Report from WG2

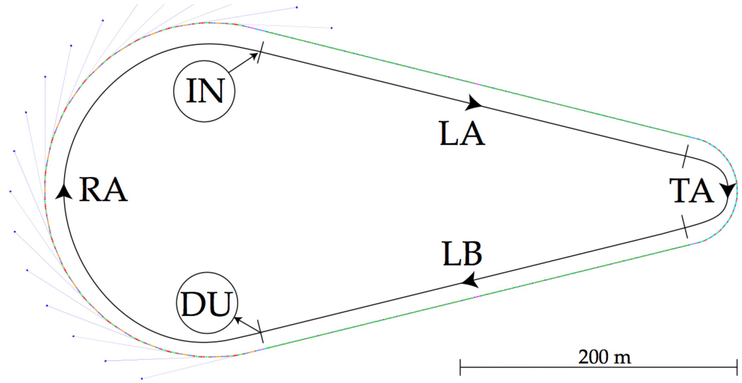
- Beam optics, dynamics, and diagnostics -

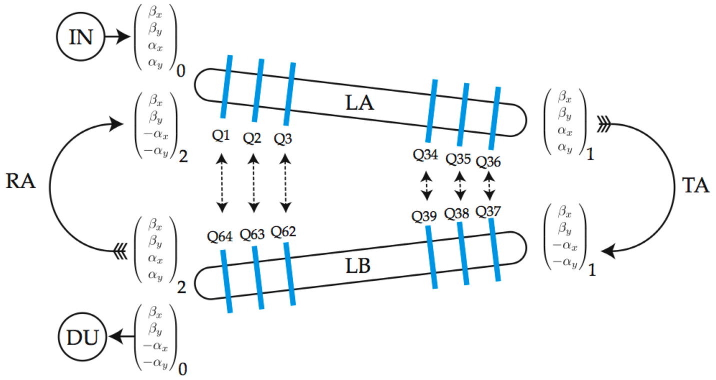
M. Borland and S. Sakanaka
(Co-conveners)

ERL09 Workshop, June 8-12, 2009, at Schwartz Center, Cornell University

X-Ray Sources

A Minimal ERL for a Hard X-ray Lightsource (C. Mayes, Cornell)





X-ray Requirements

- Accelerate particles to high energy (5 GeV)
  - LA & LB, linked by TA
- Bunches have a specified transverse size in undulators
  - Small Beta Functions & Dispersion in RA
  - Preserve Emittance
- Bunches have a specified length in undulators

Controlled Time of Flight in RA

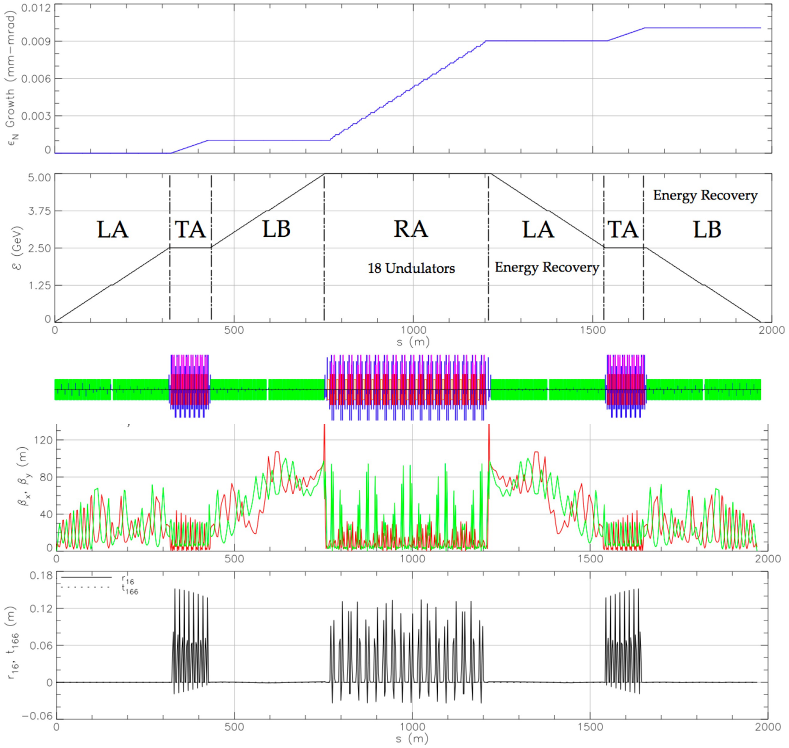
ERL Requirements

- Ensure survival of the beam
  - Controlled Beta Functions & Dispersion everywhere
  - Test by Particle Simulations
- Decelerate these bunches and recover their energy

Controlled Time of Flight everywhere

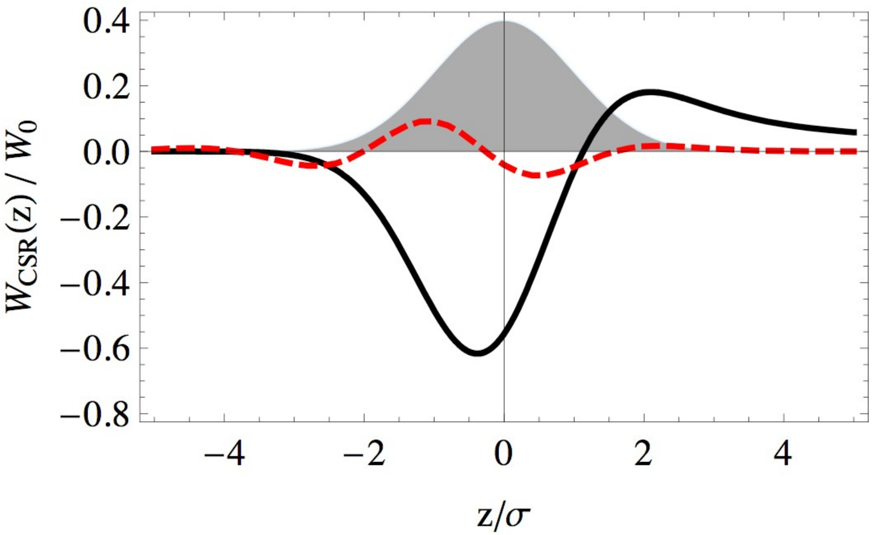
Practical Considerations

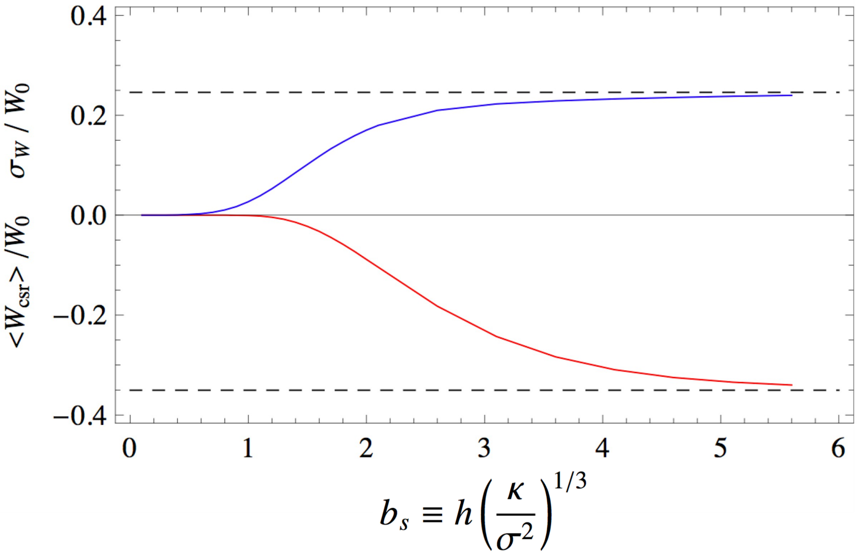
- Limit heat load on the chamber wall
  - Have sufficiently large dipole bending radii
- Limited number of unique elements, simplicity
  - Standard length dipoles, quadrupoles, etc., symmetry
- . . .



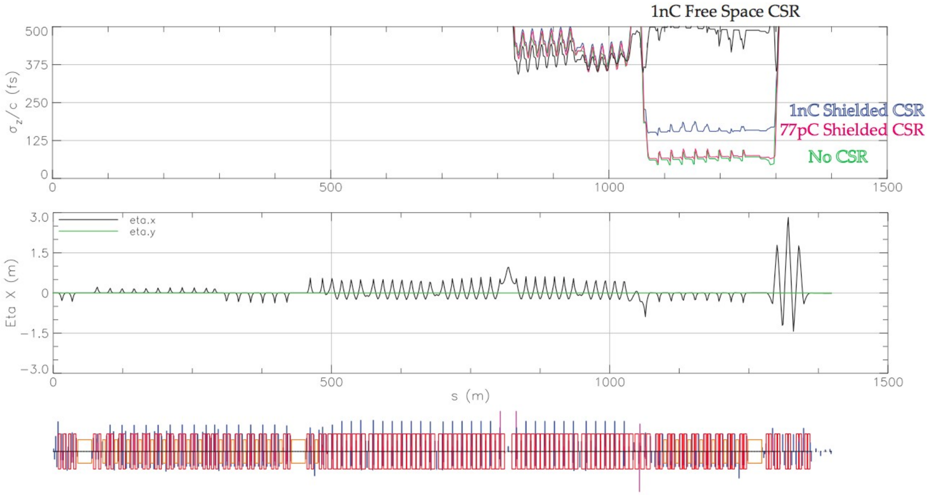
CSR in ERL Lightsources (C. Mayes, Cornell)

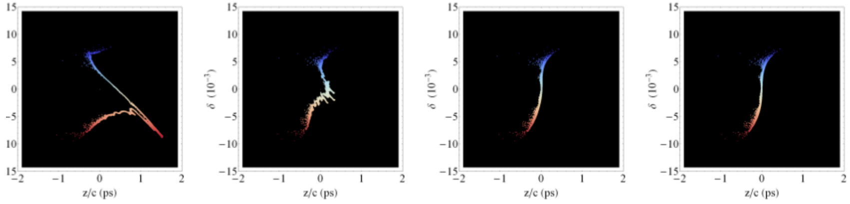
CSR Wakefield in **Free Space** and with **Shielding**



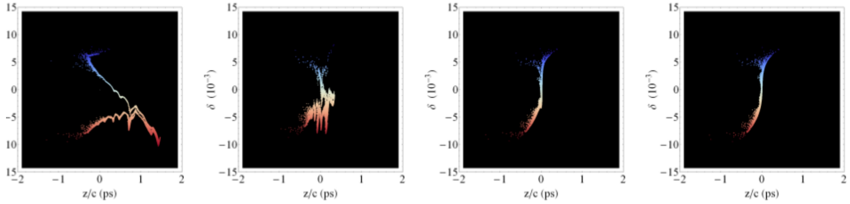


Cornell ERL Bunch Compression with CSR and Shielding: 2 ps to 100 fs (BMAD Simulations)



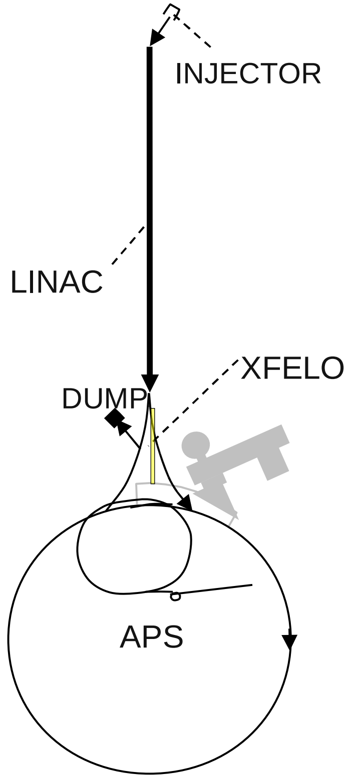


(a) 1 nC free space (b) 1 nC shielded (c) 77 pC shielded (d) No CSR

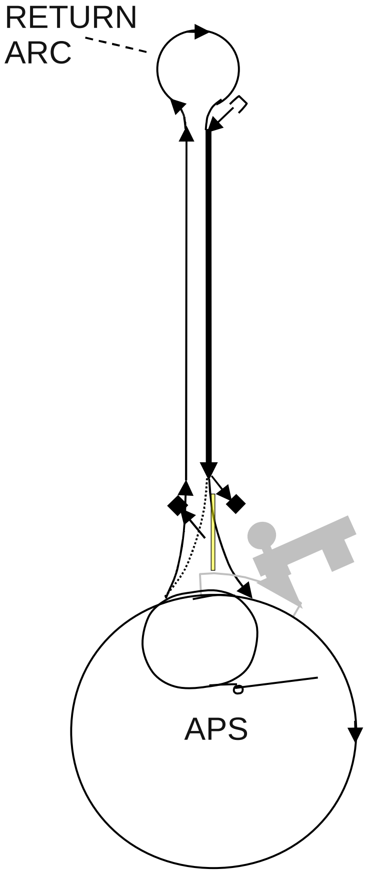


(e) 1 nC free space (f) 1 nC shielded (g) 77 pC shielded (h) No CSR

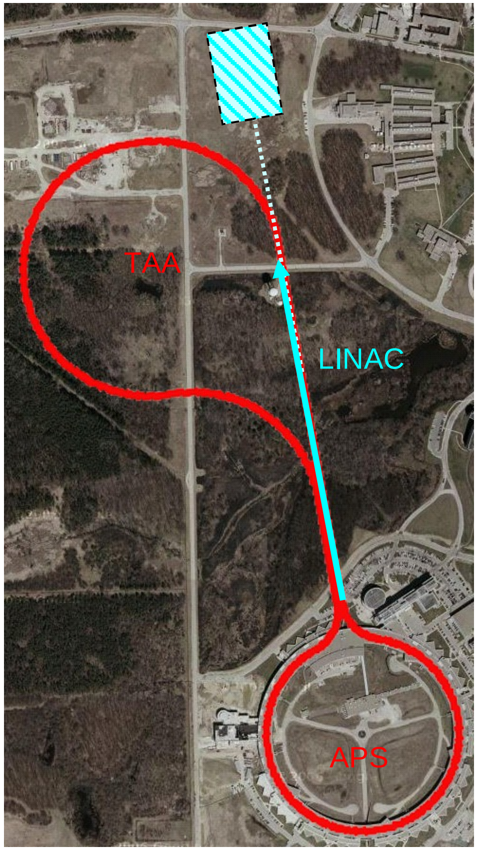
ERL Staging: ERL Upgrade in Steps (K. Harkay, ANL)[1]



Stage 1: No E.R.
150 µA
High coherence
Break-even brightness



Stage 2: w/E.R.
>>150 µA
High coherence
High brightness

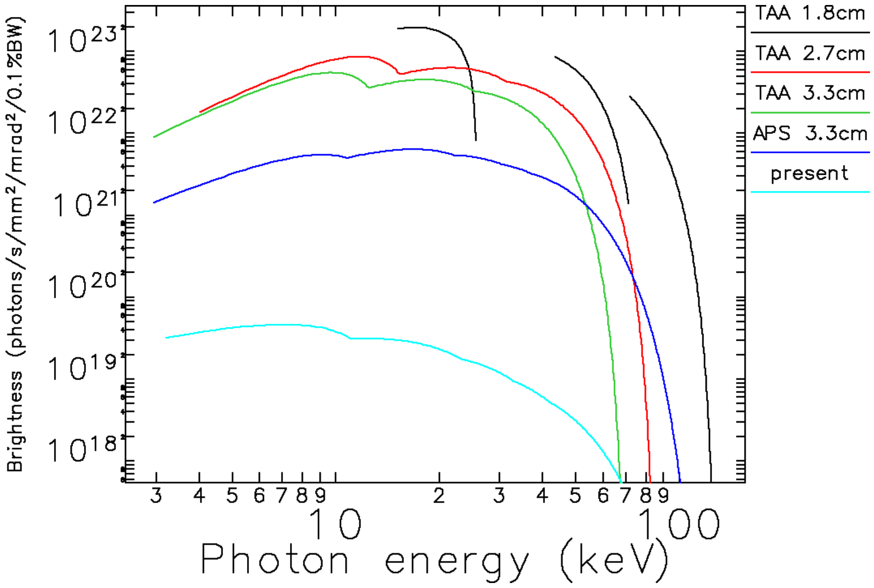


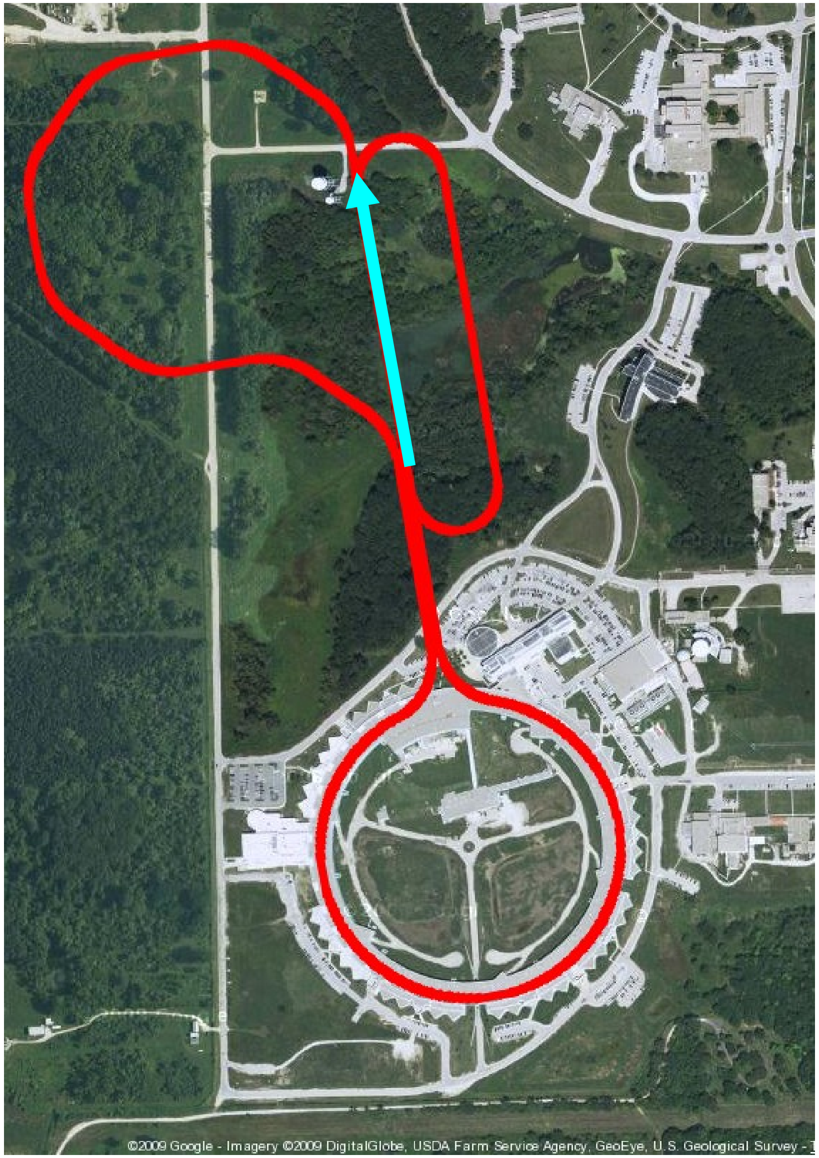
Stage 3:
Expanded facility with many more beamlines, higher flux and brightness

[1] K. Harkay *et al.*, Proc. PAC 09, TU5RFP079.

An APS Upgrade Design with Many Long Undulators (M. Borland *et al.*, ANL)

- Two-pass linac
- Turn-around accommodates nine 48m undulators
- S2E simulations with IMPACT-T and parallel elegant show 10^{23} brightness
- Very high brightness to 100 keV and beyond
- Booster cavities after undulators allow independent gap variation

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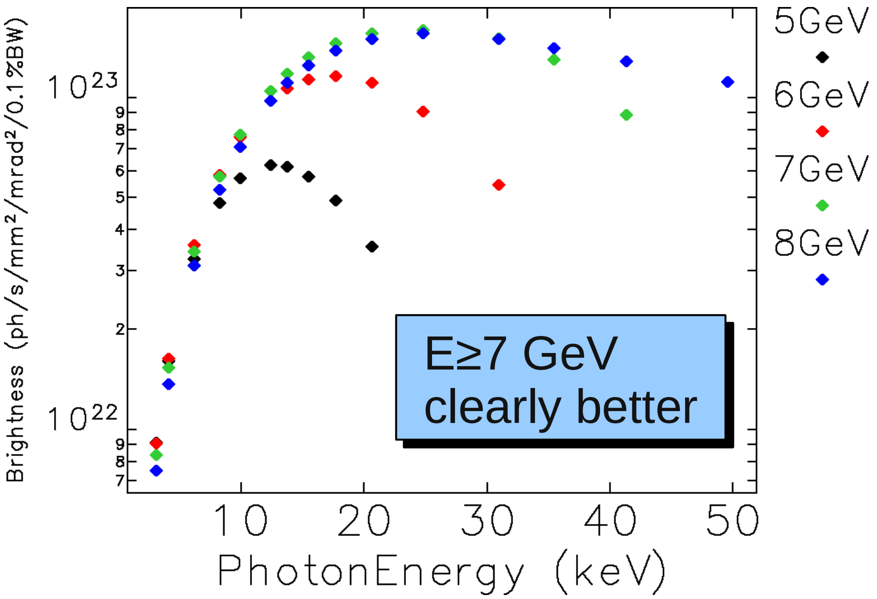
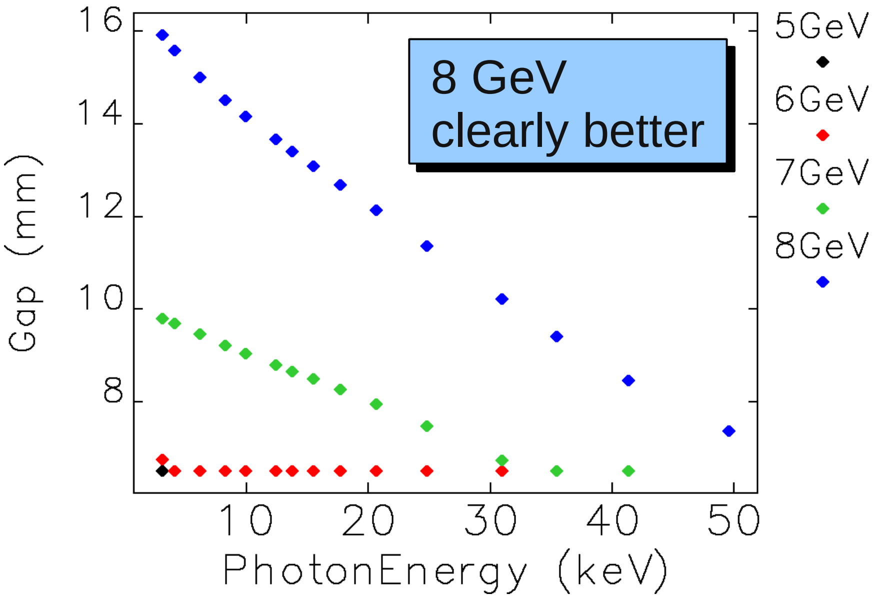
Optimum Beam Energy for ERL@APS (M. Borland, ANL)



E≥7 GeV clearly better



8 GeV clearly better

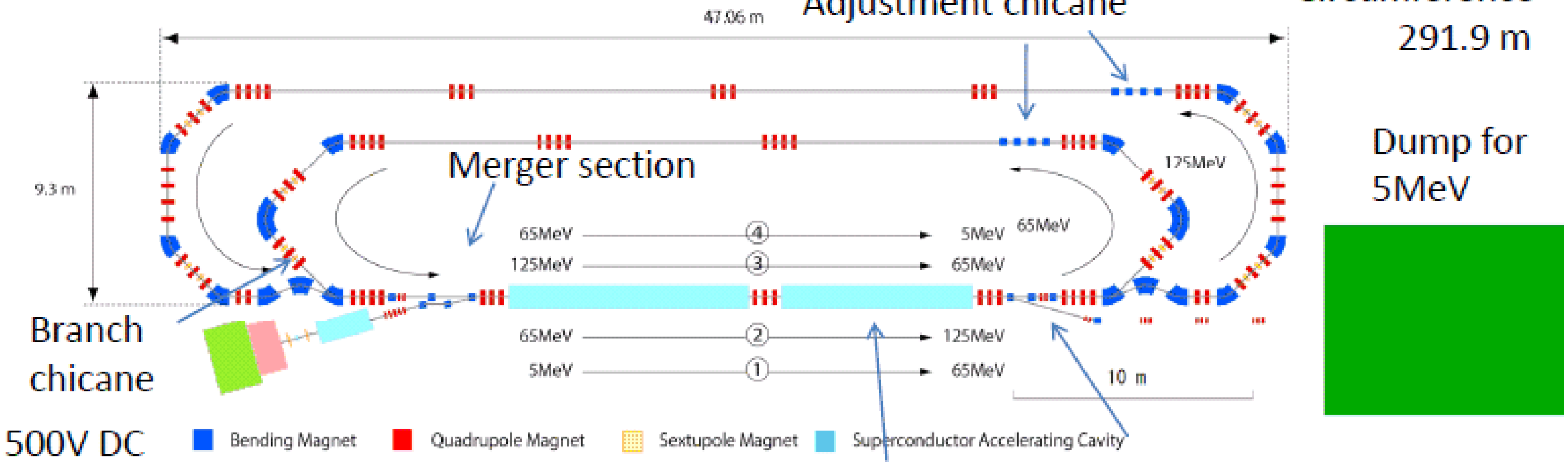
- Performed optimization of HPM undulator period and K for various beam energies from 5 to 8 GeV
- For each beam energy, maximized brightness for a series of photon energies
  - Included power and power density limits
- For hard x-rays, higher energy gives much higher brightness
  - Advantage for 3rd harmonic even more significant
- Higher energy gives larger ID gap, reduced impedance, reduced beam loss concerns
- APS designed for up to 7.7 GeV

Discussion Points and Comments

- Experimental verification of CSR shielding is not very firm
  - Effect on energy spread is not (always) in agreement with expectations
- Need to consider viability of medium-energy ERLs vs medium-energy rings
- Energy optimization should include wall-plug power considerations
- Upgrade options must consider downtime and likely inability of beamlines to use both ERL and storage-ring beams effectively
- Any reason to build an ERL instead of XFEL-O?

Multi-Turn ERLs

Lattice design of 2-loop compact ERL (cERL)



Adjustment chicane

Circumference 291.9 m

Merger section

Dump for 5MeV

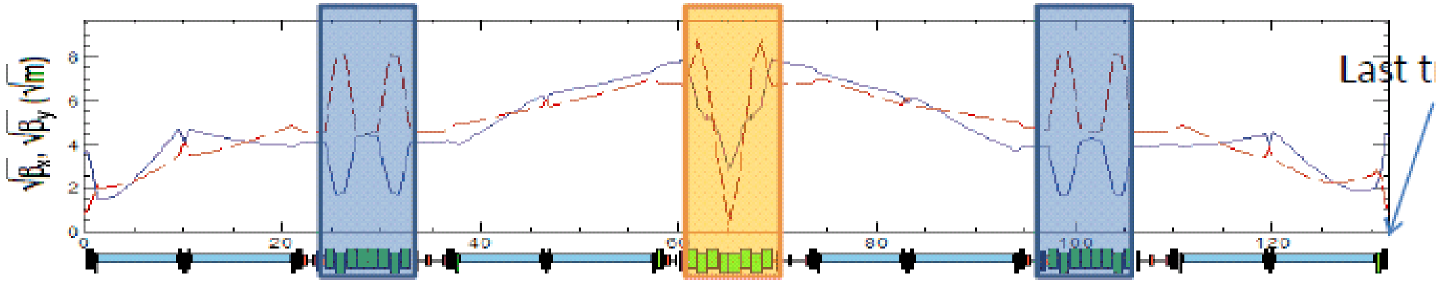
Branch chicane

500V DC electron gun

Extract section

Main superconductor cavities

Lattice design result 2

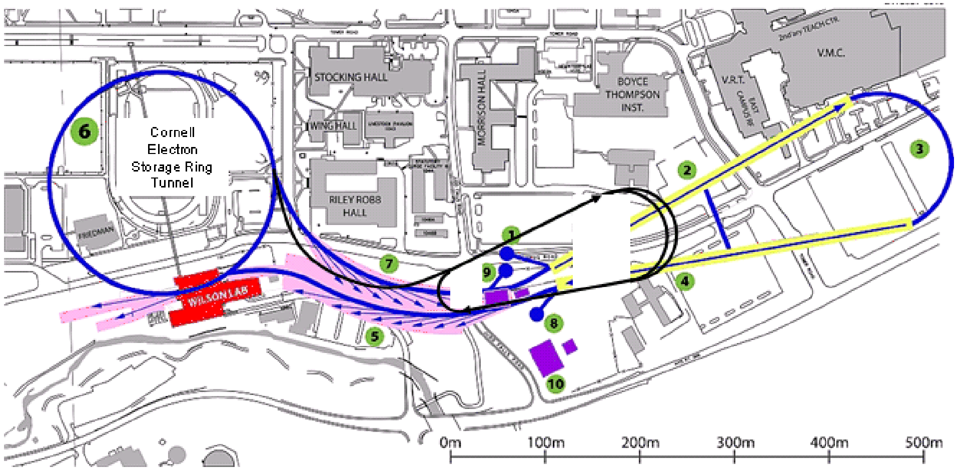


Last triplet

- Maximum horizontal betatron function at the last triplet is suppressed down to 20 m if using dummy loops.

🟦 Dummy inner loop 🟨 Dummy outer loop

Miho Shimada, ERL09



Discussion:

Alternative solution: reducing rep. rate of injector beams

Primary Concerns and Conclusions

1. Must consider space charge forces for superimposed beams and emittance growth.
2. Touschek scattering between superimposed beams
3. Higher Order Mode (HOM) power will increase unless we separate bunches
4. Need more sophisticated Beam spectrum and RF control.
5. Must cope with tighter orbit and return time tolerances.
6. **Reduced Beam-Breakup (BBU) tolerances, esp. with cavity errors.**
7. **Reduced effectiveness of polarized cavities and coupled optics for fighting the BBU instability.**
8. Impedance budget and increased energy spread.

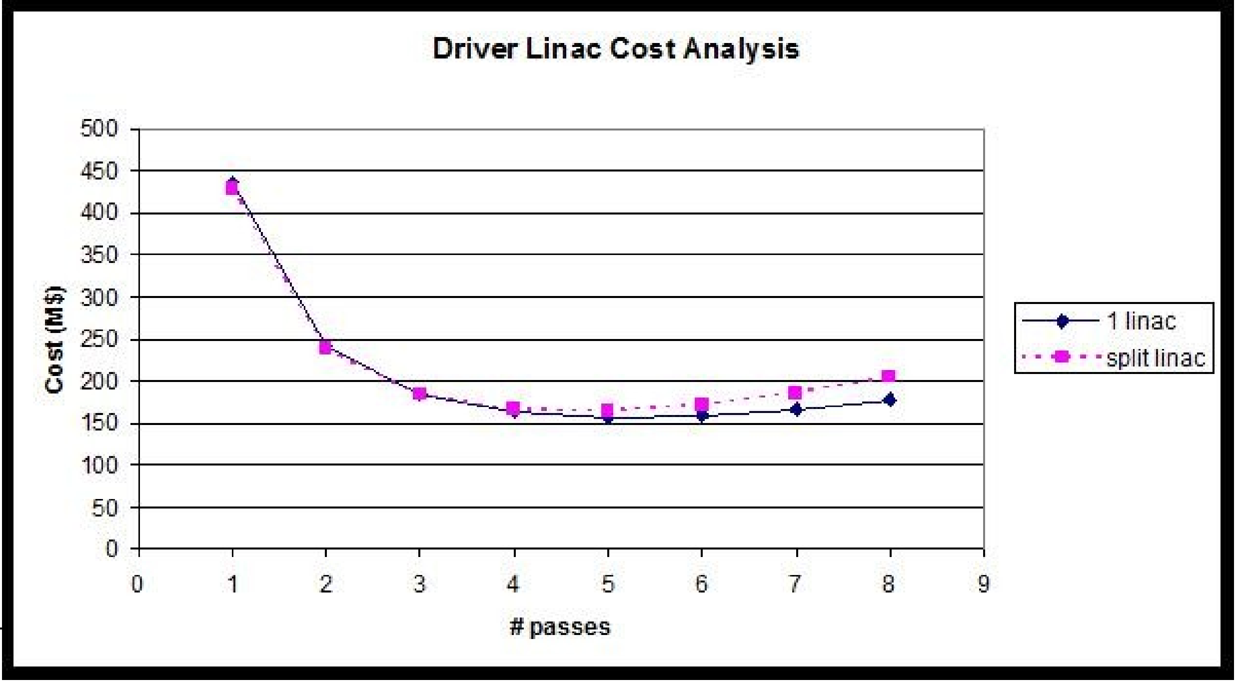
Multi-turn is a considerable risk.

Use of Recirculation in Large Systems (D. Douglas, JLab)

- Potentially large cost savings through use of recirculation
  - SRF Costs high
  - Multipass ERL/recirculated XFEL driver could save 100s M$ in costs
- But… Recirculation poses challenges
  - System size, quantum excitation, CSR/LSC/MBI, BBU…

Solutions are emerging (work by Borland, others)

Cost savings high enough to pay for years of R&D; not clearly "impossible" to manage the effects (risk/benefit)



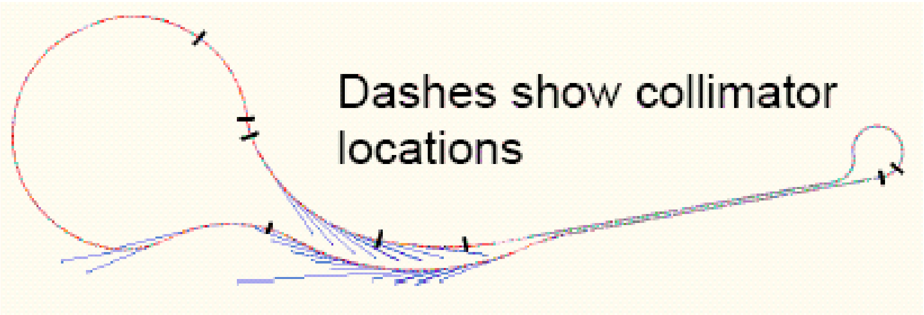
Beam Loss
and
Halo

Intrabeam Scattering in ERLs and Collimation

CLASSE

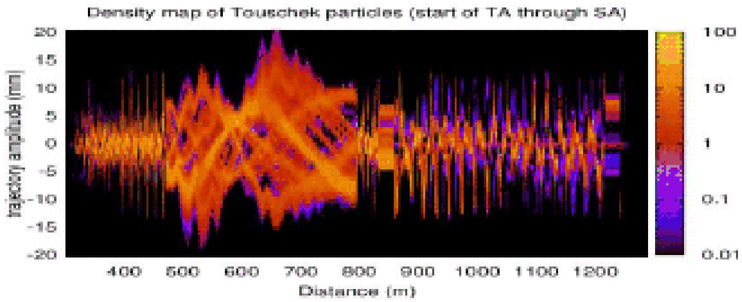
A simulation approach based on formulas that give the rate at which Touschek particles are produced.

$$R = \frac{\sigma_h r_e^2 c}{16\sqrt{\pi}\epsilon_x\epsilon_y\sigma_p\sigma_s\gamma_0^4\beta_0^4}\int_{\tau min}^{\infty}\frac{\sqrt{\tau}}{\sqrt{1+\tau}}\left[\frac{1}{\tau}\left(4+\frac{1}{\tau}\right)\log\left(\frac{1}{B}\right)-B+1+\left(\frac{1}{\tau}+2\right)^2\left(\frac{1}{B^2}-1\right)\right]\times$$
$$\exp\left[-2\frac{k_{\theta x}+k_{\theta y}}{\gamma_0^2\beta_0^2}\tau\right]I_0\left[2\frac{\sqrt{l^2+(k_{\theta x}+k_{\theta y})^2}}{\gamma_0^2\beta_0^2}\tau\right]d\tau\boxed{+\mathcal{O}(\chi)+\mathcal{O}\left(\frac{\Delta E}{E_0}\right)+\mathcal{O}\left(\frac{1}{\gamma_0}\right),}$$

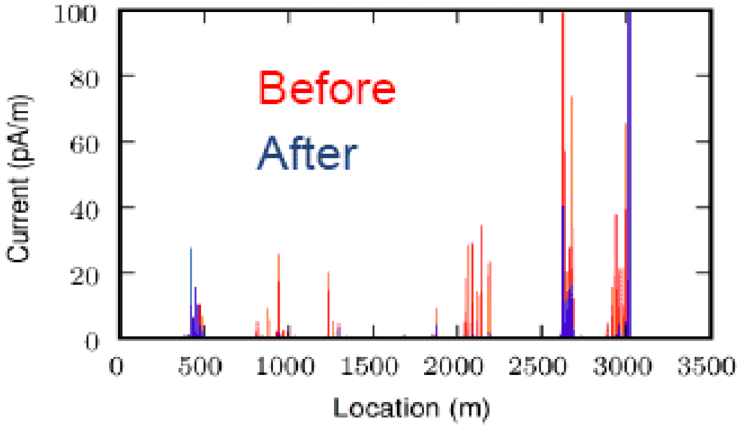


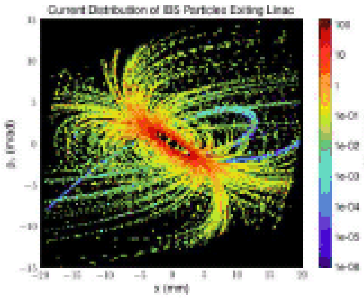
Dashes show collimator locations

Trajectories of scattered particles are analyzed to determine best locations for collimator placement.



End-to-end profile of Touschek particles lost along chamber walls for CERL 3.0





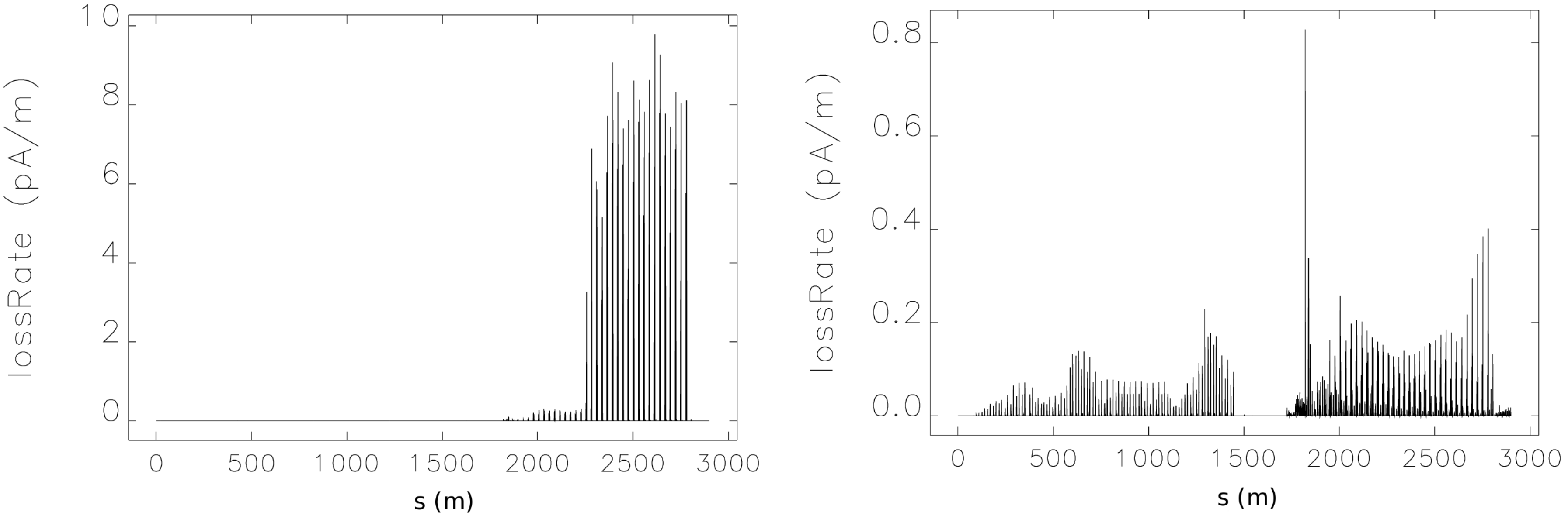
Total current between 10-sigma of the beam and the beam pipe:

413 nA

Michael Ehrlichman, ERL09

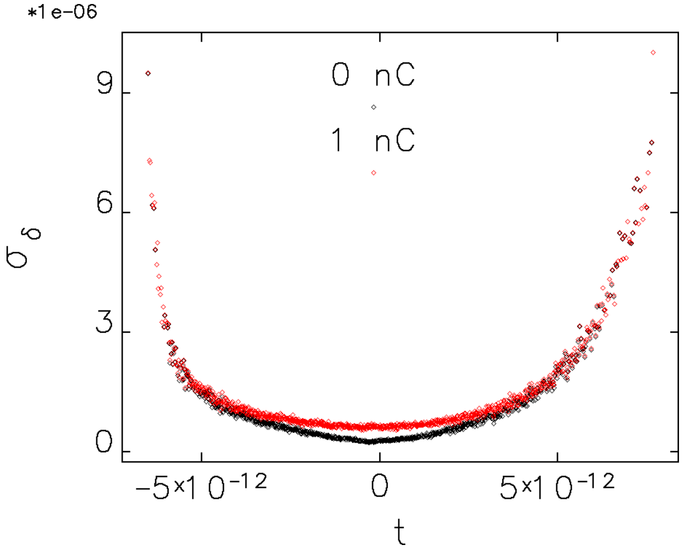
Monte Carlo Simulation of Touschek Effect (A. Xiao, ANL)

- Touschek scattering effect is no longer negligible for ERLs.
- Simple beam loss estimation can be obtained from Piwinski's formula.
- To obtain detailed information on beam loss and halo, a Monte Carlo simulation was implemented in **elegant**
- A strategy to speed up the simulation makes use of fact that not all collisions contribute equally to the scattering rate.
- Application to ERL@APS shows that sextupole correction is essential for controlling beam loss



ERL@APS Intrabeam Scattering Simulation (A. Xiao, ANL)

- An IBS simulation module which can treat a non-Gaussian-distributed linac beam was added to **elegant**.
- The algorithm involves slicing the beam longitudinally to resolve the local beam properties (e.g., energy spread)
- An application to the APS-ERL lattice shows a noticeable local energy spread increase but little change in the full bunch properties.
- These results may be important for studying other issues, for example, CSR effects or FEL gains, which depend on the slice energy spread.



Discussion Points and Comments

- Predicted Touschek scattering rate much lower for two beams of very different energies
    - Might be worthwhile if calculation was done for CEBAF
- Any possibility to benchmark these codes against storage ring experiments?
- Contention was made that slice-based IBS simulation may be invalid.

Test Facilities

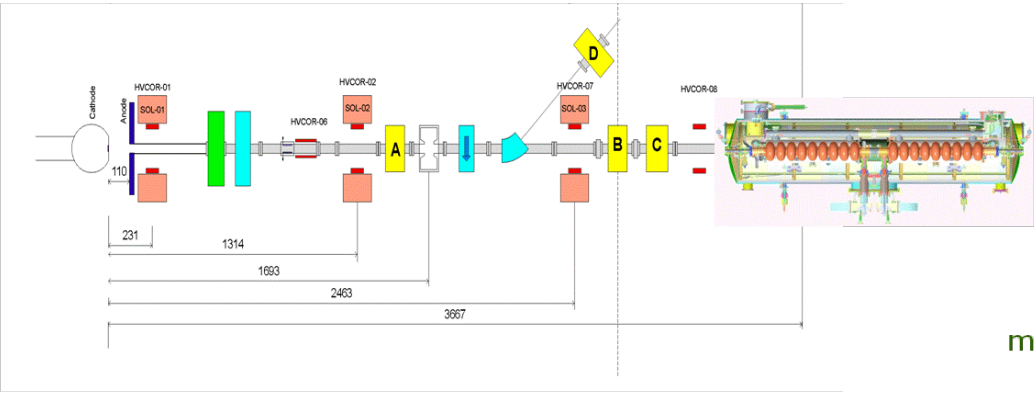
Future R&D @ ALICE
Susan Smith
Daresbury

- Aims
  - Show briefly what we have at DL
  - Highlight some collaborative efforts on our facility
- Encourage collaborations!

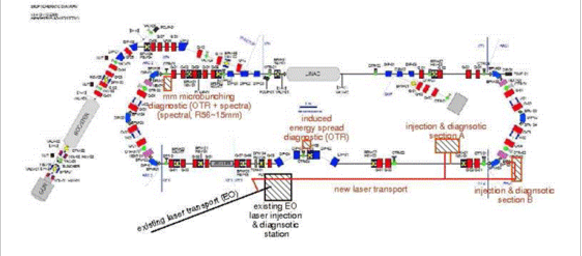
- ALICE setup optimisation
  "standard" settings at various bunch charges;
  emittance minimisation etc …
- Short pulse commissioning
- Compton Backscattering X-ray source (Phase I and II)
- Diagnostics, Feedback, timing and synchronisation & feedback
  - Electro-optic diagnostic commissioning
- THz development
  ALICE and THz transport beamline optimisation
  THz spectra
  Tissue Culture Facility experiments (inc. human tissue exps)
- Laser-THz synchronisation experiments
  (for novel solar cells research; collaboration with Manchester Uni.)
- IR FEL commissioning

- EMMA research
  first non-scaling FFAG
- Three major upgrades:
  1) installation of the gun load-lock system
  2) extended gun beamline
  3) installation of a new improved SC RF cryomodule
- Photocathode research on a stand-alone testbed
  ~15% QE has been already achieved
- Other smaller scale projects
  in parallel with EMMA … x

Extended beamline



Potential test-bed for micro-bunching instability physics expts



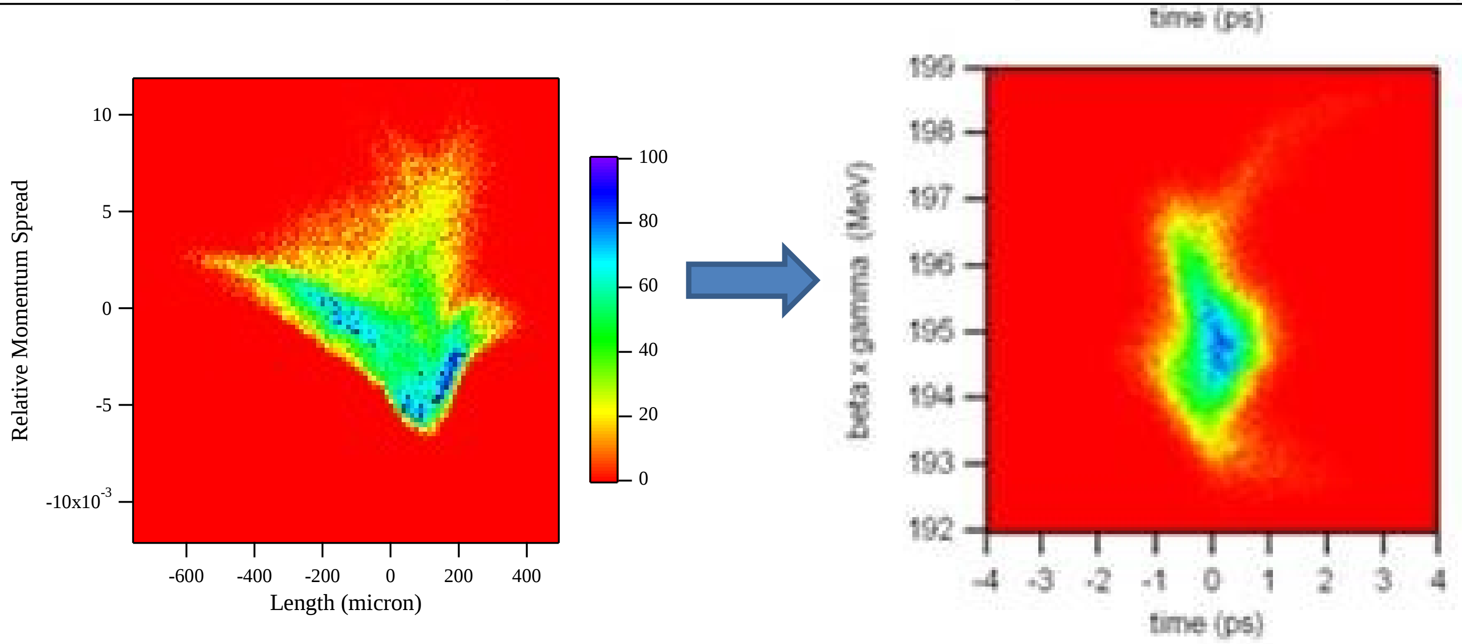
Extension to EO laser transport system,
with laser/THz preparation/injection after Arc-1

mini-chicane (<1m) can be installed in vacant straight.. $\Delta\gamma(\tau) \rightarrow \Delta\rho(t)$

Built & commissioned through collaborations, encouraging new ones!

Longitudinal Matching; CSR Management (D. Douglas, JLab)

- Appropriate selection/control of momentum compactions ($M_{56,}$ $T_{566,}$ $W_{5666,}$ …) allows bunch length compression/energy compression
  - Without harmonic Rf
  - With larger momentum/phase acceptance (15%, 30^{o} observed)
- CSR degradation of beam quality can be alleviated by
  - Rapid compression (large dispersion in compression dipole)
  - Use of small-angle final bend & dispersion matching



Roles of Test Facilities (R. Hajima, JAEA)

Test facilities are in operation and under proposal for

- integration of components,
- demonstration of beams,
- data for "real" facilities.
- ……

Roles of them are

- Diagnostics
  - prepare much space for beam monitors
  - both low-energy and high-energy
- Beam dynamics studies on controversial / critical issues
  - Halo
  - Trapped ion
  - Benchmarking of S2E simulations
  - Shielding of CSR
  - Superposing 2-color bunches in the same bucket
  - HOM power in SRF
- Hardware evaluation
  - SRF, LLRF, Gun …..

Tolerances

Tolerances for Errors in ERL Linacs

Tsukasa Miyajima[1] and Norio Nakamura [2]
[1] KEK, High Energy Research Organization
[2] University of Tokyo

- We calculated tolerance of errors in ERL linacs using particle tracking code, GPT.
  - Ripple of gun HV source < 0.1 %
  - Amplitude error in RF cavities < 0.1 %
  - Phase error in RF cavities < 0.1 degree

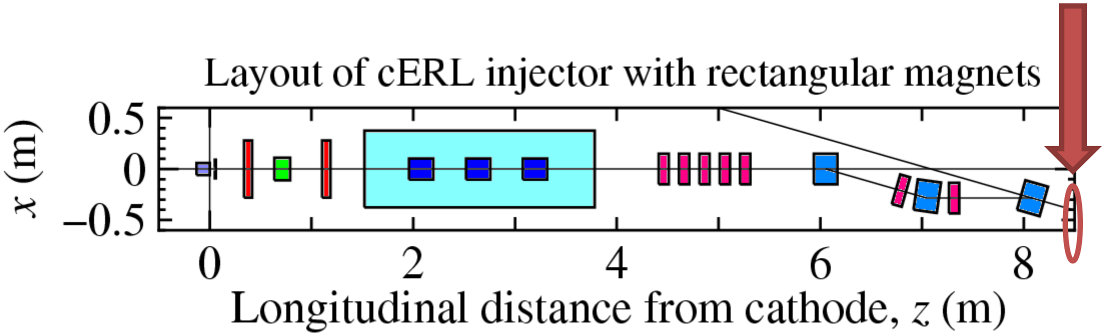
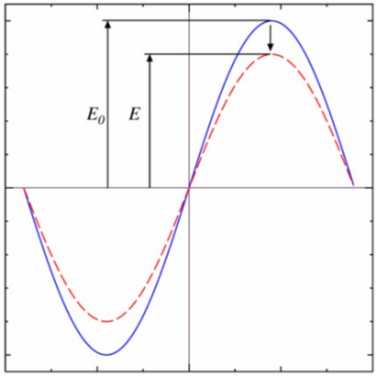

Layout of cERL injector with rectangular magnets

Table of tolerances

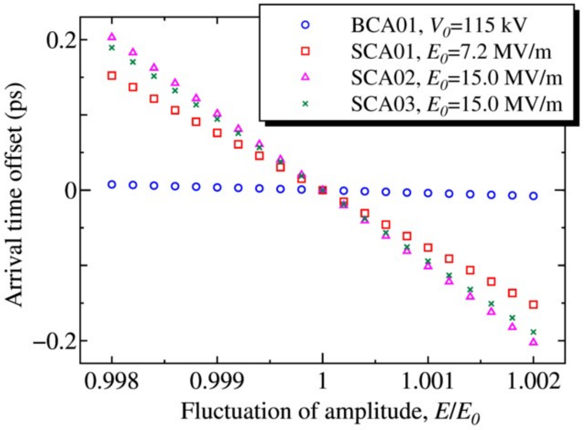
	Gun ripple	RF amplitude	RF phase
Error	0.1 %	0.1 %	0.1 degree
Difference of arrival time	-120 fs	-100 fs	-120 fs
Kinetic energy	99.96 %	100.05 %	99.98 %
Emittance	3.5 % (for ±0.1% error)	1.5 % (for ±0.1 % error)	2.5 % (for ±0.1 degree error)

Amplitude error in RF cavities



- Arrival time
- 0.1% error: -100 fs

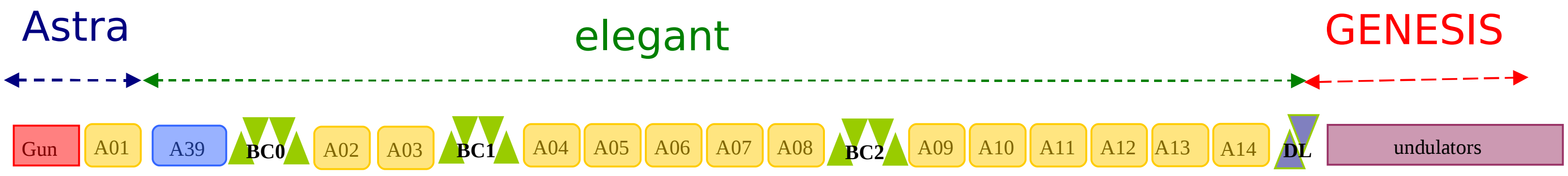
1.0 m from exit of merger



Initial tolerance studies for UKs New Light Source project

(D. Angal-Kalinin)

- The FEL performance can be severely spoiled by jitter in the electron beam characteristics
- Wakefield effects and jitter issues under consideration along with a thorough tolerance analysis for NLS single pass linac
- Plan similar tolerance studies for the re-circulation :
  - Effect of additional beam transport in the re-circulation
  - WG recommendation to use *LiTrack (P. Emma)* for quick estimations of effects of phase and amplitude errors.



Astra

elegant

GENESIS

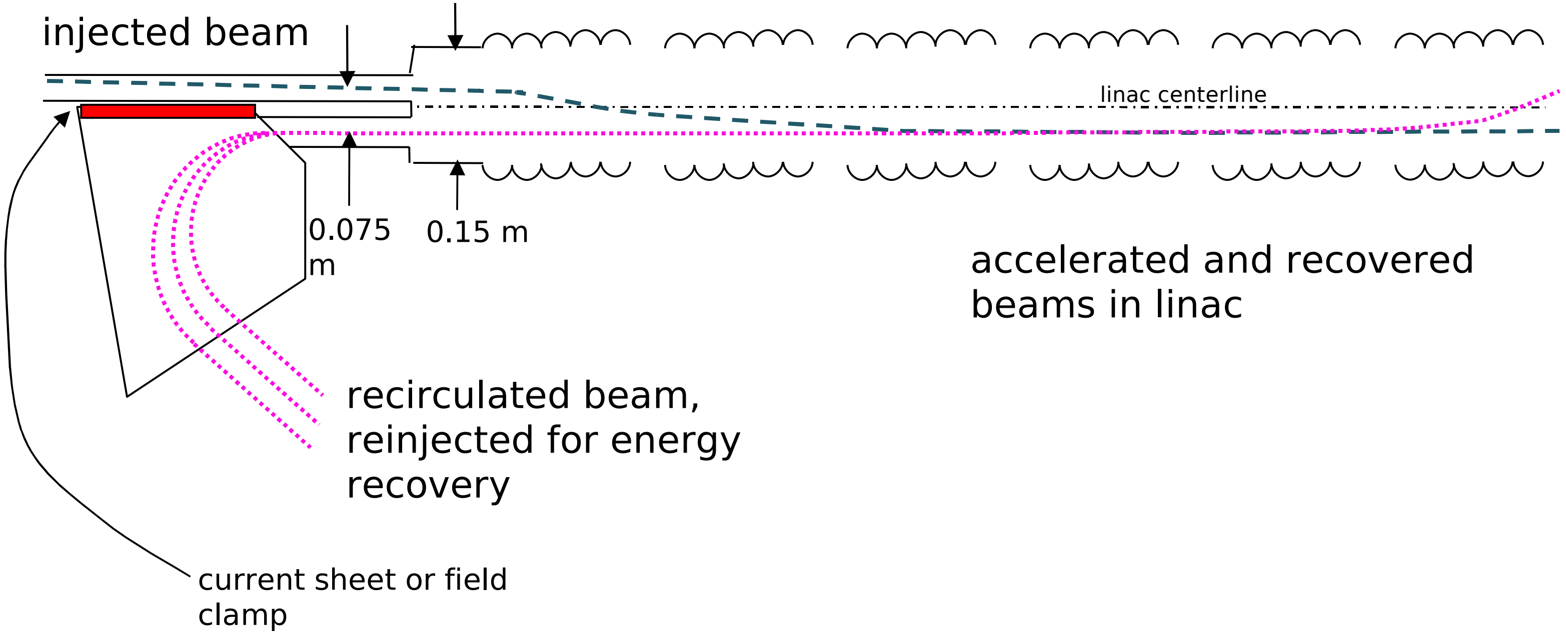
Gun A01 A39 BC0 A02 A03 BC1 A04 A05 A06 A07 A08 BC2 A09 A10 A11 A12 A13 A14 DL undulators

Injectors and Other Topics

Joint Session with WG1

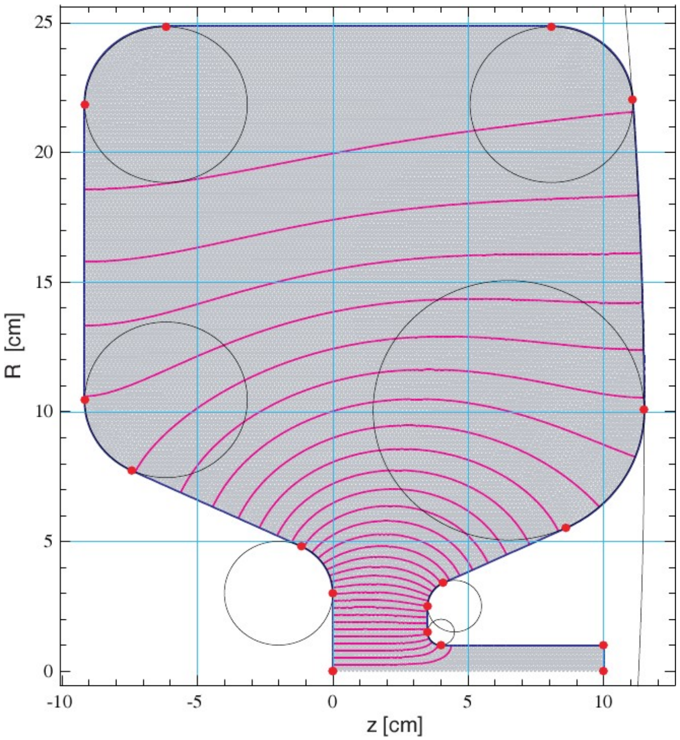
“Direct” (off-axis) Injection (D. Douglas, JLab)

- Rather than merge beams using DC magnetic fields, inject beam into linac at large amplitude and use RF focusing & adiabatic damping to bring orbit into line
- Can use reverse process for extraction of energy-recovered beam



Multi-beam injector and quasi-cw ERL (C. X. Wang, ANL)

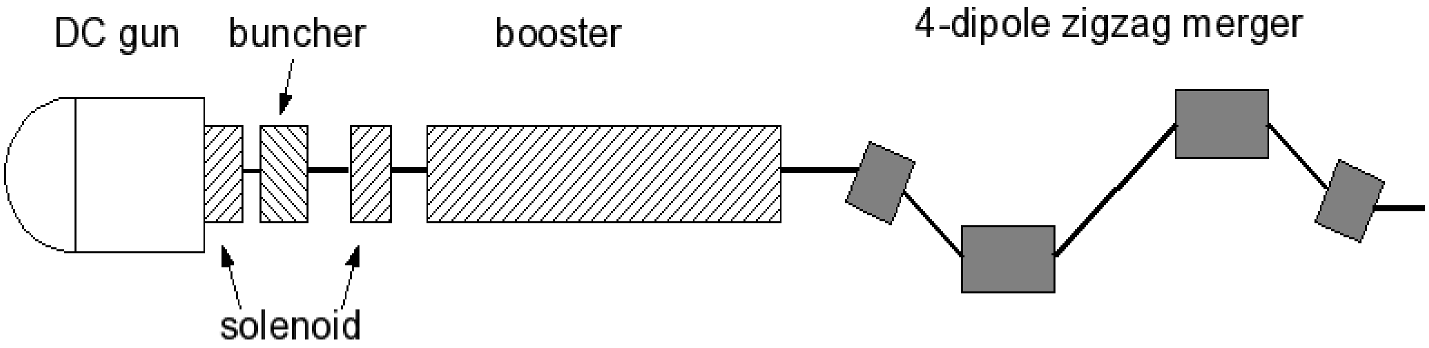
- A new scheme has been developed to address the challenges of ERL injectors
- Scheme rests on three pillars:
  - *Low-frequency rf gun*:
    Addresses voltage limitations while giving high brightness
  - *Multi-beam injection using chicanes and subharmonic cavity*:
    Increases average current
  - *Quasi-CW operation*:
    Provides lower-cost operation
- 325 MHz NC gun designed[1] with **geneticOptimizer** and ASTRA[2]
  - Meets HC and HF requirements at 4 times normal charge
  - Needs integration with merger.



[1] C-X Wang, Proc. PAC09, MO6RFP048.

[2] K. Flöttmann, http://www.desy.de/~mpyflo

Injector Design with Merger[1] (X. Dong, ANL)

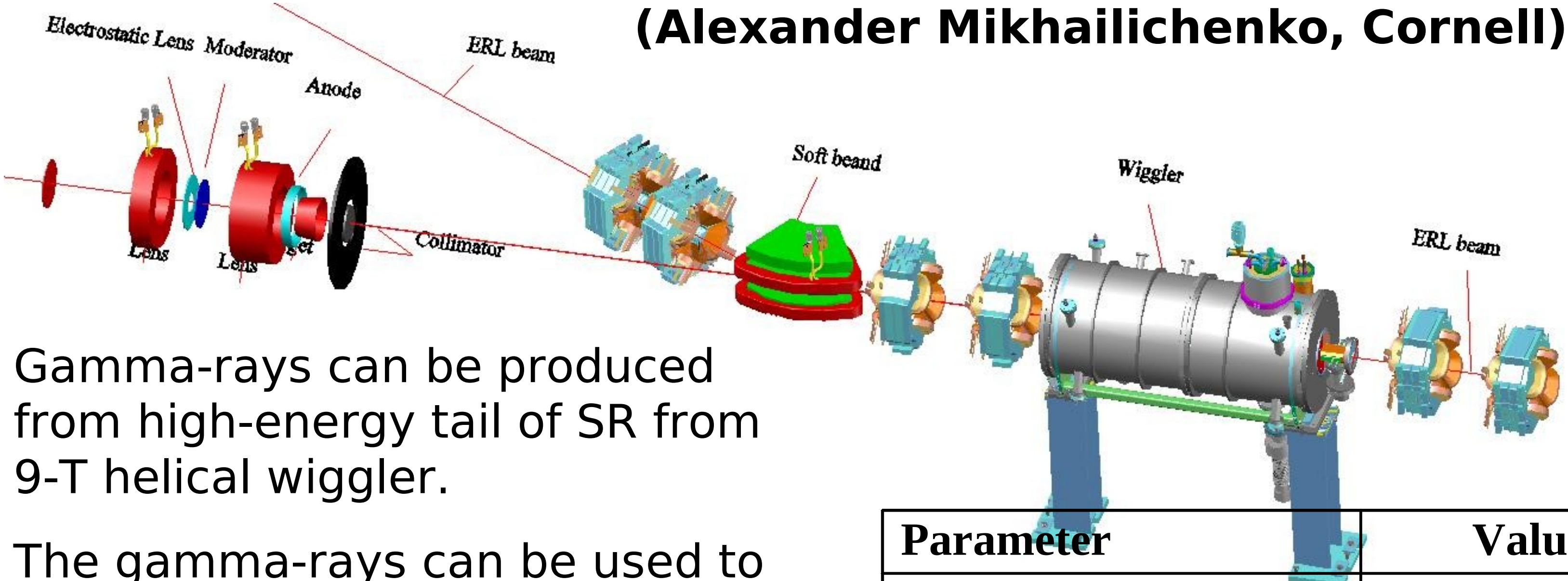


- We keep the "standard" features of the JLab[2] and Cornell[3] injectors:
  - DC gun + solenoid + buncher + solenoid + booster configuration
- A zigzag-type merger[4] is used to merge the beam from DC injector and high energy beam
- Optimized design with **geneticOptimizer**[5] and IMPACT-T[6]
  - Meets requirements for high-coherence and high-flux modes[7]
  - No emittance growth seen in the merger even for 77 pC/bunch.
  - Uses quasi-ellipsoidal laser pulse
  - Requires DC high voltage (~750 kV) that is not easily achievable

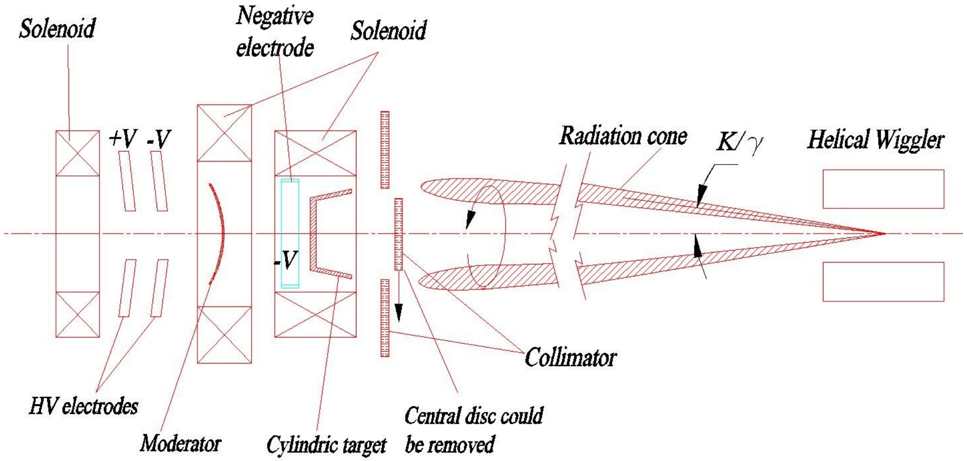
[1] X. Dong *et al.*, Proc. PAC09, MO6RFP044.
[2] T. Siggins et al., NIM A 475 (2001) 549.
[3] I. Bazarov et al., PRSTAB 8, 034202 (2005).
[4] V. Litvinenko et al., NIM A 557 (2006) 165.
[5] M. Borland, H. Shang.
[6] J. Qiang *et al.*, J. Comp. Phys. 163 (2000) 434.
[7] G. Hoffstaetter, "Status of Cornell ERL Project,"

Production of Thermal Positrons in ERLs

(Alexander Mikhailichenko, Cornell)



- Gamma-rays can be produced from high-energy tail of SR from 9-T helical wiggler.
- The gamma-rays can be used to produce positrons, which are thermalized using a moderator.

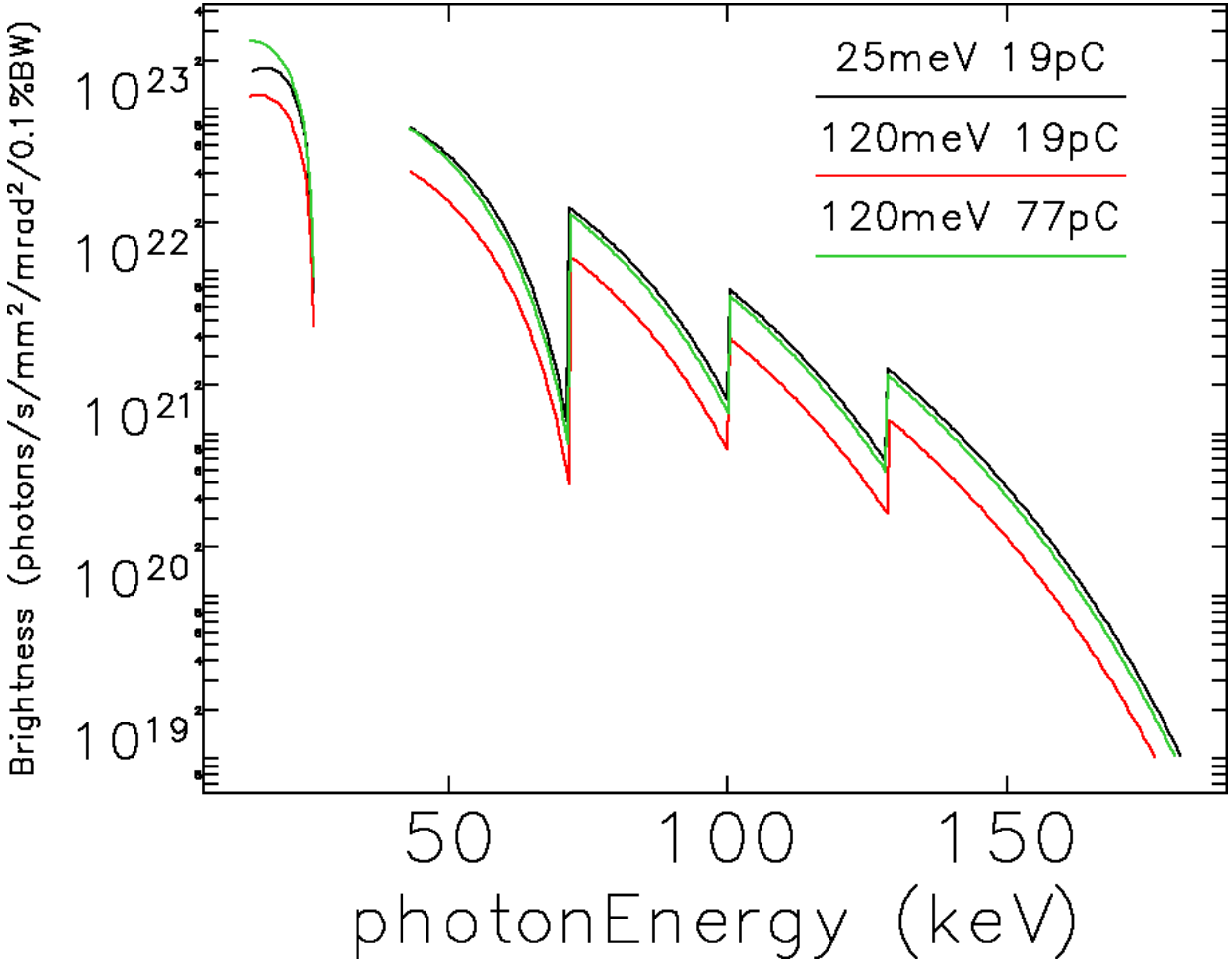


Parameter	**Value**
Energy of the beam	5 GeV
Current	100 mA
Magnetic field	~9T
Period	~0.3m
Number of periods	3
K factor	~250
Emittance grows	negligible
Energy spread grows	~0.75 *MeV*$^{*)}$
Positron flux	10^{8}-10^{11}/sec$^{**)}$
Polarization	>30%

Discussion Points and Comments

- Mergerless merger may work only for low frequency linacs
  - May be complicated to operate due to coupling of focusing and steering
- Seems that using transverse CW deflecting cavities should be possible in addition to accelerating cavities for beam merging
- Controversy over reasonableness of assuming future use of GaAs in rf gun
- Controversy over intrinsic emittance of GaAs (25 meV, 120 meV, 300+ meV)

S2E Simulation with Various Intrinsic Emittances (M. Borland, X. Dong, ANL)



- Effect of 120 meV intrinsic emittance is fairly modest
- High-flux case outperforms high-coherence case (accidental improvement in energy spread?)

IMPACT-T ➔ elegant ➔ sddsbrightness

HOM Damping and Wakefields

Joint Session with WG3

ERL'09

Promise for a brighter future.

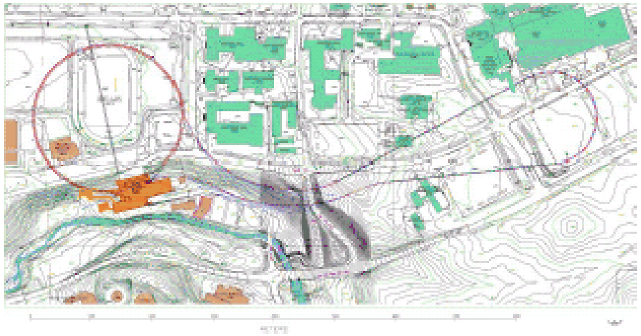
Recent Progress on Beam-Breakup Calculations for the Cornell X-Ray ERL

James A. Crittenden for the ERL Design Group
CLASSE, Cornell University
10 June 2009

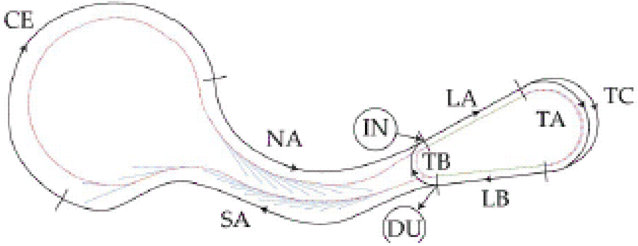
Beam-breakup instabilities arising from the excitation of higher-order modes in the RF cavities are important contributions to the operational current limit in multi-pass linacs.

The tracking calculations of Hoffstaetter, Bazarov and Song (PRST-AB 10, 044401 (2007)) have been generalized for multi-pass ERLs in the Cornell beam physics design and optimization software utility BMAD.
The BBU threshold current calculation has been validated by comparison to analytic approximations in the limits where the HOM decay time is long or short relative to the recirculation time.

Cornell X-Ray ERL



Two-turn ERL under study



Cavity HOM Parameters

	PRSTAB 2007 (TTF)	*New 55-55 mm Design*
Cornell ERL	*12 mA*	*36 mA*
Two-turn ERL	*6 mA*	*8 mA*
Cornell ERL (σ_f/f=0.4%)	*235 mA*	*307 mA*
Two-turn ERL (σ_f/f=0.4%)	*53 mA*	*87 mA*

These new results are consistent with the detailed published results for the Cornell ERL design. The calculations for the two-turn lattice remain under development.

These BBU instability threshold calculations will be an important tool for the optimization of the evolving design of the Cornell ERL X-ray source.
The lattice optics design must depend on fabrication tolerances of the superconducting RF cavities.
Mitigating effects such as the cavity-to-cavity RF frequency spread and the introduction of coupling in the transverse planes will be quantitatively studied.

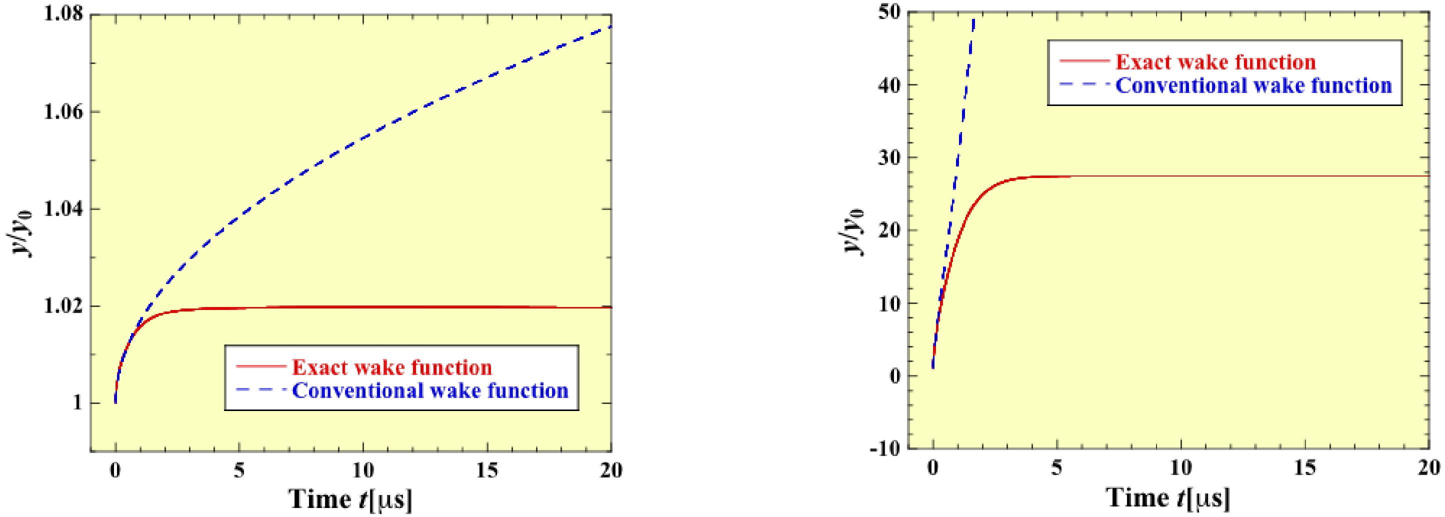
Jim Crittenden, ERL09

Wakes and Impedance Budgets for ERLs (M. Billing, Cornell)

- Wake fields estimated for a large fraction of components
  - Max{$W_{||}$} ~ 100% of proposed limit
    (Limit is ΔE= 2.5 MeV for 10 MeV beam at the dump)
    (RF Cavity & Roughness Wakes dominate)
  - Should consider compensation methods
  - Have only included self-wakes, ignoring
    - Wakes from preceding bunches
    - Wakes from any resonant trapped modes
  - Future considerations
    - Remaining discontinuities, e.g. Vacuum pump ports, X-ray crotches
    - Effect on longitudinal dynamics, esp. bunch compression & higher bunch charge options

Effects of Resistive-Wall Wakefields on ERLs
(N. Nakamura, Univ. of Tokyo)

- Exact longitudinal and transverse RW impedances of round pipes were analytically derived and exact transverse wake functions were calculated.
- Parasitic loss calculated for typical ERL parameters is higher than that of the 3rd generation light sources because of the shorter bunch length. Copper coating is effective for reducing the parasitic loss.
- Since beam position saturates in a short time, transverse RW BBU may be manageable. However further simulations should be done.


SS pipe, *b*=25mm, *d*=1mm, *L*=56.4m

SS pipe, *b*=3mm, *d*=1mm, *L*=56.4m

Simulated transverse beam position due to RW wake
(E=60MeV, I=100mA, f_{RF}=1.3GHz)

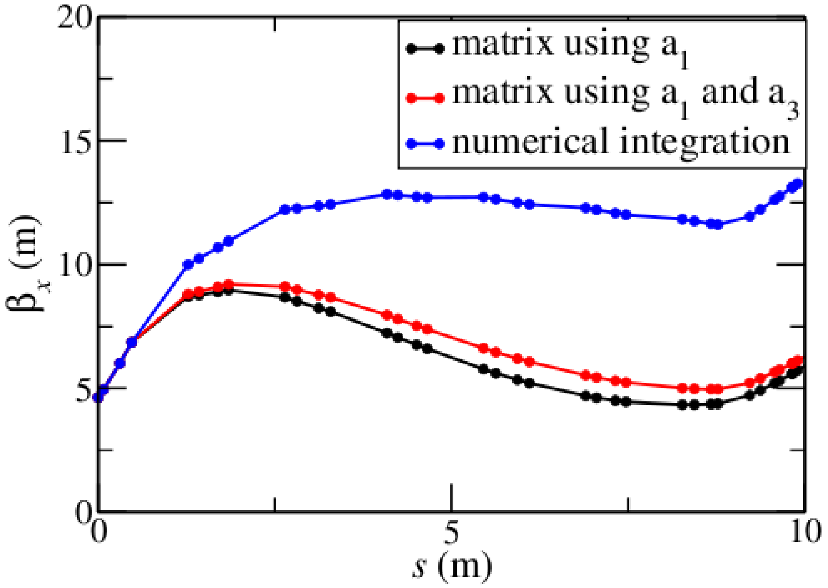
Discussion Points and Comments

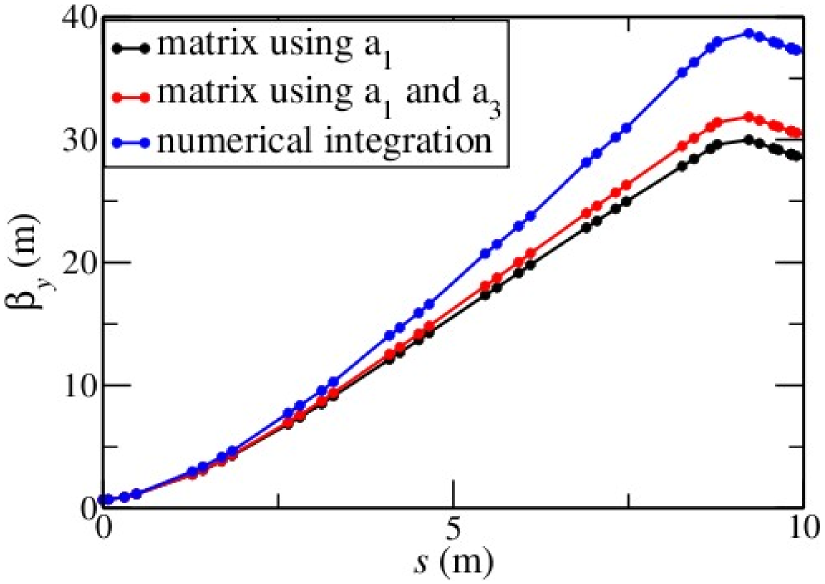
- Controversy over whether the optics for the two-turn operation was fully optimized to suppress BBU
  - JLab sees 4-fold drop in threshold for two turns, Cornell sees 6-fold drop
  - Somewhat consistent
- Question about whether using bunches with energy spread will result in higher predicted BBU thresholds (tune spread from chromaticity)
- Is it possible to reduce the roughness wake contribution for a very long beam pipe (2.5km)?
- RW simulations may be pessimistic due to assumption that all bunches start with the same offset.
- Large variation in cavity Q's needs to be understood to make BBU predictions more reliable.

Optics Design and Optimization

Influence of Cavity Focusing in ERL Optics
(R. Bjorkquist, Reed College)

- Codes commonly use Rosenzweig and Serafini's expressions for the transfer matrix of a linac cavity
- Many codes make the further approximation that the cavity field is sinusoidal
- We checked both of these approximations for acceleration from 10 MeV to 100 MeV
- Next, need to check effects at high energy



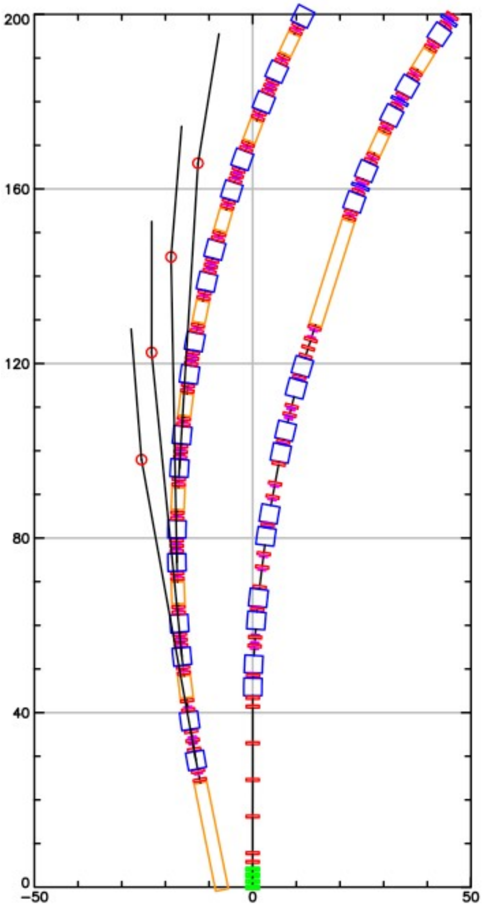


Upgrading BMAD for Combined Beam and X-ray Optics Design (D. Sagan, Cornell)

✓Bmad is a toolkit for relativistic charged particle simulations. It has been developed in a modular, object oriented fashion which makes it a flexible tool for all manner of calculations.

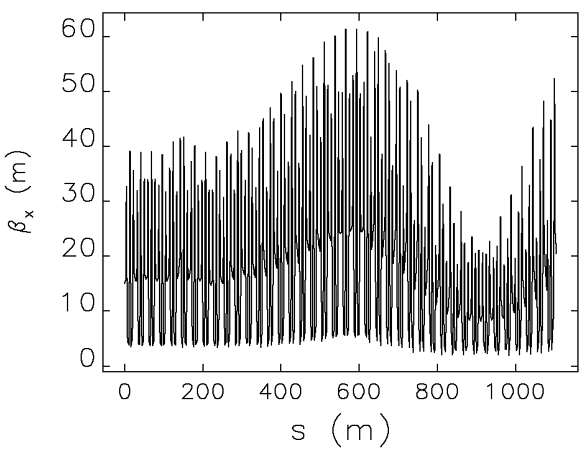
✓We are now developing modules for X-ray optics simulations. This, combined with integrating ImpactT with Bmad, will give Bmad the ability to do complete source to X-ray end-station simulations.

✓Bmad is open source:
Web page: www.lepp.cornell.edu/~dcs/bmad

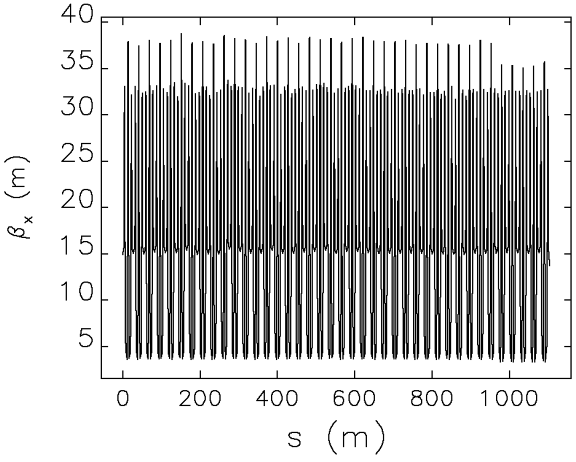


Simulation of Optics Correction in an ERL (V. Sajaev, ANL)

- Linear optics measurement and correction was simulated using the response matrix fit method
- Multiple trajectories were generated using two correctors in the beginning of the lattice instead of usual multiple single-corrector measurements used in storage rings
- We have found that response matrix fit can be used to measure and correct linear lattice successfully to accuracy of a few percent
- We have tested a piece-by-piece approach when one can measure and correct only a part of non-closed beamline which might be useful for large ERLs
- We have found that the errors in the beginning of the beamline are harder to determine, therefore one might use the piece-by-piece approach with overlapping pieces



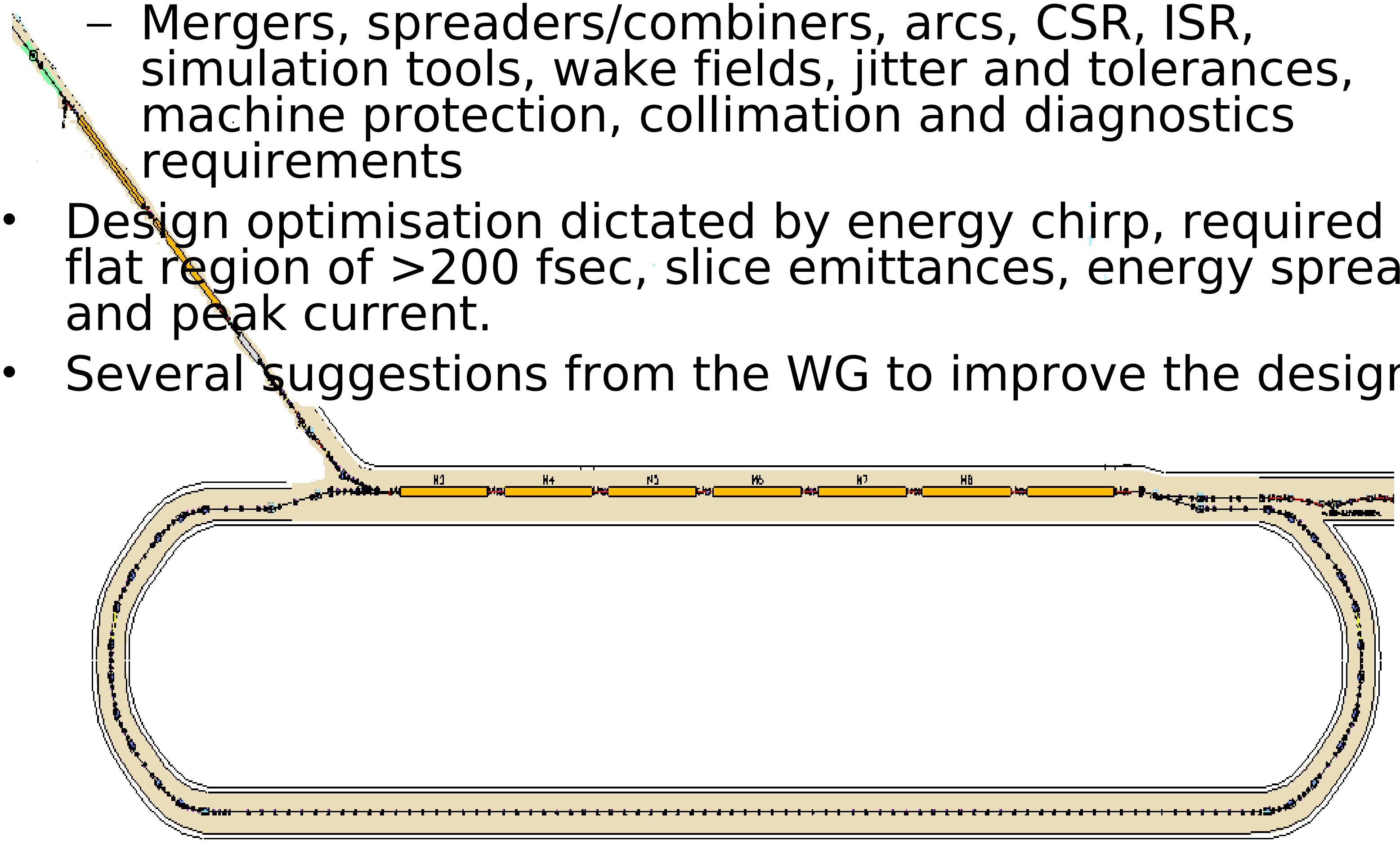
Twiss parameters—input: /data1/sajaev/090601-104517-1698sajaev0-calculateElegantBetas.ele lattice: /data1/sajaev/NewJobs/Jobs-fitAll-2QS-QC/3/aps.lte.uniqueBpms



Twiss parameters—input: initialCond.ele lattice: /data1/sajaev/CONFIG/006/aps.lte

Re-circulation Linac option for NLS (D. Angal-Kalinin, ASTeC)

- Straight through Linac and Re-circulation design options for UKs New Light Source project : performance and cost, effect of additional transport for re-circulation
- Synergies with ERLs
  - Mergers, spreaders/combiners, arcs, CSR, ISR, simulation tools, wake fields, jitter and tolerances, machine protection, collimation and diagnostics requirements
- Design optimisation dictated by energy chirp, required flat region of >200 fsec, slice emittances, energy spread and peak current.
- Several suggestions from the WG to improve the design.



Discussion Points and Comments

- JLab confirms that matrix approach has issue when starting from low energy
- A test of single-pass optics correction should be performed in an APS transport line

Items for S2E joint paper (Hajima *et al.*)

- Purpose or goal
  - Achieve better performance of ERLs
    - Light source performance
    - Small beam loss
    - Minimizing cost
- Tools or strategy
  - Tight integration or loose integration
    - Parallel computing availability
  - Switching codes: space charge on (slow code) → off (fast code)
  - New physics: CSR shielding, cathode model, wake function, ions
  - Long range: BBU
- Make table of available codes and features
  - Elegant, Impact-T, ASTRA, GPT (easy to integrate via SDDS)
  - PARMELA, BMAD
  - CSRtrack, TRAFiC4
  - Brightness calculation: SDDSbrightness, BMAD-upgrade support non-Gaussian? Convolution or first-principle
- Halo
  - Shower propagation
- Benchmarking across codes (for example, use LCLS injector, PITZ)

Diagnostics
and
Machine Protection

See P. Evtushenko's talk