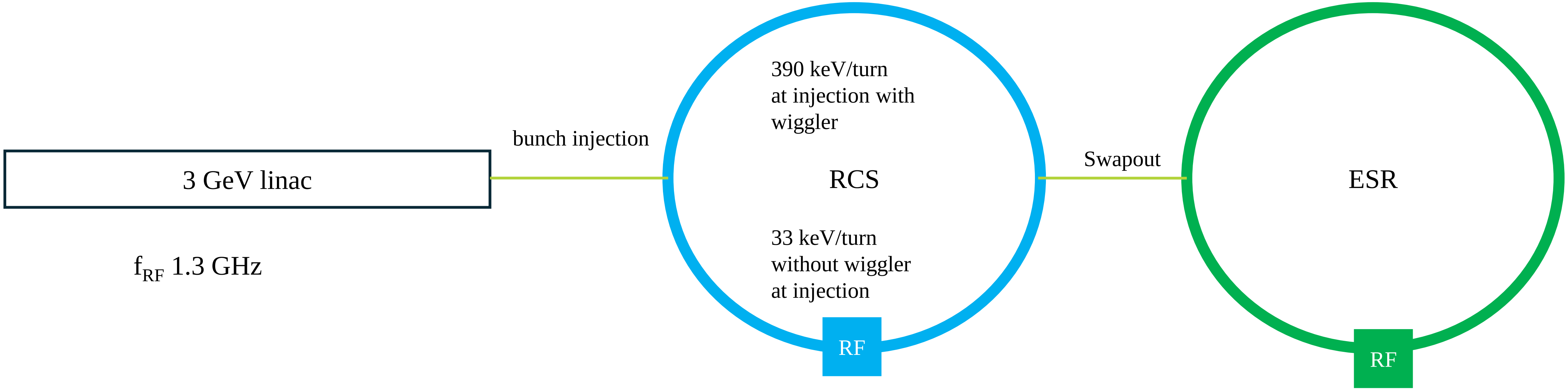


Realistic AWA/LCLS-II cell/cryomodule dimensions, wakefields used for preliminary design

# What we expect from Pre-Injector

| Mode | 1 | 2 |
|---|---|---|
| Linac energy [MeV] | 3000 | 3000 |
| Linac freq. [GHz] | 1.3 | 1.3 |
| Charge [nC] | 7 | 4 |
| RMS bunch length [mm] | 2.3 | 1.5 |
| RMS norm. emittance [mm-mrad]* | 36 | 30 |
| RMS energy spread [%] | 0.4 | 0.2 |

Two Modes of Operation: → 4 and 7 nC operations



$f_{RF}$ 1.3 GHz

C ~3800 m
$f_{RF}$ = 591 MHz

C ~3800 m
$f_{RF}$ = 591 MHz
$P_{SR}$ ~4 MeV/turn

# RCS Lattice Design

- Design driven by polarization transmission needs:
    - Requires high periodicity and tune
    - Special Spin - canceling approaches to handle arc - connecting regions which break symmetry.

- Design also guided by need for good off-momentum dynamic aperture to facilitate charge accumulation (target >= +/- 1.5% dp/p)

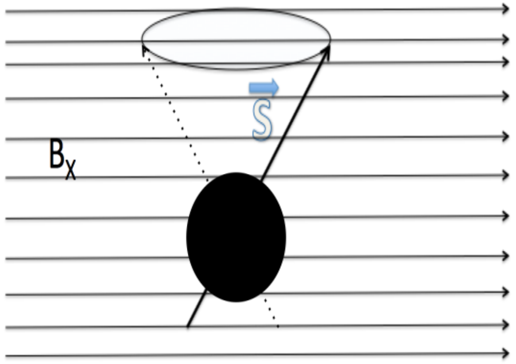
- Design needs low average beta and low gamma transition value to reduce collective effects that would prevent charge accumulation

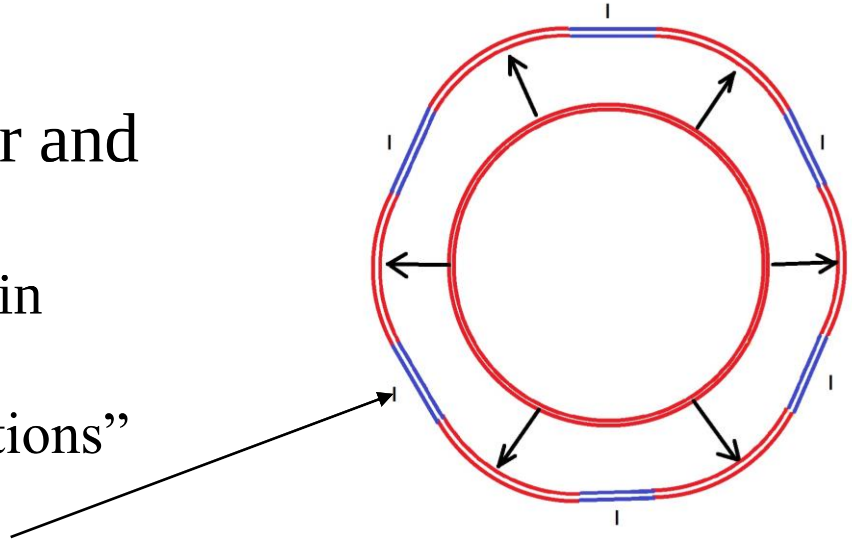
# Spin Resonance Free Lattice Design

- Spin precesses at a rate of **$G\gamma$** in a planar dipole - dominated ring, where G is the anomalous g-factor.
- This "Spin Tune" ramps with energy and can cause depolarization when the horizontal fields 'kick' the spin coherently → **Spin Resonance**
- Strong intrinsic and imperfection Spin resonances occur at:
  - $K = nP \pm Q_y$
  - $K = nP \pm [Q_y]$ (integer part of tune)

Here **P** is the lattice Periodicity and **n** any integer and **$Q_y$** the vertical betatron tune.

- If we pick **P** and **$Q_y$** correctly we can avoid all strong spin resonances in a given energy range
- To make it work with Symmetry breaking "Straight-sections" make vertical phase advance → 2π





# Other possible methods:

1. If there are no dipoles in the straights → make the vertical optical phase advance which breaks the super periodicity unitary.
2. If there are dipoles in the straights → make quad-induced spin kicks cancel between dipoles i.e.:

$$\int z'' e^{iK\theta} ds = \sum_n k_n z_\beta$$
$$= \sum_n k_n \sqrt{\beta_n} \cos(\mu_n + \phi) e^{iK\theta_n}$$

→ 0 between dipoles

$$0 = \sum_n k_n \sqrt{\beta_n} \cos(\mu_n)$$
$$0 = \sum_n k_n \sqrt{\beta_n} \sin(\mu_n).$$

3. Drive Resonances down in Gɣ = K → 0 to 41 with an optimizer coupled with DEPOL spin resonances calculator.

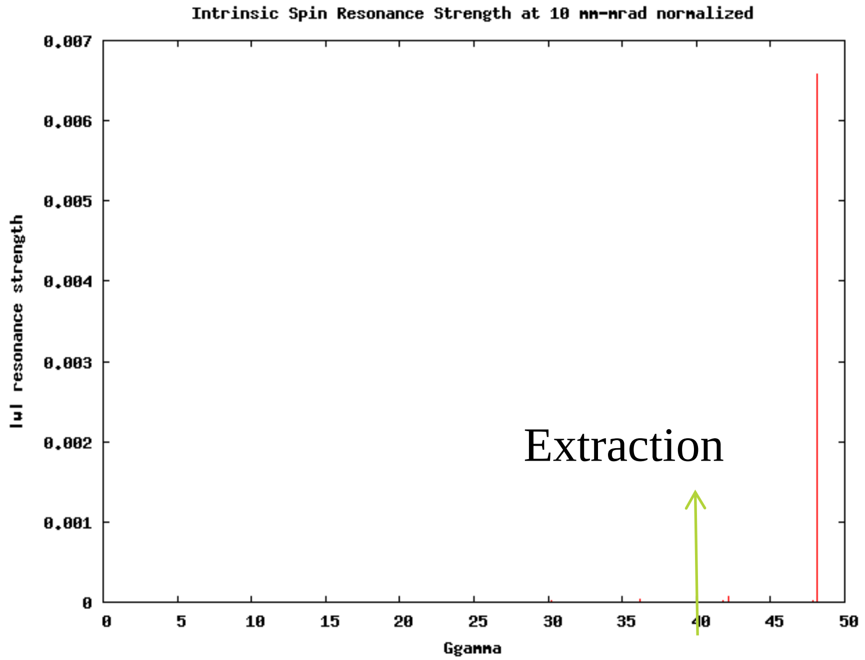
Spin resonance free electron ring injector Phys. Rev. Accel. Beams 21, 111003 – Published 27 November 2018

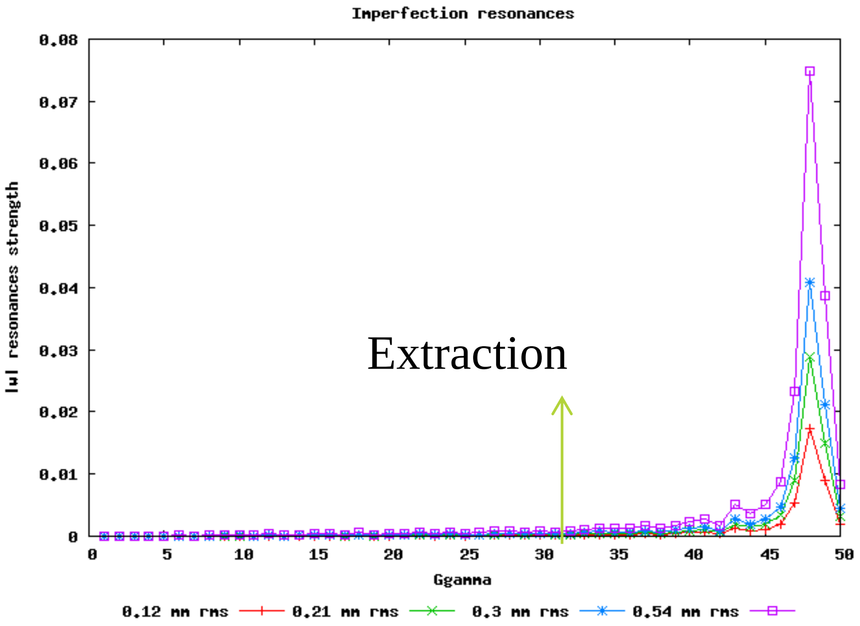
Spin resonance canceling lattice cell design principles

V. H. Ranjbar

Phys. Rev. Accel. Beams **26**, 061001 – Published 5 June 2023

# Calculating Spin Resonances





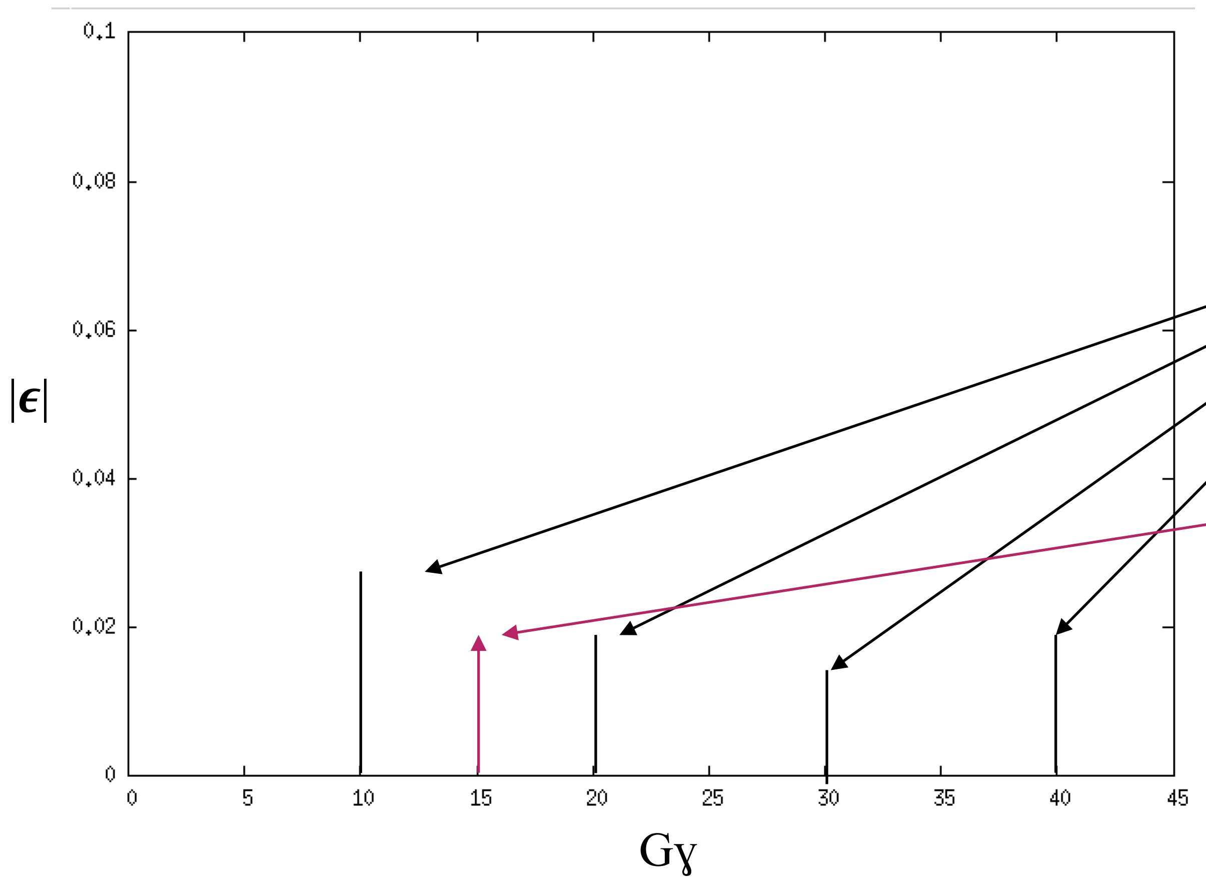
- No polarization loss from cumulative effective of intrinsic spin resonances for distributions over 100 msec ramp.
- Issue to control: Imperfection spin resonances ~ vertical rms orbit 0.5 mm to keep losses < 5%.

# Imperfection Bump → In case Orbit Smoothing isn't enough

- Using Correctors can create imperfection spin resonances to cancel out existing imperfection spin resonances

- Measure Polarization continuously during the acceleration ramp to identify polarization drops.

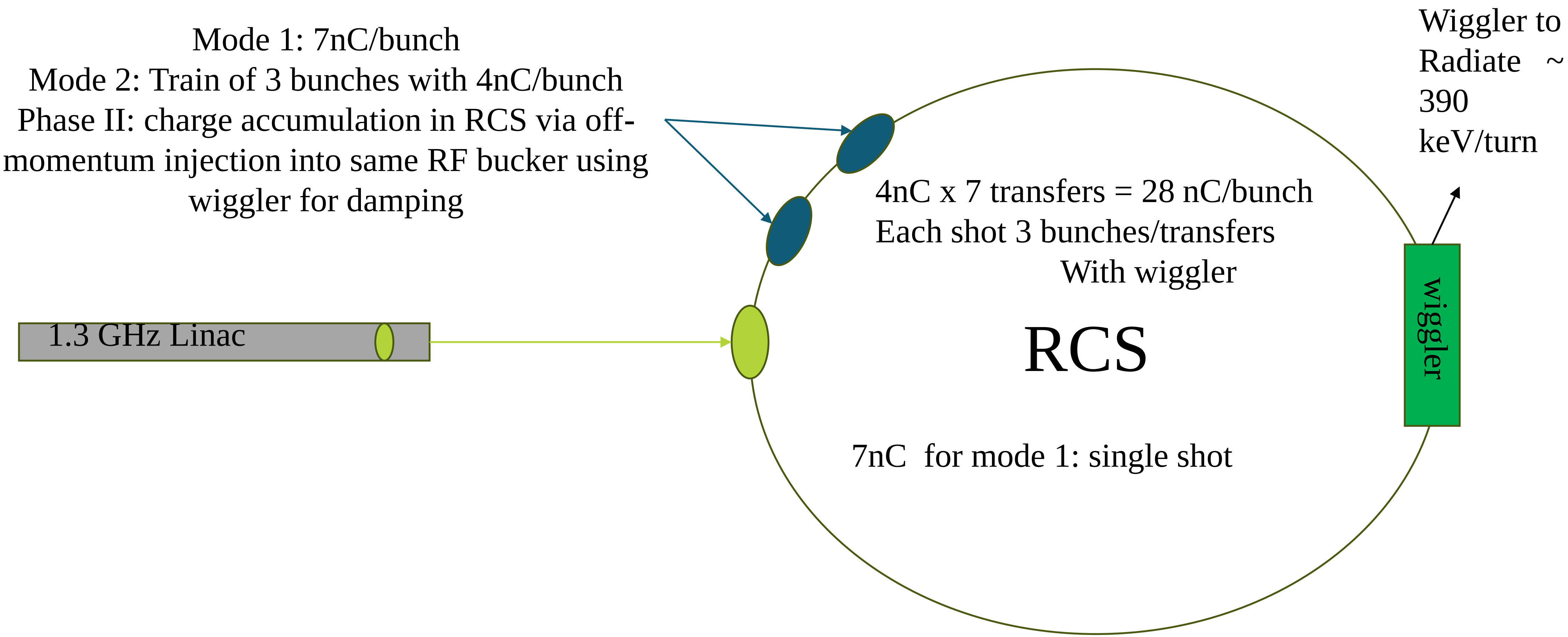
- Tune them out using these bumps.



- Similar to harmonic bumps → Sin(10*θ) used in AGS for many years
- Get imperfection at every Gɣ=n*10

- Using SVD to invert Imperfection to corrector response matrix, I can create resonance "bump" exactly at Gɣ=15 and nowhere else.

# Injection/Charge Accumulation Approach



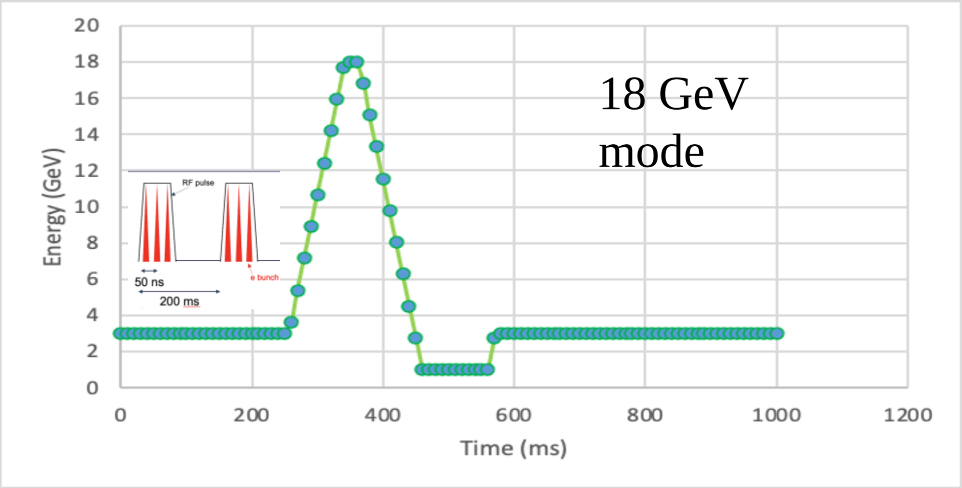
Mode 1: 7nC/bunch
Mode 2: Train of 3 bunches with 4nC/bunch
Phase II: charge accumulation in RCS via off-momentum injection into same RF bucker using wiggler for damping

Wiggler to
Radiate ~
390
keV/turn

4nC x 7 transfers = 28 nC/bunch
Each shot 3 bunches/transfers
With wiggler

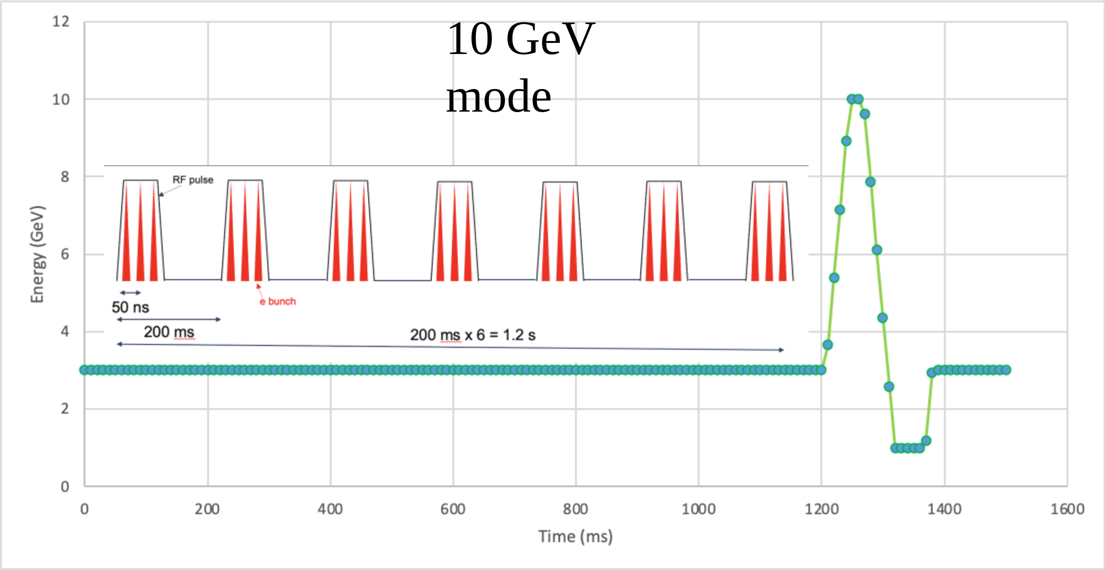
7nC for mode 1: single shot

# RCS Ramp Cycle (mode 2 )

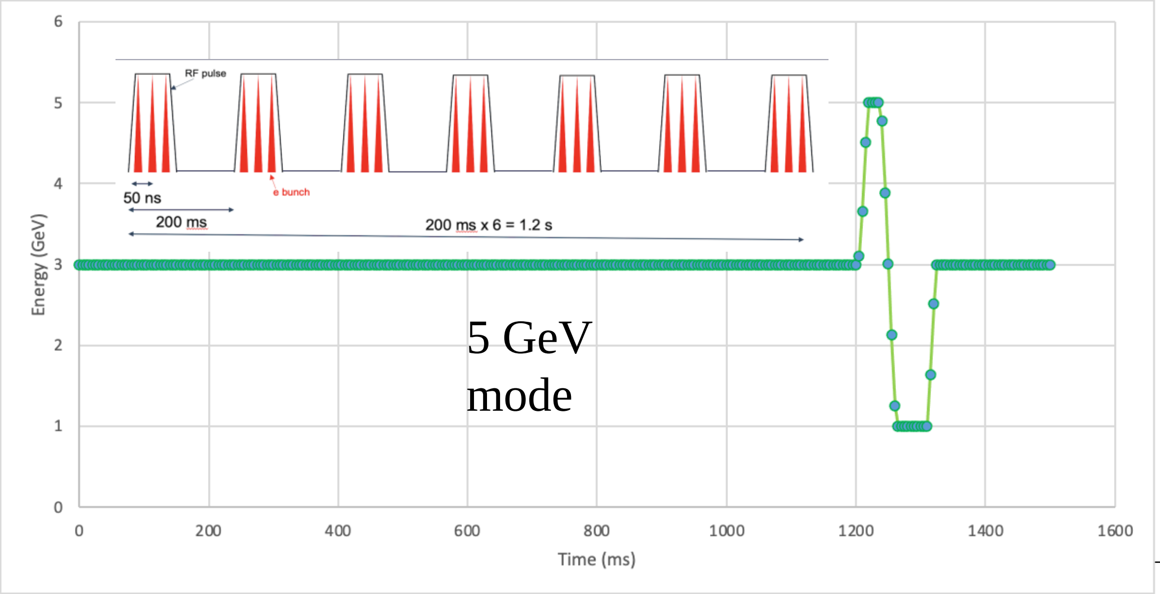


18 GeV mode

- Three Physic Operational Machine States
- Bunch injection and ramp cycle are shown for accumulating max charge (mode 2).



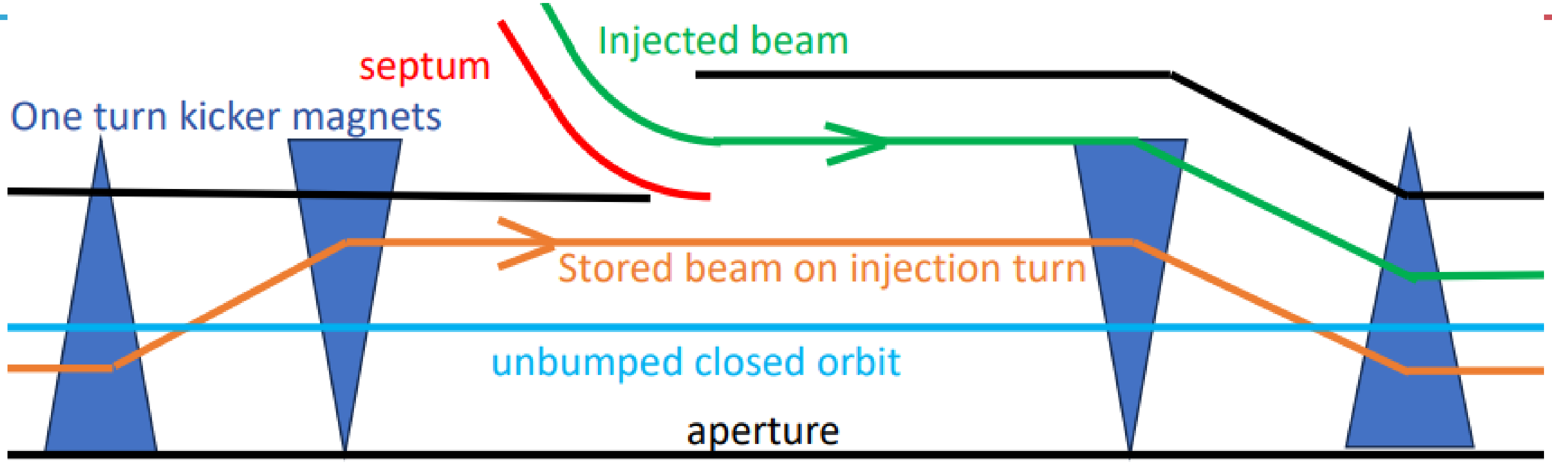
10 GeV mode



5 GeV mode

# Momentum stacking with 4nC bunches

Thanks Mike Blaskiewicz



- Before injection, RF gymnastics give the stored beam a coherent synchrotron oscillation. Injection occurs at minimum energy.
- A one-turn horizontal bump with ferrite kickers is turned on.
- Beam with positive momentum offset is injected onto its closed orbit.
- After both beams are in, the bump is dropped.
- Bunch-length damping can be used to stop emittance growth to shorten time between injections

# Summary

Electron Injector System for EIC consists of :

Pre-Injector

- SRF 1.3 GHZ LINAC plus polarized source and Wien Filter → up to 7 nC bunches at 3 GeV

Rapid Cycling Synchrotron for 5, 10 and 18 GeV operational modes up to 28 nC.

- Special Lattice for Polarized Transport
  - Orbit control
  - Imperfection Spin Bump cancelation
- Off-momentum charge accumulation injection
  - Wiggler/damping magnets