The Roles of ECR Ion Sources in Radioactive Beam Facilities

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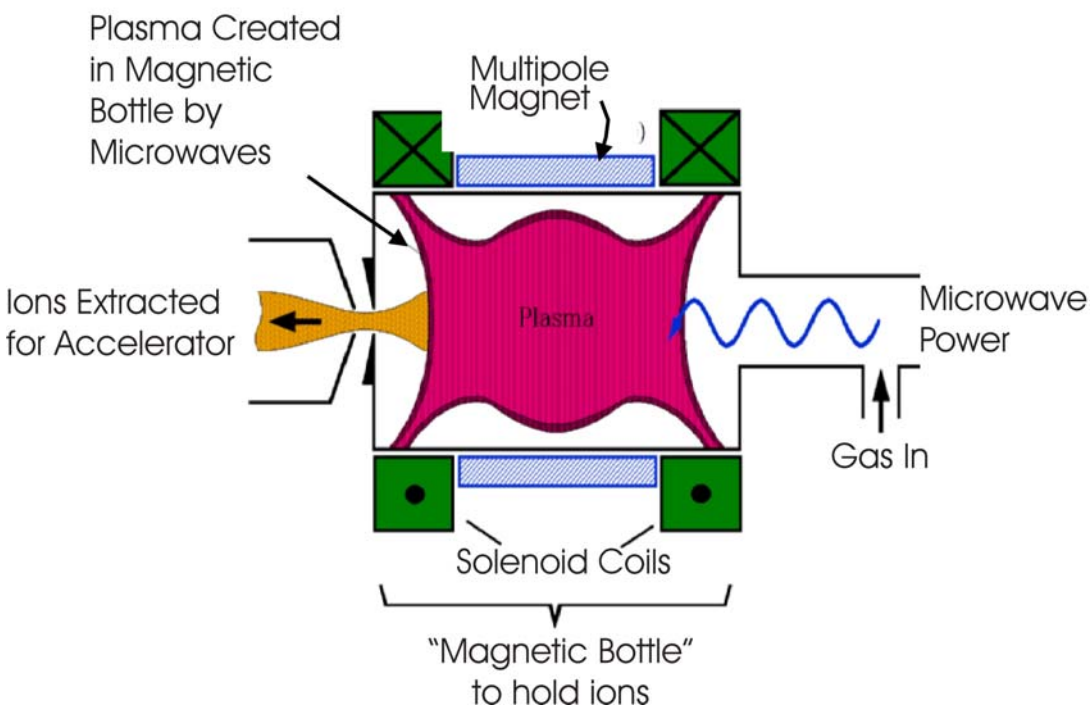
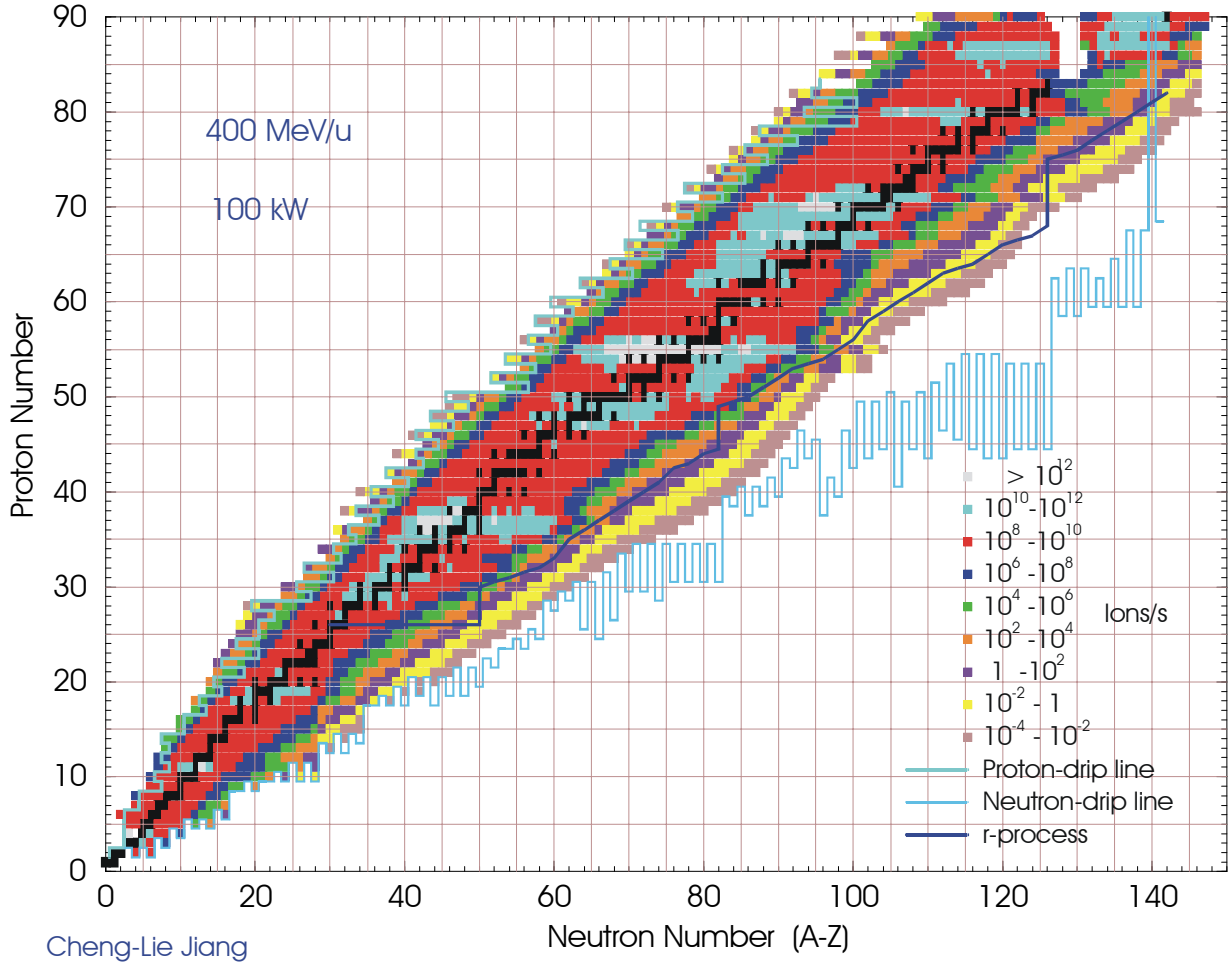
ECR Ion Source

- **Invented in 1975 by Richard Geller**
- **High charge states, moderate to high currents**
- **Good emittance, low energy spread**

Electron Cyclotron Resonance Ion Source

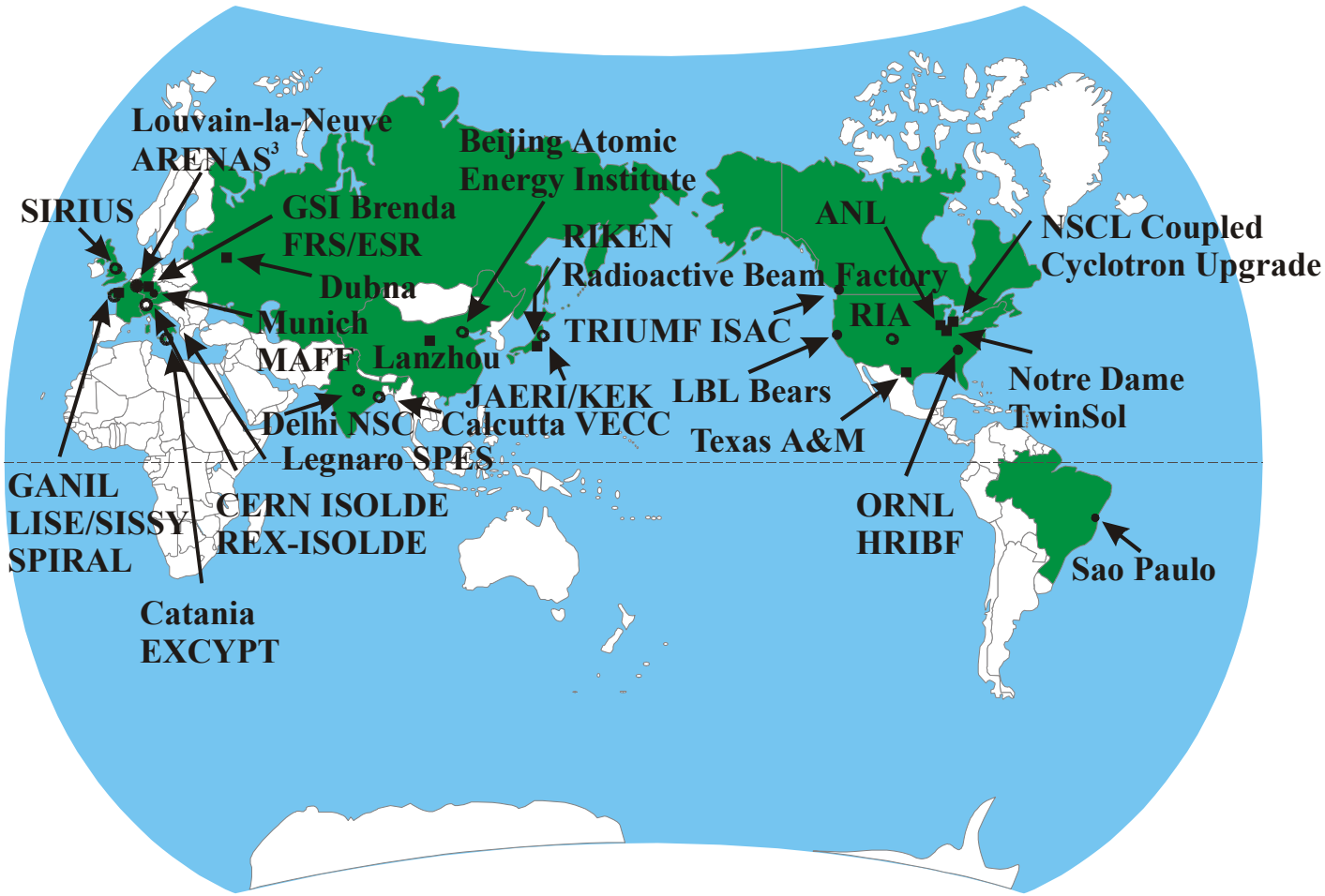


Radioactive Beams:
New Frontier in Nuclear Physics



Cheng-Lie Jiang

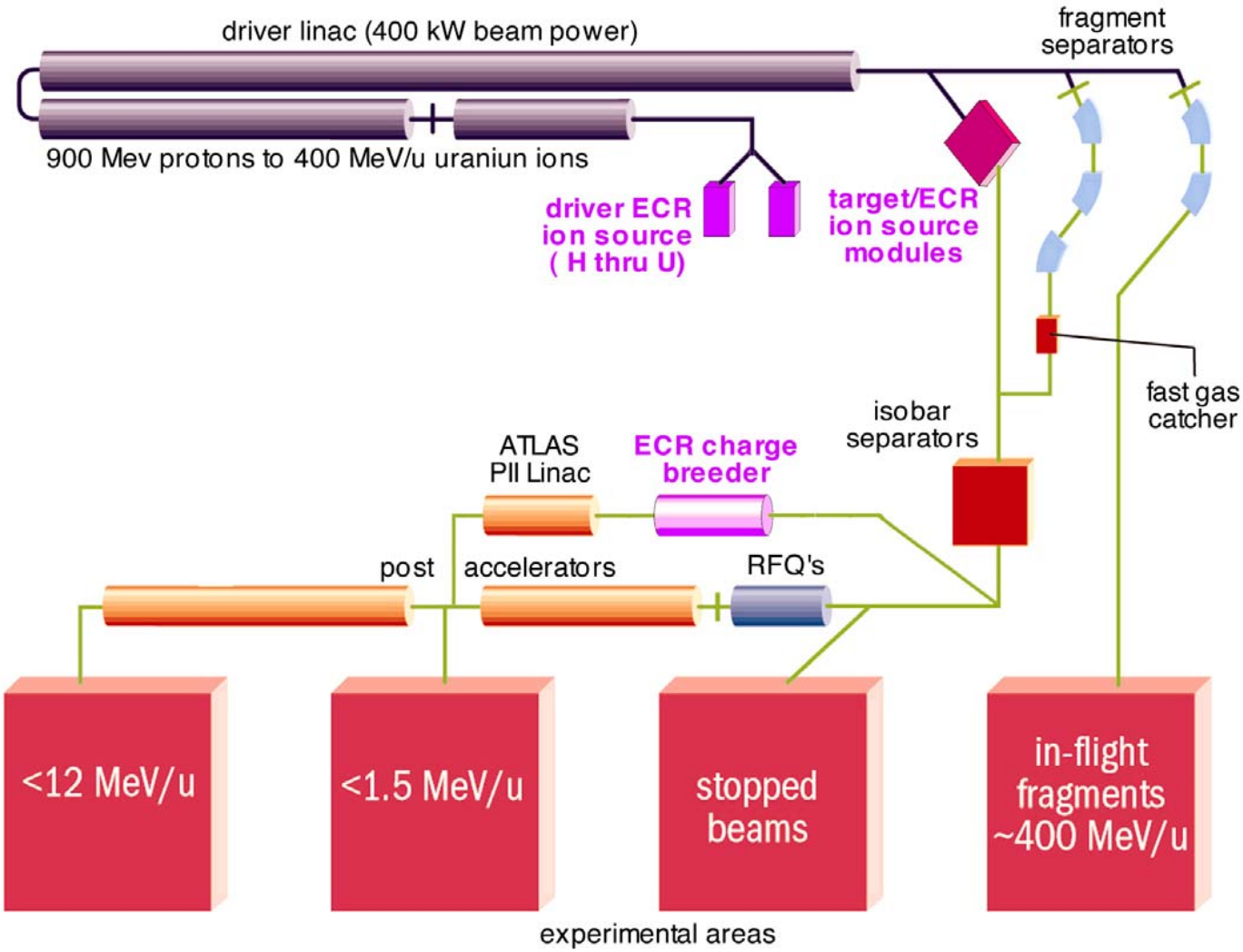
Planned/Future RIB Facilities



Role of ECR Ion Sources in RIB's

Application	Driver Accelerator Ion Source	Radioactive Beam Ionizer	Charge-State Multiplier
Properties	High Current Moderate/High Charge State Good Emittance High Reliability	High Efficiency Low Charge State Good Emittance Radiation Resistant	High Efficiency Moderate Charge State Good Emittance
Example Facilities	RIA, GANIL, NSCL, RIKEN	ISAC-I, GANIL, ARENAS, RIA, EXCYT	MAFF, ISAC-II, RIA, GANIL

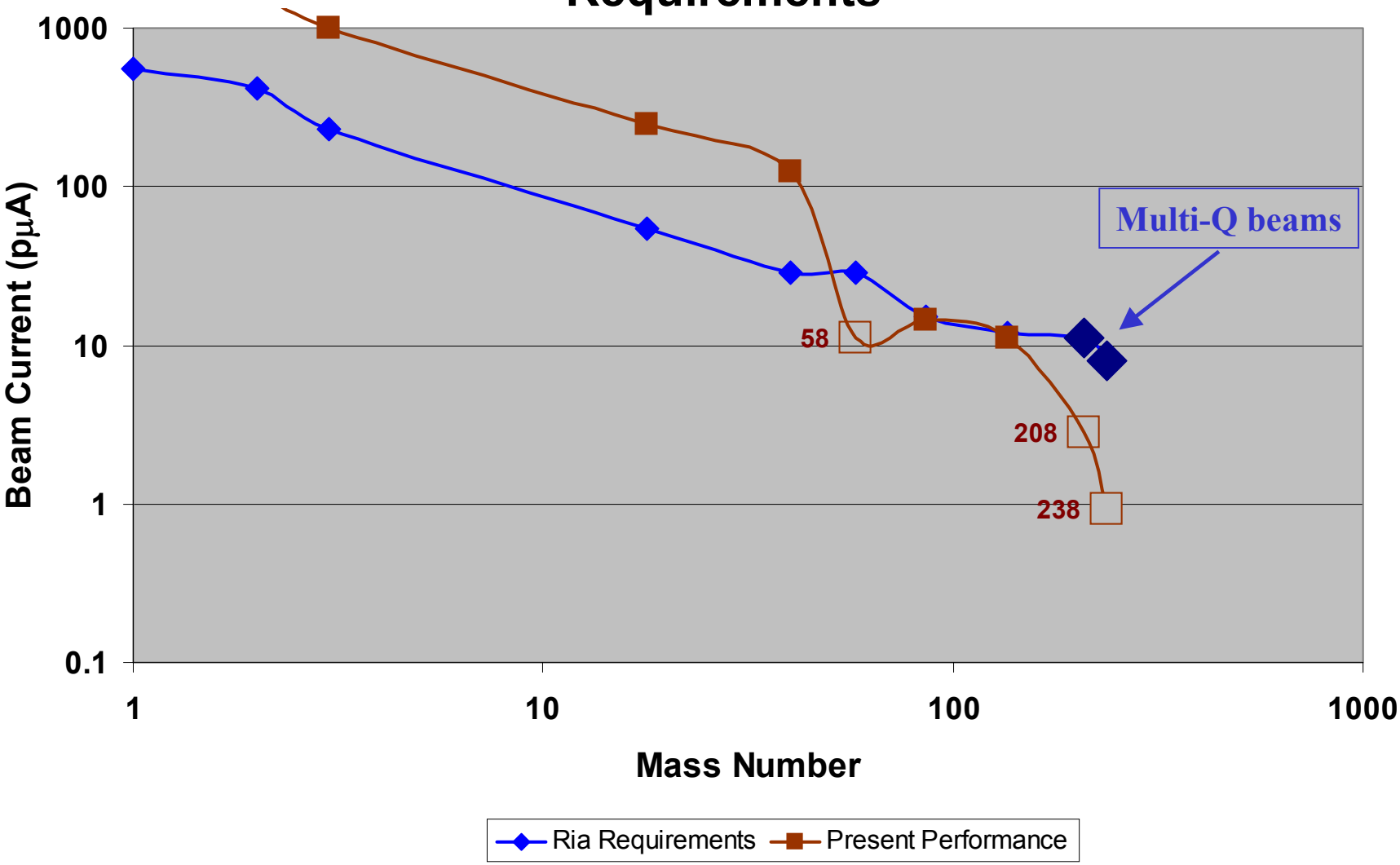
ECR Source Applications at RIA



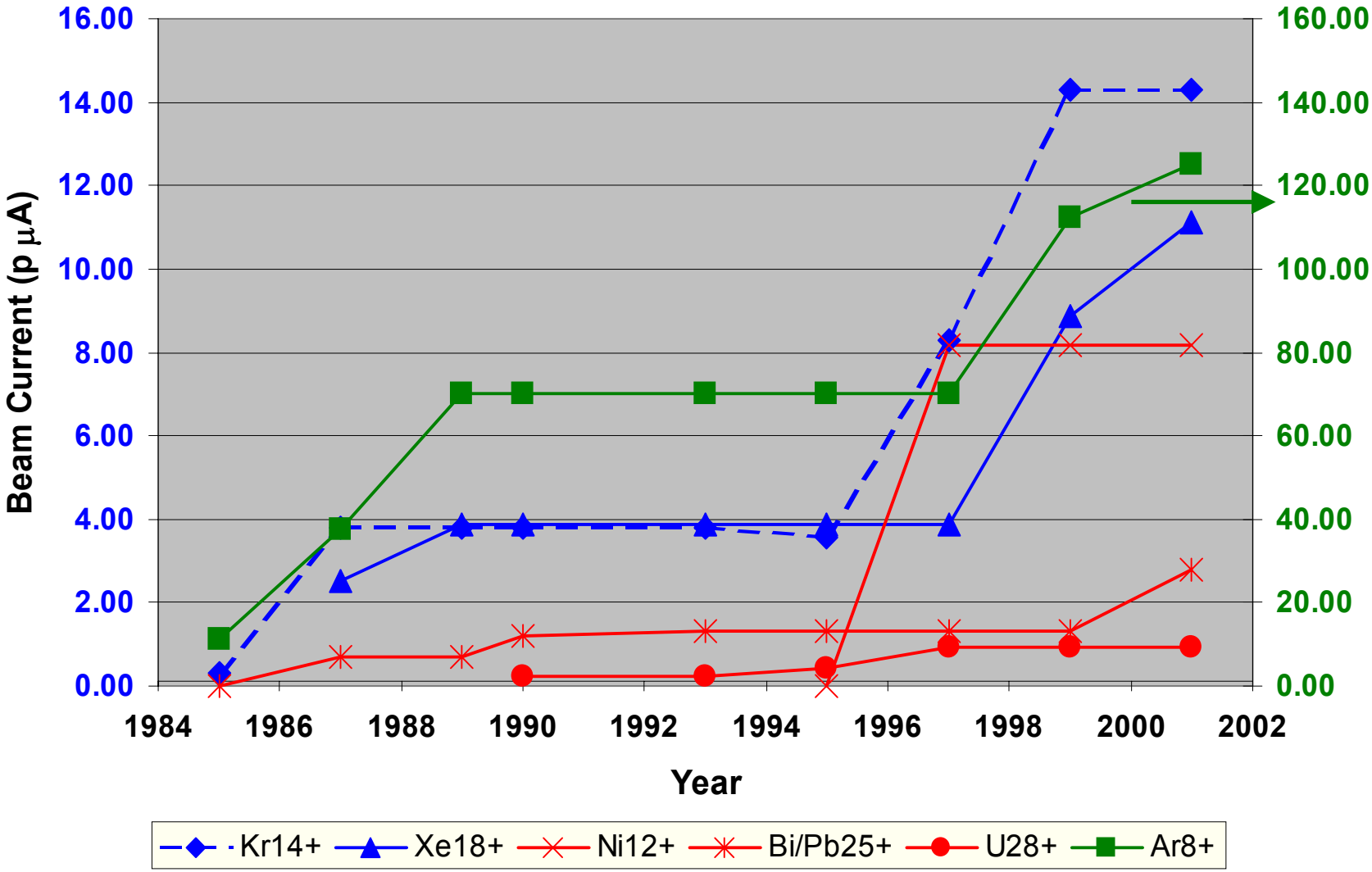
RIA Driver Linac Beam Requirements and Present ECR Source Capabilities
400 kW Beam Power

Mass	Q_{inj}	Q_{strip1}	Q_{strip2}	U/A (MeV/A)	$I_{Required}$ (pμA)	$I_{Achieved}$ (pμA)
1	1	--	--	899	556	>>1000
2	1	--	--	600	416	>>1000
3	2	--	--	717	232	>1500
18	6	8	8	551	56	>150
40	8	18	18	554	29	~150
58	12	28	28	585	29	8
86	15	33-34	36	515	15	14
136	18	46-48	53-54	476	12	11
209	25-26	63-65	79-83	440	11	2X2.8
238	28-29	69-73	87-90	403	8	2X0.93

ECR Performance Compared to RIA Driver Requirements



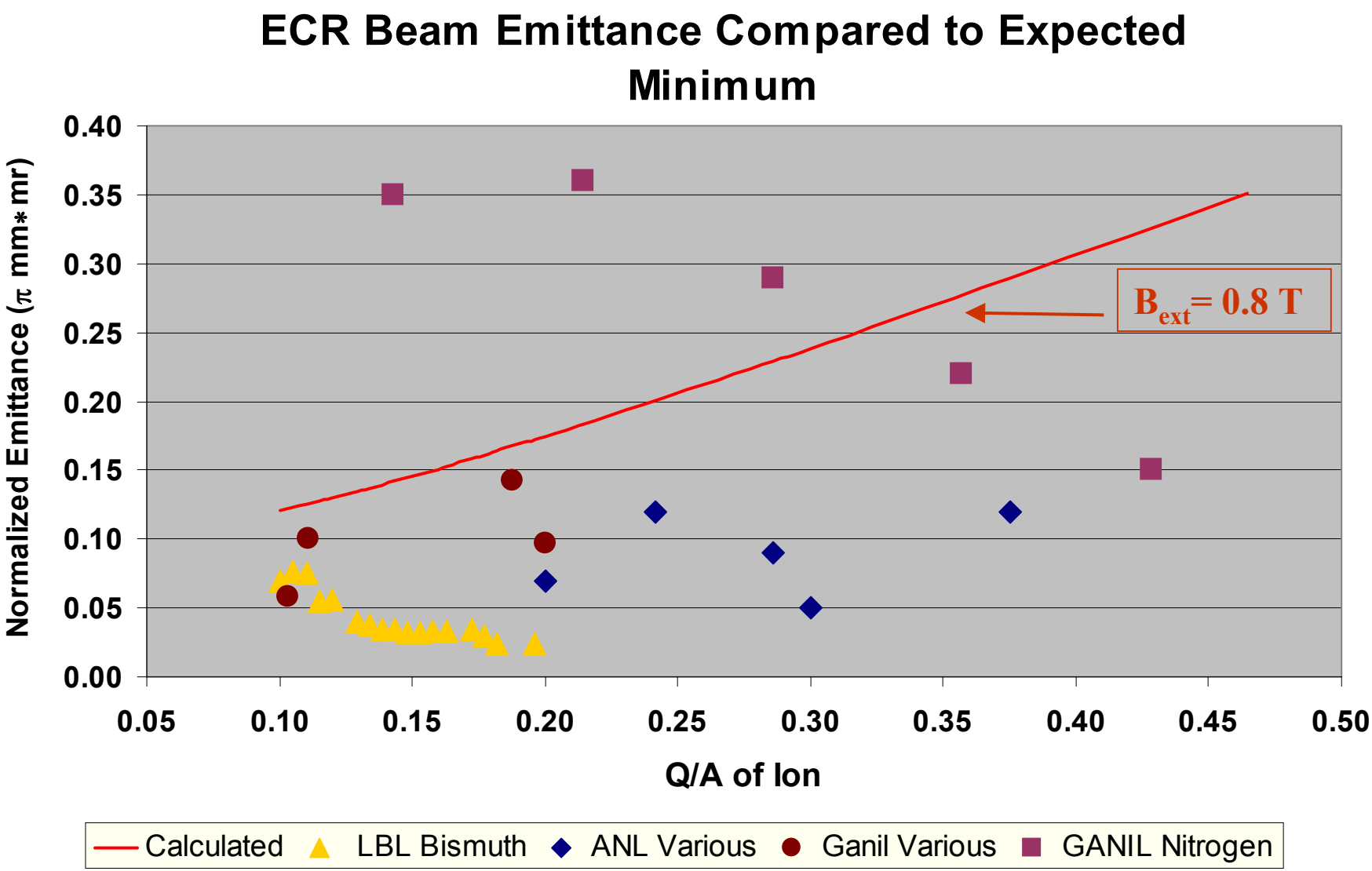
History of ECR Beam Current Performance



ECR Beam Quality Limitations

- Ions made in high magnetic field
- Conserve angular momentum on exit
- Possible limitation on beam emittance
- $kT_i = 5Q_i$ to $15Q_i$

$$\varepsilon_c = 0.5r * \sqrt{\frac{kT_i}{m_i c^2} + \frac{Q_i^2 e^2 r^2 B^2}{8 m_i^2 c^2}}$$


ECR Beam Emittance Compared to Expected Minimum
Normalized Emittance (π mm* mr)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Q/A of Ion
B_ext = 0.8 T
Calculated
LBL Bismuth
ANL Various
Ganil Various
GANIL Nitrogen

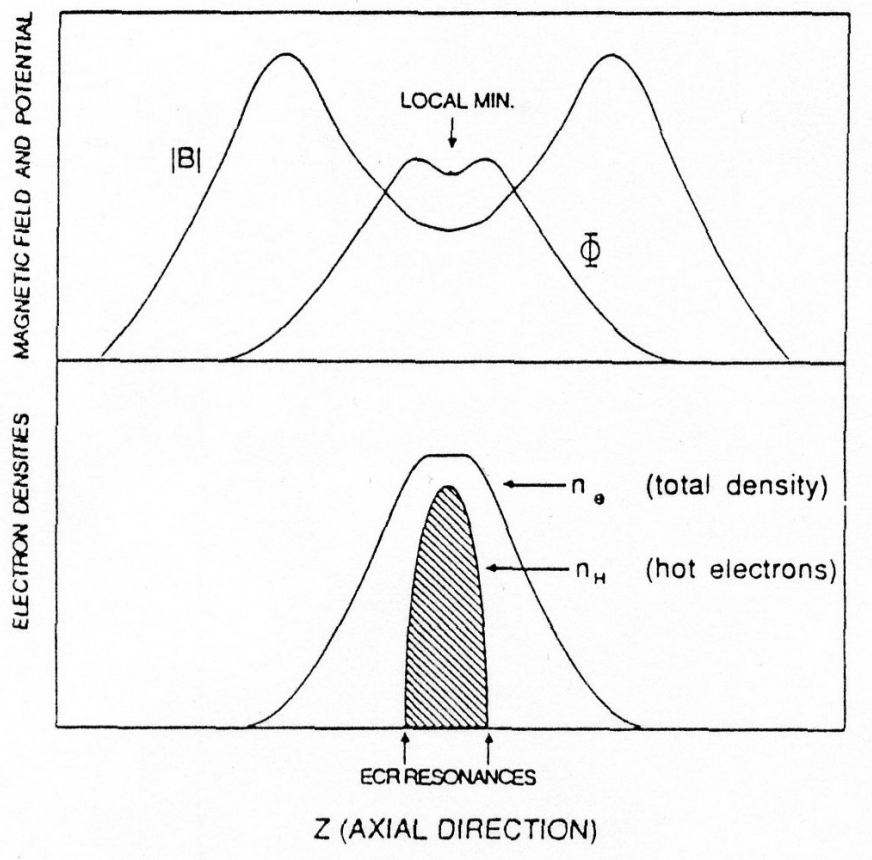
Direction of ECR Development to Improved Performance

- **Improve Electron Confinement**
  - High Mirror Ratio Solenoid Field
  - $B_{max}/B_{res} \geq 2$
  - High Radial Field Provides Closed Field Lines

- **Increase Plasma Density**
  - Limited by RF cutoff due to plasma frequency
  - $n_e = (\omega_p^2 m_e \varepsilon_o)/e^2$
  - $\omega_p = \omega_{rf}$

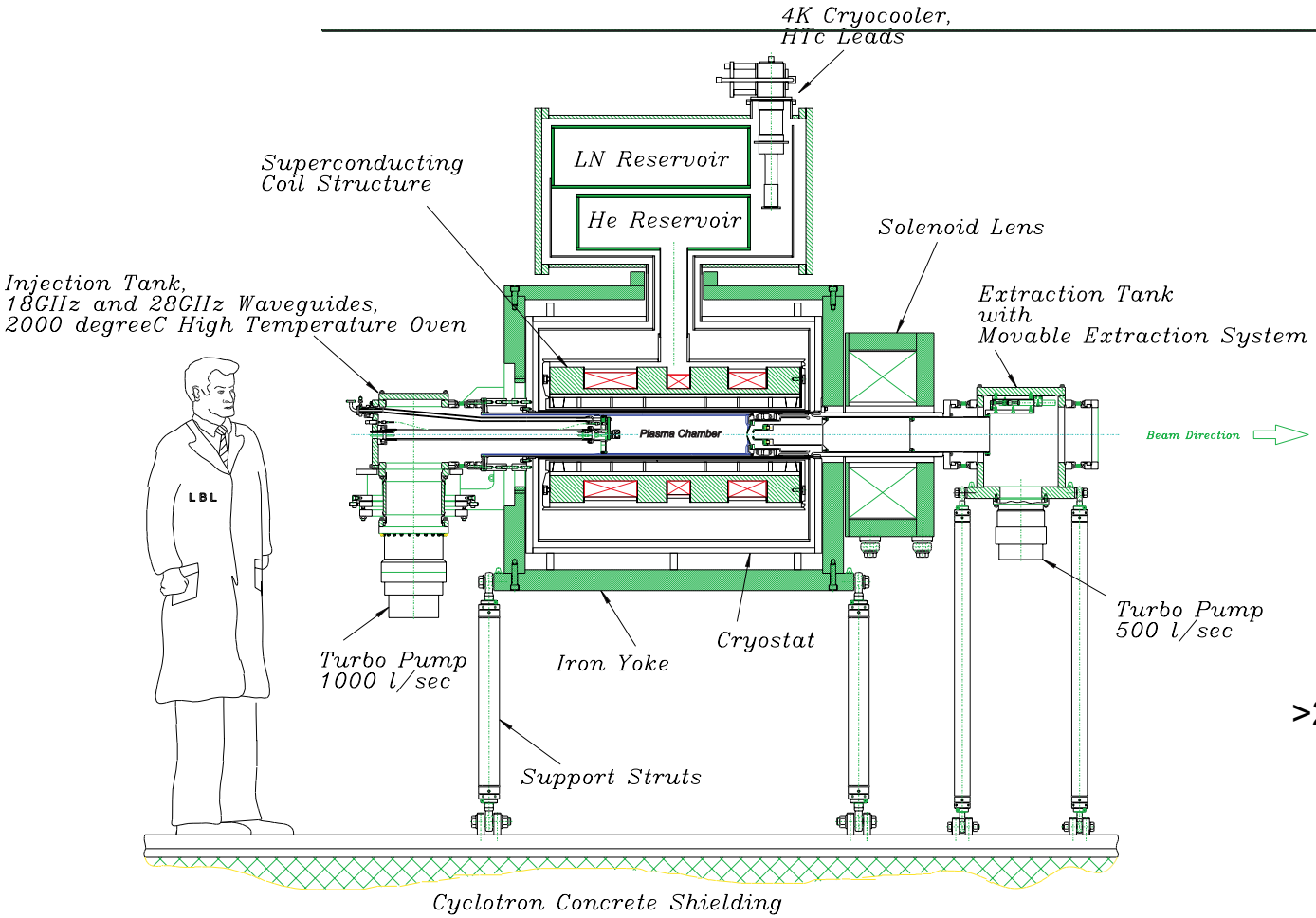
Direction of ECR Development to Improved Performance

- **Use Large Plasma Volume**
  - Ion confinement due to plasma potential
  - Large volume allows potential to develop
  - Large volume requires large total RF power



Venus 18/28 GHz SCECR Source

Berkeley Lab



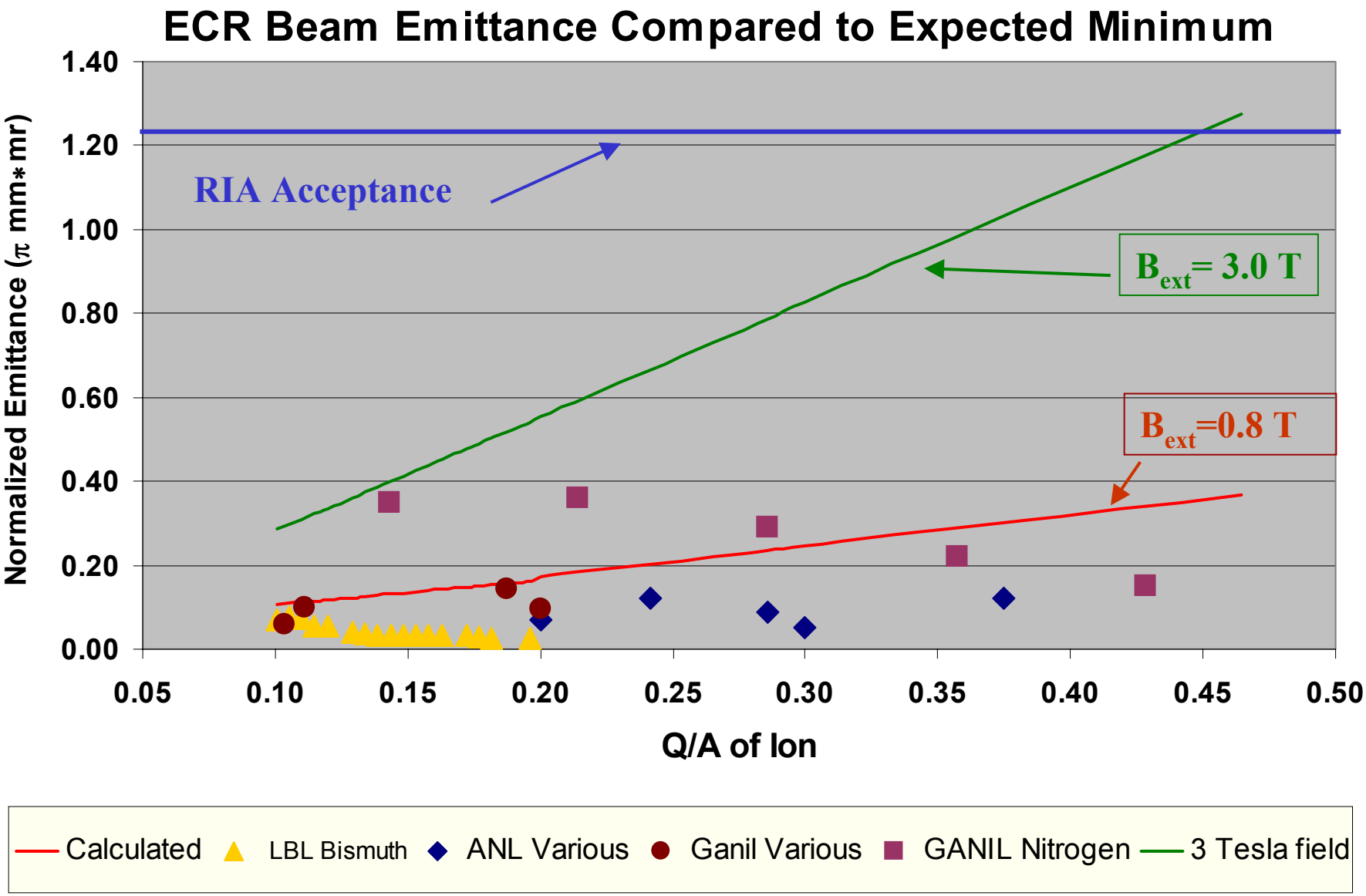
Magnetic Field:
4.0 Tesla at Injection
3.0 Tesla at Extraction
2.0 Tesla at Walls

Superconductor:
NbTi

Microwave Heating:
4 kW CW 18 GHz
10 kW CW 28 GHz

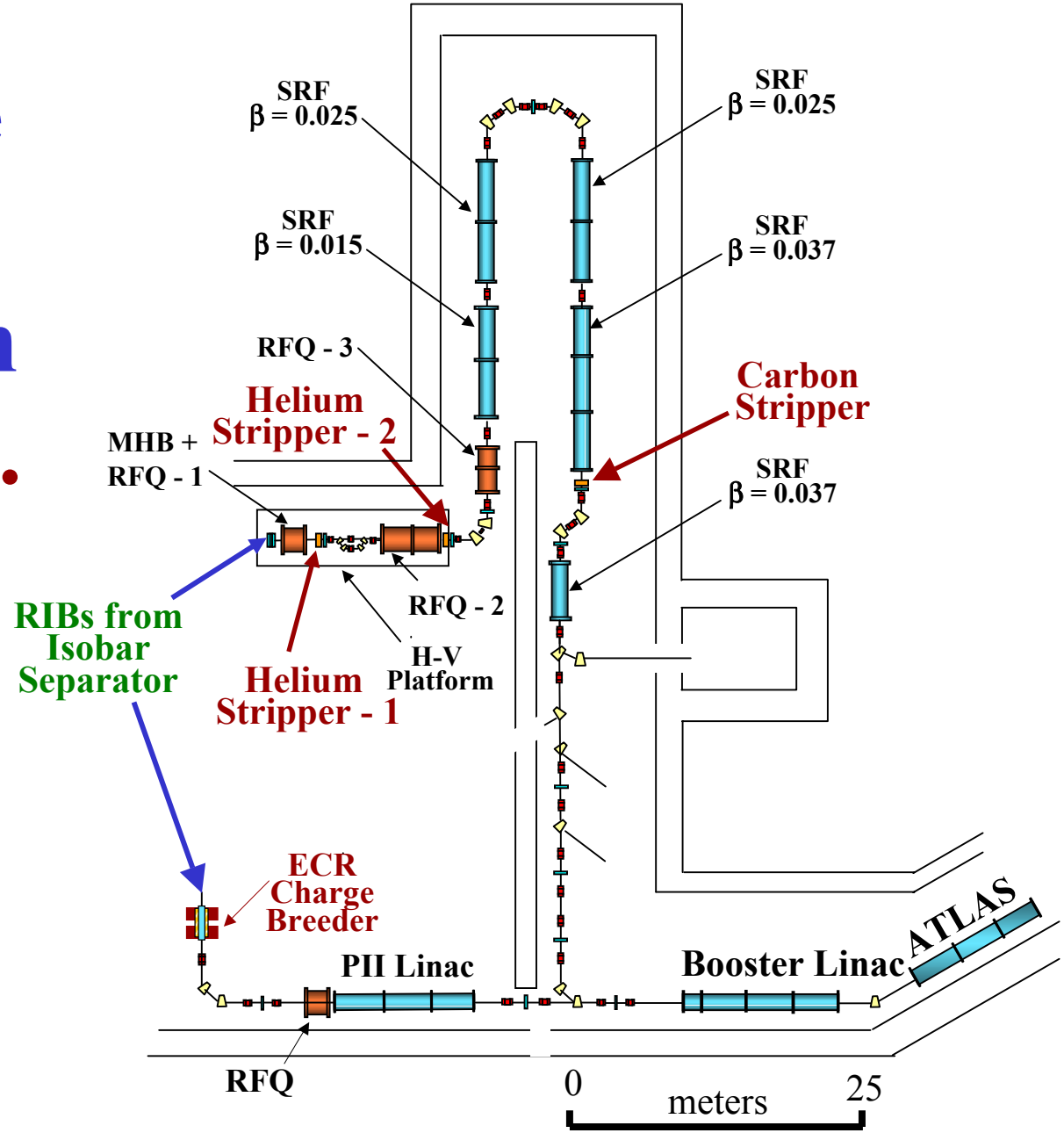
Extraction Potential:
Up to 40 kV

High Temp. Oven:
>2000 degree Centigrade


ECR Beam Emittance Compared to Expected Minimum
Normalized Emittance (π mm∗mr)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Q/A of Ion
RIA Acceptance
B_ext= 3.0 T
B_ext=0.8 T
Calculated
LBL Bismuth
ANL Various
Ganil Various
GANIL Nitrogen
3 Tesla field

Radioactive Beam Acceleration

Stripping vs. Charge Breeding



Facilities planning to use Charge Breeder

- ISAC-II
- GANIL
- MAFF
- EXCYT
- TAMU
- RIKEN
- RIA???

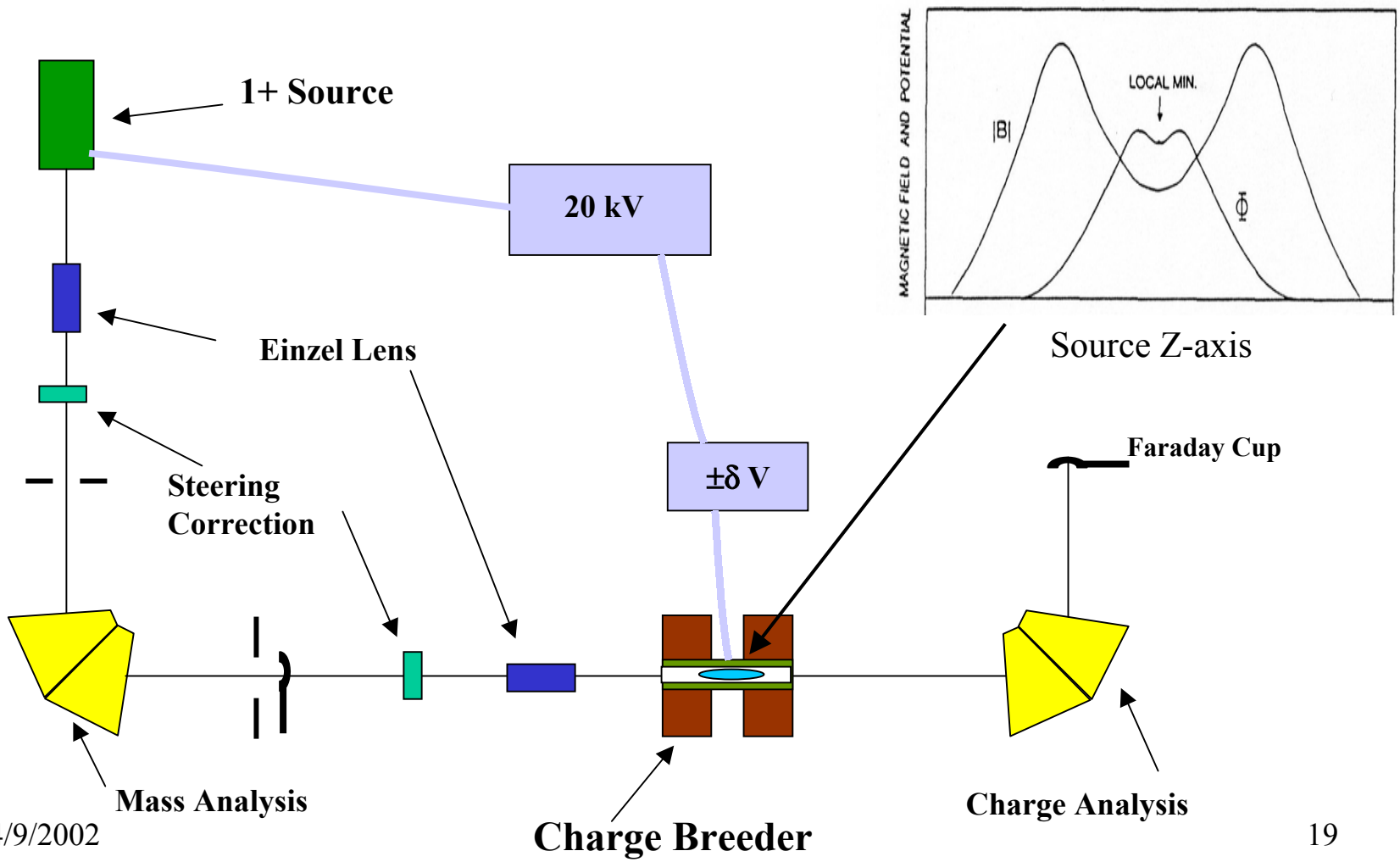
Requirements for Charge Breeding

- **Must achieve minimum necessary A/Q ratio**
  - ISACII: A/Q = <7
  - RIA/ATLAS: A/Q = 8 to 10

- **High efficiency required**
  - Capture of 1+ ions from ionizer or gas catcher
  - Narrow charge-state distribution desired

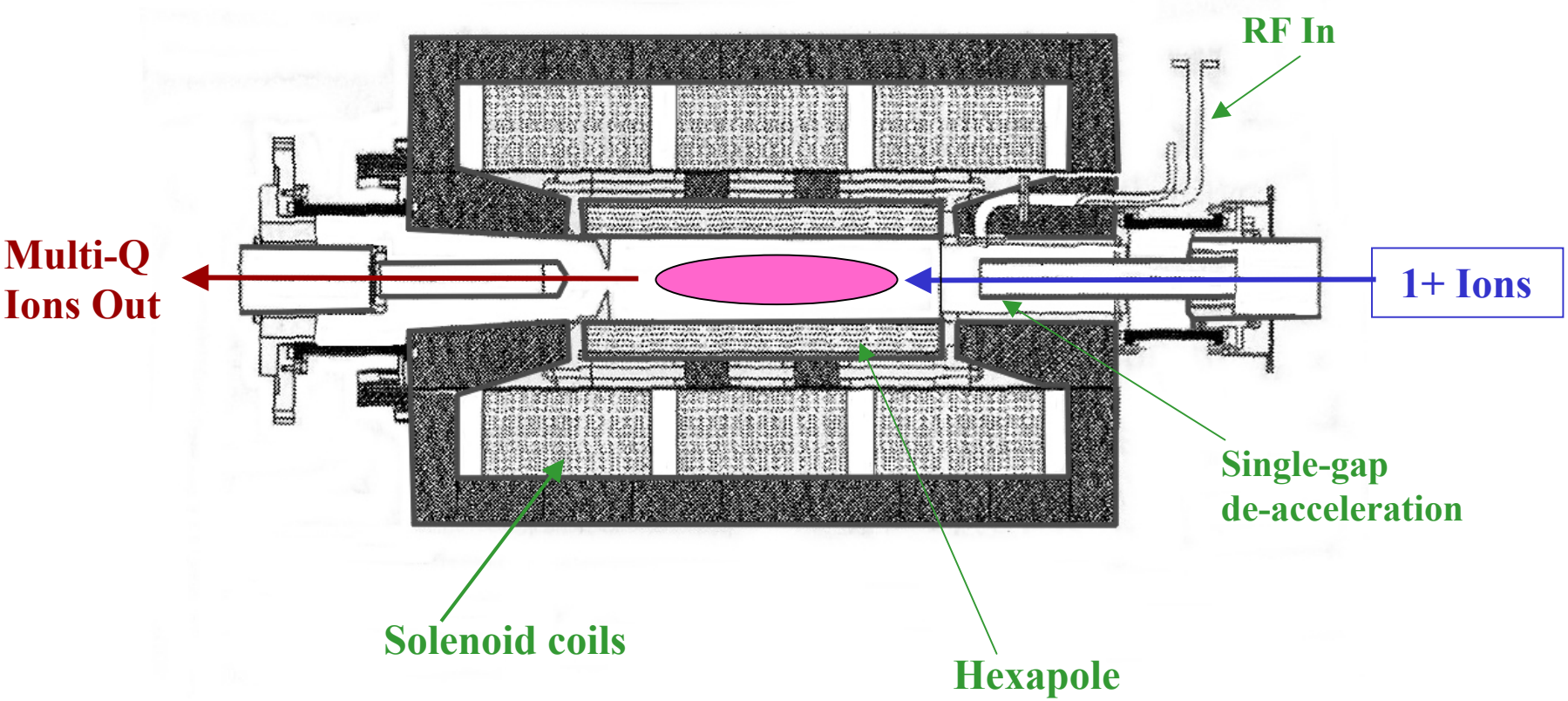
- **High reliability**

Charge-Breeder Scheme



Phoenix ECR Charge Breeder

ISN Grenoble



Phoenix Ionization Efficiency vs. RIA Stripping Scenario

ISN/TRIUMF

	Efficiency	A/Q	Time(ms)	RIA Strip. Eff.
• Gases				
– $^{40}Ar^{9+}$:	11.9%	4.4	25	33%
– $^{84}Kr^{14+}$:	10.3%	6.0	60	12%
• Solids				
– $^{115}In^{18+}$:	4.6%	5.8		9.5%
– $^{109}Ag^{19+}$:	3.9%	5.7	25	9.5%
– $^{120}Sn^{22+}$:	4.0%	5.5	20(19+)	9.5%

- 1+ beam emittance used: 55π mm•mr
- For E/A<0.7 MeV/u & A<66, RIA: No stripping

Summary

- **Driver Beam Requirements**
  - **Intensity from gaseous material beams: OK**
  - **Intensity from solid material beams: Need >2X gain**
- **Charge Breeder**
  - **Concept well demonstrated**
  - **Efficiency gains realized, more desired. (2X)**
- **Low Charge-State Ionizer**
  - **Generally meet minimum needs**