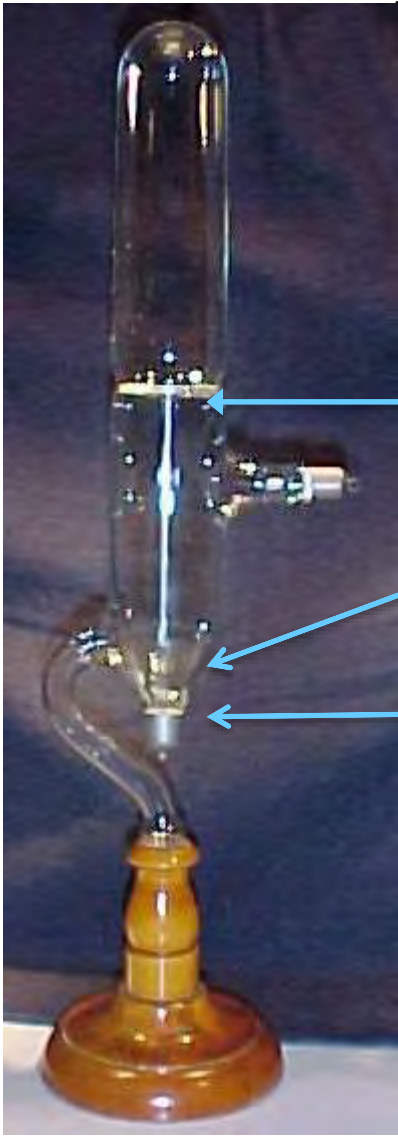
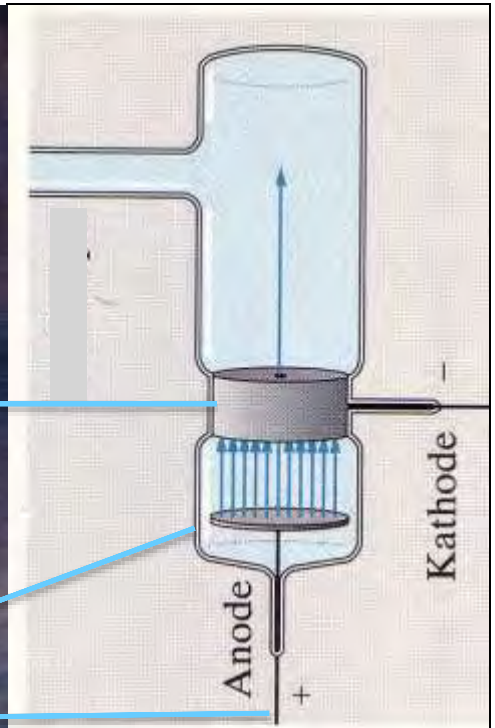
ECR Ion Sources-Past, Present and Future

- Production of Highly Charged Ion Beams
  - Physics
  - Technology
  - Challenges
  - Recent experiments at Berkeley





128 Years of Ion Sources CANAL RAY TUBE

Eugen Goldstein
Sitzungsbericht Berl. Akad. 25. July 1886
Wied. Ann. **64** (1898)38

4. *Ueber eine noch nicht untersuchte Strahlungsform an der Kathode inducirter Entladungen; von E. Goldstein.*

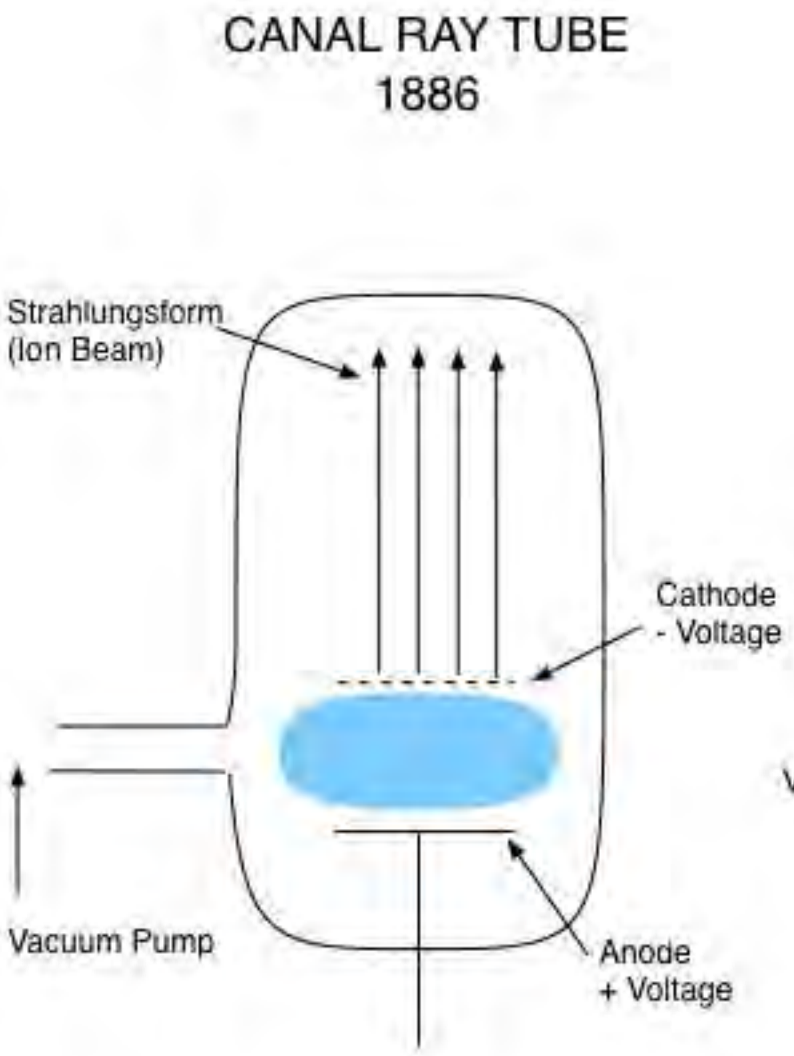
4. *Ueber eine noch nicht untersuchte Strahlungsform an der Kathode inducirter Entladungen; von E. Goldstein.*

(Sitzungsber. d. k. Akad. d. Wissensch. zu Berlin vom 29. Juli 1886.)

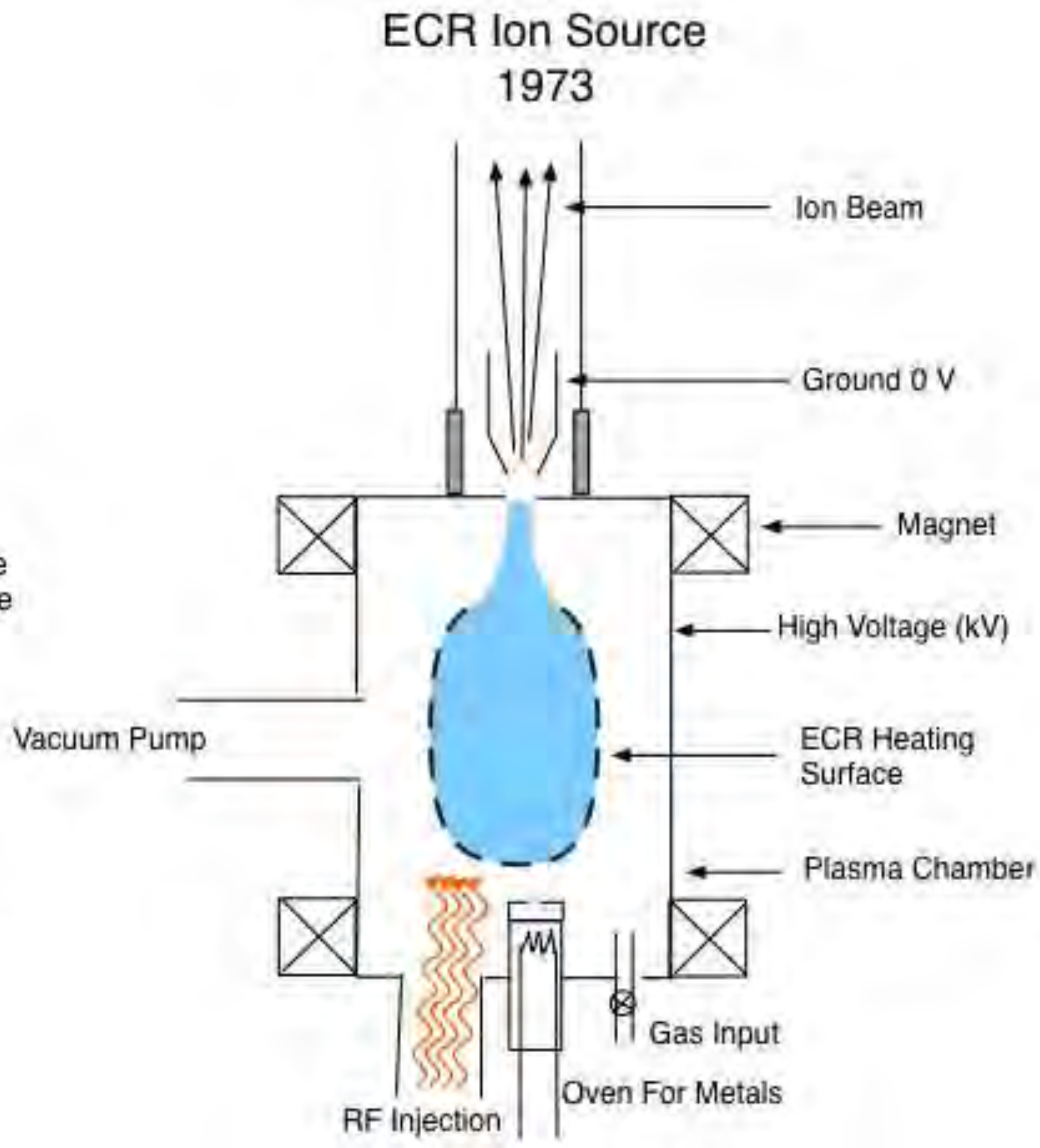
Das Kathodenlicht der Entladung des Inductoriums durch verdünnte Gase besteht aus mehreren verschieden gefärbten Schichten. In verdünnter Luft ist die der Kathode unmittelbar anliegende Schicht chamoisgelb gefärbt, die zweite erscheint blau und lichtschwach, die dritte violettblau und hellleuchtend. Die erste Schicht ist ungeachtet ihrer Helligkeit von der weitaus grössten Zahl von Autoren ganz ignorirt worden; die wenigen, die ihrer gedenken, gehen meist über die Constatirung ihrer Existenz nicht hinaus. Untersuchungen

Spark Inductor

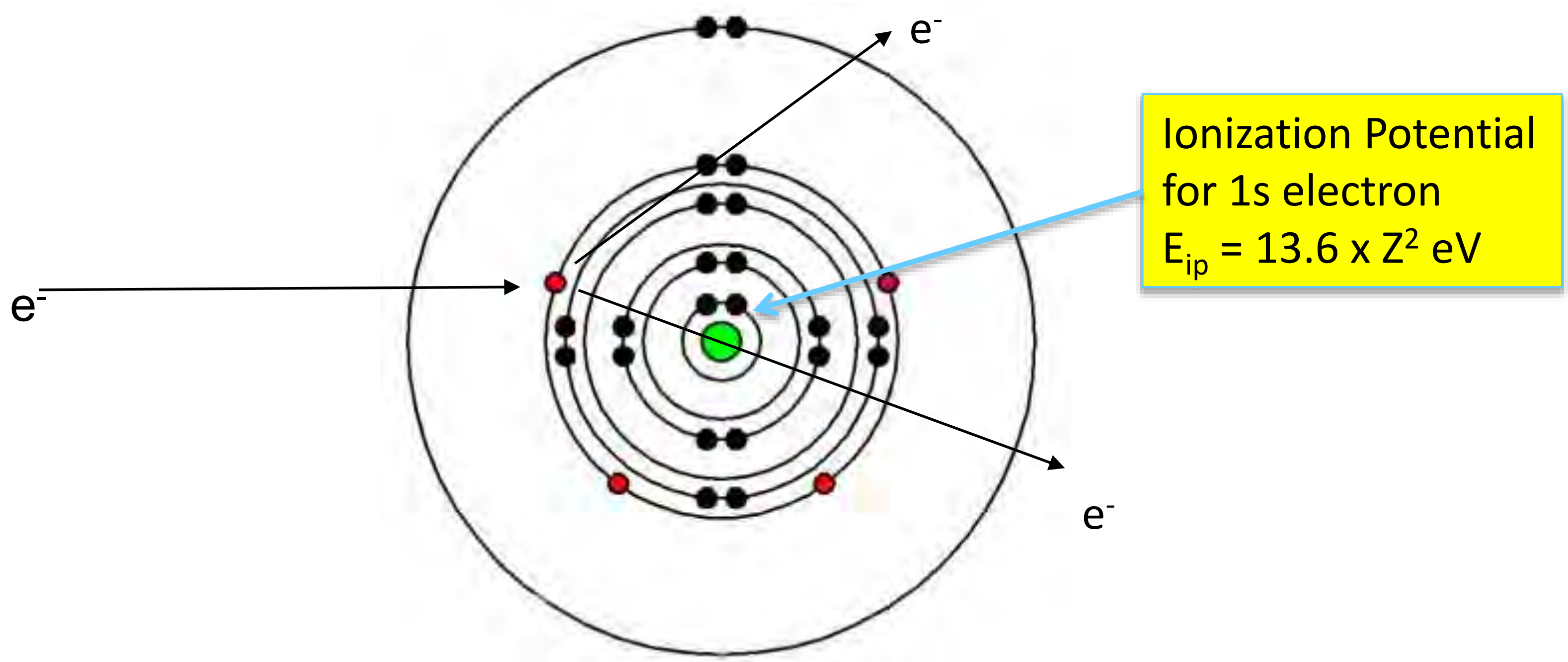
E Goldstein



R. Geller



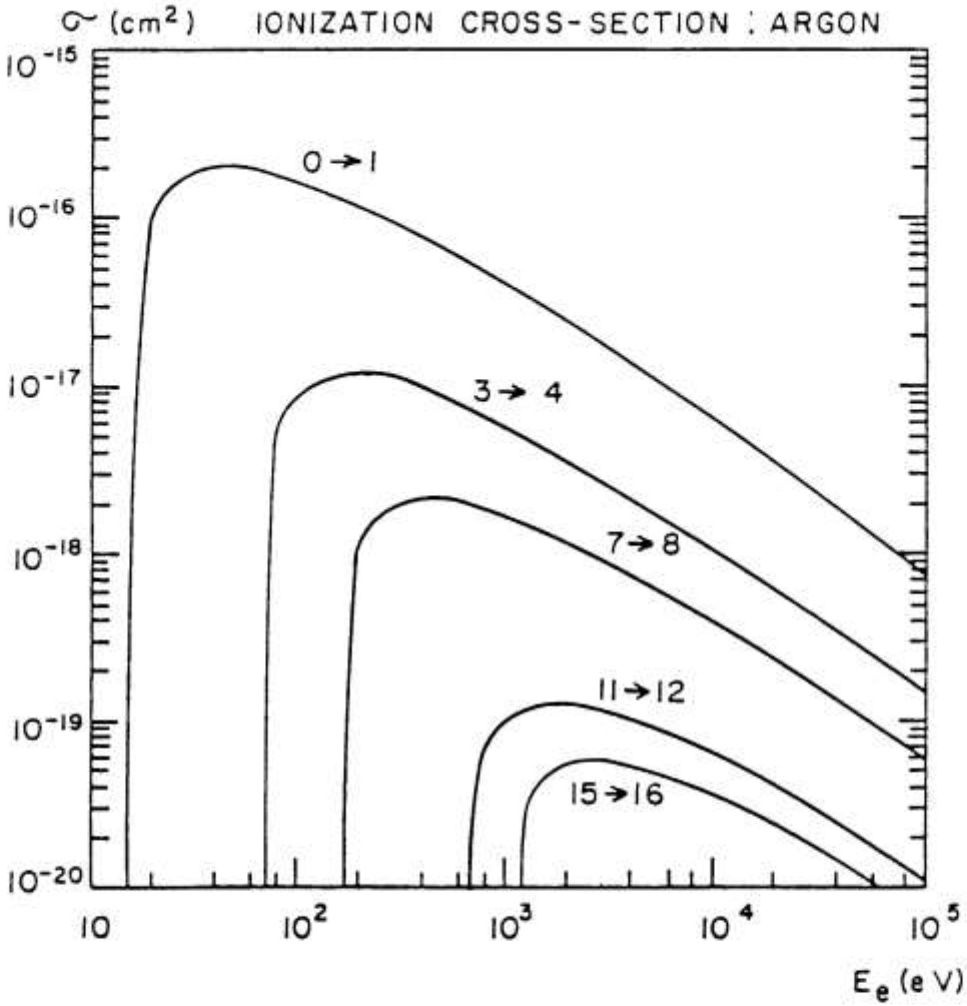
Electron impact ionization



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

Atomic Physics is well known and the CSD can be modeled if the plasma parameters are known

- 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

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

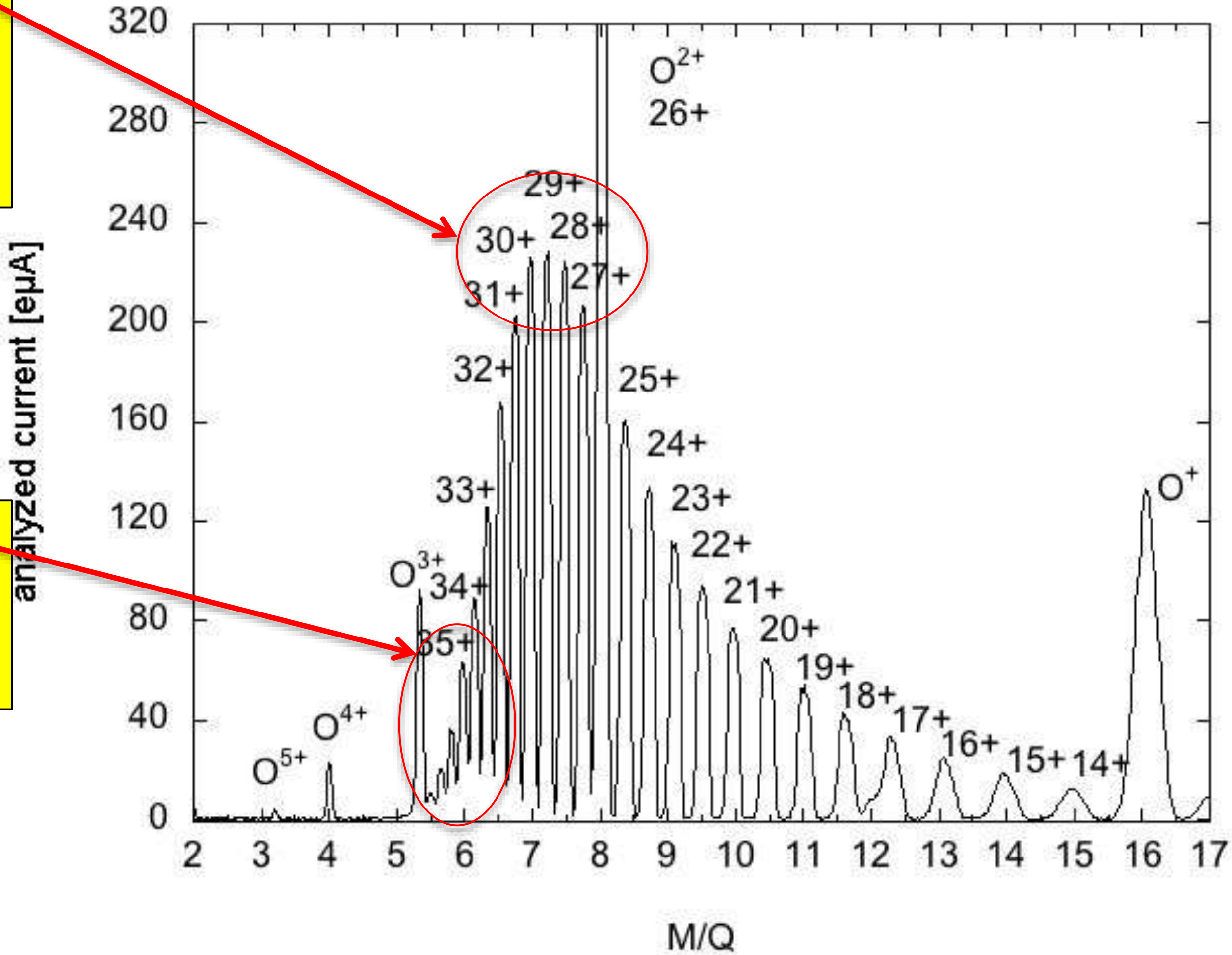
- n_i ion density with charge state i
- σ , cross section of microscopic process
  - Electron impact or charge exchange here
- τ_i is the confinement time of ion in the plasma
- $-\frac{n_i}{\tau_i}$ represents the current intensity for species i
- Free Parameters: ne, f(ve), τ_i , n_0
- Model can be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

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

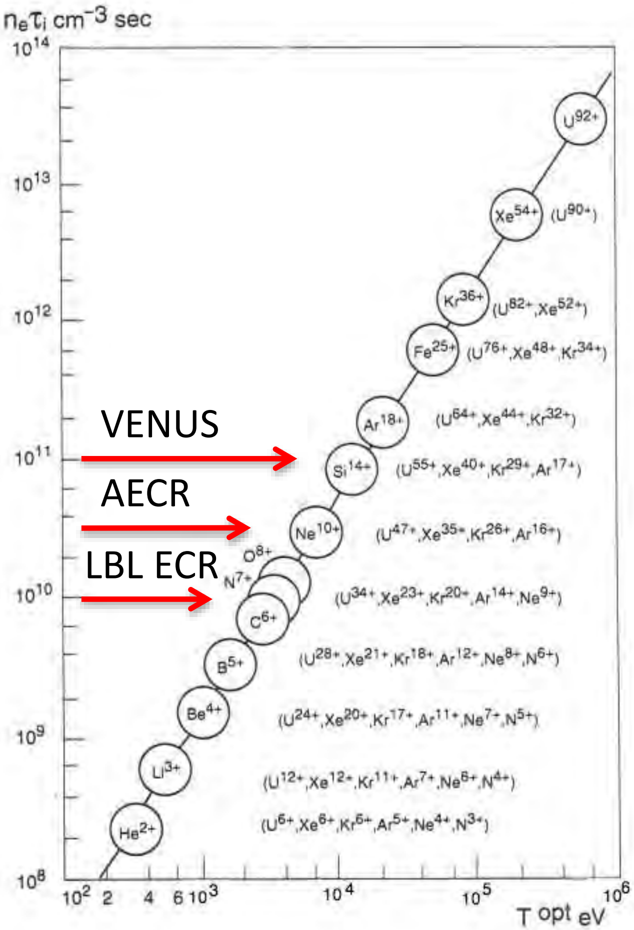
Charge State Distribution for Bismuth from VENUS

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)



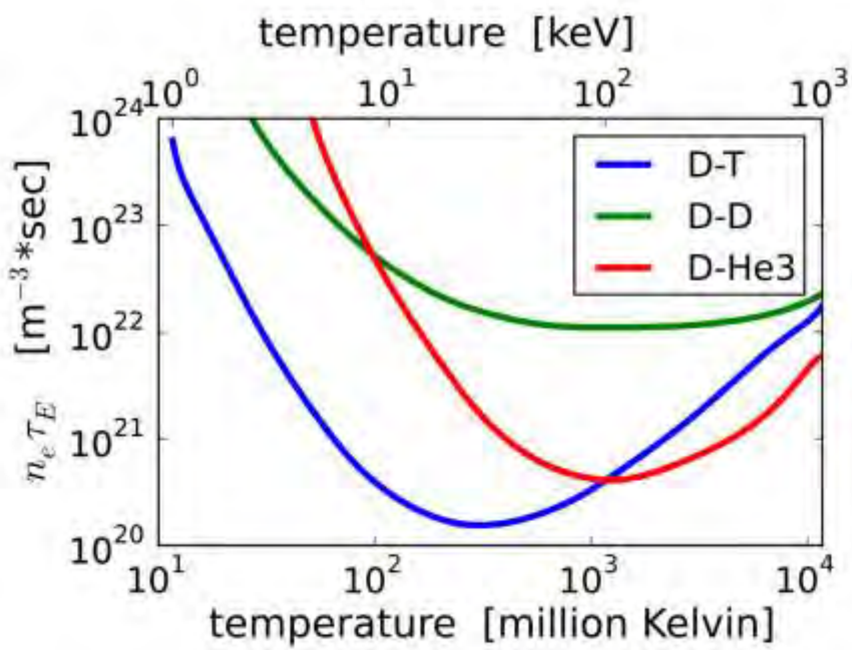
ECR Ion Source



Golonvaniskii criterion

$n_e\tau_i \sim 1\text{x}10^{17}$ s/m^3 at 9 keV for VENUS

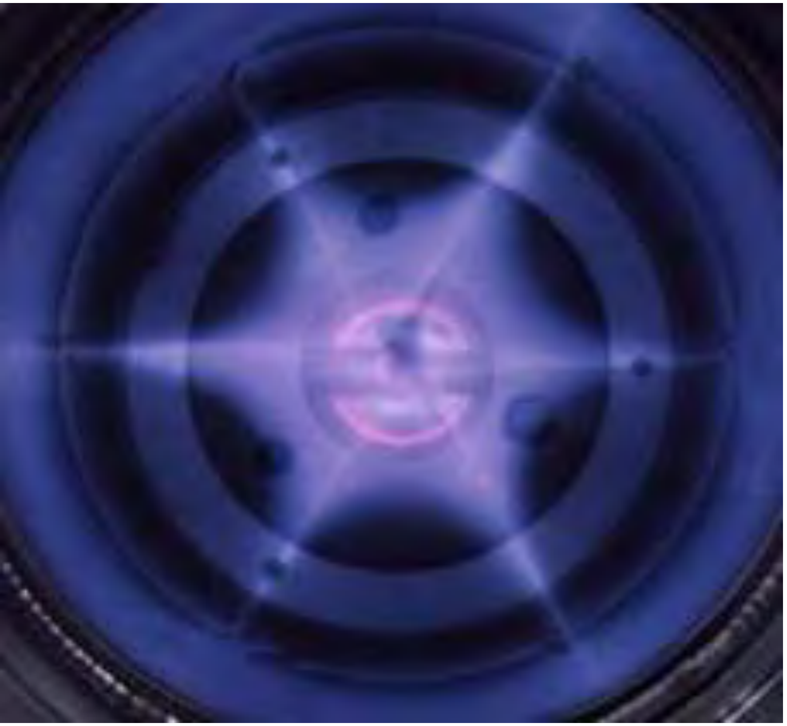
Fusion



Lawson criterion for D-T fusion

$n_e\tau_E \geq 1.5 \text{ x } 10^{20}$ s/m^3 at 25 keV

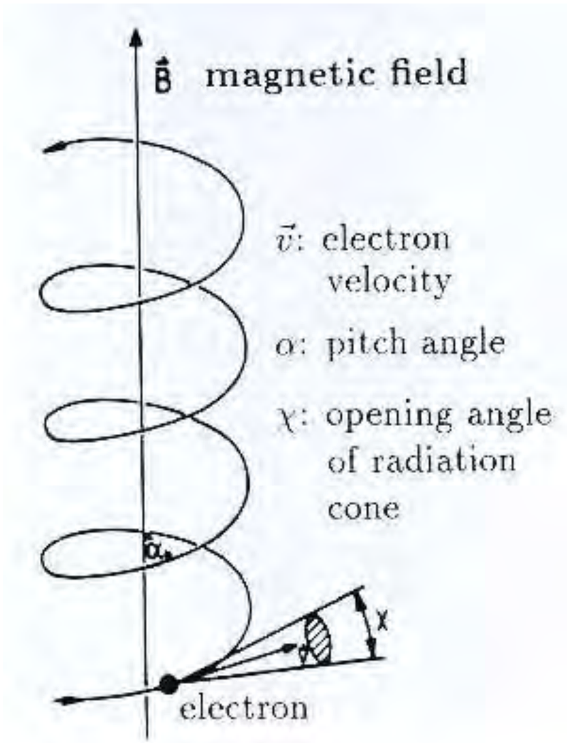
Plasma Properties

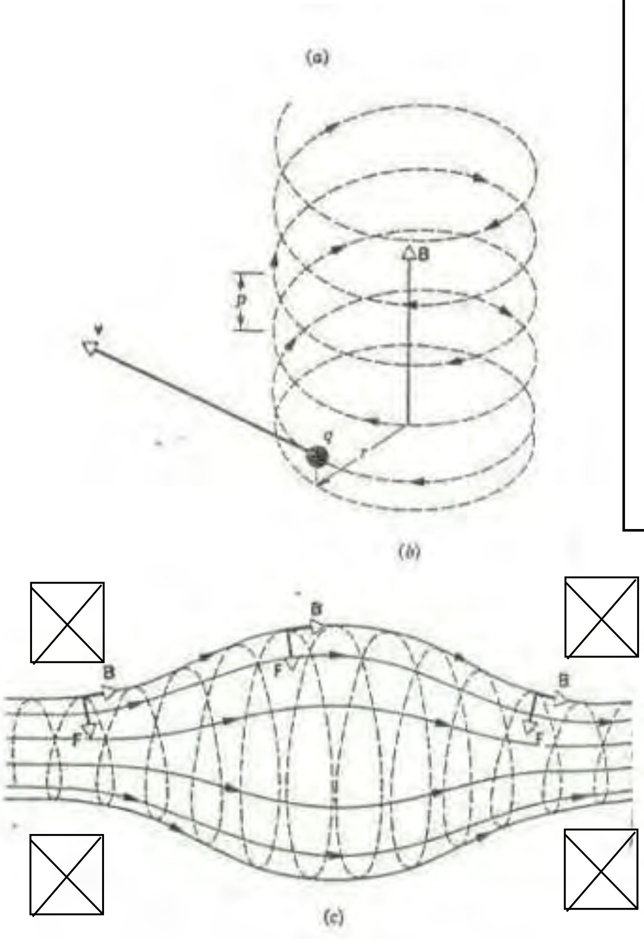


ECR plasma

- Partially or fully ionized gas consisting of free electrons and free ions as well as neutral atoms and molecules
- Overall neutral: $N_e=\Sigma q_{ion} \cdot N_{ion}$
- Need to be constantly heated to be sustained (fusion in stars, on earth energy must be added)
- Must be confined if it should be sustained for some time (gravity in stars, on earth with 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

Electrons in a magnetic field





- Electron cyclotron frequency
- ω_{ec} = eB/m_e
- 28 GHz ~ 1 Tesla
- Magnetic mirror can trap electrons
- Mirror ratio R_m

  $R_m = B_{max}/B_{min}$

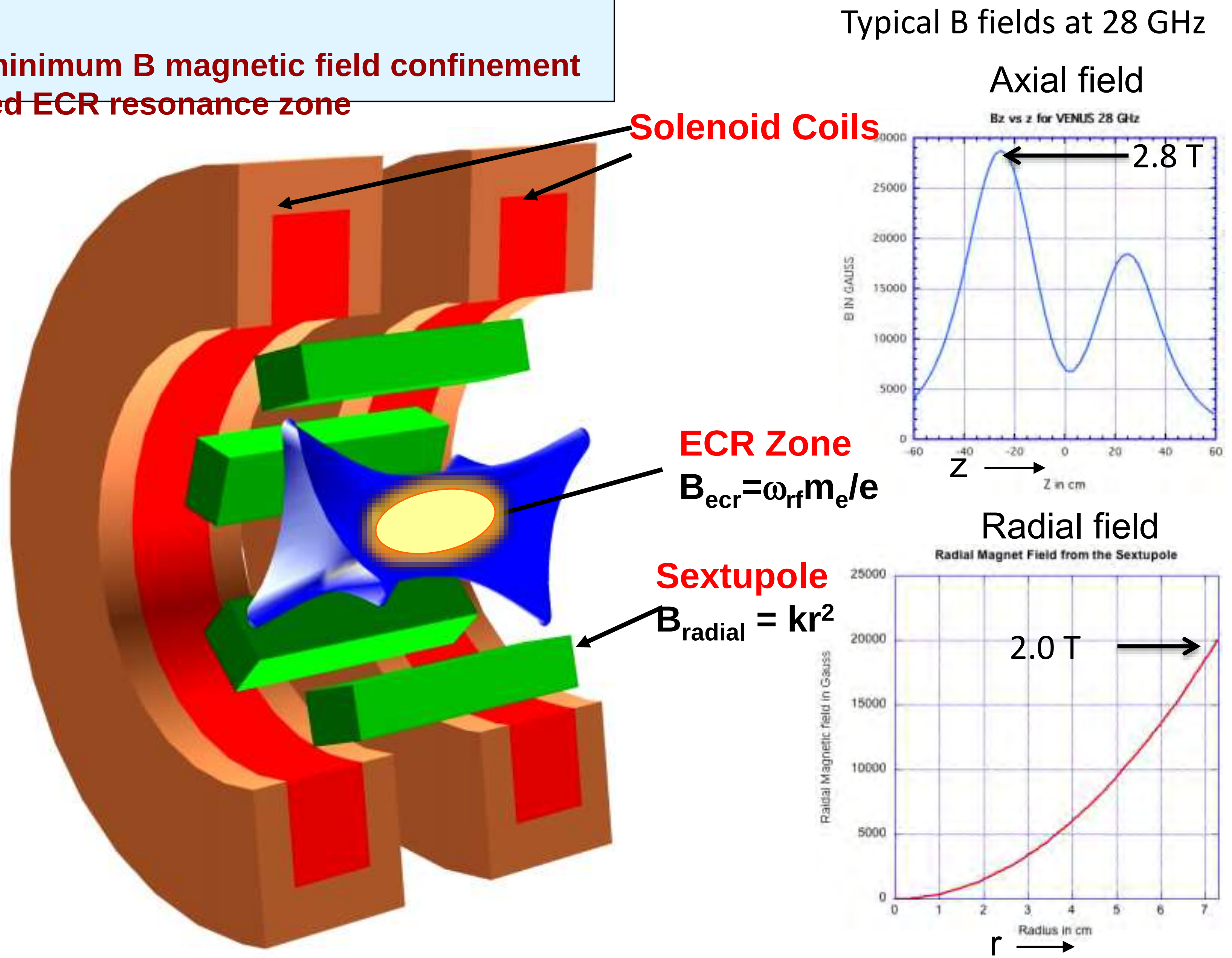
ω_{ec} electron cyclotron frequency

e electron charge

B magnetic field

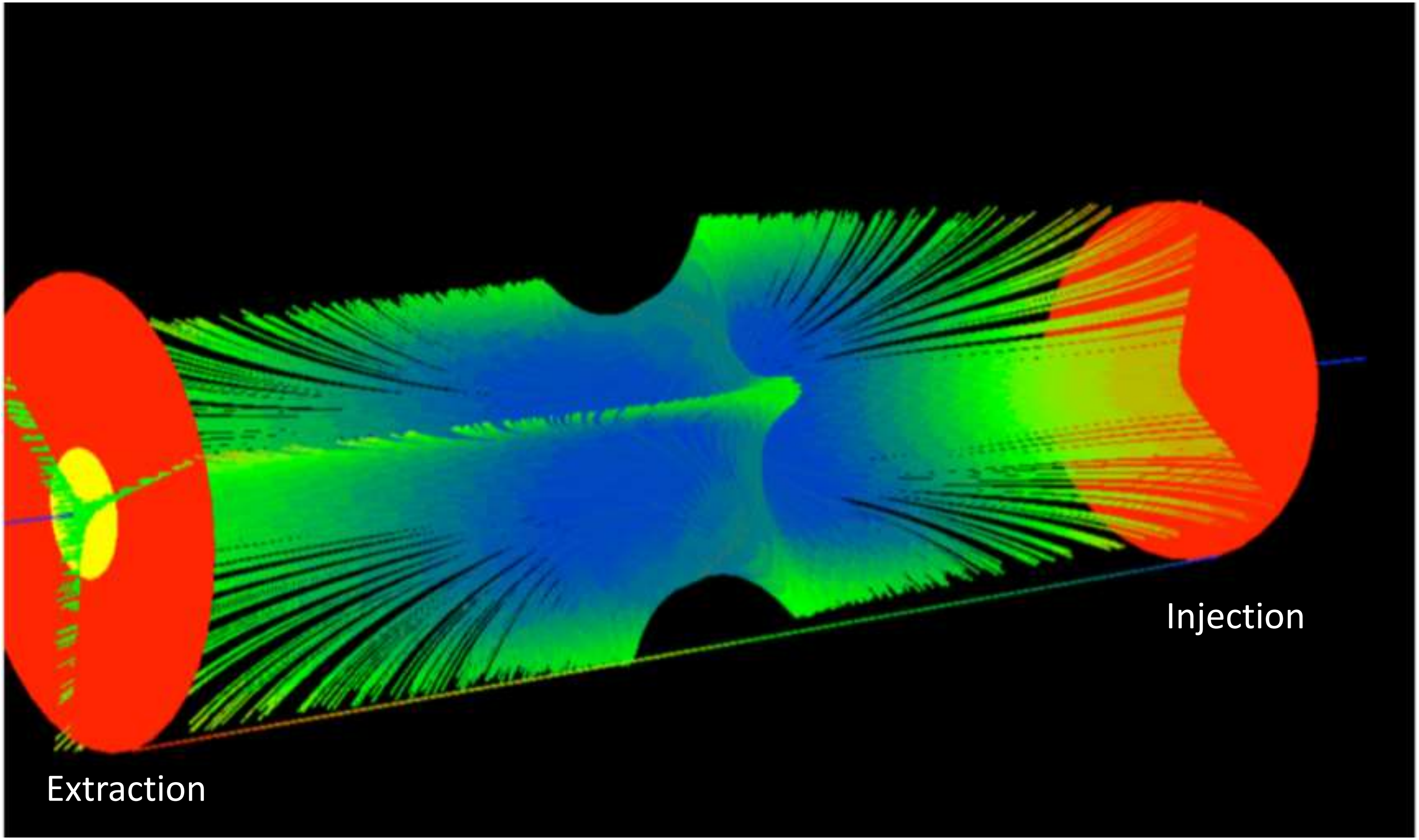
m_e electron mass

The superposition of axial mirrors and a sextupole provide a minimum B magnetic field confinement and a closed ECR resonance zone

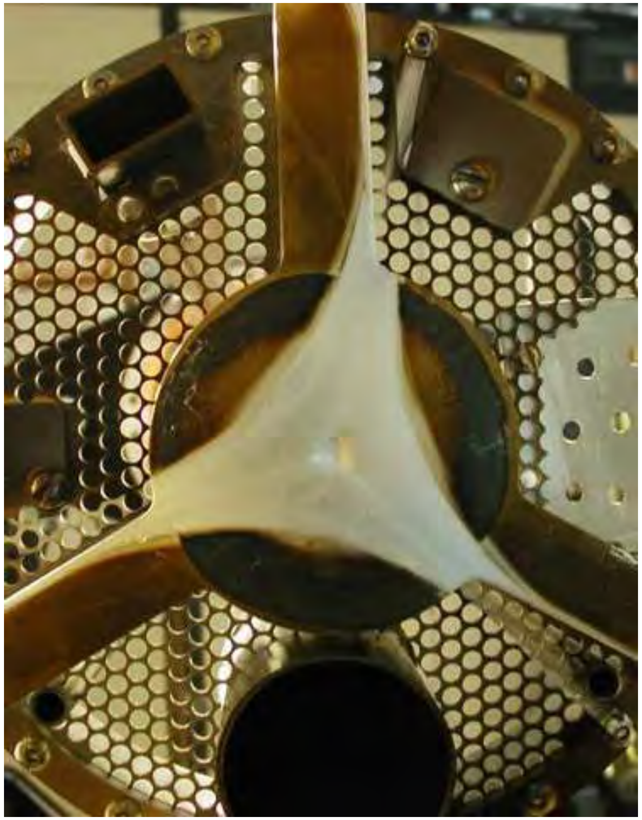


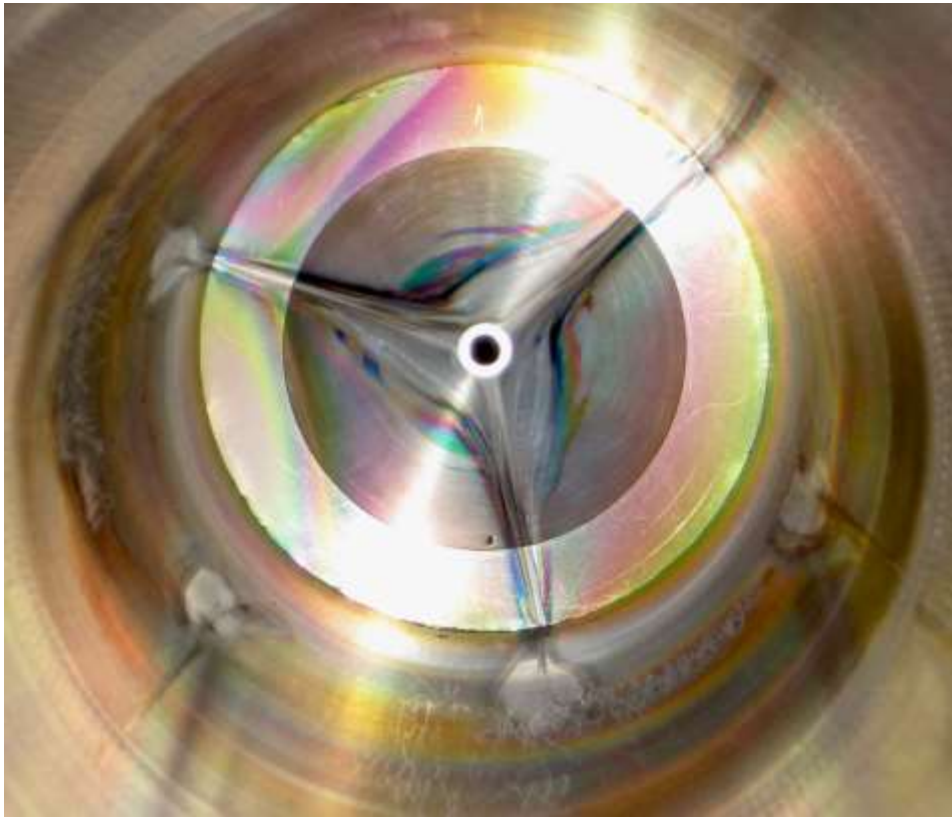
Magnetic field geometry

Field lines crossing the ECR zone and terminating on the plasma chamber walls for VENUS



Plasma marks on VENUS

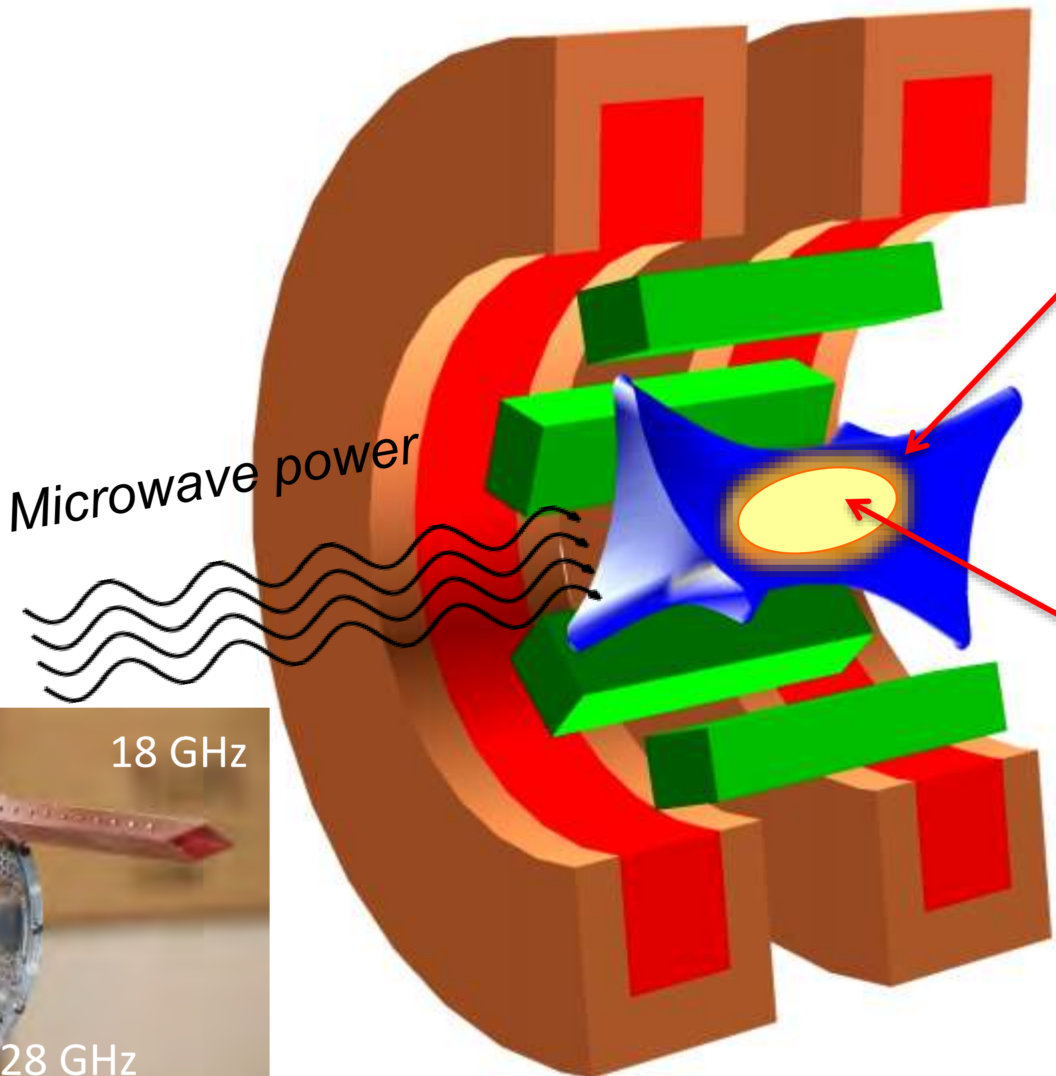




Injection
(bias probe)

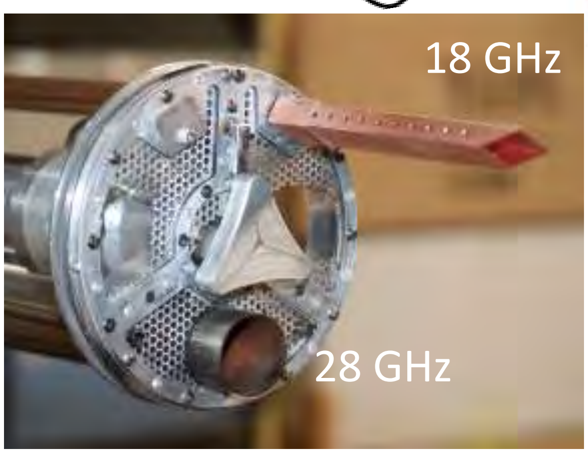
Extraction

Launching Microwave Power into an ECR Ion Source

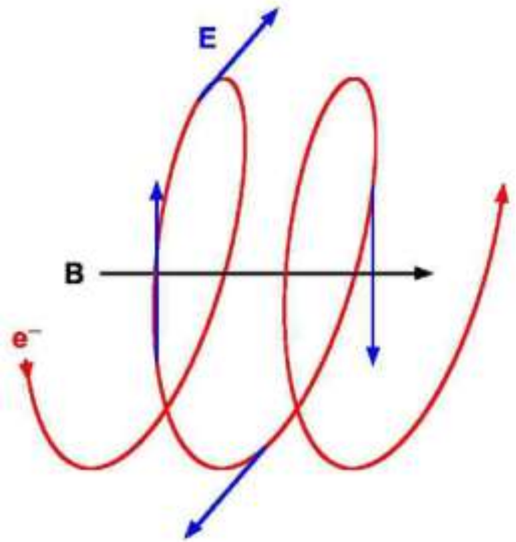


ECR Zone
$B_{ecr}=\omega_{rf} m_e/e$
Microwaves couple to the electrons at the ECR surface

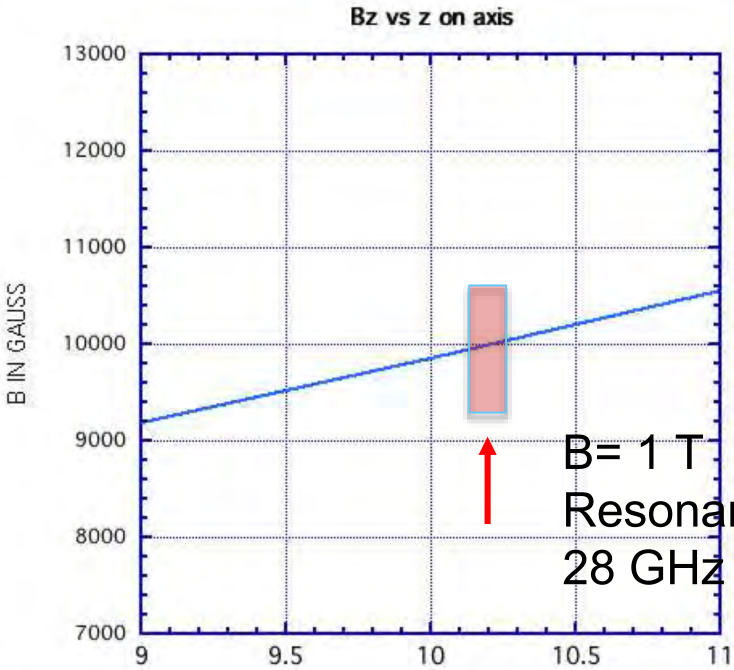
High density plasma inside The ECR Zone— "Plasmoid"



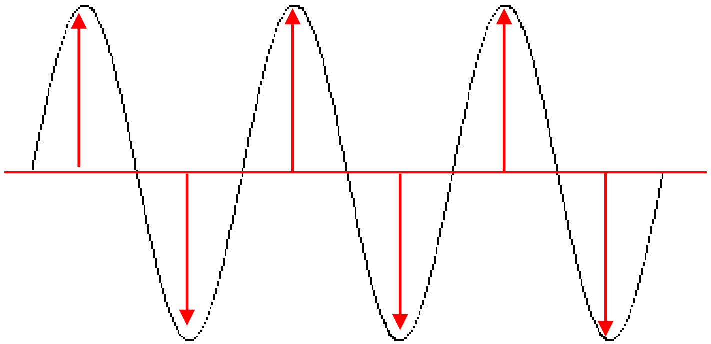
Simplified Model for Electron Cyclotron Resonance Heating



$\omega = eB/m_e$



B_z vs z



RF E field vs time

ECR heating occurs when the electron cyclotron frequency equals the RF frequency. Depending on the phase of the electron and the RF wave the electron can be heated or cooled. If stochastic heating is assumed, on average energy is gained

Plasma density in High Charge State ECR ion sources

- The plasma frequency ω_p is the natural oscillation frequency of a plasma with the electrons oscillating against ions … where n_e is plasma density

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

- Simplest dispersion relation of EM wave in a plasma is

$$\omega^2 = \omega_p{}^2 + k^2 c^2$$

- EM propagates if $n_e < \dfrac{m_e \varepsilon_0 \omega^2}{e^2}$

- Plasma critical density $n_{critical}$ when $n_e = \dfrac{m_e \varepsilon_0 \omega^2}{e^2}$

- Above the critical density many EM waves no longer propagate
- High charge state ECR ion sources are believed to operate below the critical density
- $n_{critical}$ at 28 GHz is 9.9×10^{18} /m^3

Frequency scaling in ECR ion sources

- Geller proposed scaling for ECR ion sources 1987
  - Plasma density $n_e \sim f^2$
    - Based on the assumption $n_e < n_{critical}$ and measurements at 10 to 18 GHz
  - Beam current $I \sim n_e \sim f^2$

$$B_{ecr} = \frac{m\,\omega_{rf}}{e}$$ (Electron cyclotron resonance condition)

- In the 1990's experiments showed there is an optimum magnetic field for confinement
  - $B \geq 2\,B_{ecr}$ at the plasma chamber walls
  - $B_{inj} \sim 3\,B_{ecr}$ on axis
  - $B_{rad} \geq 2\,B_{ecr}$ on the walls
  - $B_{ext} \sim B_{rad}$
  - $B_{minimum} \sim 0.4\text{-}0.8\,B_{ecr}$ on axis

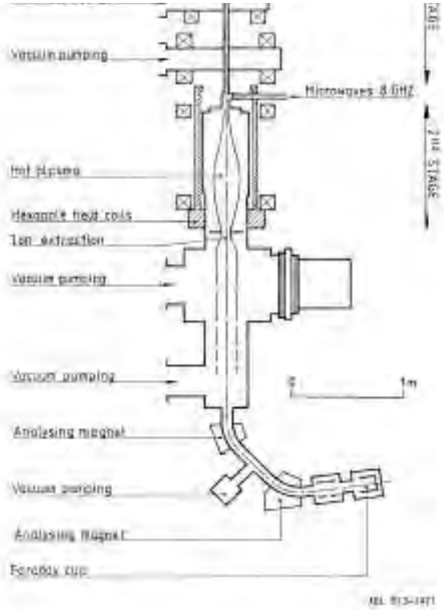
ECR Ion Source Pioneers

6^{th} Workshop on ECR Ion Sources Berkeley 1985

High Charge State Ion Sources----ECRIS

Supermafios (Geller, 1974)

15 eμA of O^{6+}



VENUS (2011)

3000 eμA of O^{6+}

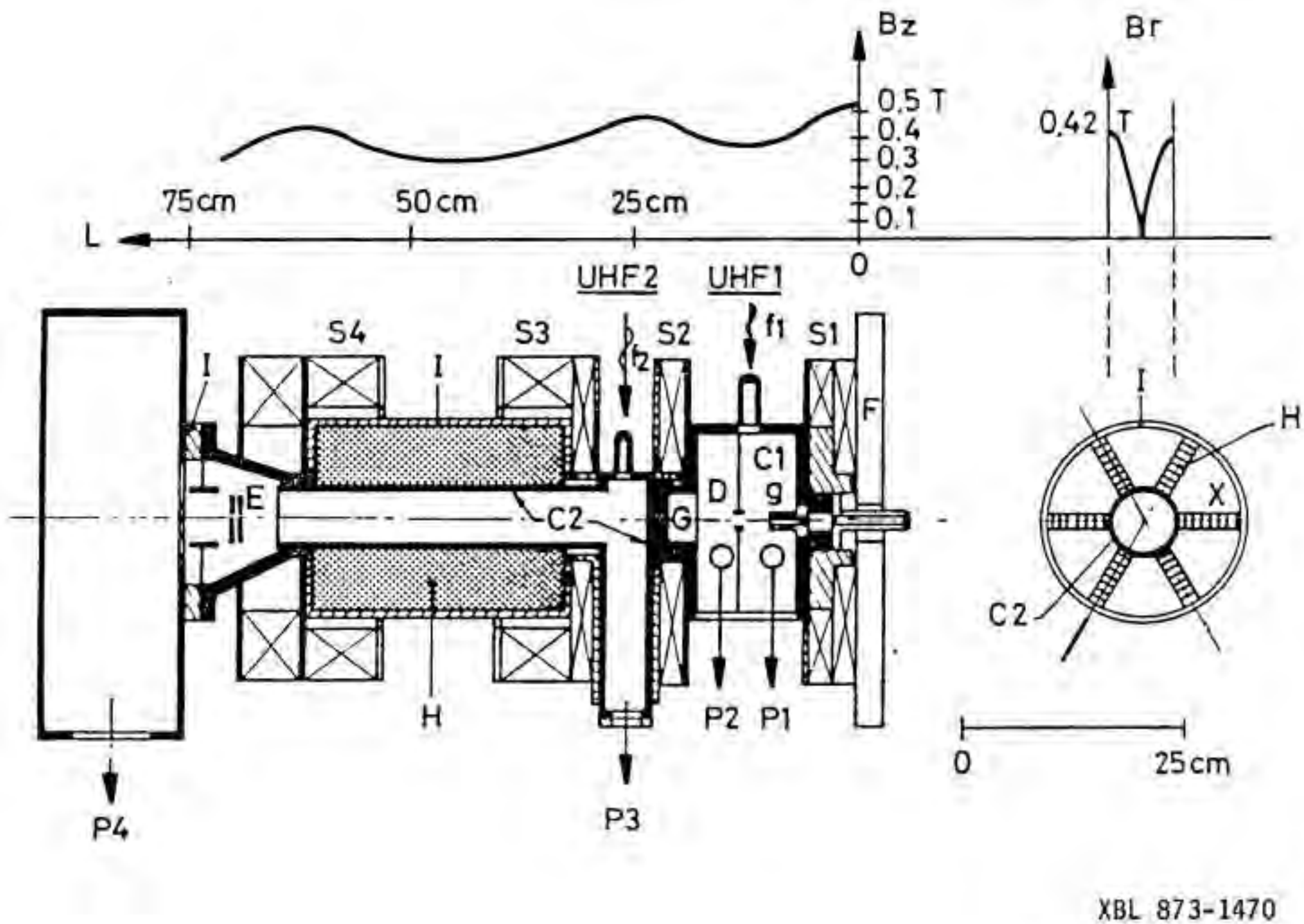
Power consumption 3 MW

Solenoid, Sextupole, Axial Extraction

Power consumption 100 kW

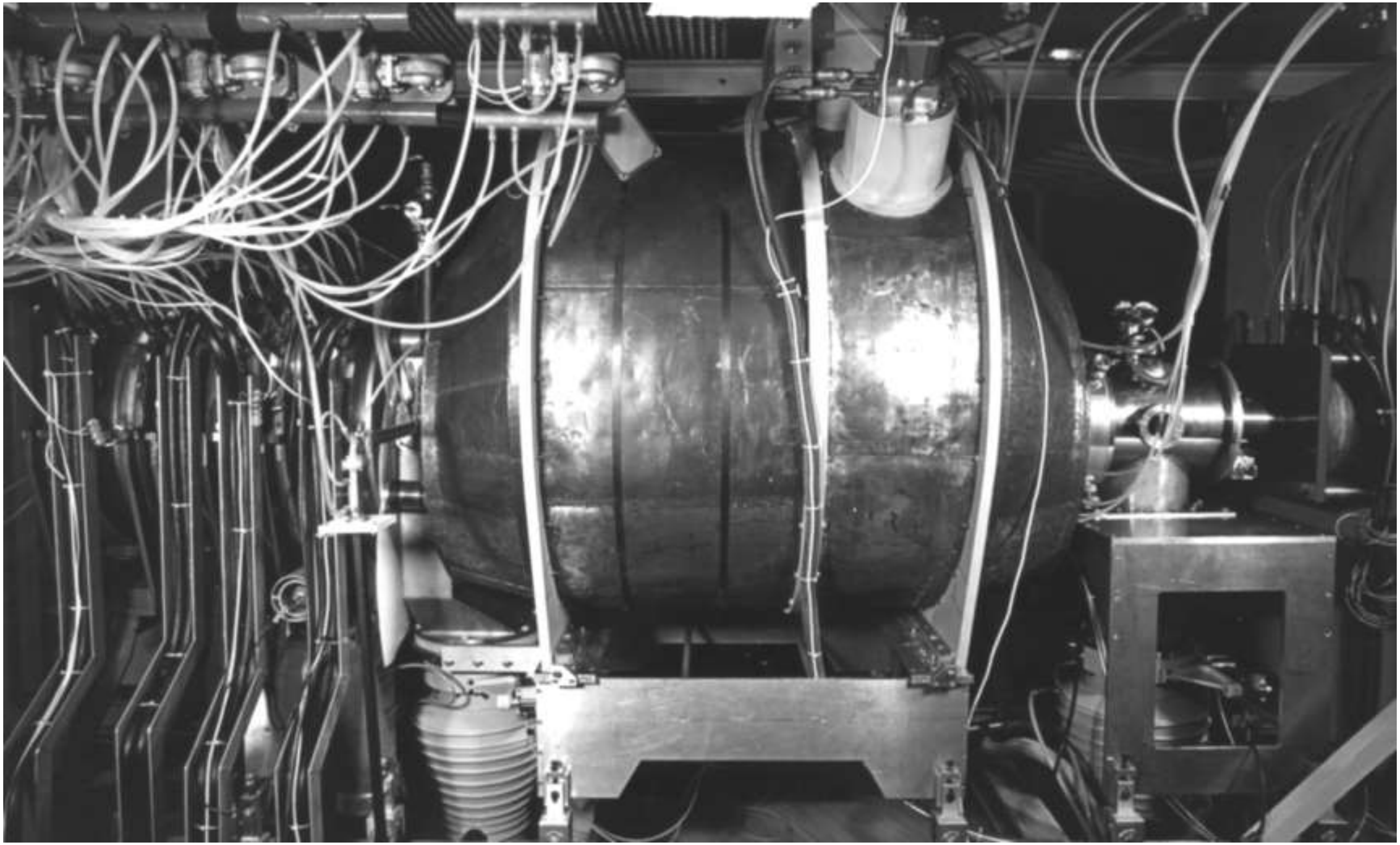
Solenoid, Sextupole, Axial Extraction

Minimafios Grenoble ~1979 Geller's group



ECREVIS circa 1983

First successful superconducting ECR ion source



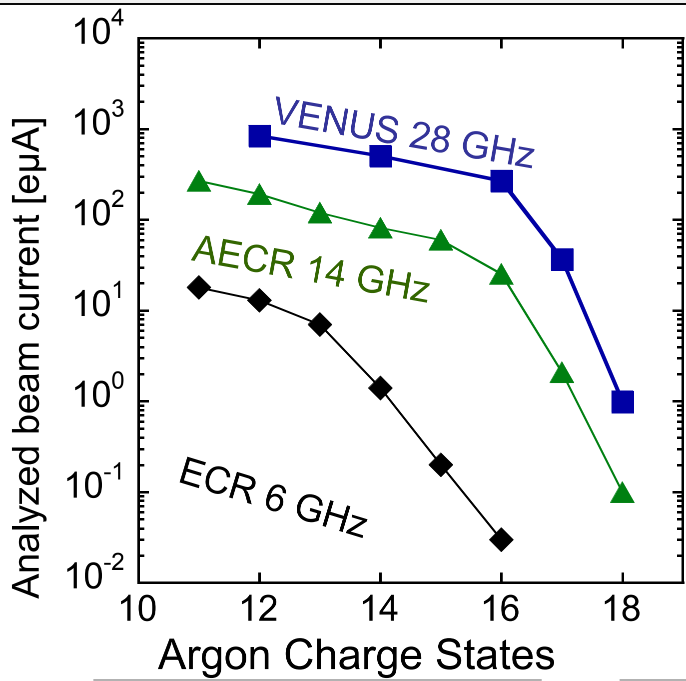
Yves Jongen, Louvain-la Neuve, Belgium

Microwave power for ECR Ion sources

- 6.4 to 18 GHz klystrons are used
  - (2-3 kW CW)
  - narrow bandwidth typically ~100 MHz
- 5 to 18 GHz TWT's
  - 300—500 W
  - Broadband width ~ several GHz
- Above 18 GHz and below 31 GHz
  - 24 and 28 GHz 10 kW cw gyrotrons can be used
  - 1 kW CW EIO (extended interaction oscillators commercially available)
  - CPI has devices at ~1 kW and frequencies 27-31 GHz
- Above 30 GHz existing gyrotrons are pulsed with peak powers ≥100 kW, but these could be de-rated to operate at CW (~30 kW)

10 kW, 28 GHz gyrotron

Higher magnetic fields and higher frequencies are the key to higher performance



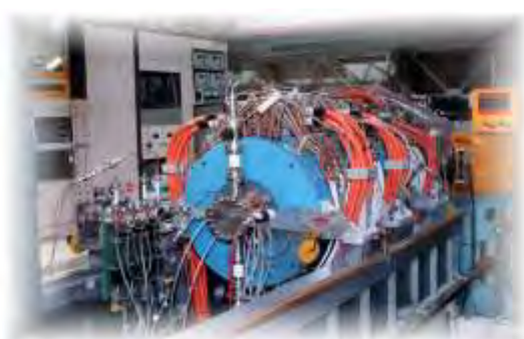
Normal conducting

⇩

Super conducting

ECR (1983)
0.4 T, 0.6 kW, 6.4 GHz

AECR-U (1996)
1.7 T, 2.6 kW, 10 + 14 GHz



VENUS (2004)
3.5 T, 14 kW, 18 + 28 GHz

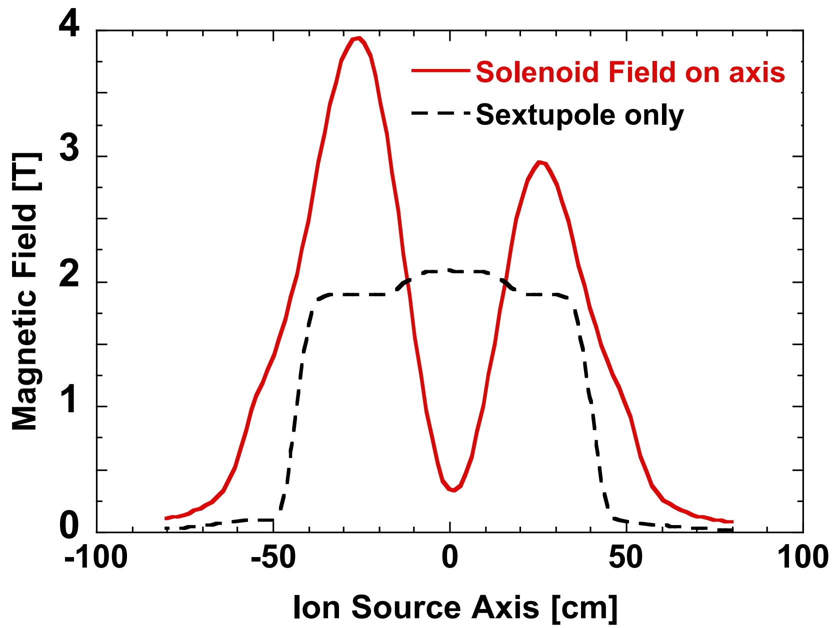
Time, Money, Technical Complexity →

VENUS 28 GHz Superconducting ECR Ion Source

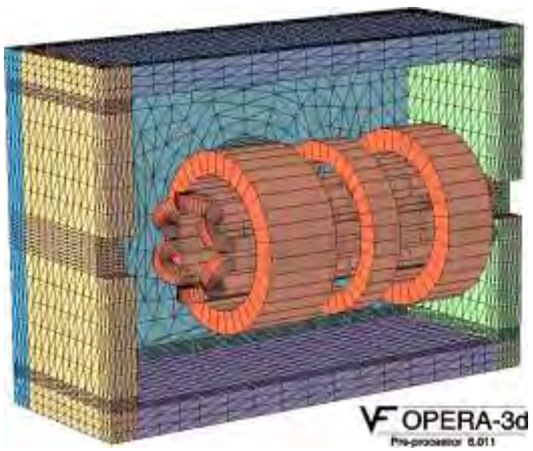
First plasma 2002
28 GHz operation in 2004

VENUS Magnet Development and Performance

28 GHz VENUS



Main challenge are the forces between the sextupole and solenoid magnet coils



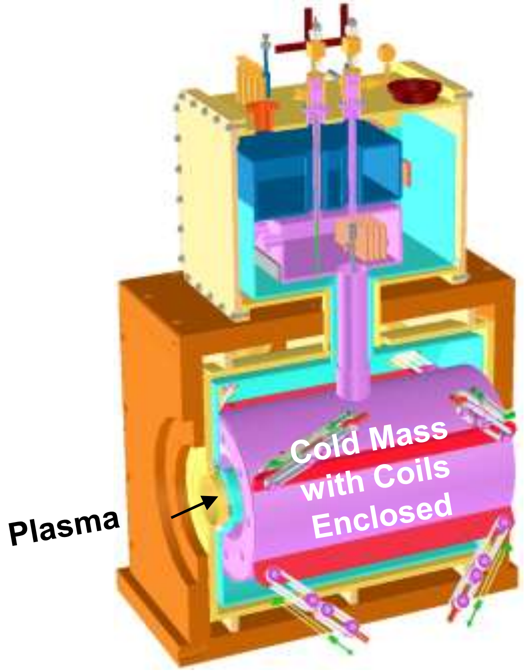
Special clamping technique has solved this problem for the VENUS source

The sextupole magnet is routinely run above design currents

Achieved
4T, 3T (inj,ext)
2.2 T plasma wall

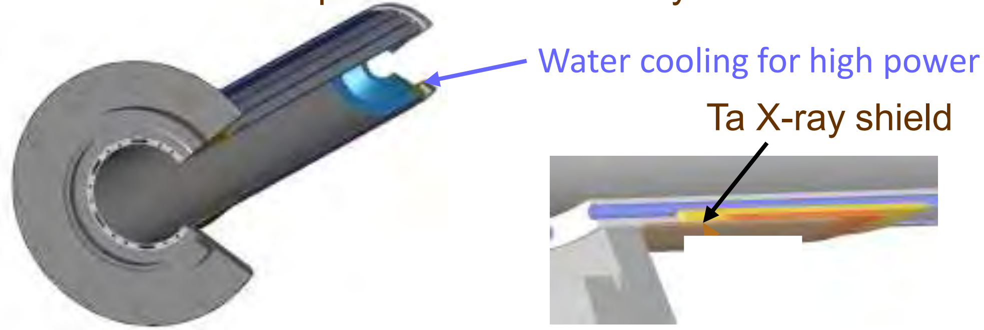
VENUS Technology Development
Now Incorporated Into Other 3rd Generation Sources

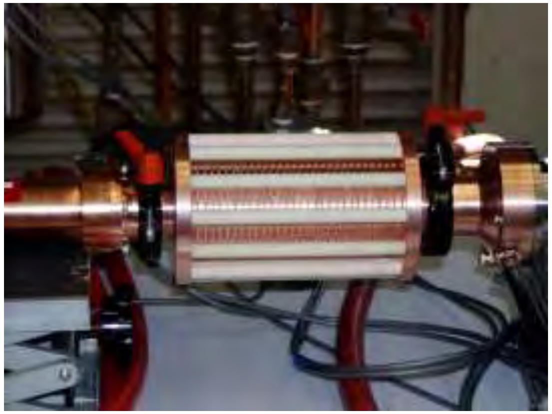
Advanced cryostat with cryocoolers



Beam transport with high transmission dipole magnet

Aluminum plasma chamber for high power operation with incorporated tantalum x-ray shield



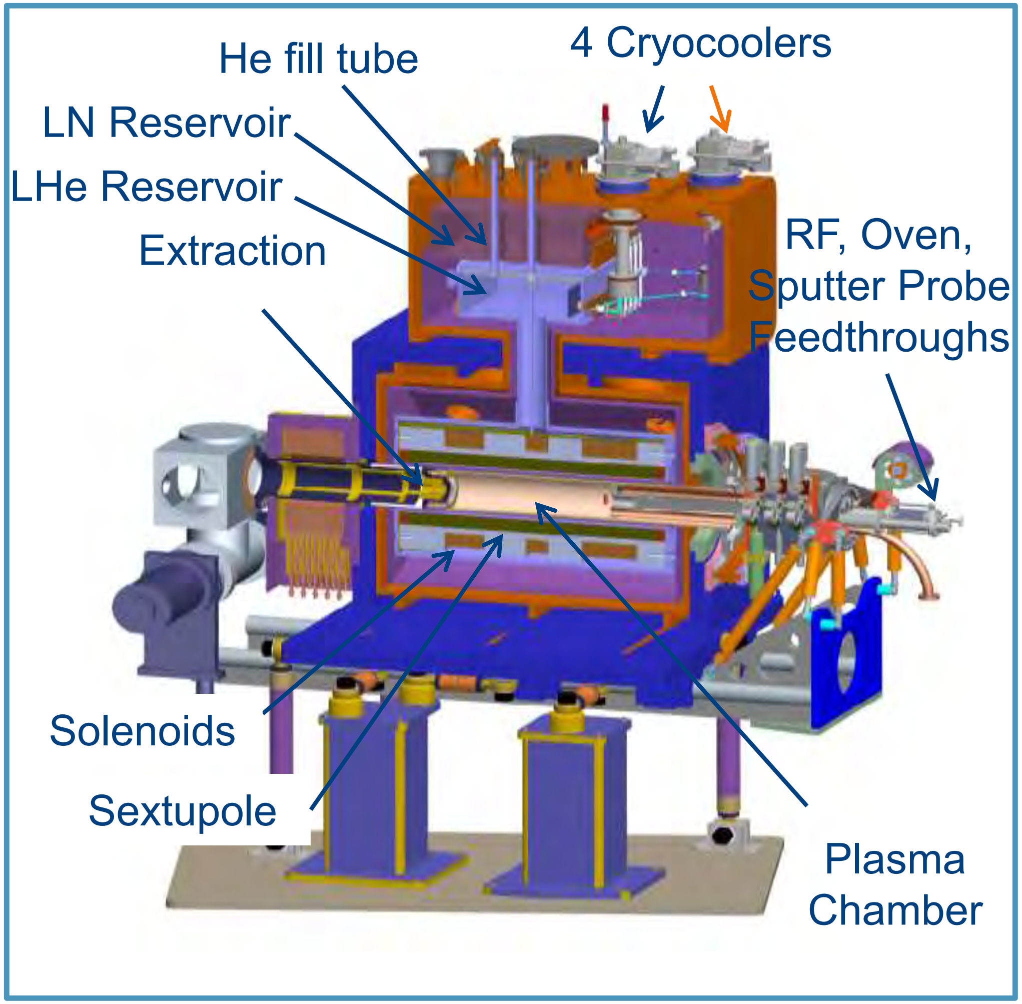


28 GHz ceramic 30 kV HV break

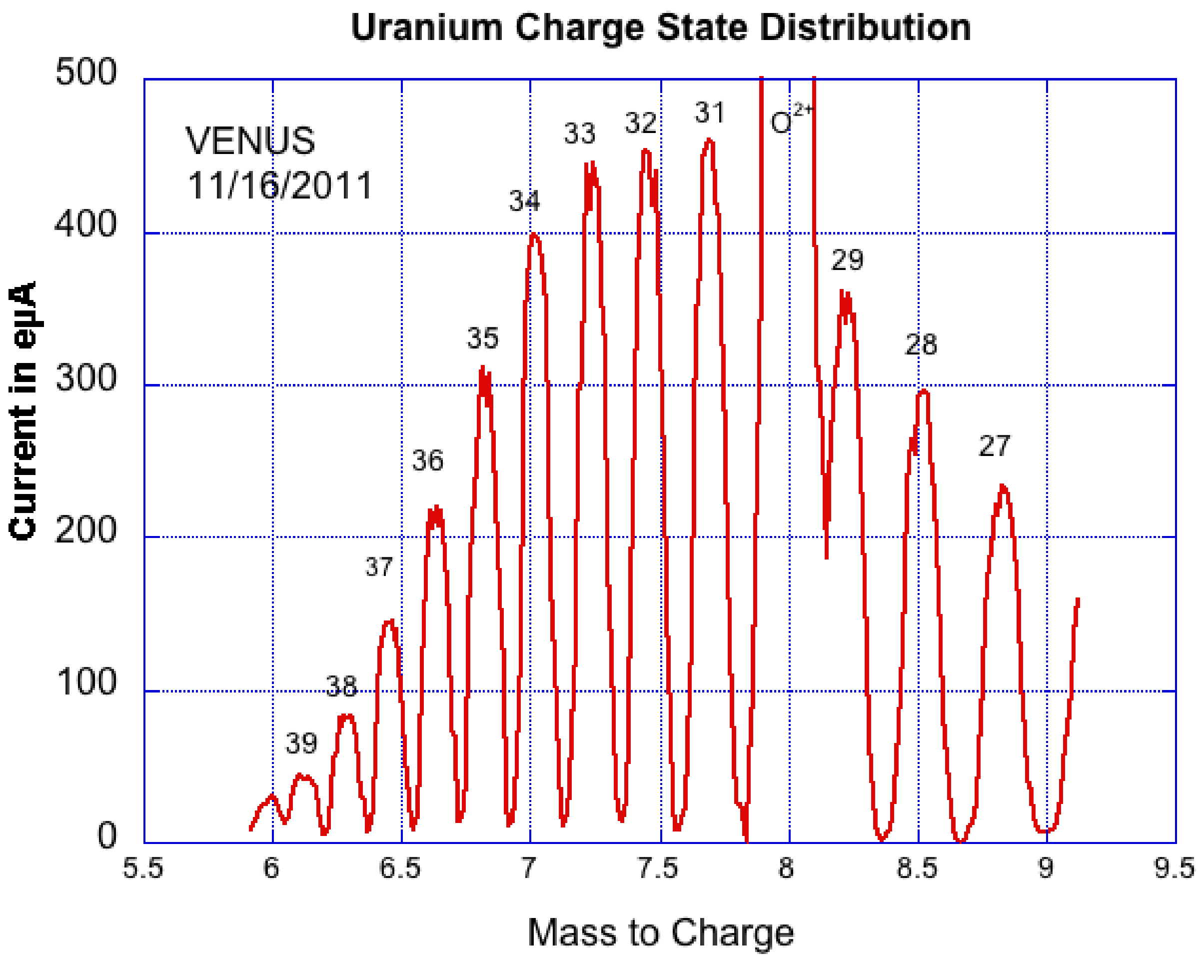
Overview of VENUS

- **Fully superconducting**, Niobium-Titanium sextupole & 3 solenoids enclosed in LHe
- **LN Reservoir** : 70K, dissipates heat from normal conducting leads
- **LHe Reservoir**: 4.2K
- **Four two stage cryocoolers** which provide **6W total cooling power at 4.2K**, recondense evaporated He, 1st stage (45K) cools part of the Cu leads

Maximum Injection Field, on axis	4.0T
Maximum Extraction Field, on axis	3.0T
Maximum Radial Field, at wall	2.2T
Chamber Diameter	14cm
Chamber Length	50cm
18 GHz Maximum Power	2kW
28 GHz Maximum Power	10kW
28 GHz Maximum Power Injected	6.5kW
18+28 GHz Maximum Power Injected	8.5kW



VENUS Recent Results



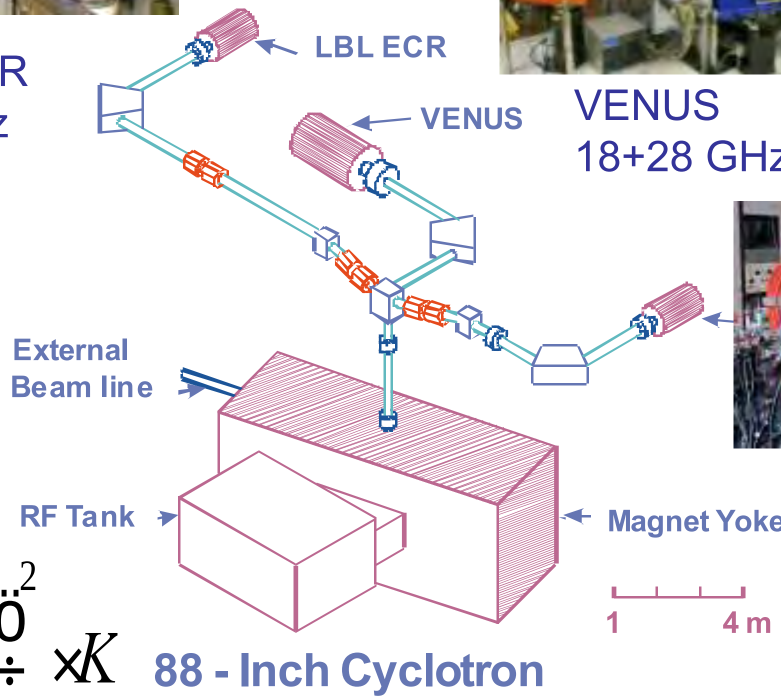
Ion	Intensity eμA
He^{2+}	11,000
O^{6+}	3,000
Ar^{11+}	860
Ca^{11+}	400
Bi^{31+}	300
Bi^{50+}	5
U^{33+}	440
U^{50+}	13

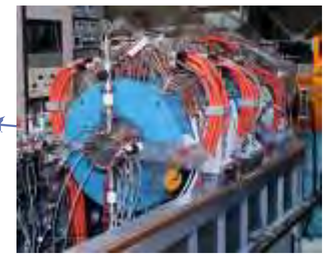
88-Inch Cyclotron Facility

LBL ECR
6.4 GHz

VENUS
18+28 GHz

VENUS Applications
- Heavy element research
  - 70 eμA Ca^{11+}
- Space radiation effects testing
  - 100 enA Xe^{43+}
  - ECR Ion Source R&D





AECR-U
10+14 GHz

AECR-U Applications
- Nuclear physics research
- Space radiation effects

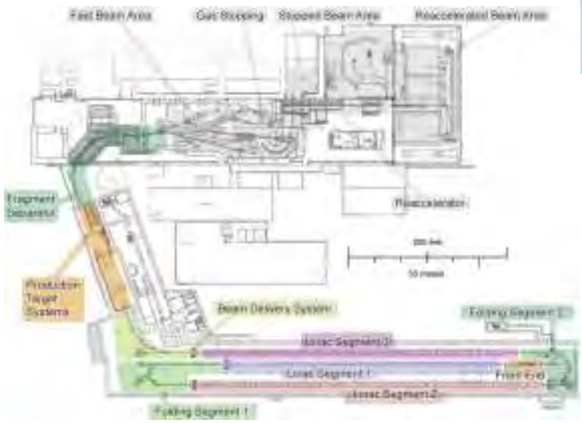
$$\frac{E}{M} = \left(\frac{Q}{M}\right)^2 \cdot K$$

K =130

5 MeV/nuc   M/Q $\leq$ 5

Demand for increased intensities of highly charged heavy ions from ion sources continues to grow

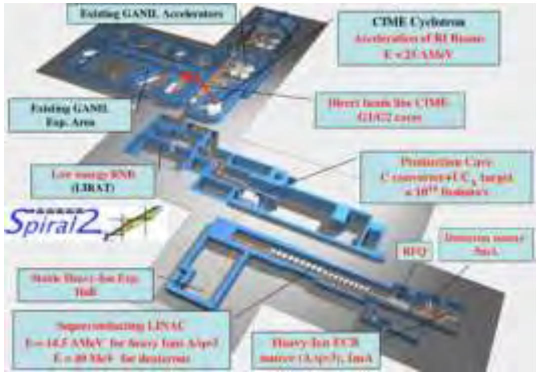
FRIB
MSU, USA



270 eµA U^{33+}
and
270 eµA U^{34+}

SPIRAL 2, GANIL, France

1mA Ar^{12+}



IMP HIRFL, LANZHOU, China

750 µA Bi^{35+}

RIKEN, Japan

525 eµA U^{35+}

RAON, S. Korea

400 µA U^{33+}

Research and Applications for High Charge State Ions

- Accelerator Applications
  - Nuclear and High Energy Physics
    - Heavy-ion Accelerators for nuclear physics research
    - Driver linacs for rare isotope beam production
    - Charge breeders for is rare isotope post accelerators
    - Heavy-ion synchrotrons (CERN LHC)
    - EIC (Electron Ion Collider—Next Nuclear Physics Initiative)
  - Space Radiation Effects Testing (simulating cosmic ray environment)
    - Testing of electronic devices for space vehicles
  - Particle Therapy
    - Proton Therapy
    - Hadron Therapy (Carbon Beam Therapy)
- Atomic Physics
    - Charge exchange cross section
    - Astrophysics (effect of high charge state plasmas on optical transmission)
- Fusion Materials Testing
  - High intensity proton sources $\geq$ 100 mA
  - First wall lifetime studies

Fourth Generation ECR Ion Sources

GenIV-ECR

$$B_{ecr} = \frac{m\,\omega_{rf}}{e}$$

For a 56 GHz ECR B_{ecr} = 2 T

Confinement criterion

$Bconf \geq 2\ B_{ecr}$ at walls

$B_{inj} \sim 3\ B_{ecr}$ on axis

$B_{rad} \geq 2\ B_{ecr}$ on the walls

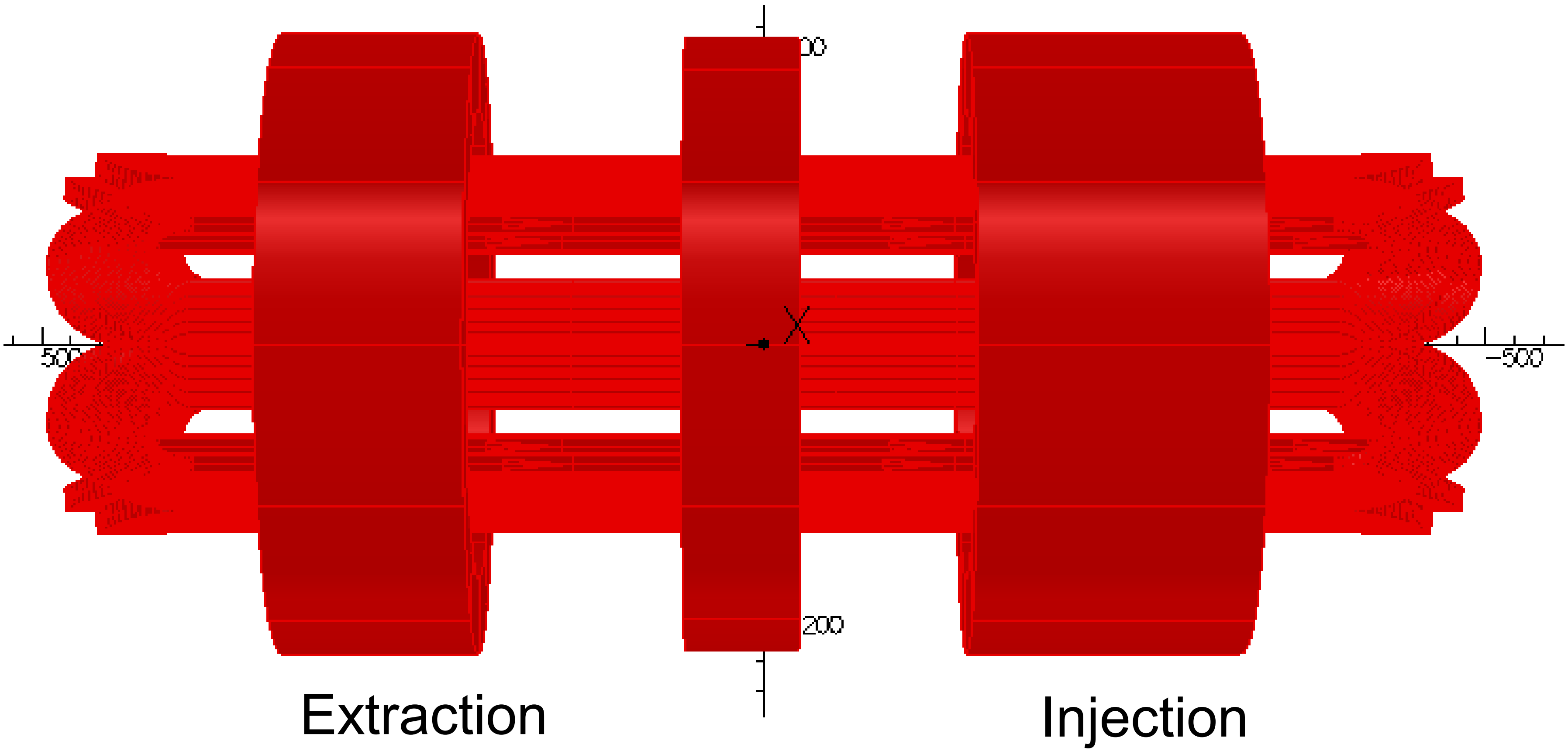
GenIV-ECR

$B_{inj} \sim 6$ T

$B_{ext} = 4$ T

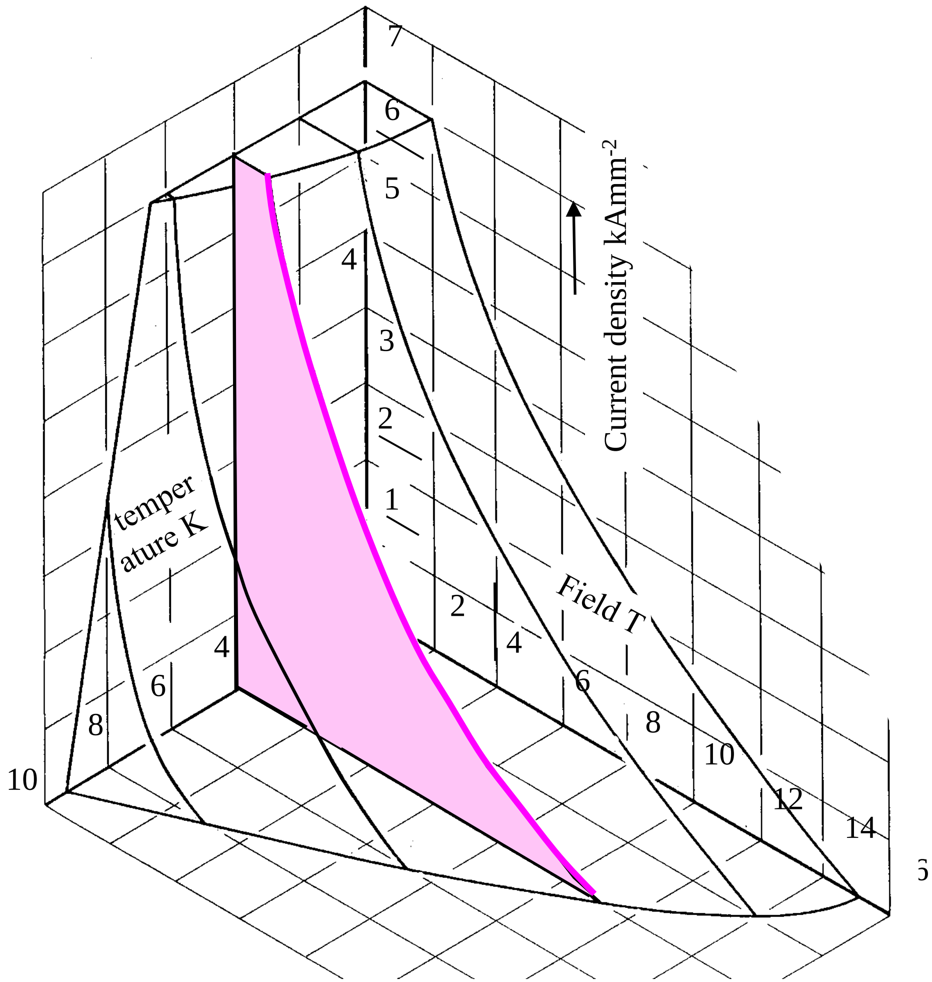
$B_{rad} = 4$ T

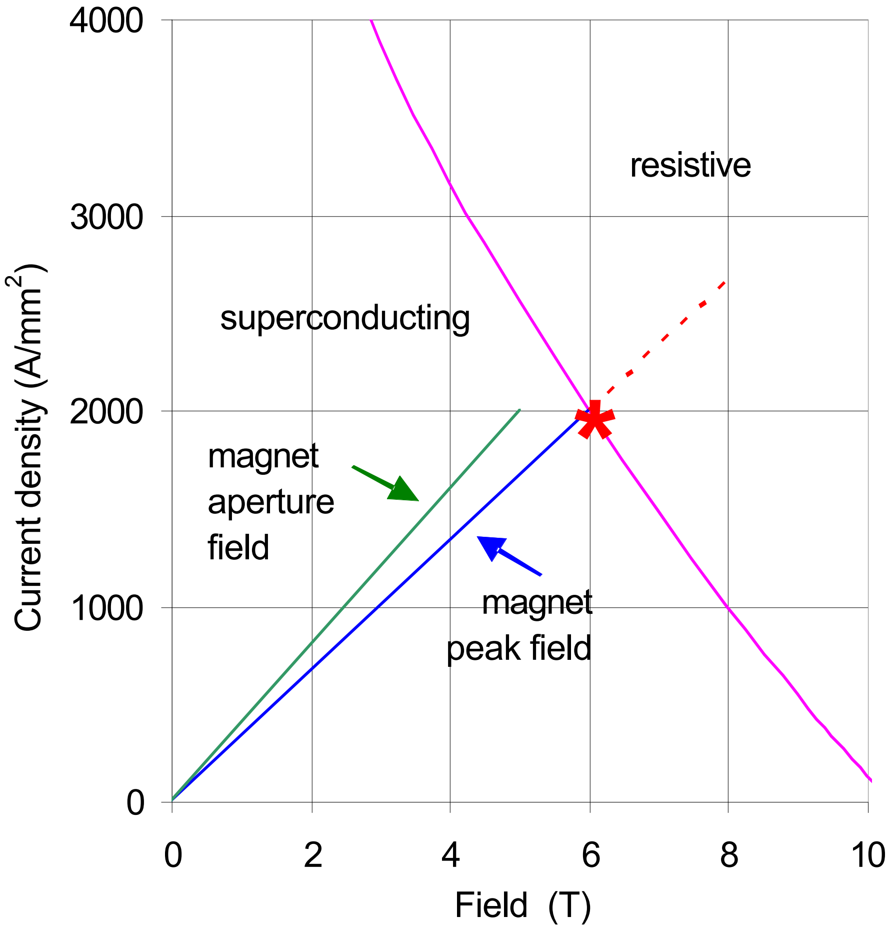
Starting point—VENUS Geometry
Frequency---56 GHz (twice that of VENUS)



Superconducting ECR Magnets-Challenge 1

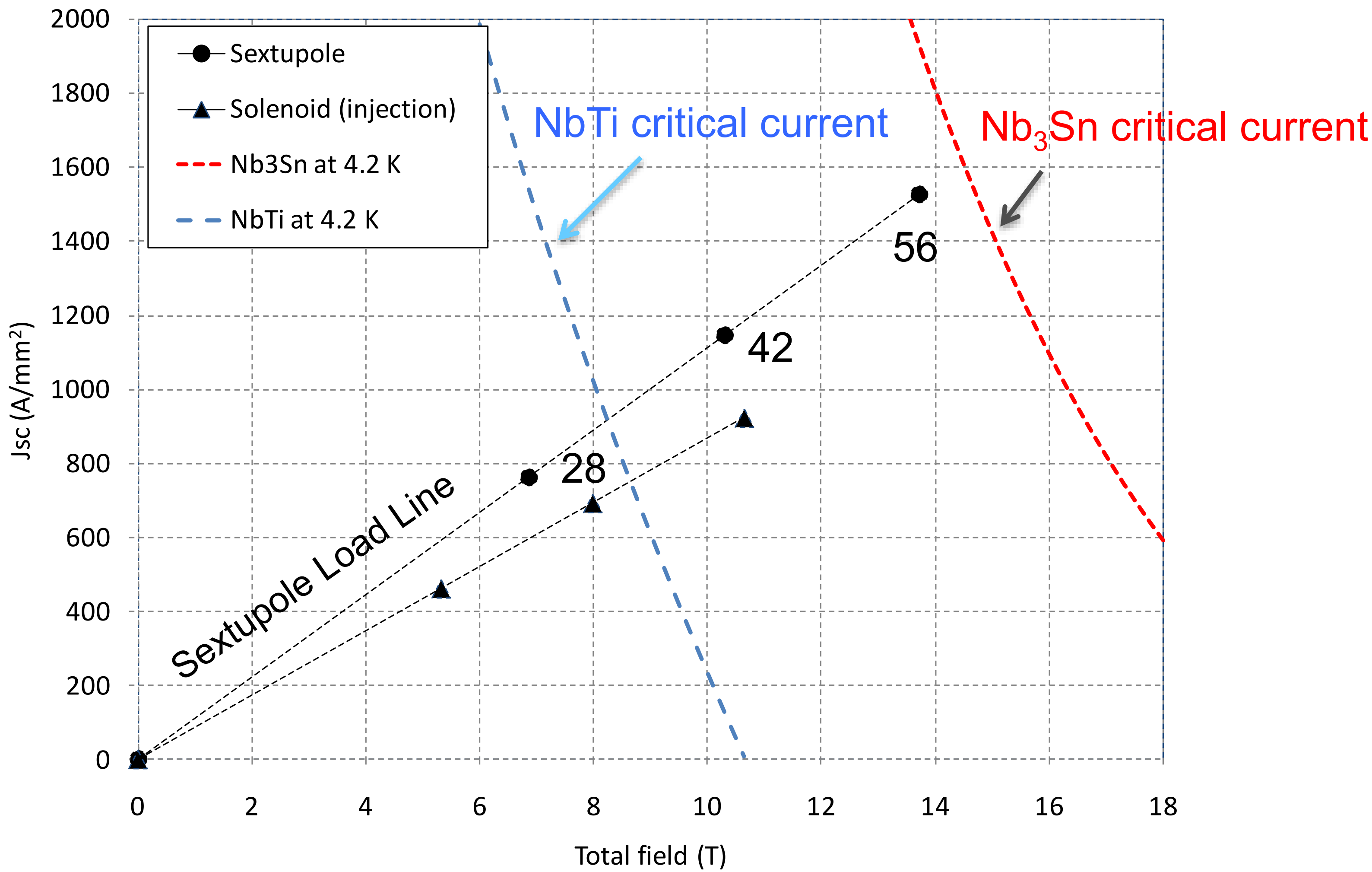
Critical line and magnet load lines





we expect the magnet to go resistive ***'quench'*** where the peak field load line crosses the critical current line *

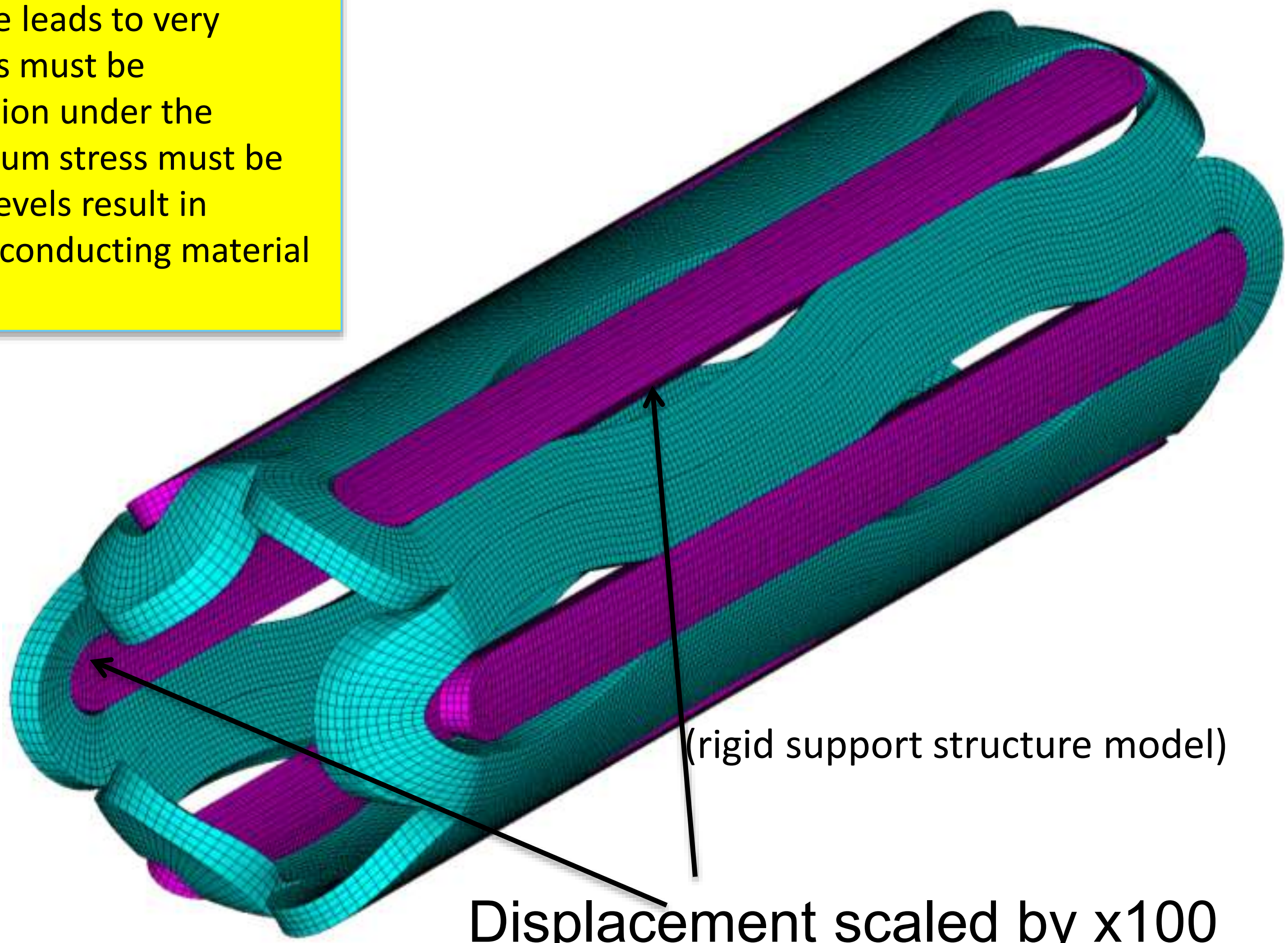
Operational condition at 28 – 42 – 56 GHz
($B_{injection}$ = 3.5 B_{ecr})



Deformed shape of sextupole under combined e.m forces

The super position of solenoid and sextupole magnets in an ECR source leads to very complex forces. Magnets must be prestressed to avoid motion under the Lawrence forces. Maximum stress must be ≤160 MP. Higher stress levels result in degradation of the superconducting material properties.

Challenge 2

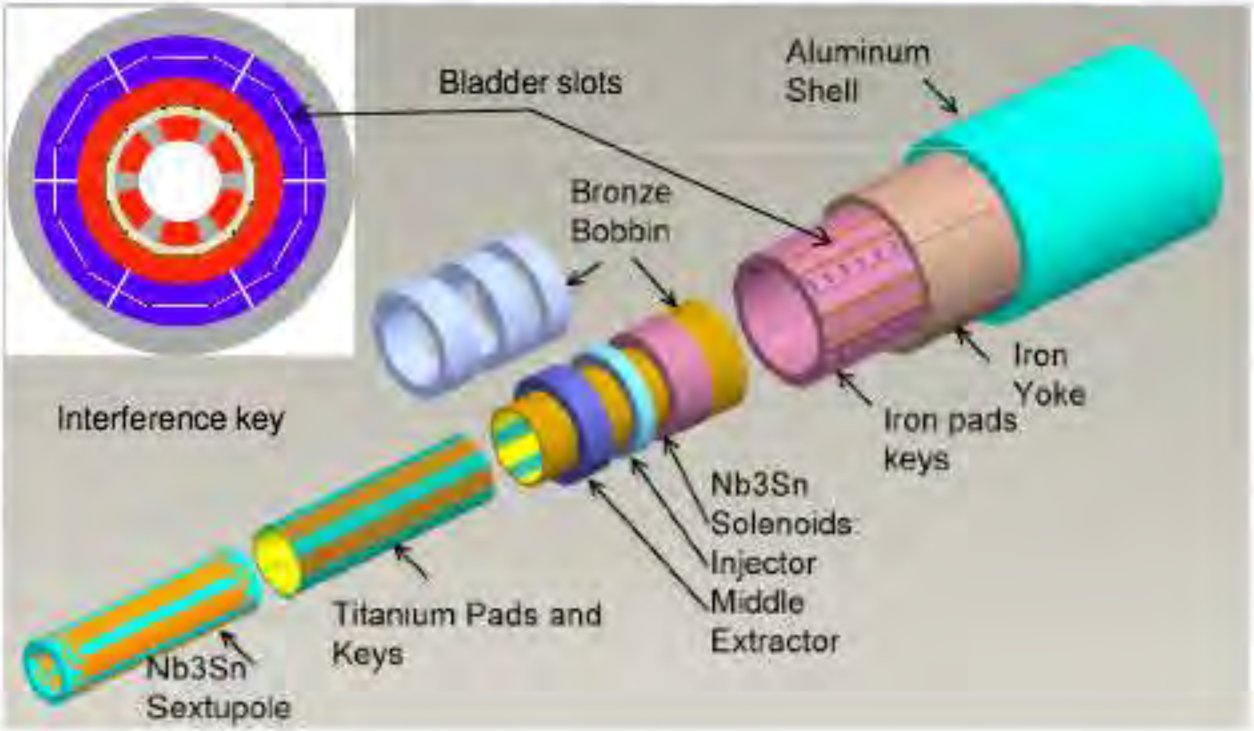


(rigid support structure model)

Displacement scaled by x100

Shell-based Mechanical Structure

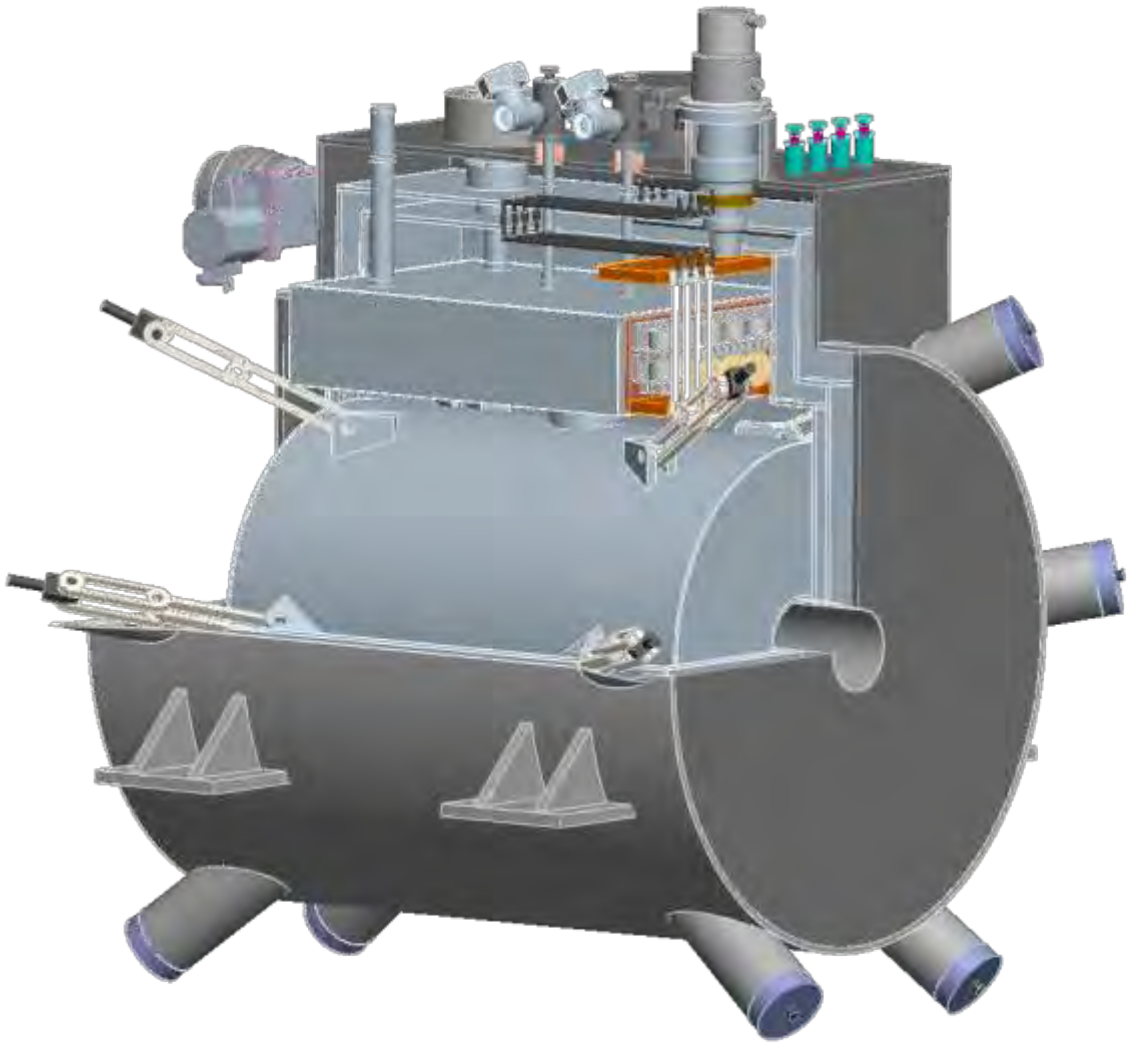
- Primary mechanical support is provided by a thick Aluminum shell
- Assembly (warm) pre-load by pressurized bladders and interference keys
- Pre-load increase at cool-down due to shell-yoke differential contraction
- The coils remain in compression up to the operating point



GenIV-ECR Cryostat Design

- Two 5 W GM-JT cryocoolers at 4.2 K
- One shield cryocooler 6 W at 20 K and 120 W at 77 K
- High Tc leads
- Static heat load 1.5 W
- Magnets on + 0.15 W
- Warm bore 170 mm ID

- Designed for HV platform
- No LN cooling



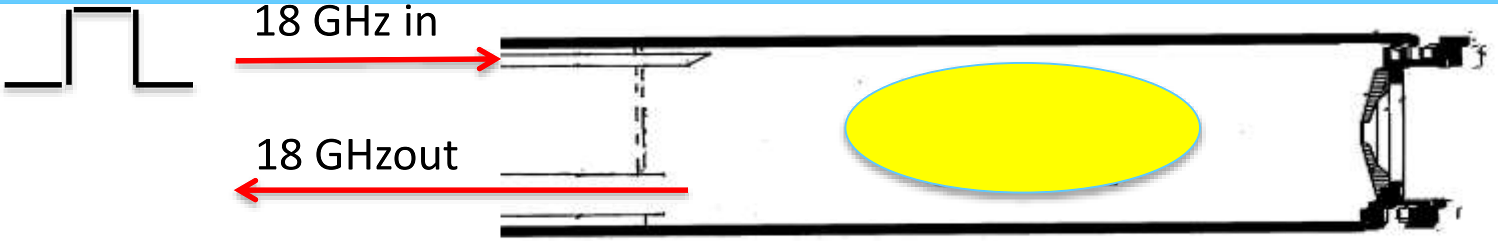
RF coupling, plasma density and diagnostics

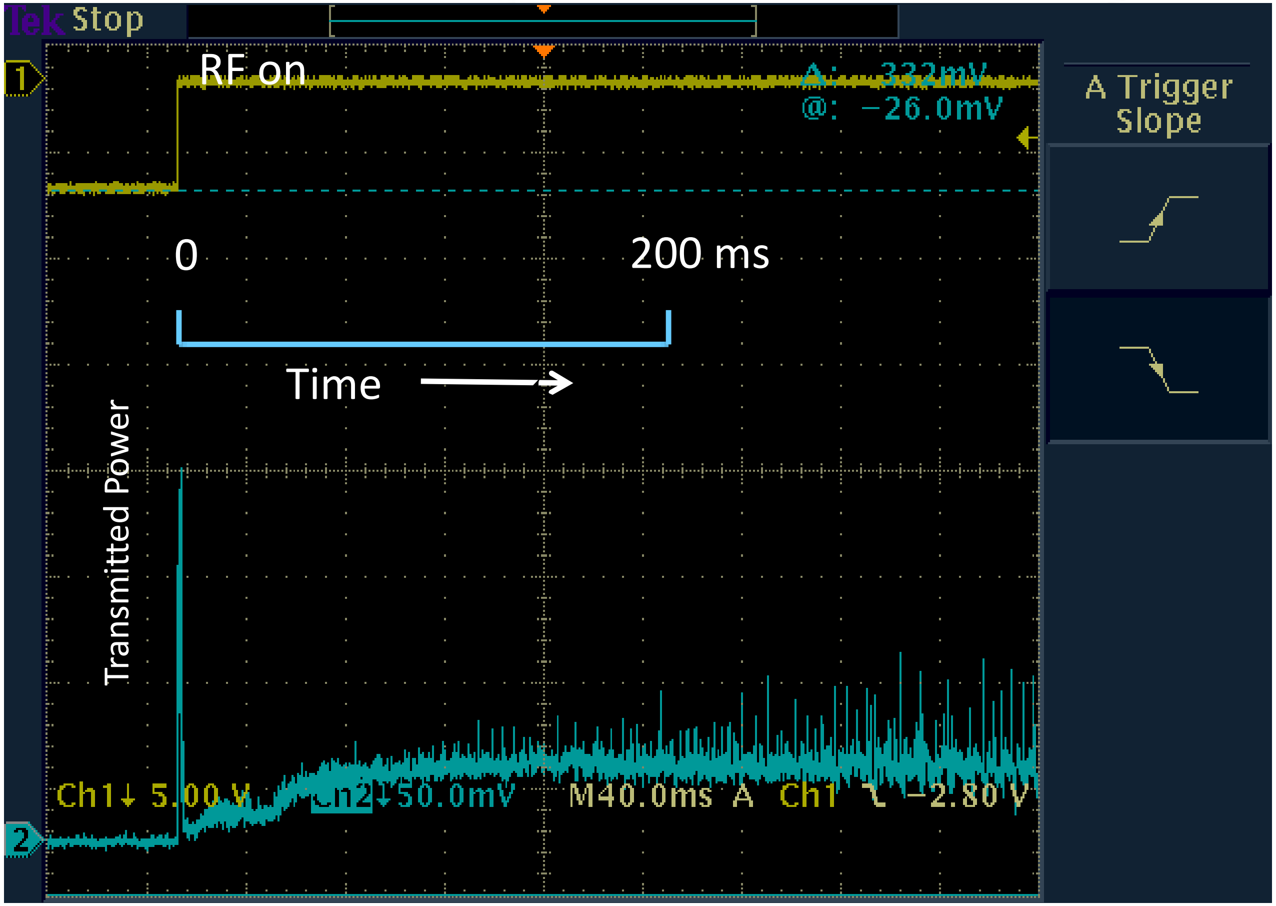
- In the ECR community, much of the experimental knowledge is based to the properties of the extracted ion beams, such as charge state distributions, extracted current intensities and time evolution of the charge state distributions
- However the ions are relatively passive participants, they are cold ~ a few eV, they don't couple to the RF heating and the instabilities are from the plasma electrons
- To improve our understanding of ECR ion source plasma, we need to focus on the electron dynamics and develop/apply diagnostics to study the electrons.
- Questions:
  - How strong is the RF coupling/damping in an ECR plasma chamber?
  - What limits the plasma density?
  - How can we get a handle on these questions?

RF coupling models

- The plasma chamber can be considered a multimode cavity filled with a lossy material.
  - Typical ECR plasma chambers are highly over-moded, so the eigenmodes of the cavity are very closely spaced
  - Models often assume a single mode is excited, but except at very low densities the modes will overlap
  - Models often neglect the plasma loading and assume the chamber has a Q_0 similar to an empty chamber ~2000 to 5000 would be typical of an aluminum chamber at vacuum
- The few pass approach assumes strong damping for the RF launched from in injection waveguide
  - Single pass damping is not well know and depends on density
  - RF not adsorbed in the first pass is then reflected by the chamber walls—Complex to model

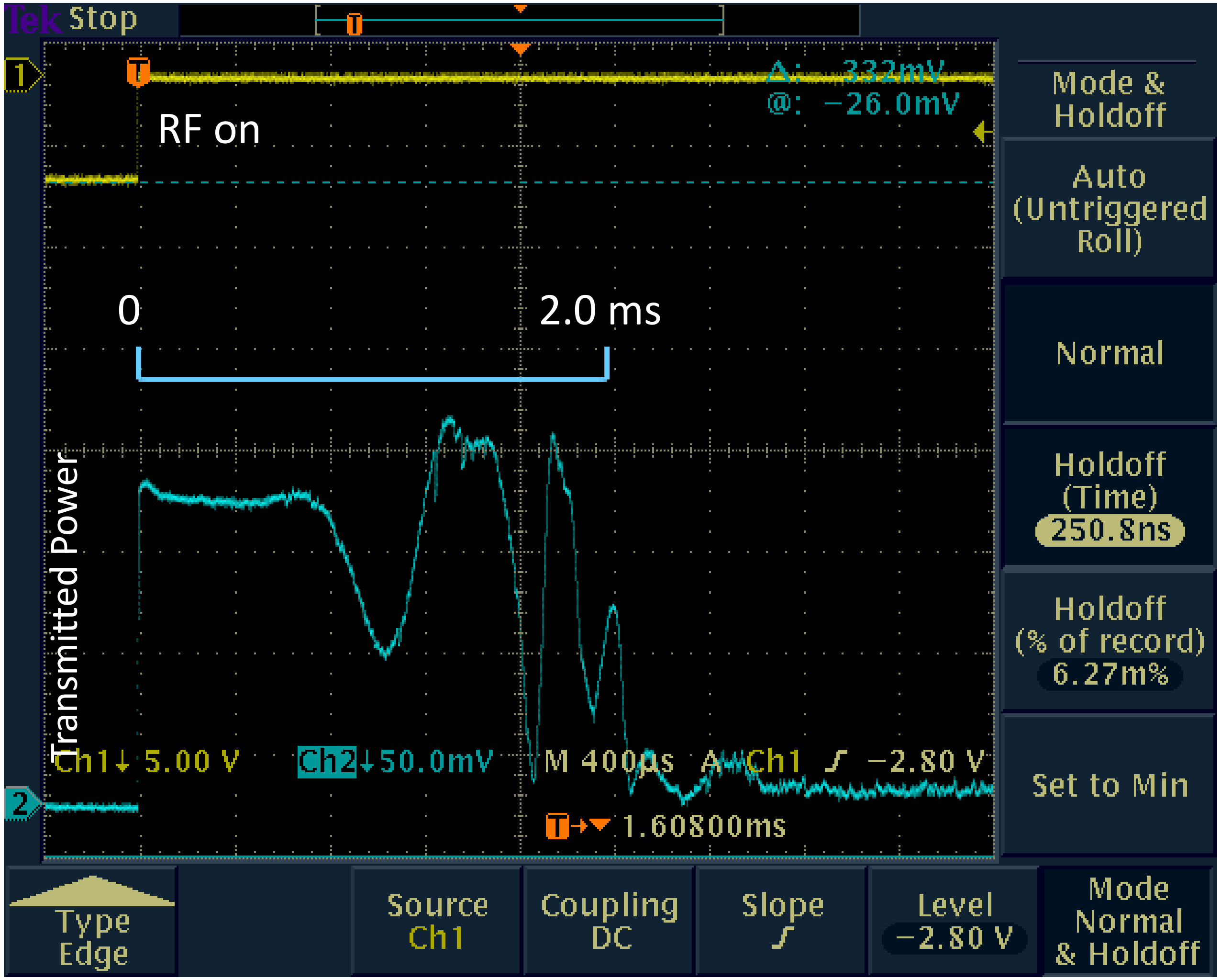
Pulsed Microwave Transmission Measurements On VENUS at 18 GHz





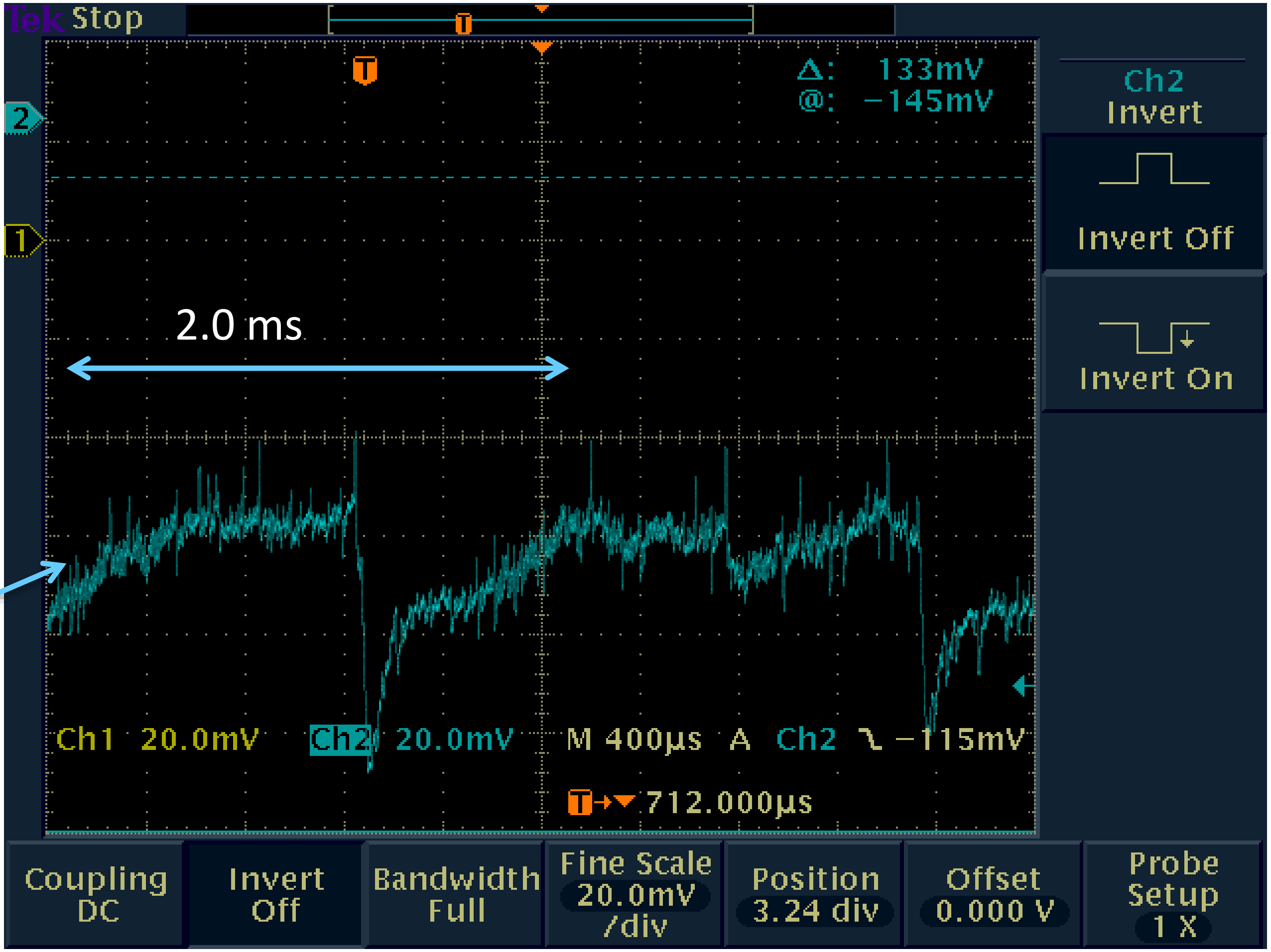
Time scale 40 ms/cm

400 µs/cm



Time scale 400 µs/cm

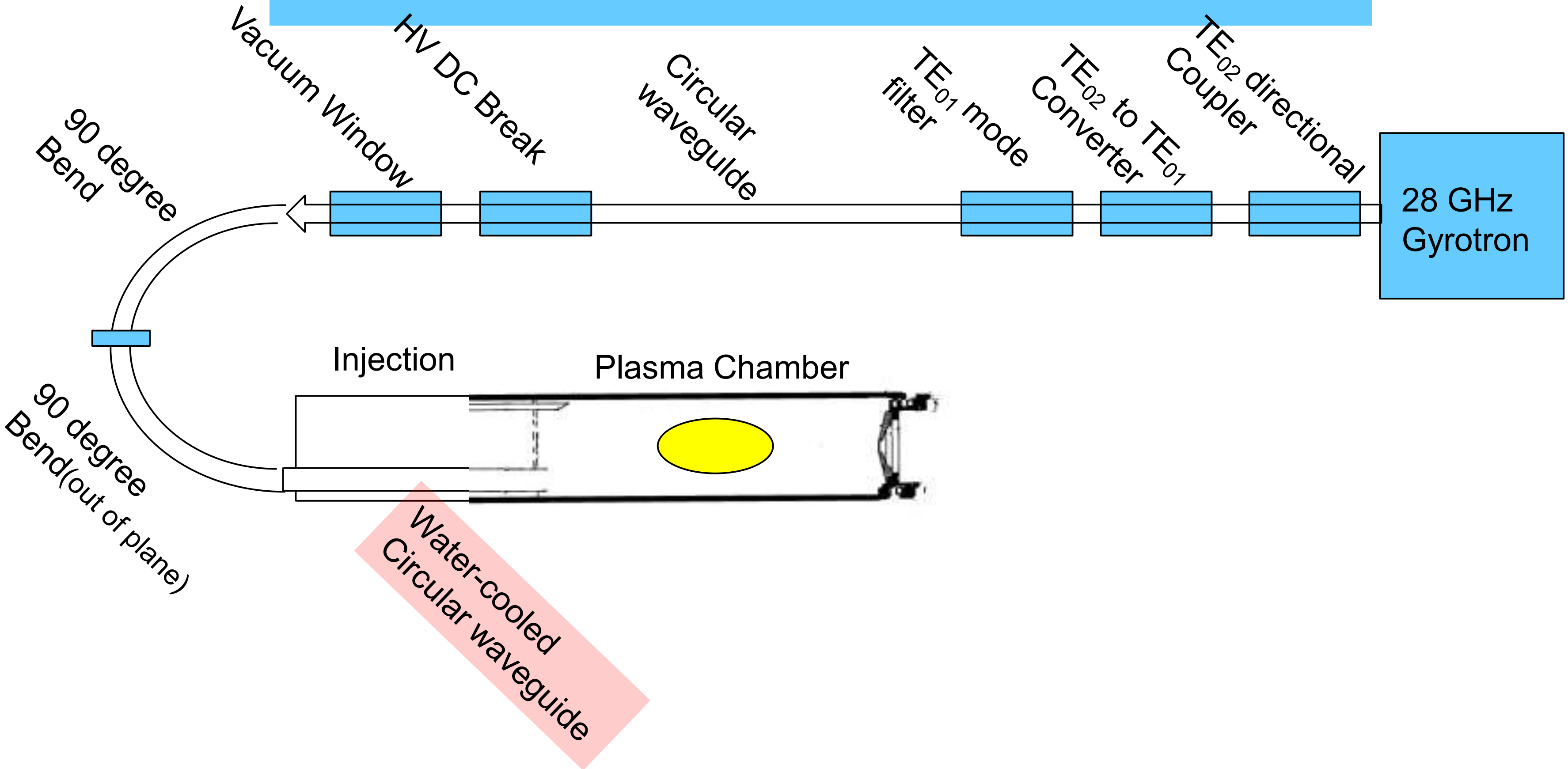
Instabilities after RF On for ~ 300 ms



Transmitted 18 GHz (inverted)

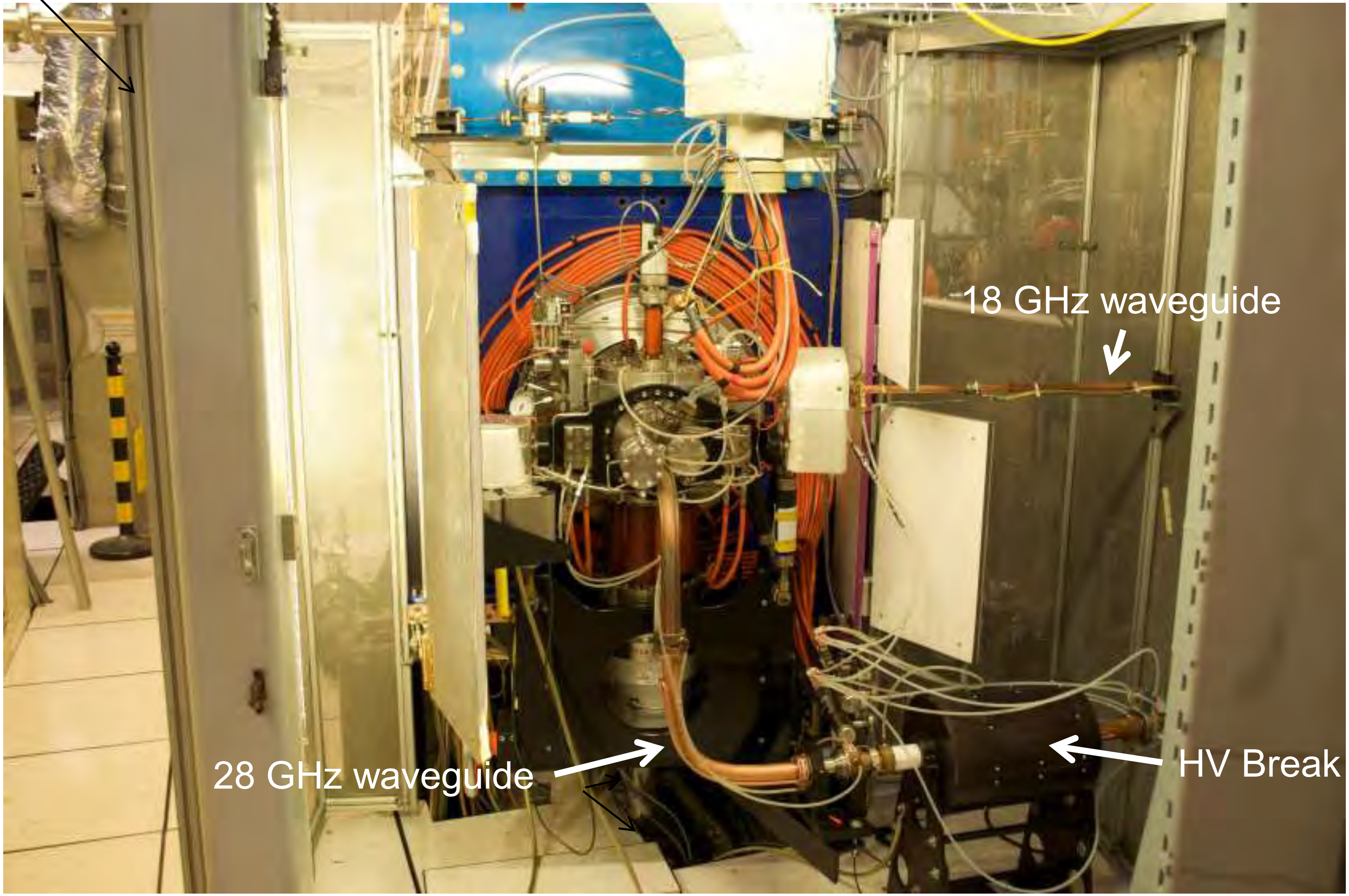
Time scale 400 µs/cm

28 GHz system for VENUS

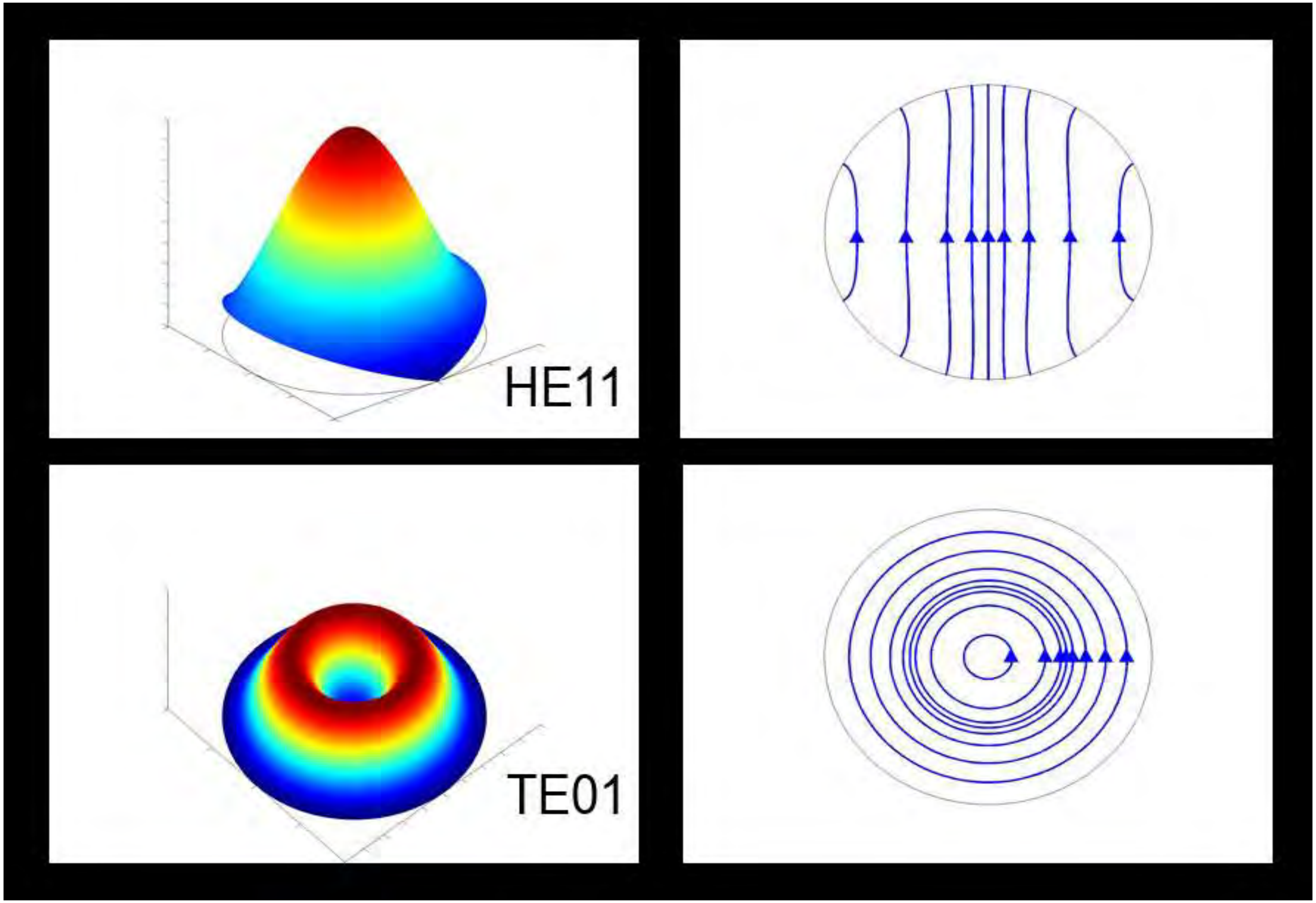


- Modifications needed to launch 28 GHz quasi-Gaussian microwaves
  - Move injection of 28 GHz closer to the axis
  - Convert from TE_{01} to HE_{11} in the injection section
  - Minimize the required changes to the VENUS system

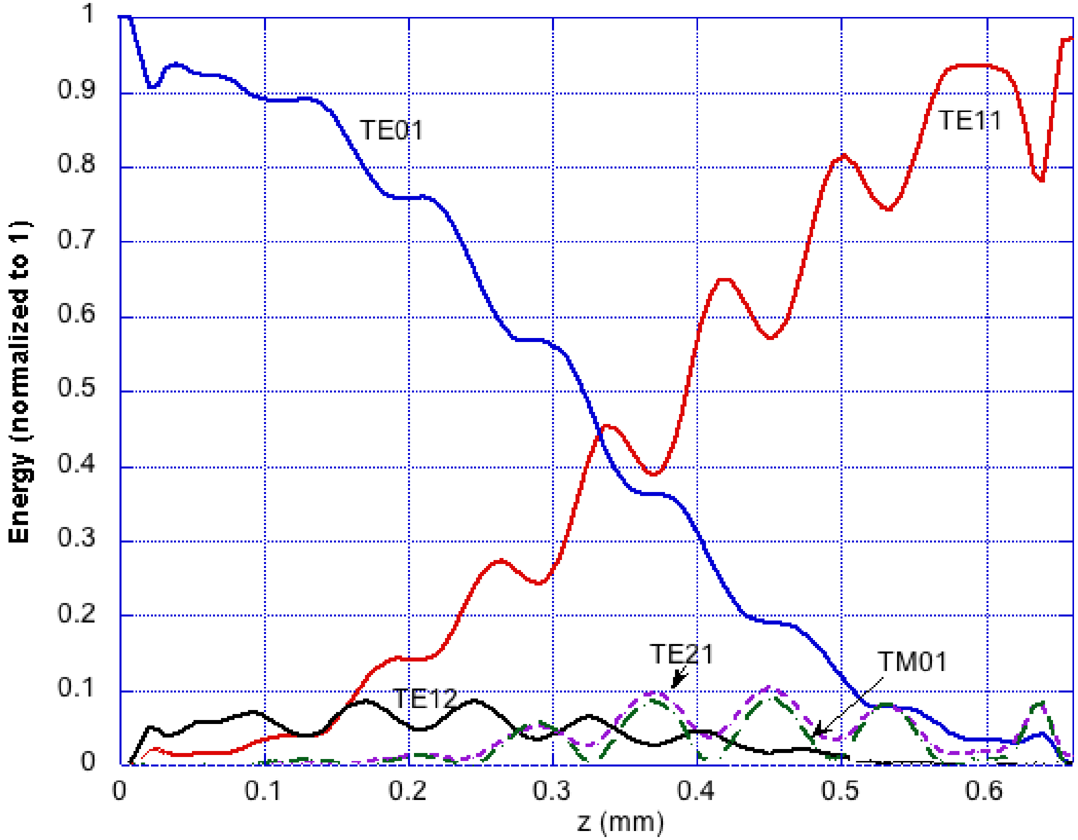
VENUS Injection



HE_{11} and TE_{01} modes



Calculated mode conversion and excitation of undesirable modes



97% into TE11

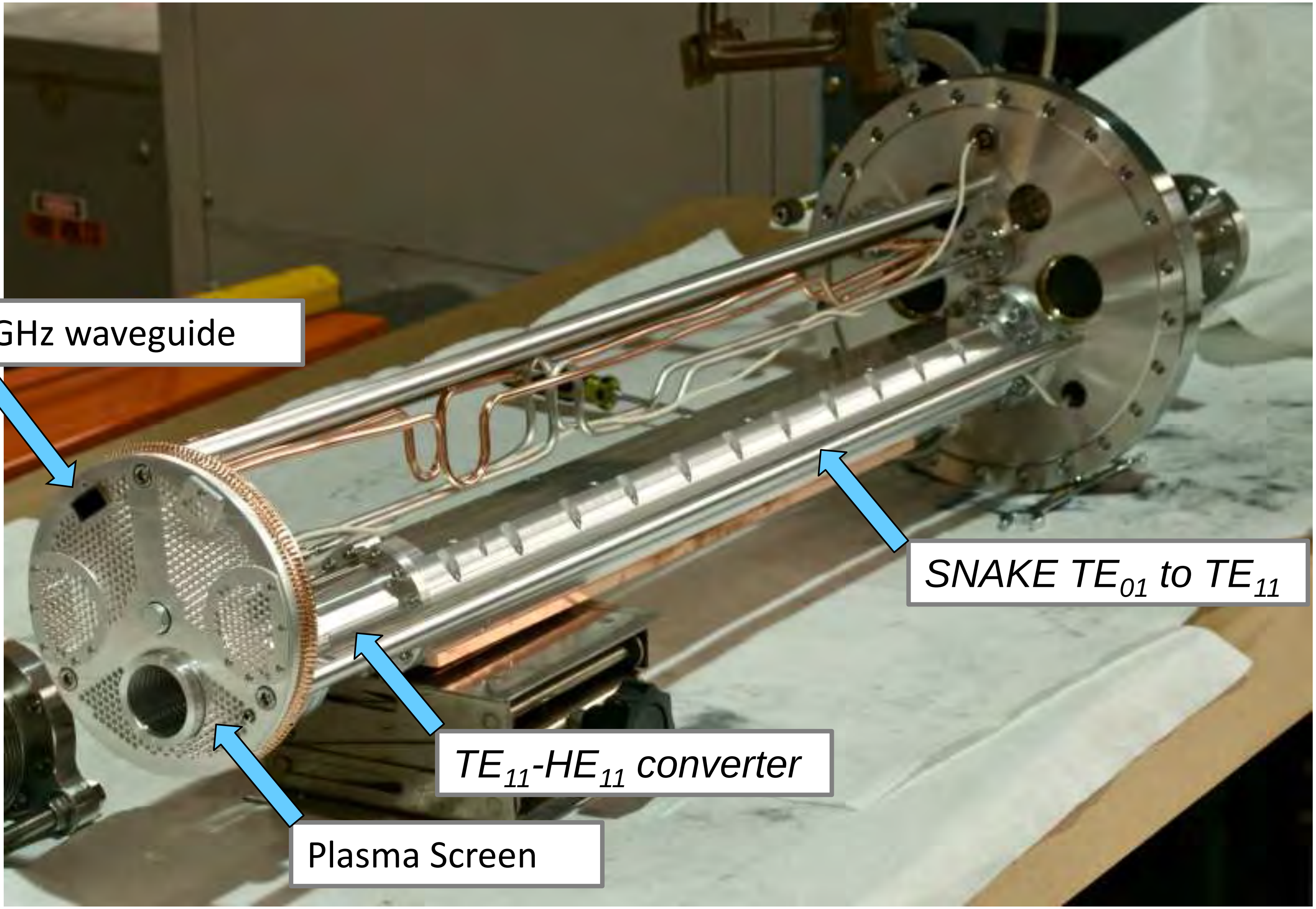
Modes	
Curvature Coupling Coefficients	
TE11-TM21	0.2605380
TE11-TE22	-0.0883540
TE11-TM22	-0.0970206
TE11-TE02	0.1590250
TE11-TM02	-0.313236
TE11-TM01	3.5267400
TM11-TM02	-1.724160
TM11-TM01	3.3100900
TE01-TE11	-1.6289790
TE01-TE12	2.489450
TE01-TE13	-0.1800641
TE11-TE21	2.6557800
TE12-TE21	-0.8366008
TE01-TM11	1.7056530
TM11-TE21	1.4960860
TM11-TM21	2.4503221

Designing TE_{O1} to TE_{11} mode converter

- To convert TE_{01} into TE_{11} with a snake we used a circular over-moded waveguide where the diameter is constant but the center is displaced in the y direction as a function of path length.
- As the microwave power flows down the waveguide the curvature of the waveguide couples the different microwave modes, which are eigenmodes in a smooth waveguide.
- A short corrugated waveguide then converts TE_{11} into HE_{11}

This technology was developed in the fusion community between 1980 and 2000

New VENUS Injection Assembly



Initial tests with HE_{11} mode launcher

- Installation beginning of August 2013
- It has performed very well in the early tests.
  - Up to 5 kW of power
  - No problems with arcing or parasitic mode generation
- Compared to the old system
  - Tuning appears to be broader
  - Smoother dependence on 28 GHz power (more monotonic)
  - Some indications of improvements when used in two frequency mode with the 18 GHz
- While it works well, no significant improvement has been demonstrated yet.

Conclusion

- The performance of ECR Ion Sources has steadily improved over the last 40 years
  - Although from 2006 to present performance is relatively flat
- A detailed theoretical picture of the plasma physics is still open for improvement
- More plasma diagnostics for the hot electron parameters and for RF adsorption would be welcome
- Frequency scaling is roughly correct from 6 to 28 GHz and is expected to work for 4th generation ECR's at ~50 GHz
- The technical challenges at 50 GHz make it attractive to look for new approaches