Negative Ion Beam Extraction

Dr. Scott Lawrie
Ion source section leader

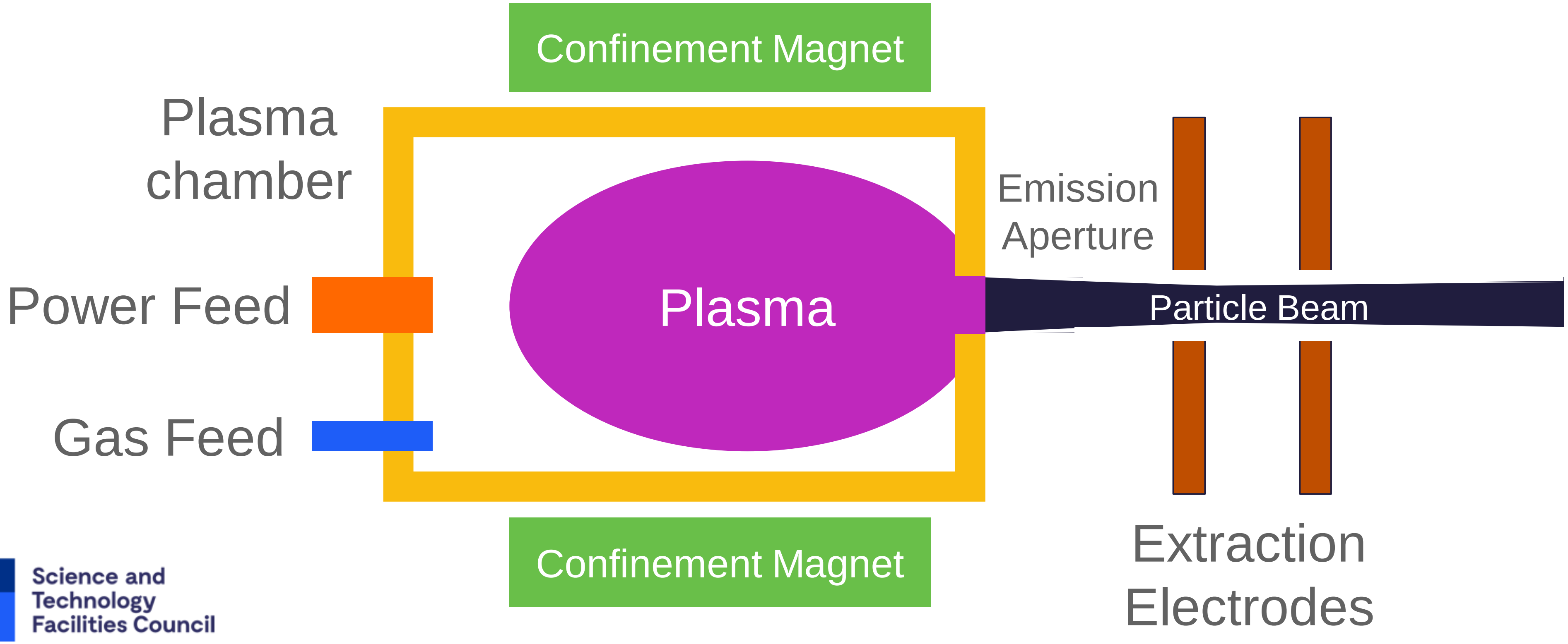
ISIS pulsed spallation neutron & muon facility
Rutherford Appleton Laboratory, UK

Many thanks to Taneli Kalvas for use of his slides

The Typical Ion Source

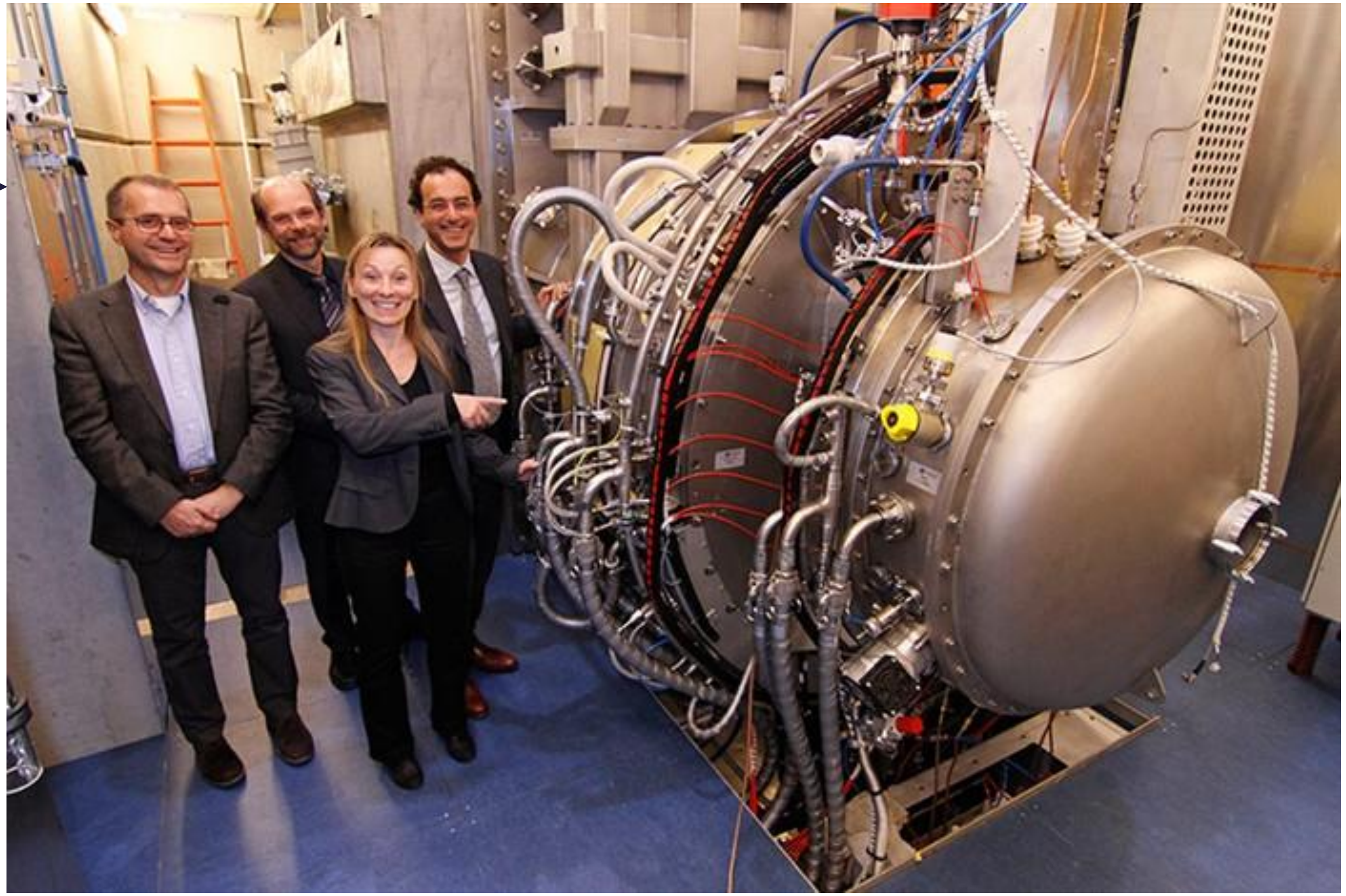
Every ion source basically consists of two parts:

1. **Ion production** inside a plasma
2. **Beam extraction** from the plasma

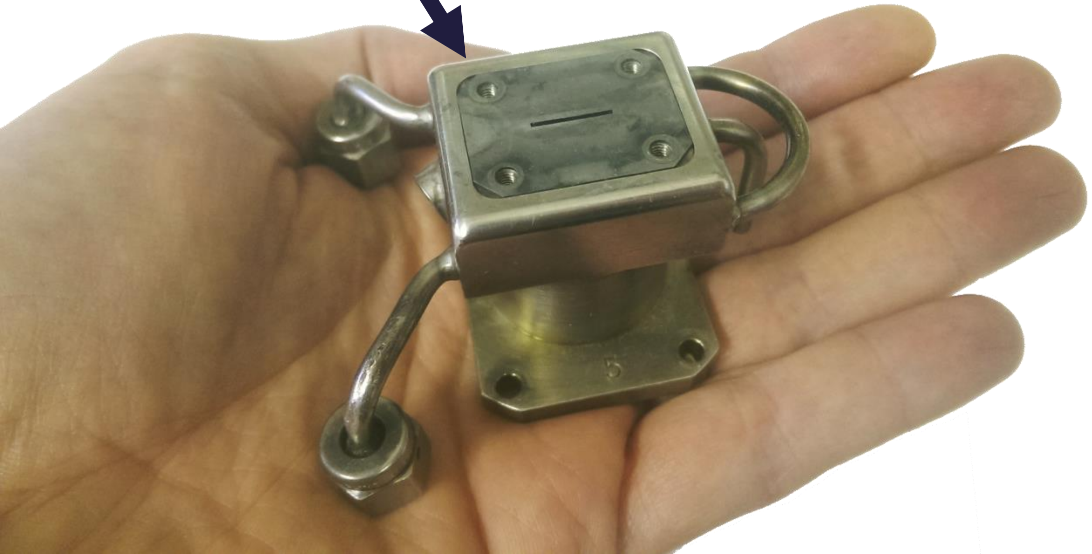


No ‘Typical’ Ion Sources!

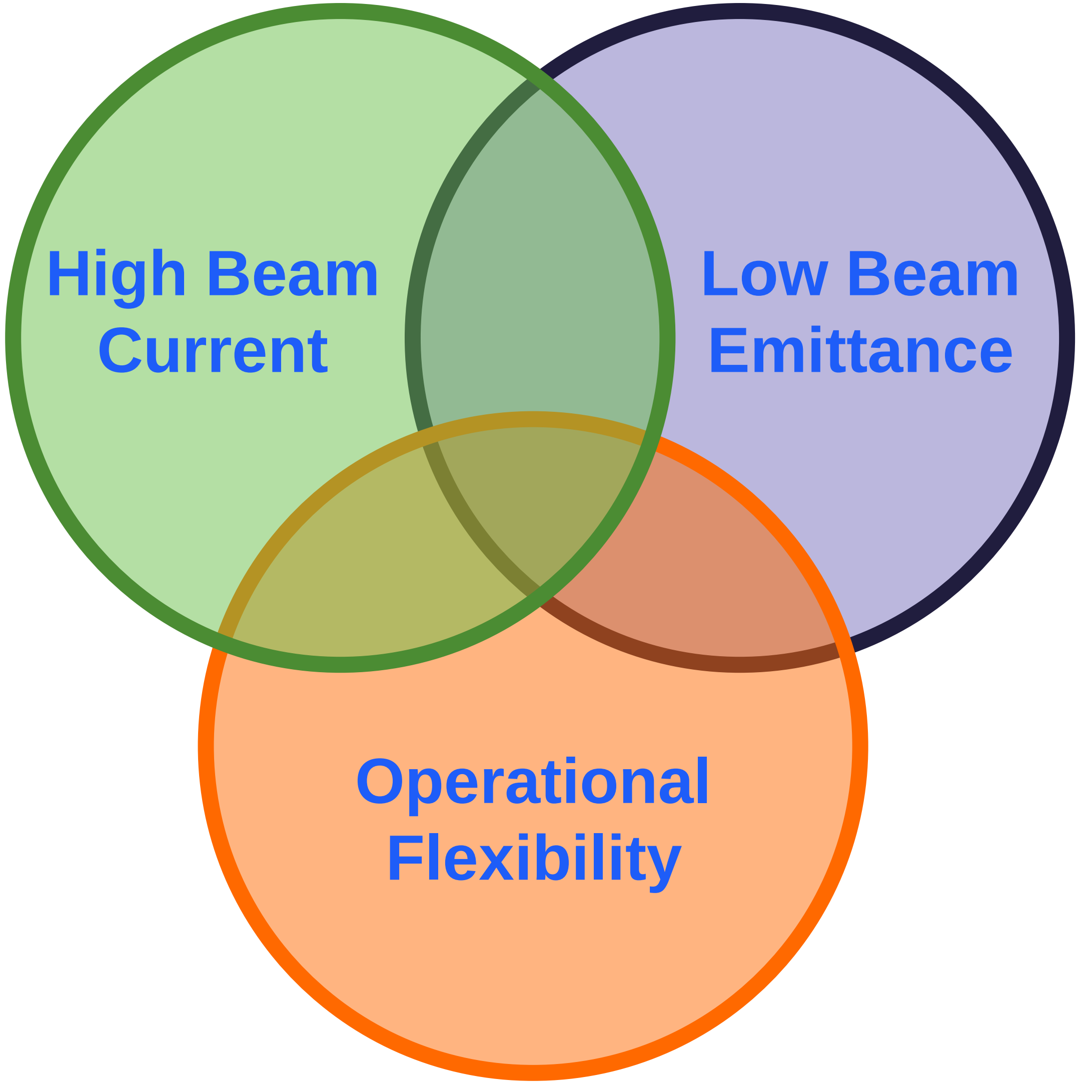
‘ELISE’ ITER
Demonstration
H⁻ Source



ISIS
H⁻ Source



Goals of any Extraction System



Science and Technology Facilities Council

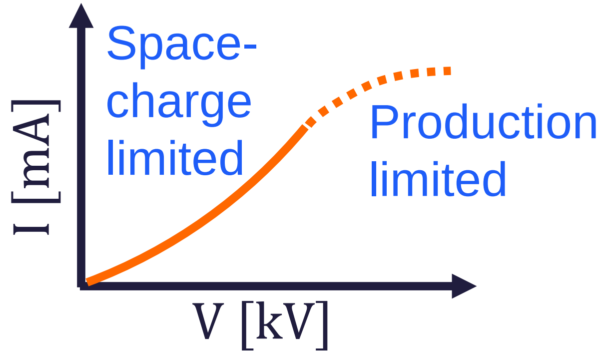
Beam Current: Child-Langmuir Law

Emission current density, ***J*** is:

$$J = \frac{4}{9}\varepsilon_0 \sqrt{\frac{2q}{m}}\frac{V^{3/2}}{d^2}$$

Total extracted current, ***I*** from an area, ***A*** is thus:

$$I = JA = PV^{\frac{3}{2}}$$



where:

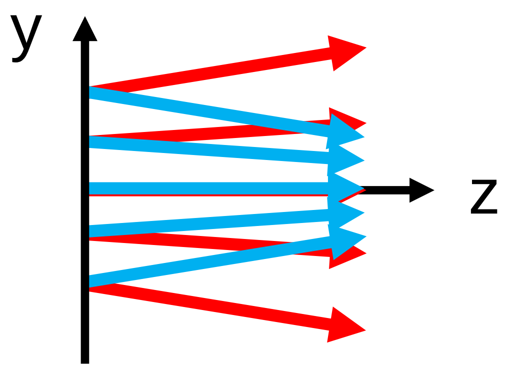
$$\boxed{\boldsymbol{P = \frac{4}{9}\varepsilon_0 \sqrt{\frac{2q}{m}}\frac{A}{d^2}}}$$

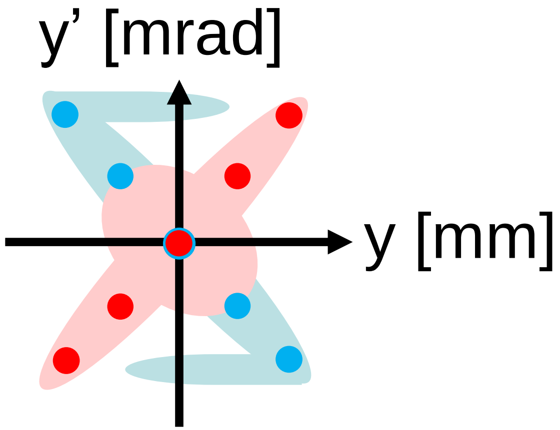
- This P is the **perveance:** depends only on source geometry
- Real measured beam perveance always lower than this
- Assumes infinite, thin, plane electrodes (usually far from true)
- Assumes particles starting with zero velocity (not true from a plasma)
- **$V^{3/2}$ law** only holds if plasma can actually deliver the current

Science and Technology Facilities Council

Emittance

- Quality of beam just as important as quantity
  - Emittance affects machine luminosity and beam-loss
  - Want beam emittance < machine acceptance
- Particles occupy 6-dimensional phase space (x, P_x, y, P_y, z, P_z)
- Practical measurements use position-angle (‘trace’) space
- Emittance scan can tell immediately how a beam is focused
- Also shows up important **aberrations** (not just pure ellipses)



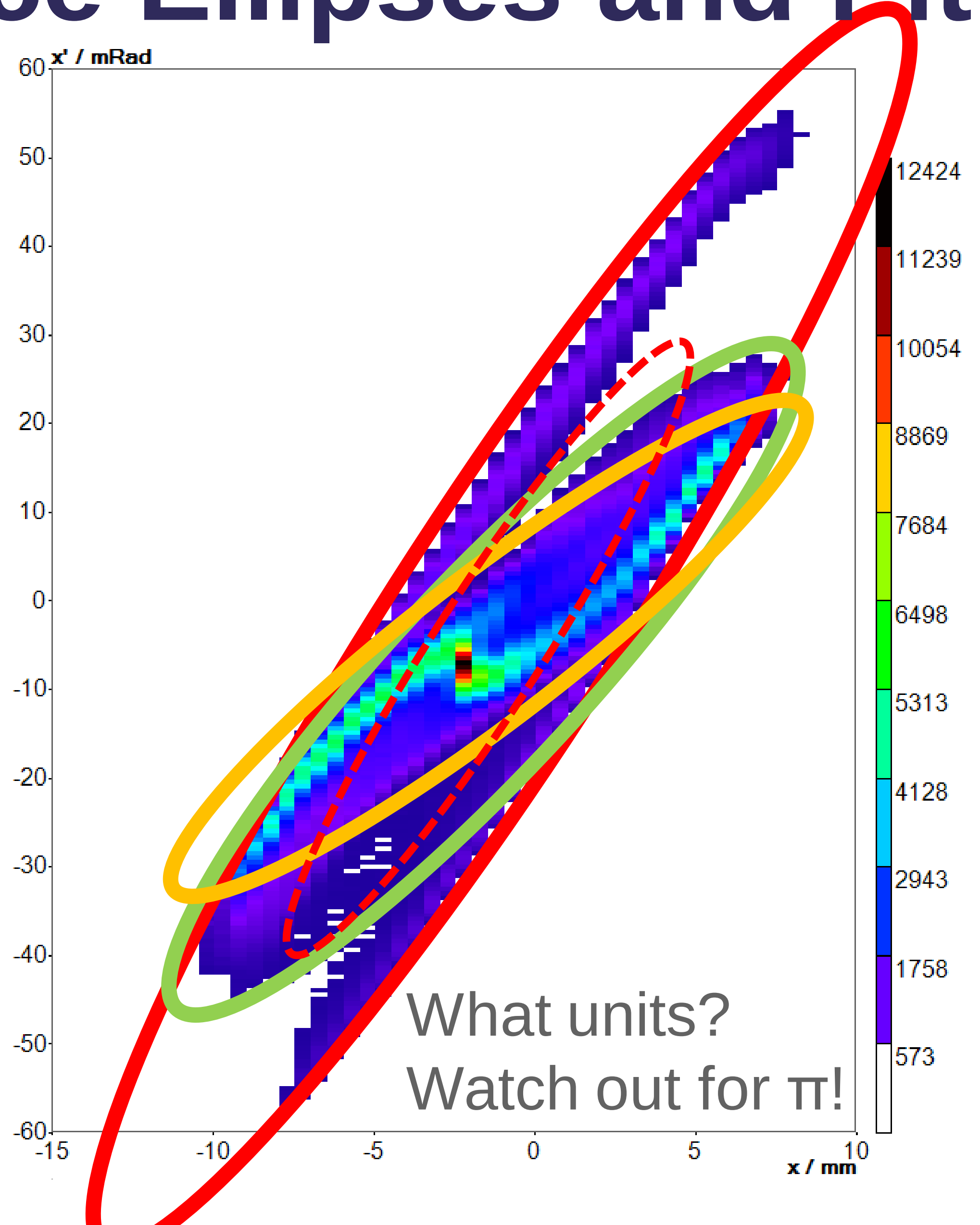


Science and Technology Facilities Council

Emittance Ellipses and Pitfalls

What is the best fit ellipse?

Do we use RMS, 4.RMS, 90%, or something else?



Ellipse defined by:

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \epsilon_x$$

where: $\beta\gamma - \alpha^2 = 1$

are the **Twiss parameters**

For real, non-elliptical data sets, calculate 4.RMS emittance statistically:

$$\epsilon_{4.rms} = 4\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

Units usually given in [π mm mrad], but varies

Science and Technology Facilities Council

Operational Flexibility

- Accelerator runs in different modes
  - Required beam current
  - Duty factor
  - Chopping fraction
- Emission current density, J can vary over time
  - Source erosion and aging
  - Caesium and other temperature dynamics
  - Diurnal variation
- Slight changes in spare source characteristics
  - Alignment repeatability
  - Each source needs tuning
  - Steering/focussing sensitive to exact B-field strength

Also: real system won't be the same as simulated, so need some flexibility in the design

Extraction system must have several **tuning knobs**

Triode extraction or at least an **einzel lens** is mandatory to be able to adjust to changing plasma conditions

Extraction Complications

- Plasma-beam interaction
  - Plasma parameters: density, potential, temperature etc
  - Uniformity of current density, quality, intensity
  - Influence of surface-produced negative ions on edges of emission aperture
- **Co-extracted electrons**
  - Usually higher current than negative ions, high space charge influence
  - Must be removed from beam, how to dump significant power safely
  - Dumping scheme creates asymmetry in extraction system and thus onto beam
- Application-specific requirements
  - Adjustable focussing, steering, chopping, pulsed extraction, large area
- Practical engineering constraints
  - Space left for nuts & bolts, connectors, insulators, diagnostics, pumps, gate valves etc
  - Voltage-holding, required materials, power supplies, budgets, lifetime, maintenance

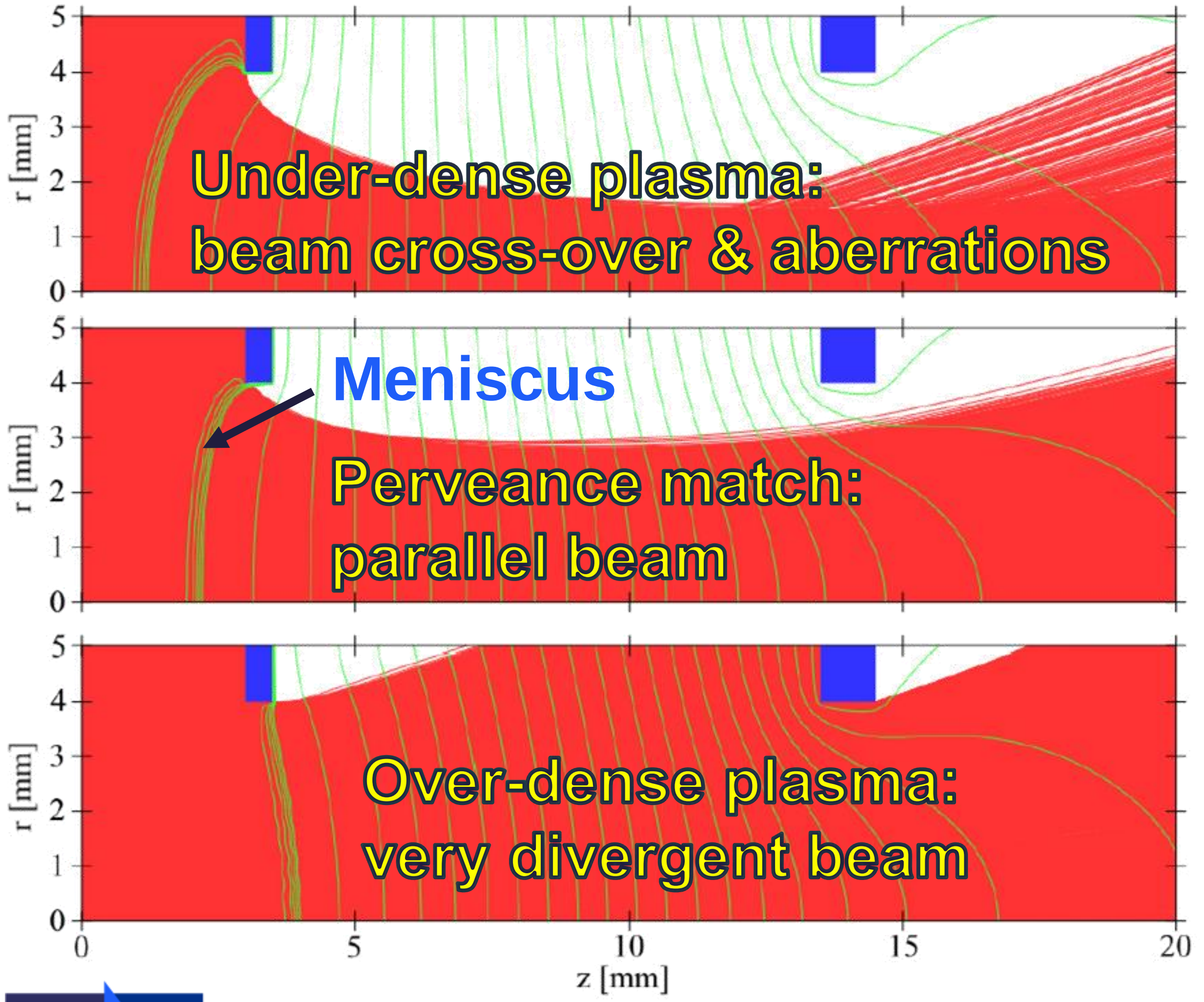
Electrodes and Grids

- Most negative ion sources have triode extraction, consisting of three electrodes
- Naming convention different for accelerator or fusion applications:

Application	Electrode #1	Electrode #2	Electrode #3
Accelerator	Plasma Electrode	Extraction (or ‘Puller’) Electrode	Ground Electrode
Fusion	Plasma Grid (PG)	Extraction Grid (EG)	Grounded Grid (GG)
Function	Biased few volts relative to plasma to suppress co-extracted electrons	Adjustable ~1-10 kV to provide initial acceleration and dump electrons	Fixed, much higher voltage to bring beam to required energy

UKRI Science and Technology Facilities Council

It All Starts at the ‘Plasma Meniscus’



Particle dynamics at emission aperture *defines* the beam performance throughout entire accelerator: *crucial!*

Plasma meniscus is *notional* ‘boundary’ where beam originates

Meniscus sets beam **current, emittance and focussing**. Shape varied by emission current density, extraction voltage and electrode geometry

Science and Technology Facilities Council

Particle Tracking to Model the Meniscus

- **Discretise** the problem space on a mesh
- Calculate E-field on the mesh, based on input electrode geometry & voltage
- Calculate (or import) local magnetic fields
- Track particles through the E- and B-fields
- Deposit space charge along **particle tracks**
- Re-calculate electric field based on particle charges
- **Iterate** until converged

Alternatively: Particle in Cell (**PIC**) calculation, where point particles are used (not ‘tracks’). Particles are moved and fields re-calculated in short time steps. Useful if external fields are changing and/or particle **collisions** present.

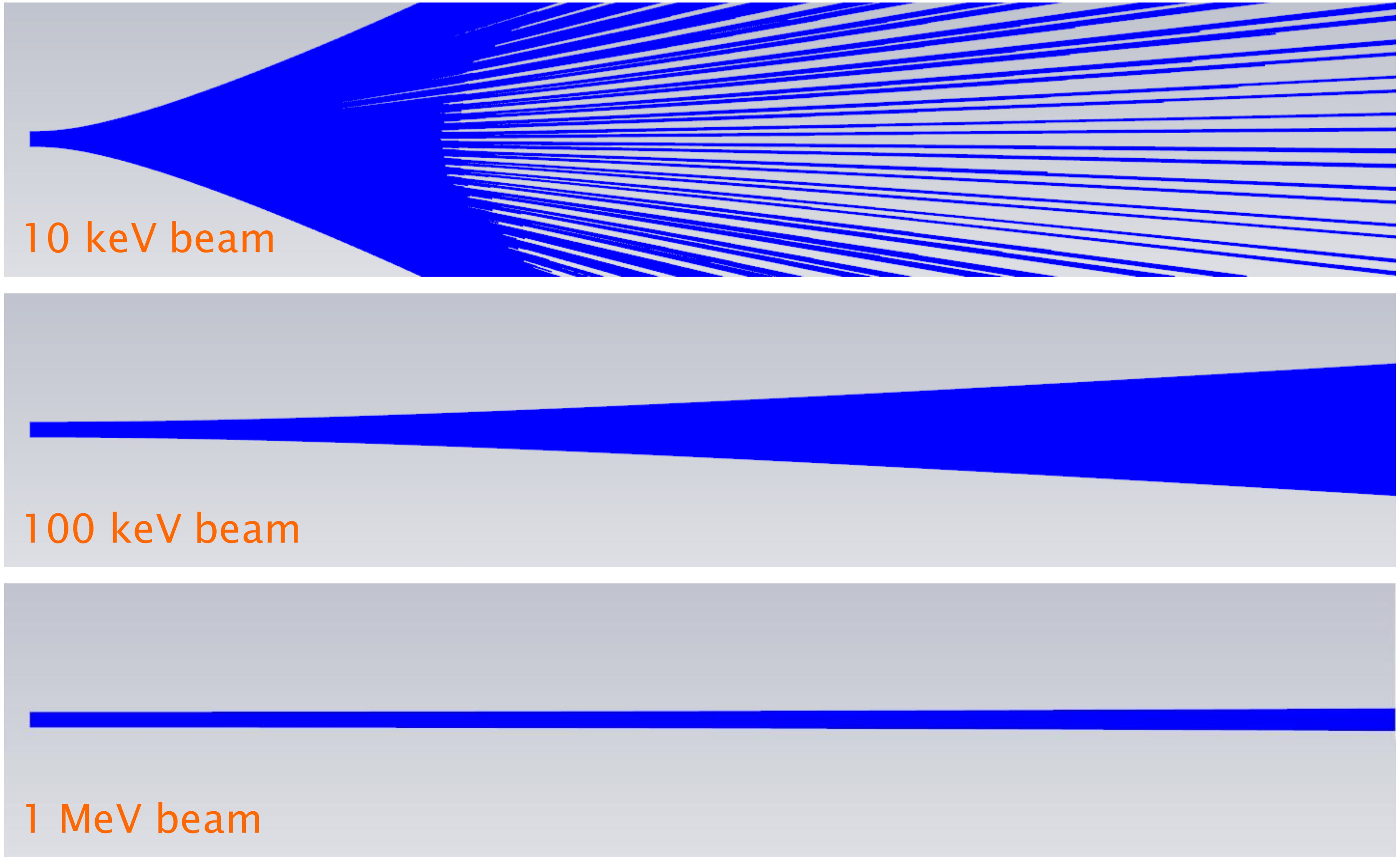
Suitable Extraction Tracking Codes

- (n)IGUN: Plasma modelling for positive and negative ions. 2D only.
- PBGUNS: Plasma modelling for positive and negative ions. 2D only.
- SIMION: Simple 3D E-field solver and particle tracer. Basic space charge solver and no plasma modelling
- KOBRA: More advanced 3D E-field solver with positive ion plasma model and PIC capability.
- LORENTZ: State of the art 3D EM solver and particle tracer. Lots of features but no plasma modelling.
- CST Studio: Another feature-rich general-purpose EM, PIC and particle modeller. No plasma modelling.
- **IBSIMU:** Plasma modelling for positive and negative ions in 1D, 2D, 2D-axisymmetric & 3D. CAD import. Open source, free, **benchmarked**.

Science and Technology Facilities Council

Space Charge

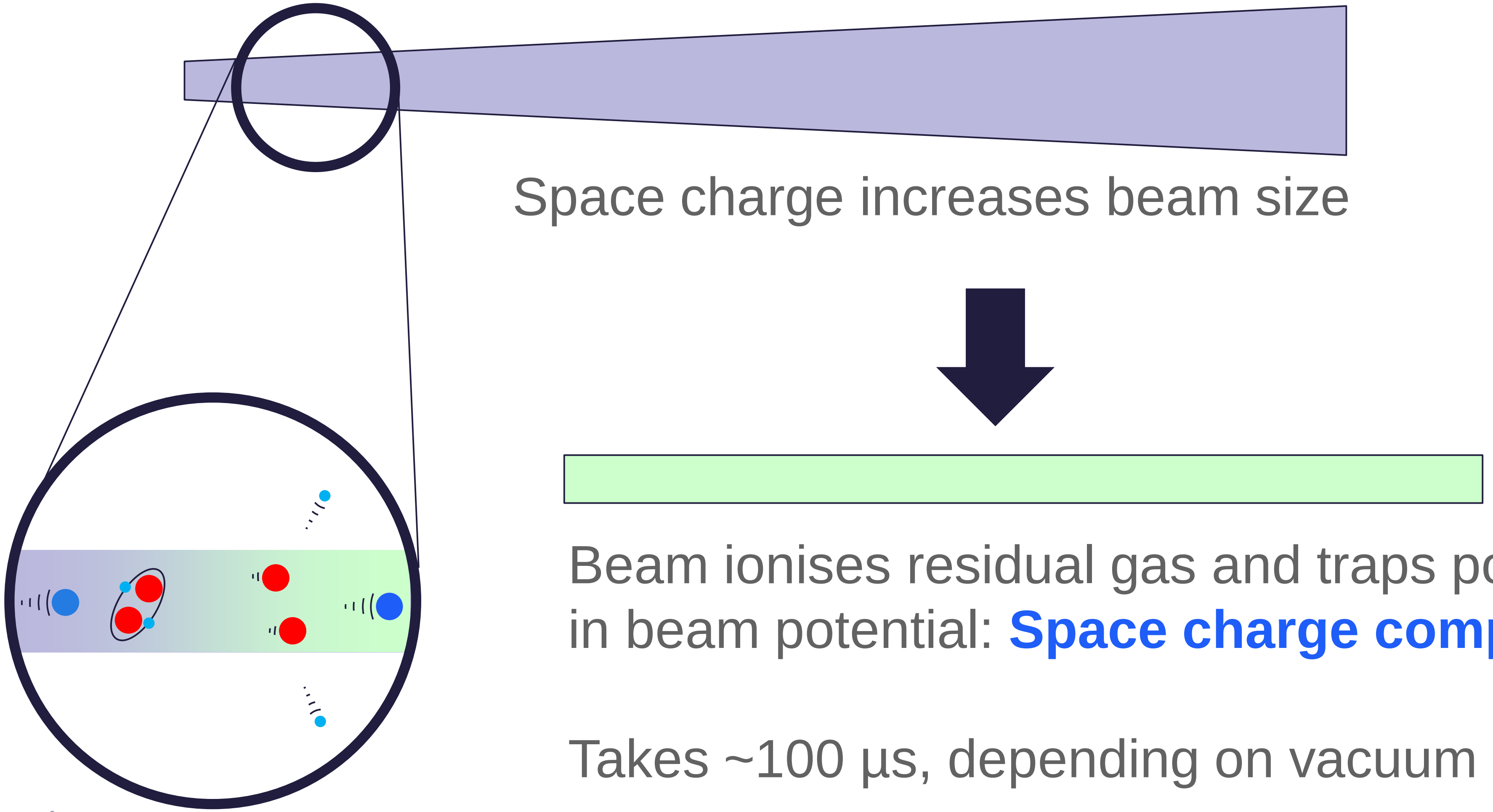
- 50 mA H^{-} beam
- 5 mm initial radius
- 1000 mm drift distance
- Expands due to its own **'space charge'**
- Space charge forces velocity dependent



Science and Technology Facilities Council

Conclusion: Need to focus and accelerate low energy beams *hard*

Space Charge Compensation



Space charge increases beam size

Beam ionises residual gas and traps positive ions in beam potential: **Space charge compensation**.

Takes ~100 µs, depending on vacuum pressure.

Negative ion beams can get **over-compensated**!

Science and Technology Facilities Council

Electron Dumping (‘edump’)

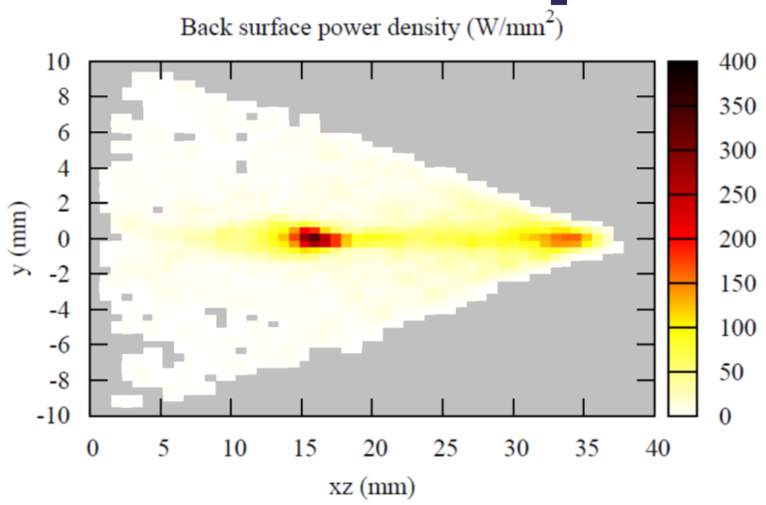
- Removing co-extracted electrons is the bane of H^- extraction design!
- Electron current often tens of times higher than H^- current
- If dumped at full extraction energy, can be a LOT of power to remove
    - Cooling of extraction system
    - Material choice to avoid sputtering/heat damage
    - Defocus electron beam to reduce surface power density
- Require mass-separation i.e. magnetic deflection
- Turns simple 2D problem into a messy 3D problem
    - Larger mesh, more memory, slower solve time
    - Cannot ignore transverse space charge deflection
    - Secondary particles
    - How to correct for deflected ion beam?

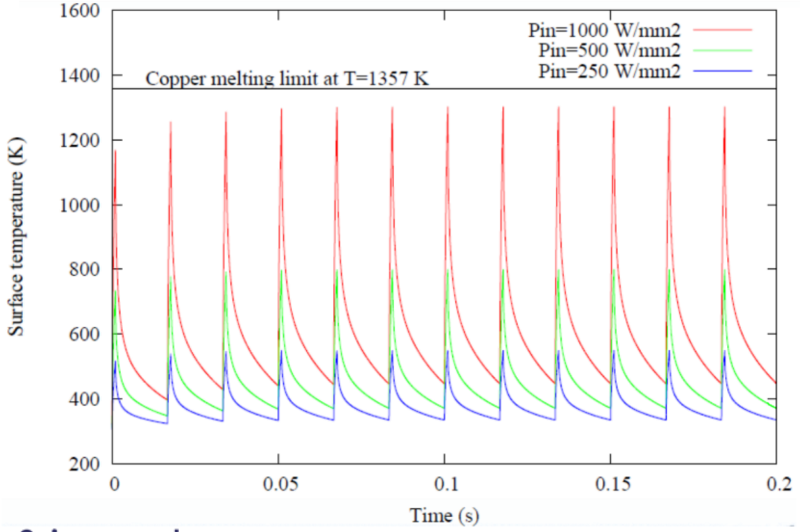
Science and Technology Facilities Council

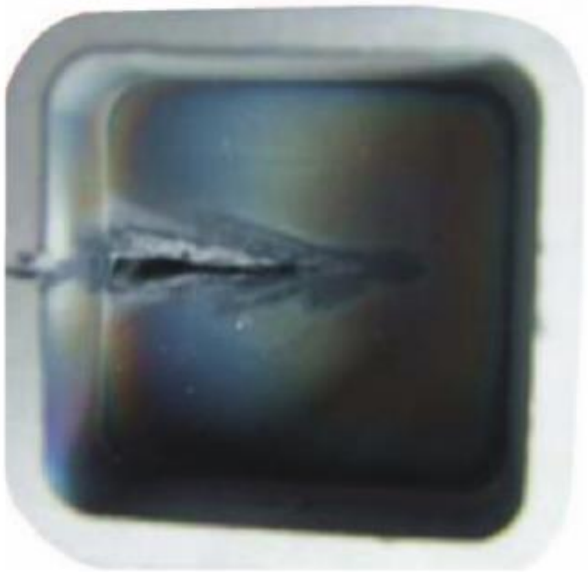
Electron Dumping Possibilities

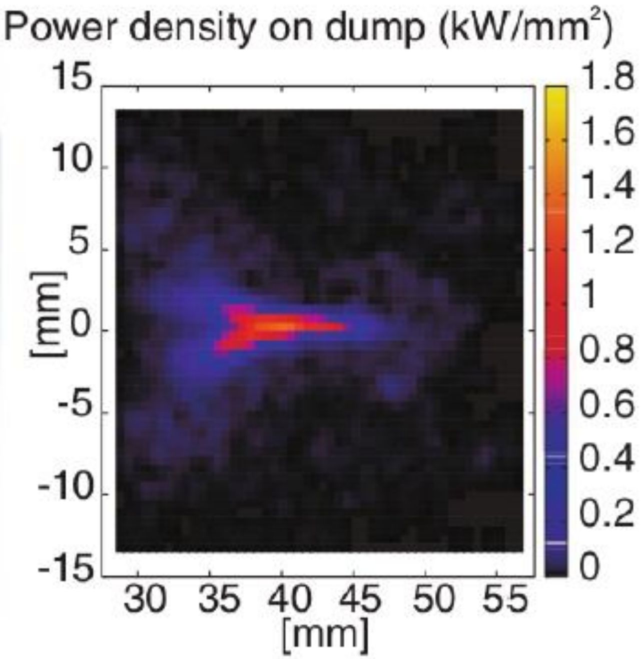
Option	Benefit	Drawback
Dump at low energy	• Low deposited power	• Low perveance • Asymmetric beam
Dump at high energy	• More beam current • Better focussing • Less beam deflection	• High power dump • Erosion damage
Extract at full energy, then reduce energy to dump before re-accelerating	• High perveance • Lower dumped power • Einzel focussing • Flexible	• Complicated • More space required • HV sparking • Secondary electrons

Electron Dump Cooling & Material Choice









Rule of thumb: keep dumped electron power density well below 1 kW/mm^2

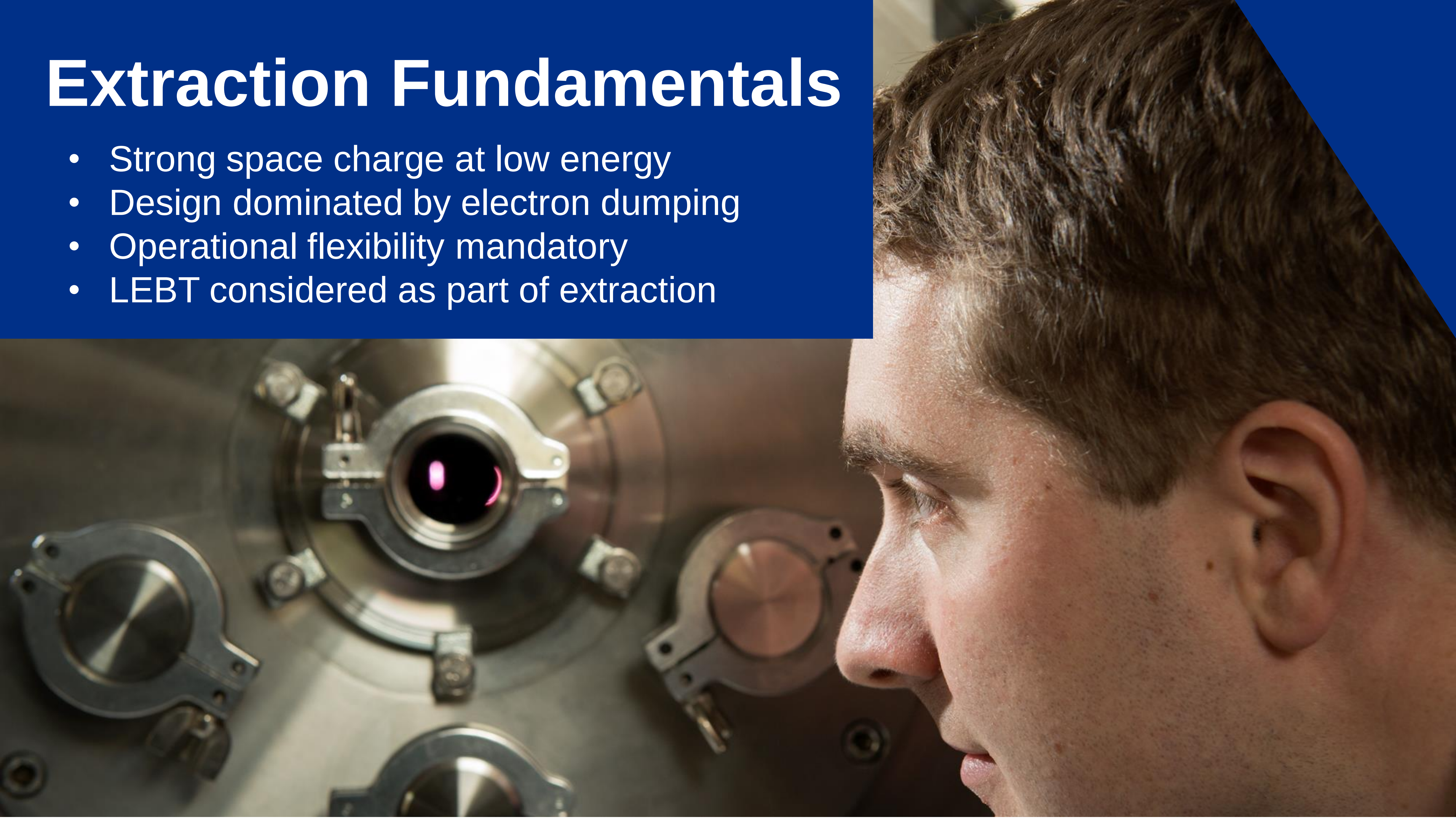
Science and Technology Facilities Council

LEBT as Part of Extraction?

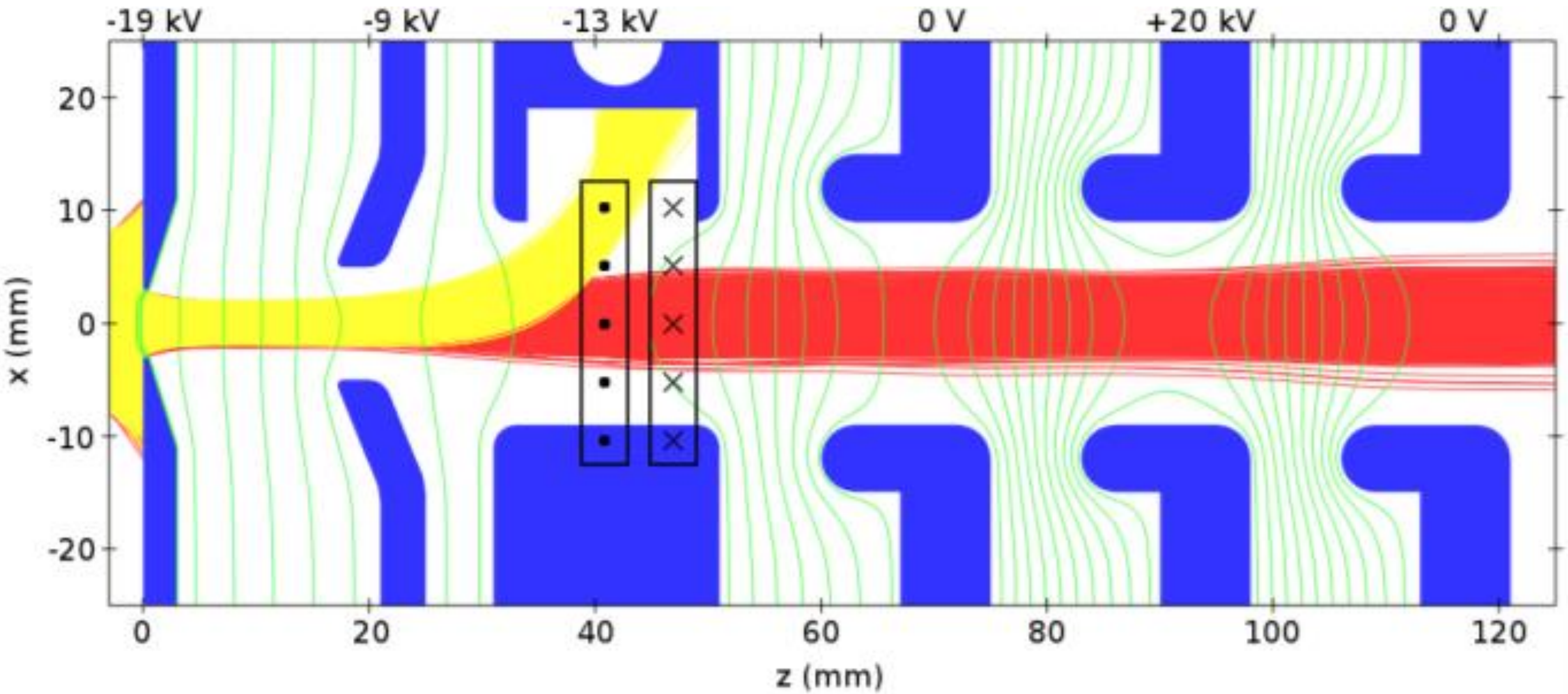
- For negative ion sources, we (usually) require:
  - Magnetic filter field
  - Magnetic edump field
  - Strong focussing immediately after extraction
  - Correction of position/angle caused by edump
- Since all these deflection and focussing fields are closely intertwined, we cannot really separate the ion source, extraction and LEBT.
- When reporting beam currents, it's usually more genuine/honest to state the transported current after the LEBT, rather than just what is extracted.
- For example, the ISIS Penning source easily produces 100 mA, but only 35 mA is transported to the RFQ! (Major project underway to rectify this…)

Extraction Fundamentals

- Strong space charge at low energy
- Design dominated by electron dumping
- Operational flexibility mandatory
- LEBT considered as part of extraction



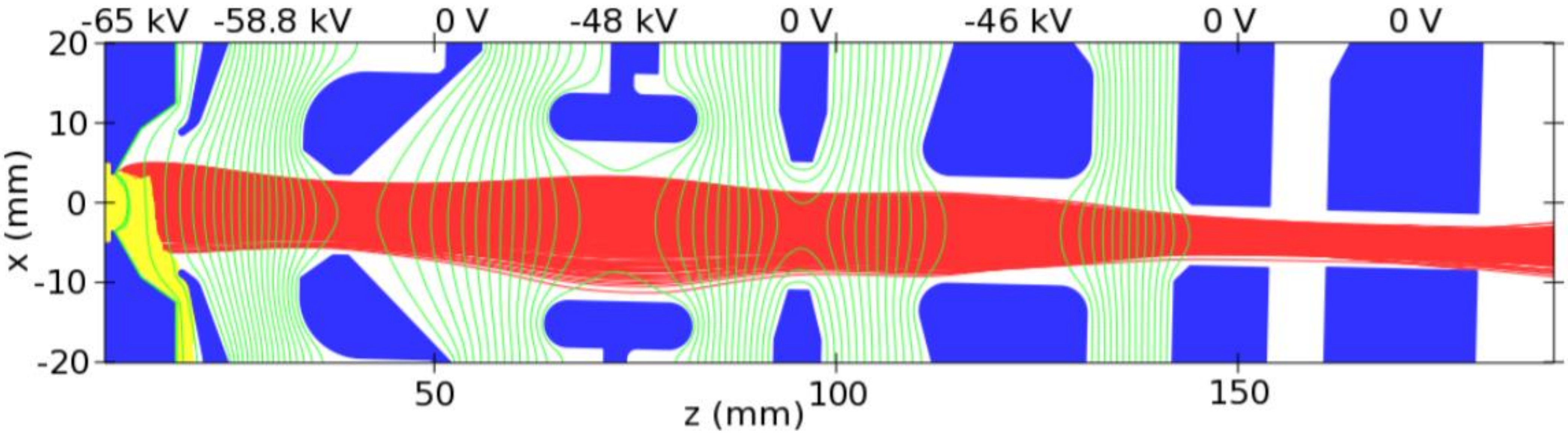
RADIS



- Field clamp prevents filter field leaking into extraction
- Decelerate beam before dumping electrons
- Dipole/antidipole eDump B-field
- Dump independent of adjustable puller voltage
- Accelerating einzel lens to control focus

Science and Technology Facilities Council

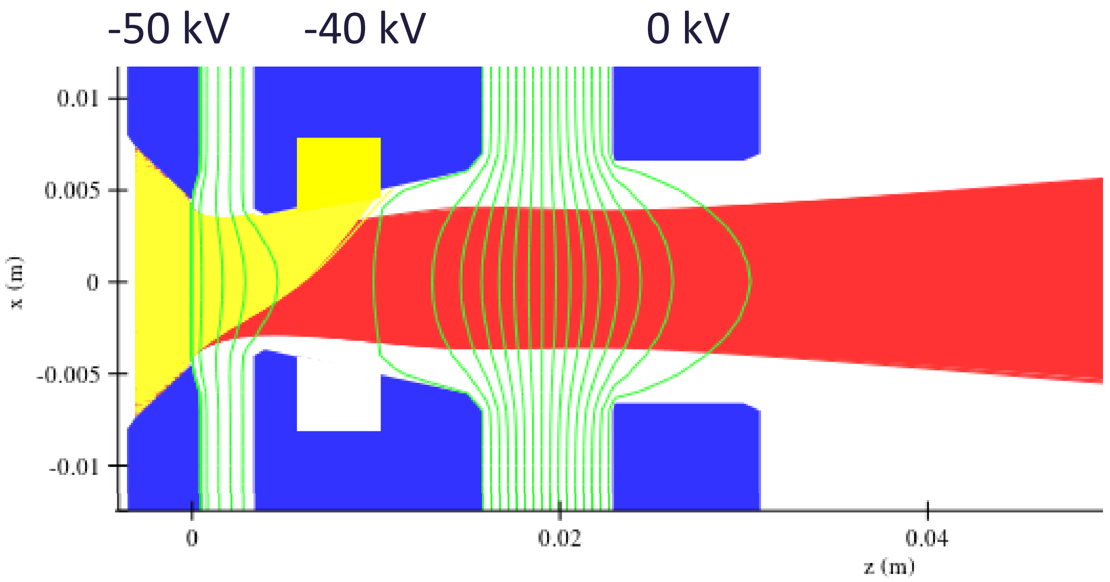
SNS

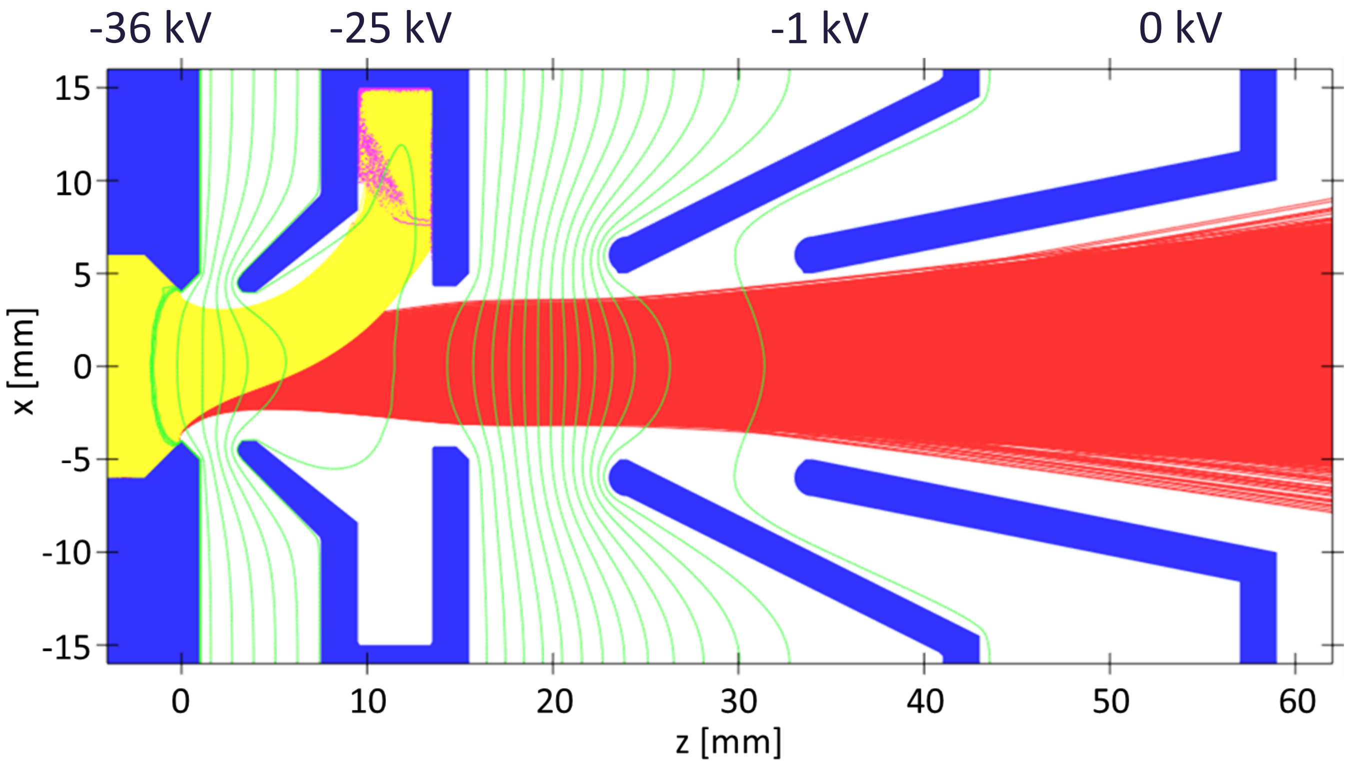


- Combined extraction and electrostatic LEBT
- Dump electrons immediately at low energy
- Low extraction E-field creates convex meniscus
- Accelerate quickly to full 65 keV energy
- Two decelerating einzel lenses to control focus
- Tilted extraction
- Electrostatic xy steerer/chopper before RFQ

UKRI Science and Technology Facilities Council

JPARC & RAL

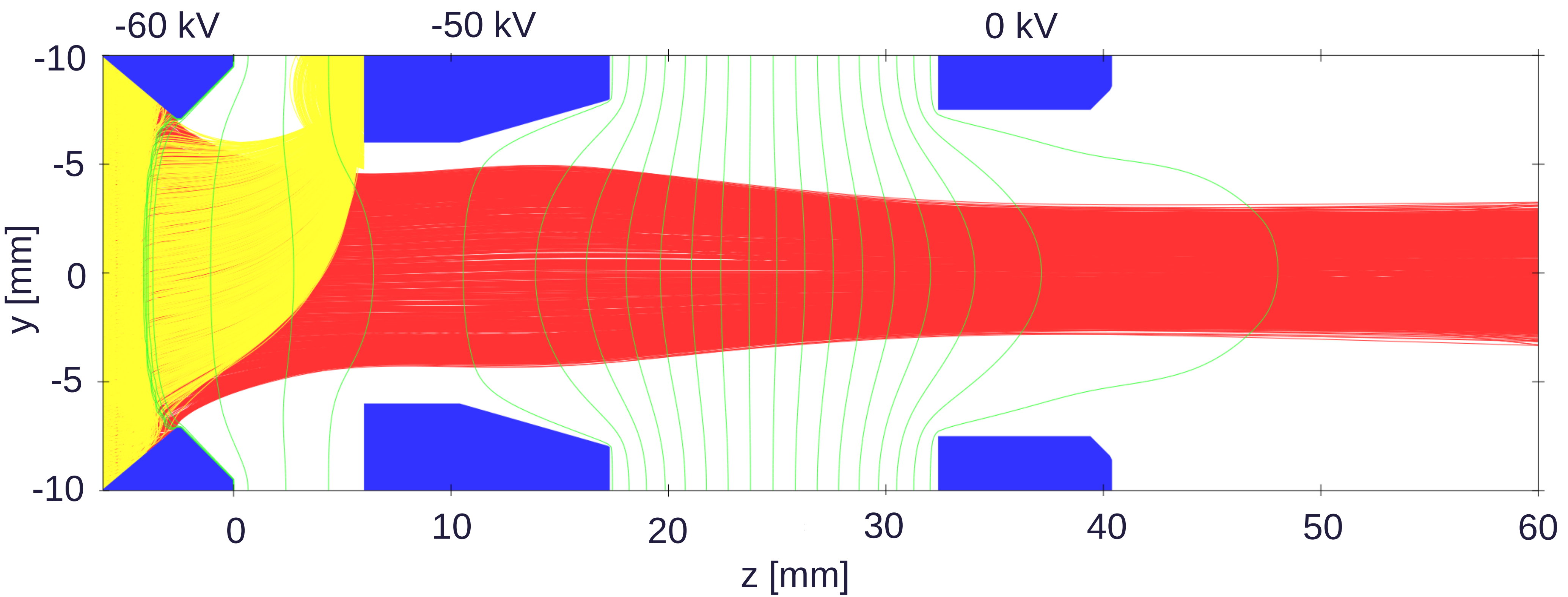




- Large emission aperture reduces initial space charge
- eDump field same direction as filter to aid deflection
- Slightly divergent beam for solenoid LEBT injection
- JPARC: beam offset corrected by magnet downstream
- RAL: beam offset corrected by tilted vessel c.f. LEBT

Science and Technology Facilities Council

ELISE



- Multi-aperture source for fusion application
- Three grid structure (eventually MUMAG up to 1 MeV)
- Slightly different edump magnet arrangement
- Electrons dumped onto upstream surface of extract grid
- Require almost parallel beam to avoid losses downstream

Science and Technology Facilities Council

Conclusion

- Dealing with electrons is hard
- Necessarily requires 3D model
- Many methods to remove them
- All have engineering compromises
- Many experts at NIBS: get in touch

Good luck!

Credit to Taneli Kalvas for use of some of his slides

Science and Technology Facilities Council