Diagnostics Needs for Energy Recovery Linacs

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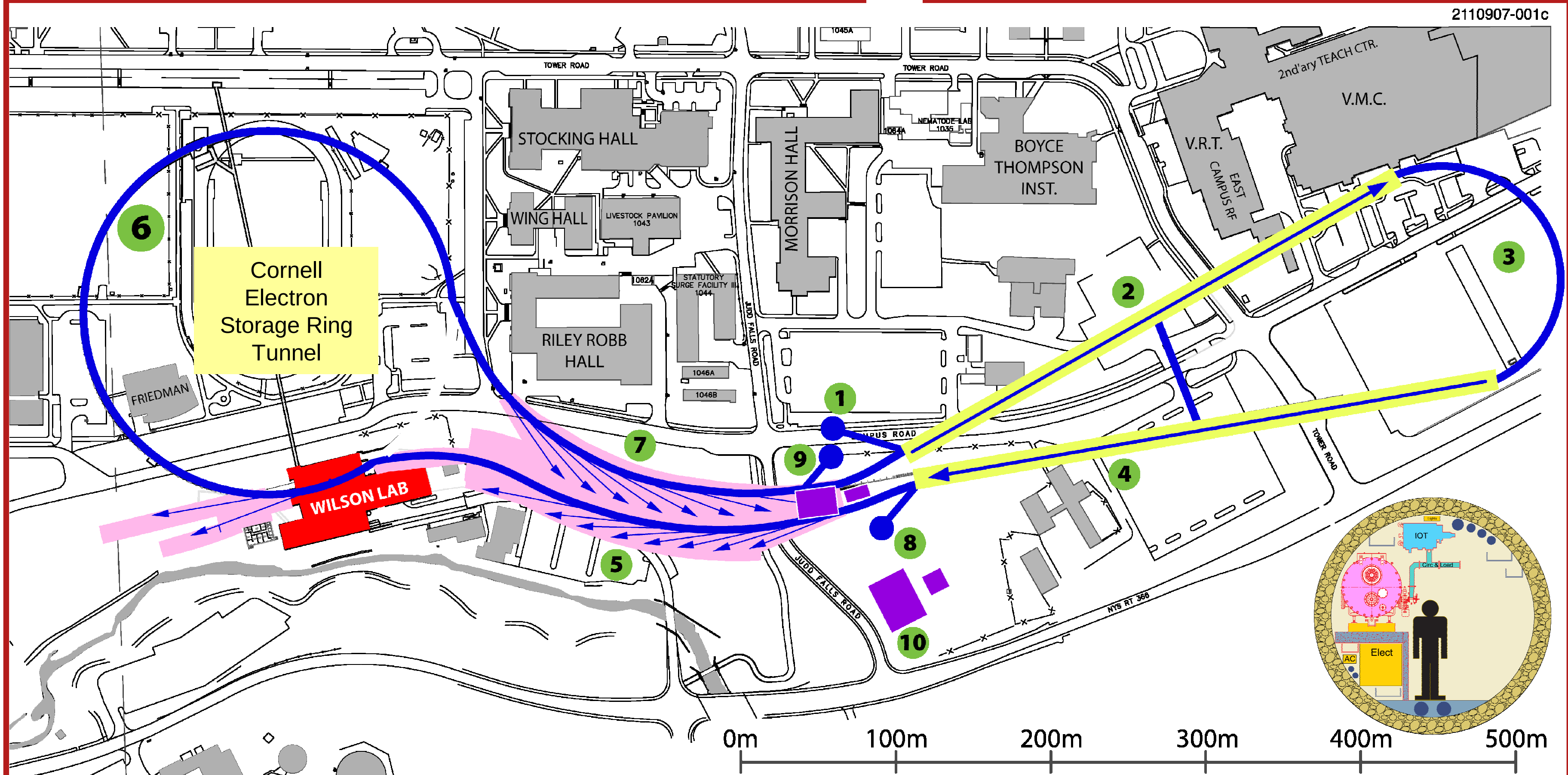
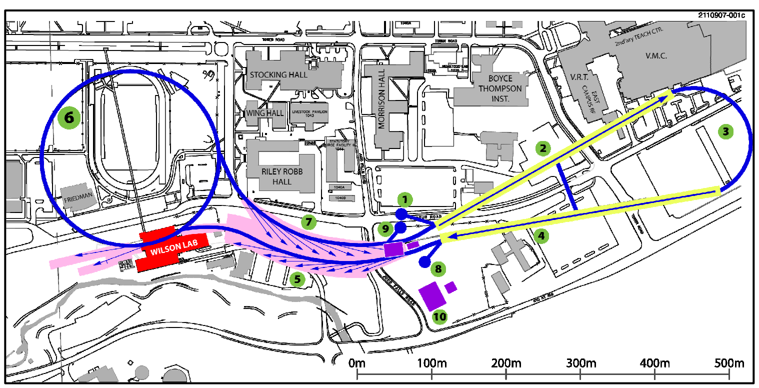
- Plans for x-Ray ERLs
- x-Ray ERL challenges
- x-Ray ERL diagnostics needs
- Ongoing R&D
- High current FEL-ERL challenges
- High current ERL-FEL diagnostics needs

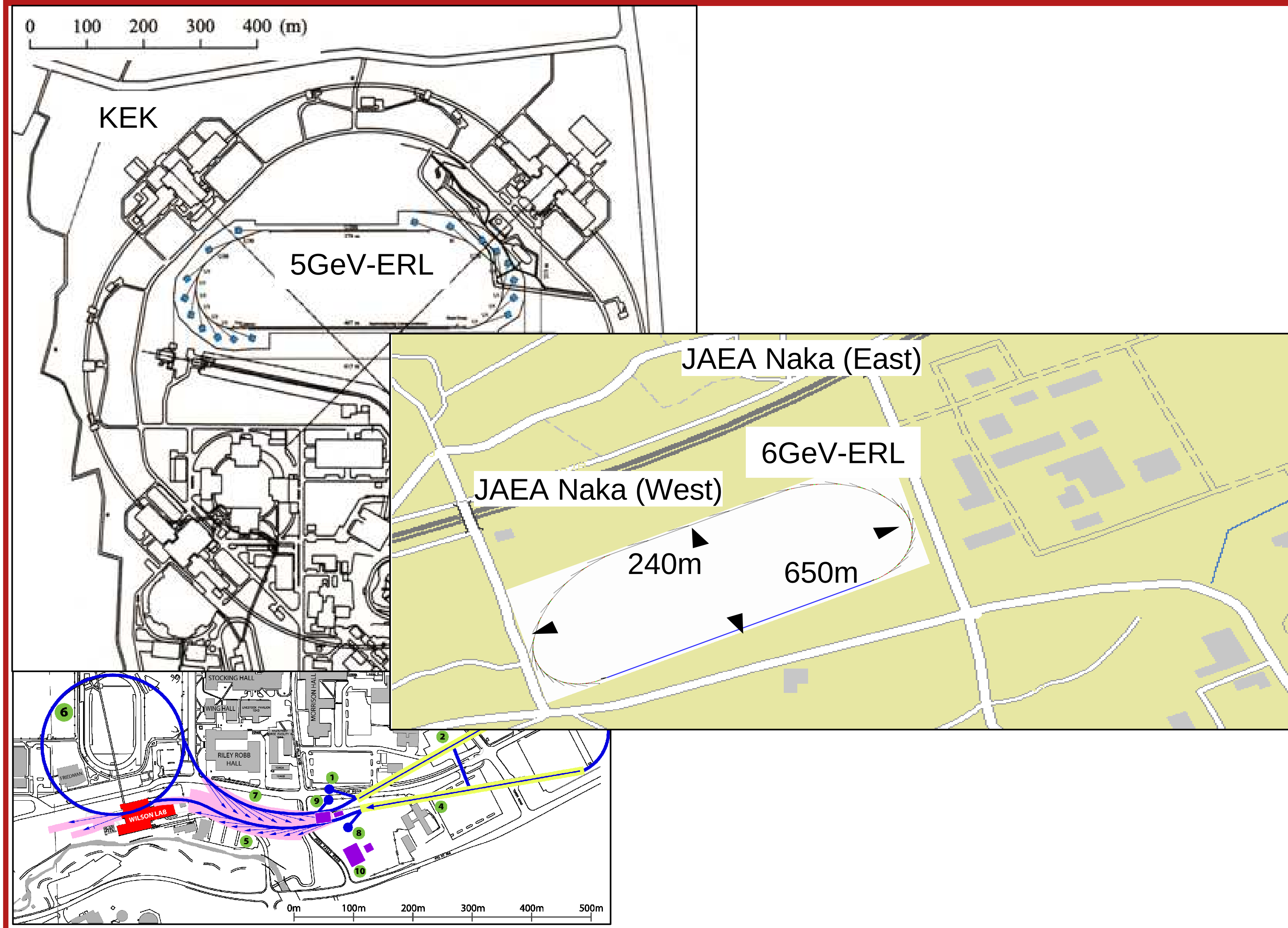
x-Ray ERL upgrade to CESR



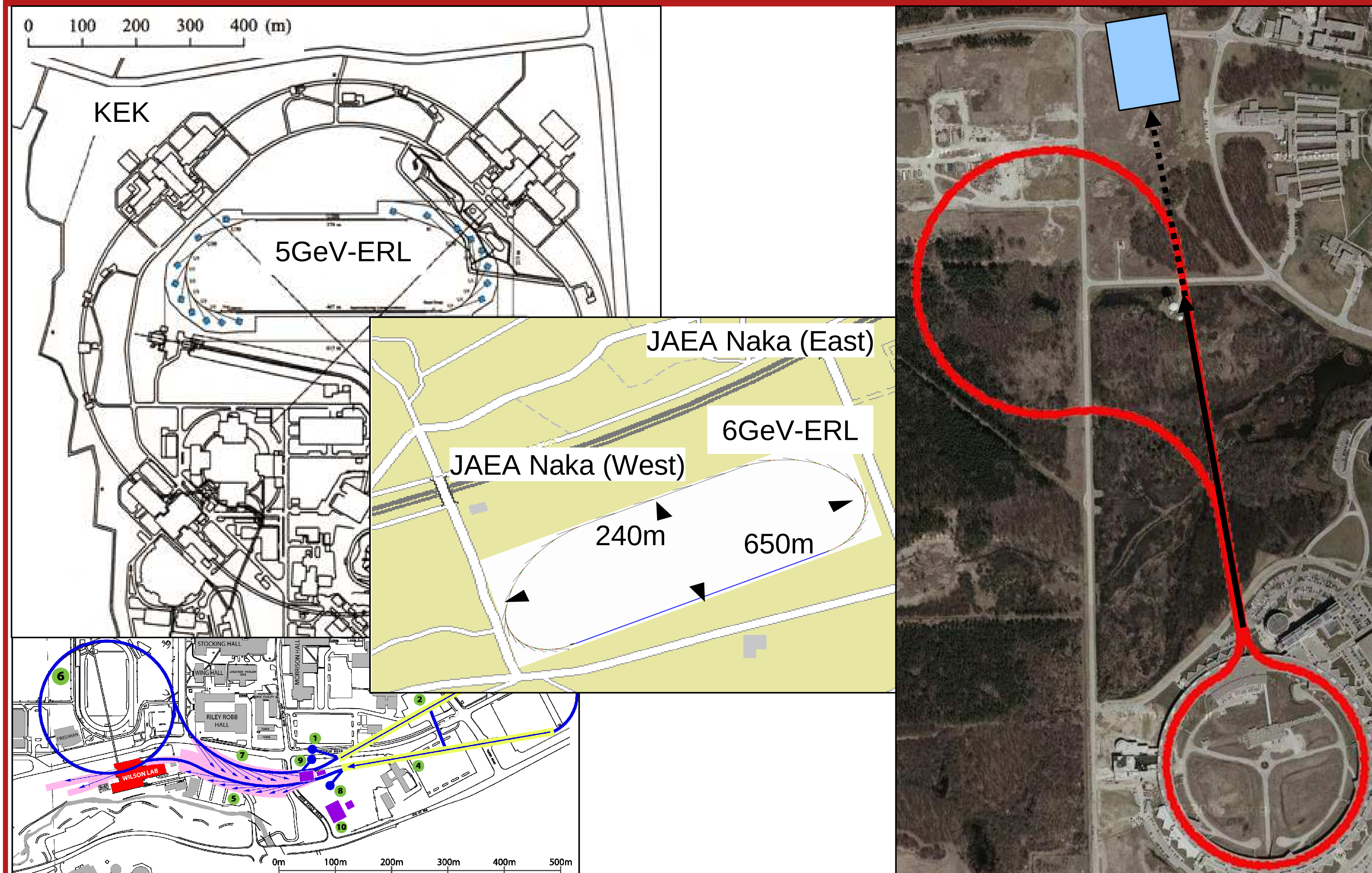
Key: 1) injector, 2) north linac, 3)turn-around arc, 4) south linac, 5) south x-ray beamlines, 6) CESR turn-around, 7) north x-ray beamlines, 8) 1st beam dump, 9) 2nd beam dump and 10)distributed cryoplant. Tunnel cross-section of 12' ID shown on lower right.


STOCKING HALL
WING HALL
RILEY ROBB HALL
MORRISON HALL
BOYCE THOMPSON INST.
V.R.T.
V.M.C.
WILSON LAB
0m
100m
200m
300m
400m
500m

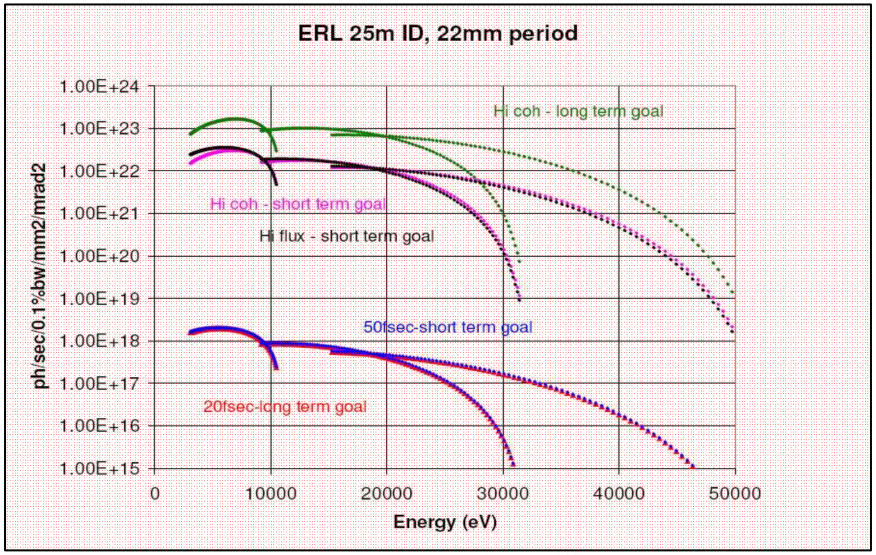
Cornell / KEK / JAEA ERLs

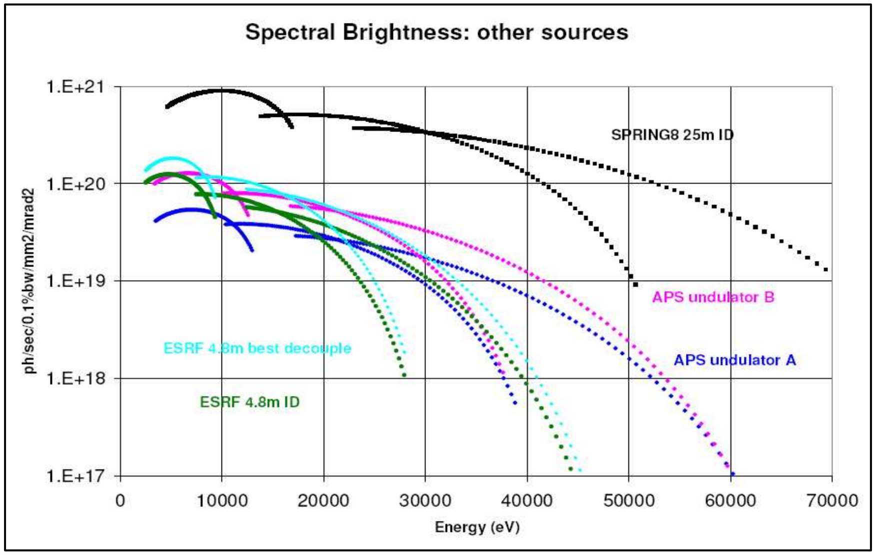


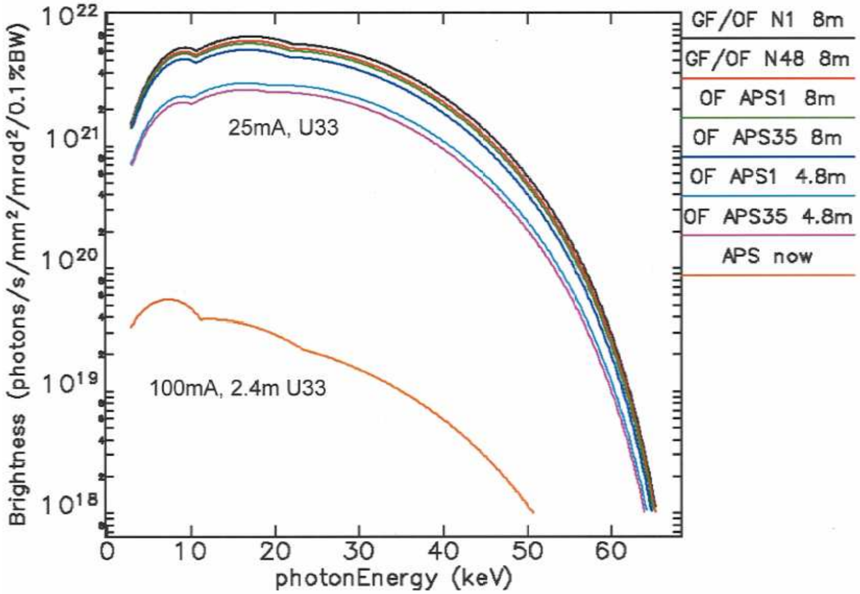
Cornell / KEK / JAEA / APS ERLs



How large is the advantage of ERLs ?







The injector: goals for the ERL

	Energy recovered modes			One pass	
Modes:	(A) Flux	(B) Coherence	(C) Short-Pulse	(D) Short & High charge	Units
Energy	5	5	5	5	GeV
Current	100	25	100	0.1	mA
Bunch charge	77	19	77	1000	pC
Repetition rate	1300	1300	1300	0.1	MHz
Norm. emittance	0.3	0.08	1	5.0	mm mrad
Geom. emittance	31	8.2	103	1022	pm
Rms bunch length	2000	2000	tbd by CSR	100	fs
Relative energy spread	0.2	0.2	1	3	10^{-3}
Beam power	500	125	500	0.5	MW
Beam loss	< 1	< 1	< 1	<1	micro A

(1) Challenges for x-ray ERLs

- **Production of low emittances**
  - Space charge compensation in the injector
- **Diagnostics needs**
  - Phase space measurement for injector setup
  - Laser diagnostics for bunch position and bunch timing feedback
  - Laser diagnostics for transverse and longitudinal profile

Multivariable optimization to worlds highest electron brightness

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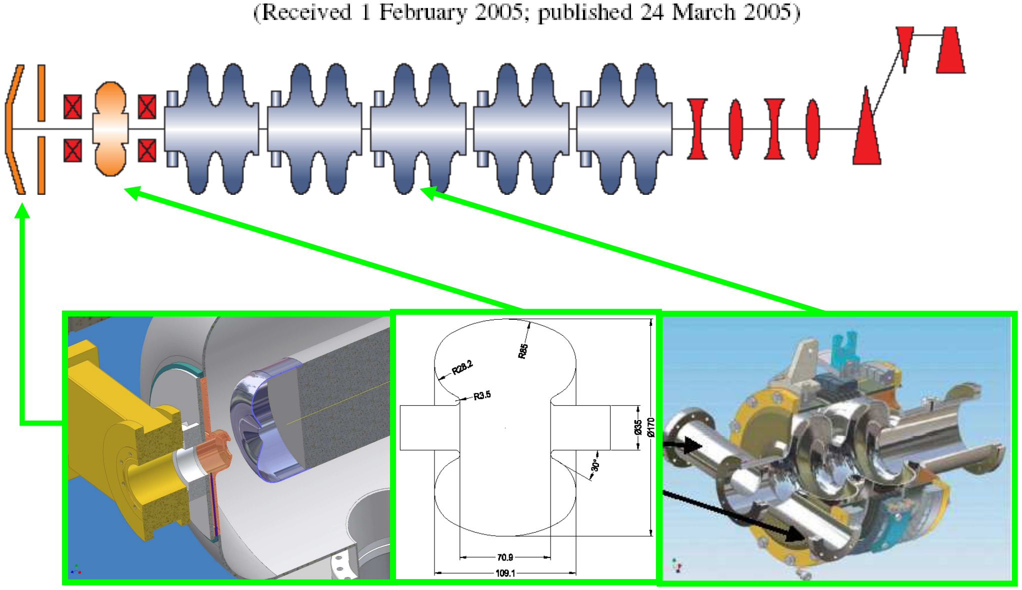
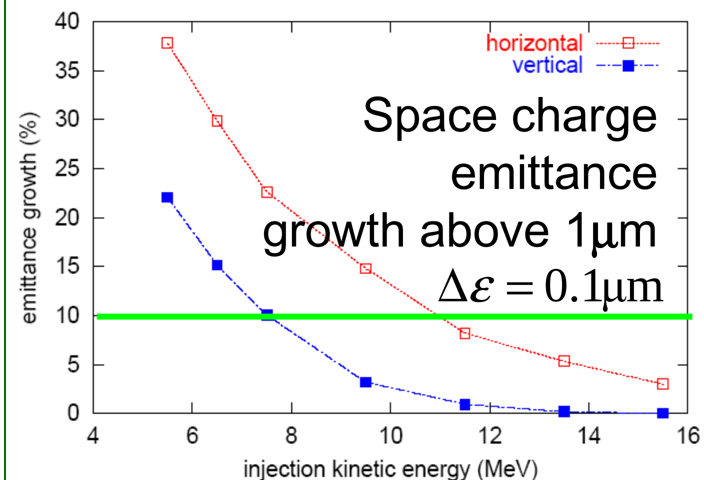
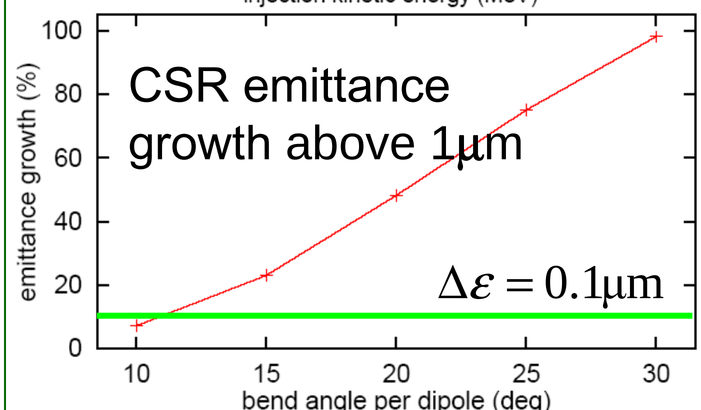
Multivariate optimization of a high brightness dc gun photoinjector

Ivan V. Bazarov* and Charles K. Sinclair†
Laboratory for Elementary Particle Physics, Cornell University, Ithaca, New York 14853, USA
(Received 1 February 2005; published 24 March 2005)



Some initial, promising results





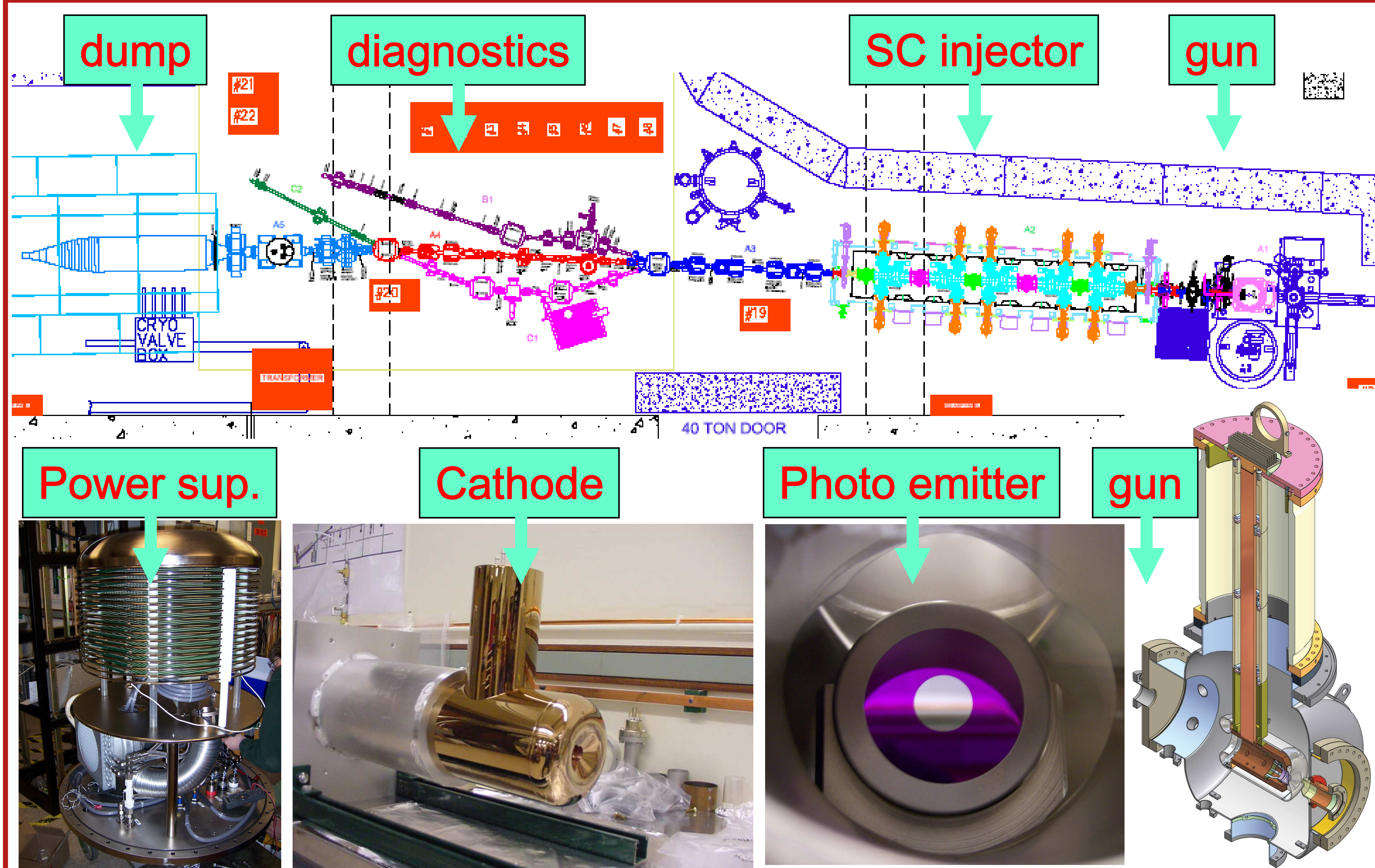
lead to further study, and experimental tests …

This work has continued steadily, currently being optimized for a detailed injector design to:

15MeV injection energy,

3ps bunch length, **0.3µm** emittances for **77pC**.

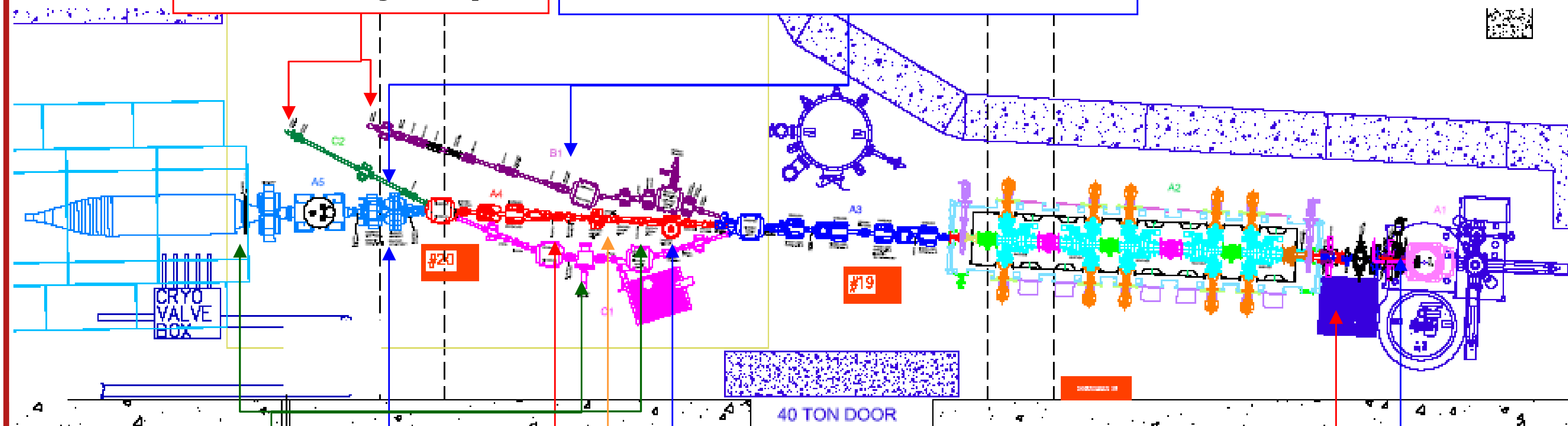
Cornell Injector prototype: Verification of beam production



Cornell Injector prototype: Diagnostics

Faraday cup

View screens, BPMs



- Flaying wire
- Quadrant detector

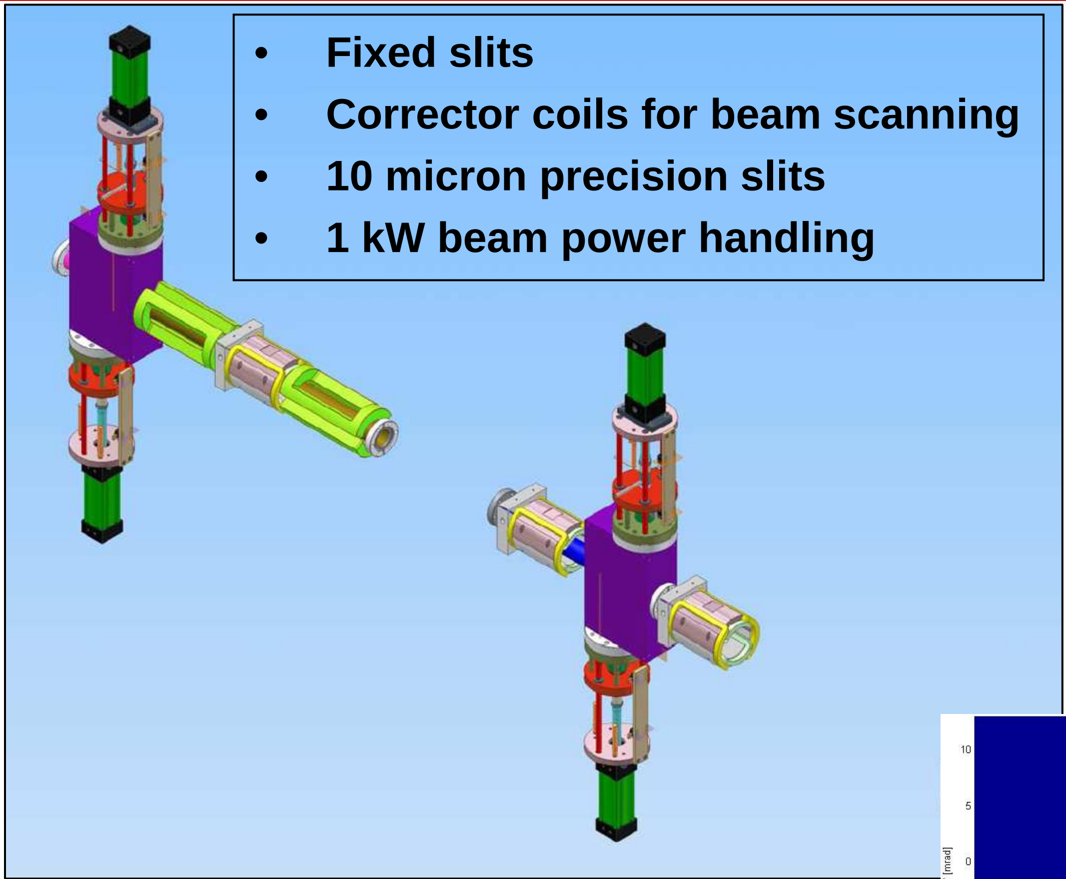
- Fast current detector
- Faraday cup

Two slit emittance measurement

- View screens
- BPMs

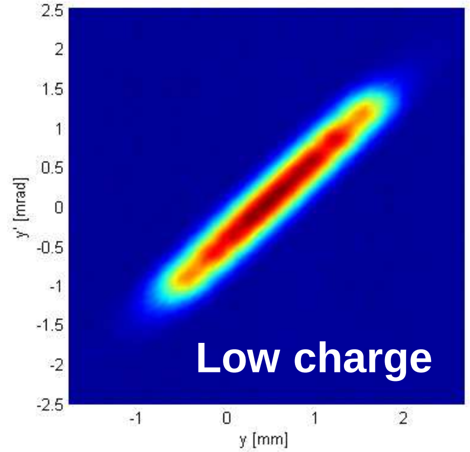
Emittance Measurement System

- Fixed slits
- Corrector coils for beam scanning
- 10 micron precision slits
- 1 kW beam power handling



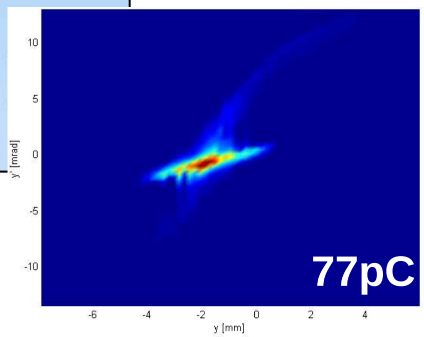
Highest current: 25mA
Highest voltage: 430kV
Highest bunch charge: 80pC
Highest Q.E.: 14%

Measured phase space

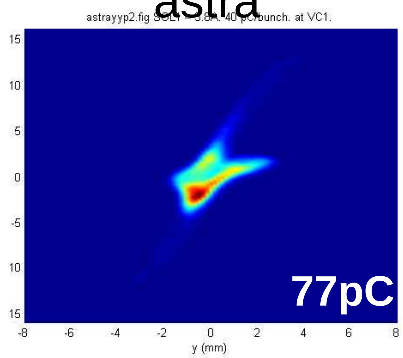


Courtesy Ivan Bazarov

data



astra



Good agreement with Astra calculation for a misaligned solenoid.

(1) Comparison to HIGH POWER ERL-FELs

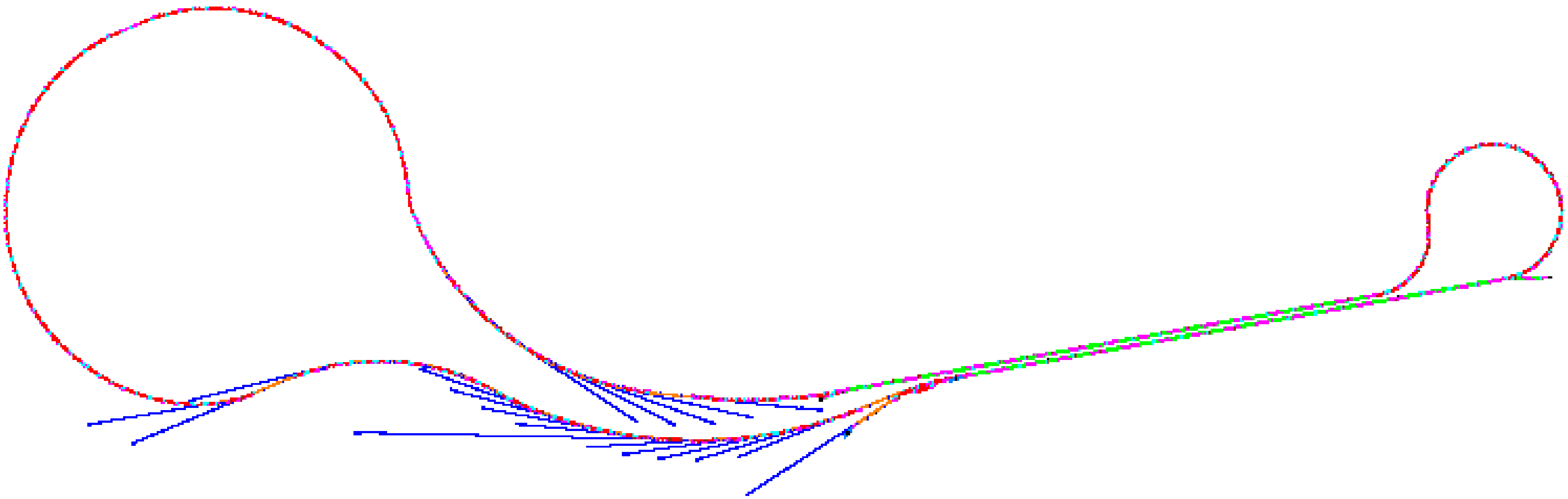
- **Production of low emittances**
  - Space charge compensation in the injector – less critical by >10
- **Diagnostics needs**
  - Phase space measurement for injector setup – still important
  - Laser diagnostics for bunch position and bunch timing feedback
    - still relevant
  - Laser diagnostics for transverse and longitudinal profile
    - less critical

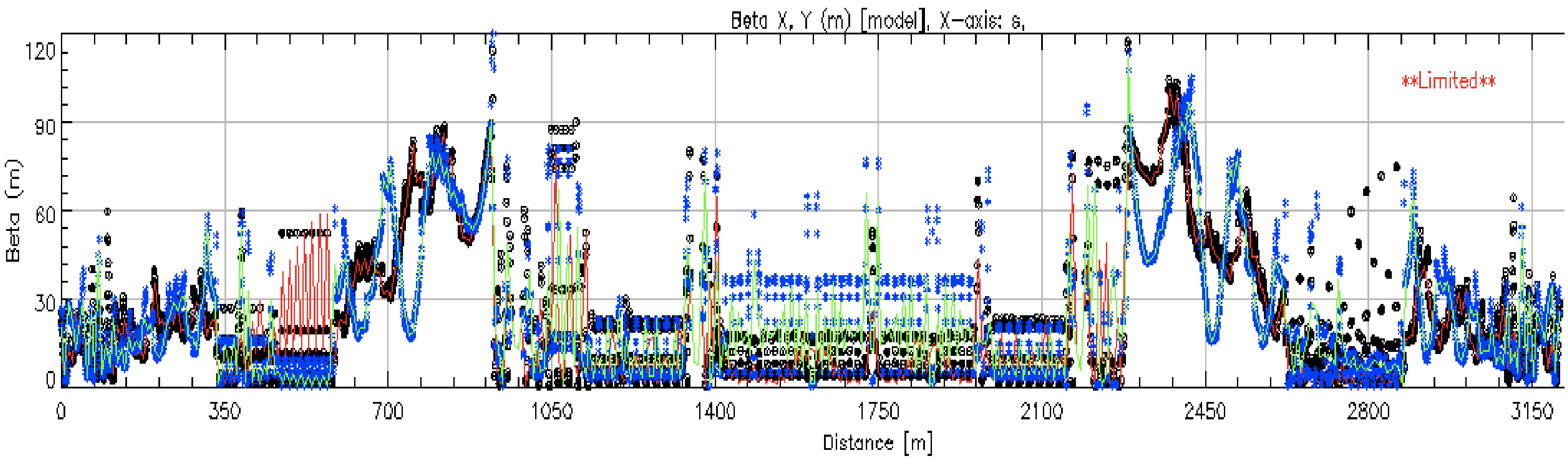
(2) Challenges for x-ray ERLs

- **Limited emittance growth**
  - Beam stabilization to fraction of the very small beamsize
  - Optics in the linac for very different energies (0.01 - 5GeV)
  - Low emittance growth optics similar to light sources
  - Limit optics errors and adjust fields to radiated energy
  - Limit coupler kicks / cavity misalignments

- **Diagnostics needs**
  - Sub micron BPMs
  - Beam position measurements for two simultaneous beams
  - High energy beam-size measurements
  - High energy emittance measurements

Linear Optics





Incoherent Synchrotron Radiation (ISR)

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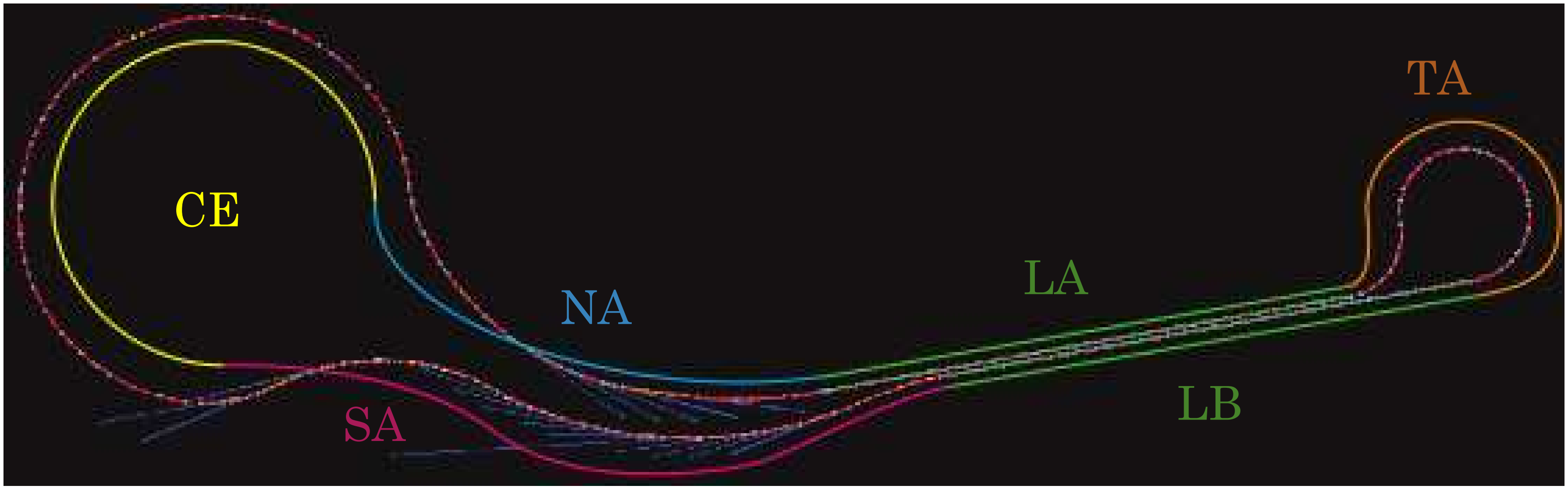
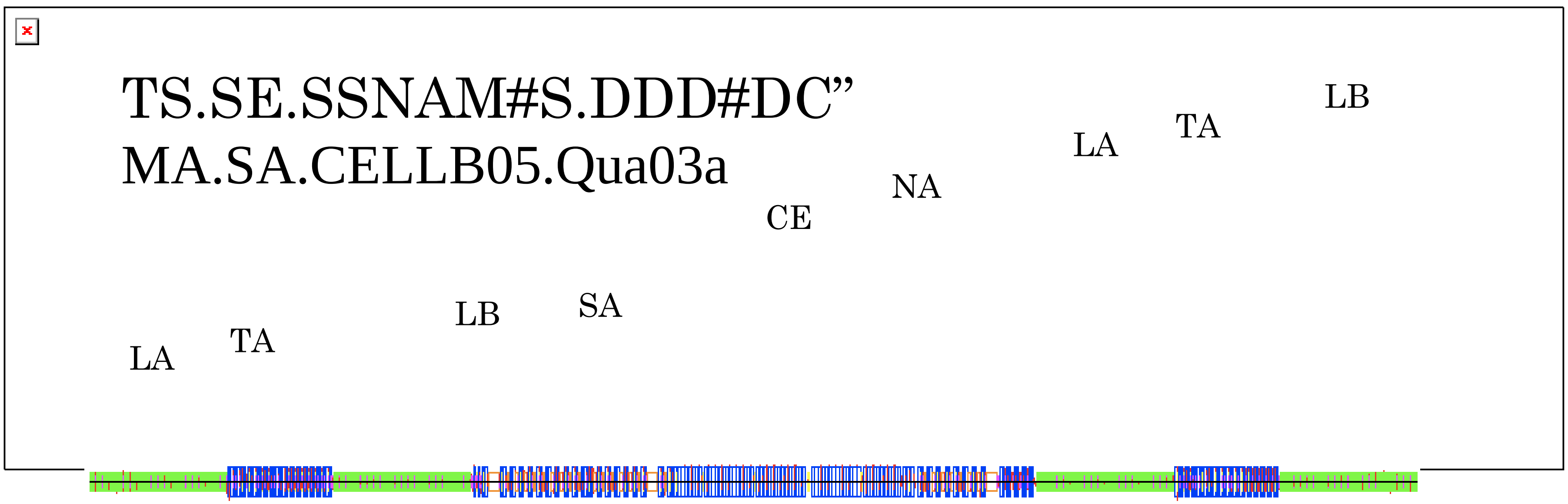
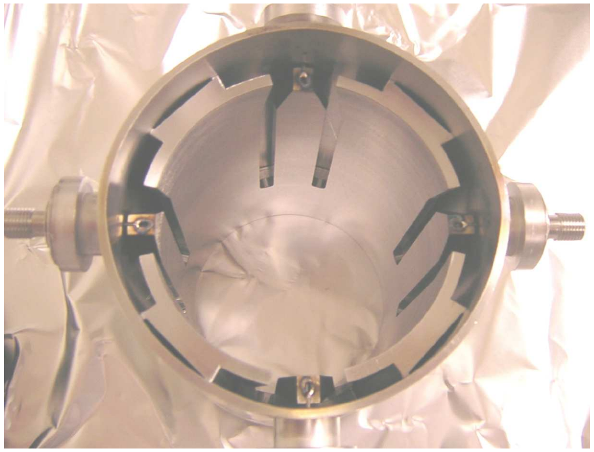




BPMs for the Cornell ERL

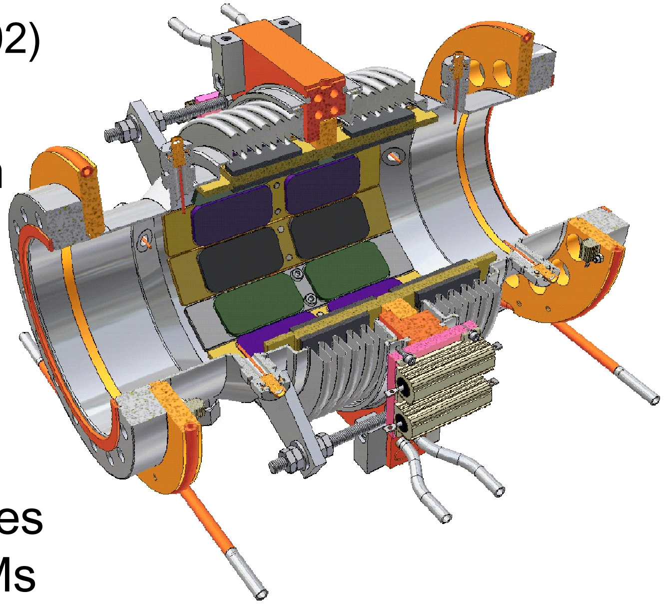
Challenges:

1) Two beams of different energy have to be measured simultaneously in much of the ERL
2) Tolerances of transverse motion are very stringent, 0.3μm in some places: 0.5μm at 10kHz and <0.1μm at 10Hz for 77pC, 1.3GHz.
3) Wake-field heating and energy spread from wake fields has to be tolerable
4) BPMs have to work in 80K environment, or use HOM bpms (< 4micron resolution, PRST-AB 9/112802)



Possible solutions:

1) Read out a difference orbit at 1.3GHz and a sum orbit at 2.6GHz.
2) Buttons: ok
   Strip line: size for 1/6 of the rf wavelength
   No Cavity BPM: would need a resonance at
   1.3GHz and 2.6GHz.



Strategy: Use buttons all around the ring and strip lines at a few critical places for low currents, use HOMs

Button Beam Position Monitors

Design: four 10mm buttons in a 25.4mm beampipe

1. **Initial injection tune-up mode:** 50MHz, 1ms bunch train, 2-10pC per bunch

   Resolution: **+/- 20 – 4micron** at 10kHz readout

2. **Orbit refinement mode**: 50MHz, 1ms bunch train, 10-77pC per bunch

   Resolution: **+/- 4 – 0.5micron** at 10kHz readout

3. **Low current CW tune-up mode:** 1300MHz, 1ms bunch train, 2-10pC per bunch

   Resolution: **+/- 20 – 4micron** at 10kHz readout

4. **High current CW ramp-up mode:** 1300MHz, 1ms bunch train, 10pC per bunch

   Resolution: +/- **4micron** at 10kHz readout

5. **High current CW ramp-up mode:** 1300MHz, CW, 10-77pC per bunch

   Resolution: **+/- 4 – 0.5micron** at 10kHz readout

6. **Stable ERL operational mode:** 1300MHz, CW, 77pC

   Resolution: **+/- 0.5micrometer** at 10kHz readout at 0.1micron at 10Hz

Alignment requirements

General comment about DC alignment requirements:

These are similar to that in ring light sources because the vertical beam size in such sources is as small and smaller than the vertical and horizontal size in the ERL.

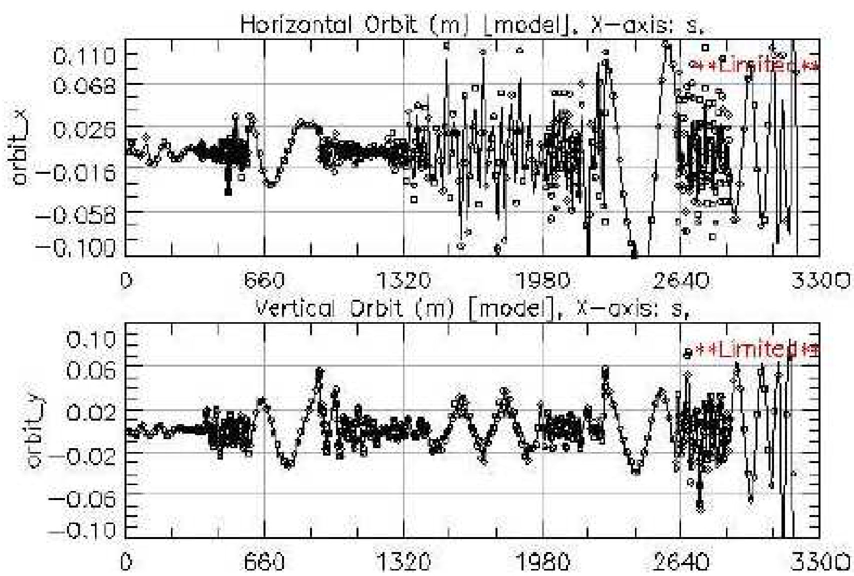
Achieved orbit stability in 3rd generation light sources:

	Horizontal Orbit [μm]		**Vertical Orbit** y [μm]	
	Requirement	Achieved	Requirement	Achieved
APS	14.0	12.6	0.45	0.59
ESRF	N/A	1.0	N/A	0.6
ALS	10.3	2	1.2	0.5
ELETTRA	5.0	0.85	5	0.47
SPring-8	28.0	4	0.4	1
SLS	N/A	1.0	0.7	0.6

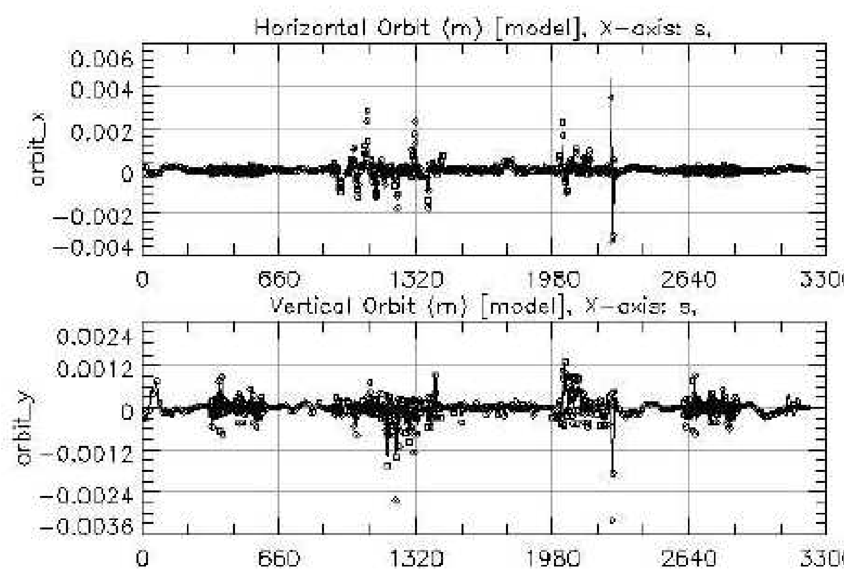
BPM and corrector placement

The orbit can be controlled with the placement of BPMs and correctors.

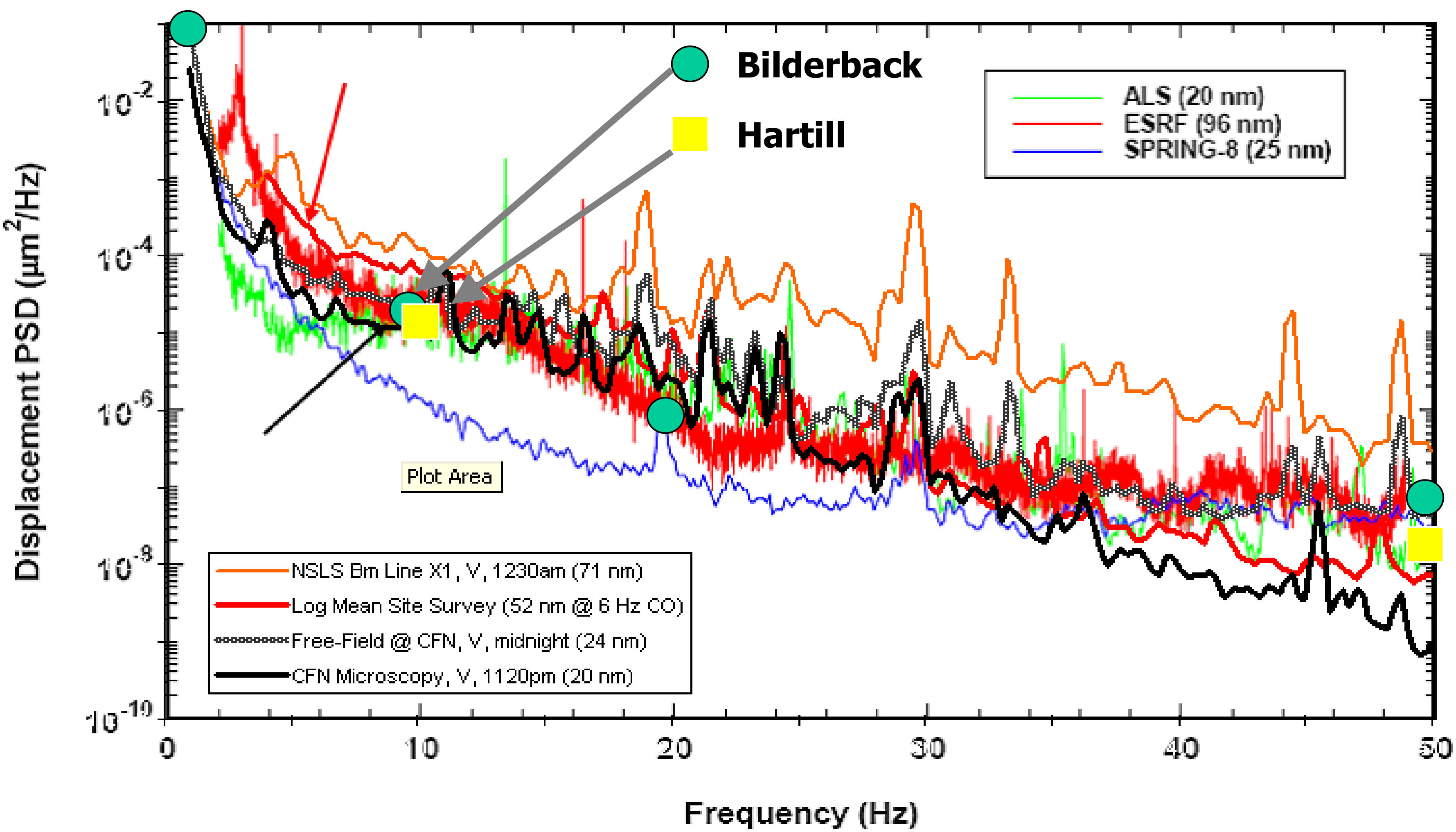
Uncorrected orbit for 0.3mm rms quadrupole misalignments:



Corrected orbit for 0.3mm rms quadrupole misalignments:



Vibration measurements



(2) Comparison to HIGH POWER ERL-FELs

- **Limited emittance growth**
  - Beam stabilization to fraction of the very small beamsize
    - much less critical – but probably much more vibrations
  - Optics in the linac for very different energies (0.01 - 5GeV)
    - much less critical (approx. 7-100MeV)
  - ~~Low emittance growth optics similar to light sources~~
  - ~~Limit optics errors and adjust fields to radiated energy~~
  - ~~Limit coupler kicks / cavity misalignments~~

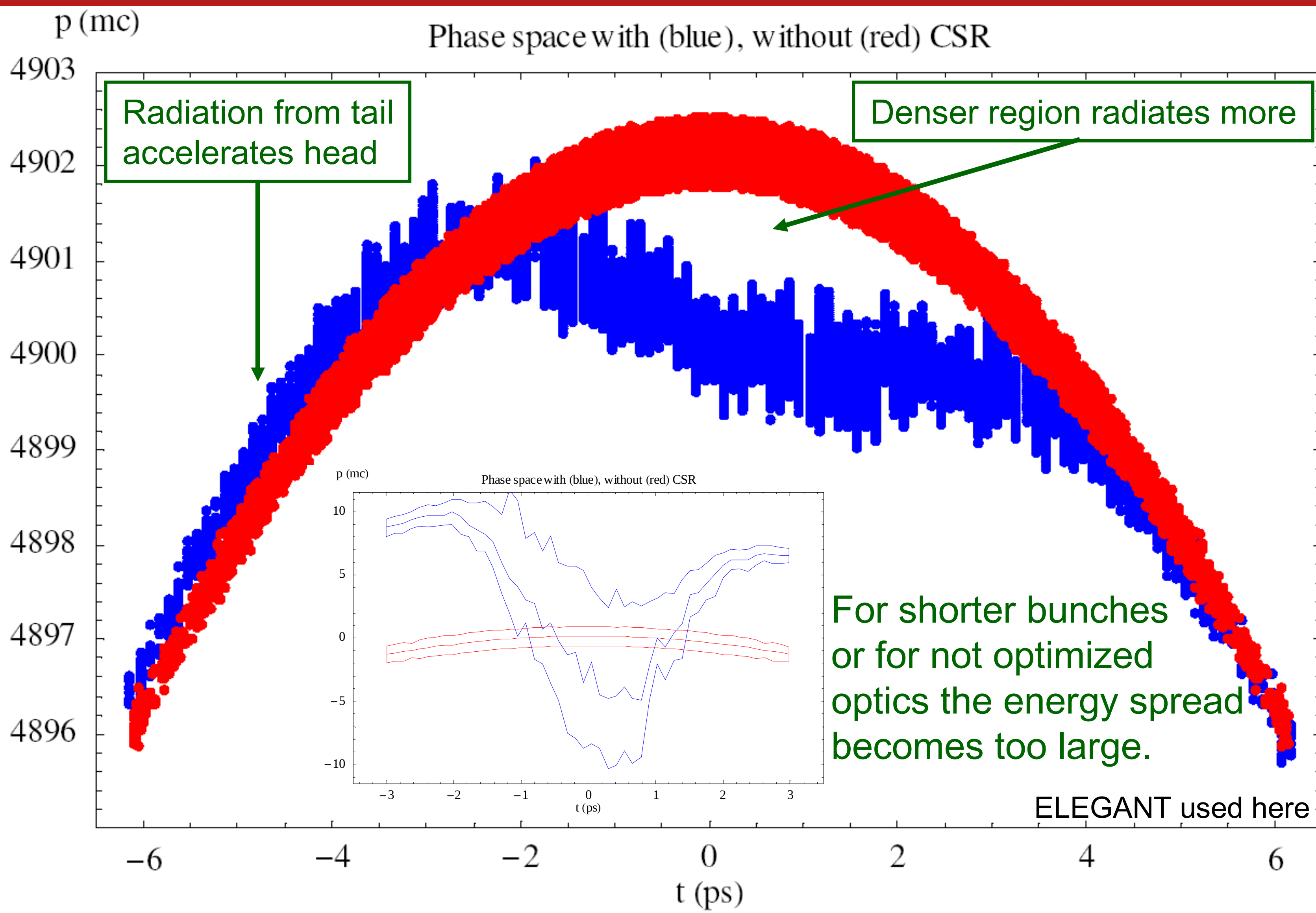
- **Diagnostics needs**
  - ~~Sub micron BPMs~~
  - Beam position measurements for two simultaneous beams
  - ~~High energy beam-size measurements~~
  - ~~High energy emittance measurements~~

(3) Challenges for x-ray ERLs

- **Limit energy spread after deceleration, e.g. 5GeV to 10MeV**
  - Accurate time of flight correction, including sextupoles
  - Limit energy spread from wake fields
  - Limit energy spread from intra beam scattering (IBS) and rest gas scattering
  - Limit energy spread from incoherent / coherent synchrotron radiation (ISR / CSR)
  - Dumping a beam with very large energy spread

- **Diagnostic needs**
  - Bunch arrival time diagnostics
  - Halo diagnostics after deceleration (end of linac and dump)
  - X-ray diagnostics for personal and electronics protection
  - Dump diagnostics, based on beam loss

CSR in ERL bends



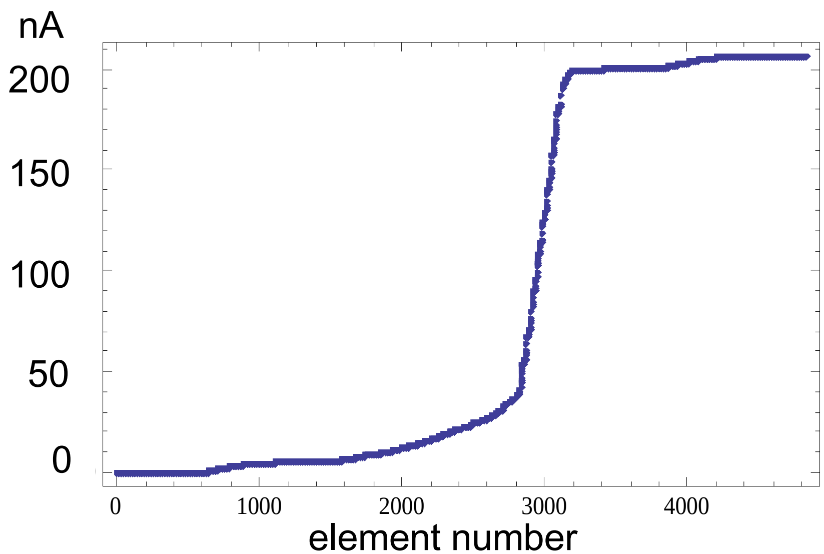
Timing and Bunch Arrival Diagnostics

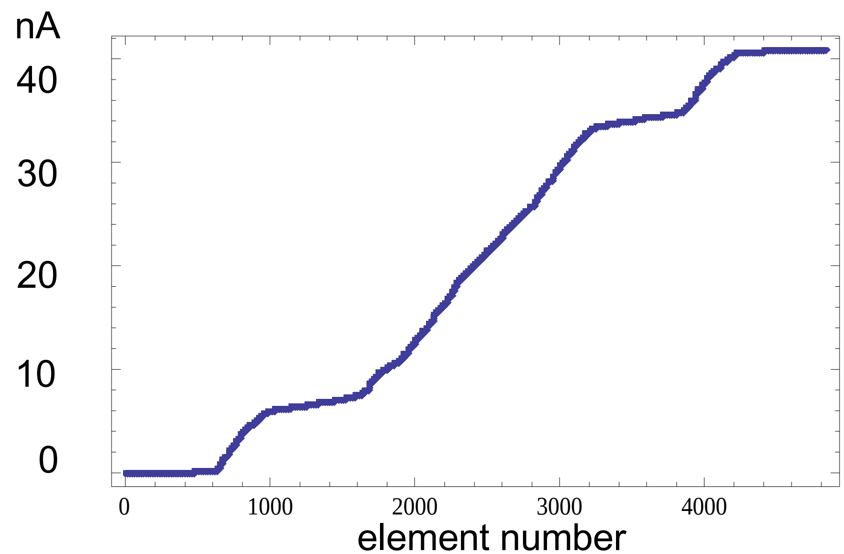
- Orbit length correction (to about 150mm):
  Master oscillator correction (slow) and dispersive bump correction (fast)

- State of the art: Electro optical sampling with a laser pulse in a birefringent medium co-propagating with electrons – 30fs (e.g. Hacker et al., FEL06).

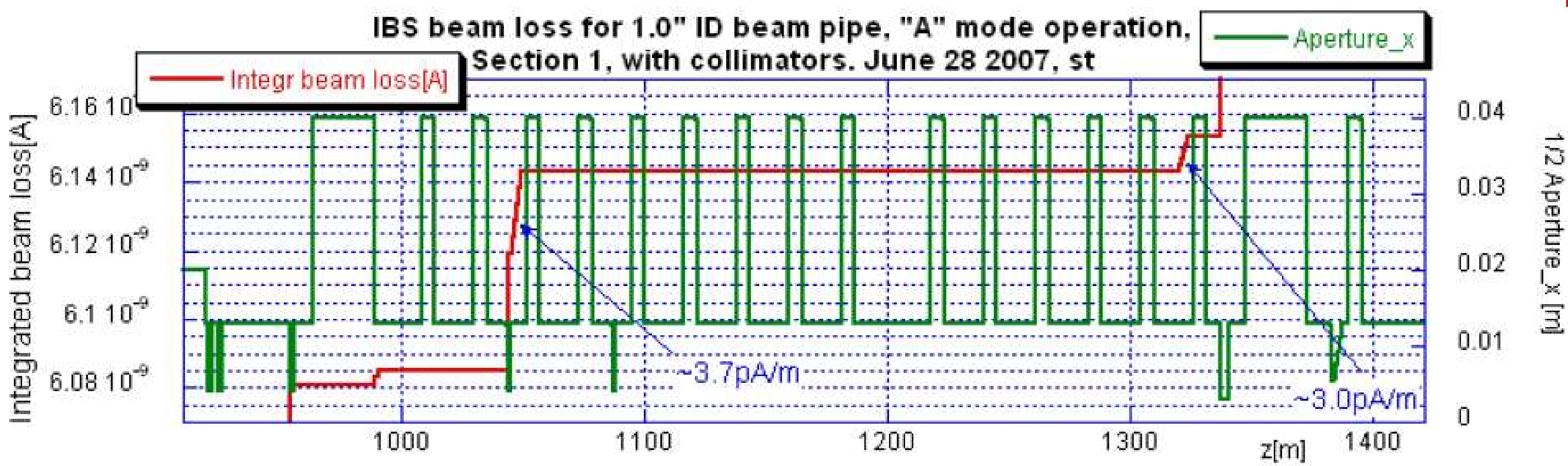
- State of the art: Timing signal propagation for bunch to RF synchronization – < 10fs (e.g. Loehl et al., PAC07).

Scattering and background: IBS



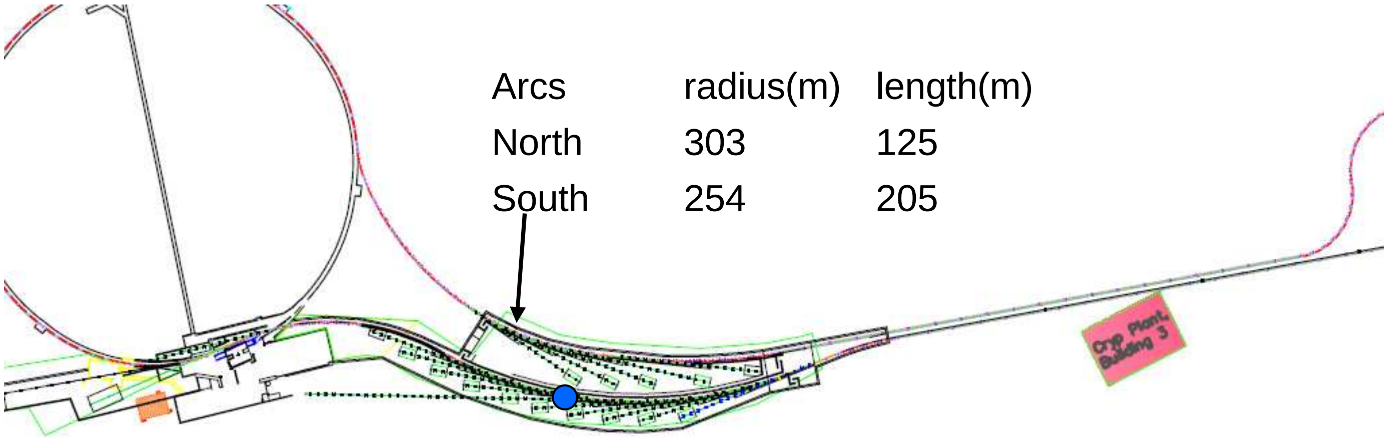


Courtesy Sasha Temnykh



Radiation shielding

Estimate following H.J. Moe in APS-LS-141 & -272



Arcs	radius(m)	length(m)
North	303	125
South	254	205

Three contributions to background from continuous uniform e$^-$ loss: Bremsstrahlung, giant resonance neutrons, & high-energy neutrons

For average beam loss 1 pA/m over 205m southern arc, shield wall: for 2' heavy concrete + 2" Pb→0.058mrem/hr just outside the wall, at arc center.

Moe's estimate for APS (300mA,10 hour lifetime or 1/57 pA/m) → 80cm normal concrete wall limits dose to 8 mrem/yr @ 50m

Public: limit to less than 100mrem/year, occupational limit to less than 5000mrem/year

(3) Comparison to HIGH POWER ERL-FELs

- **Limit energy spread after deceleration, e.g. 5GeV to 10MeV**
  - Accurate time of flight correction, including sextupoles – more severe
  - Limit energy spread from wake fields – less severe (less deceleration)
  - Limit energy spread from intra beam scattering (IBS) and rest gas scattering – less severe (less deceleration)
  - Limit energy spread from incoherent / coherent synchrotron radiation (ISR / CSR) – much more severe due to FEL induced spread
  - Dumping a beam with very large energy spread

- **Diagnostic needs**
  - Bunch arrival time diagnostics - similar
  - Halo diagnostics – probably more severe (FEL energy spread)
  - X-ray diagnostics for personal and electronics protection – similar
  - Dump diagnostics based on beamloss – 4 times worse and larger

(4) Challenges for x-ray ERLs

- **Beam loss concerns**
  - Disturbance from ions / ion removal
  - Halo development
  - Component failures and machine protection system
- **Diagnostics**
  - Ion composition monitor
  - Halo detectors
  - Beam Loss monitors (e.g. fiber BLMs, W. Goettmann et al., DIPAC05)

Ion focusing

- Ion are quickly produced due to high beam density

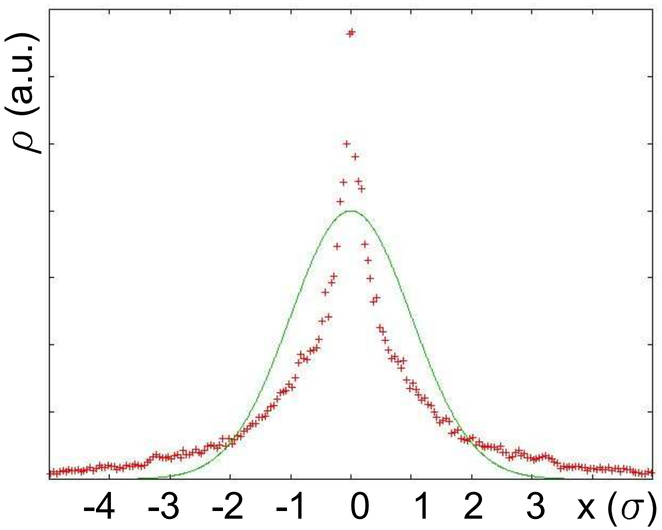
Ion	σ_{col}, 10MeV	σ_{col}, 5GeV	τ_{col}, 5GeV
H_2	$2.0 \cdot 10^{-23}\mathrm{m}^2$	$3.1 \cdot 10^{-23}\mathrm{m}^2$	5.6s
CO	$1.0 \cdot 10^{-22}\mathrm{m}^2$	$1.9 \cdot 10^{-22}\mathrm{m}^2$	92.7s
CH_4	$1.2 \cdot 10^{-22}\mathrm{m}^2$	$2.0 \cdot 10^{-22}\mathrm{m}^2$	85.2s

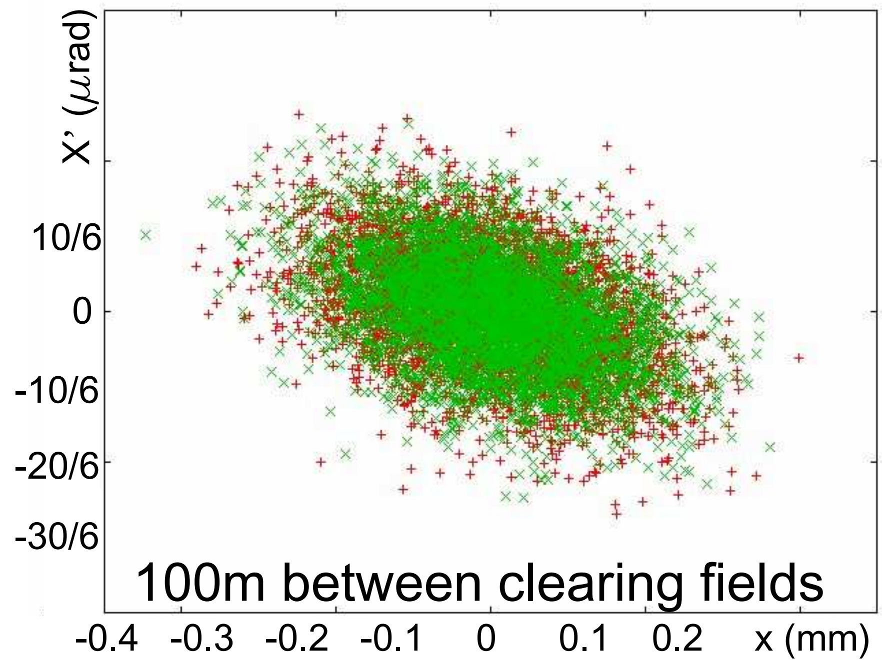
- Ion accumulate in the beam potential. Since the beam is very narrow, ions produce an extremely steep potential – they have to be eliminated.

- Conventional ion clearing techniques:
  1) Long clearing gaps have transient RF effects in the ERL [2ms every 7ms].
  2) Short gaps have transient effects in injector and gun and produce more beam harmonics that excite HOMs [0.4 ms every 7ms].
  3) DC fields of about 150kV/m have to be applied to appropriate places of the along the accelerator, without disturbing the electron beam.

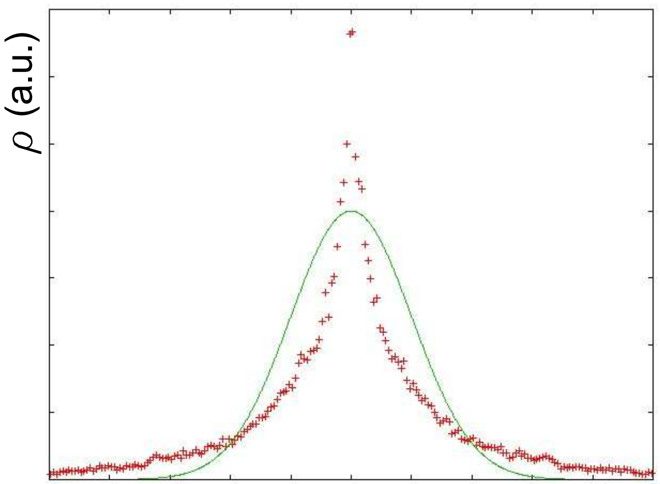
     But remnant ion density before clearing can still cause emittance growth.

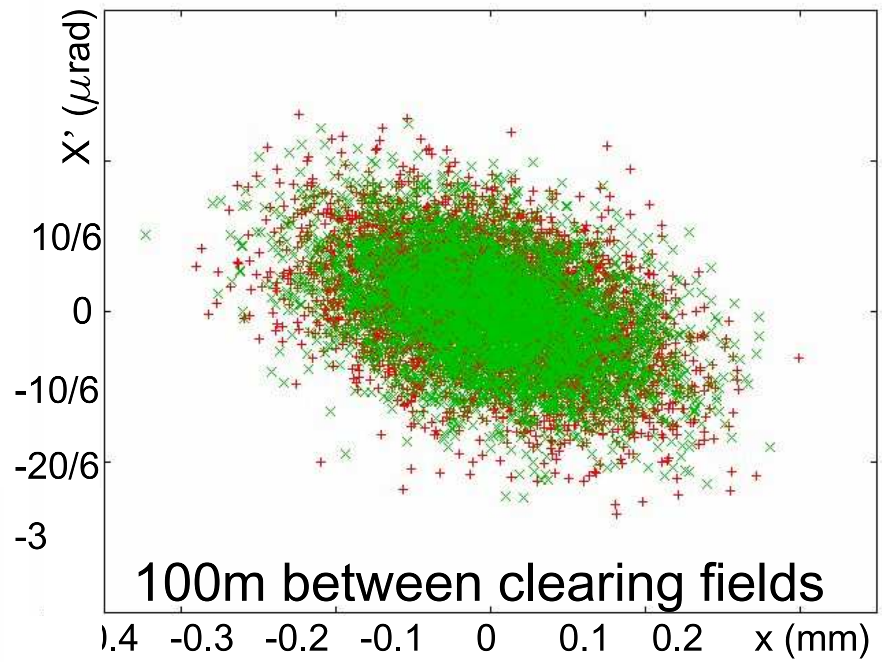
Ions in an ERL beam

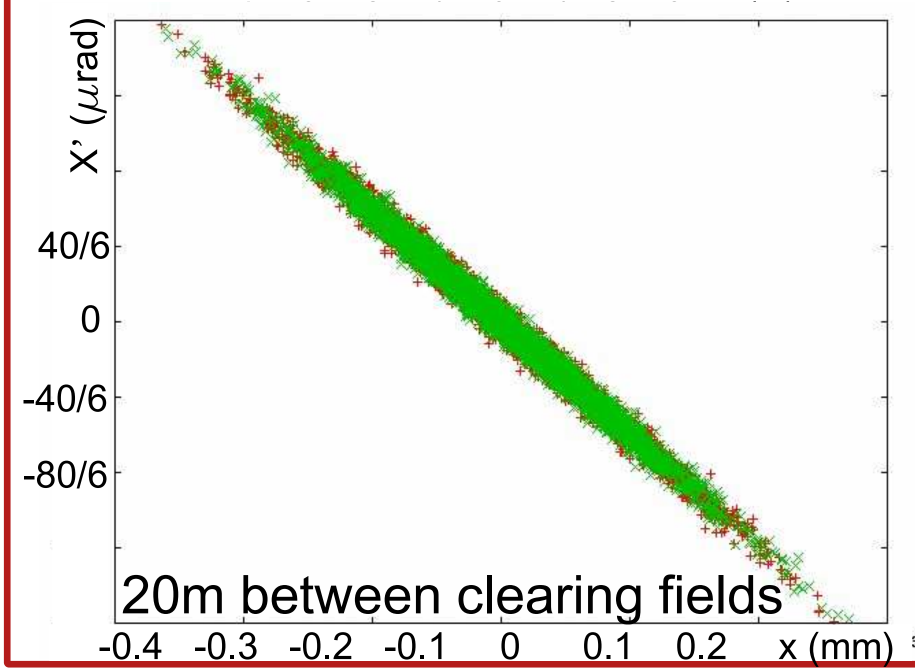




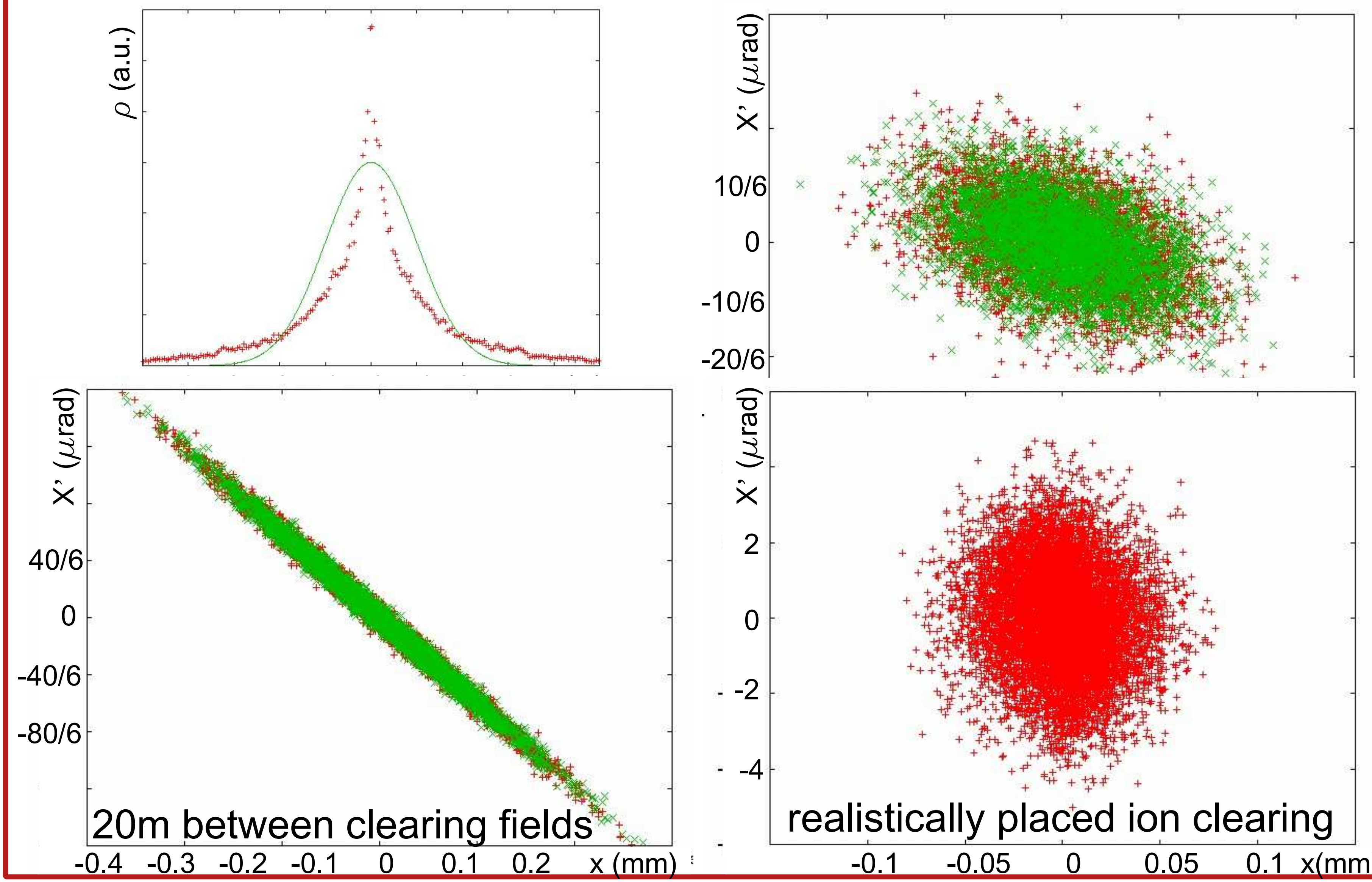
Ions in an ERL beam







Ions in an ERL beam



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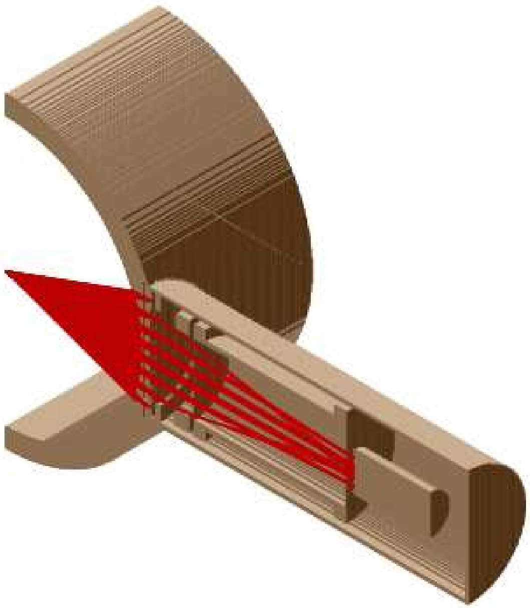
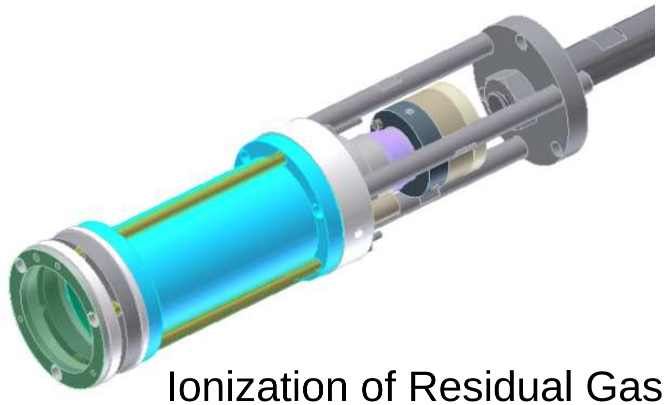
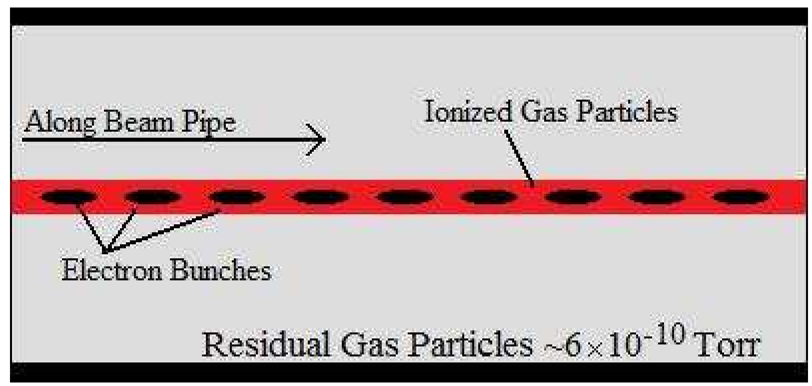
Ions concentration diagnostics





Ionization of Residual Gas Particles by Electron Beam Creates Ion Column



Problems Introduced by Ions:

1. Distortion of Accelerator Optics
2. Coupled Oscillations Between Beam and Ions

(4) Comparison to HIGH POWER ERL-FELs

- **Beam loss concerns**
  - Disturbance from ions / ion removal
    - less severe (less cross section, more gap between bunches)
  - Halo development
    - similar significance before undulator
    - more significant after undulator
  - Component failures and machine protection system
    - similar for electron beam, more severe for photon beam

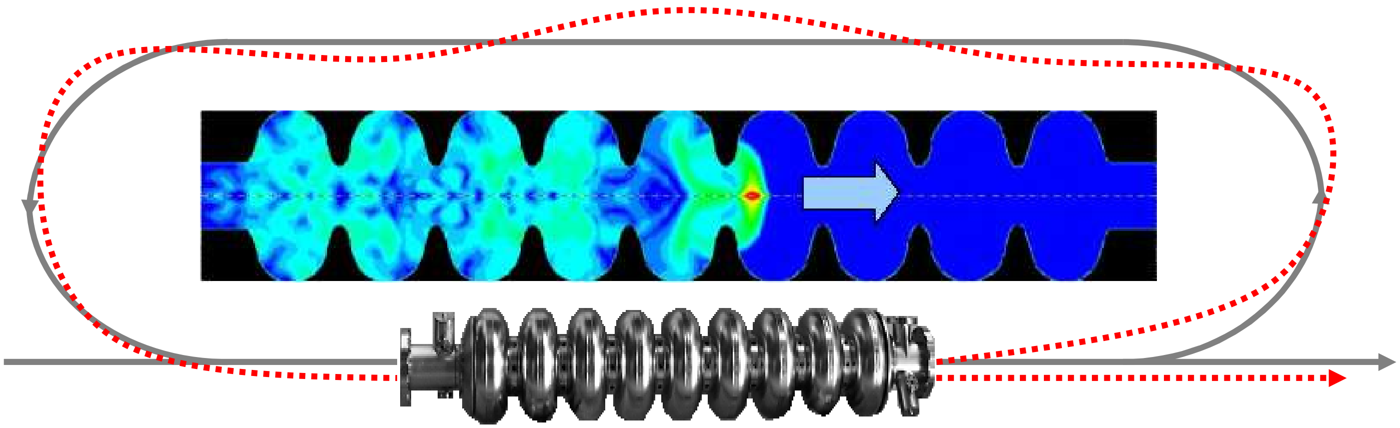
- **Diagnostics**
  - ~~Ion composition monitor~~
  - Halo detectors – more severe after undulator
  - Beam Loss Monitors (e.g. fiber BLMs, W. Goettmann et al., DIPAC05)
    - similar

(5) Challenges for x-ray ERLs

- **Superconducting RF challenges**
  - Phase and amplitude control for very narrow frequency window (10^{-8}) in the presence of microphonics
  - Avoid heating / Higher order mode absorption
  - Limit cooling power

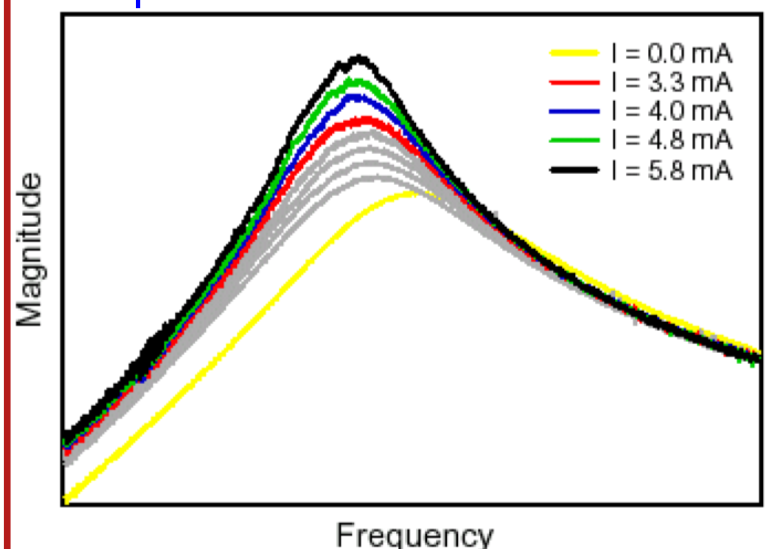
- **Diagnostics**
  - Cavity field diagnostics, input coupler diagnostics
  - Thermometry, HOM-power diagnostics
  - Cryogenic diagnostics
  - Microphonics diagnostics, e.g. Piezo electric

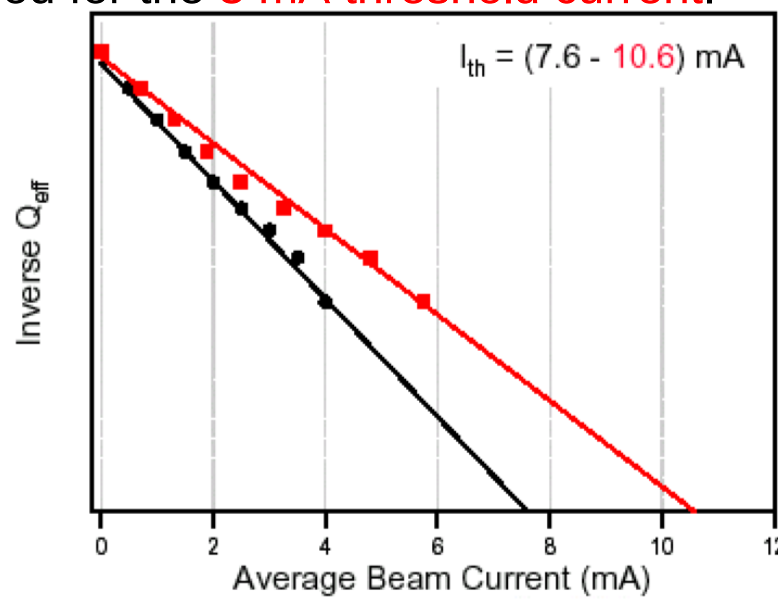
Beam instabilities collaboration with JLAB



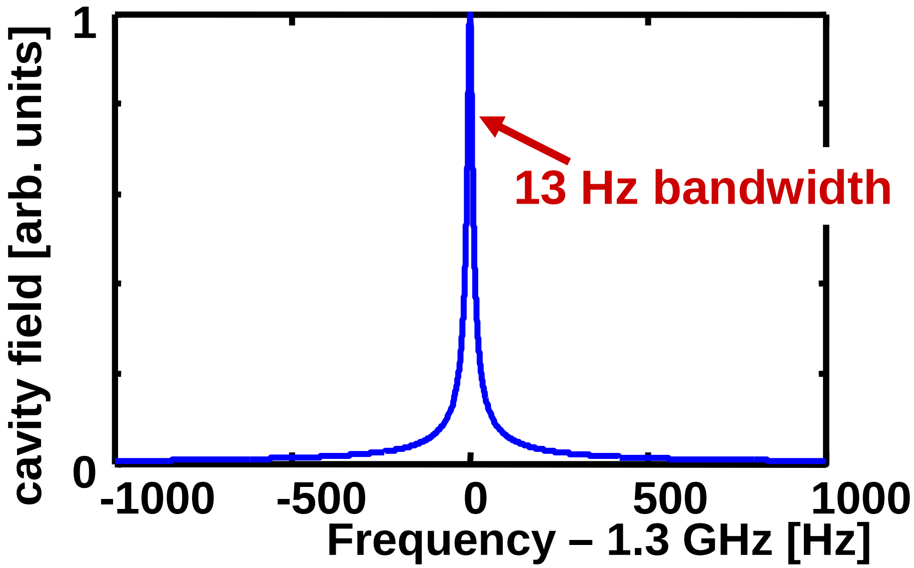
Beam breakup instability (BBU) can limit the current in an ERL to below 100mA

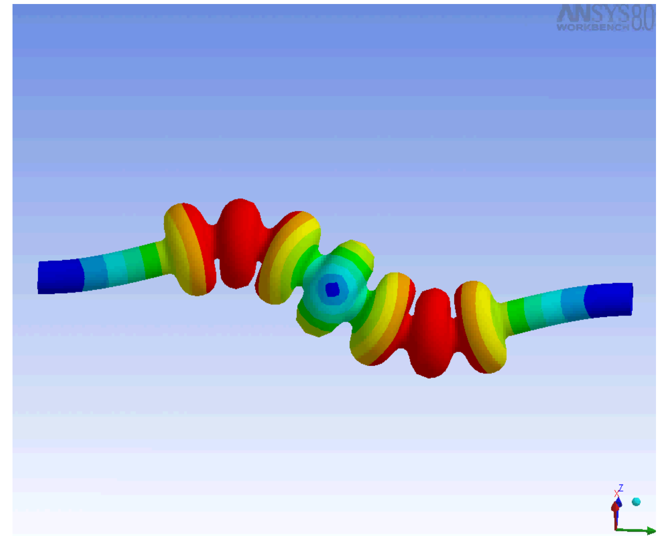
Experiments with JLAB: BBU is well understood for the 3 mA threshold current.





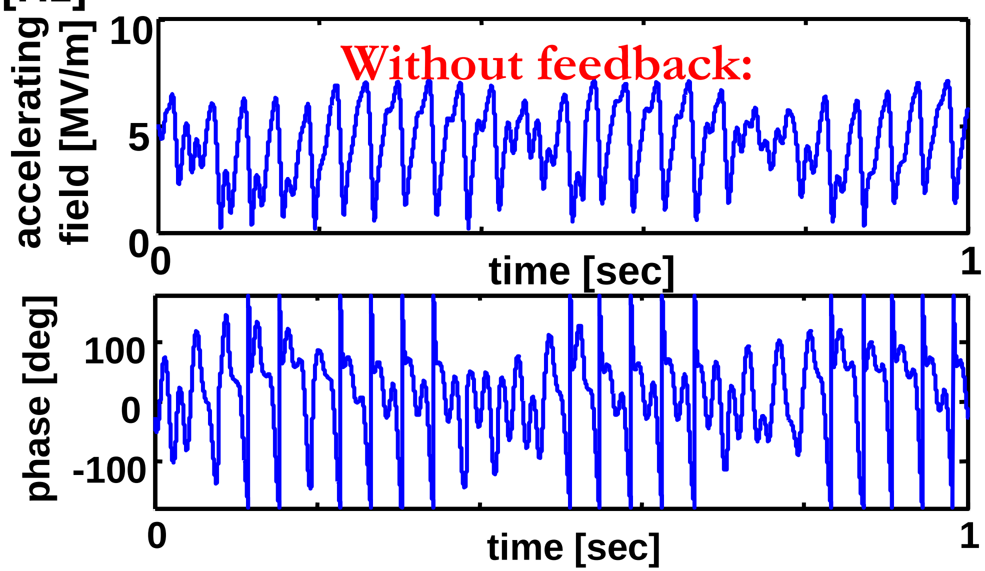
Cavity control for SC linacs (ERL & ILC)





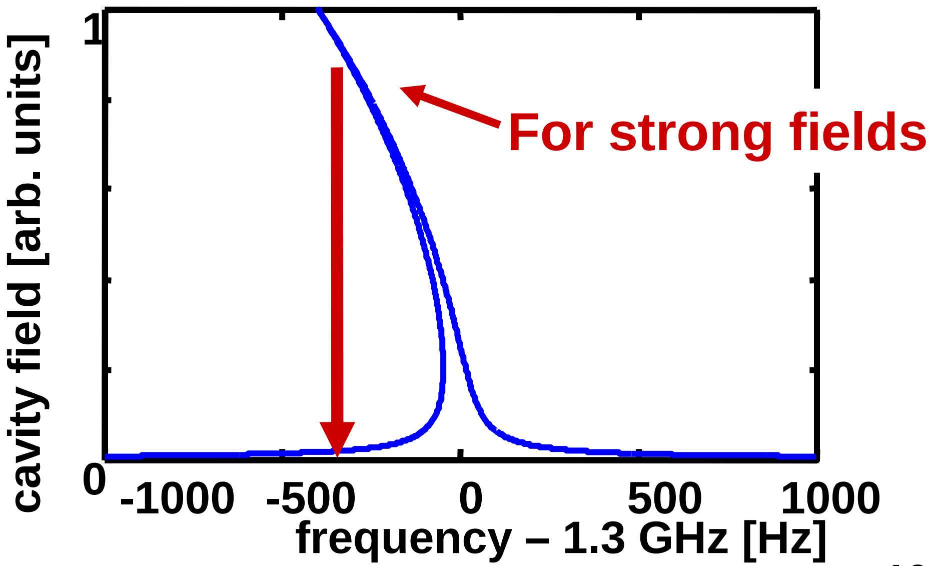
Courtesy Matthias Liepe

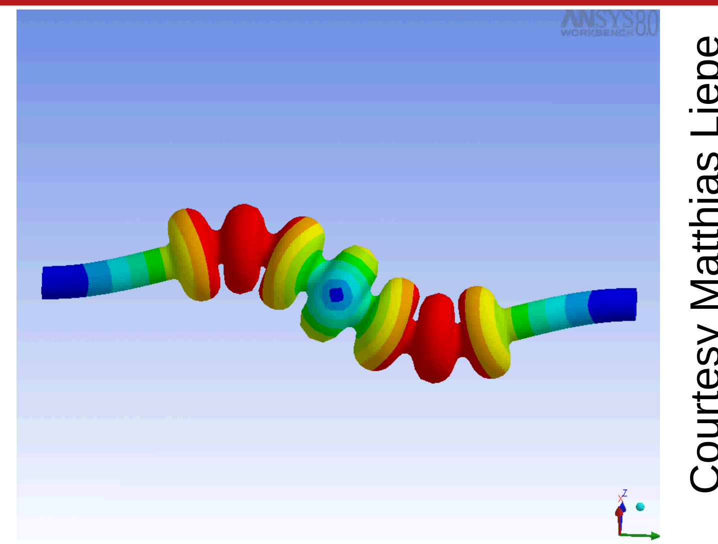
- Run cavity with lowest possible bandwidth for ERL.
- But frequency stabilization becomes very critical.



Cavity control for SC linacs (ERL & ILC)

CLASSE





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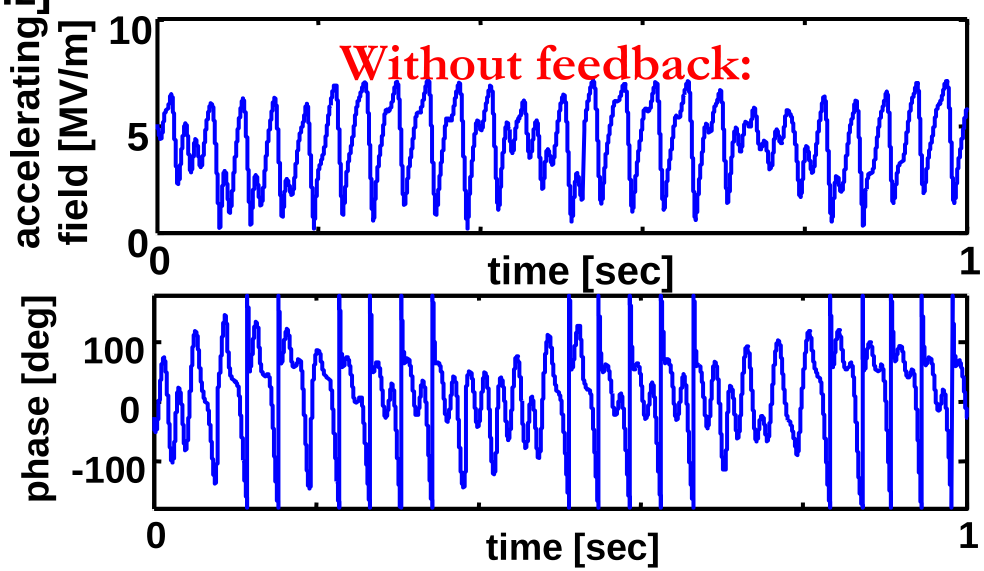
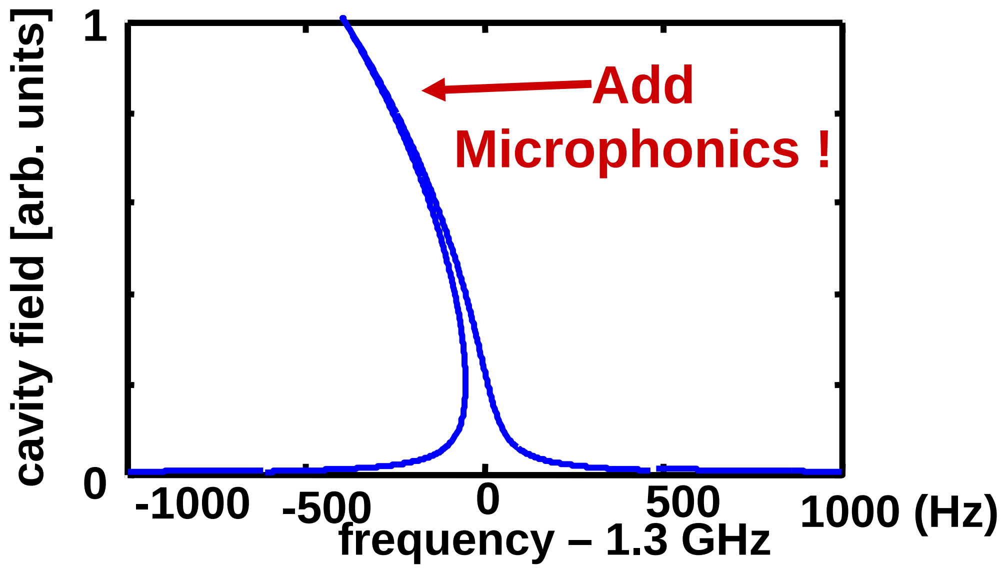
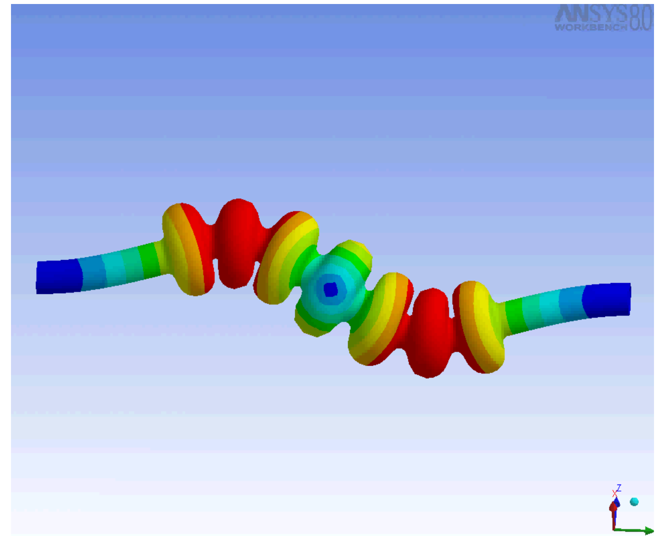


Cavity control for SC linacs (ERL & ILC)





Courtesy Matthias Liepe

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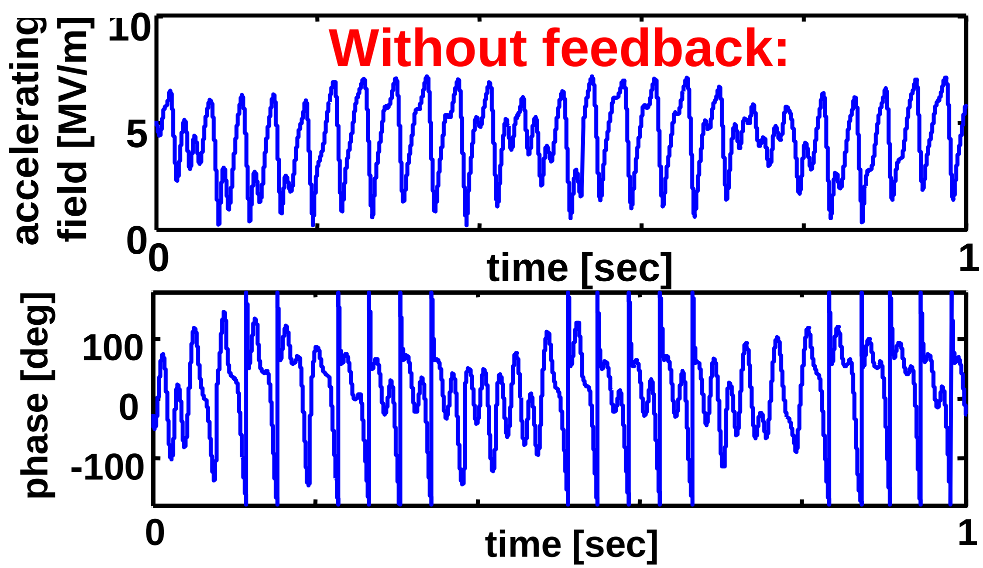
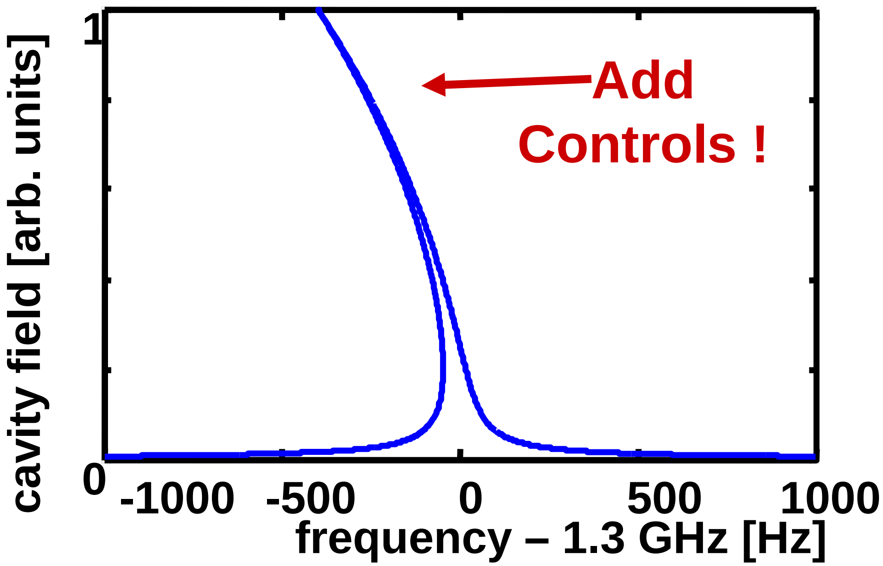
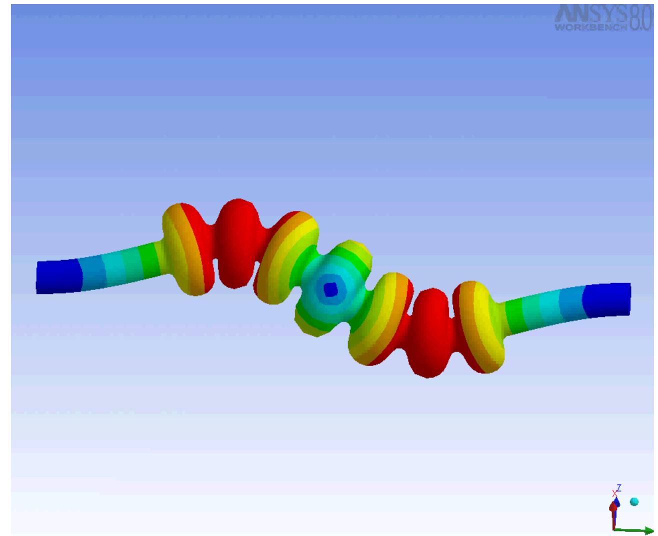
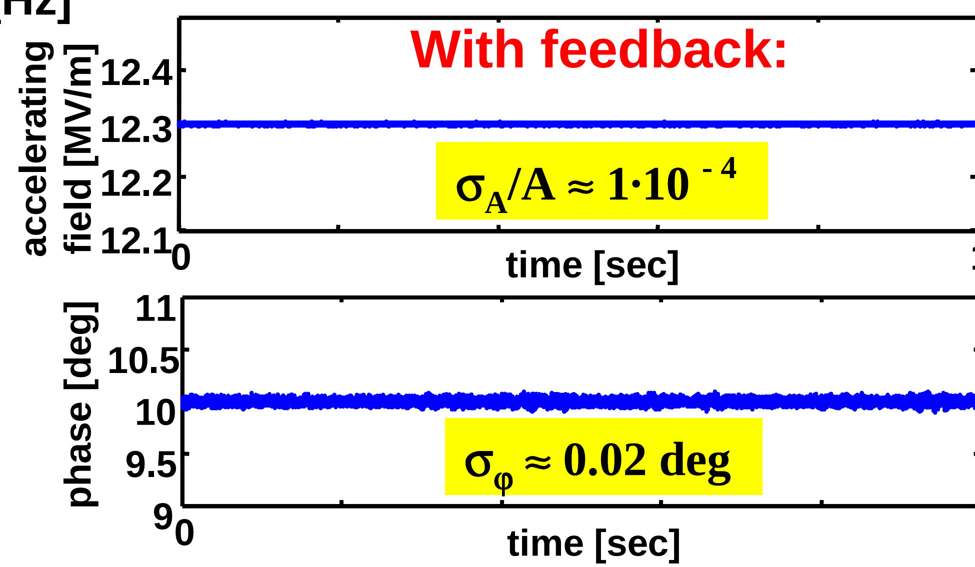


Cavity control for SC linacs (ERL & ILC)





Courtesy Matthias Liepe



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- But frequency stabilization becomes very critical.

(5) Comparison to HIGH POWER ERL-FELs

- **Superconducting RF challenges**
  - Phase and amplitude control for very narrow frequency window (10^{-8}) in the presence of microphonics – more microphonics
  - Avoid heating / Higher order mode absorption
    - more significant (denser bunch spectrum)
  - Limit cooling power – similar

- **Diagnostics**
  - Cavity field diagnostics, input coupler diagnostics - similar
  - Thermometry, HOM-power diagnostics - similar
  - Cryogenic diagnostics - similar
  - Microphonics diagnostics, e.g. Piezo electric – even more relevant