Scaling Laws in Electron Cyclotron Resonance Ion Sources

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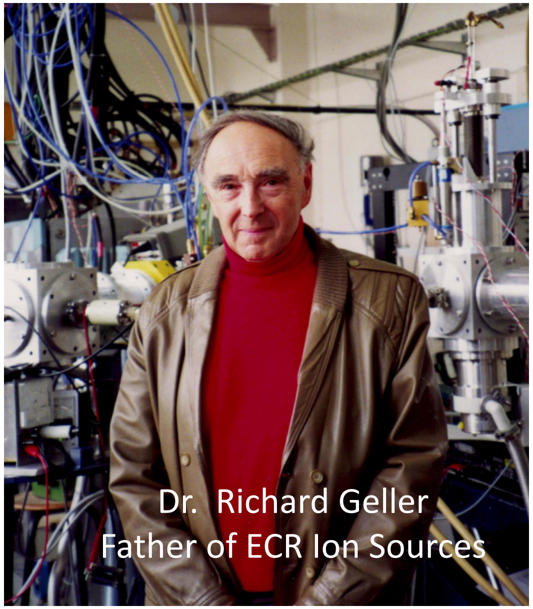
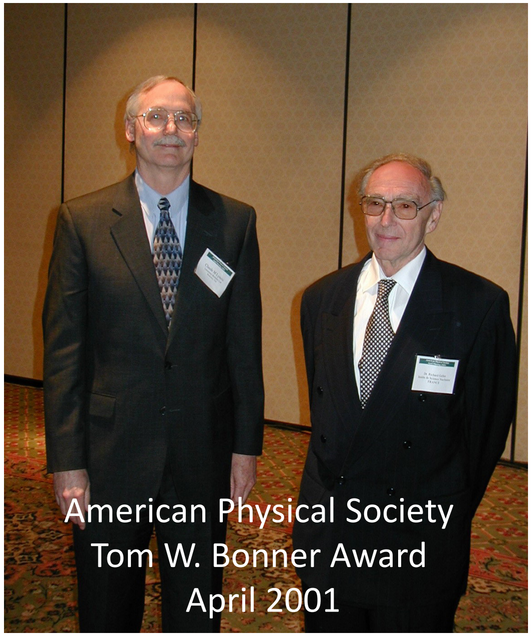
Chronology of ECR Ion Source Workshops

No.	Year	Date	Location
1.	1978	6 November	Karlsruhe, Germany
2.	1979	12 November	Louvain la Neuve, Belgium
3.	1980	8 December	Darmstadt, Germany
4.	1982	14-15 January	Grenoble, France
5.	1983	21-22 April	Louvain la Neuve, Belgium
6.	1985	17-18 January	Berkeley, California USA
7.	1986	22-23 May	Jülich, Germany
8.	1987	16-18 November	East Lansing, Michigan USA
9.	1988	15-16 September	Grenoble, France
10.	1990	1-2 November	Knoxville, Tennessee USA
11.	1993	6-7 May	Groningen, The Netherlands
12.	1995	25-27 April	Tokyo, Japan
13.	1997	26-28 February	College Station, Texas USA
14.	1999	3-6 May	Geneva, Switzerland
15.	2002	12-14 June	Jyväskylä, Finland
16.	2004	26-30 September	Berkeley, California USA
17.	2006	17-21 September	Lanzhou, China
18.	2008	15-18 September	Chicago, Illinois USA
19.	2010	23-26 August	Grenoble, France
20.	2012	25-28 September	Sydney, Australia
21.	2014	24-28 August	Nizhny Novgorod, Russia.
22.	2016	29 August-1 September	Busan, South Korea

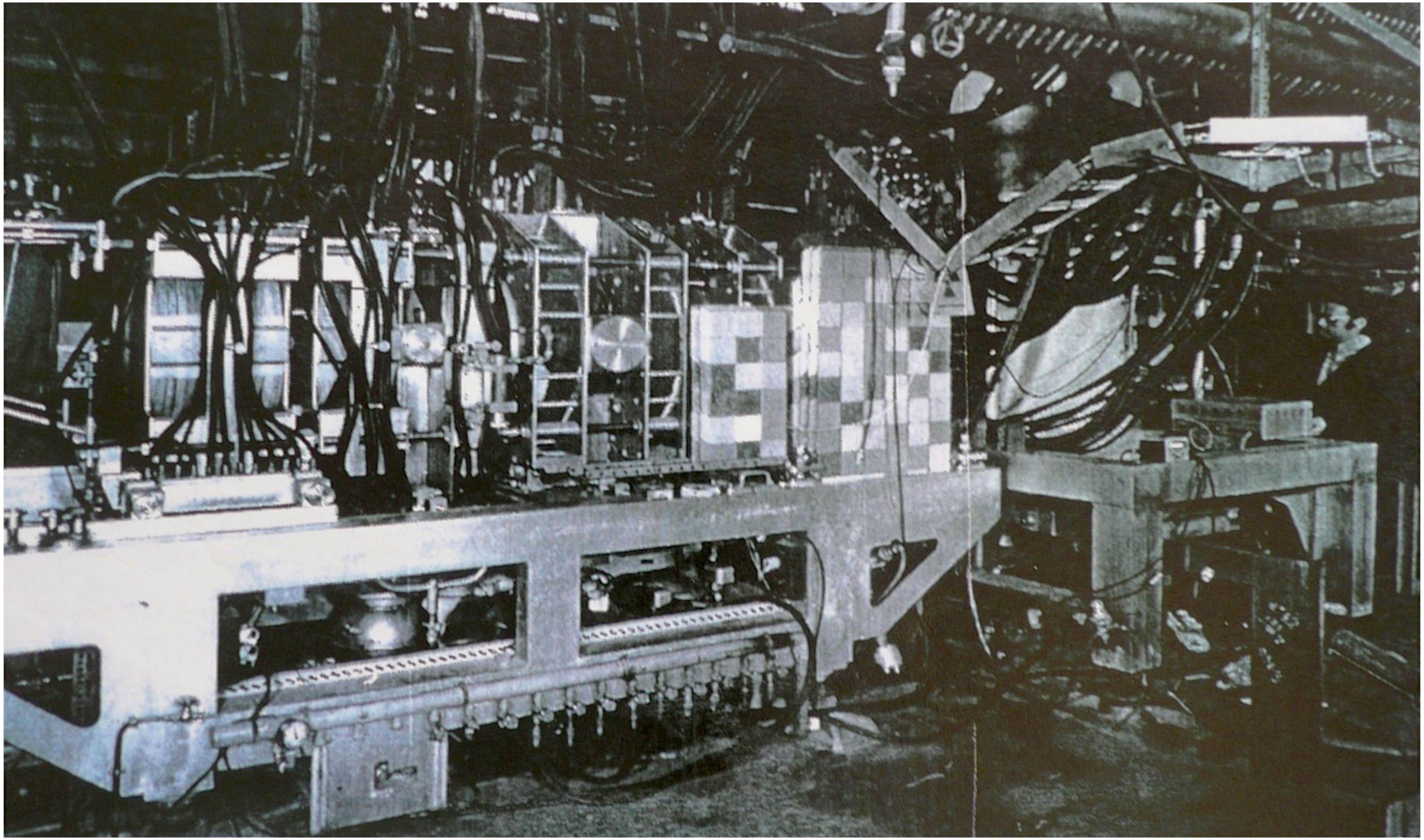

Dr. Richard Geller
Father of ECR Ion Sources


American Physical Society
Tom W. Bonner Award
April 2001

Supermafios

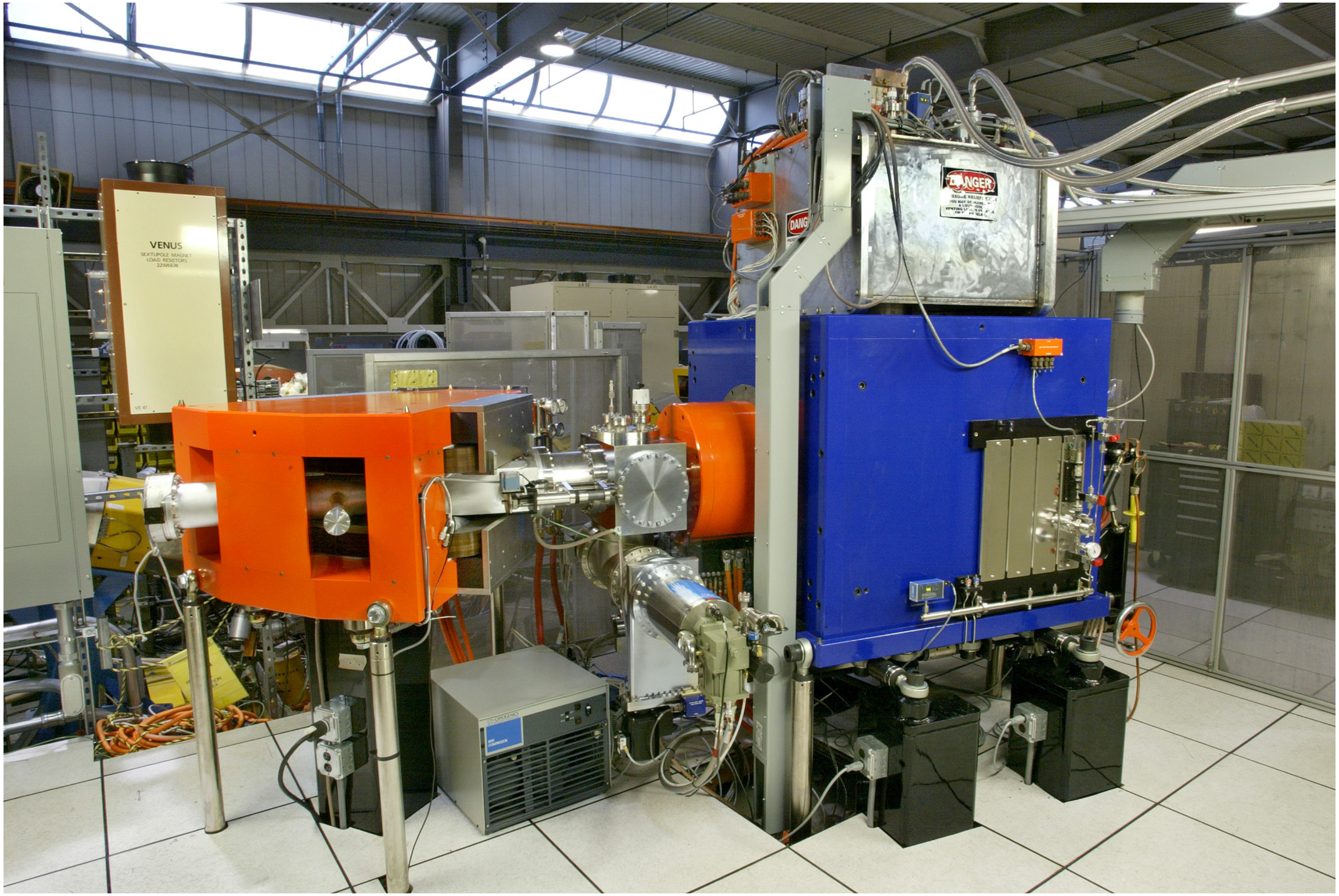
First High Charge State ECR Ion Source (circa 1974) Grenoble, France

Oxygen 6+ ~15 eμA

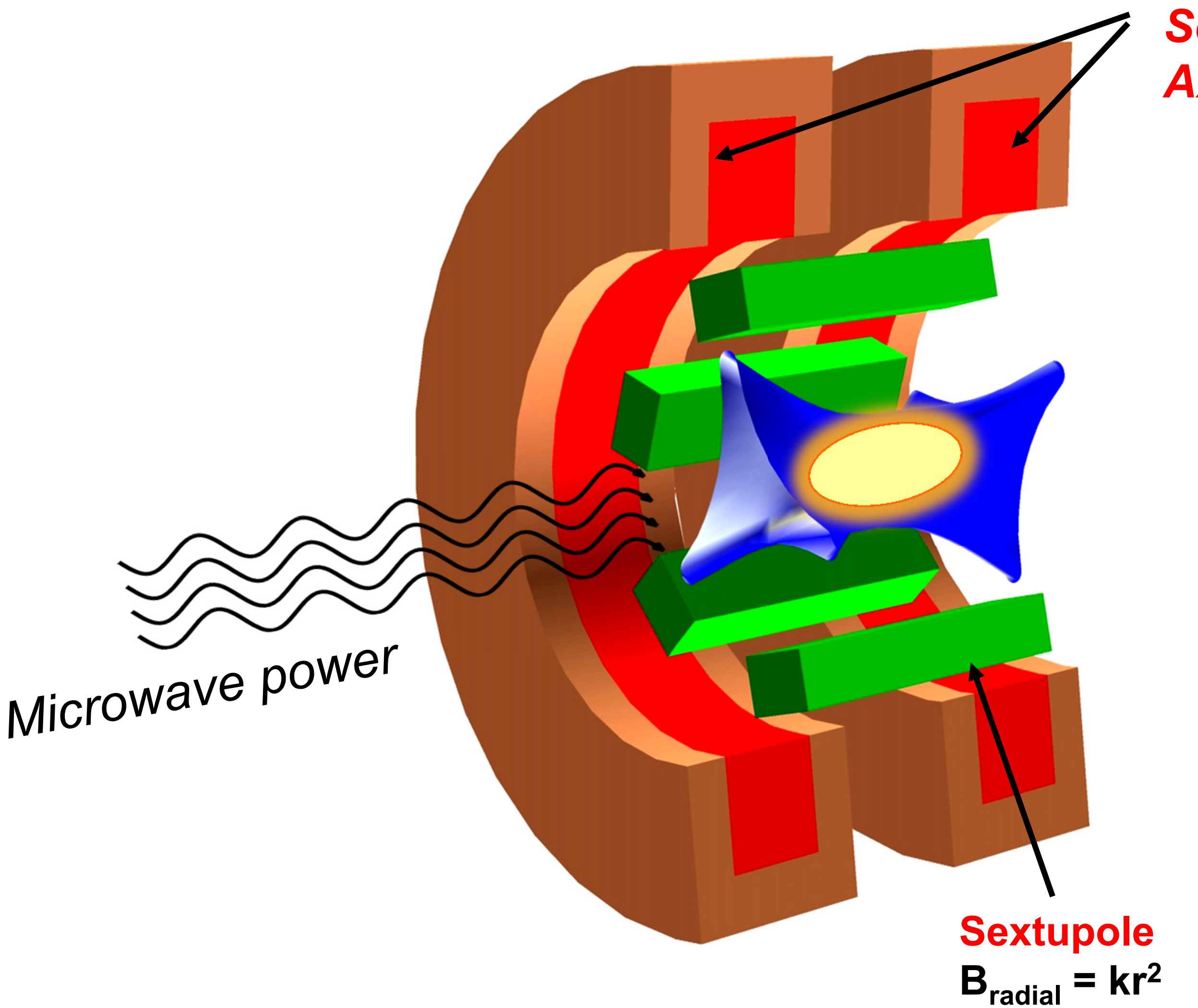


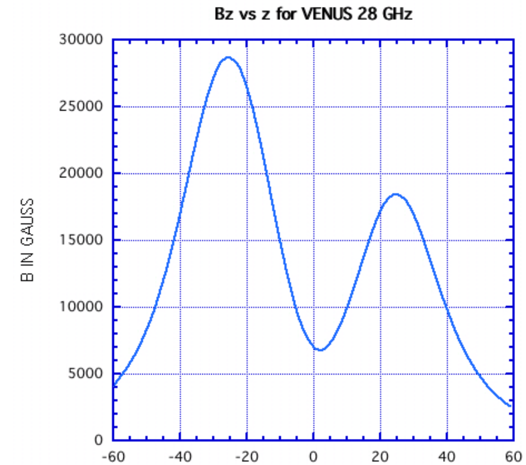
Oxygen 6+ 4700 eμA (2016)*

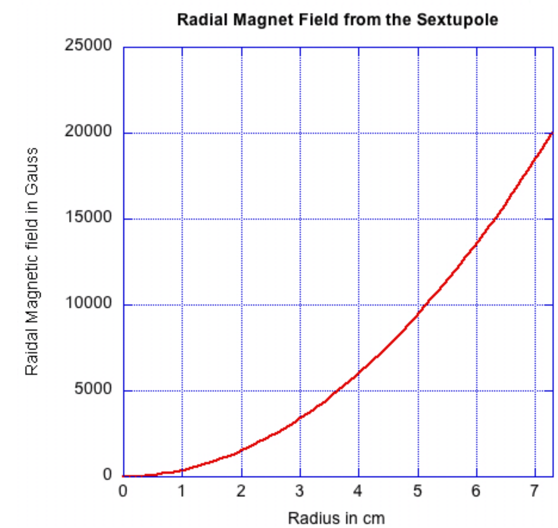
*(Dan Xie--THAO01: THURSDAY)



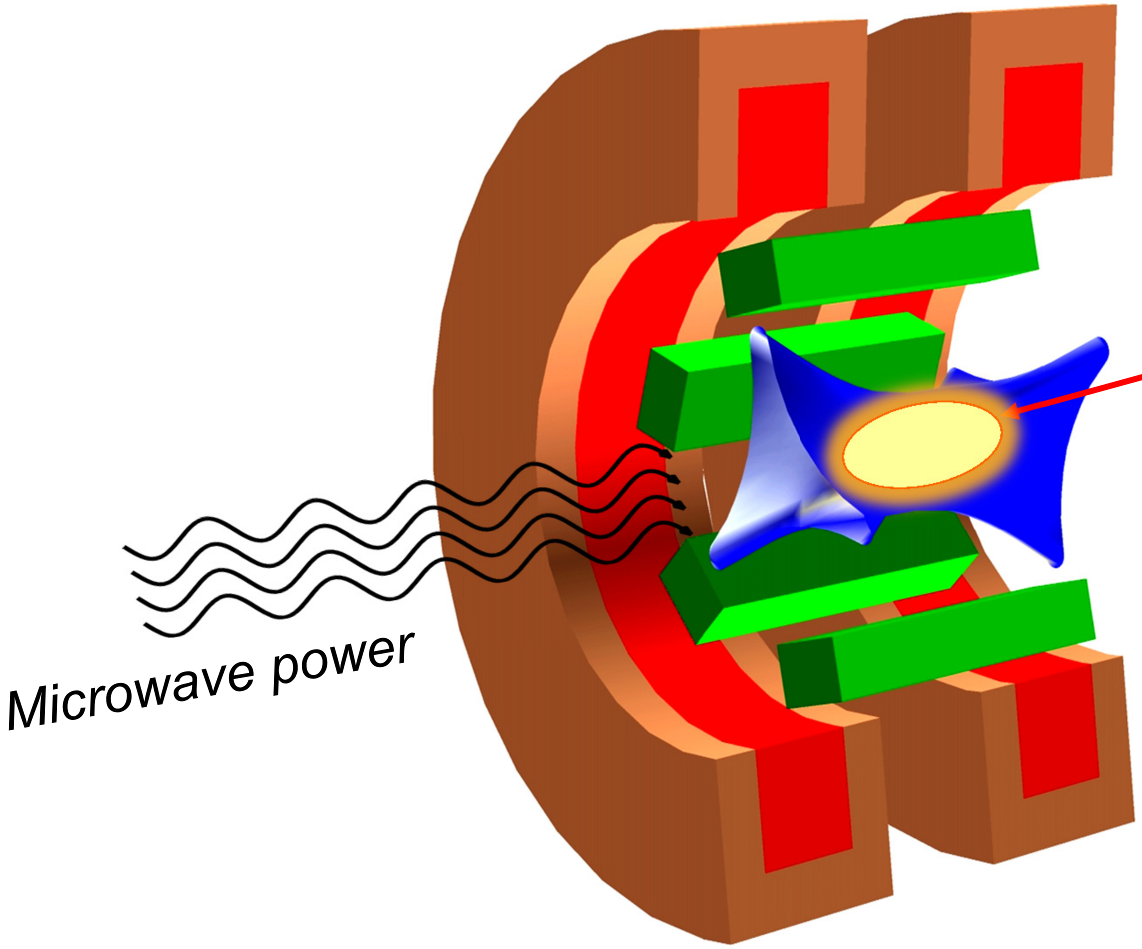
Solenoid Coils + Sextupole   Minimum B field







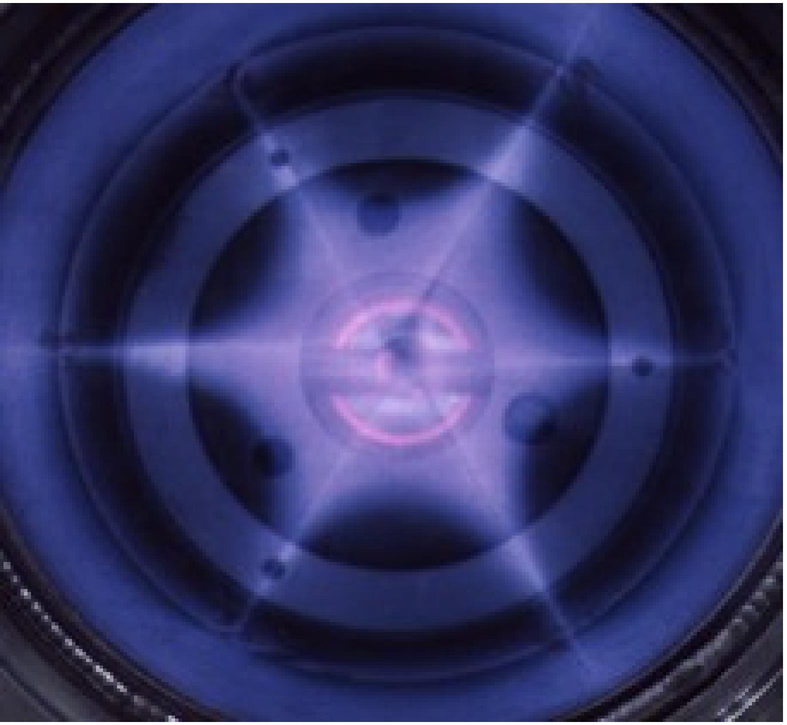
Launching Microwave Power into and ECR Ion Source



ECR Zone
High density plasma
$B_{ecr}=\omega_{rf} m_e / e$

Microwaves couple to the electrons on the ECR surface

Plasma Properties



ECR plasma

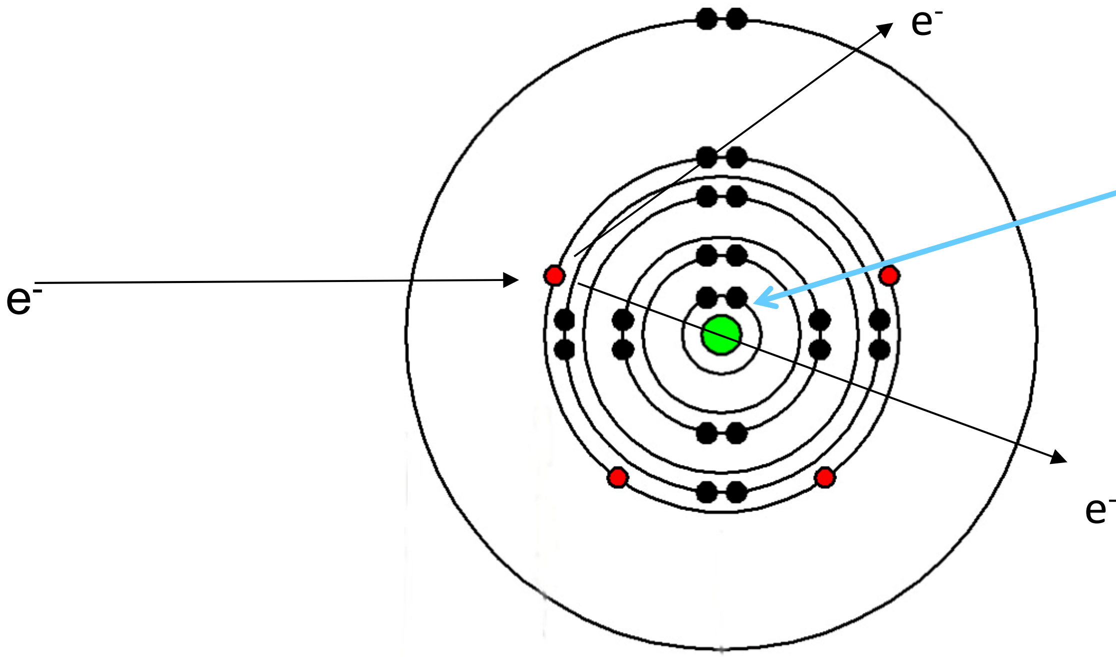
- Partially or fully ionized gas
  - free electrons, free ions, neutrals
  - ECRIS $n_e >> n_o$
  - Electrically neutral : $N_e = \Sigma q_{ion} \cdot N_{ion}$
- Heating to be sustained
  - Microwave power
- Confinement
  - Magnetic fields
  - Plasma frequency scales as the square root of density
- $\omega_p = \text{sqrt}\ \{n_e e^2/\varepsilon_o m\}$ where
  - ω_p plasma frequency
  - n_e plasma density
  - e electron charge
  - m electron mass

Critical Plasma Density-Microwave Propagation

- Plasma critical density n_{crit} is defined when the plasma frequency equals the microwave frequency
- $n_{crit} = 1.26 \times 10^{10}\ (f_{rf})^2$ electrons/cm^3 --critical density scales as $(f_{rf})^2$ -- (f in GHz)
- At low plasma densities the microwave propagate without a problem
- Above the critical density certain microwave modes no longer propa gate
- High charge state ECR ion sources operate below the critical density
- 1+ ECR ion source can operate above the critical density, but no hig h charge states are formed.
- $n_{crit} = 1.26 \times 10^{10}\ (f_{rf})^2$ electrons/cm^3 (f in GHz)

$N_{crit} \sim 1 \times 10^{13}$ e/cm^3 at 28 GHz

Electron impact ionization



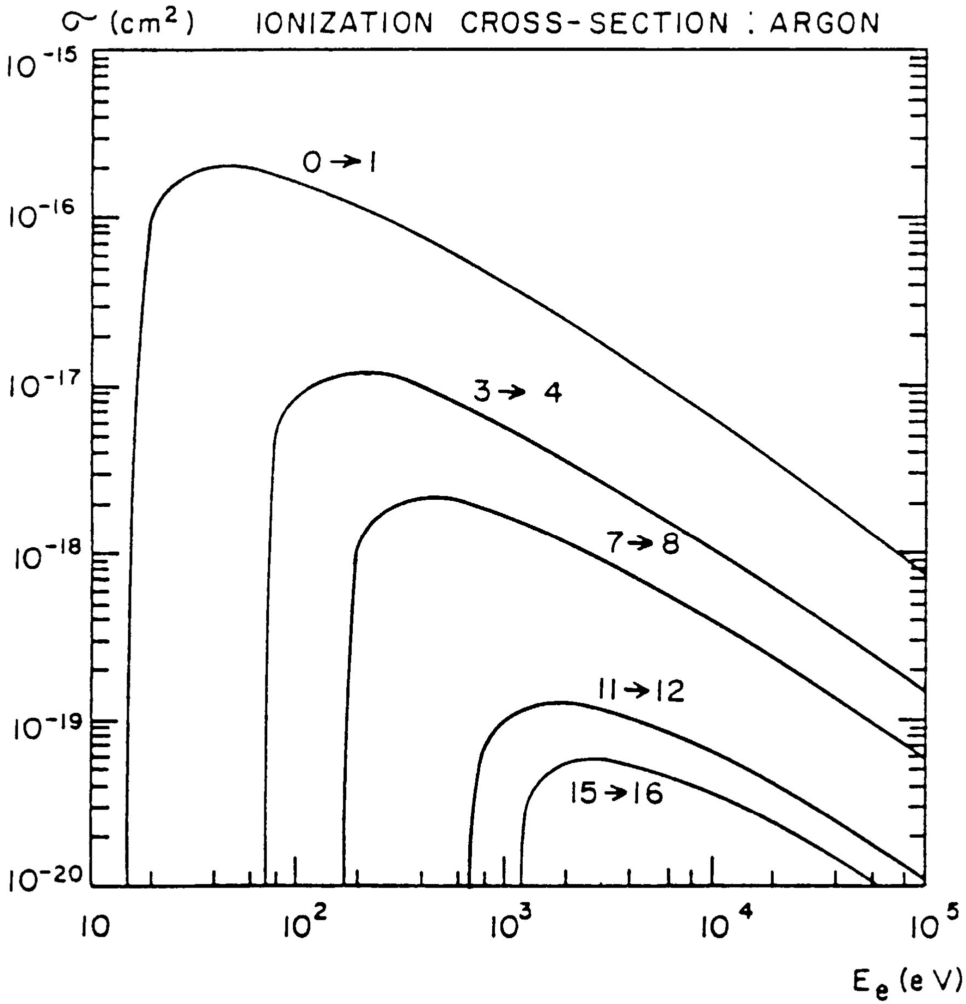
Ionization Potential for 1s electron
$E_{ip} = 13.6 \times Z^2$ eV

H $^{1+}$ 13 eV
U $^{92+}$ 115 keV

Incoming electron must have kinetic energy greater than the ionization potential of the electron in the shell.

Highest cross section for E_e~3-5 x ionization potential

Electron Impact Ionization



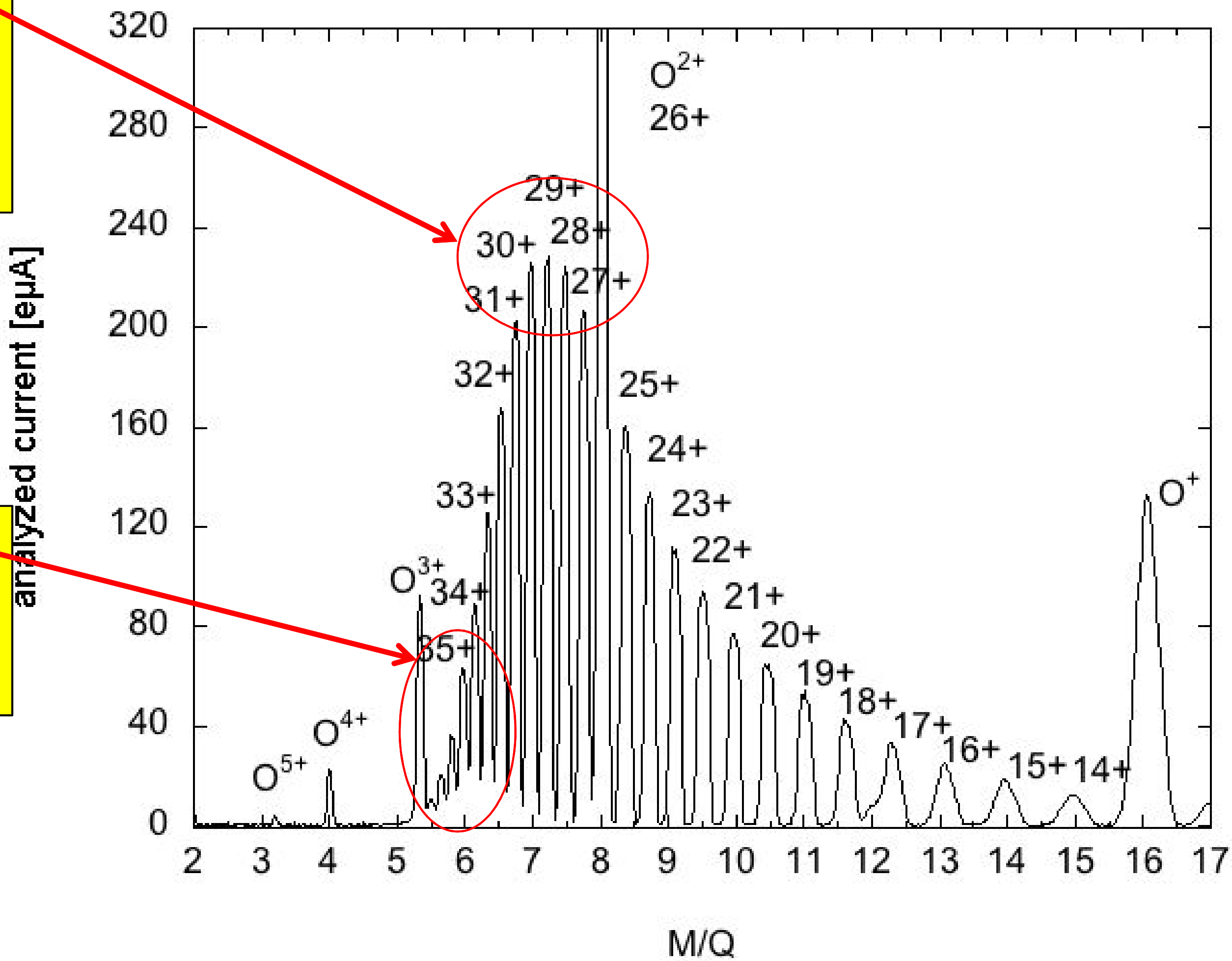
- Low charge states
  - high cross sections
  - low ionization potentials
  - 0 to 1^+
    - 10^{-16} cm^2
    - I_p~16 eV
    - E_{opt} ~ 60 eV
- High charge states
  - low cross sections
  - high ionization potentials
  - 15^+ to 16^+
    - 10^{-19} cm^2
    - I_p~939 eV
    - E_{opt}~3000 eV

Production of high charge states requires a high density of hot electrons and long confinement time

Charge State Distribution for Bismuth from VENUS

The peak of the CSD is mainly determined by the product of the plasma density and ion confinement time $n_e \tau_i$

Highest charges states are determined by the neutral density n_0 (charge exchange)



- The ion charge state distribution in an ECRIS can be reproduced with a 0 Dimension model including a set of balance equations:

Ionization — Charge Exchange With Neutrals — Ion Ion Exchange — Ion Losses

$$\frac{\partial n_i}{\partial t} = \sum_{j=j_{\min}}^{i-1} n_e n_j \left\langle \sigma^{EI}_{j\to i} v_e \right\rangle + n_0 n_{i+1} \left\langle \sigma^{CE}_{i+1\to i} v_{i+1} \right\rangle - n_0 n_i \left\langle \sigma^{CE}_{i\to i-1} v_i \right\rangle - \sum_{j=i+1}^{j_{\max}} n_e n_j \left\langle \sigma^{EI}_{i\to j} v_e \right\rangle - \frac{n_i}{\tau_i}$$

- n_i ion density with charge state i
- σ , cross section of microscopic process
  - Electron impact or charge exchange here
- τ_i is the confinement time of ion in the plasma
- $-\frac{n_i}{\tau_i}$ represents the current intensity for species i
- Free Parameters: ne, f(ve), τ_i , n_0
- Model can be used to investigate ion source physics

- Needed parameters
- Plasma density
- Electron energy dist
- Ion confinement time
- Neutral density

Optimum magnetic field vs microwave frequency

Scaling

$$B_{ecr} = \frac{m_e f_{rf}}{q_e}$$

$B_{ecr} = f_{rf}/28$

where B_{ecr} is in Tesla and f_{rf} is in GHz,

** for 28 GHz B_{ecr} =1 Tesla**

- In the 1990's experiments showed there is an optimum magnetic field for confinement
- Closed surface with $B_{mag} \leq 2\ B_{ecr}$
  - $B \geq 2\ B_{ecr}$ at the plasma chamber walls
  - B_{inj} ~3 to 4 B_{ecr} on axis
  - $B_{rad} \geq 2\ B_{ecr}$ on the walls
  - Bext ~ B_{rad}
  - $B_{minimum}$ ~ 0.4-0.7 B_{ecr} on axis—(MOC004 14:30 Today Janilee Benitez)

Frequency or Magnetic Field Scaling

Scaling

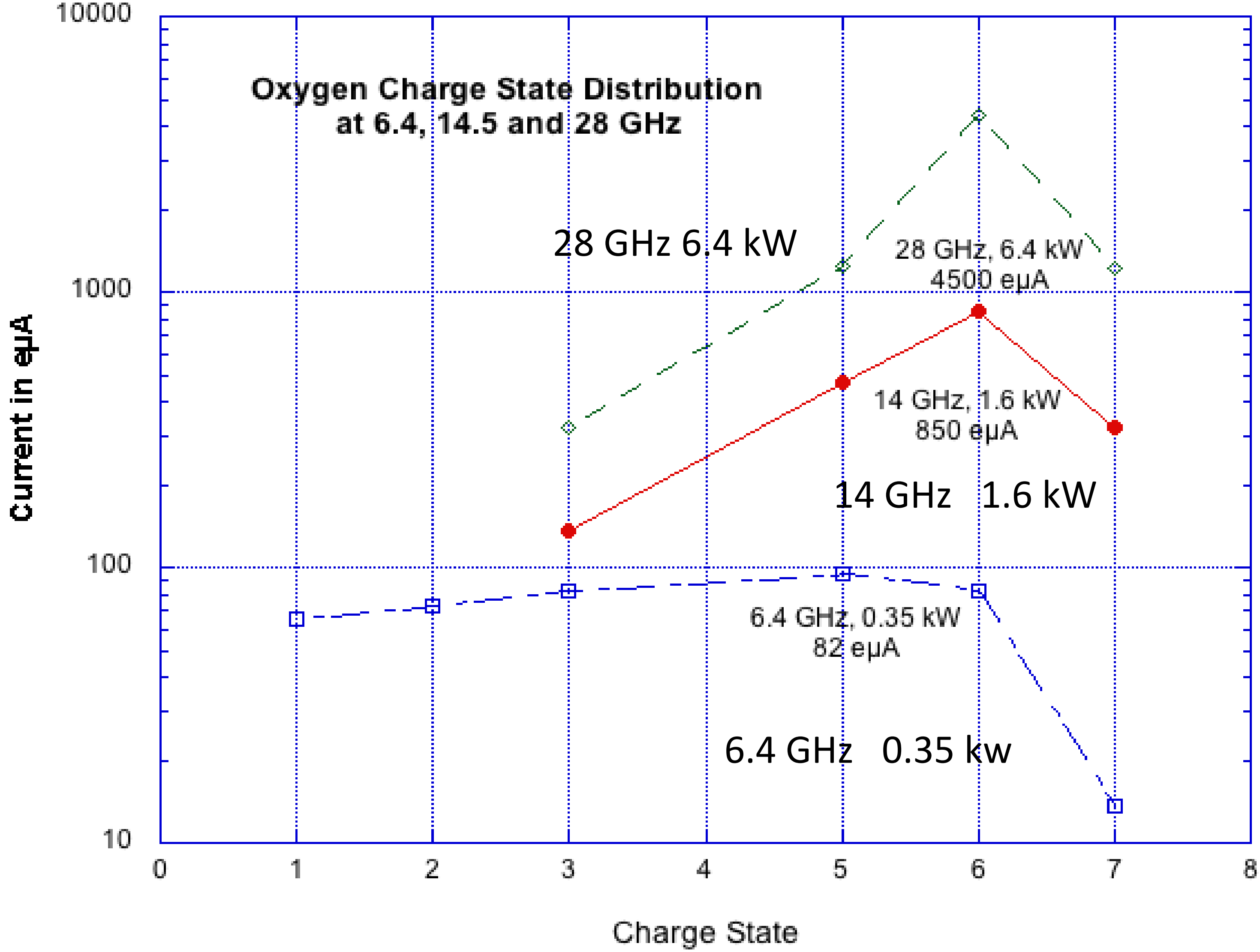
- Geller proposed scaling for ECR ion sources 1987
  - Beam current should scale as the square of the frequency
  - $I_q \propto f_{rf}^2$.
  - Based on the assumption plasma density is less than the critical density which scales as frequency squared and on measurements at 10, 14,16 and 18 GHz in miniMAFIOS and CAPRICE sources
  - $I_q \propto ne \propto f_{rf}^2$ where $ne < n_{crit}$ and $n_{crit} \propto f_{rf}^2$

- The alternative view is that the current scales with the confinement field B, not with f_{rf}
- $I_q \propto B_{conf}^2$

Since B_{conf} scales with f_{rf} -- Both views give the same dependence of f_{rf}

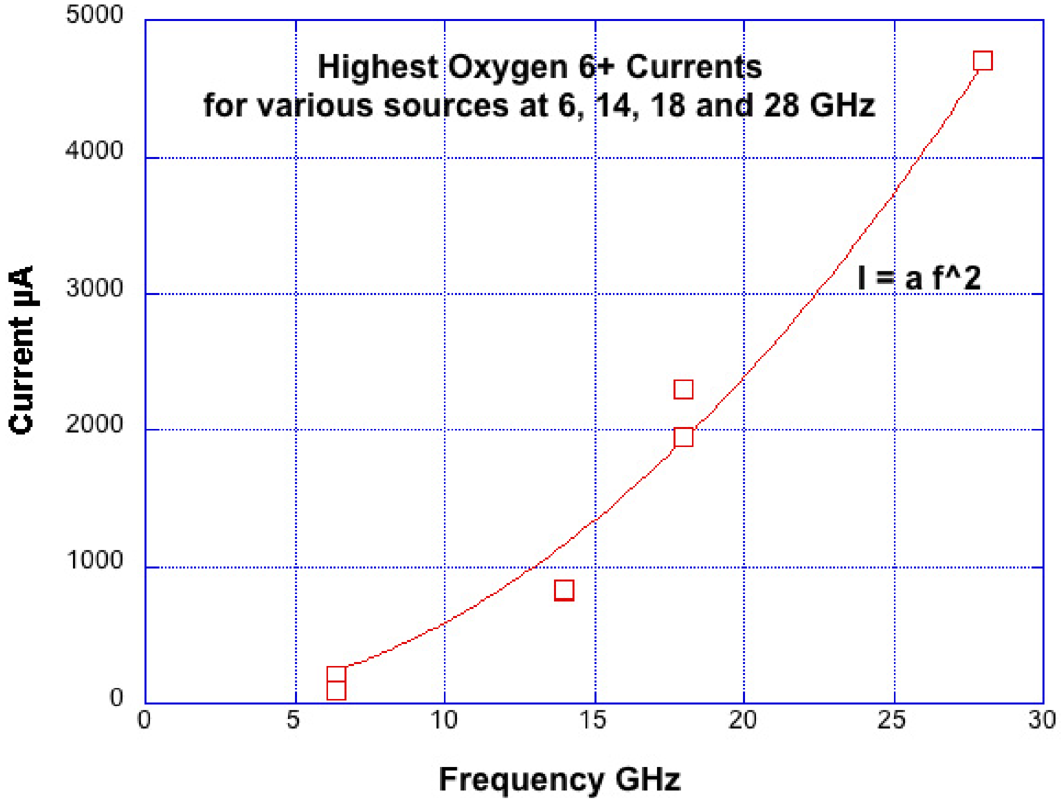
Dependence of oxygen ion currents on operating frequency

Scaling



Scaling of O^{6+} for various Sources

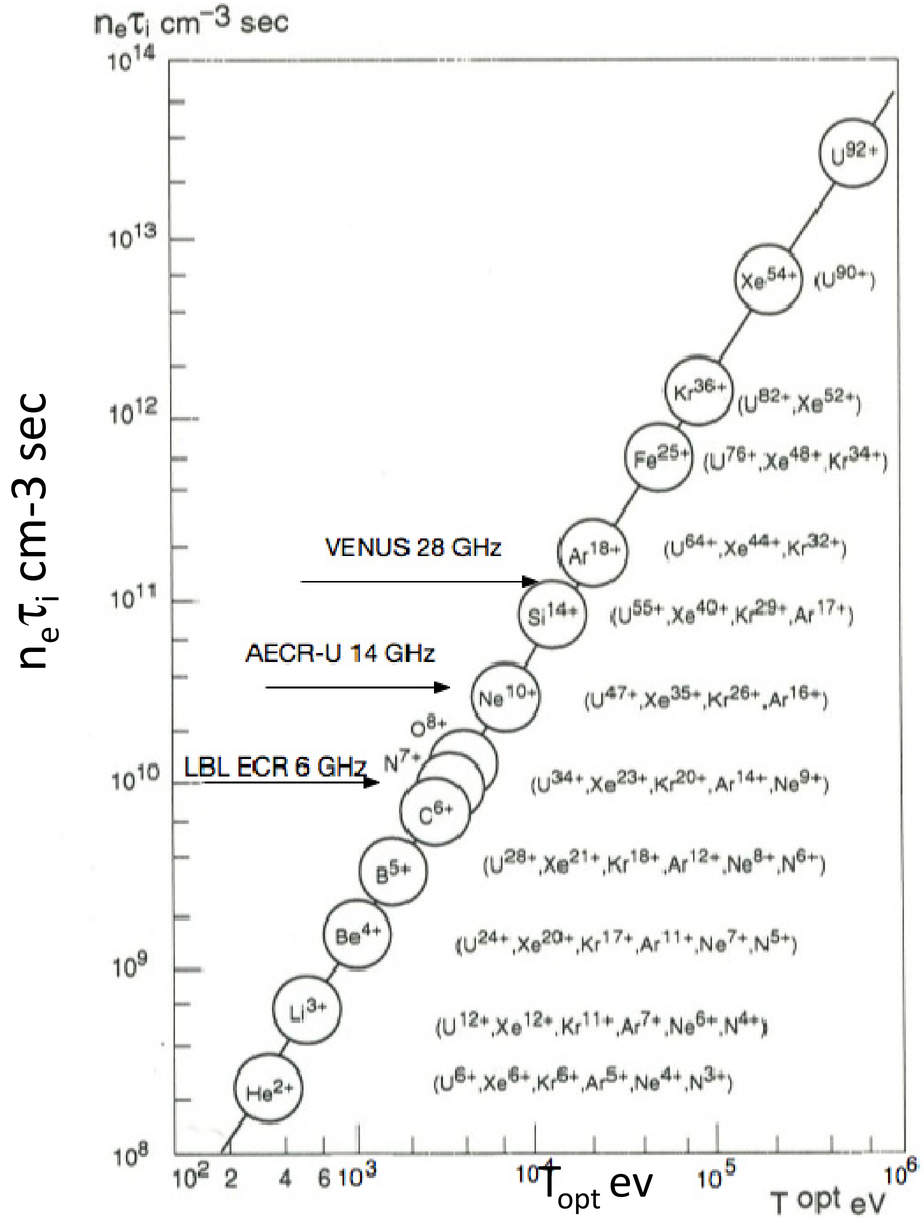
Scaling



The plot illustrates that maximum O^{6+} vs f_{rf} fits roughly to frequency squared or B_{conf} squared for the highest performing ECRIS but there is a lot of scatter in the data

For charge states >>q_{opt} I_q scales much faster than f^2 because $n_e\tau_i$ increases with f
And the CSD goes up in charge state

Scaling



Golonvanivsky criterion

$n_e\tau_i \sim 2\text{x}10^{17}$ s/cm^3 at

20 keV for VENUS

at 28 GHz

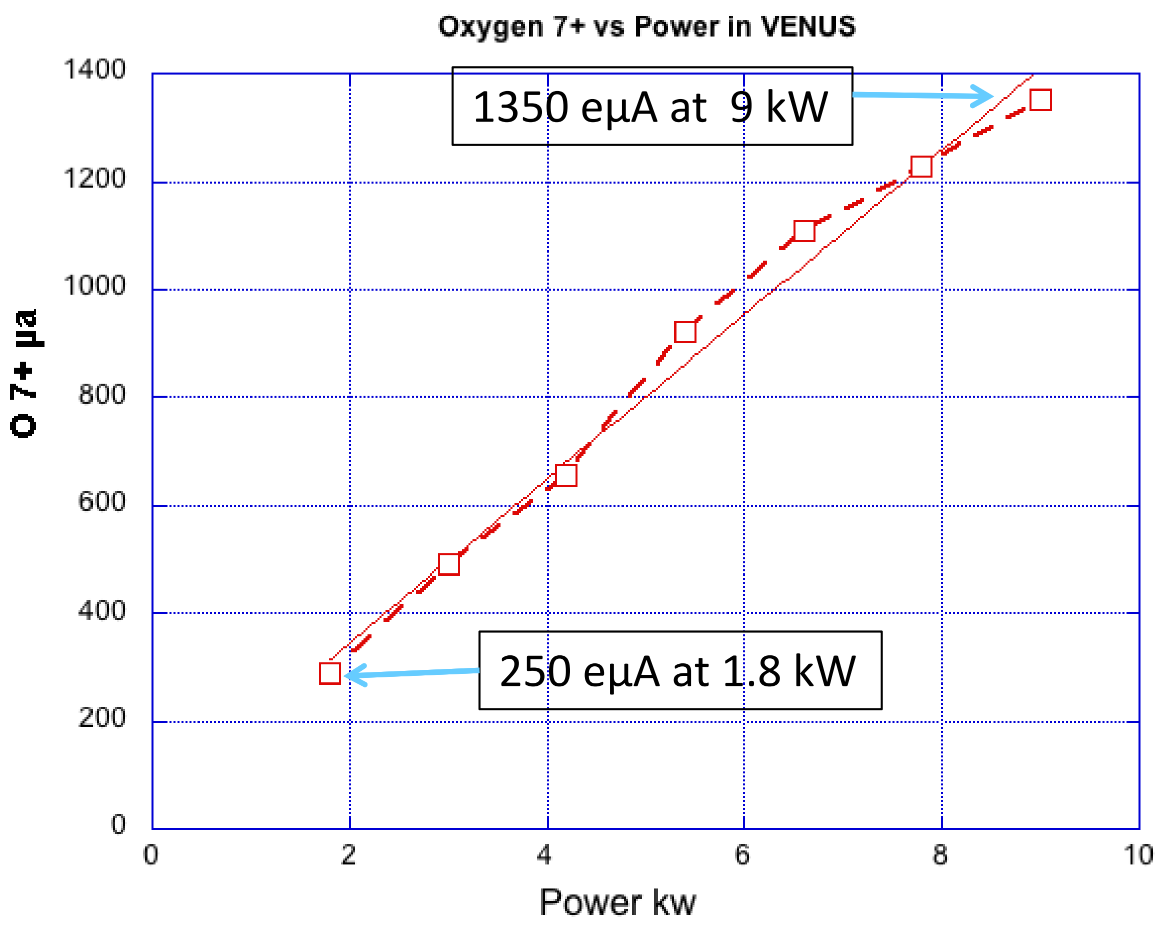
Increase in $n_e\tau_i$ by x 10

over the 6.4 GHz LBL ECR

Scaling Ion Current With Microwave Power

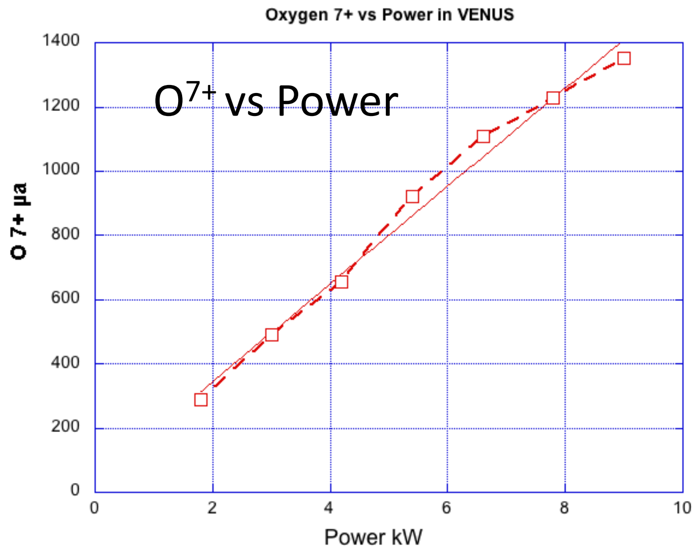
Scaling

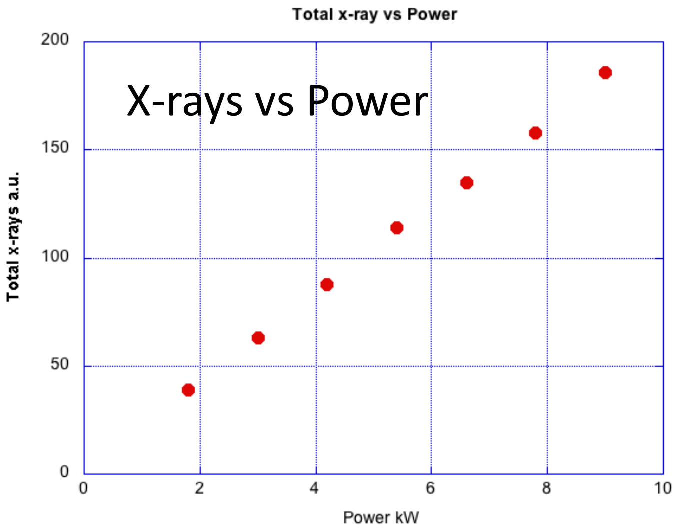
VENUS O^{7+} Linear dependence on power at constant injection pressure
Oxygen gas flow increased with power to offset plasma pumping

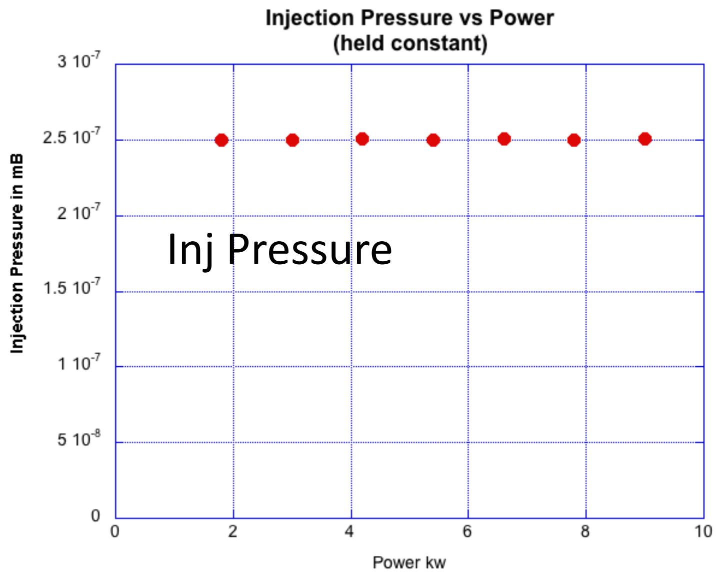


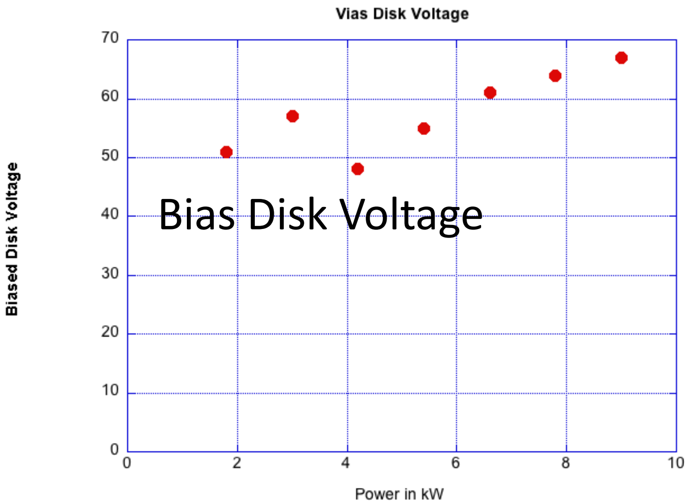
Oxygen 7+ scaling with Power

Scaling



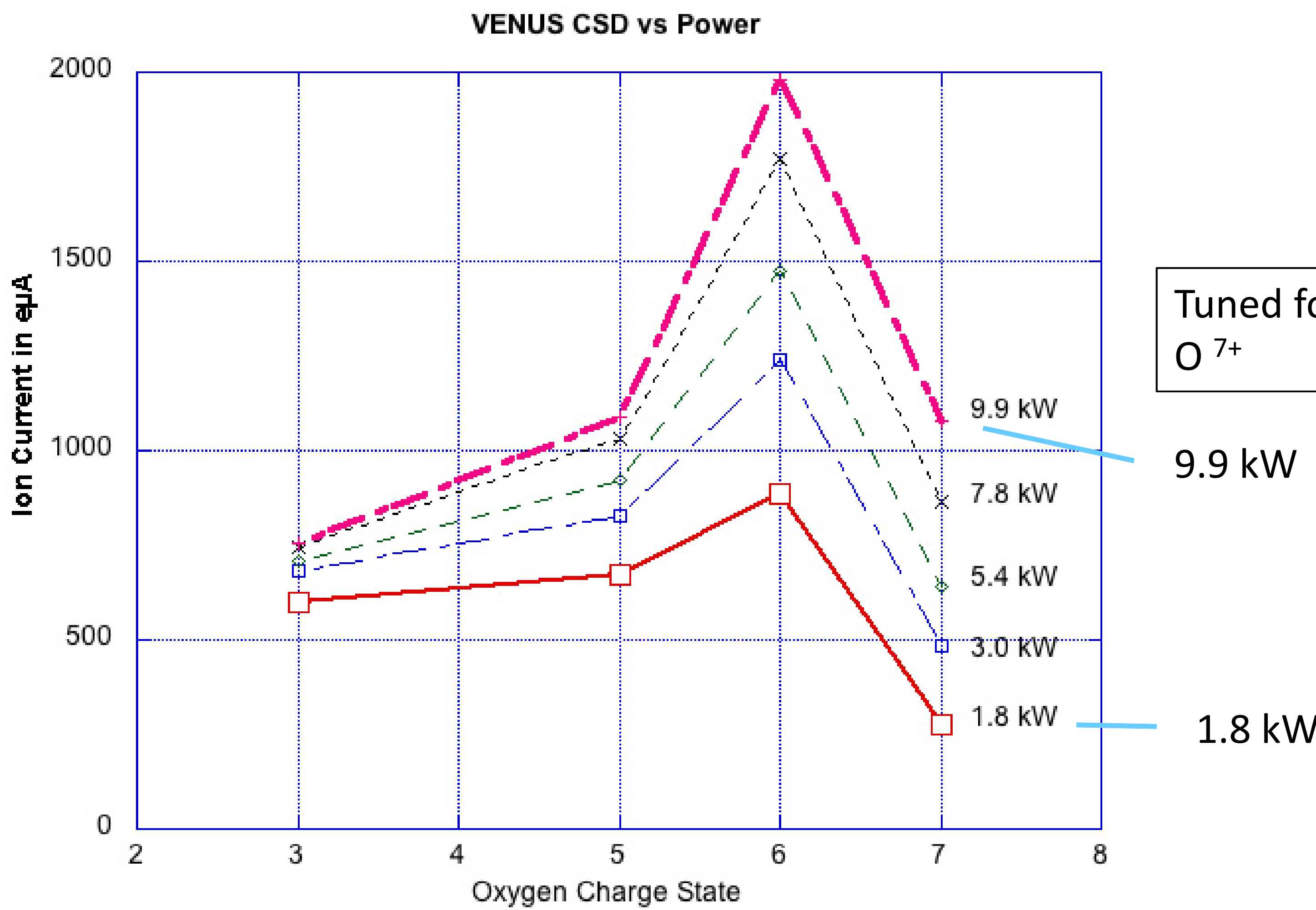






Oxygen CSD vs Power in VENUS

Scaling



Tuned for max O^{7+}

Scaling Ion Current With Microwave Power

- VENUS (high power, high current oxygen beams)
  - B field fixed,
  - gas flow adjusted to maintain constant injection pressure
  - CSD stays relatively constant
  - Total x-ray flux scales linearly with power
  - Spectral Temperature stays the same
  - O^{6+} or O^{7+} scale linearly with power

- How can this be understood?
  - $n_e \tau_i$ arguments are based on a "static model"
  - The Flow Model

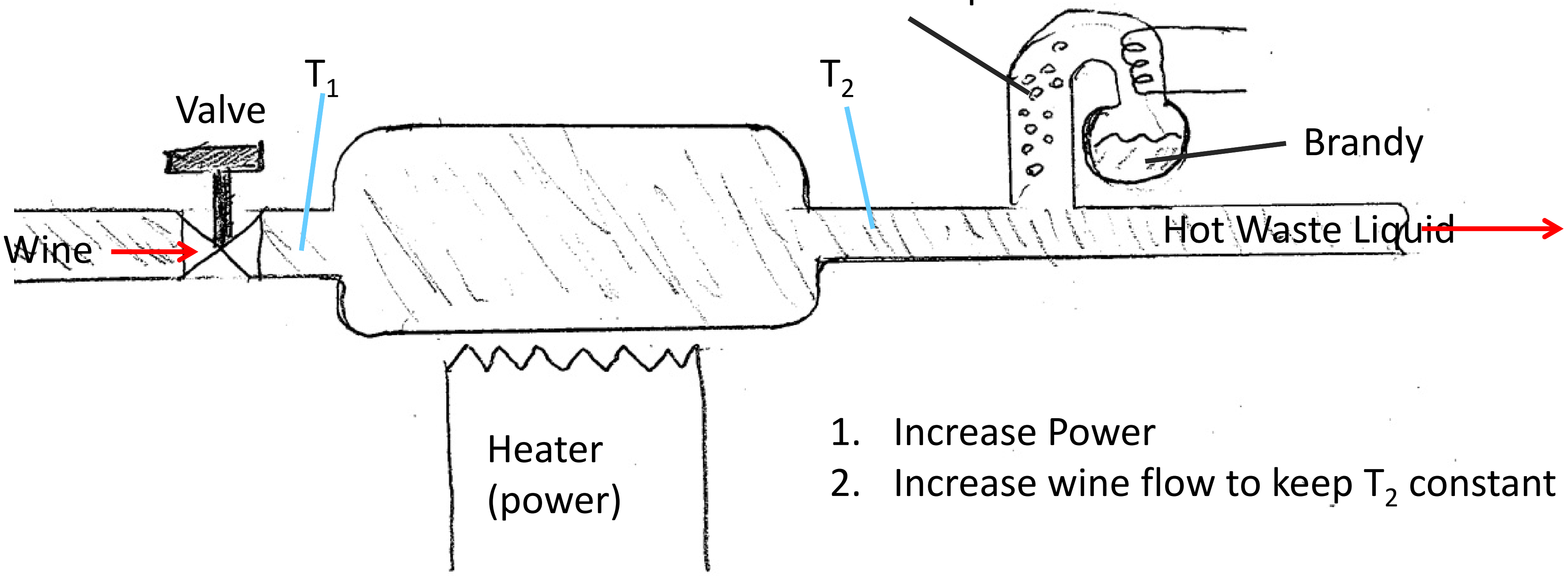
Charge State Model

Scaling

- CSD is a function ($n_e\,\tau$) for constant T_e
- Ion Current proportional to n/τ
- For ion current to scale linearly with power and the CSD to stay constant then
  - $n\tau$ is constant with power
    - $n_e/\tau_e \propto$ power
      - then
- $n_e \propto (\text{power})^{1/2}$ and $\tau_e \propto \tau_e \propto 1/(\text{power})^{1/2}$ and Te is constant
  - Does that make sense?

ENERGY FLOW DISTILLERY

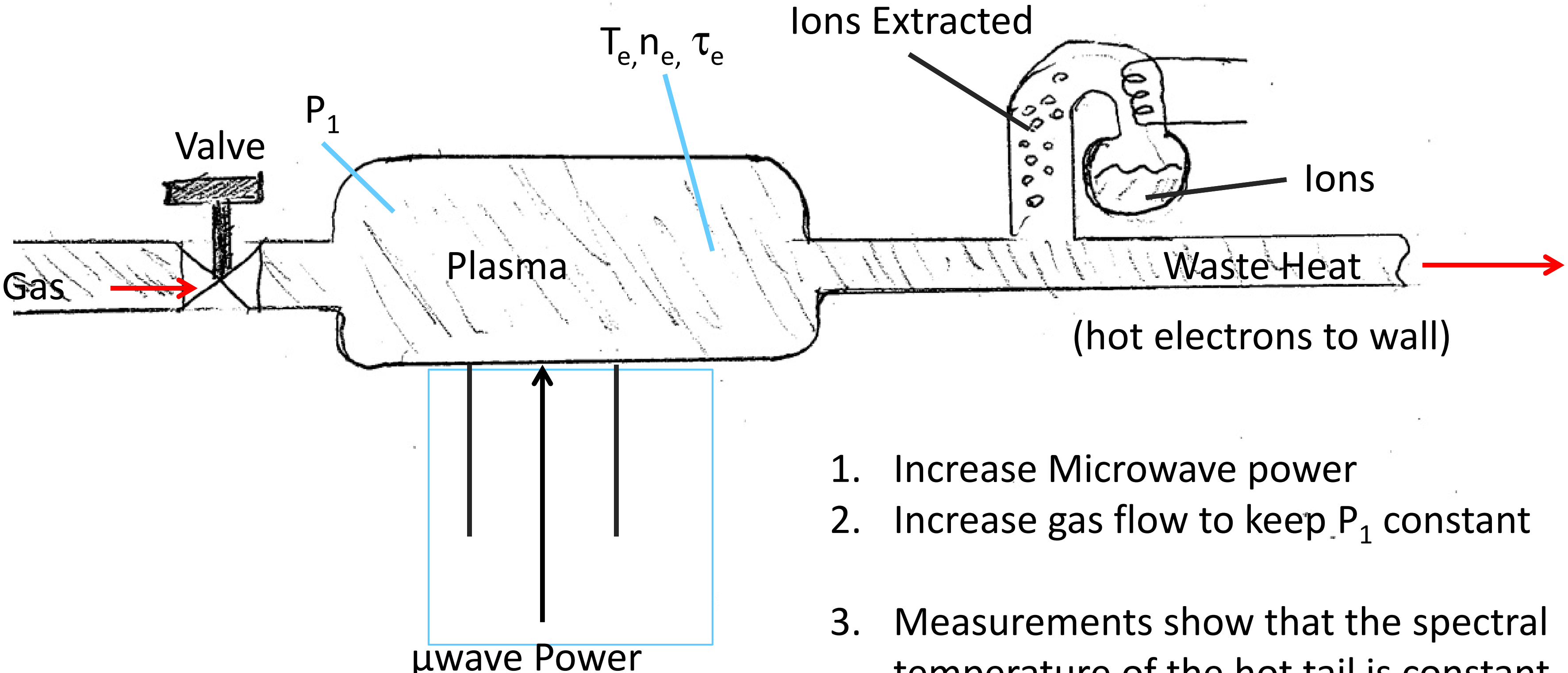
Linear Flow Distillery
Wine In---Brandy Out



1. Increase Power
2. Increase wine flow to keep T_2 constant

Scaling

Linear Ion Source
Oxygen In---Ions Out



1. Increase Microwave power
2. Increase gas flow to keep P_1 constant

3. Measurements show that the spectral temperature of the hot tail is constant
4. Total x-ray flux scales linearly with power

Scaling VENUS as 28 GHz to a 45 GHz Gen IV ECRIS

The maximum ion current scales as f^{2}

For a fixed frequency the current is linear with power

How will a 4th Generation (45 GHz) scale from VENUS at 28 GHz

$Iq = Iq(45\ \text{GHz}/\ 28\ \text{GHz})^{2}$

For Power $(45/28)^{2} * 10$ kW   Microwave Power= 26 kW

For space charge and beam transport V_{ext} will scale as

$I_{tot}^{\ 2/3}$ so $V_{ext} \geq (f_{rf})^{4/3}$ 30 kV goes to $V_{ext} \geq$ 56 kV

THE END