Beam dynamics for ERLs

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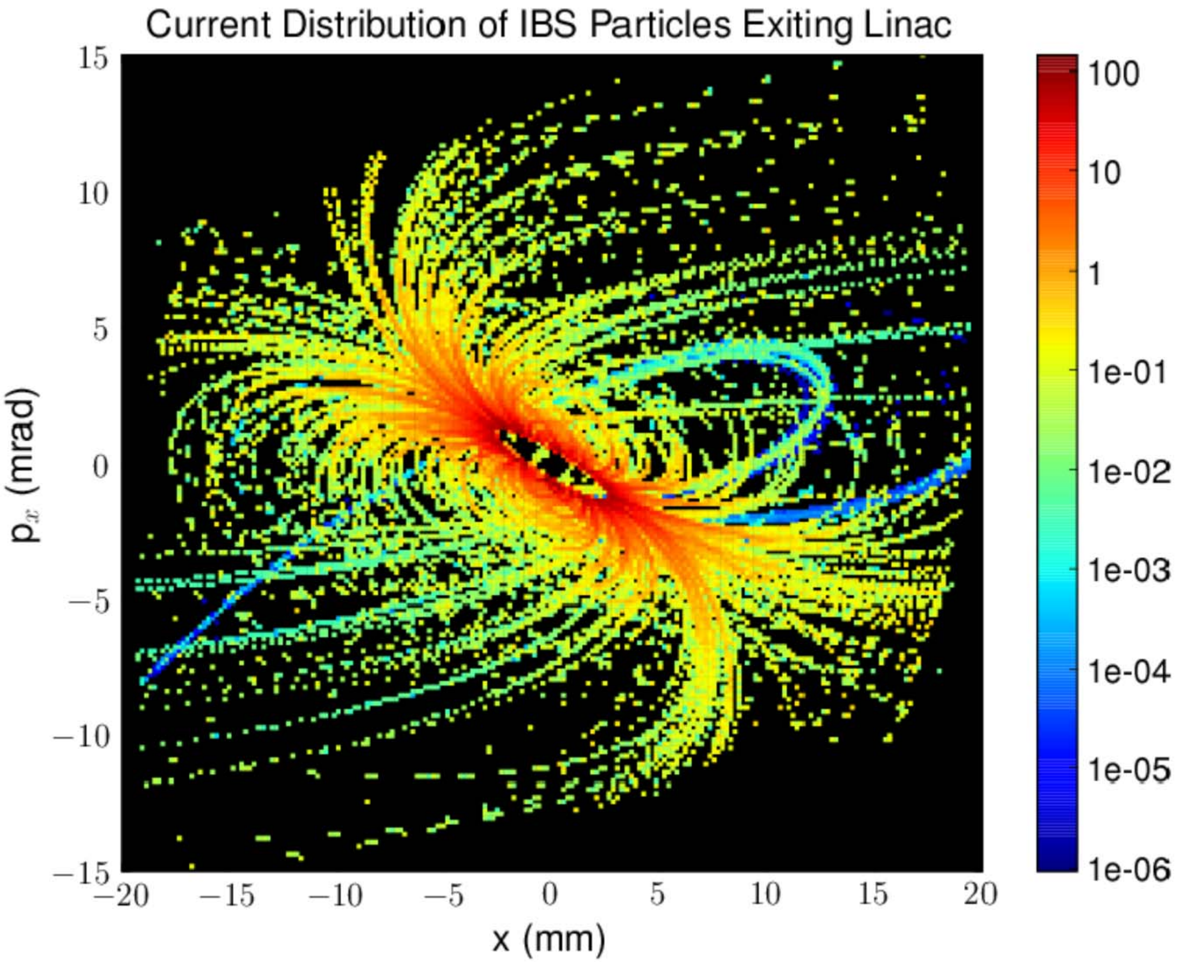
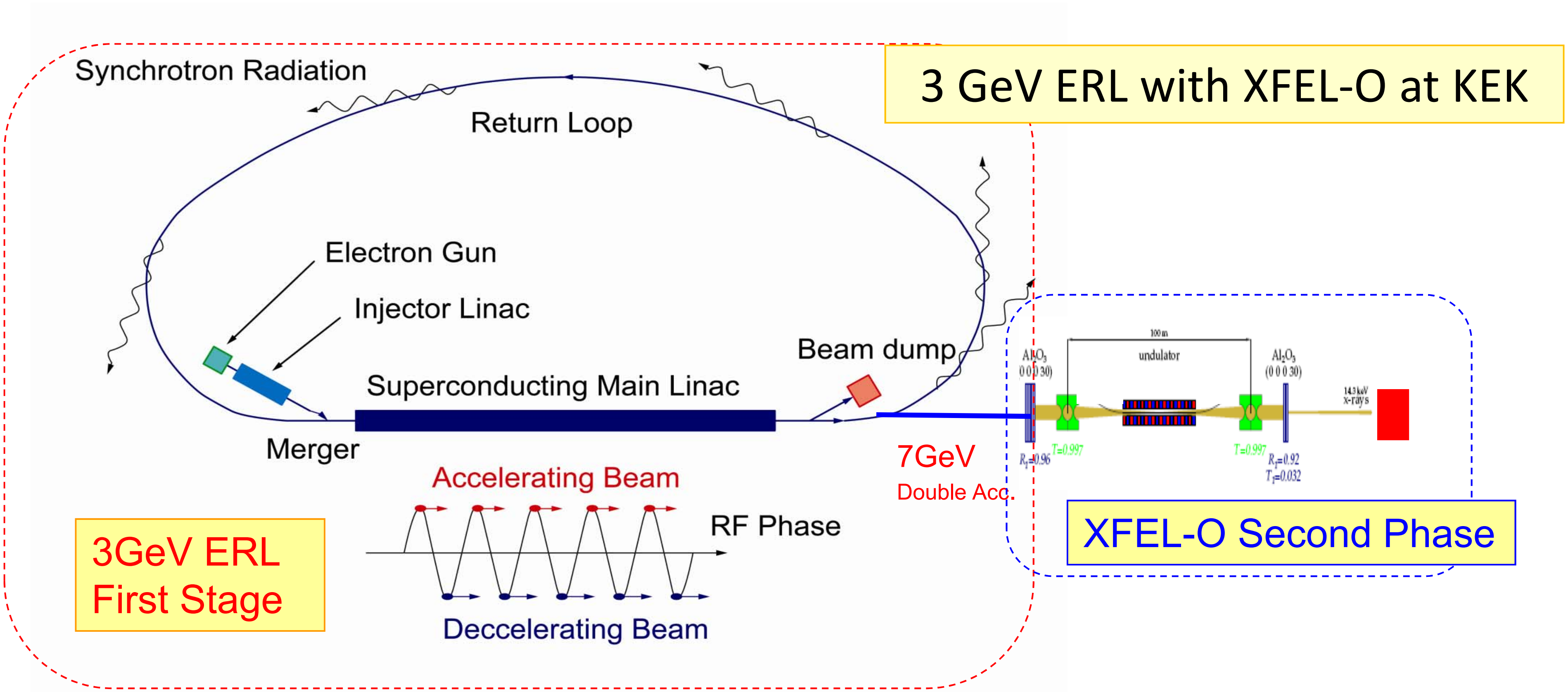


ERLs – so what ?

- Narrower and less divergent e-beams
- More mono-energetic e-beams
- Shorter pulses

} all of the above



Beam goals for Cornell ERL

	Energy recovered modes			One pass	
Modes:	(A) Flux	(B) Coherence	(C) Short-Pulse	(D) 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	100	50	fs
Relative energy spread	0.2	0.2	1	3	10^{-3}
Beam power	500	125	500	0.5	MW

Differences to more conventional beams

1. Simultaneous small emittances with large currents
2. Continuous large currents from an electron source
3. Continuous operation of a high-voltage Linac
4. Deceleration
5. Two path through the same linac

1. Linacs have small emittances, rings have large current. ERLs have both simultaneously.
   a) Large Touschek-loss current, Touschek halo, rest-gas-scattering halo
   b) IBS emittance growth
   c) Large Ion densities and related emittance growth and instabilities
2. Halo production as in linacs, but for currents as in rings.
   a) Halo from laser (reflections, phantom pulses, pedestal)
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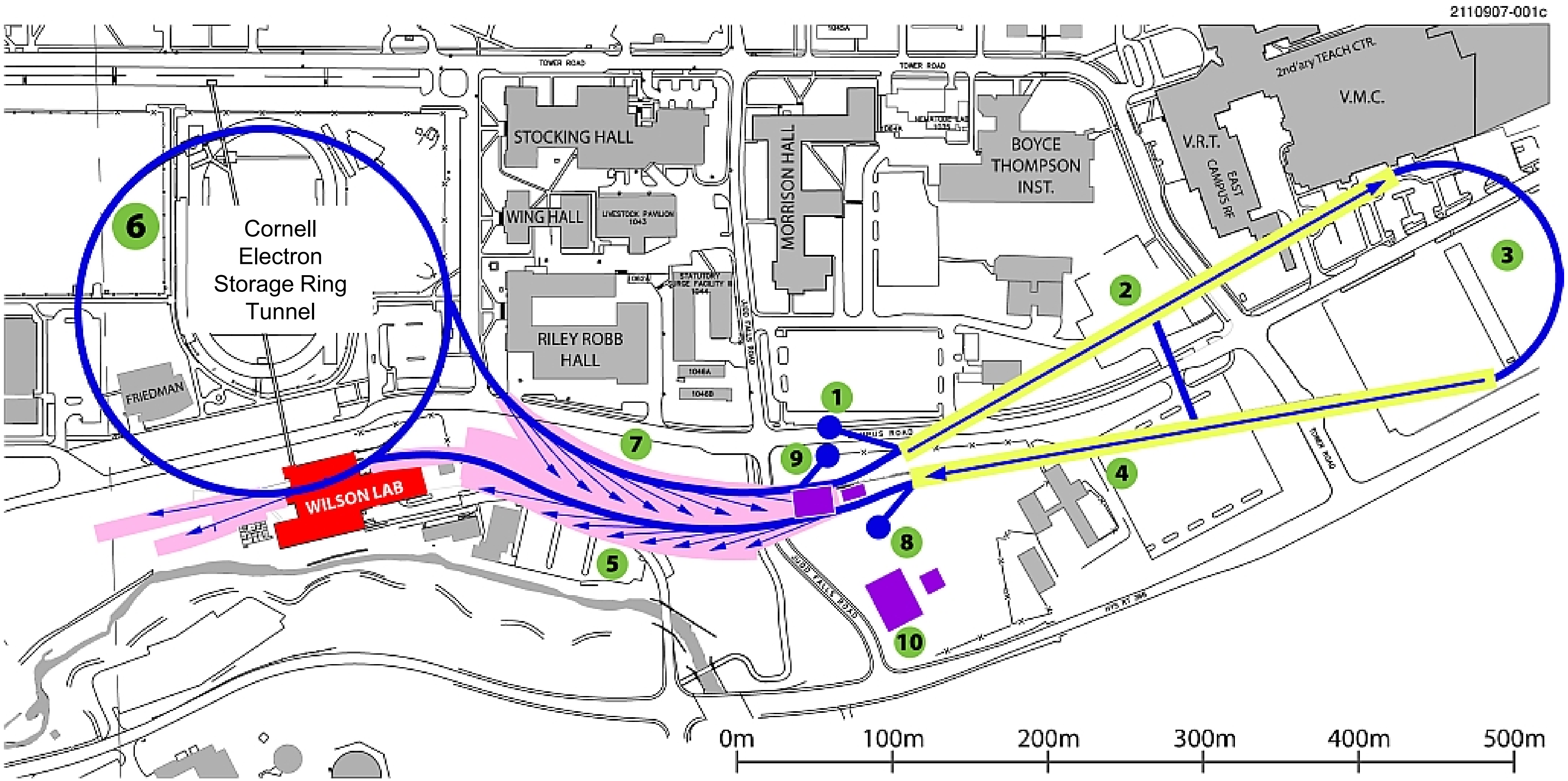
3. Rings have cw beams, linacs are often pulsed but have high voltage, ERLs have both.
   a) Halo from field emission in the Linac
   b) Halo from secondary emission in the linac due to electron loss
4. Large sensitivity to energy spread, e.g. wakes.
   a) Large energy spread after deceleration
   b) Sensitivity to linear and nonlinear time of flight
5. Rings have multiple paths, Linacs have one path through many cavities, ERLs have both.
   a) Simultaneous optics for different energies
   b) BBU and HOM heating

ERLs' more conventional beam topics

- Layout
- Optics
- Orbits and optics errors
- Space charge effects for low emittance, space charge limited beams
- Beam sizes
- Emittance Growth from ISR
- Coherent Synchrotron Radiation for short bunches
- Emittance growth from coupler kicks / cavity misalignments
- Fast and slow orbit stabilization, during startup and operation
- Timing for short pulse options
- …

Beam study examples: Cornell ERL



1: injector
2: acceleration to 2.8GeV
3: turn around with 2.8GeV
4: acceleration to 5GeV

5: to x-ray beamlines
6: return through CESR
7: further x-ray beamlines

2: deceleration to 2.2GeV
3: turn around with 2.2GeV
8: dump at 10MeV

Find suitable radii and numbers of bends For General Beam Transport

A) Radius needs to be achievable with reasonable fields: $0.9\mathrm{T}\,\frac{E}{2.5\mathrm{GeV}}\,\frac{9\mathrm{m}}{R}$

B) Radiative effects in the commissioning return loop:

1) Power deposition per length of bend: $1.3\,\frac{\mathrm{kW}}{\mathrm{m}}\,\frac{I}{200\mathrm{mA}}\left(\frac{E}{2.5\mathrm{GeV}}\right)^4\left(\frac{9\mathrm{m}}{R}\right)^2$

2) Power deposition per area $31\,\frac{\mathrm{W}}{\mathrm{mm}^2}\,\frac{I}{200\mathrm{mA}}\left(\frac{E}{2.5\mathrm{GeV}}\right)^{9/2}\left(\frac{9\mathrm{m}}{R}\right)^2\left(\frac{30\mathrm{m}}{\beta y}\right)^{1/2}\left(\frac{0.3\mu\mathrm{m}}{\varepsilon ny}\right)^{1/2}$

1) Resulting energy loss: $0.19\mathrm{MeV}\,\frac{\theta}{\pi}\left(\frac{E}{2.5\mathrm{GeV}}\right)^4\frac{9\mathrm{m}}{\mathrm{R}}$

2) Incoherent-radiation emittance growth: $0.007\,\mu\mathrm{m}\left(\frac{\theta}{\pi}\right)^4\left(\frac{10}{N}\right)^3\left(\frac{E}{2.5\mathrm{GeV}}\right)^6\frac{9\mathrm{m}}{R}$

3) Incoherent-radiation energy spread: $0.1\cdot 10^{-4}\left(\frac{\theta}{\pi}\right)^{1/2}\left(\frac{E}{2.5\mathrm{GeV}}\right)^{5/2}\frac{9\mathrm{m}}{R}$

4) Incoherent-radiation energy spread: $0.3\%\left(\frac{\theta}{\pi}\right)^{1/2}\frac{10\mathrm{MeV}}{E_{\mathrm{dump}}}\left(\frac{E}{2.5\mathrm{GeV}}\right)^{7/2}\frac{9\mathrm{m}}{R}$

5) Coherent-radiation energy loss: $-119\mathrm{keV}\left(\frac{Q}{77\,pC}\right)^3\left(\frac{\rho}{28\,m}\right)^{1/3}\left(\frac{2\,ps}{\sigma_t}\right)^{4/3}\left(\frac{\theta}{2.6\,\pi}\right)$

1a) Touschek-loss currents and Touschek halo

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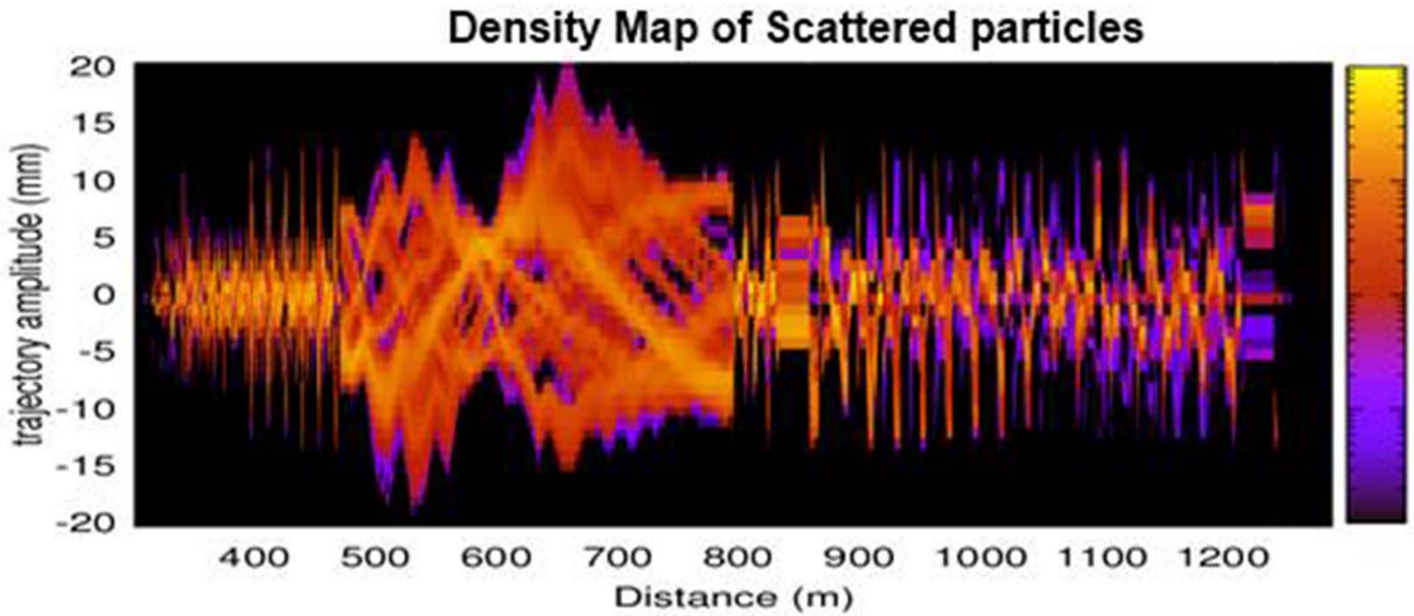
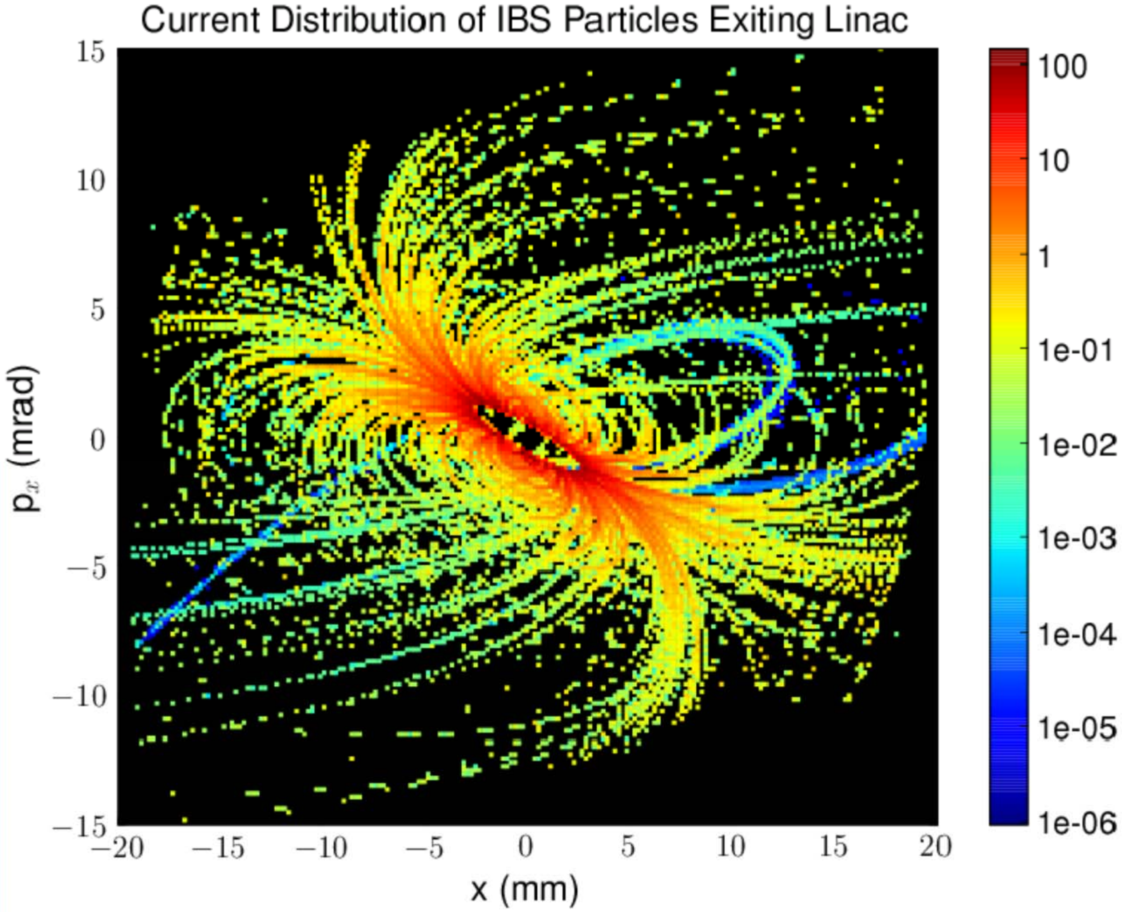
Creation of Touschek particles for linac beams and placement of collimators



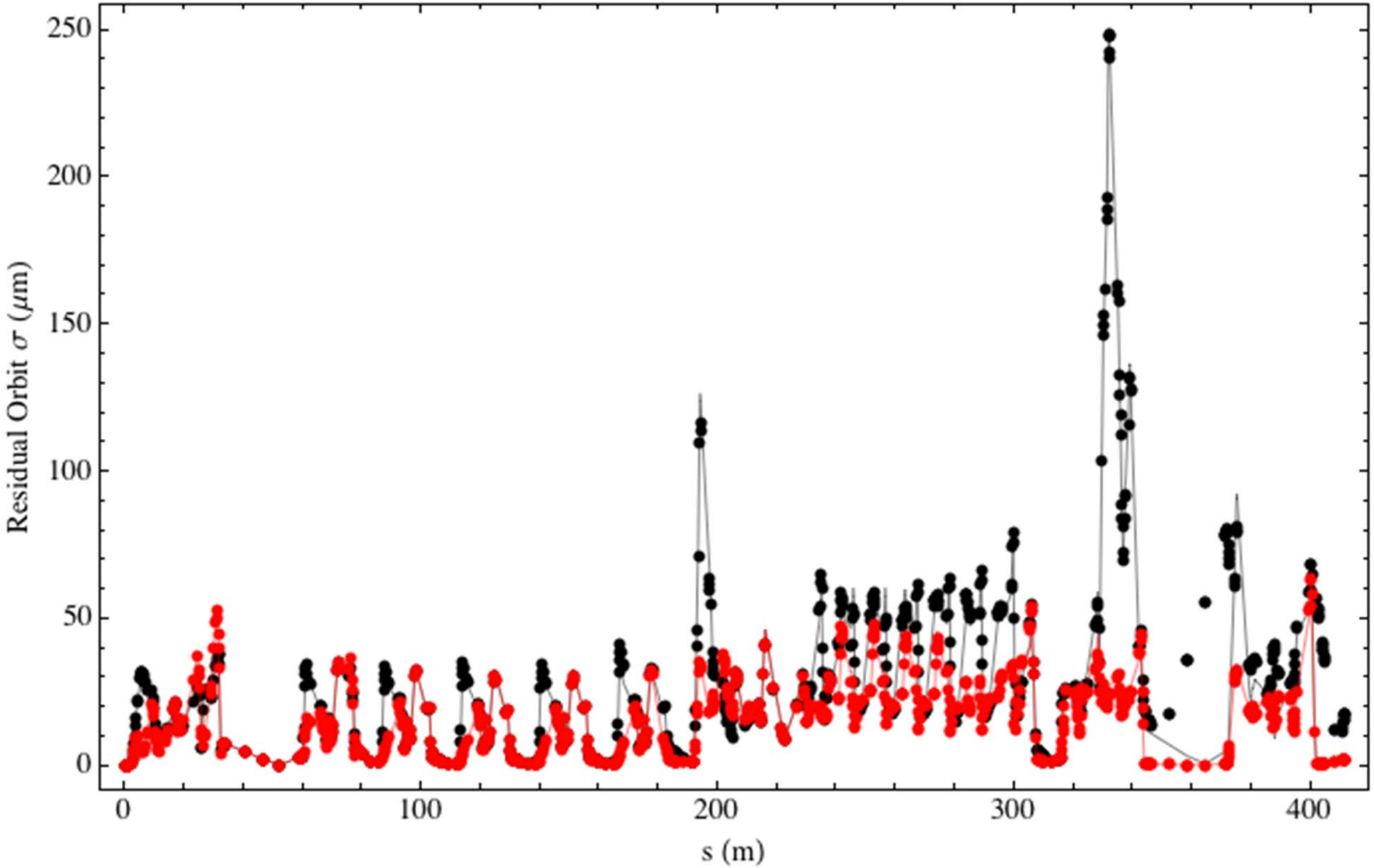
1. **Once one knows the creation and propagation of Touschek particles, one can optimize the placement of collimators.**
2. **Choice: No collimator should take more than 1nA**
3. **Choice: No section in the user region should take significantly more than 3pA/m**
4. **Once can then simulate the x-ray and neutron background in collimation regions and design effective shielding for personnel and electronics.**

Touschek calculations for linac beams

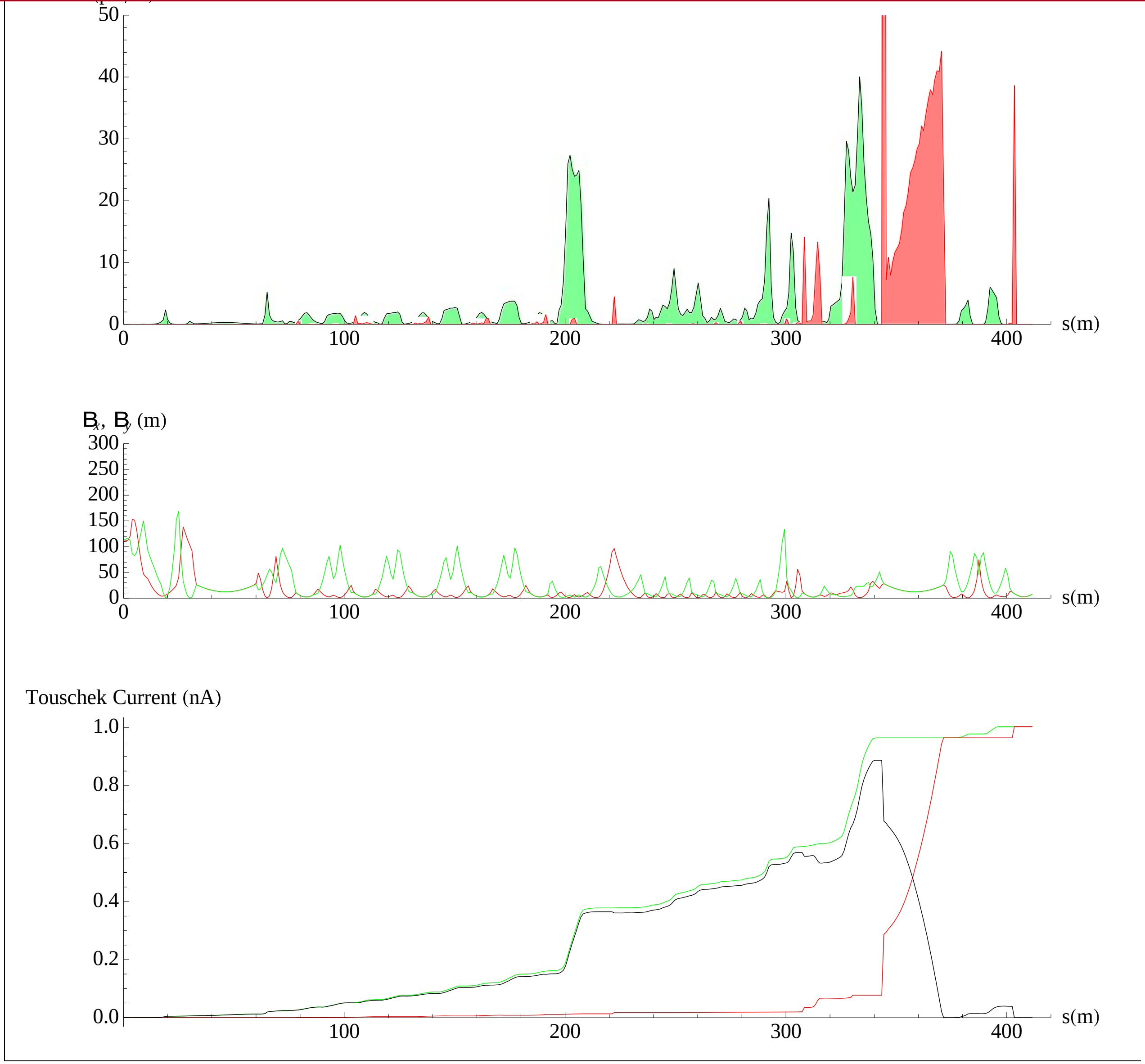


- **Halo distribution from intra beam scattering after deceleration**
- **The distribution can be computed along the ERL and be used for collimator placement**

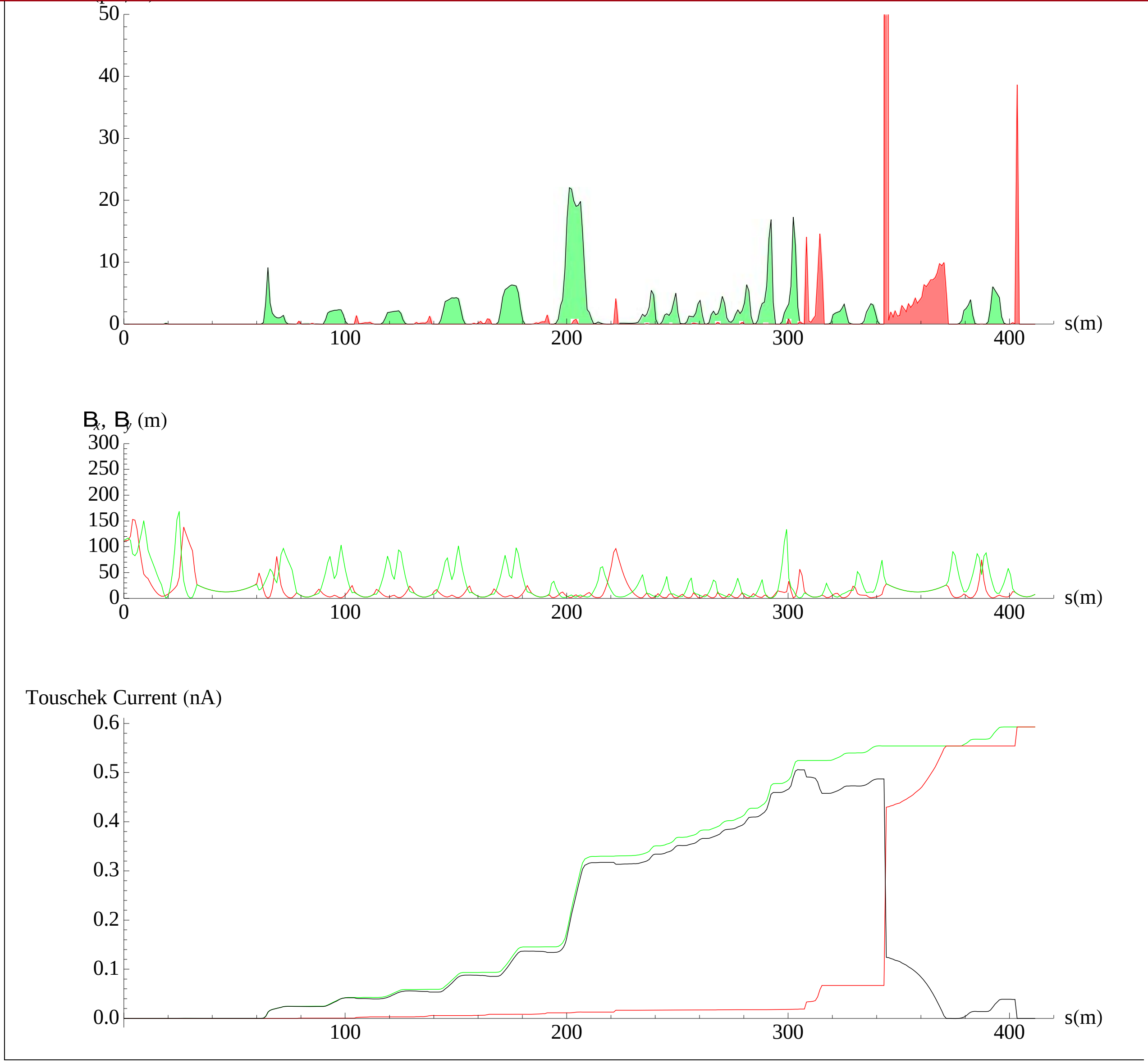
Optimize orbit correction scheme !



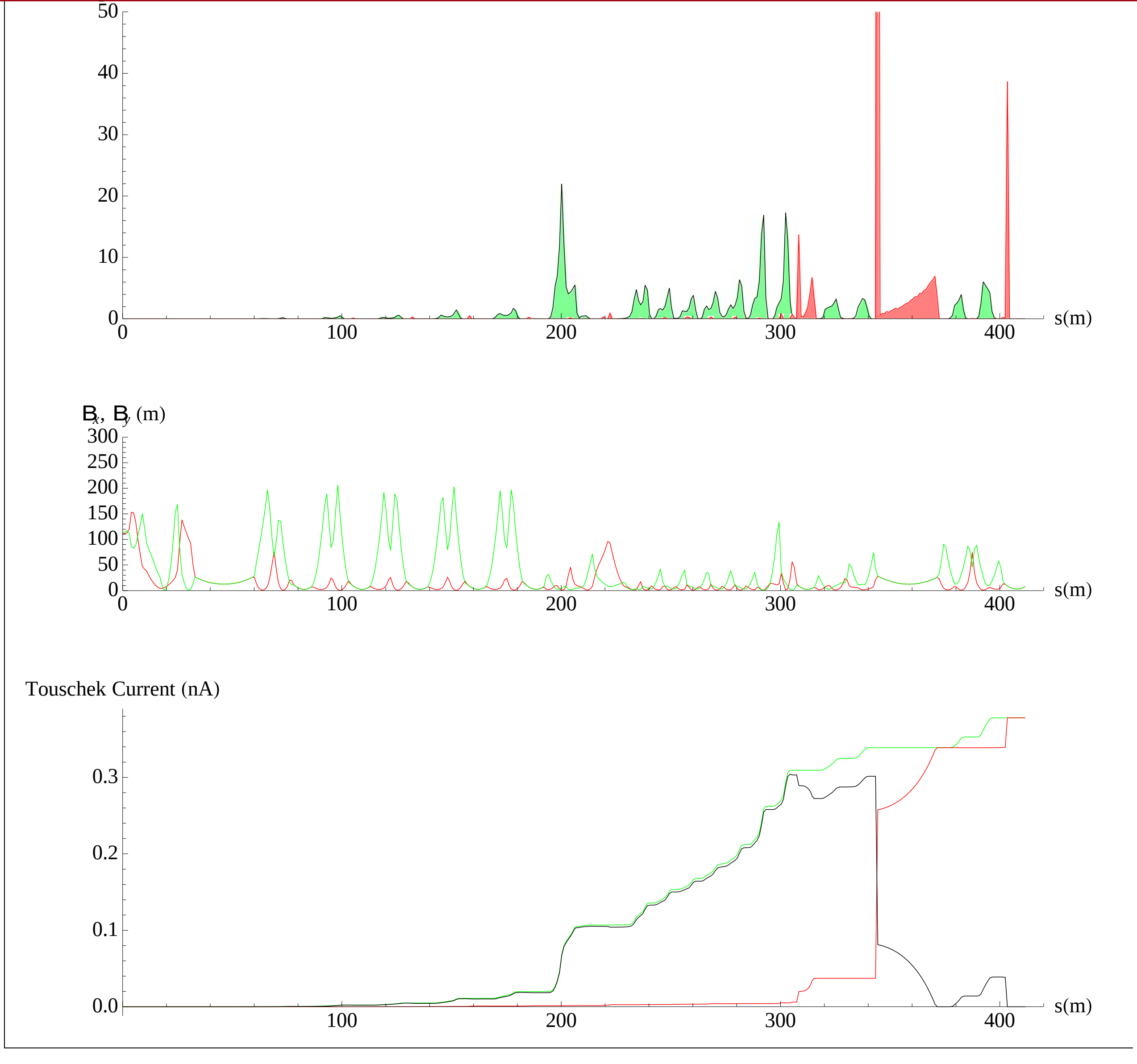
Touschek scattering - 1st optics



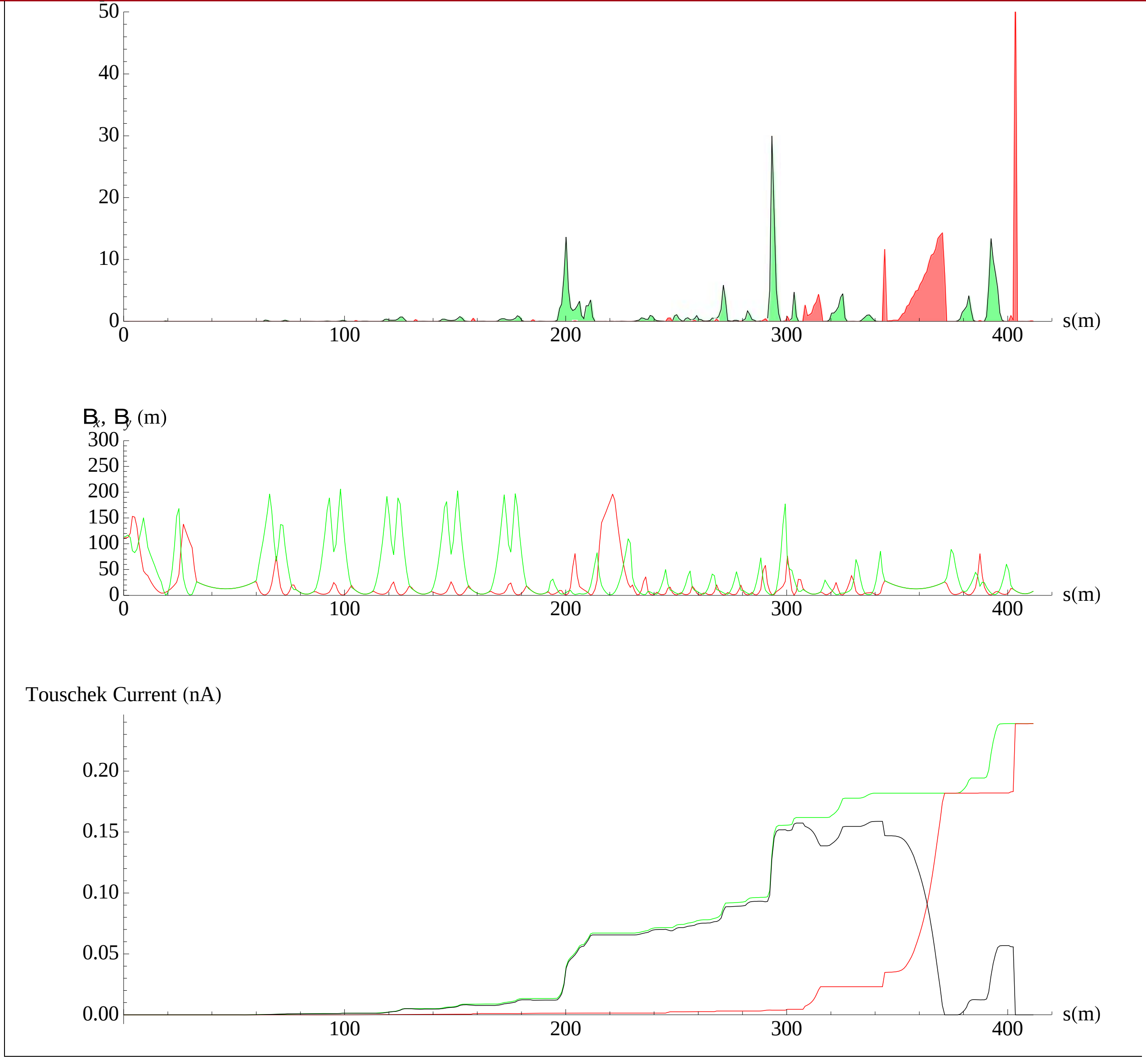
Touschek scattering – 2nd optics



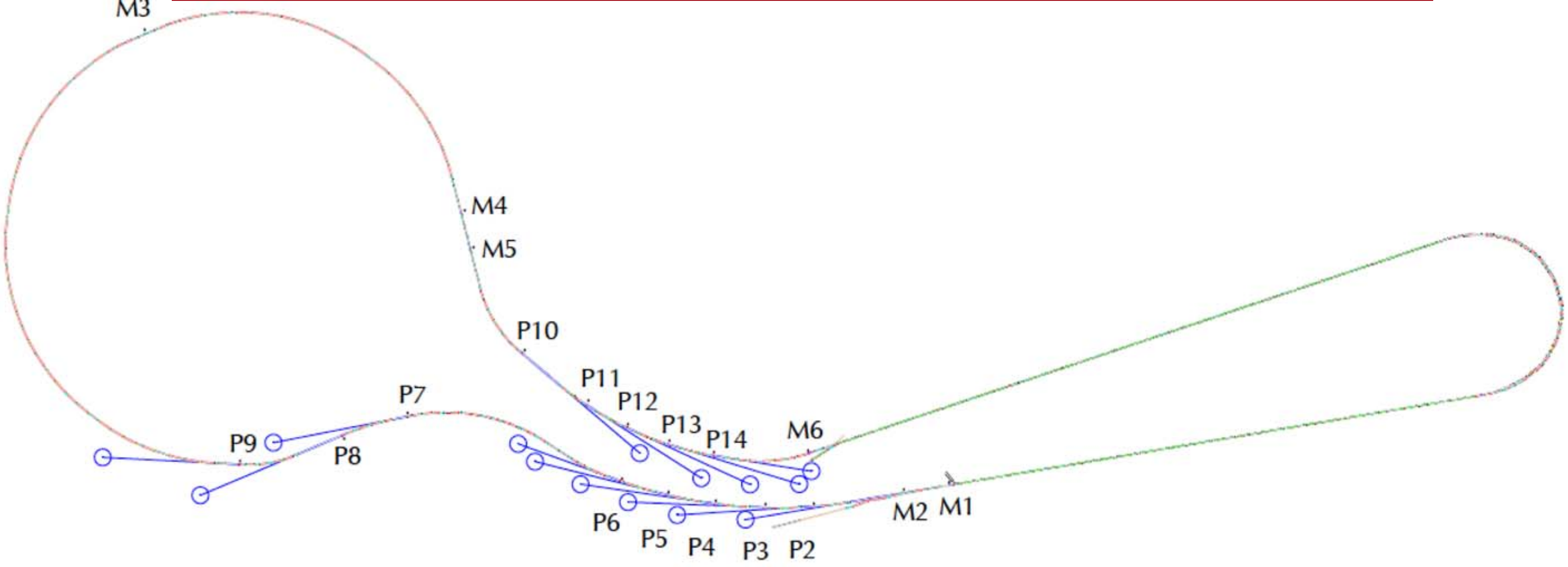
Touschek scattering - 3rd optics



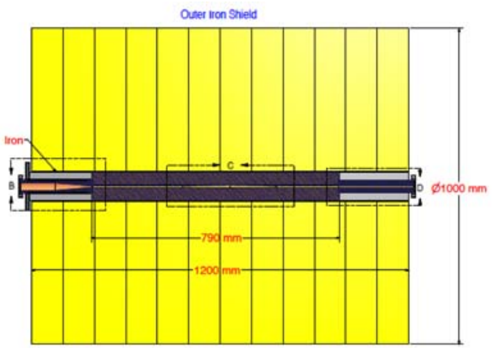
Touschek scattering – 4th optics



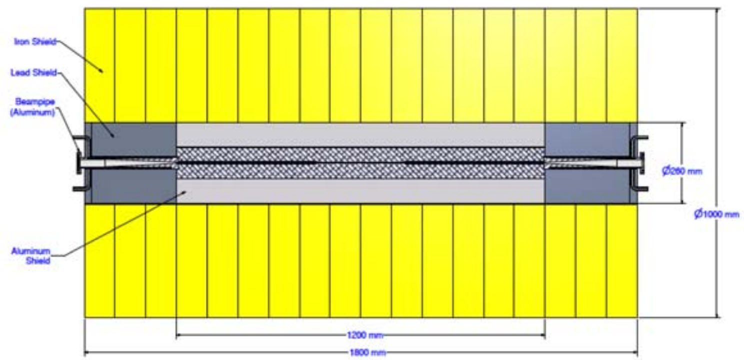
Halo Collimation



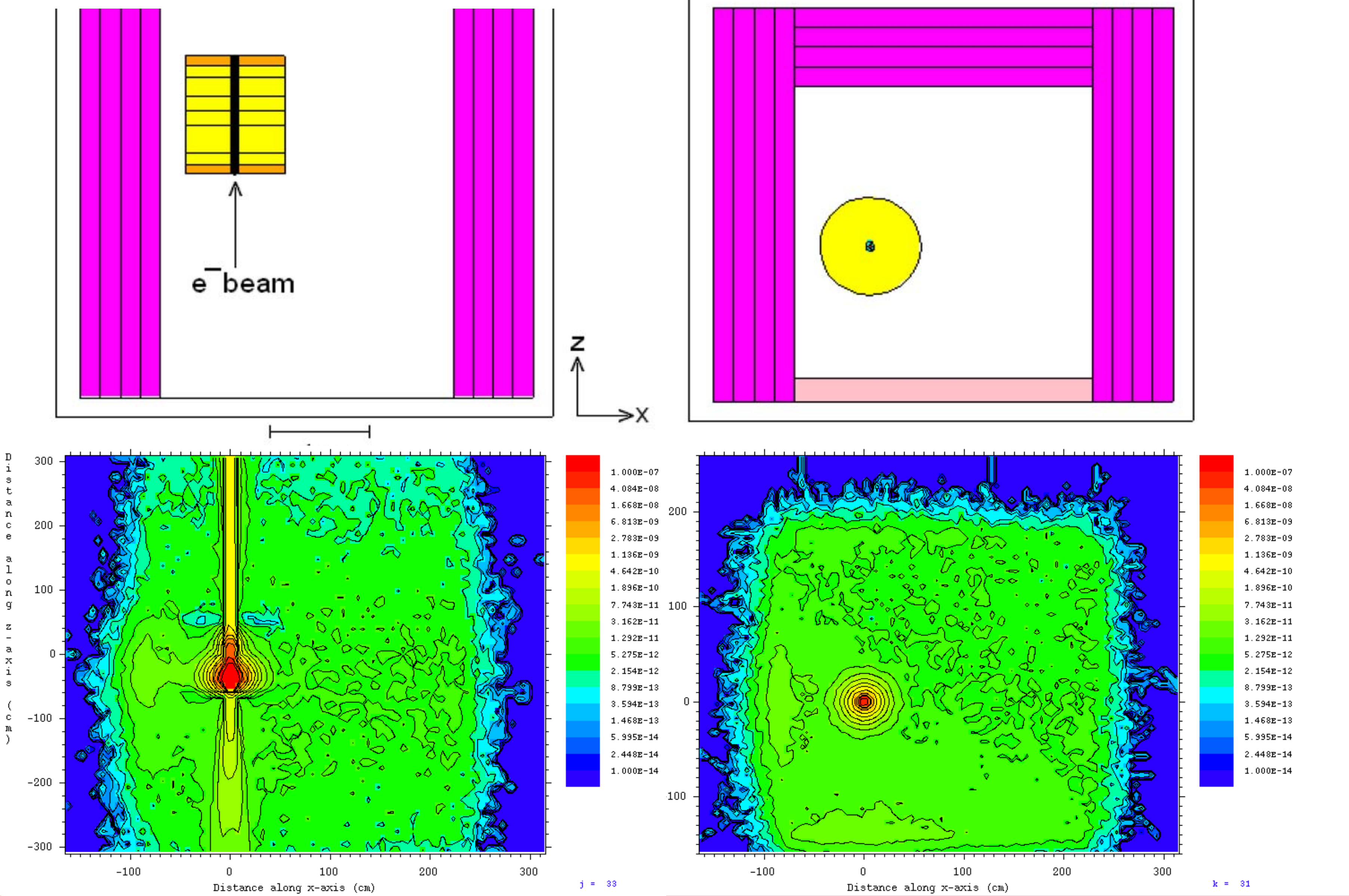
Protector



Collimator



X-Ray Dose Rates for Shielding Design



1b) IBS emittance growth

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5. Two path through the same linac

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   b) IBS emittance growth

In one path, for the Cornell ERL this growth is significantly below 8pm, but can be relevant for higher energy, and smaller real-emittance beams in ERLs.

Large Ion Densities: (A) emittance growth

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Avoiding beam growth during acceleration i.e. by Ion focusing

- Ion are quickly produced due to high beam density

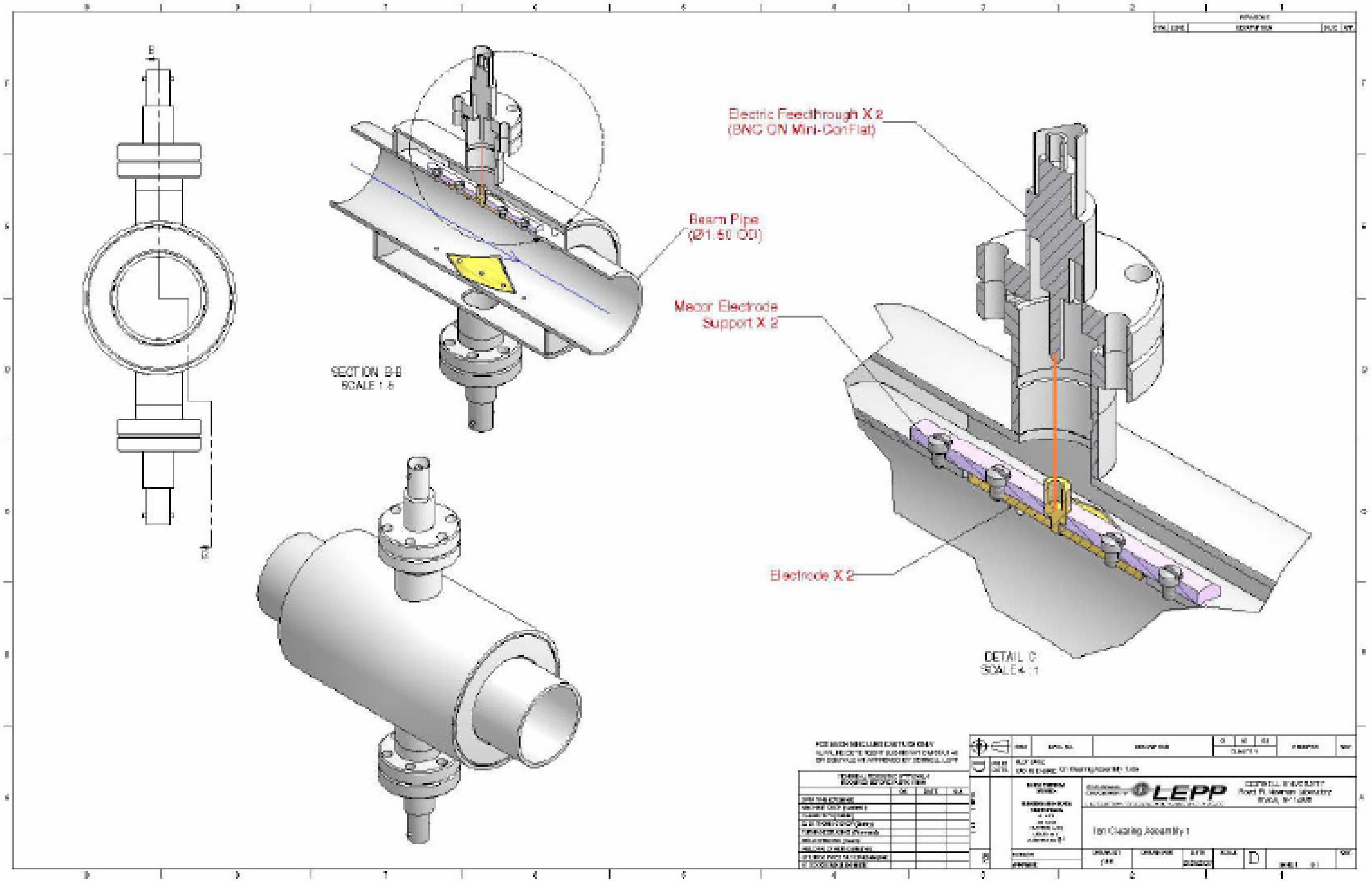
Ion	σ_{col}, 10MeV	σ_{col}, 5GeV	τ_{col}, 5GeV
H_2	$2.0 \cdot 10^{-23}\mathrm{m}^2$	$3.1 \cdot 10^{-23}\mathrm{m}^2$	5.6s
CO	$1.0 \cdot 10^{-22}\mathrm{m}^2$	$1.9 \cdot 10^{-22}\mathrm{m}^2$	92.7s
CH_4	$1.2 \cdot 10^{-22}\mathrm{m}^2$	$2.0 \cdot 10^{-22}\mathrm{m}^2$	85.2s

- 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.

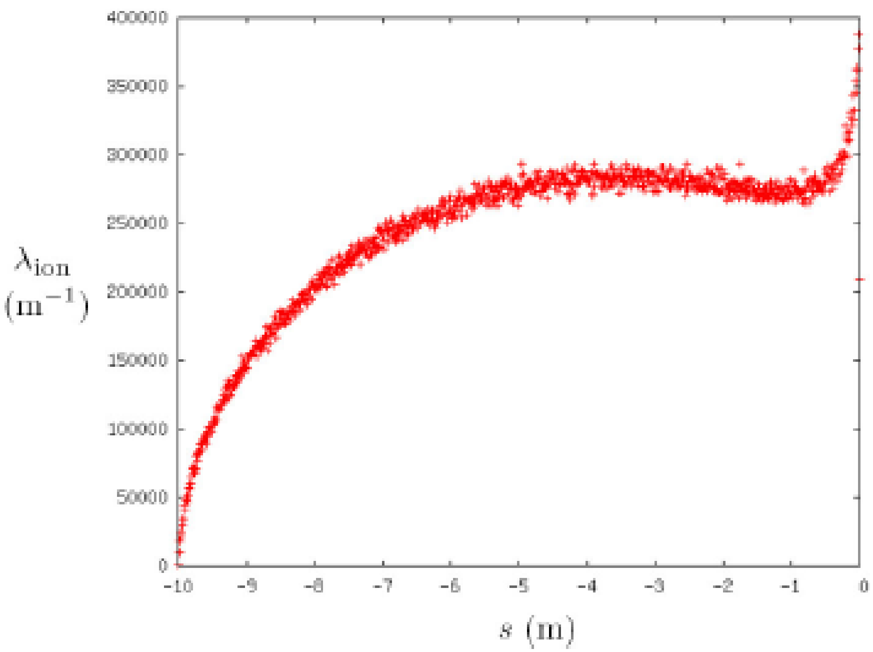
  But remnant ion density before clearing can still cause emittance growth.

Ion - clearing electrodes

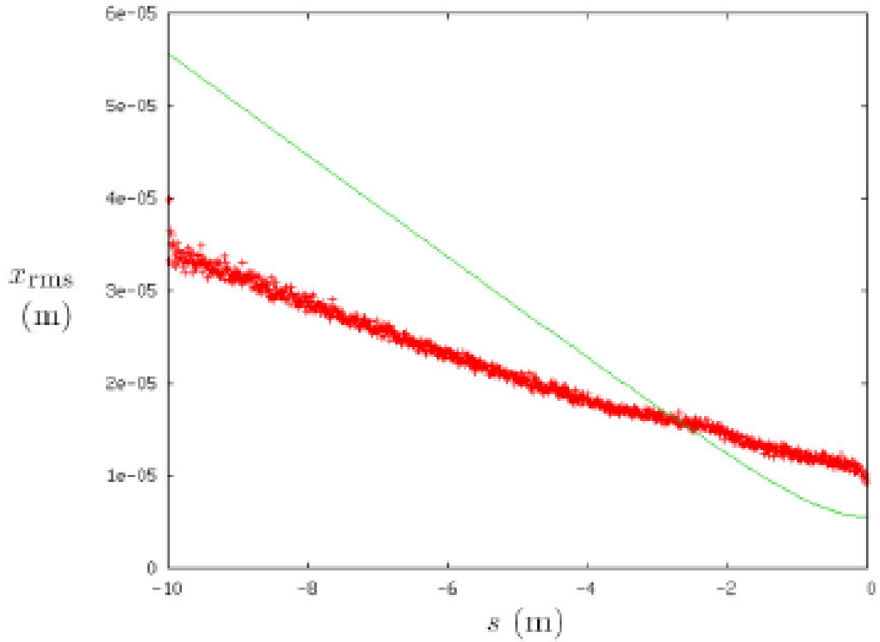


Equilibrium ion distributions

Plot of ion line density as a function of s:



Transverse distribution: rms values for ions and beam



- Longitudinal ion forces proportional to Twiss-a so ions created near minimum move slowly
- All ions pass through region near electrodes

⇒ sharp ion density peak near beam waist

- Ions oscillate through beam

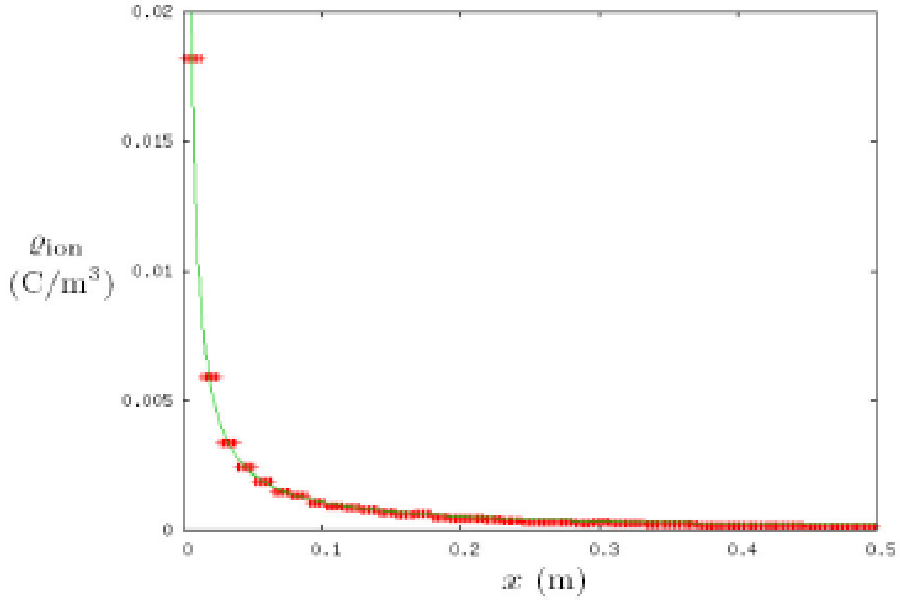
⇒ ion rms initially smaller than beam rms

- Beam contracts, ion action remains constant

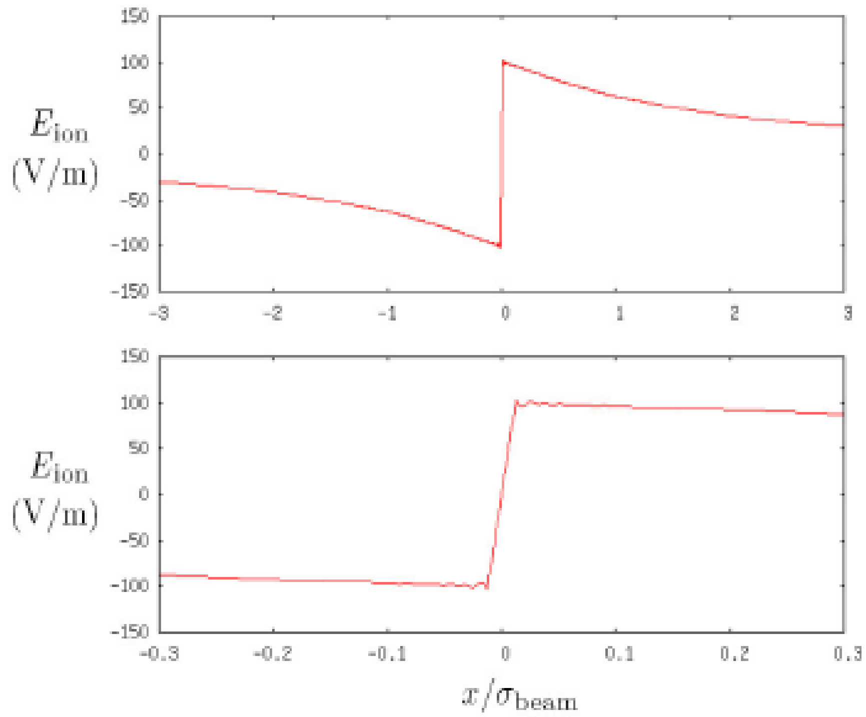
⇒ ion rms near electrode larger than beam rms

Forces from the ion distribution

Transverse charge density distribution:



Transverse ion electric field:



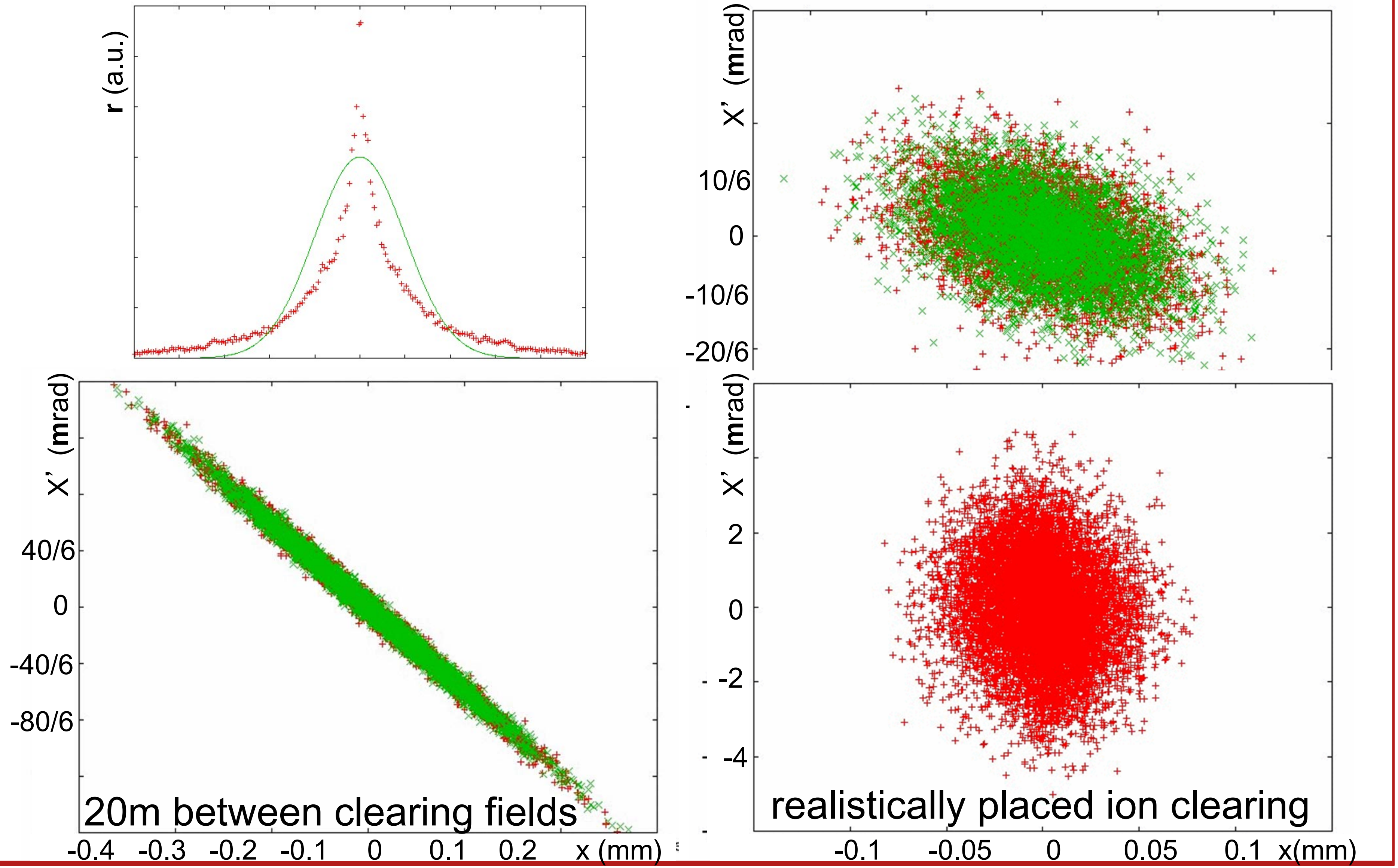
- Ions with all oscillation amplitudes contribute to center density

⇒ Ion charge density has 1/r peak at center of beam

- repulsive ion on ion forces are nevertheless many orders of magnitude weaker than electron on ion forces

- Ion field approaches constant for r → 0
- Ion on electron fields in center damage beam

Ions in an ERL beam



Large Ion Densities: (B) Fast ion instability

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Fast Ion Instability growth along the length of a bunch train, however the ERL's beam bunch train is infinitely long.

While growth rates are in the order of microseconds, times to clear any individual ion is on the order of ms.

This problem is still under analysis.

Halo creation

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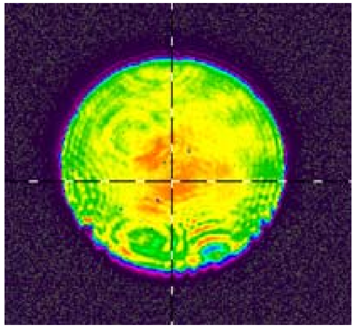
More studies are needed: experimental halos currently seem too high to be comfortabel.

Halo Generation – Many sources

Image on the cathode using normal dielectric mirror



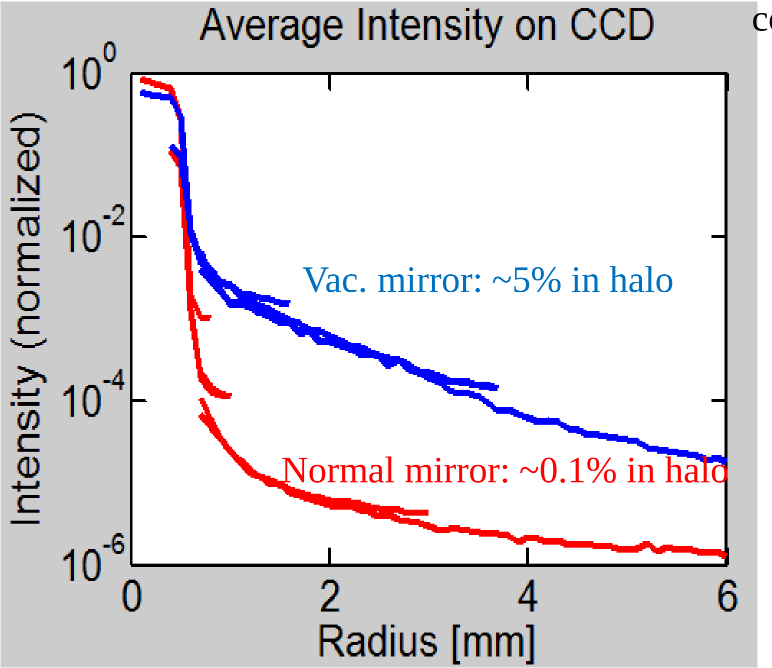
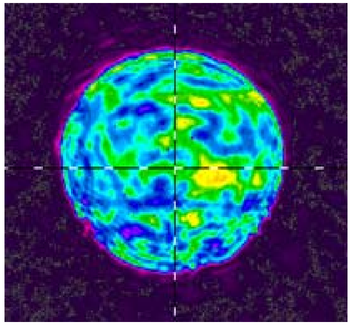


Image on the cathode using coated metal mirror



Our current laser mirror (in-vacuum) scatters ~50x more light compared to dielectric mirrors (which we cannot use). This can generate halo from the cathode, so we are having new ones made soon. Need better than 2 nm rms surface roughness

Following work by a group at DESY

Halo from emission in Linac

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As reported by Chris Mayes ERL11, Thursday plenary session: Calculation efforts are under way at DESY, FNAL, KEK, and Cornell.

Cornell computes x-ray and neutron backgrounds from Linac dark currents and in a collaboration with JLAB currently compares to measurements in CEBAF.

Sensitivity to wakes

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CSR in ERL bends

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Compensation of wakefield-driven energy spread in energy recovery linacs

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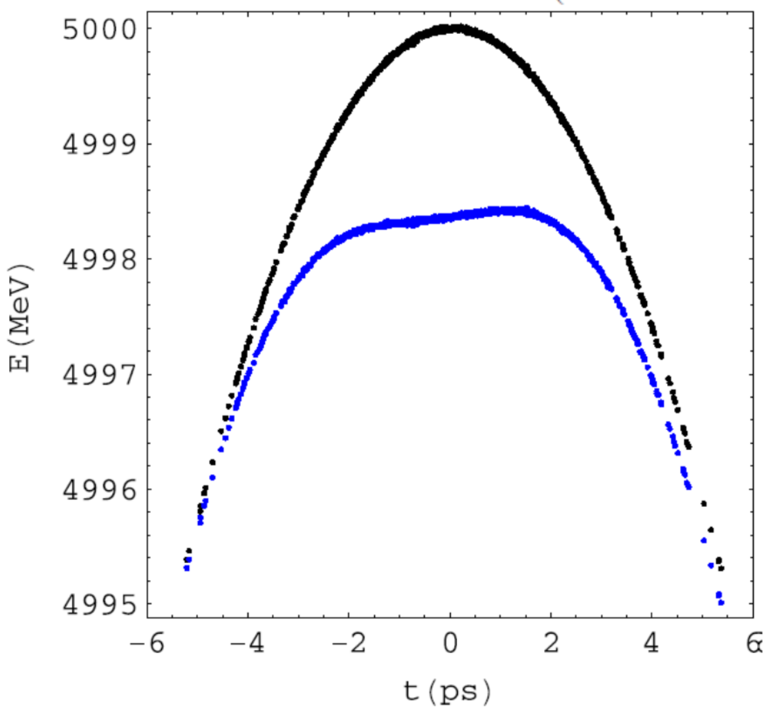


FIG. 4. (Color) Wake-induced bunch profiles at CESR. Black-top: Cosinelike correlated longitudinal phase space from accelerating on crest with a $\sigma_t = 2$ ps bunch length. Blue-bottom: Longitudinal profile after suffering half the Cornell ERL's wakefield, $\frac{W(t)}{2}$.

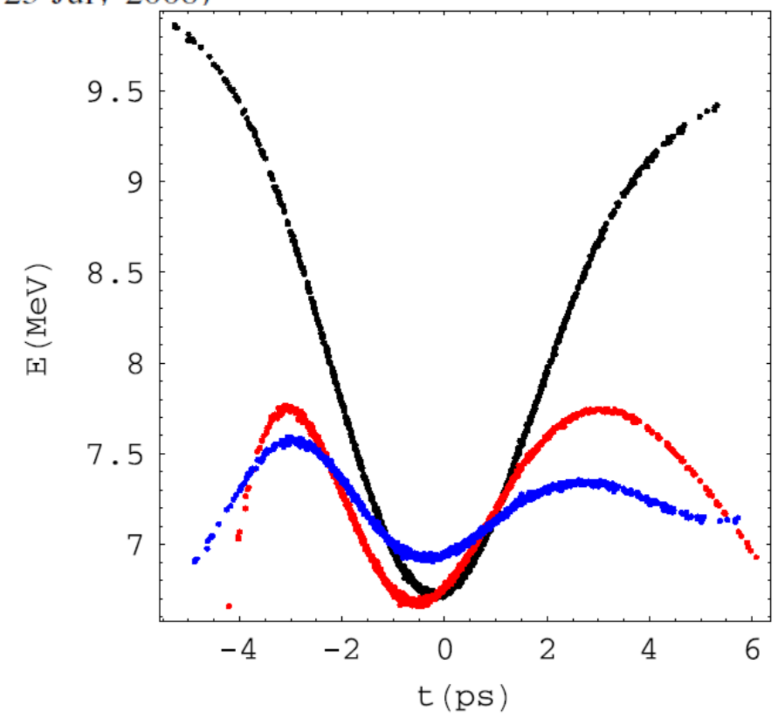
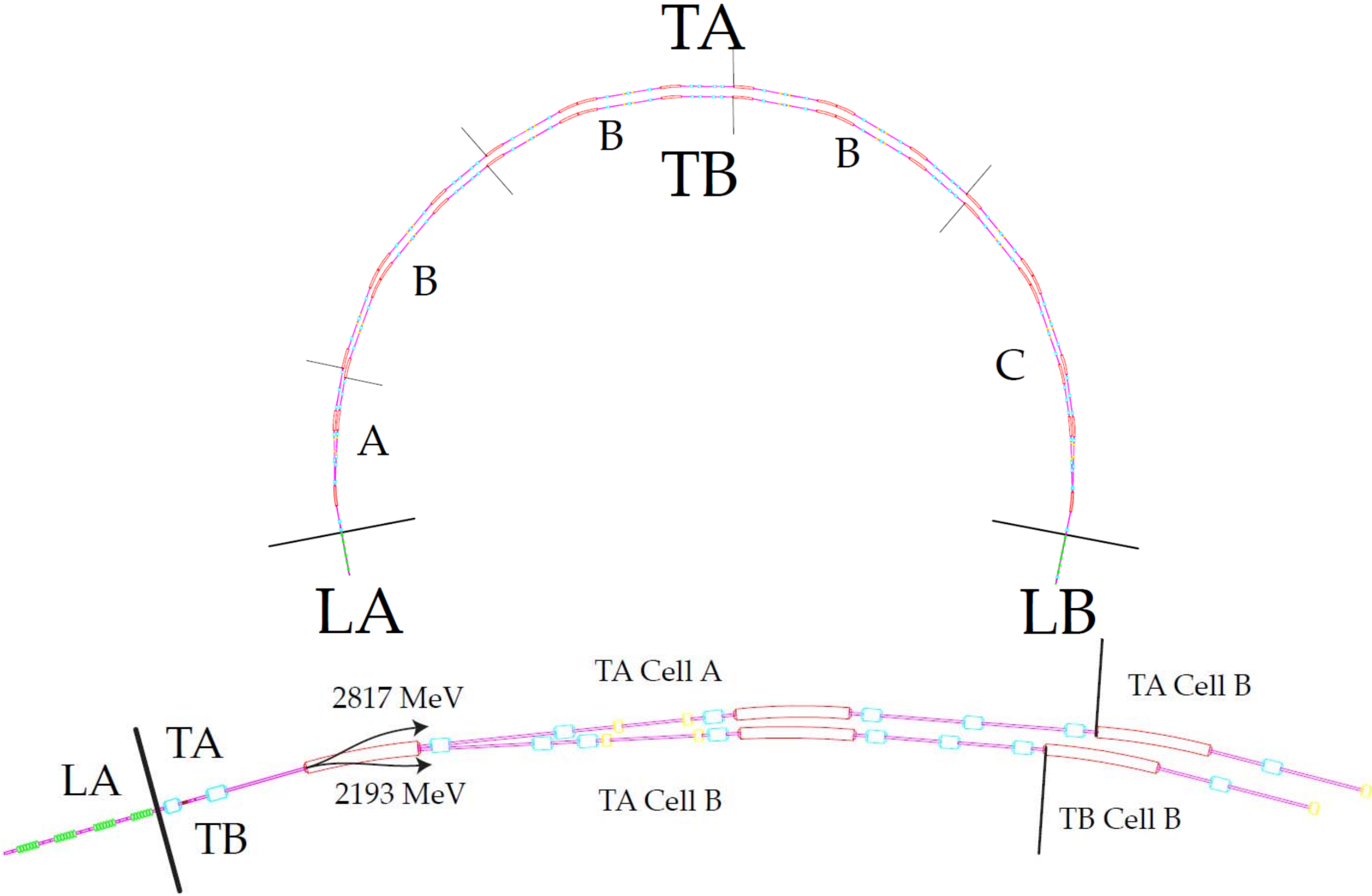


FIG. 11. (Color) Results. Black-top: Longitudinal profile at dump without wake correction. Blue-middle: Dump profile with harmonic-wake correction. Red-middle: Dump profile with nonlinear time-of-flight wake correction. Harmonic-wake correction reduces energy spread more but is less feasible than nonlinear-wake correction.

Number of Turn Around loops within Linac



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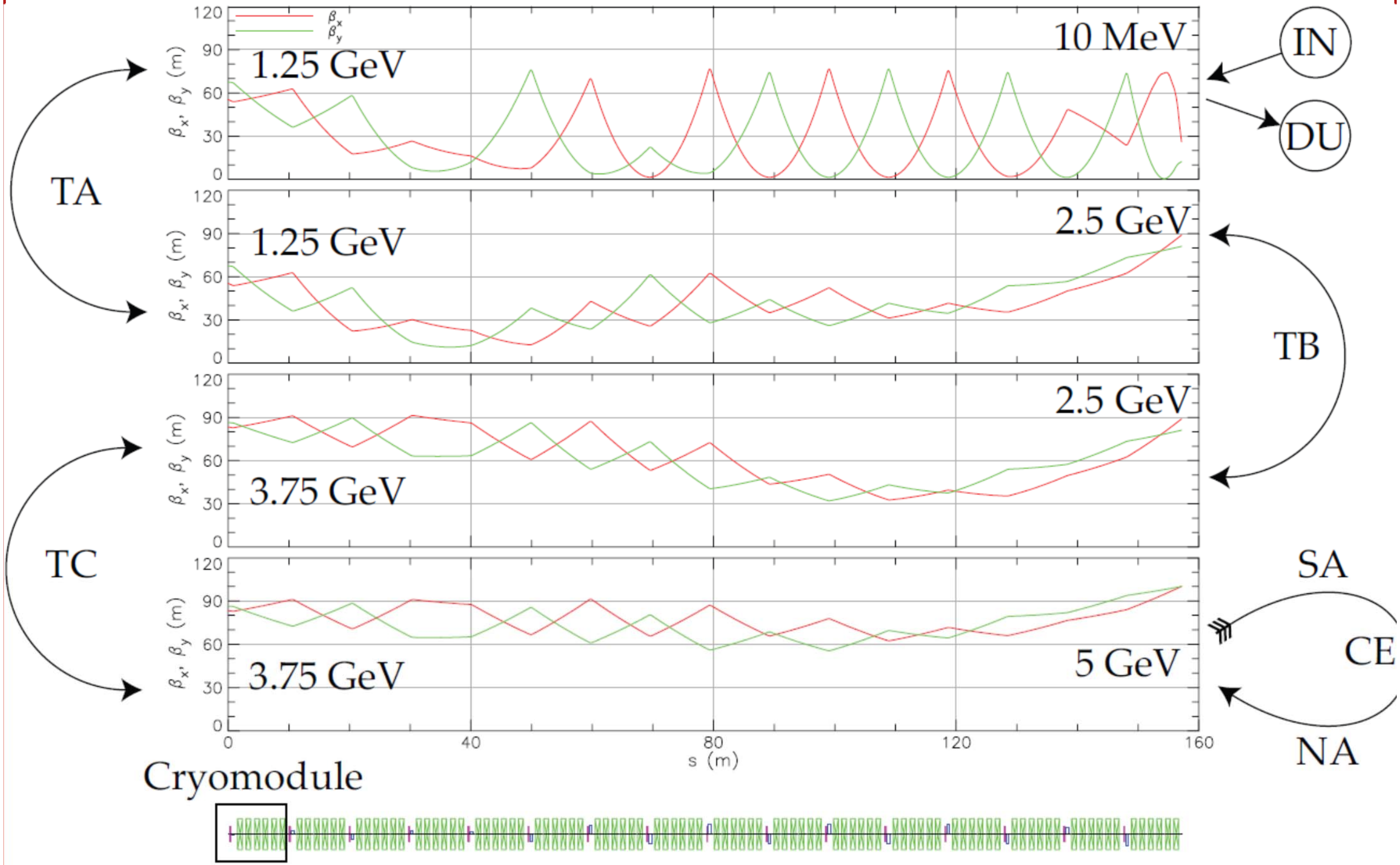
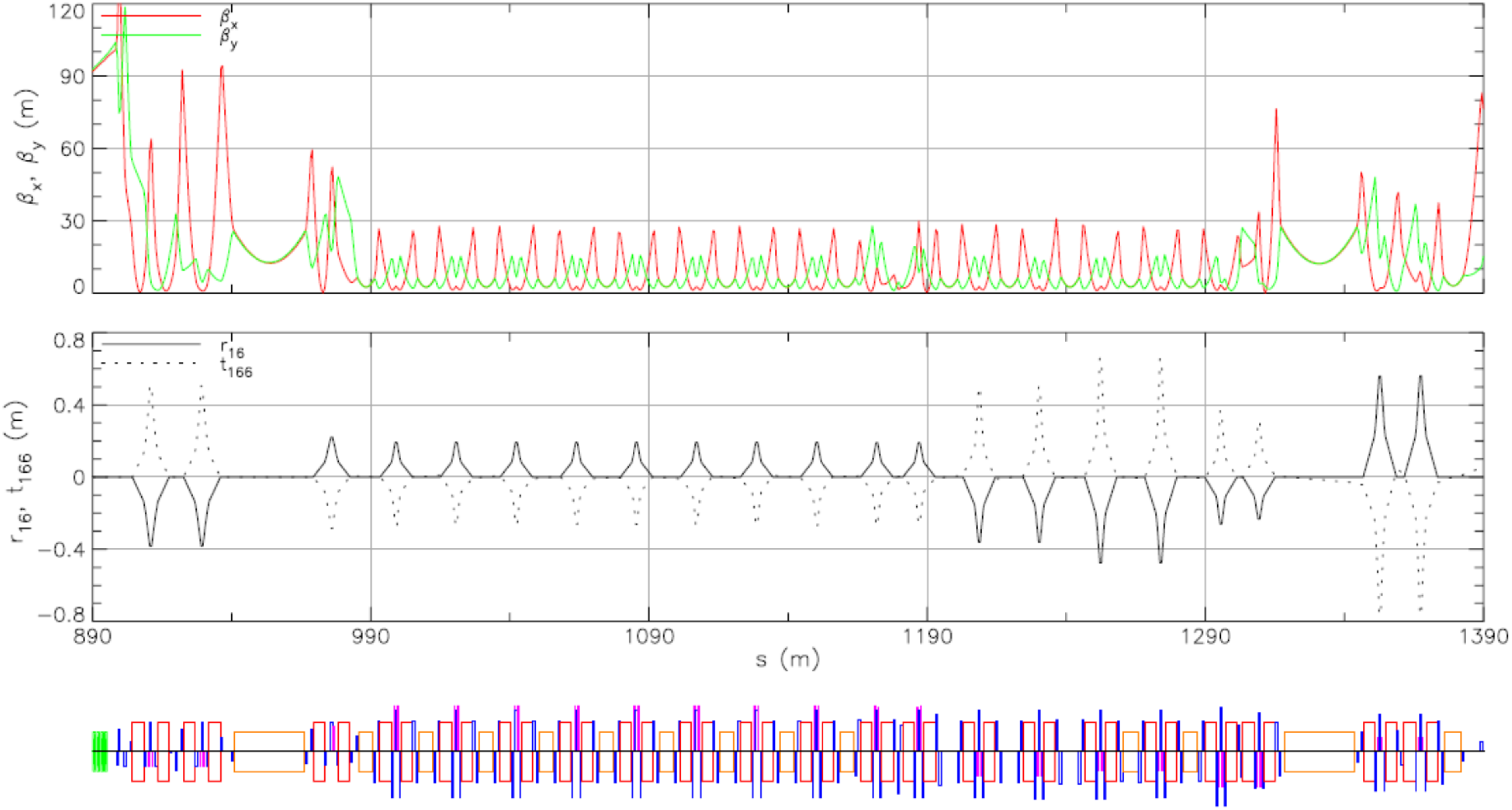
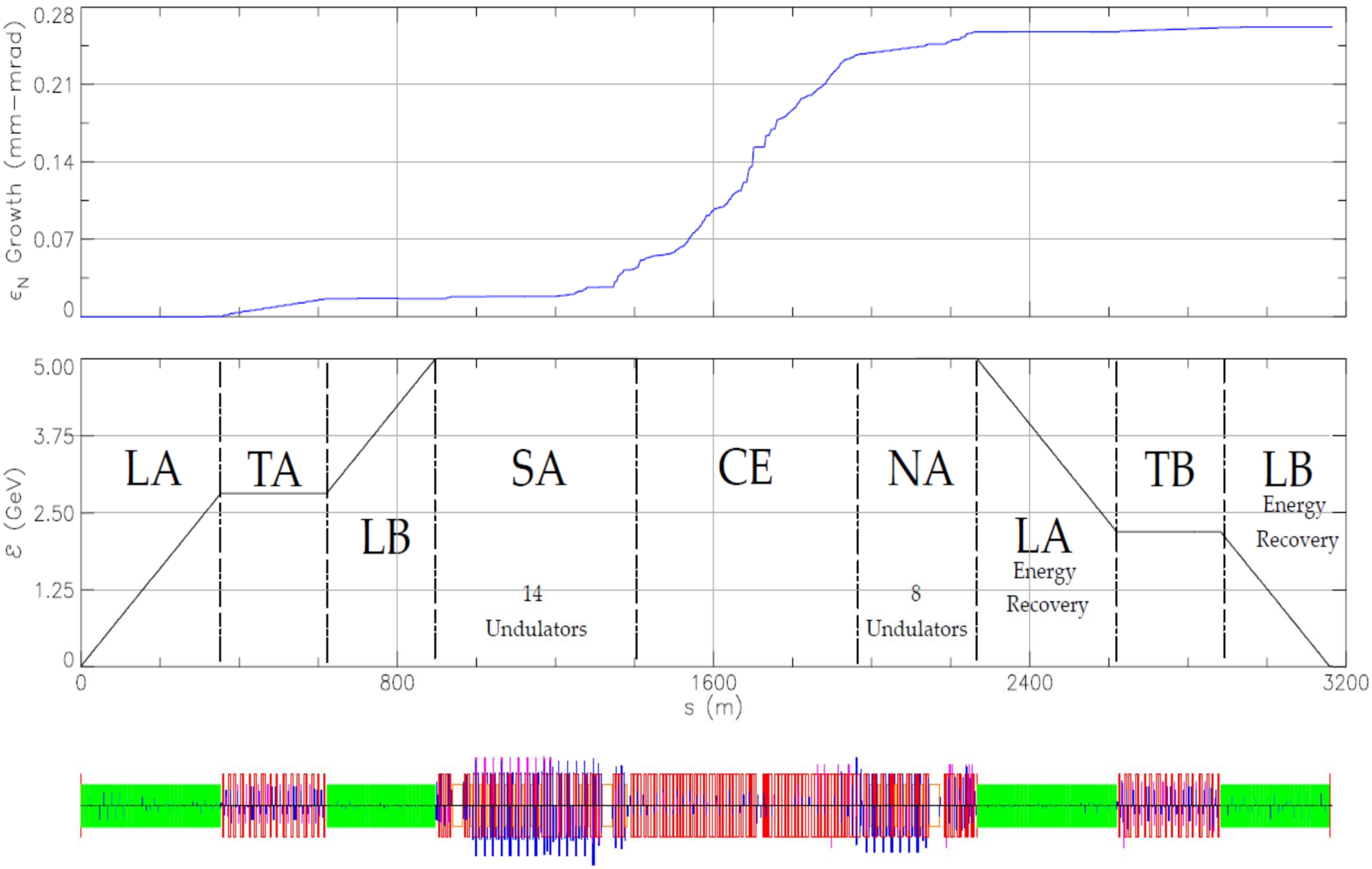
4-beam optics



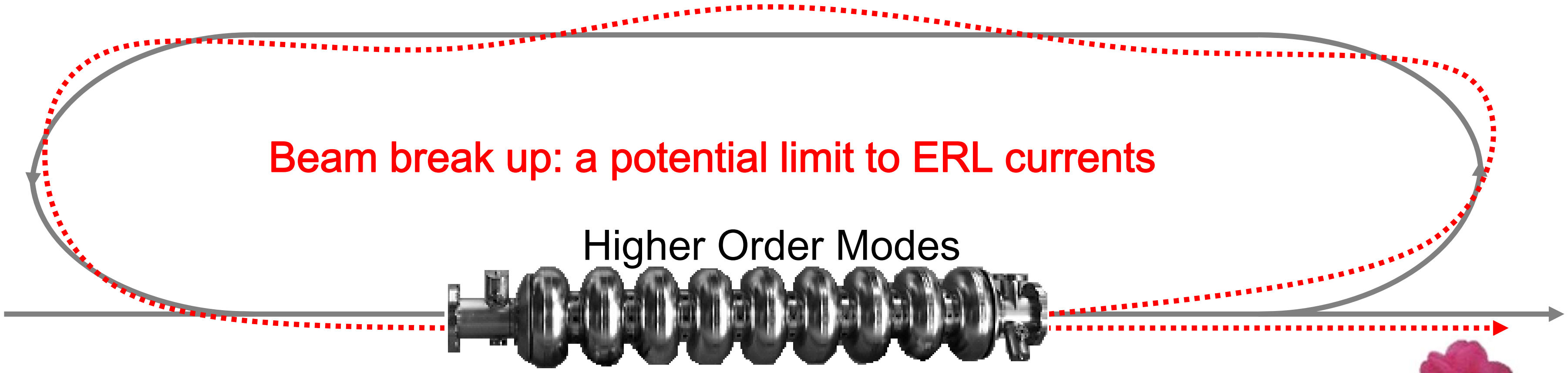
Achromatic and Isochronous optics to 2nd orders



4-beam optics: ISR emittance growth



BBU: Collective Instabilities



$$V_x(t) = T_{12} \frac{e}{c} \int_{-\infty}^{t} W_x(t-t')V_x(t'-t_r)I(t')dt'$$

- Similar instabilities would occur in the Linear Collider

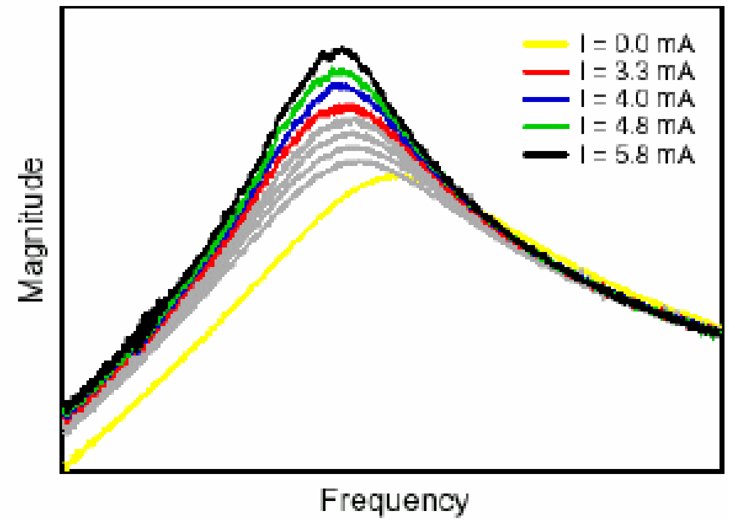
HOM with BBU: Starting from Noise

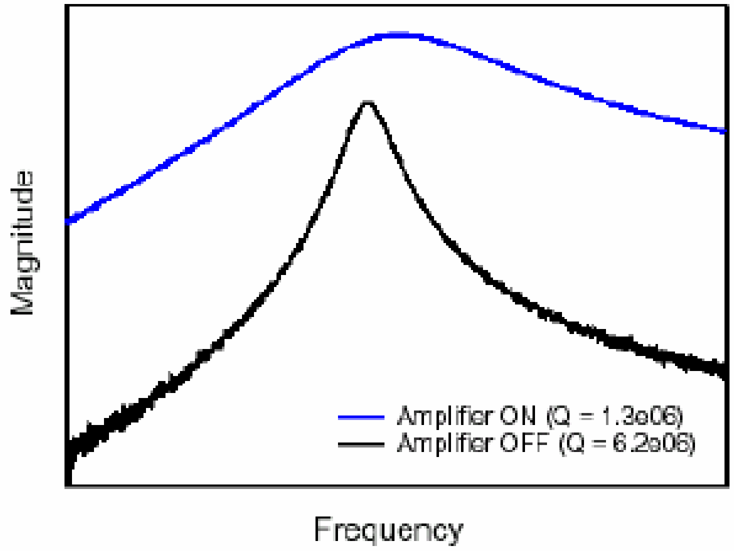
Recall… $I_{threshold} \propto \frac{1}{Q_{HOM}}$

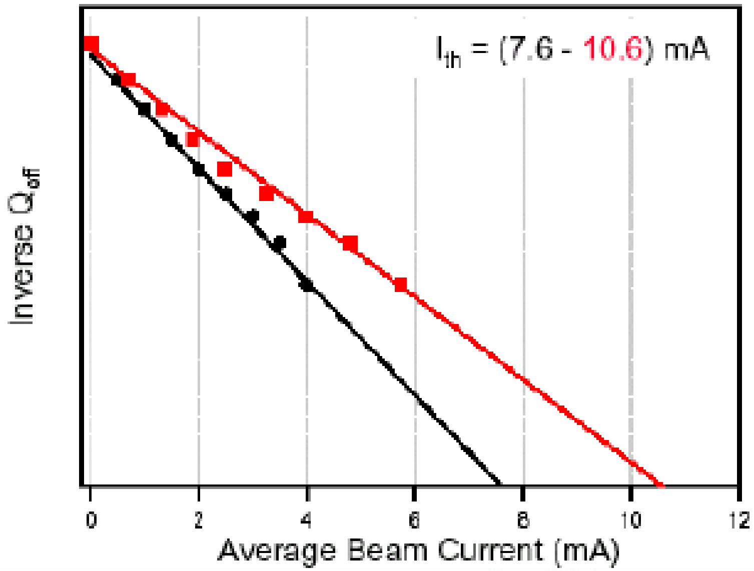
- Damping circuit easily reduced the *Q* of the 2106 MHz mode by a factor of 5

  (Above a factor of about 10, the system becomes sensitive to external disturbances)

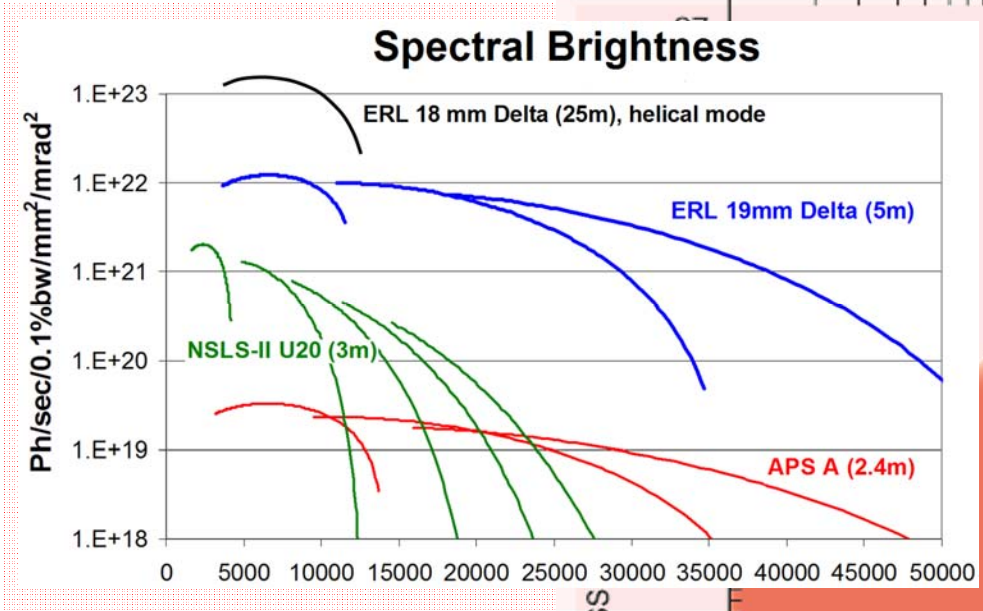
- The threshold is increased accordingly: from 2 mA to ~10 mA

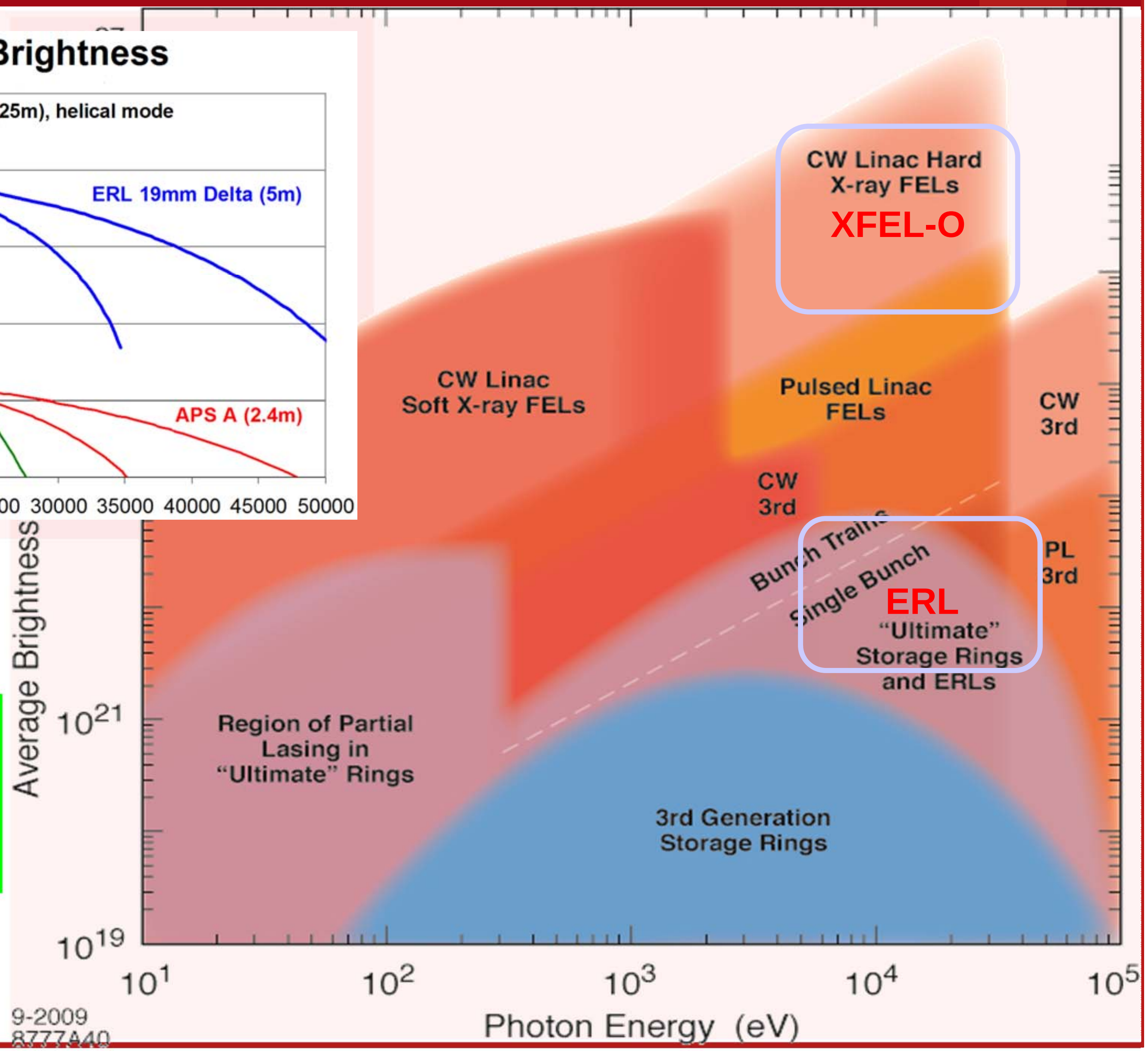






Once e-s are under control: x-ray beam dynamics !





Exceedingly large average spectral brightness is one large advantage for ERLs, but by far not the only one.

But once all is under control – the big reward !

The END