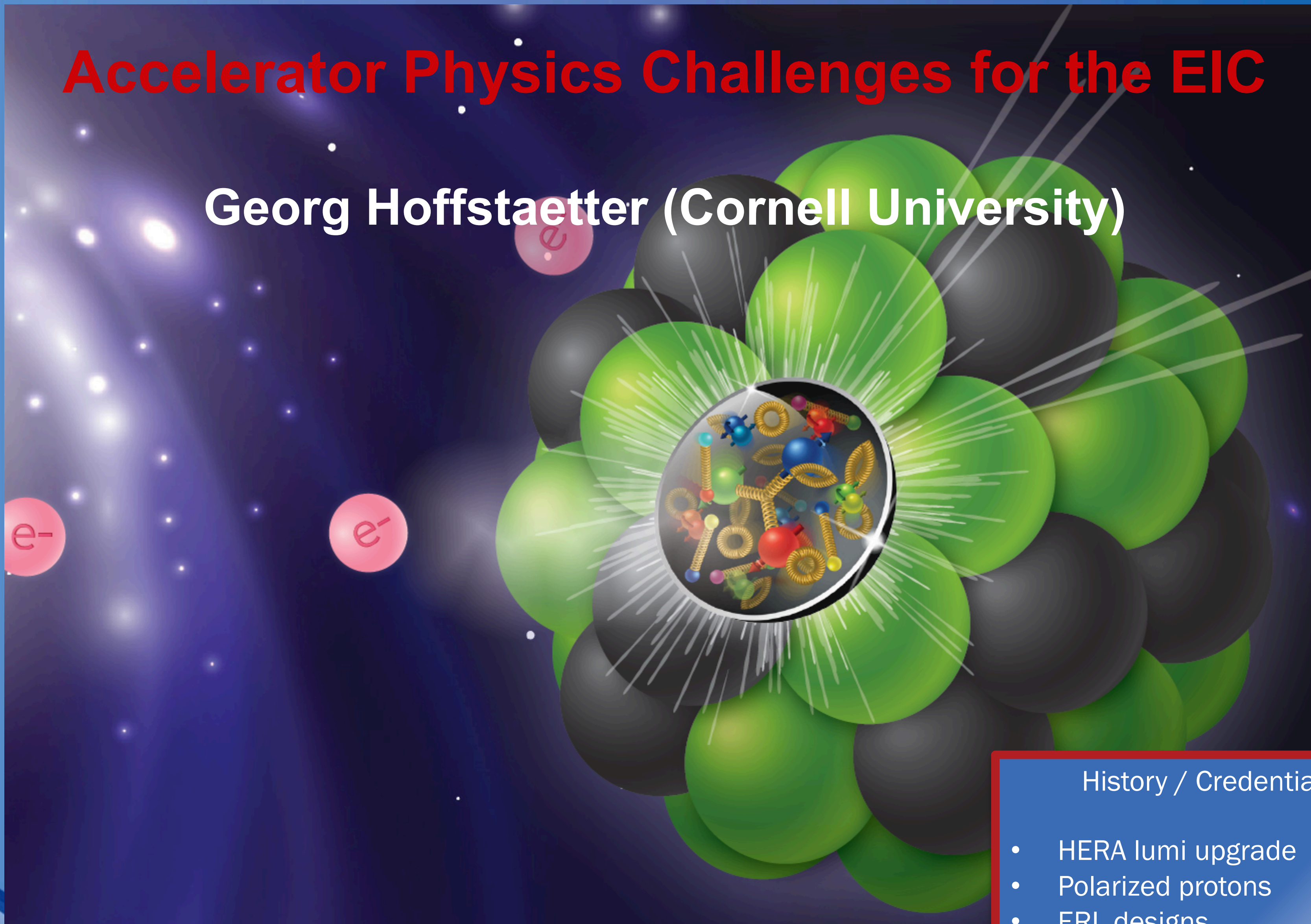
Accelerator Physics Challenges for the EIC

Georg Hoffstaetter (Cornell University)



History / Credentials

- HERA lumi upgrade
- Polarized protons
- ERL designs
- SRF linacs
- CBETA high-current ERL
- BNL/JLAB/LHeC groups

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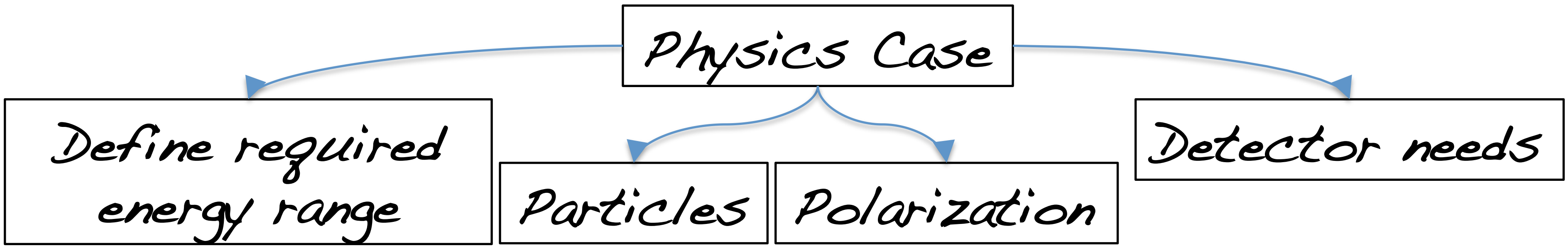
Tim Hallman: This ship is ready to sail

Louis Vuitton Foundation, by Frank Gehry

However the sails are made of glass.
So intricately designed in a wind channel that they can withstand any storm.

Designing an Electron Ion Collider



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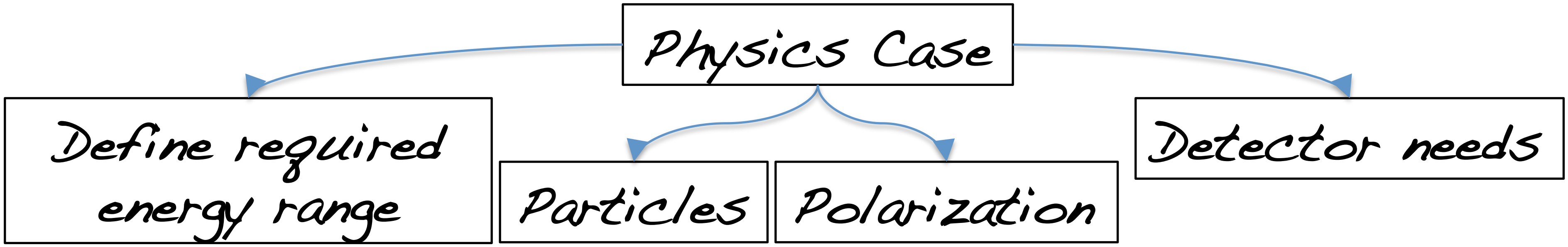

The EIC is designed to meet the requirements set forth in NSAC Long Range Plan, which was emphasized by the NAS report:

Highly **polarized** (~70%) electron and nucleon beams
Ion beams from **deuterons to the heaviest nuclei** (uranium or lead)
Variable center of mass energies from ~20 - **~100 GeV**, upgradable to **~140 GeV**
High collision luminosity ~10^{33} – 10^{34} $cm^{-2}s^{-1}$
Possibilities of having **more than one interaction region**

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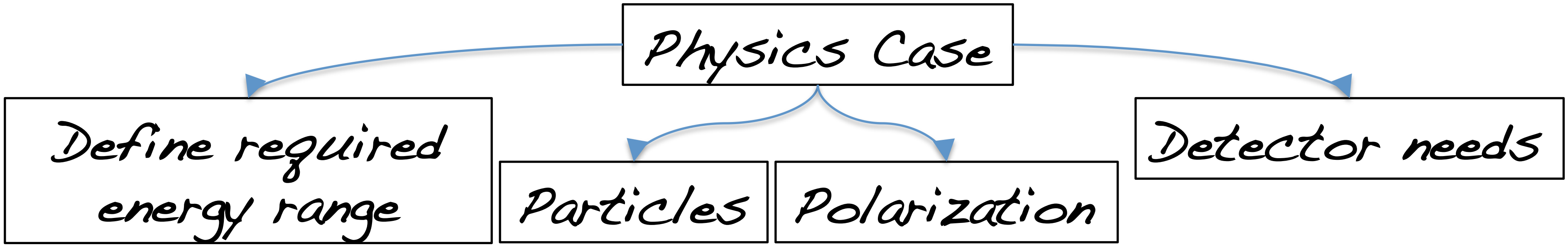


U.S. DEPARTMENT OF ENERGY | Office of Science

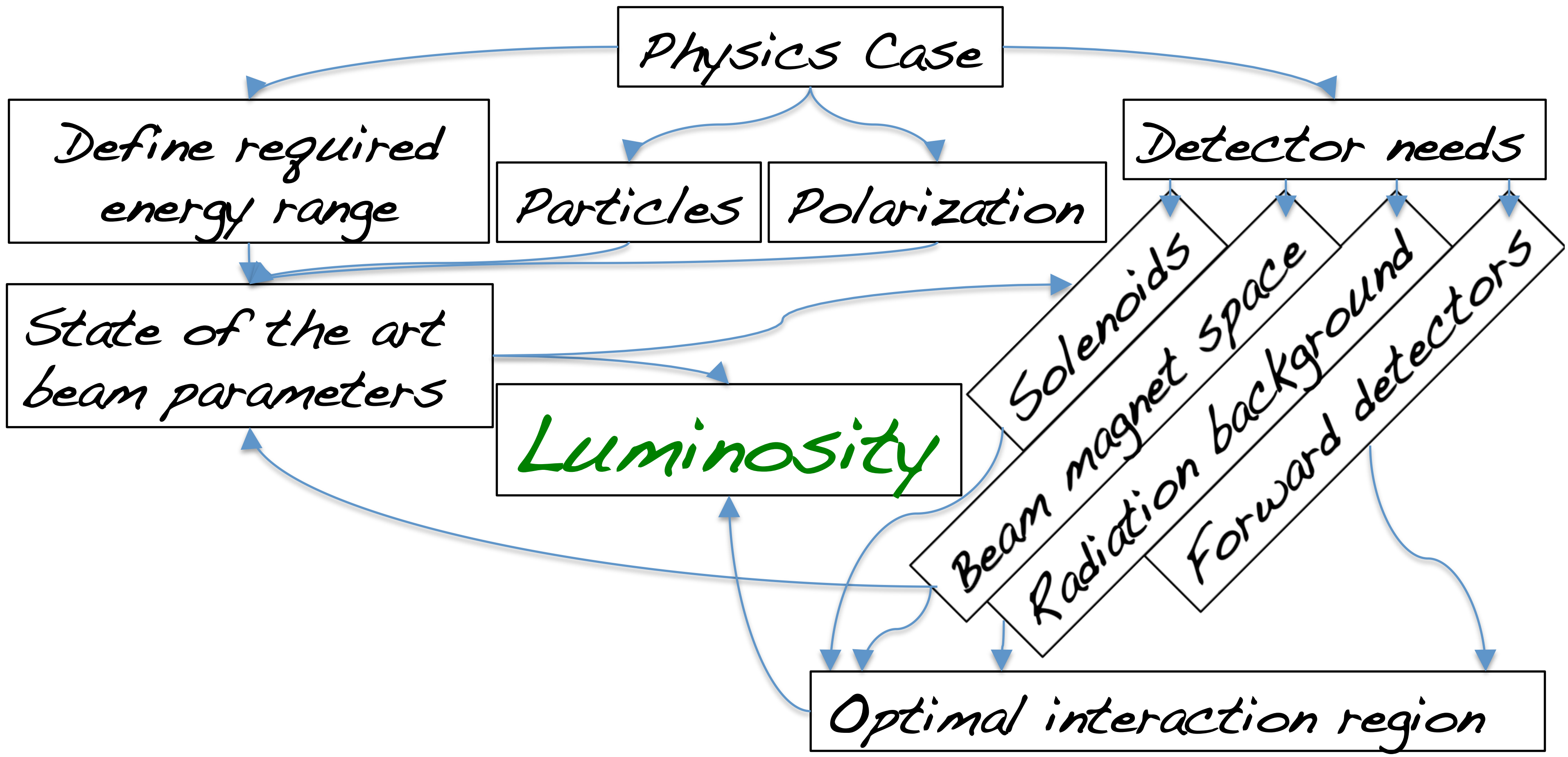
Technical Challenges for EIC

EIC will be one of the most complex collider accelerators ever to be built. It will push the envelope in many fronts including high degrees of beam polarizations, high luminosity, beam cooling, beam dynamics, crab cavities for both beams, and an interaction region with complex magnets.

DOE Support to EIC Accelerator R&D and FOA Landscape

Manouchehr Farkhondeh
DOE Office of Nuclear Physics

Designing an Electron Ion Collider



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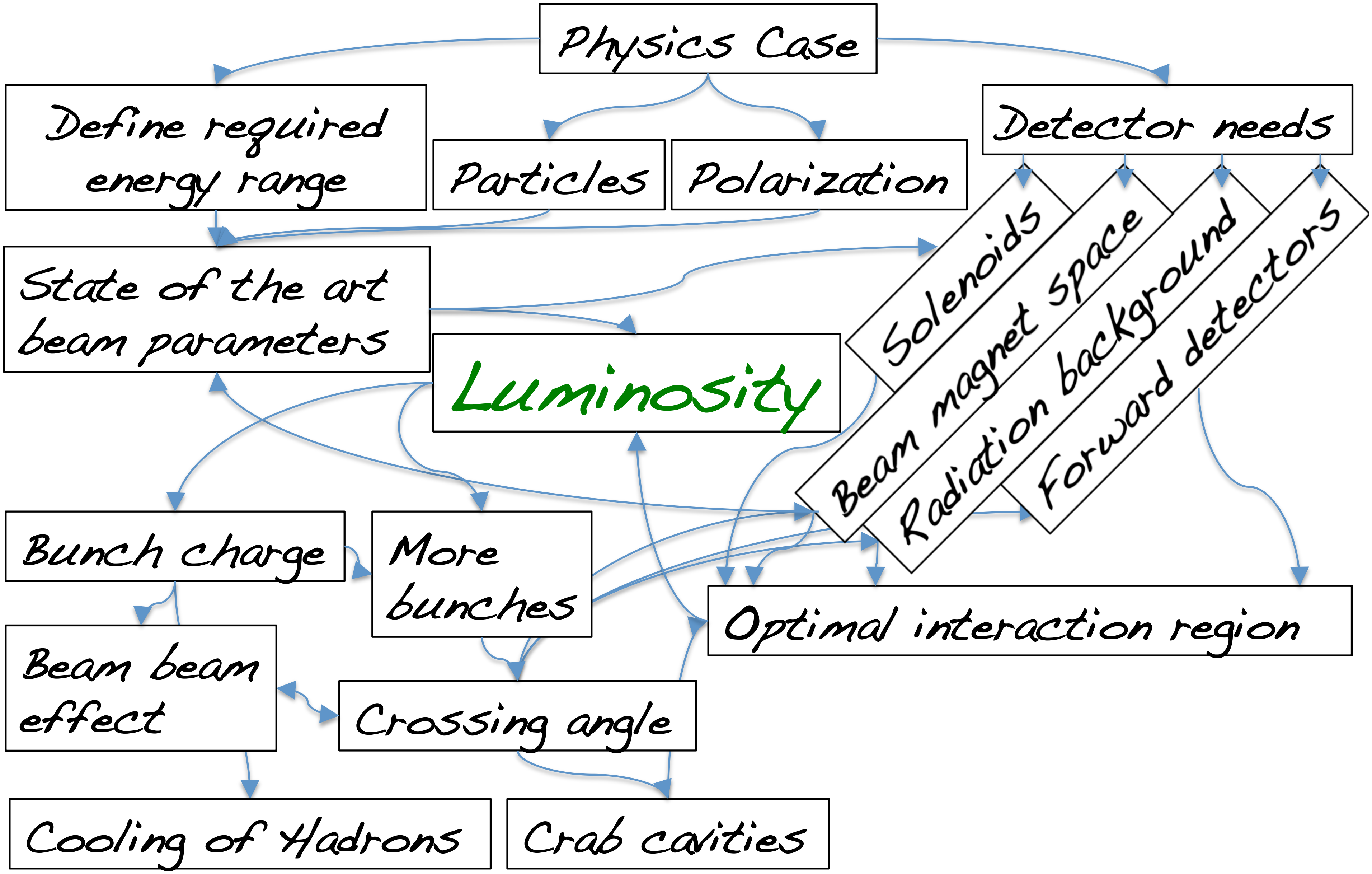
Designing an Electron Ion Collider



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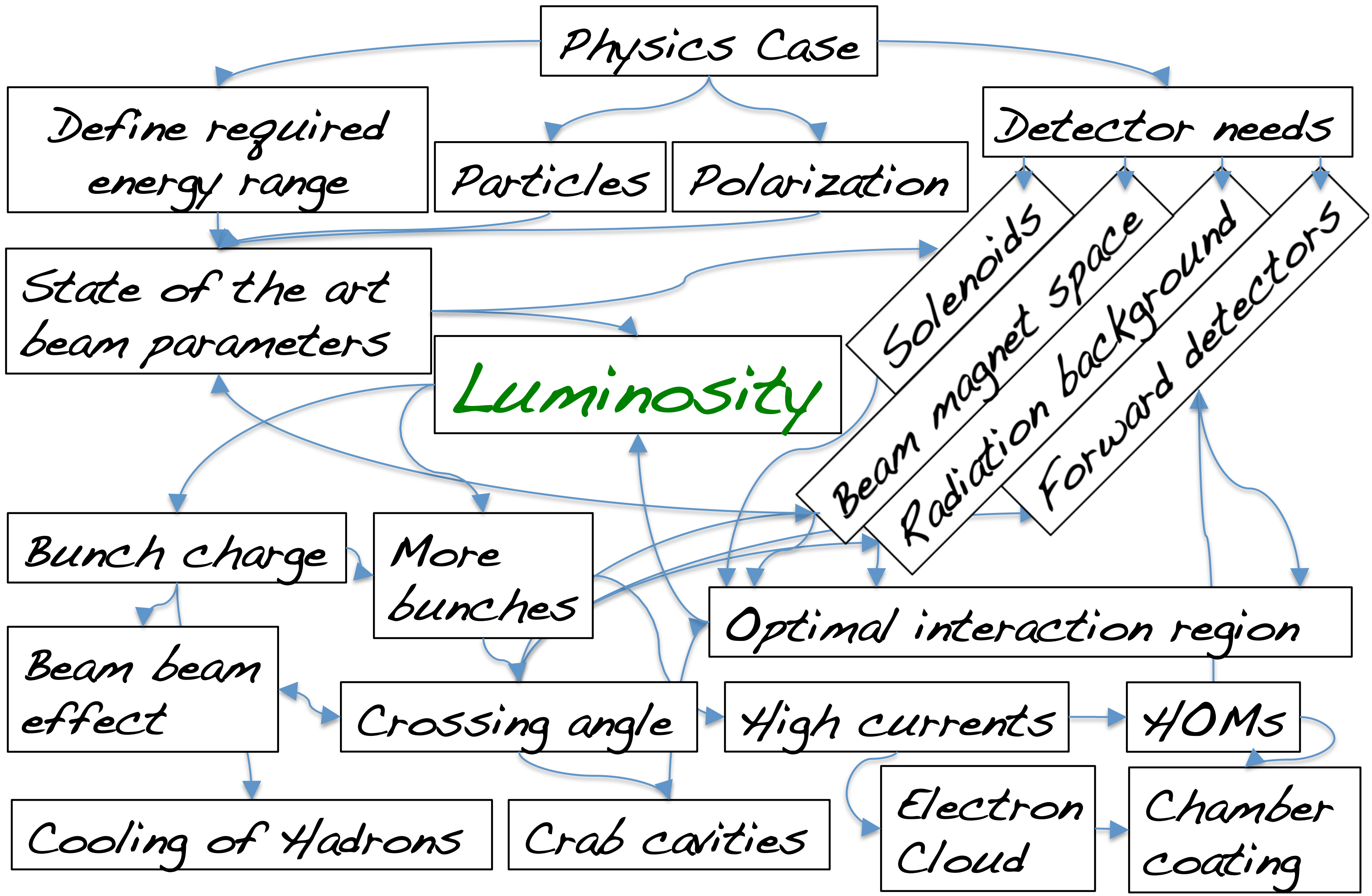

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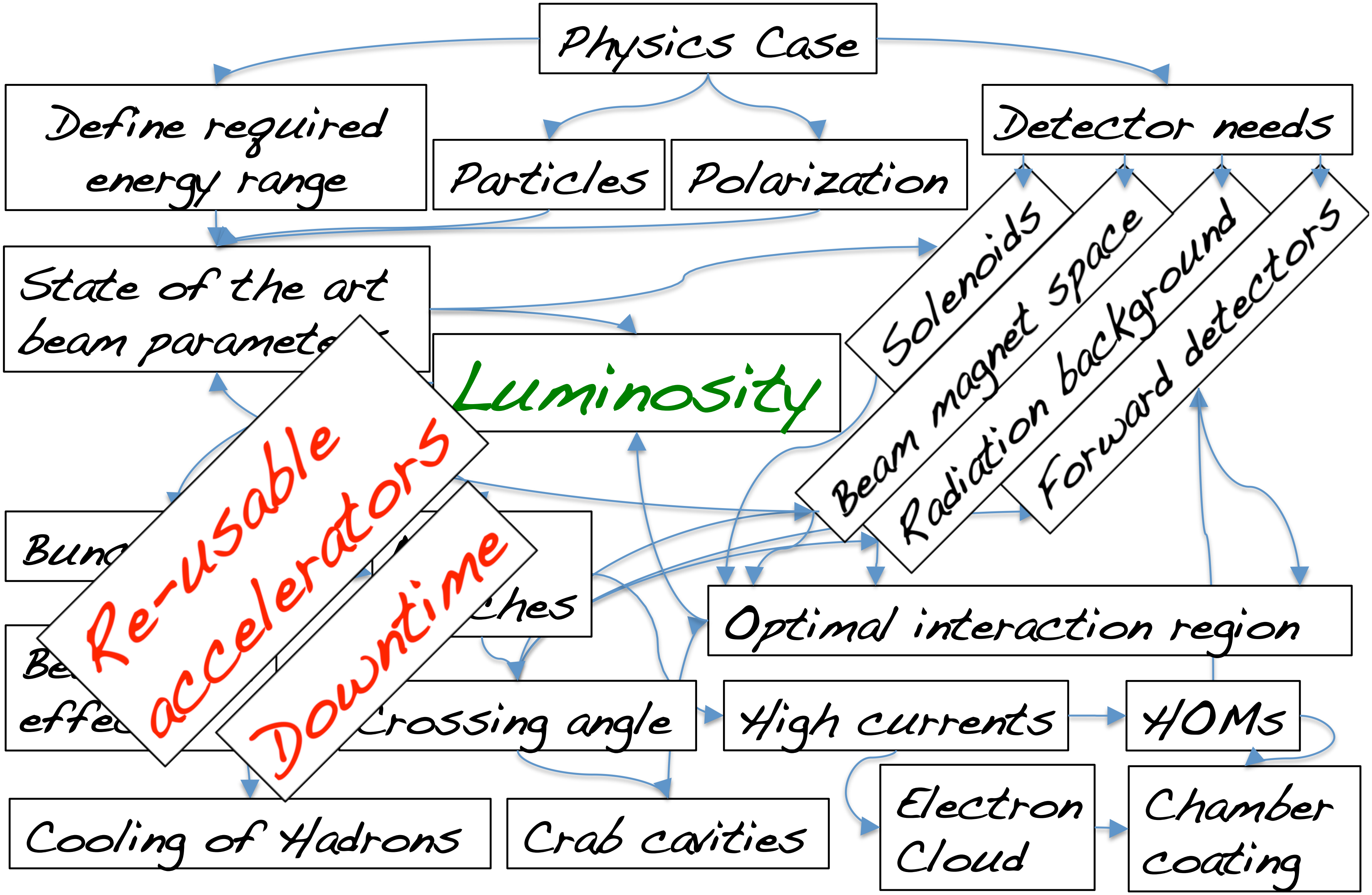
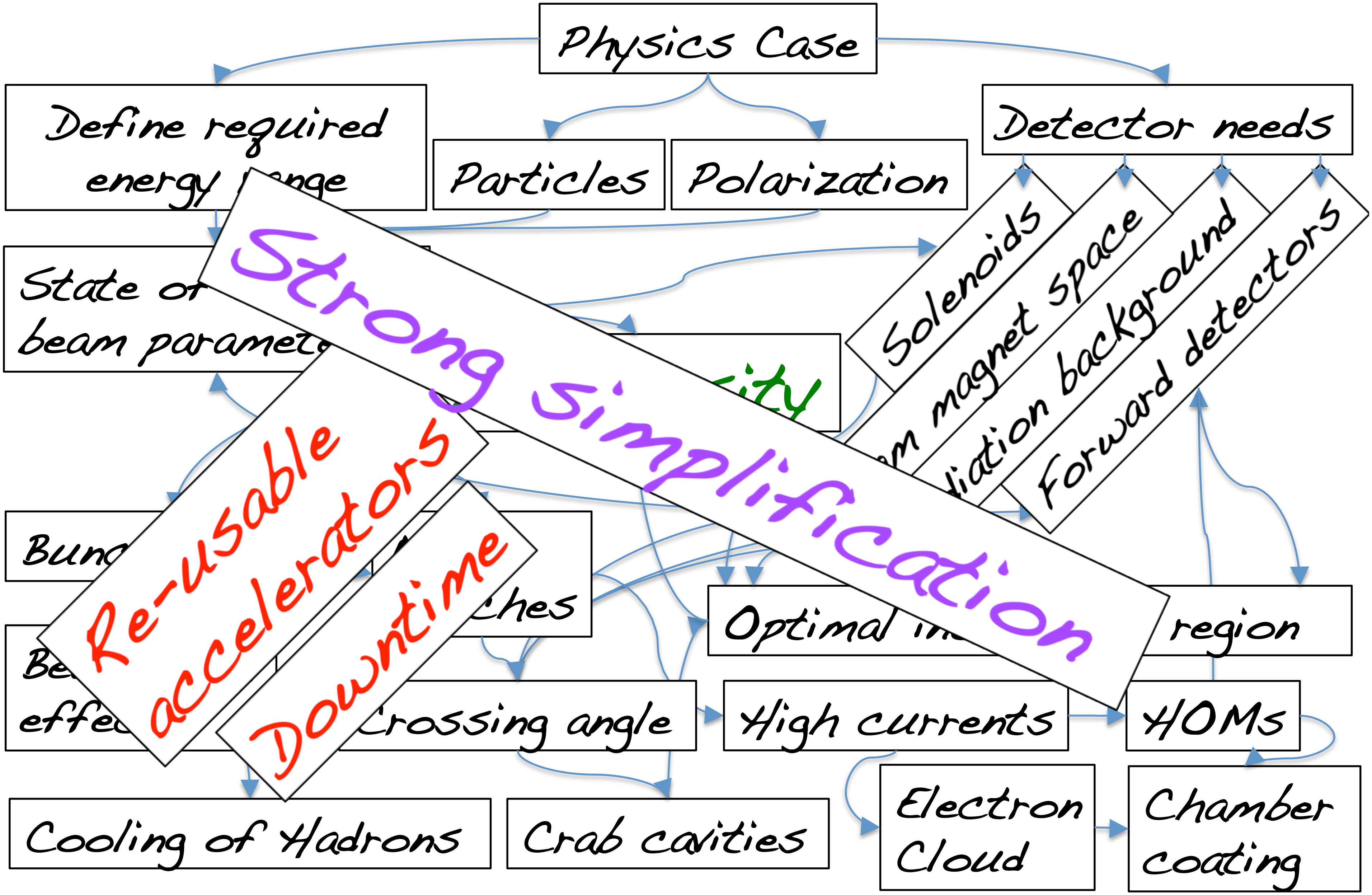


Designing an Electron Ion Collider



Lists of EIC accelerator challenges/opportunities

- The 2017 “Jones-Panel” Report was charged by DOE-NP to evaluate Challenges and R&D needs for an EIC.
- The 2015 NSAC and the 2018 NAS study on the EIC point out challenges and opportunities.

R&D suggestions of the **Jones-Panel** are still **quite up to date**, even though the designs have significantly changed in order to reach higher CM energy.

Good progress was made toward risk elimination:

e.g. avoidance of super-ferric magnets and of gear change for low energies.

and toward technology validation:

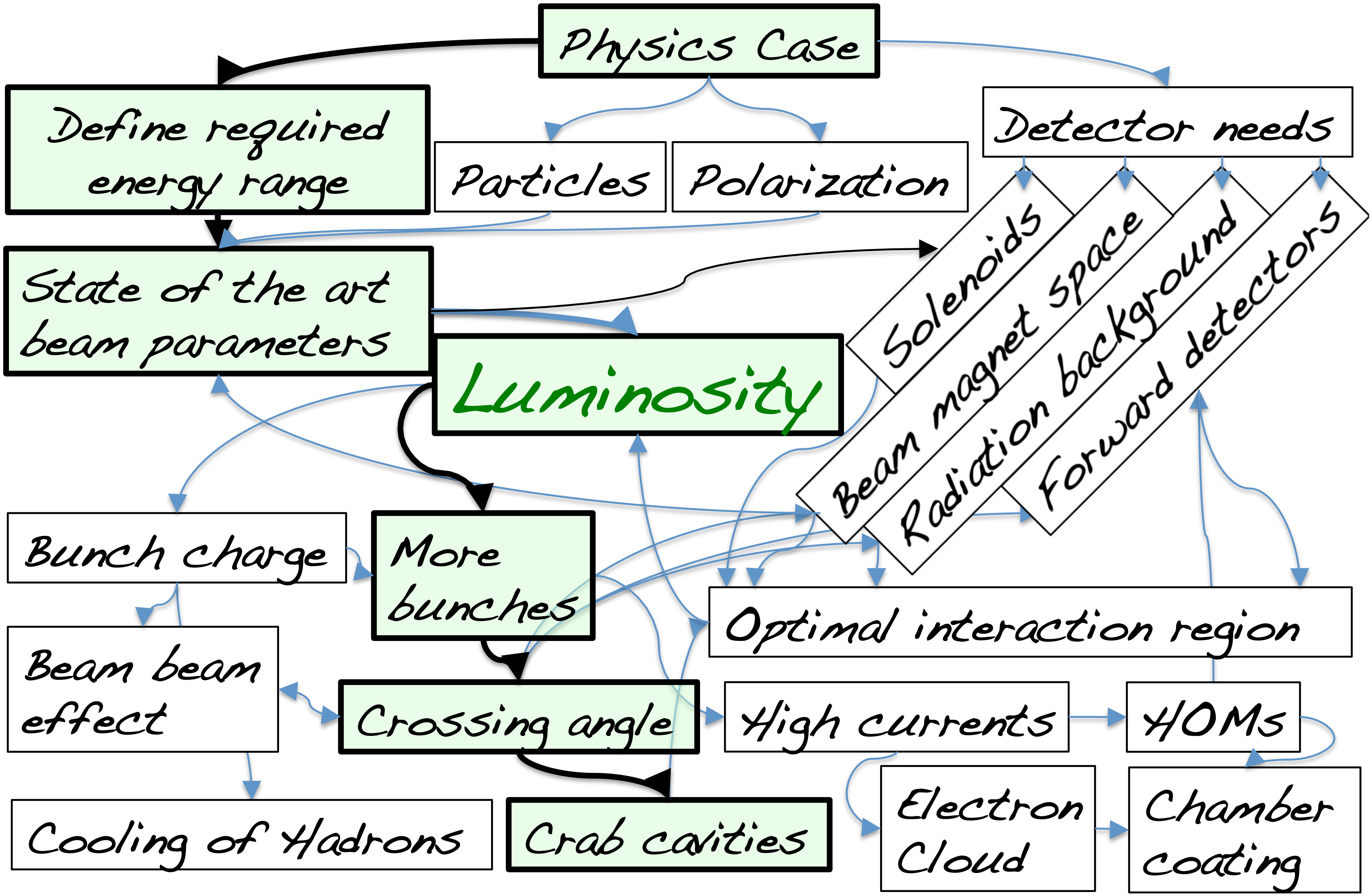
e.g. test of LHC crab cavities in the SPS.

This presentation will follow the threads of the dominant challenges, focusing on those

a) common to different designs, being genuine EIC challenges.

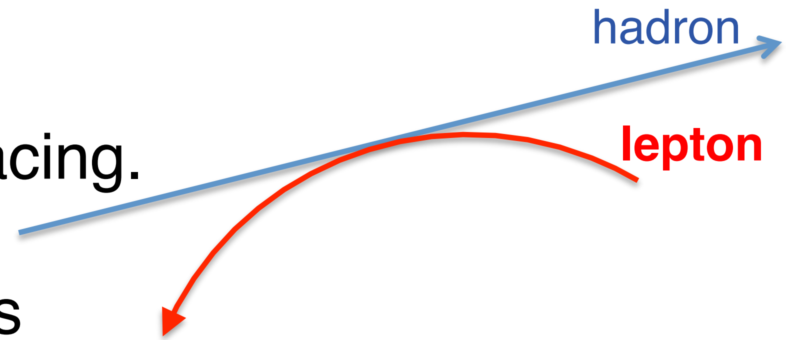
b) with not yet full experimental verification.

Designing an Electron Ion Collider



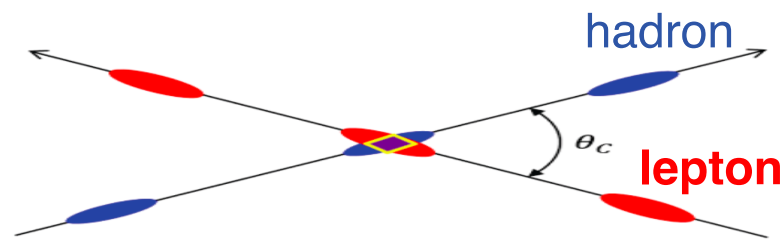
Crab Cavities

More bunches lead to more luminosity.



More bunches have smaller bunch spacing.

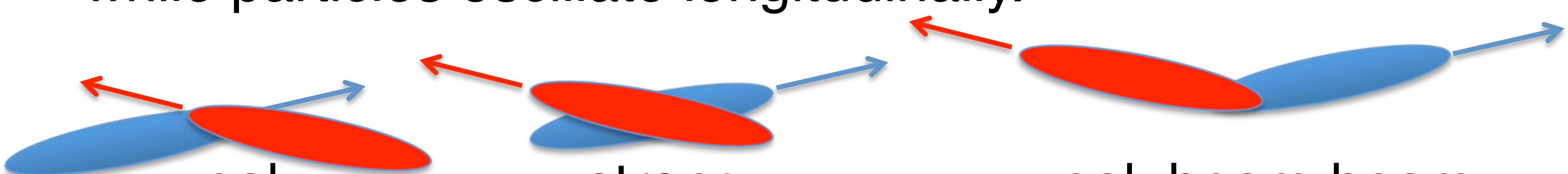
To separate electrons from the hadrons one would need magnets in the detector.



Solution: Crossing angle

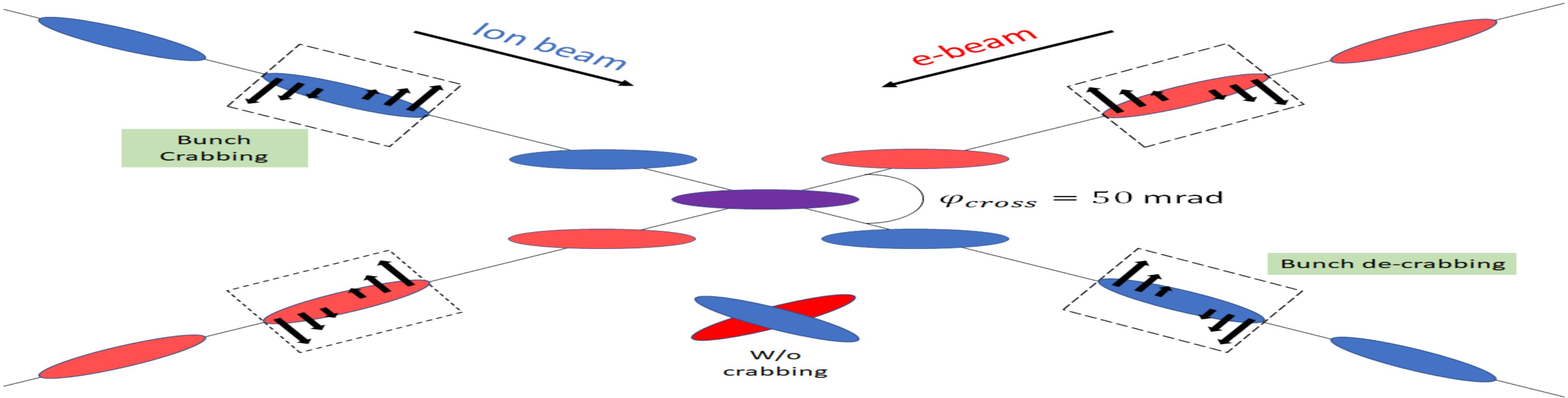
Drawback:

1) Luminosity loss: Bunches don't fully overlap.
2) Resonances: beam-beam force changes along the bunch while particles oscillate longitudinally.

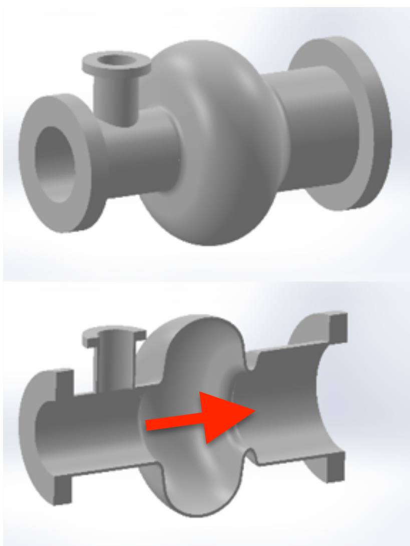


weak - strong - weak beam-beam

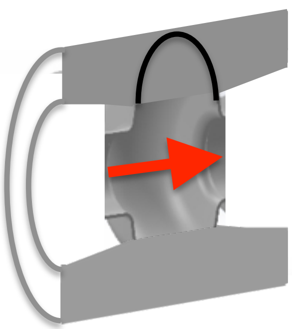
Solution to Crossing angle: Crab cavities



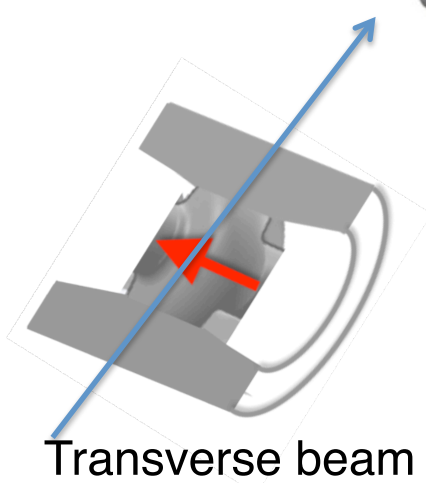
How to make a transverse mode (crab) cavity ?



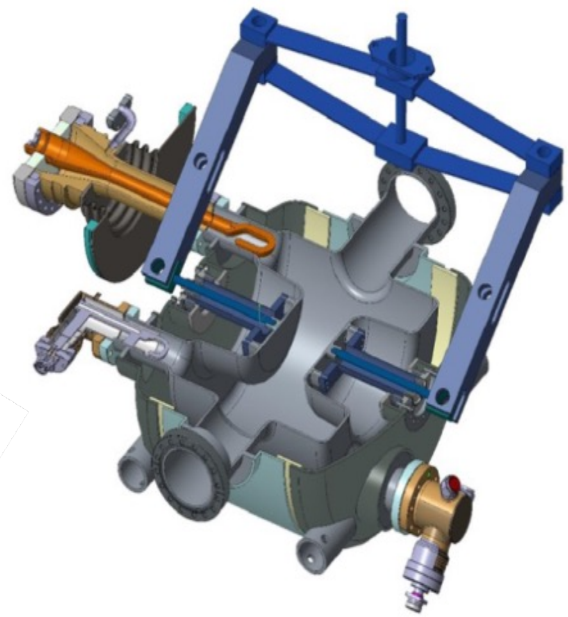
Accelerating cavity



Reentrant cavity



Transverse beam



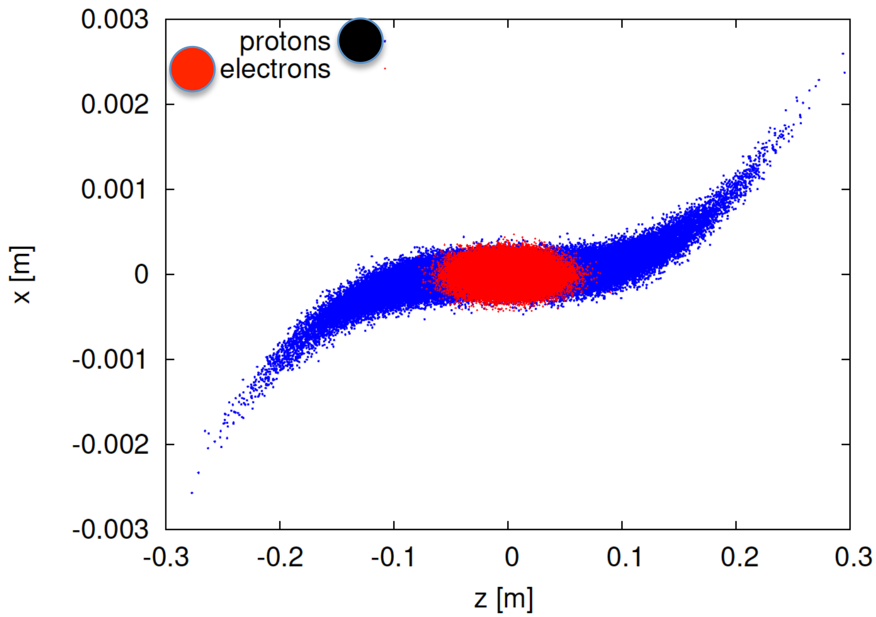
Technical realization

The Crab Cavity Challenge

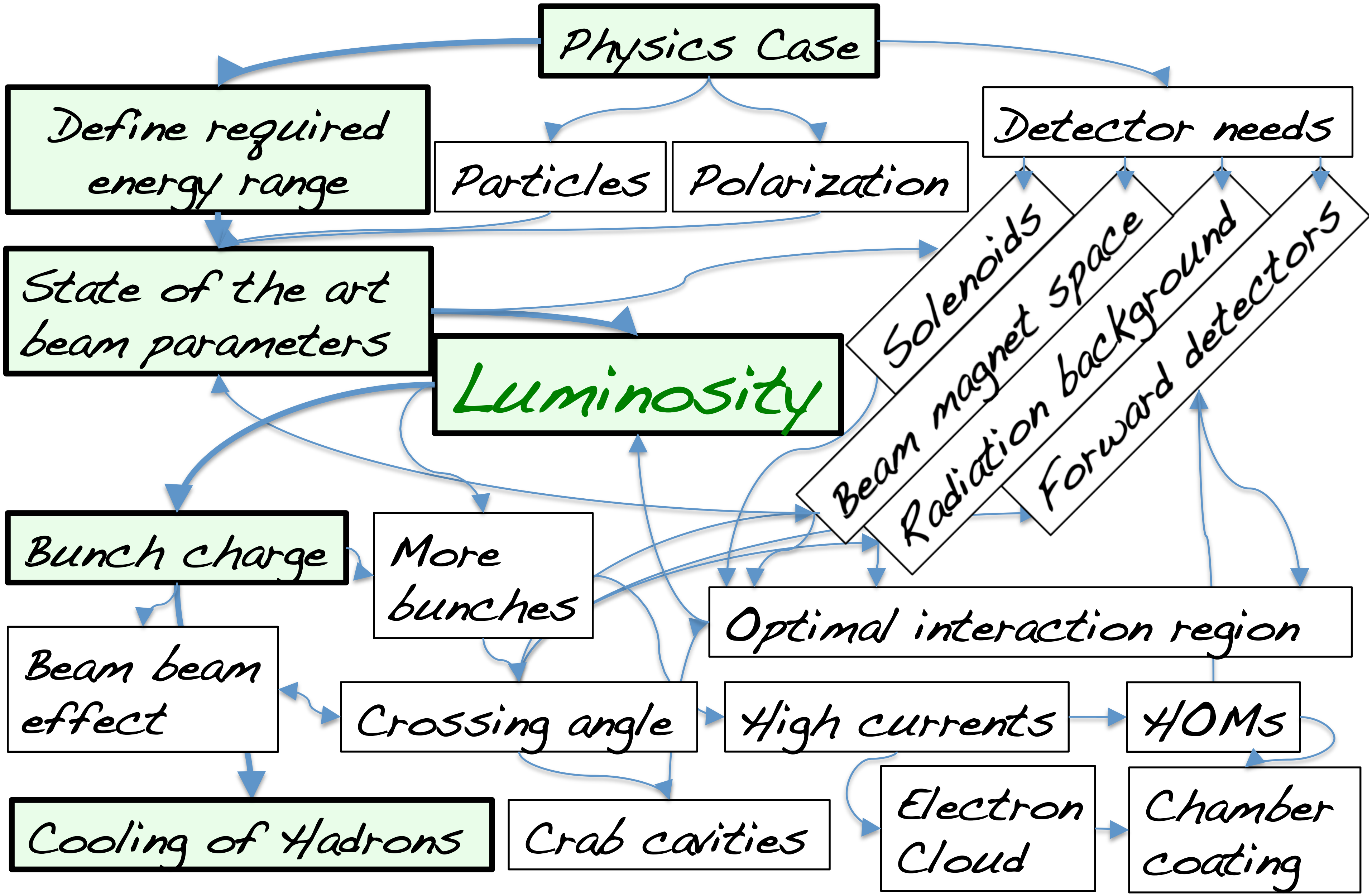
1) Crab Cavity Prototype: The LHC 400MHz crab cavity is an excellent prototype and was tested in the SPS.

2) Adjustments need to be made for different currents, HOMs, and frequency.

3) The behavior within a hadron collider has not been tested.
=> For example, the beam-beam force become asymmetric.



Designing an Electron Ion Collider



Hadron Cooling

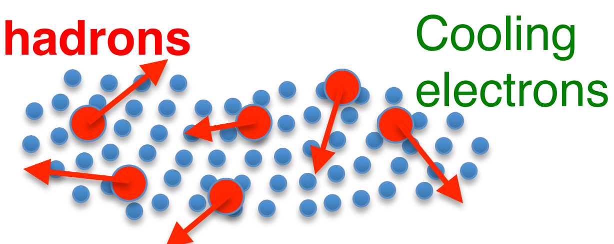
Higher bunch charges lead to more luminosity,
but also to more beam-size growth through internal scattering and nonlinear dynamics.

Solution: cool hadron beams or replace frequently.

Both 1.E34 luminosity designs need cooling.

(A) Scattering Cooling:

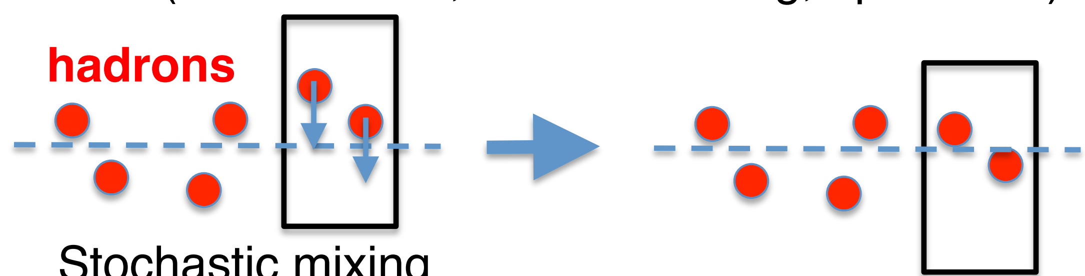
(both magnetized or not, and storage ring cooling)



In the rest frame of both beams

(B) Stochastic cooling:

(Coherent eC, micro bunching, optical SC)



Stochastic mixing of who is in the slice.

Correct the dipole moment of slices.

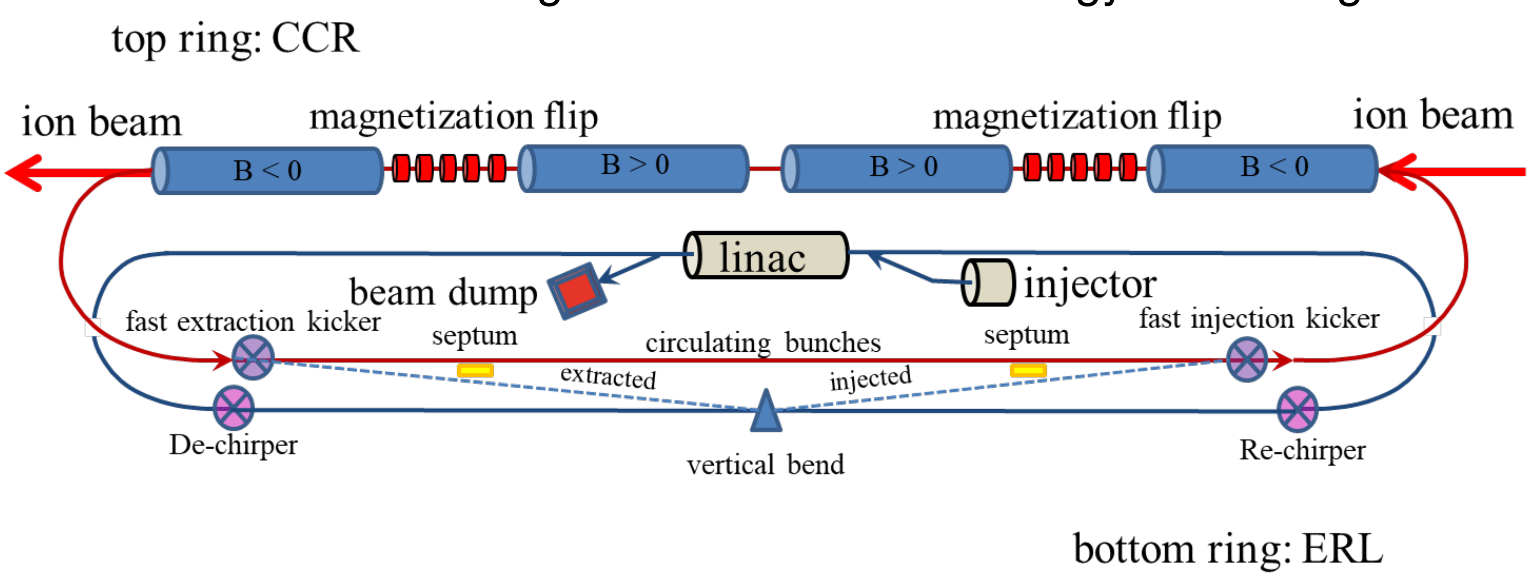
The correcting kick is done by an electron beam.

High Electron Currents are needed

Both cooling methods need **very high current** electron beam with **very little divergence** to be effective.

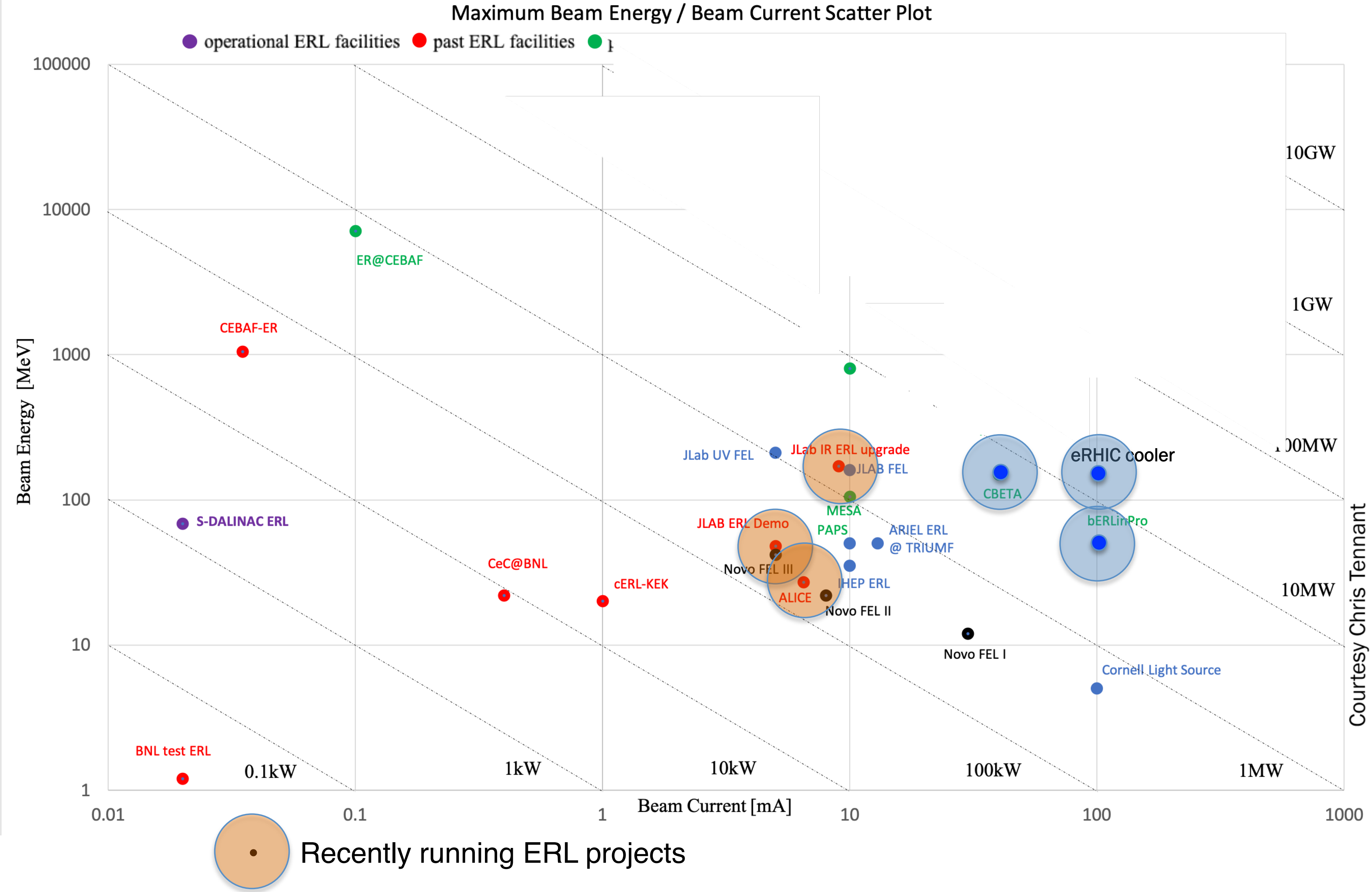
As the NAS study maintains, such beam can only be produced by Energy Recovery Linacs (**ERLs**)

(A) Scattering cooling with keeping electrons parallel in a B field: **1 Ampere**
Fast harmonic kicker fills a ring for 11 turns before energy recovering that beam.



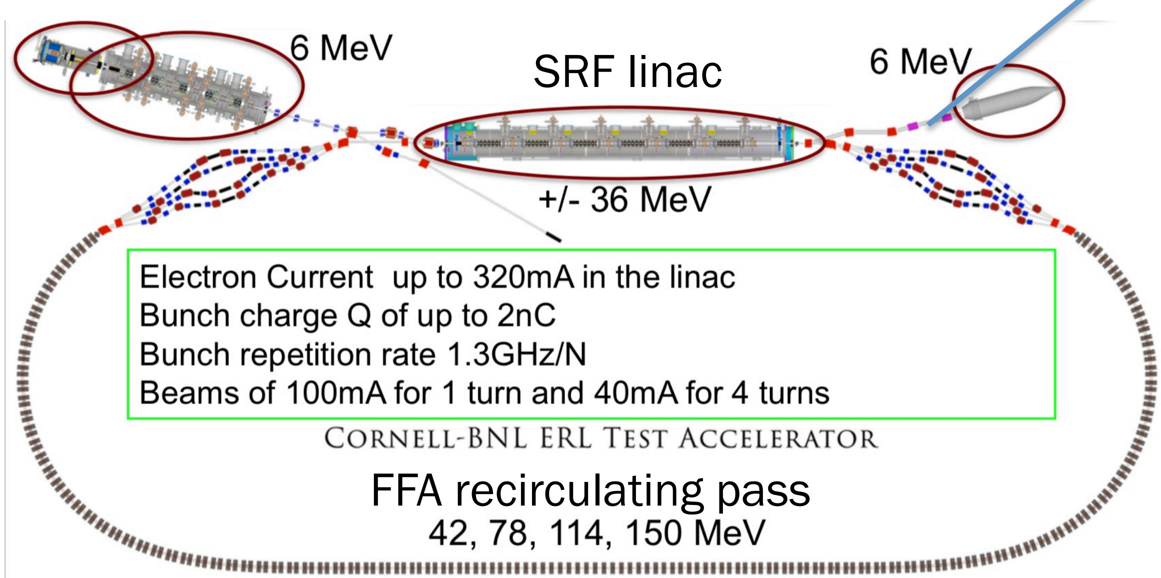
(B) Stochastic cooling has designs for : **0.1 Ampere of the 150MeV beam => 15MW**
Factor of 10 more than what was done before.

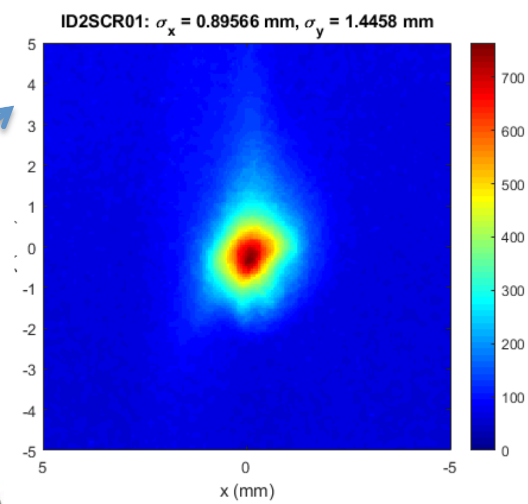
The beam power frontier



Cornell-BNL ERL Test Accelerator

- At least 100 mA current will be needed for eRHIC hadron cooler (design limit for 1-turn CBETA)
- BNL and collaborators gained and demonstrated expertise in high-power ERLs
- Successful operation, including energy recovery in each cavity (June 24^{th}, 2019).
- Full 4-turn construction is underway.





First energy-recovered beam spot @ CBETA

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CBETA installation at Cornell
Magnet work at BNL before transport to Cornell

CBETA

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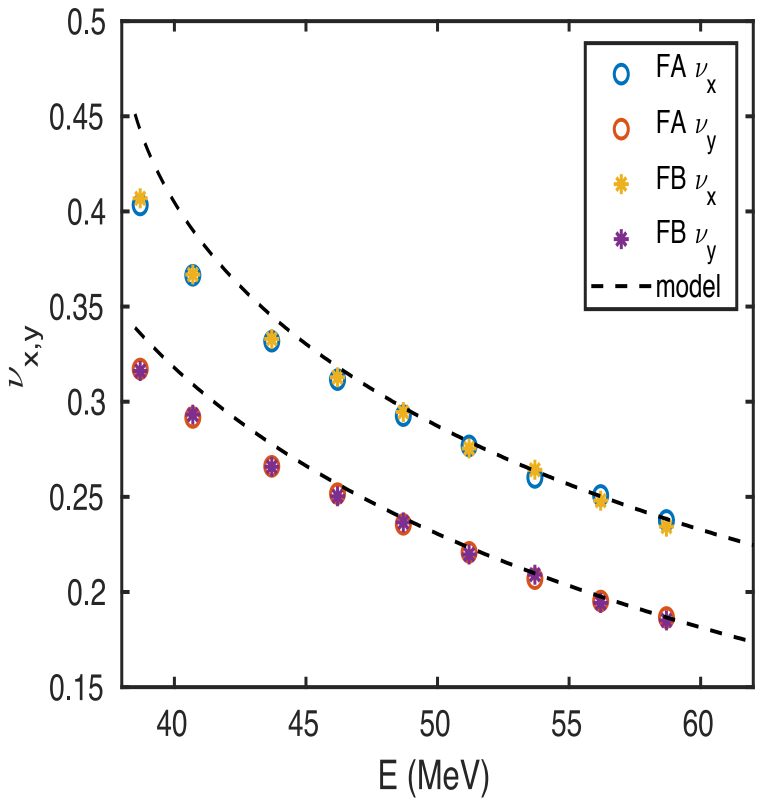
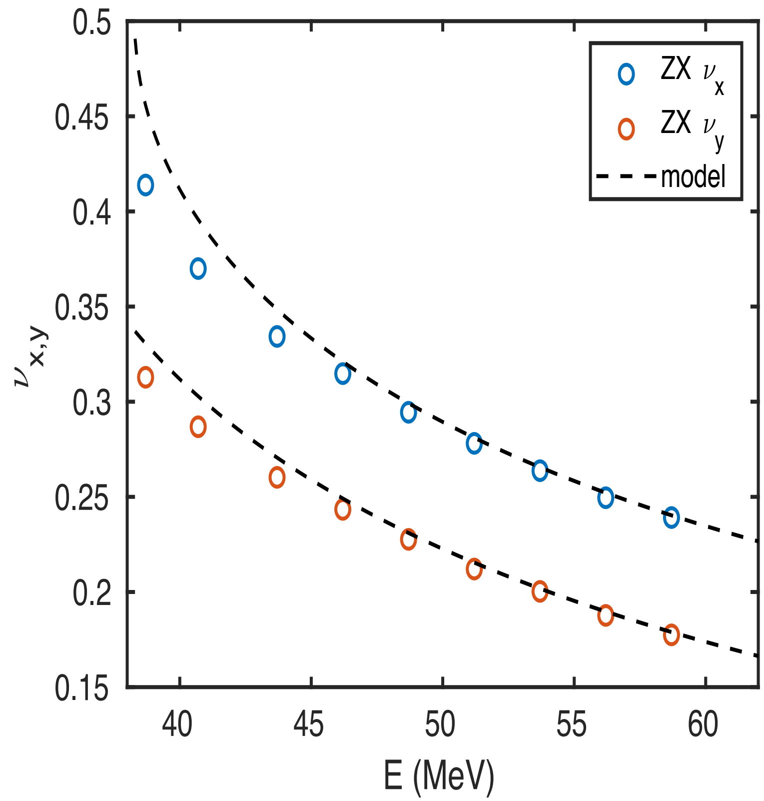
High acceptance lattice

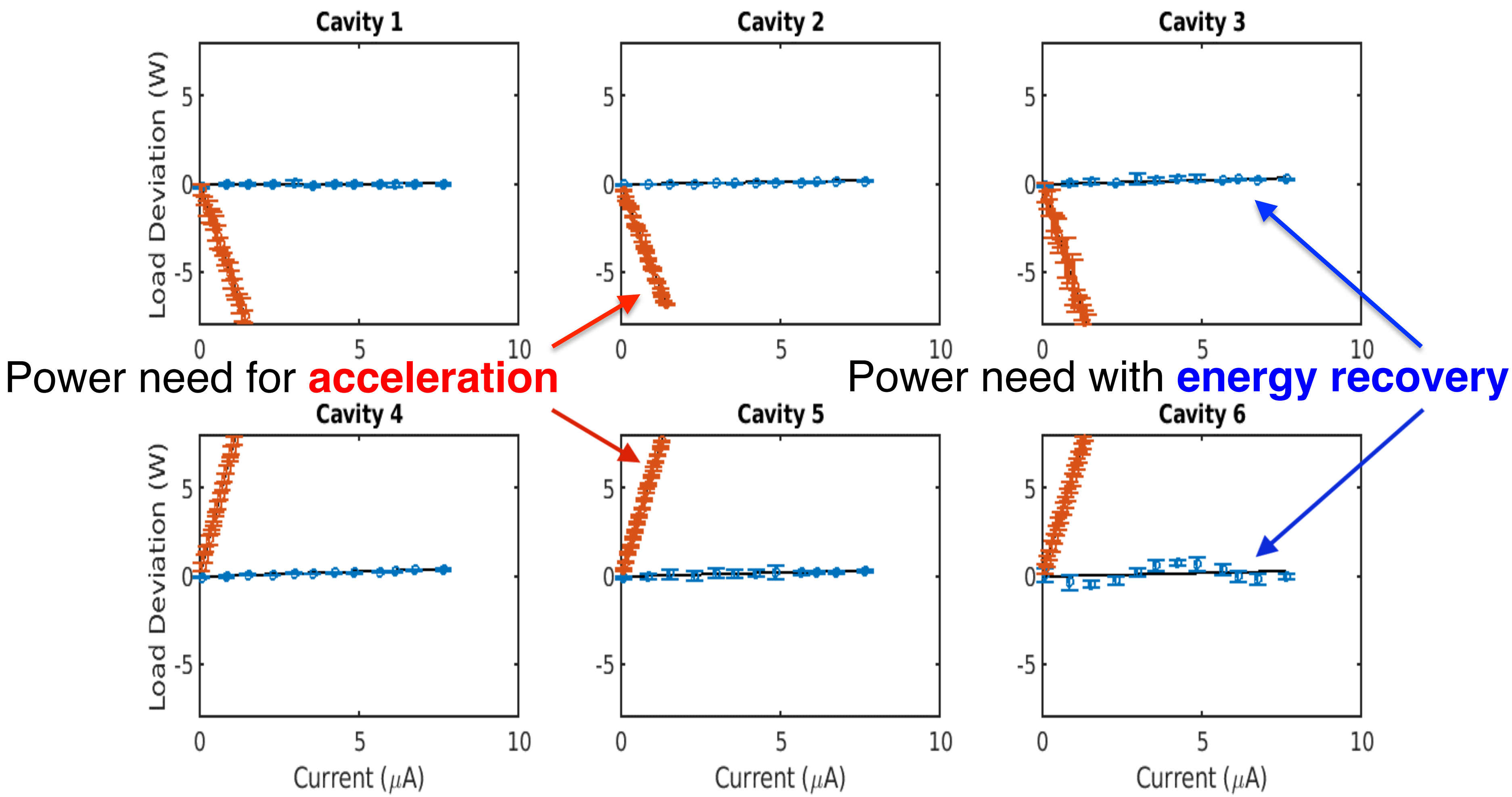
- Beam energy into the permanent magnet arc: 39 - 59 MeV (same B field)
- Energy dependent phase advances agrees well with the model
- Permanent magnet region is very clean - beam losses are hardly measurable, far dominated by other regions.





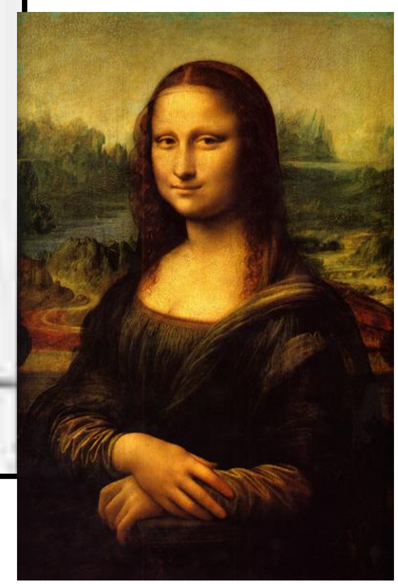
Energy Recovery in every cavity

- Transmission 99.6 ± 0.1% ; energy recovery > 99.8%
- Measured up to 8 μA
- Each cavity accelerates beam **without** receiving **external power** for it.



A good idea … ?

Leonardo da Vinci
(1452-1519)
France from 1516

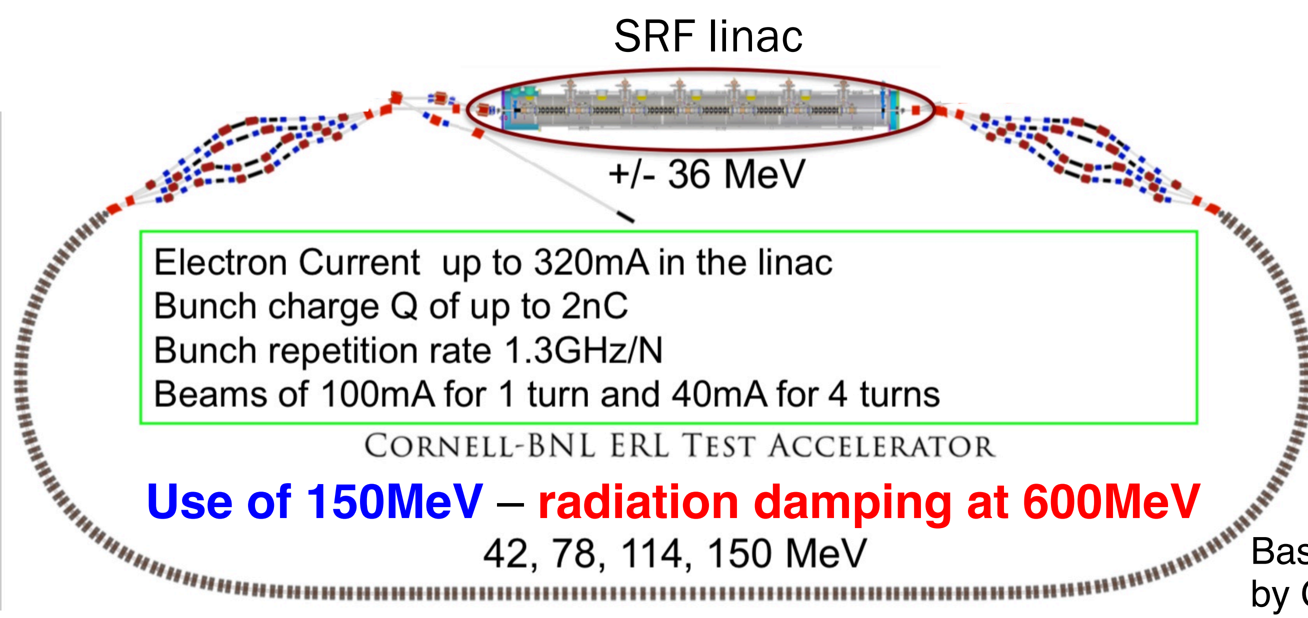


Weaker storage-ring cooling

Solutions without cooling have less luminosity,
e.g. 0.44E34 at BNL, and the luminosity decay becomes faster as well.

Weaker cooling (e.g. storage ring) could help to at least keep the luminosity constant at this level, e.g. by storage ring cooling.

New thoughts being discussed: Storage ring cooling could be increase by 1-2 orders of magnitude by increased damping in an ERL.



For 150MeV cooling, one would radiation damp at about 600MeV, with 64 times more radiation damping.

Based on a related idea by Geoff Kraft (JLAB)

Alternative to Cooling: Replace frequently

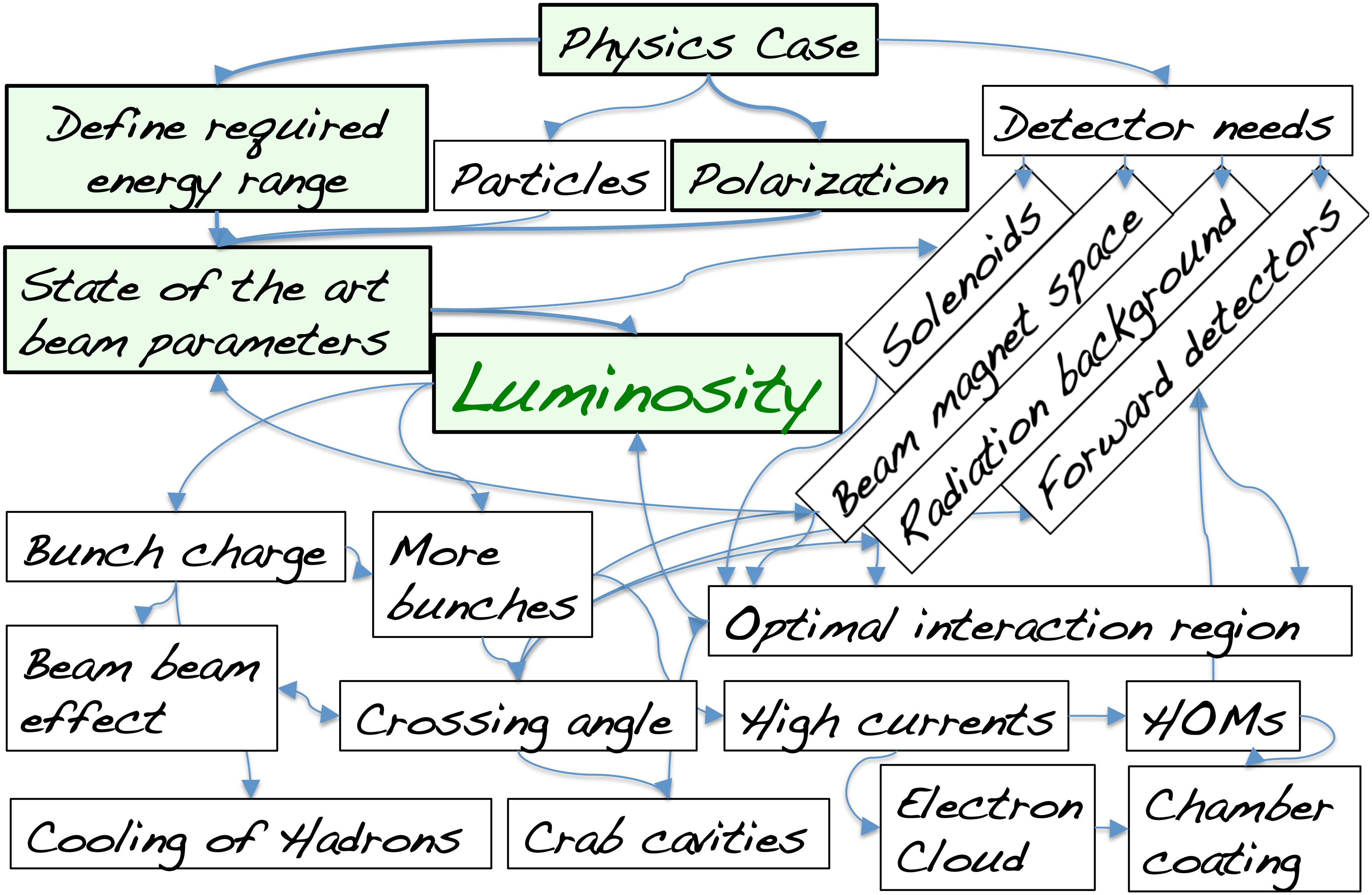
BNL and the JLAB designs have a backup where bunches are replaced frequently, at BNL through the spare ion ring.

Drawback: Detectors would need to be protected and need reduced voltage during each hadron injection.

The luminosity would suffer marginally, if a solution to the detector protection could be found.

But nevertheless, it is great to have a backup for cooling!

Designing an Electron Ion Collider



Proton, Deuteron, He3, and electron polarization

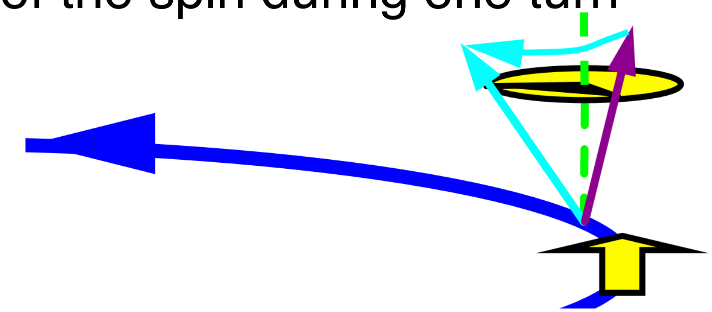
Polarization is hard to produce, hard to accelerate, and hard to maintain.

Problems and solutions are different for all 4 types of particles.

1) Source
a) Electrons: solved for high bunch charge. There is high current progress.
b) Hadrons: progress (as of presentation this morning)

2) Acceleration: Crossing resonances can cause depolarization

Spin tune: precessions
of the spin during one turn



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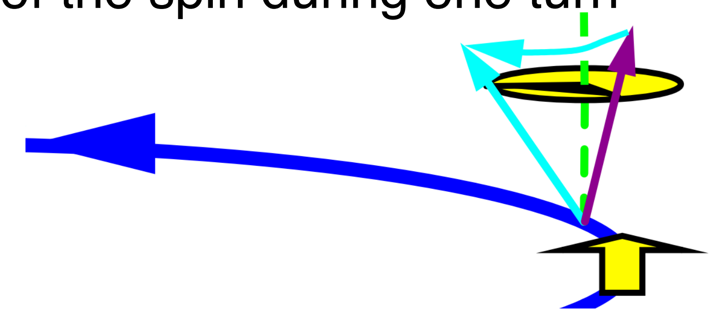

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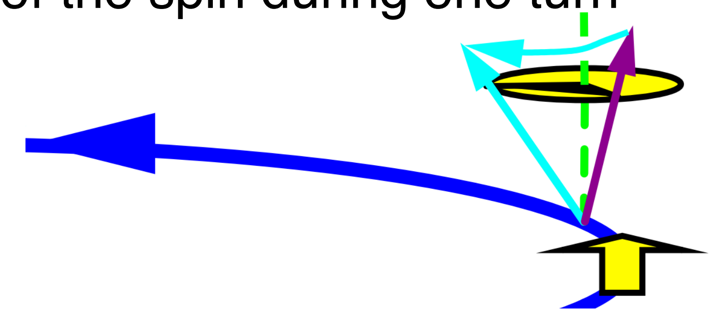

Spin as it returns every turn, i.e. in the **Poincaré section**

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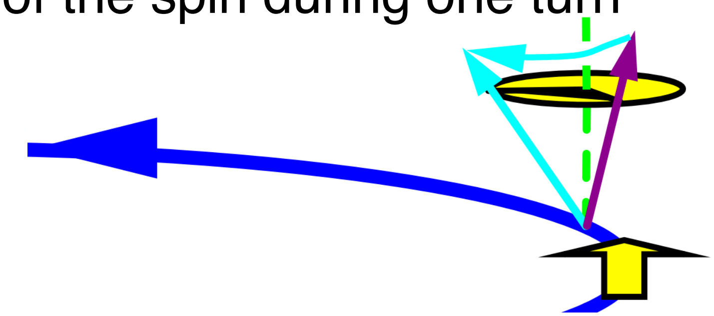
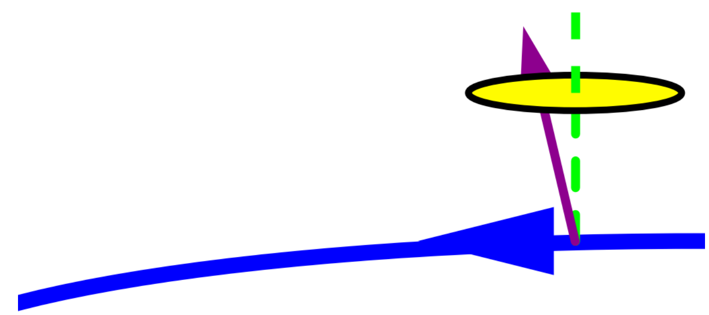


Problem: such cases can happen often during acceleration.
Solution: **Siberian snakes** or **Symmetries**

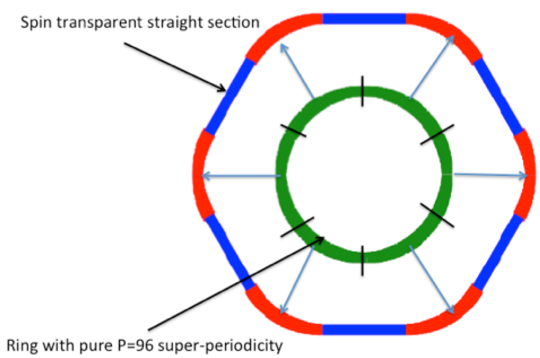
Spin tune = integer
No precession !

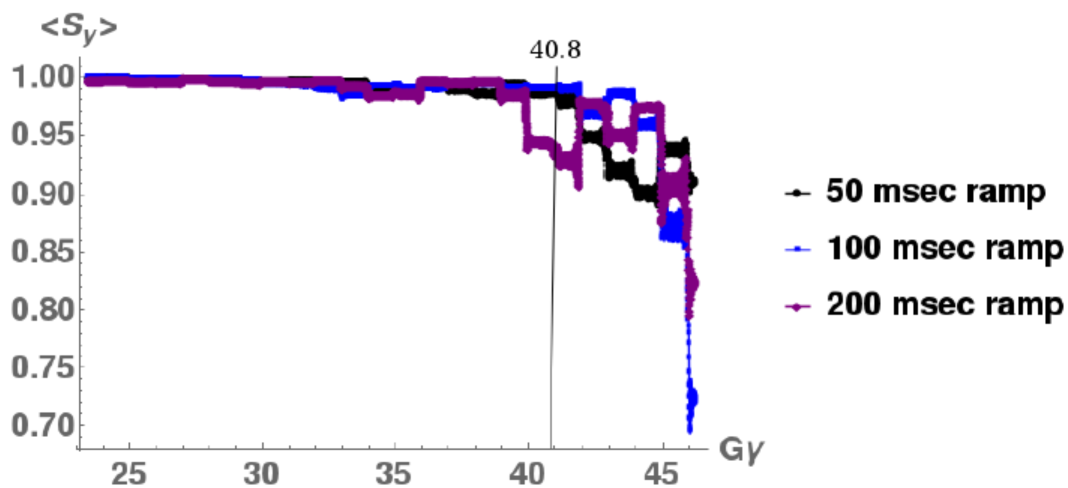


Spin rotations is now **dominated by error fields!**

Electron polarization in 6-fold symmetric RCS

Ingenious optical design: High periodicity arcs and unity transformation in the straights
=> **Symmetry cancels** all depolarizing resonances spin tune < 46
=> **no loss of polarization** up to 18GeV, **if there are small error fields**





For well aligned quadrupoles and rms orbit ≤ 0.5 mm and good reproducibility
(Within the present orbit control and achieved today by NSLS-II Booster synchrotron)

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Hadron polarization in figure 8 rings

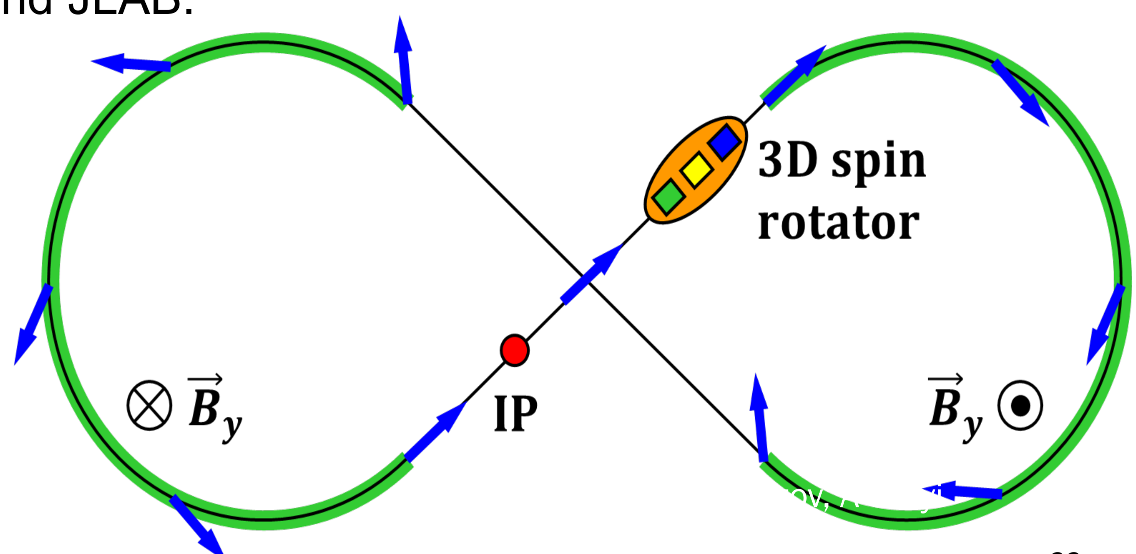
Figure-8 concept: Symmetric spin precession in one arc is cancelled in the other

Great: **works for all particle types**

Problem: **Spin tune = 0** (i.e. integer)

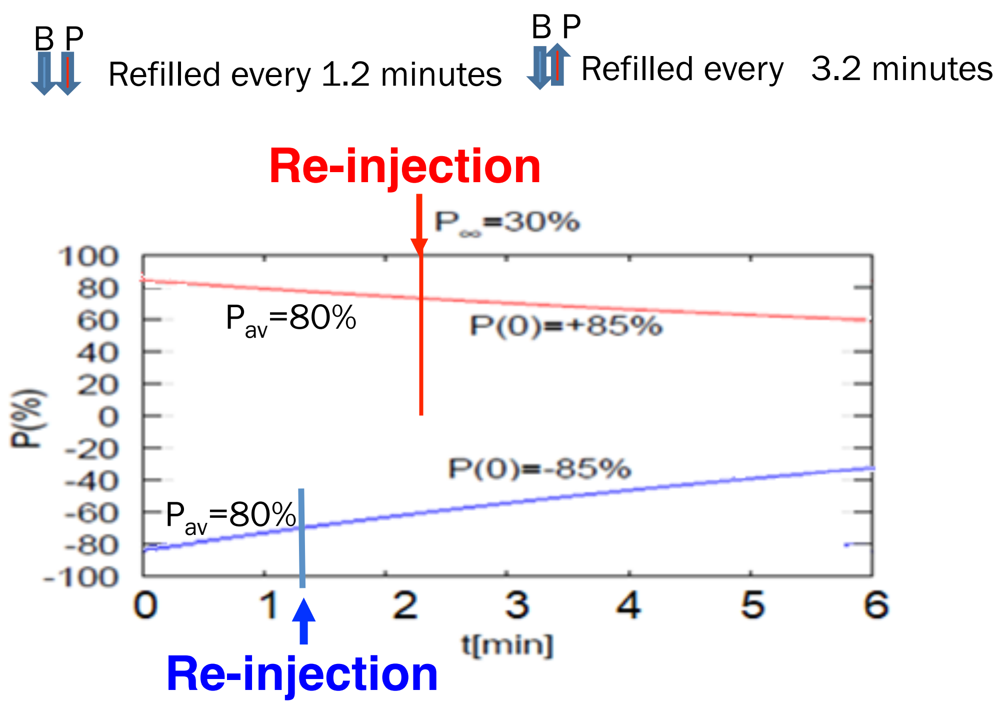
Solution: Spin stabilization by small fields to have
induced spin rotation >> spin rotation due to orbit errors

This can and will be **tested** by producing **spin tune = 0** with Siberian Snakes **in RHIC** in a nice collaboration between BNL and JLAB.



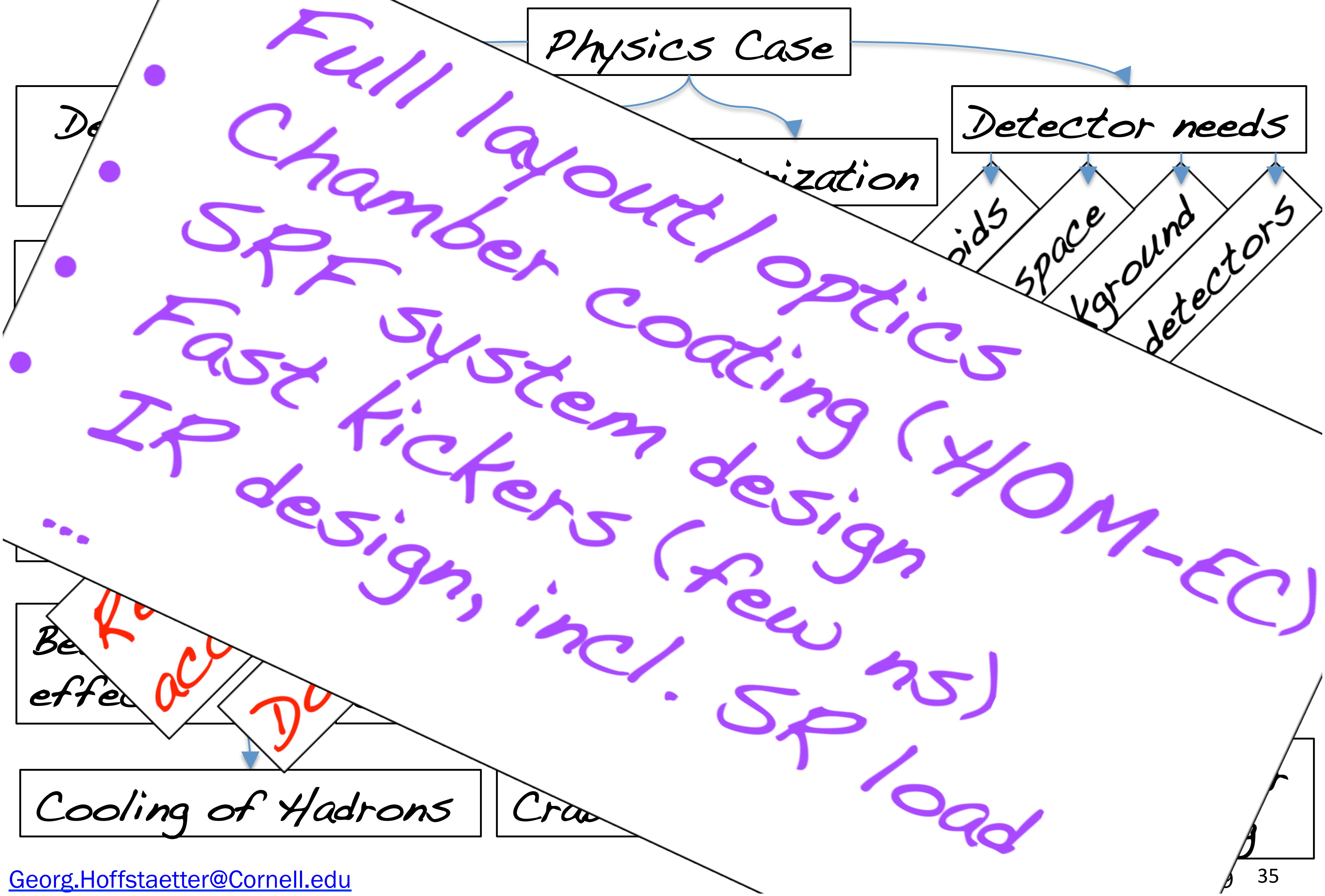
Polarization in the electron storage ring

- Electrons self polarize to an equilibrium P_∞, but not fast enough for the EIC.
- Electrons also self depolarize toward the equilibrium P_∞.
- Electrons therefore have to be replenished regularly an each EIC design.



- Which needs fast kickers when bunches need to be exchange …

Some Remaining Challenges/Opportunities



- Full layout/optics
- Chamber coating (HOM-EC)
- SRF system design
- Fast kickers (few ns)
- IR design, incl. SR load

…

Conclusion

- Designs and technical validation of EIC made **significant progress** since the last EICUG meeting
- Goal luminosity **$L = 10^{34} cm^{-2} s^{-1}$** achieved with strong hadron cooling. And there are **backup options** with somewhat reduced **L** without cooling.
- There is **good collaboration** on accelerator physics and accelerator R&D between accelerator laboratories
- Most technical components are close to **state of the art**, incl. Crab cavities, IR magnets, and ERL components
- **Effectiveness with beam** will receive more analysis and testing, in particular for crab cavities, hadron cooling, and polarization.

Much progress has been made,
More progress is needed, as … ***The ship is ready to sail*** (Tim Hallman)

Remember what Shakespeare lets Henry V say at the battle of Argincourt:
The fewer the men, the greater share of honor … wish not one more men.
He who has no stomach for this fight, let him depart.
We few, we happy few … - *and he did win!*

Questions ?