Intense High Charge State Heavy Ion Beam Production for the Advanced Accelerators

L. Sun

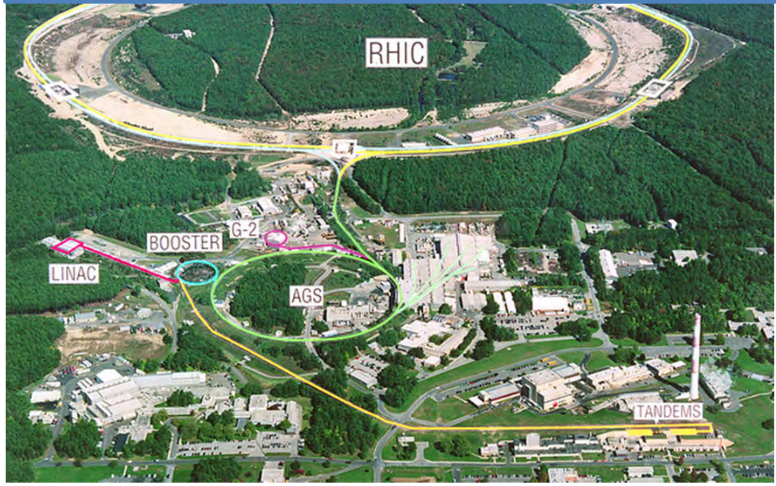
Institute of Modern Physics, CAS, Lanzhou 730000, China

Outline

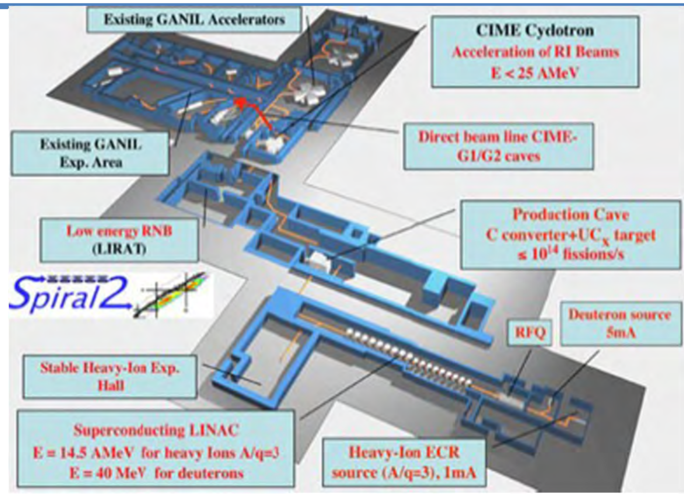
- Introduction
- Physics of HCI
- Introduction to the State-of-the art HCI sources
  - ECRIS
  - EBIS
  - LIS
- Next generation HCI sources

Introduction: Global Needs of HCI Sources

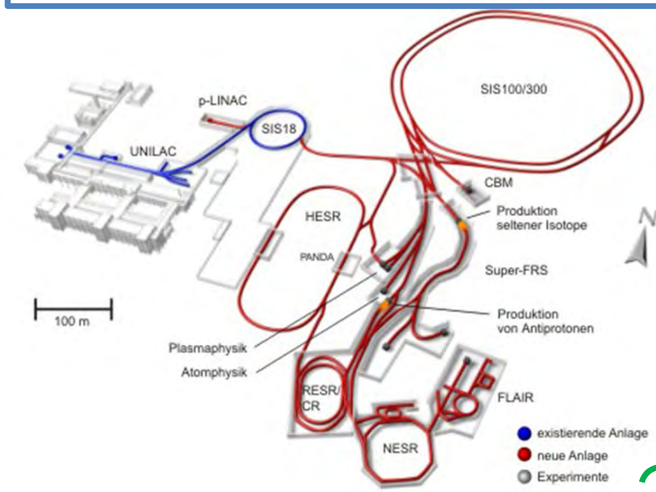
RHIC (BNL), USA: EBIS (1.7emA Au^{32+}/10μs)



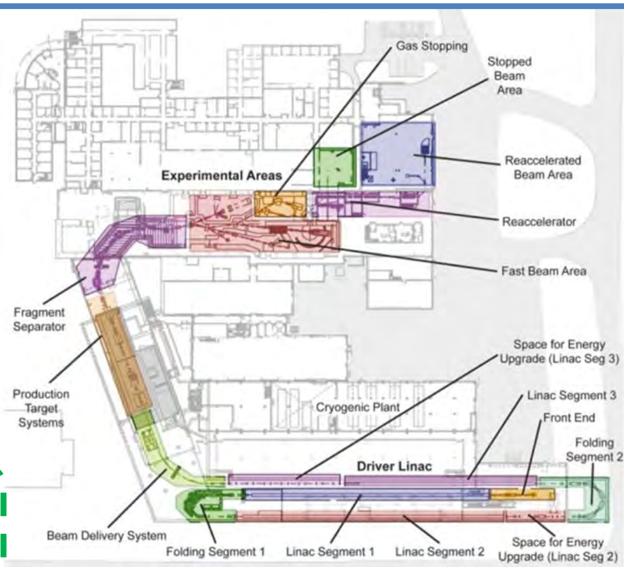
SPIRAL2 (GANIL), France: ECRIS(1emA Ar^{12+})



FAIR (GSI), Germany: ECRIS (1emA U^{28+})



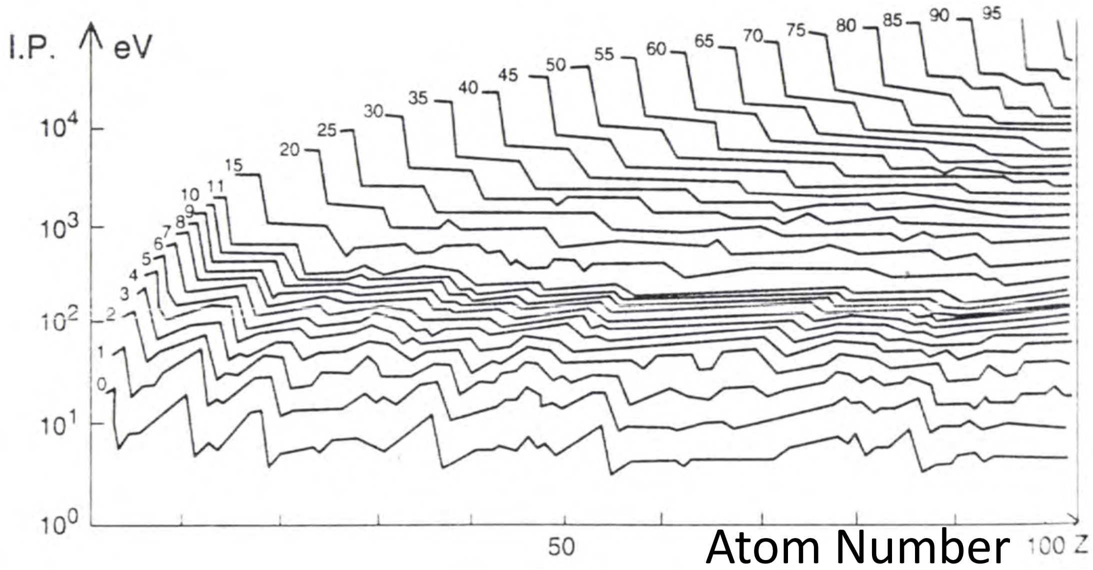
FRIB (MSU), USA: ECRIS (270euA U^{33+} & U^{34+})

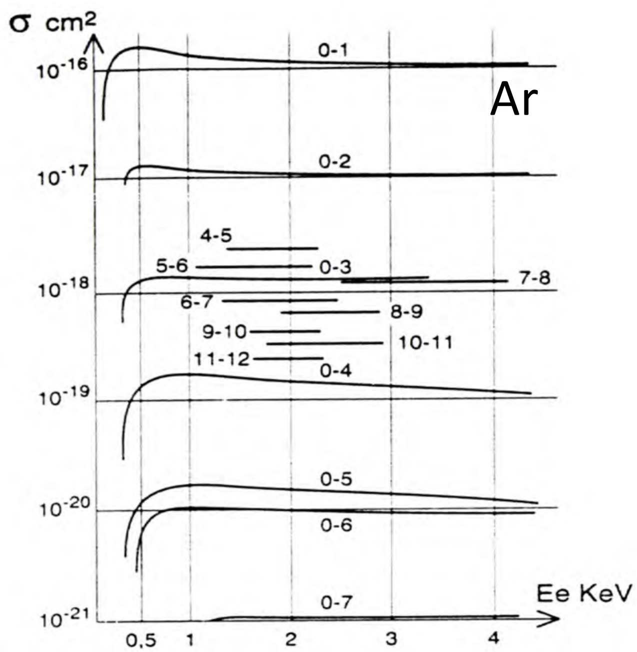


$$U^{+} * 34\ MV = U^{34+} * 1MV$$

Principle of HCI Production

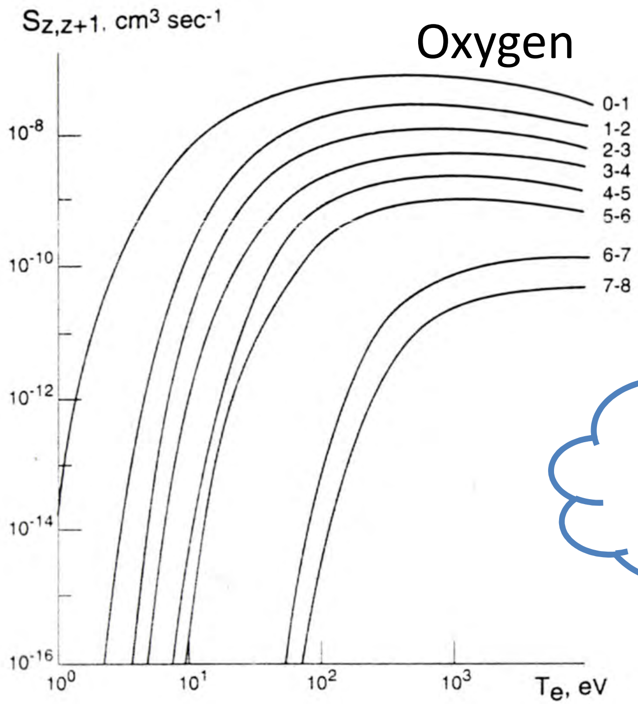
- Electron impact ionization is the main mechanism to produce ions:
  v (collision frequency) = $n_e \sigma v_e$
- Electron energy E_e must be enough to remove the outer electron of the atom to produce HCI



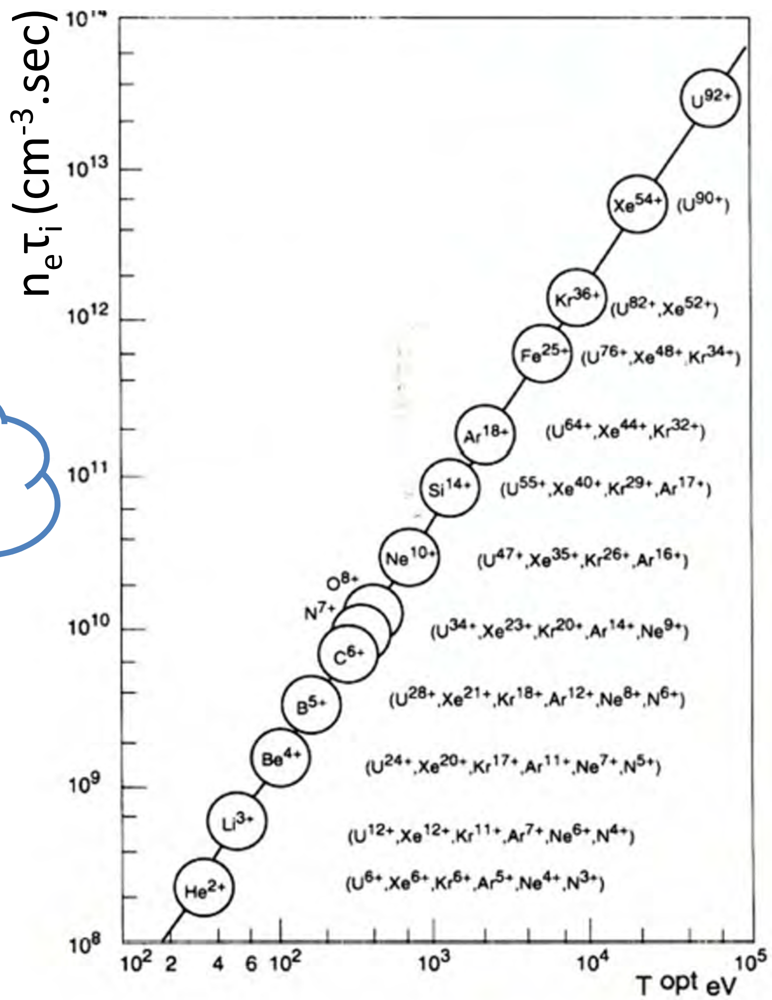


- Single impact ionization: A + e^- → A^{z+} + (z+1)e-
- Successive impact ionization A^{z+} + e^- →$A^{(z+1)+}$ + $2e^-$
- For mono-charge state and very low charge sate, single impact ionization may dominate
- For HCI ion production, especially HCI of heavy elements, successive impact ionization dominates

Principle of HCI Production



n_e, T_e, τ_i



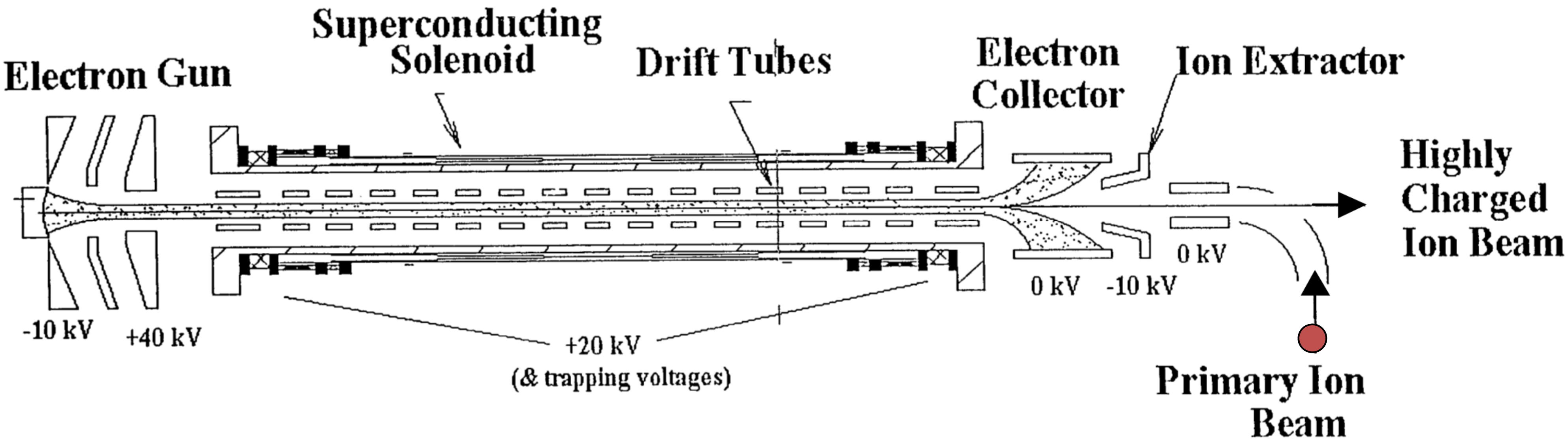
- For desired charge state *z*, optimum T_e is needed, and the higher *z*, the higher T_e;
- Even works with optimum T_e, the ionization rate drops sharply
- $T_e^{opt} \approx 3\sim 5\ W_j$

- Golovanivsky's diagram of the $(n_e\tau_i)T_e$ criteria
- $\xi n_e\tau_i \geq 3\sim5 \times 10^4\ (T_e^{opt})^{3/2}$, ξ is the total number of electrons in the outer shell

High Charge State Ion Sources

- EBIS or Electron Beam Ion Source
  - Invented by Dr. Donets in 1965
  - Control precisely and independently n_e, T_e and τ_i
- LIS or Laser Ion Source
  - Proposed by Dr. Bykovskii et al. and Peacock, Pease in 1969
  - Least control of the three key factors
- ECRIS or Electron Cyclotron Resonance Ion Source
  - proposed by Prof. Geller in late 1960s
  - Reasonable control of the n_e, T_e and τ_i factors but not independently, and they are coupled

EBIS Principles



Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrostatic potentials at ends of trap.

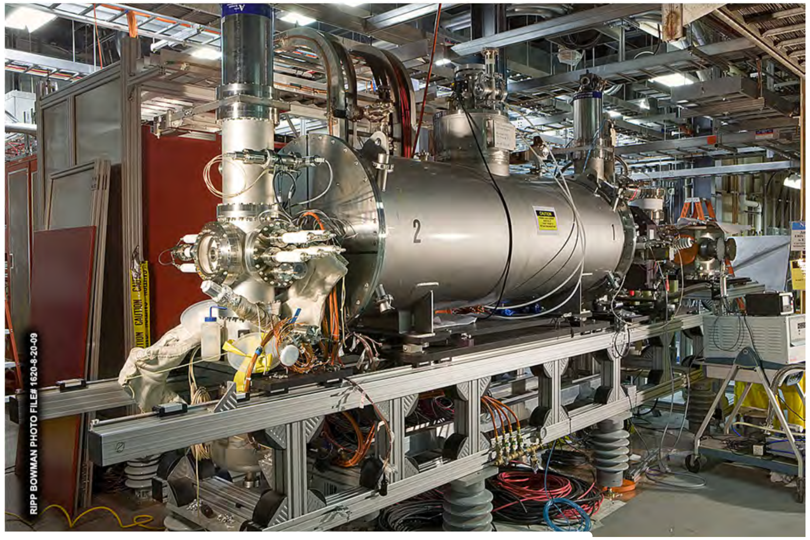
$$C^+ = 3.36 \times 10^{11} I_e L E_e$$

- **The total charge of ions extracted per pulse is ~ (0.5 – 0.8) x (# electrons in the trap)**
- **Ion output per pulse is proportional to the trap length and electron current.**
- **Ion charge state increases with increasing confinement time.**
- **Output current pulse is ~ independent of species or charge state!**

Pros and Cons

- Pros:
  - Easily produces high intensity short pulse HCI beams
  - Very high charge state ions (from EBITs):
    - SuperEBIT (LLNL)→~100 U^{90+} ions/s
    - Tokyo EBIT→ Bi^{81+}
  - Narrow charge state distribution, peaked on interested charge state
  - Produces beams of any species and intensity is independent of species
  - Pulse width can be precisely controlled
  - Fast beam species switching (~1 second)
- Cons:
  - Possibility of instability issues at high electron beam currents
  - High energy spread of fast-extracted ions
  - High technical challenges : ultrahigh vacuum, very well collimated superconducting solenoid field …

BNL EBIS for RHIC



Courtesy of E.Beebe, BNL

Design Parameters		RHIC EBIS
Max. electron current	I_{el}=	10 A (up to 12A)
Electron energy	E_{el}=	20 keV
Electron density in trap	j_{el}=	575 A/cm^2
Length of ion trap	l_{trap}=	1.5 m
Ion trap capacity	Q_{el}=	1.1x10^{12}
Ion yield (charges)	Q_{ion}=	8.1x10^{11} (9.6 A)
Yield of ions Au^{32+}	$N_{Au}{}^{32+}$=	3.4x10^9

Superconducting solenoid specs	
Maximum magnet field	5.0 T
“Warm” ID	204 mm
Length of solenoid	1900 mm
He refilling period	30 days

RHIC EBIS Performance

Beam intensity measured at Booster ring input:

EBIS I_e (A)	Ion	Booster Input (ions)	EBIS All Ch States (Charges)	Charge Fraction EBIS to Booster
8.3	$^{63}Cu^{11+}$	6.1×10^9	6.9×10^9	9.7%
9.5	$^{197}Au^{32+}$	1.5×10^9	9.4×10^9	5.0%
9.6	$^{238}U^{39+}$	1.1×10^9	8.1×10^9	5.2%

Transmission to Booster input is ~56% of what is expected, and there are additional shortfalls in the Booster/AGS rings. We believe that the early losses are due to a broadening of the EBIS charge state distribution with high neutralization coupled with a 30% decrease in the RFQ/Linac transmission efficiency due to mismatch and/or emittance growth due to misalignment.

LIS Definition

Ion source for selective ionization of isotopes

-Multi-photon ionization of atoms

Ion source using extremely high power density (> 10^{18}W/cm^2) of fs-lasers

-Irradiation of thin foil

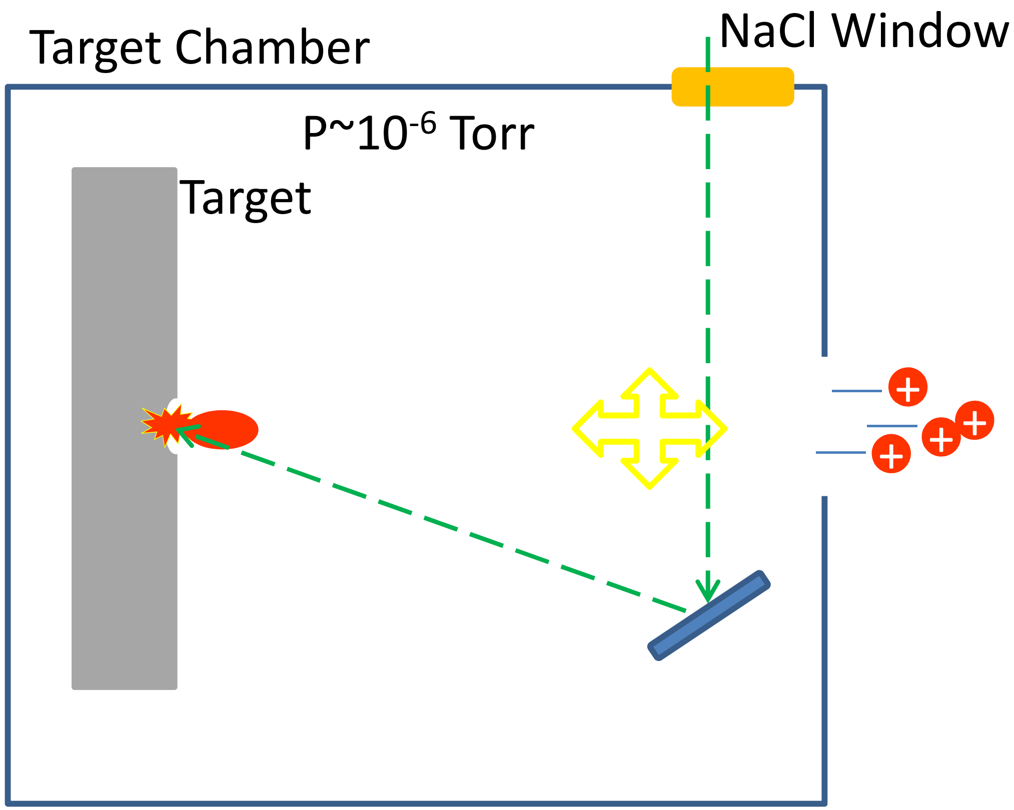
-Ionization by extremely strong electric field caused by separation of hot electrons and cold ions in space

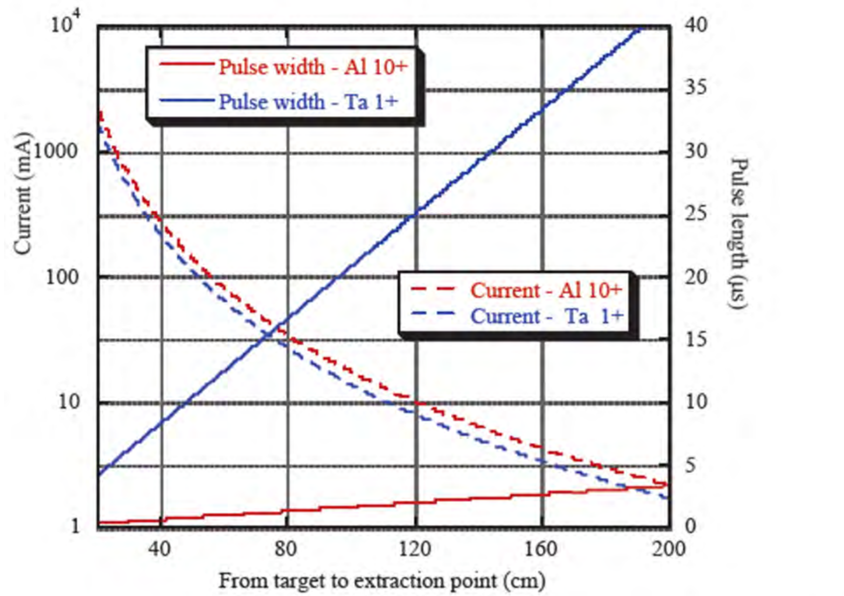
Ion source using moderate laser power densities (< 10^{15}W/cm^2)

-Irradiation of thick target

-Ionization by electron impact into laser produced plasma

LIS Principles





Al - 3 J/30 ns Nd-glass 1062 nm laser (10^{11} W/cm^2)
Ta - 1 J/5 ns Nd-YAG 532 nm laser (10^{9} W/cm^2)

Laser pulse: ns

Drift Length: L

Pulse Length： 2-10 µs

$$\tau \propto L$$
$$J \propto L^{-3}$$

τ： Beam Pulse length；

J： Beam intensity

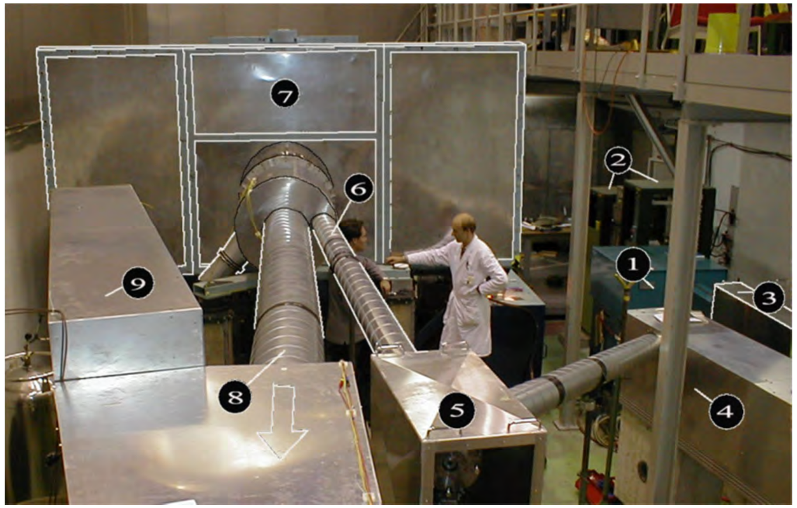
Advantage：

- Short pulse
- High charge state, high intensity
- Ion beams any solid material

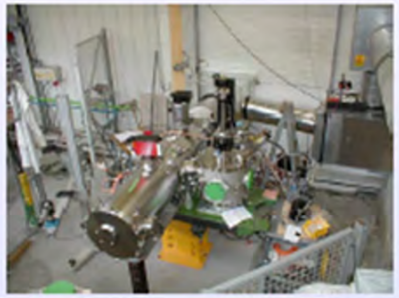
Pros and Cons

- Pros:
  - Simple system setup
  - Very high beam current of HCI
  - Short pulses→ LIS + RFQ is the best combination
- Cons:
  - Low reliability and stability
  - Short continuous operation time (very picky on target surface conditions)
  - Pulse to pulse beam current fluctuations
  - Target erosion, coating of optics by evaporated target material
  - Beam species limited to solid target (cryogenic target is costly)
  - Large beam emittance and energy spread

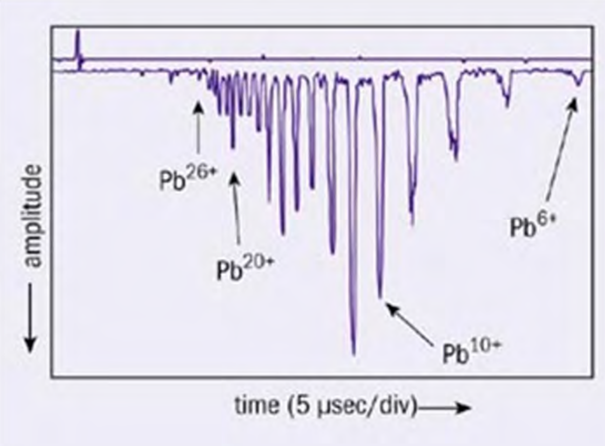
CERN/ITEP LHC LIS (1993-2003)

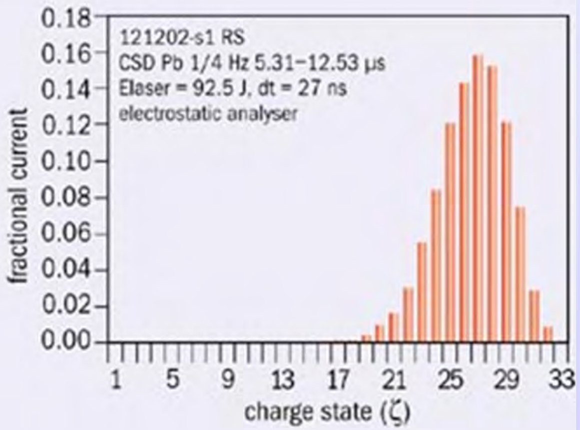


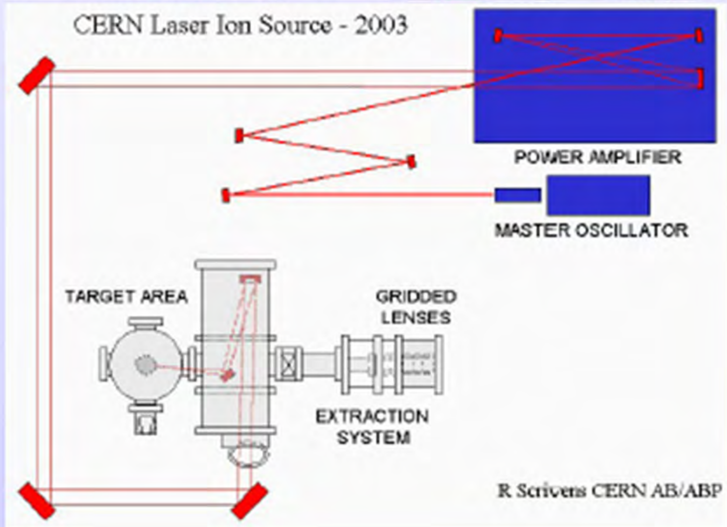
CERN LIS:
CO_2 laser
λ=10.6 μm, 100 J, 1 Hz
Laser pulse 15-30 ns
Power density 10^{13} W/cm^2
Ion pulse 1-10 μs



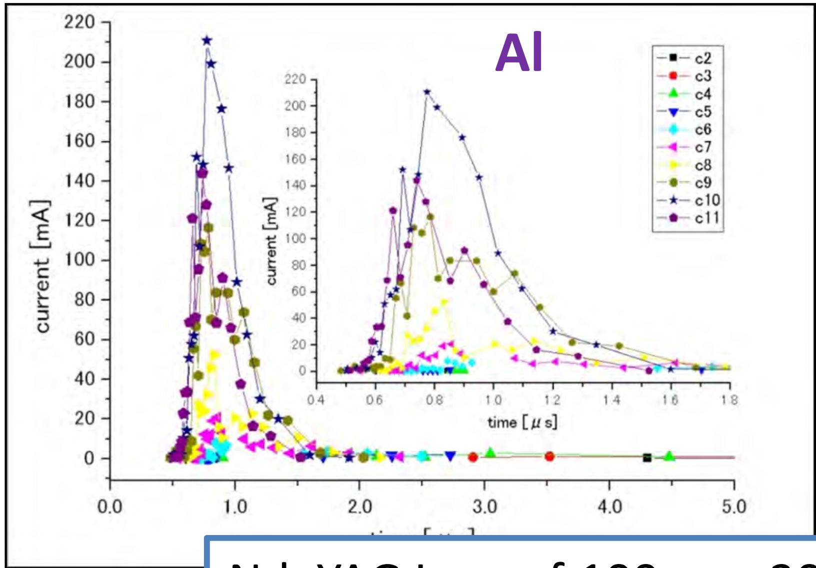
- Statistical fluctuations in pulse amplitude and pulse width from shot to shot were less than ±15%. 1 Hz pulse trains lasting more than 60-70 minutes.
- 1-2 x 10^{10} Pb^{27+} in a pulse of 3-4 μs.

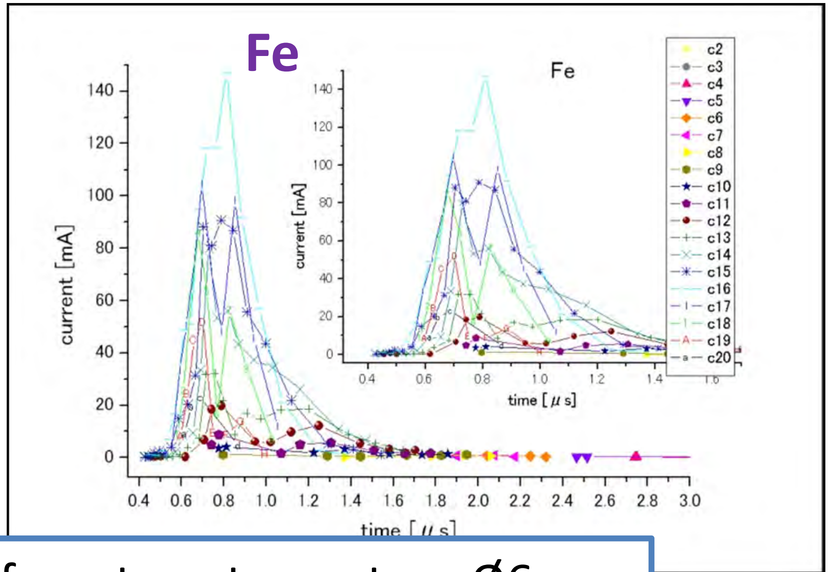




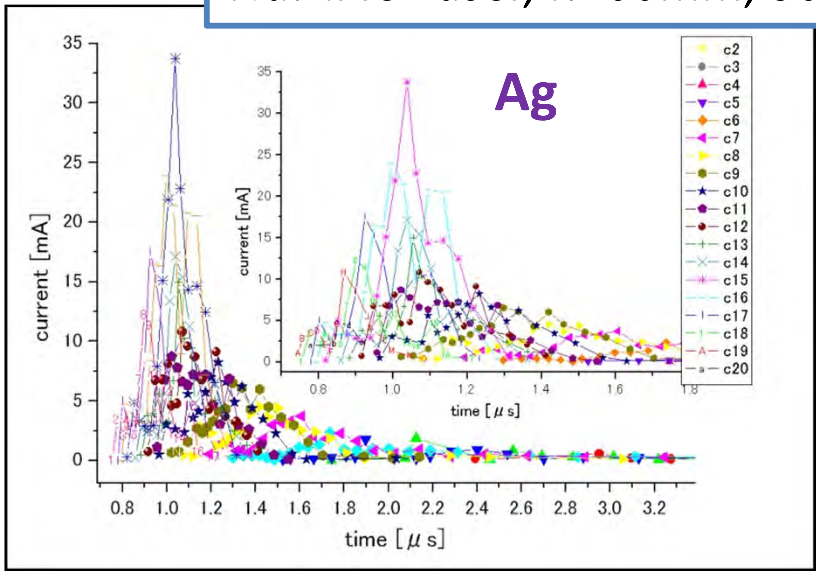


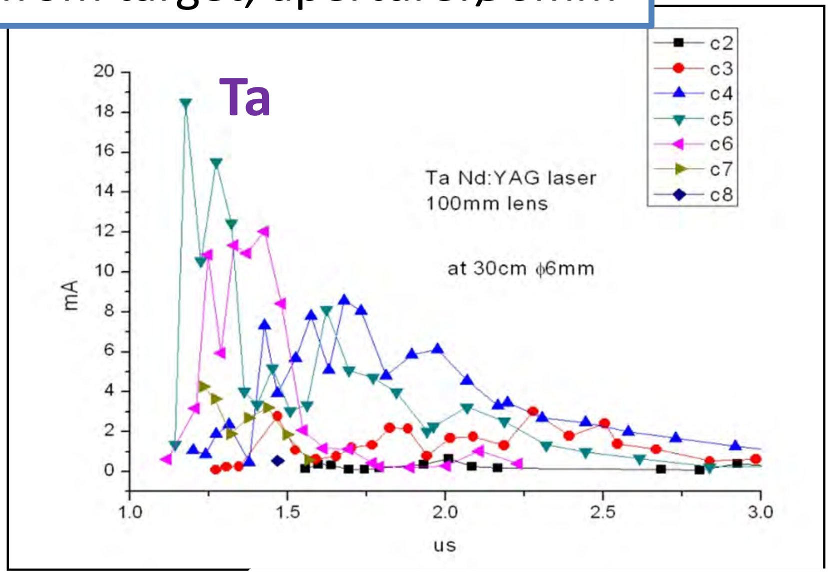
BNL LIS Performances





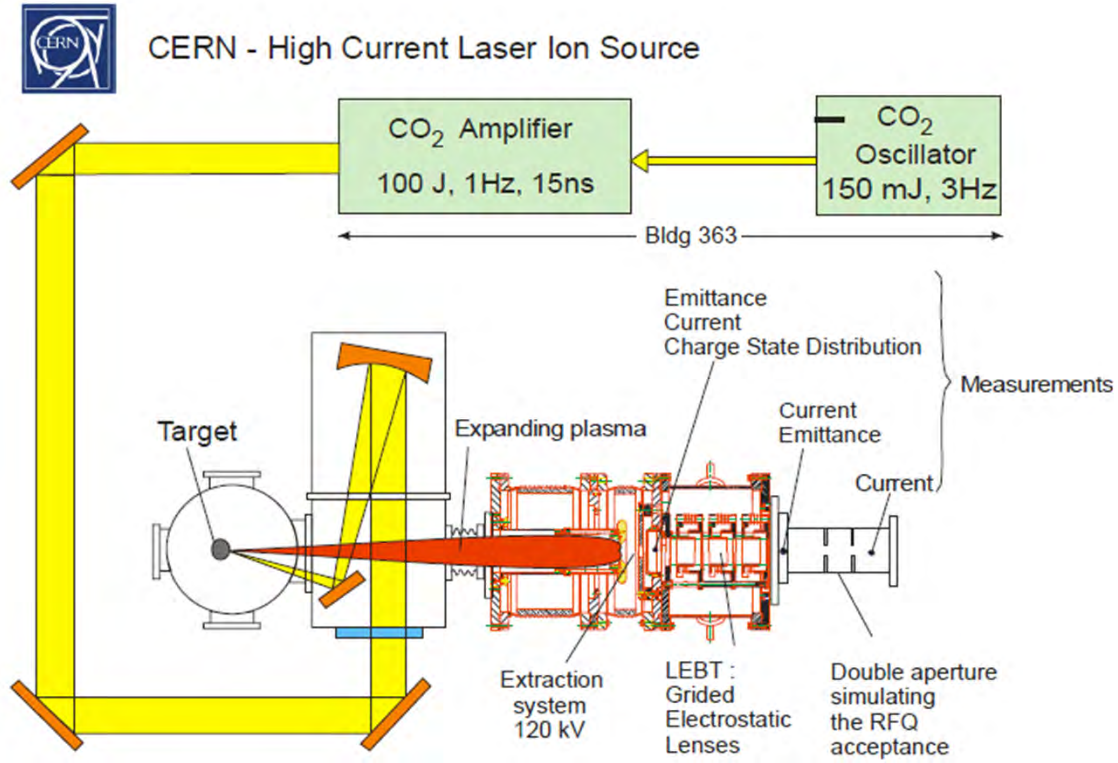
Nd: YAG Laser, f:100mm, 30cm from target, aperture:Ø6mm





Courtesy of M.Okamura, BNL

Traditional Injection Scheme for RFQ



Main Components:
- Laser
- Target illumination unit
- Plasma expansion region
- Extraction system
- LEBT

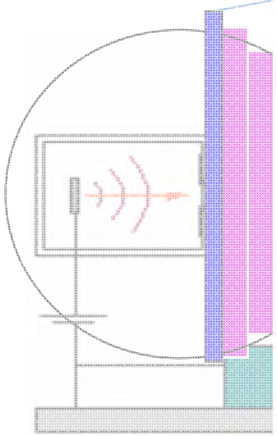
Disadvantages

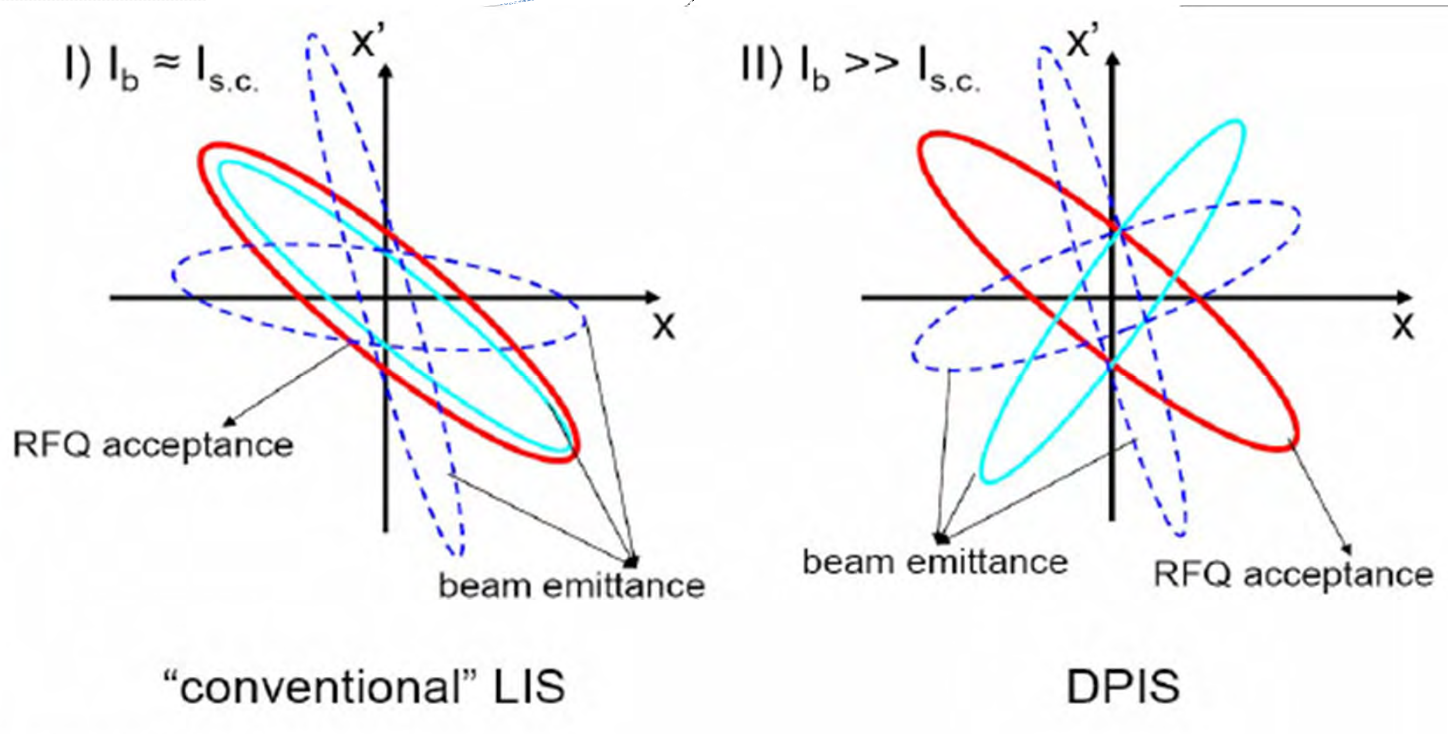
- Strong space charge effect : Due to the low energy and highly charged states.
- Matching to the RFQ : Time variation of the beam emittance from the pulsed source.
- Multiple charged states : Effects from un-wanted charged state particles.

Direct Plasma Injection Scheme (DPIS)

ION

ELECTRON





Plasma

Extract ion beam

Advantages

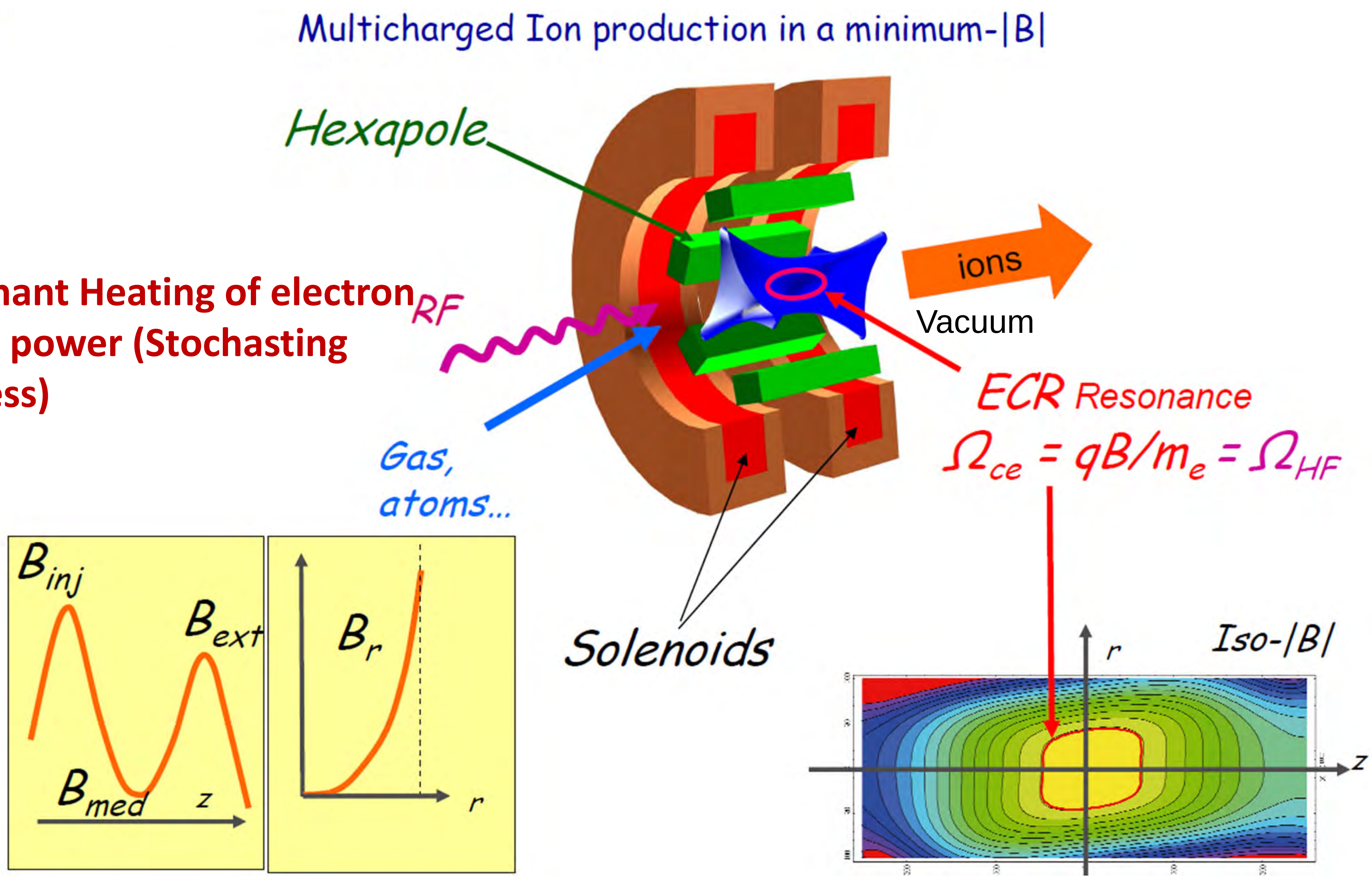
- OVERCOM
- NO NEED T
- NO NEED ANY FOCUING OR EXTRACTION SYSTEM
- EXTREMELY SIMPLE

Next Generation LIS?

- Plasma cutoff density: $n_{cr} \propto f^2$
- Empirically: $J \sim d^2{}_f * P \sim E_l$
  - E_l of 10 -200 J
- T_e & Q $\propto P$ [W/cm²]
- Special techniques
  - DPIS or LEBT injection to RFQ?
  - Plasma transverse confinement
  - Beam pulse length expansion without density decrease
  - $P=10^{10}$-10^{12} W/cm² for very intense LCS ion beams
  - $P=10^{14}$-10^{16} W/cm² for intense HCI ion beams
- Issues:
  - Stable operational time
  - Reliability and stability
  - Energy spread

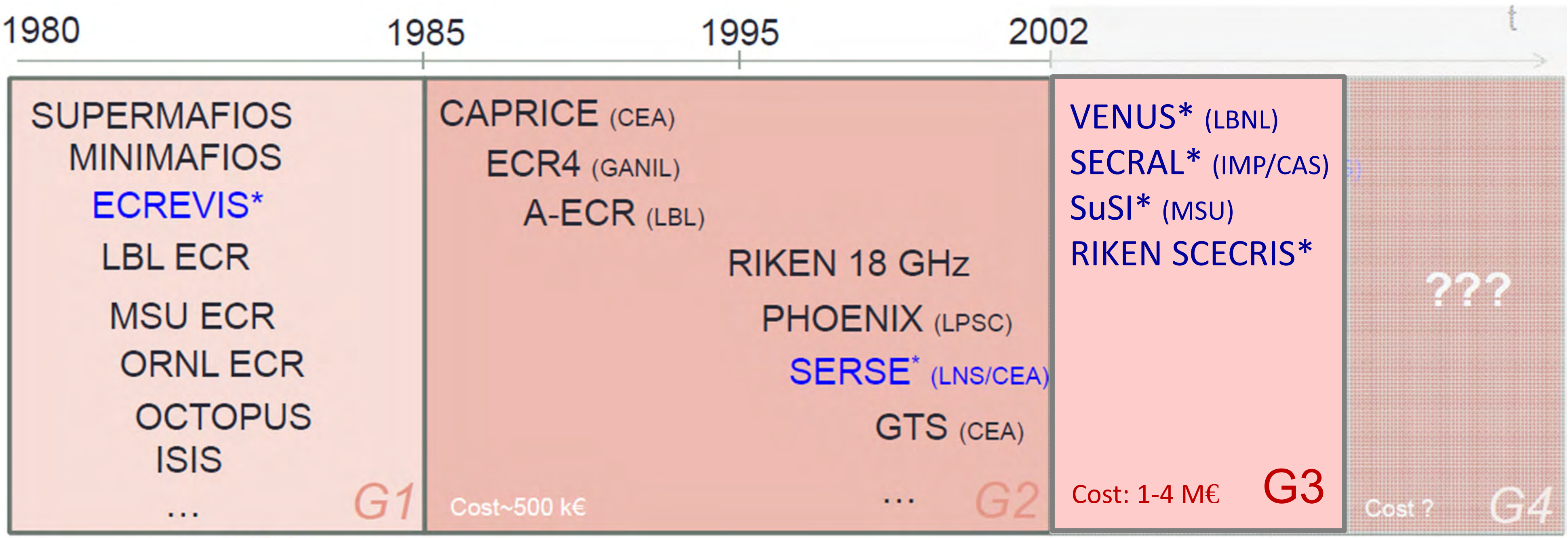
Principles of ECRIS

Resonant Heating of electron by RF power (Stochasting process)



Family Tree of ECRISs

All permanent magnet ECRIS	Classical RM ECRIS	Hybrid SC-ECRIS	Fully SC-ECRIS
Nanogan series ion sources	GTS source	RAMSE, SHIVA	SERSE 18 GHz
BIE series ion sources	AECR-U	A-PHOENIX	VENUS 28GHz
LAPECR1, LAPECR2	LECR2, LECR3	PKDELIS	SECRAL 18~28 GHz
Kei1, Kei2	RIKEN 18 GHz	Dubna 18 GHz	SUSI 18~24 GHz
SOPHIE	ECR4, Caprice		RIKEN SCECRIS 28 GHz
Operated 2.45 ~ 14 GHz	Operated 10 ~ 18 GHz	Operated 14 ~ 28 GHz	Operated 18 ~ 28 GHz



*Superconducting ECRIS

Why Superconducting?

- $I_i^q = \frac{1}{2}\frac{n_i^q\, q\, e V_{ex}}{\tau_i^q}$ n_i^q ion density for species i charge q; τ_i^q Confinement time for species i charge q $\sum_{i,q} n_i^q\, q_i = n_e$ (Plasma neutrality)

- From RF dispersion equation at resonance : $(n_e T_e) \approx (\frac{m_e \varepsilon_0 \omega_{rf}^2}{e^2}) m_e c^2$ $I^q \propto f^2_{ECR}$

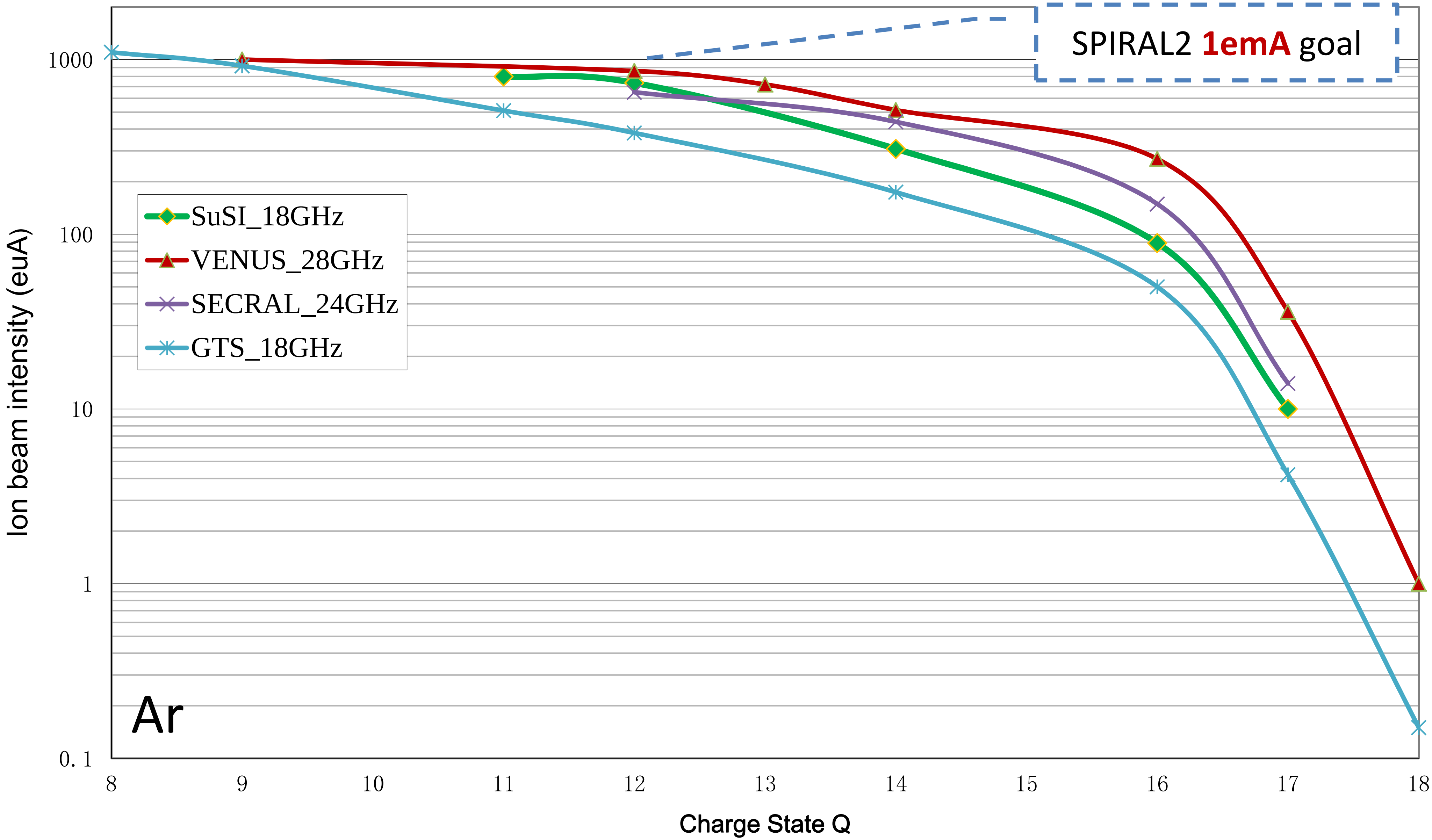
- Plasma Stability condition : $\beta = \frac{n_e k_b T_e}{(\frac{B^2}{2\mu_0})} < 1$ As $n_e \nearrow$ $B \nearrow$

- B_{inj} ~ 3 - 4 B_{ecr} on axis
- B_{ext} ~ 2.2 B_{ecr} on axis (T)
- B_{rad} ~ $2B_{ecr}$ on plasma chamber wall
- Last closed Bmod inside chamber is ~2 B_{ecr}

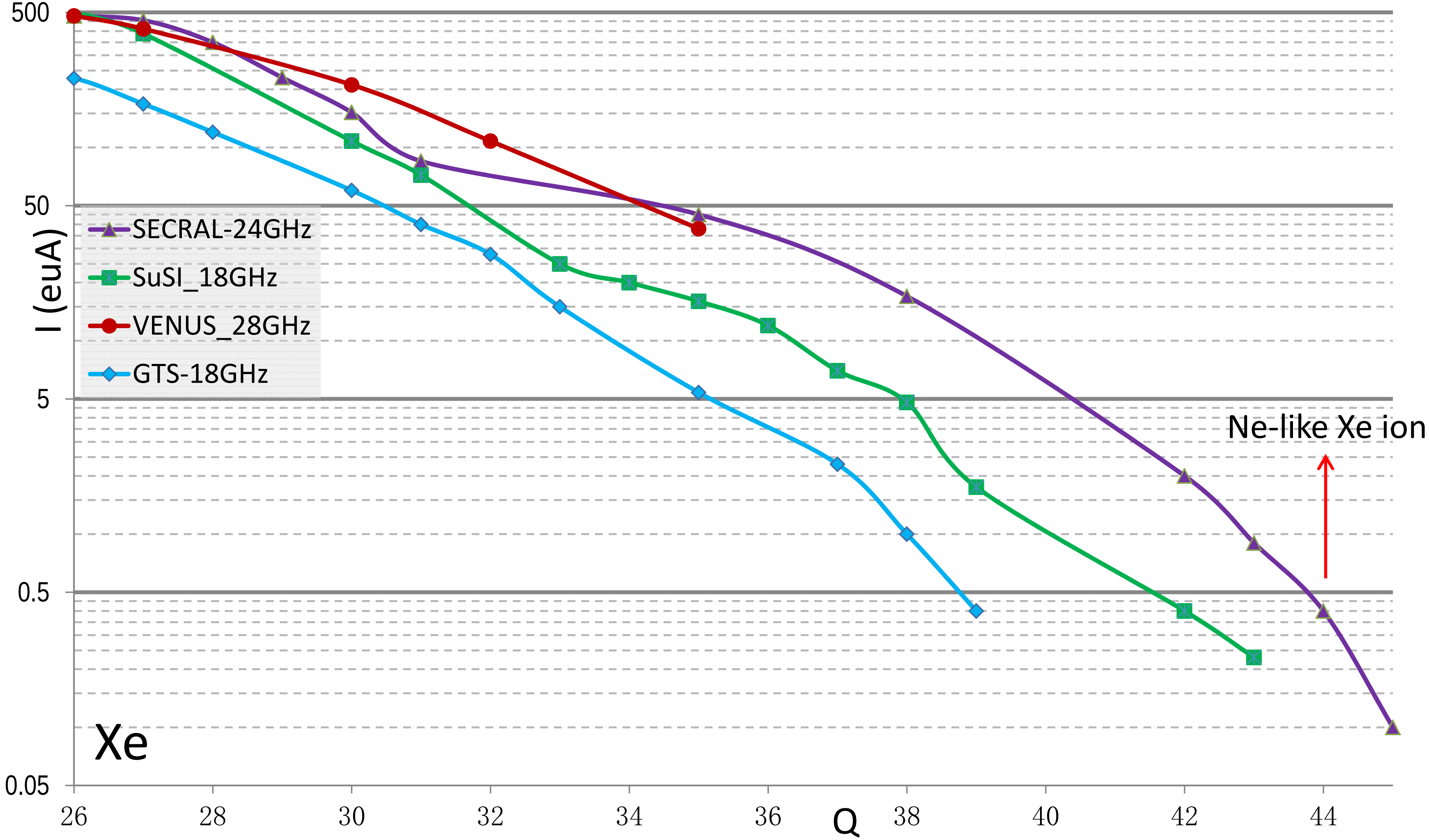
Semi-empirical rules

f_{ECR}	B_{ECR}	B_{inj}	B_{rad}
14 GHz	0.5 T	2 T	1 T
28 GHz	1 T	4 T	2 T

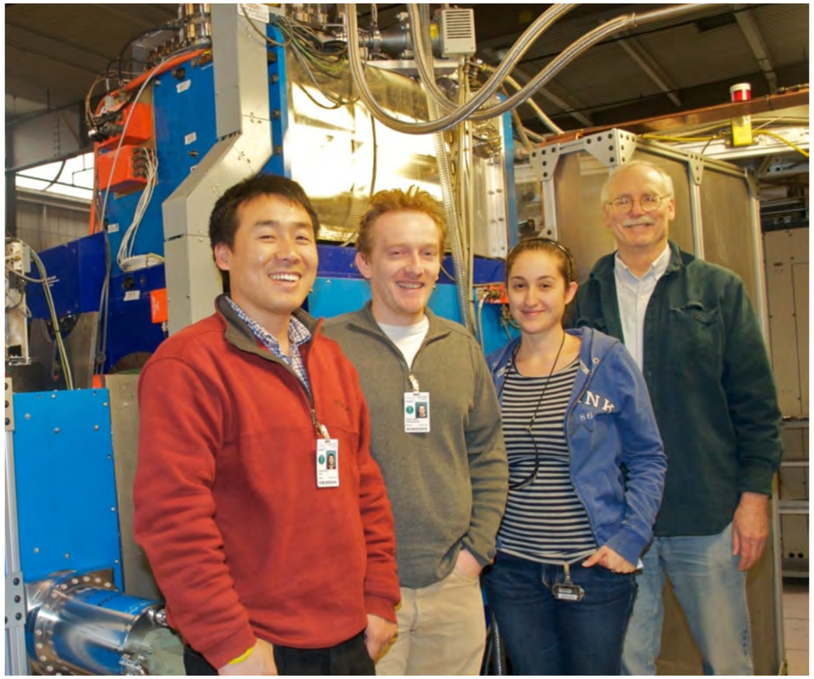
Performance of the 3rd Generation ECRISs



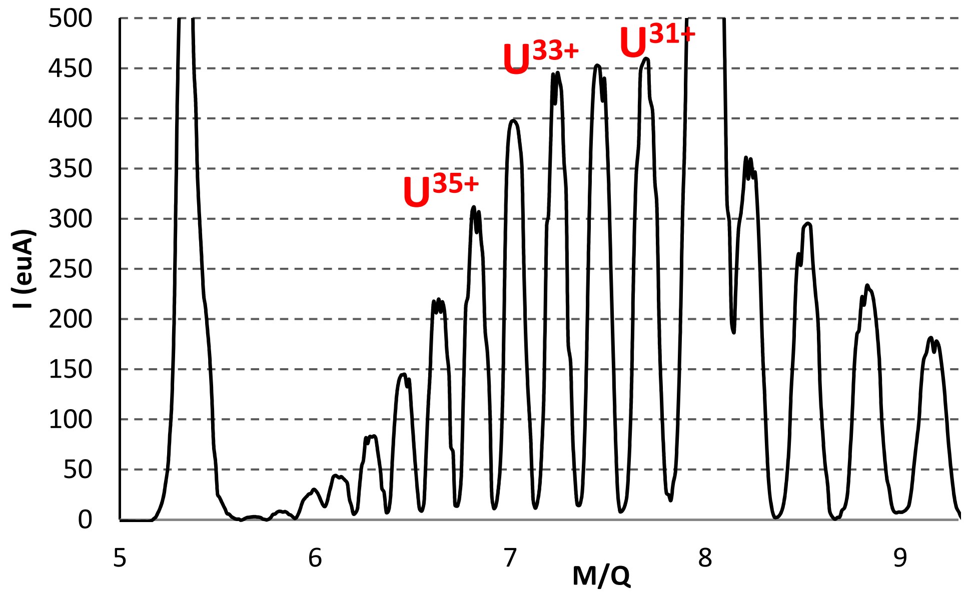
Performance of the 3rd Generation ECRISs



Breakthrough of U Beam



Liangting Sun, Guillaume Machicoane, Janilee Benitez and Claude Lyneis



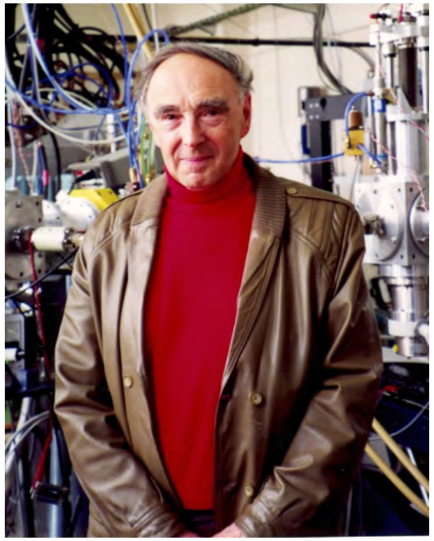
VENUS: 6.5kW 28GHz + 1.7kW 18GHz, HV: 22kV

Redesigned Re Oven

Uranium ion	Beam current in eμA
28+	295
29+	361
31+	460
32+	453
33+	443
34+	400
35+	311

88 Inch Lab, LBNL, USA

Next Generation ECRISs



Geller's Scaling Laws:

$I(q) \propto B_{ecr}^2 \sim \omega_{rf}^2$

$Q_{opt} \sim \log \omega_{rf}^3$

450euA U^{33+} @28GHz

↓

~1.8emA U^{33+} @56GHz

Typical beam intensity enhancement in the last 10-30 years

Ions	Year Intensity By ECRIS	Year Intensity By ECRIS	By factor
O^{6+}	1974 15 eμA Supermafios	2011, ~2-3 emA LBL VENUS IMP SECRAL	~37 ys ~200
Xe^{30+}	1997-1998 10-15 eμA RIKEN 18 GHz, LBL AECR-U	2011, ~236 eμA IMP SECRAL	~14 ys >15
Xe^{35+}	1997 1.5 eμA LBL AECR-U	2011 ~64 eμA IMP SECRAL	~14 ys >40
U^{34+}	1997 20 eμA LBL AECR-U	2011 ~400 eμA LBL VENUS	~14 ys >20

Choice of SC-magnet?

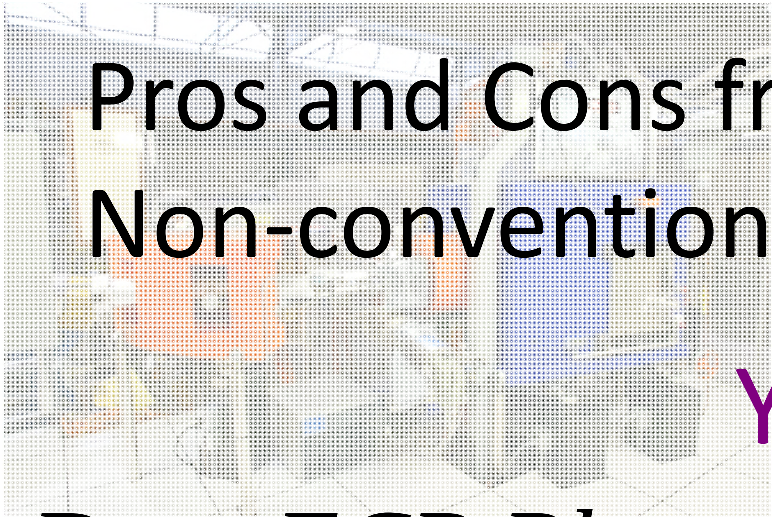
- Pros and Cons from Conventional and Non-conventional Structure?

  Yes!!

- *Does ECR Plasma care about the structure?*

  No!!

- So long as the magnetic field strengths are high enough!



VENUS

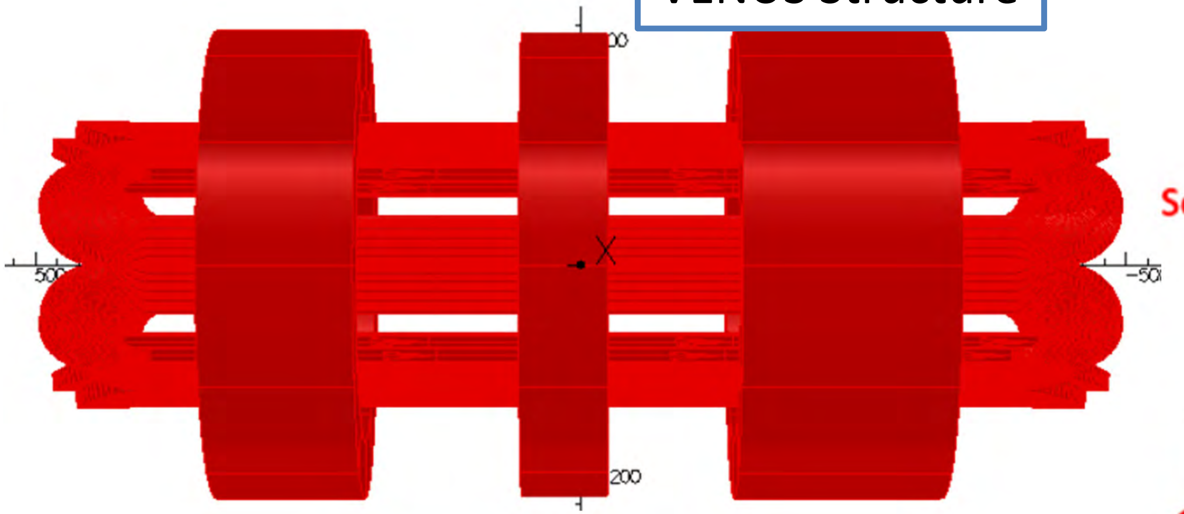
SECRAL

A Few Example Beams from SECRAL and VENUS

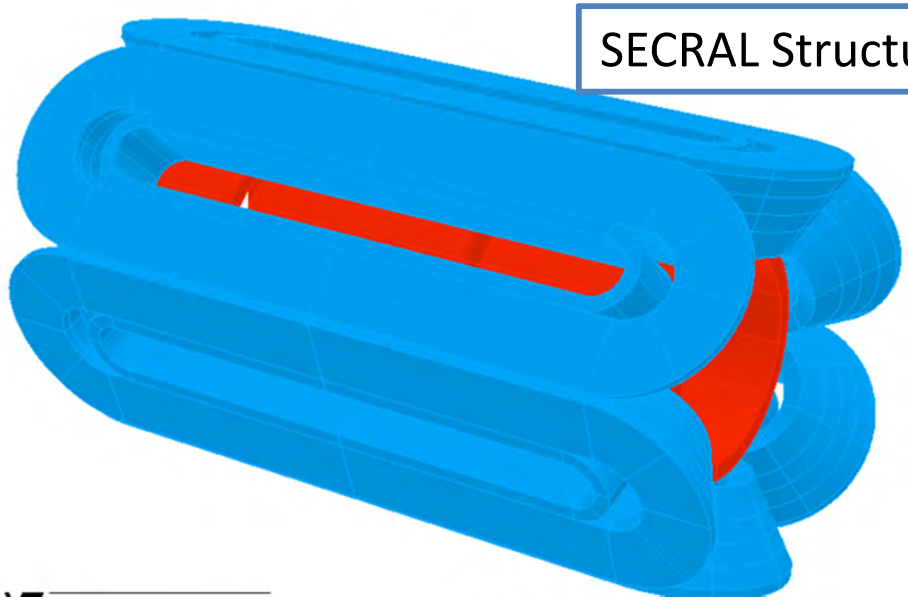
	Q	SECRAL 18 GHz <3.2 kW μA	SECRAL 24GHz 3-4 kW μA	VENUS 28 GHz 5-9 kW μA
16O	6+	2300		2860
	7+	810		850
40Ar	12+	510	650	860
	[illegible]	73	149	270
	17+	8.5	14	36
129Xe	27+	306	455	270
	35+	16	64	28
	42+	1.5	3	0.5
209Bi	31+	150	242	310
	41+	22	[illegible]	[illegible]
	50+	1.5	4.3	5.3
238U	31+			460
	35+			311

Available Magnet Choices?

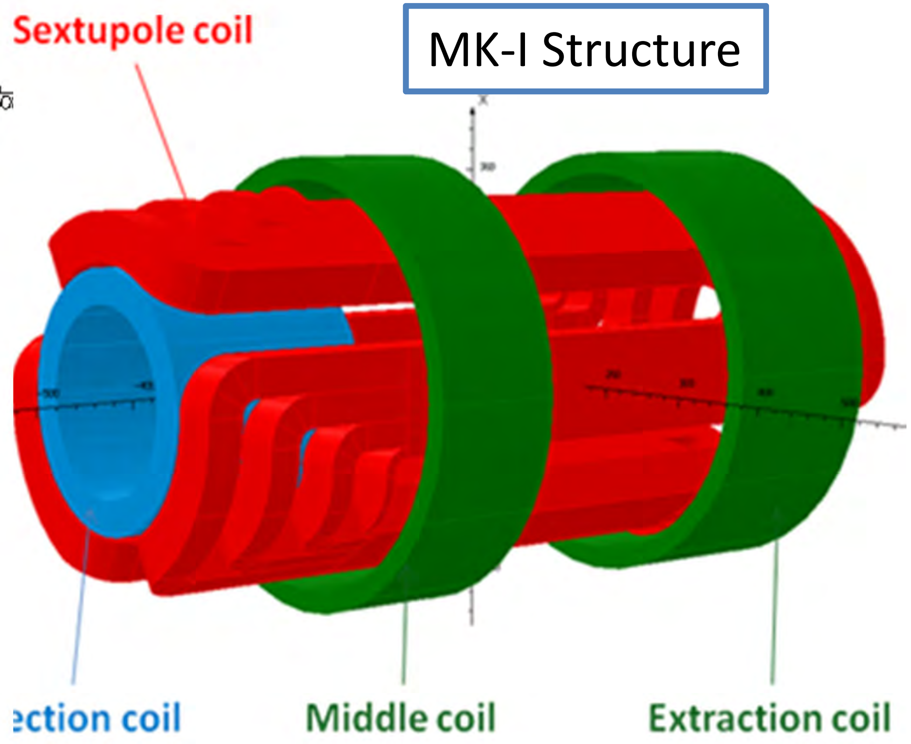
VENUS Structure



SECRAL Structure



MK-I Structure



Comparison

Next Generation ECRIS' Field

	24 GHz	28 GHz	18GHz	56GHz
B_{inj} (T)	3.4	4.0	2.6	8.0
B_{ext} (T)	1.8	2.2	1.4	4.4
B_{min} (T)	0.7	0.8	0.5	1.6
B_{rad} (T)	1.7	2.0	1.3	4.0

Cons of the different options

VENUS	SECRAL	MK-I
• Complicated forces at hexapole ends • Bulky magnet body • Much higher stored energy • Nb_3Sn wire problems	• Lower radial field • Smaller plasma chamber • Nn_3Sn wire problems	• Complexity of the sextupole windings • Coil clamping method is very challengeable • Stepped cryostat and partial hexagonal warm bore and plasma chamber

Other Challenges

- Effective coupling to the plasma of 10-20 kW/50-60GHz microwave power
- Strong ECR plasma bremsstrahlung radiation problems
  - Heat sink in cryostat
  - HV insulator degradation
- Intense high charge state ion beam (20-40emA) extraction and transmission and beam quality；
- Ion beam quality and stability from the ion source working at 10-20 kW/50-60GHz is unkown
- Intense metallic beam production, especially ion beams of refractory materials

Acknowledgement

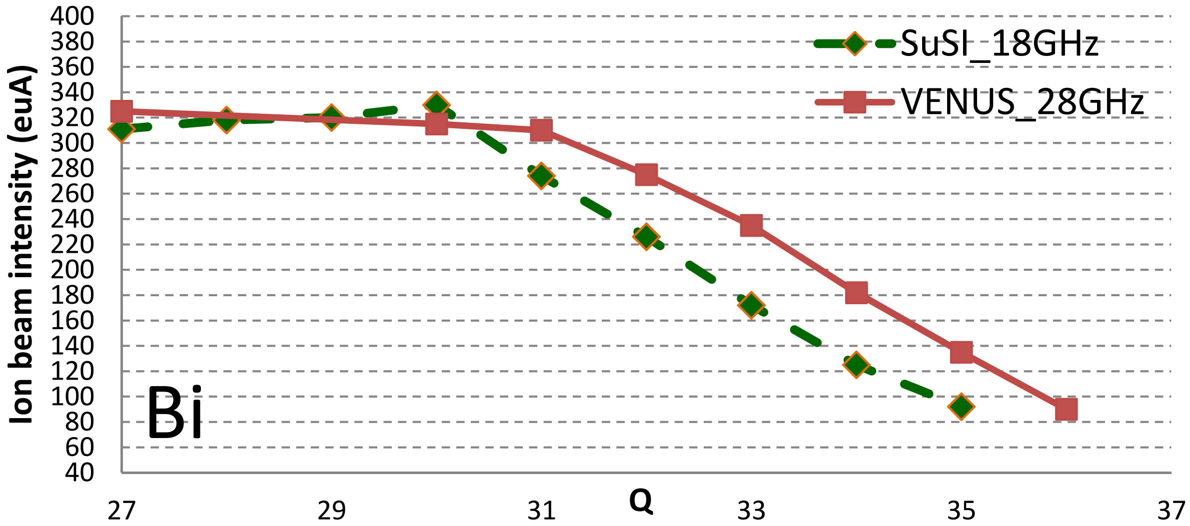
Thanks for the fruitful discussion and data!!

E. Bebee BNL/USA
D. Hitz CEA/France
C. Lyneis LBNL/USA
G. Machicoane MSU/USA
M. Okamura BNL/USA
T. Thuillier LPSC/France
D. Xie IMP/China

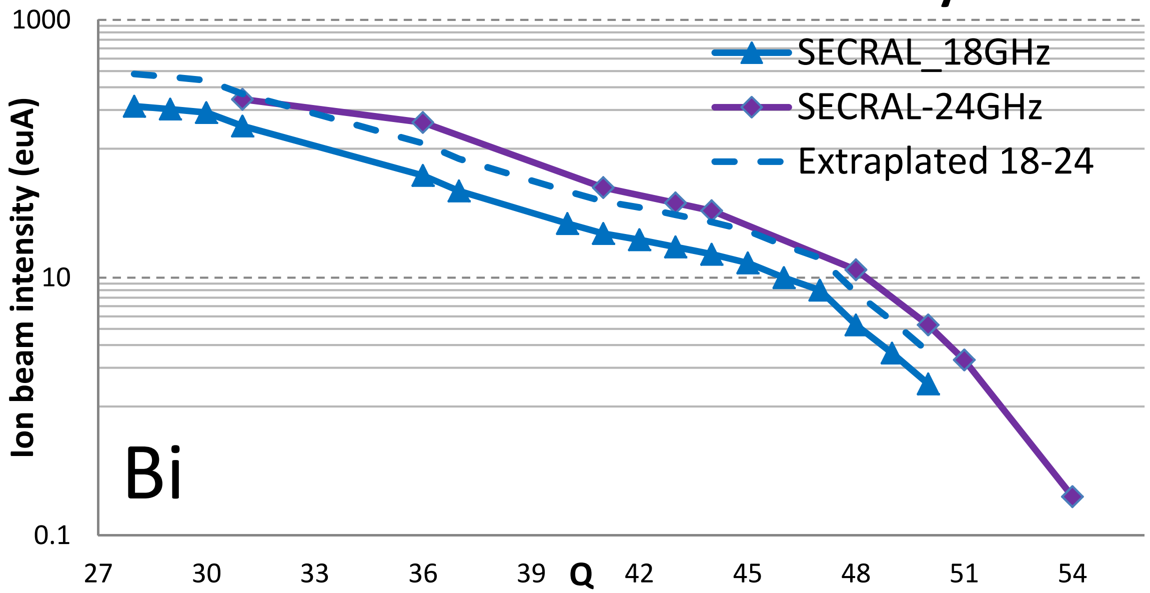
Thank you for your attentions!!

Backup slides

Performance of the 3rd Generation ECRISs



Bismuth beam results recently obtained



- Solid material feeding is still a challenge for intense beam production
- Frequency scaling is still applying well to ECRISs