Highlights and Reflections on EIC Accelerator Collaboration Meeting

120 registered attendees
JLab: 27, JLEIC: 27+6

Suggested two times each year, next one at JLab

Slides at https://indico.bnl.gov/conferenceDisplay.py?confId=3492

Outline

1. Highlights on the present *eRHIC* Design
2. Highlights on the present *JLEIC* Design
3. Staging for eRHIC and JLEIC
4. EIC Accelerator Collaborations
    1) BNL and JLab
    2) With Other labs/Institutions
5. Impressions and Reflections by Others

About the eRHIC Design

V. Ptitsyn 's talk

eRHIC Design Goal

- **L ~10^{33}-10^{34} cm^{-2}s^{-1}** *(exceeding HERA luminosity by 2 orders of magnitude)*
- **High electron & proton polarization (>70%)**
  Realizing complex spin pattern for electrons and protons
- **Large acceptance detector**
  with detector elements integrated in the accelerator IR for forward particle detection
- **Minimizing the construction & operational cost of accelerator**

Present baseline design concept

- ***Ring-ring***
- Add electron storage ring (5-18 GeV)
  - Up to 2.1 A electron current.
  - < 10 MW RF power (*administrative* limit)
- Flat proton beam formed by cooling
- ***On-energy*** **polarized electron injector**
  - RCS is a cost-effective injector option
  - Polarized electron source and 400 MeV injector linac: 10 nC @ 1 Hz rep rate

eRHIC pCDR

- The goal: document ready in March 2018
- Include sufficiently detailed design of accelerator systems to allow for a confident construction and operation cost estimate
- Present efforts are fully concentrated on preparation of detailed design document

V. Ptitsyn's talk

eRHIC Design Parameters

	No cooling		Baseline with cooling	
Species	p	e	p	e
energy [GeV]	275	10	275	10
cm energy [GeV]	104.9		104.9	
bunch frequency [MHz]	28.146		112.6	
circumference, m	3833.918	3833.940	3833.918	3833.940
bunch intensity [10^10]	11.9	29.9	6	12.1
number of bunches	330		1320	
beam current [A]	0.49	1.24	1	2
rms norm. emit. h/v [um]	4.5/1.9	495/68	2.6/0.5	495/19.7
rms emittance h/v [nm]	15.5/6.5	25.3/3.5	8.8/1.7	25.3/1.0
beta* h/v [cm]	92/4.5	56/8.4	67/2.0	23/3.4
IP rms beam size h/v [um]	119/17		77/6	
IR rms ang. spread h/v [urad]	130/379	212/203	115/292	330/172
b-b parameter (/IP) h/v	0.014/0.005	0.094/0.098	0.011/0.004	0.051/0.097
Longitudinal bunch area, eV*s	0.8		0.4	
rms bunch length [cm]	7	2.3	4	1.7
rms energy spread, 10^-4	6.6	4.7	5.8	4.7
max space charge parameter	0.002	neglig.	0.004	neglig.
IBS growth time tr/long, h	8.1/8.0		2.0/3.4	
hourglass and crab crossing factor	0.81		0.76	
peak luminosity [10^33 cm-2s-1]	**2.92**		**10.2**	

Official baseline

Need cooling

High bunch rep rate

Large bunch numbers

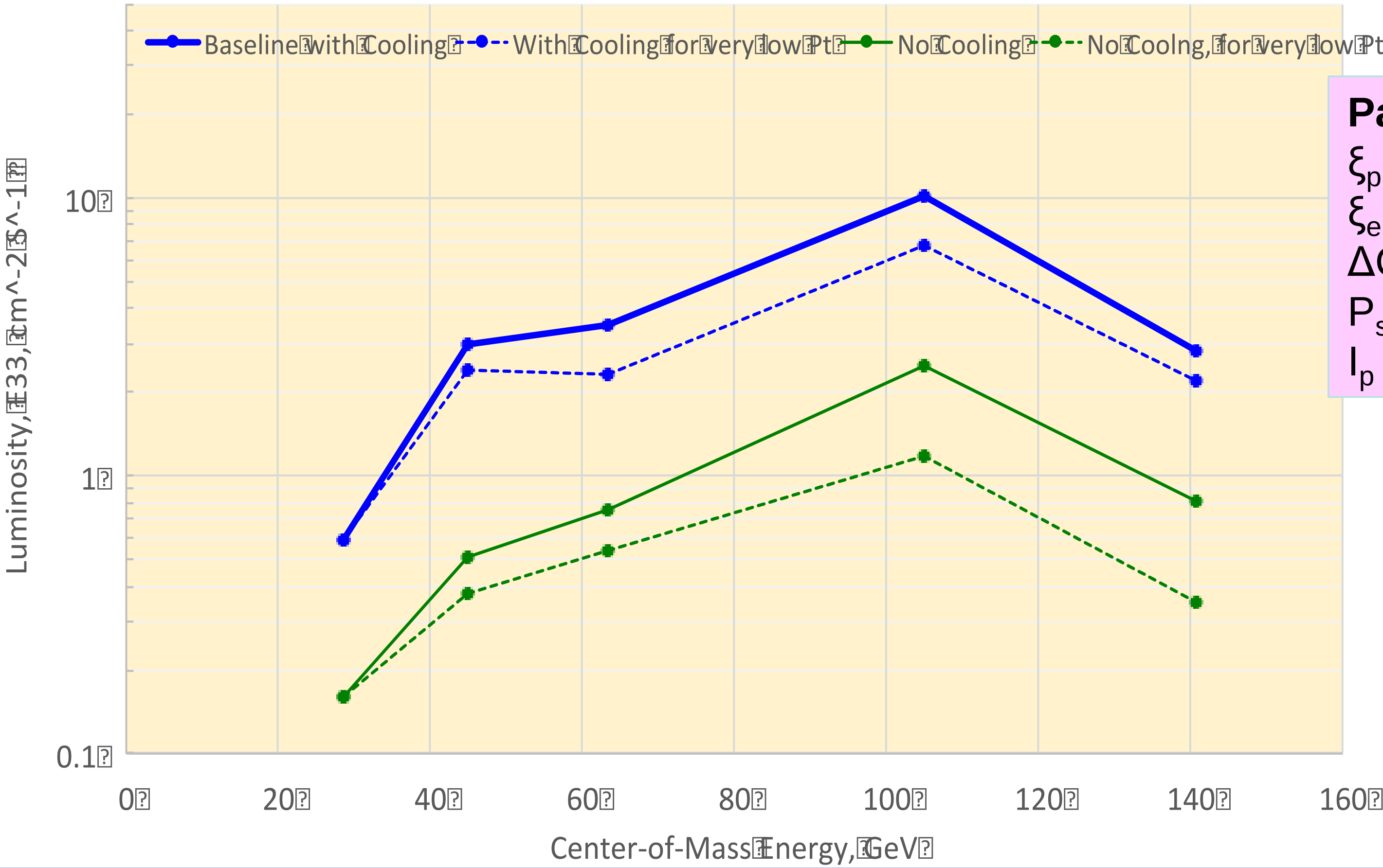
Very small β_v

Short bunch length

High luminosity

Present eRHIC Luminosity Performance

V. Ptitsyn 's talk



Parameter limits

$\xi_p < 0.015$

$\xi_e < 0.1$

$\Delta Q_{sp} < 0.05$

$P_{sr} < 10$ MW

$I_p < 1$ A

- Baseline curve relies on cooling ***just strong enough*** to reach 10^{34} $cm^{-2}s^{-1}$ (IBS growth times > 2h)
- Very low pt run curves are for collecting data with very forward proton scattering (pt ~200 MeV)
- Addressing risks of hadron cooling technology, "no cooling" curves demonstrate sufficiently high level of luminosity for realizing compelling physics program even without hadron cooling.

Upgrading RHIC Hadron Ring for eRHIC

V. Ptitsyn's talk

	Achieved at RHIC at 255 GeV	eRHIC 275 GeV No cooling	eRHIC 275 GeV With cooling	
Bunch intensity, 10^{11}	2.4	1.5	1.6	
Bunch frequency, MHz	9.4	28.2	112.6	x 12
Beam current, mA	330	620	1000	x 3
Peak current, A	12	16	39	
Normalized emittance, 1e-6 m	2.5/2.5	4.5/1.8	2.6/0.5	
beta*, cm	50/50	94/4.2	67/2	x 25
rms bunch length, cm	40	7	4	x 10

- Beam instrumentation upgrade (to address ***considerable increase of total & peak currents***). That, at least, includes BPMs and polarimeters.
- Higher harmonic RF system, for bunch splitting & for stronger focusing (***shorter bunch length***)
- Injector system upgrade; (7 ns kicker rise-time)
- ***Copper coating of RHIC beam pipe***.
- Beam dynamics evaluation: beam stability; electron cloud and associated heating load
- Flat hadron beam emittances

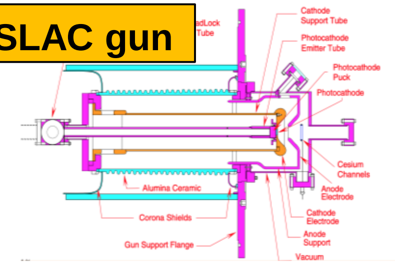
eRHIC New Electron Complex

V. Ptitsyn
E. Wang

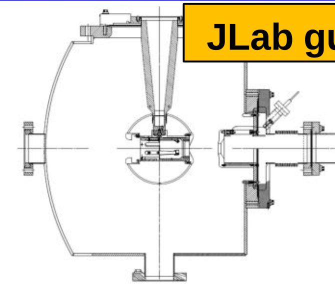
Polarized electron source

- Low rep rate, high charge (1 Hz for 10 nC)
- Bunch length ~1-2 ns
- The 350 kV polarized gun designed combining SLAC high-charge gun and JLab inverted gun technol
- SL-Ga
nm, ca

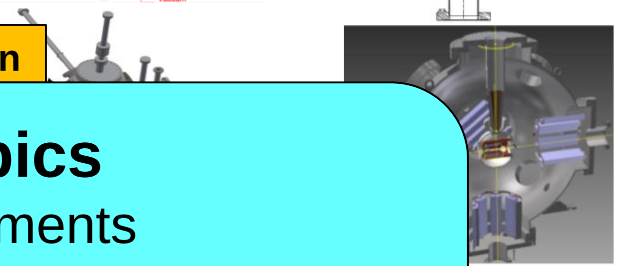
SLAC gun



JLab gun



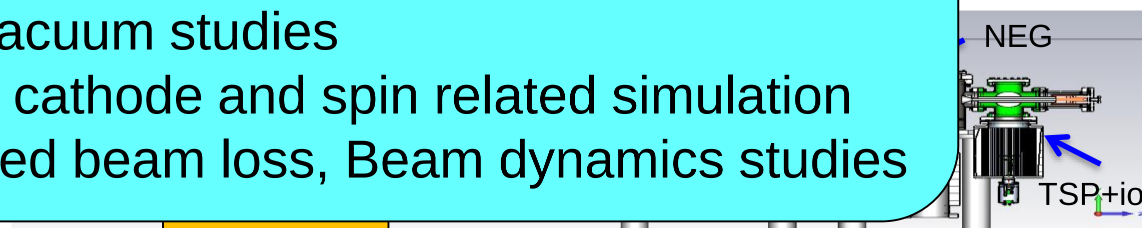
eRHIC gun



Potential R&D collaboration topics

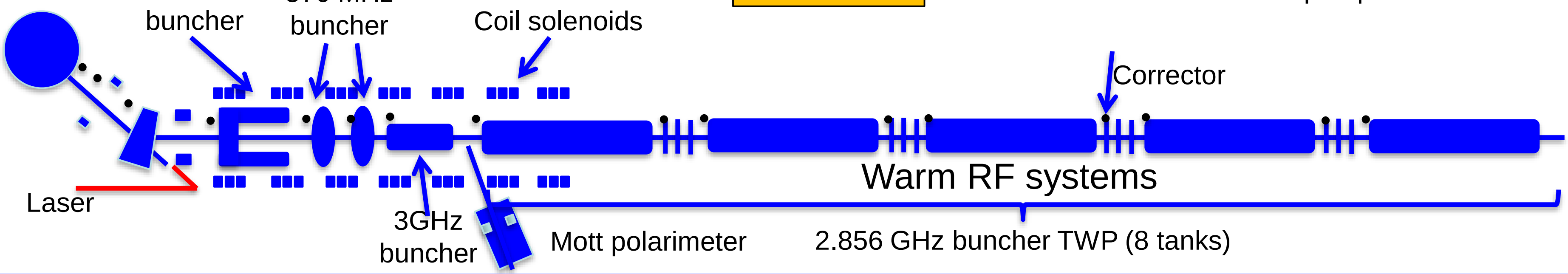
- Cathode lifetime modeling and experiments
- Large cathode gun experiments
- Extremely high vacuum studies
- High polarization cathode and spin related simulation
- Beam halo induced beam loss, Beam dynamics studies

400 MeV
linac as



Beam test

25500L/sec NEG+TSP pump



eRHIC Electron Injector

V. Ptitsyn talk

V. Ranjbar talk

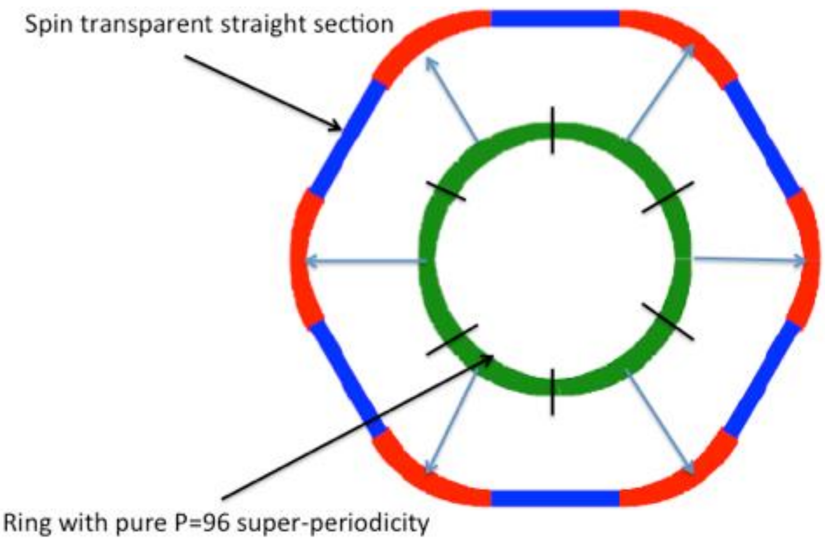
Design Status

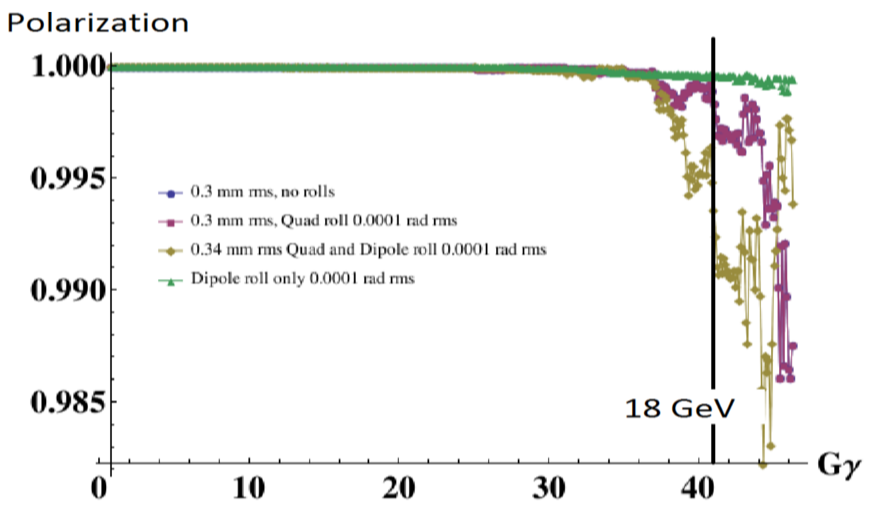
- Two injector schemes have been under consideration: RCS and RLA
- The choice of the injector scheme is scheduled to be made in November

Cost-efficient option: Rapid Cycling Synchrotron (RCS)

Magnet field ramp range: ~45

- Fit inside existing RHIC tunnel, polarization transmission losses < 5%
- Fast acceleration: 100 ms ramp from **400 MeV to 18 GeV,** 1 Hz ramp repetition rate
- Spin transparent lattice design concept: highly symmetric arcs connected by straight sections (designed with unity beam transport matrix) or detector bypasses
- So far no show-stopper found from spin simulations with misalignment & magnet errors

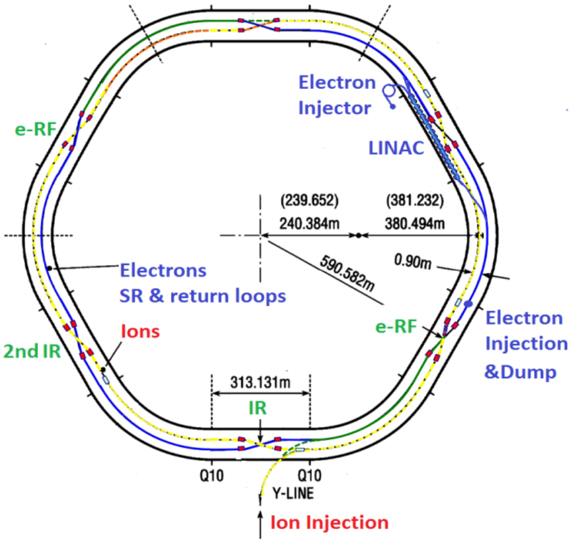




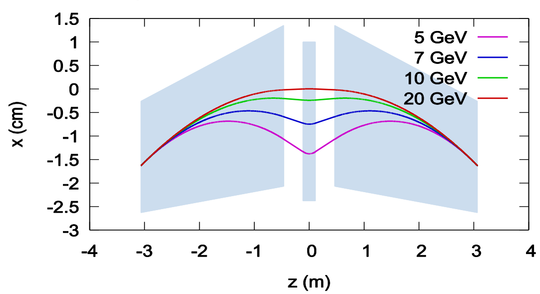
eRHIC Electron Storage Ring

V. Ptitsyn
C. Montage

- Lattice for 18 GeV has been developed including an interaction region.
- Initial variants of lattices for 5 and 10 GeV with proper emittances were demonstrated.
- Initial check of chromatic correction with distributed sextupole families: ~18σ DA.
- Beam dynamics studies: beam stability shown for design parameters
- Arc magnets (D,Q,S) have been designed; Initial design of vacuum system has been done.



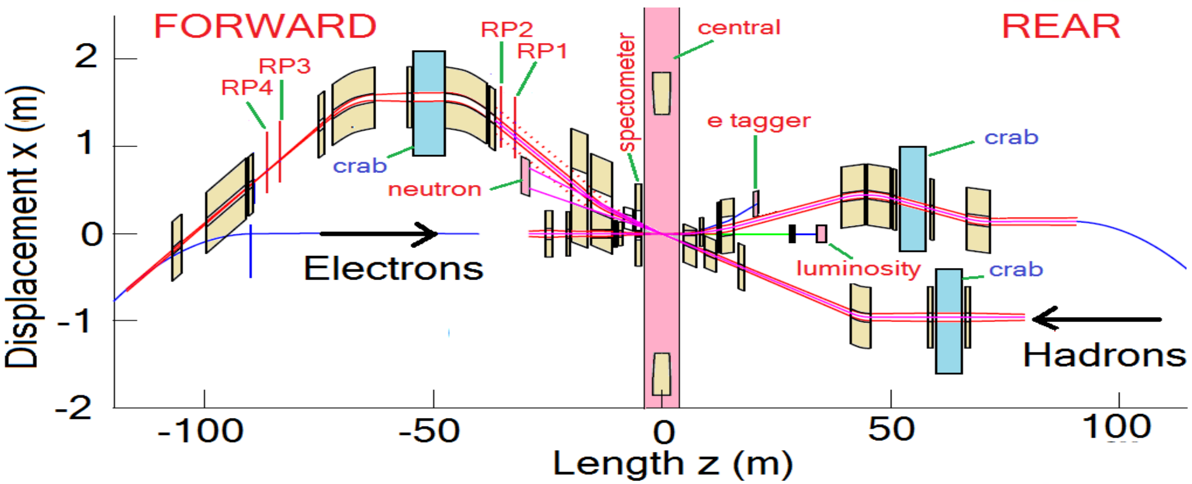
- Electron storage ring next to hadron ring (same plane)
- Rings intersect in each straight to keep circumferences equal, similar to present RHIC
- Main eRHIC detector in IR6, a possible 2nd detector in IR8
- Two locations (IR7 and IR10) for RF

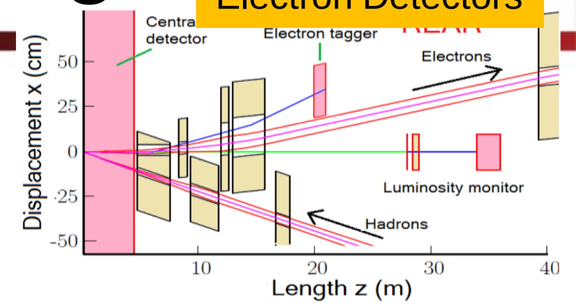


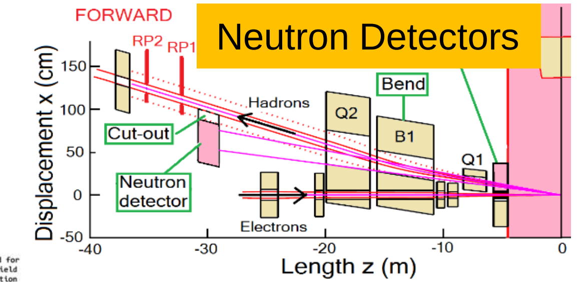
- Requires large beam-beam parameters (ξ=0.1) to reach high luminosity over the entire energy range
- This was achieved in KEKB, transverse SR damping decrement ~1/4000
- Damping decrement in eRHIC should be at least as large as in KEKB to achieve the same beam-beam tune shift at all energies

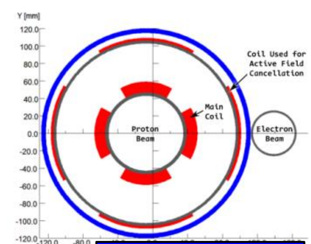
eRHIC Ring-Ring IR Design

V. Morozov / B. Palmer



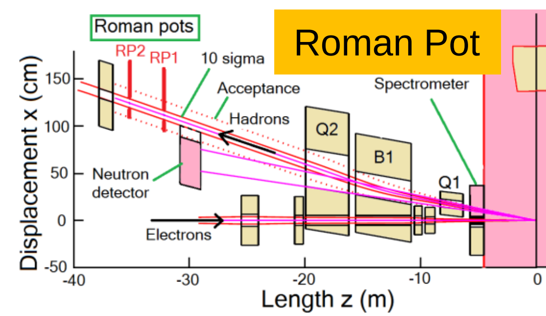


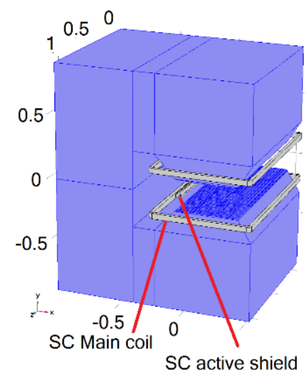


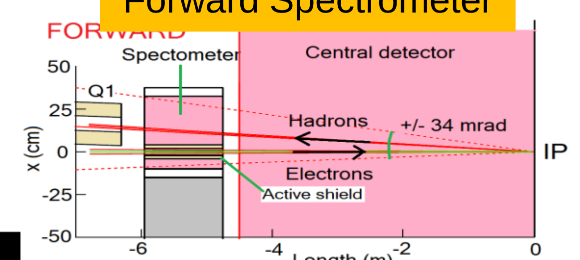


B. Parker

- 22 mrad total crossing angle; crab cavities (338 MHz) for both beams
- Integrated detector components (neutron detector, Roman Pots, e-tagger, luminosity monitor)
- Full acceptance achieved using spectrometer magnet (5-22 mrad) and Roman Pots (<5 mrad)
- Avoiding generation of synchrotron radiation which can produce significant backgrounds
- Magnet designs provide shielding electrons from strong focusing and deflection magnets for hadrons







Cooling R&D at BNL: CeC P-o-P Experiment

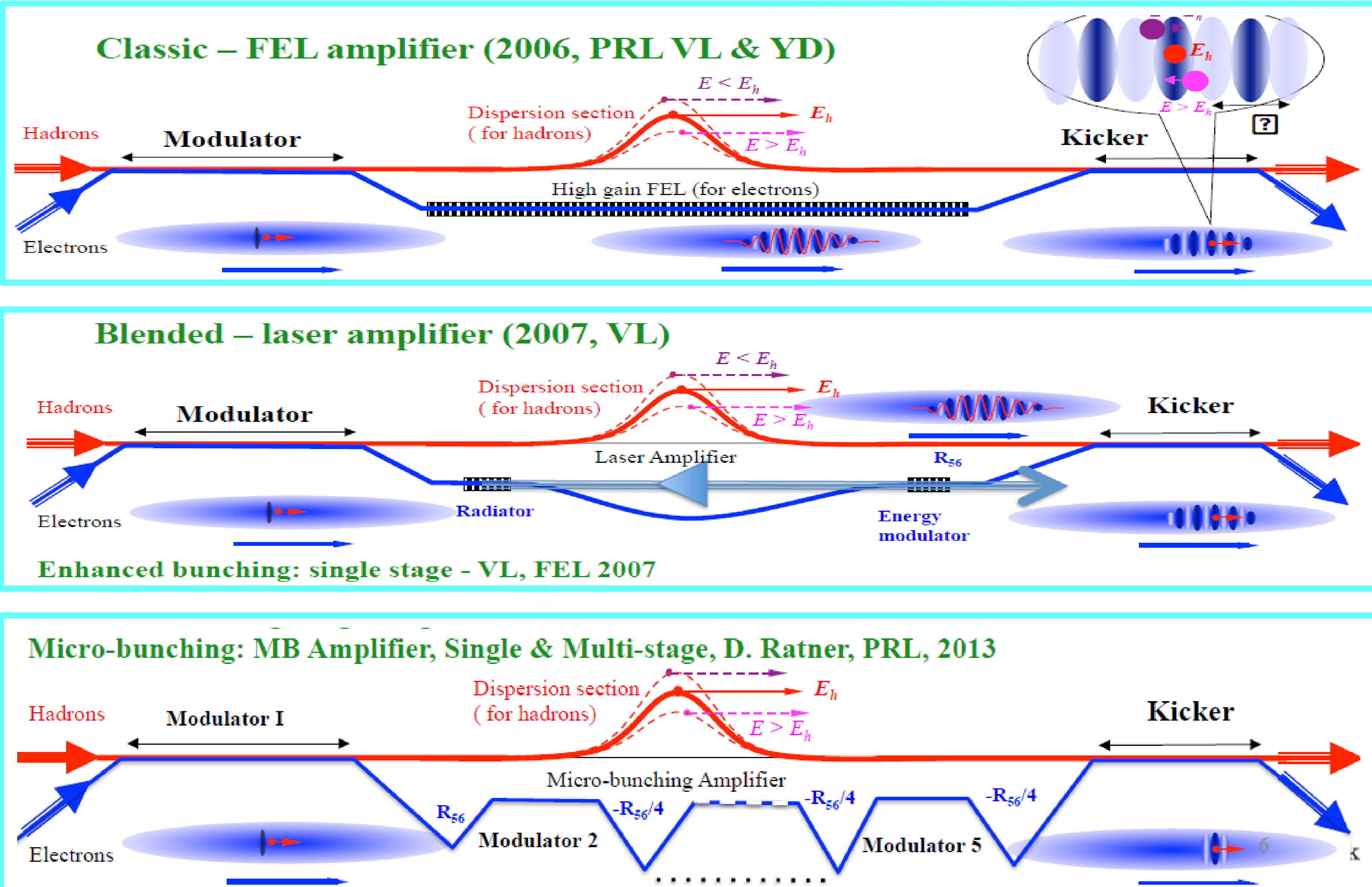
V. Litvinenko

- Presently, no cooling design concept has been identified for ring-ring eRHIC
- All cooling concepts under study, magnetized electron cooling could be a fall-back

Parameter	Design	Status	Comment
Species in RHIC	Au^{+79}, 40 GeV/u	Au^{+79} 26.5 GeV/u	To match e-beam
Particles/bucket	10^8 - 10^9	10^8 - 10^9	✔
Electron energy	21.95 MeV	**15 MeV**	**SRF linac quench**
Charge per e-bunch	0.5-5 nC	0.1- 4 nC	✔
Peak current	100 A	50 A	Sufficient for this energy
Pulse duration, psec	10-50	12	✔
Beam emittance, norm	<5 mm mrad	3 - 4 mm mrad	✔
FEL wavelength	13 µm	**30 µm**	**New IR diagnostics**
Rep-rate	78.17 kHz	26 kHz**	Temporary**
e-beam current	Up to 400 µA	40 µA	Temporary**
Electron beam power	< 10 kW	600 W	Temporary**

- Many subsystems (SRF linac, beam diagnostics, etc.) fully commissioned
- e-bunch compressed, desired peak current demonstrated
- System is ready for CeC demo during RHIC Run 18
- The test time is quite short due to RHIC scheduling

Principle of Coherent Electron Cooling (CeC)



CeC P-o-P Experiment Schedule

Activity	Proposed schedule
Re-establish CeC accelerator operation	1/15– 2/3
Establish required e-beam parameters CeC FEL commissioning	2/4 – 3/5
Establishing CeC system operations at various RHIC settings, compensating stray magnetic fields	3/5 – 3/21
Co-propagate, align and synchronize electron and ion beams, match relativistic factors of two beams	3/22 - 4/7 2 days dedicated
Develop control of the FEL amplification, observe amplification of density modulatio[n]	4/8 – 5/5 2 days dedicated
Refine tools for observation of ion beam cooling, observe cooling/anti-cooling via CeC	5/6 – 5/25 3 days dedicated
Develop various CeC accelerator settings (charge, peak current, FEL gain) and characterize CeC cooling	5/26 -6/15 4 days dedicated

Total 11 days!

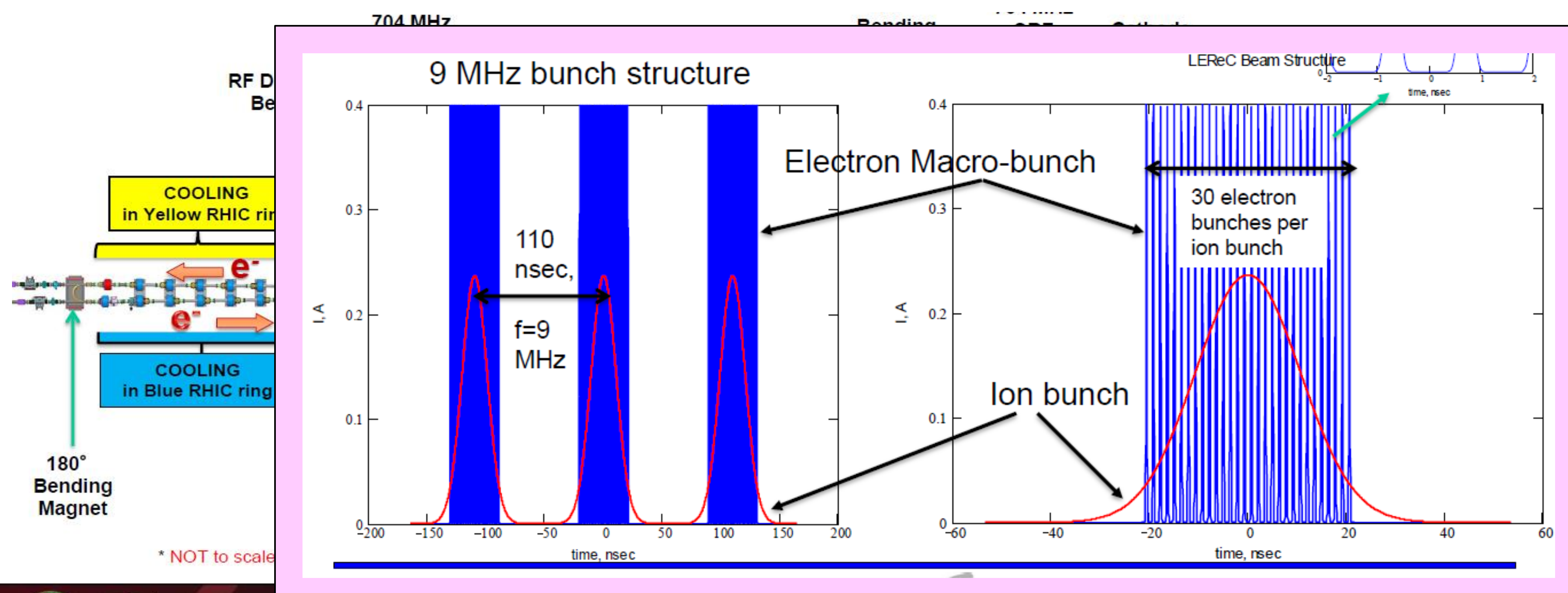
Cooling R&D at BNL: RHIC Low Energy e-Cooling

A. Fedotov

- Luminosity improvement for RHIC low energy operation to search for QCD critical point (Beam Energy Scan Phase-II Physics Program)
- 2 MeV bunched beam cooler
- Commissioning/operation by Run 19
- Test bad for high energy e-cooling

Project Mission

- ❑ Building and commissioning of new state of the art electron accelerator
- ❑ Produce electron beam with beam quality suitable for cooling
- ❑ Transport with RF acceleration maintaining required beam quality
- ❑ Commissioning of bunched beam electron cooling
- ❑ Commissioning of electron cooling in a collider



Layout/Parameters of LEReC Electron Cooler

3D LEReC layout in RHIC tunnel at

Electron beam requirement for cooling			
Kinetic energy, MeV	1.6*	2	2.6
Cooling section length, m	20	20	20
Electron bunch (704MHz) charge, pC	130	170	200
Effective charge used for cooling	100	130	150
Bunches per macrobunch (9 MHz)	30	30	24-30
Charge in macrobunch, nC	4	5	5-6
RMS normalized emittance, um	< 2.5	< 2.5	< 2.5
Average current, mA	36	47	45-55
RMS energy spread	< 5e-4	< 5e-4	< 5e-4
RMS angular spread	<150 urad	<150 urad	<150 urad

Cooling R&D at BNL: RHIC Low Energy e-Cooling

May 2015:	**Project approved by DOE for construction**
January 2016:	**Cooling section magnets installed**
April 2016:	**Laser assembled**
September 2016:	**DC gun assembled at Cornell University**
October 2016:	**DC gun delivered to BNL**
November 2016:	**Approval from DOE for DC Gun Tests received**
December 2016:	**DC gun successfully conditioned in RHIC IR2**
February 2017:	**Gun Test beamline and laser transport installed in RHIC**
April-Aug. 2017:	**Gun tests/commissioning with beam**
July-Dec. 2017:	Installation of remaining components
Dec.'17-Feb. 2018:	Systems commissioning (RF, SRF, Cryogenics, etc.)
March 2018:	Start commissioning of full LEReC accelerator with e-beam
September 2018:	Demonstrate electron beam parameters needed to start commissioning of cooling process
2019:	Commissioning of cooling with Au ion beams during RHIC Run-19.

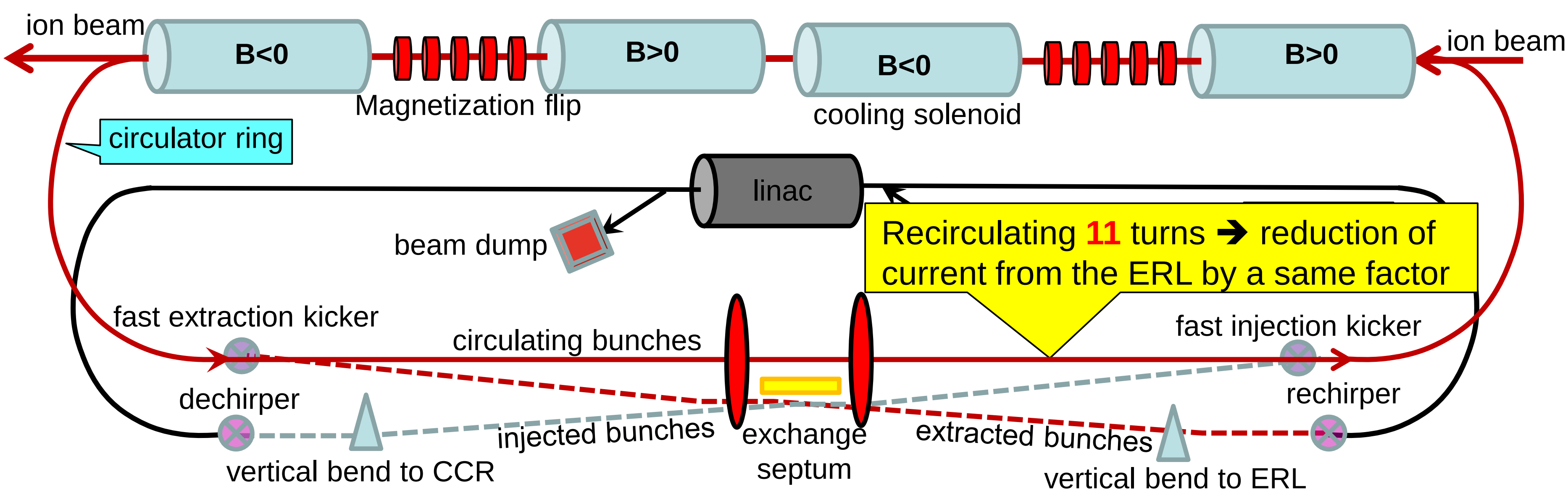
Other eRHIC Talks

- "Beam Polarization in eRHIC" by Francois Meot (BNL)
- "Dynamics with Crab Cavities for EIC" by Yue Hao (MSU/BNL)
- "Overview of Collective Effects in eRHIC" by Michael Blaskiewicz (BNL)
- "eRHIC Beam-Beam Simulation" by Victor Smalyuk (BNL)
- "Additional Beam-Beam Challenges" by Yun Luo (BNL)
- "eRHIC Machine Detector Interface" by Elke Aschenauer (BNL)
- "RF for high Intensity electron EIC Storage Ring" by Wencan Xu (BNL)
- Crab Cavity Development for EIC by Subashini De Silva (ODU)
- "Fast Track Actively Shielded Nb3Sn IR Quadrupole R&D" by Brett Parker (BNL)
- "RCS Polarization Beam Study at Cornell" by F. Meot (BNL), Karl Smolenski (Cornell)
- "CBETA Status" by Stephen Peggs (BNL)

JLEIC High Energy ERL Cooler

S. Benson

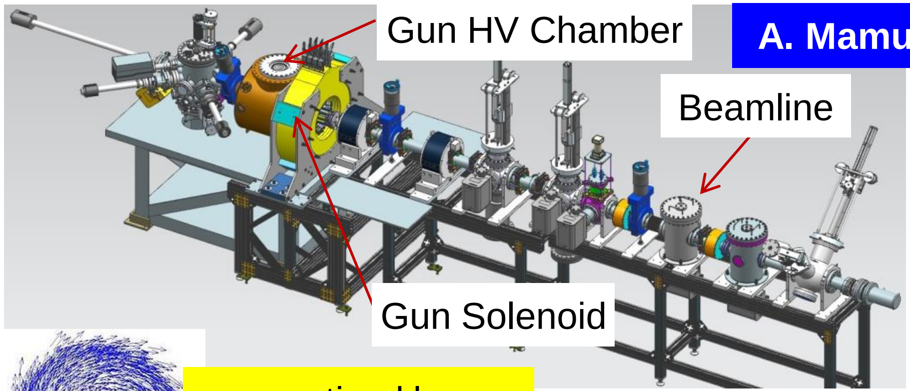
- JLEIC needs two DC coolers and one high energy ERL cooler for hadron beam cooling
- The design concept of an ERL based cooler was proposed more than 10 years ago
- The technical design of the ERL cooler started about 3 years, has made lot of progress
- Strong cooling: requires Amp class cooling electron beam ← adding a recirculator ring (11 circulation, balance between technical challenges of fast kicker & beam dynamics)
- Weak cooling: ~0.2 A cooling electron beam, simple ERL

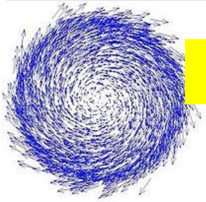


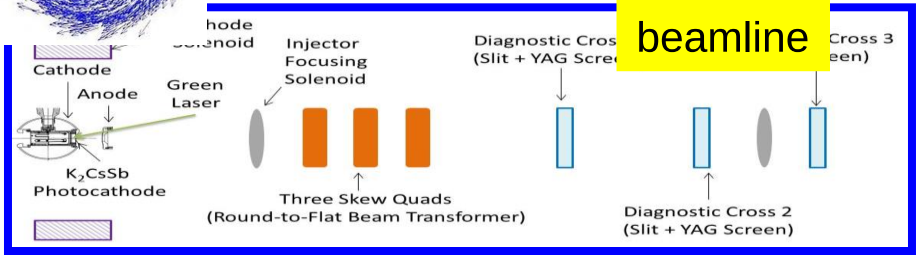
ERL-Circulator Cooler R&D

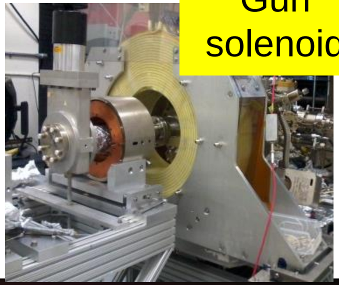
Magnetized source development

A. Mamun talk



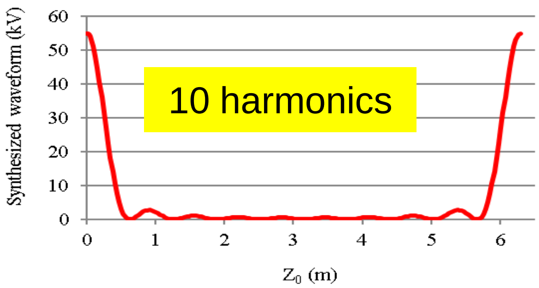


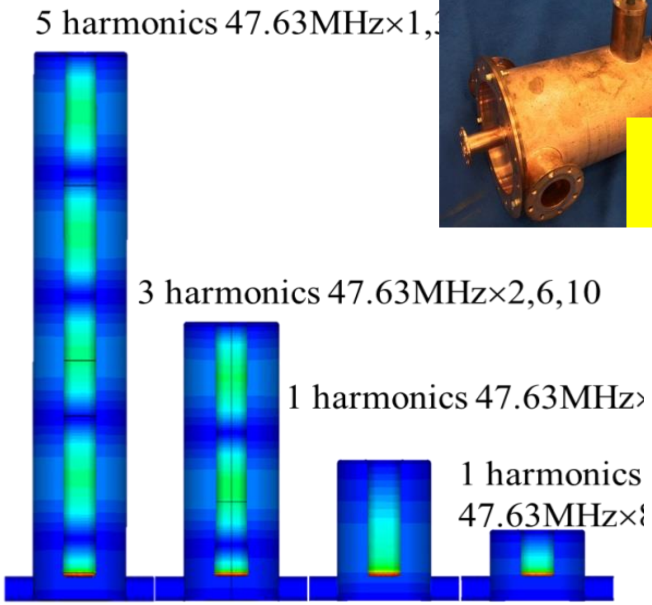




Harmonic RF Fast kicker

H. Wang talk





JLEIC ERL Cooler: Where are We & Where Do We Go?

S. Benson

✓ ERL Design
- Add doglegs and update injector design.
- Calculate collective effects (BBU, ion trapping, halo formation)

✓ Beam exchange design

✓ Linac design
- Optimize HOM damping.
- Consider 3rd harmonic cavity for CCR operation.

✓ Cooling Insertion
- Balance cooling partition
- Specify solenoid tolerances

✓ CCR Design
- Microbunching gain is low.
- Explore shielding
- Calculate collective effects (ion trapping, wakes, resonances)

○ Injector design
- Magnetization is preserved up to end of booster
- Need to try lower frequency

○ Merger Design
- Many options to explore
- Might be able to just go straight in (straight merger).

Cooler Development History

Fall 2013	Develop Figure 8 cooler CCR concept
Spring 2014	CCR option de-scoped due to µBI
Spring 2015	Magnetized cooler solution chosen
2014 – 16 µBI	suppression developed
Summer 2016	Harmonic Kicker Prototype developed
Fall 2016 ERL	solution (weak cooling) developed
Fall 2016	Change back to CCR solution

ERL Cooler Parameters and Challenges

D. Douglas

Energy	20–55 MeV
Charge	3.2 nC
CCR pulse frequency	476.3 MHz
Gun frequency	43.3 MHz
Bunch length (tophat)	2 cm (23°)
Thermal emittance	<19 mm-mrad
Cathode spot radius	3.14 mm
Cathode field (magnetized beam)	0.05 T
Gun voltage	350 kV
Normalized hor. drift emittance	36 mm-mrad
rms energy spread (uncorr.)*	3×10^{-4}
Energy spread (p-p corr.)*	
Solenoid field x length	1 T x 2x30 m
Electron beta in cooler solenoid	37.6 cm
Bunch shape	beer can

}1.5 A (charge × CCR pulse frequency)

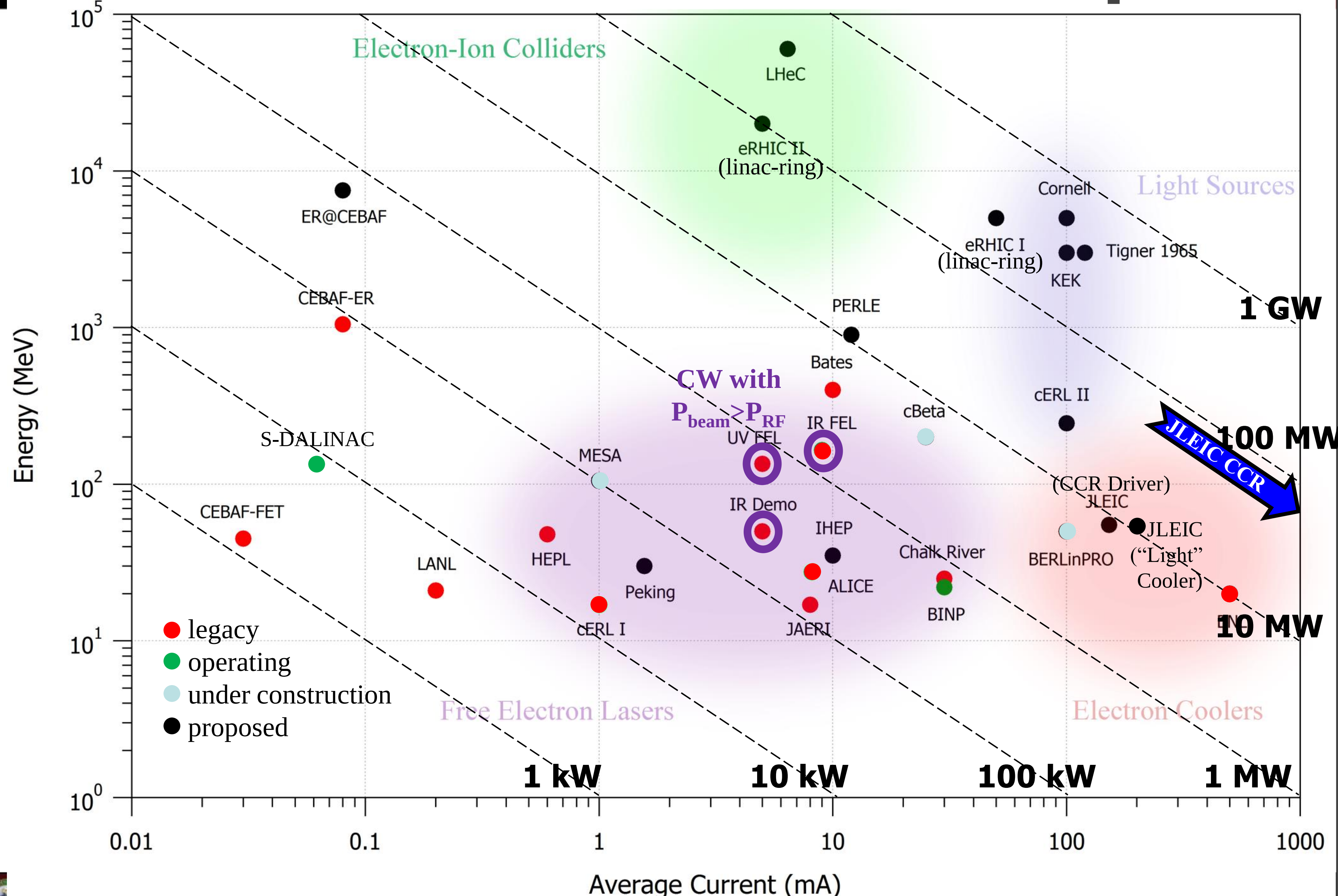
}83 MW

RF drive costs motivate use of ERL

How do these requirements compare to state-of-art?

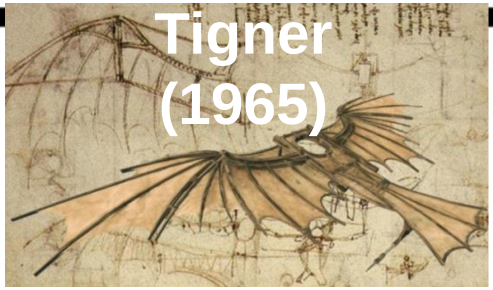
D. Douglas

State of Art: ERL Landscape



Aerospace Analog History of ERLs

D. Douglas



✓

What to Do?

D. Douglas

- Multiple generations separate state of art system readiness from required performance
- Need development in many areas, including:
  - CW/high charge magnetized source
  - merger
    - management of CSR, space charge, microbunching
  - modeling with CSR and space charge
    - model validation (1D, 2D, 3D…)
    - validate treatment of ends of bunches
    - simulation dynamic range (part per million statistics => trillion particle simulation…)
  - CSR shielding
  - methods for mB gain control
  - LSC wake control/compensation
    - Nonlinear longitudinal matching
  - magnetization-preserving beam transport
  - high-rep-rate beam transfer
  - halo (simulation statistics inadequate…)
    - Formation mechanisms (scattering: IBS, Touschek, beam/gas,…; dynamical)
    - Characterization (LDR diagnostics, tomography…)
    - Control (suppression, collimation, matching (linear and nonlinear…)
  - power scaling ("Calvin effect")
    - 100x state of art… what could possibly go wrong…?

What tests are needed, and where can these be performed…?

Where to go: Existing Opportunities

D. Douglas

- ***ASTA/IOTA/FAST*** can support single bunch studies
  - 3.2 nC magnetized bunch ⇔ can initiate evaluation of single-bunch dynamics & evolution
  - Could IOTA offer a CW analog?
- ***JLab UITF & LERF, ELBE@HZD*** can support low power/low charge CW tests for hardware and dynamics
  - JLab ERLs down for LCLS-II module tests through 2018
- ***No "true" (P_{beam}>>P_{RF}) SRF ERLs in operation at this time***
  - no immediate opportunity for high power testing in SRF environment
  - BINP capable of high charge/current/CW at low energy…
- ***2019: three SRF ERL facilities available: Cb, bERLinPRO, JLab***
  - Complementary capabilities/limitations
    - JLab is legacy generation (low charge, MW class) but fully commissioned and operationally flexible
    - Cb is "next generation", but experimental design may be operationally challenging (FFAG)
    - bERLinPRO ⇔ high current/power; design charge low but SRF gun offers possibility for high charge, but no magnetization ☹

Distributed/coordinated program of collaborative studies provides coverage for many outstanding issues

Planning forward…

D. Douglas

- **Immediately**
  - Fund and perform exploratory tests of magnetized high charge (single) bunch dynamics at ASTA
  - Design, build, and test 1st generation CW magnetized source of bunched beam
  - Run CW CAM-dominated beam in existing/upcoming ERLs
- **Intermediate term**
  - Push ERL performance to 10 MW class
  - Leverage opportunity to give input to upcoming projects (PERLE)
  - Explore options for 100 MW class system (IKEA?)
- **Long term**
  - Design, build, test 100 MW system optimized for magnetized transport, beam exchange ("CCR test")

Other JLEIC Talks

- Overview of JLEIC Ion Injector Complex — by Todd Satogata (JLAB)
- JLEIC Ion Linac Design — by Brahim Mustapha (ANL)
- Beam Polarization in Figure-8 Rings — by Vasiliy Morozov (JLAB)
- Nonlinear Beam Dynamics in JLEIC Collider Rings — by Yuri Nosochkov (SLAC)
- Dynamics with Crab Cavities for EIC — by Yue Hao (MSU/BNL)
- JLEIC Beam Synchronization Issue — by Jiquan Guo (JLAB)
- Overview of Collective Effects in JLEIC — by Rui Li (JLAB)
- Beam-Beam Simulation: JLEIC — by Yves Roblin (JLAB)
- Overview of JLEIC and eRHIC IR Designs — by Vasiliy Morozov (JLAB)
- JLEIC Machine Detector Interface — by Rik Yoshida (JLAB)
- RF for High Intensity EIC Storage Rings — by Robert Rimmer (JLAB)
- Crab Cavity Development for EIC — by Subashini De Silva (ODU)
- JLEIC Super-ferric Magnet R&D — by Peter McIntyre (Texas A&M)
- JLEIC Cooling: Conceptual Design, Simulation and Experiment — by He Zhang (JLAB)
- Magnetized Electron Source Development — by Abdullah Mamum (JLAB)
- Fast RF Kicker for ERL Cooler — by Haipeng Wang (JLAB)
- Test of CEBAF Operation Mode for JLEIC Injection — by Jiquan Guo (JLAB)

eRHIC Staging

F. Willeke

- Why staging? (just an exercise to be prepared for)
  - funding for full facility not available
  - Case that limited funding becomes available early: could be ready earlier

Stage 1 ➔ **substantial cost reduction wrt full build-out (30-40%?)**

- RHIC yellow ring for ions, minor changes from RHIC
- Storage ring for 5 GeV, only 1 of 3 dipoles installed in every cell, eventually half the quads
- RF installation for 5 GeV, 2 SC 2-cell cavities, 0.5 MW SR power
- **Rapid cycling synchrotron in AGS** 5 GeV (but good up to 10 GeV)
- Polarized source in Bld 912 adjacent to AGS
- No or little additional service and equipment buildings
- **No strong hadron cooling**
- **Only one IR/detector**

Stage 2 ➔ **Significant Cost reduction w.r.t full built-out**

- Add 2nd and 3rd dipole for 10 GeV operation in the storage ring
- Add RF cavities for 10 GeV (6.5 MW, add 5 cryomodules, add RF for RCS)
- **Reach full luminosity** — **Not clear, no hadron cooling?**

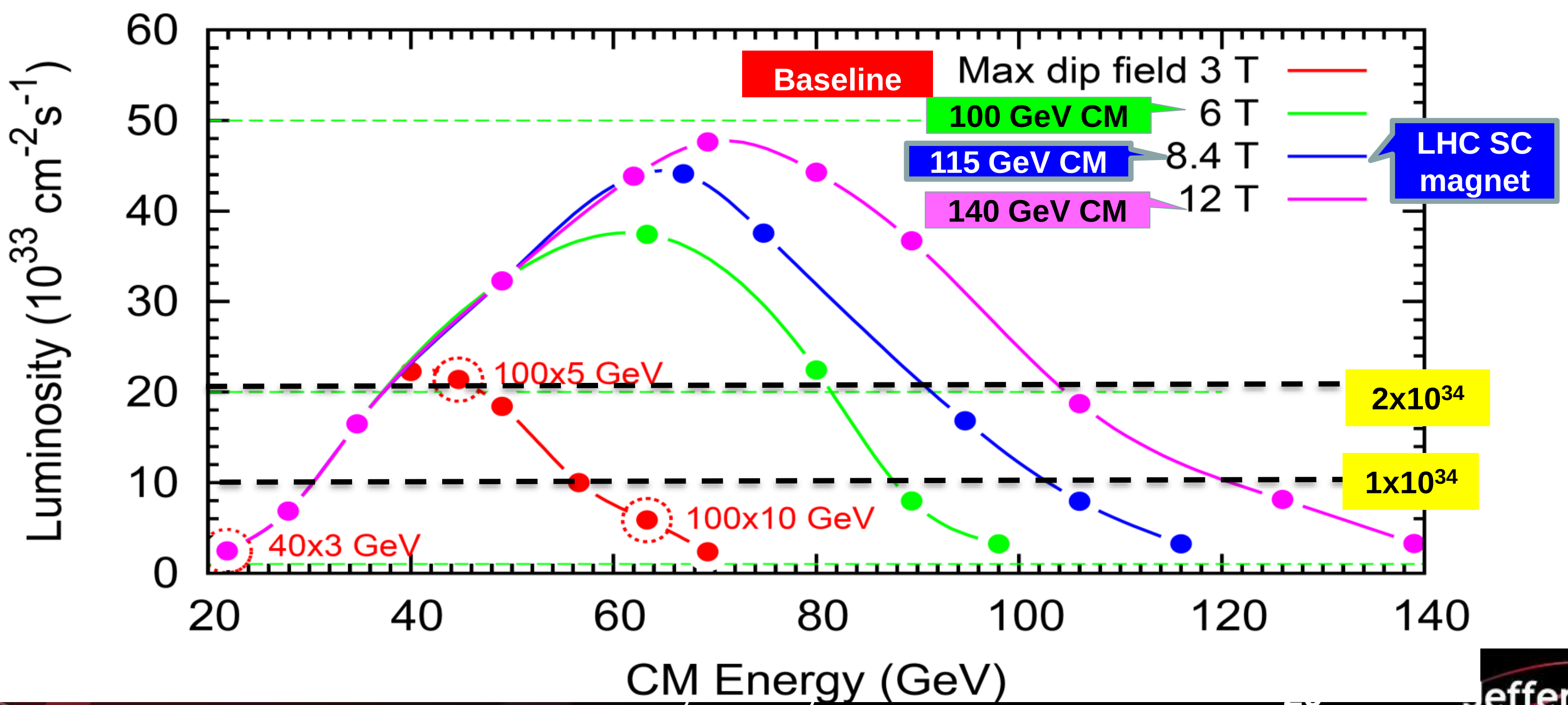
Stage 3 ➔ **cost increase wrt nominal small compared to cost of upgrade to full performance**

- Full build out of SR for 18 GeV (+ 80M$)
- **Strong Hadron cooling**
- 2nd IR and detector
- **RCS in the RHIC tunnel** 5-18 GeV (RF from AGS)

Ideas for JLEIC Staging

F. Pilat

- **Reaching high CM energy by staging**
  - Electron collider ring can go up to 15 GeV (limited by SR power and emittance)
  - Ion collider ring can go higher with high field strength of SC magnets
- **Hadron Cooling staging**
  - Weak cooling (no circulator ring)
  - Strong cooling with a circulator ring
- **Luminosity upgrade**
  - Doubling bunch rep rate and increase current
  - Higher energy also leads to high luminosity



Coordinated BNL-JLAB R&D

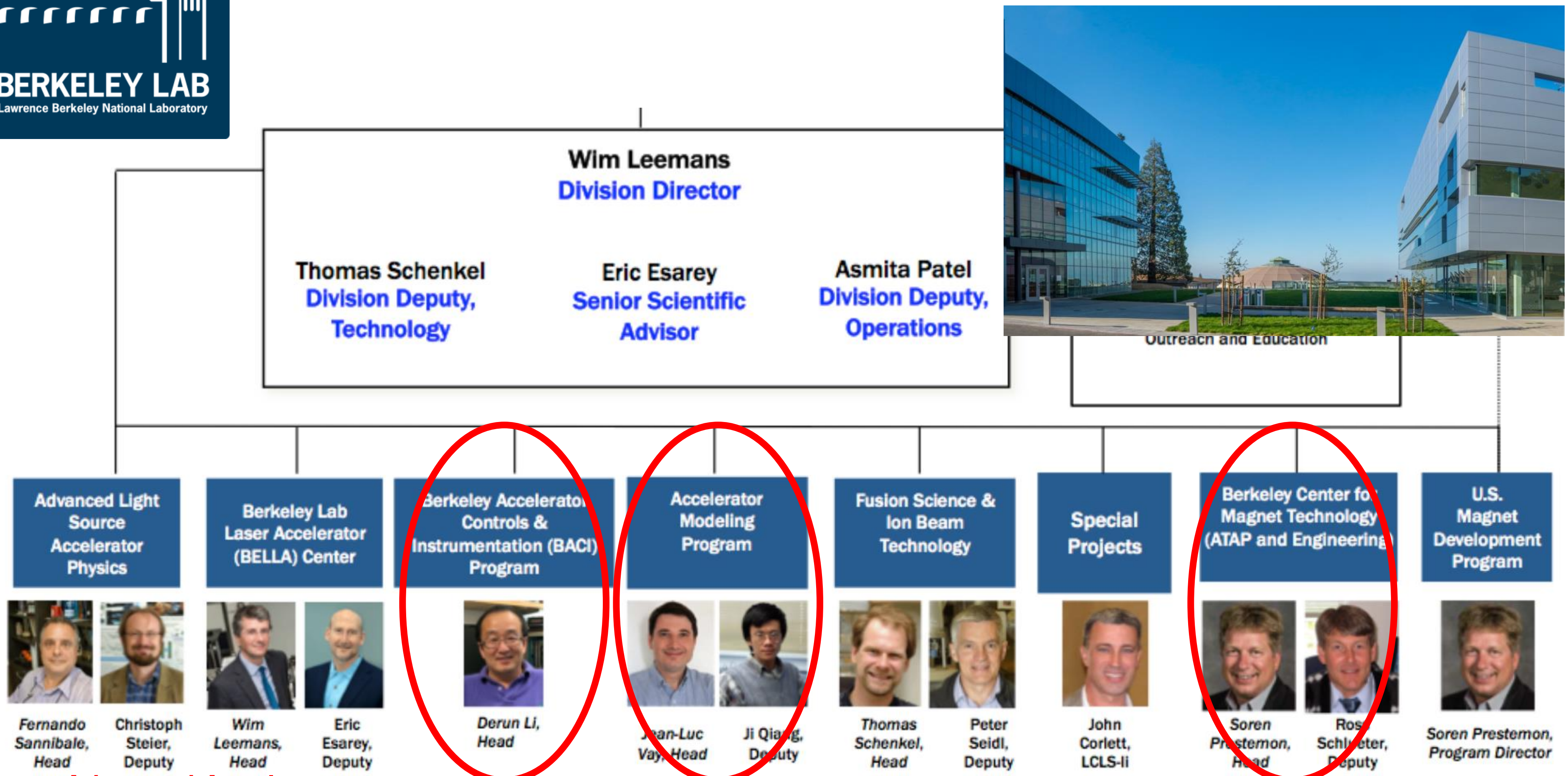
(currently under discussion)

F. Willeke

• Strong Hadron cooling for eRHIC and JLEIC,	Alexei Fedotov, Yuhong Zhang
• Augment the CBETA ERL for full test relevant for EIC ERL,	S. Brooks, D. Douglas
• Design and prototype of IR magnets,	Brett Parker, Tim Michalski
• Beam-Beam Simulation Tools Development & Application,	Yue Hao, Yves Roblin
• Design & Simulation of ERL for Beam Cooling,	W. Xu, B. Rimmer, S. Benson
• Performance Study of He-3 ion source	Anatoli Zelensky, A. Sy, R. Millner
• Study of e-Beam Polarization during Acceleration	F. Meot, F. Lin
• Crabbing integration, Dynamics, SPS Test	Y. Hao, V. Morozov, Q. Wu, B.Rimmer
• Broadband kicker for feedback systems	Michael Blaskiewicz, Bob Rimmer
• Study of electron cloud effects,	Michael Blaskiewicz, Rui Li
• Collective effects in EIC,	Michael Blaskiewicz, Rui Li
• Development of Superconducting Crab Cavities,	Q. Wu, B. Rimmer, J. Delayen
• Electron Source Development Study,	Erdong Wang, Matt Polker
• Study of ERL in CEBAF,	F. Meot, T. Satogata
• Head-on IR design, Dispersive Crabbing,	Ch. Montag V. Morozov
• Test of super-ferric 1.2 m cold mass prototype,	Tim Michalski, B. Parker

LBNL Expertise and Technologies for EIC

By Wim Leemans



Advanced Accelerator Physics R&D and the ALS testbed for some concepts

Accelerator physics and technology, advanced modeling

New integrated national SC magnet R&D program

LBNL Can Help EIC

W. Leemans

- We have strong capabilities that can contribute to EIC success:
  - Strong accelerator physics combined with high performance modeling
    - **Experience with high current storage rings** such as PEP-II, ALS, ILC damping rings, etc.
    - **Modeling of electron cloud, beam-beam interactions**
    - Exascale program to increase speed and fidelity of modeling tools
  - Specialized **RF design and high precision digital RF control, diagnostics**
  - Lead laboratory for HEP's U.S. **High Field Magnet Development**
    - Design, fabrication, testing and infrastructure for R&D in SC magnets that could be applied to EIC

- Berkeley Lab is committed to helping with the EIC
  - Funded LDRD to support collaboration with EIC.
  - Strong advocacy and connection with science through Barbara Jacak

BERKELEY LAB
Lawrence Berkeley National Laboratory

The Berkeley Accelerator Controls & Instrumentation (BACI) Center

W. Leemans

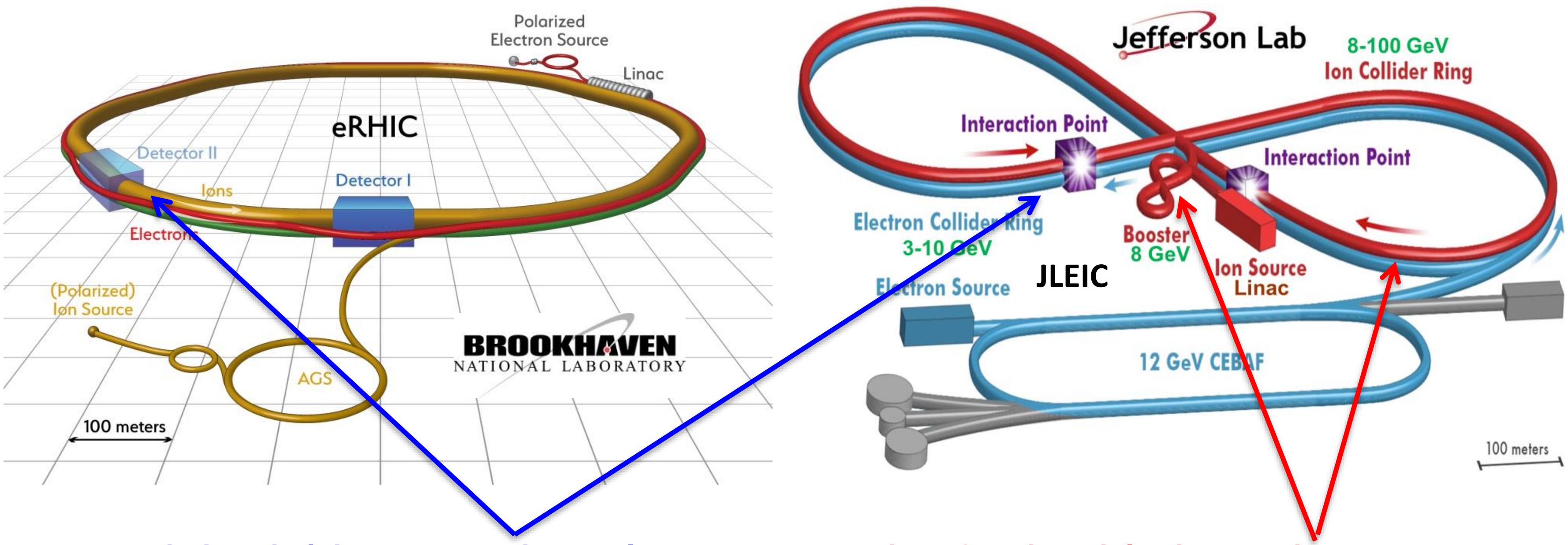
Three areas where BACI has competitive advantage, well established collaboration record and strong capabilities

1) **Advanced RF Design and Engineering**
   - CW Normal conducting cavities and RF structures, including RFQs and RF electron gun cavity (APEX and LCLS-II injector)
   - RF measurement and characterization
   - Beam impedance modeling and measurement
2) **Ultrahigh Precision Controls**
   - RF controls
   - Femtosecond synchronization
   - Controls for complex systems
3) **High Dynamic Range Beam Instrumentation**
   - Beam orbit feedback systems
   - Beam loss measurement and control
   - Femtosecond electron beams

BACI is well-positioned to respond to the R&D needs of EIC

Proposed LBNL contributions to EIC magnets

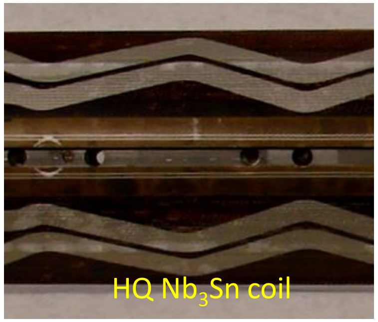
W. Leemans

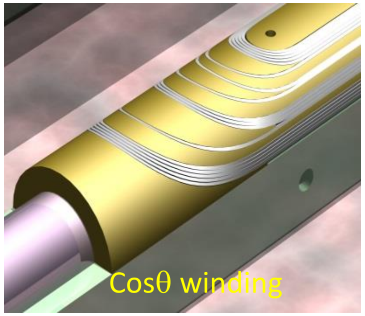


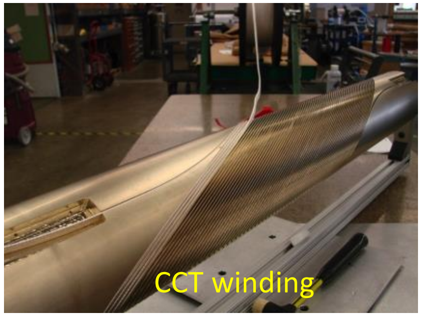
High Field IR Quadrupoles

Rutherford cable based arc magnets


LARP HQ quadrupole


HQ Nb_3Sn coil


Cosθ winding


CCT winding

LBNL proposed contributions to JLEIC Magnets

W. Leemans

1. *Fast ramping 3 T dipoles for the ion booster*
   - CIC dipole: explore feasibility of testing short model at LBNL: test goals, system requirements and supporting analysis
   - Cosq study: performance and cost estimates based on past projects
   - CCT (Canted Cosq) study: incorporates sagitta, combined function for efficient packing; and cooling of individual turns for high ramp rates
2. *Dipoles for the ion collider:*
   - Develop a cosq design for 6 T, to support operation at higher energy
3. *IR Magnets:*
   - Perform a preliminary analysis of the IR magnets to provide feedback on feasibility, design challenges, and possible iteration of the target parameters toward an optimal IR layout

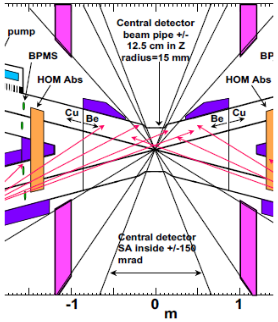
- Discussions with JLEIC are underway to prioritize topics and finalize plans
- EIC LDRD extension approved: includes magnet effort at 8% FTE in FY18

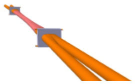
SLAC Expertise and Technologies for EIC

By Bruce Dunham

Interaction Region Design
(M. Sullivan, A. Novokhatski)

- We have already guided the JLEIC IR design to minimize the Synchrotron Radiation backgrounds in the detector
- More needs to be done to actually get background numbers in the detector from various SR sources and to optimally minimize these backgrounds
- The JLEIC detector team hopes to measure the electron beam polarization in a chicane downstream from the collision point. More work is needed to develop a polarization detector that will not be swamped by backgrounds.

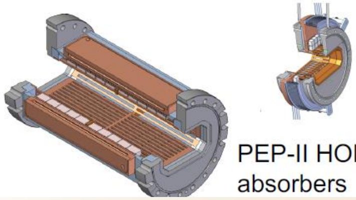




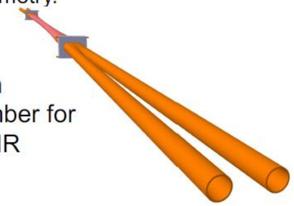
Collective Effects and Impedance Budget
(A. Novokhatski, J. Seeman, M. Sullivan)

The prime goal of this activity is to mitigate the collective effects in EIC based on our experience with high currents at the SLAC PEP-II B-factory

- Analytical estimate of the current limit for various instabilities.
- Model the wake function for simulations of the beam stability in the machine.
- Design and RF simulations of vacuum chambers
- Final simulation of beam stabilities and bunch lengthening.
- HOM heating calculations and specification for HOM absorbers
- Impedance budget of all important elements
- Summary with recommendations on the beam pipe geometry.



PEP-II HOM absorbers

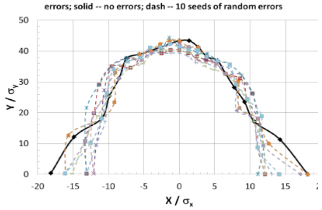


Beam Chamber for FCC IR

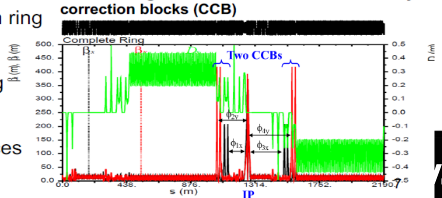
Lattice Design and Single Particle Dynamics
(Y. Nosochkov, Y. Cai)

- SLAC has extensive expertise in design and operation of colliders (PEP-II, MAP, ILC, FCC), including design of low-β IR optics, low emittance optics, non-linear compensation schemes, particle tracking, maps, error analysis, tolerance specifications
- In the past 3 years, SLAC team has already contributed to the JLEIC design of the ion and electron collider lattice, compensation of non-linear chromaticity, evaluation of dynamic aperture and error effects
- Future effort may include
  - Finalizing lattice designs of both rings
  - Compensation of detector solenoid in electron ring
  - Injection optics
  - Orbit diagnostic and correction in electron ring
  - Dynamic aperture optimization
  - Specification of field quality and error tolerances

Electron ring dynamic aperture with PEP-II non-linear field errors; solid -- no errors; dash -- 10 seeds of random errors

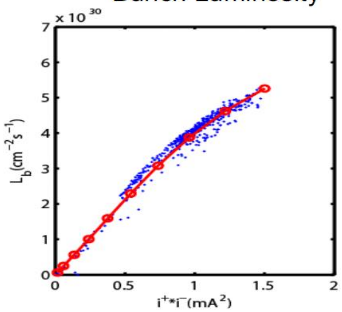


Electron ring lattice with non-linear chromaticity correction blocks (CCB)

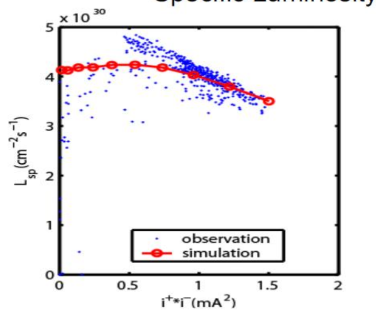


Beam-Beam Effects
(Y. Cai)

Bunch Luminosity



Specific Luminosity



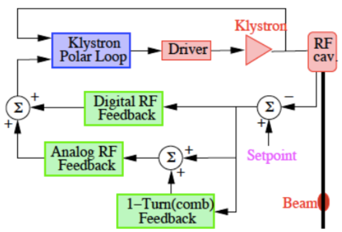
- Apply the benchmarked code at PEP-II and KEKB to study the beam-beam effects in the ion and electron collider
- Investigate the methods of mitigation in the beam-beam interaction, for example, traveling focusing

SLAC Expertise and Technologies for EIC

B. Dunham

LLRF and Beam Loading
(J. Fox)

- EIC designs have challenging goals for stored current
- The two rings have completely different RF systems and longitudinal dynamics
- Interactions of beam gaps with the RF systems lead to modulations of synchronous phase at the IP



SLAC can contribute:

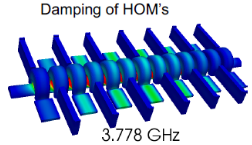
- Investigate the operational limits and impact on beam dynamics from impedance controlled RF systems.
- Time-domain non-linear simulations of beam dynamics incorporating the technology of LLRF systems
- Modeling and studies of new control techniques, based on experience gained from PEP-II and LHC
- Develop RF system tools and methods to optimize performance
- Synergistic with ongoing US-Japan high beam-loading studies for SuperKEK-B. Also have experience applying techniques at LHC and for HL-LHC studies.

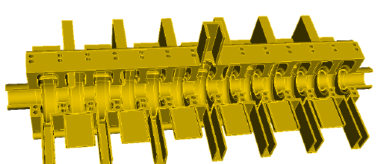
Crab Cavities – Normal and Super-conducting
(Z. Li, A. Ratti)

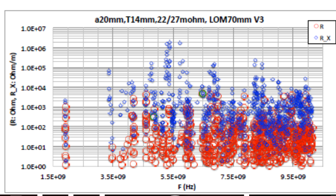
At SPEAR3, we are considering a crabbing scheme to produce short photon pulse:

- RF Crab cavity produces a rotation to the electron bunch, resulting in transverse spread of the emitted photon bunch
- A slit downstream allow a small slice to pass through producing a short photon pulse
- Kick voltage required within reach with CW NCRF technology
- Recent advances in RF technology developed at SLAC make CW NCRF approach much more affordable
- Larger aperture required to suppress short-range wakefield
- Multi-cell standing wave structure with elliptical cell shape was chosen for SSRL

Damping of HOM's





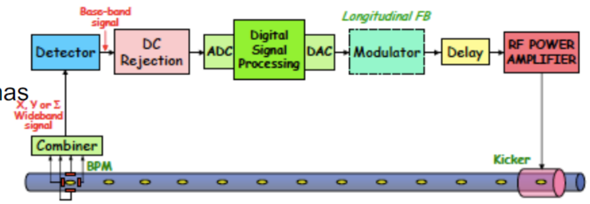


Beam Instability Feedback
(J. Fox)

SLAC can expand models (from PEP-II and SuperKEKB) to include the technical features of an EIC RF system

- Estimate growth/damping rates for all modes versus current fill patterns
- Use estimates/measurements of cavity HOM's to study coupled bunch motion
- Estimate required system gains and bandwidths for transverse and longitudinal feedback
- Understand interaction of modes within the LLRF loop bandwidth and broadband system bandwidth
- Research new control techniques for colliders

SLAC has a long history with beam instability feedback, and has developed technology and techniques that are used at accelerators around the world



Spin Tracking
(C. Mayes)

- Bmad is a well-developed software library for charged particles.
- It has been used for spin simulation studies for:
  - Fermilab g-2 ring
  - ILC
  - Julich COSY ring for future electric dipole moment (EDM) measurements
- It can be used for efficient long term tracking using one-turn symplectic maps, map normal form analysis, resonance strength analysis, spin invariant map analysis, analysis of chromatic aberrations, etc.

Validation with HERA-p calculation
Dots: Bmad
Lines: Hoffstaetter

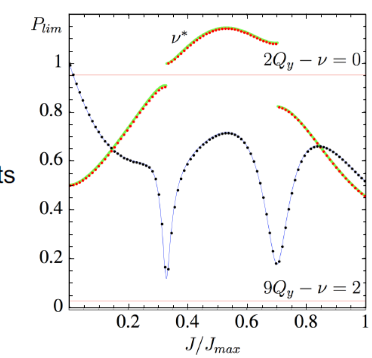


Fig. 4.19 from Hoffstaetter "High-Energy Polarized Proton Beams: A Modern View" Springer, 2006

SLAC Expertise and Technologies for EIC

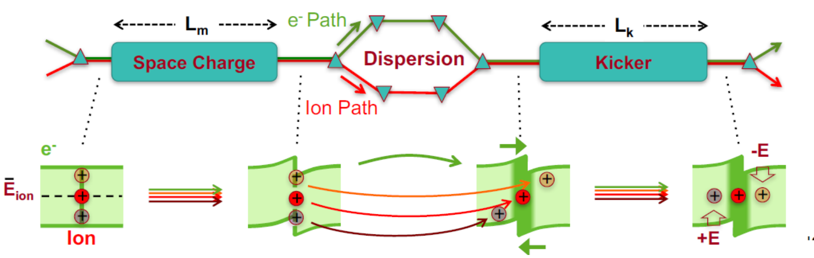
B. Dunham

Microbunching instability-based Coherent Electron Cooling
(D. Ratner, G. Stupakov)

SLAC

Goal: Use microbunching instability as an amplifier in CeC
- Relatively simple technically (requires only drifts and bends)
- Potential for very large bandwidth/fast cooling

SLAC Role:
- Theoretical studies to derive simple scaling formulas for cooling rate
- Support design of practical implementation, including proof-of-principle (e.g. L_m, L_k, R_{56}, electron current, etc.)
- Support simulations for design and tests



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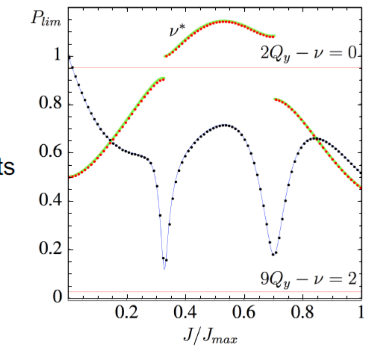
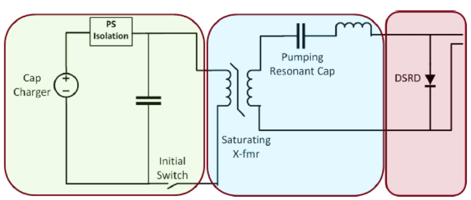


Fig. 4.19 from Hoffstaetter "High-Energy Polarized Proton Beams: A Modern View" Springer, 2006

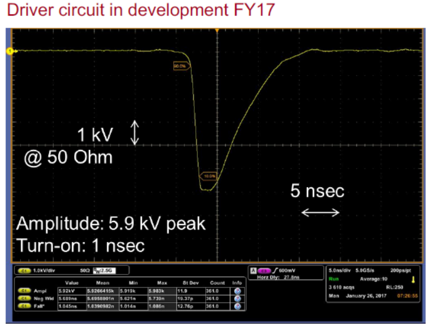
Fast Kickers
(T. Beukers, A. Krasnykh)

SLAC

- An ultrafast kicker is in development to separate bunches spaced five to ten nanoseconds apart for LCLS-II. One bunch is steered to the SXR undulator and the other to the HXR undulator. The resulting x-rays, of different color, are recombined for pump-probe experiments.
- The kick will be the sum of kicks imparted from multiple TEM mode structures.
- The ultrafast rise/fall time formation is enabled by DSRD topology. The pulser will develop 5-10 kV pulses with greater than 100pm repeatability at 10kHz.
- A development effort is underway to demonstrate these parameters, and in the future 1 MHz and up to 20 kV



Driver circuit in development FY17

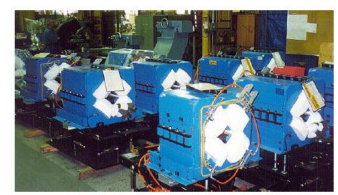


Demonstration Waveform @60 Hz

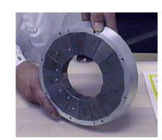
PEP-II and Linac Hardware
(J. Seeman)

SLAC





Permanent magnet construction (~1000 kg scale)
Klystrons >1 MW CW
High power Cu Cavities + HOMs
High power vacuum chambers
Dipole magnets
Quadrupole magnets ready to use
Beam diagnostics
Feedback electronics
Luminosity monitor (~1% at 1Hz)
SLAC linac sections




Accelerator Expertise at Fermilab and EIC - 10 Reasons to Call Chicago by Vladimir Shiltsev

Topics of Relevance to EIC

- Spin Dynamics
- Optics : IR and control
- Shielding, collimation and MDI
- Beam-beam and mitigation
- Electron cloud and instability simulations
- Cooling : design , systems
- SRF development
- SC magnet development
- Electron photoinjectors and tests at FAST
- Experimental R&D at IOTA

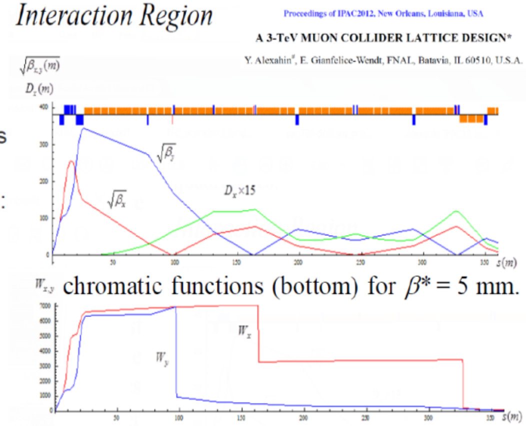
Interested? – *Call (630) 840-5241*

Fermilab

#2: Advanced IR Optics (Yu.Alexahin, D.Neuffer, et al)

Practical collider optics/IR designs:

- Tevatron (many iterations)
- LHC/HL-LHC
- *ee* & *μμ* Higgs factories
- Muon Collider
- Real-life complications:
  - Chromatic corrections
  - Dynamic aperture
  - Neutrino radiation
  - Detector background
  - Magnet irradiation by debris
  - Real magnets/errs

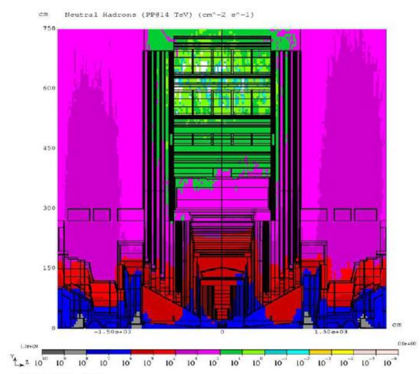


nilab and EIC 10/12/17 Fermilab

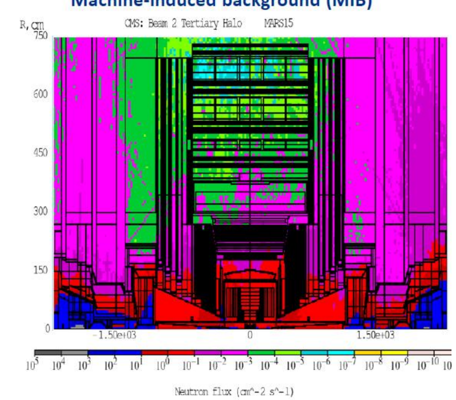
#3: Machine-Detector Interface and Detector Background MARS15 Modeling (N.Mokhov et al)

LHC pp *vs* Halo: Neutron Flux in CMS

pp "EIC: Heavy Ion Side"



Machine-induced background (MIB)



Barrel Si tracker at r=4 cm: $\Phi_n(pp) \approx 10^5\, \Phi_n(MIB_{total})$, but can differ by only a factor of 10 or so at startup conditions

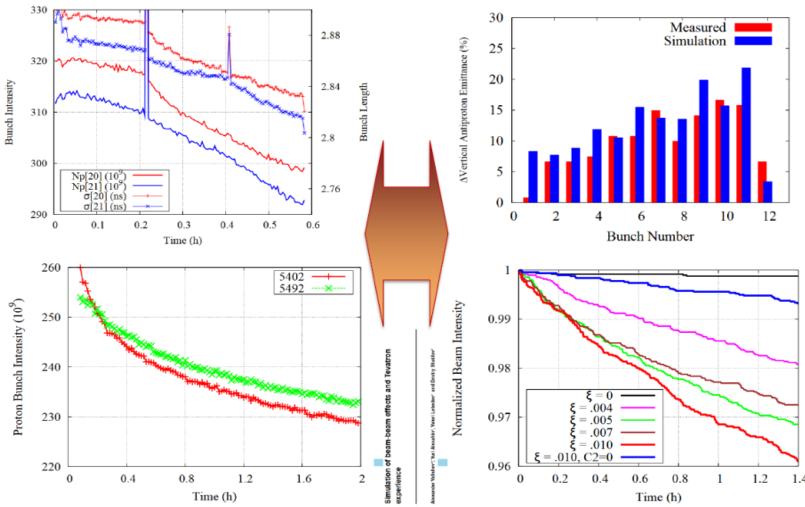
Fermilab

Accelerator Expertise at Fermilab and EIC

V. Shiltsev

#4: Beam-beam and e-lenses (A.Valishev, et al)

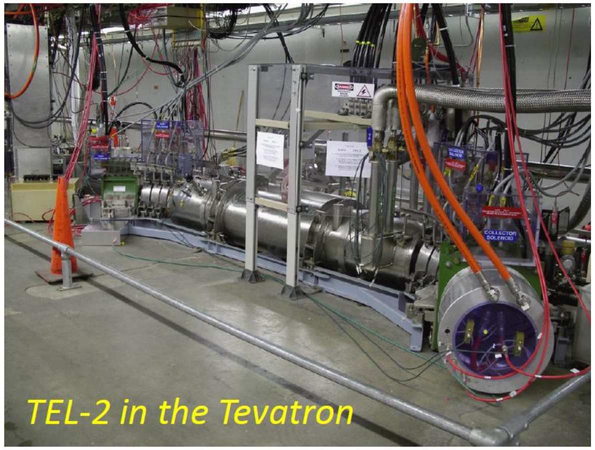
Tevatron stores | Simulated Tevatron stores



Electron Lenses (G.Stancari, V.Shiltsev, et al)

"Swiss knife"
e-lenses for:

- Long-range beam-beam compensation
- Head-on BBC
- Hollow beam collimation
- Landau damping
- Space-charge compensation

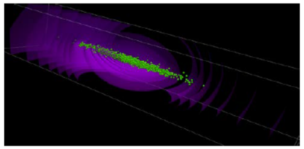


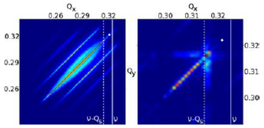
* Experimental studies of e-lens in IOTA (see below)

#5: Accelerator Modeling/Simulations/Tools

Synergia: self-consistent 3D Particle-in-cell accelerator simulation C++ code developed at Fermilab

- Specifically to simulate collective effects in accelerators and to take advantage of supercomputers *when available*
- Space charge, impedance, nonlinear single-particle optics
- Collective effects can be extended
- Single bunch, multi-bunch, multi-train simulations


Synergia particle-in-cell simulation

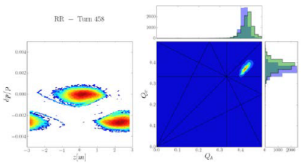

Landau damping study

Synergia is being developed as part of the SciDAC ComPASS4 collaboration, which Fermilab leads

https://compass.fnal.gov

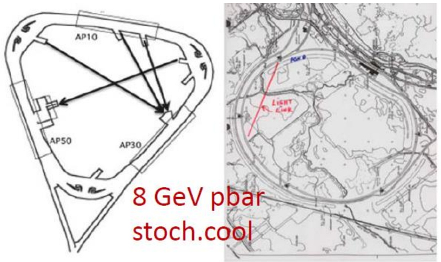
Synergia simulation activities at Fermilab include:

- Fermilab Booster space charge and impedance
- Fermilab Main Injector and Recycler space charge, impedance, slip stacking, transition Xing
- IOTA space charge, impedance and more


Slip-stacking phase space and tune footprint

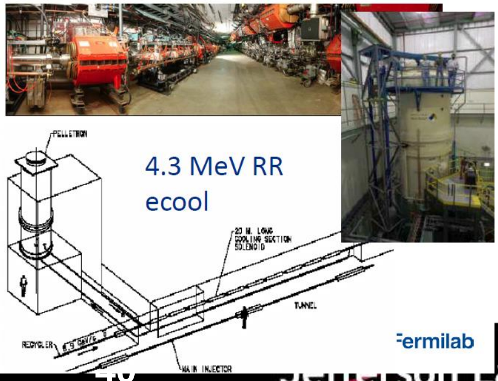
#6: Cooling

- Electron cooling
- Stochastic cooling
- Ionization cooling
- Cooling by instability
- Optical stochastic cooling



Fermilab could take on the entire EIC hadron cooling system:

- *design, prototyping*
- *construction, commiss'g*



Accelerator Expertise at Fermilab and EIC

V. Shiltsev

#7: SRF development at Fermilab

- Fermilab performs a **full cycle of work** related to R&D, design, manufacturing and testing of SRF cavities and cryomodules for High Energy Physics and other DoE programs and projects.
- Fermilab has world-recognized specialists in SRF – scientists, engineers and technicians – in all these areas as well as world-class facilities.
- Fermilab's SRF team performs a wide spectrum of **R&D related to SRF**:
  - materials research;
  - development of new cavity processing methods;
  - development of SRF cavities made from Nb/Cu, Nb_3Sn and other alternative materials;
  - development of new types of SRF cavities and components;
  - design of new types of cryomodules;
  - resonance control of the SRF cavities.

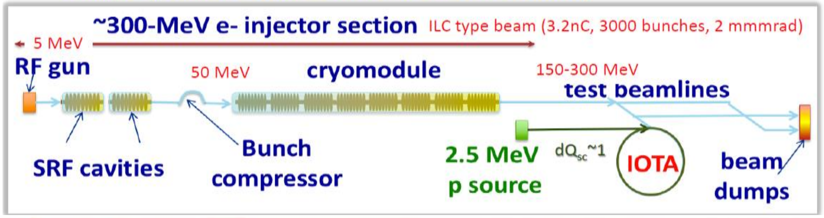
#8: Superconducting Magnets at Fermilab

Fermilab has been designing, building, and testing superconducting accelerator magnets for ~ 40 years.

- Energy Doubler/Saver → Tevatron → 774 NbTi (4.2 T) dipoles and another 216 focusing quadrupoles.
- Low beta quadrupoles for the Tevatron – complex magnets with high gradient of 140 T/m
- SSC dipole prototypes (2 left on is in the Smithsonian, one in the backyard of Fermilab)
- Low beta quadrupoles for LHC – operational until 2024, until HL upgrade
- Torus coils for JLab – 4x2 m^2, detector magnet
- LCLS-II – splittable quadrupoles
- LARP → HL-LHC Accelerator Upgrade Project (Nb_3Sn) – Fermilab is leading organization, in collaboration with BNL and LBNL
- High field magnet program (Nb_3Sn) – **15 T dipole R&D** as a part of the U.S. Magnet Development Program (MDP)

#9-10: FAST & IOTA : Overarching Motivation – R&D on Intensity Frontier Accelerators for HEP

- To enable multi-MW beam power, losses must be kept well <0.1% at the record high intensities:
  - Need <0.06% for the post PIP-II ~2.5 MW upgrade
  - Present level ~3-5% in Booster and MI synchrotrons @0.7MW
- Need to develop tools for:
  - Space-charge countermeasures
  - Beam halo control
  - Single-particle and coherent beam stability



Proposed Tests (Ya.Debenev, Yu.Zhang, et al)

- Demonstrate generation and acceleration of 3.2 nC magnetized beam
  - phase space configuration consistent with that in JLEIC Cooler: long, low dp/p bunch (fill linac phase acceptance); 6D top-hat if possible
- Test/validate single-bunch dynamics in merger designs at 5 MeV
- Characterize evolution of 3.2 nC phase space over long distances (order 100 m straight-ahead, longer distances using IOTA) in energy range 20-55 MeV
  - Assess impact of space charge, CSR
    - Emttance v. distance, degradation of magnetization, …
  - Characterize microbunching dynamics, evaluate microbunching gain
  - Provide benchmark data on evolution of different initial distributions (Gaussian, super-Gaussian, top-hat, …)
- Test Derbenev accelerating-mode-based emittance exchange (JLAB-TN-17-008); characterize evolution of resulting quasi-magnetized beam
  - existence proof will support viable alternative cooler system architecture for JLEIC
- Study of the beam-beam kicker for cooling e-beam switching between ERL and Circulator-cooler ring

Accelerator R&D in France – Main skills

- High-field superconducting magnets
- Superconducting accelerating cavities and cryotechnology
- Sources & injectors
- Radioactive beams
- Beam dynamics, final focus
- Plasma acceleration, laser/beam interactions
- Beam instrumentation
- Related technologies (RF, vacuum…)

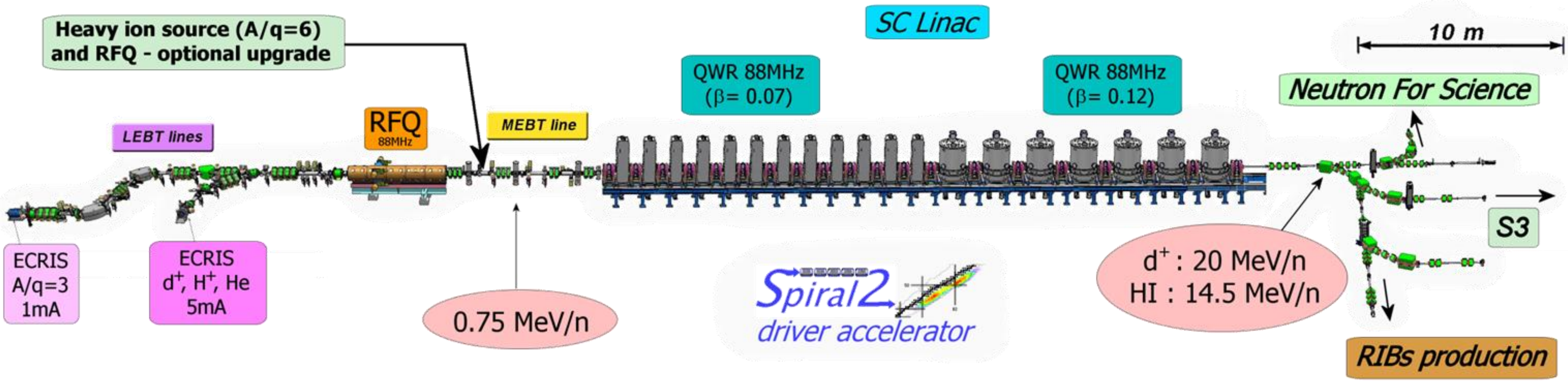
INTENSE BEAMS
LASERS
SUPERCONDUCTING
ION SOURCES
PLATFORMS
CRYOTECHNOLOGY

Accelerator R&D in France – Strategic Priorities

C. Marchand

#1 Participate to **world-class accelerator projects** development & construction

- **Support CERN for HL-LHC upgrade**
  - ❑ Prototyping & production of MQYY NbTi magnets *-> 2020+*
- **Achieve the construction and commissioning of SPIRAL2 ph.1 @GANIL**
  - ❑ SRF 200kW heavy-ion driver linac *-> first NFS experiments (2018+)*
  - ❑ Upgrade SPIRAL2 injector A/Q=7 *–> construction once S3 demonstrated*



Accelerator R&D in France – Strategic Priorities

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Secure our commitments in the construction of major accelerator projects (XFEL, IFMIF, ESS, FAIR & SARAF ph.2)

- XFEL (800+ couplers, assembly of 103 cryomodules) *-> last CM delivered to July 2017*
- IFMIF (EVEDA: HWR SRF prototype cryomodule) *-> 2018+*
- ESS (RFQ, Spoke & Elliptical SRF cryomodules…) *-> 2020+*
- FAIR (ion source, p-linac RF sources, Super-FRS…) *-> 2022+*
- SARAF ph.2 (rebunchers, HWR SRF cryomodules…) *-> 2022+*

Accelerator R&D in France – Strategic Priorities

C. Marchand

#2 Sustain an **ambitious accelerator R&D program** on selected areas

Pursue R&D on next-generation hh colliders

- Maintain & develop strong R&D collaboration with CERN *-> HL-LHC, HE-LHC, FCChh*
- R&D on high-field magnets for HE-LHC & FCC *-> Nb3Sn, HTC*
- Machine design & instrumentation *-> FCChh/EuroCircol, UA9 experiment*

Keep and develop our expertise on e+ e- colliders

- Maintain strong R&D collaboration with CERN and KEK *-> ATF2, ILC, CLIC, FCCee…*
- Commissioning of SuperKEKB-BEAST *-> luminosity monitoring, background @ IP*
- R&D SRF, couplers, beam @IP, e+ sources… *-> be ready for a possible ILC construction!?*

Develop (laser-)plasma acceleration (electrons, ions)

- Definition of a 2025 roadmap *-> experimental program at CILEX/Appolon, EuPRAXIA DS…*
- Improve French (& European) teams structuration

Accelerator R&D in France – Strategic Priorities

C. Marchand

#2 Sustain an **ambitious accelerator R&D program** on selected areas

Pursue & focus the R&D effort on high-power ion linacs

- R&D on Superconducting RF *-> multi-layer structures, mech. polishing, low beta high Qo…*
- Machine design & instrumentation *-> beam halo, reliability schemes, high power RF…*
- R&D on sources & injectors *-> p/d/HI sources, RFQs*
- R&D on exotic beam production *-> which TIS, booster, cooler for which element?*

Sustain R&D on photo-injectors and innovative e- / light sources

- R&D on high brightness short bunches photo-injectors *-> sub-ps, R&D @PHIL*
- R&D on laser-beam interaction *-> high Q optical cavities & recirculators, synchronisation*
- Keep our high expertise on X and γ Compton sources (LAL) *-> ThomX, ELI-NP*
- Ongoing brainstorming on ERLs *-> possible multi-turn demo project Perle@Orsay?*

Accelerator R&D in France – Strategic Priorities

C. Marchand

#3 Develop **partnerships** & propose **innovative accelerators for applications**

Accelerators for energy

- Keep & further develop our leadership on accelerators for ADS *–> R&D for MYRRHA, GUINEVERE experiment @SCK*CEN (Belgium)*
- Be ready for a possible construction of MYRRHA 100 MeV *–> from 2018?*
- On the fusion side, secure our comitments in IFMIF *–> demo @Rokkasho (-> 2018/19)*

Accelerators for health

- Radio-isotope production *–> ARRONAX (Nantes), CYRCE (IPHC Strasbourg)*
- R&D for therapies *–> instrum. for hadrontherapy, new concepts (eHGRT @PRAE, AB-NCT?)*

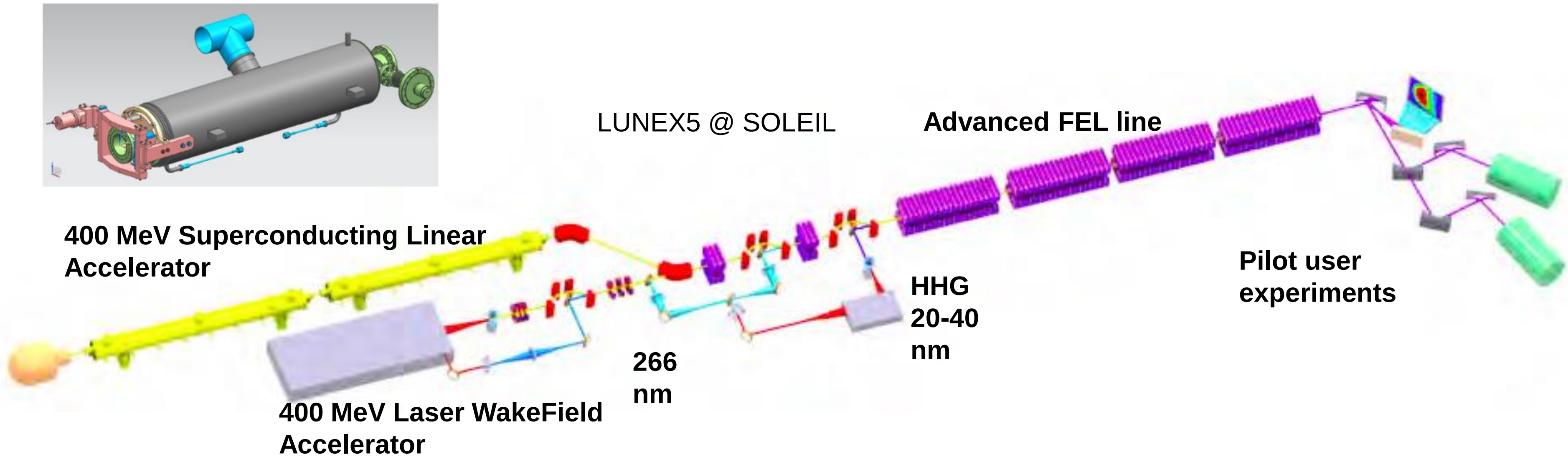
Accelerators as versatile neutron or light sources

- Secure our comitments in SARAF (Israel) and ELI-NP (Romania)
- Achieve Thom-X Compton source*–> 1st beam in 2018/19*
- Help preparing next-generation FEL *–> LCLS2, R&D for LUNEX5 @SOLEIL*
- Develop R&D on compact accelerator-driven neutron sources *–> IPHI, GENEPI2*

Accelerator R&D in France – Strategic Priorities

C. Marchand

#3 Develop **partnerships** & propose **innovative accelerators for applications**



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Accelerator R&D in France – Strategic Priorities

C. Marchand

#4 Develop forefront **research infrastrutures** and **technological platforms**

Improve national structuration of our operating research platforms

- Accelerators for nuclear physics *–> GANIL (Caen), ALTO (IPN Orsay)*
- Multi-disciplinary accelerator-based platforms (materials, radiobiology, environment…) *–> AIFIRA (CENBG Bordeaux), ANAFIRE (IPN Lyon), ANDROMEDE (IPN Orsay), ARRONAX (Nantes), CYRCE (IPHC Strasbourg), GENEPI2 (LPSC Grenoble), SCALP (CSNSM Orsay), IPHI (IRFU Saclay)*

Maintain of our technological platforms for accelerator R&D & develop partnerships with industry

- Superconducting RF technologies *–> Synergium (IRFU), Supratech (IPN+LAL Orsay)*
- Superconducting magnets technologies *–> Synergium (IRFU)*
- Ion sources & injectors R&D platforms *–> Synergium (IRFU), LPSC (Grenoble), GANIL*
- High-intensity beams R&D platform *–> IPHI (IRFU)*
- ISOL technologies platforms *–> ALTO (IPN Orsay), GANIL*
- Photo-injector & Electron-Laser Interaction R&D platform *–> PHIL (LAL Orsay)*