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Particle Sources

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(Ion source section leader 2014-2023
ISIS pulsed spallation neutron & muon facility
Rutherford Appleton Laboratory)

Many Many Types of Particle Source

Species

- Electron
- Proton
- Light Ion (1+)
- Heavy Ion (4+)
- Negative Ion
- High Charge-State (34+)
- Radioactive
- Spin-Polarised
- Neutral
- Muon
- Exotic

Technique

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

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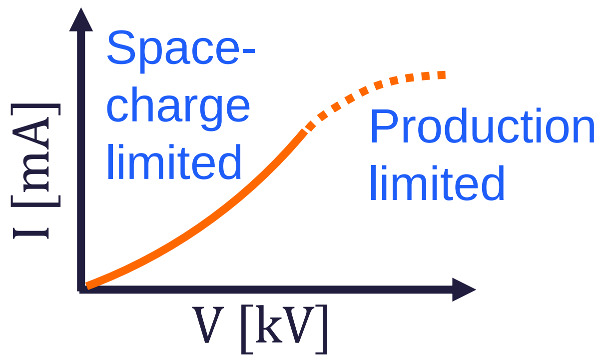
Note: previous slides hidden

Child-Langmuir Law (3)

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

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

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

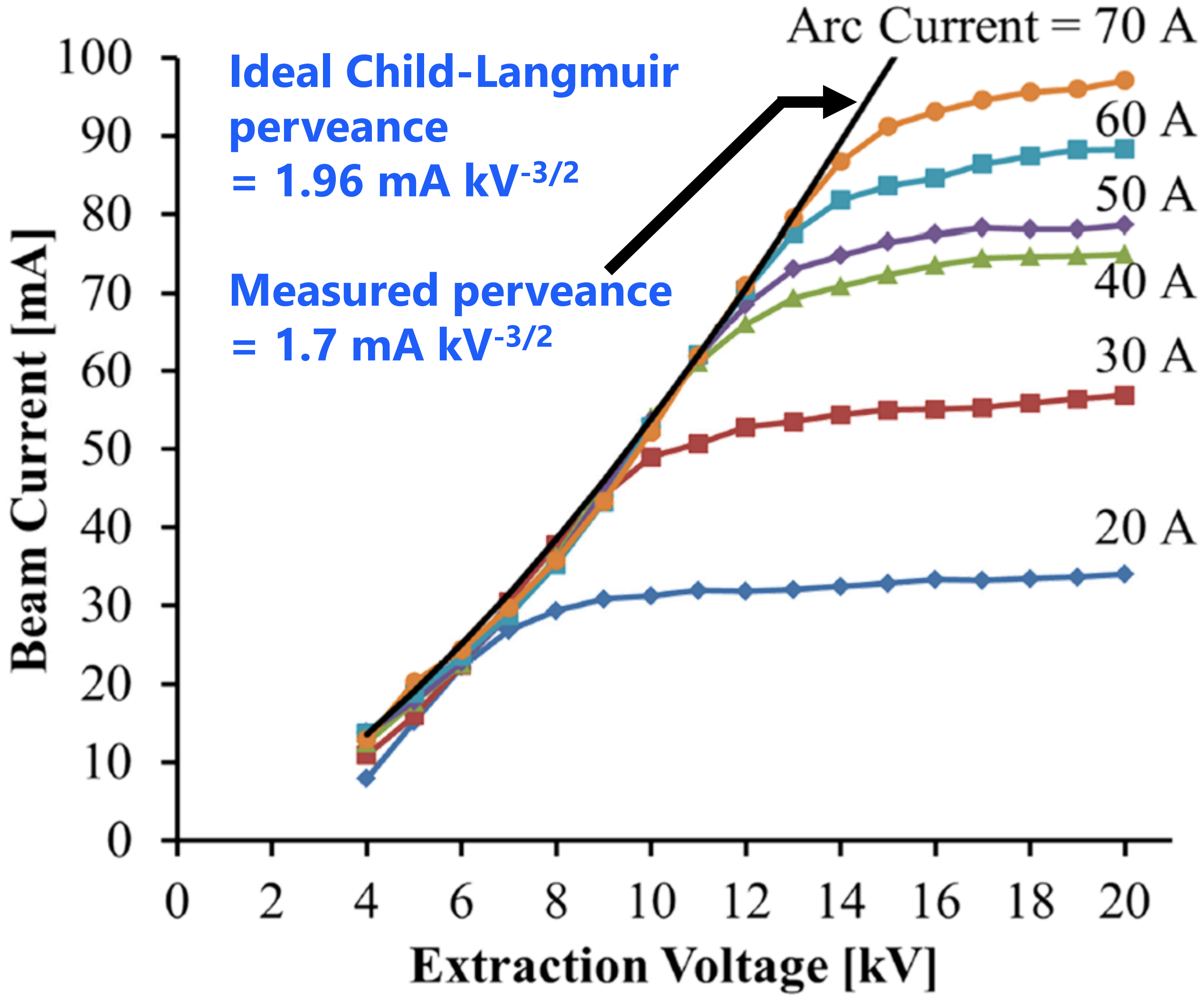


where:

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

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

Real Perveance Measurement



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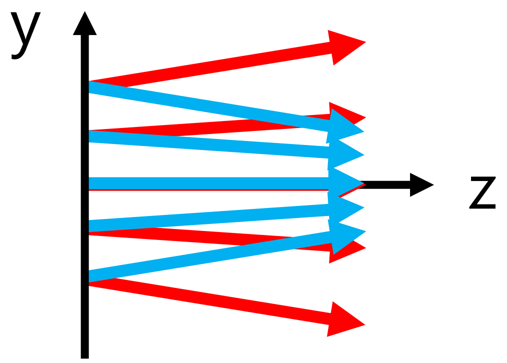
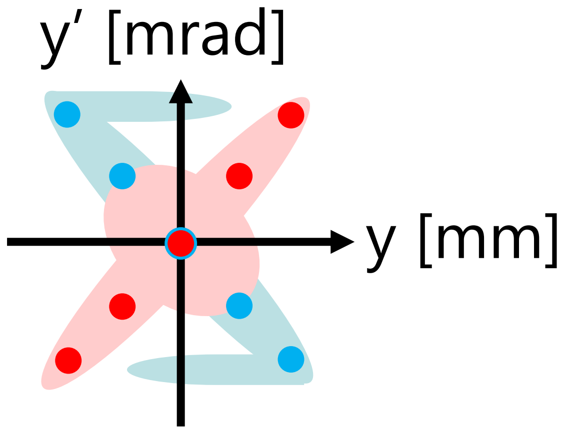
Emittance

- 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)





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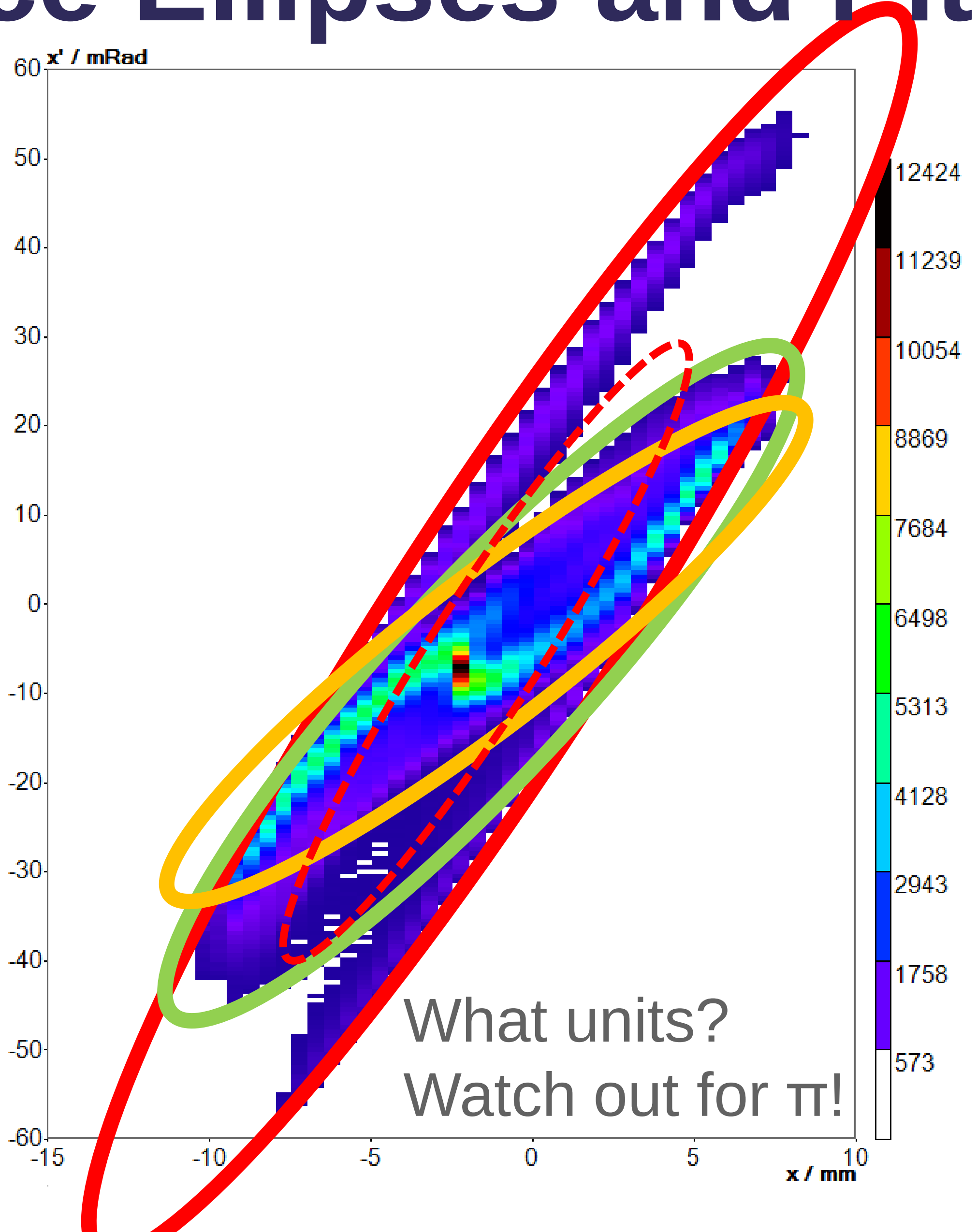
Emittance Ellipses and Pitfalls

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:

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

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

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High Voltage Considerations

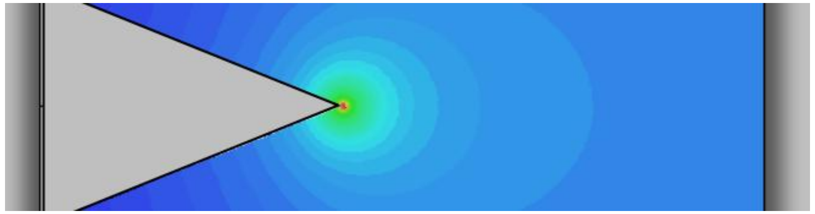
Particle sources have very low beam energy:

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

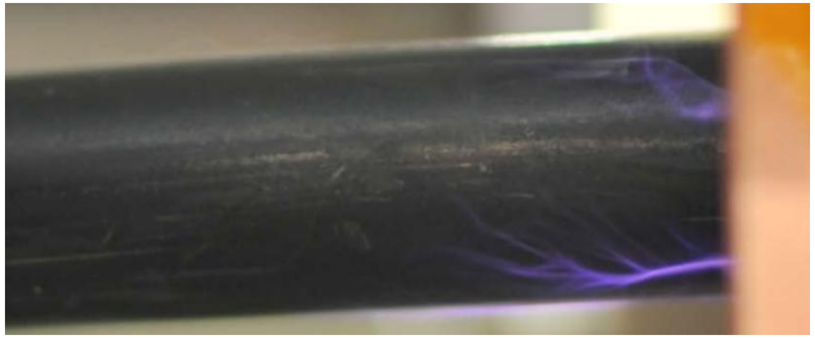
$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

HV is the only option, BUT:

Must protect insulator triple junctions



Must avoid sharp edges in E-field regions



Must ensure proper cable terminations

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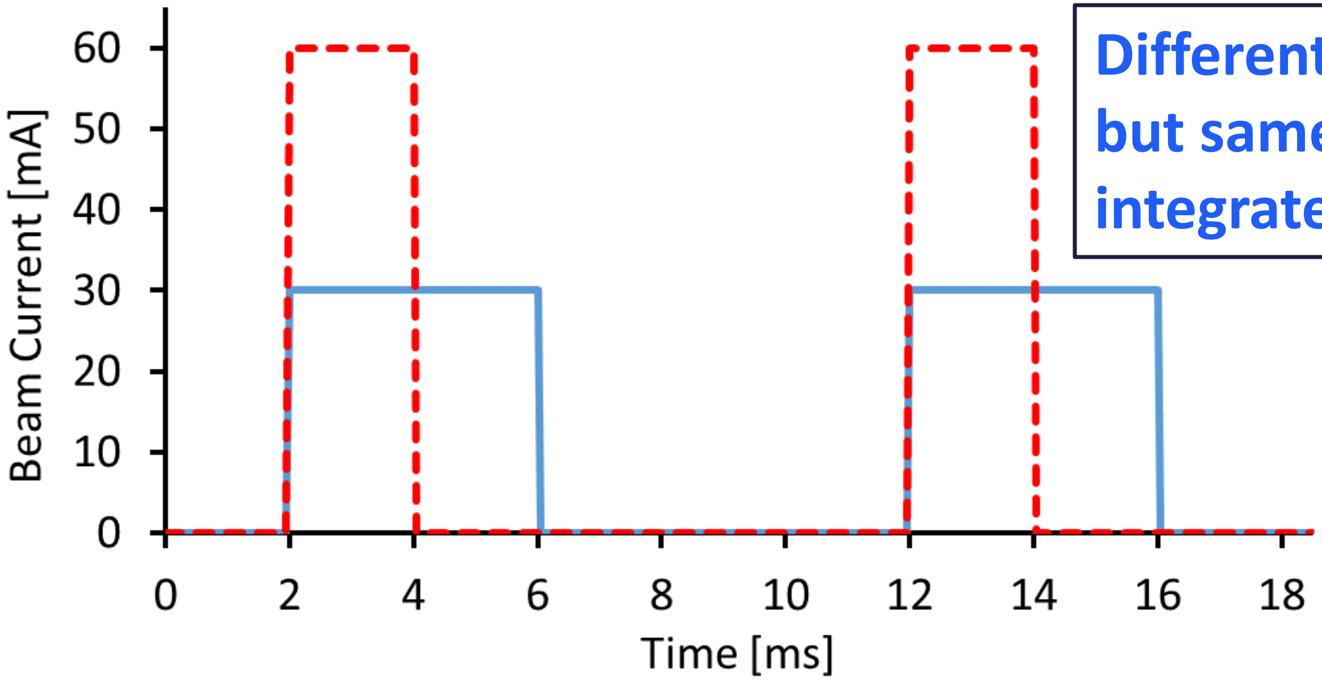
Timing in Pulsed Sources

- 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

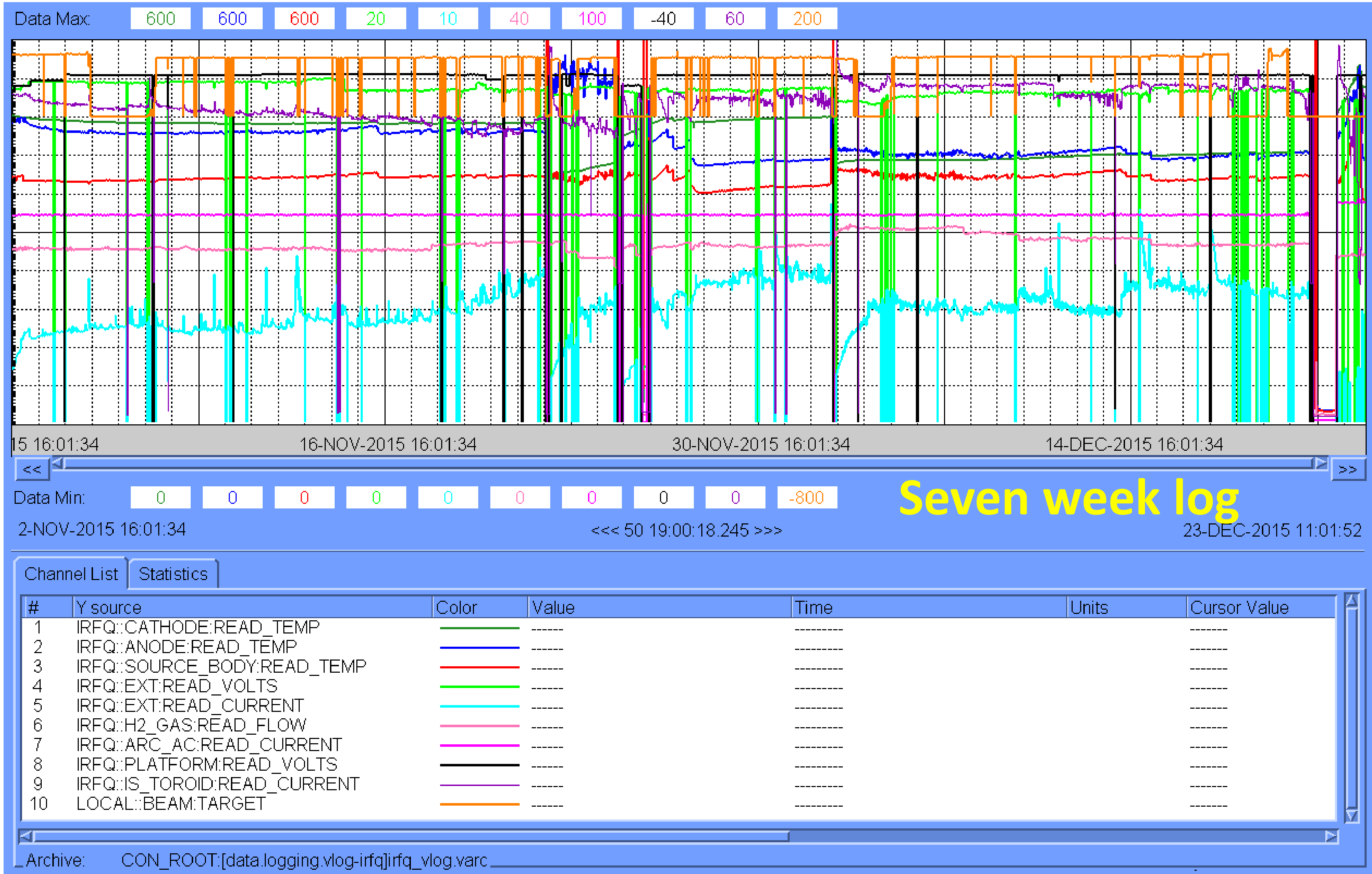
Duty Factor = Pulse Length x Repetition Rate

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

Reliability and Stability

Reliability is King!

Doesn't matter if your particle source **CAN** make 100 A of beam with tiny emittance if it will only do it occasionally!



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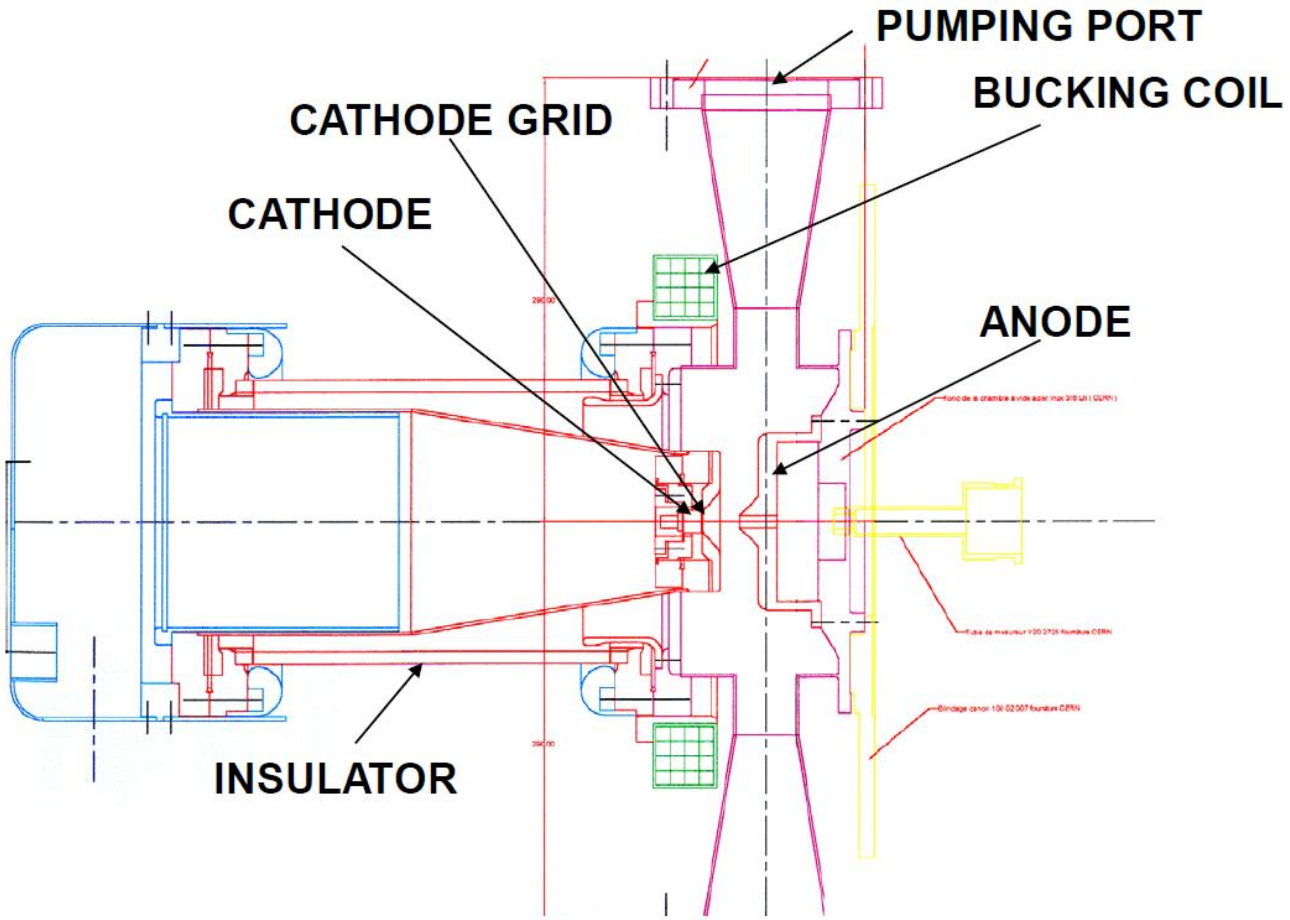
Fundamentals

- 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

Diamond @ RAL



W dispenser cathode with impregnated BaO:CaO:Al2O3

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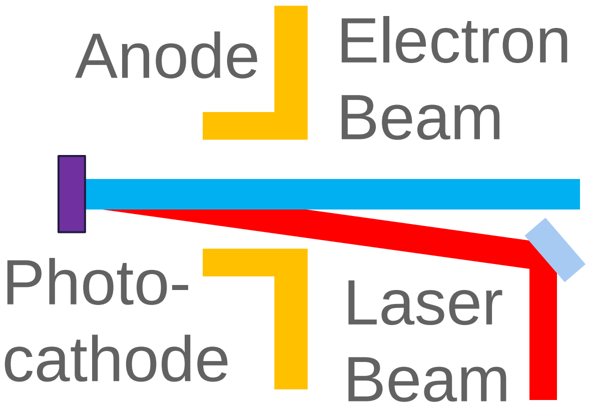
Photocathode Electron Guns



- 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

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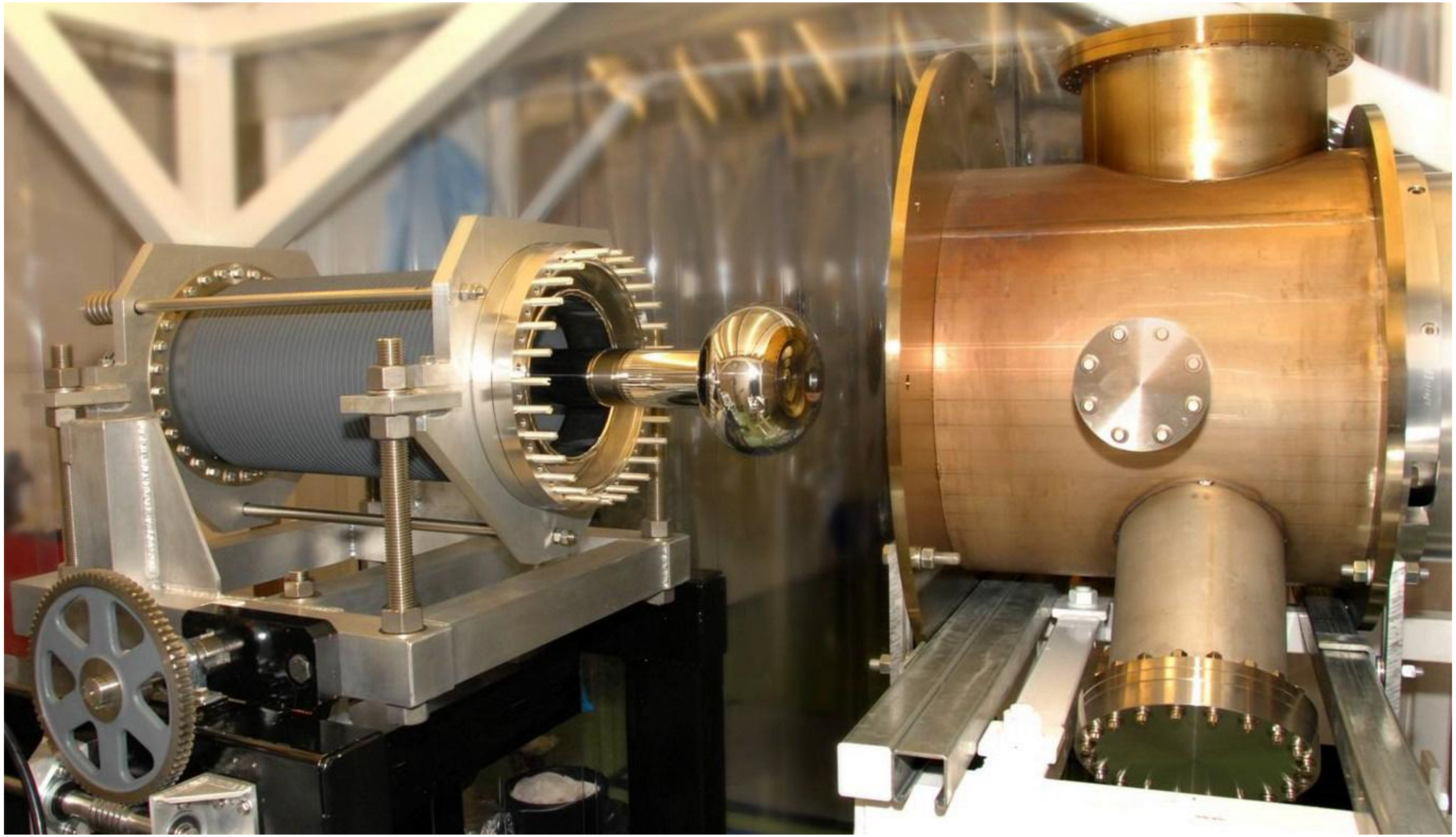
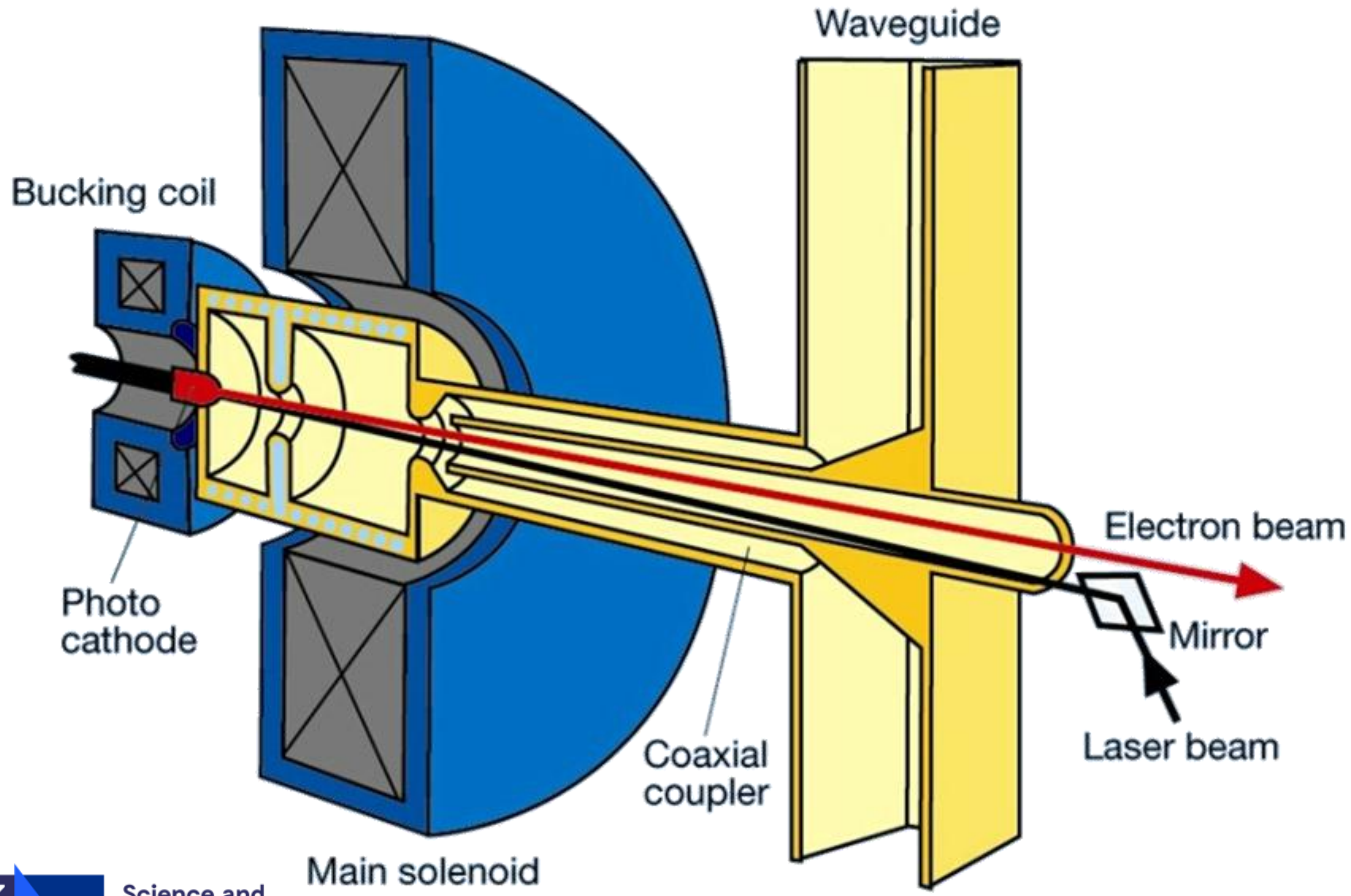
DC Photocathode Electron Gun

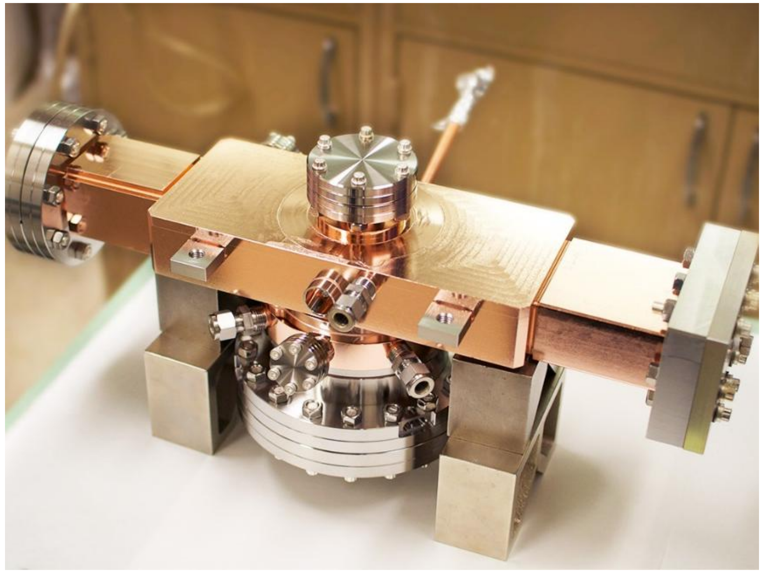
350 kV DC
80 pC bunch
GaAs:Cs



RF Photocathode Electron Gun

FERMI2 @ Trieste





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

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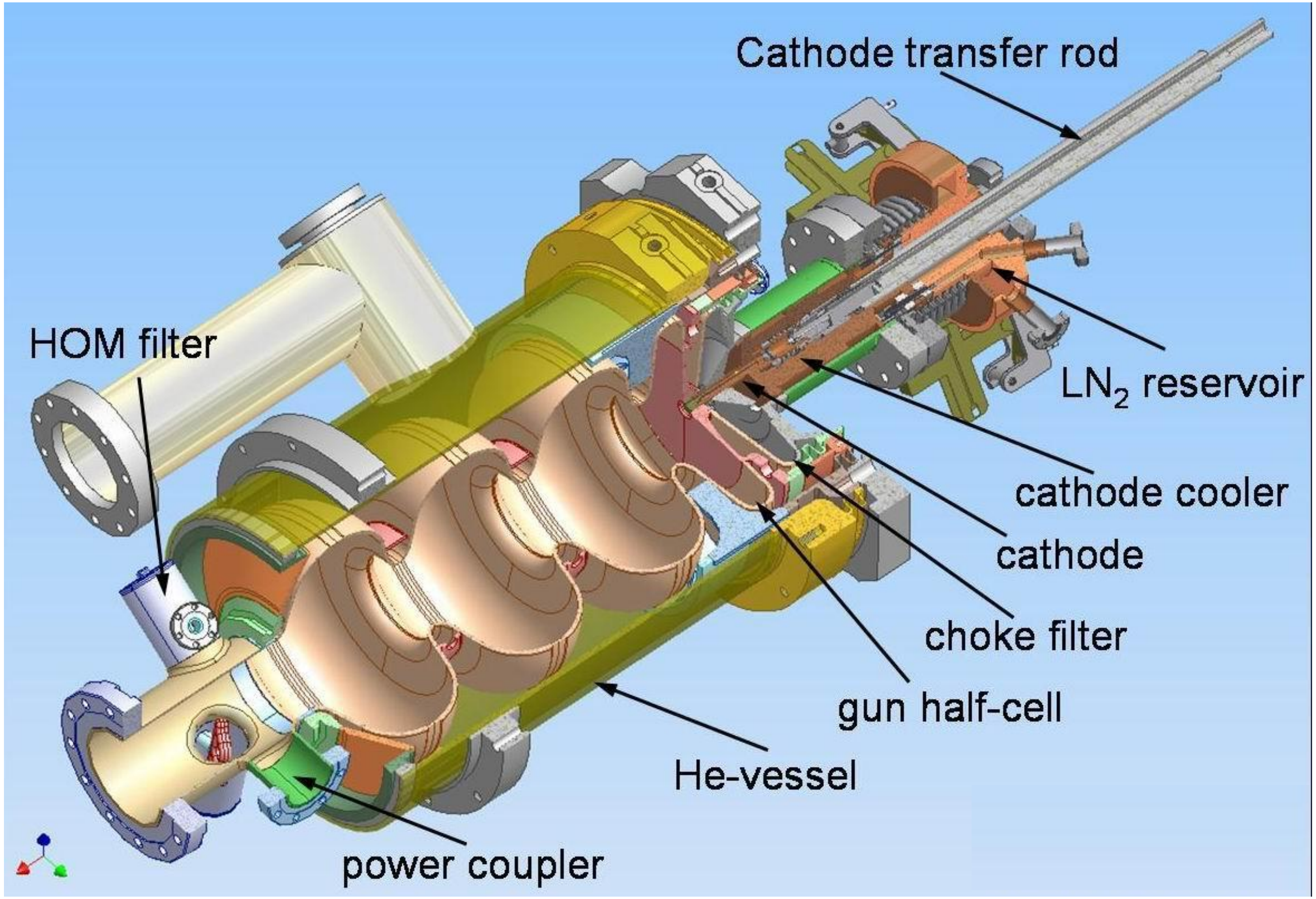
Superconducting RF Electron Gun

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



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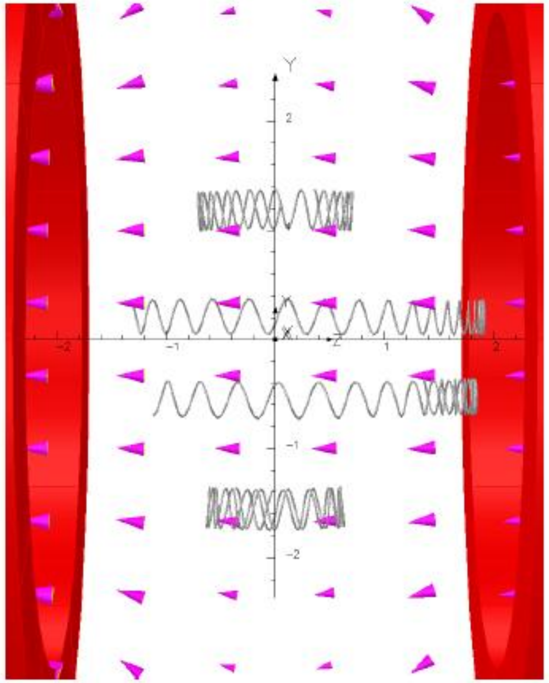
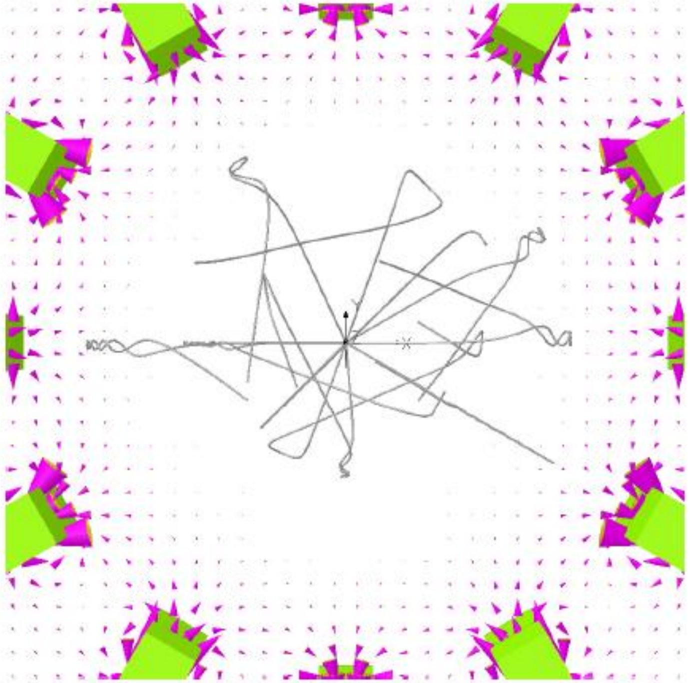
- Arc Plasma
- Laser
- Microwave
- RF
- Cyclotron-Resonance
- Duopigatron
- Duoplasmatron
- …

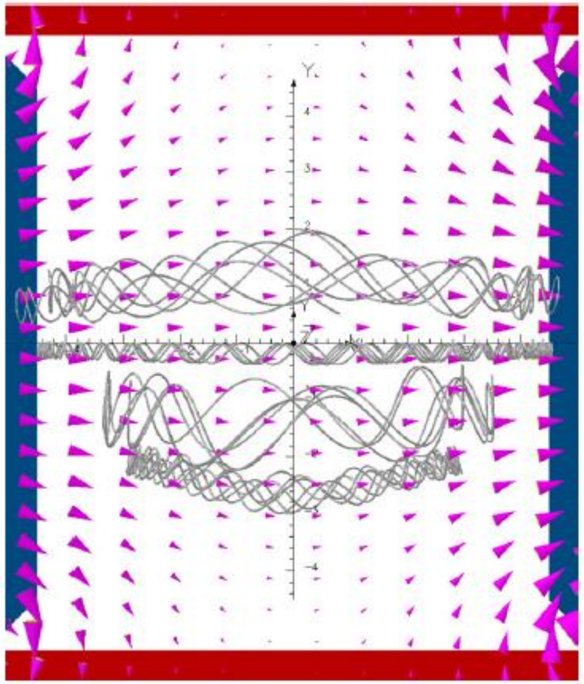
Plasma Magnetic Confinement Techniques



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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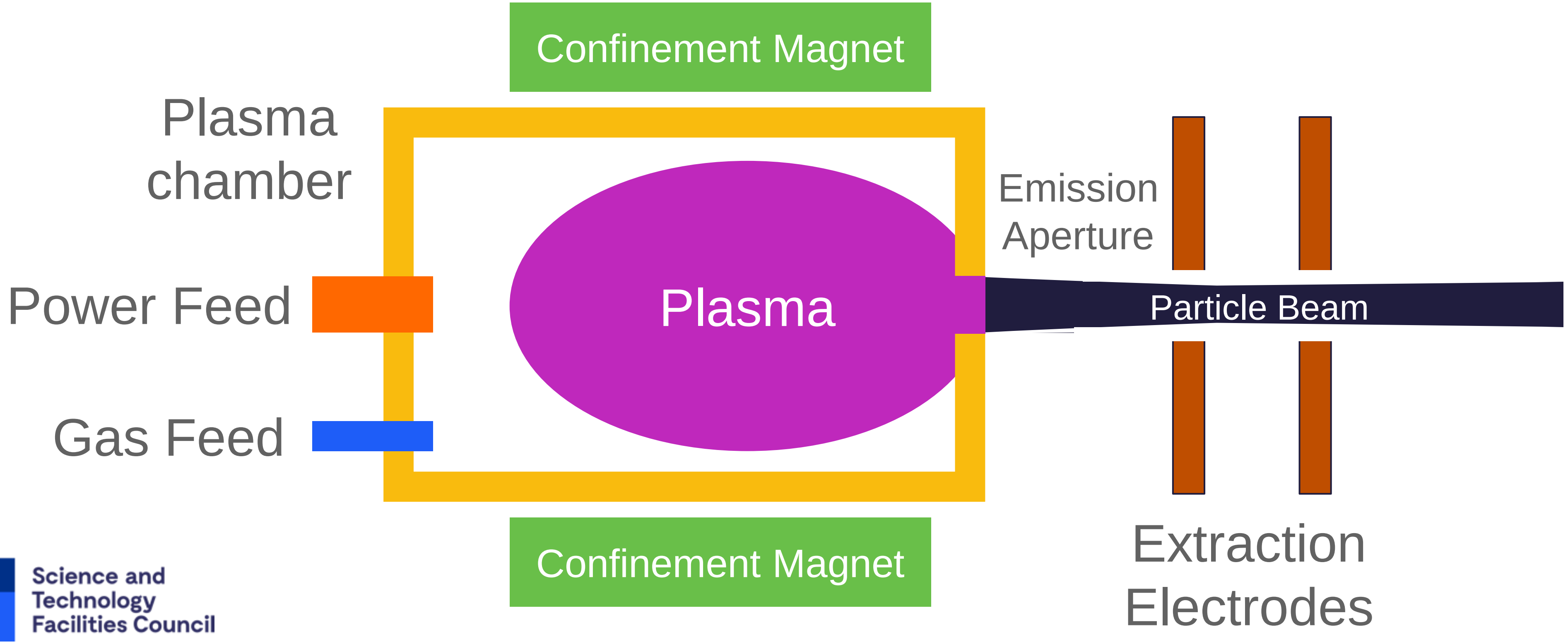
The Typical Ion Source

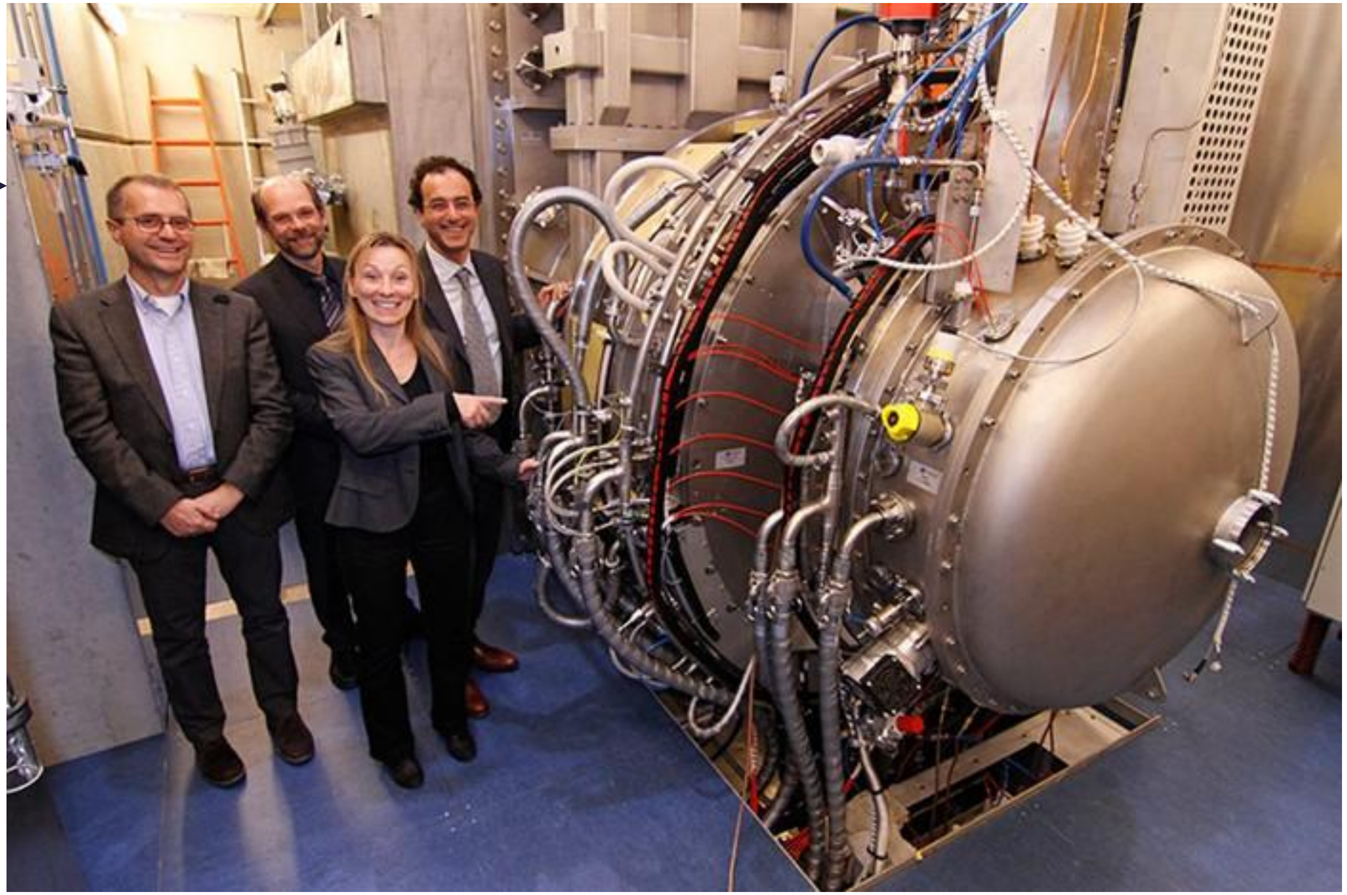
Every ion source basically consists of two parts:

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

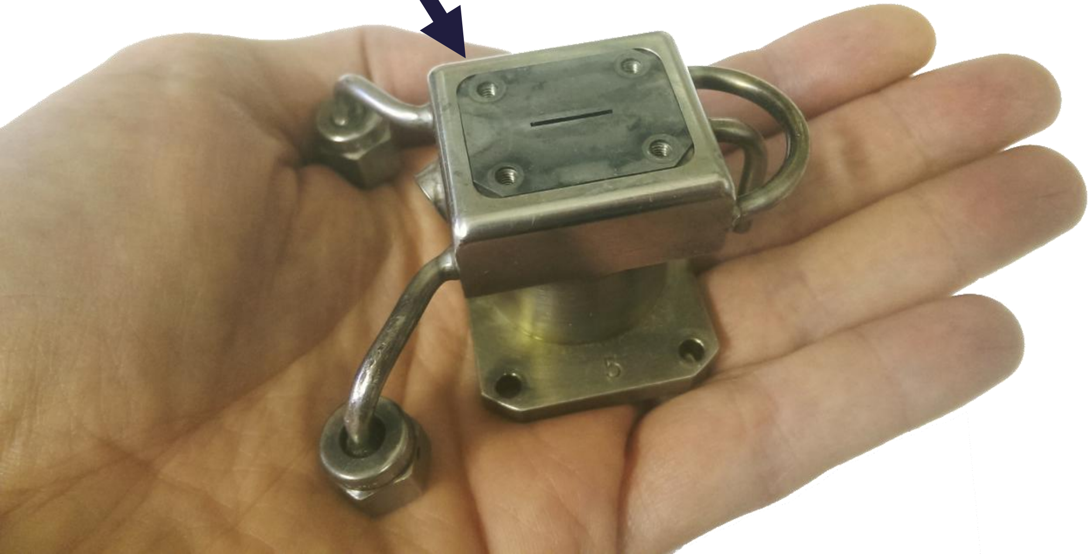


No ‘Typical’ Ion Sources!

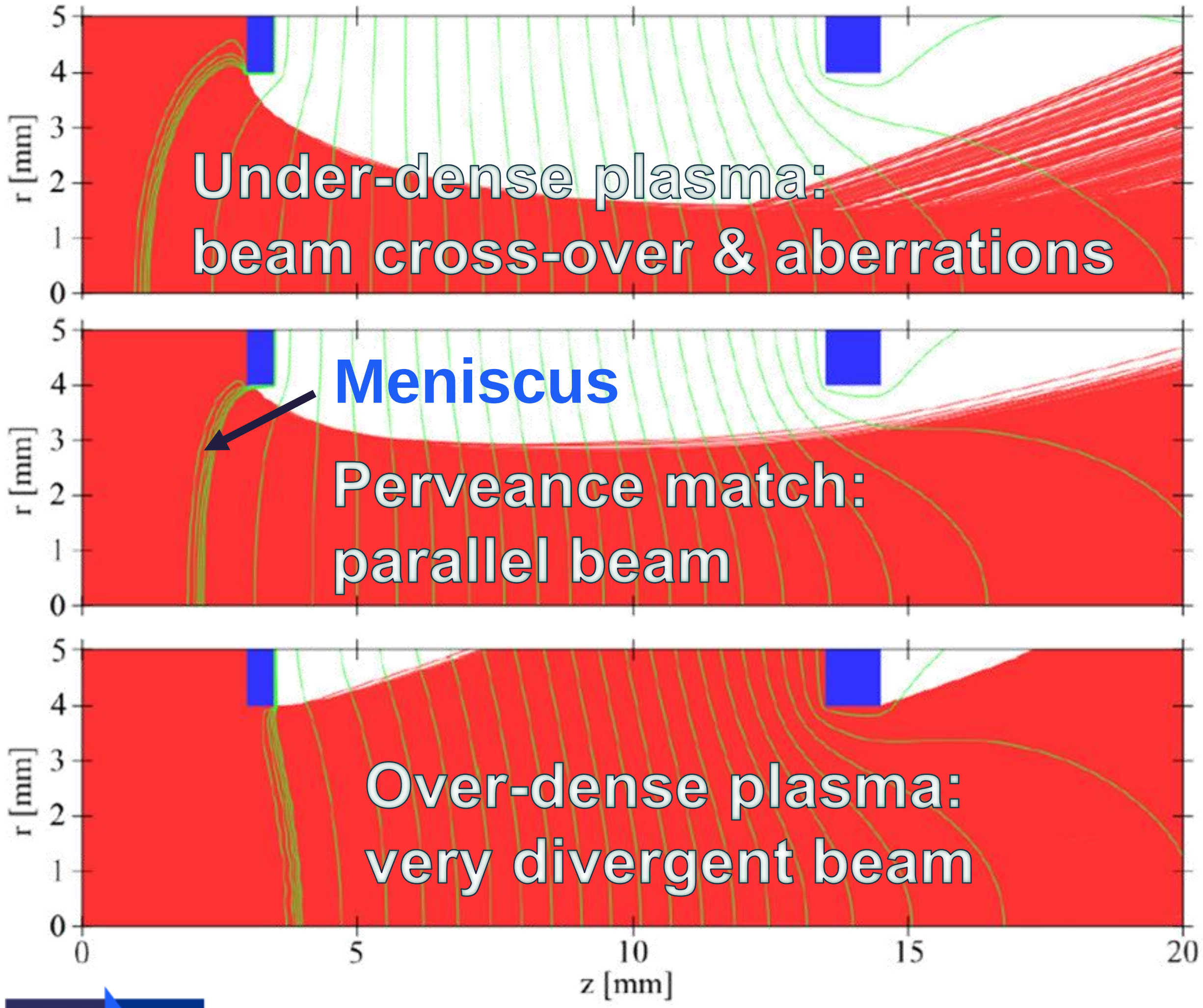
‘ELISE’ ITER
Demonstration
H^- Source



ISIS
H^- Source



Beam Extraction



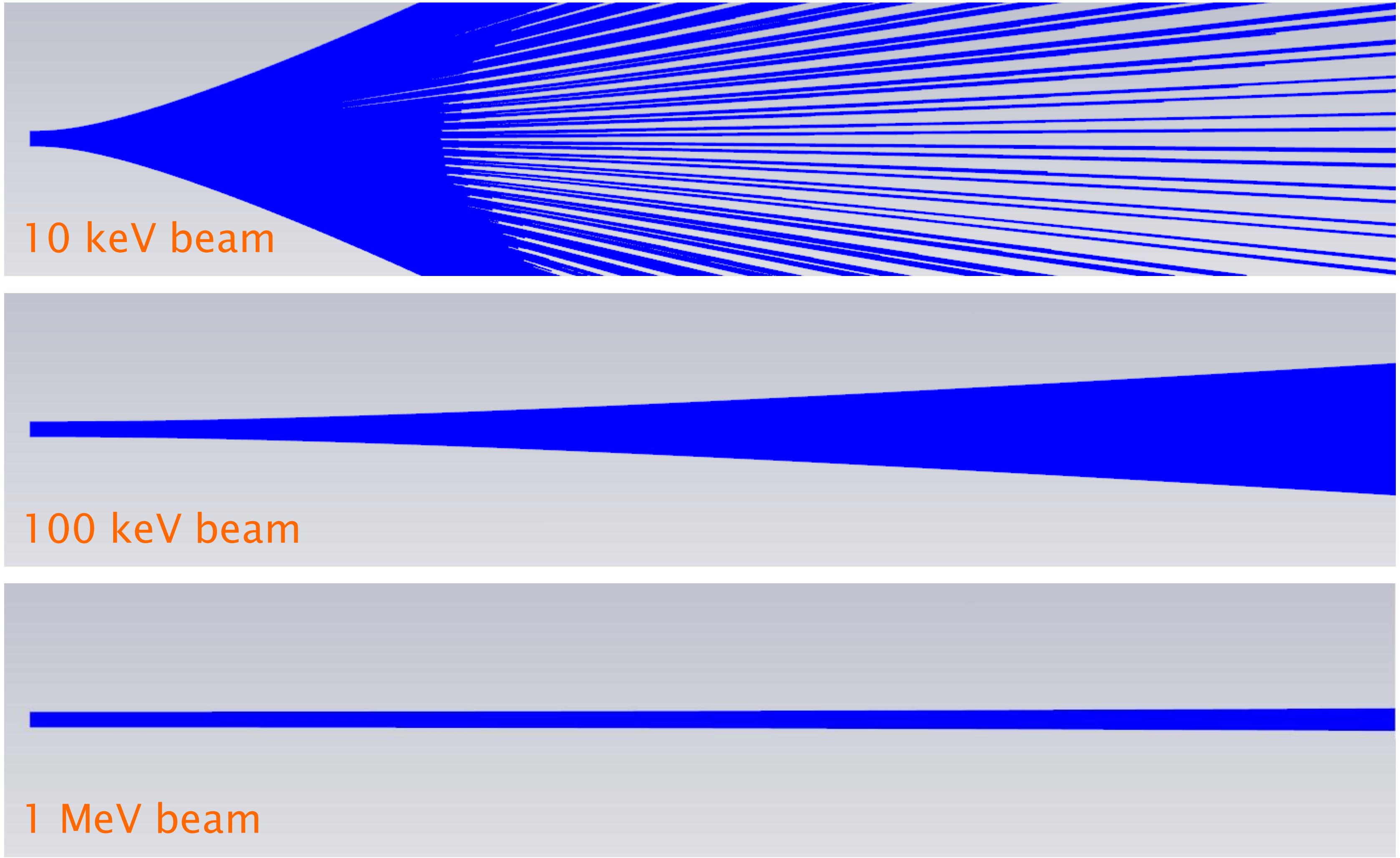
Particle dynamics at emission aperture **defines** the beam performance throughout entire accelerator: **crucial!**

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

Space Charge

- 50 mA proton beam
- 5 mm initial radius
- 1000 mm drift distance
- Expands due to its own 'space charge'
- Space charge forces velocity dependent



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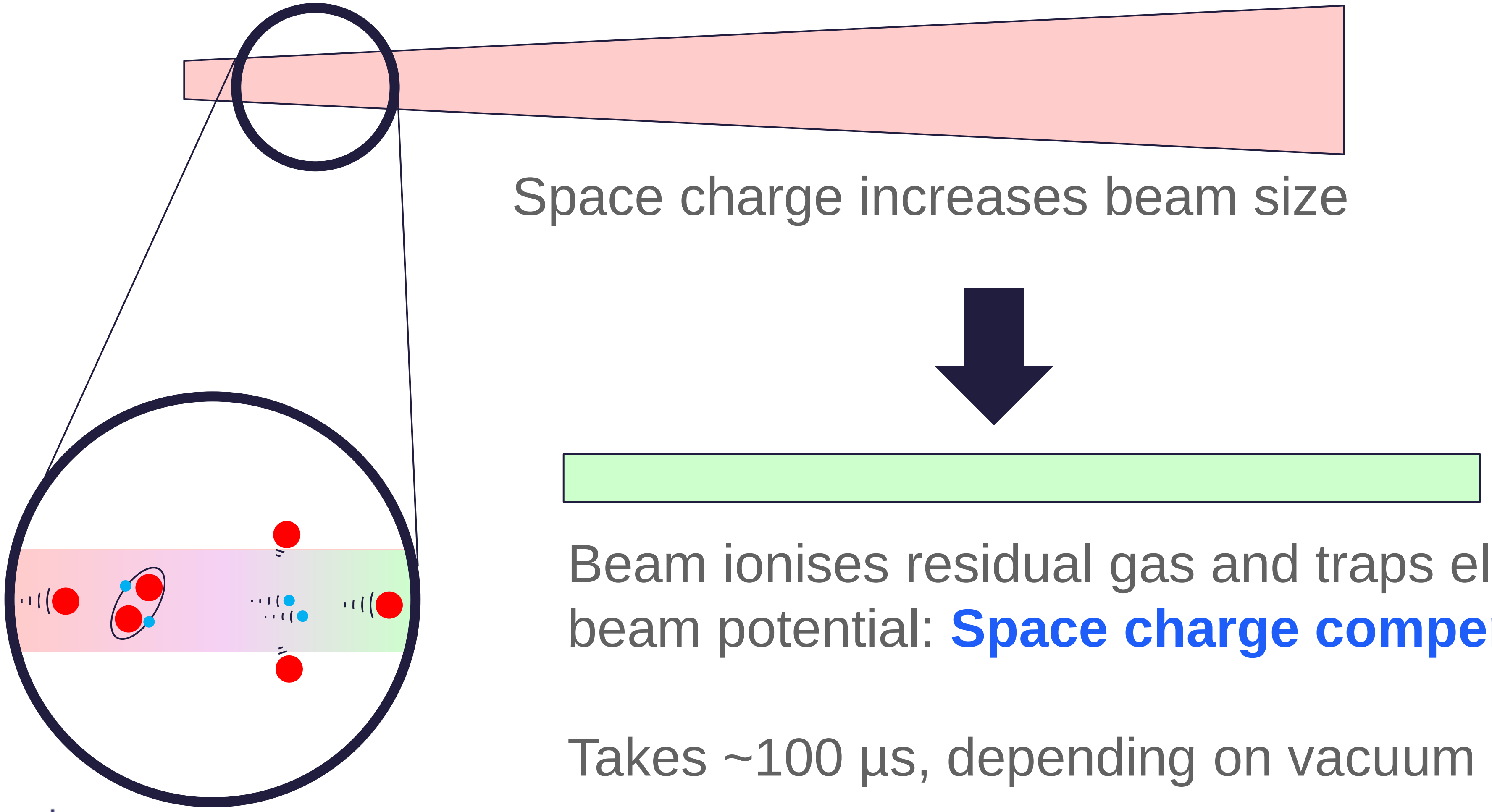
CONCLUSION: Need to focus and accelerate low energy beams <u>hard</u>

Space Charge Compensation



Space charge increases beam size

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

Takes ~100 µs, depending on vacuum pressure.

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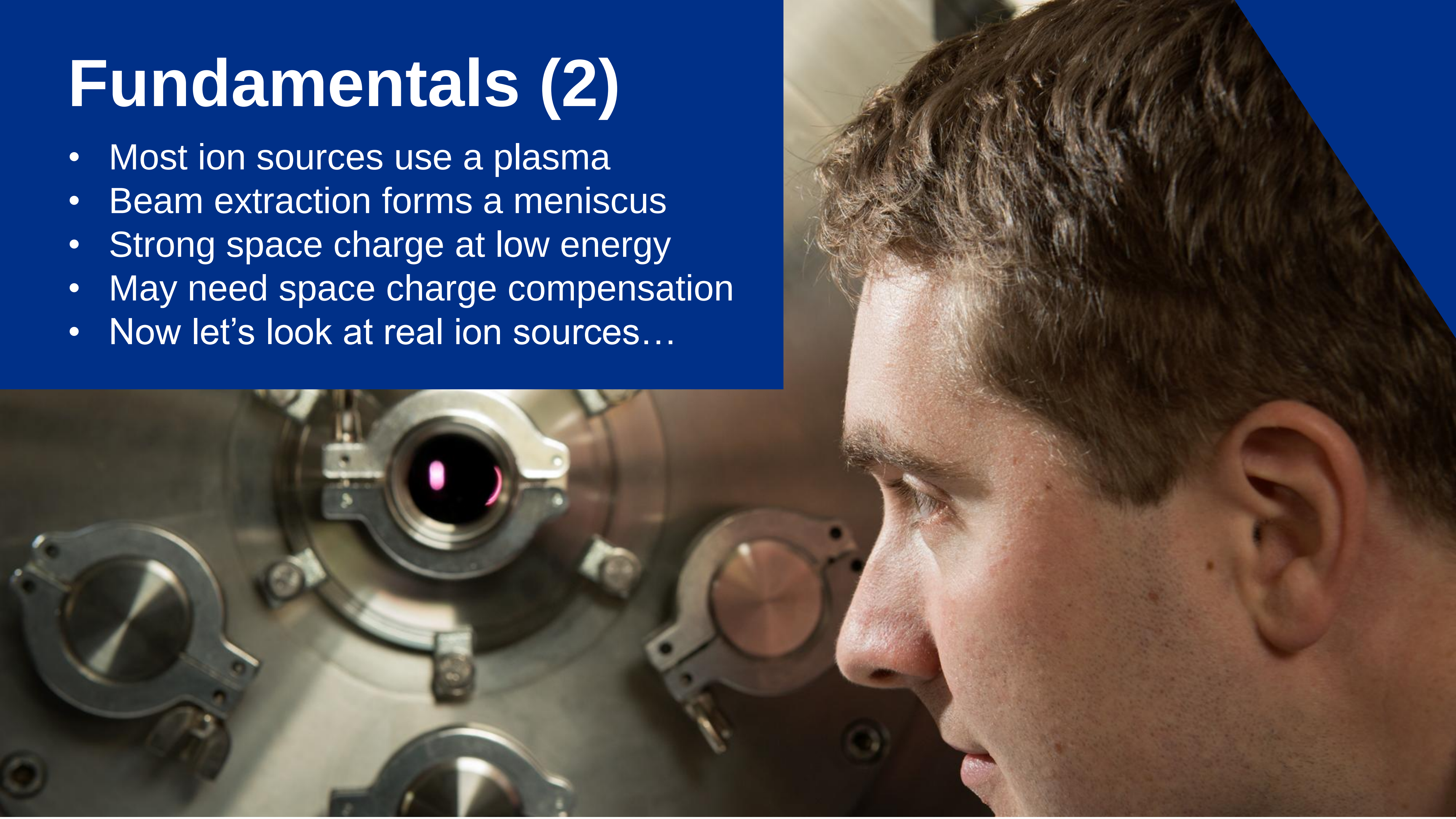
Fundamentals (2)

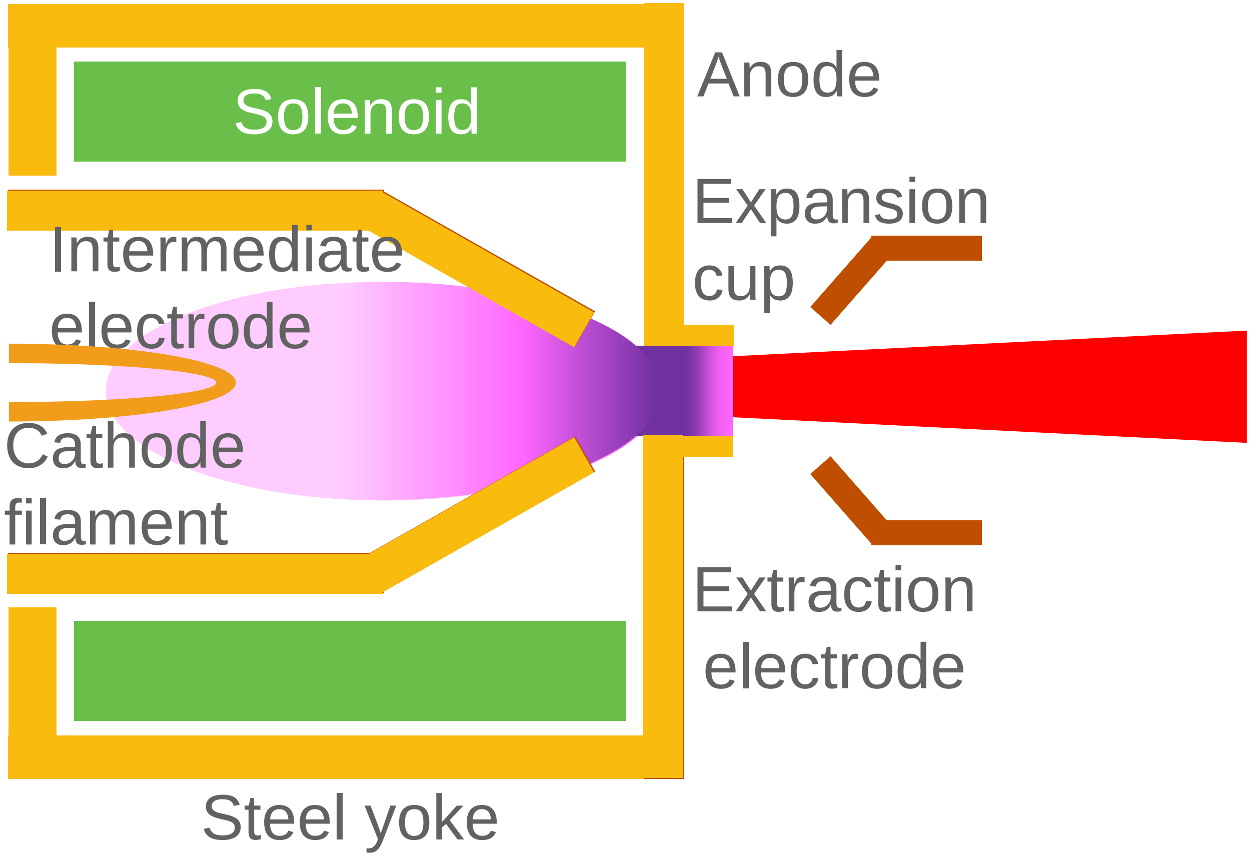
- Most ion sources use a plasma
- Beam extraction forms a meniscus
- Strong space charge at low energy
- May need space charge compensation
- Now let’s look at real ion sources…



Proton Sources

Duoplasmatron

CERN Linac2 1956
300 mA protons
150 µs, 1 Hz



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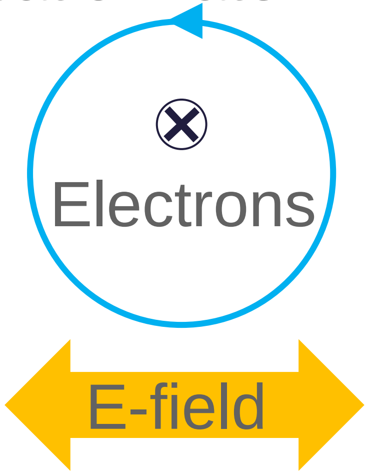
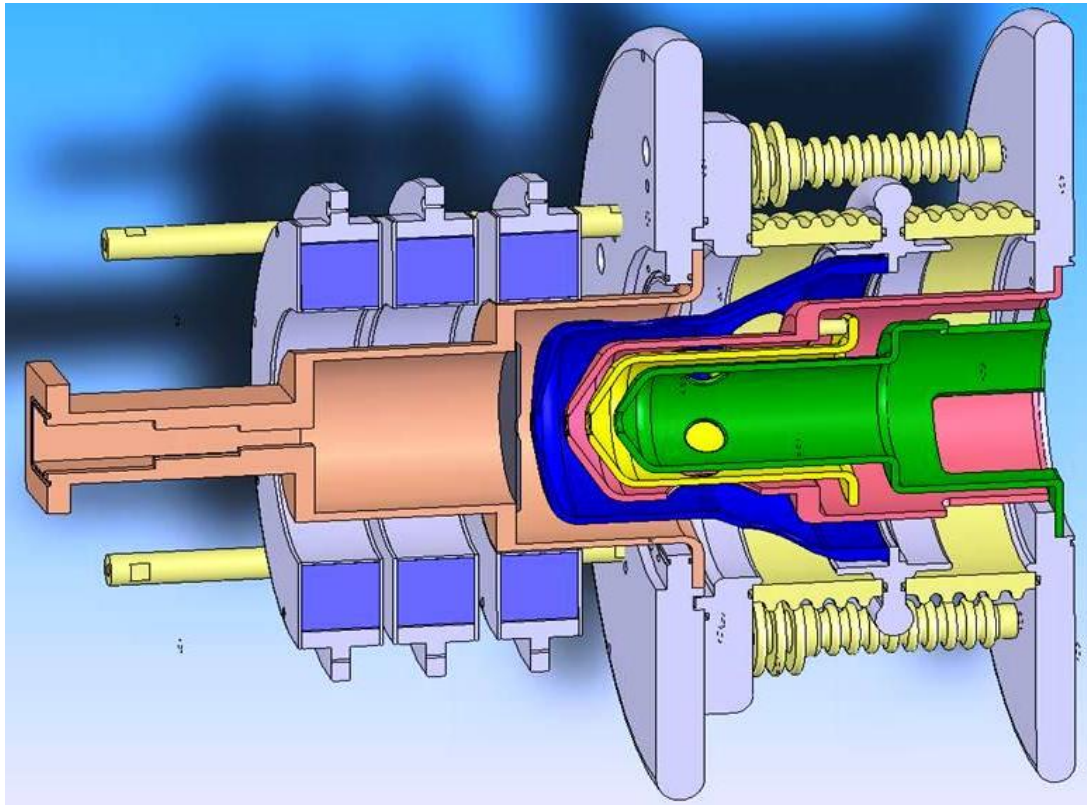
Proton Sources

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



Electron Cyclotron Resonance (ECR)

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



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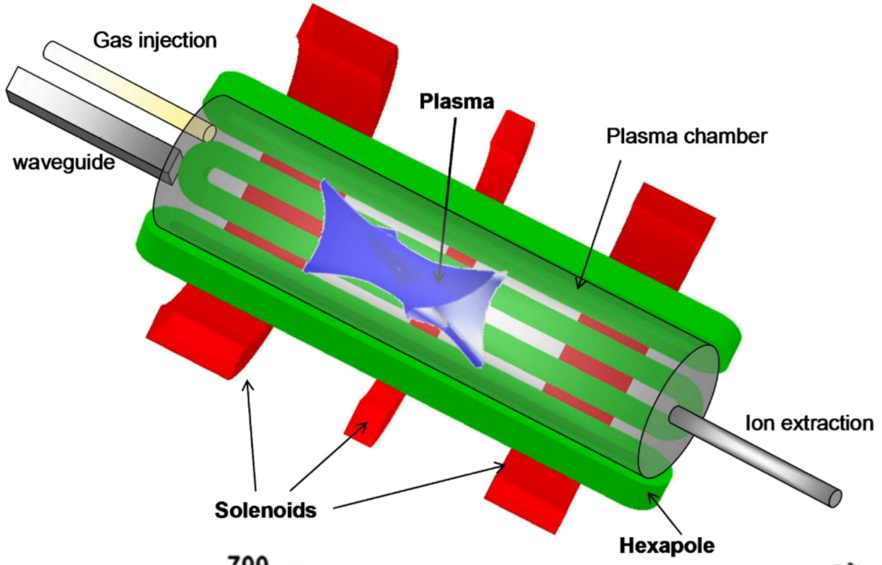
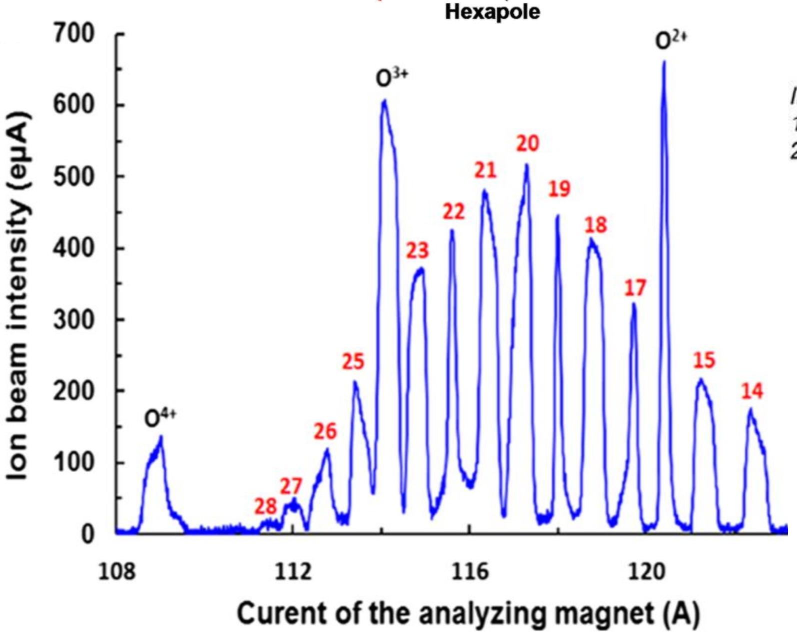
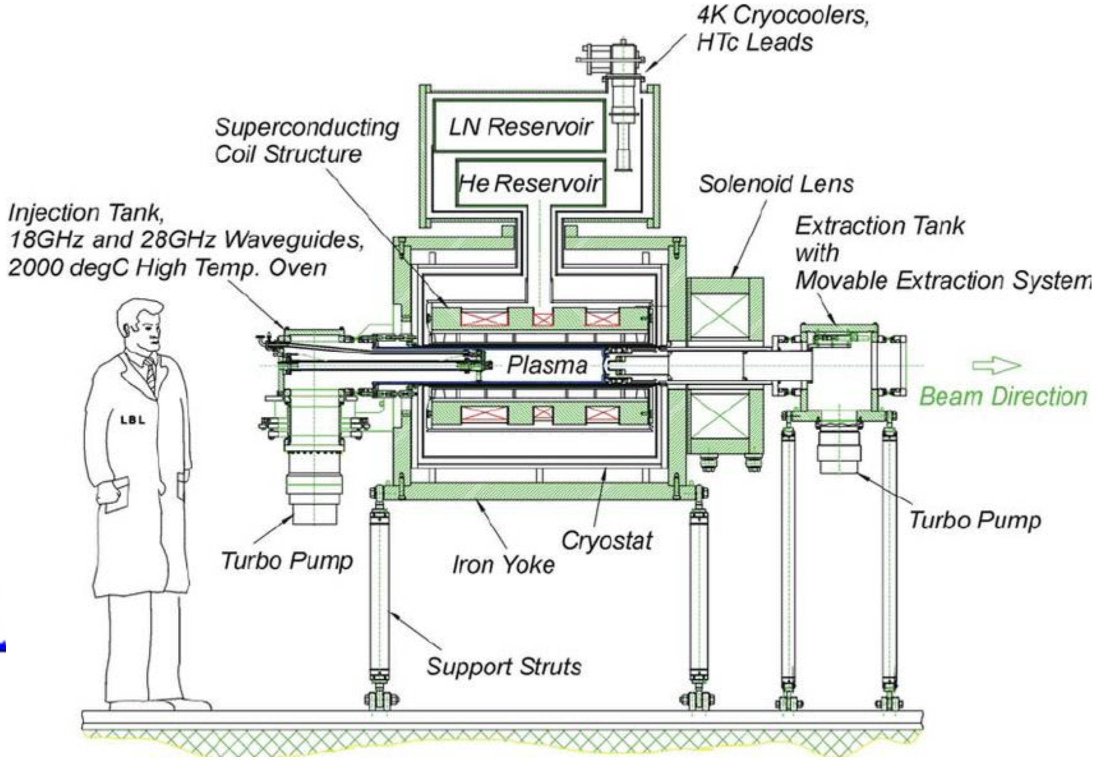
High Charge-State Sources

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







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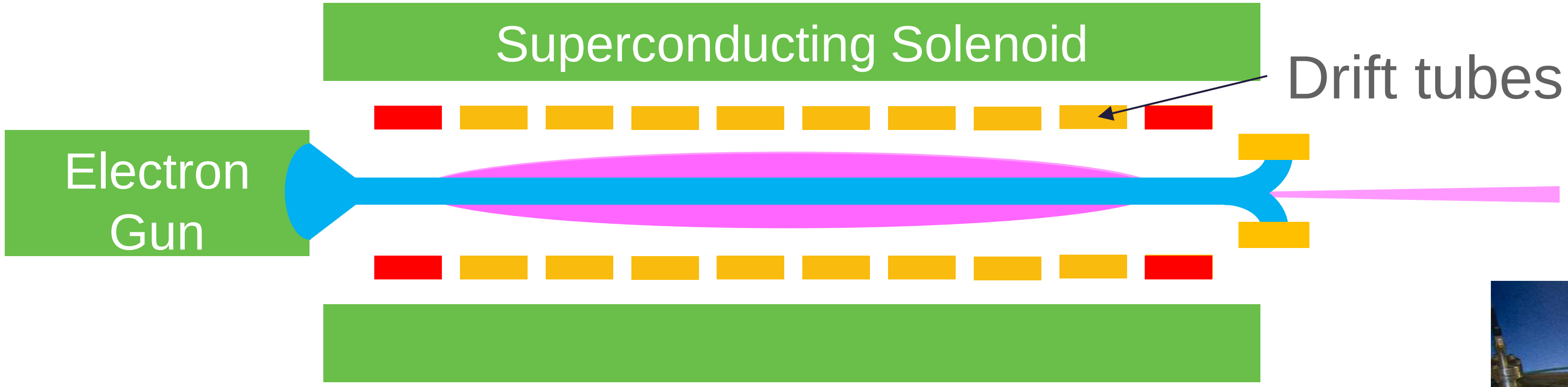
High Charge-State Sources

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

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

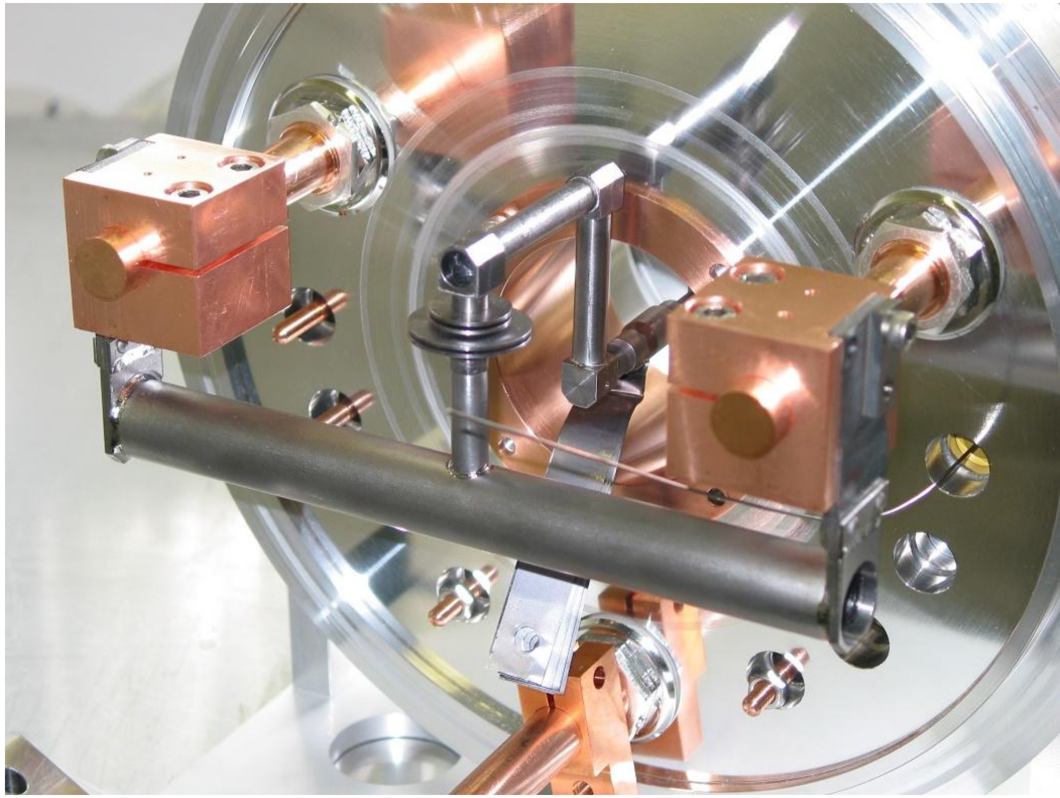


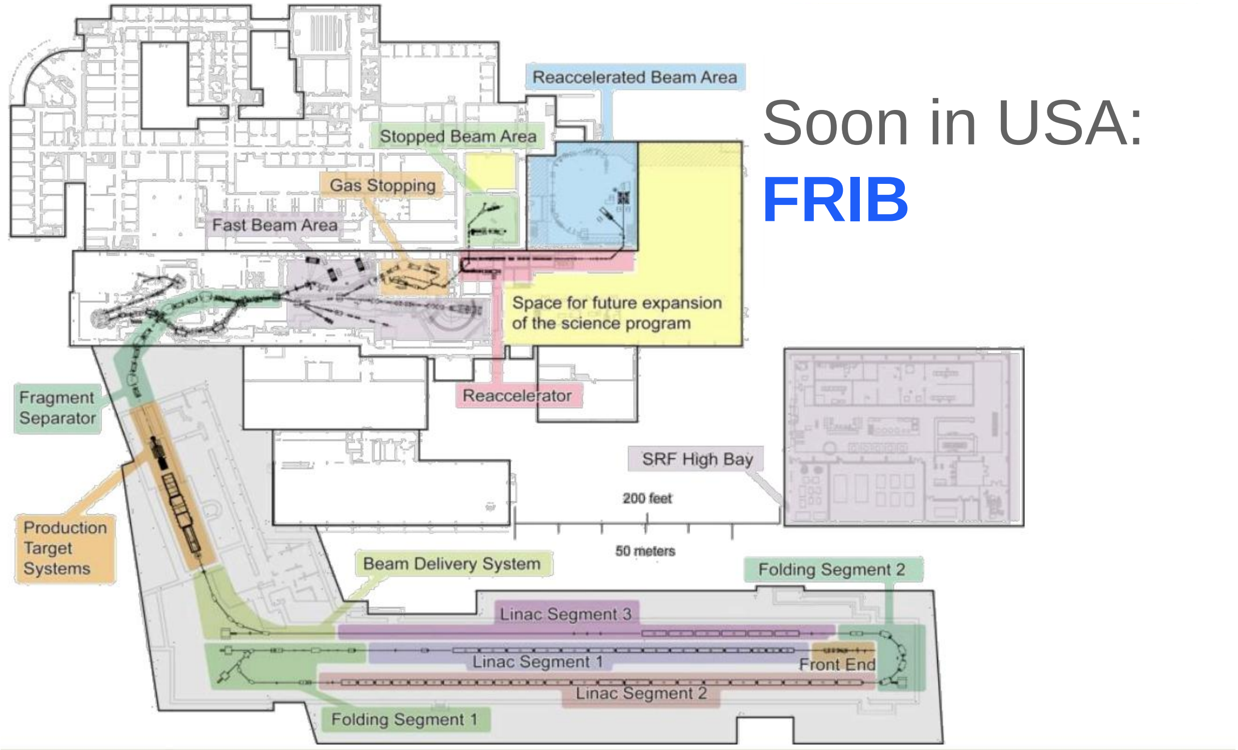
Electron Beam Ion Source (EBIS)

Charge Breeders and 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, radioactive nuclei

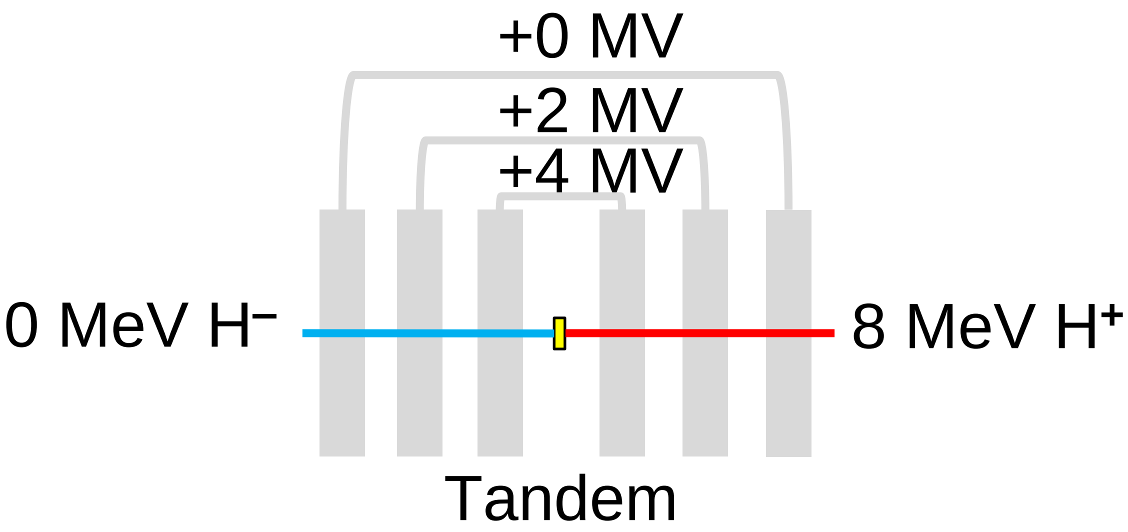
ISOLDE @ CERN
10^7 ^{132}Sn per second

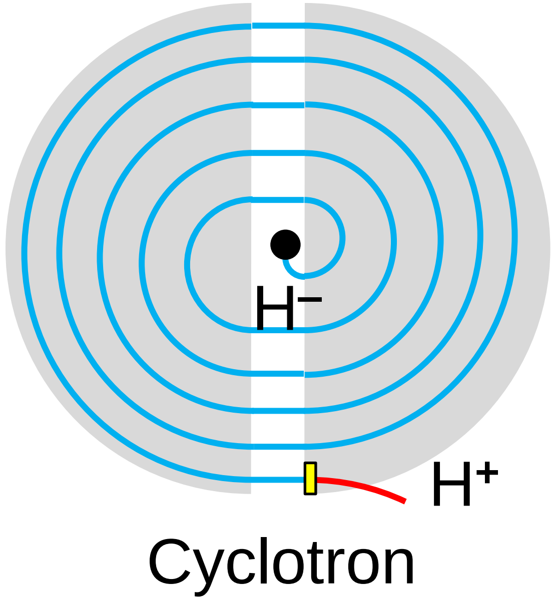


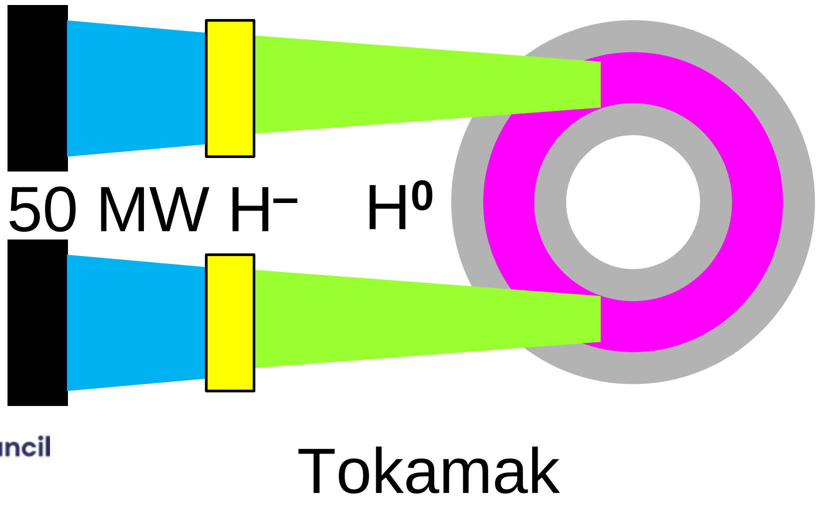


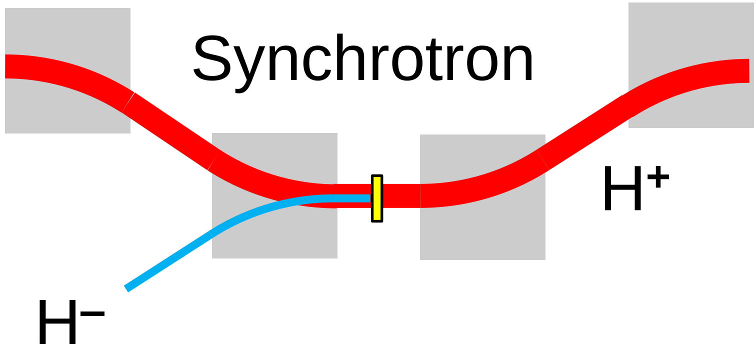
Soon in USA:
FRIB

Negative Ion Sources









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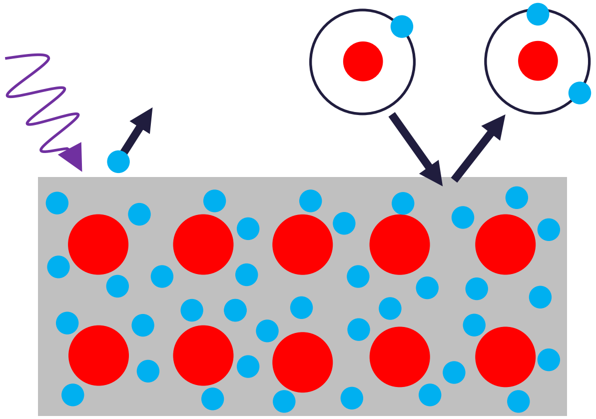
H^- Production Methods

Surface Production

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

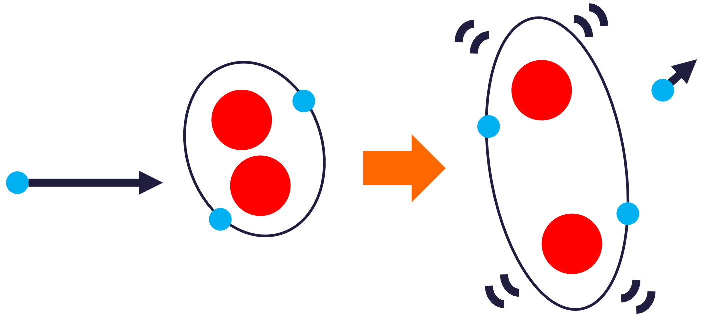


Low φ_{work} metals release electrons

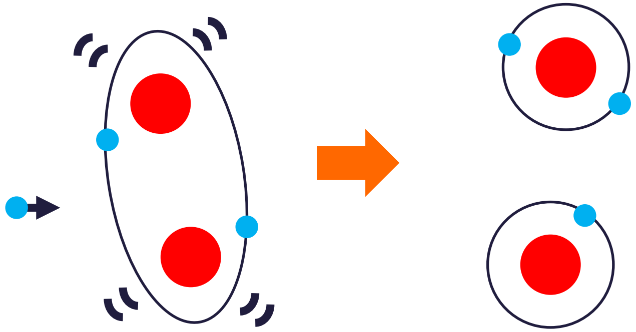
Alternatively, energetic atoms hitting surface can take a free electron, creating H^-

Volume Production

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



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



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

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Caesium: a Blessing and a Curse

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

Moral:

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

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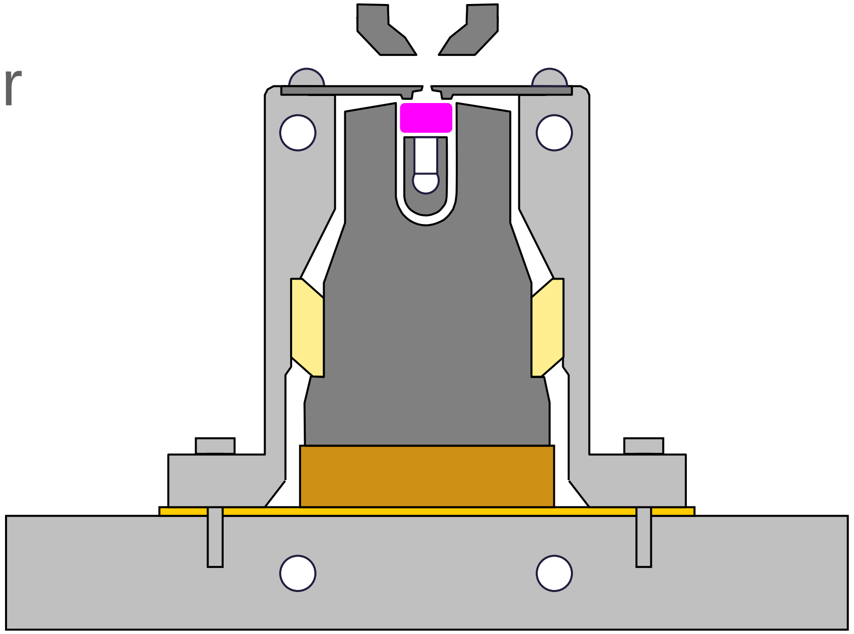
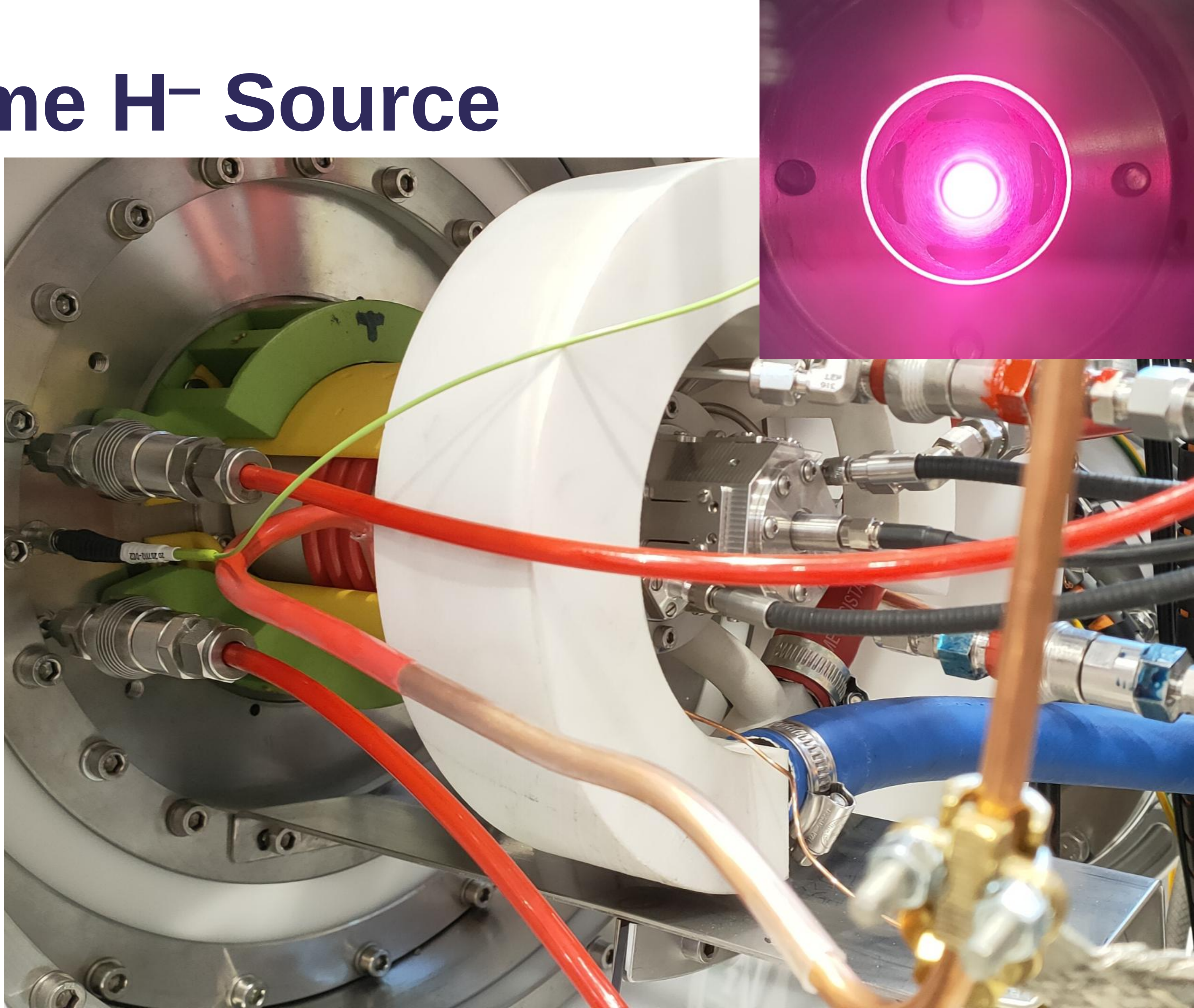
ISIS Penning Surface H⁻ Source

- Machined molybdenum, ceramic, stainless & copper
- High temperature and magnetic & electric fields
- Hydrogen & caesium feeds into the vacuum
- > 2 kW of plasma 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

- 2 MHz, 100 kW RF
- 50 Hz, 1 ms pulses
- 5% duty factor
- ECR electron ignitor
- Adjustable filter field
- 35 mA H^- beam
- $\varepsilon_{4.RMS} < 1.2\ \pi$ mm mrad
- No caesium
- Should last forever!



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Final Thoughts

Accelerator designers always want more from the particle source!

More current

Higher charge states

Higher duty factor

Lower emittance

Longer lifetime

More stability

More Gaussian Profile

Squarer pulse shape

Quicker start-up

Better vacuum

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

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Thank you

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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.
    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 beam perveance?
    c) Write a list and brief justification of the physics simulations you would need to perform to design this ion source.