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Particle Sources

Dr. Scott Lawrie

Ion Source Section Leader

ISIS Pulsed Spallation Neutron & Muon Facility

Rutherford Appleton Laboratory

Many Many Particle Sources

Species

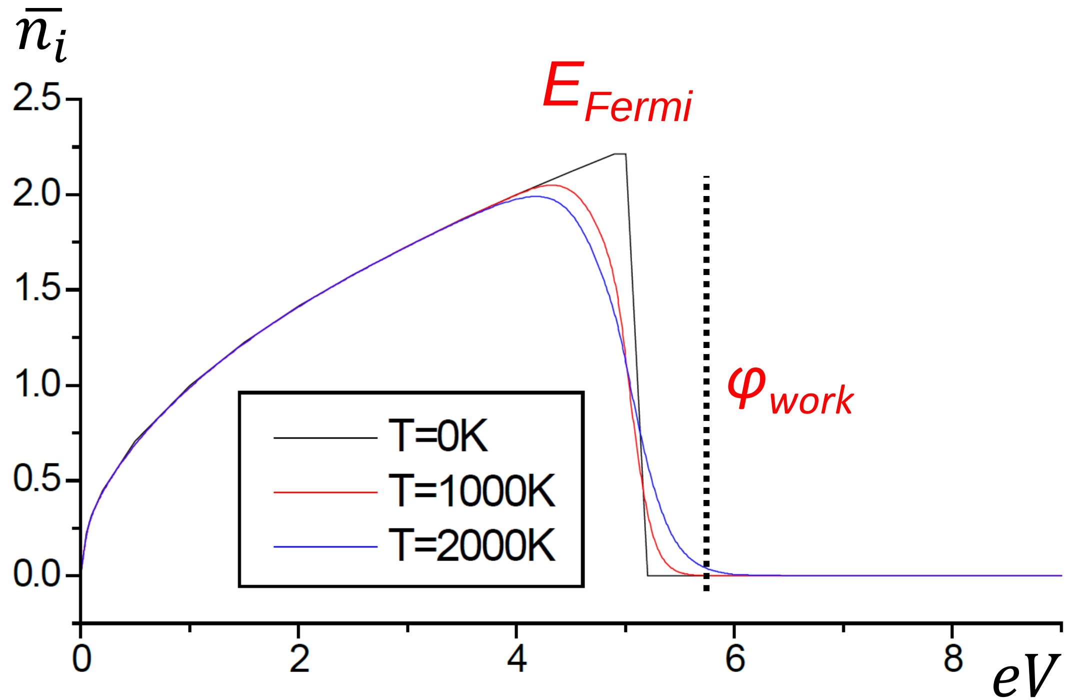
- Electron
- Proton
- Light Ion
- Heavy Ion
- Negative Ion
- High Charge State
- Radioactive
- Spin-Polarised
- Neutral
- Muon
- Exotic

Technique

- Filament
- Photocathode
- Arc Plasma
- Laser
- Microwave
- RF
- Cyclotron-Resonance
- Duopigatron
- Duoplasmatron
- …

Fermi-Stats. & Work Function

- Fermi level, E_{Fermi} is kinetic energy of electron in highest occupied state
- Work-function, φ_{work} is energy input to release an electron from the surface (basis of photoelectric effect)
- Higher temperature, T smears out the Fermi level
- Some electrons may cross work-function and escape
- Integrating the number of available released electrons gives current density, J
- To get a lot of current, need high T and a material with a high A and low φ_{work}



$$J = AT^2 e^{\left(\frac{-\varphi_{work}}{k_B T}\right)}$$

Richardson-Dushmann equation

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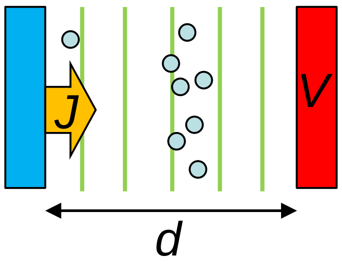
Child-Langmuir Law

- Want the released particles to go somewhere
- Apply potential difference to accelerate into a beam
- E-field of already-emitted particles shields the cathode from the accelerating E-field: space-charge-limited flow
- Cannot accelerate an arbitrarily high number of particles
- Can calculate the extractable current density:



Continuity eqn.

$$J = \rho \dot{x}$$

Kinetic energy

$$\frac{1}{2} m \dot{x}^2 = -q\varphi$$

Poisson eqn.

$$\frac{d^2\varphi}{dx^2} = -\frac{\rho}{\varepsilon_0}$$

$$\frac{d^2\varphi}{dx^2} = K\varphi^{-1/2}$$

where: $K = \sqrt{\frac{m}{2q}} \frac{J}{\varepsilon_0}$

Child-Langmuir Law (cont'd.)

$$\frac{d^2\varphi}{dx^2} = K\varphi^{-1/2}$$ Substitute: $\varphi' = \frac{d\varphi}{dx}$ Then: $\varphi' d\varphi' = K\varphi^{-1/2} d\varphi$

Integration gives: $\varphi'^2 = 4K\varphi^{1/2}$ So: $\varphi' = \frac{d\varphi}{dx} = 2\sqrt{K}\varphi^{1/4}$

Rearrange and integrate again: $2\sqrt{K}x = \frac{4}{3}\varphi^{3/4}$ Bound. cond.: $\varphi_{(x=d)} = V$

So: $K = \frac{4}{9}\frac{V^{3/2}}{d^2}$

But from the previous slide: $K = \sqrt{\frac{m}{2q}}\frac{J}{\varepsilon_0}$ Therefore:

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

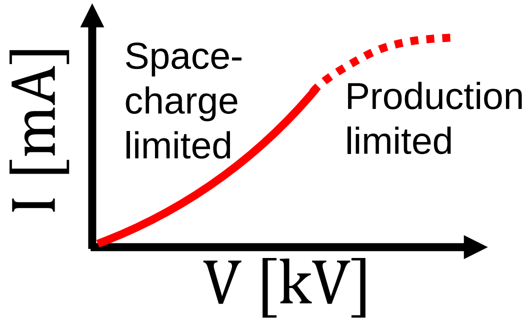
This Child-Langmuir "$V^{3/2}$" Law says that the extractable current density of a particle source depends ONLY on the voltage and electrode gap

Child-Langmuir Law (cont'd.)

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

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

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

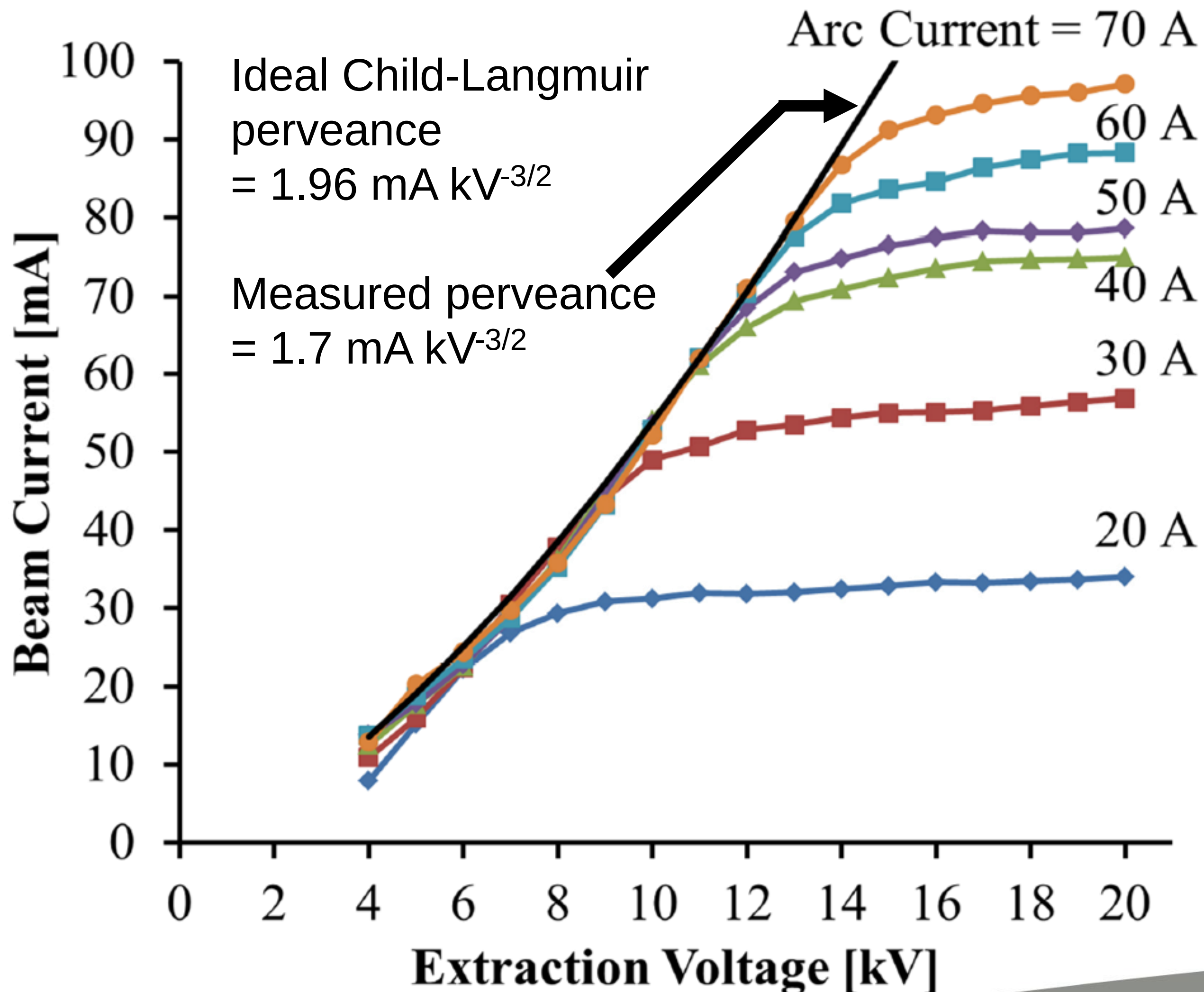


where:

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

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

Perveance Measurement



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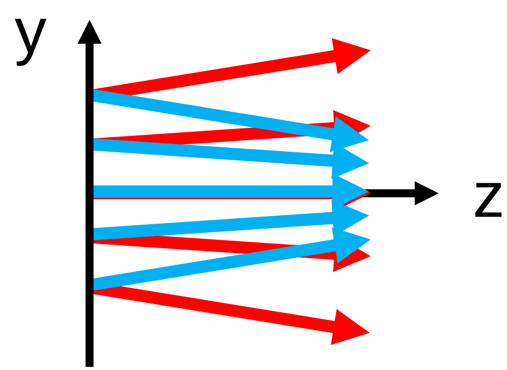
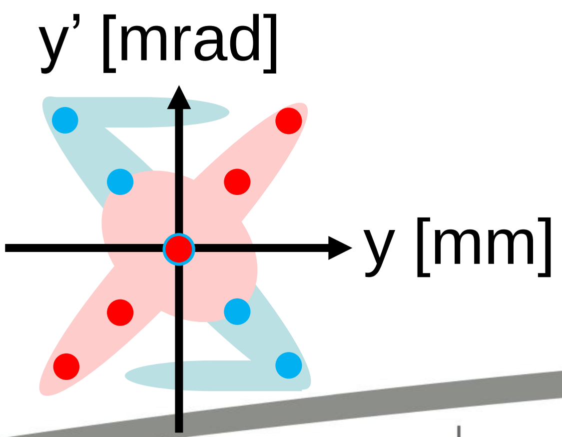
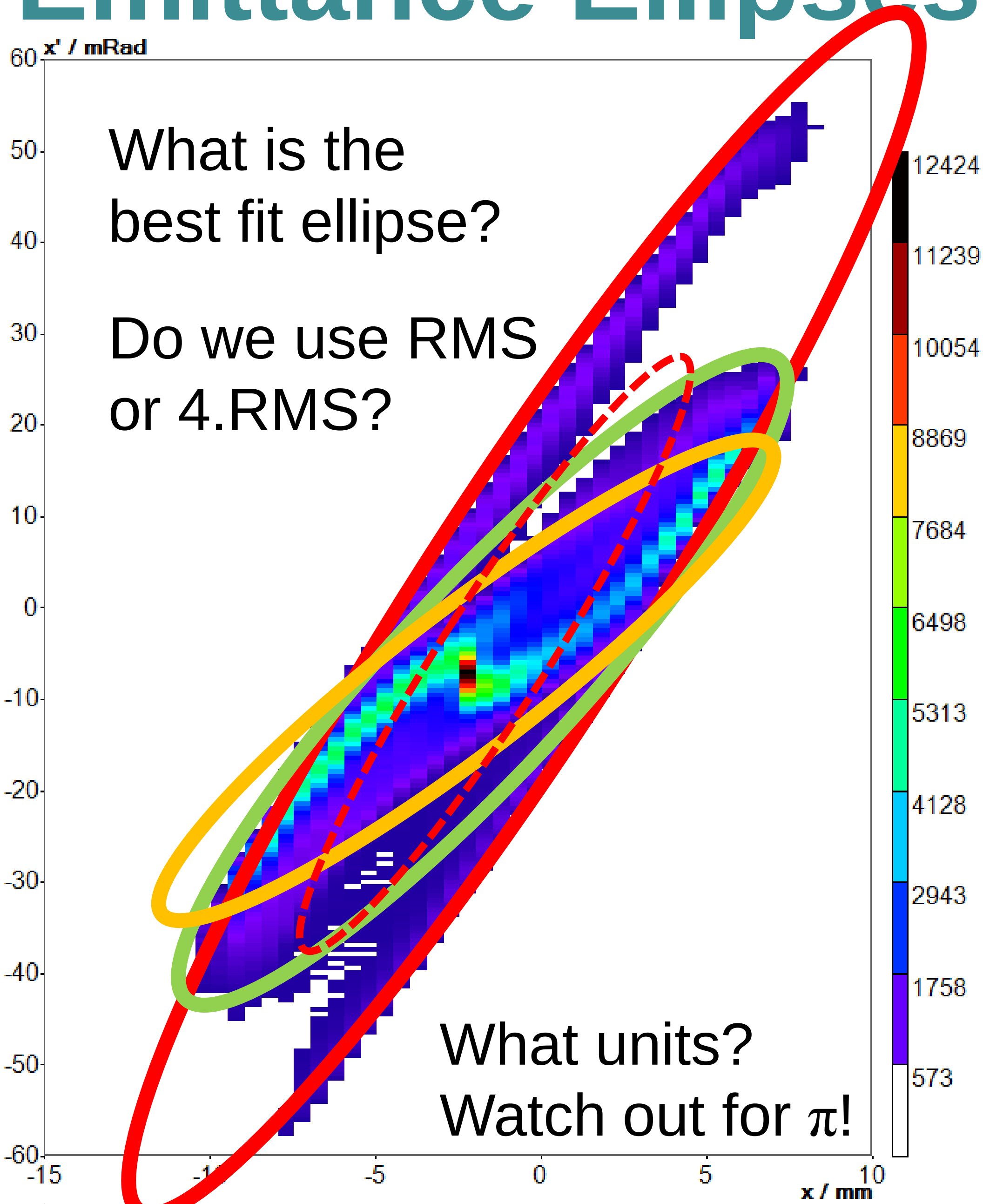
Emittance

- 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)





Emittance Ellipses and Pitfalls



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

High Voltage Considerations

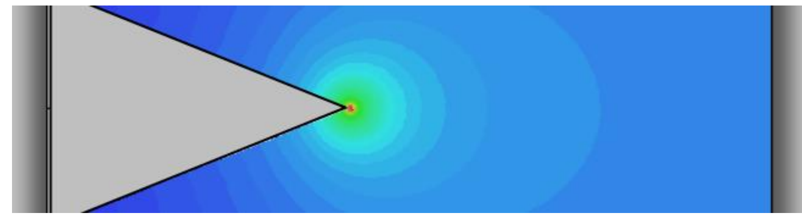
$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Particle sources have very low beam energy:

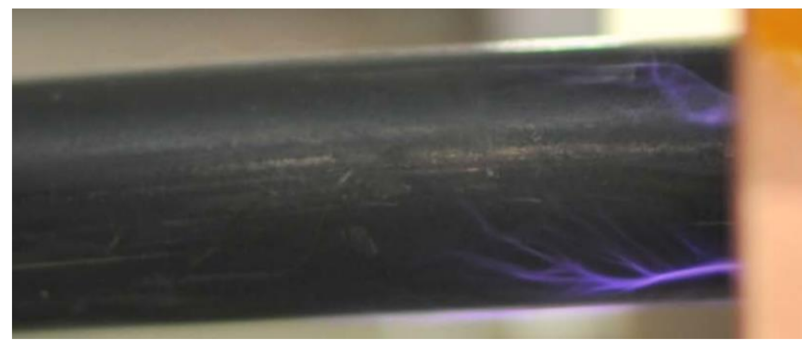
- ~~Magnetic focusing~~
- ~~Magnetic deflection~~
- ~~RF acceleration~~
- ~~Relativistic~~
- ~~Ample space~~
- High space-charge
- Dirty vacuum
- Sensitive diagnostics

HV is the only option, BUT:

Must protect insulator triple junctions



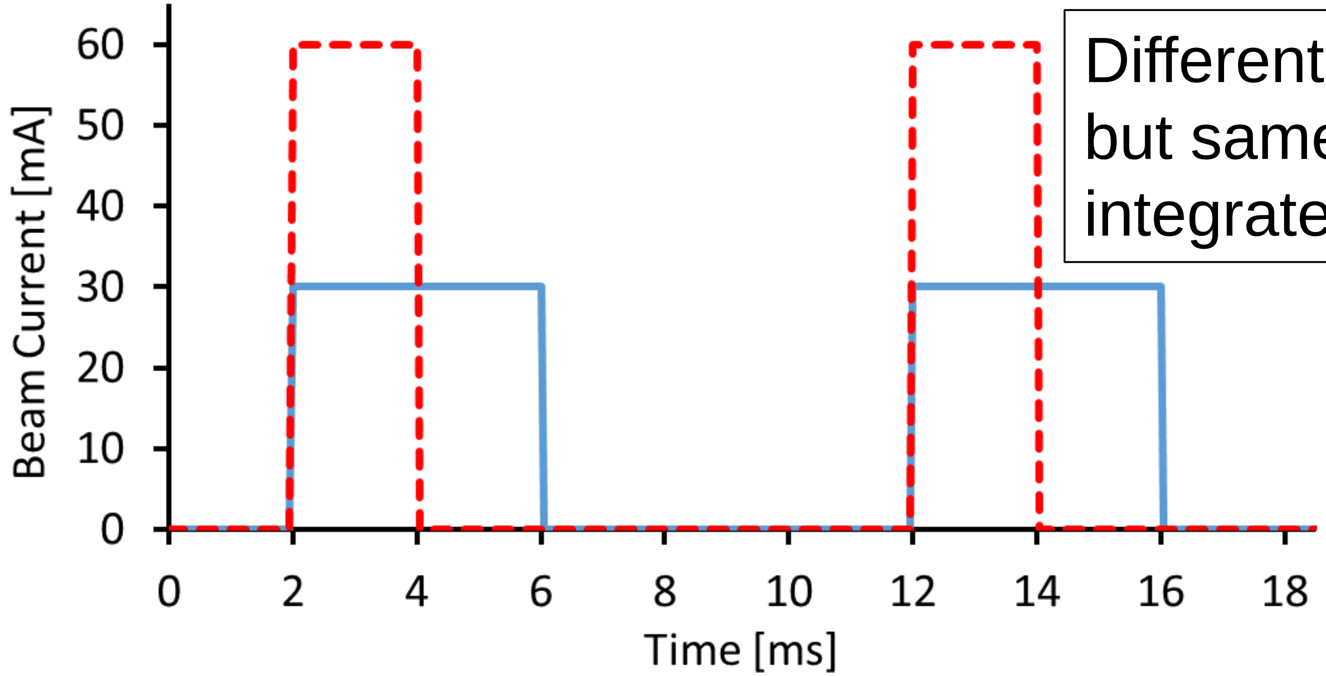
Must avoid points in E-field regions



Must ensure proper cable terminations

Timing in Pulsed Sources

- Usually only need beam a fraction of the time
- However, more difficult to make pulsed power supplies



Different D.F.%
but same total
integrated charge

Duty Factor = Pulse Length x Repetition Rate

e.g. ISIS: 200 µs x 50 Hz = 1% Duty Factor

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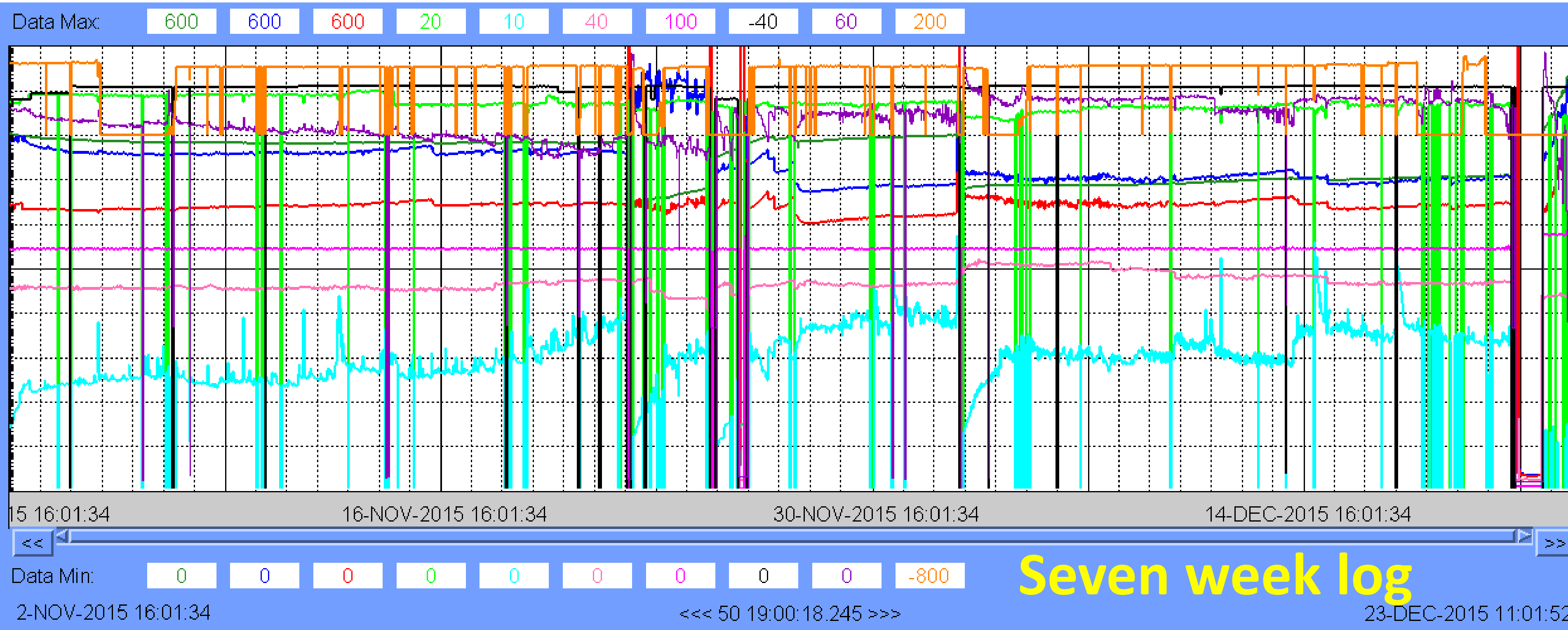
Reliability and Stability



Channel List | Statistics

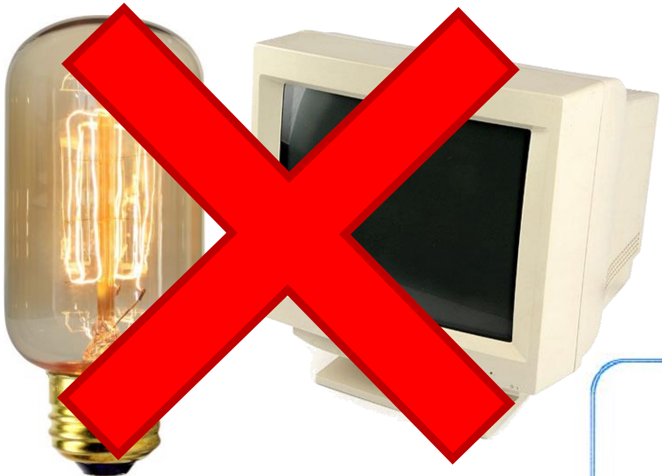
#	Y source	Color	Value	Time	Units	Cursor Value
1	IRFQ::CATHODE:READ_TEMP		------	---------		-------
2	IRFQ::ANODE:READ_TEMP		------	---------		-------
3	IRFQ::SOURCE_BODY:READ_TEMP		------	---------		-------
4	IRFQ::EXT:READ_VOLTS		------	---------		-------
5	IRFQ::EXT:READ_CURRENT		------	---------		-------
6	IRFQ::H2_GAS:READ_FLOW		------	---------		-------
7	IRFQ::ARC_AC:READ_CURRENT		------	---------		-------
8	IRFQ::PLATFORM:READ_VOLTS		------	---------		-------
9	IRFQ::IS_TOROID:READ_CURRENT		------	---------		-------
10	LOCAL::BEAM:TARGET		------	---------		-------

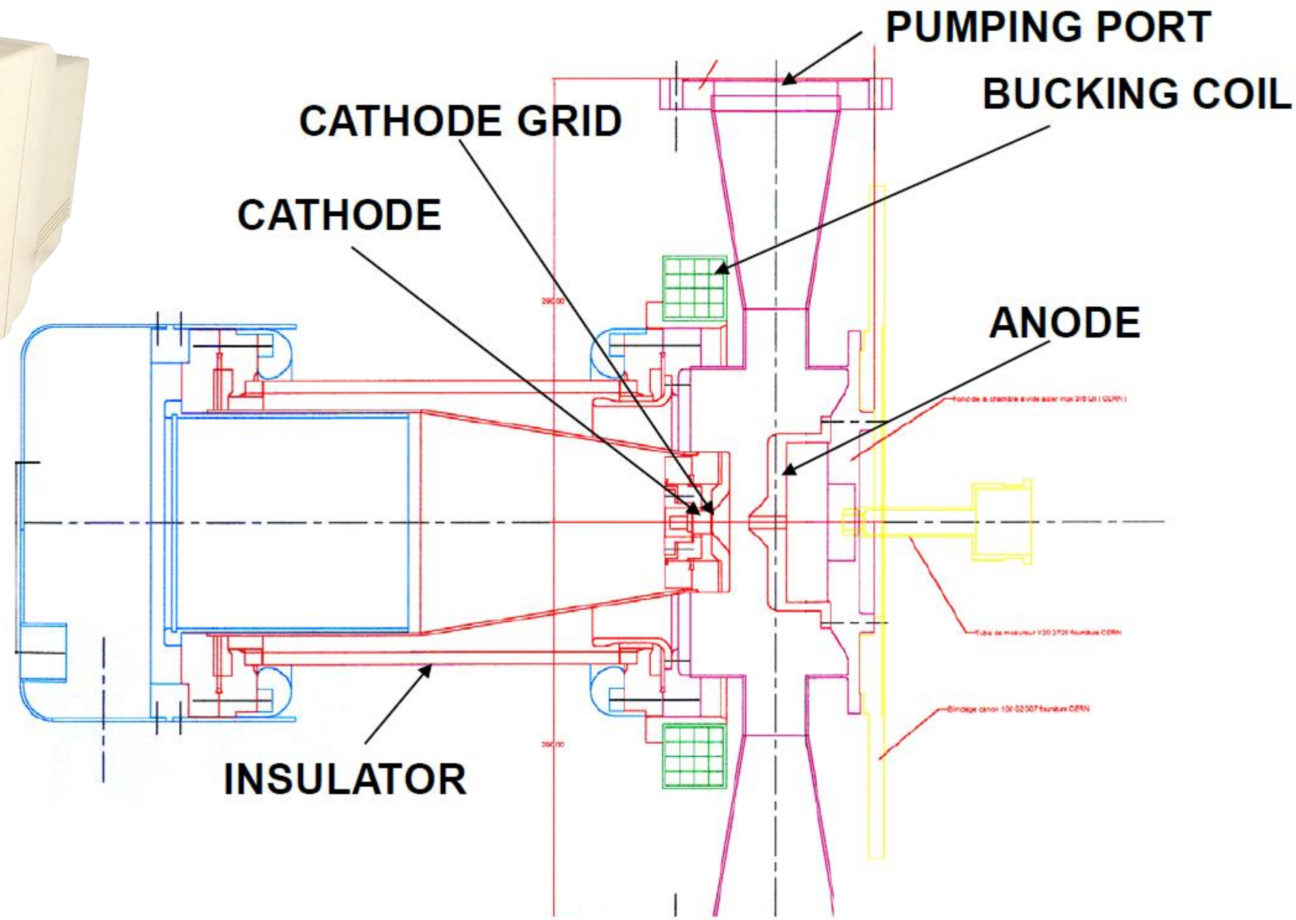
Archive: CON_ROOT:[data.logging.vlog-irfq]irfq_vlog.varc

Summary of Fundamentals

- Electrons released from hot surfaces
- Lower work-function materials release more electrons
- Space-charge limit to amount of extractable current
- Extraction systems described by their perveance
- Particle beams described by their emittance
- Many ways to define emittance and its units: be careful
- Must consider high voltage engineering requirements
- Usually need specialist pulsed power supplies
- **Reliability** dominates all other performance goals
- Now we can move onto real particle sources…

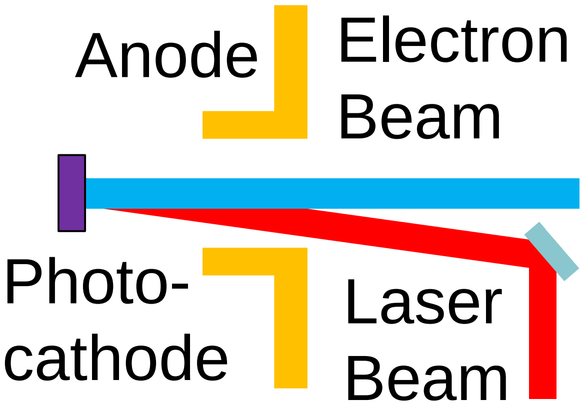
Thermionic Electron Gun





W dispenser cathode with impregnated BaO:CaO:Al2O3

Photocathode Electron Guns



- Use low work function cathode
- Raise temperature
- Fire laser onto it
- Accelerate e-beam
- Bunch timing set by laser pulses

Material	Type	(E_{gap} + E_{Aff}) * or ϕ_{work} [eV]	λ [nm]	Q.E. $
W	Metal	4.5	375	10^{-6}
W:Th	Metal	2.6	477	10^{-5}
Cs	Metal	1.81	685	10^{-3}
LaB_6	Ceramic	2.6	477	10^{-6}
GaAs:Cs	Semi-cond.	2.3	532	~0.10 &
Cs_2Te	Semi-cond.	3.5	350	0.12
K_2CsSb	Semi-cond.	2.1	590	0.29

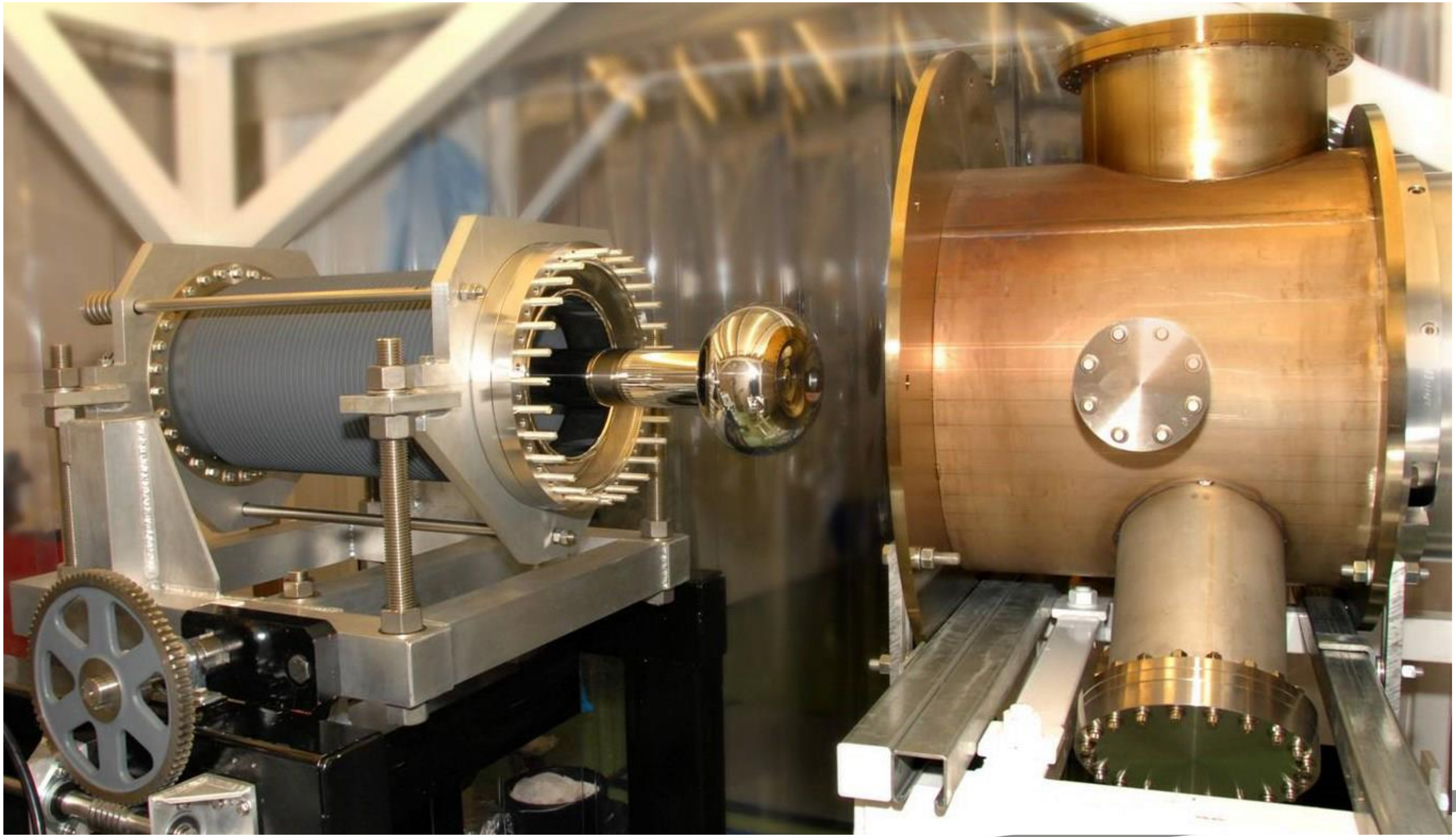
* In semi-conductors, the equivalent to work function ϕ_{work} is (band-gap + electron affinity)

$ Q.E. = Quantum efficiency = Electrons/Photon

& Vacuum-dependent

DC Photocathode Gun

ALICE @ DL



350 kV DC, 80 pC bunch, GaAs:Cs

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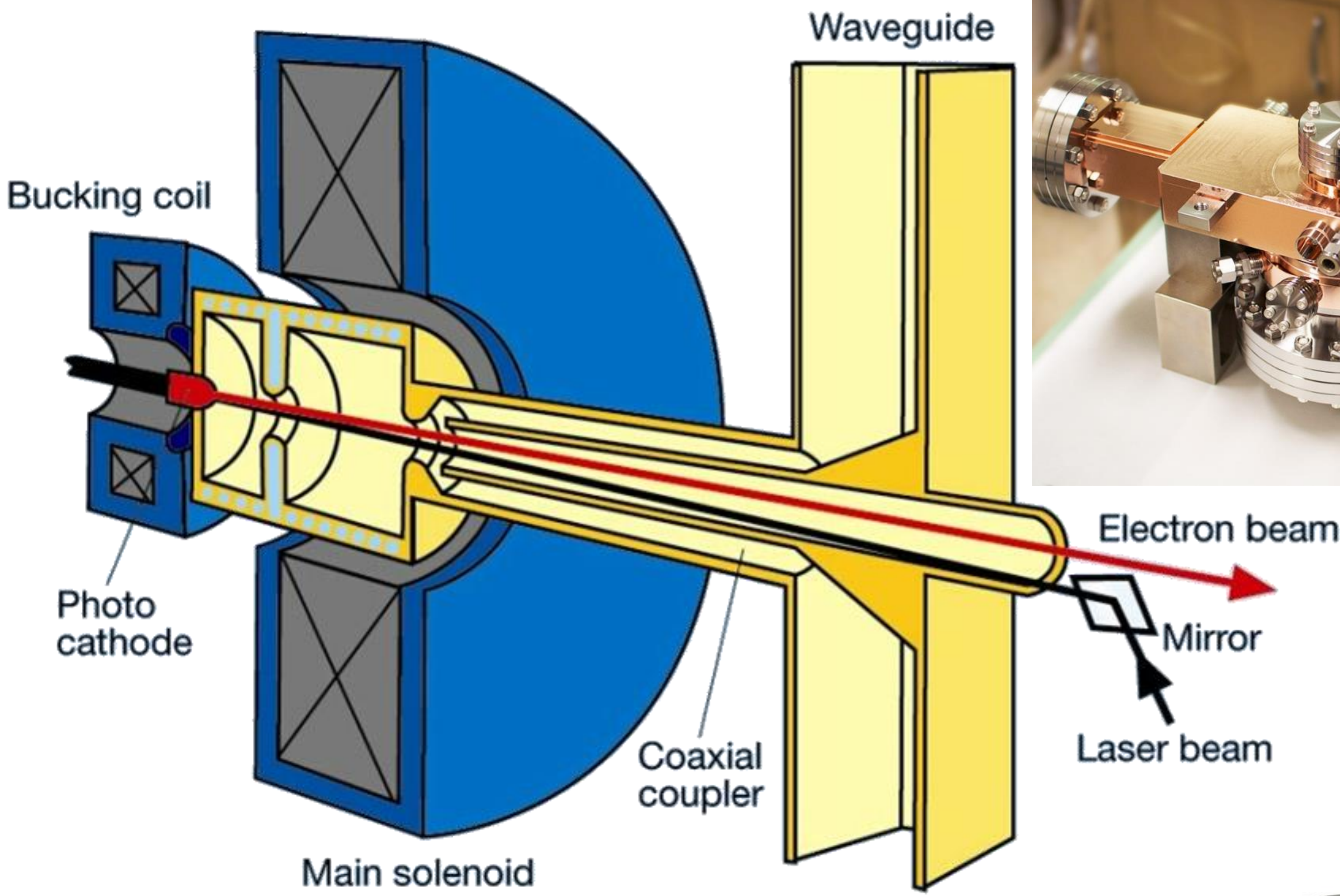
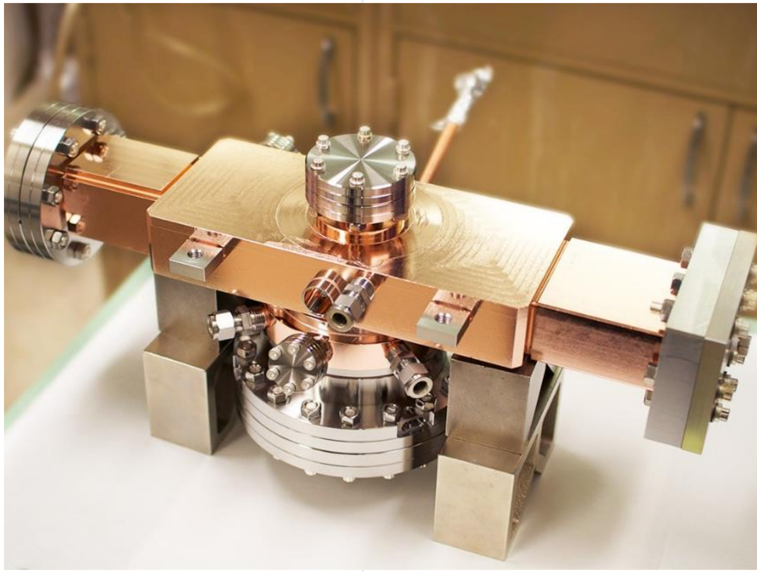
RF Photocathode Gun

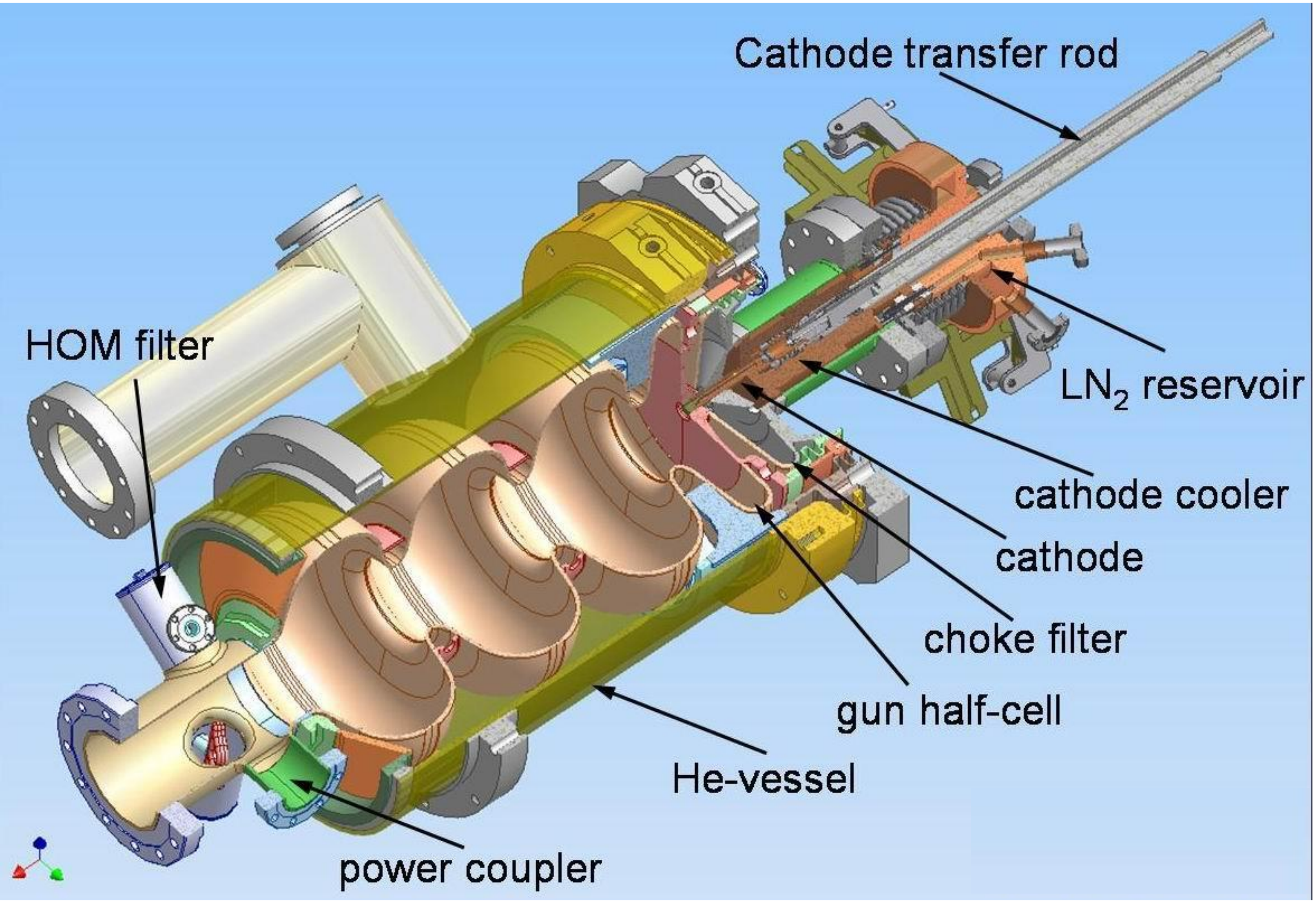
FERMI2 @ Trieste





3 GHz RF
50 Hz laser
Q.E. ~$3x10^{-5}$
500 pC bunch
5.1 MeV beam

Superconducting RF Gun SRF2 @ ELBE



Cs_2Te cathode
1.3 GHz CW RF
13 MHz UV laser
200 pC bunch
4.5 MeV beam

Main issue with all photoinjectors using Cs_2Te cathodes is the need to replace the cathode after ~100 hours

Most are Plasma-Based Sources

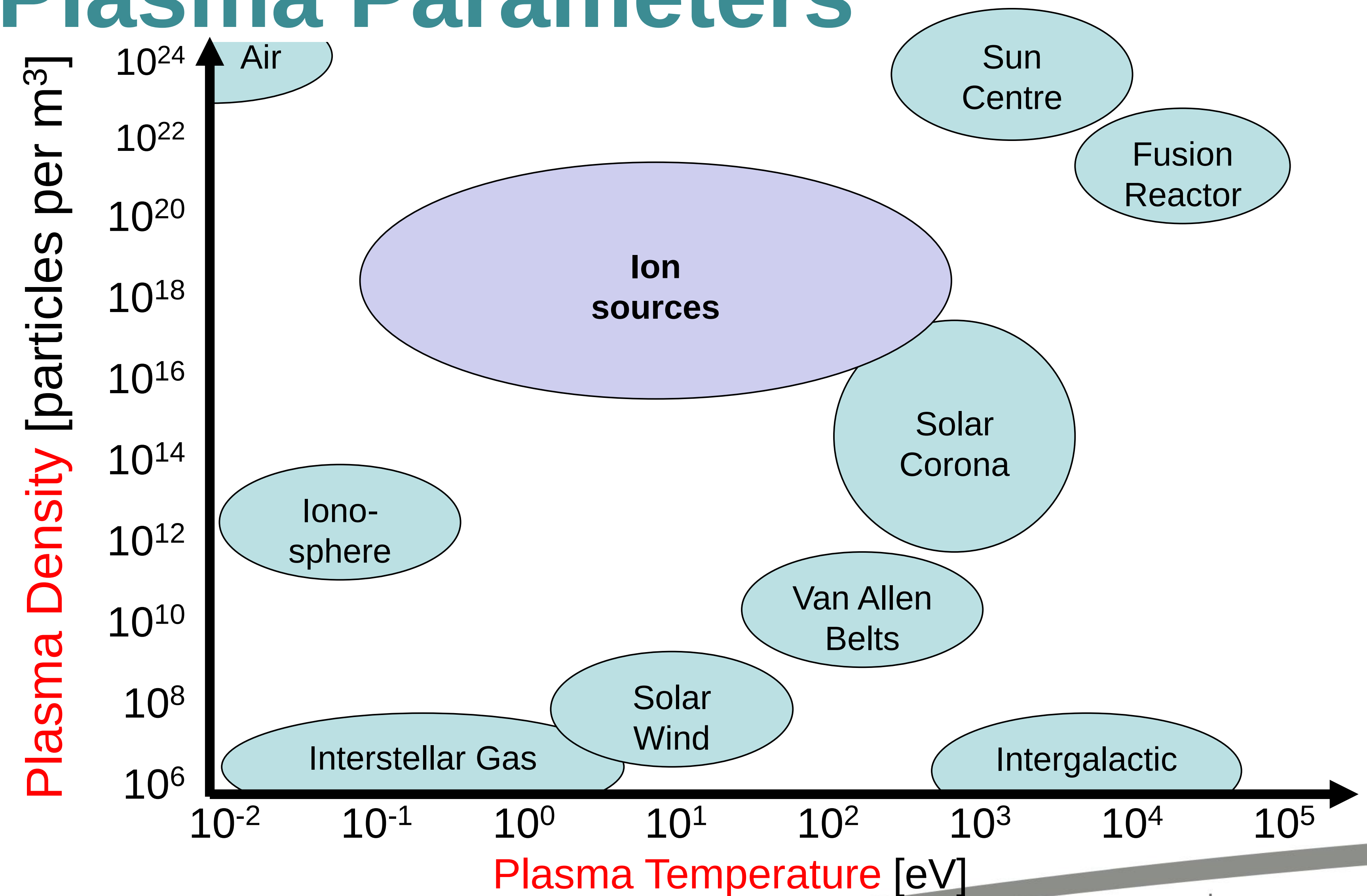
Species

- Electron
- Proton
- Light Ion
- Heavy Ion
- Negative Ion
- High Charge State
- Radioactive
- Spin-Polarised
- Neutral
- Muon
- Exotic

Technique

- Filament
- Photocathode
- Arc Plasma
- Laser
- Microwave
- RF
- Cyclotron-Resonance
- Duopigatron
- Duoplasmatron
- …

Plasma Parameters



1 eV ≈ 11,600 K

Plasma Fundamentals

- Maxwell-Boltzmann temperature-dependent velocity:

$$f(\vec{v}\,) = \frac{n}{\left(\sqrt{2\pi}\, v_T\right)^3} e^{\left(-v^2/_{2\langle v\rangle^2}\right)} \qquad \text{with} \qquad \langle v\rangle = \sqrt{\frac{k_B T}{m}}$$

- Debye length is distance charge perturbations can exist:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{n_e e^2}}$$

- Electrons react to perturbations at the plasma frequency:

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$$

Plasma Fundamentals

- Particle collision frequency depends on cross-section:

$$\langle \omega_{en} \rangle = 2\pi \, n_n \sigma_{en} \langle v_e \rangle$$

- With a mean free path between collisions:

$$\lambda_f = \frac{1}{n_n \sigma_{en}}$$

- Electron impact ionisation examples:

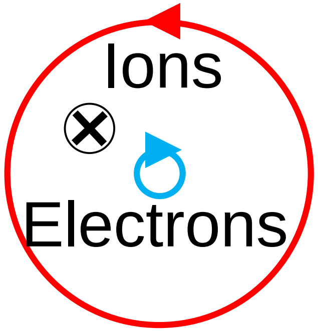
$e^- + He^0 \rightarrow He^{1+} + 2e^-$ then $e^- + He^{1+} \rightarrow He^{2+} + 2e^-$

$e^- + H_2 \rightarrow H_2^*$ then $e^- + H_2^* \rightarrow H^- + H^0$

- To ionise efficiently, need plasma confinement, usually in the form of magnetic fields

Plasma Fundamentals

- Charged particles confined transversely in a uniform B-field



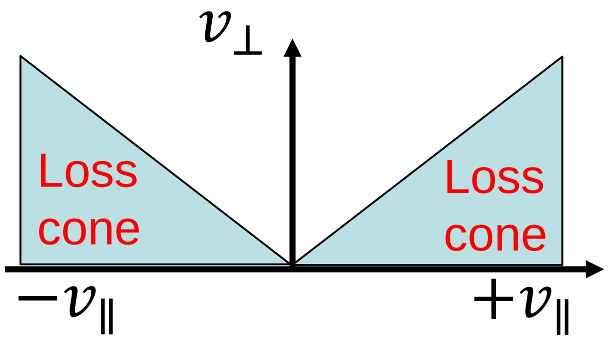
Larmor frequency: $\omega_L = \frac{eB}{m}$

(a.k.a. cyclotron)

Larmor radius: $r_L = \frac{v_\perp}{\omega_L}$

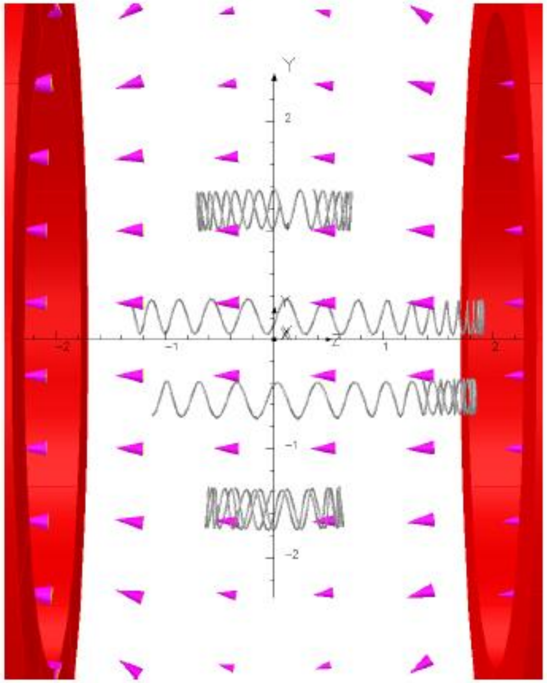
- If particles also have $v_\parallel$ and B-field is increasing into screen, get longitudinal magnetic mirror confinement with:

$$v_\parallel / v_\perp < \sqrt{\left(B_{max} / B_{min} - 1 \right)}$$

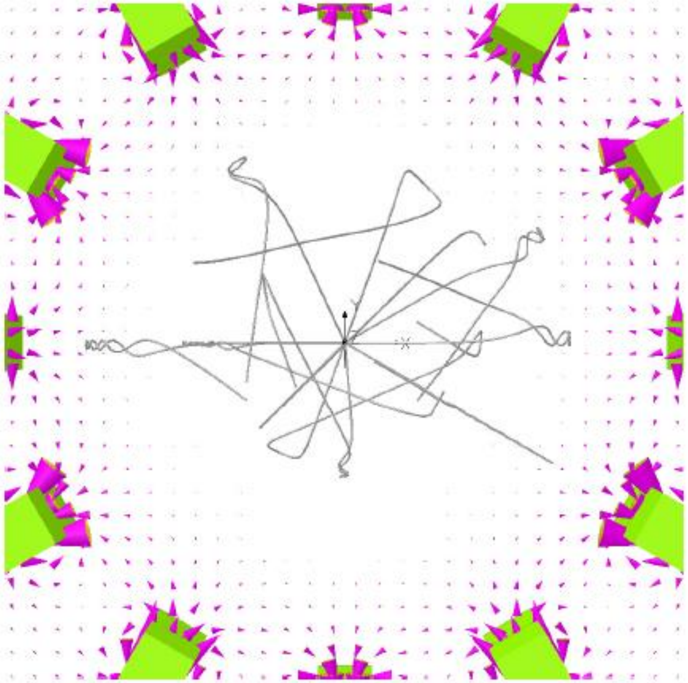


- Mirror both ends → magnetic bottle
- Also ExB, gradB, curvature & diffusion drifts

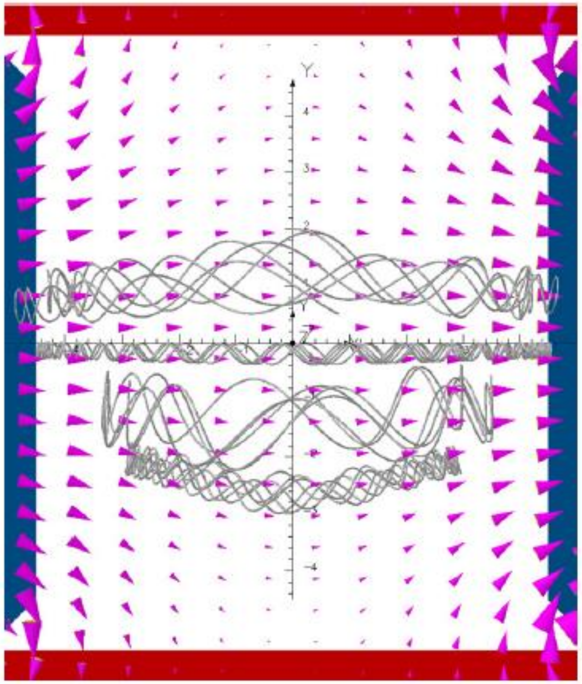
Plasma Confinement Techniques



Solenoid bottle
(often combined with hexapole cusp)



Multicusp 'bucket'
of dipoles in checkerboard pattern



Dipole magnet,
parallel cathodes and anode 'window'

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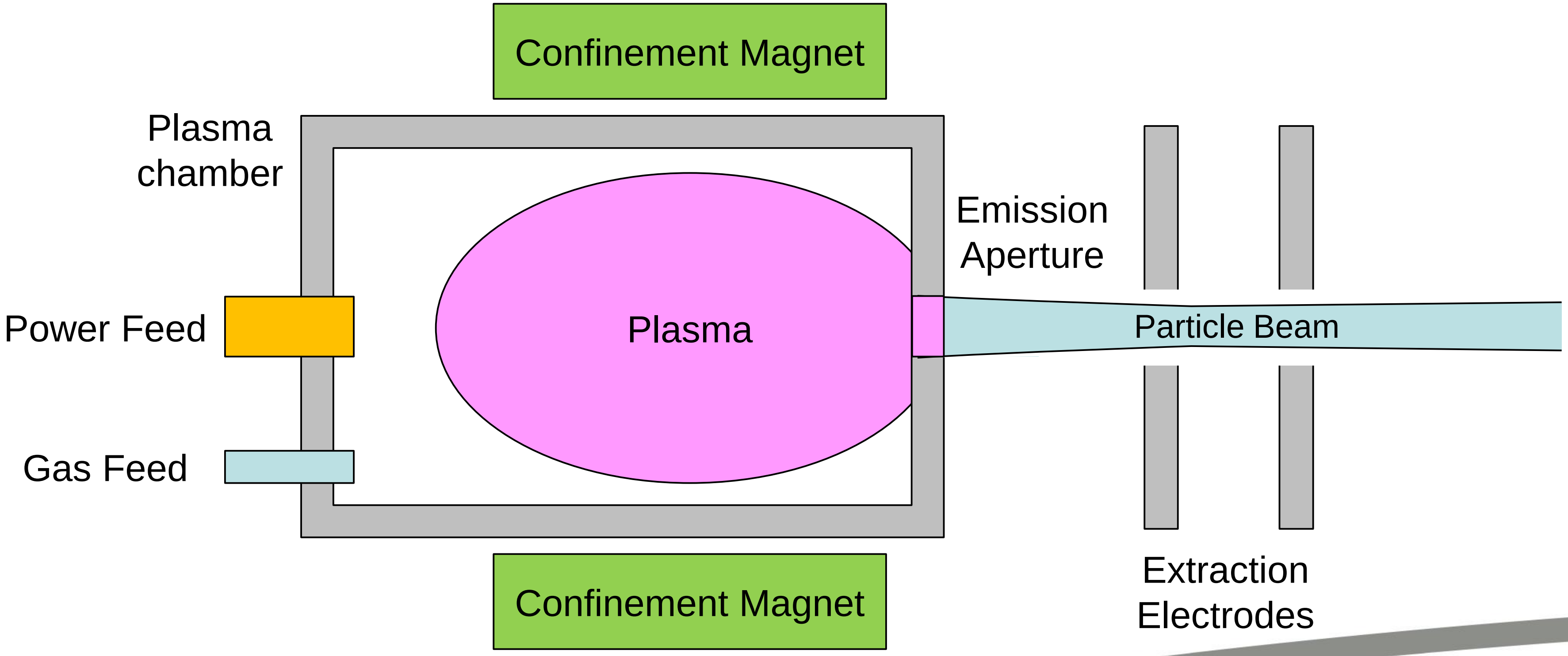
The Typical Ion Source

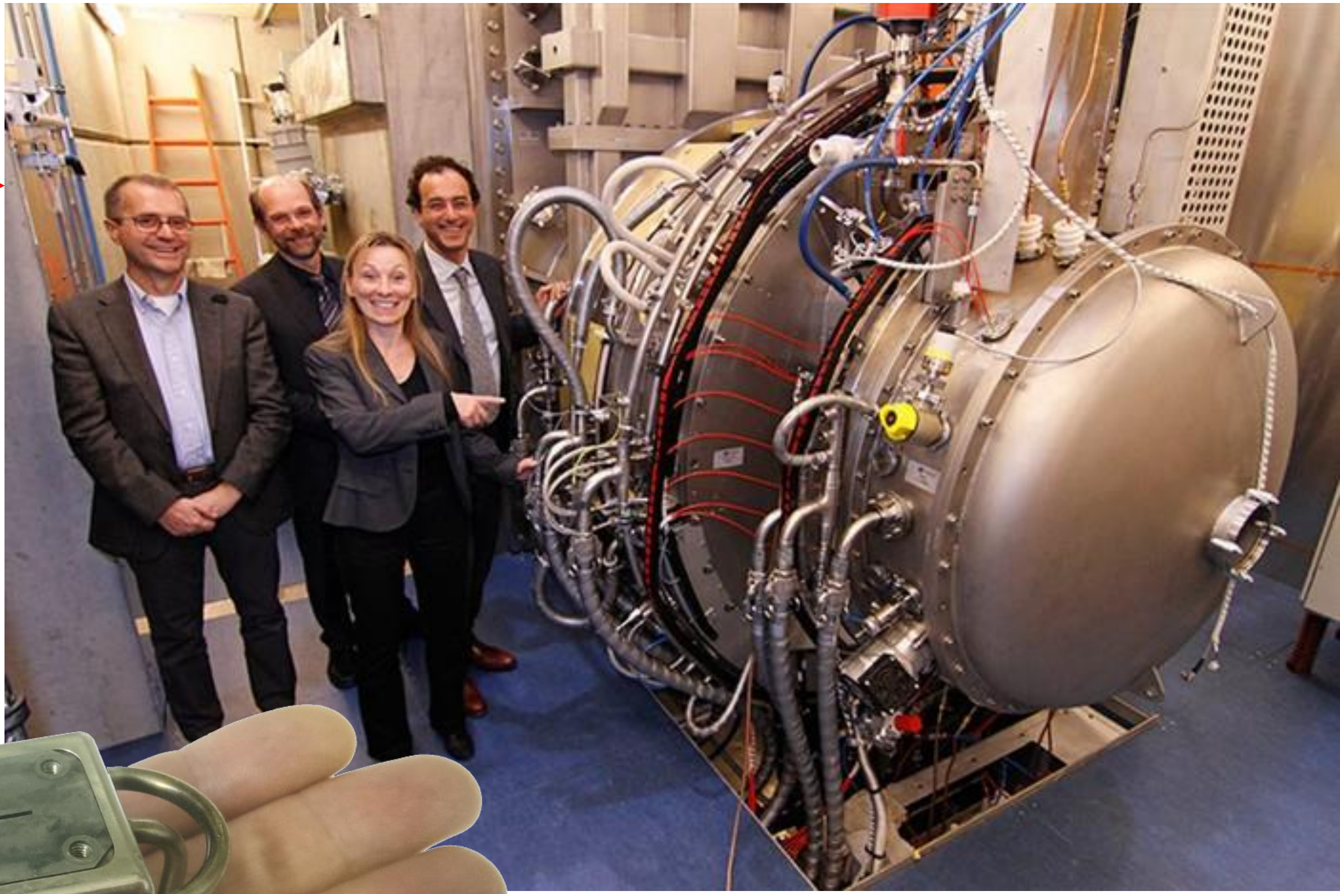
Every ion source basically consists of two parts:

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



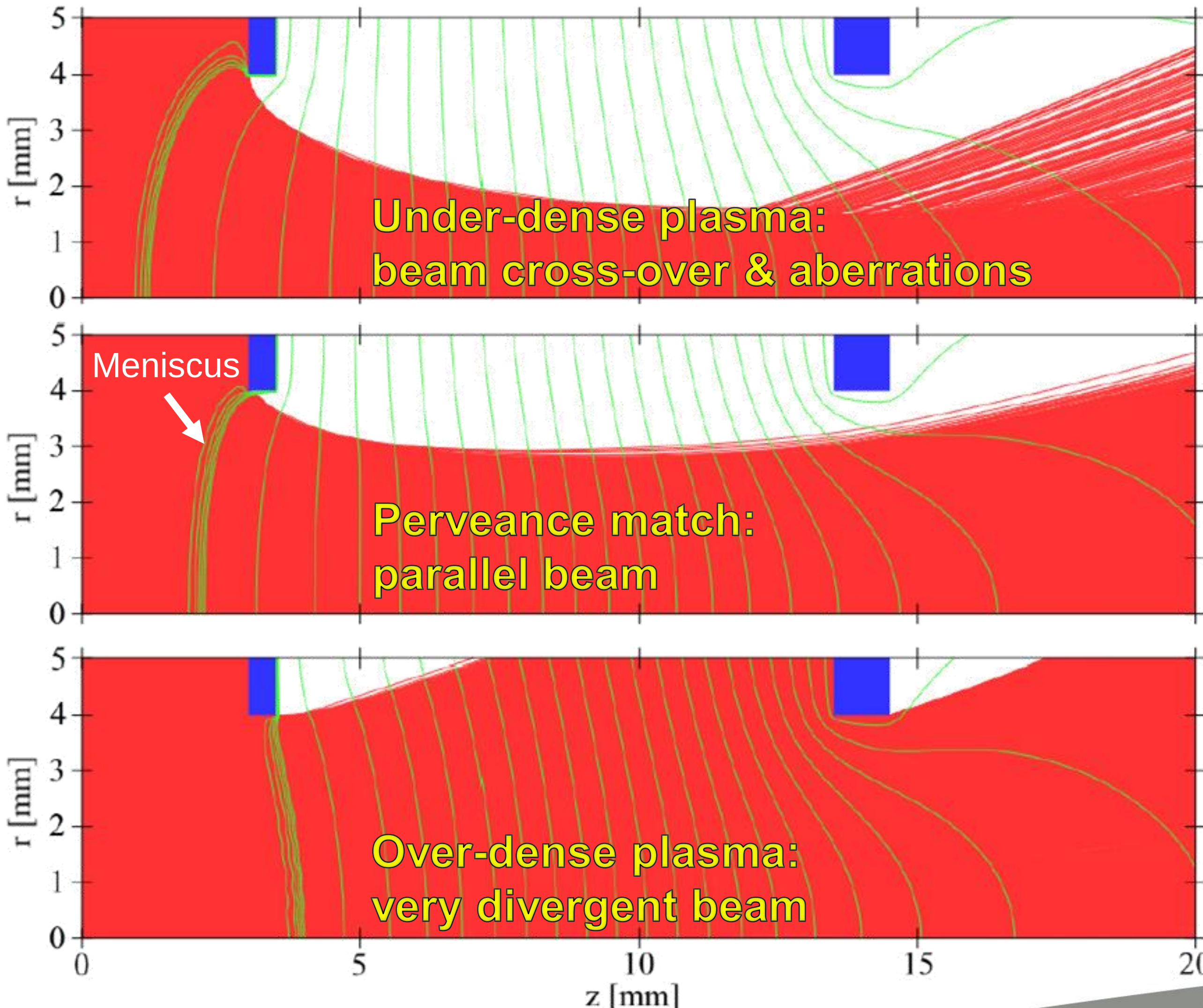
No ‘Typical’ Ion Sources!

‘ELISE’ ITER
Demonstration
H^- Source



ISIS
H^- Source

Beam Extraction



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 plasma density, extraction voltage and electrode geometry

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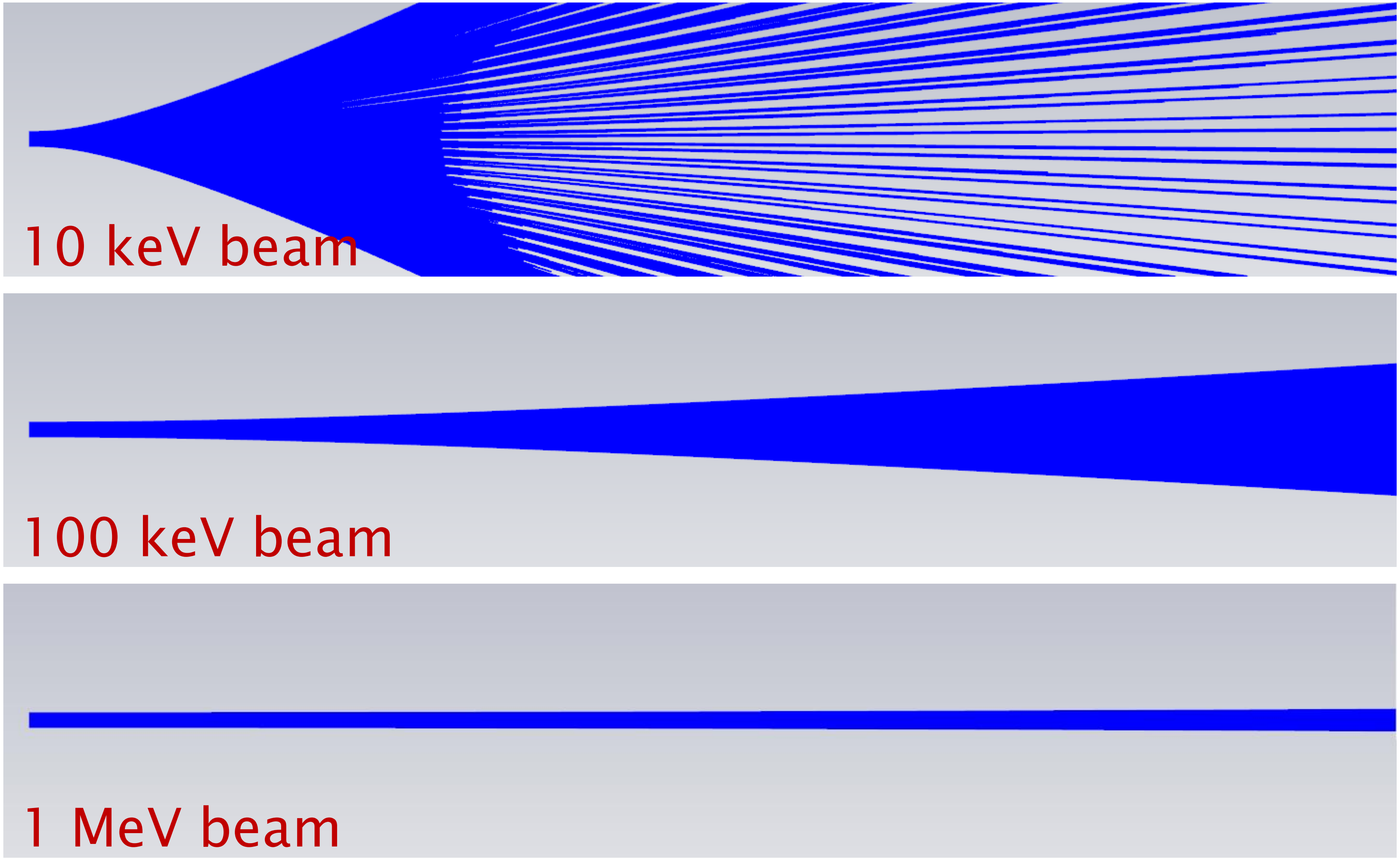
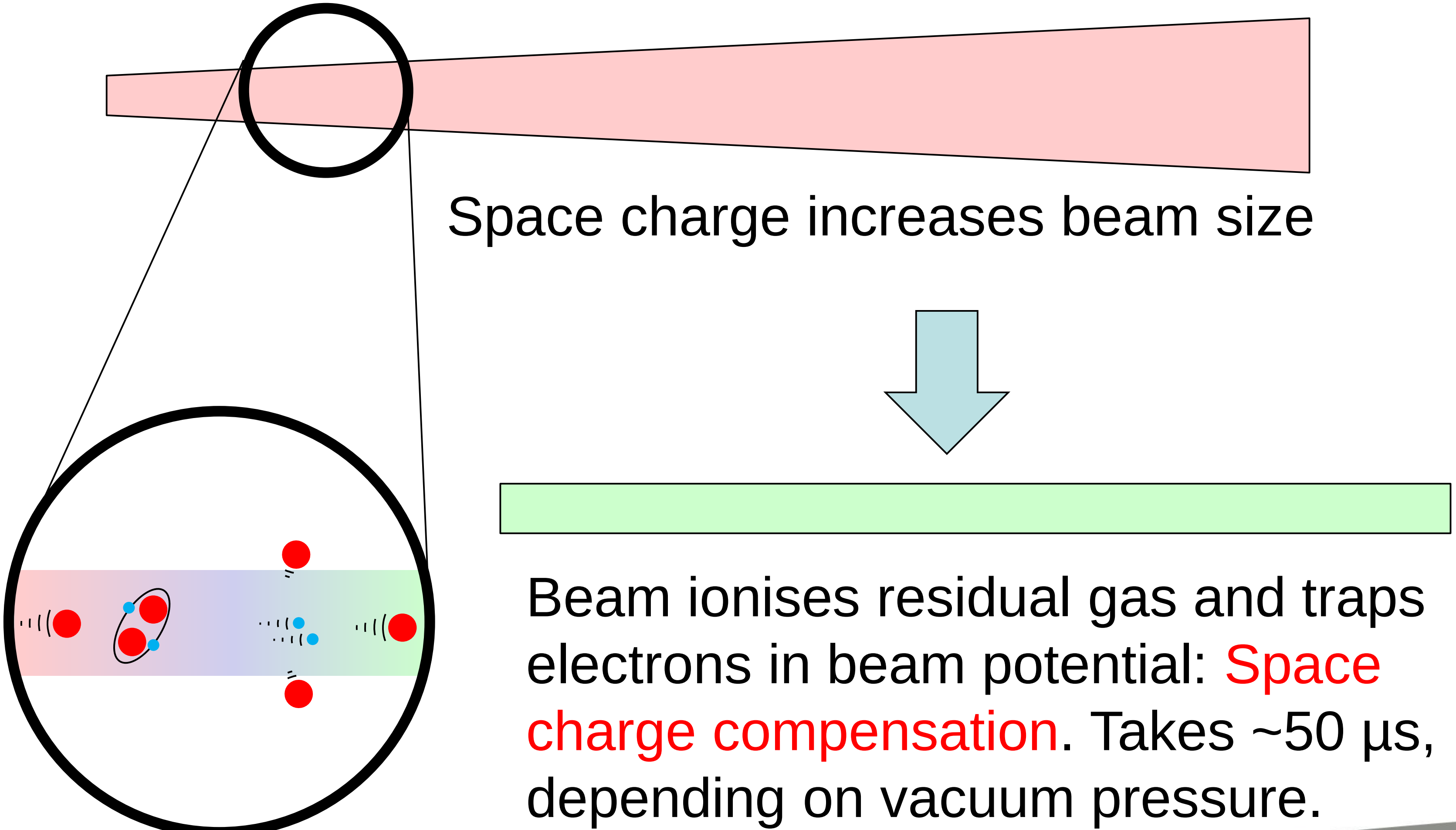
Space Charge

50mA proton beam, 5mm initial radius, drifting 1m



CONCLUSION: Need to focus and accelerate low energy beams <u>hard</u>

Space Charge Compensation



Space charge increases beam size

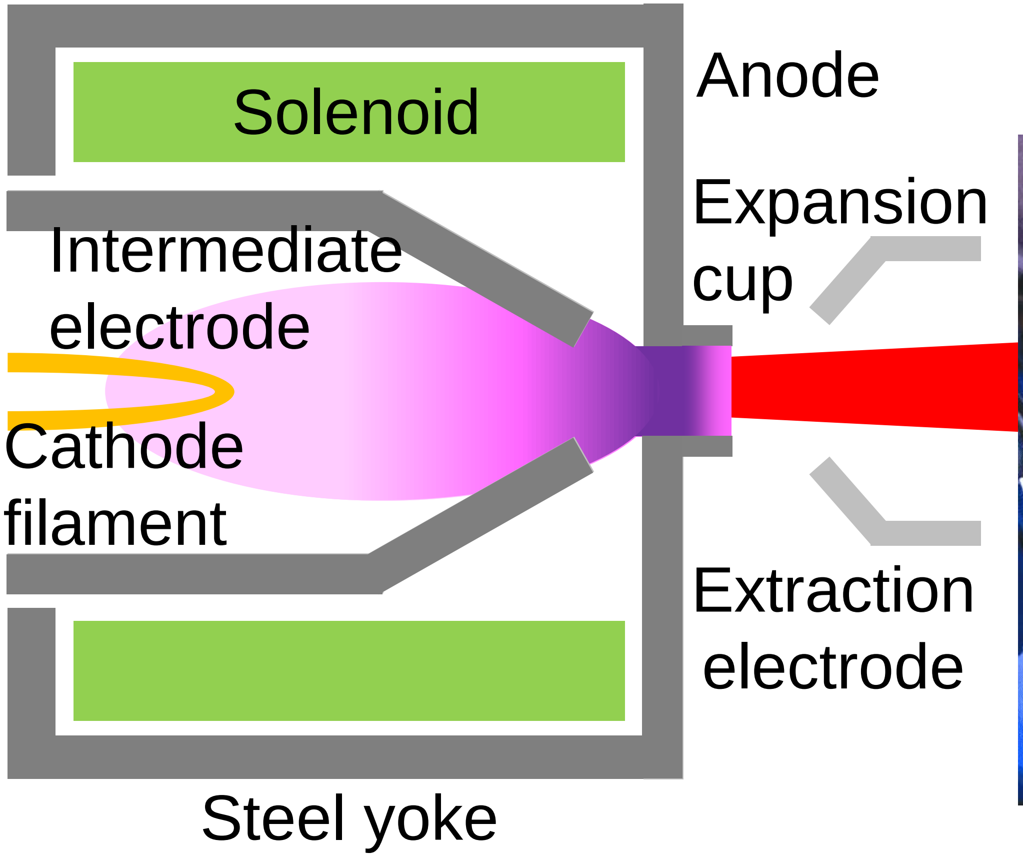
Beam ionises residual gas and traps electrons in beam potential: Space charge compensation. Takes ~50 µs, depending on vacuum pressure.

Summary of Fundamentals (2)

- Most ion sources involve plasma
- Lots of parameters to describe a plasma
- Plasmas confined with various topology magnetic fields
- After plasma is the beam extraction region
- Plasma meniscus defines initial beam focussing
- Space charge affects low energy, high mass beams
- Often attempt deliberate space charge compensation
- Now we can move onto real examples of ion sources…

Proton Sources

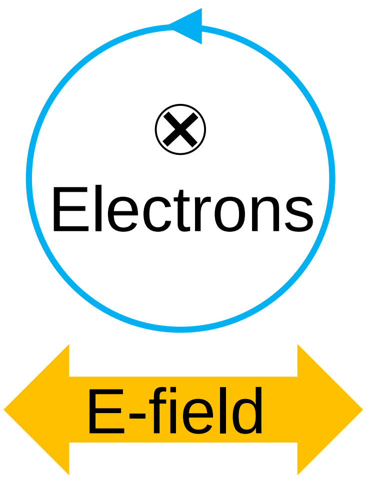
Duoplasmatron
CERN Linac2 1956
300 mA protons
150 µs, 1 Hz

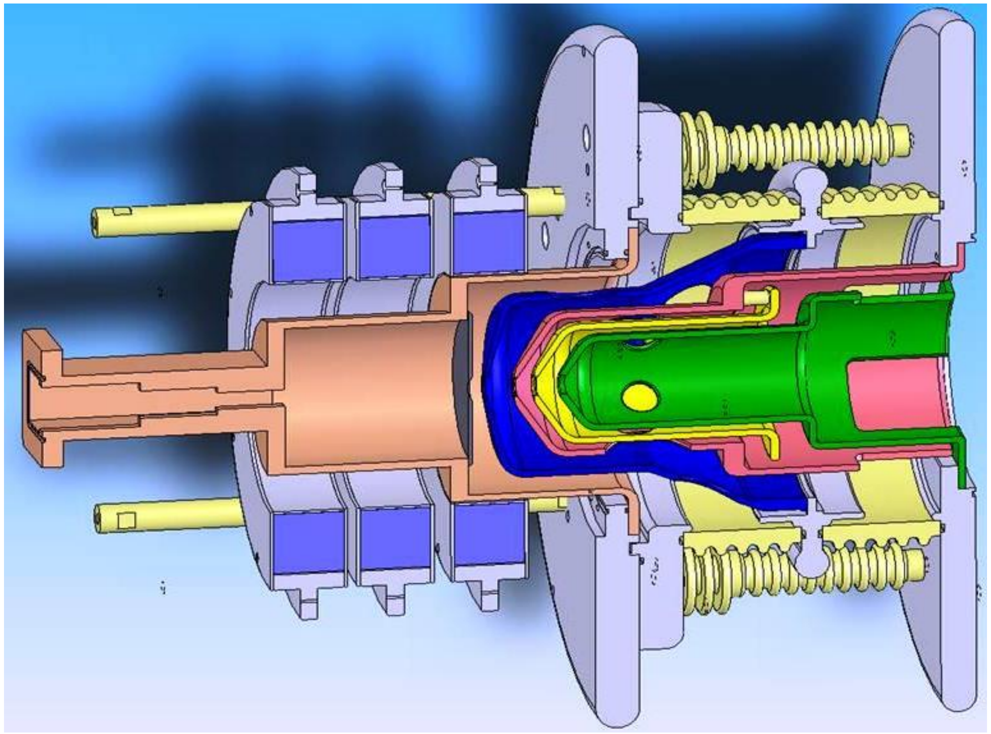


Proton Sources

2.45 GHz ECR
SILHI @ CEA, INFN, ESS…
120 mA protons
All duty factors up to 100%

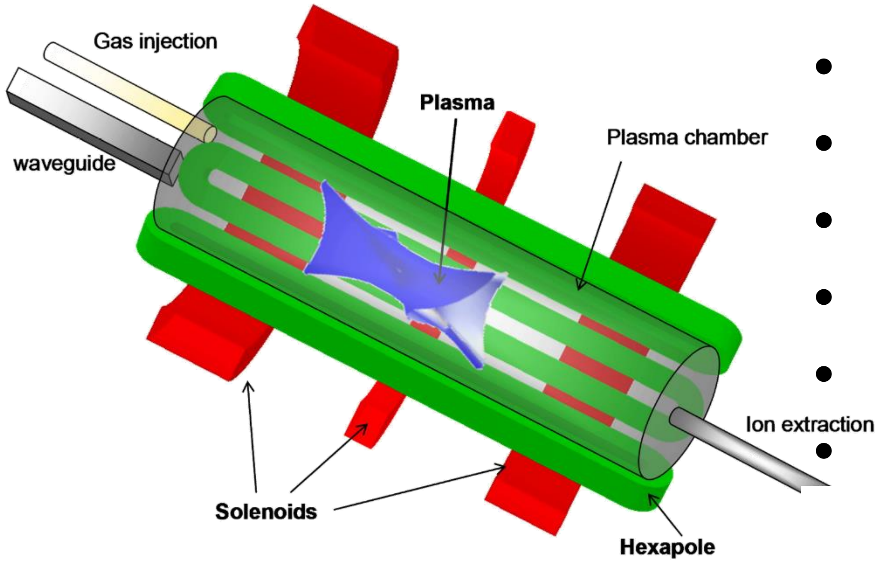
- RF cavity immersed in axial solenoid field
- Select RF frequency to match Larmor frequency
- Electrons gain energy
- Increases ionisation rate



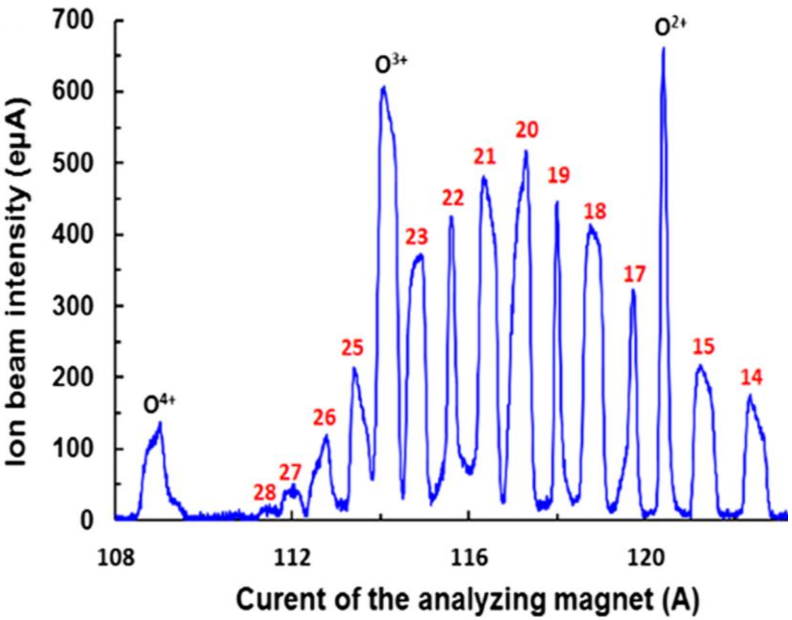


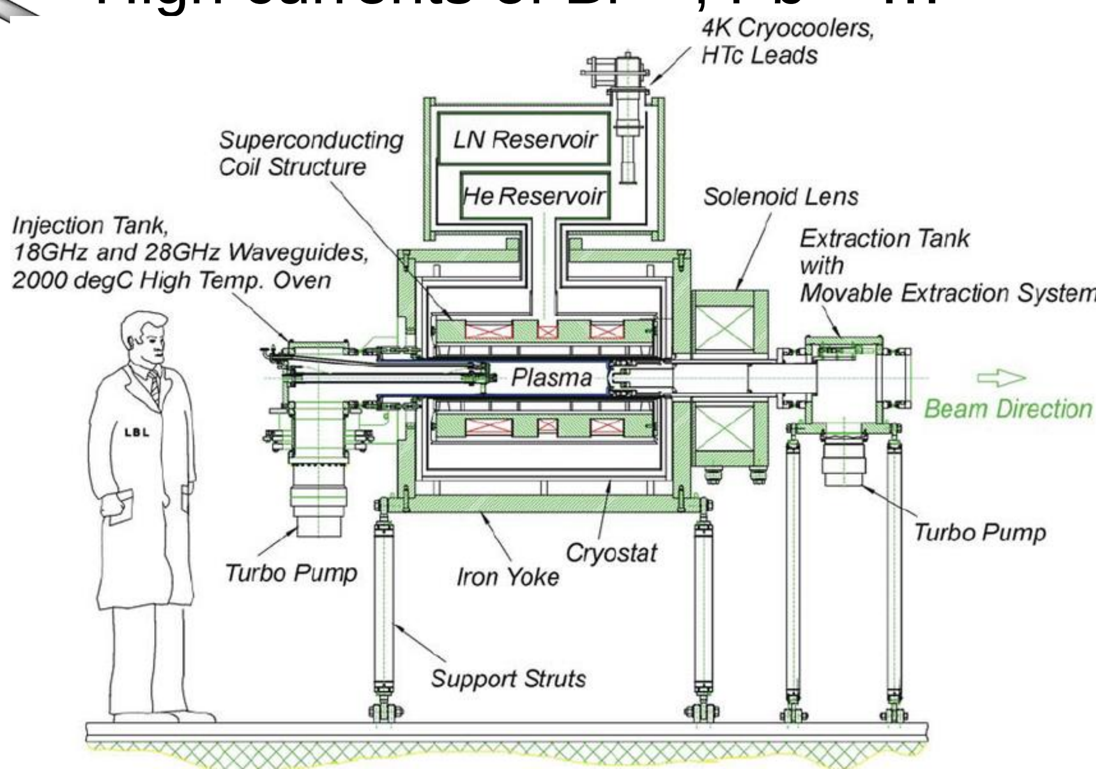
Electron Cyclotron Resonance (ECR)

High Charge State Sources



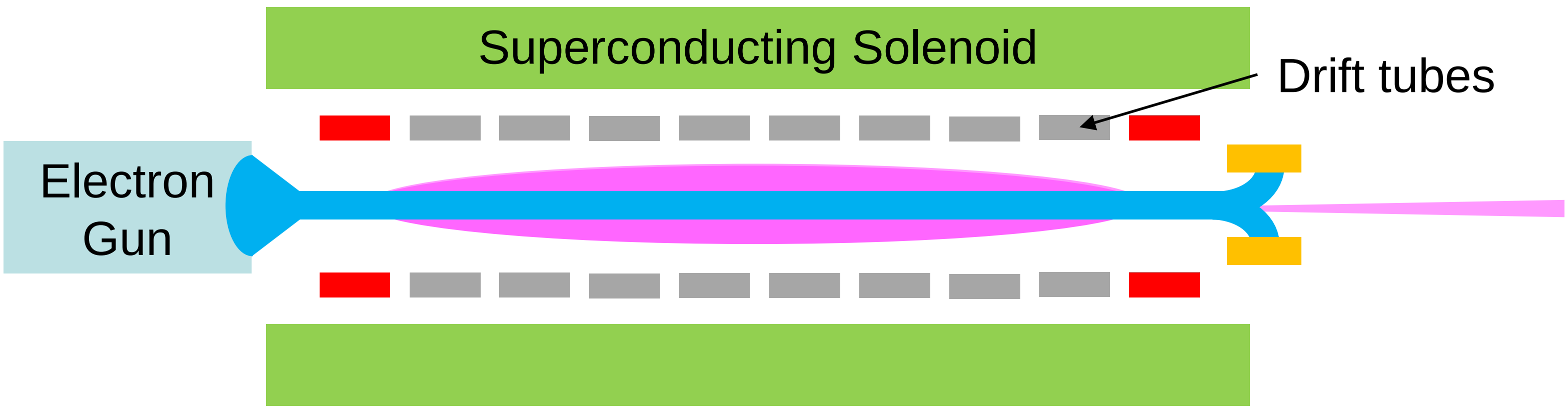
- Hexapole transverse confinement
- Higher frequency → stronger B
- Superconducting magnets
- Large and very expensive!
- SECRAL & VENUS 28 GHz ECRs
- High currents of Bi^{20+}, Pb^{34+}…





High Charge State Sources

- High power electron beam ionises gas
- Ions trapped and undergo step-wise ionisation
- Remove trapping voltage to release ions



Electron Beam Ion Source

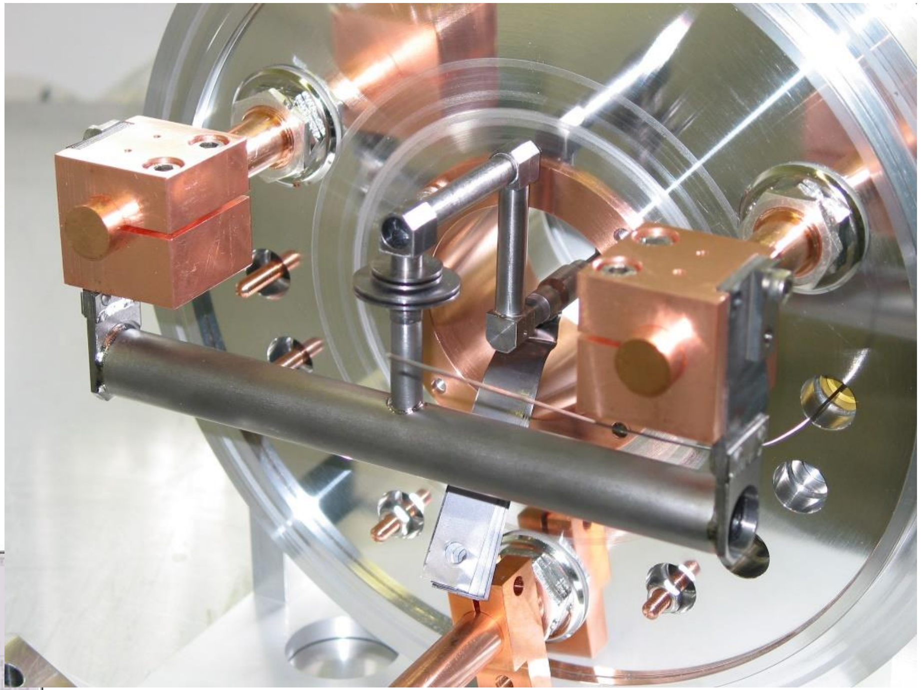
- EBIS @ RHIC
- 10 A electron gun
- 5 T, 1.9 m ion trap
- Au^{32+}, U^{39+}…
- 10 μs, 5 Hz pulses

Charge Breeders & ISOL

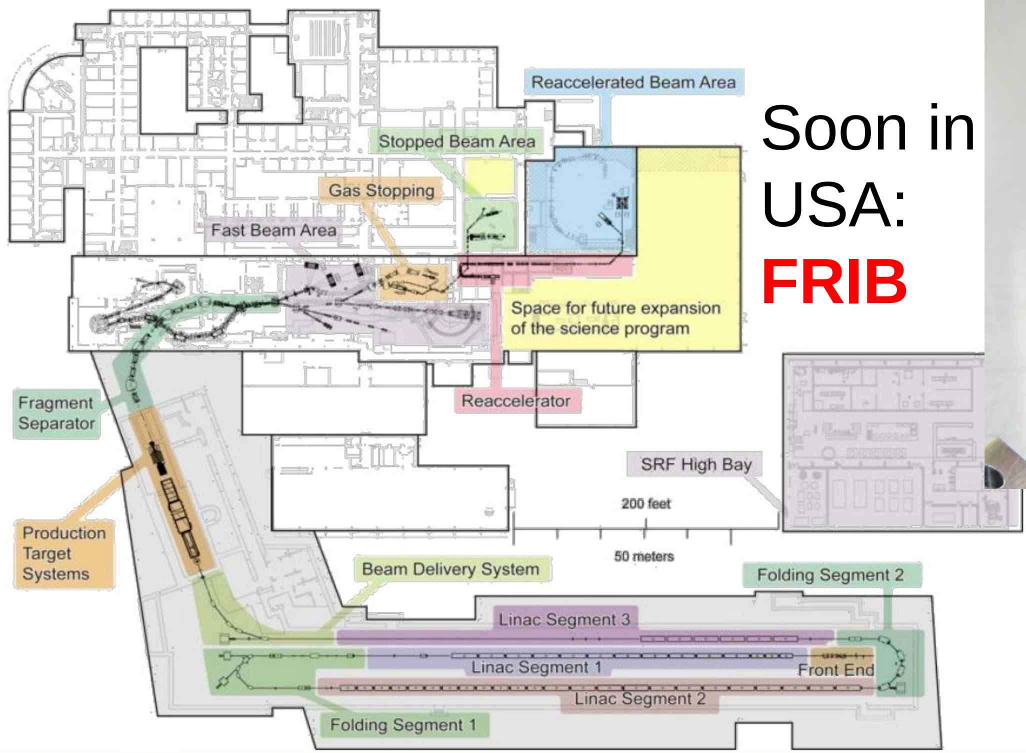
(Isotope Separation On-Line)

- Impact protons onto target
- Radioactive ions emerge
- Further ionisation in plasma
- Extract and (quickly!) accelerate and analyse
- Study very exotic nuclei

ISOLDE @ CERN
10^7 ^{132}Sn per second



Soon in USA: **FRIB**



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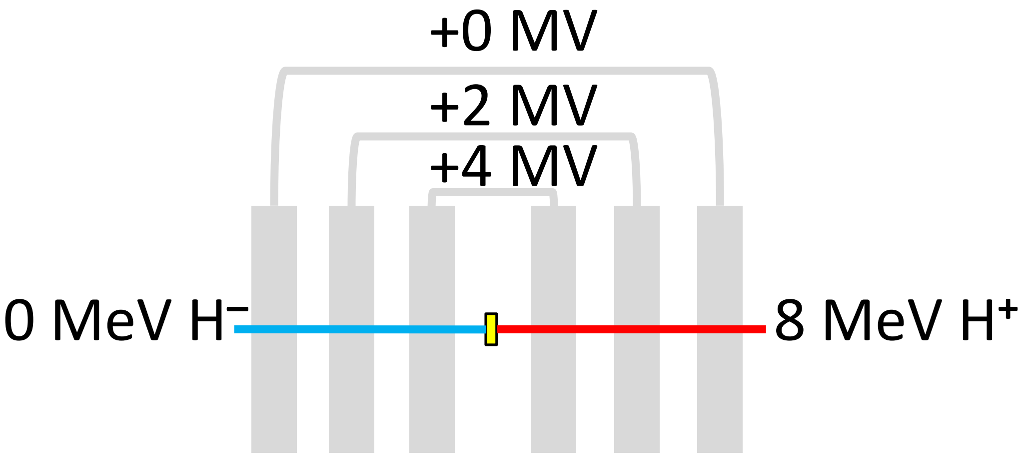
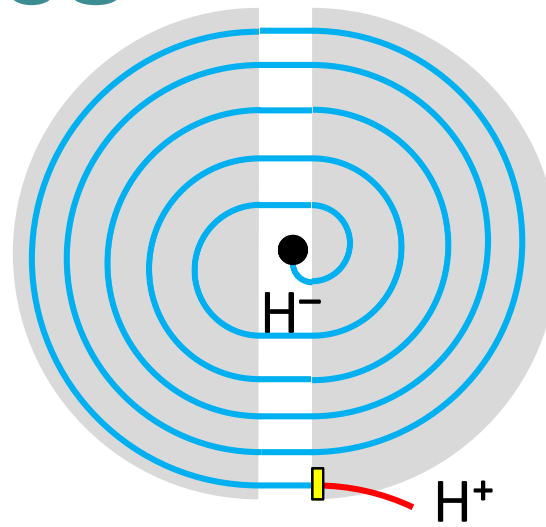
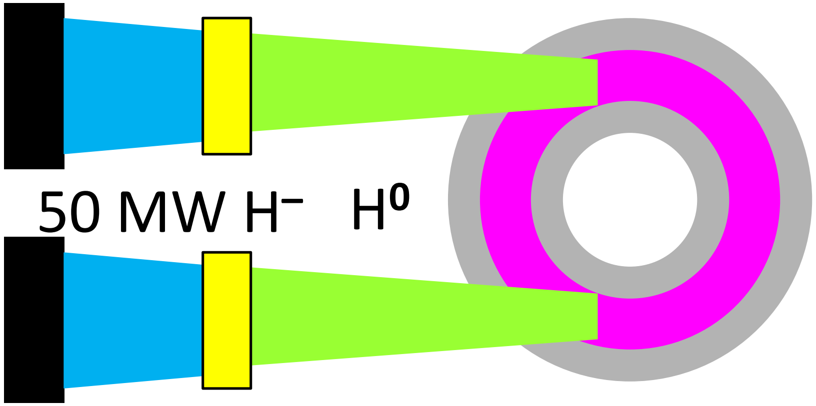
Negative Ion Sources



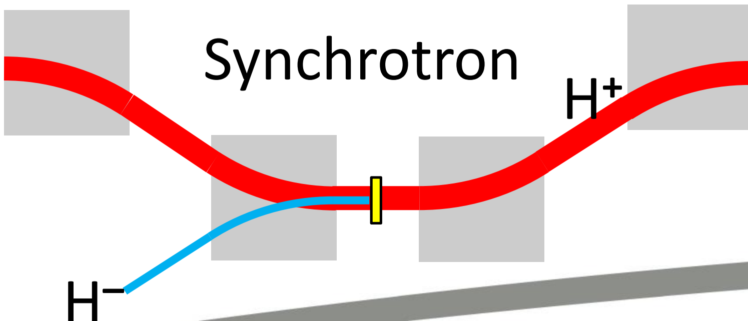
Tandem



Cyclotron



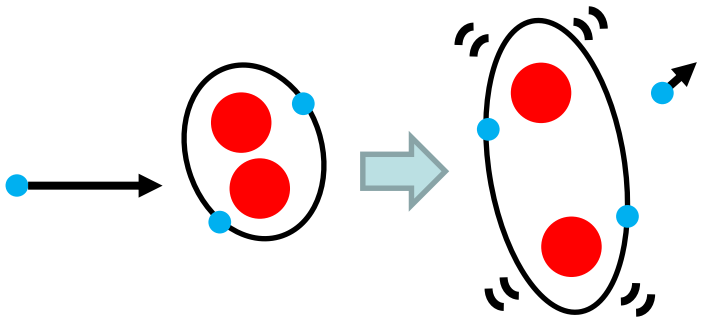
Tokamak



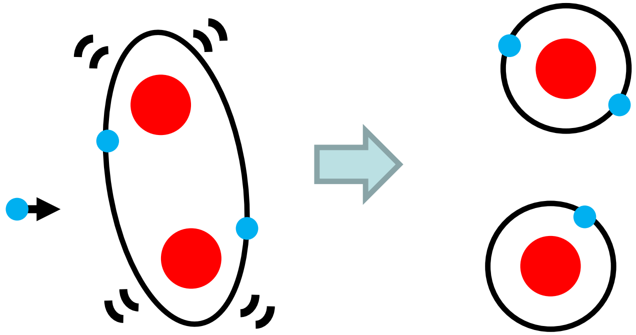
Synchrotron

H^- Ion Production Methods

Volume Production
(H^- beams $\lesssim$ 40 mA)

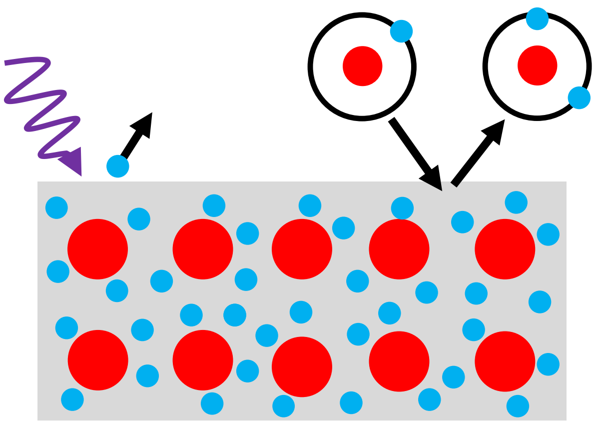


$$e_{fast} + H_2 \;=\; H_2^* + e_{slow}$$



$$e_{slow} + H_2^* \;=\; H^- + H^0$$

Surface Production
(H^- beams $\gtrsim$ 40 mA)



Low φ_{work} metals release electrons

Alternatively, energetic atoms hitting surface can take a free electron, creating H^-

Caesium: a Blessing and a Curse

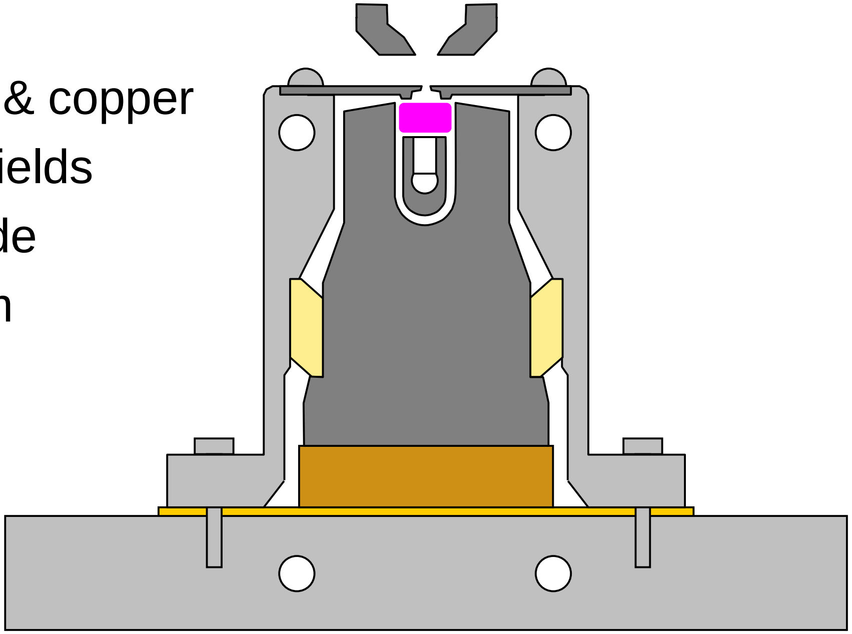
Good Points	Bad Points
• Allows copious H^- production	• Increases rate of HV sparking
• Reduces co-extracted e^- current	• Makes vacuum vessel messy
• Allows high current plasma arc	• Highly explosive AND toxic
• Stabilises plasma	• Hard to work with and expensive
• Nothing else as effective	• Reduces ion source lifetime

Moral:

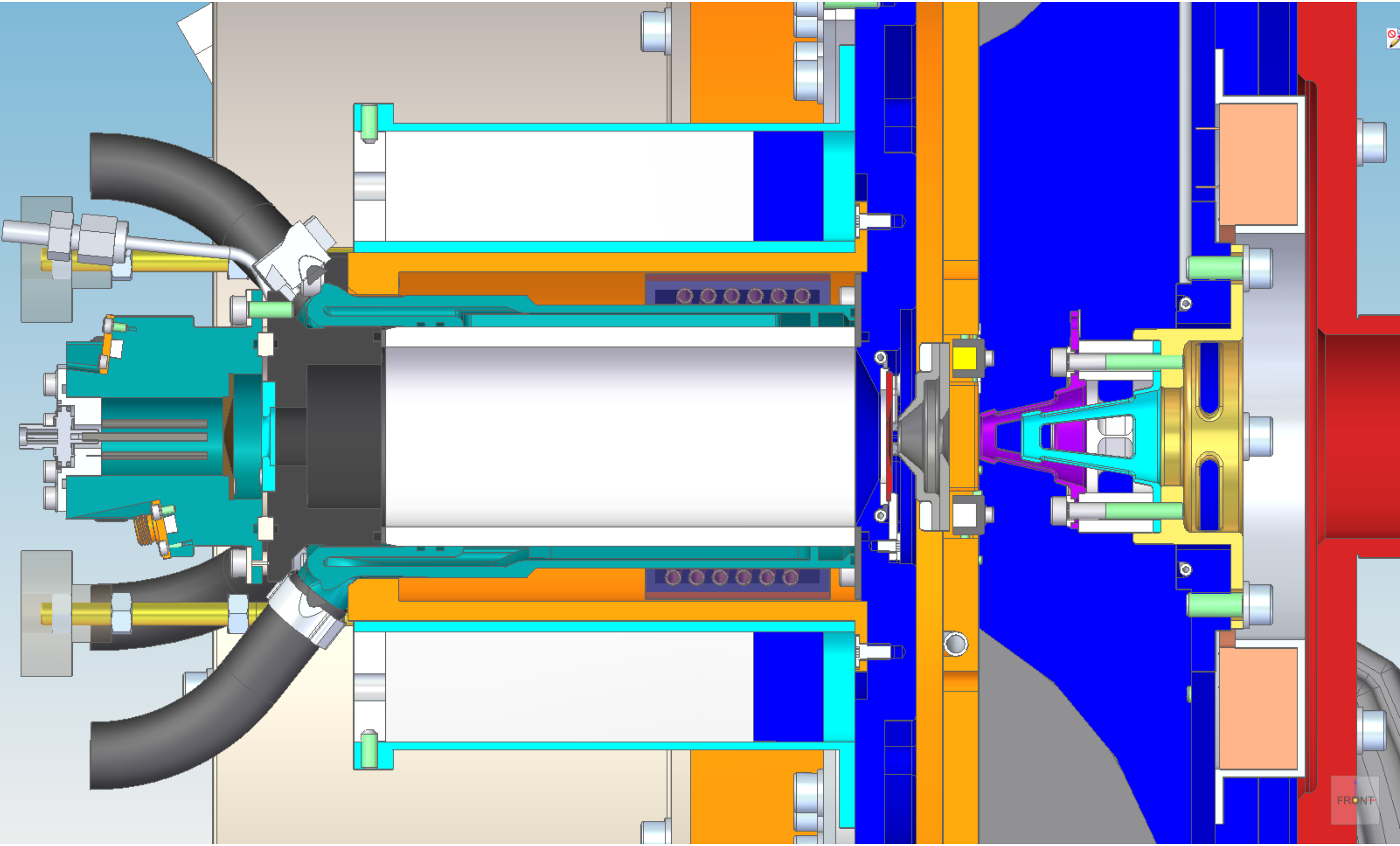
Only use 'JUST ENOUGH' caesium for acceptable ion source performance!

ISIS Penning Surface H⁻ Source

- Machined molybdenum, ceramic, stainless & copper
- High temperature and magnetic & electric fields
- Microscope alignment of extraction electrode
- Hydrogen & caesium feeds into the vacuum
- Welded 1/8” air & water cooling pipes
- Bolts torqued for good thermal contact
- > 2 kW of power damages components
- Lasts 3-4 weeks → have 10 ready to go
- 55 mA H^- at 250 µs, 50 Hz



ISIS RF Volume H^- Source



Final Thoughts

Accelerator designers always want more from the particle source!

Higher charge states

More current

Higher duty factor

Lower emittance

Longer lifetime

More stability

Squarer pulse shape

More Gaussian Profile

Quicker start-up

Better vacuum

Very active & exciting career, always in need of more minds

Science & Technology Facilities Council

UK Research and Innovation

Thank you for listening!

Feel free to contact me if you’re interested in this subject.
Please email homework answers to me by 22/03/2019.

scott.lawrie@stfc.ac.uk

Homework Questions

1. Use the ideal gas law to calculate the particle number density inside a room-temperature vacuum vessel at a (somewhat poor) pressure of 10^{-4} mbar. Assuming σ_{en} = 6×10^{-19} m^{-2}, calculate the mean free path. If the vessel is 0.5 m long, is the pressure high enough to be collisional?
2. You want to make an electron gun which can operate at 1 kHz, with an extracted charge of 500 pC/bunch. Your photocathode has Q.E. = 1×10^{-4}. What power laser would you need if it operated at a wavelength of 532 nm?
3. You want to make an H^- ion source with an output beam current of 40 mA at 45 kV extraction voltage operating at 50 Hz for the scSPS project.
   a) Discuss whether you would use caesium in this ion source.
   b) What are the benefits and drawbacks of altering the geometry terms A and d^2 to reach a suitable perveance?
   c) Write a list and brief justification of the physics simulations you would need to perform to design this ion source.