HIGH INTENSITY, HIGH CHARGE STATE HEAVY ION SOURCES

James Alessi
Collider-Accelerator Department
Brookhaven National Laboratory

Outline of Talk:

- Applications; general requirements, important features for each
- Source options
  - Basic idea for each; key technologies
  - Best matches for various applications
- Performance of various type sources
- Possible future improvements

Requirements for High Q production:

- Need high electron energy - for high Q
- Long confinement of the ions - stepwise ionization
  (electron current density *confinement time)
- High electron densities - intensity out
- Low background pressure - for low recombination of ions

EBIS ~ gives you control over these parameters independently
ECR - parameters are coupled quite a bit
LIS - least control over them independently.

Also are other considerations (depending on the application) such as ease of producing different species, time to switch species, pulse length, etc.

APPLICATIONS

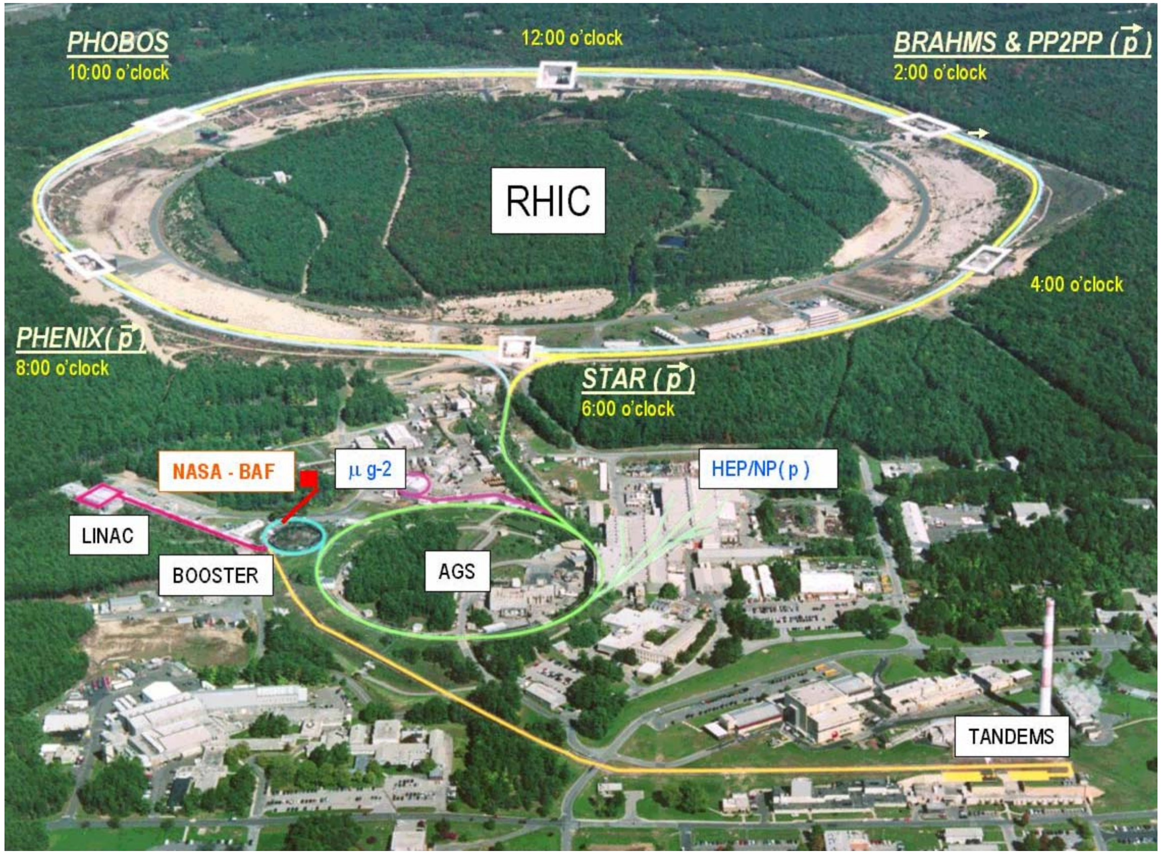
(~ a few of the ones driving the developments for the various type sources at this time)

BNL – new heavy ion preinjector for RHIC/NSRL – as a replacement for the 2 Tandems.
Requirement for RHIC (one example) : 1.7 emA of Au 32+, 10 µs; 5 Hz
plus….NSRL (NASA Space Radiation Laboratory) – *interleaved* second beam at 5 Hz:
He 2+, C 6+, O 8+, Si 14+, Ti 18+, Fe 21+, Cu 22+, all at ~2-3 emA, ~ 10 µs
--- short pulses, fast beam changes, any species

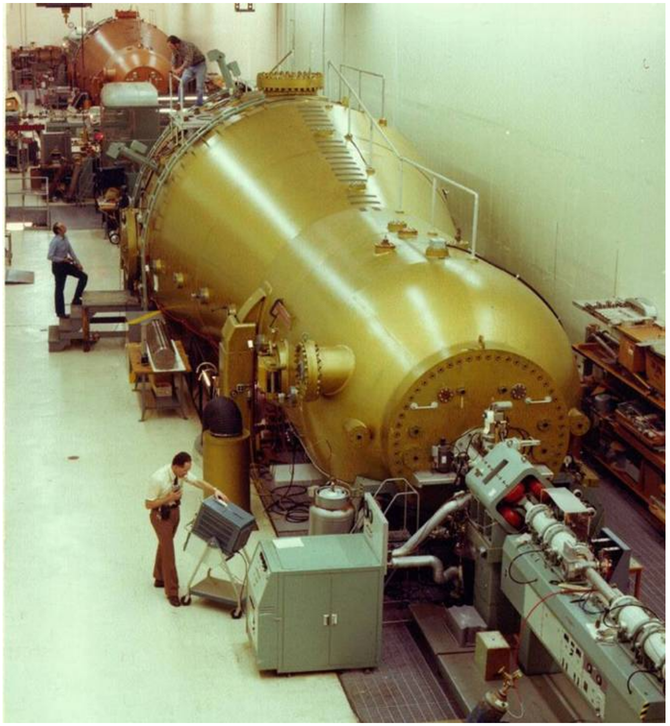
LHC – Pb, (He, O, Ar, Kr, and In ions also have been requested, but some flexibility to tailor beams to the source?)
ECR upgrade, plus LEIR: Pb 27+, > 200 eµA, 5 Hz, 200 µs
or… LIS, without LEIR : Pb 25+, ~ 5 emA, 5.5 µs, 1 Hz
or… EBIS, without LEIR; or without LEIR + without stripping
2-3 emA Pb 54+, 5.5 µs, 1 Hz

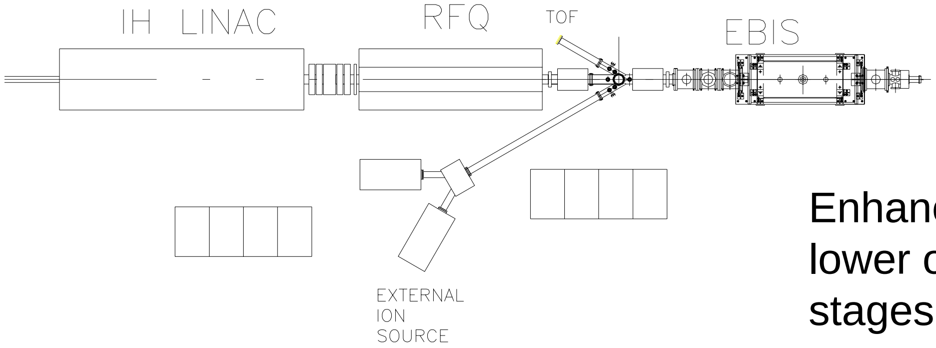
RIA – ~ all species, dc beams!
(GSI; RIKEN Radioisotope Beam Factory; etc.)

(Medical – Light ions for cancer therapy; C 4+ or 6+, ex., want simple & reliable)



Present RHIC Preinjectors

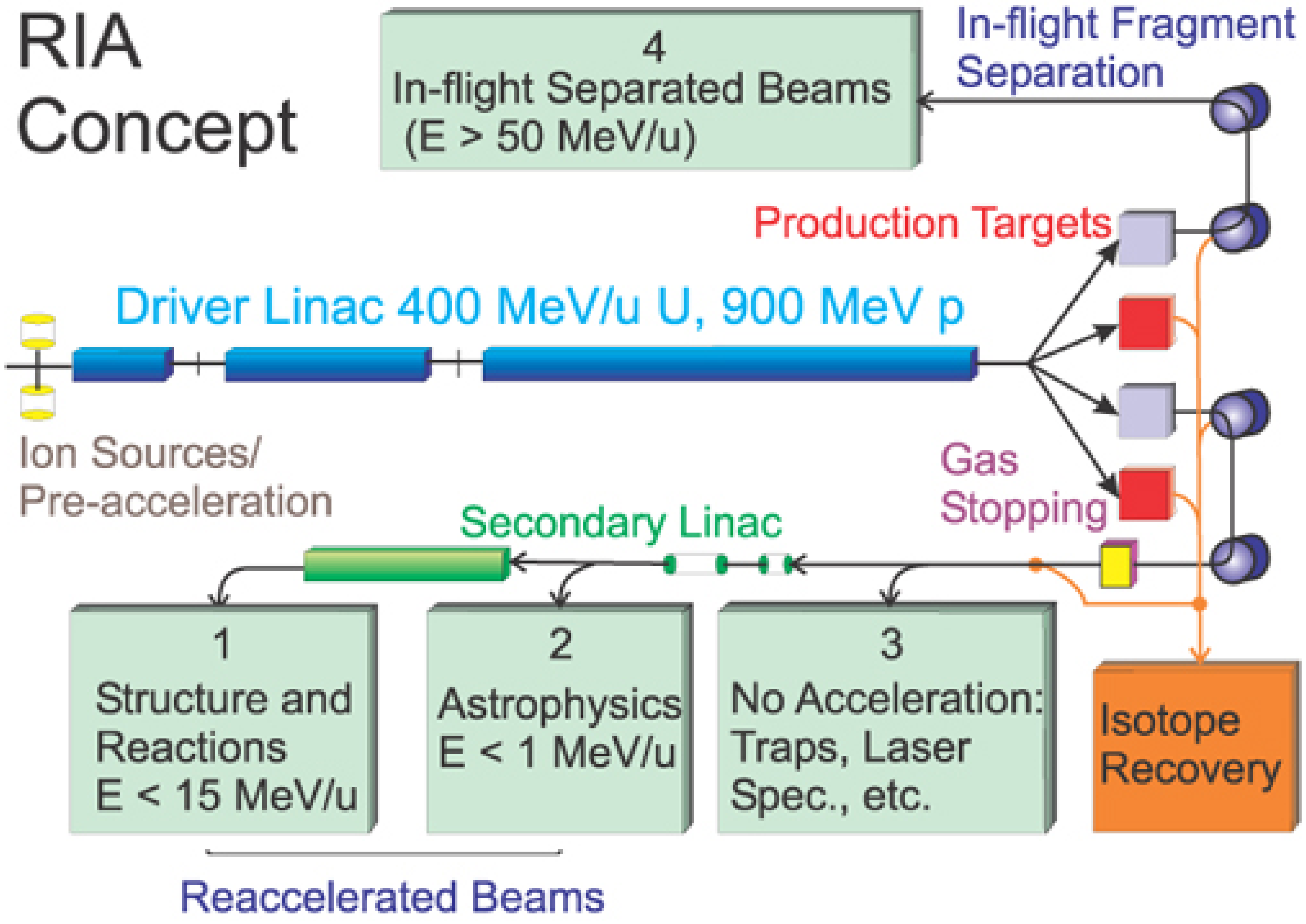




Future, EBIS-based preinjector

Enhanced capabilities, simpler, more modern, lower operating costs, eliminates 2 stripping stages, 800 m transport line, and multiturn injection

RIA Concept



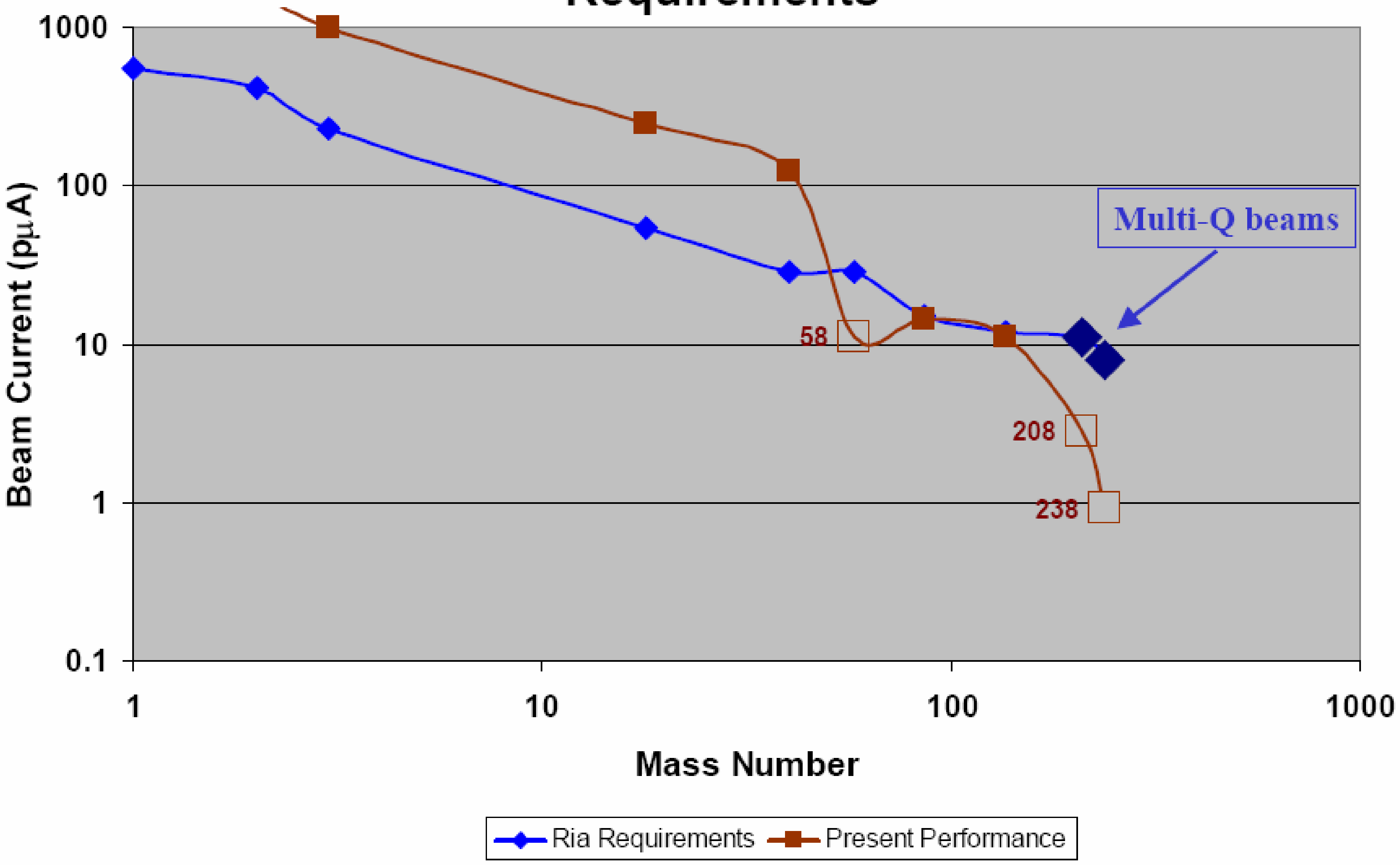
Protons to uranium
400 kW beam power

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

Mass	Q_{inj}	Q_{strip1}	Q_{strip2}	U/A (MeV/A)	$I_{Required}$ (pμA)	$I_{Achieved}$ (pμA)
^{1}H	1	--	--	899	556	>>1000
^{2}H	1	--	--	600	416	>>1000
^{3}He	2	--	--	717	232	>1500
^{18}O	6	8	8	551	56	>150
^{40}Ar	8	18	18	554	29	~150
^{58}Ni	12	28	28	585	29	8
^{86}Kr	15	33-34	36	515	15	17
^{136}Xe	18	46-48	53-54	476	12	11
^{209}Pb	25-26	63-65	79-83	440	11	2X4.0
^{238}U	28-29	69-73	87-90	403	8	2X1.5

R. Pardo

ECR Performance Compared to RIA Driver Requirements



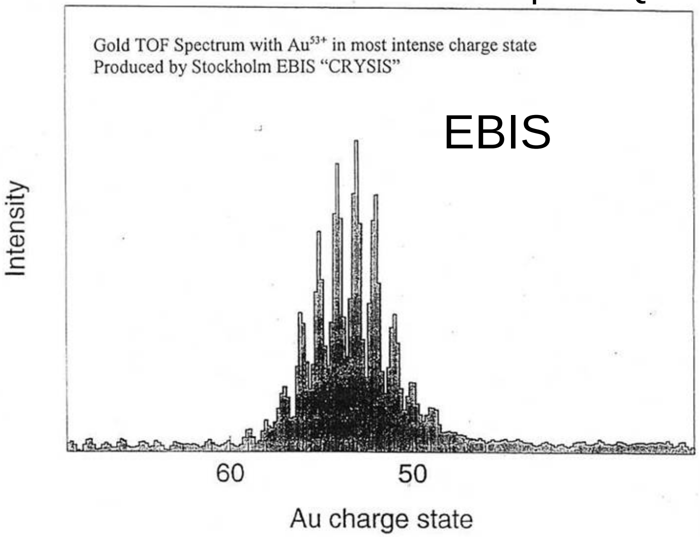
Multi-Q beams

Sources - Considerations for these applications

1. Intensity (current or charge, depending on the source)
2. Emittance
3. Pulse width / rep rate / duty factor
4. Stability (long term and pulse-to-pulse)
5. Current fluctuations (noise)
6. Lifetime / Reliability
7. Ability to produce high charge states (usually intensity/Q tradeoffs)
8. Charge state distribution (total current that you have to transport)
9. Range of species that can be produced (solids, gases?)
10. Ease of changing species (even pulse-to-pulse ?)
11. Energy spread (usually not a concern)

Initial extraction and transport has to handle the total current – can be tough!

>20% of total current can be in peak Q



1392 Rev. Sci. Instrum., Vol. 75, No. 5, May 2004

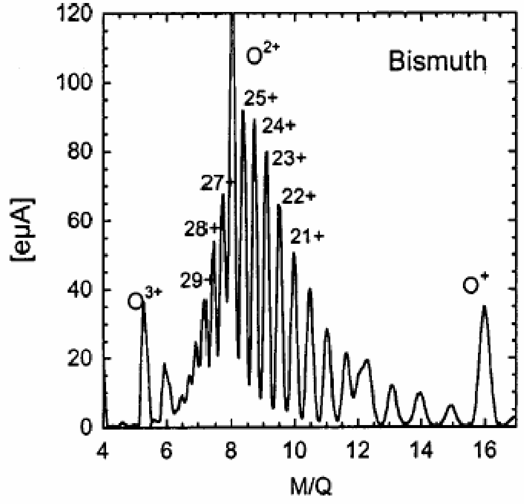


FIG. 4. Charge state distribution for bismuth from VENUS. For thi surement the source was tuned to maximize Bi^{25+}.

ECR

Peak Q < 10%

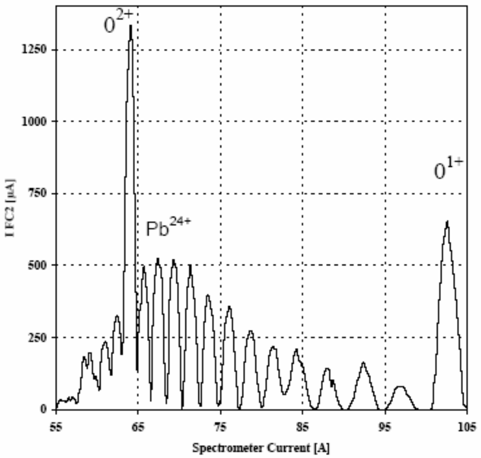


Fig. 6 :typical lead AFG spectrum of PHOENIX 28 GHz.

Ta, LIS

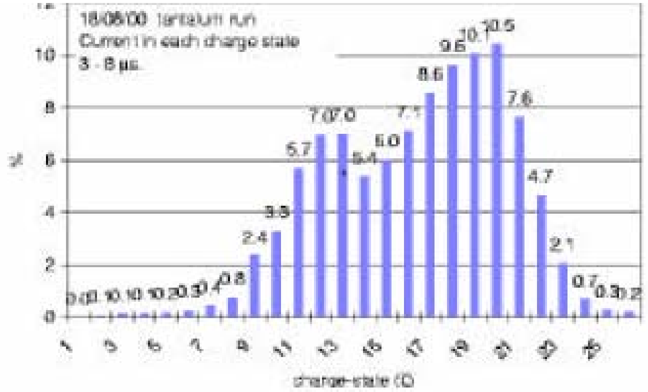


Figure 3 Charge-state distribution used for simulations.

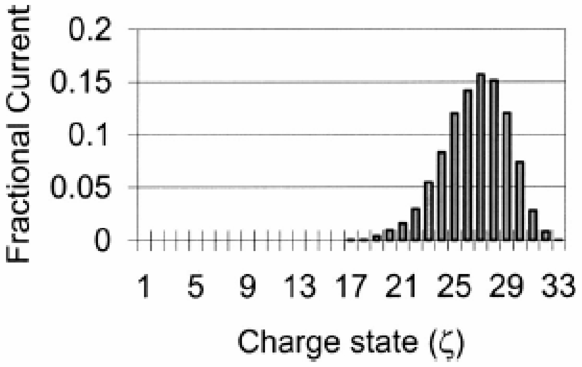
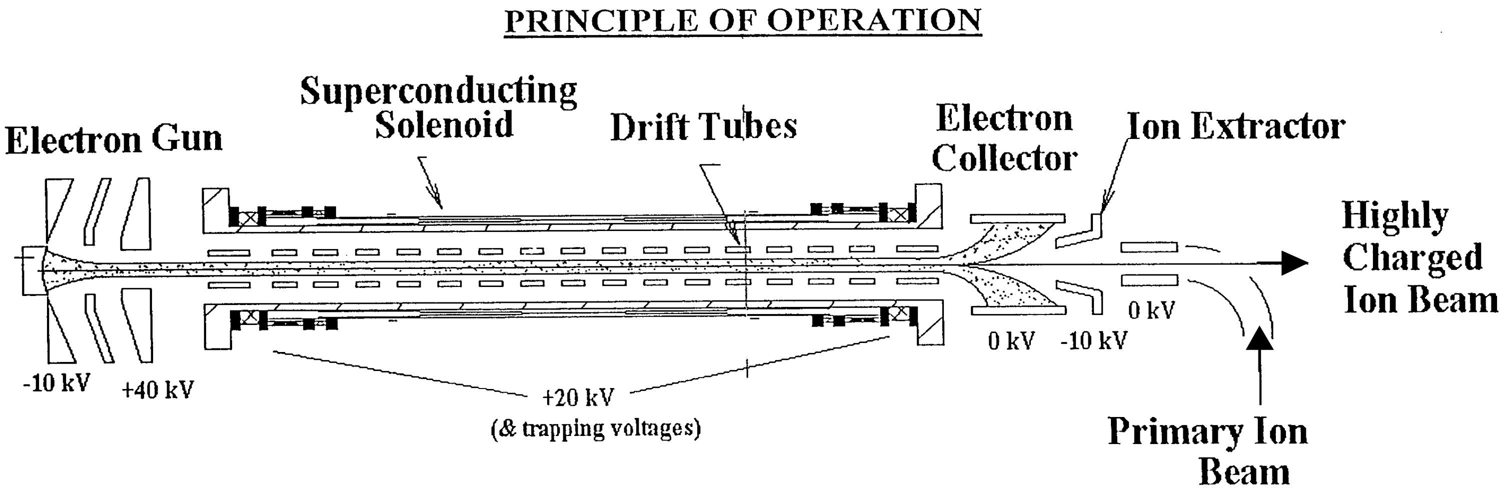


FIG. 8. Charge state distribution of Pb ions for laser power density at the target 3×10^{13} W/cm^2.

EBIS



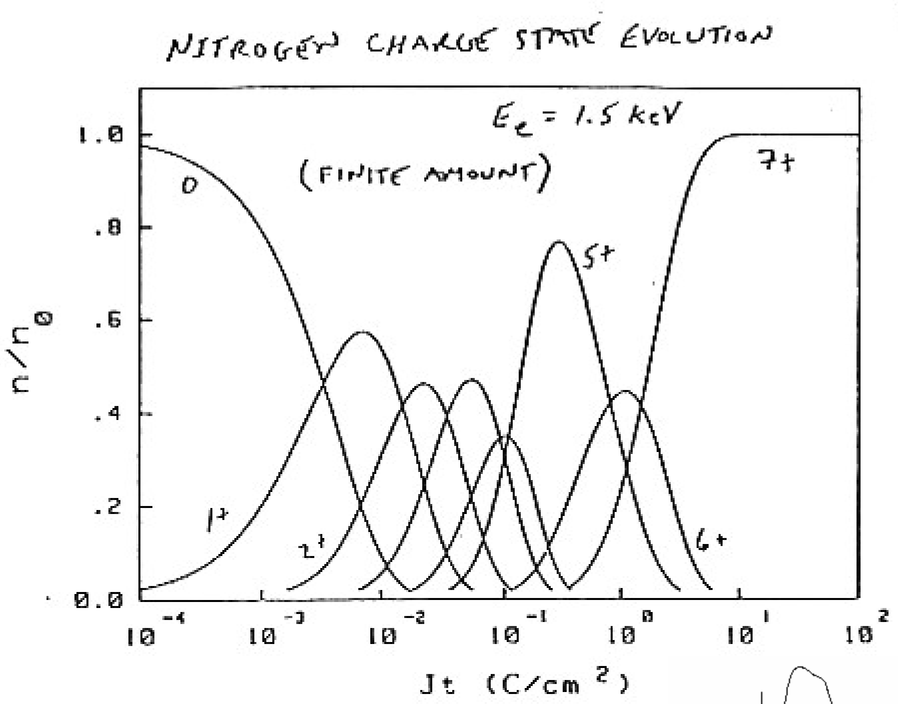
Yield of ions in charge state q:

$$N_q = \frac{I_e \times L}{q \times \sqrt{V_e}} \times K_1 \times K_2$$

I_e=electron beam current	V_e=electron beam voltage	L=trap length
K_1=neutralization factor	K_2=fraction in desired charge state	

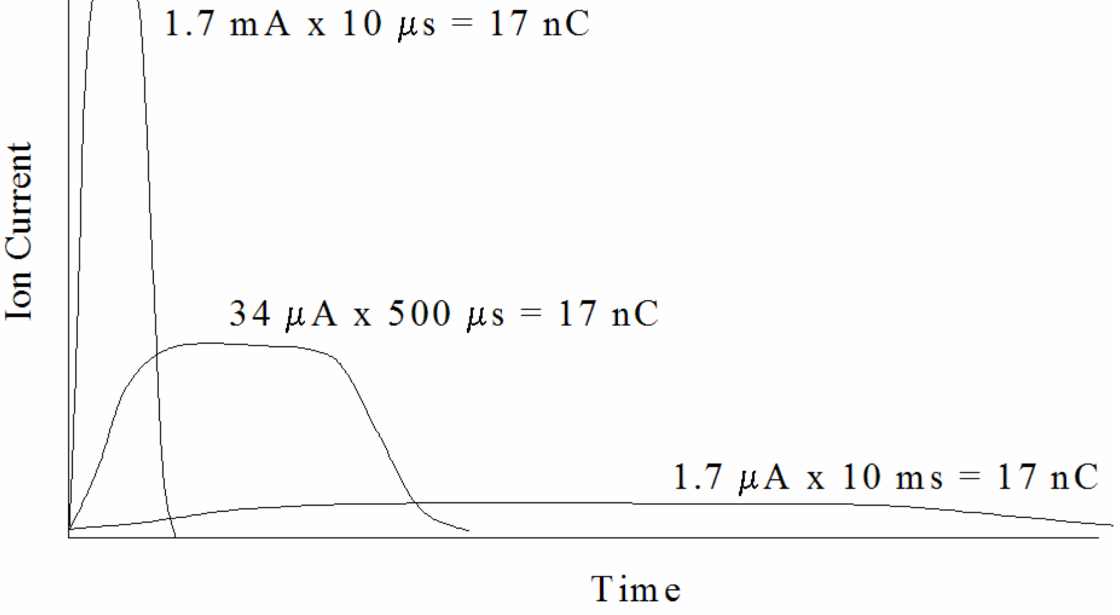
Radial trapping of ions by the space charge of the electron beam.
Axial trapping by applied electrode electrostatic potentials.

Ion output per pulse is proportional to the trap length and electron current.
Ion charge state increases with increasing confinement time.
Charge per pulse (or electrical current) ~ independent of species or charge state!

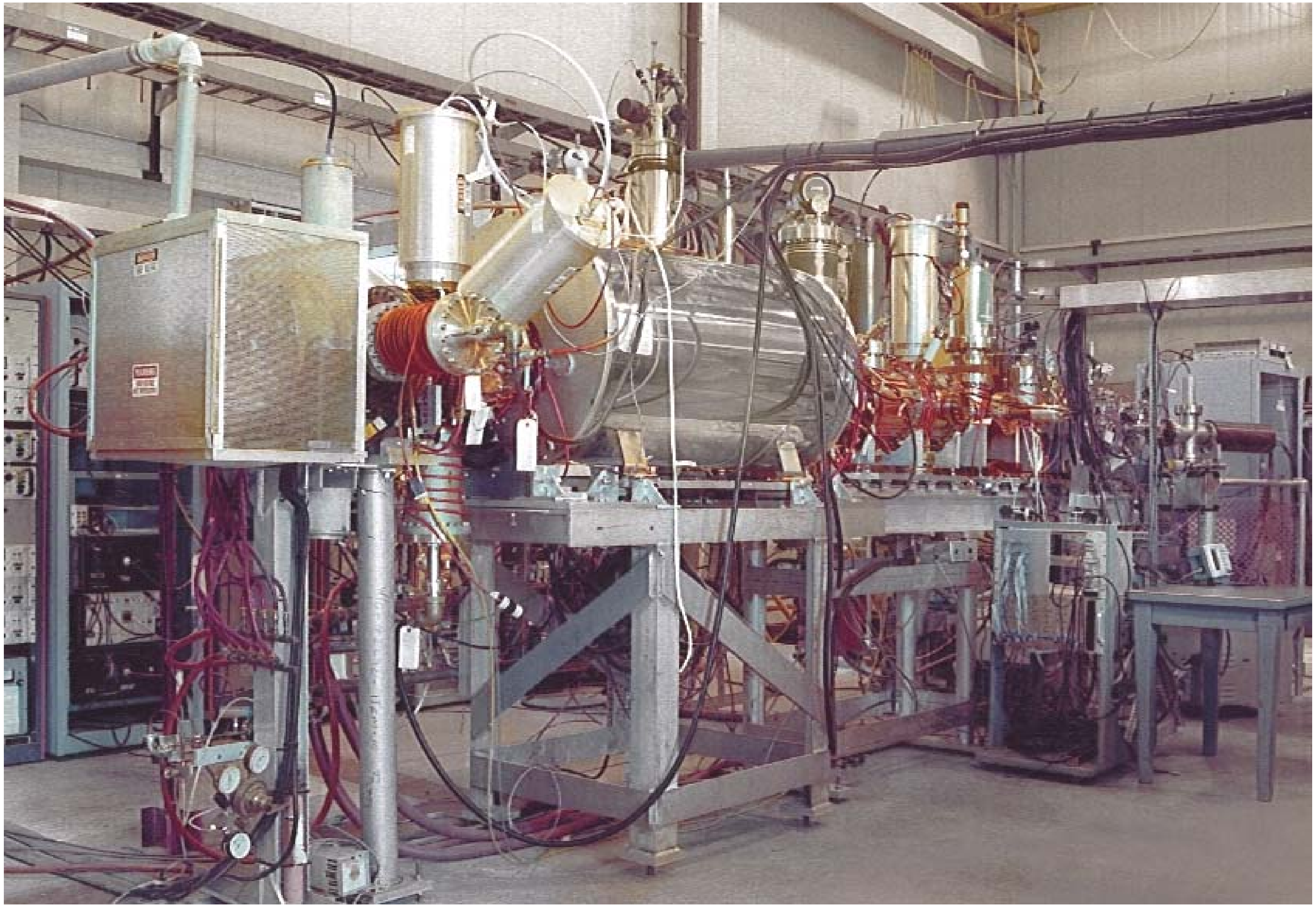


Charge state is selected by choosing the confinement time of ions in the trap

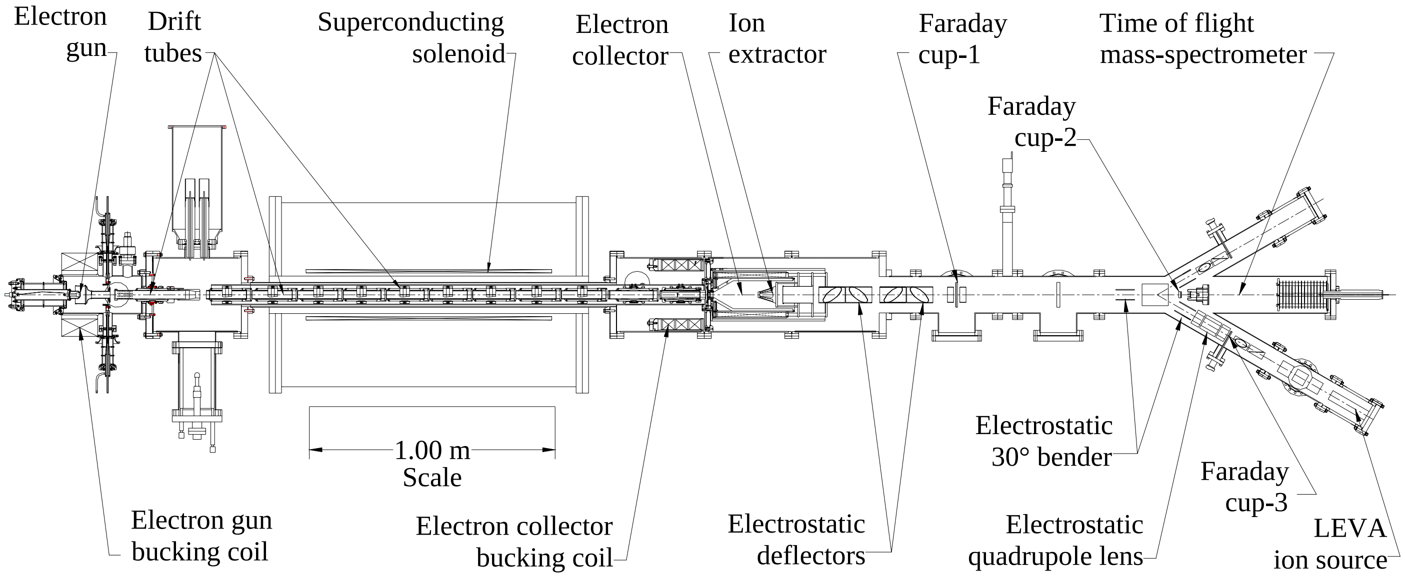
Ions are extracted from an EBIS in pulses of <u>constant charge</u>; one has control over the pulse width



EBIS Test Stand

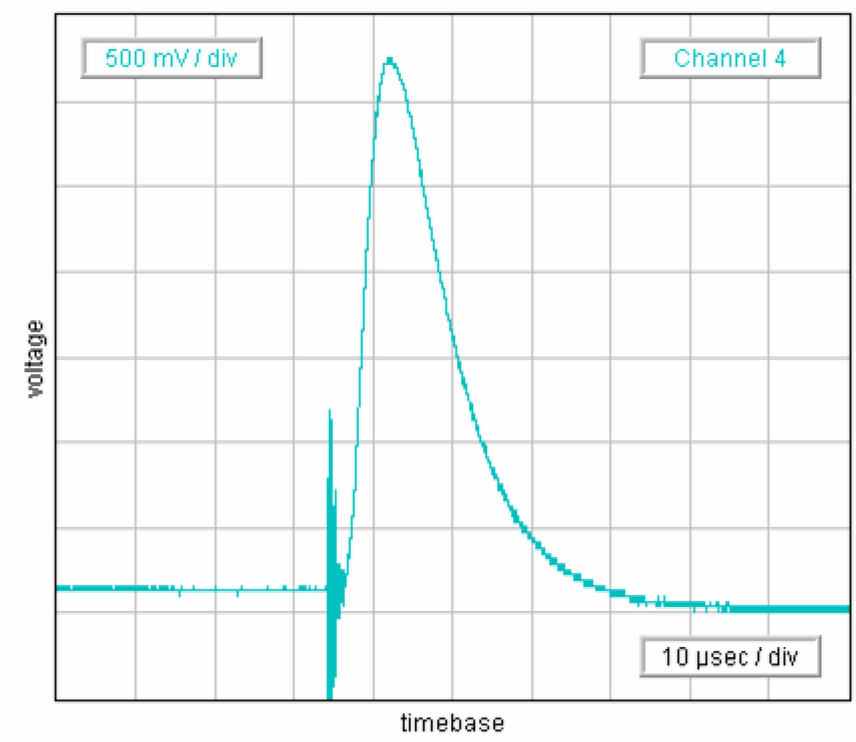


Results from Test EBIS (½ of RHIC EBIS)



	RHIC Requirements	Achieved
E-beam current	**10 A**	**10 A**
E-beam energy	**20 keV**	**20 keV**
Yield of pos. charges	**5.5 × 10^{11} (Au, 10 A, 1.5m)**	**3.2 × 10^{11} (Au, 8 A, 0.7m)**
Pulse length	**≤ 40 μs**	**20 μs**
Yield of Au^{33+}	**3.4 × 10^{9}**	**> 1.5 × 10^{9}**

Fast Extraction of Ions from the EBTS
(for single turn injection into Booster)

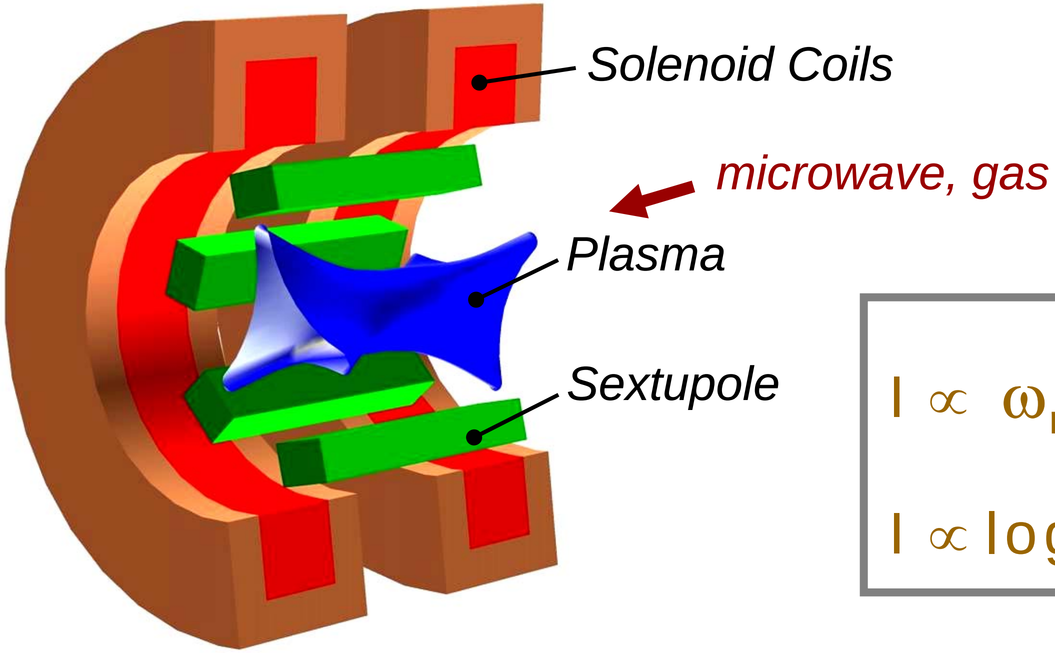


A 3.2mA, 12μs FWHM, (40nC) ion pulse was obtained at the source exit toroid using a 6.8A e-beam and Au external ion injection, after a 15ms confinement. (85 nC required for RHIC)

Faster extraction has been obtained earlier by applying a gradient to the well floor during extraction. In the future, the pulse shape will be tailored by applying an appropriate voltage pulse to the well.

ECR

$$\omega_e = \frac{B}{q \cdot m} = \omega_{rf}$$



ion extraction

D. Leitner, LBL

$$I \propto \omega_{rf}^{2} M^{-1}$$

$$I \propto \log B^{1.5}$$

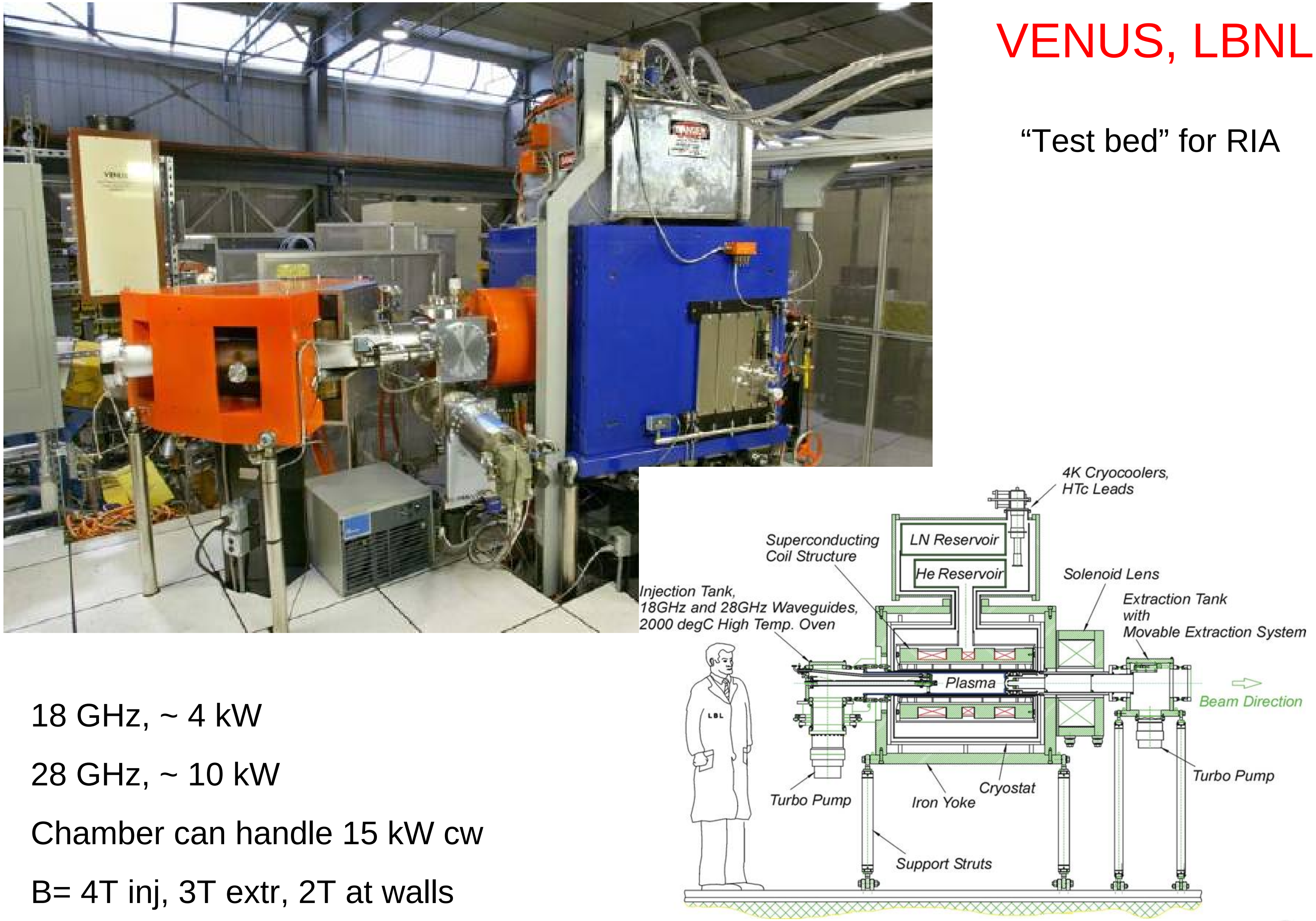
Solenoid = mirror confinement; sextupole = cusp; minimum-B in center

For high Q, want to increase electron energy and ion confinement, and keep pressure low to minimize recombination.

Afterglow – sometimes an enhanced intensity right after rf power turned off (electrons leave plasma, causing ions to leave faster)

VENUS, LBNL

“Test bed” for RIA



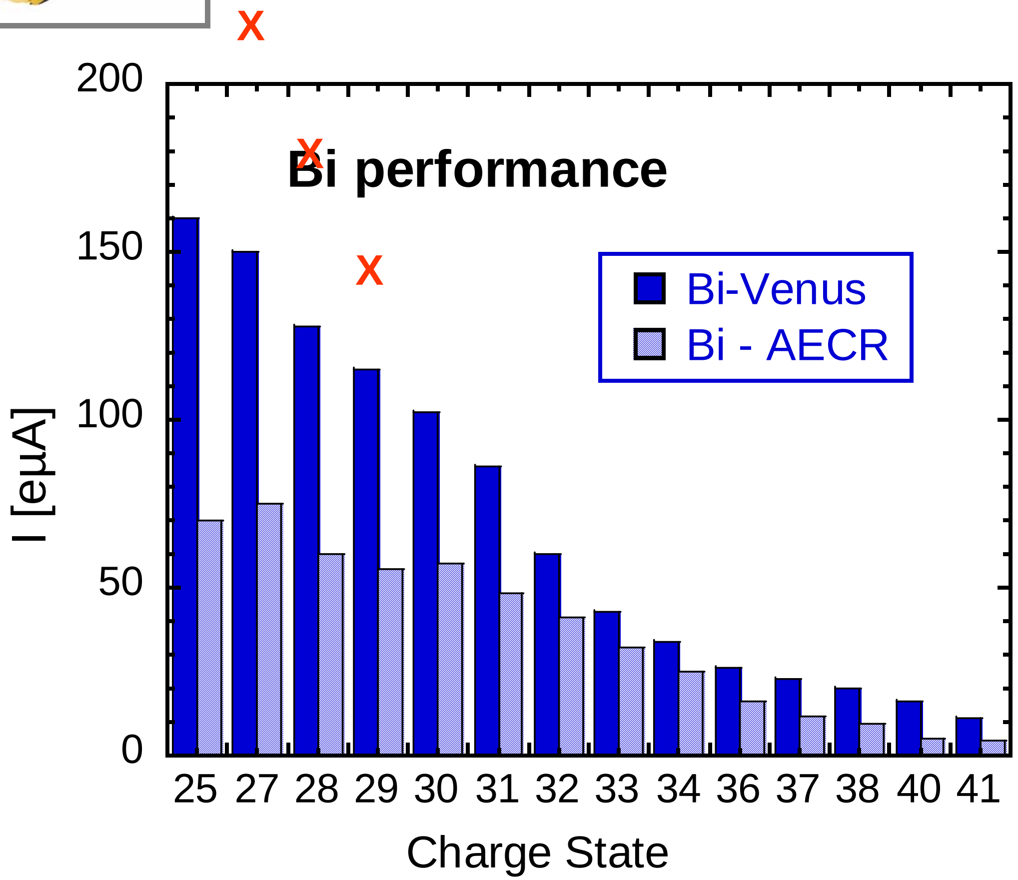
18 GHz, ~ 4 kW

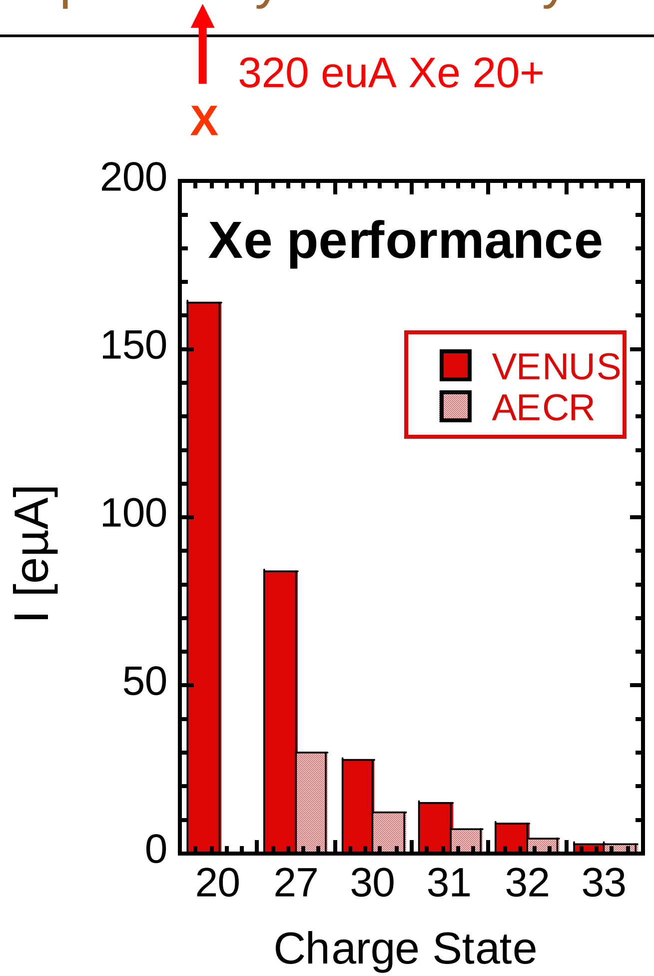
28 GHz, ~ 10 kW

Chamber can handle 15 kW cw

B= 4T inj, 3T extr, 2T at walls

Venus at 18 GHz outperforms AECR-U especially for heavy ions





Additional performance enhancement can be expected at 28 GHz Operation, 28 GHz Gyrotron is expected to arrive at LBNL in April 2004

X = initial 28 GHz results

1468 Rev. Sci. Instrum., Vol. 75, No. 5, May 2004

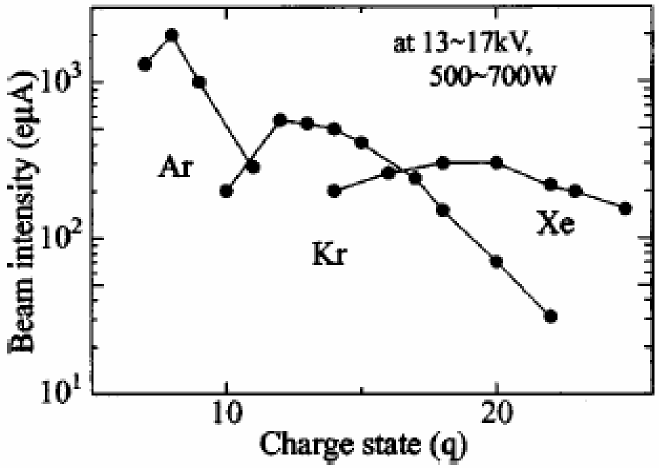


FIG. 2. Beam intensity of the Ar, Kr, and Xe ions produced from the RIKEN 18 GHz ECRIS.

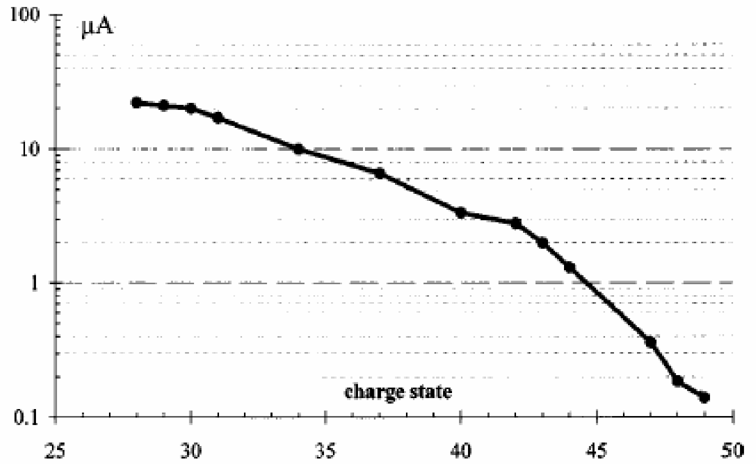


FIG. 3. Typical tantalum beam intensities obtained with the sputtering technique (GTS 18 GHz).

Hitz, et.al., Grenoble, ICIS’03

Xe, various sources
(Gammino, RSI)

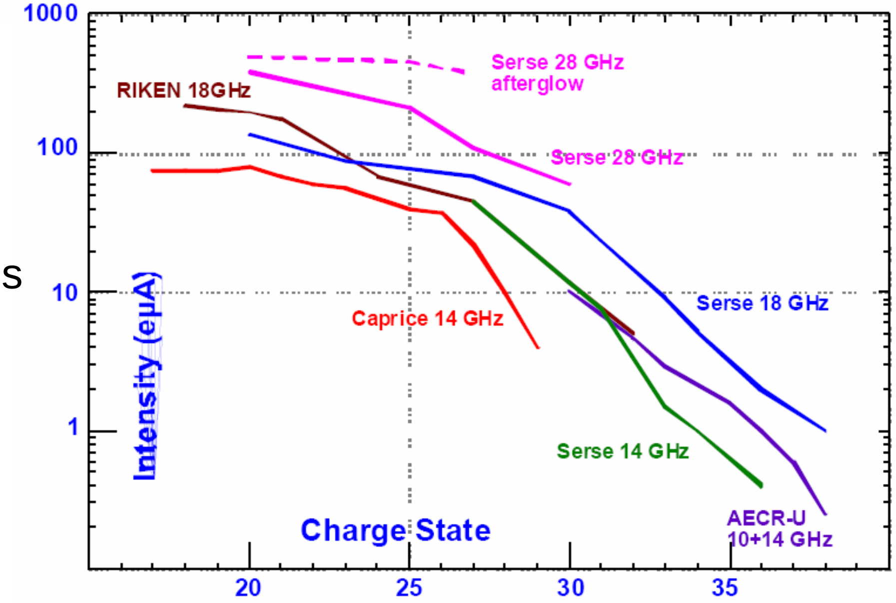


FIG. 14 : Extracted Intensities of Xenon ions for Serse at different frequencies and for other ECRIS.

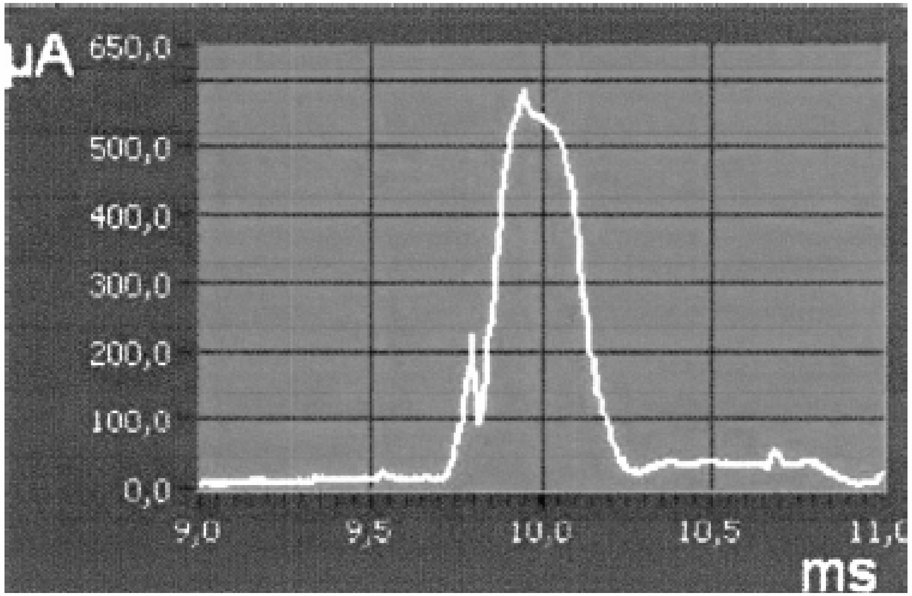


FIG. 2. Typical afterglow of very heavy ions (Pb^{27+} with PHOENIX 28 GHz).

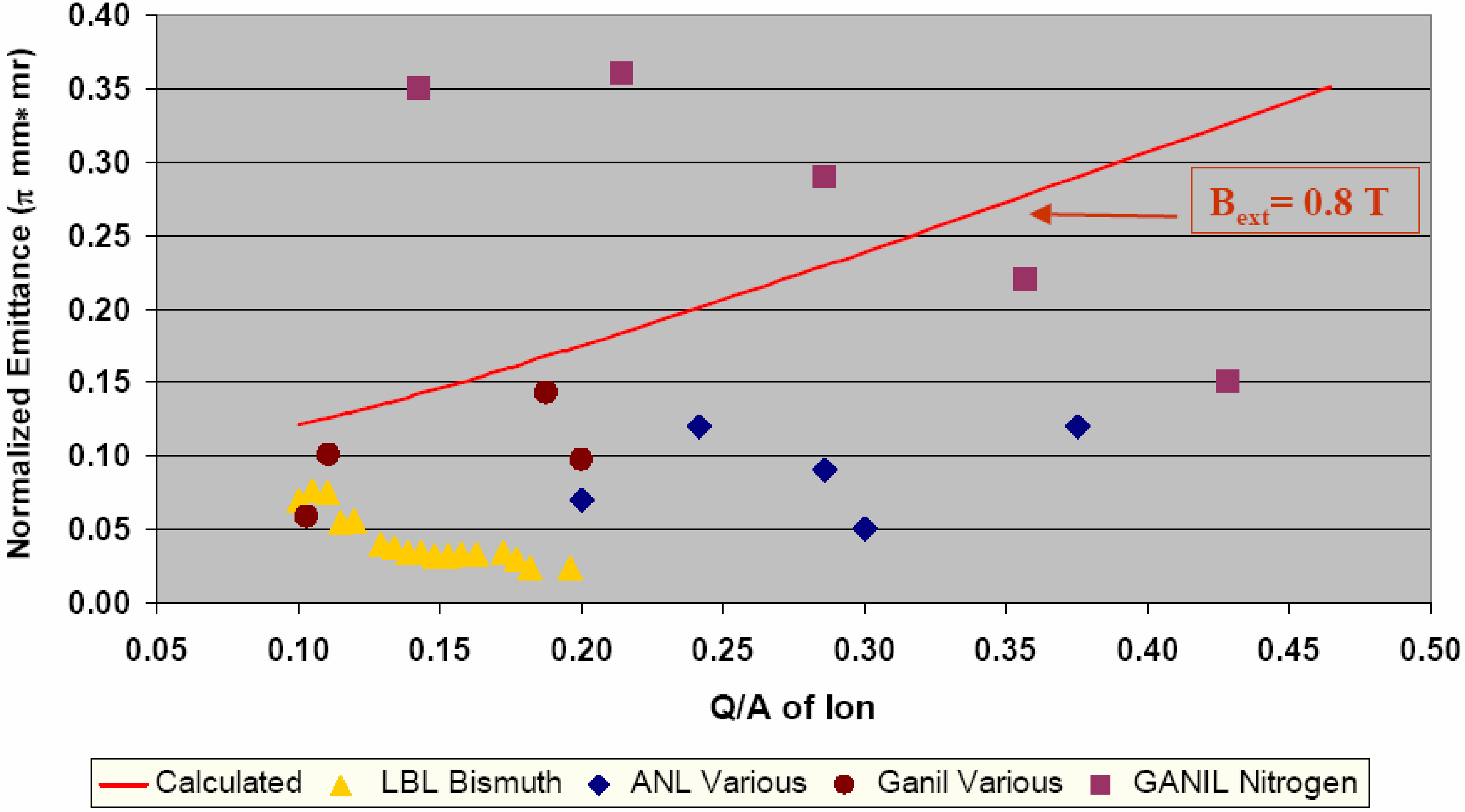
Phoenix 28 GHz

Pb 27+ in afterglow

Sortais, et.al, Grenoble, ICIS'03.

R. Pardo

ECR Beam Emittance Compared to Expected Minimum



LIS

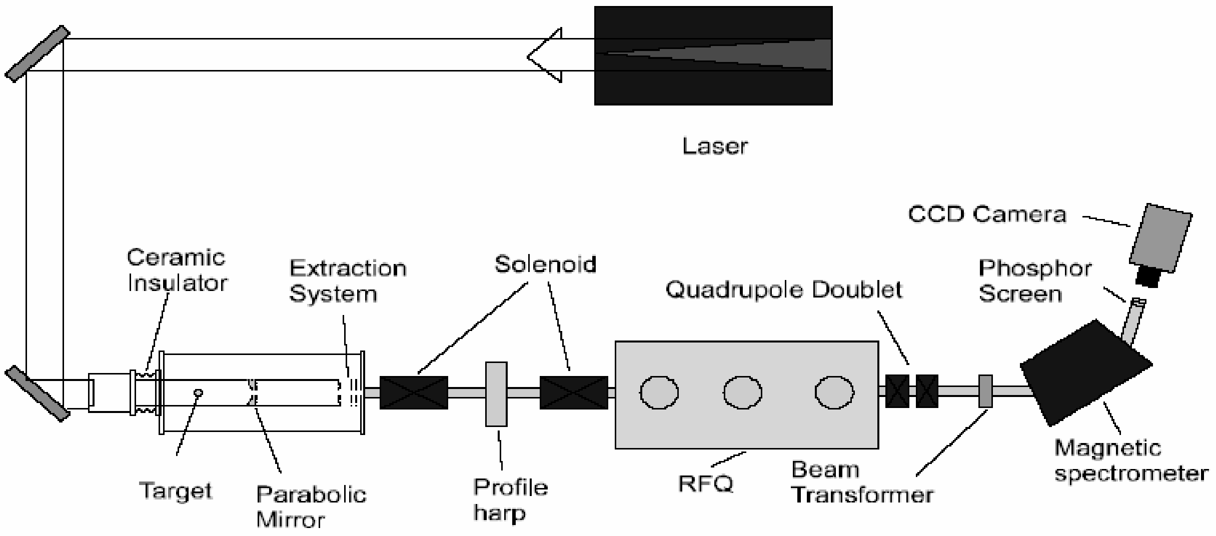


Figure 1: Scheme of the CERN Laser Ion Source

Laser, focused onto solid target, causes evaporation of target material.

Electrons in the gas absorb laser energy (inverse Bremsstrahlung), causing their energy to increase. (electron temperature increases with laser power density and wavelength)

Plasma forms, rapidly expanding normal to the target.
Plasma ions are stepwise ionized to high charge states.

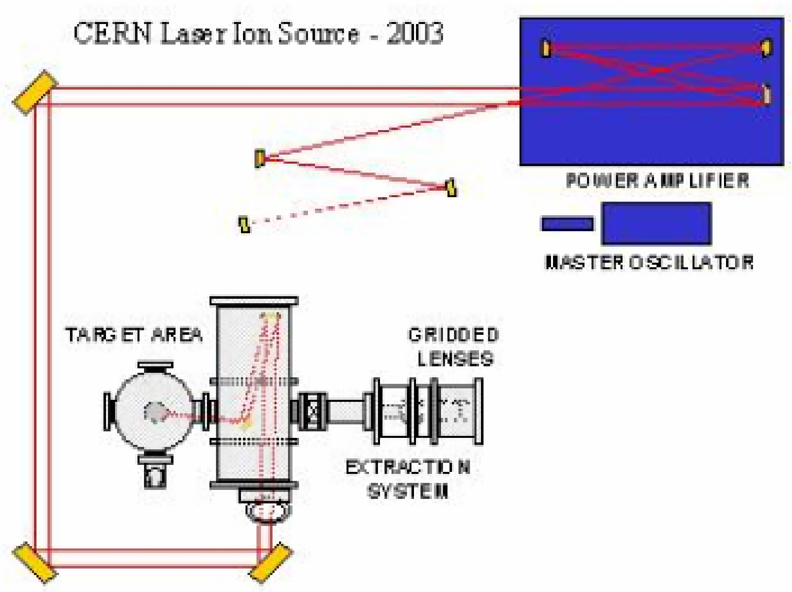


Figure 5. Layout of the Laser Ion Source experiment at CERN.

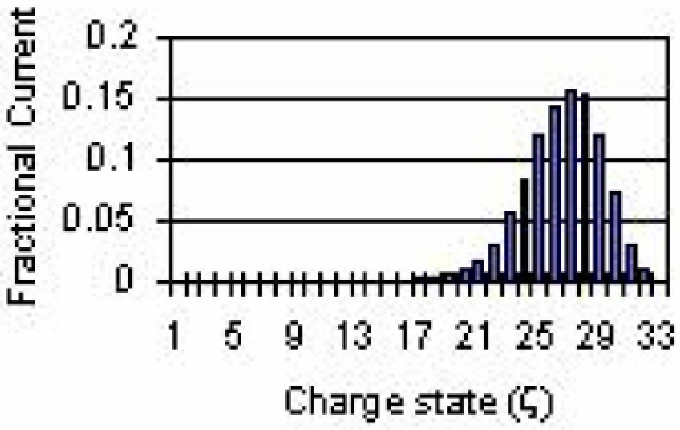


Figure 6: Charge state distribution of Pb ions for laser power density at the target $3 \bullet 10^{13}$ W/cm^2.

~ 3 emA Pb 27+
(20 emA total current)
105 kV extraction

Now being developed
for ITEP-TWAC.


REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 75, NUMBER 5

Laser ion source based on a 100 J/1 Hz CO$_2$-laser system

A. Balabaev, S. Kondrashev,[a] K. Konukov, A. Lozhkin, B. Sharkov, and A. Shumshurov
Institute for Theoretical and Experimental Physics (ITEP), 117259, B. Cheremushkinskaya 25, Moscow, Russia

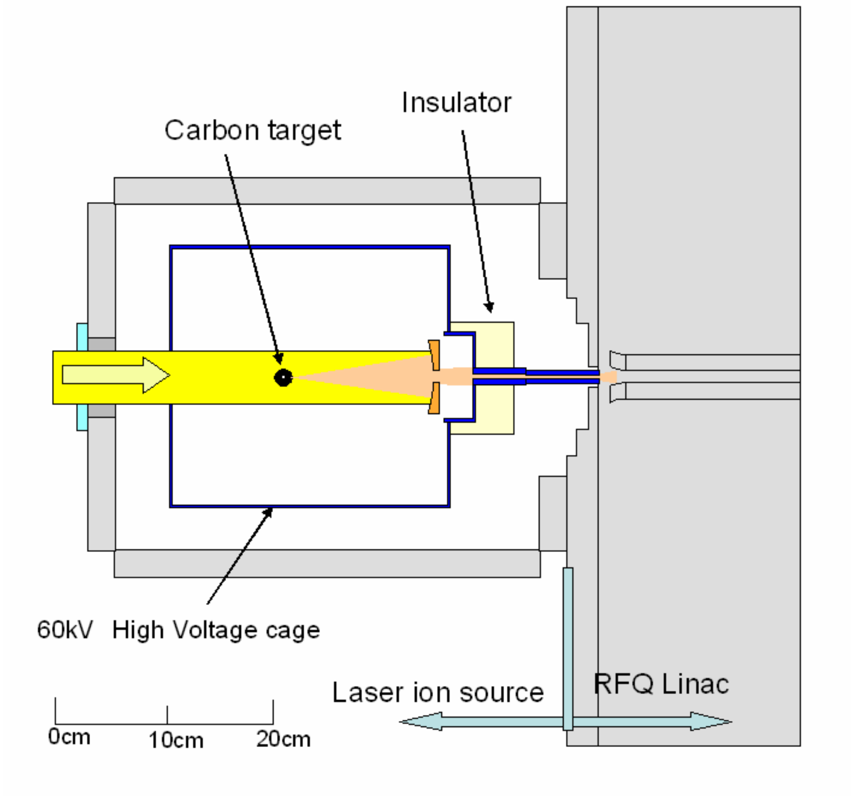
A. Charushin, K. Makarov, Yu. Satov, and Yu. Smakovskii
TRINITI, Troitsk, Moscow region, Russia

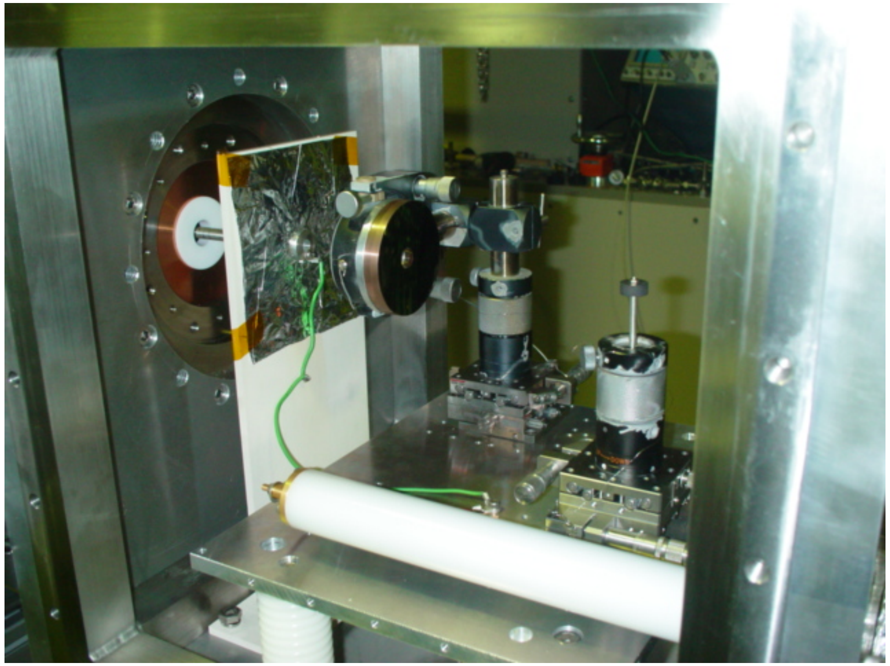
O. Camut, J. Chamings, H. Kugler, and R. Scrivens
CERN, Geneva, Switzerland

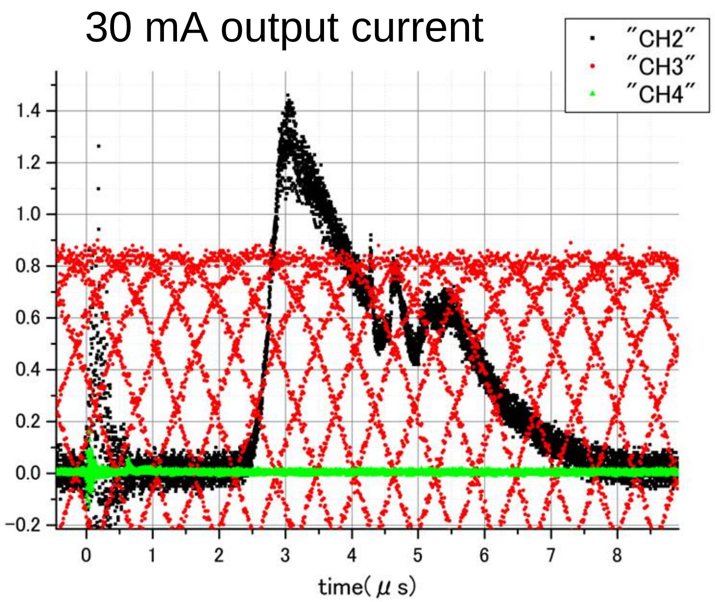
(Presented on 9 September 2003; published 17 May 2004)

EPAC'04 – longest achieved operational time for laser at 1 Hz was 75 minutes. Also observed damage to optical elements during the tests.

Kashiwagi, et.al.
Tokyo Inst. Tech.; RIKEN; ITEP







Now reporting more than 50 mA through the RFQ.

Carbon (mostly 4+) through the RFQ, with no "LEBT"

Only using a 400 mJ Nd-YAG laser

EBIS

Features, advantages

Easily produces the highest charge states

Narrow charge state distribution; typically 20% in desired Q

Produces beams of any species; intensity independent of species; can switch species pulse-to-pulse

One can control the pulse width (fixed charge/pulse)

Technologies

Electron gun (typ. 0.1A-1A, BNL 10-20A)
Electron collector (design for 15A * 15 kV = 225 kW; 50 ms* 5Hz = 25% df, to dc)
SC solenoid (5T, 8" bore, 1-2 m long)
Feeding of the trap (external injection, multiple sources feeding)
UHV (10^{-9} to 10^{-10} Torr)
Modern control system (makes operation stable, reproducible, increased flexibility)

Questions, issues?

Instabilities at high currents? (not seen at BNL)

Not much operating experience at high currents

Energy spread of fast-extracted ions

ECR

Features, advantages

~ the only choice for high current, high Q, dc applications

Reliable; lots of operating ECRs, lots of experience

Technologies

SC magnets; At high freq's, need SC sol and SC hexapole

28 GHz VENUS - 4 T injection field, 2 T hexapole at plasma chamber

RF power source - 28 GHz gyrotron, 10-15 kW; plus sometimes multiple frequencies

Questions, issues?

Broad charge state distribution, so one has to extract & transport a high total current

Performance depends on species, favoring gases and low melting point solids

“Memory” effects, slower beam switching times

LIS

Features, advantages

Produces high currents, short pulses

Technologies

High power laser – 100 J, CO_2, 15-30 ns
Optics
Targets – 3 x 10^{13} W/cm^2 on the target

Questions, issues?

Laser reliability, rep rate

Pulse-to-pulse current fluctuations

Target erosion; coating of optics by target material

Species ~ limited to solid targets, high melting point solids are best

Comment (qualitative) ….

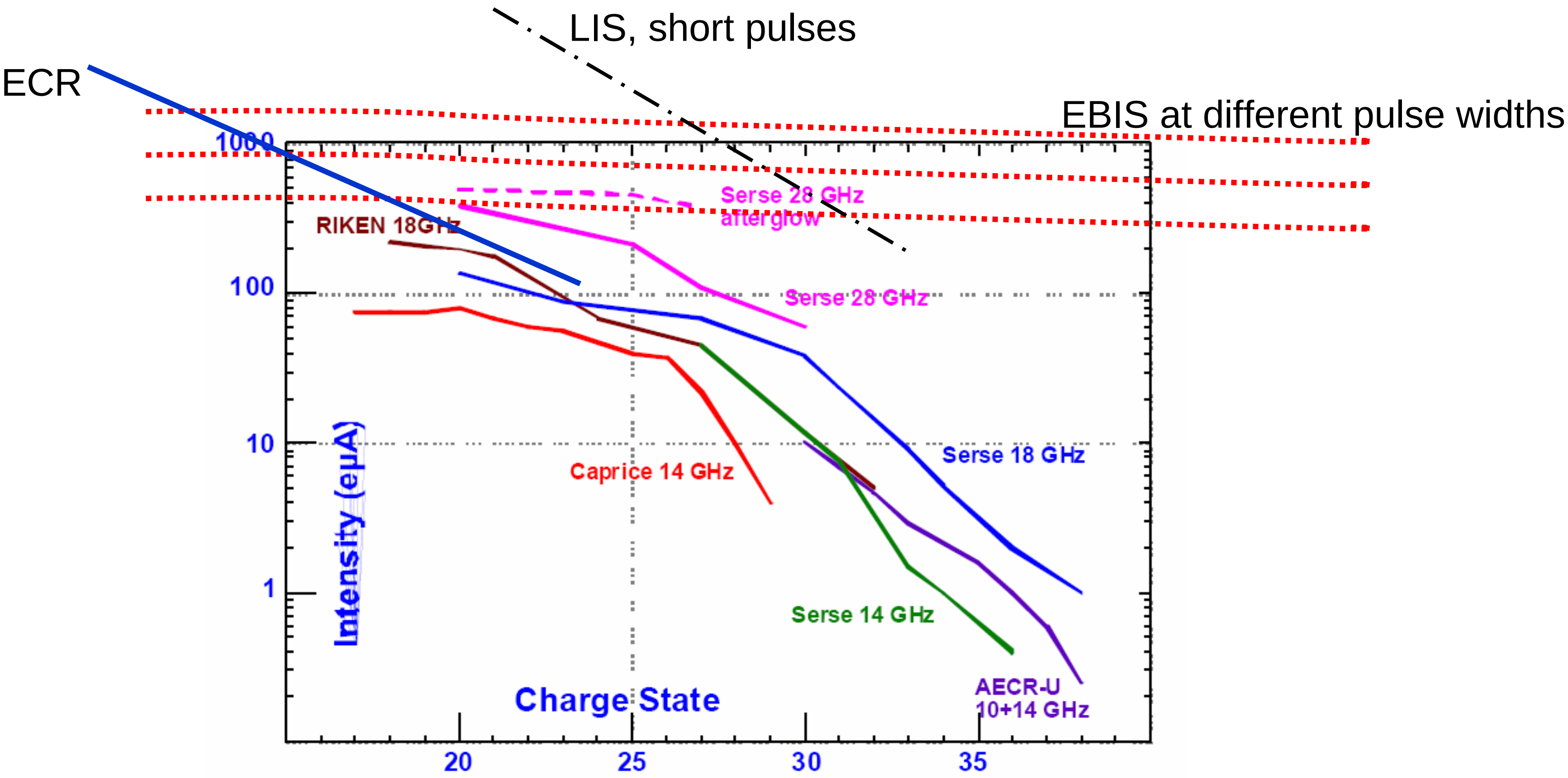


FIG. 14 : Extracted Intensities of Xenon ions for Serse at different frequencies and for other ECRIS.

				Q/m	Peak current	Pulse width
EBIS	BNL	Au	32+	0.16	(~ 550 euA) ~ 8 nC	(~ 15 uS)
ECR	CERN, 14.5 GHz afterglow	Pb	27+	0.13	120 euA	~ 200 us
ECR	SERSE 28 GHz afterglow	Xe	25+	0.19	500 euA	> 200 us
ECR	PHOENIX 28 GHz afterglow	Pb	27+	0.13	~550 euA	~ 200 us
ECR	SERSE 28 GHz	Xe	27+	0.21	~ 100 euA	dc
ECR	VENUS	Xe	27+	0.20	120 euA	dc
ECR	VENUS	Bi	27+	0.13	220 euA	dc
ECR	CEA-GTS 18 GHz	Xe	27+	0.21	168 euA	
ECR	RIKEN 18 GHz	Xe	20+	0.15	300 euA	dc
LIS	CERN	Pb	27+	0.13	~ 3 emA	?

Future developments

Reflex EBIS (Donets, Dubna) - used at JINR on Nucleotron in June '02 and June '03 runs to produce N6+ (300 uA), N7+ (350 uA), Ar16+ (200 uA), Fe24+ (150 uA)
8 uS pulses (1-turn)
Only 5-6.5 mA electron current ! (effective 50 x reflection); only 2% beam power
Fe was 1.1 sec confinement
Effective Je=150-200 A/cm2
Report good stability over 4 weeks of running.
Accelerated to 1 GeV/amu

Use LIS to feed ECR – ECLISSE (Prague, Catania, …)

Electron beam to enhance ECR charge state

Variations of MeVVA: eMeVVA, Z-MeVVA, MeVVA-M

Final thoughts….

Heavy ion sources – developments needed to reach RHIC, LHC and RIA goals, but seem to be within reach.

Different sources are better fits to different applications

RIA = ECR (dc)
RHIC = EBIS (any species, fast switching)
LHC, Medical – all 3 source types seem to be candidates

Although not covered here, as currents are increasing, transport of these beams is becoming difficult, due to space charge.