UPDATE ON ALTERNATIVE DESIGN OF JLEIC ION INJECTOR COMPLEX

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Outline

- ❑ Main Motivations of Alternative Design Studies
- ❑ Review: Alternative for the 65 GeV Design
- ❑ New Goals for the 100 GeV Design
- ❑ Options for the E-ring as Large Booster
- ❑ Options for the Pre-Booster Ring
- ❑ Summary & Future work

Main Motivations for the Alternative Ion Injector Design

❖ **The idea is not to replace the baseline design but rather to investigate alternative options for the different components of the ion complex that have the potential of lowering the cost, mitigating the risk, and be ready for possible staging and future upgrades of the project**

❑ Reduce footprint and cost of the Ion Complex

- Compact Injector Linac (130 MeV instead of 280 MeV protons)
- Small Pre-booster Ring (5-8 GeV, no figure-8)
- Consolidate Electron Ring as Large Ion Booster

❑ Lower the risk

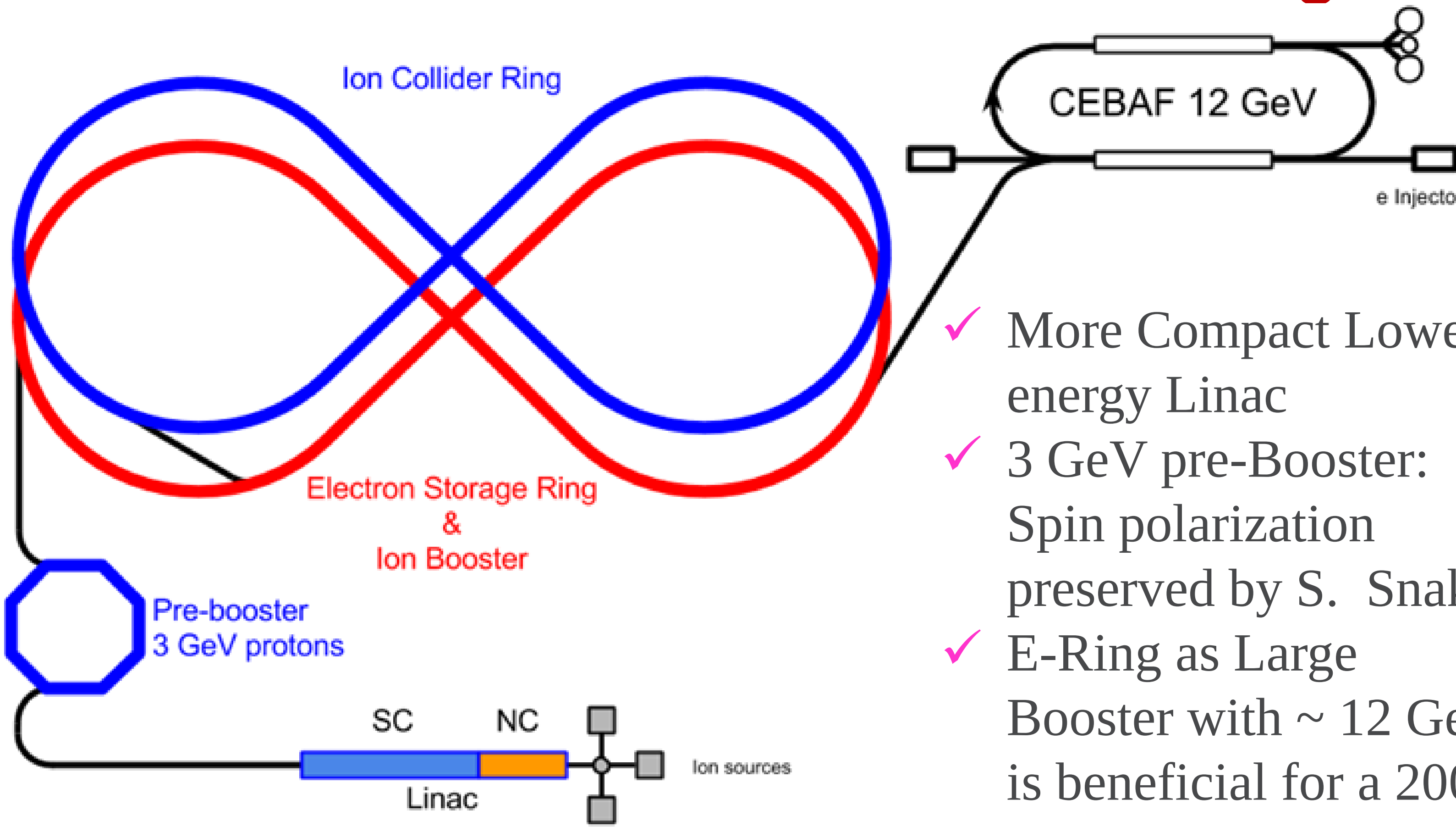
- Use RT magnets whenever possible
- Avoid transition crossing for all ions

❑ Staging / Upgrade

- Ion Injector Complex Compatible with 65, 100 and 140 GeV CM
- Only Upgrade Ion Collider Ring

Review for the 65-GeV Design

Review: Alternative for the 65 GeV Design

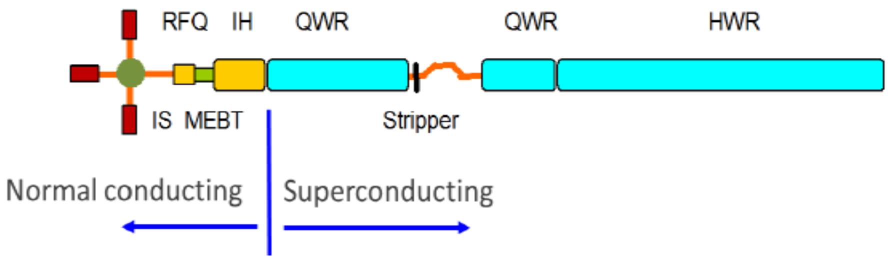


- ✓ More Compact Lower-energy Linac
- ✓ 3 GeV pre-Booster: Spin polarization preserved by S. Snakes
- ✓ E-Ring as Large Booster with ~ 12 GeV is beneficial for a 200 GeV collider upgrade
- ✓ Separate RF and spin correction sections for electrons and ions?

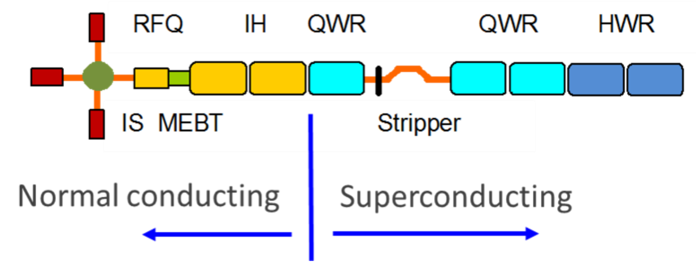
- ✓ The E-Ring and Ion Collider Ring are stacked vertically in one tunnel
- ✓ Ion injection from the E-Ring to Ion Ring is a vertical bend

A More Compact Lower-Energy Linac

Original



New

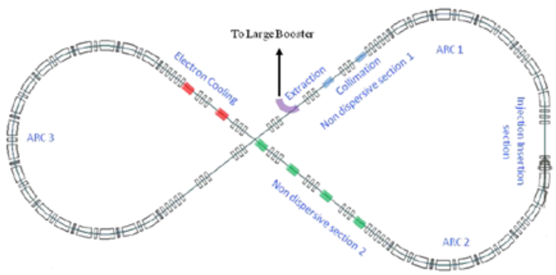


Item / Parameter	Original	New	Comments
Protons (MeV)	280	130	Lower output W
Pb (MeV/u)	100	42	Lower output W
SC modules	16	5	~ 1/3 Cost
Total Length	130	55	~ 1/2 Tunnel cost
Total Power (kW)	560	260	~ 1/2

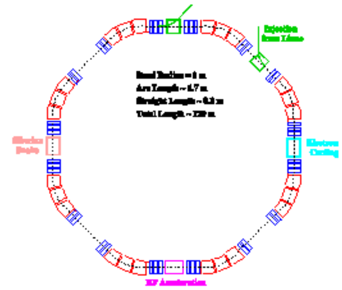
- The new design is ~ 1/3 the construction cost of the original

A More Compact Pre-Booster Ring

Original 3-GeV Pre-Booster



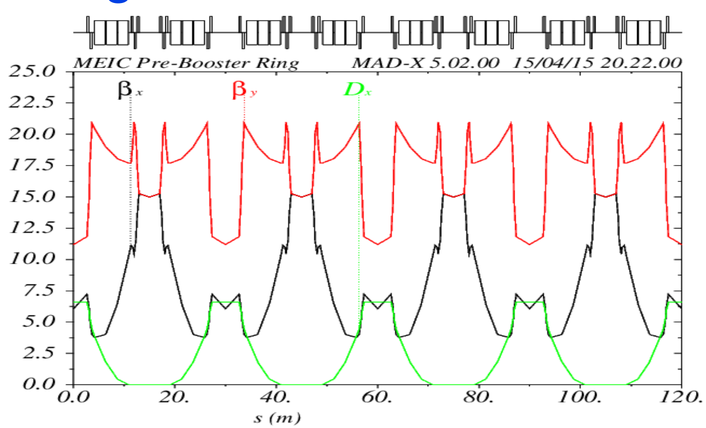
New Design



Item / Parameter	Original	New
N. of 15° Dipoles	36	24
N. of Quads	95	40
Total N. of Magnets	131	64
Total Length	234	120

- **The new design is ~ 1/2 the construction cost of the original**

Beam Optics

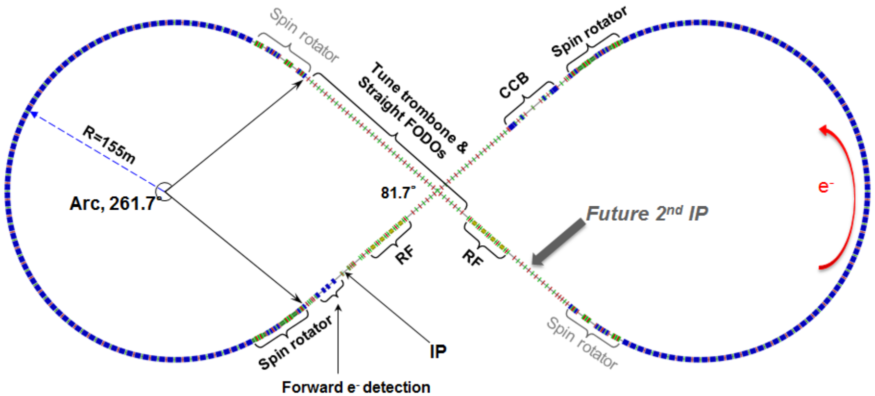


Design Parameters

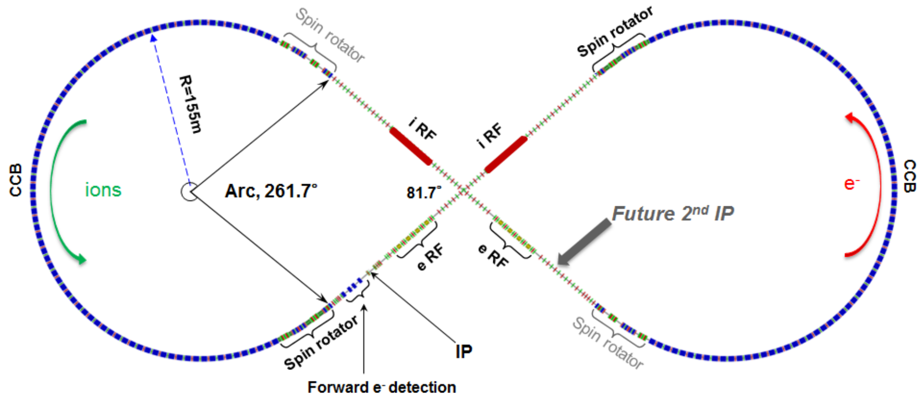
Parameter	Octagonal
Circumference, m	120
Arc length, m	6.7
Straight section length, m	8.3
Maximum β_x	15.3
Maximum β_y	21.0
Maximum dispersion	4.2
β_x at injection	6.0
Normalized dispersion at injection: $D/\sqrt{\beta_x}$	1.71
Tune in X	3.01
Tune in Y	1.18
Gamma transition	4.7
Gamma at extraction (3 GeV)	4.22
Momentum compaction factor	0.045
Number of quadrupoles	40
Quadrupole length, m	0.4
Quadrupole half aperture, cm	5
Maximum quadrupole field, T	1.5
Number of dipoles	24
Dipole bend radius, m	8
Dipole angle, deg	15
Dipole full gap, cm	5
Maximum dipole field	1.6

E-Ring As Large Booster for the Ions – Added RF Sections for Ions …

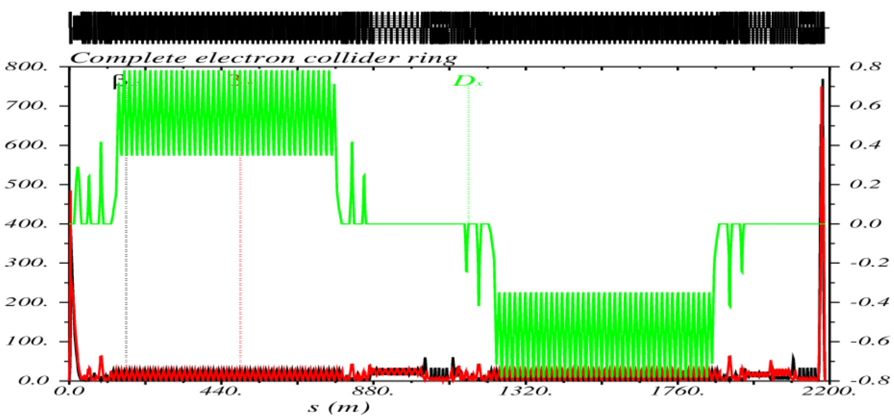
Electrons Only



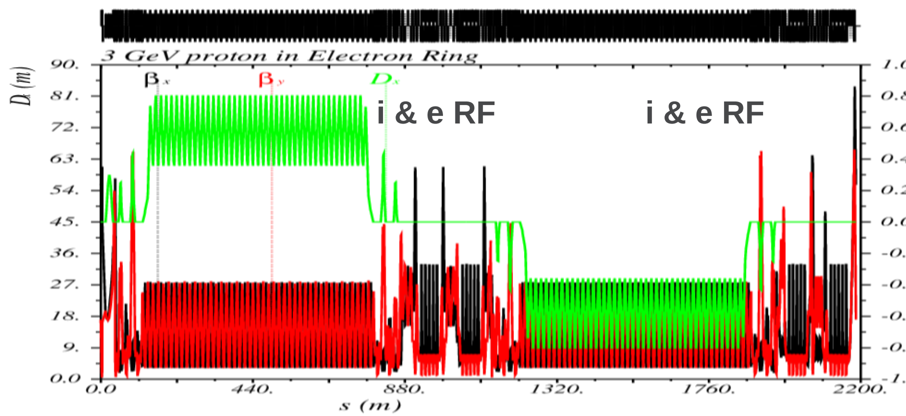
Electrons & Protons



e- Collision Optics at 5 GeV



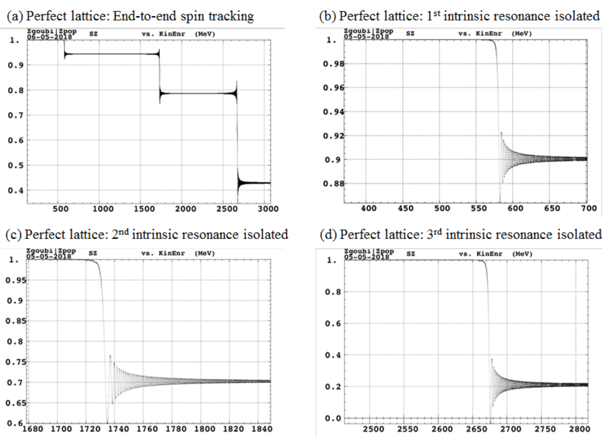
Proton optics at 3 GeV, Injection from Booster



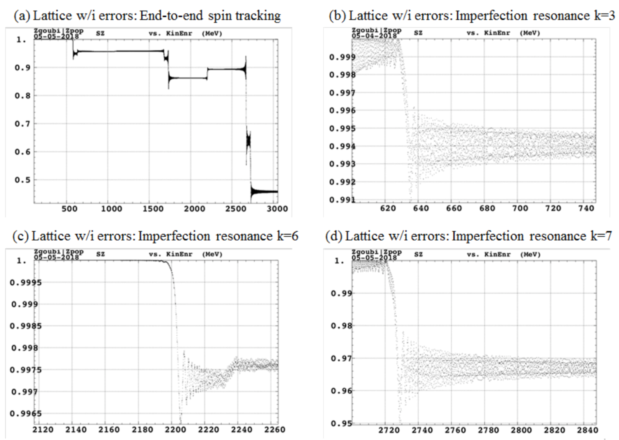
- ✓ Ion RF sections were inserted in the straight sections, across from electron RF
- ✓ Proton beam optics studied at the injection energy of 3 GeV

Spin Dynamics in 3-GeV Pre-Booster

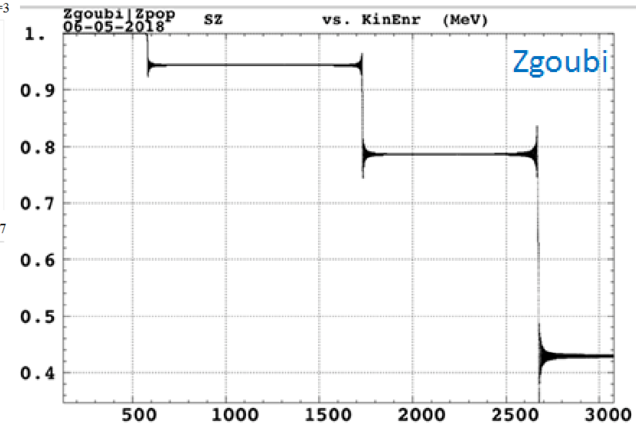
Intrinsic resonances (proton)

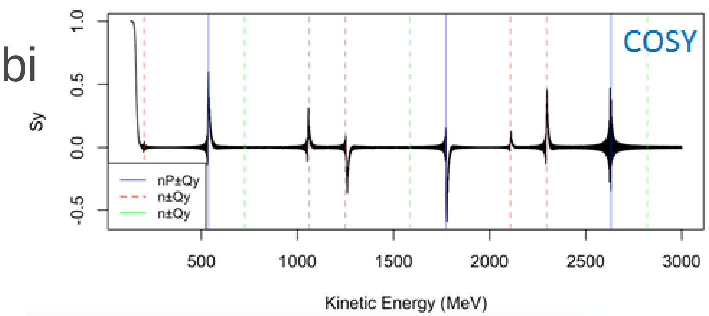


Imperfection resonances (proton)



Intrinsic : COSY vs. Zgoubi





- ✓ Good overall agreement between COSY and Zgoubi
- ✓ No resonances observed for deuterons, first one expected at ~ 5.6 GeV/u
- ✓ Possible spin correction schemes for protons are listed in table below

Option	~ 5 Imperfection	~ 2 Strong Intrinsic	~ 1 Intrinsic	~ 8 Weak Intrinsic
A	Orbit corrections	Rf Dipole	Rf Dipole	Nothing/Pulsed Quads
B	5% Siberian Snake	Rf Dipole	Rf Dipole	Nothing/Pulsed Quads
C	Orbit Correction	Pulsed Quads	Pulsed Quads	Nothing/Pulsed Quads
D	5% Siberian Snake	Pulsed Quads	Pulsed Quads	Nothing/Pulsed Quads
E	40% Siberian Snake	40% Siberian Snake	40% Siberian Snake	40% Siberian Snake

Beam Formation in Alternative 65-GeV Design

Proton beam parameters in the Rings

Parameter/Ring	Pre-Booster	Booster: E-Ring	Collider Ring
Inj. energy [GeV]	0.13	3	16
End energy [GeV]	3	16	100
Circumference [m]	120	2250	2250
Harmonic	1	18	18
Injection efficiency	90	100	100
Bunch charge [μC]	0.21	0.21	0.21
Ions per bunch [10^{12}	1.32	1.32	1.32
RMS norm. emittance [π-mm-mrad]	3	3	1
Bunch length [m]	84	84	84
SC tune shift at inj.	0.122	0.083	0.013
RF freq. at inj. [MHz]	1.21	2.322	2.394
RF freq. at end [MHz]	2.43	2.394	2.398
RF period at end [μs]	0.41	0.42	0.42
Avg. current at end [A]	0.51	0.5	0.5

Lead beam parameters in the rings

Parameter/Ring	Pre-Booster	Booster: E-Ring	Collider Ring
Inj. energy [GeV/u]	0.04	0.61	16
End energy [GeV/u]	0.61	16	40
Circumference [m]	120	2250	2250
Harmonic	1	18	18
Charge state [e]	67	82	82
Injection efficiency [%]	70	75	100
Bunch charge [μC]	0.23	0.21	0.21
Ions per bunch [1010]	2.1	1.6	1.6
RMS norm. emittance [π-mm-mrad]	3	3	1
Bunch length at inj. [m]	84	84	84
SC tune shift at inj.	0.086	0.256	0.005
RF freq. at inj. [MHz]	0.74	1.844	2.394
RF freq. at end [MHz]	2.03	2.394	2.398
RF period at end [μs]	0.49	0.42	0.42
Avg. current at end [A]	0.47	0.5	0.5

- ✓ The main issue is the high SC tune shift for Pb ions in the E-ring / Large Booster
- ✓ A 5-GeV or higher booster energy will reduce it to below 0.15

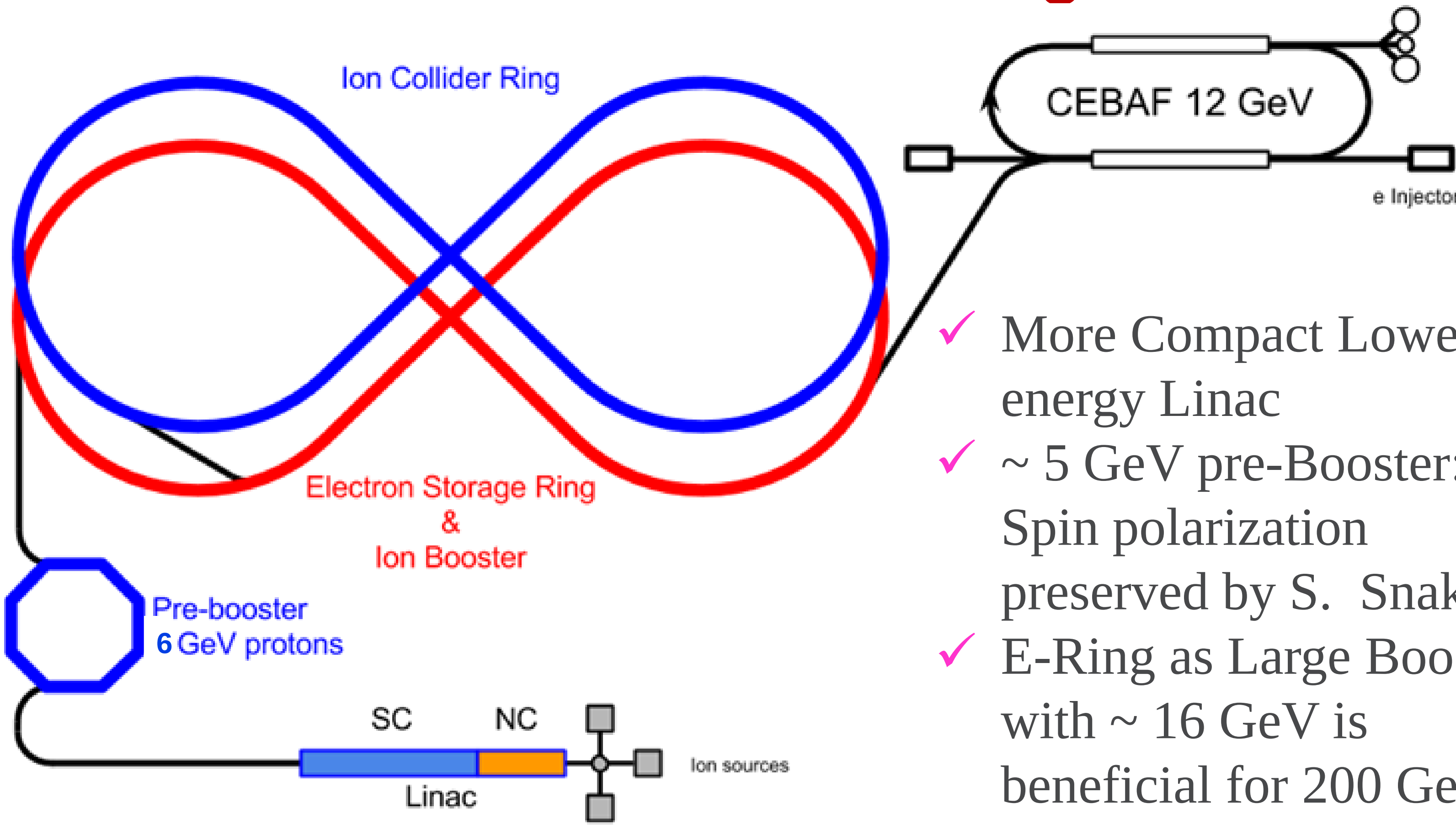
Progress Reported in Conference Proceedings …

- "An Alternative Approach for the JLEIC Ion Accelerator Complex", B. Mustapha, P. Ostroumov, A. Plastun, Z. Conway, V. Morozov, Y. Derbenev, F. Lin and Y. Zhang, Proceedings of NAPAC-2016, October 9-14, 2016, Chicago, IL.
- "A More Compact Design for the JLEIC Ion Pre-Booster Ring", B. Mustapha, P.N. Ostroumov and B. Erdelyi, Proceedings of NAPAC-2016, October 9-14, 2016, Chicago, Illinois.
- "Adapting the JLEIC Electron Ring for Ion Acceleration", B. Mustapha, J. Martinez Marin, Z. Conway, P. Ostroumov, F. Lin, V. Morozov, Y. Derbenev and Y. Zhang, Proceedings of IPAC-2017, May 14-19, 2017, Copenhagen, Denmark.
- "Beam Formation in the Alternative JLEIC Ion Complex", B. Mustapha et al, Proceedings of IPAC-18, April 29 – May 4, 2018, Vancouver, Canada
- "Spin Dynamics in the JLEIC Alternative Pre-booster Ring", J. Martinez and B. Mustapha, Proceedings of IPAC-18, April 29 – May 4, 2018, Vancouver, Canada

Main Conclusions for the 65-GeV Design …

- ❑ Lower linac energy seems reasonable for both proton and heavy-ion injection into a small pre-booster ring
- ❑ Higher energy pre-booster of 5 GeV or higher is required to lower SC tune shift for heavy ions in the e-ring
- ❑ E-ring as Large Ion Booster seems feasible from beam optics point of view
- ❑ Changes adopted to the baseline design
  - Lower-energy shorter linac → 150 MeV
  - Two boosters: 8 and 12 GeV
  - RT magnets in the boosters, SC only in collider ring

New Goals for the 100-GeV Design



- ✓ More Compact Lower-energy Linac
- ✓ ~ 5 GeV pre-Booster: Spin polarization preserved by S. Snakes
- ✓ E-Ring as Large Booster with ~ 16 GeV is beneficial for 200 GeV collider & future upgrade
- ✓ If practical limitations, Large Booster can be separate, in same tunnel

- ✓ The E-Ring and Ion Collider Ring are stacked vertically in one tunnel
- ✓ Ion injection from the E-Ring to Ion Ring is a vertical bend

Design Options for E-Ring / Large Booster

Limitation of Current E-ring as Large Booster

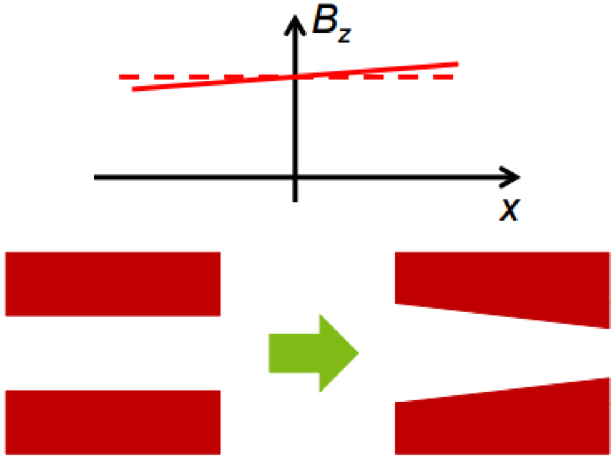
3 Options considered (NAPAC-2016 Paper)

Parameter	Baseline (PEP-II magnets)	Low-ε (New RT magnets)	TME design (RT dipoles, SC quads)
Cell length (m)	15.2	11.4	11.4
Transition γ	23	23	32
Proton (GeV)	11	15	37.5
Pb (GeV/u)	4.4	6	15
Dipole (T)	0.36	0.5	1.3
Quad (T/m)	15	25	66
Limitation	Dipoles	Quads	-

- In current e-ring lattice, SC quads are required to reach ~ 16 GeV/u for Pb
- For a room-temperature ring, a new design of e-ring/ion booster is needed
- Design it for 16 GeV/u ions then optimize it for storing electrons
- Possible options: combined function dipoles, long quads, quad doublets …

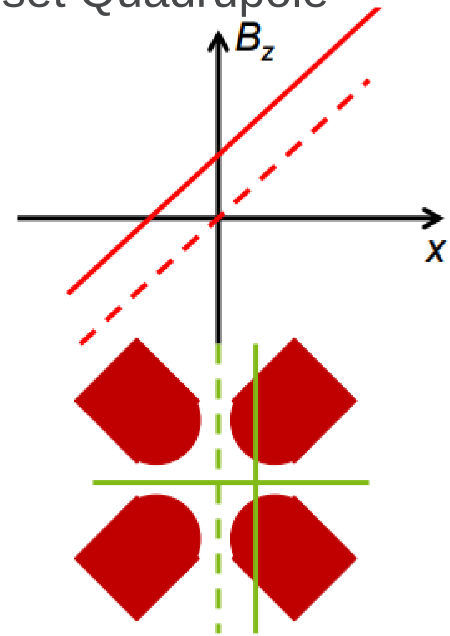
Combined Function Magnet Options

Tapered Dipole Face



High Field, Low gradient

Offset Quadrupole



High Field, High Gradient

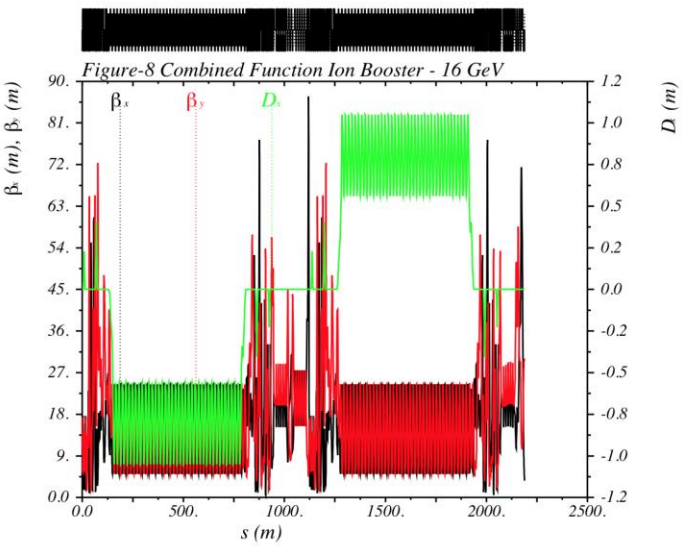
- The offset quadrupole option is not practical and more expensive, because all dipoles will need to be quadrupoles …
- Despite the low gradient, the tapered dipole face solution may provide the additional focusing required
- An electron storage was recently proposed with tapered dipoles with up to 14 T/m! C. Bailey et al, “Magnet Design for DIAMOND DDBA Lattice Upgrade”, IPAC-2014

Large Booster Solution with Tapered Dipoles

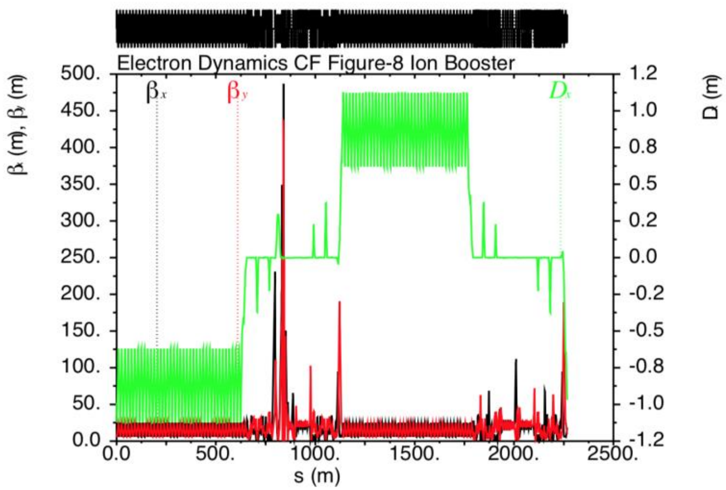
All RT Figure-8 Design

Parameter	Value
Circumference, m	2256.6
Maximum βx, m	85
Maximum βy, m	73
Maximum dispersion, m	1.05
γ	18.17
Transition γ	18.6
Quad. half aperture, cm	5
Quad. max. grad. T/m	20
Quad. length in arc, m	1
Dipole max. field, T	1.3
Dipole gradient, T/m	4
Dipole Length, m	6
Cell Length, m	16.4

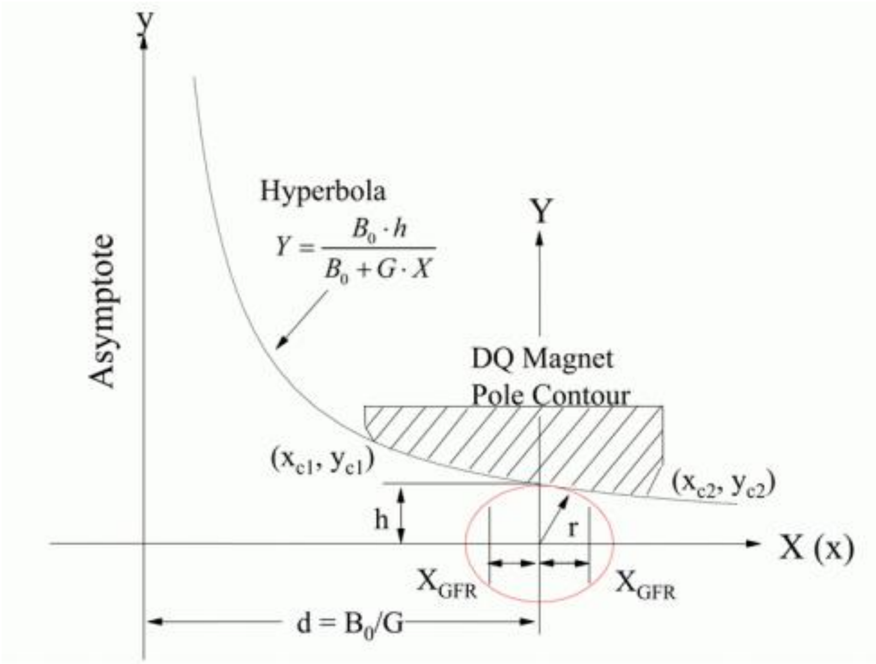
16 GeV/u Lead beam optics



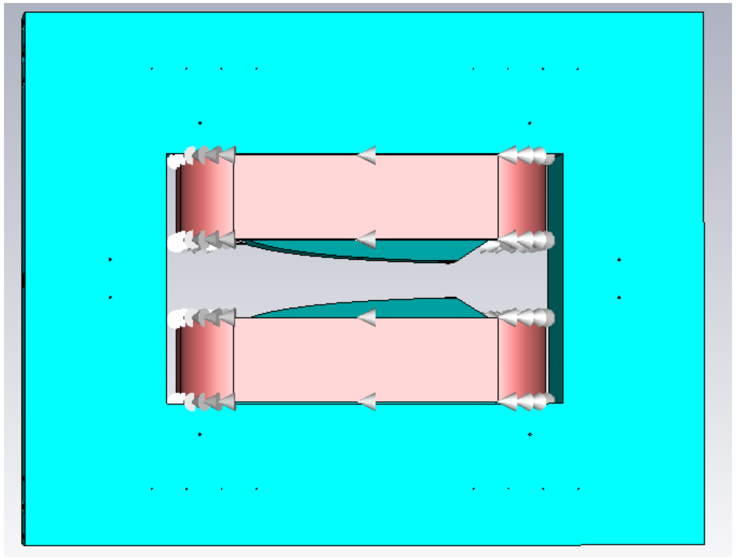
12 GeV Electron beam optics



Issues / Limitations of Tapered Dipoles



Dipole with Tapered Pole Face



Preliminary tapered magnet design:
Gap = 5 cm, Gradient ~ 3 T/m
Needs further optimization

- The gradient component reduces the bending field: Bmax=B0+G*dy ~ 1.6 T
  → this directly affect the minimum bend radius allowed
- The Maximum gradient depends on the gap and width of good field region
  → so far assuming 5 cm gap (~7*sigma) and +/- 5 cm good field region
- The dipole needs to be curved to preserve the same focusing relative to central orbit.

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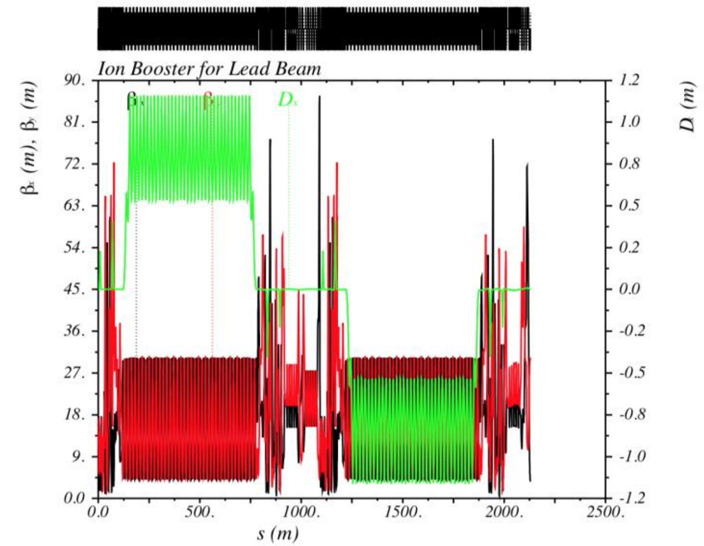
Large Booster Solution with Quad Doublets

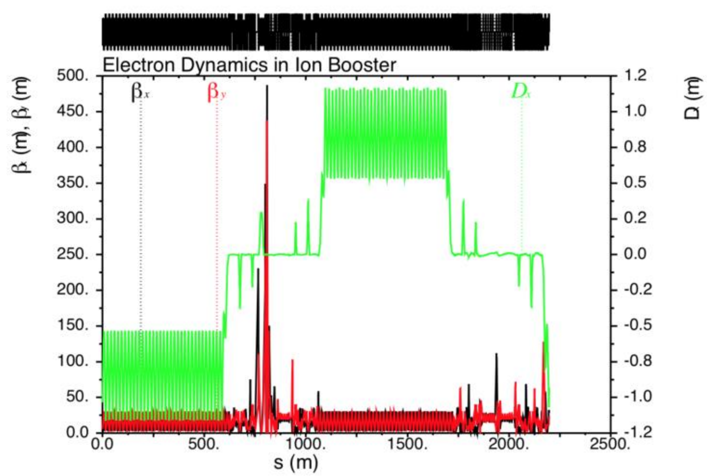
All RT Figure-8 Design

Parameter	Value
Circumference, m	2251.6
Maximum βx, m	85
Maximum βy, m	73
Maximum dispersion, m	1.16
γ	18.17
Transition γ	18.7
Quad. half aperture, cm	5
Quad. max. grad. T/m	20
Quad. length in arc, m	0.69
Dipole max. field, T	1.6
Dipole Length, m	5.4
Cell Length, m	17.3

16 GeV/u Lead beam optics



12 GeV Electron beam optics

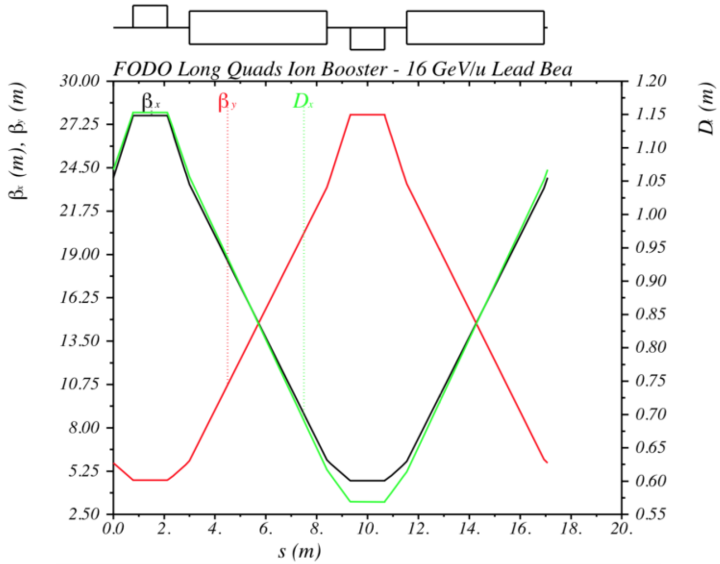


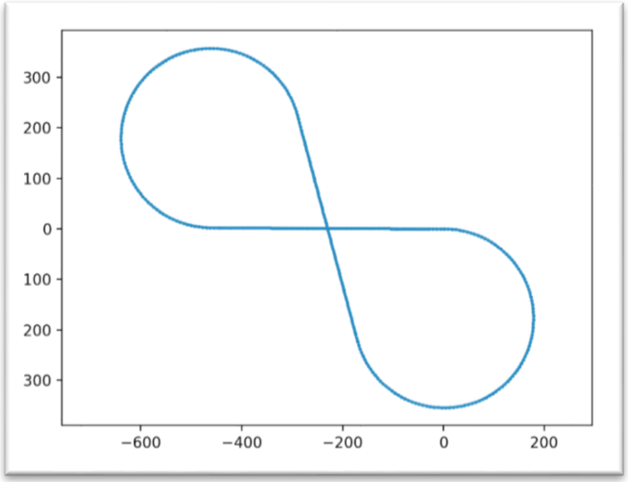
Large Booster Solution with Long Quads

All RT Figure-8 Design

Parameter	Value
Circumference, m	2220.4
Maximum βx, m	85
Maximum βy, m	73
Maximum dispersion, m	1.15
γ	18.17
Transition γ	18.3
Quad. half aperture, cm	5
Quad. max. grad. T/m	20
Quad. length in arc, m	1.35
Dipole max. field, T	1.6
Dipole Length, m	5.4
Cell Length, m	17.1

16 GeV/u Lead single-cell optics





Design Options for Pre-Booster

Pre-Booster Energy vs. Beam Size in Large Booster

Parameter	5-GeV Pre-B Proton	5-GeV Pre-B Pb^{67+}	6-GeV Pre-B proton	6-GeV Pre-B Pb^{67+}	8-GeV Pre-B proton	8-GeV Pre-B Pb^{67+}
Inj. Energy (GeV/u)	5	1.2	6	1.5	8	2
βγ value	6.2493	2.0582	7.3266	2.4111	9,4734	2.9840
RMS norm. ε (π.mm.mrad)	3	3	3	3	3	3
RMS un-norm. ε (π.mm.mrad)	0.480	1.458	0.409	1.244	0.317	1.005
Vertical βmax, m	90	90	90	90	90	90
βmax in dipole, m	30	30	30	30	30	30
σ in dipole (mm)	3.8	6.6	3.5	6.1	3.1	5.5
7σ Aperture (mm)	26.6	46.3	24.5	42.7	21.7	38.5

→5-GeV Pre-booster will require 6 cm gap for Large Booster dipoles

→ 6-GeV Pre-booster will require 5 cm gap for Large Booster dipoles (thin-wall VC)

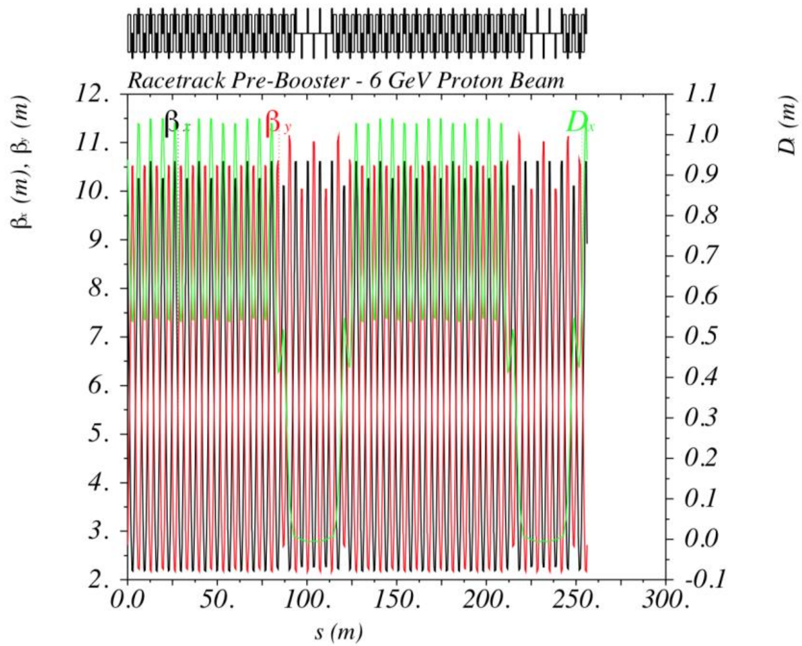
→ 8 GeV Pre-booster will require 5 cm gap for Large Booster dipoles (regular 5 mm wall VC)

6-GeV Pre-Booster Design Option

All RT Race-Track Design

Parameter	Value
Circumference, m	256.1
Maximum βx, m	10.6
Maximum βy, m	11.14
Maximum dispersion, m	1.04
Tune in X	9.45
Tune in Y	9.36
Extraction γ	7.39
Transition γ	7.91
Quad. half aperture, cm	5
Quad. max. grad. T/m	20
Quad. length in arc, m	0.56
Dipole max. field, T	1.6
Dipole Length, m	1.51

6 GeV proton beam optics



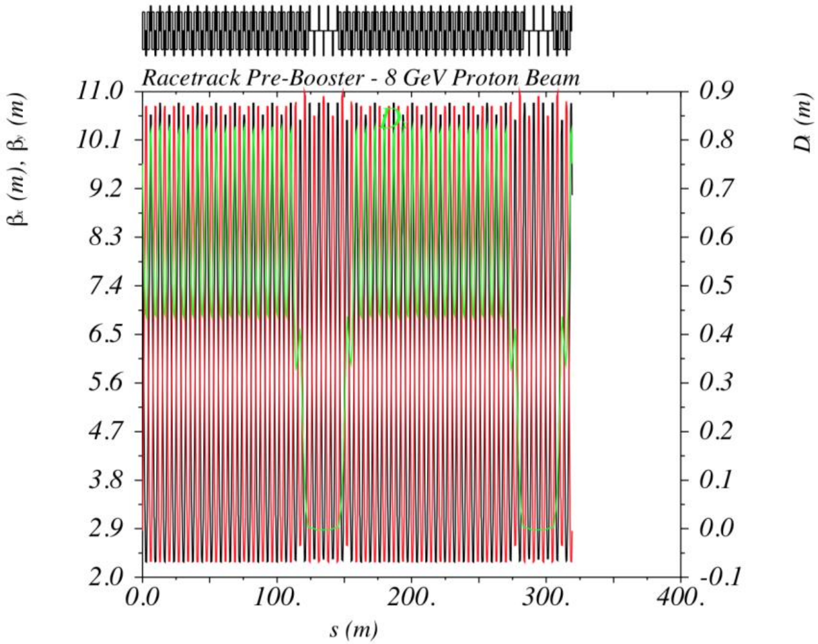
Siberian snake for p, 3He
No resonances for d

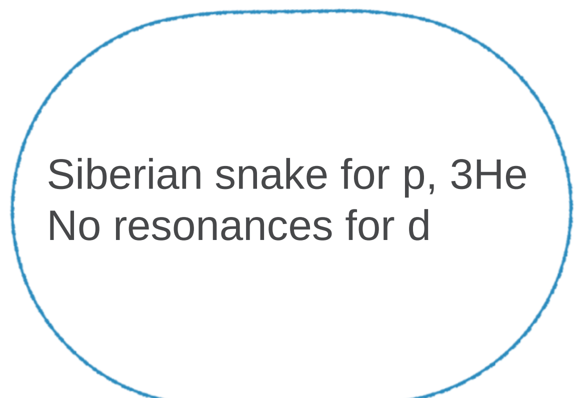
8-GeV Pre-Booster Design Option

All RT Race-Track Design

Parameter	Value
Circumference, m	319.3
Maximum βx, m	10.78
Maximum βy, m	10.99
Maximum dispersion, m	0.83
Tune in X	11.47
Tune in Y	11.41
Extraction γ	9.53
Transition γ	9.78
Quad. half aperture, cm	5
Quad. max. grad. T/m	20
Quad. length in arc, m	0.66
Dipole max. field, T	1.6
Dipole Length, m	1.62

8 GeV proton beam optics





Summary & Future Work …

- ❑ The Pre-Booster can be small RT race-track ~ 6 GeV - 250 m circumference, solves heavy-ions SC effects but will require Siberian snake for proton and 3He

- ❑ The Large Booster can be up to 16 GeV for all ions (16 GeV/u) in the same footprint as the E-Ring with all RT magnets, the high energy is beneficial for 100-GeV CM and upgrade to 140-GeV

- ❑ The new Large Booster design can be used as E-ring, beam optics seems feasible, but can be separate in case of practical or operational limitations

- ❑ Next: Optimization of a selected option – 6 GeV race-track Pre-Booster with 16 GeV/u Large Booster with quad doublets focusing

Thank you!