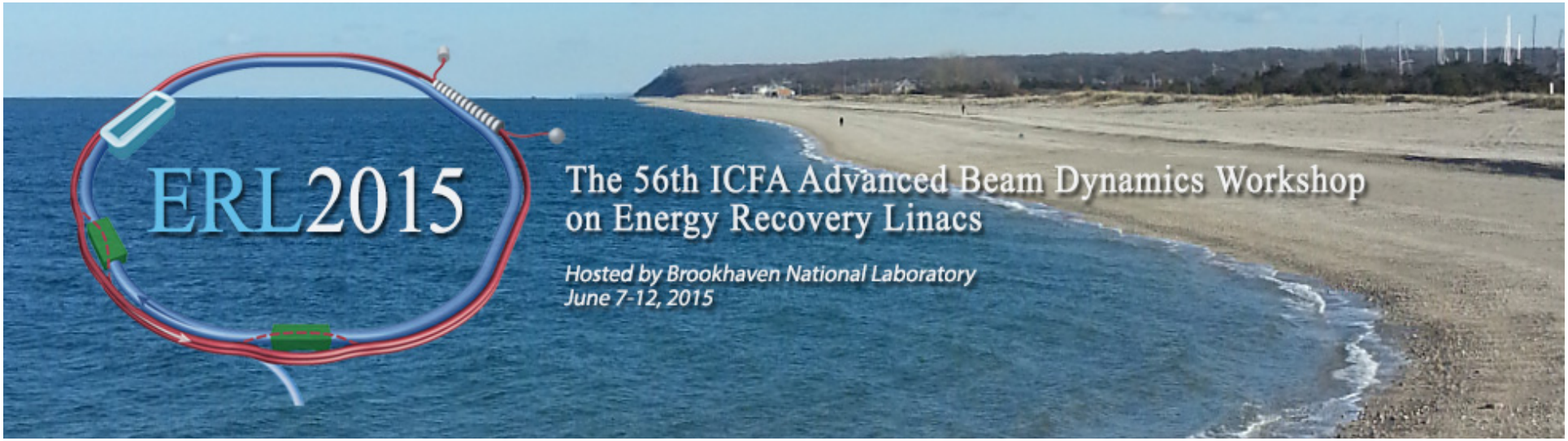


Working Group 2:

ERL Beam Dynamics and Optics: Collective Effects, Multi-Pass Effects, Halo Simulations

Michael Abo-Bakr (HZB), Vadim Ptitsyn (BNL)

15 talks presented in Plenary and Parallel sessions

WG2: working group charge

Workshop on Energy Recovery Linacs (ERL2015)

June 7-12, 2013, Stony Brook University, Stony Brook, New York

ERL: beam dynamics and optics working group charge

Dr. Michael Abo-Bakr, HZB

Dr. Vadim Ptitsyn, BNL

WG2 will address the optics and beam dynamics challenges in ERLs. It will include lessons learnt from past and present ERL operation as well as issues arising during the design work on future ERL facilities. The group scope includes design approaches for one-pass and multi-pass ERL lattices, error tolerances, preserving longitudinal and transverse beam emittances during beam transport, simulation tools suitable for ERL modelling. We also will look at beam instabilities and collective effects as well as at mechanisms defining halo formation and beam losses.

Hot Topics:

ERLs & FFAG

- Cβ (Cornell/BNL): Hoffstätter, Mayes
- eRHIC (BNL): Brooks, Tsoupas, Liu
- LHeC (CERN): Bogacz
- Beam Transport Simulation: Meot. Hao

Microbunching Instability

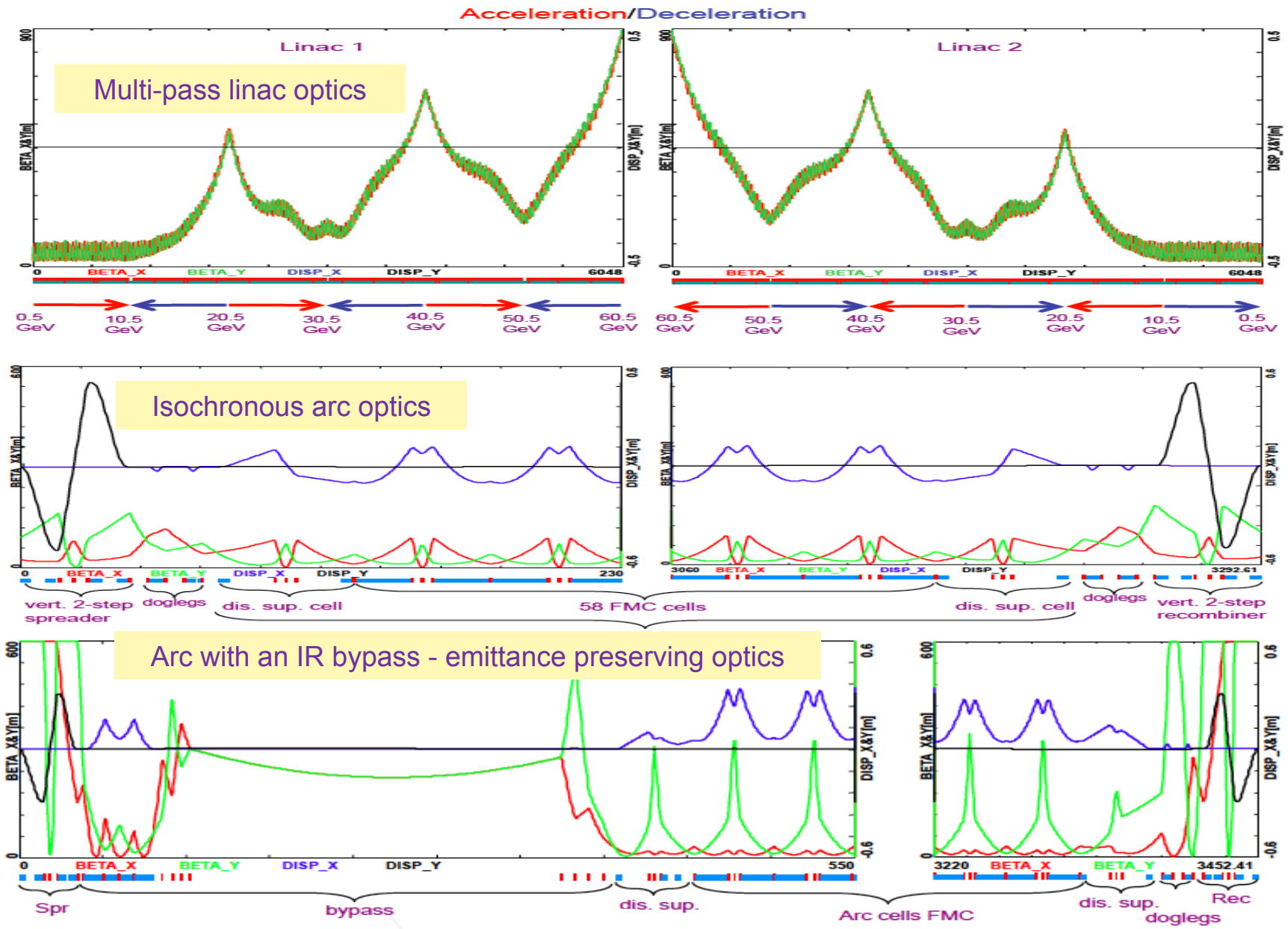
- μB in ERLs: Meseck
- μB with LSC & CSR: Tsai

Beam Break Up

- Transv. BBU: Kuerzeder
- HOM BBU (KEK ERL): Chen

A. Bogacz and D. Pellegrini

LHeC ERL – Optics Design

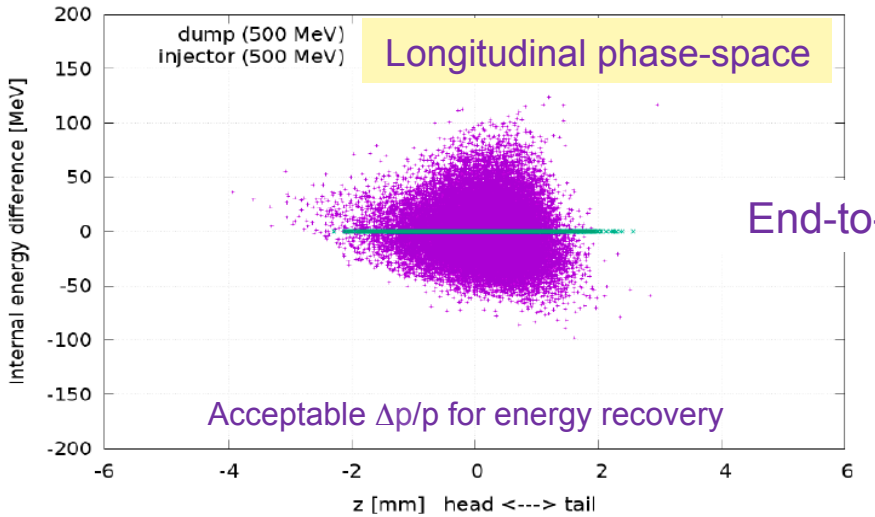


A. Bogacz and D. Pellegrini

LHeC ERL – Beam Dynamics

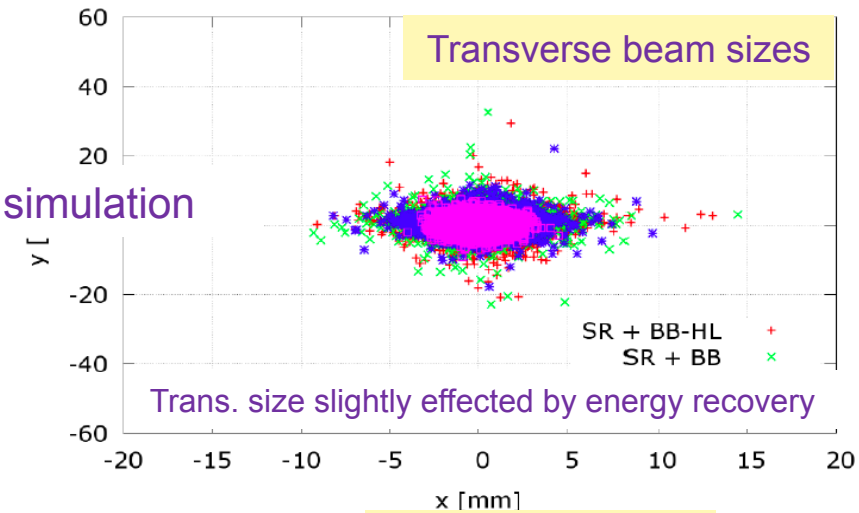
Synchrotron Radiation

Evolution of the Longitudinal Phase Space



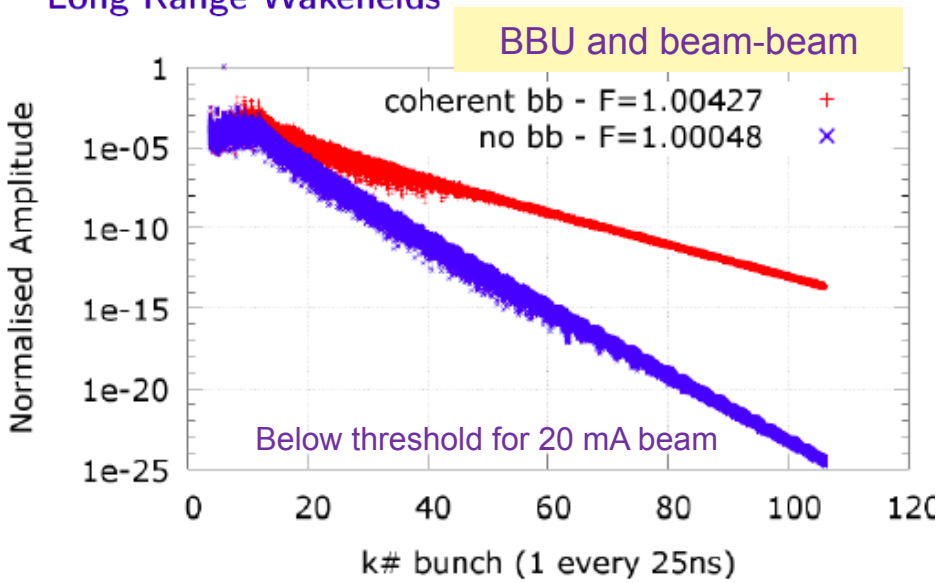
Synchrotron Radiation and Beam-Beam

Transverse Plane at Dump



End-to-end simulation

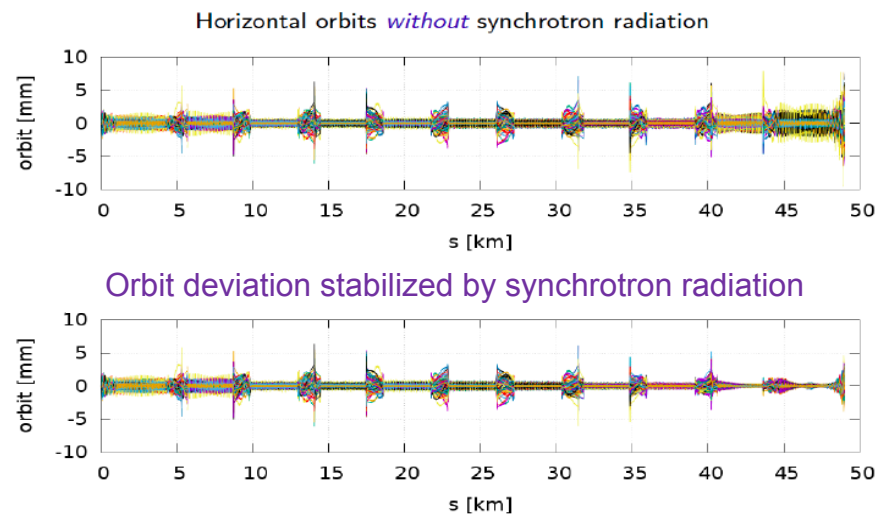
Long Range Wakefields



Cavity misalignments

300 micron rms

100 uncorrected orbits obtained for 300 μm misalignments and 300 μrad tilts.



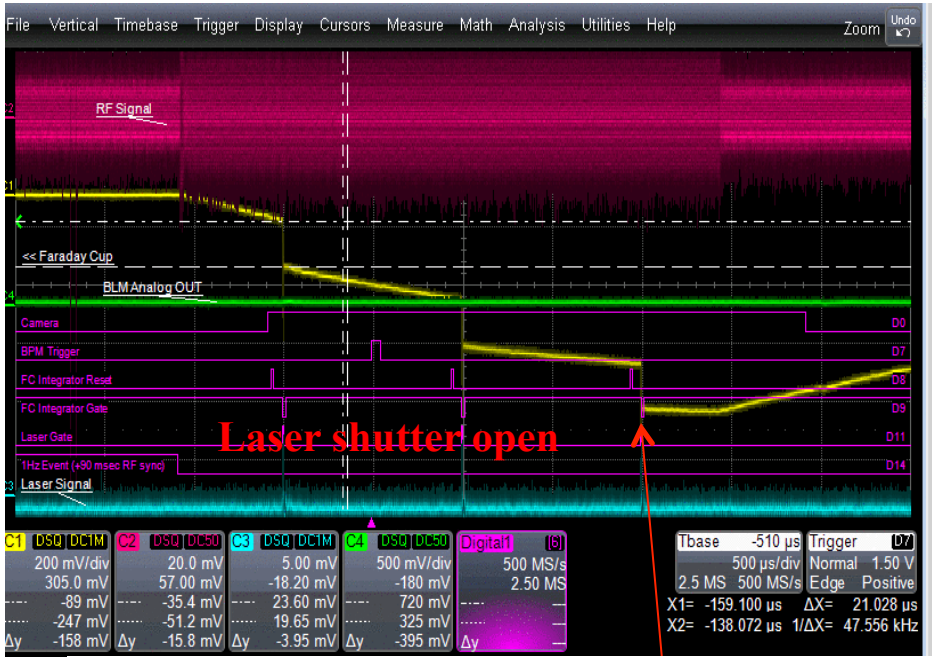
Mile stones: commissioning with beam

- First beam from the SRF gun with CsK2Sb photo cathode (Nov. 2014)
- DOE Approved to beam commissioning Gun to dump (Jan 2015)
- New cathode conditioned (Jan 2015)
- All ERL components installed, ARR for full ERL commissioning (May 2015)
- First good QE cathode (May 2015)
- High charge per bunch from the gun (achieved June 2015)

Future plans

- Gun into beam dump commissioning (Summer 2015)
- ERL beam test low current (Fall 2015)
- Laser system upgrade (Fall 2015)
- Gun to dump then ERL gradually increase current (until Feb 2017).
- Preparing for commissioning ERL components at RHIC IP2 for Low Energy RHIC electron cooler. (Feb 2017-March 2018)

Beam commissioning with new cathode June 2015.



Faraday cup signal (1MΩ termination)

Ninja star shape beam profile observed during solenoid scan

Set up

- **Laser: 0.044 mWatt, green,**

Pulse structure 5 µsec, every 500 µsec; 9.38MHz rep rate.

- **RF: 0.65 MV, 3 ms;**
- **eBeam:**

  charge per macro bunch 0.8nC/47bunches=17pC

  dark current 4 µ A;
- **Photocathode cold QE=1e-2 very Good!!!**

D. Kayran

FFAG Recirculation (eRHIC):

Basic Principle:

Strongly focusing lattice, using quadrupoles, which centers are offset

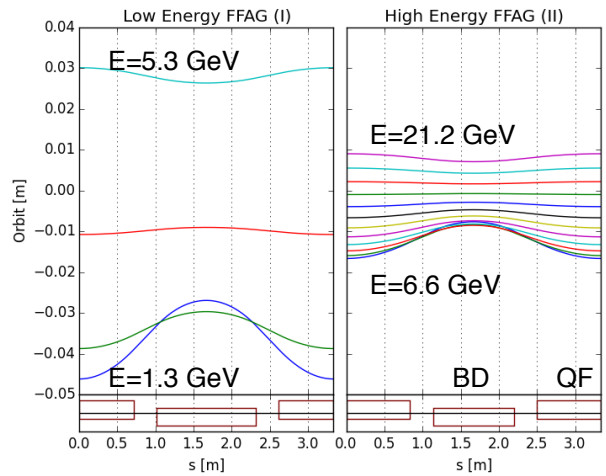
Should be able to transport beams in wide energy range (factor 4)

Used at:

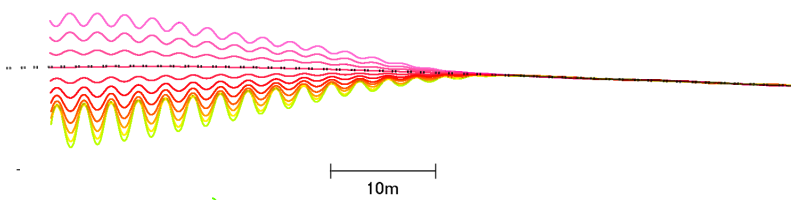
- Sub-GeV range proton accelerators
- NS-FFAG electron accelerator EMMA

Future applications:

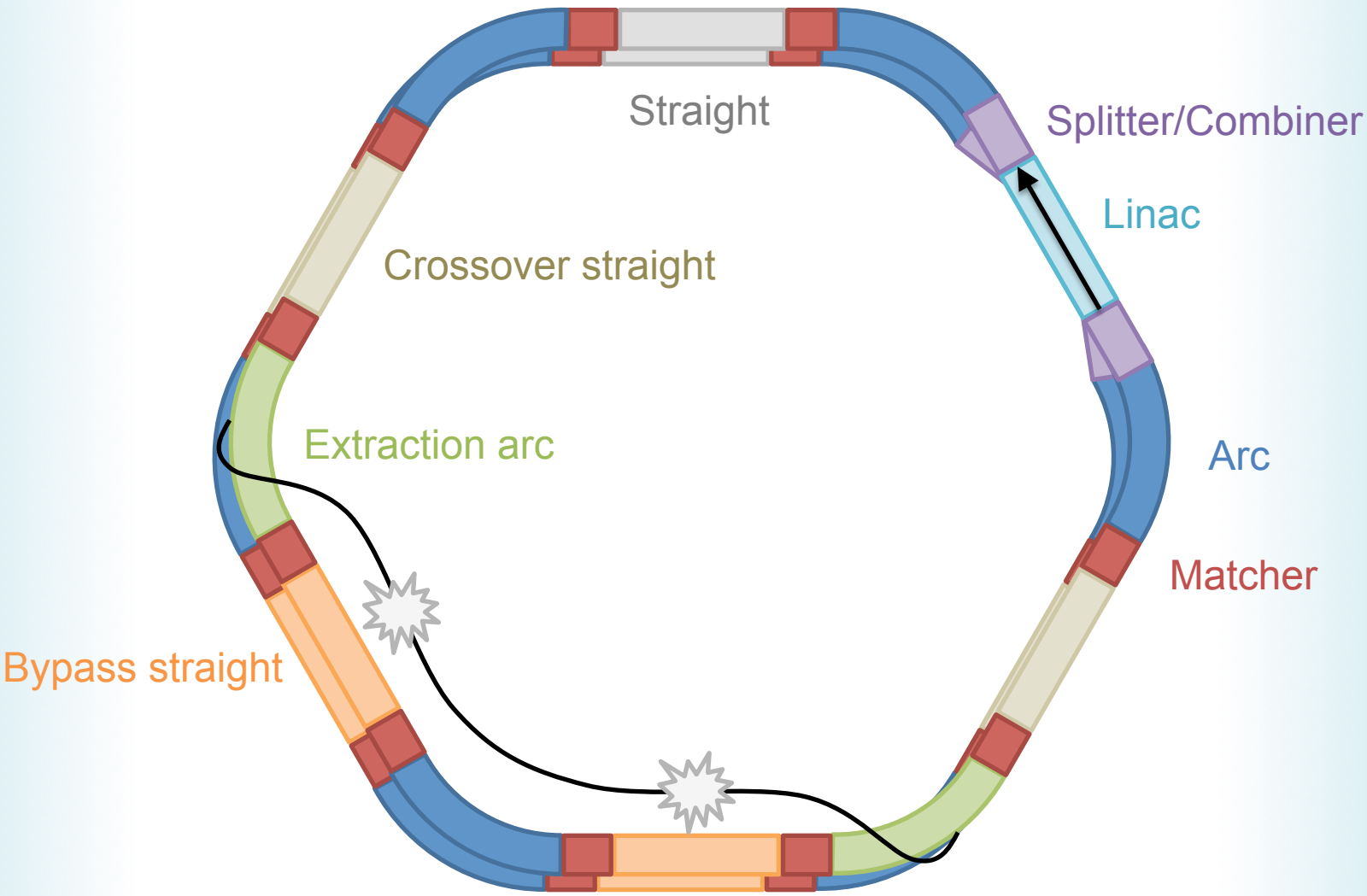
- eRHIC
- Cornel-BNL ERL-FFAG Test Facility
- Other future multiturn recirculators ?



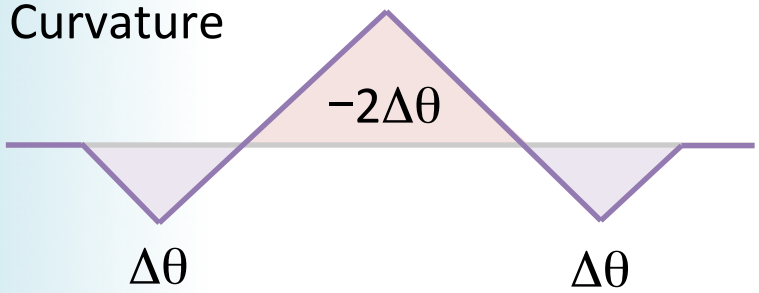
Orbits in eRHIC Transition section

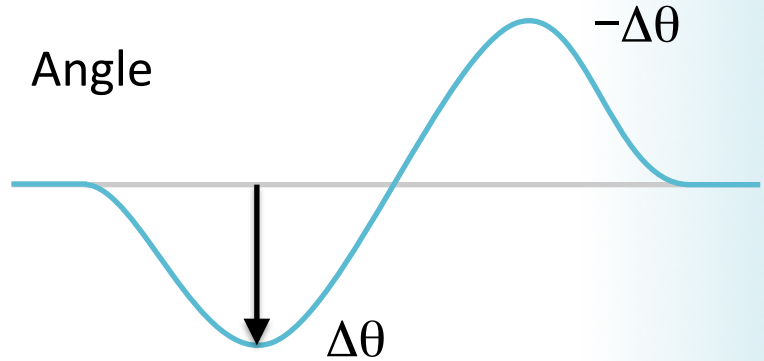


All eRHIC FFAG Special Sections



Detector Bypasses: a Flexible FFAG



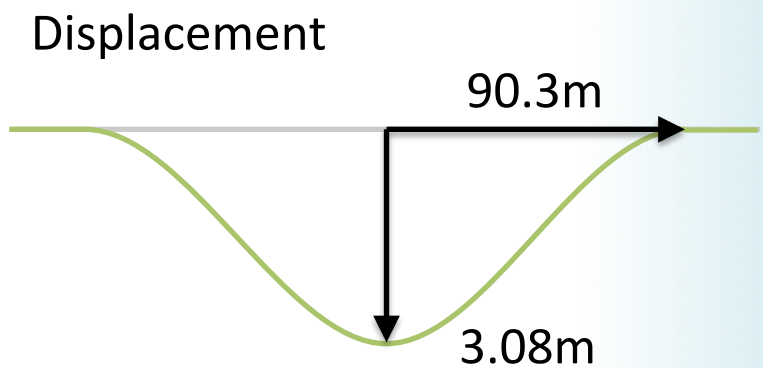


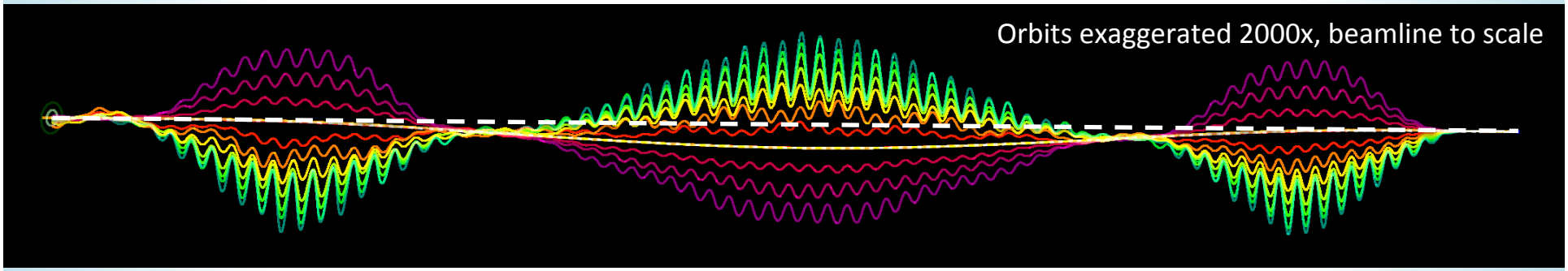
Bypass straight

3	9	9	17	17	9	9	3

Normal straight

76 cells



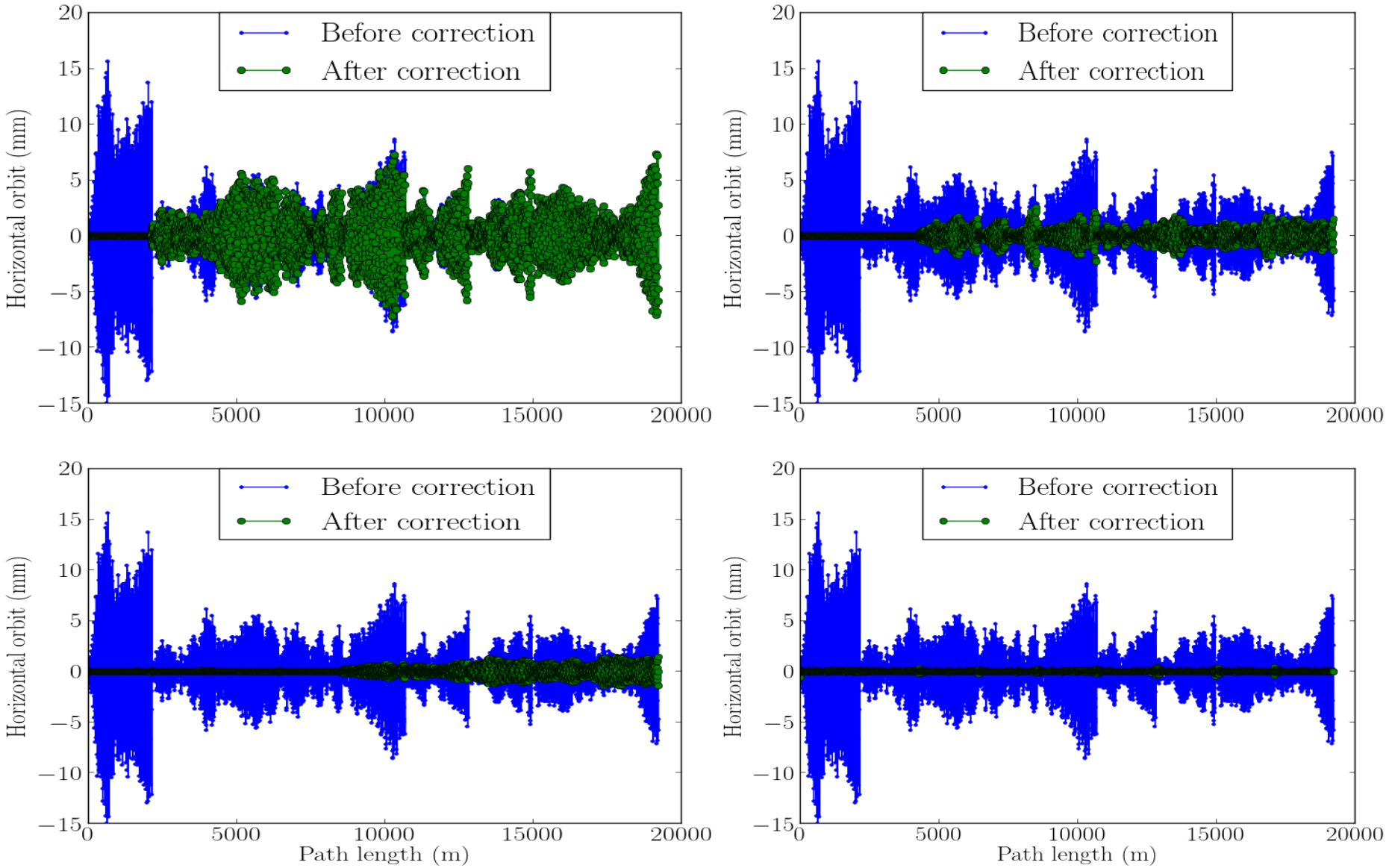


Correction Methods for Multi-Pass eRHIC Lattice with Large Chromaticity, C.Liu (BNL)

- Orbit/optics correction for FFAG eRHIC is a multi-pass, multi-particle problem.
- Simultaneous multi-pass single particle orbit correction works fine for FFAG machine in simulation.
- Orbit of eRHIC FFAG needs to be corrected based on realistic/measured orbit response due to large chromaticity.
- Single particle optics correction has been demonstrated in simulation.
- Multi-particle optics correction (with large chromaticity) to be demonstrated in simulation.
- The difficulty of both are also associated with the large dimensions (# of orbit measurement, # of correctors), in addition to chromaticity.

C.Liu (BNL)

Single particle orbit correction

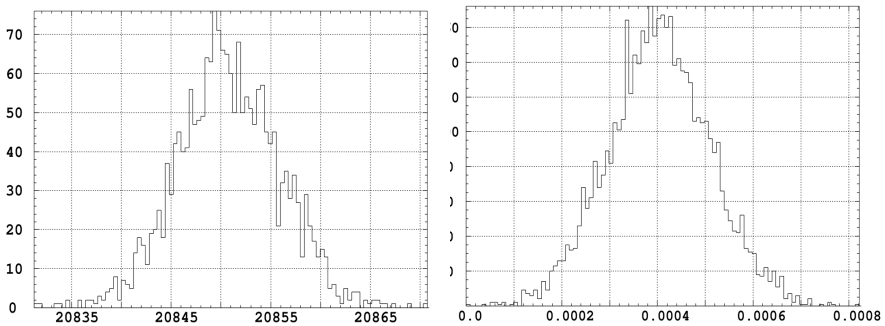


Beam and Polarization Dynamics in Electron FFAG Lattices, F. Meot (BNL)

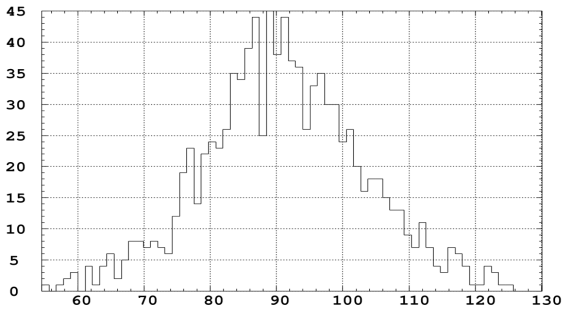
End-to-end beam and spin dynamics studies in eRHIC

SR related e-bunch properties after 11-pass acceleration to collision :

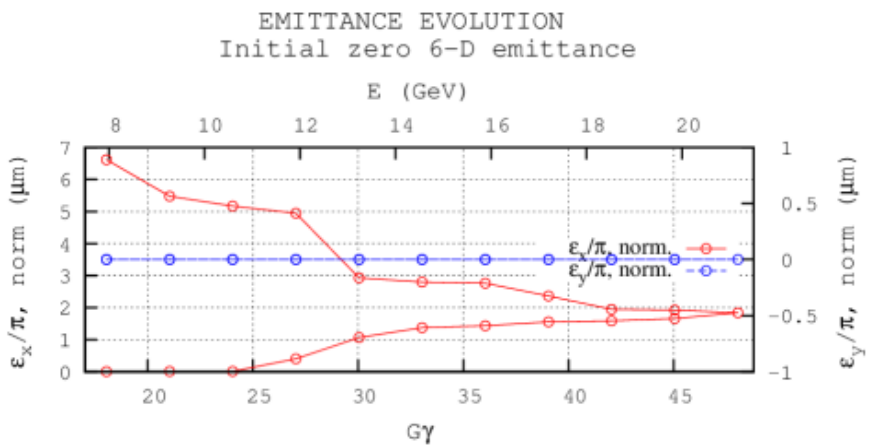
σ_E~5MeV **σ_l~100um**



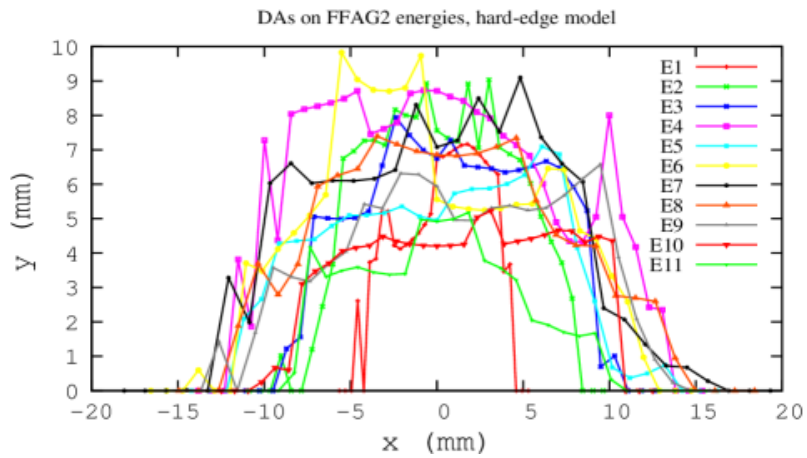
SR induced depolarization, at collision energy. Spin diffusion 12 deg, polarization >97%



SR related horizontal emittance evolution over acceleration/deceleration cycle 7.94→21.16→7.94 GeV :

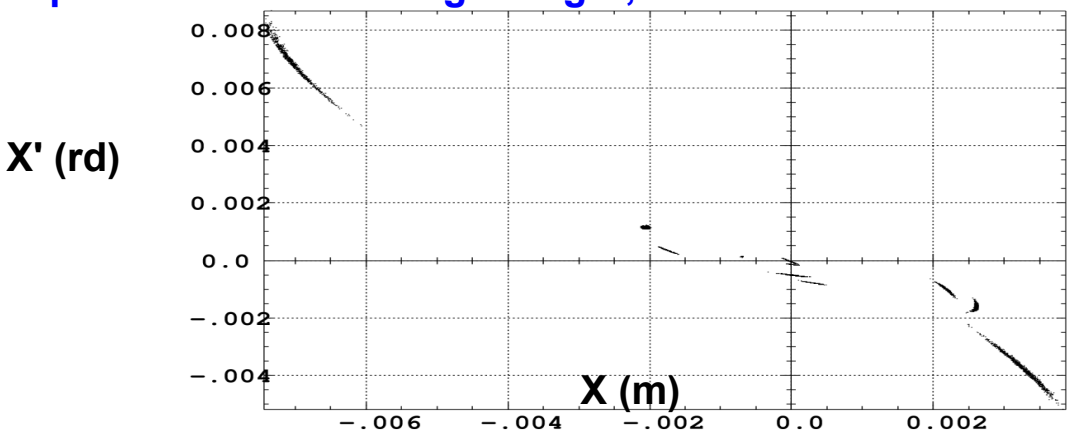


Available DA studies, *e.g.* here, effect of random 3Gauss@1cm dodecapole defect in all quads, 1-turn DA, 11 energies

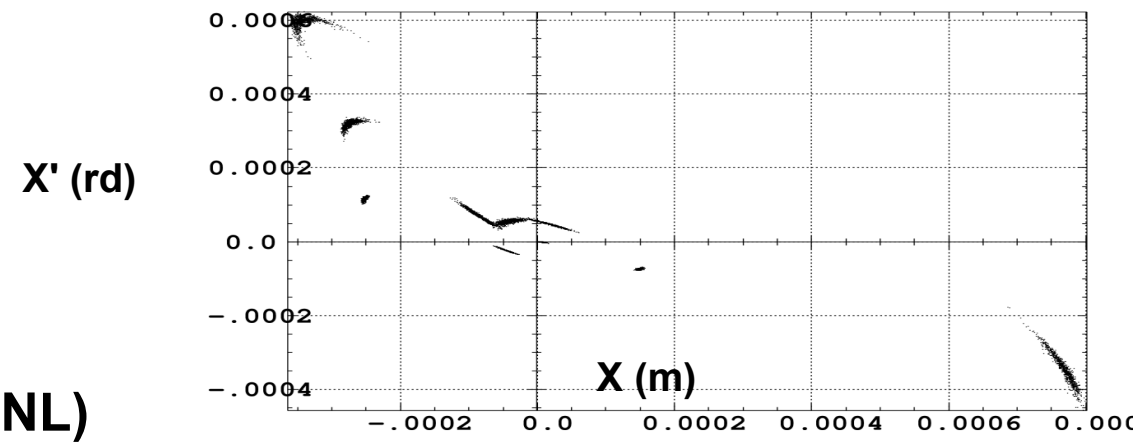


Preliminary investigations on the feasibility of ±40 µm random quadrupole misalignment defect compensation, 11 beams in one go

BEFORE CORRECTION, 11 circulating energies are far off-axis, up to 10mm apart (observation point is center of long straight, all bunches should be aligned on (x,x')=(0,0))

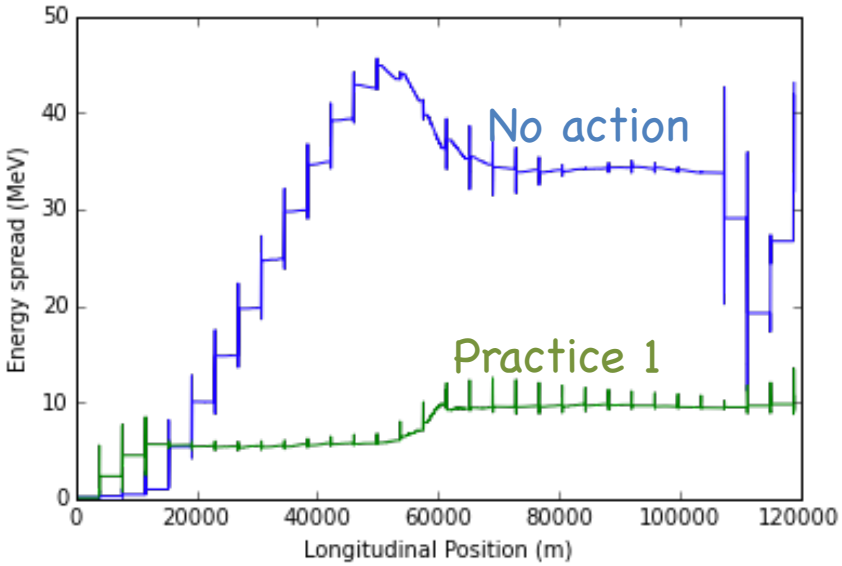


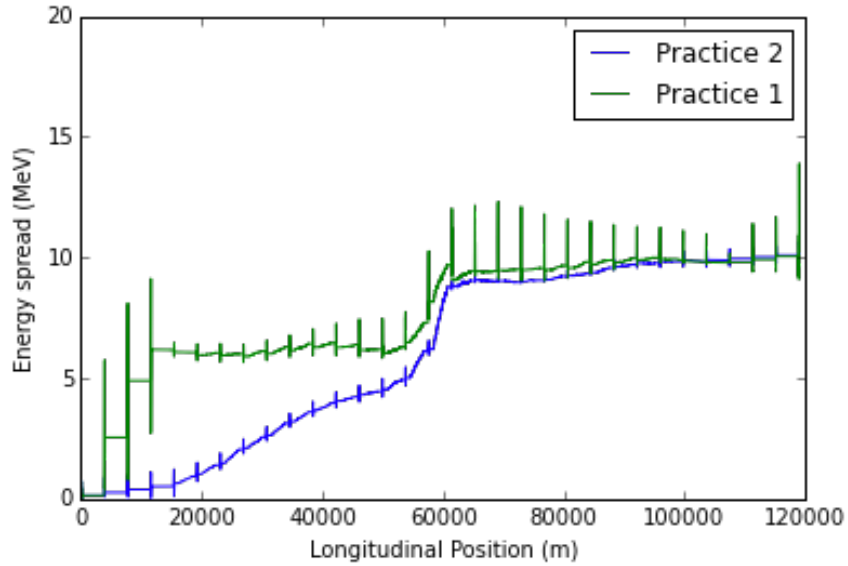
AFTER CORRECTION, using a basic fitting/constraint procedure, beam mis-centering has been reduced by a factor of ~10

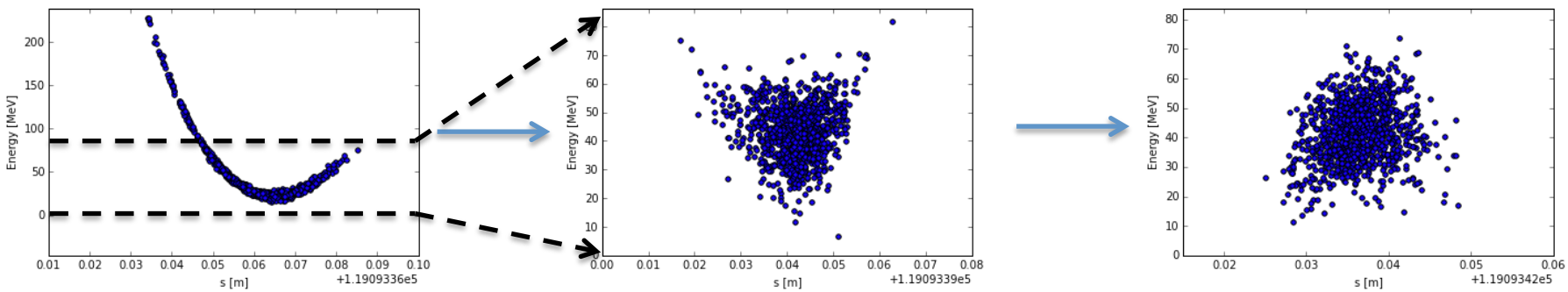


F. Meot (BNL)

Aspects of eRHIC Longitudinal Dynamics, Y. Hao (BNL)



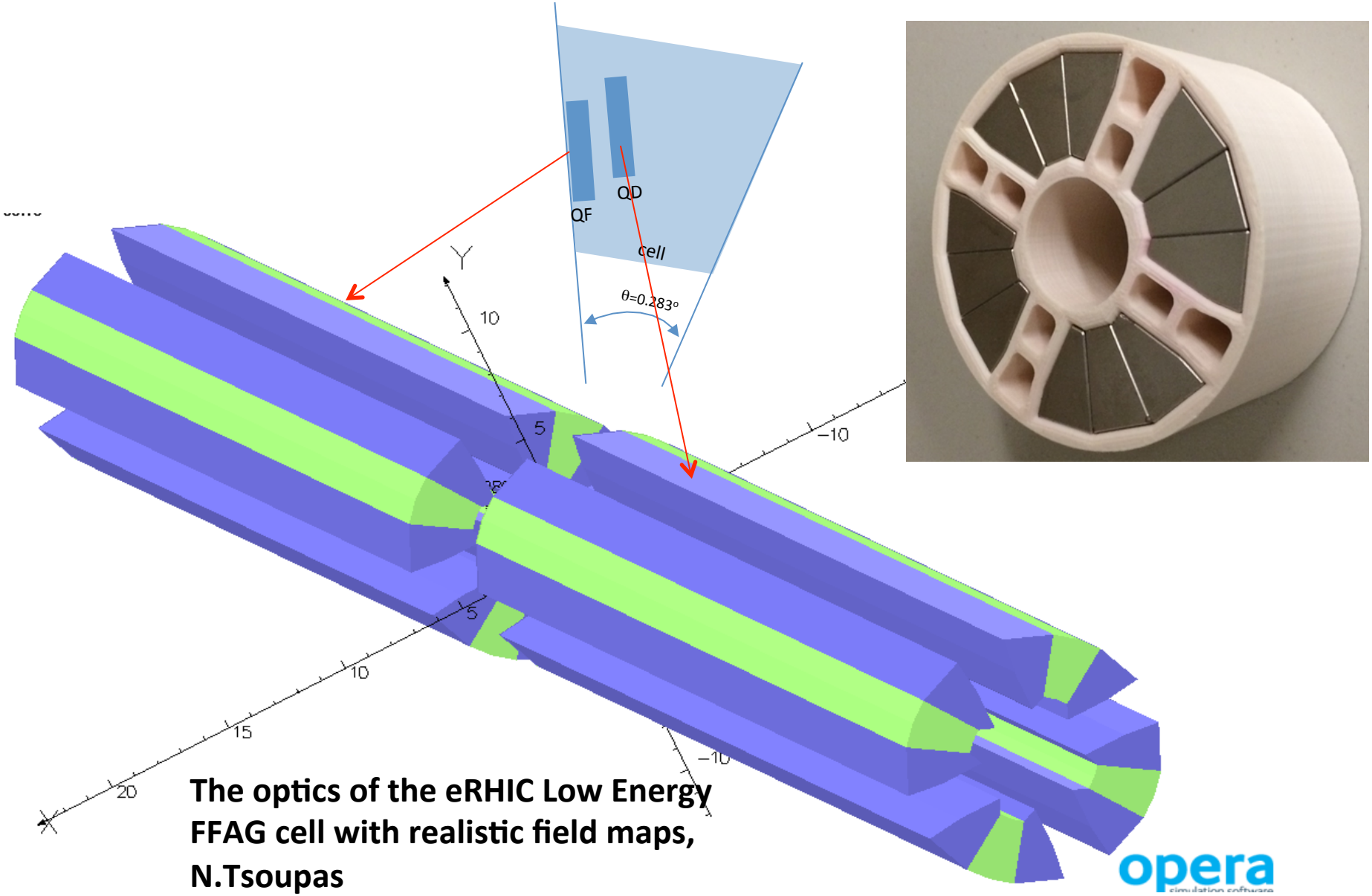




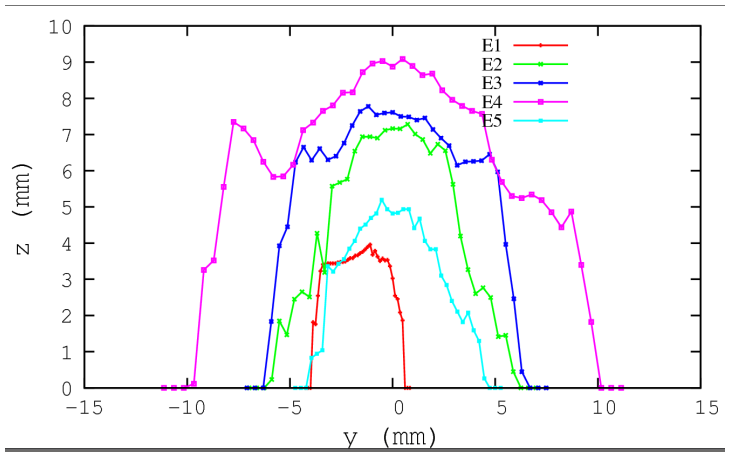
No action Practice 1 Practice 2

Due to the effect of the energy loss (mainly due to synchrotron radiation) and the cost-effective energy recovery scheme. Some action must be done to reduce the energy spread. Practice 1: pass length adjustment @ lowest/ highest energy pass. Practice 2: additional R56 in spreader and combiner to cancel the higher order energy dependence due to FFAG.

3D Magnetic field calculations for the FFAG cells



The optics of the eRHIC Low Energy FFAG cell with realistic field maps, N.Tsoupas



Particle survival acceptance through 1000 cells

N.Tsoupas

Long coil measurement of the magnetic multipoles at R=1 cm

	$\int_{-\infty}^{+\infty} B_1(r,z)\cdot dz$ **[Gauss]**	**Q_Diff/Q_{meas}**	$\int_{-\infty}^{+\infty} B_5(r,z)\cdot dz$ **[Gauss.cm^{-4}]**	**12p_diff/Q_{meas}**
SmCo R26HS Temp.=20° Calculations	18730.5		337.4	
Magnet#1 Measurement	18650.0	4.3×10^{-3}	350.6	7×10^{-4}
Magnet#2 Measurement	19096.0	20×10^{-3}	371.5	17×10^{-4}

Summary

A FFAG-ERL at Cornell, a BNL/Cornell Collaboration,

Georg Hoffstaetter (Cornell University)

Neither an FFAG loop with a factor of 4 momentum acceptance nor a multi-turn ERL has been built before. **The Cbeta FFAG ERL at Cornell will address both of these risk factors for eRHIC** adequately and rather completely.

Cornell and BNL have started to collaborate on the creation of this prototyping facility at Cornell, using ERL components from Cornell

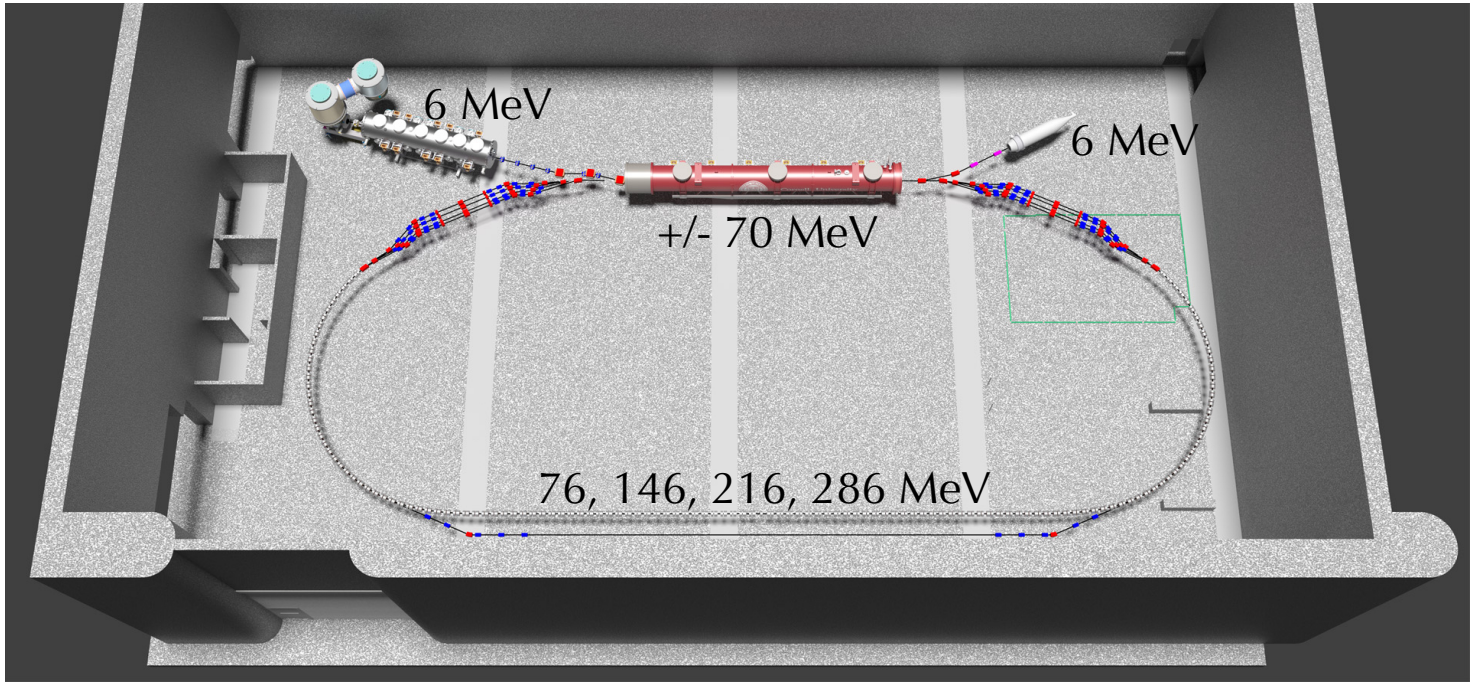
- A DC electron gun
- A low-emittance and high-current injector linac,
- An ERL-merger
- A 10m long CW SRF accelerator module
- A beam stop.

The collaboration has become rather active clearing space, testing components, produceing WBS for detailed costing and timeline, and providing an organizing structure.

Important eRHIC-ERL prototyping results can be available before 2018 !

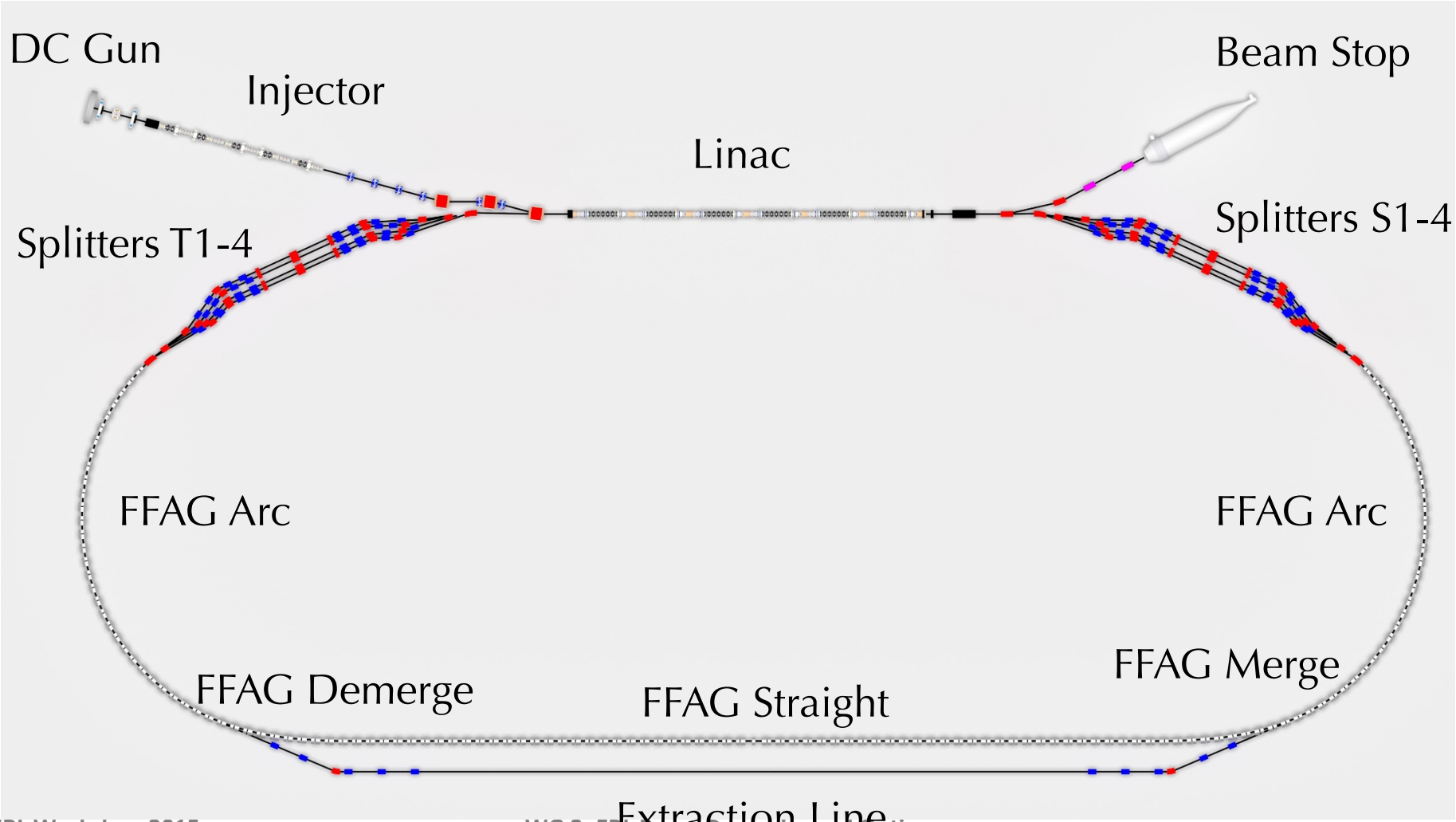
A FFAG-ERL at Cornell, a BNL/Cornell Collaboration,
Georg Hoffstaetter (Cornell University)

- NS-FFAG arcs, four passes (similar to first eRHIC loop)
- Momentum aperture of x4, as for eRHIC
- Uses Cornell DC gun, injector (ICM), dump, 70MeV SRF CW Linac
- Prototyping of essential components of eRHIC design
- Implementation in stages



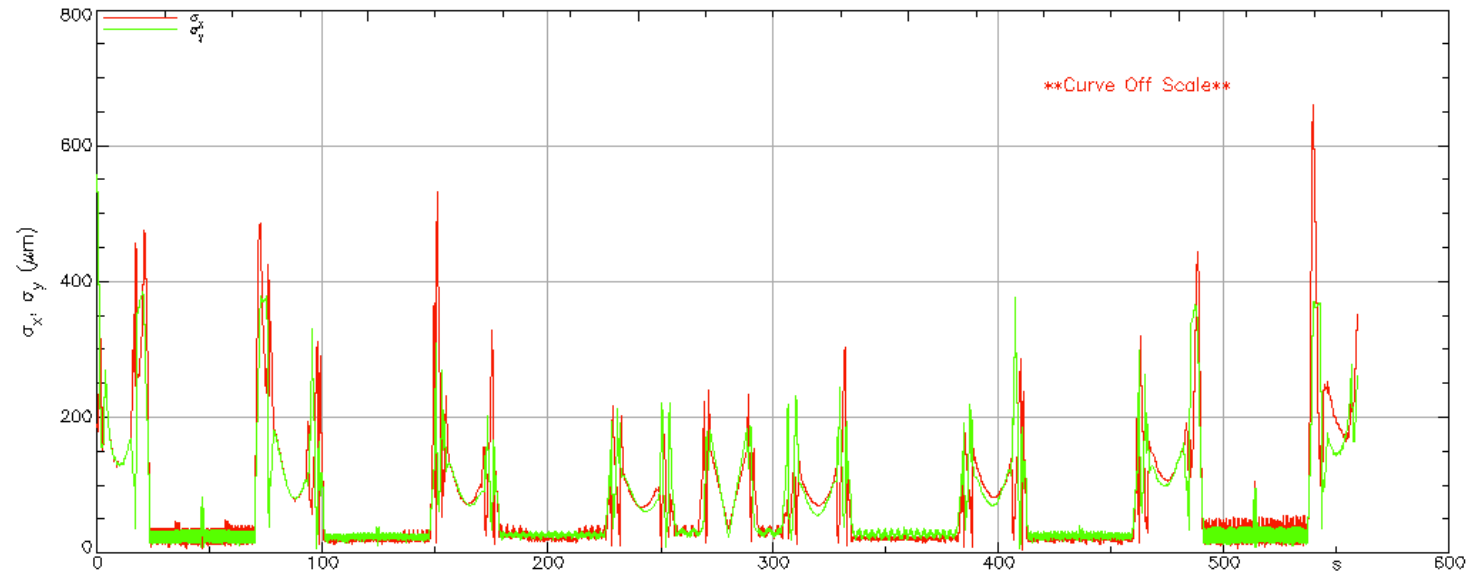
Cβ: Cornell-BNL ERL-FFAG Test Accelerator: Optics Considerations – Christopher Mayes

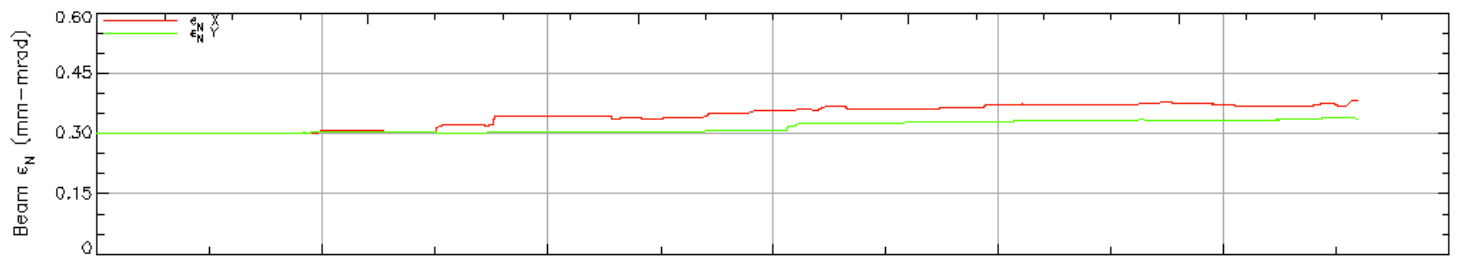
Complete layout and optics with full energy recovery
Studies will start with collective effects, halo tracking, errors & correction, etc.

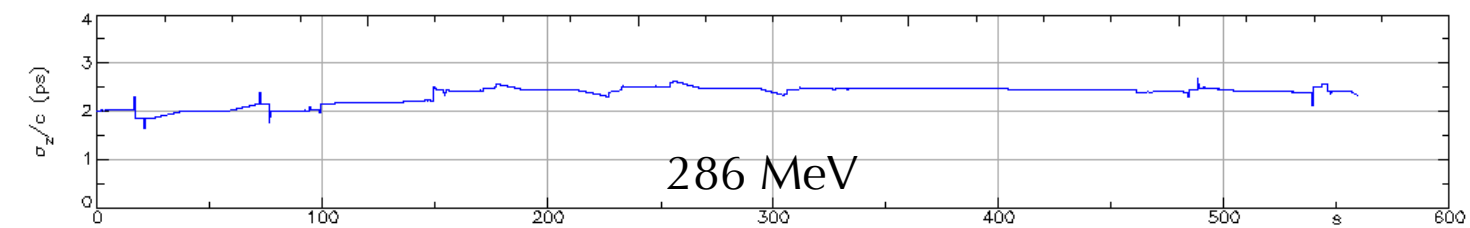


Christopher Mayes

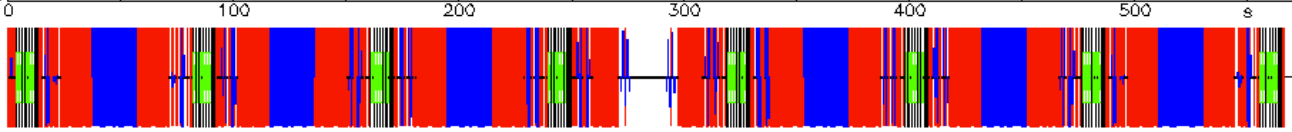
Full ERL bunch tracking





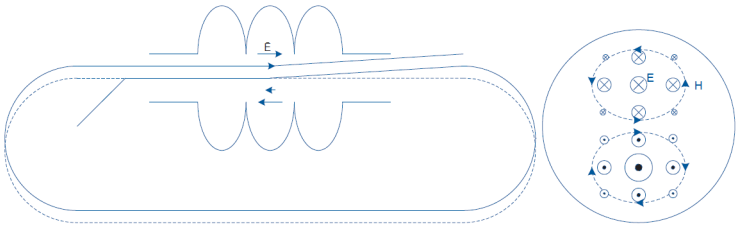


6 MeV



6 MeV

Multipass Beam-Break Up:



Basic Principle:

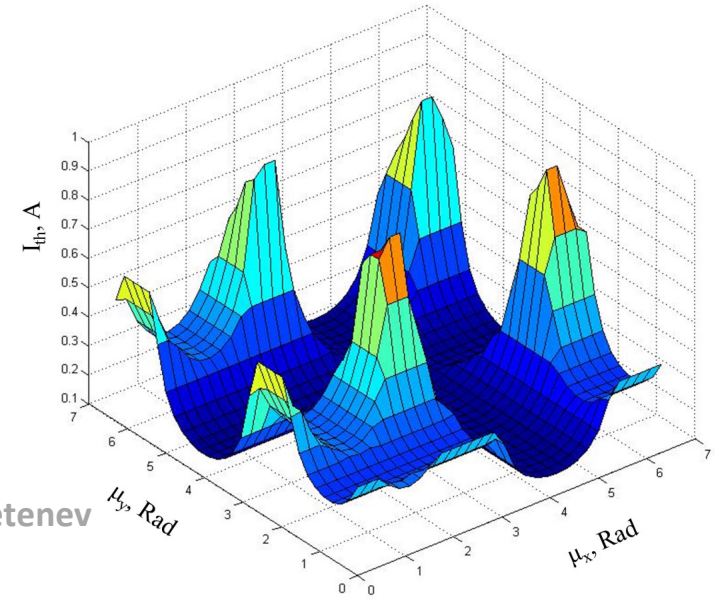
resonant interaction of bunch with High-Order cavity modes
→ pumps up HOM energy → destroys beam quality, leads to beam loss

Cures:

- Minimizing HOM power by cavity design and proper damping
- Cavity frequency spread
- Beam optics: proper phase advance, Twiss parameter, transverse beam rotation

Multipass beam-breakup thresholds
for 16 pass operation (simulation results)

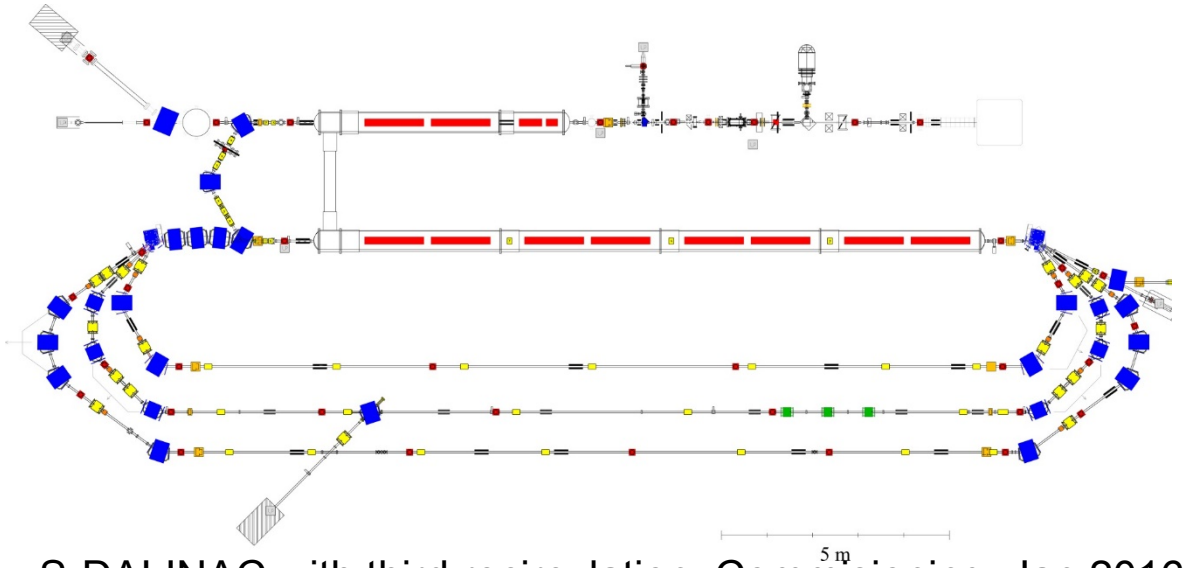
Δf/f (rms)	Current Threshold (mA)
0	53
5e-4	95
1e-3	137
3e-2	225
1e-2	329



Y. Petenev

Investigations on Transverse Beam Break Up Using a Recirculated Electron Beam

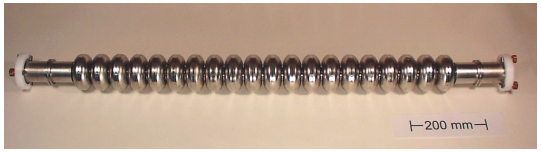
Thorsten Kuerzeder, TU Darmstadt



S-DALINAC with third recirculation. Commisioning: Jan 2016

Design Parameters:

Max. Energy:	130 MeV
Duty cycle:	cw
Frequency:	3 GHz
RF-power/cavity:	500 W



20 cell SRF cavity

- Max. beam current was only a few µA in the past (with 2 recirculations)
- We think this is because of TBBU: $I_{th} = \frac{2c^2}{e \cdot R_g \cdot Q \cdot \omega} \cdot \frac{1}{T_{12} \sin(\omega t_r)}$ G.H. Hoffstaetter, I.V. Bazarov, Phys. Rev. ST – AB **7**, 054401 (2004).
- In recirculating design this can be even worse → I_{th} scales with $1/N^2$

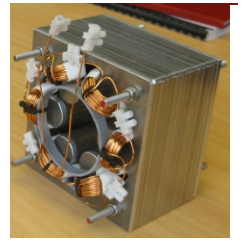
Thorsten Kuerzeder

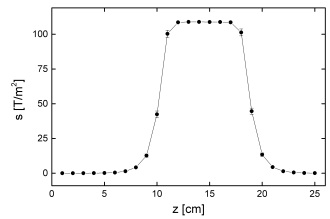
Investigations on Transverse Beam Break Up Using a Recirculated Electron Beam

- Test strageties to increase I_{th}
- Reduce the stacking of HOM effects in a multi-turn LINAC
- Therefore manipulate T_{12} with different beamline layout
- Use skew quadrupoles in the second recirc. line: Coupling x and y planes of motion can increase I_{th}
- Use sextupoles in the arcs of the accelerator: Particles might „forget“ their transverse kicks when

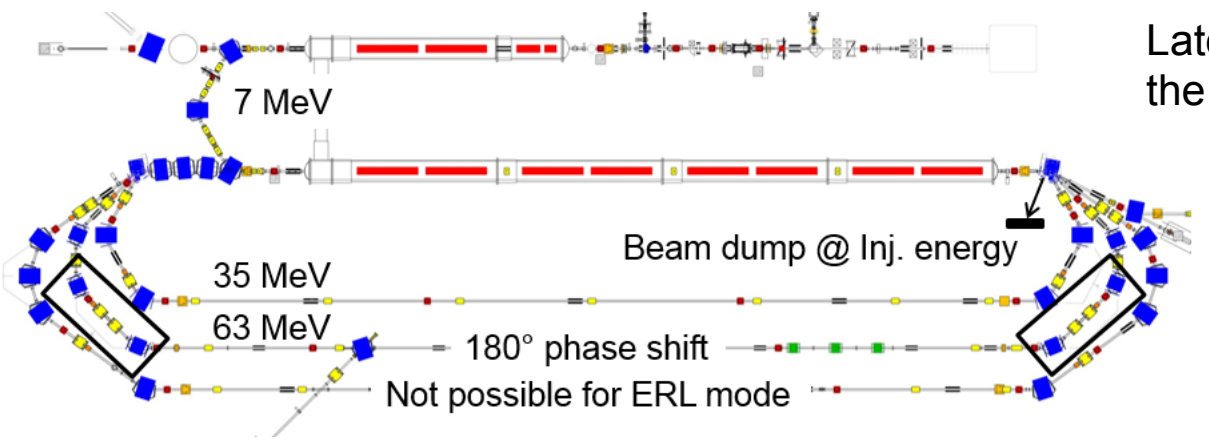
$$\left|\xi \frac{\Delta E}{E}\right| >> 1$$

V. Litvinenko, Phys. Rev. ST - AB **15**, 074401 (2012).





In house built sextupoles ready
As well as the skew quadrupoles



Later in 2016: Commissioning of the ERL mode

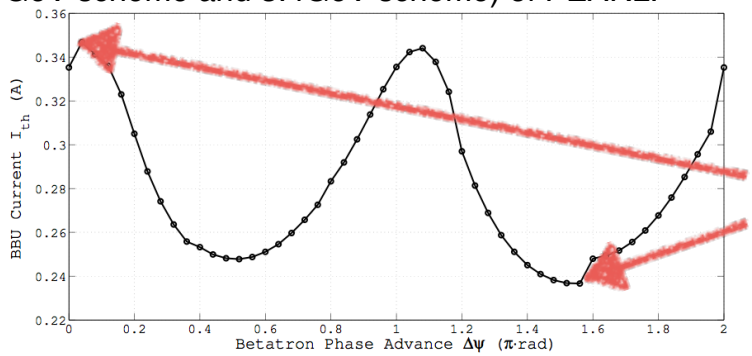
- Test again for BBU and increase I_{th}
- Do other ERL related experiments, eg LLRF control, diagnostics …

HOM-BBU Simulation for KEK ERL Light Source

Si Chen (KEK)

Detailed BBU simulations for KEK ERL Light Source using "BI" code are presented. 9-cell KEK-ERL model-2 cavity is used for the main linac of this facility.

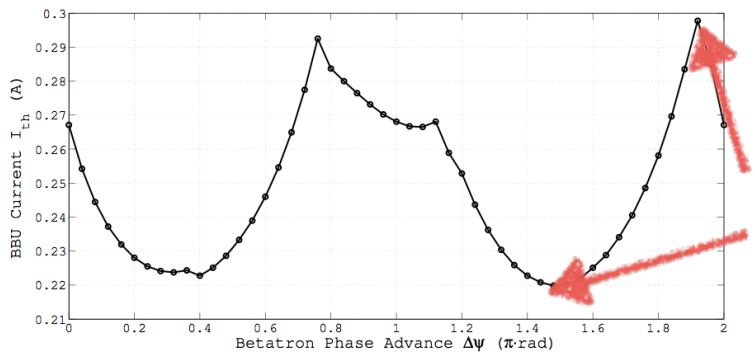
Betatron phase advance scanned over 2π of two existing designs (3.0GeV scheme and 3.4GeV scheme) of PEARL.



3.0GeV scheme:

I_{th} ***max*=345mA**

I_{th} ***min* =236mA**

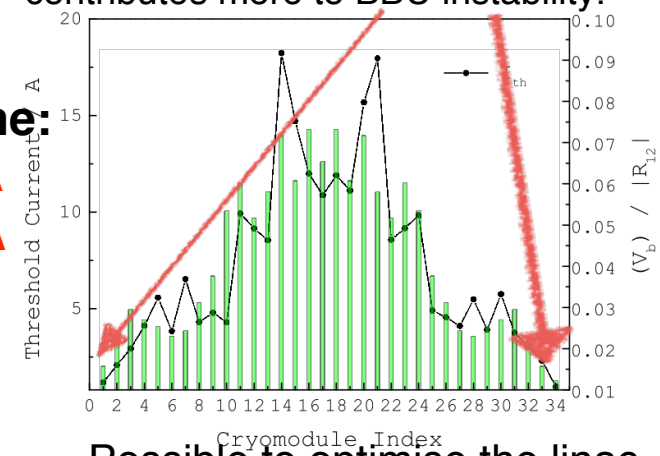


3.4GeV scheme:

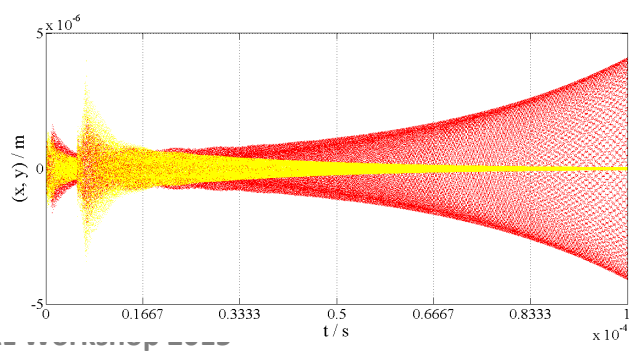
I_{th} ***max*=298mA**

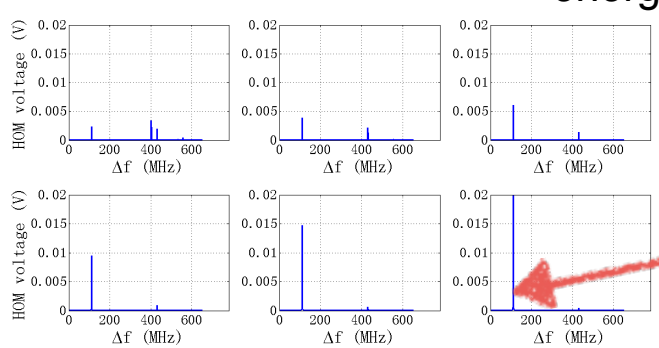
I_{th} ***min* =220mA**

Cavities at lower energy sections contributes more to BBU instability.



Possible to optimise the linac optics to improve BBU threshold. Use high current cavities at lower energy sections and high gradient cavities at higher energy sections?



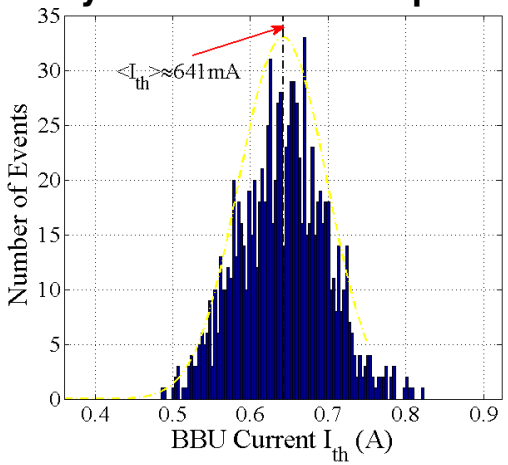


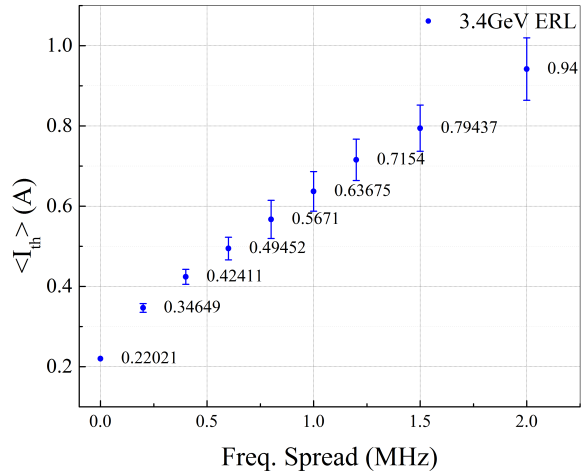
FFT to the unstable transverse oscillation when BBU occurs to get the HOM spectrum.
Most dominant HOM with frequency 4.011GHz

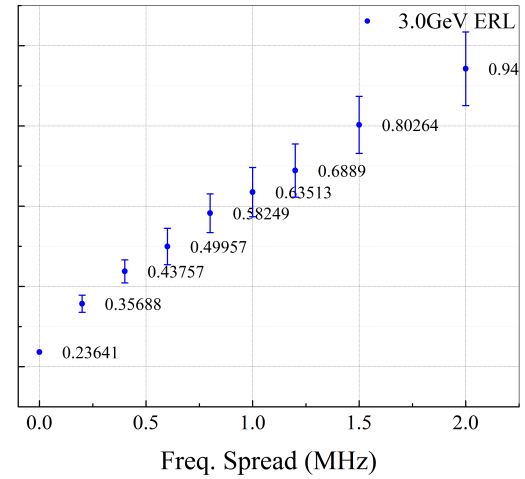
HOM-BBU Simulation for KEK ERL Light Source

Si Chen (KEK)

1000 sets of Gaussian distributed HOM frequency data with 1MHz spread.







Statistical fluctuation of BBU threshold current. Average: 641mA. Std. 56mA.

Average BBU current increases with frequency spread increase. 940mA can be achieved for 2MHz frequency spread.

	3.0GeV ERL (CDR)	3.4GeV ERL (NEW)
No. of Cavity	*28×8=224*	*34×8=272*
Linac Length	*470.4m*	*628.9m*
E_{inj}	*10MeV*	*10MeV*
E_{acc}	*13.4MV/m*	*12.5MV/m*
E_{full}	*3.01GeV*	*3.41GeV*
I_{th} (σ_f=0)	*236mA*	*220mA*
I_{th} (σ_f=2MHz)	*941mA*	*942mA*

- **With 9-cell KEK-ERL model-2 cavity, BBU threshold current more than 100mA target average current is achievable for both the 3.0GeV scheme and 3.4GeV scheme.**
- **The most dominant mode to BBU in 9-cell KEK-ERL model-2 is the mode with frequency 4.011GHz.**
- **With HOM frequency spread, average BBU current can be improved significantly.**
- **Further optimisation to the linac optics and betatron phase advance of return loop can be done to improve BBU threshold current.**
- **Possible to optimise the SC cavity to improve gradient while keeping the HOM damping efficiency.**

Micro Bunch Instability:

Basic Principle:

initial small density modulation (random noise)

→ wakes (LSC, CSR, geometric, …) transform to energy modulation

→ increased density modulation: gain > 1 → instability

Observed at:

- SR: micro bunch instability – turbulent bunch lengthening
- Linac's: bunch compression driven CSR instability

Cures:

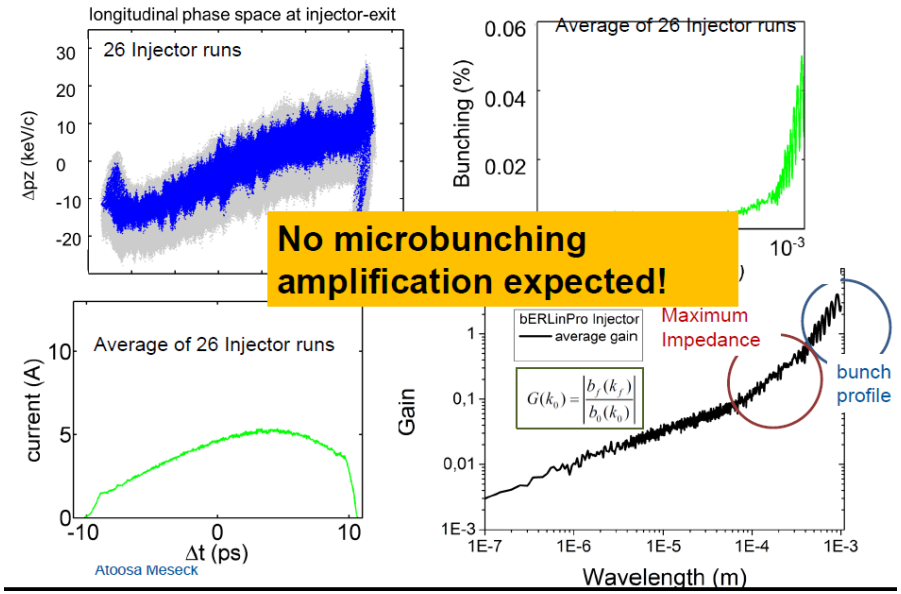
- reduction of driving wake fields:
  - avoid high bunch densities (longer bunches)
  - suppress CSR emission (chamber cut off)
  - machine optimization (impedance budget)
  - increase (sliced) energy spread (Laser Heater)

Applications:

- SR: THz CSR (bursting mode)
- Linac/ERL: coherent radiation in the VUV

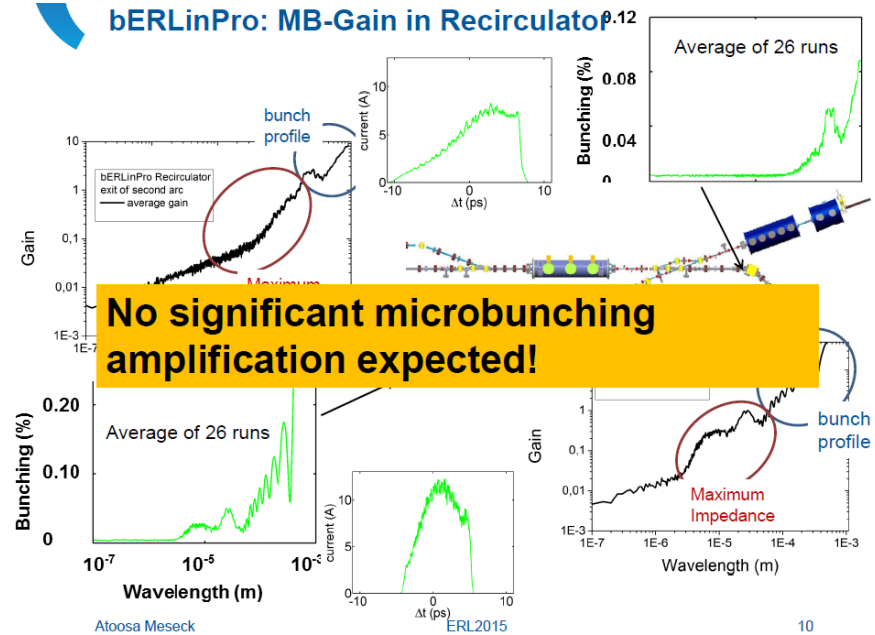
Microbunching Instability in ERLs - a Blessing or a Curse? **Atoosa Meseck (HZB)**

bERLinPro: MB-Gain in Injector



Atoosa Meseck

bERLinPro: MB-Gain in Recirculator

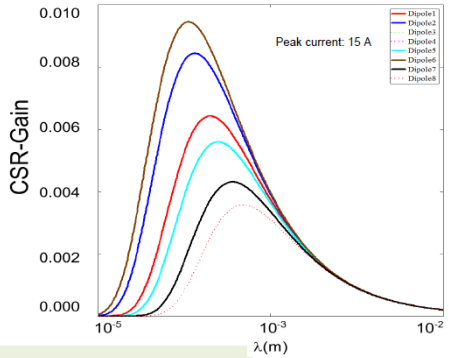


Atoosa Meseck ERL2015 10

bERLinPro: CSR and MB Amplification

From analytical calculations of the CSR-Gain in the dipoles (*, **), we do not expect CSR-driven microbunching amplification for the standard operation mode.

1D- CSR simulations (ELEGANT and CSR-track) confirm these results. However, the ELEGANT simulations show a minor increase of the emittance in the horizontal plane (mainly in the second arc).



energy loss & energy spread

$\Delta\mathcal{E}_{tot}$ *(average for dipoles in arc)**** = *289nJ* (3.8 keV per Electron) correspondes to a relative energy loss of 7.5 x10^{-5}

With 1.3 GHz => 376 W ; 8 dipoles in 2xarcs => 3 kW

3D-CSR simulations planned for bERLinPro short puls mode.

* Z. Huang and T. Shaftan, SLAC-PUB-11597
** G. Stupakov and S. Heifets, S. Krinsky, Phys. Rev. ST Accel. Beams **5**, 064401 (2002)
***E.L.Saldin, E.A. Schneidmiller, and M.V. Yurkov, NIM A 398 (1997), p373–394.

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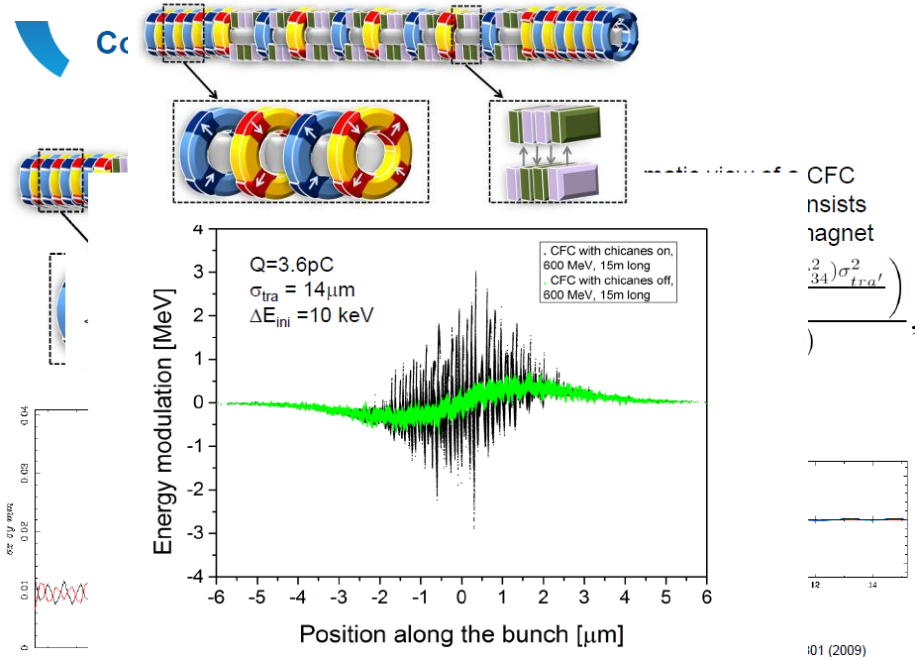
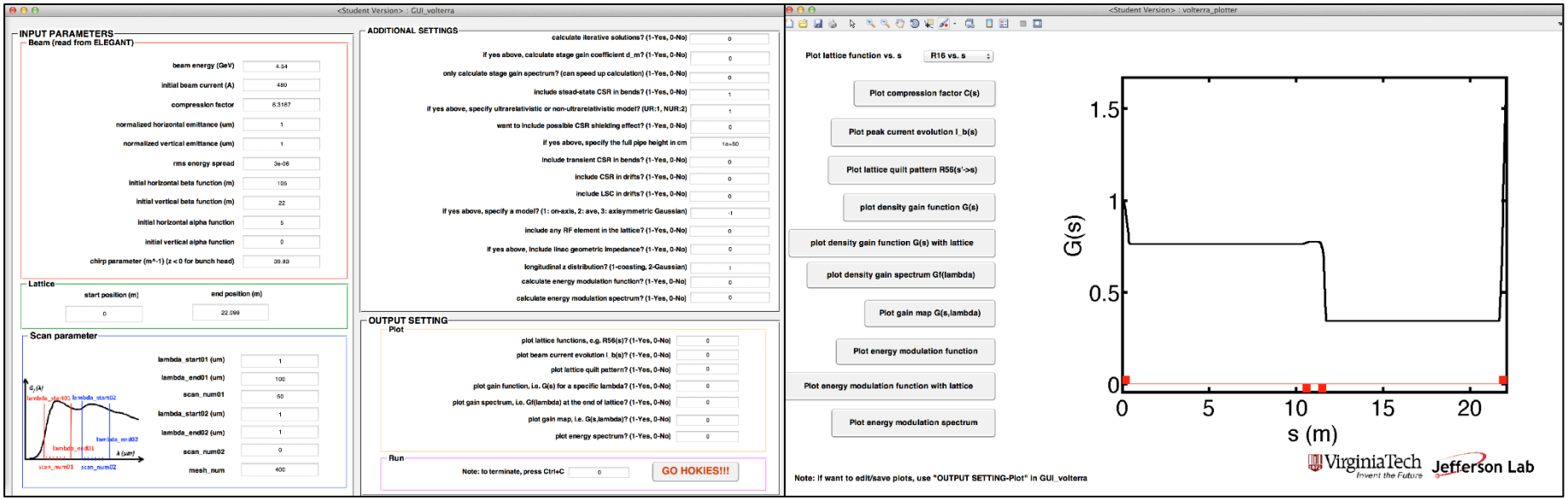
Co



CFC
nsists
nagnet

01 (2009)

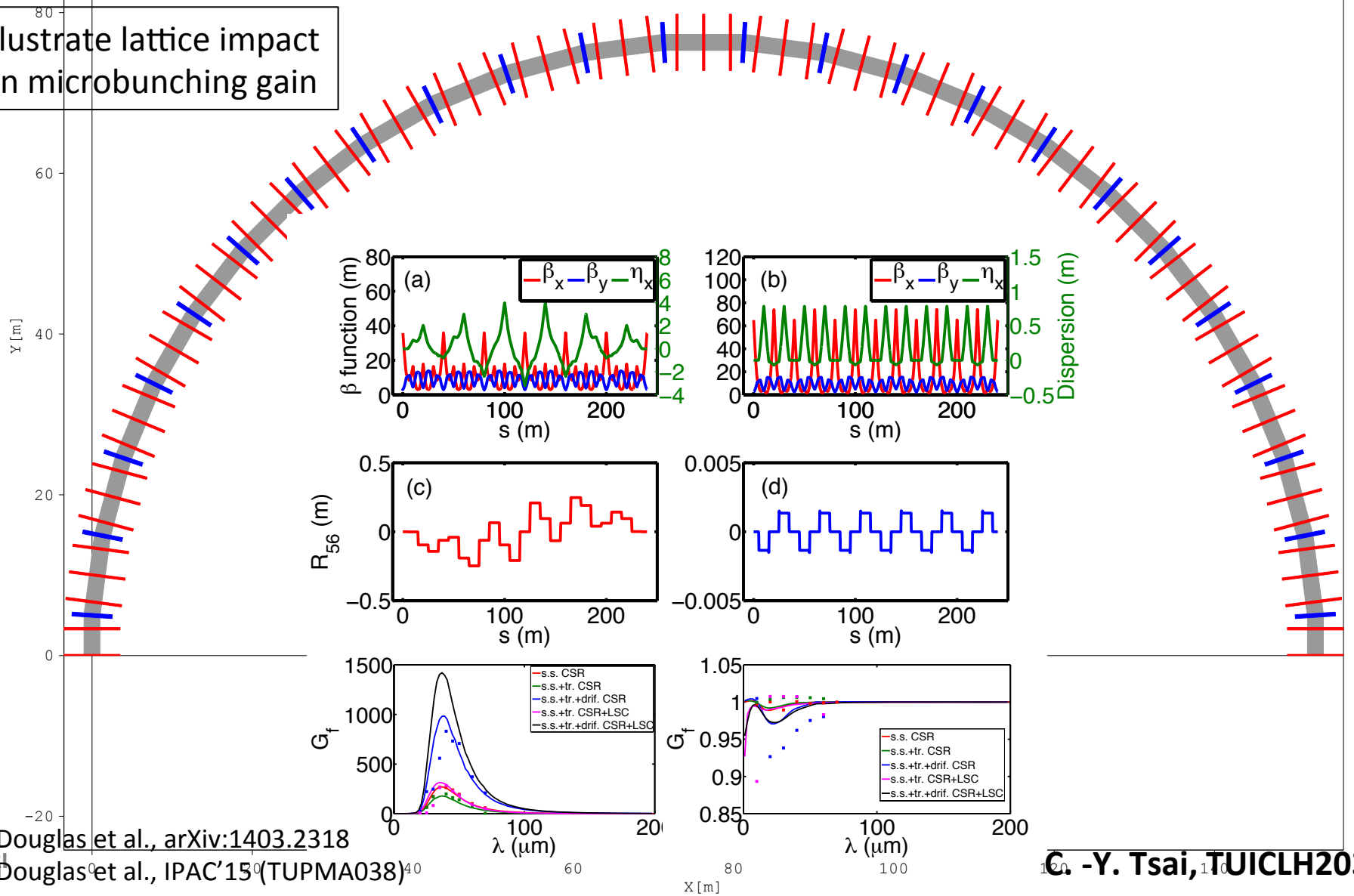
Newly developed code



- A developed code based on linearized Vlasov formulation
- Input file directly from ELEGANT
- Collective effects included: CSR (steady-state, transients, and etc), LSC
- Future improvements: include linac section and other relevant collective effects

Application: 1.3 GeV 180° transport arc

Illustrate lattice impact on microbunching gain

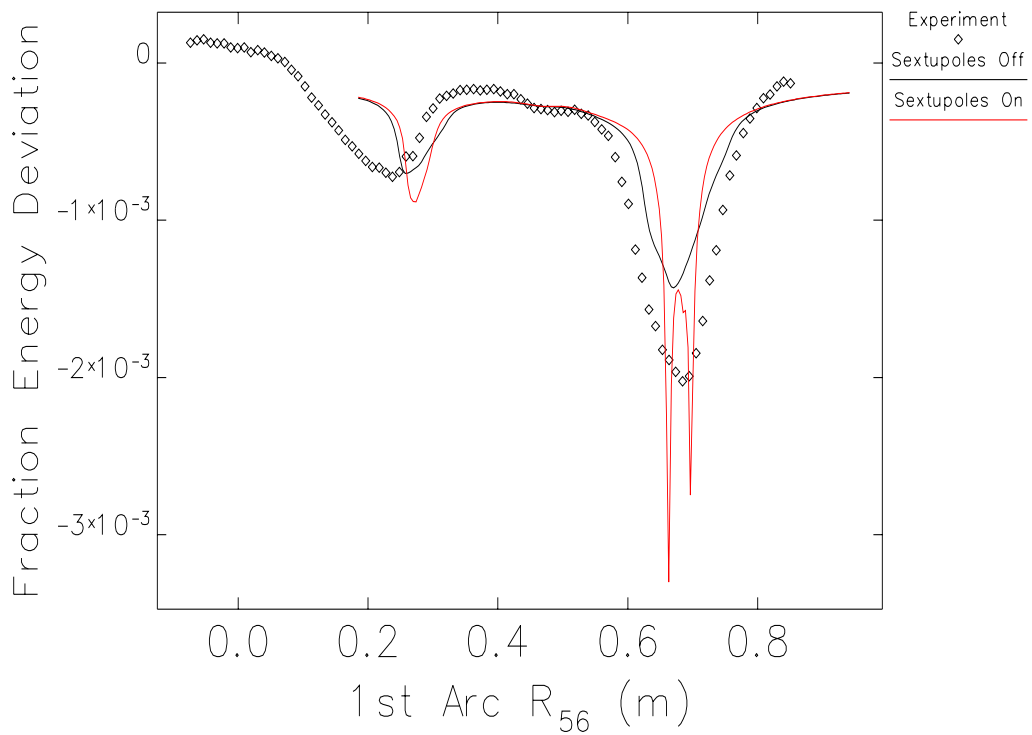


D. Douglas et al., arXiv:1403.2318
D. Douglas et al., IPAC'15 (TUPMA038)

Study of CSR Impact on Electron Beam in the JLab ERL

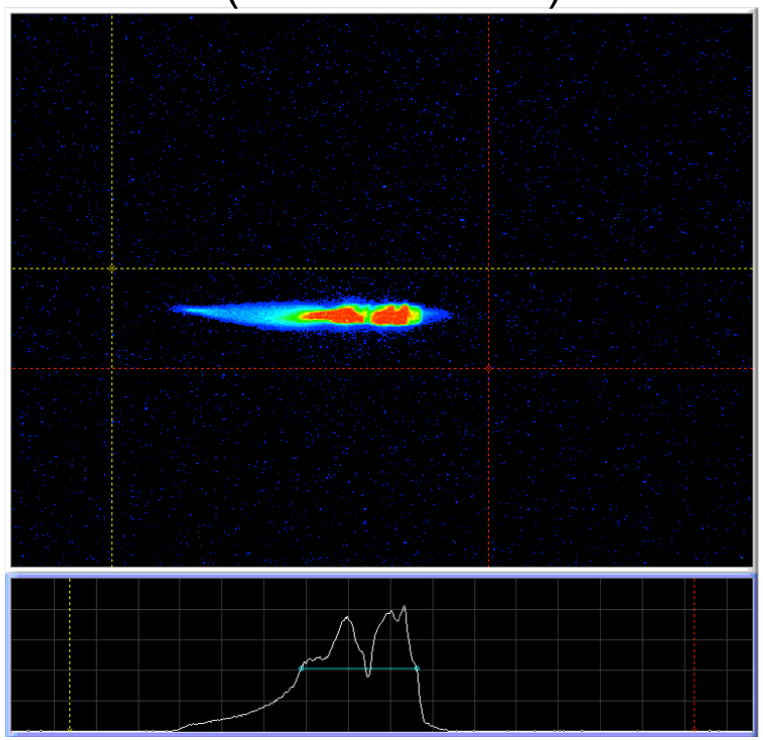
Christopher Hall (Colorado State University)

CSR-induced energy loss as function of compression



- Measurement of energy loss in JLab ERL from CSR over wide range of compression dynamics
- Matches well against simulations using 1-D CSR model

Energy spectrum measurement (horizontal axis)



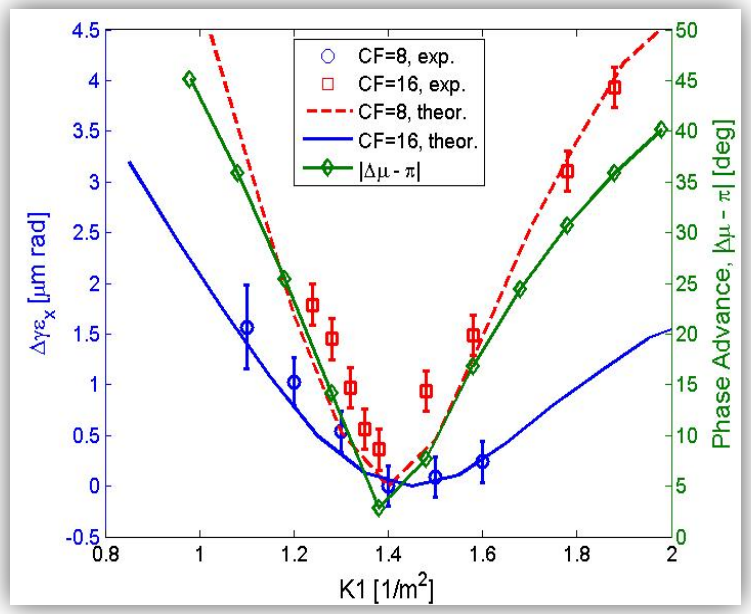
- Also observe fragmentation of energy spectrum from CSR
- Can be well reproduced in simulation

Summary

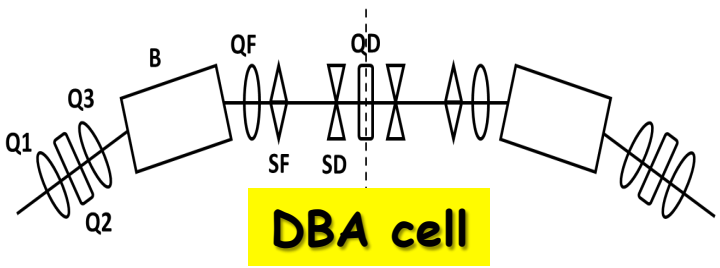
Christopher Hall (Colorado State University)

- ERLs provide much broader range of compression dynamics than conventional linac
- 1-D CSR model appears to give reasonable results over measured compression range
- Modeling of CSR in drifts downstream is essential for capturing full impact of CSR on beam
- Longitudinal linearization can help remove fragmentation from energy spectrum

Transverse Emittance Preserving Arc Compressor: Sensitivity to Beam Optics, Charge and Energy, Simone Di Mitri (Elettra - Sincrotrone Trieste)



- 1-D linear theory of CSR kicks-optics balance proved to work for:
  - Constant bunch length,
  - Small bending angle,
  - High energy multi-bend line.

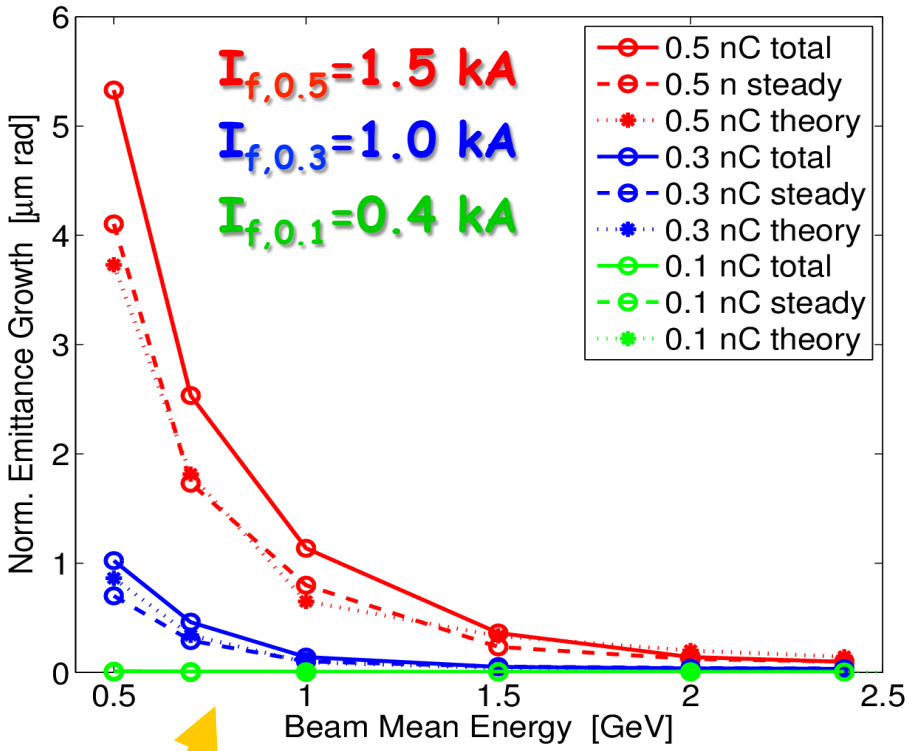


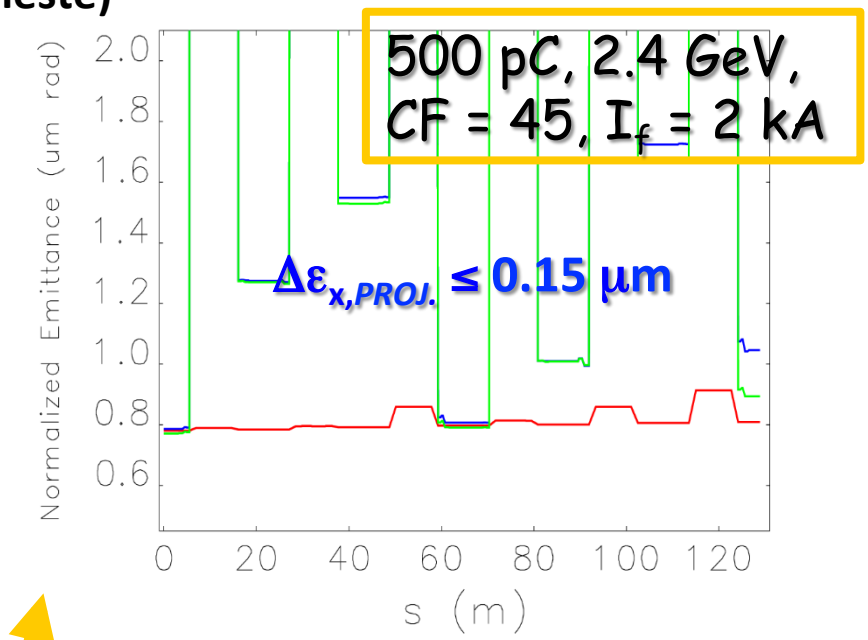
- And what, if the bunch length is compressed ? Now consider:
  - Varying bunch length,
  - Large bending angle,
  - Periodic Arc Compressor (DBA-based).

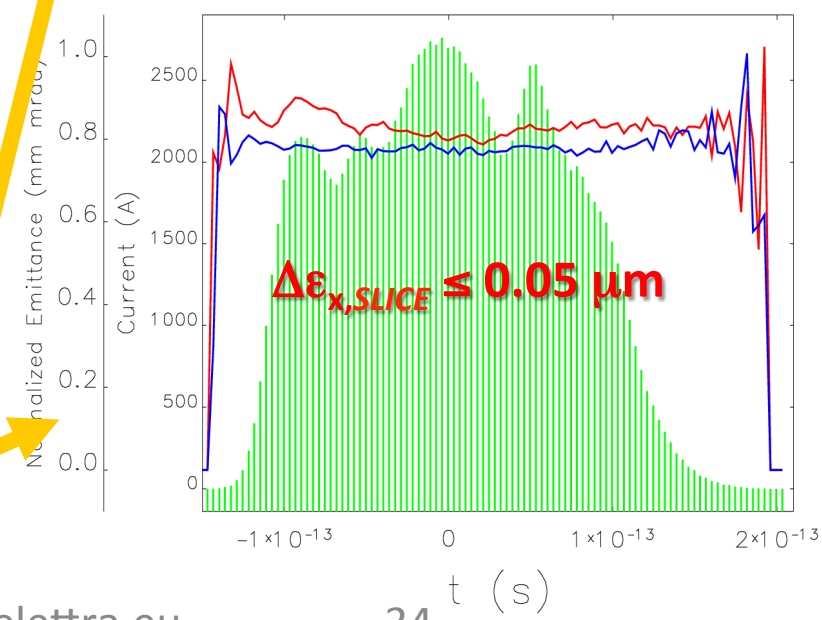
CSR-induced invariant to be minimized in the DBA cell through optics control:

$$J_3 \cong \left(\frac{k_1\rho^{1/3}\theta^2}{2}\right)^2\left[\beta_2\left(C^{4/3}+1\right)^2+\frac{1}{\beta_2}\left(\frac{l_b}{6}\right)^2\left[\left(C^{4/3}-1\right)^2+\alpha_2^2\left(C^{4/3}-3\right)^2\right]+2\alpha_2\left(\frac{l_b}{6}\right)\left(C^{4/3}+1\right)\left(C^{4/3}-3\right)\right]$$

Transverse Emittance Preserving Arc Compressor: Sensitivity to Beam Optics, Charge and Energy, Simone Di Mitri (Elettra - Sincrotrone Trieste)







100pC beam largely immune from CSR at any energy > **500 MeV**

500pC beam largely immune from CSR at any energy > **2.0 GeV**

Hot Topics Questions:

ERLs & FFAG

- momentum range: what are acceptance limits?
- multi beam sections: beam diagnostic, orbit and optics correction
- polarized beams: transport in the presence of errors/misalignments
- beam transport simulation tools

Microbunching Instability

- Blessing or Cure?
  - Cure: occurrence depending on beam parameters, compression, …: what when unwanted?
  - Blessing: how to breed?

Beam Break Up

- threshold current scaling with the number of turns?

More questions are welcome to rise up in the WG2 sessions.

Discussions:

Halo & Losses

Why is Halo an issue at all?

- ERLs as future light sources with users at the end of the beamlines → radiation constraints: SR losses @ 10E-11 per turn

Halo Sources (P. Evtushenko, Jlab)

- Drive laser: extinction ratio not high enough (no prob @ cw)
- Drive laser: stray light & reflections, UV especially problematic – emission not only from cathode
- SC dominated beam dynamics creates halo on the 10^-6 level
- Jlab: emittance compensation not ideally set up → optics setting was always trade of between halo transport and main bem parameters (as required for FEL operation)
- Jlab: no collimation by intention, minor collimation of bunch tails by chamber

Discussions:

Halo & Losses

Halo (cERL, KEK)

- Drive laser off → no (few) field emission / dark current
- Halo and collimation not fully understood so far
- Collimators generate radiation, but also help to reach high currents and to reduce radiation on the recirculator straight (Compton BS experiment)
- 0.1% is collimated (80 nA at highest current so far (80 muA))
- Sudden trajectory jump observed : charging up of something might be the cause (Jlab: beam is not allowed to see any isolator, that might charge up)
- Simulations using GPT: N=1.0E5 –1.0E6

Why is collimation (preferably close to potential halo sources) so difficult?

- Just leave a few sigma and collimate anything with larger deviation/ amplitude: effectiveness of collimation (scattering)

Discussions:

Halo & Losses

Halo

- “halo formation comes usually not from what you can simulate”, e.g QE or laser intensity =f(x,y) → but first simulations and even experiments consider this (talk on ERL2015, Cornell ???)
- Long. Halo: cathode response time (f(QE))
- What are experiences from Linacs (e,g. FLASH, collimeters upstream undulators for radiation protection of permanent magnets)

Unwanted Beam Workshop (HUB, HZB, HZDR)