Welcome!

Cockcroft Institute Lectures – Register Attendance

CI-ACC-221: Ion Sources and Secondary Beams
Dan Faircloth (DF) RAL/STFC

CI-RF-222: RF Linear Accelerators
Graeme Burt (GB) CI/Lancaster University

CI-ACC-225: Electron Sources
Boris Militsyn (BM) CI/ASTeC

CI-ACC-226: Machine Learning Methods for Particle Accelerators
Andrea Santamaria Garcia (ASG) CI/University of Liverpool

Date/time	10:30	11:45	14.00
9 Feb 2026	Ion Sources		Penning Magnetron
16 Feb 2026	High Voltage		Secondary Beams

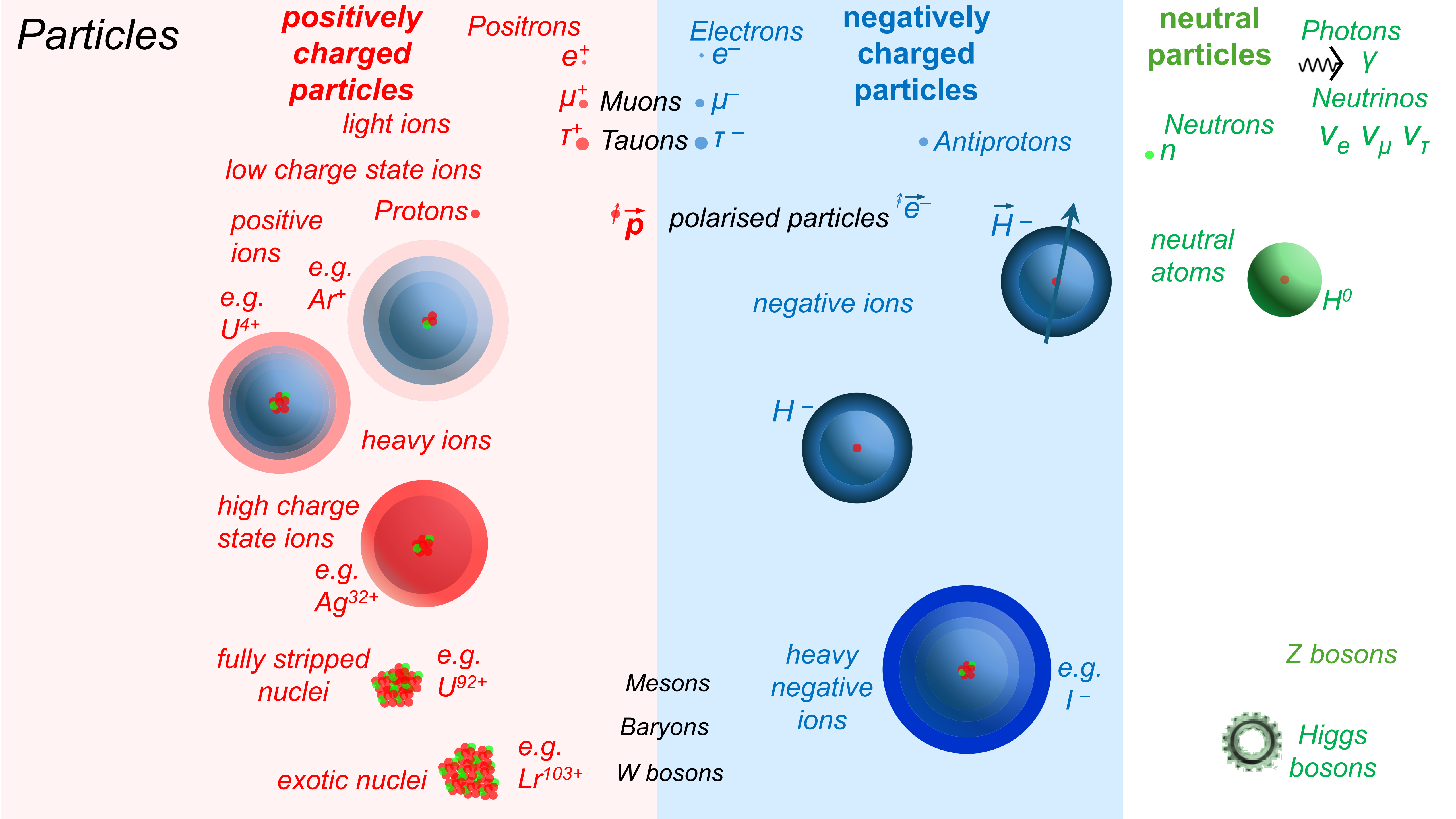
QR code will take you to a Google form

Record attendance for each day of lectures

Ion Sources

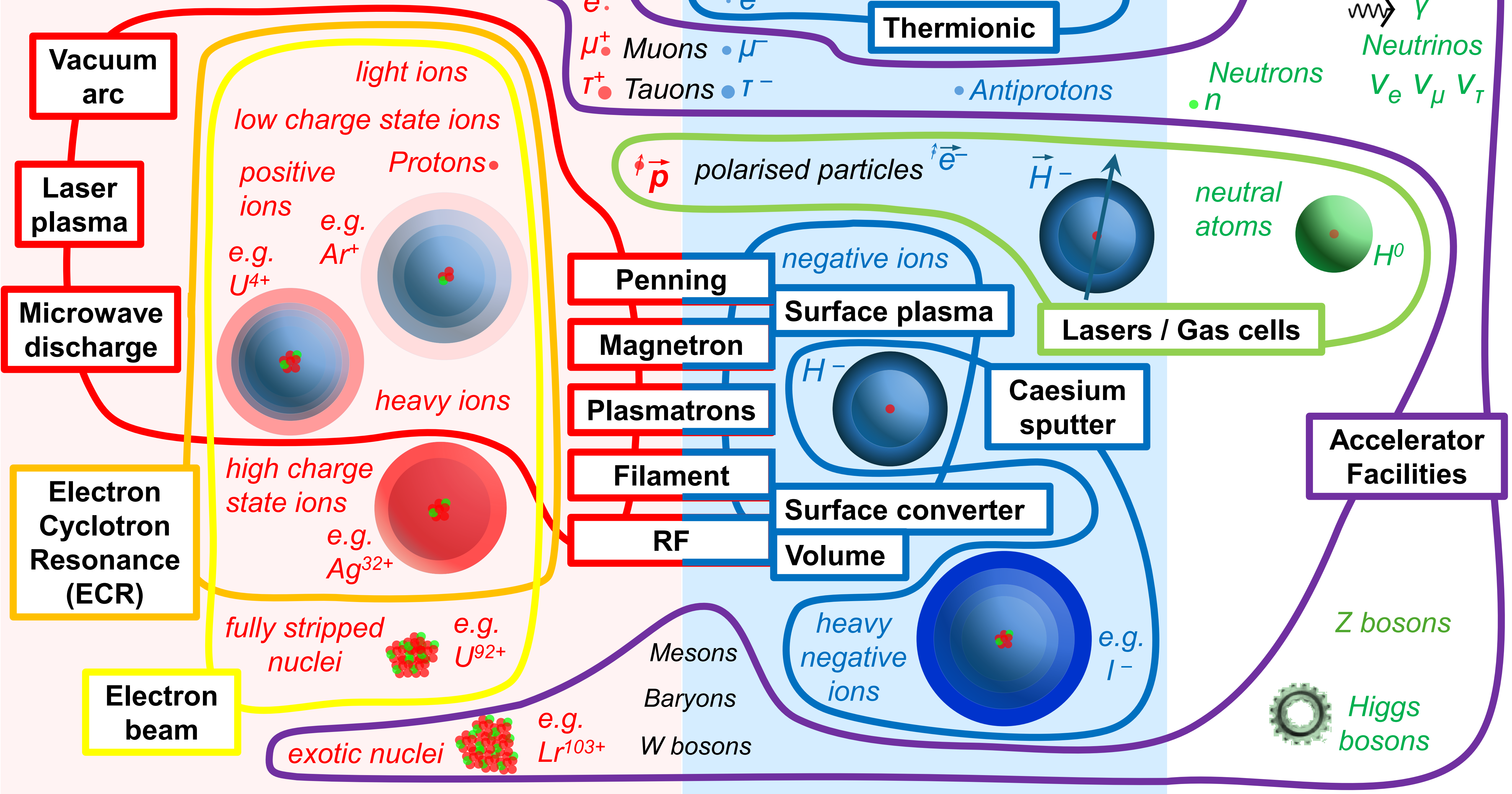
Dan Faircloth
ISIS Low Energy Beams Group Leader
Rutherford Appleton Laboratory
STFC-UKRI

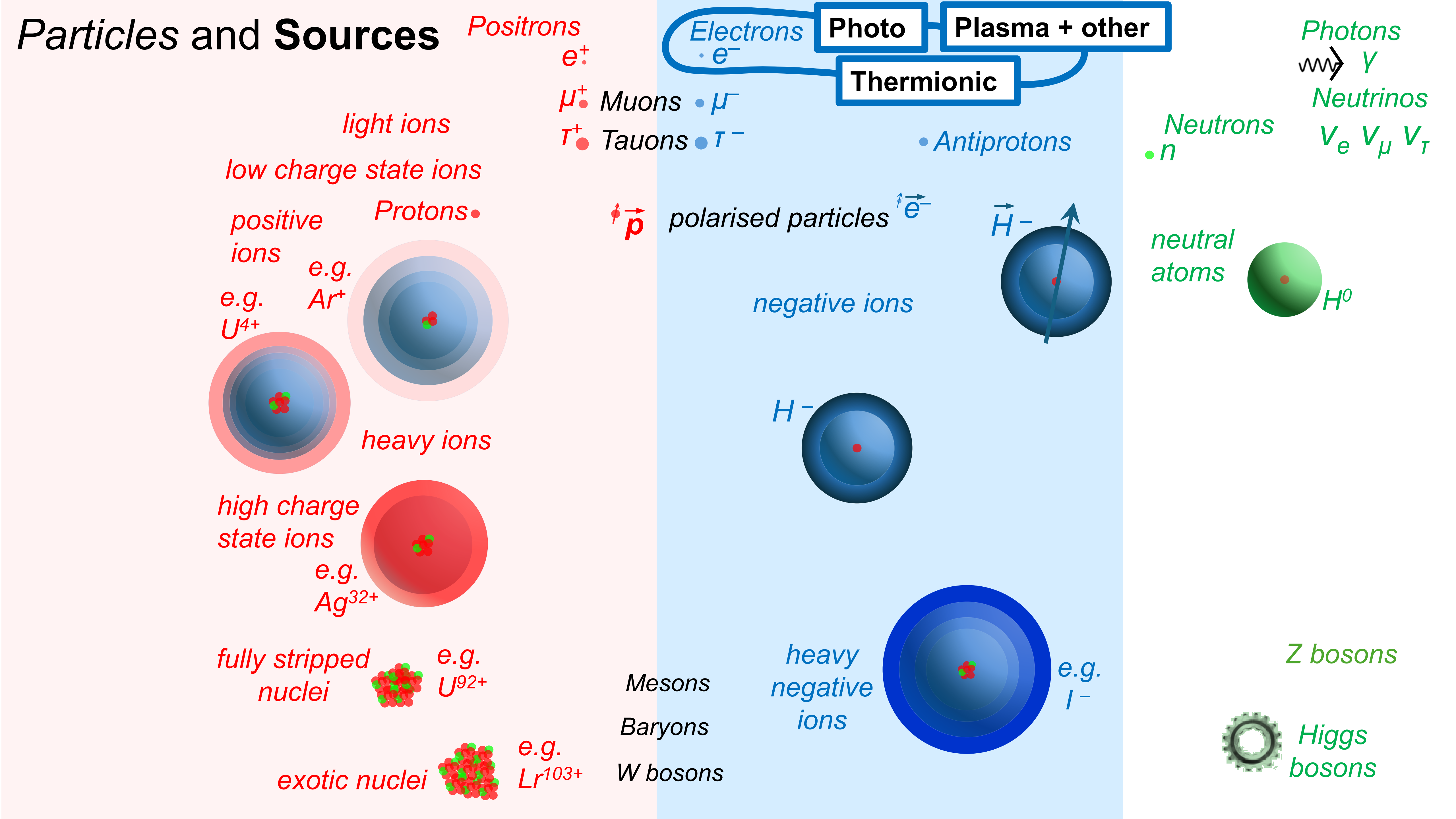
CI Lectures 2026 Daresbury



Particles
positively charged particles
Positrons
e+
μ+ Muons μ−
τ+ Tauons τ −
Electrons
e−
negatively charged particles
neutral particles
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
light ions
low charge state ions
Antiprotons
positive ions
Protons
p
polarised particles
e−
H −
e.g. Ar+
e.g. U4+
neutral atoms
H0
negative ions
heavy ions
H −
high charge state ions
e.g. Ag32+
fully stripped nuclei
e.g. U92+
Mesons
Baryons
W bosons
exotic nuclei
e.g. Lr103+
heavy negative ions
e.g. I −
Z bosons
Higgs bosons

Particles and **Sources**





Particles and Sources
Positrons
e+
μ+
Muons
μ−
τ+
Tauons
τ −
Electrons
e−
Photo
Plasma + other
Thermionic
Antiprotons
Photons
γ
Neutrinos
νe νμ ντ
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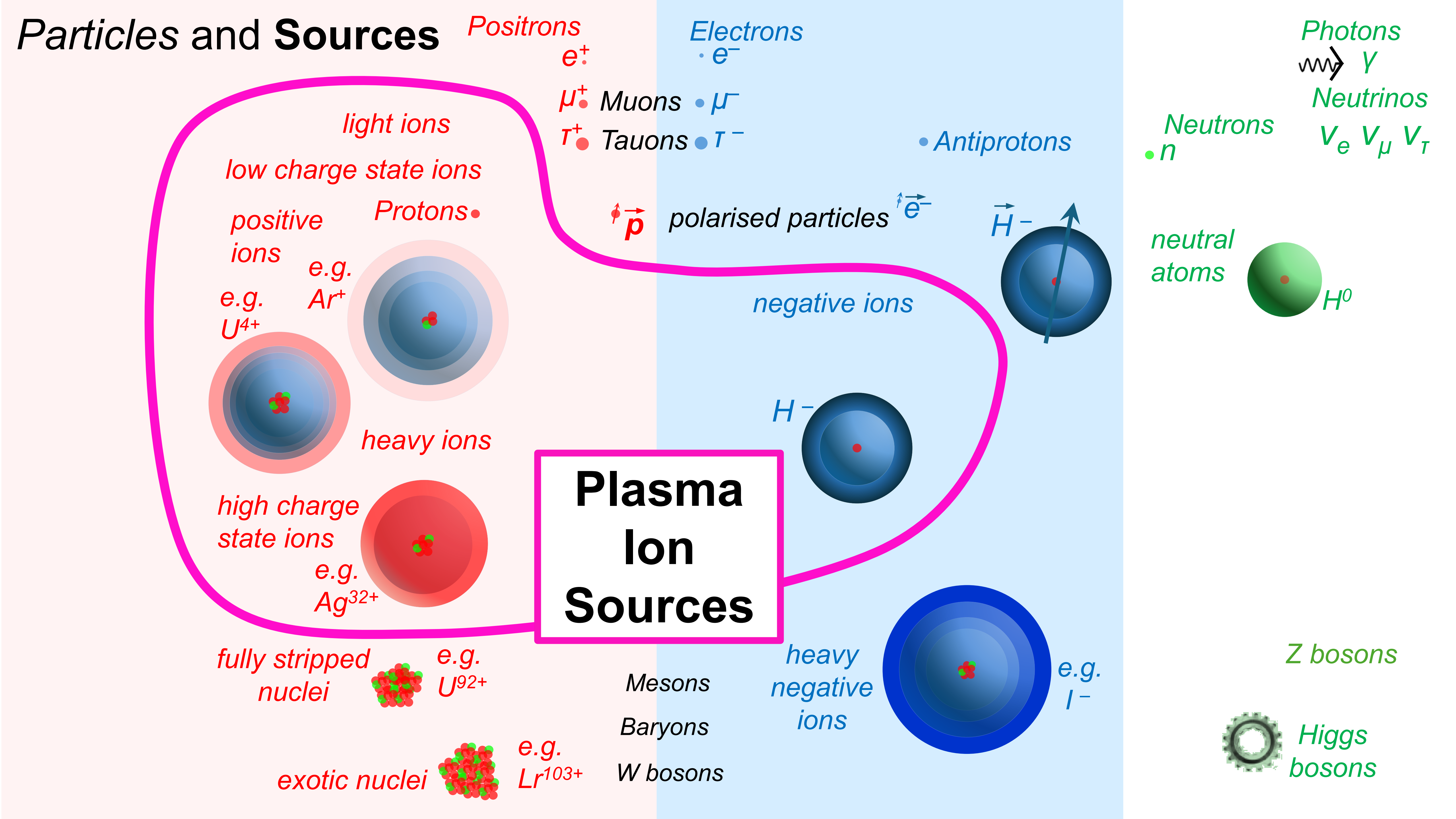
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e.g. Lr103+
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e.g. I−
Z bosons
Higgs bosons

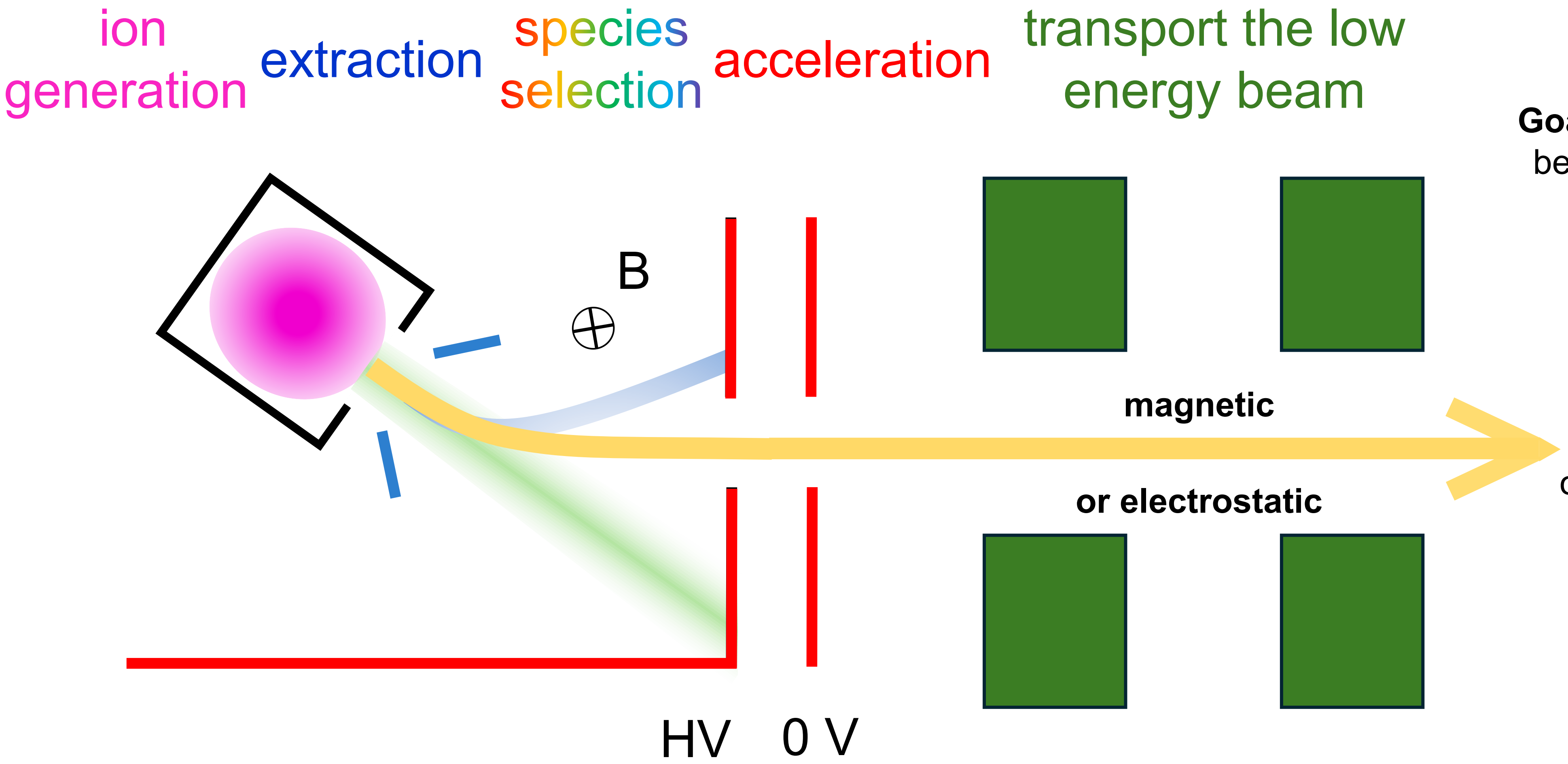
What is an ion source (and LEBT)?

Low
Energy
Beam
Transport

…what do they do?

Key functions of the ion source and LEBT:

(there are many ways to combine these functions)



Goal: deliver the required beam to the 1st stage of the accelerator

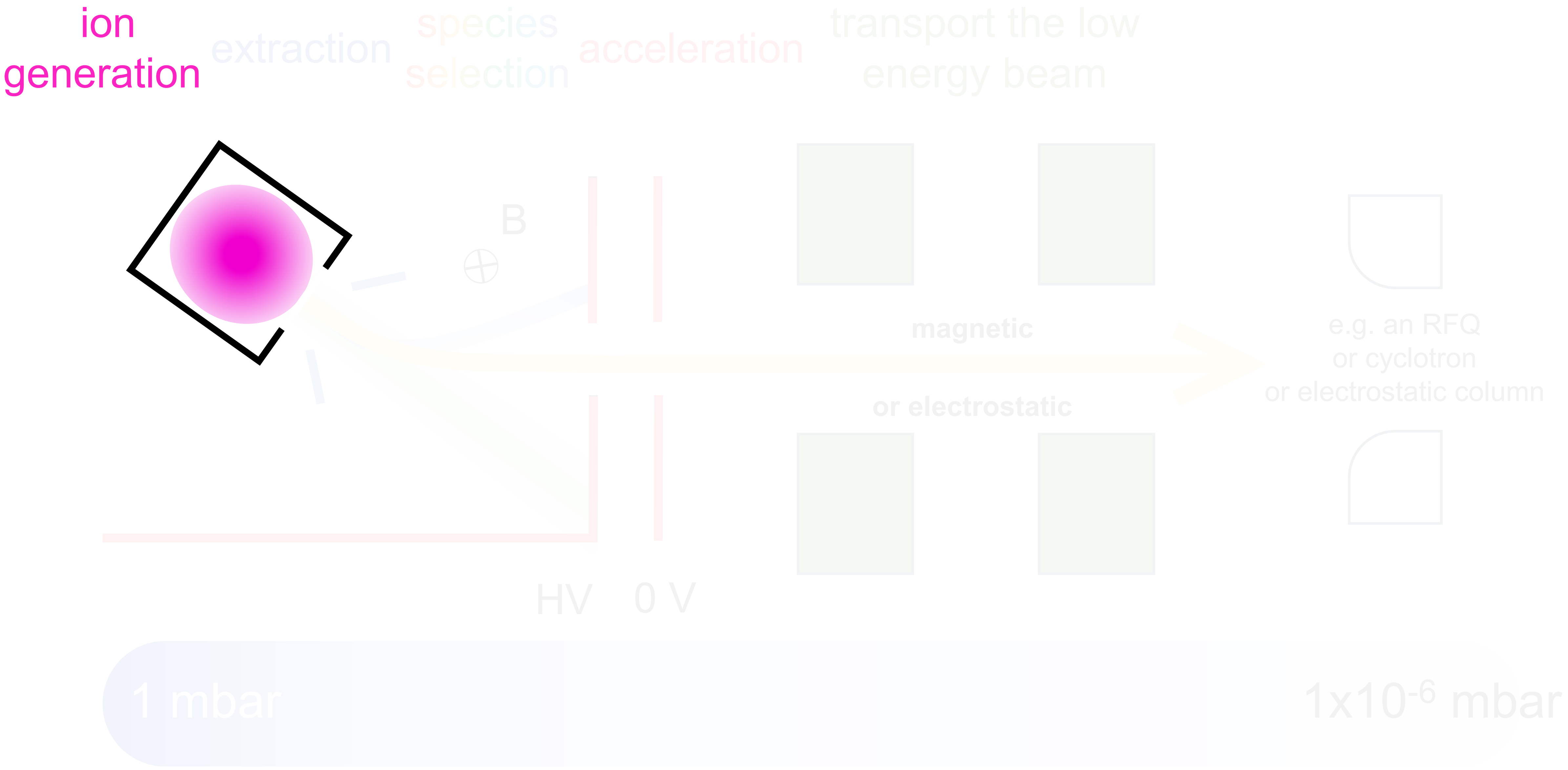
e.g. an RFQ
or cyclotron
or electrostatic column

1 mbar — drop the pressure by 6 orders of magnitude! — 1×10^{-6} mbar

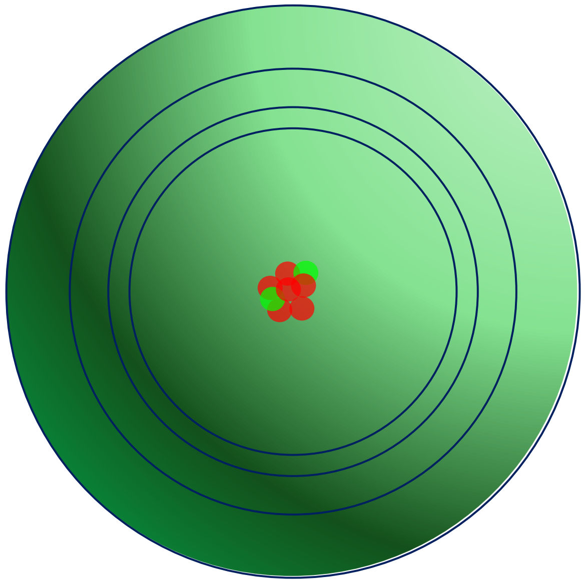
Key functions of the ion source and LEBT:

To give birth to the beam!

Key functions of the ion source and LEBT:



Plasma generation - Ionisation

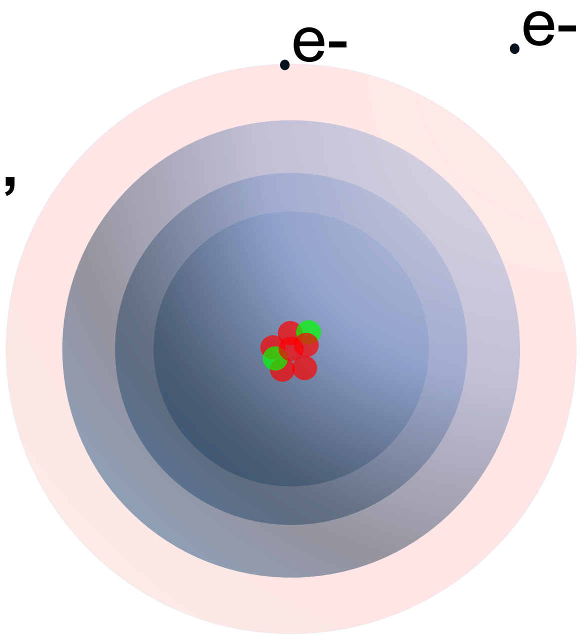


neutral atom

many sources rely on electron impact ionisation

Plasma generation - Ionisation

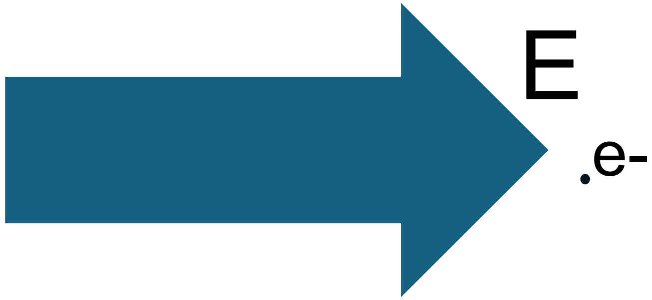
electrons also drive many other key plasma processes
(excitation, disassociation, secondary emission, etc.)



positive ion

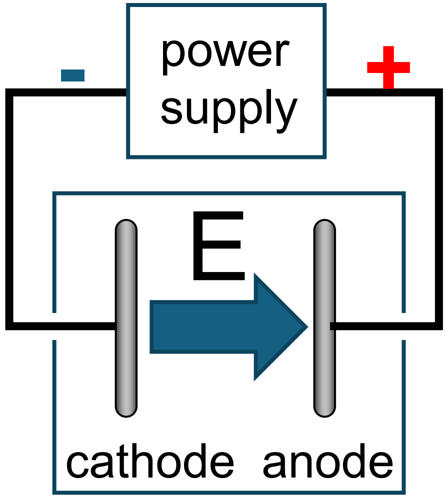
many sources rely on electron impact ionisation

Accelerating electrons



Capacitively Coupled Plasmas (CCP)

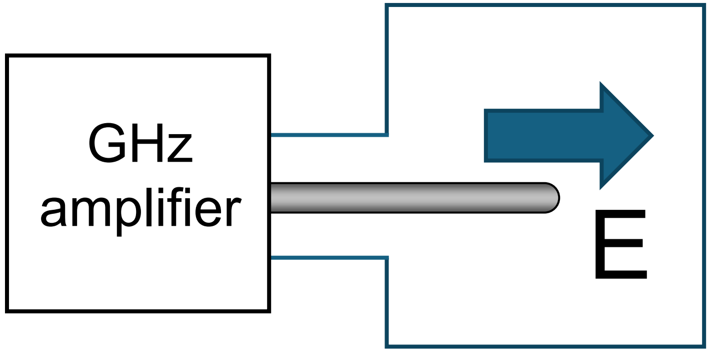
voltage applied to electrodes creates the electric field



many different electrode and magnetic field configurations
DC and AC

Electromagnetic Cavity Plasmas - waveguide or coax coupled

the electric field component of the electromagnetic oscillation in a cavity

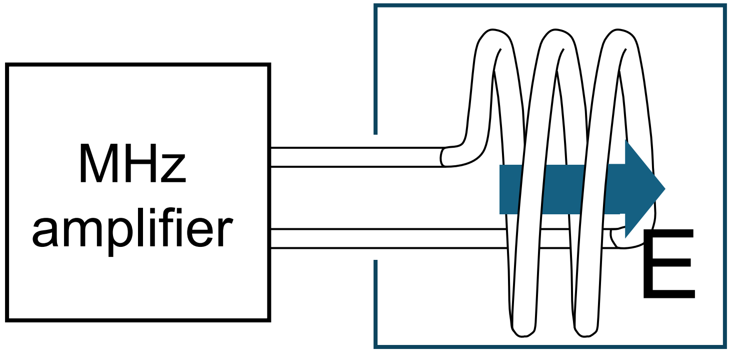


"Microwave sources"
"ECR sources"

Inductively Coupled Plasmas (ICP)

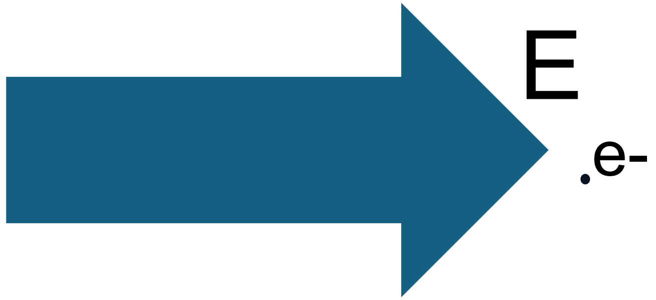
a time varying current in a coil creates a time varying magnetic field that induces a time varying electric field

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$



"RF sources"

Accelerating electrons



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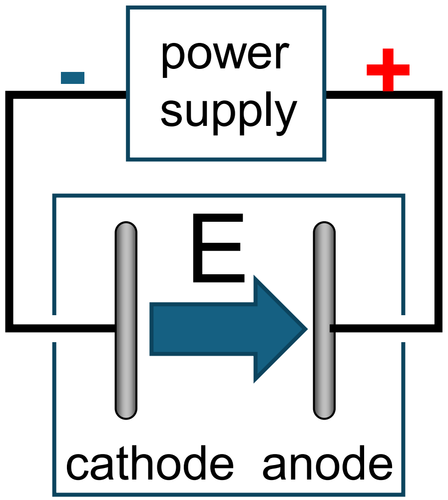

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“RF sources”

Plasma Pioneers

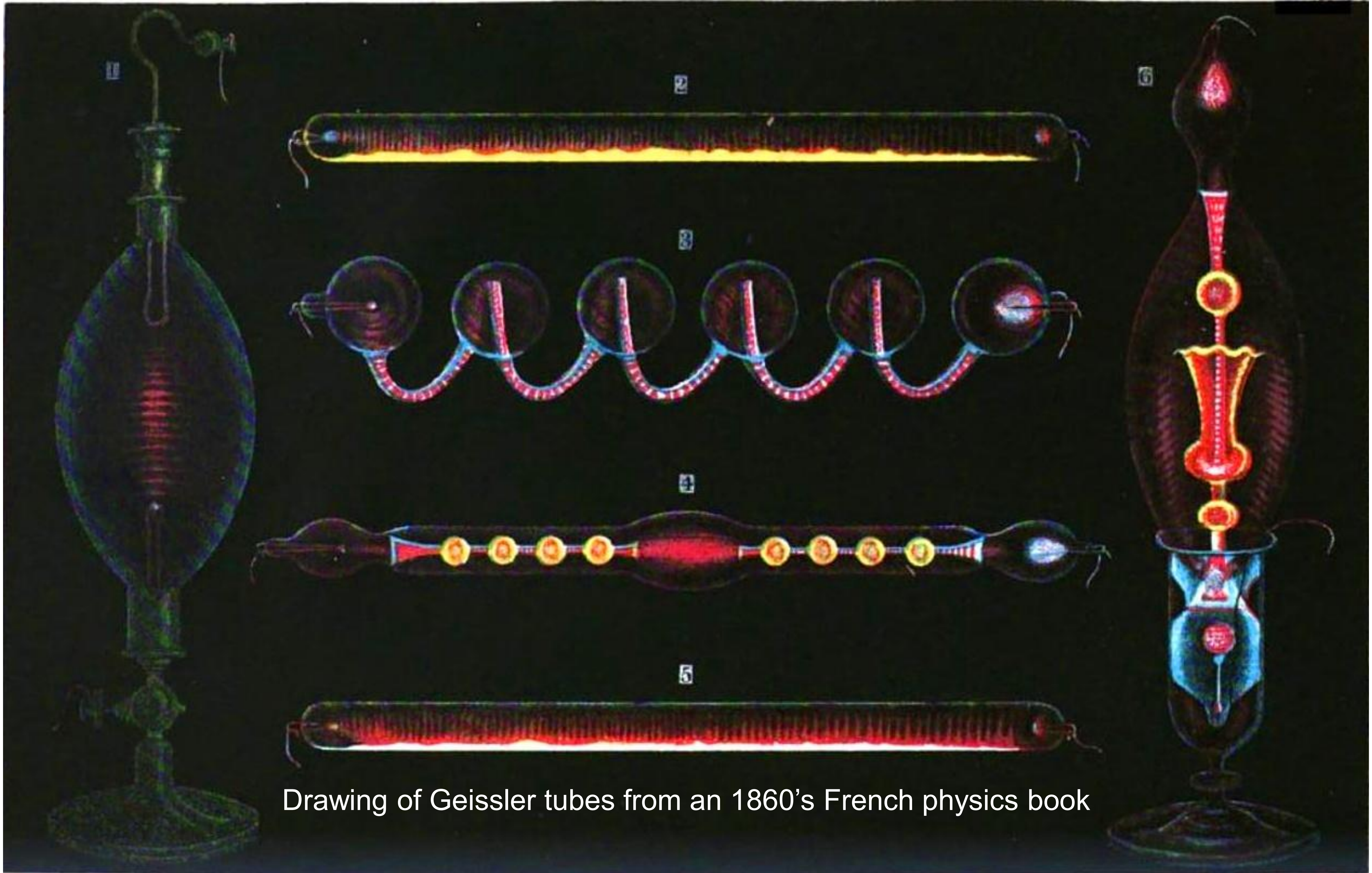
Julius Plücker

Mid 1850’s University of Bonn

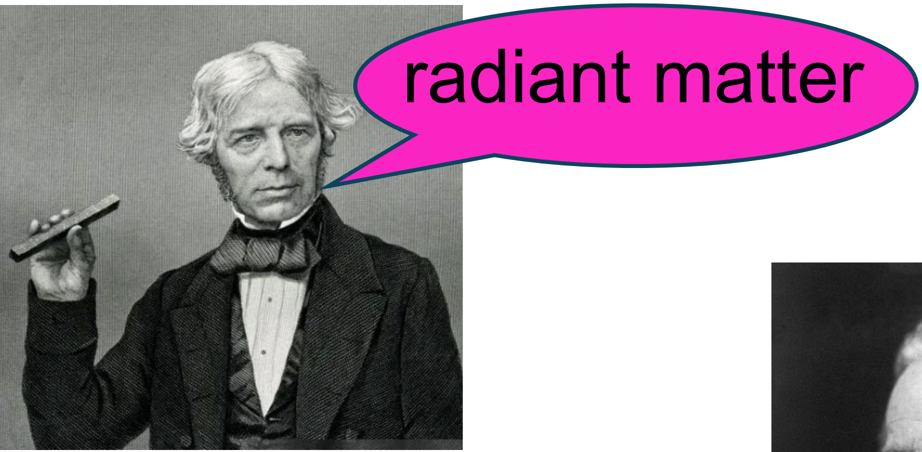
magnetism could
move the glow
discharge

Heinrich Geißler

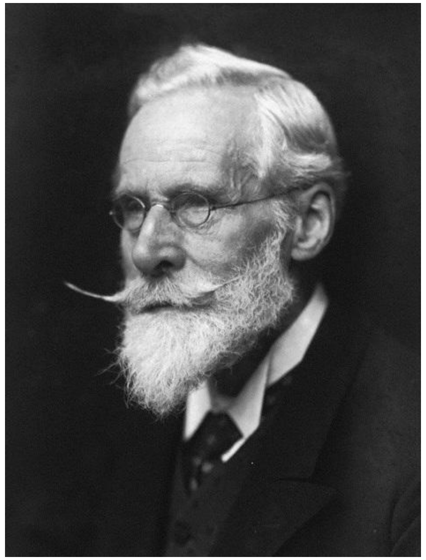
Gas discharge tube and
mercury displacement pump
just less than 1 mbar



Drawing of Geissler tubes from an 1860’s French physics book

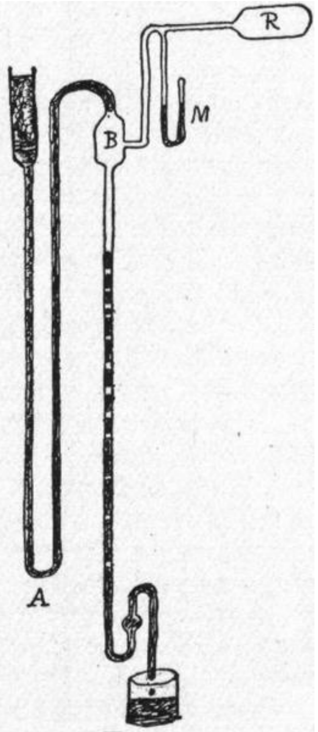


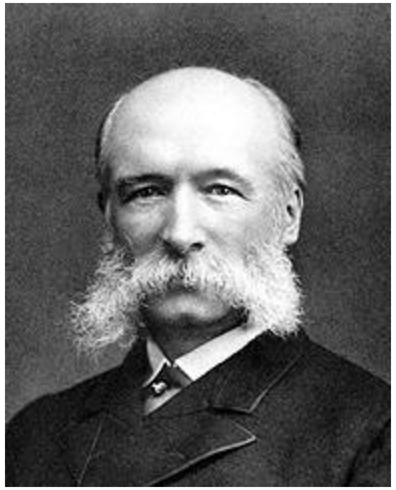
Micheal Faraday 1816



William Crookes

Early 1870's

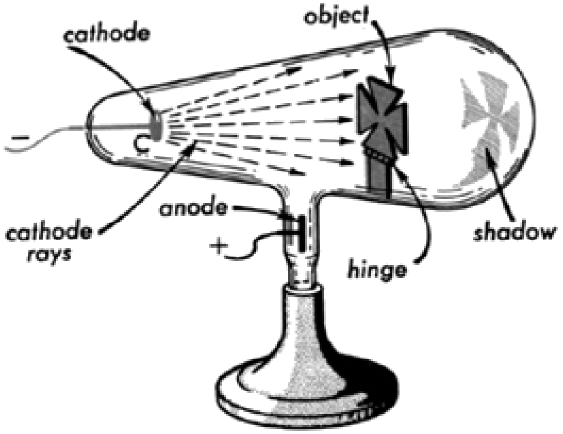


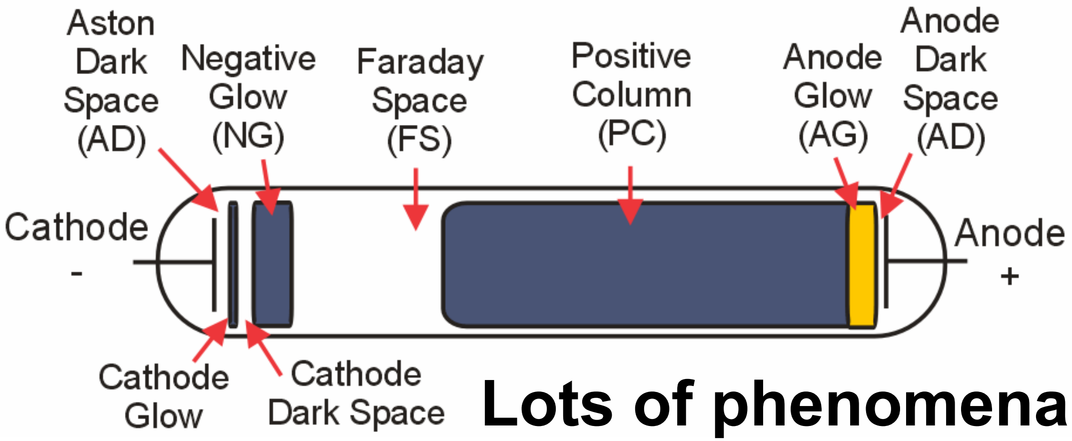


Hermann Sprengel

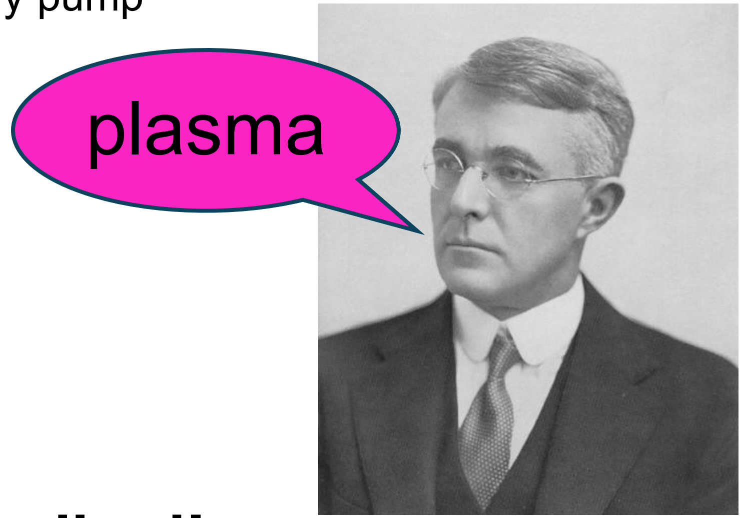
Improved mercury pump

10^{-5} mbar





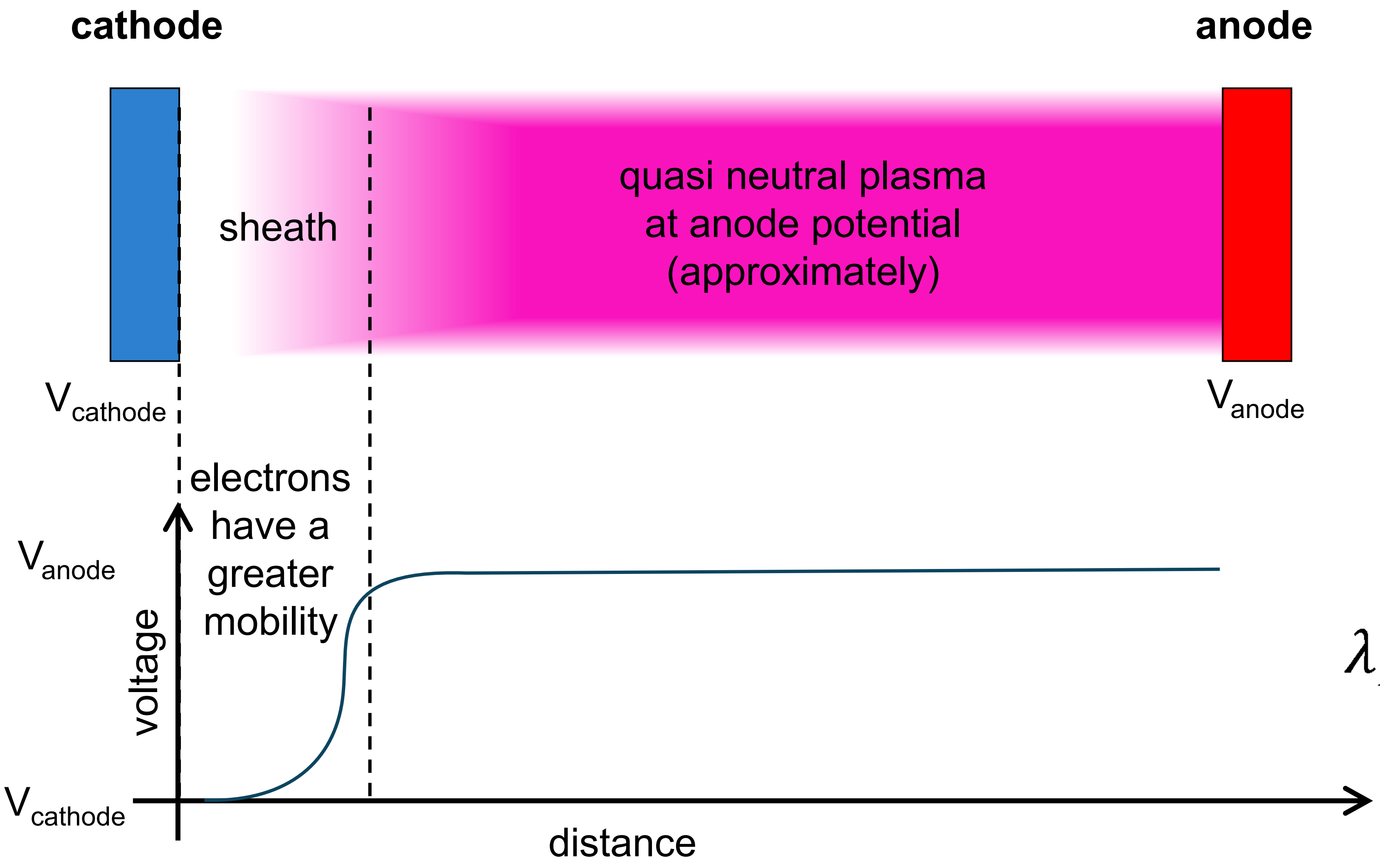
Lots of phenomena described!



Irving Langmuir 1928

Light fast electrons vs heavy slow ions

Light fast electrons - sheath phenomena

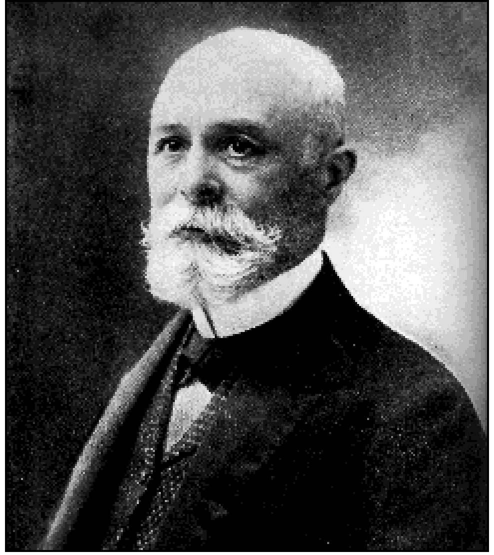


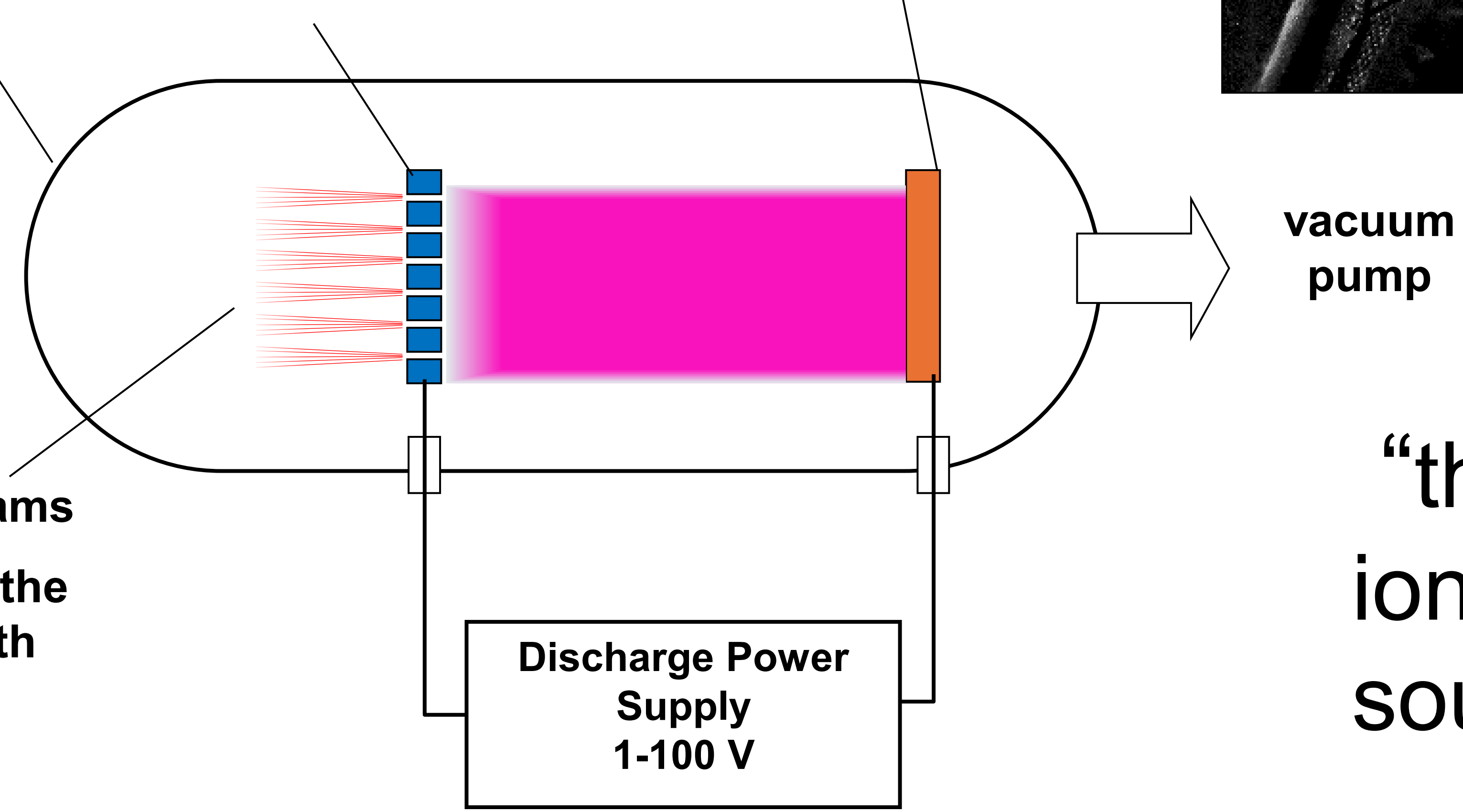
$$\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_e {q_e}^2}}$$

sheath dimensions = a few Debye lengths

Canal ray source

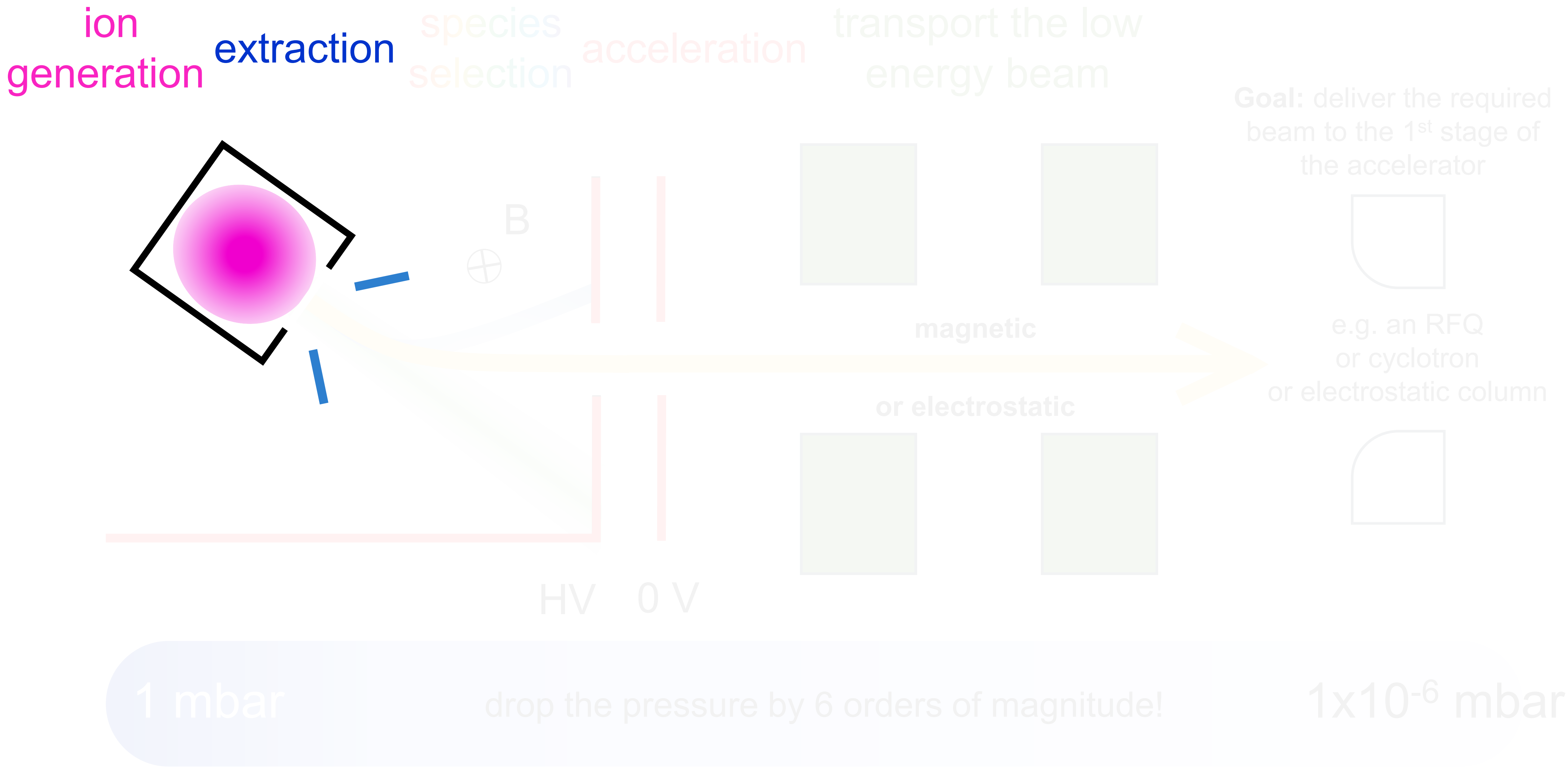
In 1886 Eugen Goldstein discovered “canal rays”



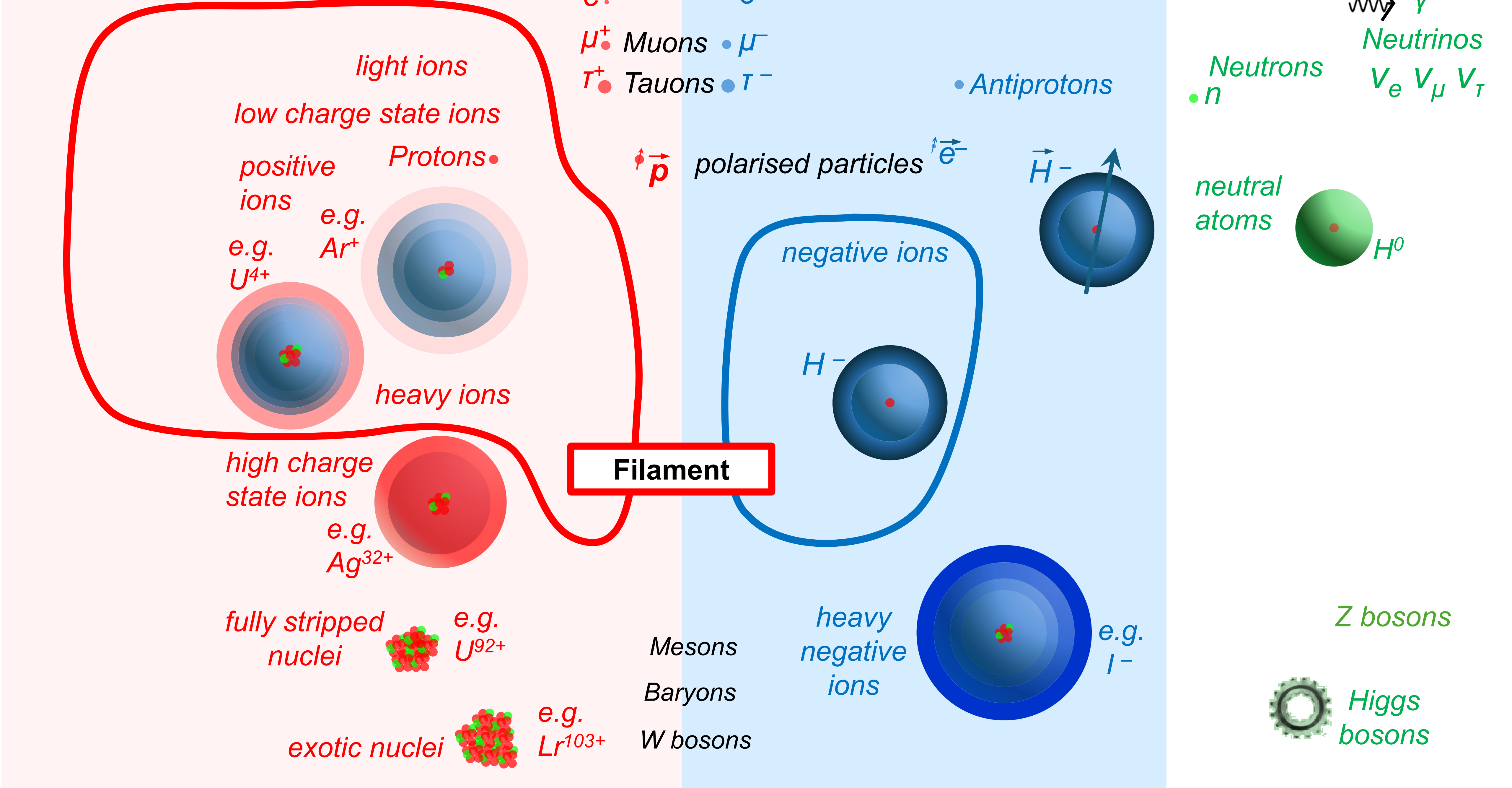


“the 1st ion source?”

Key functions of the ion source and LEBT:

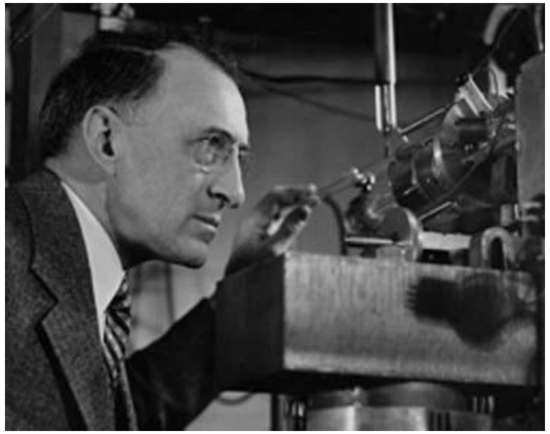


Particles and **Sources**



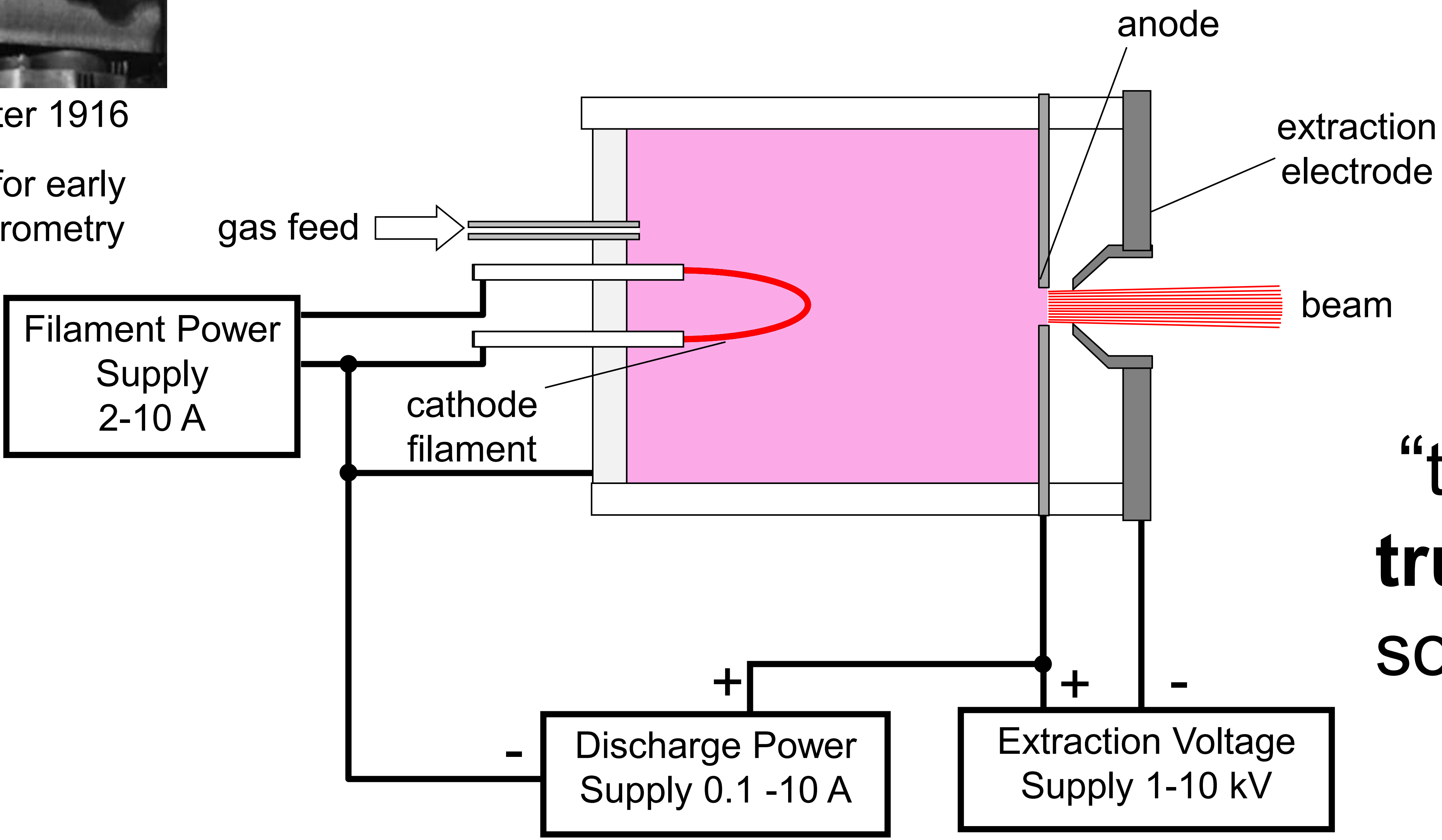
Cathode filament source

"Electron Bombardment Source"

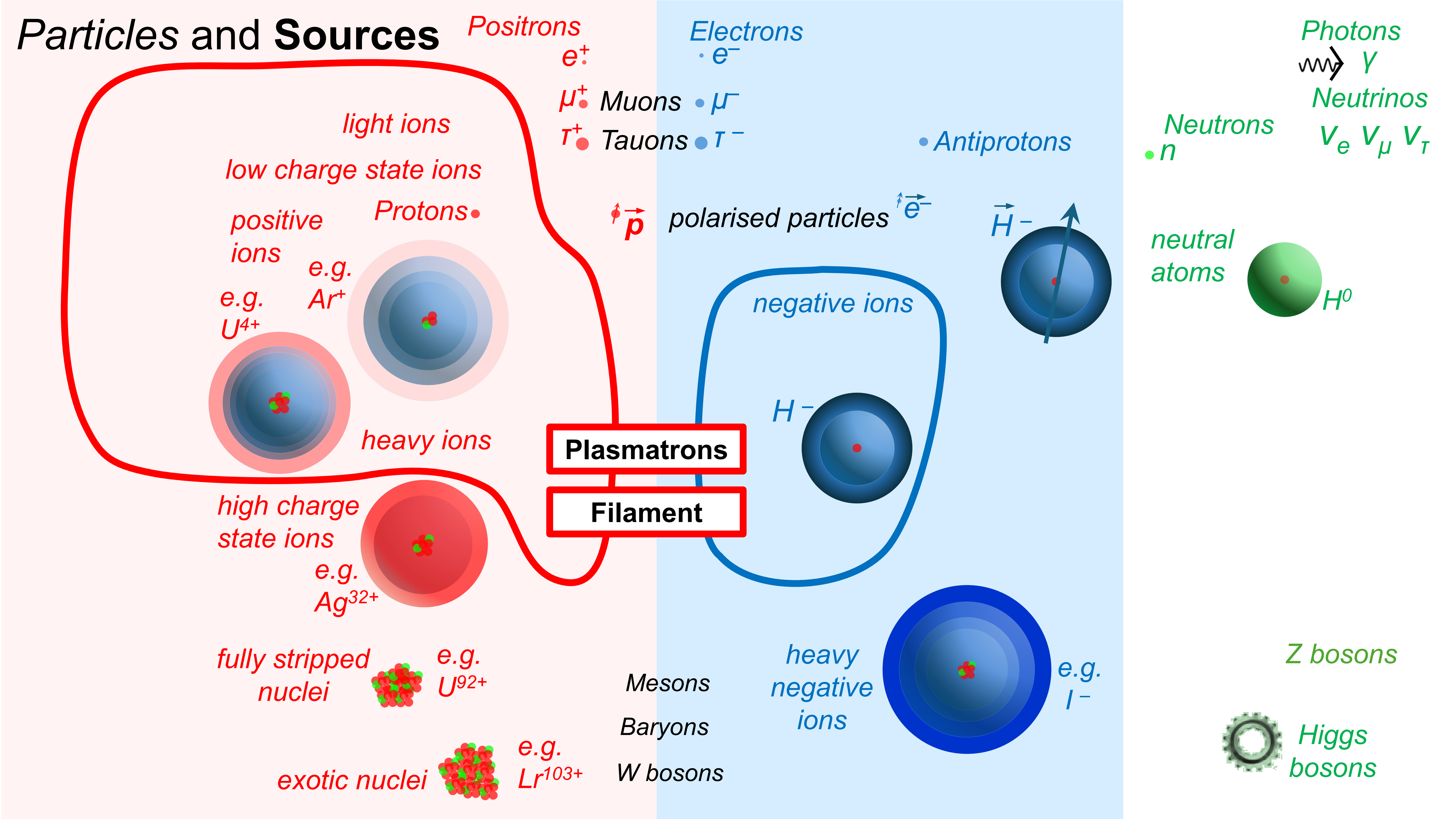


Arthur Dempster 1916

developed for early mass spectrometry



"the 1st **true** ion source"



Particles and Sources
Positrons
e+
Electrons
e−
Photons
γ
μ+ Muons μ−
τ+ Tauons τ−
Antiprotons
Neutrinos
νe νμ ντ
Neutrons
n
light ions
low charge state ions
positive ions
Protons
e.g. Ar+
e.g. U4+
p polarised particles e
H −
neutral atoms
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Plasmatrons
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Mesons
Baryons
W bosons
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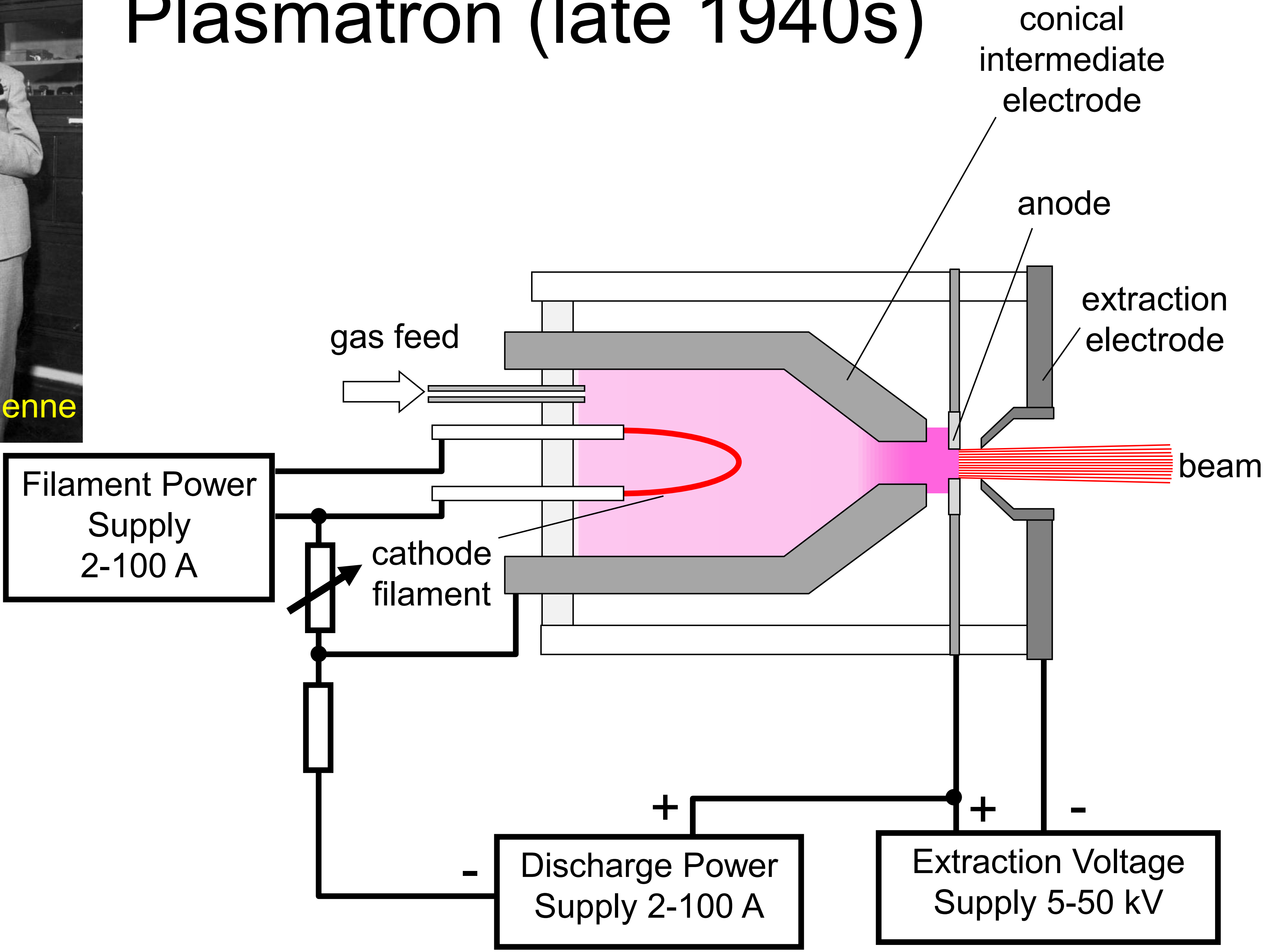
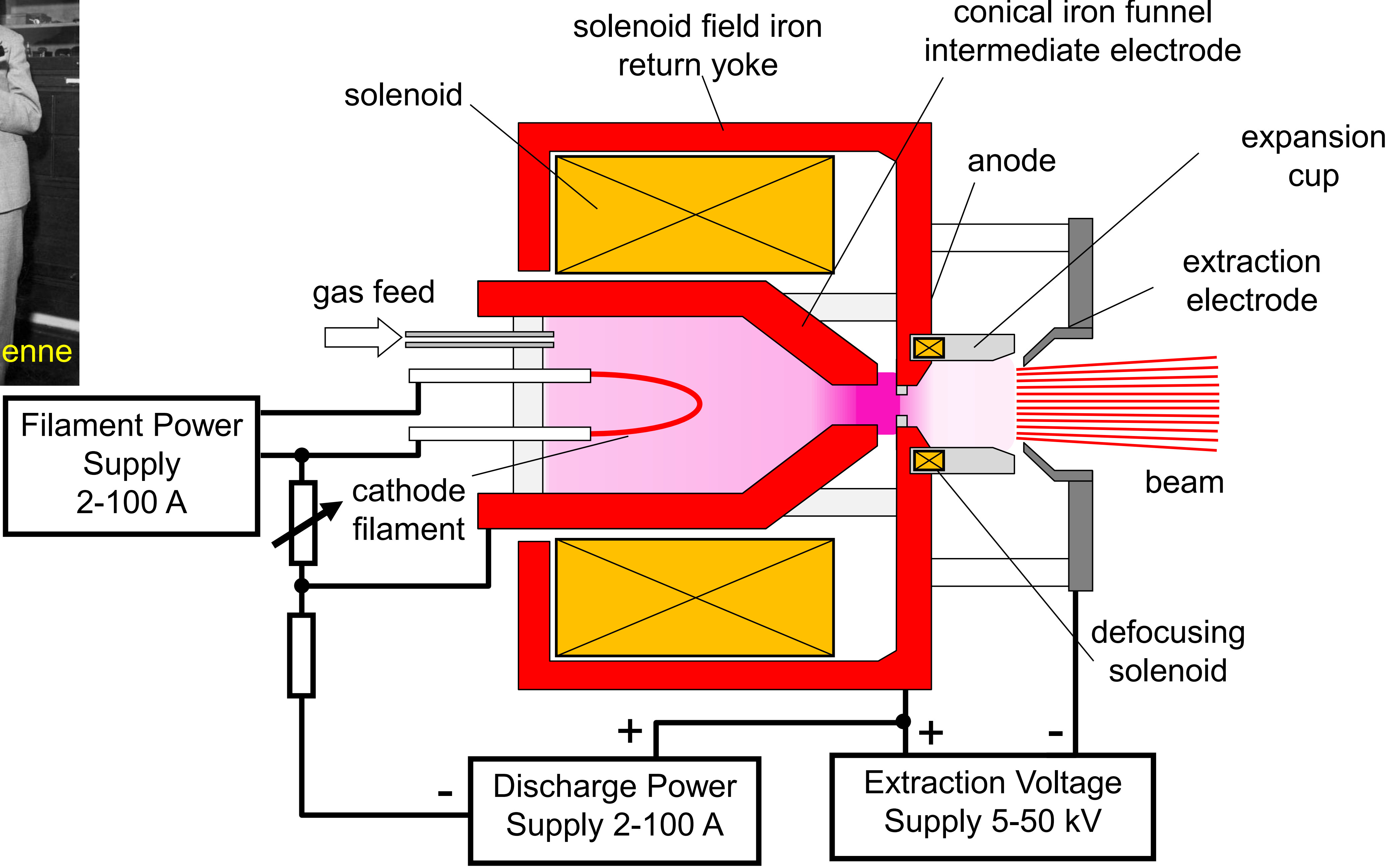
Higgs bosons

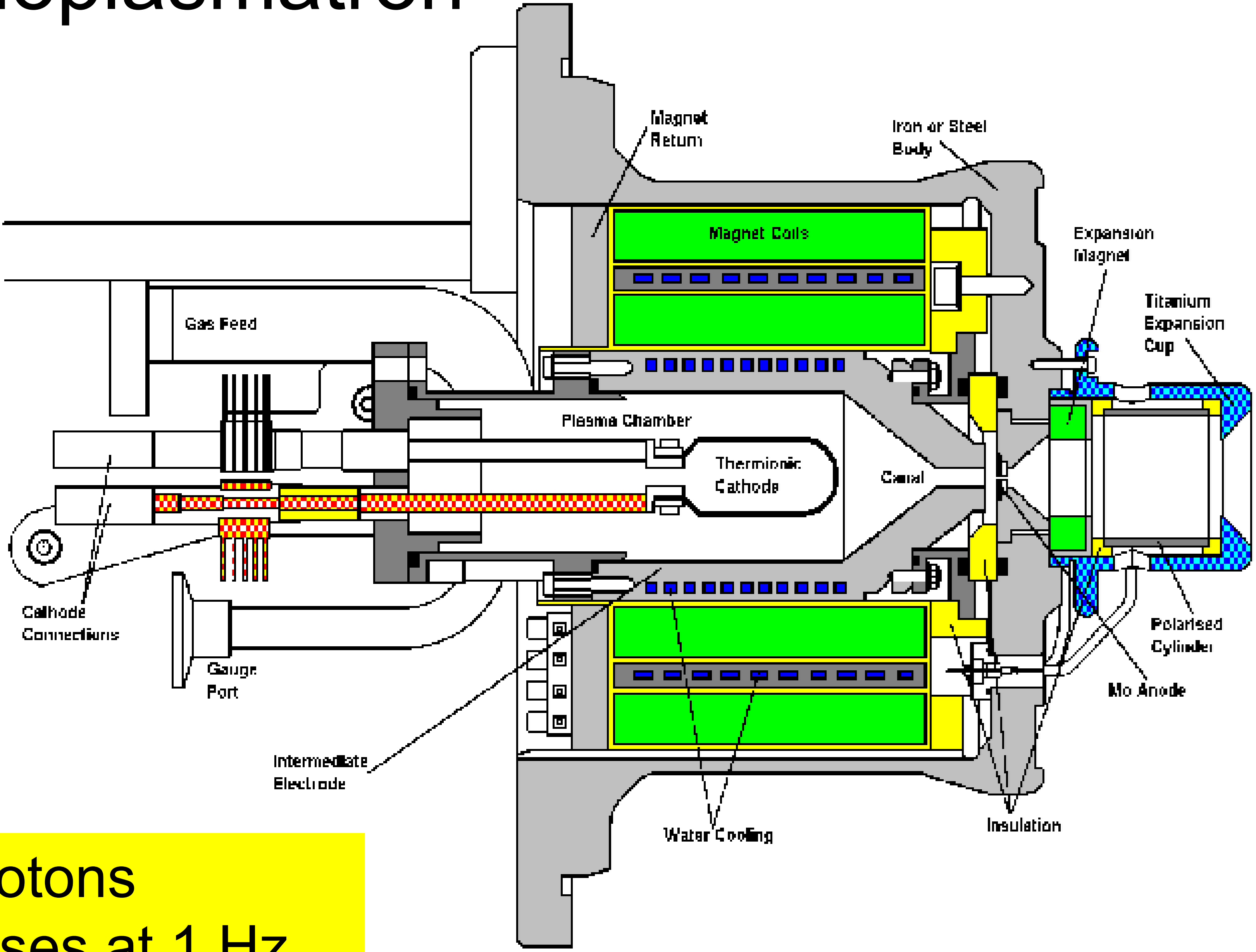
Plasmatron (late 1940s)



Duoplasmatron (1956)

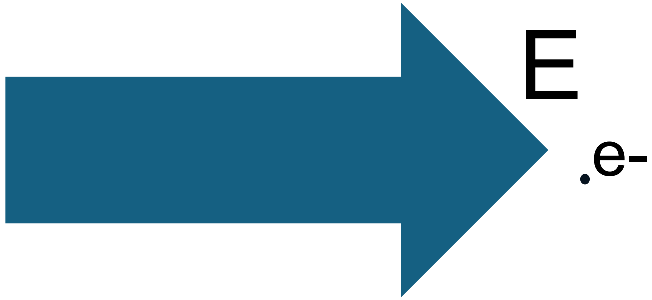


Duoplasmatron



300 mA protons
150 μs pulses at 1 Hz

Accelerating electrons



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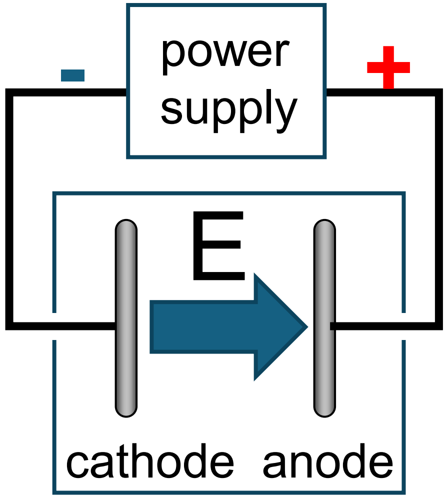

many different electrode and magnetic field configurations
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Electromagnetic Cavity Plasmas - waveguide or coax coupled

the electric field component of the electromagnetic oscillation in a cavity

"Microwave sources"
"ECR sources"

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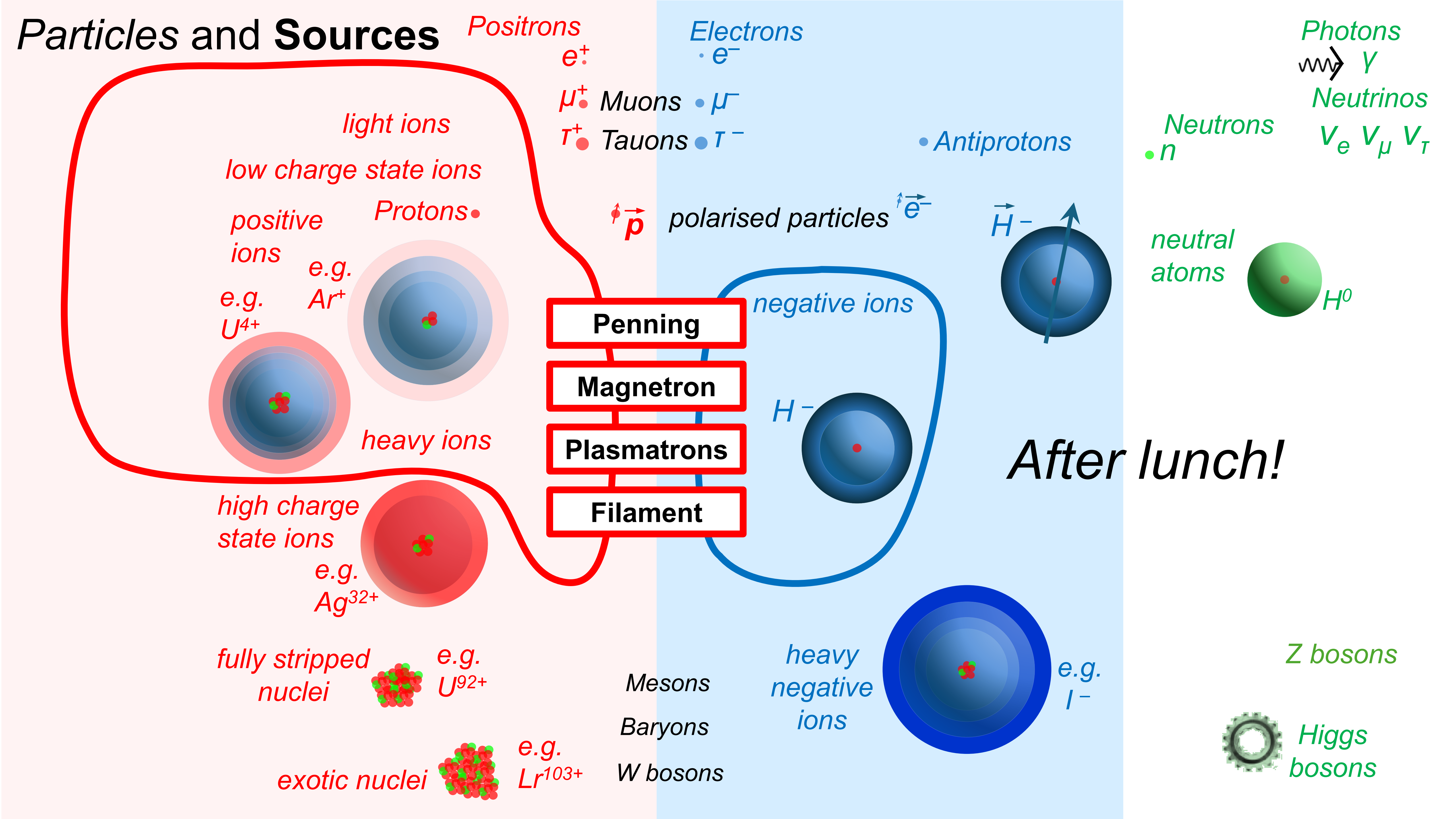
"RF sources"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After lunch!
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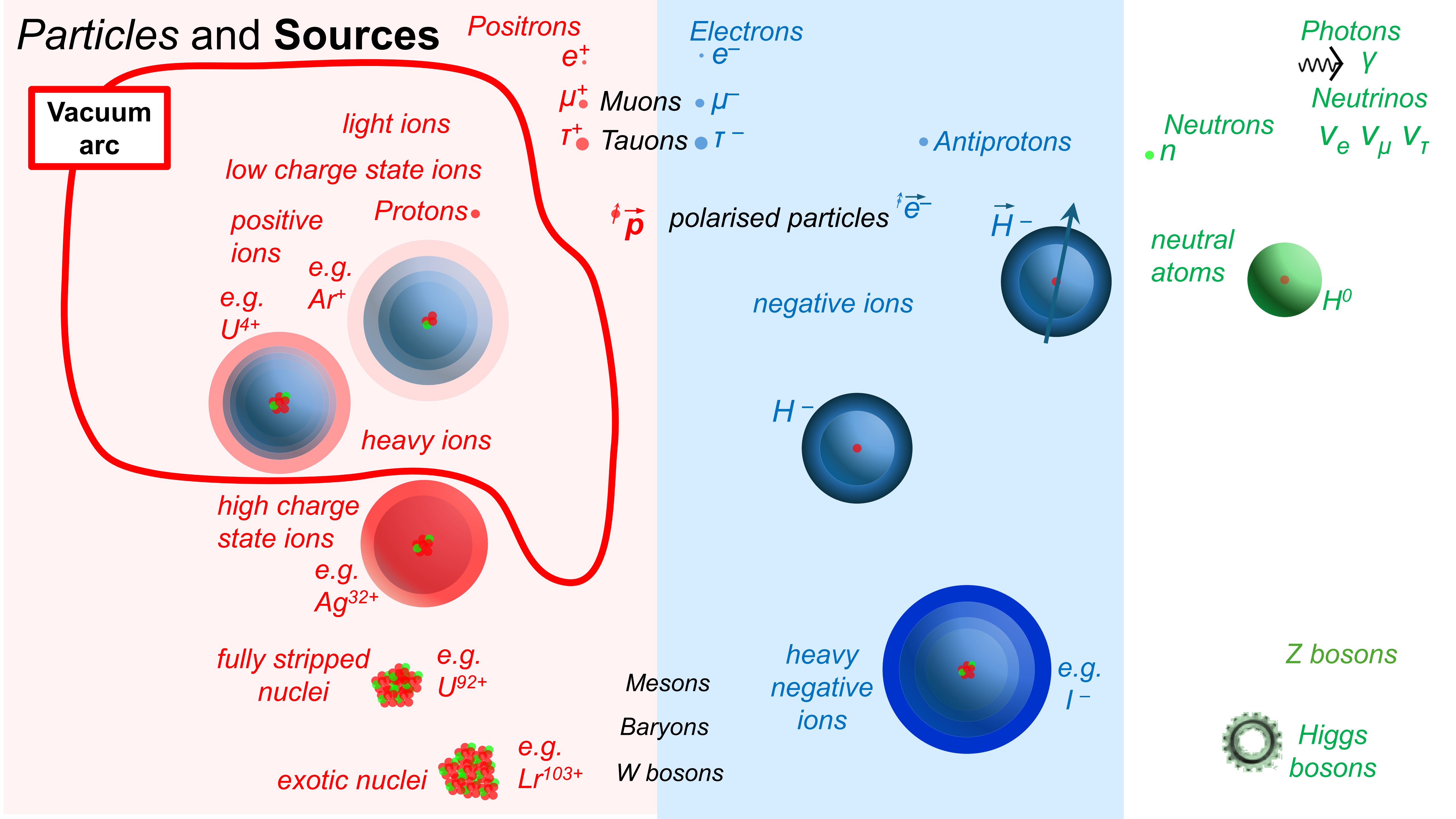
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Vacuum arc
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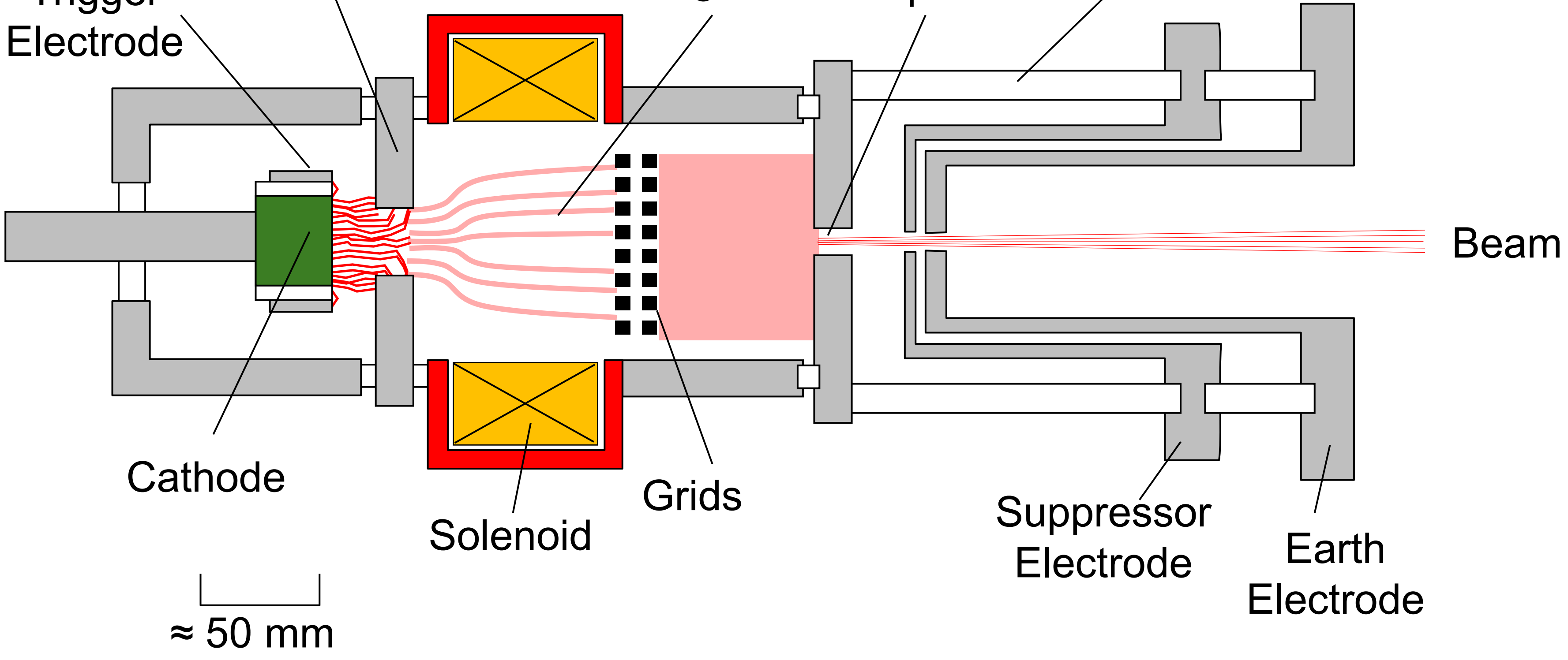
Vacuum Arc Ion Sources

1980s - Ian Brown at Lawrence Berkley Lab (and others)

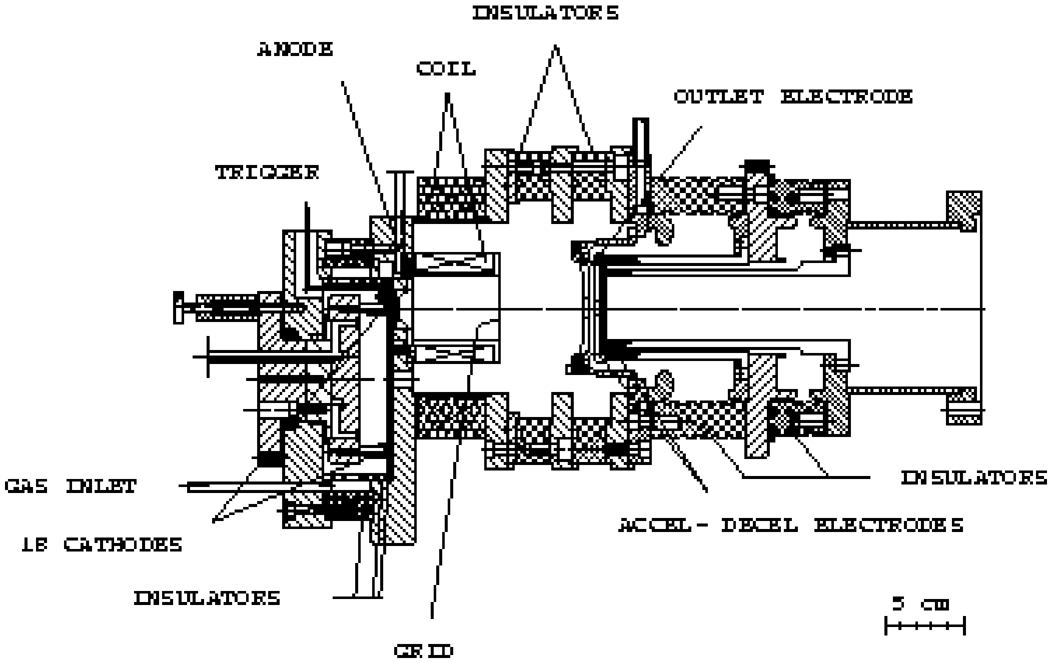


BERKELEY LAB

MEtal Vapor Vacuum Arc (MEVVA)

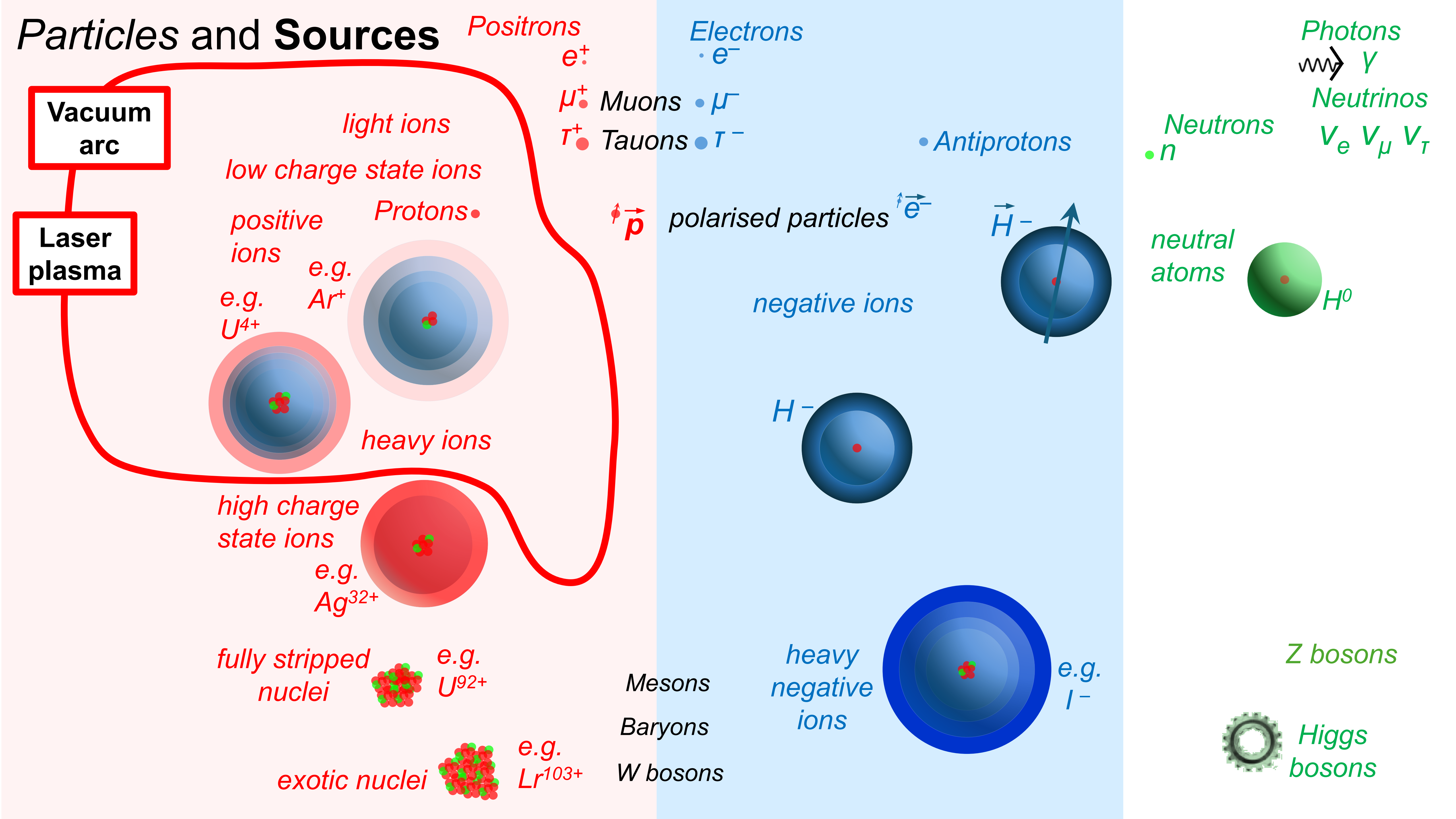
GSI

MEVVA

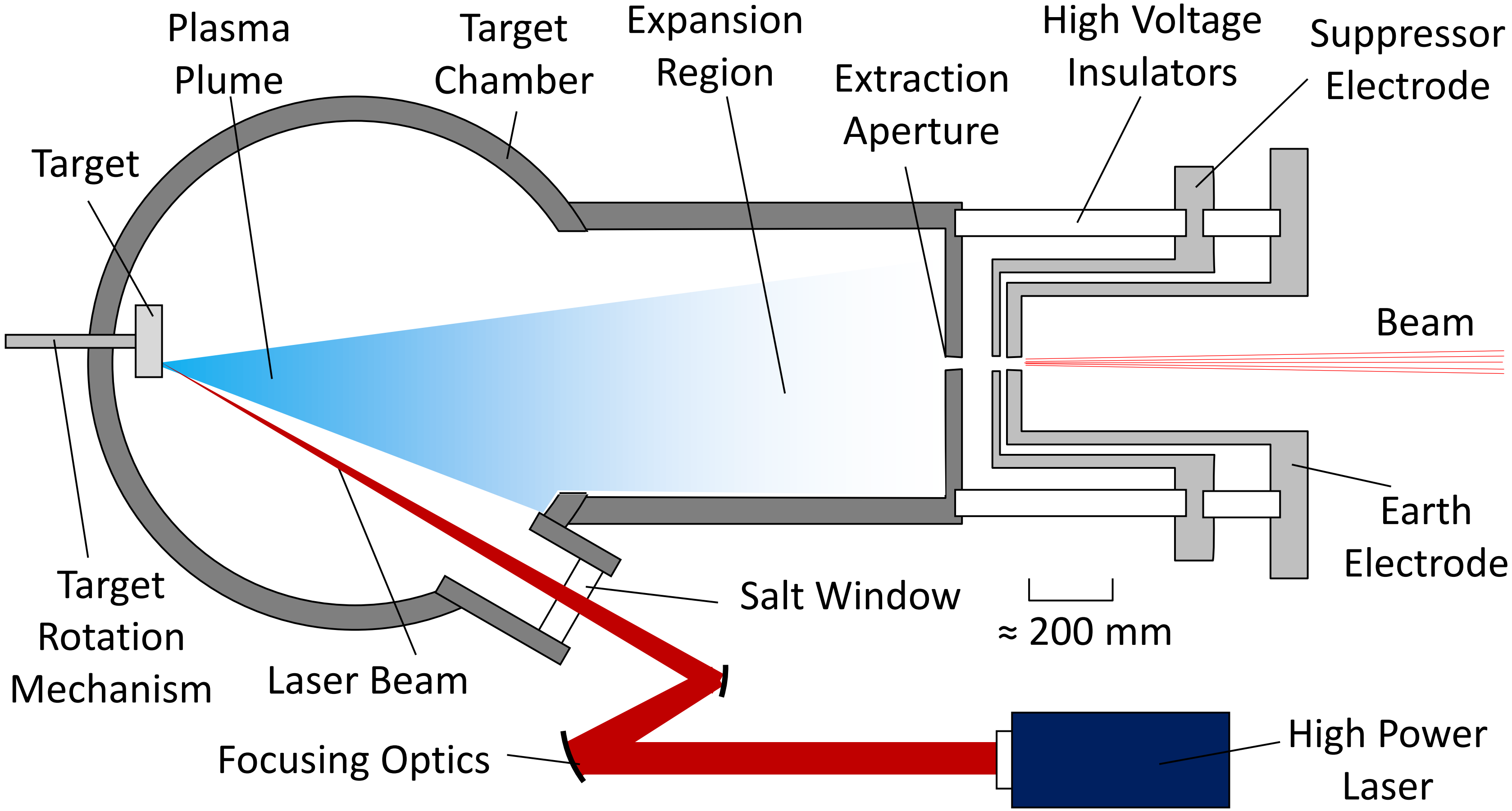


15 mA of U^{4+} ions

Particles and **Sources**



Laser plasma ion sources



1 -100 Joules per pulse!

ITEP Laser source at CERN

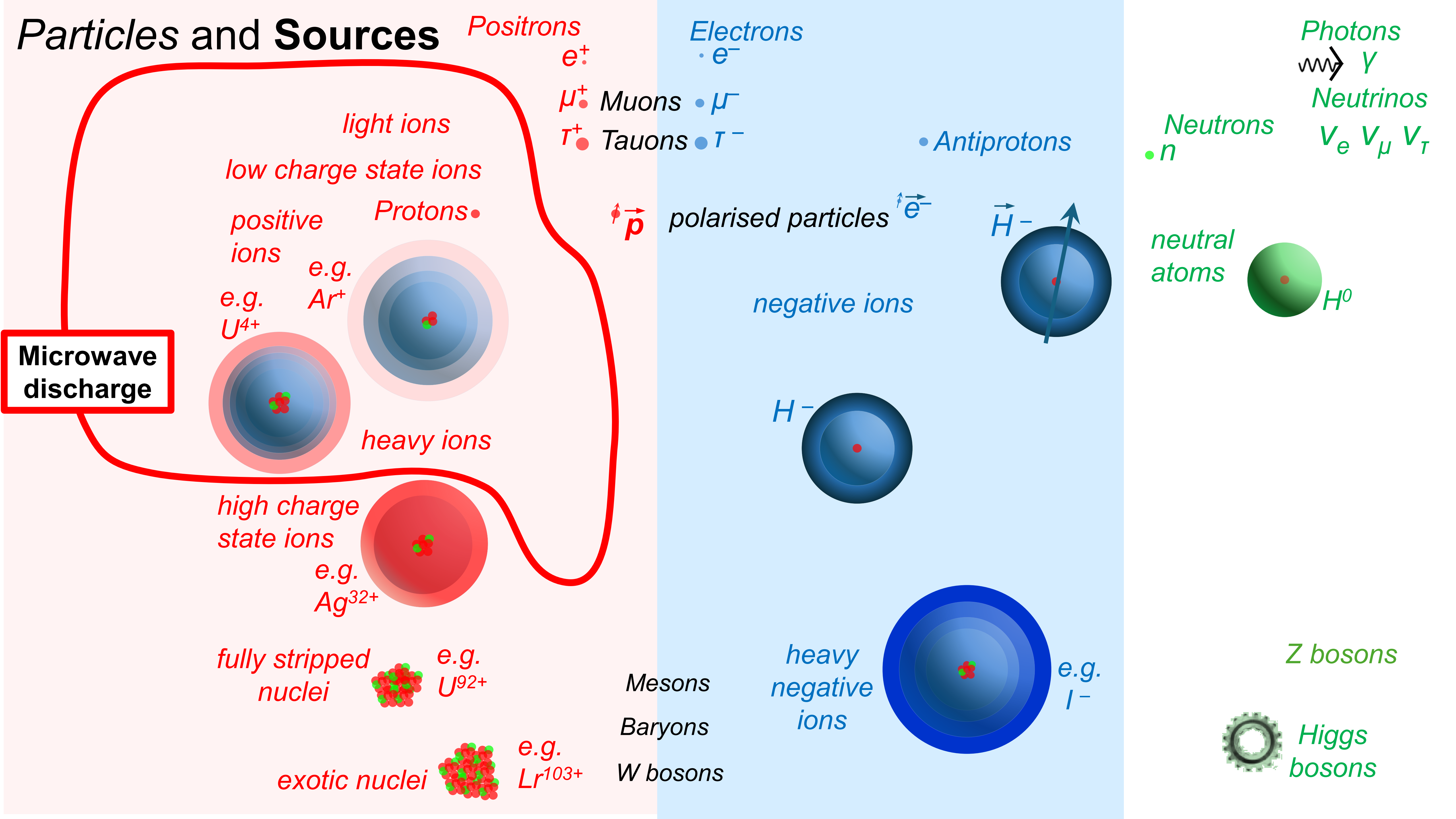
ITEP Laser source at CERN

TWAC at ITEP Moscow

7 mA, 10 μs pulses of C^{4+}

BNL and RIKEN

Masahiro Okamura has demonstrated
Direct Plasma Injection into an RFQ



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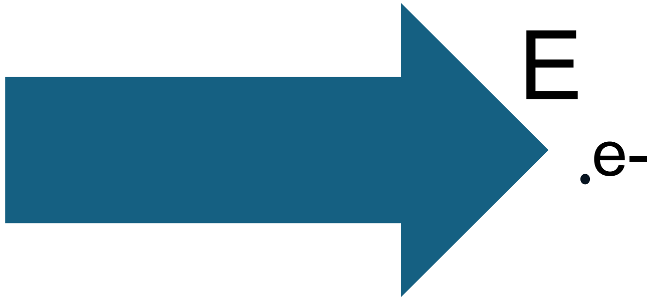
Accelerating electrons



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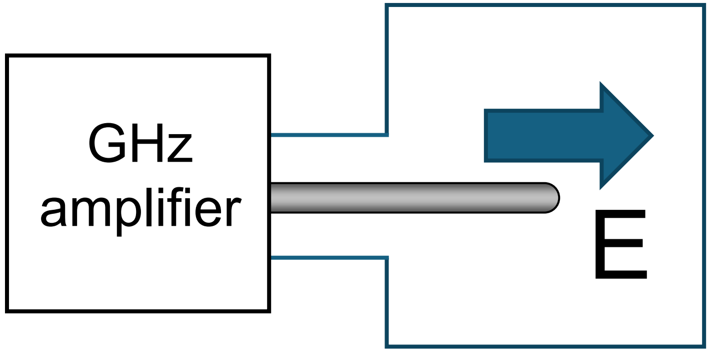

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"ECR sources"

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"RF sources"

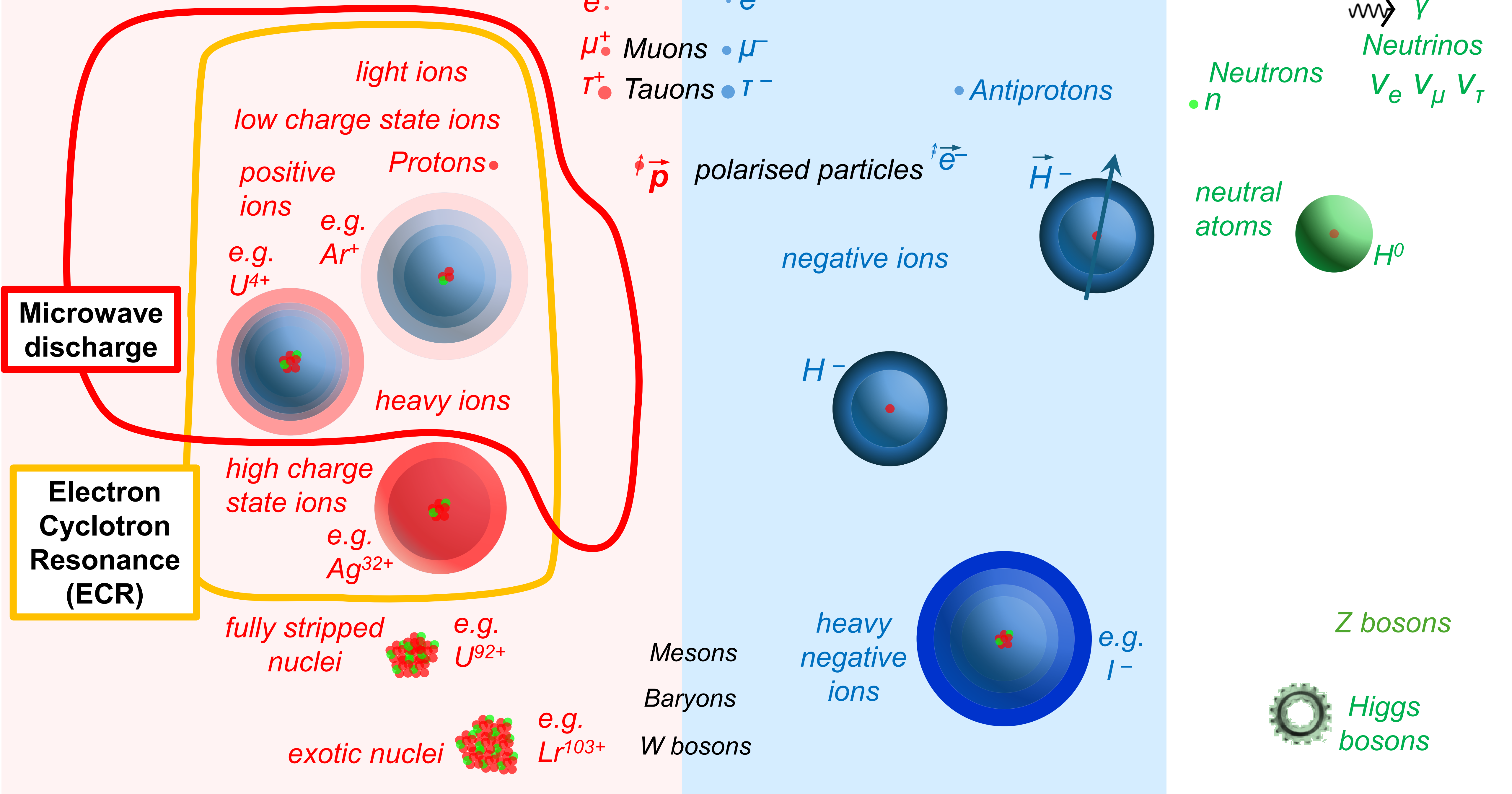
Microwave Ion Sources

There are two types of **microwave driven** ion source:

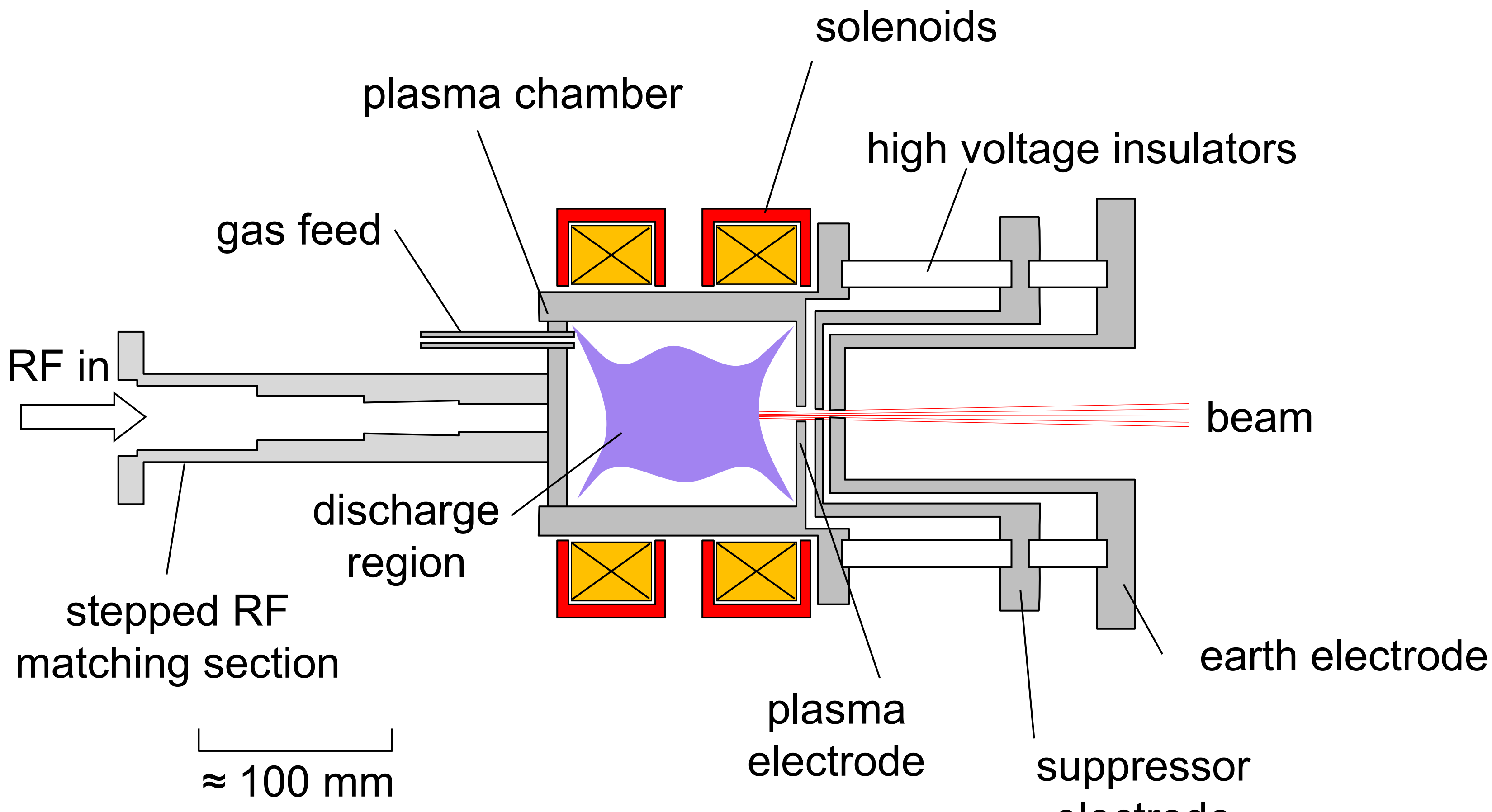
1. High pressure microwave discharge sources

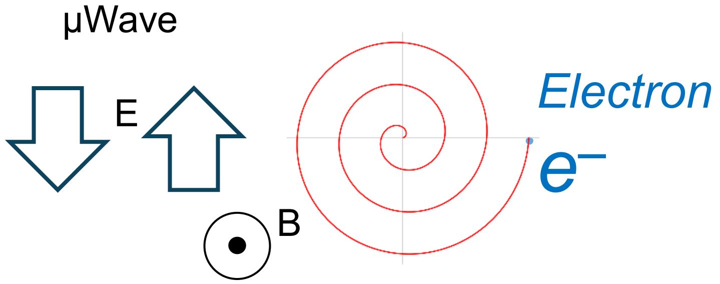
2. Electron Cyclotron Resonance (ECR) sources

Particles and **Sources**



Microwave discharge ion source





2.45 GHz
commonly used

$$\omega_{ECR} = 2\pi f_{ECR} = \frac{eB}{m}$$

87.5 mT

Microwave discharge ion source

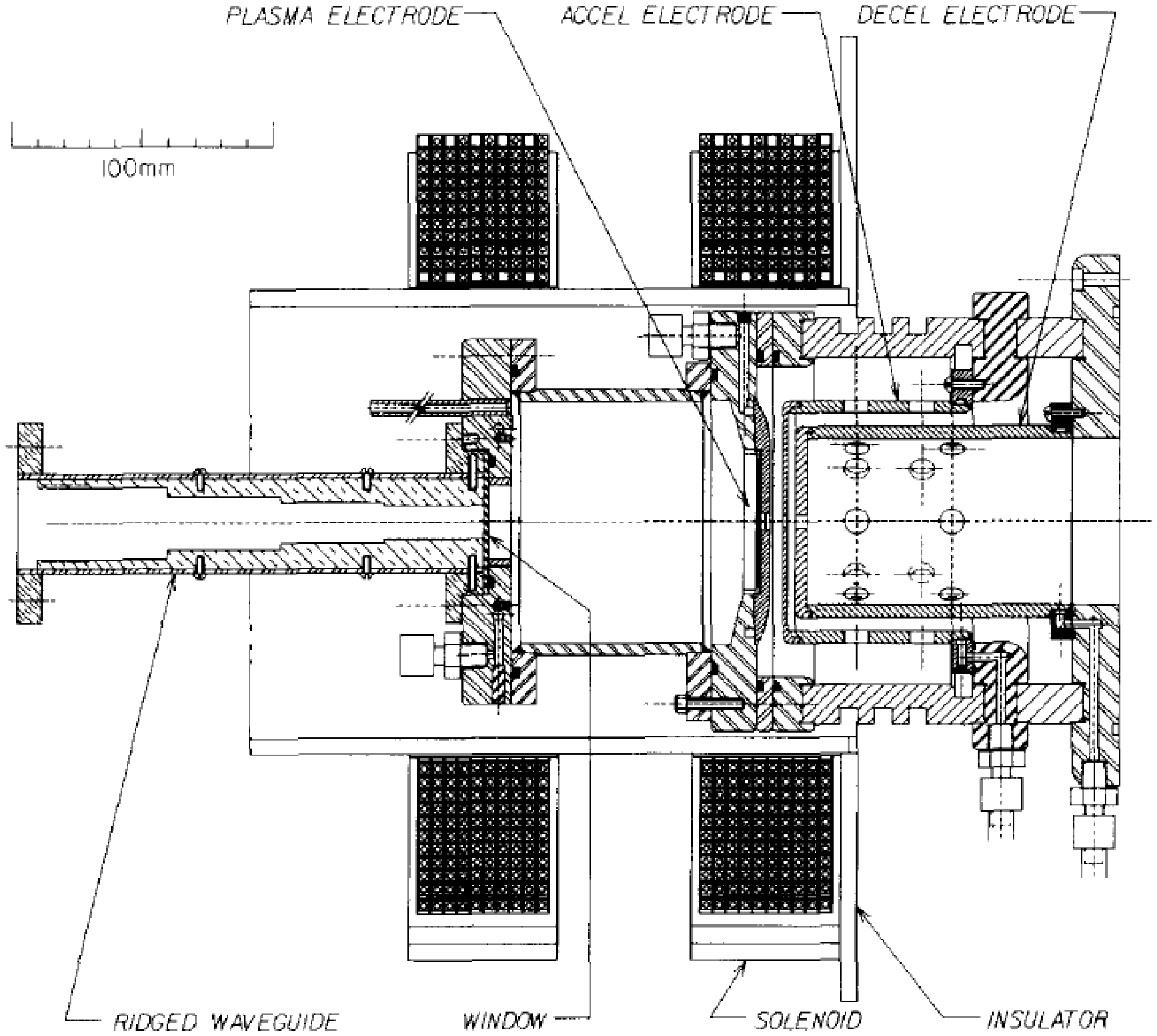
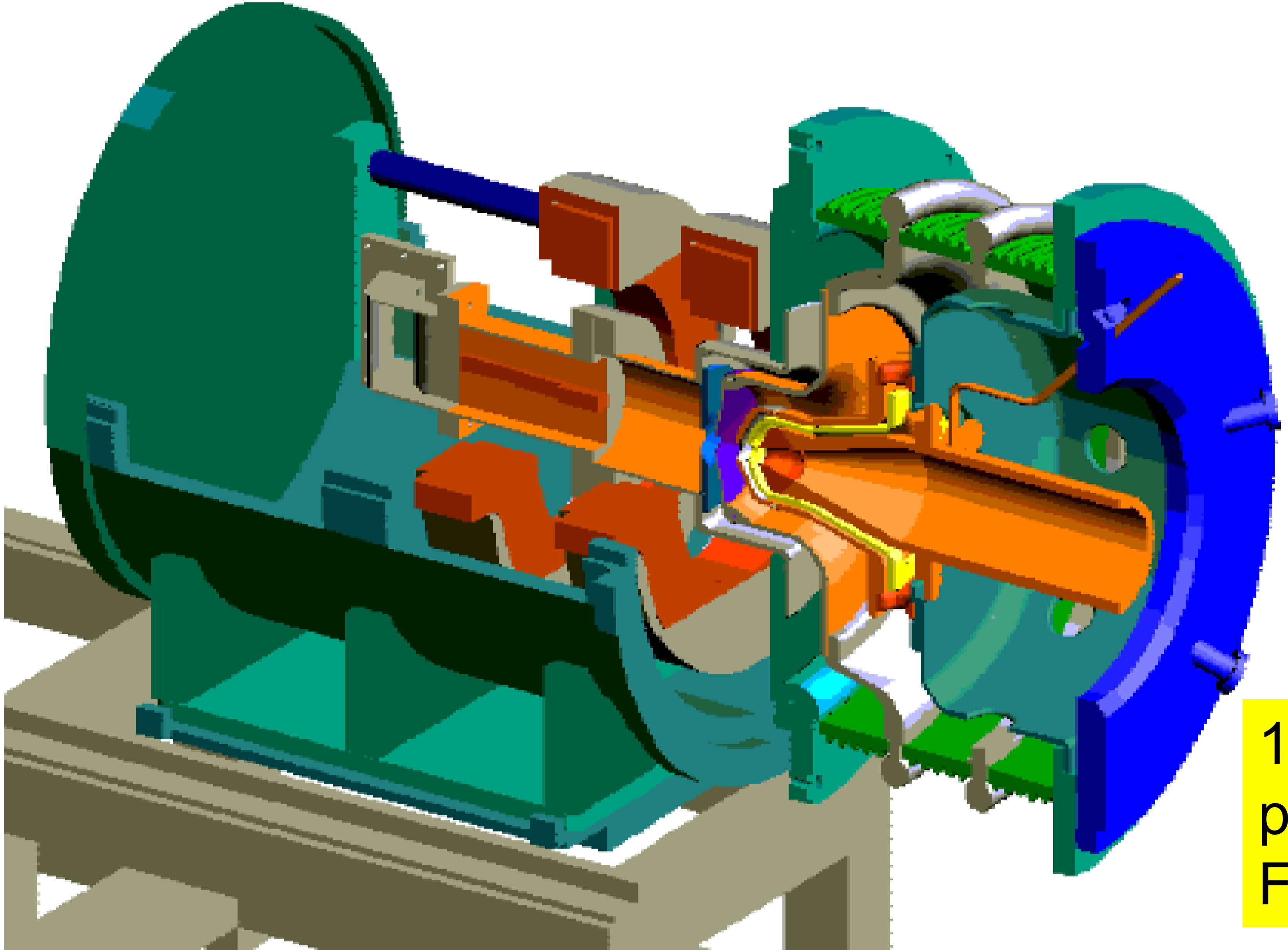


Fig. 2 High-current low-emittance microwave proton source.

Terence Taylor and Jozef F. Mouris
Chalk River Laboratories
Ontario, Canada
Early 90's

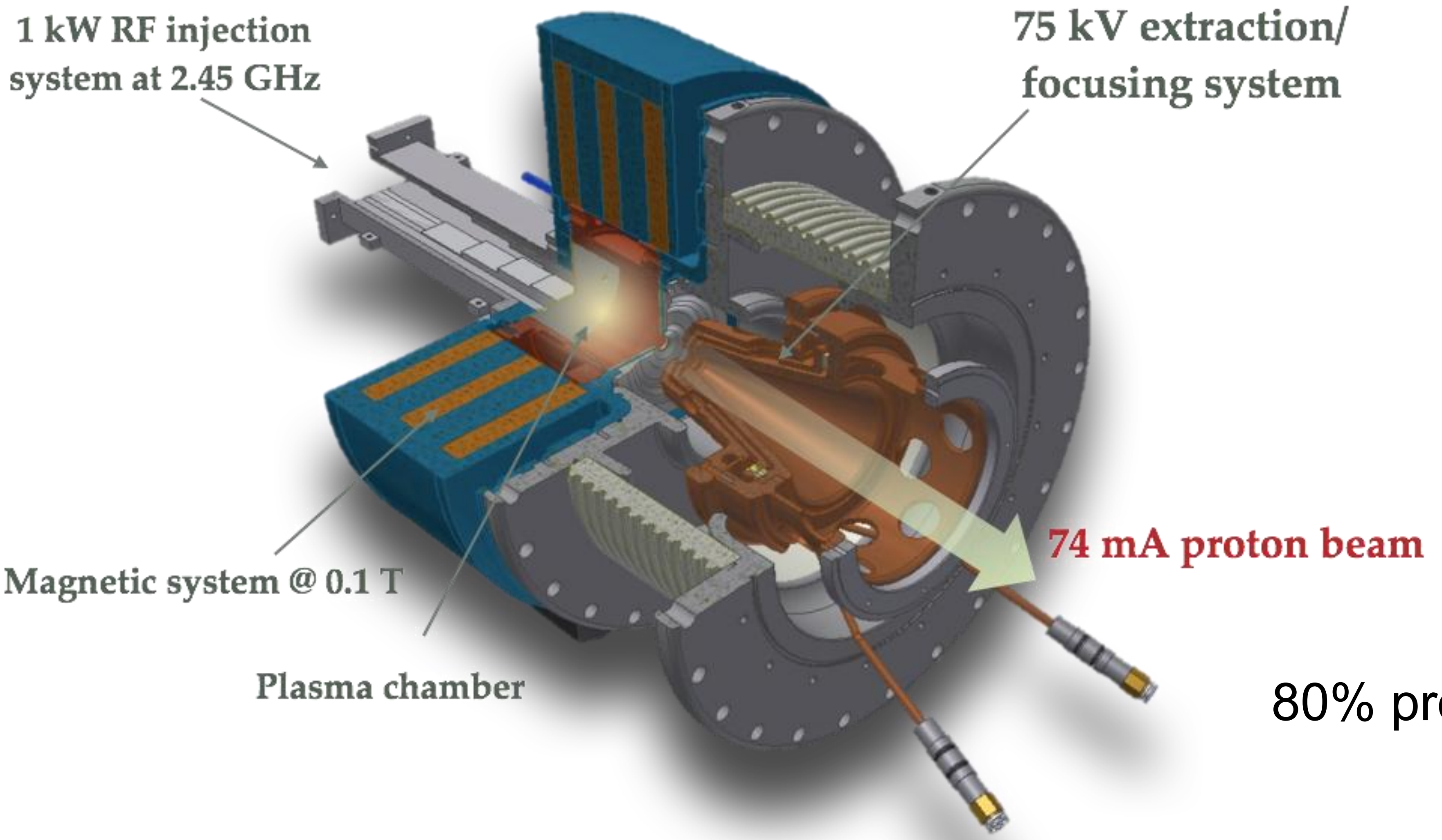
SILHI Microwave Source



Rafael Gobin
CEA Saclay
Late 1990s

140 mA DC
protons
For one year!

ESS Source



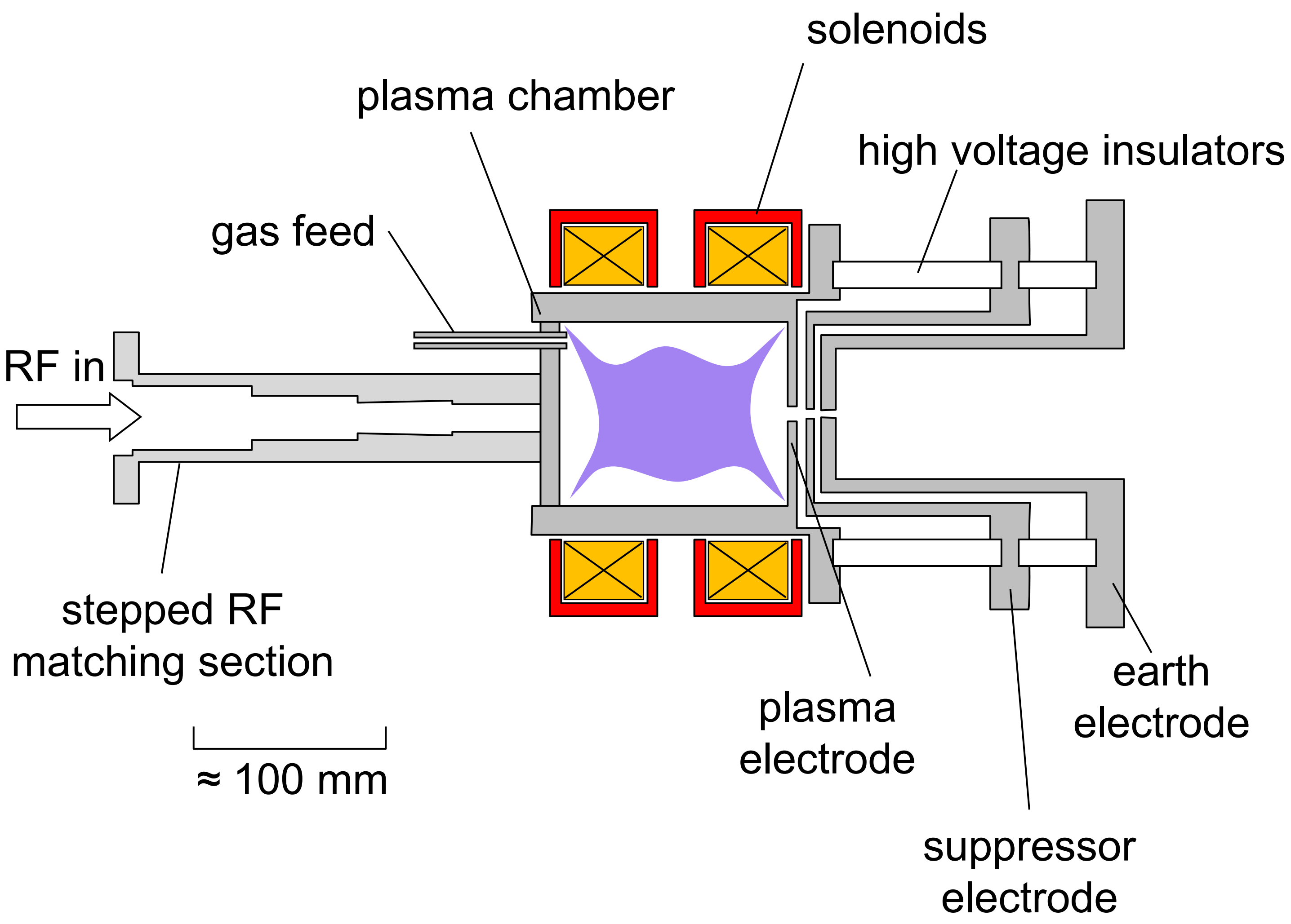
80% proton fraction

H_2^+

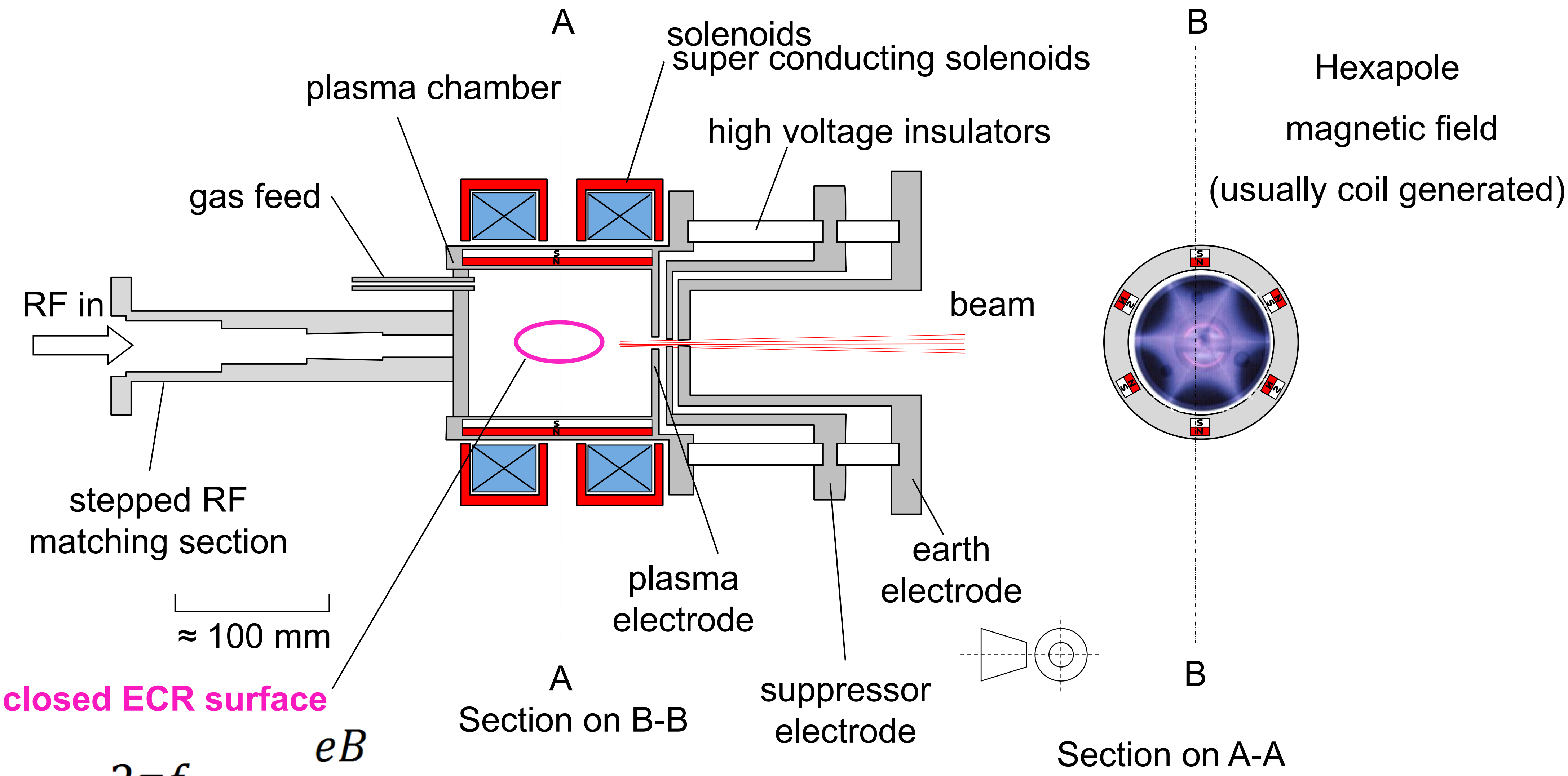
H_3^+

SILHI source via INFN

Microwave discharge ion source



ECR ion source



$$\omega_{ECR} = 2\pi f_{ECR} = \frac{eB}{m}$$

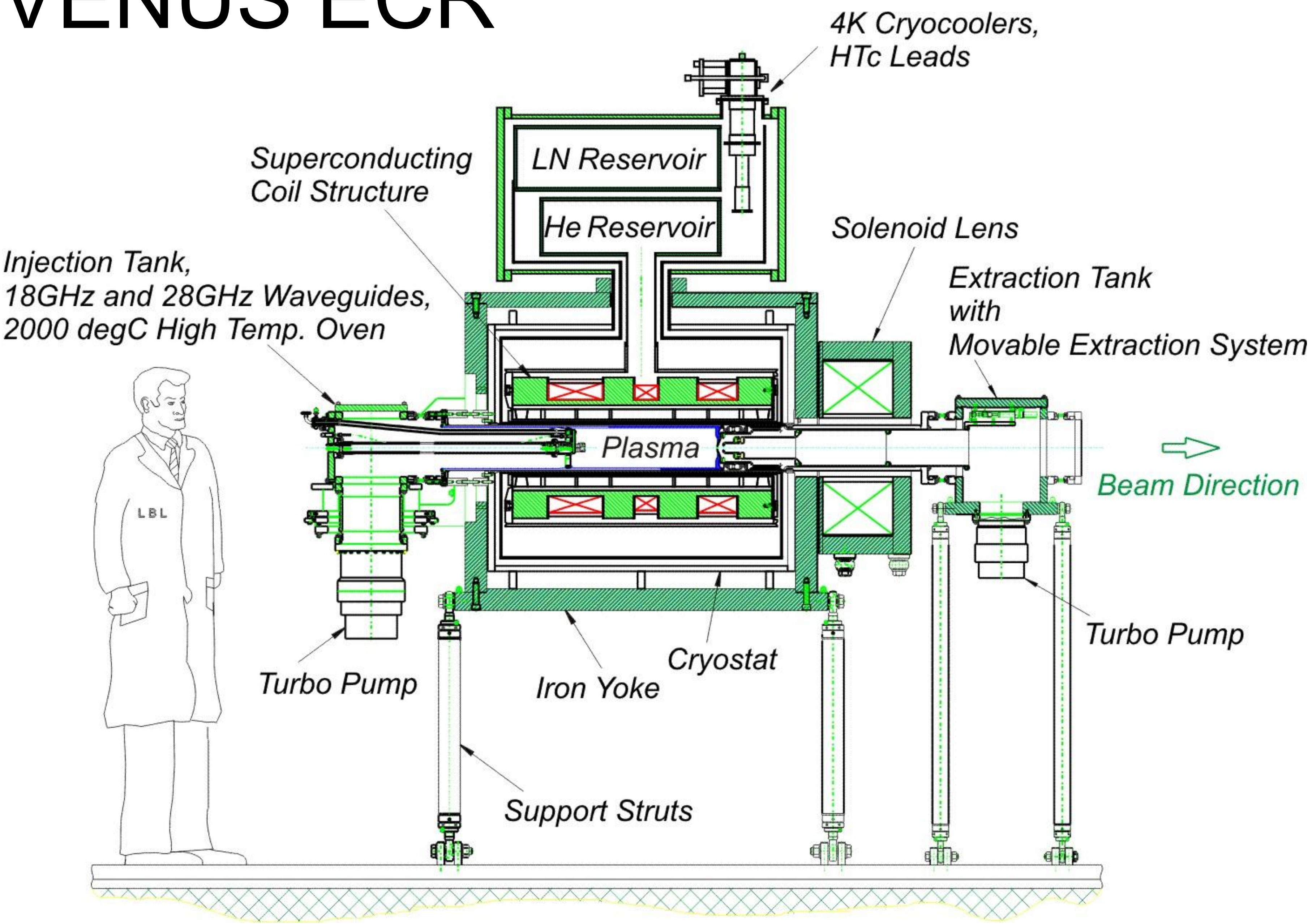
28 GHz superconducting VENUS ECR

Daniela Leitner
LBNL
Late 2000s

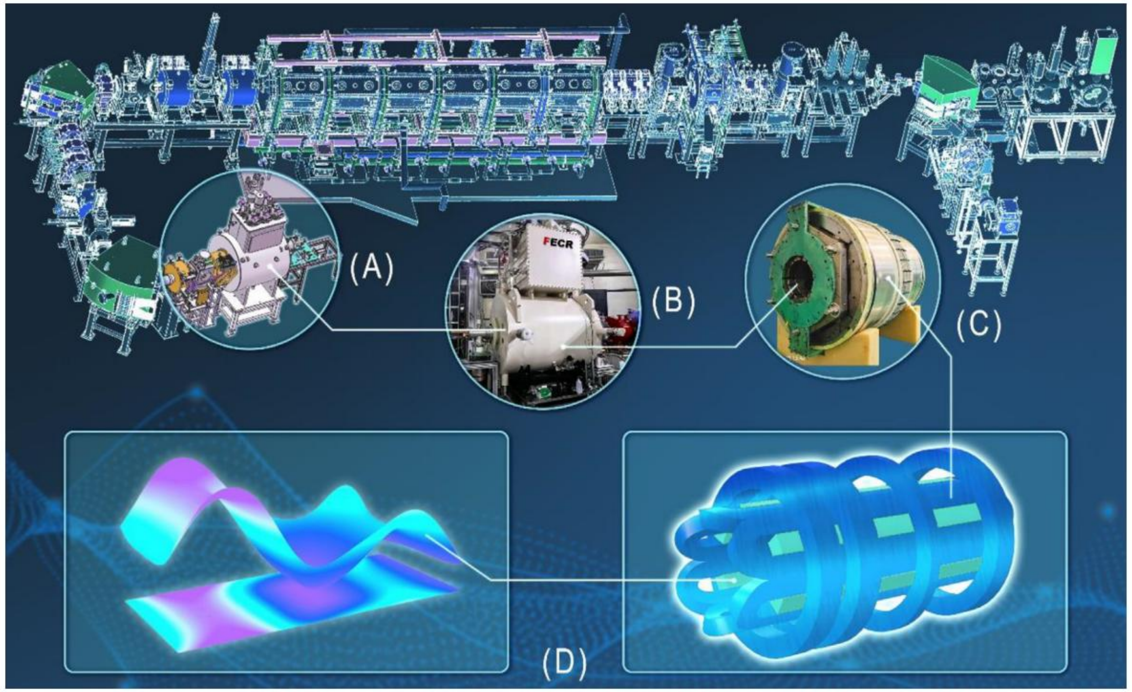
Higher frequency = higher density

200 eμA U^{34+} ions
4.9 eμA U^{47+} ions

VENUS ECR


4K Cryocoolers,
HTc Leads
Superconducting
Coil Structure
LN Reservoir
He Reservoir
Solenoid Lens
Injection Tank,
18GHz and 28GHz Waveguides,
2000 degC High Temp. Oven
Extraction Tank
with
Movable Extraction System
Plasma
Beam Direction
LBL
Turbo Pump
Cryostat
Iron Yoke
Turbo Pump
Support Struts

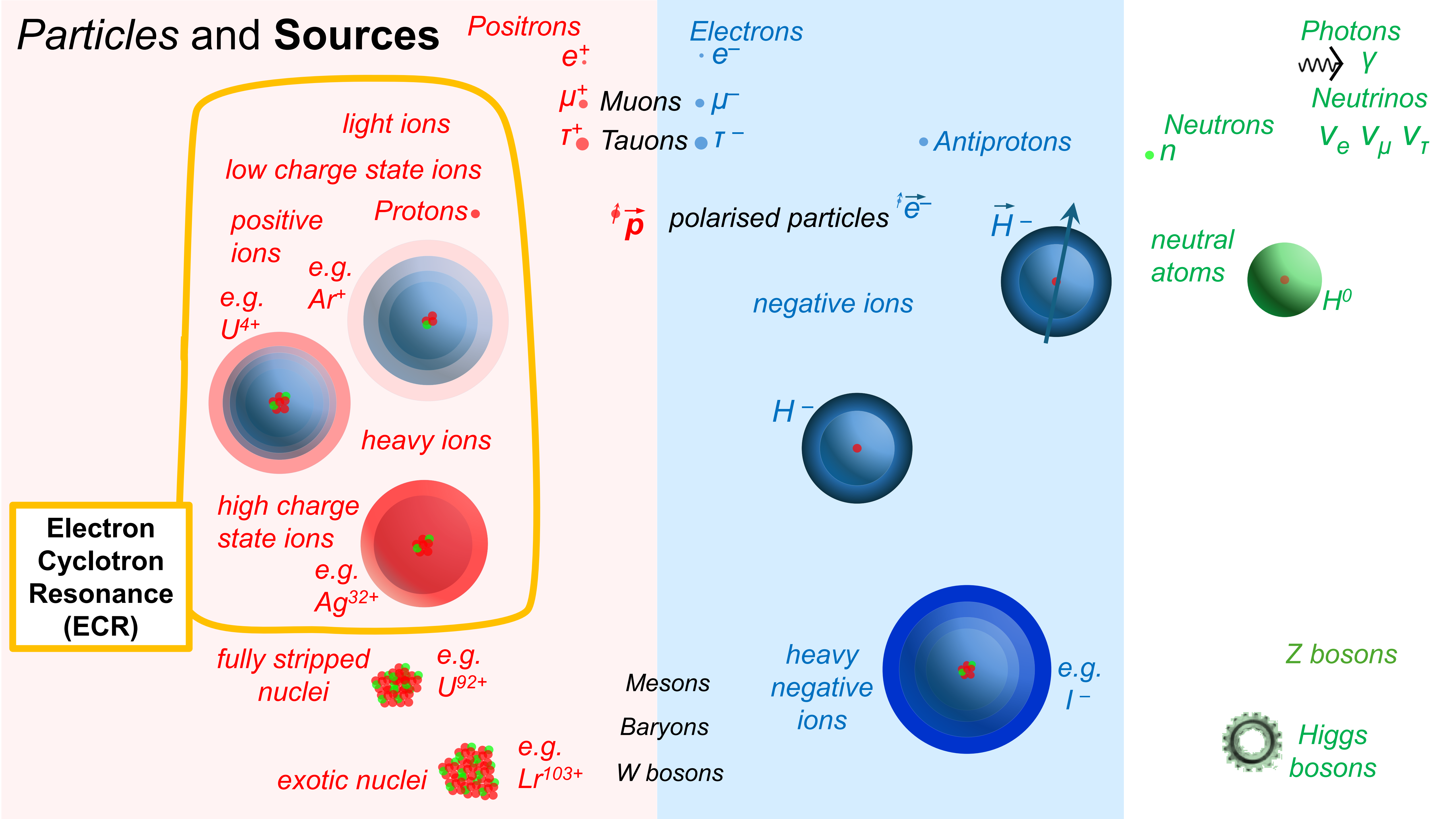
45 GHz - 4th generation ECR ion source



Liangting Sun
IMP CAS

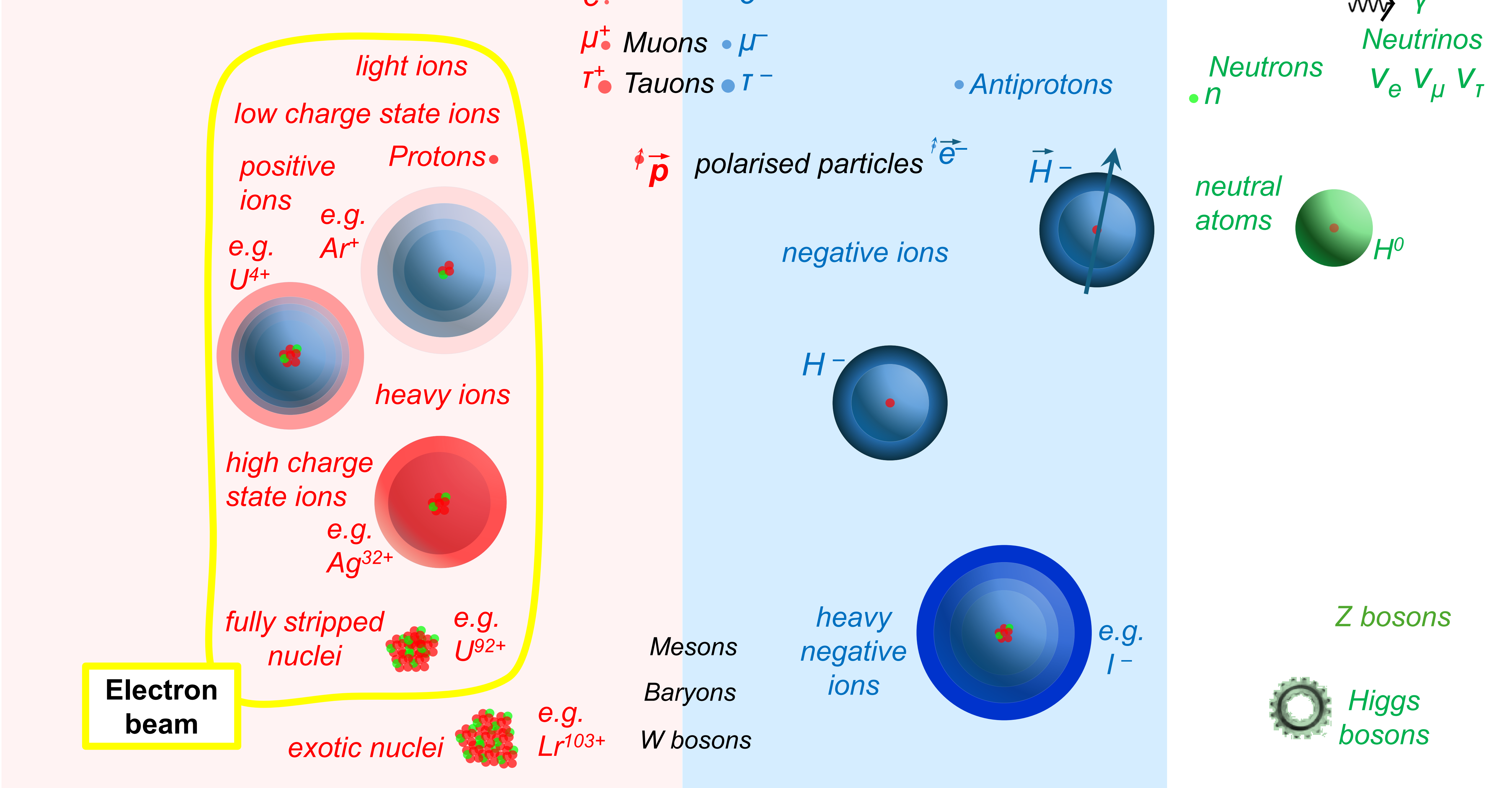
LEAF at Institute of Modern Physics, heavy ion research, Chinese Academy of Science

Higher frequency = higher density

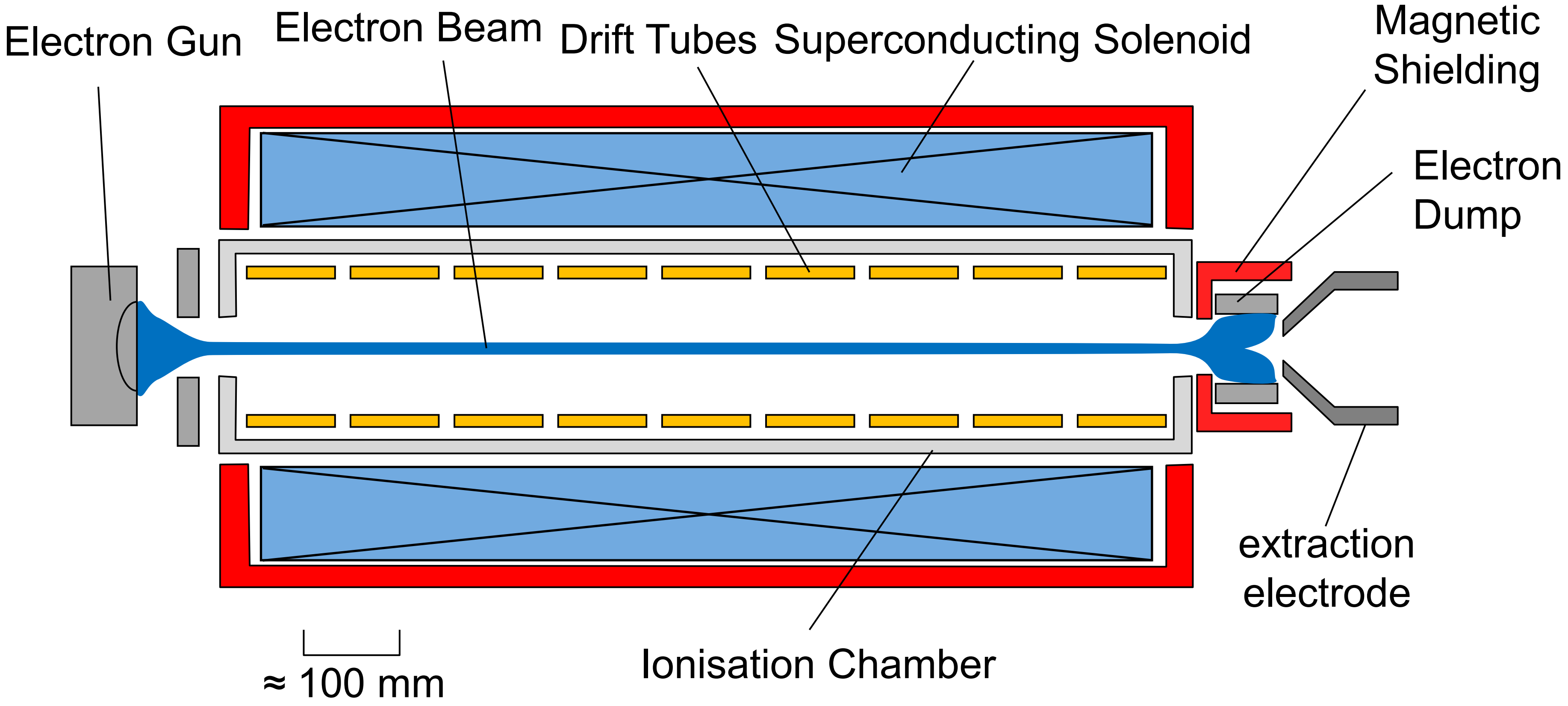


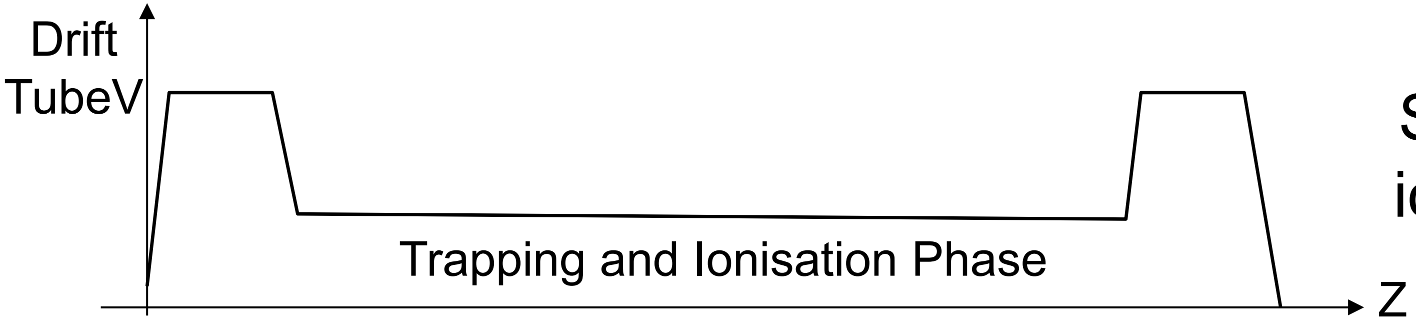
Particles and Sources
Positrons
e+
Electrons
e−
Photons
γ
μ+ Muons μ−
τ+ Tauons τ−
Neutrinos
νe νμ ντ
Neutrons
n
Antiprotons
light ions
low charge state ions
positive ions
Protons
e.g. Ar+
e.g. U4+
p polarised particles e−
H−
neutral atoms
H0
negative ions
heavy ions
H−
high charge state ions
e.g. Ag32+
Electron Cyclotron Resonance (ECR)
fully stripped nuclei
e.g. U92+
Mesons
Baryons
W bosons
heavy negative ions
e.g. I−
Z bosons
Higgs bosons
exotic nuclei
e.g. Lr103+

Particles and **Sources**



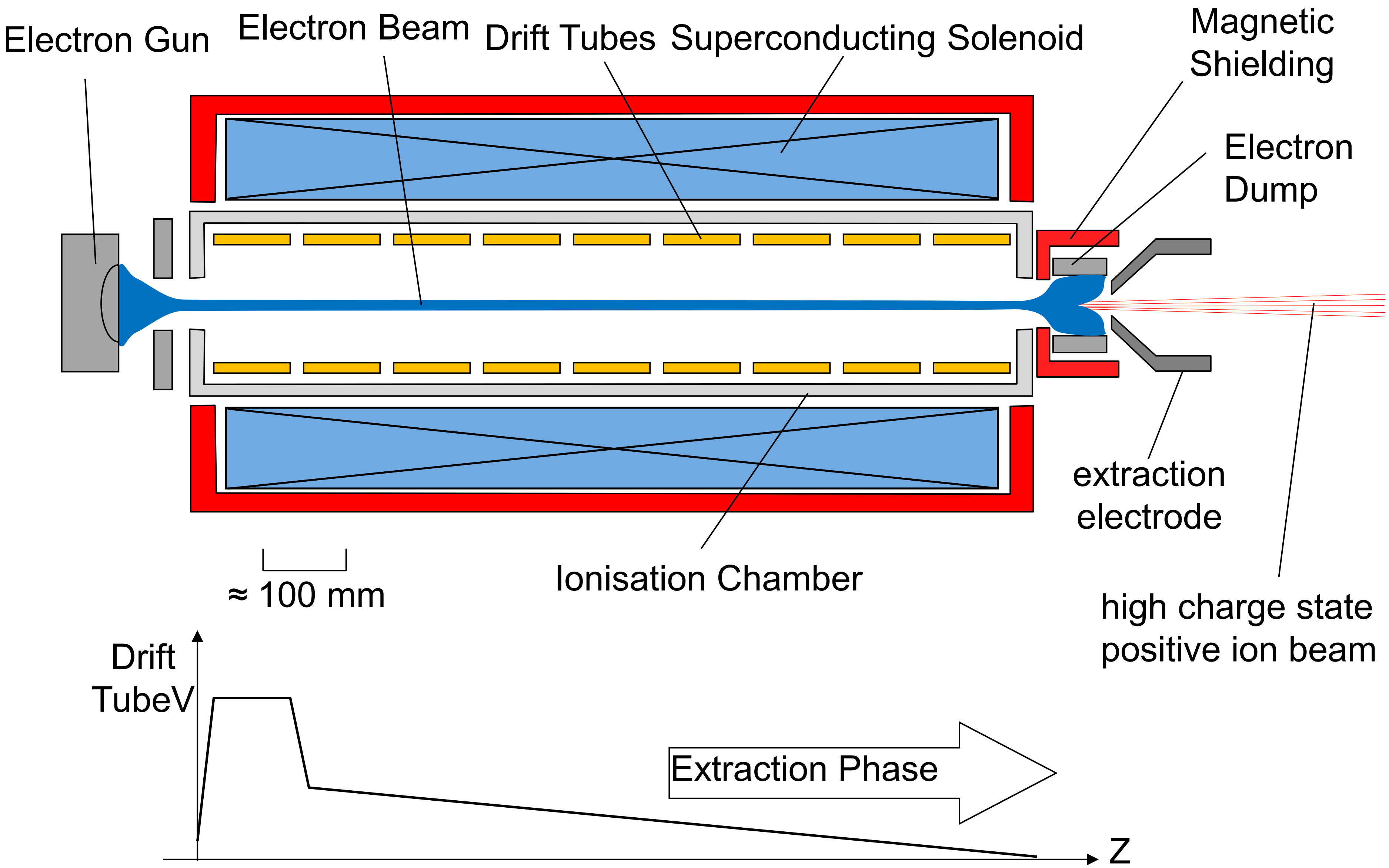
Electron Beam Ion Sources

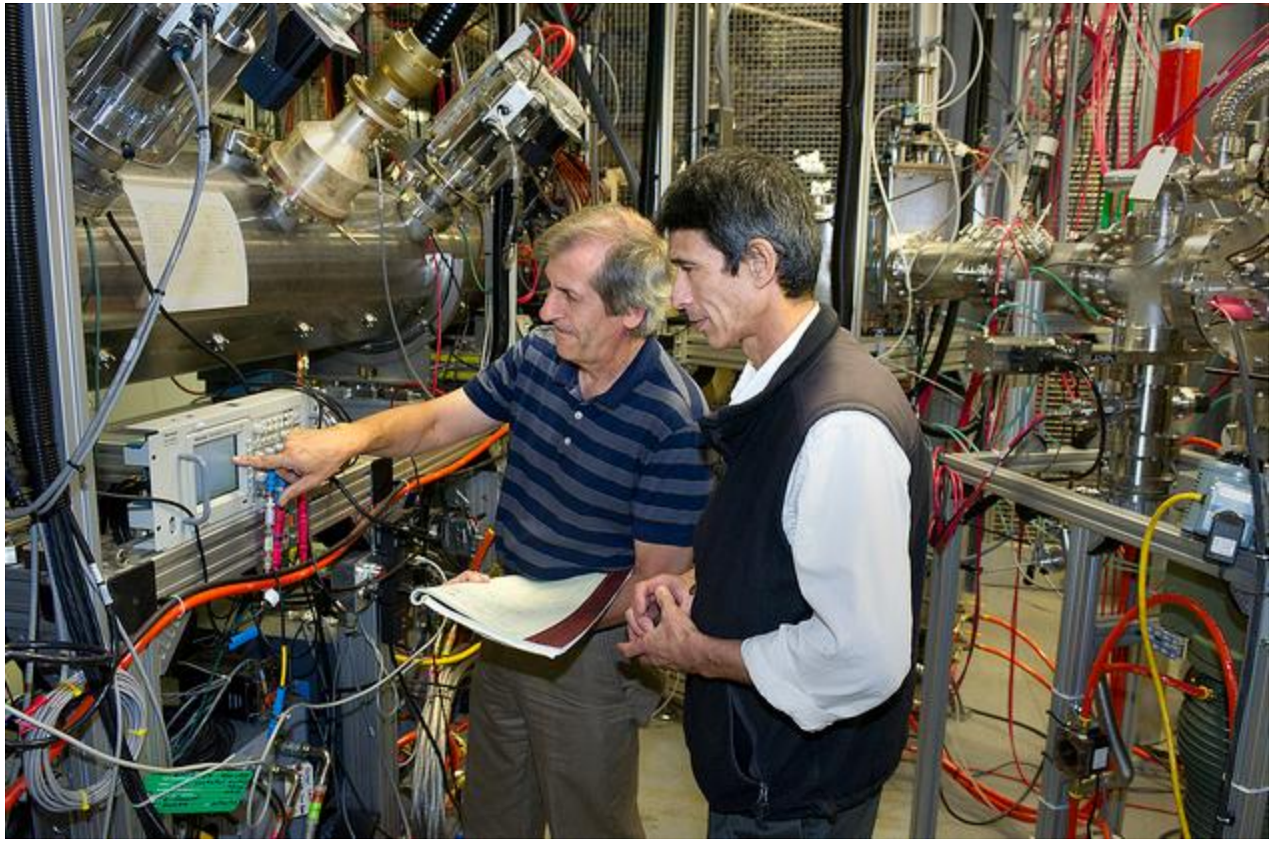




Stepwise ionisation

Electron Beam Ion Sources



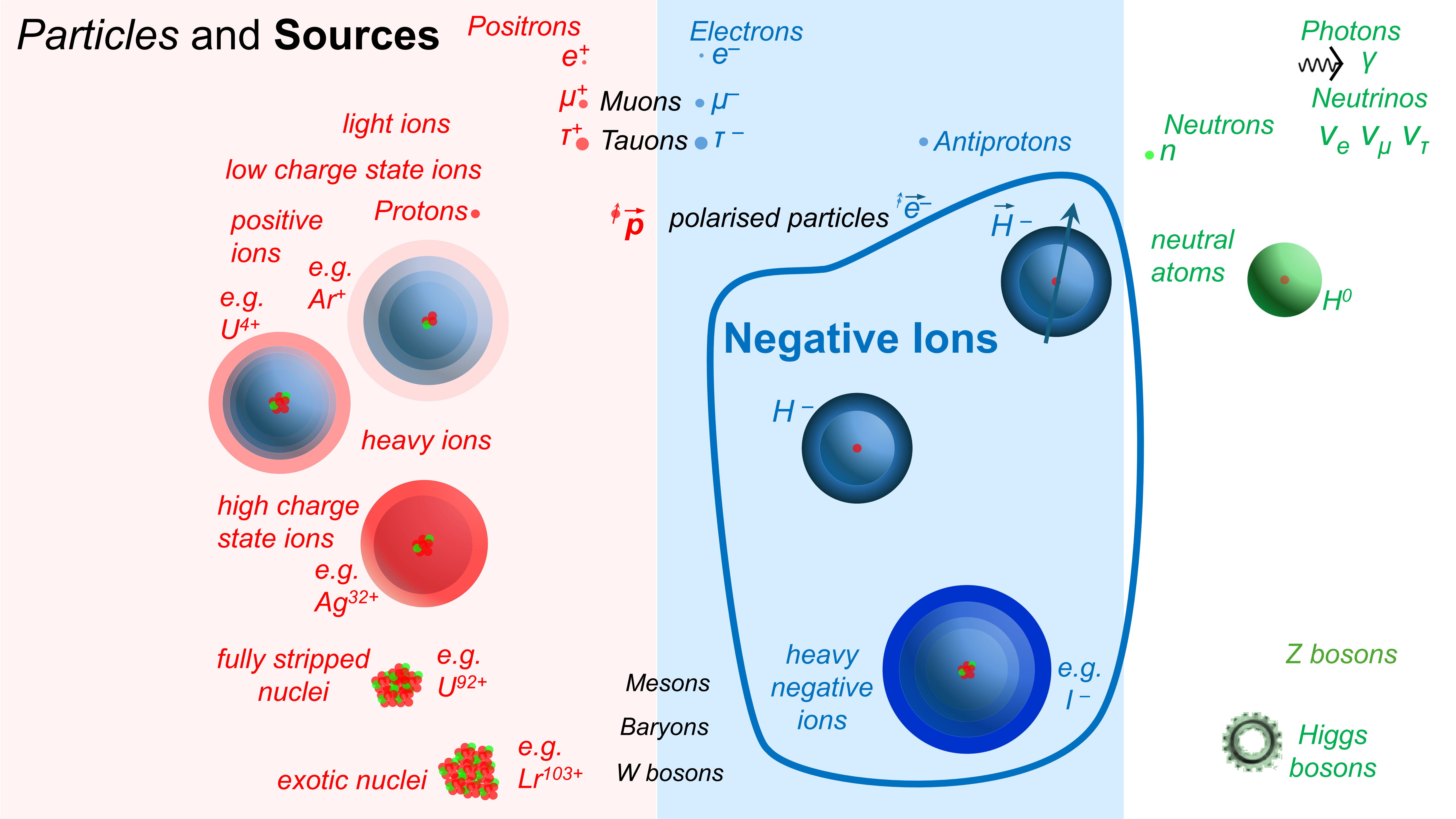


BROOKHAVEN
NATIONAL LABORATORY

Jim Alessi
BNL

1.7 emA, 10 µs, 5 Hz
Ag^{32+} ions

Fully stripped nuclei can
be obtained in EBIT mode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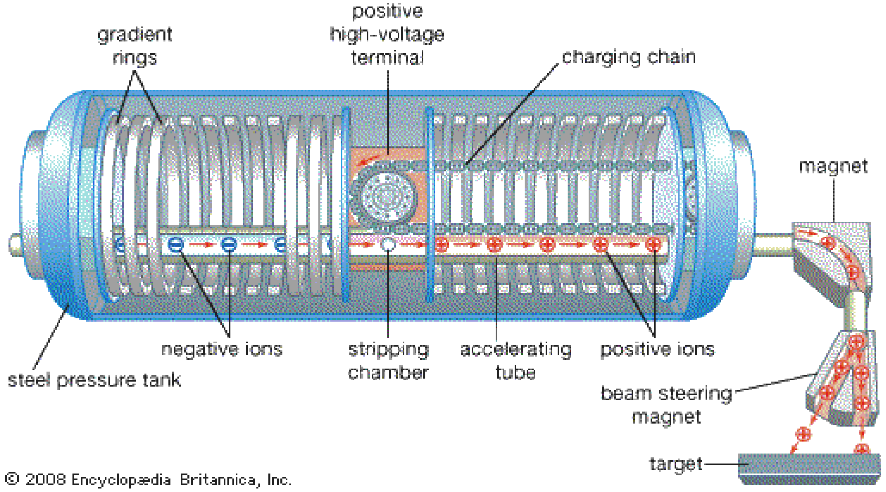
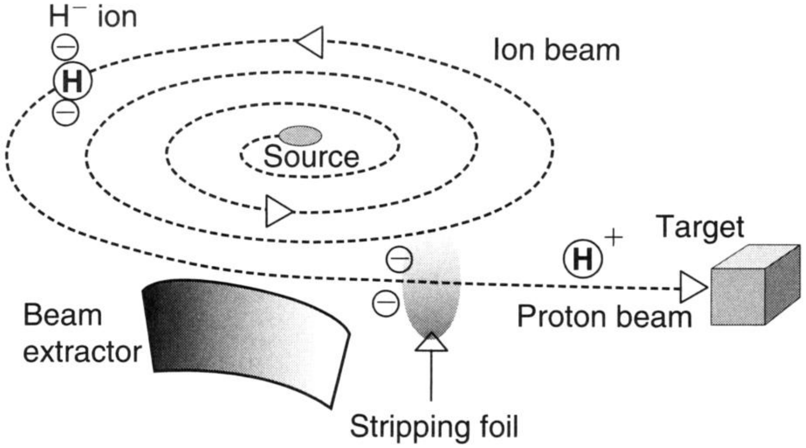
low charge state ions
Antiprotons
Neutrons
n
Photons
γ
Neutrinos
νe νμ ντ
positive ions
Protons
p
polarised particles
e−
H −
neutral atoms
H0
e.g. Ar+
e.g. U4+
Negative Ions
heavy ions
H −
high charge state ions
e.g. Ag32+
fully stripped nuclei
e.g. U92+
exotic nuclei
e.g. Lr103+
Mesons
Baryons
W bosons
heavy negative ions
e.g. I −
Z bosons
Higgs bosons

Negative Ion Applications

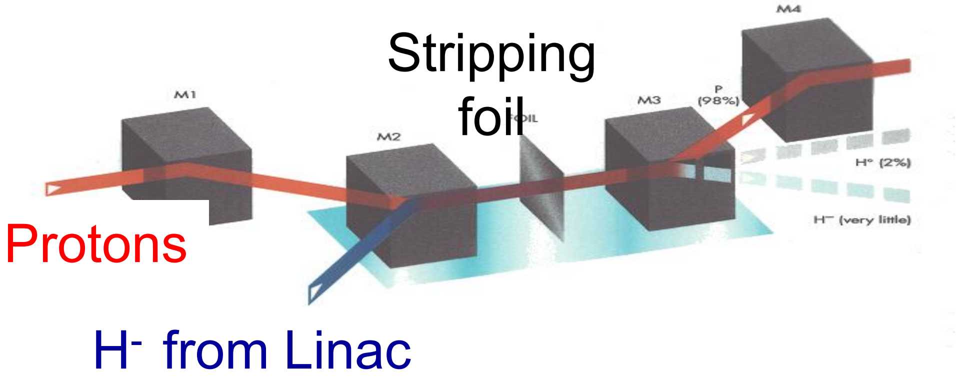
Tandem accelerators



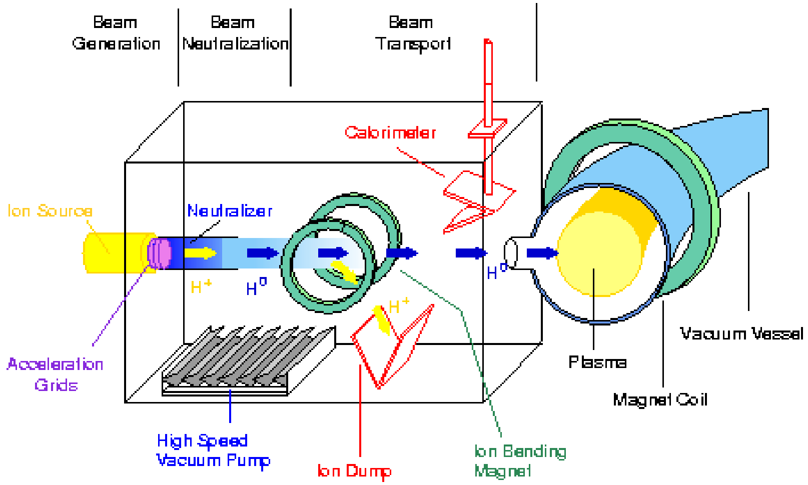
Cyclotron extraction



Multi-turn injection into rings

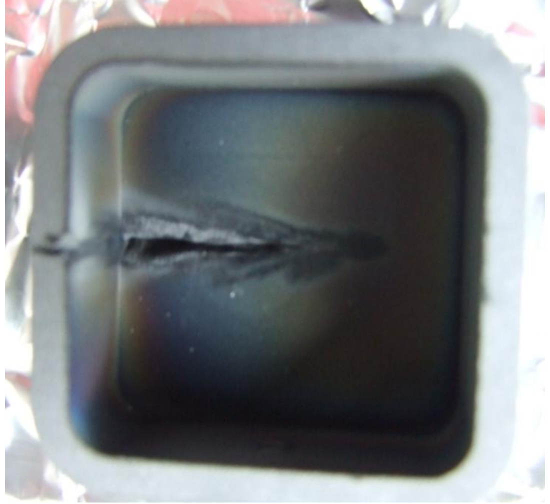


Neutral Beams



Negative Ion Sources

CERN LINAC4
e-dump surface



Knocking electrons off is easy!

- It is much harder to add them on….

Not all elements will even make negative ions

Hydrogen has an electron affinity of 0.7542 eV

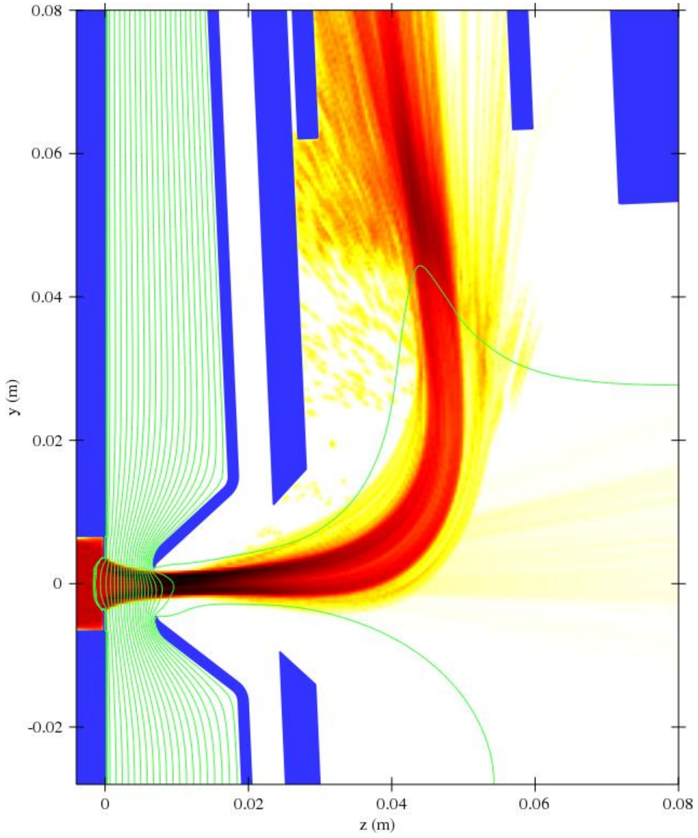
H^- has much larger cross sections than H^0

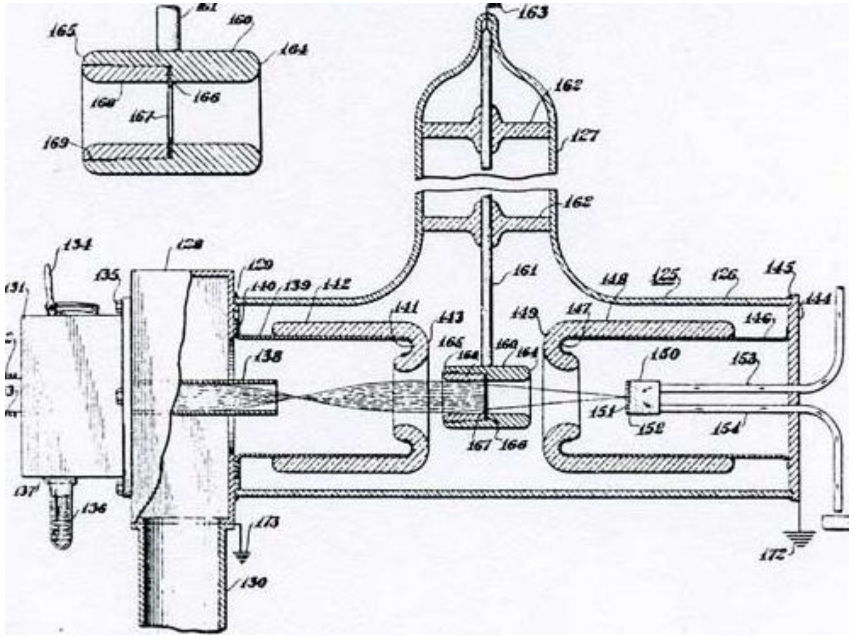
Up to 30 times for e^- collisions

Up to 100 times for H^+ collisions

H^- are very fragile!

Co-extracted electrons can be a problem





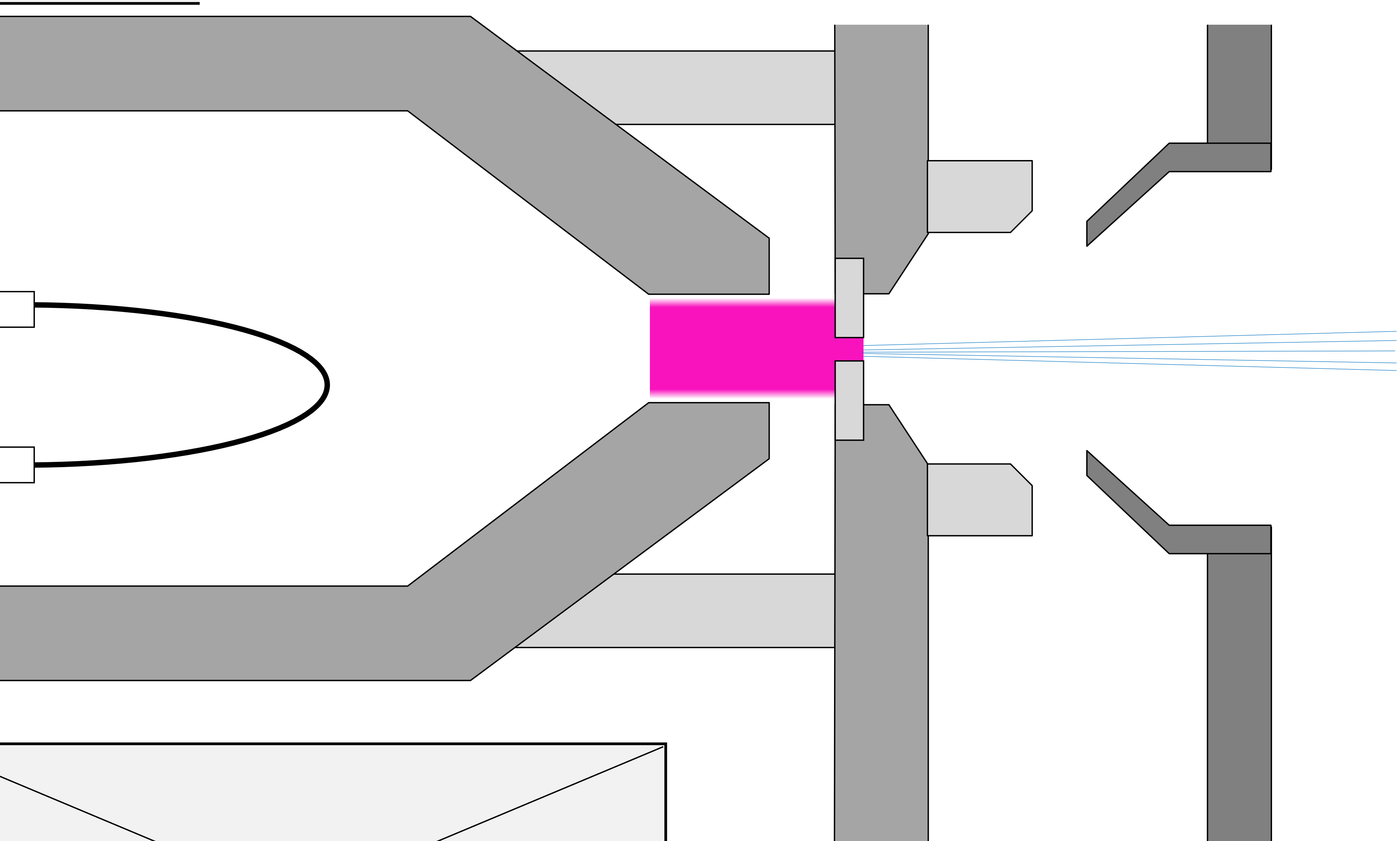
A 1937 tandem

Early attempts at producing negative ion beams:

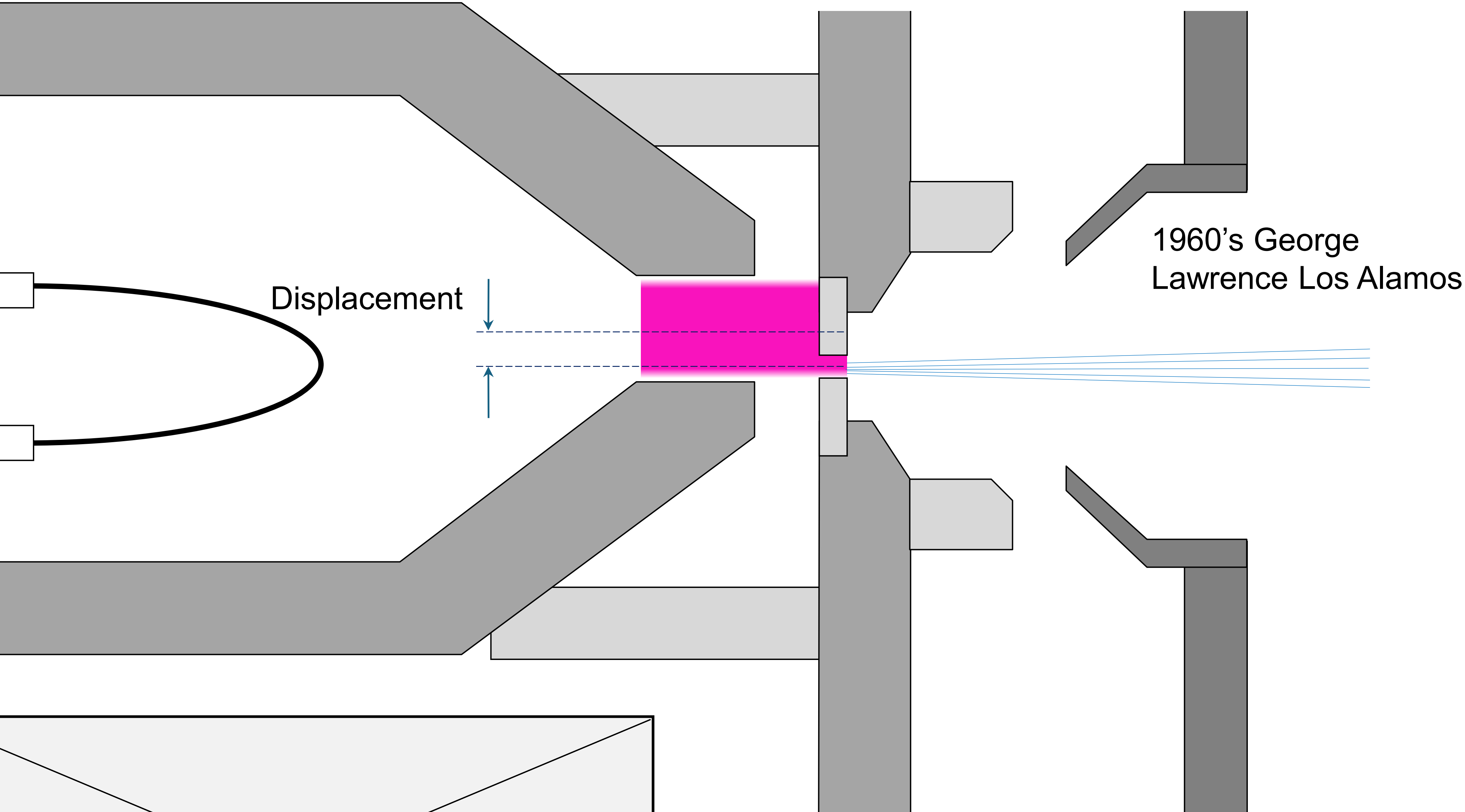
- Charge exchange of positive beams
  - stripper foils and gas cells
    - very inefficient <2%

- Extraction from existing ion sources…

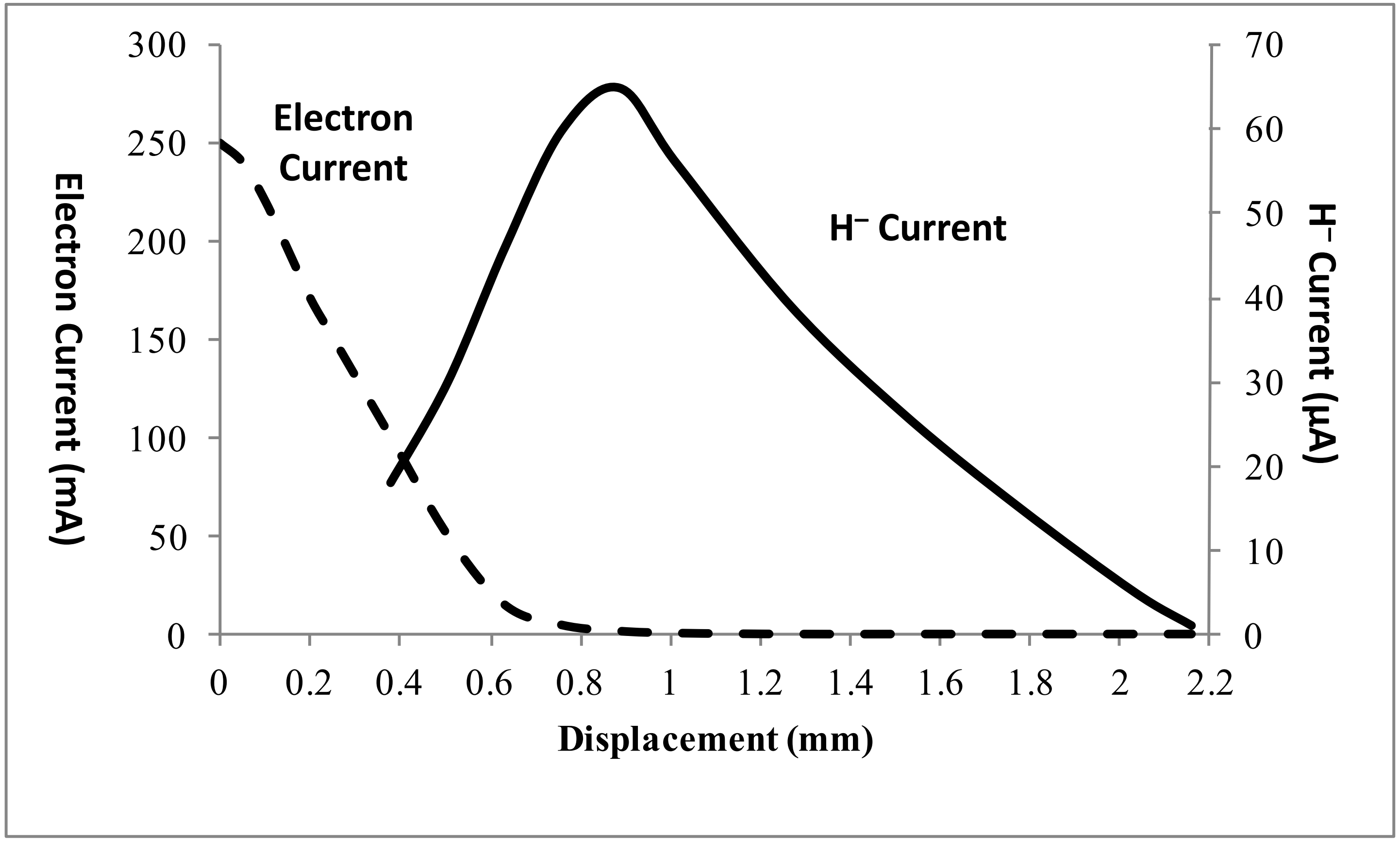
Off Axis Duoplasmatron Extraction



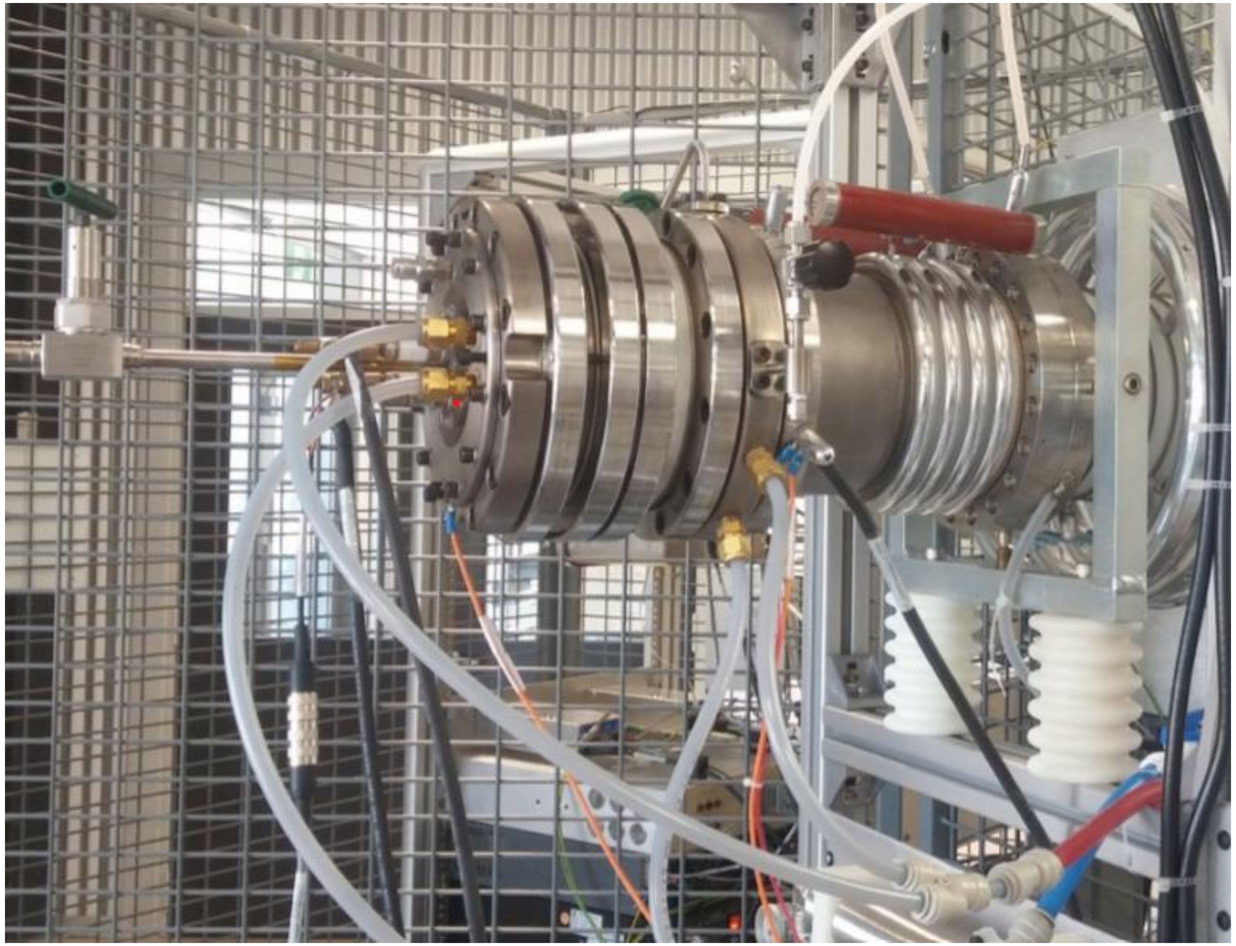
Off Axis Duoplasmatron Extraction



Off Axis Duoplasmatron Extraction



Off Axis Duoplasmatron Extraction



National Electrostatics Corp.

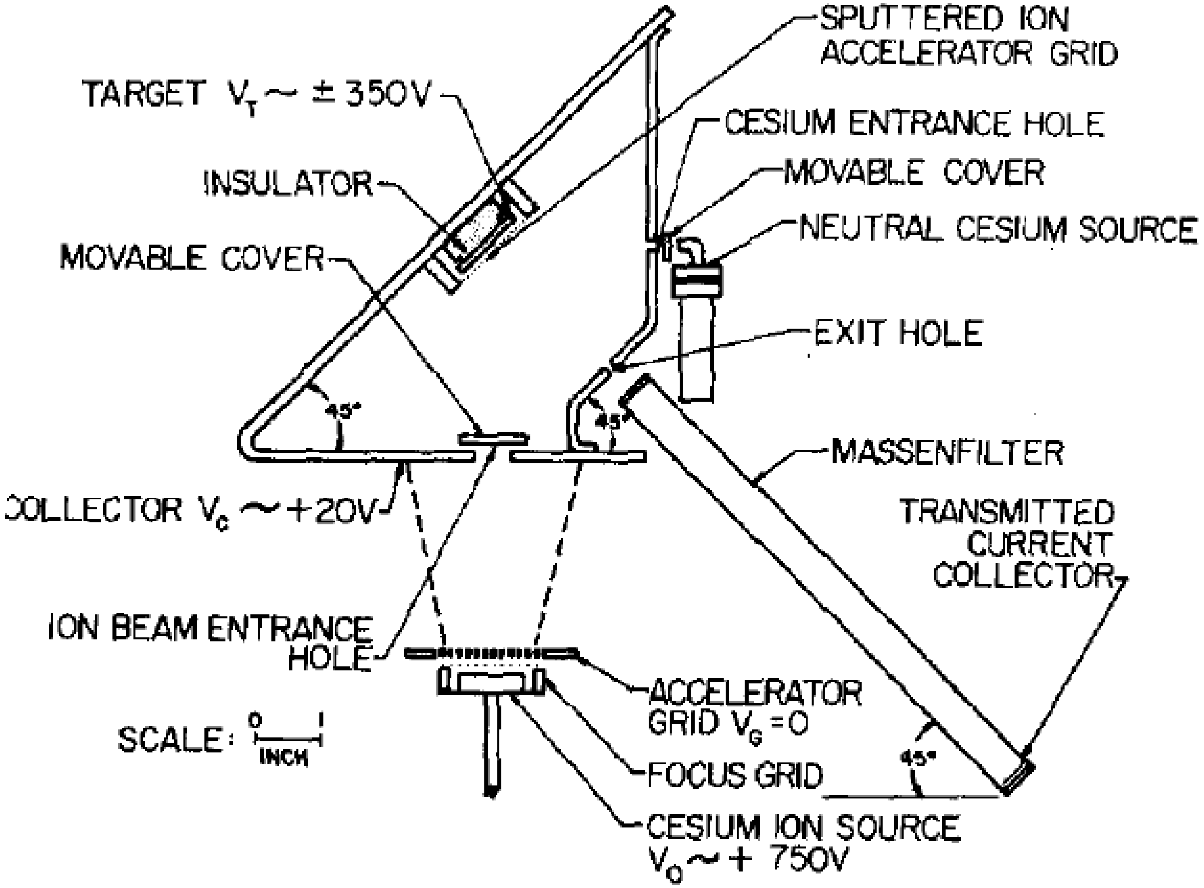
Direct Extraction
Negative Ion
Duoplasmatron

30 μA DC
H^- current

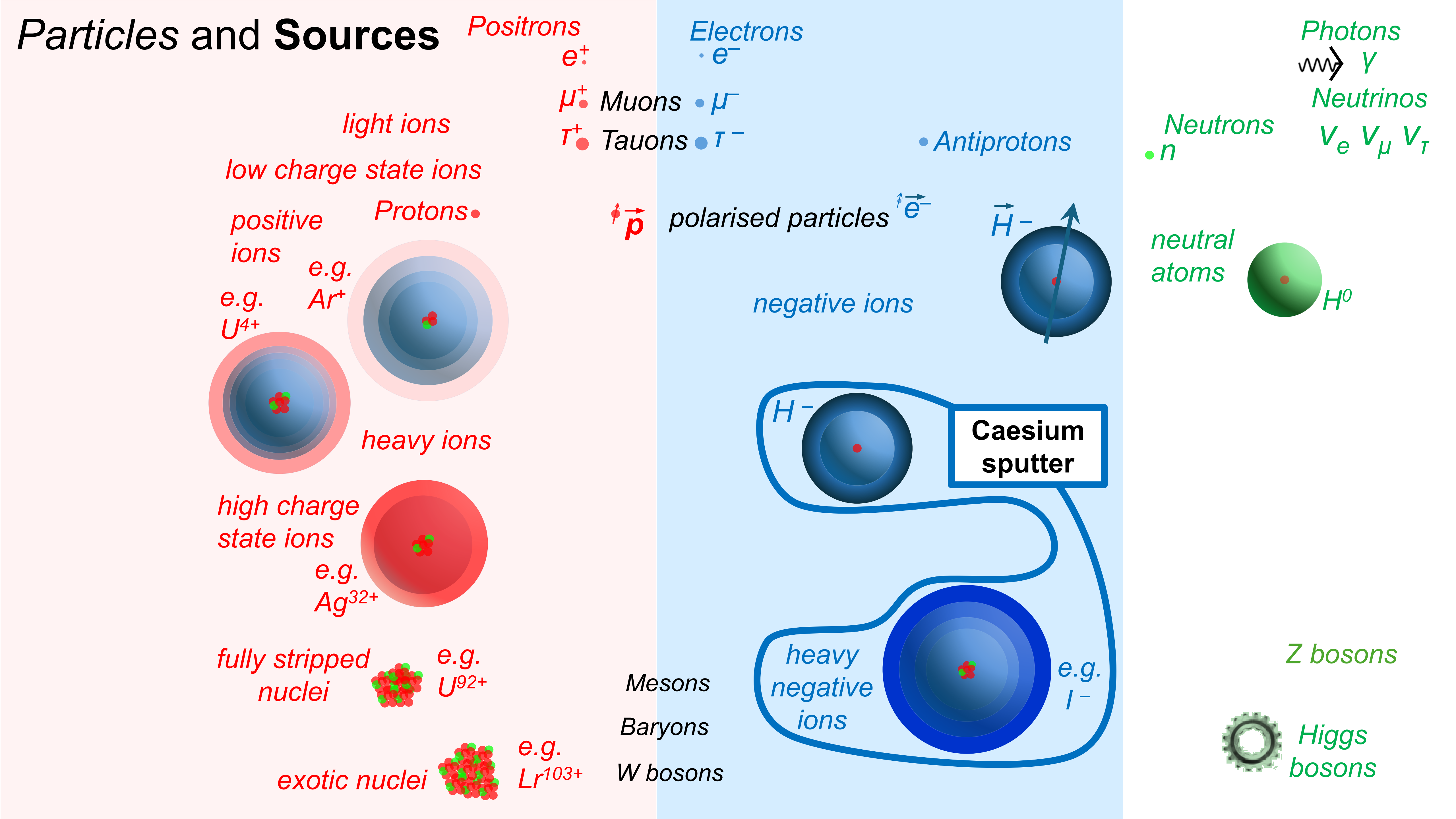
displaced
intermediate
electrode
duoplasmatron

1962 Victor Krohn

Cs^+ ions on a metal target
increase yield of sputtered negative ions
by an order of magnitude



Space Technology Laboratories inc.
Redondo Beach, California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μ+ Muons μ−
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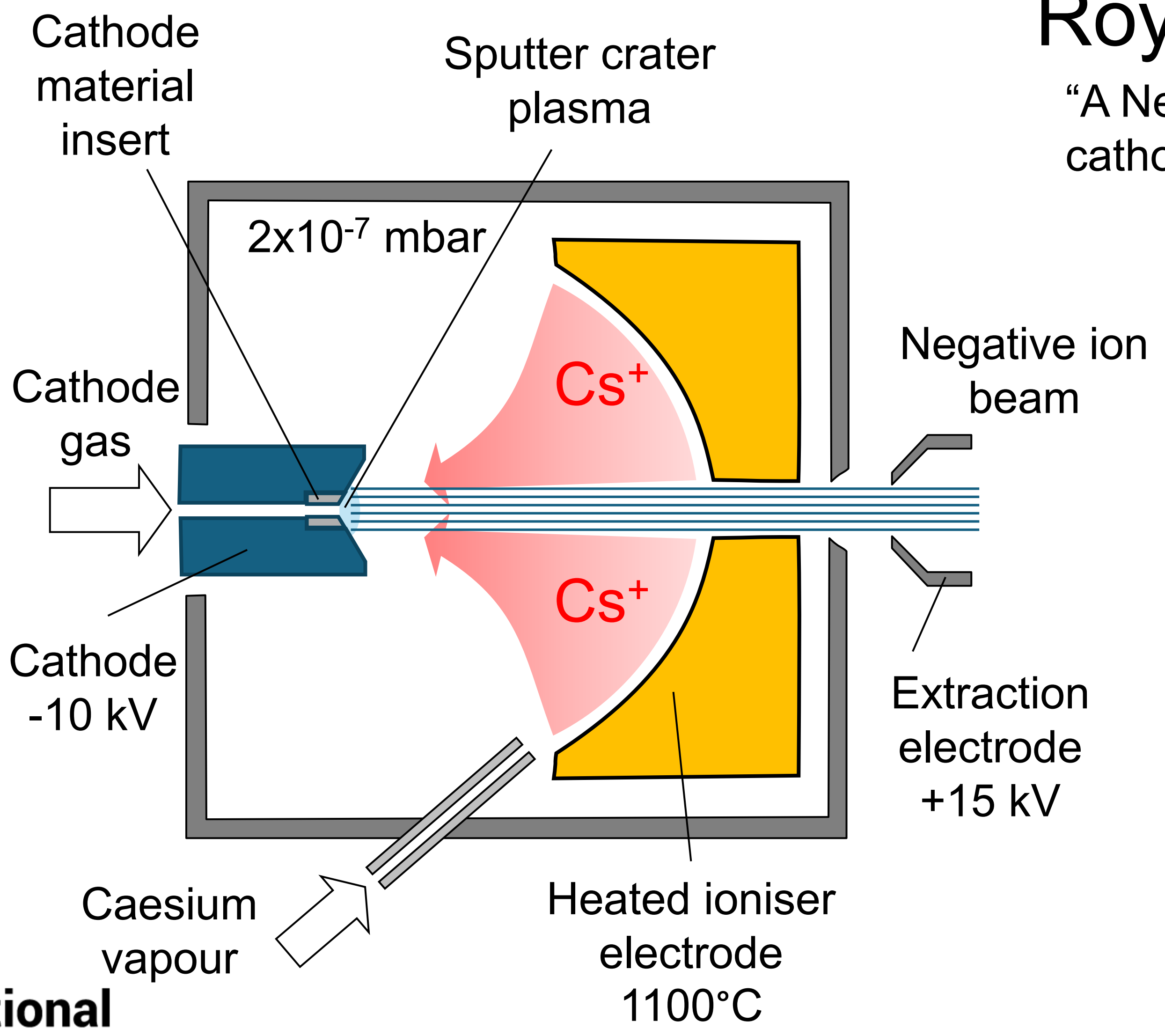
Electrons
e−
Antiprotons
light ions
low charge state ions
positive ions
Protons
e.g. U4+
e.g. Ar+
p
polarised particles
e−
H −
negative ions
neutral atoms
H0
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
heavy ions
H −
Caesium sputter
high charge state ions
e.g. Ag32+
fully stripped nuclei
e.g. U92+
heavy negative ions
e.g. I −
Mesons
Baryons
W bosons
exotic nuclei
e.g. Lr103+
Z bosons
Higgs bosons

SNICS (Source of Negative Ions by Caesium Sputtering)

Roy Middelton et. al.

"A Negative-Ion Cookbook"
cathode material and gas recipes

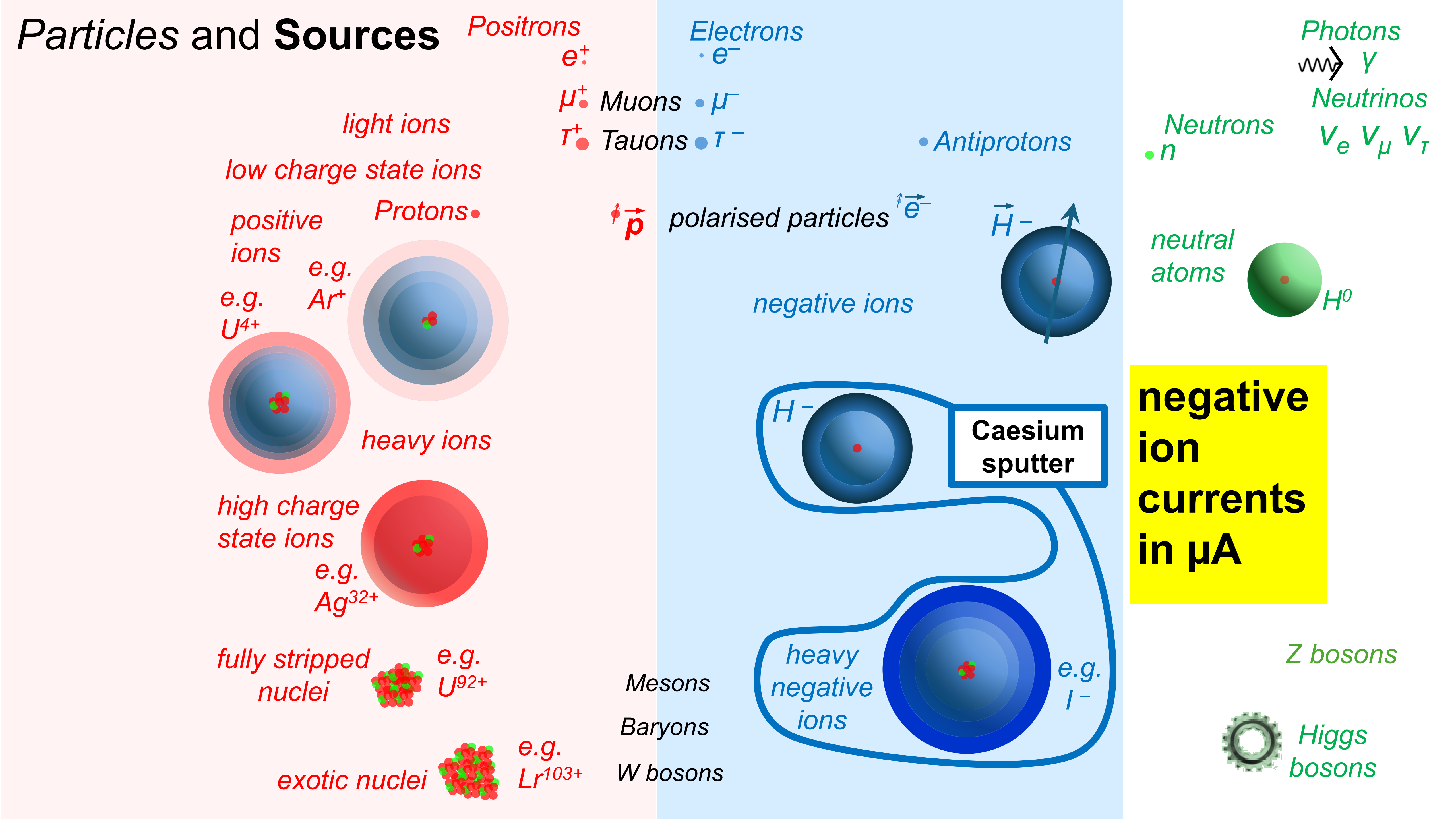


Negative ion currents (in μA)

H^- 130	Si^- 430	As^- 60	Cs^- 1.5
D^- 150	P^- 125	Se^- 10	CeO^- 0.2
Li^- 4	S^- 100	Br^- 40	NdO^- 0.3
BeO^- 10	Cl^- 100	Sr^- 1.5	EuO^- 1.0
B^- 60	CaH_3^- 0.8	Y^- 0.66	ErO^- 10
B_2^- 73	TiH^- 10	Zr^- 9.4	TmO^- 1.0
C^- 260	VH^- 25	Nb^- 7	YbO^- 1.0
C_2^- 40	Cr^- 5	Mo^- 5	Ta^- 9.5
CN^- 12	MnO^- 4	Rh^- 5	TaO^- 6
CN^-(15N) 20	Fe^- 20	Ag^- 13	W^- 2.5
O^- 300	Co^- 120	CdO^- 7	Os^- 15
F^- 100	Ni^- 80	InO^- 20	Ir^- 100
Na^- 4.0	Cu^- 160	Sn^- 20	Pt^- 250
MgH_2^- 1.5	ZnO^- 12	Sb^- 16	Au^- 150
Al^- 7	GaO^- 7	Te^- 20	PbO^- 1
Al_2^- 50	Ge^- 60	I^- 220	Bi^- 3.5

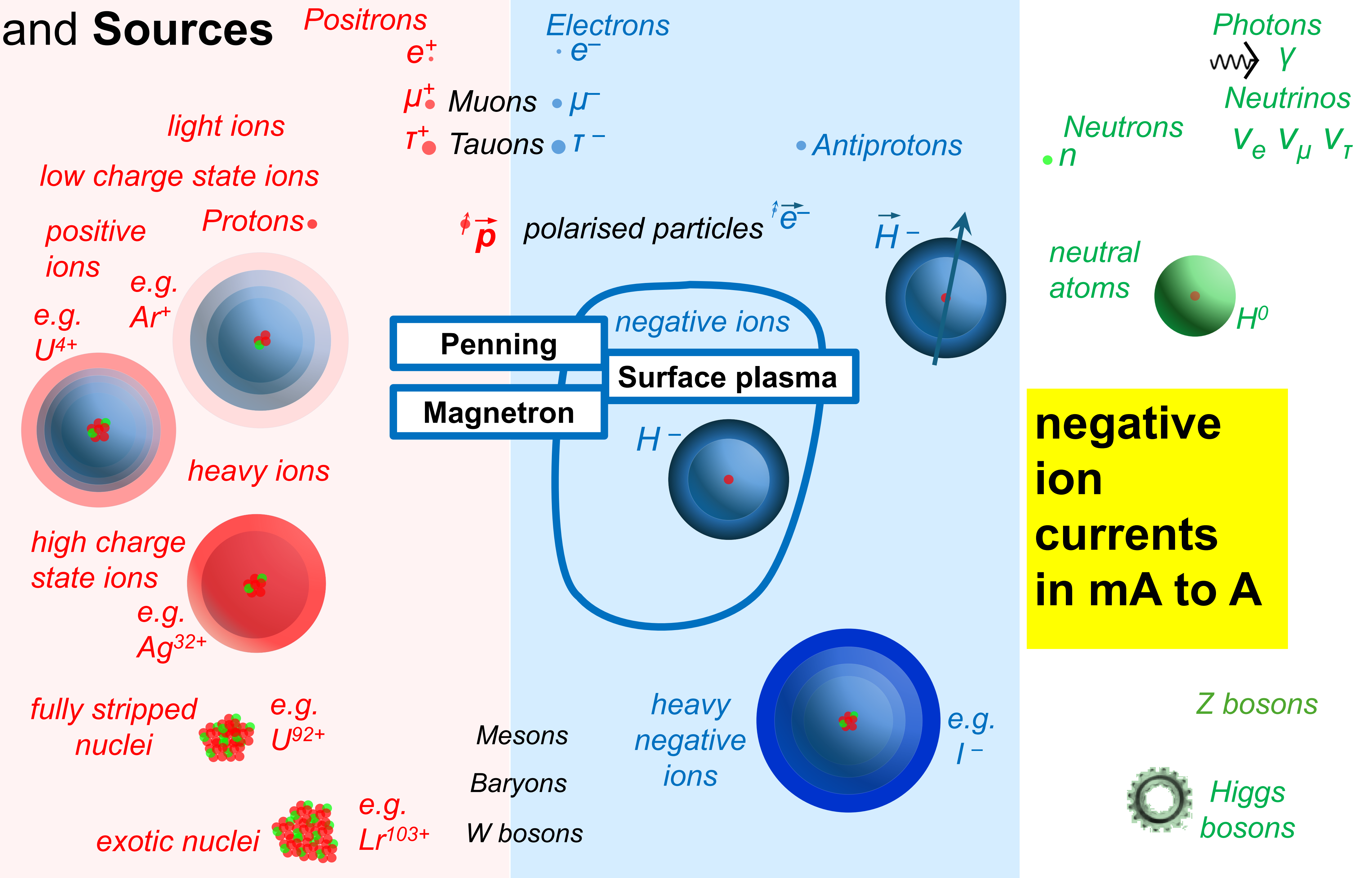
National Electrostatics Corp.

Produces a large range of different negative ions



Particles and Sources
Positrons
e^+
μ^+ Muons μ^-
τ^+ Tauons τ^-
Electrons
e^-
Antiprotons
Photons
γ
Neutrinos
ν_e ν_μ ν_τ
Neutrons
n
light ions
low charge state ions
positive ions
Protons
e.g. U^{4+}
e.g. Ar^+
heavy ions
high charge state ions
e.g. Ag^{32+}
fully stripped nuclei
e.g. U^{92+}
exotic nuclei
e.g. Lr^{103+}
$\vec{p}$ polarised particles $\vec{e}^-$
$\vec{H}^-$
negative ions
neutral atoms
H^0
H^-
Caesium sputter
heavy negative ions
e.g. I^-
negative ion currents in μA
Mesons
Baryons
W bosons
Z bosons
Higgs bosons

Particles and **Sources**



Early 1970s Budker Institute of Nuclear Physics Novosibirsk

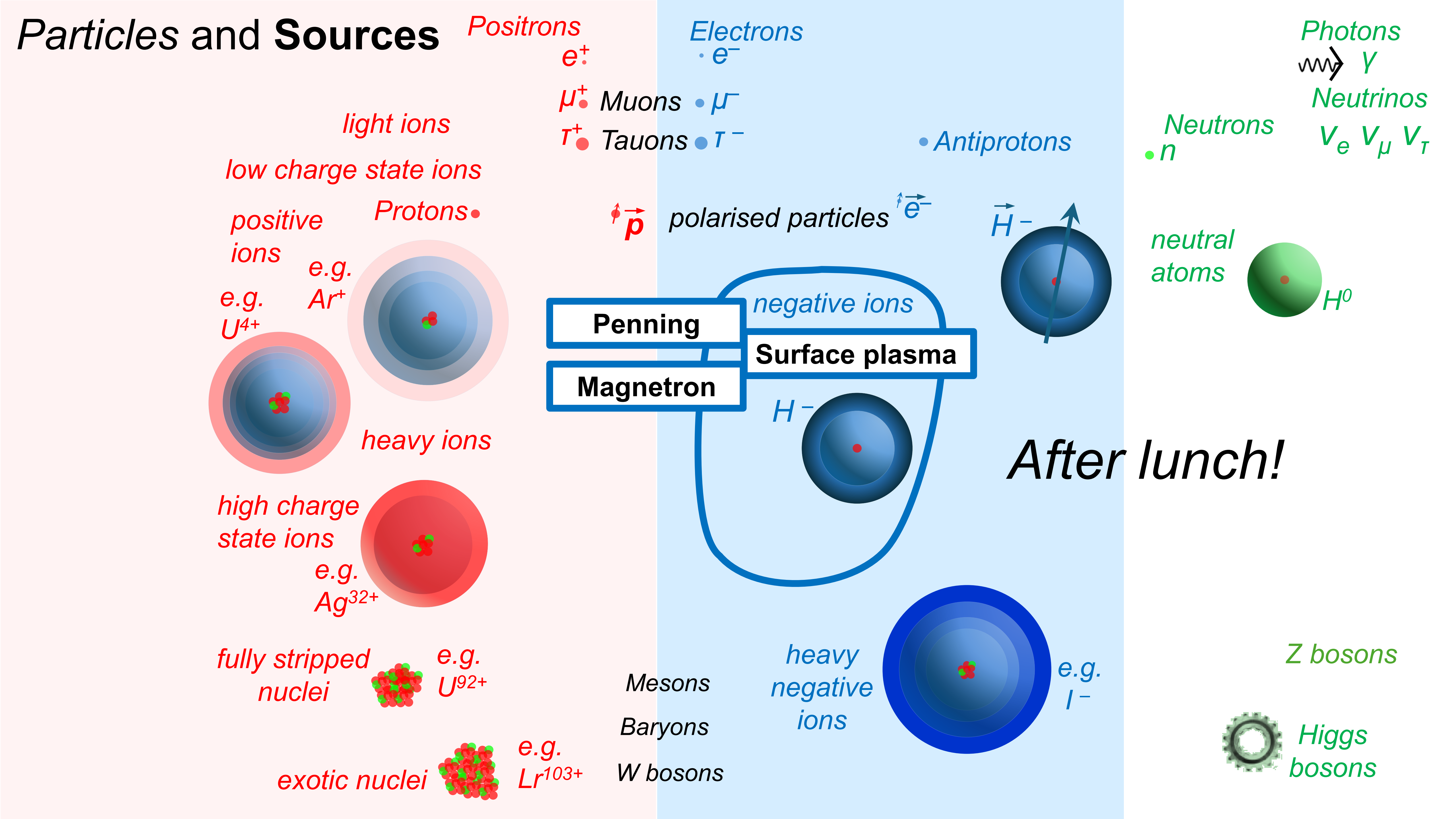
Production of H^- ions by surface ionisation with the addition of caesium

Surface Plasma Sources (SPS)

Gennady Dimov

Yuri Belchenko

Vadim Dudnikov



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Neutrons
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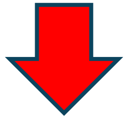
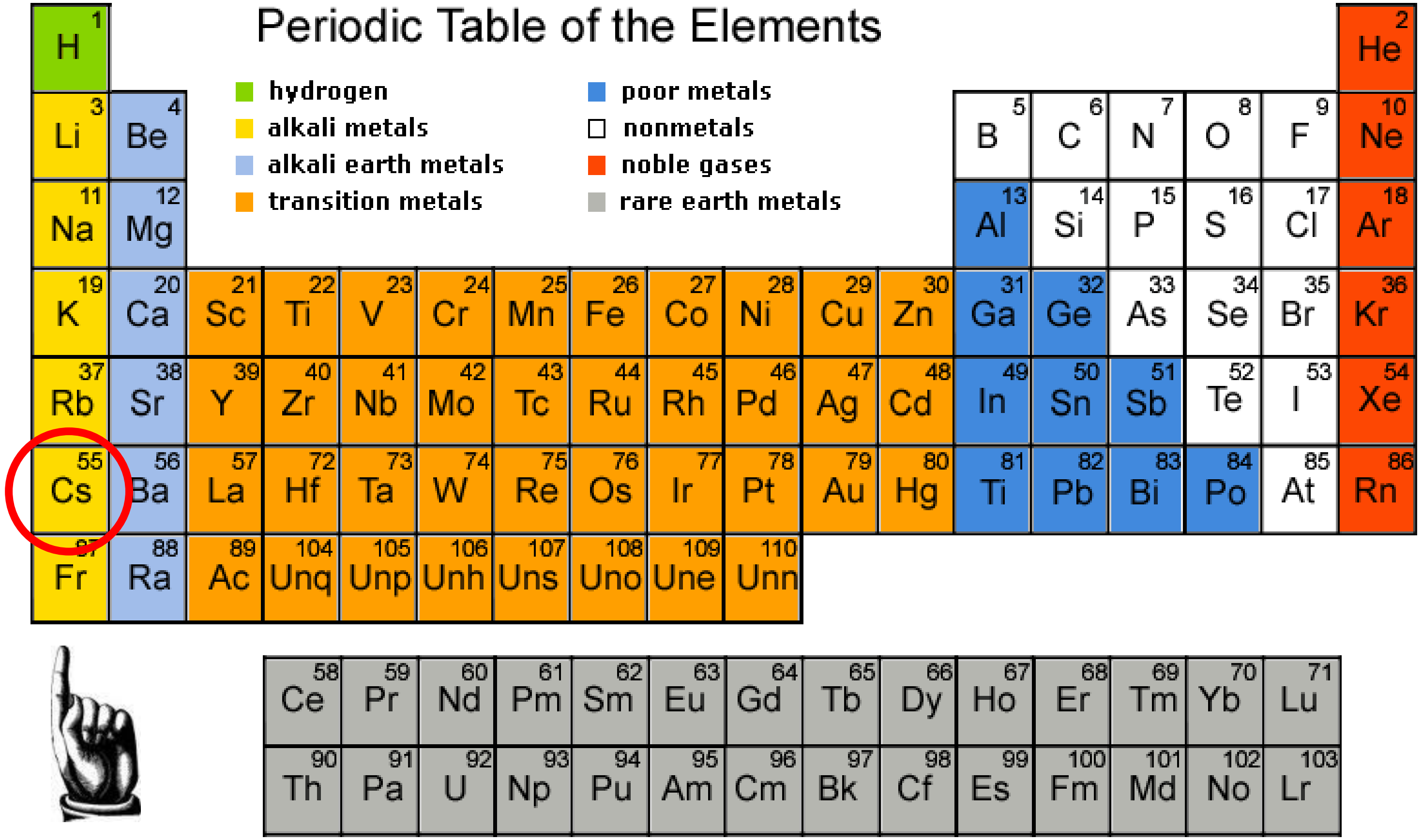
light ions
low charge state ions
positive ions
Protons
$\vec{p}$ polarised particles $\vec{e}^-$
$\vec{H}^-$
neutral atoms
H^0
e.g. Ar^+
e.g. U^{4+}
Penning
negative ions
Surface plasma
Magnetron
H^-
heavy ions
After lunch!
high charge state ions
e.g. Ag^{32+}
fully stripped nuclei
e.g. U^{92+}
Mesons
Baryons
W bosons
heavy negative ions
e.g. I^-
Z bosons
Higgs bosons
exotic nuclei
e.g. Lr^{103+}

Caesium – The magic elixir of negative ion sources!

More reactive

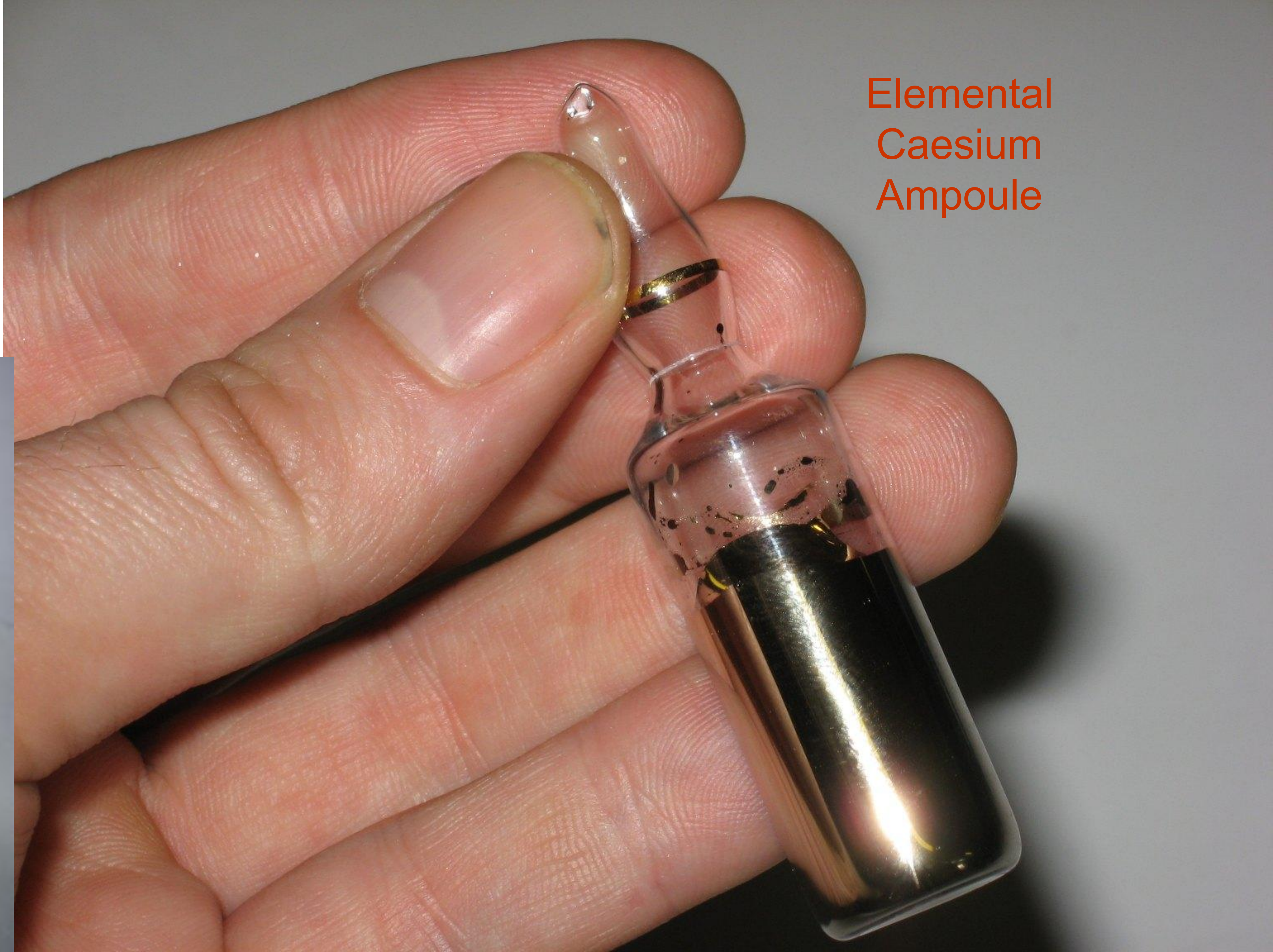




1 electron in the outer orbital

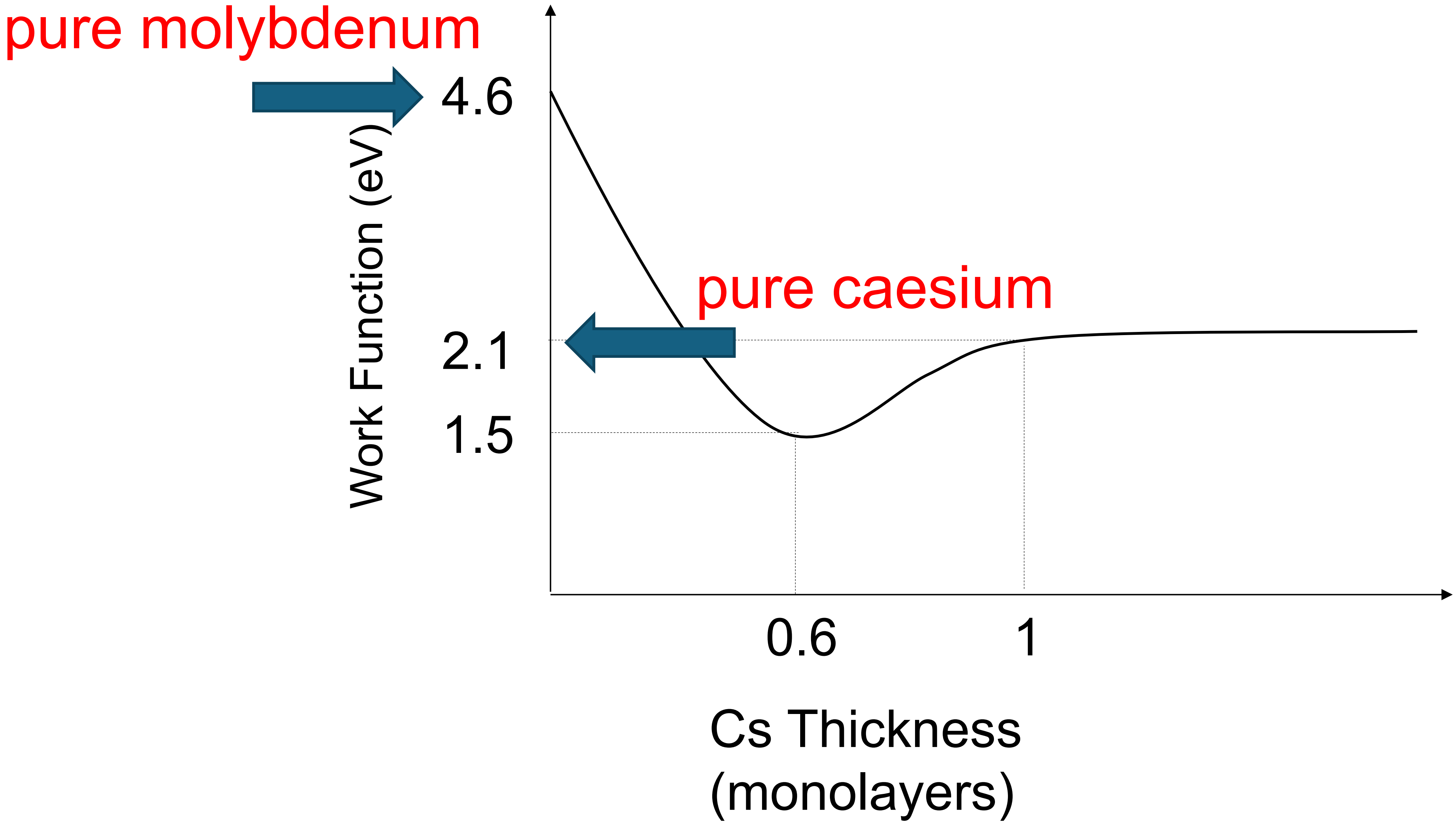
An amazing donor of electrons
= great for making negative ions

Caesium Chromate

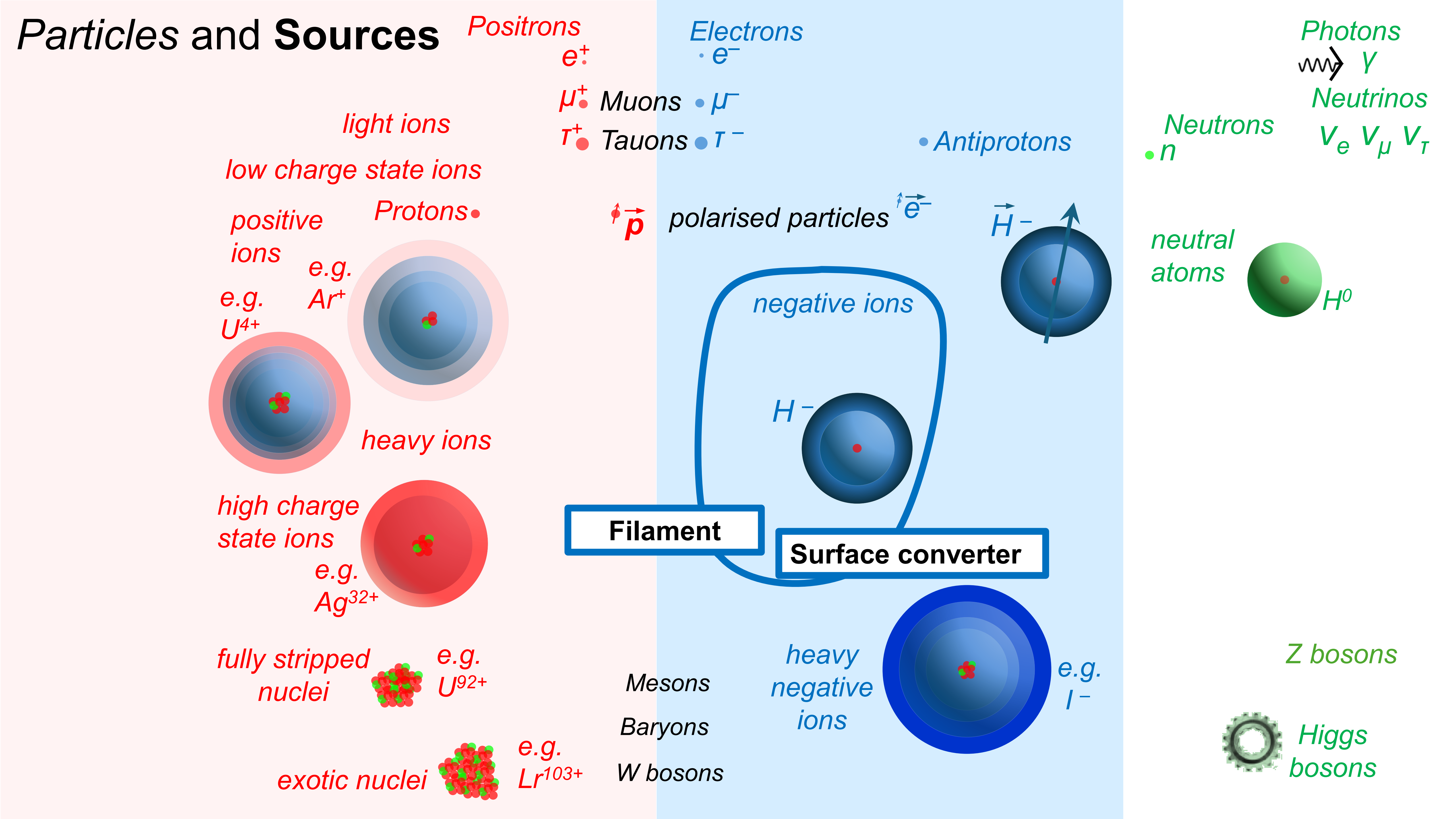


Elemental Caesium Ampoule

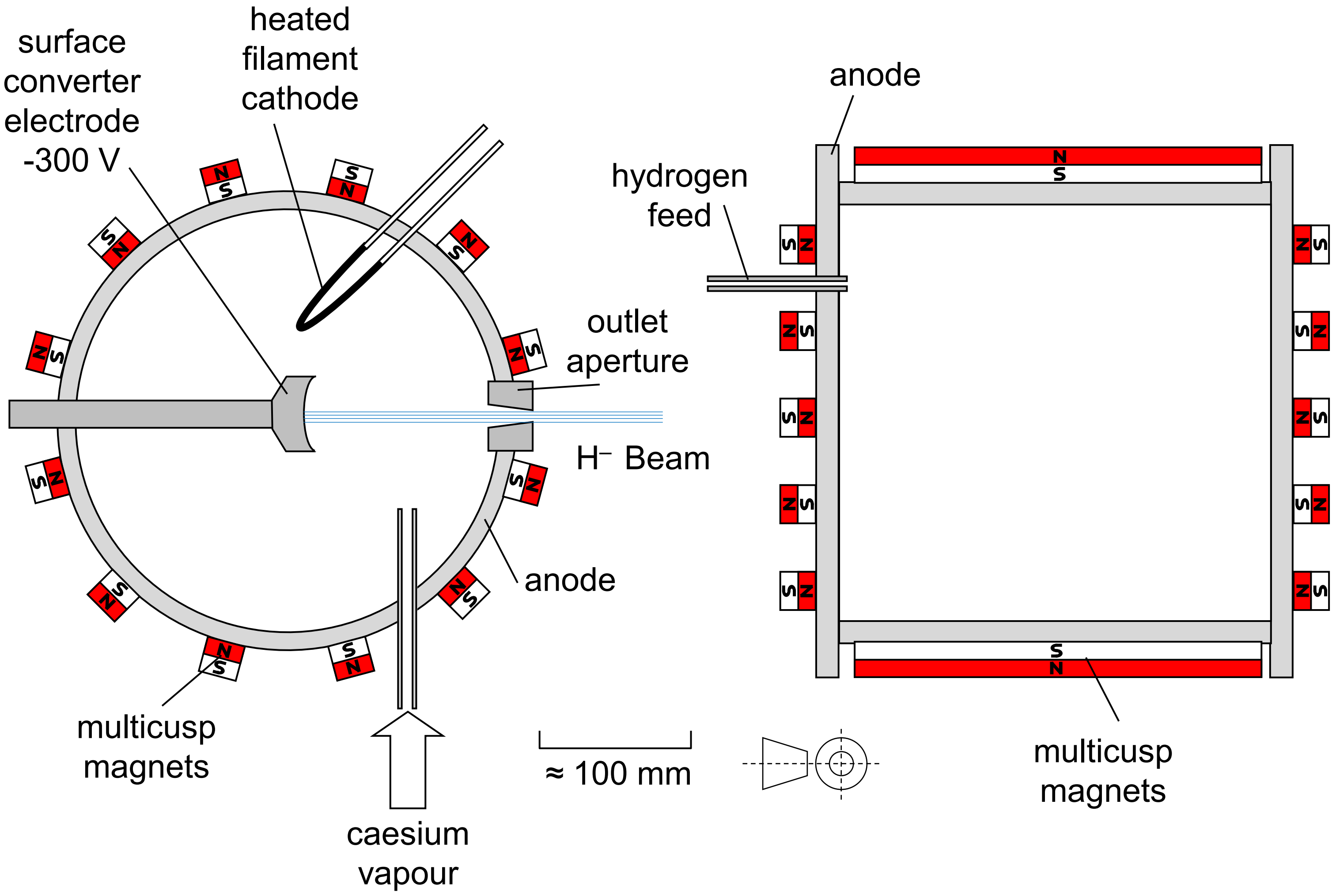
Caesium coverage and work function



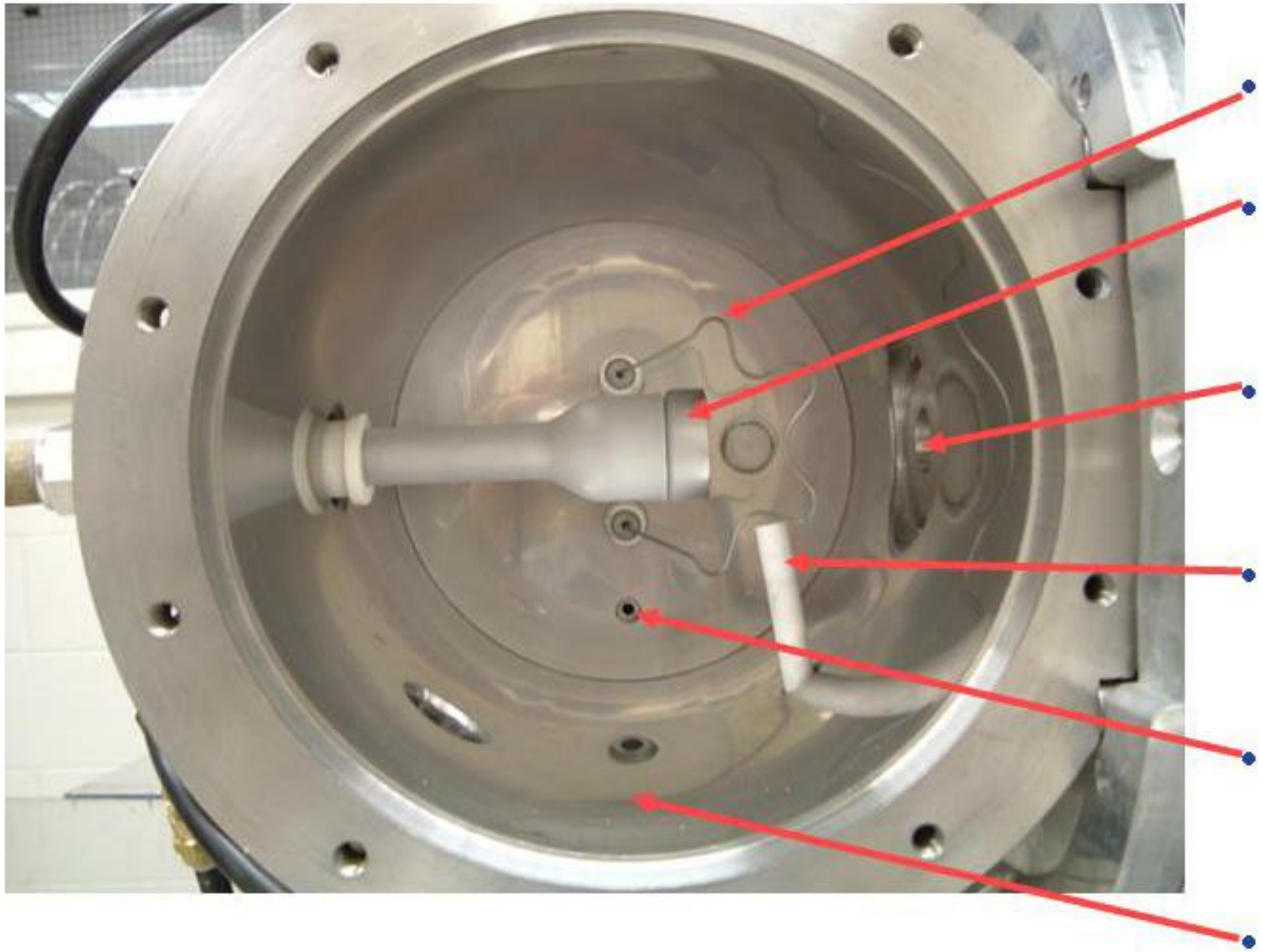
Particles and **Sources**



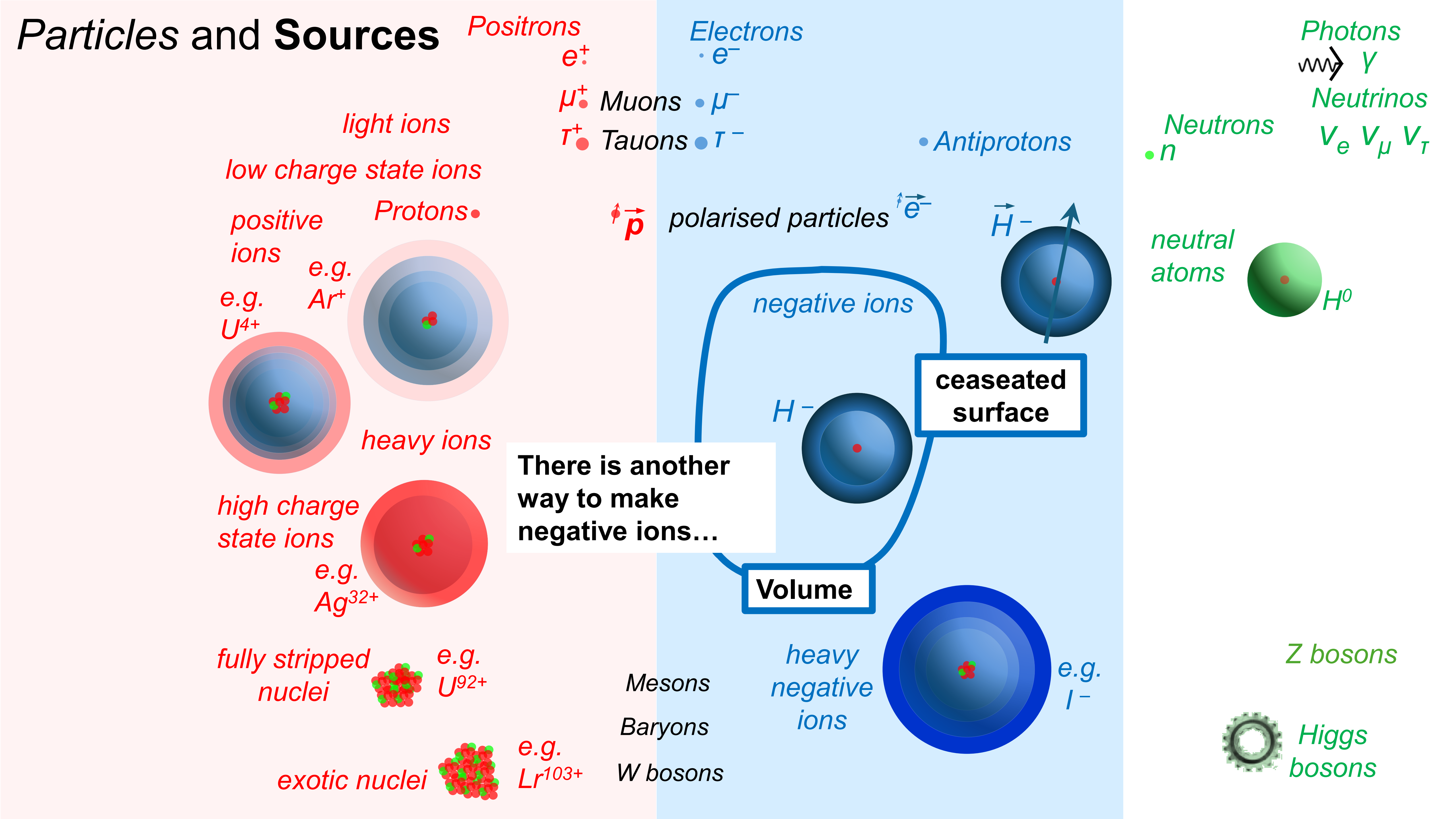
Filament cathode surface converter source



LANSE Surface Converter Source



18 mA 1 ms 120 Hz H^- beam



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ceaseated surface
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heavy ions
There is another way to make negative ions…
high charge state ions
e.g. Ag32+
Volume
fully stripped nuclei
e.g. U92+
Mesons
Baryons
W bosons
heavy negative ions
e.g. I −
exotic nuclei
e.g. Lr103+
Z bosons
Higgs bosons

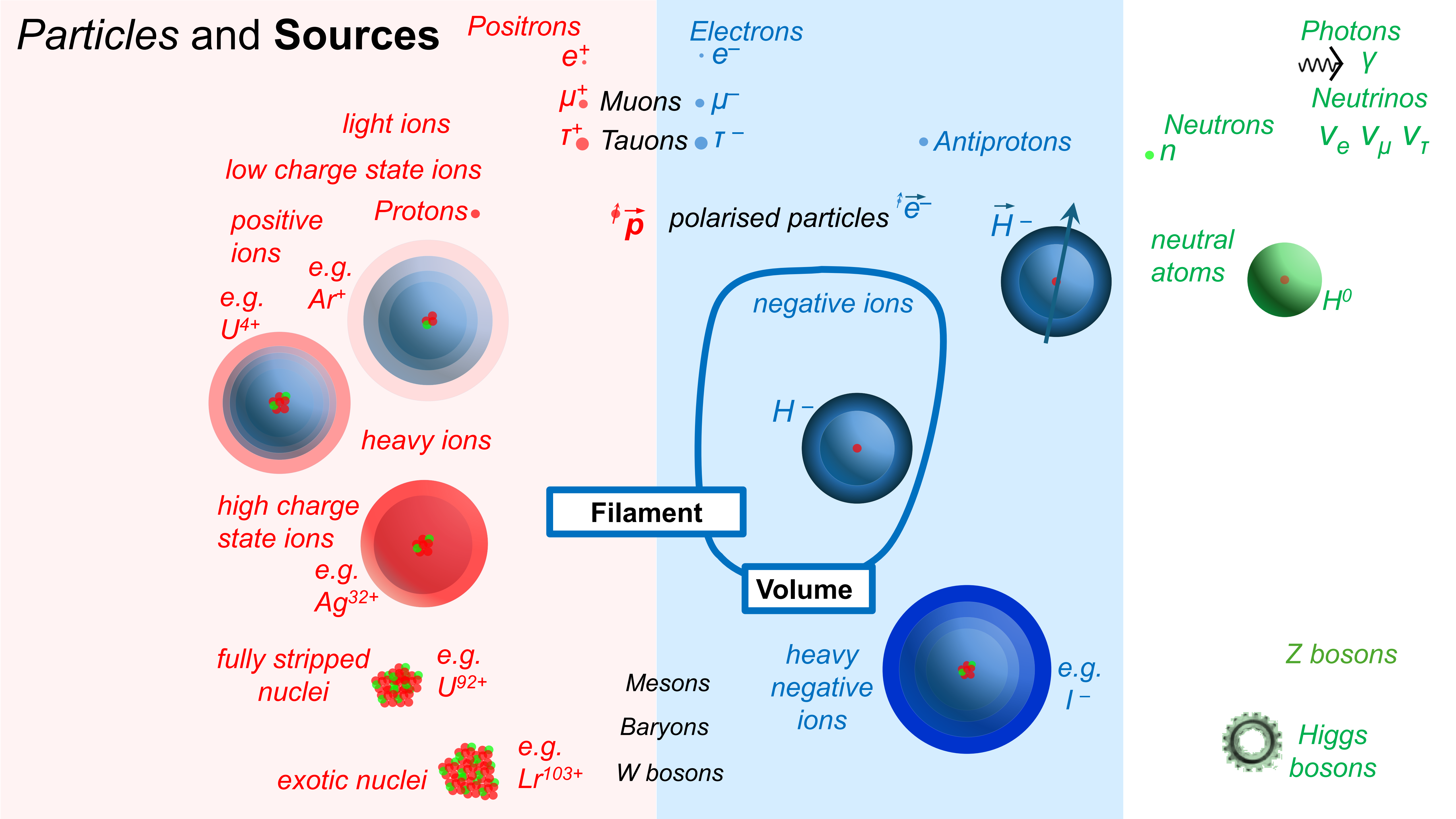
Marthe Bacal
Ecole Polytechnique
mid 1970's

Volume Production

$$H_2^* + e\ (\leq 1\ \text{eV}) \rightarrow H^- + H^0$$

Dissociative attachment of **low energy** electrons to rovibrationally excited H_2 molecules

Sources developed by Ehlers + Leung at LBNL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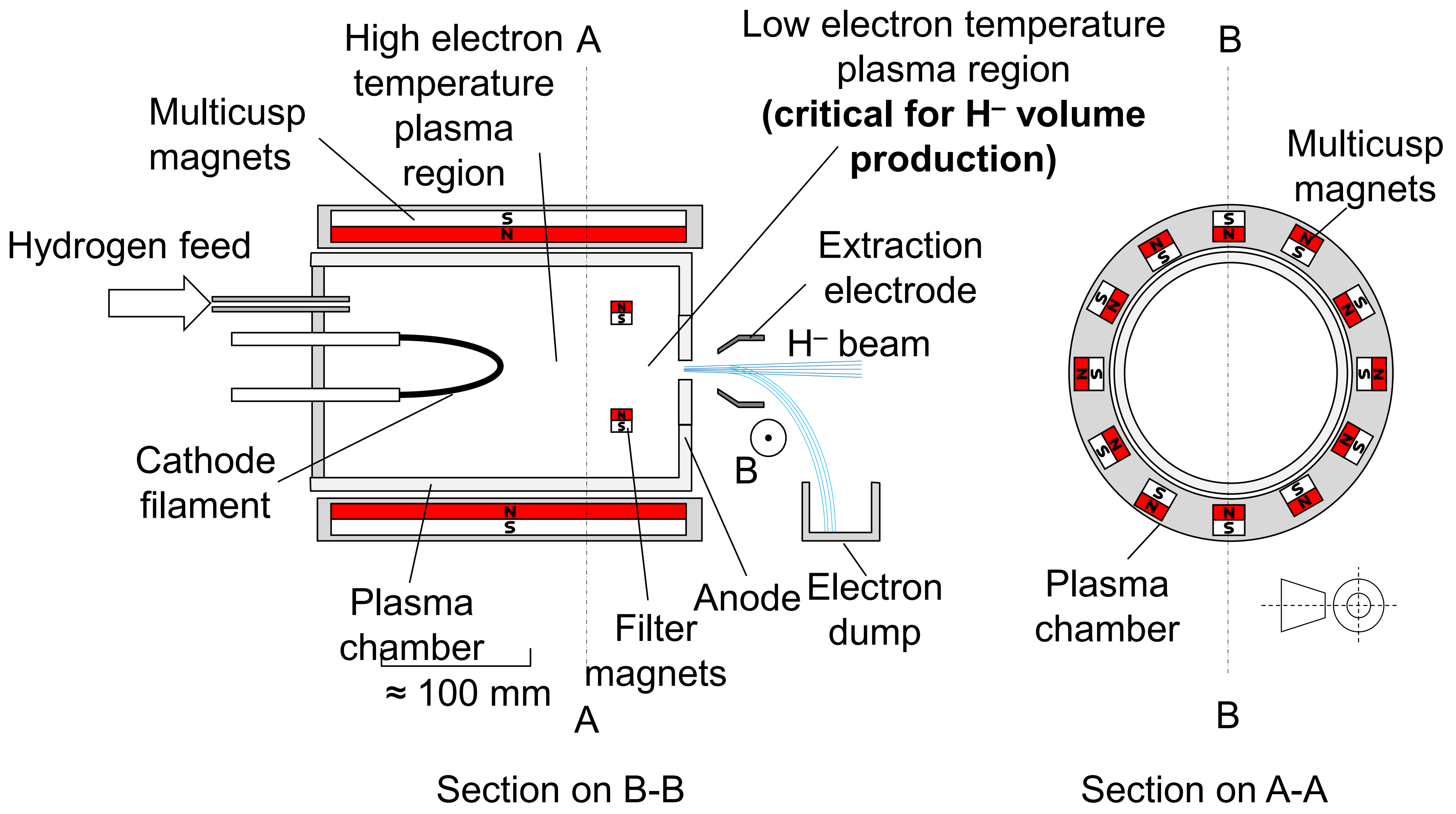
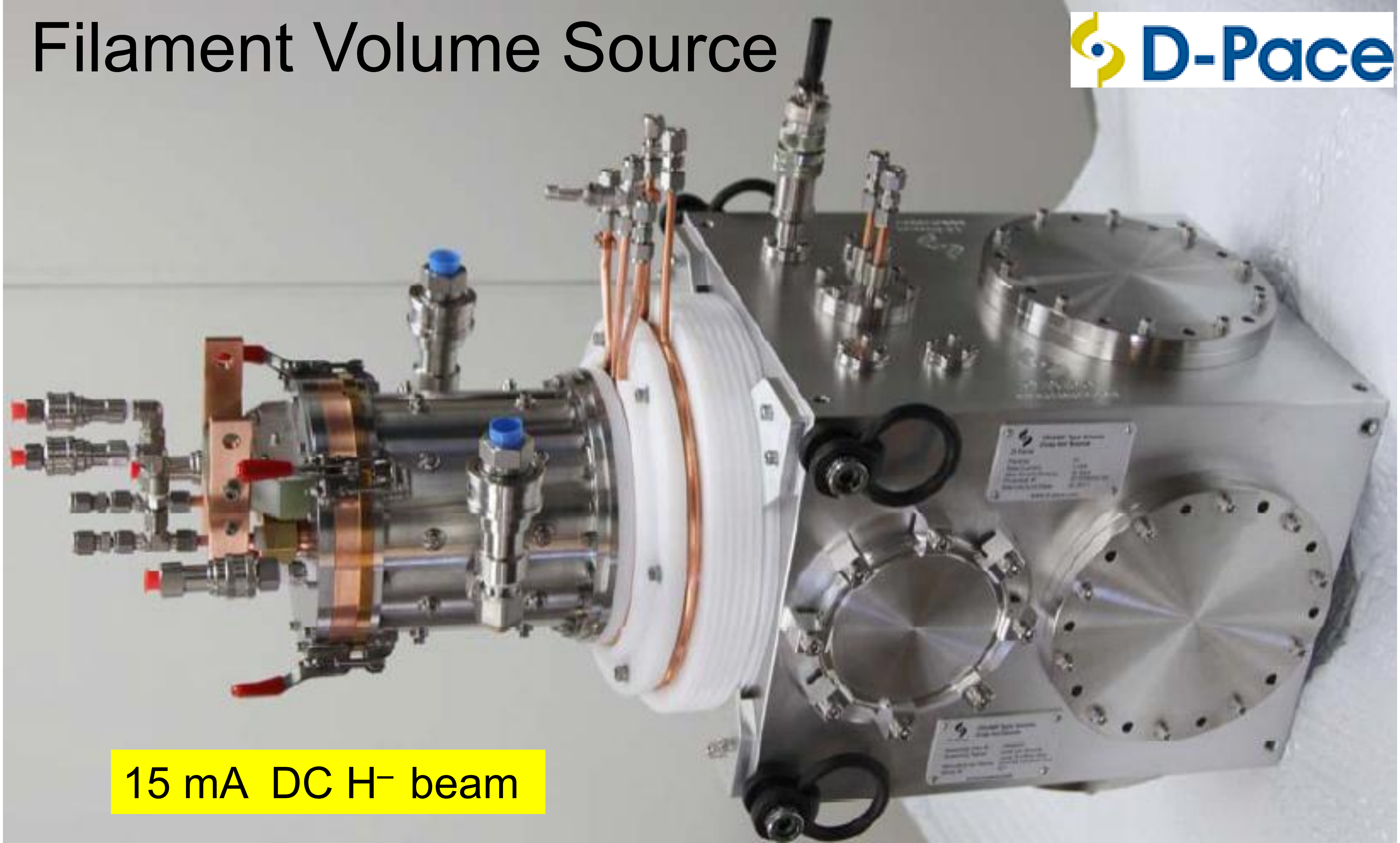
e.g. U4+
neutral atoms
H0
negative ions
H −
heavy ions
Filament
high charge state ions
e.g. Ag32+
Volume
fully stripped nuclei
e.g. U92+
Mesons
heavy negative ions
e.g. I −
Baryons
exotic nuclei
e.g. Lr103+
W bosons
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
Z bosons
Higgs bosons

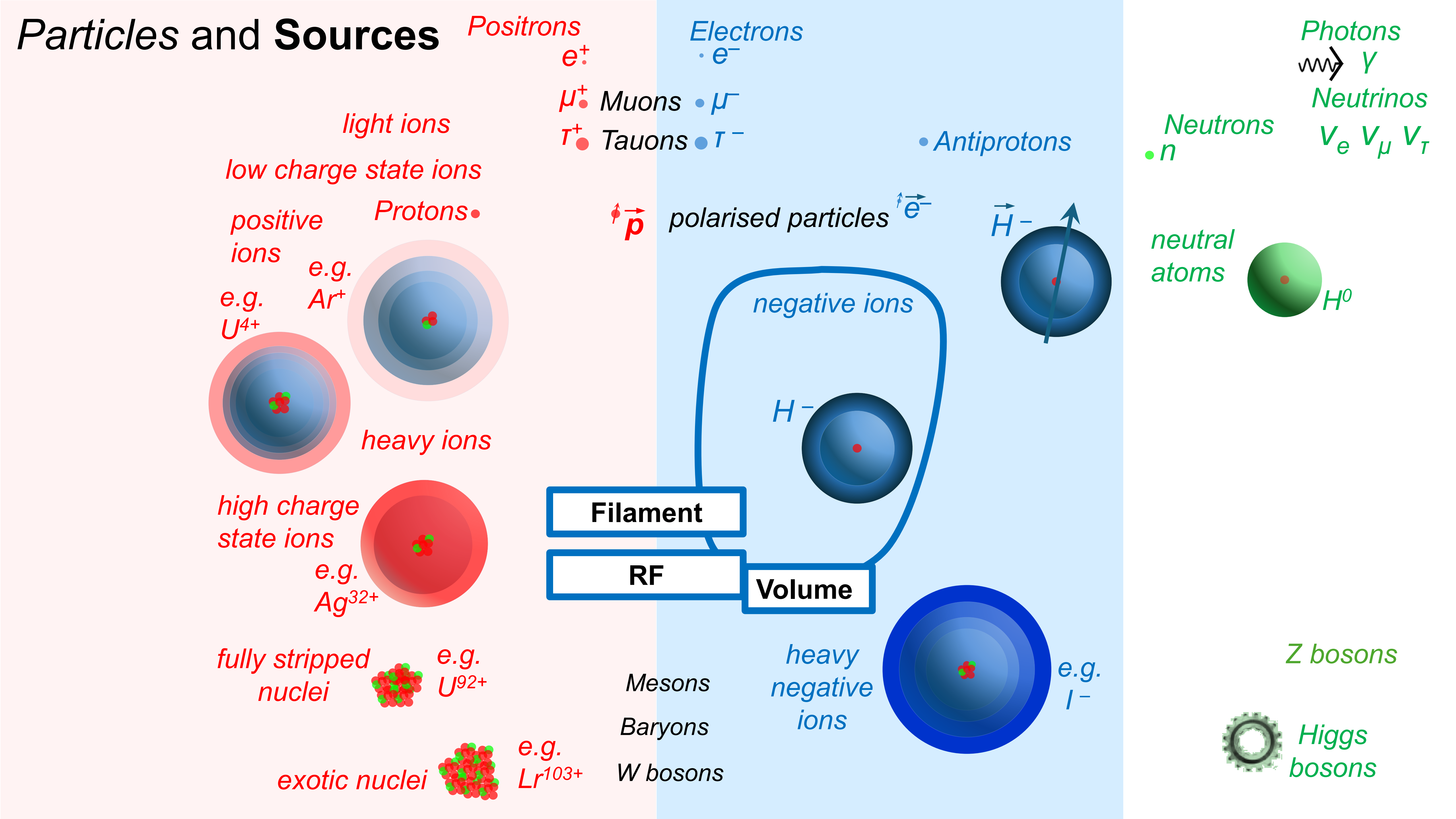
Multicusp Filament Volume Source



Filament Volume Source



15 mA DC H^- beam



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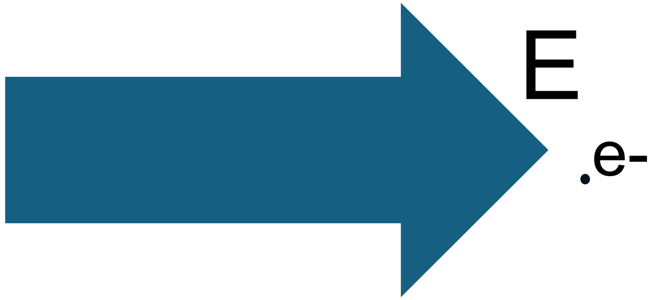
e.g. Ar+
e.g. U4+
heavy ions
negative ions
H−
H−
neutral atoms
H0
high charge state ions
e.g. Ag32+
Filament
RF
Volume
fully stripped nuclei
e.g. U92+
exotic nuclei
e.g. Lr103+
Mesons
Baryons
W bosons
heavy negative ions
e.g. I−
Z bosons
Higgs bosons

Driving electrons



Capacitively Coupled Plasmas (CCP)

voltage applied to electrodes creates the electric field

many names for different electrode and magnetic field configurations
DC and AC

Electromagnetic Cavity Plasmas - waveguide or coax coupled

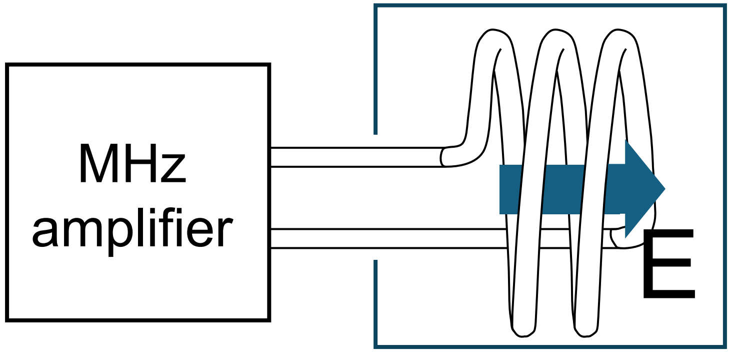
the electric field component of the electromagnetic oscillation in a cavity

"Microwave sources"
"ECR sources"

Inductively Coupled Plasmas (ICP)

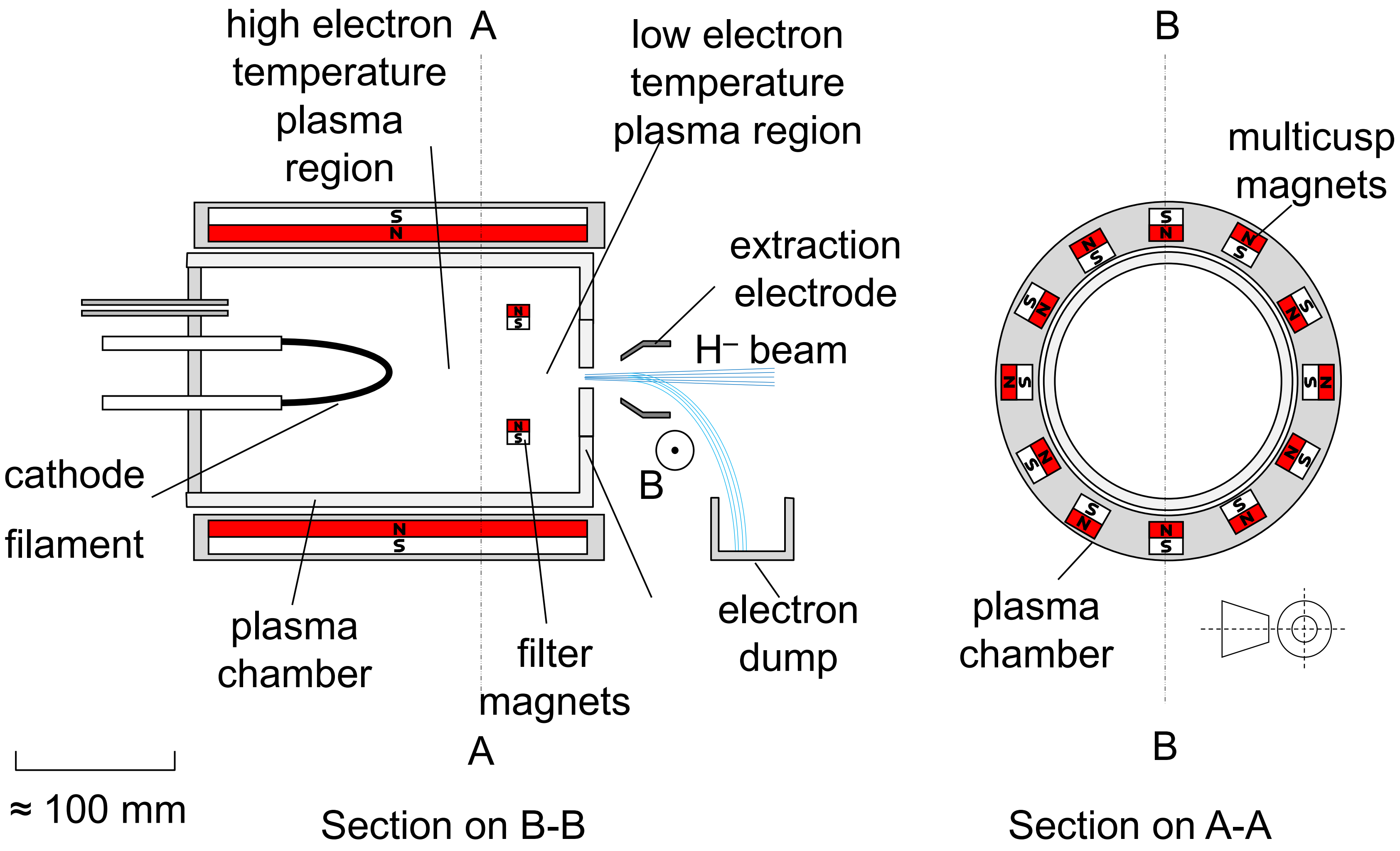
a time varying current in a coil creates a time varying magnetic field that induces a time varying electric field

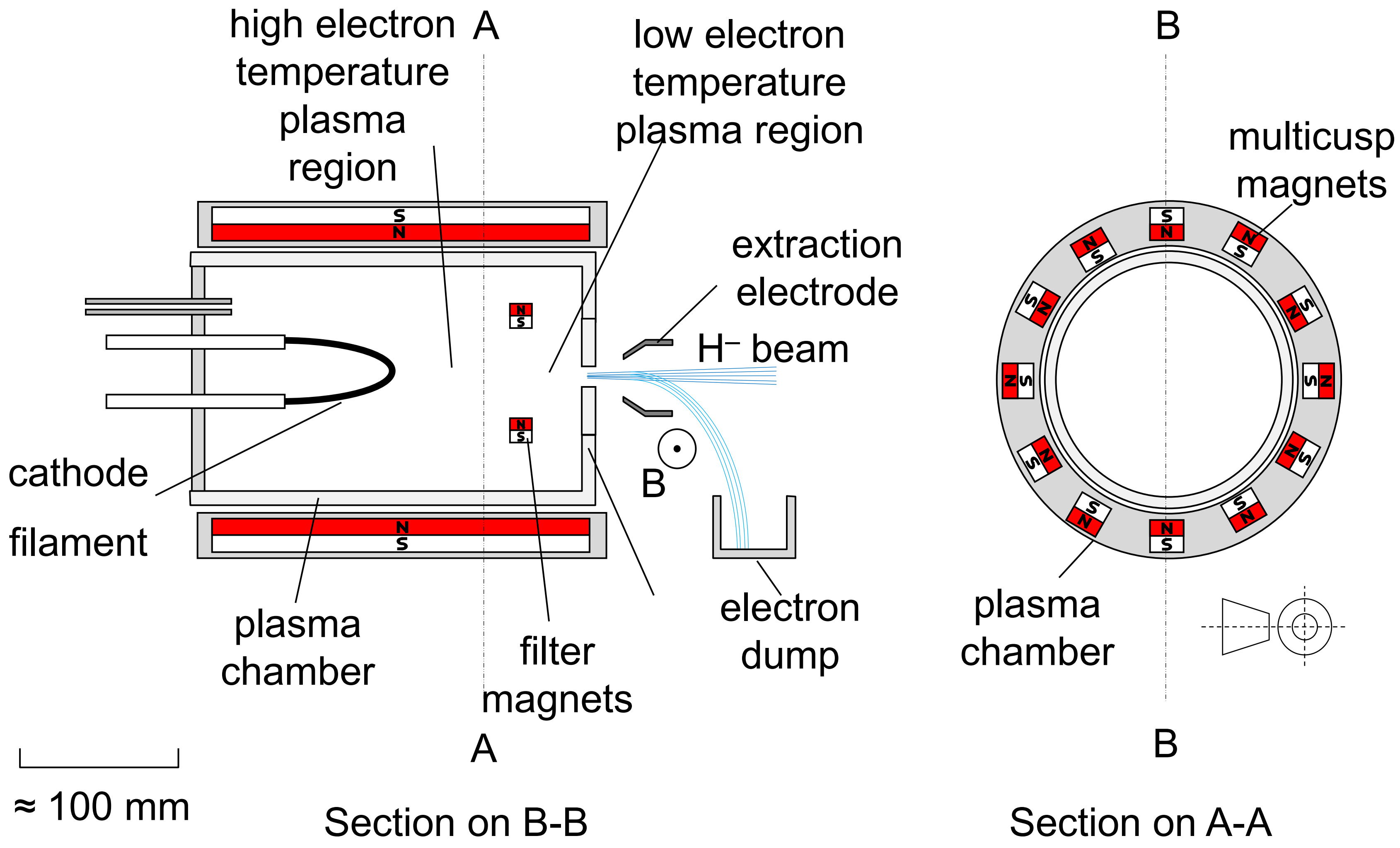
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$



"RF sources"

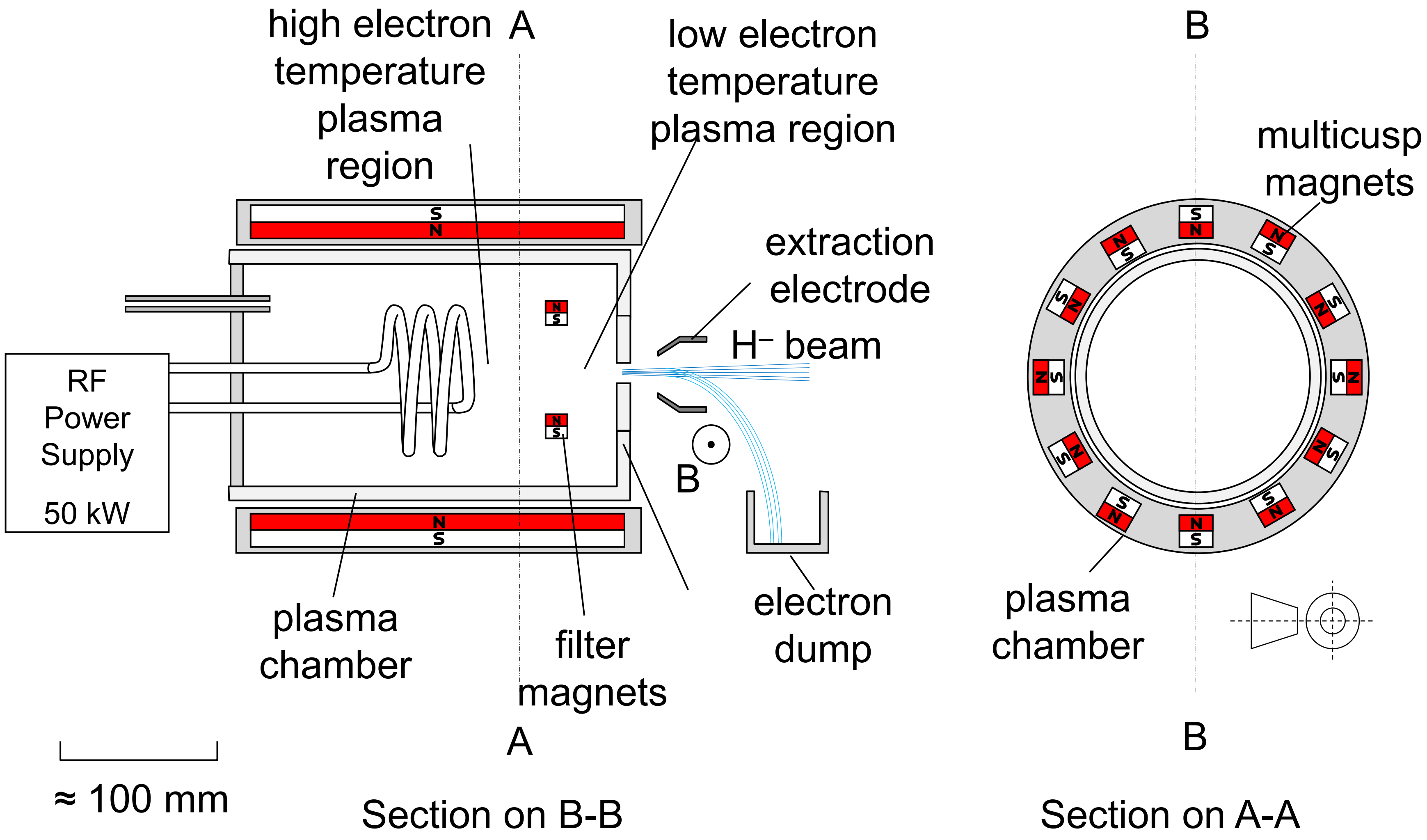
ICP are ideally suited for negative ion production because they do not produce high energy electrons like ECR and microwave sources



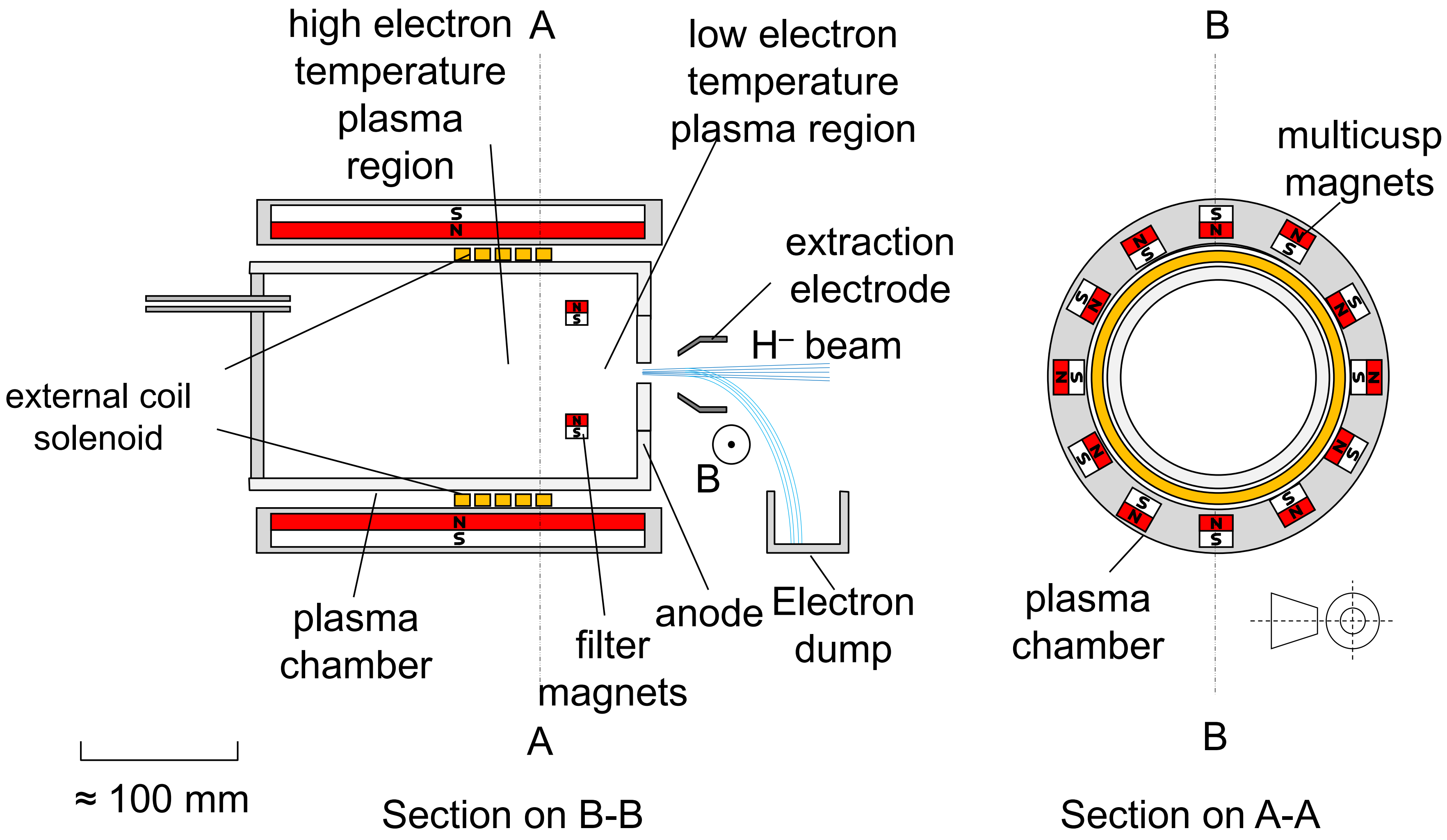


high electron temperature plasma region
A
low electron temperature plasma region
B
multicusp magnets
extraction electrode
H⁻ beam
cathode
filament
B
plasma chamber
filter magnets
electron dump
plasma chamber
A
B
≈ 100 mm
Section on B-B
Section on A-A

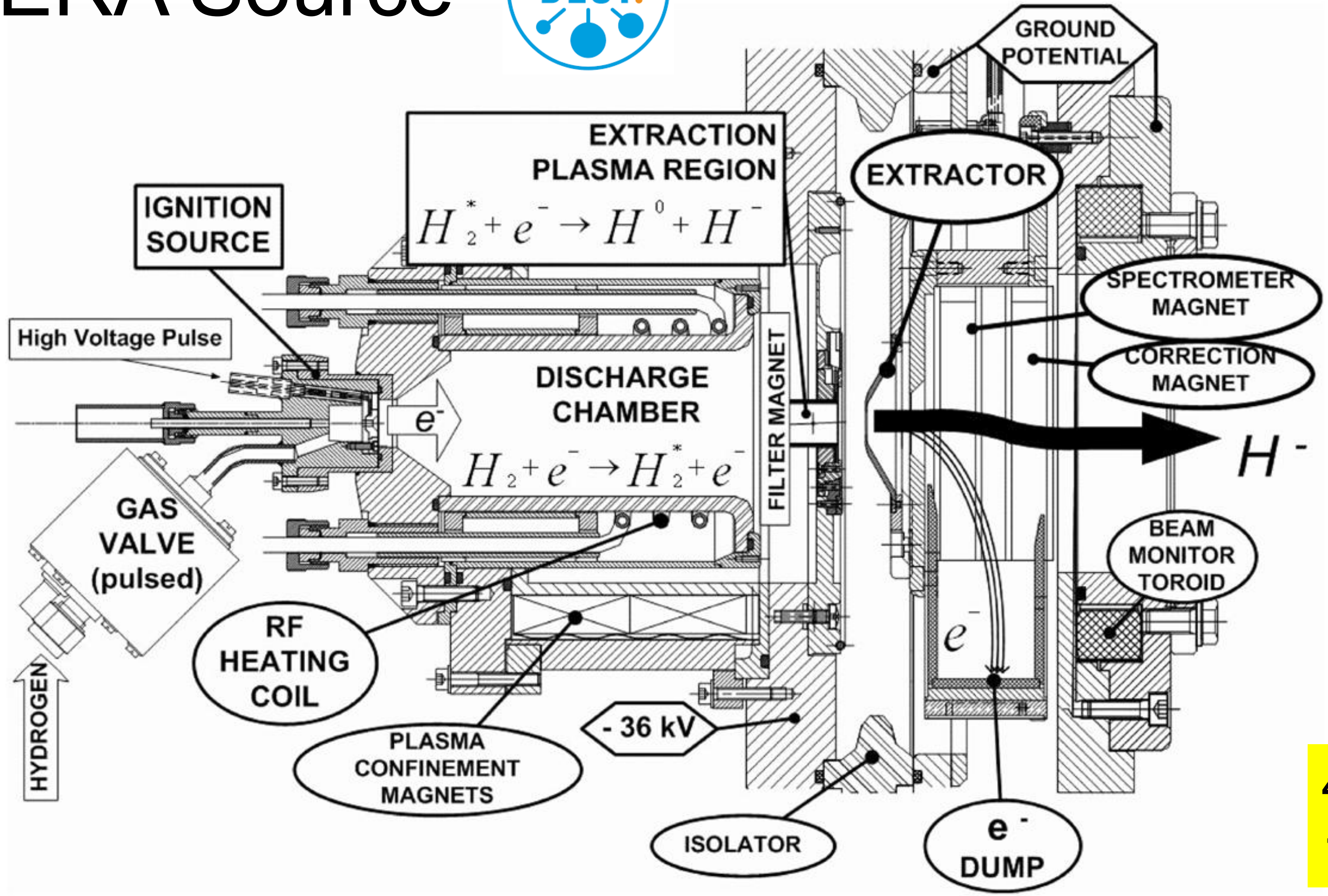
Internal RF solenoid coil volume source



External RF solenoid coil volume source



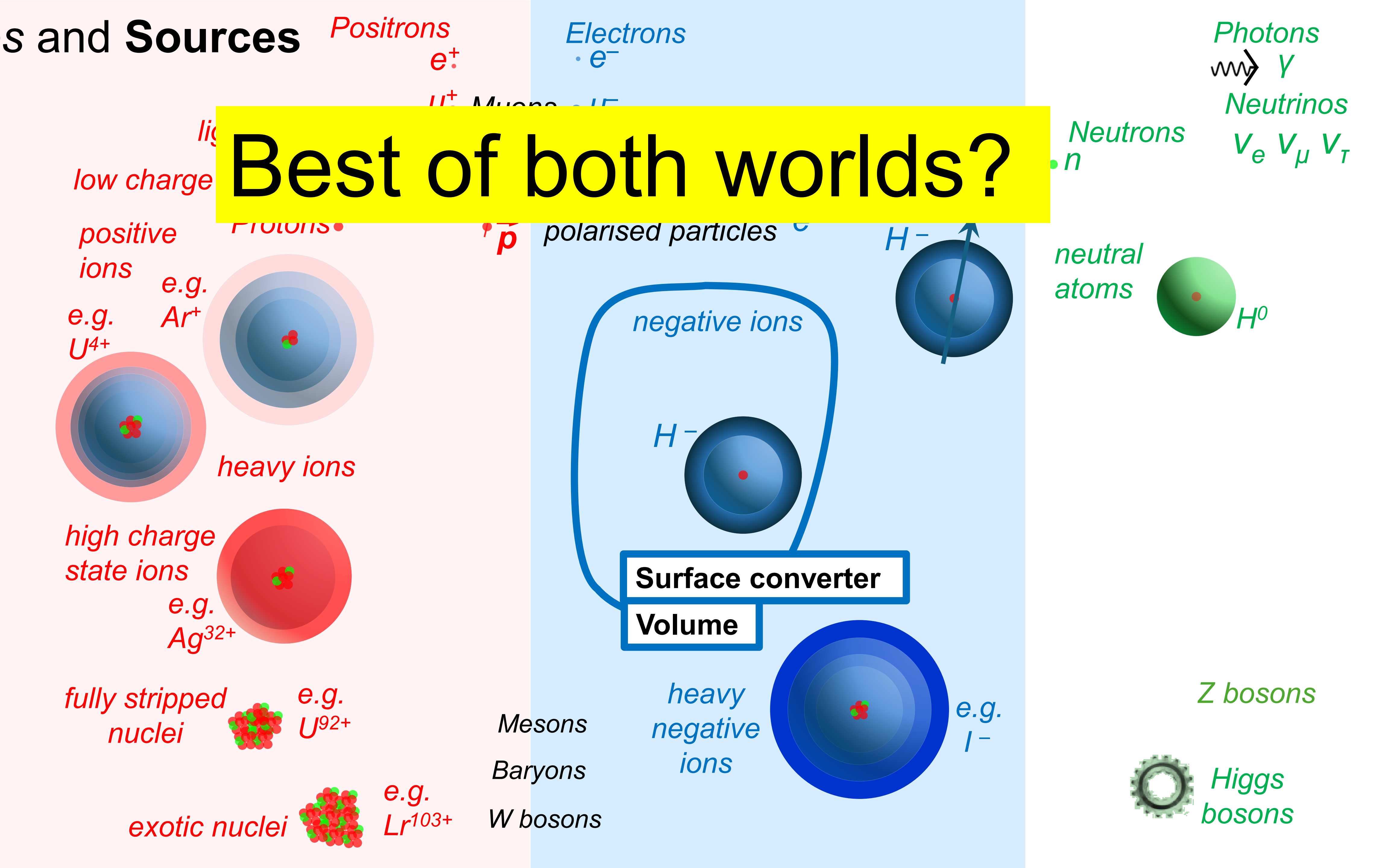
HERA Source



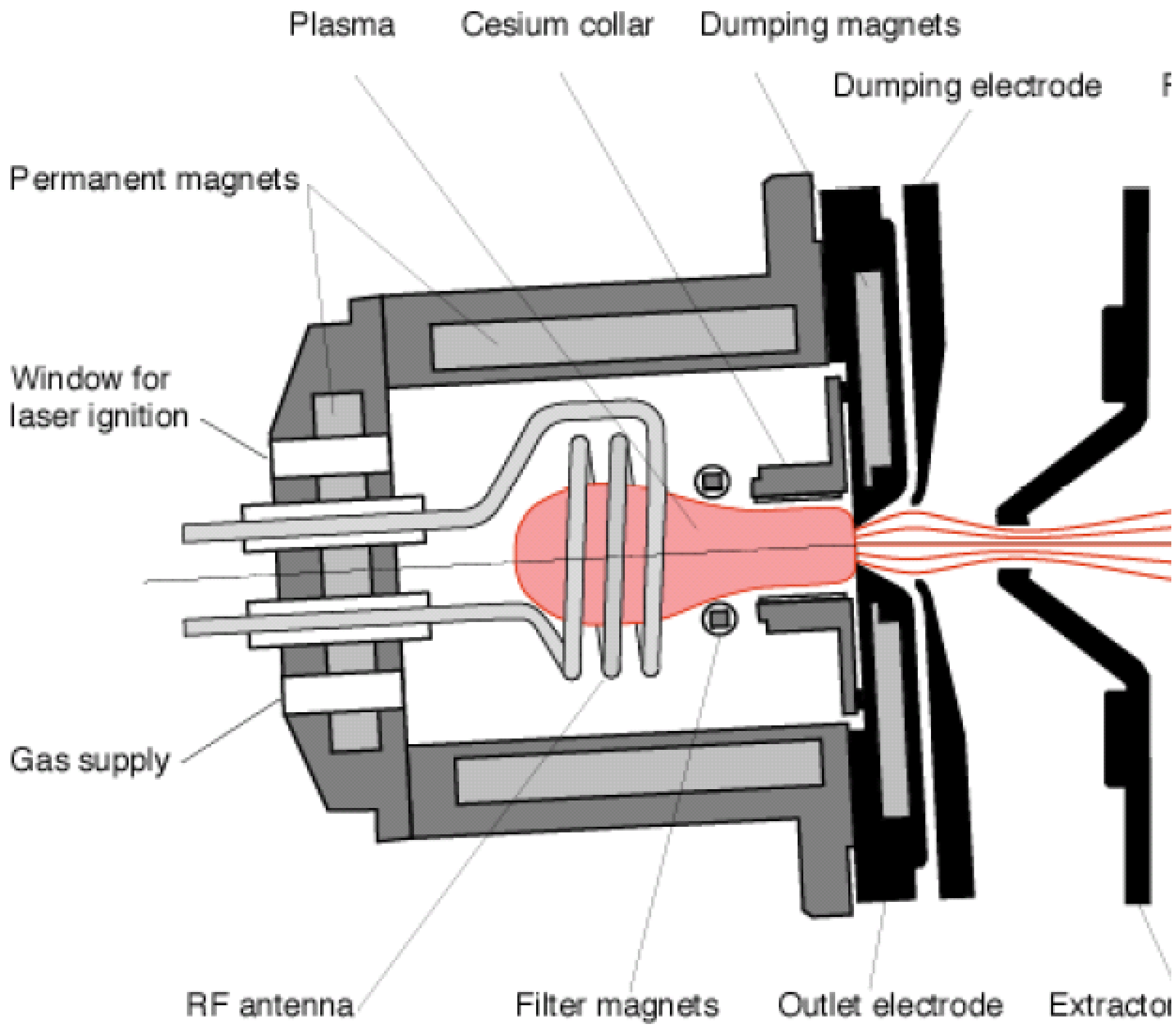
Jens Peters
Late 1990's

40 mA H⁻
150 μs, 3 Hz

Particles and **Sources**

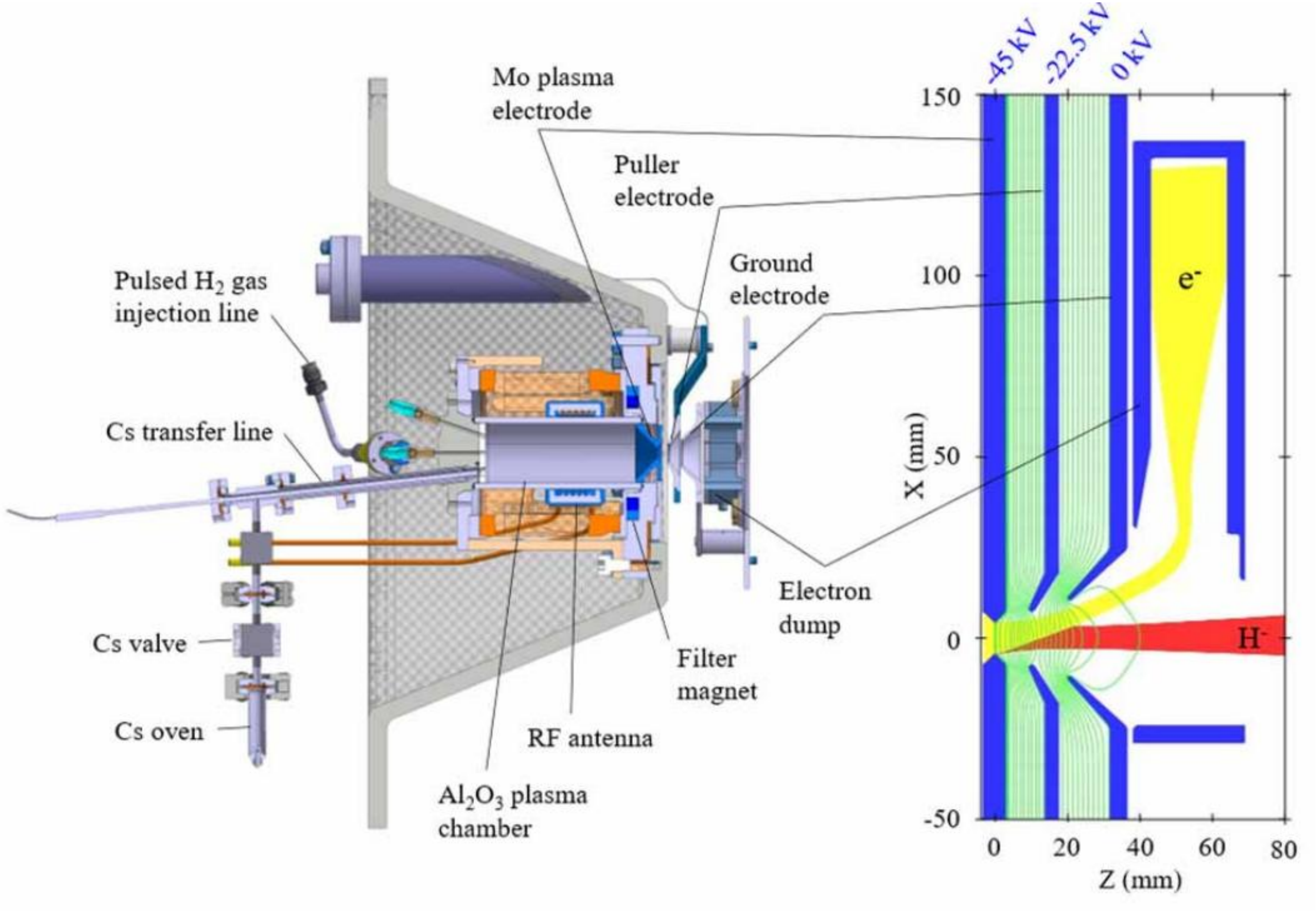


SNS ion source



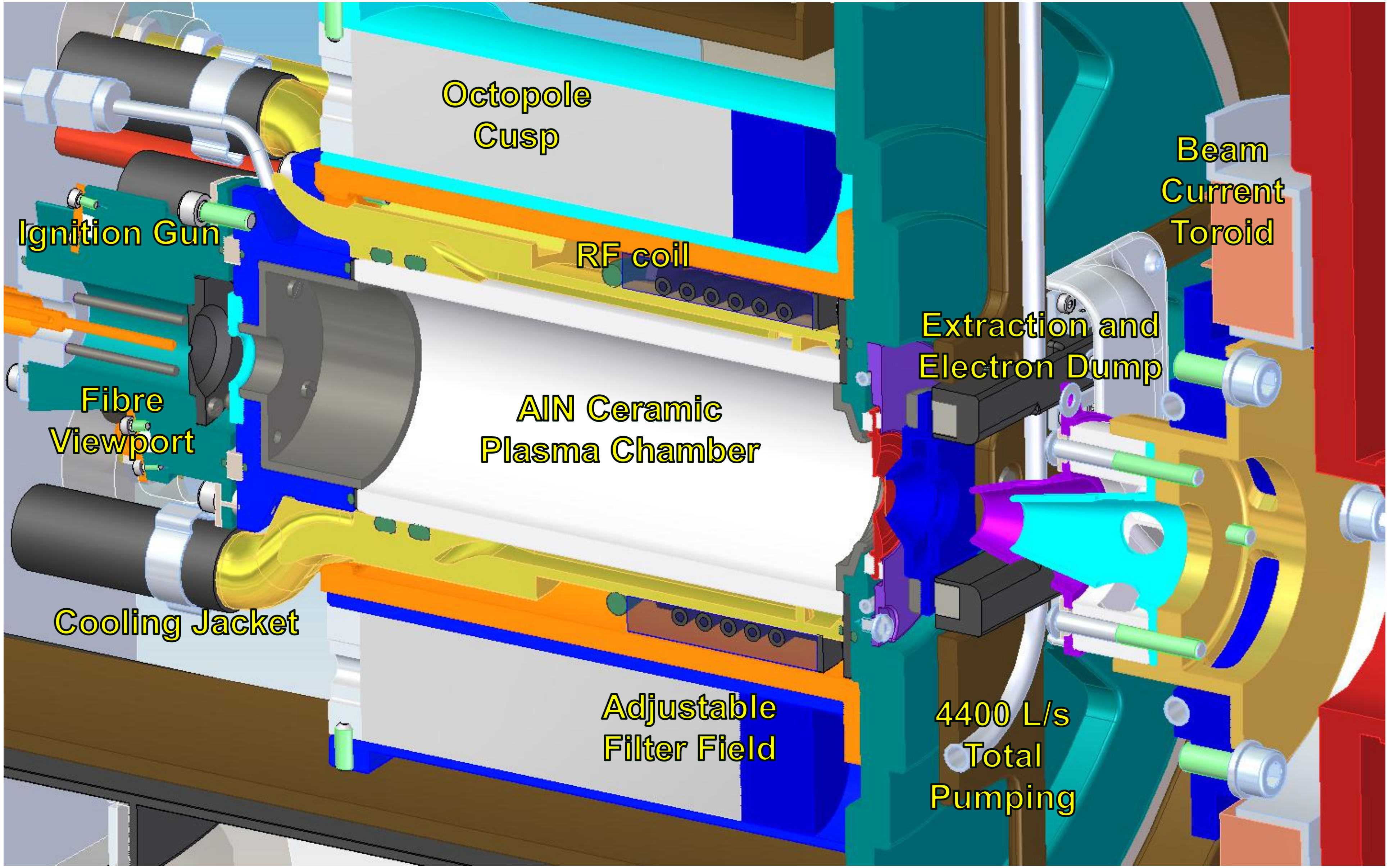
60 mA H^- 1 ms, 60 Hz

CERN LINAC 4 RF H⁻ Ion Source



50 mA H⁻
500 μs, 3 Hz

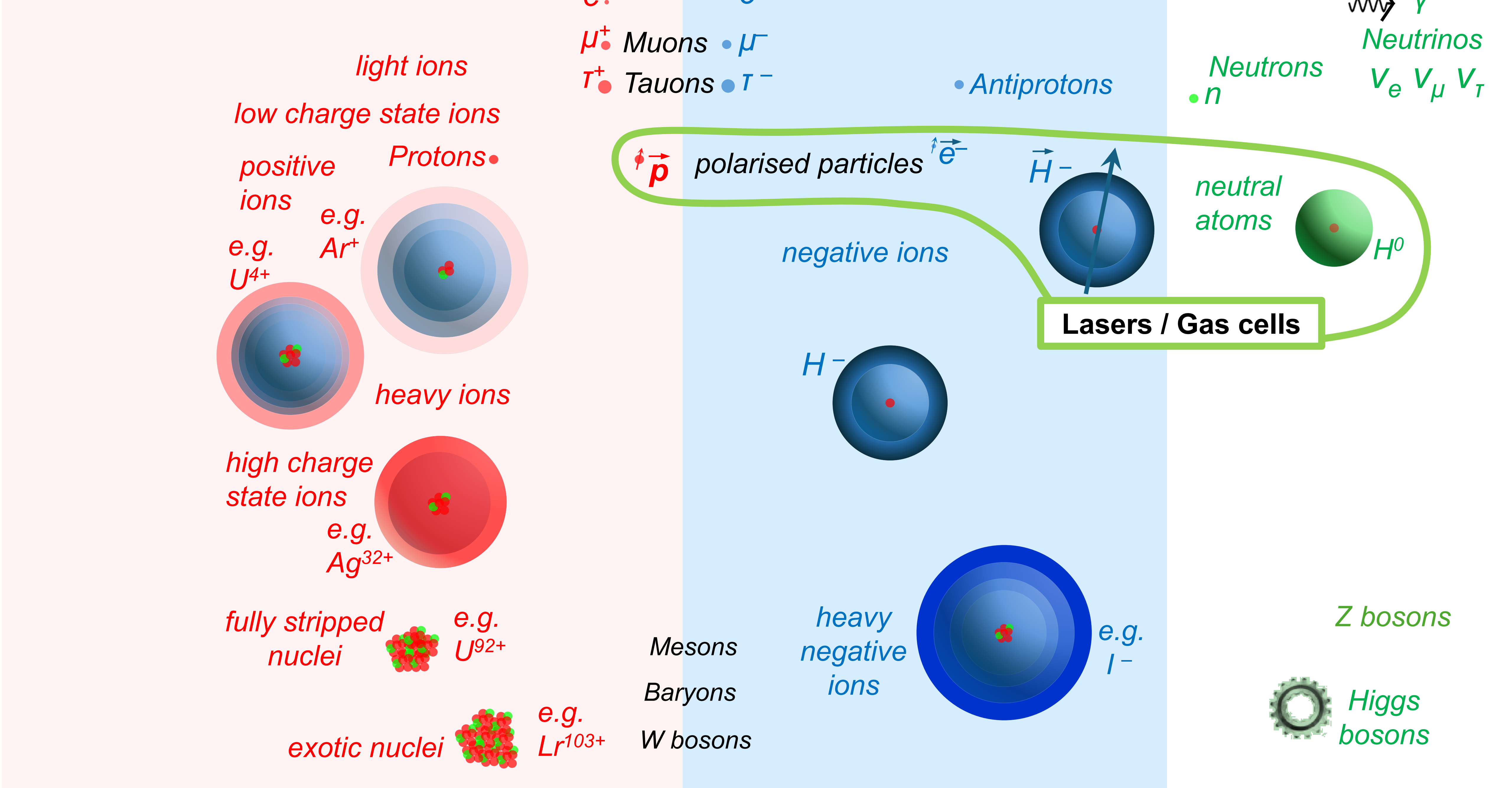
ISIS RF H^- Ion Source (currently in commissioning)



Science and Technology Facilities Council

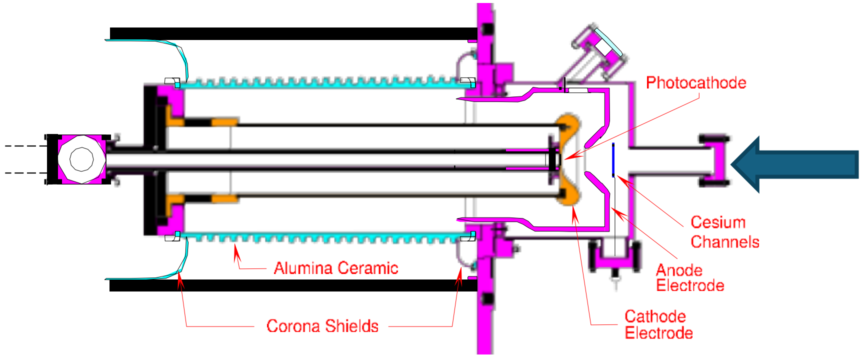
ISIS Neutron and Muon Source

Particles and **Sources**

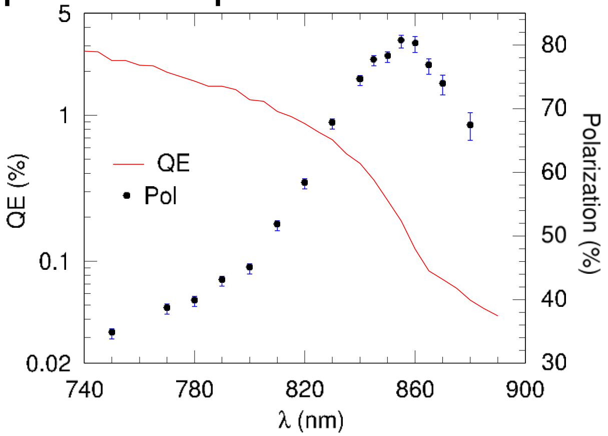


Polarised Electrons

Strained GaAs photocathode

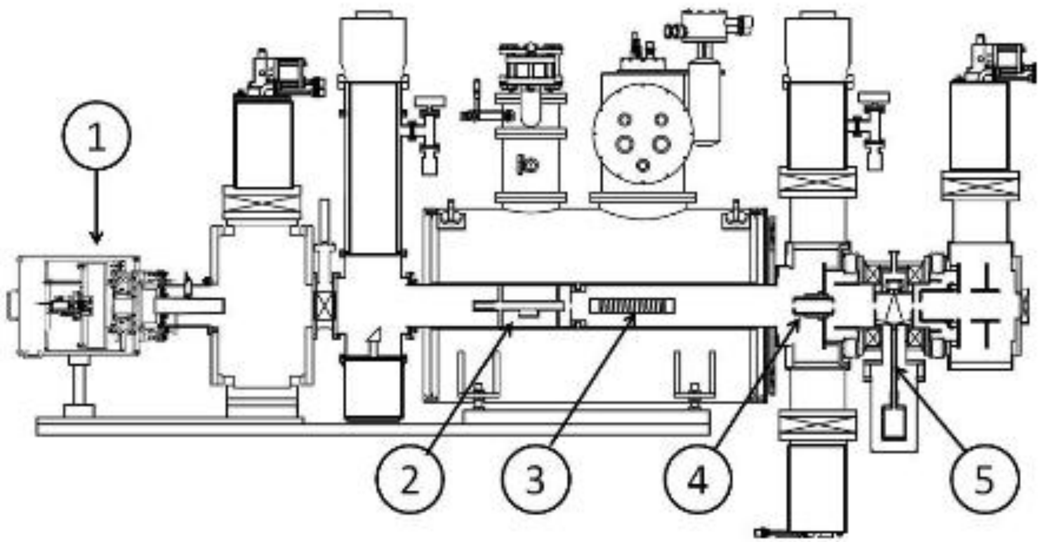


Circularly polarized laser light produces polarised electrons



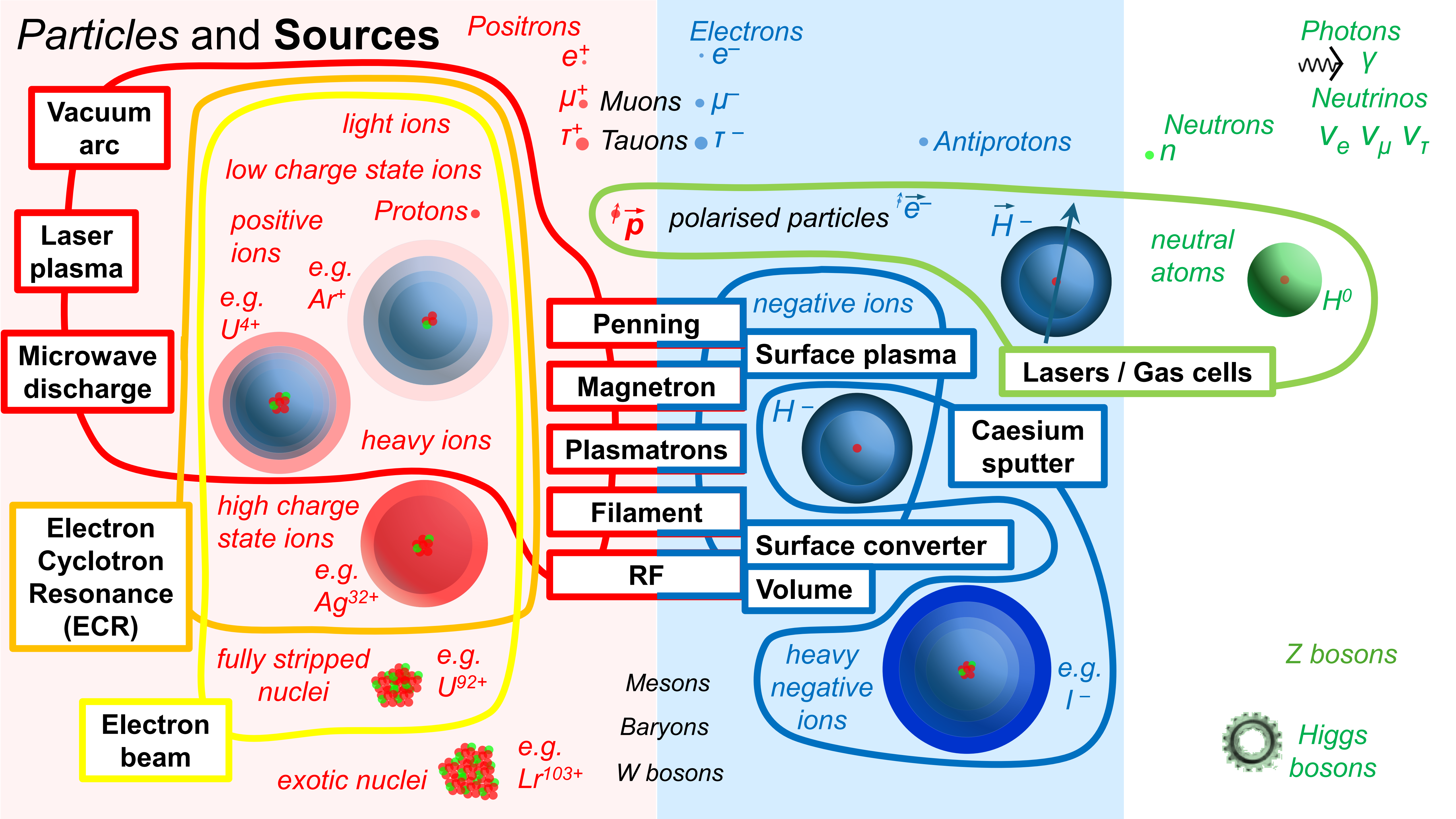
100 µA polarised e⁻

Polarised H⁻



1. High current proton source and H neutraliser cell
2. He ioniser cell
3. Laser pumped Rb-vapour cell
4. Sona-transition
5. Na jet ioniser cell

1.6 mA 400 µs polarised H⁻


Particles and Sources
Positrons
e+
Electrons
e−
Photons
γ
Neutrinos
νe νμ ντ
Neutrons
n
μ+ Muons μ−
τ+ Tauons τ −
Antiprotons
Vacuum arc
Laser plasma
Microwave discharge
Electron Cyclotron Resonance (ECR)
Electron beam
light ions
low charge state ions
positive ions
Protons
e.g. Ar+
e.g. U4+
heavy ions
high charge state ions
e.g. Ag32+
fully stripped nuclei
e.g. U92+
exotic nuclei
e.g. Lr103+
p
polarised particles
e−
H −
neutral atoms
H0
Penning
Magnetron
Plasmatrons
Filament
RF
negative ions
Surface plasma
Lasers / Gas cells
H −
Caesium sputter
Surface converter
Volume
heavy negative ions
e.g. I −
Mesons
Baryons
W bosons
Z bosons
Higgs bosons

Which Source?

- Type of particle
- Current, duty cycle, emittance
- Expertise available
- Money available
- Space available
- Lifetime

Reliability – is critical!

- Operational sources should deliver >98% availability
- Lifetime compatible with operating schedule
- Ideally quick and easy to change
- Short start-up/set-up time

cryogenic systems

timing systems

machine interlocks

communication systems

Reliability also depends on:

Everything Else!

low voltage power supplies

cooling water

human error

hydrogen

vacuum systems

temperature controllers

high voltage power supplies

compressed air supplies

control systems

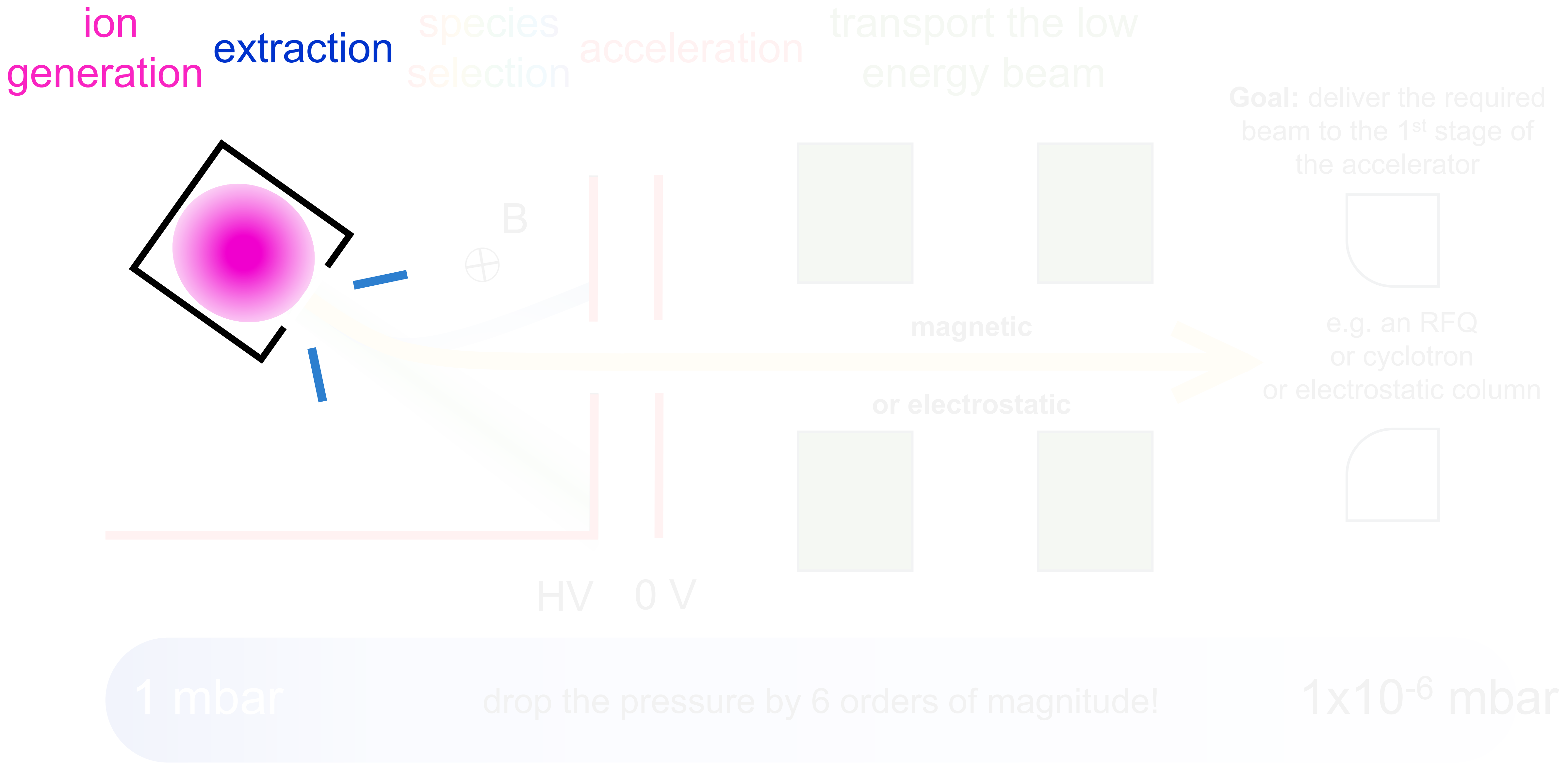
mains power

laser systems

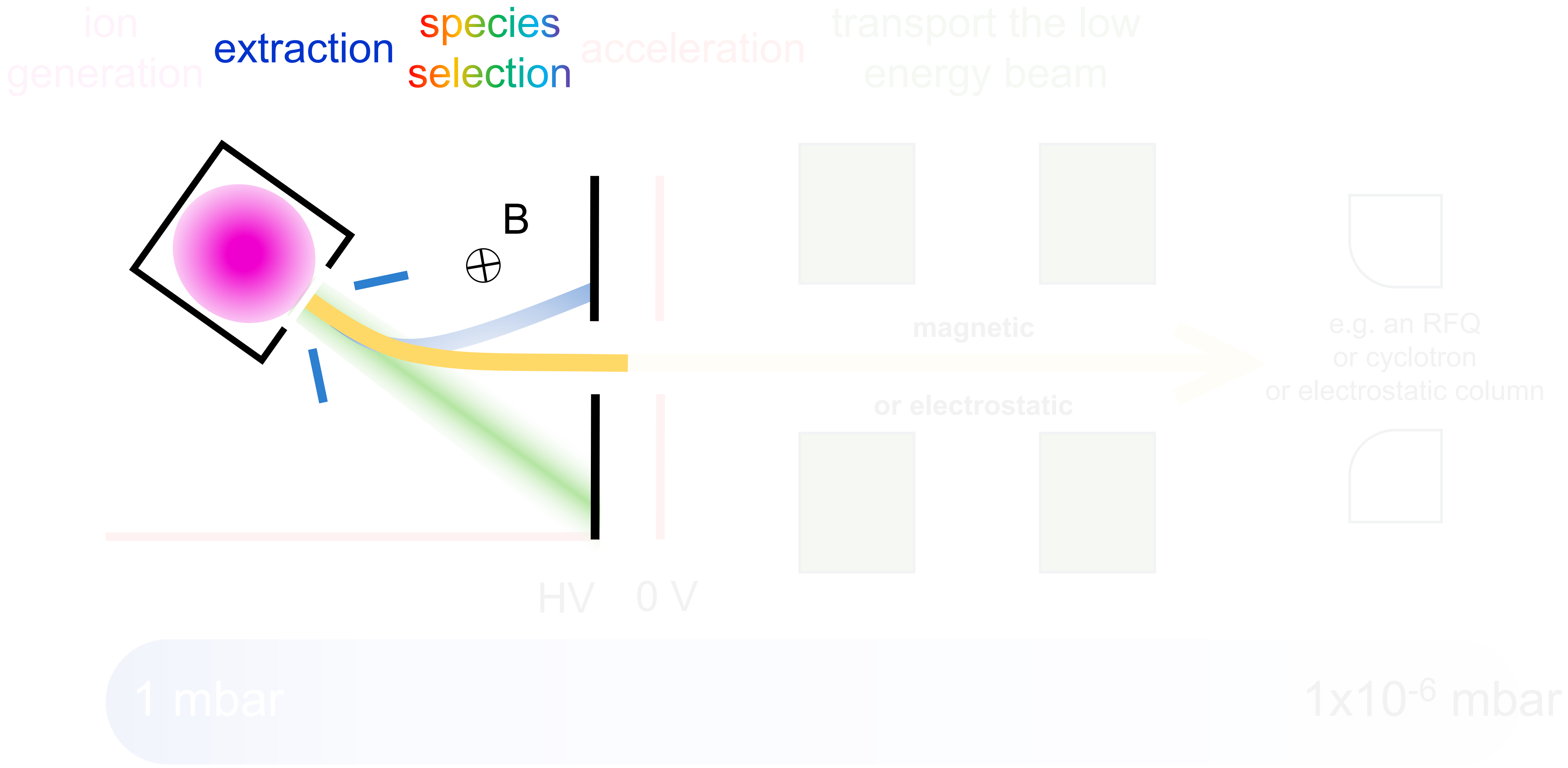
material purity

personnel interlocks

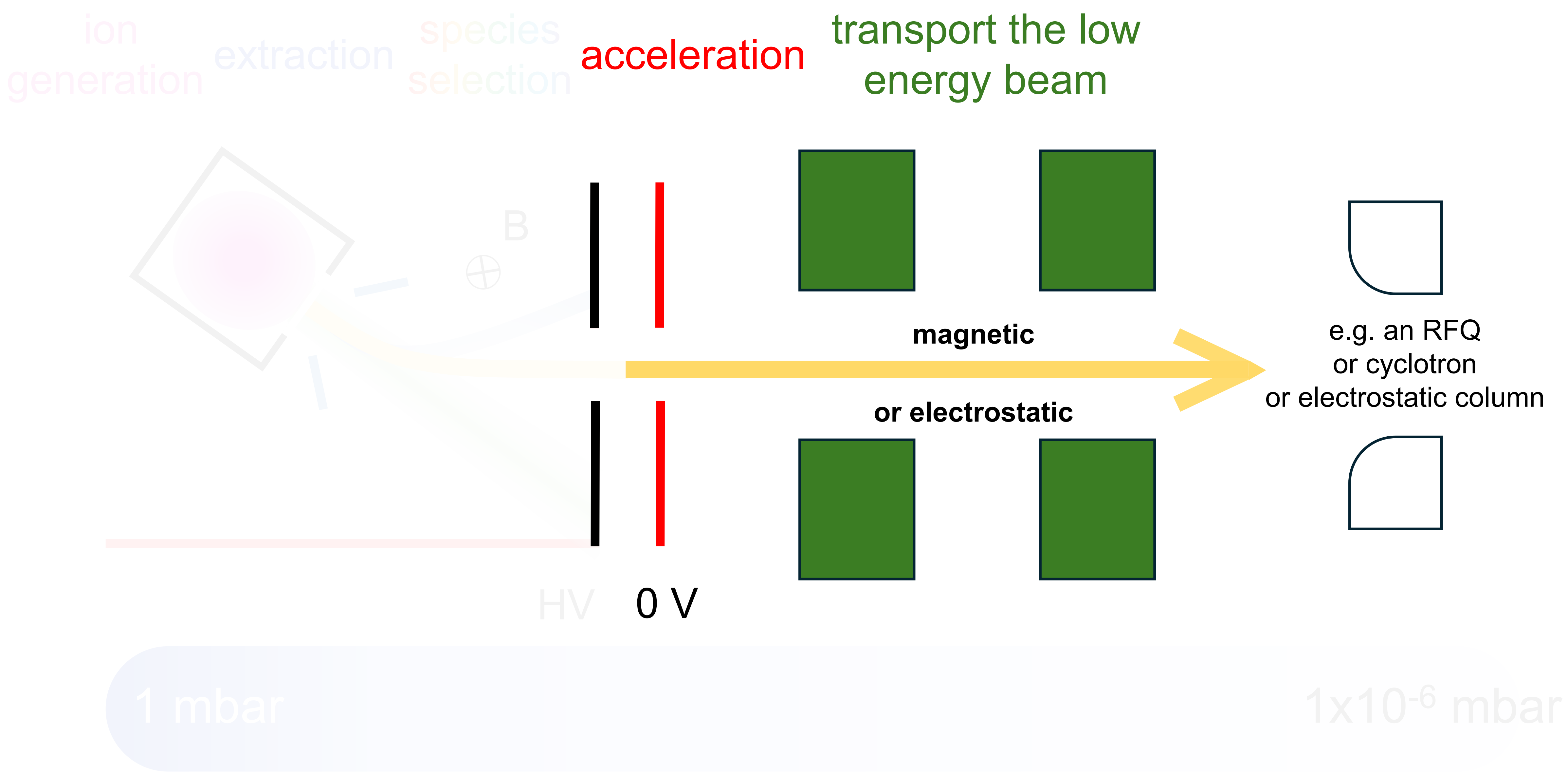
Key functions of the ion source and LEBT:



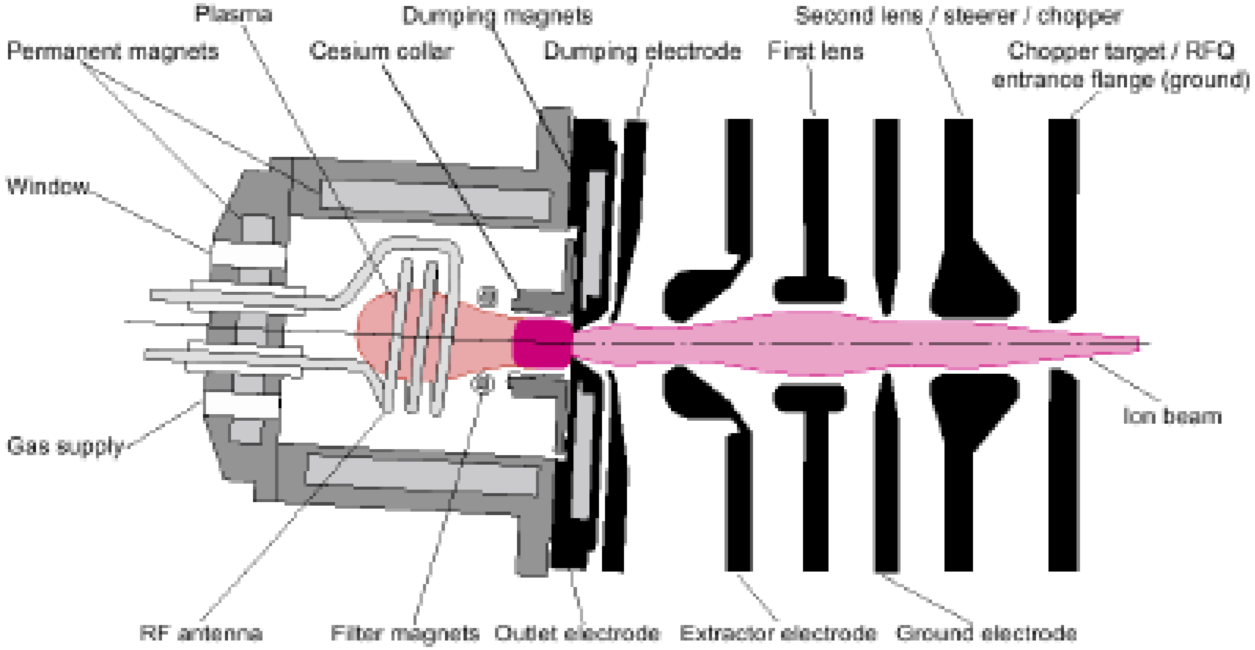
Key functions of the ion source and LEBT:



Key functions of the ion source and LEBT:

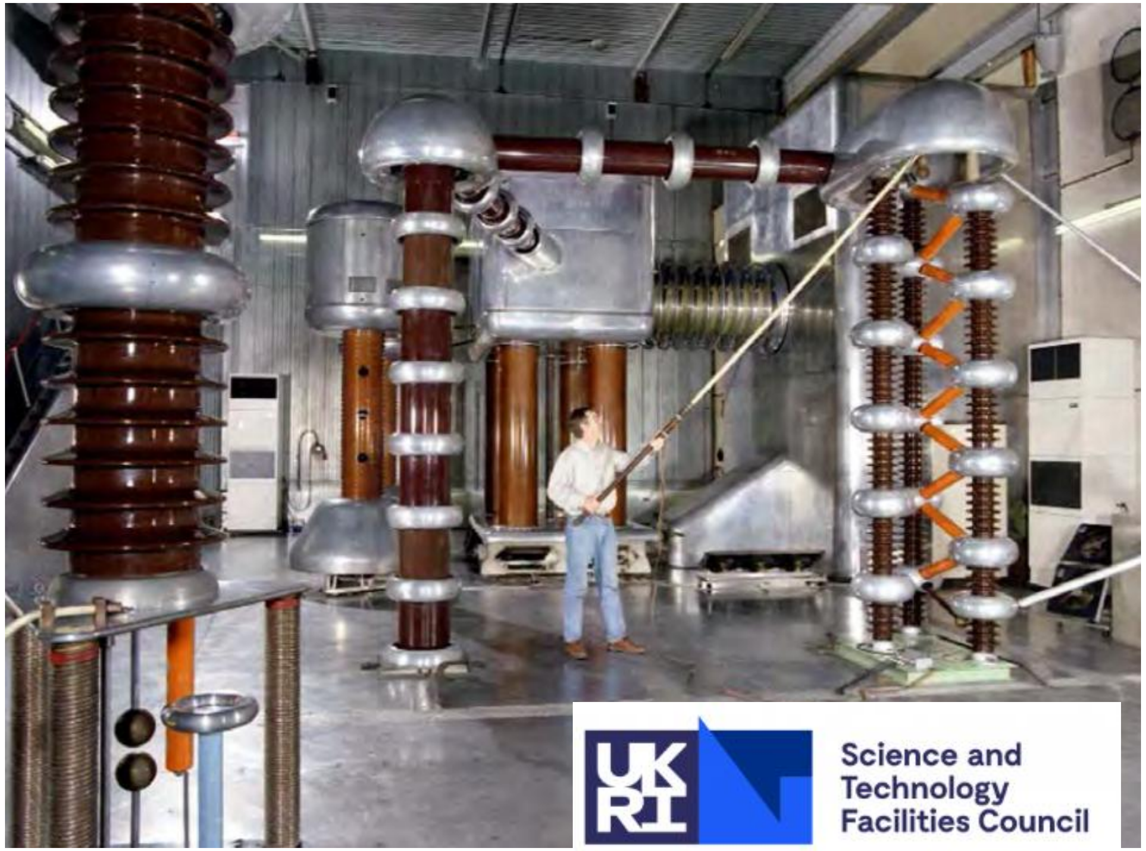


It is entirely possible to transport entirely electrostatically



Oak Ridge National Laboratory

you can go all the way to ≈1 MV:



UKRI Science and Technology Facilities Council

ISIS Neutron and Muon Source

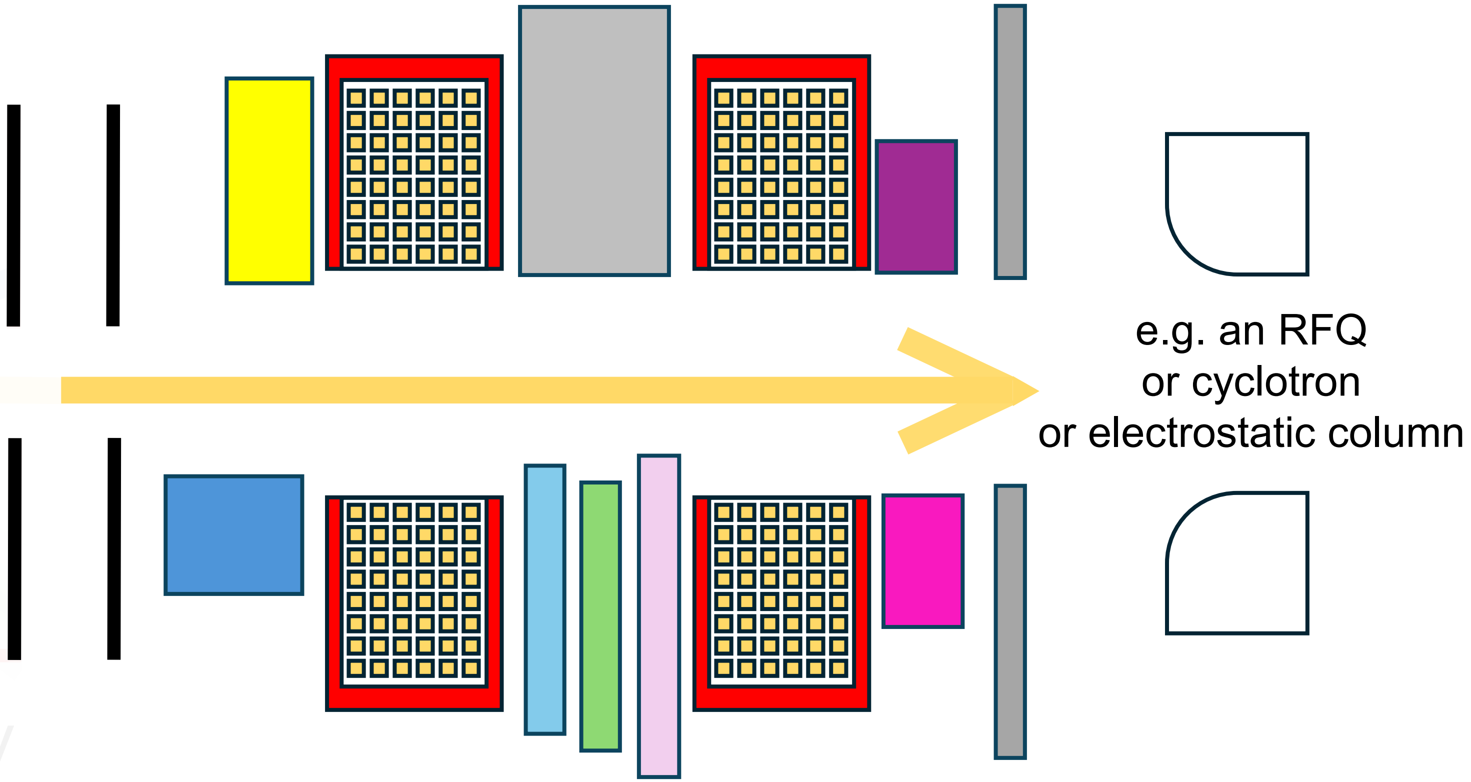
…but there is very little flexibility, with lots of sparks, x-rays and unwanted particles

Another advantage of a solenoid magnetic LEBT:

Space!

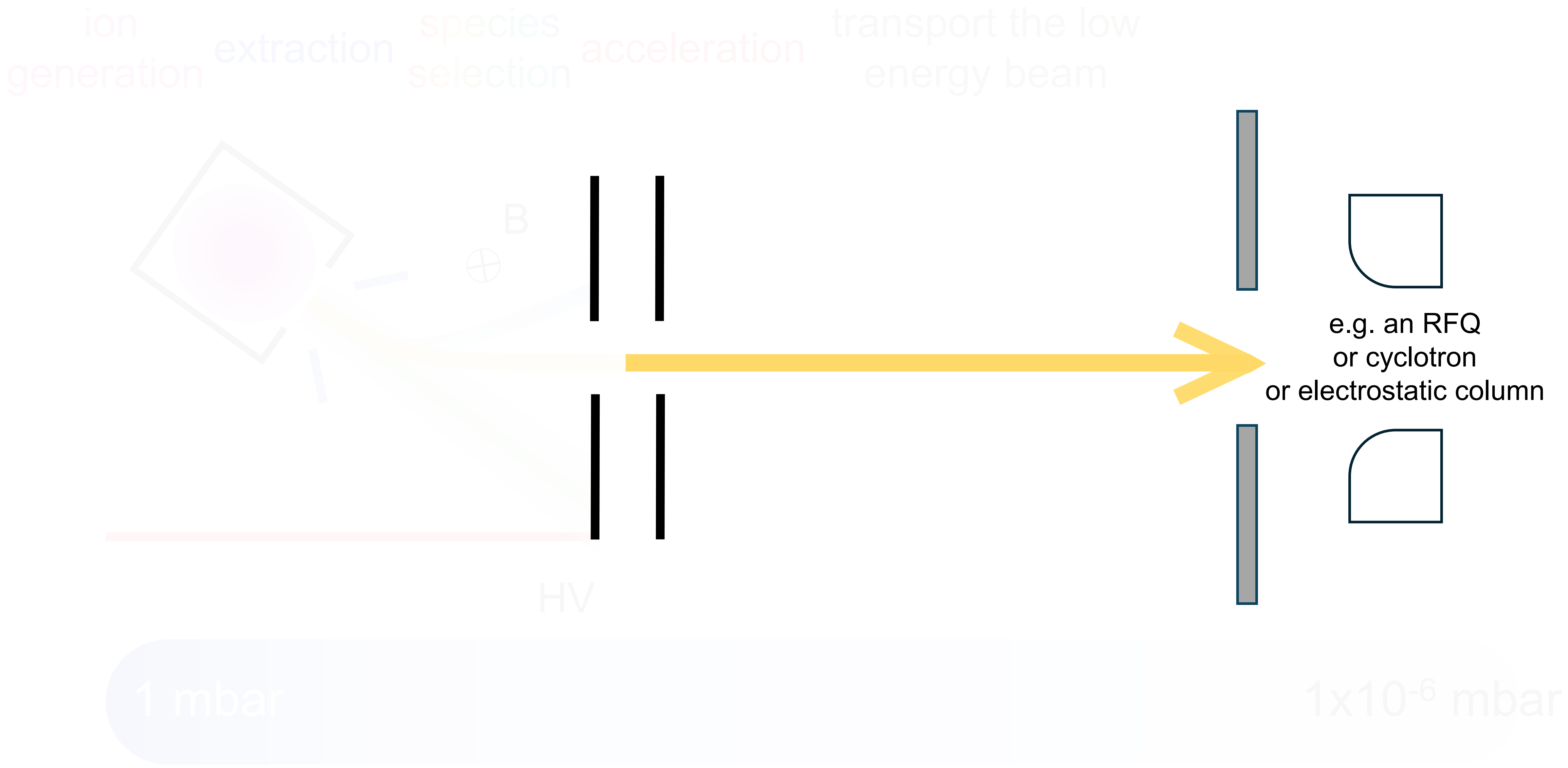
for:

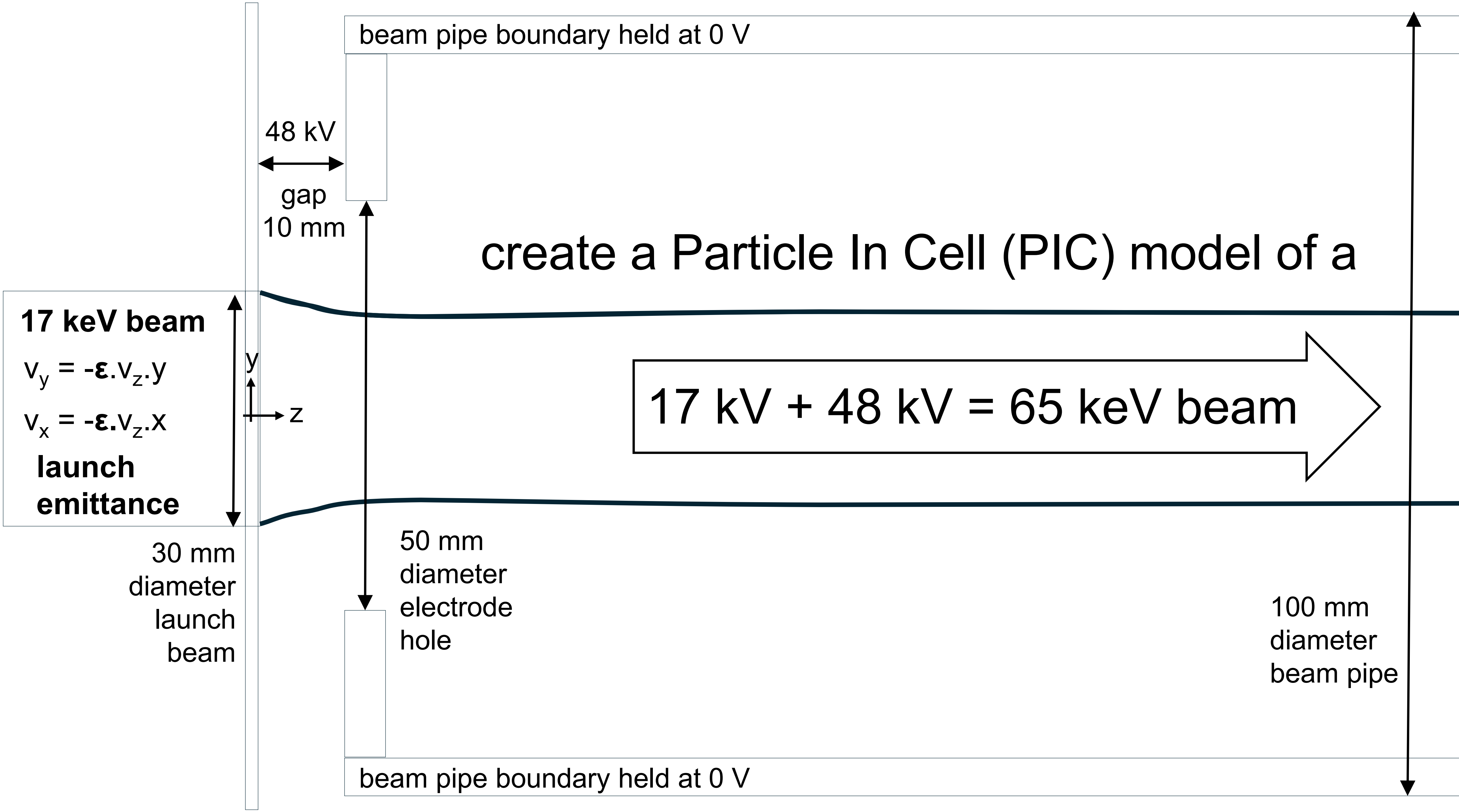
- pumping
- line valve
- beam dilution (1% 5% 10%)
- pencil beam collimation
- interlock compliant beam-stop
- beam profile measurement
- beam emittance measurement
- beam current measurement
- diagnostics
- …

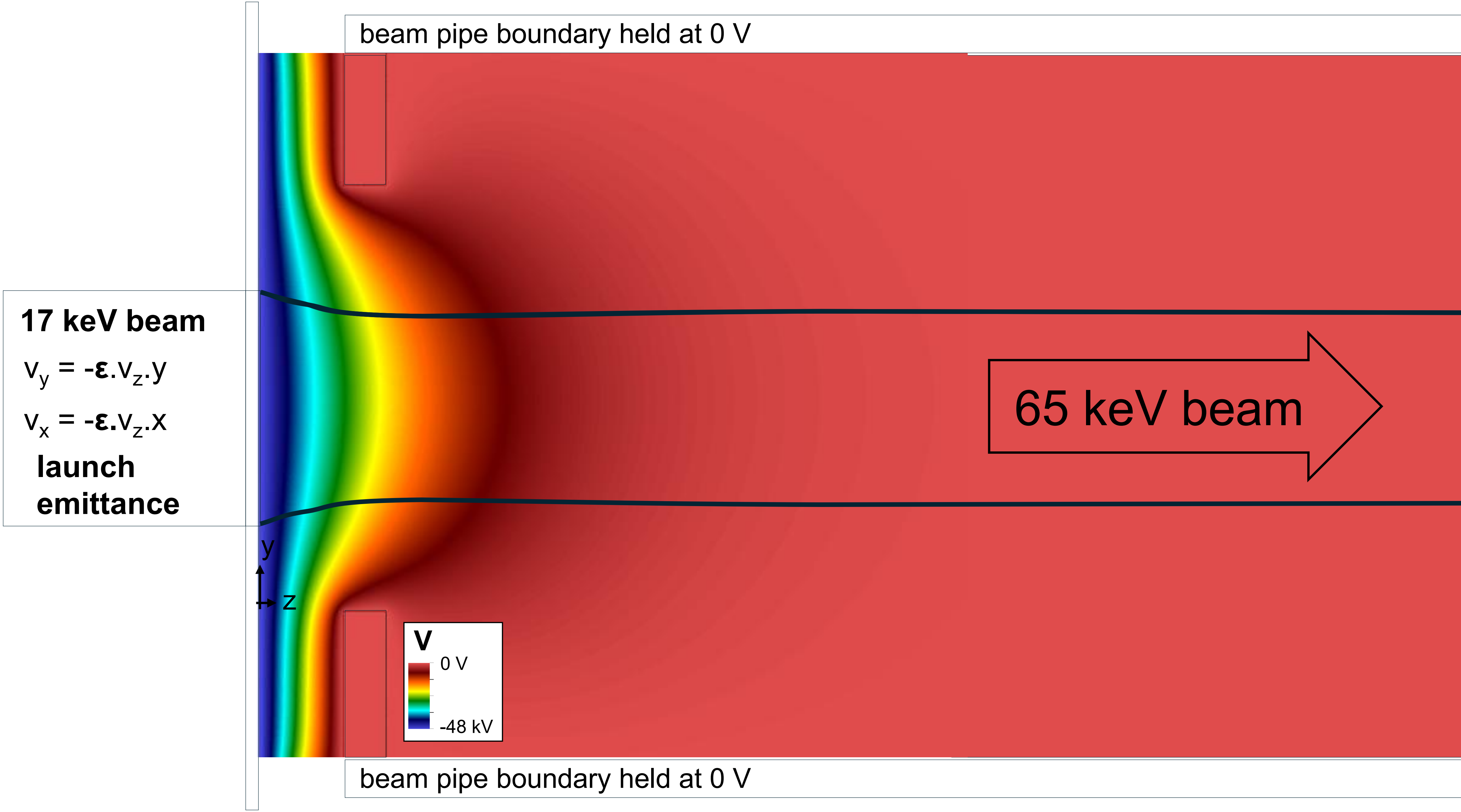


How much space do you need? Around 2 m?

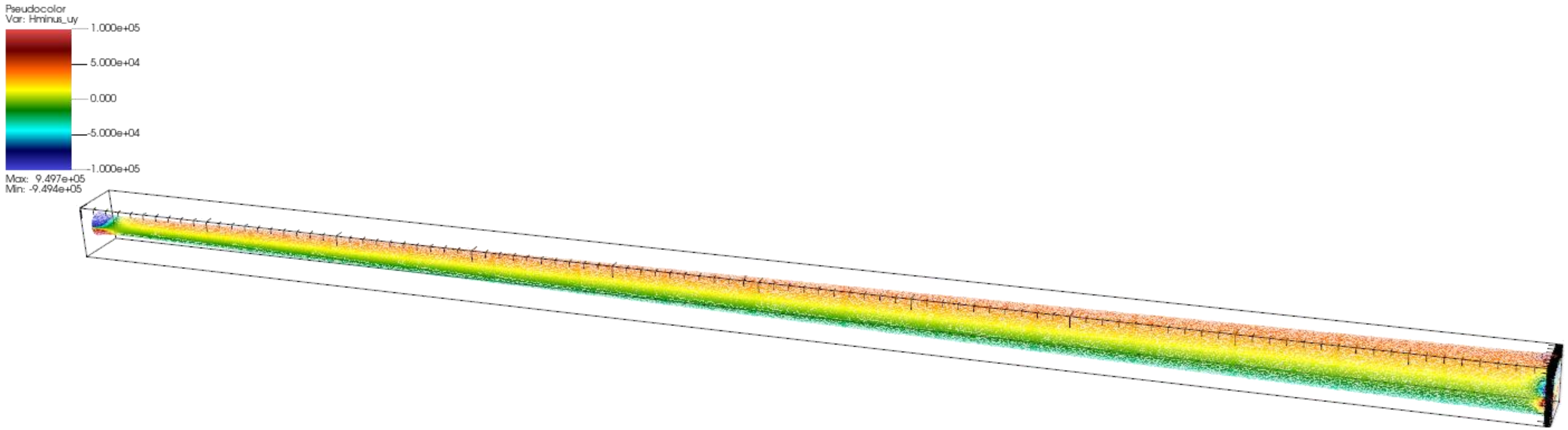
Why can’t you just drift a beam?



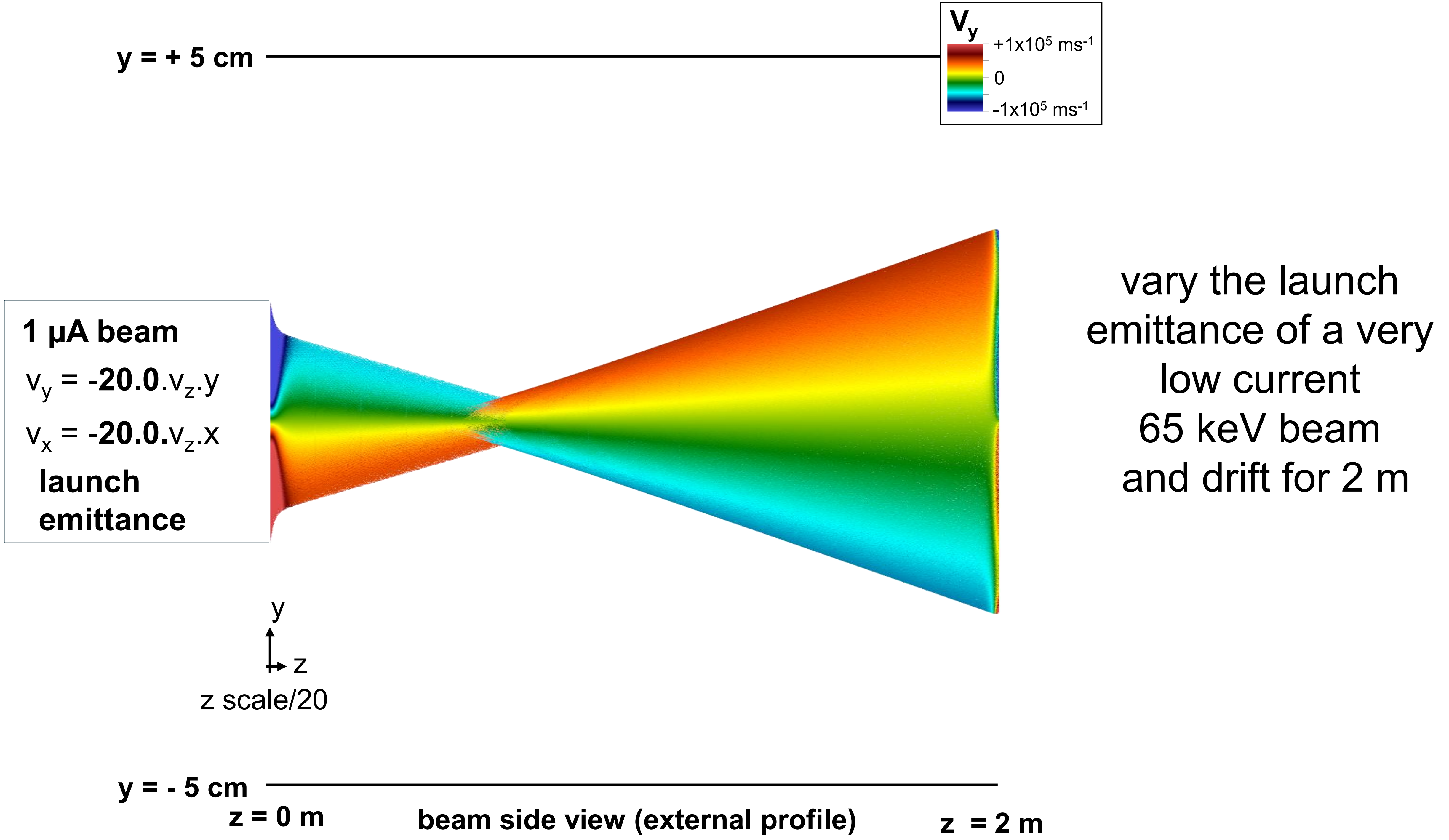

beam pipe boundary held at 0 V
48 kV
gap
10 mm
create a Particle In Cell (PIC) model of a
17 keV beam
$v_y = -\varepsilon . v_z . y$
$v_x = -\varepsilon . v_z . x$
launch
emittance
y
z
17 kV + 48 kV = 65 keV beam
30 mm
diameter
launch
beam
50 mm
diameter
electrode
hole
100 mm
diameter
beam pipe
beam pipe boundary held at 0 V



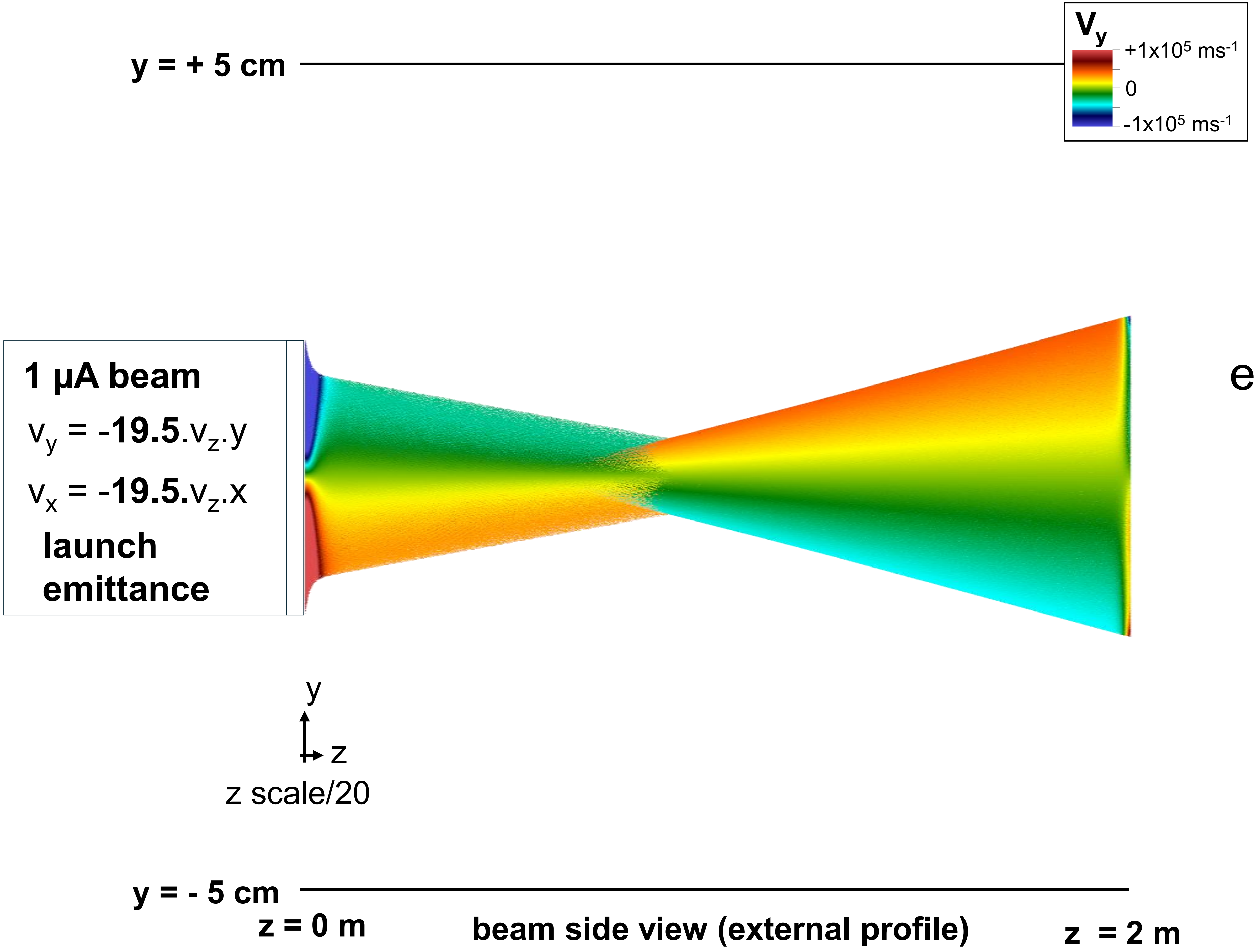
beam pipe boundary held at 0 V
17 keV beam
$v_y = -\varepsilon . v_z . y$
$v_x = -\varepsilon . v_z . x$
launch emittance
y
z
V
0 V
-48 kV
65 keV beam
beam pipe boundary held at 0 V



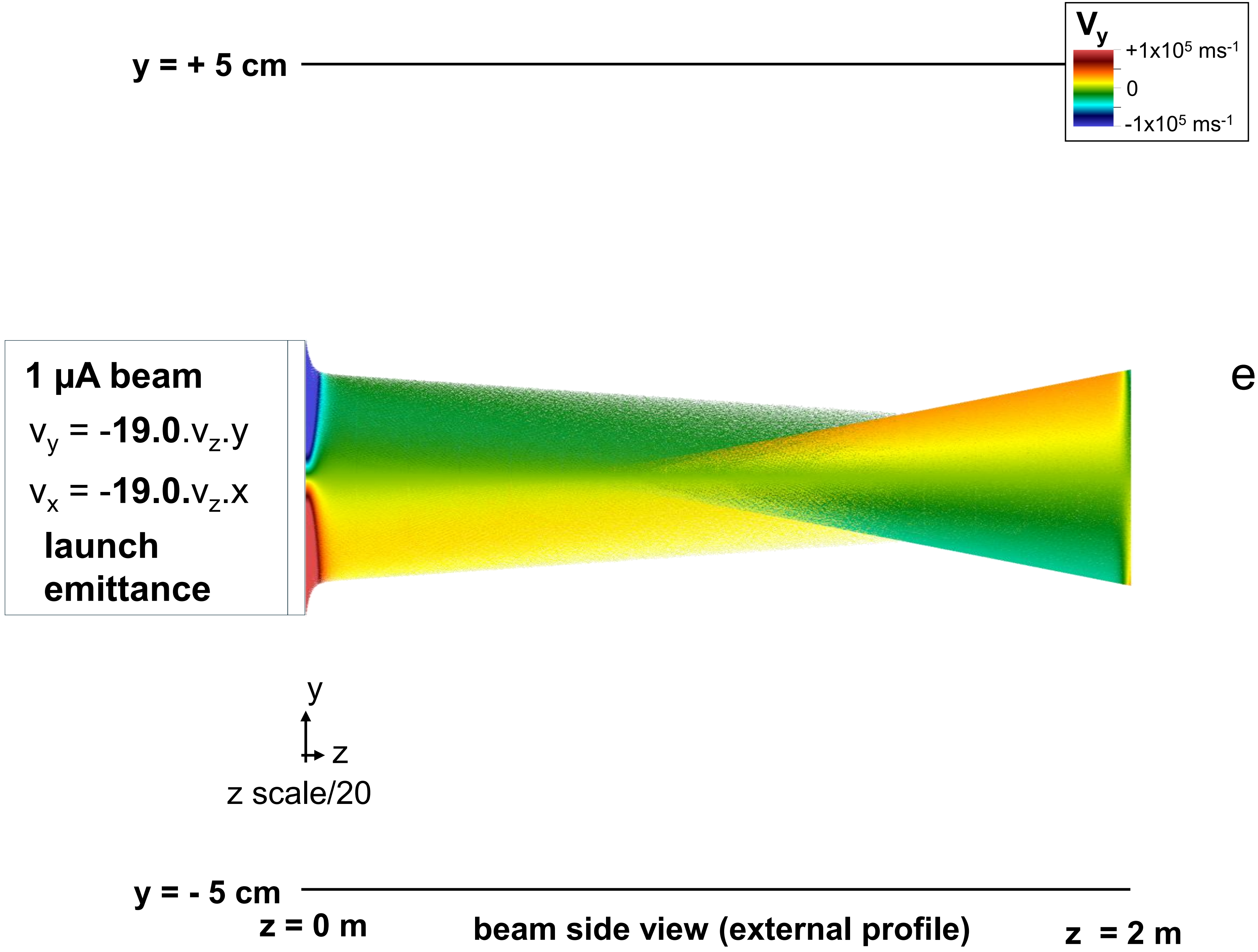
a 2 m beam is too long and thin to display, so scale z axis/20



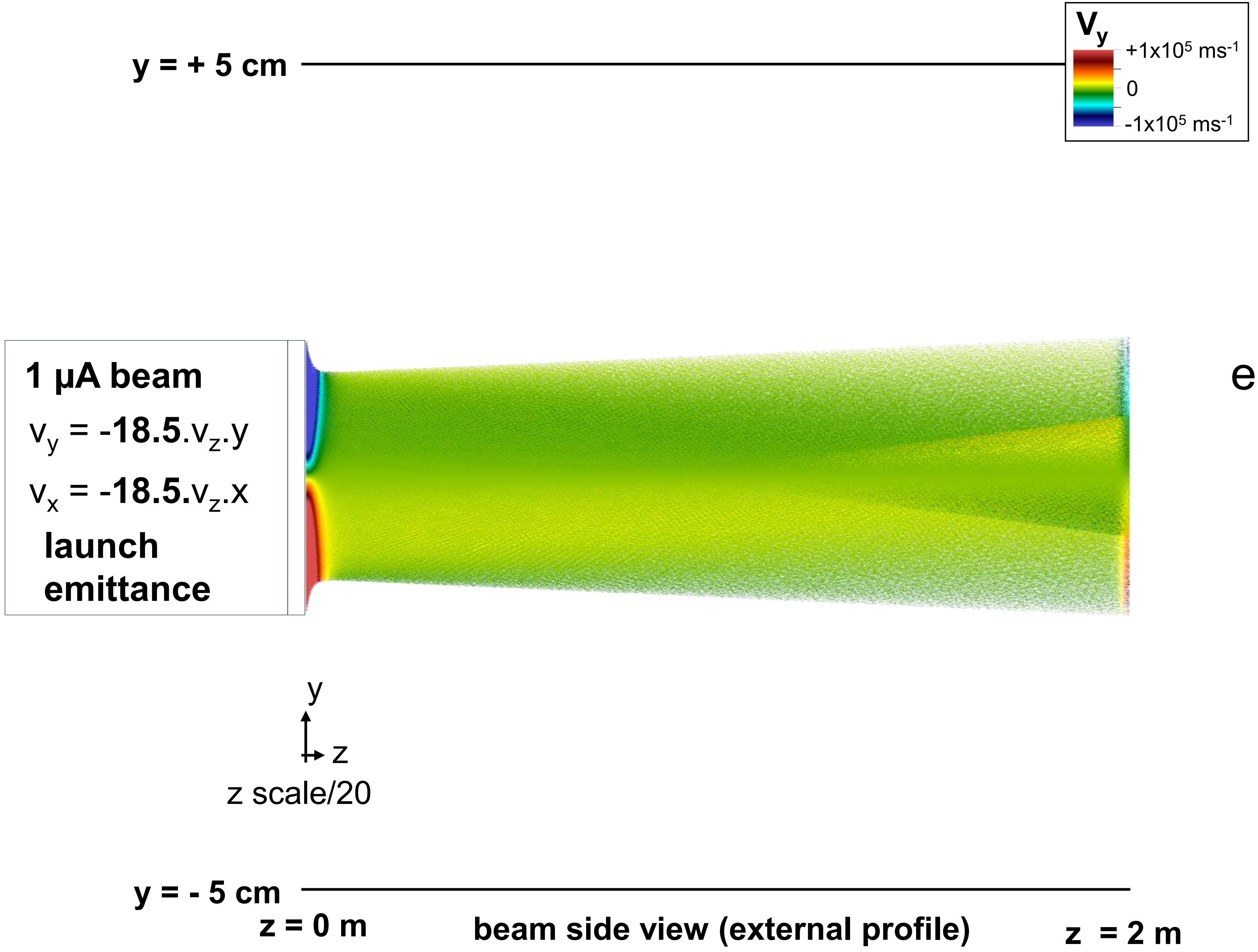
y = + 5 cm
Vy
+1x10^5 ms^-1
0
-1x10^5 ms^-1
1 μA beam
v_y = -20.0.v_z.y
v_x = -20.0.v_z.x
launch emittance
vary the launch emittance of a very low current 65 keV beam and drift for 2 m
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m



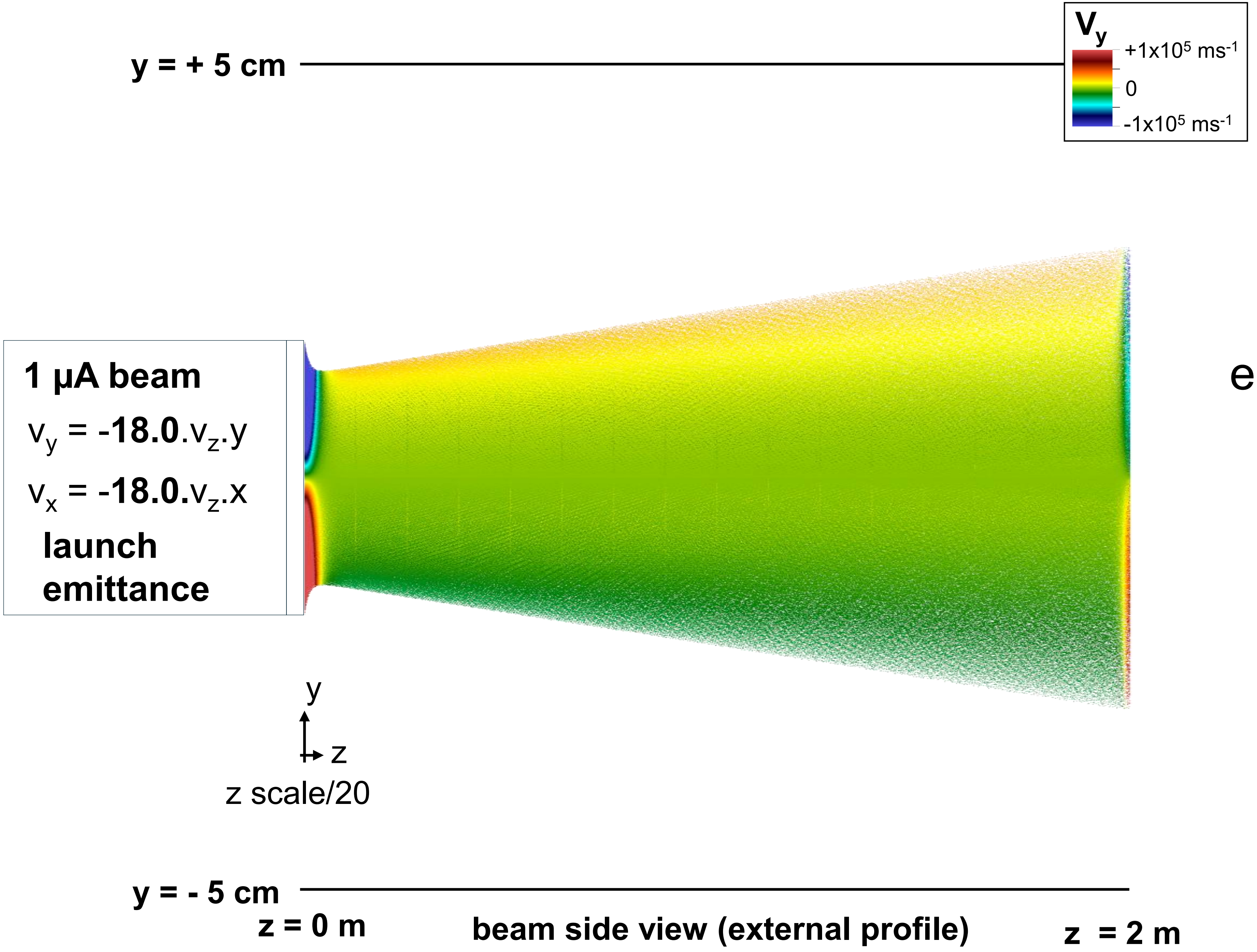
vary the launch emittance of a very low current 65 keV beam and drift for 2 m



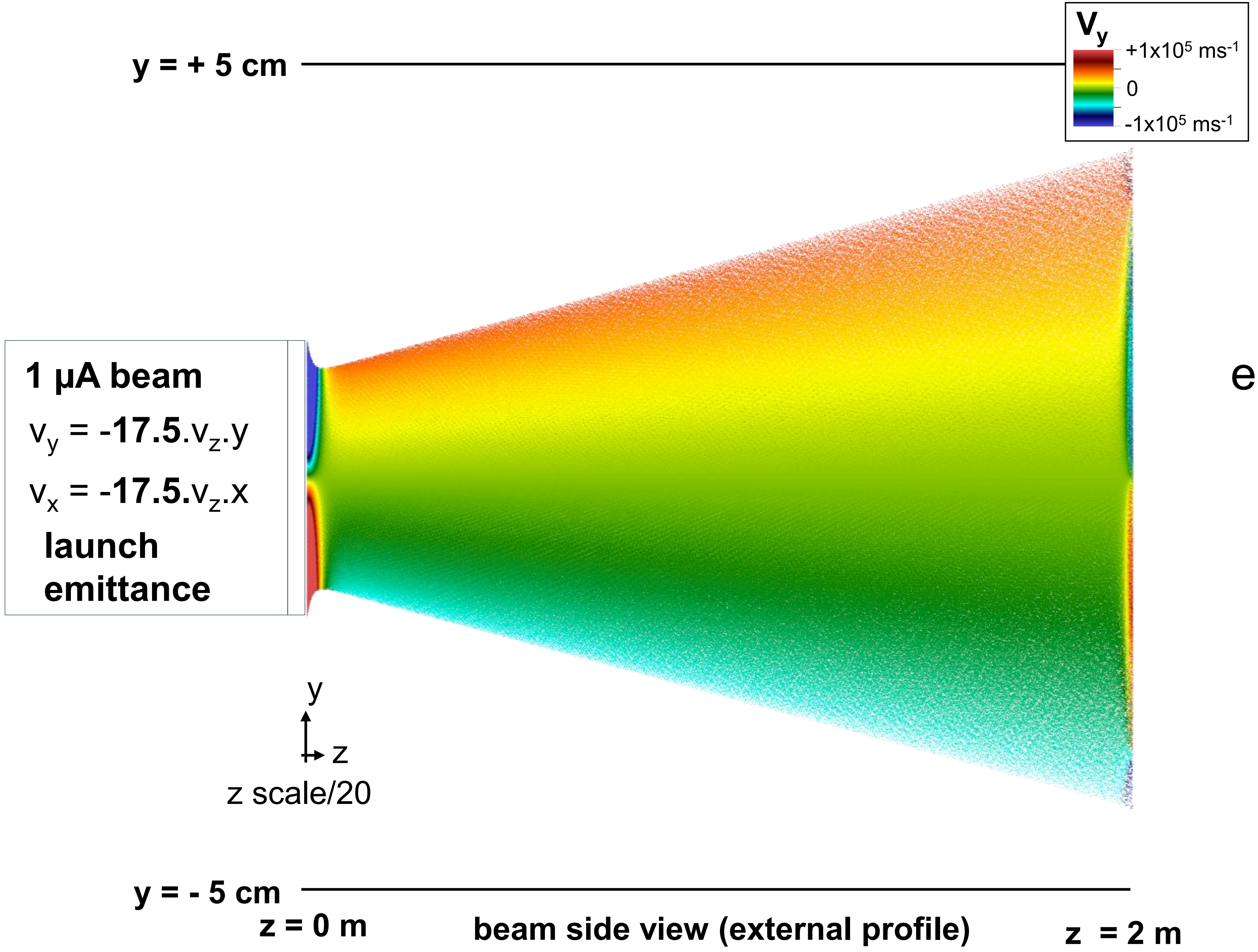
vary the launch emittance of a very low current 65 keV beam and drift for 2 m



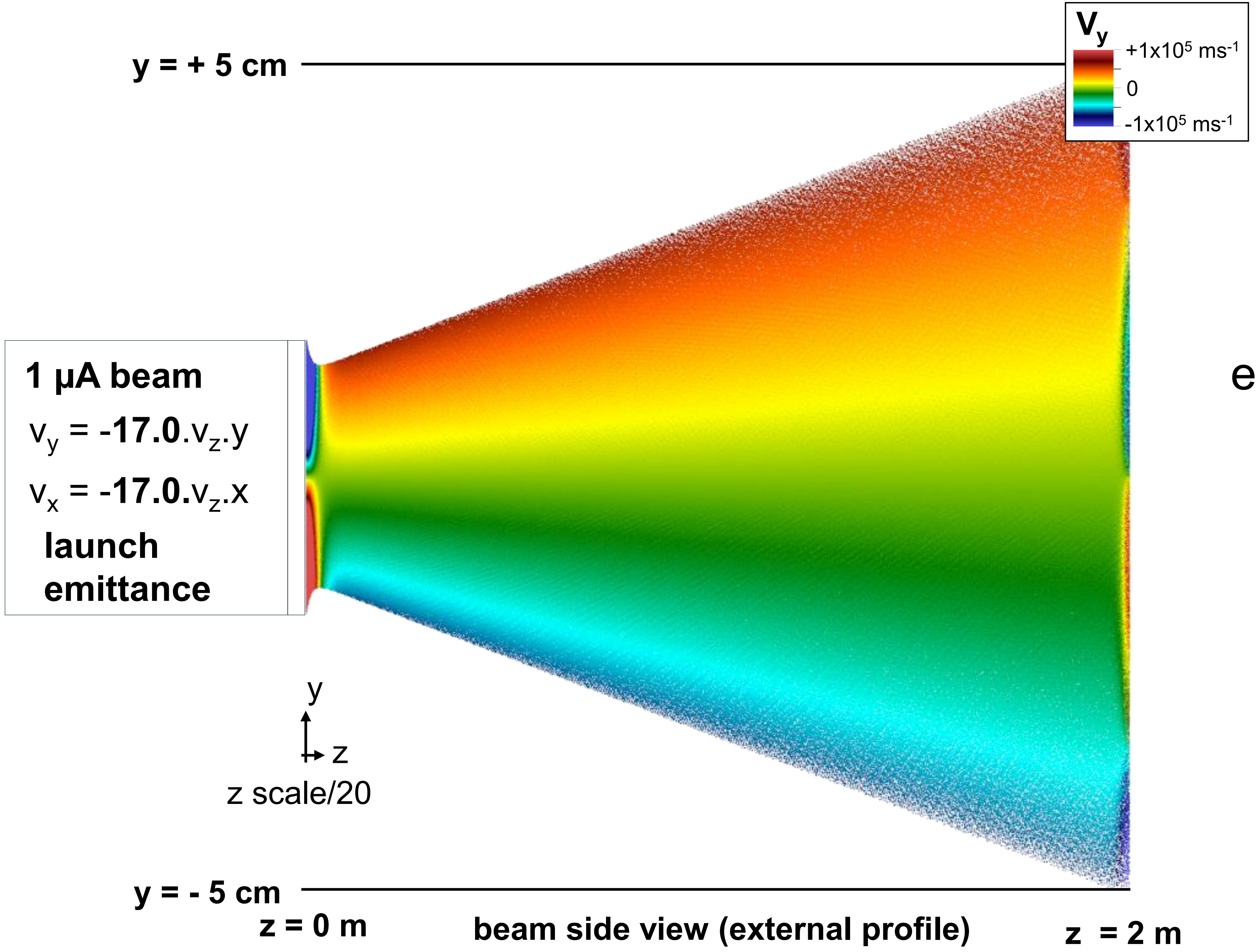
vary the launch emittance of a very low current 65 keV beam and drift for 2 m



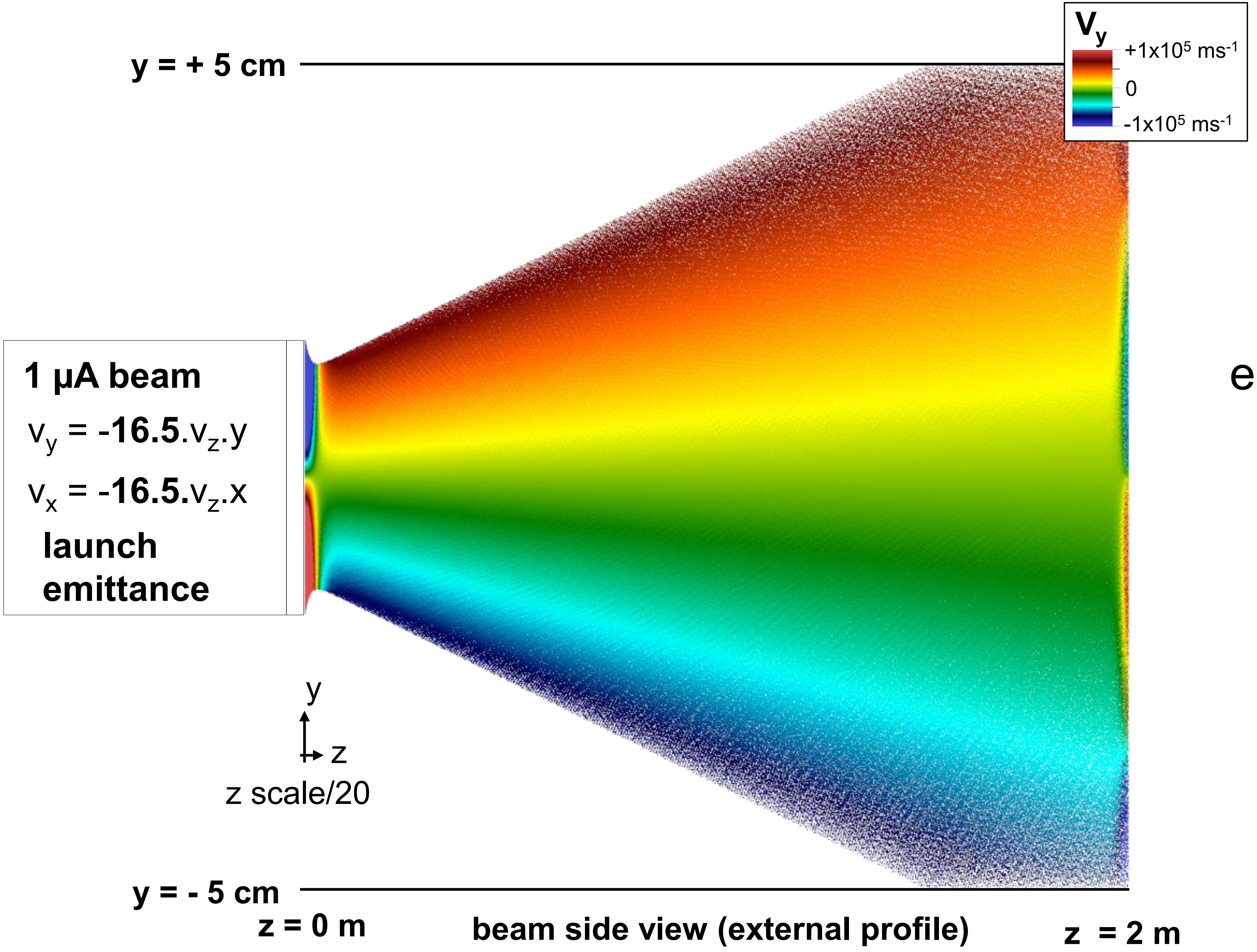
vary the launch emittance of a very low current 65 keV beam and drift for 2 m



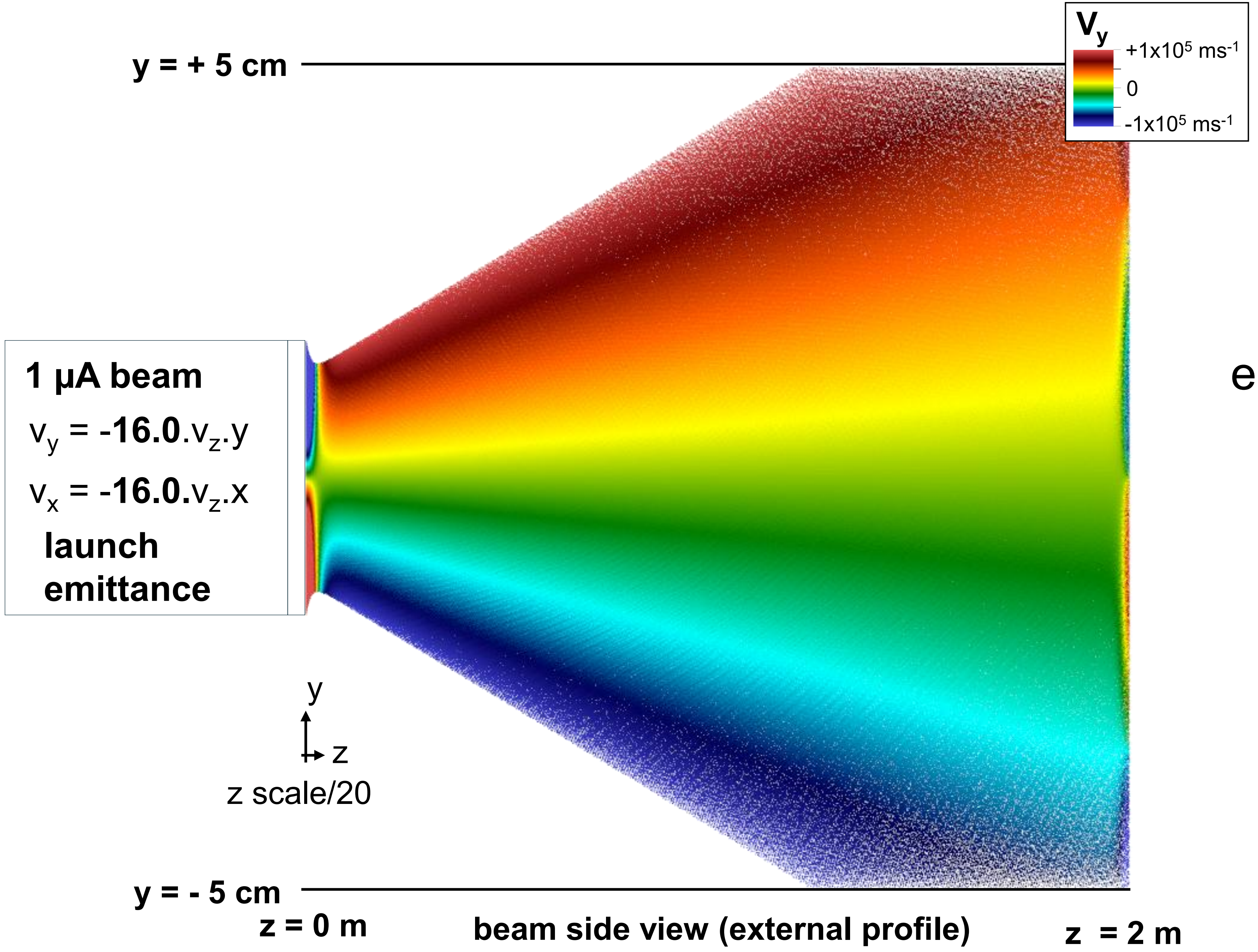
vary the launch emittance of a very low current 65 keV beam and drift for 2 m



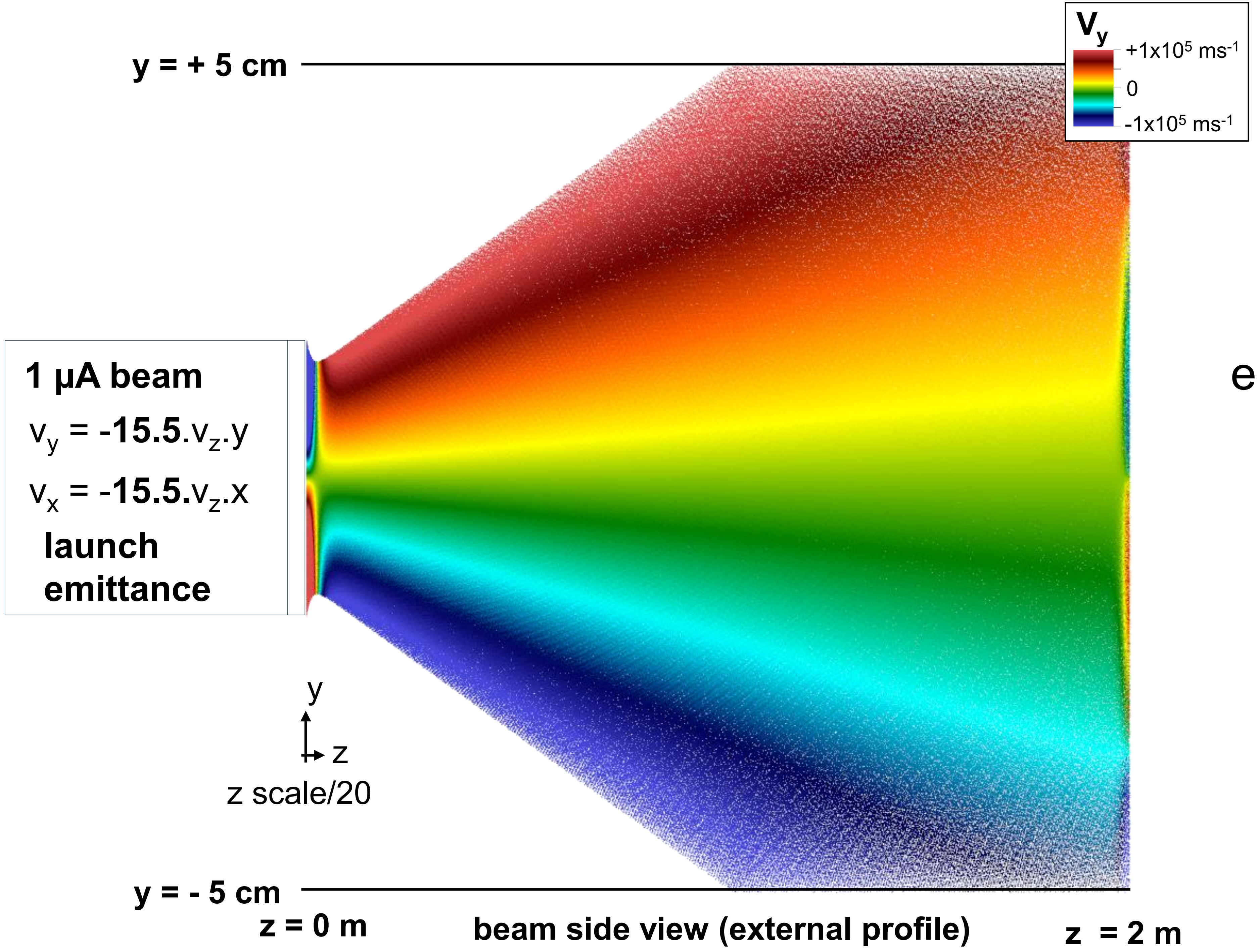
vary the launch emittance of a very low current 65 keV beam and drift for 2 m



vary the launch emittance of a very low current 65 keV beam and drift for 2 m



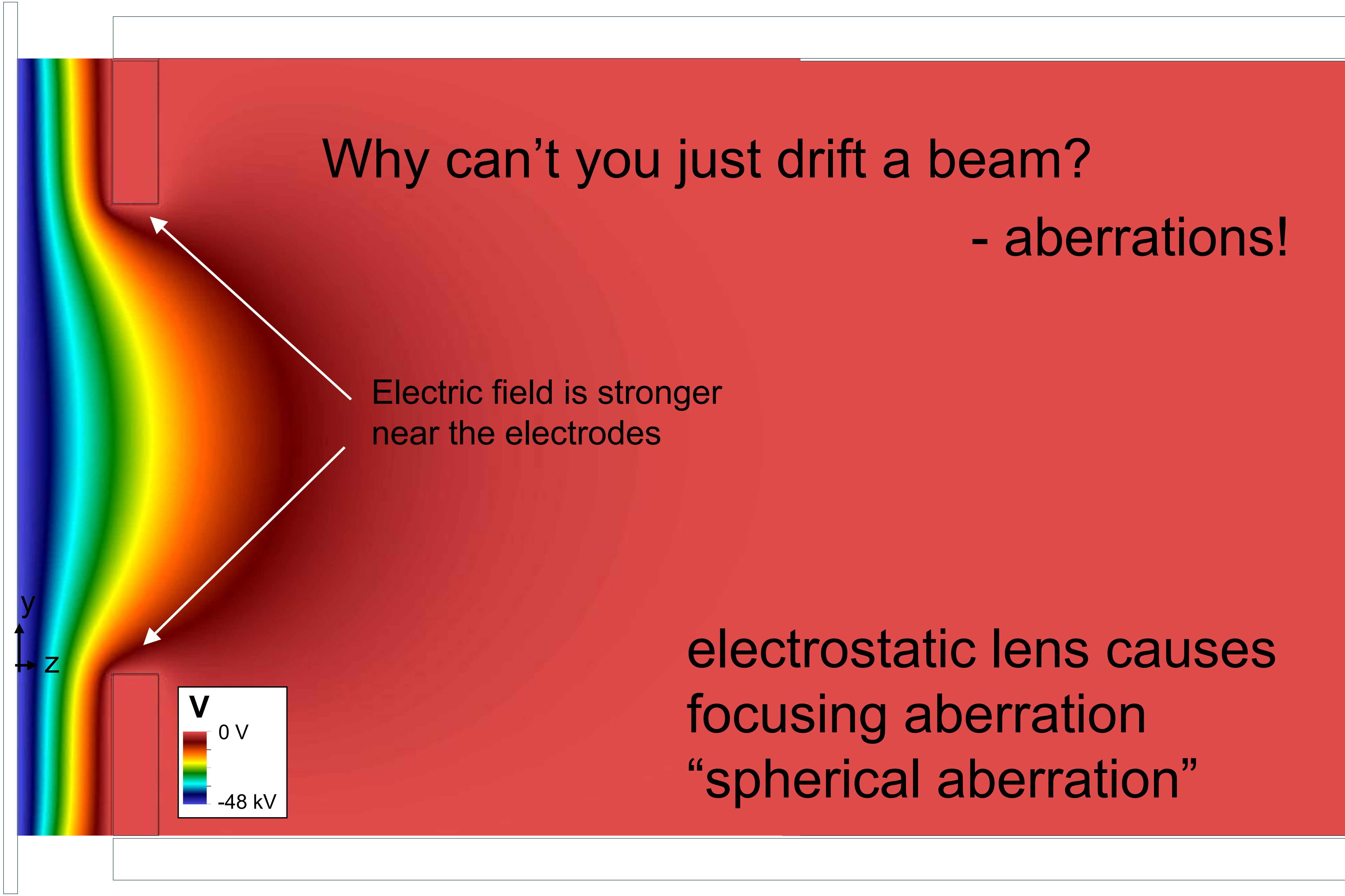
vary the launch emittance of a very low current 65 keV beam and drift for 2 m



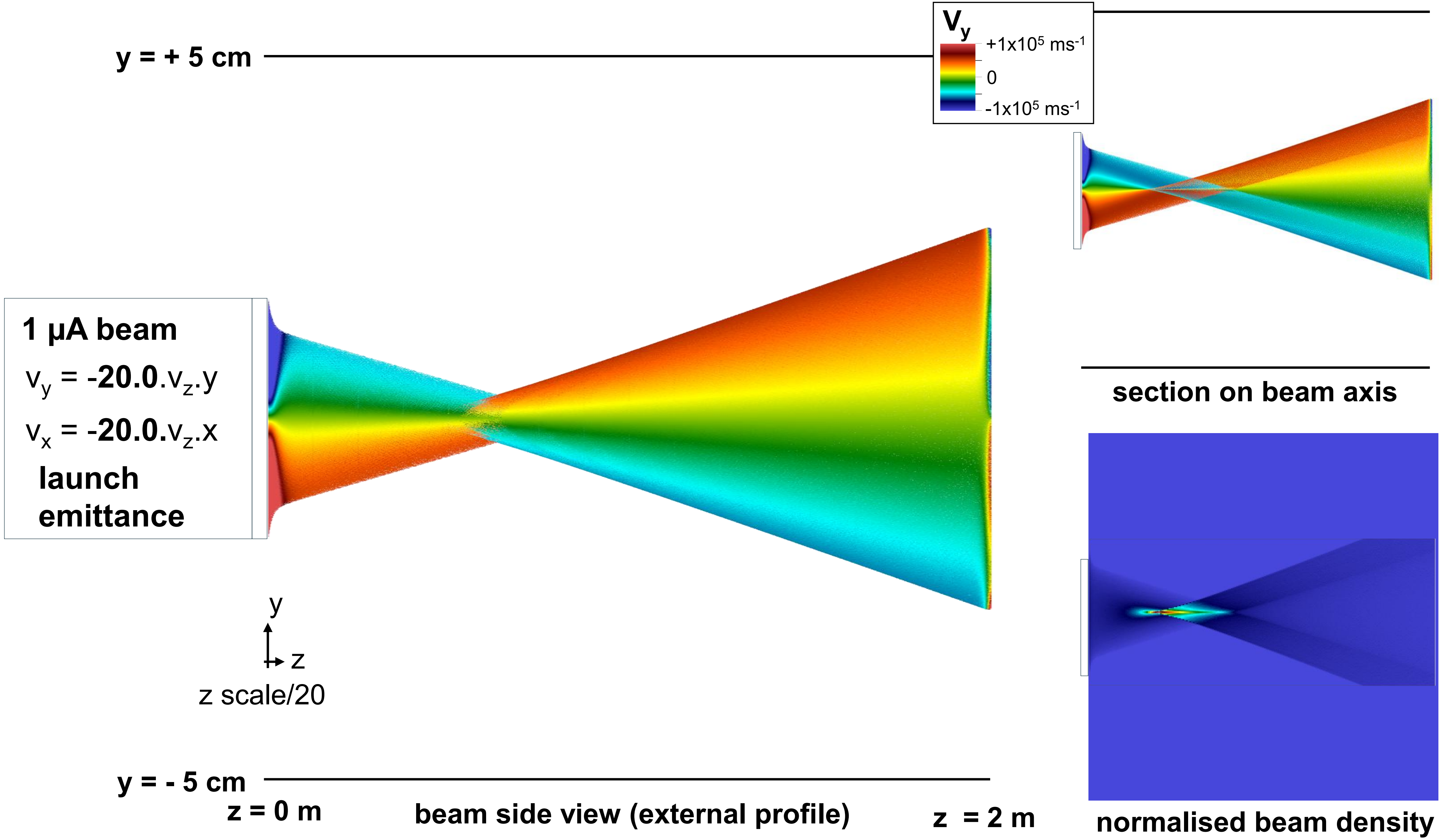
vary the launch emittance of a very low current 65 keV beam and drift for 2 m

Why can't you just drift a beam?

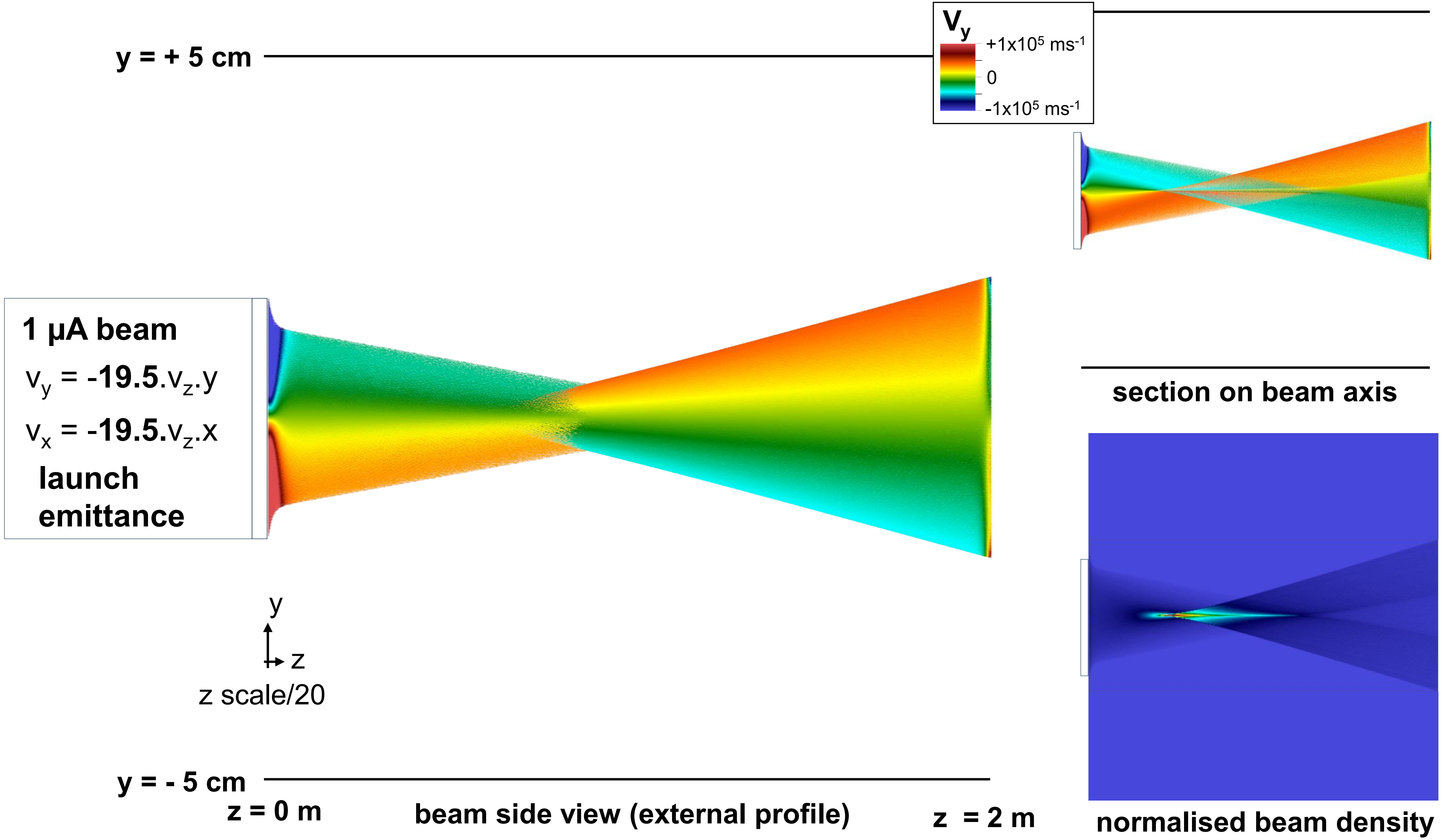
- aberrations!



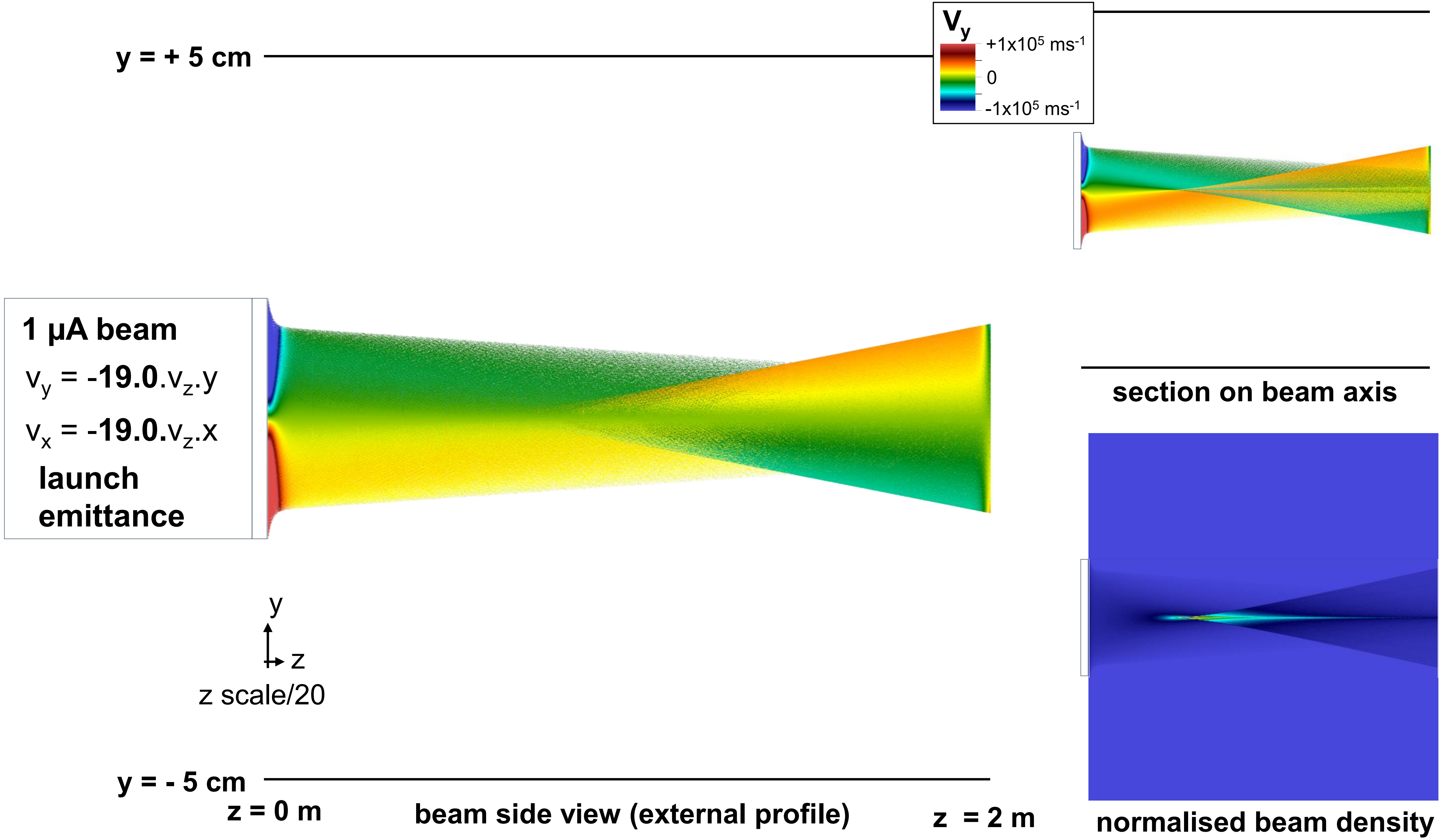
electrostatic lens causes focusing aberration "spherical aberration"



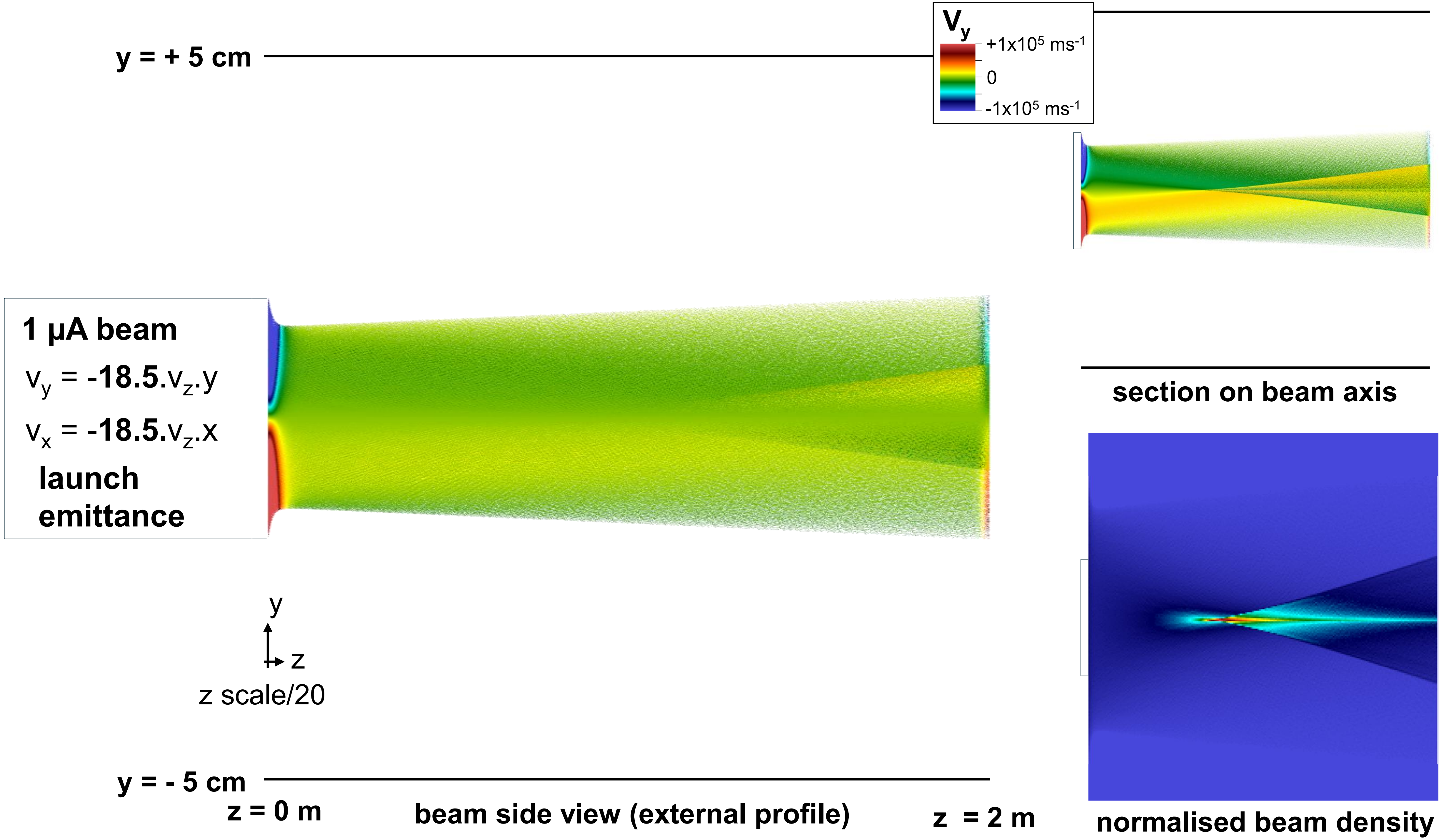
y = + 5 cm
V_y
+1x10^5 ms^-1
0
-1x10^5 ms^-1
1 μA beam
v_y = -20.0.v_z.y
v_x = -20.0.v_z.x
launch emittance
y
z
z scale/20
section on beam axis
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
normalised beam density



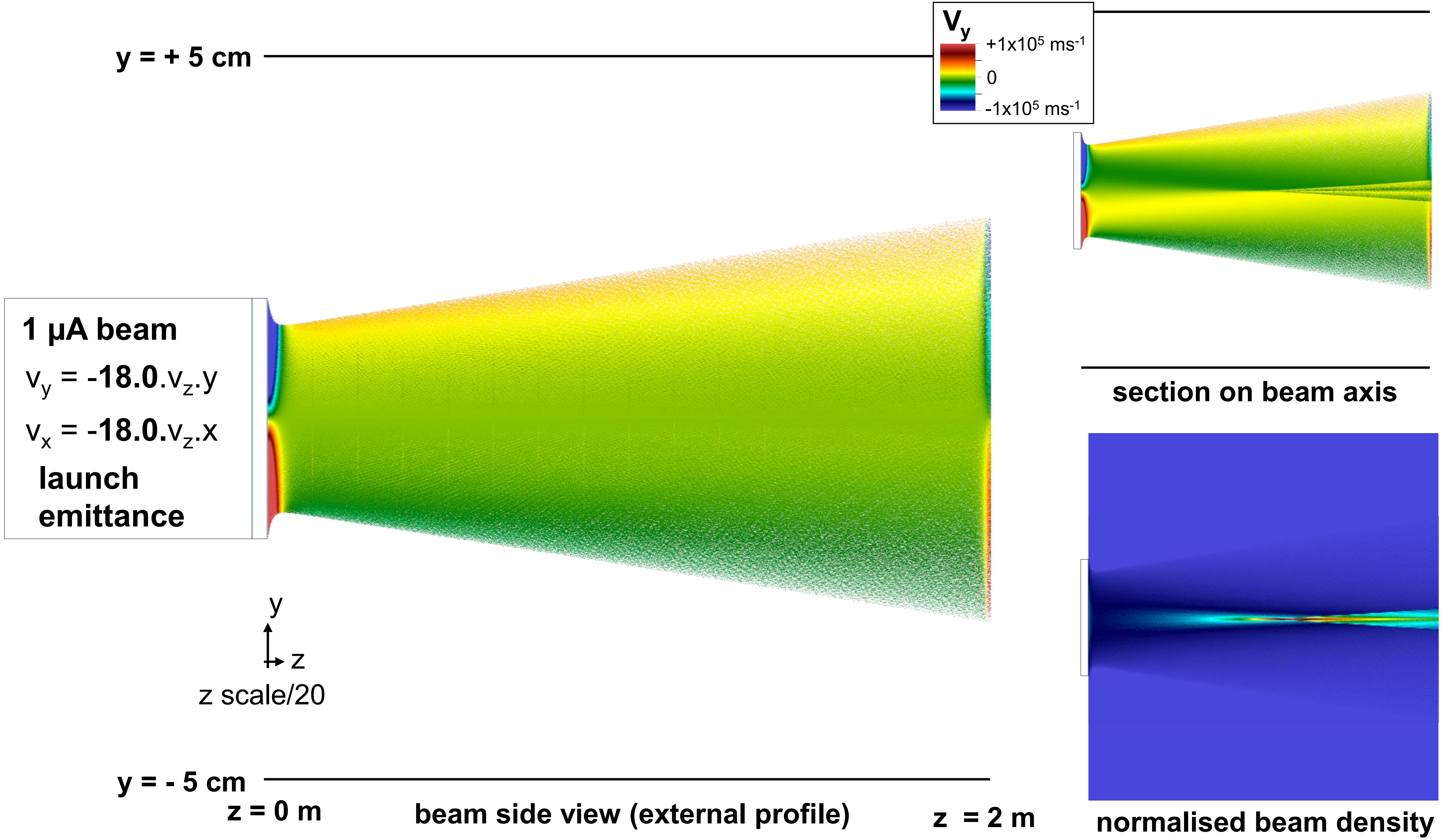
y = + 5 cm
Vy
+1x10^5 ms^-1
0
-1x10^5 ms^-1
1 μA beam
v_y = -19.5.v_z.y
v_x = -19.5.v_z.x
launch emittance
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
section on beam axis
normalised beam density

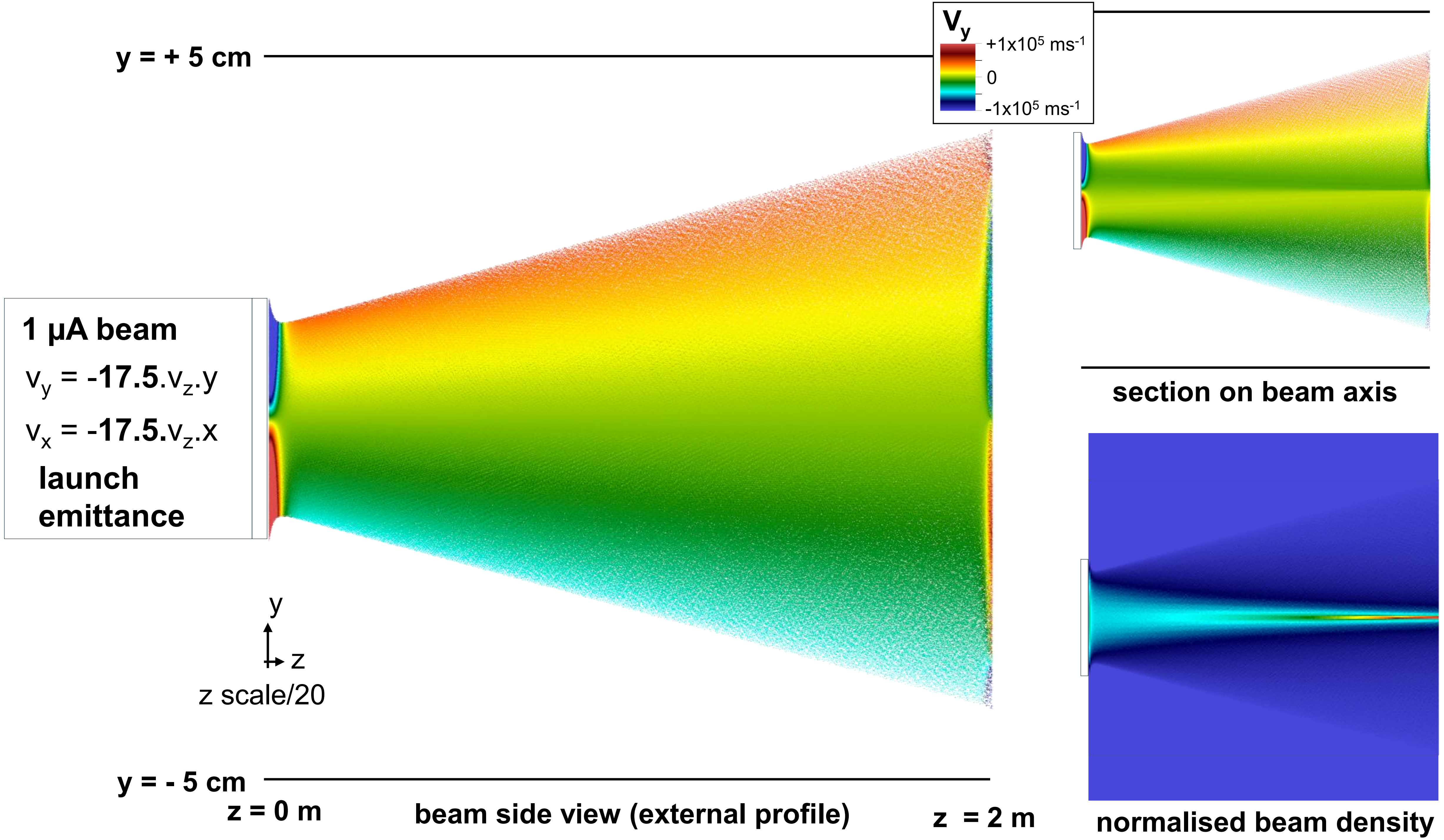


y = + 5 cm
Vy
+1x10^5 ms^-1
0
-1x10^5 ms^-1
1 μA beam
vy = -19.0.vz.y
vx = -19.0.vz.x
launch emittance
section on beam axis
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
normalised beam density

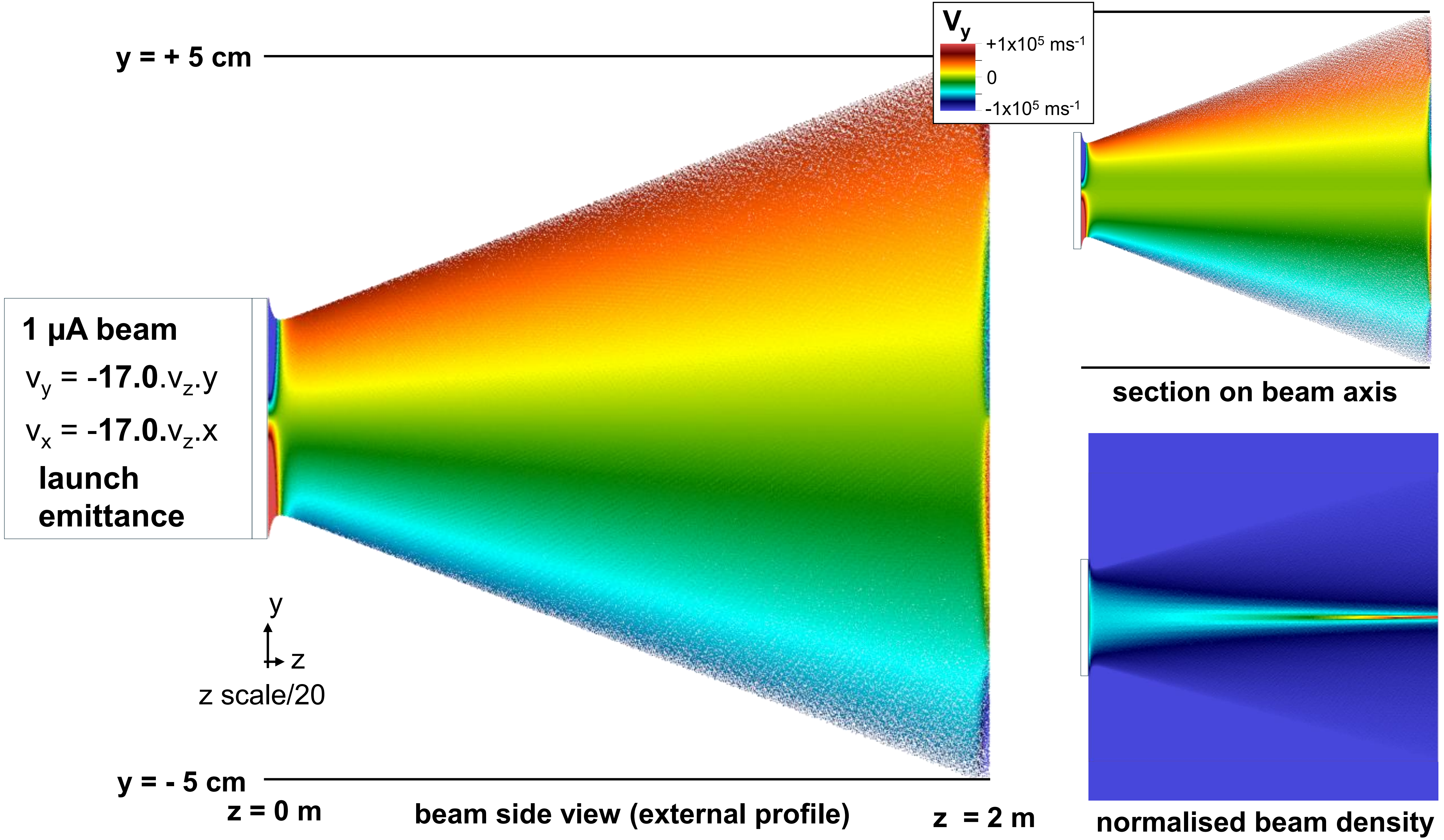


y = + 5 cm
Vy
+1x10^5 ms^-1
0
-1x10^5 ms^-1
1 μA beam
vy = -18.5.vz.y
vx = -18.5.vz.x
launch emittance
section on beam axis
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
normalised beam density

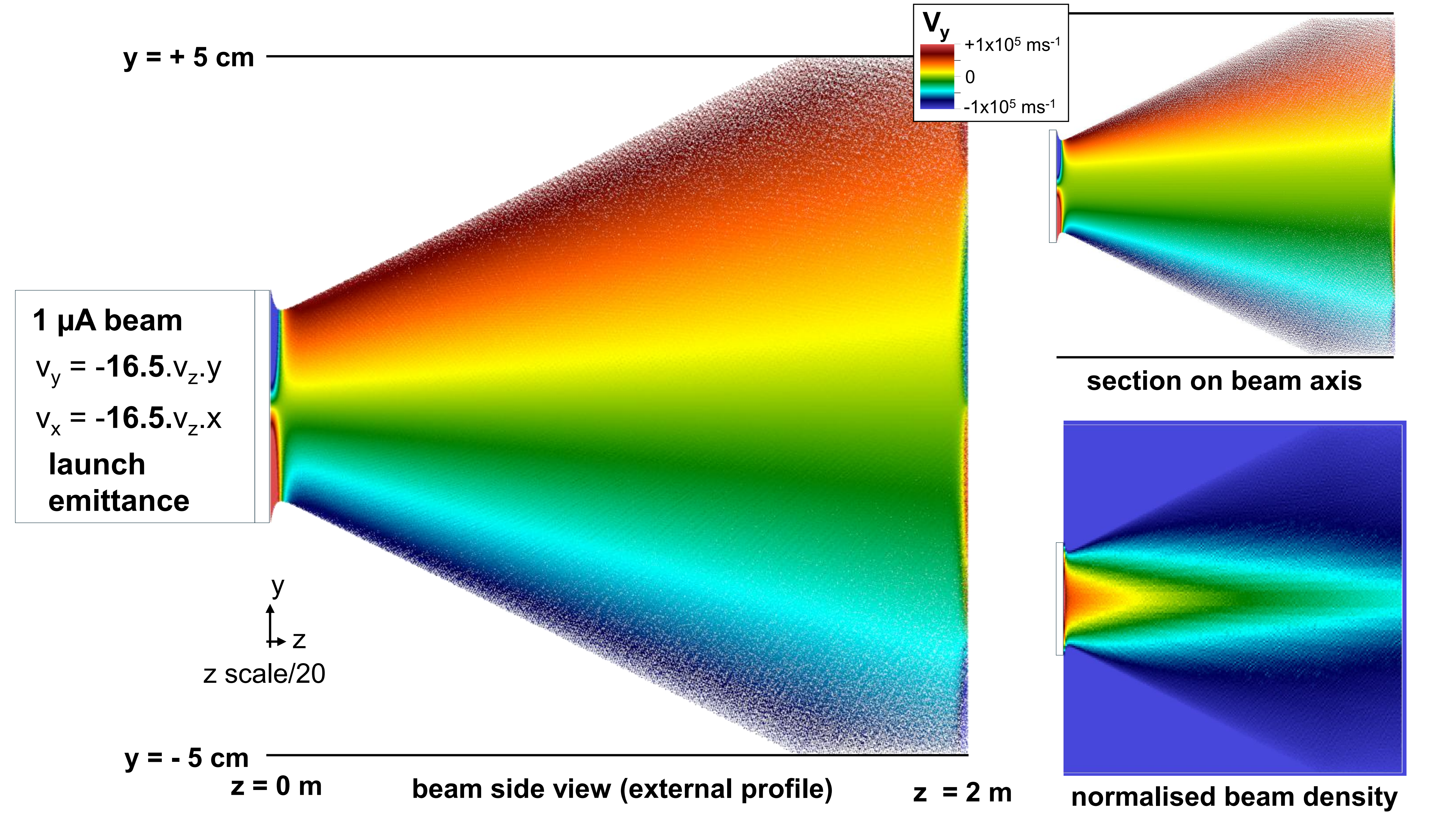

y = + 5 cm
Vy
+1x10^5 ms^-1
0
-1x10^5 ms^-1
1 μA beam
vy = -18.0.vz.y
vx = -18.0.vz.x
launch emittance
y
z
z scale/20
section on beam axis
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
normalised beam density

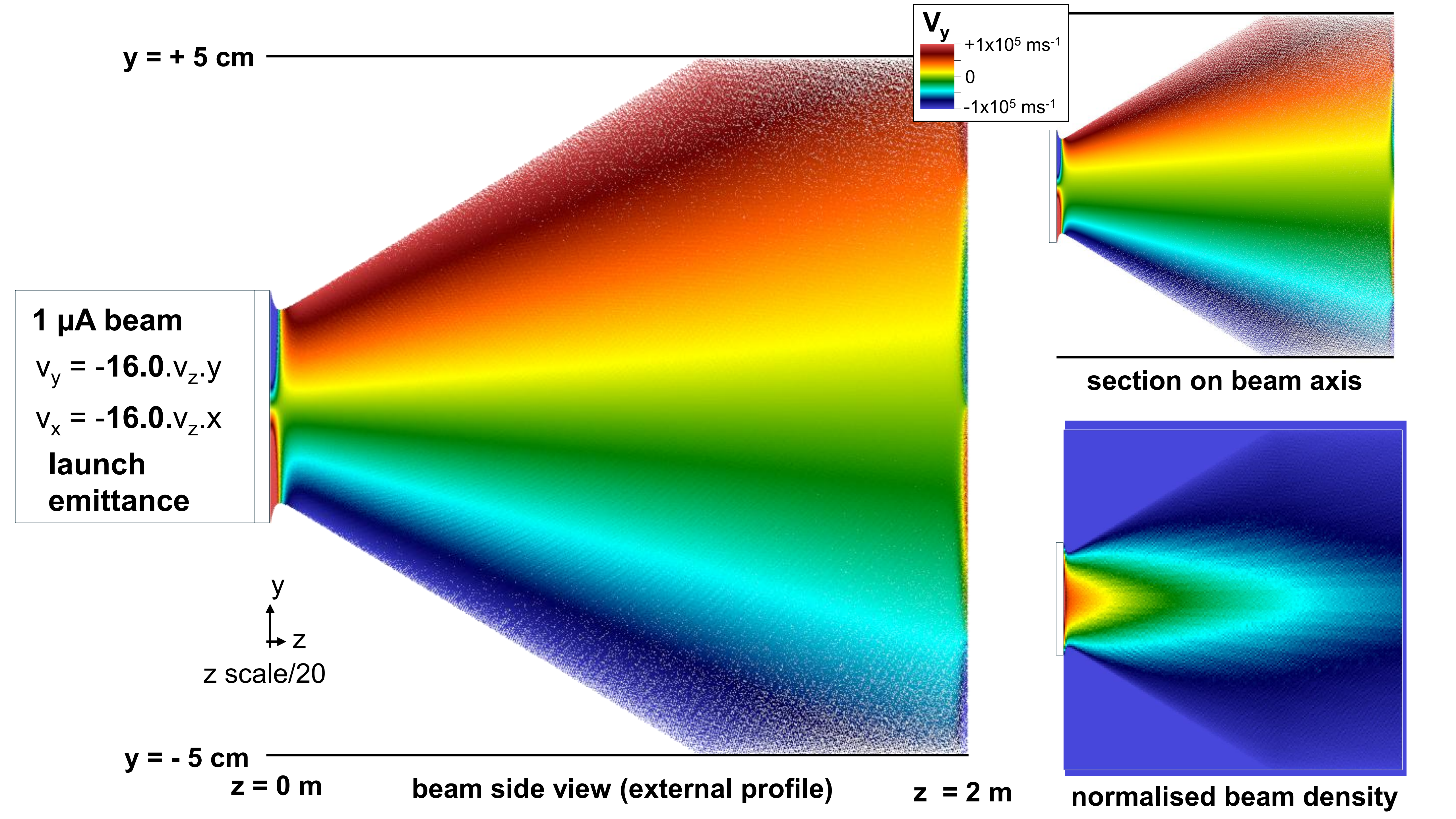


V_y
$+1x10^5 ms^{-1}$
0
$-1x10^5 ms^{-1}$
y = + 5 cm
y = - 5 cm
1 µA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch emittance
y
z
z scale/20
z = 0 m
beam side view (external profile)
z = 2 m
section on beam axis
normalised beam density

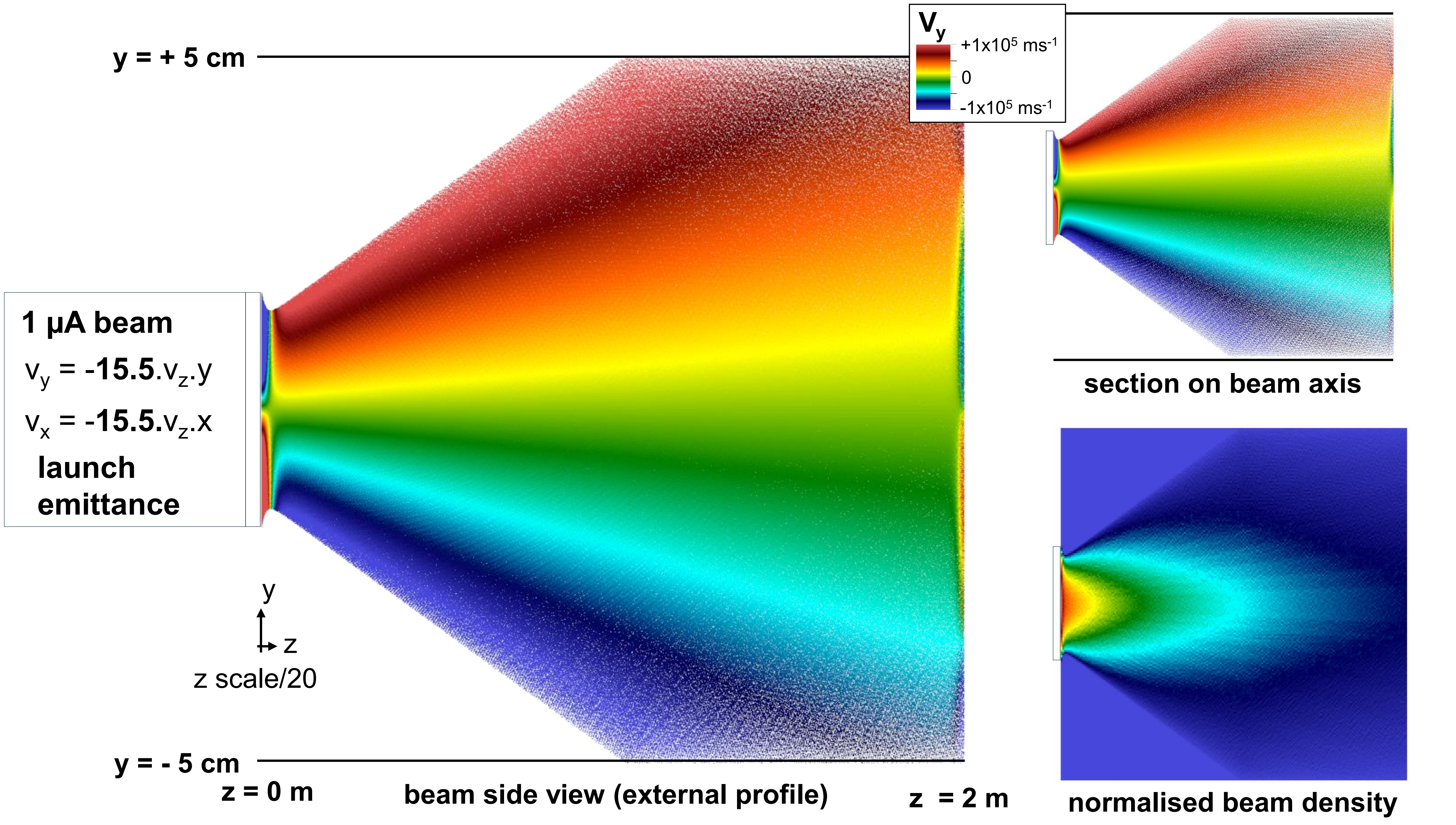


y = + 5 cm
y = - 5 cm
1 μA beam
v_y = -17.0.v_z.y
v_x = -17.0.v_z.x
launch emittance
y
z
z scale/20
z = 0 m
beam side view (external profile)
z = 2 m
V_y
+1x10^5 ms^{-1}
0
-1x10^5 ms^{-1}
section on beam axis
normalised beam density


y = + 5 cm
y = - 5 cm
1 μA beam
$v_y = -16.5.v_z.y$
$v_x = -16.5.v_z.x$
launch emittance
y
z
z scale/20
z = 0 m
beam side view (external profile)
z = 2 m
V_y
$+1x10^5 ms^{-1}$
0
$-1x10^5 ms^{-1}$
section on beam axis
normalised beam density

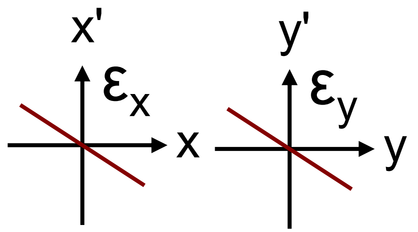


y = + 5 cm
y = - 5 cm
1 μA beam
$v_y = -16.0.v_z.y$
$v_x = -16.0.v_z.x$
launch emittance
y
z
z scale/20
z = 0 m
beam side view (external profile)
z = 2 m
V_y
$+1x10^5\ ms^{-1}$
0
$-1x10^5\ ms^{-1}$
section on beam axis
normalised beam density

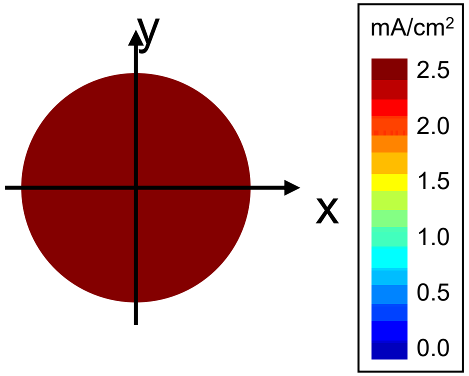


y = + 5 cm
y = - 5 cm
1 μA beam
$v_y = -15.5.v_z.y$
$v_x = -15.5.v_z.x$
launch emittance
y
z
z scale/20
V_y
$+1x10^5\ ms^{-1}$
0
$-1x10^5\ ms^{-1}$
section on beam axis
z = 0 m
beam side view (external profile)
z = 2 m
normalised beam density

complex structures emerge from mathematically perfect LEBT entrance beams:

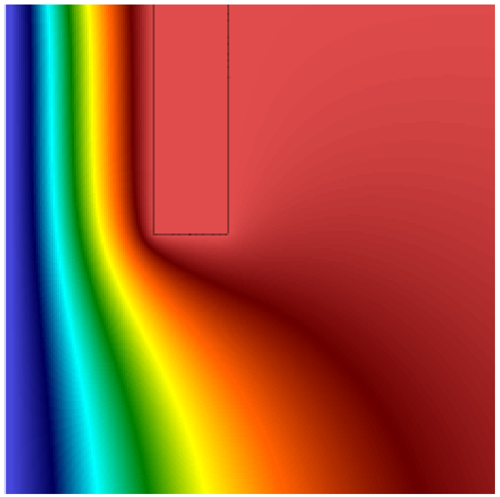


uniform emittance



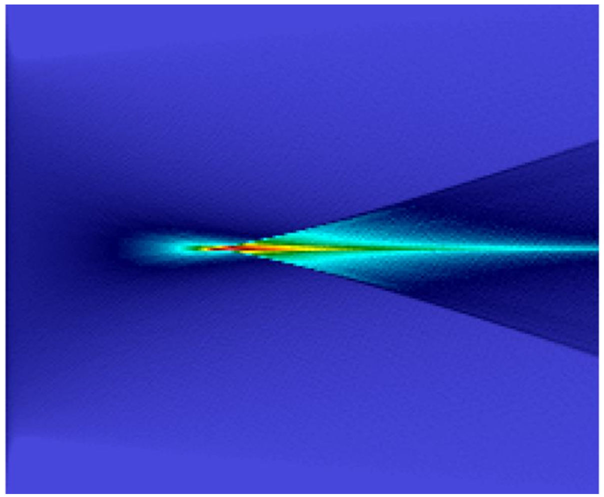
uniform beam density profile

+



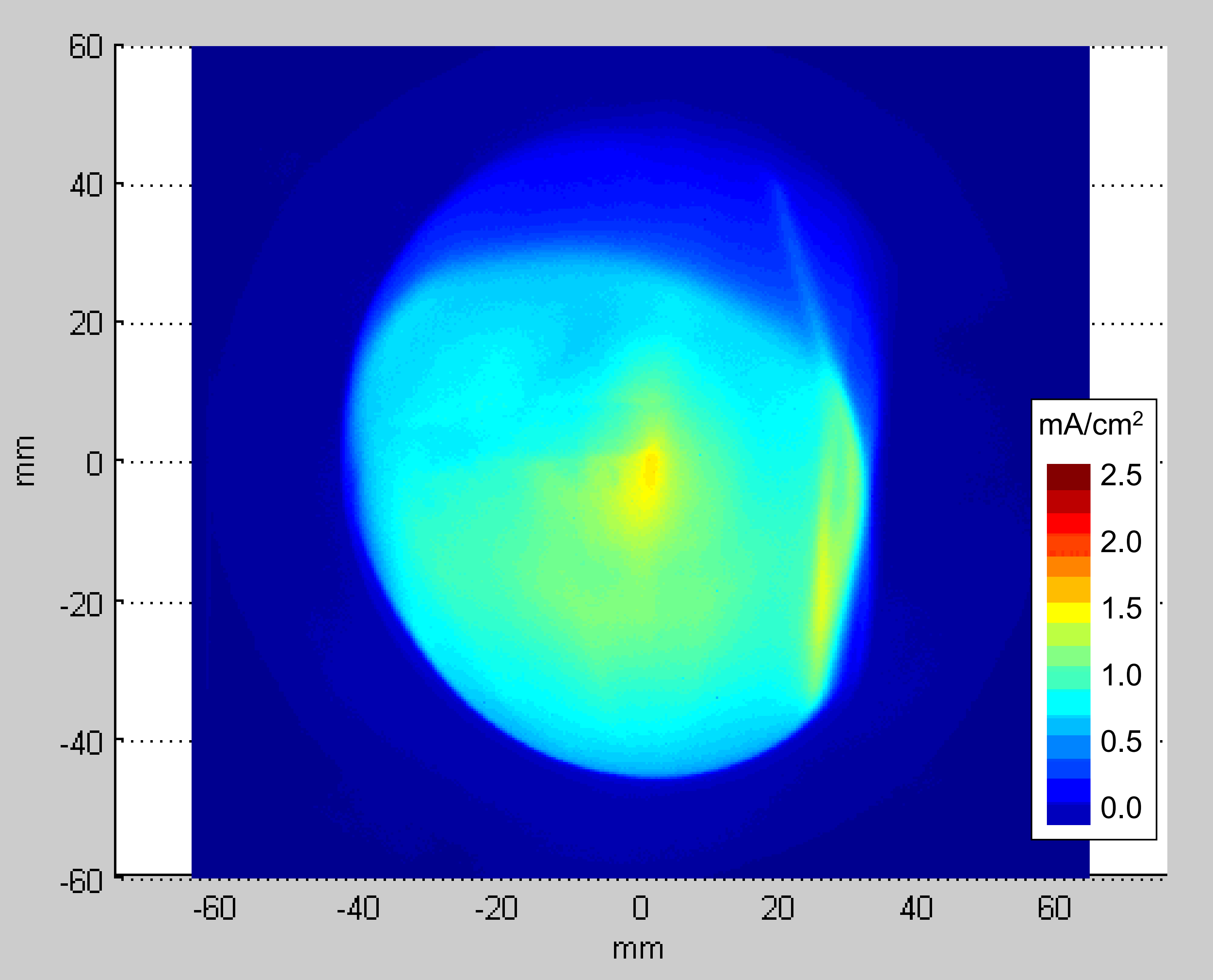
electrostatic lens with spherical aberration

=



complex beam density profiles

The actual ISIS LEBT entrance beam profile is far from mathematically perfect!…



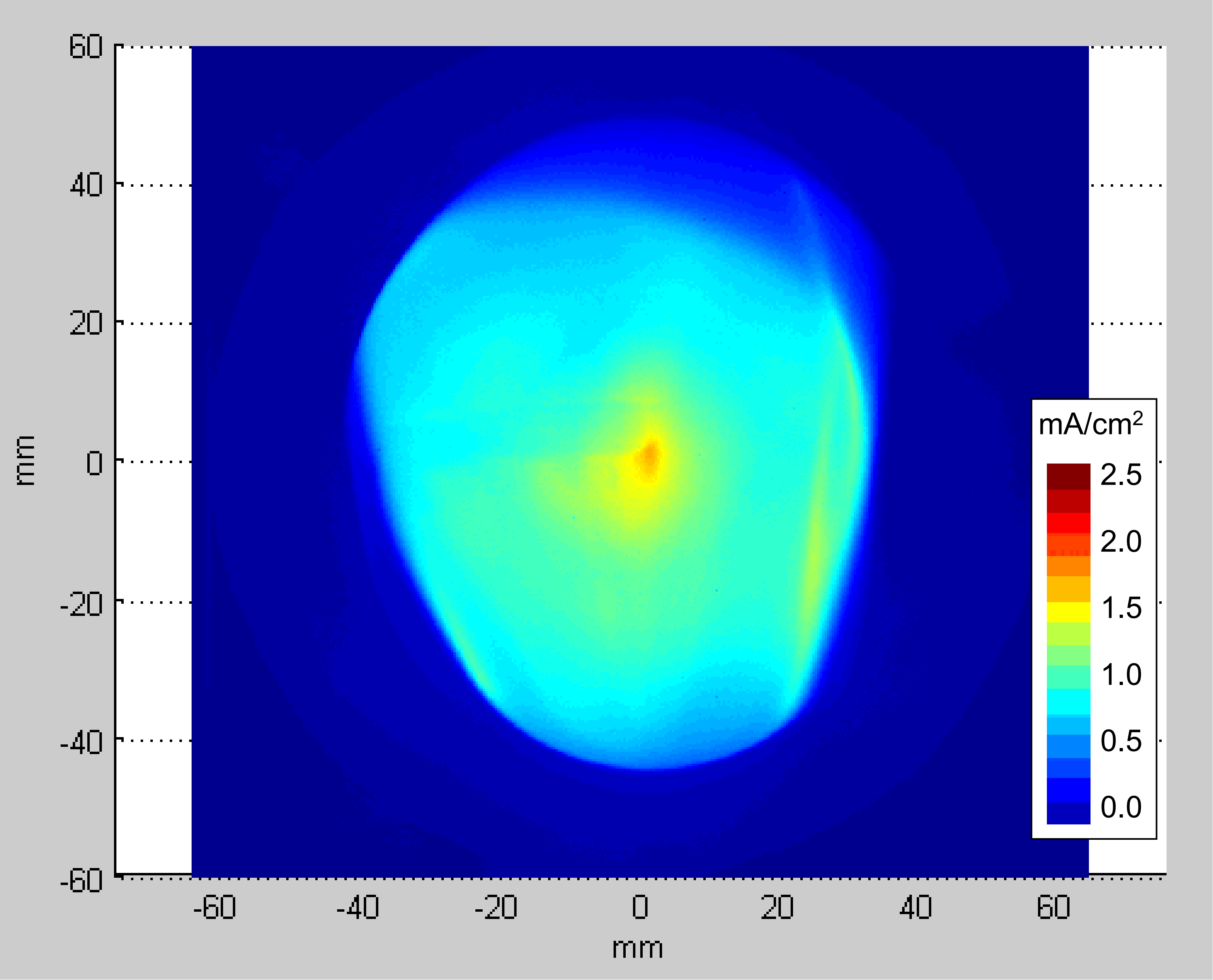
17 kV
Extraction Voltage

35 kV
Platform Voltage

18 kV
Post Acceleration Voltage

47 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



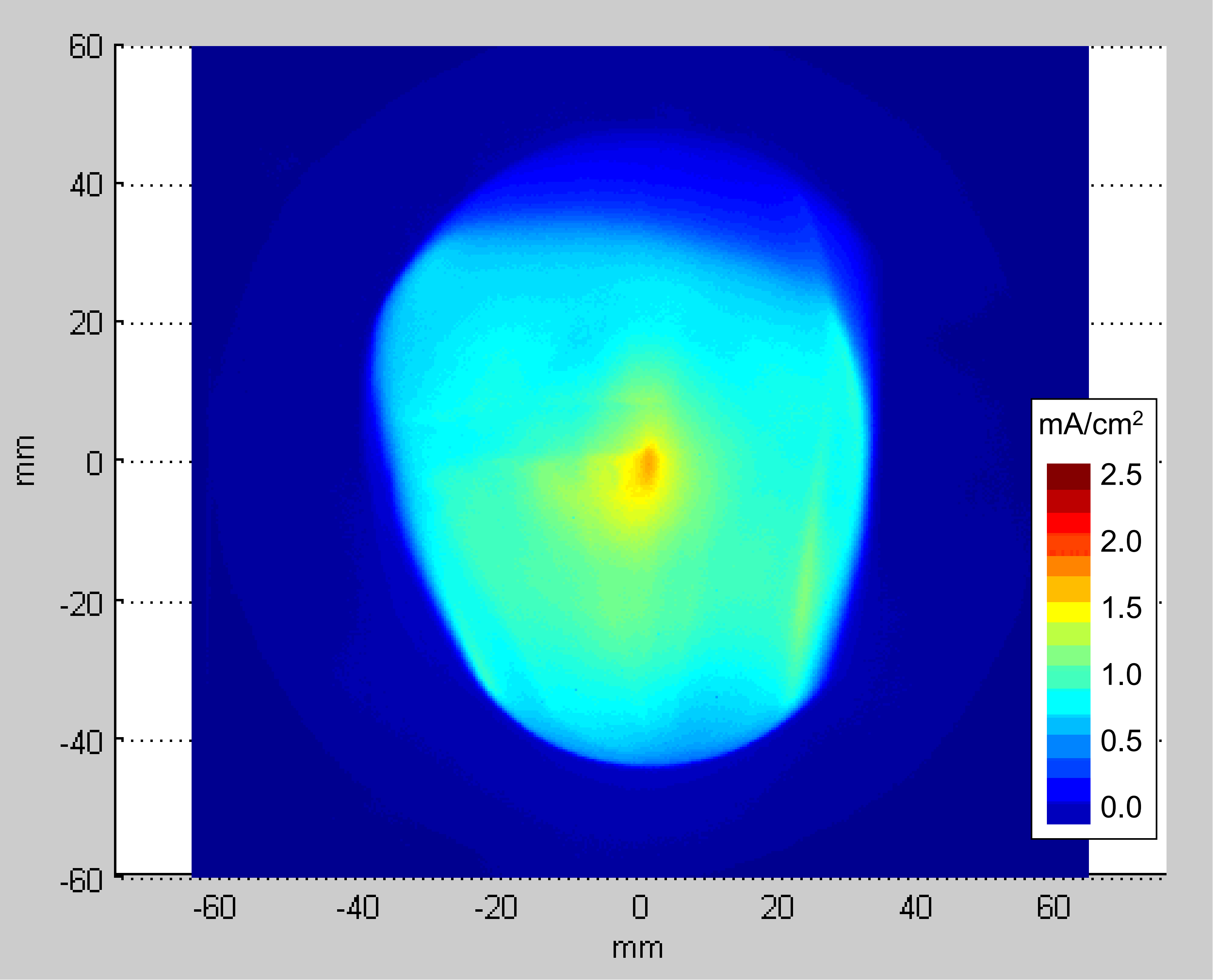
16 kV
Extraction
Voltage

35 kV
Platform Voltage

19 kV
Post
Acceleration
Voltage

42 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



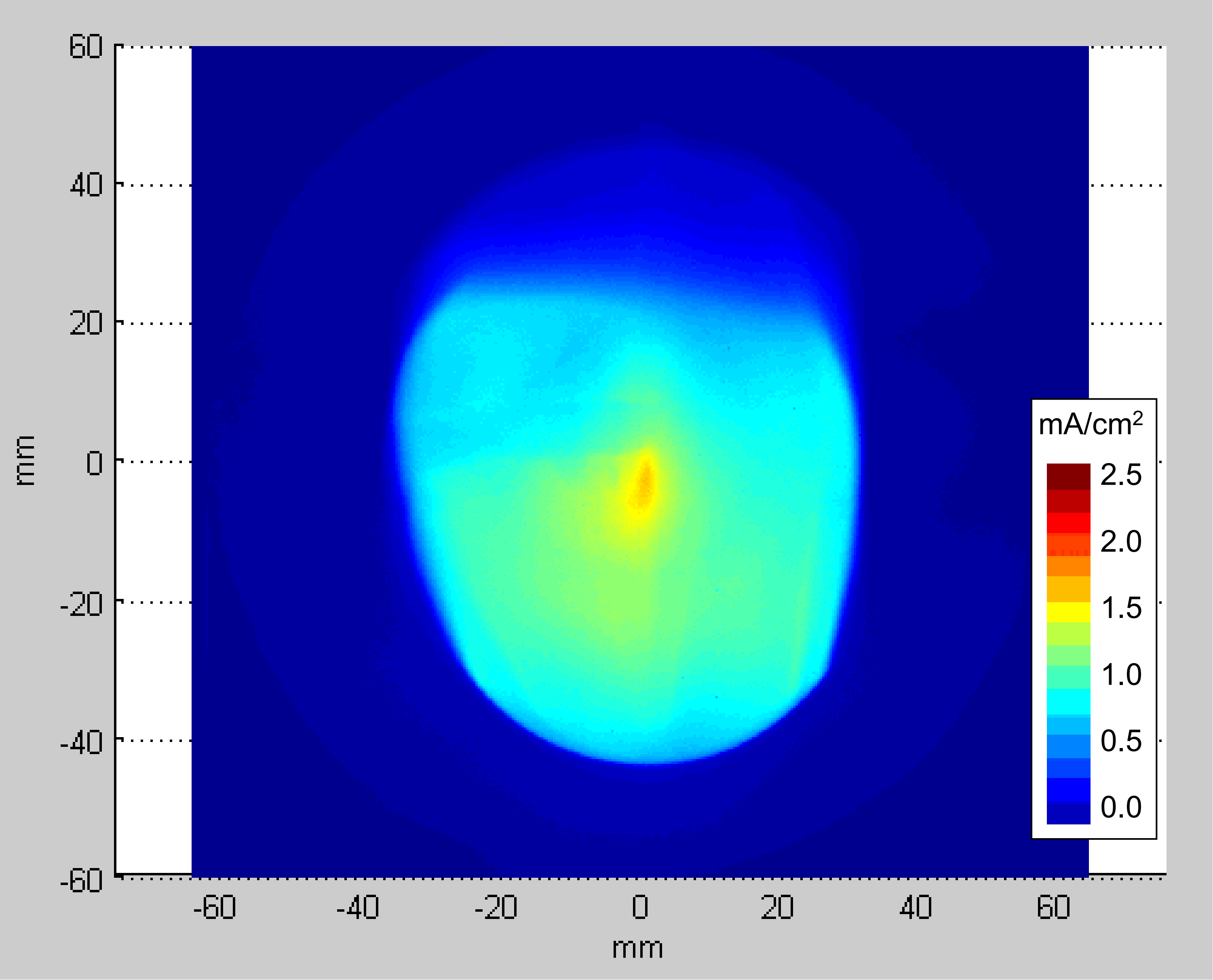
15 kV
Extraction Voltage

35 kV
Platform Voltage

20 kV
Post Acceleration Voltage

40 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



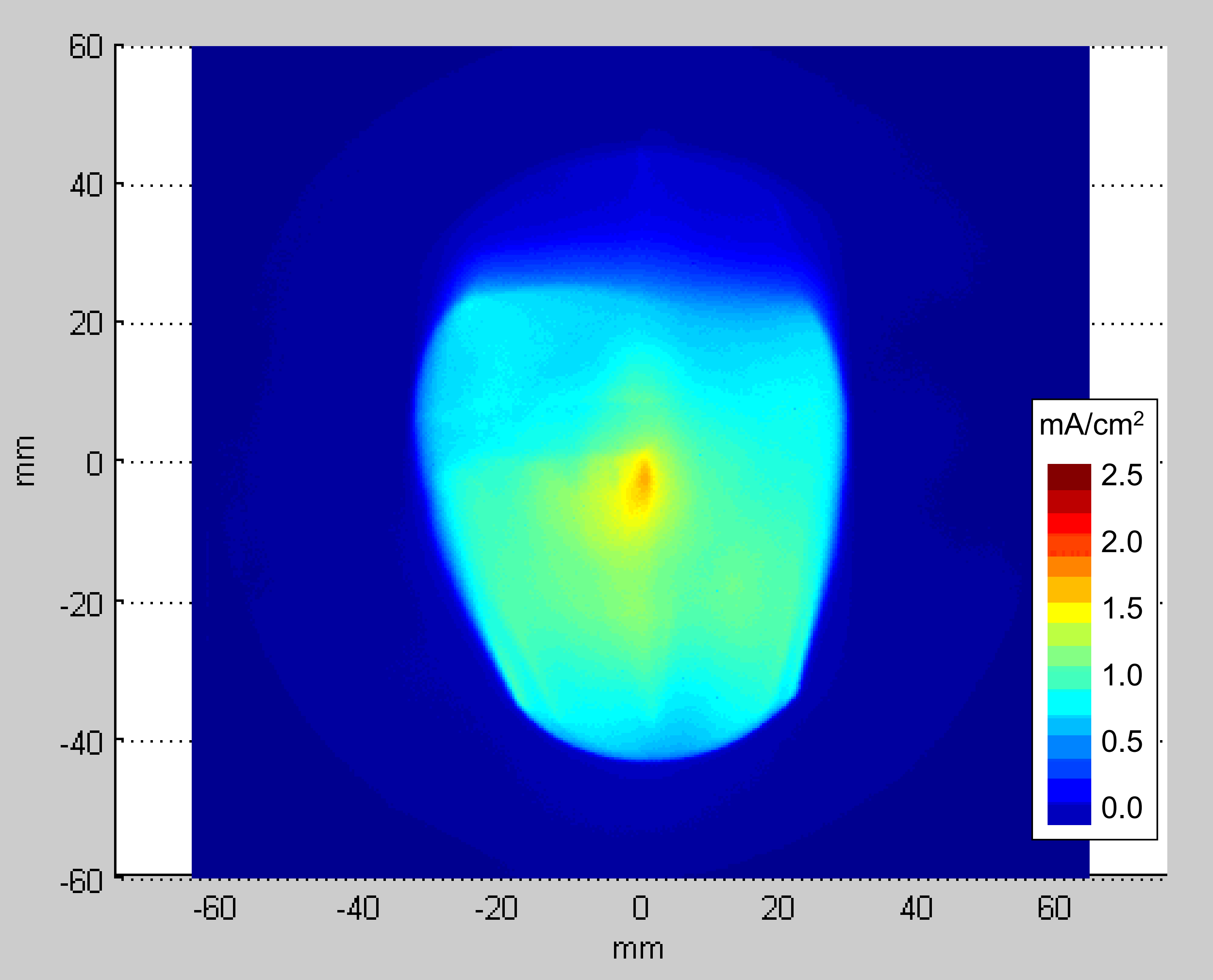
14 kV
Extraction Voltage

35 kV
Platform Voltage

21 kV
Post Acceleration Voltage

38 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



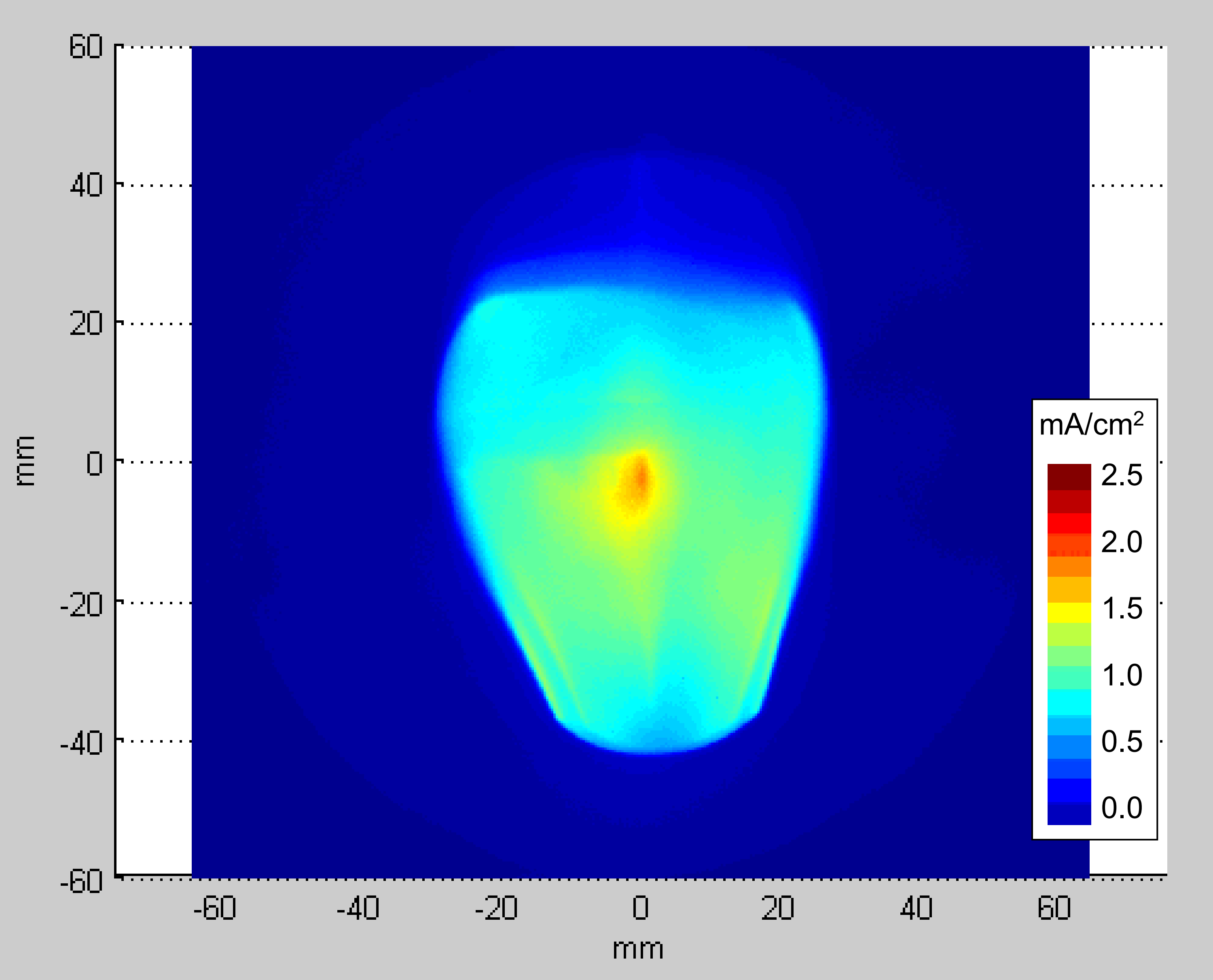
13 kV
Extraction Voltage

35 kV
Platform Voltage

22 kV
Post Acceleration Voltage

35 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



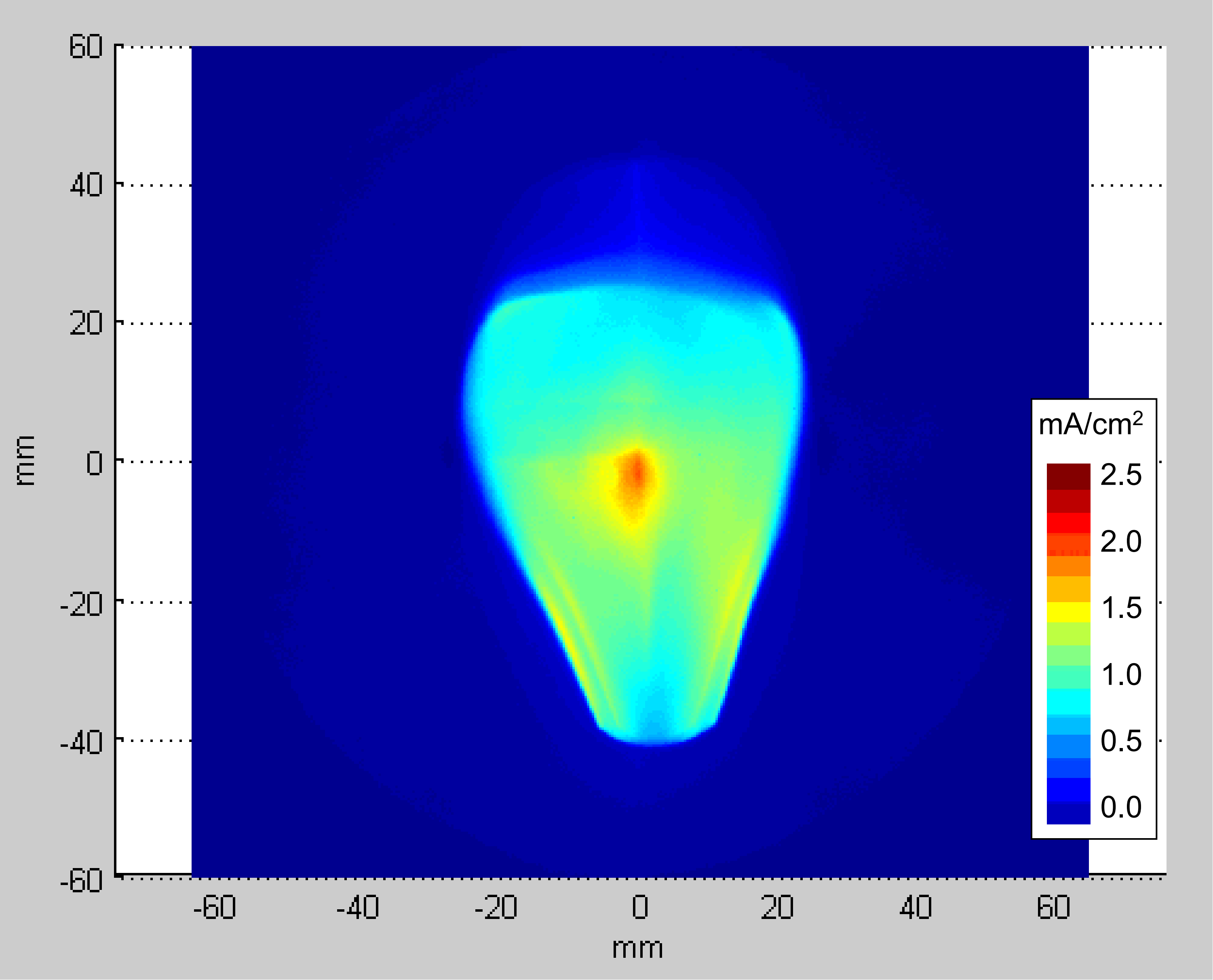
12 kV
Extraction Voltage

35 kV
Platform Voltage

23 kV
Post Acceleration Voltage

32 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



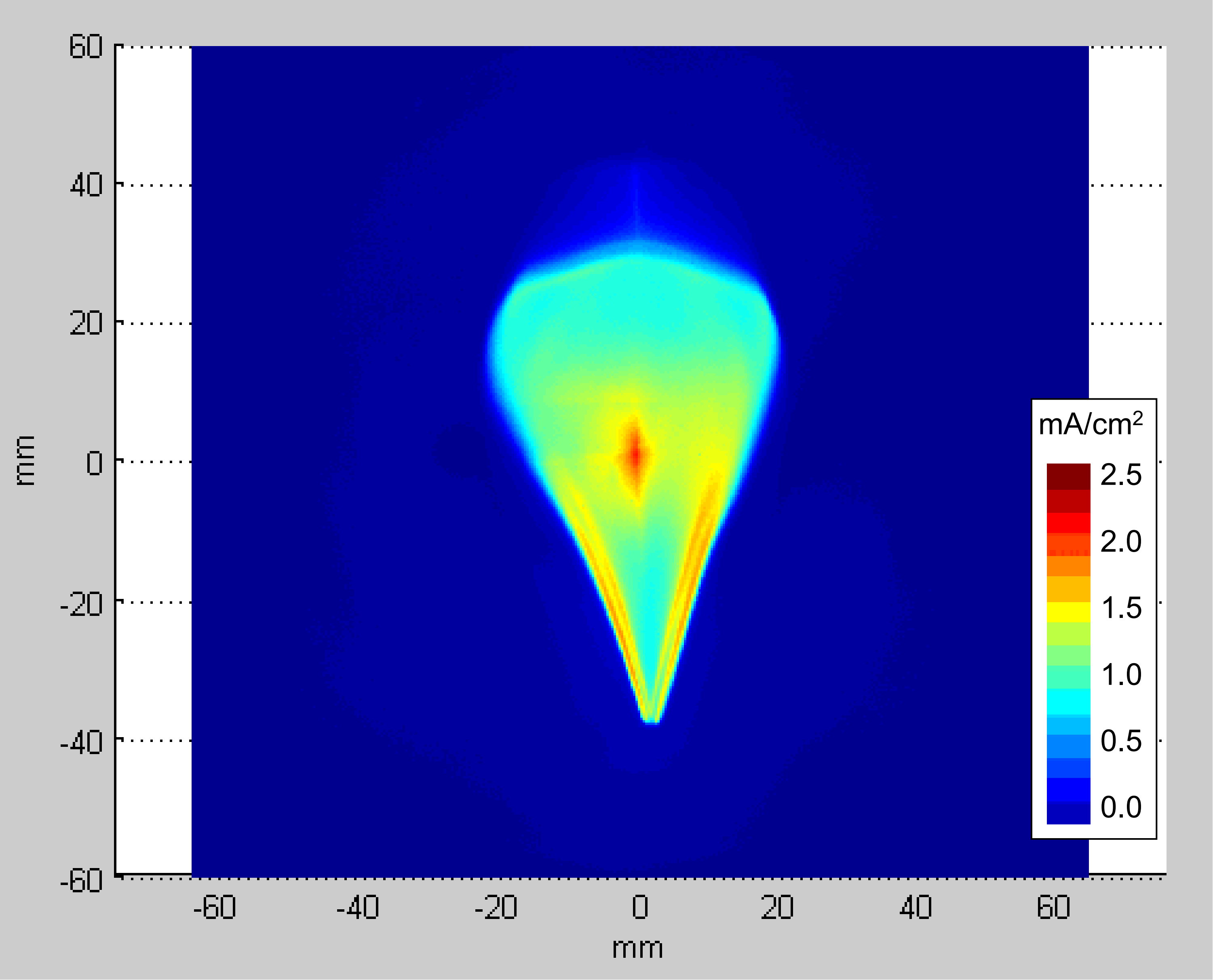
11 kV
Extraction Voltage

35 kV
Platform Voltage

24 kV
Post Acceleration Voltage

28 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



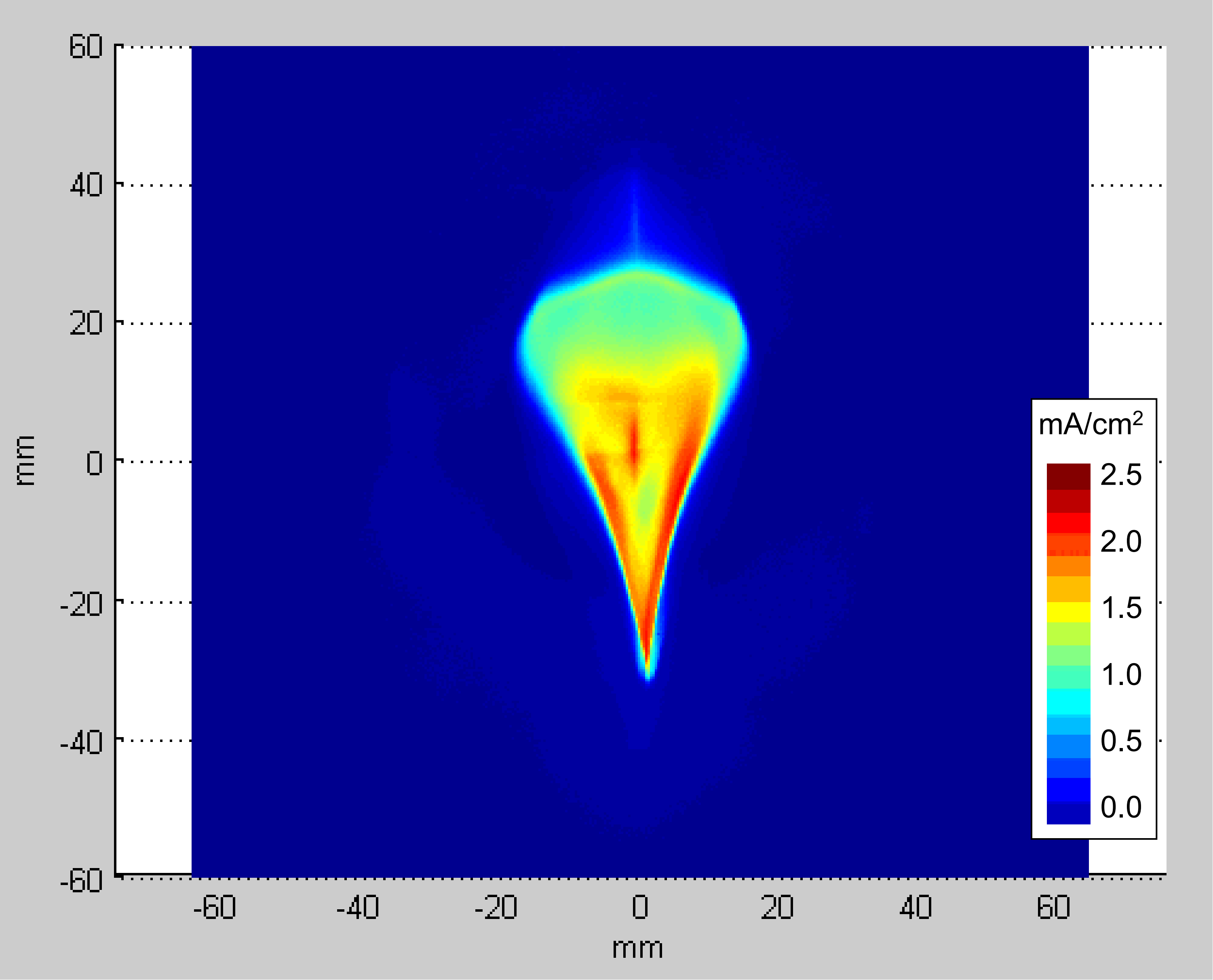
10 kV
Extraction
Voltage

35 kV
Platform Voltage

25 kV
Post
Acceleration
Voltage

25 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



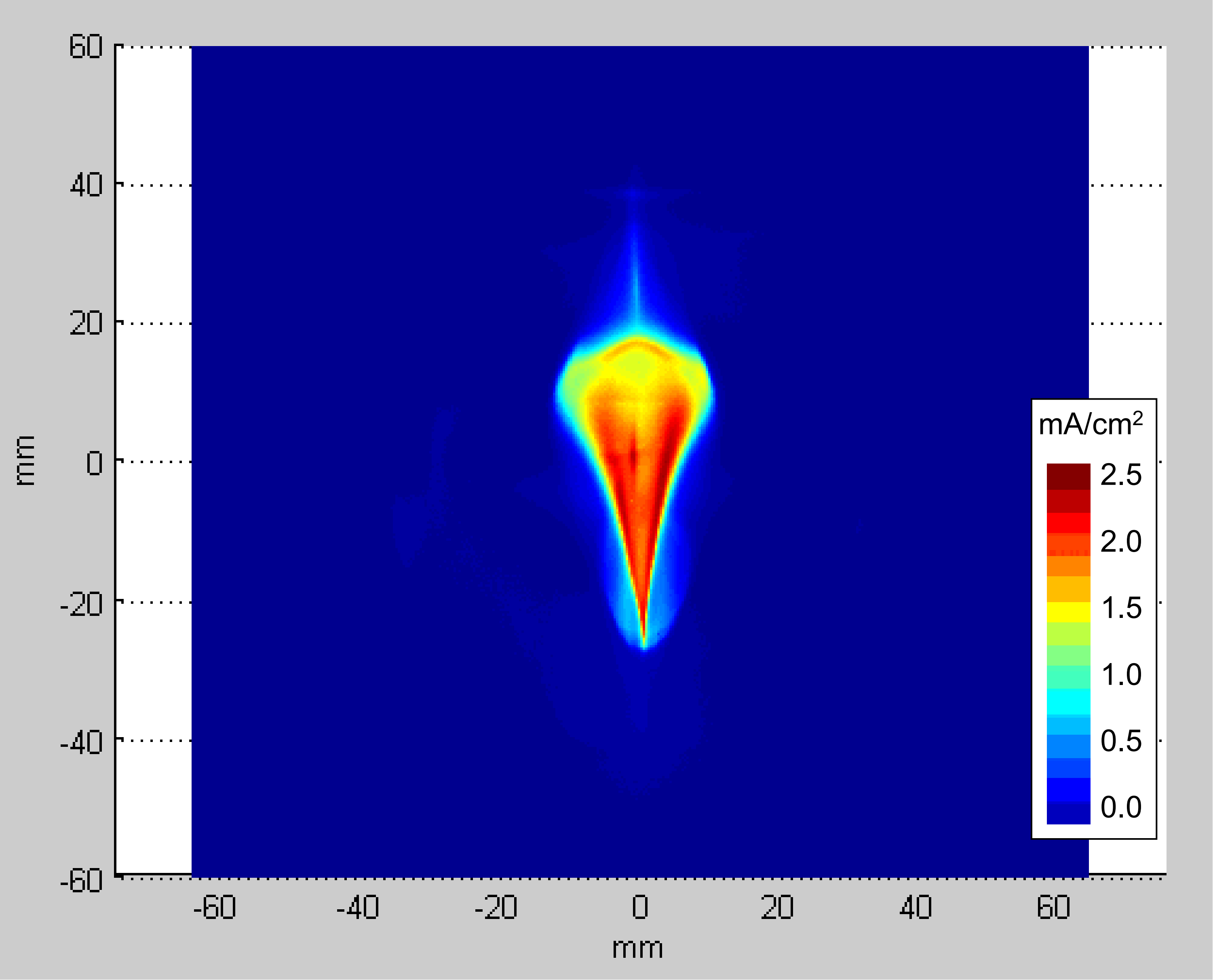
9 kV
Extraction Voltage

35 kV
Platform Voltage

26 kV
Post Acceleration Voltage

21 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



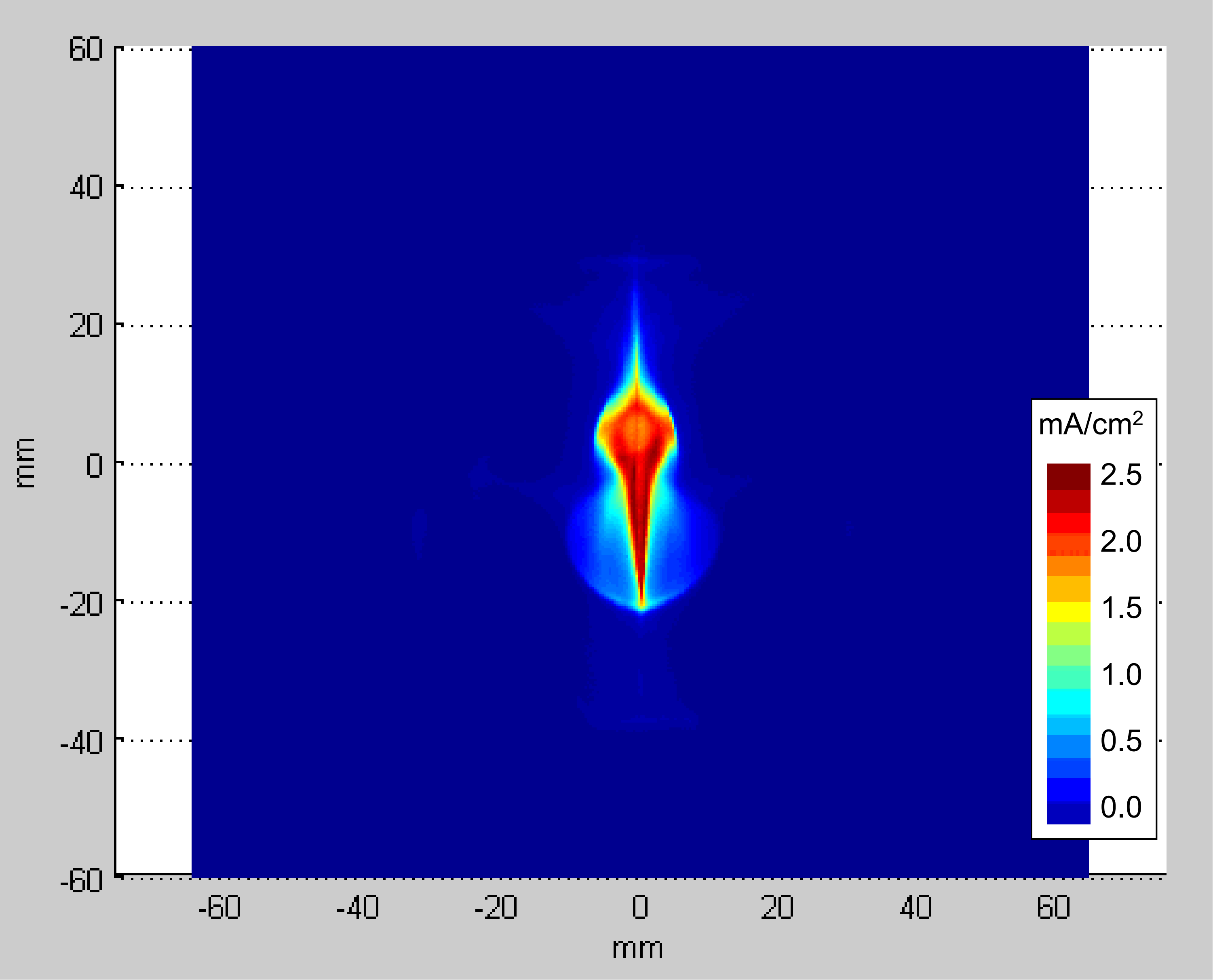
8 kV
Extraction Voltage

35 kV
Platform Voltage

27 kV
Post Acceleration Voltage

17 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



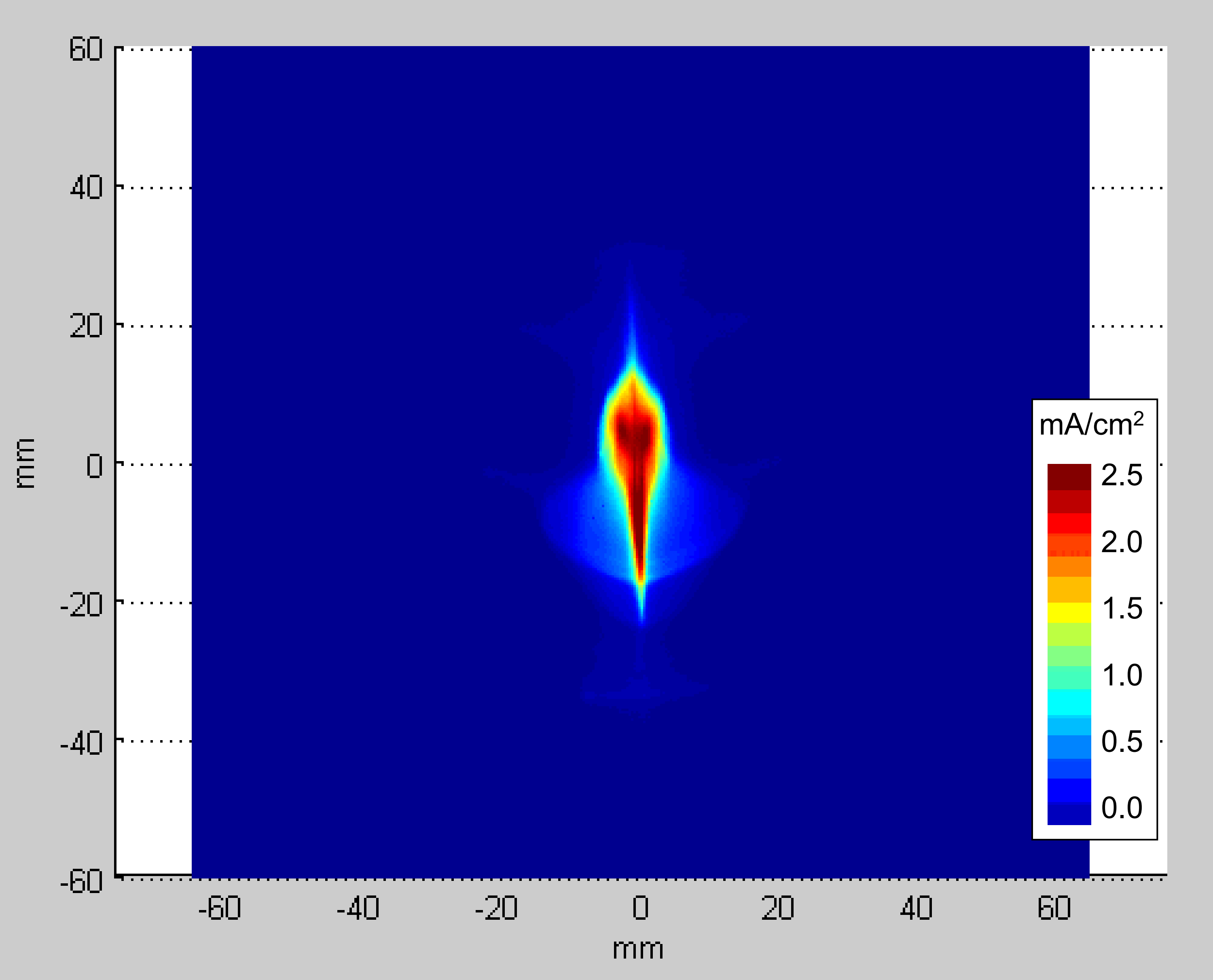
7 kV
Extraction Voltage

35 kV
Platform Voltage

28 kV
Post Acceleration Voltage

13 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



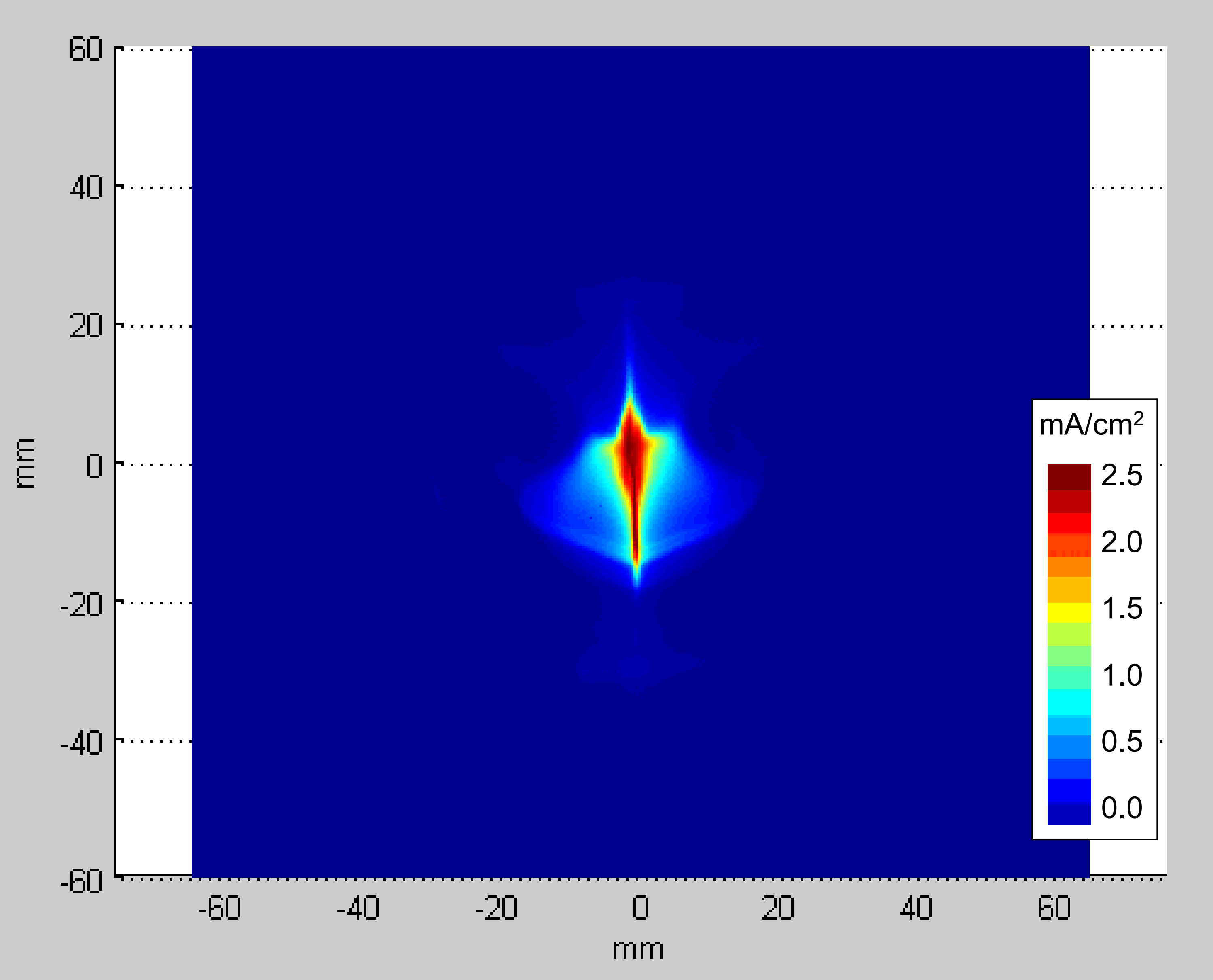
6.5 kV
Extraction Voltage

35 kV
Platform Voltage

28.5 kV
Post Acceleration Voltage

12 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



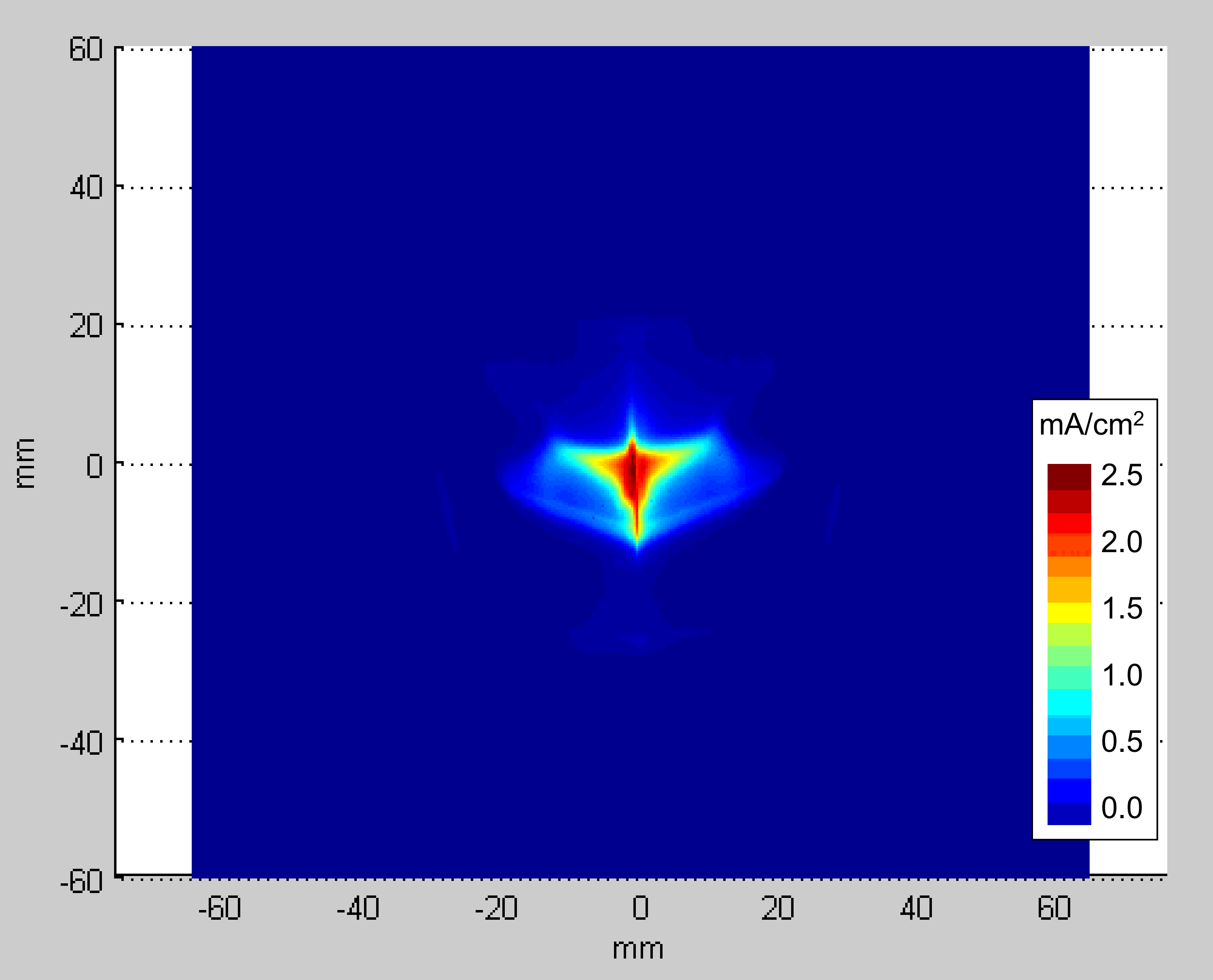
6 kV
Extraction Voltage

35 kV
Platform Voltage

29 kV
Post Acceleration Voltage

10 mA
Beam Current

the ISIS LEBT entrance beam profile from a caesiated negative Penning source



5.5 kV
Extraction Voltage

35 kV
Platform Voltage

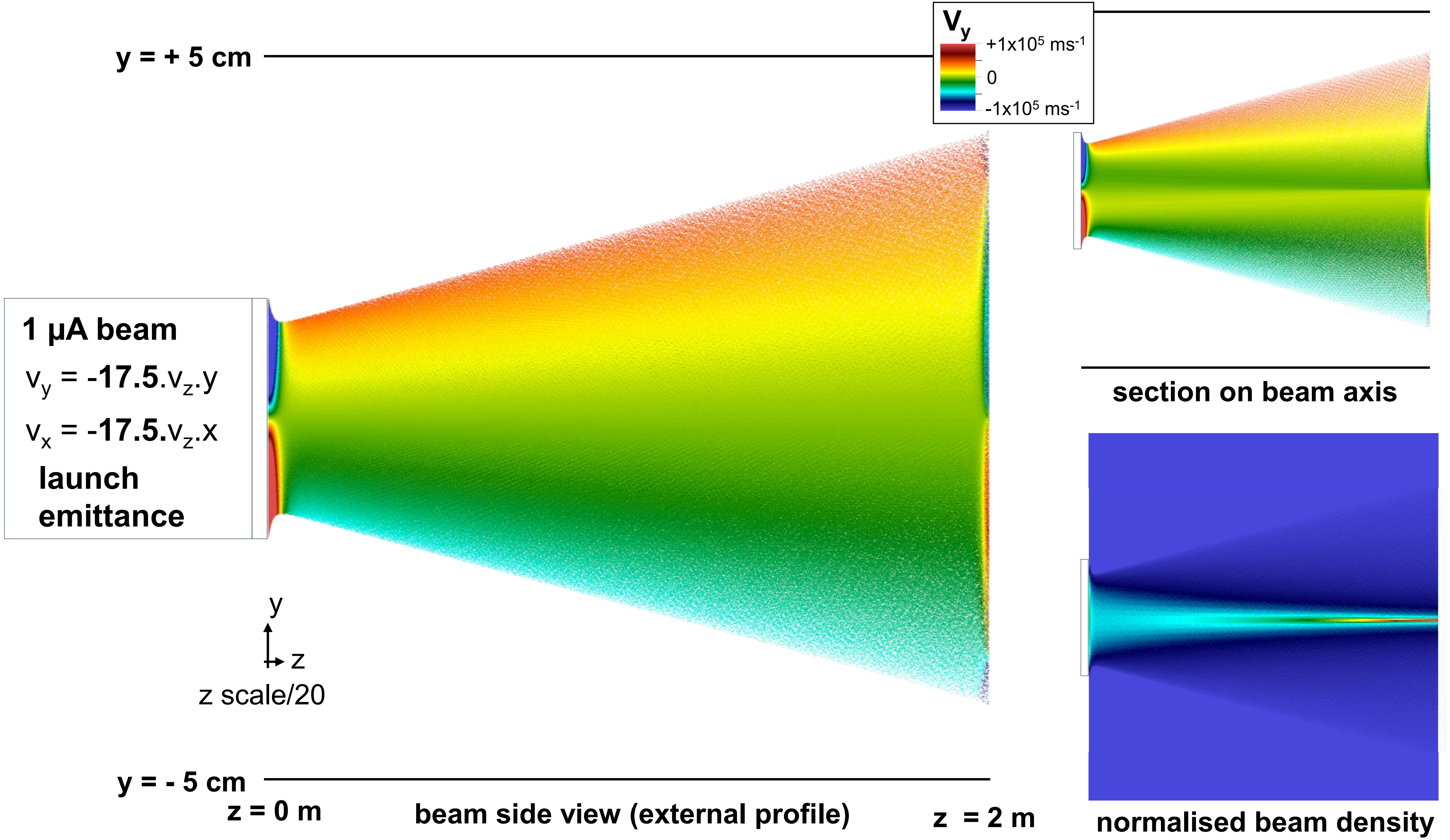
28.5 kV
Post Acceleration Voltage

9 mA
Beam Current

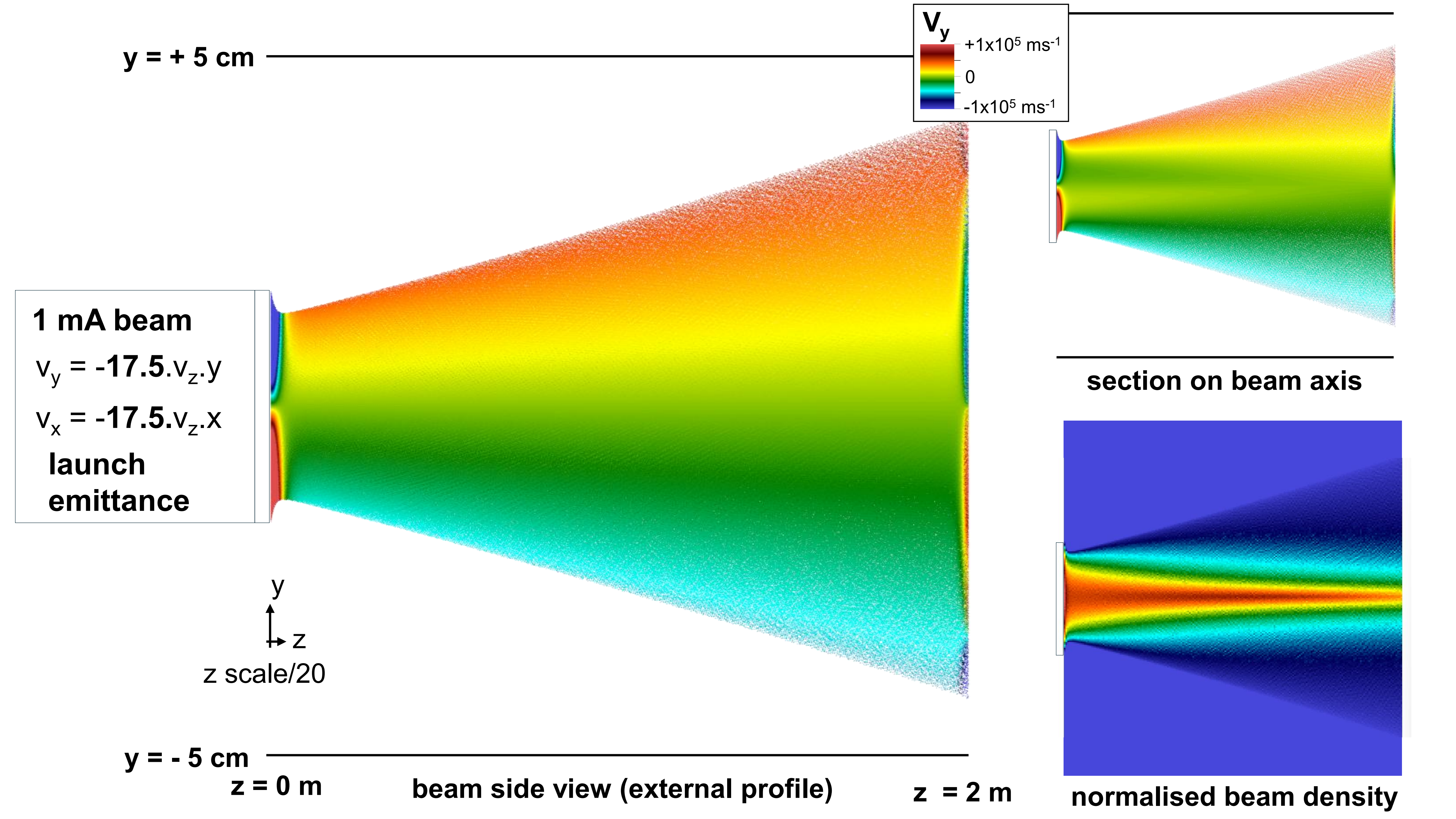
the ISIS LEBT entrance beam profile from a caesiated negative Penning source

Why can’t you just drift a beam? - aberrations!

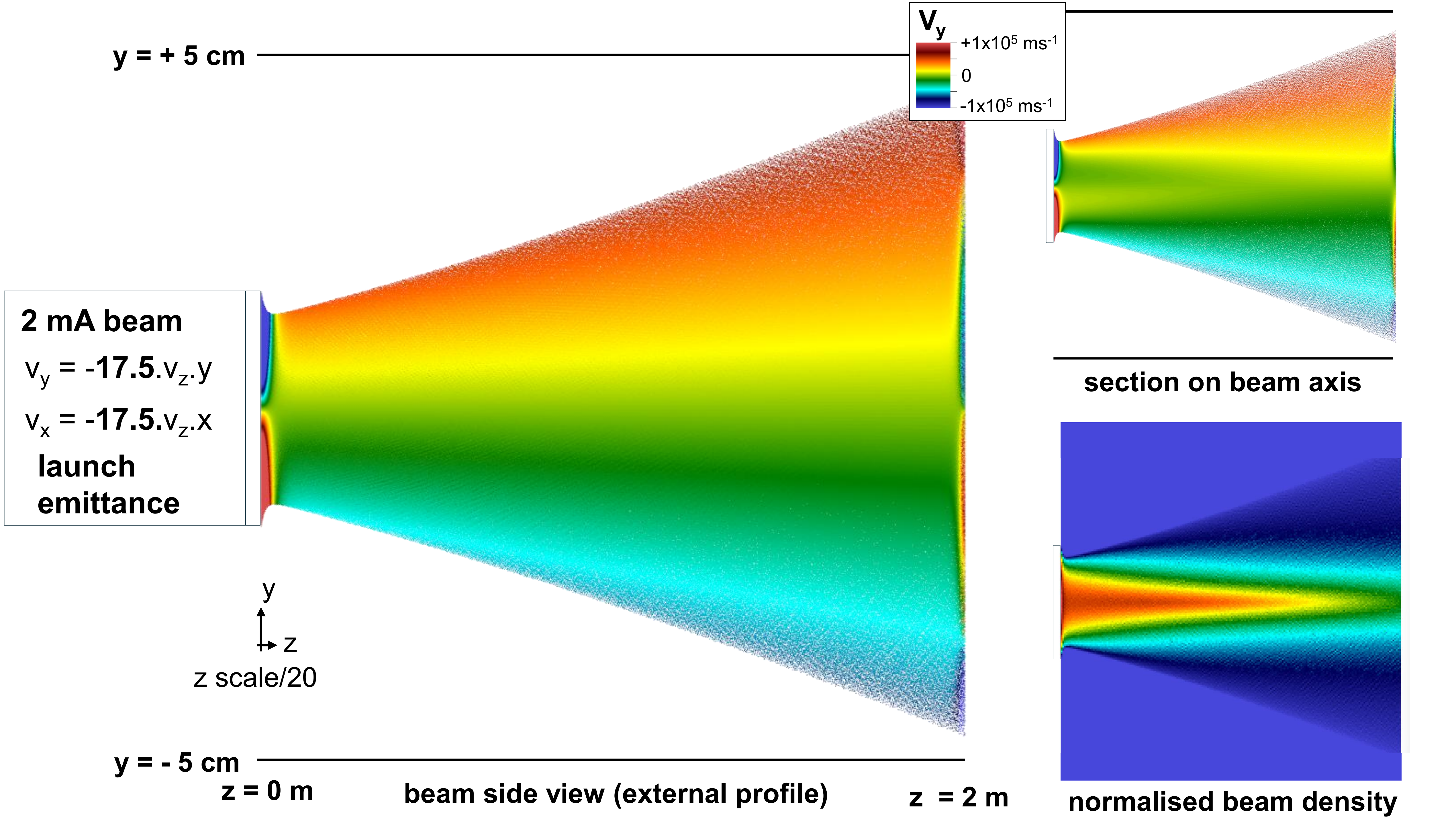
- electrostatic focusing aberration
- complex beam density and emittance from plasma and extraction
- space charge!



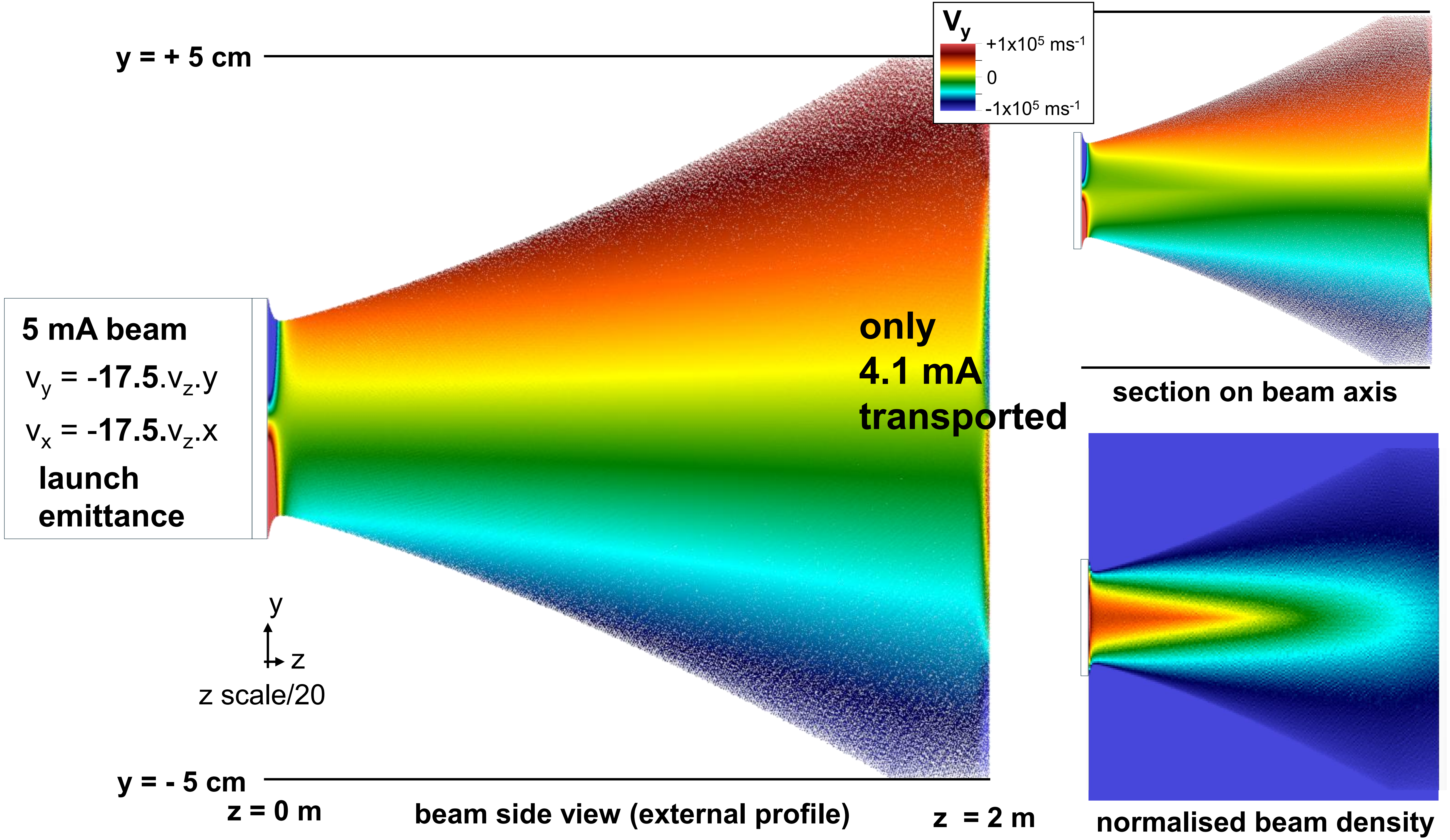
y = + 5 cm
Vy
+1x10^5 ms^-1
0
-1x10^5 ms^-1
1 μA beam
v_y = -17.5.v_z.y
v_x = -17.5.v_z.x
launch emittance
y
z
z scale/20
section on beam axis
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
normalised beam density



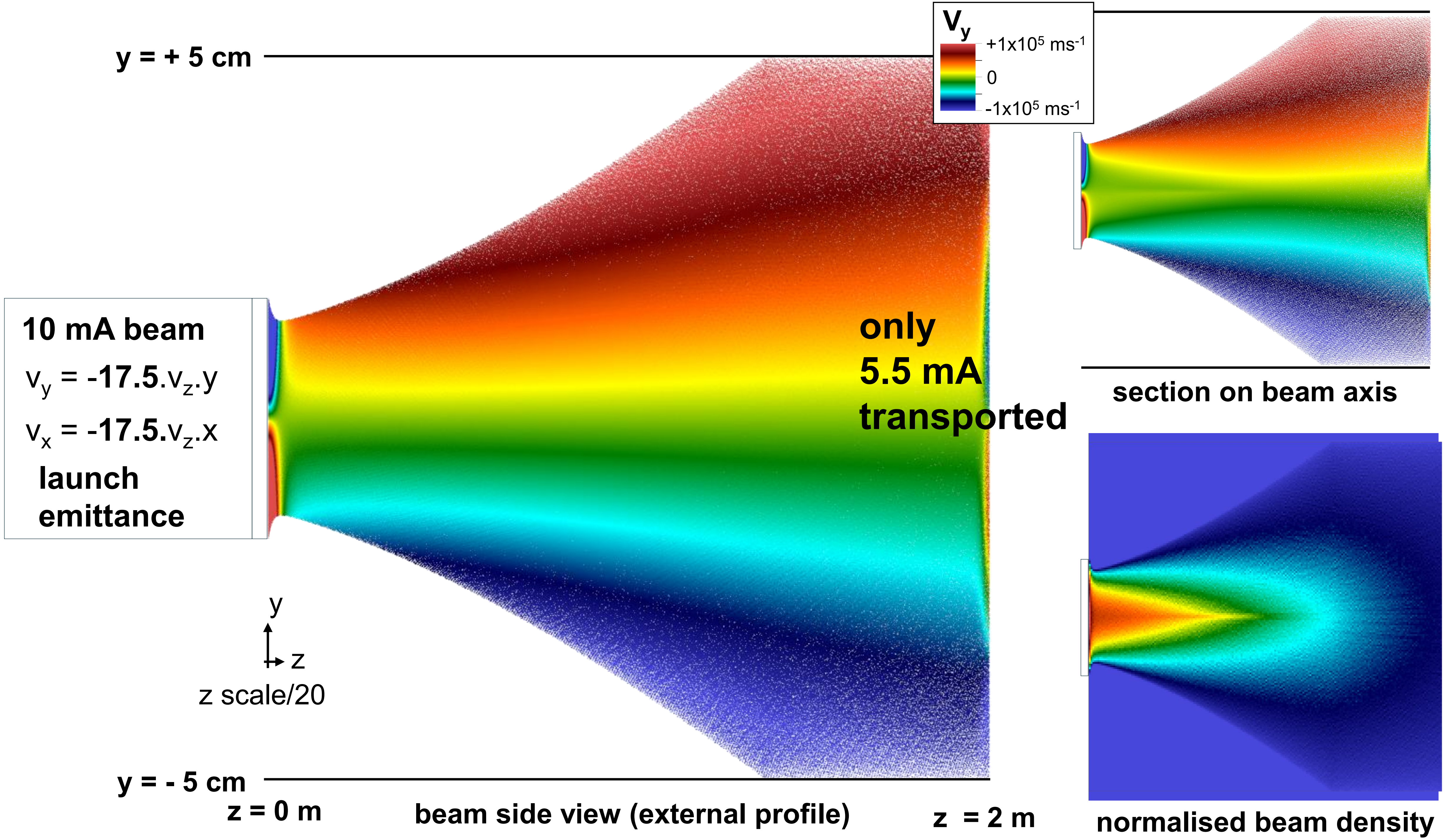
y = + 5 cm
y = - 5 cm
1 mA beam
$v_y = -17.5 \cdot v_z \cdot y$
$v_x = -17.5 \cdot v_z \cdot x$
launch emittance
V_y
$+1 \times 10^5$ ms^{-1}
0
-1×10^5 ms^{-1}
y
z
z scale/20
z = 0 m
beam side view (external profile)
z = 2 m
section on beam axis
normalised beam density



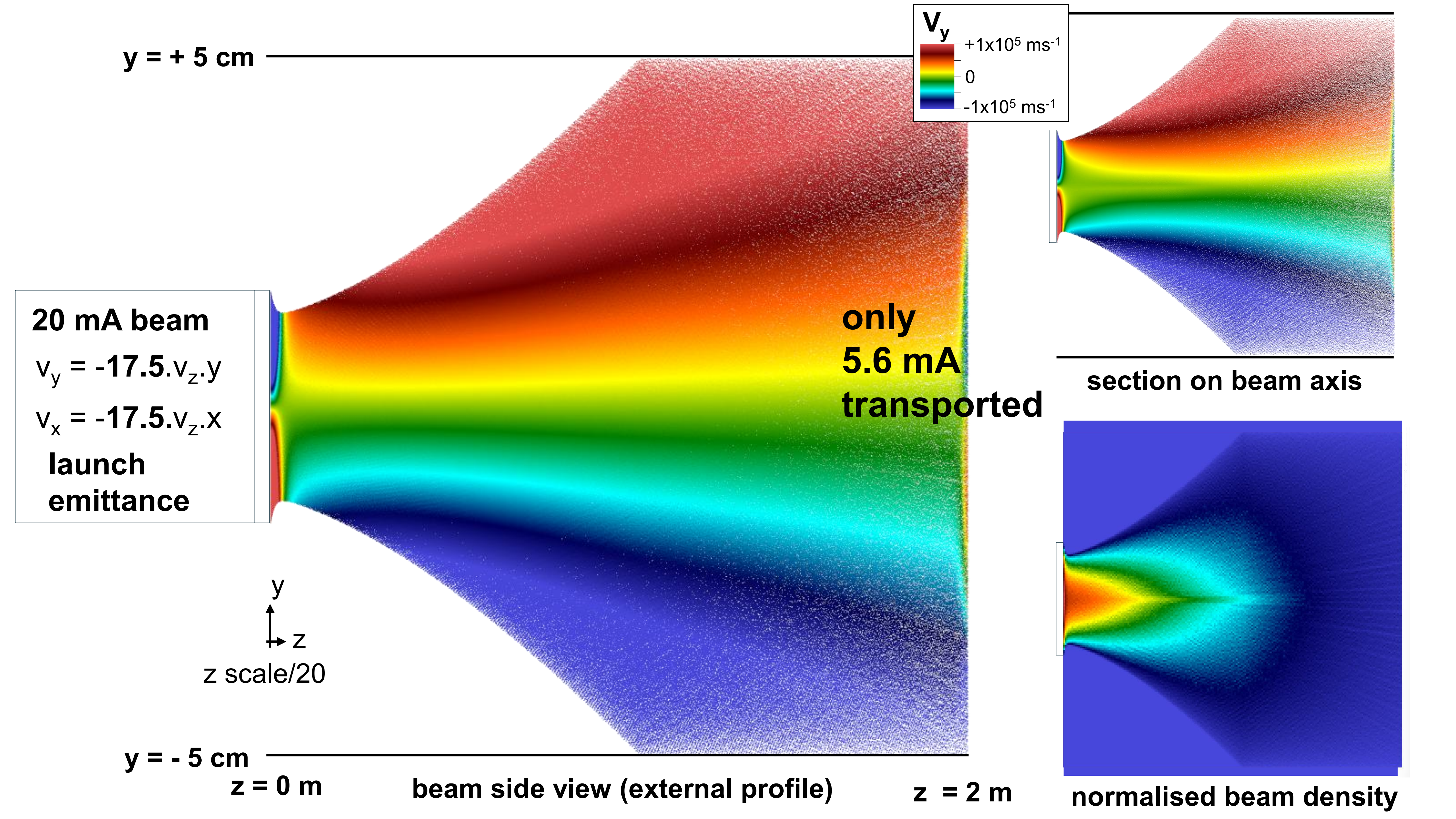
V_y
+1x10^5 ms^-1
0
-1x10^5 ms^-1
y = + 5 cm
2 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch emittance
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
section on beam axis
normalised beam density



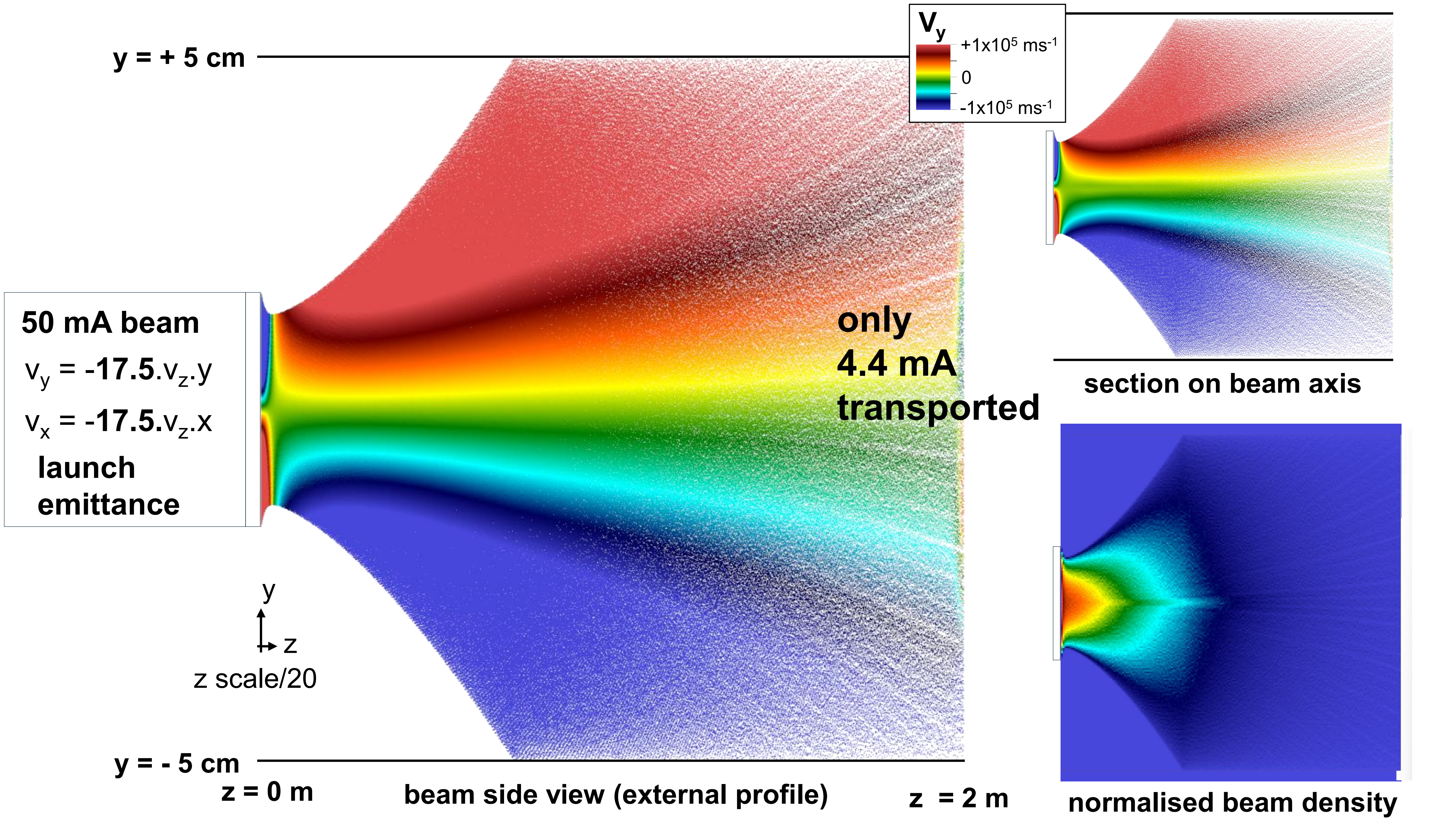
y = + 5 cm
y = - 5 cm
V_y
$+1x10^5$ ms^{-1}
0
$-1x10^5$ ms^{-1}
5 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch emittance
only 4.1 mA transported
y
z
z scale/20
z = 0 m
beam side view (external profile)
z = 2 m
section on beam axis
normalised beam density



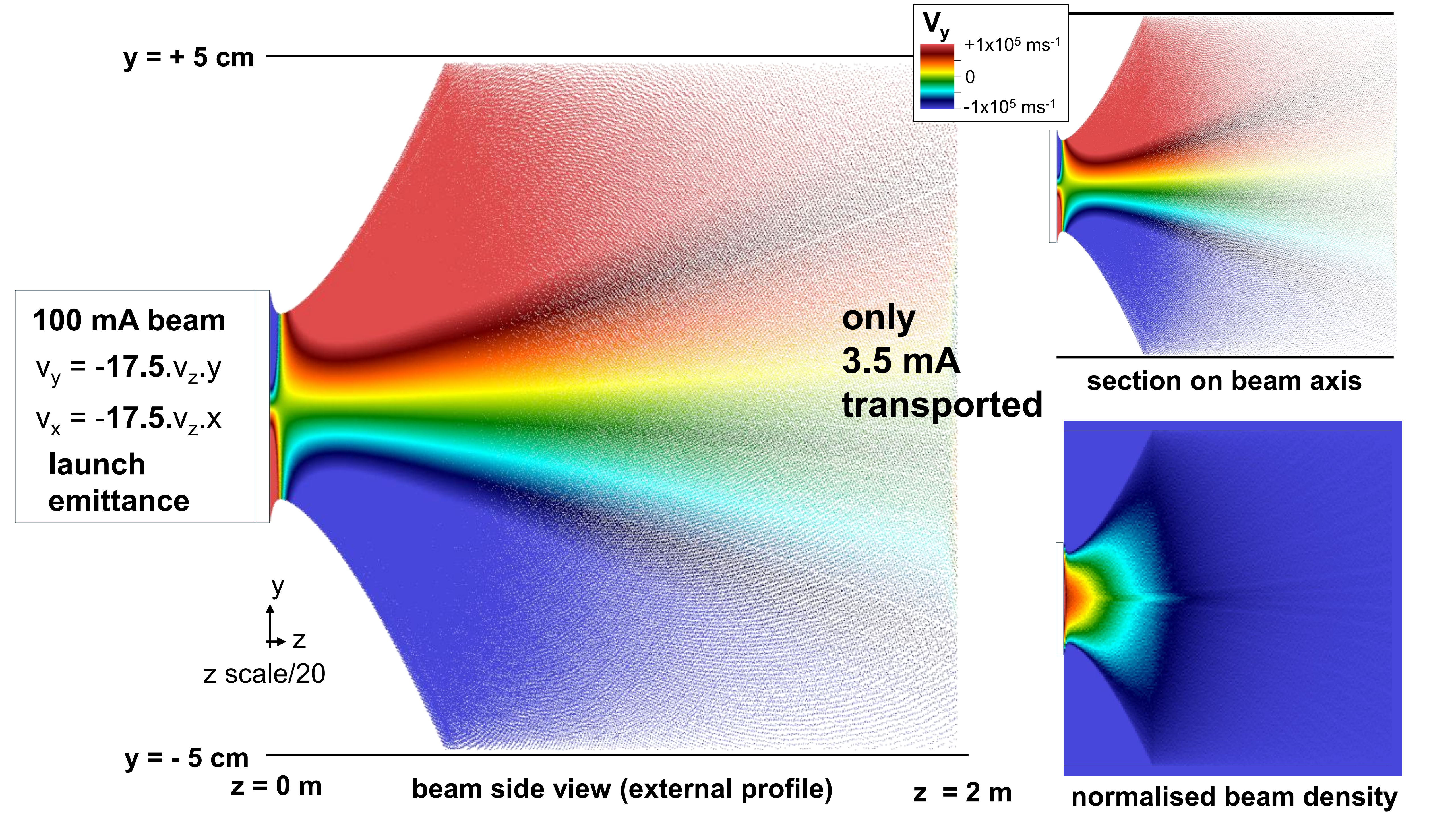
y = + 5 cm
y = - 5 cm
10 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch
emittance
y
z
z scale/20
z = 0 m
beam side view (external profile)
z = 2 m
only
5.5 mA
transported
V_y
$+1x10^5\ ms^{-1}$
0
$-1x10^5\ ms^{-1}$
section on beam axis
normalised beam density



y = + 5 cm
y = - 5 cm
20 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch
emittance
y
z
z scale/20
z = 0 m
beam side view (external profile)
z = 2 m
only
5.6 mA
transported
V_y
$+1x10^5\ ms^{-1}$
0
$-1x10^5\ ms^{-1}$
section on beam axis
normalised beam density

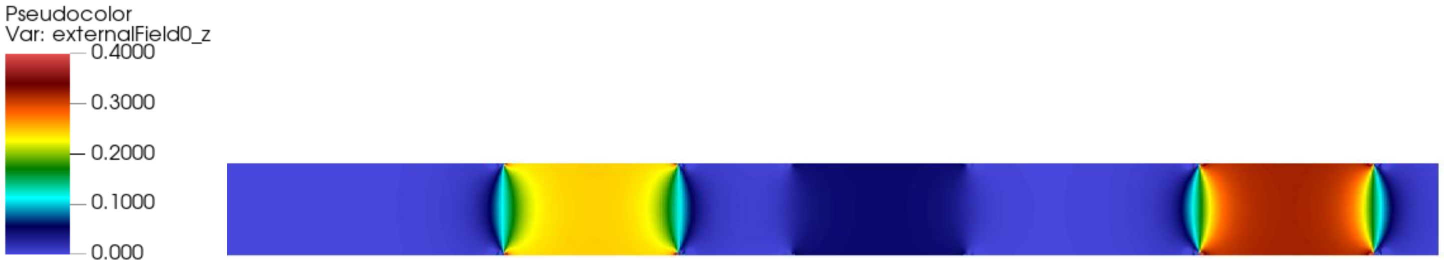


y = + 5 cm
y = - 5 cm
z = 0 m
z = 2 m
beam side view (external profile)
50 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch emittance
y
z
z scale/20
only 4.4 mA transported
V_y
$+1x10^5\ ms^{-1}$
0
$-1x10^5\ ms^{-1}$
section on beam axis
normalised beam density



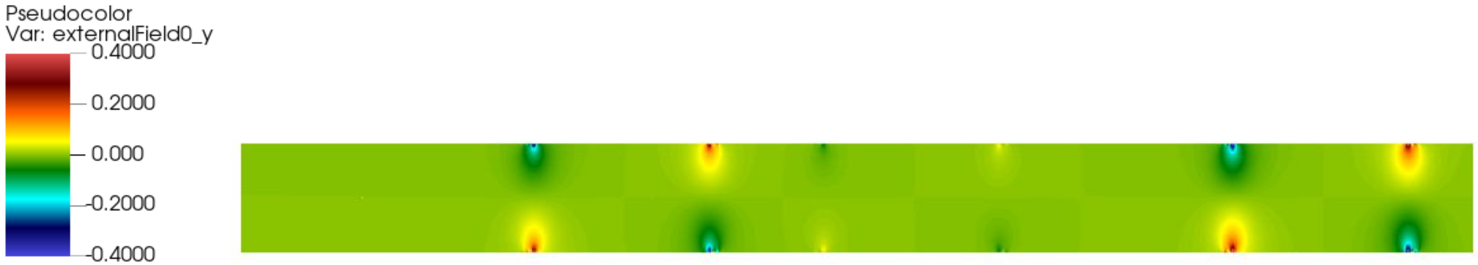
y = + 5 cm
Vy
+1x10^5 ms^-1
0
-1x10^5 ms^-1
100 mA beam
vy = -17.5.vz.y
vx = -17.5.vz.x
launch emittance
only 3.5 mA transported
section on beam axis
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
normalised beam density

add solenoids (usually 2 sometimes 3)

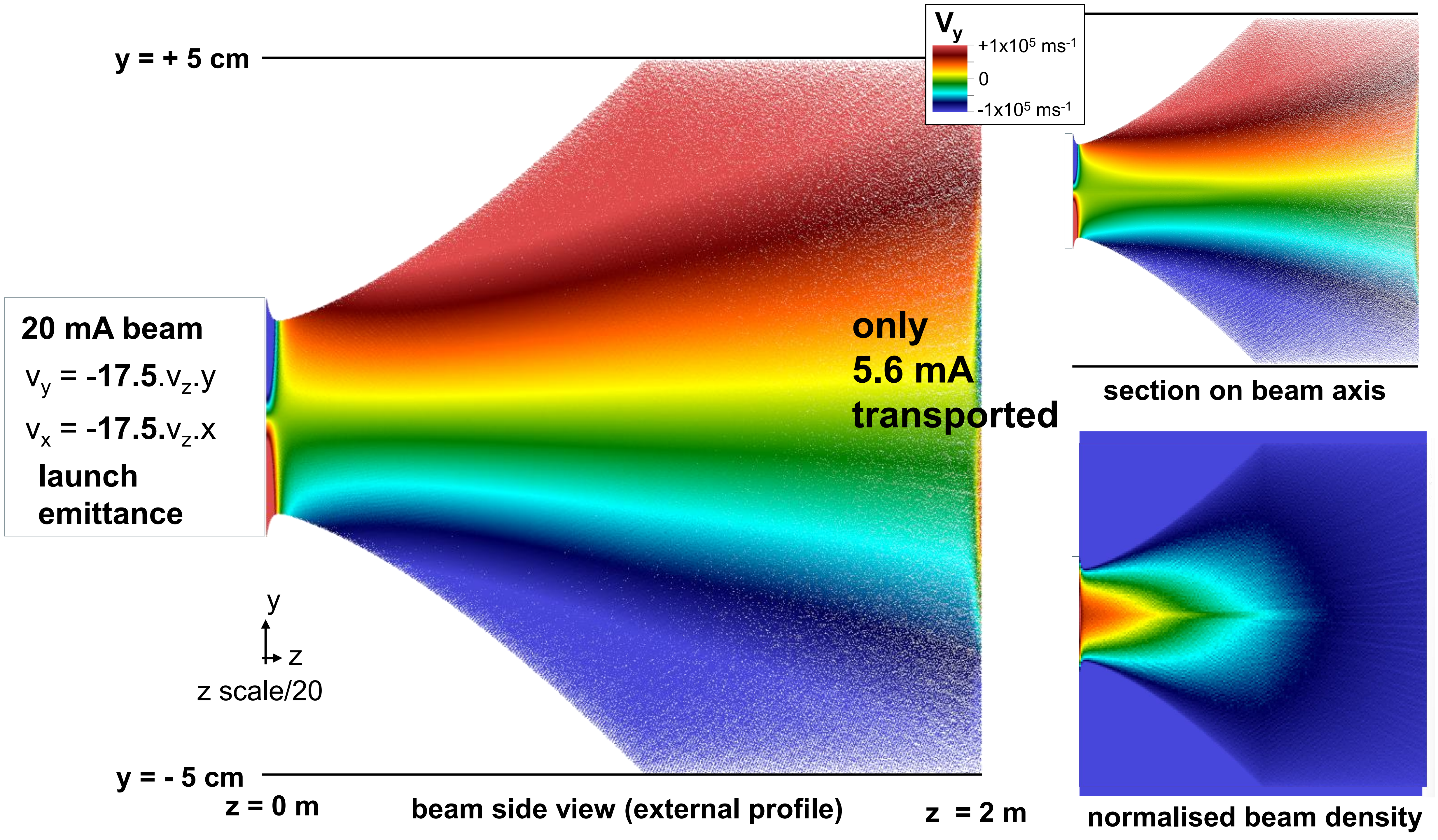


B_z

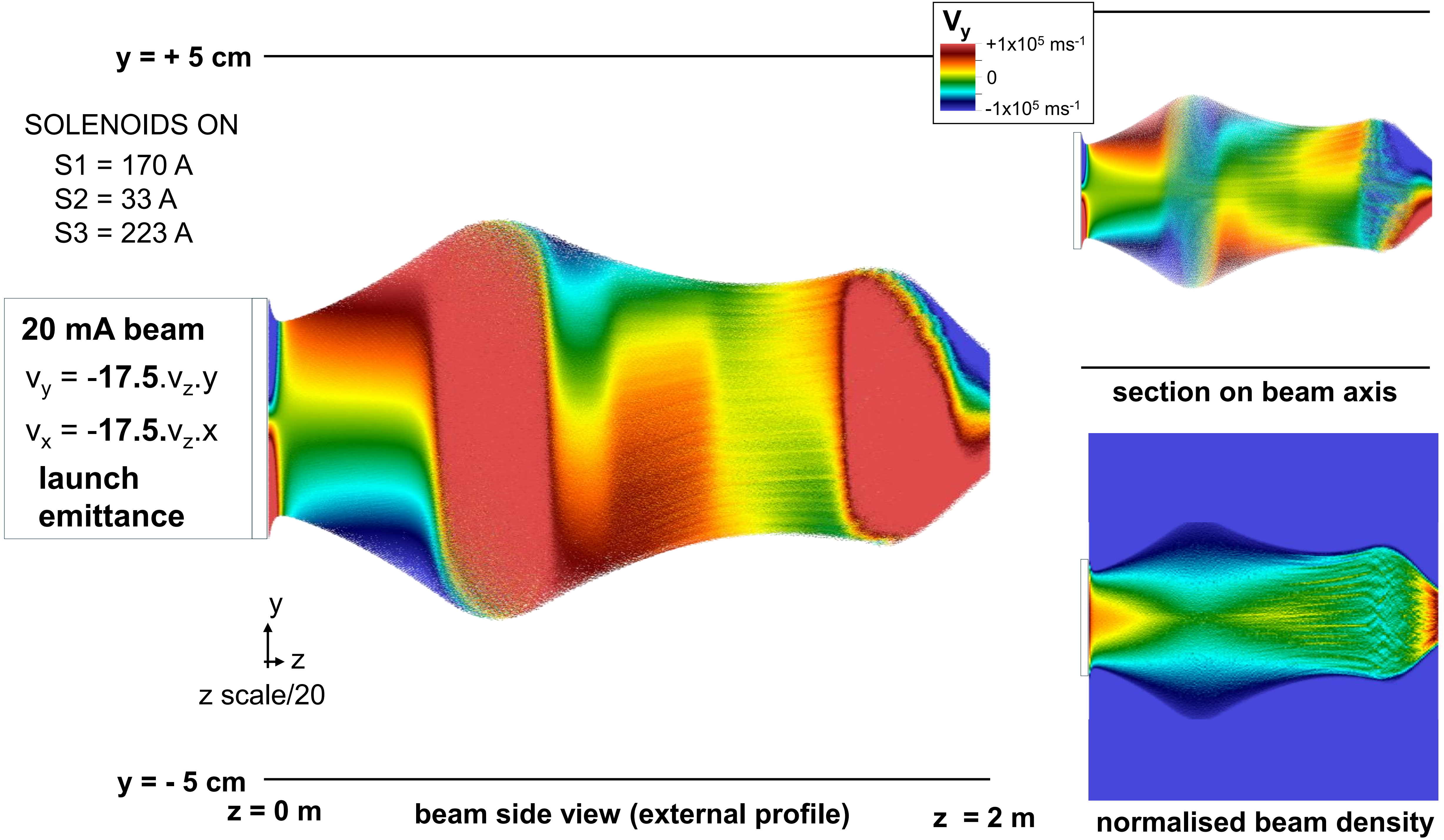
S1 = 170 A S2 = 33 A S3 = 223 A



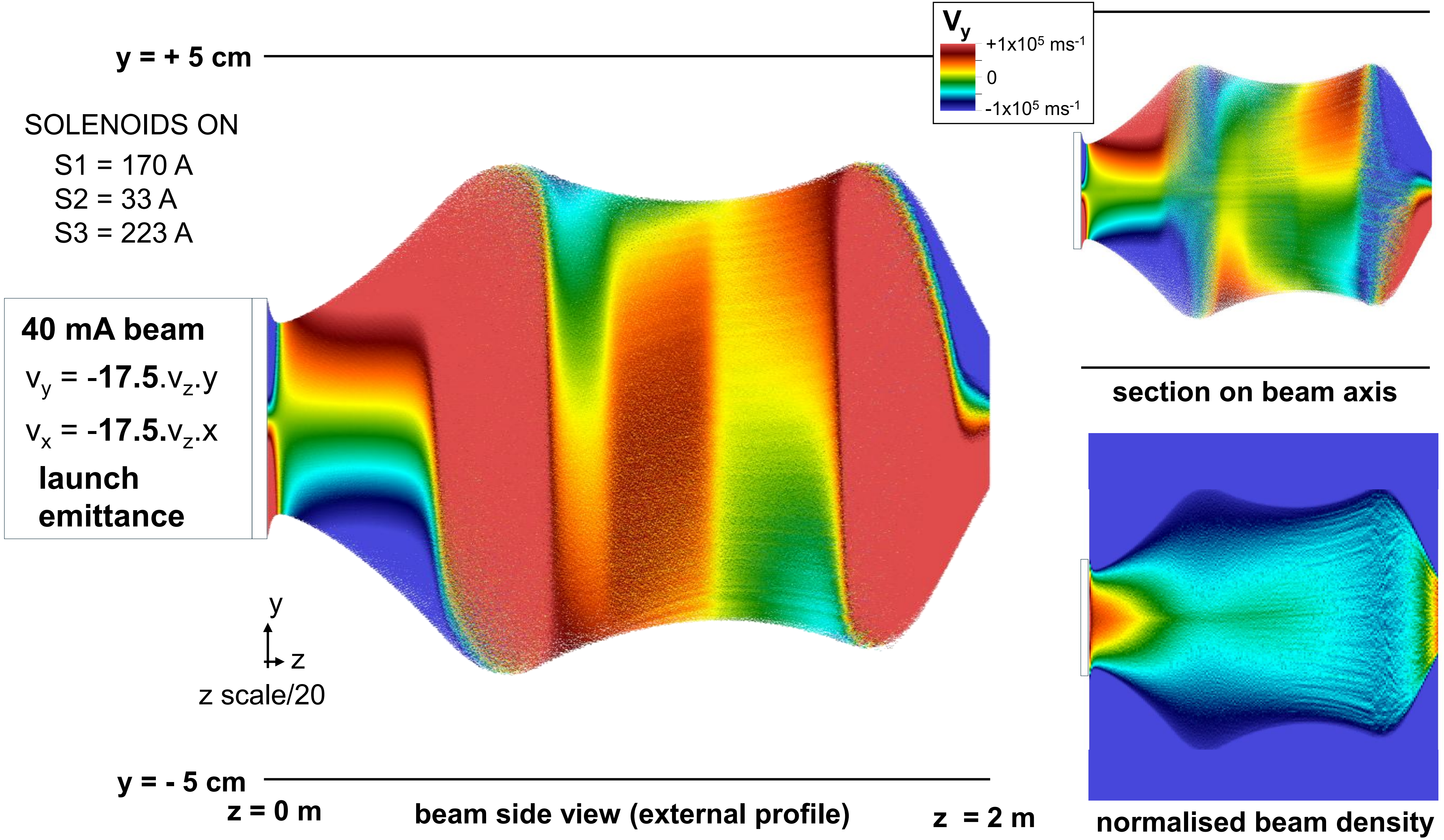
B_x and B_y

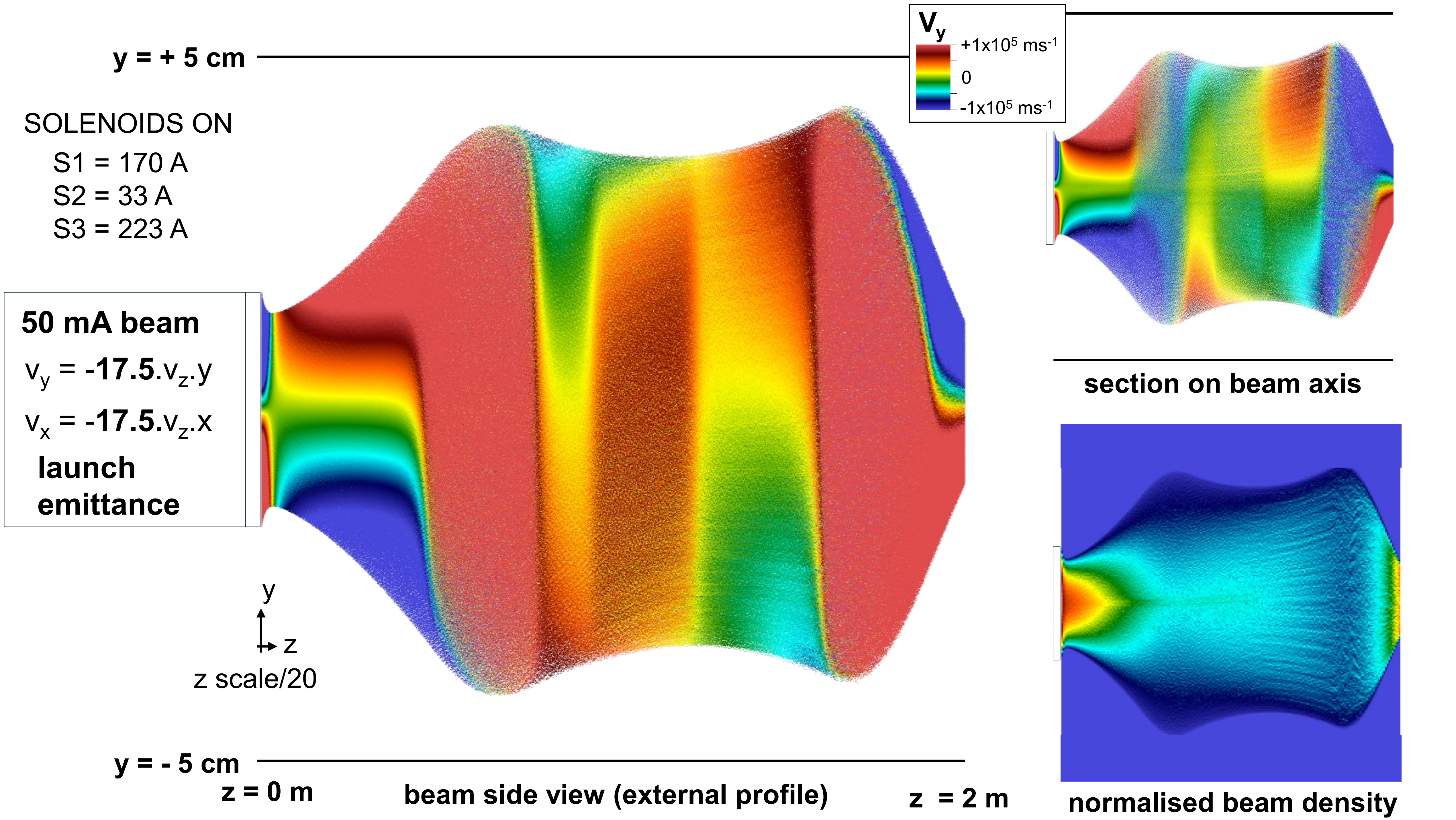


y = + 5 cm
y = - 5 cm
20 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch
emittance
y
z
z scale/20
z = 0 m
beam side view (external profile)
z = 2 m
only
5.6 mA
transported
V_y
$+1x10^5\ ms^{-1}$
0
$-1x10^5\ ms^{-1}$
section on beam axis
normalised beam density

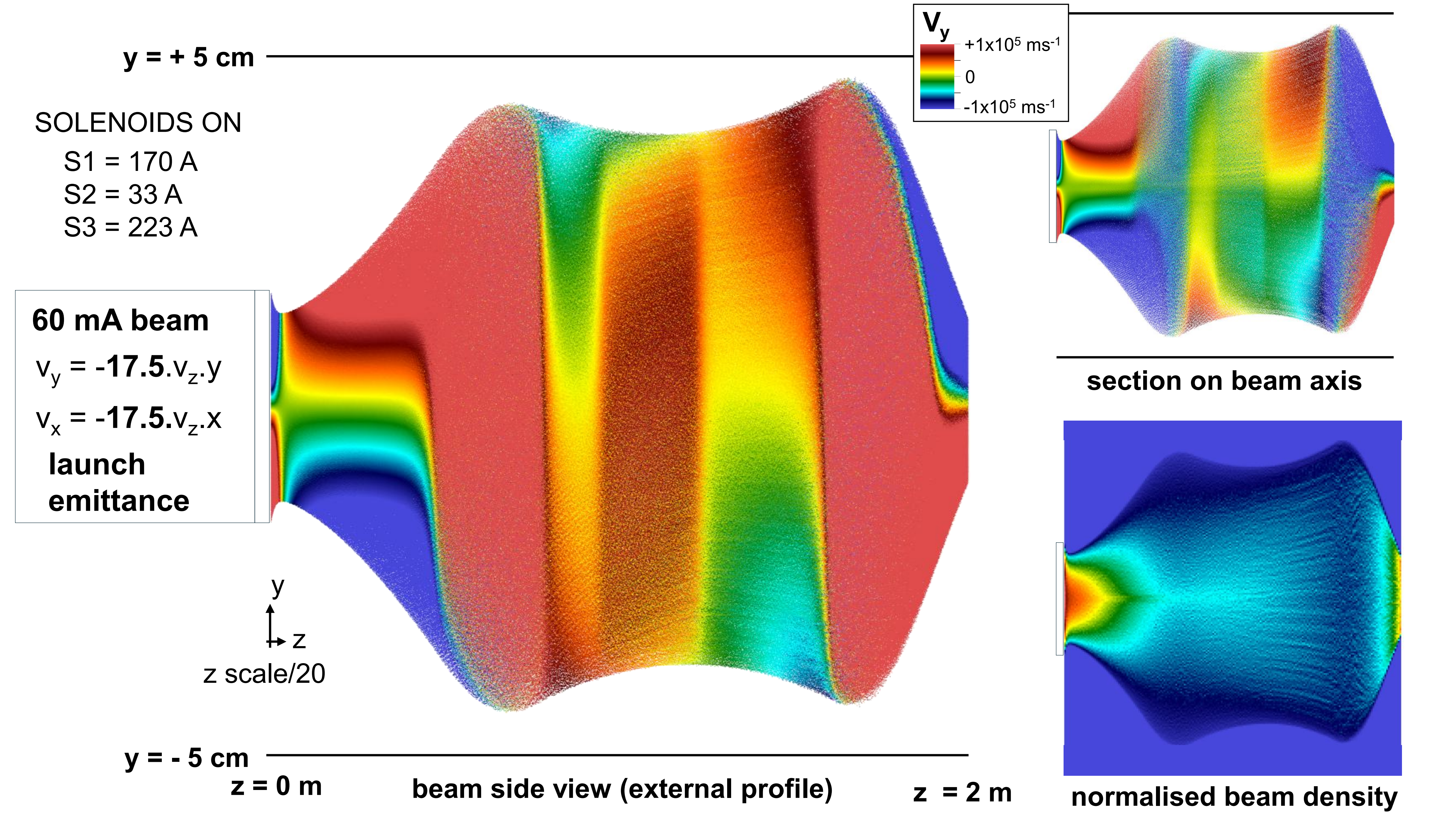


y = + 5 cm
SOLENOIDS ON
S1 = 170 A
S2 = 33 A
S3 = 223 A
20 mA beam
v_y = -17.5.v_z.y
v_x = -17.5.v_z.x
launch emittance
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
V_y
+1x10^5 ms^-1
0
-1x10^5 ms^-1
section on beam axis
normalised beam density

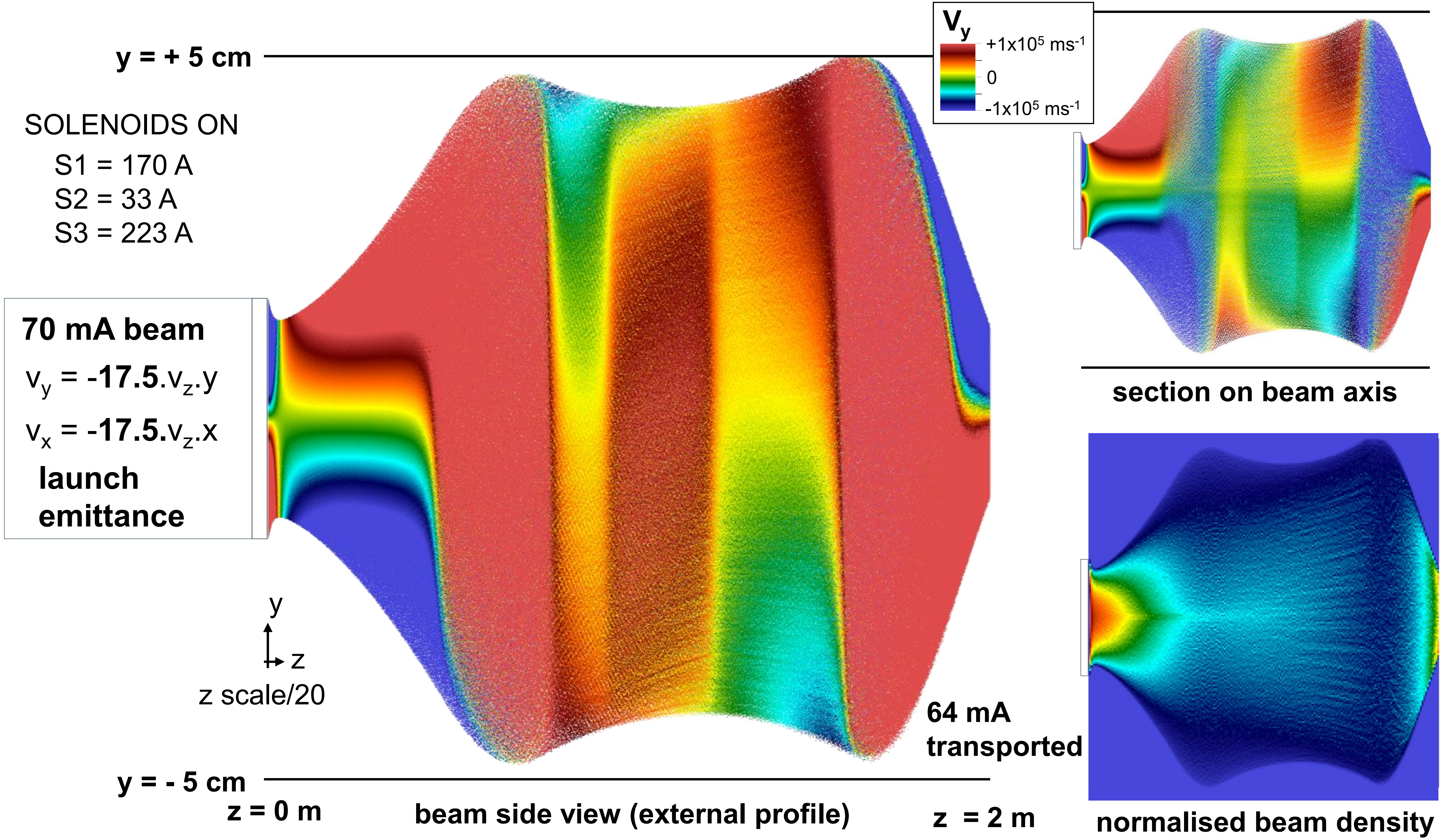

y = + 5 cm
SOLENOIDS ON
S1 = 170 A
S2 = 33 A
S3 = 223 A
40 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch emittance
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
V_y
$+1x10^5 ms^{-1}$
0
$-1x10^5 ms^{-1}$
section on beam axis
normalised beam density



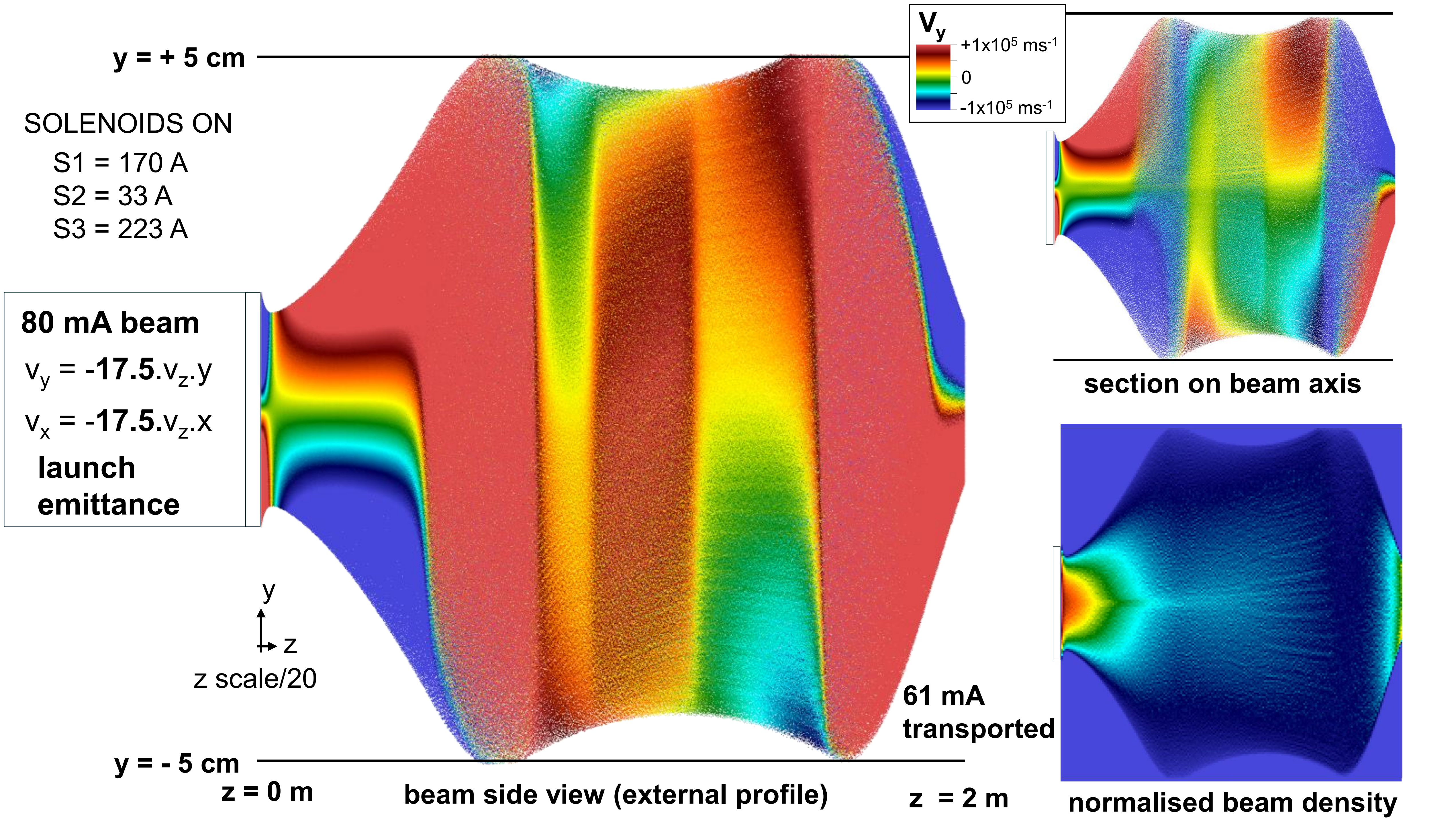
y = + 5 cm
SOLENOIDS ON
S1 = 170 A
S2 = 33 A
S3 = 223 A
50 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch emittance
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
V_y
$+1x10^5$ ms^{-1}
0
$-1x10^5$ ms^{-1}
section on beam axis
normalised beam density



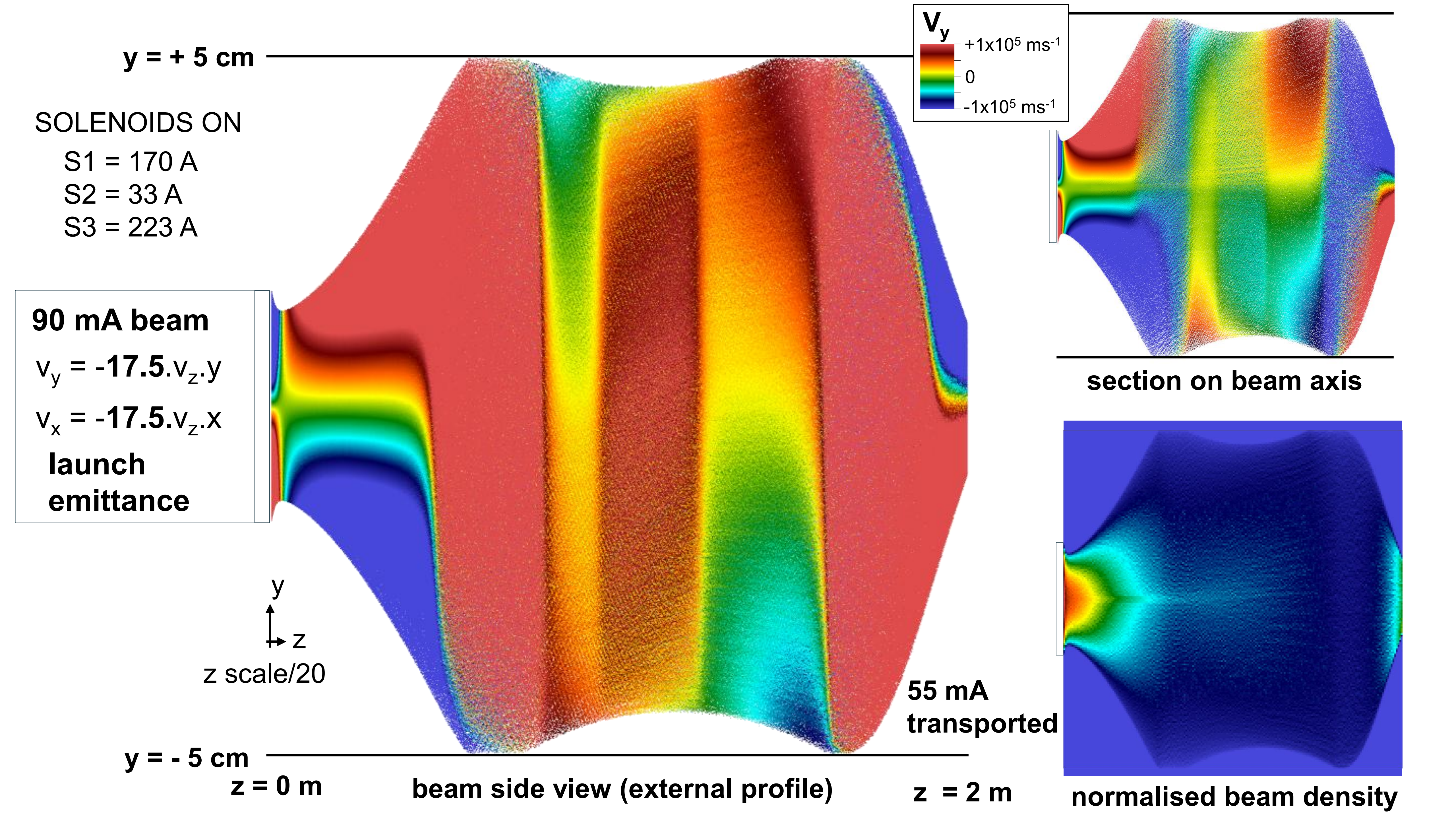
y = + 5 cm
SOLENOIDS ON
S1 = 170 A
S2 = 33 A
S3 = 223 A
60 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch emittance
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
V_y
$+1x10^5$ ms^{-1}
0
$-1x10^5$ ms^{-1}
section on beam axis
normalised beam density



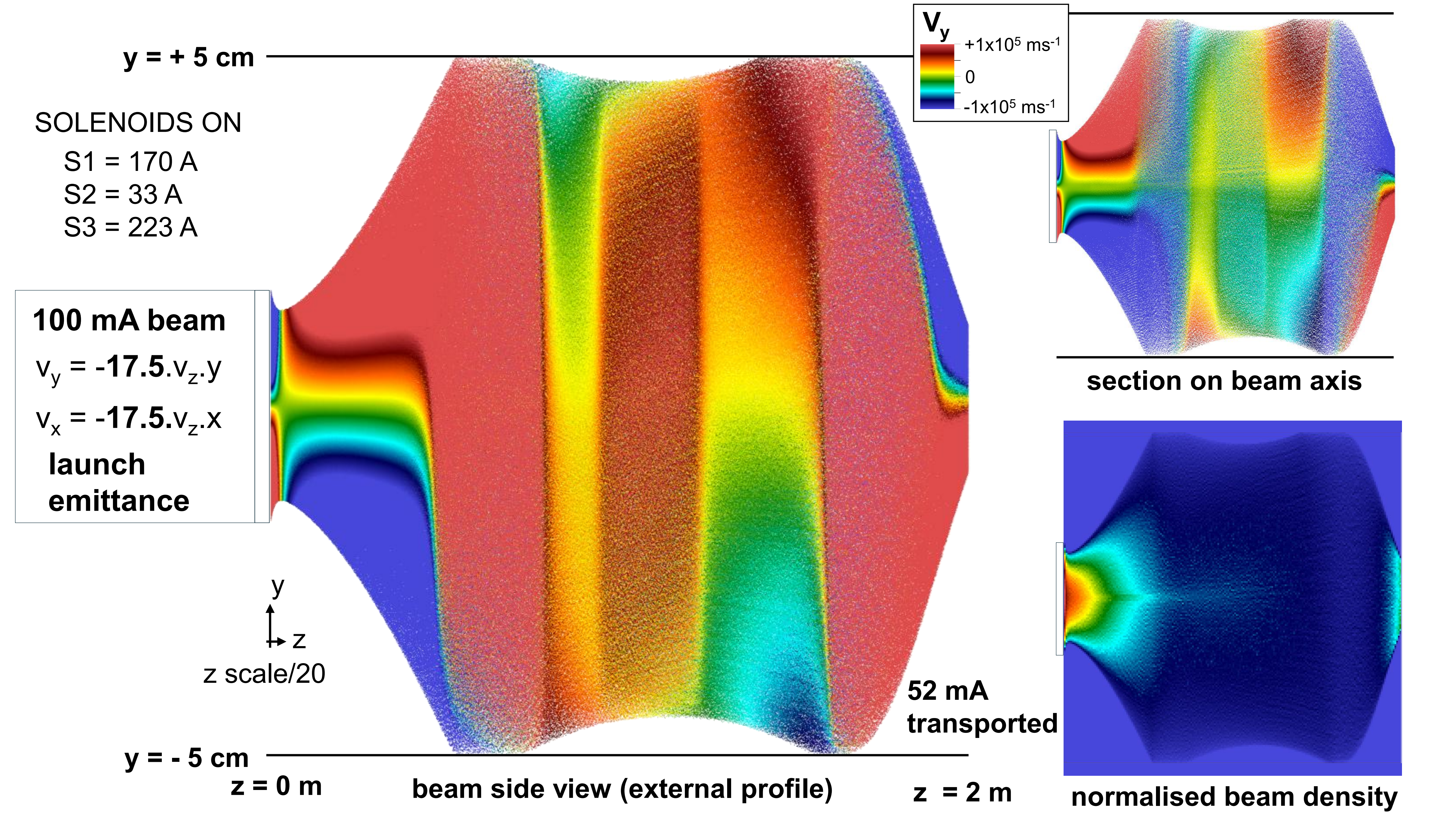
y = + 5 cm
SOLENOIDS ON
S1 = 170 A
S2 = 33 A
S3 = 223 A
70 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch emittance
y
z
z scale/20
64 mA transported
y = - 5 cm
z = 0 m
beam side view (external profile)
z = 2 m
V_y
$+1x10^5\ ms^{-1}$
0
$-1x10^5\ ms^{-1}$
section on beam axis
normalised beam density



y = + 5 cm
SOLENOIDS ON
S1 = 170 A
S2 = 33 A
S3 = 223 A
80 mA beam
$v_y = -17.5.v_z.y$
$v_x = -17.5.v_z.x$
launch emittance
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
61 mA transported
z = 2 m
V_y
$+1x10^5$ ms^{-1}
0
$-1x10^5$ ms^{-1}
section on beam axis
normalised beam density



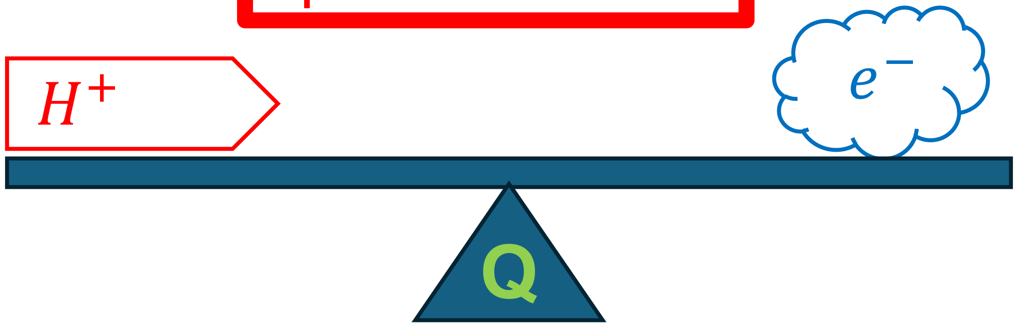
y = + 5 cm
SOLENOIDS ON
S1 = 170 A
S2 = 33 A
S3 = 223 A
90 mA beam
v_y = -17.5.v_z.y
v_x = -17.5.v_z.x
launch emittance
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
55 mA transported
z = 2 m
V_y
$+1x10^5\ ms^{-1}$
0
$-1x10^5\ ms^{-1}$
section on beam axis
normalised beam density



y = + 5 cm
SOLENOIDS ON
S1 = 170 A
S2 = 33 A
S3 = 223 A
100 mA beam
v_y = -17.5.v_z.y
v_x = -17.5.v_z.x
launch emittance
y
z
z scale/20
y = - 5 cm
z = 0 m
beam side view (external profile)
52 mA transported
z = 2 m
V_y
$+1x10^5$ ms^{-1}
0
$-1x10^5$ ms^{-1}
section on beam axis
normalised beam density

Space charge compensation reactions and compensating particles

proton beams

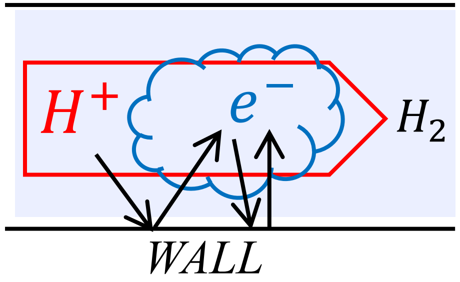


ion beam impact ionisation

$H^+ + H_2 \rightarrow H^+ + H_2^+ + e^-$

electron impact ionisation

$e^- + H_2 \rightarrow H_2^+ + 2e^-$



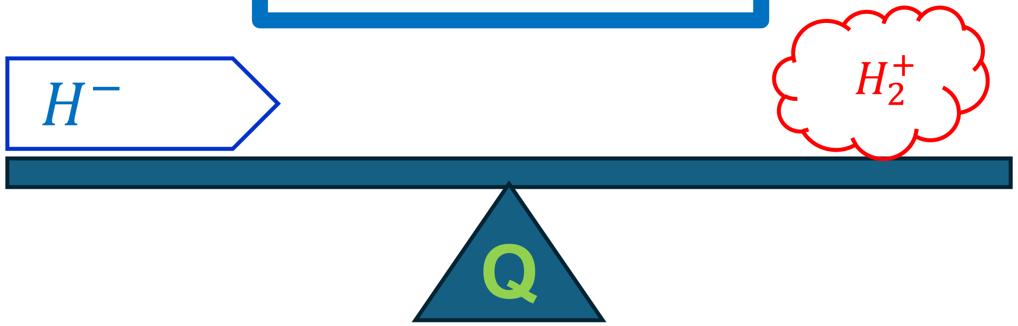
secondary electron production

$H^+ + WALL \rightarrow H^+ + e^-$

$e^- + WALL \rightarrow 2e^-$

compensation times in μs

Hminus beams

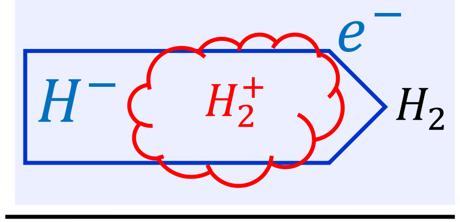


ion beam impact ionisation

$H^- + H_2 \rightarrow H^- + H_2^+ + e^-$

electron impact ionisation

$e^- + H_2 \rightarrow H_2^+ + 2e^-$



electron detachment

$H^- + H_2 \rightarrow H + H_2 + e^-$

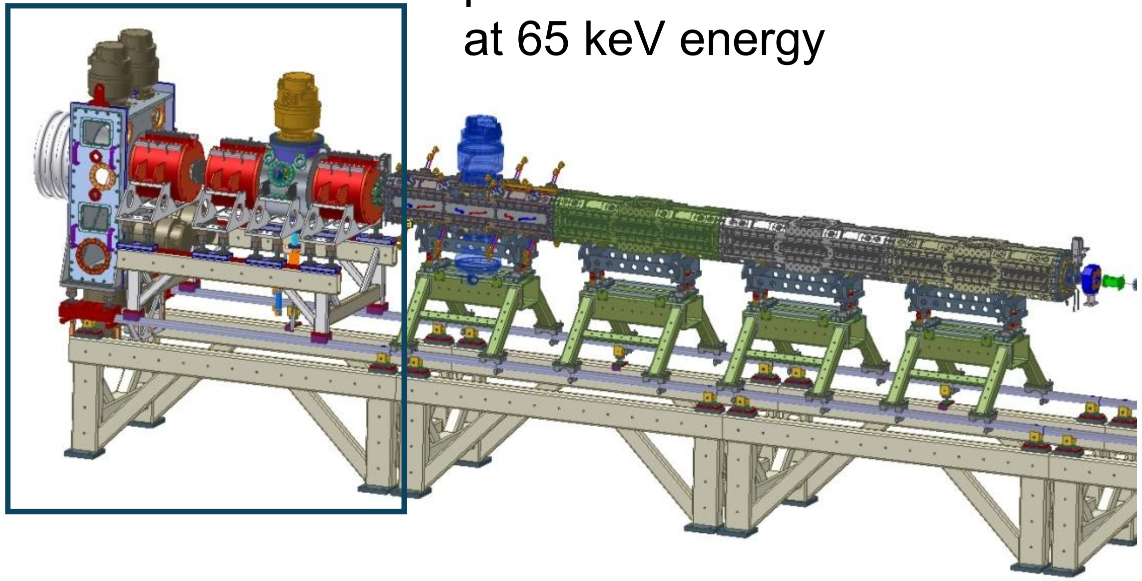
compensation times 10's of μs

compensating particle production rate is dependent on background gas pressure

Front End Test Stand (FETS) at RAL

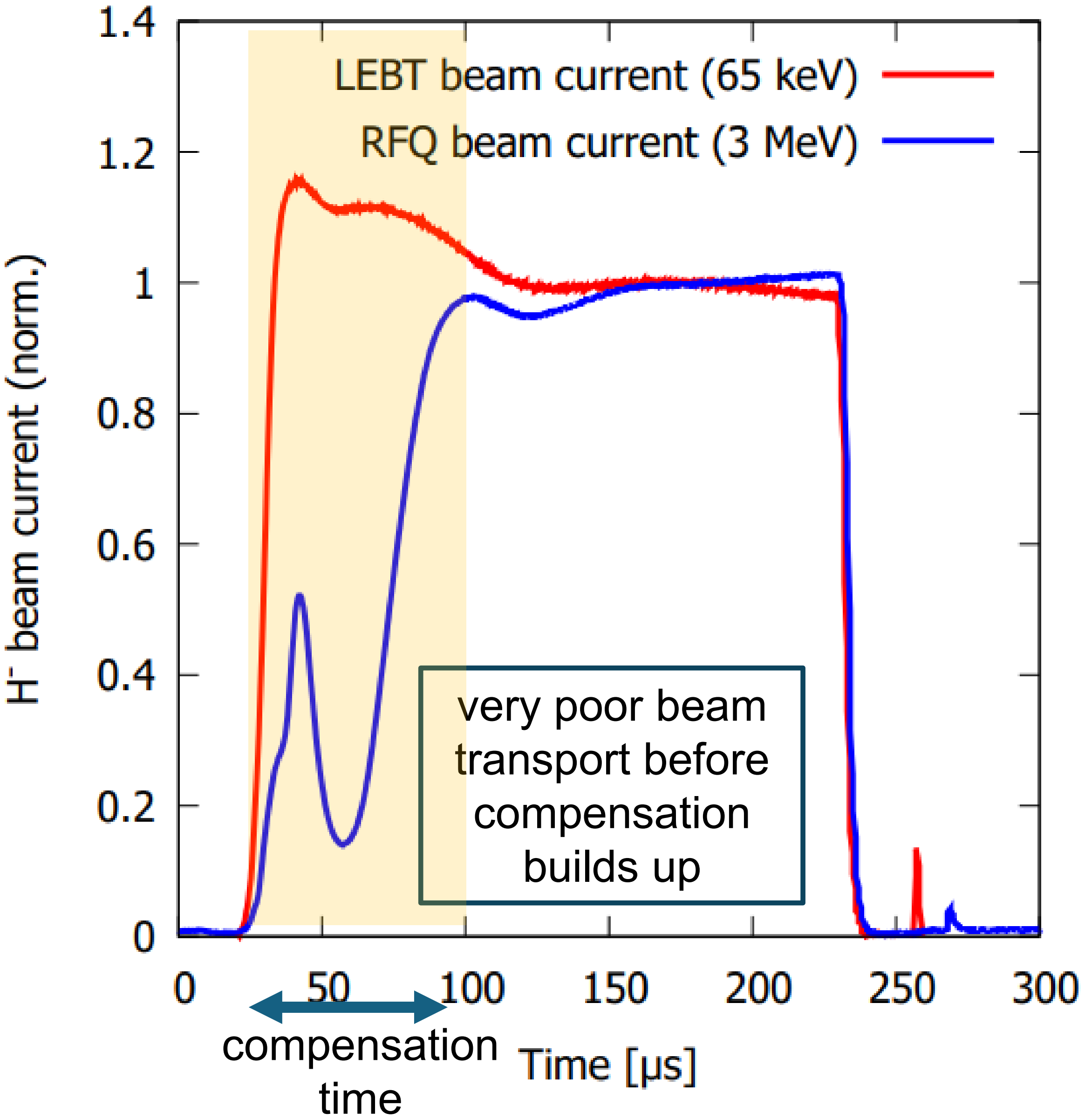
1.9 m long LEBT

pulsed 60 mA H^- beam
at 65 keV energy



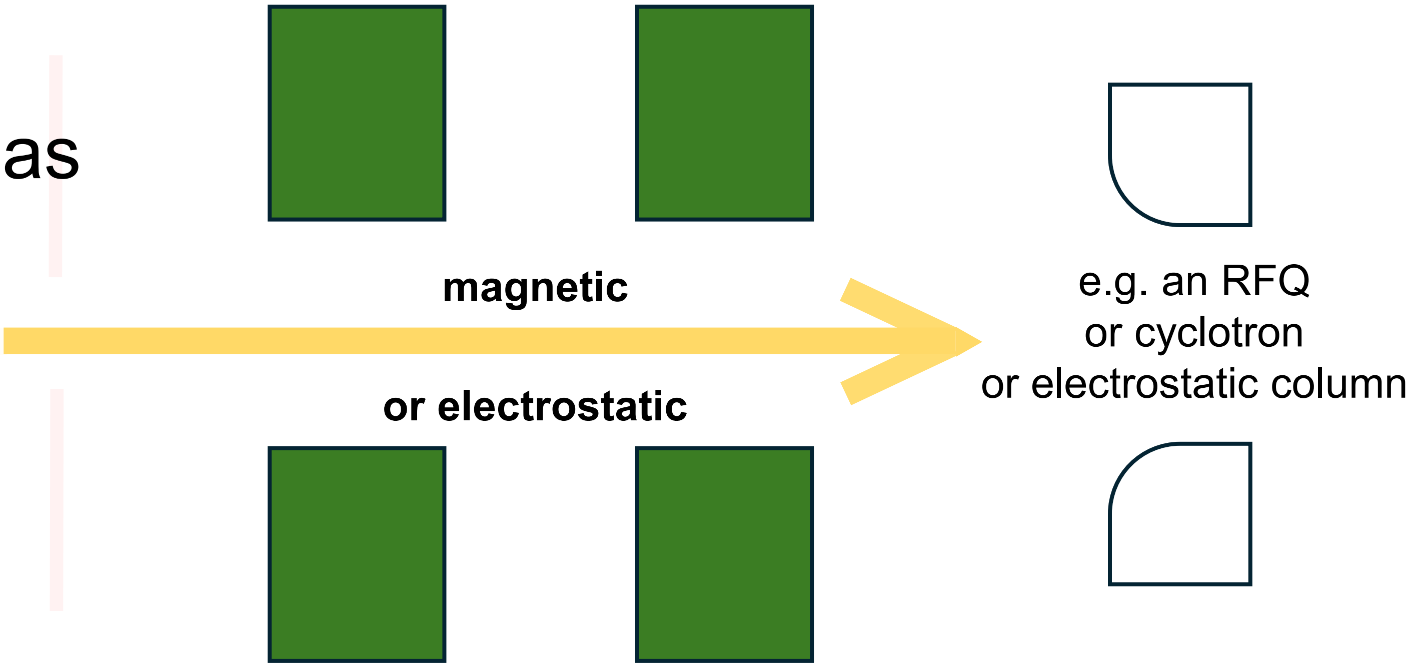
The degree of compensation varies,
It can reach 90%

Experimental and PIC research
program in progress…



For both positive and negative beams both the degree of space charge compensation can be increased by bleeding gas into the LEBT

transport the low energy beam



higher pressures in the LEBT can lead to increased sputtering damage in the RFQ

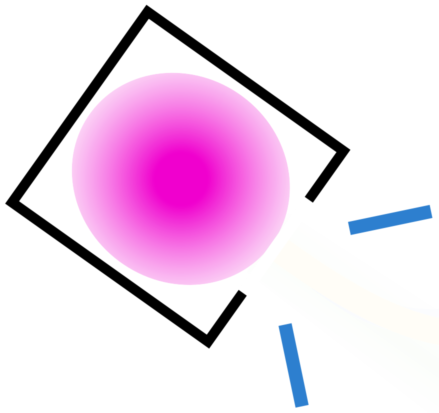
Summary

- Particle sources are a huge interesting subject
- A perfect mixture of engineering and physics
- We have only scratched the surface

Thank you for listening
Questions?

Additional slides

extraction in ion sources is **NOT** limited by

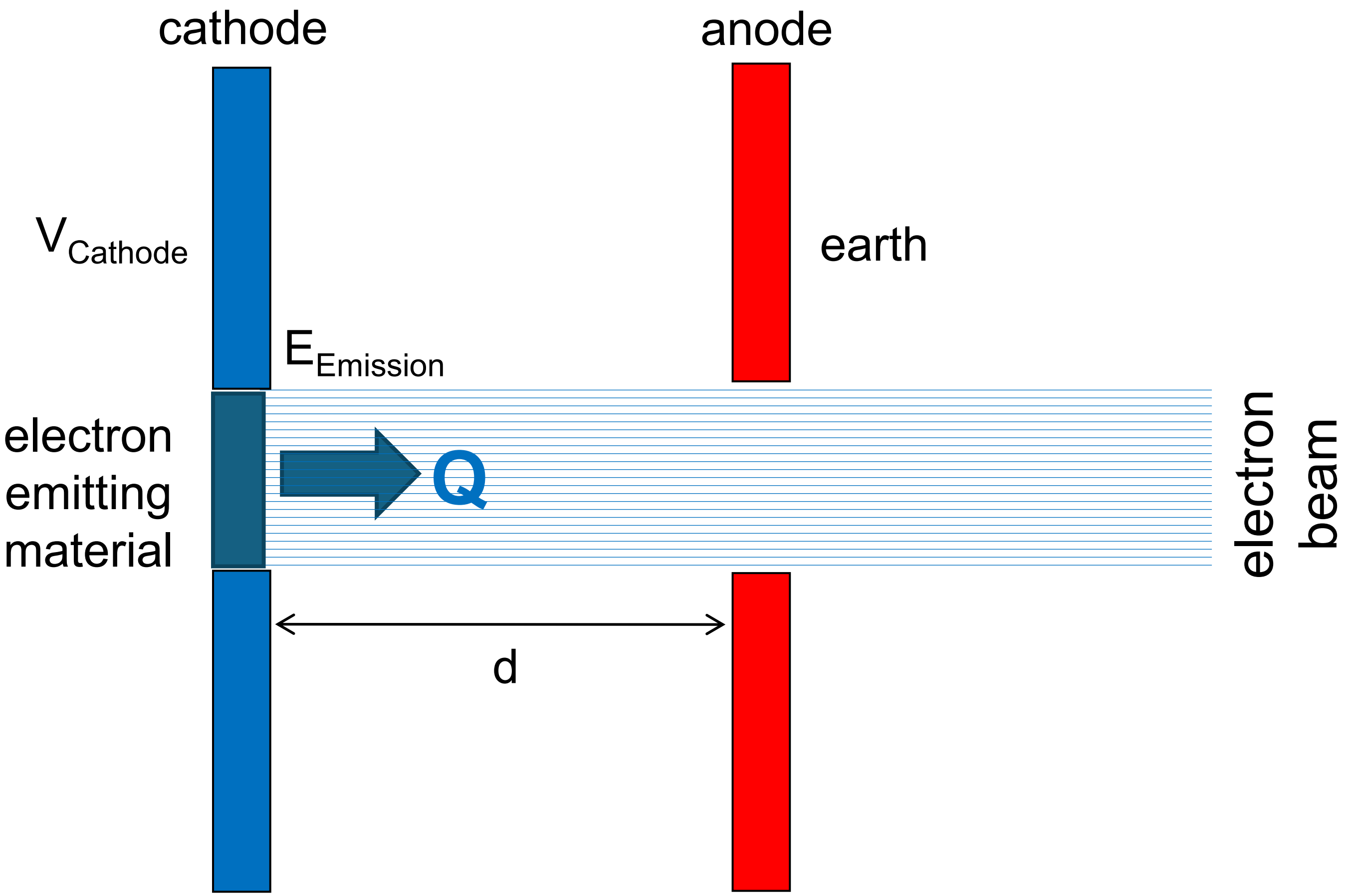


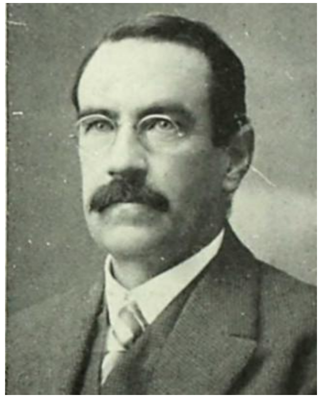
C.D Child
1911

I Langmuir
1913

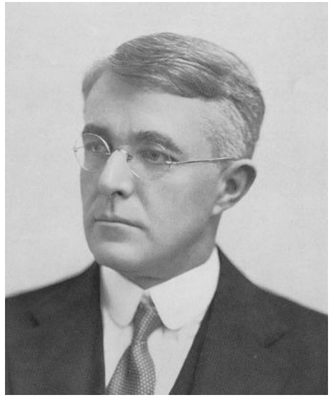
Child-Langmuir Law

(Space charge limited extraction)





C.D Child
1911



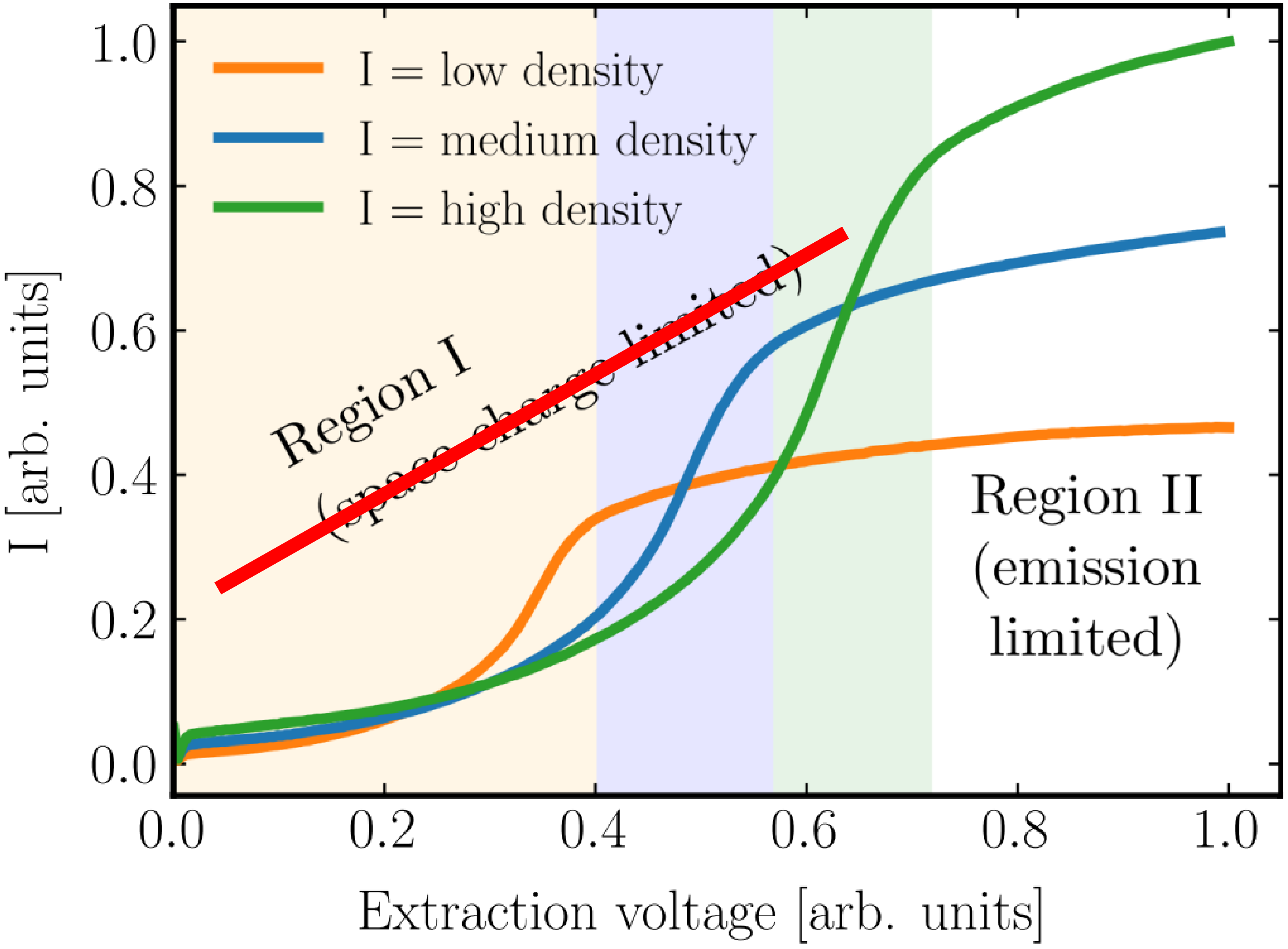
I Langmuir
1913

$$j = \frac{\frac{4}{9}\varepsilon_0 \sqrt{\frac{2e}{m_e}} V^{\frac{3}{2}}}{d^2}$$

Assumptions

1. There are infinitely many particles available to be emitted. ✗
2. The emitted particles have zero initial velocity. ✗
3. The emitted particles have non-relativistic velocities. ✓
4. The electrodes are parallel and infinite in the plane normal to the beam. ✗
5. Constant spatial distribution of particles perpendicular to the direction of beam propagation. ✗
6. Zero electric field at the emitting surface. ✗

Accepted wisdom



As espoused by:

The physics and technology of ion sources 2nd Ed.
Brown I. 2004
(Wiley-VHC)

Theory and design of charged particle beams
Reiser M. 2009
(Wiley-VHC)

Particle Sources
Faircloth D. 2011-2023
(CERN Accelerator School)

… and many others

Recent Work

Critical assessment of the applicability of the Child-Langmuir law to plasma ion source extraction systems

S T Kosonen, T Kalvas, V Toivanen, O Tarvainen, D Faircloth

Plasma Sources Sci. Technol. **32** 075005
Published 12 July 2023
DOI 10.1088/1361-6595/ace0d7

UNIVERSITY OF JYVÄSKYLÄ

UKRI Science and Technology Facilities Council

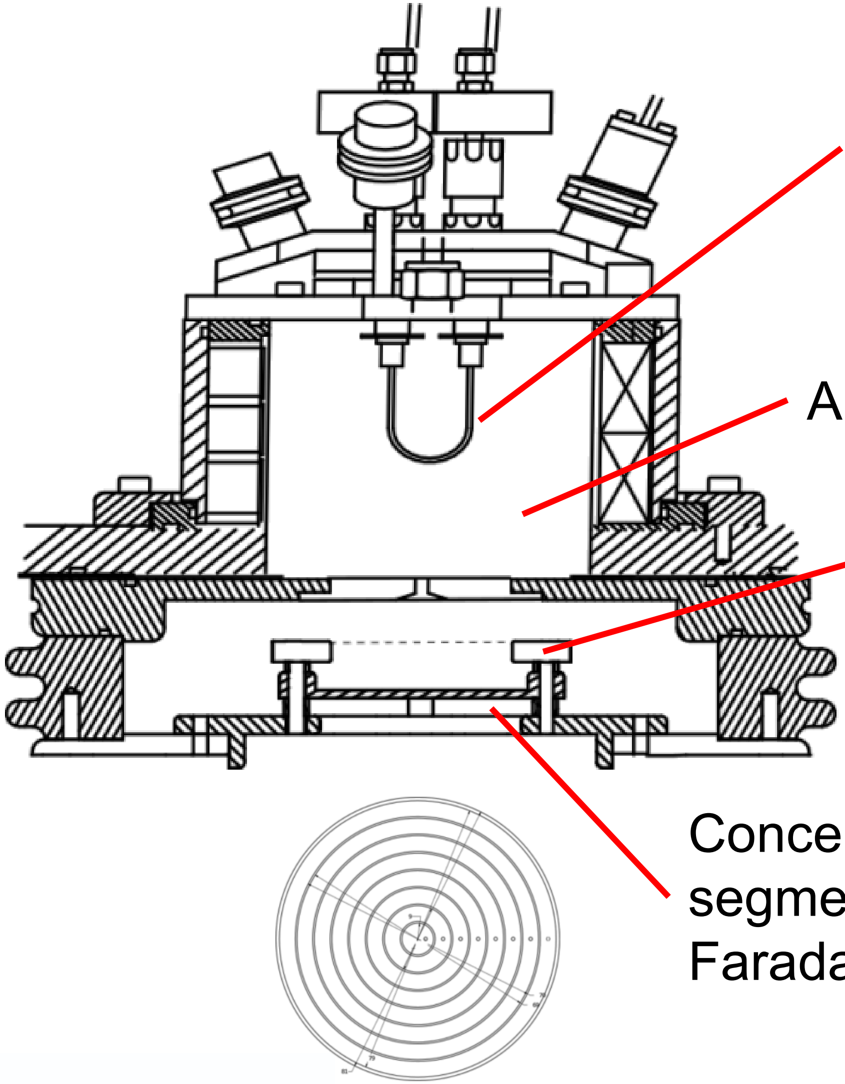
The Child Langmuir Illusion

D. Faircloth, T Kalvas, S Kosonen, O Tarvainen and V Toivanen

J. Phys.: Conf. Ser. 2743 012085
Published 12 Jan 2024
DOI 10.1088/1742-6596/2743/1/012085

Experiments + Modelling = Confirmation that the observed power law is caused by meniscus focusing and collimation

Experiments

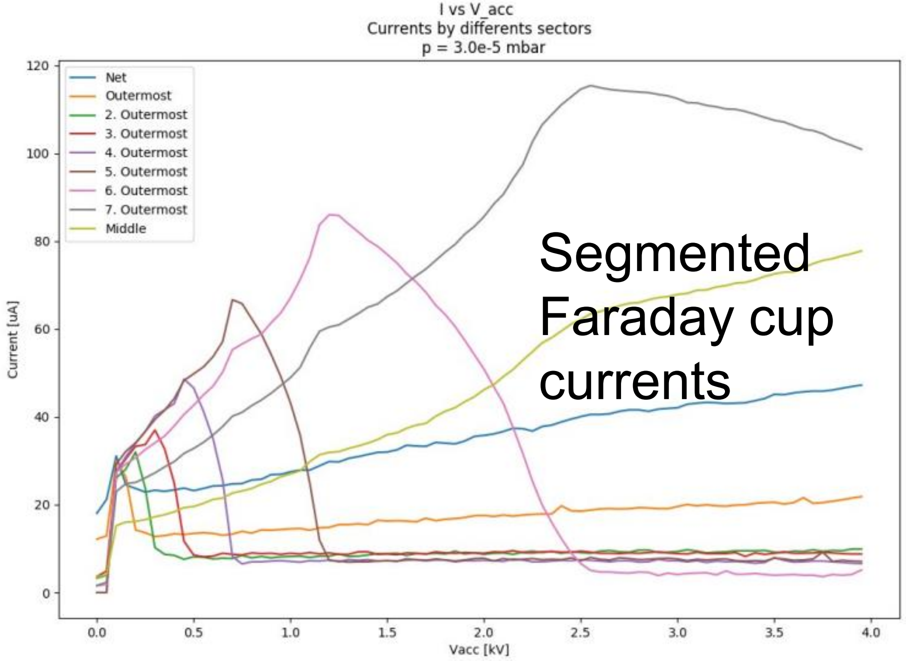


Simple filament source

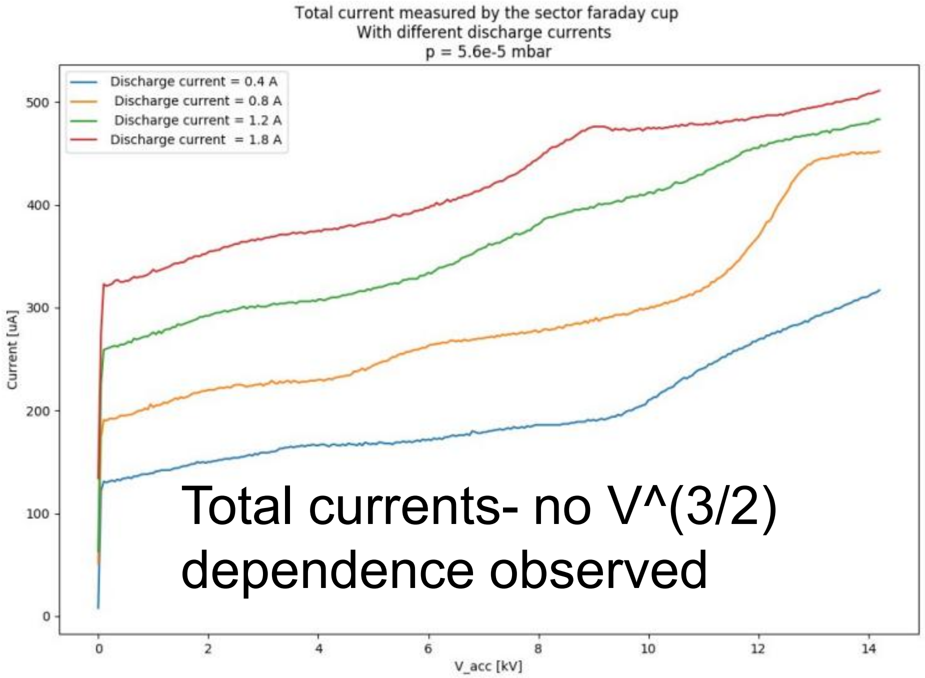
Argon plasma

Grid extraction (no collimation)

Concentric segmented ring Faraday cup



Segmented Faraday cup currents



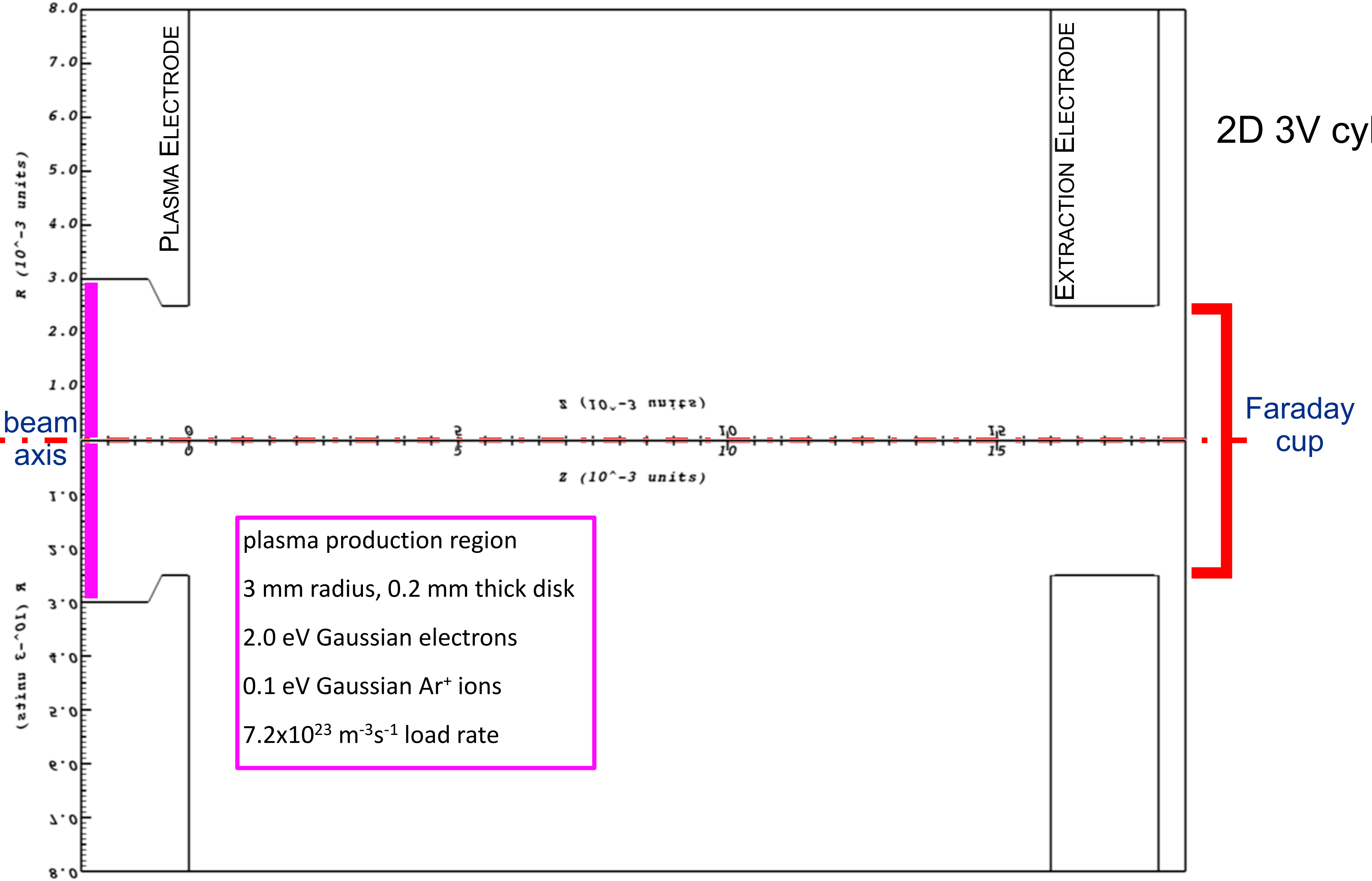
Total currents- no V^(3/2) dependence observed

100 µA beams

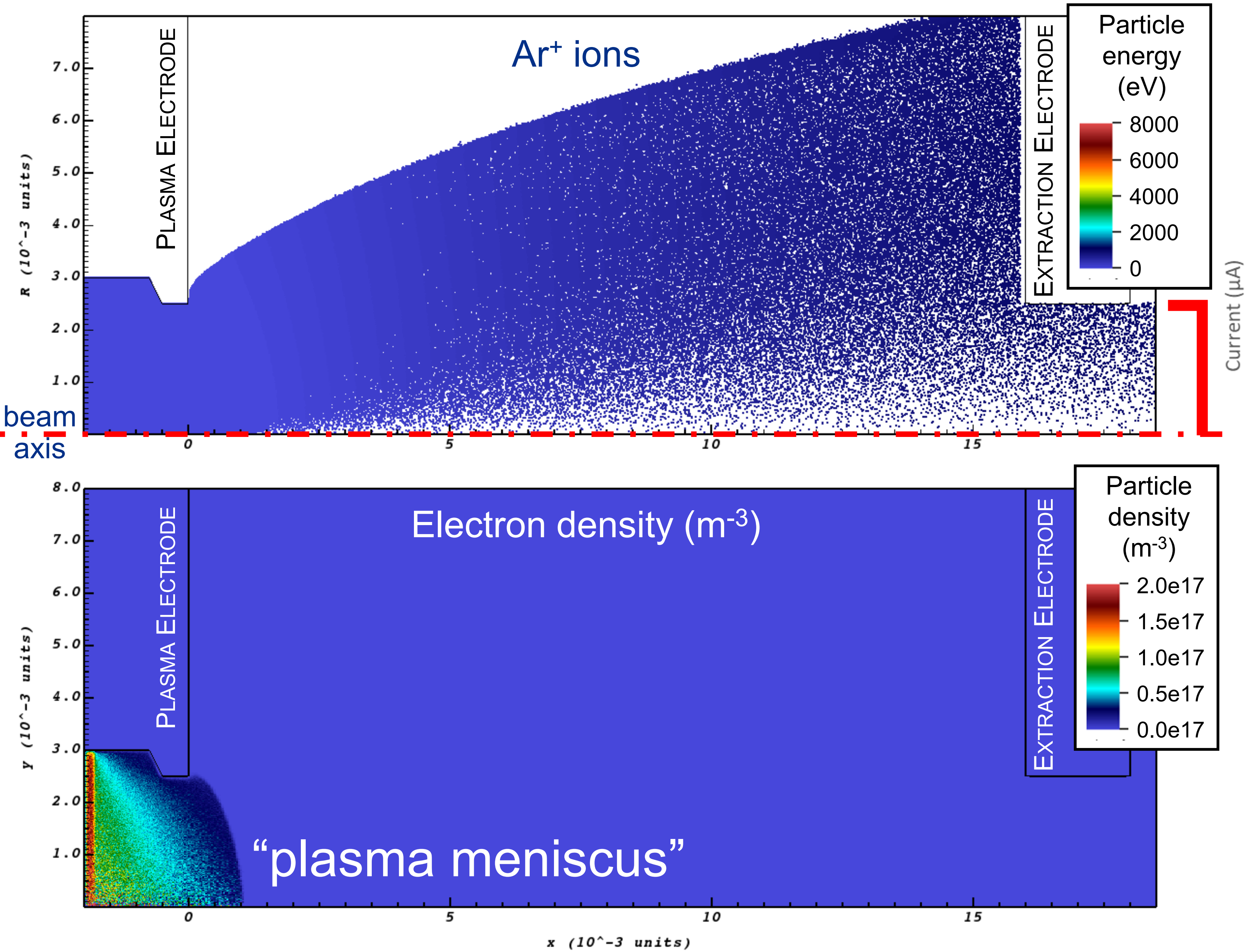
The true cause of the observed “power law” is meniscus focusing and collimation on the extraction (puller) electrode

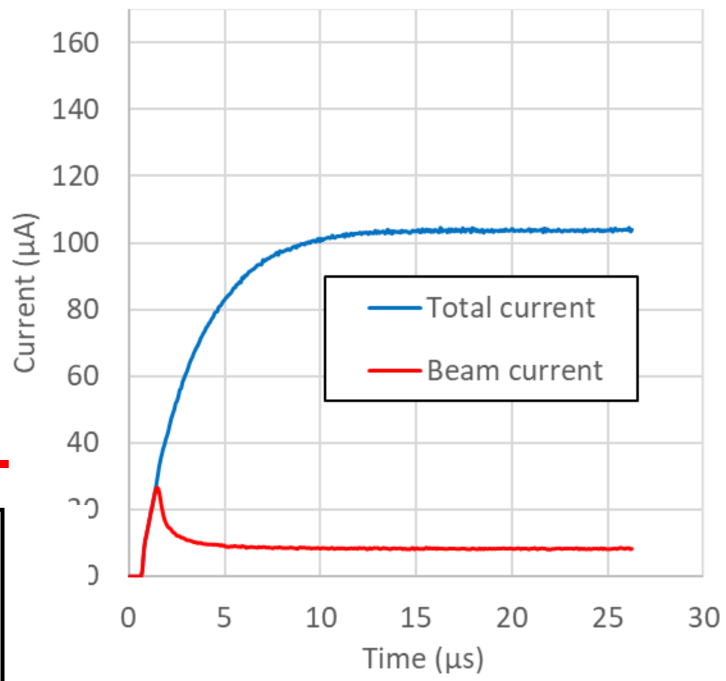
Particle In Cell (PIC)

2D 3V cylindrical symmetric model



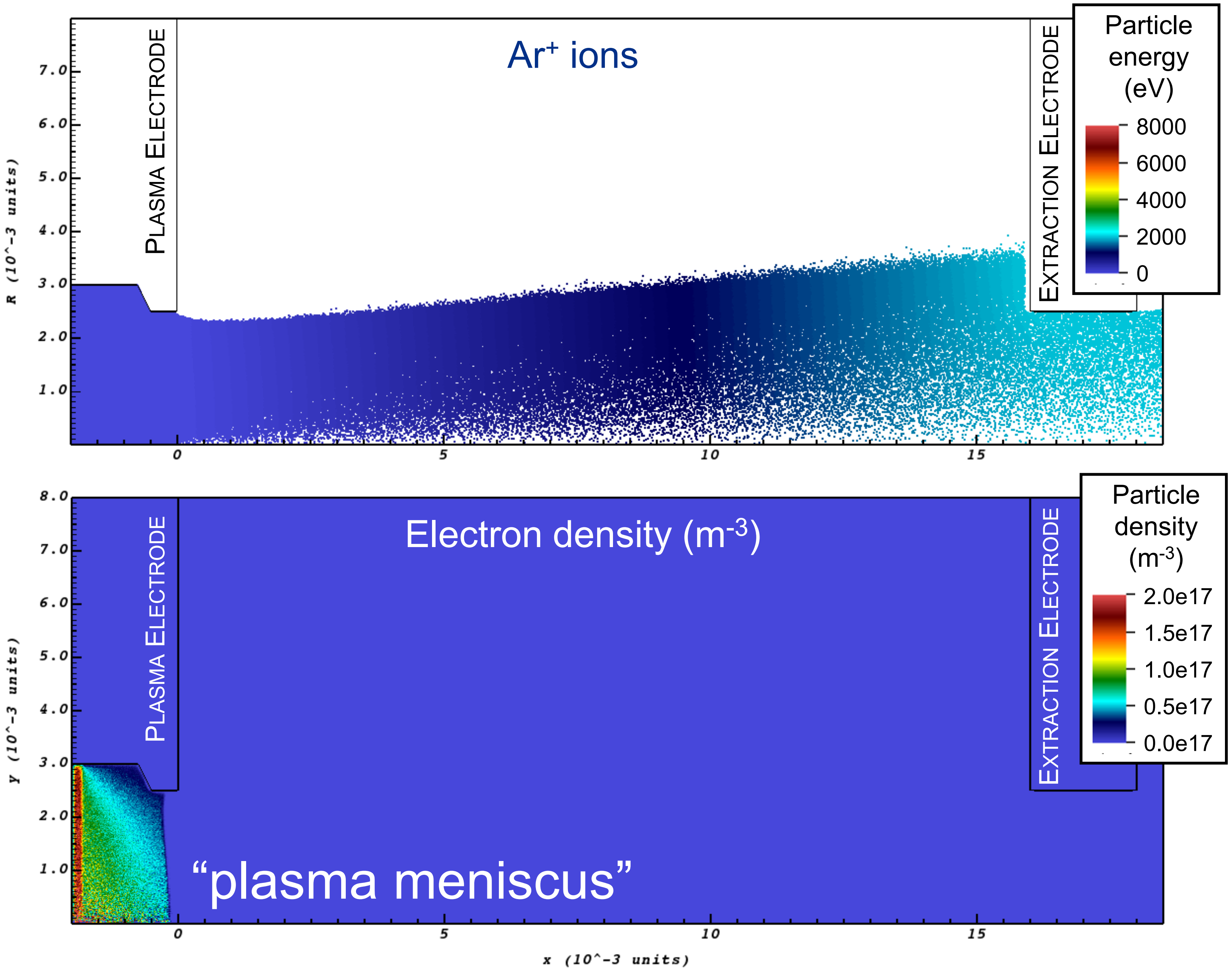
1 kV Extraction Voltage

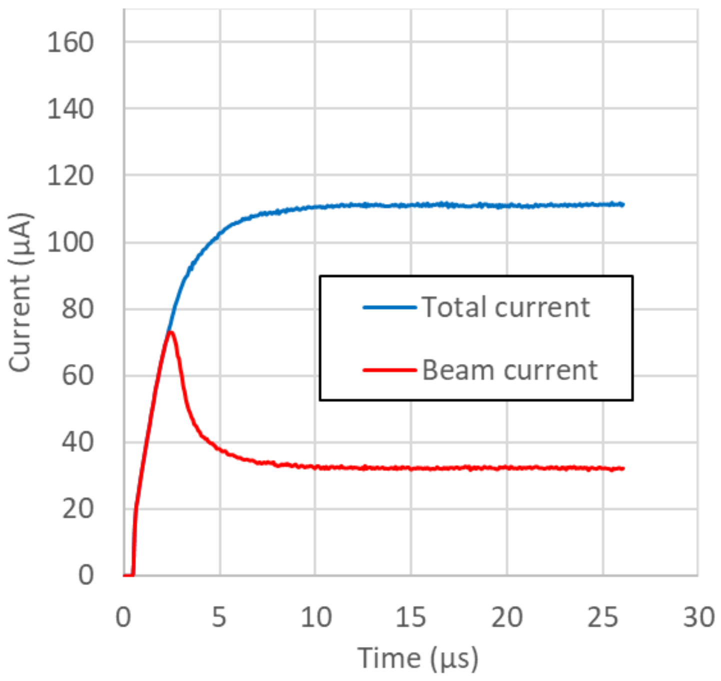




The plasma density balances the applied extraction field to form a “meniscus”

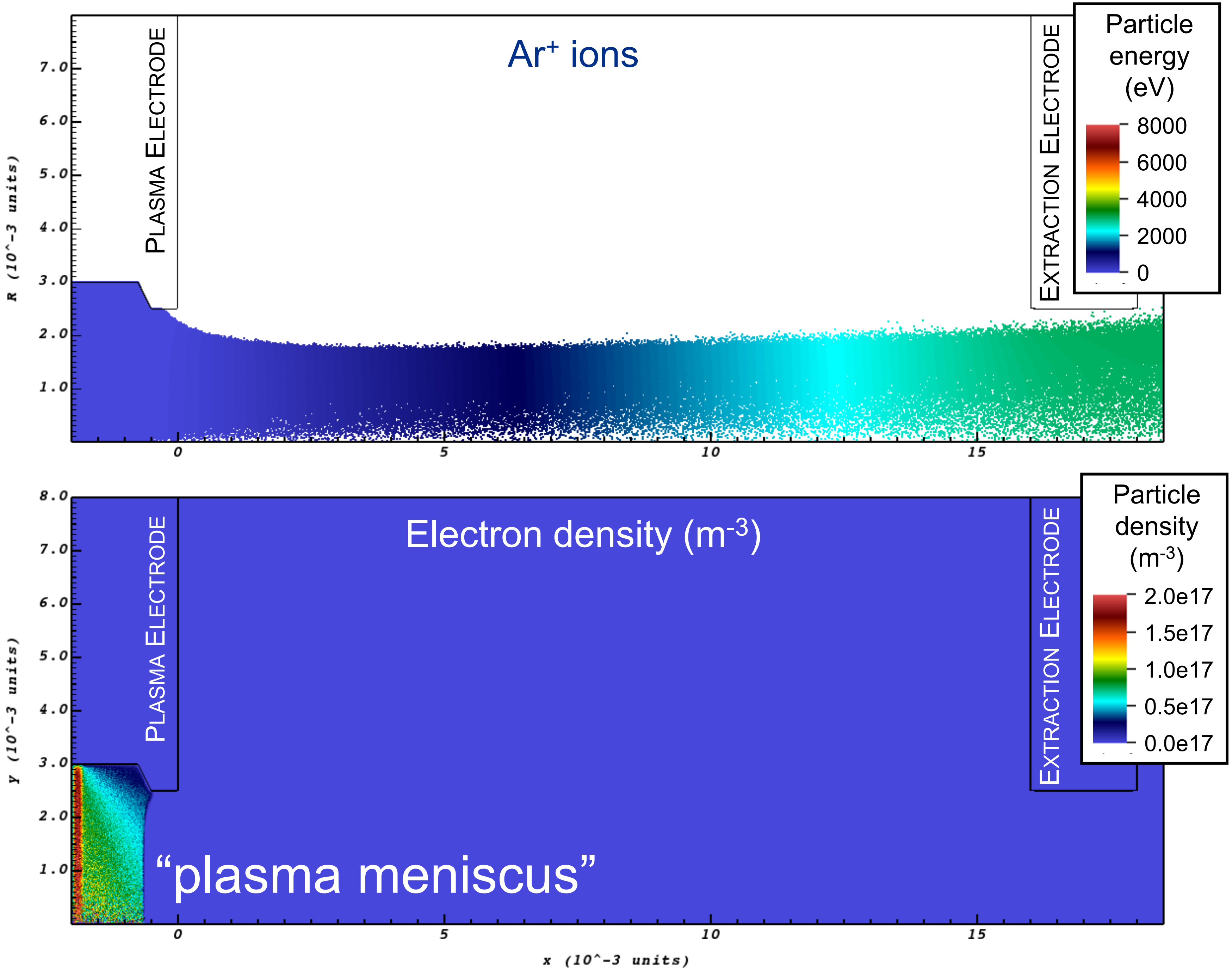
2 kV Extraction Voltage

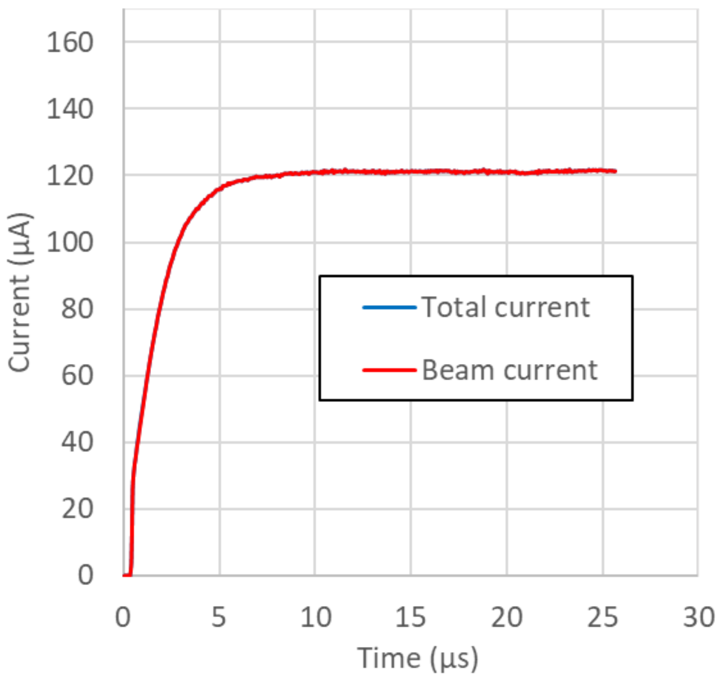




The "meniscus" is pushed back as the extraction voltage is increased

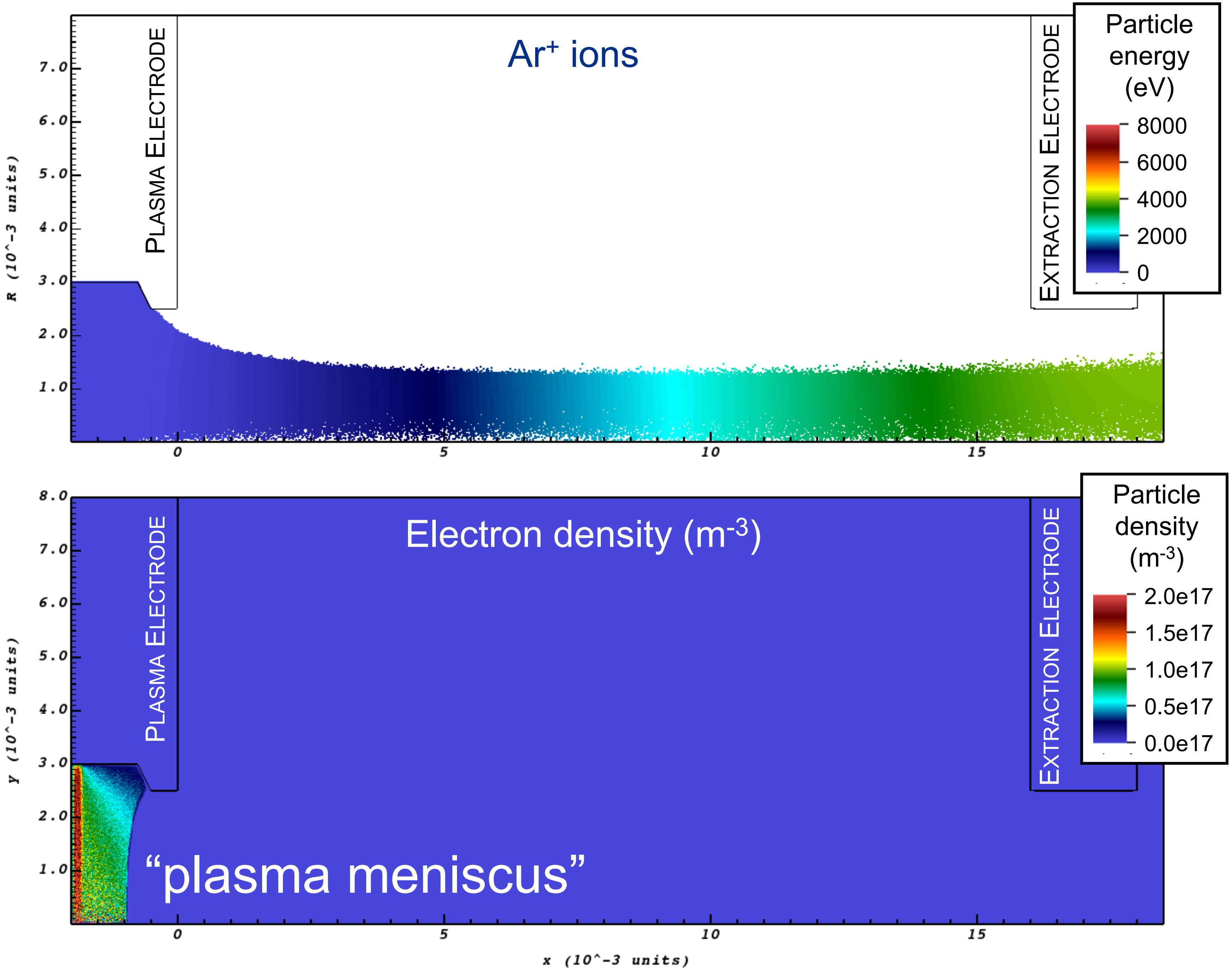
3 kV Extraction Voltage

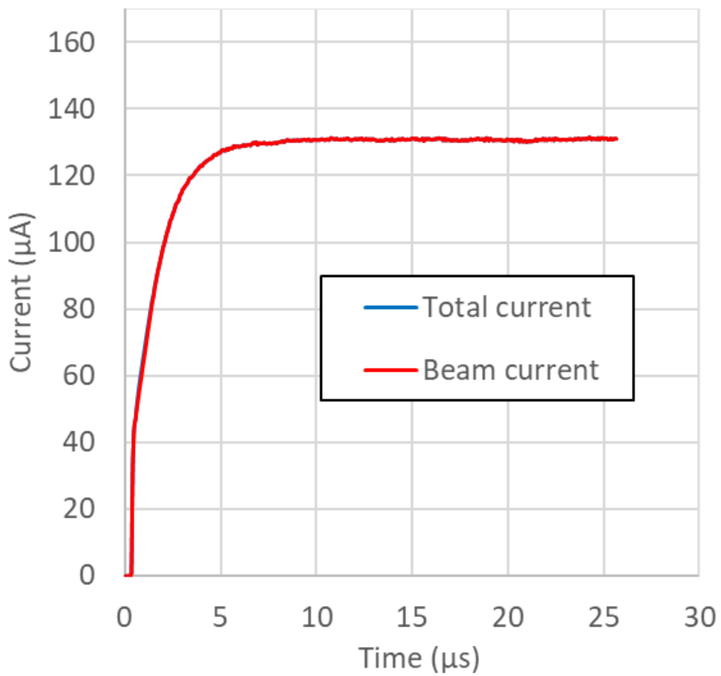




The "meniscus" is pushed back as the extraction voltage is increased

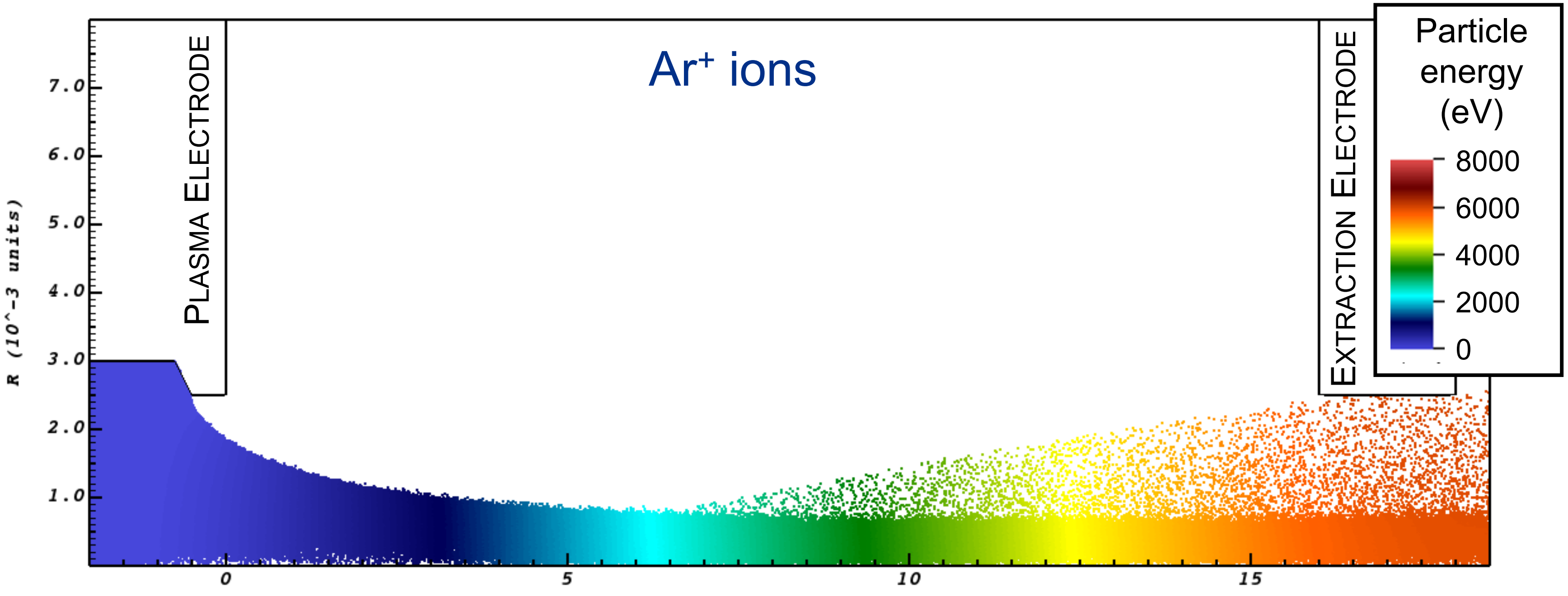
4 kV Extraction Voltage

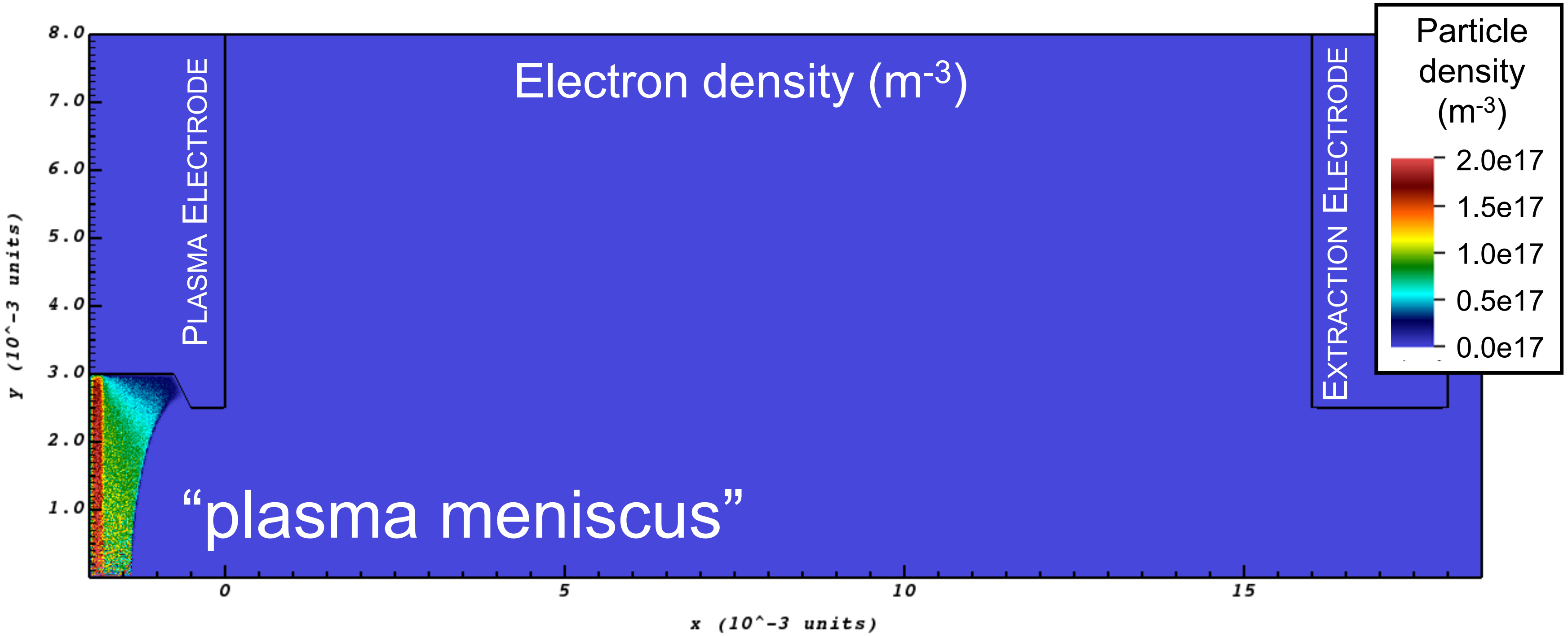


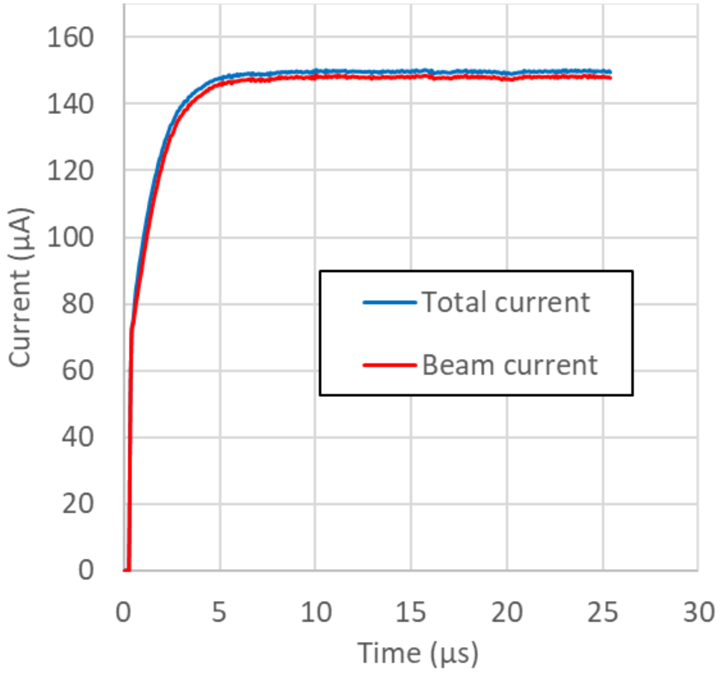


causing the beam to change shape as the extraction voltage changes

6 kV Extraction Voltage







causing the beam to change shape as the extraction voltage changes

Beam current and total current vs extraction voltage