High-Power and Long-Pulse Injection with Negative-Ion-Based Neutral Beam Injectors in Large Helical Device

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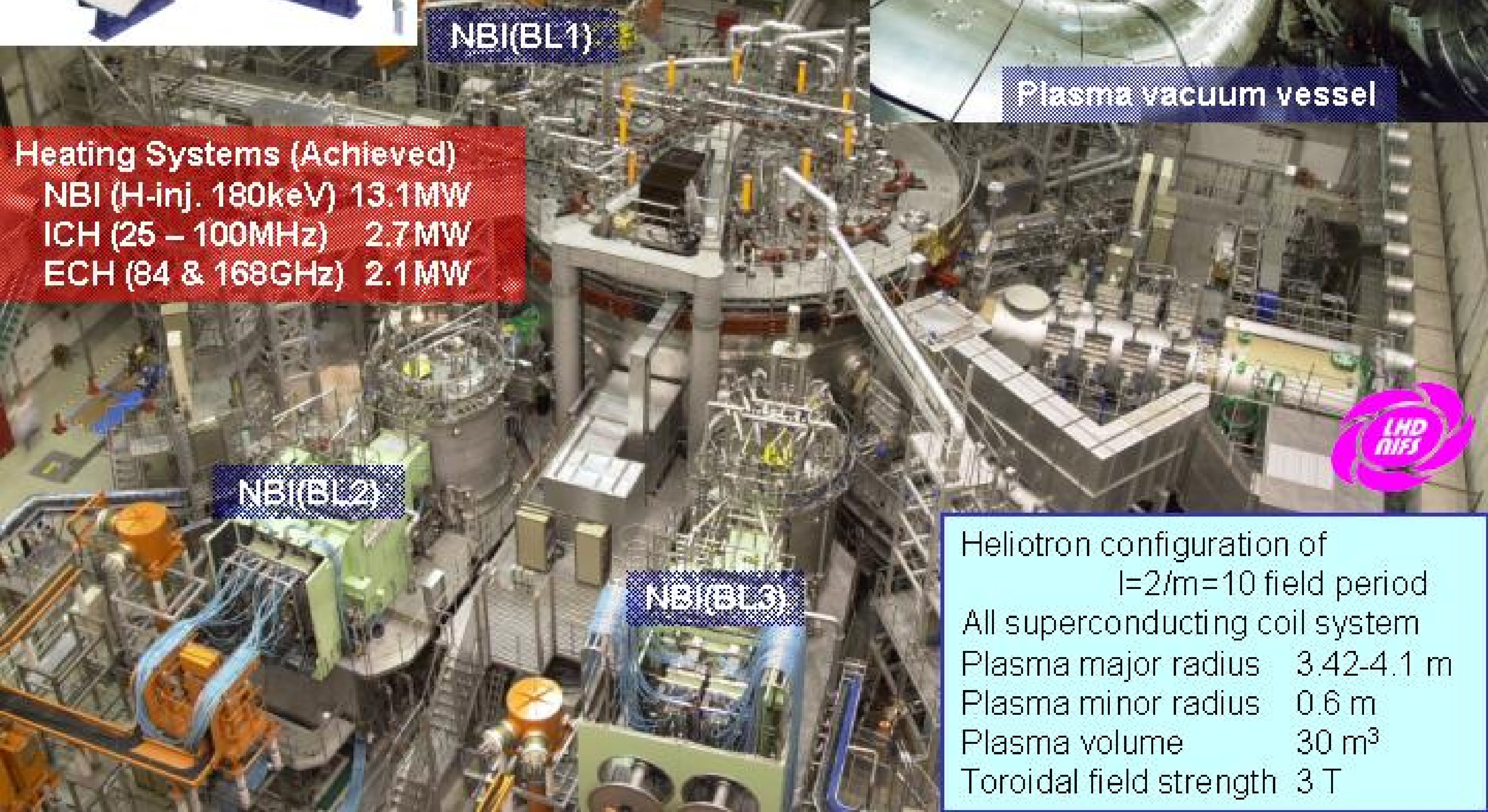
Contents

- Outline of the negative-NBI system in Large Helical Device
  - Progress of the injection power
  - Plasma parameters achieved with the negative-NBI in LHD
- Structure of the injector and the negative ion source
- Recent improvement of the negative ion source
  - Optimization of magnetic field configuration in the arc chamber
  - Modified ion source with multi-slotted grounded grid
  - Beam uniformity with individual control of the local arc discharge
  - (- Cs consumption and W-filament lifetime) →→ CCNB
- Experiences of long-pulse injection with the negative-NBI
  - Progress of the long-pulse plasma sustainment with the negative-NBI
  - Direct cooling of the plasma grid
- Summary

Large Helical Device (LHD)



Heating Systems (Achieved)

NBI (H-inj. 180keV) 13.1MW
ICH (25 – 100MHz) 2.7MW
ECH (84 & 168GHz) 2.1MW

Heliotron configuration of
l=2/m=10 field period
All superconducting coil system

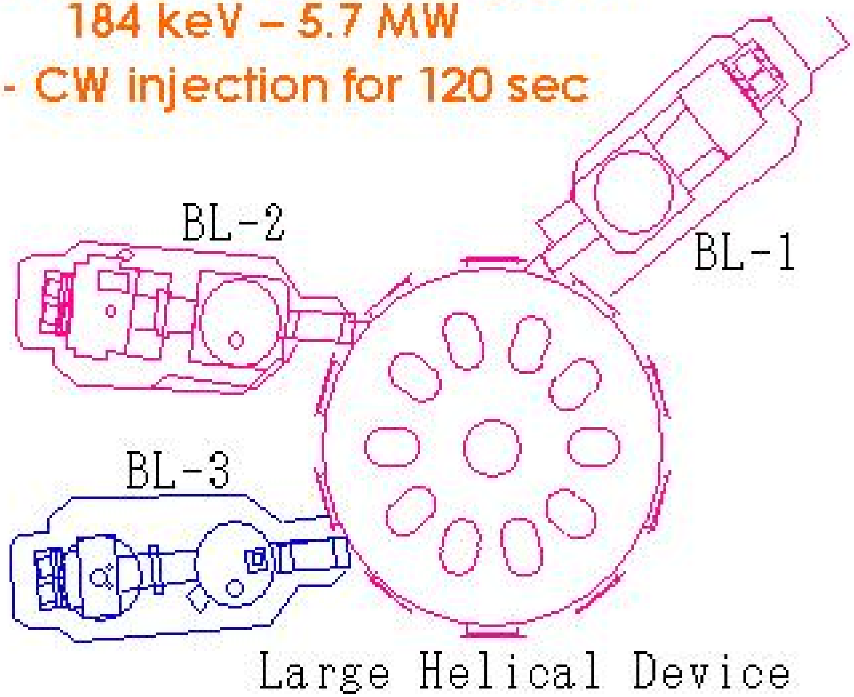
Plasma major radius	3.42-4.1 m
Plasma minor radius	0.6 m
Plasma volume	30 m^3
Toroidal field strength	3 T

Negative-Ion-Based LHD-NBI

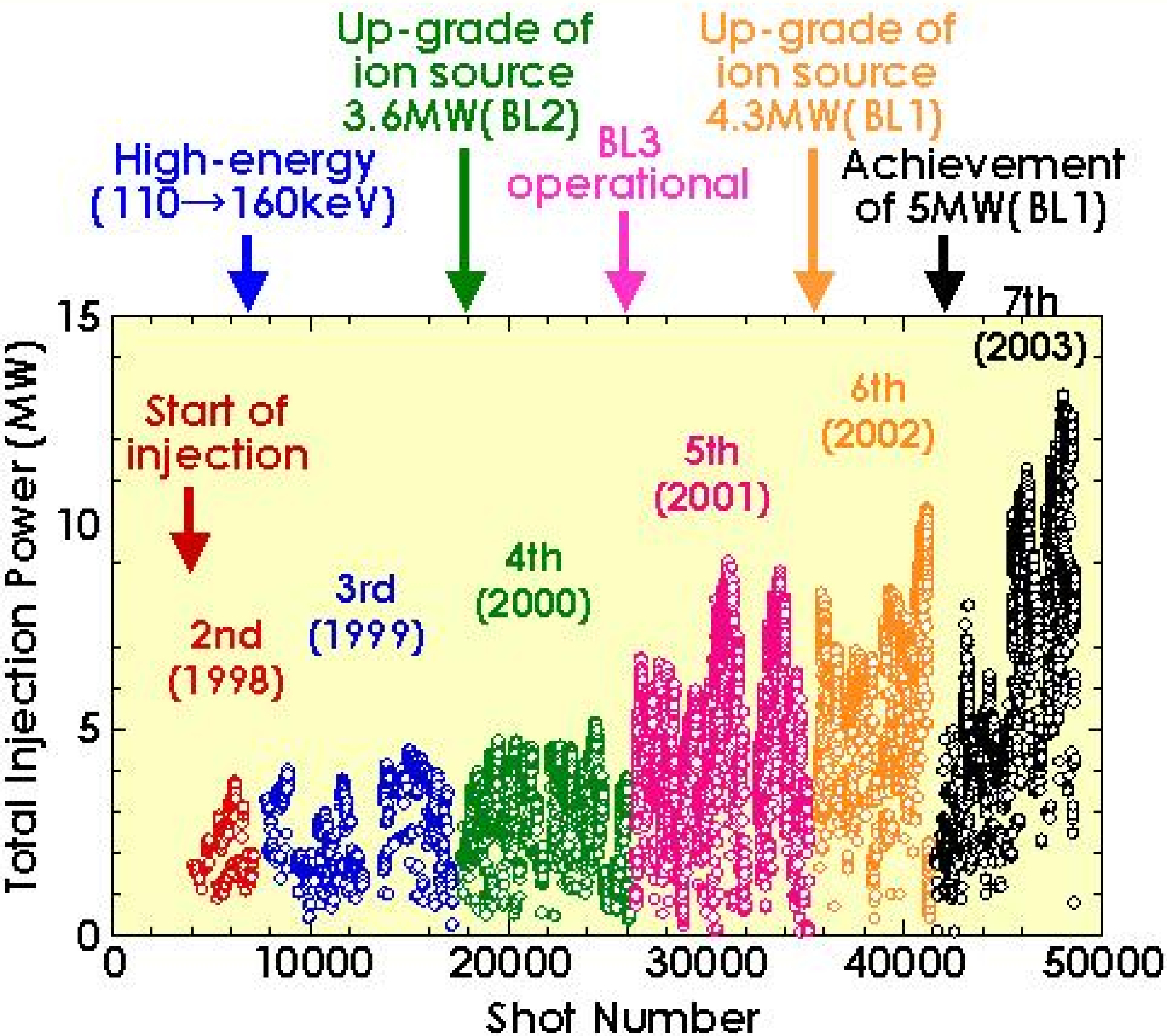
- Three injectors with six negative ion sources.
- Negative-NBI is a main heating device in LHD.

- 180 keV – 5 MW (specification of 1 injector)
- Operational in 1998 with 2 injectors (BL1 & BL2), and 1 injector in 2001 (BL3)

- Total achieved power of 13 MW
- Achievement in 1 injector
  184 keV – 5.7 MW
- CW injection for 120 sec



Injection power with the negative-NBI has gradually increased year by year.

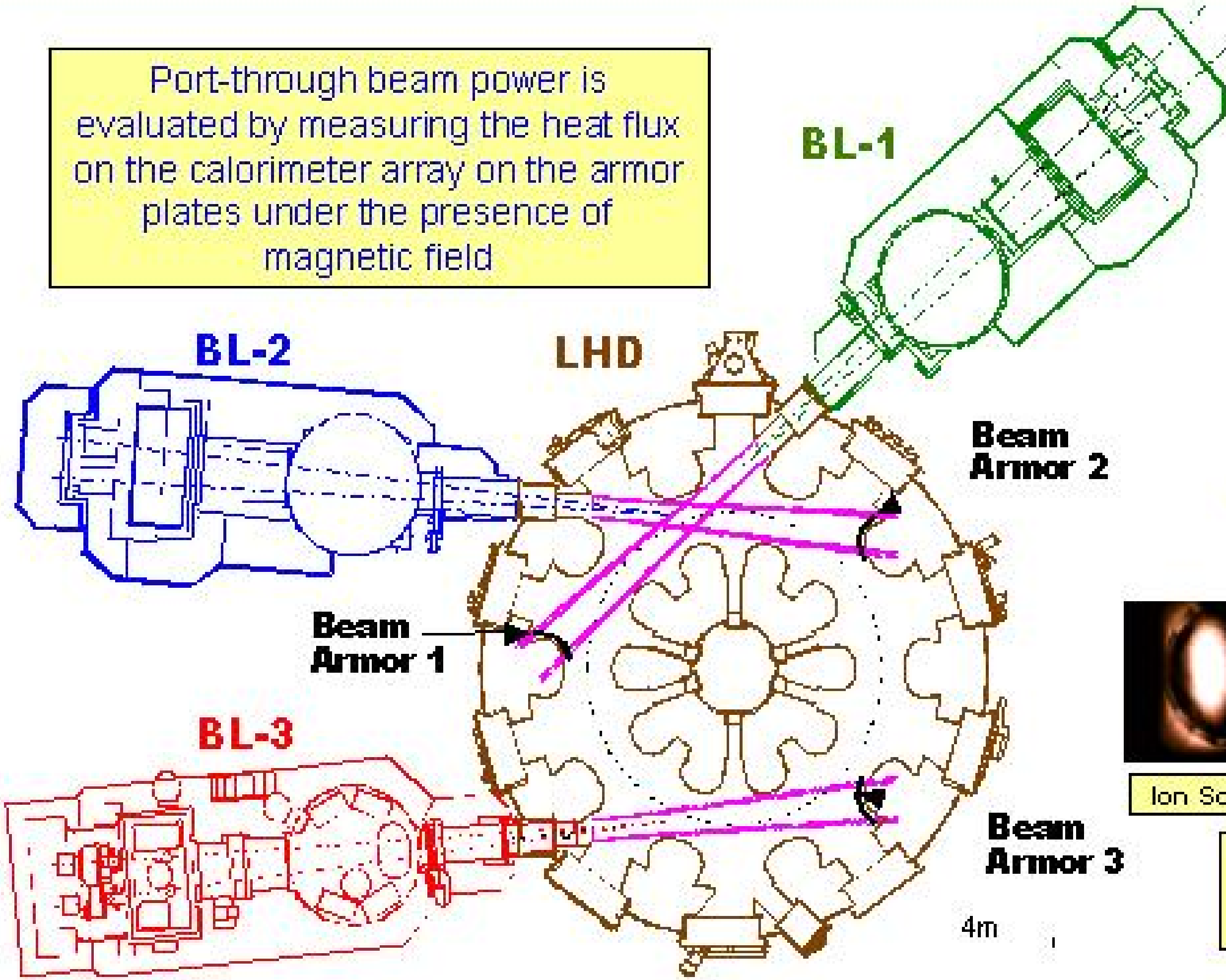


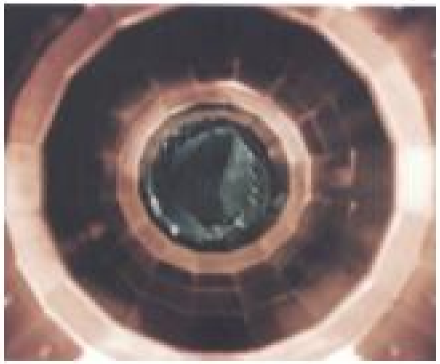
- Performance of the negative-NBI system has been still improved by continuing the R&D in parallel with the operation.
- Total injection power of 13.1MW has been achieved.
- Nominal injection energy of 180keV and nominal injection power for one injector of 5MW were simultaneously achieved in BL1.

High-power injection is reliably carried out at a high repetition rate of every 3 min in LHD.

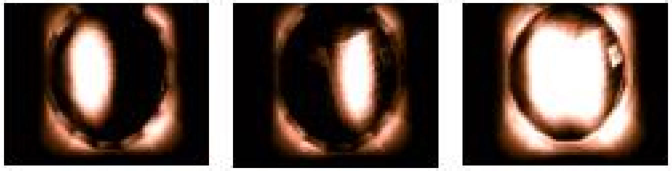
- Injection shot number is counted to around 100 shots a day, and summed up to 6000 shots in an experimental campaign for 4 months.

Port-through beam power is evaluated by measuring the heat flux on the calorimeter array on the armor plates under the presence of magnetic field





Carbon armor plates viewed from the injection port

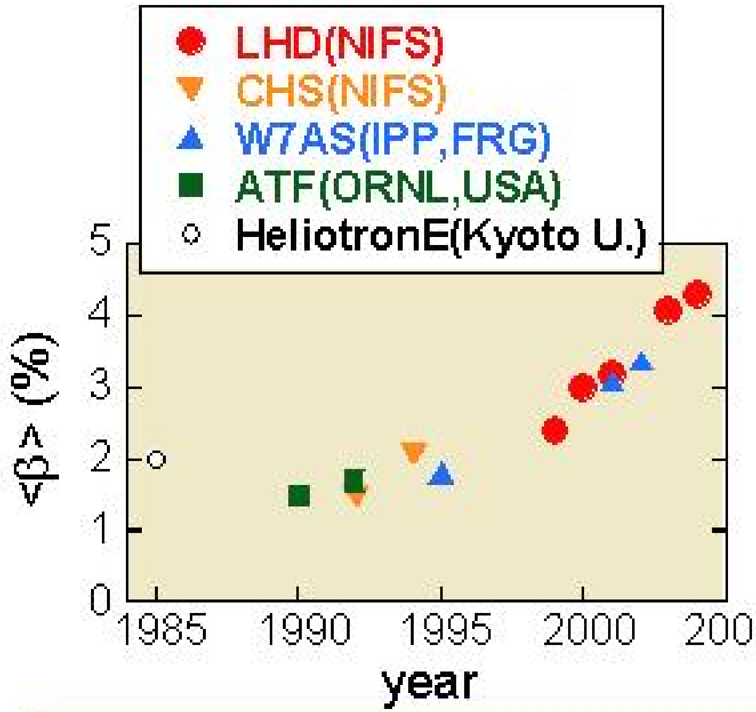


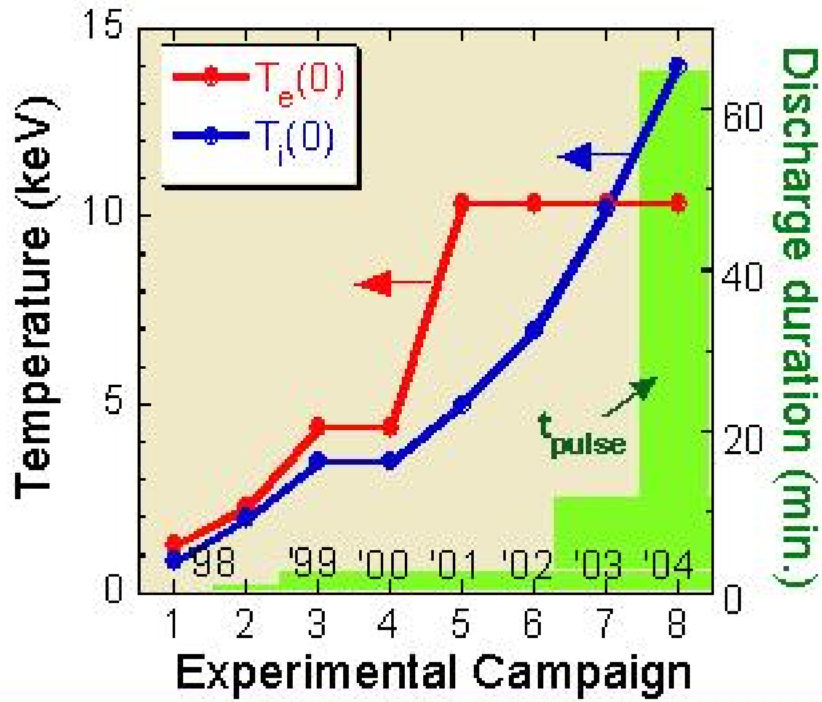
Ion Source A | Ion Source B | A & B

Infra-red images of armor plates viewing from a beamline after beam injection

Negative-NBI is a main heating device in LHD.

- Major plasma parameters have been achieved with the negative-NBI in LHD.
- Plasma parameters progress with an increase in NBI power.

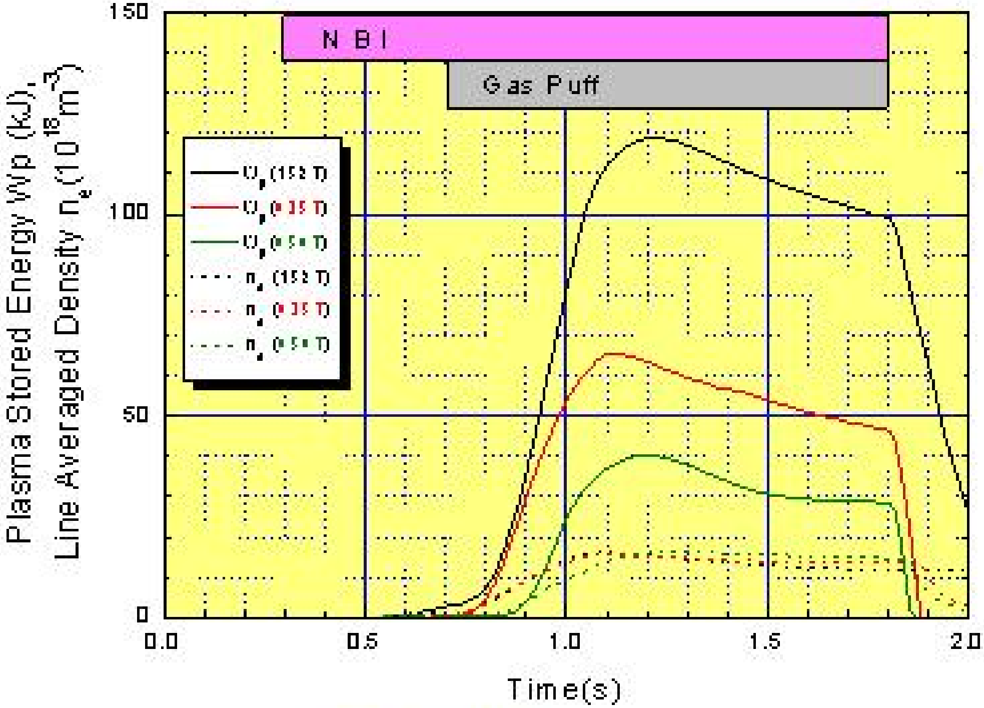


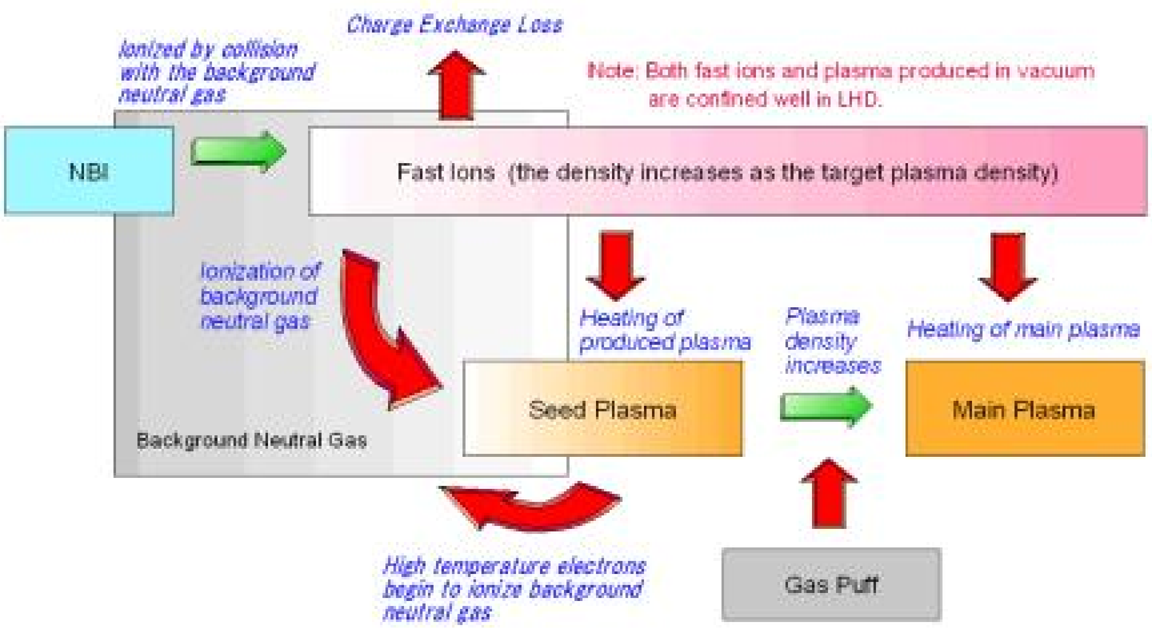


Achieved major parameters in LHD

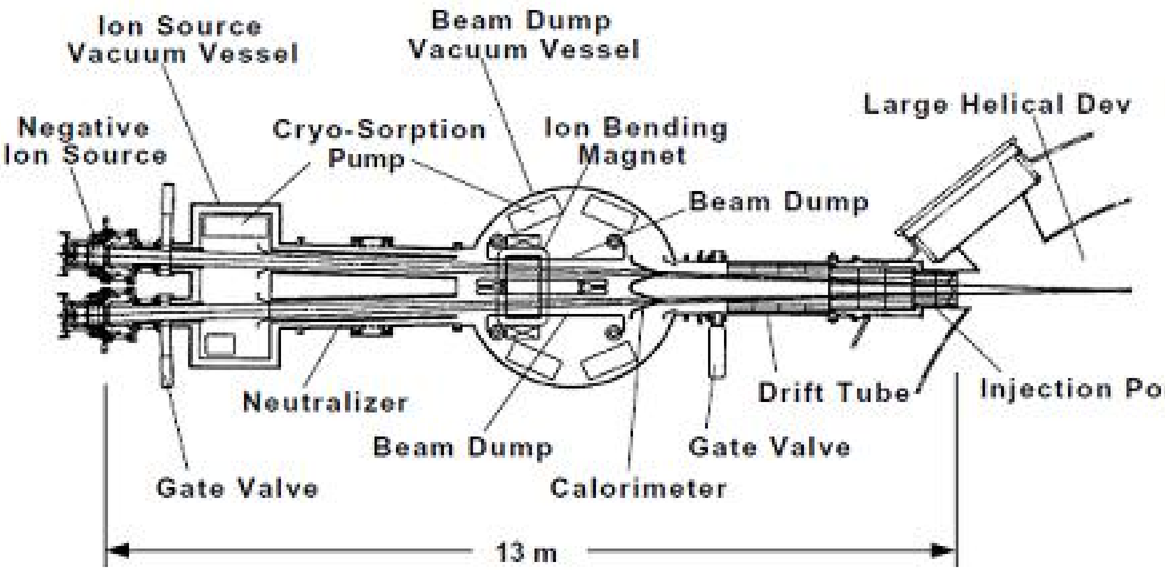
- Pressure — β : 4.3 % (by NBI)
- Temperature — $T_e(0)$: 10 keV, $T_i(0)$: 13.5 keV (by NBI)
- Density — n_e : 2.4×10^{20} m^{-3} (by NBI)
- Triple fusion product — $n\tau_E T_i$: 4×10^{19} m^{-3} s keV (by NBI)
- Discharge duration — 65 min by ECH (100kW) and 32 min by ICH (700kW)

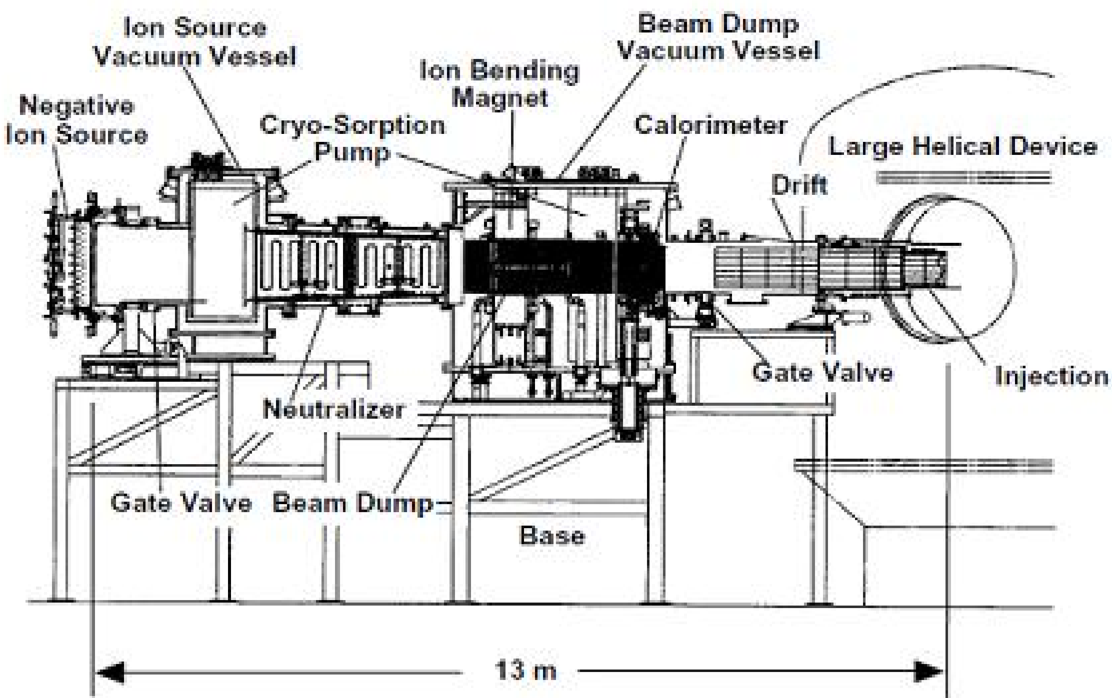
Plasma start-up with NBI alone.





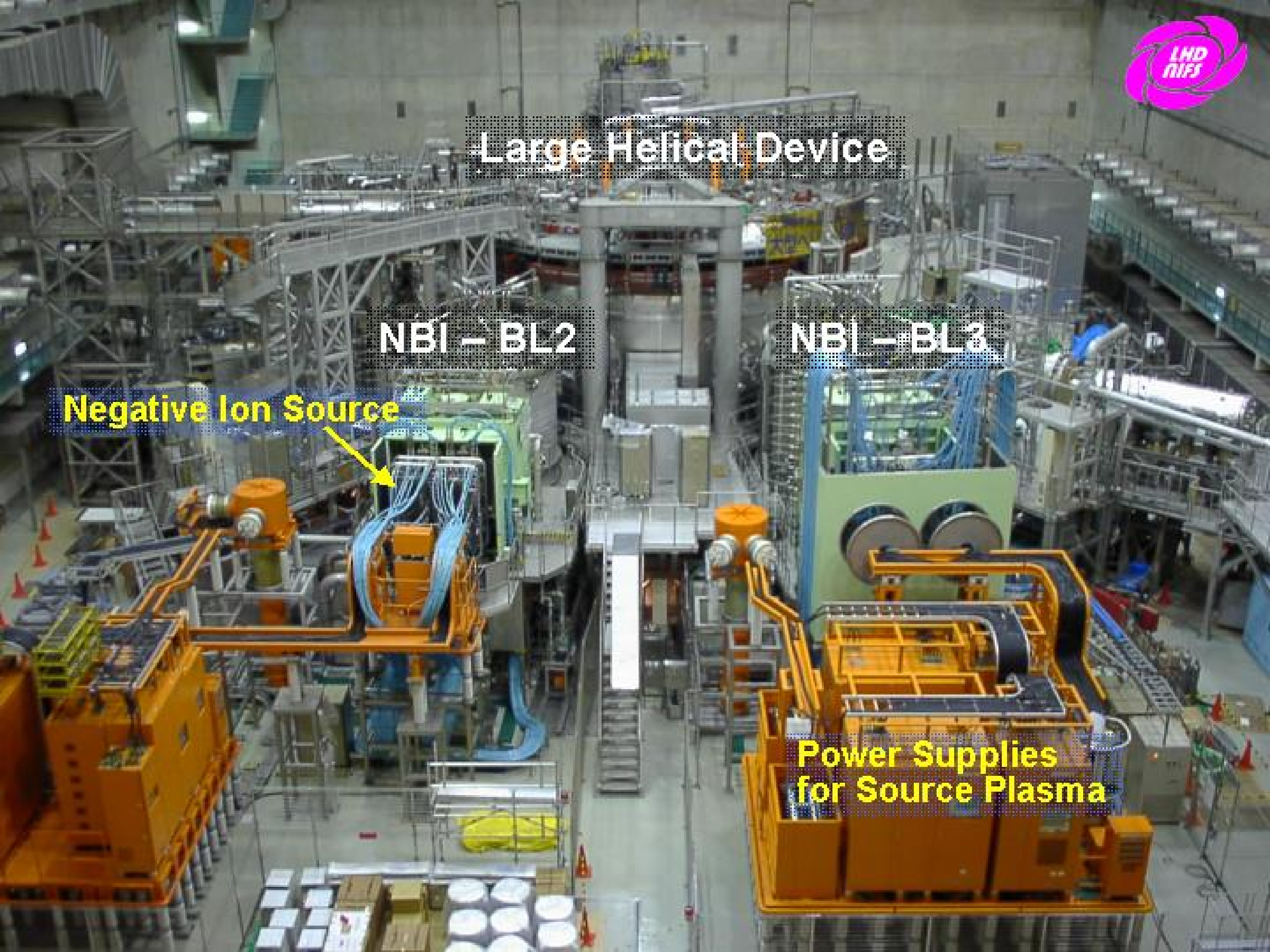
- Plasma can be initiated simply by injecting the neutral beam, and, successively and simultaneously, the plasma is heated by NBI.
- Although confinement magnetic field is required, the NBI start-up is independent of the magnetic field strength.
- Plasma initiation by NBI is a common method for target plasma production in LHD, as well as plasma initiation by ECH.

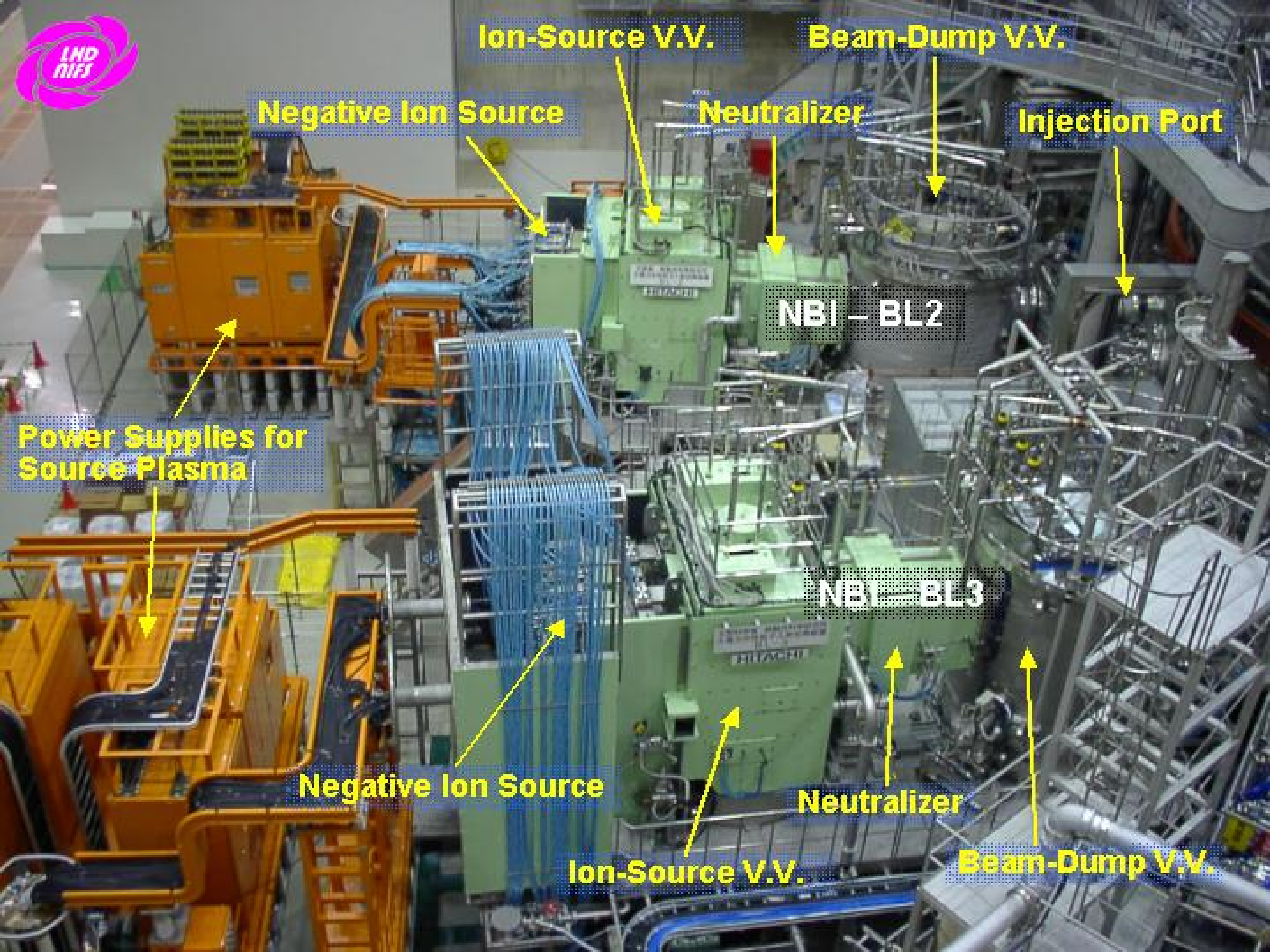




Structure of the negative-ion-based injector

- Hydrogen injection of 180keV – 5MW for 1 injector.
- Two negative ion sources are attached side-by-side.
- Effective neutralization length is 5m.
- Focal length of the ion source is 13m, and the pivot point of two sources is located 15.4m downstream.
- Injection port is about 3m long with the narrowest part of 52cm in diameter and 68cm in length.


Large Helical Device
NBI – BL2
NBI – BL3
Negative Ion Source
Power Supplies
for Source Plasma
LHD
NIFS

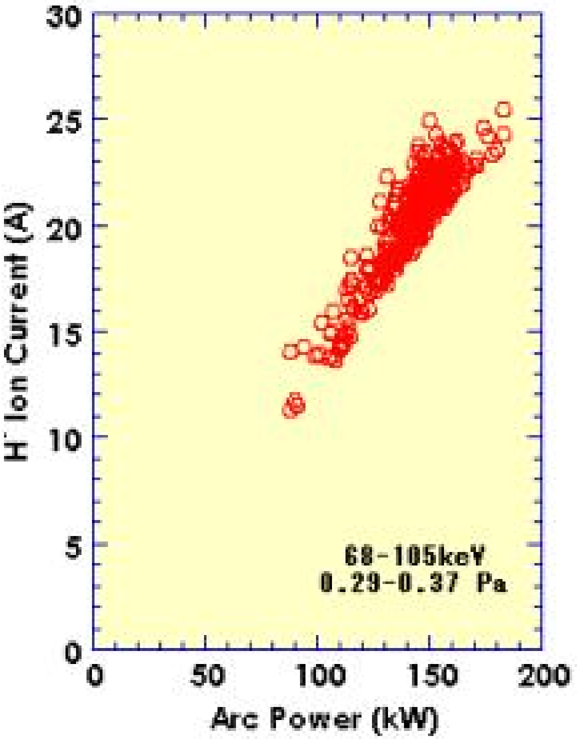

LHD NIFS
Ion-Source V.V.
Beam-Dump V.V.
Negative Ion Source
Neutralizer
Injection Port
NBI – BL2
Power Supplies for Source Plasma
NBI – BL3
Negative Ion Source
Neutralizer
Ion-Source V.V.
Beam-Dump V.V.

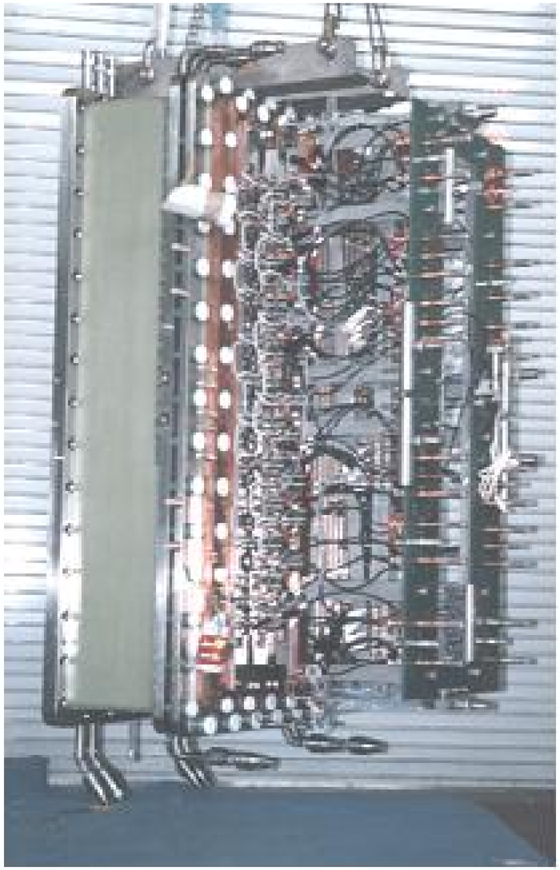
High-Current Negative Ion Source (Original)

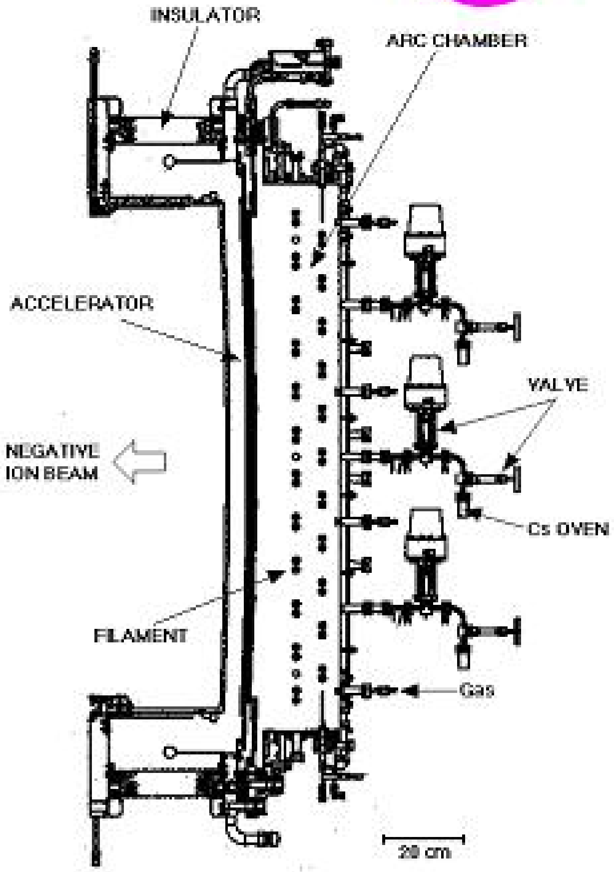
- Cs-seeded volume production source with an external filter
- Large arc chamber of 35cm(width)x145cm(length)x21cm(depth)
- Three-grids single-stage accelerator (grid area : 25x125 cm^2)
- Beamlet steering by aperture displacement

25 A of H^- ions

10 mrad of div. angle

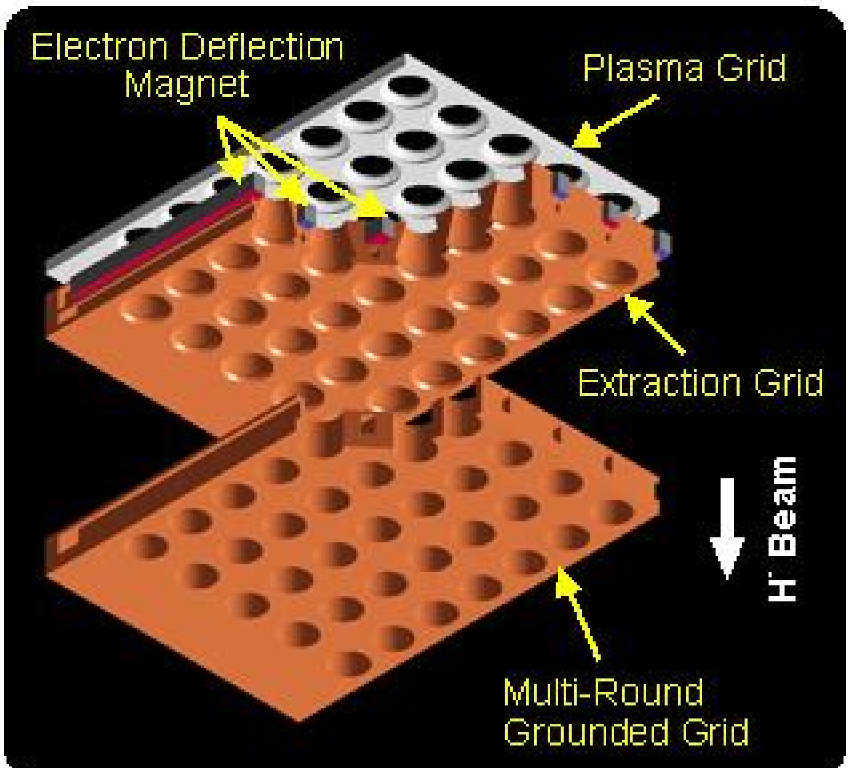


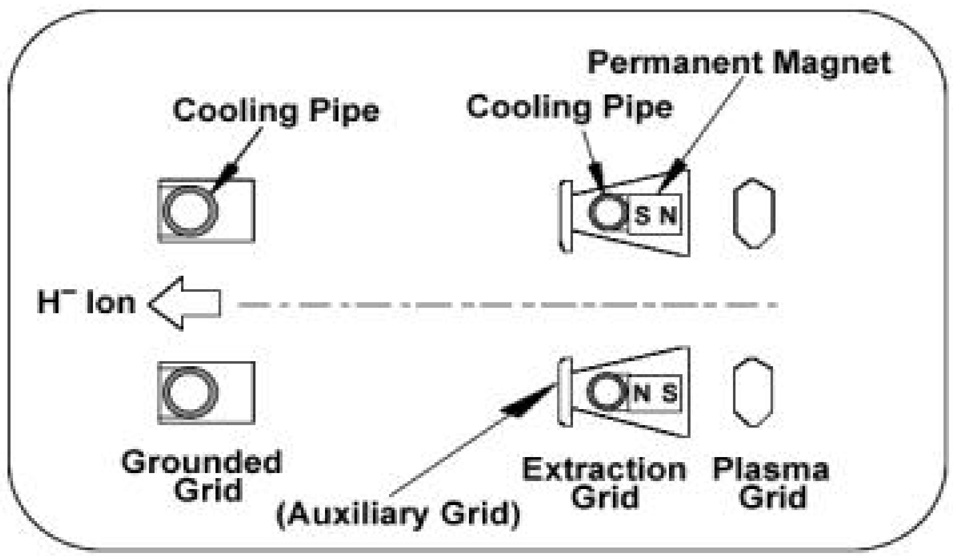




Negative ion accelerator with multi-round grounded grid (original)

- Single-stage accelerator with three grids of PG, EG, and GG.
- Extraction grid (EG) has electron deflection magnets.
- Beamlet steering for compensation of the beamlet deflection due to the electron deflection magnetic field is made at auxiliary grid with aperture displacement technique.
- Auxiliary grid also works as a shield for the secondary electrons from the acceleration electric field, leading to reduction of the electron leakage.

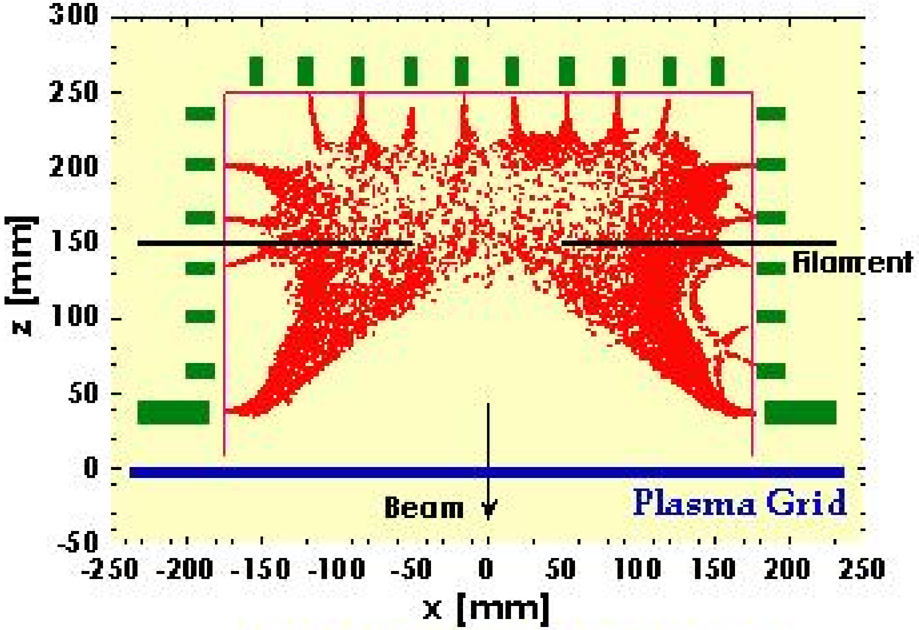




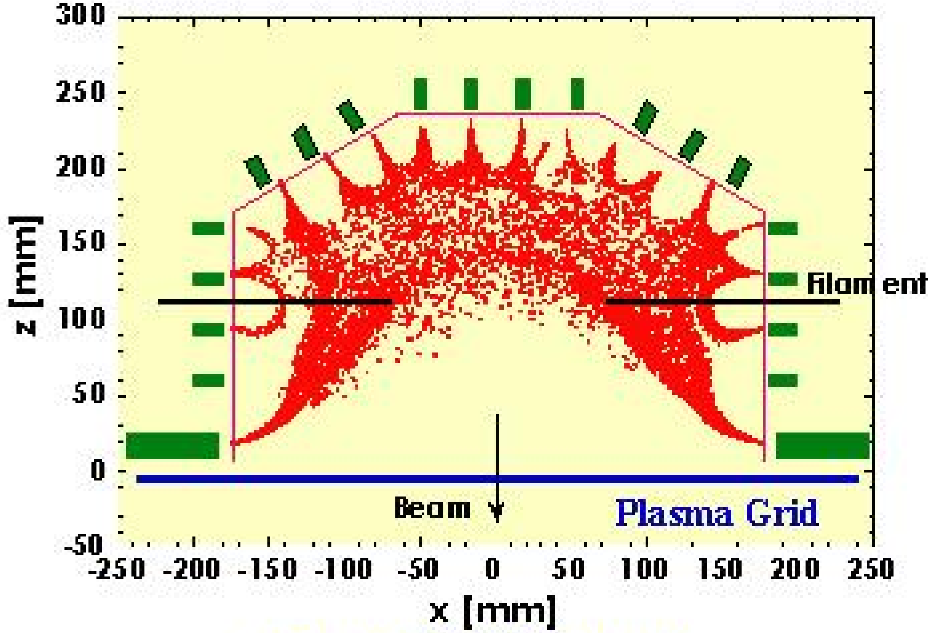
Negative Ion Accelerator

Magnetic configuration is optimized for efficient negative ion production.

- Local connection of the filter field with the cusp filed could result in plasma loss and plasma localization in the external source.
- In the non-optimized configuration, orbit calculation of primary electrons emitted from the filaments shows local trap of the electrons at mirror fields near the wall.
- In the optimized configuration, where the filter field is not strongly connected to the cusp field, the primary electron distribution is relatively uniform in the driver region.



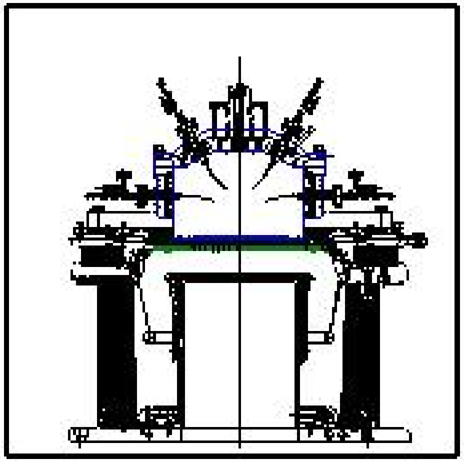
Non-optimized configuration (original arc chamber)

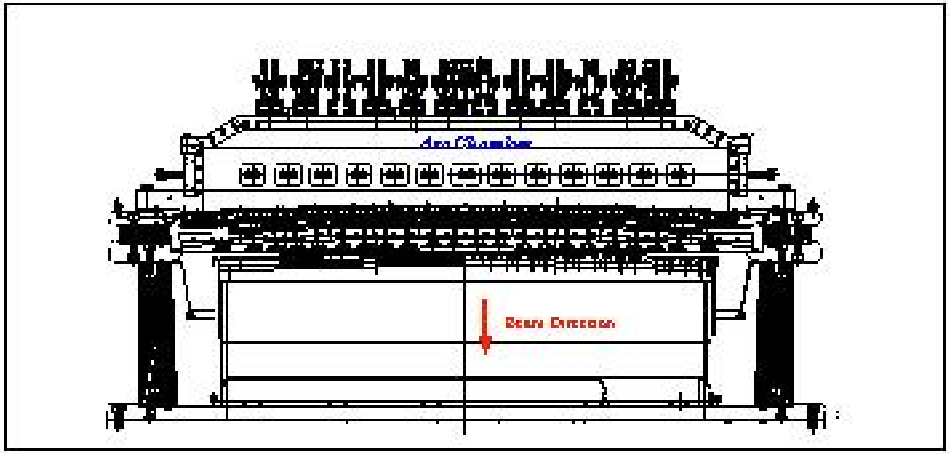


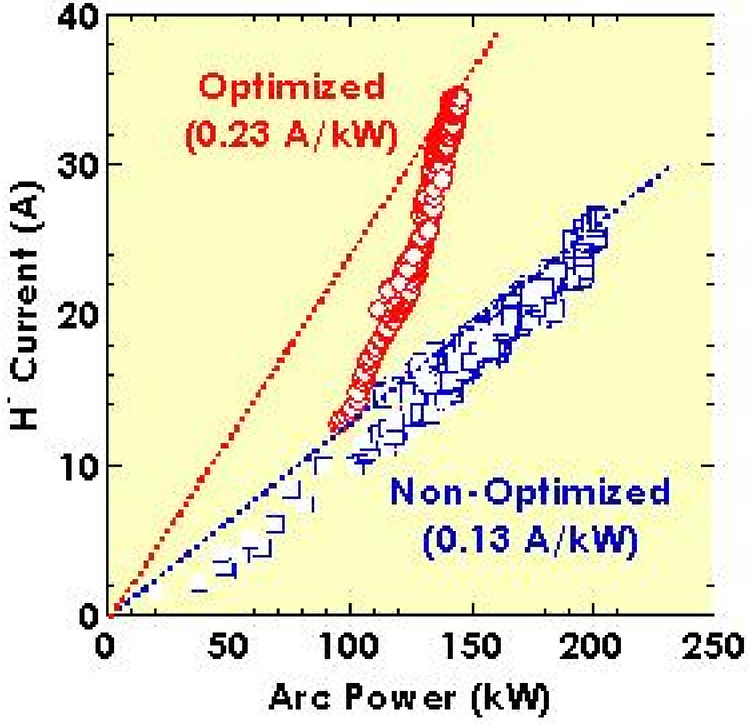
Optimized configuration (modified arc chamber)

Production efficiency of negative ions is much enhanced in the optimized arc chamber.

- In the optimized arc chamber, where the cross-sectional shape is hexagonal, the local connection of the filter field with the cusp field is reduced.
- Arc efficiency for negative ion production is much increased and H^- ion current exceeds 30 A in the optimized arc chamber.

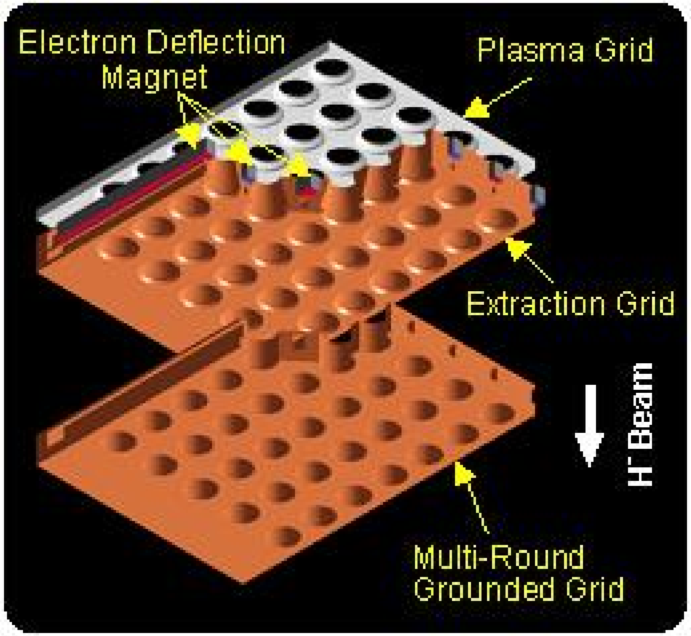


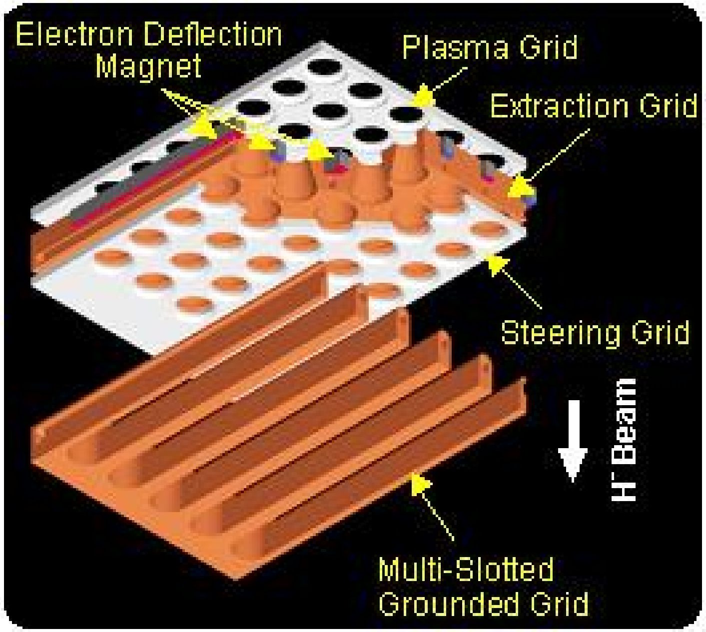




Modification of the accelerator – multi-round GG to multi-slotted GG –

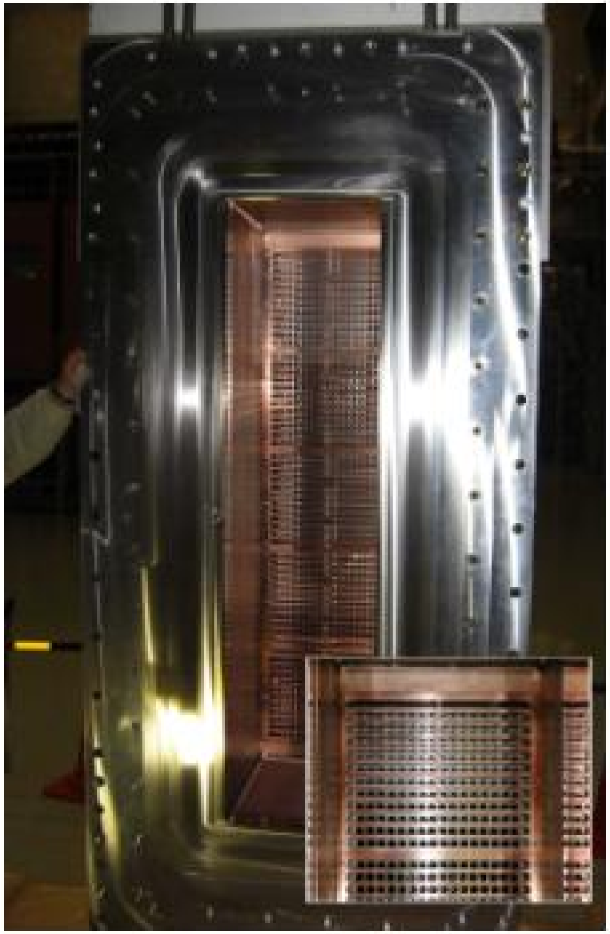
- Grounded grid is changed to multi-slotted structure from multi-round structure in one injector (BL1).
- Steering grid (SG) is added on the exit side of EG with a space for the beamlet steering for the multi-beamlet focusing and the compensation of the beamlet deflection by the EG magnetic field along the slot.

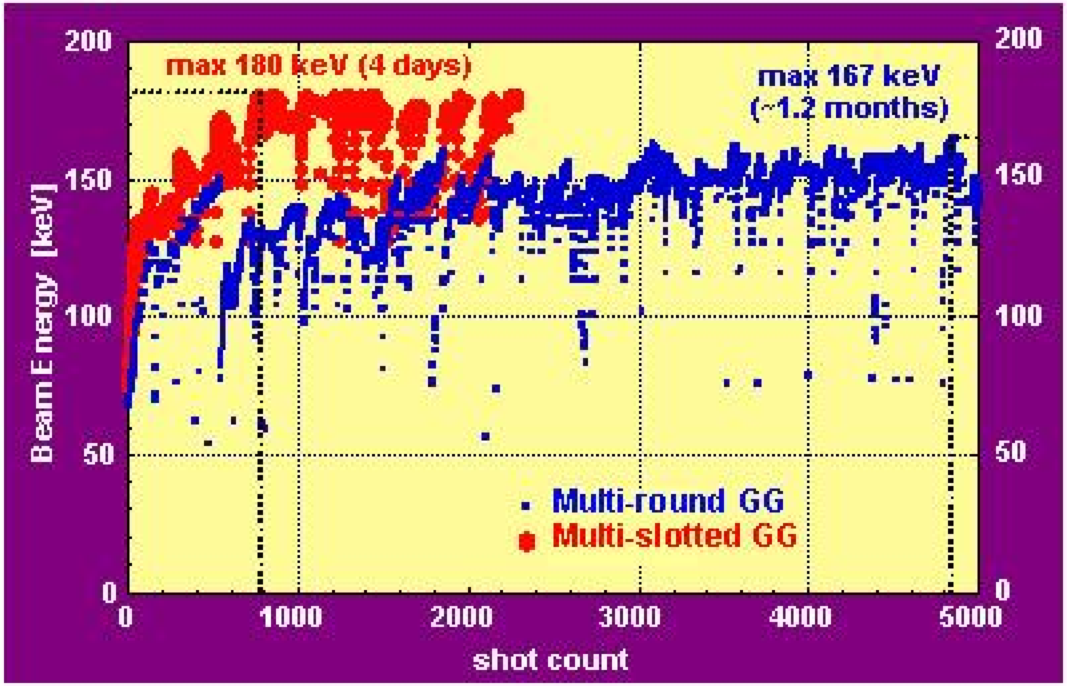




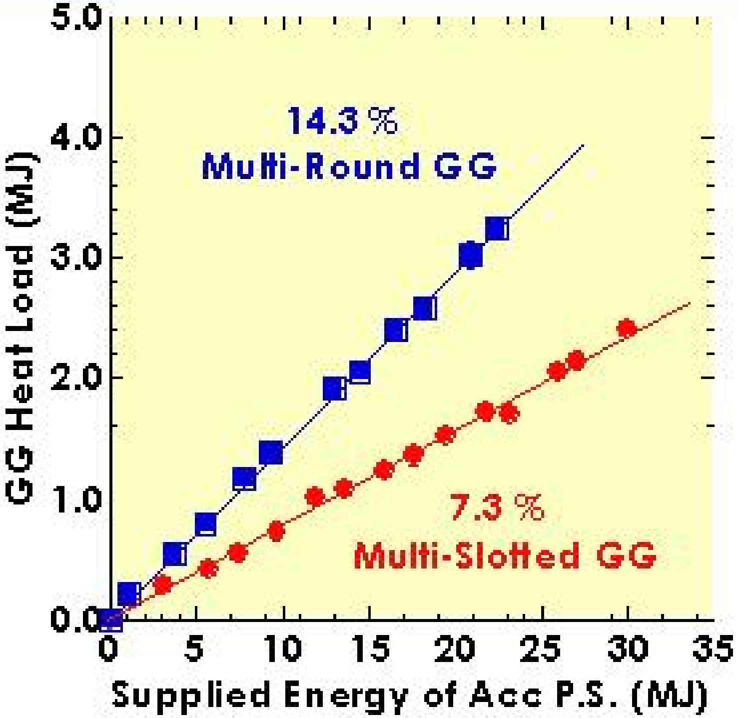
Voltage-holding ability is much improved with multi-slotted GG

- Conditioning period in the cesium-seeded operation is much shortened to 4 days for 180keV from 1.2 months for 167keV.
- Gas pressure in the acceleration gap is lowered, and the heat load of the GG is reduced with the multi-slotted GG.

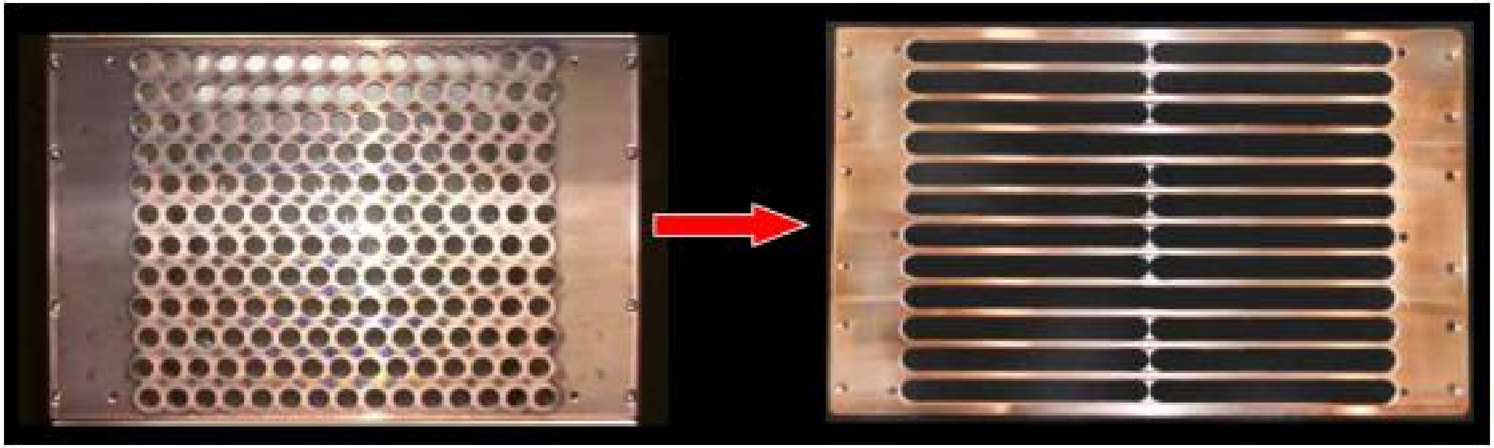




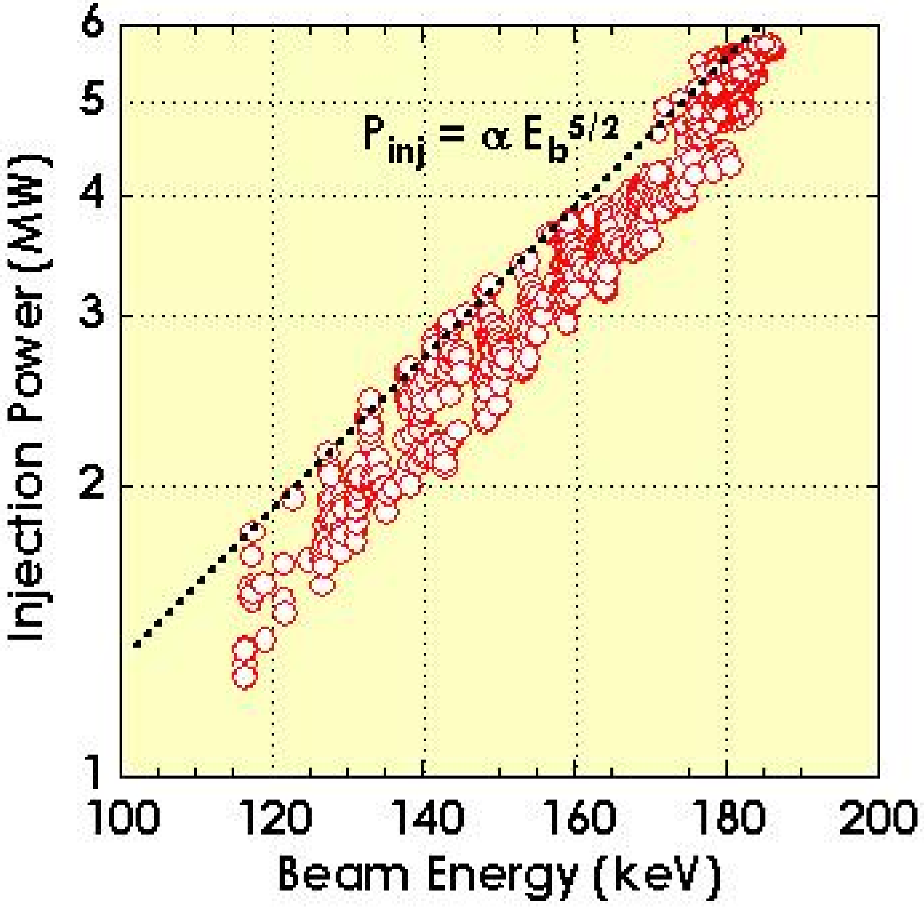
Heat load of the GG is much reduced with multi-slotted GG



- Transparency is increased by a factor of about 2 in the multi-slotted GG, and, thus, the electron and ion beam intersection area is much reduced.
- Gas pressure in the acceleration gap is calculated to be lowered by a factor of about 2.5, and the stripping loss is estimated to be reduced to about a half.
- As a result, heat load of the GG is reduced to about a half.

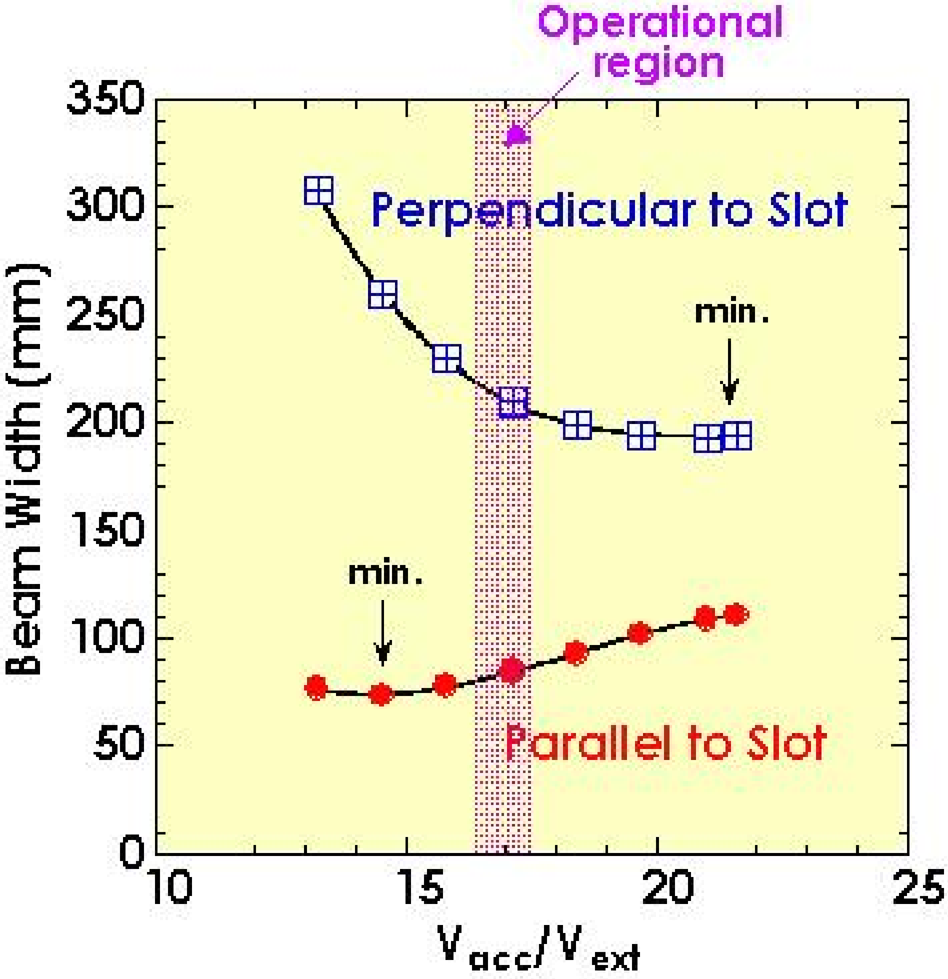


Injection power is increased according to the 5/2 power of the beam energy.



- Beam energy has been raised to 186keV, beyond the rated value (180keV), with the multi-slotted GG.
- H^- current is increased linearly to the 3/2 power of the beam energy without saturation with the optimized arc chamber.
- As a result, the injection power has been much increased, and now the achieved injection power with one injector (BL1) is 5.7MW with an energy of 184keV for 1.6sec.

Optimum condition for beam convergence is different between parallel and perpendicular direction to the slots.

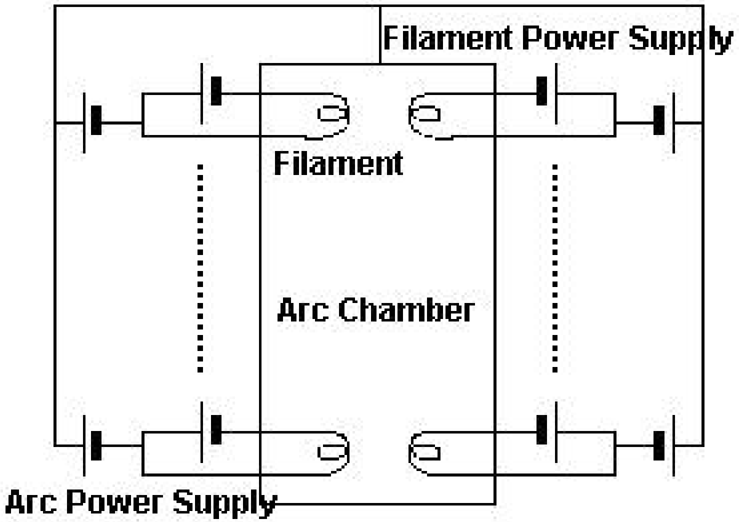


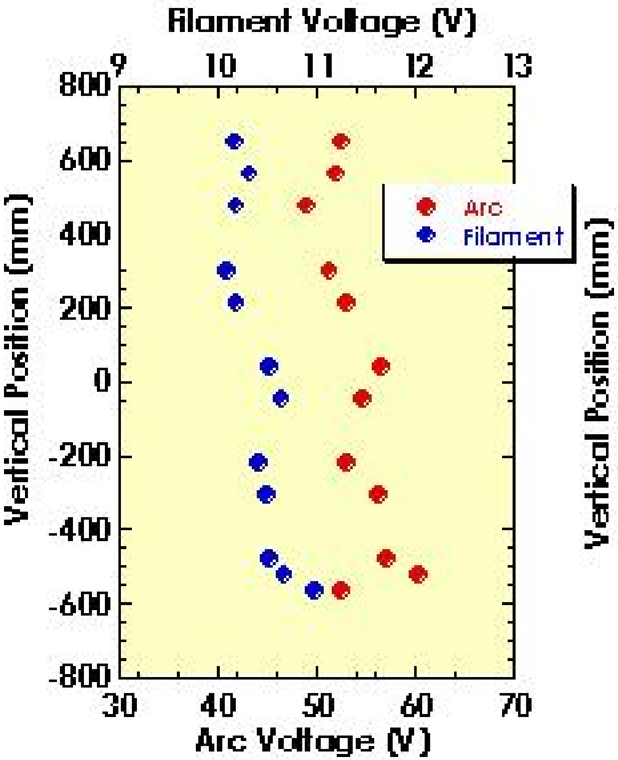
at calorimeter 8.5m downstream from the ion source with a focal length of 13m

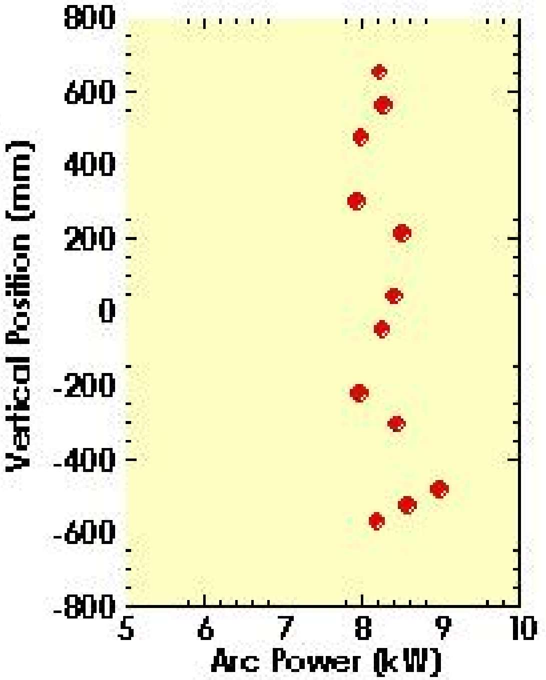
- Electrostatic lens effect is different in the direction between parallel and perpendicular to the slot at the GG.
- Voltage ratio to give a minimum beam width in the direction perpendicular to the slot is larger than that in the direction parallel to the slot.
- In the actual injection, the voltage ratio is determined at an intermediate value between both optimum conditions.
- However, the perpendicular divergence is larger itself, and a part of the vertically diverged beam intersects the injection port.
- Modification of the aperture shape of SG is being tested for the compensation of this anisotropic properties.

Local arc discharge can be controlled with both individual arc and filament voltages.

- 12 arc power supplies are connected to electrically isolated 12 filament power supplies, and both voltages can be adjusted independently and remotely in one injector (BL3).
- Compared with the adjustment of individual output resistances of the arc circuits, controllability of the local arc discharge is much improved, and the uniformity of the arc plasma should be improved.

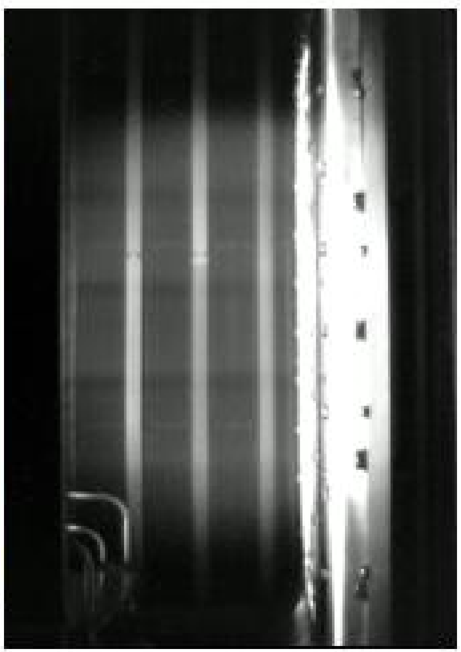




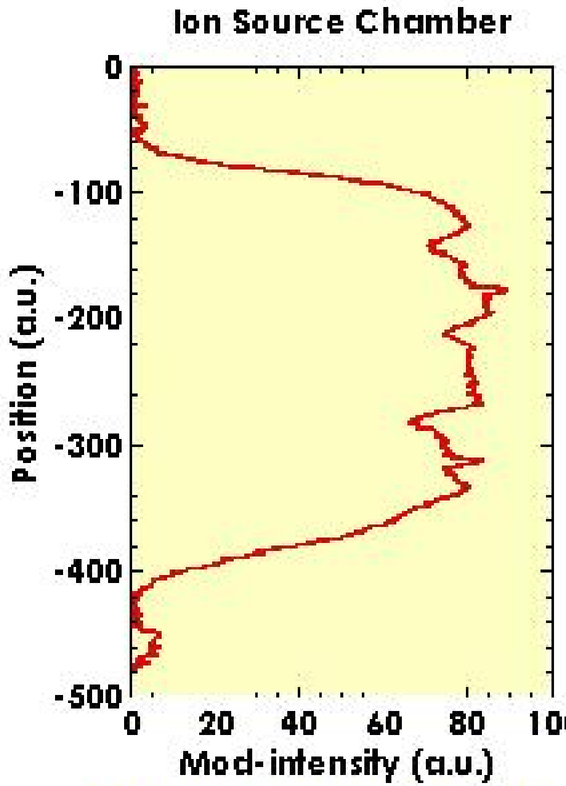


Individual control of the local arc discharge is effective to uniform beam production.

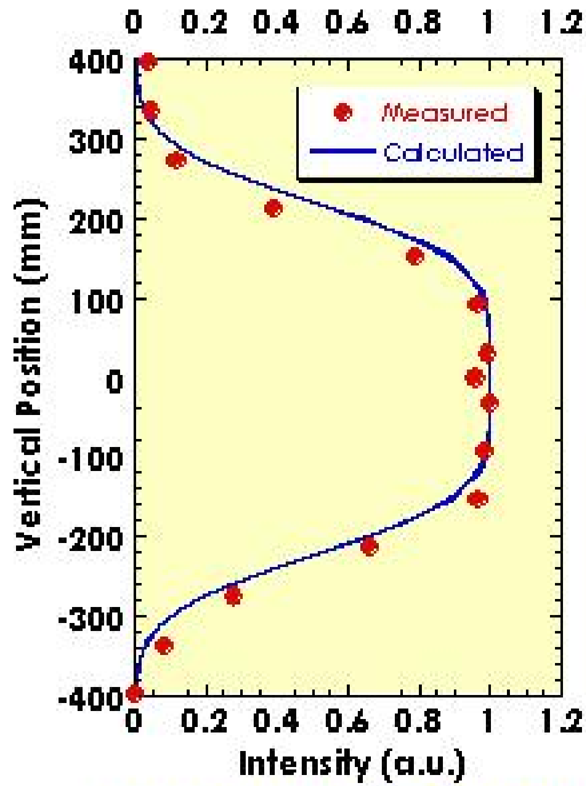
- Control of the local arc-discharge distribution leads to improvement of the beam uniformity.
- Beam profile on the calorimeter 8.5m downstream is well fitted to the calculated profile for uniform beam production with a divergence angle of 10mrad.



CCD view of Hα intensity 2.2m downstream



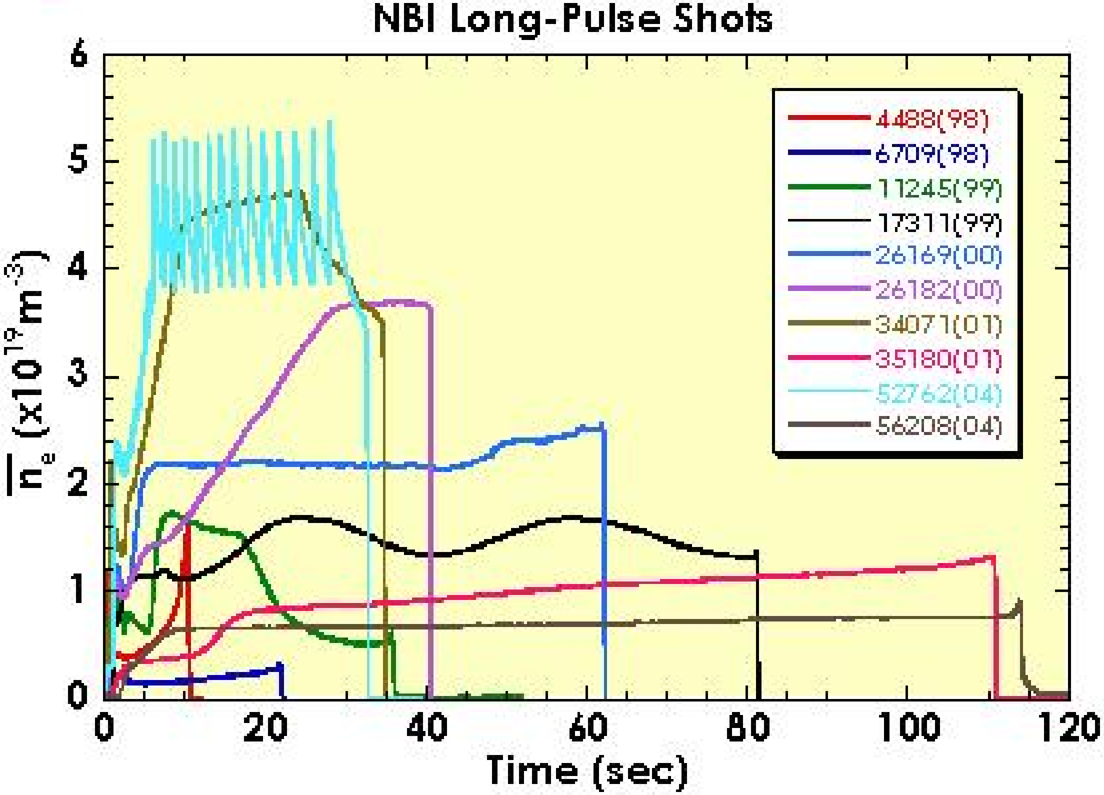
Distribution of Hα intensity 2.2m downstream



Beam profile on calorimeter 8.5m downstream

Extension of injection duration leads to long-pulse sustainment of the LHD-Plasmas.

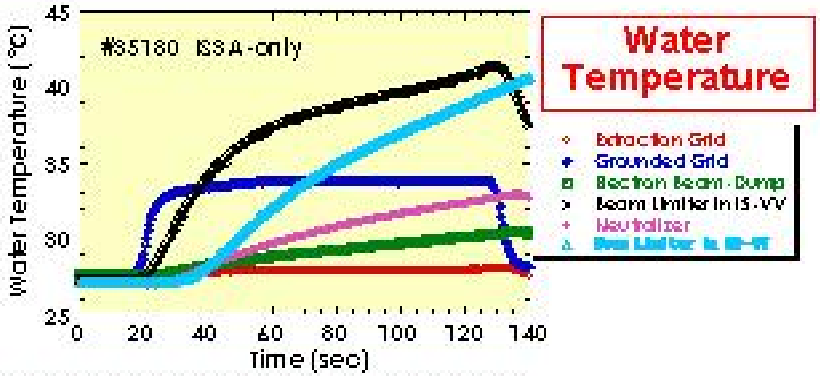
- Injection duration of the negative-NBI has been gradually extended with a reduced injection power.
- Injection duration is limited below 40 sec with use of the MG, and the injection power is restricted below 0.6 MW with use of the commercial line.
- High-density plasmas of above $4x10^{19}m^{-3}$ and varying-density plasmas by repetitive pellet injection can be sustained for an extended pulse length with the negative-NBI alone.

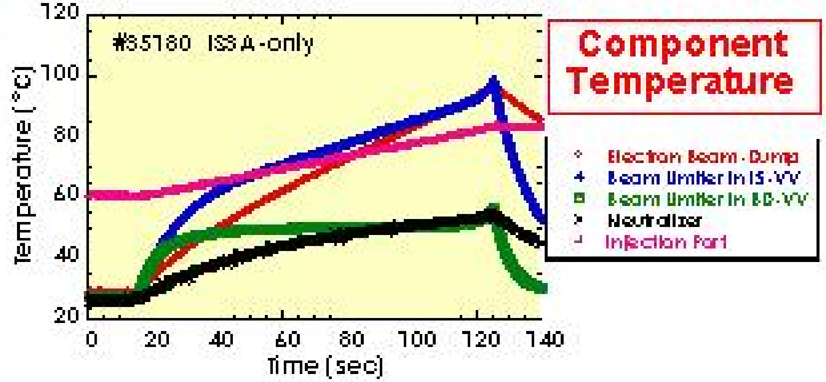


Summary of the long-pulse shots with the negative-NBI in LHD

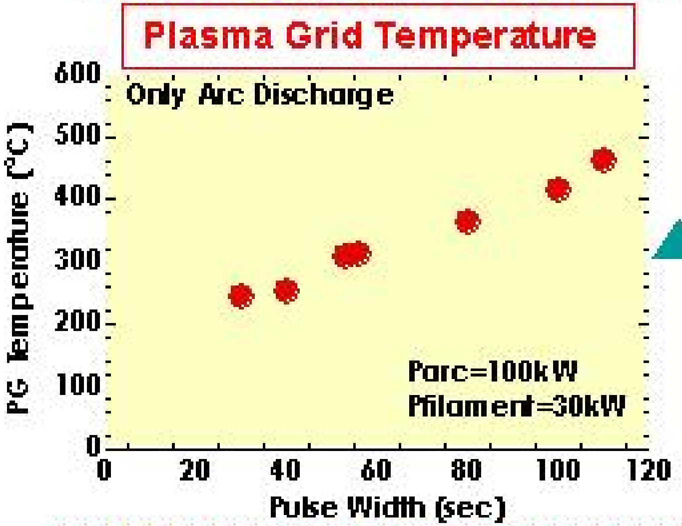
LHD Exp. Cycle (FY)	Shot Number	Injection Energy (keV)	Injection Power (MW)	Pulse Duration (sec)	Electron Density ($x10^{19}m^{-3}$)	Electron Temp. (keV)	Ion Temp. (keV)	Stored Energy (kJ)	Gas R_{axis}/B (m)/(T)	Comments
II (1998)	4488	80	1.1	10	0.5	1.3 (ECE)	1.3 (CXRS)	30 - 100	He 3.75/1.5	BL2 MG
	6709	66	0.6	21	0.3		0.8 (CXRS)		He 3.75/1.5	BL2 MG
III (1999)	11245	104	0.75	35	1.8	1.7 (ECE)		200	He 3.6/2.75	BL2 MG
	17311	100	0.5	80	1.5 - 2.0	2.0 (ECE)	1.5 (Crystal)	100	He 3.6/2.75	BL2 Line
IV (2000)	26169	80	0.55	64	2.1	1 (ECE)			He 3.6/2.75	BL2 MG
	26182	80	0.55	40	1 - 3.7	1.8 - 0.6 (ECE)			He 3.6/2.75	BL2 MG
V (2001)	28869	106	0.6	33	1.5	1.3 (ECE)			H 3.6/2.75	BL3 MG
	31972	108	0.7	35	4.0				He 3.6/2.75	IS2B+IS3B MG
	34071	111	1.1	35	4.5	0.5 (TS)			H 3.5/2.88	BL2/MG Every 10.5min
	35180	80	0.11	110	1.0	0.35 (TS)			He 3.6/2.75	IS3A Line
VIII (2004)	52762	100-122	1.2	32	4.0-5.4 (cw-pellet)				H 3.6/2.75	IS2B+BL3 MG
	56208	90	0.2	128	0.7				He 3.65/2.712	IS2B Line

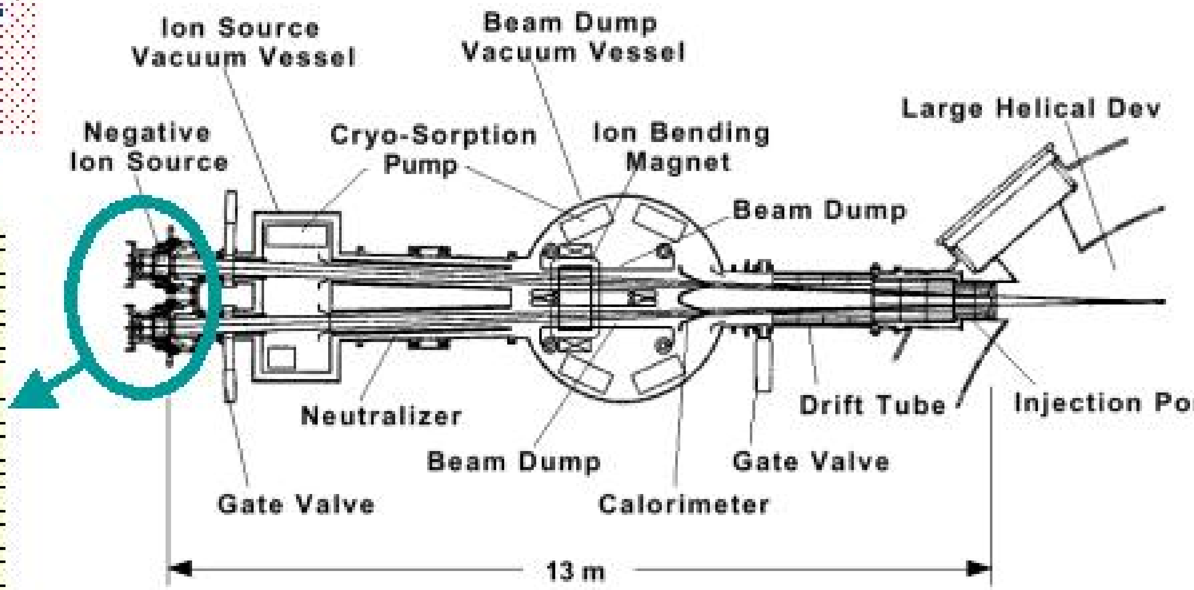
PG temperature control is a key issue to the extension of injection duration.





- Temperature rise of the beamline components tends to be saturated.

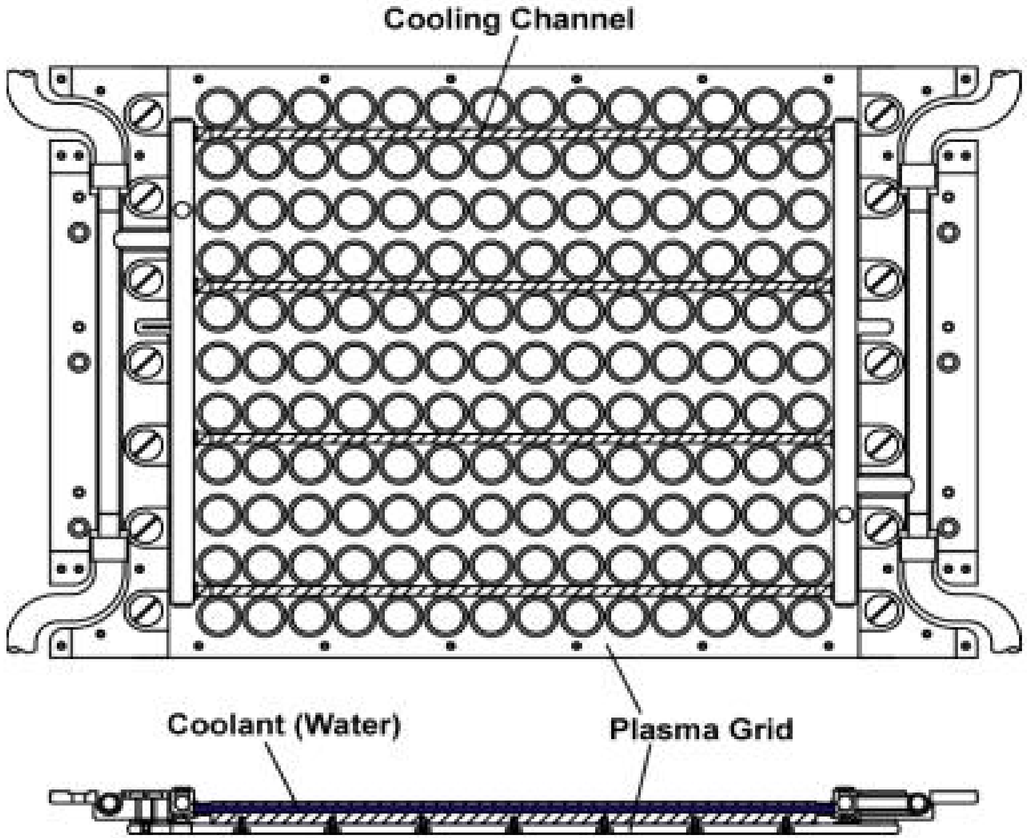




- PG temperature is increased monotonously with an extension of the pulse duration due to the thermal insulation for the short pulse operation.

Stainless steel cooling channels are attached to the PG for long-pulse operation.

- Cooling channels are in mechanical contact with the PG surface for long-pulse injection for a few minutes.
- Thickness of the cooling channel is determined so that the heat diffusivity to the PG is lower than that of the molybdenum PG itself, for maintaining the segmented PG temperature uniform.

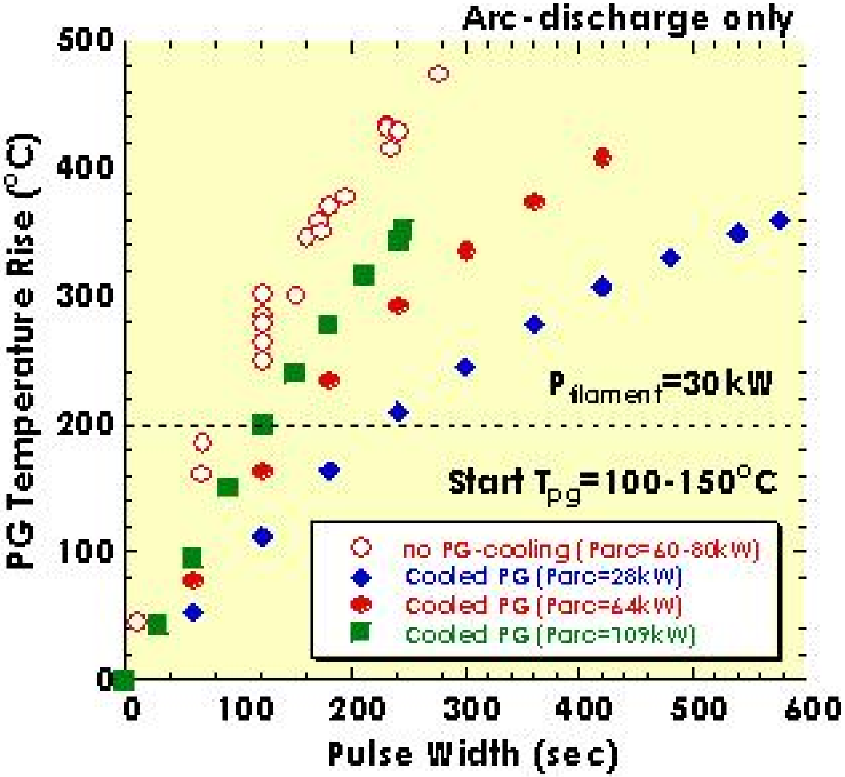


- In the short pulse injection for 2 – 3 sec in every 3 min, the pri-arc duration before the beam production must be extended to around 15 sec to raise the PG temperature to an appropriate value.

Temperature rise rate is reduced although the PG temperature is not saturated.

Plasma Grid
with cooling channels

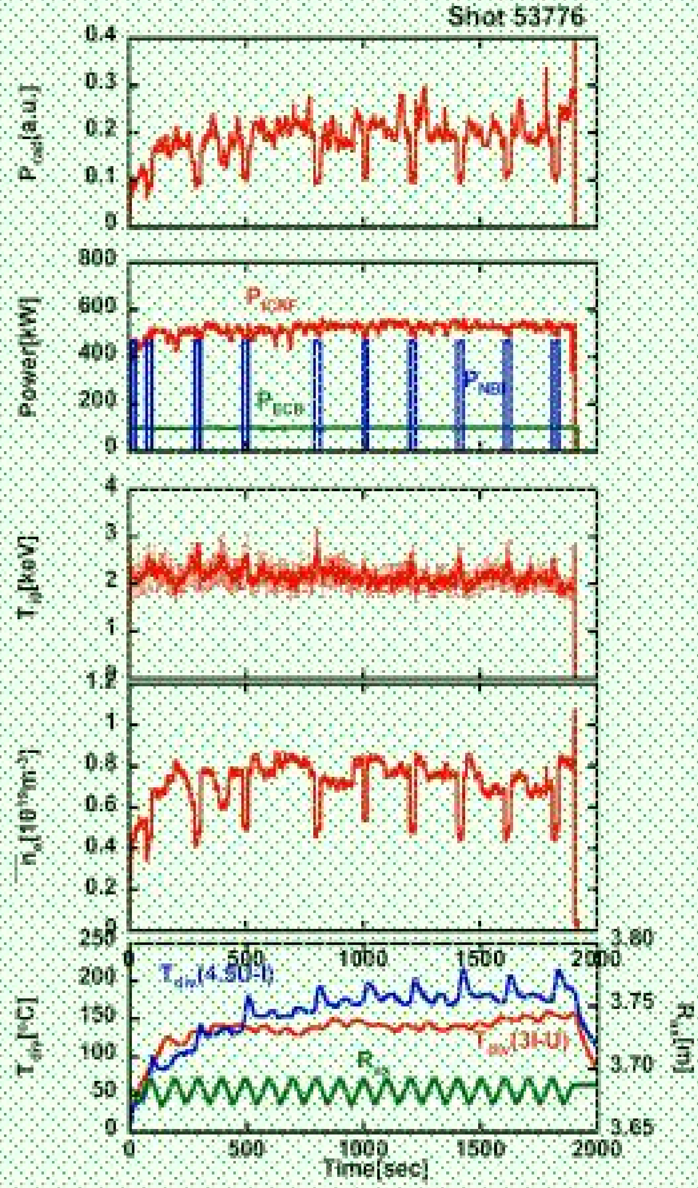
- It takes about 160sec to exceed 200°C of the PG temperature rise in the cooled PG while about 80sec in the no-cooled PG for an arc condition corresponding to 0.2–0.3MW injection with one ion source.



Results of the long-pulse injection with the cooled plasma grid

- High repetition of the long-pulse injection due to the improvement of the cooling ability of the PG.
  - 1MW–10sec in every 3min (one injector)
  - 0.5MW–25sec in every 3min (alternate two ion sources, equivalent to 1MW–25sec in every 6min with one injector)
- Extension of the injection duration
  - (0.2–0.25)MW–128sec (one ion source) Injection is manually stopped due to radiation collapse of the target plasma.

However,
PG cooling ability is not enough for long-pulse injection towards steady-state operation.



31min-45sec Long-Pulse Discharge in LHD
Total input energy : 1.3GJ
Averaged Heating Power : 680kW
ICRF(38.5MHz) : 520kW (CW)
ECH(84Gz) : 100kW (CW)
NBI : 60kW (average),
500kW (25sec in every 3min)

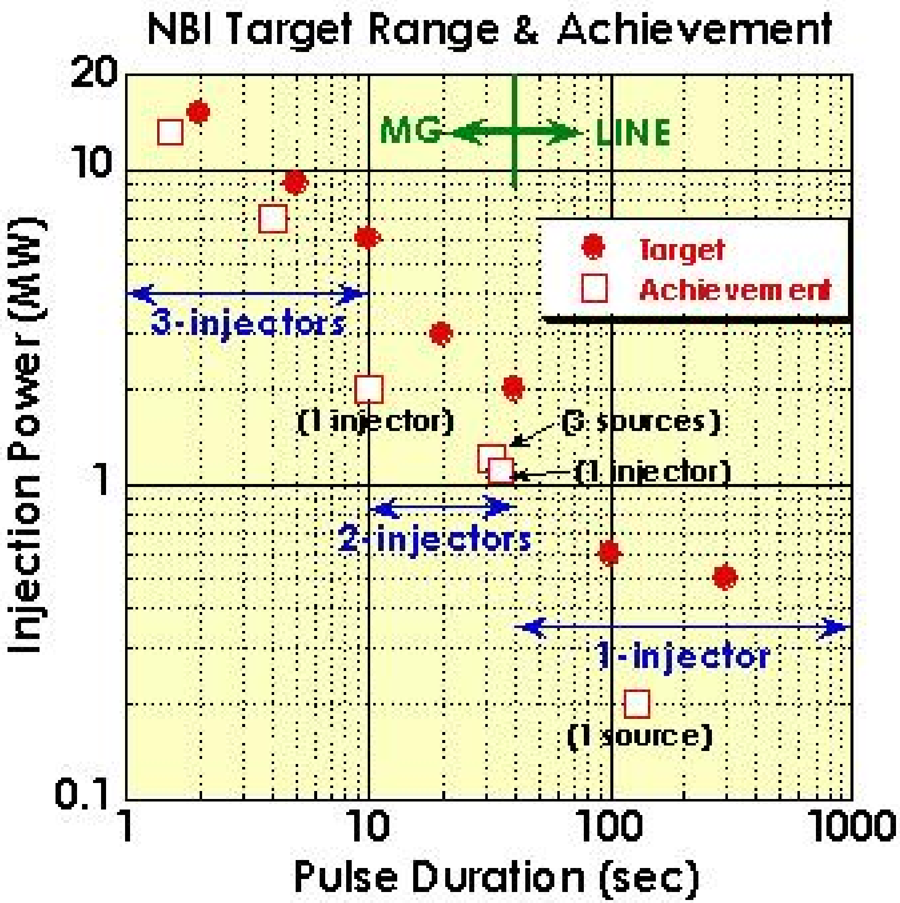
Summary

- Negative-ion-based NBI system, 180keV – 5MW for one injector, started its operation in 1998 in LHD.
- Total injection power has reached 13.1MW with three injectors, and one injector with modified ion sources with multi-slotted grounded grid has achieved 184keV – 5.7MW injection.
- In the modified ion source with the multi-slotted GG, reduction of the GG heat load together with lowering of the gas pressure in the acceleration gap results in improvement of the voltage holding ability.
- Modification of the arc chamber from a point of view of optimization of the filter and cusp magnetic field configuration leads to enhancement of the negative-ion production efficiency.
- Injection power is increased linearly to the 5/2 power of the beam energy and reached 5.7MW with an energy of 184keV.
- Individual control of the local arc discharge with the 12-divided output voltages of the arc and filament power supplies is effective to uniform beam production.
- Injection duration has been extended to 120sec in a source equipped with cooled PG, where the stainless-steel cooling channels are attached.

(- Maintenance period of the ion source is determined by the filament lifetime, and the tungsten vapor from the filaments should be a dominant contaminant for the cesium effect.) →→ CCNB

- LHD negative-NBI operates with high reliability and is a main and indispensable heating device for high-performance plasma experiments in LHD.

Present/target operational space with the negative-NBI in LHD



- Usual pulse duration for the short-pulse and high-power injection is 2 – 3 sec.
- High-power injection duration is restricted by the GG heat load.
- PG temperature rise determines the injection duration and power in the long-pulse injection.
- Inertially cooled injection port also limits the injection duration and power.
- Two injectors can extend the pulse duration beyond the rated value of 10sec, and the commercial line allows the injection power below 0.6MW.
- Incompatibility for the PG temperature control between the short-pulse operation and the long-pulse operation restricts the operational range.

Tungsten vapor from the filaments should be a dominant contaminant for cesium.

- Distribution of the W-filament weight loss is observed to correspond to the local arc distribution, indicating that the evaporation of the W-filaments is related to the local arc discharge.
- With the cooled PG, the pri-arc duration is extended doubly, and the W-filament life time is shortened to a half.
- Correspondingly, the Cs consumption rate is 2 times increased, suggesting that the tungsten vapor would deteriorate the Cs effect as a dominant contaminant.

W-Filament Lifetime	Cs Consumption	Number of Shot	Beam Duration	Arc Duration	Filament Duration	(BL2)
10,000 shots	14 – 15 g	22,000	1 – 2 s	7 – 8 s	17 – 18 s	7th (2003)
5,000 shots	13 – 14 g	12,500	1 – 2 s	13 – 15 s	23 – 25 s	8th (2004)
Filament weight loss for 10,000 shots 2 g			1 – 2 s	7 – 8 s	17 – 18 s	6th (2002)

6th & 7th : Same operational condition with non-cooled PG.
8th : Extension of the pri-arc duration before the beam with cooled PG.

W-filament life time means the replacement period that is judged from an indication of the filament fatigue such as the snapping.