Dark current and halo tracking in ERLs

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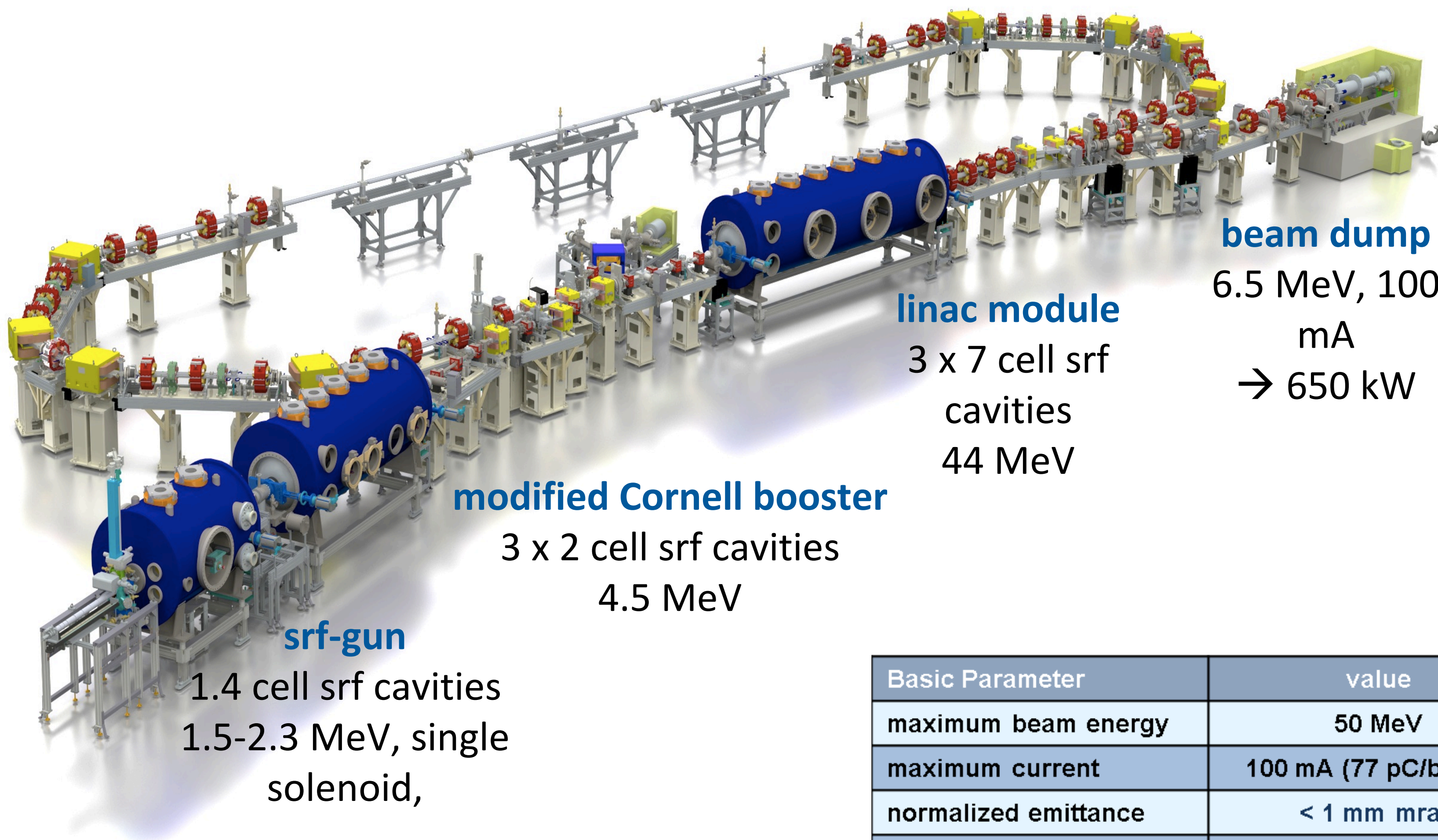
CONTENTS

- Modeling the formation and transport of unwanted beam
    - halo generated from nonlinear effects
    - incompletely extinguished laser pulses
    - stray light on cathode
    - dark current from field emission
- Tracking results in bERLinPro

SOURCES OF UNWANTED BEAM

- Two effects that produce “in-time” unwanted beam:
  - Halo formed by tails of laser pulse and by nonlinear dynamics within bunch
  - Incompletely blocked laser pulses that produce low-charge (but properly timed) electron bunches
- Two effects that produce “out-of-time” unwanted beam:
  - Stray light from the laser onto the cathode
  - Electrons generated from field emission from cathode and cavity surfaces

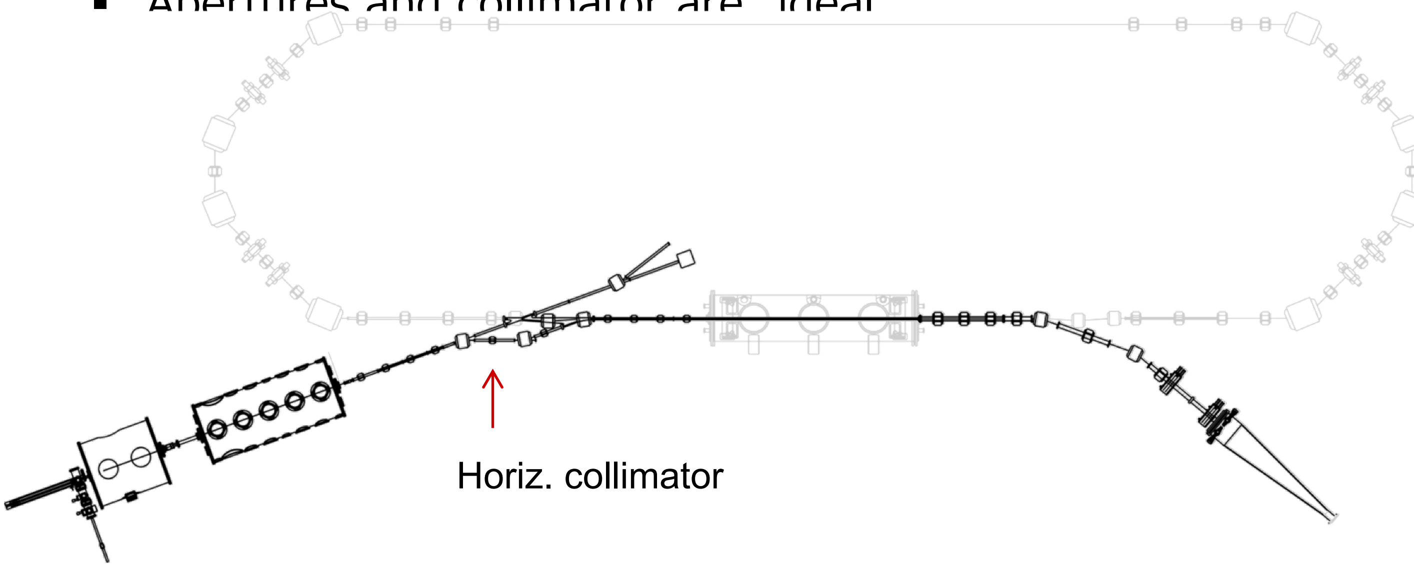
OVERVIEW OF BERLINPRO



Basic Parameter	value
maximum beam energy	50 MeV
maximum current	100 mA (77 pC/bunch)
normalized emittance	< 1 mm mrad
bunch length	2 ps (~100 fs)
repetition rate	1.3 GHz
relative losses per turn	$< 10^{-5}$

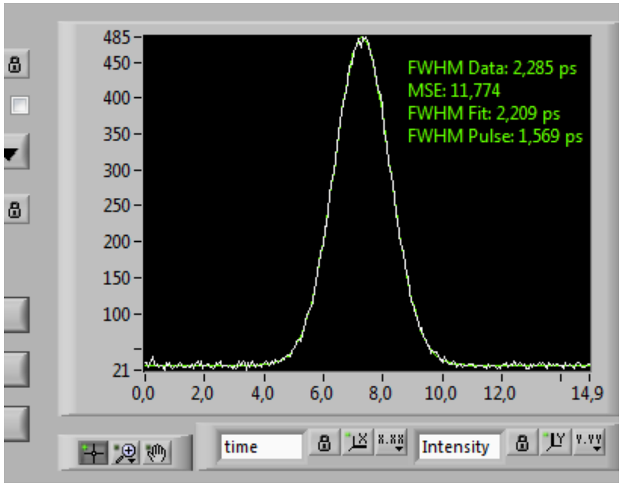
ASTRA MODEL OF bERLinPro INJECTOR

- Particle distributions are tracked from cathode through merger using Astra
  - Distribution on cathode is based on expected laser pulse shape
  - Halo particles are modeled as passive particles (excluded from space charge grid)
- Model includes nonlinear descriptions of accelerator elements
  - 3D field maps for gun cavity and booster cavities from Superfish simulations
  - Multipole errors for quadrupoles up to n=6 from field measurements of bERLinPro magnets
- Apertures and collimator are “ideal”

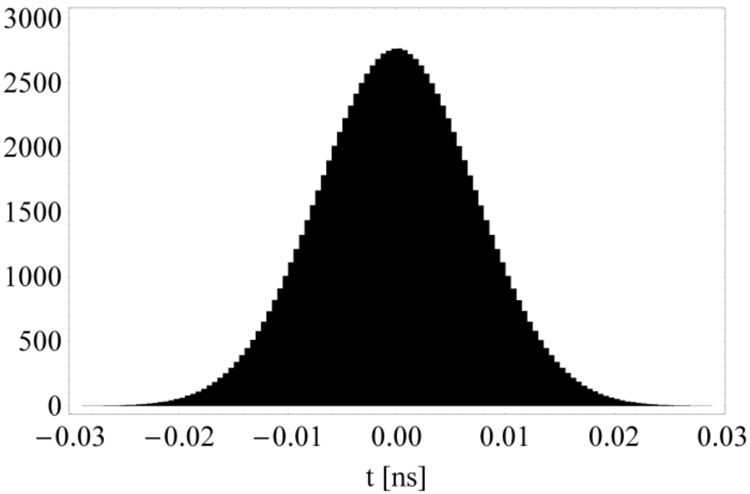


MODELING OF LASER SPOT ON CATHODE: LONGITUDINAL PROFILE

- Longitudinal laser pulse profile approximately gaussian with some cropping of tails (exact shape of tails not yet known)
  - Autocorrelator measurements have ~2σ noise floor; higher-precision measurements possible soon
- Pulse duration for Astra simulation modeled as gaussian w/ σ=7.21 ps, cropped at 4.5 σ
  - Tails of distribution more heavily populated with lower-charge macroparticles reduce statistical noise
- Emission time of cathode not taken into consideration



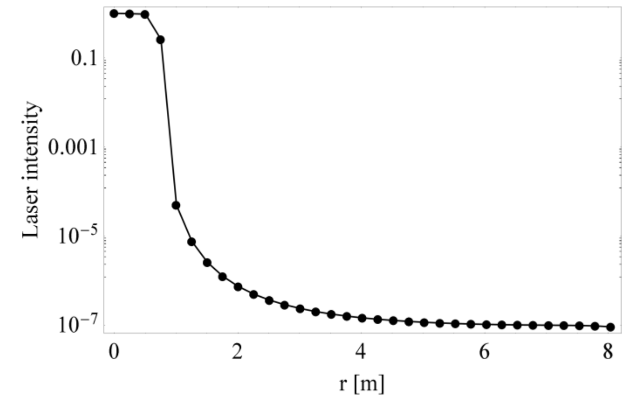
Laser pulse measurements with autocorrelator (courtesy G. Klemz)



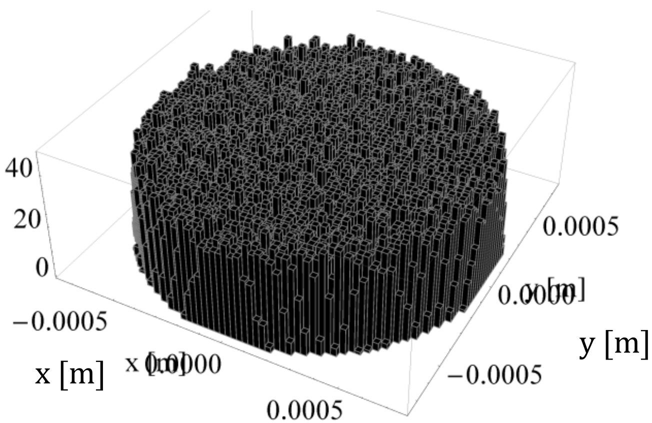
Time distribution of bunch on cathode for Astra simulations (Gaussian w/ 4.5 σ cutoff)

MODELING OF LASER SPOT ON CATHODE: TRANSVERSE PROFILE

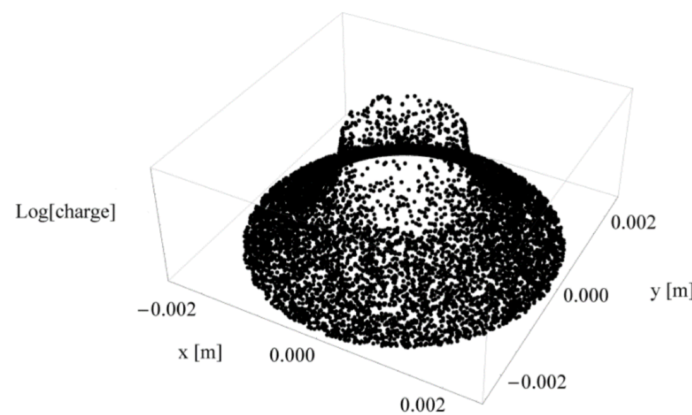
- "Flat-top" transverse profile created by passing laser with Gaussian profile through a small circular aperture
  - Ratio of pulse width to aperture is adjustable (σ/3 aperture used here)
- Some transverse halo is expected due to diffraction from window into cryomodule
  - Transverse halo modeled as macroparticles w/ varying charge, following Zemax simulations of diffraction by G. Klemz



Zemax simulations of laser spot profile on cathode (simulations by G. Klemz)



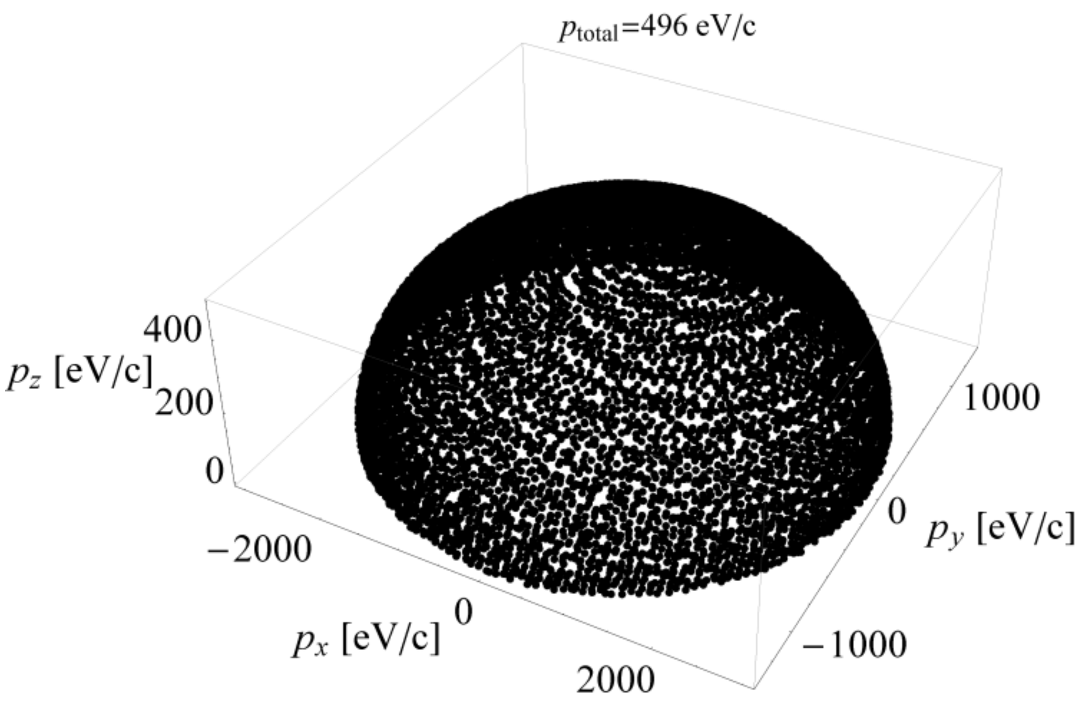
"Flat-top" transverse distribution of beam core at cathode used for Astra simulations.



Transverse halo particles on cathode used for Astra simulations.

MODELING OF LASER SPOT ON CATHODE: MOMENTUM DISTRIBUTION

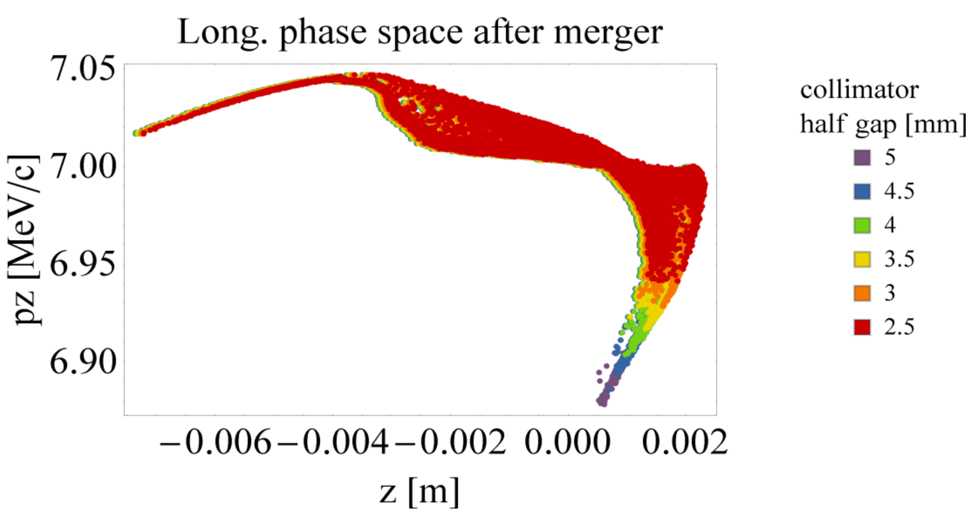
- Electrons emitted from cathode are modeled as having isotropic momentum distribution w/ p=496 eV/c
  - assuming ~half of momentum is lost to scattering processes during emission



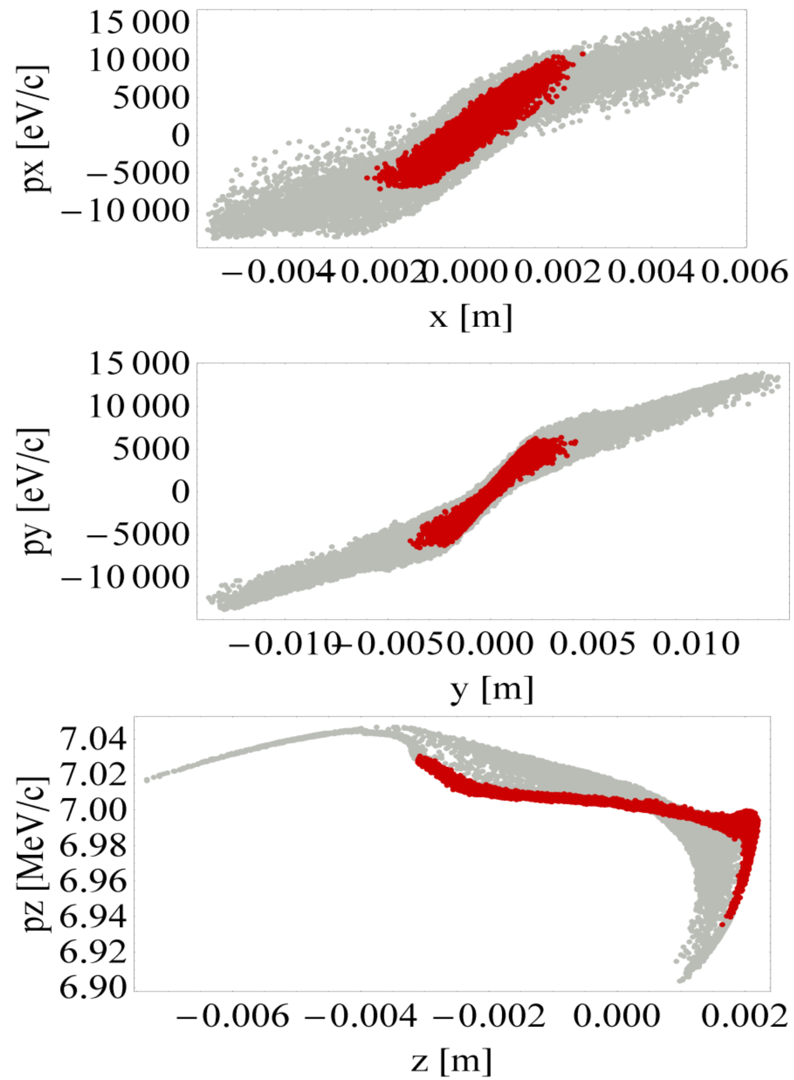
Momentum of particles on cathode for Astra simulations.

TRACKING HALO THROUGH INJECTOR AND MERGER

- Distribution w/ long. and trans. halo was tracked through injector w/ nonlinear cavity and quadrupole fields
- No particles are lost on beam pipe aperture in this simulation
- 3% of beam is lost on collimator (w/ 2.5 mm half gap)



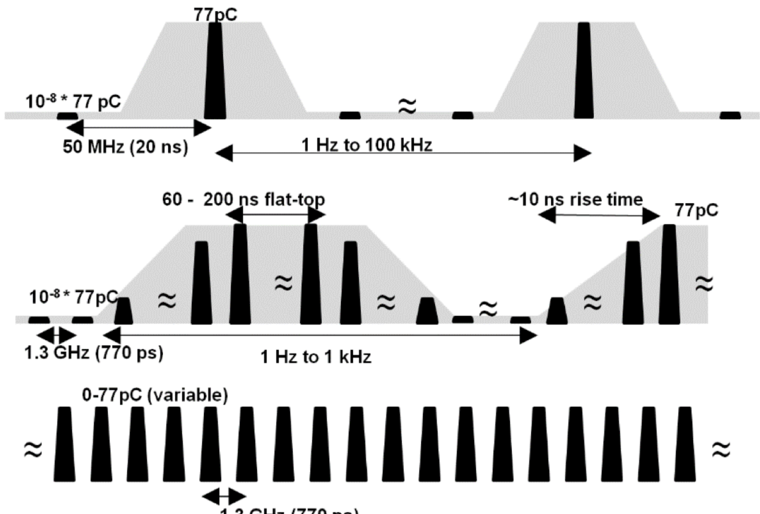
Longitudinal phase space of beam downstream of merger, with varying collimator gap.



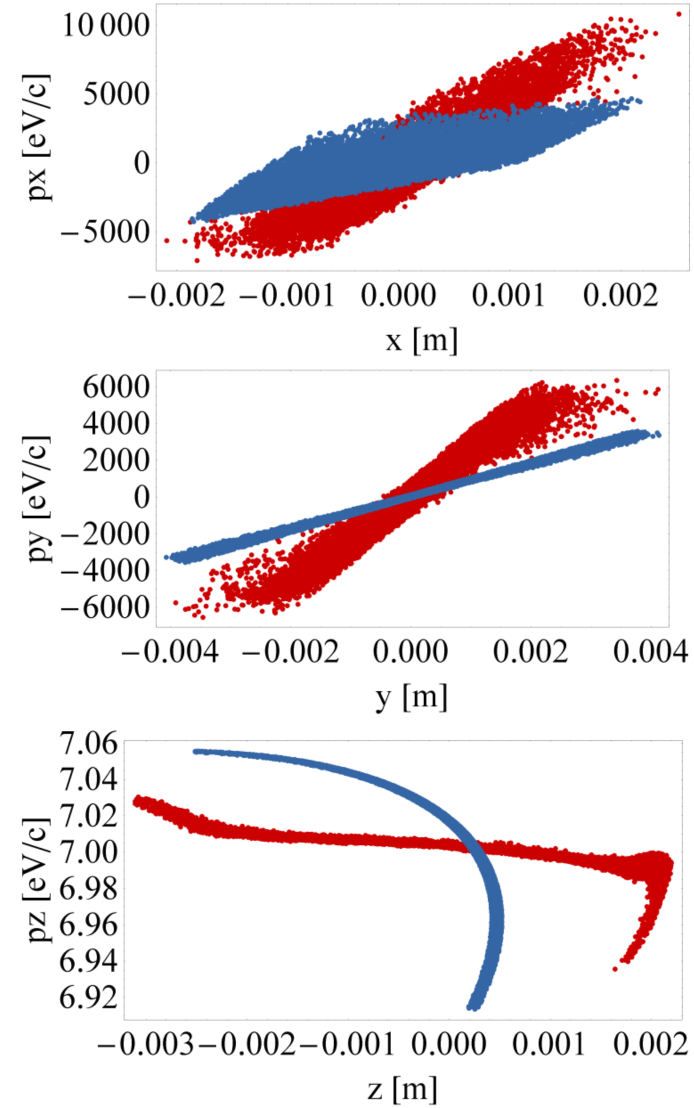
Phase space of distribution after merger (core particles in red, halo particles in gray).

INCOMPLETELY EXTINGUISHED BUNCHES

- In low-current modes, most laser pulses are gated using Pockels cells (nominal extinction ratio 10^{-8})
- Ghost pulses have different dynamics due to low space charge
- In diagnostics mode all but $\leq 10^{-4}$ of laser pulses are gated, so ghost current can be significant if extinction ratio is higher than expected



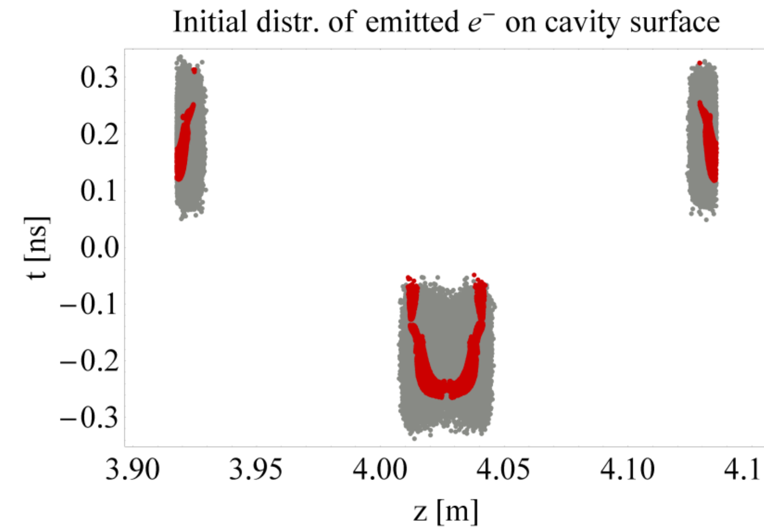
Laser pulse patterns for single bunch, pulsed, and CW modes.

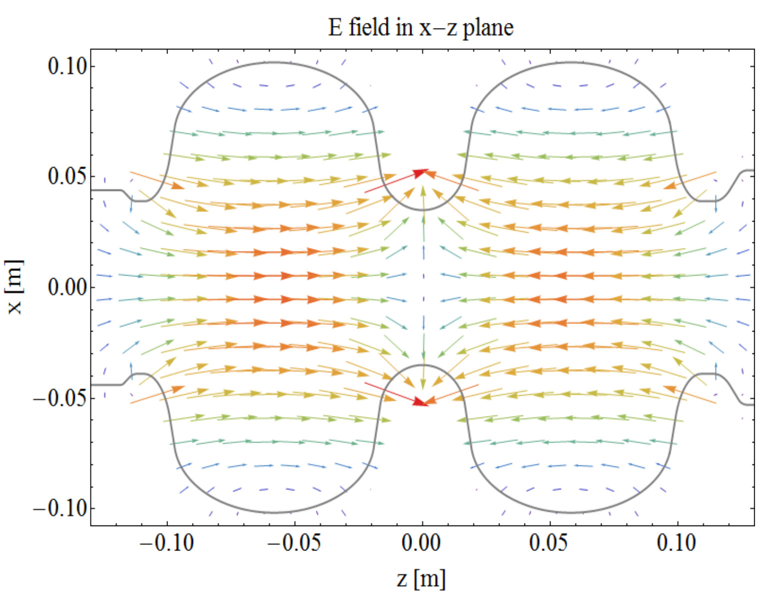


Phase space of distribution after merger (full-charge bunch core in red, ghost bunch core in blue).

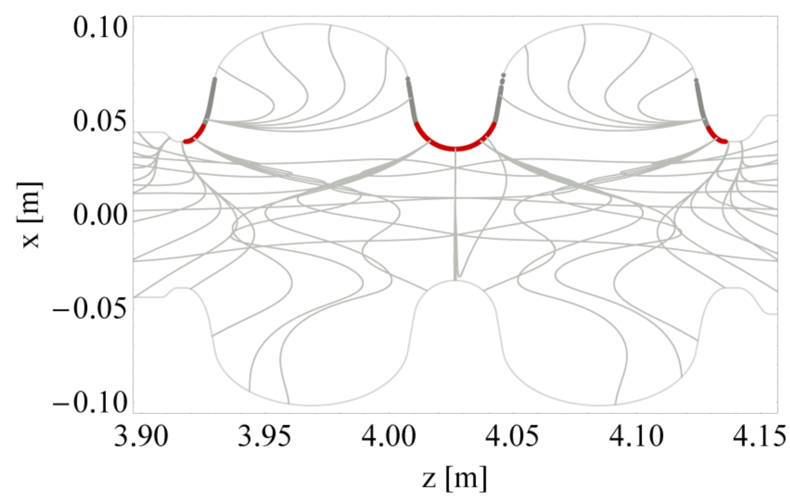
DARK CURRENT FROM BOOSTER CAVITIES

- Two of three booster cavities will have gradients of ~16 MV/m
- Initial distribution of field emission electrons on cavity surface was modeled following Fowler-Nordheim and tracked with Astra
- About 75% of emitted electrons remain in cavity, 25% escape





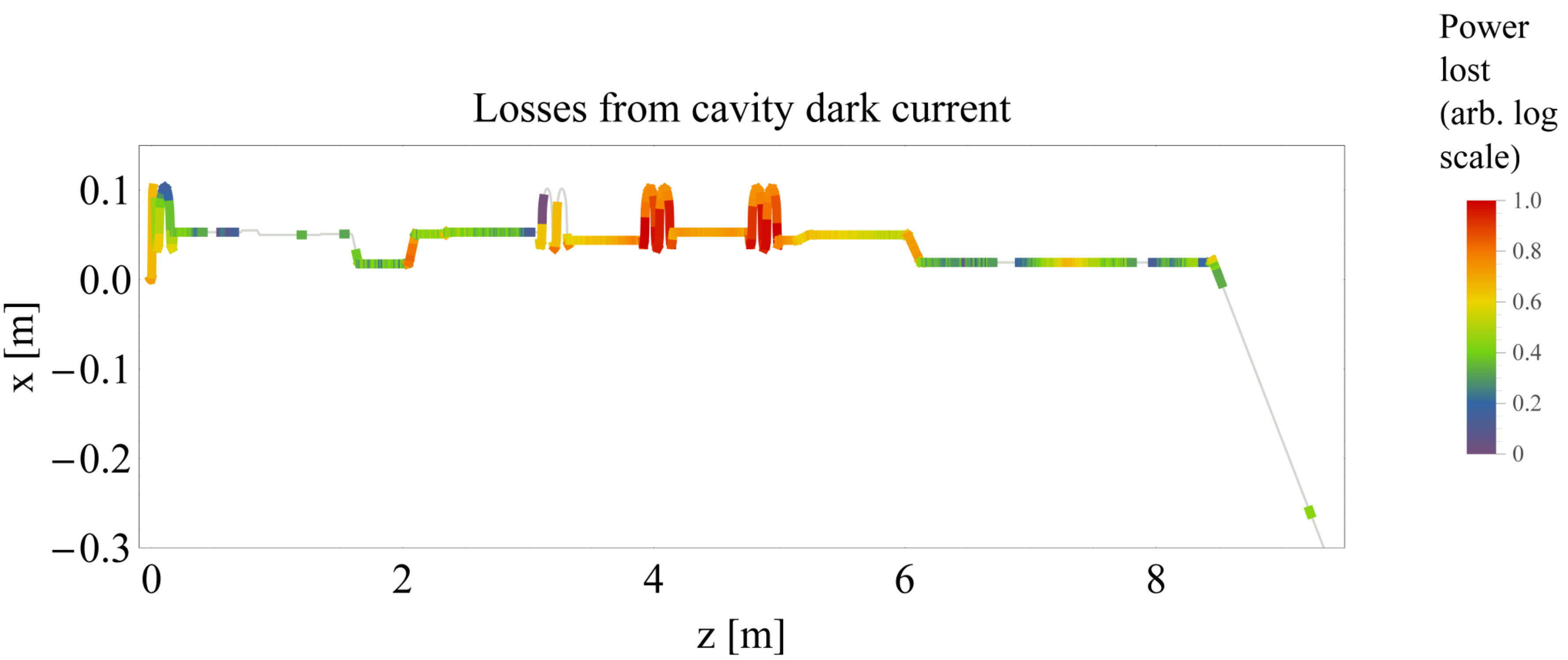
Booster cavity field in xz plane.



Distribution of dark current particles for Astra simulation. Particles in red escape cavity.

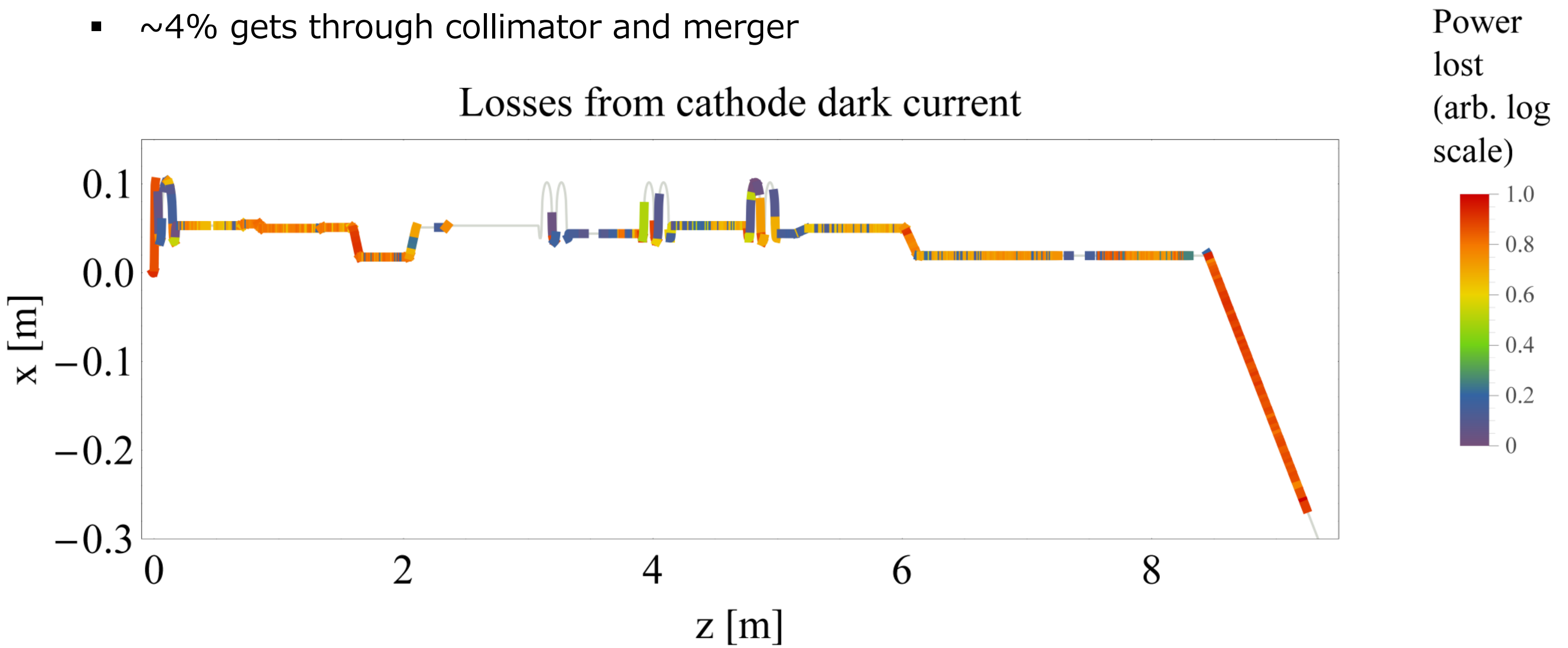
DARK CURRENT FROM BOOSTER CAVITIES

- ~75% of emitted electrons remain within cavity
- ~0.1% of electrons strike cathode
- A few per mil gets through the merger and collimator



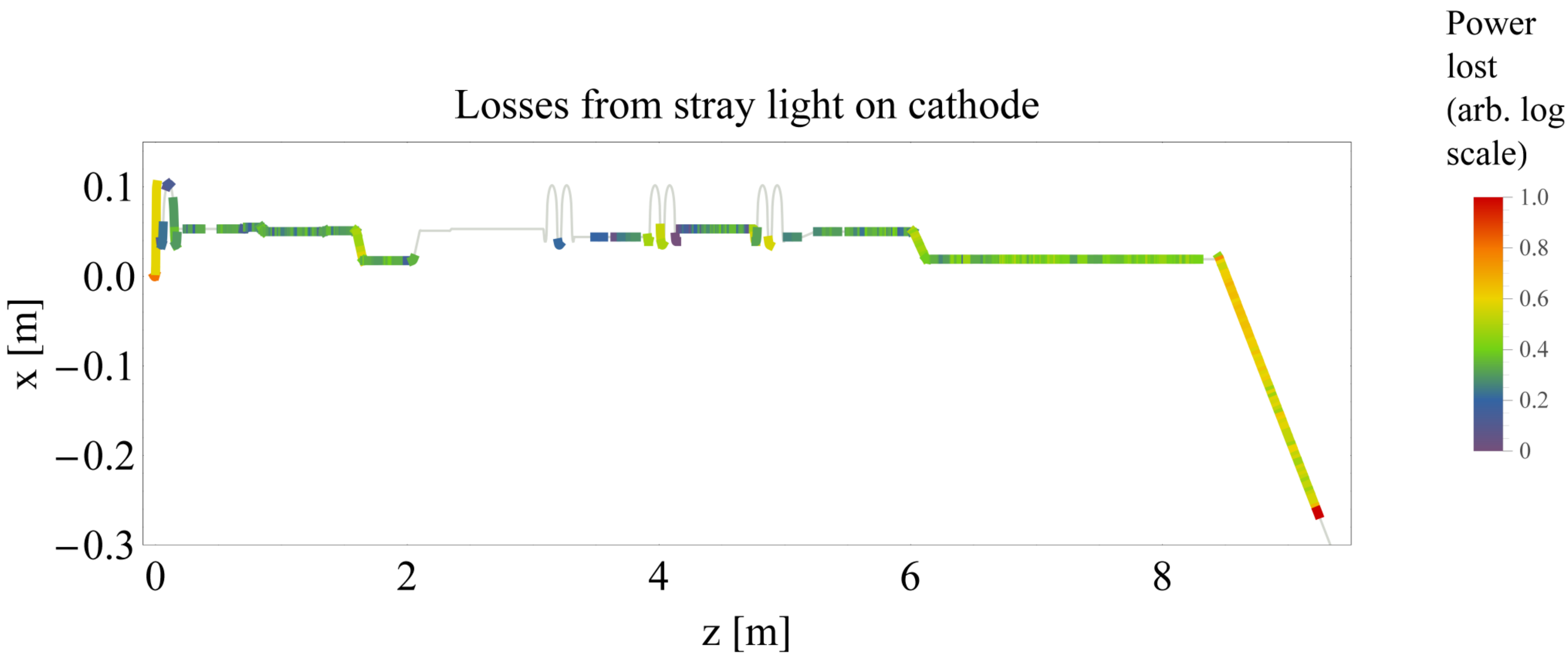
DARK CURRENT FROM THE CATHODE

- Field emission electrons on cathode and plug modeled following Fowler-Nordheim; higher current emitted from edge of plug
- The peak of the DC distribution is emitted ~40 deg later than the bunch from laser pulse
- What happens to DC electrons emitted from cathode:
  - ~7% of dc electrons turn around in gun and strike cathode
  - ~10% is lost in or shortly after first merger dipole
  - ~15% is lost at collimator (w/ 4mm half-gap)
  - ~4% gets through collimator and merger



STRAY LIGHT ON CATHODE

- Photons can be scattered within laser system and arrive out of time and space; modeled simply as a uniform distribution in time and space on the surface of the cathode
- What happens to electrons emitted from stray light:
  - ~40% turn around in gun and strike cathode
  - ~20% is lost on aperture in injector or in first merger magnet
  - ~20% is lost on collimator (w/ 4mm half-gap)
  - ~20% gets past collimator



SUMMARY

Results of tracking “on-time” unwanted beam from tails of laser pulse, nonlinear beam dynamics, and partially blocked laser pulses:

- Halo of main bunch did not cause losses before collimator
- Ghost pulses did not lead to beam loss in the merger in these simulations, but the optics are significantly different from full-charge bunches

Results of tracking “out-of-time” unwanted beam from field emission from cavity surfaces and from scattered/reflected laser light hitting cathode:

- Dark current from booster cavities
  - Mostly lost on beam pipe in the injector
  - ~0.1% reaches cathode
  - Very little passes collimator and merger
- Dark current from cathode
  - Significant losses on cathode, in taper after gun, and in first merger dipole
  - ~4% gets through collimator and merger
- Electrons from scattered laser light
  - ~40% returns to strike cathode w/ low energy
  - ~20% is lost on collimator, ~20% gets past collimator and merger
  - Little loss in other parts of injector

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