CeC Simulations –
Summary of presentations & discussion

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ICFA Mini-Workshop

"Coherent Electron Cooling – Theory, Simulations and Experiment"

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U.S. DEPARTMENT OF ENERGY

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Session 3: Presentations

- *"Beam dynamics in CeC accelerator"*
  - *Yichao Jing (BNL)*

- *"Coherent Electron Cooling Simulations"*
  - *Jun Ma (BNL)*

- *Active discussion participants:*

David Bruhwiler	John Cary	Fritz Caspers
Yaroslav Derbenev	Aliaksei Halavanau	Yichao Jing,
Rui Li	Vladimir Litvinenko	Jun Ma
Irina Petrushina	Gang Wang	Ilya Zilberter

Beam dynamics in CeC accelerator

Yichao Jing
CeC mini workshop
July 25, 2019

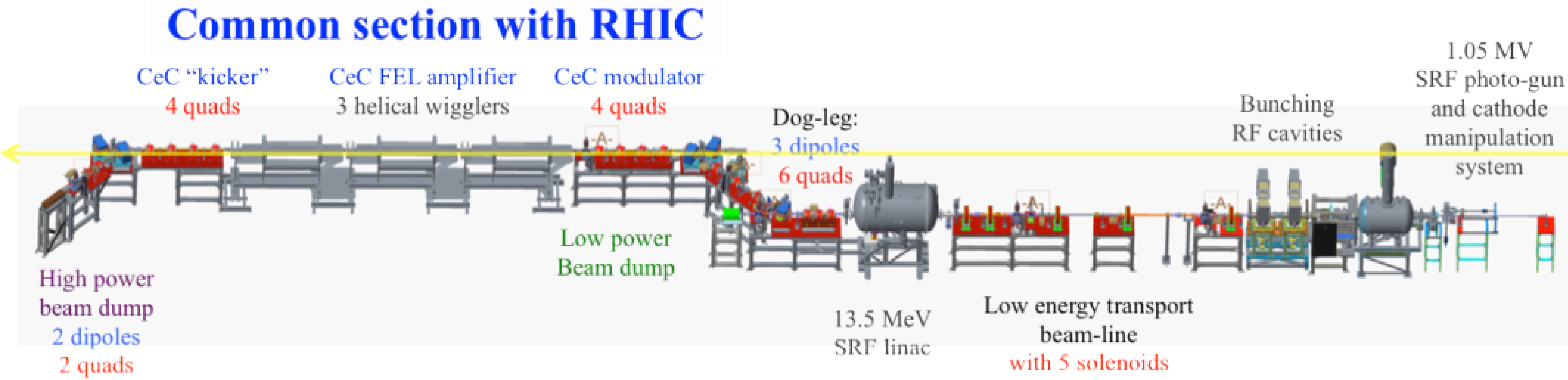
70 YEARS OF DISCOVERY
A CENTURY OF SERVICE

U.S. DEPARTMENT OF ENERGY
BROOKHAVEN NATIONAL LABORATORY

Outline

- Low energy beam transport
  - Electron Linac Simulation and Optimization
  - Multi-pacting and wakefields
  - Microbunching instability in LEBT
- Dogleg
  - Chromatic Effect
  - Coherent Synchrotron Radiation Effect
- Common section
  - Optics Matching
  - Space charge effect
  - FEL gain, evolution and saturation

Electron Linear Accelerator Simulation



- Start to end electron beam dynamics simulation from photocathode to the common section
  - Each element is modeled with real geometry with measured fields
  - Lattice matching design (Dogleg and Common section)
- Collective effects
  - Space Charge effect (ASTRA/GPT/IMPACT-T/PARMELA)
  - Chromatic aberration and Coherent Synchrotron Radiation effect (ELEGANT)
- Demonstrate required electron beam can be generated using simulation
  - peak electron current (50 - 100A), slice Emittance < 5 micro, Energy spread~0.1%
  - Flat top longitudinal distribution

Summary

- ✓ The low energy beam transport line was designed and optimized to fulfill cooling requirement. The simulation results for low energy beam transport was demonstrated in CeC PoP commissioning.
- ✓ We start a self-consistent simulation of the photo-injector cavity including wakefields and the beam distribution was used to setup a S2E simulation of CeC accelerator.
- ✓ We studied various collective effects, especially in dogleg and proposed possible fix for these issues in case that they are significant.
- ✓ We studied FEL section and demonstrate its performance is sufficient for cooling purpose.

Coherent Electron Cooling Simulations

Jun Ma

Collider-Accelerator Department
Brookhaven National Laboratory

ICFA mini-workshop CeC 2019
July 25, 2019

- Start-to-end simulations of FEL based CeC has been performed, with detailed study of modulator section.
- Amplification of density modulation in the PCA has been demonstrated in numerical simulations.
- Preliminary start-to-end simulations of PCA based CeC has been conducted for center and off-center ions.

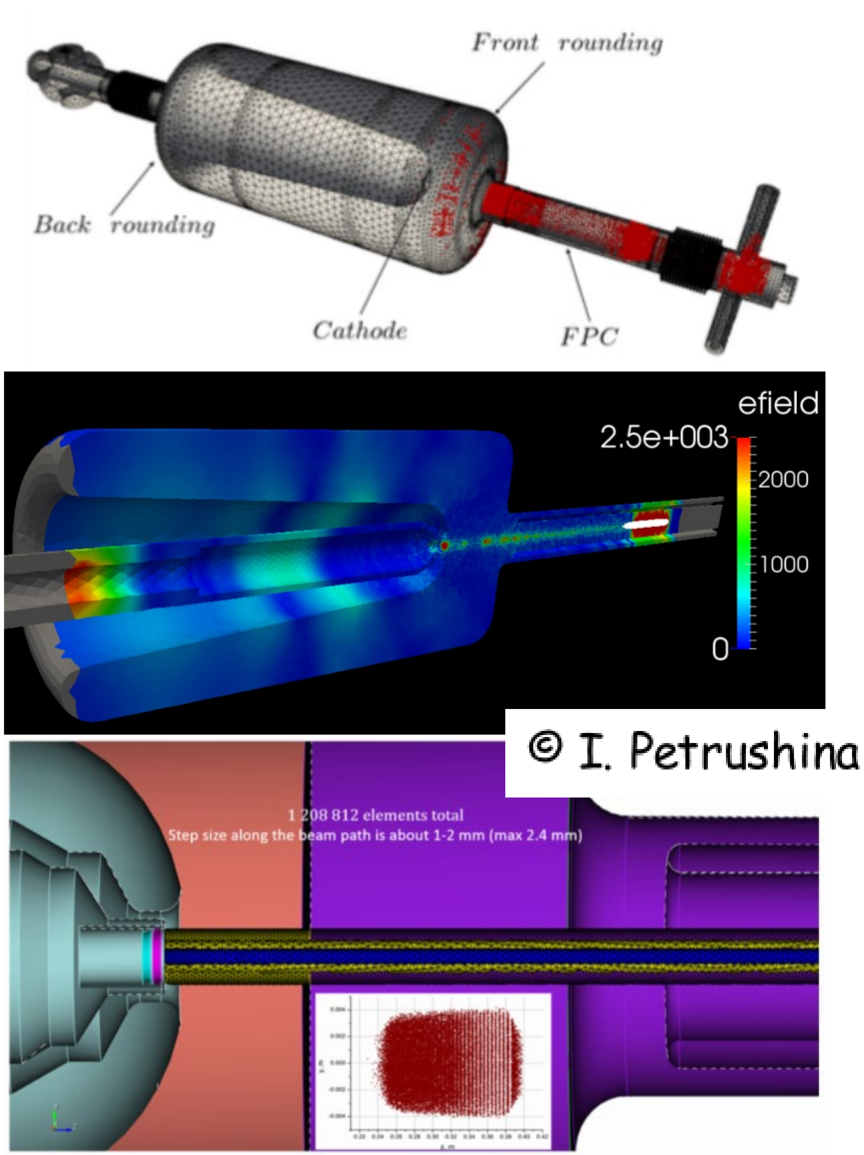
Future work

- Perform sensitivity study of PCA for various parameters including peak current, emittance, waist beam size.
- Optimize modulator length for PCA based CeC.
- Optimize transverse offset in the PCA.
- Suggestions ?

Required Simulations *(present & future)*

- *SRF electron gun*
  - *complex structure, wakefields, laser/cathode, multipactor*
- *Low-energy beam transport (LEBT)*
  - *design, compression, space charge, impedances, CSR*
  - *multibunch instabilities, e.g. multiple solenoids → PCI*
  - *sufficient diagnostics to achieve high beam quality*
- *Acceleration, high-energy beam transport*
  - *same list as above*
- *CeC modulator*
  - *Debye shielding in relativistic unmagnetized e- cooler*
- *CeC amplifier*
  - *FEL or multiple solenoids or a sequence of chicanes*
  - *modulator details must be captured correctly*
  - *μm-scale beam structures must be created & preserved*
- *CeC kicker*
  - *looks like modulator, but different physics must be captured*

Simulating the BNL SRF Electron Gun



- *Fast community codes*
  - *Astra, GPT, Impact-T, Parmela*
  - *ignore geometry & EM wakes*
- *Electromagnetic PIC codes*
  - *CST Particle Studio*
    - *slow, expensive*
    - *imprints mesh on beam*
  - *Pic3P (part of ACE3P suite)*
    - *free, runs on NERSC*
    - *conformal mesh*
    - *imprints mesh on beam*
  - *VORPAL / VSim*
    - *structured mesh w/ cut cells*
    - *runs on NERSC*
    - *not tried yet for this gun*

Low-energy beam transport (LEBT)

- *Beamline design*
  - *Mad-X, elegant, other codes*
- *Space charge, impedances*
  - *benchmark multiple codes: Astra, Impact-T, Parmela, GPT*
    - *other space charge codes to consider: Opal, Synergia*
  - *no code "gets it right", best results with Parmela (here)*
- *Comments:*
  - *Slava Derbenev: critical to accurately model longitudinal space charge; consider L_{bunch}, R_{pipe}/γ, impedance, …*
  - *John Cary: try using one multiphysics code with full EM*
- *Bunch compression*
  - *sensitive to all details of the system; over-compression is fatal*
  - *coherent synchrotron radiation (CSR) is a fundamental concern*
    - *1D model in elegant provides good initial check*
    - *2D and 3D models (space charge + CSR) required for the future*

Acceleration & subsequent beam transport

- *…many issues from previous slide apply here*
- *Linac*
  - *cavity design (many codes to choose from)*
  - *particle tracking: same list of codes from previous slide*
  - *wakefields are important, as in the SRF gun*
    - *ignore, import from outside simulation, or else do full EM PIC*
- *Energy recovery linac (ERL)*
  - *most common suggestion for conceptual designs*
    - *CBETA project at Cornell offers prototype for essential studies*
  - *modeling challenges become more severe:*
    - *space charge, CSR, high-order modes, beam break up (BBU)*
- *Comments:*
  - *Rui Li: start-to-end modeling should be coupled into modulator*
  - *Vladimir Litvinenko: this may be computationally intractable*

Coherent synchrotron radiation

- *The community has been working on CSR for decades*
- *1D models are very useful, but limited*
  - *elegant's 1D model is perhaps the most used*
  - *combines 1D CSR effects with tracking (no space charge)*
- *There are many 1D, 2D and 2D+ models*
  - *Rui Li (JLab) has a Vlasov model*
  - *CSRtrack by Dohlus & Limburg (DESY) is 2D+*
  - *GPT code can include a 2D+ model*
- *3D CSR codes are required for the future*
  - *CSR3D by R. Ryne (LBL) (space charge + CSR), but not complete*
  - *others…?*
  - *theoretical papers continue to appear in the literature*

CeC modulator simulations

- *Several codes and algorithms have been used*
  - *Vorpal / VSim: ES PIC with smoothing, δf-PIC*
  - *Elizarov et al.: Vlasov*
  - *Space (J. Ma et al.):* adaptive Particle-in-Cloud
    - differences results with/without hadron to reveal signal from noise
- *Many subtle effects to consider under perturbations*
  - *benchmarking is needed; more than one simulation group*
- *Comments:*
  - *David Bruhwiler: To date, all modulator simulations reduce numerical noise (as much as possible) and ignore shot noise. I believe shot noise should be included.*
  - *Vladimir Litvinenko: Shot noise is understood*

CeC amplifier simulations

- *Free electron laser (FEL) SASE instability*
  - *simulated with Genesis*
  - *coupling modulator results into Genesis is subtle*
    - *density and energy 'bunching parameters' must be calculated*
    - *Genesis will *not* use an external particle distribution*
  - *coupling Genesis results into the kicker simulation is difficult*
    - *the particle distribution in Genesis has artifacts*
    - *for subsequent ES PIC simulation, these must be addressed*
- *Plasma cascade instability (PCI)*
  - *has only been simulated with Space code*
    - *adaptive particle-in-cloud, with simulation differencing technique*
  - *many subtle effects to consider under perturbations*
    - *benchmarking is needed; more than one simulation group*
- *Multi-chicane microbunching*
  - *not yet simulated in any detail*

CeC kicker simulations

- *Physical system looks the same as the modulator*
  - *essentially, a relativistic unmagnetized electron cooler*
  - *consider non-relativistic plasma physics in the beam frame*
  - *however, the physics to be simulated is very different*

- *High-fidelity 3D electrostatic PIC*
  - *Vorpal/VSim has been used (after the FEL amplifier)*
    - *electrostatic PIC with quadratic and cubic spline macro-particles*
  - Space code is being used now (J. Ma *et al.*)
    - adaptive cloud-in-cell
    - applied after the FEL and plasma cascade (PCI) amplifiers
  - *many subtle effects to consider under perturbations*
    - *benchmarking is needed; more than one simulation group*

Concerns & Present Limitations

- *Initial beam distribution in modulator is idealized*
  - *be careful about claiming "end to end" modeling*
  - *see comments (above) from Rui Li*
- *Micron-scale 3D beam structures*
  - *must be created, amplified and controlled*
    - *initial beam microstructures must be understood*
    - *3D ES plasma dynamics must be understood (multiple approaches)*
    - *effects of e- beam energy structure must be understood*
      - *total $\delta E/E$, slice $\delta E/E$, interaction with dipoles*
    - *shot noise must be understood (and included, like SASE FEL)*
    - *numerical noise must be understood (and minimized)*
    - *does dipole dynamics disrupt micron-scale structures in other ways?*
      - *see next slide*
  - *timing with individual hadrons is critical*
    - *R_{56} techniques → e- beam energy must be well-controlled*
      - *very small δE of electrons will shift structure locations wrt hadrons*

EM PIC vs ES PIC and the problem of dipoles

- *ES PIC is used for the modulator, amplifier & kicker*
  - *work is done in the beam frame*
  - *system looks like thermal e- and hadron plasmas*
  - *ES PIC is quieter, faster and easier than EM PIC*
    - *can EM effects be quantified as small…?*
    - *can ES PIC simulations be validated with experimental diagnostics?*
- *Most CeC concepts require doglegs or chicanes*
  - *effect of dipoles on μm-scale structures must be considered*
  - *tracking codes treat dipoles with a crude approximation*
    - *full EM PIC treatment is problematic for several reasons*
  - *a proper Liénard-Wiechert approach could be the solution*
    - *this captures both space charge and CSR simultaneously*
    - *CSR3D code by R. Ryne is being developed to do this*
  - *perhaps there are other approaches*

Summary

- *BNL/Stony Brook team presented very good results*
  - *detailed simulations of accelerator*
    - *multiple codes, with benchmarking*
    - *quantitative comparison with experimental diagnostics*
    - *discovery of plasma cascade instability (PCI)*
  - *idealized simulations of FEL and PCI based CeC configurations*
    - *use of novel algorithm: adaptive particle-in-cloud code, "Space"*
- *Needs for future work have been identified*
  - *solutions still need to be developed*
- *Role of simulations on the road to EIC success*
  - *identify physics and engineering concerns*
    - *explore non-ideal issues to help establish requirements*
  - *support experimental demonstrations and EIC design*
    - *experimental demonstrations are essential*
- *External collaboration & alternate efforts are important*