The 2015 eRHIC Ring-Ring Design

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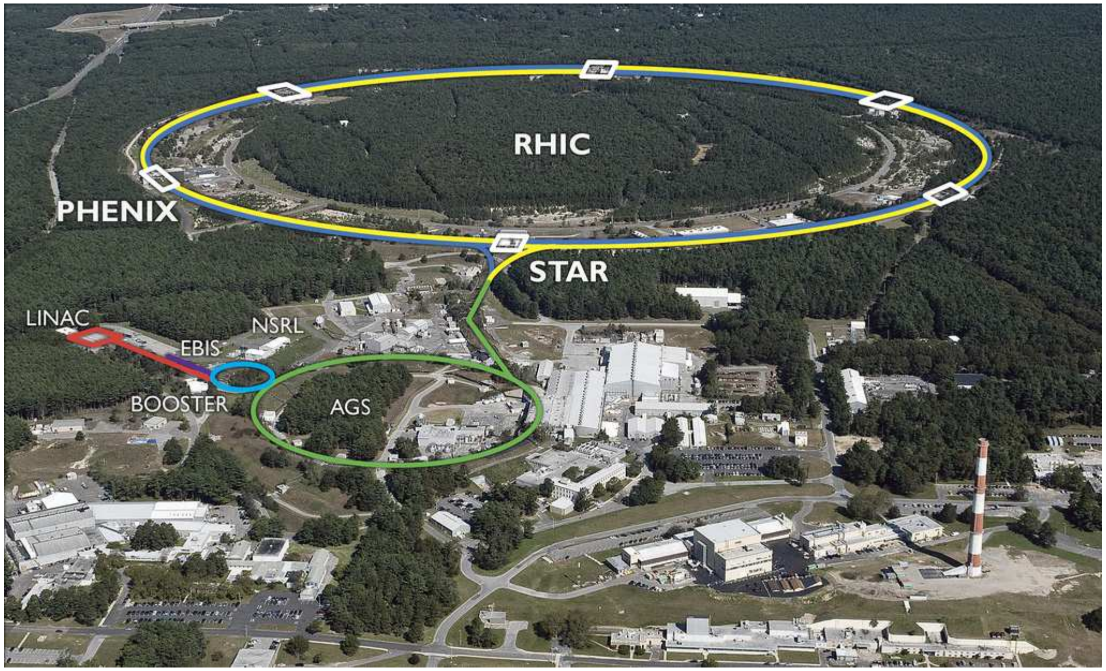


The Relativistic Heavy Ion Collider RHIC

- Two superconducting storage rings
- 3833.845 m circumference
- Energy range 25 - 250 GeV polarized protons, or 10 - 100 GeV/n gold
- Virtually all ion species, from (polarized) protons to uranium
- Two collider experiments, STAR and PHENIX
- Siberian snakes to preserve proton polarization on the ramp
- Spin rotators to manipulate spin orientation at IPs
- Operating since 2000

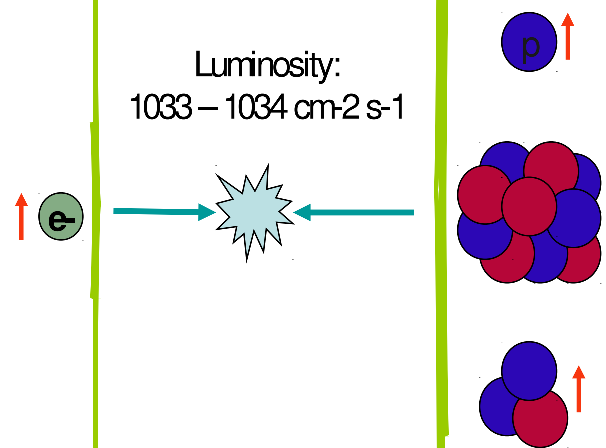
Electron-ion collider physics

eRHIC: Electron Ion Collider at BNL

Add an electron accelerator to the existing $2.5B RHIC
including existing RHIC tunnel, detector buildings and cryo facility

Luminosity:
1033 – 1034 cm-2 s-1

80% polarized electrons:
1.3 – 21.2 GeV

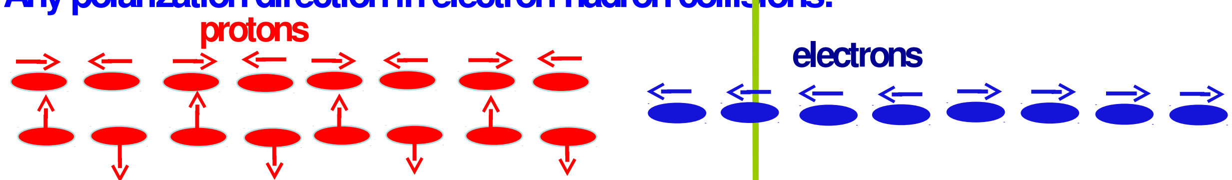


70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

Pol. light ions (He-3)
17 - 167 (184*) GeV/u

- **Center-of-mass energy range: 20 – 145 GeV**
- **Full electron polarization at all energies**
  Full proton and He-3 polarization with six Siberian snakes
- **Any polarization direction in electron-hadron collisions:**



* It is possible to increase RHIC ring energy by 10%

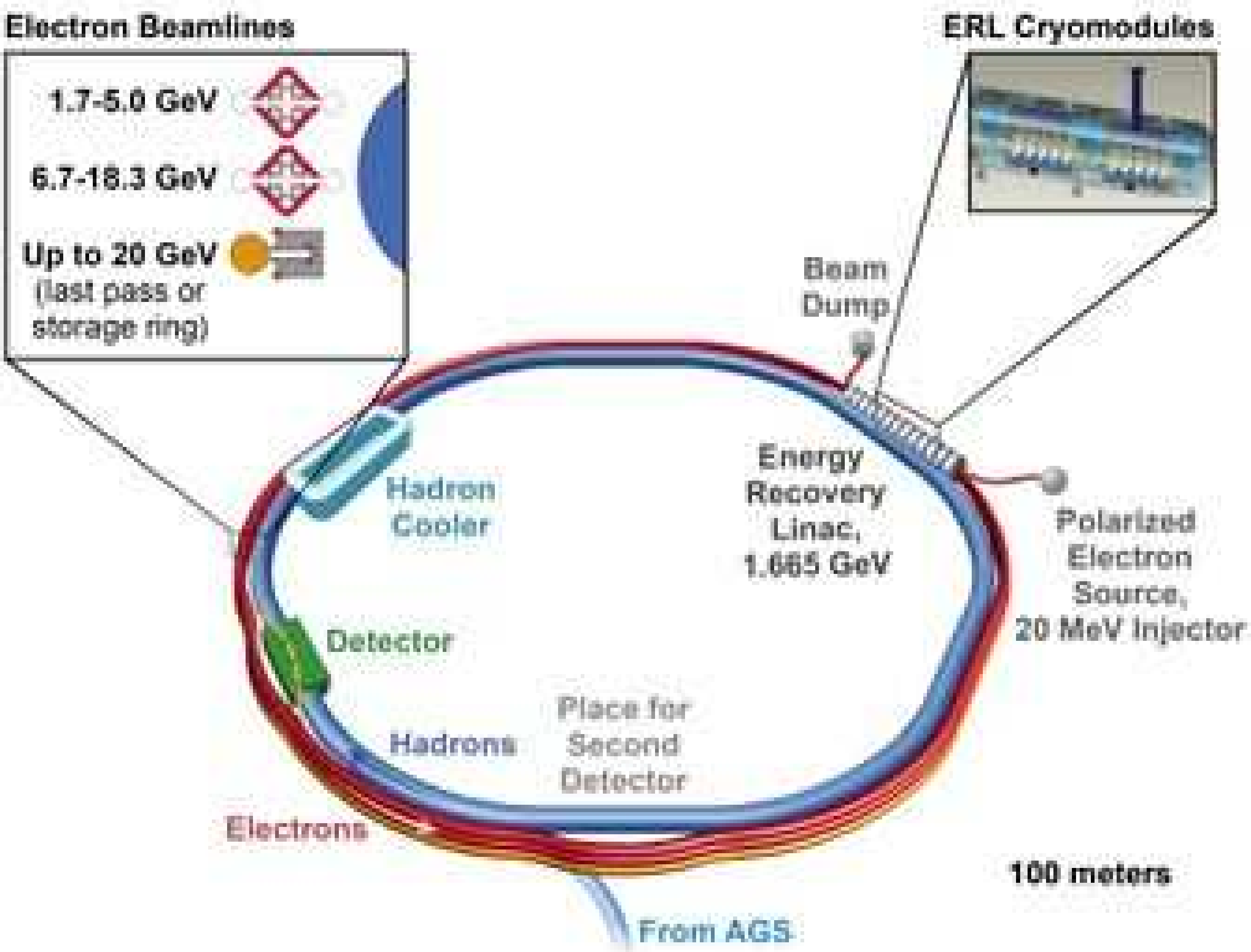
Electron-ion collider design studies

Electron-ion collider design studies are being pursued at two labs:

• JLab: Figure-8 ring-ring design, based on CEBAF as electron injector (JLEIC)
• BNL: ERL-based linac-ring design, based on existing RHIC facility (eRHIC)
(An early version of eRHIC in 2003 proposed adding a small circumference 10 GeV electron ring)

Both designs use novel high-risk techniques

The eRHIC linac-ring design



- Up to 1E34 luminosity
- Multi-turn energy recovery linac (ERL), with 2 GeV 650 MHz RF section
- 50 mA polarized electron current from multiple guns, or multiple cathodes in common vacuum ("Gatling gun")
- Fixed-field alternating gradient arcs (FFAG) - very tight focusing to allow simultaneous transport of beams with vastly different energies
- Coherent electron cooling (CeC) - hybrid between electron cooling and stochastic cooling, using an electron beam as pick-up and kicker, and an FEL as amplifier

Two paths of risk reduction in eRHIC

- Staged linac-ring approach, initially limiting number of new technologies

- Ring-ring design using a 20 GeV electron ring in RHIC tunnel, largely based on existing technology

Risk-reduction effort started in 2015

Either approach aims at an initial luminosity in the 1E33 range

Ring-ring design goals

- Low-risk approach
- Full energy range (up to 250 GeV protons on 20 GeV electrons) from the beginning
- Full physics reach in terms of interaction region design
- 80 percent electron polarization, 70 percent proton polarization
- Baseline design luminosity around 1E33
- Luminosity upgradeable towards 1E34

Beam parameters and luminosities

- 360 bunches (requires in-situ beam pipe coating and new injection kickers; now 120)
- Normalized proton emittance $\epsilon_{n,p} = 2.5\,\mu\text{m}$ (achieved in RHIC)
- Proton rms bunch length $\sigma_s = 20\,\text{cm}$ (achievable in RHIC at 250 GeV; requires electron cooling at low energies)
- Electron emittances $\epsilon_{x,e} = 53\,\text{nm}$, $\epsilon_{y,e} = 9.5\,\text{nm}$
- Proton β-functions $\beta^*_{x,p} = 2.16\,\text{m}$, $\beta^*_{y,p} = 0.27\,\text{m}$ at all energies, 50 - 250 GeV

- Proton beam-beam parameter $\xi_x = 0.015$, as routinely achieved in RHIC

- Maximum proton bunch intensity $N_p = 3 \times 10^{11}$ (25 percent higher than achieved in RHIC)

- Electron beam-beam parameter: $\xi_y = 0.1$, with a damping decrement of $\delta = 2 \times 10^{-3}$
  (Note: KEKB reached $\xi_y = 0.12$ with ten times smaller damping decrement)

- Use damping wigglers to increase damping decrement at electron energies below 20 GeV

Synchrotron radiation power losses

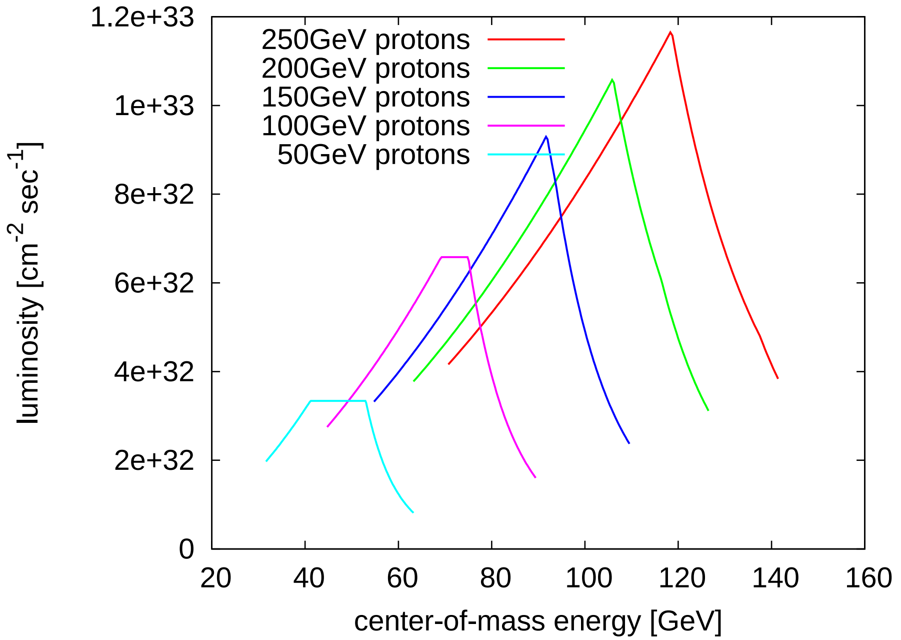
- Technical limit for linear synchrotron radiation power loss is 10 kW/m in the arcs

- With a total RHIC arc length of $2\pi \cdot 380\,\mathrm{m} = 2390\,\mathrm{m}$, that corresponds to 24 MW of RF power

- Typical klystron efficiency is about 60 percent, so we would need 40 MW of electrical power for the RF alone - very high operating cost

Design based on 10 MW RF power

Luminosity curves for 10 MW RF, $\xi_{max} = 0.1$



- Limited RF power reduces luminosity at high electron energies
- Limited electron beam-beam parameter reduces low energy luminosities
- Flattop due to proton bunch intensity cap at 3×10^{11}

Curves corrected for hourglass effect, crab crossing, and abort gap

Parameters for highest luminosity

	electrons	protons
energy [GeV]	13.7	250
bunch intensity [10^{11}]	2.1	2.1
beam current [mA]	935	935
emittance h/v [nm]	53/9.5	9.5/9.5
β^* h/v [m]	0.38/0.27	2.16/0.27
beam-beam parameter	0.1	0.015
RMS bunch length [cm]	1	20
polarization [%]	80	70
luminosity [$cm^{-2}\,sec^{-1}$]	$1.2 \cdot 10^{33}$	

IR design requirements

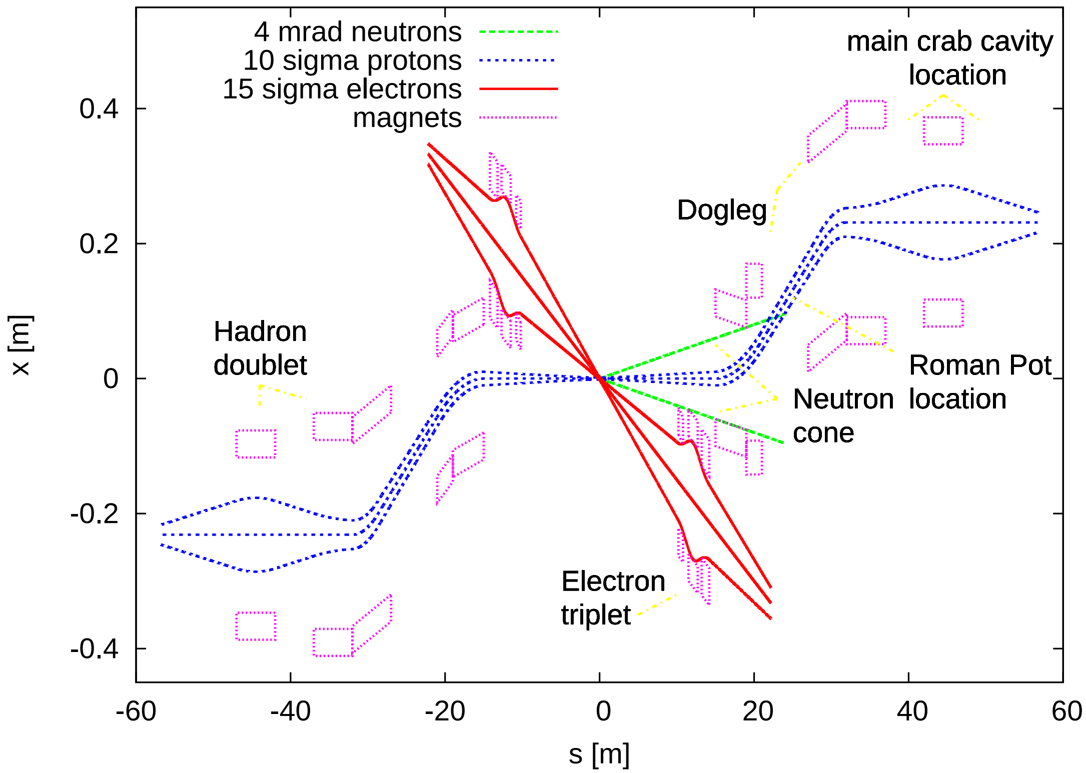
- ± 4.5 m element-free space around IP

- Unobstructed path for ± 4 mrad neutron cone in forward proton direction. Dipole magnet to separate neutrons from charged particles.

- ≈ 2 m space for "Roman Pots" to detect protons with very small scattering angle, transverse momentum acceptance of $p_\perp \geq 200$ MeV/c

- Design aperture $10\sigma_p$ for protons, $15\sigma_e$ for electrons

IR layout (top view)



- Full dogleg and $> 2\,\mathrm{m}$ space for Roman Pots
- 15 mrad crossing angle with crab cavities
- Proton magnet apertures allow the same β^* at all energies down to 50 GeV

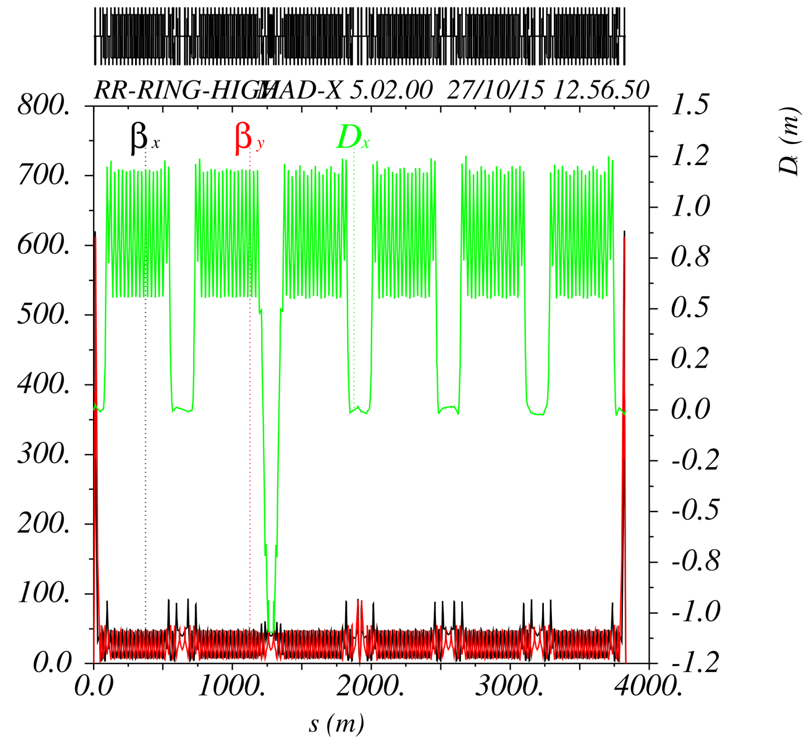
Electron ring lattice

- High dipole packing factor to limit synchrotron radiation power - FODO lattice

- 53 nm horizontal emittance for collisions with 250 GeV protons, tuneable to 106 nm for 50 GeV protons, over full electron beam energy range 5 - 20 GeV

- 20 GeV lattice needs 90 degrees phase advance to achieve 53 nm emittance - difficult chromatic correction

- 60 degrees produce 150 nm at 20 GeV; need radial shift and/or Robinson wiggler to reduce it to 53 nm



- Complete electron ring lattice with IR and Robinson wiggler for emittance adjustment
- 300 m dipole bending radius in 380 m radius tunnel
- No damping wigglers yet
- Work on chromatic correction, dynamic aperture maximization in progress

Circumference adjustment for lower hadron energies

- Proton energy range from 50 (25?) to 250 GeV requires circumference adjustment to keep revolution frequencies in the two rings idential

- Circumference adjustment is most easily done in electron ring, using additional beamlines at an increased radius of $\Delta r = 1\,\mathrm{m}$ over a fraction of an arc

- Required length of those arc bumps:

beam energy [GeV]	ΔC [m]	bump length [m]
50	0.655	294
100	0.142	75
150	0.048	35

Hadron ring crab cavities

- High RF frequency generally preferred to lower voltage

- 20 cm long proton bunches require low crab cavity RF frequency

- Dual frequency crab cavity system, 168 and 336 MHz to linearize crab kick

- Even harmonic numbers of 6 and 12 allow for bunch splitting, if desired

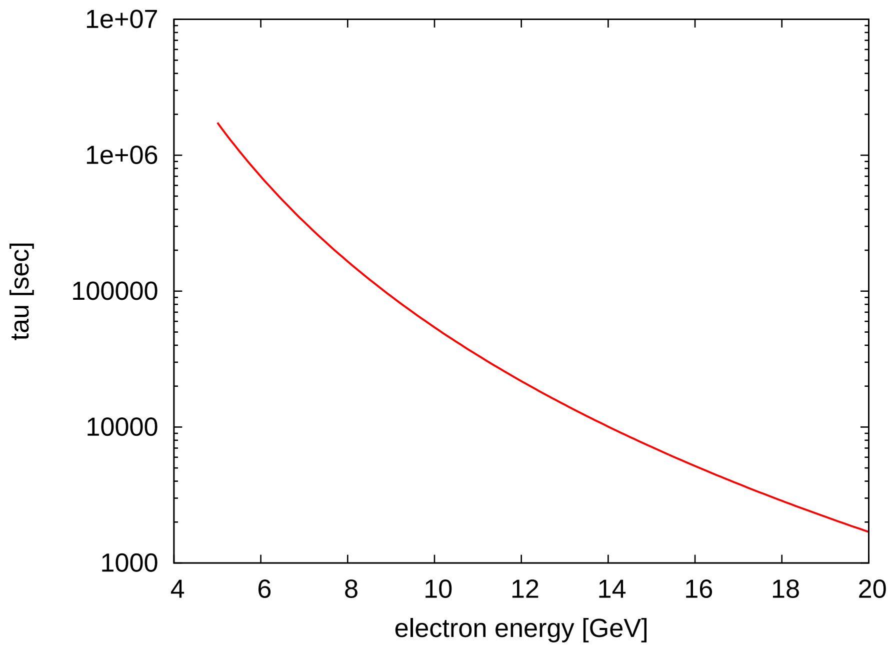
Luminosity reduction due to hourglass effect and crab crossing combined is less than 12 percent

Electron cloud

- Short bunch spacing (35 nsec) likely to result in electron cloud instability
- LHC ran routinely at 50 nsec bunch spacing in 2012, with $1.6 \cdot 10^{11}$ protons/bunch
- Electron cloud effects observed at 25 nsec; achieved $1.15 \cdot 10^{11}$ protons/bunch while running at refrigerator capacity
- eRHIC ring-ring is just in-between, at 35 nsec
- To be studied in simulations; success with 25 nsec at LHC is re-assuring
- In-situ beam pipe coating needed for eRHIC
- In-situ beam pipe coating is also required for LHC triplets
- CERN has successfully coated SPS pipes with amorphous carbon

Electron polarization

Ramping would destroy electron polarization
Electrons self-polarize at store due to synchrotron radiation:



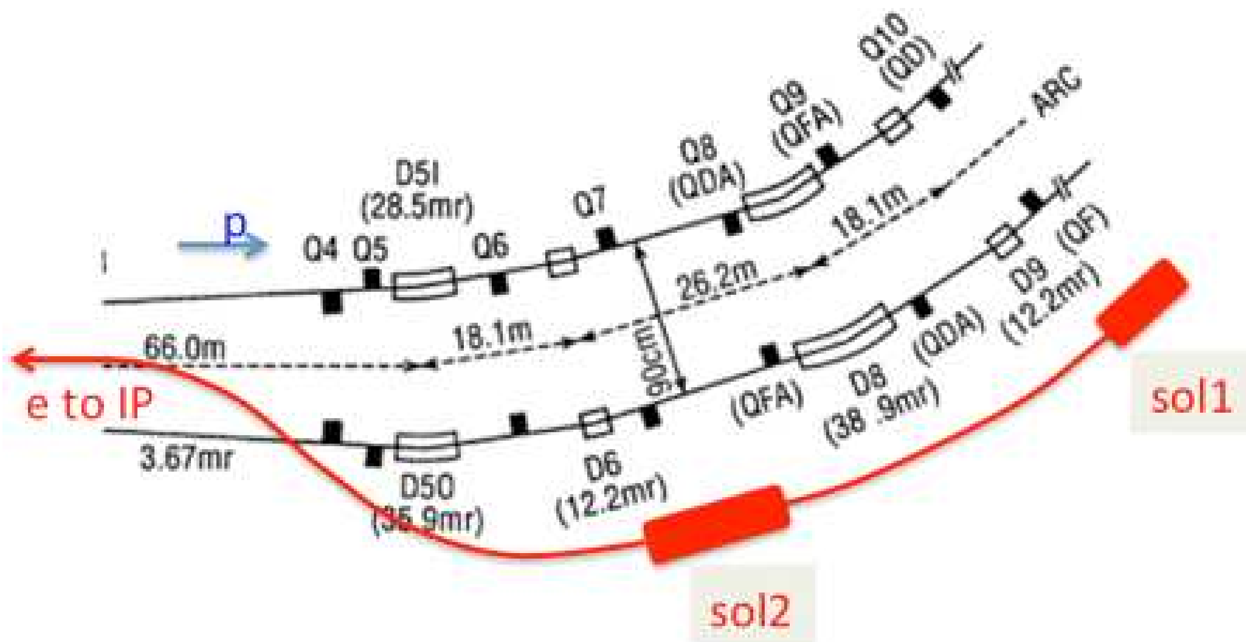
Self-polarization is not viable except at highest energies
$\Rightarrow$ Need a full-energy polarized injector

Advantage of a full-energy polarized injector:

- Electron spin patterns with alternating polarization (as in RHIC proton fills) are required for single-spin physics
- Such fill patterns can be generated by a full-energy polarized injector
- Bunches with the "wrong" (unnatural) polarization direction will slowly flip into the "right" orientation. Time scale given by Sokolov-Ternov self-polarization time
- Bunch-by-bunch replacement at 1 Hz (360 bunches in 6 min) yields sufficient polarization even at full energy with $\tau_{S-T} = 30\,\text{min}$
- Requires good intensity lifetime $> 1\,\text{h}$ to limit beam-beam effect of electron bunch replacement on proton bunches

Electron spin rotators

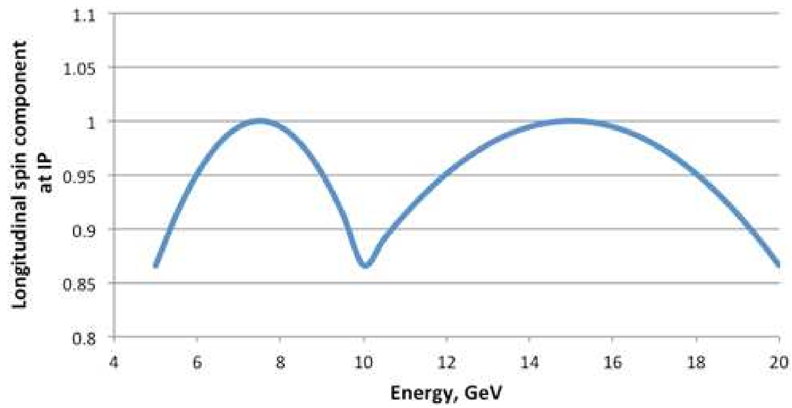
• Experiments require longitudinal polarization; spin is vertical in the arcs



• Solenoidal spin rotators
• Integrated fields: $B \cdot l[\mathrm{Tm}] = 5.24E[\mathrm{GeV}]$;
26-53 and 52-105 Tm, resp.

Longitudinal spin vs. energy

- Longitudinal spin component with two solenoidal spin rotators, optimized at 7.5 and 15 GeV:



- Detector solenoid causes additional spin rotation if polarization is not longitudinal.
- Using both solenoids simultaneously spin can be perfectly longitudinal over the entire energy range
- Effect of damping wigglers on polarization and depolarizing effects of spin rotators to be studied/minimized

Electron injector options

1. Linac-ring style injector

- Hardware-wise virtually identical to linac-ring eRHIC
- 650 MHz recirculating linac
- FFAG arcs
- Can be converted to full linac-ring design once high-risk items (cooling, high current polarized gun,...) are demonstrated

2. Dedicated recirculating linac injector

- A dedicated recirculating linac (no later ERL option), based on pulsed ILC cavities (1.3 GHz) can reach higher gradients (35 MV/m) than ERL cavities

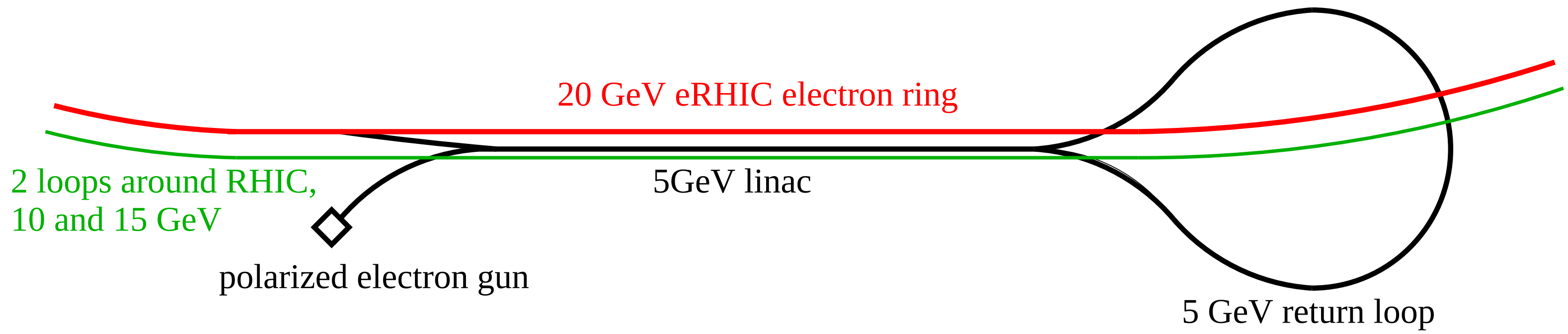
- 5 GeV linac seems feasible in 200 m straight section

- Higher linac energy requires fewer passes

- Fewer passes could be built as separate loops, not FFAG

- Acceleration up to $\approx$ 10 GeV does not require large bending radii - small, single loop to turn 5 GeV beam around after first pass would be sufficient

Recirculating linac injector layout



Acceleration up to 10 GeV in one 200 m long RHIC straight, plus two recirculating loops at 15 and 20 GeV around entire RHIC tunnel

3. Highly symmetric rapid-cycling (or rapid-ramping) synchrotron (RCS)

- At 20 GeV, electron $G \cdot \gamma = 45.4$
  ($G = 0.00115965219$: anomalous gyromagnetic ratio)

- Assume a circular RCS, made up of identical periods

- Superperiodicity $P = 48$ and a tune of $\nu = 48.2$ results in depolarizing resonances at $G\gamma = k \cdot P \pm l \cdot \nu$

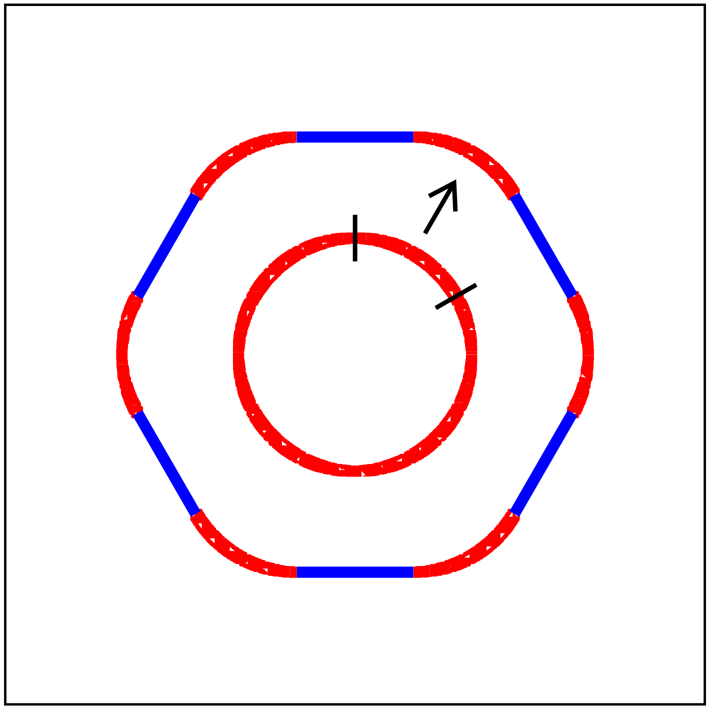
- Resonance condition fulfilled at $G\gamma = 2 \cdot P - \nu = 47.8$
  - outside the energy range

- High superperiodicity requires a circular ring, unlike the RHIC tunnel with its six straights

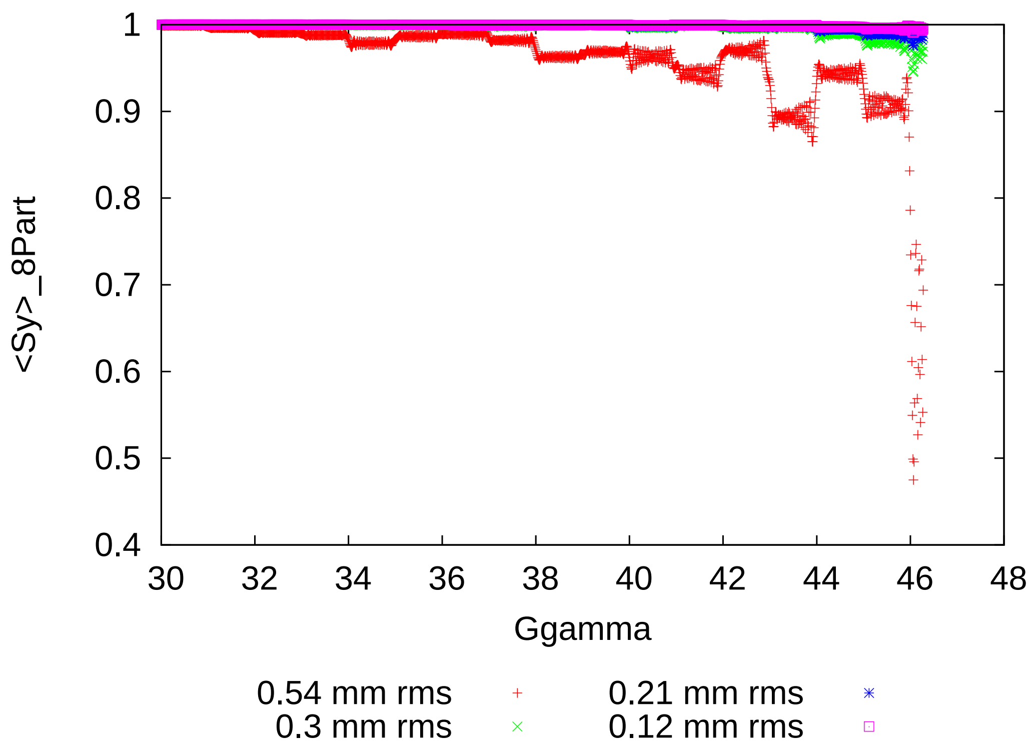
- However, if transfer matrices of straights are unit matrices

$$M_{\text{straight}} = I,$$

energy range remains resonance free



Polarization in RCS with orbit errors



- Spin tracking confirms validity of RCS concept
- 4000 turns used in simulation
- Faster ramping in only 400 turns technically feasible, further improving polarization preservation

Leading risks

1. Electron cooling

   - Required to maintain 20 cm RMS bunch length at low proton energies (50-100 GeV)

   - Without cooling, luminosity with 50 GeV protons drops by factor 3, with 100 GeV protons by 40 percent

   - High energy requires bunched electron beam with RF acceleration

   - Low Energy RHIC electron Cooler (LEReC)) is a prototype for bunched beam electron cooling up to 6 GeV. Installation in progress

   - Challenging design due to high proton beam energy: High energy, high intensity ERL; high intensity, low emittance electron gun and beam transport

2. Crab cavities

- IR design with 15 mrad crossing angle requires crab cavities to restore luminosity
- Required 168 MHz crab cavities with 7.5 MV seem feasible
- Proof-of-principle exists at KEKB, but not for hadron beams. Test experiment planned at SPS (CERN), but without beam-beam interaction. To be studied mainly by tracking.
- Eliminating the crossing angle requires a dipole field that generates several hundred kW of synchrotron radiation power with a critical energy of 120 keV or more, having serious impact on detector design and acceptance

3. Beam-beam

- eRHIC electron and proton beam-beam parameters have been achieved in e^+e^- colliders and RHIC, resp., but not in e-p collisions (HERA)

- Effect of crab crossing with long (20 cm) proton bunches on both beams needs to be studied in simulations - in progress

- Strong-strong simulations to study coherent beam-beam, kink instability in collaboration with LBNL

- Rapid electron bunch replacement (each bunch every 6 minutes) introduces noise-like disturbance onto proton beam. Requires long electron beam lifetime

4. Electron polarization

- Spin matching of IR with spin rotators seems manageable - in progress
- Maintaining a large synchrotron radiation damping decrement at all electron beam energies requires damping wigglers
- Effect of damping wigglers on polarization unknown; to be studied in simulations

Luminosity upgrade options

Two possible luminosity upgrade paths towards 1e34:

1. Conversion to original linac-ring design, including:
    - Energy Recovery Linac (ERL)
    - Fixed-Focus Alternating Gradient (FFAG) arcs
    - Coherent electron Cooling (CeC)
    - Multi-cathode elecron gun (Gatling gun), or multiple conventional guns

    To be cost effective this upgrade path requires a CEBAF-type injector virtually identical to linac-ring eRHIC for the ring-ring baseline

2. Ring-ring with (coherent) electron cooling and tighter focusing:

   - Electrons need to be focused to small β^* to limit beam-beam parameter

   - Low-β quadrupoles need to be moved closer to the IP to limit chromaticity contribution

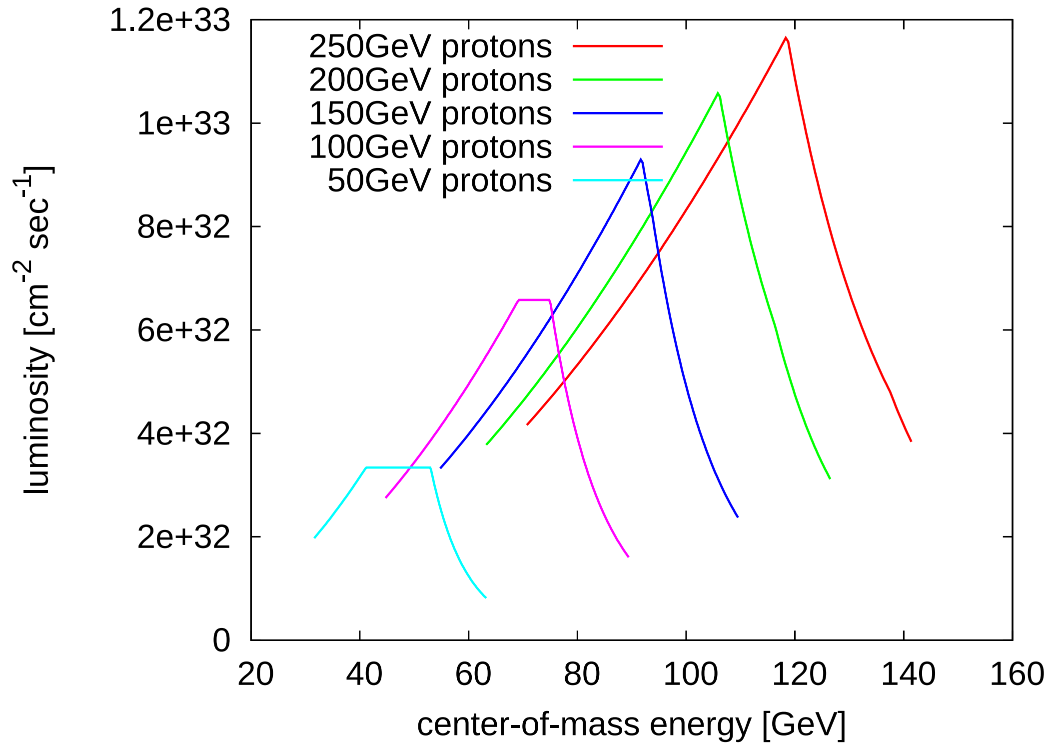
   - Biggest obstacle is the 4 mrad neutron cone

   Work in progress; up to $7.8 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ feasible with "flat" proton beam emittances if cooling works at all energies

Next steps

- Spin matching
- Damping wiggler design
- Tracking studies: Dynamic aperture, beam-beam (including realistic crab crossing), spin (including damping wigglers and spin rotators)
- Spin tracking in rapid cycling injector synchrotron
- Detailed crab cavity design
- Electron cooler design

Summary



- Ring-ring approach provides up to $1.2 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ luminosity over the required energy range, depending on beam energies

- IR design meets Physics requirements
- Low risk approach - electron cooling and crab crossing are main technical risks
- Longitudinal electron cooling only needed for low proton energies (up to $\approx 100\,\mathrm{GeV}$)
- Crossing angle requires crab cavities
- Developed a preliminary electron ring lattice design. Chromatic correction in progress

- Electron ring SC cavities similar to KEKB. Need 10 MW at 46 MV - about 30 KEKB cavities

- Electron cloud in RHIC requires in-situ beam pipe coating. Under development at BNL and CERN

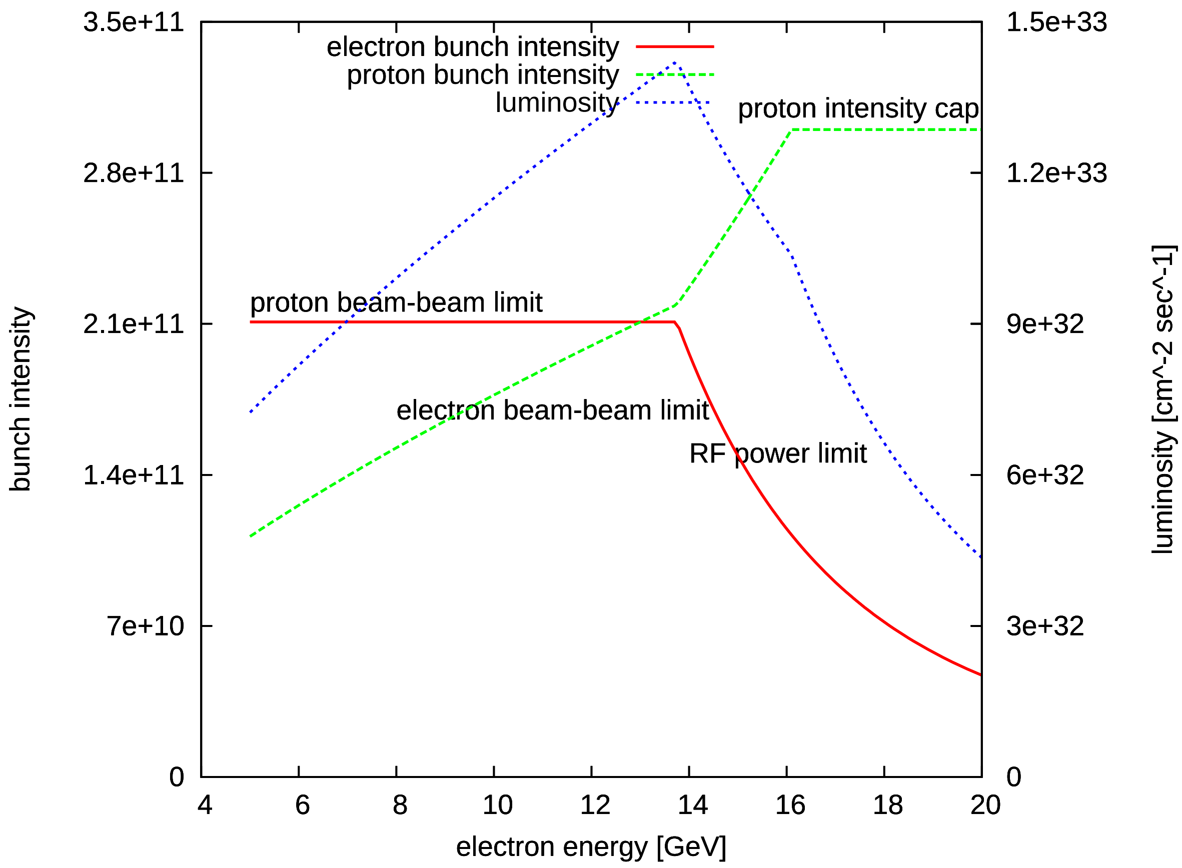
- Different electron injector options under consideration to reduce injector cost.
  If 10 GeV electrons are sufficient to get started, dogbone-shaped recirculating linac with ILC cavities would be most cost effective

- Multiple luminosity upgrade paths, including possible conversion to linac-ring

Thank you!

Backup slides

Bunch intensities for 250 GeV protons, 10 MW power limit



Luminosity reduction due to abort gap, hourglass effect, and finite crab cavity wavelength not included

Electron ring RF cavities

- RF cavities have to provide 10 MW of power at 46 MV
- Assuming 30 KEKB-type superconducting cavities that supply 2 MV and 380 kW each, with $h = 18 \times 360$, $f = 508$ MHz
- Cavity detuning for eRHIC beams computes as $\delta f = 17.1$ kHz - significant fraction of 78 kHz revolution frequency
- Feedback filtering similar to KEKB required

Proton injection kickers

- Increasing no. of bunches from present 120 to 360 requires new, faster injection kickers
- Full bunch length of $\tau_b = 15\,\text{nsec}$, spaced at $\tau_s = 35\,\text{nsec}$
- Strip line kickers, $L = 1.25\,\text{m}$ long give rise time $\tau_r = \tau_s - \tau_b - 2L/c = 12\,\text{nsec}$
- Deflection angle $\phi = 2\,\text{mrad}$ requires 16 modules for 24 GeV protons
- Present RHIC injection area needs to be modified to make room for 25 m long kicker section
- Kicker design vetted by Pulsed Power Group

Electron injection kickers are similar; somewhat easier due to shorter bunch length

Collective effects

- Electron beam single bunch instabilities studied using TRANFT code

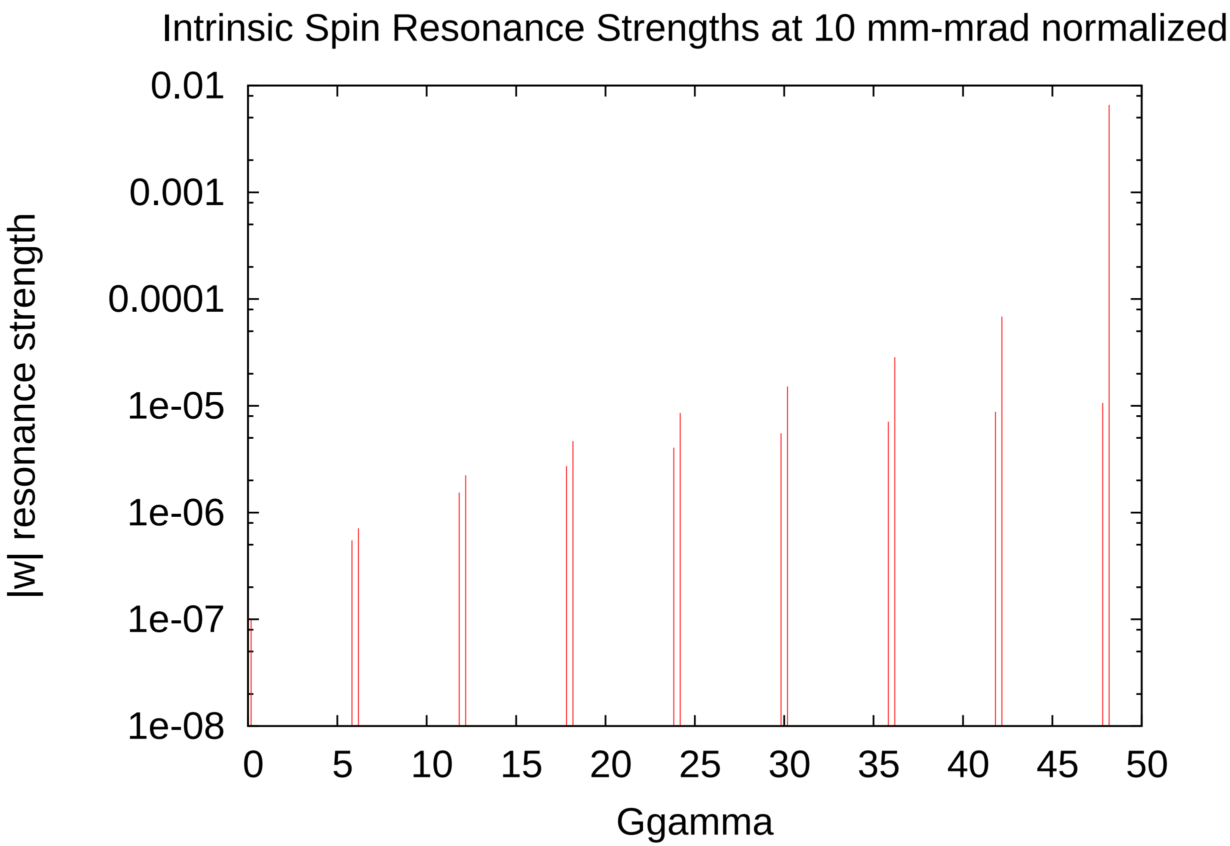
- Longitudinal and transverse impedances modeled as resonators with $Q = 1$ a $f_{\text{res}} = 10\,\text{GHz}$

- Longitudinal impedance adjusted to $\Im\left(\frac{Z}{n}\right) = 1\,\Omega$, transverse impedance at low frequency $Z_x = Z_y = 1.4\,\text{M}\Omega/\text{m}$

- $V_{\text{RF}} = 40\,\text{MV}$, $h = 18 \times 360$

Stable for 10^{12} electrons/bunch at 10 and 20 GeV, and for $3 \cdot 10^{11}$ at 5 GeV

DEPOL confirms lack of strong intrinsic resonances



Imperfection resonances