Studies of CSR and Microbunching at JLab

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Outline

Past: FEL Demo

Present: LERF & CEBAF

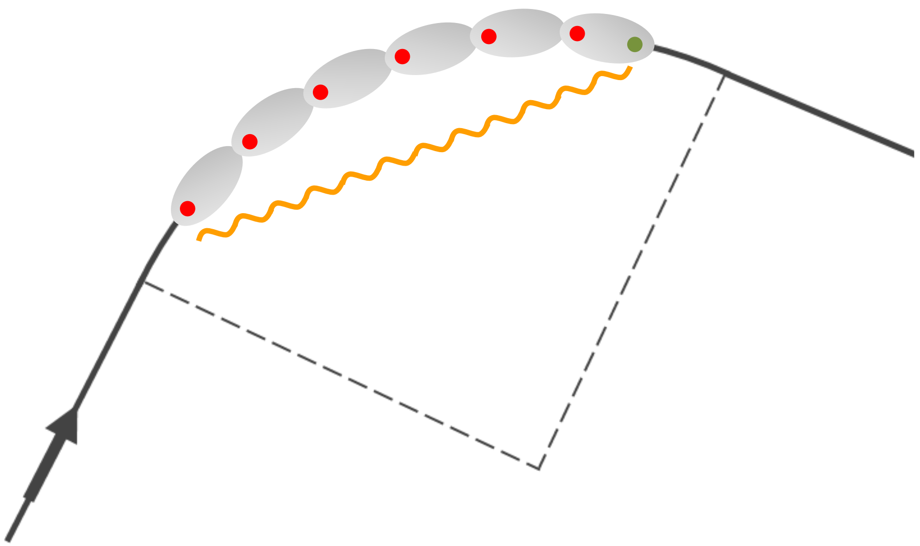
- ✓ “bulk” CSR studies
- ✓ isochronous arc design
- ✓ development of a microbunching gain code

Future: Electron-Ion Collider

- ✓ microbunching with magnetized beams

What is CSR?

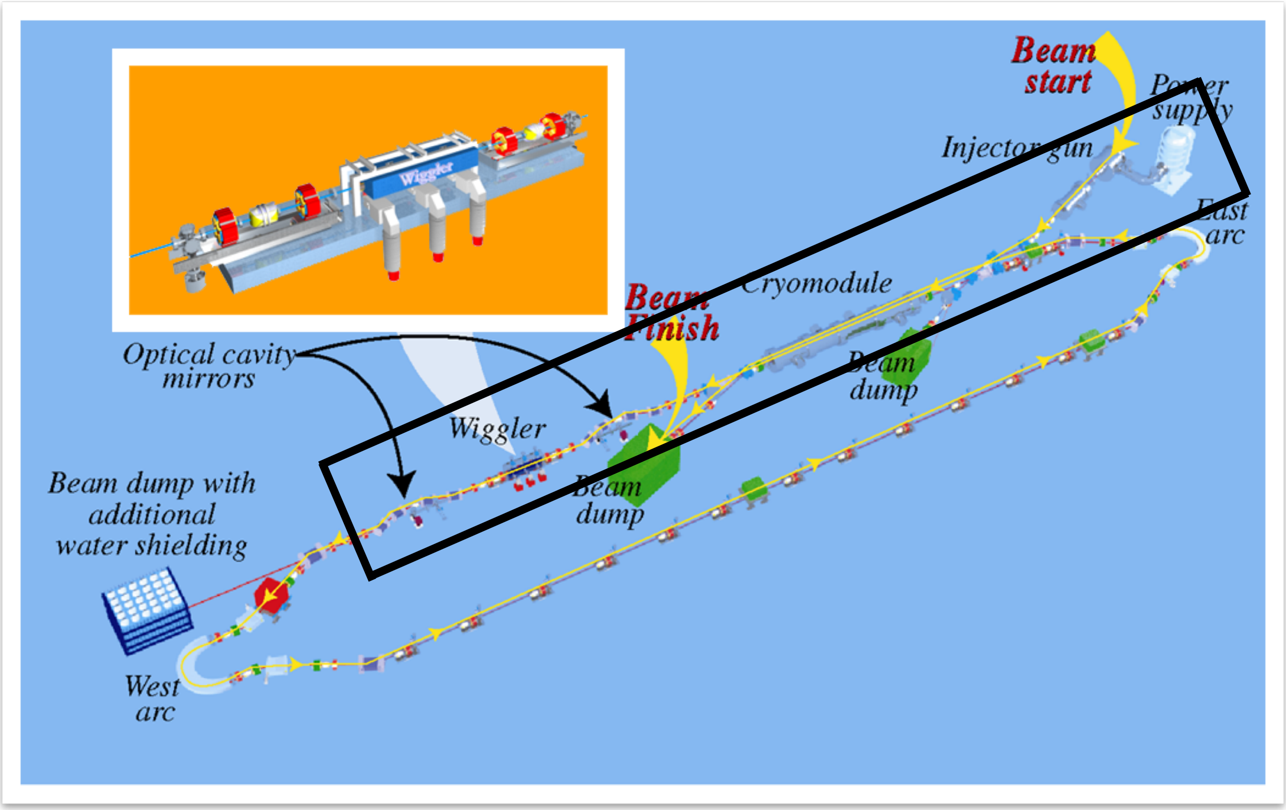
- mechanism:
  - ✓ for a high brightness bunch is on a curved orbit, fields emitted from the tail can overtake and interact with the head of the bunch
  - ✓ tail loses energy, head gains energy (tail-head effect)
  - ✓ is an issue at all energies



- the results are a redistribution of particles (in an undesirable way):
  - ✓ projected emittance growth
  - ✓ projected energy spread growth
  - ✓ centroid energy loss

"bulk"

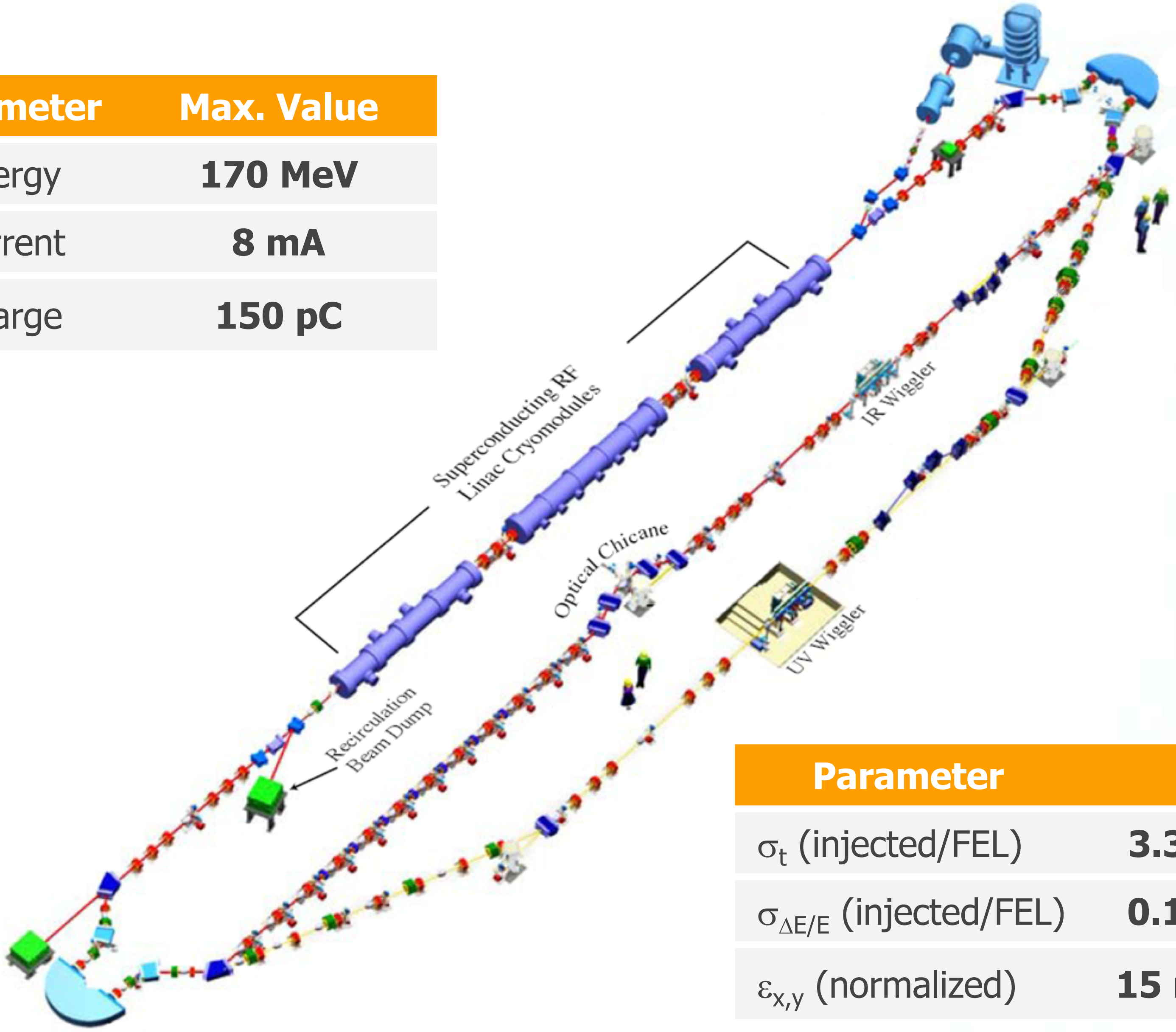
Jefferson Lab ERL Demo (1997-2001)



- the ERL Demo recovered 48 MeV of 5 mA beam through a single cryomodule
- CW operation allows high average output power at modest charge per bunch (2.3 kW)
- note similarity with linac-driven light source topology

Jefferson Lab LERF (2001-)

Parameter	Max. Value
Energy	**170 MeV**
Current	**8 mA**
Charge	**150 pC**

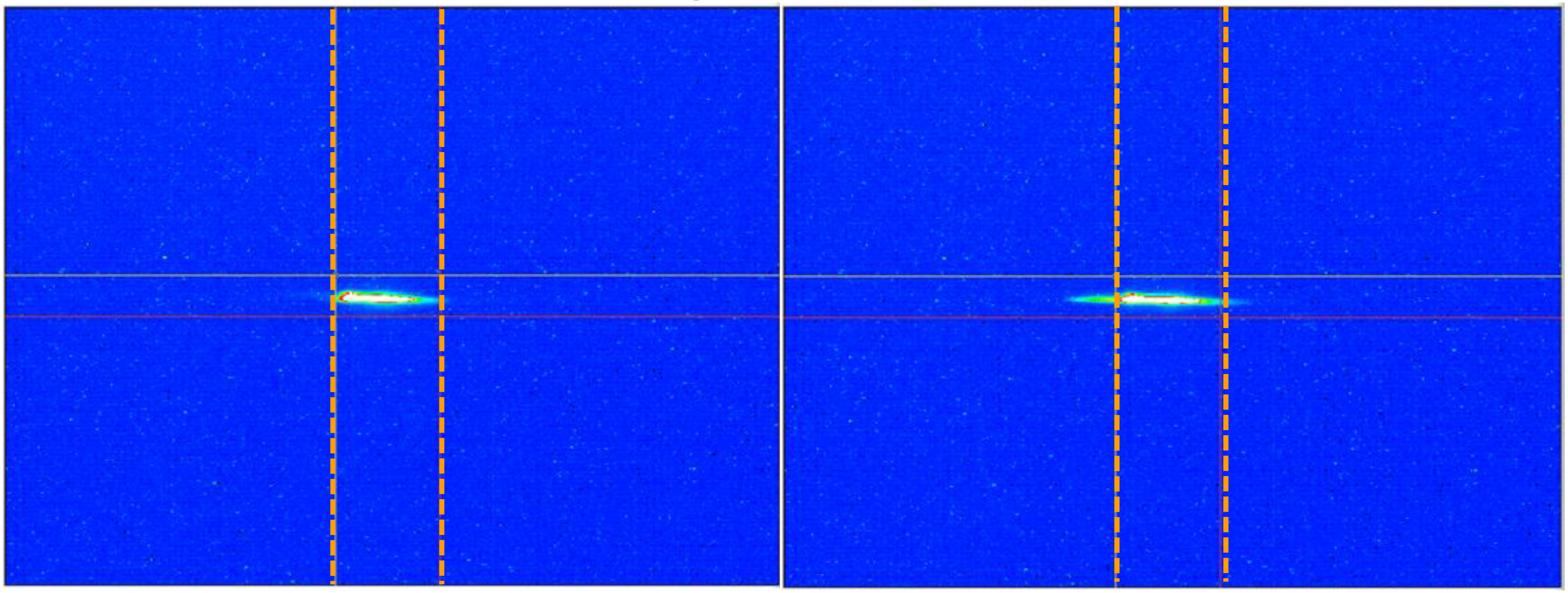


Parameter	RMS
σ_t (injected/FEL)	**3.3/0.12 ps**
$\sigma_{\Delta E/E}$ (injected/FEL)	**0.15/0.5 %**
$\varepsilon_{x,y}$ (normalized)	**15 mm-mrad**

Coherent Synchrotron Radiation

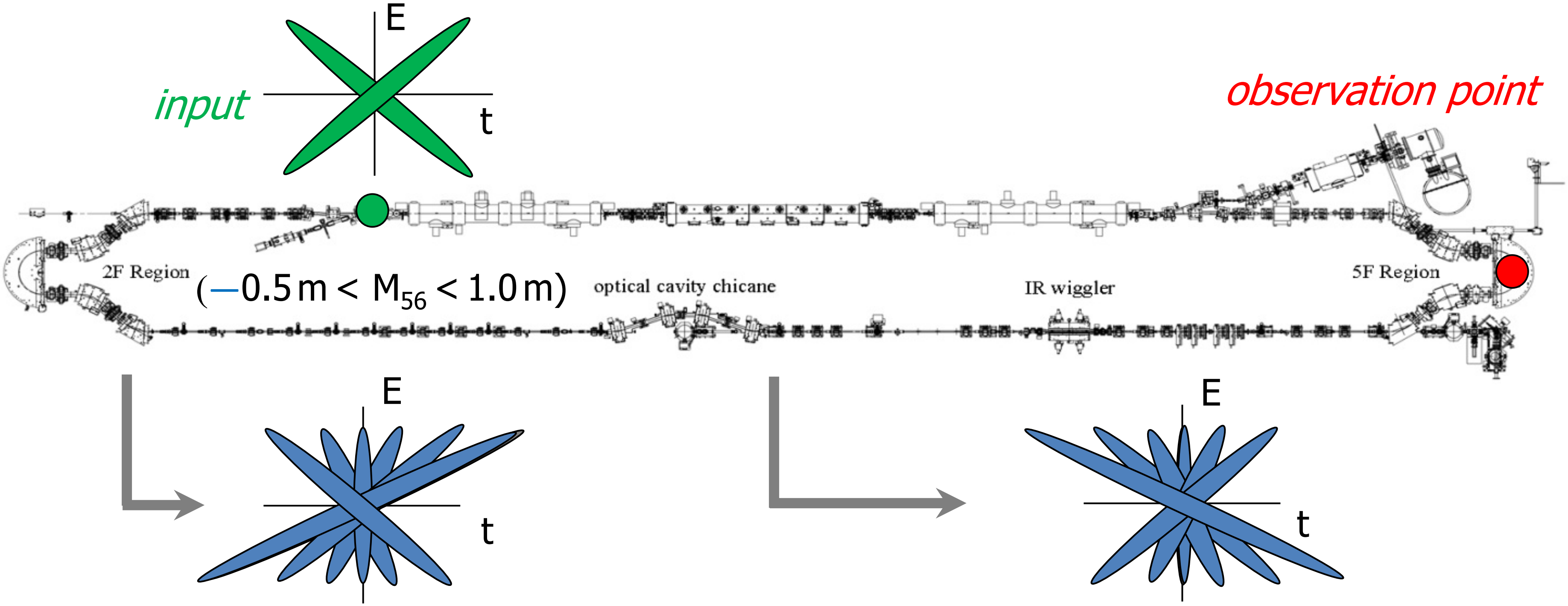
- excessive CSR hitting downstream mirror and limiting power output → decompressor chicane
- CSR does not present an operational impediment
- CSR used as diagnostic aid in daily machine setup ("miniphase")
  - ✓ tune longitudinal match and verify full bunch compression when CSR-enhancement is observed on downstream SLM

Synchrotron Light Monitor: Second Arc



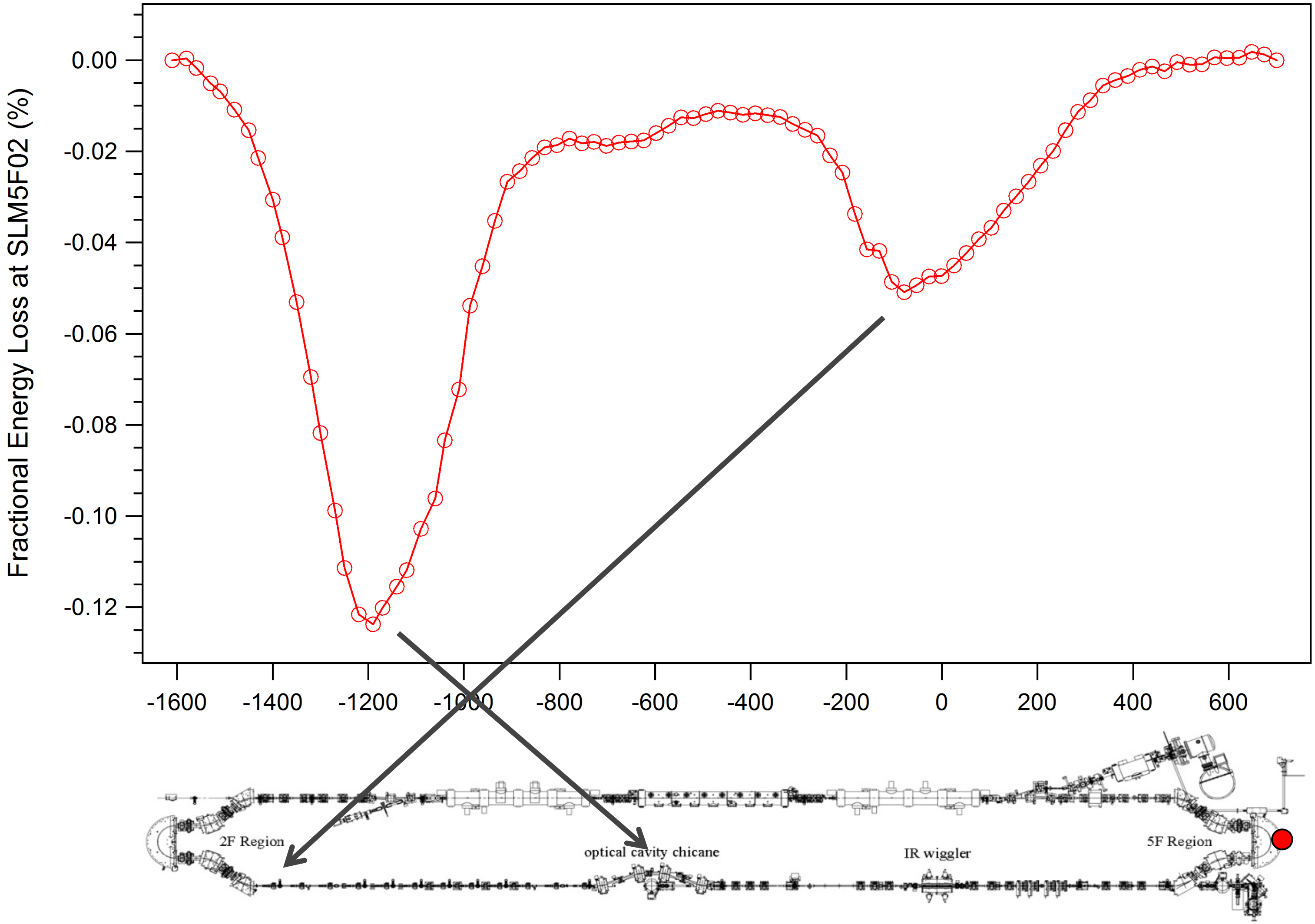
LERF

- ERL-based FEL driver
  - ✓ **Injector:** DC photocathode gun (135 pC) + booster accelerated to 9 MeV
  - ✓ **SRF Linac:** accelerated to 130 MeV at $-10°$ to impart a ϕ-E correlation
  - ✓ **Recirculator:** bunch rotated upright and RF-induced curvature eliminated
- experimentally characterize the effects of CSR on the beam through an *unconventional compressor*



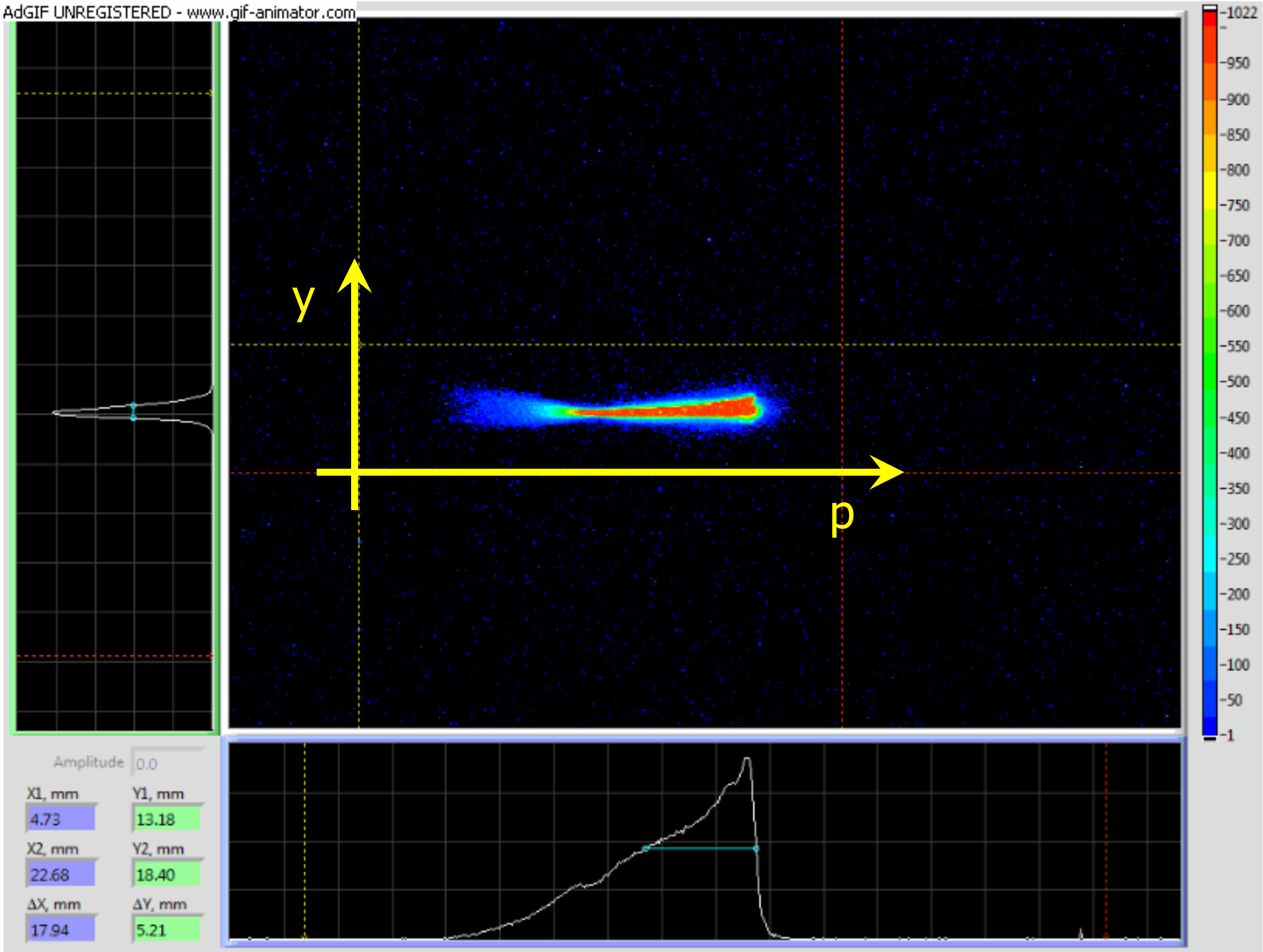
CSR-Induced Energy Loss

- measure energy loss by recording BPMs in dispersive region

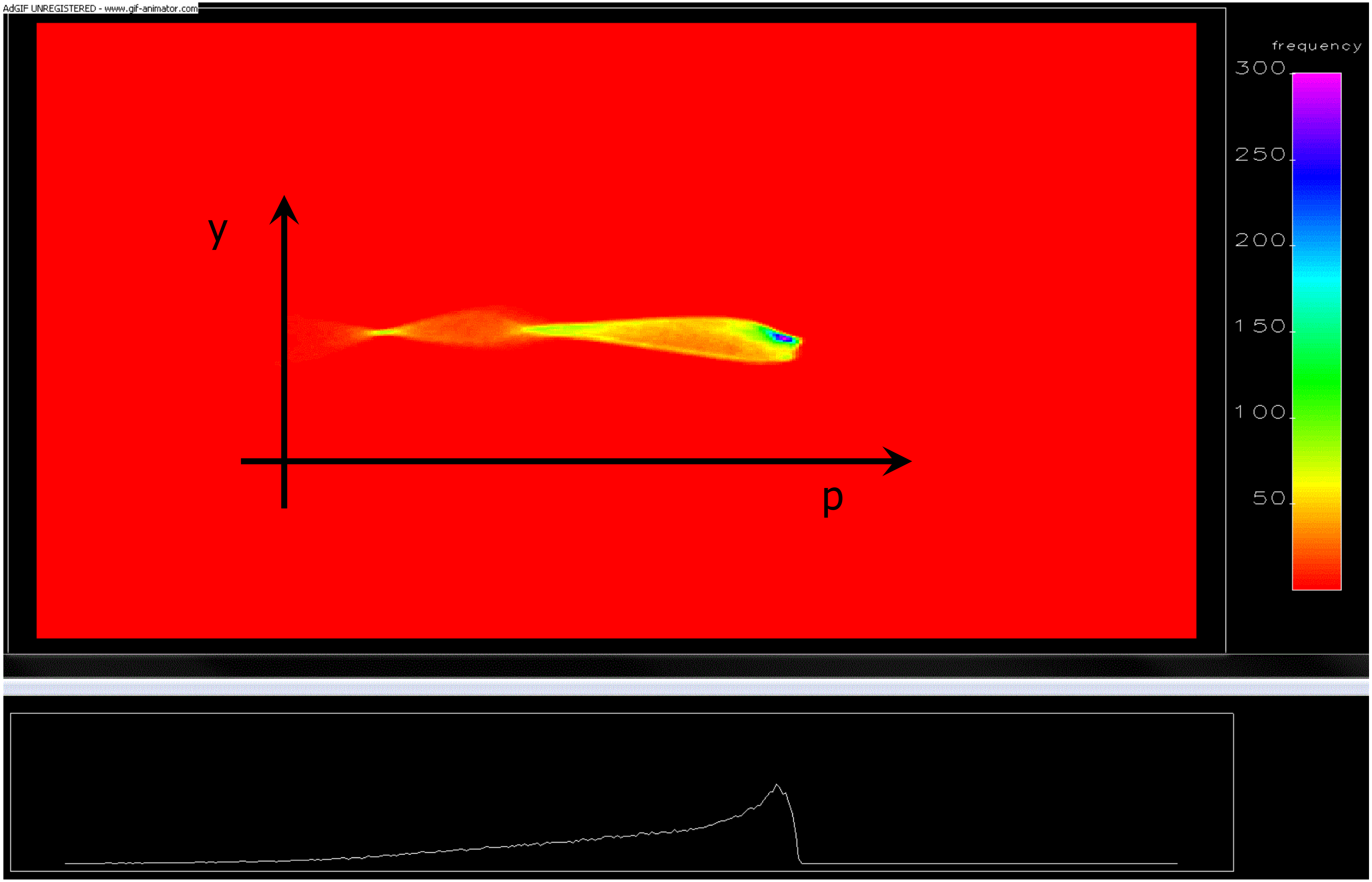


Energy Distribution vs Compression

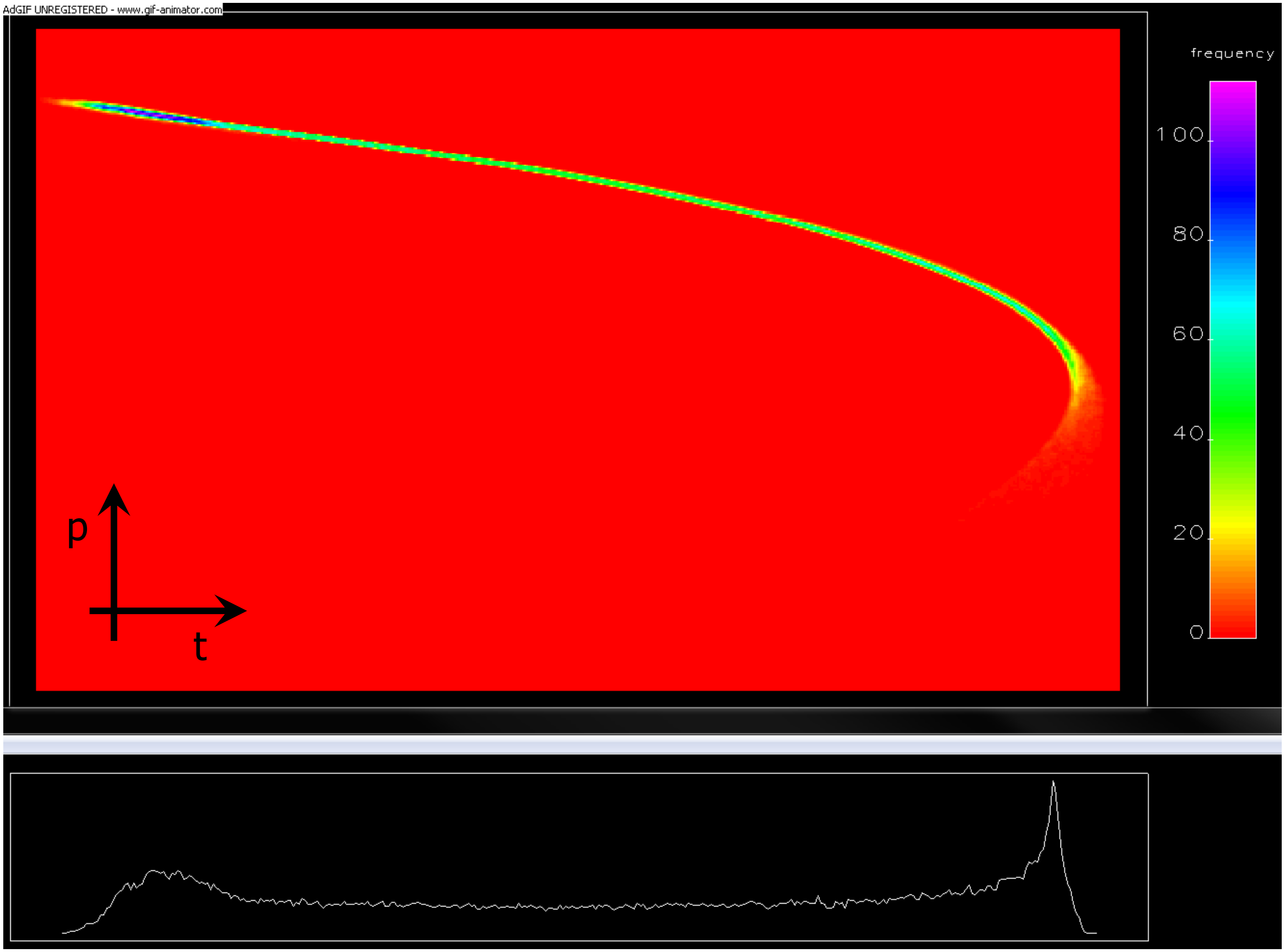
- record momentum distribution on SLM as function of compression



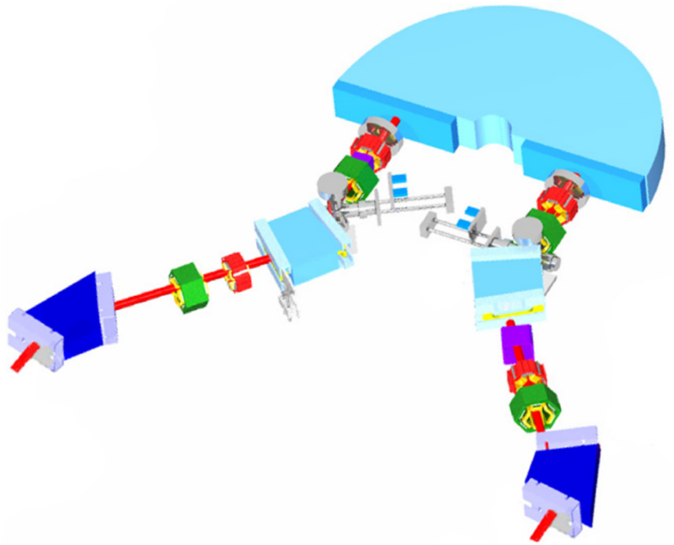
Simulated Energy Distribution



Evolution of (t,p)-Space



Beam Characterization

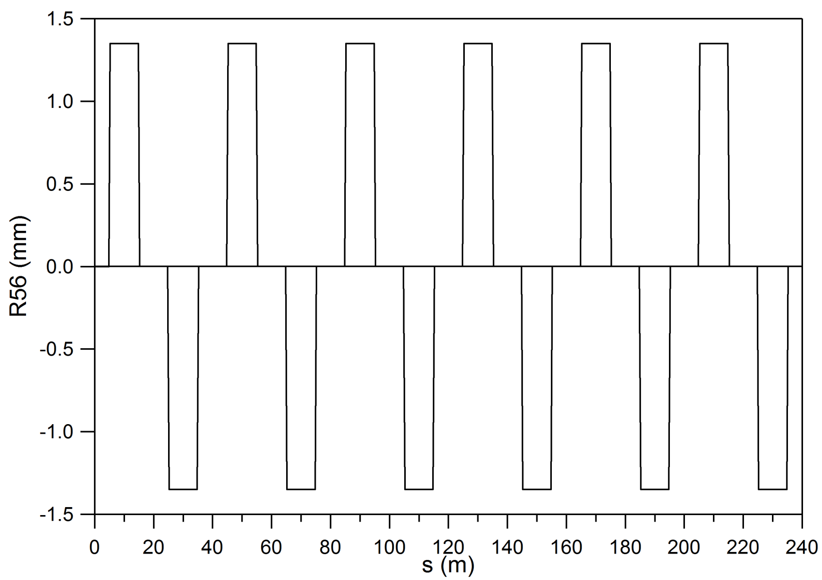


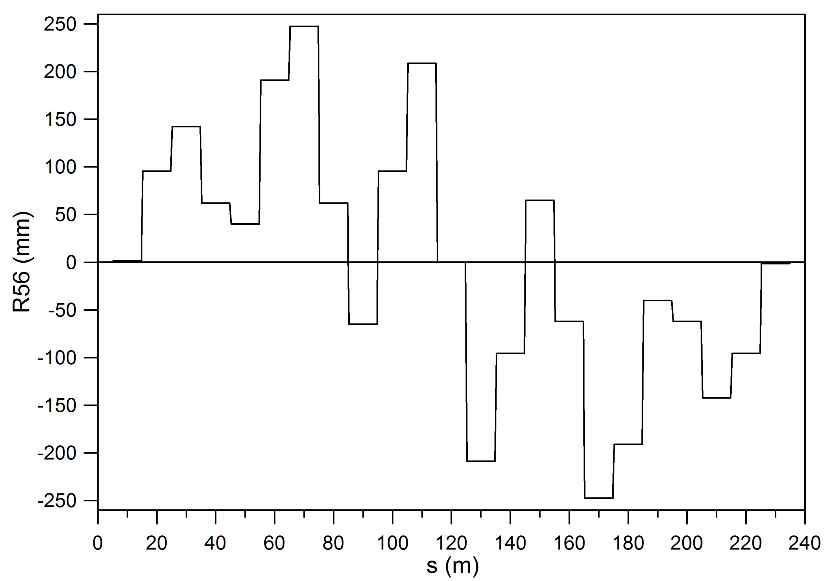
- nominal operation decompresses the bunch through arc
  - ✓ experiences two parasitic compressions in Bates bend
  - ✓ experiences a single parasitic compression in chicane

	Cross-Phased			Nominal		
	ε_x *(mm-mrad)*	β_x *(m)*	α_x	ε_x *(mm-mrad)*	β_x *(m)*	α_x
0F	15.2	11.2	-0.1	15.2	11.2	-0.1
2F	17.5	11.8	6.3	17.9	12.9	6.6
3F	20.8	3.7	-1.0	30.5	3.1	-0.7
4F	21.3	11.8	-5.5	41.8	16.8	-8.0

Isochronous Arc Study

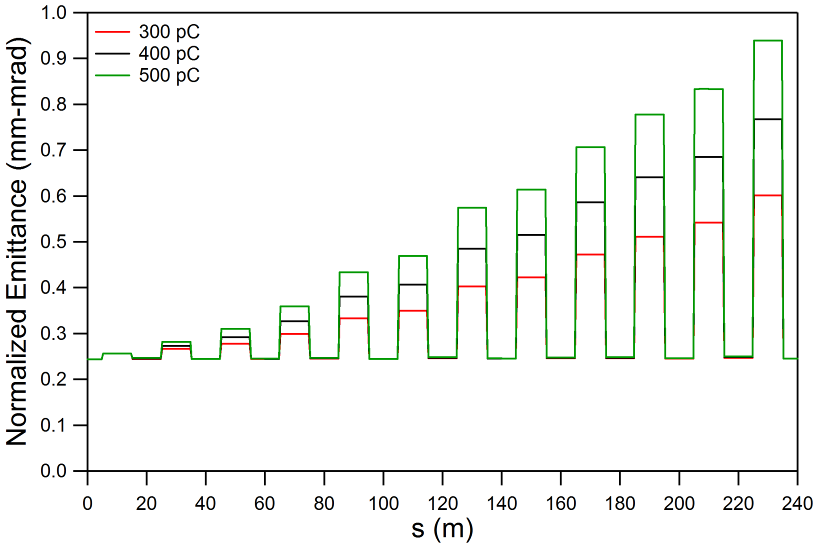
	Example A	Example B
Energy (GeV)	**1.3**	**1.3**
$\varepsilon_{x,y}$ (mm-mrad)	**0.25**	**0.25**
$\sigma_{\delta E/E}$	$\mathbf{9\times10^{-6}}$	$\mathbf{9\times10^{-6}}$
σ_t (ps)	**3.0**	**3.0**
Structure	**Periodically isochronous & achromatic**	**Globally isochronous & achromatic**

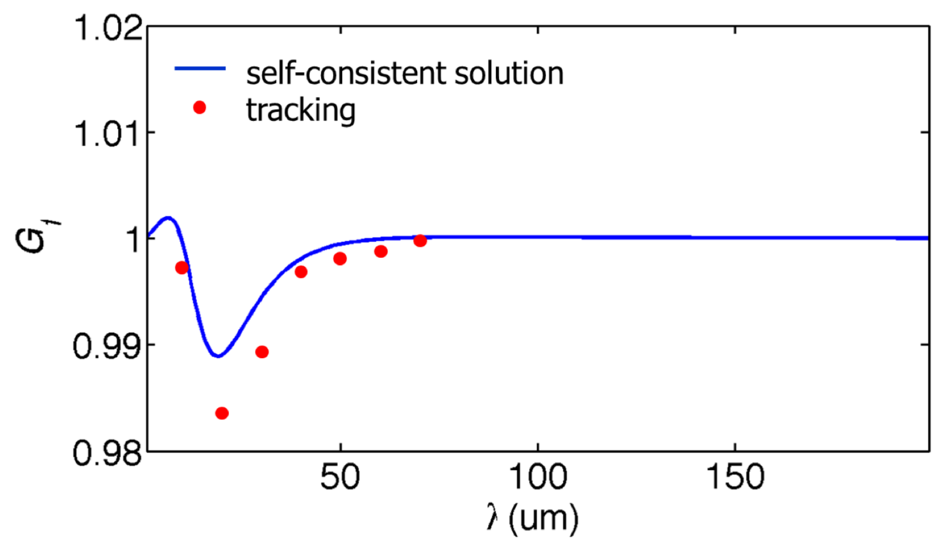




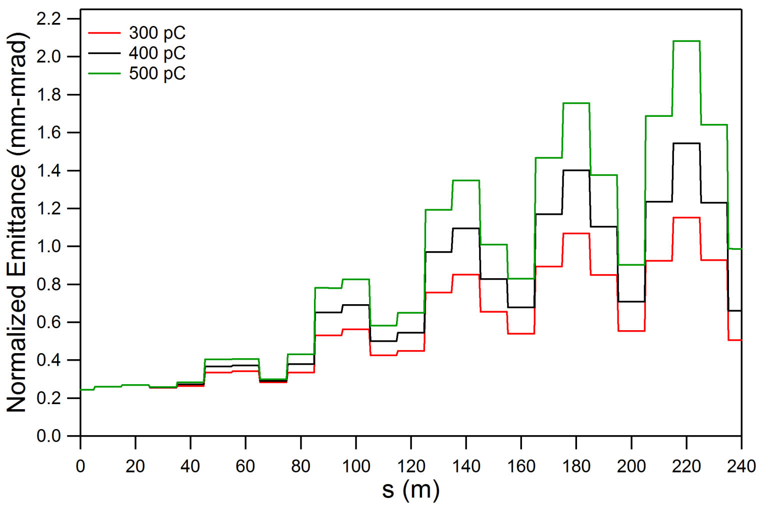
Arc: Example A

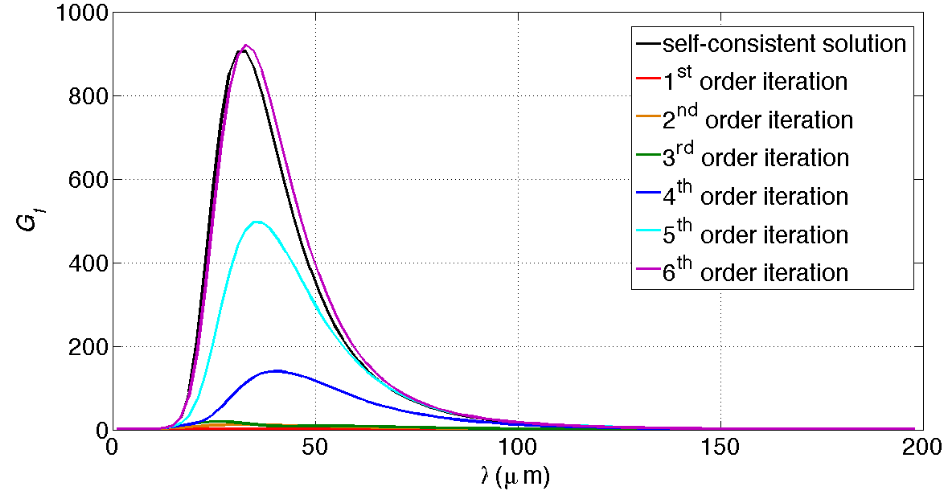
- effective suppression of CSR-induce emittance growth
  - ✓ an initial CSR kick is cancelled by a second kick a half-betatron wavelength away
- design manifests *no evidence* of microbunching gain

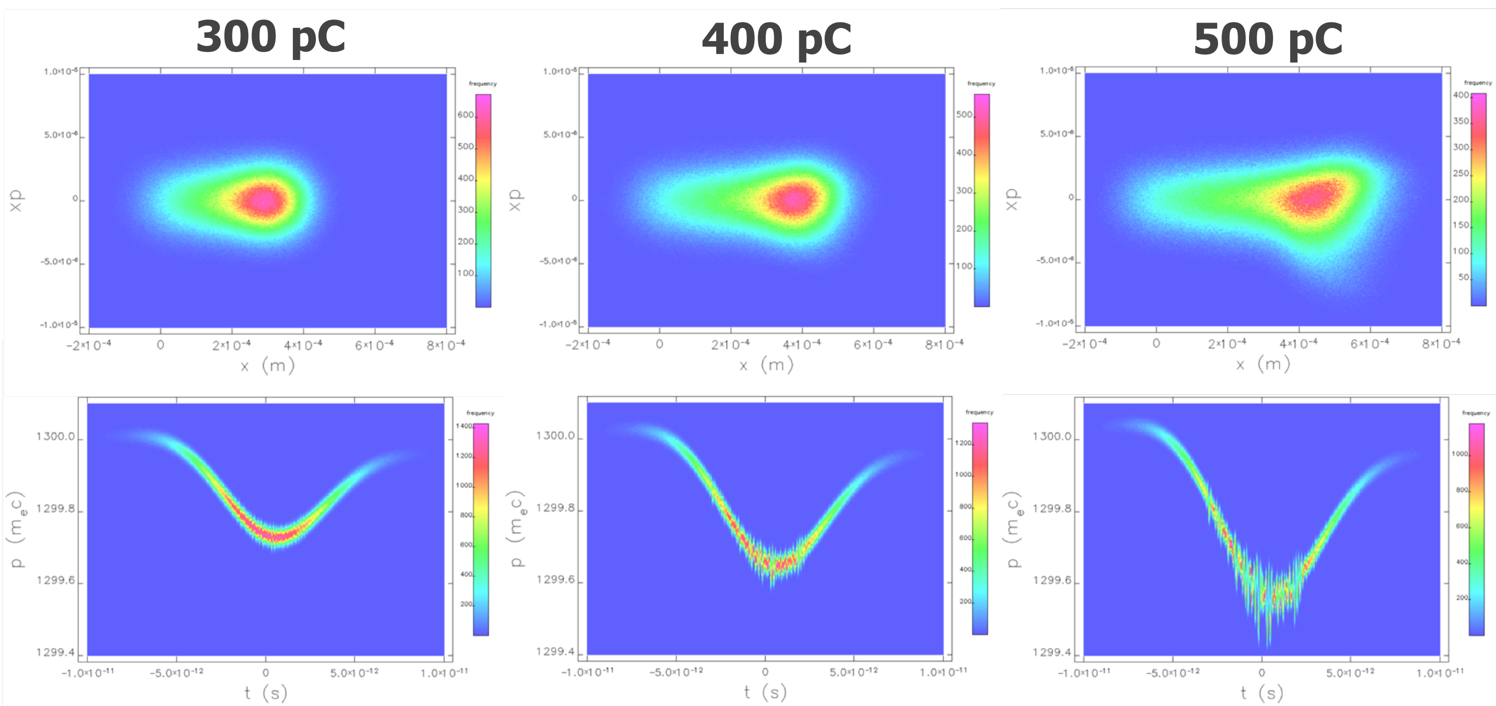




Arc: Example B

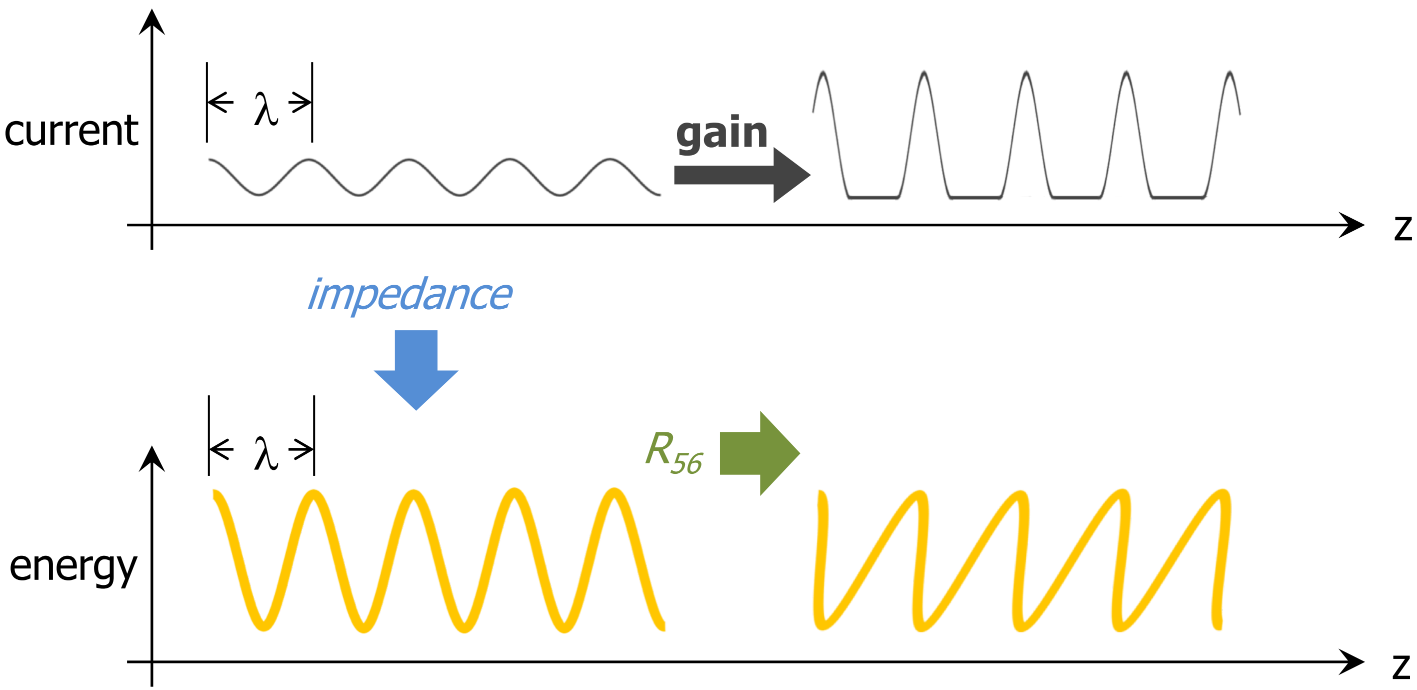






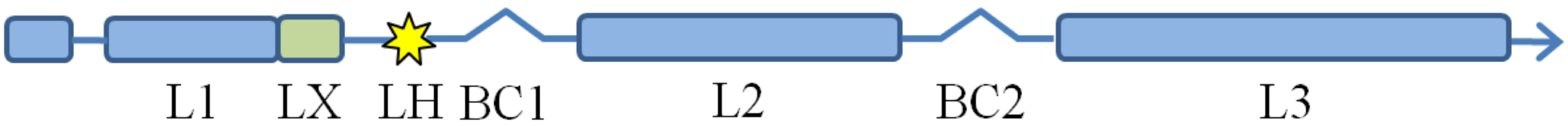
What is Microbunching?

- initial **density** modulation can induce **energy** modulation due to the presence of short-range wakefields (e.g. **LSC** or **CSR**)
- the **energy** modulation can be converted to **density** modulation via the R_{56} in the beamline
- process may result in an enhancement of the initial **density** modulation → ***microbunching instability***



Why is it Important in ERLs?

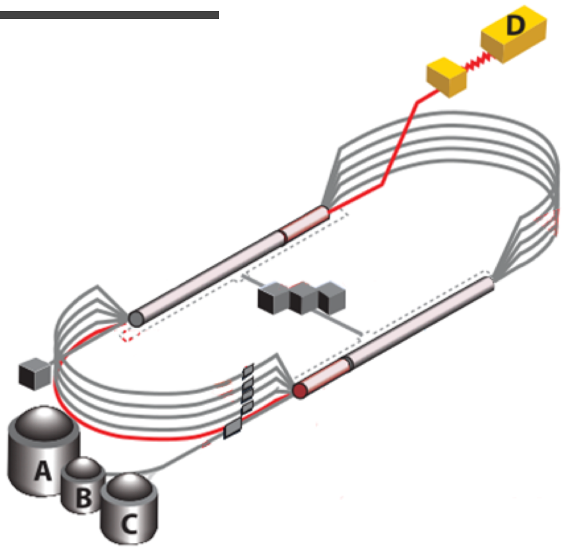
- microbunching is a relatively new collective effect
- a lot of work has been done investigating chicanes



- recent efforts address CSR and microbunching in recirculation arcs
- ERLs have potential to seed microbunching instability
  - ✓ low injection energy *(efficiency)*
  - ✓ long linac sections
  - ✓ large numbers of dipoles *(merger, arcs, chicanes)*
- ERL-driven light sources (short bunch, high peak current) must contend with microbunching, but so do other applications (e.g. bunched beam cooler)

Possible Experimental Tests at JLab

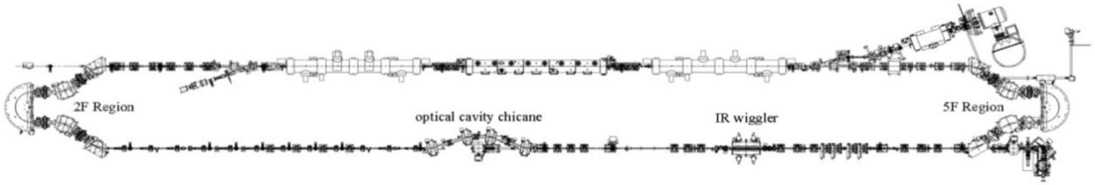
CEBAF *(Y. Roblin)*



- compare different tunings of arc transport
- measure effectiveness of optics balance
- challenge to generate a bright enough beam
  - ✓ would require a modified front end

LERF *(R. Li)*

- could generate microbunching with high charge
  - ✓ (60-250) pC demonstrated
- could vary contributions from LSC or CSR
  - ✓ change injector energy (5-9) MeV
- "controlled" microbunching with initial DL induced modulation
- study CSR at low energy

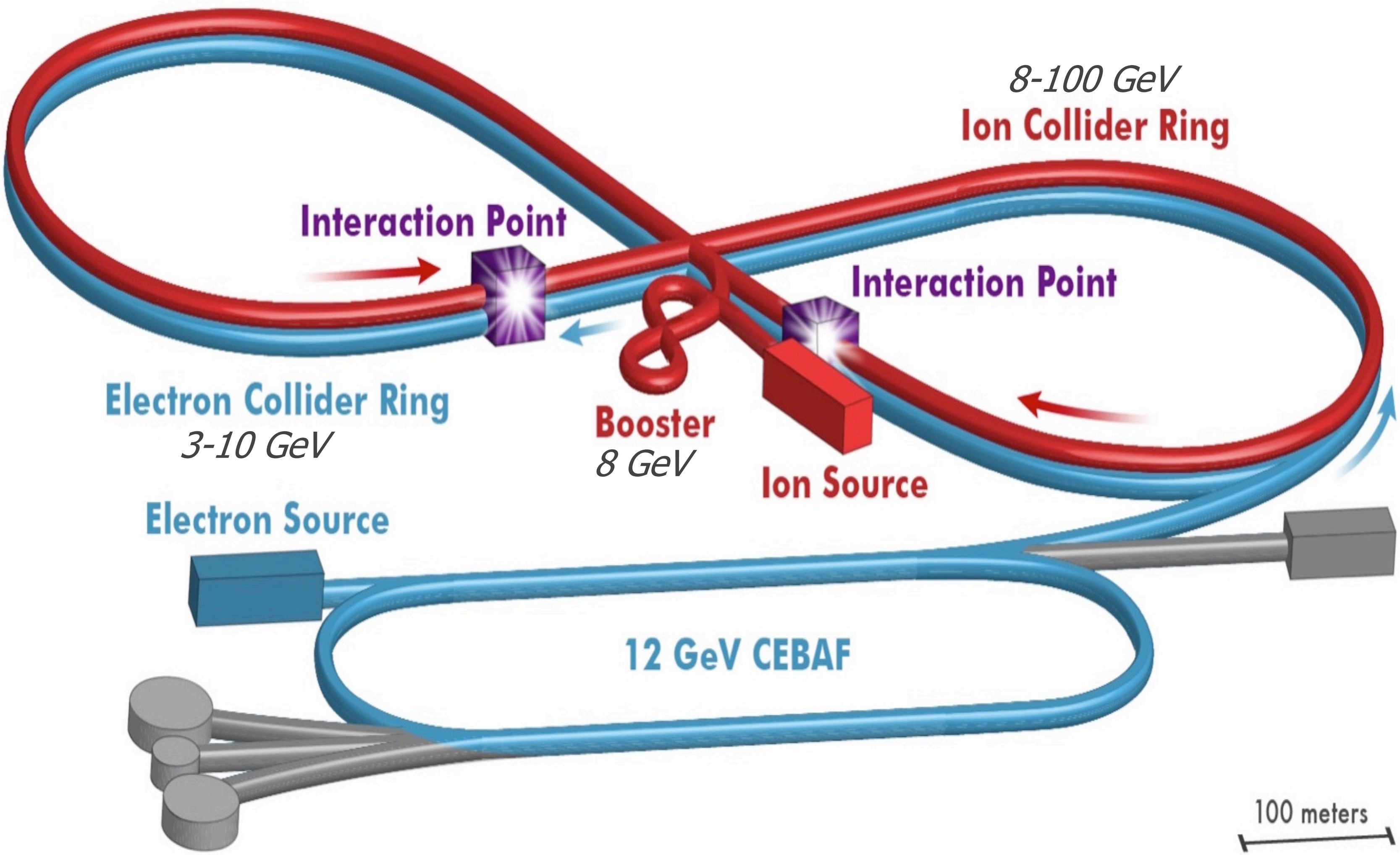


Fast Microbunching Gain Code

- developed by Cheng-Ying Tsai *(see ERL'15 Proceedings)*
- semi-analytical linear Vlasov-solver which includes relevant impedances:
  - ✓ CSR (steady-state – relativistic and non-relativistic, with shielding, transient)
  - ✓ LSC and linac geometric wakes
- includes acceleration and deceleration, allows for horizontal and vertical bending, handles magnetized beams
- allows start-to-end gain calculations
  - ✓ **not** enough to compute gain for each section and multiply (underestimates gain)
- benchmarked with `elegant` (i.e. time-domain method)
- limitations:
  - ✓ linear → does not include sextupoles, curvature from RF, etc.
  - ✓ coasting beam model → not valid when modulation wavelength is comparable to bunch length

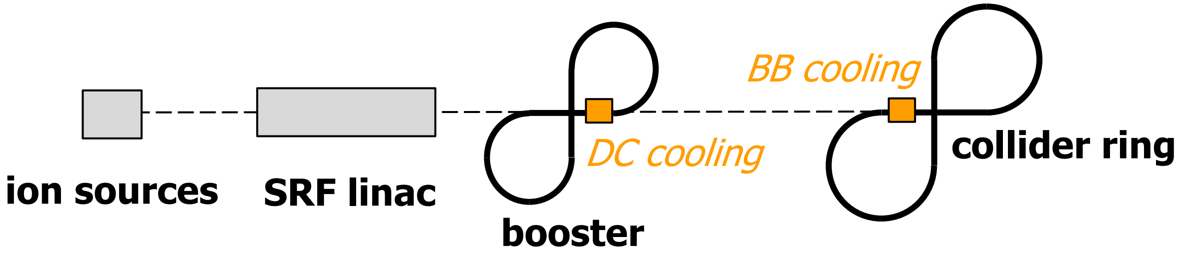
JLab Electron Ion Collider *(future)*

- a ring-ring design for colliding polarized electrons (originating from CEBAF) with medium energy ions (new ion complex)

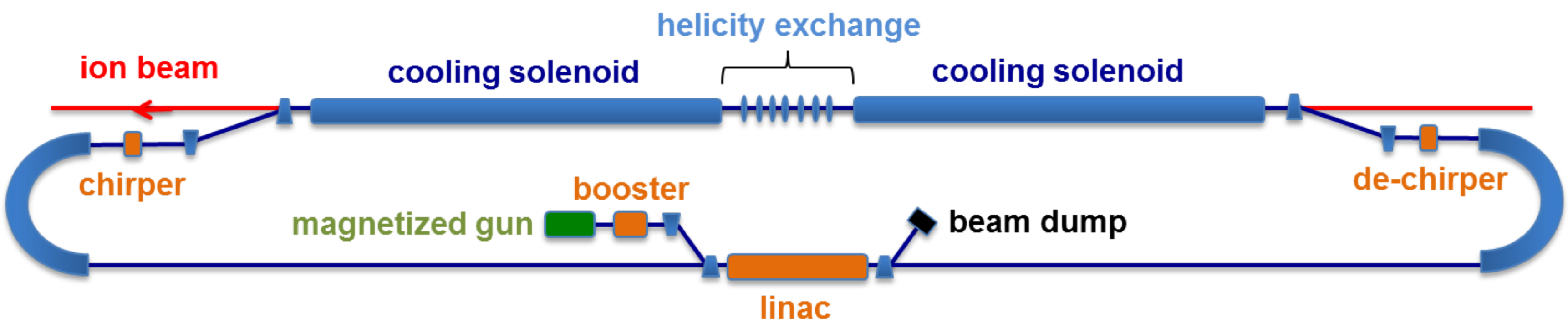


Weak Cooling: Backup

- DC cooling for emittance reduction
- BB cooling to combat intra-beam scattering

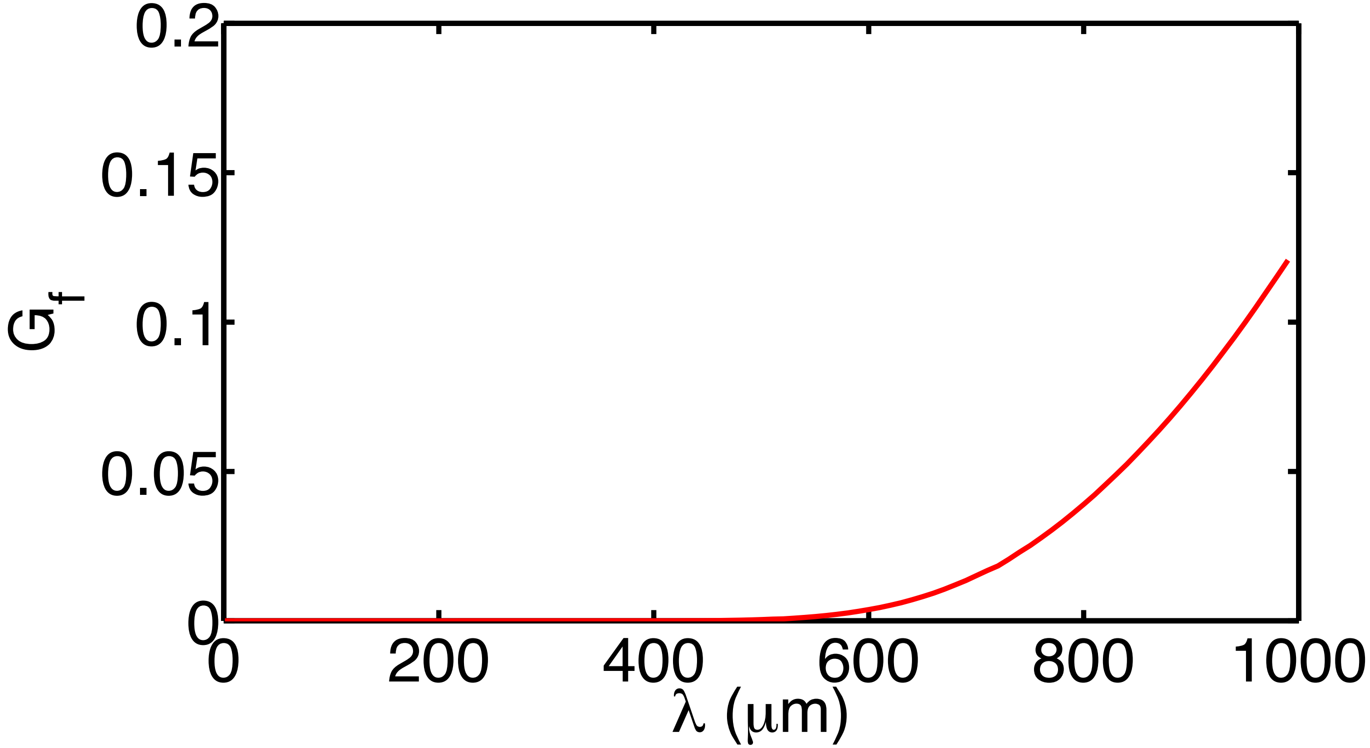


- single-pass, ERL-driven cooler which invokes a magnetized beam
  - ✓ immerse cathode in solenoid field
- characterized by a **Larmor** (defines the beam temperature in the cooling solenoid) and **drift** emittance (defines the beam size in the solenoid)



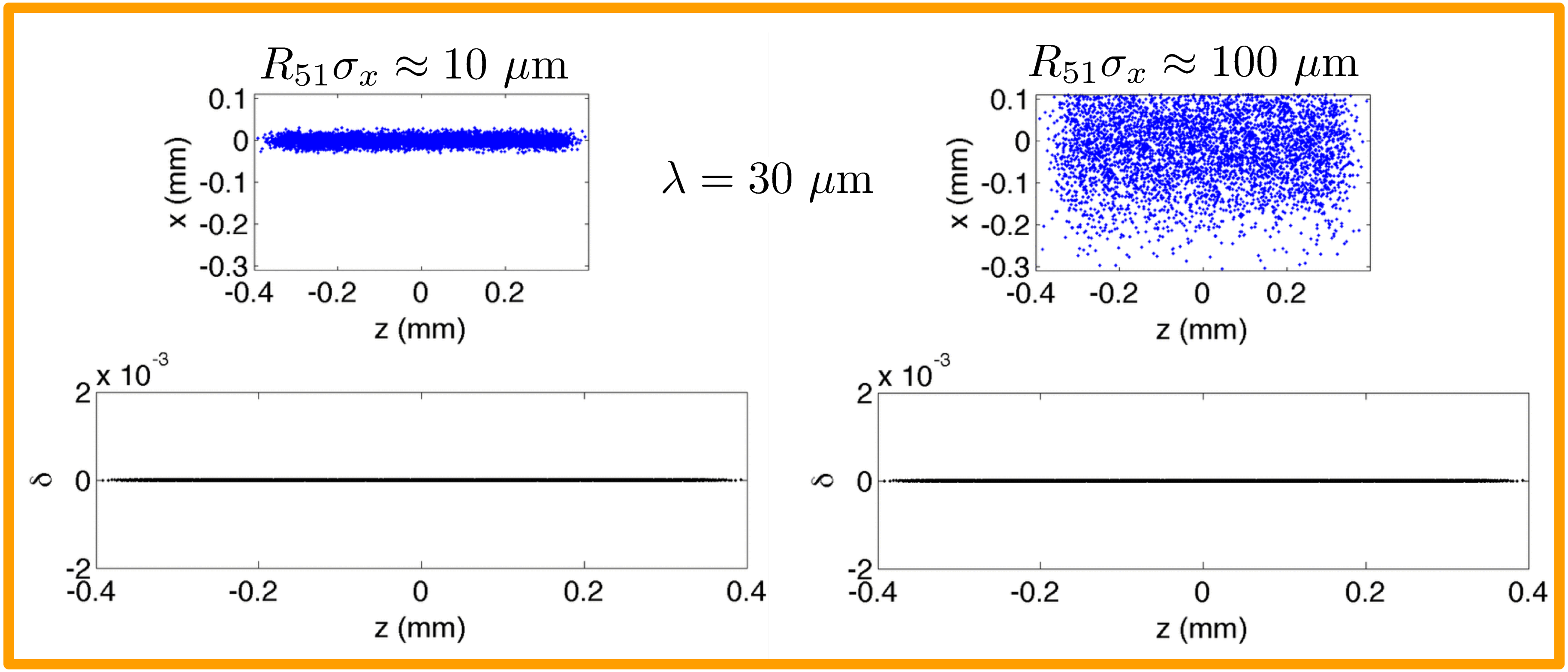
Results for Weak Cooling

Name	Value	Unit
Beam energy	55	MeV
Bunch charge	420	pC
Compression factor	0.28	
$\Delta E/E$ *(uncorrelated)*	2.4×10^{-3}	



Landau Damping

- smearing of horizontal phase space (due to R_{51})
- effective phase mixing when $R_{51}\sigma_x > \lambda$



Summary

- performed initial studies on the "bulk" effects of CSR in the LERF
- demonstrated bunch length compression – with lasing – running on the "wrong side" of the RF waveform
- possibility of doing interesting experimental work using existing infrastructure
  - ✓ CEBAF: optics balance for CSR and microbunching suppression
  - ✓ LERF: SC and CSR driven microbunching
- development of fast and efficient microbunching gain solver
  - ✓ enabled quick analysis of beamlines
  - ✓ provided insights into lattice requirements for gain suppression
- electron-ion collider design requires working carefully through CSR and microbunching issues and involves working in an interesting parameter regime
  - ✓ low energy (SC), high charge (SC+CSR), lots of dipoles (CSR)
  - ✓ do not have adequate tools at present to model

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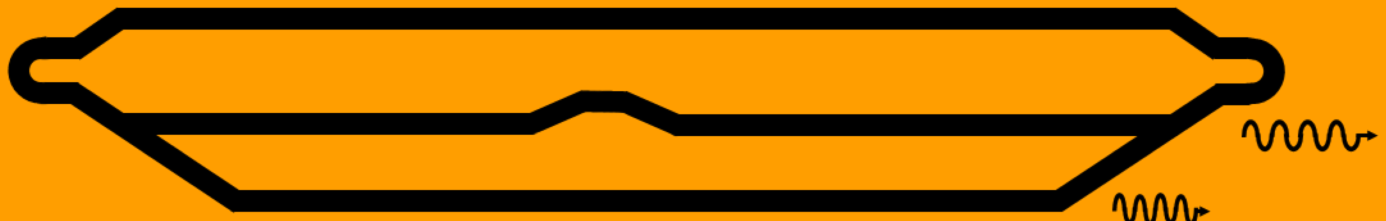
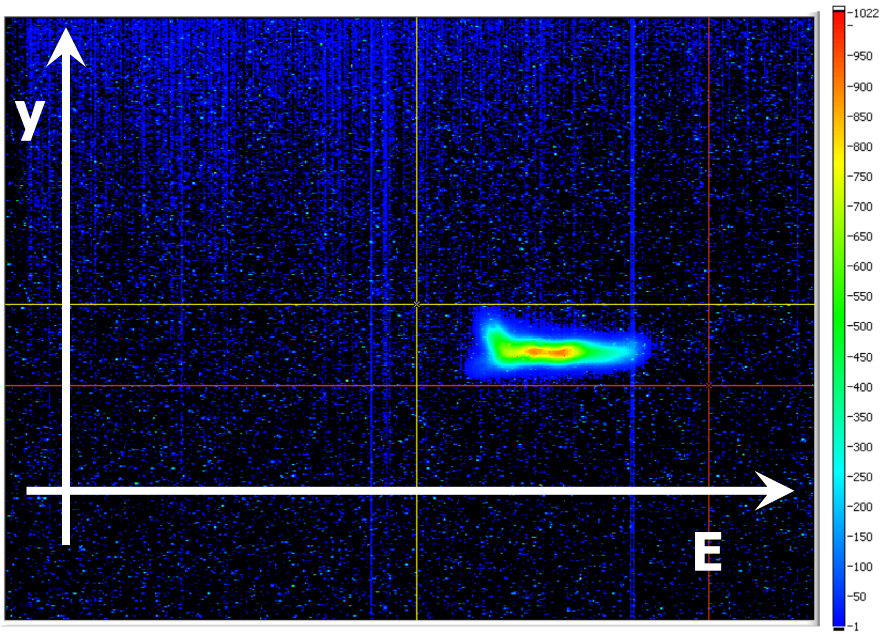
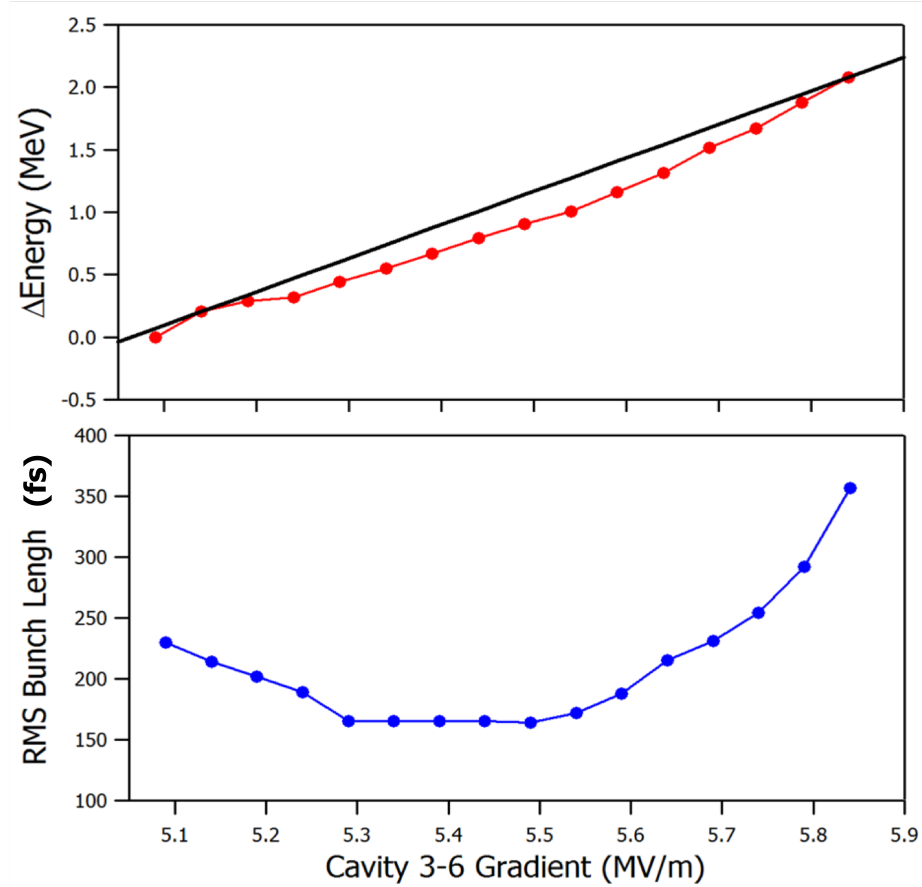
THANK YOU



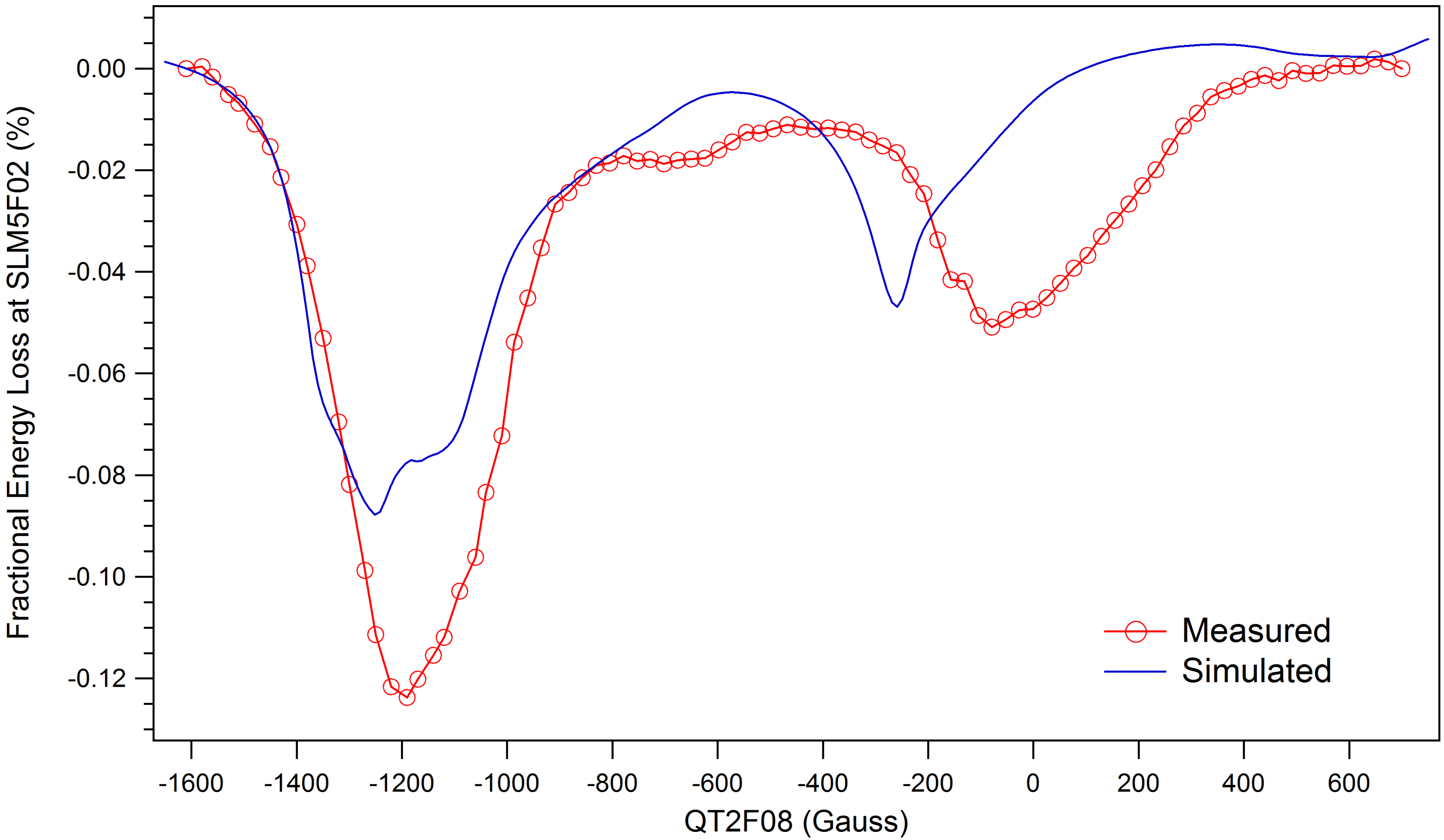
Coherent Synchrotron Radiation

- excessive CSR hitting downstream mirror and limiting power output → decompressor chicane
- CSR does not present an operational impediment
- observe beam filamentation as we vary bunch length compression

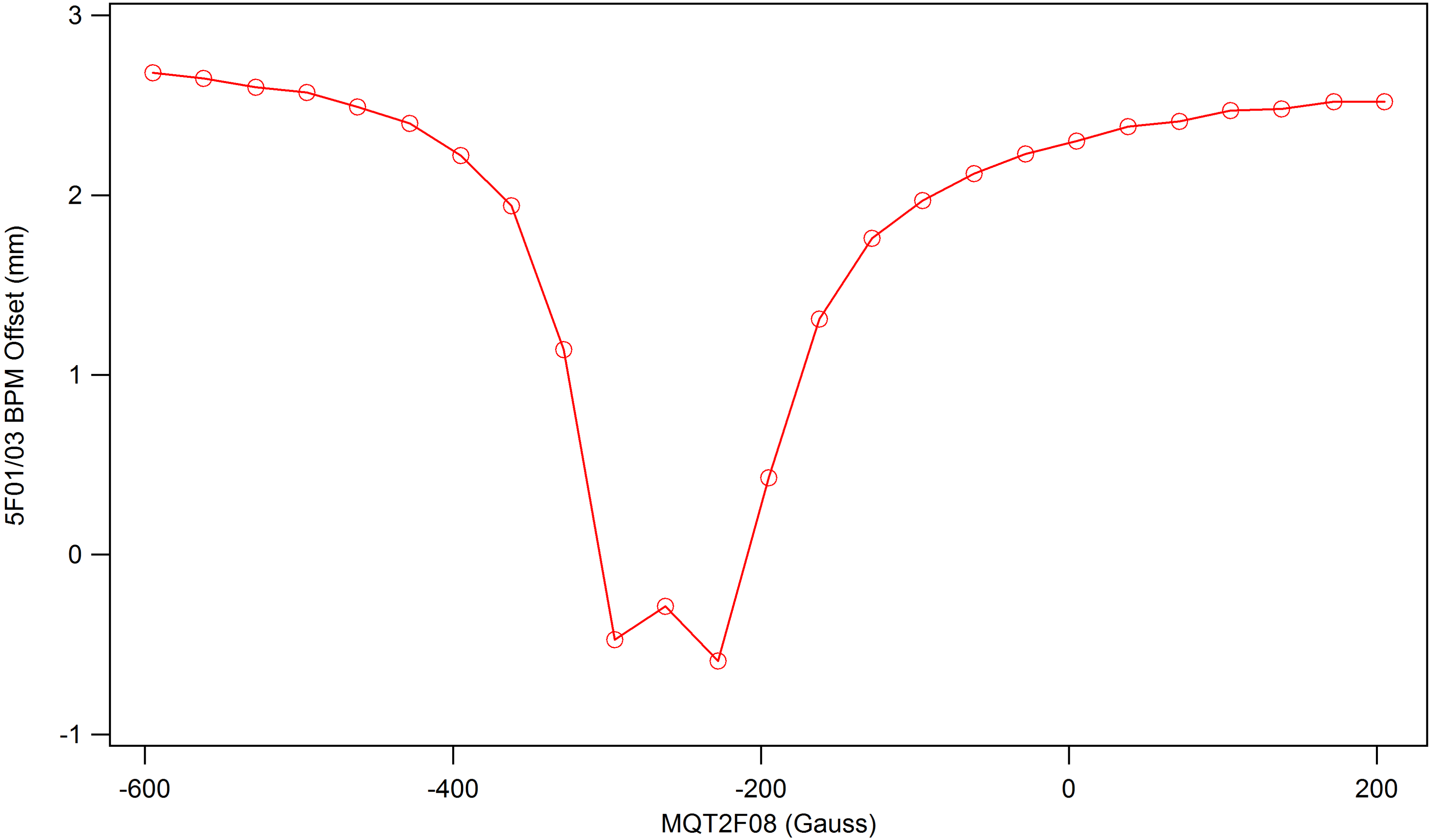




Measurement vs Simulation

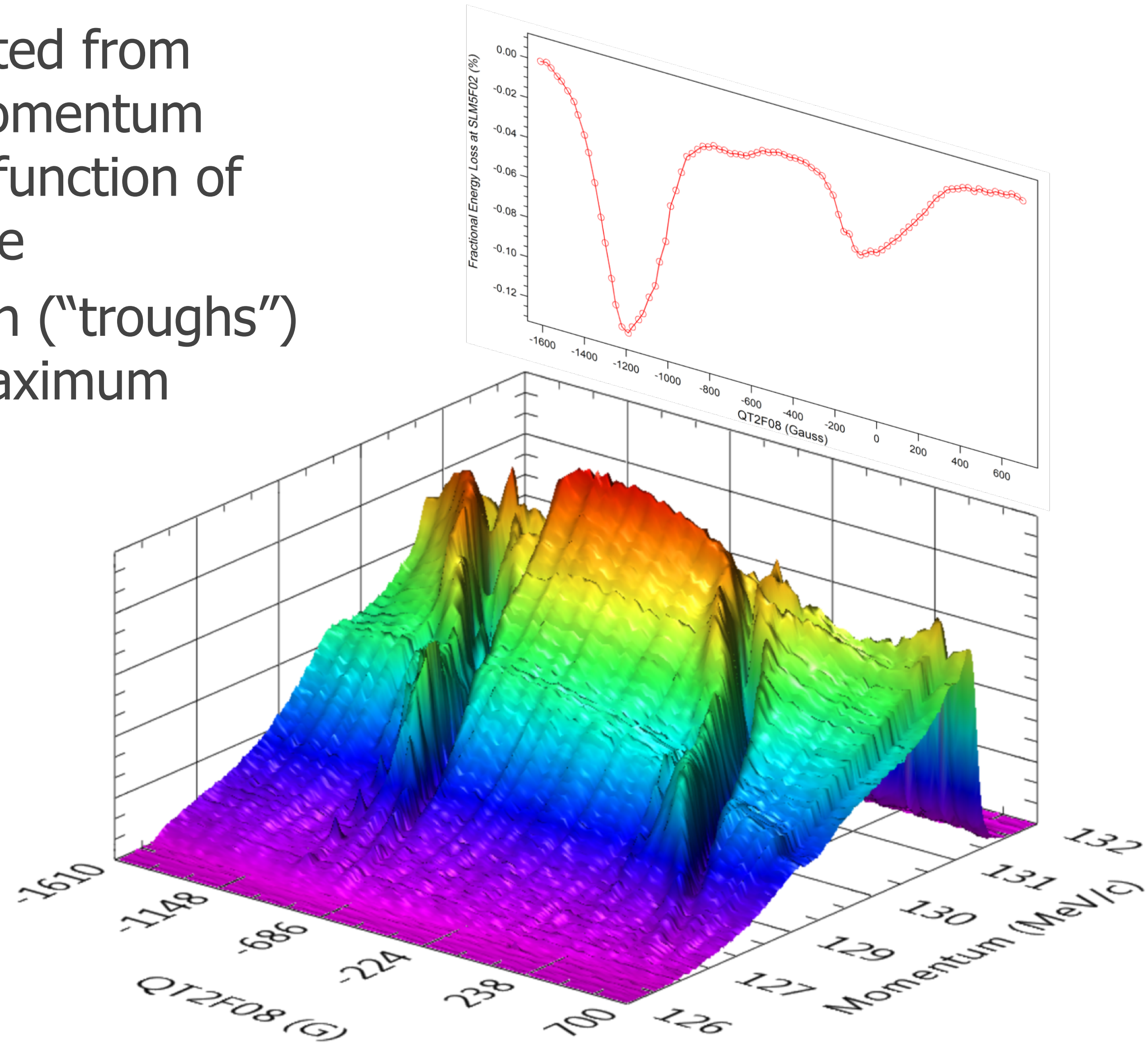


CSR-Induced Energy Loss

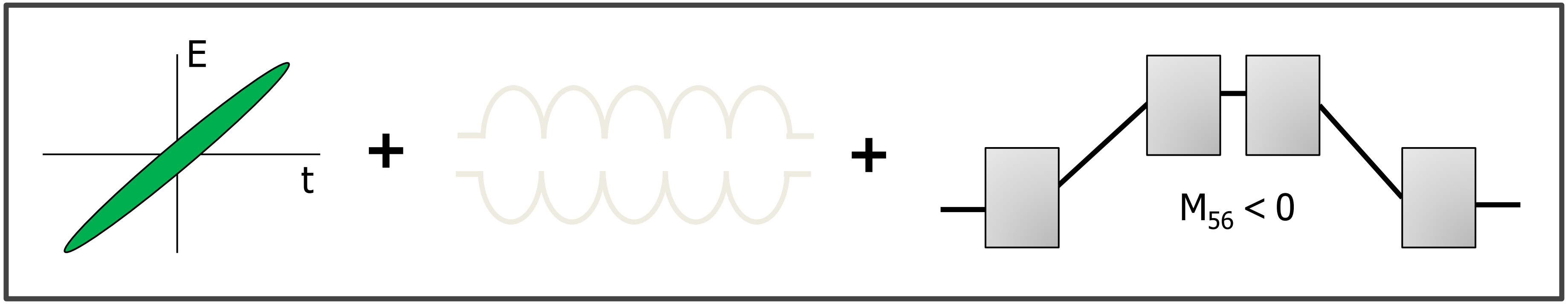


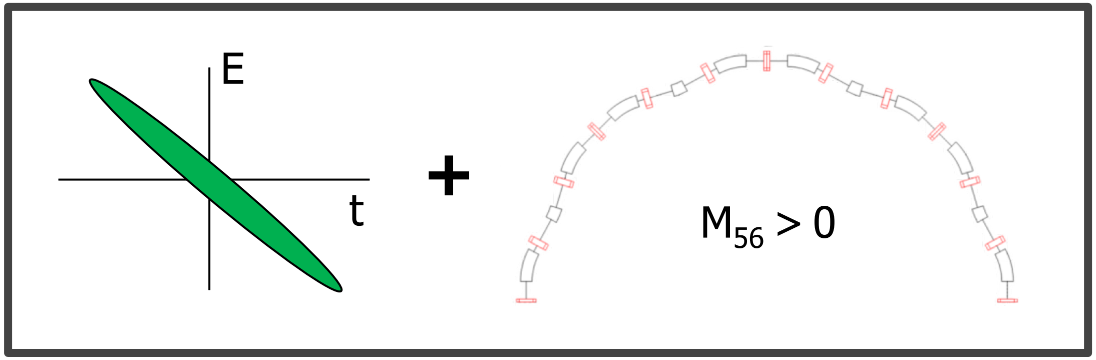
Energy Distribution vs Compression

- surface plot created from projections of momentum distribution as a function of compression state
- areas of depletion ("troughs") correspond to maximum energy loss



Implications for Bunch Compression

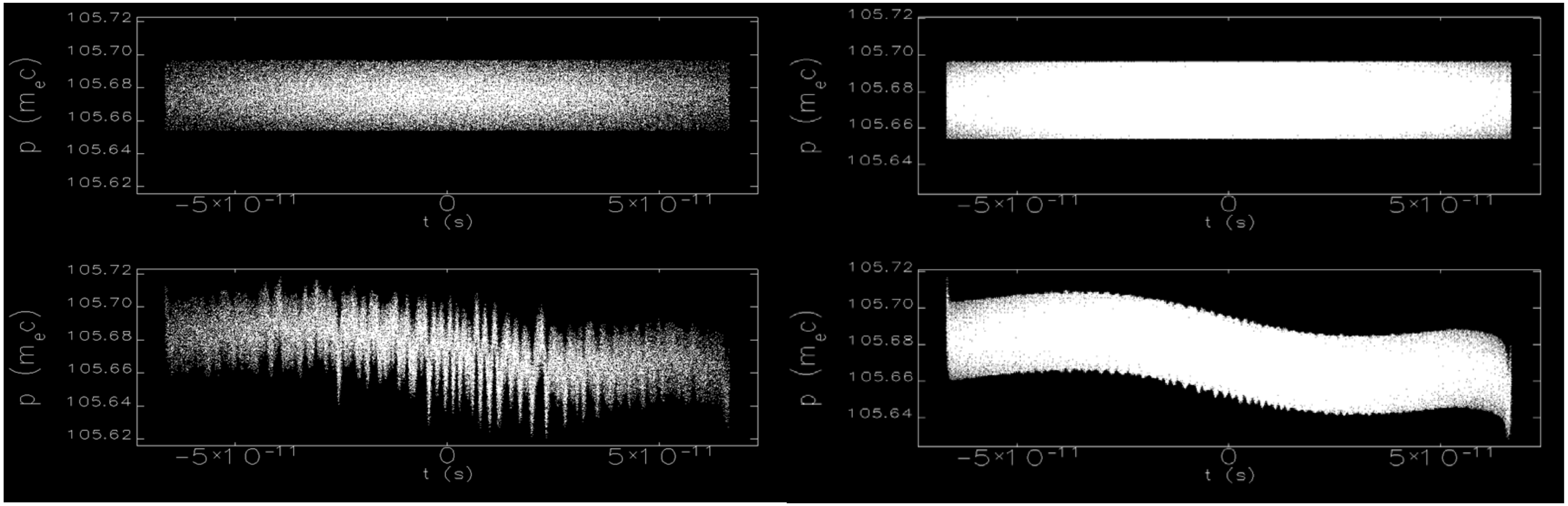




1. use momentum compactions (M_{56}, T_{566}) of arc to linearize bunch
2. accelerating after crest, LSC increases phase-energy correlation
3. can design final compression to occur at end of last dipole

Modeling Microbunching

- time-domain analysis of microbunching (particle tracking) is a challenge
- initial density modulation needs to be small enough to remain in linear regime but large enough to avoid numerical artifacts → large numbers of particles and computationally intensive
- difficult to do parametric scans



Suppression of CSR-induced μBI Gain

- For the conditions of CSR gain suppression, it is key to make $R_{56}(s_i' \to s_f)$ as small as possible

$$K(s,s') = \frac{ik}{\gamma}\frac{I(s)}{I_A}C(s')\boxed{R_{56}(s' \to s)}Z\left(kC(s'),s'\right) \times [\text{Landau damping}]$$

- For the simplest case of **dipole-straight-dipole**, the simplified expression of $R_{56}(s_i' \to s_f)$ can be obtained by matrix multiplication

$$R_{56}(s_i \to s_f) \simeq \left[\left(\frac{s_i - L_b}{\rho_b^2}\sqrt{\beta_i\beta_f} + \frac{s_i L_b \alpha_i}{\rho_b^2}\sqrt{\frac{\beta_f}{\beta_i}}\right)\sin\psi_{if} + \left(\frac{s_i L_b}{\rho_b^2}\sqrt{\frac{\beta_f}{\beta_i}}\right)\cos\psi_{if}\right]s_f$$

- To keep the amplitude of $R_{56}(s_i' \to s_f)$ as small as possible, we need to:
  - keep β functions as small as possible
  - keep $|\alpha|$ function not too small, so as to meet
  - phase difference between dipoles $\psi_{if} = \psi_f - \psi_i$ close to $m\pi$ (m: integer)
  - keep bending radius ρ_b as large as possible

(courtesy C.-Y. Tsai)

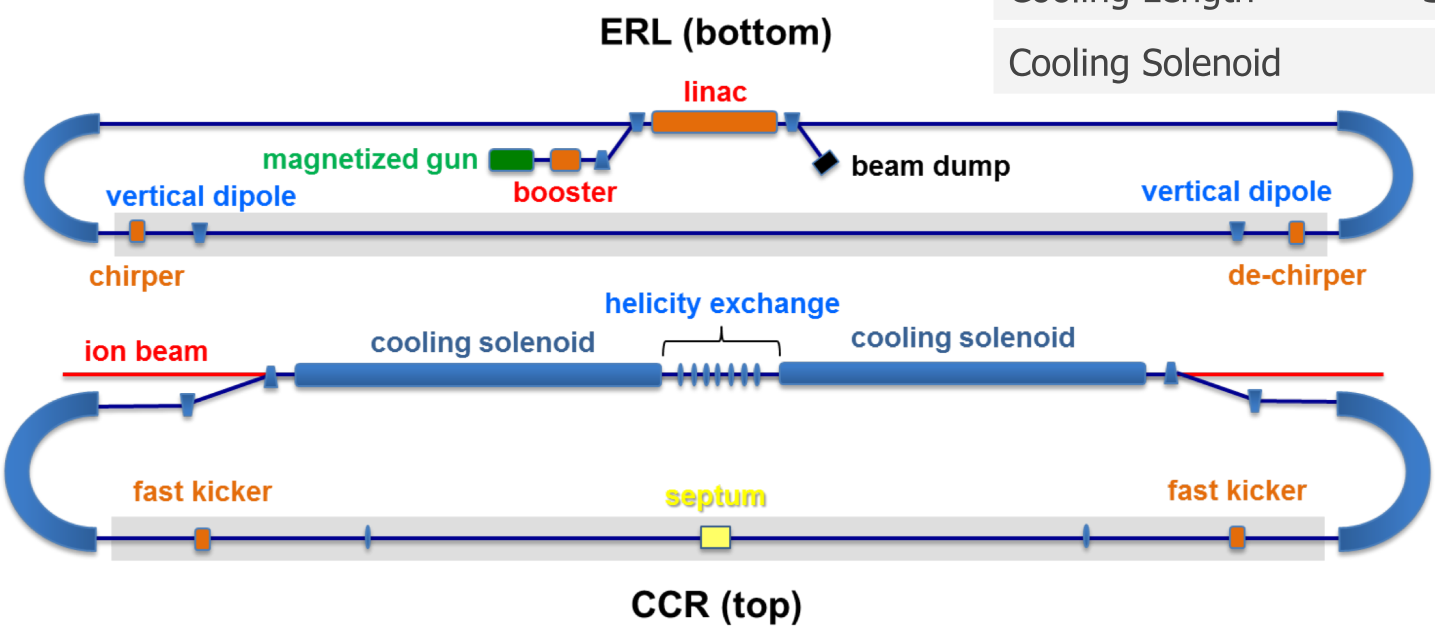
JLEIC Baseline Parameters

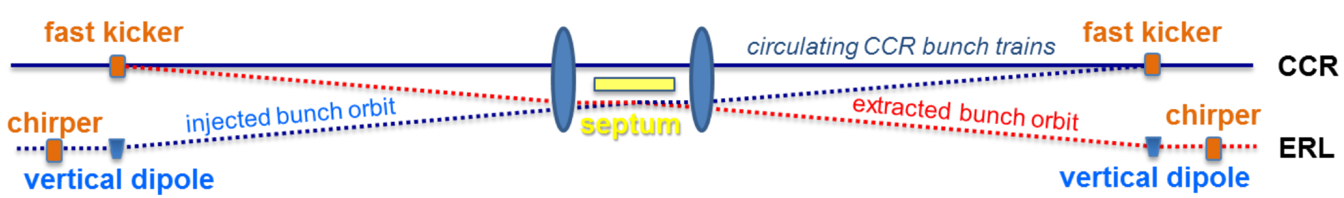
CM Energy	GeV	21.9 *(low)*		44.7 *(medium)*		63.3 *(high)*	
		p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		476		476/4=119	
Particles per bunch	10^{10}	0.98	3.7	0.98	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	3	1	1	1	2.2	1
Norm. emitt., hor./vert.	μm	0.3/0.3	24/24	0.5/0.1	54/10.8	0.9/0.18	432/86.4
Horizontal/vertical β*	cm	8/8	13.5/13.5	6/1.2	5.1/1	10.5/2.1	4/0.8
Vert. beam-beam param.		0.015	0.092	0.015	0.068	0.008	0.034
Laslett tune-shift		0.06	7×10^{-4}	0.055	6×10^{-4}	0.056	7×10^{-5}
Detector space, up/down	m	3.6/7	3.2/3	3.6/7	3.2/3	3.6/7	3.2/3
Hourglass (HG) reduction		1		0.87		0.75	
Luminosity/IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	2.5		21.4		5.9	

Strong Cooling: Baseline

- All of the issues of weak cooling
- **plus**, the challenge of a 20-turn CCR
- … and at a higher bunch charge

Parameter	Value
Energy	**up to 55 MeV**
Bunch Charge	**up to 3.2 nC**
Cooling Length	**30 m**
Cooling Solenoid	**1 T**

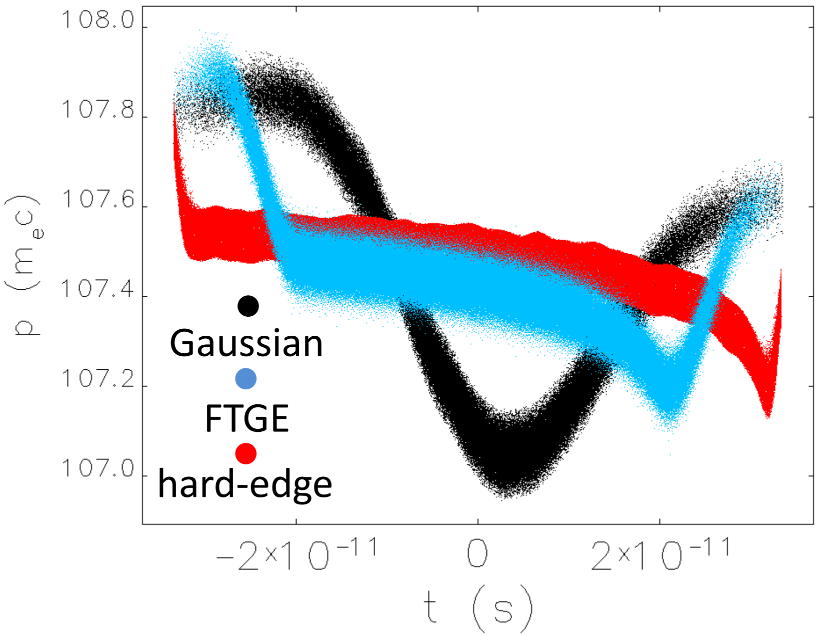


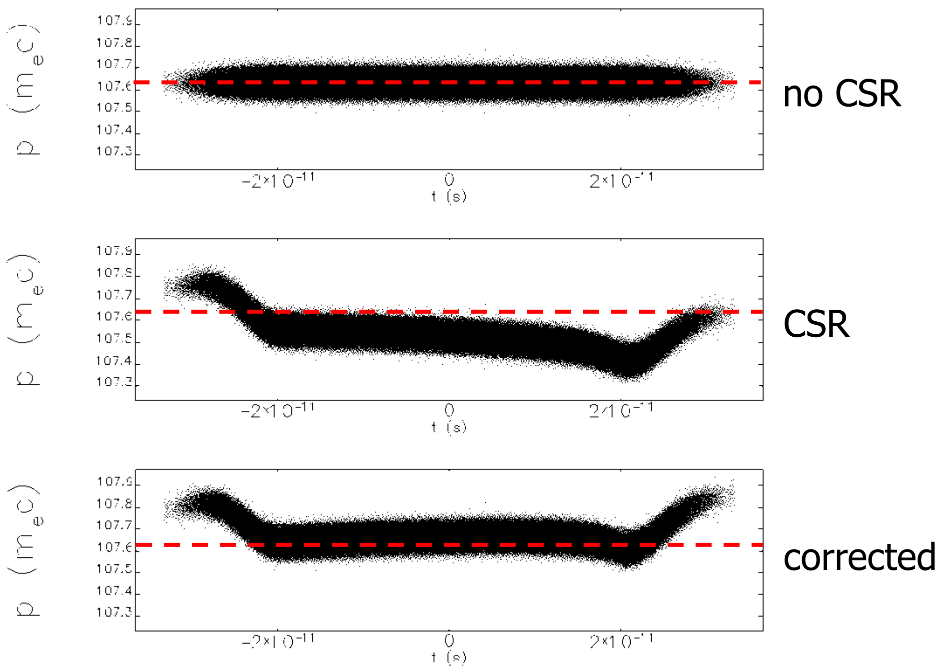


Beam Exchange (side)

CSR for Multiple Recirculations

- CSR wake is proportional to derivative of bunch distribution
- for a flat-top, wake is roughly linear across the bunch
  - ✓ use RF cavity to correct slope and energy loss each turn





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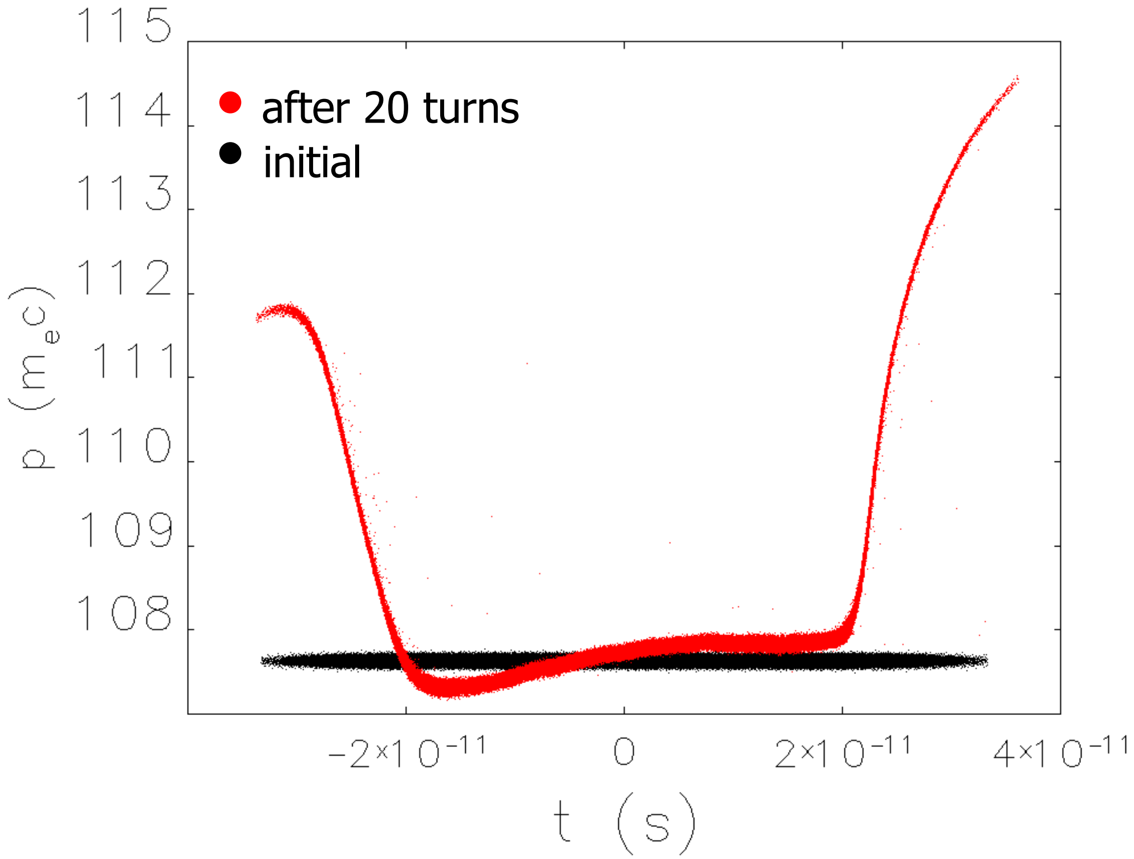

Miscellaneous

- scaling: $\lambda_{opt} \propto R_{56}^{ARC}\sigma_{\delta}$