Bigger, Better, Faster, More: High Power Proton Accelerator Development at the Front End Test Stand

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John Adams Seminar

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Abstract

"High power proton accelerators (HPPA's) with beam powers in the megawatt range have many possible applications, including drivers for spallation neutron sources, neutrino factories, accelerator driven sub-critical reactors and nuclear waste transmuters. These applications typically propose beam powers of 5 MW or more, compared to the highest beam power achieved from a pulsed proton accelerator in routine operation of 0.2 MW at the ISIS spallation neutron source at RAL. Achieving such high powers is not straightforward: significant reductions in beam losses – below 1 W/m – are required, coupled with the necessary increase in beam current and quality.

The Front End Test Stand (FETS) is an accelerator test assembly currently under development at RAL, in collaboration with Imperial, Warwick and the Basque University, Bilbao. The aim of FETS is to demonstrate the production of a high quality 60 mA, 2 ms, 50 Hz, chopped H^- beam at 3 MeV. This requires the development of a high current H^- source, an accelerator section based on RadioFrequency Quadrupoles (RFQ's), a fast beam chopper and corresponding beam transport. Also under development are a series of novel beam diagnostics. This talk will focus on the accelerator background behind FETS and where the current technical challenges lie."

The Lesson For Today…

- Why is low emittance and high beam quality important?
- How do we create our H^- beam?
- How do we measure it?
- How do we bunch and accelerate it?
- How do we chop out the parts we don't want?

From Luminosity to Emittance

High energy physics with colliding beams is like banging two bags of potatoes together and trying to get out chips…

The key quantity for the experiment is Luminosity, L:

$$L = \frac{k_b N_b^2 H_D f_r}{4\pi\sigma_x^* \sigma_y^*}$$

k_b: number of bunches, N_b: particles per bunch

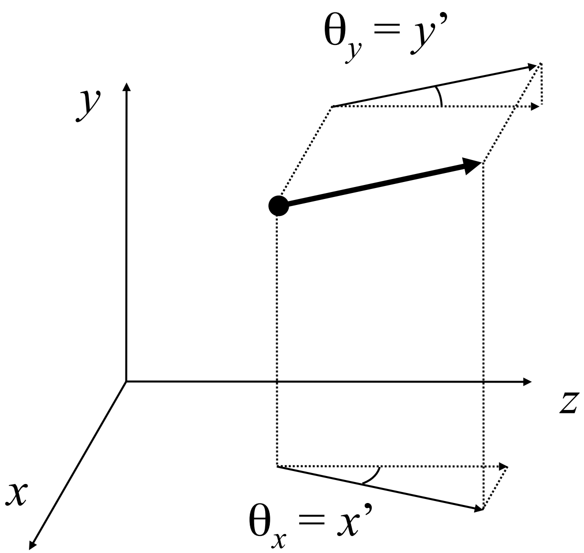
f_r: revolution frequency, H_D: pinch enhancement

σ_x^*/σ_y^*: beam size at IP

Luminosity is a measure of the "interaction rate" of the collider. To get high luminosity, you need low emittance…

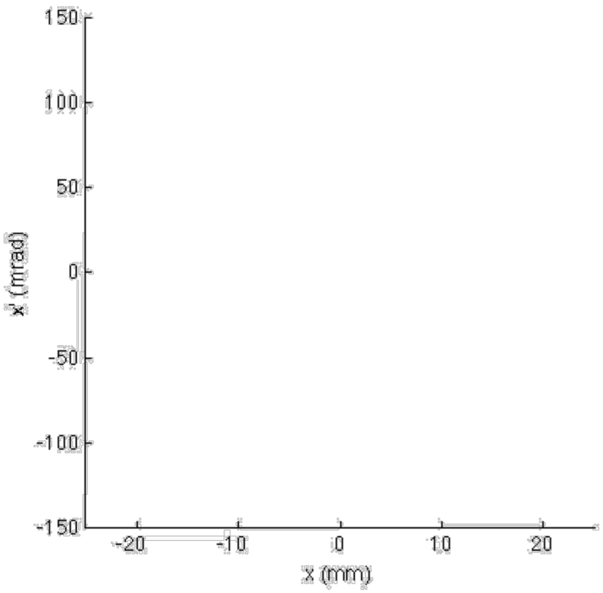
Definition of Emittance

Define position of each particle in transverse phase space: $\varepsilon_x(x,x')$, $\varepsilon_y(y,y')$



Each particle has coordinates in 6-D: x, x', y, y', z, E.

Make phase space plot of all particles:



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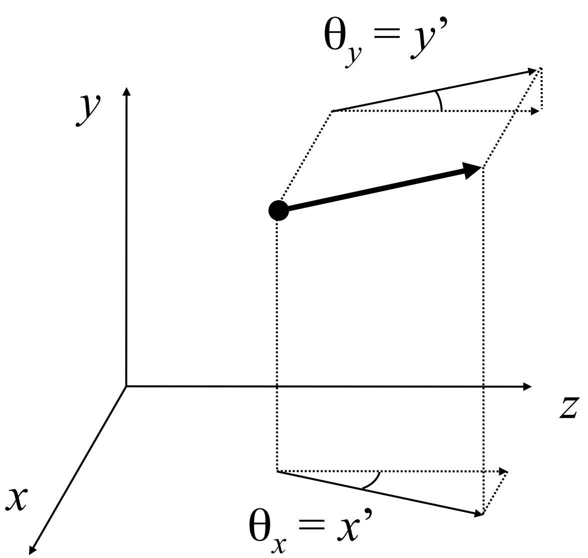

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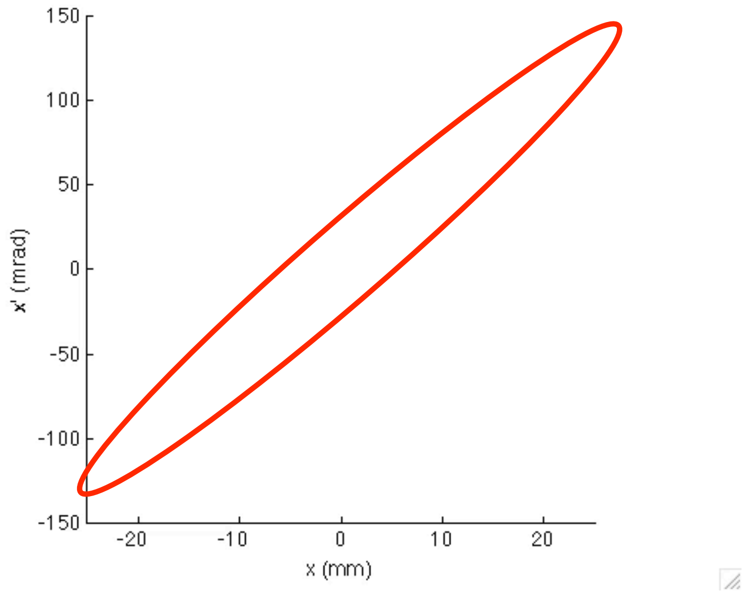
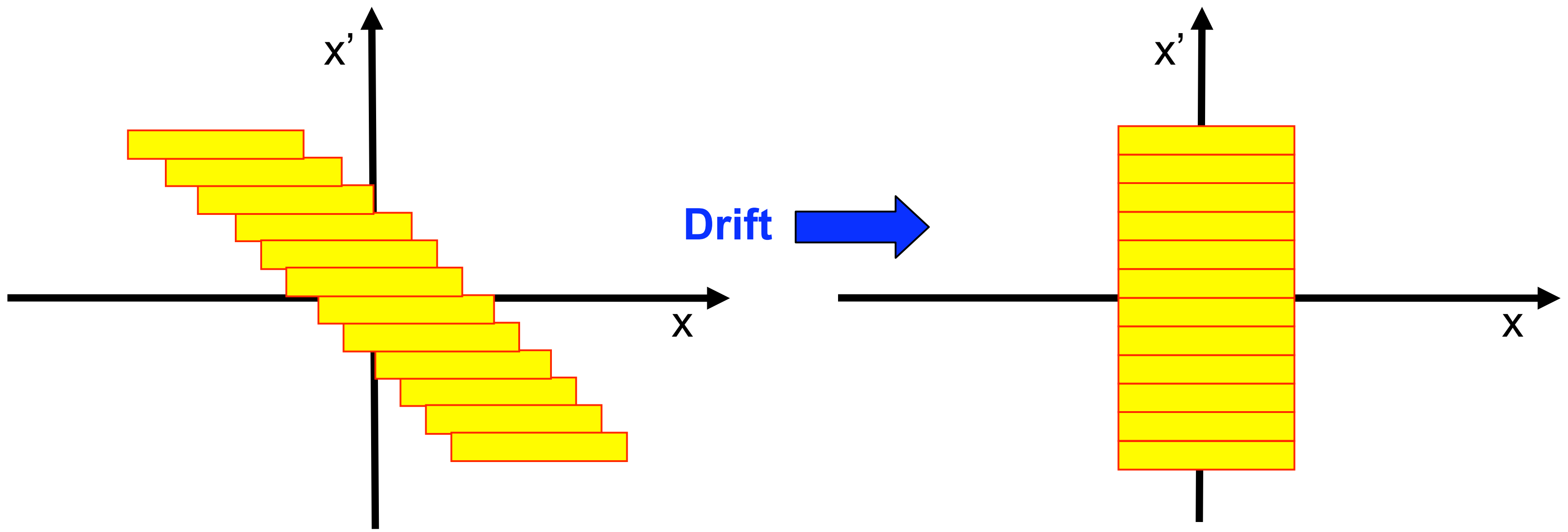
Make phase space plot of all particles:



Area of ellipse gives ε_x & ε_y.

Liouville's Theorem



Liouville's Theorem states that, for a "conservative system" (ie. an accelerator beamline), phase space volume is conserved. In other words: things can only get worse!

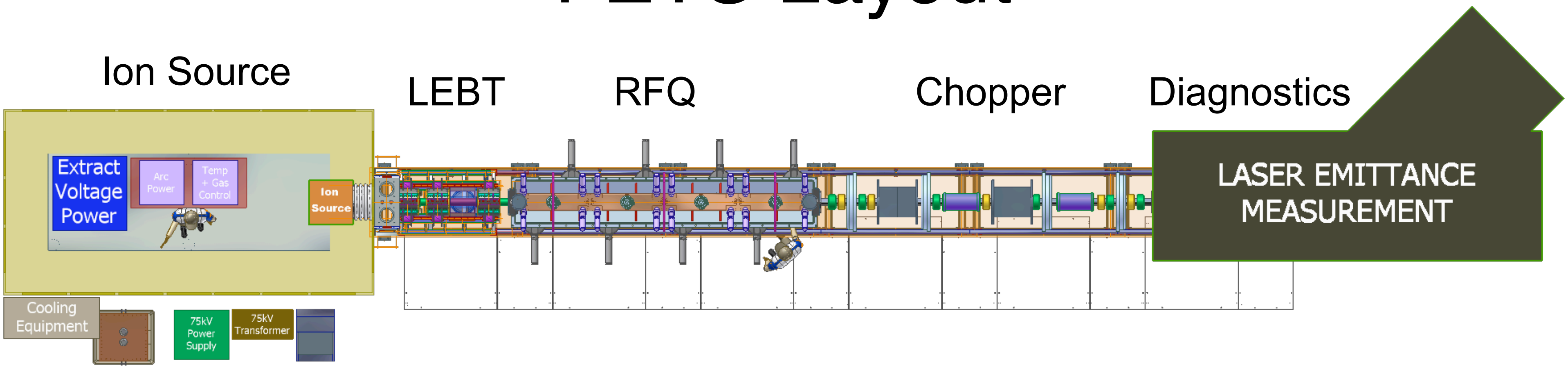
High Power Proton Accelerators (HPPA's)

- New generation of High Power Proton Accelerators (HPPA's) required for:
  - neutron spallation sources.
  - Neutrino Factory.
  - Accelerator Driven Systems (ADS): transmutation, power reactor systems.
- Absolute loss levels in future machines (1 – 10 MW beam power) must be similar to that on ISIS (160 kW beam power): reduce fractional loss by orders of magnitude.
- A significant reduction in beam loss by chopping beam in injector linac so as to precisely fill the ring RF bucket: no trapping loss, much reduced extraction loss.
- This is where FETS comes in…

The Front End Test Stand (FETS)

- Low emittance essential to minimise beam losses and maintain beam current and quality.
- High beam quality essentially set by front end of accelerator: must get it right first time…
- FETS will demonstrate the early stages of acceleration (0-3 MeV) and beam chopping required for HPPA's.
- FETS specification:
  - 2 ms pulse length.
  - 50 pps rep. rate.
  - 60 mA H^- beam current.
  - 'Perfect' chopping.
- H^- beam used for early stages of acceleration to make ring injection easier.

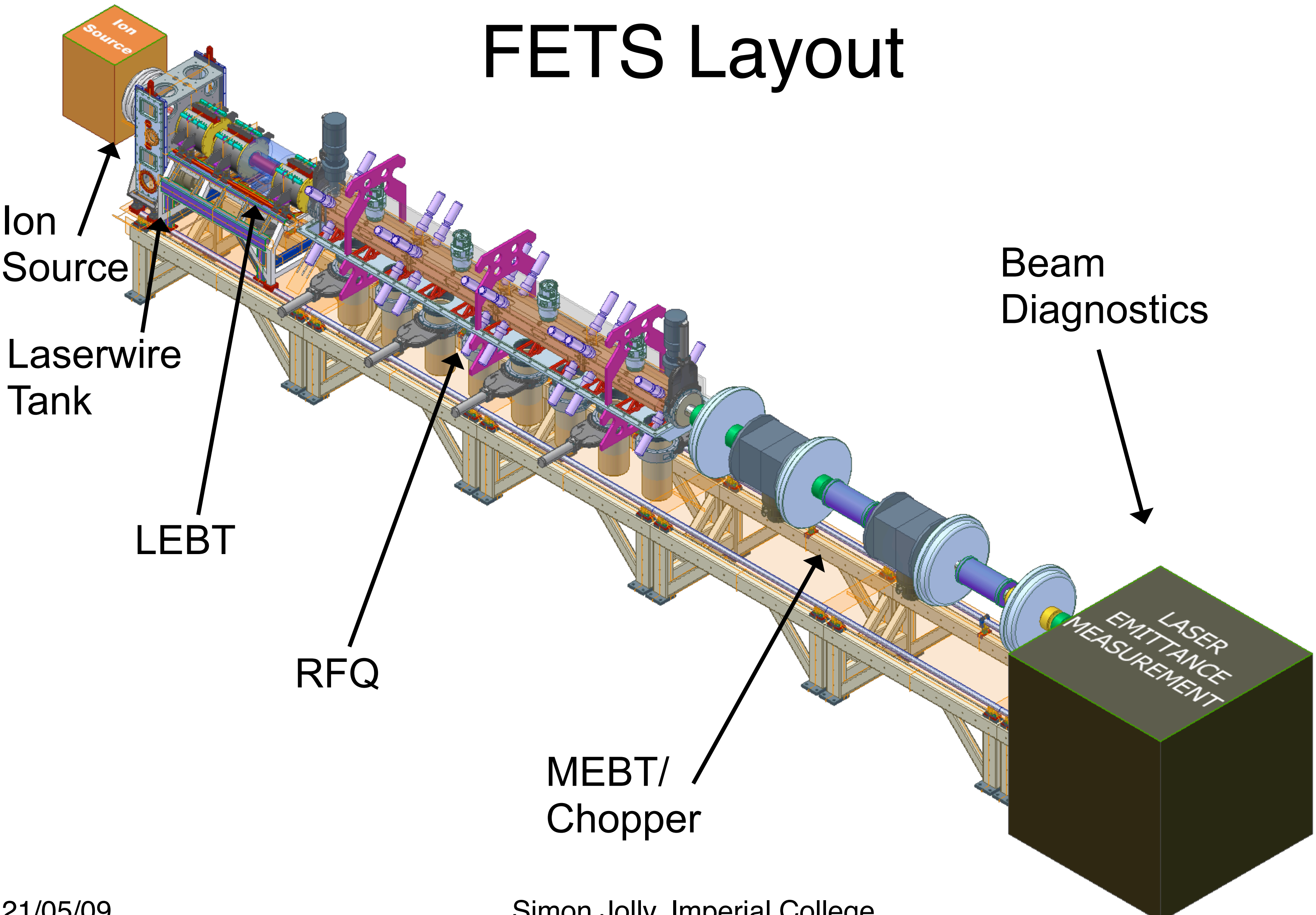
FETS Layout



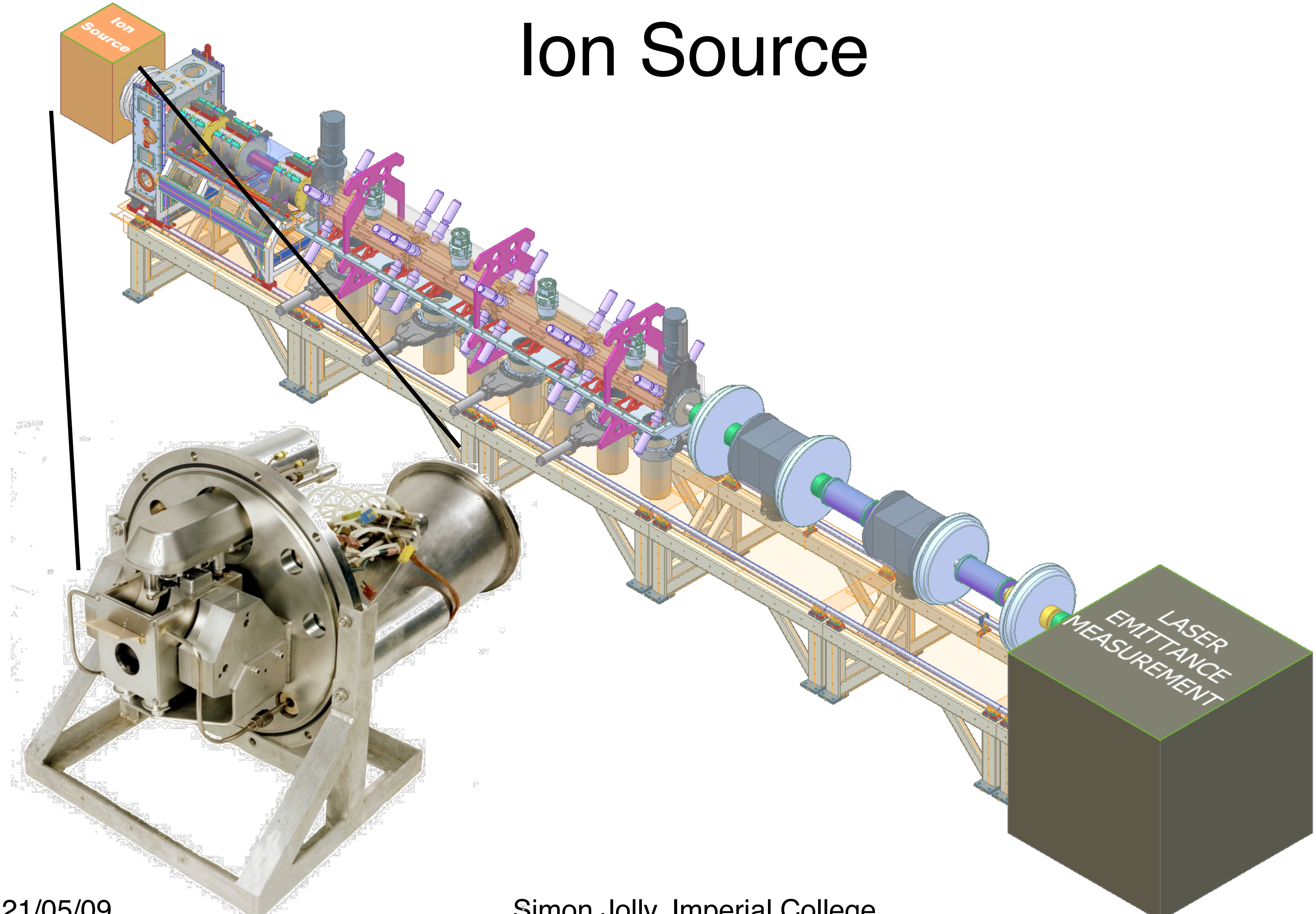
FETS main components:

- High brightness 70 mA H^- ion source.
- 65 keV 3 solenoid Low Energy Beam Transport (LEBT).
- 324 MHz, 3 MeV Radio Frequency Quadrupole (RFQ).
- Very high speed beam chopper & MEBT.
- Conventional and non-destructive diagnostics.

FETS Layout

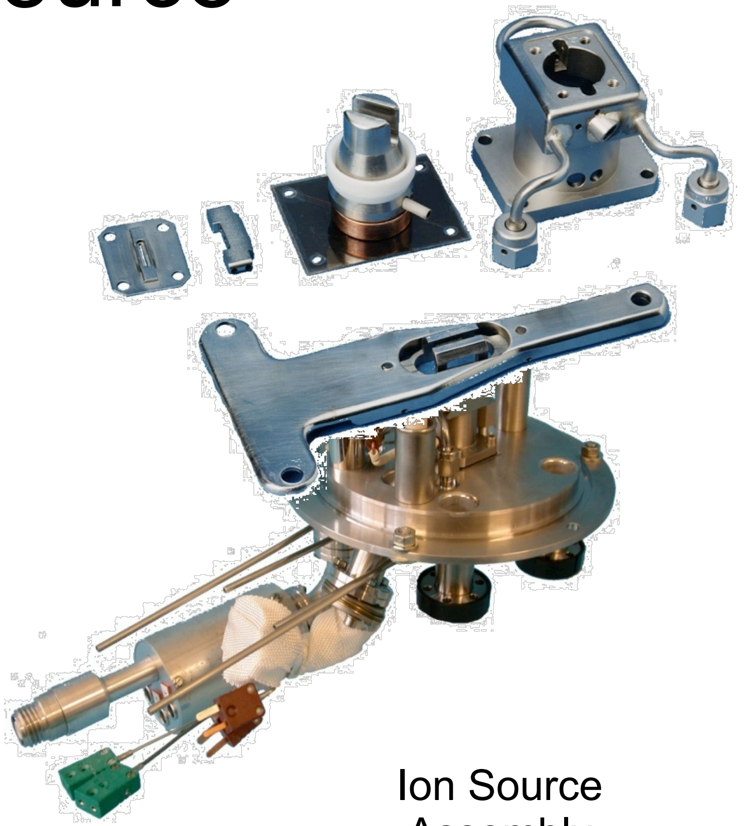

Ion Source
Ion Source
Laserwire Tank
LEBT
RFQ
MEBT/ Chopper
Beam Diagnostics
LASER EMITTANCE MEASUREMENT

Ion Source



FETS Ion Source

- FETS ion source design based on Penning source used for ISIS:
  - Surface Plasma Source (SPS).
  - 45 mA through 0.6×10 mm aperture (750 mA/cm^2).
  - 200-250 μs, 50 Hz ≈ 1% d.f.
- Need higher current, better duty factor, longer pulse…

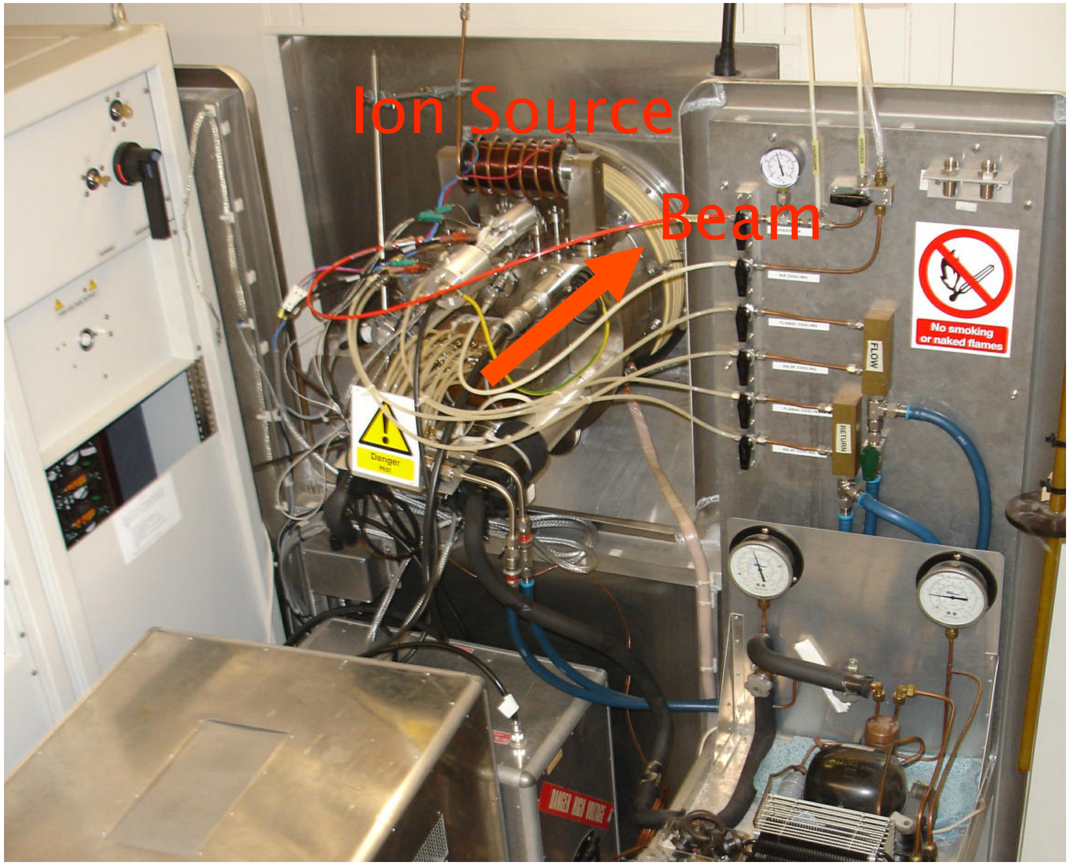


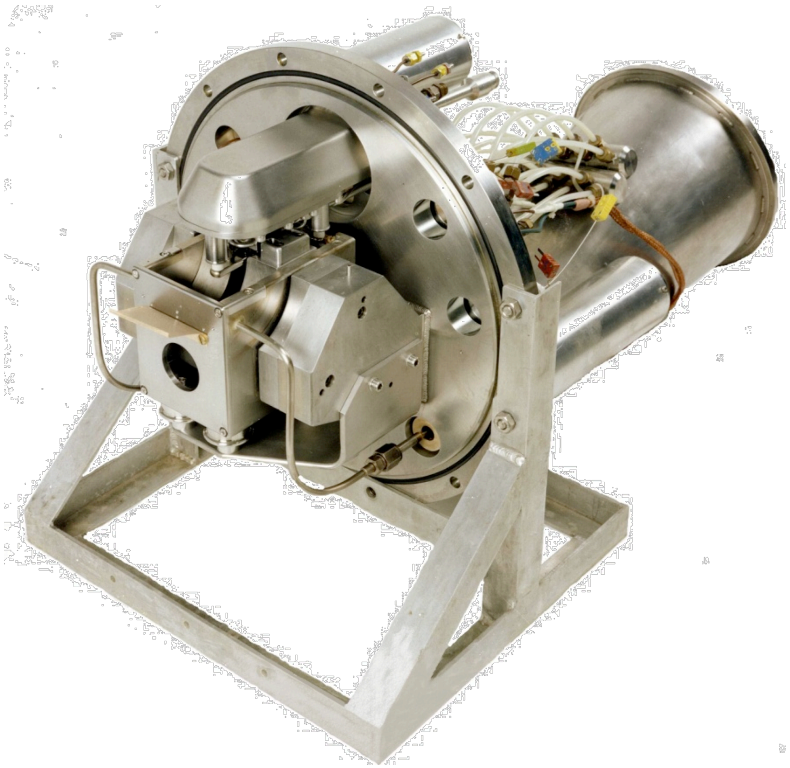
Ion Source Assembly

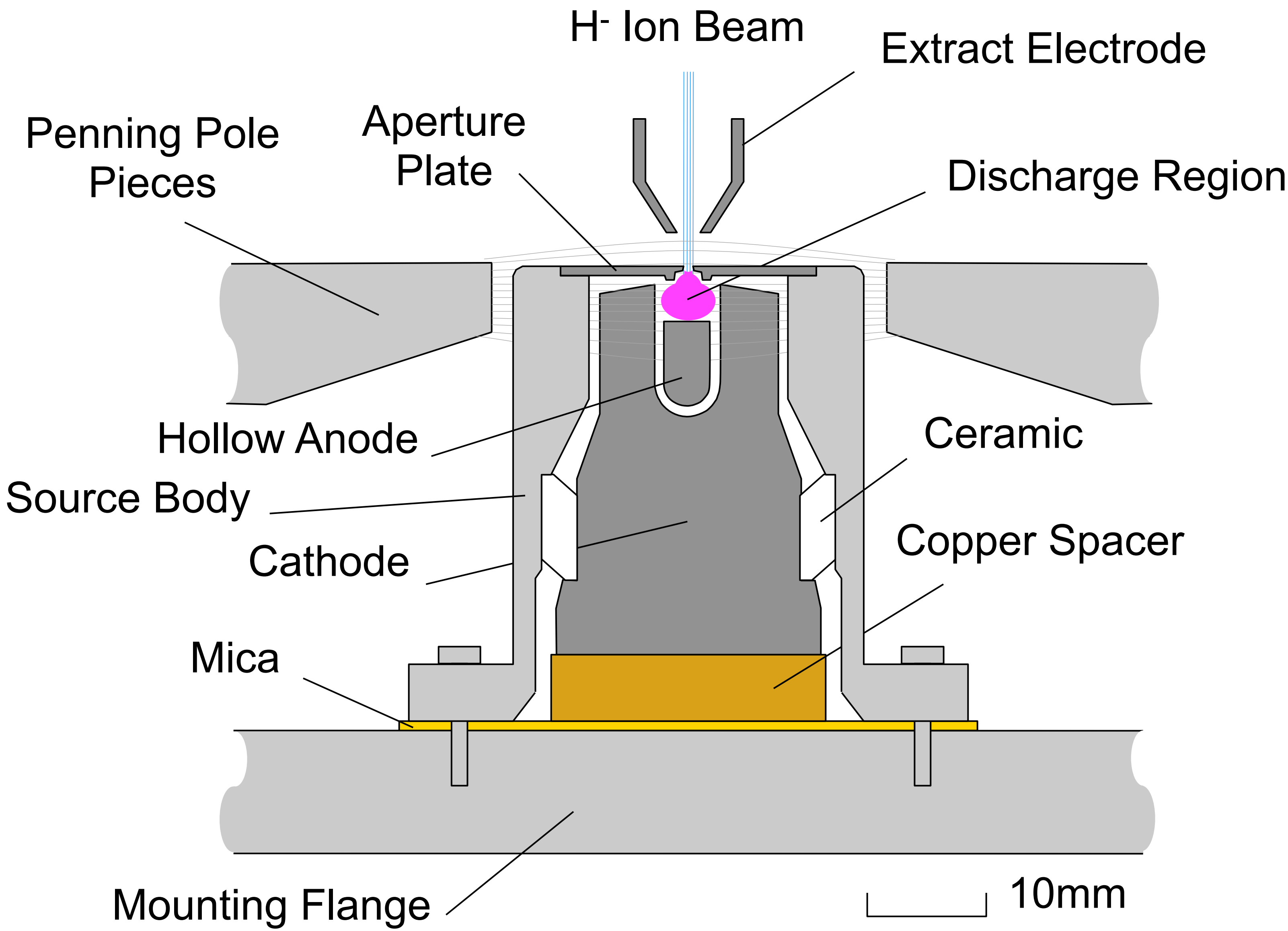
Ion Source Targets (vs. ISIS)

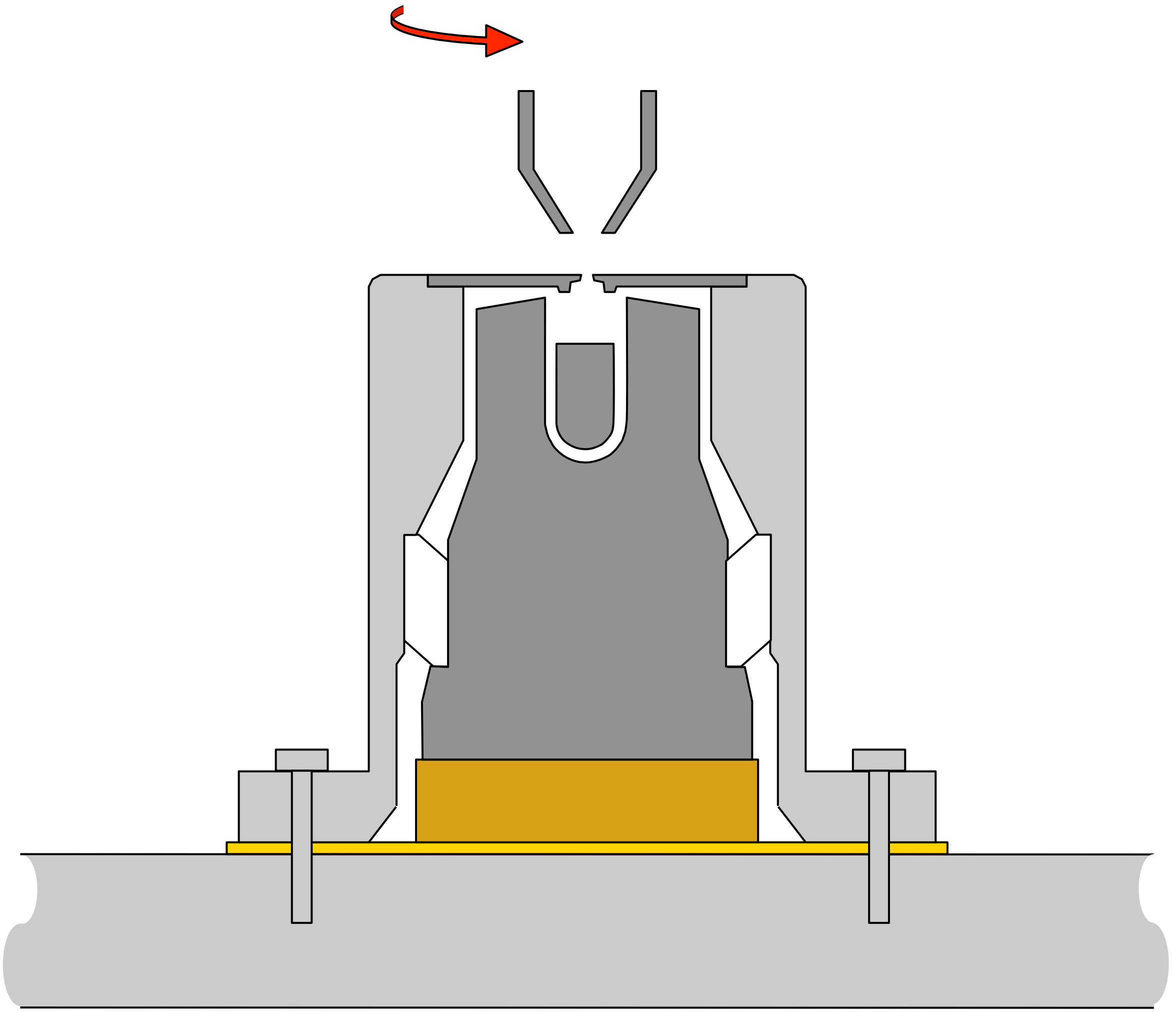
Beam Parameter	ISIS Ion Source (presently)	FETS Ion Source (desired)
Total Energy	35 keV	65 keV
Current	55 mA (but only 35 mA to LEBT!)	60 – 70 mA
Rep. Rate	50 Hz	50 Hz
Pulse Length	200 μs	2 ms
Normalised x emittance	0.9 π mm mRad	0.3 π mm mRad
Normalised y emittance	0.8 π mm mRad	0.3 π mm mRad

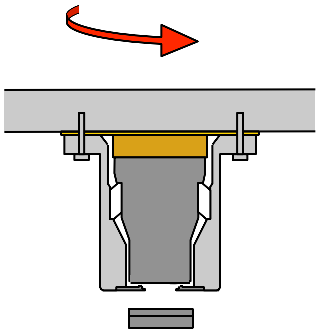
Ion Source Development Rig (ISDR)

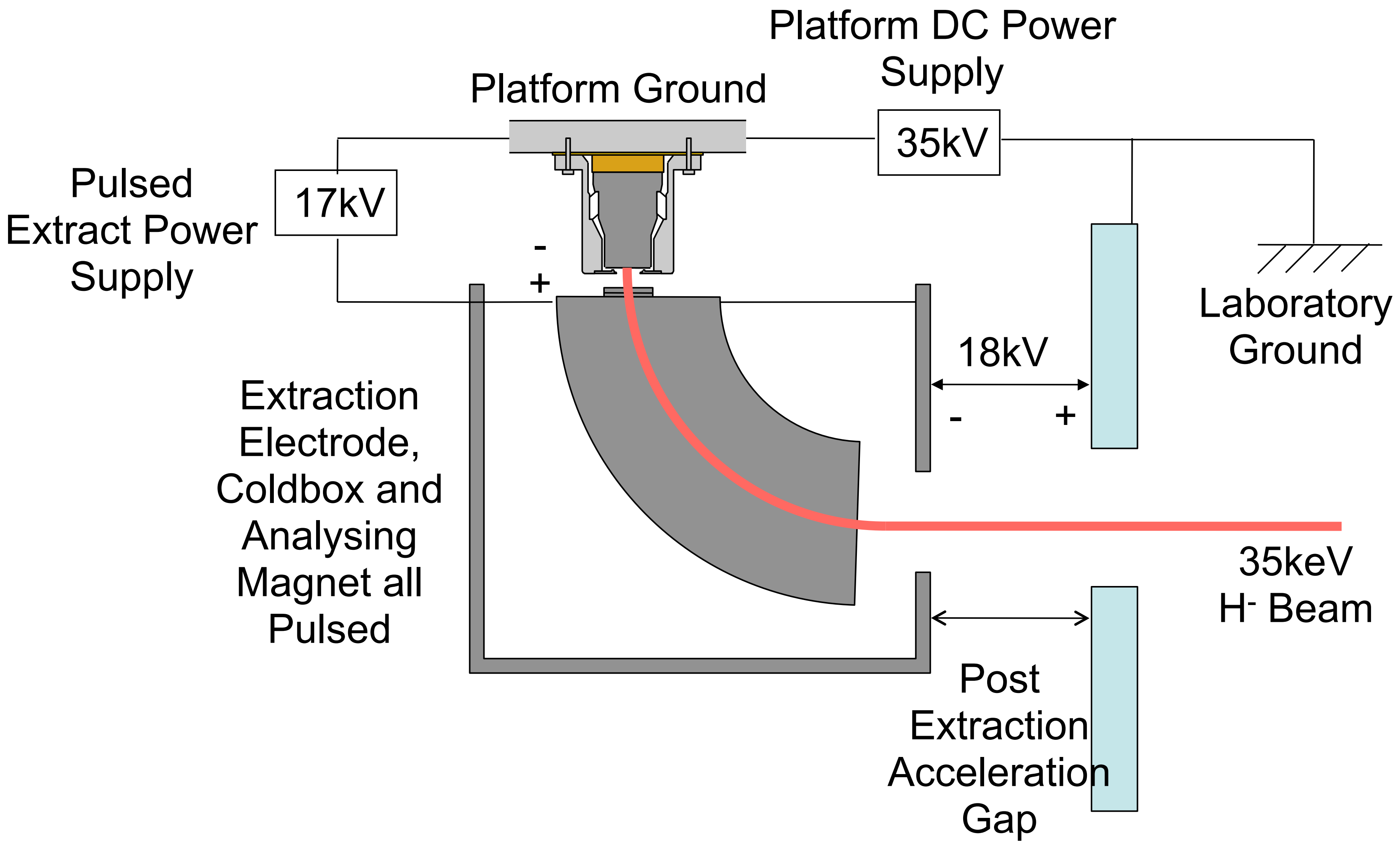





H- Ion Beam
Extract Electrode
Penning Pole Pieces
Aperture Plate
Discharge Region
Hollow Anode
Ceramic
Source Body
Cathode
Copper Spacer
Mica
Mounting Flange
10mm

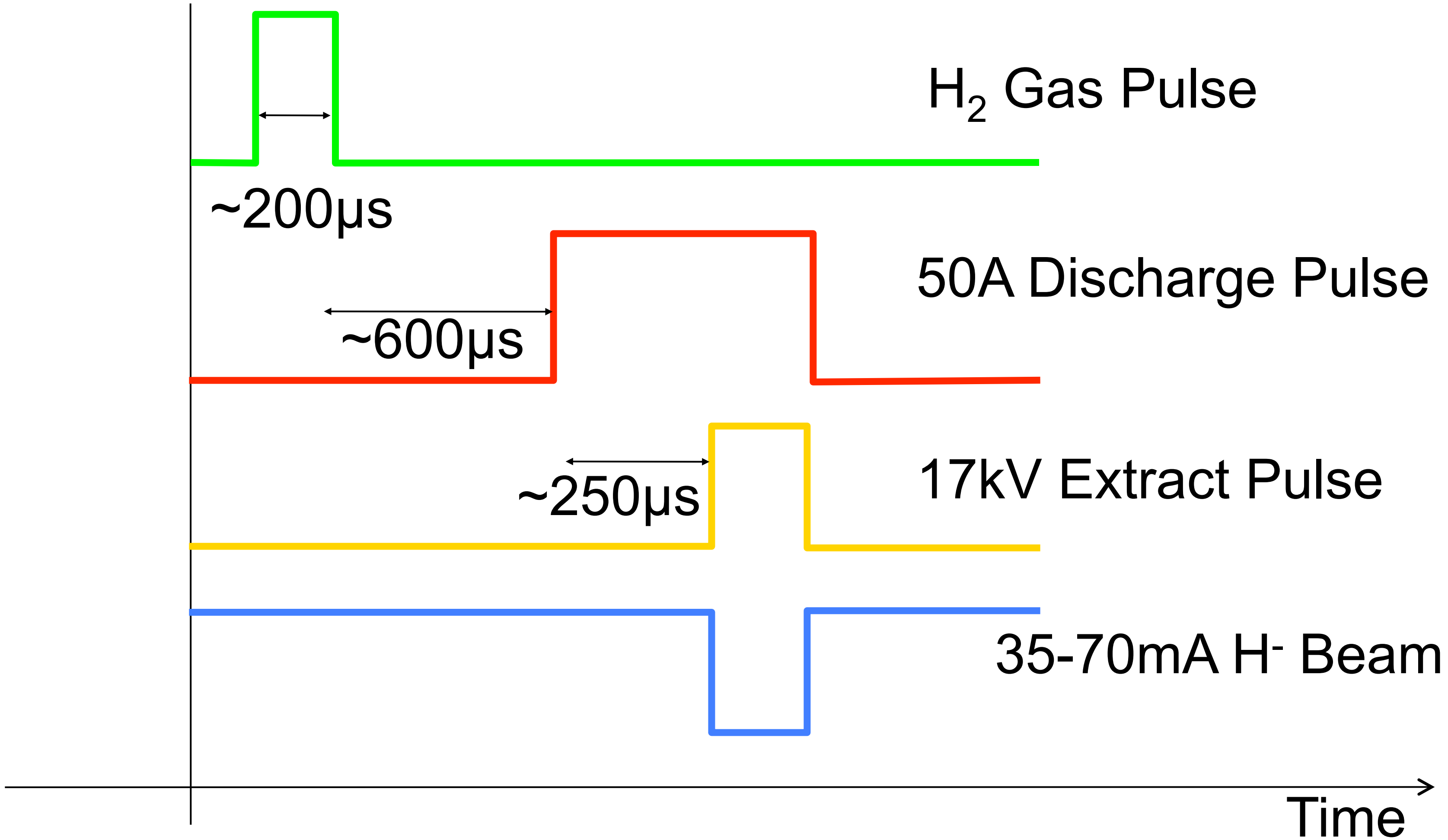


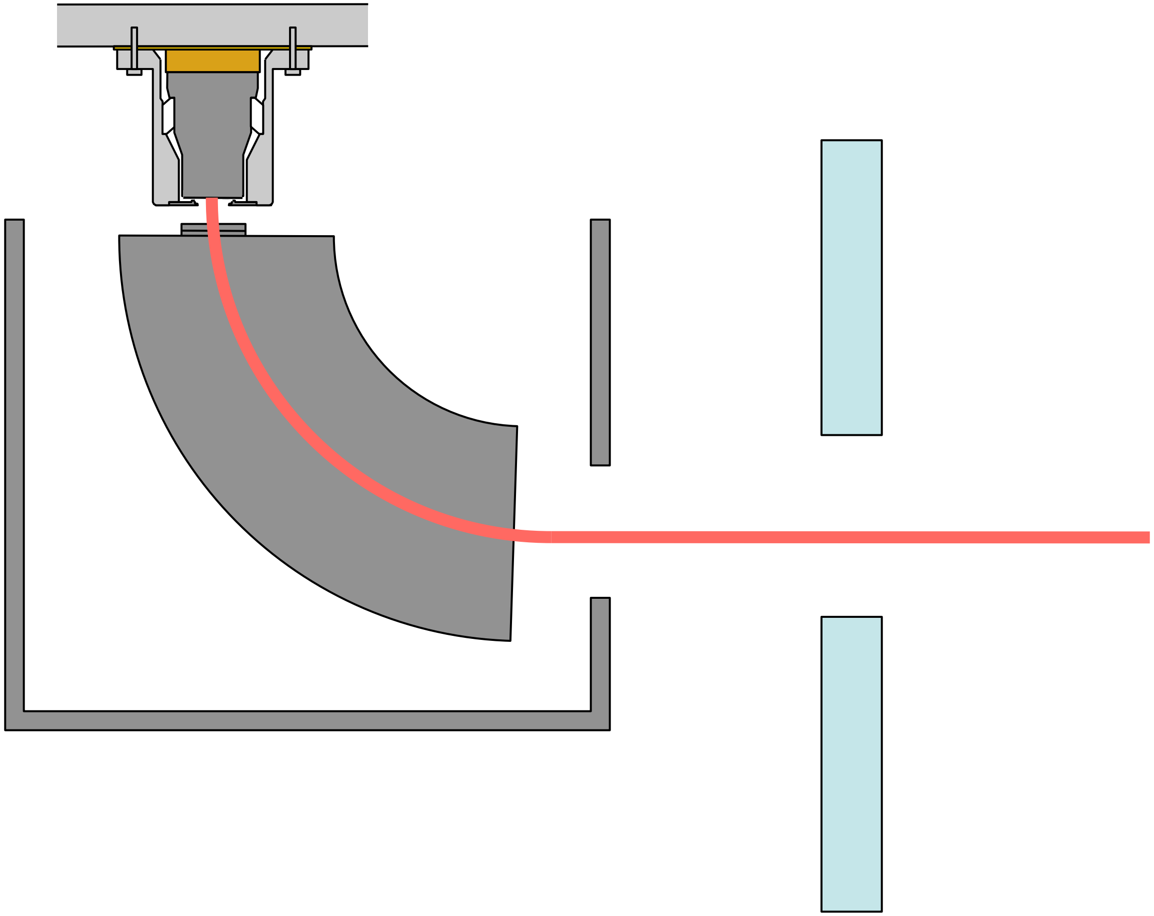


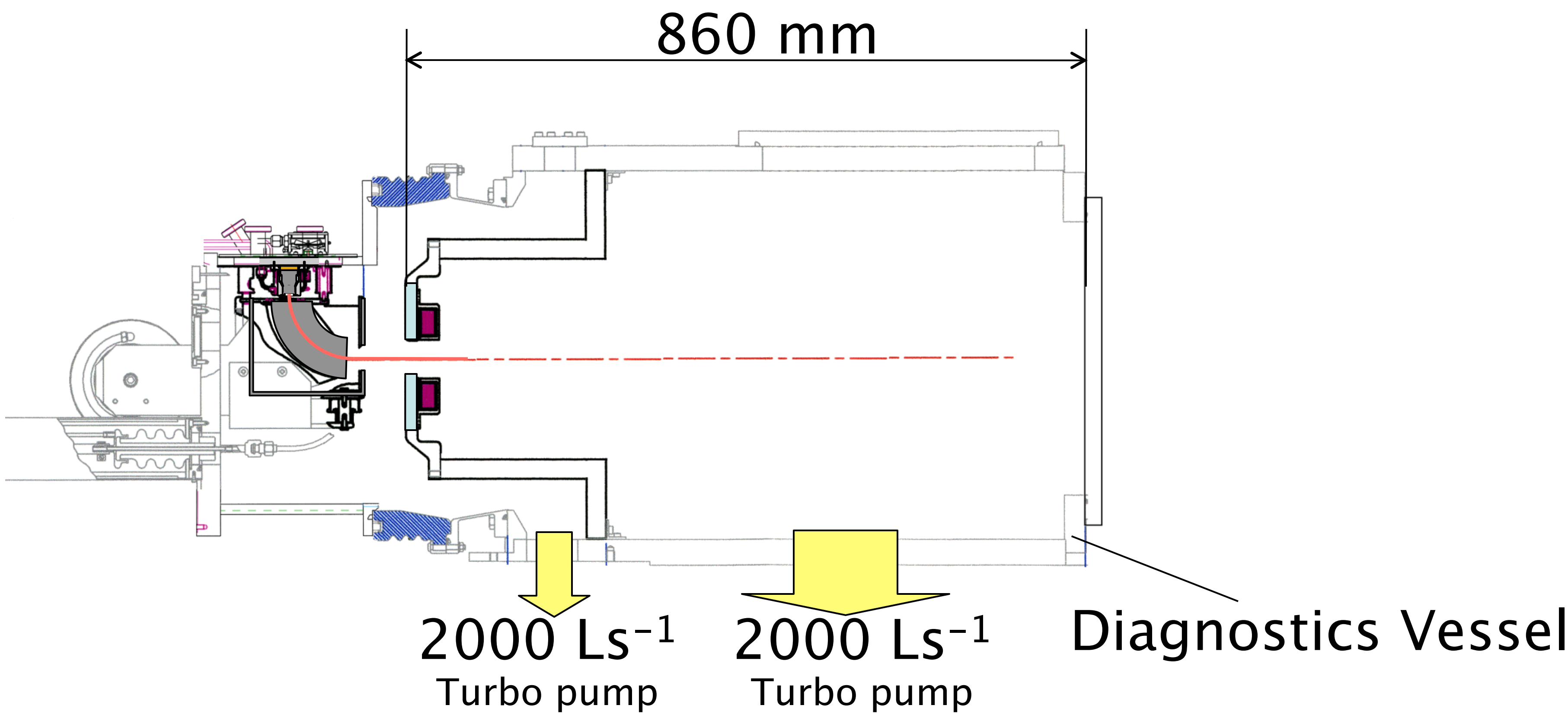


Platform DC Power Supply
Platform Ground
35kV
Pulsed Extract Power Supply
17kV
-
+
18kV
-
+
Laboratory Ground
Extraction Electrode, Coldbox and Analysing Magnet all Pulsed
35keV H- Beam
Post Extraction Acceleration Gap

Ion Source Mode of Operation

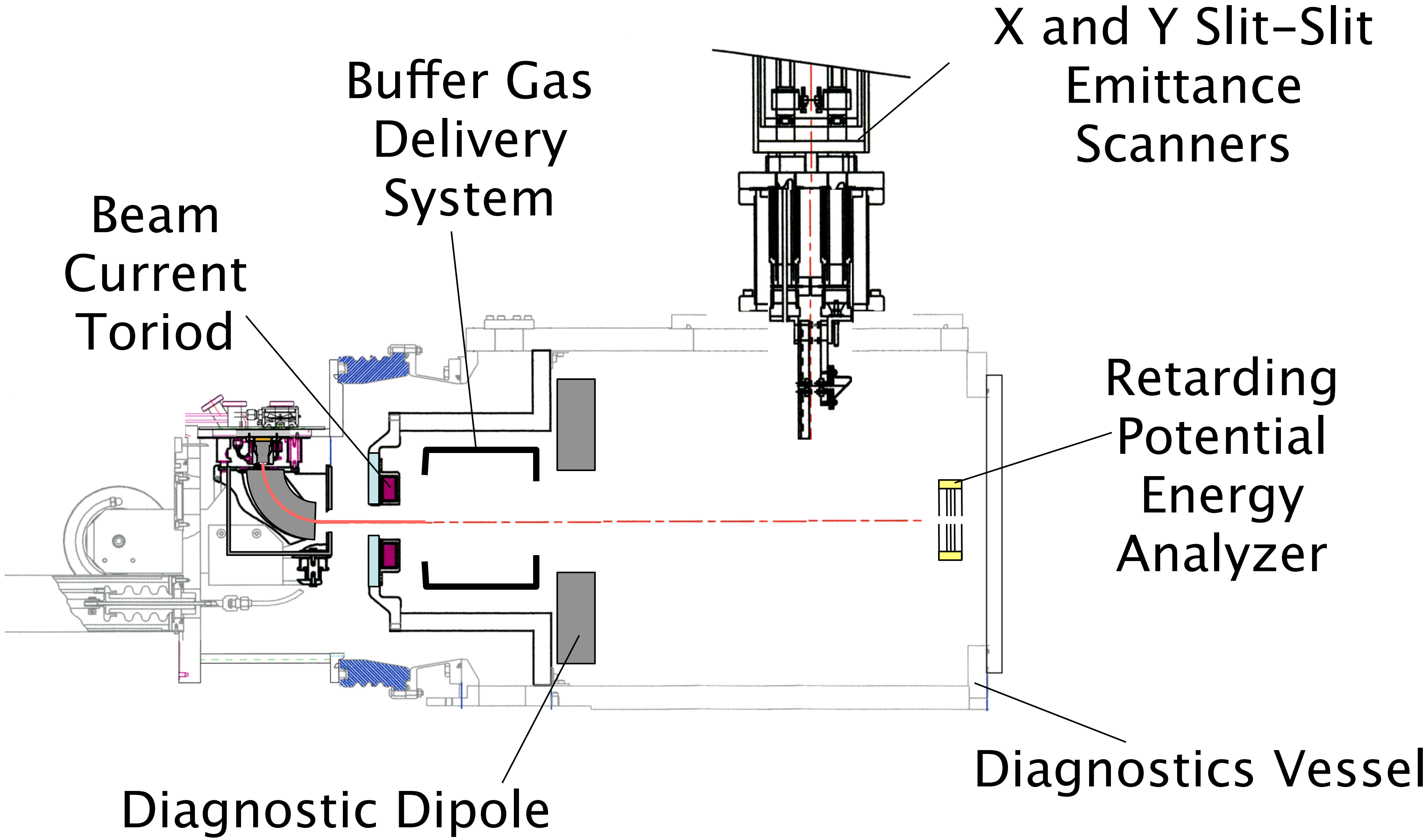




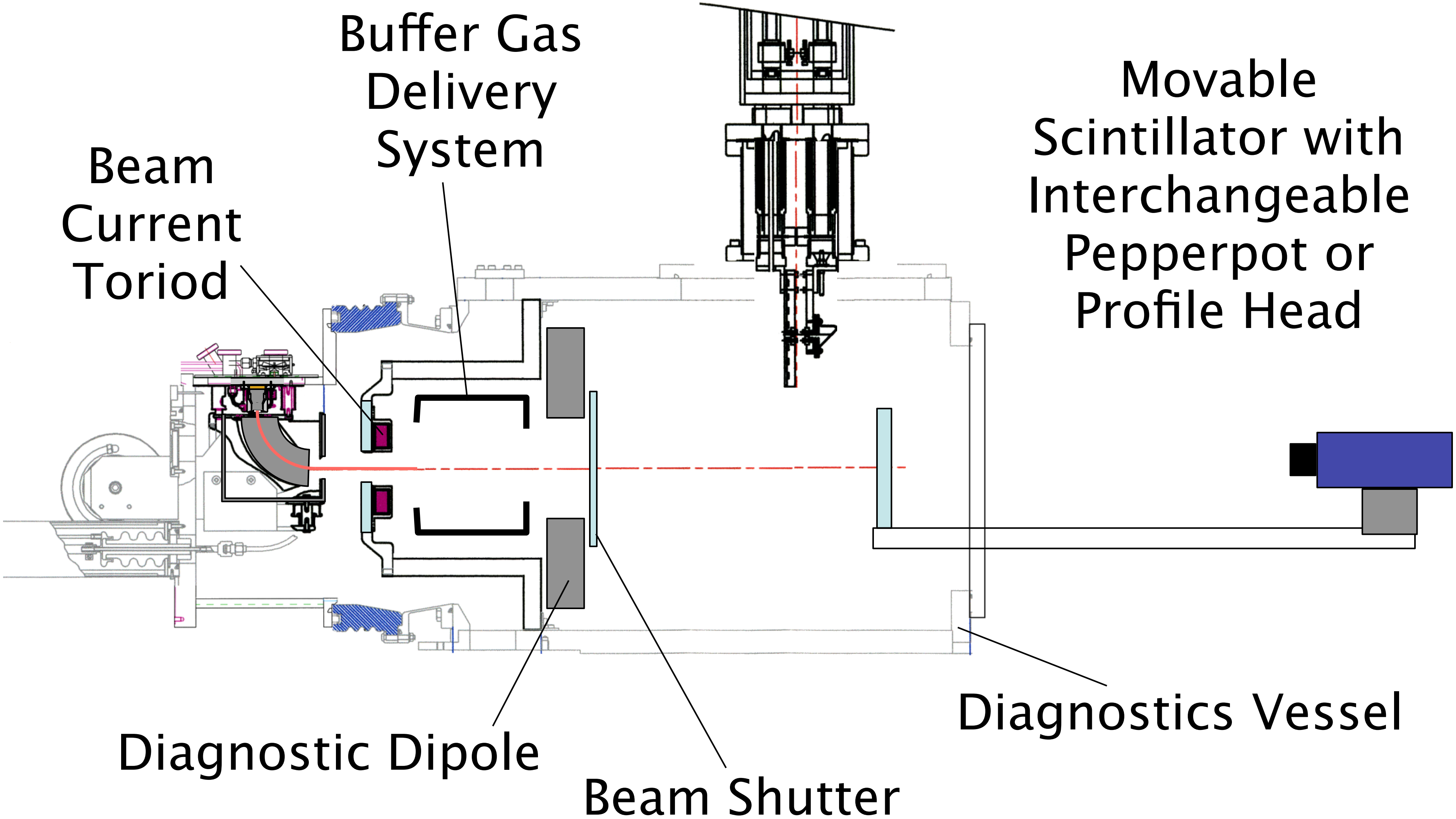


860 mm
2000 Ls⁻¹
Turbo pump
2000 Ls⁻¹
Turbo pump
Diagnostics Vessel

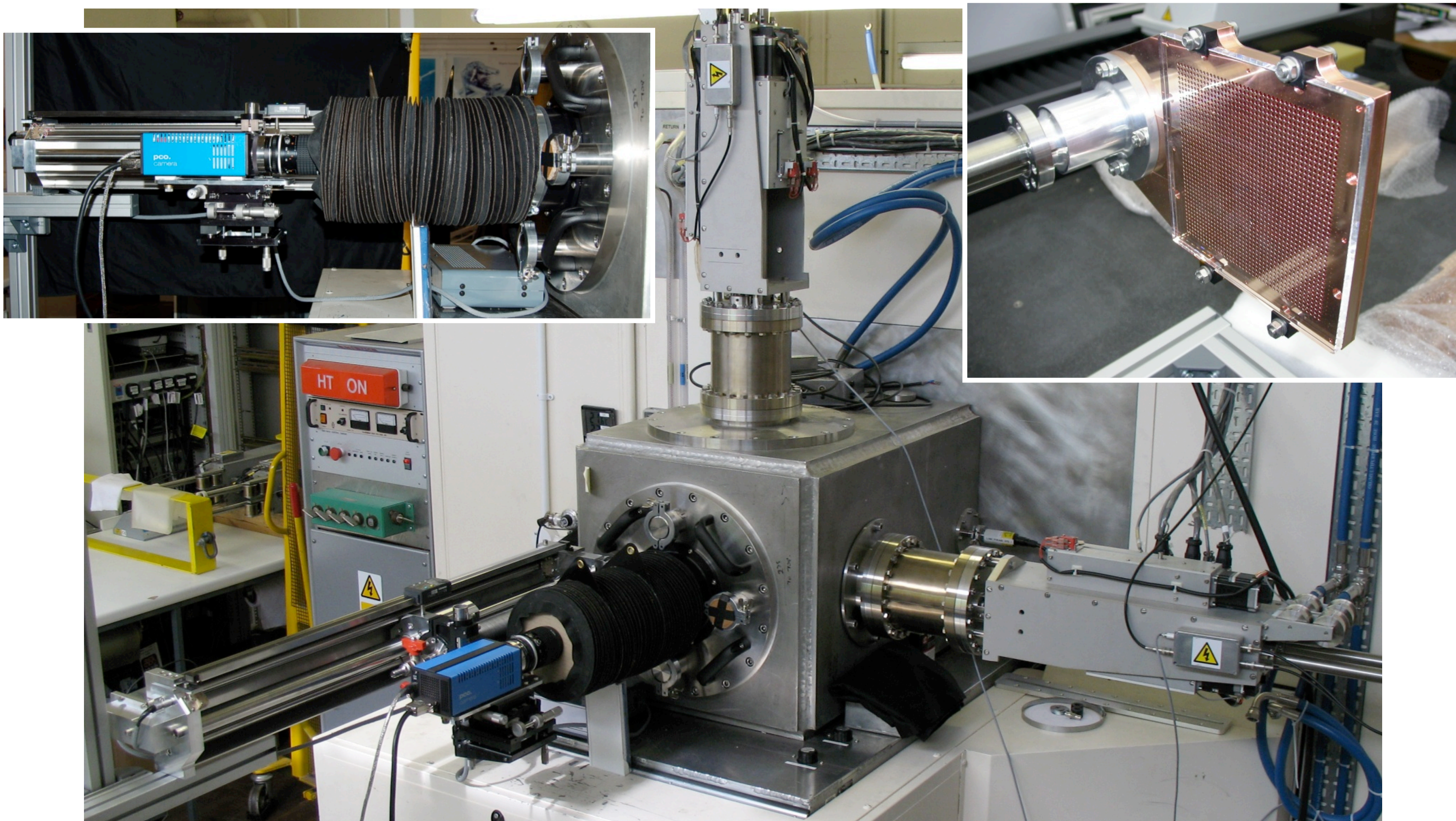
ISDR Diagnostics



ISDR Diagnostics

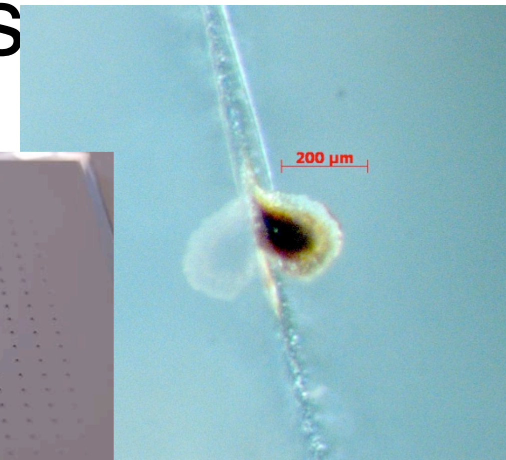


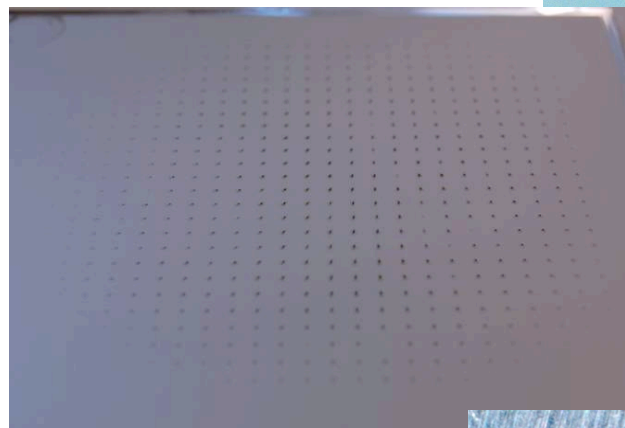
Pepperpot and Slit-Slit Scanners

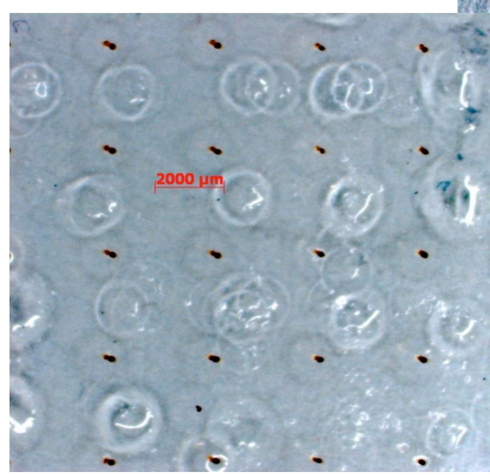


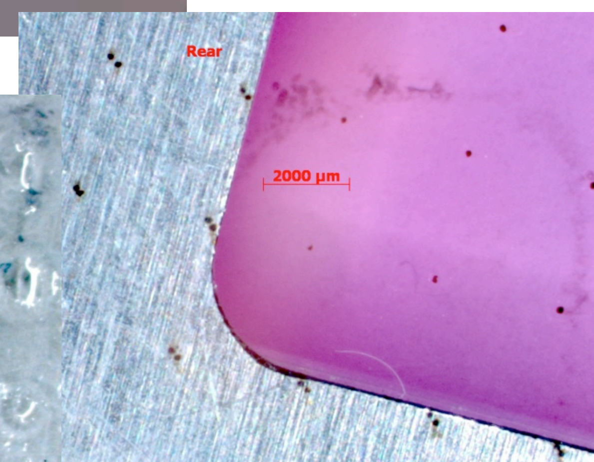
Scintillator Problems

- Pepperpot rapidly became “scintillator destruction rig”.
- Scintillator requirements:
  - Fast (down to 500ns exposure).
  - High light output.
  - Survives beam (<1 micron stopping distance).
- High energy density from Bragg peak causes severe damage.
- Finally chose Ce-Quartz.

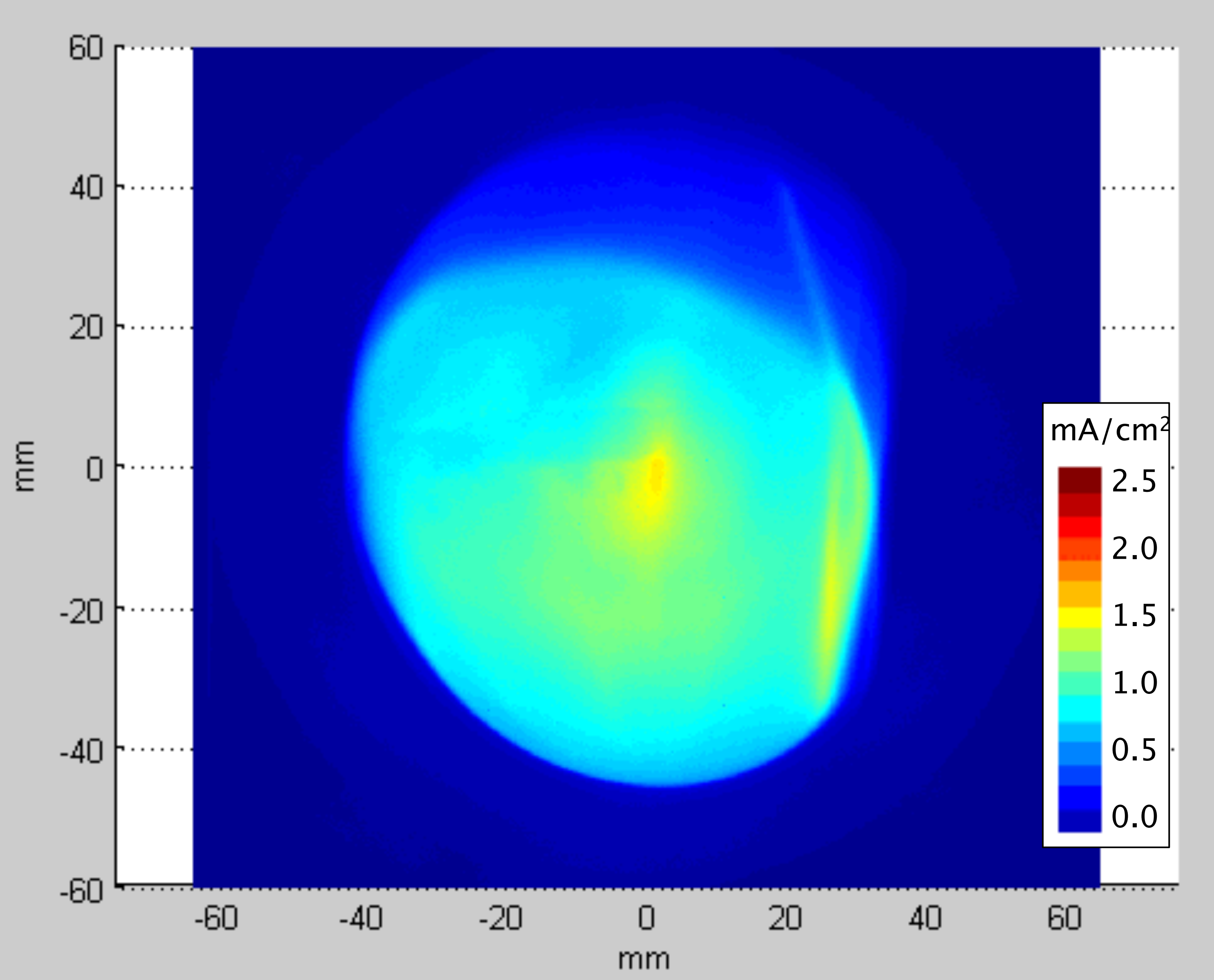








Profile Measurements for Different Extraction Voltages

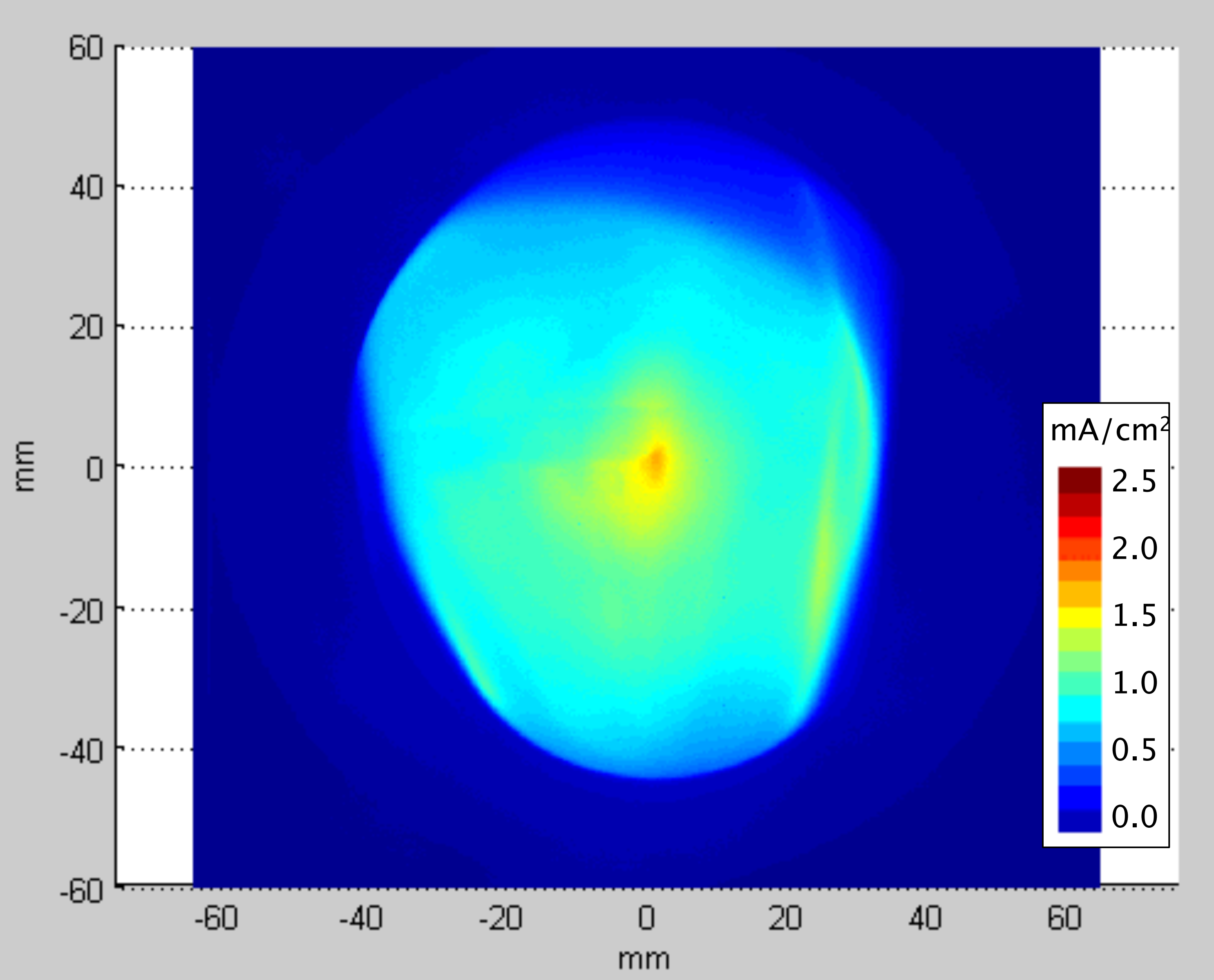


17 kV
Extraction Voltage

35 kV
Platform Voltage

18 kV
Post Acceleration Voltage

47 mA
Beam Current

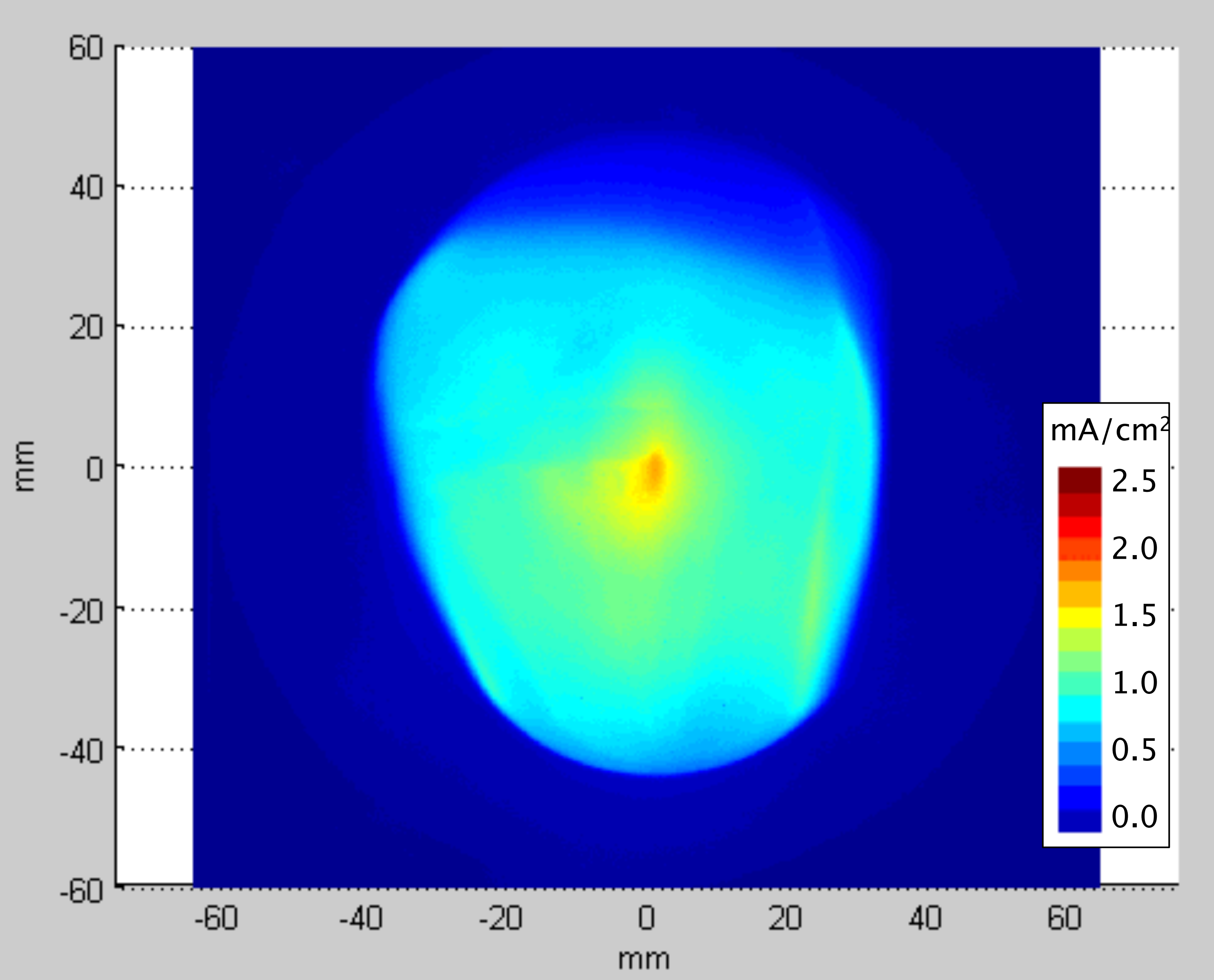


16 kV
Extraction Voltage

35 kV
Platform Voltage

19 kV
Post Acceleration Voltage

42 mA
Beam Current

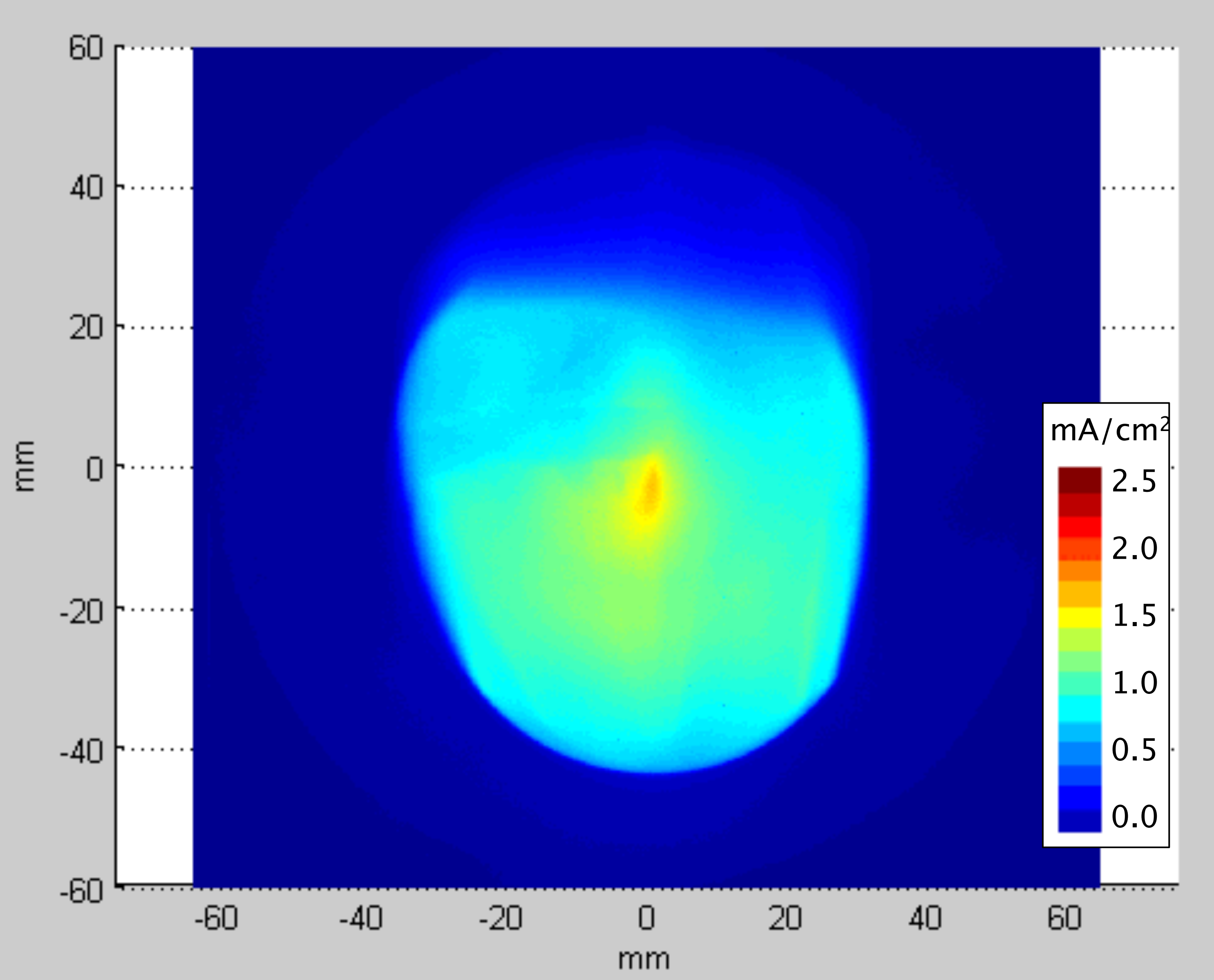


15 kV
Extraction Voltage

35 kV
Platform Voltage

20 kV
Post Acceleration Voltage

40 mA
Beam Current



14 kV

Extraction Voltage

35 kV

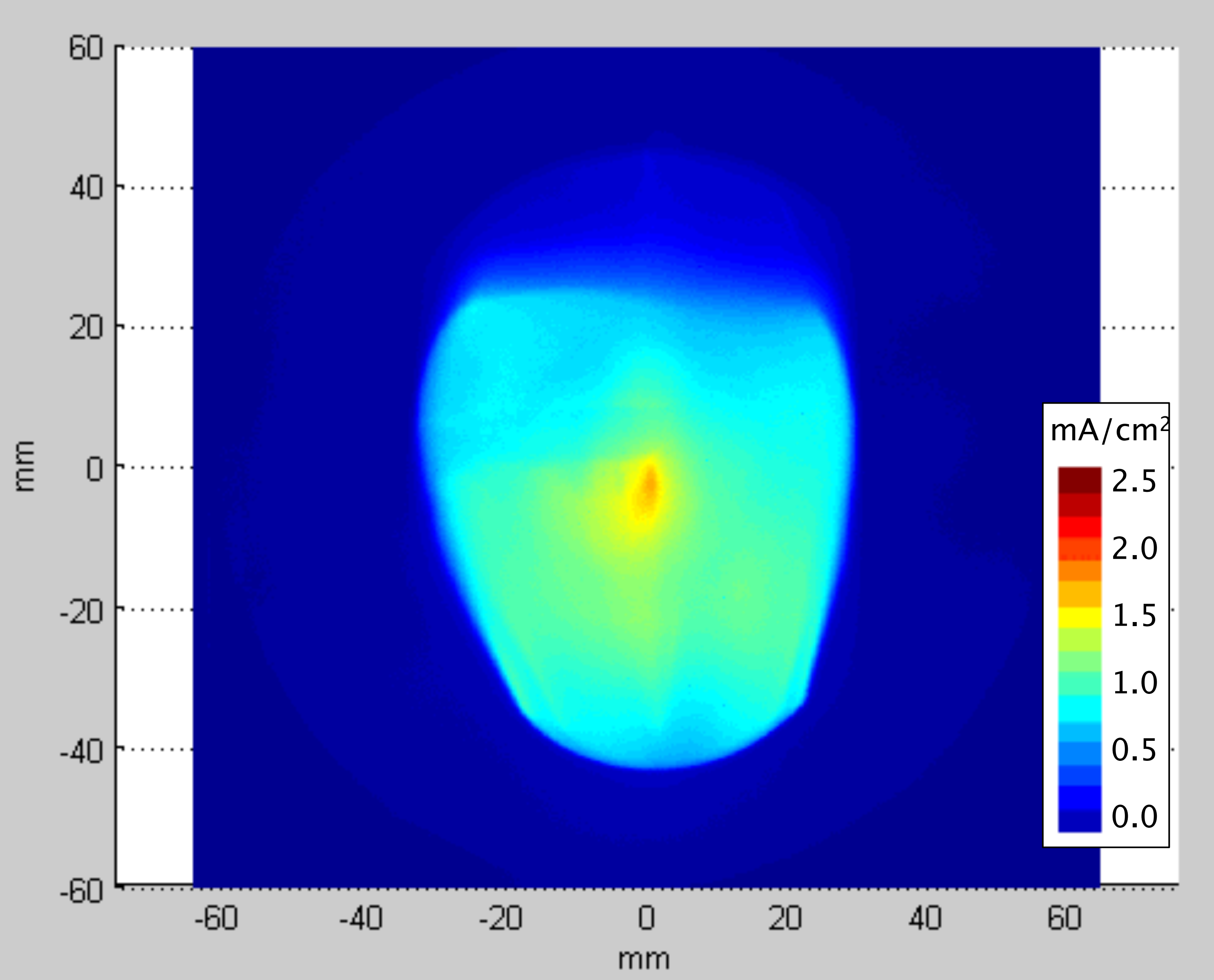
Platform Voltage

21 kV

Post Acceleration Voltage

38 mA

Beam Current

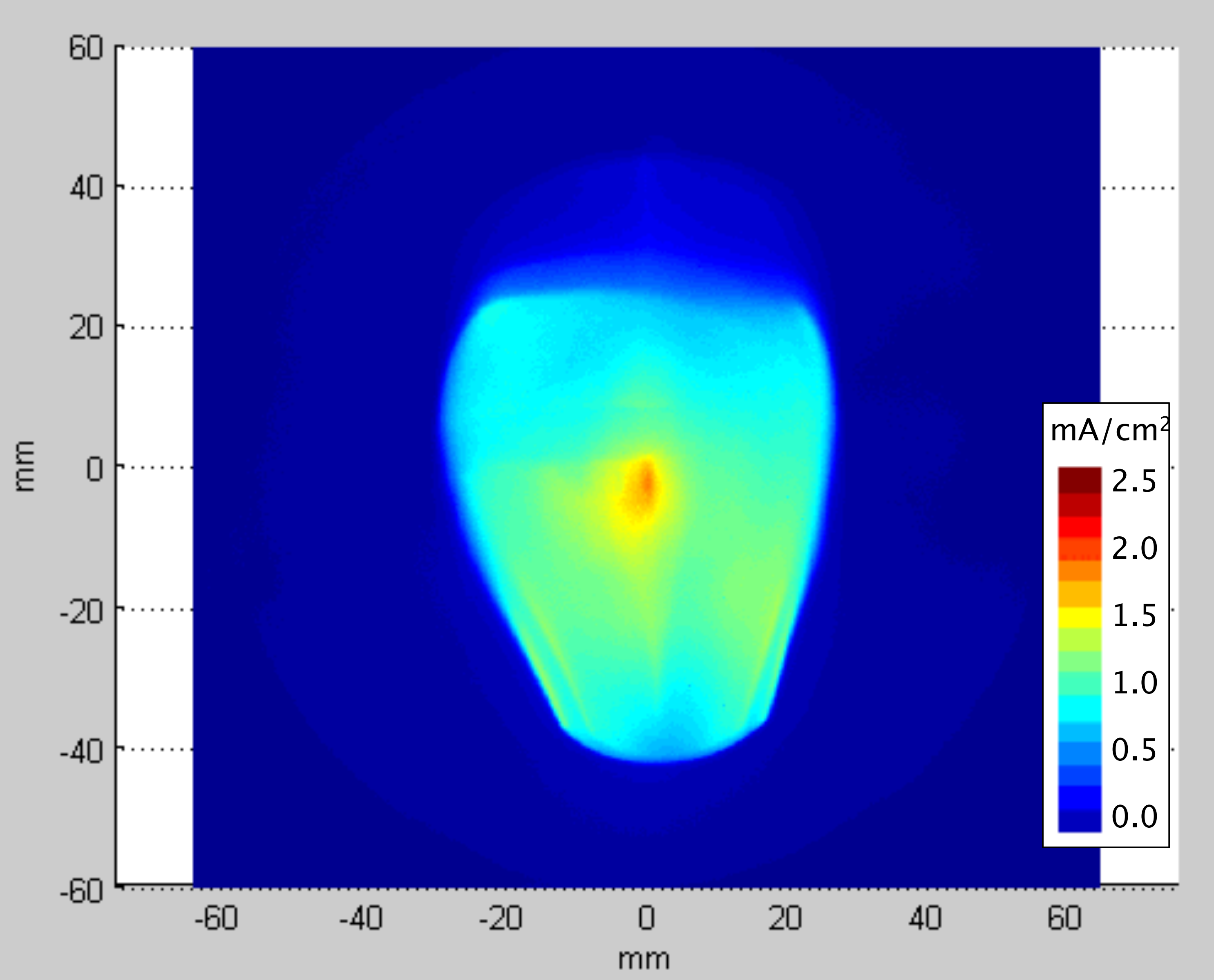


13 kV
Extraction Voltage

35 kV
Platform Voltage

22 kV
Post Acceleration Voltage

35 mA
Beam Current

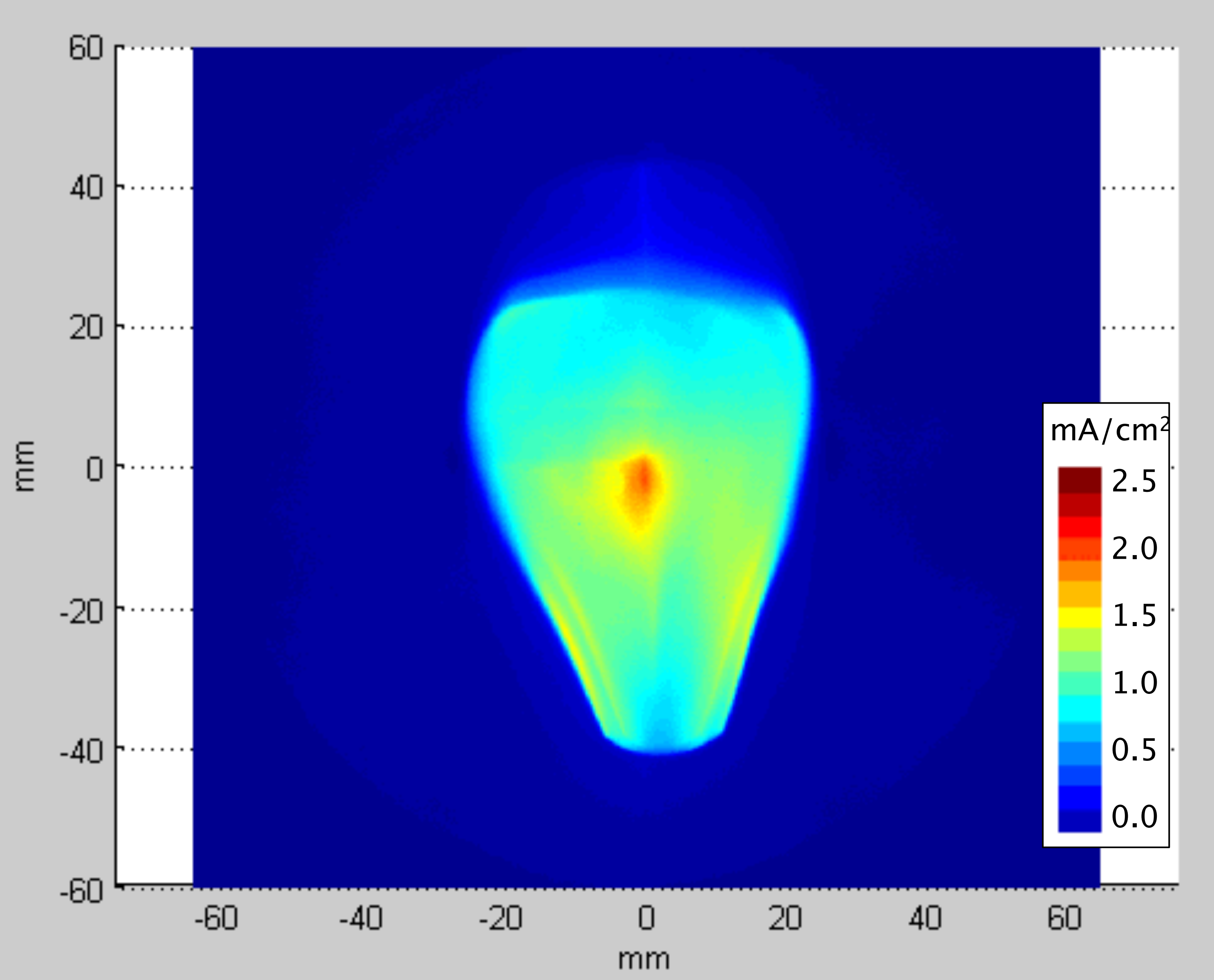


12 kV
Extraction Voltage

35 kV
Platform Voltage

23 kV
Post Acceleration Voltage

32 mA
Beam Current

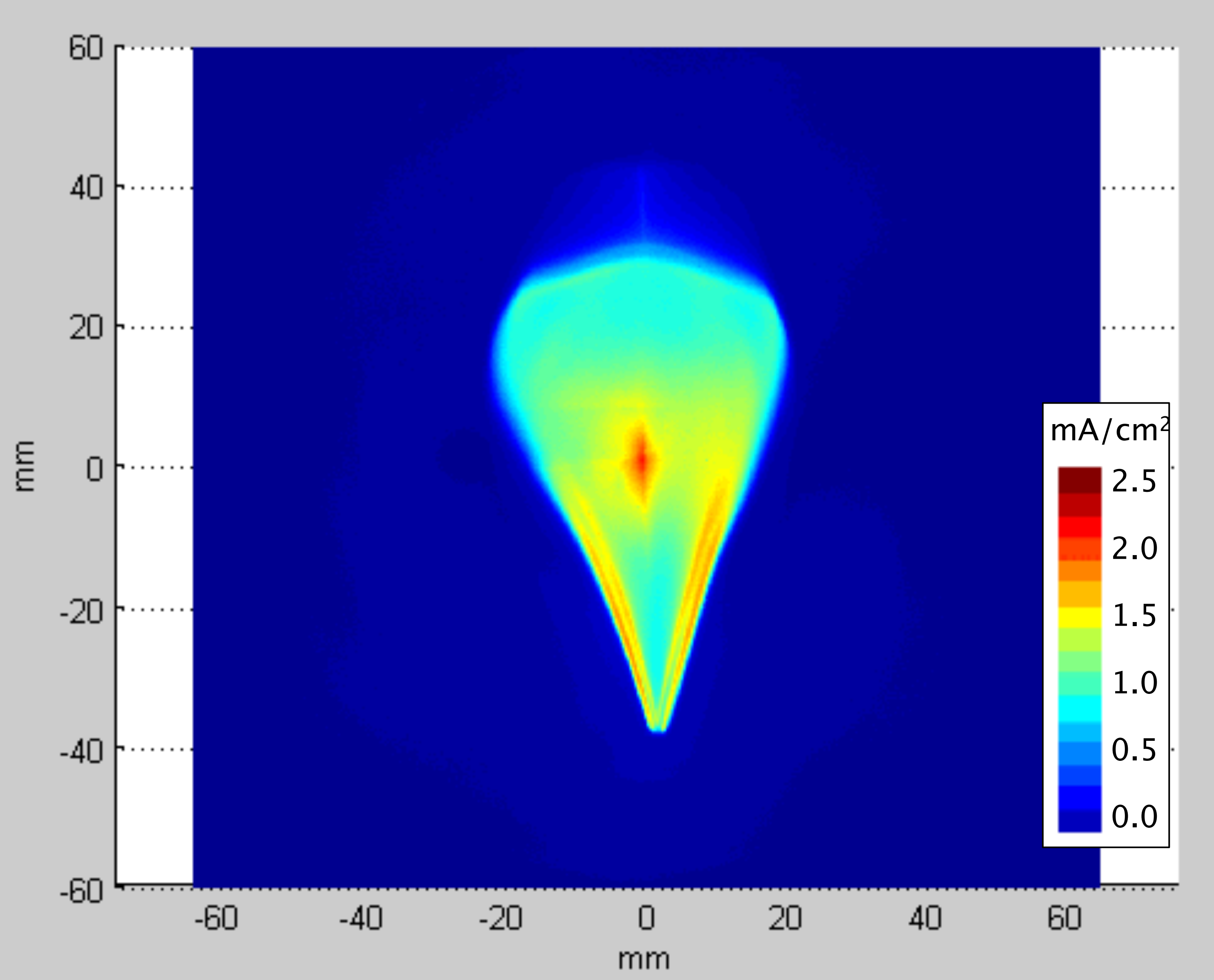


11 kV
Extraction Voltage

35 kV
Platform Voltage

24 kV
Post Acceleration Voltage

28 mA
Beam Current

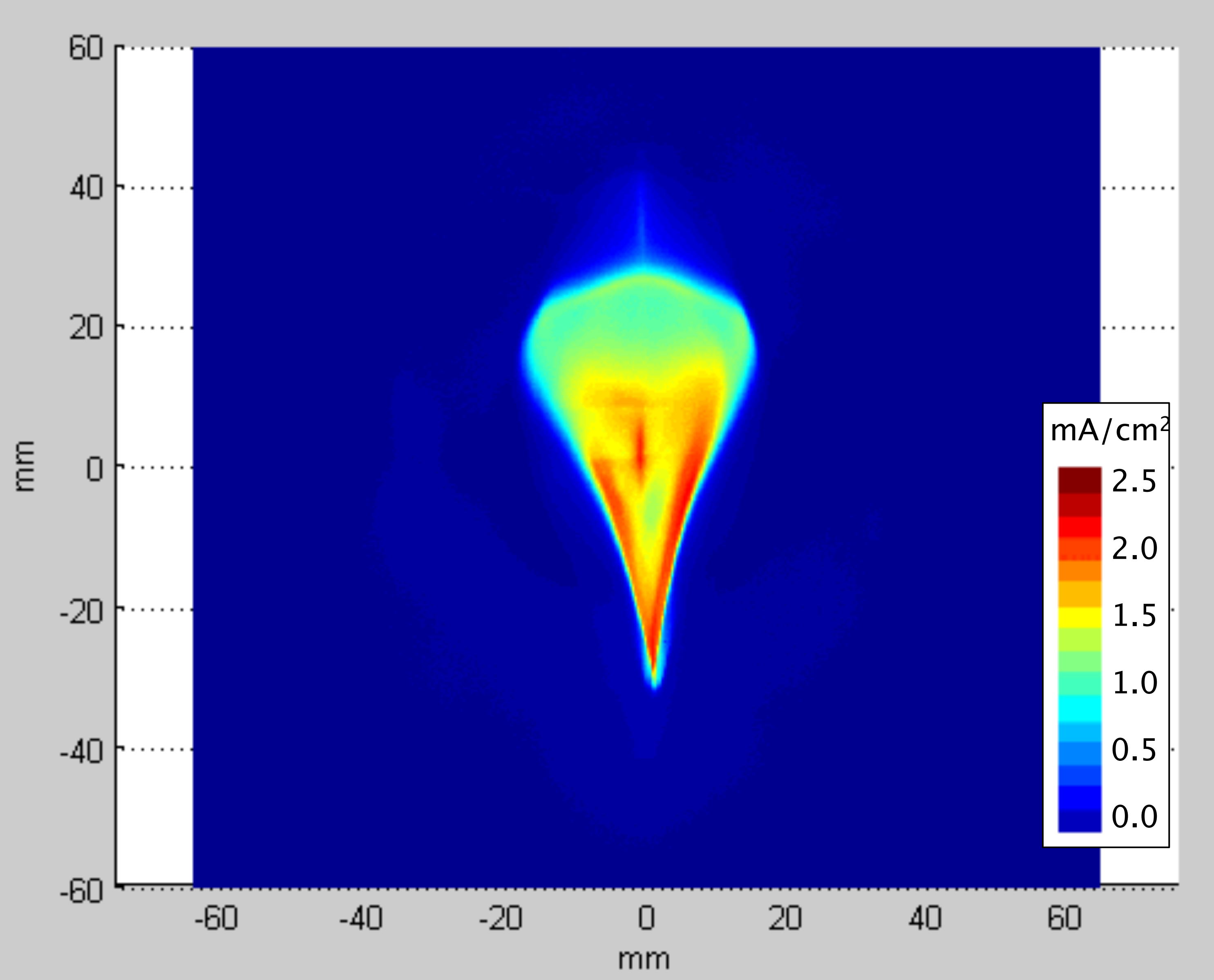


10 kV
Extraction Voltage

35 kV
Platform Voltage

25 kV
Post Acceleration Voltage

25 mA
Beam Current

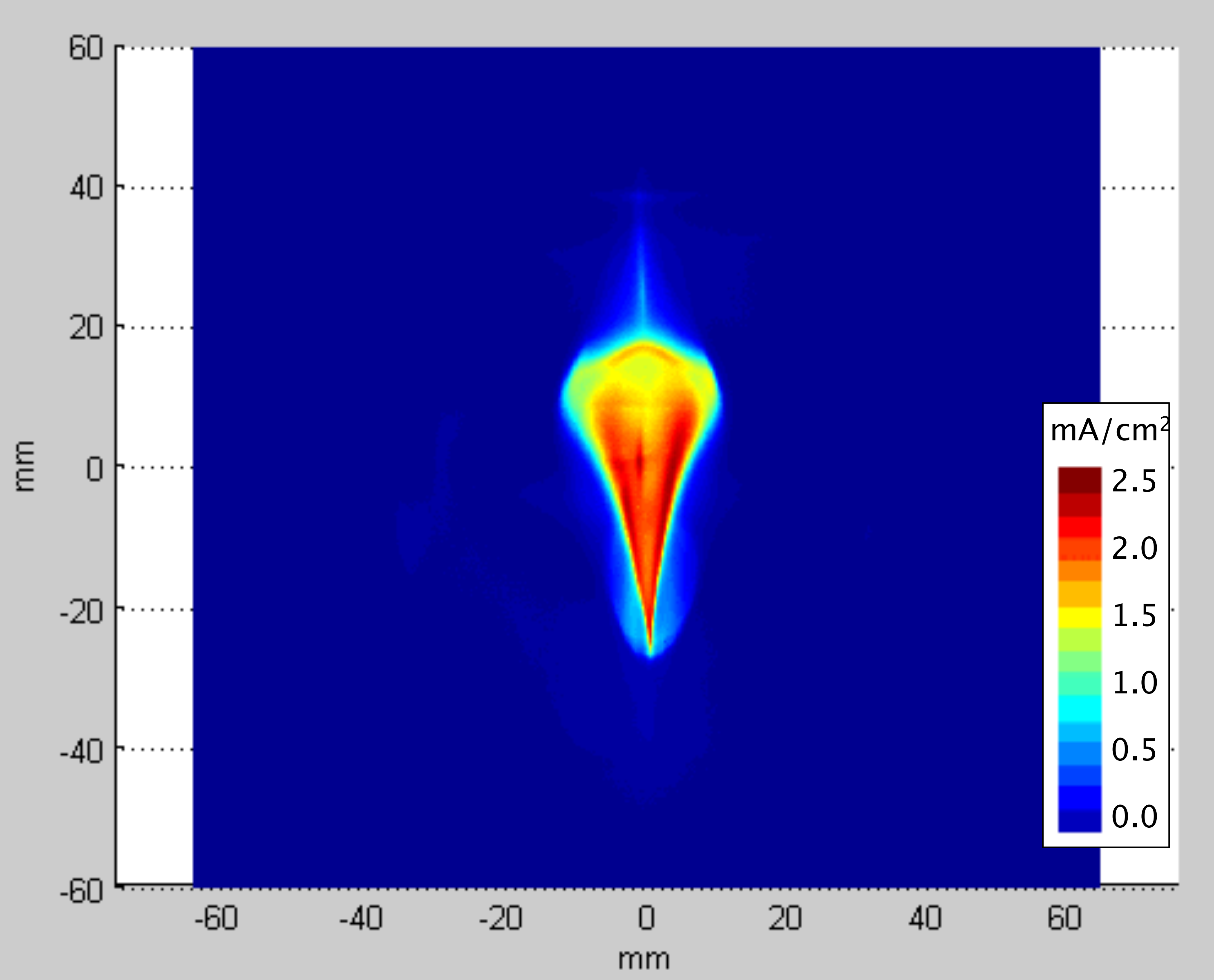


9 kV
Extraction Voltage

35 kV
Platform Voltage

26 kV
Post Acceleration Voltage

21 mA
Beam Current

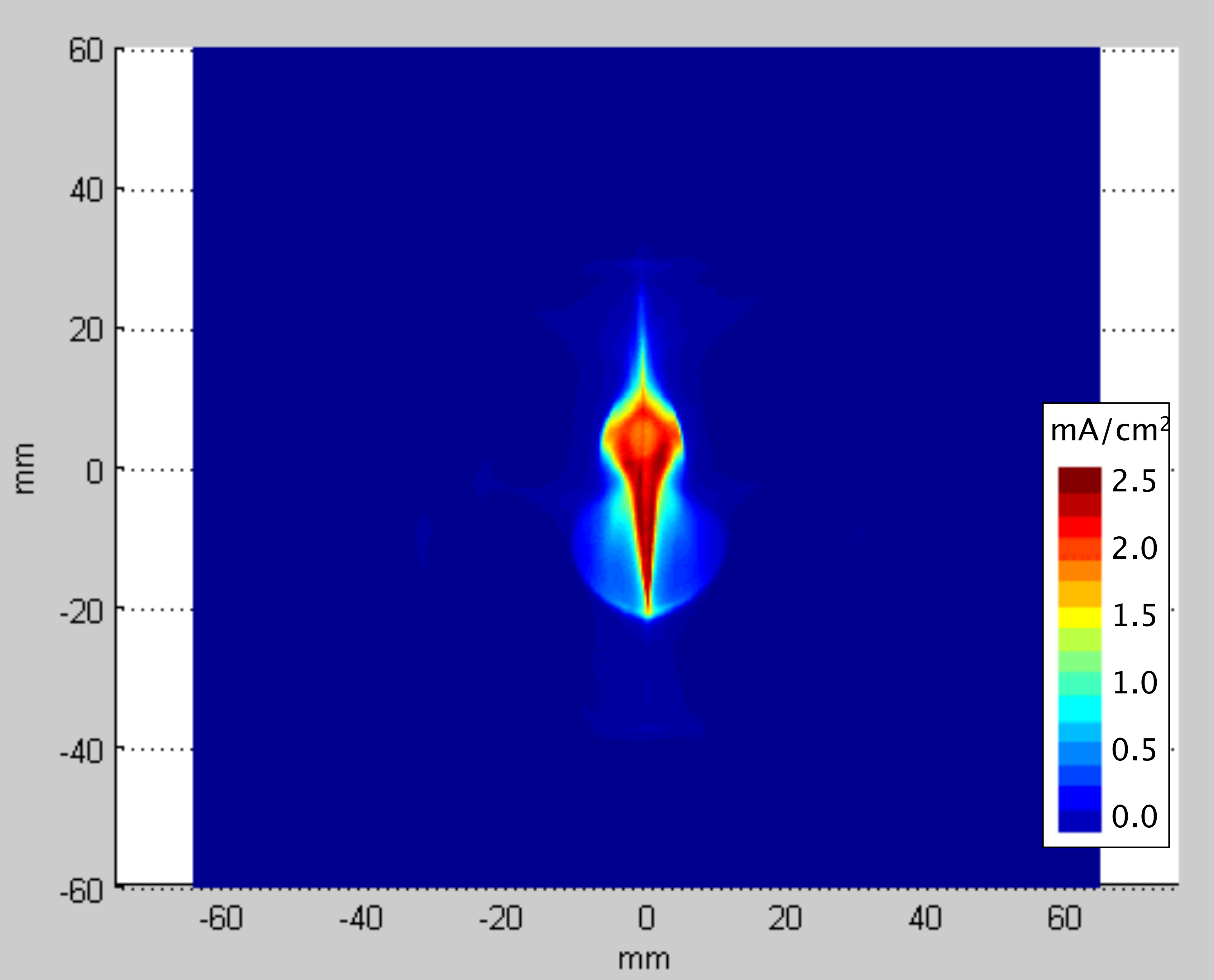


8 kV
Extraction Voltage

35 kV
Platform Voltage

27 kV
Post Acceleration Voltage

17 mA
Beam Current

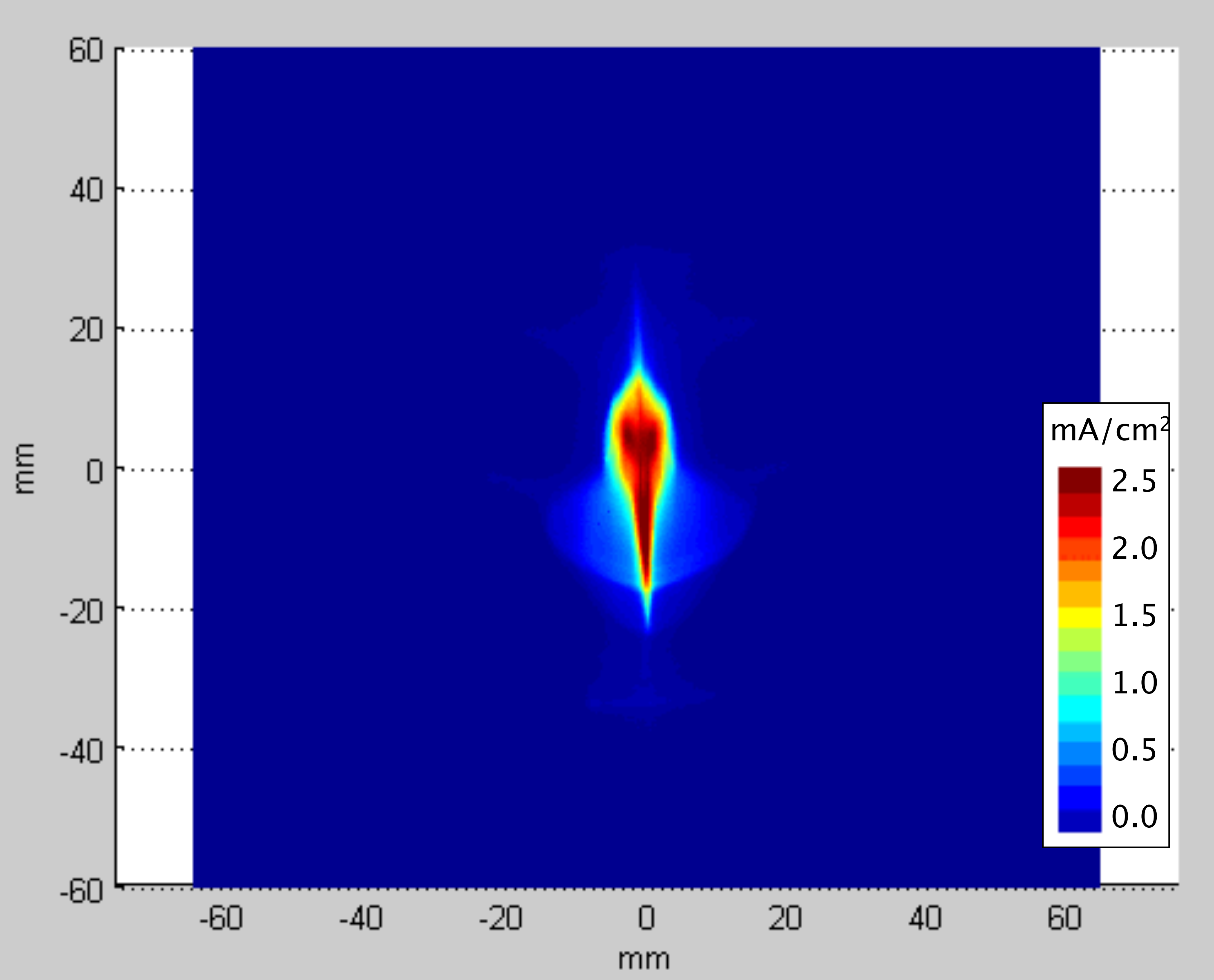


7 kV
Extraction Voltage

35 kV
Platform Voltage

28 kV
Post Acceleration Voltage

13 mA
Beam Current

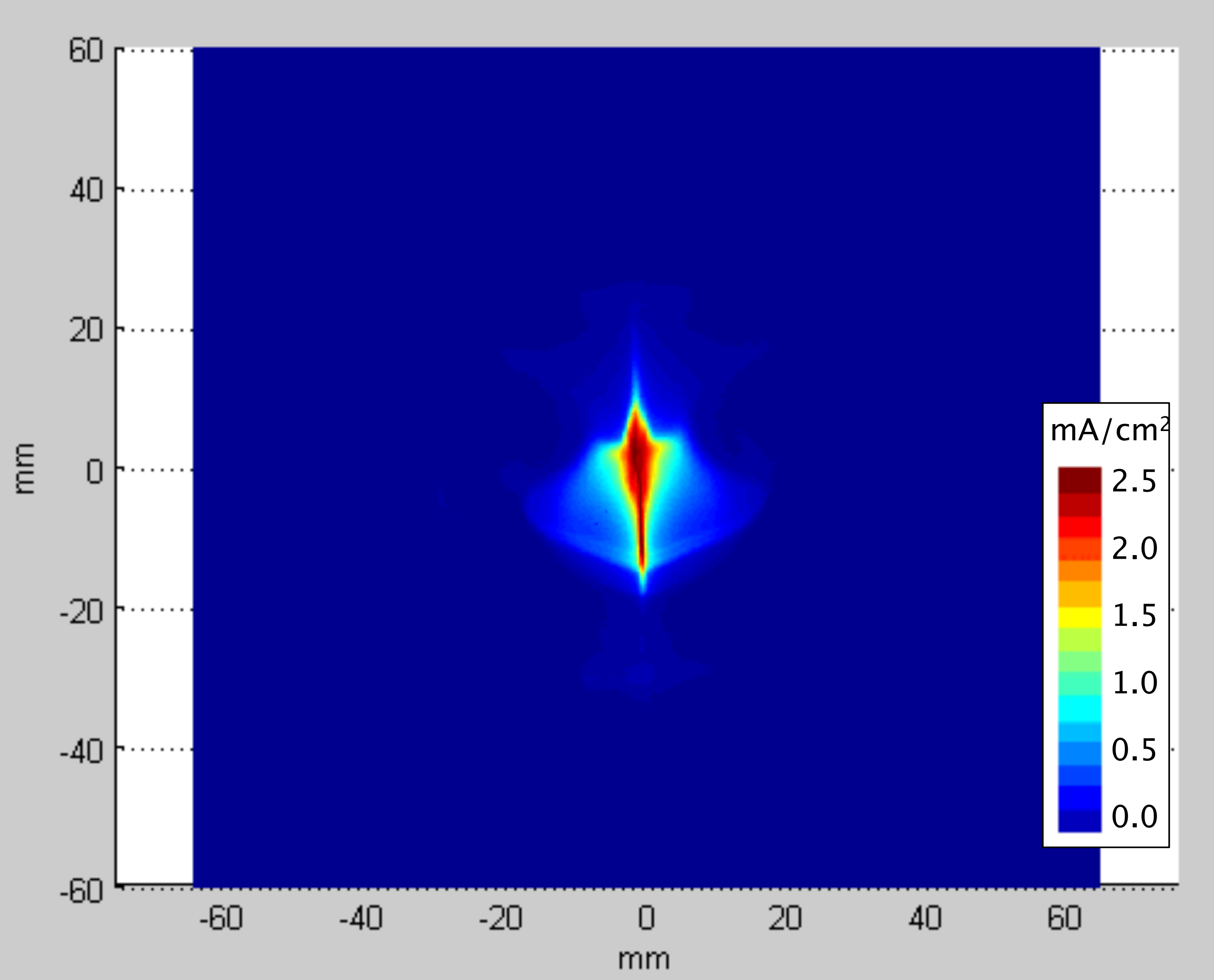


6.5 kV
Extraction Voltage

35 kV
Platform Voltage

28.5 kV
Post Acceleration Voltage

12 mA
Beam Current

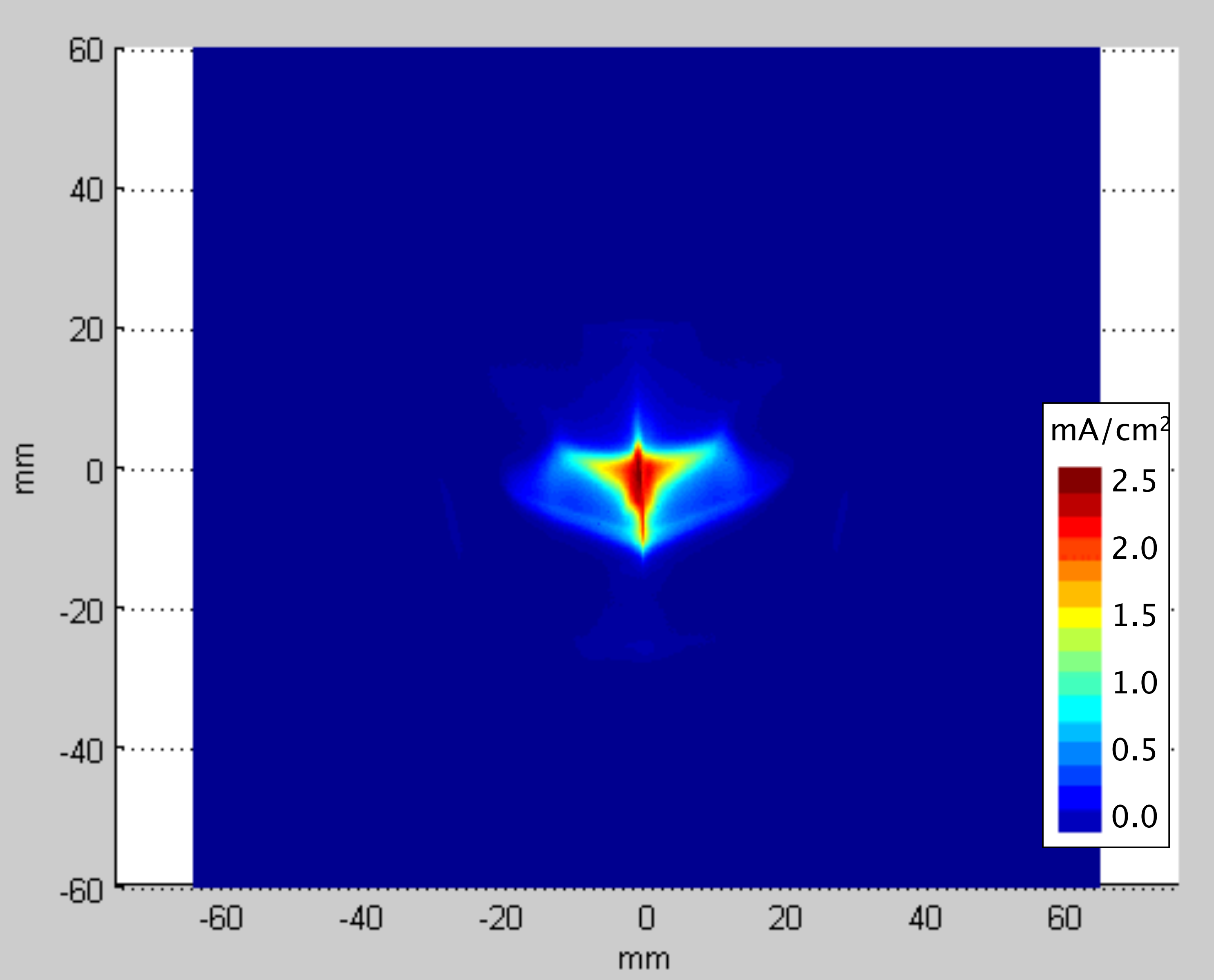


6 kV
Extraction Voltage

35 kV
Platform Voltage

29 kV
Post Acceleration Voltage

10 mA
Beam Current



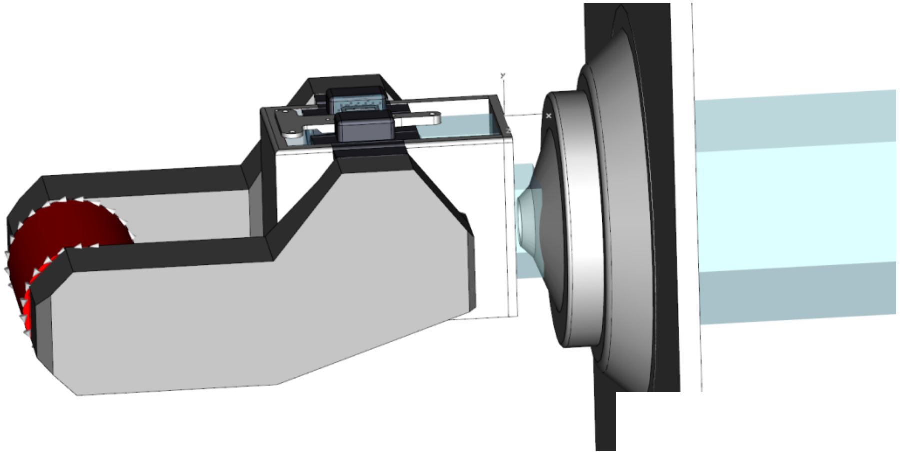
5.5 kV
Extraction Voltage

35 kV
Platform Voltage

28.5 kV
Post Acceleration Voltage

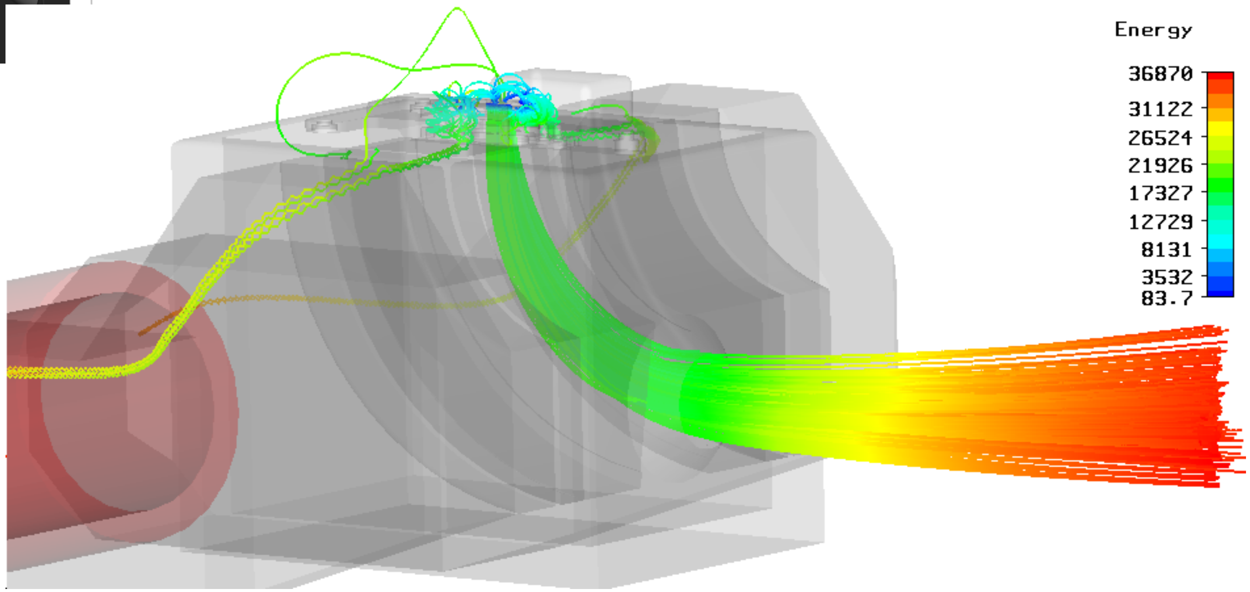
9 mA
Beam Current

Ion Source MAFIA Model

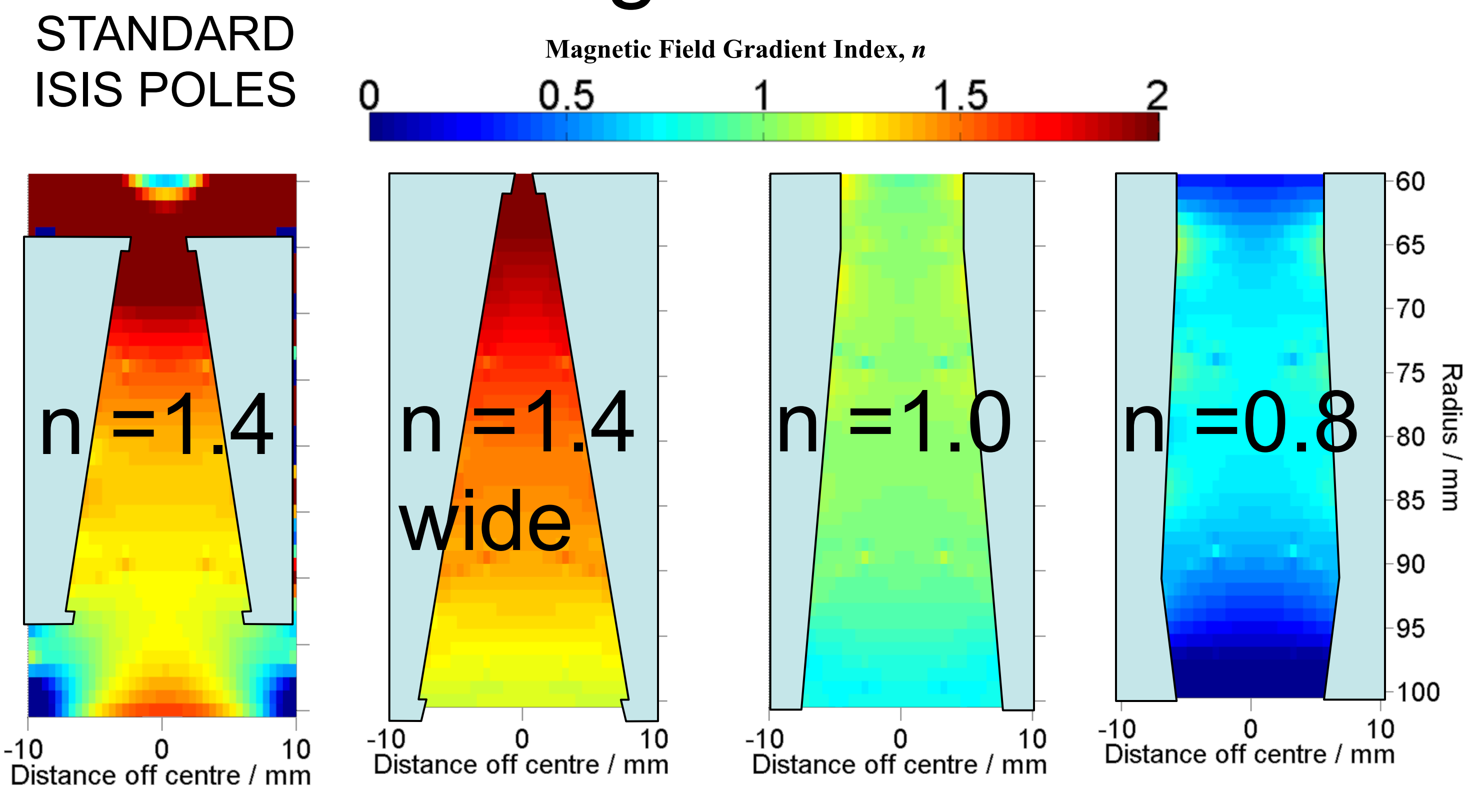


MAFIA modelling indicates problems with Dipole magnet field and extract geometry.

Large vertical beam spread at dipole exit due to over-focussing within dipole field



Sector Magnet Pole Pieces



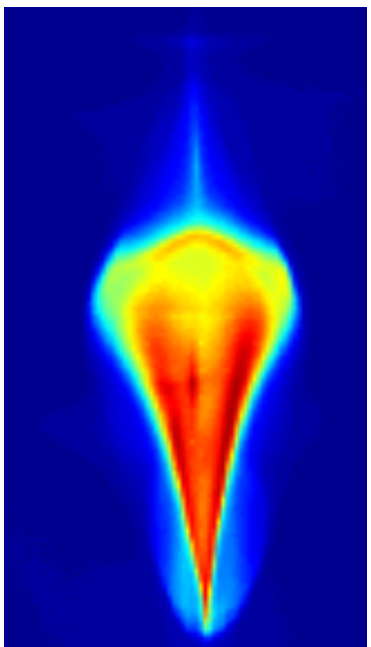
$$n = -\frac{R_e}{B_e}\left(\frac{dB}{dR}\right)$$

Scott Lawrie

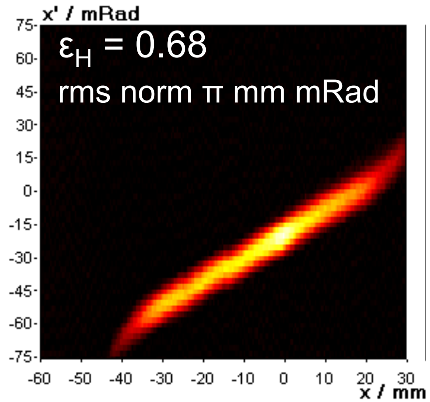
Development Rig Results

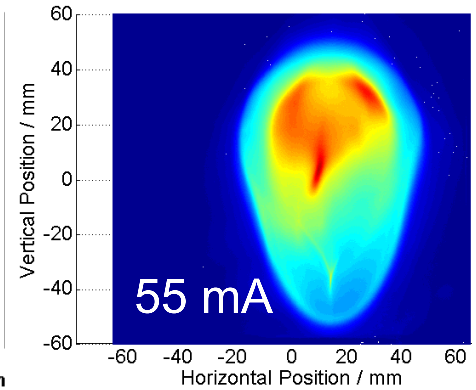
Test new pole pieces:

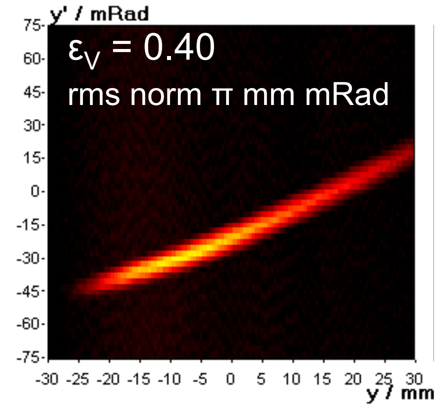
n = 1.4 Old



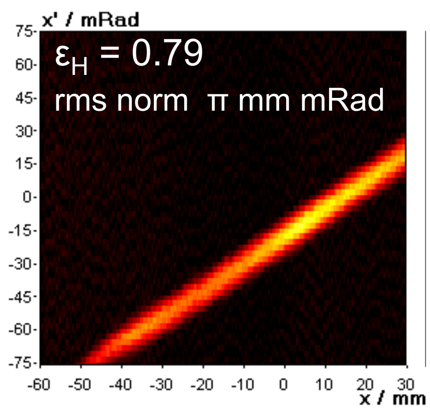
n = 1.4 Large Good Field

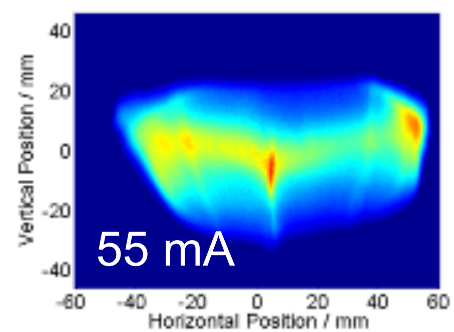


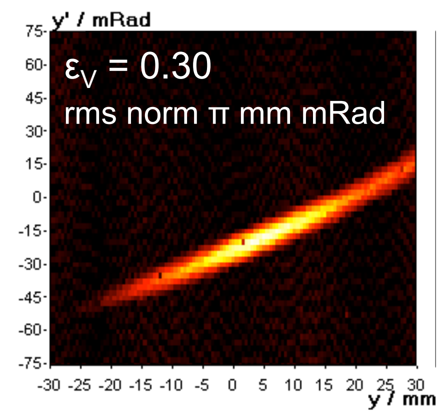




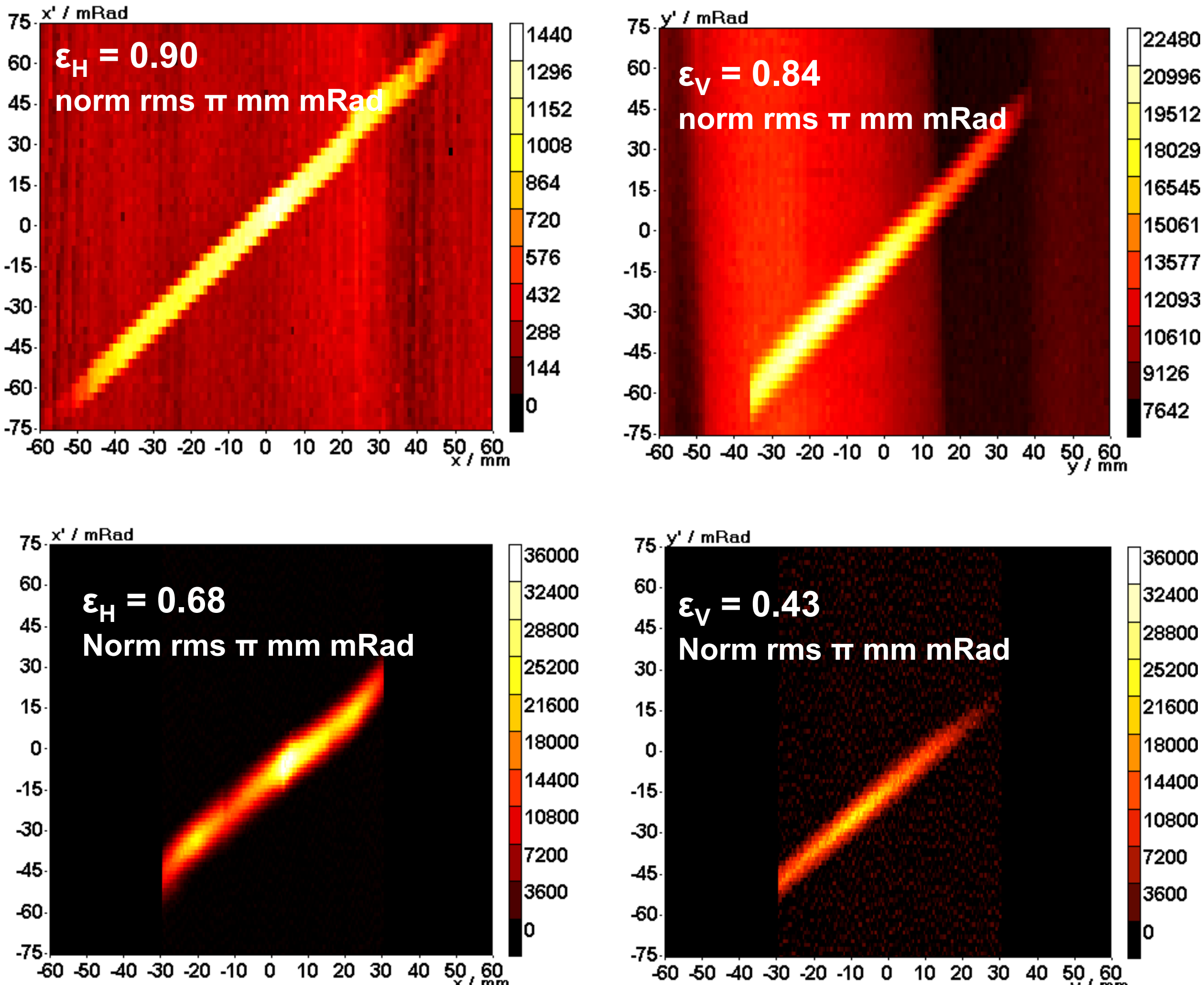
n = 1.0







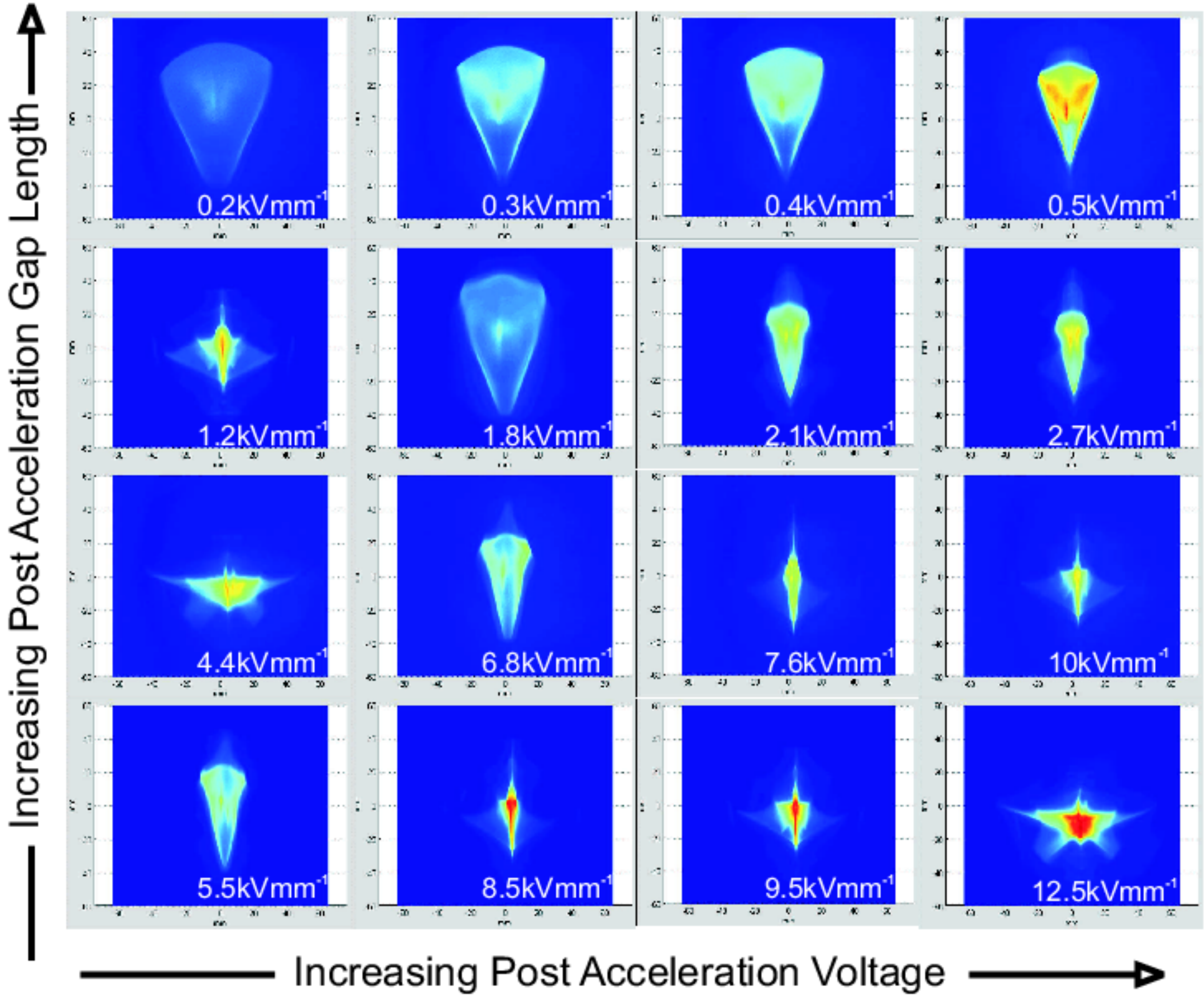
Decrease Post Acceleration Gap



55 mm Post gap

2 mm Post gap

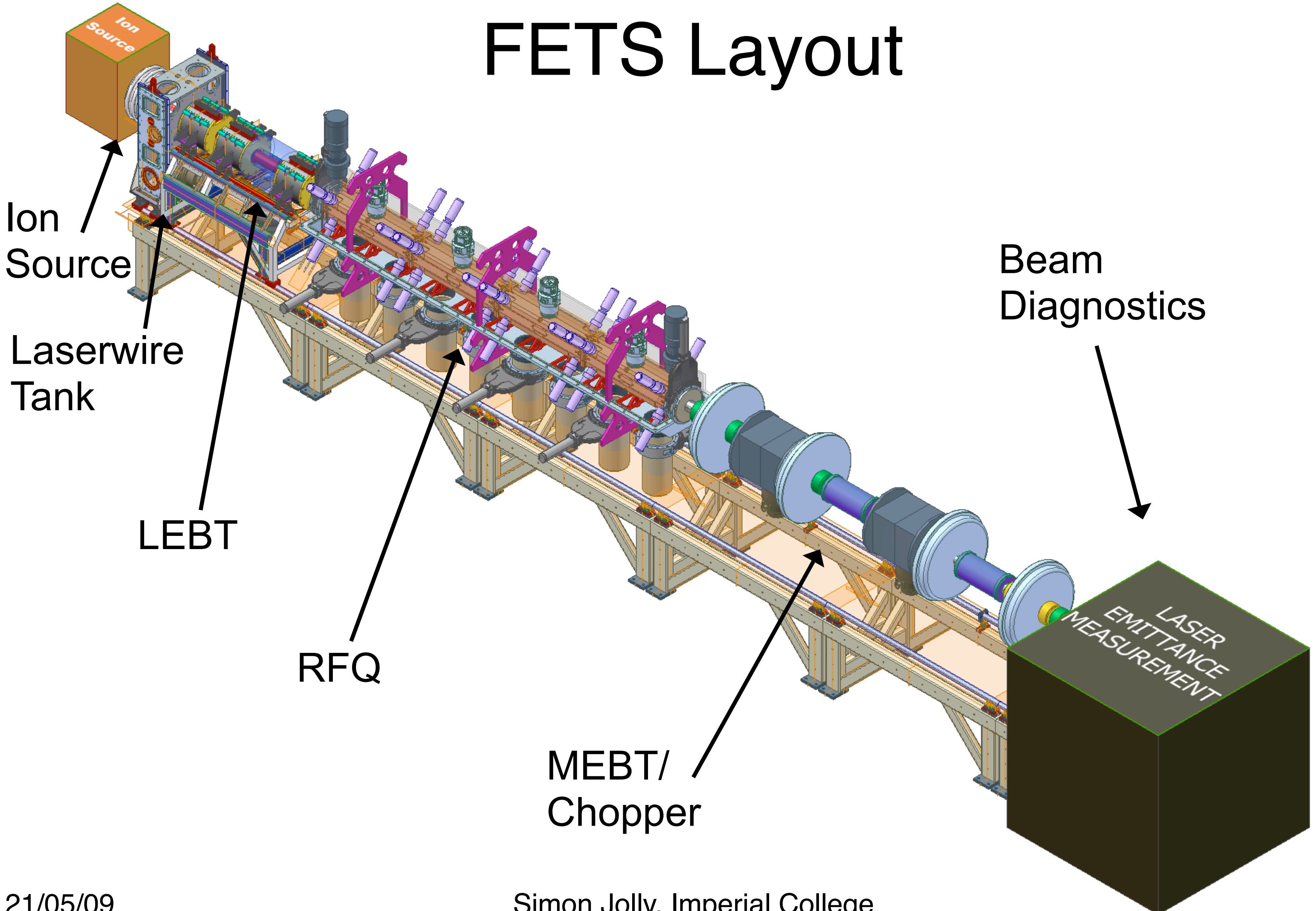
FETS Beam Profile Variation



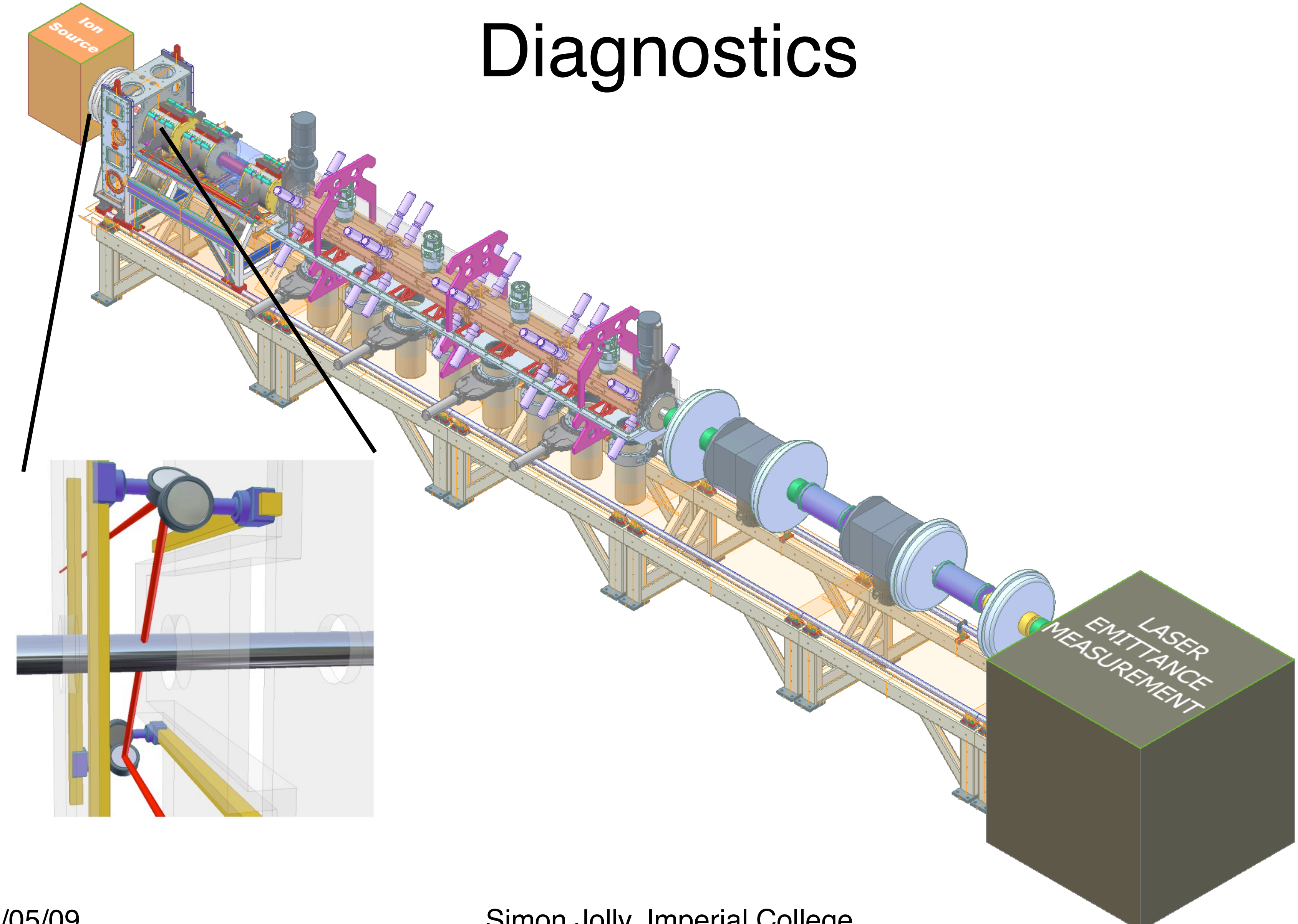
Ion Source Current Status

- At normal operating conditions (17 kV Extraction Voltage) the beam is collimated into a round beam by the post acceleration electrodes.
- The beam is asymmetrically focused in the horizontal plane.
- Severe vertical defocusing present: CST simulations show incorrect dipole field index.
- Modifications to post-acceleration geometry reduce emittance.
- More work required to understand effect of extract geometry.

FETS Layout


Ion Source
Ion Source
Laserwire Tank
LEBT
RFQ
MEBT/ Chopper
Beam Diagnostics
LASER EMITTANCE MEASUREMENT

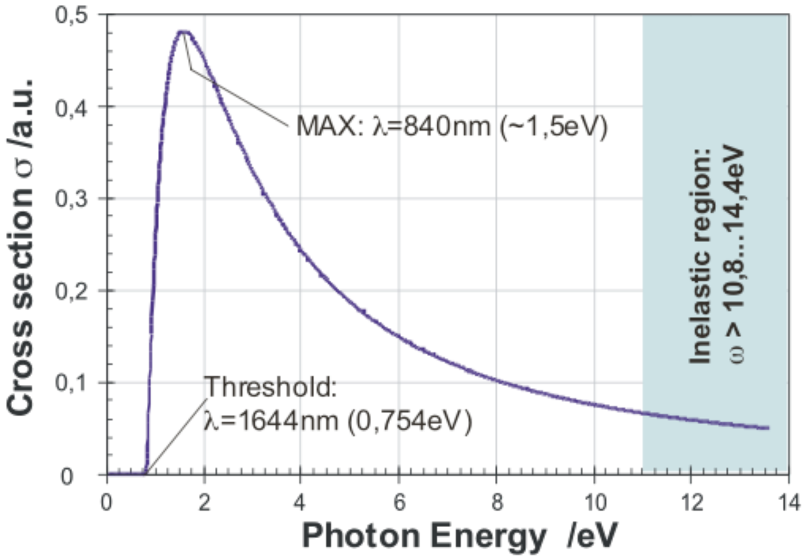
Diagnostics



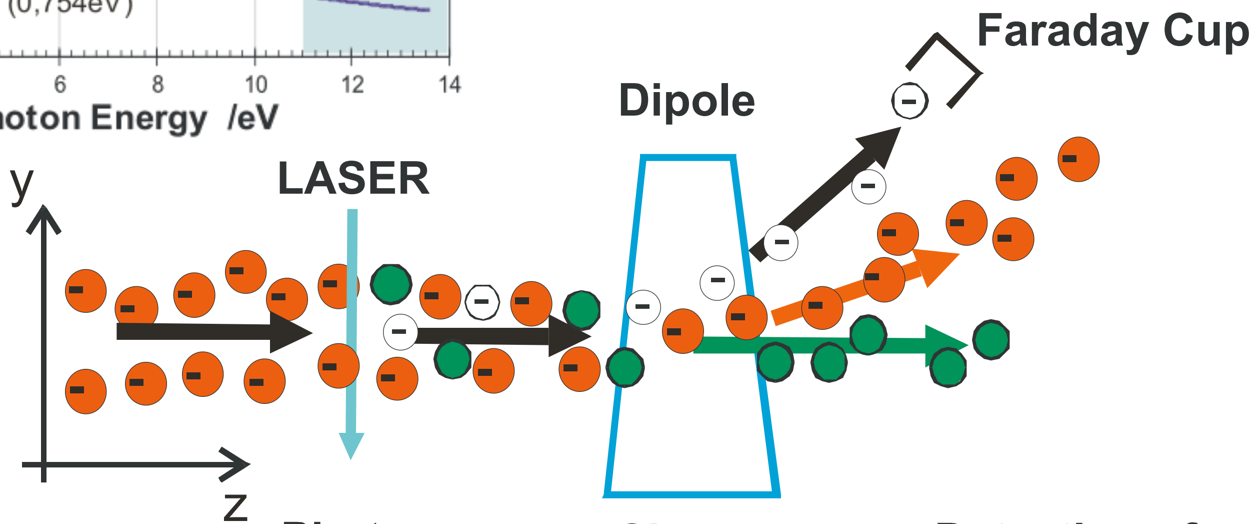
FETS Beam Diagnostics

- Conventional beam diagnostics currently used for FETS (eg. pepperpot, slit-slit) are destructive: a bit like sticking your finger in a plug socket to see if it's live…
- Need non-destructive diagnostics to make measurements while accelerator is running.
- 2 types of beam diagnostic under development, based on photo-detachment by laser:
  - 4-D emittance measurement (+ longitudinal profile) downstream of chopper.
  - 2-D profile measurement, between ion source and LEBT.

Photo Detachment for Beam Diagnostics



Photodetachment	"Threshold energy"
$\hbar\omega + H^- \longrightarrow H^o + e^-$	$E_D = 0.754\text{eV}$
$\sigma_{max} = 4.0 \times 10^{-17}\ \text{cm}^2$	Maximum $E_{photon} = 2E_D$
H^0: no significant momentum transfer	



Laser-based H^{-} Diagnostics

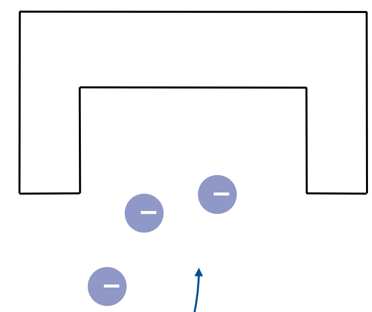
- To measure
  - Beam profiles
  - Longitudinal emittances

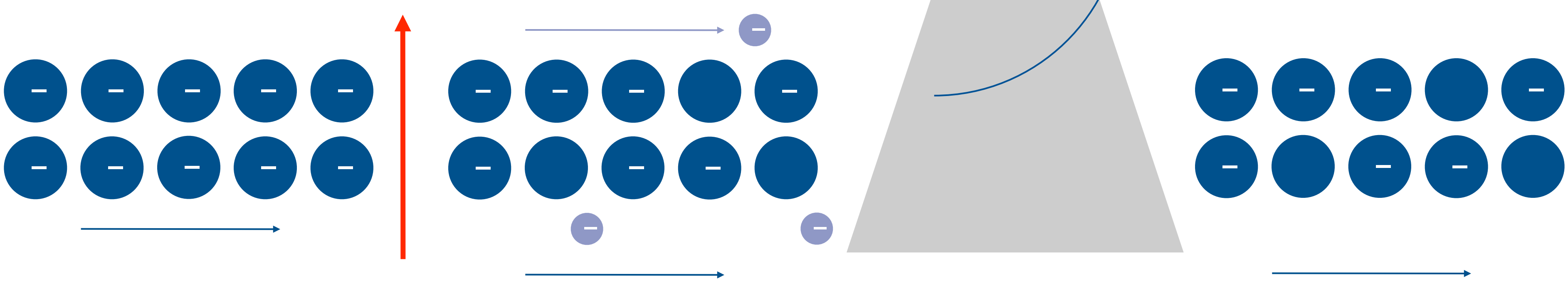
  use photo-detached electrons

Laser-based H⁻ Diagnostics

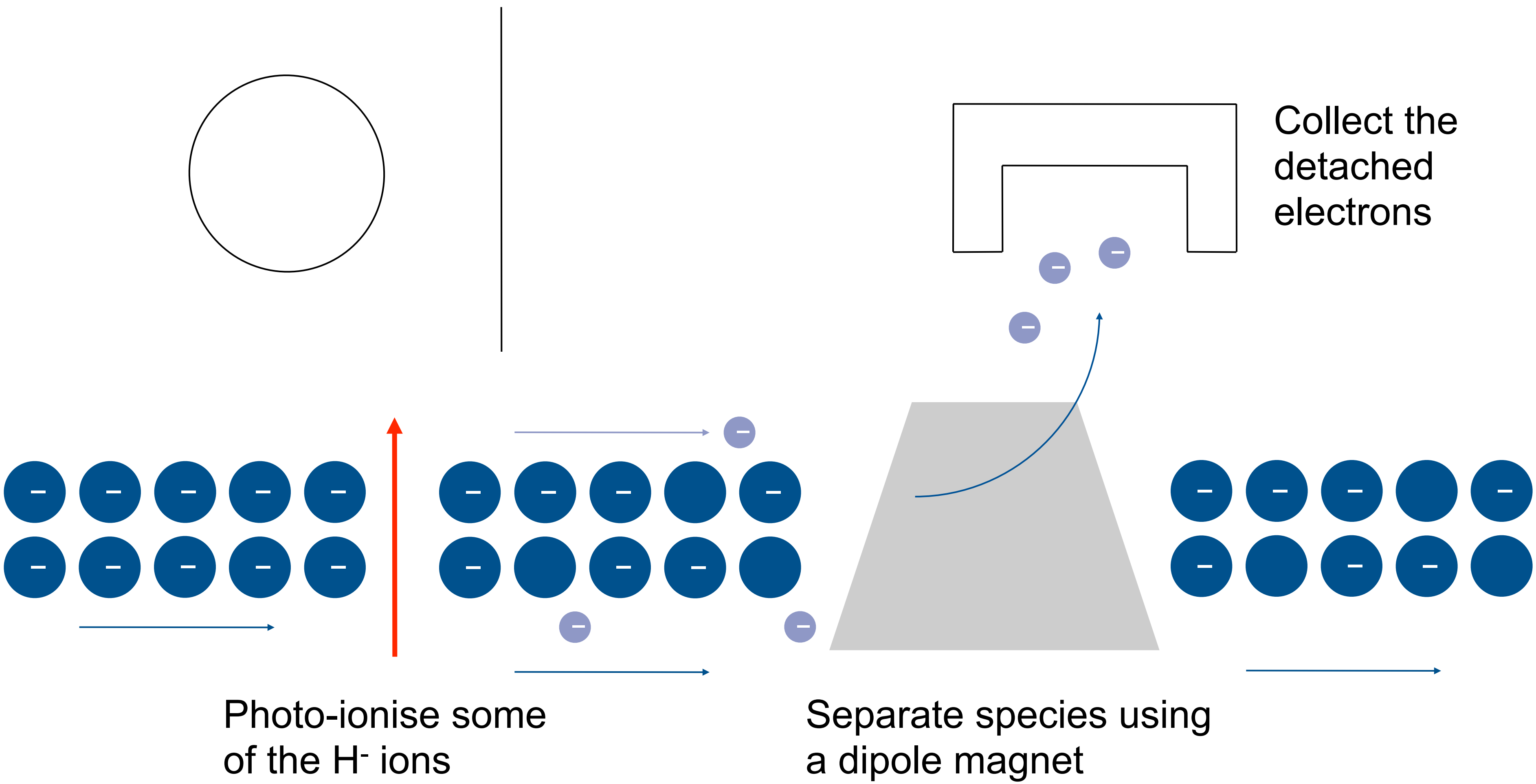
- To measure
  - Beam profiles
  - Longitudinal emittances

use photo-detached electrons

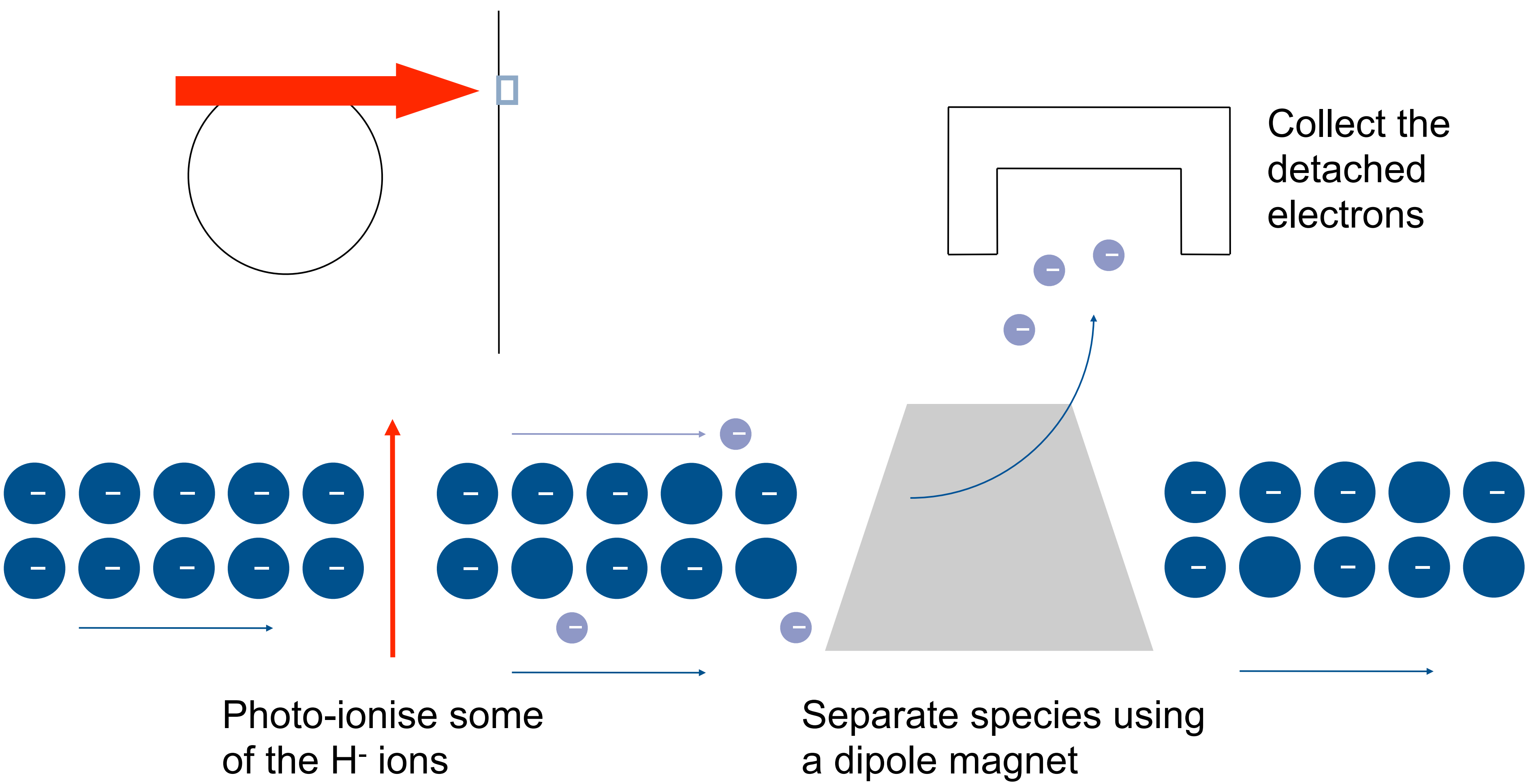




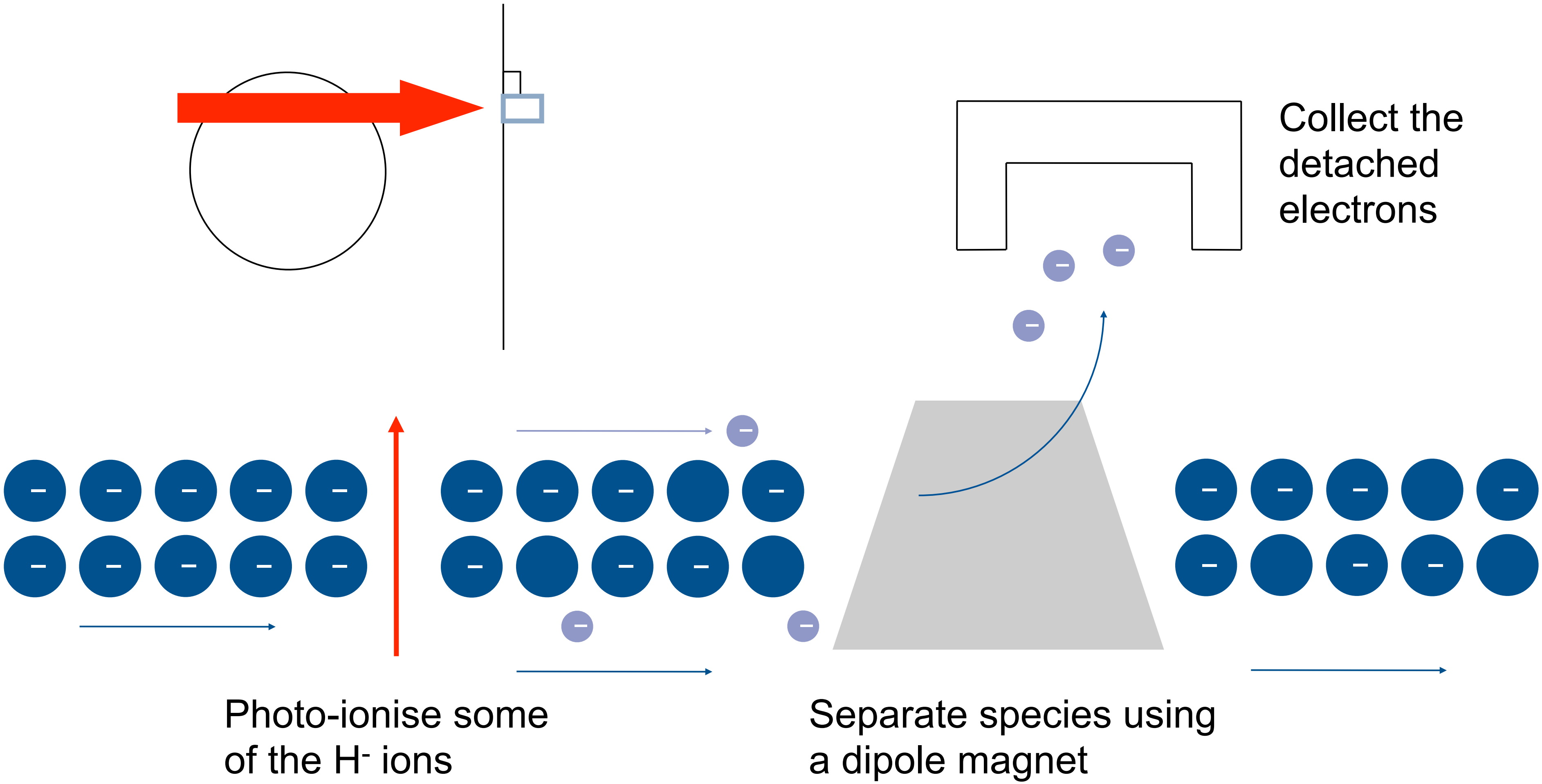
Laser-based H⁻ Diagnostics



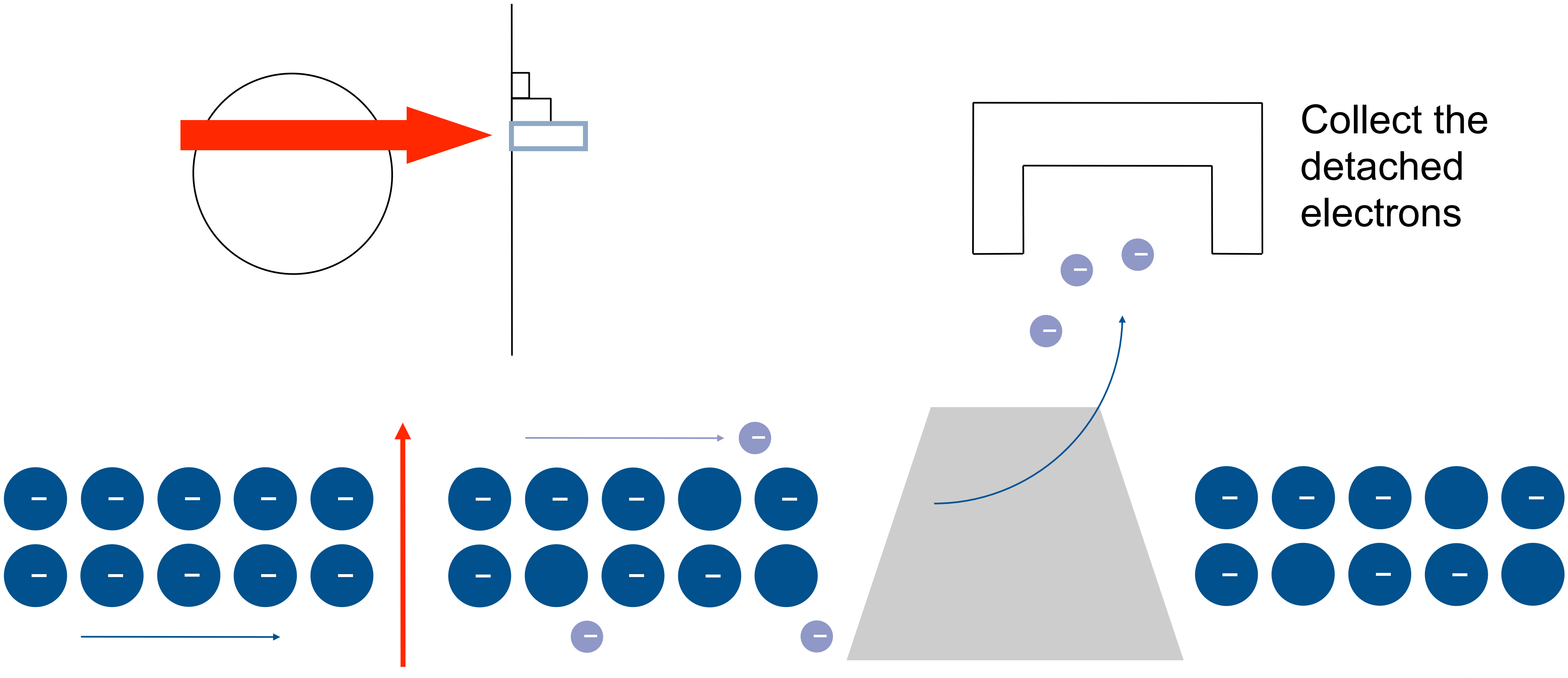
Laser-based H⁻ Diagnostics



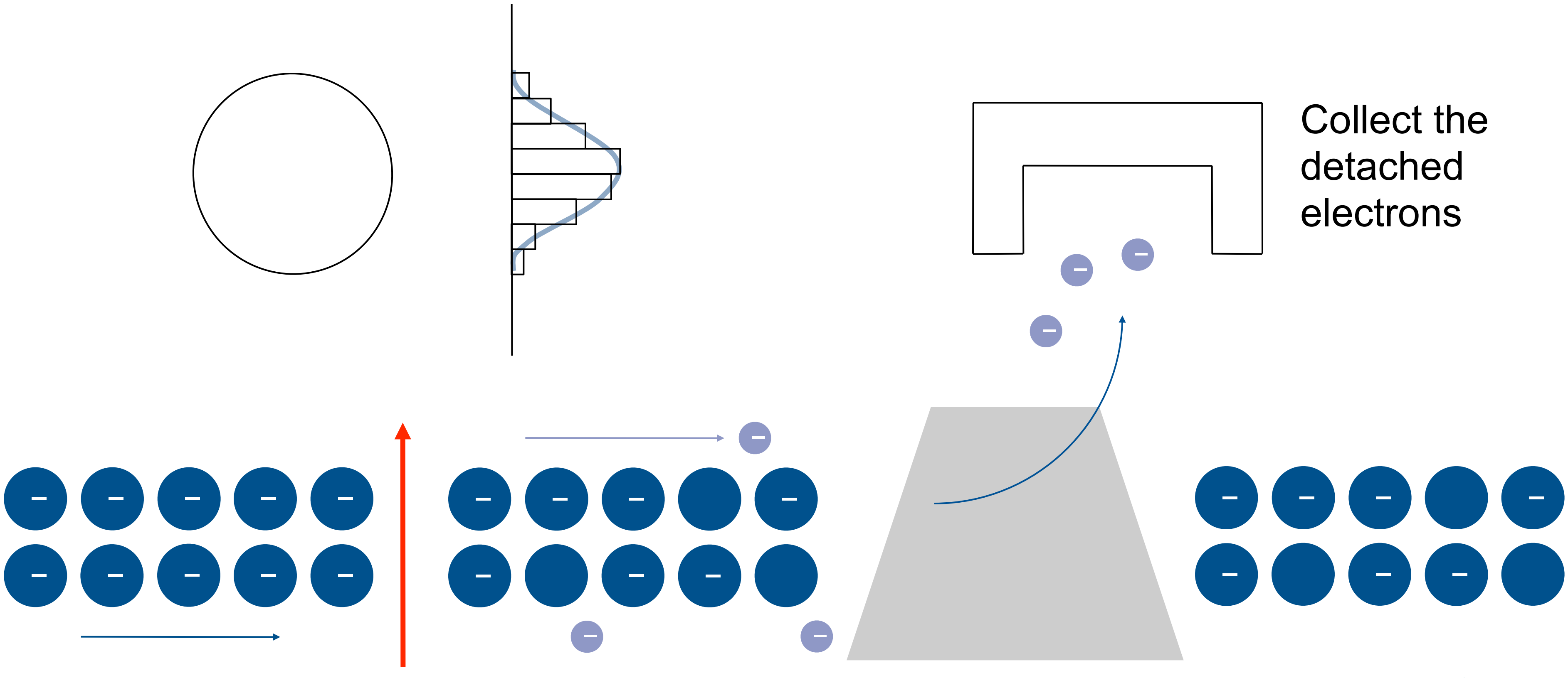
Laser-based H⁻ Diagnostics



Laser-based H⁻ Diagnostics

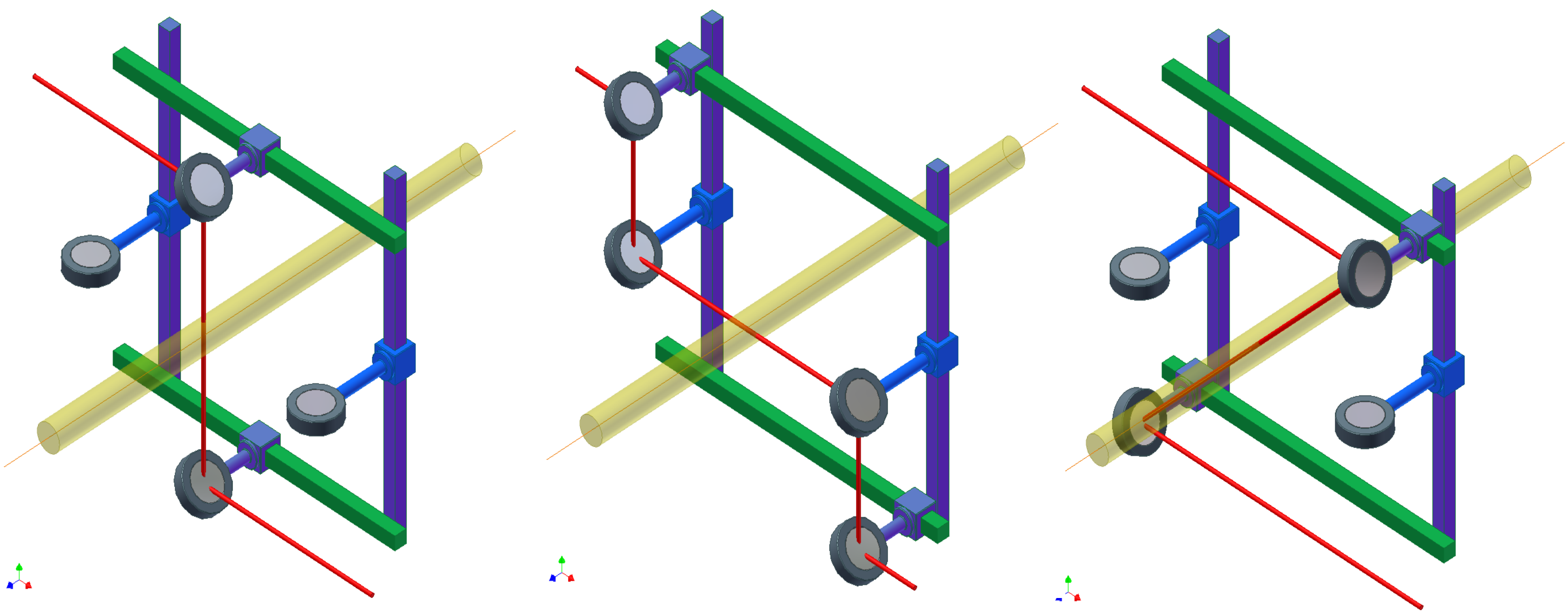


Laser-based H⁻ Diagnostics

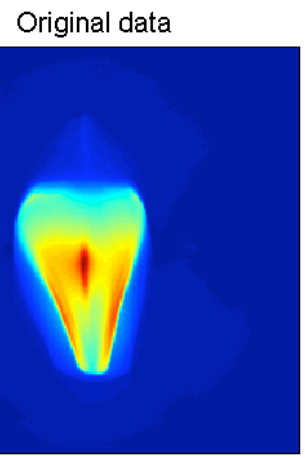


Laserwire Profile Concept

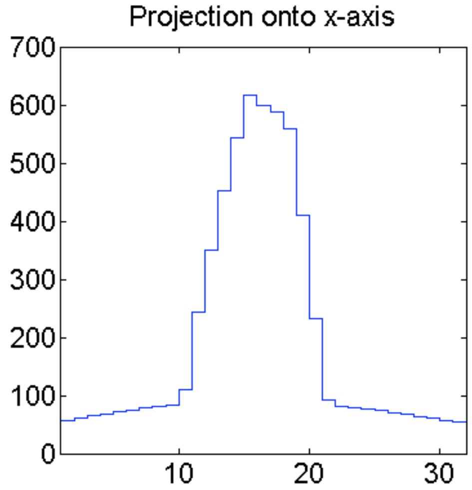
Multiple mirror setup allows laser to sample beam from all directions

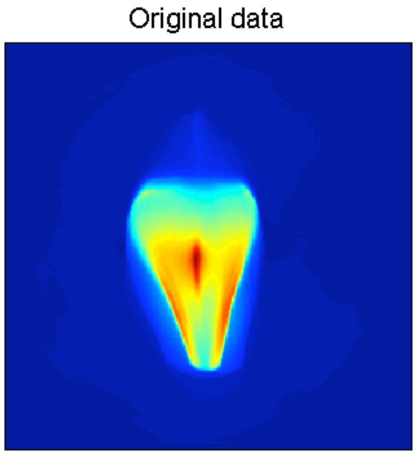


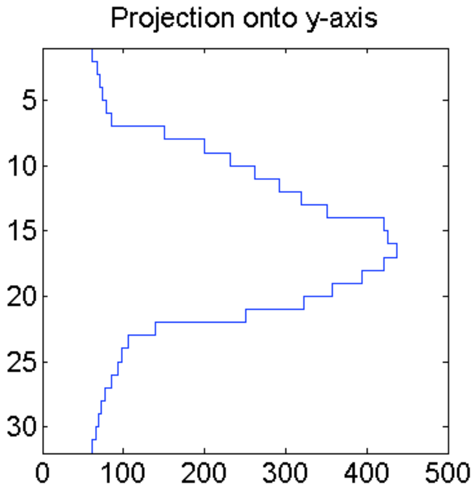
Benefit Of Multiple Projections (>2)



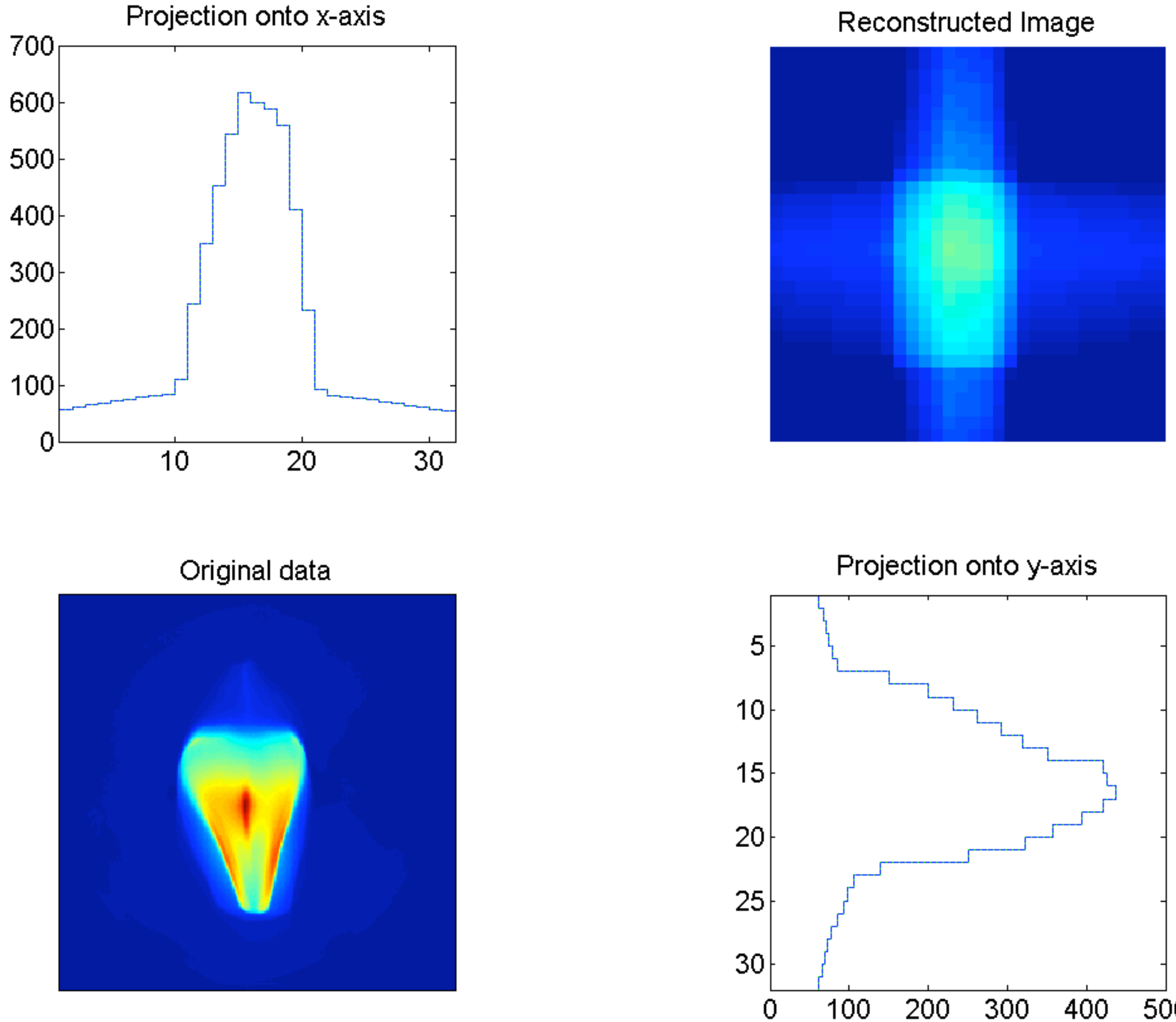
Benefit Of Multiple Projections (>2)



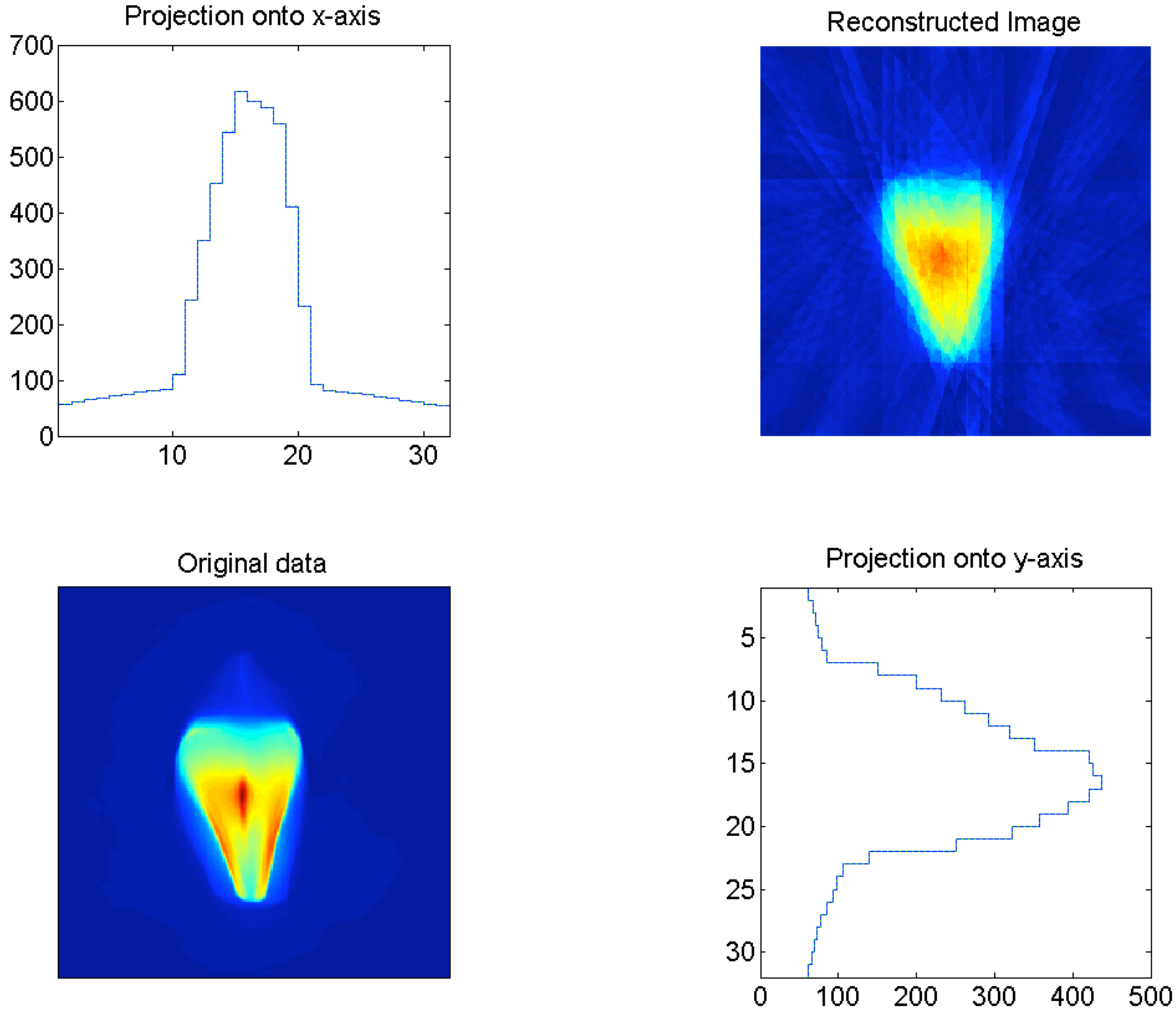




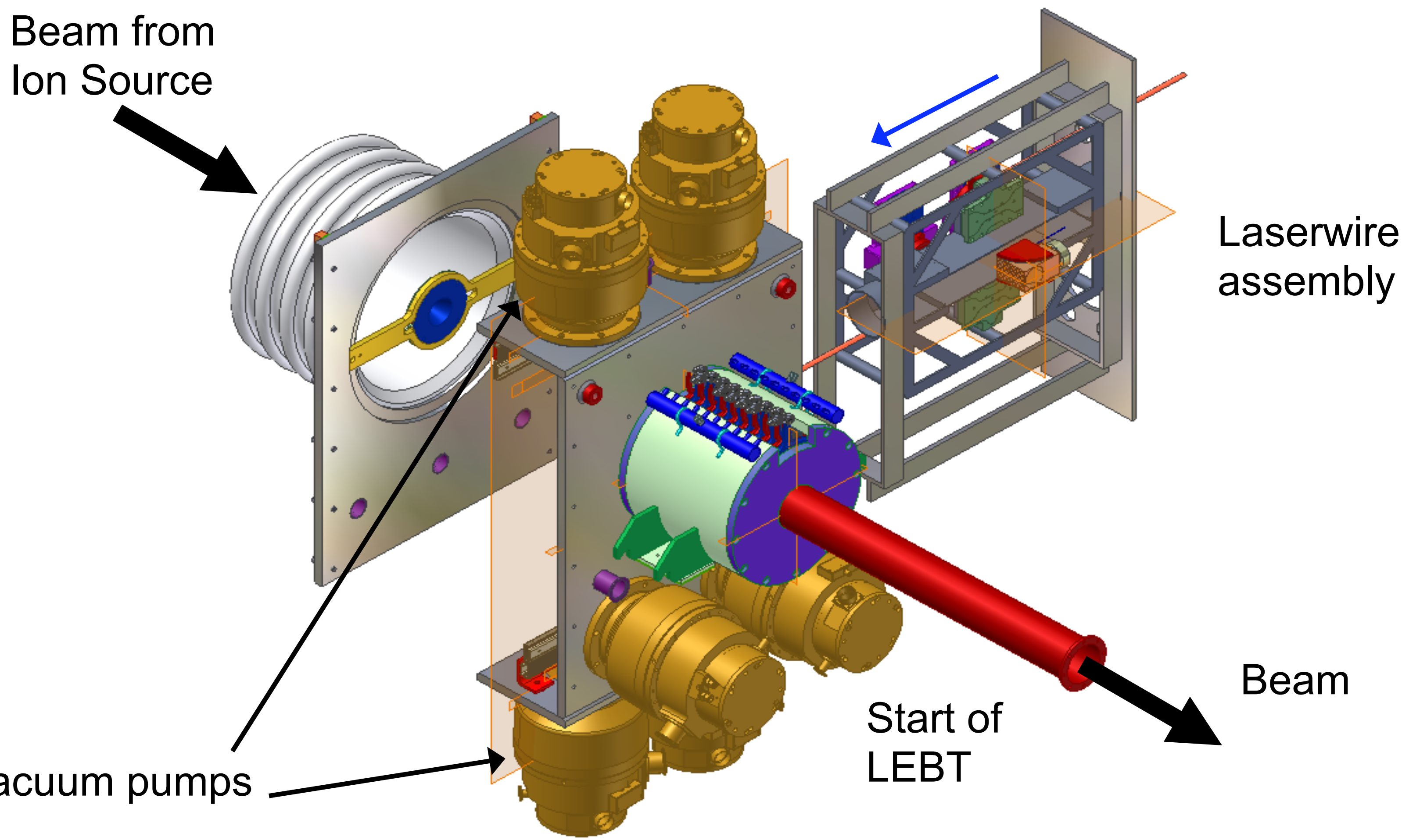
Benefit Of Multiple Projections (>2)



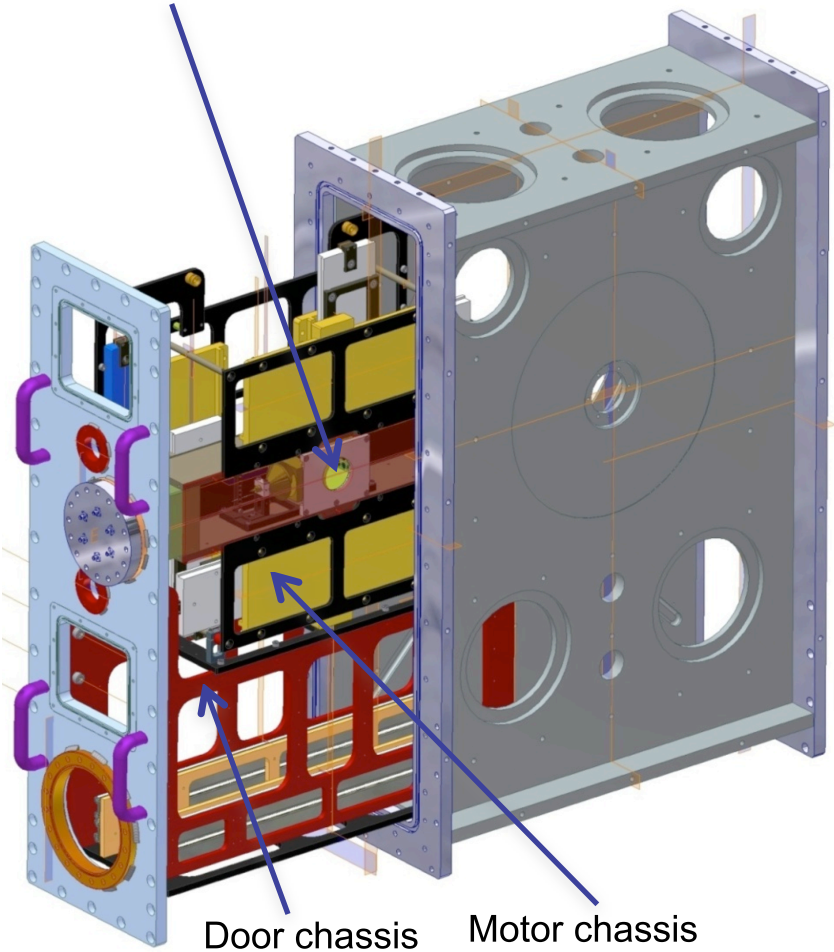
Benefit Of Multiple Projections (>2)

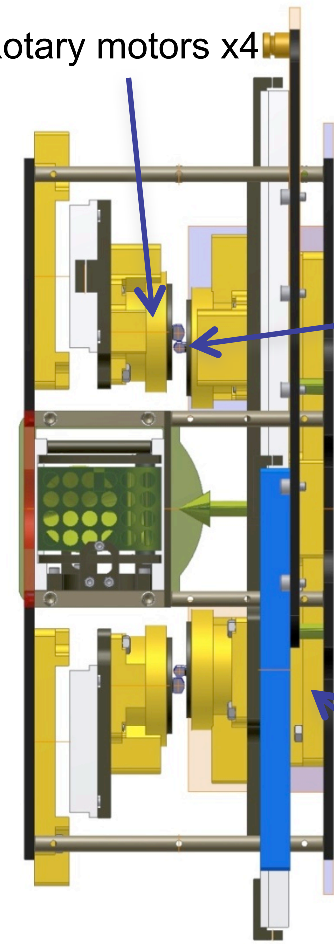


Laserwire Vacuum Tank

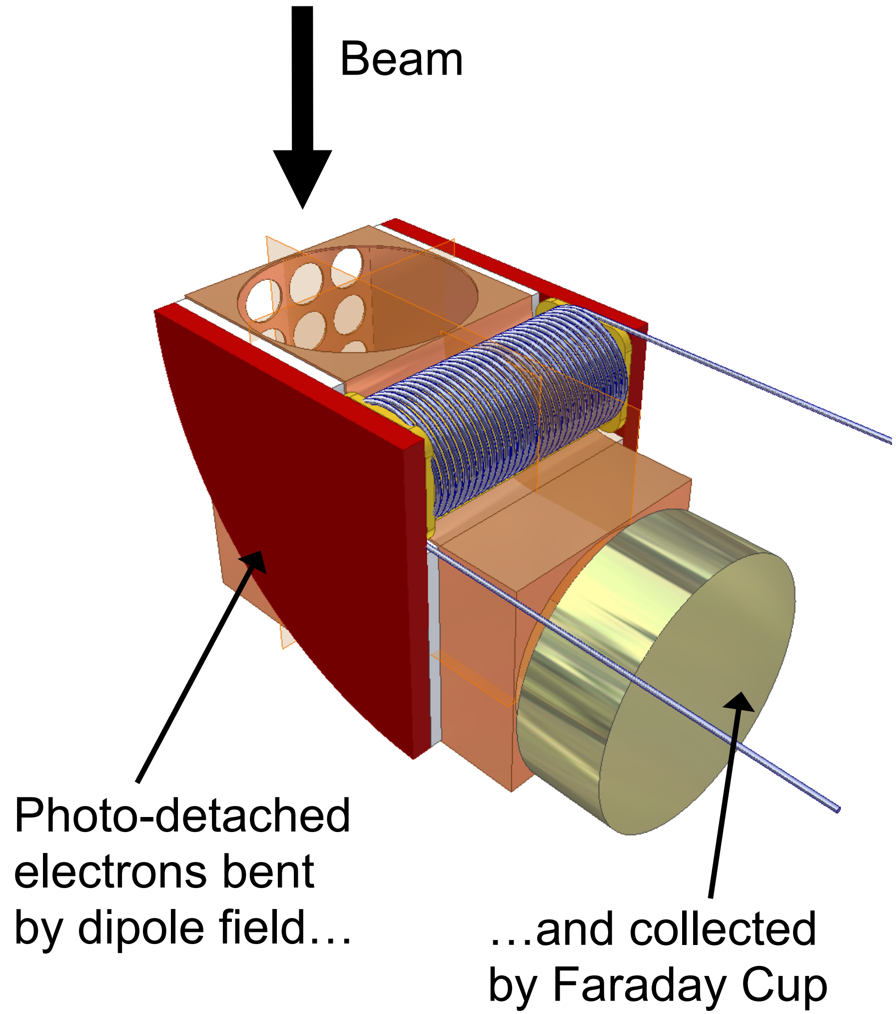


Laserwire Vacuum Tank (2)

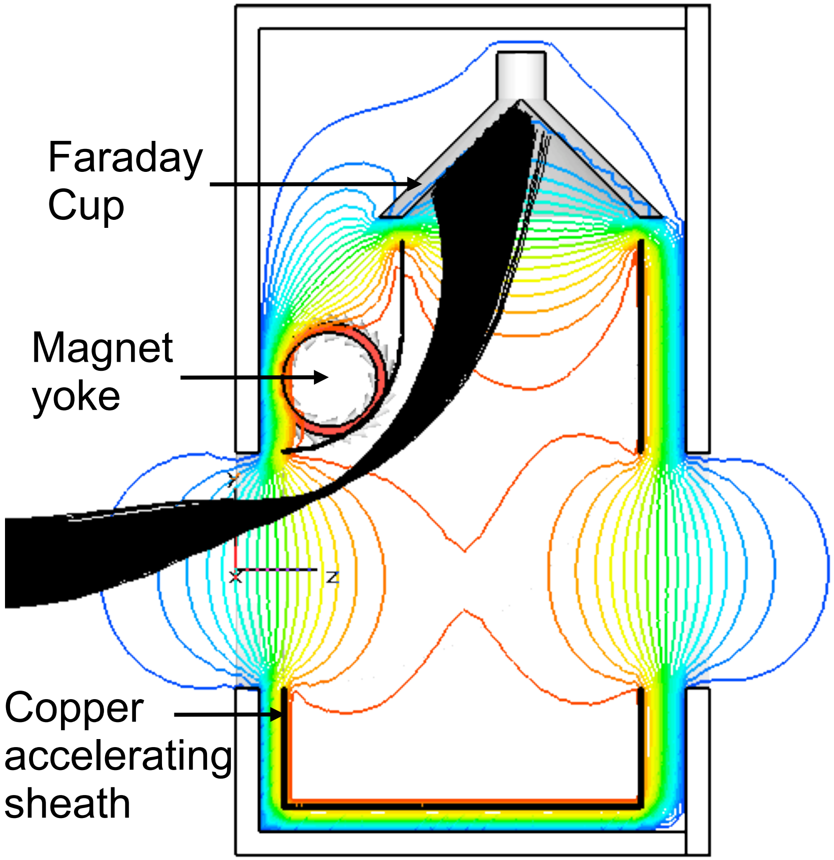




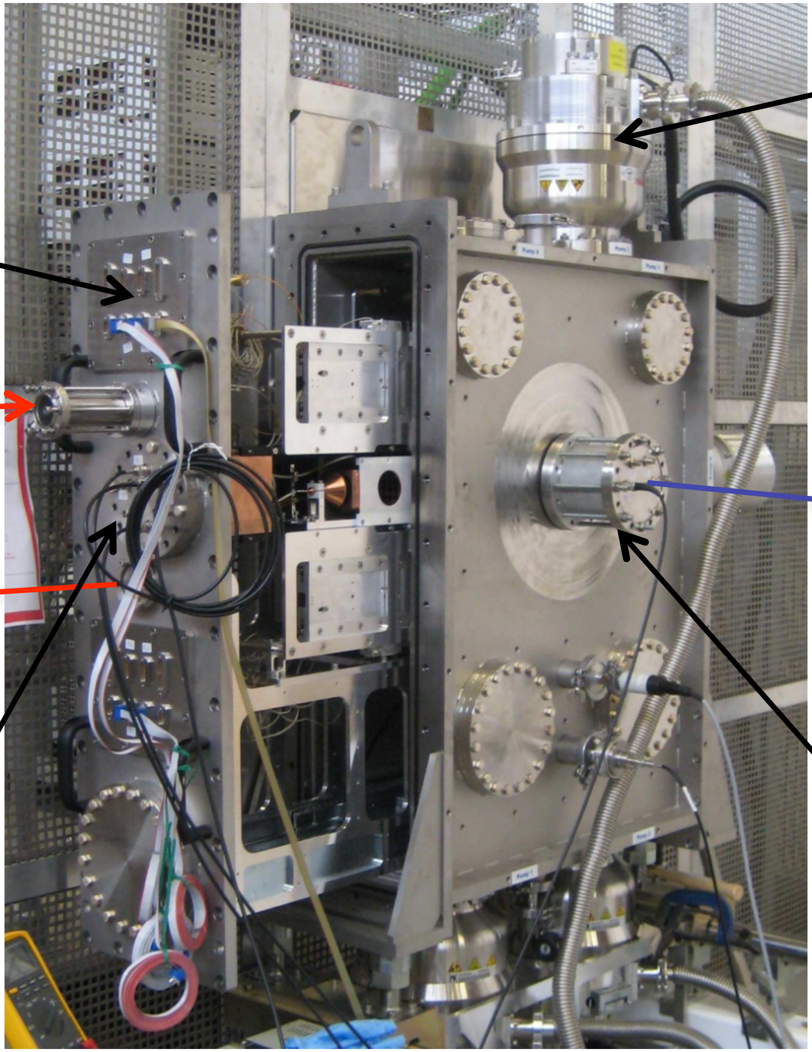
Laserwire Electron Collector



Collector Field Map/Trajectories



LEBT Vacuum Tank (Installed)



Sub-D feed-through panel for linear and rotary motors

Vacuum Pumps 3 x 800 l/s

Laser in

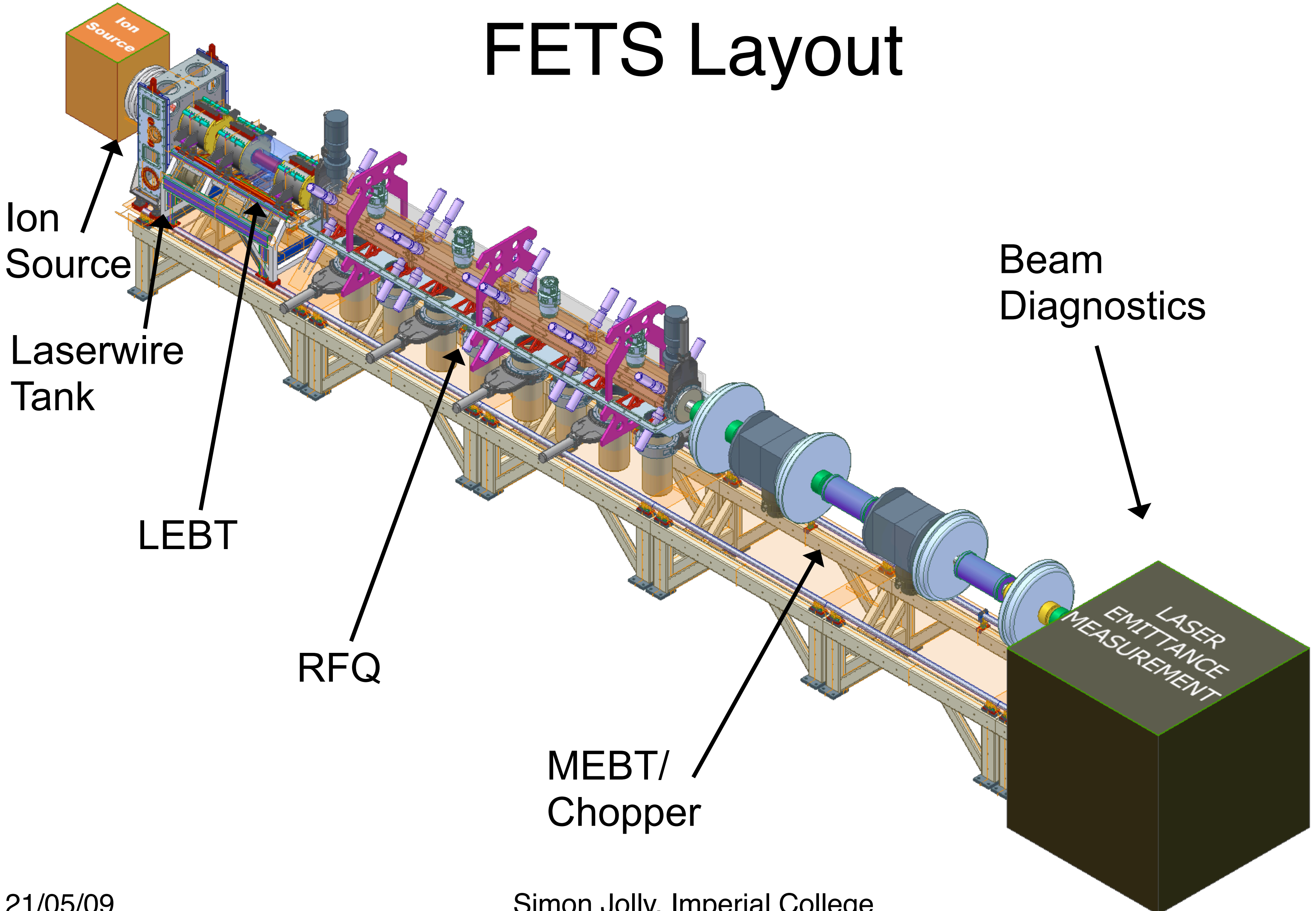
Beam

Laser out

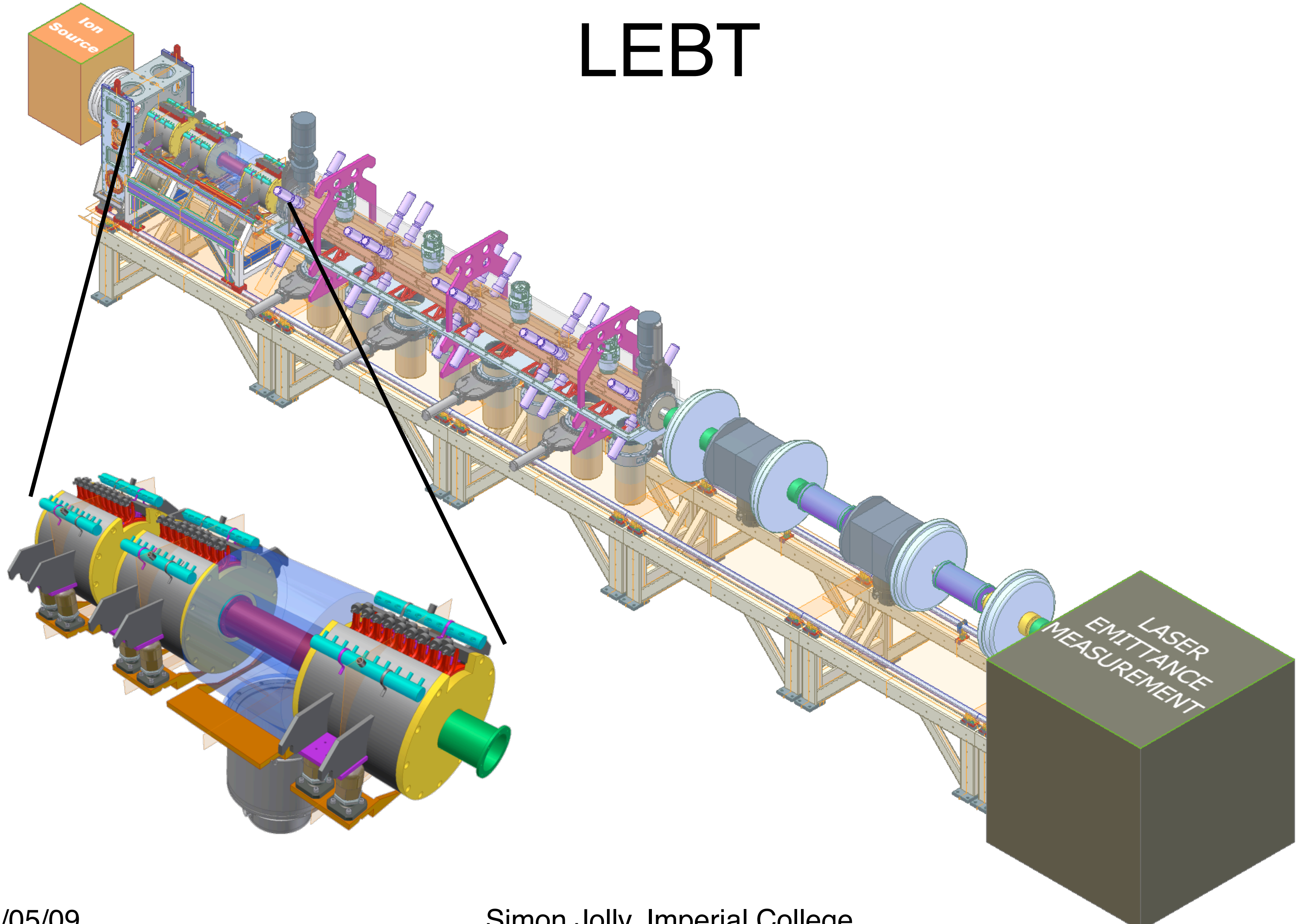
BNC feed-through flange for detector

Faraday cup assembly / beam stop

FETS Layout

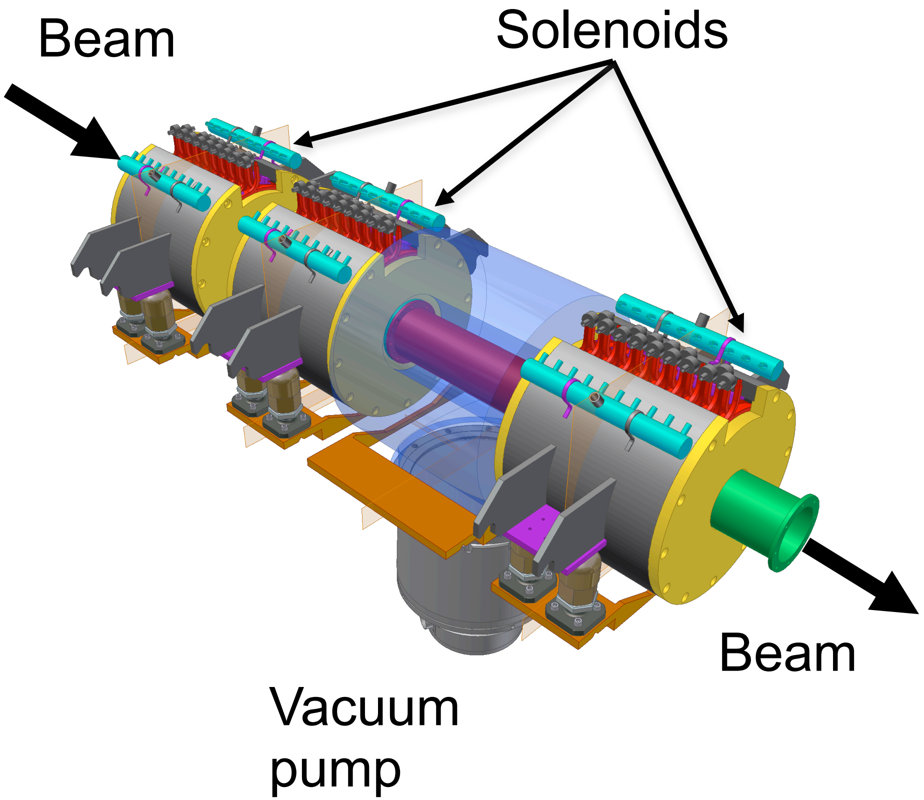

Ion Source
Ion Source
Laserwire Tank
LEBT
RFQ
MEBT/ Chopper
Beam Diagnostics
LASER EMITTANCE MEASUREMENT

LEBT

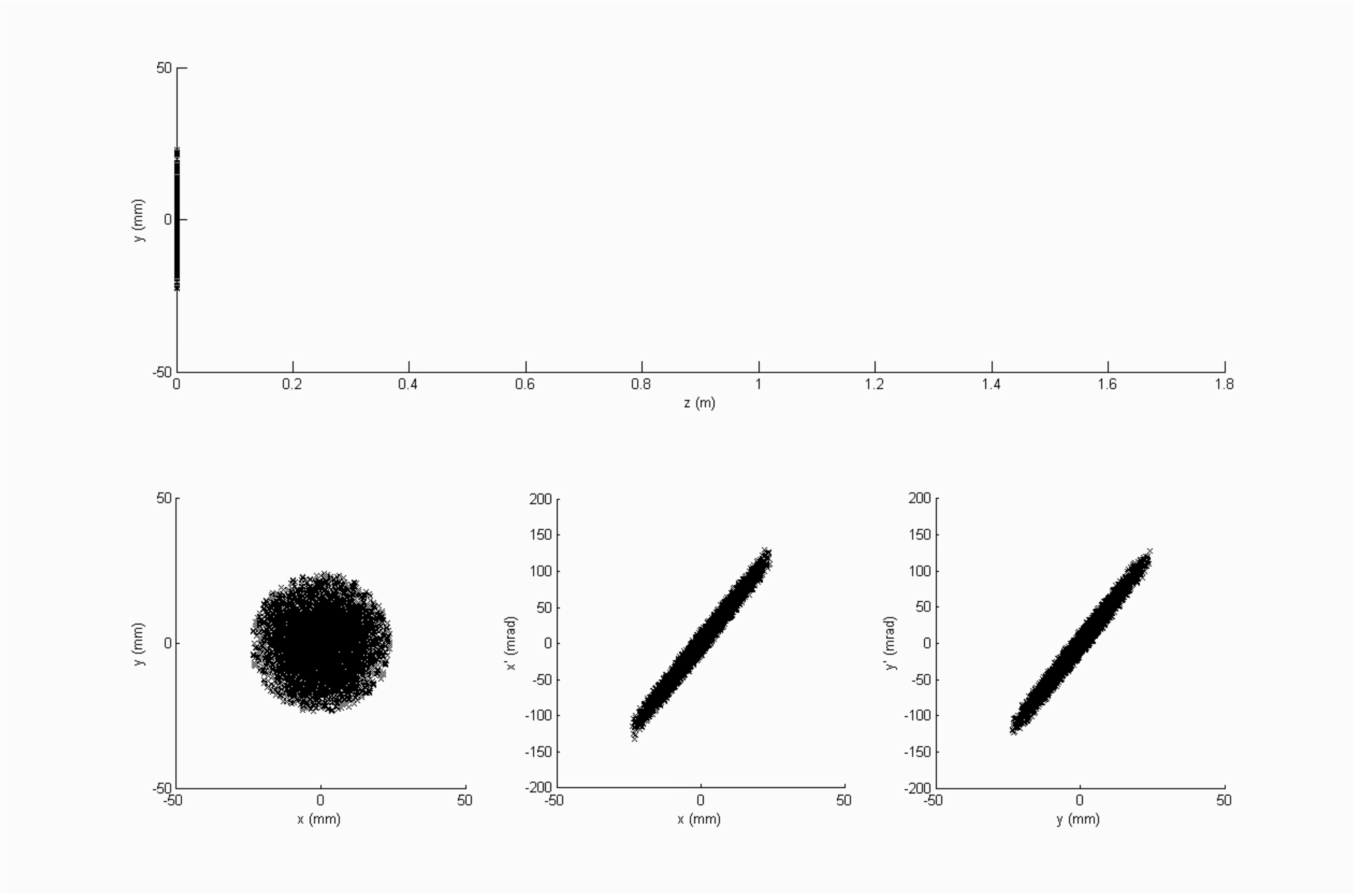


FETS Low Energy Beam Transport

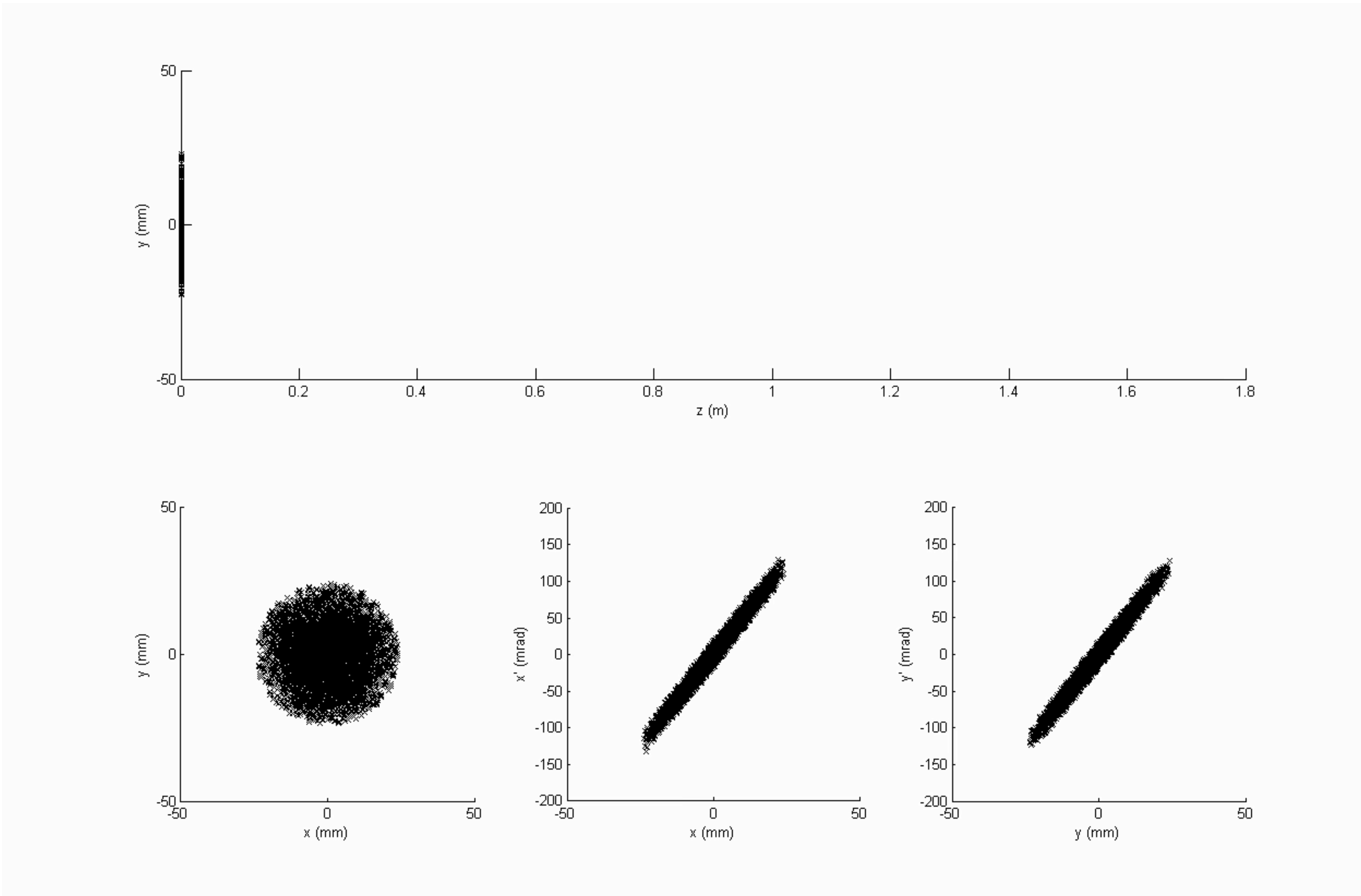
- Beam must be focussed from >20mm at Ion Source to 2-3mm at RFQ.
- Large dynamic range required to handle beam size and space charge.
- 3 solenoid design with "weak focussing" provides effective focussing with minimal emittance growth



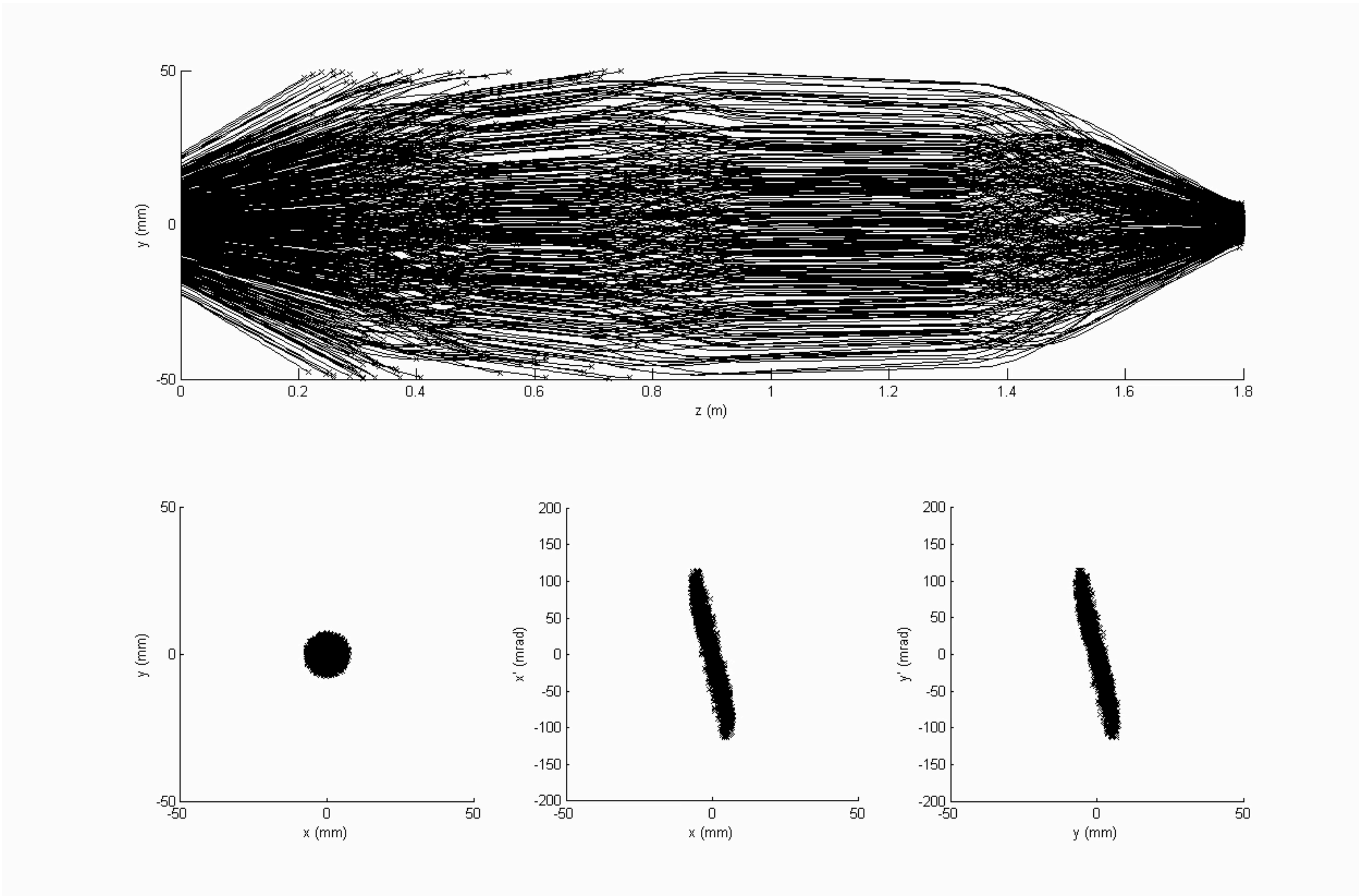
Beam Trajectories in 3-Solenoid LEBT



Beam Trajectories in 3-Solenoid LEBT

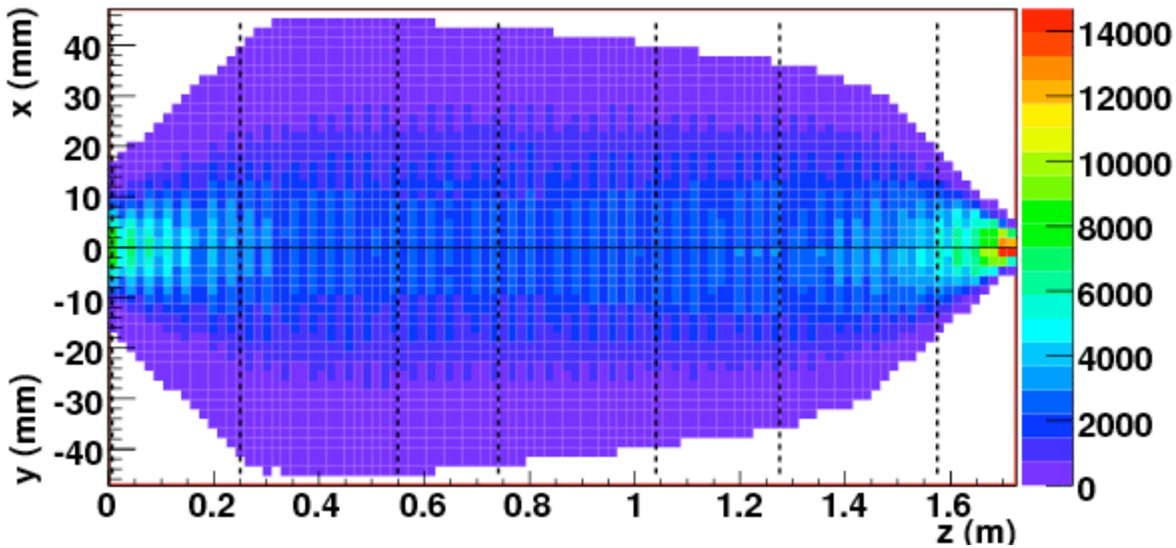


Beam Trajectories in 3-Solenoid LEBT

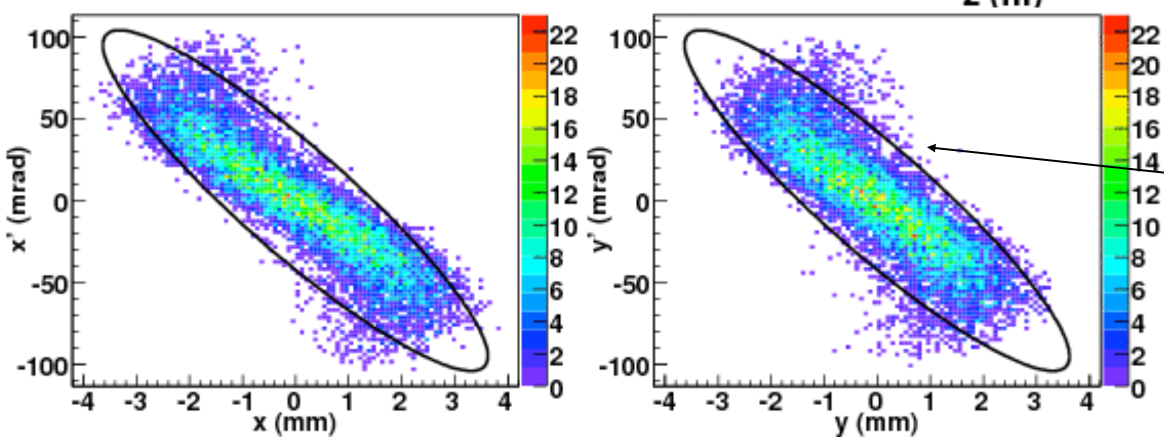


LEBT Performance for Ideal Beam

Vertical lines: Drift and solenoid regions

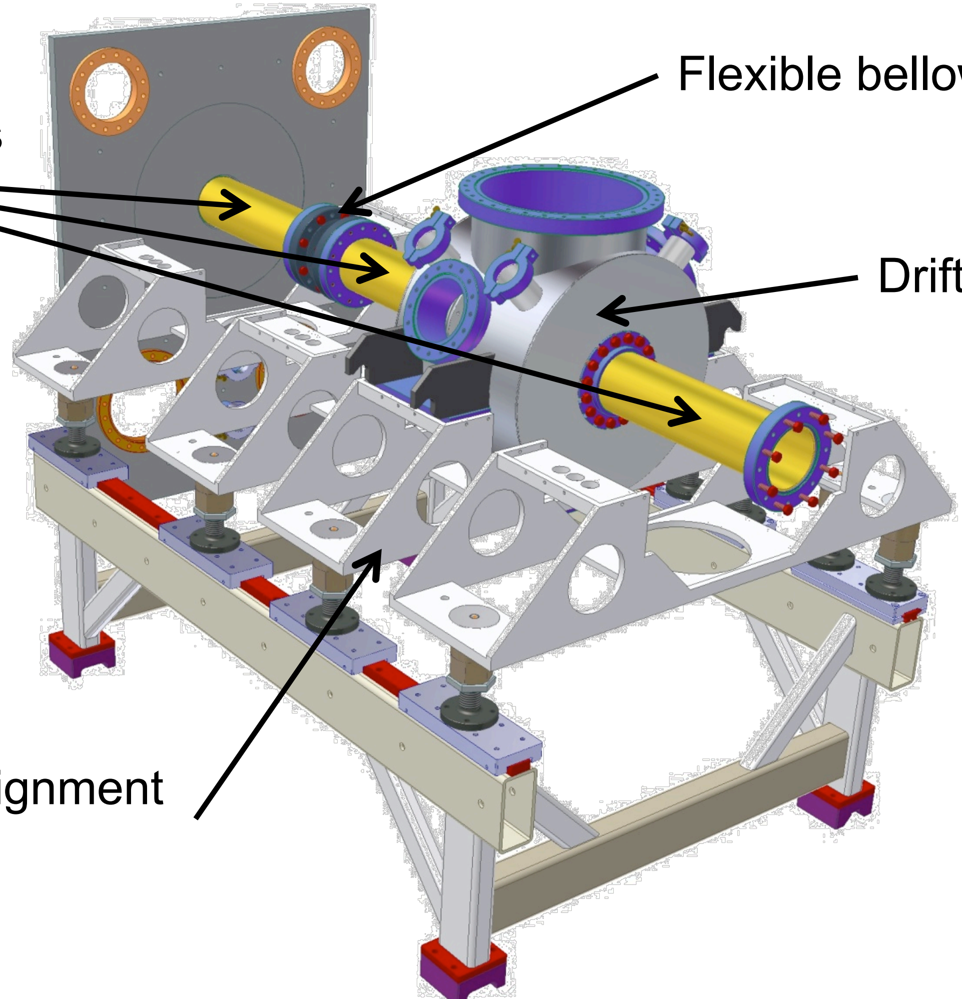


End of LEBT:



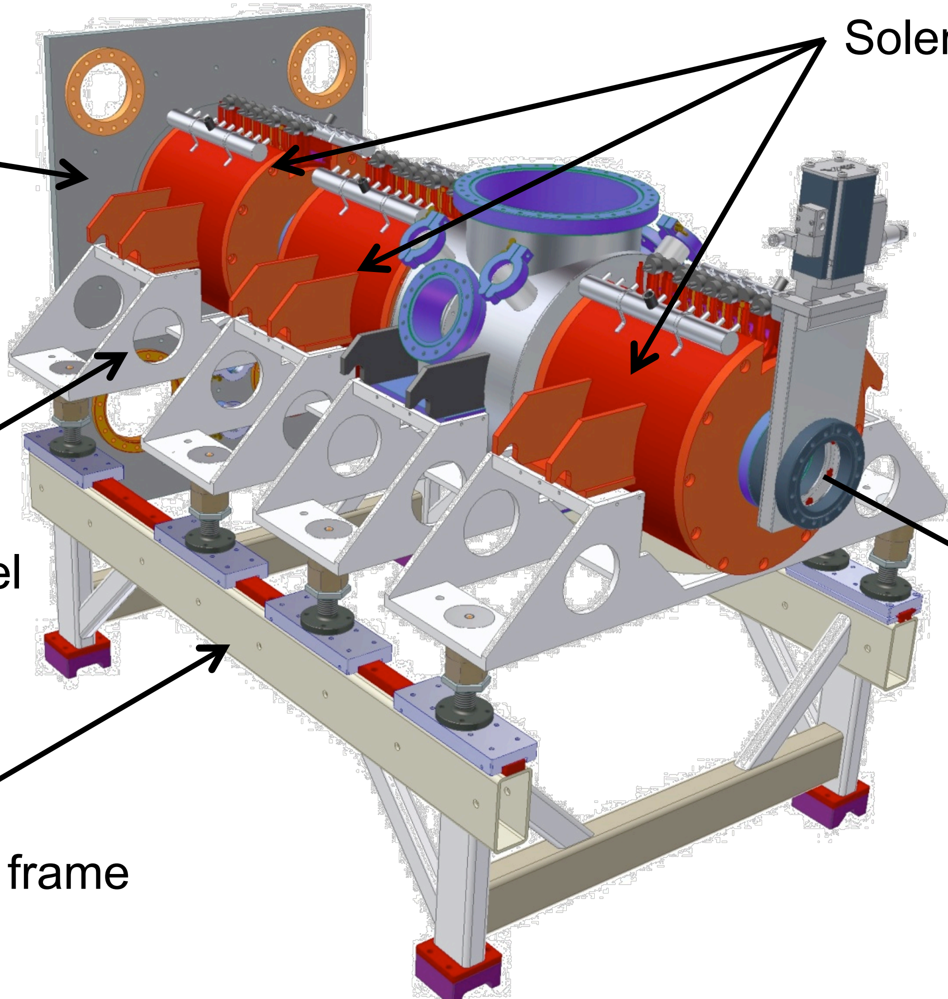
RFQ Acceptance Ellipse

LEBT Support Structure

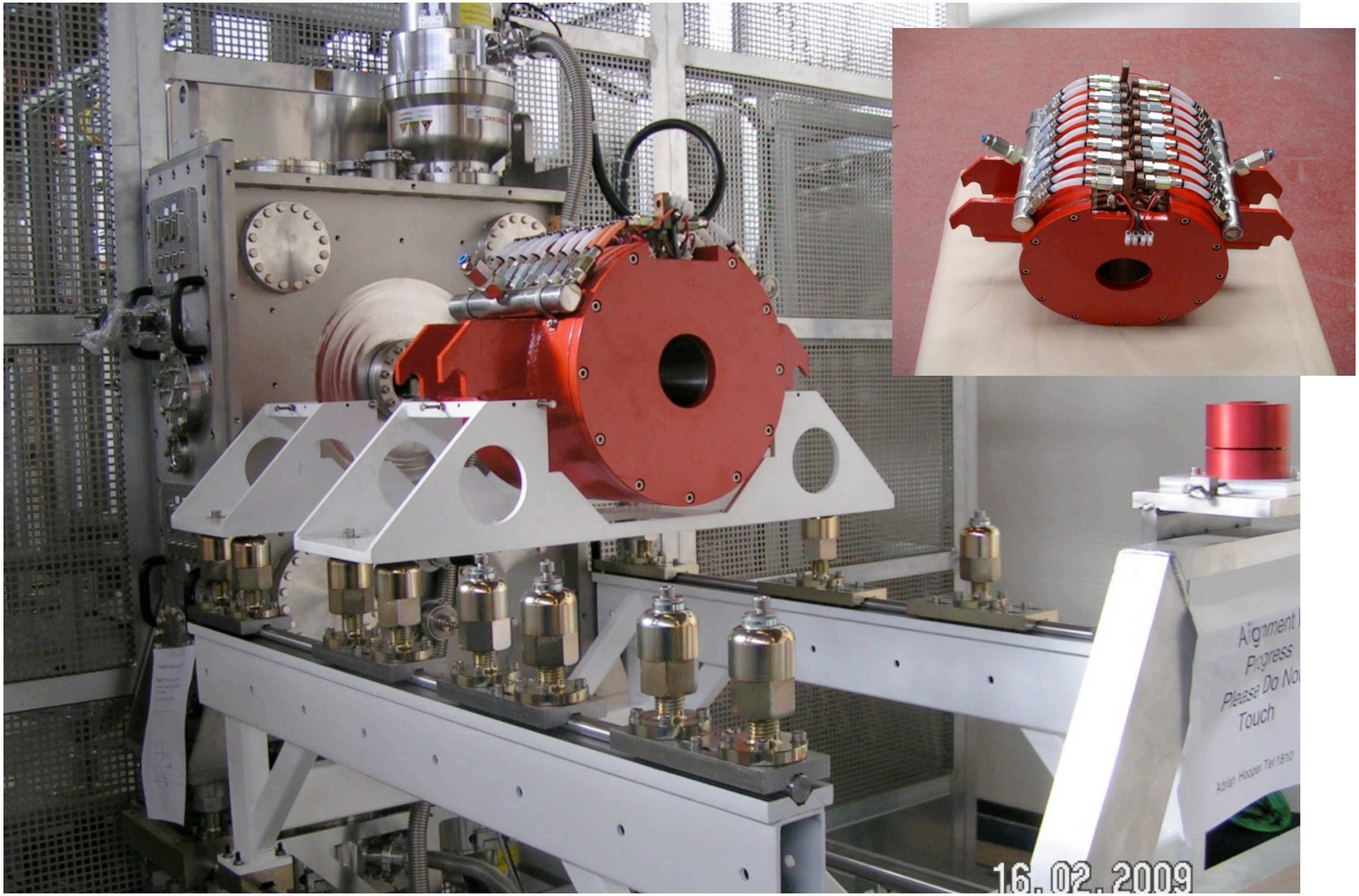


Drift lengths:
d1 = 25cm
d2 = 13.5cm
d3 = 35cm
d4 = 17cm

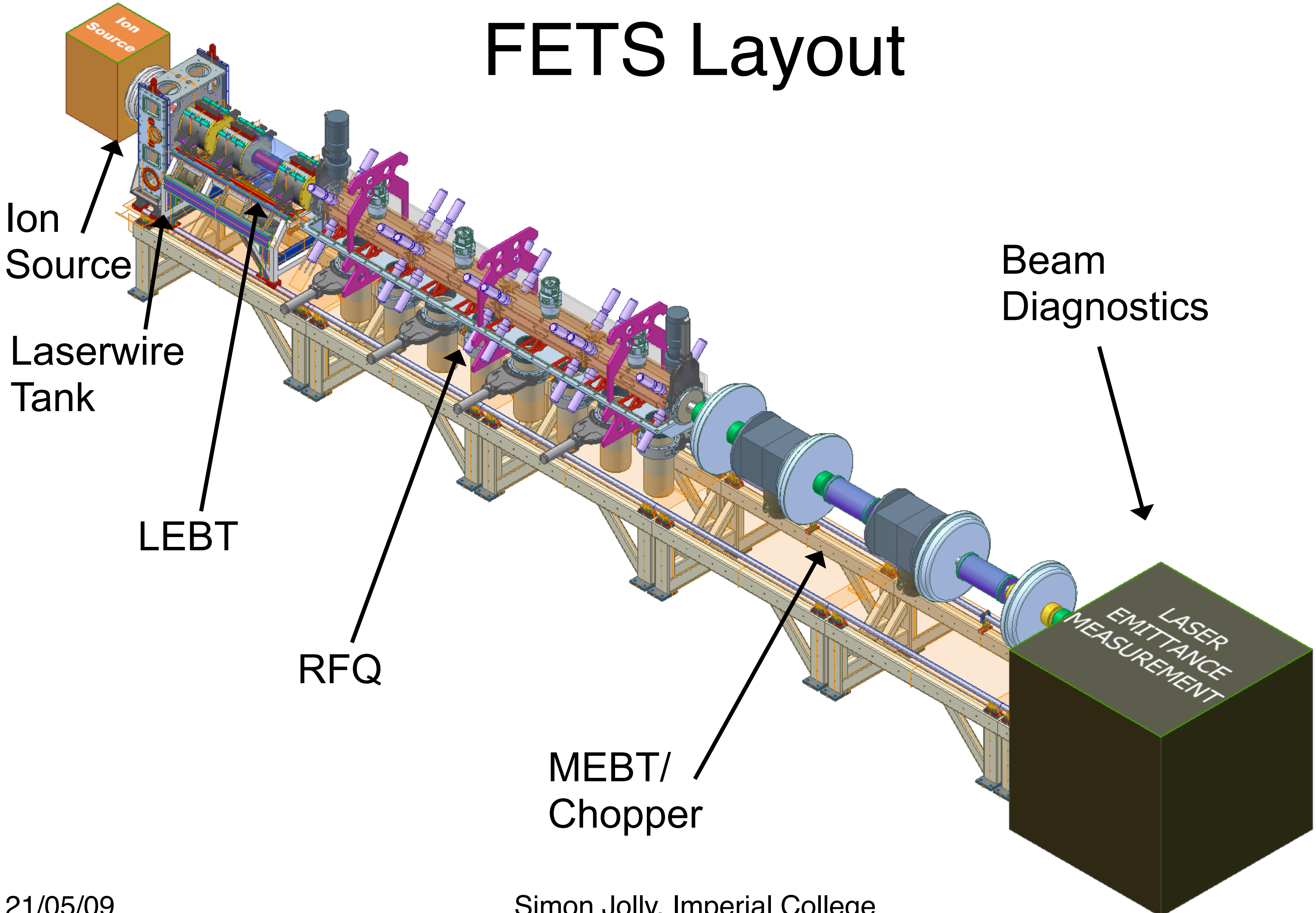
Complete LEBT



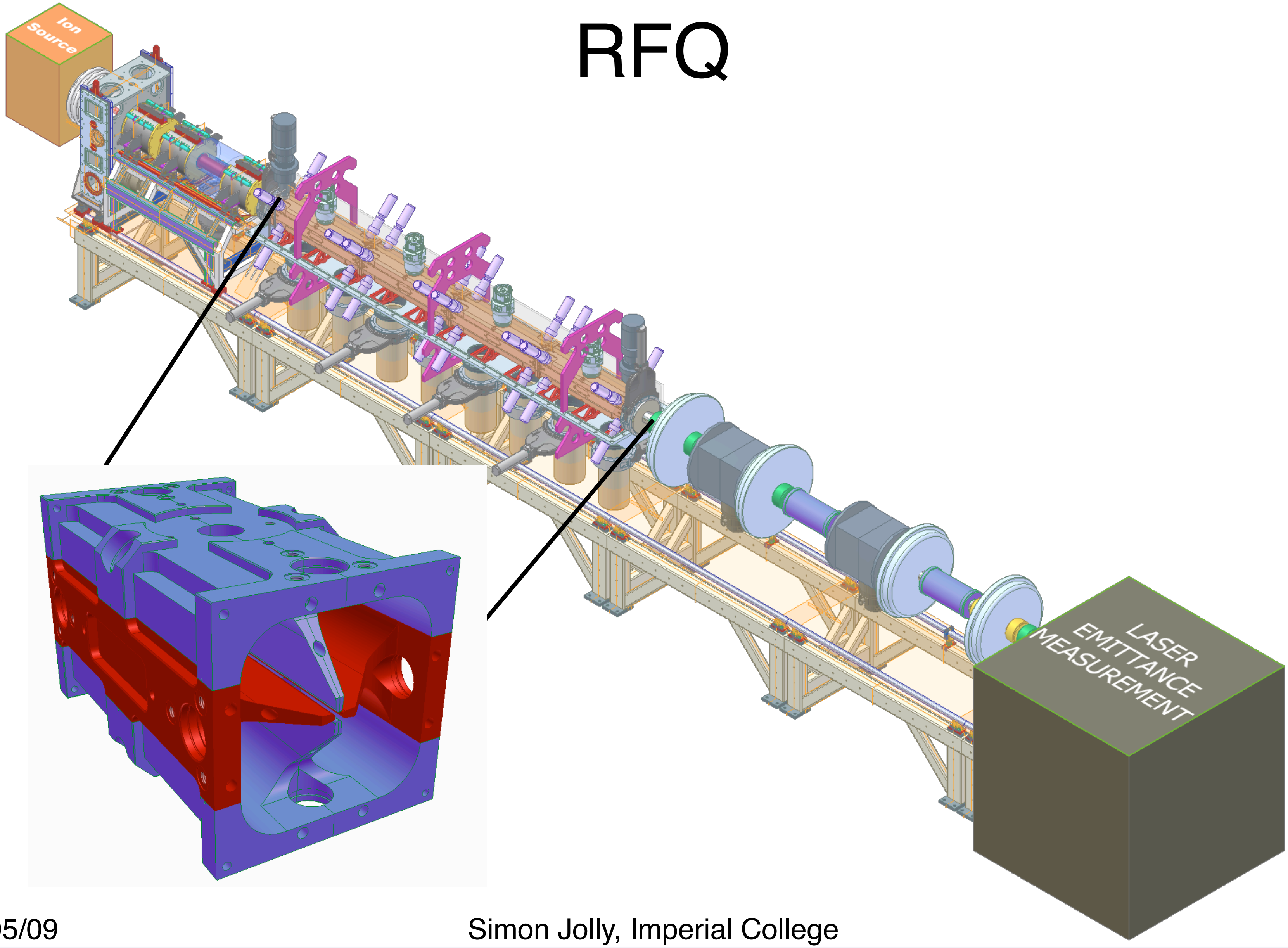
Solenoid Installation



FETS Layout


Ion Source
Ion Source
Laserwire Tank
LEBT
RFQ
MEBT/ Chopper
Beam Diagnostics
LASER EMITTANCE MEASUREMENT

RFQ

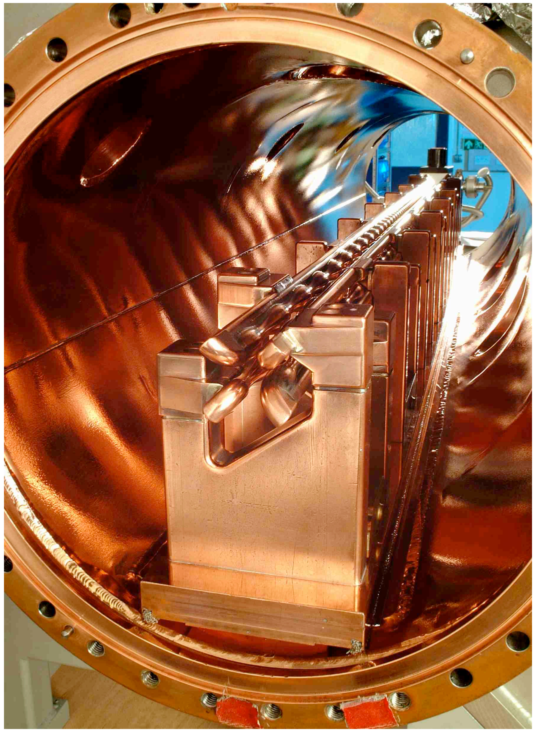


Accelerators: Go Small, Go Swift…

- Two main aims of accelerator beamline:
  - Focussing (go small).
  - Acceleration (go swift).
- For relativistic beams, we can do this with a FODO lattice, interleaved with accelerating structures.
- However, at low energies things become more complex:
  - Variation in β means RF cavity length must increase as beam is accelerated.
  - Space charge puts a premium on continuous focussing.
- Perhaps we can accomplish the whole thing in one go…

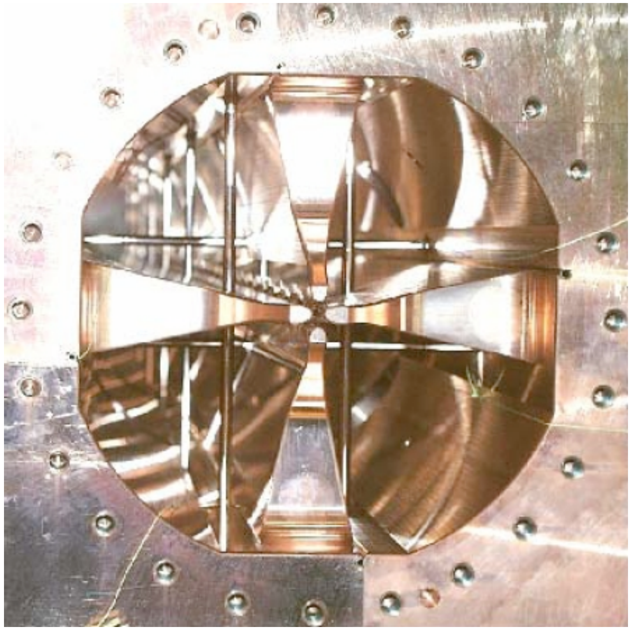
The RadioFrequency Quadrupole (RFQ)

RFQ's accelerate, bunch AND focus all at once!



2 types: 4-rod and 4-vane

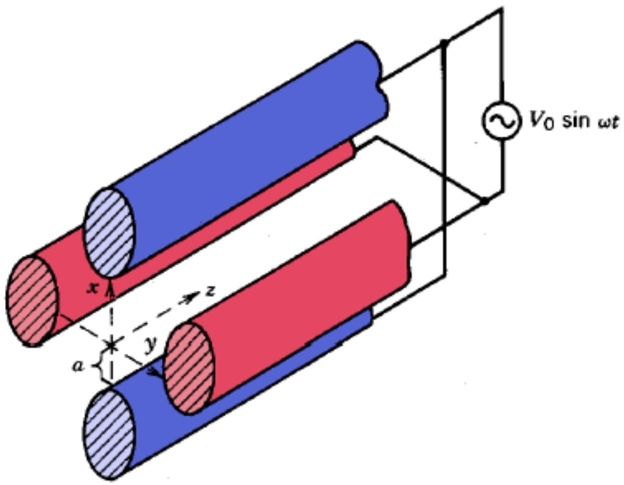
4-rod RFQ



4-vane RFQ

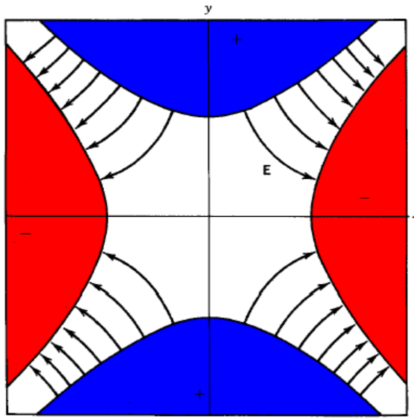
RFQ Focussing

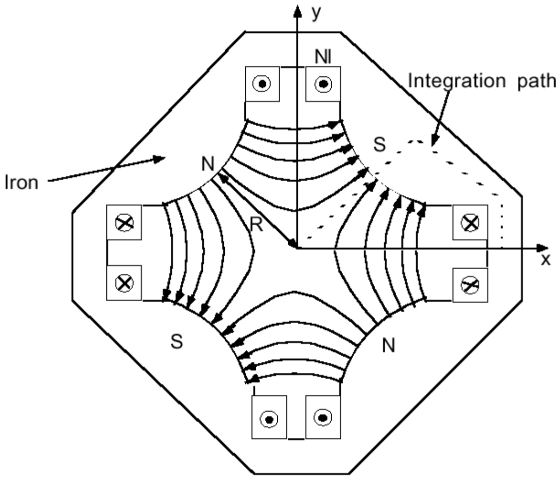
- RF field causes positive/negative charges on pairs of vanes.
- Since field varies with time, alternate focussing/defocussing mimics FODO.



RFQ vane tips

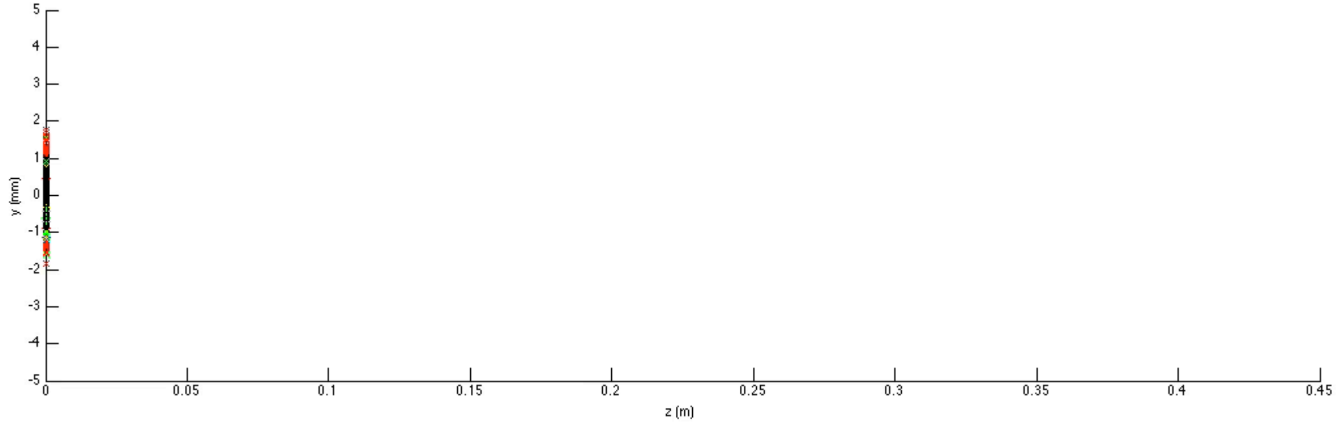
RFQ E-field

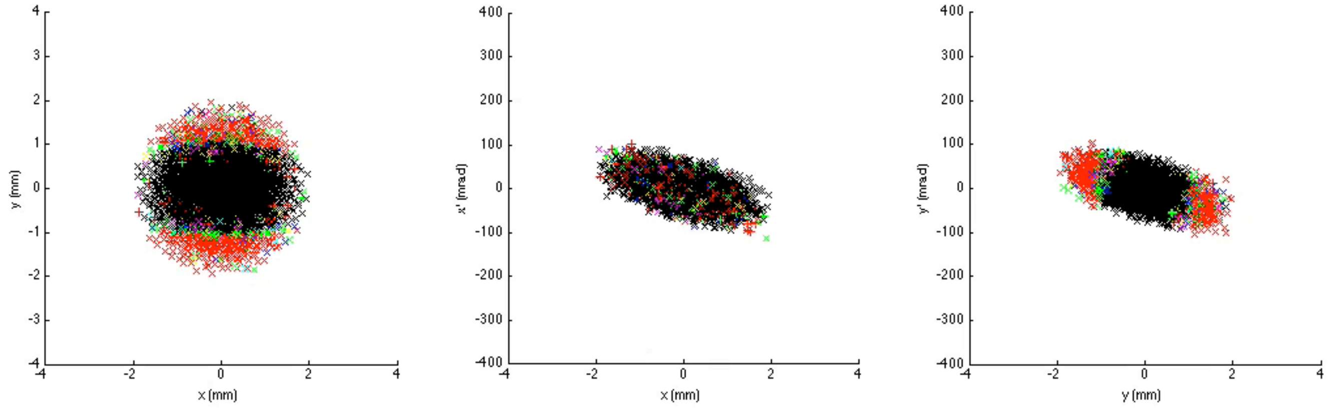




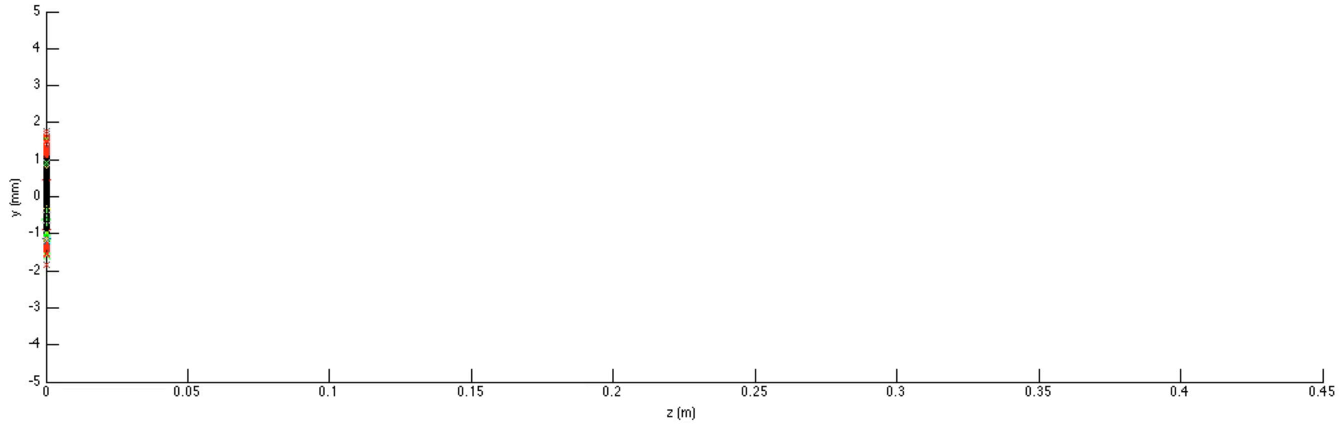
Standard Quad

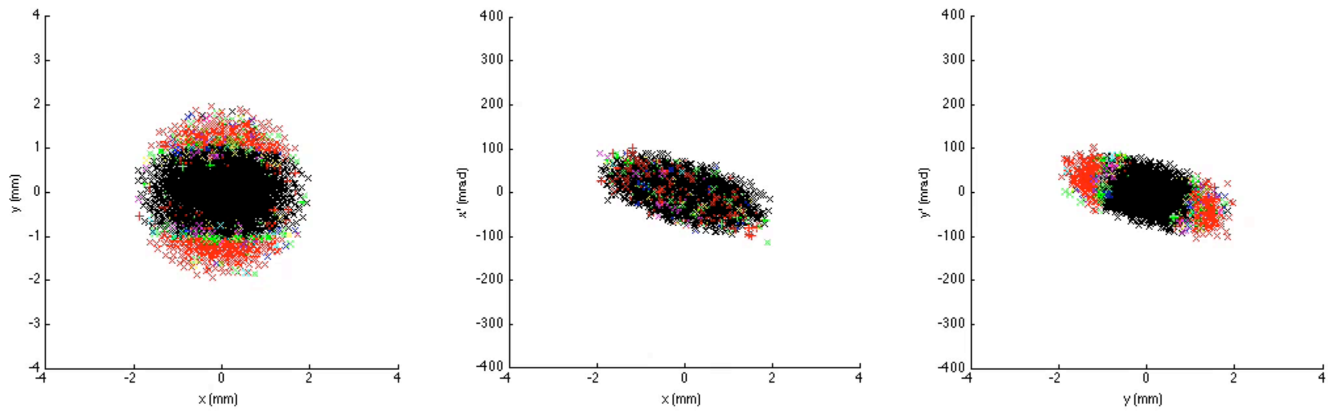
Beam Trajectories in RFQ Cold Model



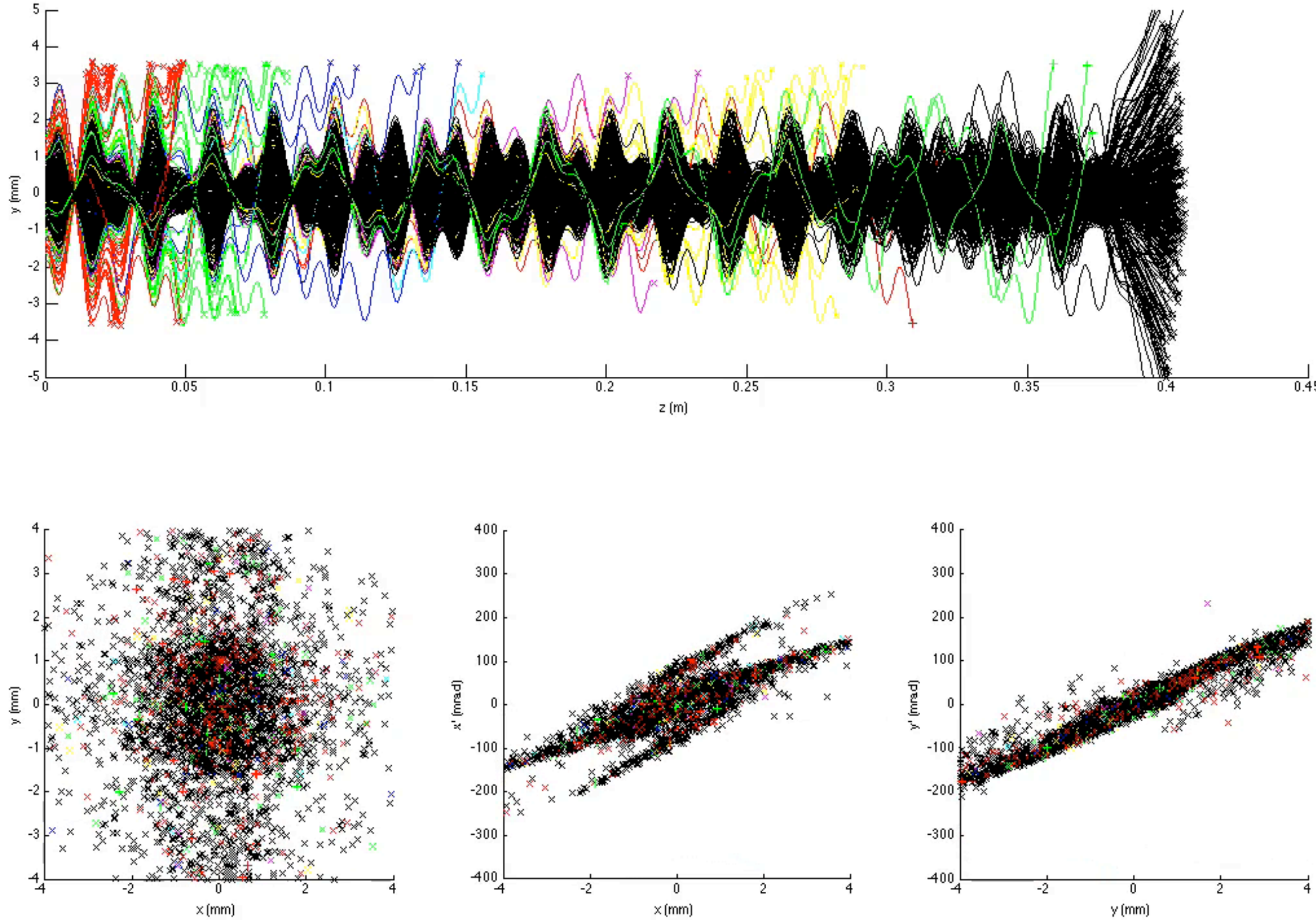


Beam Trajectories in RFQ Cold Model





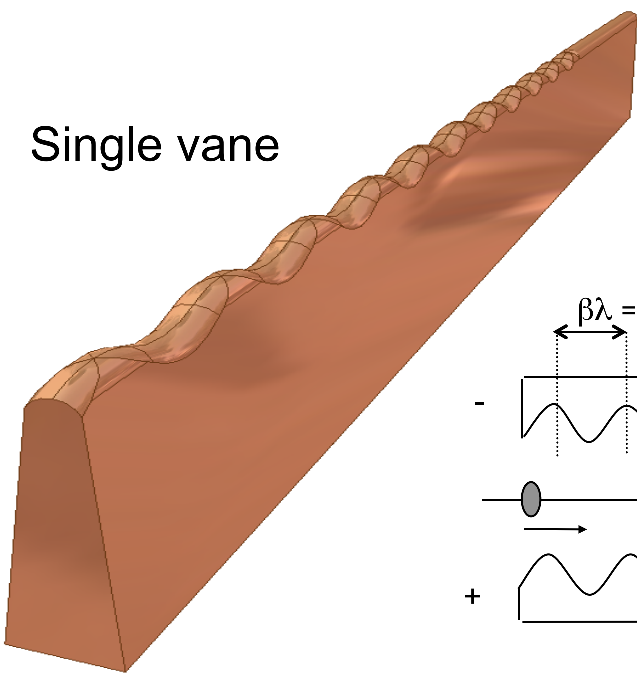
Beam Trajectories in RFQ Cold Model



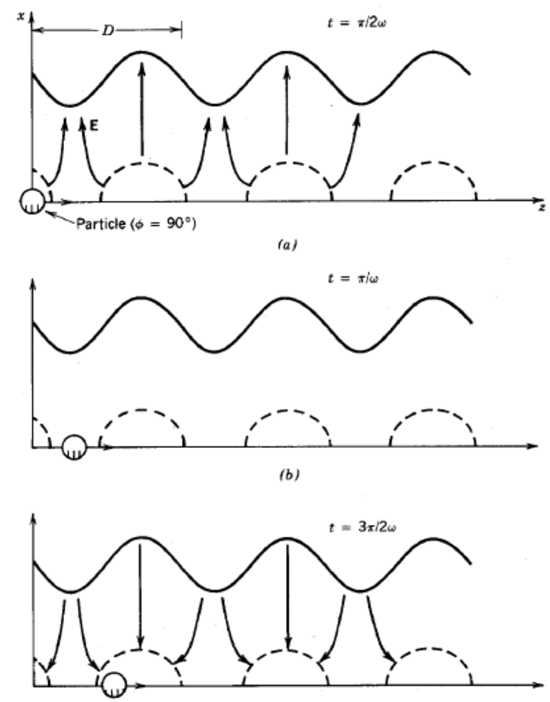
RFQ Acceleration/Bunching

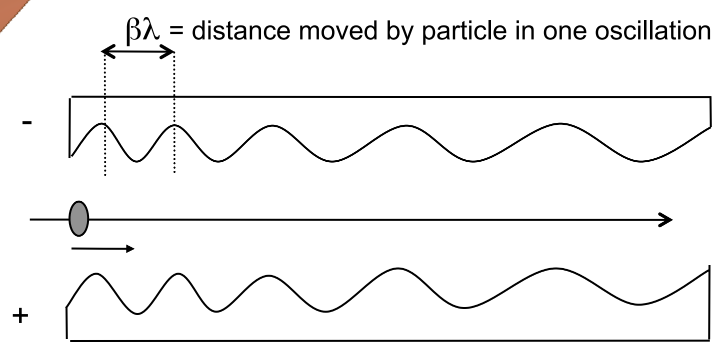
- RFQ vane tips modulated longitudinally.
- Curved field lines produce longitudinal field: acceleration and bunching.

Single vane



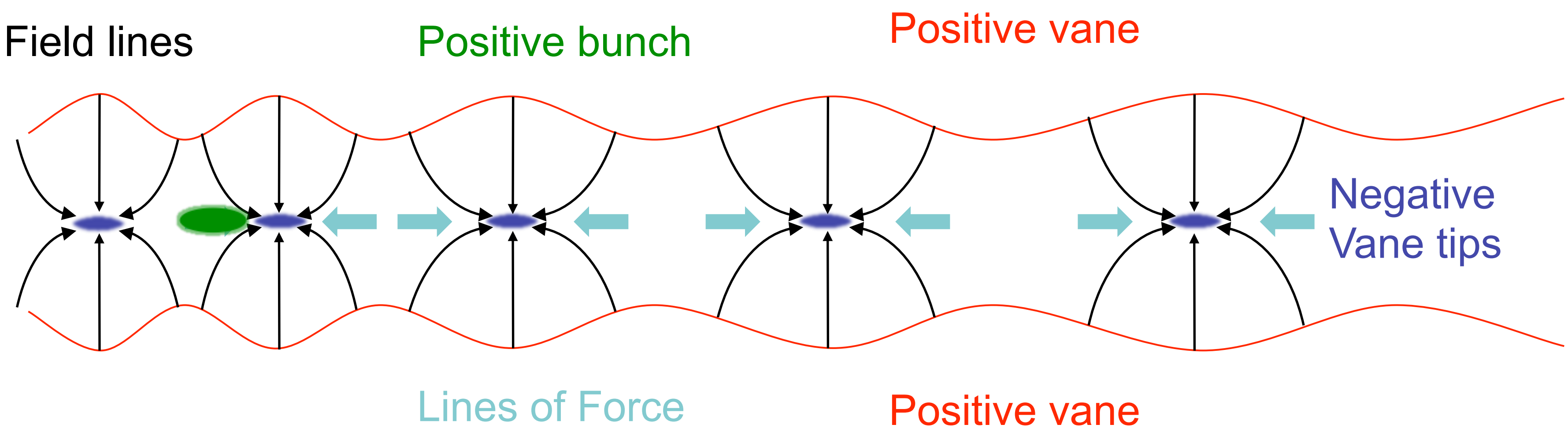
Alternate modulation gives acceleration





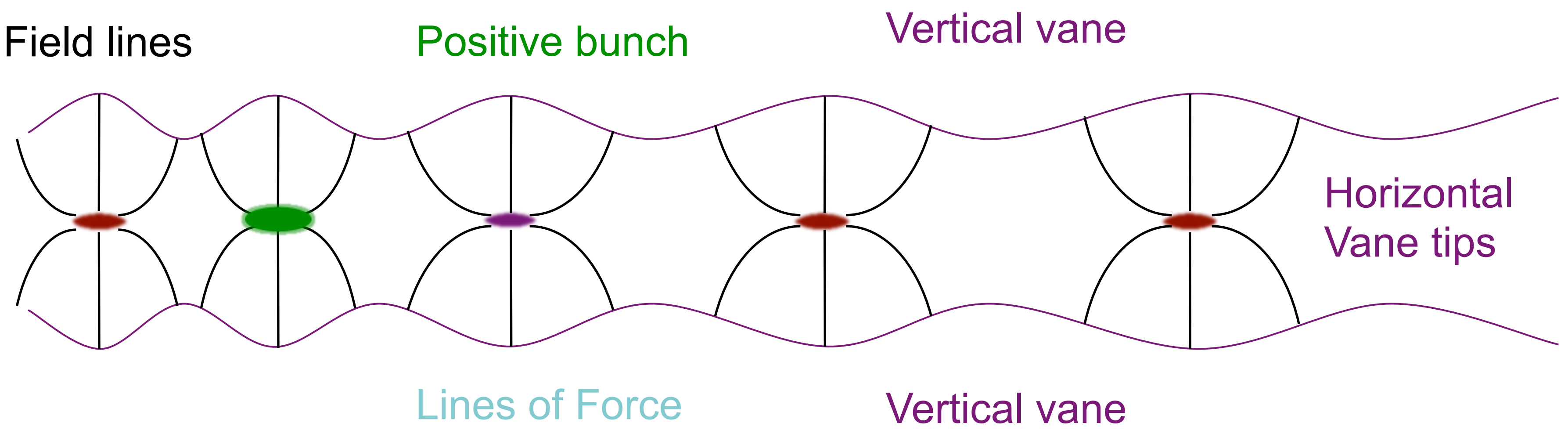
RFQ Field Lines

- On-axis field gives longitudinal force from curved vanes, plus time-varying.
- Vertical vanes initially positively charged, horizontal vanes negatively charged.
- Bunch feels accelerating force from curved field lines.



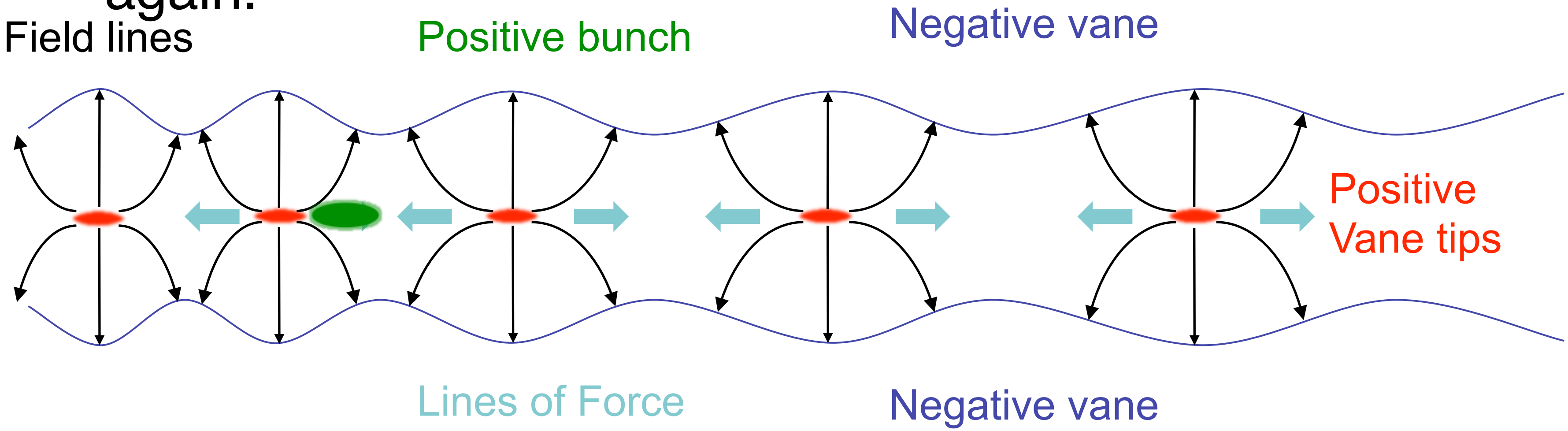
RFQ Field Lines

- After a quarter RF period, RF field drops to zero.
- Bunch feels no accelerating force.



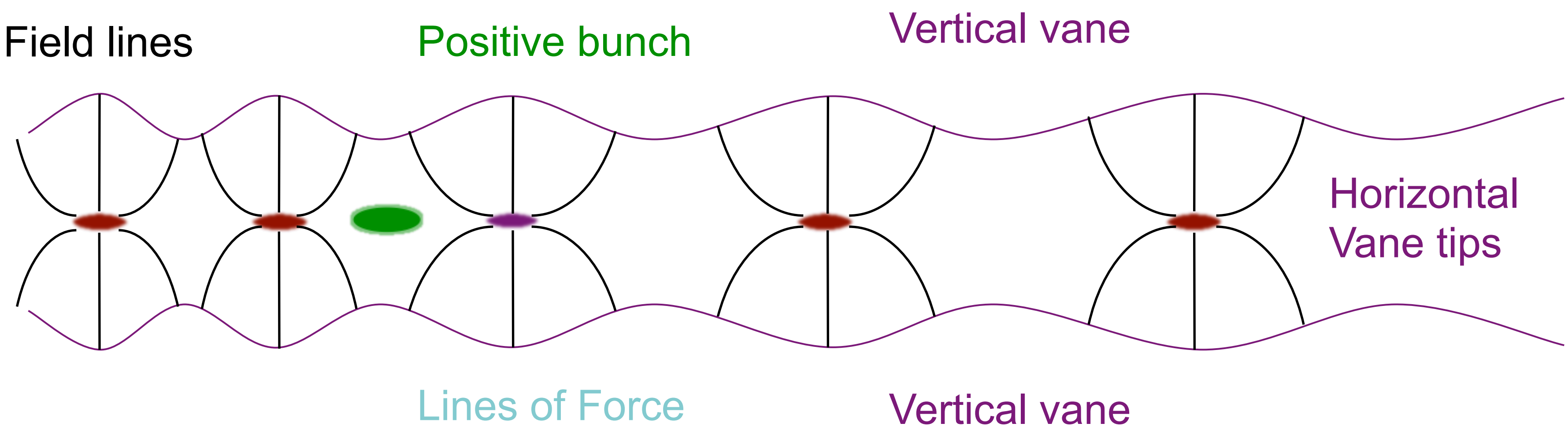
RFQ Field Lines

- After a half RF period, RF reaches maximum again but sign is reversed.
- Vertical vanes now negatively charged, horizontal vanes positively charged.
- Bunch feels accelerating force from curved field lines again.



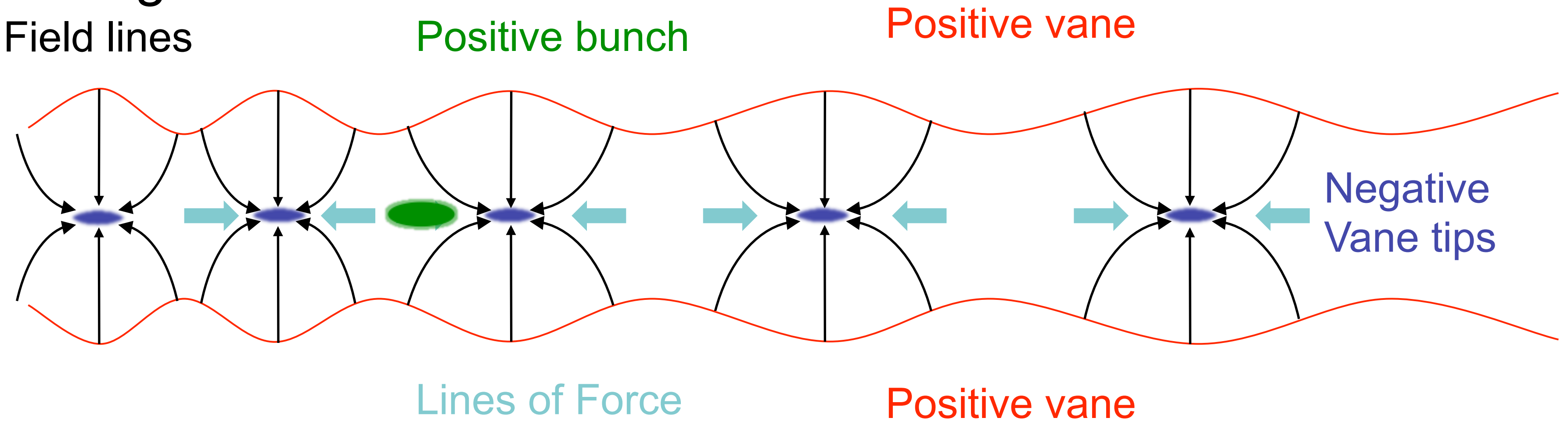
RFQ Field Lines

- After three-quarters of an RF period, RF field drops to zero again.
- Bunch feels no accelerating force.



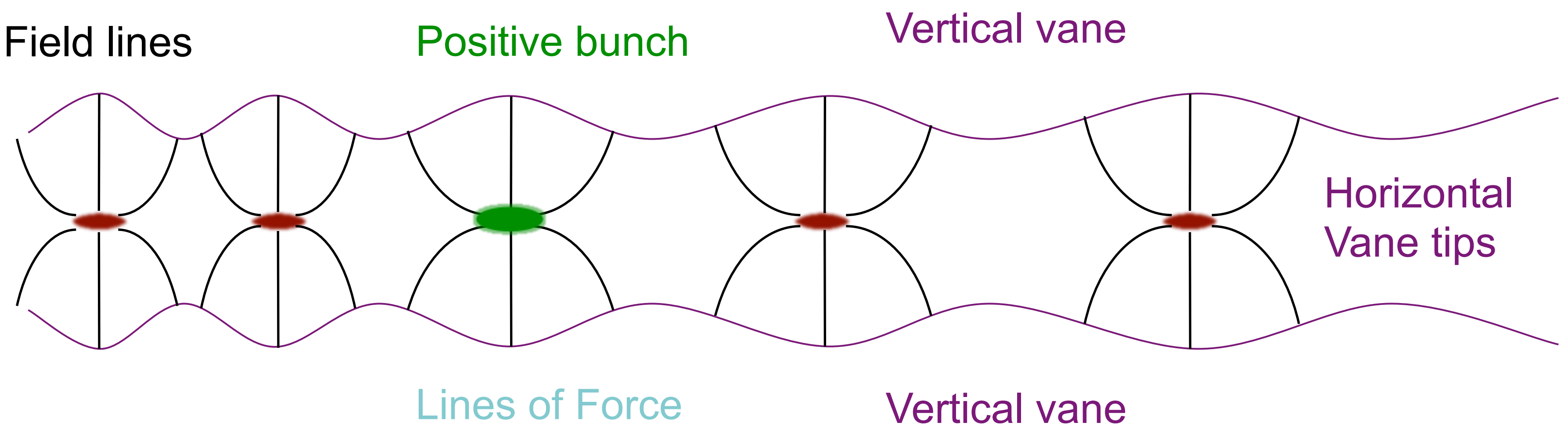
RFQ Field Lines

- After a full RF period, RF reaches maximum again but sign of field reverts to original direction.
- Vertical vanes again positively charged, horizontal vanes negatively charged.
- Bunch feels accelerating force from curved field lines again.



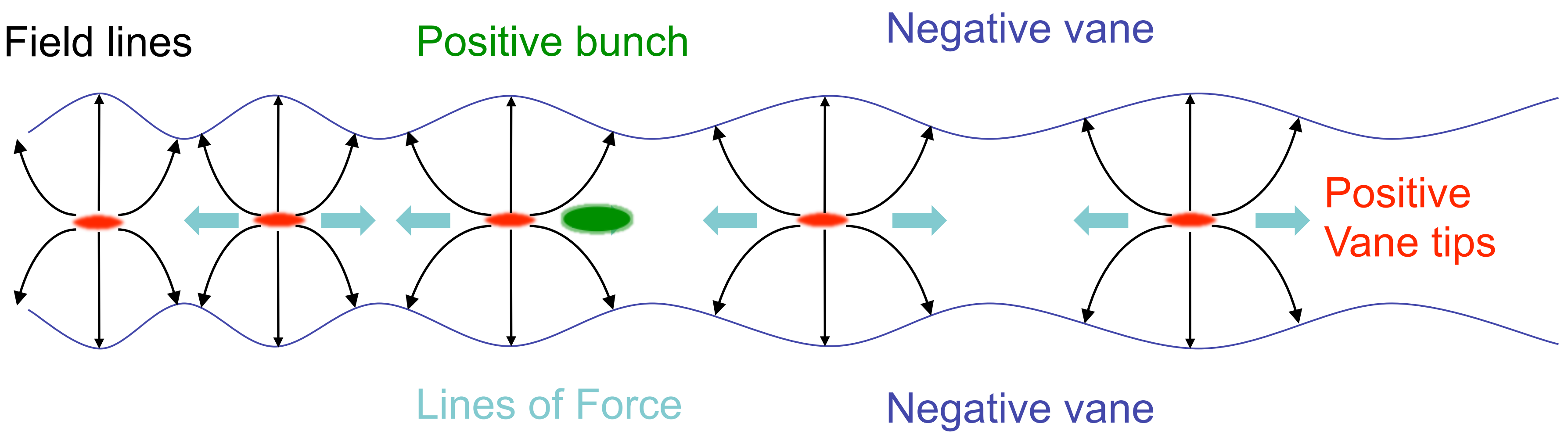
RFQ Field Lines

- And so we continue…



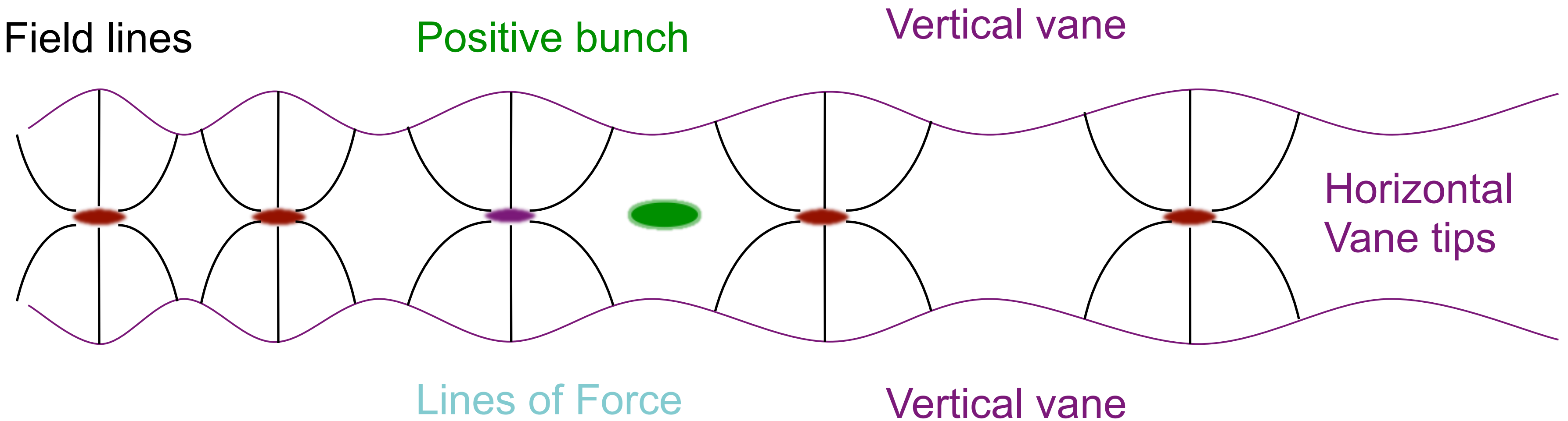
RFQ Field Lines

- And so we continue…



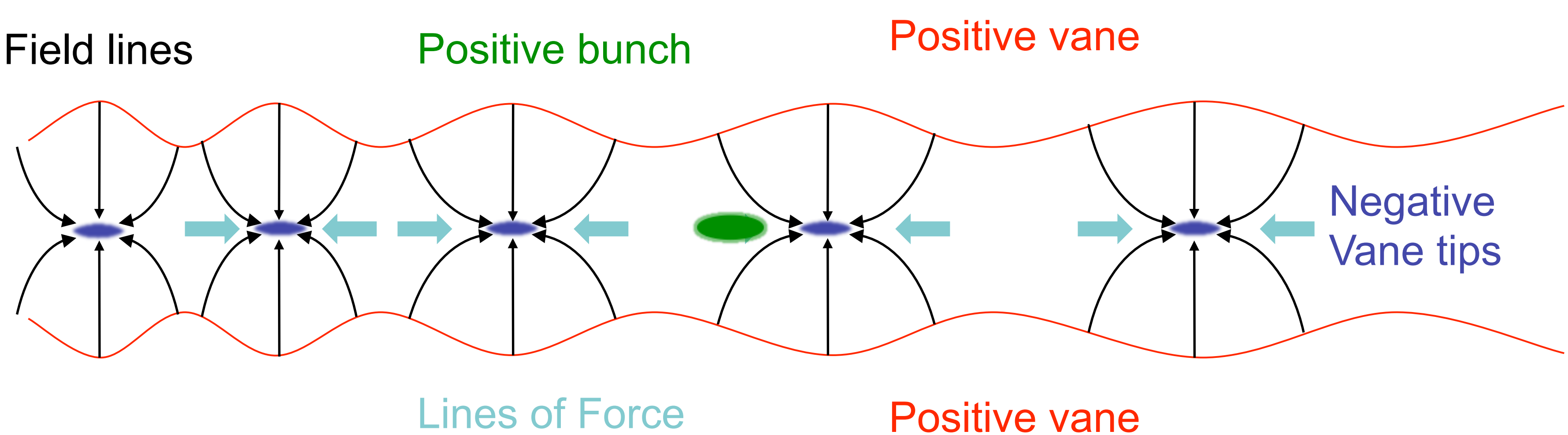
RFQ Field Lines

- And so we continue…



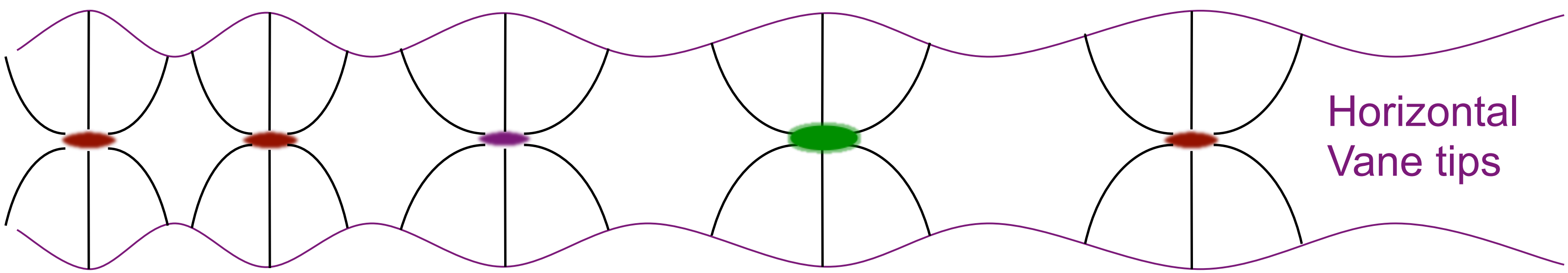
RFQ Field Lines

- And so we continue…



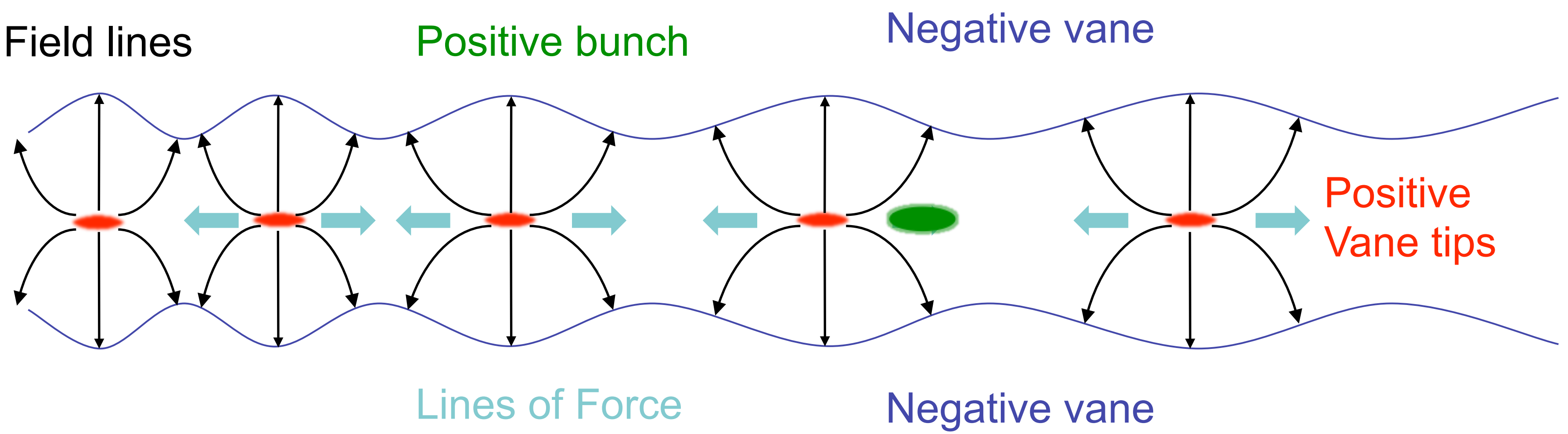
RFQ Field Lines

- And so we continue…



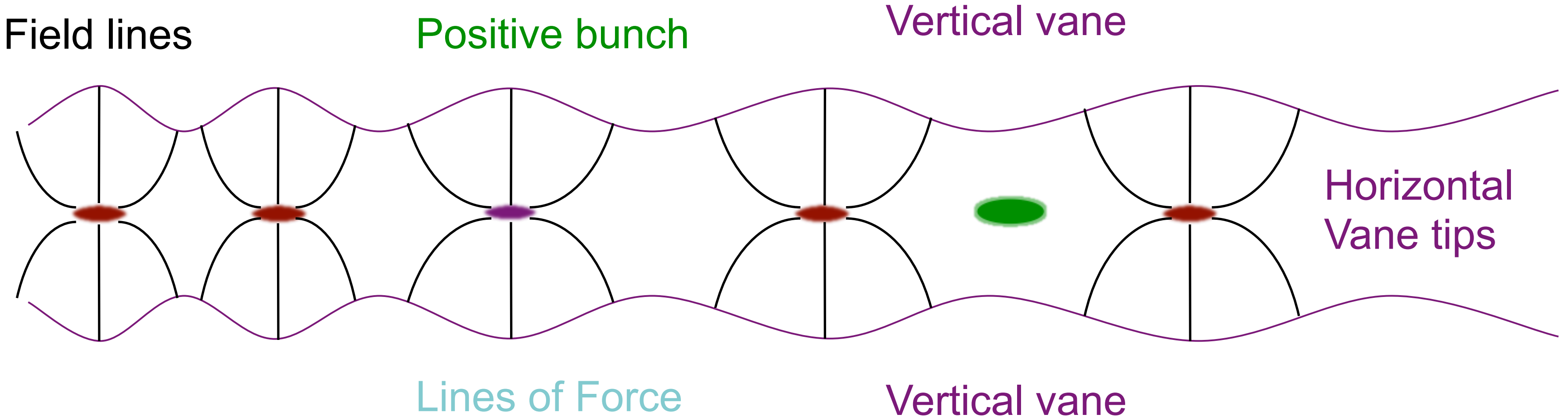
RFQ Field Lines

- And so we continue…



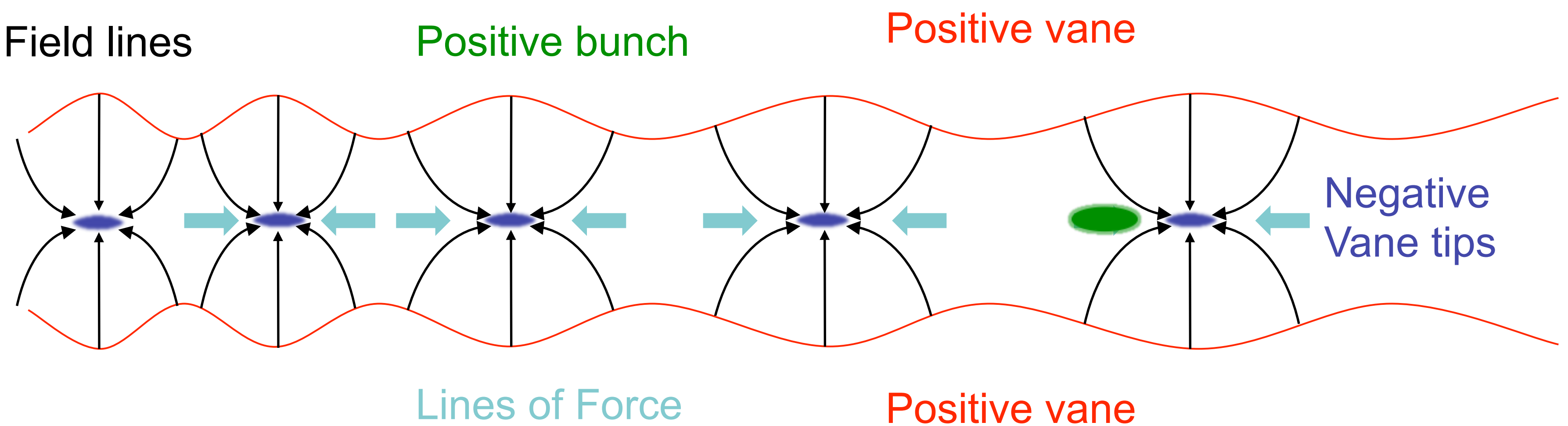
RFQ Field Lines

- And so we continue…



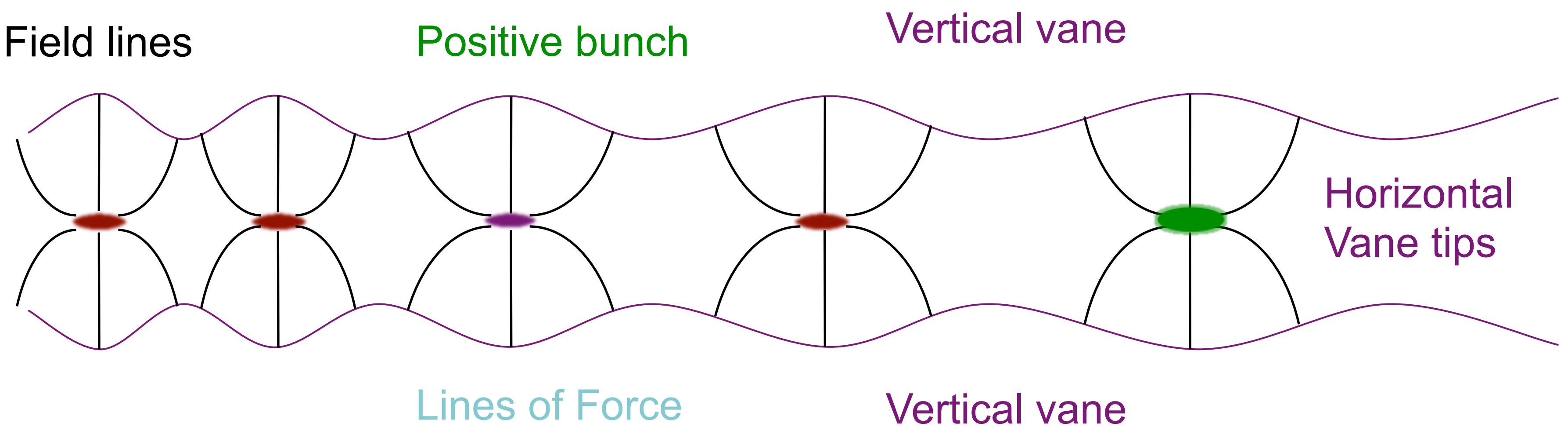
RFQ Field Lines

- And so we continue…



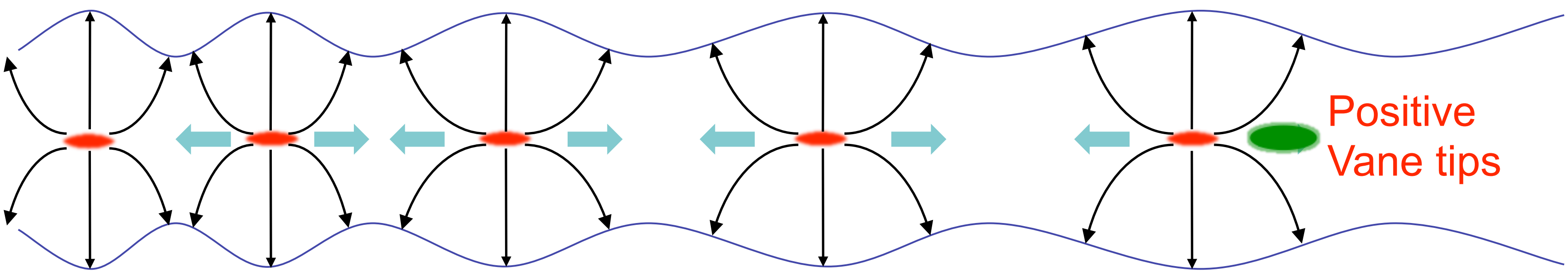
RFQ Field Lines

- And so we continue…

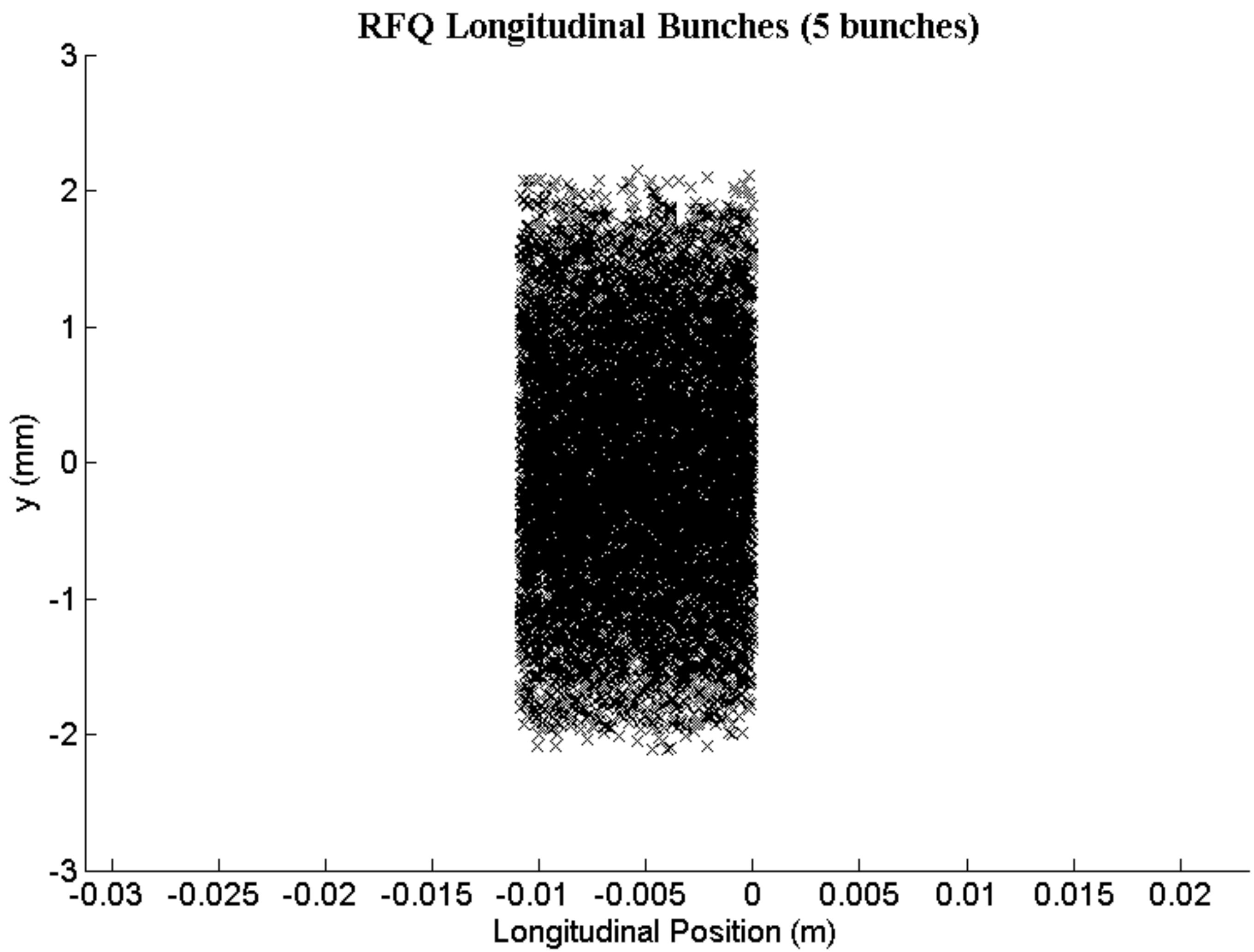


RFQ Field Lines

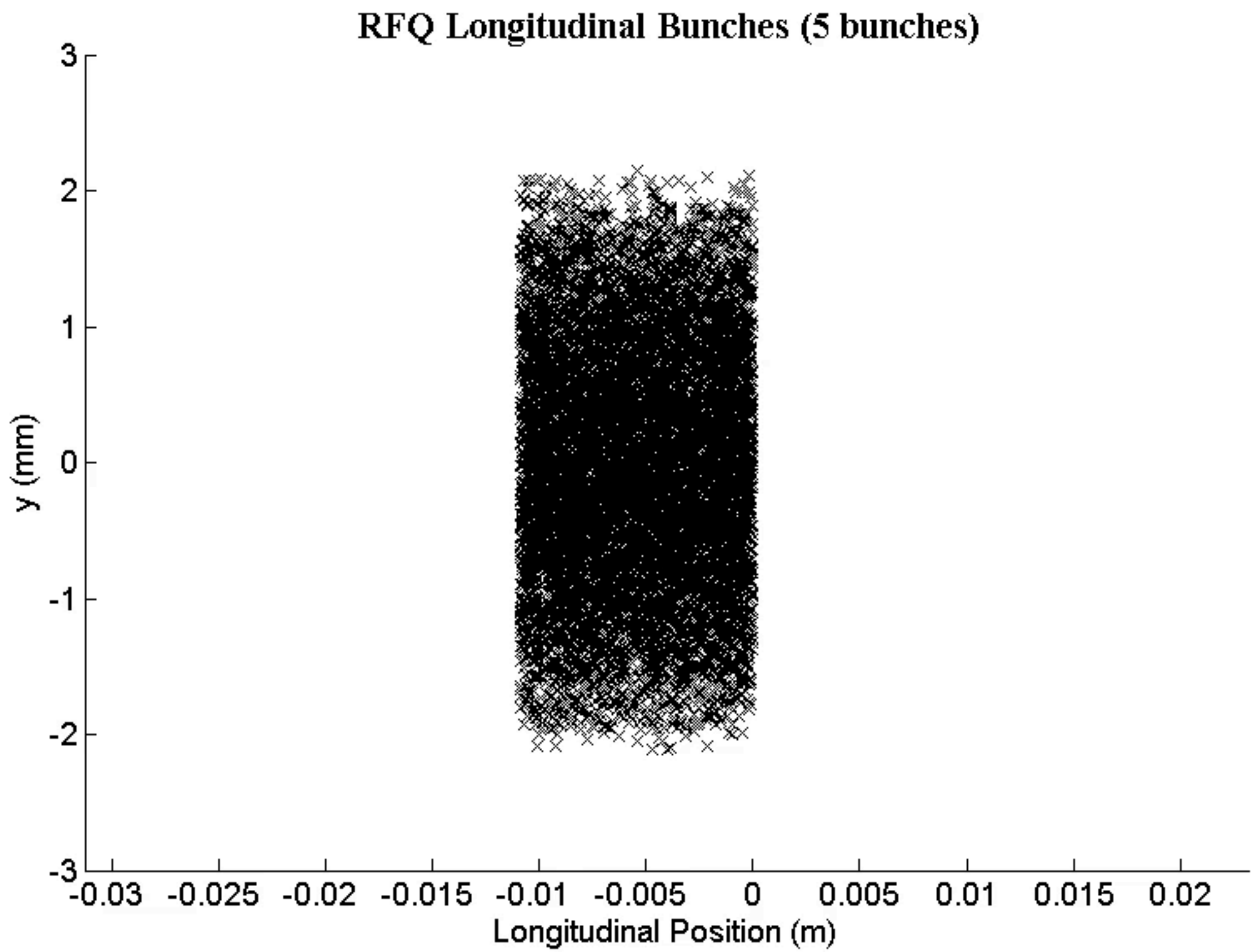
- And that's how an RFQ accelerates the beam!



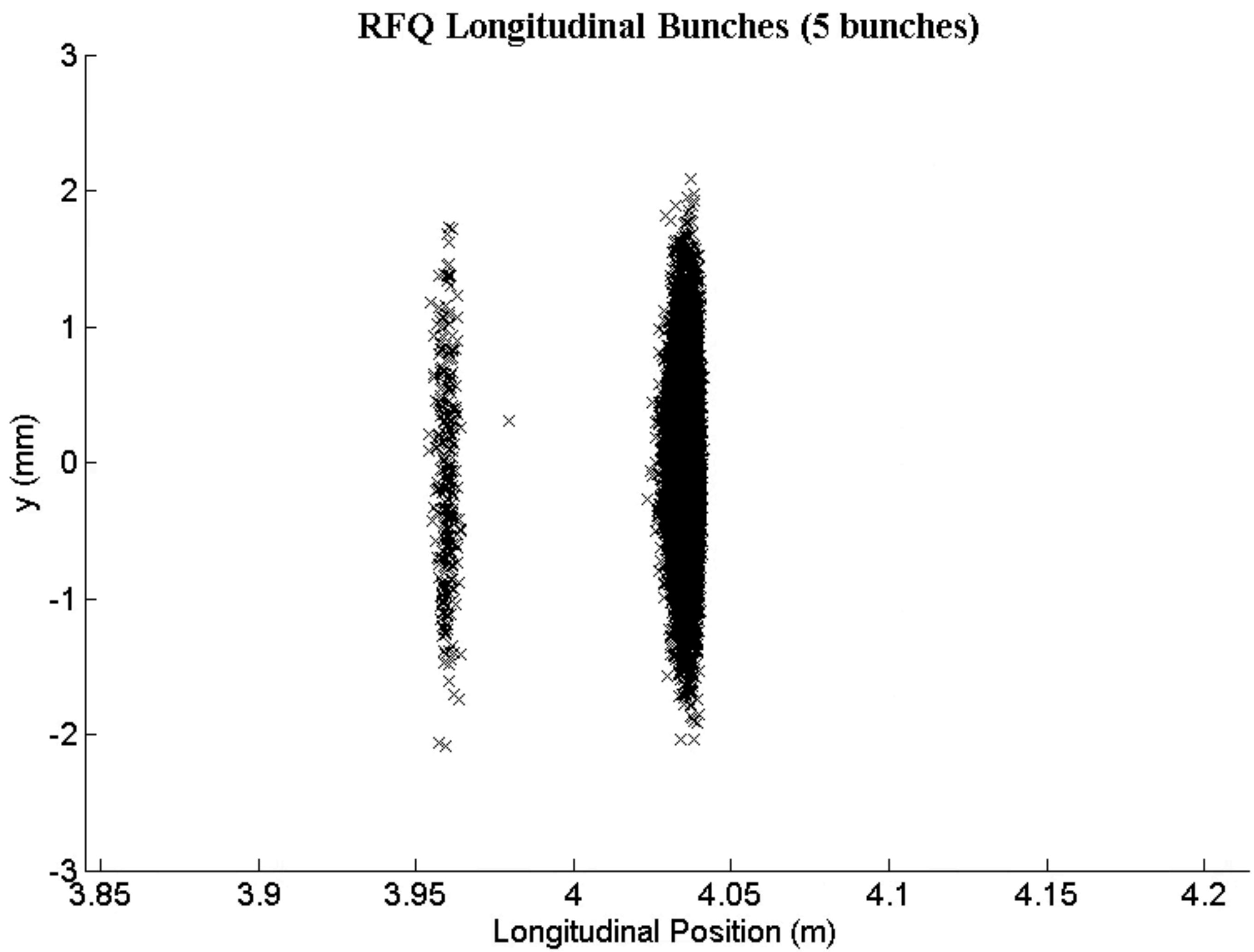
Full RFQ Simulation: Z-Y, 5 bunches



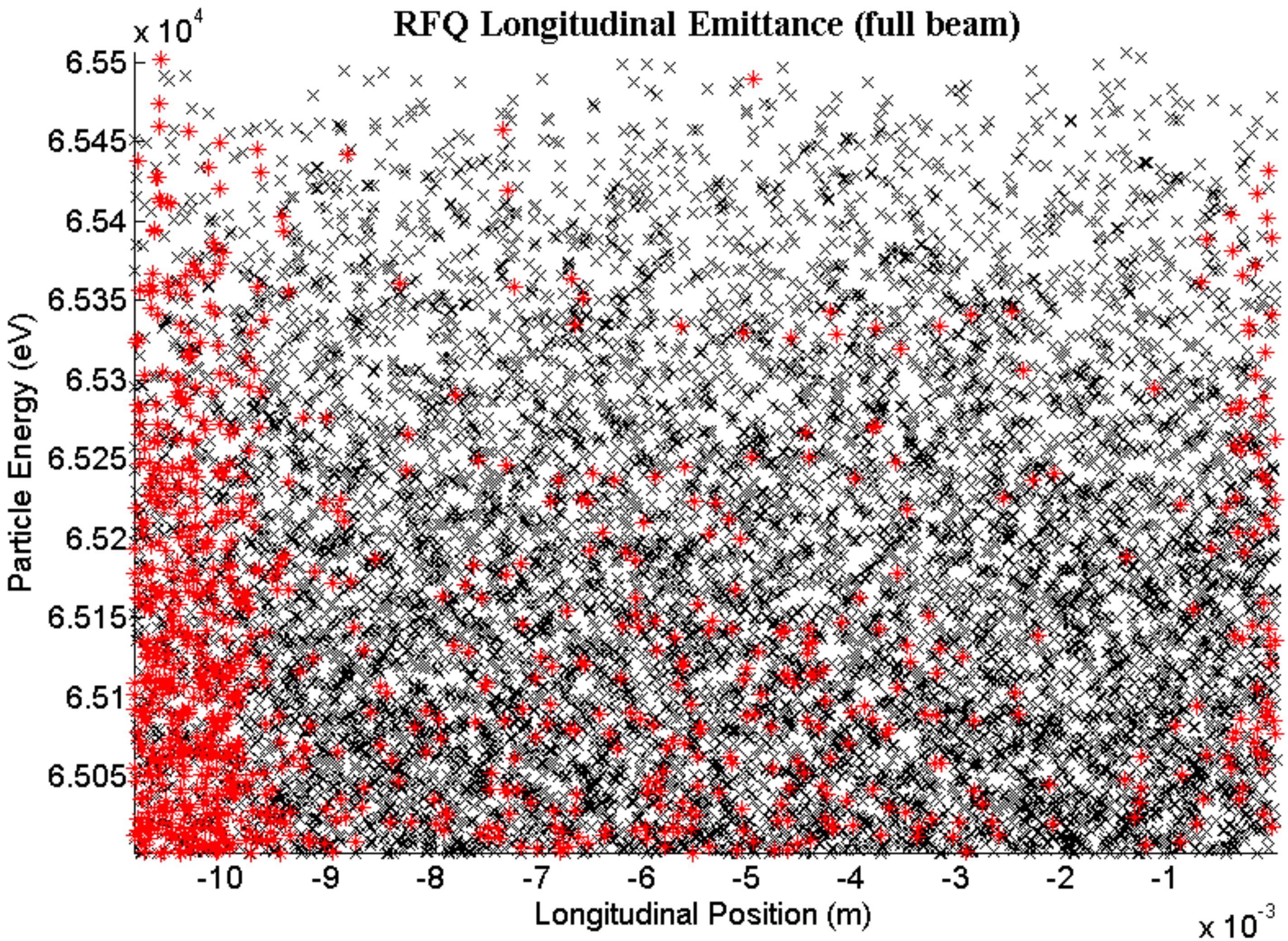
Full RFQ Simulation: Z-Y, 5 bunches



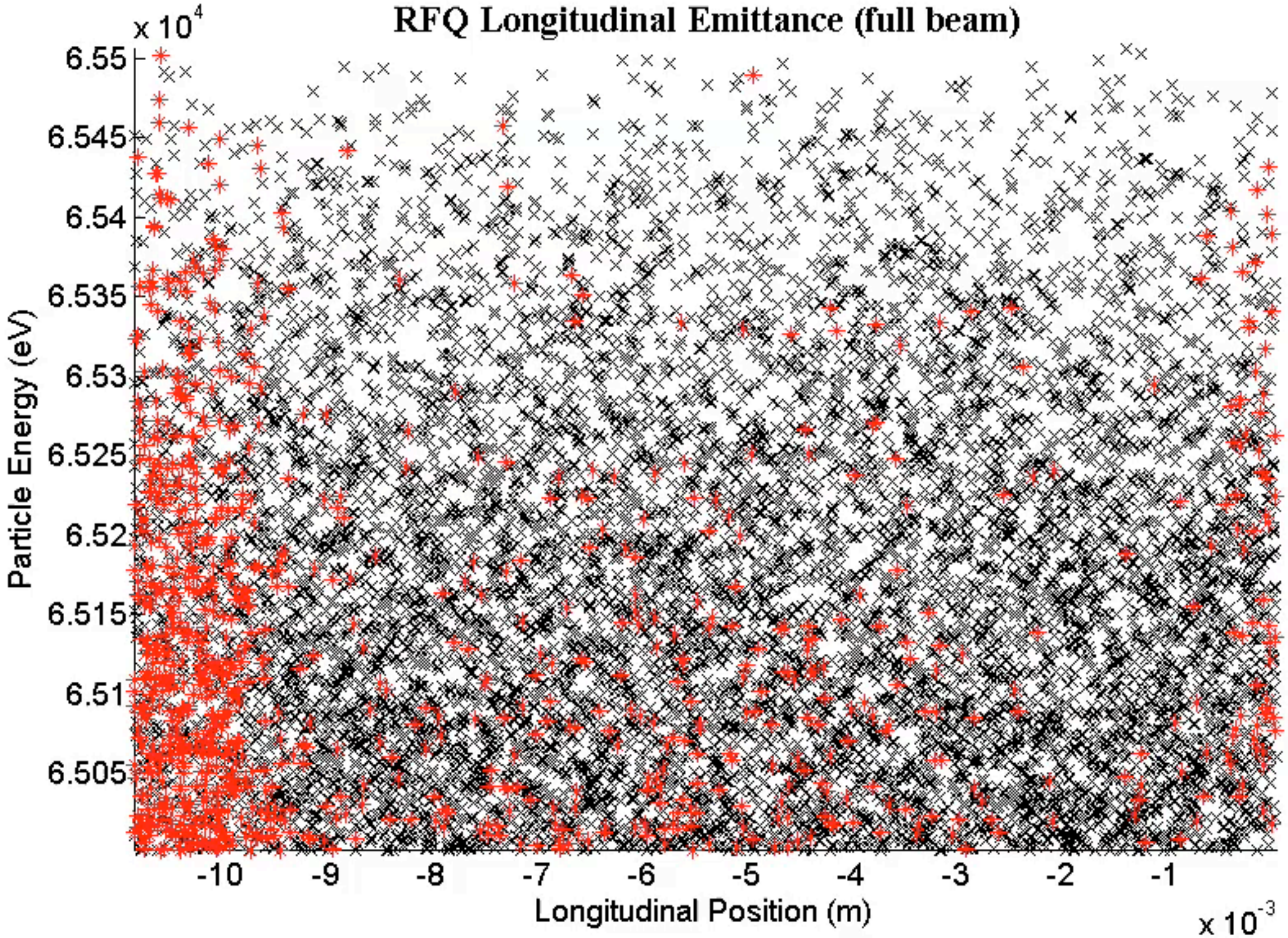
Full RFQ Simulation: Z-Y, 5 bunches



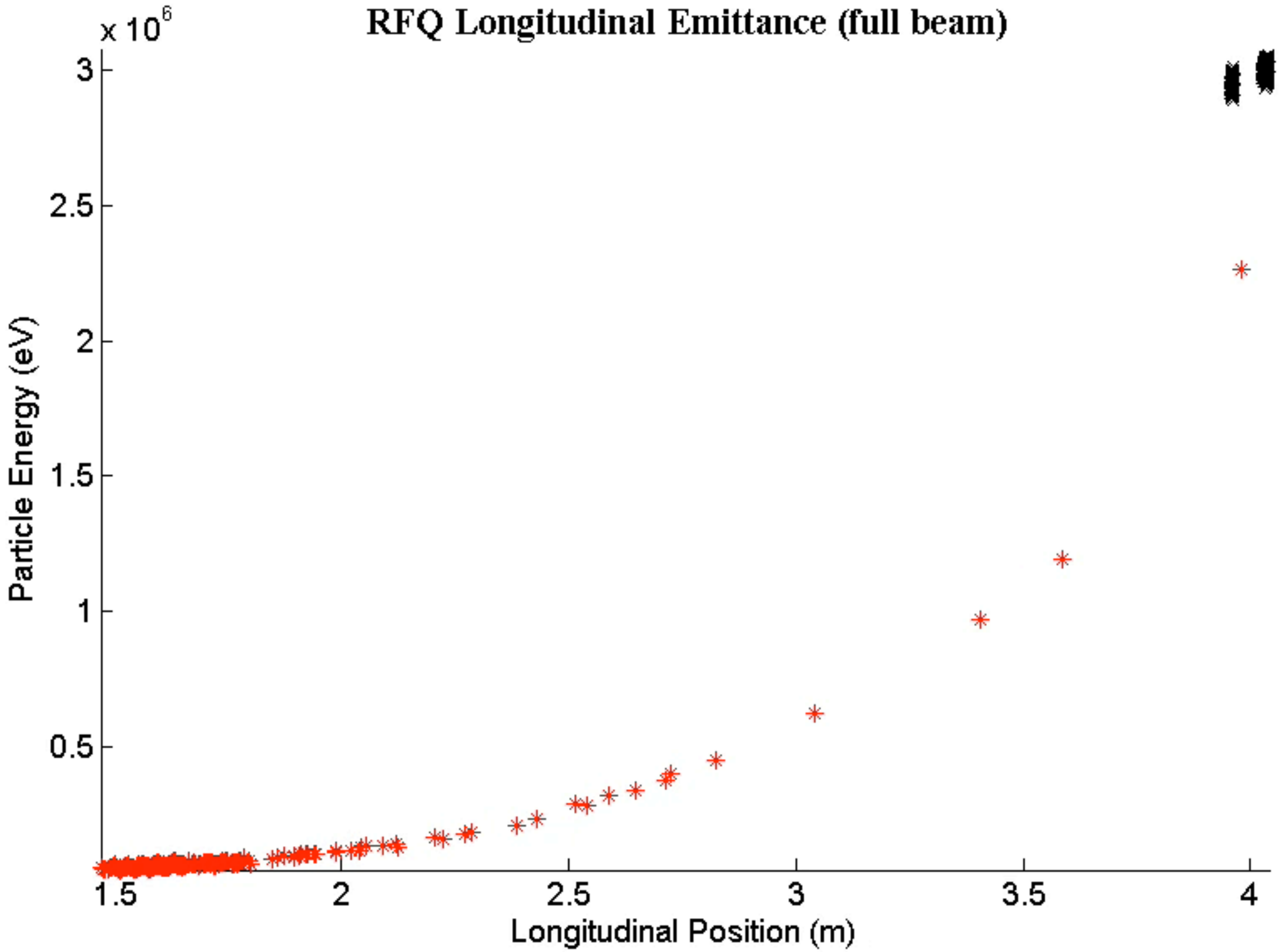
Full RFQ Simulation: Z-E, full beam



Full RFQ Simulation: Z-E, full beam



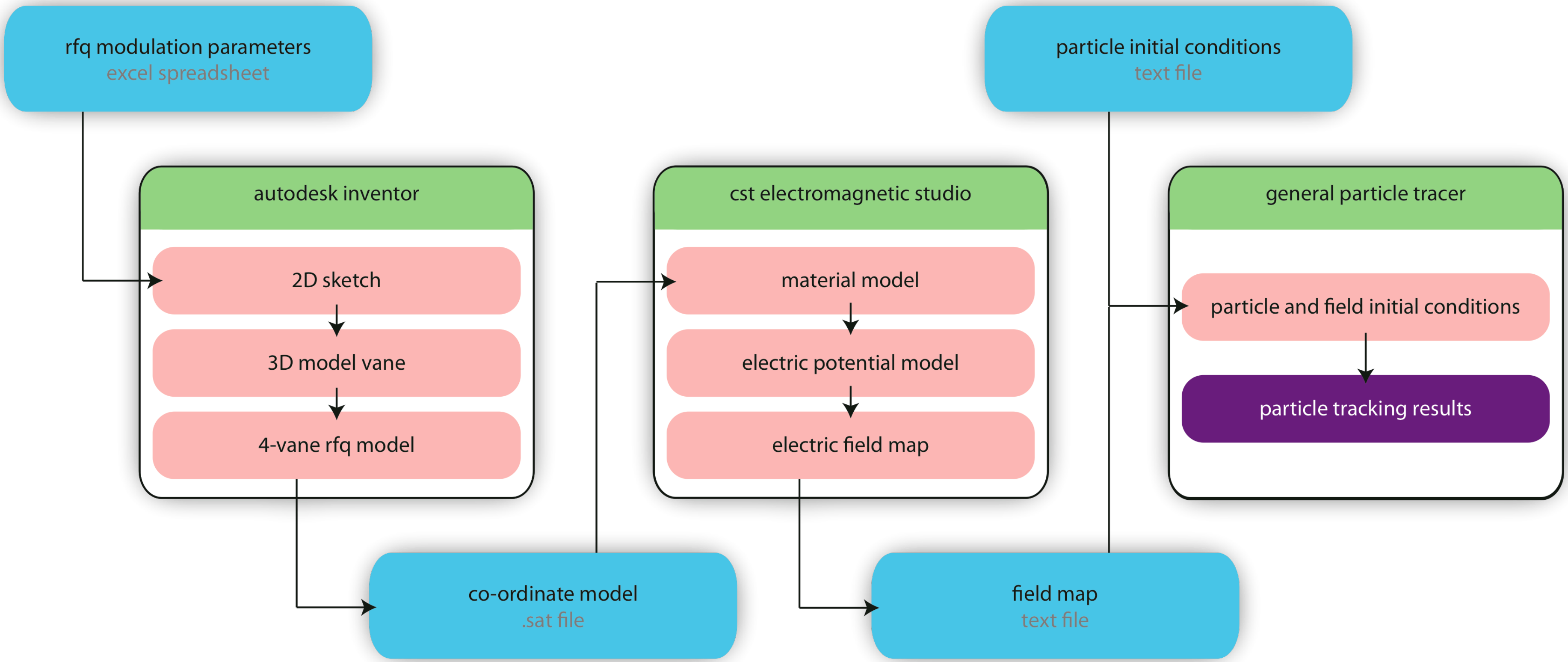
Full RFQ Simulation: Z-E, full beam



RFQ Integrated Design

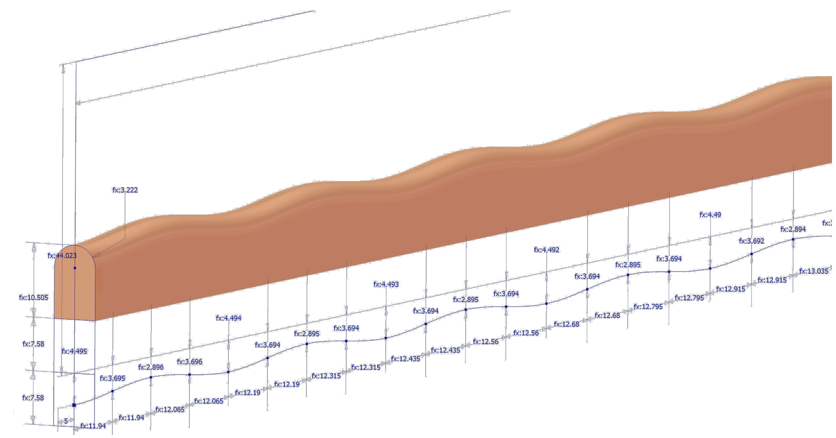
- RFQ parameterised by *a* and *m* parameters for modulations, ρ for vane radius and *L* for cell length.
- These parameters generated using field approximation code, then handed to Frankfurt for RFQ manufacture.
- Would like to have a method of designing RFQ where all steps are integrated:
  - Engineering design.
  - EM modelling.
  - Beam dynamics simulations.
- Integrating design steps allows us to characterise effects of:
  - Fringe fields and higher order modes.
  - Particular CNC machining techniques and options on beam dynamics.

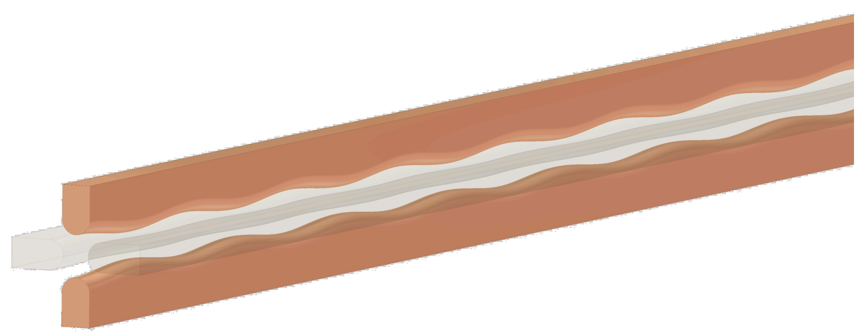
RFQ Design Stages



RFQ CAD Modelling

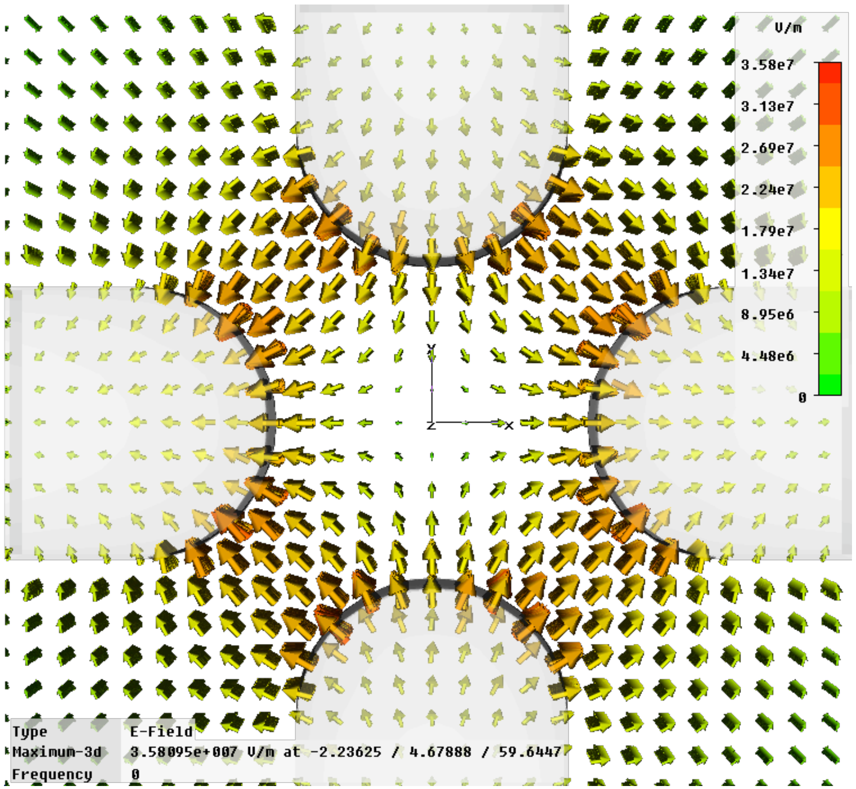
- Autodesk Inventor CAD package used to model RFQ cold model (and a lot more besides…).
- Inventor can dynamically link to parameters in Excel spreadsheet:
  - Change spreadsheet parameters and model updates automatically.
  - Use spline to approximate sinusoidal vane shape: only 2% difference.





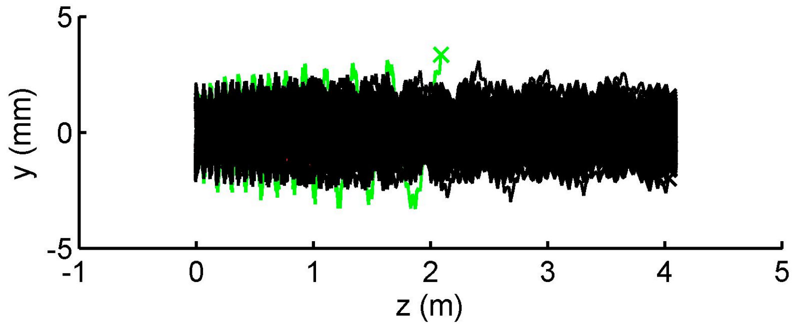
CST MicroWave Studio E-field Modelling

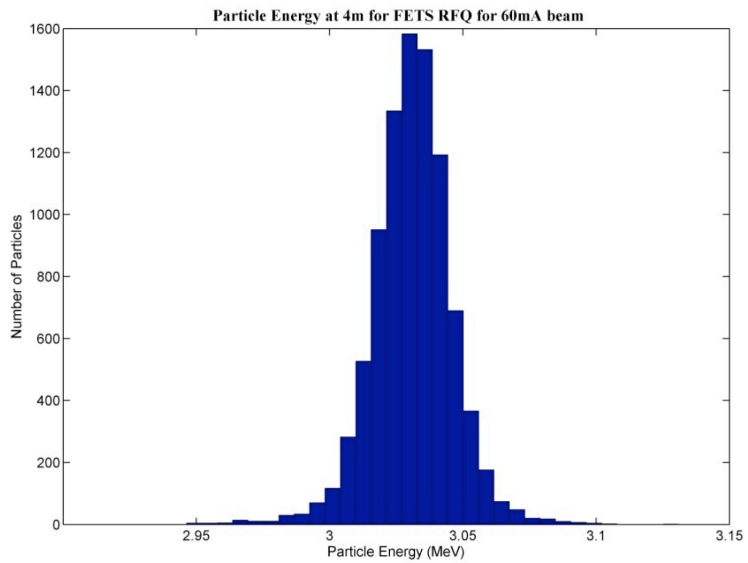
- Four vanes from inventor imported by a macro.
- Model cut into 6 sections (5 plus matching section) for ease of modelling and to increase CST mesh density.
- Potentials and boundary conditions defined in the macro.
- Run solver to produce electrostatic field map.



Beam Dynamics Simulations

- GPT used for beam dynamics simulations.
- Import electrostatic field map from text file produced by CST.
- Integration algorithm traces particle movements through time-varying field.
- Compare results to field map from optimised RFQ field expansion.

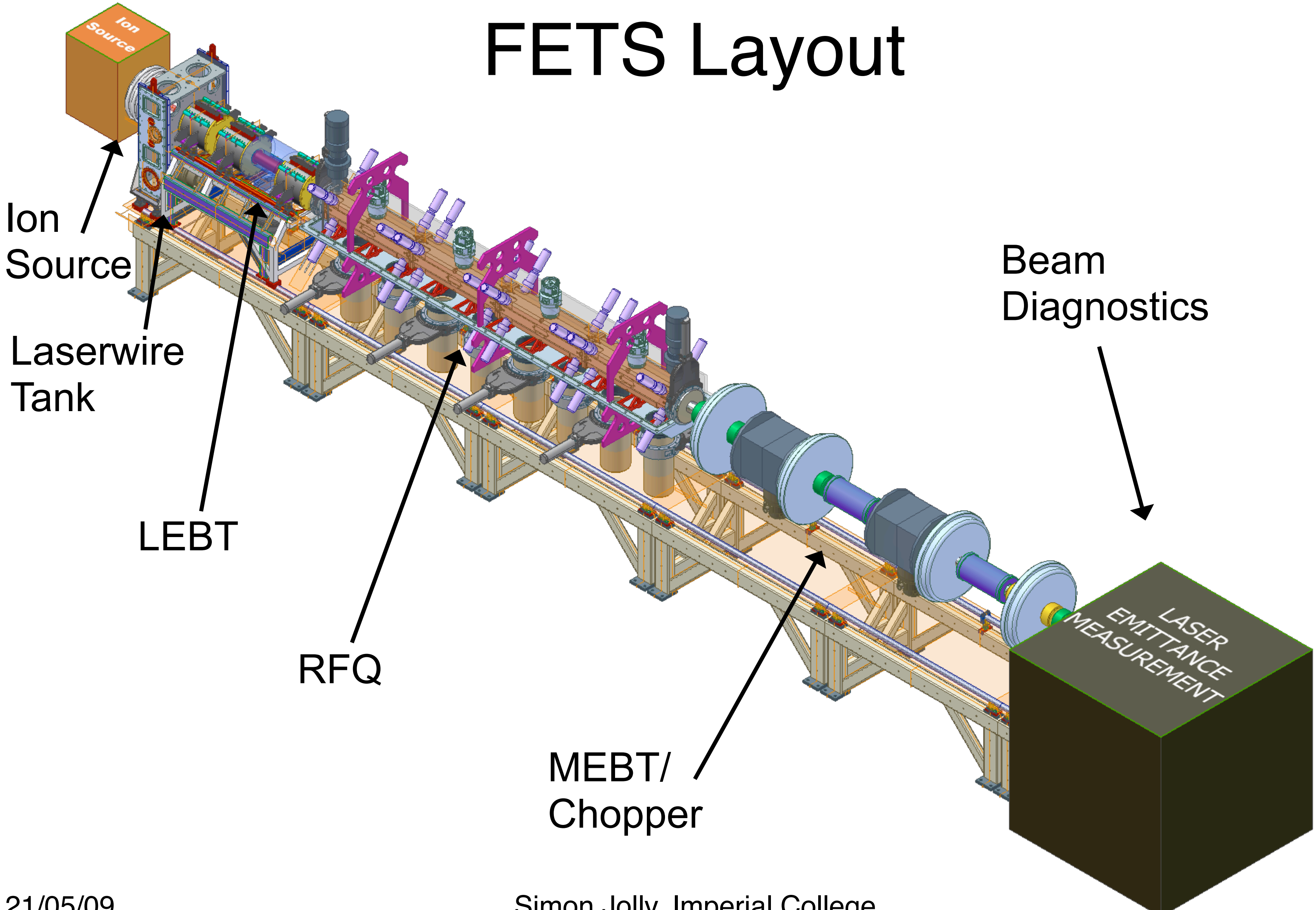




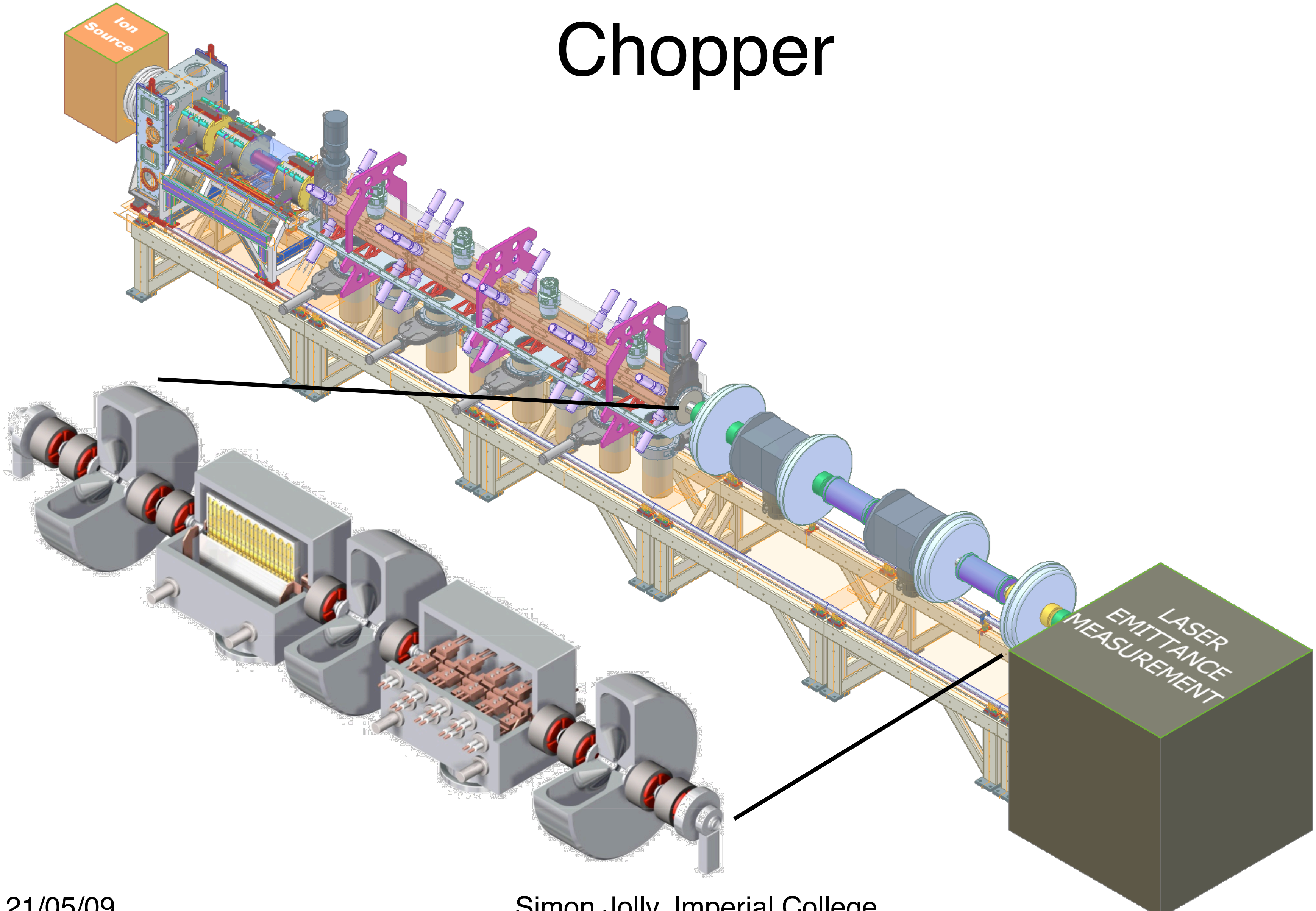
RFQ Conclusions

- CAD modelling process now pretty mature: can model vane, rod and "vod" with parameter adjustment on-the-fly (everything except no. of cells).
- Models import into CST and output to GPT: beam dynamics simulations well understood.
- Need to ensure we're not re-inventing the wheel: RFQ's have been designed before without this process.
- Need to ensure CAM systems will understand our CAD models so we can manufacture what we're designing (this is the point…).

FETS Layout


Ion Source
Ion Source
Laserwire Tank
LEBT
RFQ
MEBT/ Chopper
Beam Diagnostics
LASER EMITTANCE MEASUREMENT

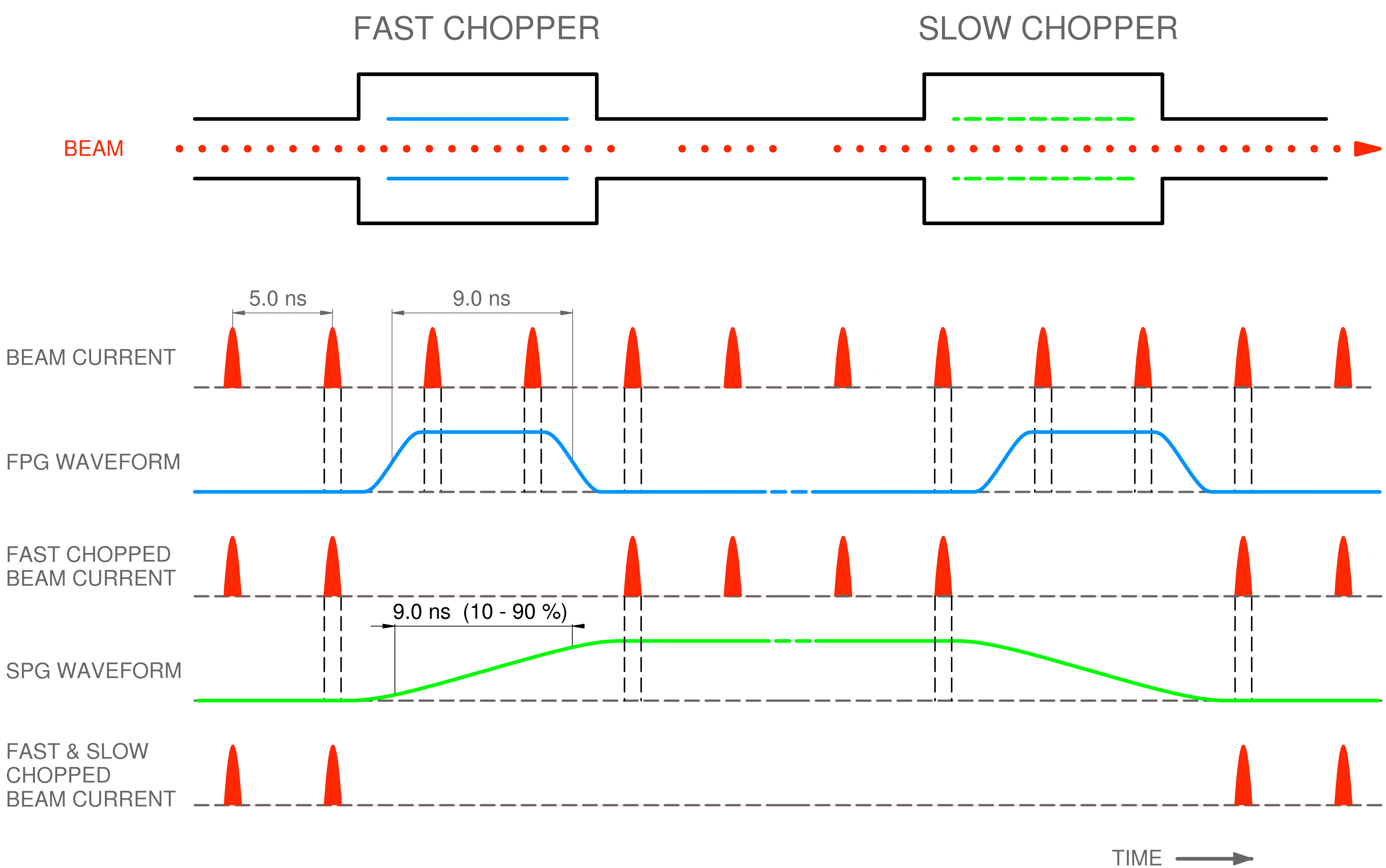
Chopper



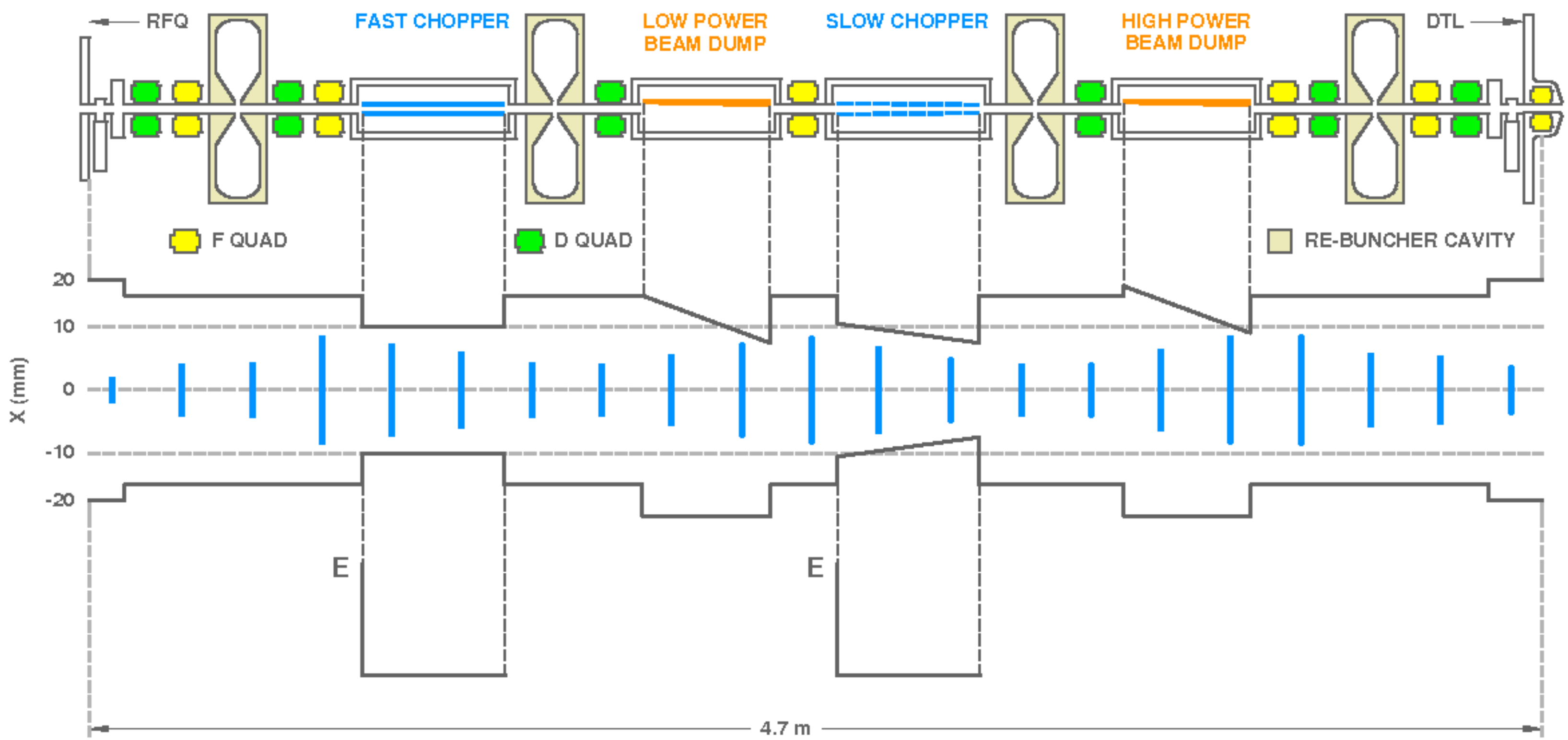
High Speed Beam Chopper

- A novel tandem chopper technique has been developed at RAL to overcome the conflicting requirements of fast rise time (< 2ns) and long flat-top (up to 100 μs).
- A ‘fast’ chopper creates a short, clean gap in which a ‘slow’ chopper can switch on.
- Fast pulser is limited in flat-top but can switch between bunches. The slow pulser cannot switch between pulses but can generate the required flat-top.

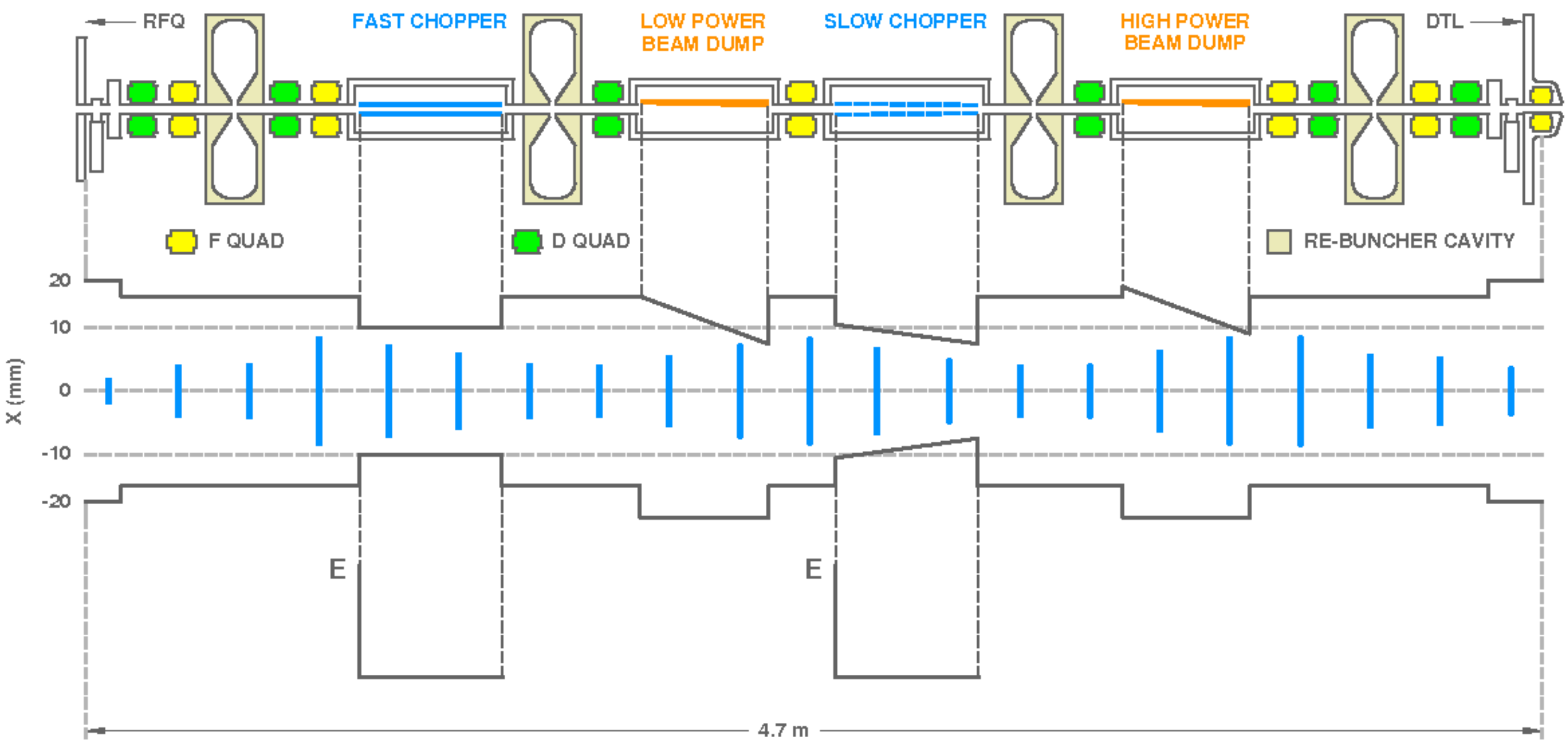
FETS Chopping Scheme



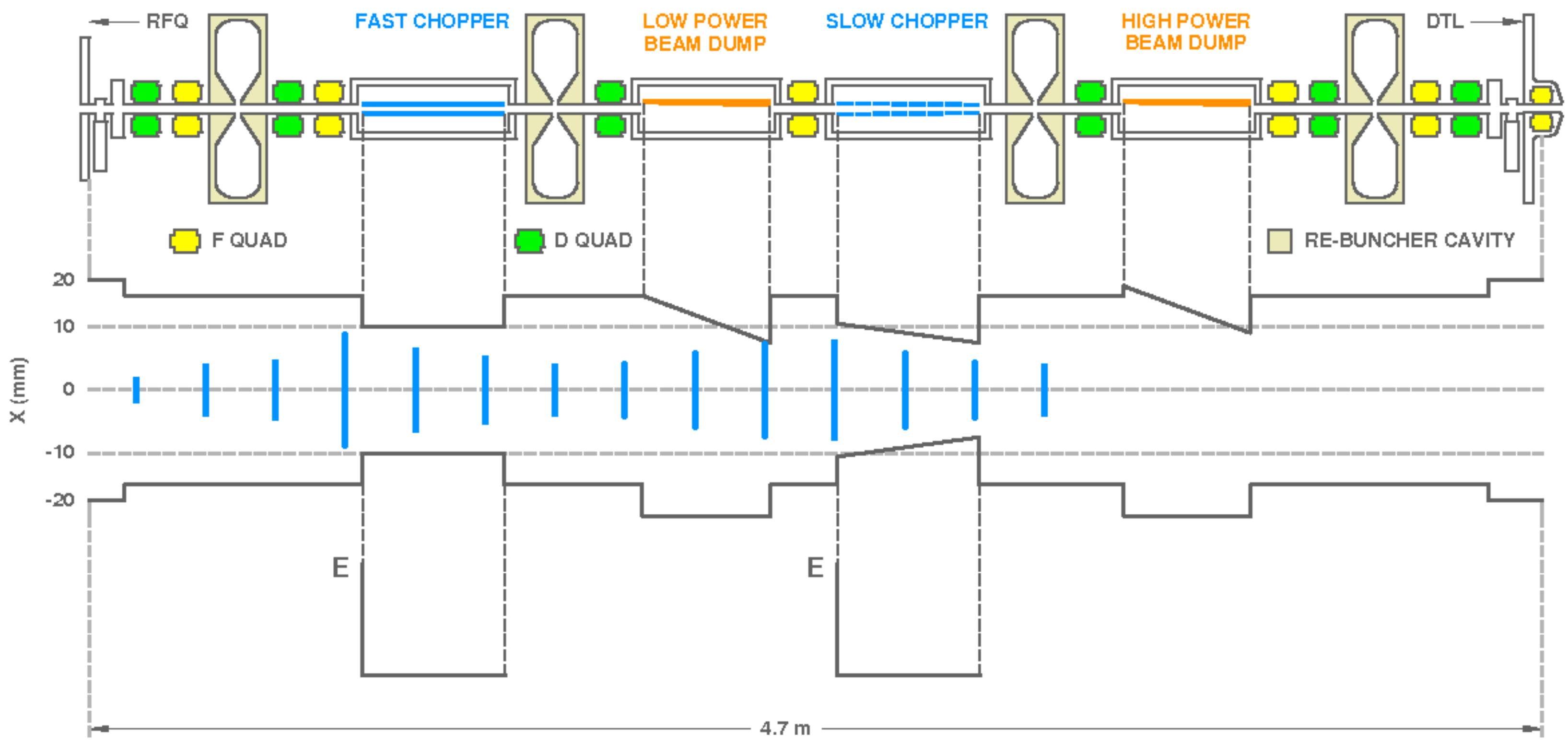
FETS Chopping Scheme



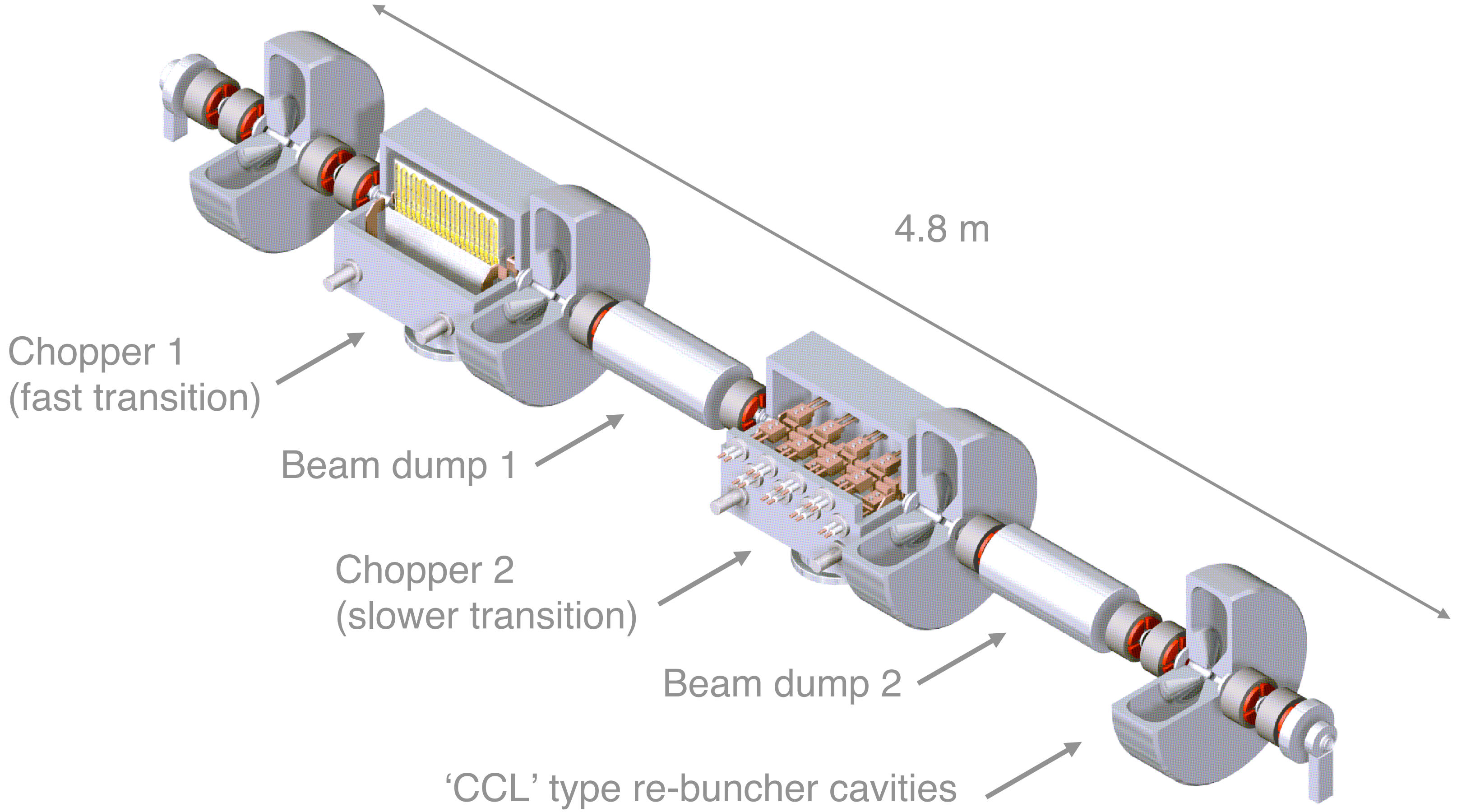
FETS Chopping Scheme



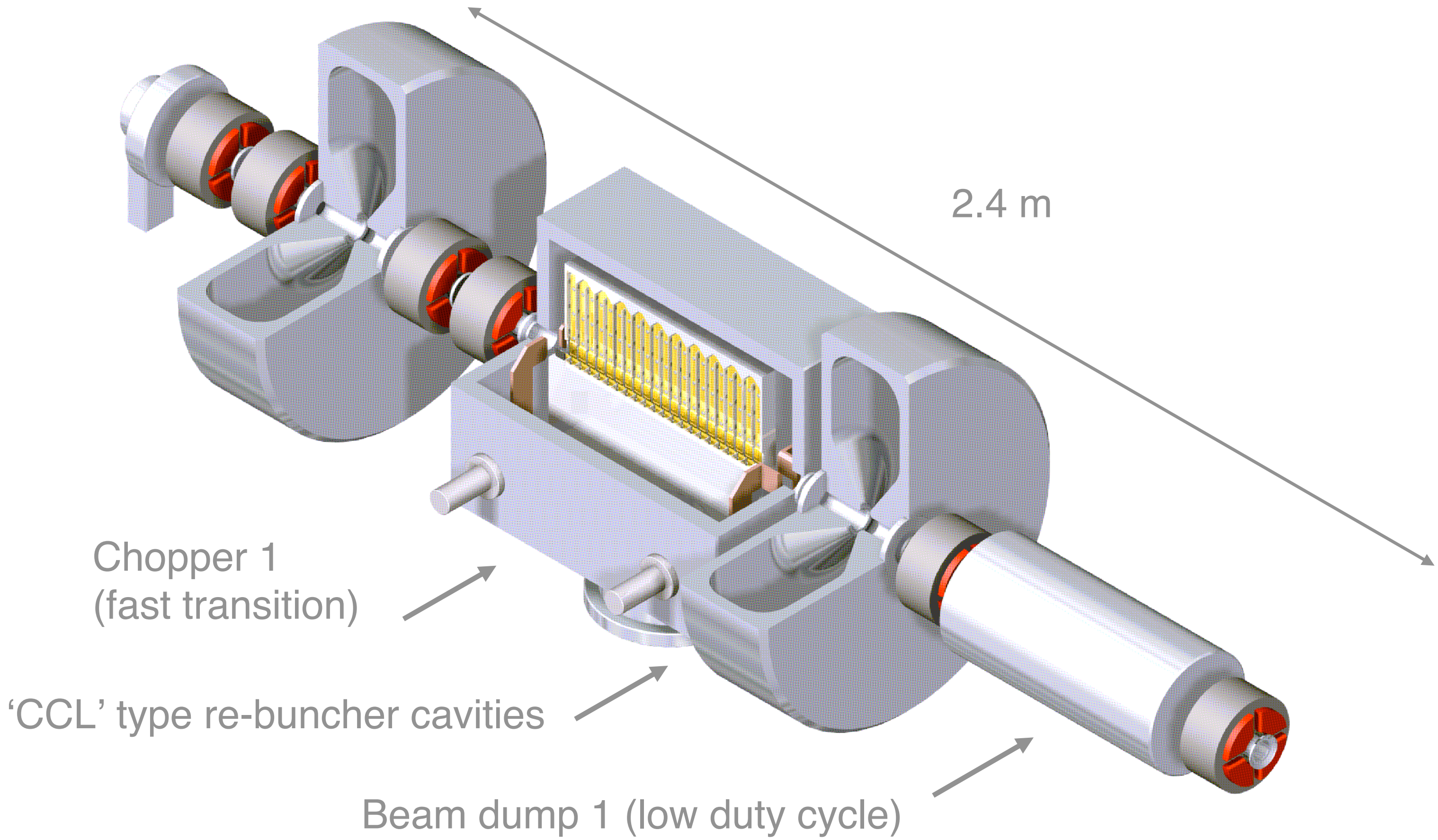
FETS Chopping Scheme



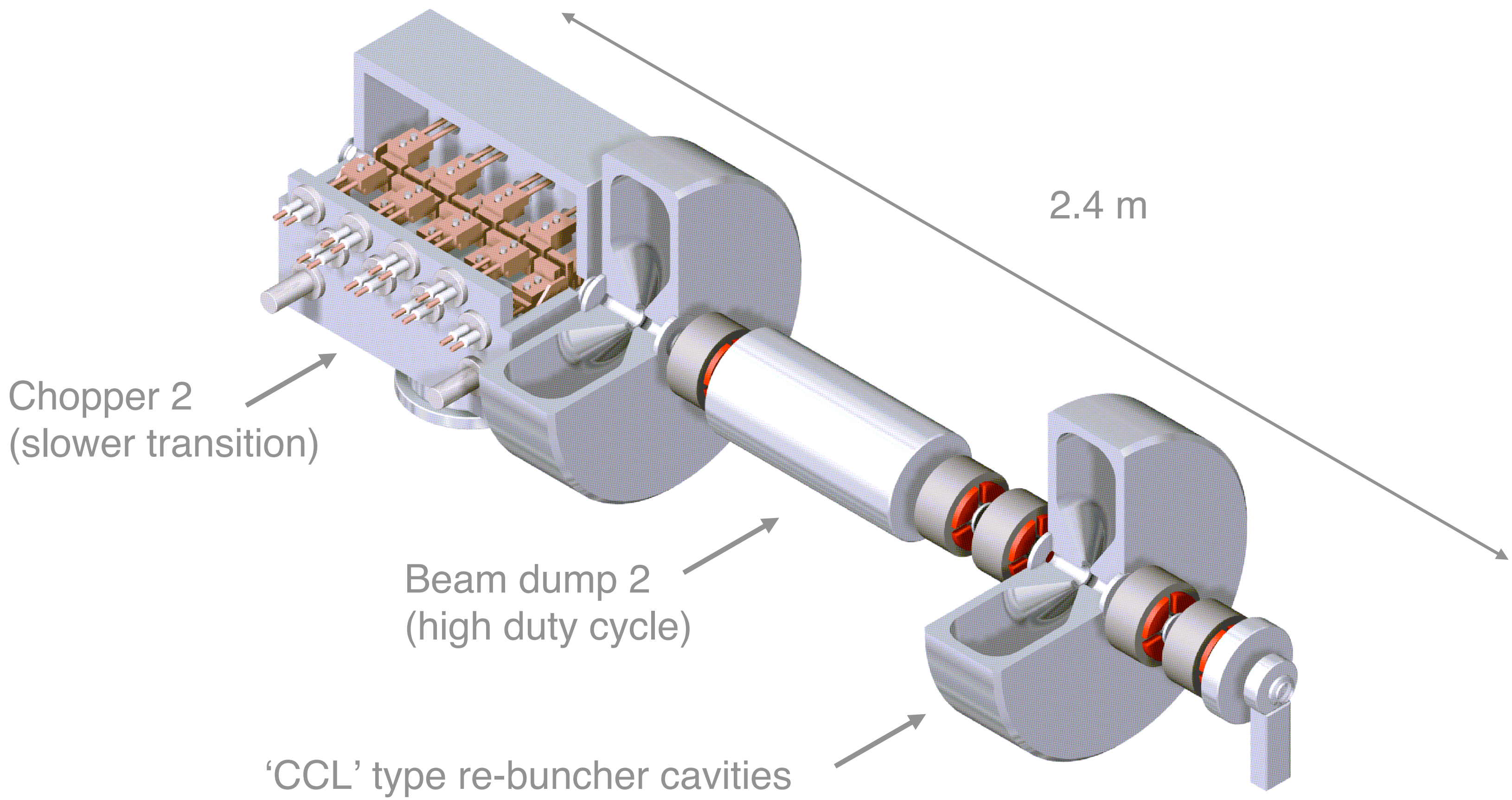
3 MeV MEBT Chopper (FETS Scheme A)



3 MeV MEBT Chopper (FETS Scheme A)



3 MeV MEBT Chopper (FETS Scheme A)

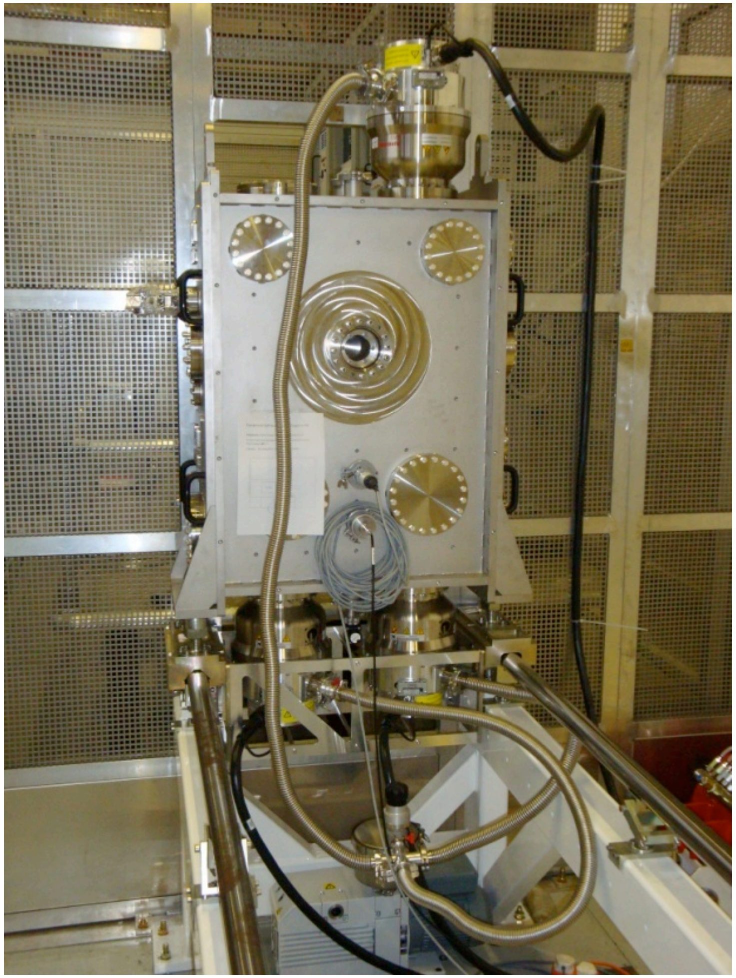


The State Of The Nation…

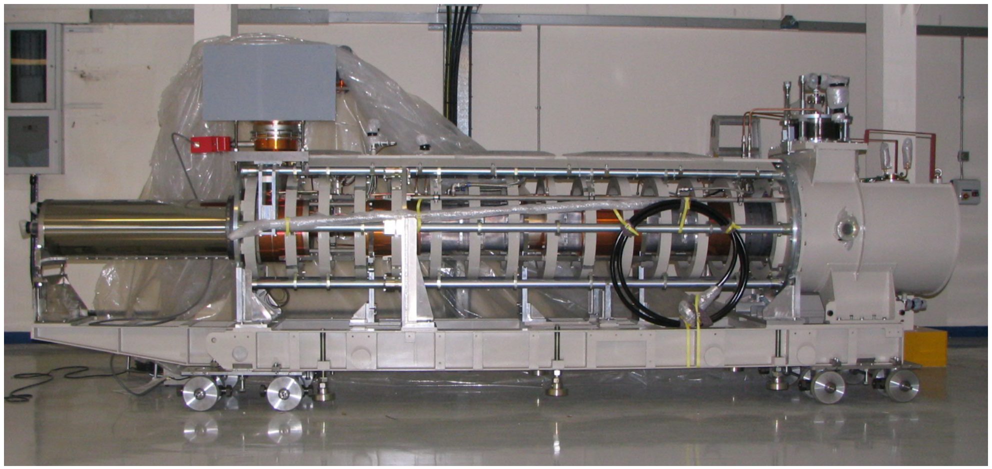
- Installation in R8 (RAL): rails, ion source platform, LEBT tank and solenoids.
- 2MW Klystron and power supply delivered and commissioned.
- LEBT solenoids and power supplies installed and commissioned.
- Vacuum vessel and laser diagnostic constructed and vacuum tested.
- First beam from Ion Source into first LEBT vessel 2 weeks ago!
- RFQ design well under way: need to finalise design for end of 2009.
- Design of high power beam dump.

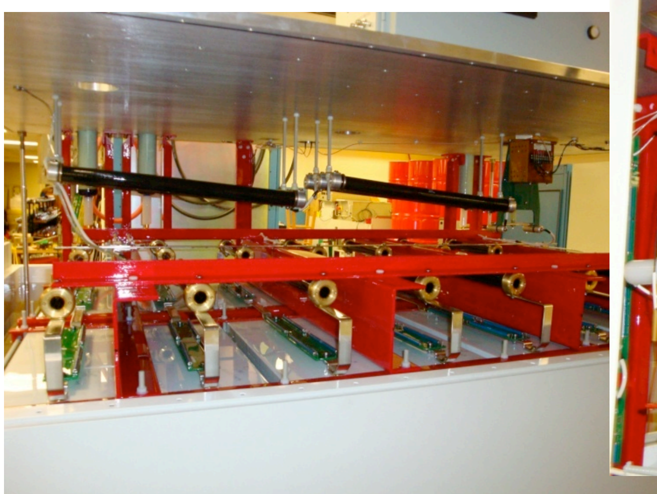
FETS Installation: R8

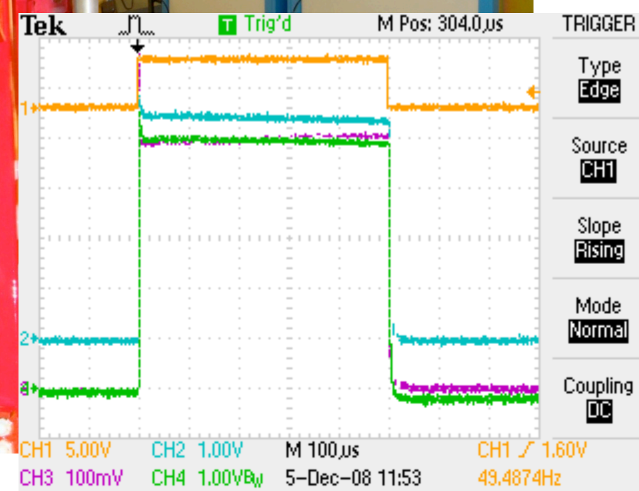
FETS Installation: Ion Source



Klystron/Power Supply







The FETS Collaboration

I have shamelessly pilfered slides from all members of the FETS Collaboration:

- John Back (Warwick).
- Mike Clarke-Gayther, Adeline Daly, Dan Faircloth, Christoph Gabor, Scott Lawrie, Alan Letchford, Ciprian Plostinar (RAL).
- Ajit Kurup, David Lee, Jürgen Pozimski, Pete Savage (Imperial).

…and probably a few more besides…

Spare Slides

Simon Jolly

John Adams Seminar

21st May 2009

Emittance Calculation

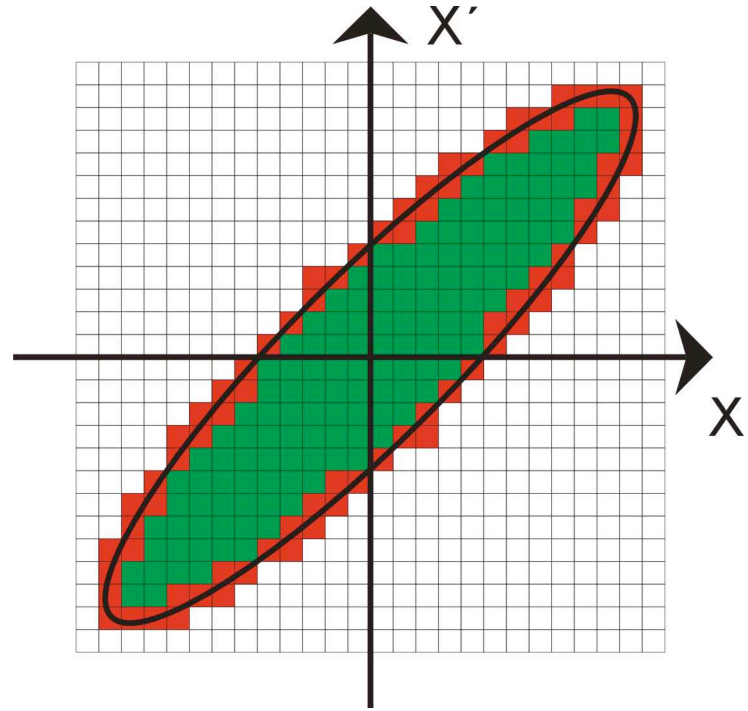
RMS emittance is defined as:

$$\varepsilon_{RMS} = \sqrt{\overline{x}^2 \cdot \overline{x}'^2 - \overline{xx}'^2}$$

$$\overline{x}^2 = \frac{\sum_i \rho_i \cdot x_i^2}{\sum_i \rho_i} \qquad \overline{x}'^2 = \frac{\sum_i \rho_i \cdot x_i'^2}{\sum_i \rho_i}$$

$$\overline{xx}'^2 = \frac{\sum_i \rho_i \cdot (x_i x_i')^2}{\sum_i \rho_i}$$

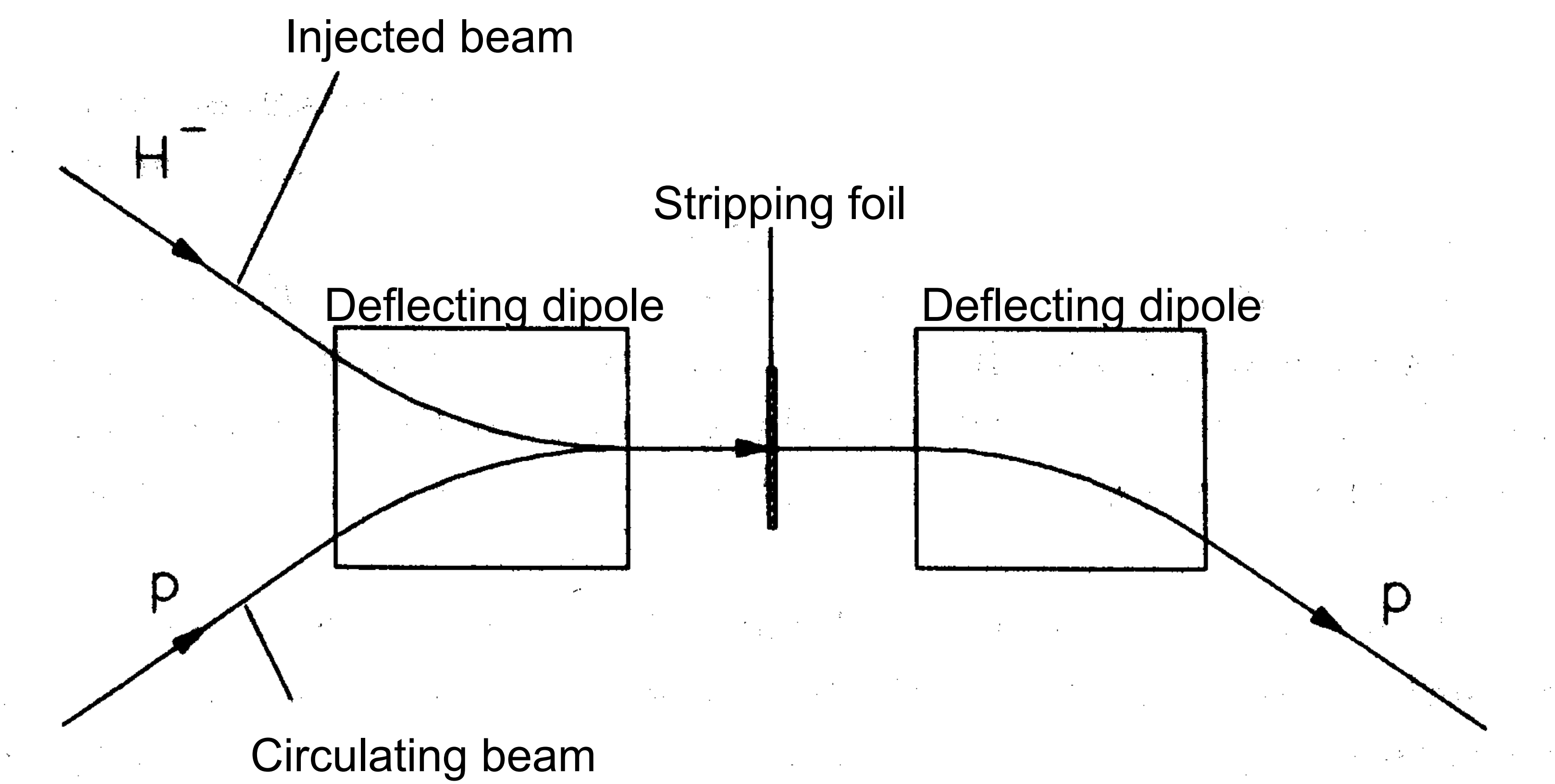
position x, angle x', phase space cell density ρ



Emittance is an invariant quantity…

Non-Liouvillian Stacking: H^- Injection

By accelerating and injecting H^-, then stripping it to H^+ using foils or lasers, we can get around Liouville: this is “charge exchange injection”.

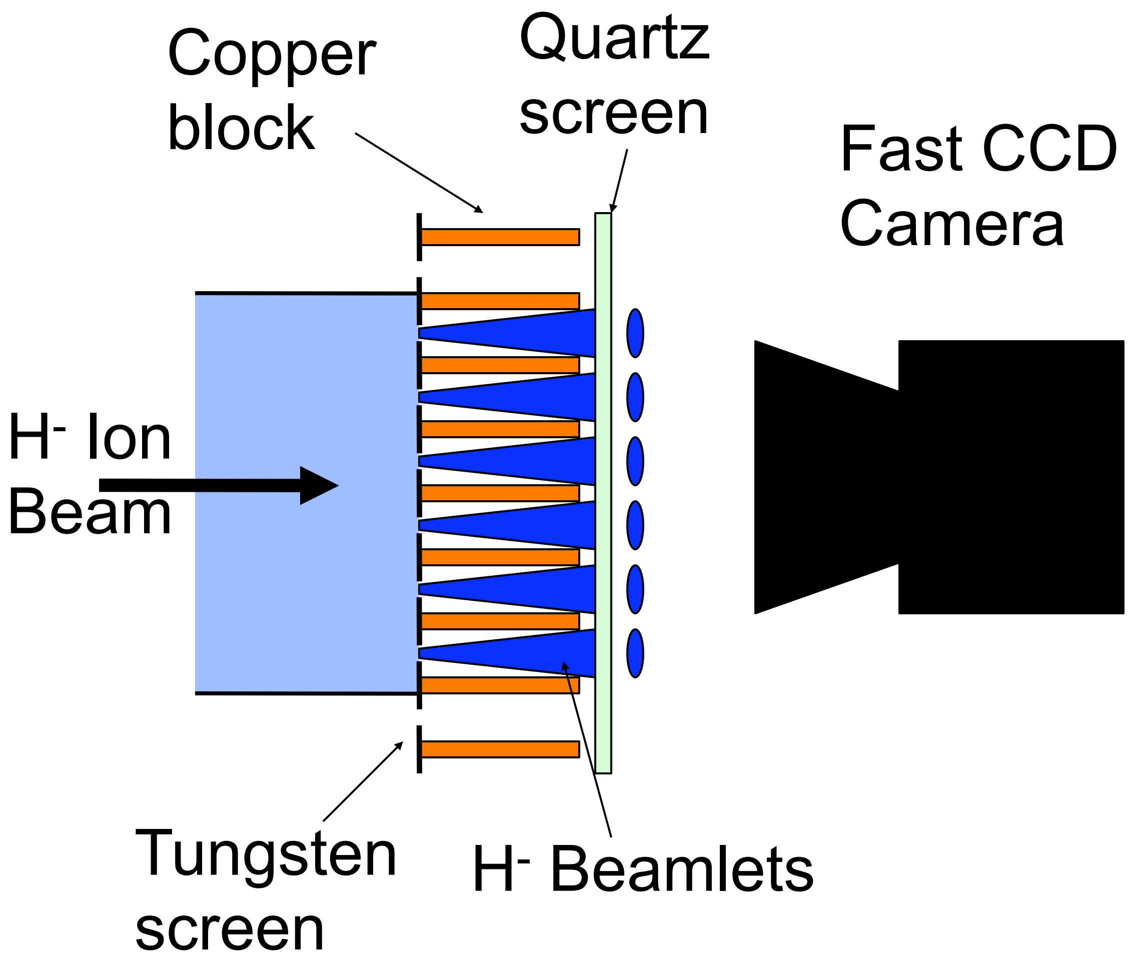


The Pepperpot Emittance Scanner

- Current slit-slit scanners give high resolution emittance measurements, but at fixed z-position and too far from ion source.
- X and Y emittance also uncorrelated, with no idea of x-y profile.
- Correlated, 4-D profile (x, y, x', y') required for accurate simulations.
- Pepperpot reduces resolution to make correlated 4-D measurement.
- Moving stage allows measurement at different z-locations: space charge information.
- Possible to make measurements within a single pulse.
- High resolution x-y profile measurements with second head.

Pepperpot Principle

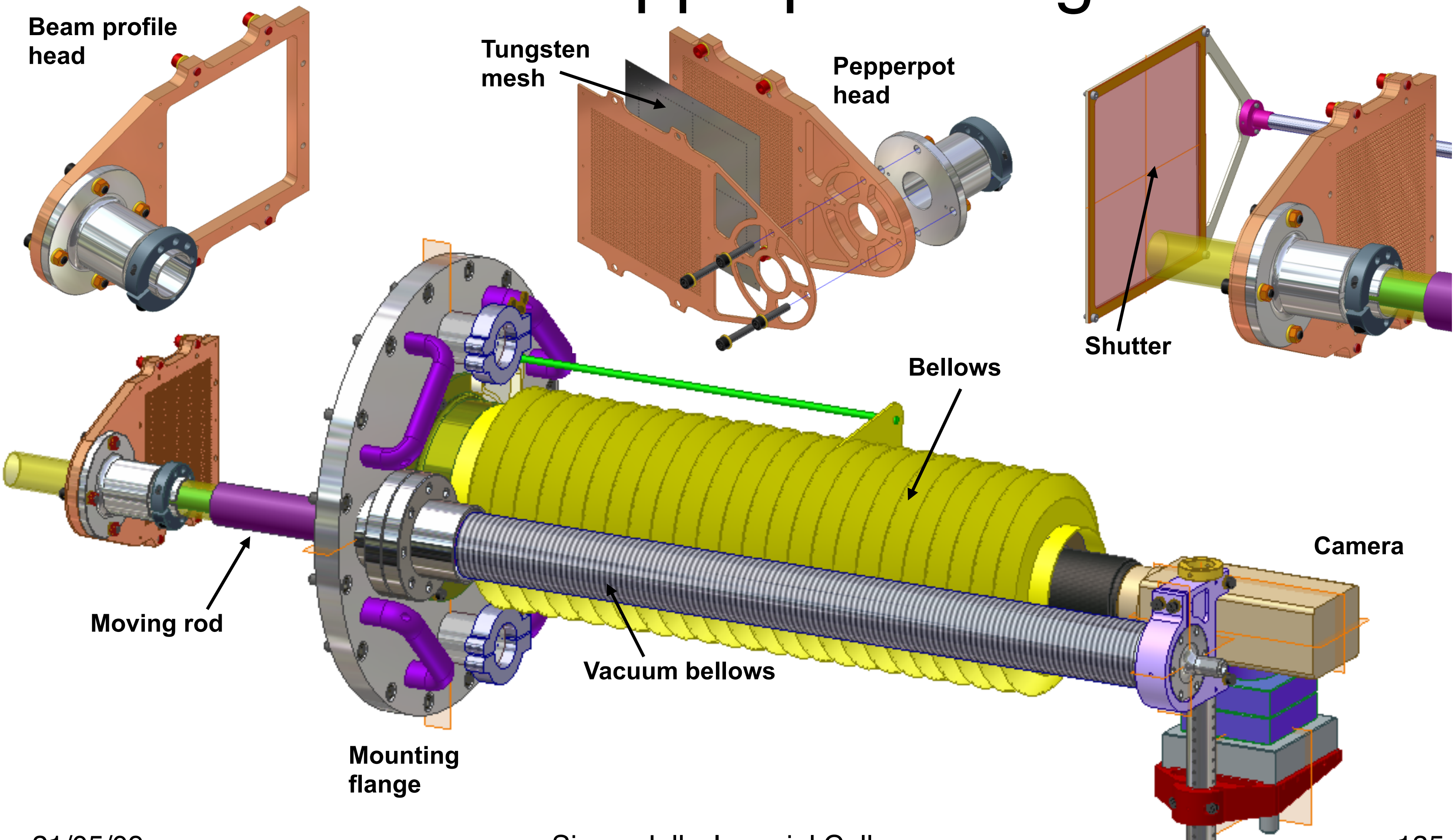
- Beam segmented by tungsten screen.
- Beamlets drift ~10mm before producing image on quartz screen.
- Copper block prevents beamlets from overlapping and provides cooling.
- CCD camera records image of light spots.
- Calculate emittance from spot distribution.



Pepperpot Components

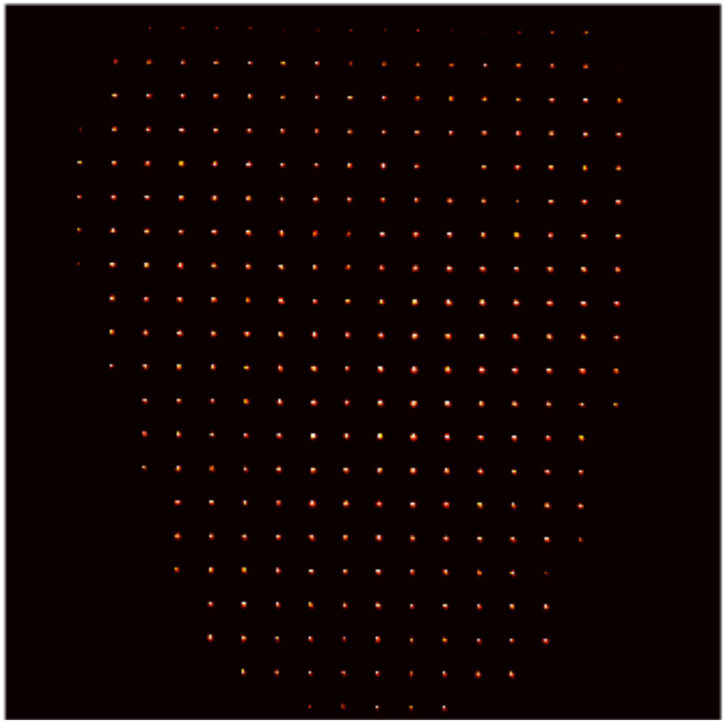
- Pepperpot head:
  - Tungsten intercepting screen, 50μm holes on 3mm pitch in 41x41 array.
  - Tungsten sandwiched between 2mm/10mm copper support plates.
  - Quartz scintillator images beamlets.
- Camera system:
  - PCO 2000 camera with 2048 x 2048 pixel, 15.3 x 15.6 mm CCD.
  - Firewire connection to PC.
  - 105 mm Micro-Nikkor macro lens.
  - Bellows maintains light tight path from vacuum window to camera.
- Main support:
  - Head and camera mounted at either end of 1100 mm linear shift mechanism, with 700 mm stroke.
  - All mounted to single 400 mm diameter vacuum flange.

FETS Pepperpot Design



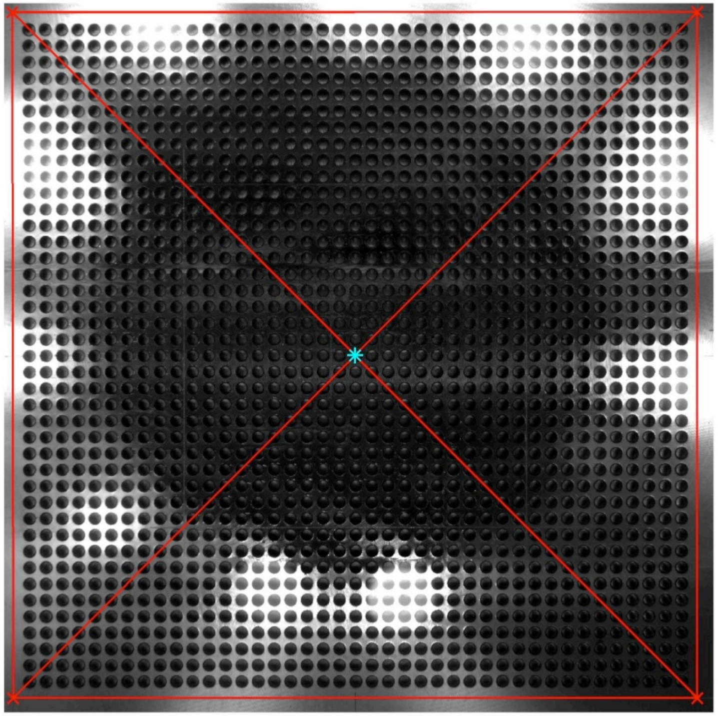
Pepperpot Data Image

Raw data



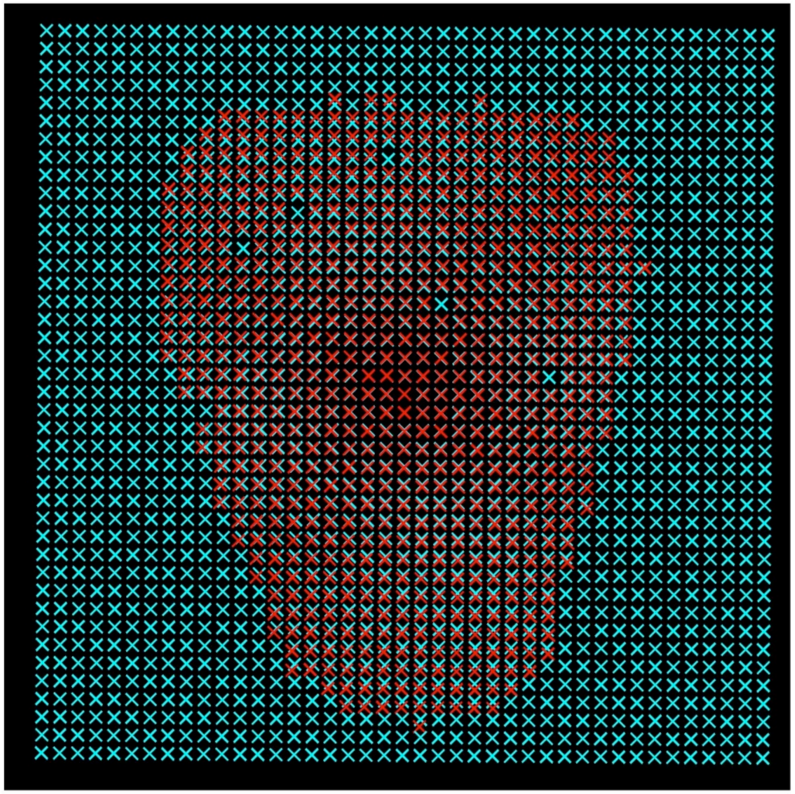
Colour enhanced raw data image, 60 x 60 mm^2.

Calibration image



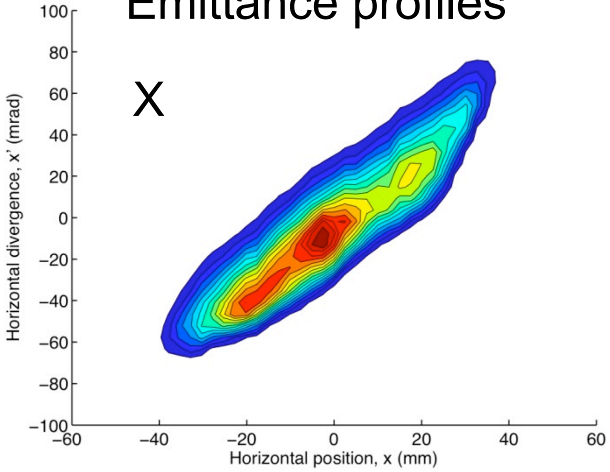
Calibration image: use corners of 126 x 126 mm square on copper plate to give image scaling, tilt and spot spacing.

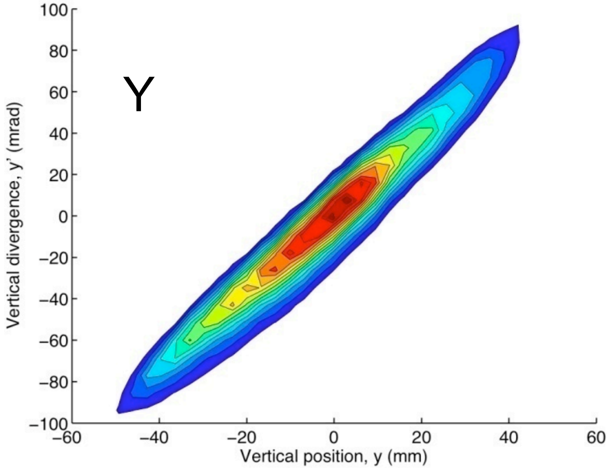
Pepperpot Emittance Extraction



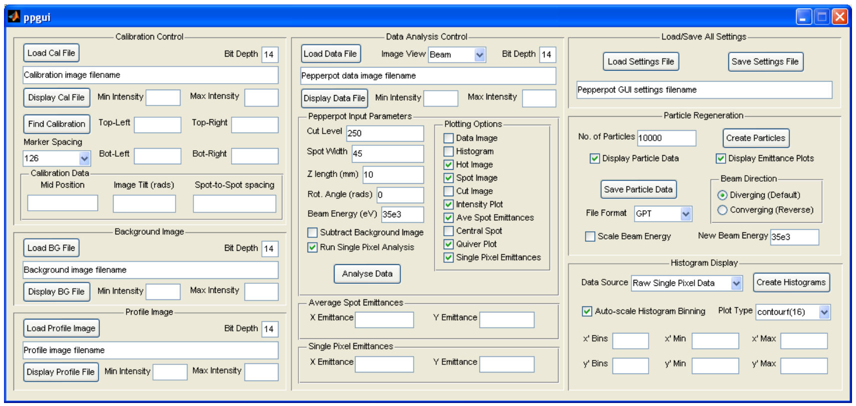
Pepperpot image spots: hole positions (blue) and beam spots (red)

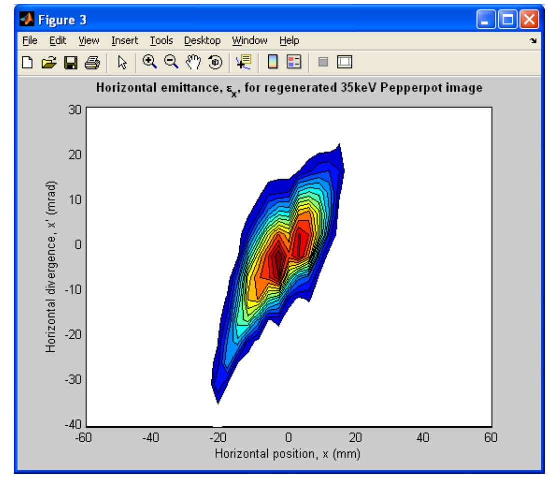
Emittance profiles

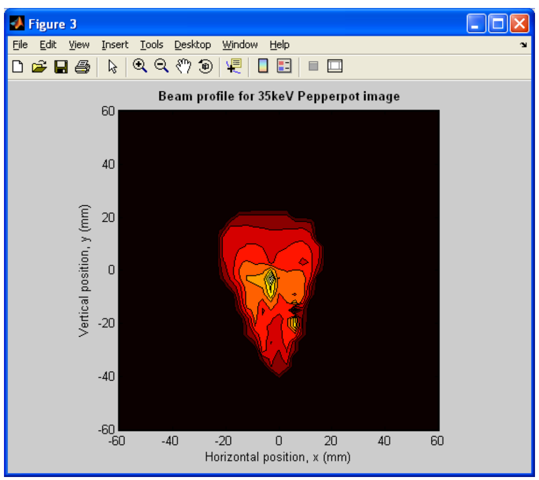


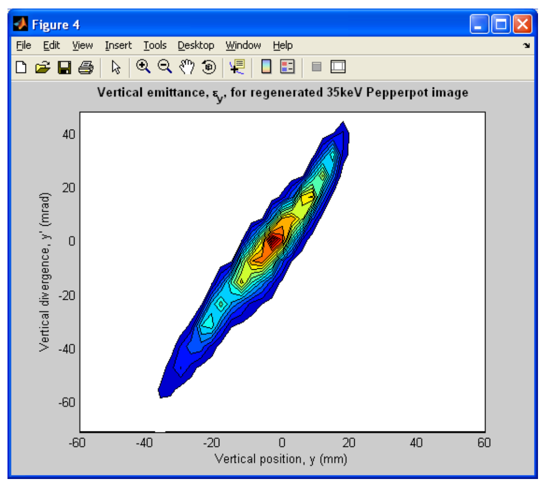


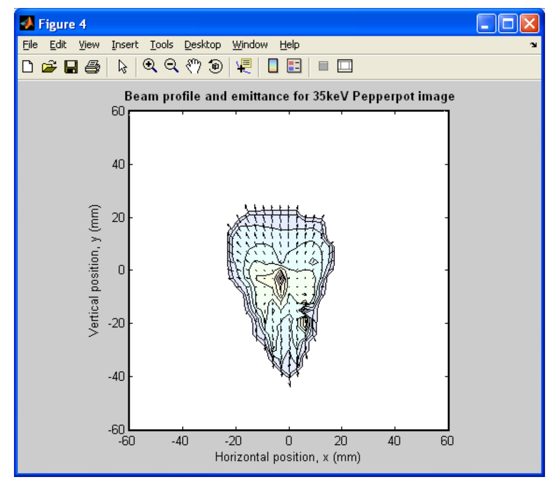
Pepperpot GUI and Data Analysis



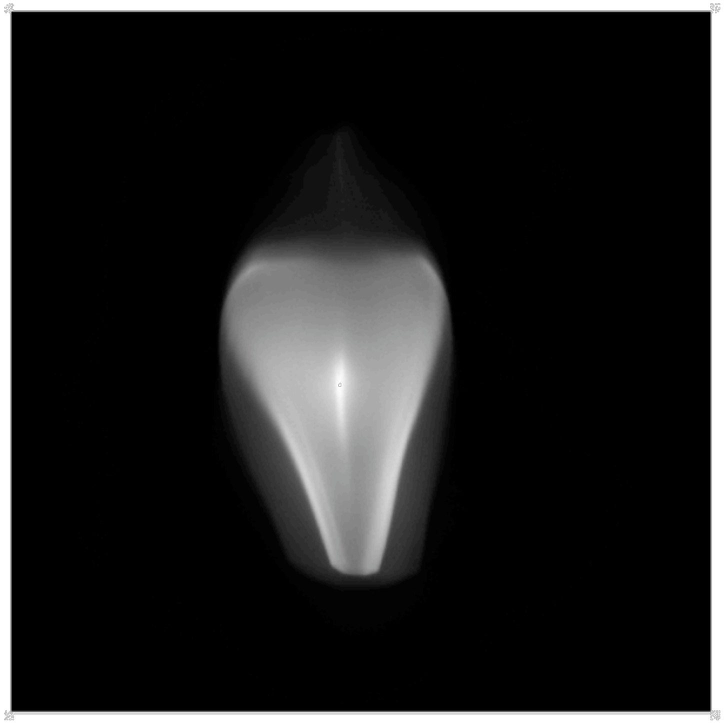


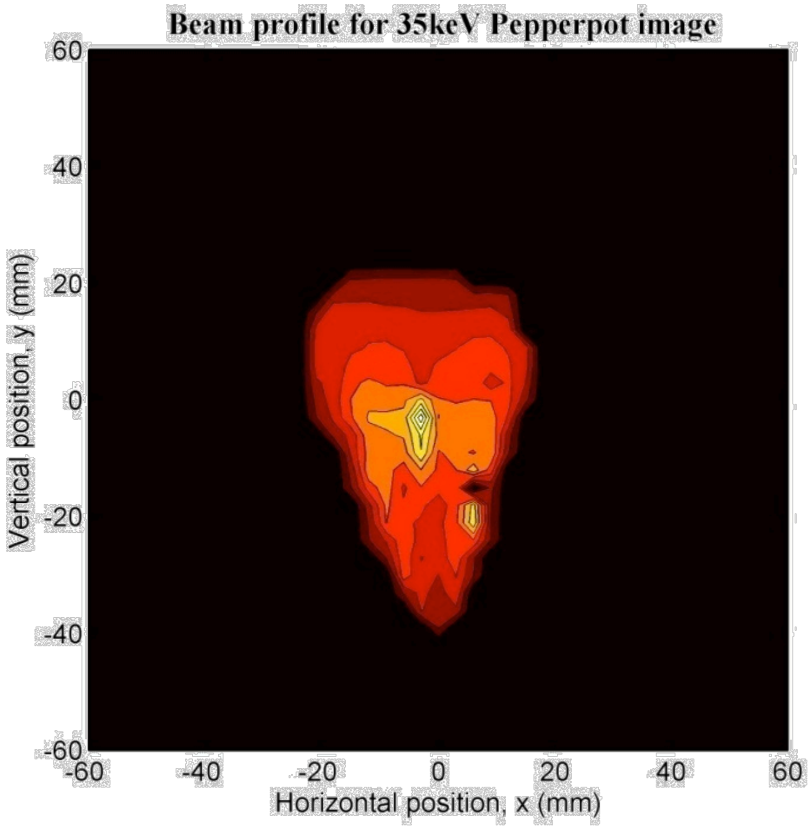






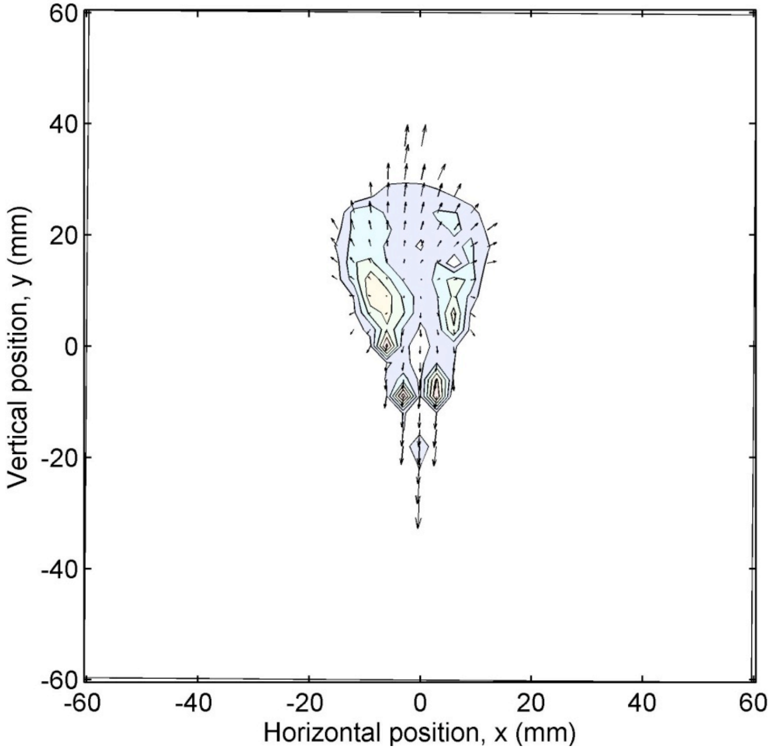
Pepperpot/Profile Comparison



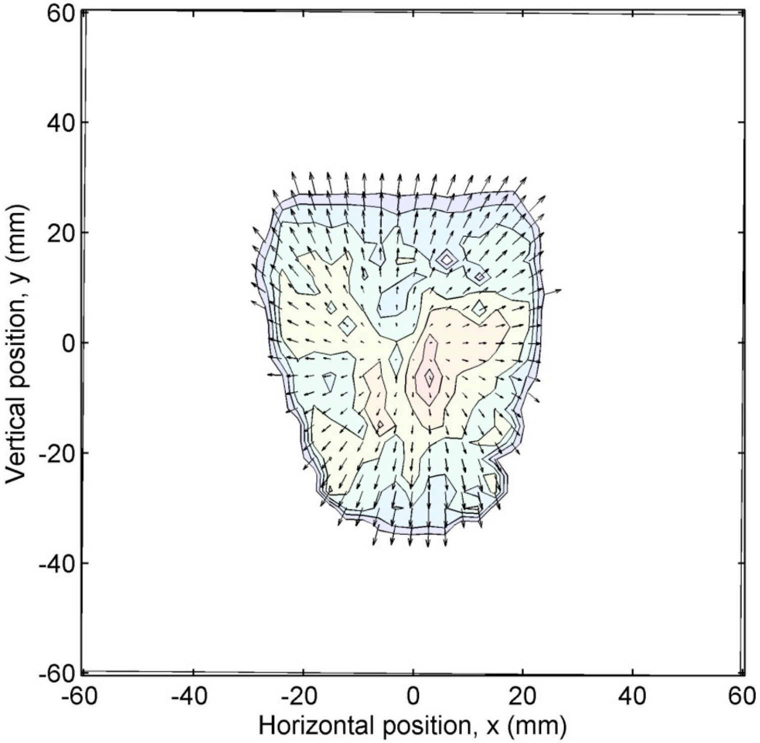


Pepperpot Quiver Plots

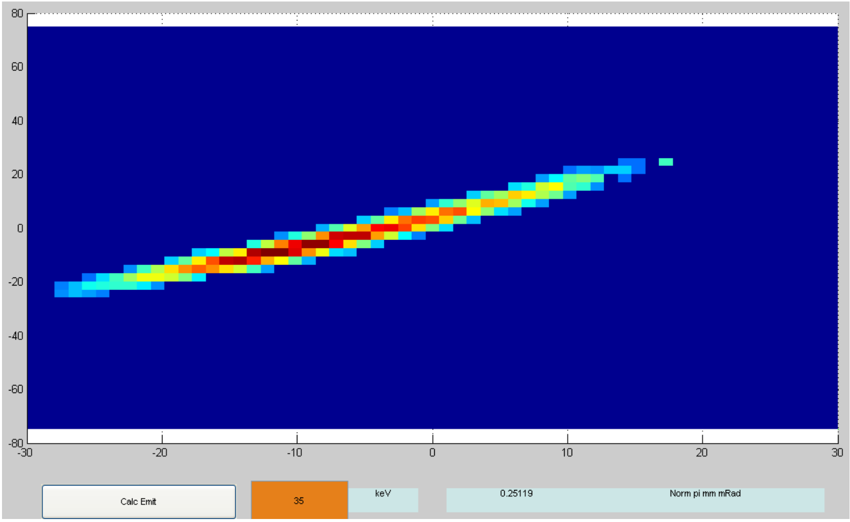
9 kV Extract

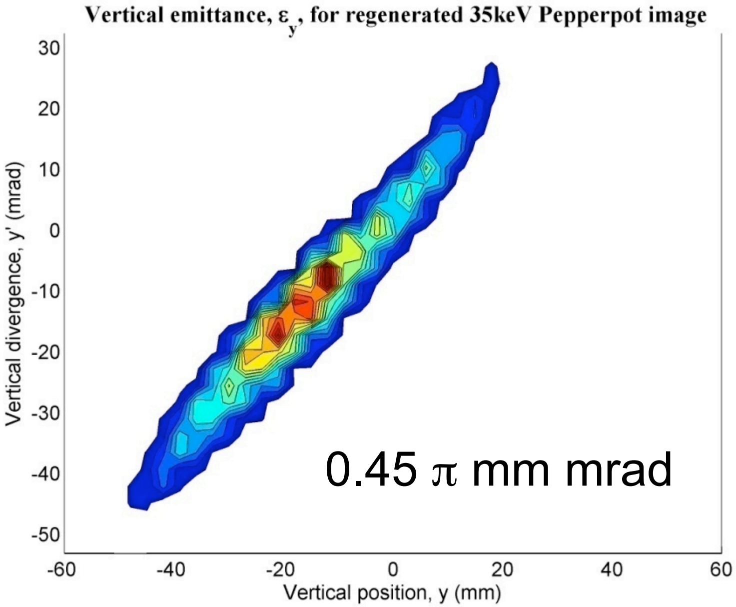


13 kV Extract



Pepperpot vs. Slit-Slit: 11kV Y Emittance

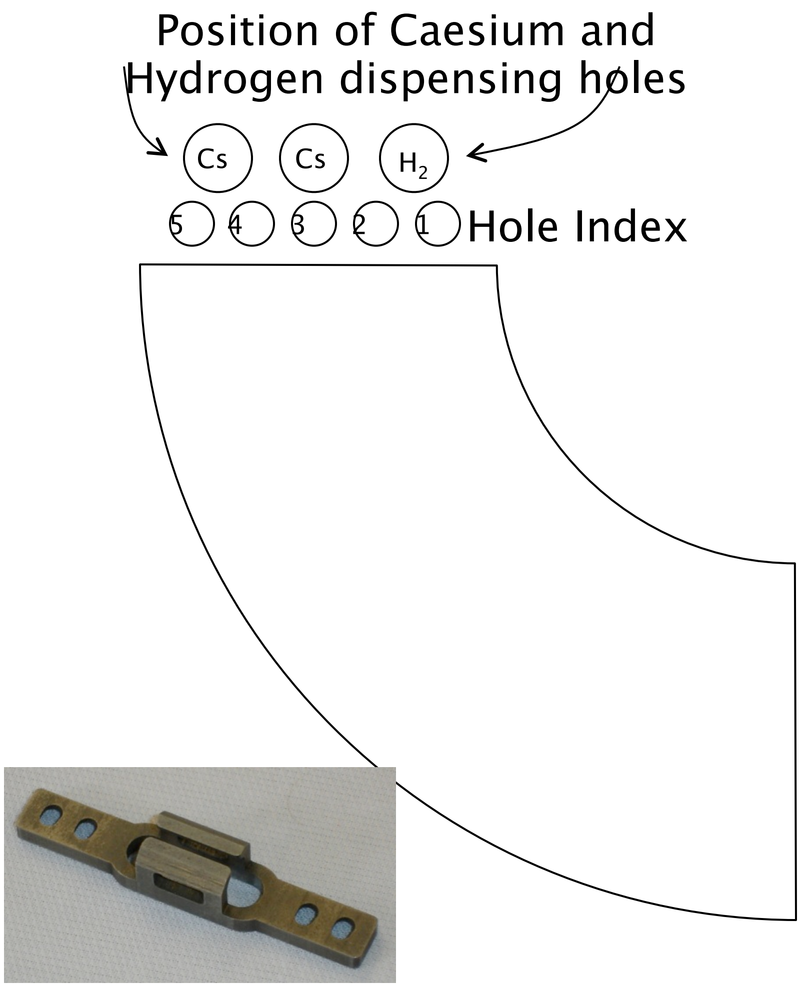


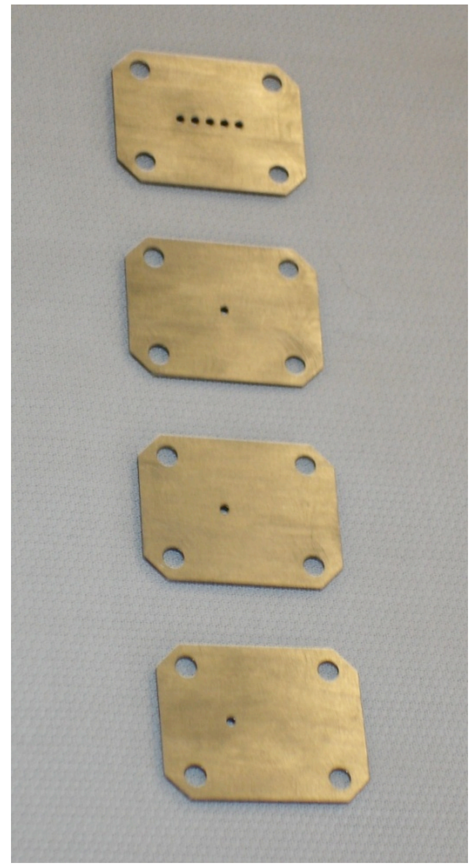


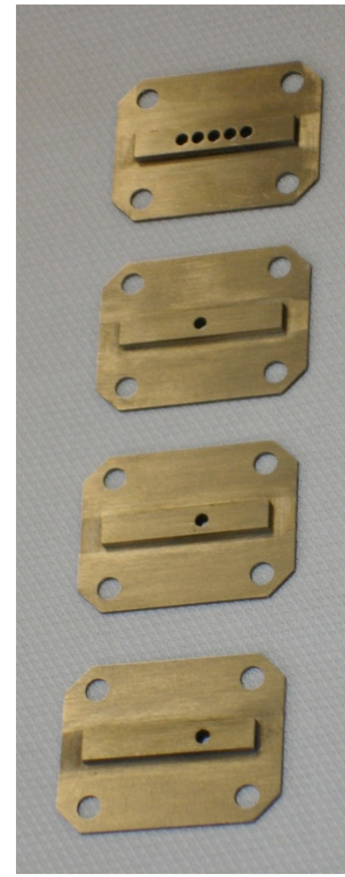
Multi-Beamlet Aperture Plate

- Beam size unexpectedly large, with curious "cobra-head" shape.
- New multi-aperture extraction plates made with different extraction geometries to "select" parts of the beam.
- If cobra-head comes from within plasma, should see a difference…

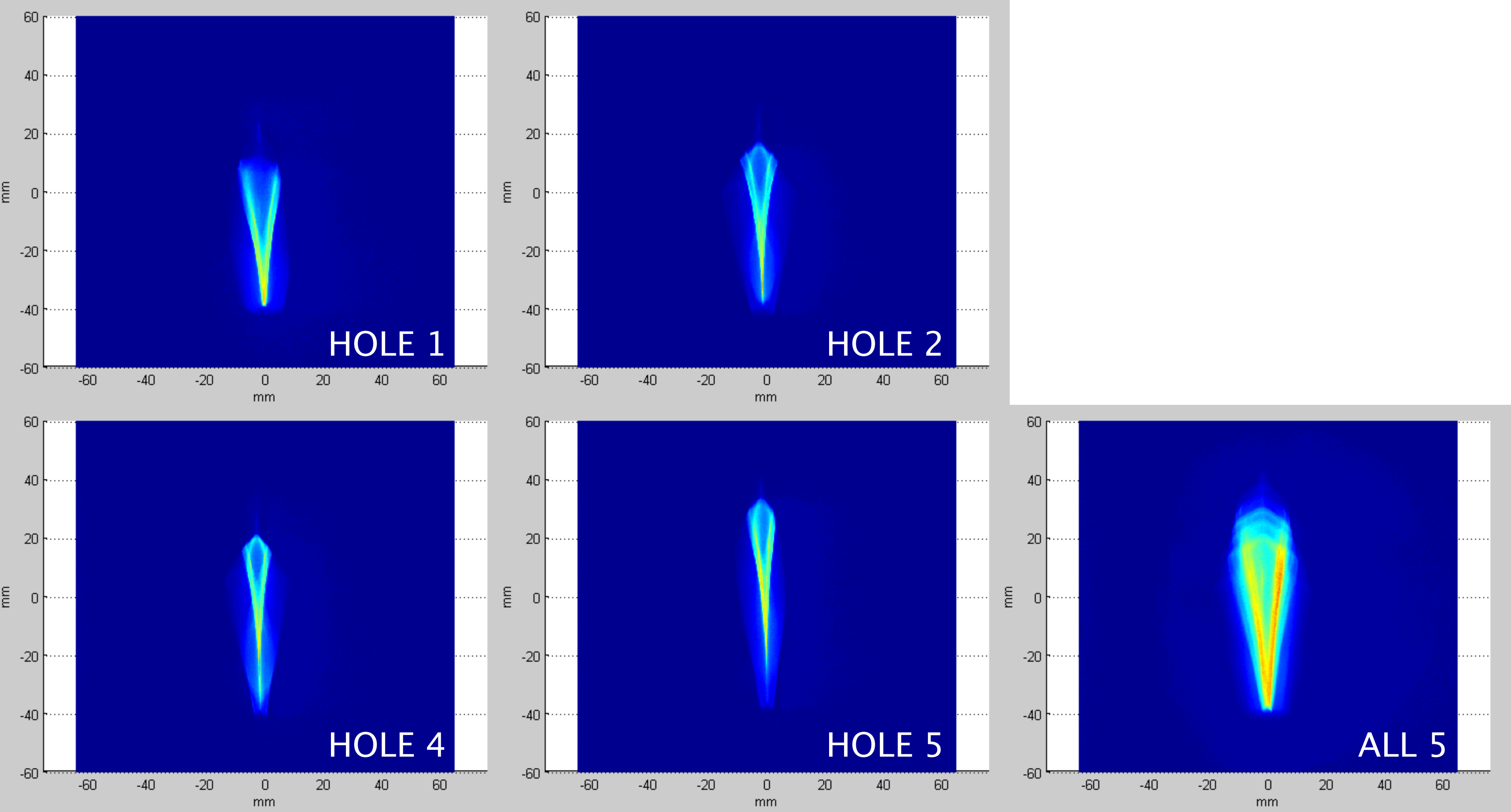
Multi Beamlett Extraction







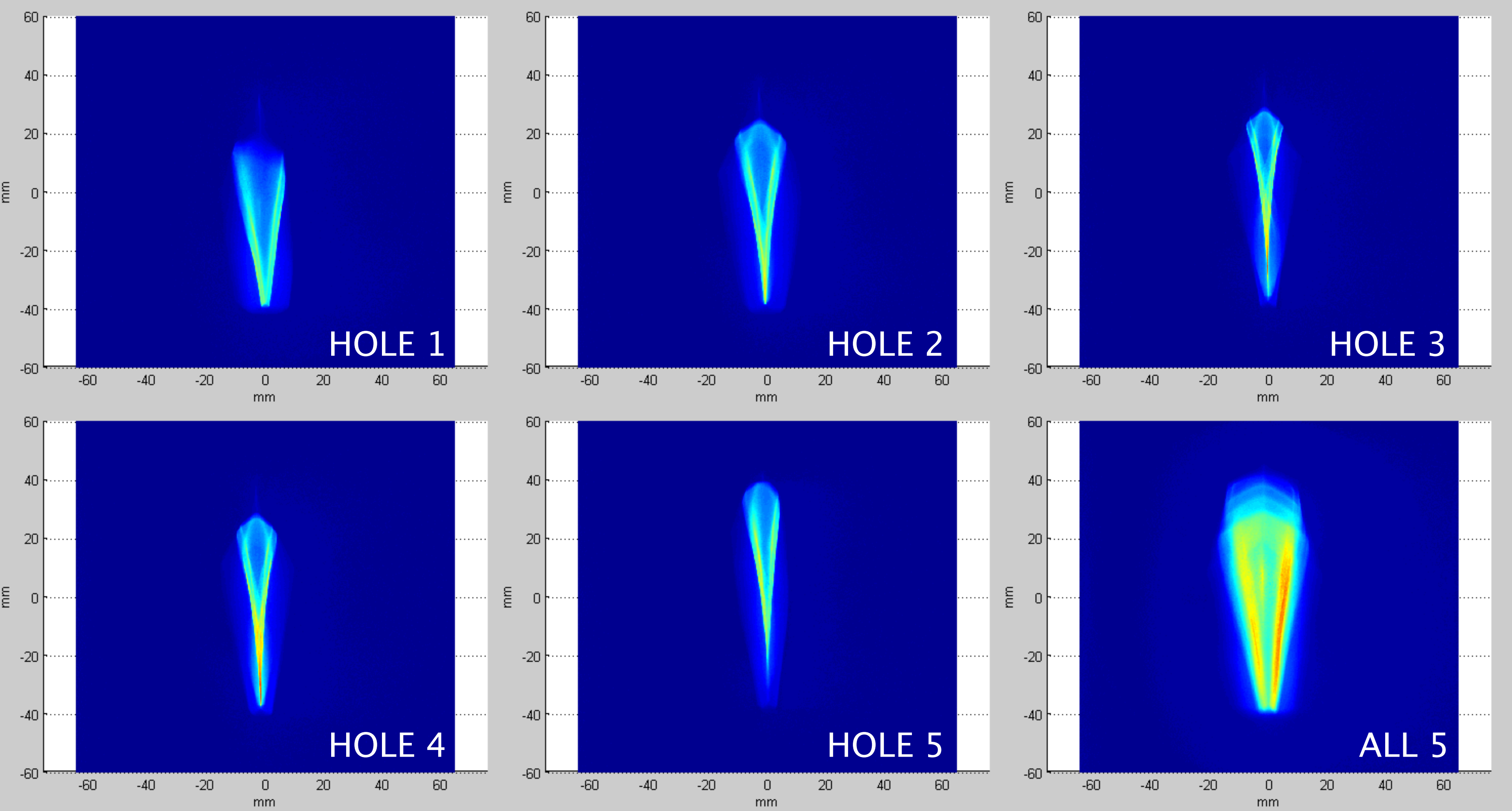
To study beam transport aperture plates with 5 separate 1 mm diameter holes have been constructed.



7 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

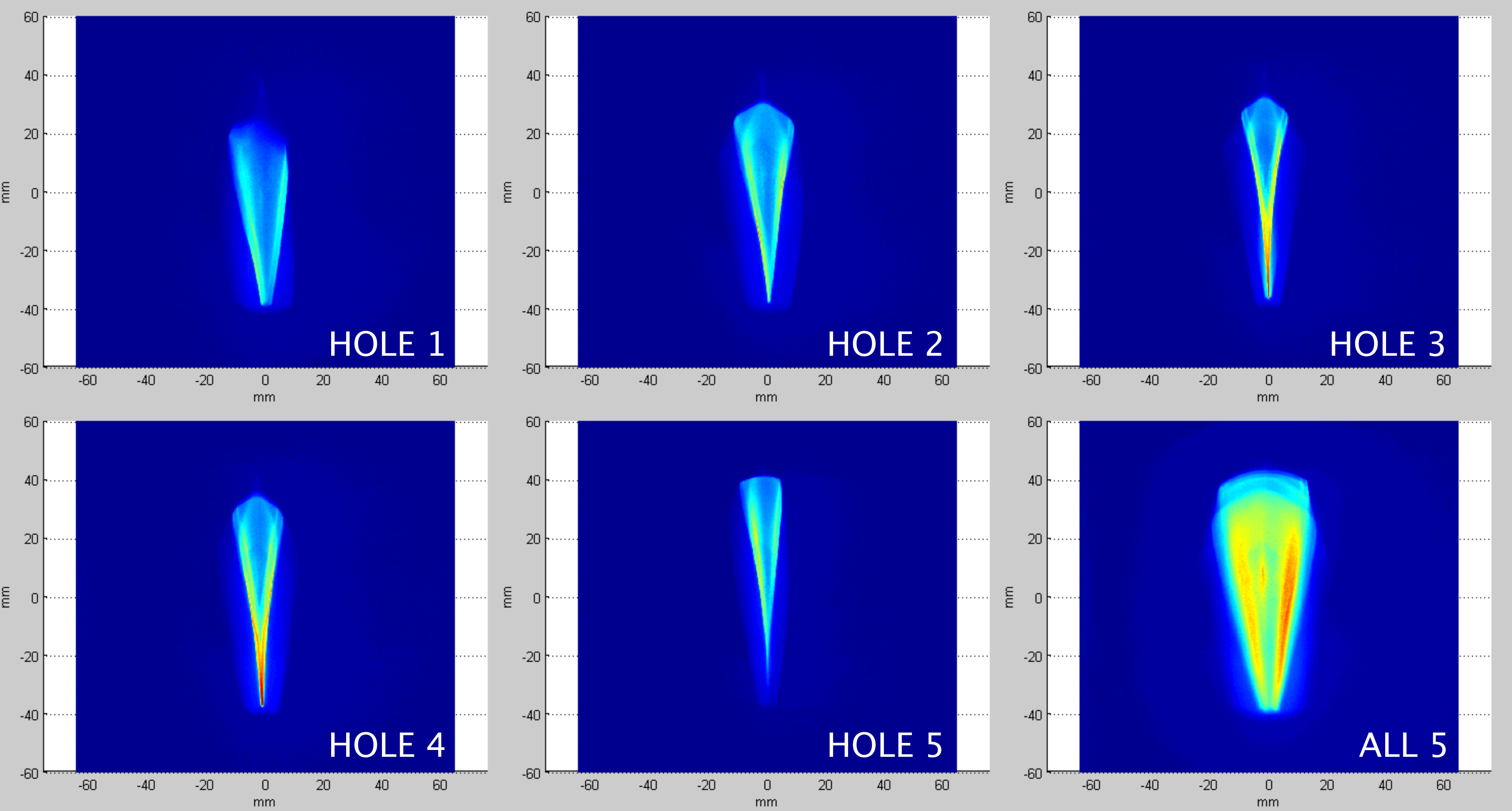
18 kV Post Acceleration Voltage



8 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

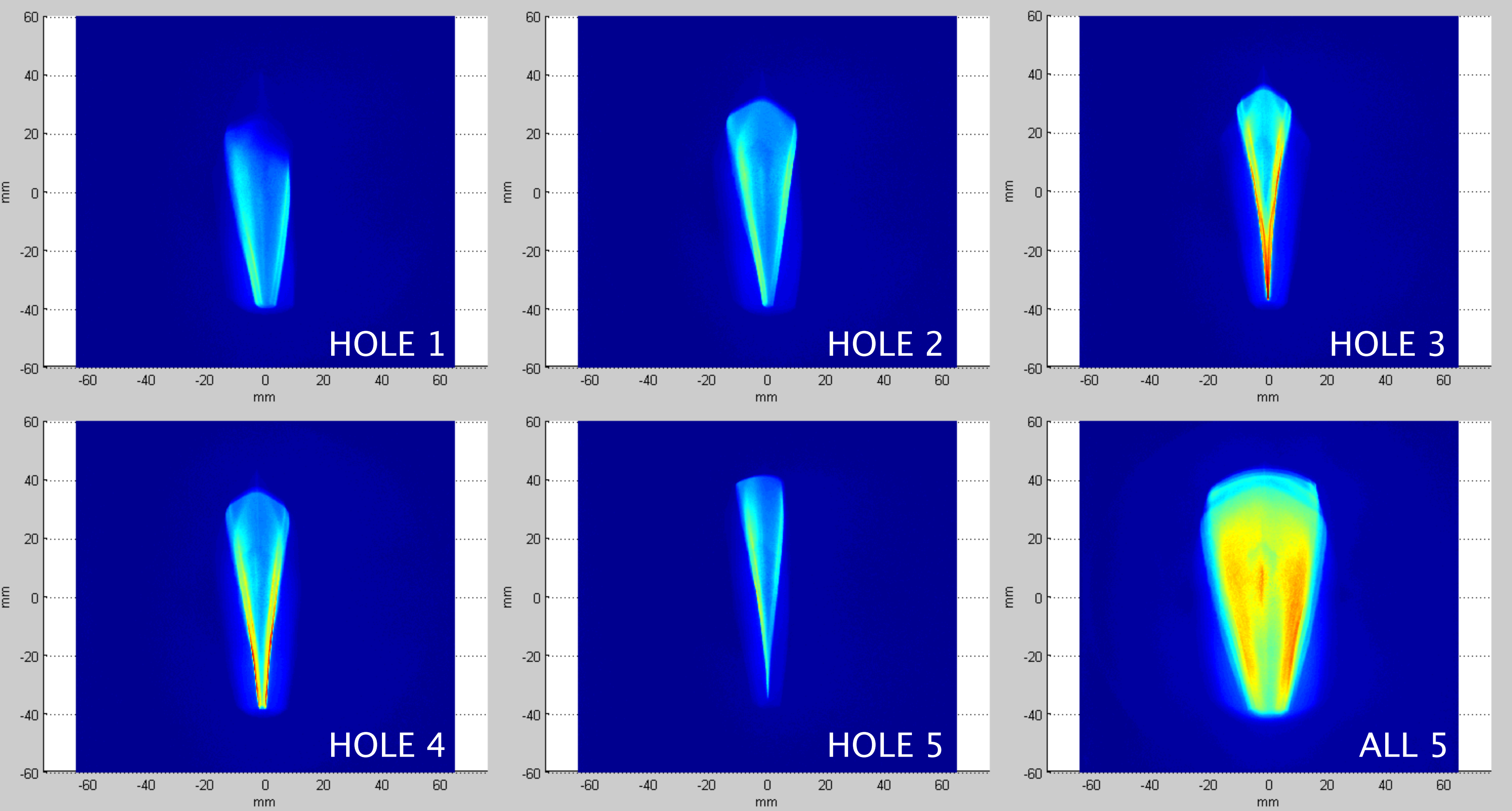
18 kV Post Acceleration Voltage



9 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

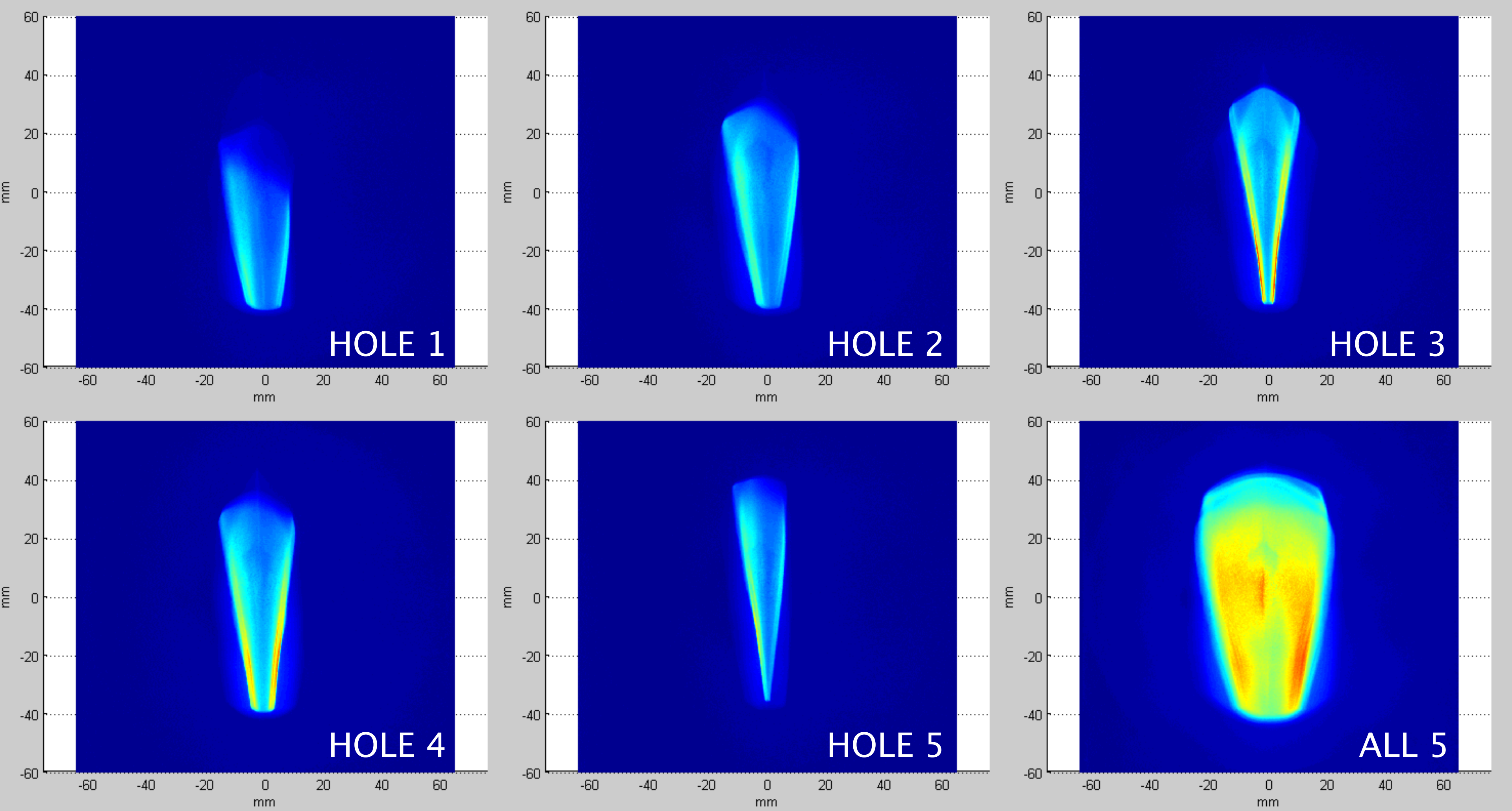
18 kV Post Acceleration Voltage



10 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

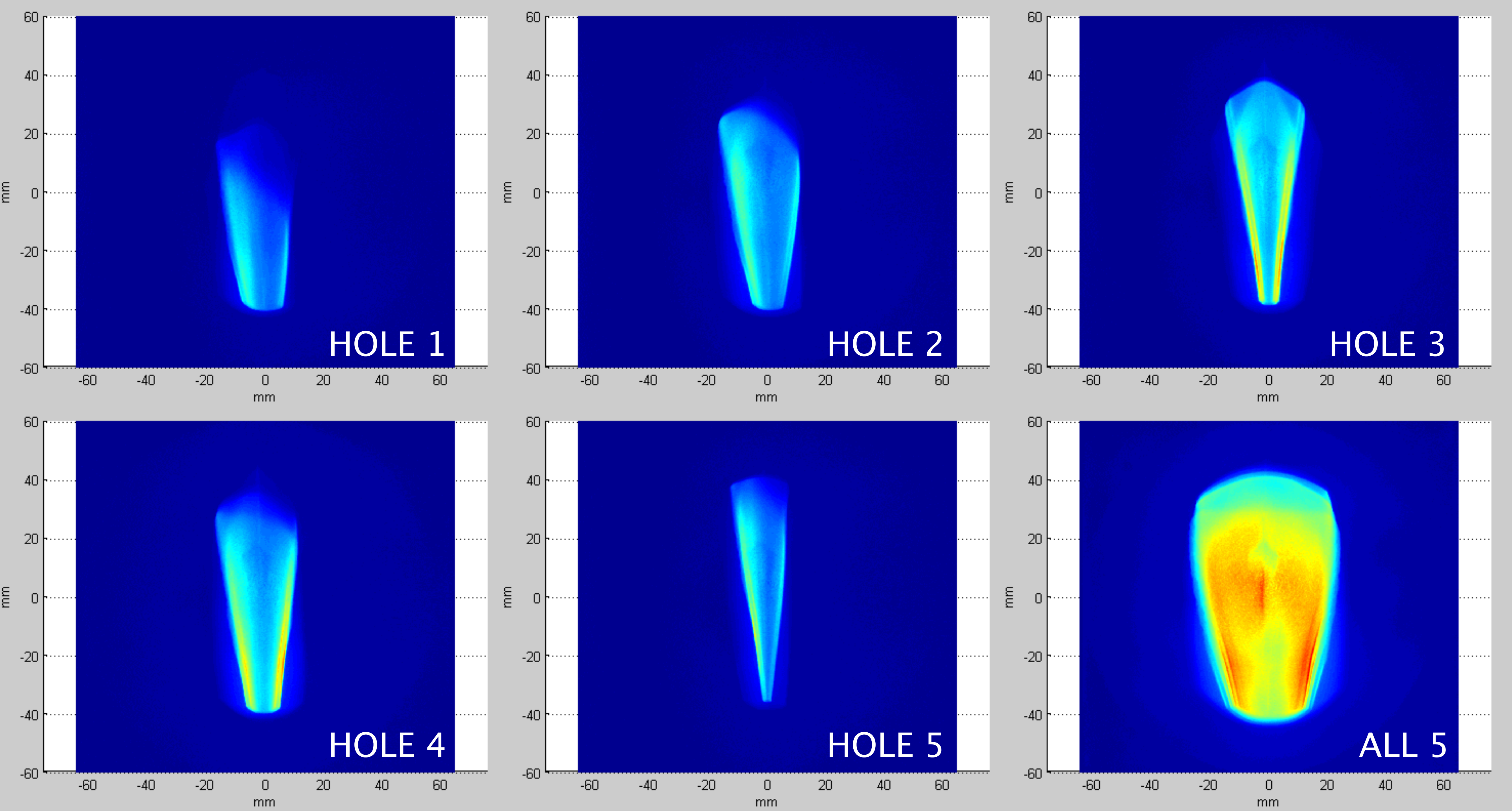
18 kV Post Acceleration Voltage



11 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

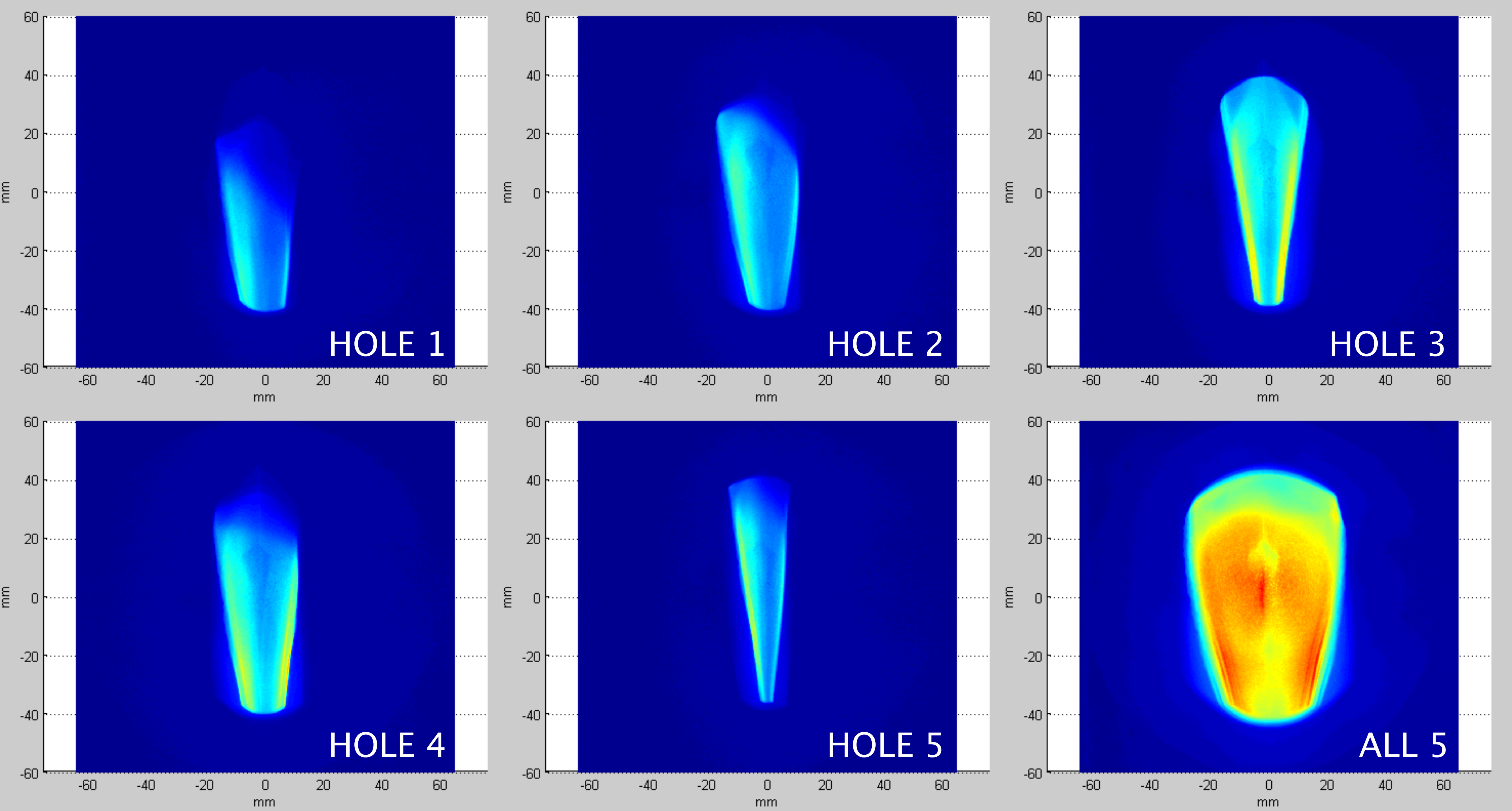
18 kV Post Acceleration Voltage



12 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

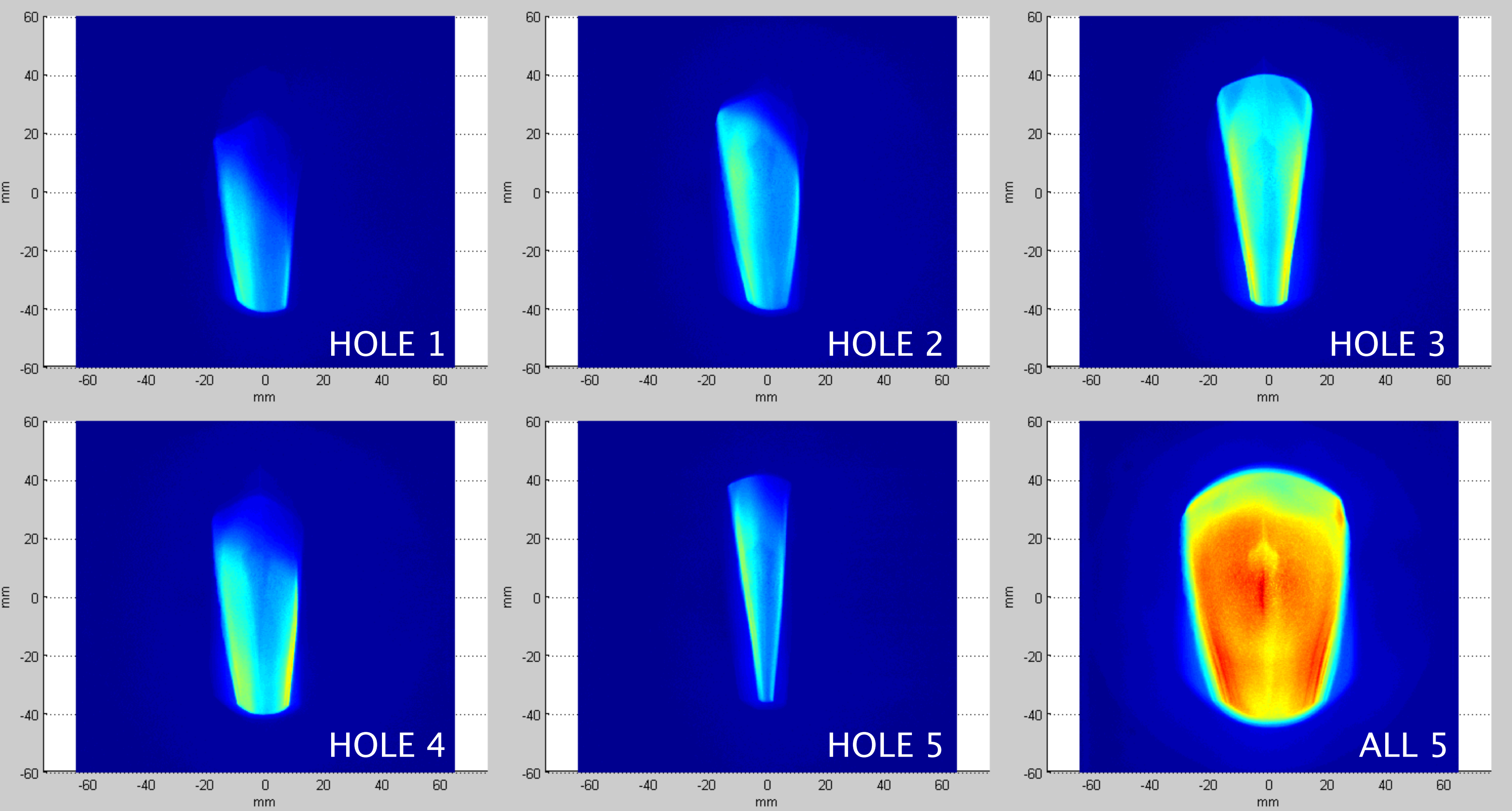
18 kV Post Acceleration Voltage



13 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

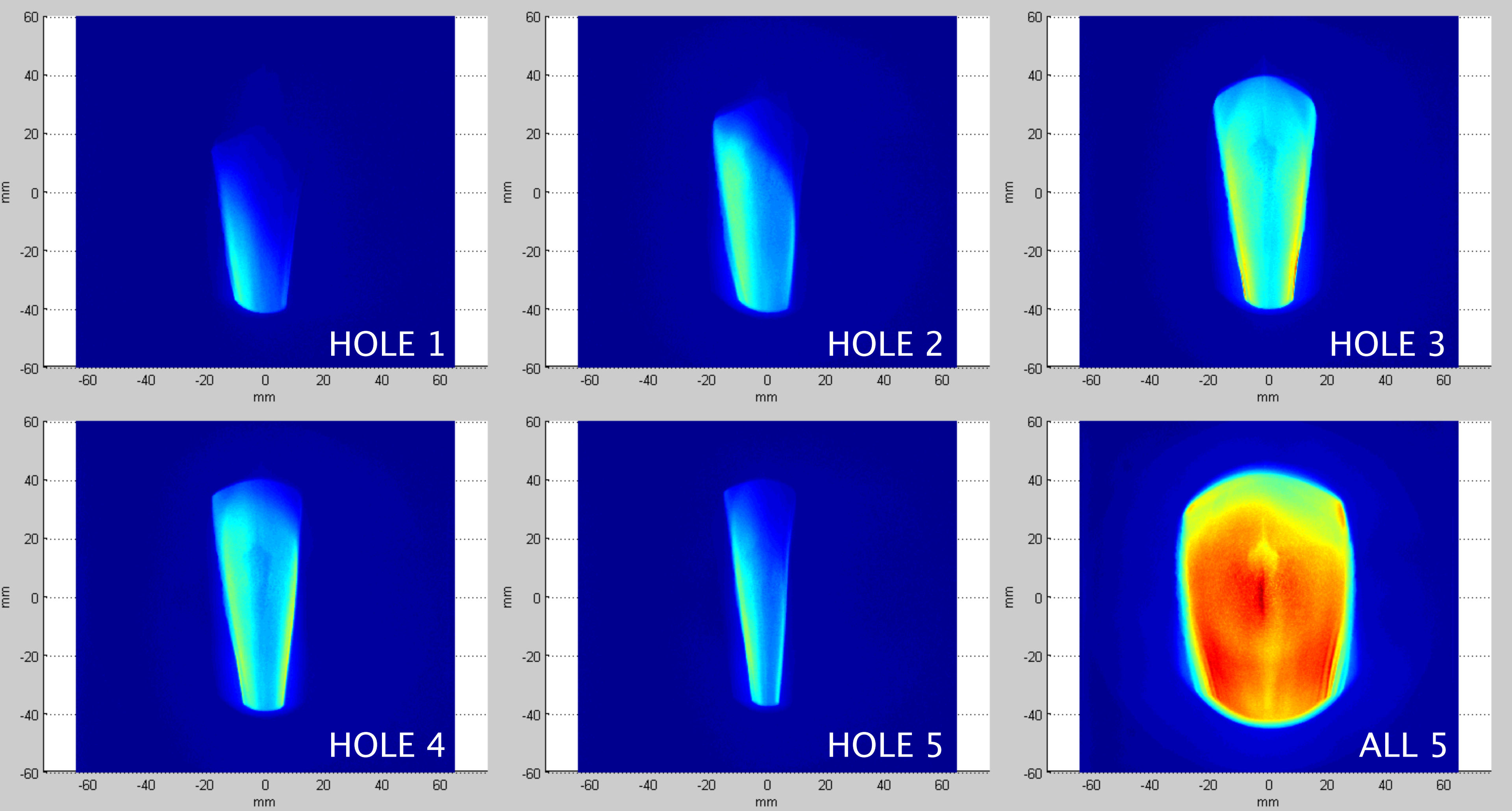
18 kV Post Acceleration Voltage



14 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

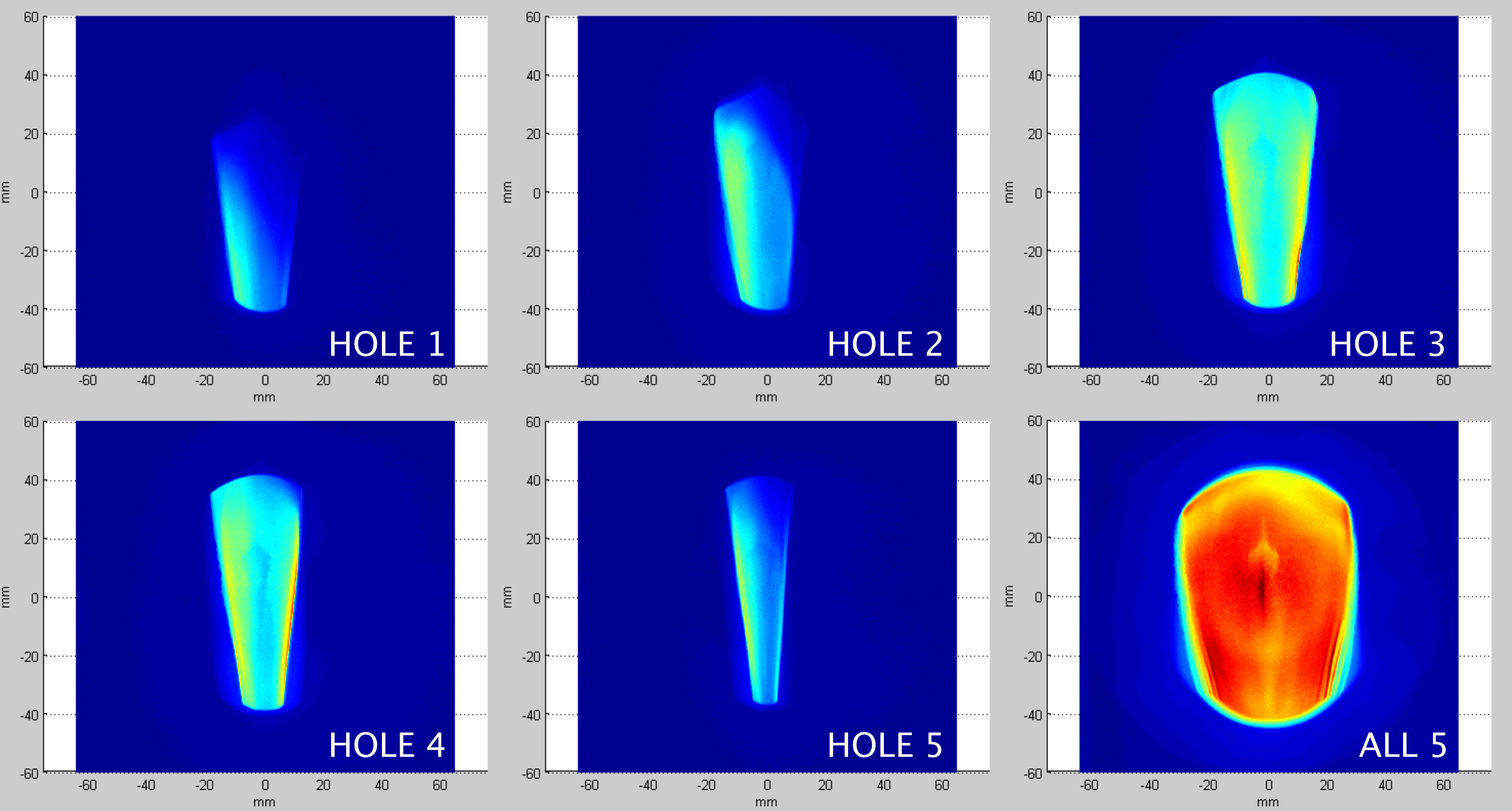
18 kV Post Acceleration Voltage



15 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

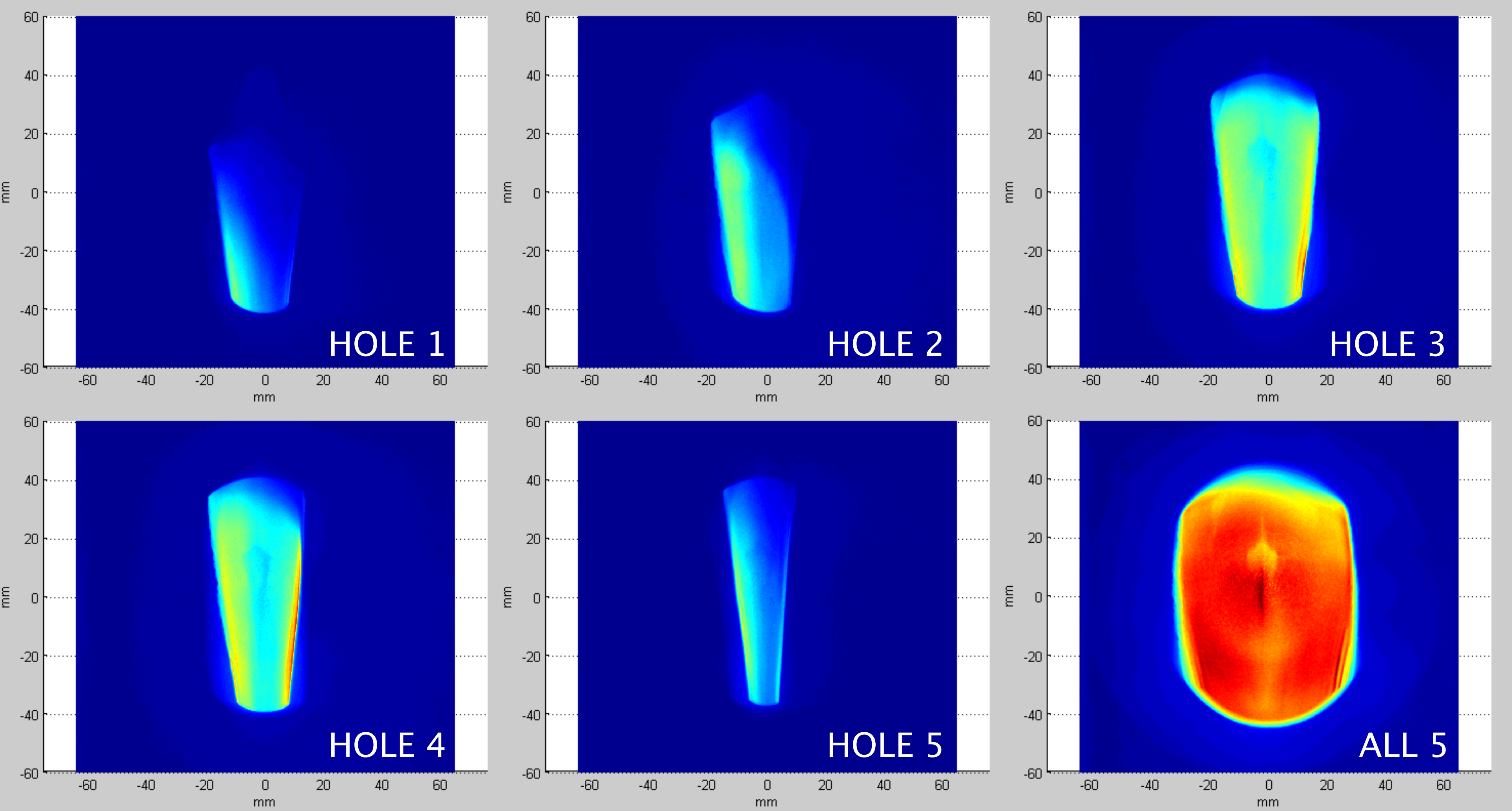
18 kV Post Acceleration Voltage



16 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

18 kV Post Acceleration Voltage

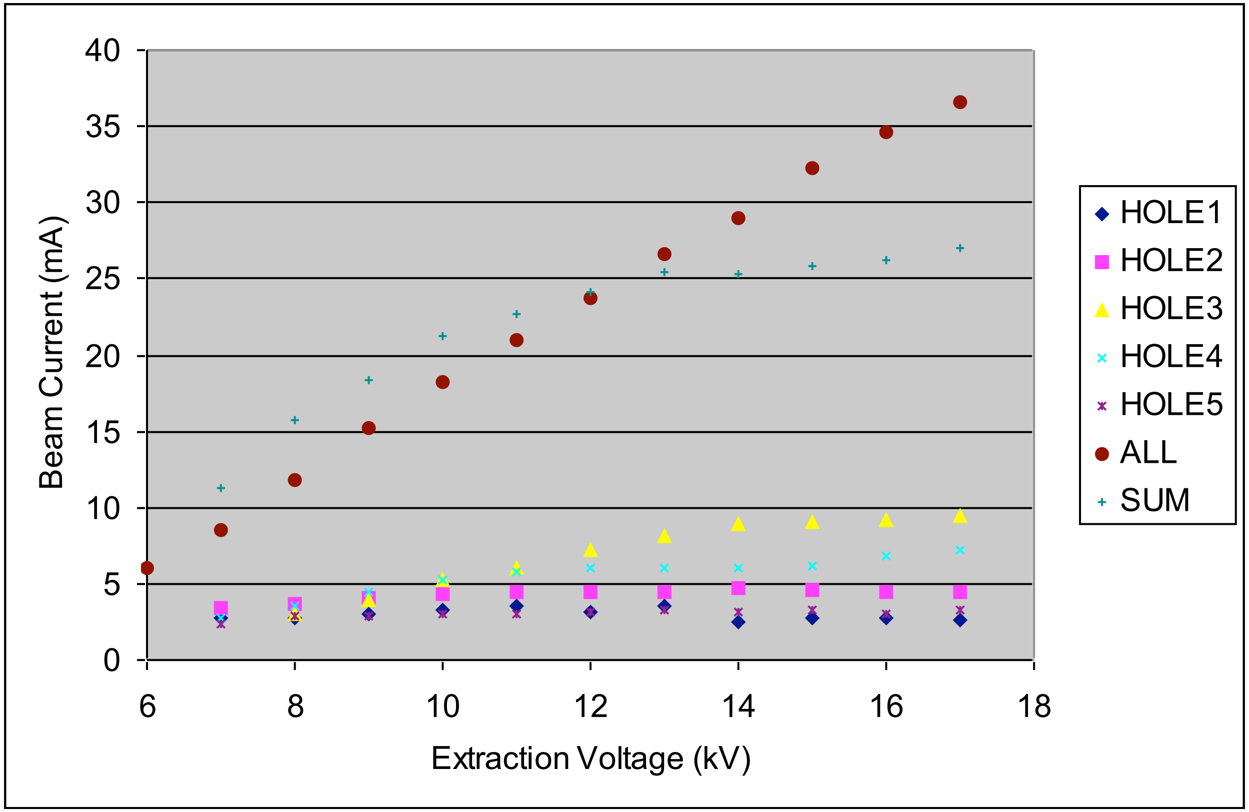


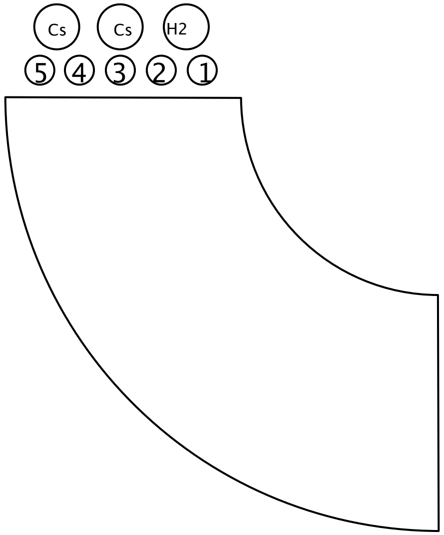
17 kV Extraction Voltage

355 mm downstream from ground plane of post acceleration gap

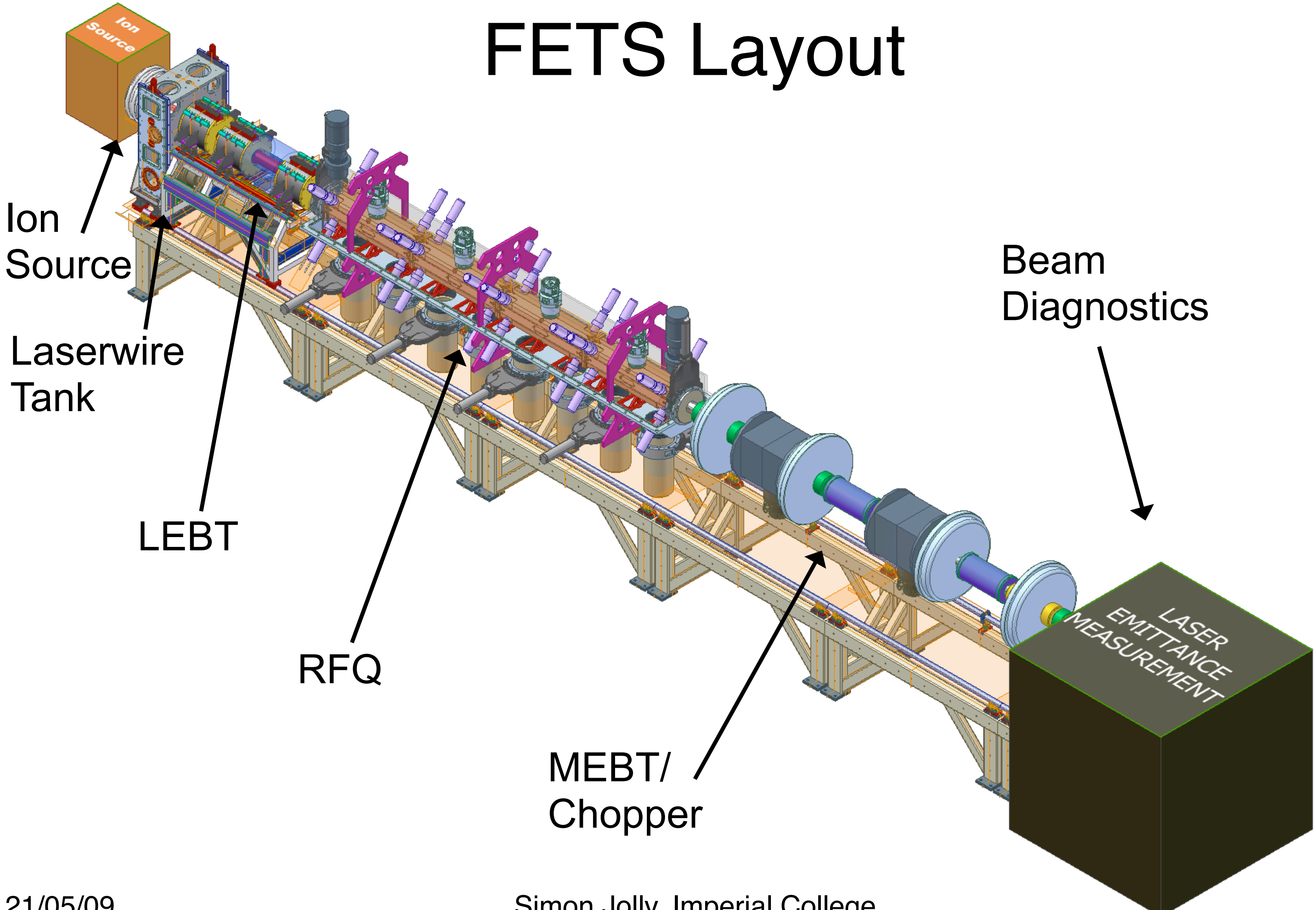
18 kV Post Acceleration Voltage

Beam Current Variation with Extraction Voltage





FETS Layout


Ion Source
Ion Source
Laserwire Tank
LEBT
RFQ
MEBT/ Chopper
Beam Diagnostics
LASER EMITTANCE MEASUREMENT

Diagnostics (2)

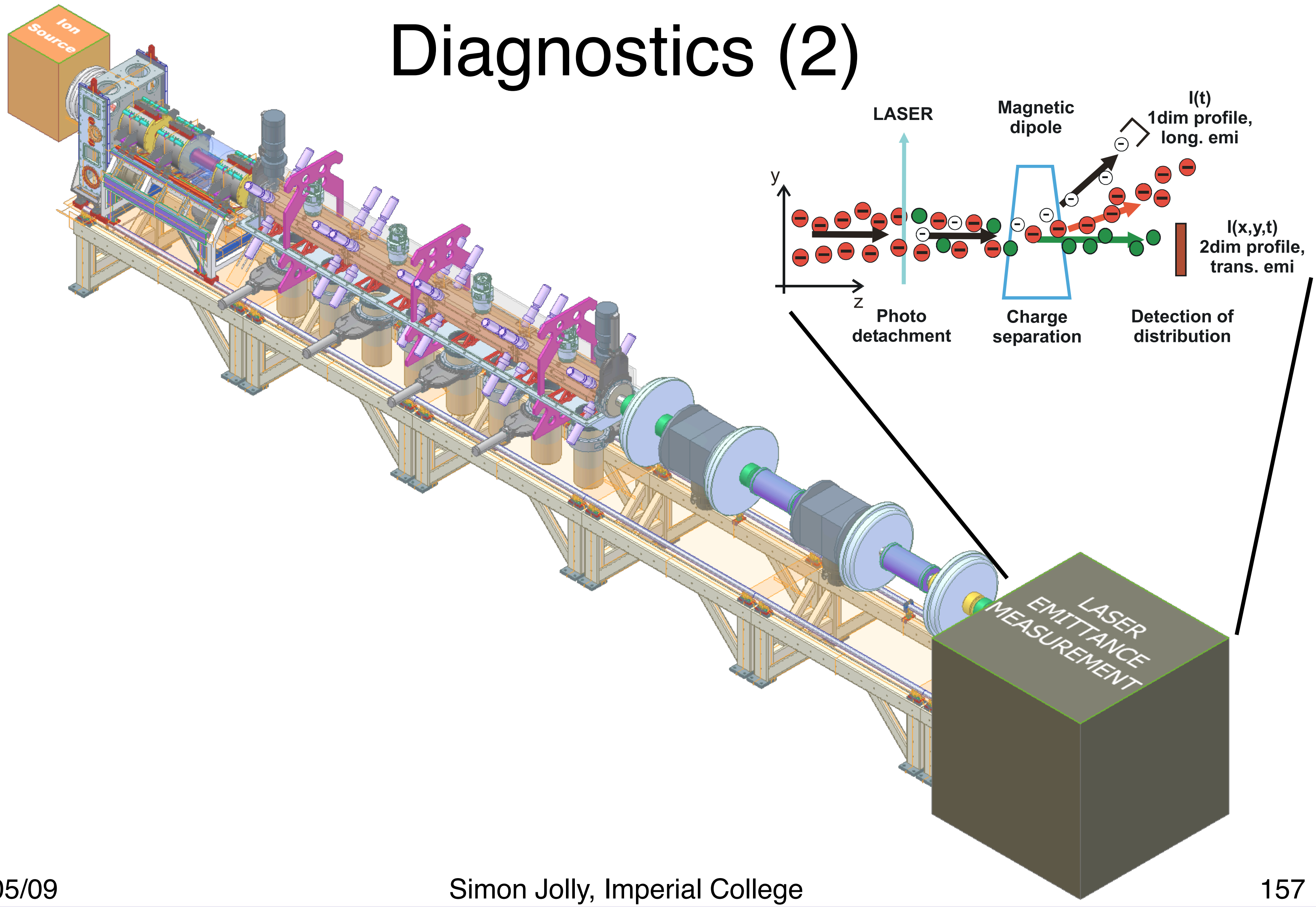
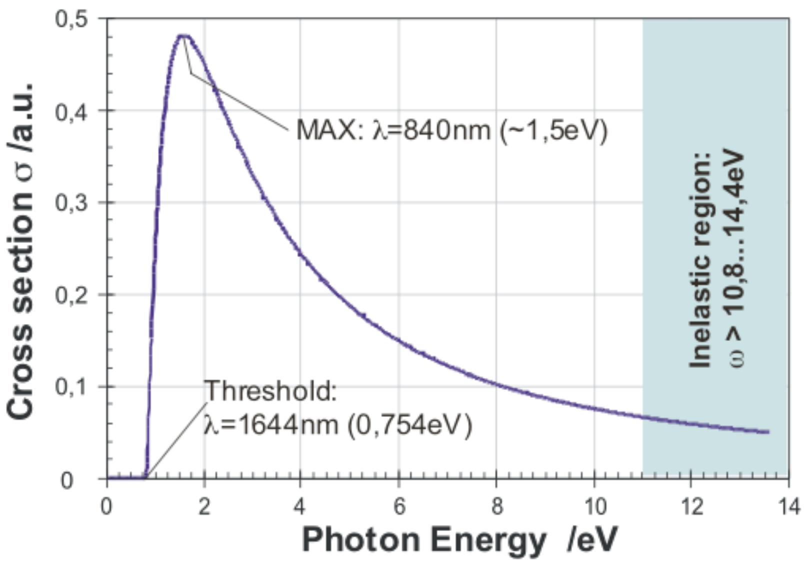
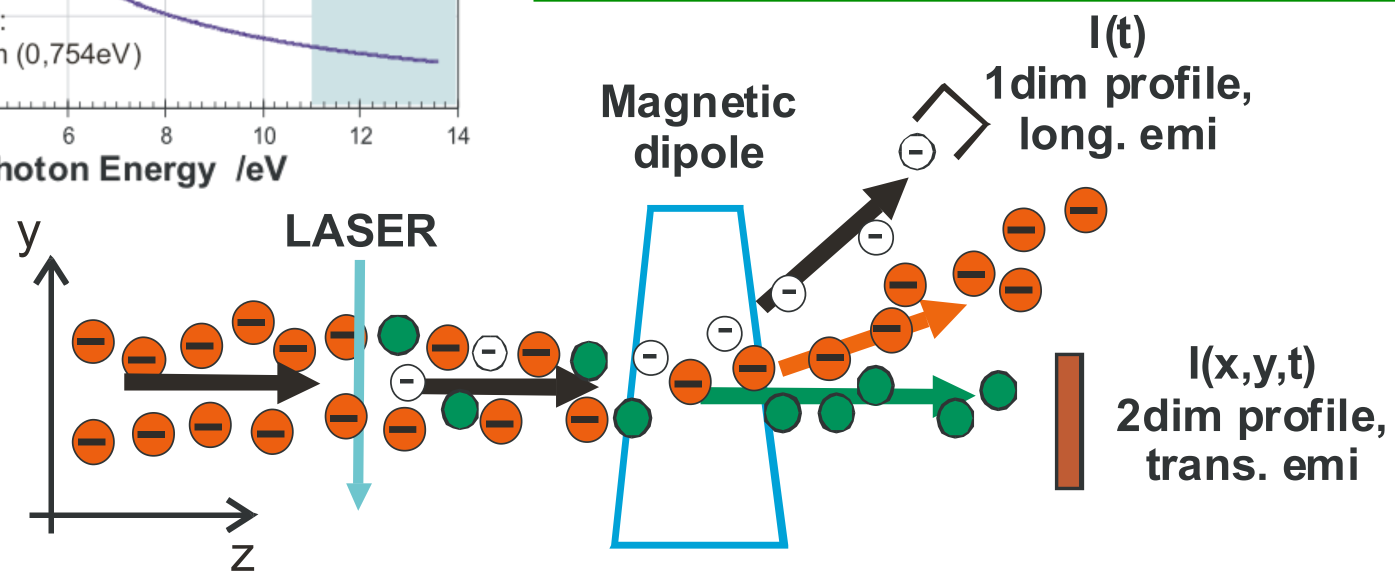


Photo Detachment for Beam Diagnostics

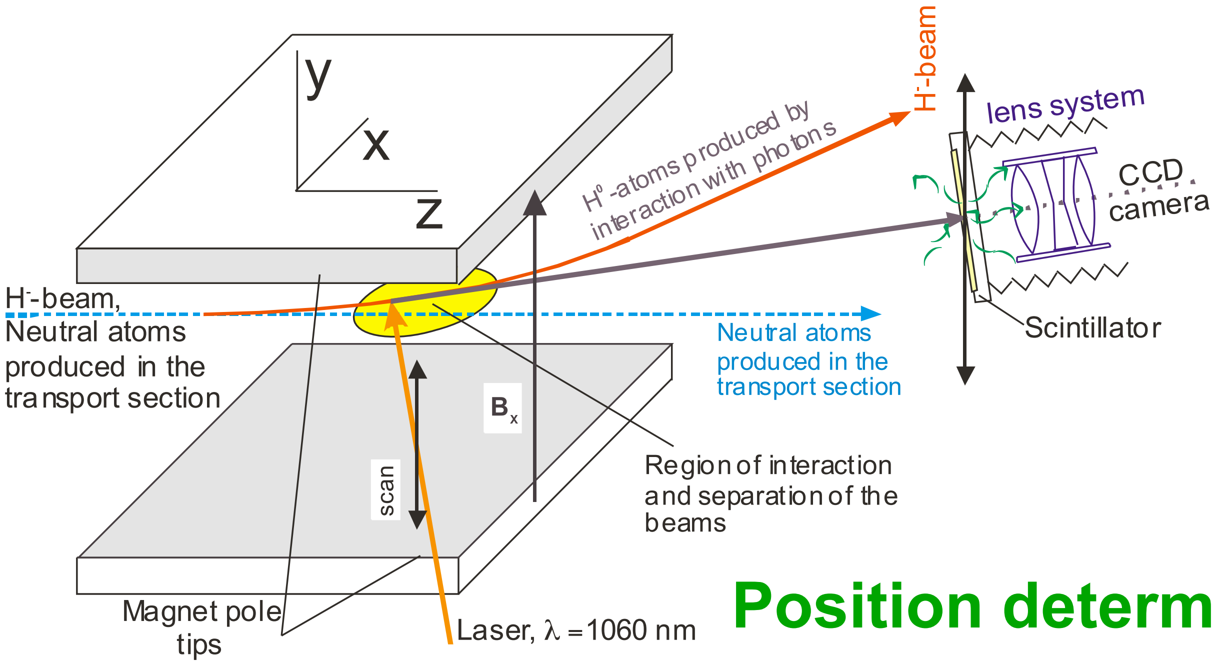


Photodetachment	"Threshold energy"
$\hbar\omega + H^- \longrightarrow H^o + e^-$	$E_D = 0.754$eV
$\sigma_{max} = 4.0 \times 10^{-17}$ cm^2	Maximum $E_{photon} = 2E_D$

H^0: no significant momentum transfer



Transverse Emittance Measurement



Angle determination

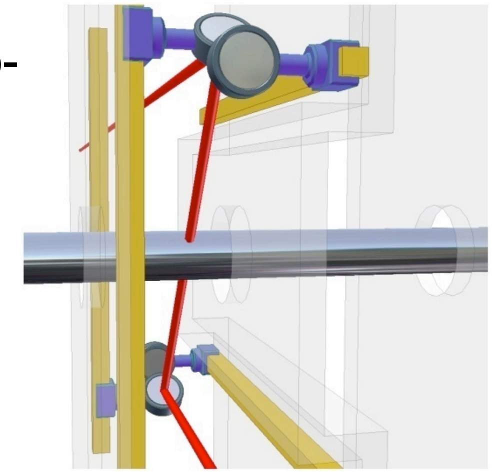
Position determination

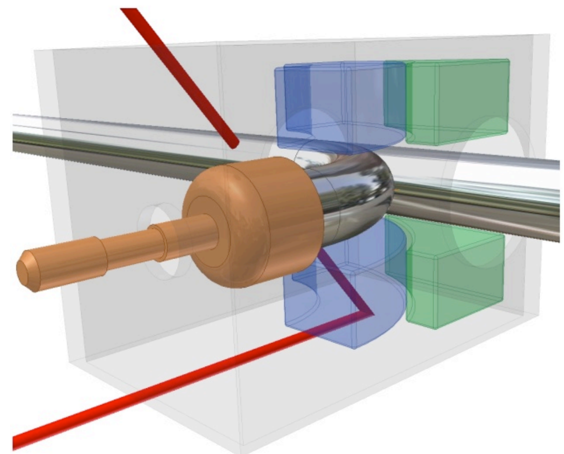
- ~ non-destructive, i.e. no mechanical parts inside the ion beam
- ~ good signal to noise ratio due to distinction between “PD-neutrals”/ “RGI-neutrals”
- ~ compared with a slit-slit emittance measurement the 1st slit is replaced by a laser, 2nd slit is replaced by a scintillator with CCD-camera
  ➔ slit-point transfer function offers more information (phase space distribution)
- ~ in terms of transfer function “proof of principle” experiment showed good agreement between simulation and measurements

Laserwire Beam Profile Measurement

- Non-destructive, non-invasive measurement of the X-Y beam profile.
- Integrated into vacuum vessel after ion source.
- Movable mirrors in the vacuum vessel enable many profiles to be measured.
- Reconstruction of the 2D density distribution will be possible.

Laser photo-dissociation





Electron collection with Faraday Cup

Laser-based H^- Diagnostics

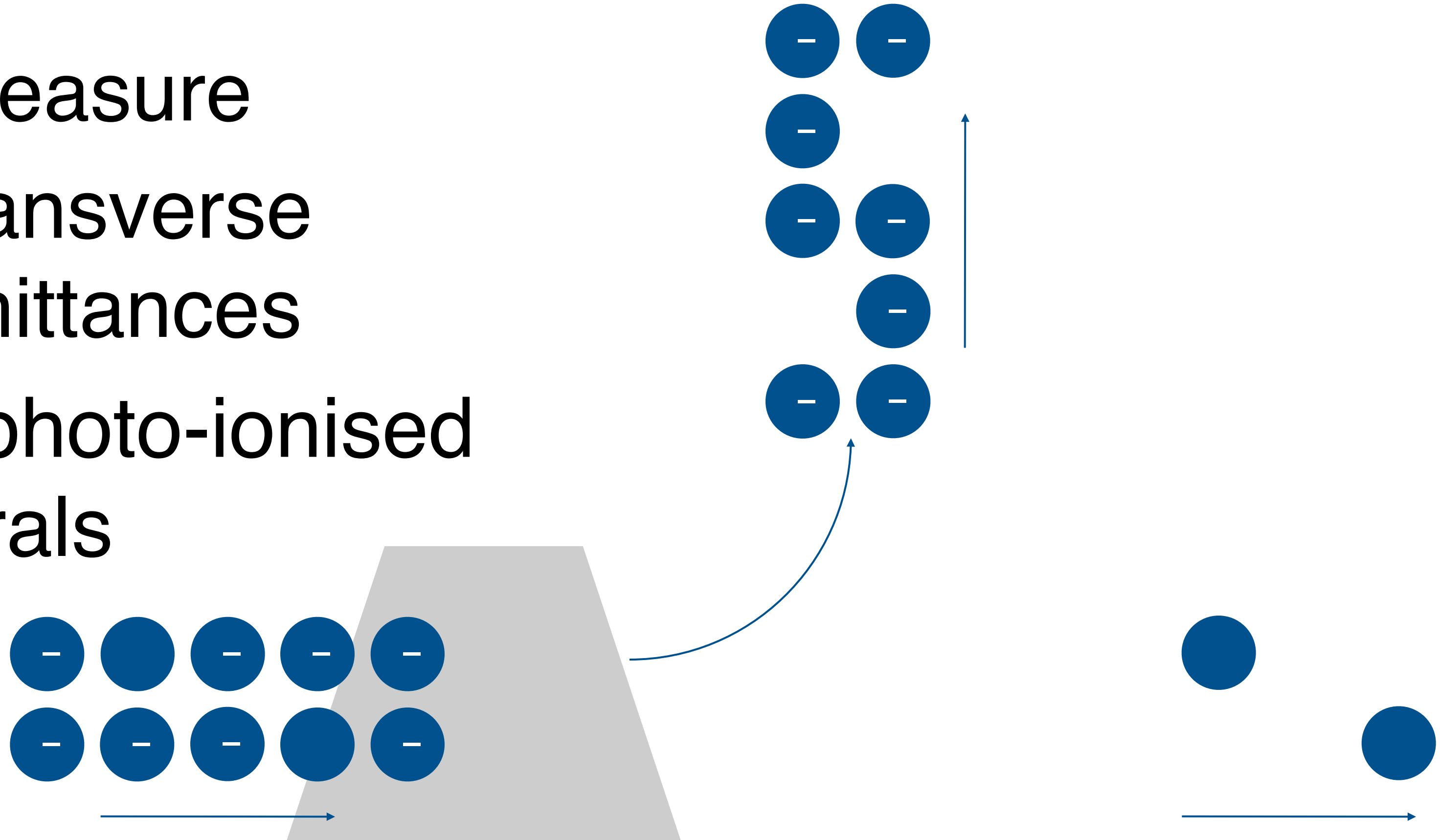
- To measure
  - Transverse emittances

use photo-ionised neutrals

Laser-based H^- Diagnostics

- To measure
  - Transverse emittances

use photo-ionised neutrals

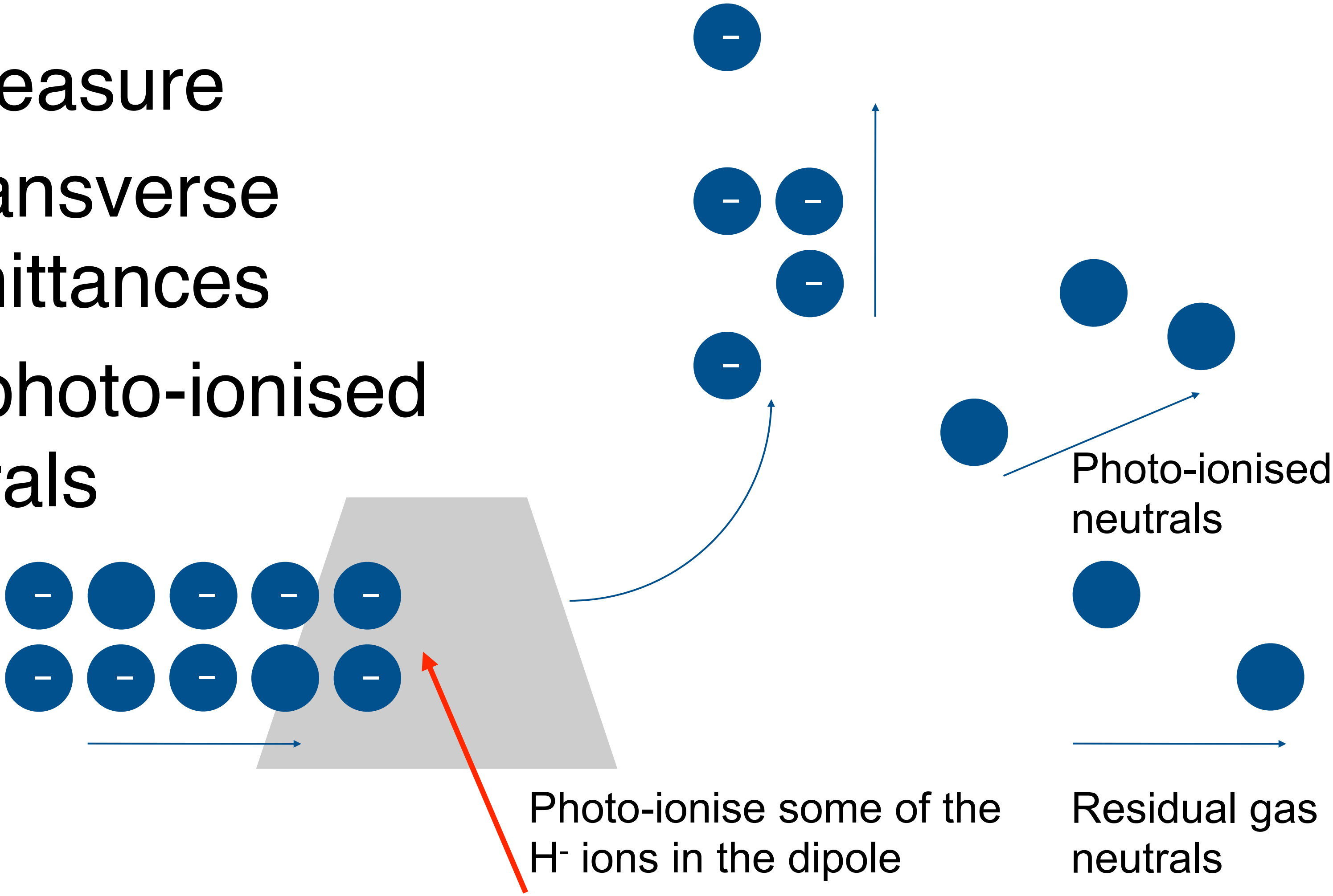


Use a dipole to separate out the particles neutralised by residual gas interactions

Laser-based H⁻ Diagnostics

- To measure
  - Transverse emittances

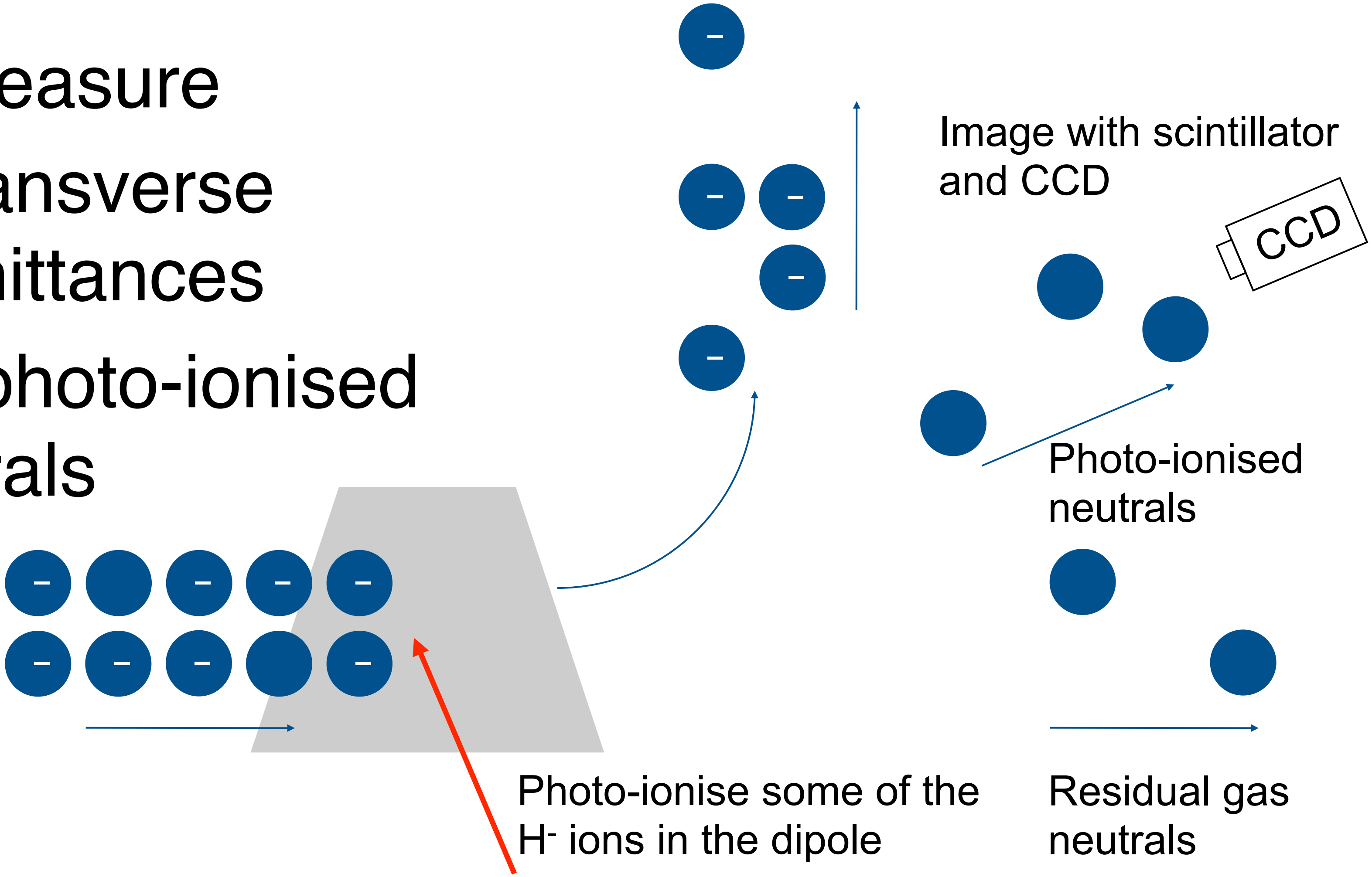
use photo-ionised neutrals



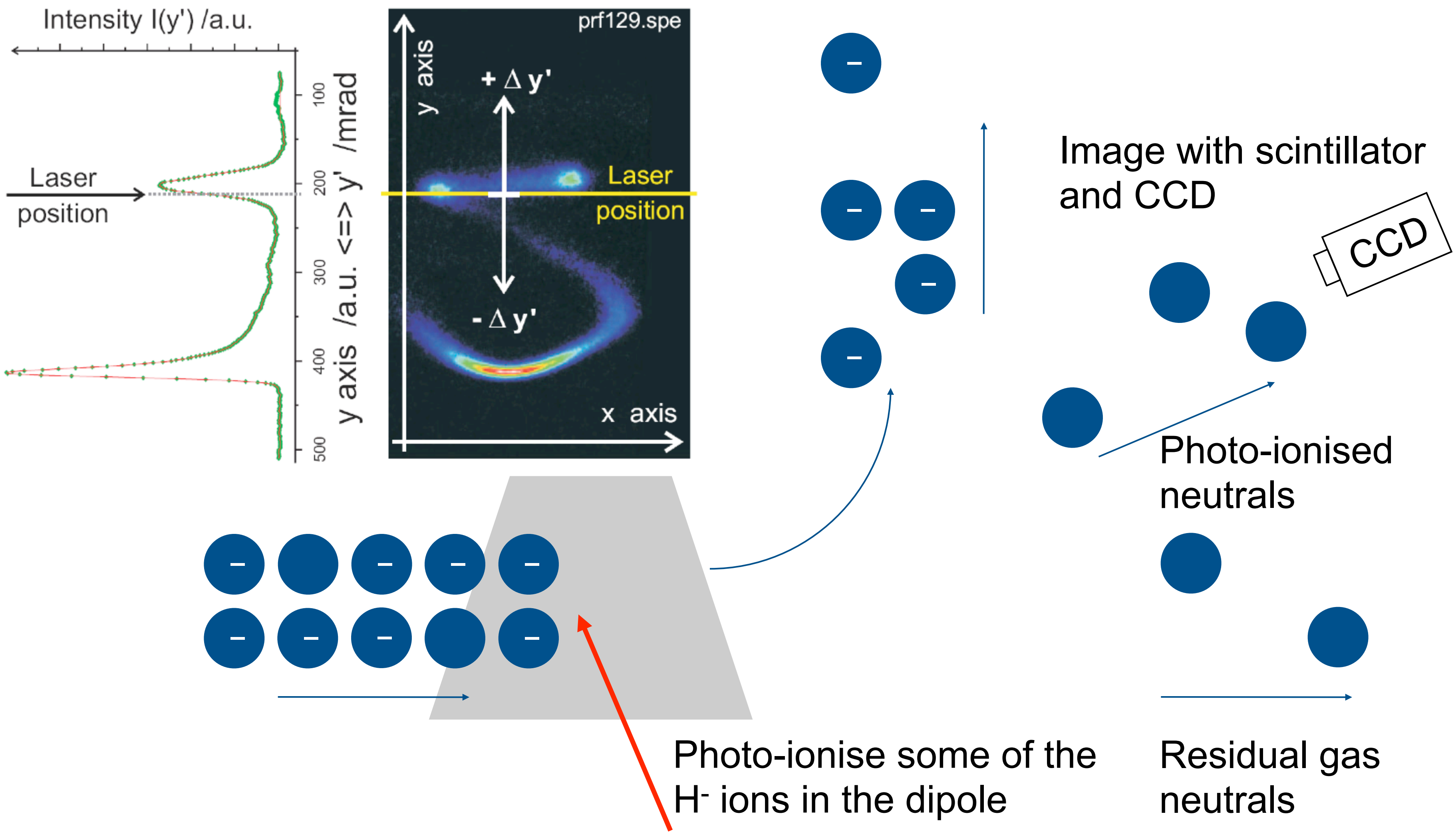
Laser-based H⁻ Diagnostics

- To measure
  - Transverse emittances

use photo-ionised neutrals

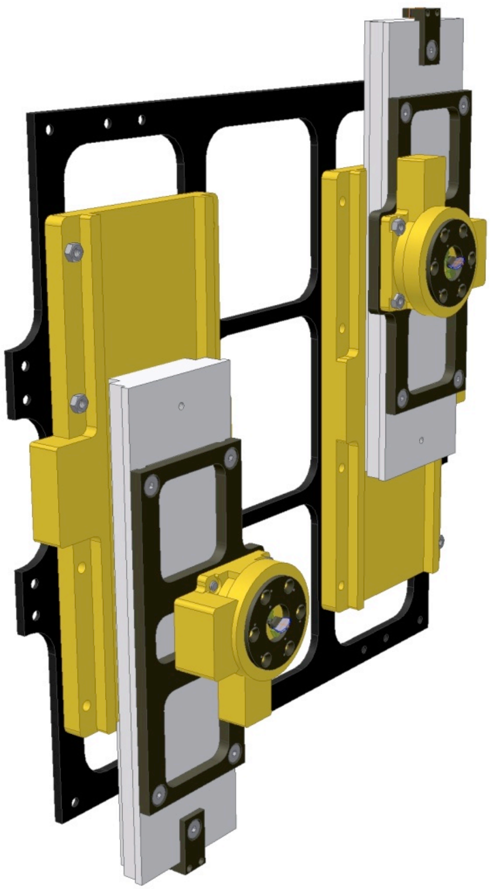


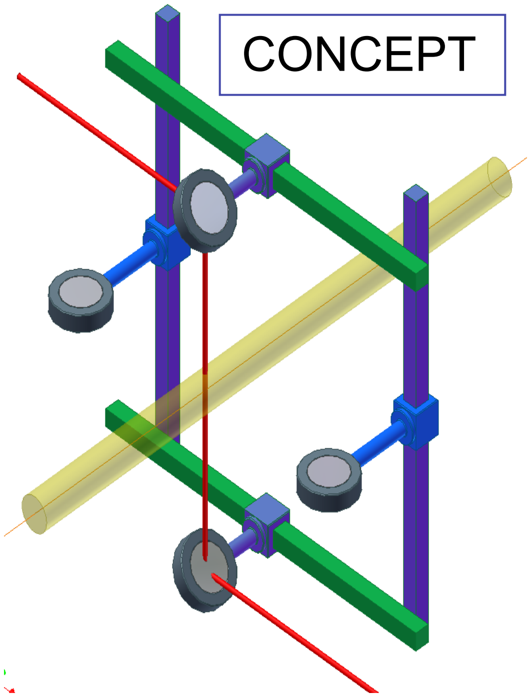
Laser-based H^- Diagnostics



Beam Profile Measurement System

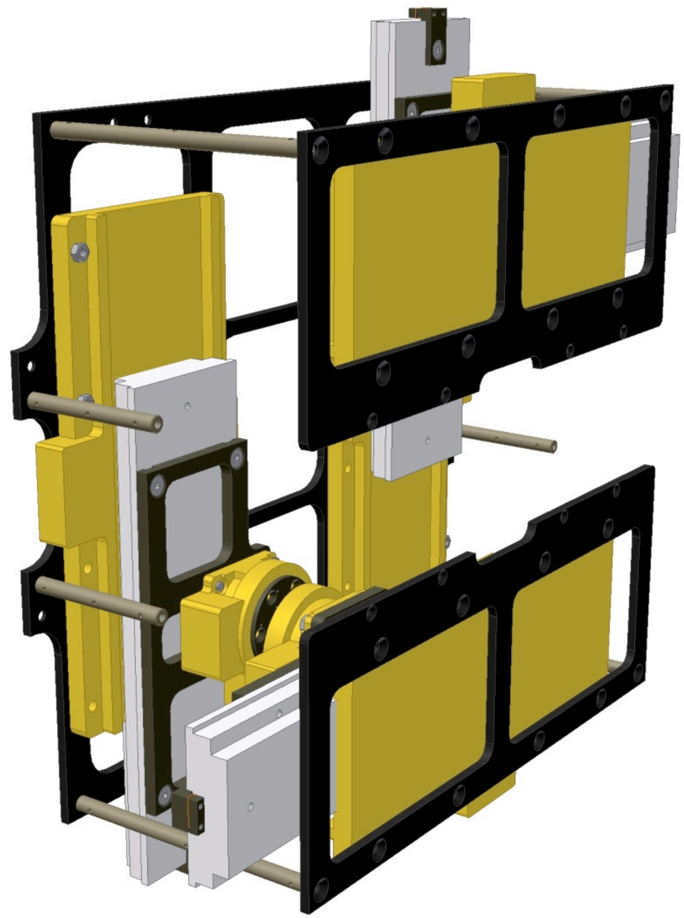
2 linear drives, each with an attached rotary drive mounted to a back plate in the vertical position.

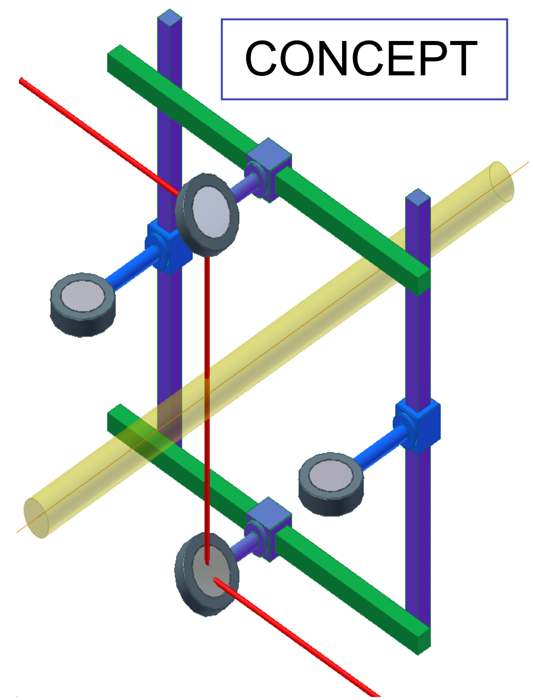




Beam Profile Measurement System

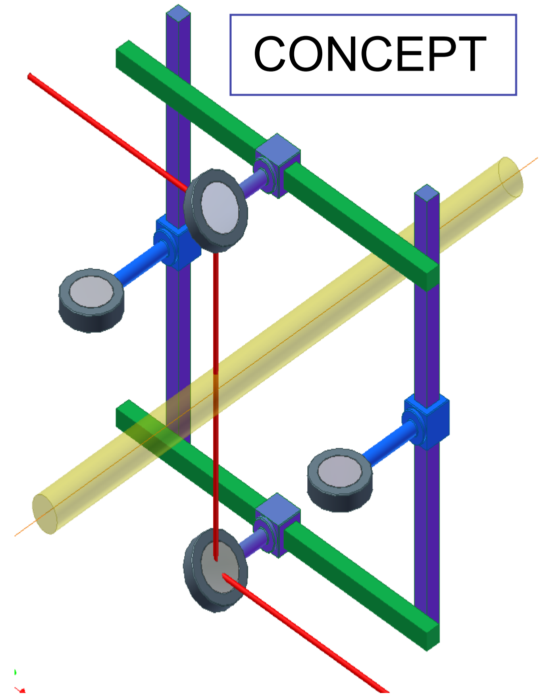
Now the horizontal linear / rotary drive pairs have been added to the motor chassis





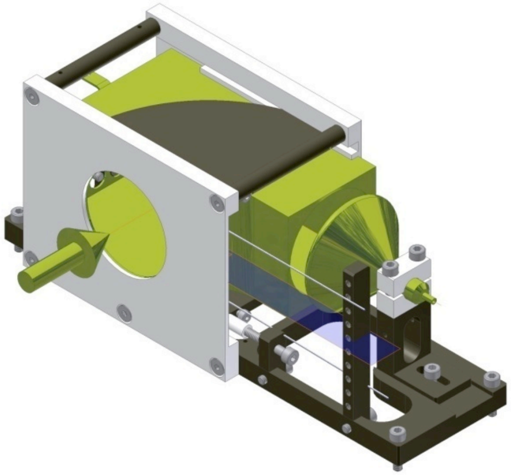
Beam Profile Measurement System

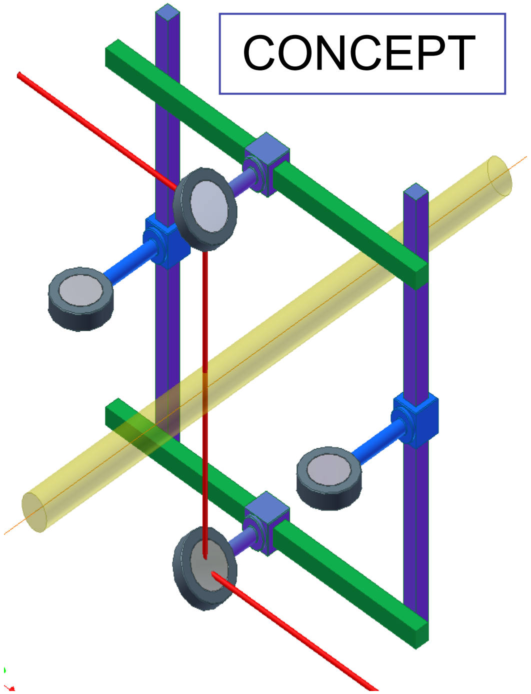
A tunnel has been placed between the horizontal drives, this volume will be pumped separately from the main vessel and will contain diagnostics.



Beam Profile Measurement System

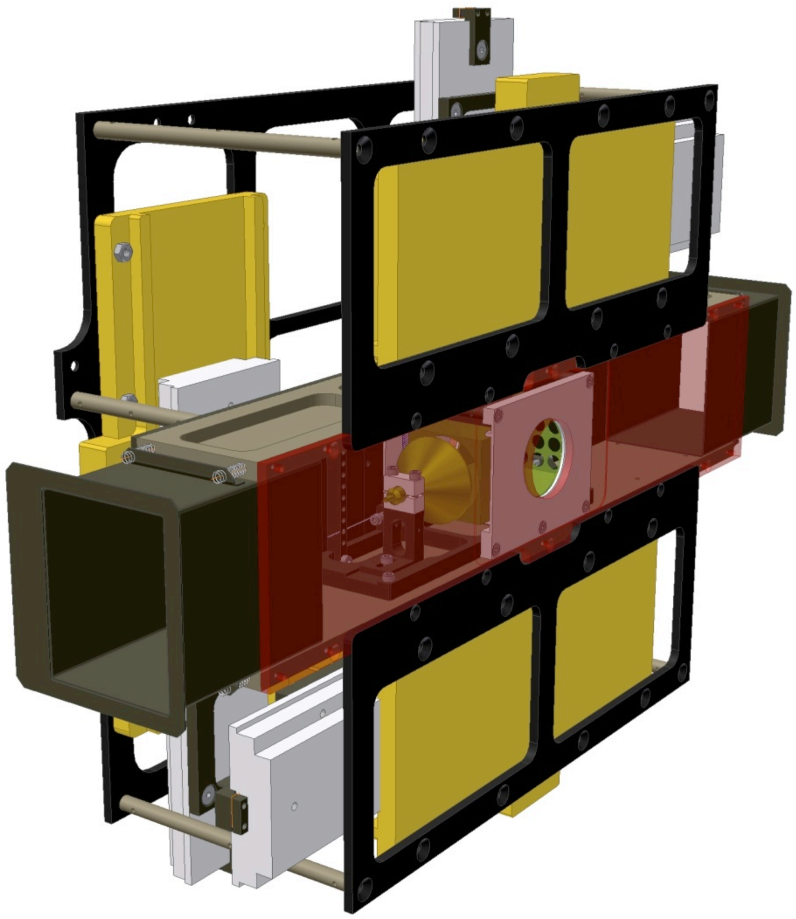
The detector has been added to the differentially pumped tunnel.

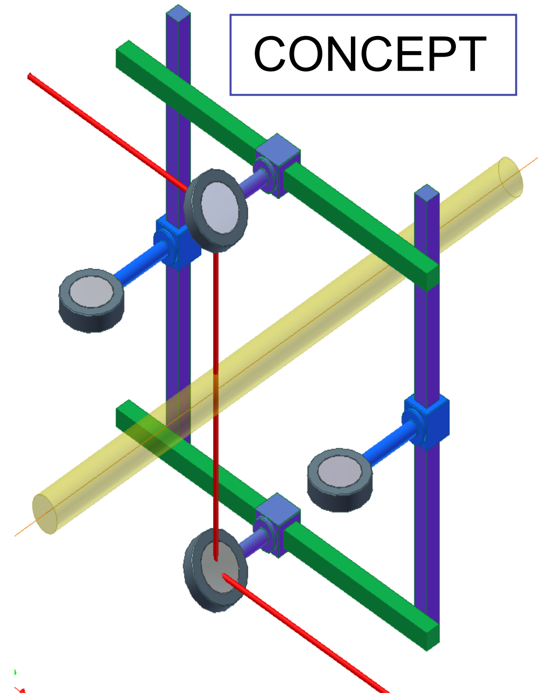




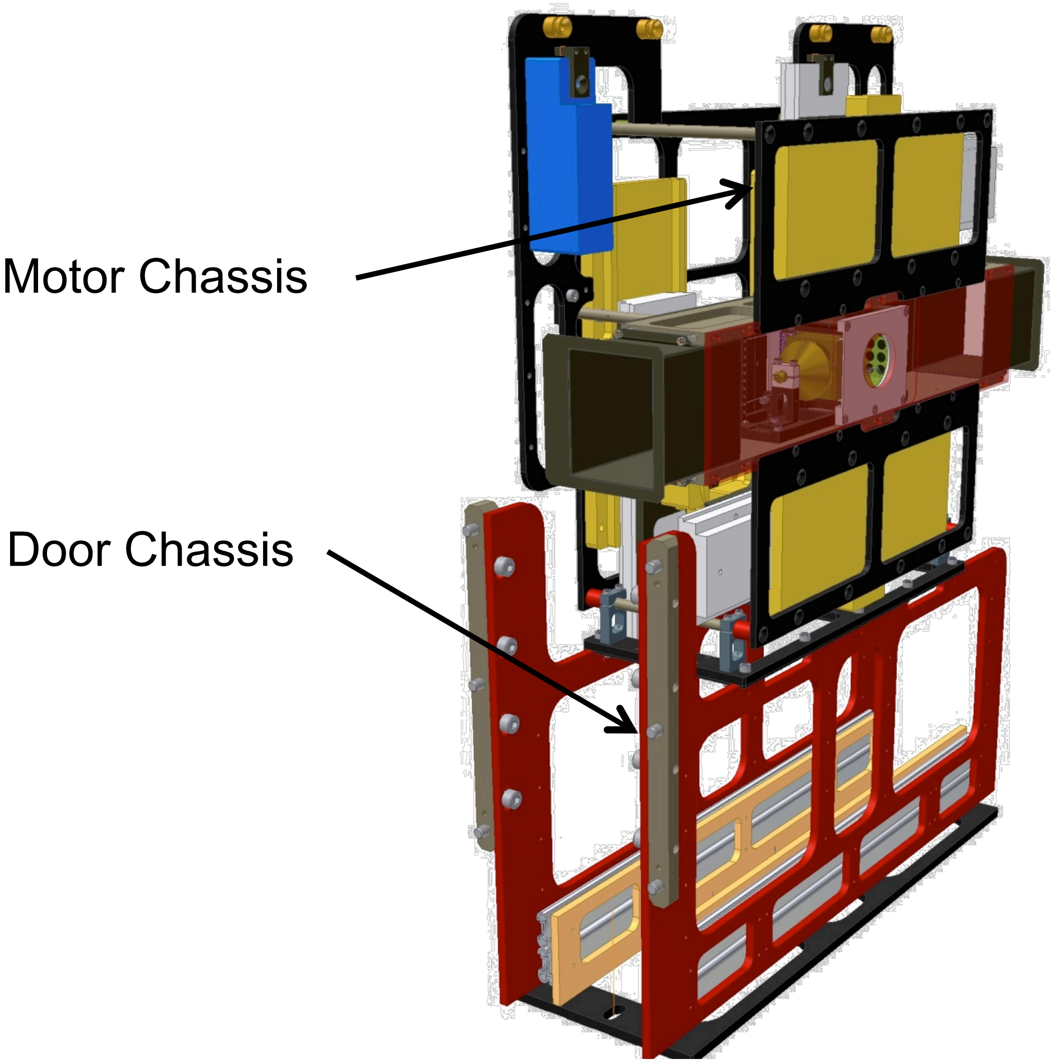
Beam Profile Measurement System

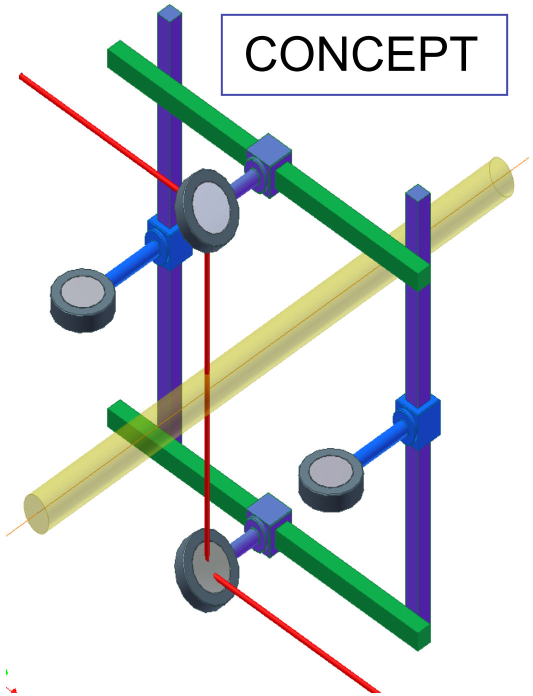
... And the tunnel has been closed and extended with sprung ends to mate with the internal faces of the containing vessel.



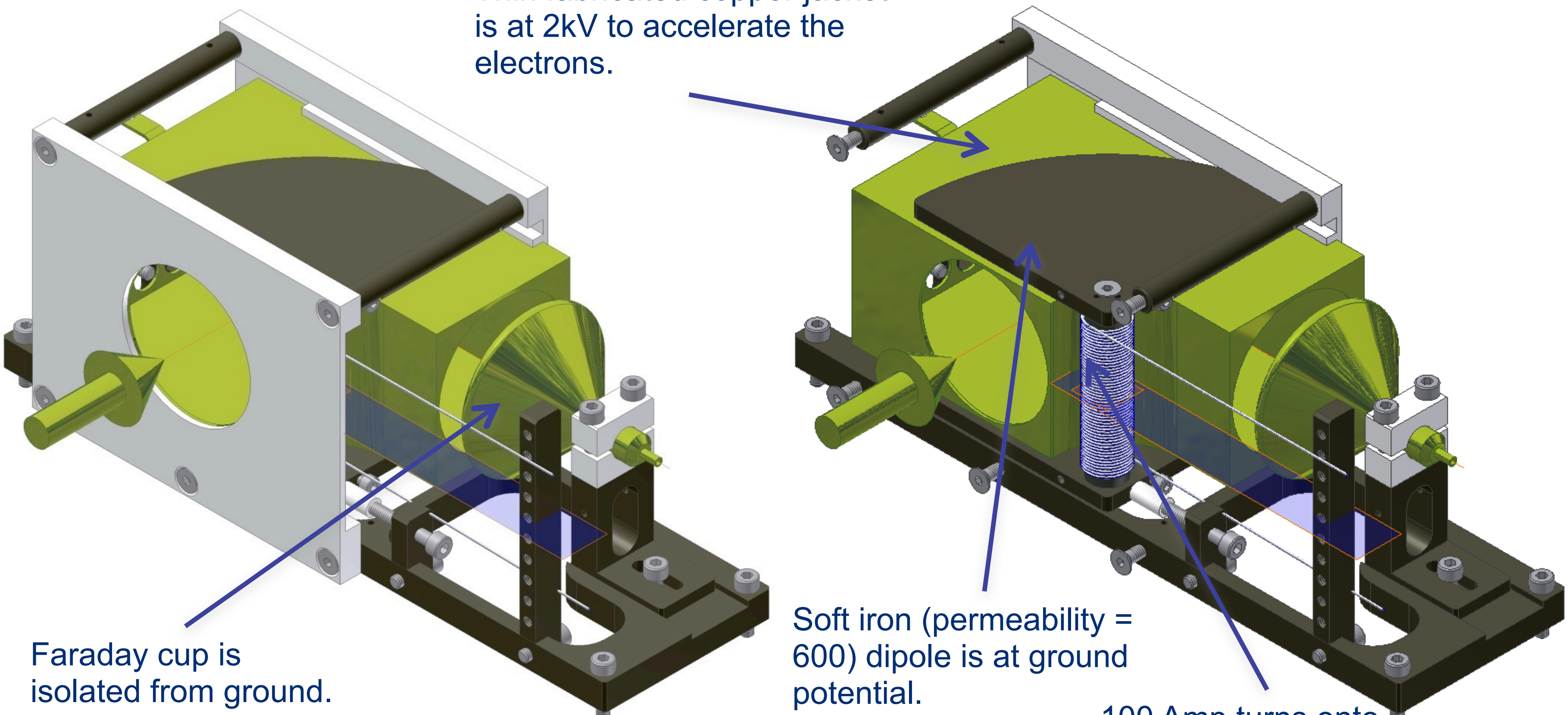


Beam Profile Measurement System





Beam Profile Measurement System



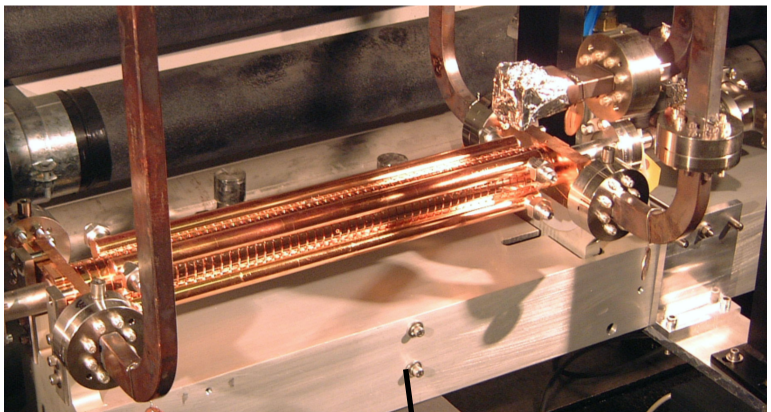
Thin fabricated copper jacket is at 2kV to accelerate the electrons.

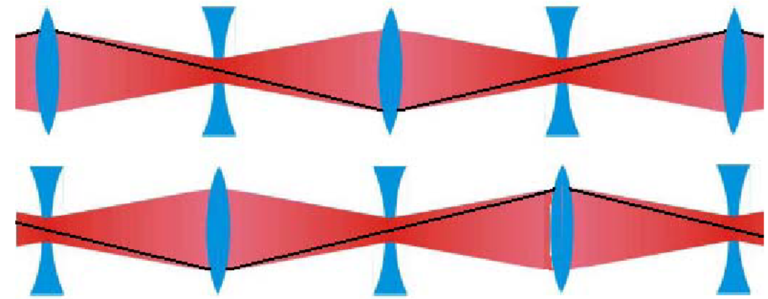
Faraday cup is isolated from ground.

Soft iron (permeability = 600) dipole is at ground potential.

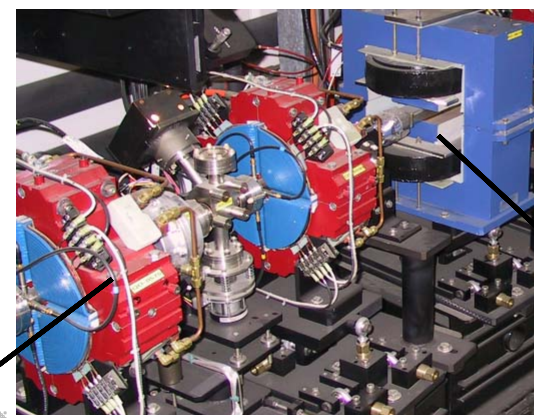
100 Amp turns onto soft iron yoke.

The FODO Lattice

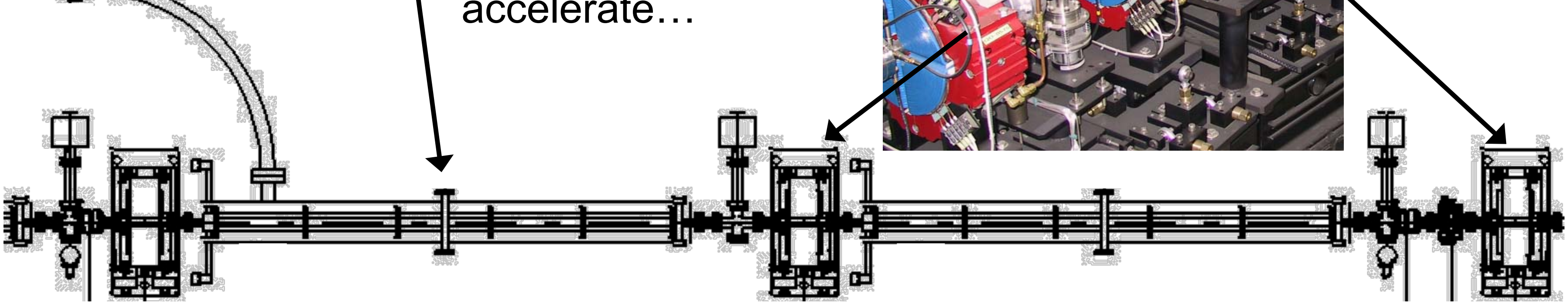




…magnets to focus/bend

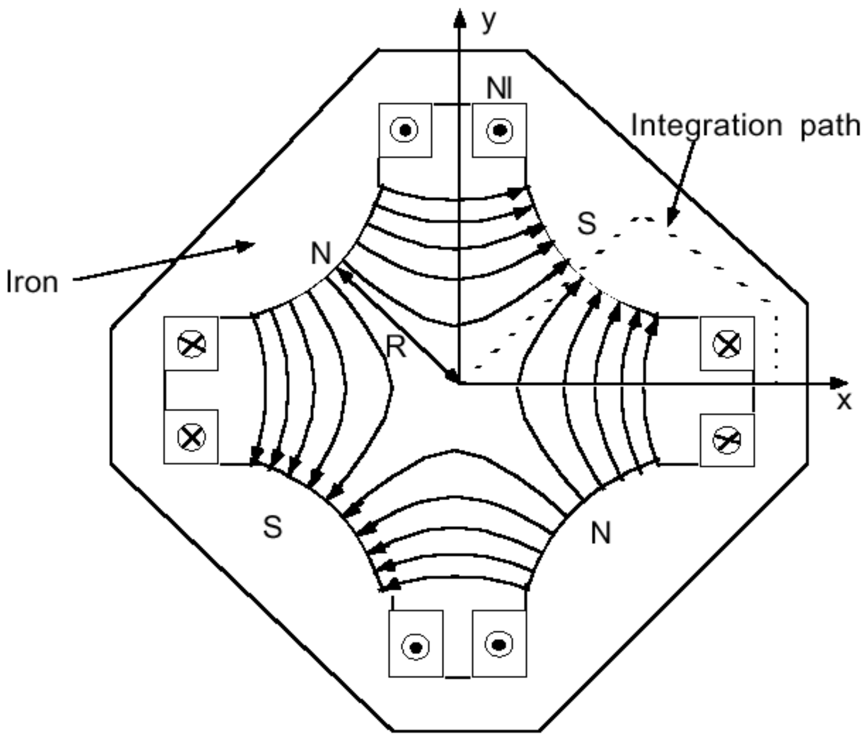


Cavities to accelerate…

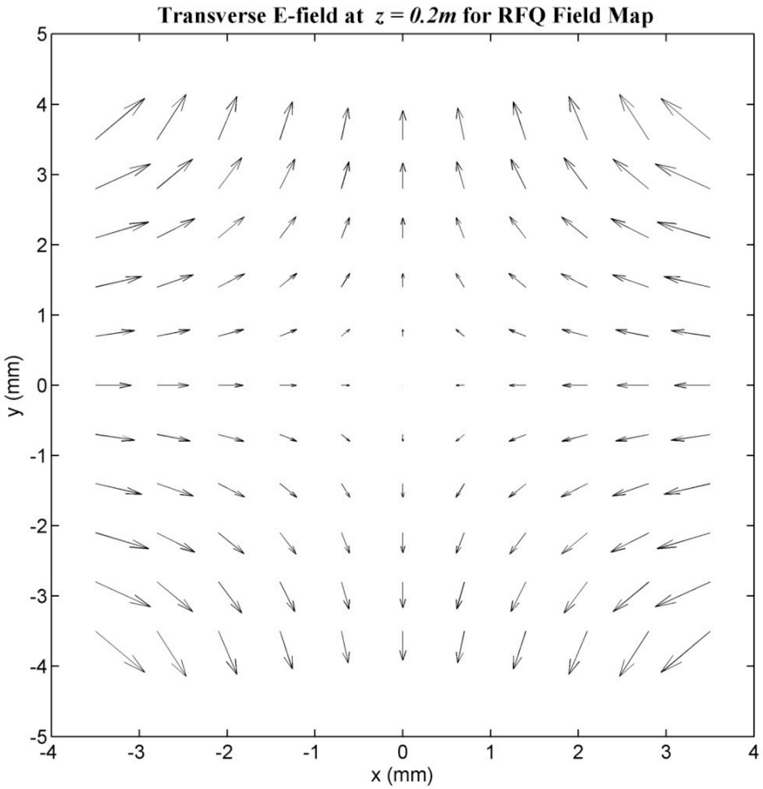


RFQ Transverse Focussing

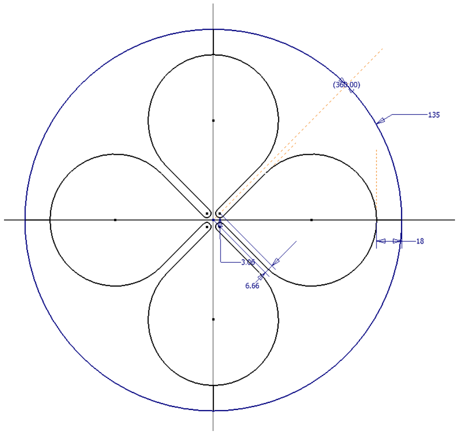
Standard Quad



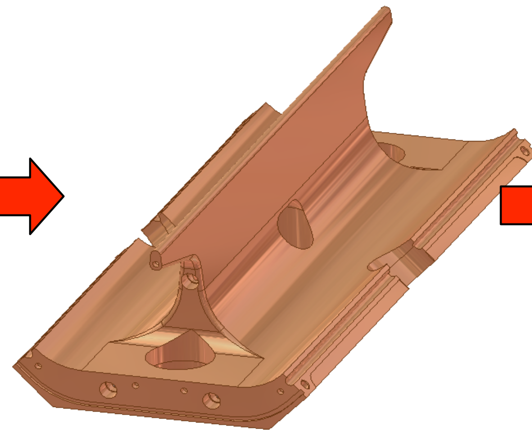
RFQ Transverse Field Map



RFQ Development

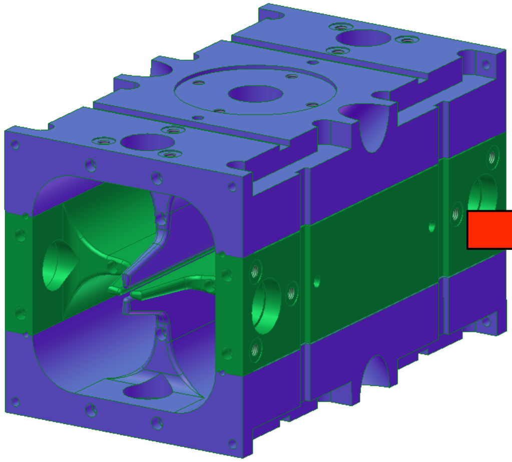


Physics design

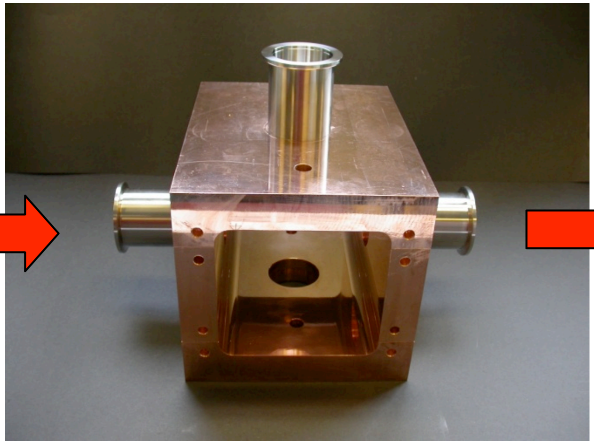


1st Engineering design

Manufacturing test



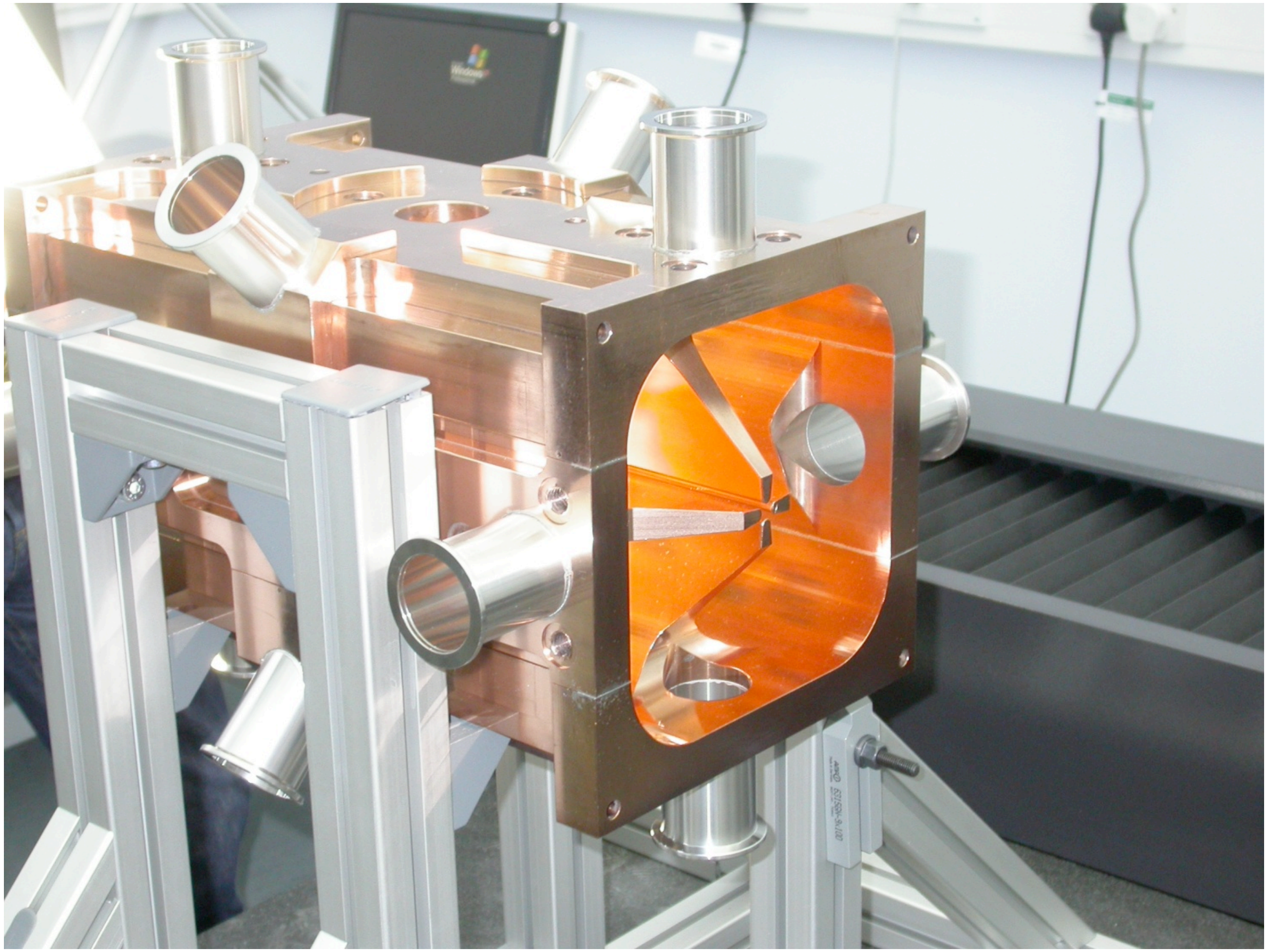
2nd Engineering design



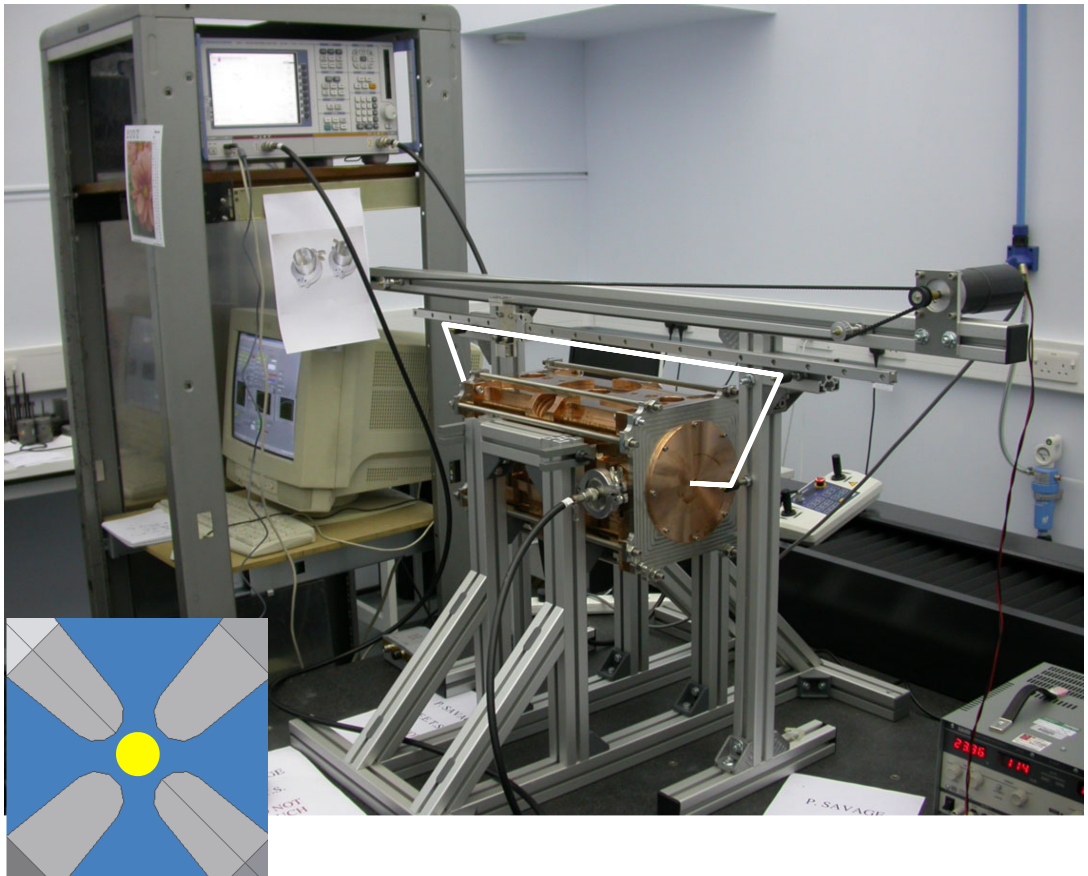
Brazing test

Manufactured RFQ sections

Brazed RFQ in Mounting Frame

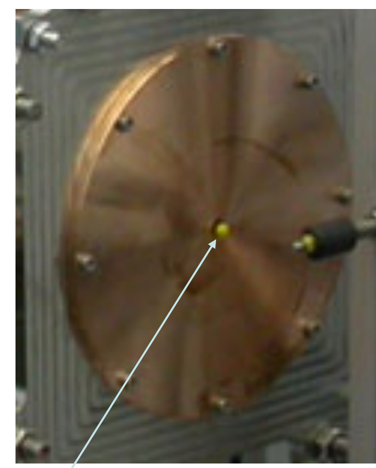


Bead-pull E-Field Measurements



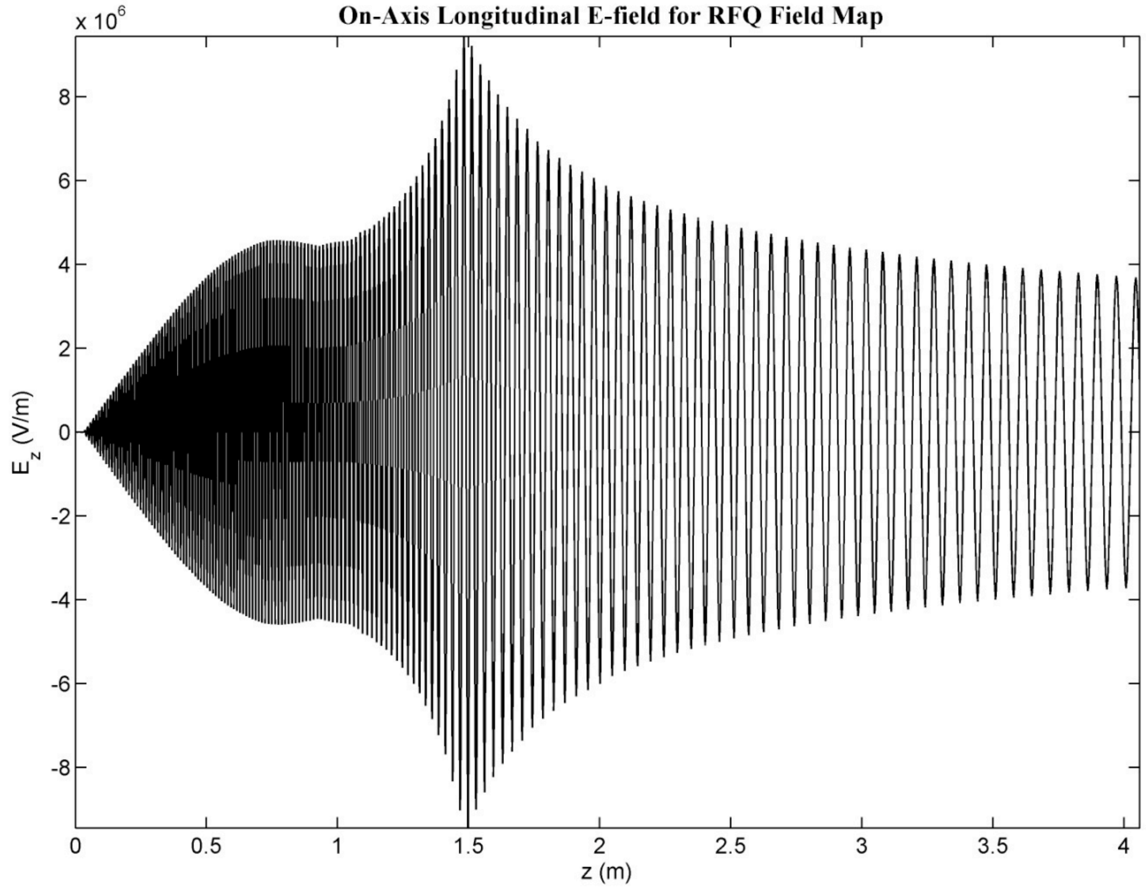
Bead causes perturbations in E-field: measure change in resonant frequency ω.

$$\frac{\Delta\omega}{\omega} \propto E^2$$

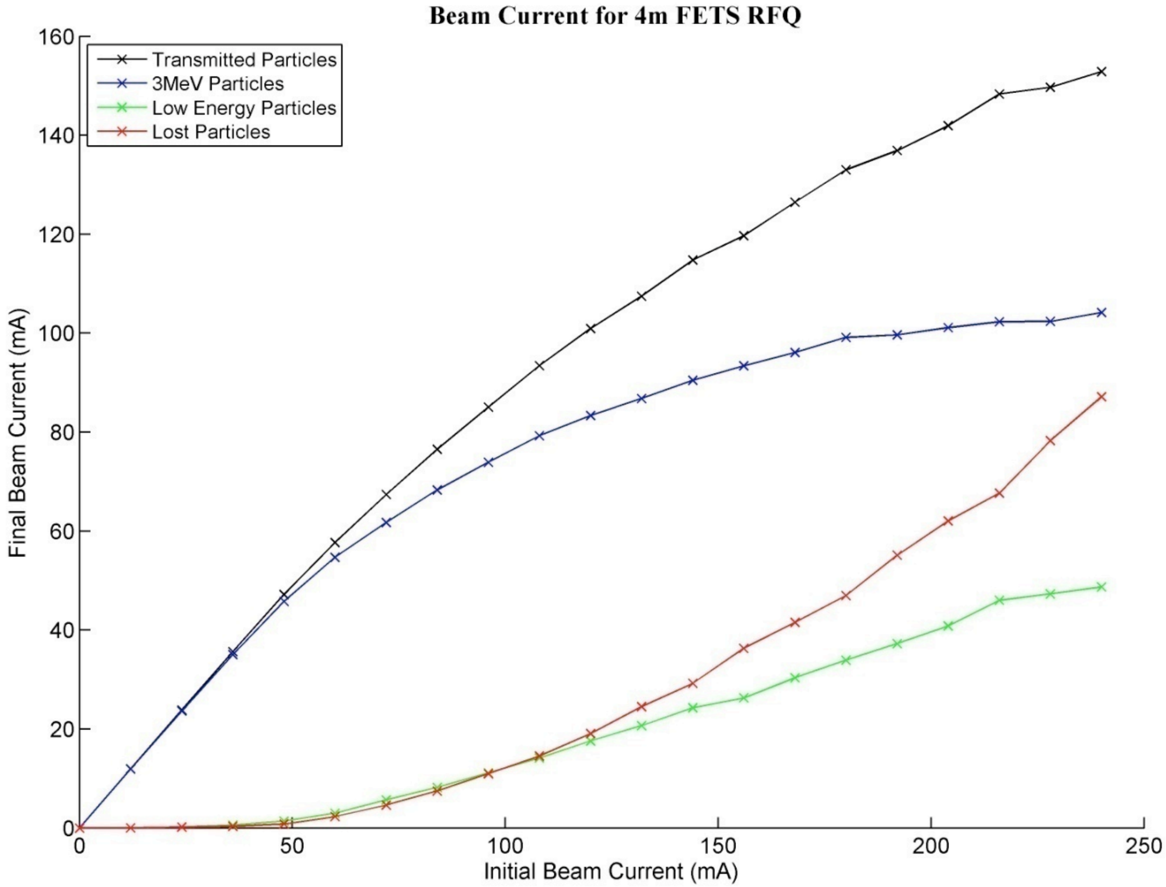


ø6mm dielectric bead

RFQ On-Axis Ez Field



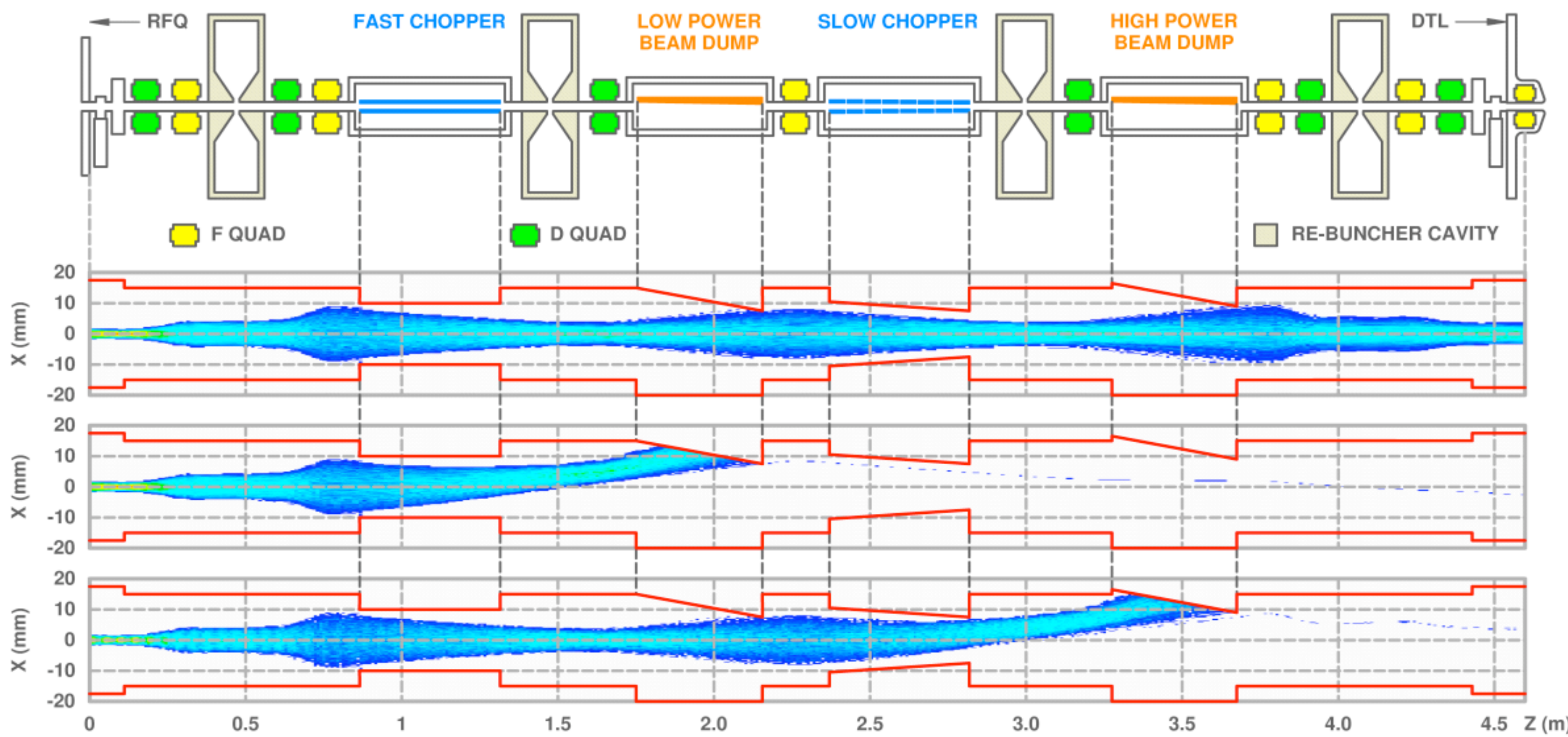
RFQ Transmitted Current



Fast Chopper Schemes (MCG)

Design	Project	Position	Type	Chopping	Status
RAL	ESS & FETS	MEBT	Slow-wave & Array	Uni-directional	Prototype
CERN	SPL	MEBT	Slow-wave	Uni-directional	Advanced prototype
LANL/LBNL	SNS	MEBT & LEBT	Slow-wave & Discrete	Uni & quad	Installed & tested
JAERI	JPARC	MEBT & LEBT	Cavity & Induction	Bi & Longitudinal	Installed & tested?
FNAL	'X'	MEBT	Slow-wave	Uni	Prototype

FETS Scheme A: GPT Trajectories



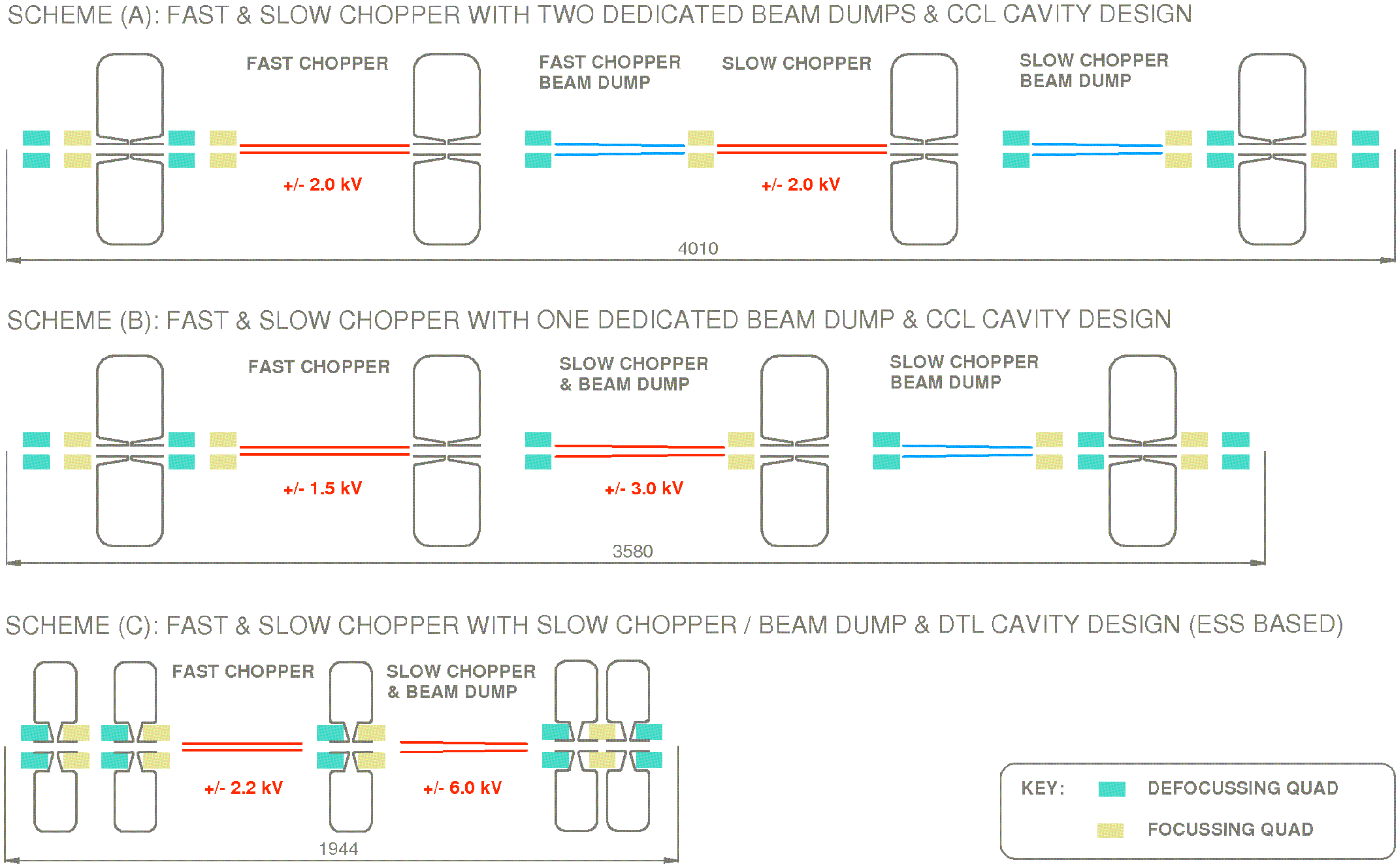
Voltages:
Chop 1: +/- 1.28 kV (20 mm gap)
Chop 2: +/- 1.42 kV (18 mm gap)

Losses:
0.1 % @ input to CH1, 0.3% on dump 1
0.1% on CH2, 0.3% on dump 2

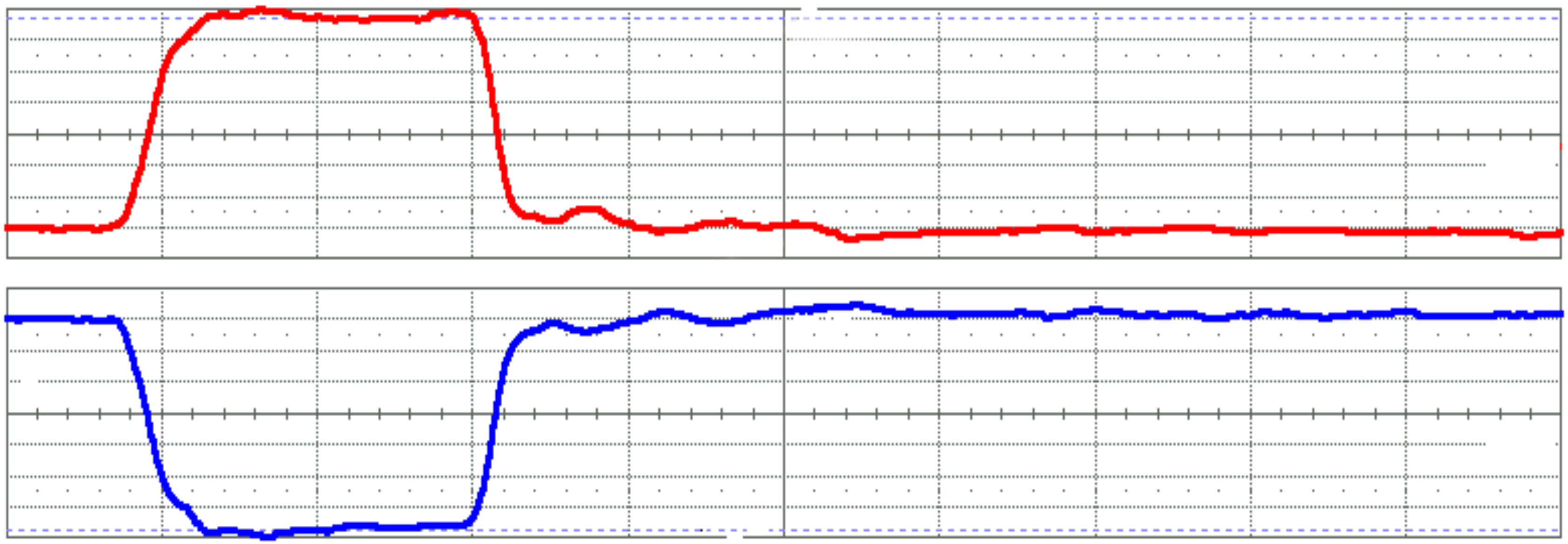
FETS Scheme A Chopper Paramaters

KEY PARAMETERS	SCHEME A
ION SPECIES	H-
ENERGY (MeV)	3.0
RF FREQUENCY (MHz)	324
BEAM CURRENT (mA)	40 - 60
NORMALISED RMS INPUT EMITTANCE IN X / Y / Z PLANES (π.mm.mr & π.deg.MeV)	0.25 / 0.25 / 0.18
RMS EMITTANCE GROWTH IN X / Y / Z PLANES (%)	6 / 13 / 2
CHOPPING FACTOR (%)	30 - 100
CHOPPING EFFICIENCY (%)	99.9
FAST CHOPPER PULSE: TRANSITION TIME / DURATION / PRF/ BURST DURATION / BRF	2 ns / 12 ns / 2.6 MHz / 0.3 – 2 ms / 50 Hz
FAST CHOPPER ELECTRODE EFFECTIVE LENGTH / GAPS (mm)	450 x 0.82 = 369 / 20
FAST CHOPPER POTENTIAL(kV)	± 1.3
SLOW CHOPPER PULSE: TRANSITION TIME / DURATION / PRF/ BURST DURATION / BRF	12 ns / 250 ns – 0.1 ms 1.3 MHz / 0.3 – 2 ms / 50 Hz
SLOW CHOPPER EFFECTIVE LENGTH / GAPS (mm)	450 x 0.85 / 18
SLOW CHOPPER POTENTIAL (kV)	± 1.5
POWER ON FAST / SLOW BEAM DUMPS (W)	150 / 850
OPTICAL DESIGN CODE(S)	IMPACT / TRACEWIN / GPT

Three chopper line optics designs are under investigation. A short line keeps the emittance growth low but makes chopping harder and requires some challenging technology. A long line is 'easier' but controlling the emittance is more challenging.

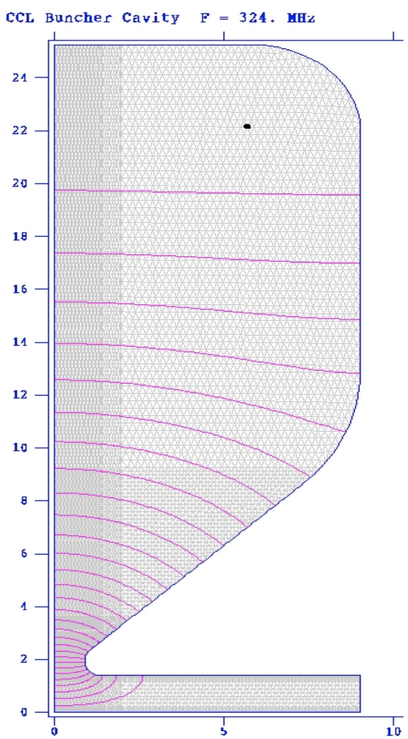


A state of the art fast switch developed for RAL has achieved ±1.4 kV with rise and fall times less than 2 ns.

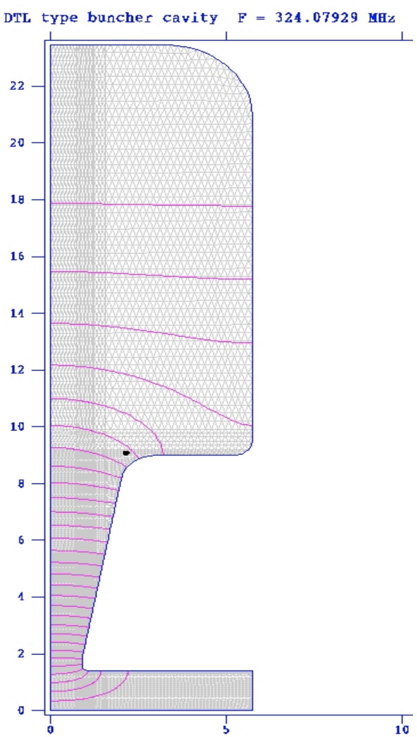


Measure	P1:rise(C2)	P2:fall(C2)
value	1.765 ns	1.119 ns
status	✓	✓

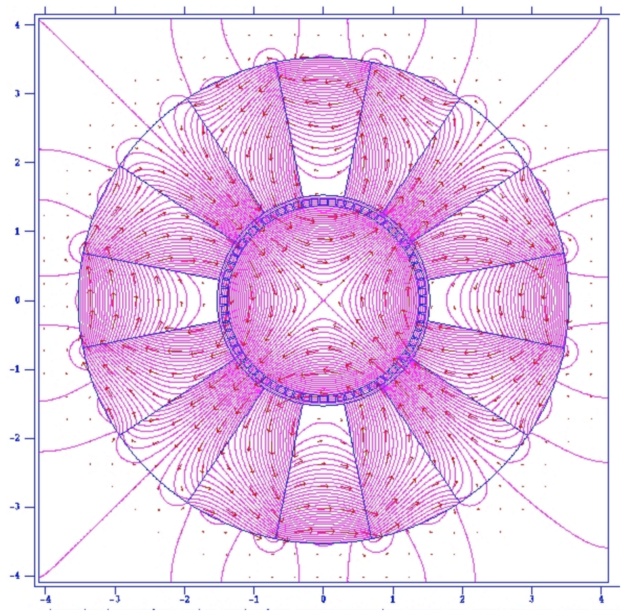
The shortest solution will require novel, compact, high gradient quadrupoles and DTL-like cavities.



CCL type cavity

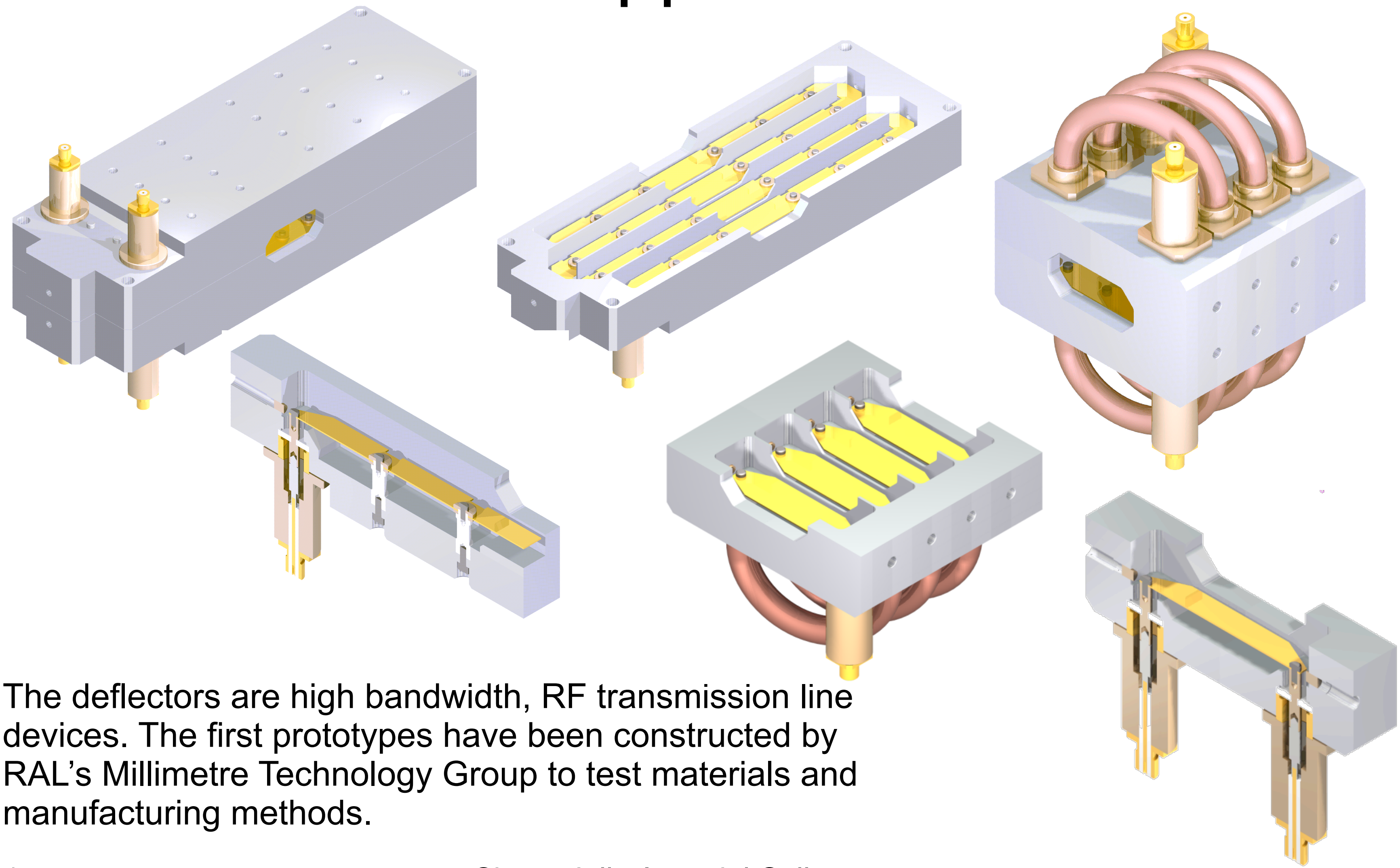


DTL type cavity



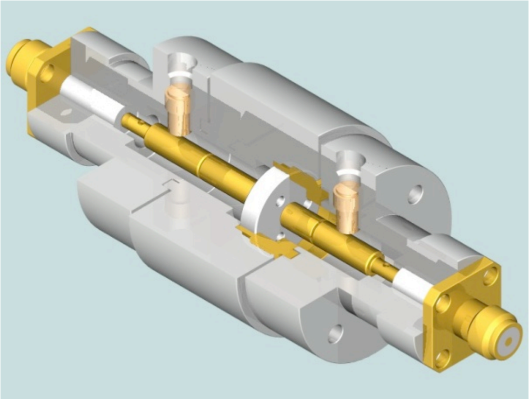
Hybrid PM and EM quads are being investigated.

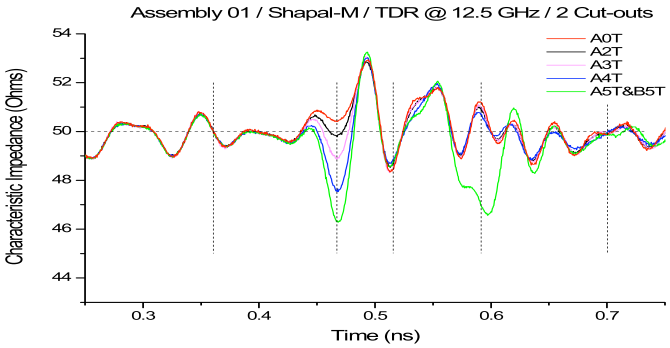
Beam Chopper & MEBT

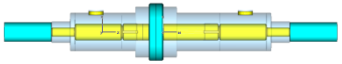


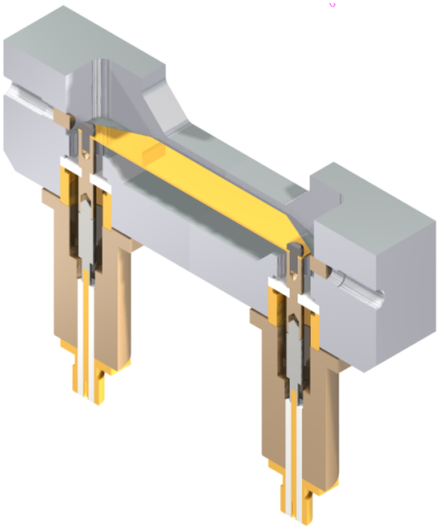
The deflectors are high bandwidth, RF transmission line devices. The first prototypes have been constructed by RAL's Millimetre Technology Group to test materials and manufacturing methods.

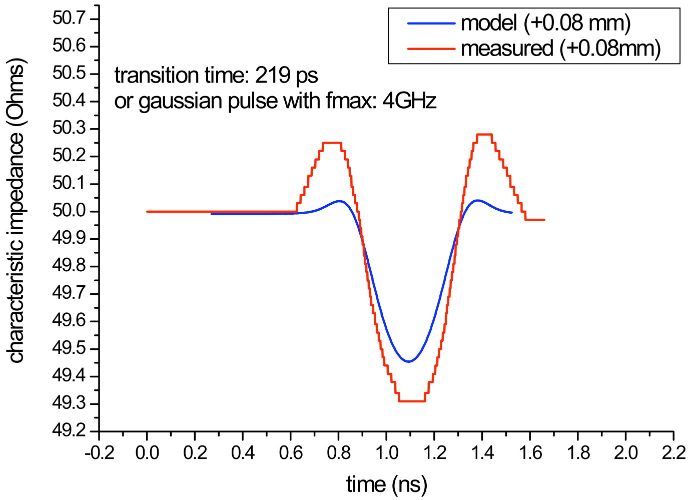
Beam Chopper & MEBT





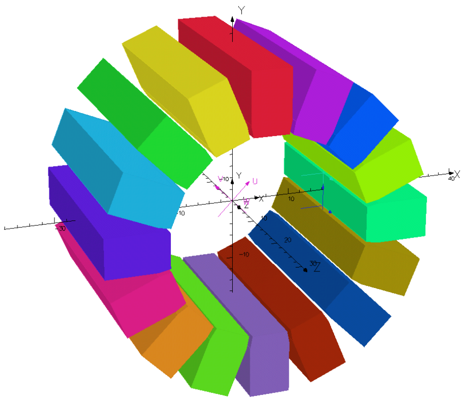


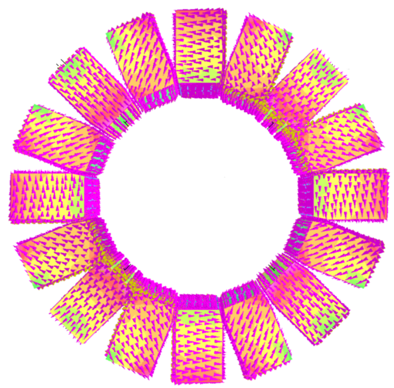


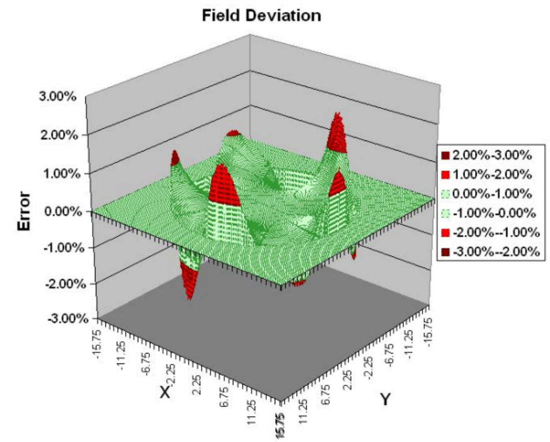


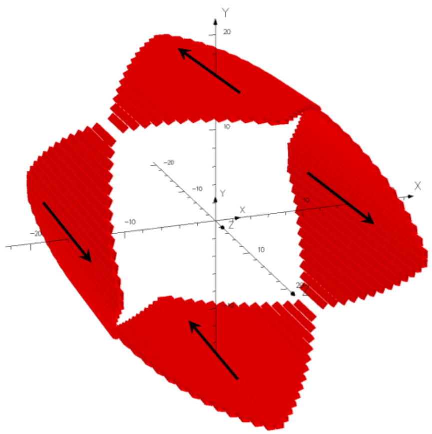
High speed time domain reflectometry is used to determine the characteristics of the first prototype assemblies.

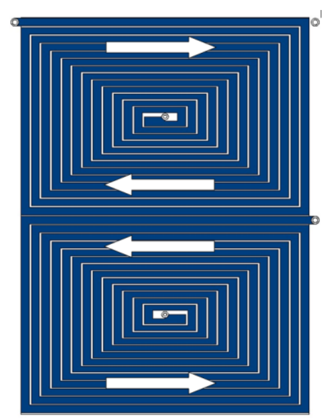
Beam Chopper & MEBT

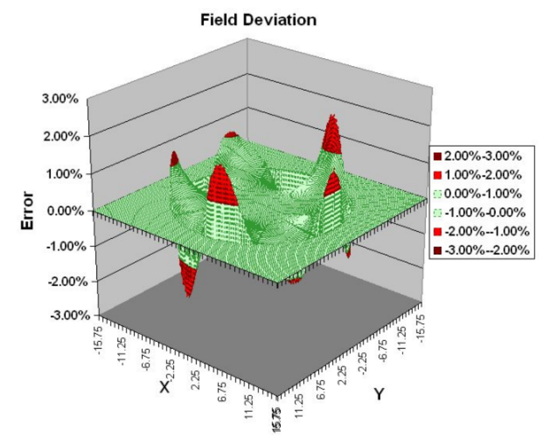












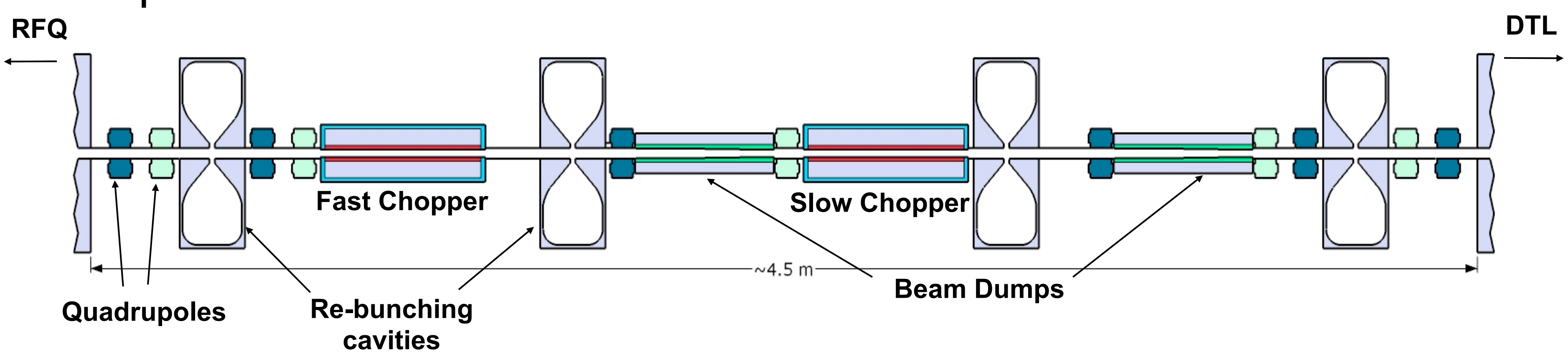
Compact hybrid electromagnetic-permanent magnet quadrupoles are being investigated for the MEBT. The first, SNS type PMQ prototype will be field mapped at Daresbury

MEBT Design Considerations

- The beam energy in the MEBT is sufficiently low for the space charge forces to have a considerable impact on the beam dynamics. In order to control the emittance growth, the lattice optics has to be regular and provide strong focussing. Transversally, the requirement is for regular betatron oscillations amplitudes as equal as possible in both planes. For a typical FODO cell, this is equivalent to having a zero current phase advance below 90° and it's achieved by choosing the right quadrupole gradients. A strong and uniform longitudinal focusing is also imposed, this being accomplished by adjusting the voltages in the re-bunching cavities.
- On the other hand, in order to minimise beam losses and induced radioactivity at injection into downstream circular accelerators, beam chopping at low energy is required. At RAL, a "fast-slow" novel chopping scheme will be employed creating the required gaps in the bunch train. The choppers, however, are large devices and long drift spaces will have to be reserved in the MEBT line.
- The MEBT design is especially challenging as it has to take into account the two conflicting requirements mentioned above: uniform focusing and long drift spaces without focusing elements, reserved for choppers and beam dumps.

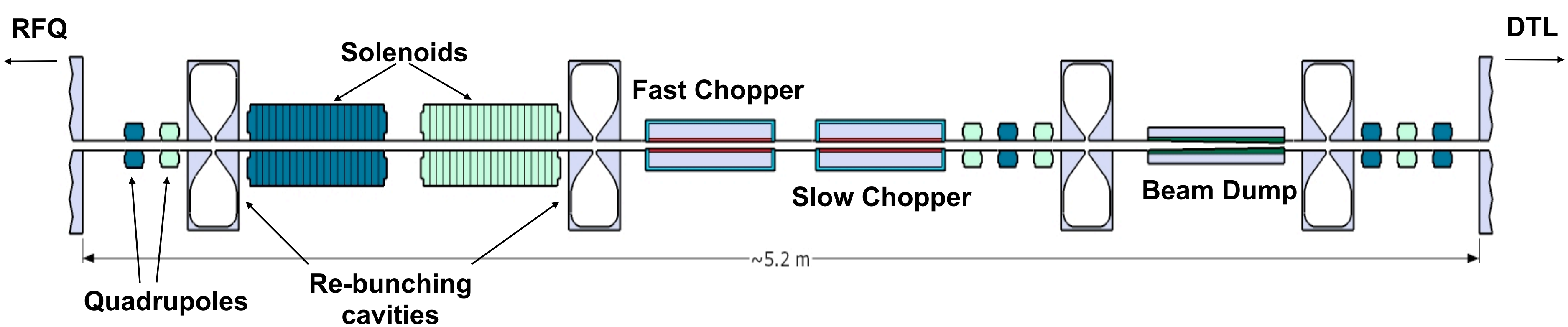
Possible MEBT Schemes

- **Scheme 1** represents the preferred design for the FETS project. The front and the end matching sections are similar and consist of a two doublet quadrupole configuration and a 324 MHz CCL-type re-bunching cavity. The choppers are arranged symmetrically, each followed by a dedicated beam dump and a defocusing quadrupole. The defocusing quadrupoles are used to amplify the deflection given by the choppers, thus reducing the required voltage on the chopper plates.



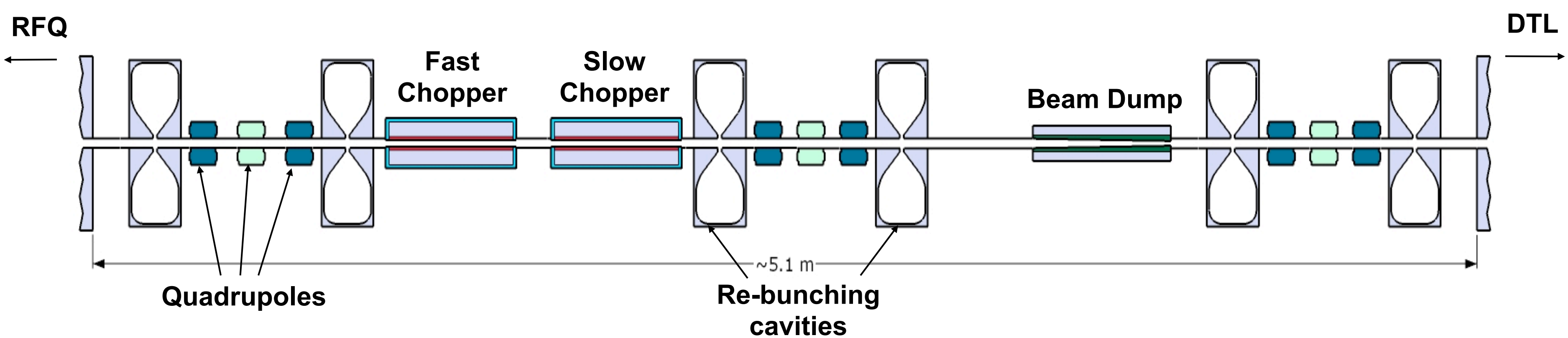
Possible MEBT Schemes

- **Scheme 2** is currently being used in the ISIS upgrade linac design and it comprises of two input quadrupoles, two solenoids, two sets of asymmetric triplet quadrupoles and four 324 Mhz re-bunching cavities. The input quadrupoles are used for matching the beam from the RFQ, while the solenoids focus the beam into a ~1.5 m long drift where the two choppers are placed. This is followed by a first set of triplets, a ~1.1 m long drift section for the beam dump, and a second set of triplets to match the beam into the DTL.



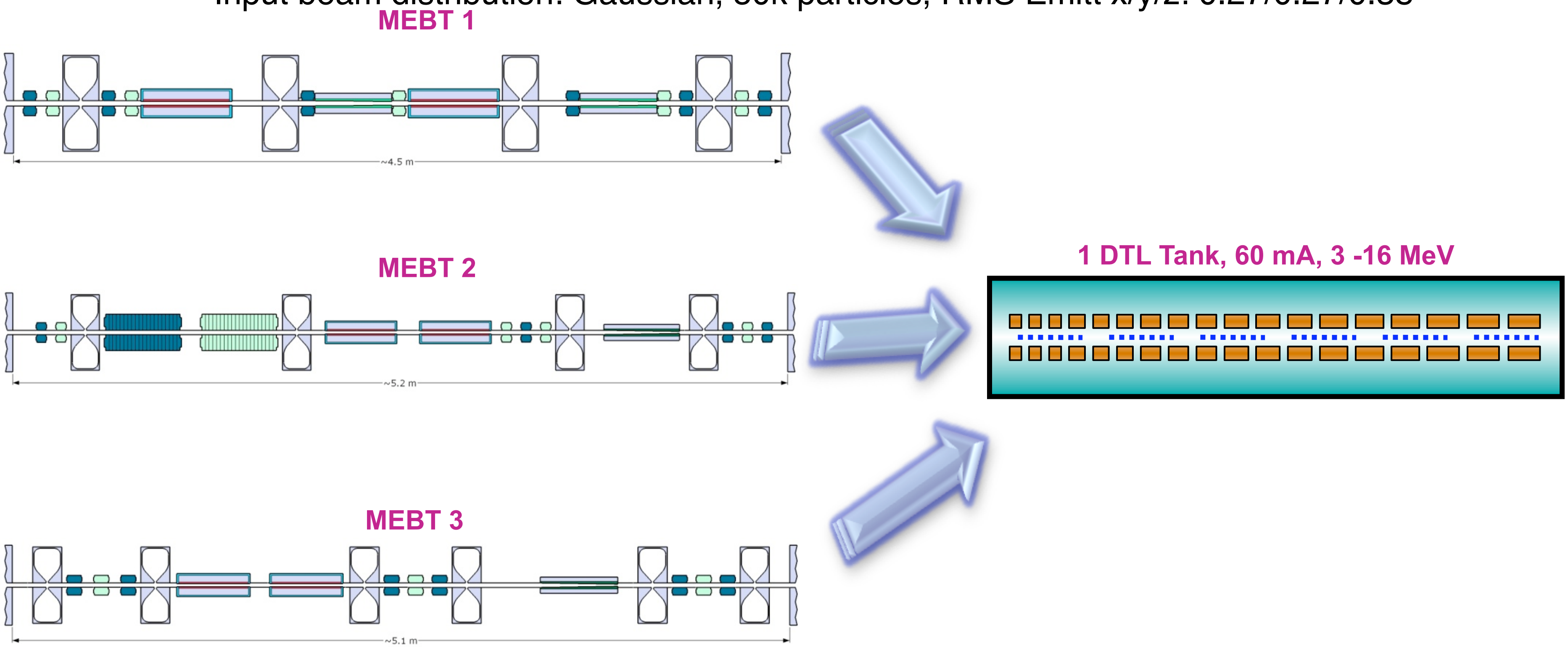
Possible MEBT Schemes

- **Scheme 3** investigates the possibility of using a more regular lattice. For this purpose, three sets of symmetric triplet quadrupoles and six re-bunching cavities are being used. They are equally spaced by long drift tube sections reserved for the two choppers and for the beam dump.



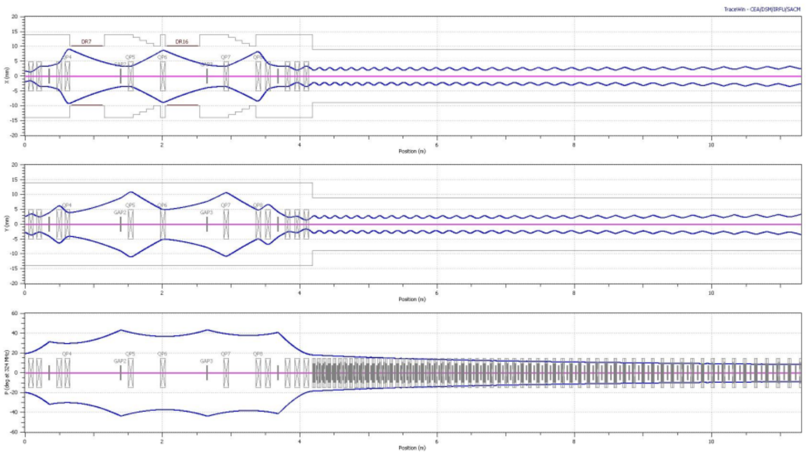
MEBT + DTL

- Beam tracking studies indicate that the MEBT design has a strong influence on the beam quality in the downstream accelerators (ISIS Upgrade Linac)
- 3 MEBT Schemes + DTL (1 tank), DTL:
  - 3–16 MeV, 60 mA, 324 MHz
  - Input beam distribution: Gaussian, 50k particles, RMS Emitt x/y/z: 0.27/0.27/0.38

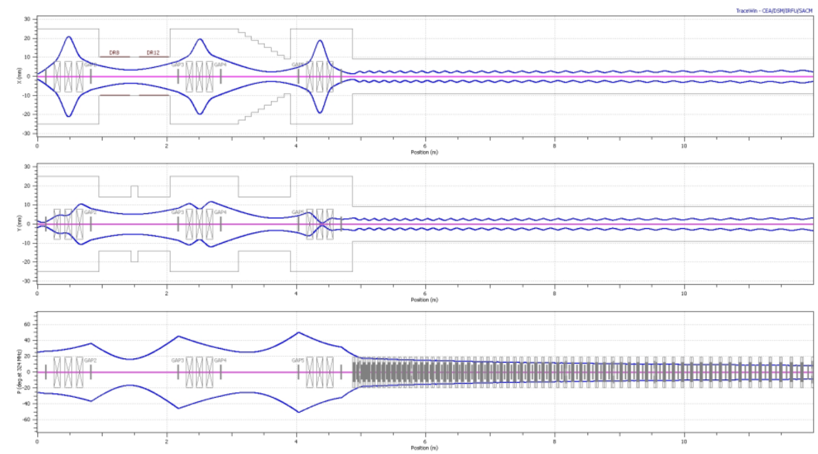


MEBT + DTL Beam Envelopes

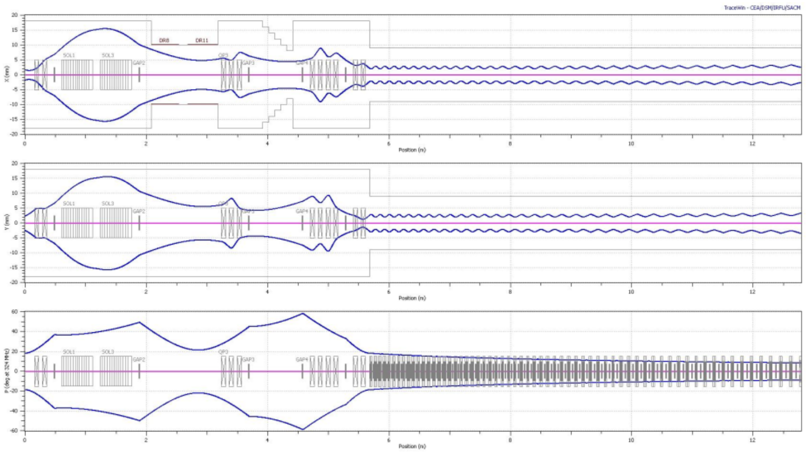
MEBT 1 + DTL

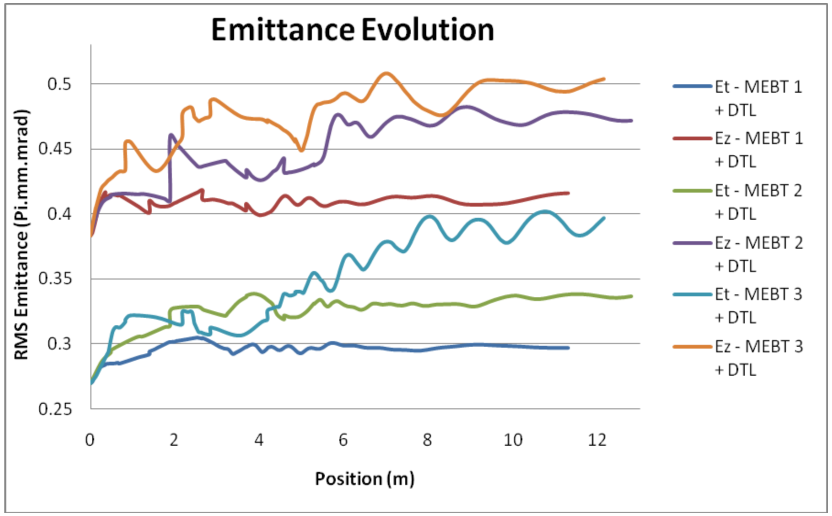


MEBT 3 + DTL



MEBT 2 + DTL

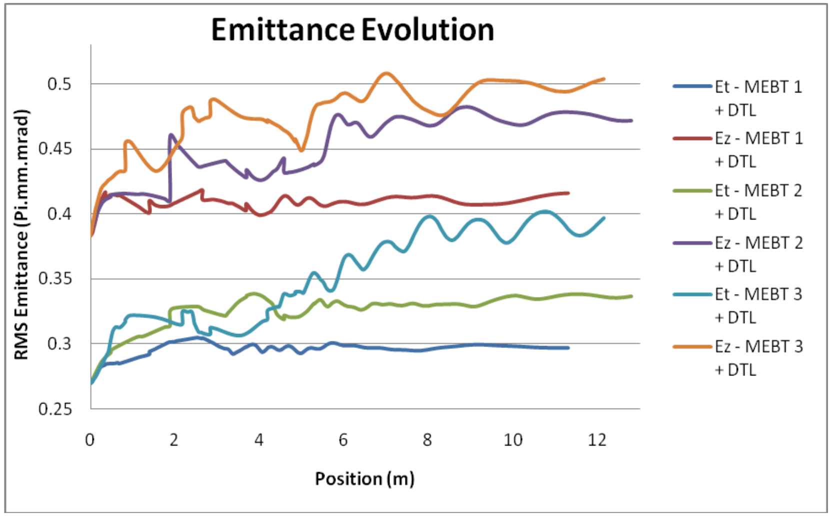




MEBT + DTL Discussion

Emittance growth

Emittance Growth		DTL	MEBT 1 + DTL	MEBT 2 + DTL	MEBT 3 + DTL
MEBT (%)	tr	-	10.1	22.3	25.6
	z	-	4.5	21.7	17.3
DTL (%)	tr	4	0	1.9	17
	z	6.5	3.9	1.1	12
Total (%)	tr	4	10.1	24.7	46.9
	z	6.5	8.6	23.1	31.5
Halo(%)	tr/z	~15	~30	~60	150



In the first design, the two long choppers create an irregular lattice for the central section of the MEBT. However, by having a symmetrical scheme, the drift lengths are reduced to ~ 0.5 m. Shorter drifts are desirable from the beam optics point of view, and by carefully choosing the quadrupole gradients, the beta functions can be kept comparable in both transverse planes. Consequently, the emittance growth and the halo development are reasonably controlled, both in the MEBT line and the DTL.
For the second scheme, the chopper sections have a similar effect on the lattice. However, the reserved drift spaces are much longer (~1.5 and ~1.1 m) and as a result, the strong space charge forces will distort the beam structure more than for the first scheme, leading to a higher emittance growth.
The third MEBT also includes two long drift sections (~1.1 m each) but has the advantage of a periodic lattice. However, the betatron oscillations amplitudes vary significantly in the two transverse planes and the beam quality is deteriorating rapidly.