Recent Developments in Hadron Sources

Jim Alessi
Collider-Accelerator Department
Brookhaven National Laboratory

H+; H-
Polarized H-
Low-to-high charge state positive heavy ions

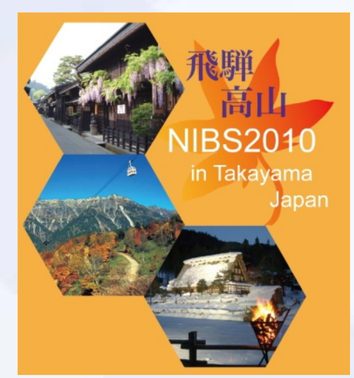
The field of ion sources is very active, so there are many conferences, workshops, symposia, etc. devoted to sources

- 14th International Conference on Ion Sources, next week in Sicily
- 19th International Workshop on ECR Ion Sources, Grenoble, 2010
- International Symposium on Negative Ions, Beams and Sources, Takayama, Japan, 2010

also for polarized ion sources, laser ion sources, etc.

I will only be able to touch on a few types of sources, but hopefully this will give you a general feel for where things stand for producing some of the different types of ions.

Most active now are probably ECR and H- ion sources, but there have been big advances in other type source as well.



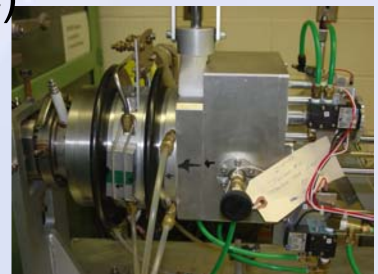
My bias....

within the BNL Preinjector Group there are four type sources in use,

EBIS (Heavy Ion Linac)

Au^{32+}, Fe^{20+}, He, U, etc.

Cs sputter (Tandem)

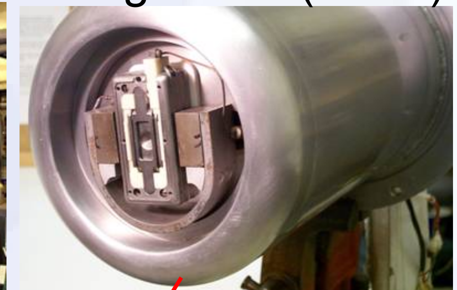


Au-, Fe-, etc.

OPPIS (Linac)

$\vec{H}$-

Magnetron (Linac)



H-

Single Event Upset

Relativistic Heavy Ion Collider

NASA Space Radiation Lab

Brookhaven Linac Isotope Producer

Plus R&D on a 5th type (laser ion source)

Proton sources

Quite a few new applications….

FAIR –	70 mA,	short pulse	4Hz,
PEFP –	20mA,	2ms,	120 Hz
ESS –	60 mA,	2 ms;	20 Hz
SPIRAL2 –	5 mA,	DC **(p/D)**	
IFMIF -	140 mA	DC (**D**)	

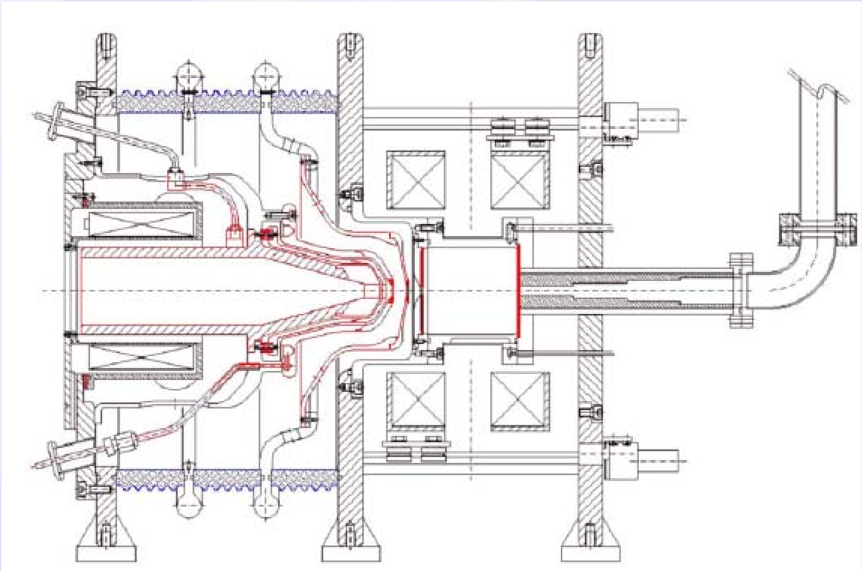
The duoplasmatron is still used, and is a good choice for some applications,
(ex. INR RAS - 50-120 mA, 50 Hz, 200 μs; 1500 hrs without any failure)

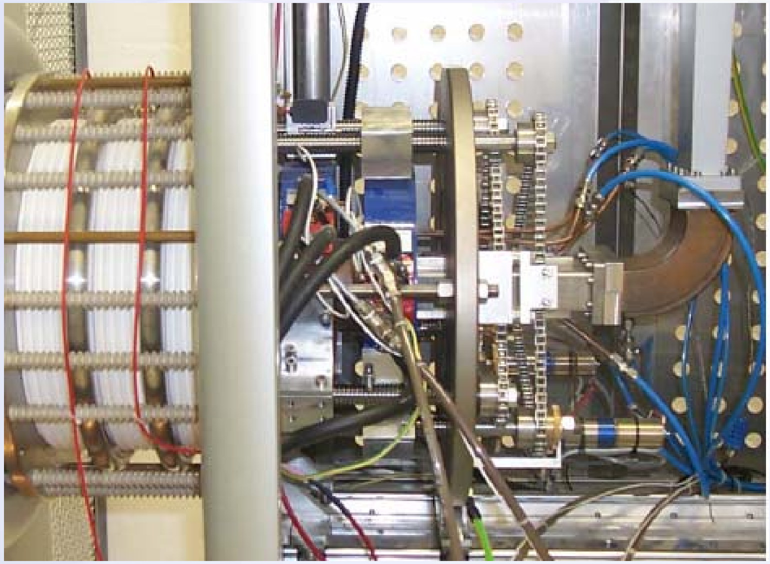
The **ECR (microwave)** proton source is used in almost all new applications
"ECR" vs. "microwave" depending whether one operates on of off resonance, but it is essentially the same source. (on resonance gives somewhat higher proton fraction, but the long term plasma stability can be worse)

Evolution ~ Chalk River, CEA Saclay (SILHI), used on LEDA (117 mA CW), ….

Versions have existed for more than 10 years which give DC current >100 mA (H and D)

Almost always operates at 2.45 GHz





SILHI ECR source (CEA, Saclay) - > 100 mA, 95 keV, CW or pulsed, routinely 130 mA H or D

> 80% H+ fraction (> 95% D+ fraction)

RMS normalized emittance < 0.2 pi mm mrad

7 day run, 114 mA +/- 0.2 mA

>100 mA/kW (more efficient than H- ion sources)

Also developments at other labs (INFN, Catania VIS source for ESS, etc.)

Very impressive performance. Usually the clear choice for H+

Beam transport and matching to the RFQ is the challenge for these high power beams.

CEA/SACLAY LIGHT ION SOURCES STATUS AND DEVELOPMENTS
R. Gobin*, et.al.; ECRIS 2010

H- Sources

Unlike H+ sources, not one clear choice here…

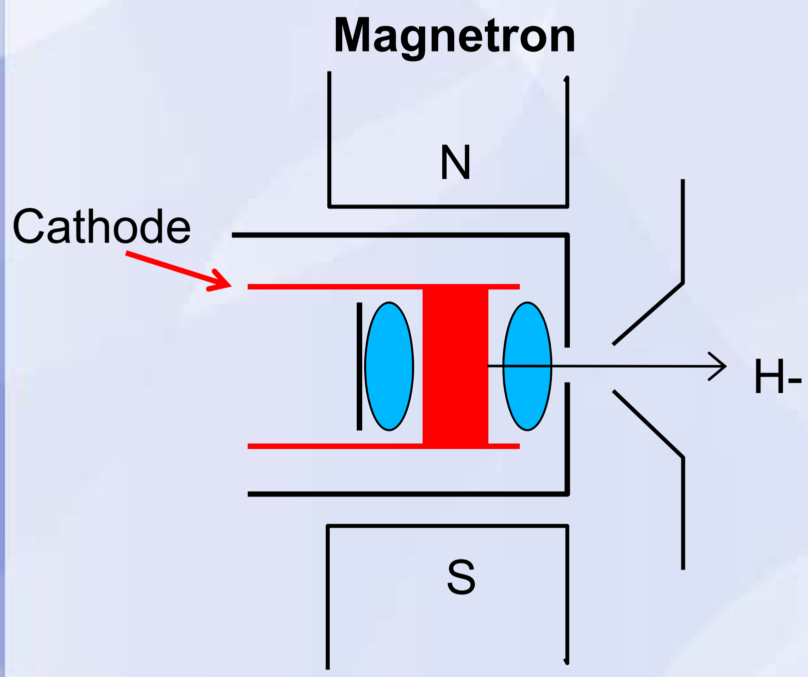
Surface production - surface-plasma sources (H- production on a low work function surface)
V. Dudnikov – Cs catalysis, in '72, was the major breakthrough for surface plasma sources.
These sources have been the "workhorses" for decades – BNL, FNAL, ISIS, DESY, etc.

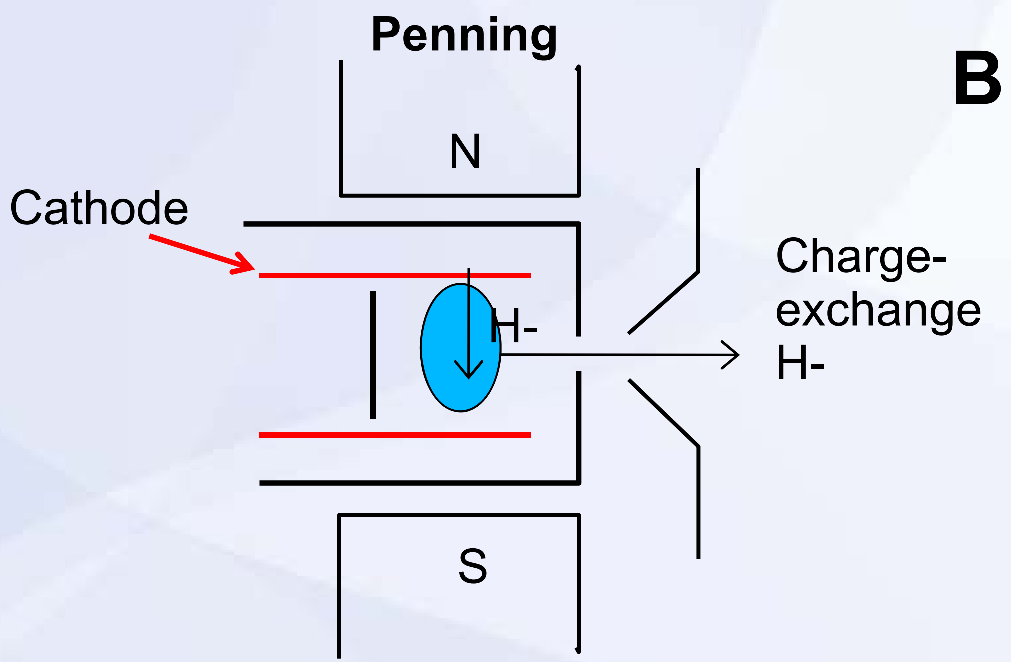
Volume production - In the '80's– discovery of H- production via dissociative attachment of vibrationally excited H_2 (M. Bacal) → production of H- without Cs

These sources have a **"driver region"** – plasma generation with high energy electrons to produce vibrationally excited molecules, and a **"filter field"** → vib molec and low energy electrons pass to the front of the source, but fast electrons don't. Here you have favorable conditions for H- ion production

These "volume" type sources have evolved….
Cs free → Cs "seeded" ; enhancement of surface production on the collar….
Filaments → rf (internal antenna) → external antenna → saddle antenna, etc.

Surface – plasma sources





Plasma produced by ExB motion of electrons

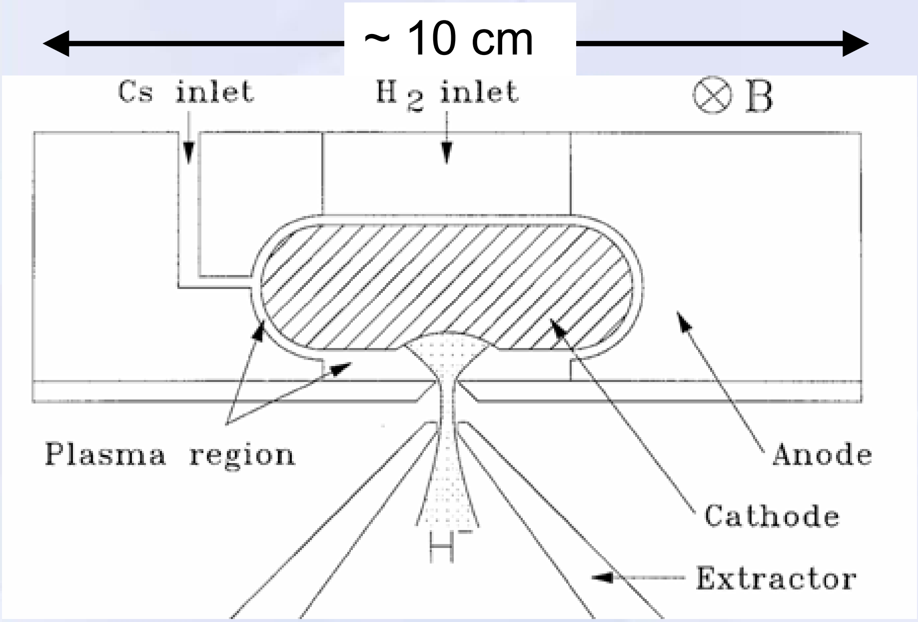
Surface-produced H- is directly extracted

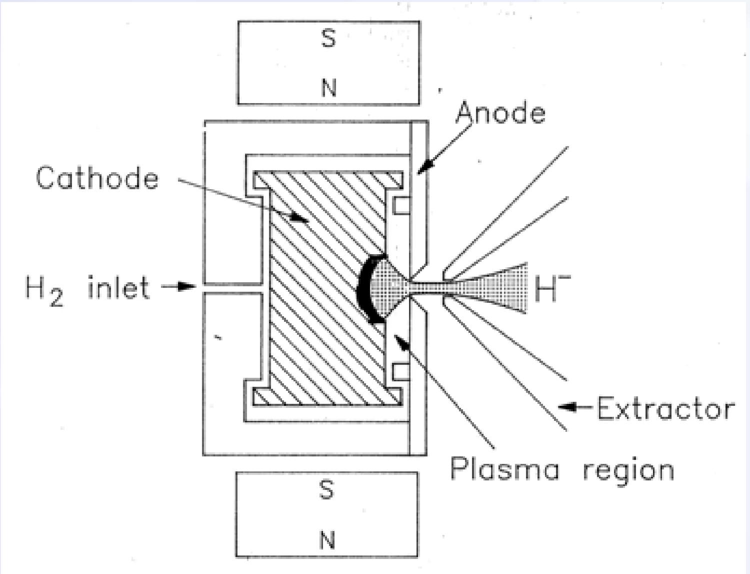
Plasma produced by electrons oscillating along the magnetic field, between two cathodes

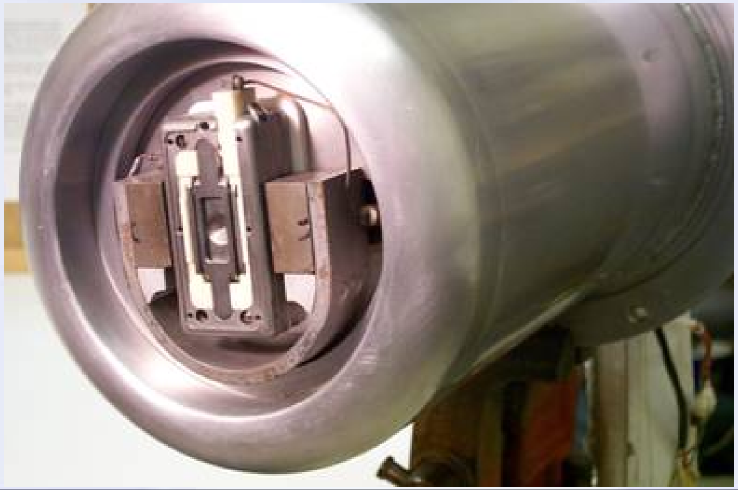
Charge-exchange H- is extracted
H- (surf) + H → H (surf) + H-

Magnetron H- Source (Invented in Novosibirsk; used at BNL, FNAL, ANL, DESY)

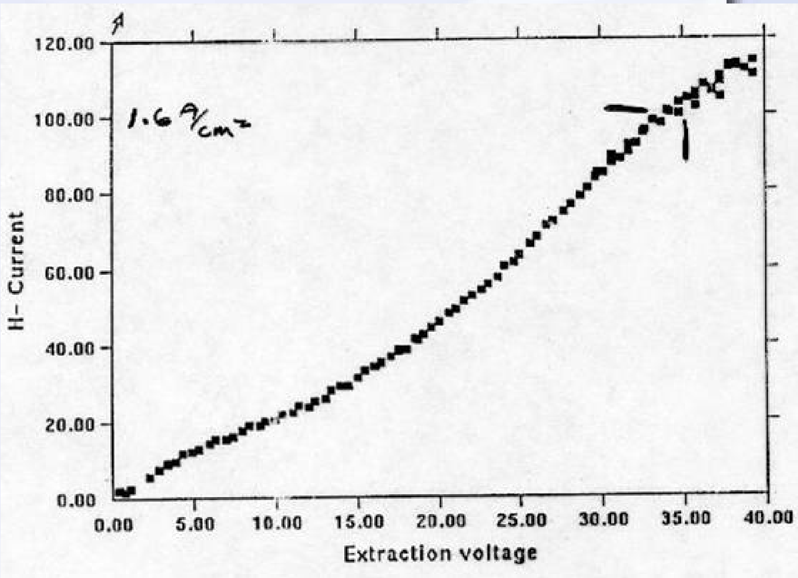
A source based on a version from C. Schmidt at FNAL has used at BNL for ~30 years, and > 20 years with circular aperture, injecting into an RFQ (2 solenoid LEBT)







Typical Running Parameters



H- current 90 - 100 mA (1.5 A/cm^2)
10A, 150V → 60 mA/kW!
(almost as good as H+ source)
Extraction 35 kV
e/H 0.5 - 1.0
Rep rate 6.7 Hz
Pulse width 700 μs
RMS emittance ~ 0.4 π mm mrad (normalized)
Cs consumption < 0.5 mg/hr (5 gm lasts >6-9 months)

Times between source maintenance are approximately 6 months continuous (3-9 months; almost always shutting down when program ends, rather than due to failure).

This type source is the "backup" choice for CERN Linac4

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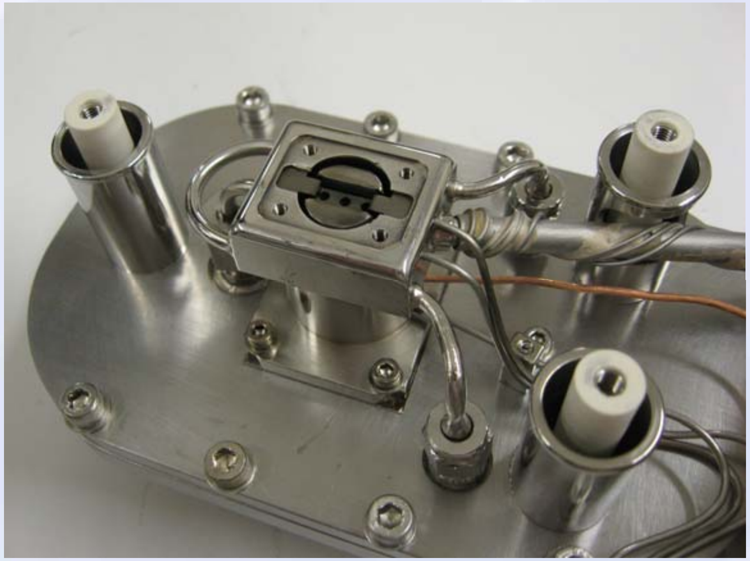
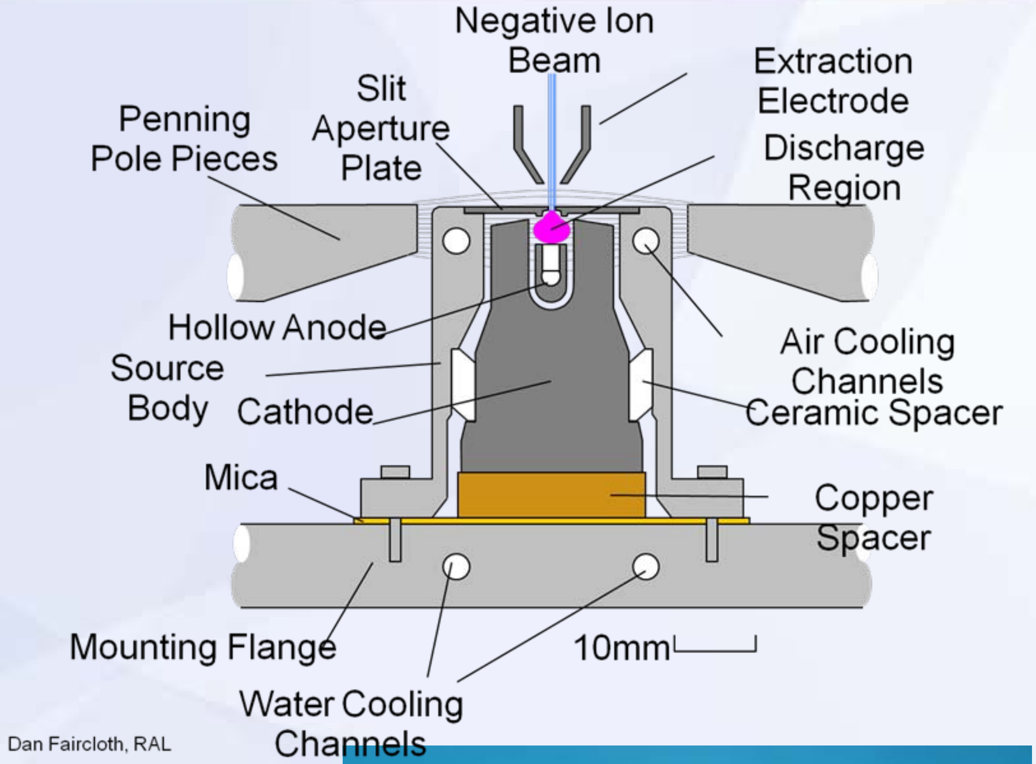
Penning SPS; RAL





D. Faircloth, RAL

The ISIS operational ion source routinely produces 55 mA of H^- ions during a 200-250 μs pulse at 50 Hz for uninterrupted periods of up to 50 days. The average lifetime of a source is about 21 days.

Discharge current	55 A
Discharge voltage	60-70 V
Discharge pulse length	**600 - 800 μs**
Repetition rate	**50 Hz**
Extraction voltage	17 kV
Extraction current	100 – 500 mA
Extraction pulse length	**200 - 250 μs**
Cesium oven temperature	160 - 190 °C
Cesium consumption	≈ 3 g/month
Hydrogen consumption	10 – 20 mL/min
H^- beam current at ground plane of post extraction acceleration gap	**50 – 55 mA**
H^- beam current at entrance to linac	**30 - 35 mA**

CSNS will also use this Penning – 20 mA, 25 Hz, 500 us, 50 kV

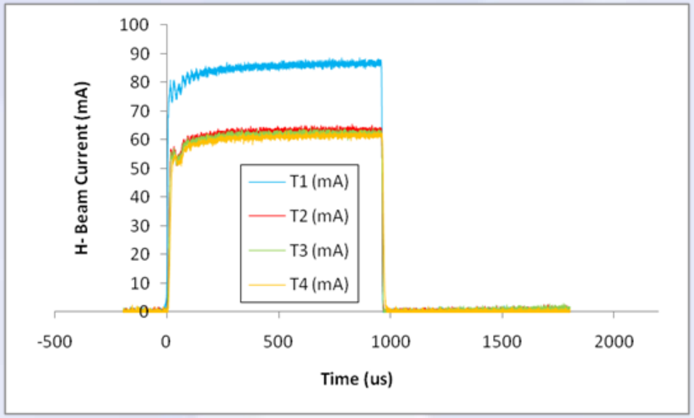
Front End Test Stand (FETS) – RAL

To demonstrate the production of a 60 mA, 2 ms, 50 Hz chopped H- beam at 3 MeV with sufficient beam quality for future applications.

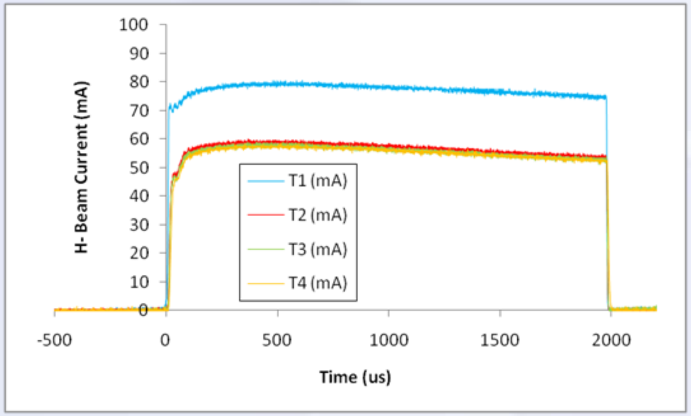
Desired current is routinely achieved
Emittances as low as 0.3-0.35 π mm mrad normalised rms)

Droop in H- current during the pulse has so far prevented achievement of the full specs (electrode surfaces don't stay at the optimum condition for H- production).

Possible solution is to increase the electrode surface area (reduce the surface power density)



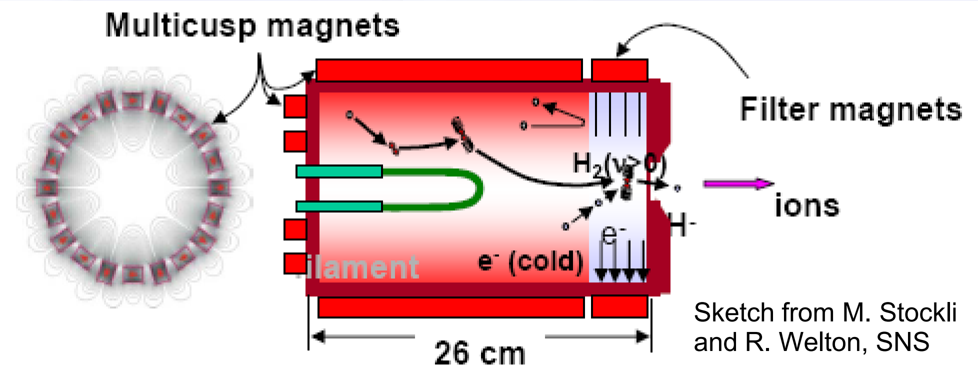
50 Hz 1 ms



25 Hz 2 ms

19.6 kV extraction voltage, 65 keV beam; T4~1.8 m from source

Volume H- Sources

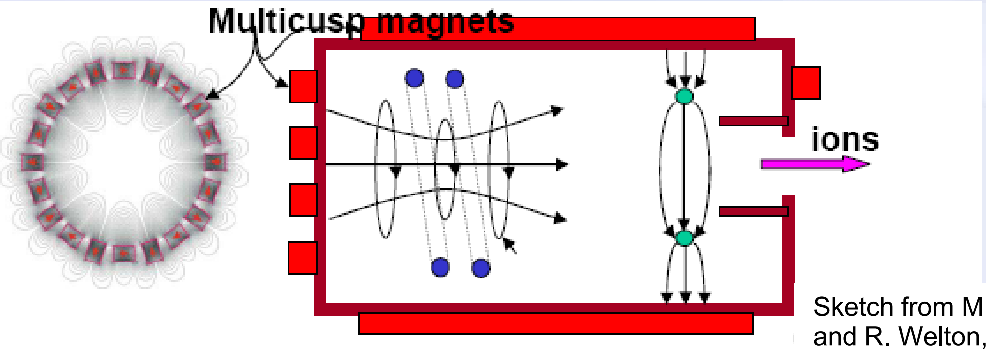


Sketch from M. Stockli and R. Welton, SNS

Filaments – ok for Cs-free sources, but output is low and electron current is high without Cs.

With Cs-seeding to get higher H- currents, filament material covers up the cesium monolayer → need to keep re-cesiating.

↓



Sketch from M. Stockli and R. Welton, SNS

RF-driven -
Cs is longer lasting, but now problems with antenna lifetime in the discharge

↓

So, ….antenna was moved outside the discharge (Peters, DESY). RF must now penetrate through ceramic wall.
Works well at low duty factor (DESY), but at high df, outgassing from the ceramic seems to poison the Cs, resulting in frequent recesiations……
(presumably, this will be solved…..)

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Some examples….

<u>TRIUMF</u> – W filaments, Cs-free, 6 mA **CW** (20 mA max), 600 hr lifetime

<u>J-PARC</u> – 36 mA, 25 Hz, 600 us;
Cs free (LaB_6 filament),
600 hr continuous run;

Need >60 mA for J-PARC final stage.
→ Cs will be essential

<u>On test bench:</u>
70 mA, Cs seeded, W filament
(~100 hr filament lifetime)

They are going to rf driven, for its lower Cs consumption and longer life.

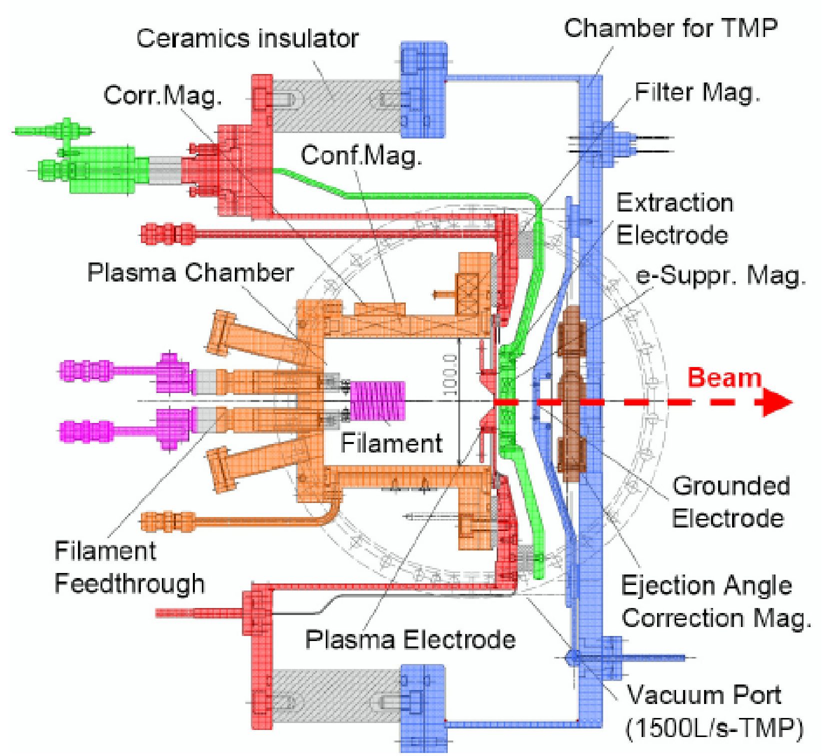


Figure 1: Cross-sectional view of the present J-PARC ion source.

SNS

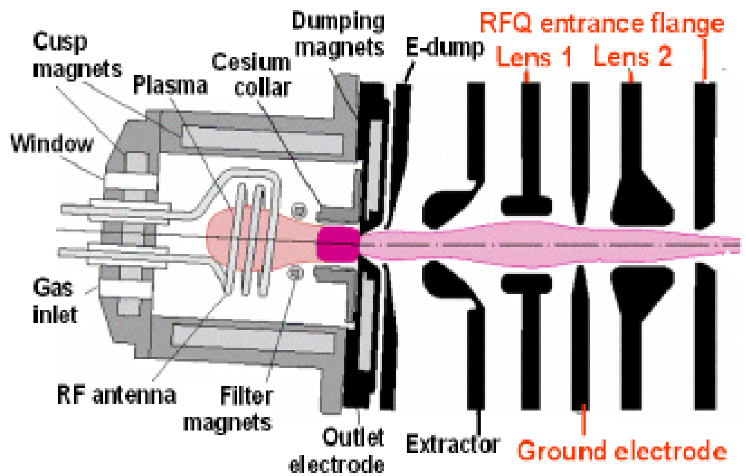


FIGURE 1. Schematic of the LBNL ion source and LEBT.

RF-driven, internal antenna
Cesiated
65 kV extraction
60 Hz rep rate, 5.4% df

Source service cycle ~4 weeks

Routinely achieves **~50 mA** and a ~99% availability.

Up to 5 weeks without noticing a degradation, and without adding Cs after the initial dose of ~5 mg.

Since 2008 about one antenna failure per ~20-week run causes ~8 hours of downtime.

External antenna source:

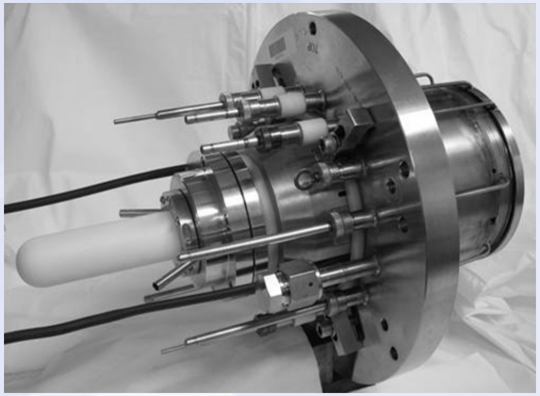
Al_2O_3 plasma chamber was not able to withstand the stress of 6% duty factors .

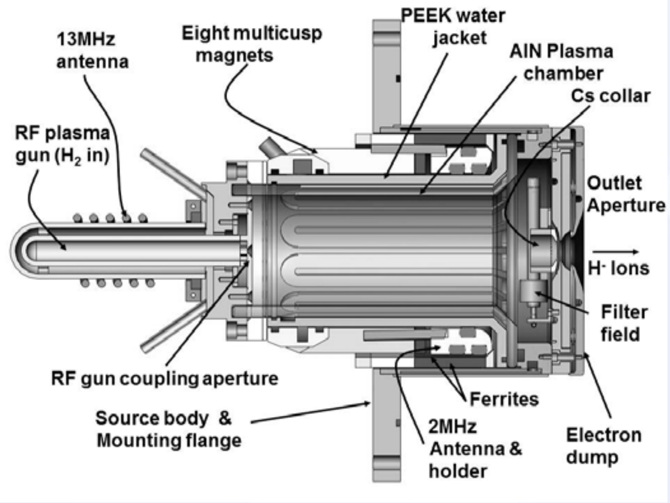
→ AlN plasma chamber. This need frequent recesiation (poisoning?)

Still using internal antenna source for production.

Testing “saddle antenna “ (V. Dudnikov).

up to 65mA, same H-/kW, in promising initial tests.





2nd generation external antenna, AlN

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Summary on H- sources

Surface production:

Good power efficiency
High current density
Lower extracted electrons
Erosion by sputtering
Cs, but experience shows that this is not a problem (except for "learning curve", and slow startup of sources).

Cs-seeded volume:

Cs consumption is *much* less
Have to deal with a lot of extracted electrons
Antenna lifetime issues

	BNL (Magnetron)	ISIS (Penning)	SNS (Volume)
Pwr efficiency	60 mA/kW	14 mA/kW	1 mA/kW
J(H-)	1.6A/cm2	0.8 A/cm2	0.13 A/cm2
e/H	0.5-1	1-5	>10 (dump at low E)
DF	0.5%	1% (→ 5%)	5.4%
Lifetime	~ 6 month	3 wks avg.	4-5 wks

Polarized H- Ions

Few facilities (RHIC, INR), but impressive progress

20 years ago, BNL polarized H- source was state-of-the-art at 20 μA.

Now, 1 mA is routine, and 10 mA planned.

Belov, INR Moscow - Polarized source of H-/D- using nearly resonant charge-exchange plasma ionizer

$\vec{H}$ + D- → $\vec{H}$- + D (D- ions are surface produced)

- Peak H^- ion current — 4 mA,
- (3 mA-200us)
- Polarization — 85-90%
- Normalized emittance — 2 π mm mrad
- Unpolarized D^- ion current — 60 mA (~20 mA/cm^2)
- Pulse duration (FWHM) — 170 μs
- Rep. rate — 5 Hz

Operational Polarized H^- Source at RHIC.

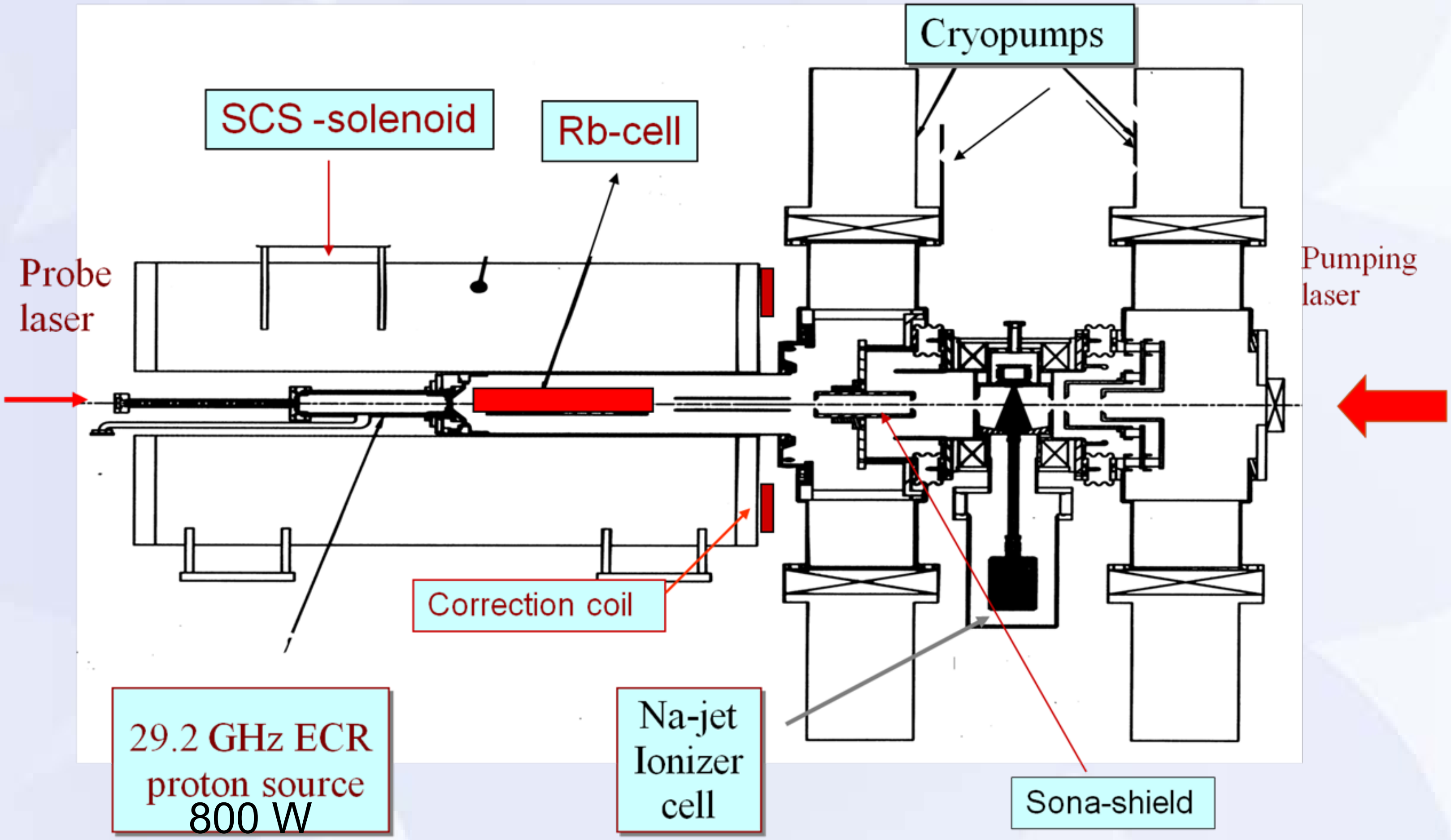
RHIC OPPIS produces reliably 0.5-1.0mA polarized H^- ion current.
Polarization at 200 MeV:
P = 80-85%.
Beam intensity (ion/pulse) routine operation:

Source	- 10^{12} H^-/pulse
Linac	- $5 \cdot 10^{11}$
AGS	- $1.5\text{-}2.0 \cdot 10^{11}$
RHIC	- $1.5 \cdot 10^{11}$ (protons/bunch).

Components include:
- 29 GHz ECR H+ source
- 795 nm laser
- 2.5 T SC solenoid
- Rb vapor cell
- Na jet ionizer

A. Zelenski

SCHEMATIC LAYOUT OF THE RHIC OPPIS.



H^+ - (Rb)→ $\vec{H}^0$ - (Na)→ $\vec{H}^-$
50% 8.4%

Na cell is at 35 kV, to give 35 keV H-

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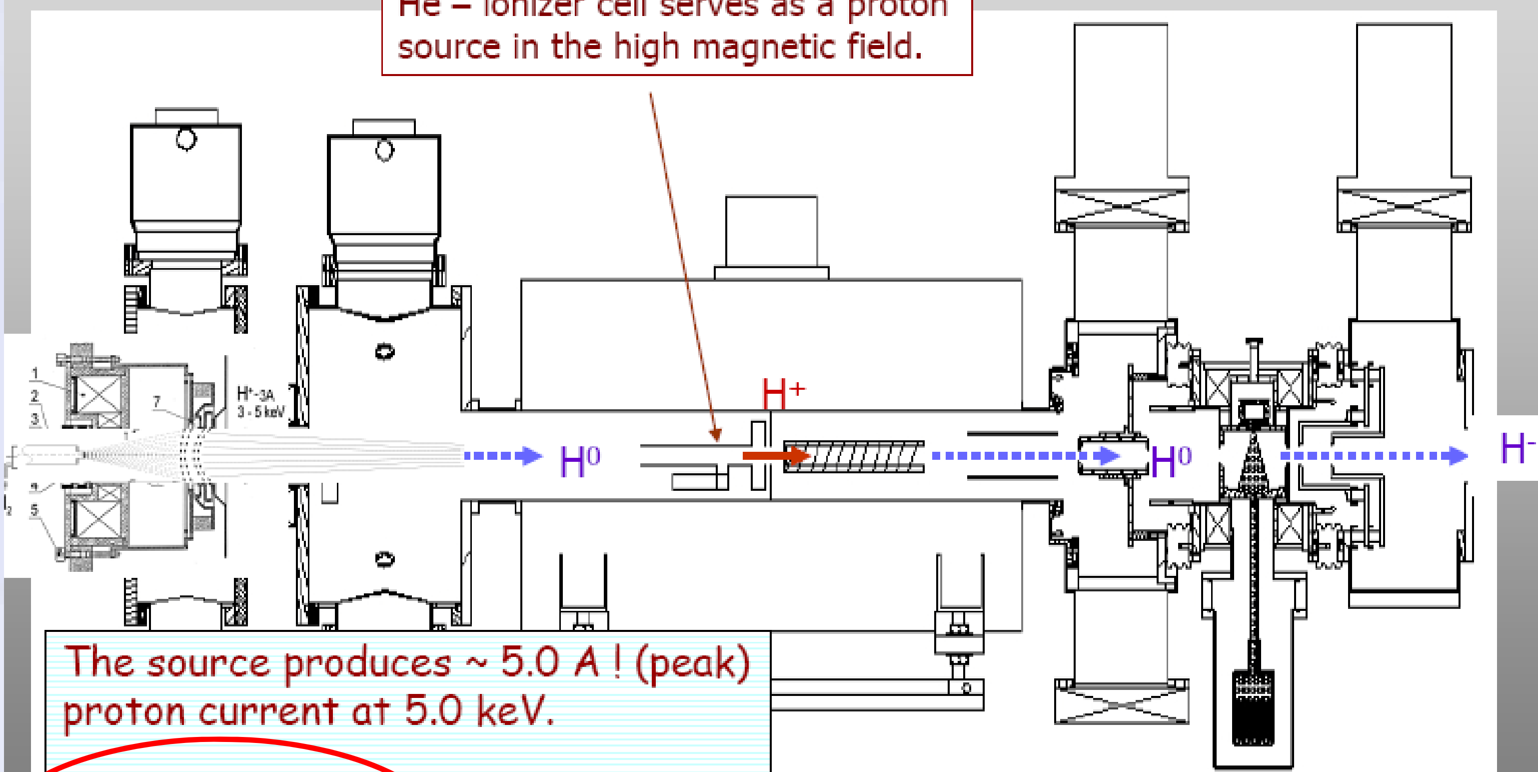
BINP, Novosibirsk & Brookhaven collaboration

OPPIS upgrade with the Fast Atomic Beam Source (FABS). The Third- Generation.

He – ionizer cell serves as a proton source in the high magnetic field.



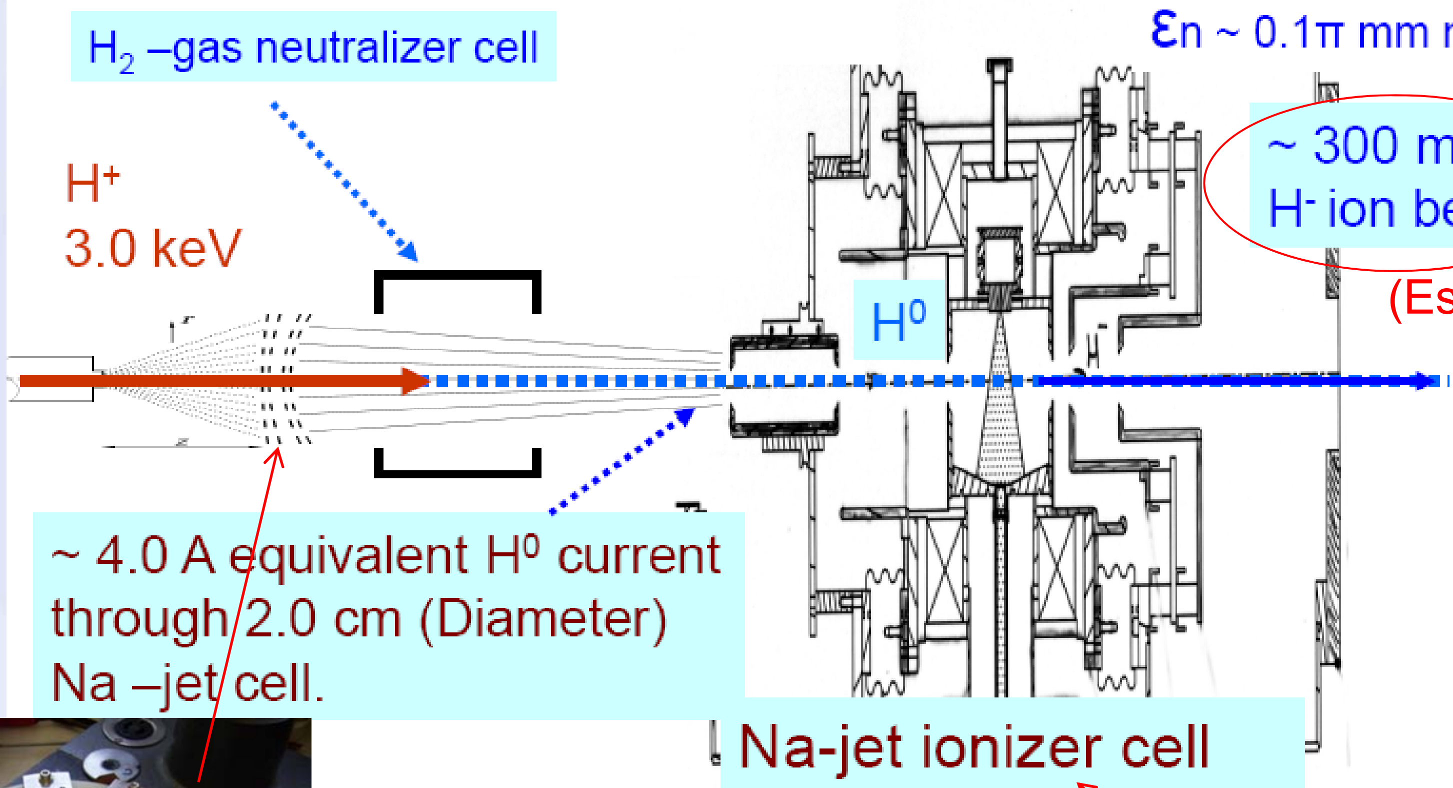
The source produces ~ 5.0 A ! (peak) proton current at 5.0 keV.

~ 10 mA H^- current, P = 85-90%.
~ 300 mA (high-brightness) unpolarized H^- ion current.

This source is presently being assembled for tests

H+ --(H)→ H0 – (He) → H+ --(Rb)→ H0 –(Na)→ H-
95% 60% 50% 8.4%

High- brightness un-polarized H^- ion beam production **(still to be be tested)**



Mo electrodes, ~5 cm diameter, ~2000 holes, 0.8mm diam each, 3 gap (accel/accel/decel)

Biased to 35 kV (very reliable, trouble free on OPPIS)

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Heavy Positive Ions

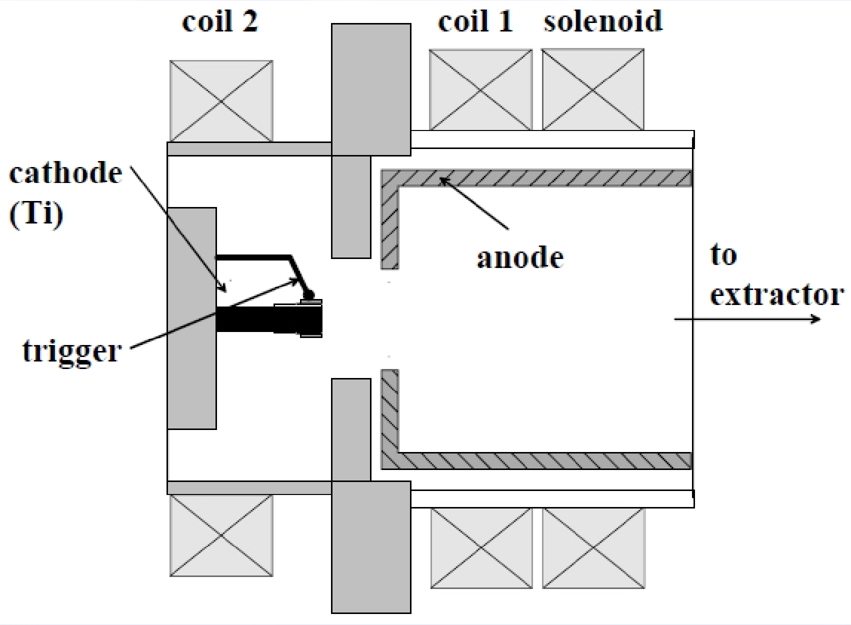
FAIR –
15 emA of U^{28+} at SIS18 input.
→ up to 30 mA of U^{4+} needed in front of the RFQ within 200 mm mrad
2.6 Hz, 0.5 ms

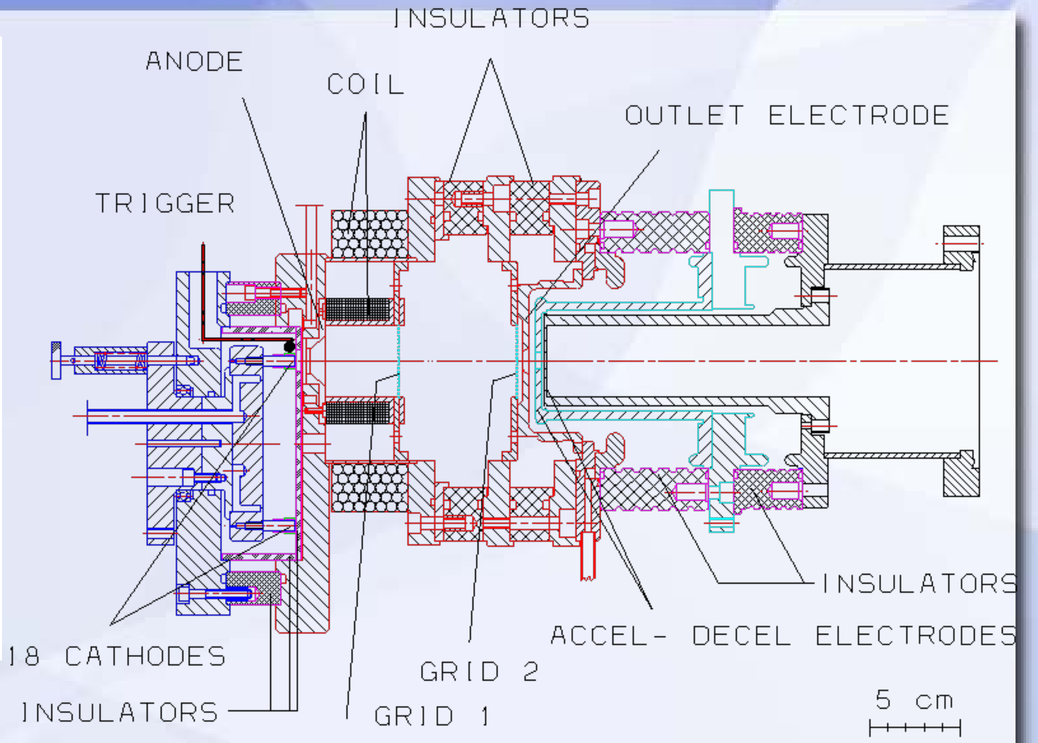
VARIS – MeVVA with solenoidal and cusps magnetic fields added to enhance higher charge states.

Also improved stability and lifetime, since it is more power efficient.

20 mA of U^{4+} is delivered to the RFQ entrance point.

17 cathodes, which gives it a lifetime of 7 days at 0.02% duty factor.





MEVVA having two additional coils, co-linear to the active cathode to influence the discharge impedance (increase the discharge current to the order of 1000A).

This source runs with up to 3Hz, 500 microsecond.
The 4+ fraction is 67%.
Pulse-to-pulse reproducability better +/-5%, by using also a much more powerful trigger.

Conditions for the production of high charge state ions

- High energy electrons in the source
- A high density of these high energy electrons - to produce the desired intensity and charge state.
- Ions must interact with the electron beam or plasma for a time long enough to reach the desired charge state through stepwise ionization.
- Desirable to keep the background pressure as low as possible to minimize the recombination of ions.

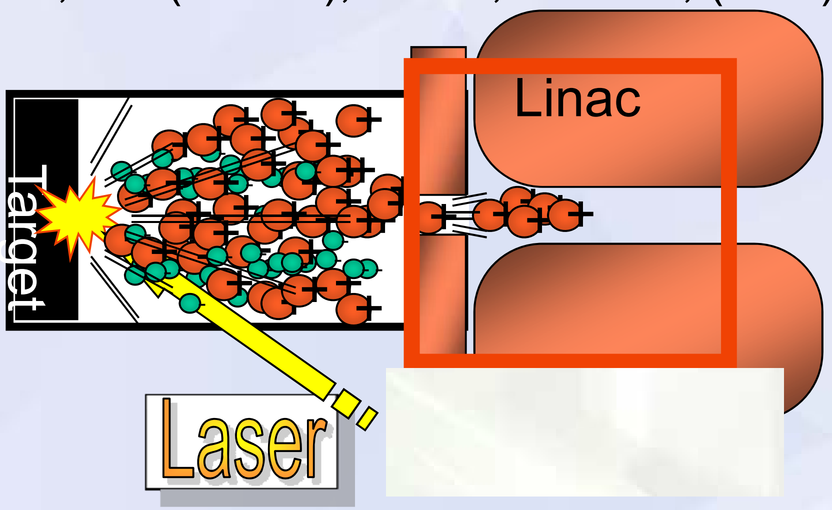
In most high charge state sources these parameters are coupled to a large extent.

Will cover 3 types –

Laser source – few "knobs", little control over individual parameters
EBIS - all these parameters are well controlled pretty much independently
ECR – somewhere in between the other two…

Laser ion source –
Direct plasma injection scheme (DPIS) - M. Okamura

BNL, TIT (Hattori), China, Toshiba, (KEK)



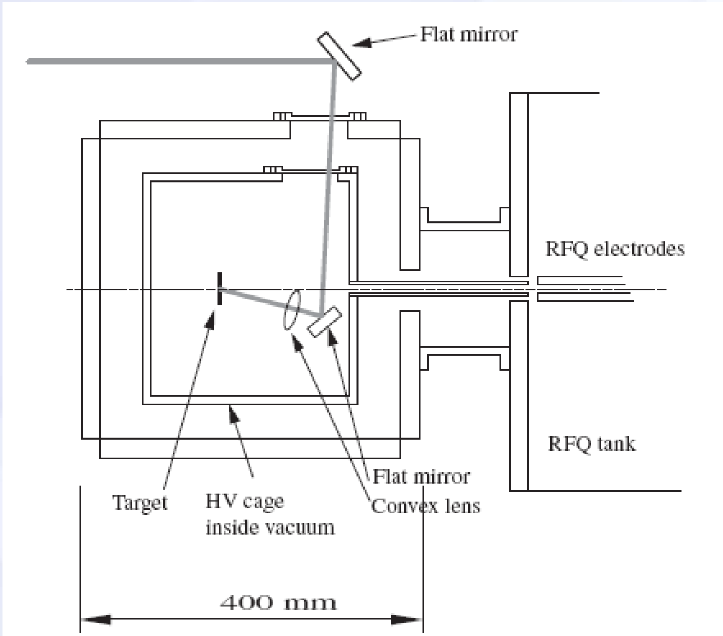
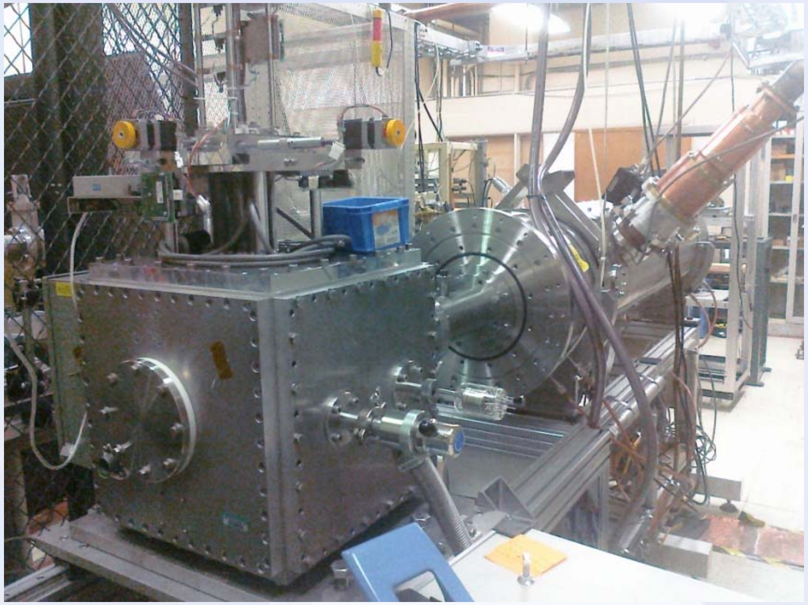


Fig. 1. A laser ion source with direct plasma injection scheme.



Allow a laser-produced plasma, containing the heavy ions of interest, to drift to the entrance of an RFQ, where the ions are then accelerated. This avoids the problem of space charge in matching a high current source to a subsequent accelerator. Ion extraction from the plasma occurs within the RFQ,

Some DPIS achievements:

- Uses conventional, table-top laser (6ns, 2J, Nd-YAG)

- >30 mA of C6+ out of the RFQ in ~3.5 microseconds pulses

- Stretching of the ion beam pulse width by drifting the plasma over several meters before the RFQ. Using a weak solenoidal magnetic guide field in this drift length, one can reduce the current loss over the drift.

- Production of ions from gaseous materials by applying the laser pulse to a frozen layer condensed on a cryo-cooled surface.

- By decreasing the laser power density on target to $<10^9$ W/cm^2, 1+ ions can be produced from many solid materials. Intensities are in the 10's of mA range and pulse widths of ~5 μs.
  Following a plasma drift of 1.6 m before extraction, 0.3 mA of Au 1+ was produced with a 110 us pulse width and an emittance of norm, rms = 0.025 pi mm mrad. C^{1+}, Al^{1+}, Si^{1+}, Fe^{1+}, Nb^{1+}, and Ta^{1+} have also been demonstrated.

Potential applications:
High current 1+ for HIF, C^{6+} for therapy synchrotron, 1+ source for EBIS, …

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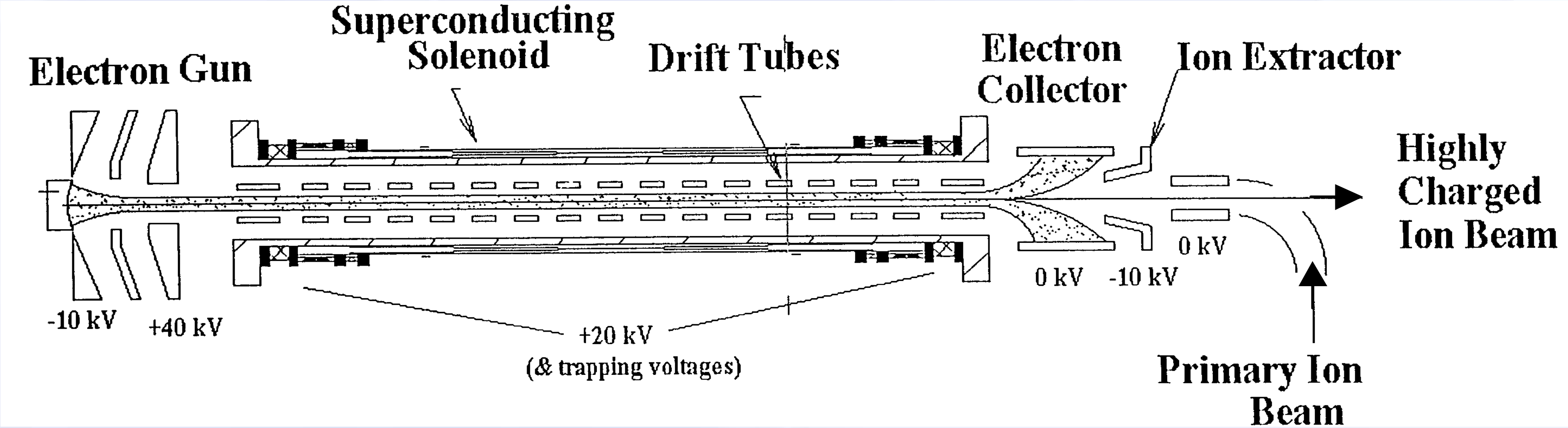
Electron Beam Ion Source (EBIS)



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

- 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 I(e)
- Ion charge state increases with increasing confinement time.
- Output current pulse is ~ independent of species or charge state!

High current, short pulsed output – good for injection into for synchrotrons

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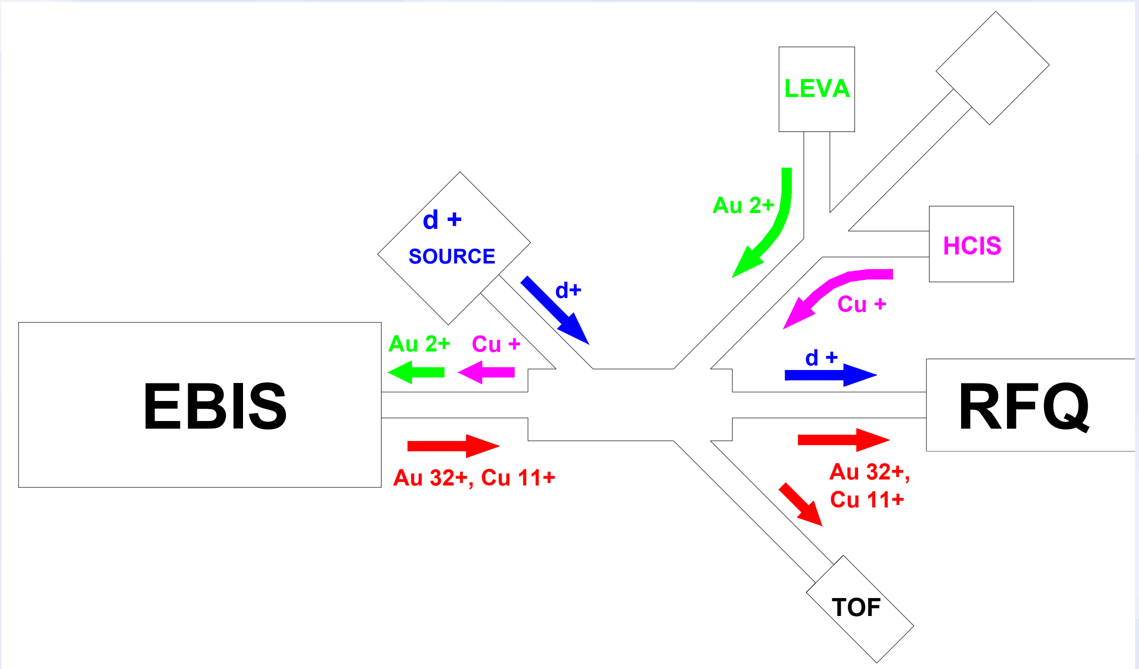
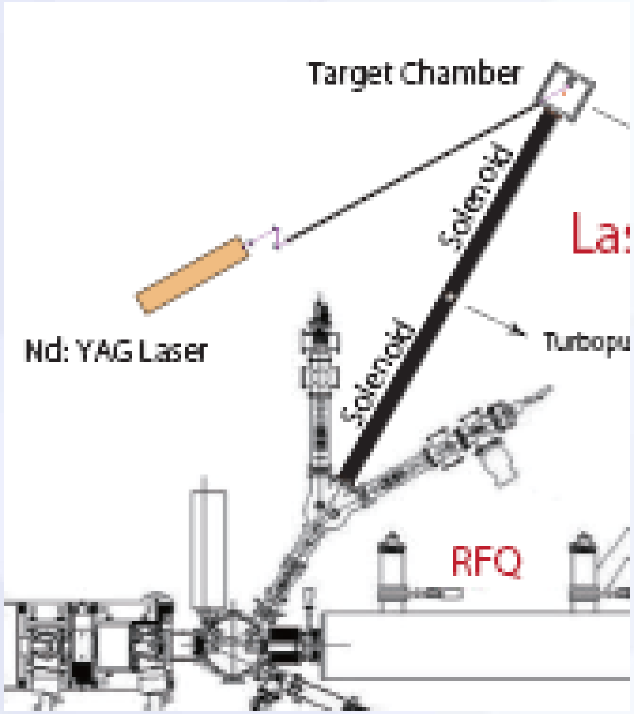
Ion Injection and Extraction from the RHIC EBIS



Future:



External ion injection provides most ion species (~ a charge breeder).

- One can easily change species and charge state pulse to pulse
- There is virtually no contamination or memory effect

LIS – in a given pulse, laser irradiates any one in an array of target materials, to inject 1+ ions of that species into EBIS. This will allow fast switching of a larger number of species (R&D phase; supported by NASA)

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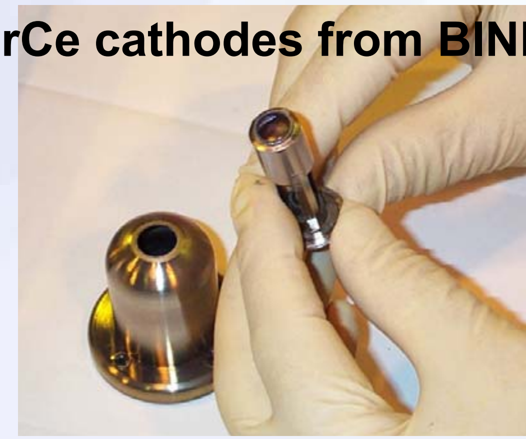
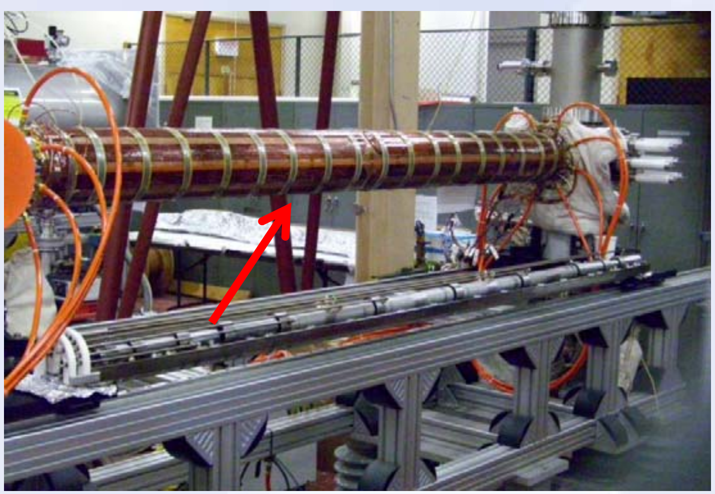
Brookhaven EBIS

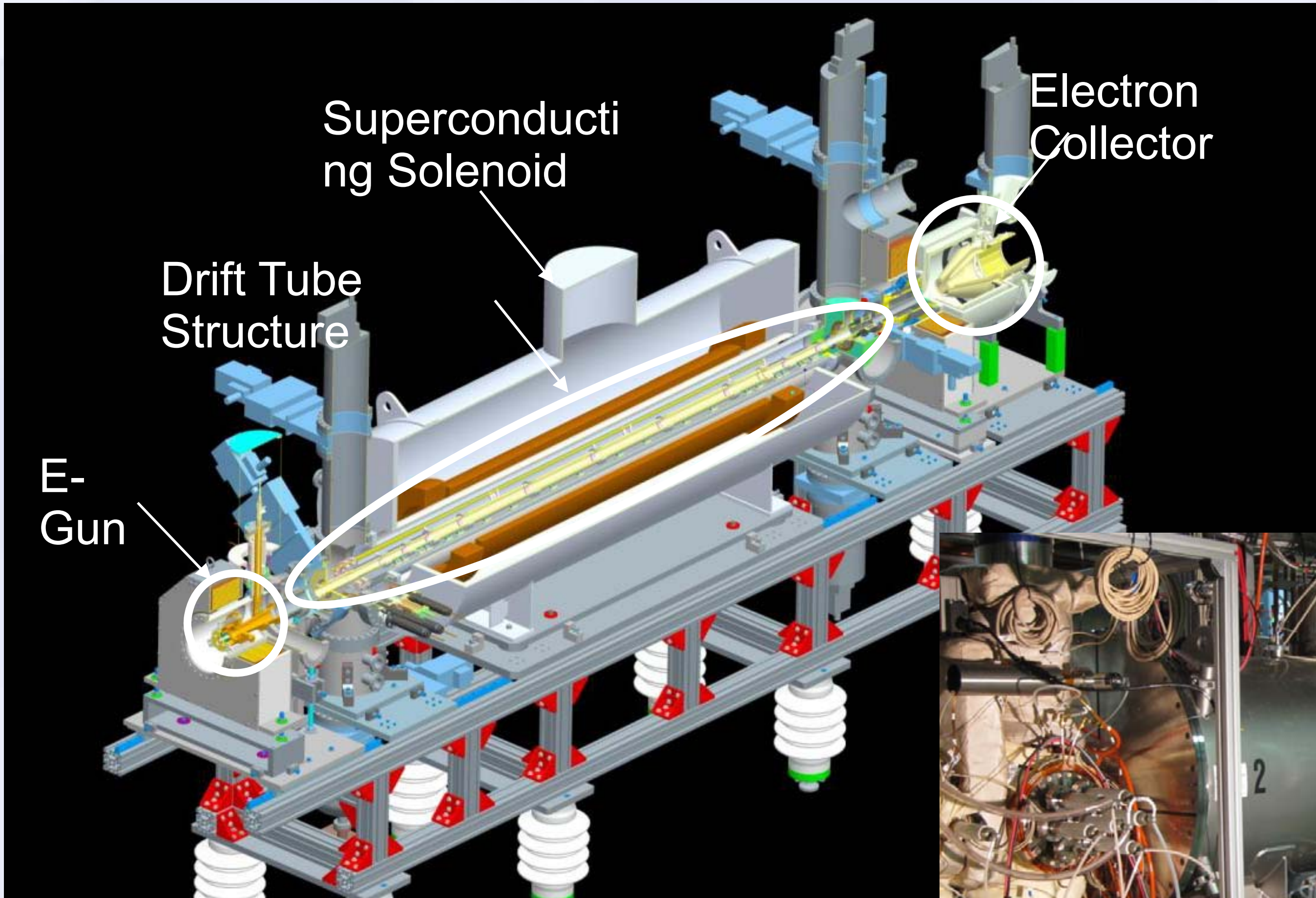
- *10A electron beam* (very stable, reproducible)
- 1.5 m trap
- 5T, 1.9m SC solenoid, 8” warm bore
- Pressure in trap in 10^{-11} Torr range, even when running 10A, 65 ms electron beam pulses
- 2 external ion source / injections lines for pulse-to-pulse switching of species

IrCe cathodes from BINP

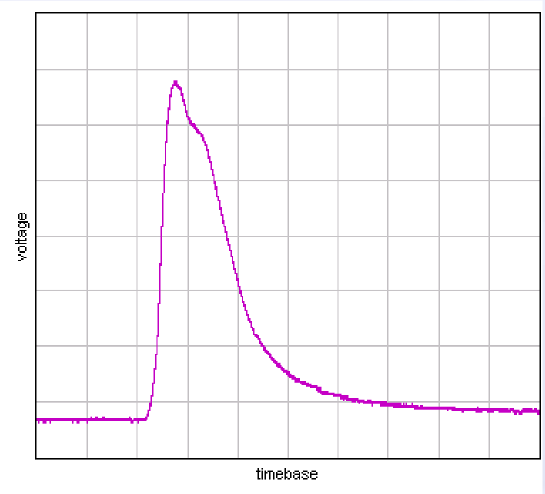


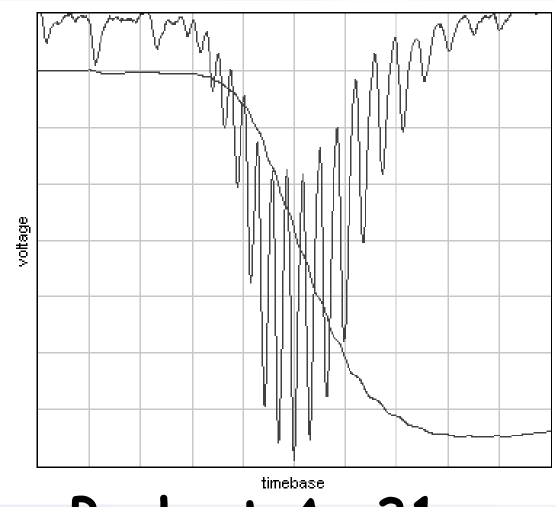


Brookhaven Electron Beam Ion Source



6 mA EBIS output
Au pulse (all charge states)
1 mA/div, 10 μs/div
I(e)=7.6A, 65 ms confinement
Est. ~0.9mA, 15uS of Au^{31+}

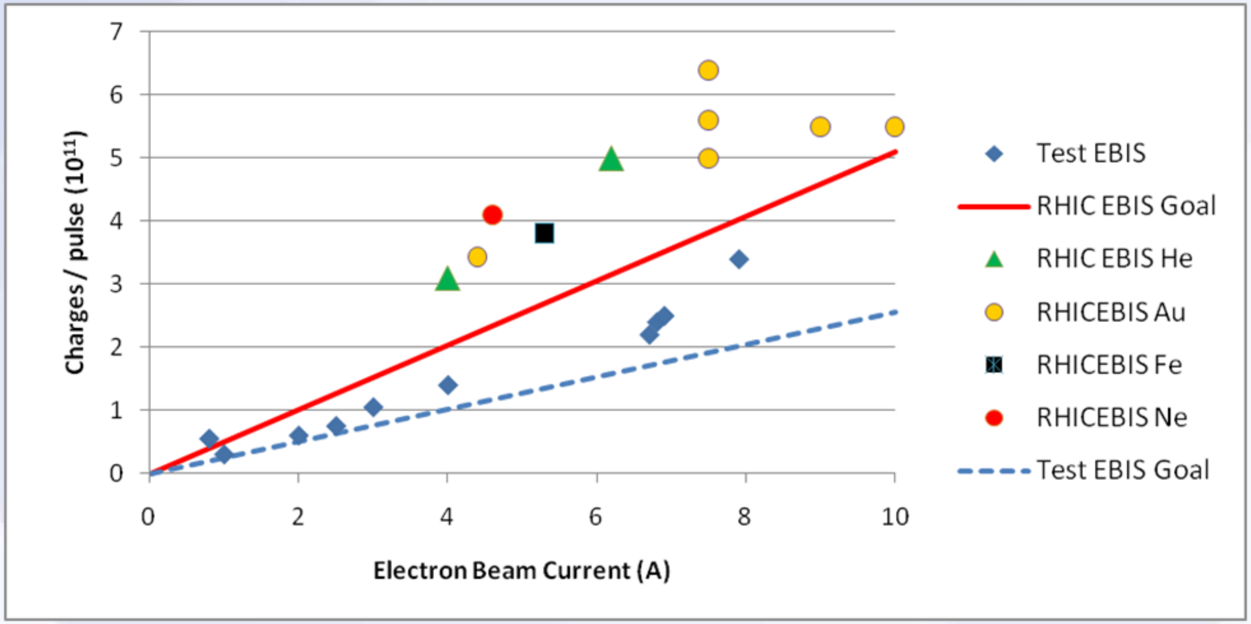




Peak at Au 31+
(adjust confinement time to make peak Q higher or lower)

Short pulses can be well matched to synchrotron injection. Control of pulse width by control of how ions are released from the trap.

Exceeding design goal at 10A, but there will be further increases (presently limited by the intensity of the injected Au 1+)

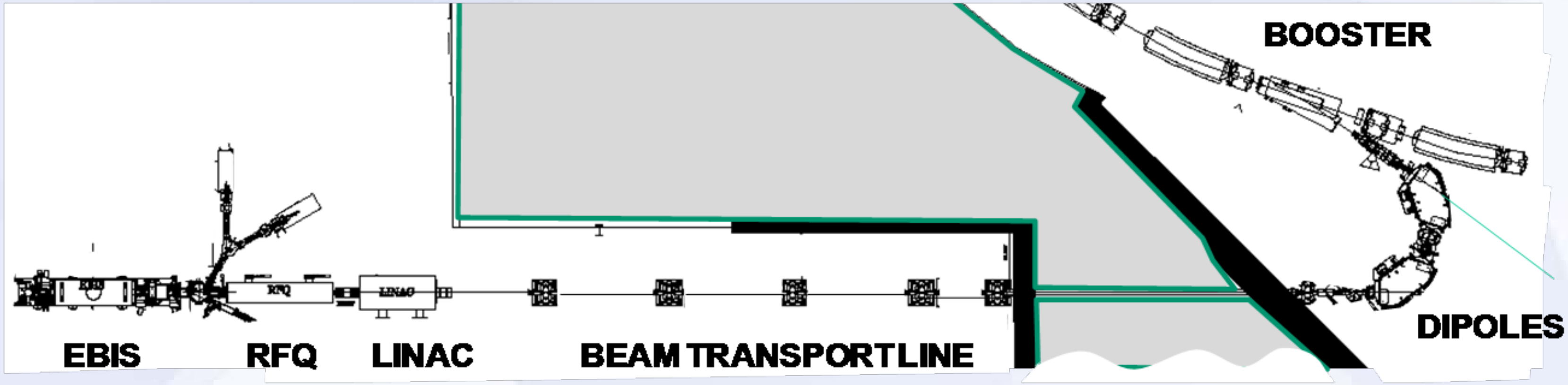


BROOKHAVEN NATIONAL LABORATORY

Operation with alternating Au^{32+} and Fe^{20+} beam pulses at Booster input has been demonstrated

- 0.5 Hz repetition rate
- Ion injection into the EBIS trap alternating between Fe^{1+} and Au^{1+} (two sources)
- EBIS confinement time switching between 65 ms for Au^{32+} and 130 ms for Fe^{20+}
- Switching pulse-to-pulse: platform high voltage, power to all RF systems, current to the large dipoles, and all transport line elements.

This rapid switching of species will be a frequent mode of operation when RHIC and NSRL are both taking beams from EBIS.

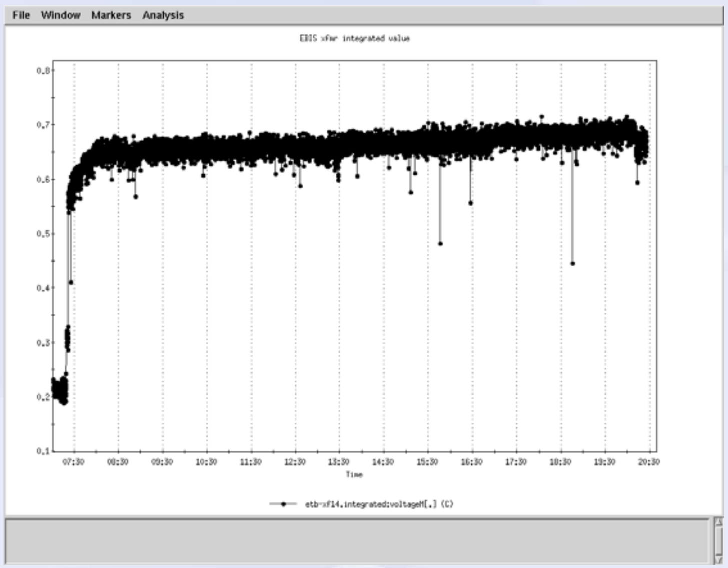


BROOKHAVEN NATIONAL LABORATORY

First EBIS run

38 days for NASA biology experiments

- He^{2+}, Ne^{5+}, Ar^{10+}, Ti^{18+}, and Fe^{20+} beams
- No downtime, excellent stability (eventually got to where it ran for days without any adjustments)



Fe to NSRL – each point on the plot is one EBIS pulse.

13 hours without a missed pulse

EBIS will provide U^{39+} beam for the 2012 RHIC run.

Electron String Ion Source (ESIS) – E. Donets, Dubna

Looks like EBIS, but….
EBIS - dumps the ionizing electron beam after a single pass through the trap region
ESIS - utilizes an **oscillating electron beam** between cathode and electron reflector in the magnetic field.

ESIS has produced beams such as N^{7+} (350 μA), Ar^{16+} (200 μA), and Fe^{24+} (150 μA), with ~8 μs pulse width for single turn injection into the Nucleotron.

This was achieved with **only ~6 mA electron current**, representing an effective 50-times reflection of electrons through the trap, substantially reducing electron beam power dissipation.

A new Krion-6T ESIS is being built
6T SC solenoid, 1.2m length
Expectation is 2-8 times increased ion yield

ECR

For high charge states (long plasma confinement time), the ion source needs "minimum B" configuration - axial mirror magnetic field and radial multi-pole magnetic field.

Output current scales with $(\text{frequency})^2$ → direction of advances
B must increase with f, to maintain resonance condition

For >18GHz, the move was to superconducting magnets

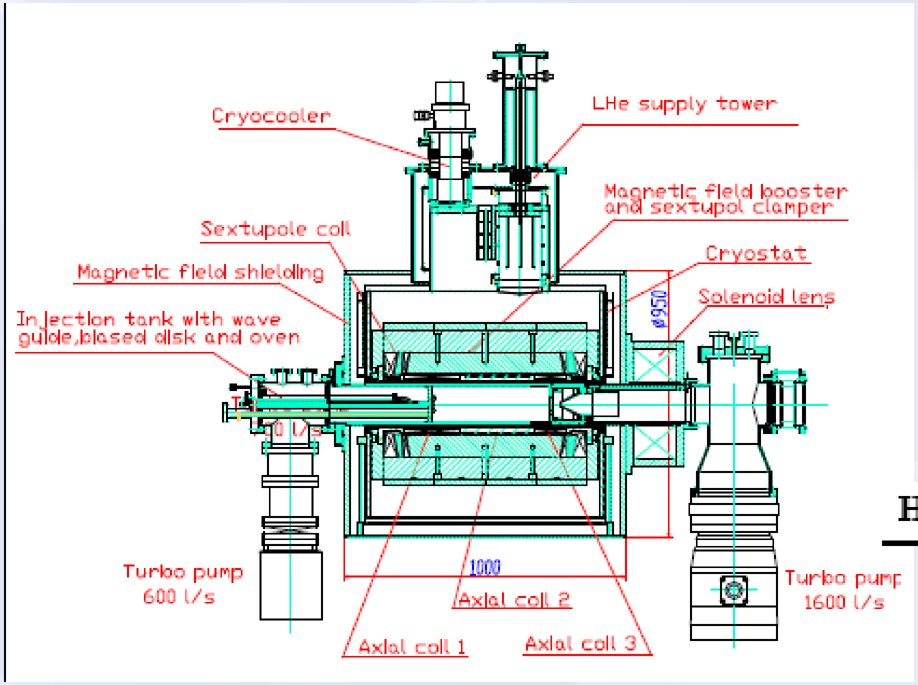
Most advanced ECRs are VENUS (28 GHz) at LBL and SECRAL (24 GHz) at Lanzhou.

RF powers are in the 10 kW range
(sometimes multiple frequencies are used, requiring multiple rf sources)

The required superconducting solenoid and sextupoles push the state-of-the-art in superconducting magnet technology (very high Lorentz forces between solenoid and 6-pole, extreme tensions in coils supports).

Bremstrahlung from the plasma can be a heat load on the cold mass of the superconducting magnets.

SECRAL - 24 GHz

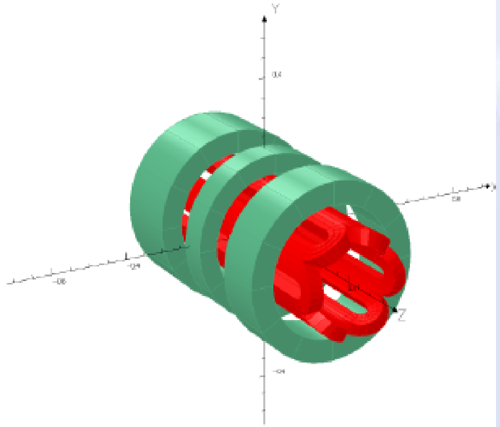


H.W.Zhao, IMP, Lanzhou, ECRIS10, Grenoble, August 2010

VENUS - 28 GHz

Quench (low LHe level) caused evaporation of a sextupole lead. Repaired, and now meeting/exceeding previous performance.

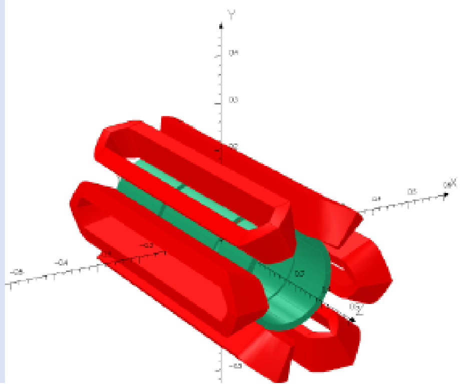
Sextupole-in-Solenoid Geometry (VENUS)



- Minimizes the peak fields in the coil
- Strong influence (forces) of the solenoid field on the sextupole ends

D. Leitner, ECRIS 10

Solenoid-in-Sextupole Geometry (SECRAL)



- Minimizes the influence of the solenoid on the sextupole field
- Significantly higher field required for the sextupole magnet surface due to the larger radius of the coils
- Strong forces on the solenoid coils

	VENUS 28+18 GHz	SECRAL (24 GHz)	
Results 2006-2008			
O^{6+}	2860 eμA	2300 eμA	
O^{7+}	850 eμA	810 eμA	
Ar^{12+}	860 eμA	510 eμA	650
Ar^{16+}	270 eμA	149 eμA	
Ar^{17+}	36 eμA	14 eμA	18.5
Xe^{30+}	116 eμA	152 eμA	
Re -commissioning (3 weeks) 2010			
Xe^{26+}	480 eμA	480 eμA	
Xe^{27+}	411 eμA	450 eμA	455
Xe^{30+}	211 eμA	152 eμA	236
Xe^{32+}	108 eμA	85 eμA (31+	190
Xe^{35+}	38 eμA	45 eμA	64

SECRAL reported this week

Only SECRAL has this magnet structure. Smaller magnet assembly and simplifies somewhat the fabrication process.

FRIB:

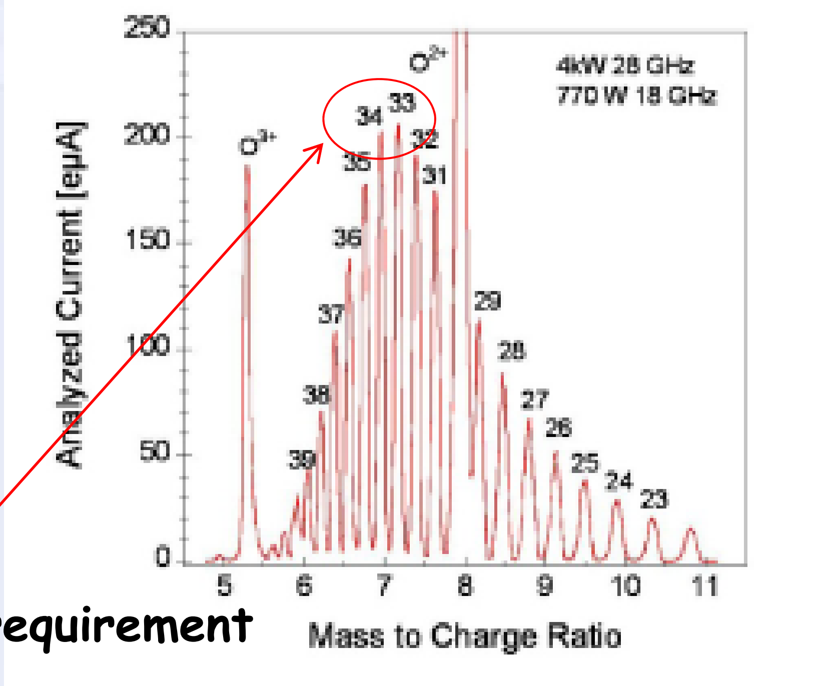
Two ECRIS's on HV platforms
~400 eμA 12 keV/u ion beams, oxygen to uranium

Ex. 424 euA U 33+34 out of the ECR, within 0.6 pi mm mrad (each charge state)

FRIB ECR = based on VENUS + "lessons learned"
28 GHz, cryostat needs 13-15W at 4.2K for heat from x-rays

	Charge State	Maximum Intensity Extracted [puA]	FRIB Intensity [puA]
Uranium	33 or 34	6.21	12.7
Bismuth	28 or 29	8.45	14.2
Xenon	20	16	18.5
Argon	11	90.91	47.3 (8+)
Oxygen	6	475	103

ECRIS 2010 – G. Machicoane, MSU-NSCL



VENUS – U 33+34 ~meeting FRIB requirement

"Fourth-generation" ECR – work is starting on magnet designs for 50-60 GHz operation

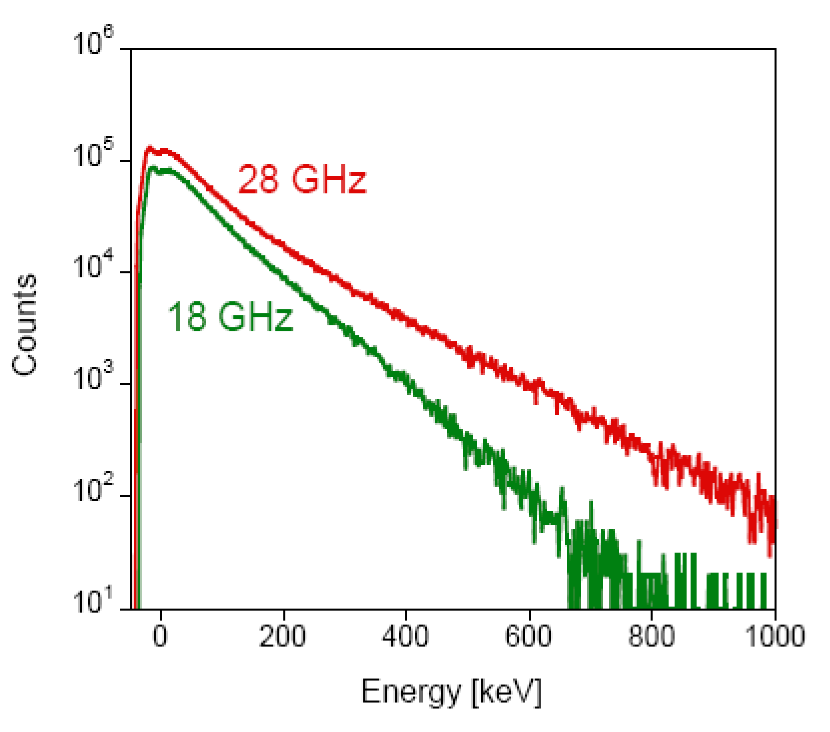
Magnetic Design		28 GHz	56 GHz
Max solenoid field	on the coil	6 T	12 T
	on axis	4 T	8 T
Max sextupole field	on the coil	7 T	15 T
	on plasma wall	2.1 T	4.2 T
Superconductor		NbTi	Nb_3Sn

D. Leitner, LBL, ECRIS'10

Xie, et.al., Lanzhou – ecris10:
Design of a SC ECR with a maximum axial field of 7.0 T and a radial field of 3.5 T at the plasma chamber wall of ID 110 mm, and operating frequency up to 50 GHz.

Force among the solenoid coils and the sextupole coils and its resulting torque was "much more than quadrupled" in comparison to the SECRAL (7.8 x)

Grenoble – 60 GHz prototype magnet studies



VENUS

The high energetic x-ray (> several 100 keV) can penetrate easily through plasma chamber wall and wall of cryostat.

Heat load from x-ray on the order of 1W/kW at 4.2K (→ 5-10 W)

Final comments on ECR's

The number and variety of ECR's is overwhelming!
(A tribute to its success)

Permanent magnet versions, cryogen free, high temp SC, Compact, etc.

CERN (LHC) - ECR is from Grenoble, 2005. Pb 29+,
200uA out of source, 200 us injected (70 turns)
RIKEN SC-ECRIS – 18 GHz in '09; now going to 28 GHz
SuSI (MSU) –2 x 18 GHz amps, 3 kW
etc.

Big advances in the understanding of ECR plasma and parameter optimization.

Summary

Unfortunately, I've only managed to scratch the surface of what's being done. There is ***a lot*** of careful work and good new ideas.

H+ sources – >100 mA CW, pretty much can meet requirements

H- sources – steady progress towards filling future needs

Polarized H- - big advances, needs pretty much being met

High charge state heavy ions – a lot of activity, because even though great progress continues to be made, the users want more!

Very different sources depending on the application:

Laser –short pulse, high current, high Q/m for lower masses, simplicity of DPIS

EBIS –short pulses, high current at highest Q's, a lot of flexibility

ECR –The only choice for dc, but superior even in many pulsed applications. The technology is getting tougher for the highest masses and Q/m's.