Improving X-ray streak cameras on NIF

NIF diagnostics workshop, Los Alamos

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and the streak camera team

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Lawrence Livermore National Laboratory

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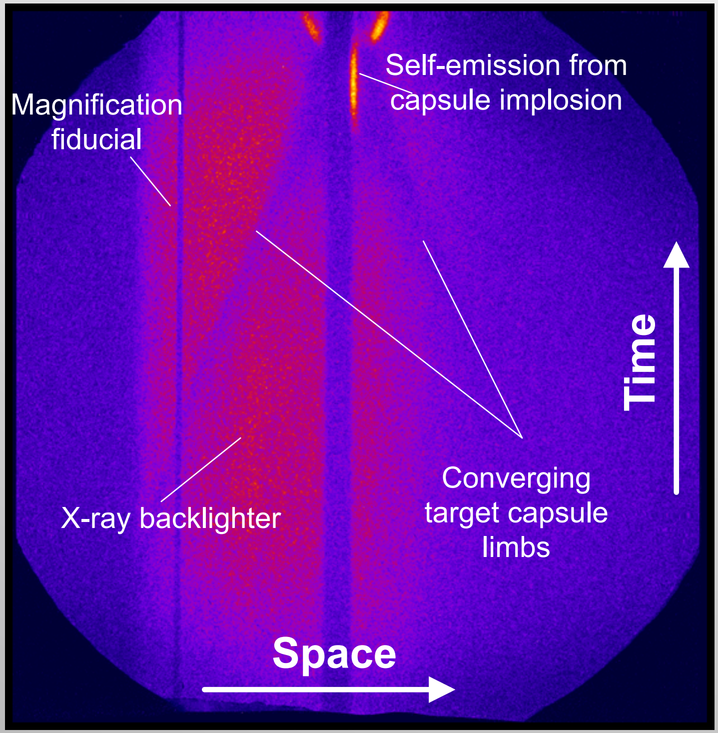
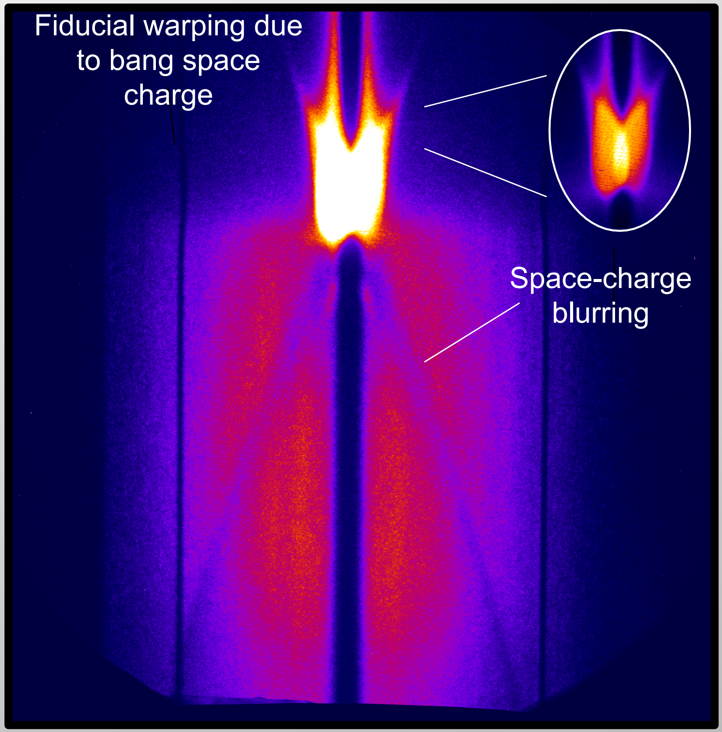
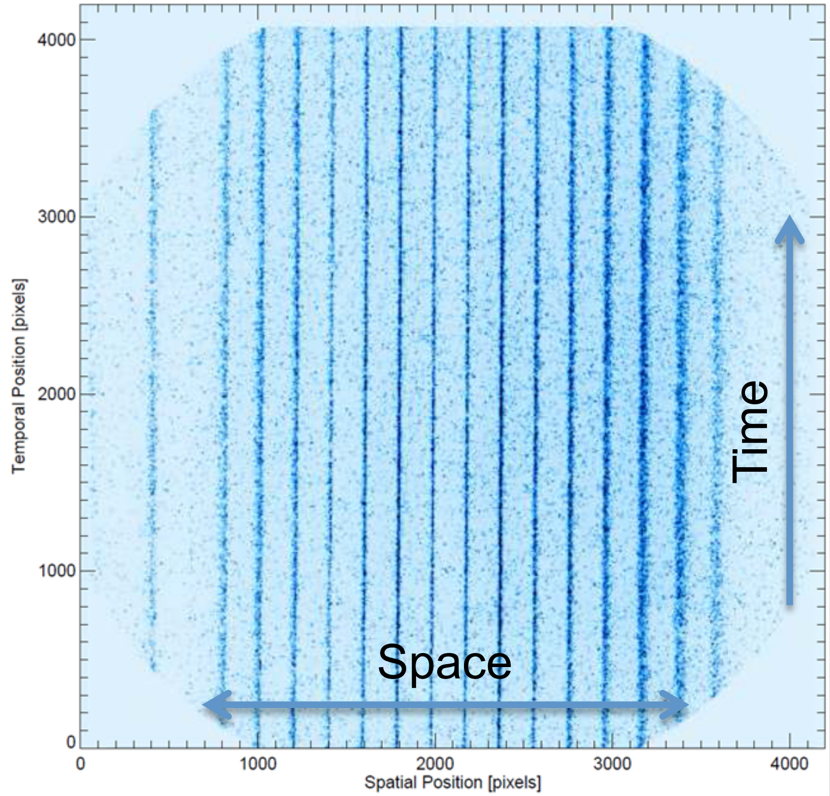
There is an ongoing push for improved spatial resolution and dynamic range for Spectroscopy and ConA on NIF





ConA self emission can vary dramatically leading to space-charge blurring
In extreme cases significant warping can also occur

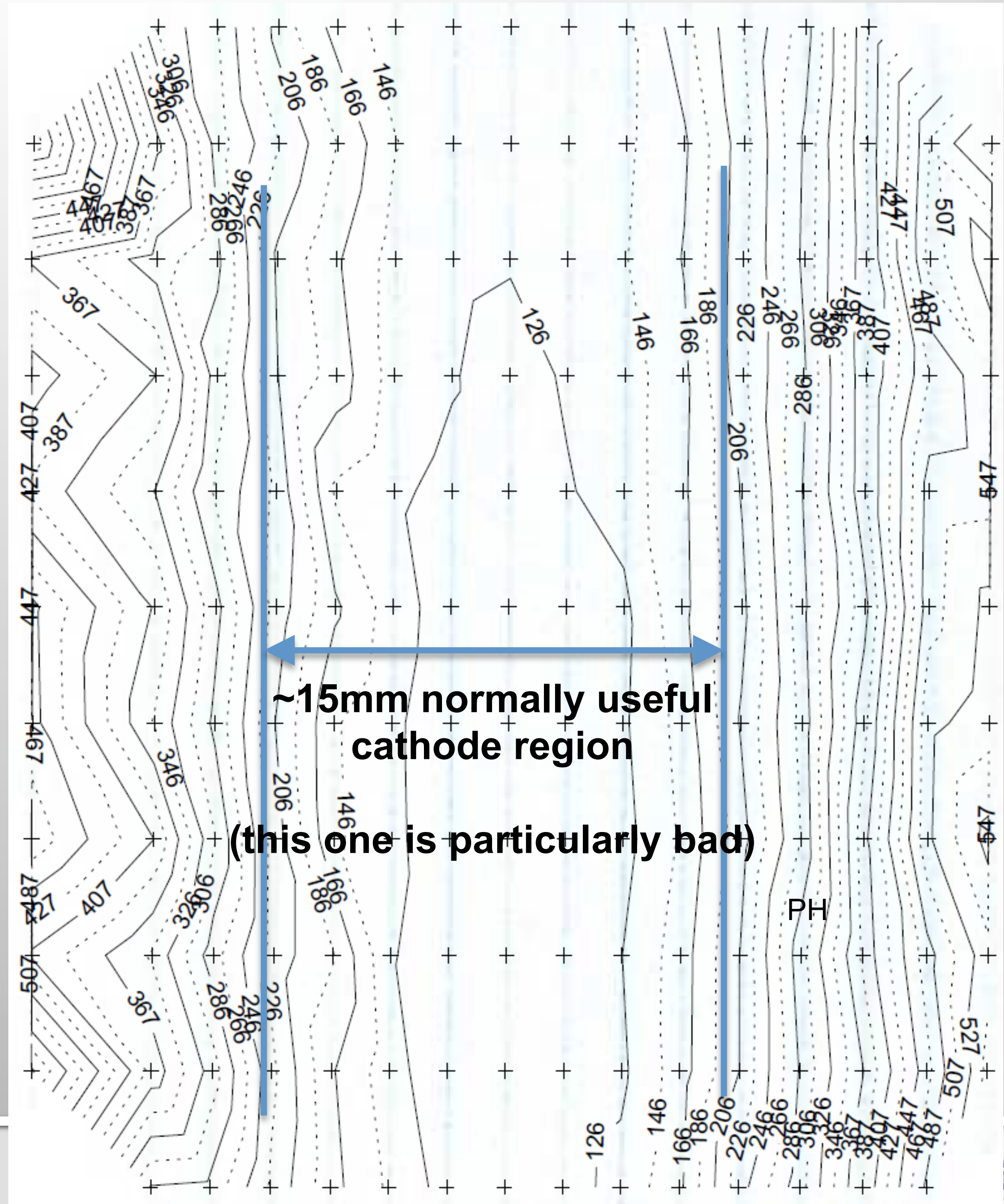
DISC: Spatial resolution ~100μm in center ~500μm at edge



~100um resolution for central 15mm of cathode
→ 150 useful spatial resolution elements

Would like to increase this to ~300 spatial resolution elements

Time is ok for now, we have ~180 temporal resolution elements→ 25ps on 5ns sweep)

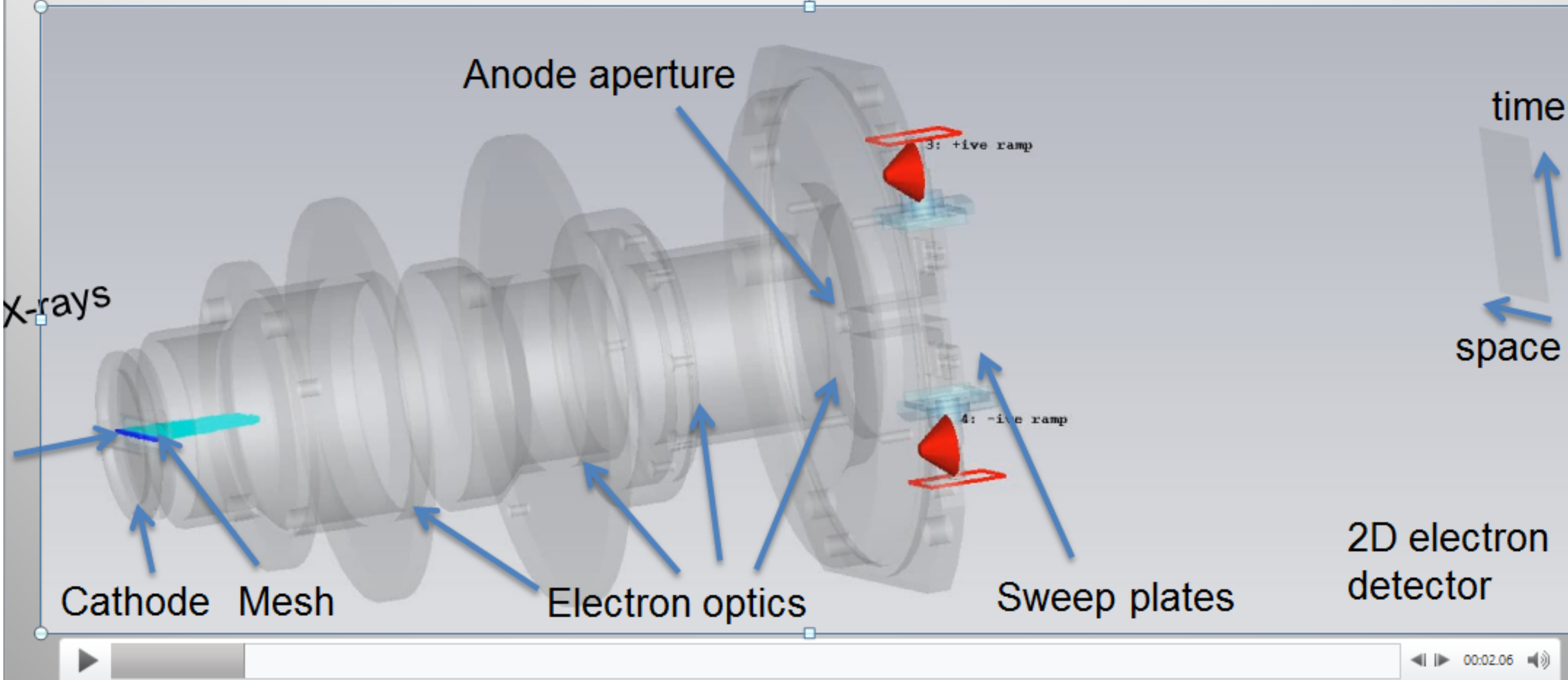


Strategy for improving NIF X-ray streak camera

- Model existing streak tubes to compare resolution and dynamic range
  - So far we have modeled DISC in detail
  - Started modeling PJX tube (Paul Jaanimagi LLE)
  - NSTec EG&G tube (assembling cad model and voltages)
- If one design is good enough already build a version of it that fits a DIM
- Otherwise identify the aberrations and apply a correction or redesign it
- In the meantime, find an interim solution to improve DISC resolution
  - Will mostly concentrate on the interim solution for this talk

DISC stands for: DIM Imaging Streak Camera

Records 1D intensity distribution vs time by converting x-rays to electrons and applying a ramp field



DISC uses an electrostatic immersion lens giving a single crossover at the anode aperture

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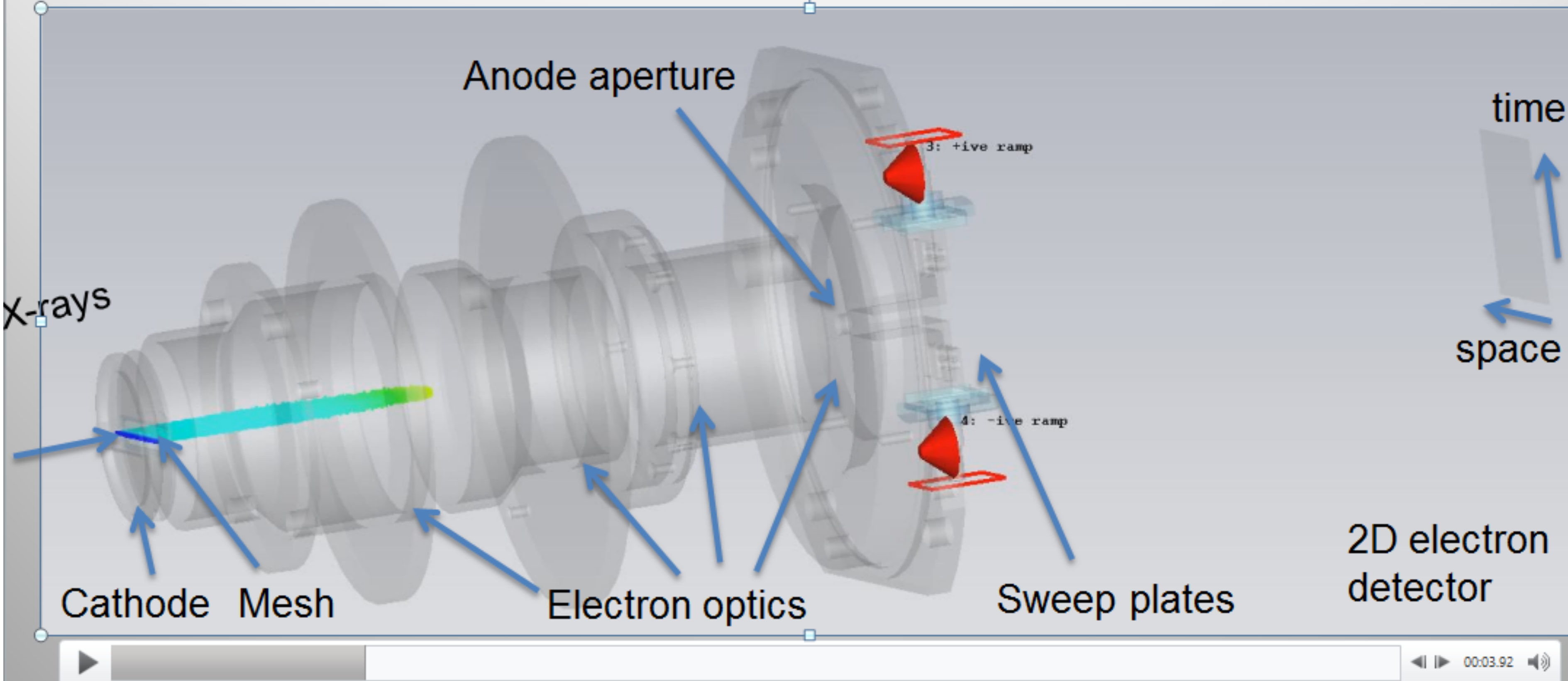

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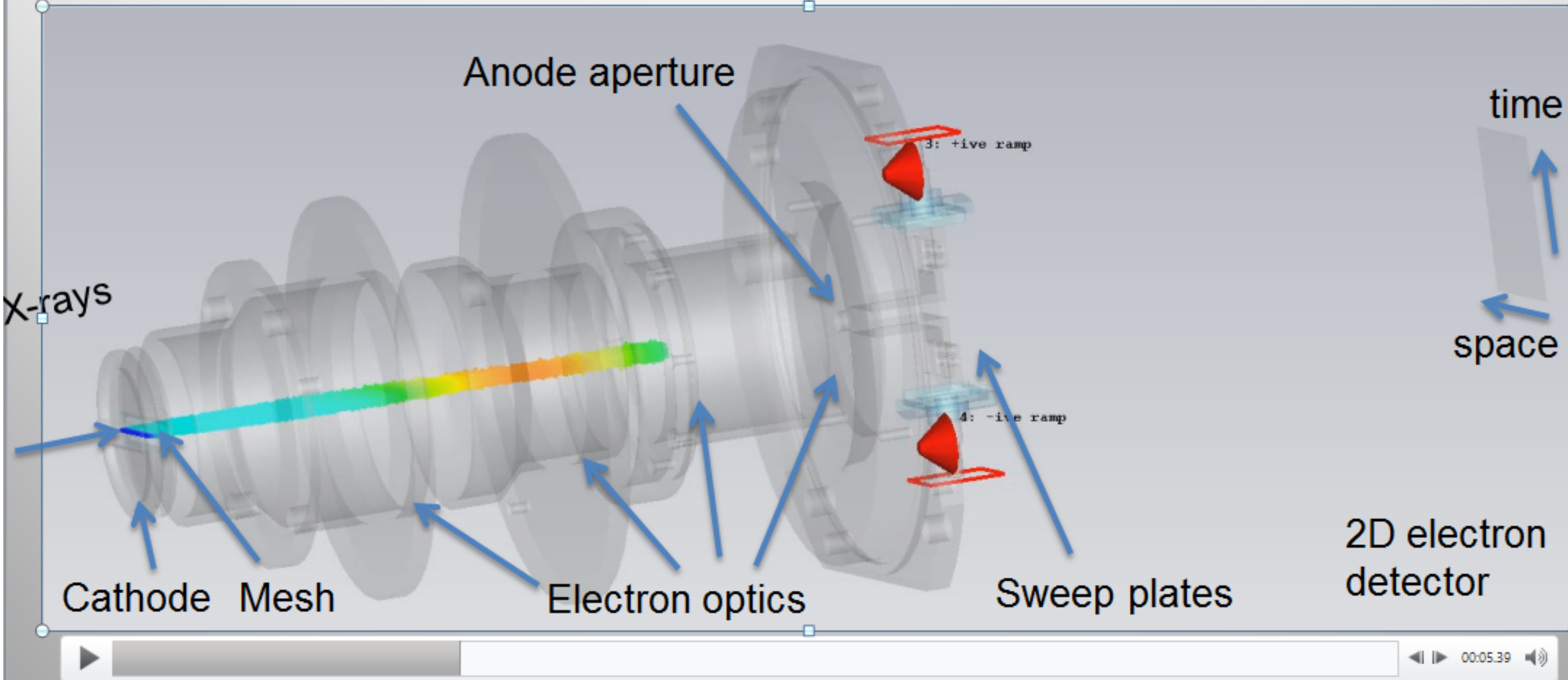

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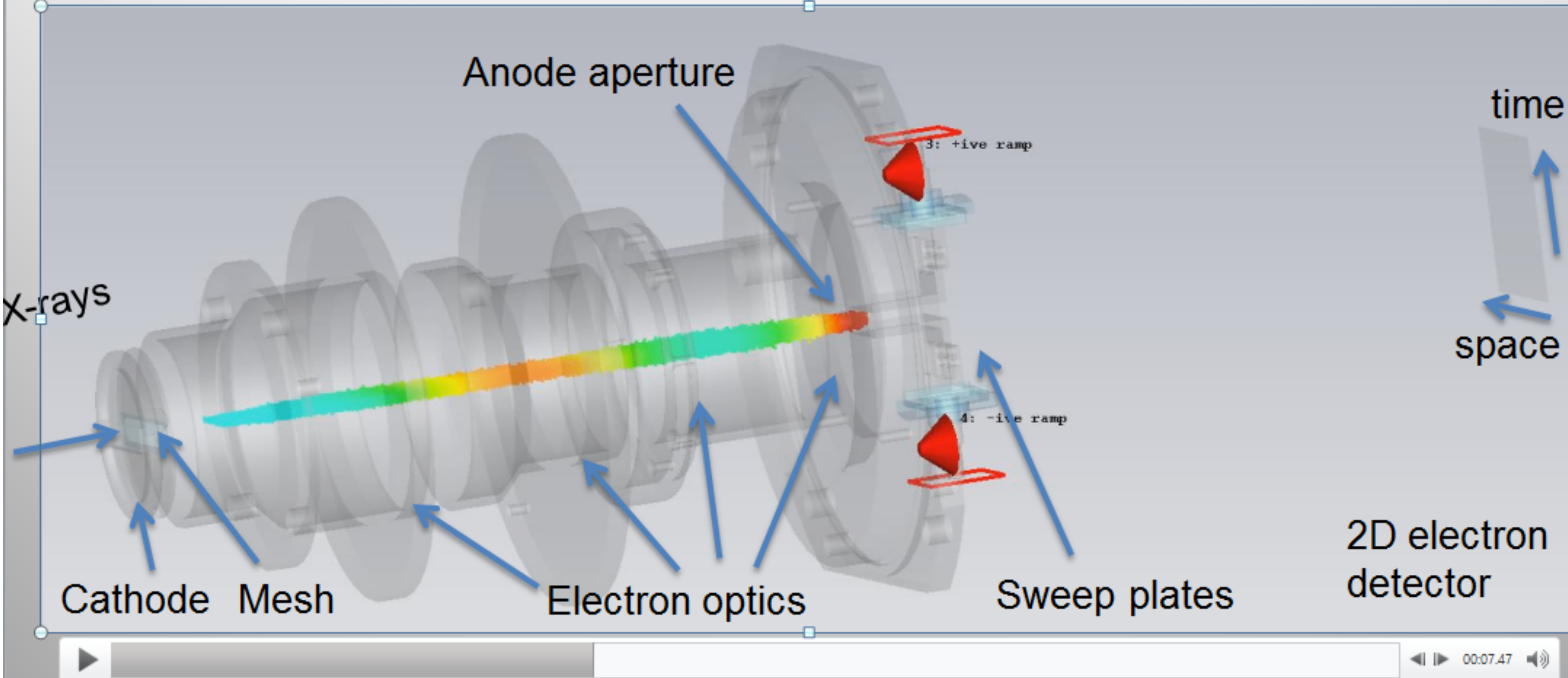

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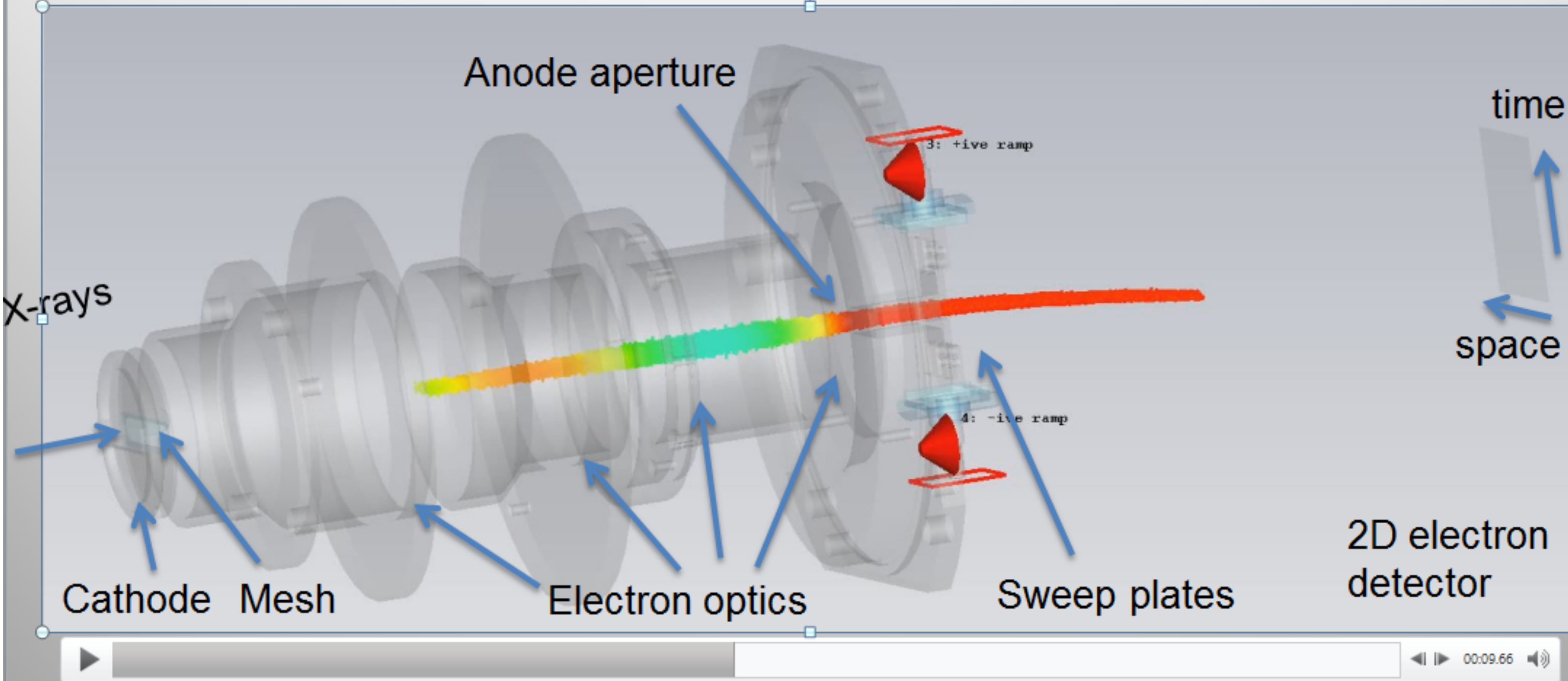

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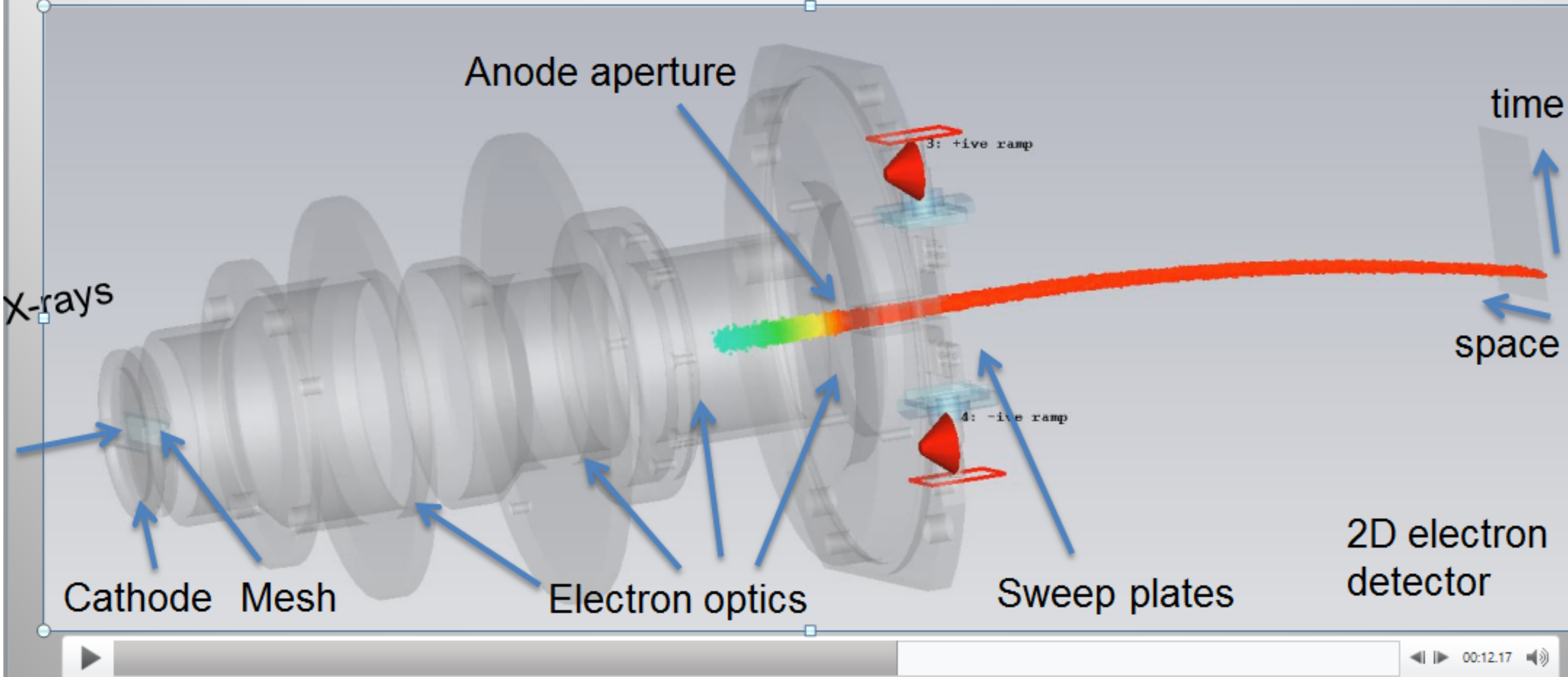

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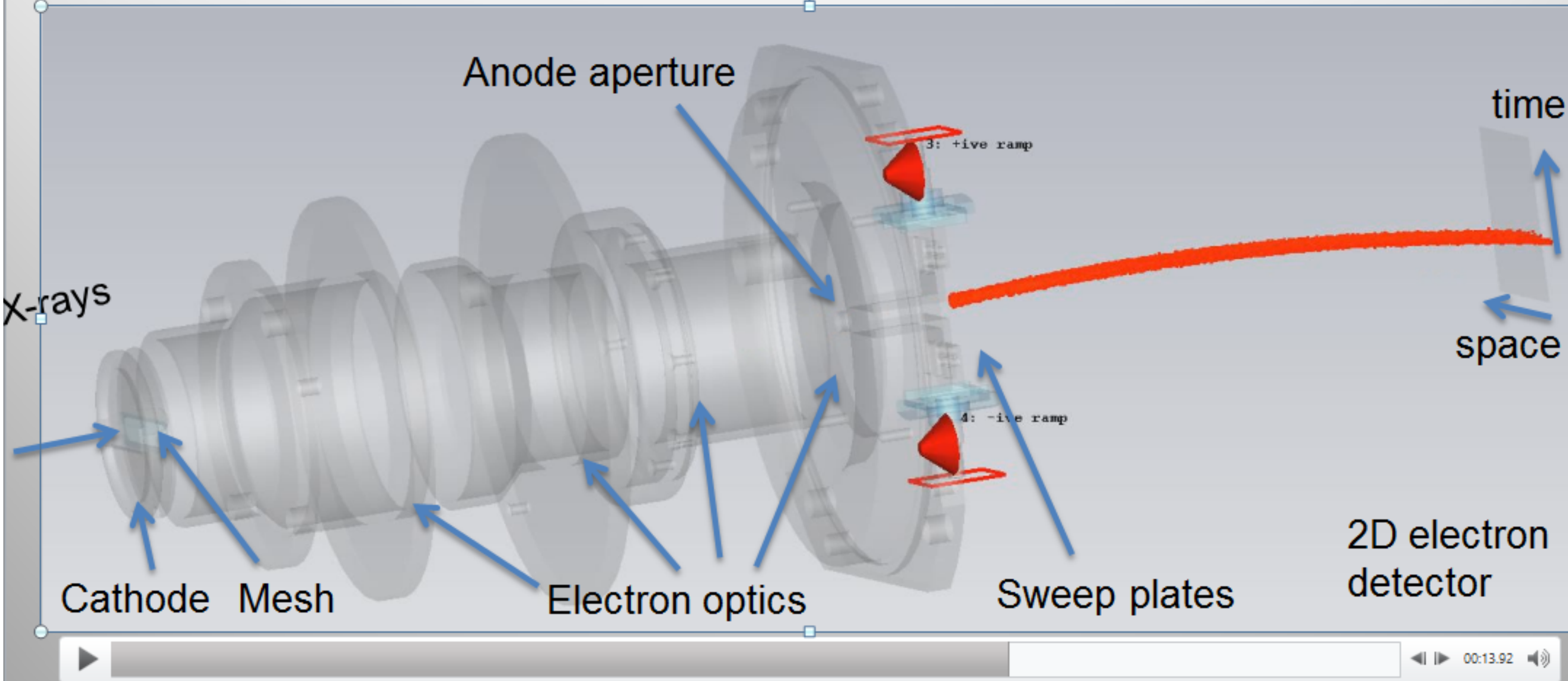

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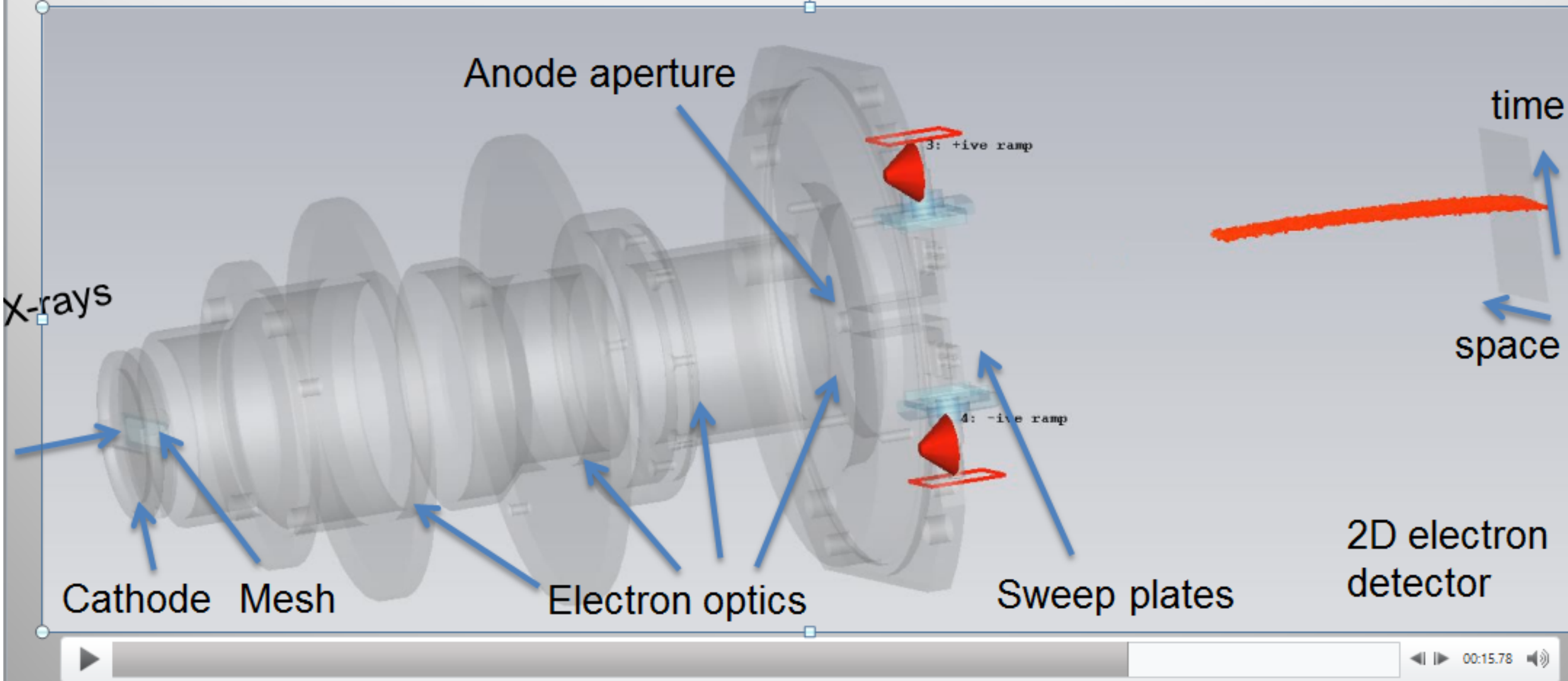

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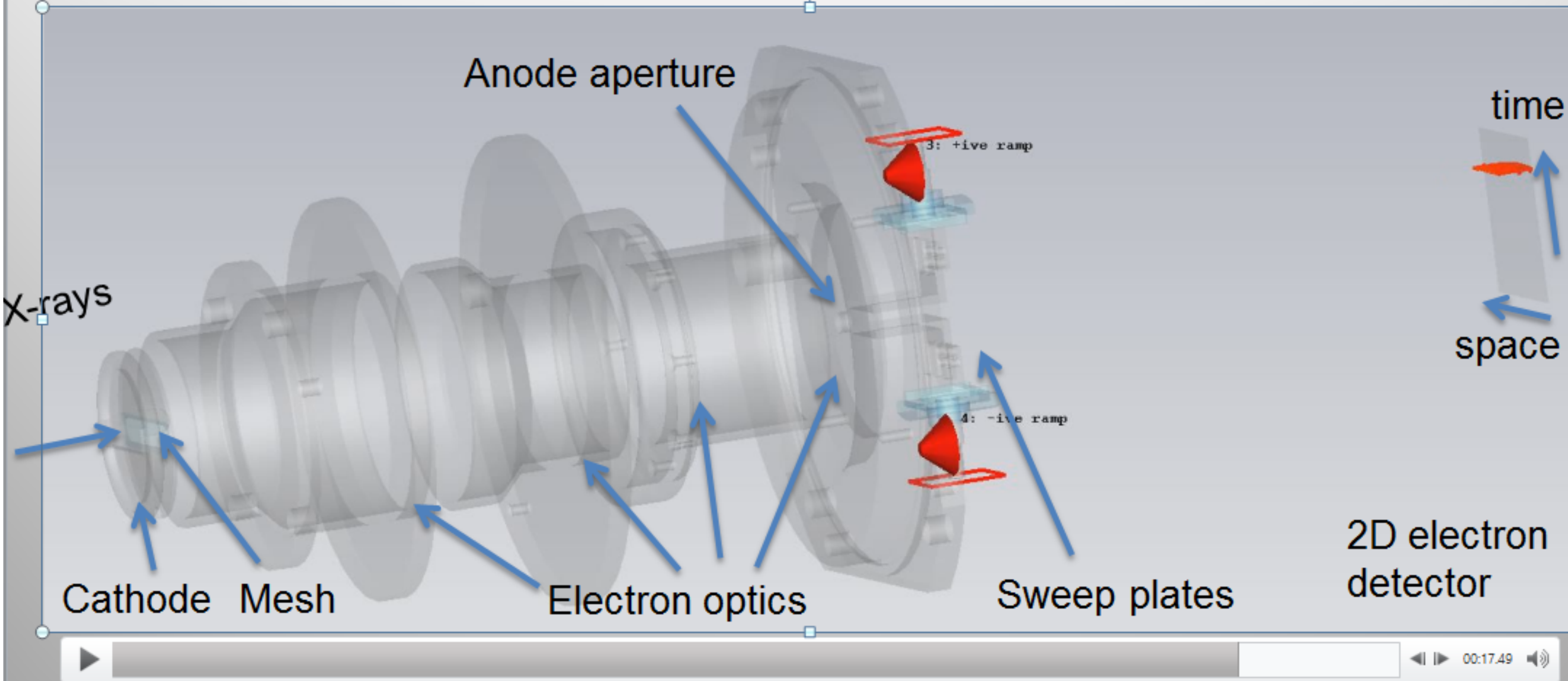

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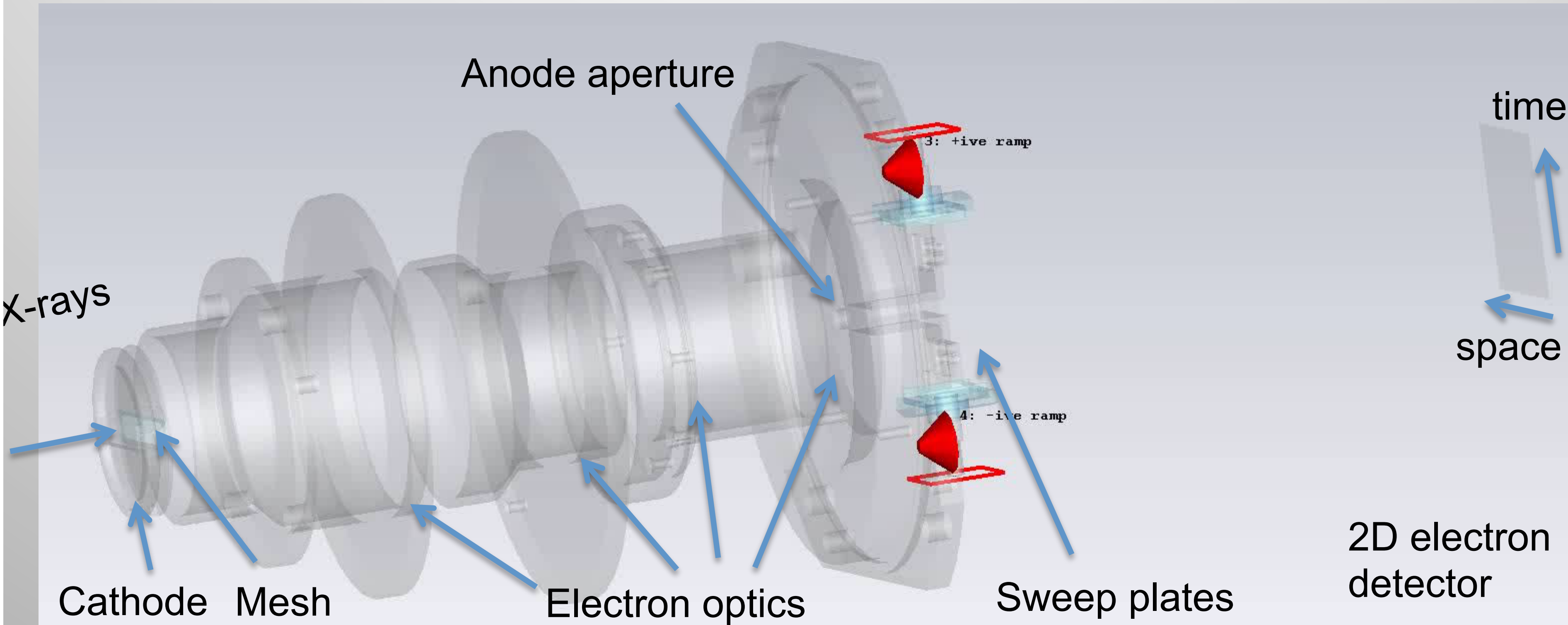
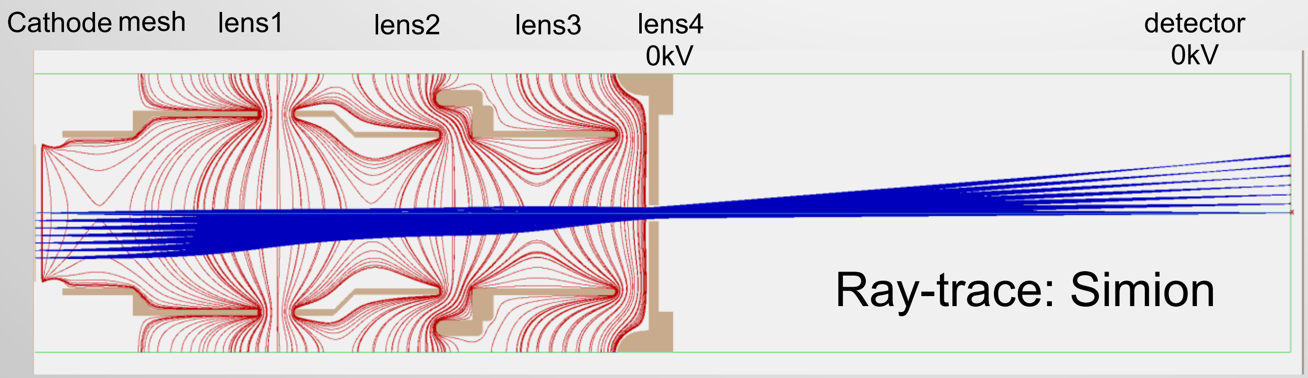
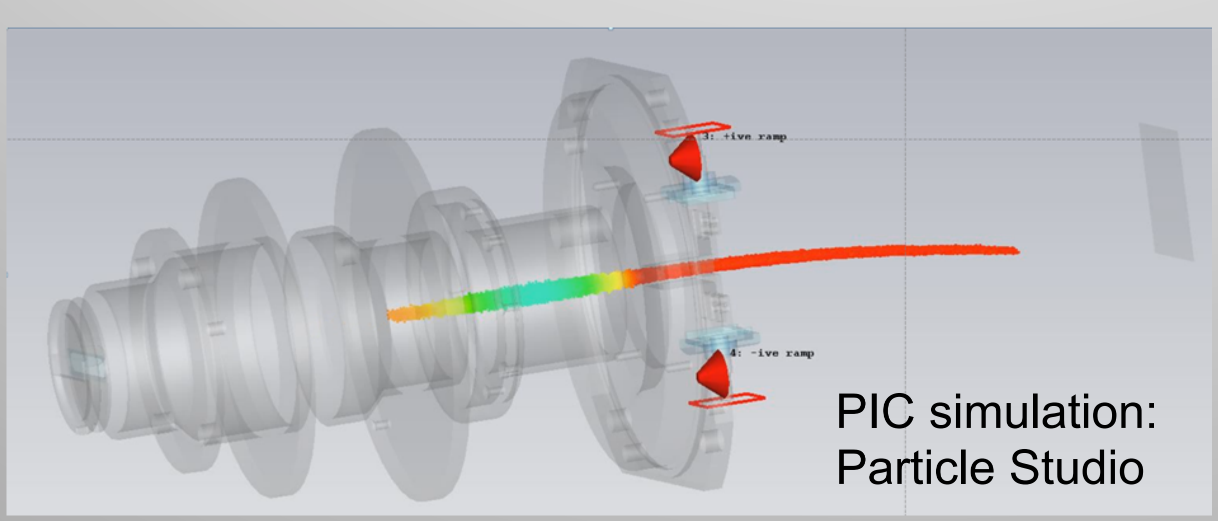


DISC uses an electrostatic immersion lens giving a single crossover at the anode aperture

We model the streak tubes using ray-tracing for fast tuning and PIC simulations to include dynamic fields and space-charge effects



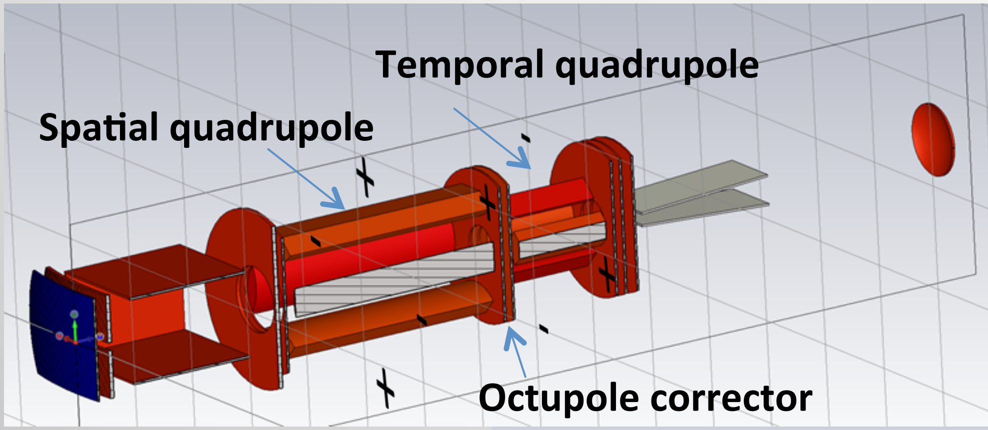
SIMION (ray-tracing) Solves Laplace's equation for the applied potentials in 3D throughout a uniform grid then solves the trajectories for the rays. Quick, ~few mins 100k rays ~1M mesh cells



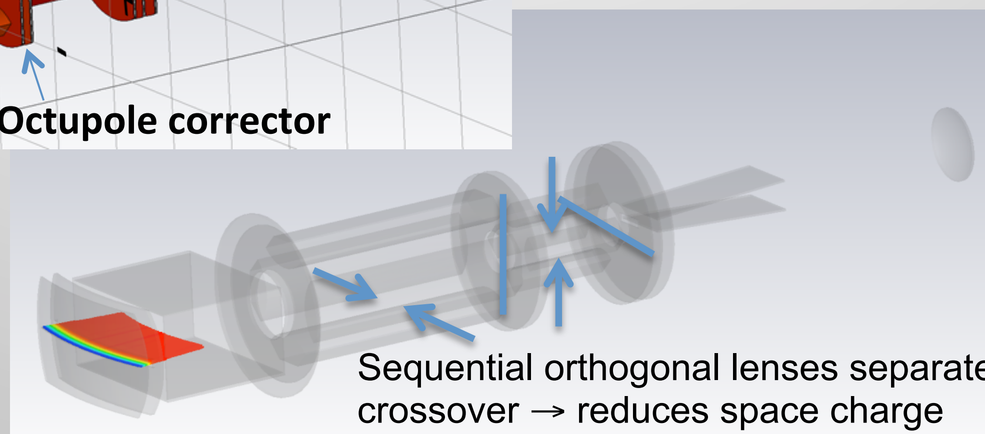
CST Particle Studio is a commercial time domain PIC solver for designing particle accelerators etc. Uses finite integration technique and includes relativistic equations of motion, space-charge effects and dynamic fields (sweep). 20M cells 10M particles 9ns ~8hrs on 12 cores + Fermi GPU. LC libraries next year

PJX is a QoQ design (Quadrupole-octupole-Quadrupole) similar for mass spectrometers and electron microscopes

Archard: Quadrupole instead of cylindrical lens: 1954
Deltrap: QO corrector for spherical aberrations: 1964
Thompson: QOQOQOQ : 1968



Spherical cathode and detector reduces field curvature
Octupole corrector reduces this further

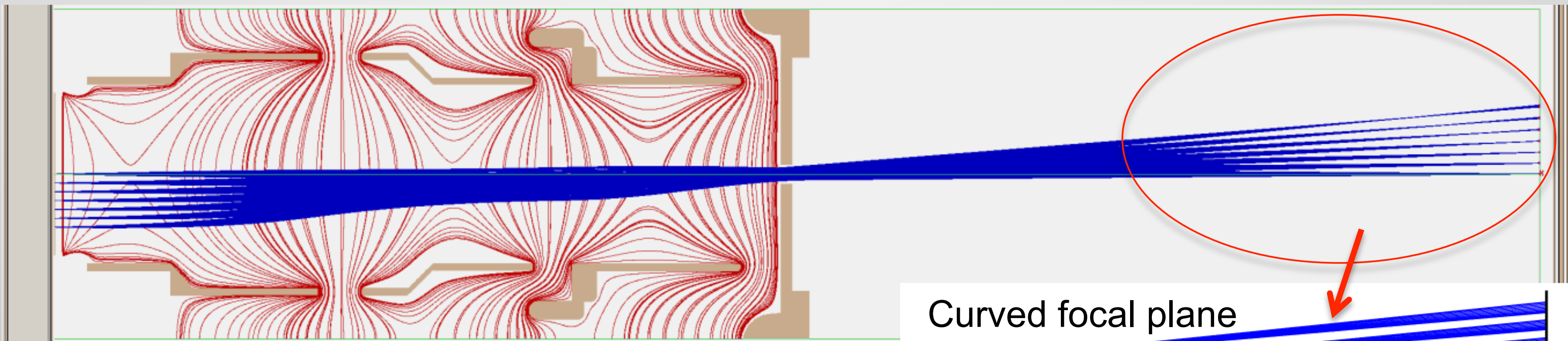


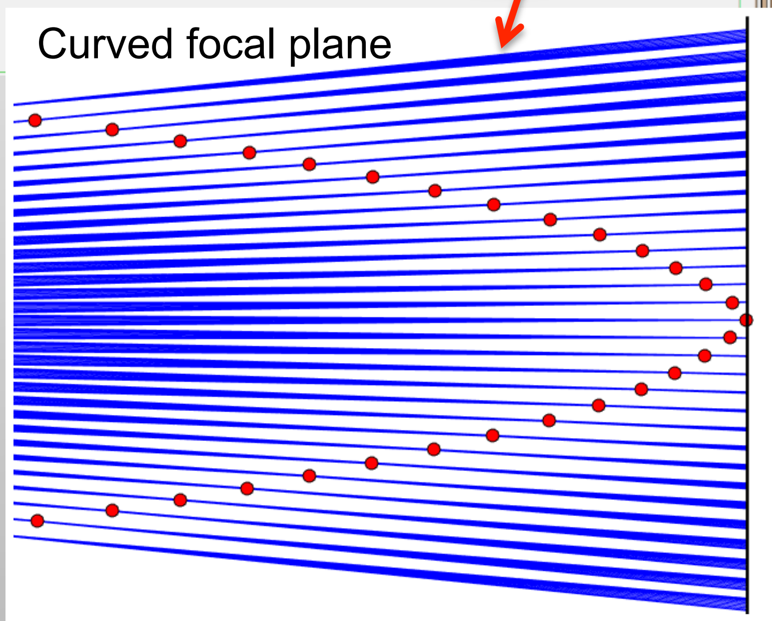
The octupole lens imposes astigmatism, but as it is located where the beam is elliptical it only applies in 1D as there are no rays in the other direction! ⇒ Corrects field curvature

Ultimately we may go to a differentially magnified tube design if the reduced space charge more than compensates for the intrinsically longer transit time required for 2 image relays

We have implemented DISC and PJX in both Simion and CST. The EG&G tube will follow soon but for the rest of the talk I will concentrate on the interim DISC solution

Interim solution: Improve DISC resolution while we develop a new high dynamic range DIM based camera





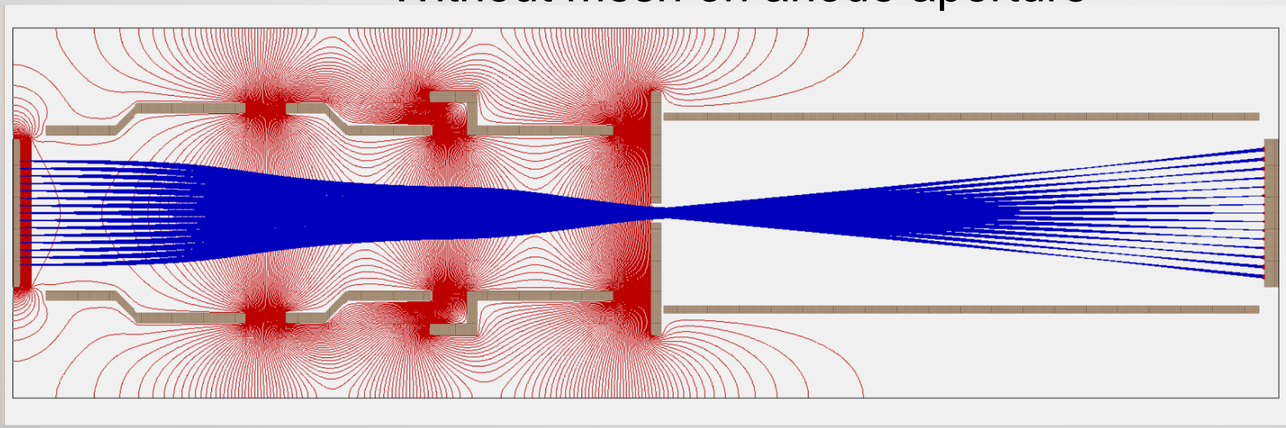
DISC's main problem is field curvature:

Find the focal plane by launching rays from several points along cathode

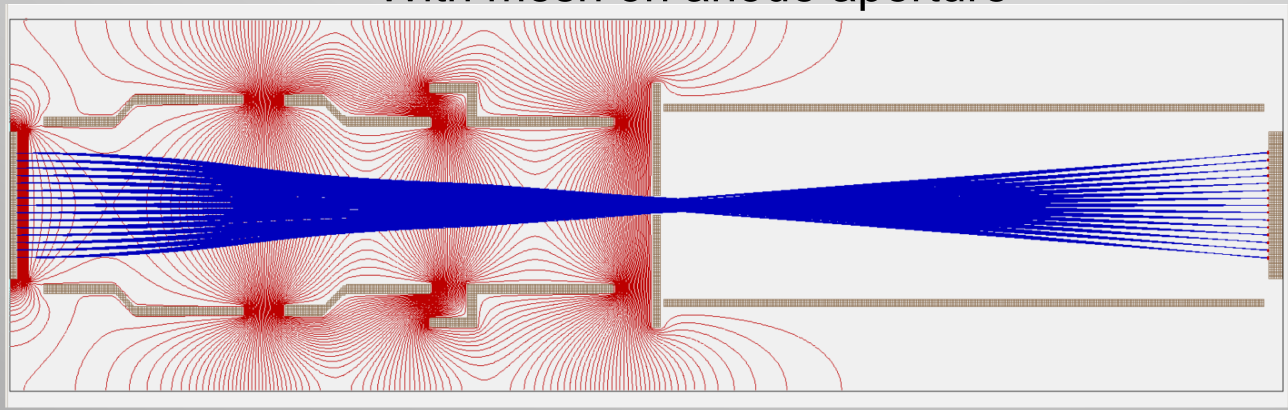
Solution is found by fitting the locus of the minima formed by each bundle of rays

The lens produced by the anode aperture significantly enhances intrinsic field curvature. A mesh on the aperture eliminates this lens and reduces field curvature

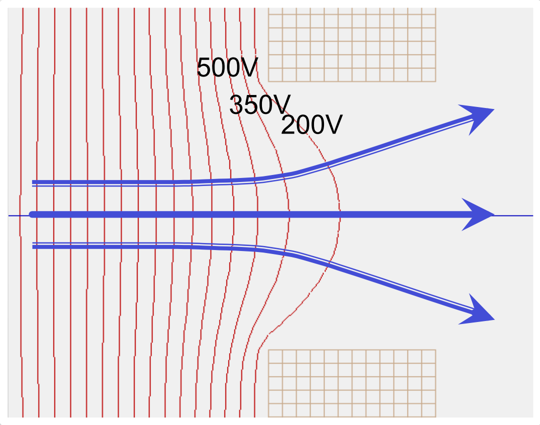
Without mesh on anode aperture

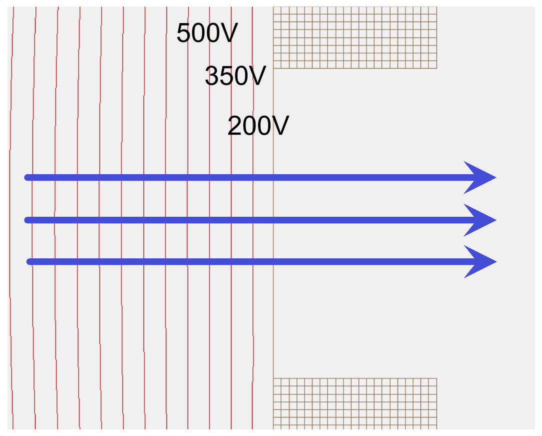


With mesh on anode aperture

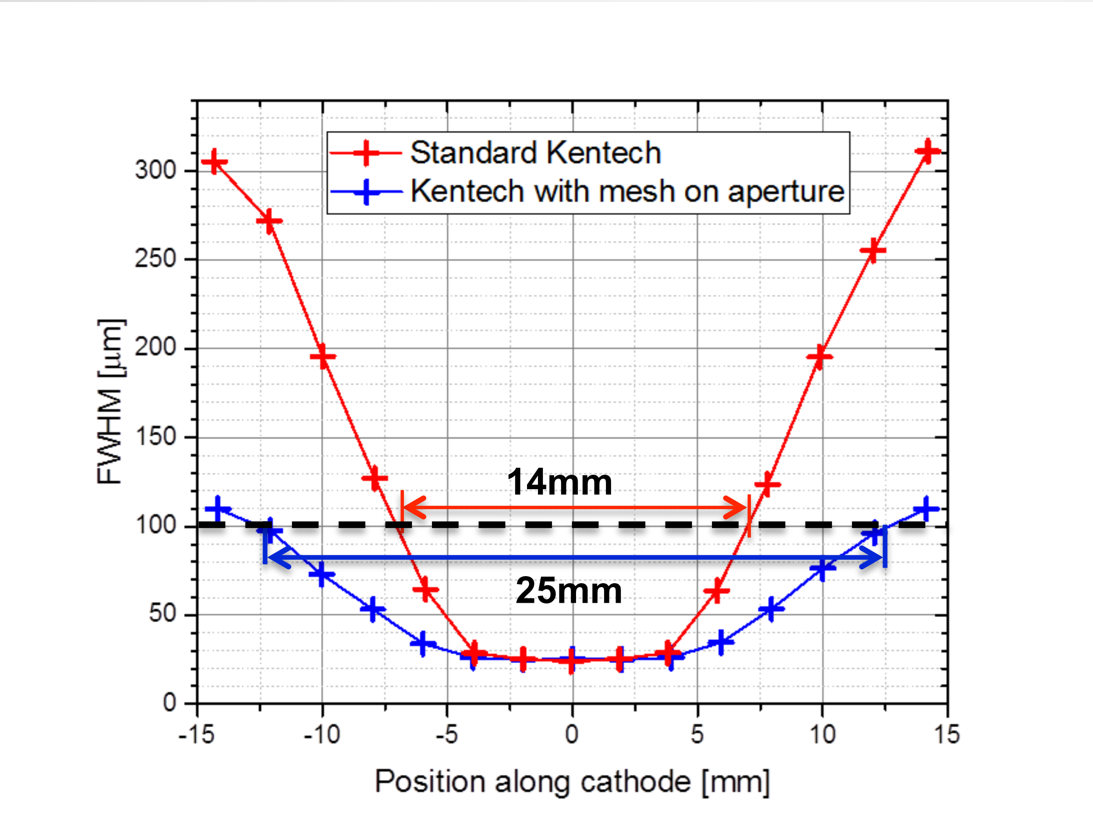


Equipotentials and trajectories in the anode aperture region

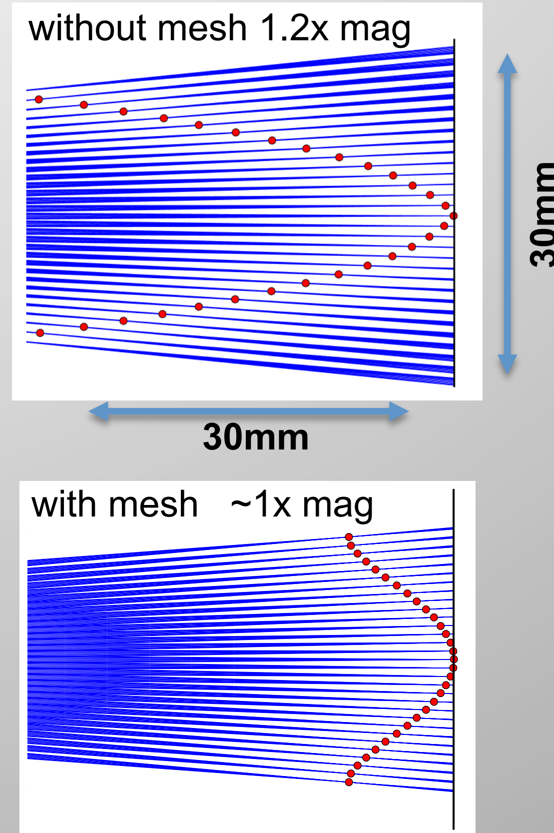




Reduced field curvature increases useful length of the photocathode

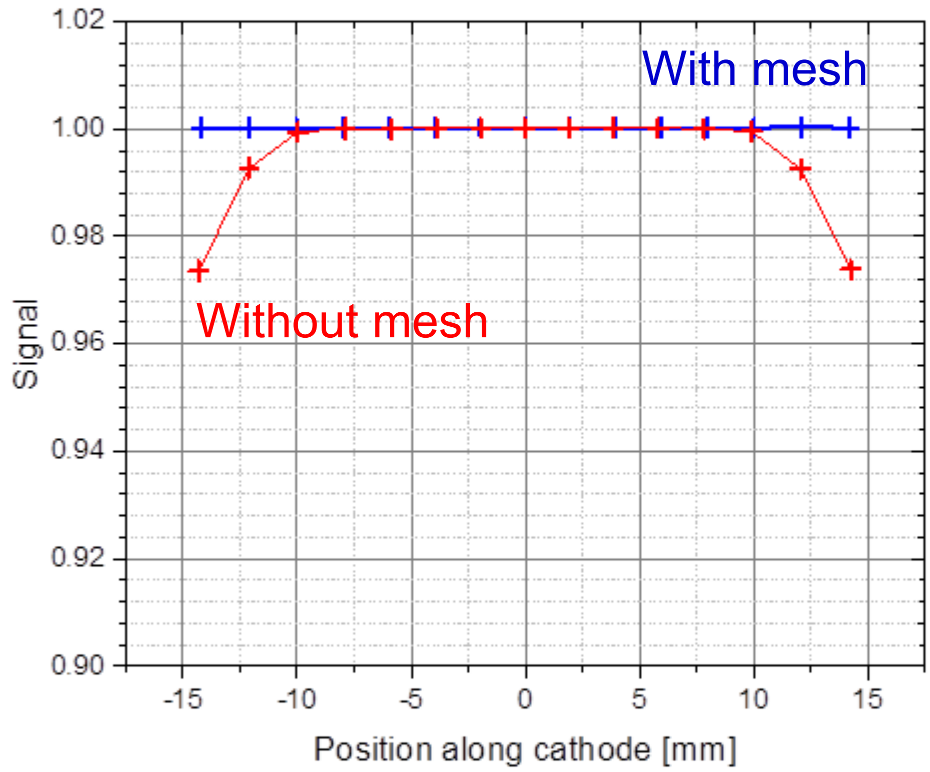


Field curvature at detector:



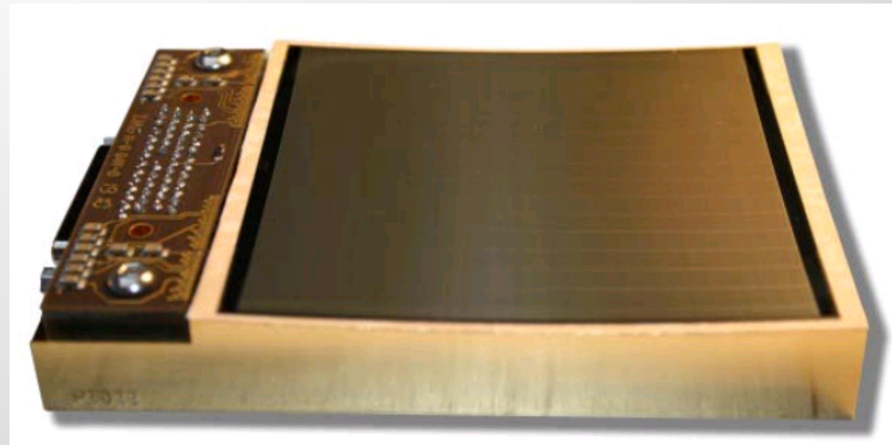
Increases region with 100µm res from ~14mm to ~25mm
Number of swept channels increases from ~150 to ~250

Relaxing the fields in the focus region also reduces vignetting



And straighter trajectory likely reduces other aberrations too

We can compensate for residual field curvature by curving the detector

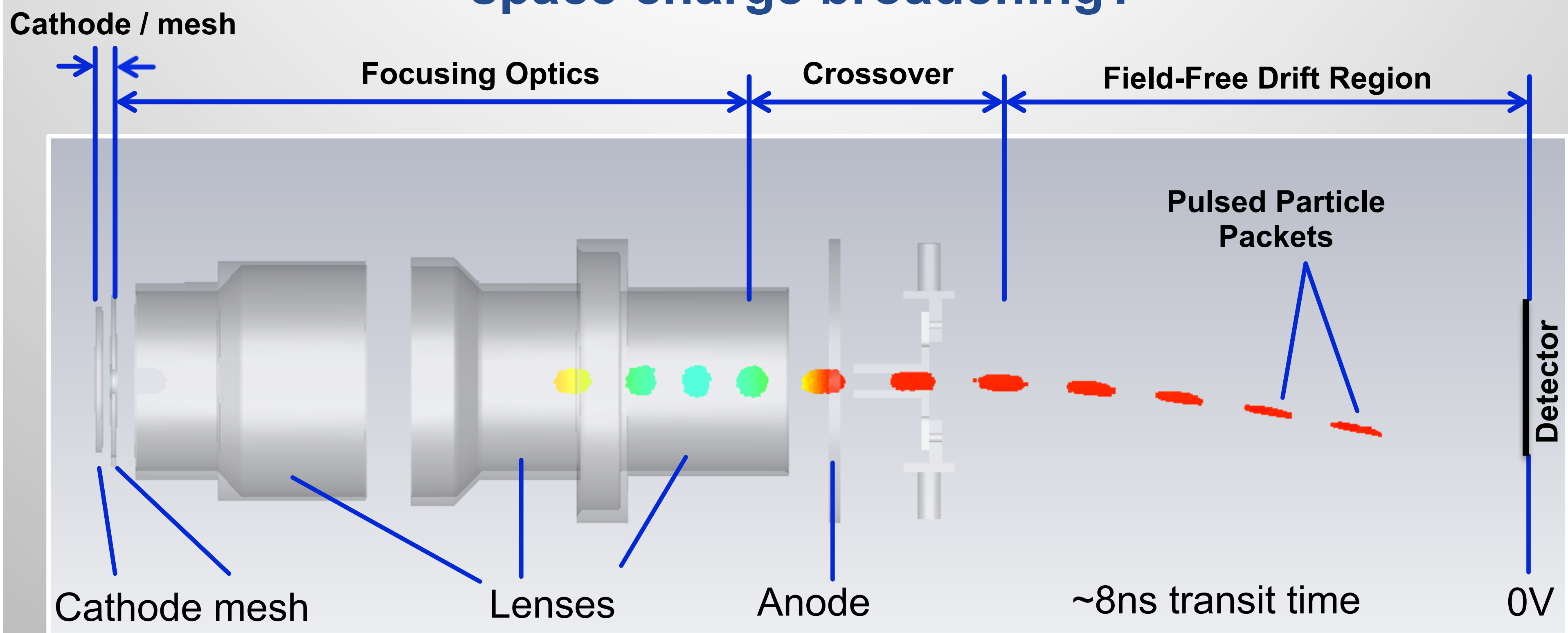


Spherically and cylindrically bent CCDs (Andanta) and CMOS sensors (Sony) are becoming available (back thinned)
Cylindrical may be sufficient

Unfortunately only Sony's long radius sensor has been demonstrated so far

Alternatively a toroidal fiberoptic (matched to the sweep radius in time direction and field curvature radius in the other) coated with an optimized phosphor and couple to an optimized CCD may be sufficient

Which regions in the streak tube contribute most to space charge broadening?



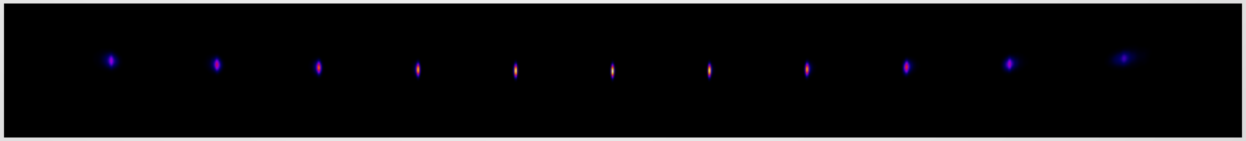
Ultimately we need to minimize space charge to increase the dynamic range

We have performed several PIC end to end simulations with space charge enabled only for certain regions in the tube. This lets us identify the regions that contribute most to space charge so we can focus effort to reduce it

Space charge degrades resolution when charge density is highest (like at the anode aperture) or moderately high for a long period (so need to keep transit time low)

With space charge switched off for the entire run we just observe the geometric distortion of the streak tube

space charge switched off



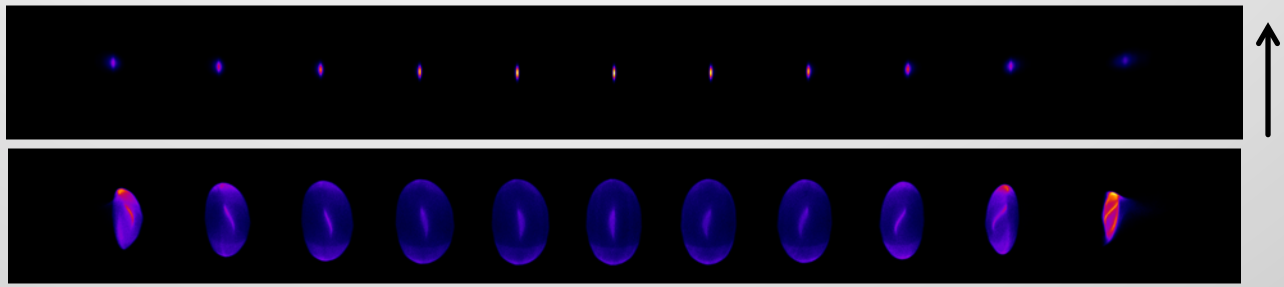
Time

Position along cathode

Same number of electrons, space charge switched on throughout the simulation

space charge switched off

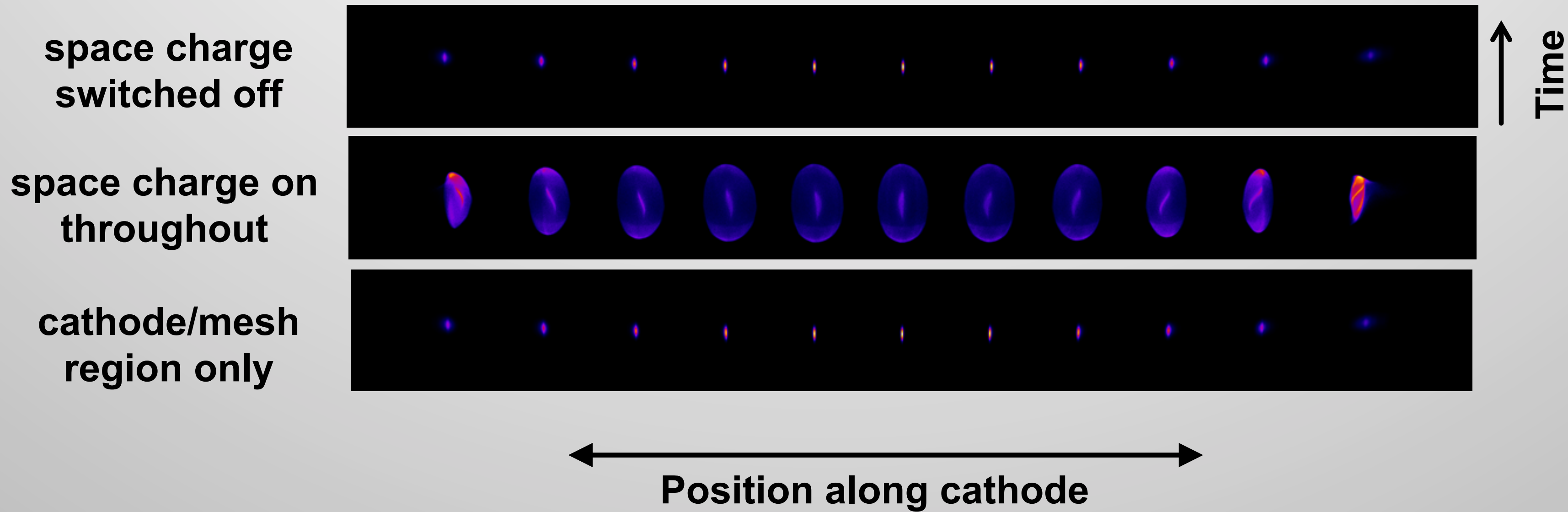
space charge on throughout



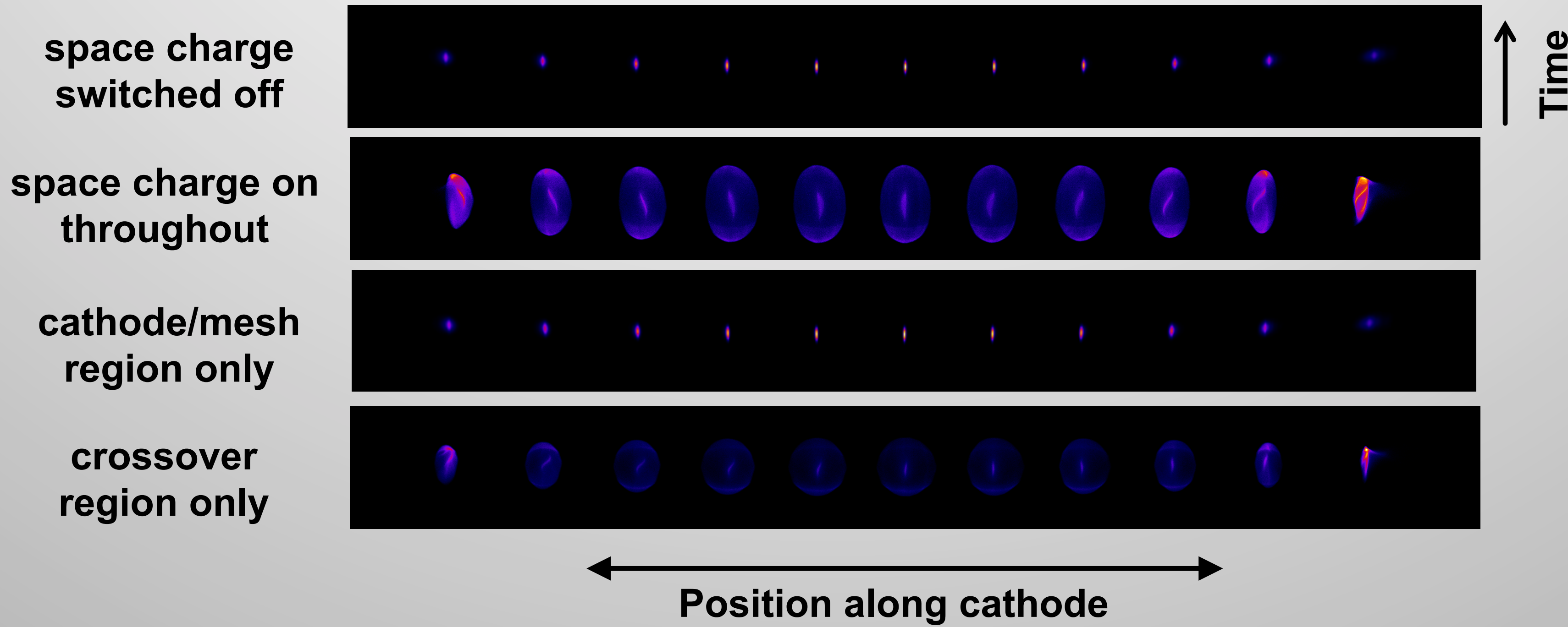
Time

Position along cathode

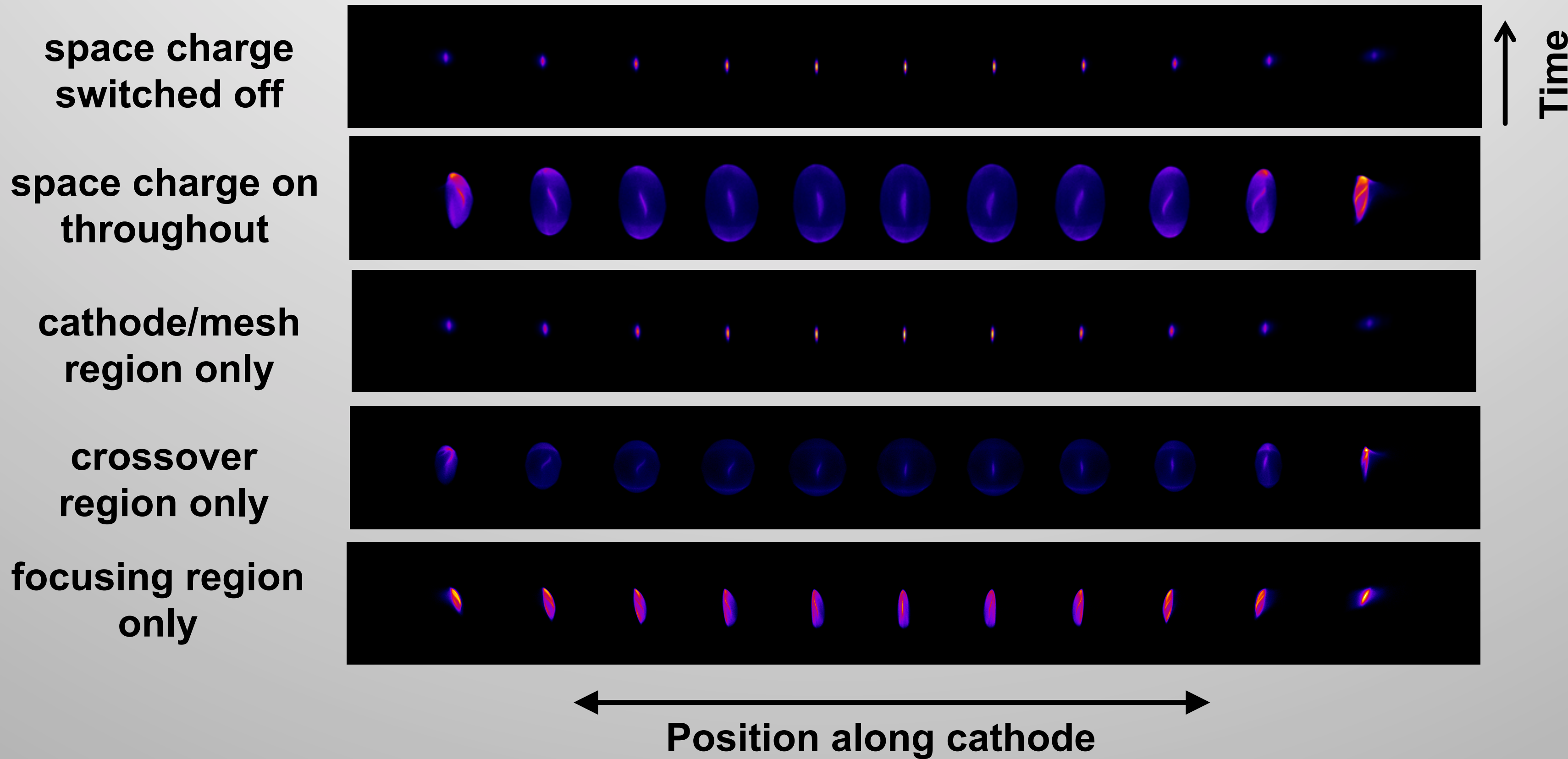
Space charge on for cathode mesh region only, contributes surprisingly little (given the electrons spend time at low E)



The crossover region clearly contributes a large fraction of the total space charge effect

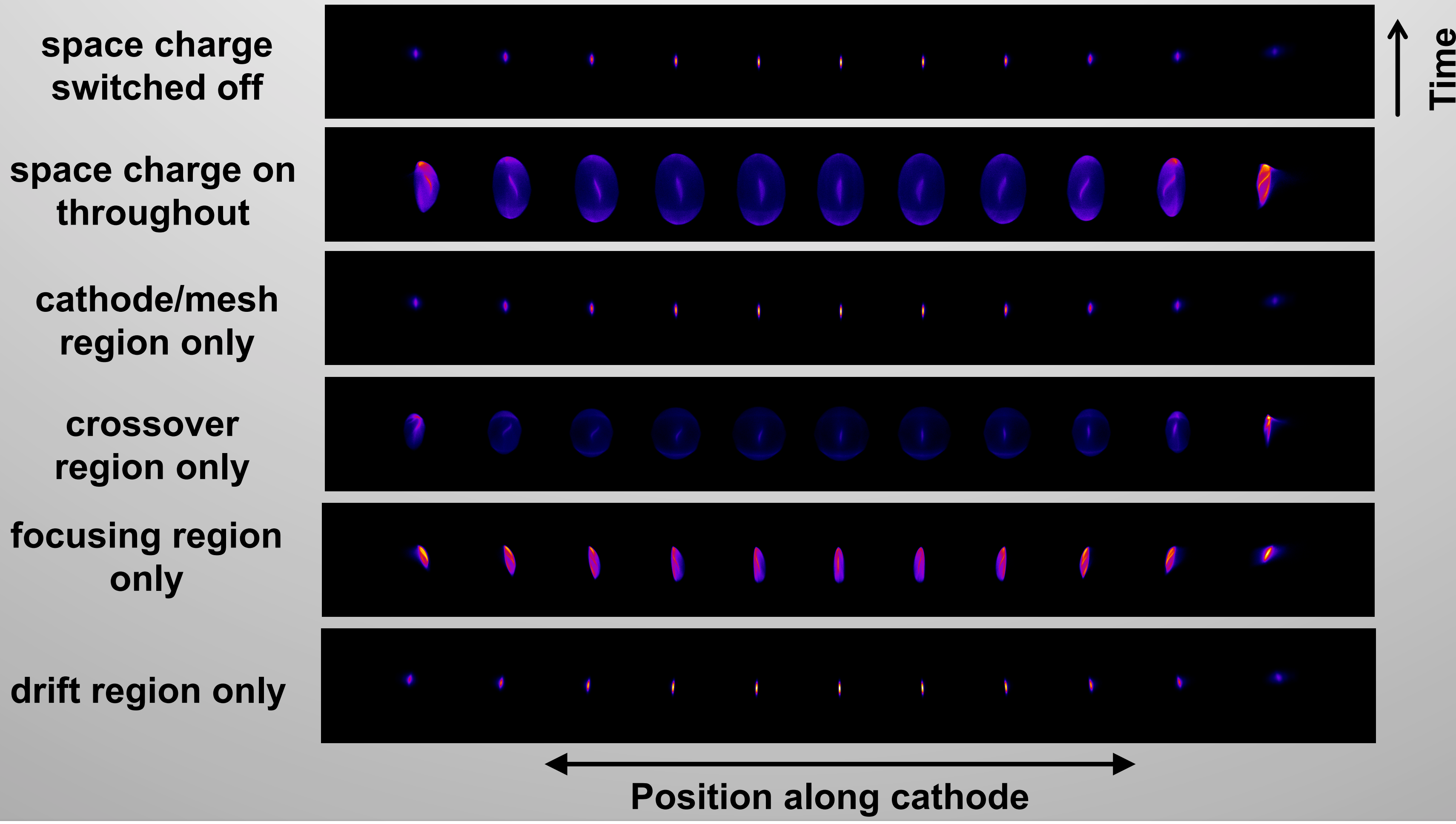


The focus region contributes most of the residual space charge effect. Likely enhanced by transit time

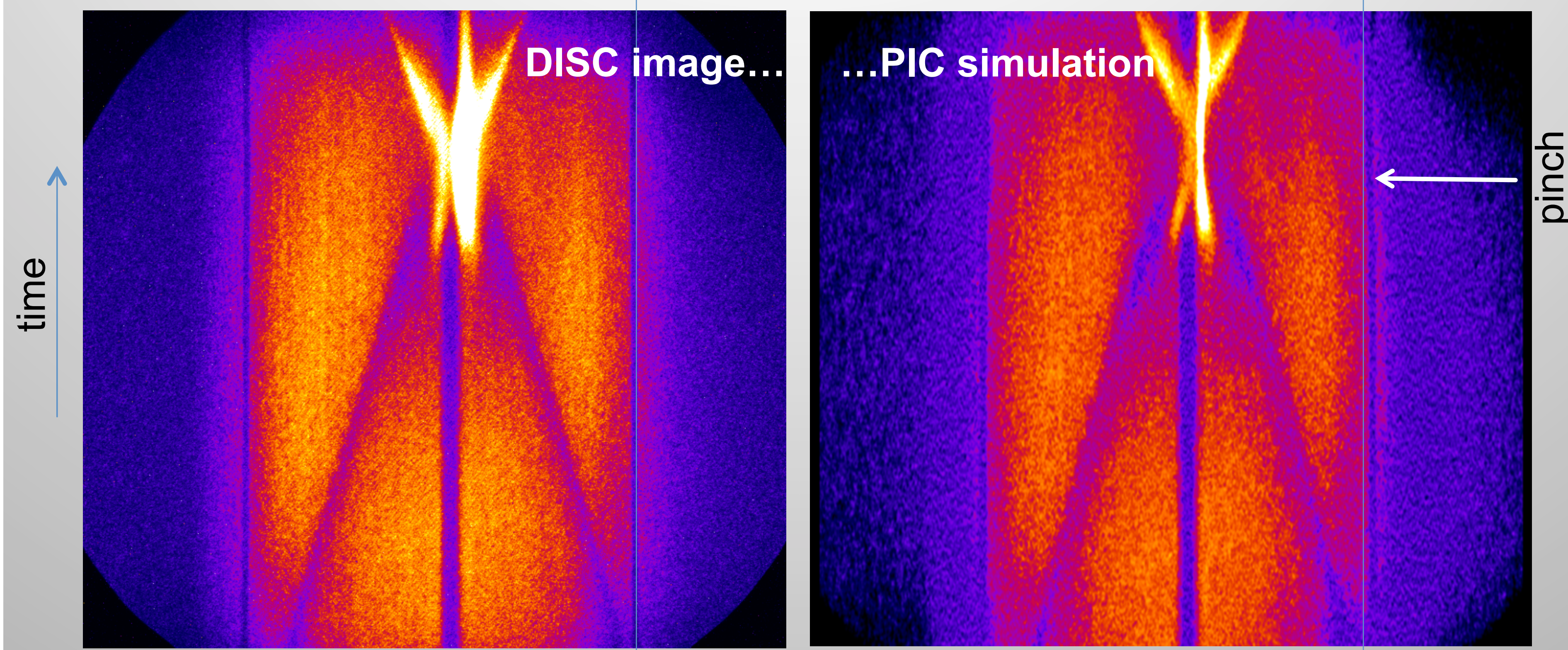


The drift region contributes relatively little. Space charge associated with the aperture dominates blurring as expected

(although keeping the flight time low is also important)



We now have a tool to simulate the effect of space charge on pre-shot simulations on NIF



This example uses DISC image from a convergent ablator shot

Increased charge density a little to induce pinching at bang time

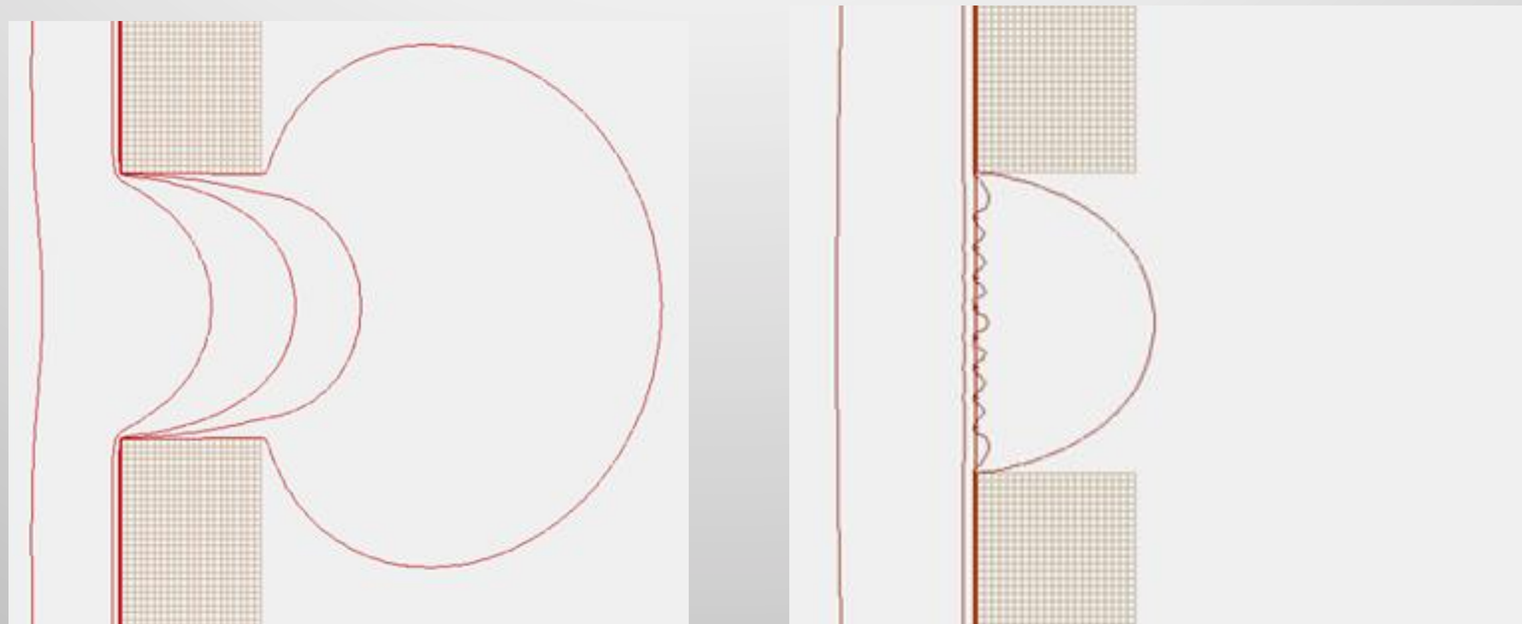
Will enables us to go into experiments with a better expectation of outcome

Summary

- **Can we improve DISC?**
- Yes, we have identified an interim solution for an improved spatial resolution x-ray streak camera
- Expect useful cathode length increase from ~14mm to ~25mm
- Corresponding increase in number of resolution elements from 150 to 250
- Confirmed crossover contributes most to space charge (as opposed to the extraction region)
- We can now perform realistic end to end dynamic streak simulations including space charge, without the need for super particles and in a reasonable time
- We are now in a position to start to quantify the uncertainty in streak data

Backup slides: streak

Equipotentials at 1000V, 100V, 25V, 10V, 1V



Optimizing the PIC mesh

- Divide the problem into regions with dissimilar field gradients to allow efficient mesh generation:
    - high mesh density in cathode / anode region, sweep
    - Lower mesh density in drift region

  - Establishing an effective mesh for DISC was one of the goals Jeremy successfully achieved for his summer student project

  (When the particle distribution in the image plane is no longer sensitive to increased mesh density within the resolution requirement, the density is sufficient)

- Maintaining high mesh density throughout a single problem may not be practical:
  - Break the model into separate regions to allow variable mesh density -> multiple decoupled simulations output of one is the input to the next
  - (So far not required for DISC but this might change with curved optics)

- Also identify and remove irrelevant features from cad model to enable more efficient mesh generation (like threads!)

A system of 4 quadrupoles and 3 octupoles is a standard arrangement to correct for spherical aberration in electron microscopes

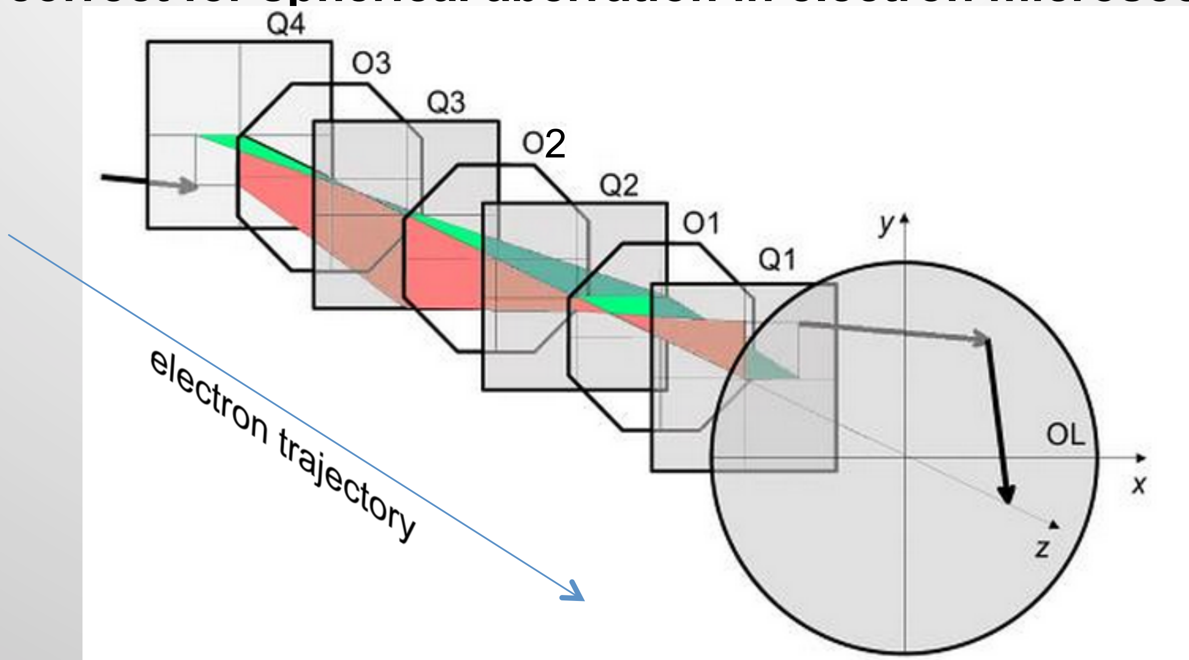


Figure from handbook of electron optics

Uses astigmatism in 1D in x, 1D in y, then 2D in x and y with opposite sign

Q4 forms an elliptical focus along the y-axis at the O3 plane
O3 induces negative spherical aberration C_3 in the y direction
Q3 (opposite polarity) undoes the elliptical distortion of Q4 so a round beam enters O2 (ignore for now)

Q2 forms an elliptical focus along the x-axis at the O1 plane
O1 induces negative spherical aberration C_3 in the x direction
Q1 (opposite polarity) undies the elliptical distortion of Q2 so a round beam enters OL

Why O2?
Q4O3 / Q2O1 correct spherical aberration in x and y but introduce fourfold astigmatism A_3
O2 corrects this by inducing 4-fold astigmatism with opposite sign $-A_3$ (because the beam is ~round at O2 rather than elliptical like at O1 and O3)!

CST PIC solver details

Calculates field generated by charged particles at each time step

Field estimated at discrete points, particles tracked in continuous phase space

Field calculation uses leapfrog updating scheme (v_{xyz}, s_{xys}, v_{xyz}, $s_{xys,}$ …)
Self-consistent method for particle tracking, interpolates fields to provide feed-back on the particle motion and calculate particle currents for the field computation.

Stable with sufficiently small time step (well defined and related to the minimum mesh)

Based on MAFIA4 [1] a general purpose electromagnetic simulation software package. Uses finite integration technique: discretisation scheme which defines Maxwell's equations in integral form on a dual non-co-ordinate grid doublet. The non-co-ordinate discretisation scheme was introduced as an extension of the standard co-ordinate scheme in order to improve the capability of the grid to approximate curved boundaries. A discretisation of space into the doublet results in the Maxwell's Grid Equations [2]

[1] The Electromagnetic Simulation Software Package MAFIA 4 M. Clemens *et al.*, Computational Electromagnetics and Its Applications, Proc (ICCEA '99)
[2] Time domain electromagnetic field computation with finite difference methods Weiland T, *International Journal of numerical modelling: electronic networks, devices and fields* **9** 295 (1996)