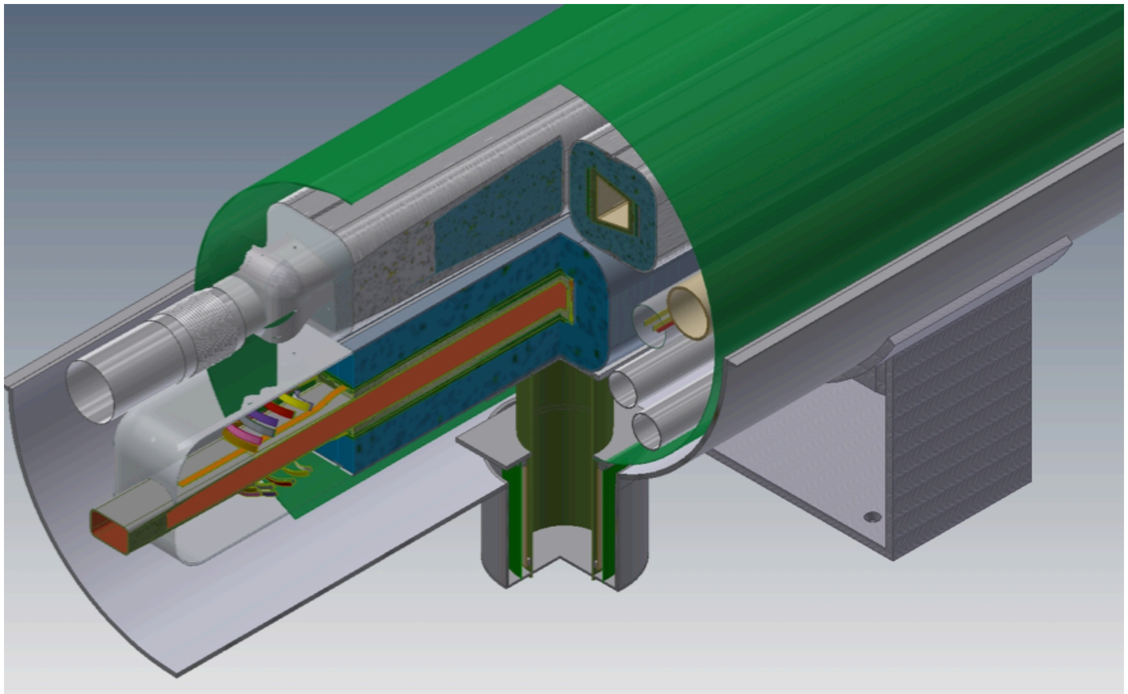
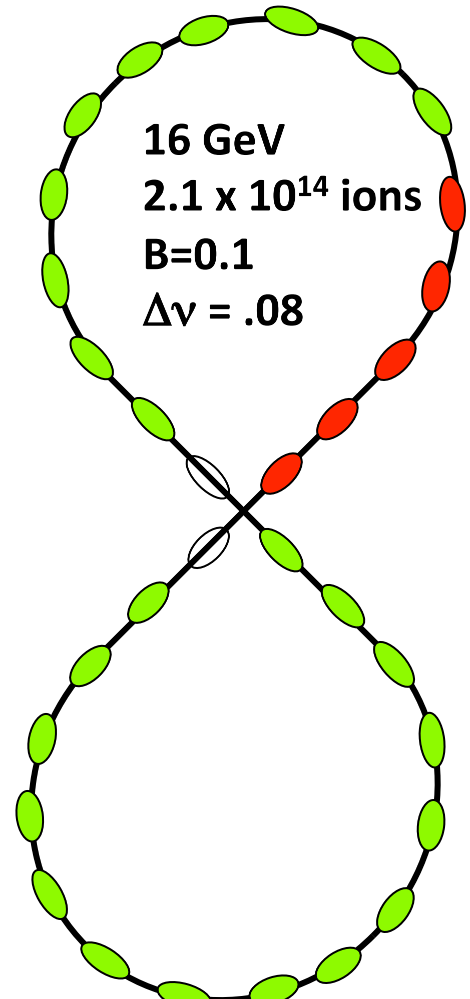
E-Cooler, Stacker integrated with Ion Ring: x8 boost in Ion Current, MEIC Luminosity





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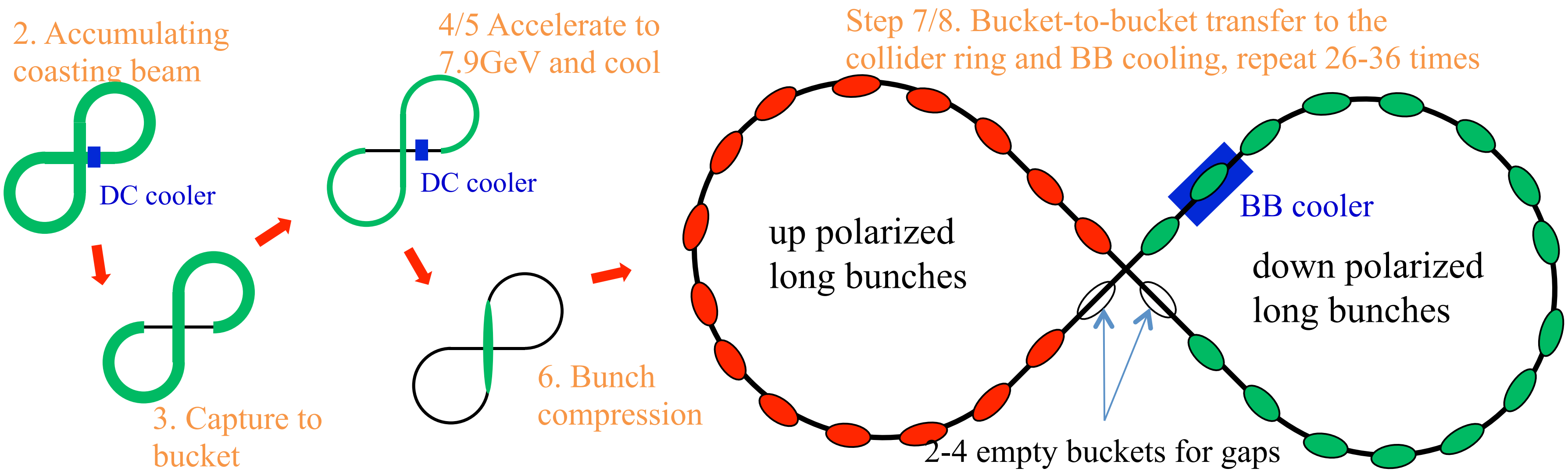
Ion Beam Formation Cycles - MEIC baseline

Guo



1. Eject the used beam from the collider ring, cycle the magnets
2. Multi-turn strip-injection of up polarized ion from linac to booster (non-polarized for heavy ions)
3. Capture beam into a bucket (~0.7× booster ring circumference)
4. Ramp energy (to 7.9GeV proton or equivalent) and perform DC cooling in the booster
5. Compress the bunch length to ~$0.7/Nh_0\times$ of the collider ring circumference (Nh_0 is the harmonic # for long bunches)
6. Bucket-to-bucket transfer the long bunch into collider ring
7. Repeat step 2-6 for ($Nh_0/2-1$) times, each cycle ~1 min
8. Switch to down polarized ions and repeat step 1-5 for another ($Nh_0/2-1$) times, total cycles ~Nh_0-2
9. Ramp collider ring to collision energy, perform bunch splitting to harmonic # Nh (~3400-3600)
10. If needed, manipulate the beam to create several extra empty buckets (476 MHz) in the gap, as required by beam synchronization.

Ion Collider Ring SC Tune Shift at Injection Energy

Guo

Particle	Proton		Lead		Deuteron	
Booster ring circumference (m)	226.7					
Collider ring circumference (m)	2267 (Nh=3600)					
Collider ring beam current (A)	0.5	1.0	0.5	1.0	0.5	1.0
Collider ring charge (μC)	3.78	7.56	3.78	7.56	3.78	7.56
Booster cycles	28	28	36	28	28	28
Booster extraction energy (GeV/u)	7.9	7.9	2.65	2.65	3.55	3.55
Booster extraction momentum (GeV/c/q)	8.79	8.79	8.79	8.79	8.79	8.79
Booster ring charge (μC)	0.14	0.27	0.11	0.27	0.14	0.27
Normalized emittance, step 8 (μm)	0.5	1.0	1.0	1.5	1.0	1.2
Collider ring SC tune shift, step 8	0.09	0.09	0.12	0.15	0.09	0.15
6σ aperture, step 6-8 (mm)	5.19	7.34	11.7	14.3	10.4	11.4

7.9GeV booster energy is sufficient at least for 1.5A proton and 1.0A Pb beam current in collider ring

Particle flow in MEIC is limited by space charge and intrabeam scattering

- Space charge tune shift and intrabeam scattering both limit the line charge density that can be accelerated and accumulated in the acceleration sequence.

$$\Delta\nu_{SC} = \left(\frac{RIr_i\beta_y}{h\nu\sigma_y(\sigma_x+\sigma_y)}\right)\frac{N}{\beta^2\gamma^3\sigma_s} \qquad \Gamma_{IBS} = \left(\frac{r_i^2 c L_C I}{64\pi^2 h\epsilon_x\epsilon_y\sigma_p}\right)\frac{N}{\beta^3\gamma^2\sigma_s}$$

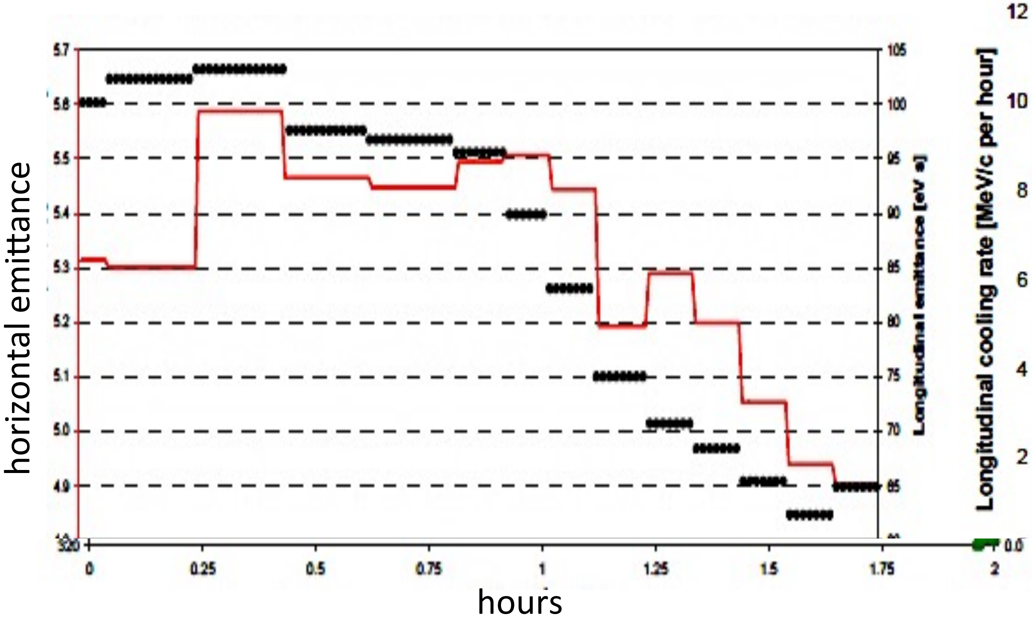
- Both effects are worse at low energy, short bunch length. We need to start with single long bunches of $\sim 10^{12}$ in the Booster, and end with 3150 short bunches of $\sim 10^{11}$ in the Ion Ring.
- *To get there, we must cool and stack at an energy high enough that SC and IBS don't kill us.*

Cool and accumulate using d.c. electron cooling in dedicated cooling rings

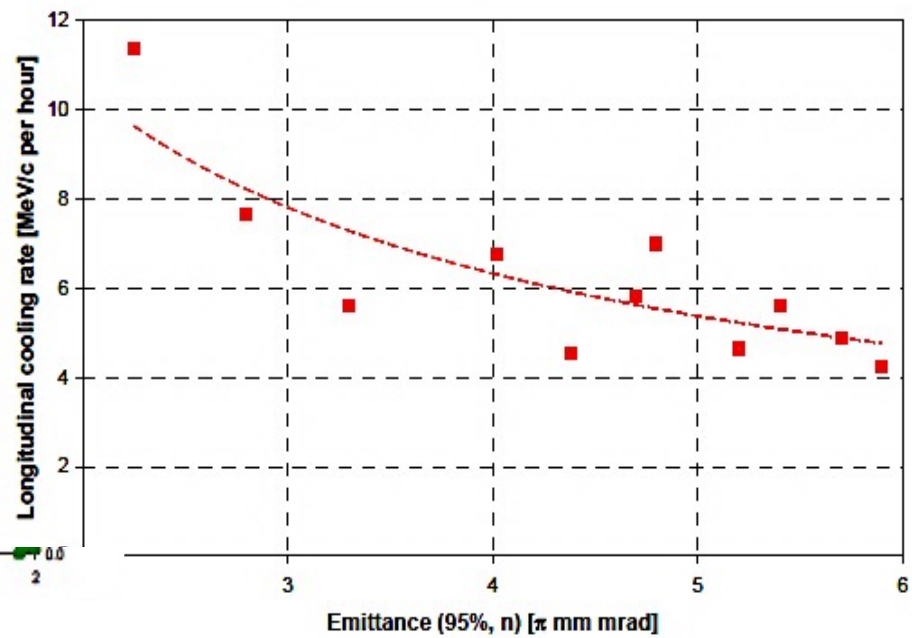
- Integrate a Cooling Ring that cools and coalesces Booster bunches at ~8 GeV, keeping $\Delta\nu < .2$
- Accelerate the stack to ~16 GeV and transfer to a fixed-energy Stacking Ring, shorten bunch length and coalesce multiple cycles, keeping $\Delta\nu < 0.1$
- This works most naturally if the Cooler and Stacker are piggy-backed on the Ion Ring itself, sharing a common cryostat.
- One 6-8 GeV Fixed-Energy Cooling Ring helps a lot,
- Combined with a 16 GeV Stacker Ring it makes possible a factor 8 increase in ion intensity for a given limit from space charge and IBS>

Fixed-energy e-cooling at ~8 GeV

Fermilab's Recycler was a highly successful fixed-energy 8 GeV e-cooler. It ***cooled and stacked*** antiprotons, and was at the heart of the world-record antiproton accumulations. It makes an inspiring start to the needs for MEIC ion cooling…



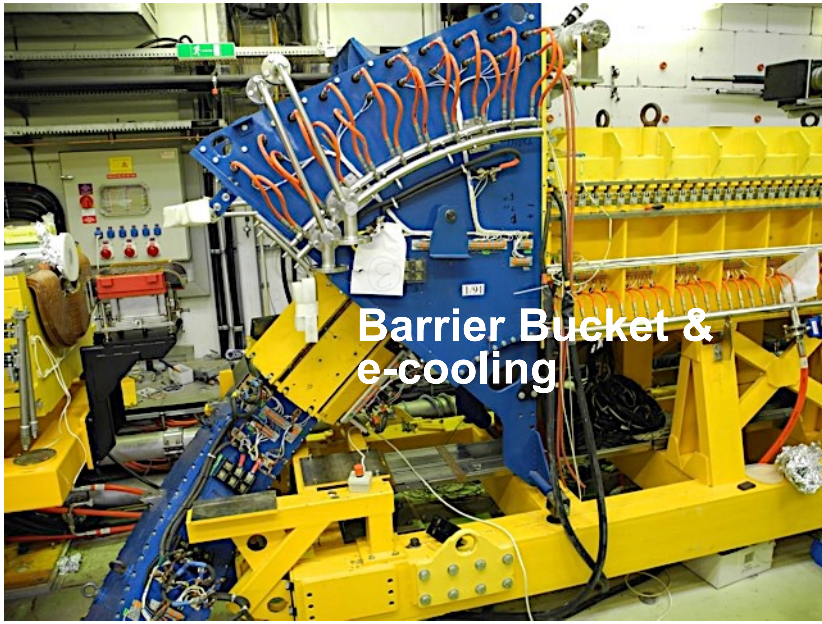
with 200 mA e-beam

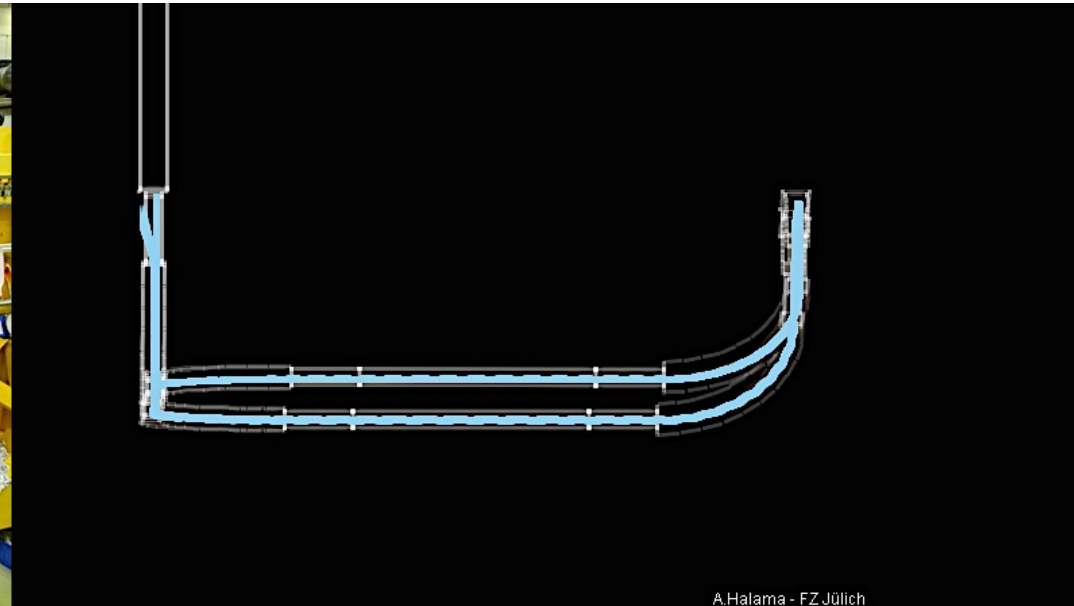


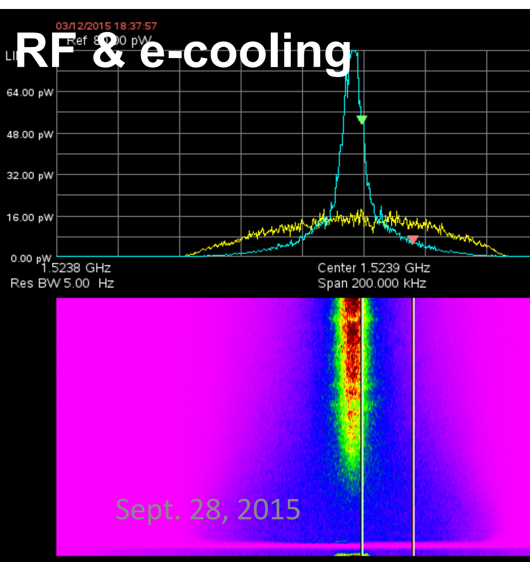
with 100 mA e-beam

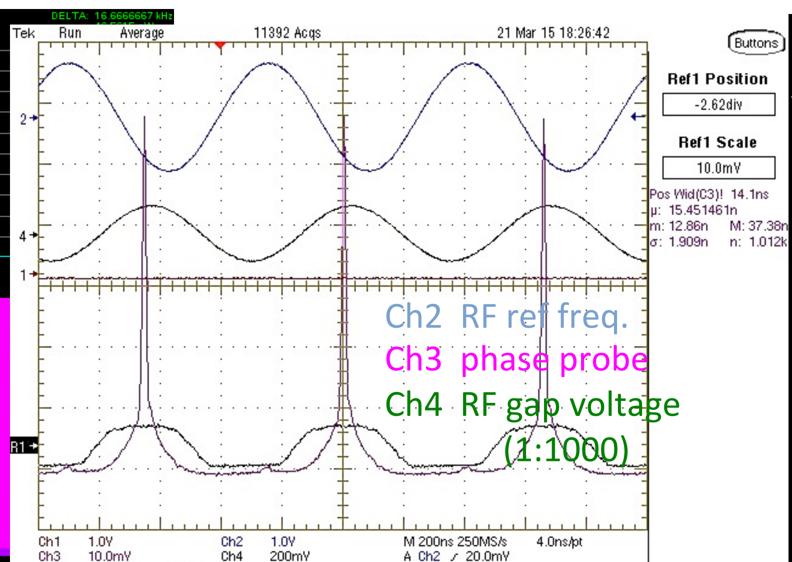
COSY is a new model for magnetized e-cooling and stacking ions with high energy

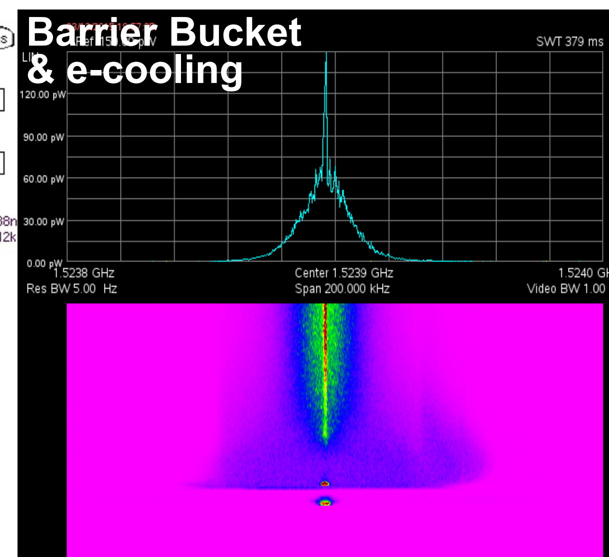
Kamerdzhiev











Summary

- The 2 MeV electron cooler at COSY is a unique device as it combines high energy and high magnetic field
- Low intensity 1.6 GeV proton beam was cooled within:
  - 100 s longitudinally
  - 200 s transverse
- Need to establish model-based automated e-beam setup procedures (work in progress) to carry out systematic studies on cooling time vs energy and vs B under reproducible conditions

even shorter cooling time?

Mount E-Cooler, Stacker superferric half-cells above Ion Ring half-cell *in the same cryostat*

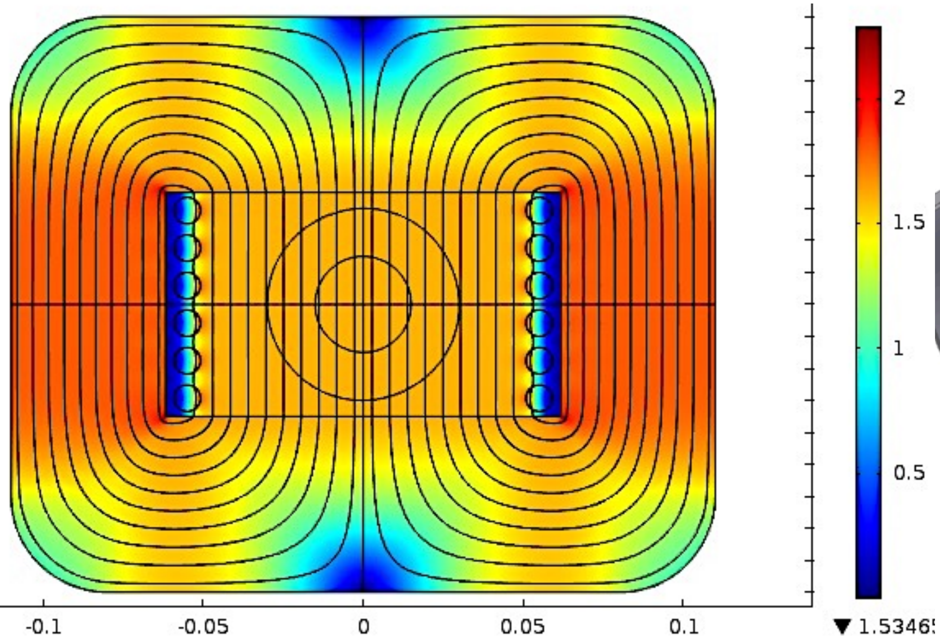
Each dipole is 1.3 m long, 1.5 T field, mounted on top of Ion Ring dipole.

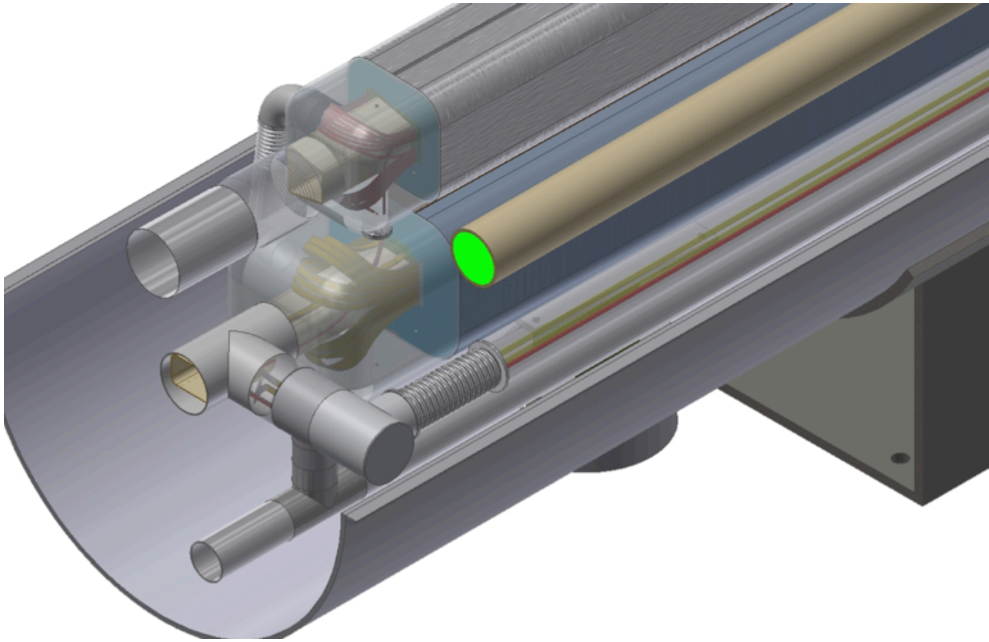
Lock lattice to that of Ion Ring, but 2 C/S ½ cells in each Ion Ring ½ cell.

Transition energy is 19.76 – *ions never pass through transition.*

C/S dipoles have ½ field, ⅓ length, ~¼ cost of Ion Ring dipoles.

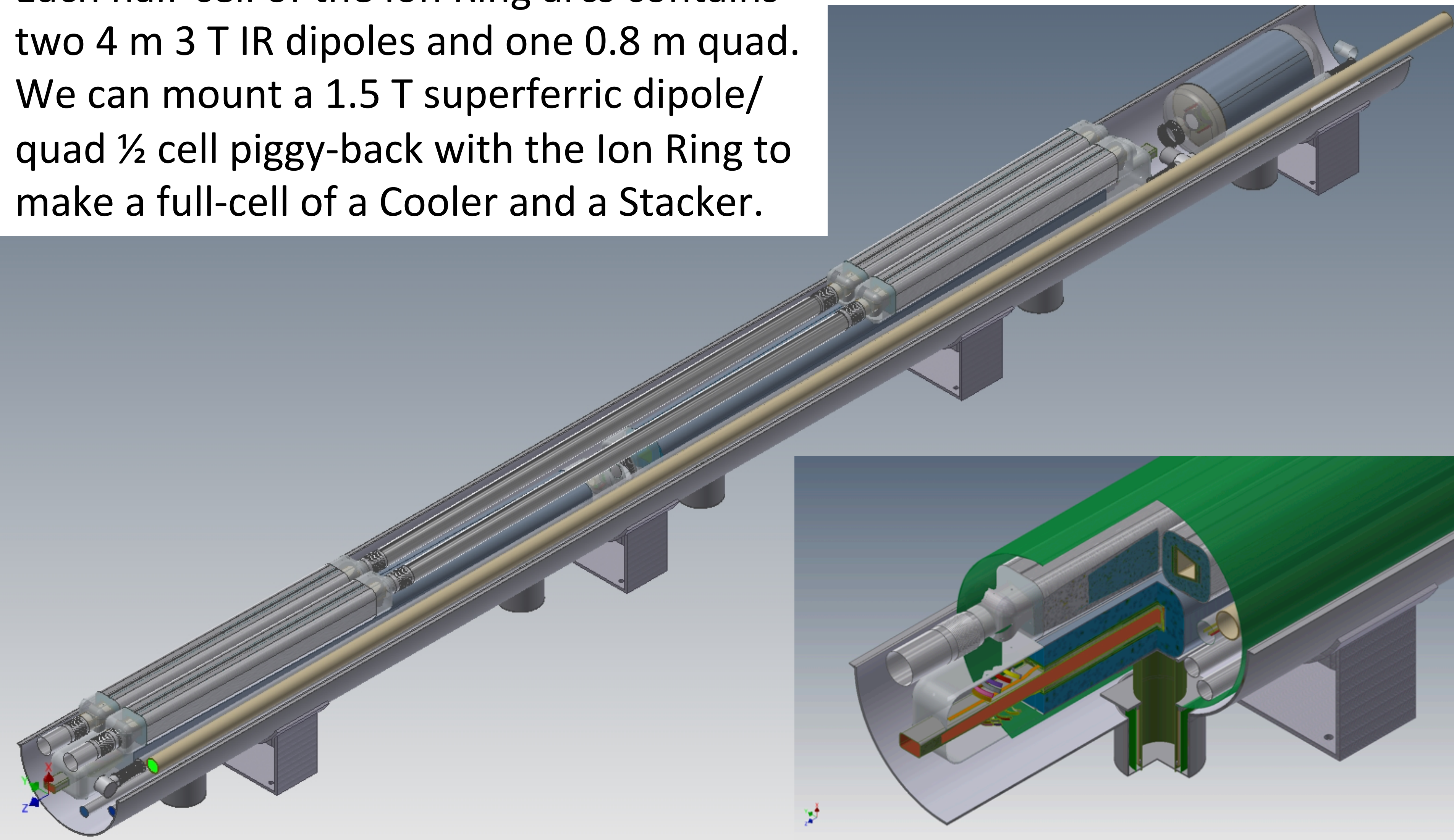
~No additional cryostat cost. *These are very modest magnets.*



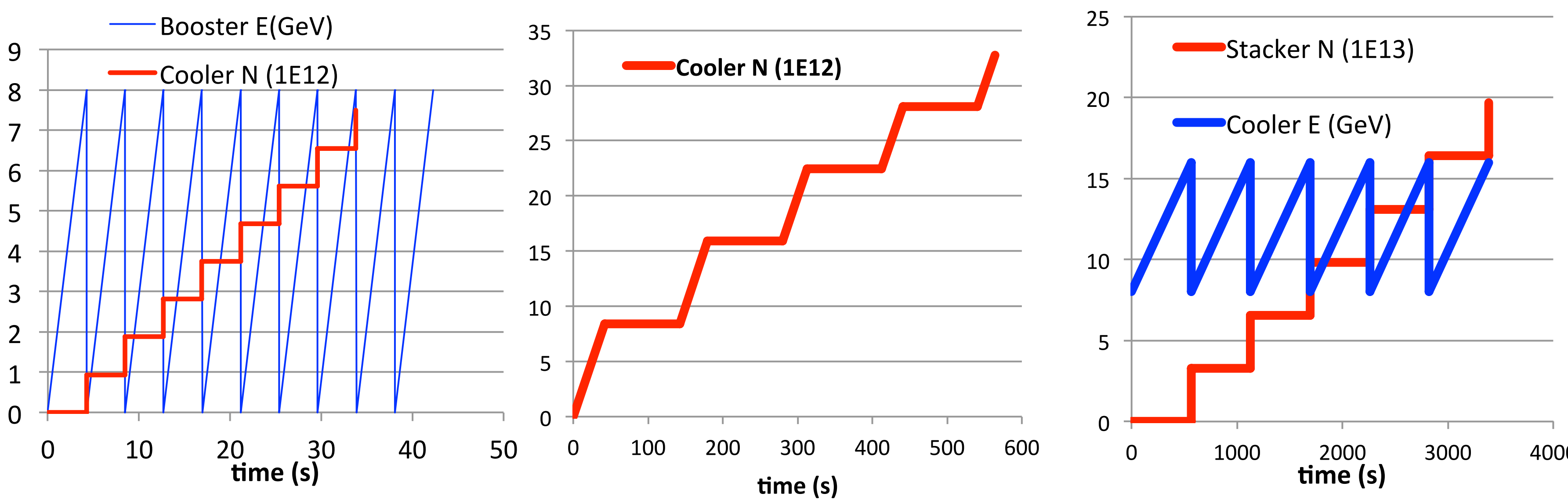


Chiller and Stacker Piggy-Back on Ion Ring

Each half-cell of the Ion Ring arcs contains two 4 m 3 T IR dipoles and one 0.8 m quad. We can mount a 1.5 T superferric dipole/ quad ½ cell piggy-back with the Ion Ring to make a full-cell of a Cooler and a Stacker.



Cool and stack Booster cycles in Cooler. Accelerate to 16 GeV, stack in Stacker.



Because Cooler and Stacker have full circumference of Ion Ring, the entire fill of ions is cooled with its final line charge density.

Stack in Cooler until IBS lifetime approaches cooling time.

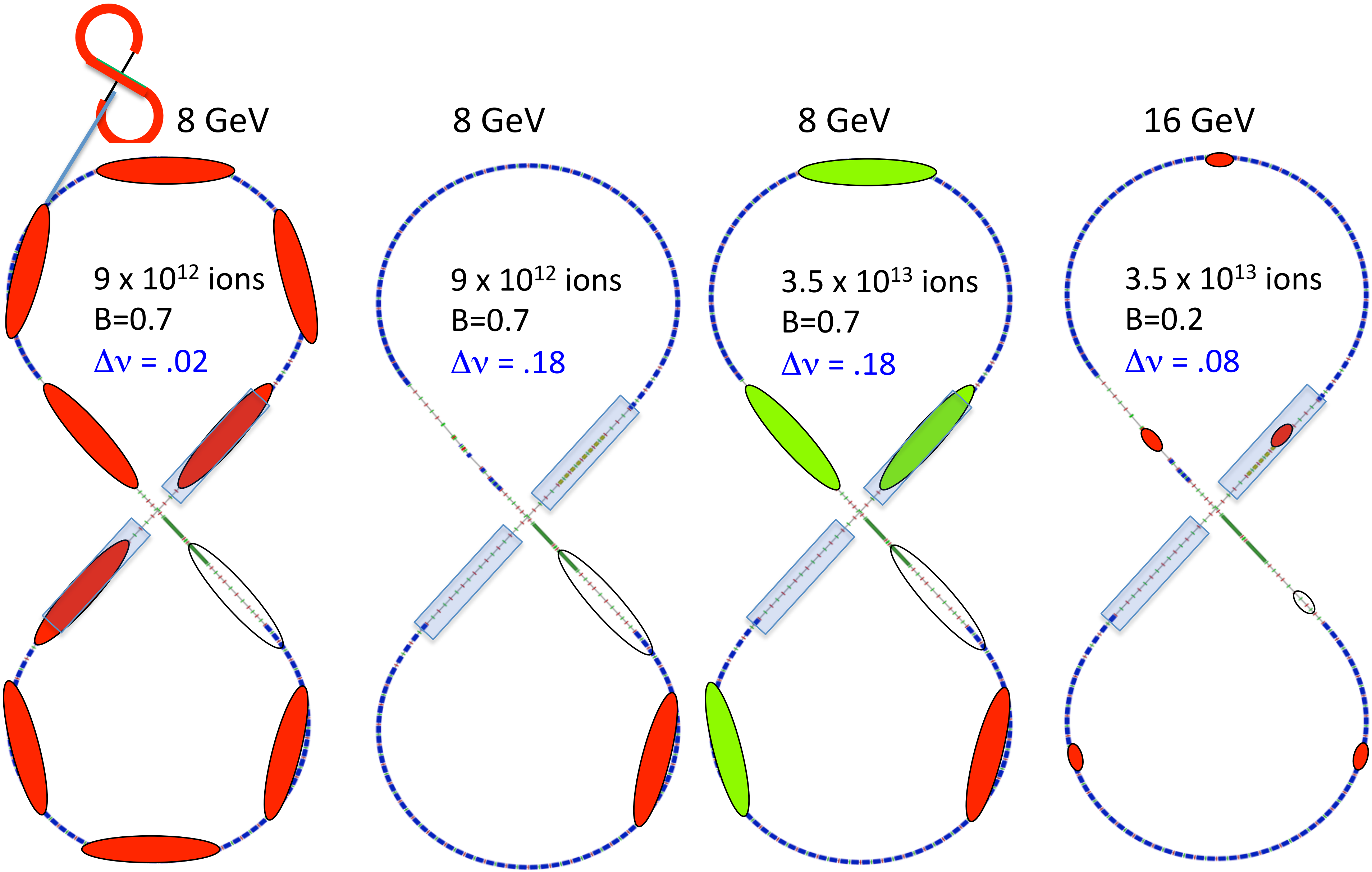
Then accelerate to 16 GeV (IBS time 4 times longer), continue to stack to >2 x 10^{14}.

Cooler and Stacker have twice the tune of the Ion Ring, so twice its γ_t.

Cooler and Stacker always operate below their γ_t (24 GeV).

Stacker transfers to Ion Ring at 16 GeV, above its γ_t (12 GeV).

So ion beam is never accelerated through transition.



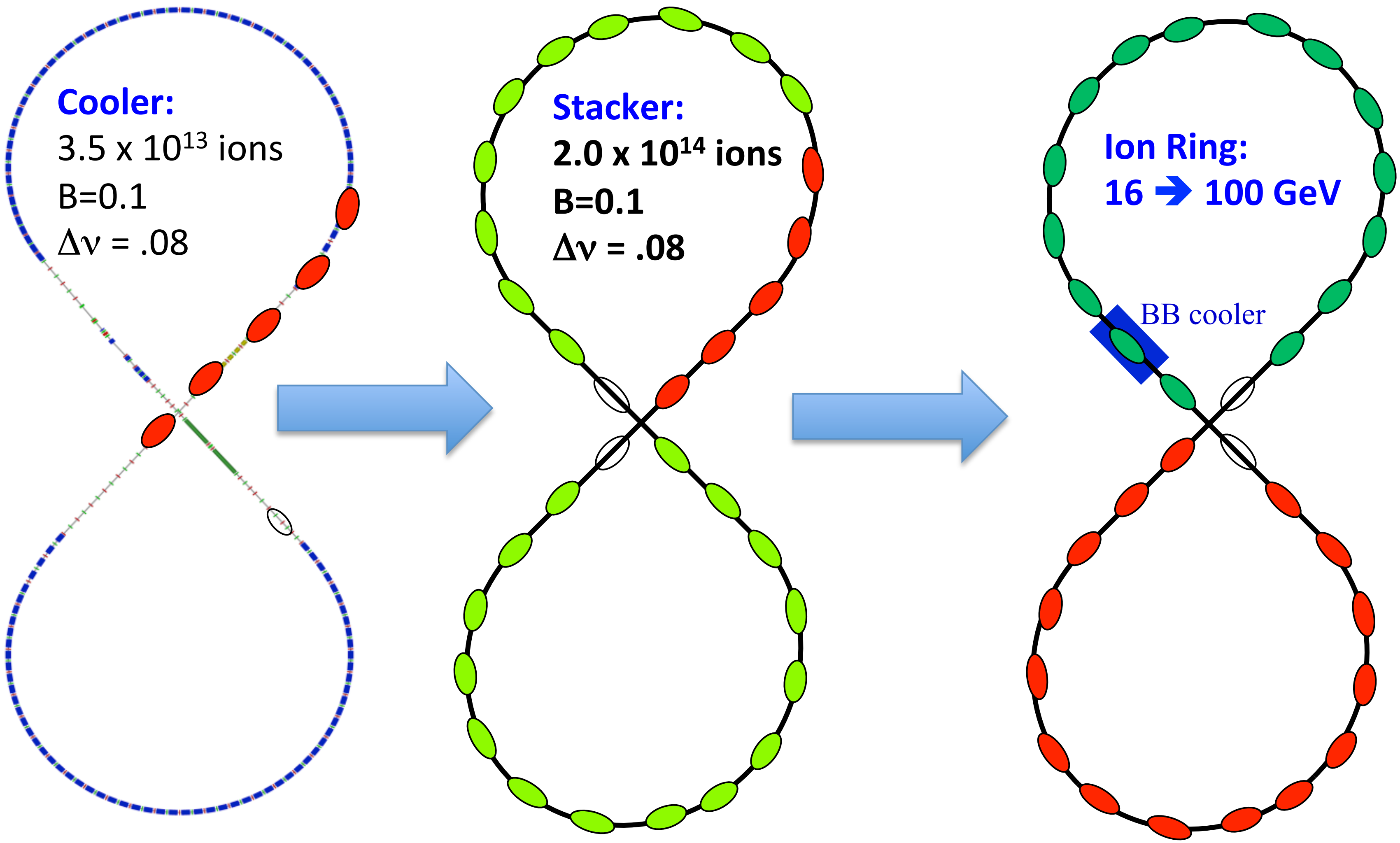
1.E-cool 9 h=1 Booster bunches into h=10 Cooler.

2.Cool and coalesce 9 bunches to 1.

3.Repeat the process, accumulate 8, 7, 6, 5 more Booster bunches.

4.Accelerate to 16 GeV, increase RF to make short bunches.

Bottom line: We can stack 8x more ions at 16 GeV in the Stacker



5. Cog bunches using slip-stacking RF.

6. Transfer bunch string to Stacker. Repeat 1-4 six times.

7. Transfer full aperture to Ion Ring, do 2^n e-bunching, accelerate, collide.

Three reasons to integrate the Cooler and Stacker in the Ion Ring cryostat

- 8x more ions for same SC tune shift as MEIC baseline.
- Bunches never pass through transition. Space charge forces spread bunch below transition. With C/S we stack/compress bunches at 16 GeV.
- All number-related limits also scale strongly with energy: IBS ($1/\gamma^2$), longitudinal instabilities ($1/\gamma$).

But now a caution: In doing slip-stacking at 16 GeV below transition in the Cooler, the *slip-factor* $\eta_c = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}$ is *positive*, so the non-linear forces from space charge act to *lengthen the bunch*. Cons did experiments on this at Fermilab. It may be necessary to add higher-harmonic RF to stabilize the slip-stacking.

I need the support of the collaboration if we are to be able to develop these ideas further…

- We are collaborating with RadiaSoft in an SBIR to simulate the ~4 MeV electron beam for magnetized neutralized cooling.
  - We need MEIC endorsement for their 10/19 submission.
- I am preparing a proposal to NP division for support under their university accelerator R&D program.
  - I need MEIC endorsement for my presentation to DOE at their 11/12 Germantown meeting.

And so the question: does MEIC see the potential value of the Cooler/Stacker that we see?

If so, I need your support.