Progress in the Negative Ion Sources Development

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SUMMARY 1

•Recent progress in development of advanced negative ion sources was connected with optimization of cesiation in surface plasma sources (SPS).

•**Cesiation** is indispensable for high intense high brightness negative ion beam production(CERN project).

•SPSs with cesiation are "sources of life" and "work horses" in almost all high intense proton accelerators.

•Operation of these accelerators were not limited or compromised by SPS operation during last 30 years.

SUMMARY 2

•For new project as SNS were developed new SPS with a DF 6% at pulsed current ~40 mA, norm. emittance <0.3 pi mm mrd and lifetime up to ~1000 hours(Integrated beam lifetime (IBLT) ~2.5 A hours).

•Cs consumption was reduced from ~1 mg per hour to ~1 mg per week(LA has Cs consumption 1 g per day)

•Intensity of PD SPS was increased up to 60 mA at 5% DF.

•Efficiency of Semiplanotron SPS was increased to ~100 mA/kW, similar to best proton sources.

SUMMARY 3

- However, for internal and external cyclotron injection are used Cesium-less hot cathode discharge NISs with low energy and gas efficiency and high electron current.
- Improving performance of H-/D- sources is important for isotopes production industry.
- In high energy heavy ion tandem implanters are used charge exchange NISs with Mg targets.
- Improving intensity of B- (B_2 -) beam above 1-2 mA is important for semiconductor applications.

SUMMARY 4

- Intensity of H-/D- beams for NBI were increased to >40 A at emission current density up to 30 mA/cm2 and electron current less than H- current (Used for regular operation in LHD and JT-60). Acceleration up to 1 MeV under development.
- DC H- beams from PD SPS was increased to 25 mA with emission current density J~100 mA/cm2. Push button operation is developed.

SUMMARY 5

•Improve reliability and availability of SPS, lower ownership cost and push button operation are main task of negative ion sources development now.

•Lest developments of SPS are promising to increase the lifetime of SPS with average current ~10 mA to ~1000 hours (IBLT ~10 Ahours).

Recent Reviews of Ion Sources

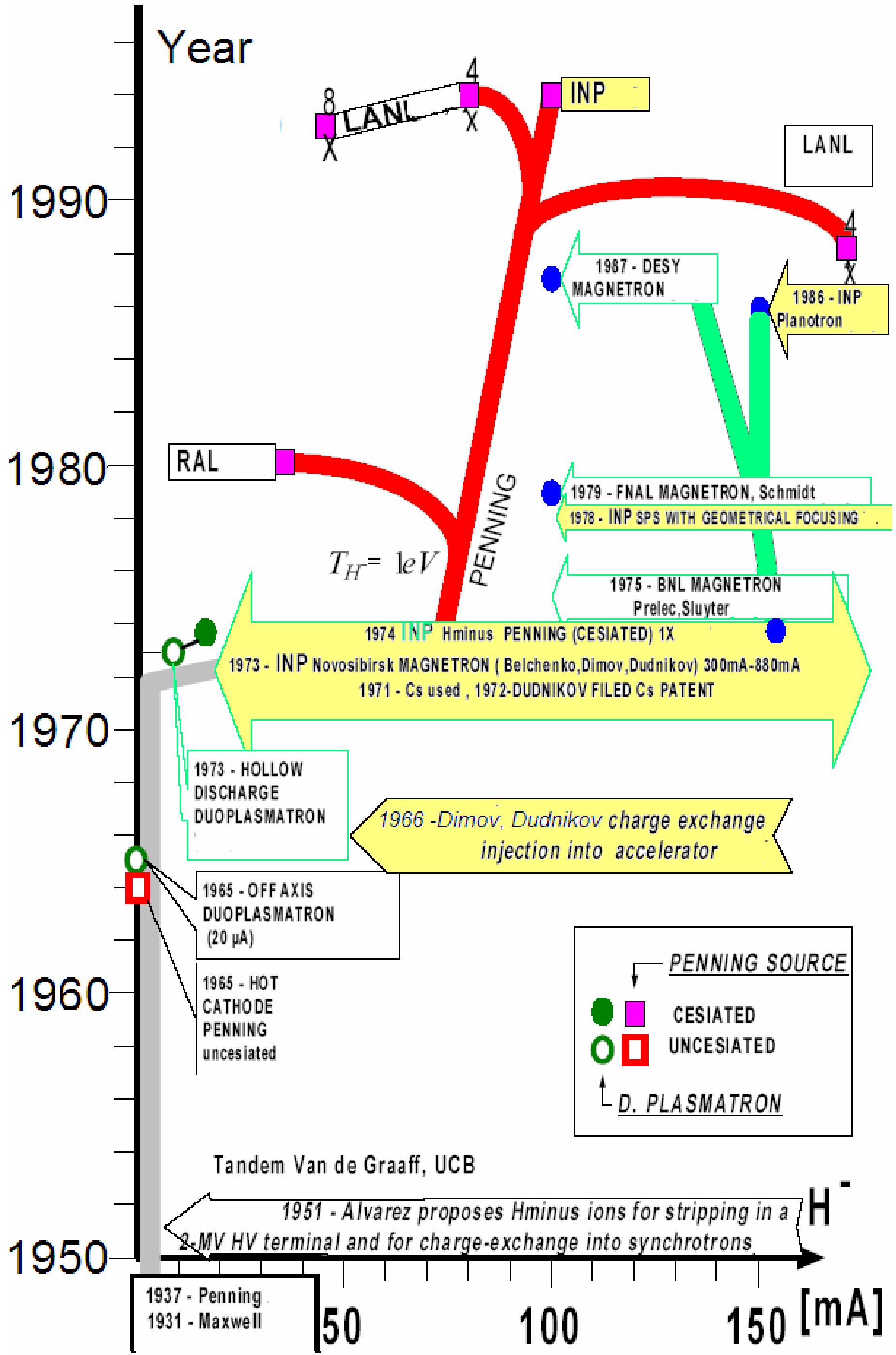
- J. Alessi , Recent Developments in Hadron Sources
  accelconf.web.cern.ch/accelconf/IPAC2011/talks/frxba01_talk.pdf
- D. Faircloth, " Negative Ion Sources (Magnetron, Penning)"; CERN Accelerator School , Slovakia, 2012; *http://cas.web.cern.ch/cas/Slovakia-2012/Lectures/Faircloth Negative.pdf*
  http://www.adams=institute.ac.uk/lectures/?scheme=1&id=55
- V. Dudnikov, "Fourty Years of Surface Plasma Sources Development", Rev. Sci. Instrum., 83 (2) pt. 2, 02A708(2012); 02A724 (2012).

IPAC 2012, Dudnikov et al….

ICIS 2009, 2011; NIBS 2010, 2012

Dudnikov Source…. ИОННЫЕ ИСТОЧНИКИ

- *N. Wells, Rand Corporation reports.*



History of Negative Ion Sources development

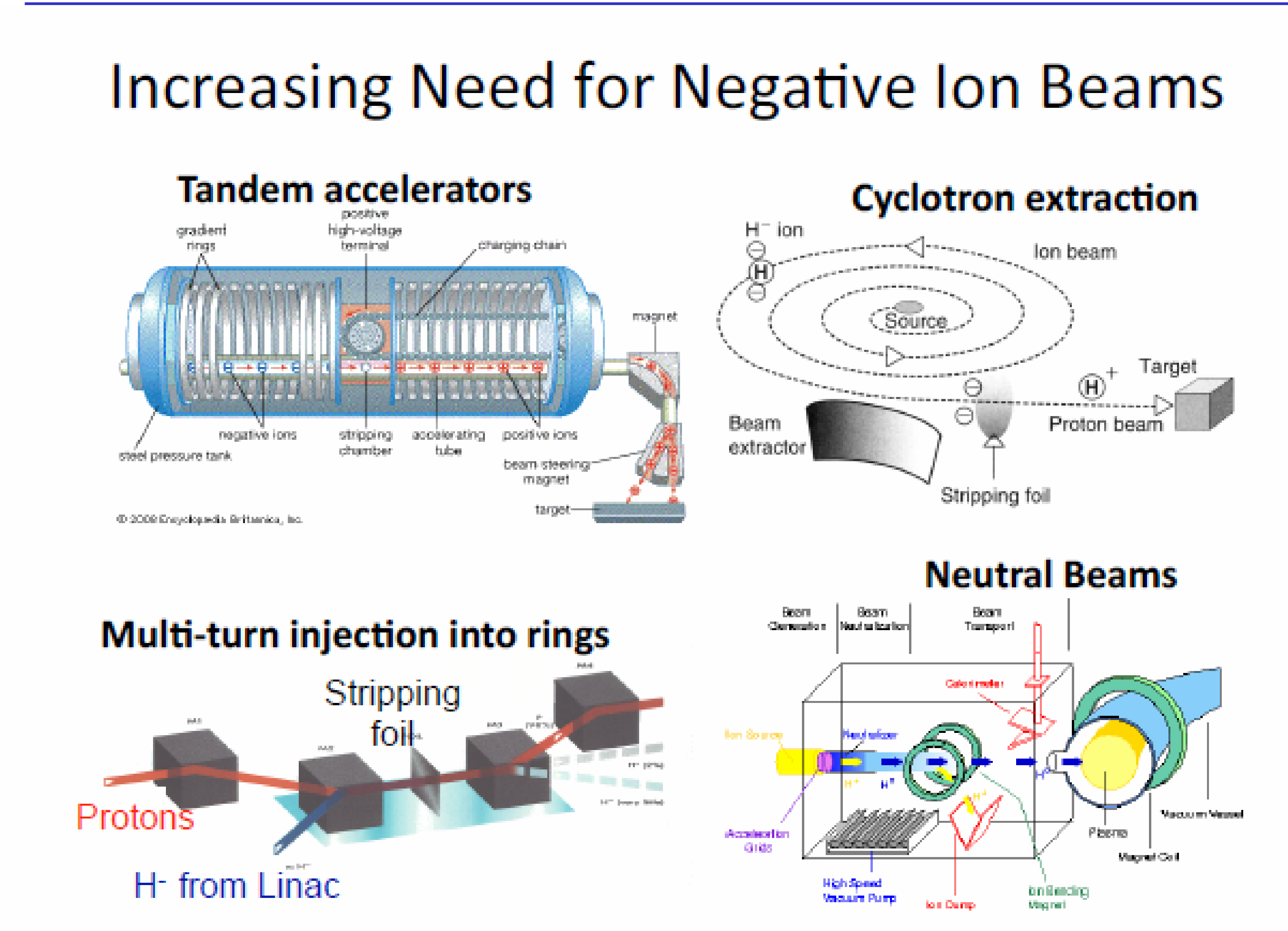
(J.Peters, RSI, v.71, 2000)

L. Alvarez, RSI, 1951, Tandem accelerators, stripping injection.
K. Ehlers, Cyclotron extraction. Ehlers's PD source, 1965, 3 mA.
BDD, Charge exchange injection, 1965.
SDI….BEAR experiment Los Alamos
NBI for Fusion

Cesiation, discovered 1971, BINP

Method of negative ion production comprising admixture into the discharge a substance with a low ionization potential, such as cesium". Increase of NI emission with decrease of co-extracted electron current.

Negative Ion Sources Applications

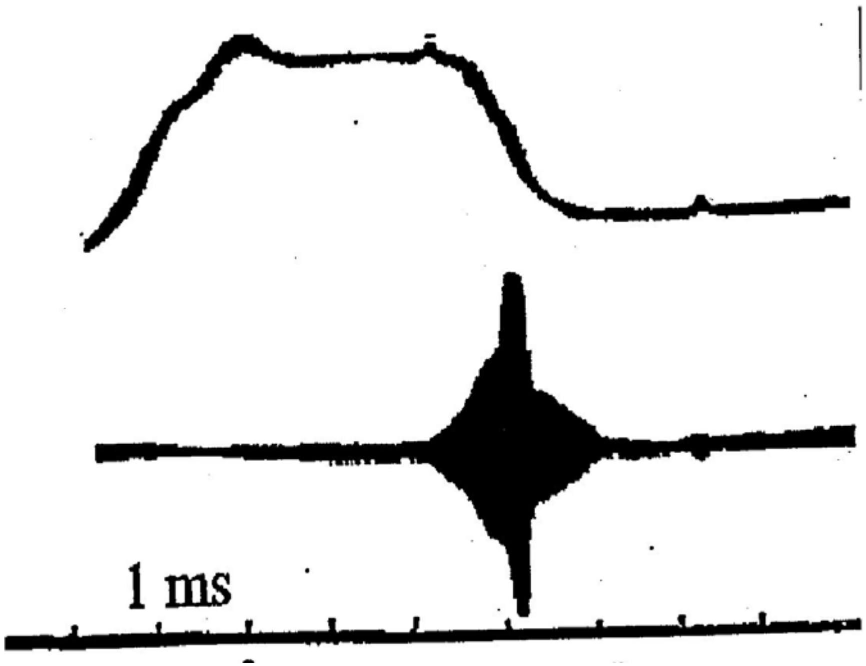


History of Charge Exchange Injection

(Rees, ISIS , ICFA Workshop)

1. 1951 Alvarez, LBL (H-) ;
   1956 Moon, Birmingham Un. (H+2)
2. 1962-66 Budker, Dimov, Dudnikov, Novosibirsk ;
   first achievements; discovery of e-p instability.IPM
3. 1968-70 Ron Martin, ANL ; 50 MeV injection at ZGS
4. 1972 Jim Simpson, ANL ; 50-200 MeV, 30 Hz booster
5. 1975-76 Ron Martin et al, ANL ; 6 10^{12} ppp
6. 1977 Rauchas et al, ANL ; IPNS 50-500 MeV, 30 Hz
7. 1978 Hojvat et al, FNAL ; 0.2-8 GeV, 15 Hz booster
8. 1982 Barton et al, BNL ; 0.2-29 GeV, AGS
9. 1984 First very high intensity rings ; PSR and ISIS
10. 1980,85,88 IHEP, KEK booster, DESY III (HERA)
11. 1985-90 EHF, AHF and KAON design studies. SSC
12. 1992 AGS 1.2 GeV booster injector
13. 1990's ESS, JHF and SNS 4-5 MW sources

Discovery of electron proton instability (Electron Cloud Effect) INP Novosibirsk, 1965, bunched beam



<u>Other **INP PSR 1967**</u>:
Coasting beam instability suppressed by increasing beam current;
fast accumulation of secondary plasma is essential for Stabilization 1.8×10^{12} in 6 m

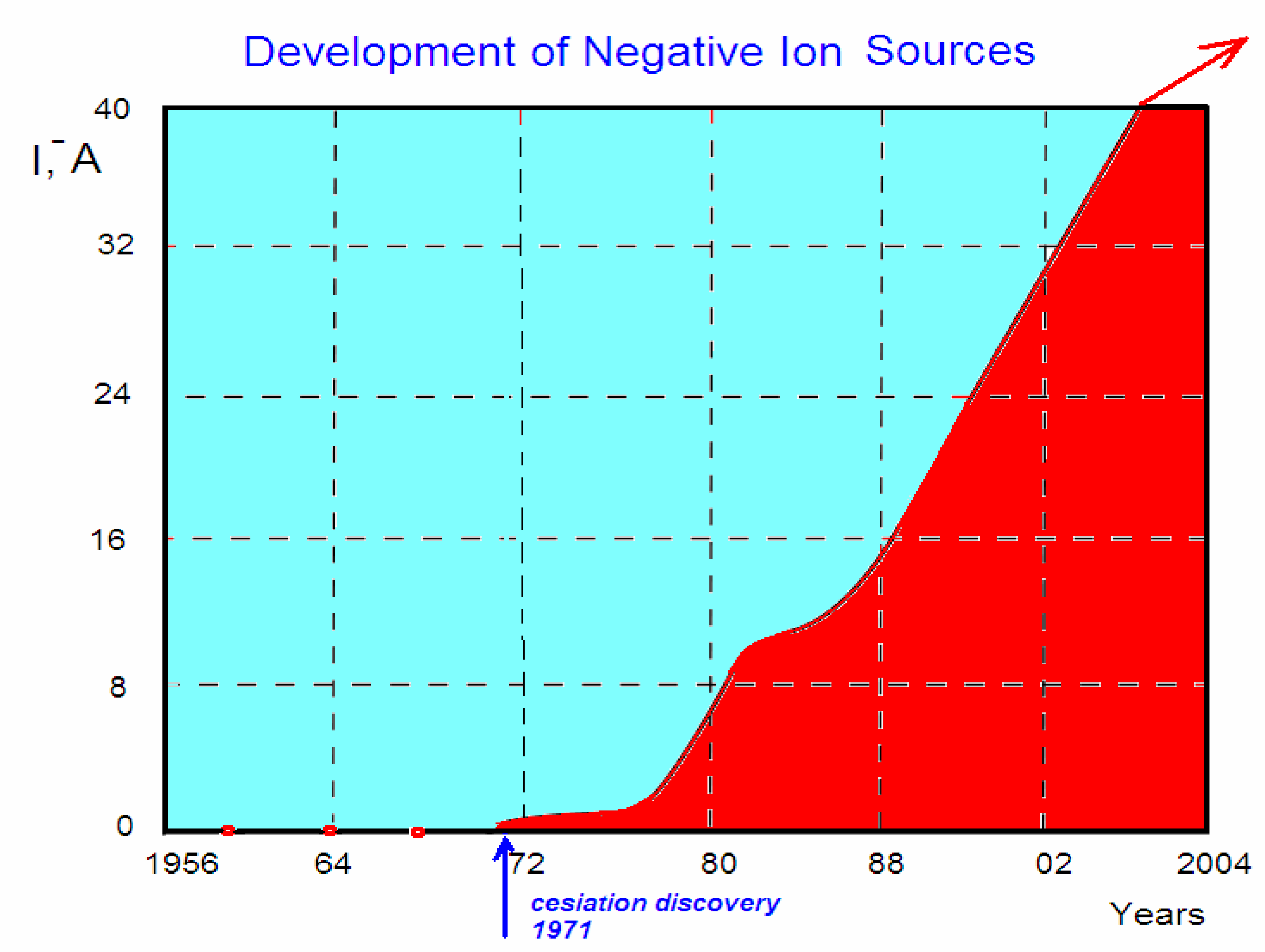
Martin Reiser, “Theory and design of charged particle beams”, 2 edition

first observation of an e$^-$ driven instability.
coherent betatron oscillations & beam loss
with bunched proton beam; **threshold** ~1-1.5x10^{10}, circumference 2.5 m, **stabilized by feedback**
(G. Budker, G. Dimov, V. Dudnikov, 1965).
F. Zimmermann

V. Dudnikov, PAC2001, PAC2005

- In the early 1970s Gennadii Dimov, Yuri Belchenko and Vadim Dudnikov at the Budker INP started experimenting with caesium in ion sources.
- Using a magnetron ion source, Vadim Dudnikov added Cs vapour to the discharge for the first time. A dramatic increase in H– current was observed along with a decrease in co-extracted electrons. The Dimov team went on to extract a colossal 880 mA pulsed H– beam from an experimental magnetron source. This success led them to develop a Penning type source that could produce 150 mA of H– beam current with only 250 mA of extracted electrons. The H– currents produced were orders of magnitude higher than anything seen previously. When these revolutionary results were published interest in caesiated sources took off. Researchers all over the world started using caesium in their ion sources and a large number of new source designs were developed.

Intensity of Negative Ion Beams: 1971-discovery of Cesium Catalysis



IEEE Transactions on Nuctear Science, Vot.NS-23, No.2, Apit 1976

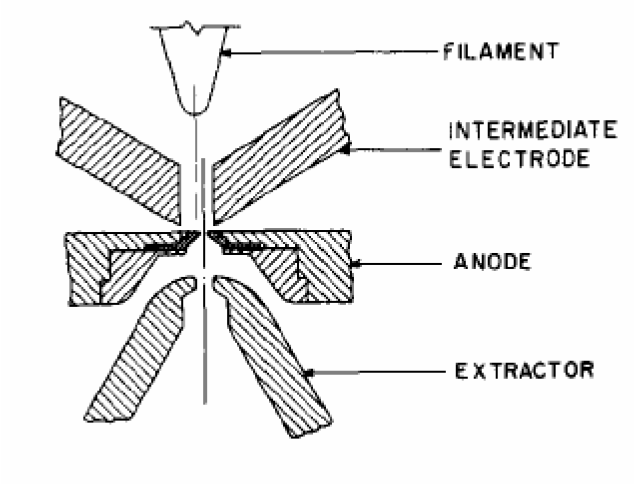
A Review of Sputter Negative Ion Sources

Roy Middleton

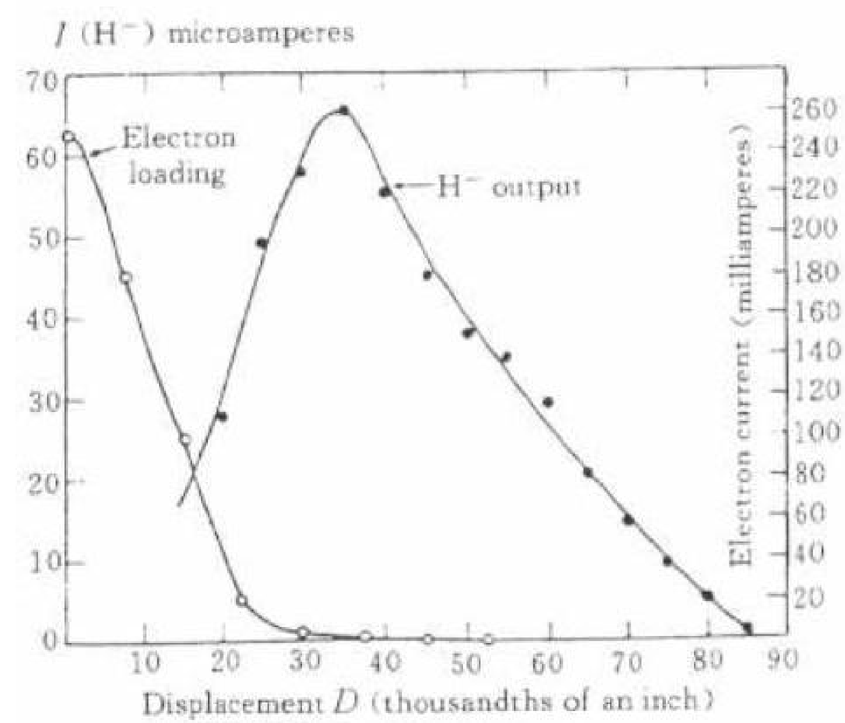
- During the past 5 years numerous advances have been made in negative ion source technology, so much so that it might not be inappropriate to describe it as a revolution. Hopefully, we are on the threshold of seeing **completely new types of negative ion sources which will differ from their predecessors in much the same way as the transistor differs from the thermionic vacuum tube.**

Duoplasmatron with of Axis Extraction

G.P. Lawrence *et al.*, Nucl. Instrum. & Methods, 32 (1965), 357-359.
L.E. Collins and R.H. Gobbett, Nucl. Instrum. & Methods, 35 (1965), 277-282.



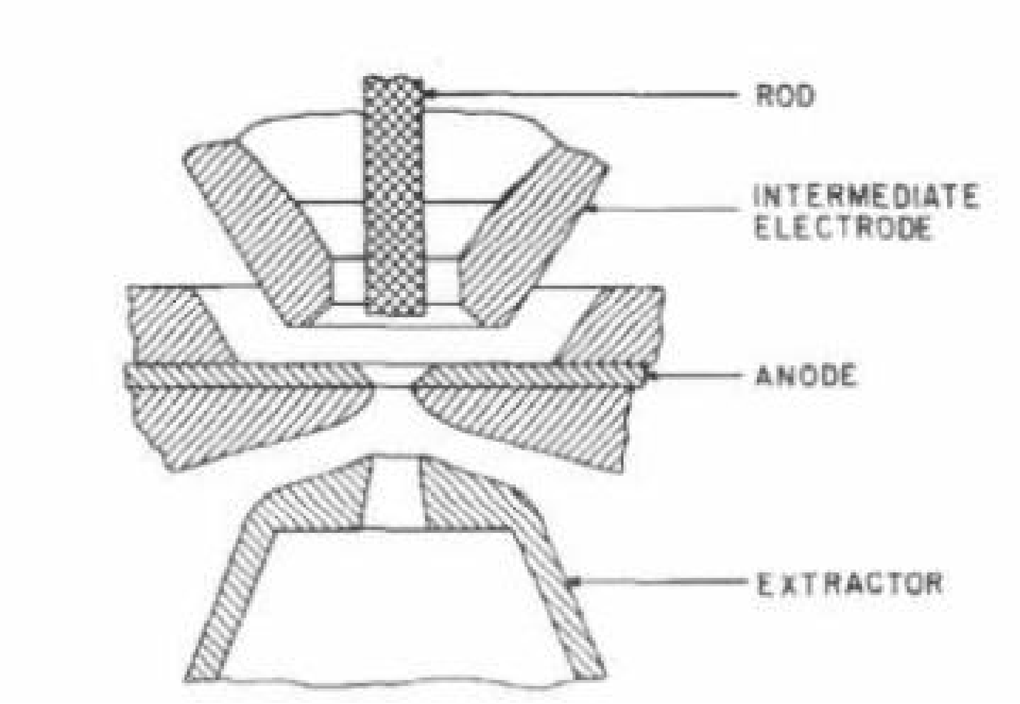
The dependence on source conditions has been studied and 80 μ A of H- have been obtained with a total source e1ectron load of 2-4 mA. Wittkower et a1. have investigated the geometry and condtions which give best output and they obtained 70 μA of H- at 20 keV accompanied by 65 mA of e1ectrons.



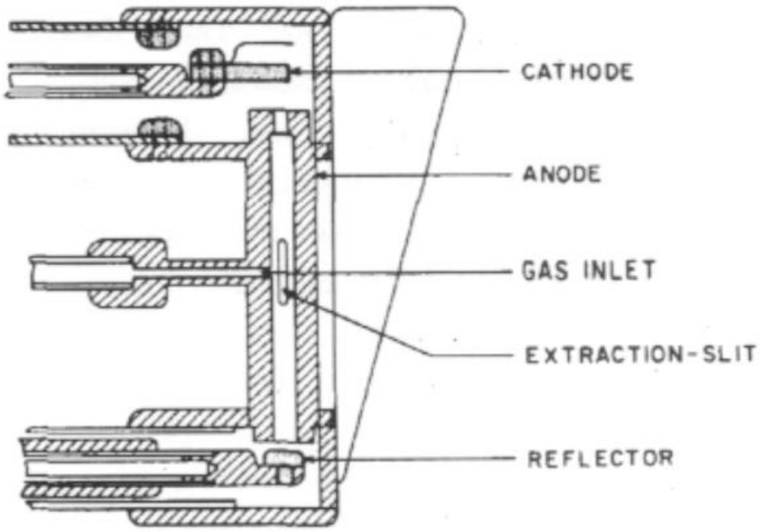
H- and electron currents in of axis extraction Duoplasmatron, as function if emission aperture displacement

Hollow Discharge Duoplasmatron

(V.Golubev at al. NIIEFA, 1972), 6 mA, Ie~0.5 A. Extende up to 18 mA after cesiation

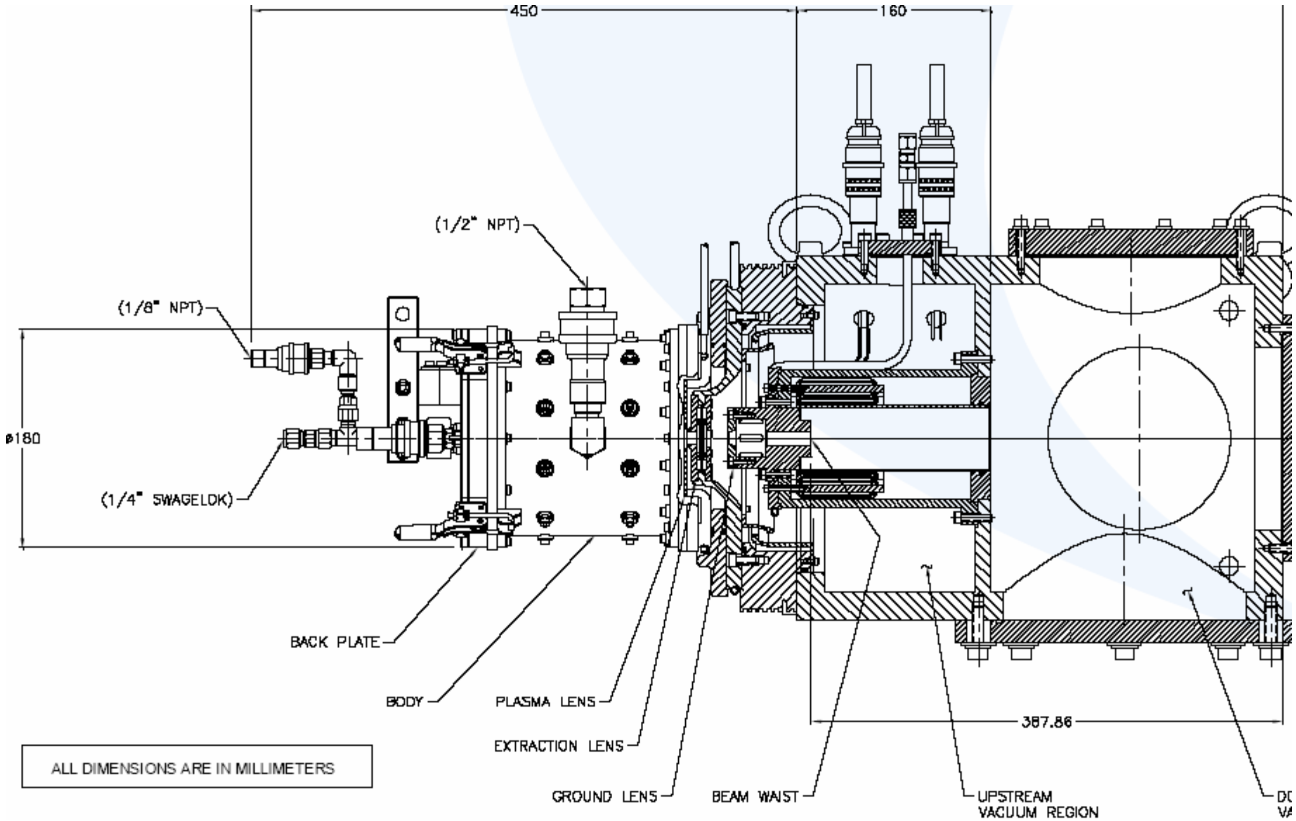


Ehler's type Penning source , 3 mA, Ie~50mA, extended to 40 mA H- after cesiation



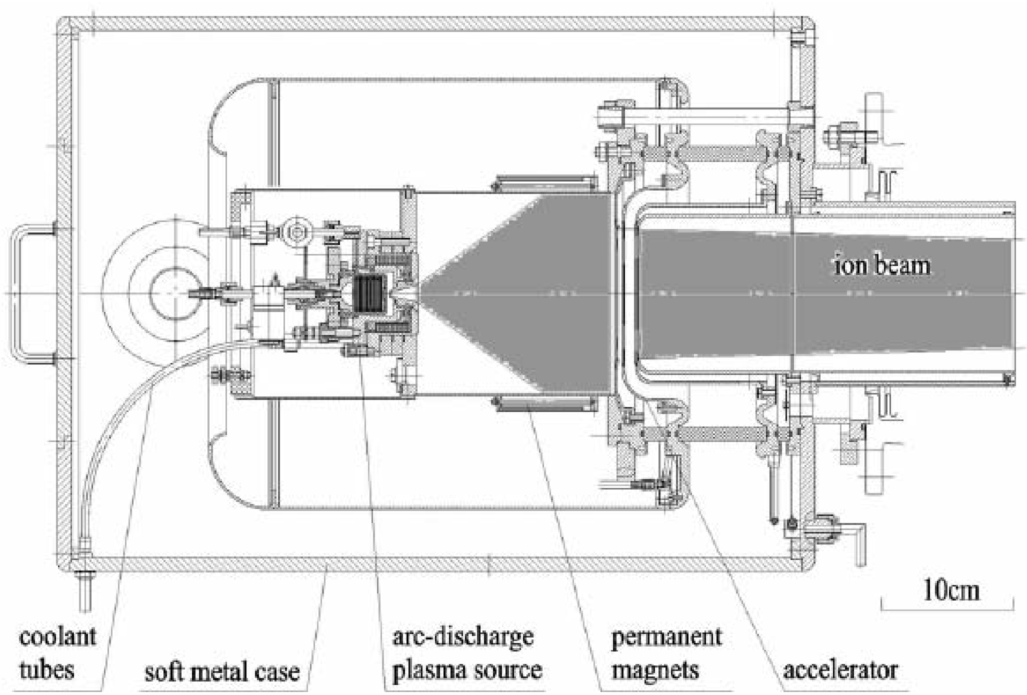
K. W. Eh1ers, B. F. Gavin and E. U Hubbard, Nuc1. Instr. and Meth. 22 (1963) 87.

Drawing of the TRIUMF (D-Pace) multicusp, filament-driven source, up to 15 mA, Ie~60mA, extended to 20 mA H- after cesiation, Je~9 mA/cm2



T. Kuo, D. Yuan, K. Jayamanna, M. McDonald, R. Baartman, P. Schmor,and G. Dutto, Rev. Sci. Instrum. **67**, 1314 (1996)..

H- Ch. Ex. source with expansion of plasma jet.
Dimov's Source, BINP 1962, 15 mA H- with H_2 target,
200 mA of D- and 10 mA He- with Na target.
Ions cooling to Ti~0.005 eV by expansion.



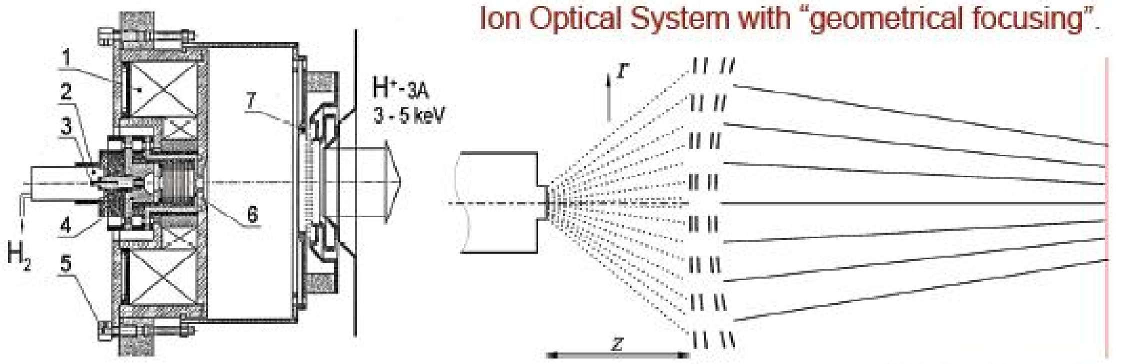
Ion sources at the Novosibirsk Institute of Nuclear Physics,

Belchenko Yu.I., , et al. Rev. Sci. Instrum. 61, 378-384 (1990).

H- Ch. Ex. source with expansion of plasma jet (Dimov's Source development) OPPIS, BNL, INR

Proton "cannon" of the atomic H injector.

Ion Optical System with "geometrical focusing".



The source produced 3 A ! pulsed proton current at 5.0 keV.

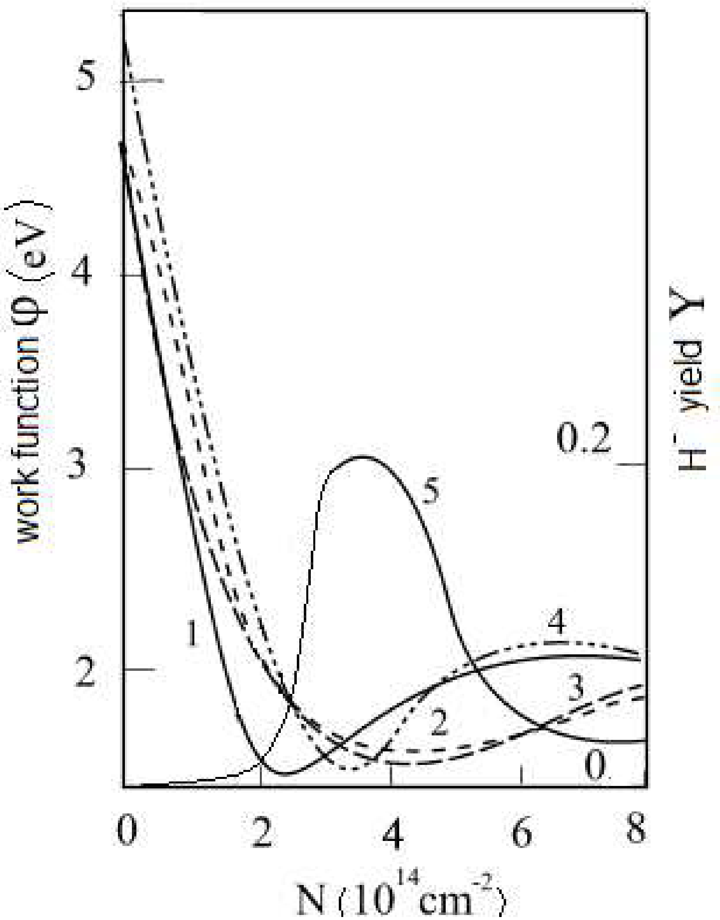
~20-50 mA H^- current. P=75-80%
~10 mA , P $\geq$ 90%.
~ 300 mA unpolarized H^- ion current.

Cesiation Effect

- **Cesiation effect, a significant enhancement of negative ion emission from gas discharges (from 1.5 mA to 15 mA) with decrease of co-extracted electron current below negative ion current was observed for the first time by location into discharge chamber a compound with one milligram of cesium on July 1, 1971 (7/1/71) in Institute of Nuclear Physics, Novosibirsk, Russia (Now BINP).**

- **This result was not published because was recognised as a "top secret" without permeation for publication. After strong effort of Gennadii Dimov it was permeated only application for patent (Author sertificat): Vadim Dudnikov,** "The Method for Negative Ion Production", SU patent, C1.H013/04, No 411542, Appl. 3/10/72.

Probability of H^- emission as function of work function (cesium coverage)



The surface work function decreases with deposition of impurities with low ionization potential and the probability of secondary negative ion emission increases greatly from the surface bombarded by plasma particles.

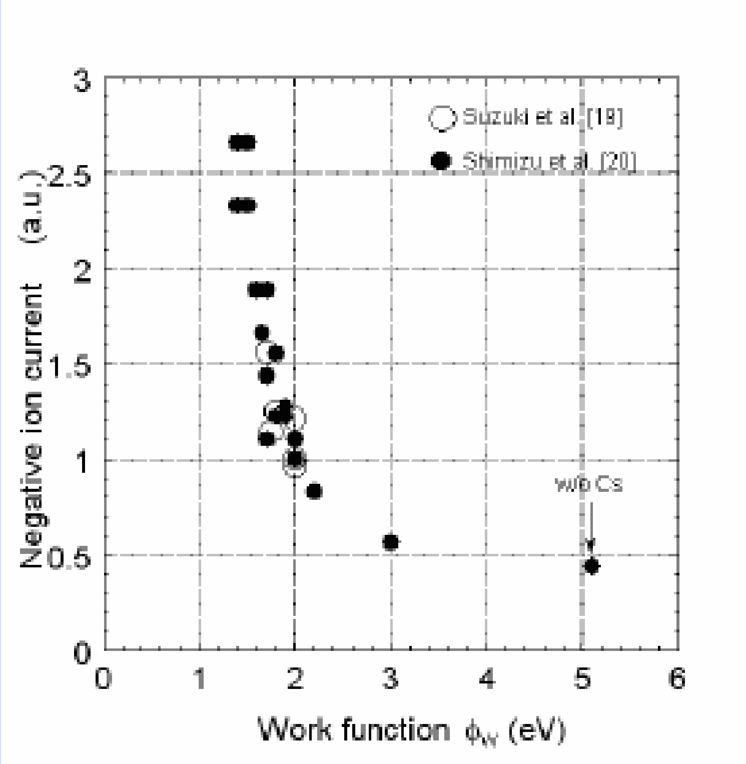
Dependences of work function on surface Cesium concentration N for different W crystalline surfaces: 1-(001); 2-(110); 3-(111); 4-(112) (left scale) and estimated relative yield Y of H- secondary emission for surface index (111) and particles energy ~3 eV (right scale).

Probability of H^- emission as function of work function

BEAM SOURCES FOR FUSION → **Negative ion sources**

KEK and JAERI measured the work function of the plasma grid and the negative ion current while introducing Cs into the source gradually.

The result is consistent with a negative ion current increase as the work function of the plasma grid surface is lowered.



SPS was developed (1971) by cooperation BDD, Yu. Belchenko, G. Dimov and V. Dudnikov

- **First International publication was permeated in 1974 when H- beam current was increased up to 0.9 A :**
- **BELCHENKO Y.I., DIMOV G.I., DUDNIKOV V.G., "POWEFUL INJECTOR OF NEUTRAL S WITH SURFACE PLASMA SOURCE OF NEGATIVE IONS", NUCLEAR FUSION Volume: 14 Issue: 1 Pages: 113-114 , 1974**

- **Before this publication it "was ringing, that in Dimov's Lab. was produced 200 mA of H- by admixture of Cs into the gas discharge". It was several publications in 1973-74 with statement "intensity of negative ion beams can be increased by injection of cesium into discharge" without any references but successful cesiation was not repeated at this time.**

Development of a Negative Ion-based Neutral Beam Injector in Novosibirsk

A.A.Ivanov, G.F.Abdrashitov, V.V.Anashin, A.N.Dranichnikov, Yu.I.Belchenko, A.V.Burdakov, V.I.Davydenko, P.P.Deichuli, G.I.Dimov, V.A.Kapitonov, V.V.Kolmogorov, A.A.Kondakov, S.G.Konstantinov, I.V.Shikhovtsev, N.V.Stupishin, A.L.Sanin, A.V.Sorokin, S.S.Popov, M.A.Tiunov, R.V.Voskoboinikov, V.V.Kobets, A.I.Gorbovsky, V.P.Belov, V.N.Khrestolubov

Budker Institute of Nuclear Physics, 630090 Novosibirsk, RUSSIA

M.Binderbauer, S.Putvinski, A.Smirnov, L.Sevier

Tri Alfa Energy Inc., Rancho Santa Margarita, CA 92688, USA

Multiaperture Negative Ion Source

Yu.I.Belchenko, A.I.Gorbovsky, A.A.Ivanov, S.G.Konstantinov, A.L.Sanin, I.V.Shikhovtsev, and M.A.Tiunov

Budker Institute of Nuclear Physics,
av. Lavrentieva 11, 630090, Novosibirsk, Russia

- Development of high brightness H^- sources was stimulated by first success of high current proton beam accumulation with using a charge-exchange injection [1] and supported by interest of “Star War” [2].
- A recent circumstance was the reason of difficulties and long delay of first publications, but nonofficial communication was relative fast.

- [1] G. Budker, G. Dimov, V. Dudnikov, Sov. Atomic. Energy, 22, 348, 1967; Proc. Int. Symp. on Electron and Positron Storage Ring, France, Sakley,1966, rep. VIII, 6.1 (1966).
- [2] C. Robinson, Aviation Week&Space Tech., p.42, Oct., 1978;
- Rev. Mod. Phys., 59(3), Part II (1987).

- At 1945 **N. Semenov** propose to suppress a nuclear explosion by irradiation of nuclear bomb by flux of neutrons.
- Big program of accelerator development was established.
- **V. Teplyakov** invent RFQ (**Teplyakov Accelerator**) in frame of this program.
- Similar idea was expressed by R. Welson (Physics Today, 2011).
- At 1968 (after development of charge exchange injection) **was** proposed to used a high energy neutral beams in space for irradiation of nuclear devises in satellites and development of high brightness negative ion source has been initiated.
- At 1977 in USA was started similar program involving all National Laboratories and European cooperation.
- BNL Symposiums were established sponsored by DOD and Strategic Defence Commander.
- Fortunately, DEVELOPMENT OF NEGATIVE ION SOURCES BECOME PEACEFUL DIRECTION AND BECOME A FIELD FOR INTERNATIONAL COOPERATION.

- **What were changed ?**
- **Staff working for development and use Surface Plasma Sources with cesiation was increased to**

  > thousand high qualified scientist, engineers, technicians, workers, administrators,...having excellent jobs.
- **Negative ion beam intensity were increased ~10**4 times from record 3 mA to >40 A.**
- **Cost of SPS was increased from ~1k$ to ~ M$.**
- **SPS with cesiation become "Sources of life and Working horces" for big installations such as SNS, LANSCE, BNL, Fermilab, ISIS, KEK,...JT 60, LHD...**
- **Under development SPS for LHC and for ITER**

Second Internal Symposium on Negative Ions, Beams and Sources (NIBS2010)

The author is grateful to many groups in different countries for courage and creativity in development and adaptation of the SPS with cesiation for many applications.

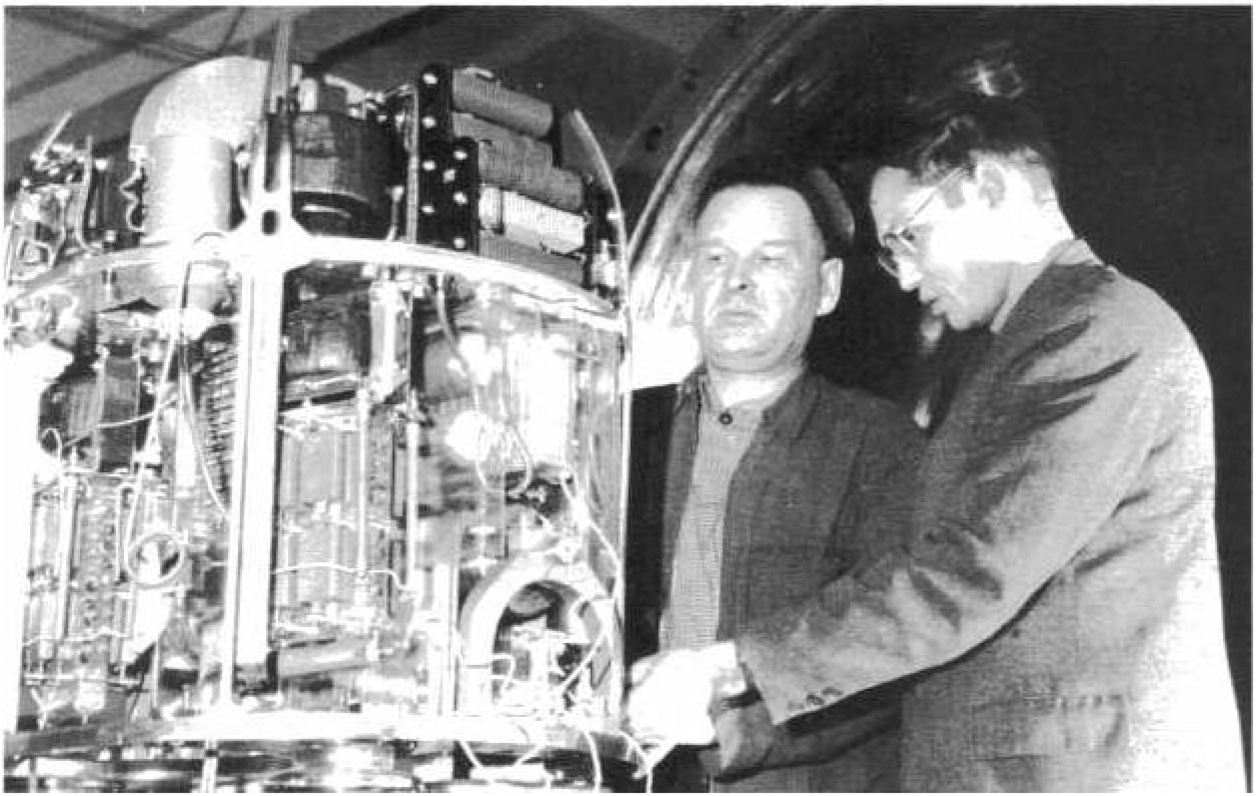
Participants: Total 94

Japan 41, USA 9, France 9 , India 7, Germany 6, Italia 5, Korea 3, UK 3, Switzerland 3, Russia 2, Finland 2, Bulgaria 2, China 1, Netherlands 1

Conference Presentation: Total 94

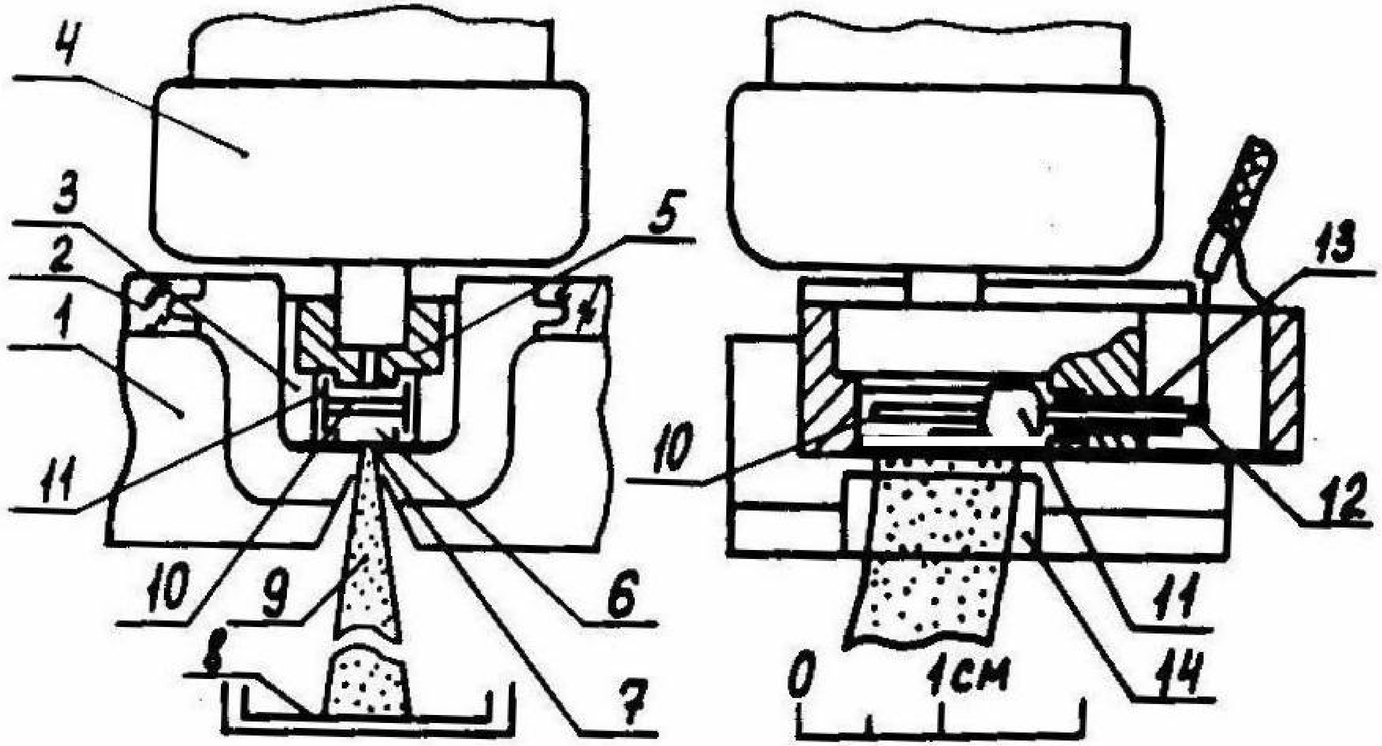
Review talk 3, Oral talk 43, Poster presentation 48

Charge exchange injection was developed (1965) with using of Ehlers type H- source in high voltage terminal of Van de Graf accelerator (1 mA, 1.5 MeV) in high pressure gas tank

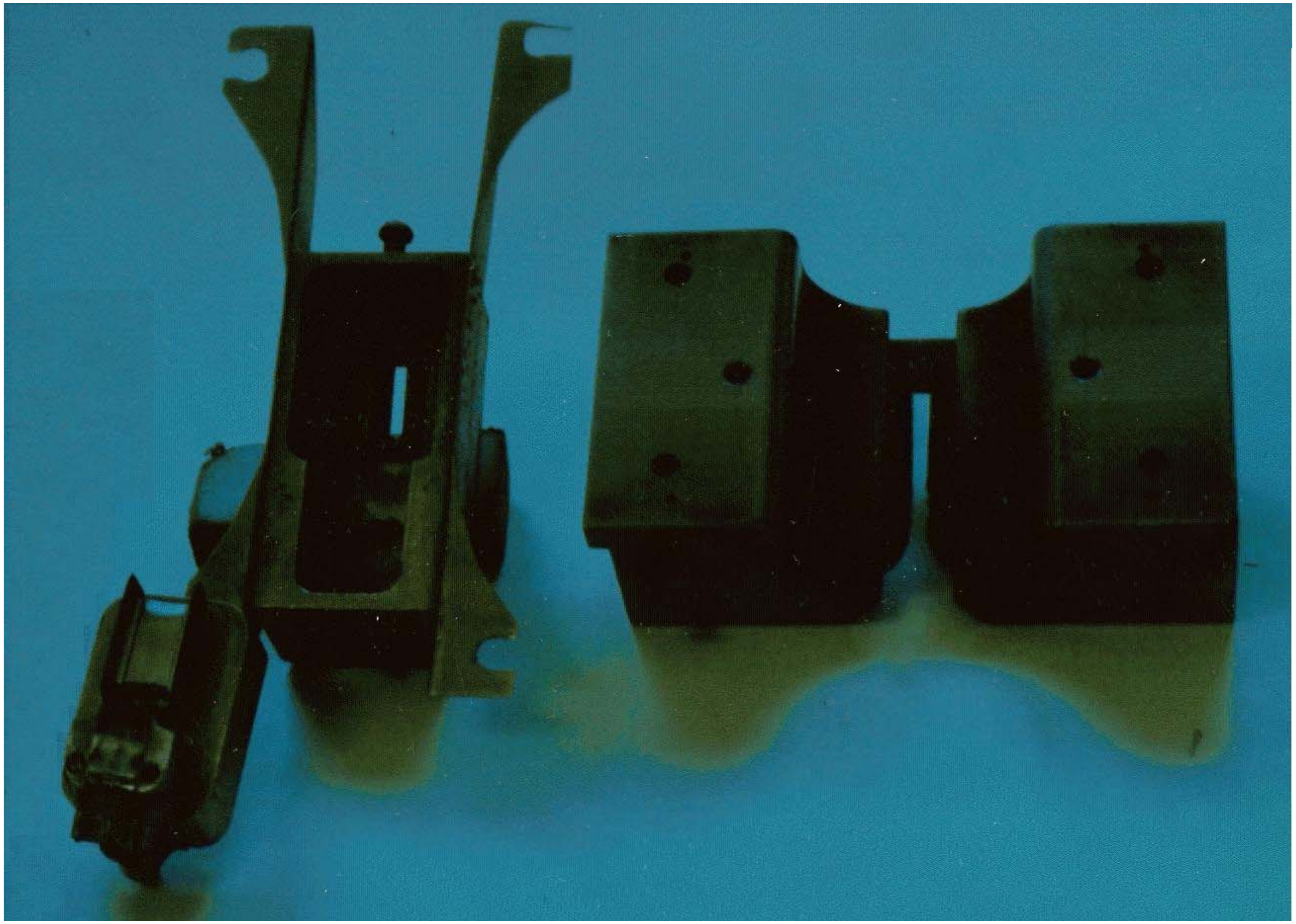


First version of Planotron (Plain Magnetron) SPS, INP, 1971,

Beam current up to 230 mA, 1.5x10 mm^2 , J=1.5 A/cm^2 with Cs



First version of Planotron (Plain Magnetron) SPS, INP, 1971, Beam current up to 230 mA, 1.5x10 mm2 , J=1.5 A/cm2 with Cs



First Cesiation July 1, 1971 (Cs2CrO4 + Ti; ~mg, heated by discharge)

1.VI.71. различные формы →

1) Не хватает давления газа.
2) Короткий слой на катод.

бархатка – 63 [illegible]

$\boxed{1/\text{VII}-71.}$!

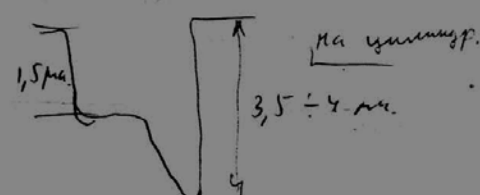
Изменили геометрию щели.

катод Ti.

Вставлена таблетка цезия. 11 отверстий [illegible]

общий ток увеличился (в среднем с 2 ма до 1 ма). 3 гц.

форма. всплеск.



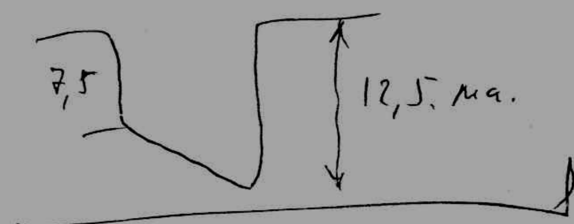
после 20 минут работы.

по-видимому, выброс в конце обусловлен поступлением цезия в объем.

Изменили геометрию.

На катод положили Cs. таблетки.

при частоте 2 герца устойчивая картинка.



$P_{H_2} = 11$ атм.

$U_{отс.} \simeq 8$ кв.

$B = 50$ дел.

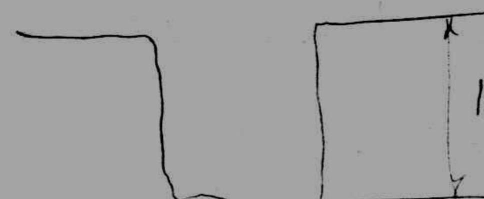
от этих параметров зависит слабо.

при выключении запуска $U_{бат.} = 2,1$ кв.

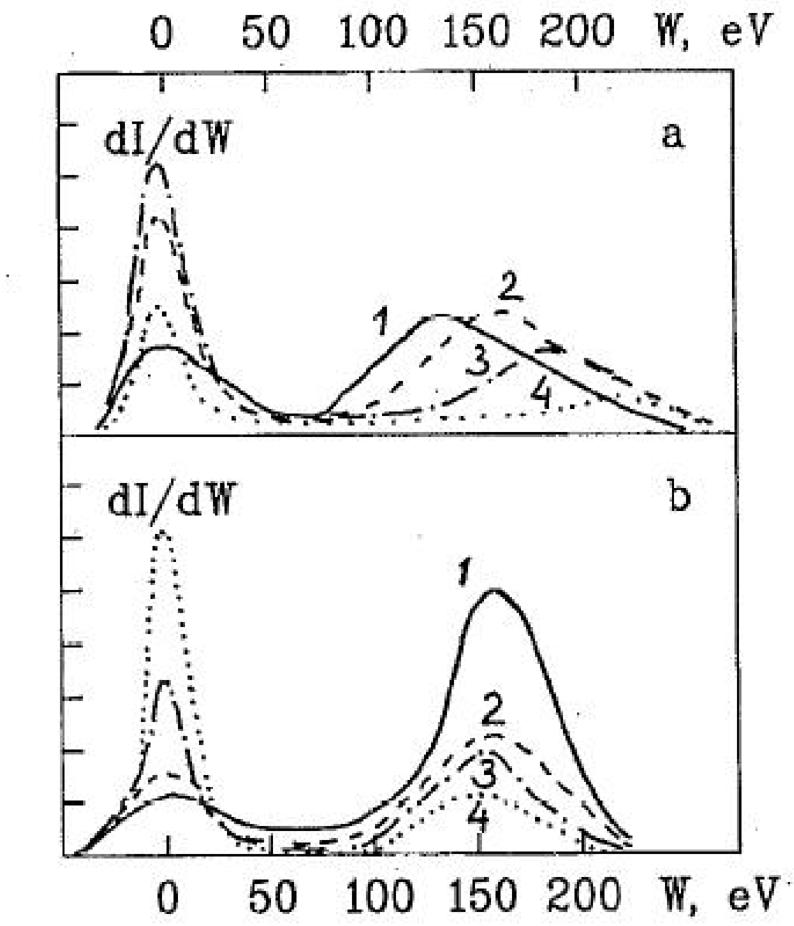
после

при $f = 3$ гц.

после выкл. запуска $U_{б.} = 2,2$ кв.

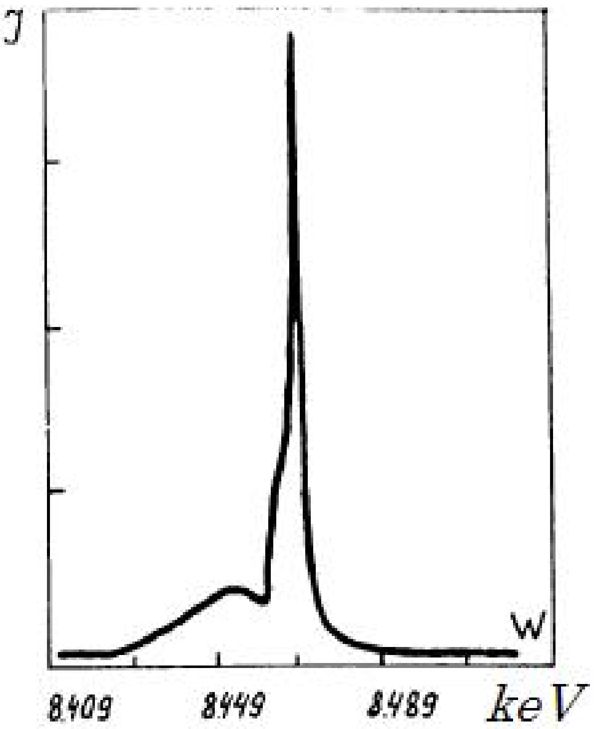


H- energy spectra from planotron



The ion spectra from a planotron usually have two peaks separated by a valley. The location of the first peak coincides with the energy *eUex* imparted to the negative ions by the extraction voltage. The ion energy of the second peak is higher than that of the first peak by an amount close to *eUd*. The oscillograms in the upper part of illustrate the change in the spectra, as a result of increasing the discharge voltage *Ud* from *120 V* (1) to *210 V* (4) by reducing the cesium supply. The oscillograms (1-4) in the lower part of *Figure* illustrated how the spectra vary as a result of increasing the hydrogen supply to the discharge chamber

H- Energy Spectra from Penning SPS

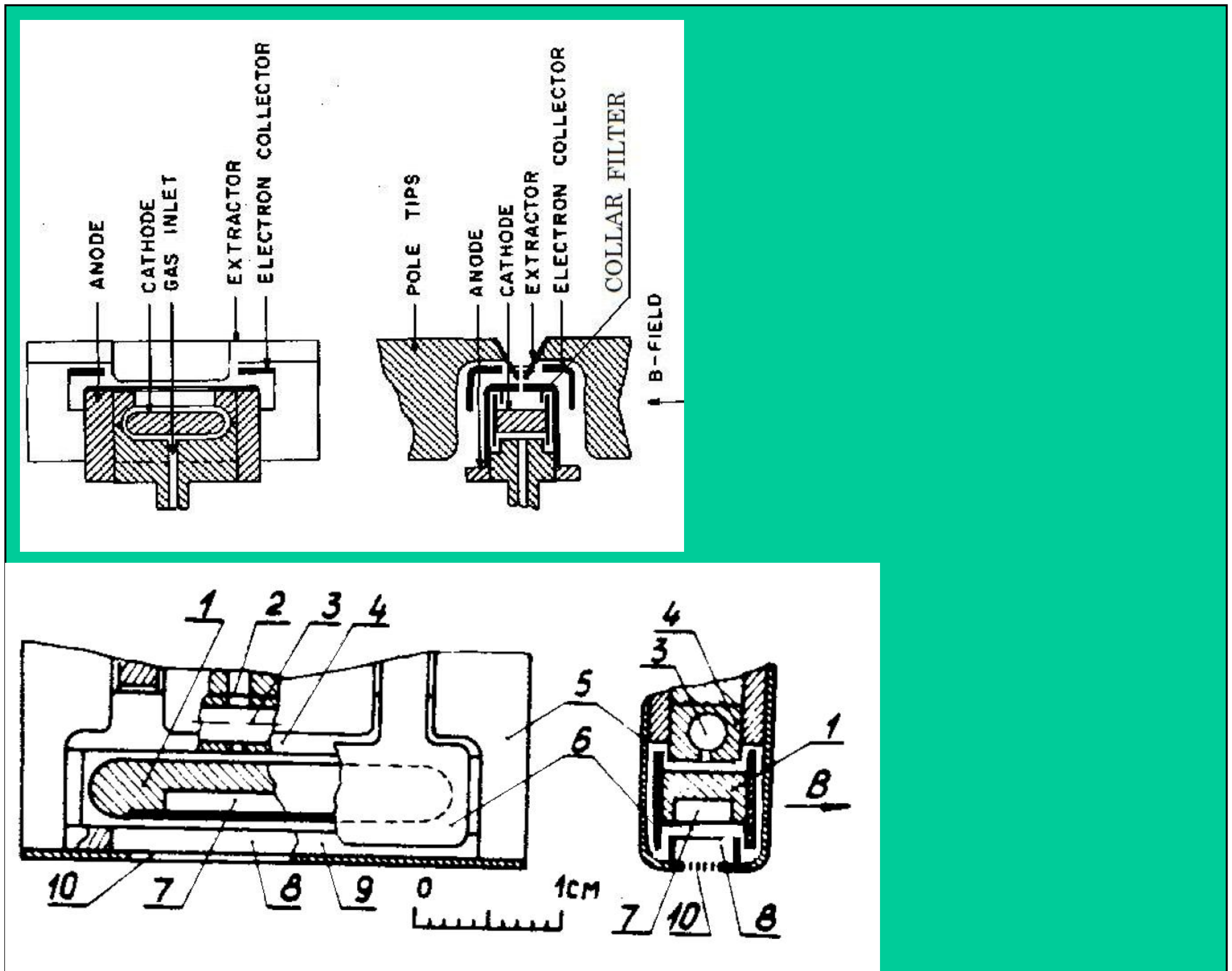


H- formation by secondary emission from surface and charge exchange with cold H atoms.

Anode surface-plasma generation and charge exchange cooling.

High brightness.

Cross sections of Planotron (Magnetron) SPS of second generation: 3.7 A/cm^2 with Cs (0.75 A/cm^2 without Cs)

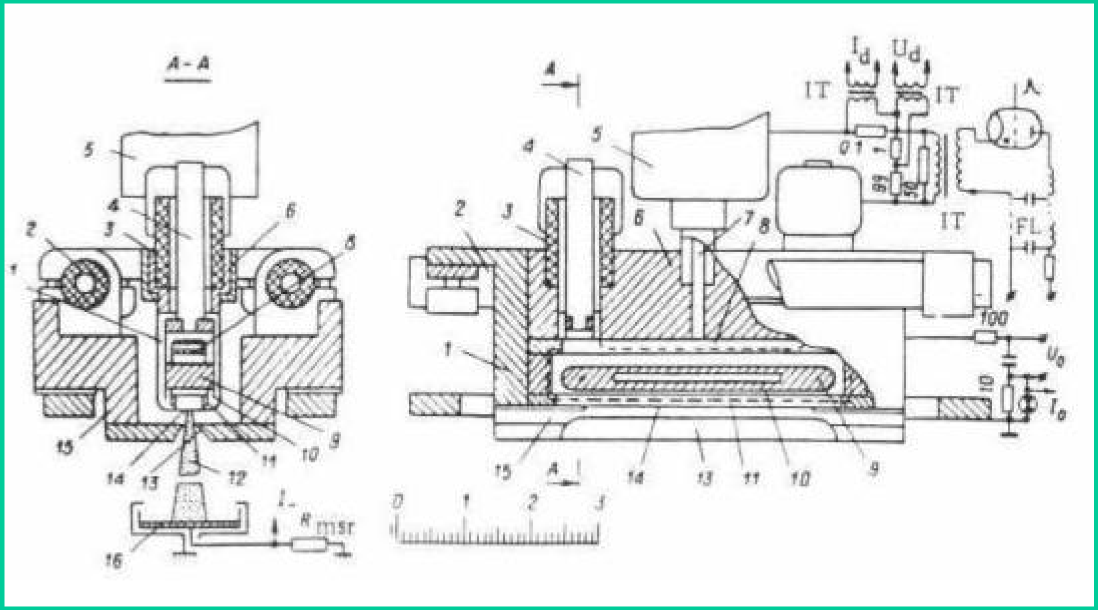


3x10 mm^2

0.9 A, H-

1 ms, 10Hz

Cross sections of Planotron (Magnetron) SPS of second generation: 1x30 mm2; 0.9 A, 1ms, 10Hz

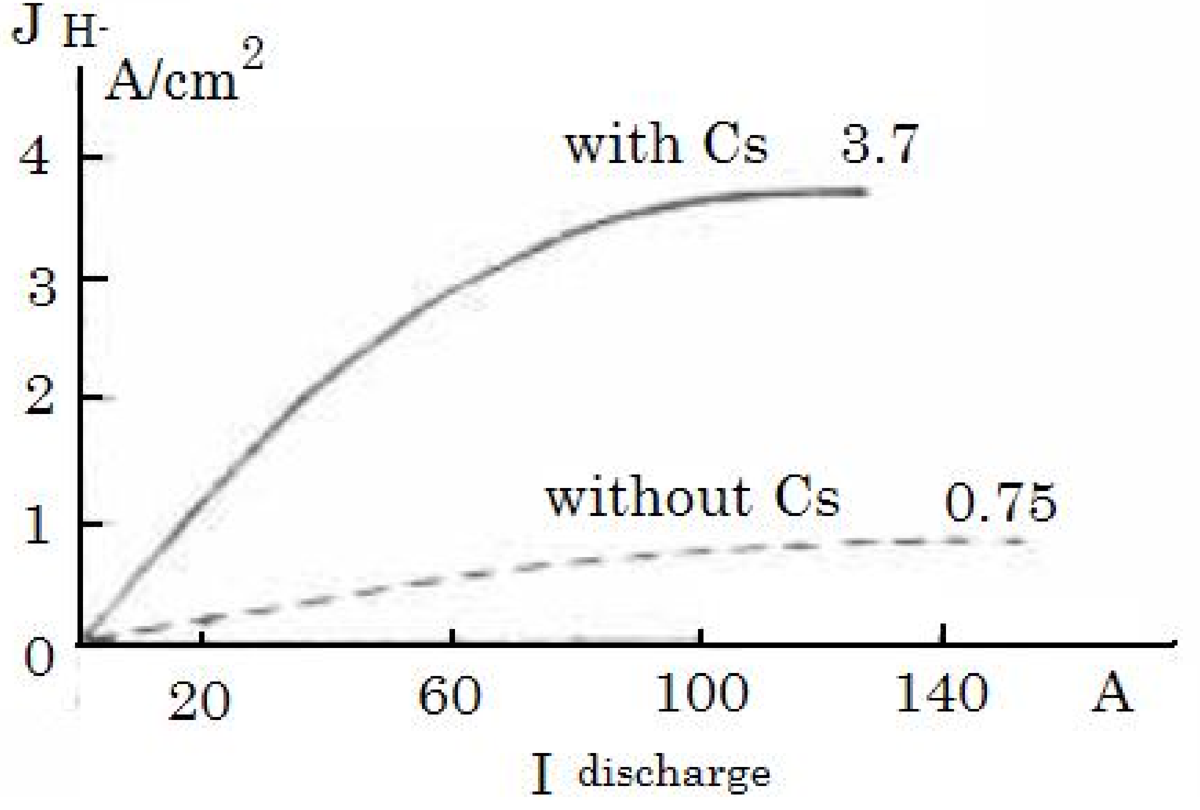


1x30 mm^2

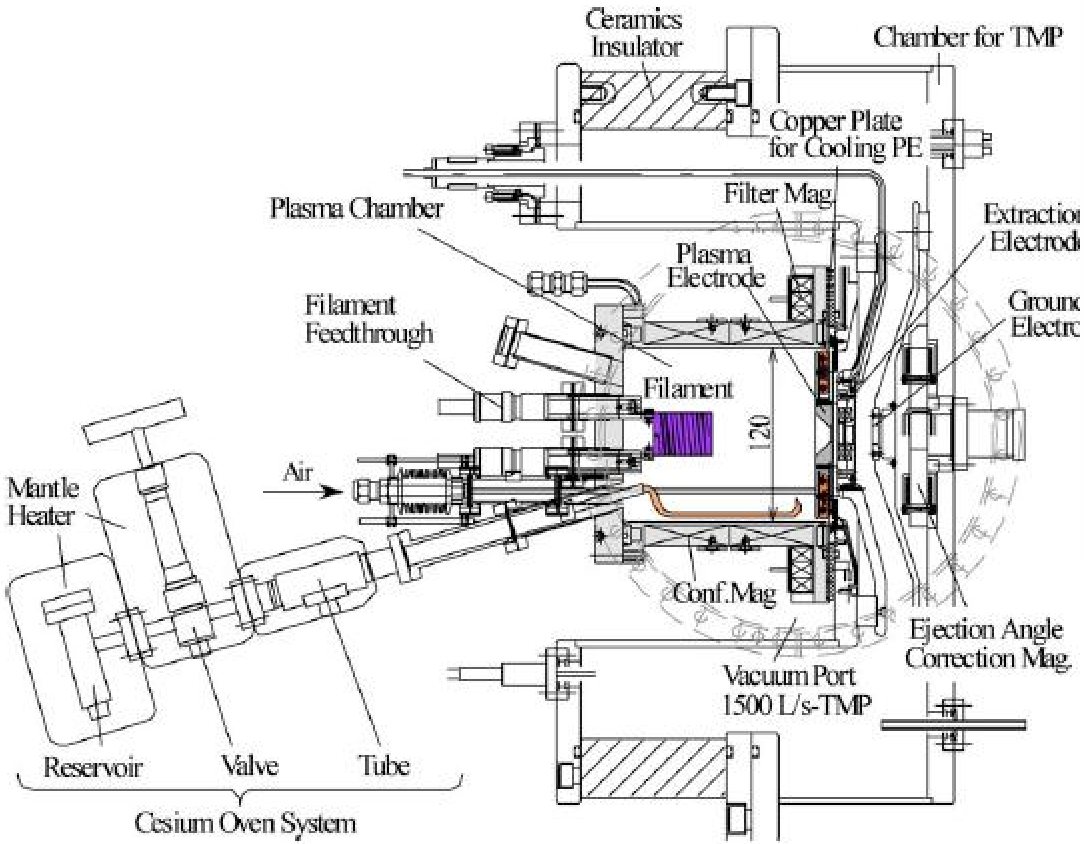
0.9 A, H-

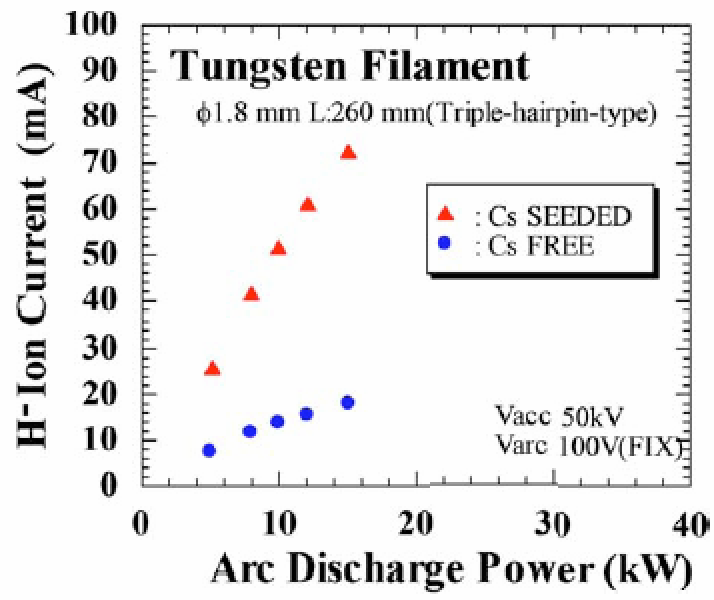
1 ms, 10Hz

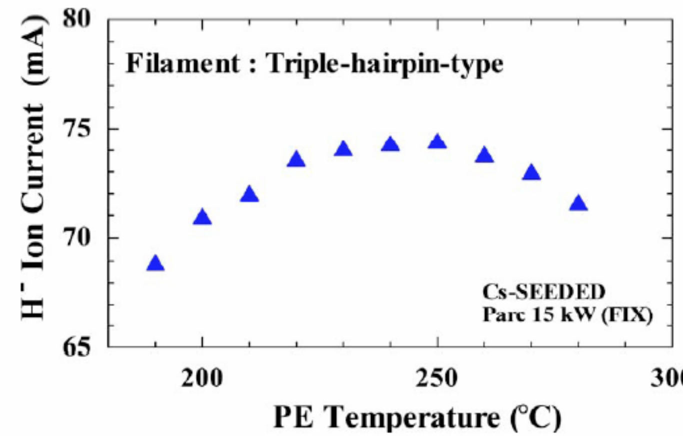
H- current density from planotron with Cs ($3.7 A/cm^2$) and without Cs ($0.75 A/cm^2$), INP, Novosibirsk, 1972



Cross-sectional view of J-PARC test ion source







SPS for Accelerators was developed in cooperation with G. Derevyankin

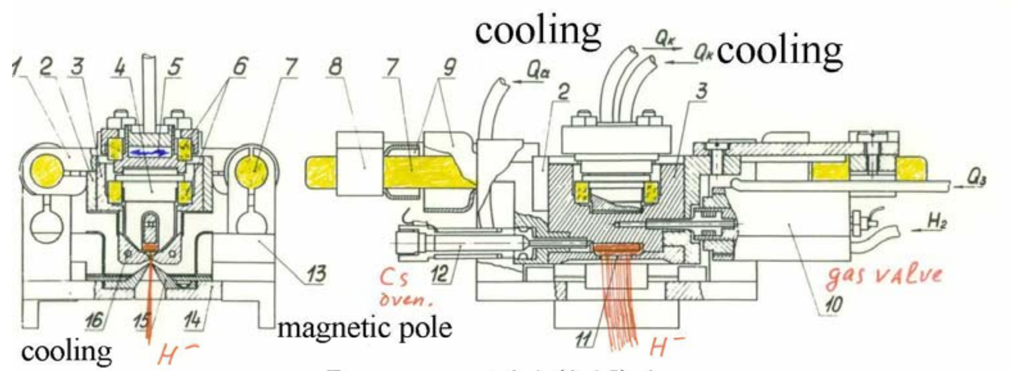
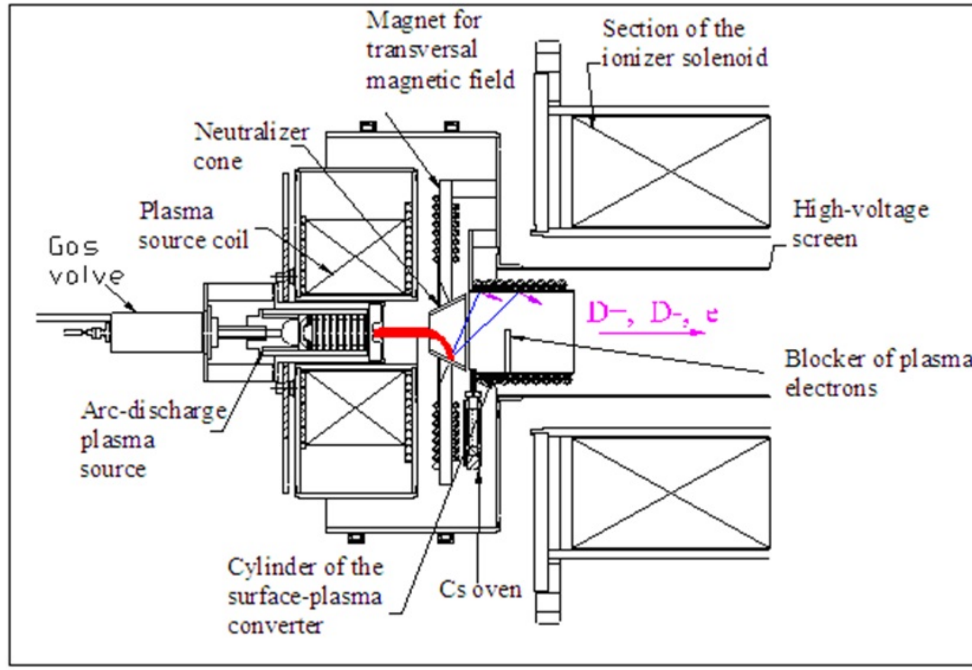


FIG. 8. Surface-plasma negative ion source with Penning discharge (Dudnikov type ion source). (1) support; (2) gas discharge chamber; (3) anode insert; (4) cathode; (5) cathode cooler; (6) cathode insulator; (7) high-voltage insulator; (8) support; (9) insulator screens; (10) gas valve; (11) emission slit; (12) cesium container; (13) magnetic pole; (14) base plate; (15) extractor; (16) cooling channal.

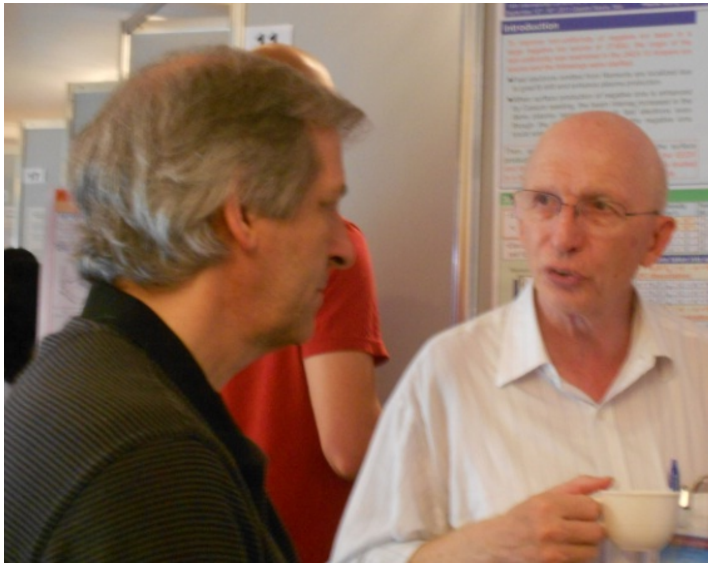
Rev. Sci. Inst. 61(1) 378(1990) 381

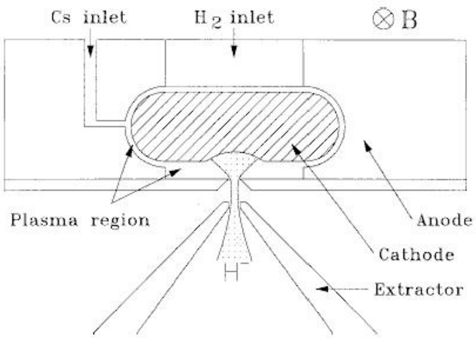
Beam current 0.1 (0.15) A,
Extraction 22 kV
Repetition 100 Hz(teste up to 400Hz)
Puls 0.25 ms
discharge volume 6x3.5x15 mm^3
emission slit 0.5x10mm^2

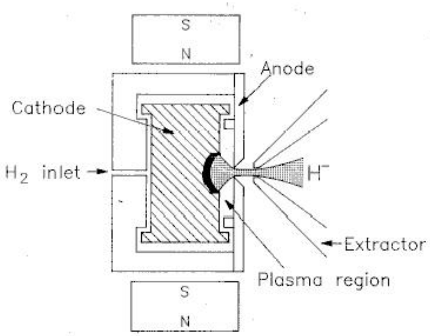
Team of INR adopting SPS in INP LINAC, Polarized H-/D- source development.
A. Belov, V.Klenov



BNL team magnetron SPS adaptation for NF and BNL linac. T. Sluyters, C. Prelec, J. Alessi; BNL SYMPOSIUMS.

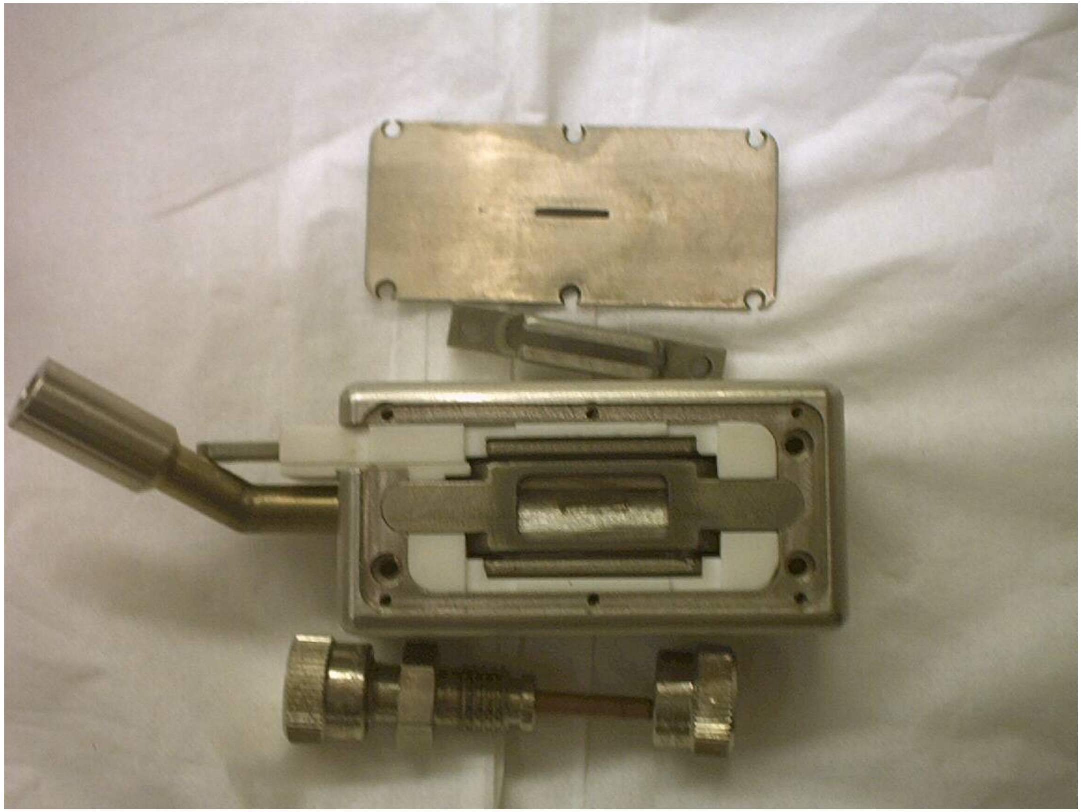




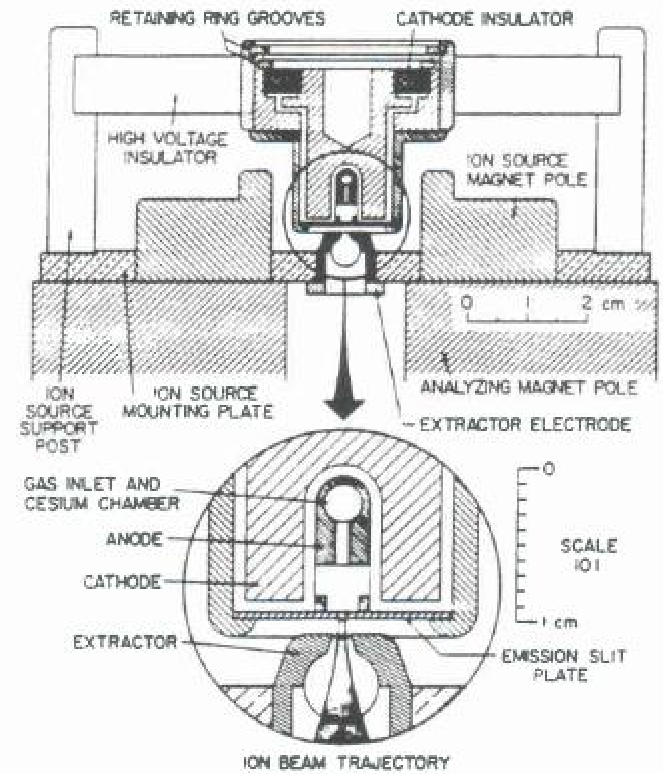


LBL Team developing Large Volume SPS with cesiation,
K. Ehlers

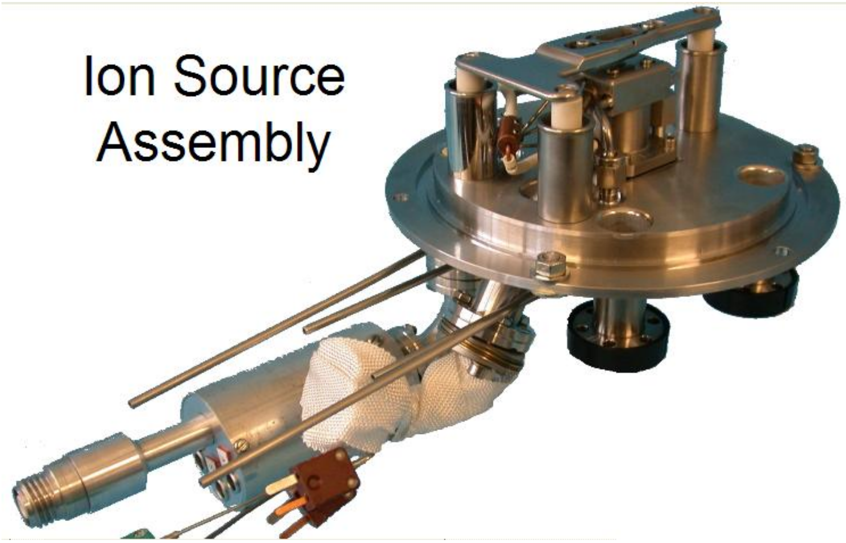
FermiLab team: magnetron SPS adaptation for FNAL, INPS, DESY linacs. Ch. Schmidt



Los Alamos team (P. Allison group) for high brightness H- beam production.



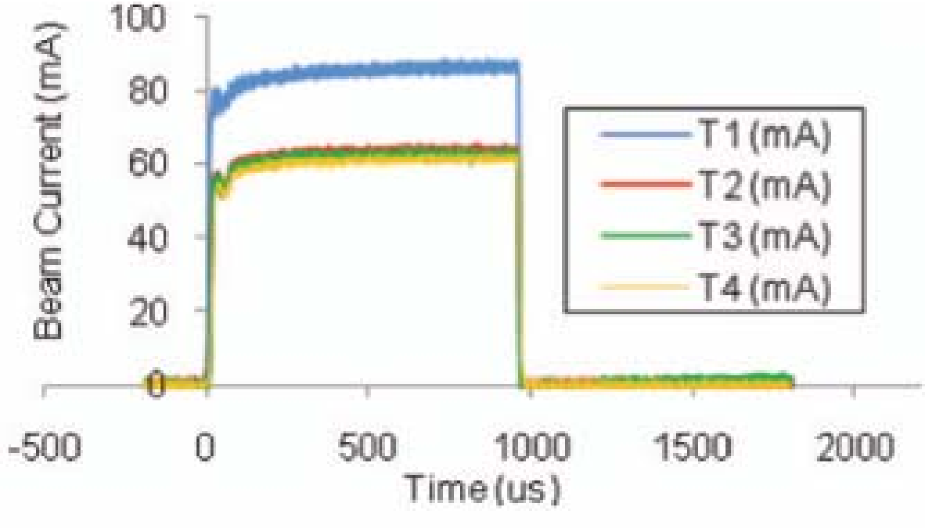
RAL ISIS team adopting PD SPS in ISIS

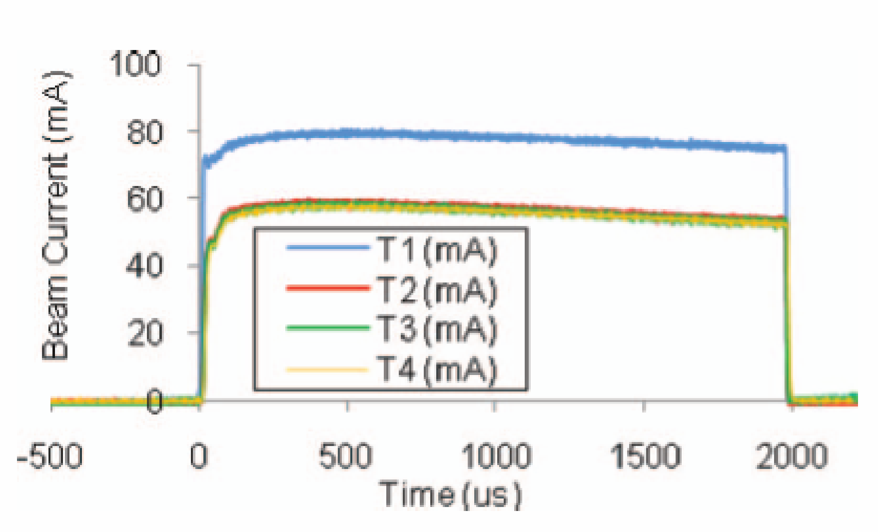


Penning Discharge SPS

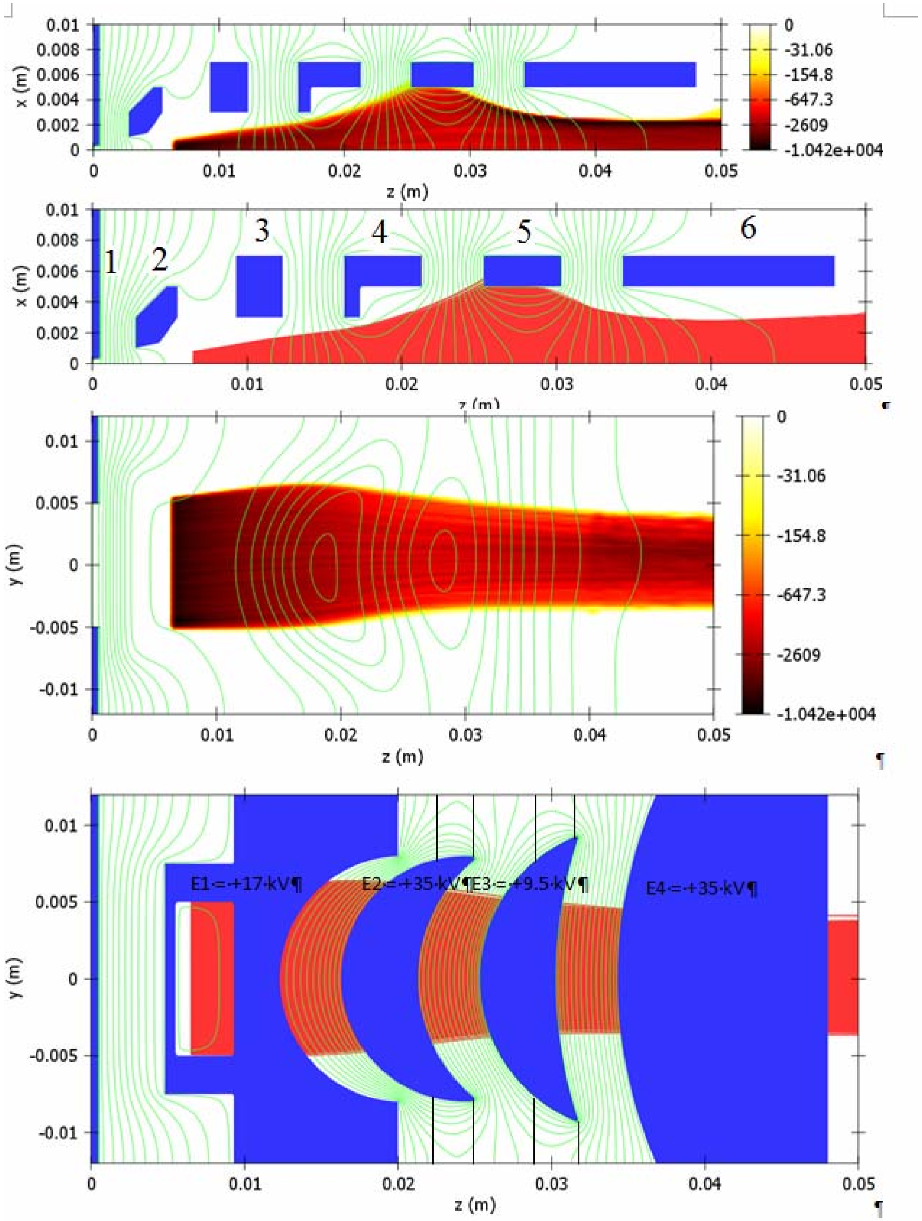
- The operational ISIS PD SPS has very small discharge cell (5x3x11 mm^3) and for noiseless discharge production it is necessary to use a high gas and cesium density. A narrow 0.6 mm emission slit is needed to prevent extraction voltage arcing. Very high emission current densities of 1.5 A/cm^2 and high discharge current densities of J~150 A/cm^2 are destructive for discharge cell electrodes. However, it can operate for up to 48 days (1100 hours) with pulsed beam current ~50 mA after bending magnet with discharge duty factor 2.5%
- To use a more relaxed discharge parameter and corresponding increased lifetime it is necessary to produce the noiseless discharges with low gas and cesium density (like in large volume SPS). Experiments with modified discharge cells for noiseless discharge production are described below.

RAL, ISIS PD SPS; Beam current profiles of at 50 Hz 1 ms. (1.2 ms, 60 A discharge, 19.6 kV extraction voltage, 65 keV beam, 180 ◦ C cesium oven, Q=16 sccm H_2.)





Simulation CSPS with transaxial lenses



1—plasma electrode with emission slit;

2-extraction electrode;

3-grounded electrode of transaxial immersion lens;

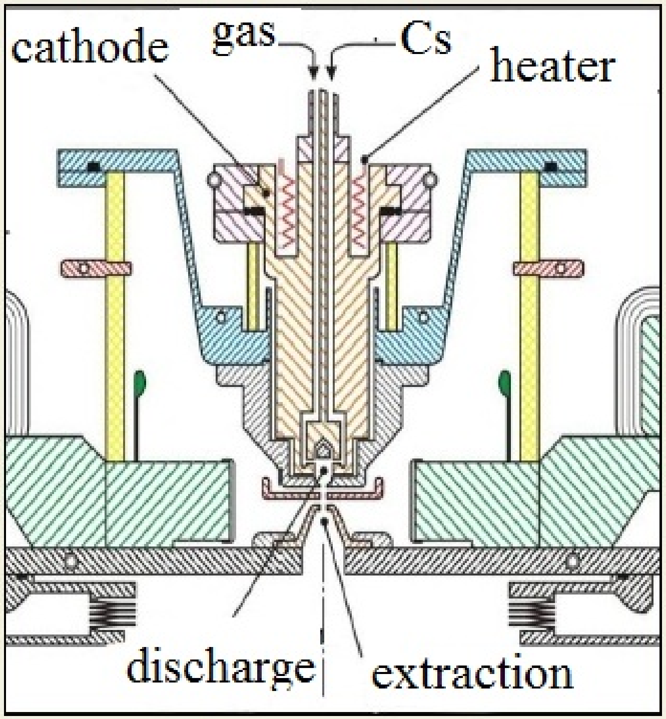
4-first transaxial lens ;

5- second transaxial lens.

H- beam 100 mA, 17 ++18 keV

IBSimu, S. Lawrie.

DC SPS with Penning discharge (BINP)
A.Sanin et al, P-214, poster session



Penning discharge SPS

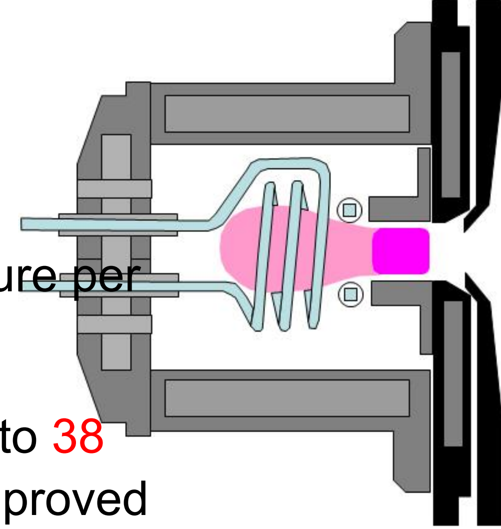
CW H- beam 25 mA

DC H- beam up to 25 mA at 0.8 kW of discharge power

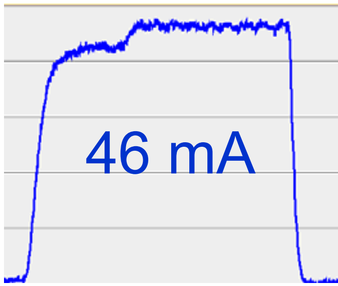
VITA BNCT. BINP-NGU team.

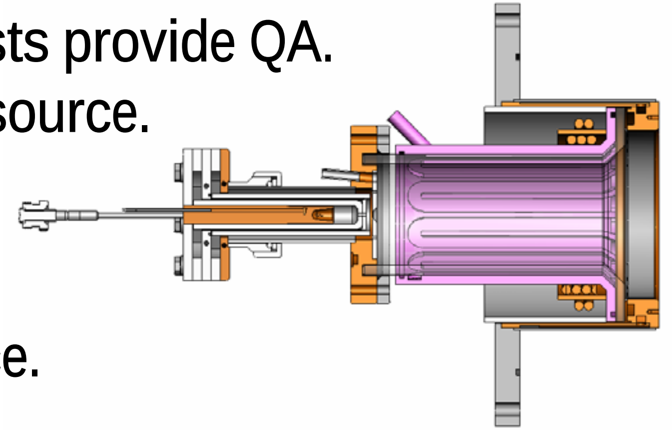
Supported by DOE grant through BTG, Inc as business partner 1.3 M$

The State of the SNS Ion Source (M. Stockli) :



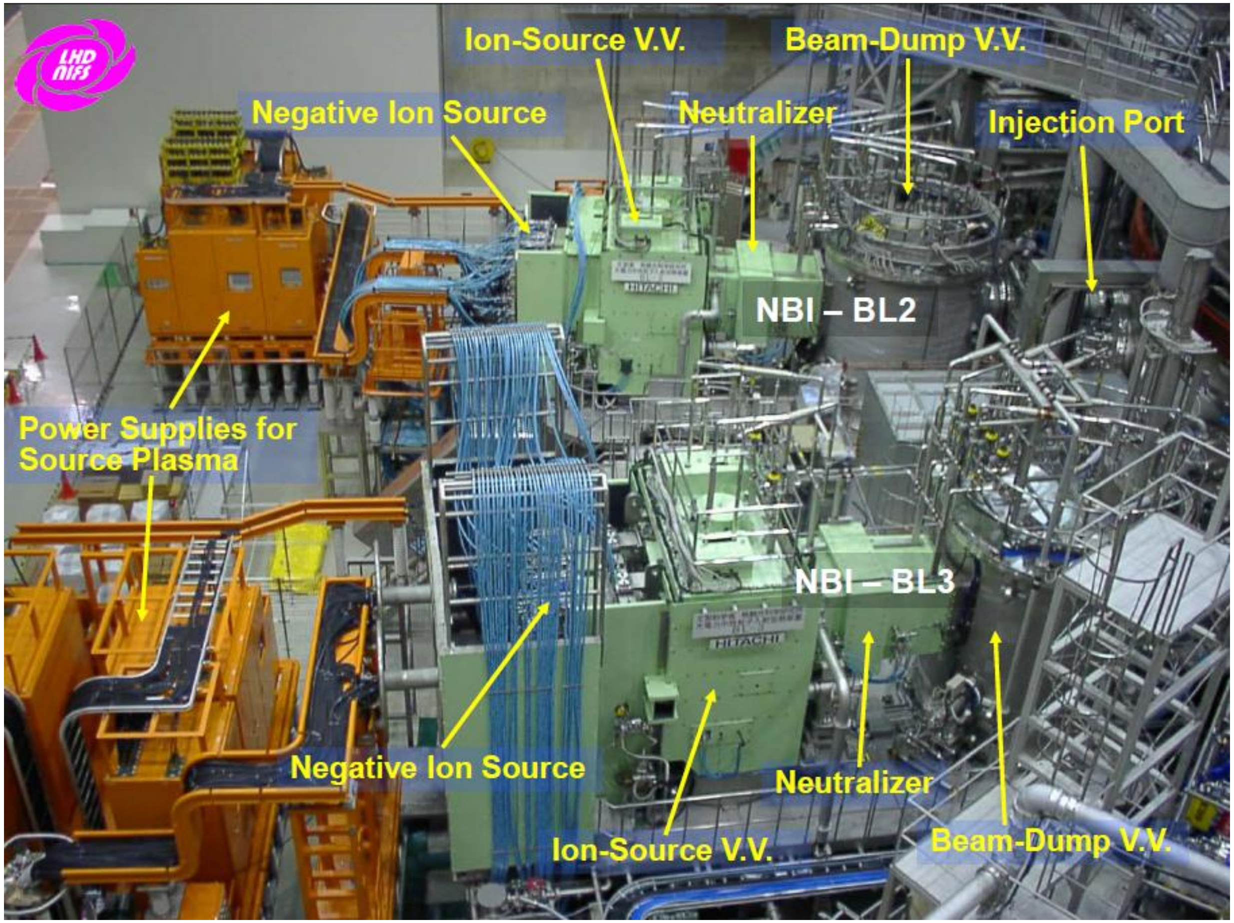
- The source duty factor has been increased from 4 to 5.4%.
- The source life cycle has been increased from 3 to 4 weeks.
- The source availability remains >99.5% due to one antenna failure per ~20 week run.
- The cesiation period has been reduced from 30 to 20 minutes.
- The “routine” LINAC beam current has been increased from 32 to 38 mA, mainly by capitalizing on the higher e-dump voltage and improved alignments. We have reached the 1.4 MW requirement.
- Tighter source assemblies have lowered the H_2 consumption.
- Optimized pumping have reduced the LEBT beam losses by ~30%.
- One 4-week run was executed with 42 mA MEBT beam current.
- 46 mA were demonstrated for 32 hours in the MEBT beam stop.
- The focus was on availability an therefore no attempt was made to break the 56 mA record of 11-2008.
- We have completely proceduralized the ion source refurbishments, replacements and startup. Checklists provide QA.
- We thank LBNL for developing a highly capable H^- source.



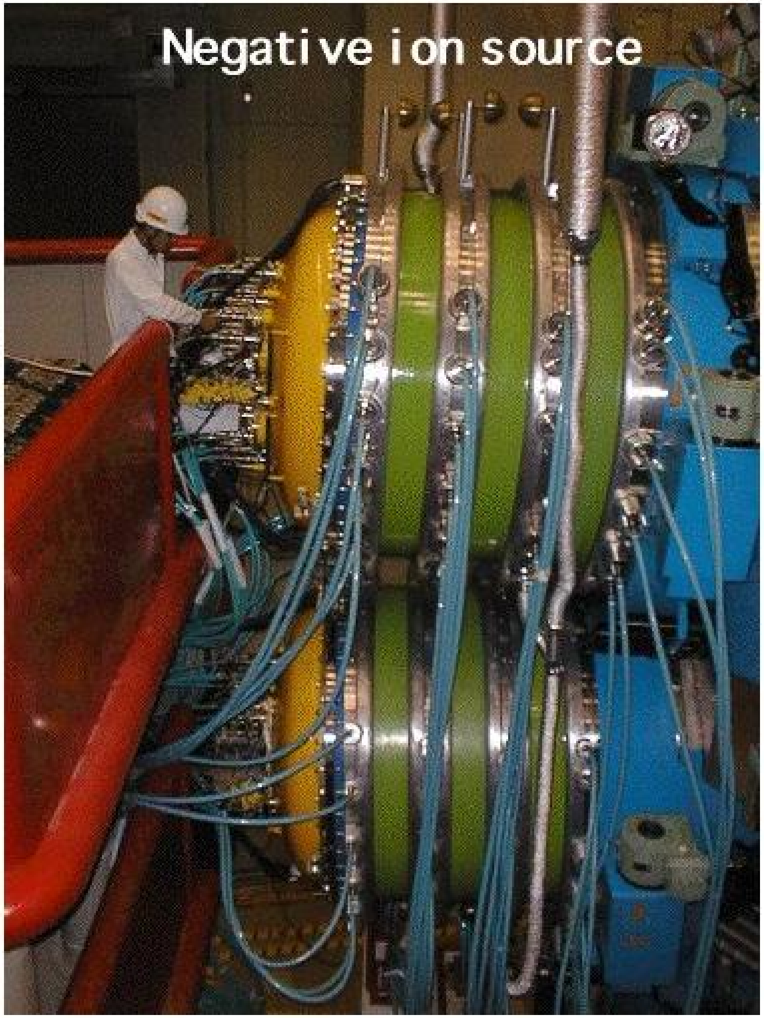


- We continue to develop better RF power systems.
- We continue to develop the external antenna source.

Fantastic work of Japanese teams for development of LV SPS with cesiation for NBI



Negative Ion Sources for JT-60U



H-/D- LV SPS for Tokomak Neutral Beam Injectors

~40A, ~1 MeV, 1000s,…

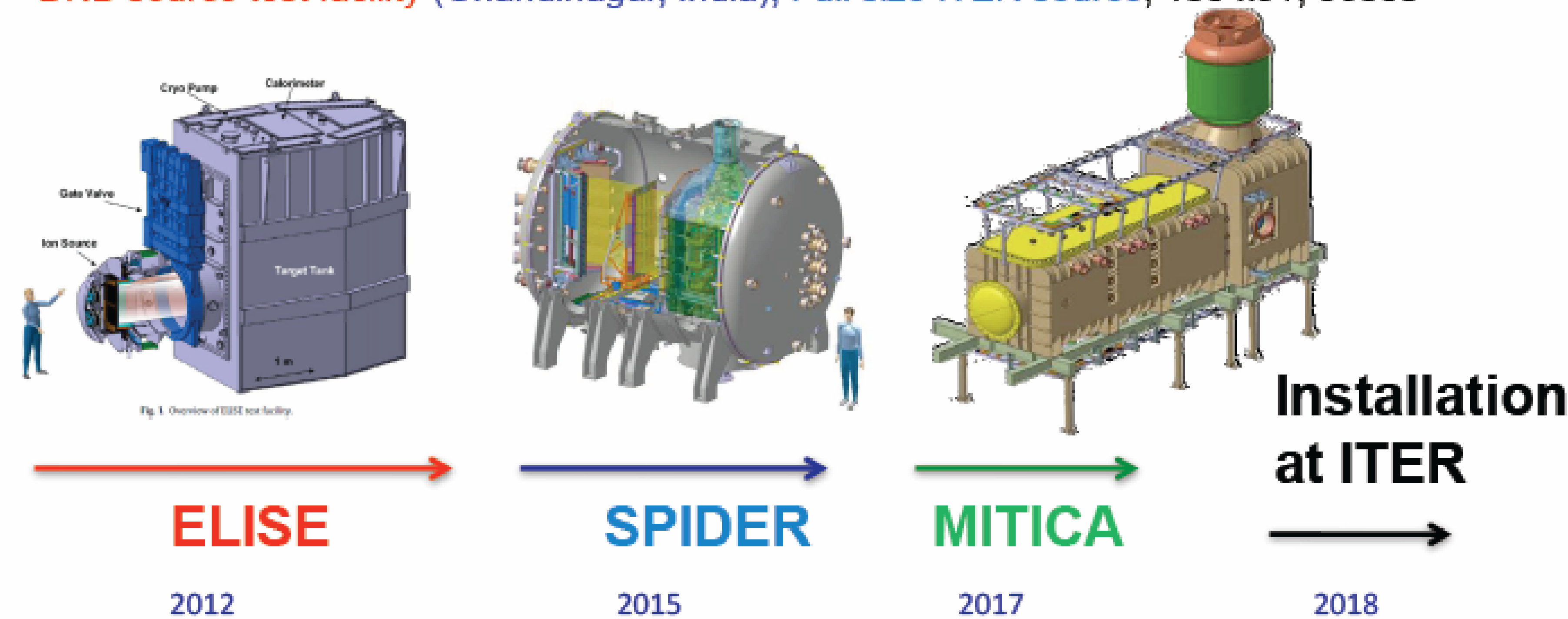
~1 Billion $

Parameters of NBI for Fusion

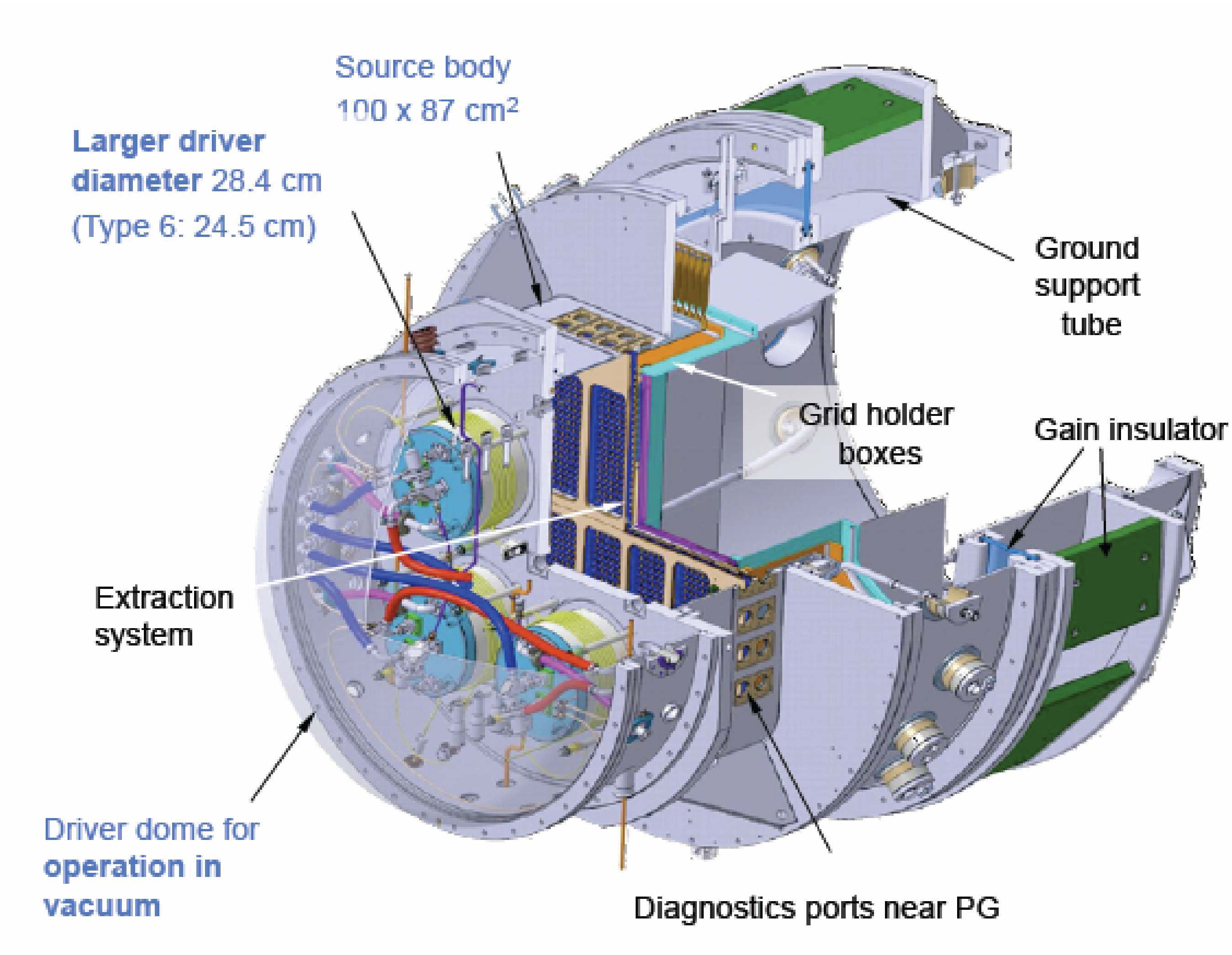
		ITER (rf)	LHD (arc)	JAEA JT60U (arc)		JAEA MV TF (arc)	IPP (rf source)	
Species		D^-	H^-	D^-	H^-	H^-	H^-	D^-
Energy	MeV	1000	180	400		937		
Voltage holding	MV	1000	190	500		1000		
Source height	m	1.95	1.45	1.22			0.59	
Source width	m	1.55	0.35	0.64			0.3	
No. of apertures		1280	770	1080				
Accelerated current	A	40	30	17		0.33	1.4	
Source power	kW	800	180	350			100	
Extracted current density	A/m^2	285	250			144		280
Pulse length	s	3600	2	2		2	3600	4

Fantastic work of ITER, Italian, India teams for development of LV SPS with cesiation for NBI

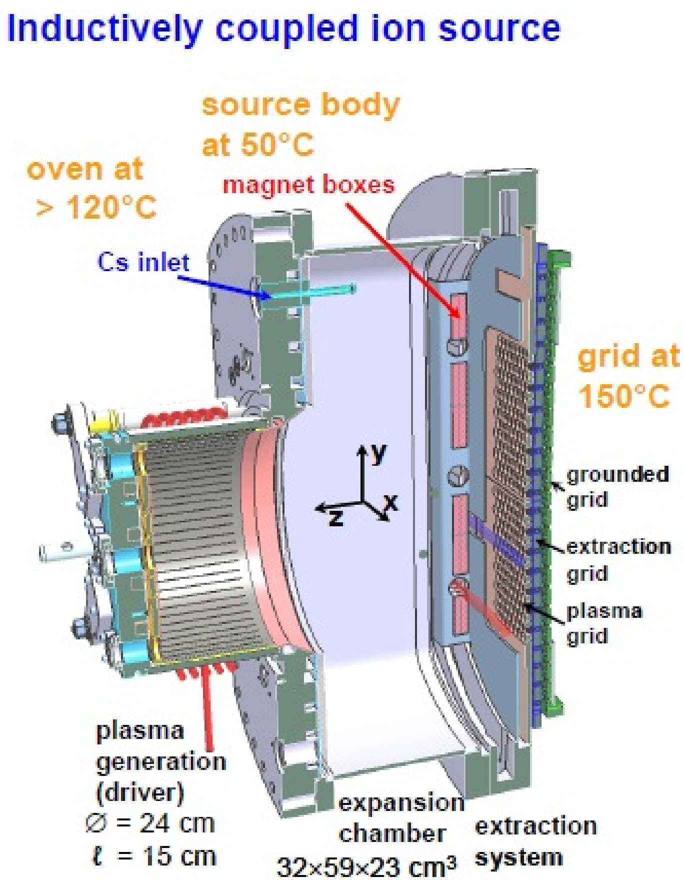
- ELISE (IPP Garching): Half-size ITER-type source in cw operation with 60 kV/10s beam extraction.
  → to assess spatial uniformity of negative ion flux, validate or alter source concept
- SPIDER (RFX, Padua): Full size ITER source with full extraction voltage 100 keV, 3600s → to validate or alter source and extractor
- MITICA (RFX, Padua): Full size ITER source, 1 MeV, 3600s
  → to validate or alter accelerator and beamline components
- DNB source test facility (Ghandinagar, India), Full size ITER source, 100 keV, 3600s

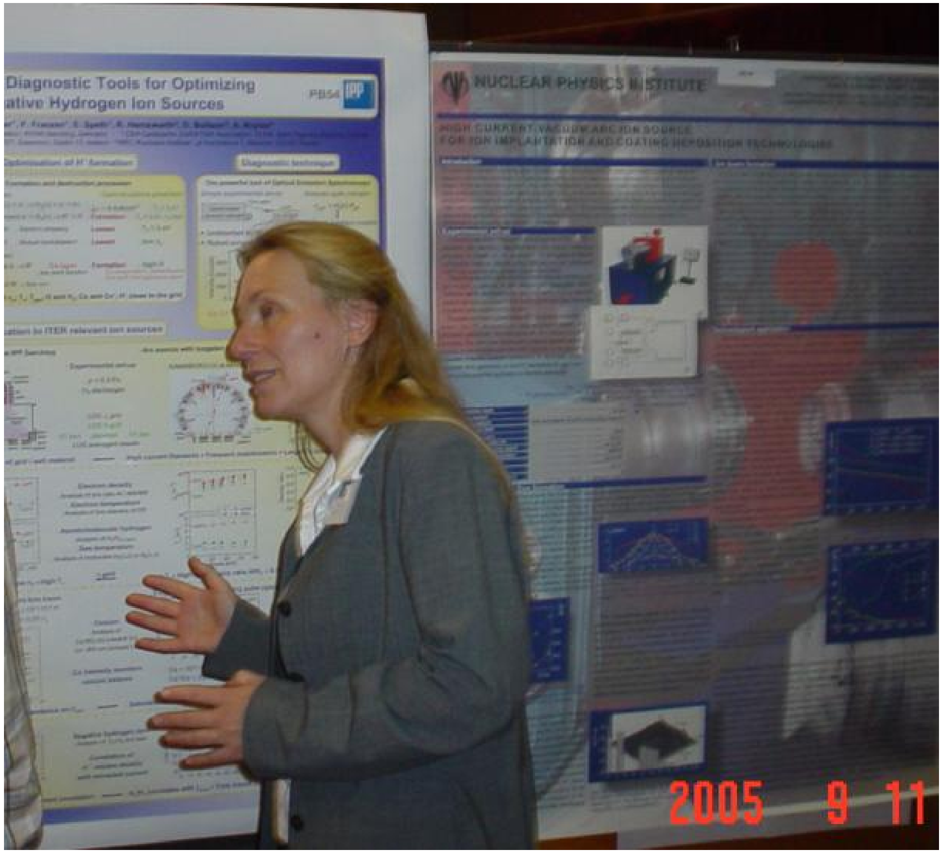


Fantastic work of IPP teams for development of LV SPS with cesiation for NBI



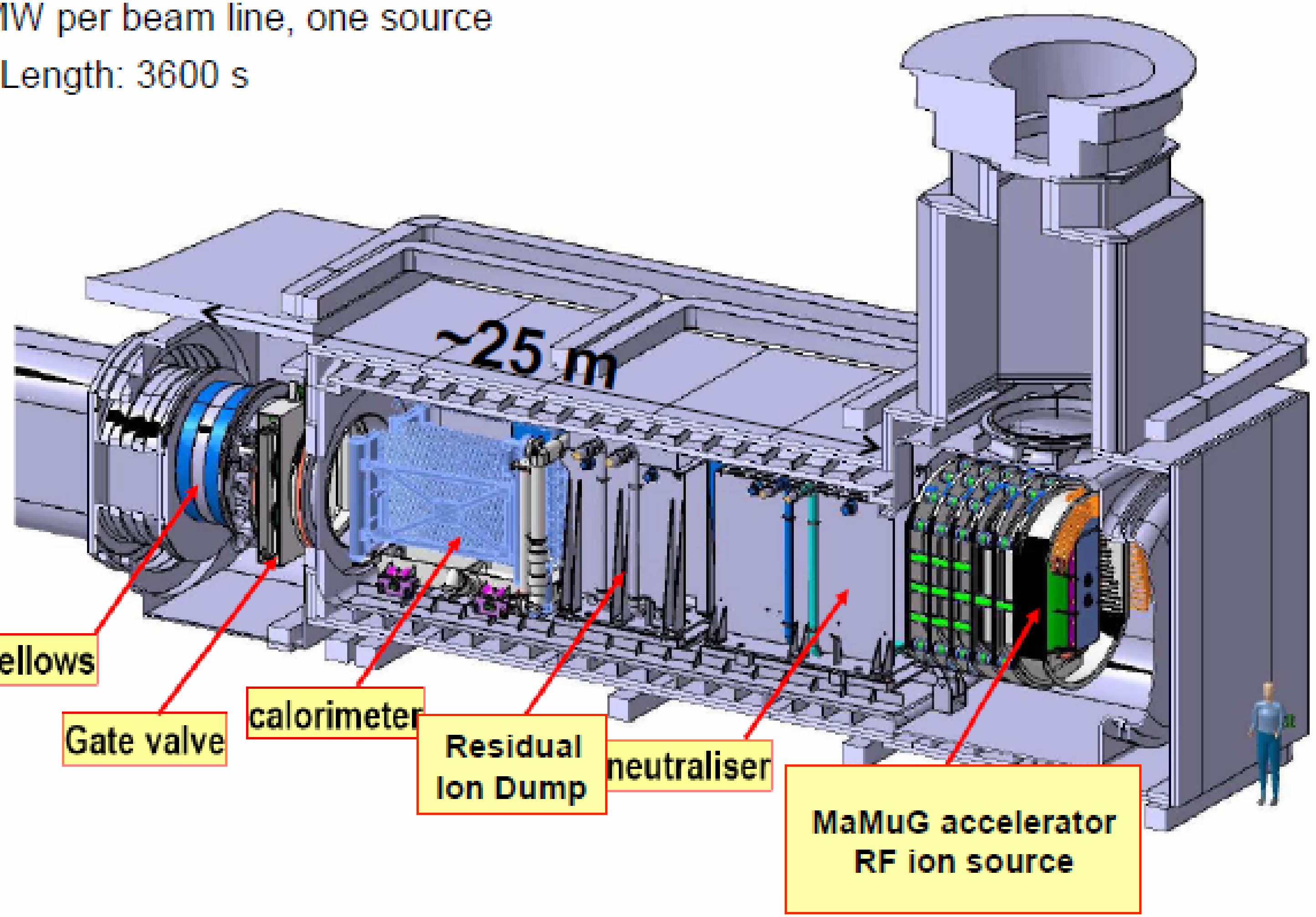
Good progress of IPP teams in development of LV RF SPS with cesiation for NBI





Development of LV SPS with cesiation for ITER NBI

Two beam lines
16.7 MW per beam line, one source
Pulse Length: 3600 s



Nanolithography by fine focused ion beam
BINP, Novosibirsk, 1990, lines ~ 100 nm

ACKNOWLEDGEMENTS

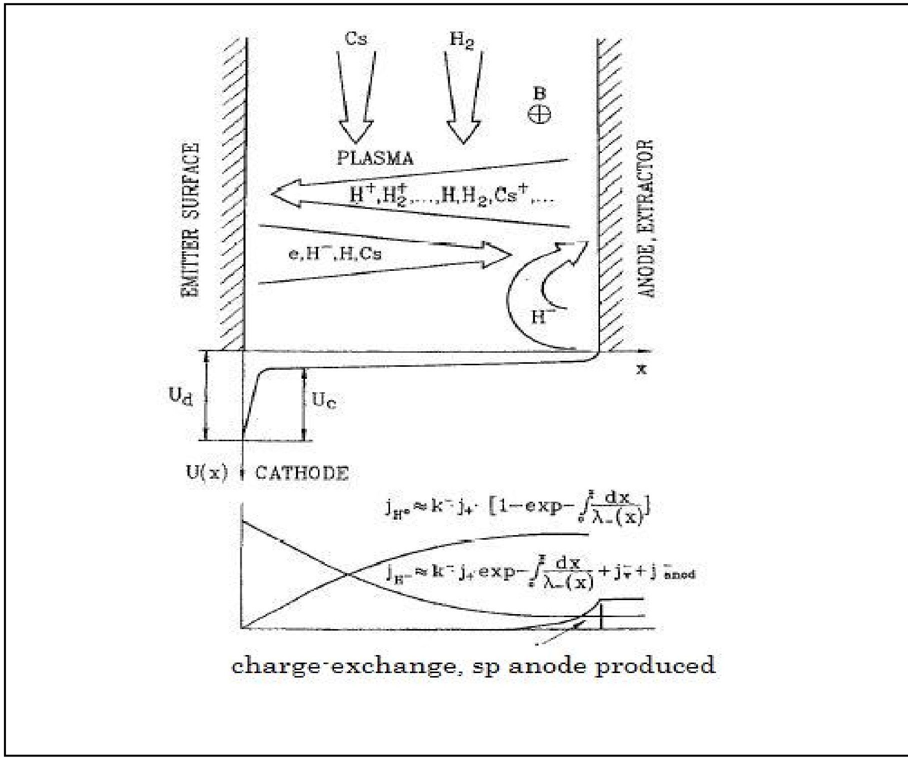
•The author is grateful to many groups in different countries for courage and creativity in development and adaptation of the SPS with cesiation for many applications.

It is important and necessary that the R&D activity of ITER source would be open for the world wide collaboration to promote it (O. Kaneko; NIBS 2010)

•Thank you for your ATTENTION!

- Back up slides for explanation

General diagram of the Surface-Plasma Generation of negative ions in a gas discharge

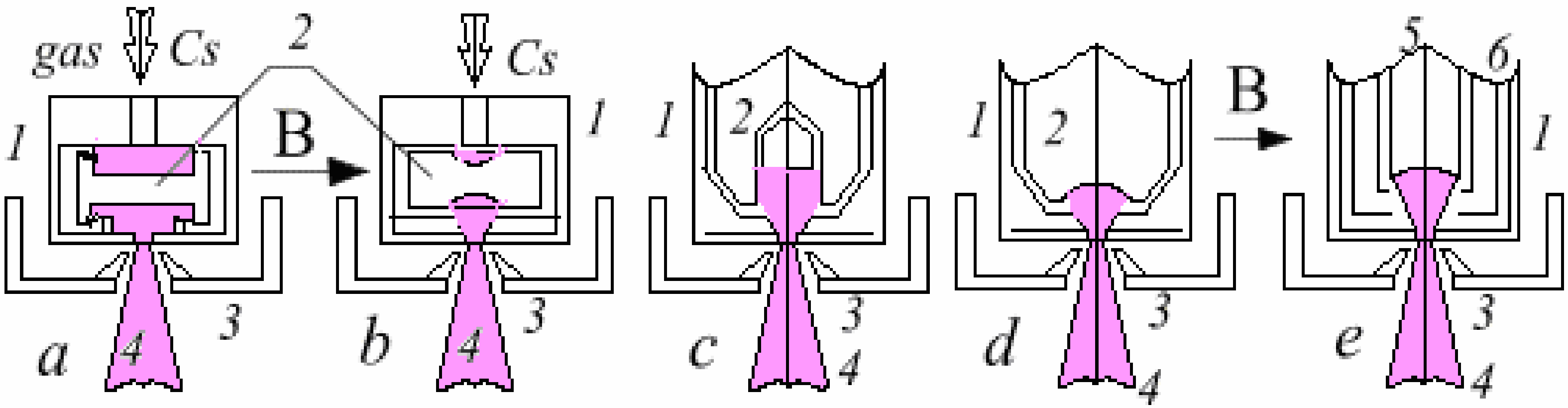


Surface plasma generation of H^- on the anode often is the dominant process of H^- formation in discharges without Cs, as well as with Cs.

Accumulation of elements with low ionization potential on the emission surface is important. The negative potential of this surface helps this accumulation

As negative ions pass through the plasma and gas to the anode, the weakly bound electrons are easily removed creating accelerated neutral atoms. The majority of accelerated negative ions will **survive** to reach the beam forming region **only if the layer of plasma** and gas between the emitter and the beam forming system **is very thin**.

Schematic diagrams of Compact SPS



(a) **planotron (magnetron) flat cathode**
(b) **planotron geometrical focusing (cylindrical and spherical)**
(c) **Penning discharge SPS (Dudnikov type SPS)**
(d) **semiplanotron**
(e) **hollow cathode discharge SPS with independent emitter**

1- anode
2- cold cathode emitter
3- extractor with magnetic system
4- ion beam
5- biased emitter
6- hollow cathode

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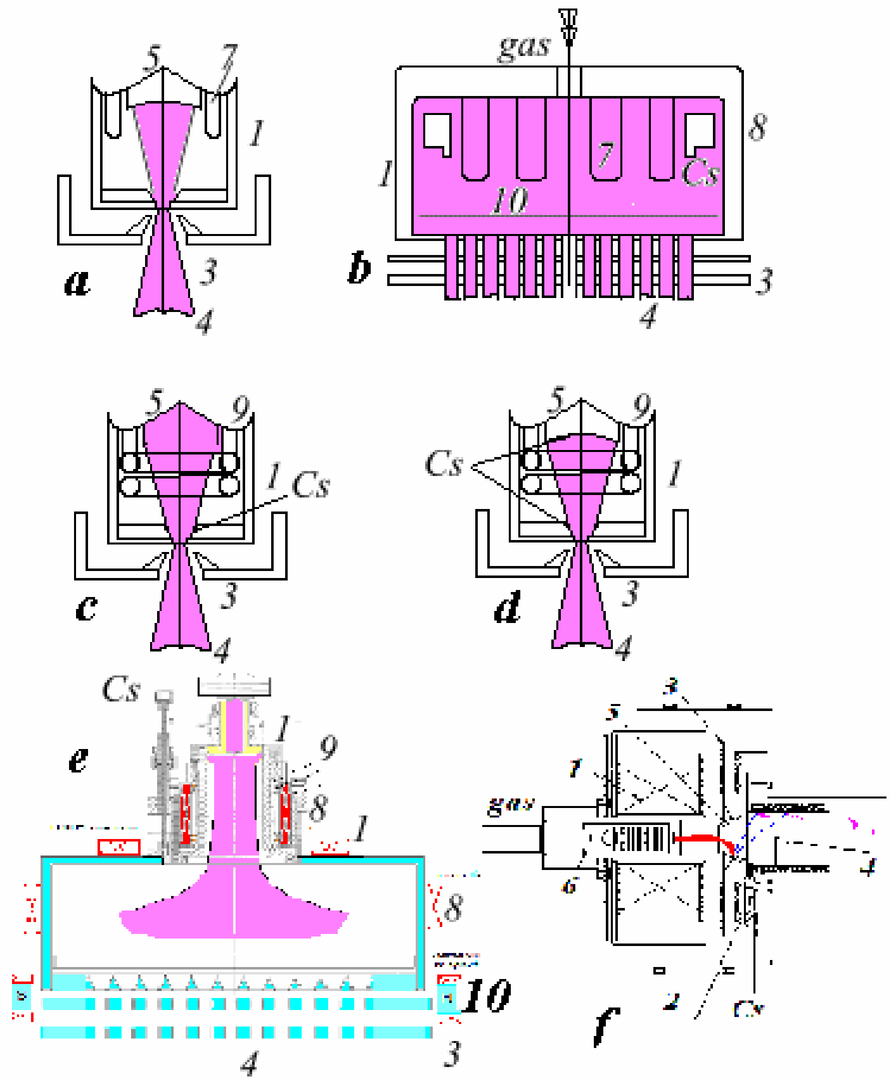
Schematic diagrams of LV SPS



(a) **large volume SPS with filament discharge and biased emitter**

(b) **large volume SPS with filament discharge** and **anode negative ion production**

(c) large volume SPS with RF plasma generation anode NI production

(d) **large volume SPS with RF plasma production and emitter**

(e) large volume SPS with RF plasma generation and anode NI production

(f) SPS ionizer for polarized NI production

1- anode	6- hollow cathode
2- cold cathode emitter	7- filaments
3- extractor with magnetic system	8- multicusp magnetic wall
4- ion beam	9- RF coil
5- biased emitter	10- magnetic filter

Negative ion formation in gas discharge

Volume Generation (VG)

2 steps:

1. Vibrational excitation

   e(fast) + $H_2 \rightarrow H_2^* + e$

2. Dissociative attachment:

   $H_2^* + e$ (slow) $\rightarrow H + H^-$

Volume generation needs:

- high density of molecules,
- low degree of dissociation,
- high rate of recombination,
- high density of electrons in the extraction region,
- high current of co-extracted electrons.

Surface-Plasma Generation (SPG):

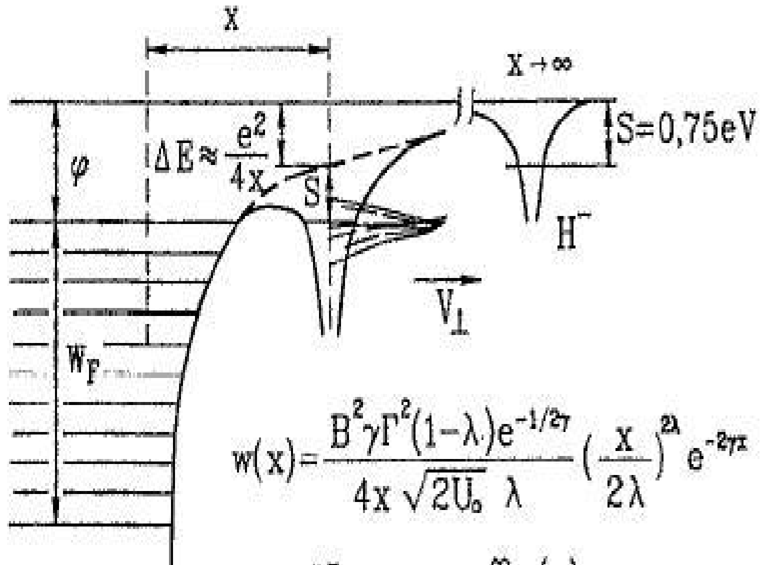
- collision of plasma particles with surface: secondary emission of negative ions- desorption, reflection with capture of electron from the surface;
- lowering of work function increases the probability of electron capture (Cs deposition; Cesiation);
- needs energetic atoms and to lesser degree, positive ions;
- high degree of dissociation, flux of hyperthermal atoms;
- doesn't need electrons in extraction region;
- results in low current of extracted electrons.

Accumulation of elements with low ionization potential on the emission surface is important. Negative potential of this surface helps this accumulation

$J_{VG} << J_{SPG}$

Schematic of negative ion formation on the surface

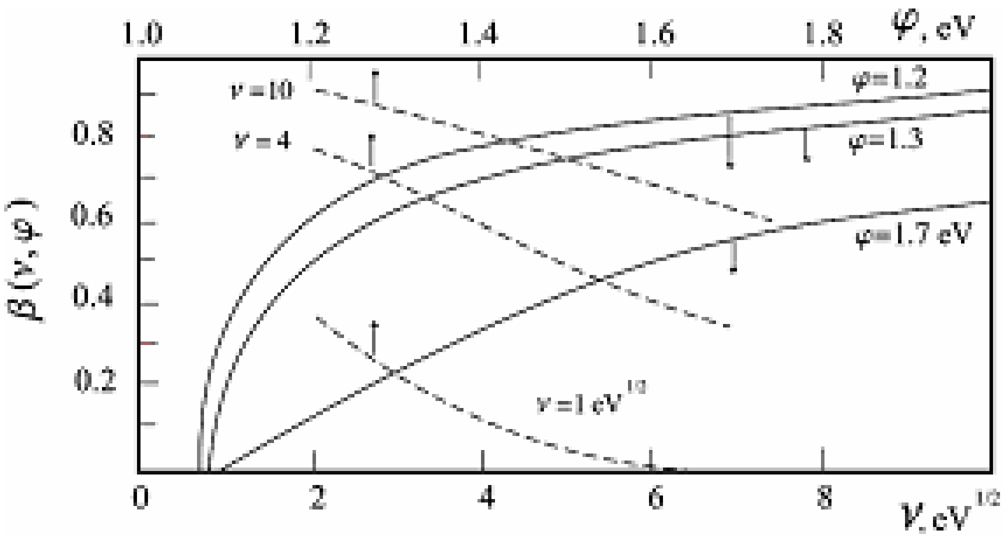
Michail Kishinevsky, Sov. Phys. Tech. Phys, 45 (1975)



$$w(x) = \frac{B^2 \gamma \Gamma^2 (1-\lambda) e^{-1/2\gamma}}{4x\sqrt{2U_0}\;\lambda} \left(\frac{x}{2\lambda}\right)^{2\lambda} e^{-2\gamma x}$$

$$\beta^- = \frac{I^-}{I_\Sigma} = \exp - \left[\int_{x_0}^{\infty} \frac{w(x)}{v_\perp}\, dx\right]$$

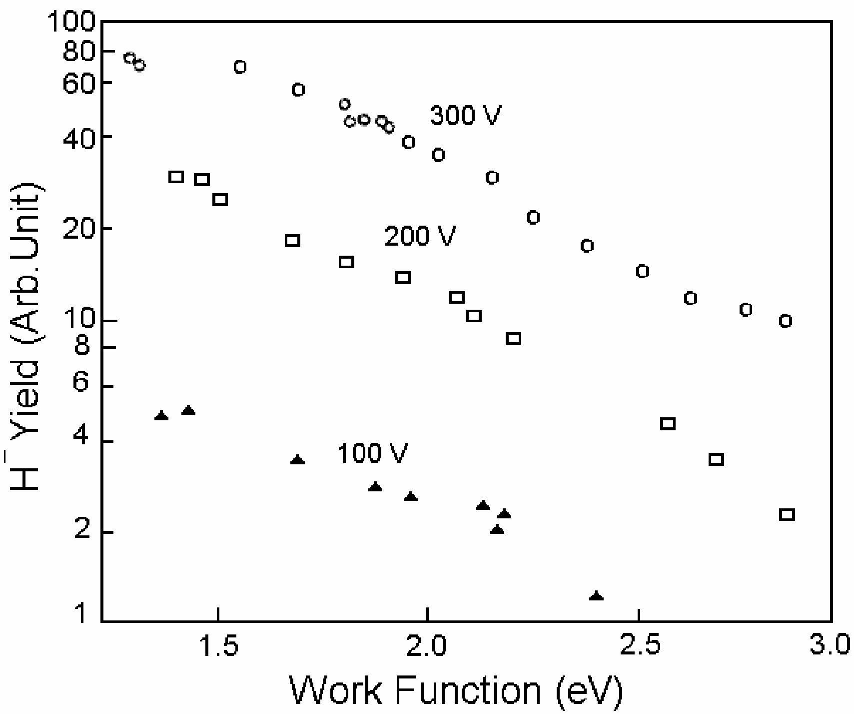
Coefficient of negative ionization as function of work function and particle speed



$$\beta_{\Sigma}^{-} = \frac{j^{-}}{j_{\Sigma}} = \int_{v_0}^{\infty} \beta^{-}(v_{\perp}, \varphi)\, f(v_{\perp})\, dv_{\perp}$$

Kishinevskiĭ M E, *[Sov. Phys. Tech. Phys.*, **48** (1978), 773; **23** (1978), 456]

Experimental secondary emission yield as a function of surfaces work functions for different velocities



Dependence of H - production upon the work function of a Mo surface
in a cesiated hydrogen discharge for different biasing voltage.
M. Wada,R. V. Pyle and J. W. Stearns, J. Appl Phys., Vol. 67, No. 10,15 May 1990, p. 6334

Detection of emitted negative ions from surface bombarded by H+ ions with deposition of Cs

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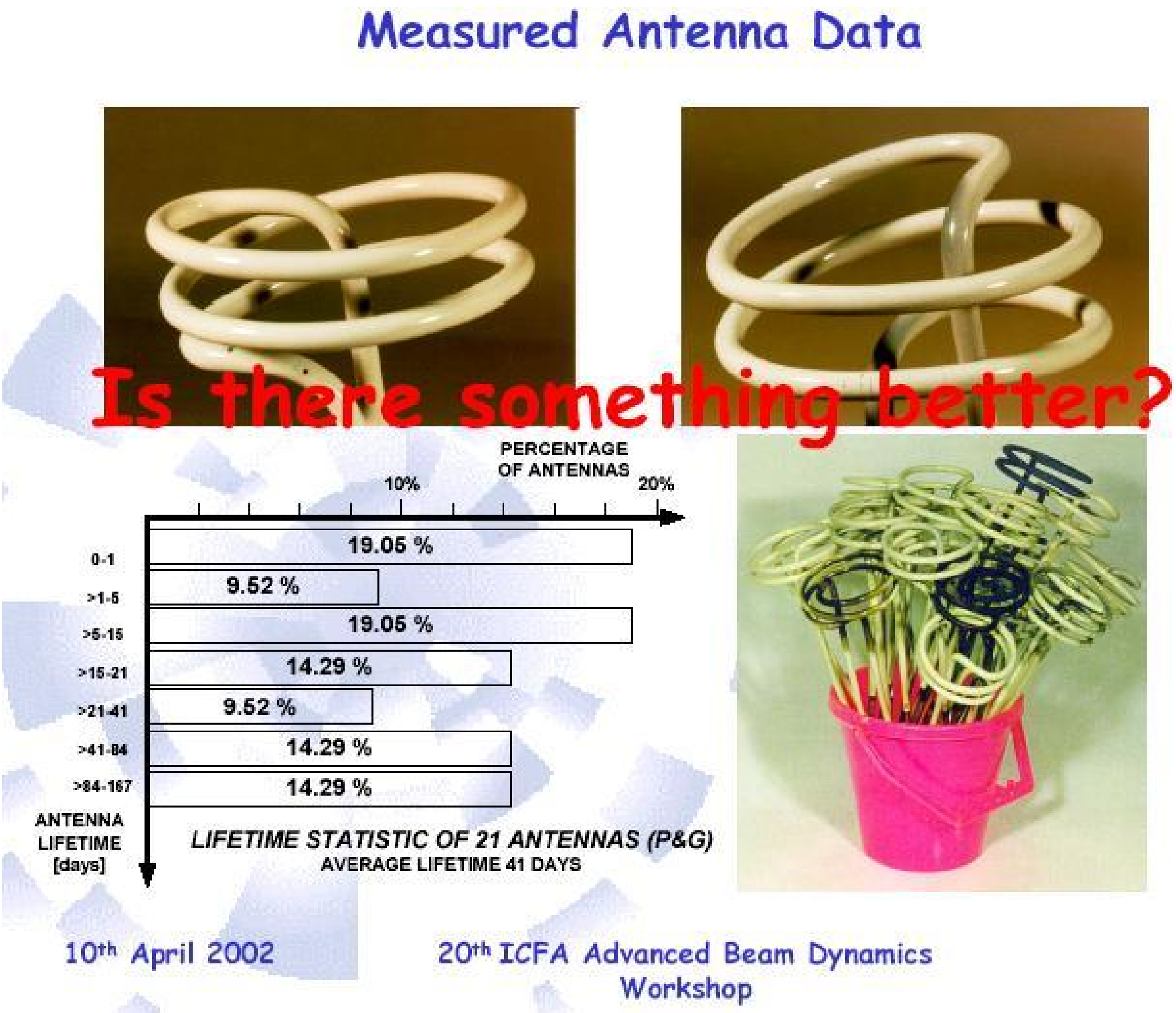
Listing of Institutions working for development of negative ion sources

- Oak Ridge National Laboratory (ORNL),
- Lawrence Berkeley National Laboratory (LBNL),
- Los Alamos National Laboratory (LANL),
- Fermi National Accelerator Laboratory (FNAL),
- Brookhaven National Laboratory (BNL)
- TRIUMF, Canada, D-Pace.
- Rutherford-Appleton Laboratory (RAL),
- Deutsche Elektronensynchrotron (DESY), Germany
- Frankfurt University, Institute fuer Angewandte Physik (IAP),
- Commission of Atomic Energy (CAE) Saclay, France,
- High Energy Accelerator Research Organization (KEK), Japan
- Japan Atomic Energy Research Institute (JAERI), Japan,
- Japan Fusion Institute Nagoya Japan
- CERN Intense Proton Linac (IPL), Geneva, Switzerland,
- Budker Institute of Nuclear Physics (BINP) Novosibirsk, Russia,
- Nuclear Research Institute (INR), Troitsk, Russia,
- Joint Institute of Nuclear Research (JINR), Dubna, Russia,
- Seoul National University (SNU), Korea,
- China Institute of Atomic Energy, (CIAE), Beijing, China,
- IPP Gartching, Germany.
- ITER Cadarache, France
- Dehnel Consulting, (D-pace) Vancouver, BC, Canada
- IBA, Belgium
- NIIEFA, Russia
- Jyvascular University, Finland
- ****

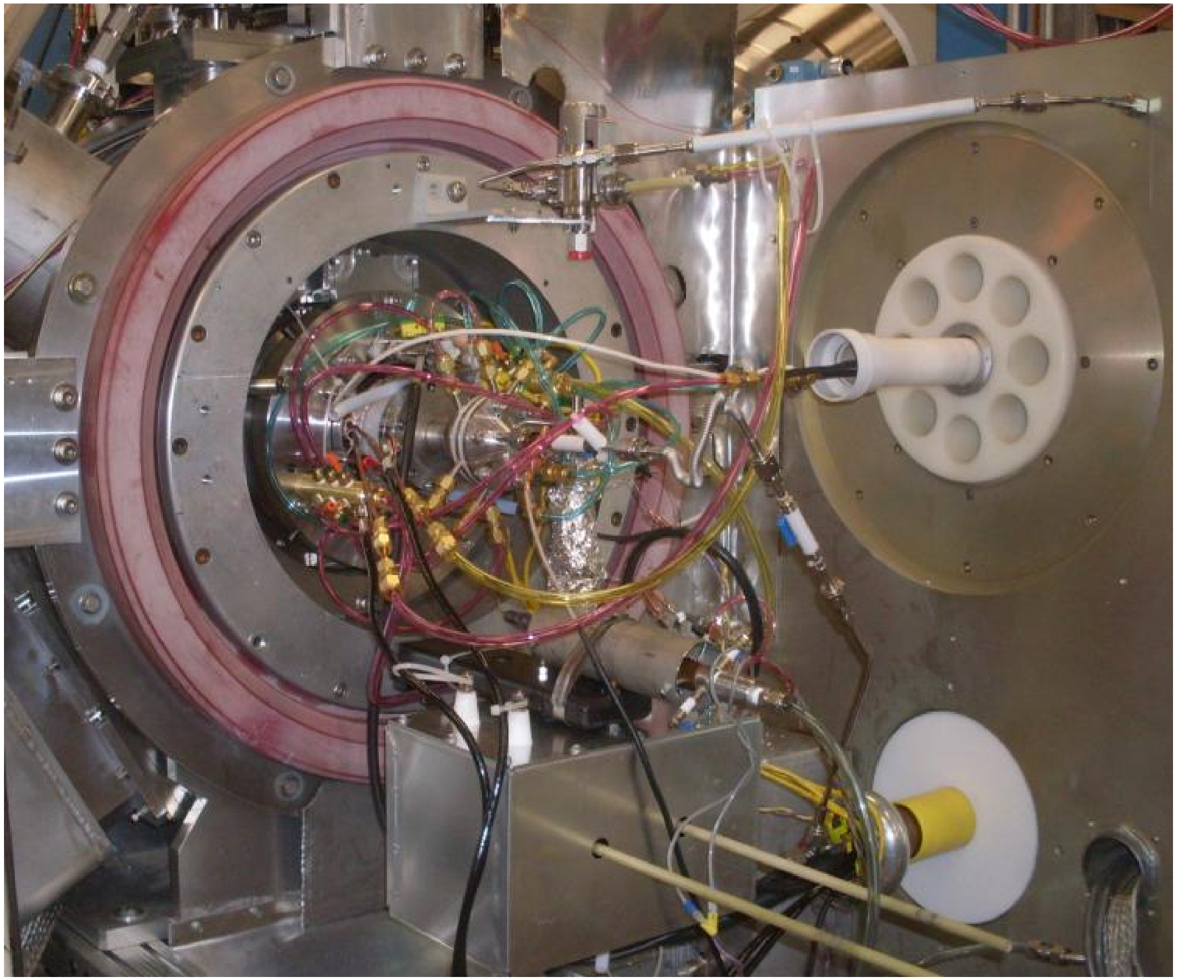
Work with SNS team for improving of RF SPS.

RF SPS is a source of life for SNS and other proton drivers
Problems: RF internal antennas LBL/SNS LV SPS can be unexpectedly destructed by plasma with SNS downtime

Low energy efficiency: 1mA/kW
For compact SPS up to 100 mA/kW;
Solutions:
External antenna;
Enhance energy efficiency



The Saddle Antenna RF LV SPS with , magnetic coil and external Cs source attached to the SNS test stand.



Self increase of H- current from 8 mA to 42 mA during a heating of collar by compressed Air and by Discharges with Prf ~24 kW.

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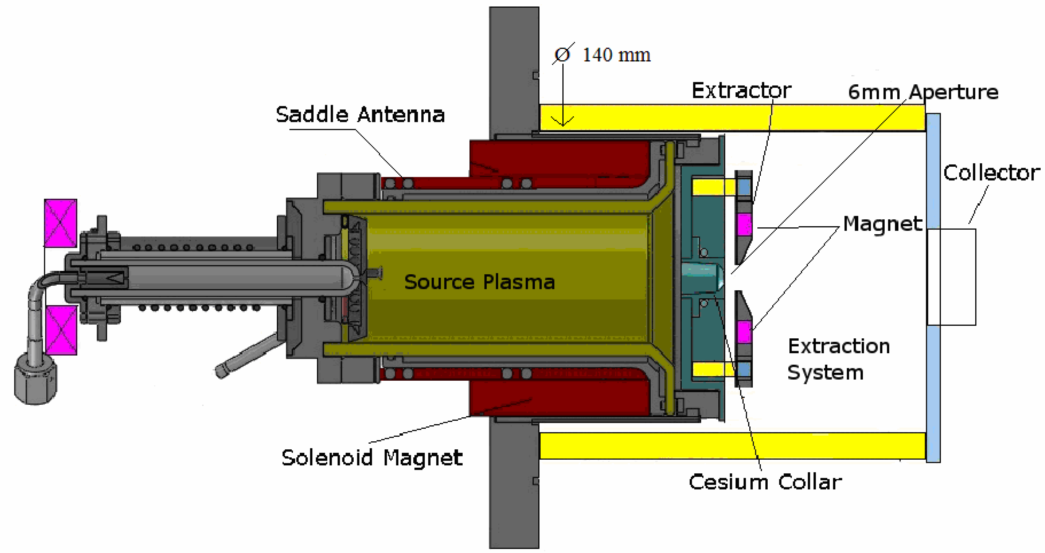
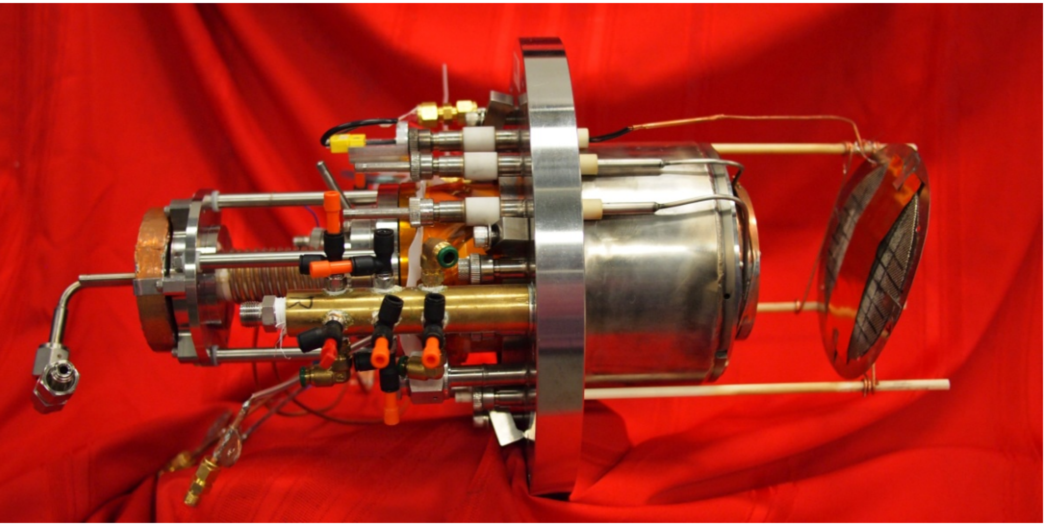
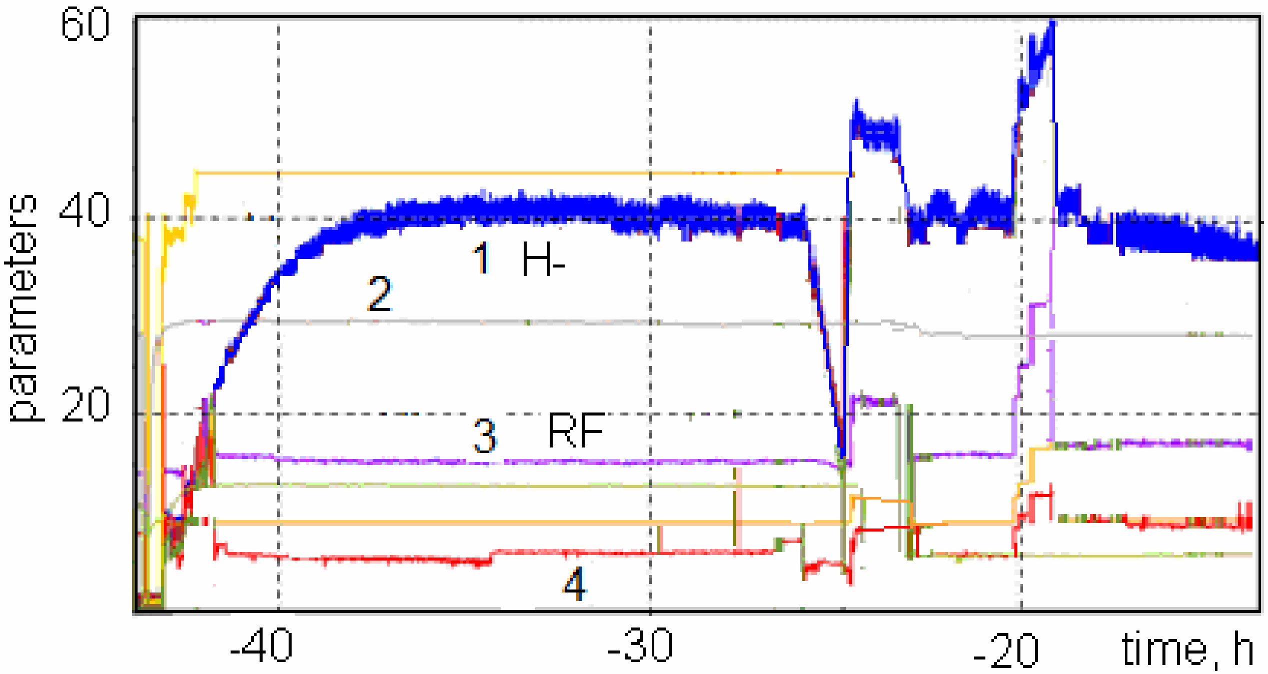
Design of SA RF SPS





General Design of SA RF SPS with TPG, Extractor and Collector and photograph of Assembled SA SPS OD of SPS 140 mm. ID of ceramic chamber 68 mm

Evolution of H- beam intensity of the saddle antenna RF LV SPS without Cs supply;



1- ion beam current (blue);

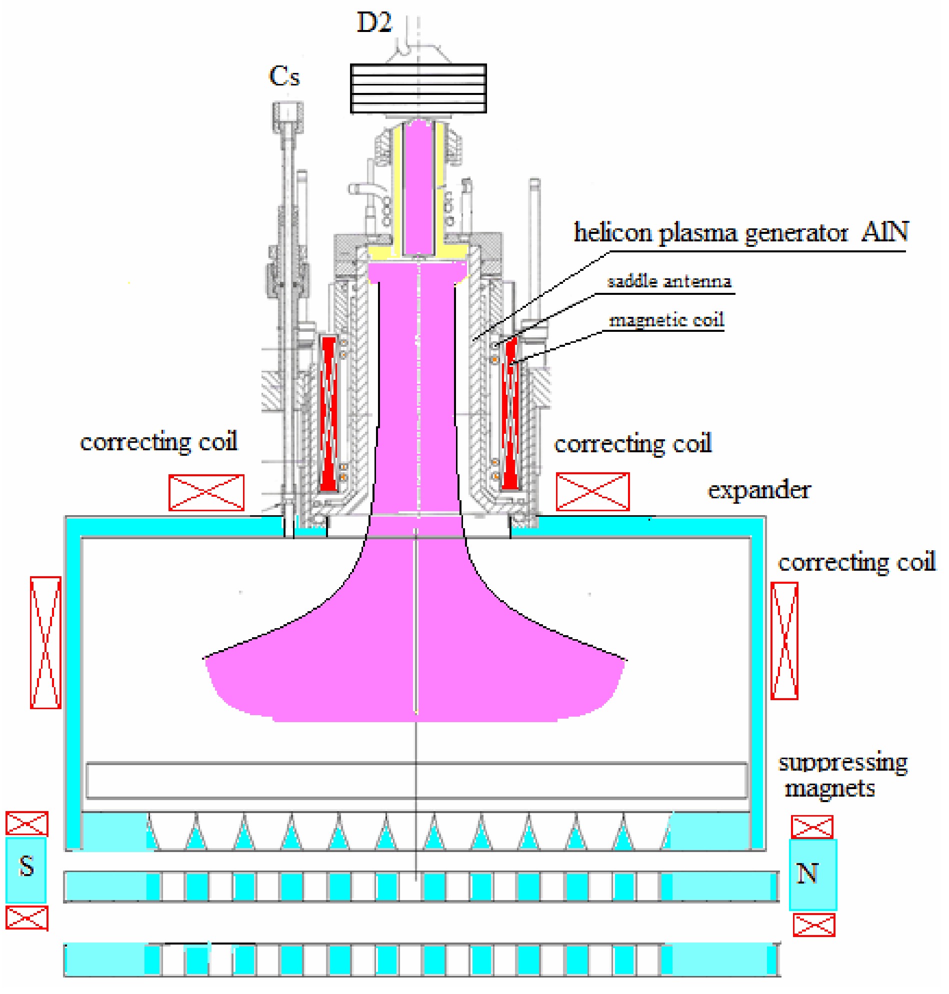
2- gas flow sccm(gray);

3- RF power (magenta);

4- reflected RF power (red).

Electrode activation with self increasing H- beam current from 8 to 42 mA during 4 hours collar heating by discharge (Accumulation of ILIP)

SPS with Helicon Plasma Generation and Ion/Atom Converter



Helicon plasma generator. Plasma flux conversion into hyperthermal atoms in converter. Slit extraction with a Stronger magnetic filter. Local cesium delivery. Laser diagnostics and control cesium distribution. Cesium trapping in discharge chamber. Cesium implantation

Horst Klein (20 ICFA Workshop summary).

"The ion sources, and especially the H^- sources, are still somewhat a black magic. Therefore intense theoretical and experimental work has to be performed in different labs to achieve the new requirements. In Europe the Negative Ion Source network, supported by the European Union, with its 8 partners will help to reach the goal. But also such a meeting as we have had in Femilab is very helpful and intensifies the worldwide collaboration. Concerning the different types of ion sources, I think the most promising candidates for H- are the Penning (Dudnikov type)ion source and the volume source (Large Volume SPS). The ECR source may be a hope for the future".

Intuition and hand experience are important components for H- sources development.

A learning period for new team is ~8 years.

Proper cesiation *is vital for efficiency and stable operation*

Contents

First project of proton/antiproton collider VAPP, in the Novosibirsk INP (BINP), 1960

- Development of charge-exchange injection (and negative ion sources) for high brightness proton beam production. First observation and damping of e-p instability.
- Development of Proton/ Antiproton conversion.
- Development of electron cooling for high brightness proton and antiproton beam production.
- Production of space charge neutralized proton beam with intensity above space charge limit. Inductance Linac, Inertial Fusion, Neutron Generators.
- *History of ZGS 500MeV Booster. www.ipd.**anl**.gov/**anl**pubs/2006/05/56304.pdf*
- *Martin Reiser, Theory and Design of charged particle beam.*

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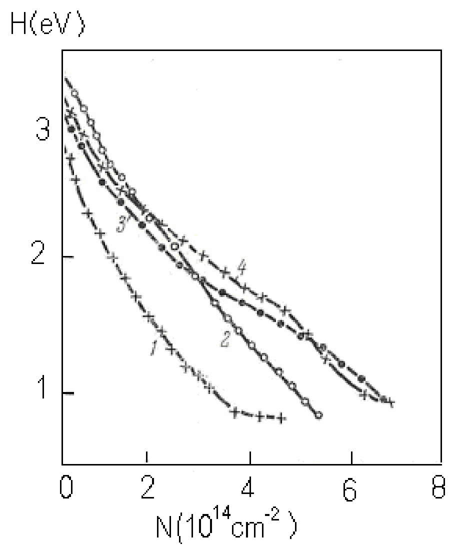
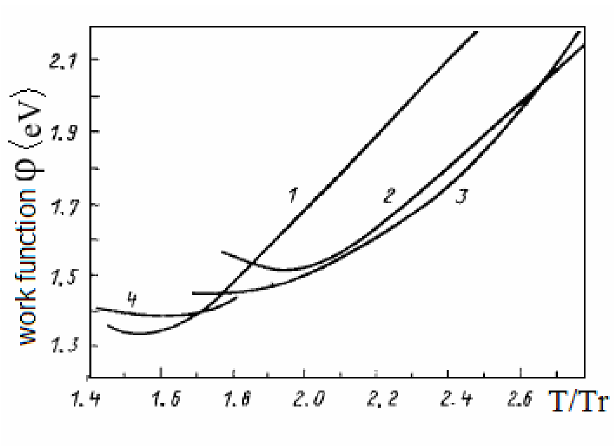
Production of surfaces with low work function (cesium coverage)



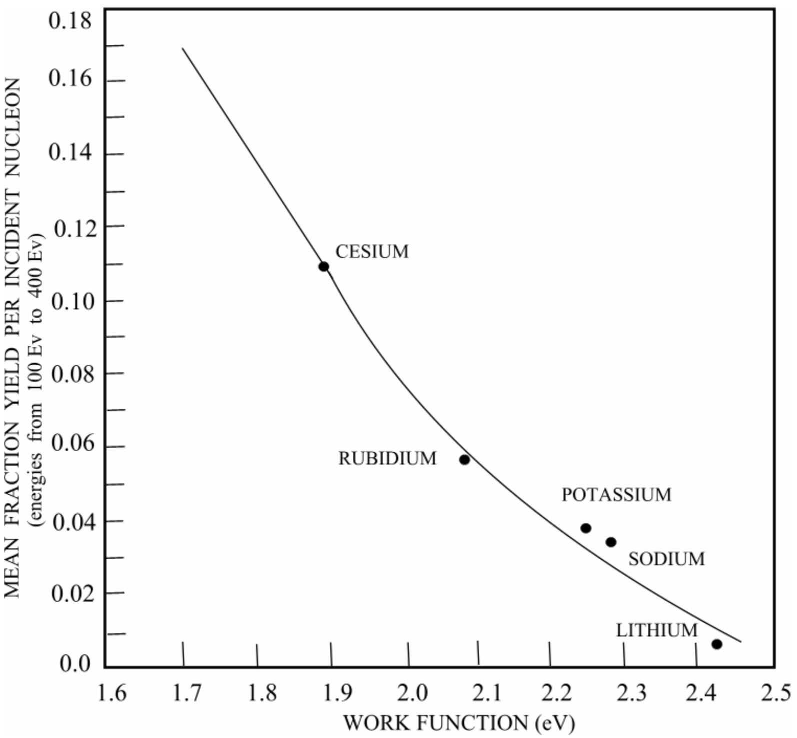


The surface work function decreases with deposition of particles with low ionization potential (CS) and the probability of secondary negative ion emission increases greatly from the surface bombarded by plasma particles.

Dependences of desorption energy H on surface Cesium concentration N for different W crystalline surfaces: 1-(001); 2-(110); 3-(111); 4-(112).

The work function in the case of cesium adsorption in dependence upon the ratio of sample temperature T to cesium-tank temperature TCs for collectors of 1) a molyb-denum polycrystalline with a tungsten layer on the surface, 2) (110) molybdenum, 3) a molyb-denum polycrystalline, and 4) an LaB6 polycrystalline.

Experimental and extrapolated secondary emission yield for surfaces with different work functions



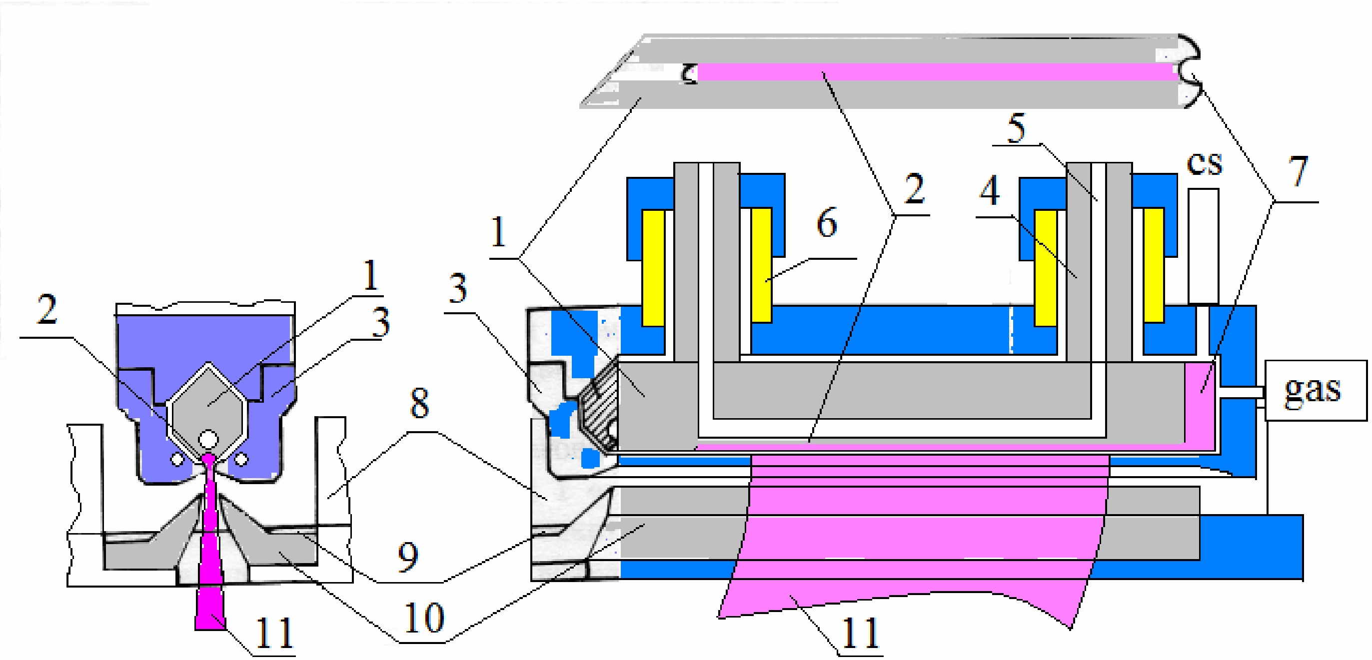
P.J. Schneider, K.H.Berkner, W.G.Graham, R.V.Pyle, and J.W.Sten, BNL 50727, 63 (1977).

Detection of emitted negative ions from surface bombarded by D+ ions with deposition of differed substances with low ionization potential (Li, Na, K, Rb, Cs)

Muons, Inc.

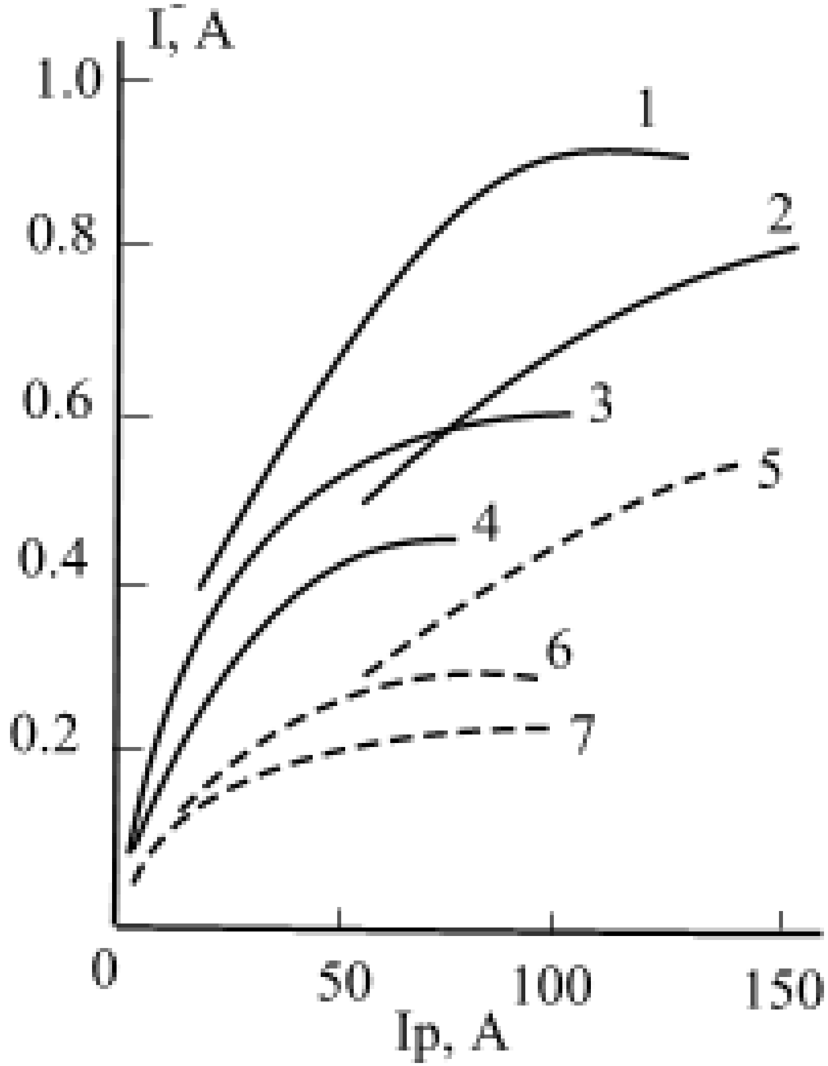
Design of the first Version of Semiplanotron SPS

V. Dudnikov, INP, 1976



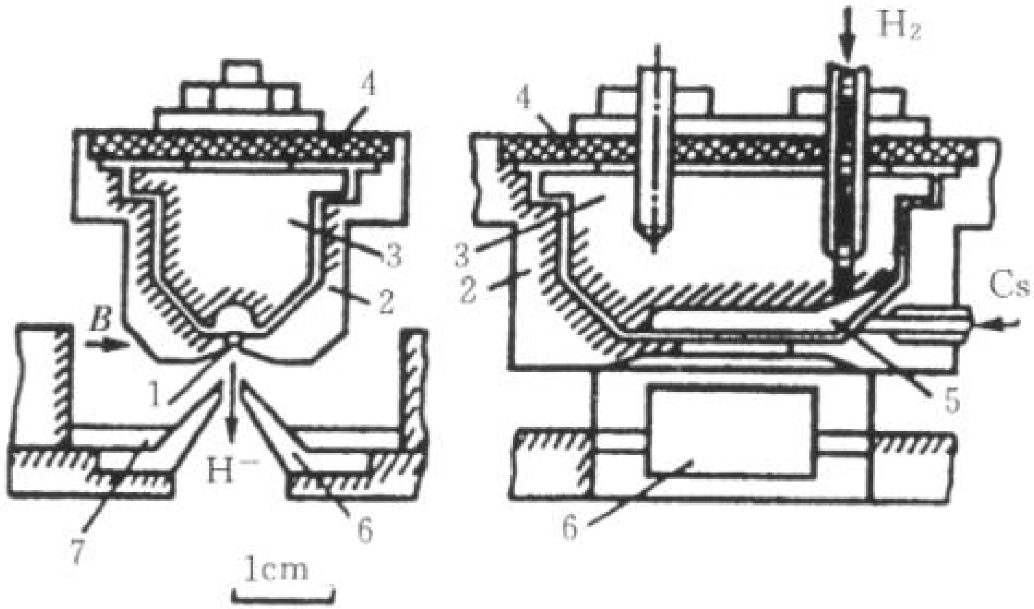
1- Cathode 5cm long; 2- Cathode's groove for plasma confinement; 3-Anode - discharge chamber; 4- cathode holders; 5-cathode cooling; 6-insulators; 7- cathode groove for discharge triggering; 8-Magnetic poles; 9- Magnetic insert; 10- Extractor; 11- Ion beam; H- Beam up to 0.9 A, 1 ms, 10 Hz, slit 0.7x45 mm^2 ; 0.22 A, slit 1x10 mm^2 .

NI Beam intensity as function of discharge current in the Semiplanotron SPS



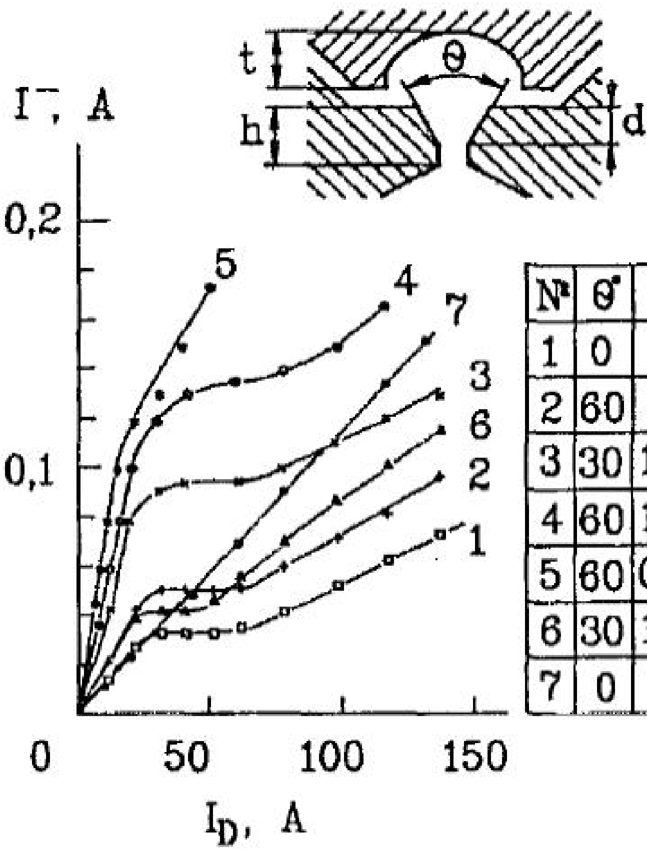
In Fig. are shown intensities of H- beams extracted from different emission slits: (1-0.72x45 mm2; 2-0.5x41 mm2; 3-1x40 mm2 ; 4-1x20mm2) and D- beams (5-0.5x41mm2; 6-1x40 mm2;7-1x20 mm2). With narrower emission slit extracted beam current is lower at lower discharge current but beam is saturated at higher level at higher discharge current.

Schematic of semiplanotron SPS



1- emission aperture;
2- anode;
3- cathode;
4- cathode insulator;
5- discharge channal;
6- extractor;
7- magnet with magnetic insertions.

Beam Current vs an Arc Current for Different Slit Geometry in the Semiplanotron

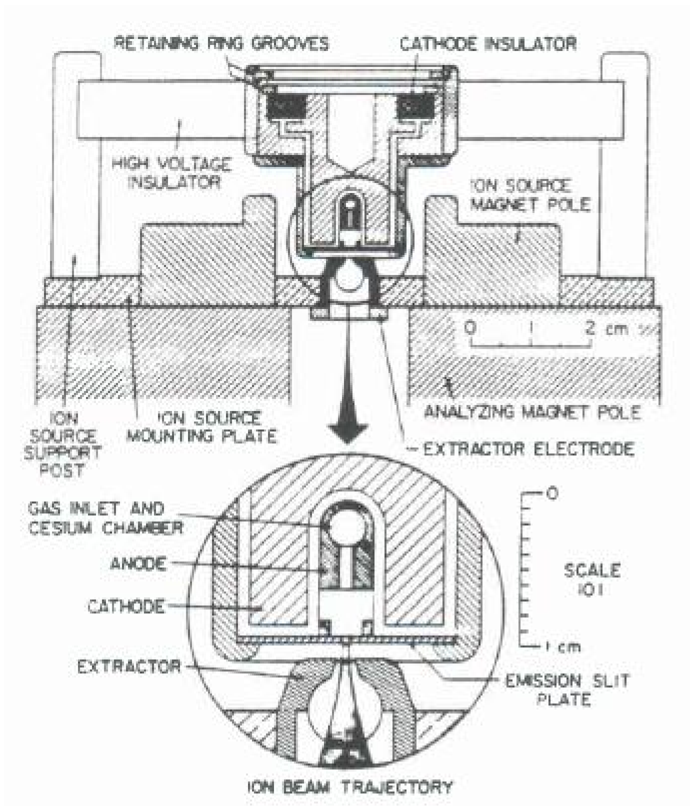


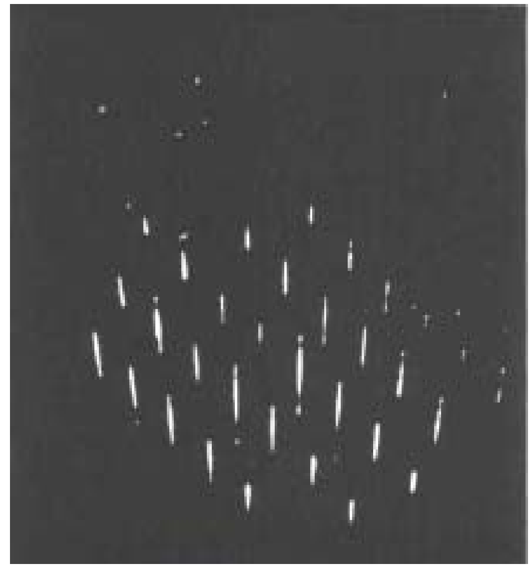
N°	θ°	d	h	t
1	0	0	2	1
2	60	1	2	1
3	30	1,8	2	1
4	60	1,8	2	1
5	60	0,8	1	1
6	30	1,5	2	2,5
7	0	0	0,5	–

Dependences of the H- ion beam current on the discharge current have the N-shaped form with three sections: linear growth at small discharge currents, saturation or a falling section at medium currents, and linear, but slow growth at the high currents.

Semiplanotron SPS with a Slit Extraction

Cross section through LANL version of SPS with Penning Discharge (Dudnikov-type source).



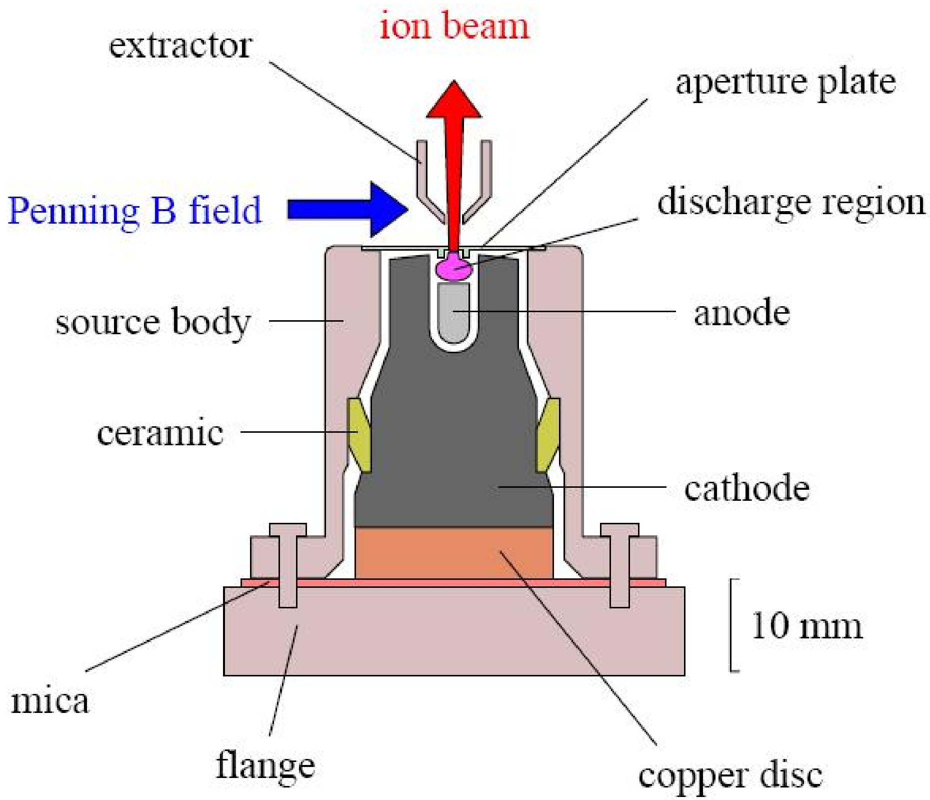


In LANL in first SPS transverse ion temperature was ~ 1keV.

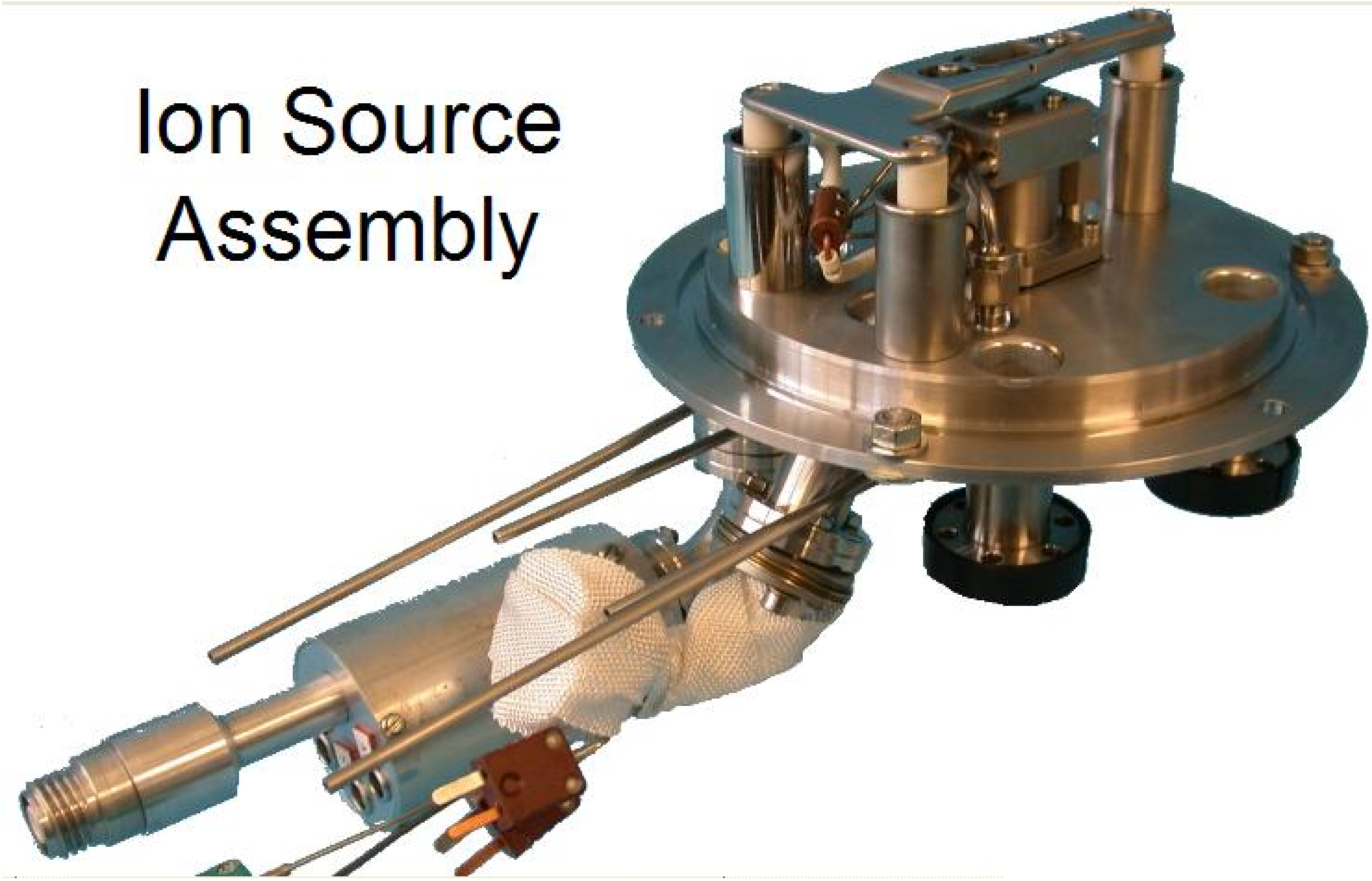
It was decreased to ~1eV.

Beamlet images at pepper-pot scintillator (noiseless discharge). Emission slit 0.5x10 mm^2.
Vertical: Y Plane
Horizontal: X Plane

Schematic of ISIS version of Penning discharge SPS



ISIS Penning SPS



Cathode and Plasma Plate of ISIS Penning SPS after long time operation

Design of SPS with Penning Discharge

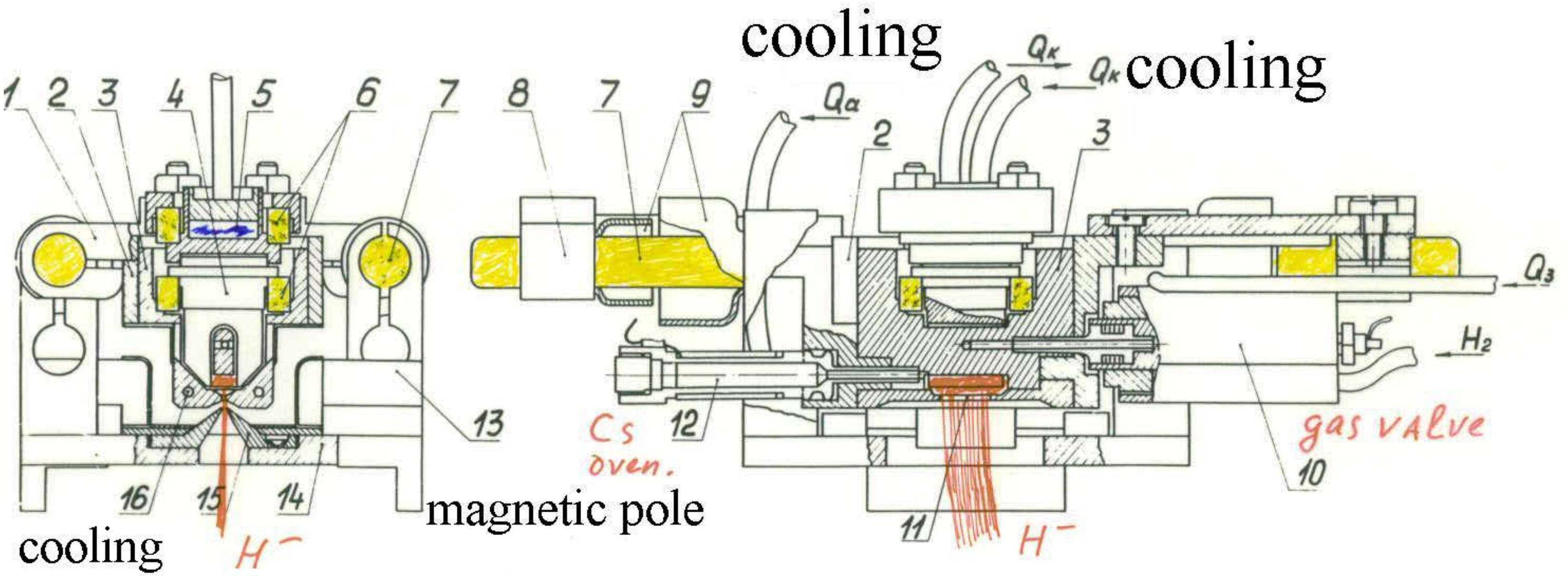


FIG. 8. Surface-plasma negative ion source with Penning discharge (Dudnikov type ion source). (1) support; (2) gas discharge chamber; (3) anode insert; (4) cathode; (5) cathode cooler; (6) cathode insulator; (7) high-voltage insulator; (8) support; (9) insulator screens; (10) gas valve; (11) emission slit; (12) cesium container; (13) magnetic pole; (14) base plate; (15) extractor; (16) cooling channal.

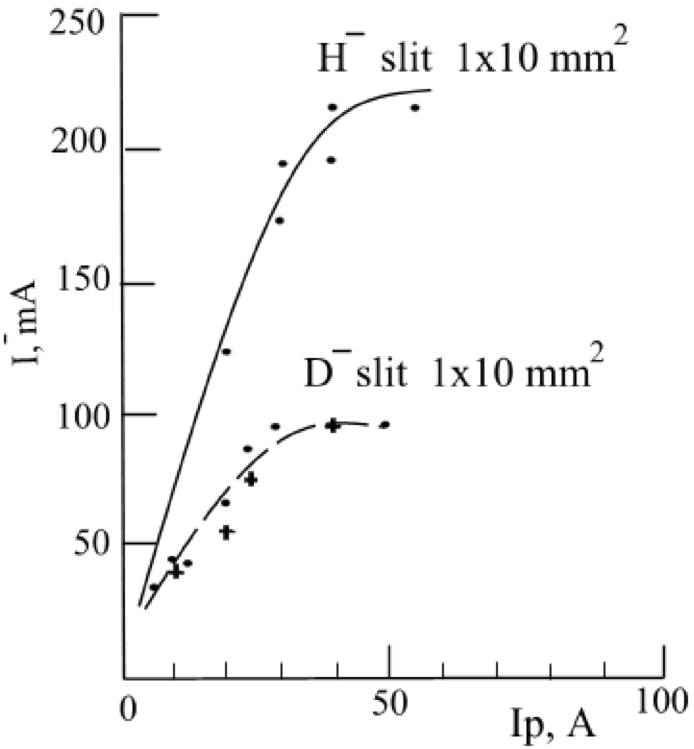
Rev. Sci. Inst. 61(1) 378(1990) 381

Beam current 0.1 (0.15) A,
Extraction 22 kV
Repetition 100 Hz(teste up to 400Hz)
Puls 0.25 ms
discharge volume 6x3.5x15 mm^3
emission slit 0.5x10mm^2

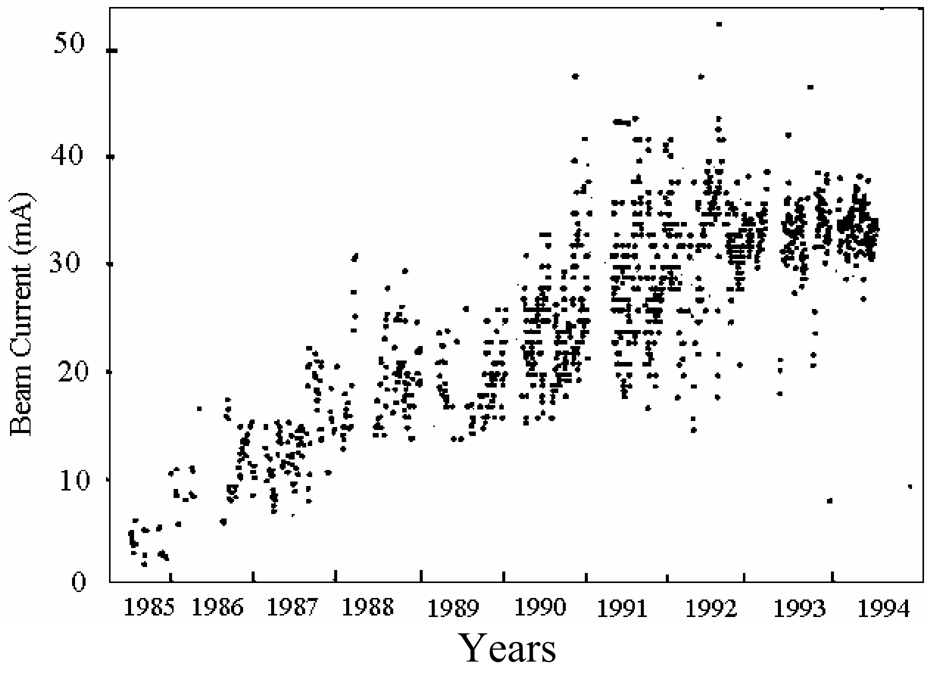
CSPS with Penning discharge

All metal and ceramic. Can be heated to 1000C for activation.

H^- Beam Intensity of SPS

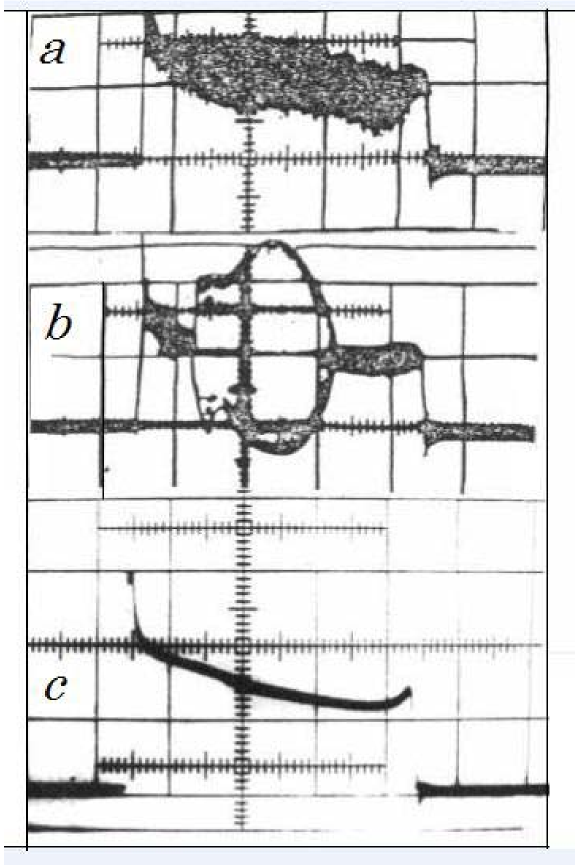


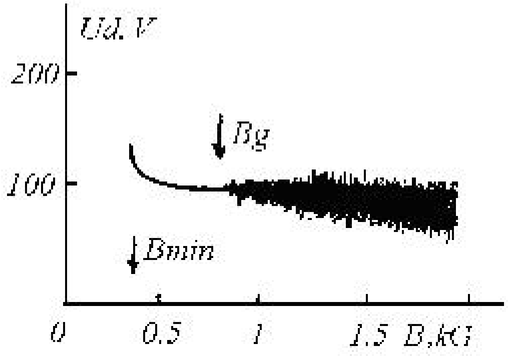
Beam intensity vs discharge current for first version of semiplanotron 1976



Evolution of H^- beam intensity in ISIS SPS

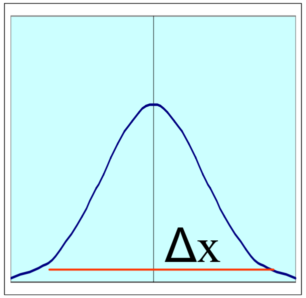
Noise of discharge voltage

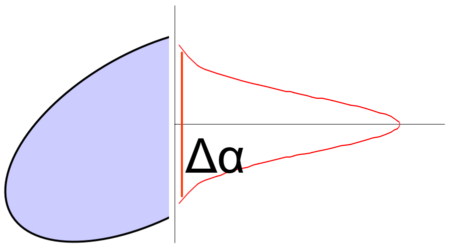




Dependence of discharge noise of magnetic field

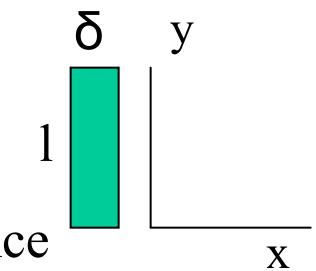
Emittance, Brightness, Ion Temperature





Emission slit

$$\delta \times l = 0.5 \times 10 mm^2$$



Emittance

$$V_x = \Delta x \cdot \Delta \alpha_x$$
$$V_y = \Delta y \cdot \Delta \alpha_y$$

Normalized emittance

$$E_x = V_x \cdot \beta = \Delta V_x \cdot \Delta x / c$$
$$E_y = V_y \cdot \beta = \Delta V_y \cdot \Delta y / c$$

$\beta = V_z / c$

Normalized brightness

$$B = \frac{2I^-}{\pi^2 E_x E_y} = \frac{2jc^2}{\pi^2 \Delta V_x \Delta V_y} = \frac{2jMc^2}{\pi^2 \sqrt{\Delta W_x}\sqrt{\Delta W_y}} \approx \frac{2jMc^2}{\pi^2 T_{if}}$$

Half spreads of energy of the transverse motion of ions

$$\Delta W_x = \frac{Mc^2 E_x^2}{2\Delta x^2} \qquad \Delta W_y = \frac{Mc^2 E_y^2}{2\Delta y^2}$$

Reduced to the plasma emission slit

$$\Delta W_{ox} = \frac{2Mc^2 E_x^2}{\delta^2} \qquad \Delta W_{oy} = \frac{2Mc^2 E_y^2}{l^2}$$

Characteristics of quality of the beam formation: $\Delta W_{0x} = 5keV \rightarrow 0.5eV$

Discharge Stability and Noise

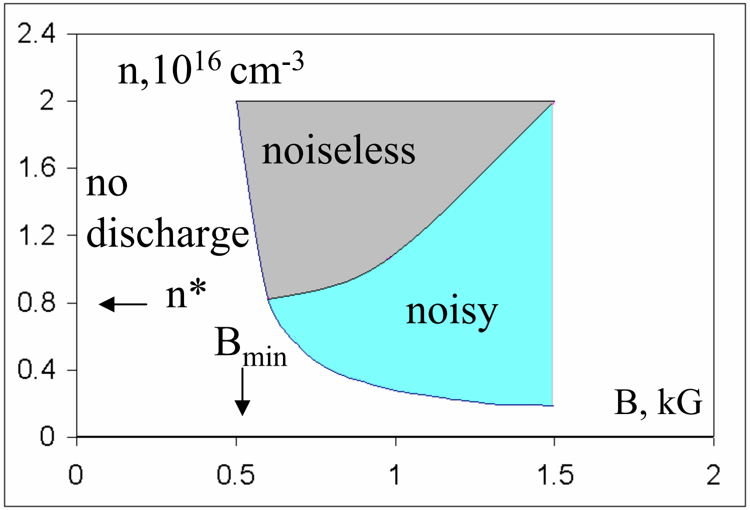
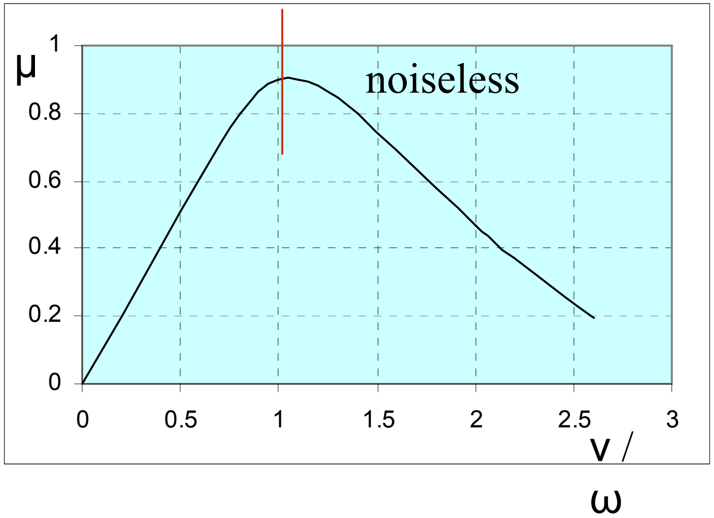


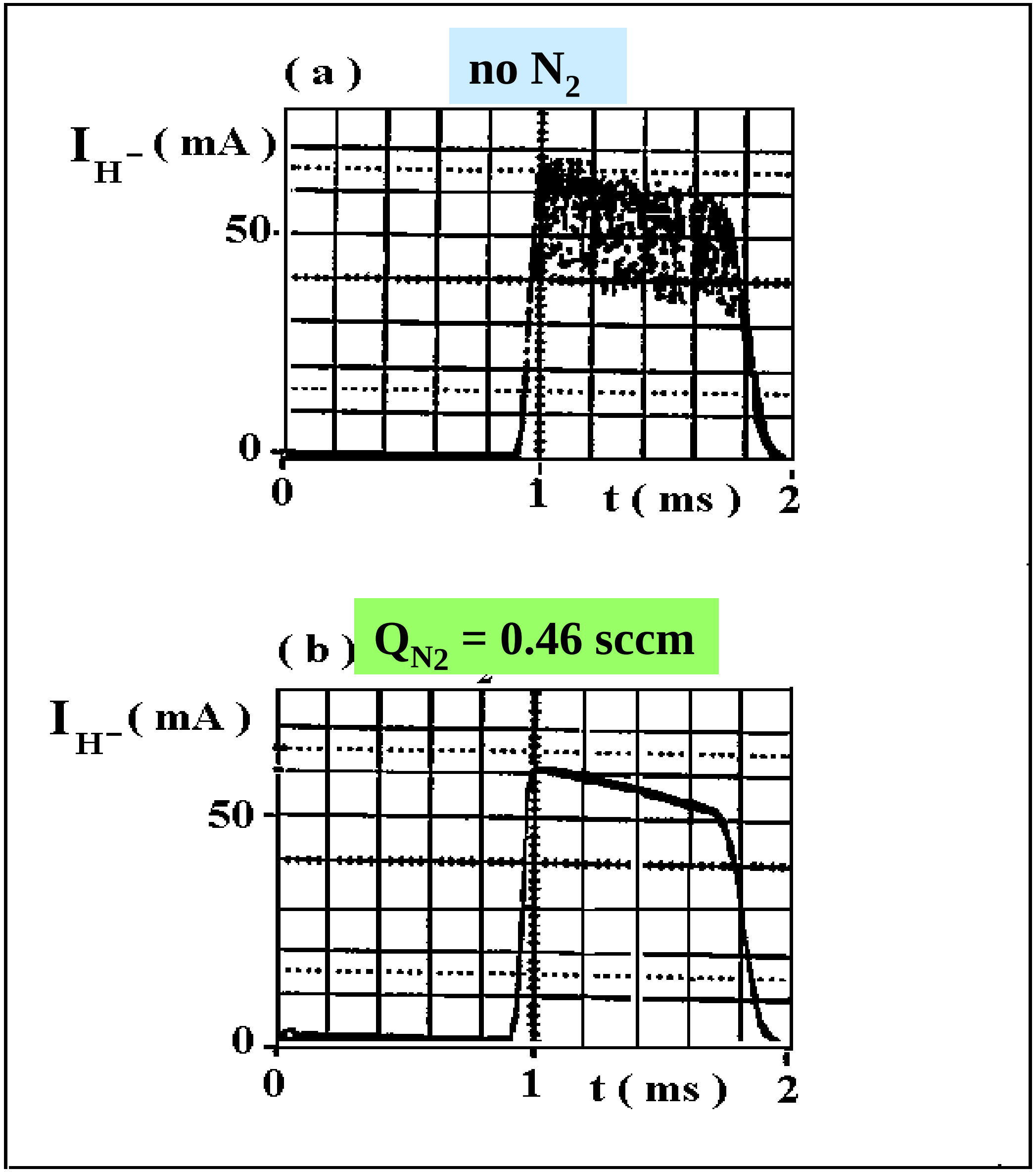
Diagram of discharge stability in coordinates of magnetic field B and gas density n

$\mu = e\nu/m\,(\nu^2 + \omega^2)$



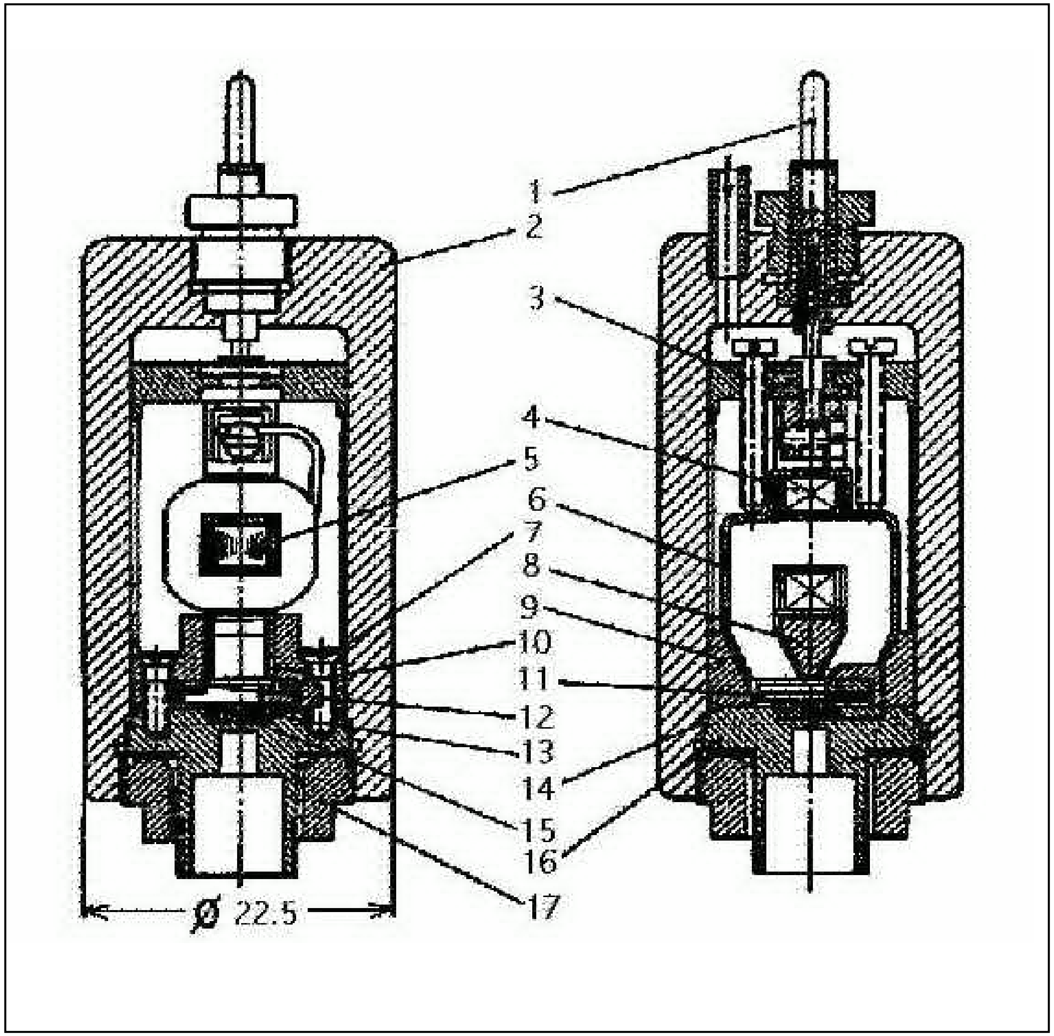
The effective transverse electron mobility μ vs effective scattering frequency ν and cyclotron frequency ω

Discharge Noise Suppression by Admixture of Nitrogen



P.Allison, V. Smith, et. al. LANL

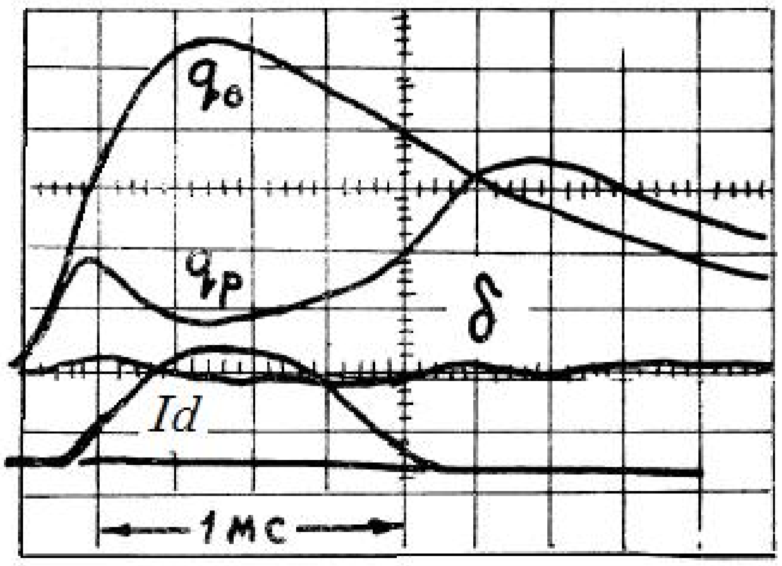
Fast, compact gas valve, 0.1ms, 0.8 kHz; tested for 10^9 p.



1 -current feedthrough; 2- housing; 3-clamping screw; 4-coil; 5- magnet core; 6-shield; 7-screw; 8-copper insert; 9-yoke; 10-rubber washer-returning springs; 11-ferromagnetic plate-armature; 12-viton stop; 13-viton seal; 14-sealing ring; 15-aperture; 16-base; 17-nut.

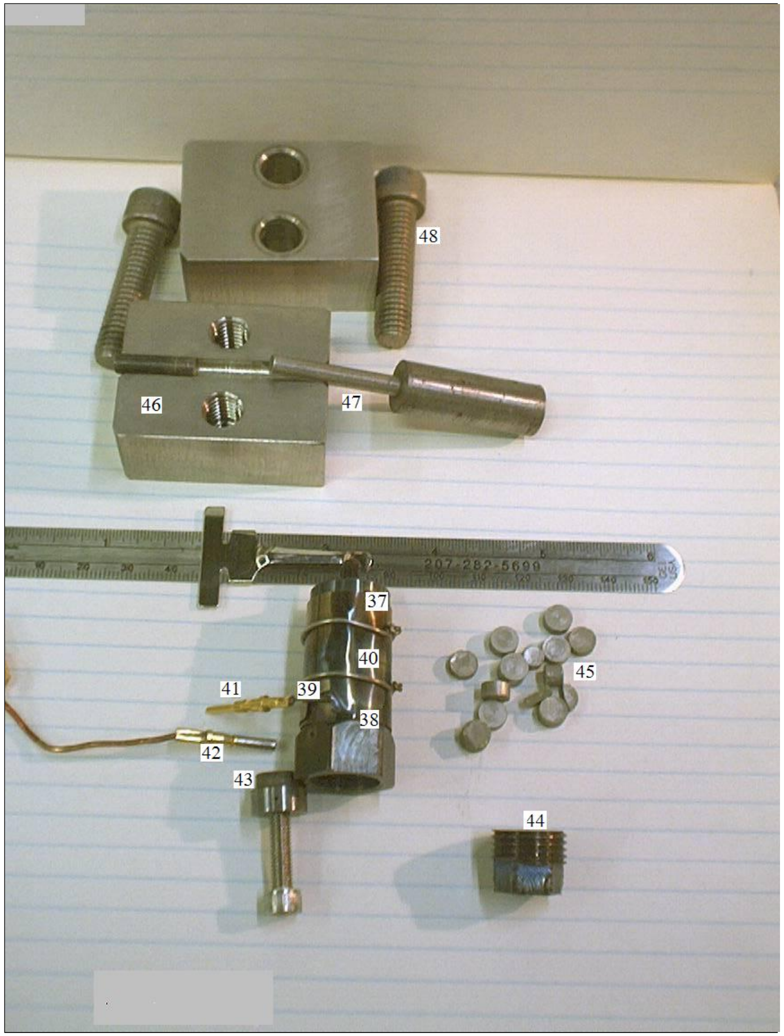
Photograph of a fast, compact gas valve

Gas trapping by discharge in CSPS



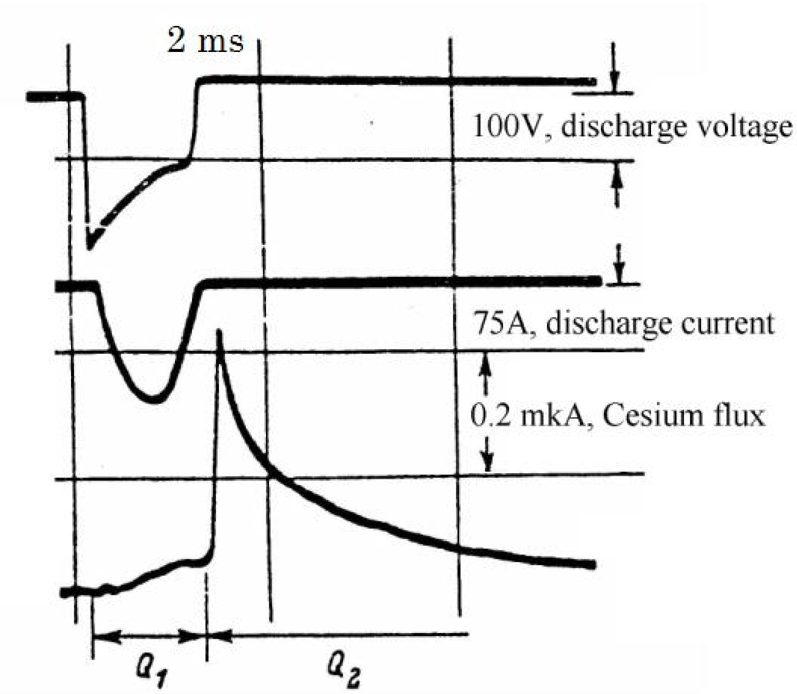
- q_o-gas flux without discharge
- q_p- gas flux with discharge
- I_d- discharge current

Cesium oven with cesium pellets and press-form for fast cesiation.



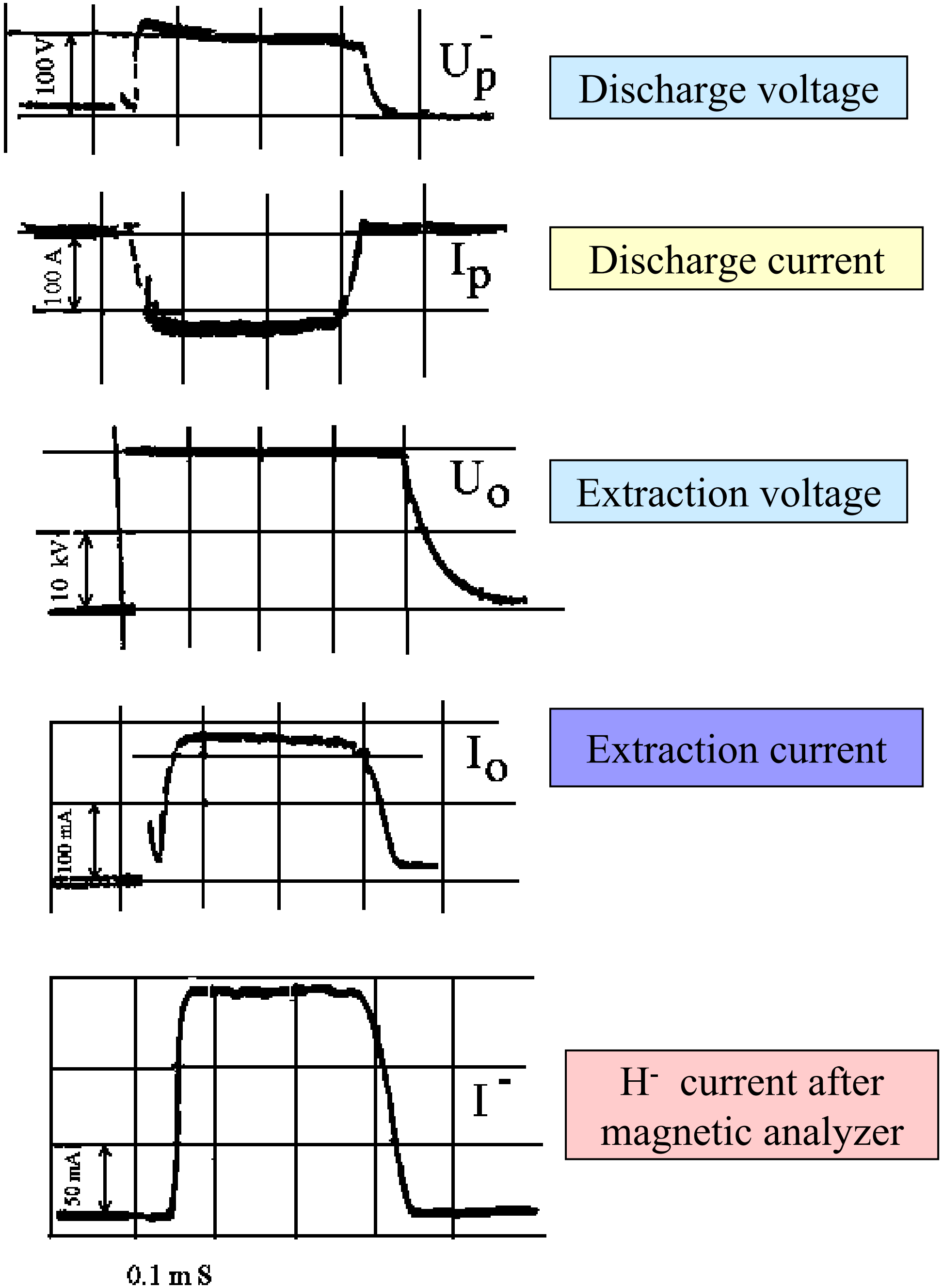
37- cesium oven body;
38- oven assembly;
39- heater;
40- thermal shield;
41- heart connector;
42- wire with connector;
43- plug with copper gasket;
44-press nut;
45- cesium pellets;
46- press form body;
47- press form piston;
48- press form bolt.

Cesium escaping from a pulsed discharge in SPS



there is a strong suppression of the gas and cesium flow from the emission slit by the high density plasma of the discharge.

Cesium flux can be high after discharge. Discharge between pulses can prevent cesium escaping

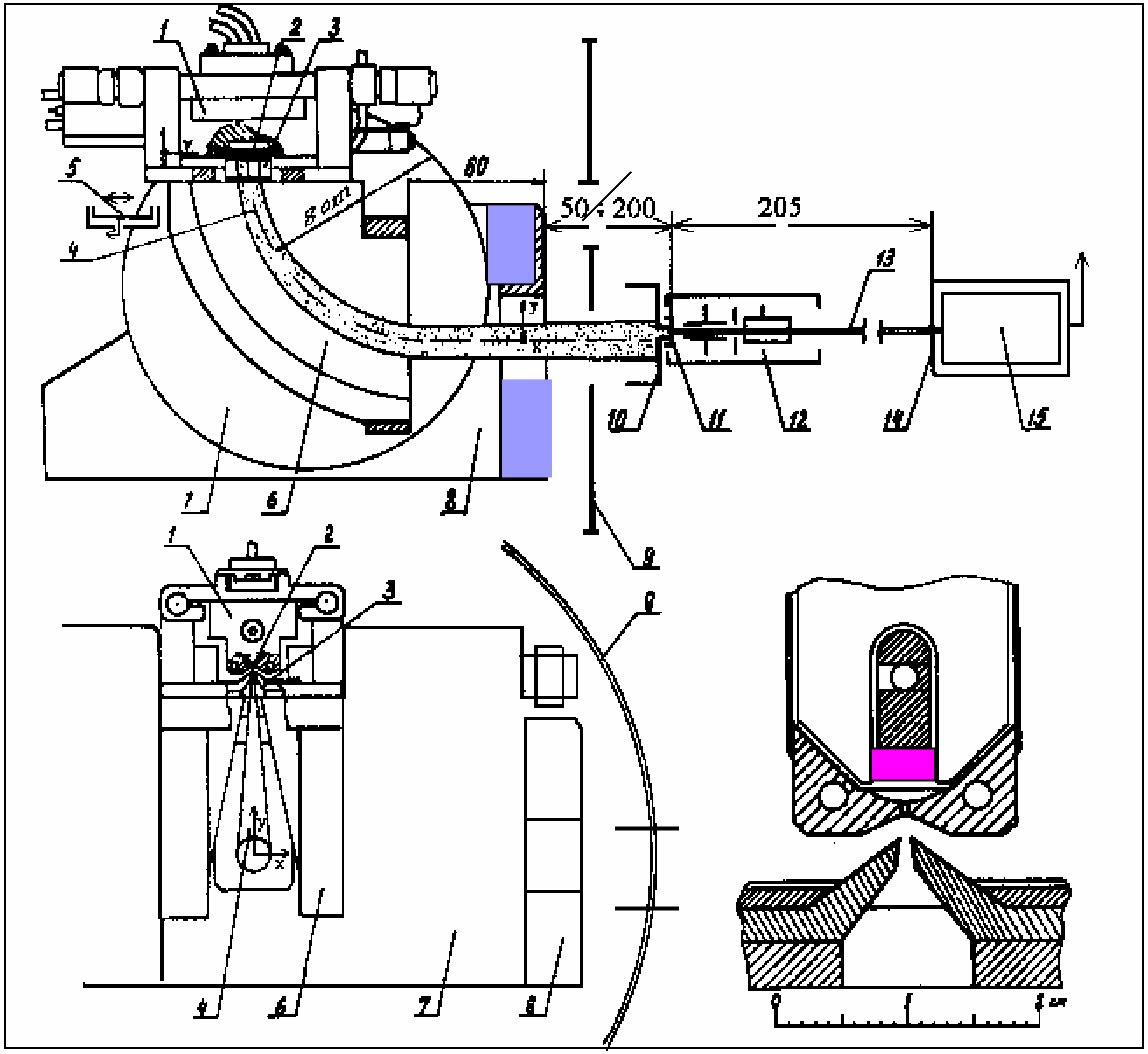


Noiseless operation

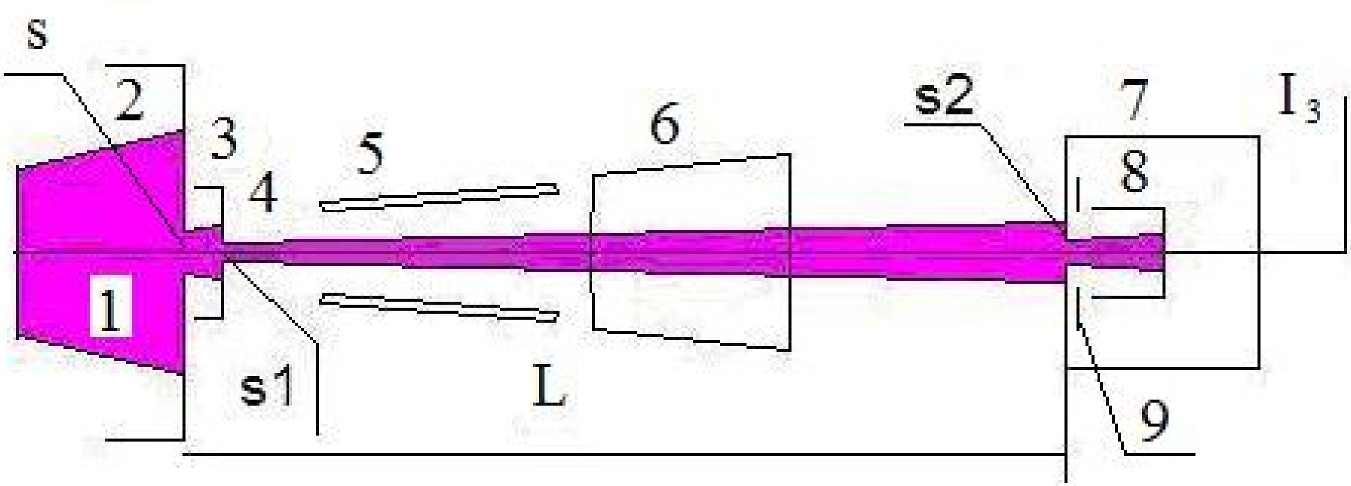
100 Hz

Tested for 300 hs of continuous operation with H- Current>100mA

Beam Formation and Diagnostics of SPS with Penning Discharge



Emittance measurement, Direct Brightness determination



1- Ion beam; 2 Collector with collimator S for J;

3- Second collector with collimator s1 for B; 4-Beamlet;

5-Deflector Vertical; 6- Deflector Horizontal; 7-Screen with collimator s2 for B detection; 8-

Third Collector for B detection; 9-Suppressor.

$B = I_3 L^2/s1\ s2$, $s1=0.1\ mm^2$; $s2=03\ mm^2$, $L=240mm$,

$I \sim 10^{-8}$ A.

Emittance diagramms

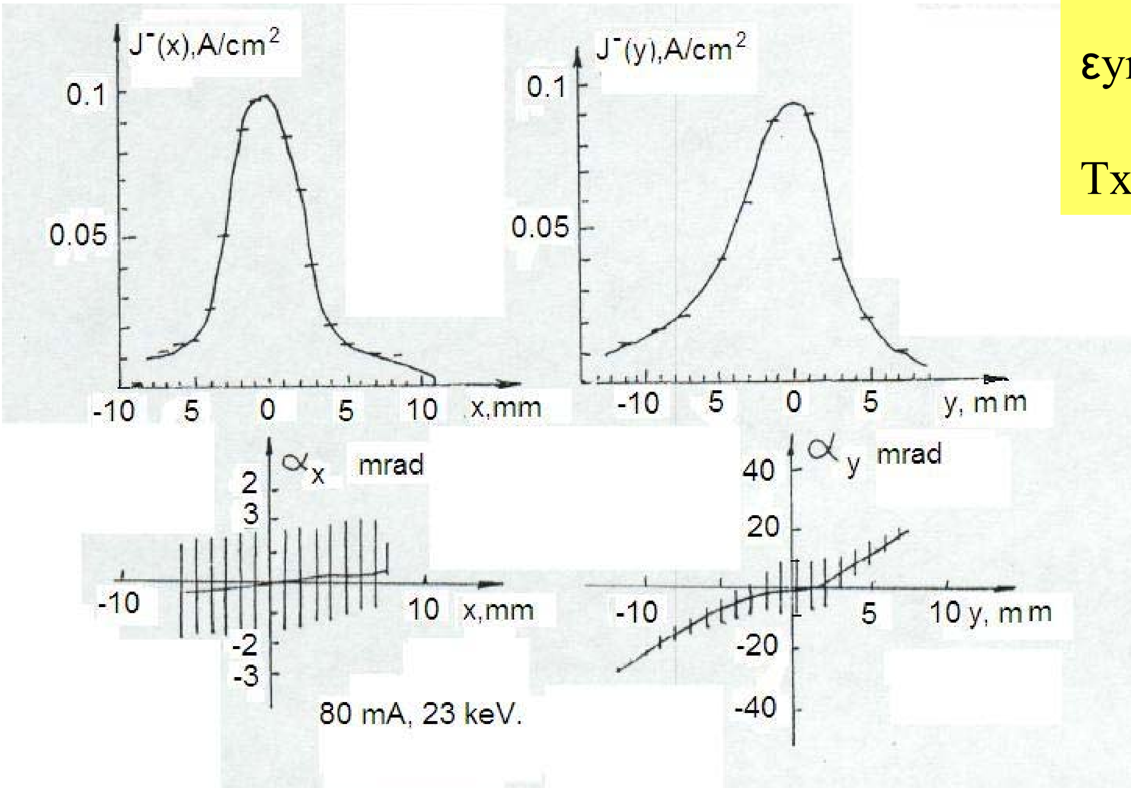
H- beam current 80 mA, Energy 23 keV,

0.5X10 mm mm

εxn rms =0.05 π mm mrad

εyn rms =0.2   π mm mrad

Tx~ 16 eV, Ty~2 eV



Emittance diagramms

H- beam current 80 mA, Energy 20 keV,

0.5x10 mm mm

εxn rms =0.05 π mm mrad

εyn rms =0.2   π mm mrad

Tx~ 27 eV, Ty~2 eV

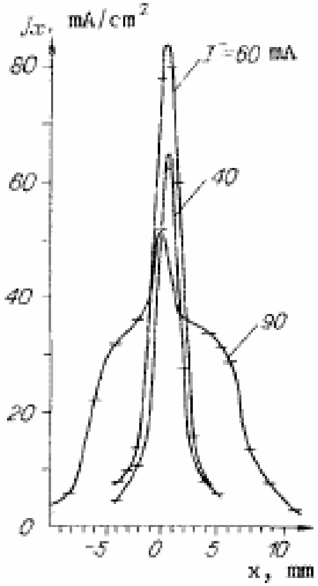


Fig. 12

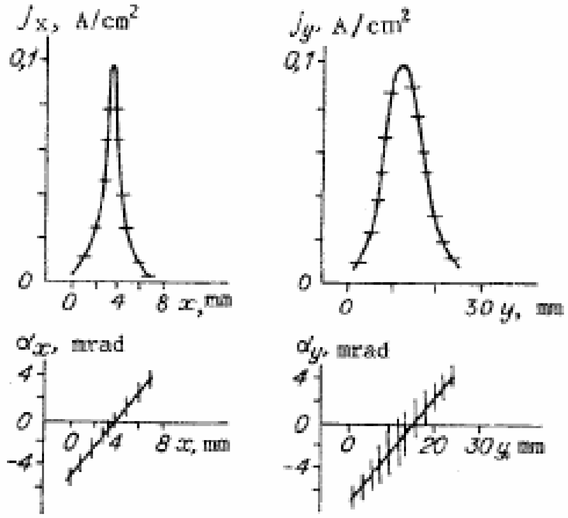
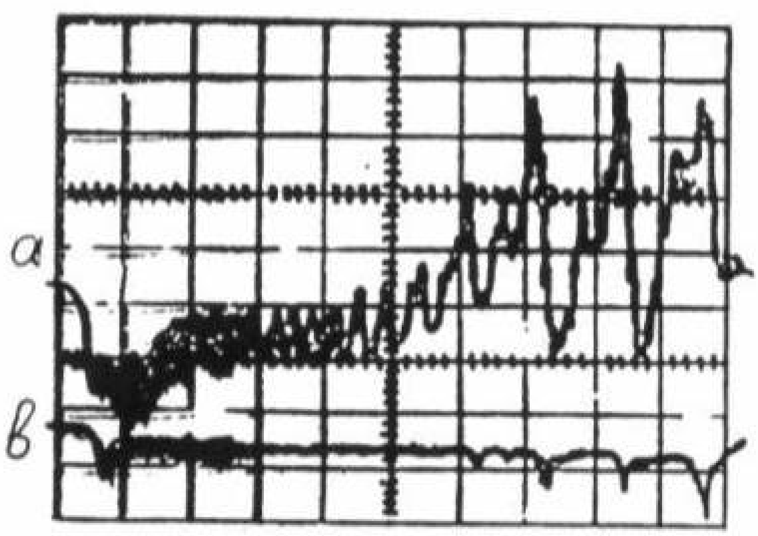
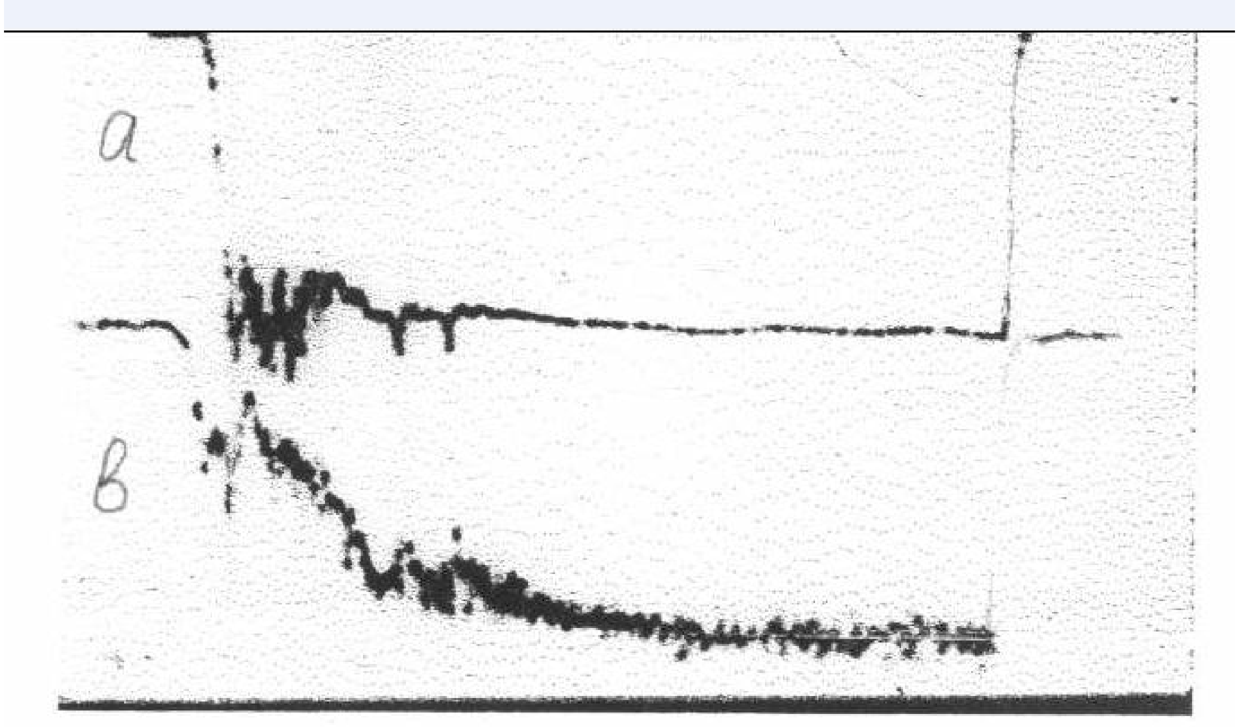


Fig. 13

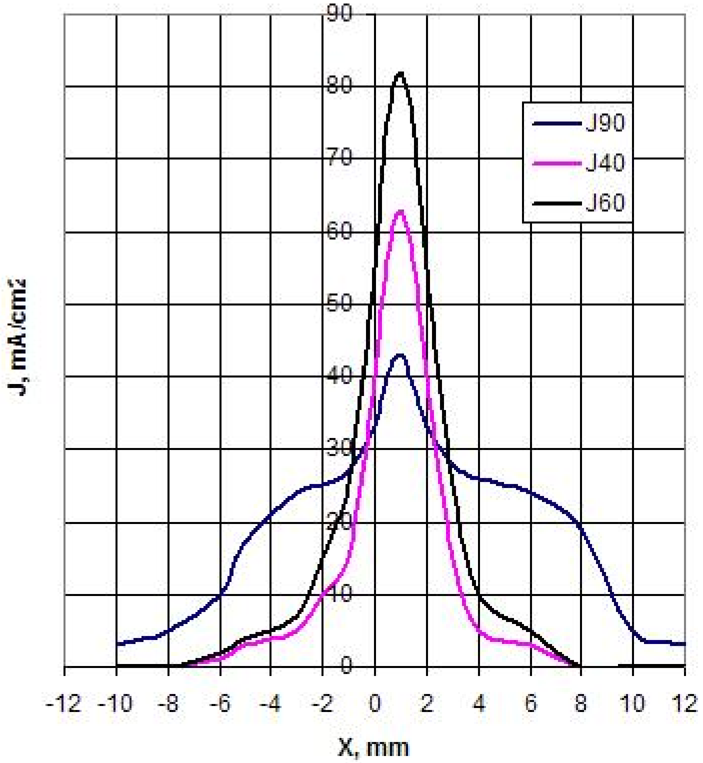
Beam instability with a secondary electron emission



Beam instability with current density fluctuation

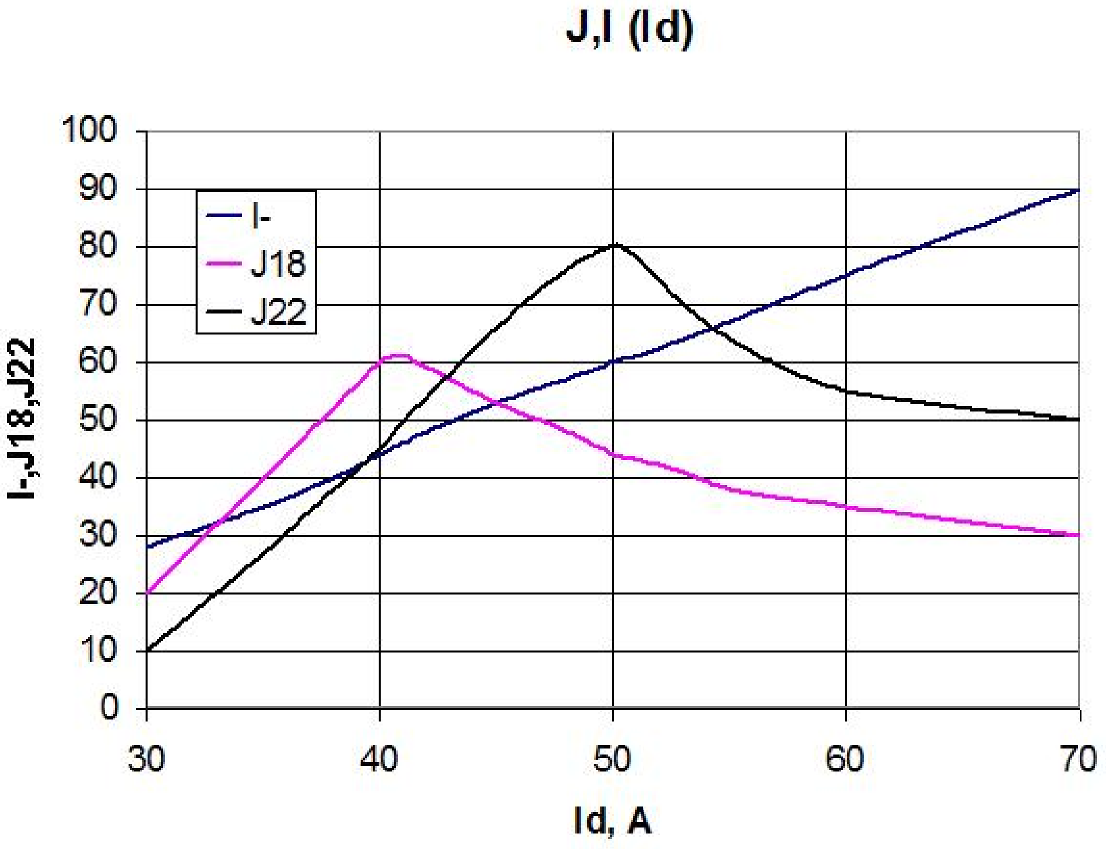


Beam current density distribution for different currents/extraction voltages



For extended beam was observed an overheating through overcooling

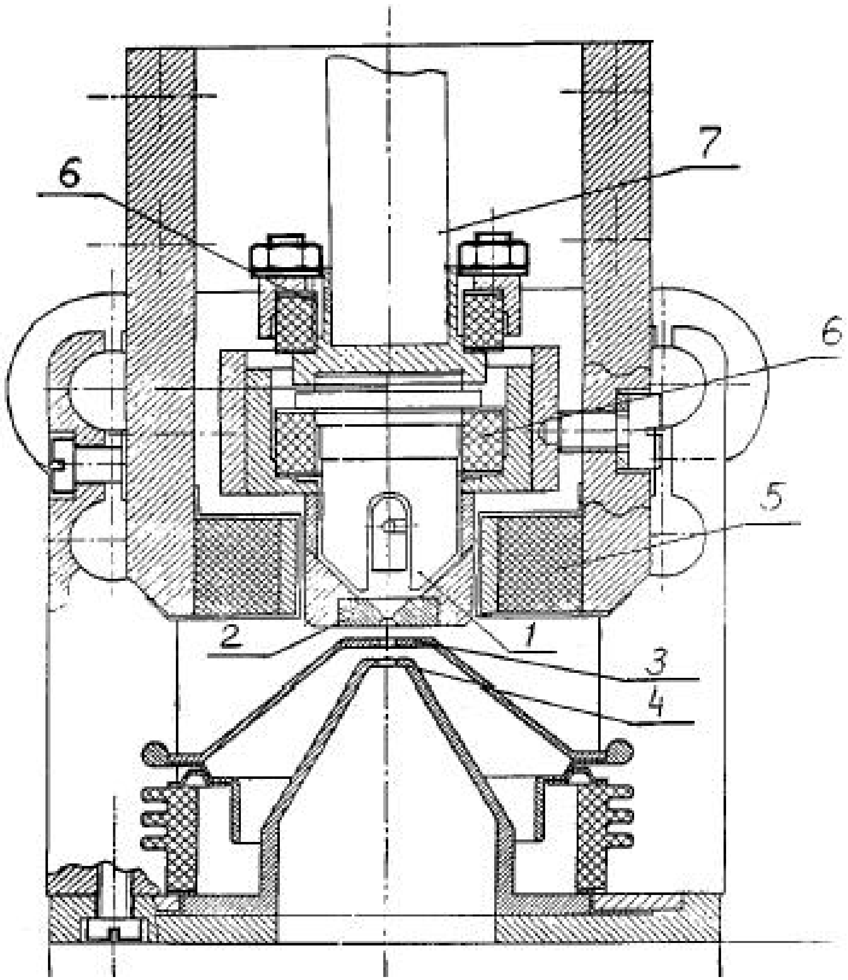
Dependence of current and pick current density for different extraction voltages on discharge current



H- current density on collector for extraction voltage 18 kV and 22 kV.

Emittance is minimal for optimal current density with a minimal angle divergence.

BINP version Penning DT SPS for UMD



1- cathode;

2-anode;

3-extractor;

4- ground ext.;

5-magnet;

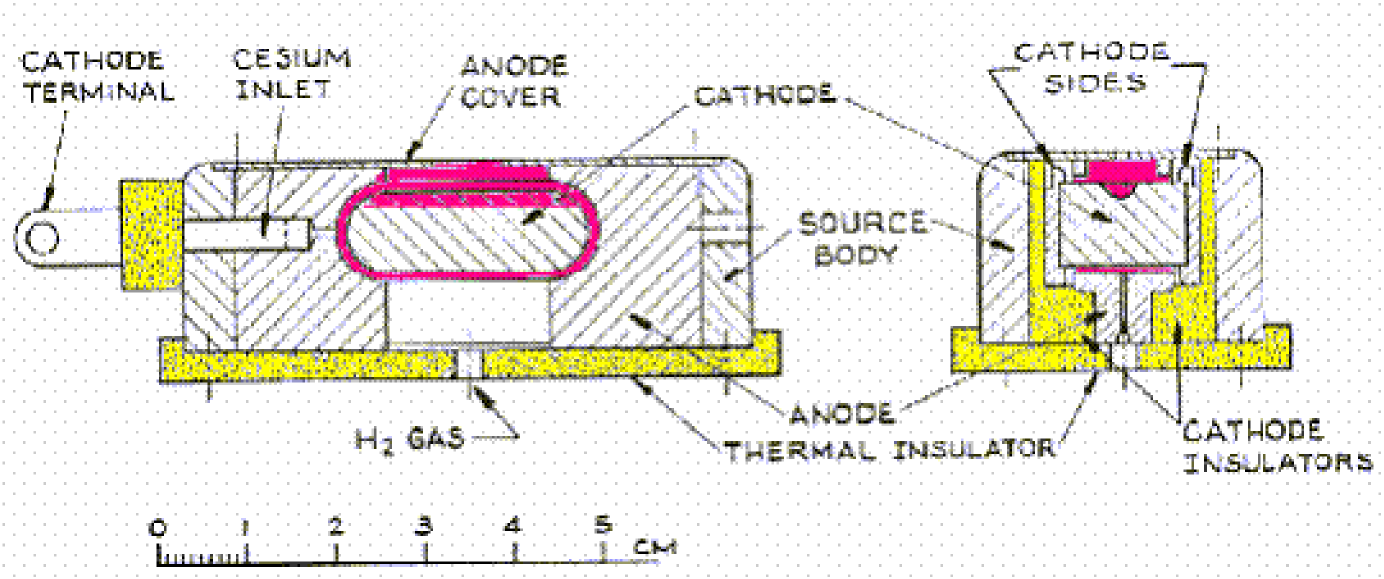
6-insularors;

7-cooler.

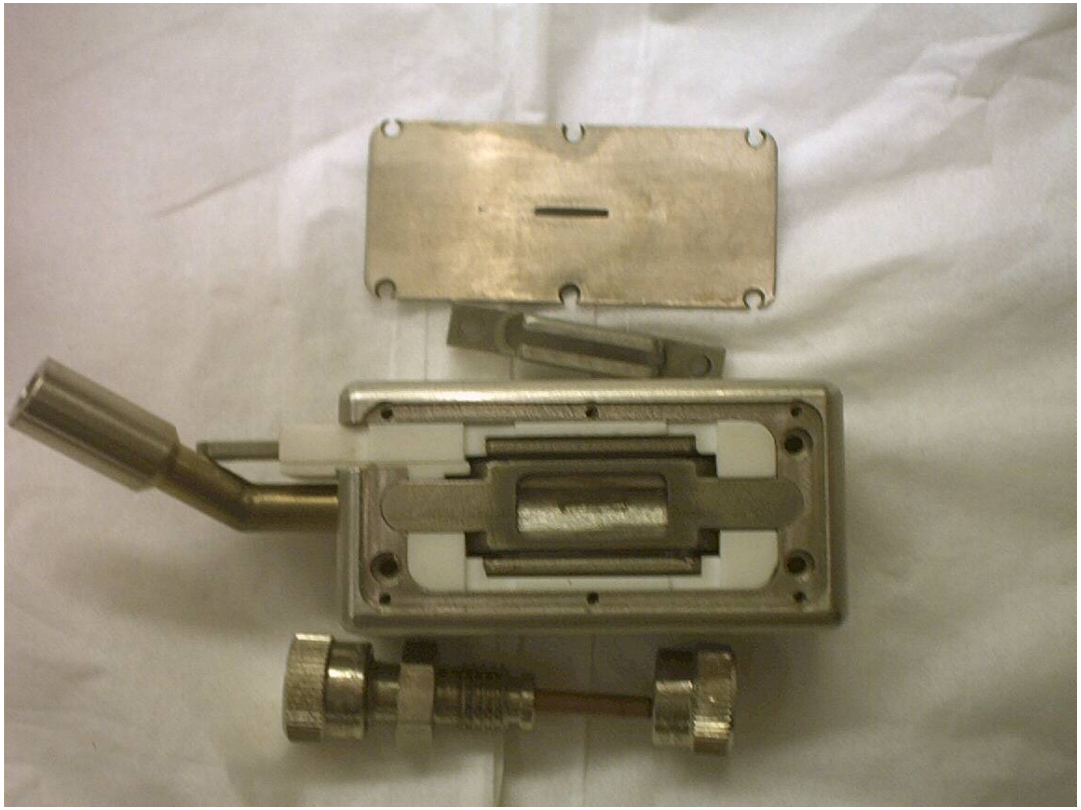
1 ms, 10 Hz, 1 A/cm^2

Teff ~1 eV

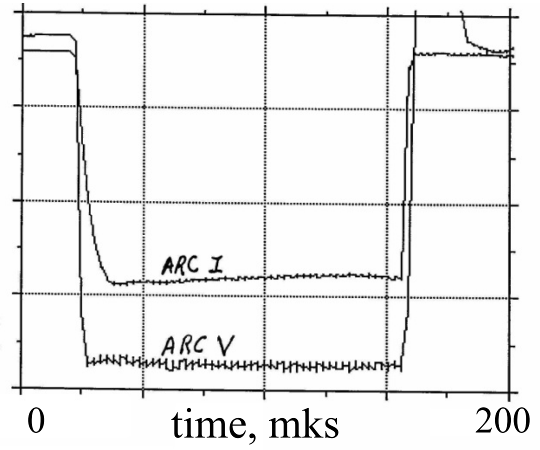
Design of Fermilab Magnetron with a Slit Extraction

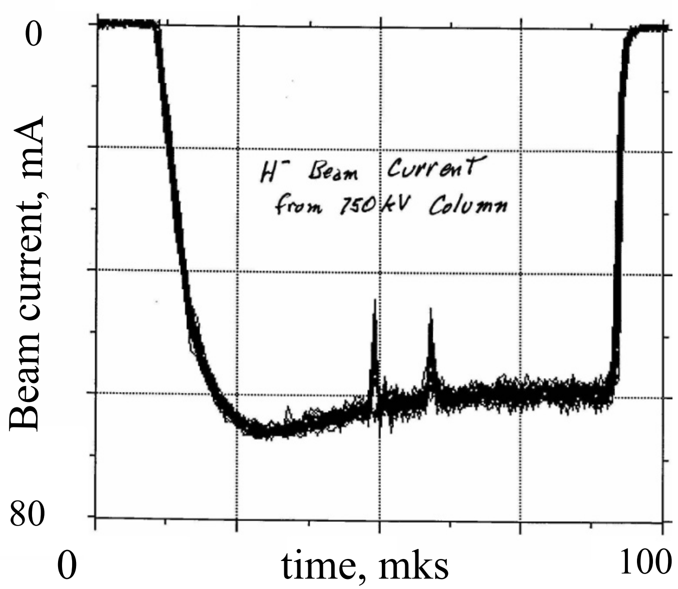


Fermilab Magnetron with a Slit Extraction

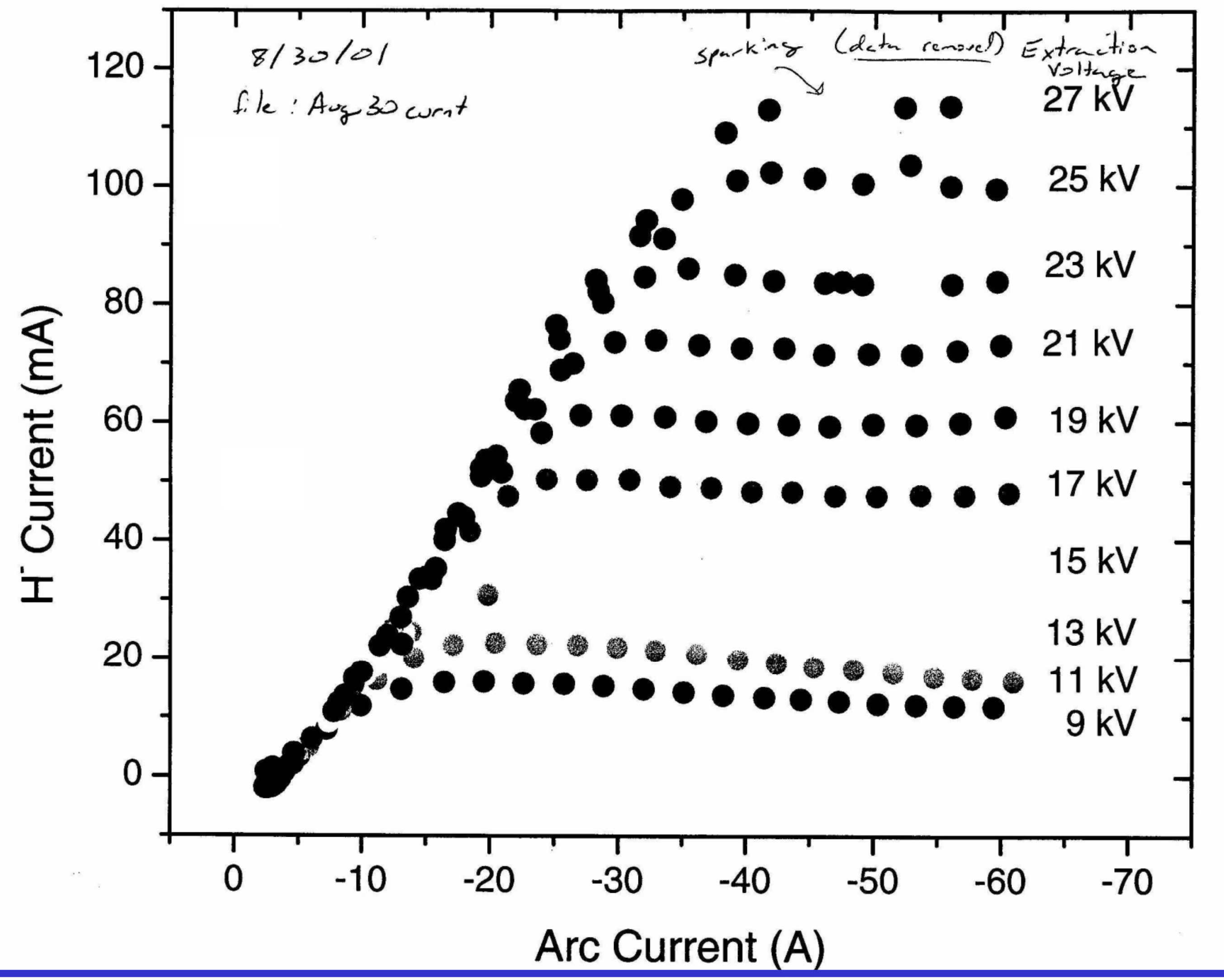


Discharge Parameters and Beam Intensity in Fermilab Magnetron

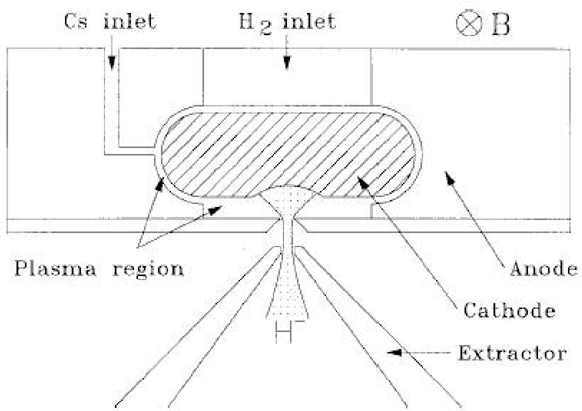


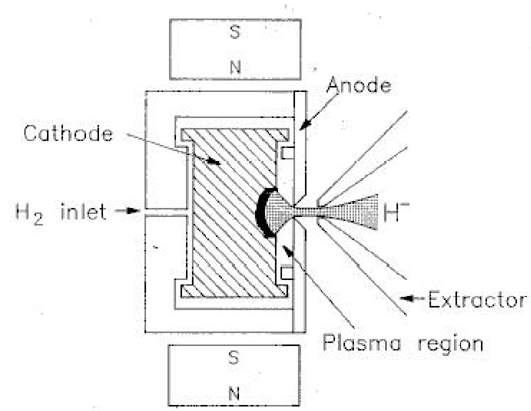


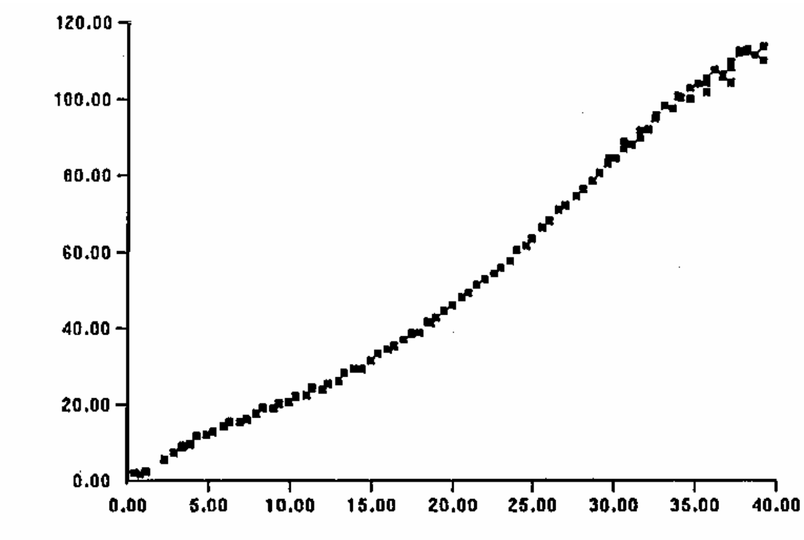
Beam Intensity vs Discharge Current and Extraction Voltage in Fermilab Magnetron



BNL magnetron with a spherical focusing.



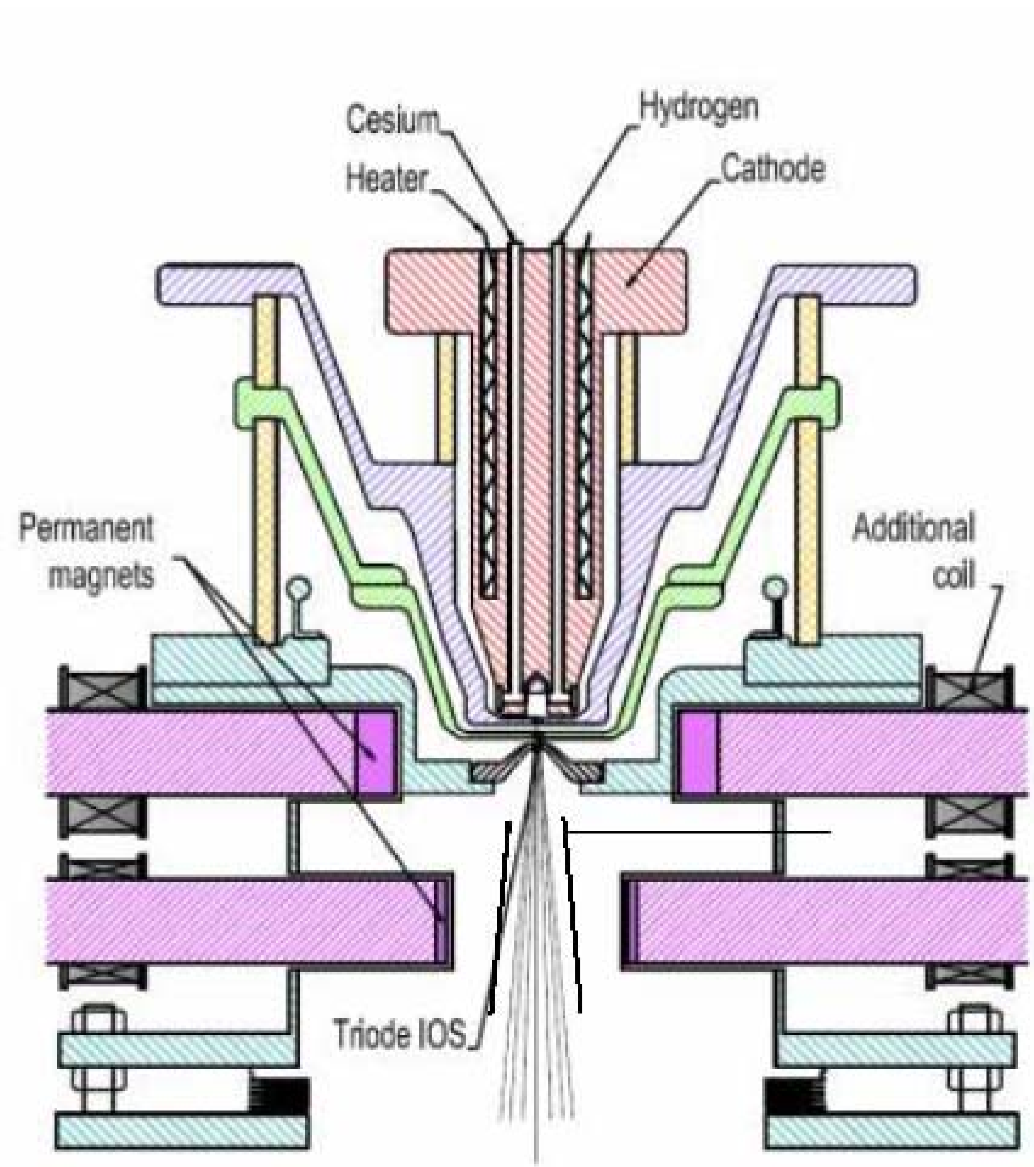




I- 0.1 A, Id~ 15 A, Ud~100V; 7.5 Hz, 0.5 ms. 9 month operation.

LEBT two solenoids lens; RFQ 0.75 MeV.

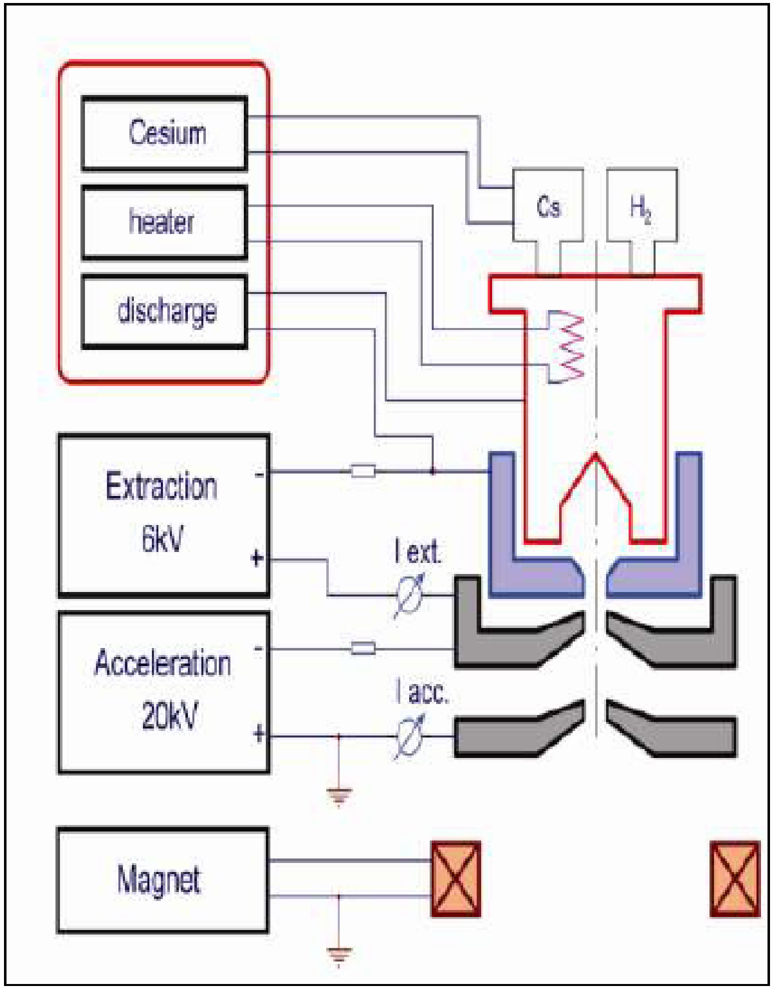
DC SPS with Penning discharge (BINP)

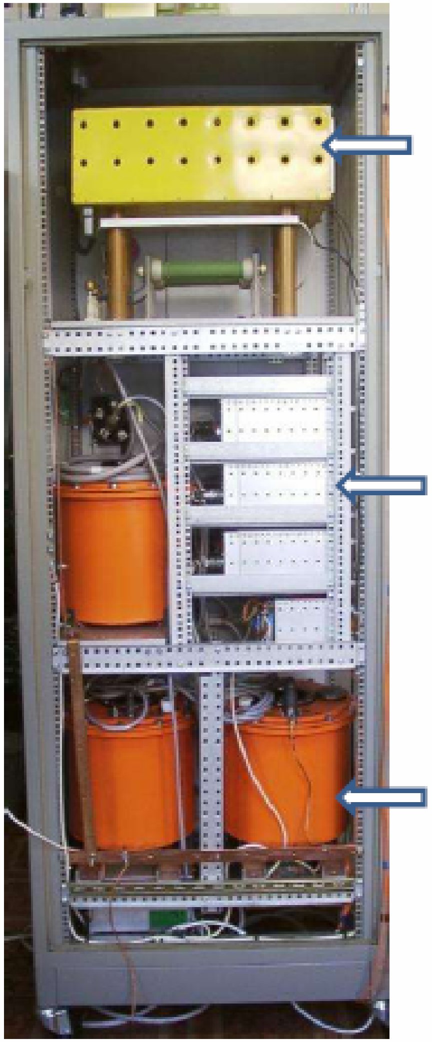


DC H- beam up to 20 mA at 0.7 kW of discharge power;

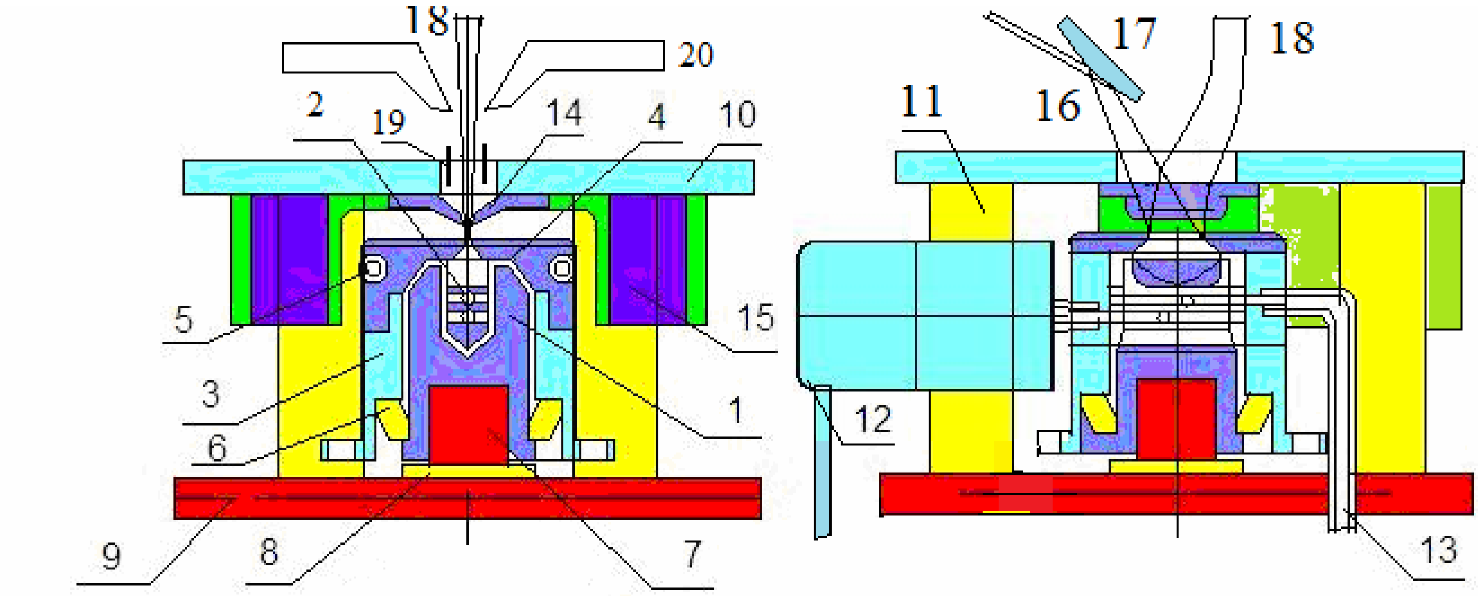
Emittance < 0.2 π mm mrad 1 rms

Power supply of Dc Penning SPS



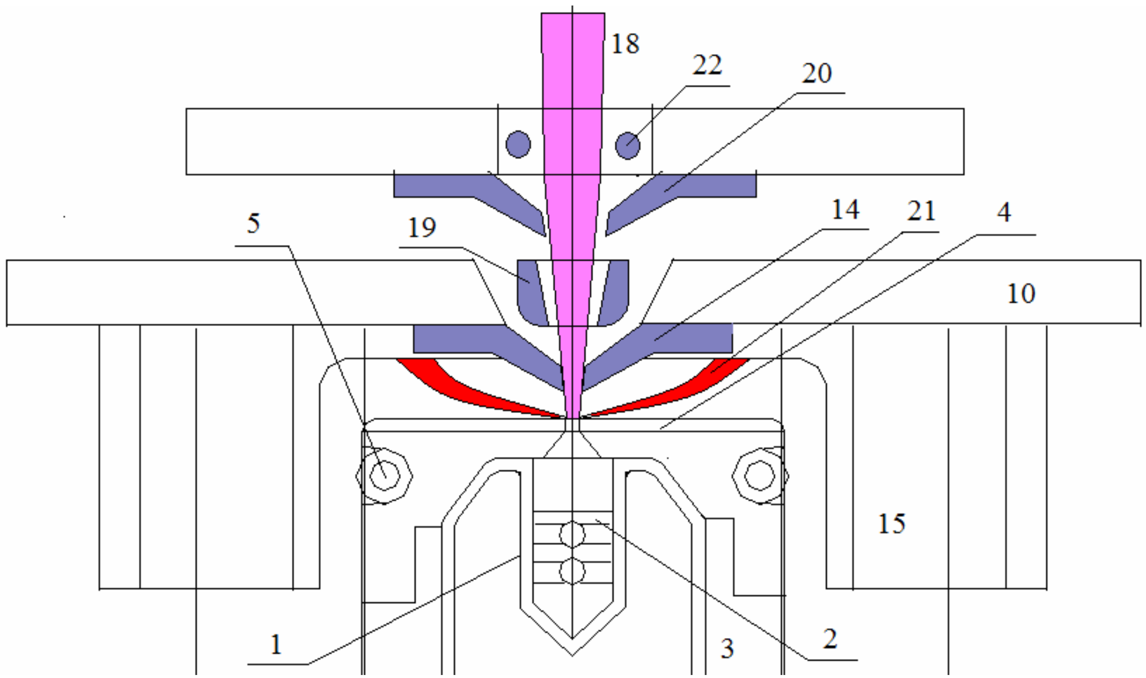


SPS with Penning discharge, post-acceleration and cesium suppression by laser.



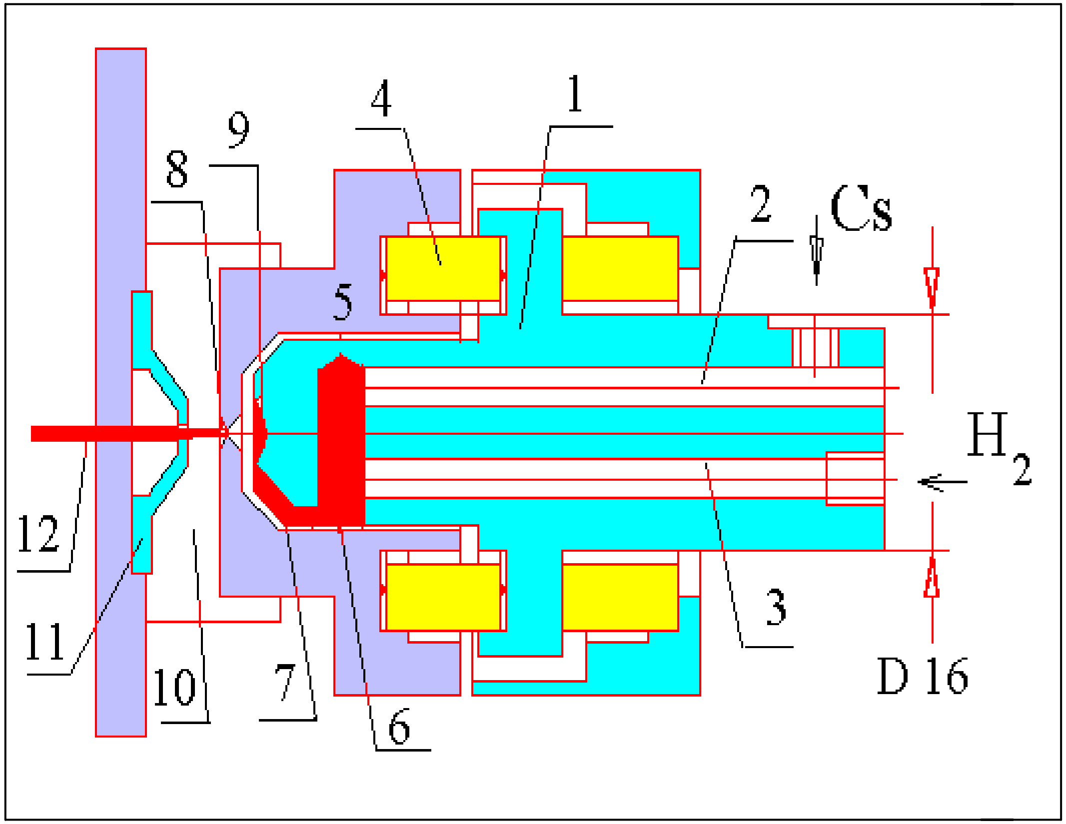
1- cathode (Mo); 2-anode (W); 3-source body (St.St.); 4- cooled plasma plate (Mo); 5- anode cooling; 6- cathode insulator; 7-cathode cooler (Cu); 8- thermal conductive insulator (AlN); 9-cooled flange (Cu); 10- base plate (St.St.);11-high voltage insulator (ceramic AlN); 12- gas delivery system(pulsed valve); 13- cesium delivery system;14- extractor (Mo); 15- magnet (SmCo) + coils; 16- laser beam; 17-mirror; 18-negative ion beam; 19-suppressor/deflector; 20- accelerating electrode.

Ion extraction and electron suppression in CSPS



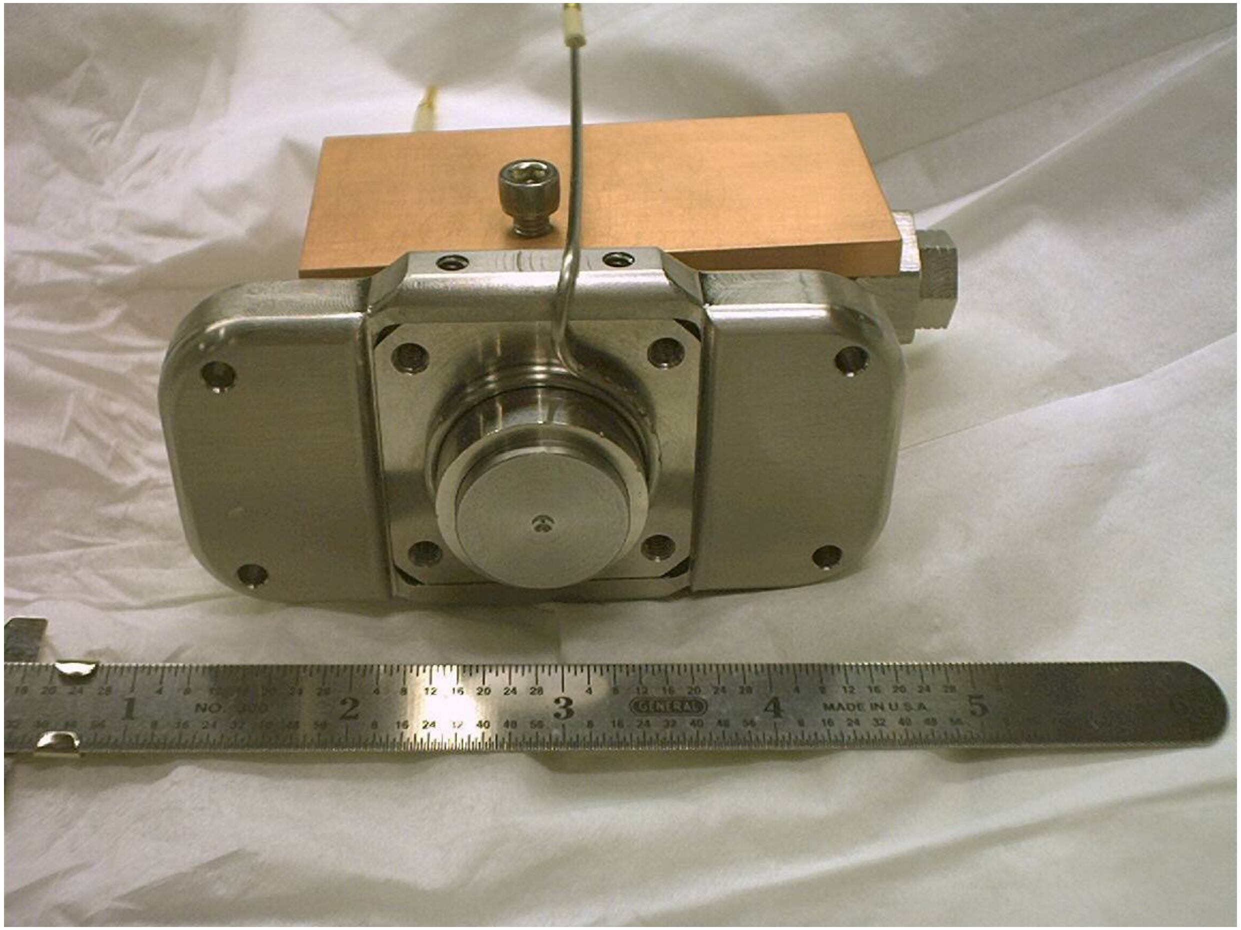
1- cathode (Mo); 2- anode (W); 3-source body (St.St.); 4- cooled plasma plate (Mo); 5- anode cooling; 6- cathode insulator; 14- extractor (Mo); 15- magnet (SmCo) + coils; 18-negative ion beam; 19-deflector; 20-accelerating electrode; 21- electrons.

Compact DC SPS with Hollow Cathode Discharges

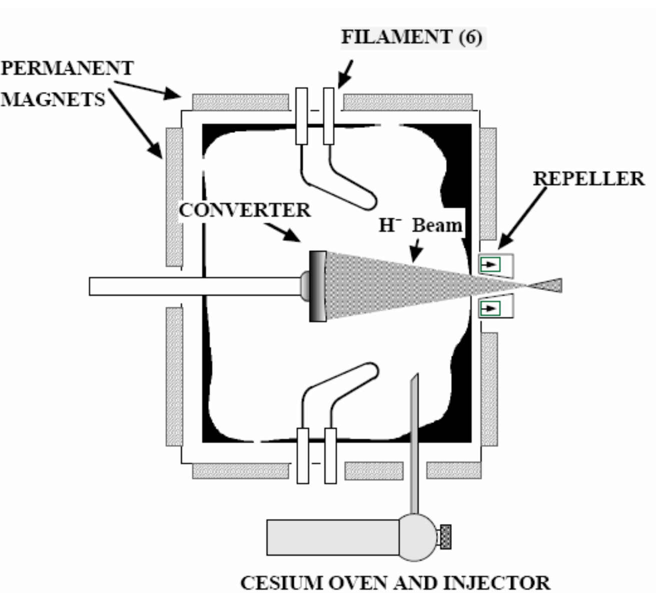


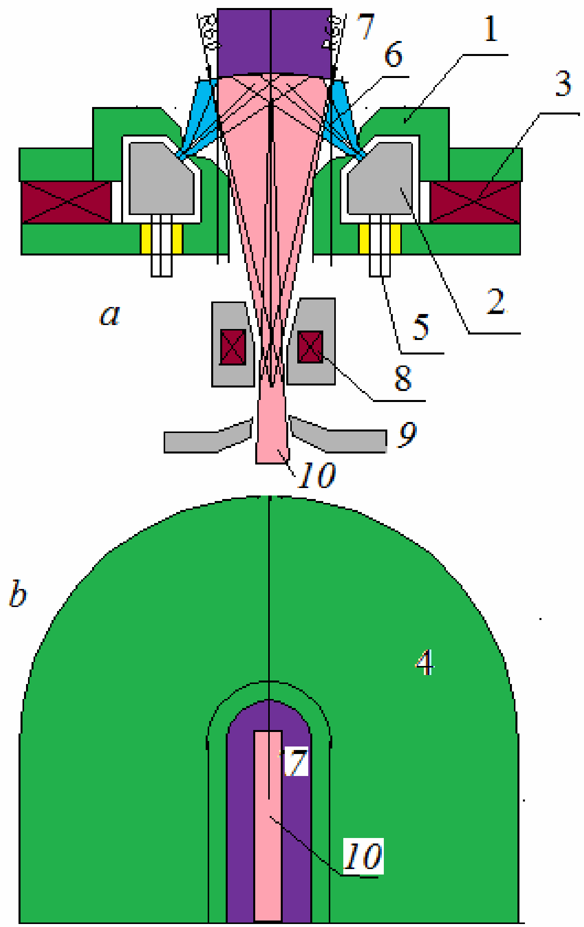
1- cylindrical cathode body;
2- channel for cesium delivery;
3- channel for working gas;
4- insulator (ring);
5- anode chamber;
6- hollow cathode channel;
7- drifted plasma;
8- extraction aperture;
9- spherical emitter;
10- magnetic pole;
11- extractor;
12- ion beam.

DC SPS
with a High Emission Current Density



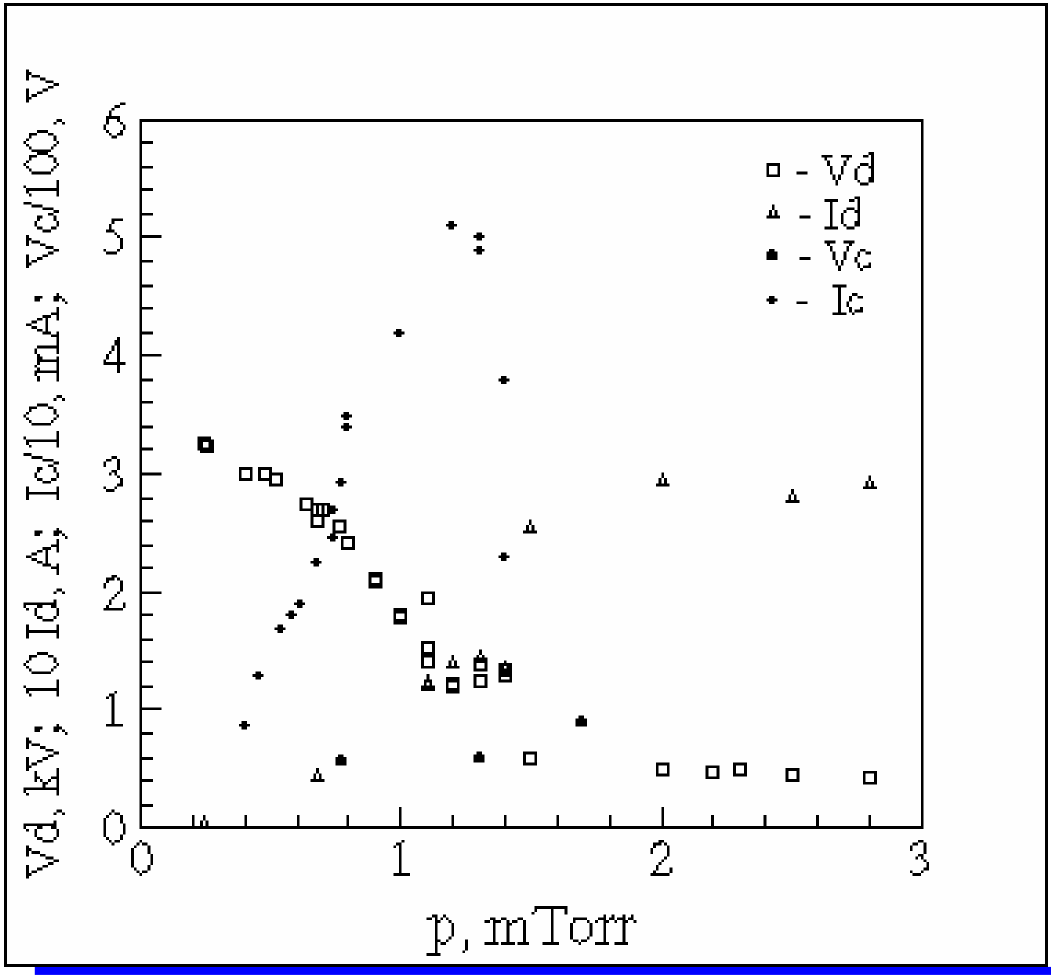
Surface Conversion SPS





7- negative ion emitter); 6- anode layer plasma accelerator generating a flux of positive ions . This emitter (7) is bombarded by ions (6) for generating the secondary negative ion beam (10).

Discharge characteristics of ALPA as function of gas N2 pressure in vacuum chamber

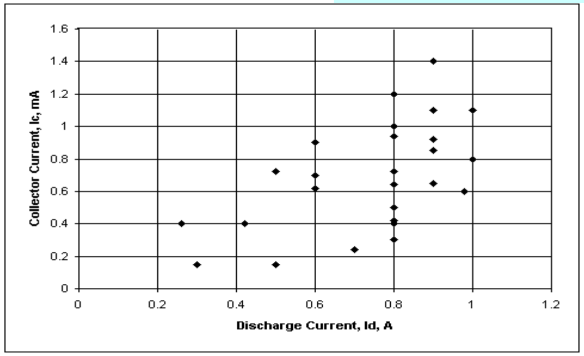


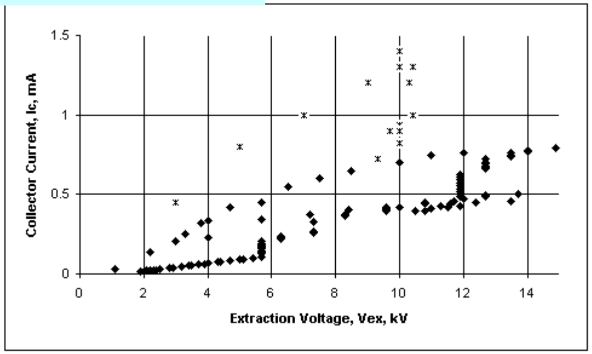
Anode of DC SPS

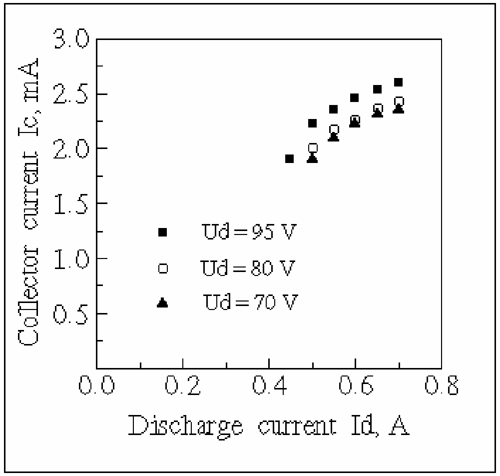
Fig.1-4. Sputtering around extruction aperture by negative ions from spherical emitter

Collector current Ic vs. discharge current Id and extraction voltage Vex

Extraction aperture of D=0.4 mm

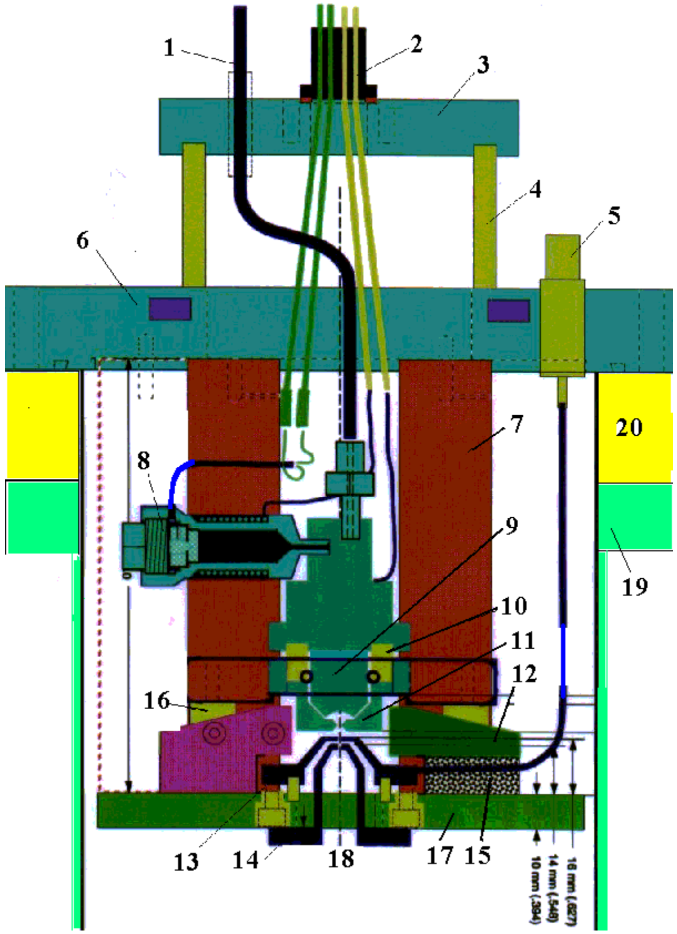






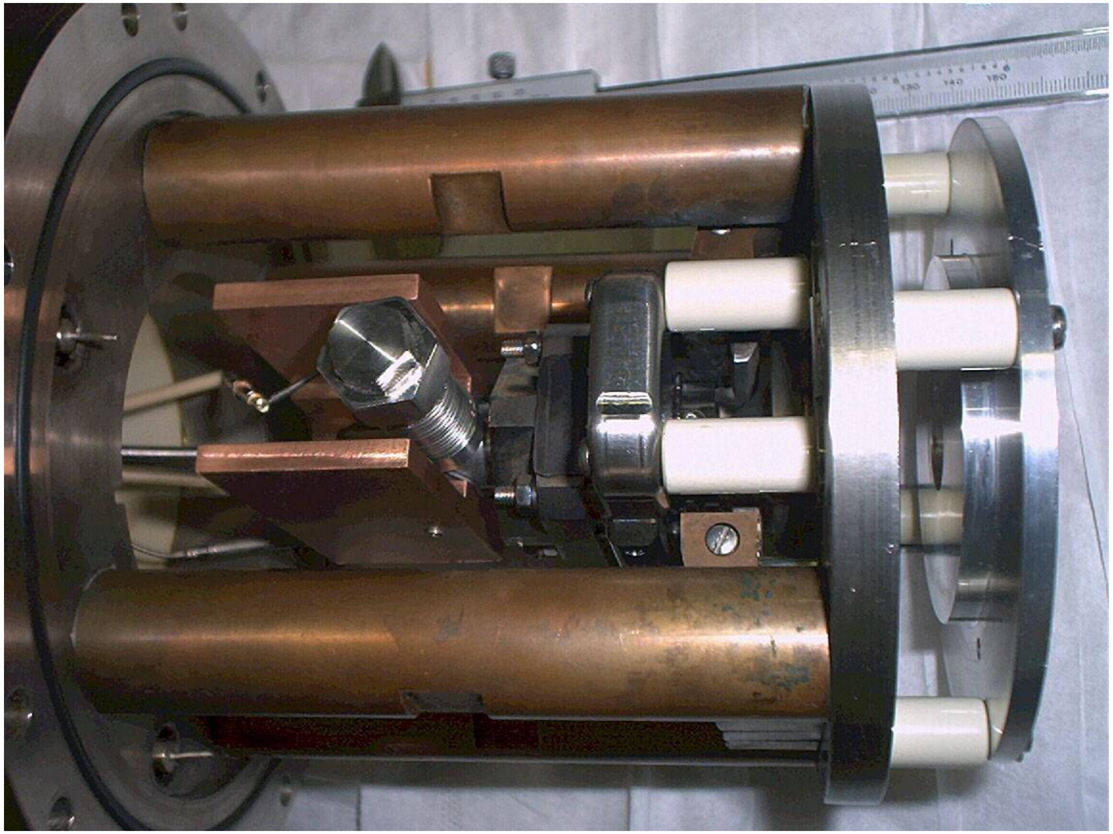
Extraction aperture of D=1 mm

Assembly of the negative ion source in vacuum chamber

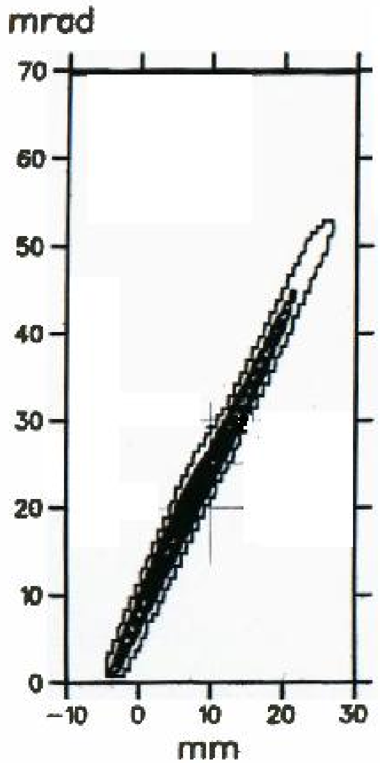


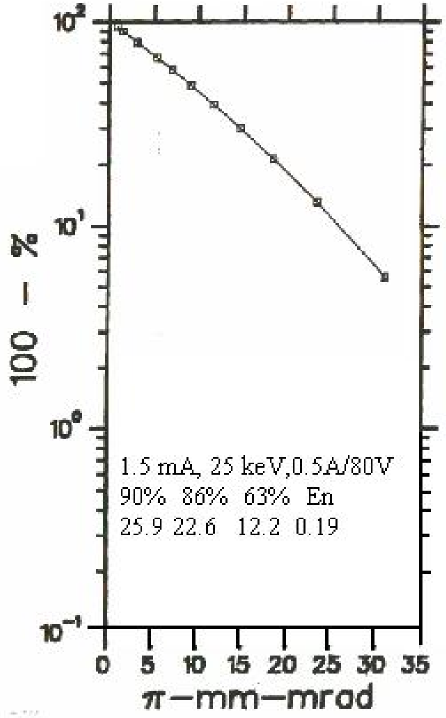
1- gas tube;
2- electric vacuum feedthroughs;
3- high voltage flange;
4- high voltage insulator;
5- high voltage feedthrough;
6- base flange;
7- cooling rods;
8- Cs catalyst supply;
9- cathode-emitter;
10- cathode insulator;
11- gas discharge chamber anode;
12- magnet poles;
13- suppression electrode;
14- extraction electrode;
15- permanent magnet;
16- high voltage insulators;
17- base plate-magnetic yoke;
18- ion beam;
19- vacuum chamber;
20- high voltage insulator.

Typical Assembling of CSPS on the Vacuum Flange

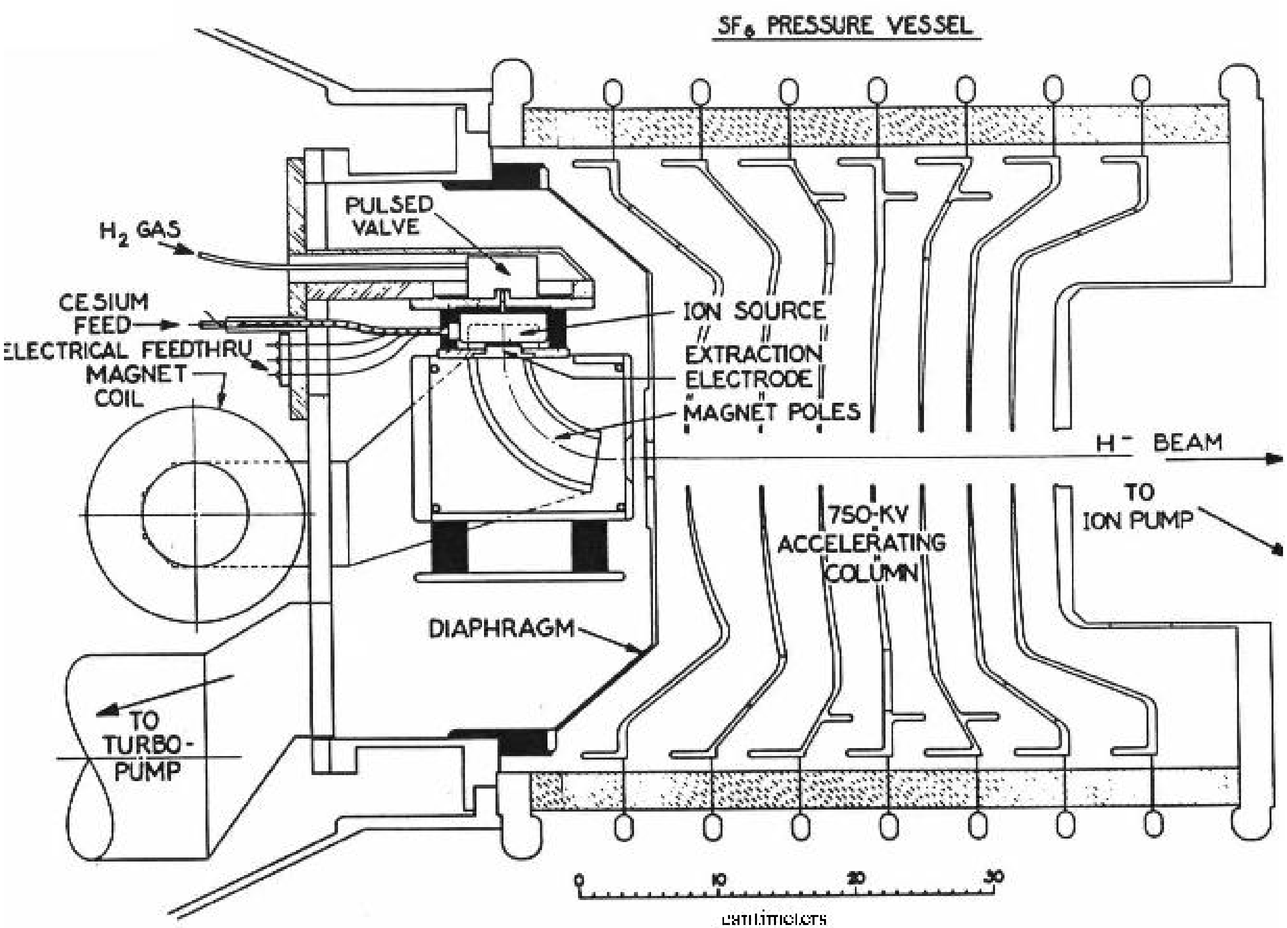


Emittance of DC SPS, 25 keV, 1.5 mA



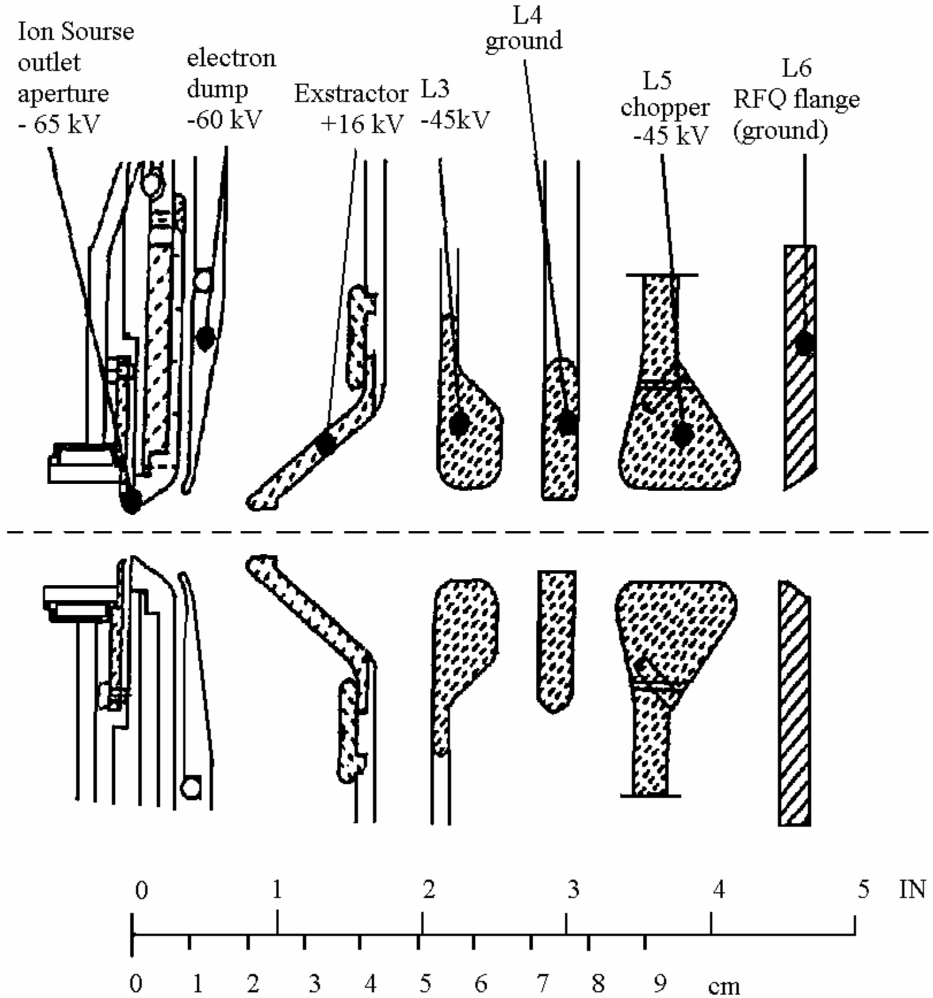


FNAL SPS in preaccelerator, 0.75 MV, 0.1 A

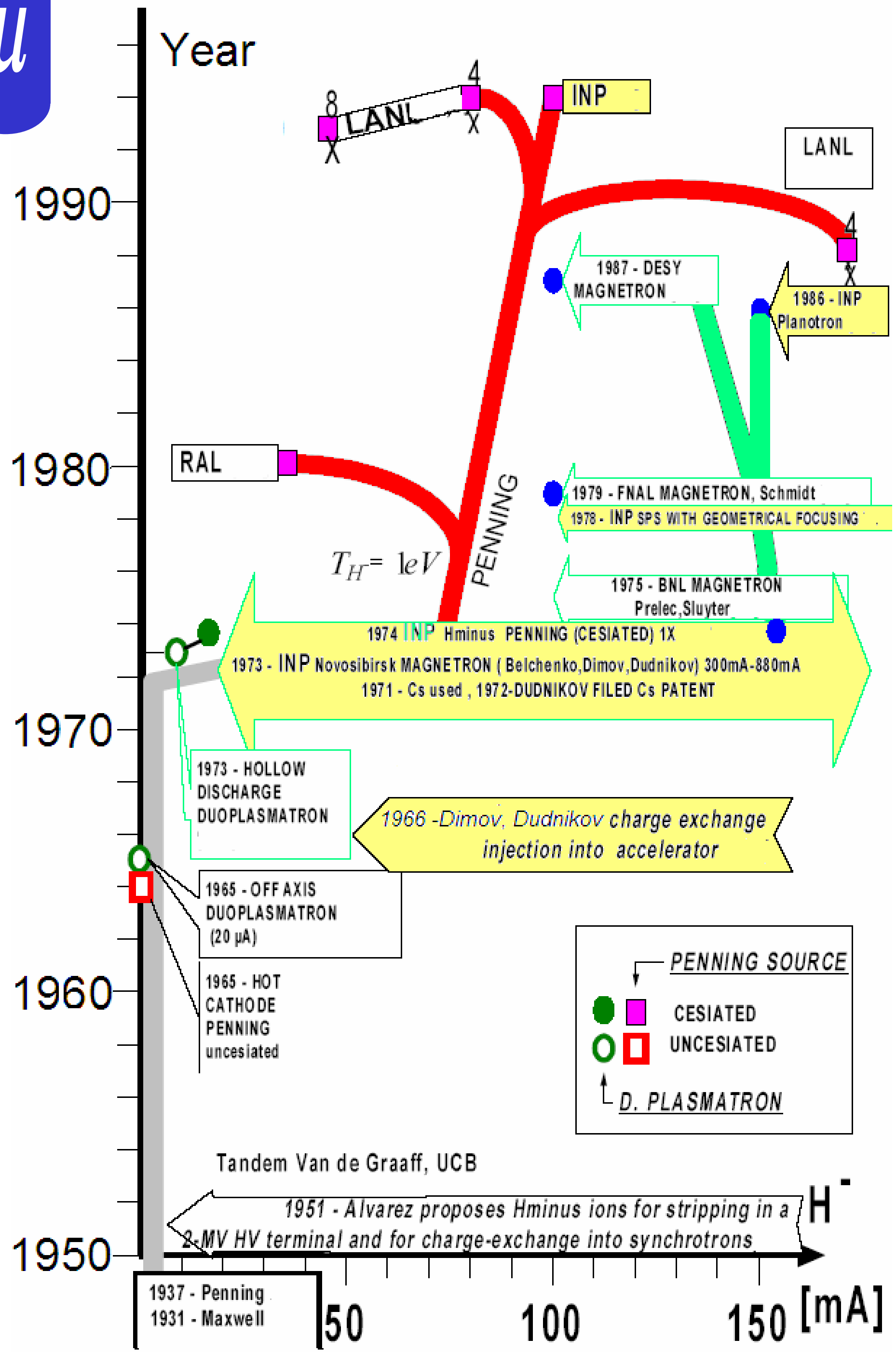


ION SOURCE ASSEMBLY

Cross section of LEBT electrodes with ion source outlet aperture, electron dump, and REQ endwall (LBL, for SNS).



Penning SPS in the ISIS RFQ



History of Surface Plasma Source development

(J.Peters, RSI, v.71, 2000)

Cesiation patent

V. Dudnikov. The Method for Negative Ion Production, SU Author Certificate, C1.H013/04, No. 411542, Application filed at 10 Mar., 1972, granted 21 Sept,1973.

Invention formula:

"Method of negative ion production comprising admixture into the discharge a substance with a low ionization potential, such as ***cesium****".*

Operation of Dudnikov type Penning source with LaB6 cathodes

K.N. Leung, G.J. DeVries, K.W. Ehlers, L.T. Jackson, J.W.Stearns, and M.D. Williams (LBL)
M.G. McHarg, D.P. Ball, and W.T. Lewis (AFWL)
P.W. Allison (LAML)

The Dudnikov type Penning source has been operated successfully with low work function LaB6 cathodes in a cesium-free discharge. It is found that the extracted H– current density is comparable to that of the cesium-mode operation and H– current density of **350 mA/cm²** have been obtained for an arc current of 55 A. Discharge current as high as 100 A has also been achieved for short pulse durations. The H– yield is closely related to the source geometry and the applied magnetic field. Experimental results demonstrate that the majority of the H– ions extracted are formed by volume processes in this type of source operation.

Review of Scientific Instruments -- February 1987 -- Volume 58, Issue 2, pp. 235-239

Cesiation PATENT

V. Dudnikov, The Method of Negative Ion Production, SU Author Certificate, C1.H01 3/04, No. 411542, Application, 10 March,1972 http://www.fips.ru/cdfi/reestr_rupat.htm; patent number 411542,

СОЮЗ СОВЕТСКИХ СОЦИАЛИСТИЧЕСКИХ РЕСПУБЛИК

ГОСУДАРСТВЕННЫЙ КОМИТЕТ СОВЕТА МИНИСТРОВ СССР
ПО ДЕЛАМ ИЗОБРЕТЕНИЙ И ОТКРЫТИЙ

АВТОРСКОЕ СВИДЕТЕЛЬСТВО

№ 411542

На основании полномочий, предоставленных Правительством СССР, Государственный комитет Совета Министров СССР по делам изобретений и открытий выдал настоящее авторское свидетельство

ДУДНИКОВУ Вадиму Георгиевичу

на изобретение "Способ получения отрицательных ионов"

в соответствии с описанием изобретения и приведенной в нем формулой, по заявке № 1758285 с приоритетом от 10 марта 1972г.
заявитель изобретения: Институт ядерной физики Сибирского отделения АН СССР

Зарегистрировано в Государственном реестре изобретений Союза ССР
21 сентября 1973 г.

Действие авторского свидетельства распространяется на всю территорию Союза ССР

Председатель Госкомитета

Начальник отдела

"Enhancement of negative ion production by admixture into discharge a substance with a low ionization potential, such as cesium".

- **Invention formula:**
- *“Method of negative ion production comprising admixture into the discharge a substance with a low ionization potential, such as **cesium**”.*
- **There is big difference between “surface production” and “surface plasma production”, because without plasma it is possible to have only microAmpers of negative ions as in sputtering type (Middleton) sources.**
- *Further development of SPS was conducted by Belchenko, Dimov, Dudnikov in INP and many teams in many laboratories.*

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