Design of a Neutral Beam Injection System for STOR-U

Presented by

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Division of Plasma Physics

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Tokamak

- Confines plasma using magnetic fields
- Induce plasma current for heating until resistance becomes very low
- Injected energetic neutral fuel particles heat by collisions, ionize, then join plasma
- STOR-U, University of Saskatchewan

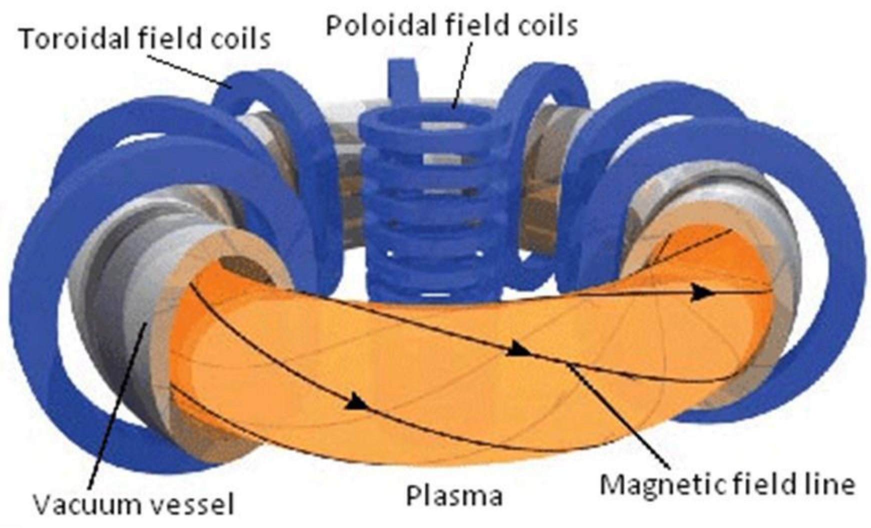


Image modified from [1]

Neutral Beam Injector Subsystems

- Ion source: high current, hydrogen ions
- Accelerator: beam energy, focusing
- Neutralizer: charge exchange
- Residual ion dump, then drift to plasma

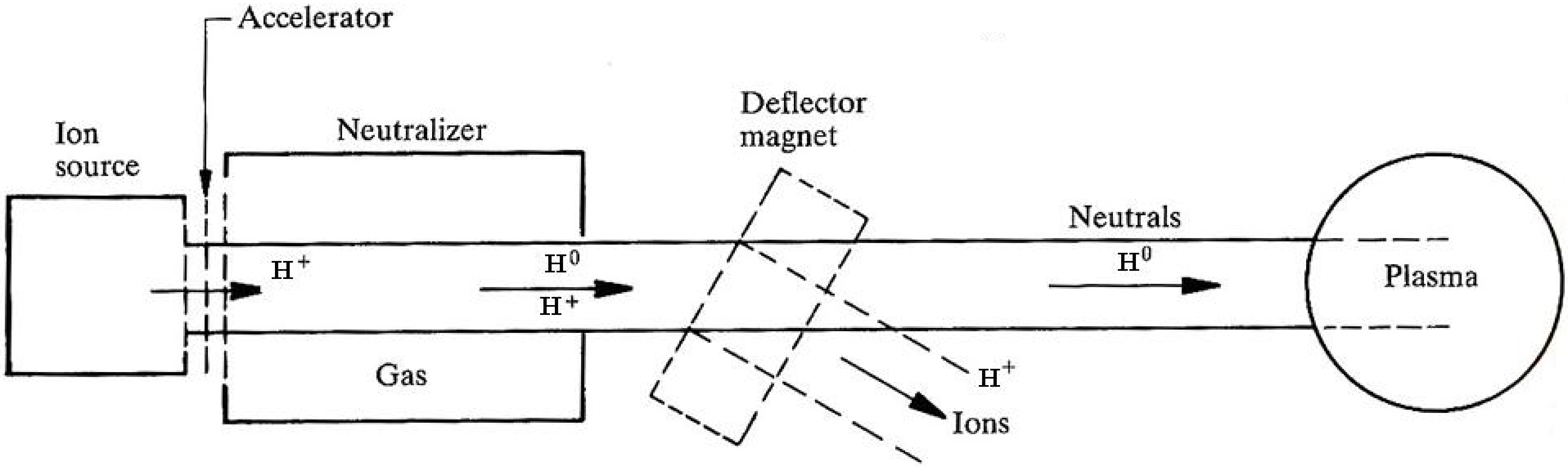
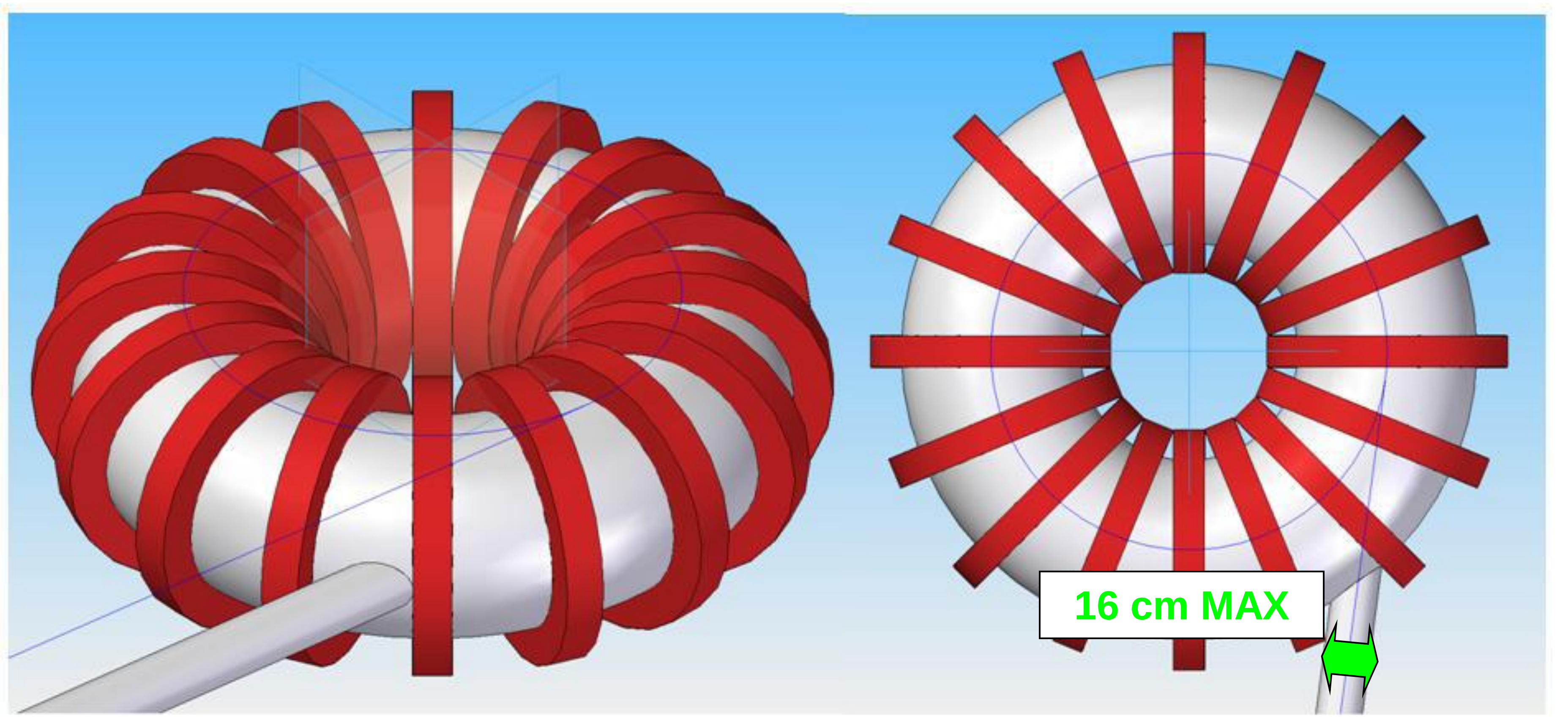


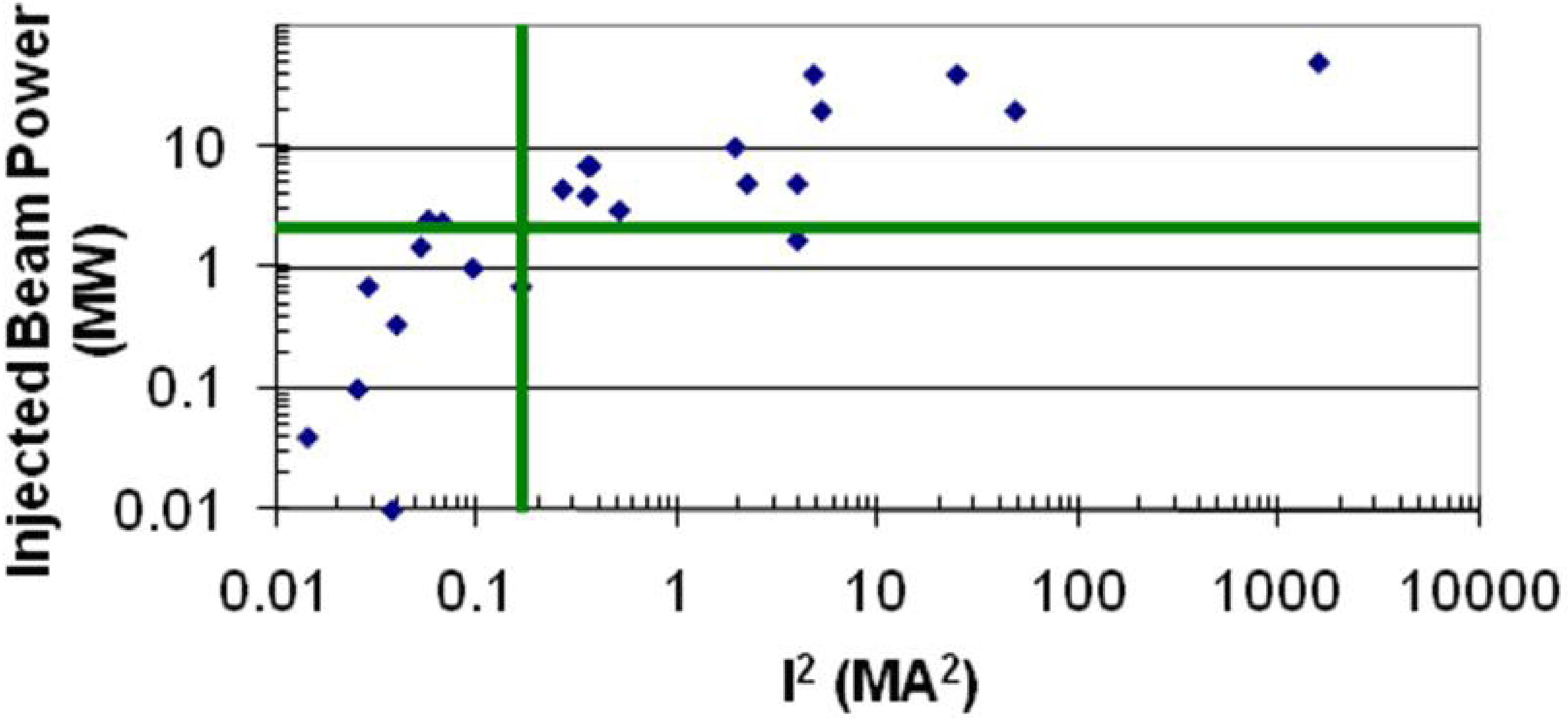
Image modified from [2]

NBI Port Size

- Determined max port dimension
- Assumed maximum toroidal field coil size
- Tangential injection



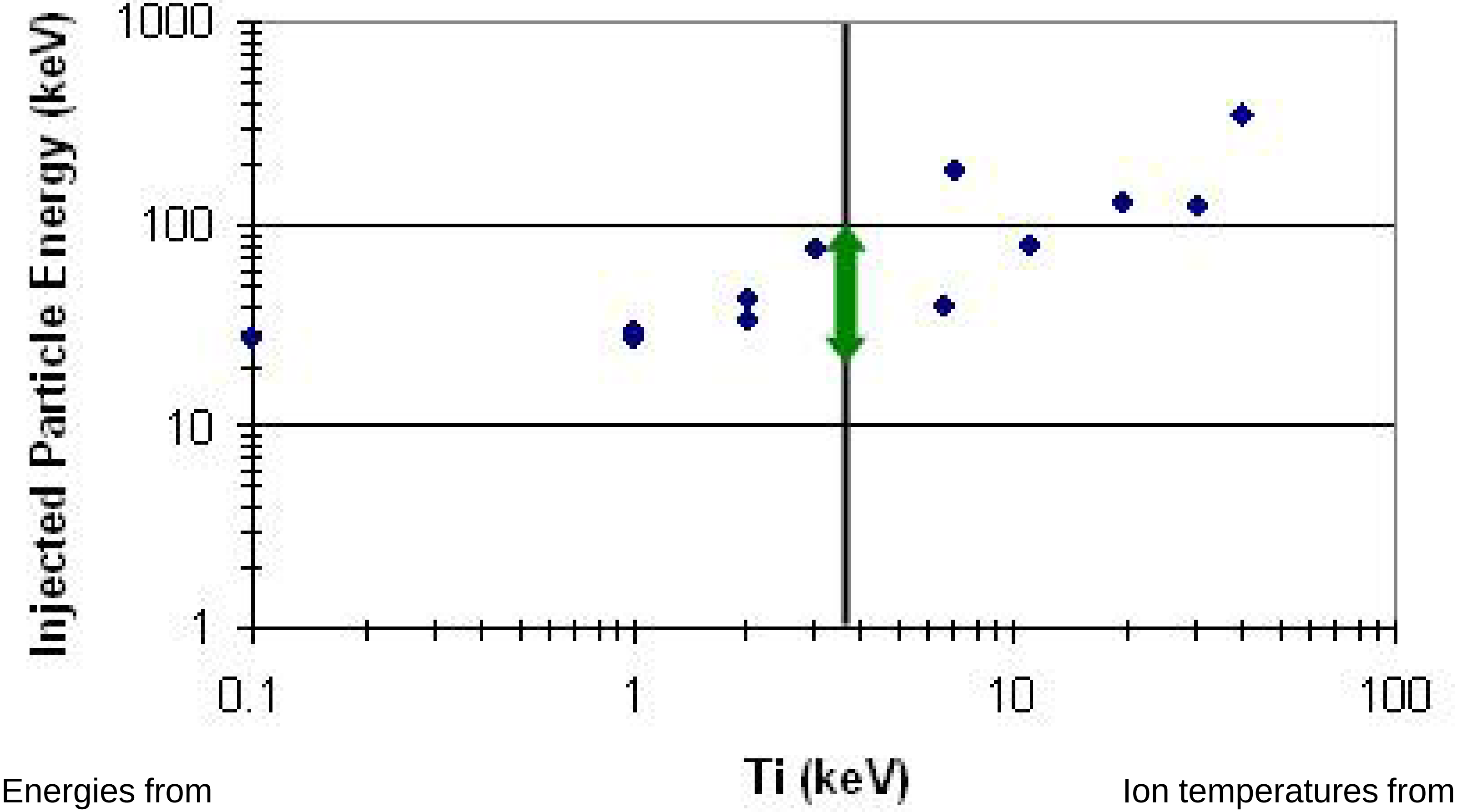
Beam Power



Data from [2].

- $P = I^2R$, compare P_{NBI} to I^2 of previous tokamaks
- For STOR-U, I = 0.4 kA → ~2 MW NBI

Beam Energy



Energies from [3][4][5][6][7][8][9][10][11][12][13][14]

Ion temperatures from [15][16][17][18][19][20]

- Beam must penetrate plasma, but not pass through
- For STOR-U, T_i = 3.5 keV → ~20-100 keV NBI

Calculating Neutral Fraction

$\sigma_{\bar{1}0}$:	$\underline{\mathrm{H}}^- + \mathrm{H}_2 \rightarrow \underline{\mathrm{H}}^0 + \mathrm{e} + \mathrm{H}_2$
$\sigma_{\bar{1}1}$:	$\underline{\mathrm{H}}^- + \mathrm{H}_2 \rightarrow \underline{\mathrm{H}}^+ + 2\mathrm{e} + \mathrm{H}_2$
σ_{01}:	$\underline{\mathrm{H}}^0 + \mathrm{H}_2 \rightarrow \underline{\mathrm{H}}^+ + \mathrm{e} + \mathrm{H}_2$
$\sigma_{0\bar{1}}$:	$\underline{\mathrm{H}}^0 + \mathrm{H}_2 \rightarrow \underline{\mathrm{H}}^0 + \mathrm{H}_2^+$
σ_{10}:	$\underline{\mathrm{H}}^+ + \mathrm{H}_2 \rightarrow \underline{\mathrm{H}}^0 + \mathrm{H}_2^+$
$\sigma_{1\bar{1}}$:	$\underline{\mathrm{H}}^+ + \mathrm{H}_2 \rightarrow \underline{\mathrm{H}}^- + 2\mathrm{H}^+$

$$\frac{\mathrm{d}n^-}{\mathrm{d}z} = N(z)[n^0\sigma_{0\bar{1}} + n^+\sigma_{1\bar{1}} - n^-(\sigma_{\bar{1}0} + \sigma_{\bar{1}1})]$$

$$\frac{\mathrm{d}n^0}{\mathrm{d}z} = N(z)[n^-\sigma_{\bar{1}0} + n^+\sigma_{10} - n^0(\sigma_{0\bar{1}} + \sigma_{01})]$$

$$\frac{\mathrm{d}n^+}{\mathrm{d}z} = N(z)[n^-\sigma_{\bar{1}1} + n^0\sigma_{01} - n^+(\sigma_{1\bar{1}} + \sigma_{10})]$$

- Cross sections tabulated by ORNL [21]
- N neutral gas density
- Initial N estimate from tokamak pressure [22]
- *z* distance
- $n^0(0) = n^-(0) = 0$
- $n^+(0)$ arbitrary

$$\sigma_{\bar{1}0}: \quad \underline{H}^- + H_2 \rightarrow \underline{H}^0 + e + H_2$$

$$\sigma_{\bar{1}1}: \quad \underline{H}^- + H_2 \rightarrow \underline{H}^+ + 2e + H_2$$

$$\sigma_{01}: \quad \underline{H}^0 + H_2 \rightarrow \underline{H}^+ + e + H_2$$

$$\sigma_{0\bar{1}}: \quad \underline{H}^0 + H_2 \rightarrow \underline{H}^0 + H_2^+$$

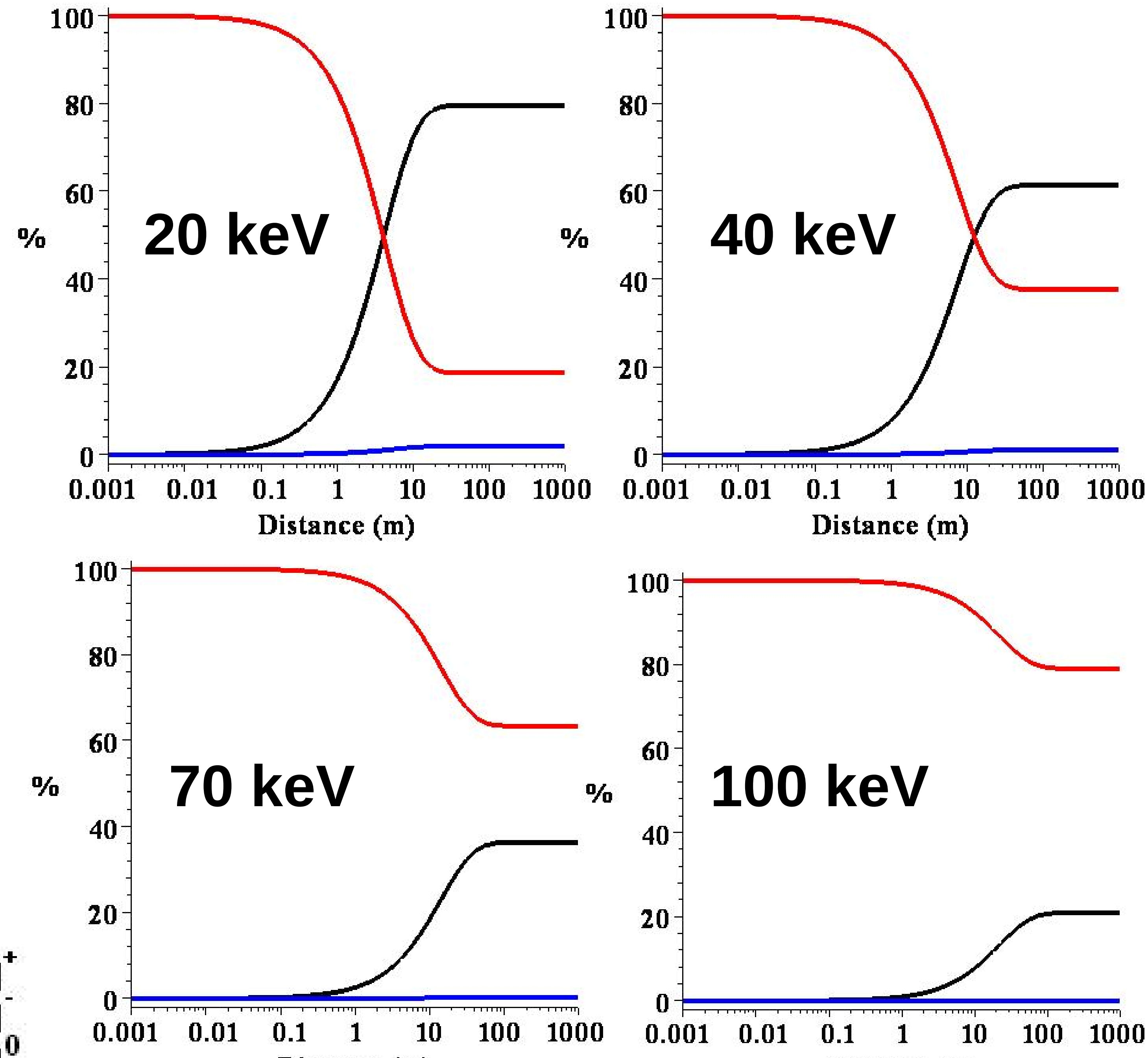
$$\sigma_{10}: \quad \underline{H}^+ + H_2 \rightarrow \underline{H}^0 + H_2^+$$

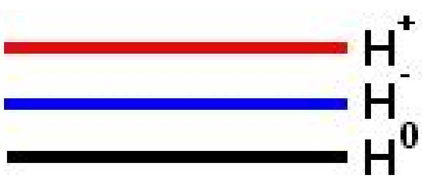
$$\sigma_{1\bar{1}}: \quad \underline{H}^+ + H_2 \rightarrow \underline{H}^- + 2H^+$$

(cm^2)	20 keV	40 keV	70 keV	100 keV
$\sigma_{\bar{1}0}$	$8.36x10^{-16}$	$6.33x10^{-16}$	$4.82x10^{-16}$	$3.95x10^{-16}$
$\sigma_{\bar{1}1}$	$4.11x10^{-17}$	$3.97x10^{-17}$	$3.36x10^{-17}$	$2.84x10^{-17}$
σ_{01}	$1.36x10^{-16}$	$1.54x10^{-16}$	$1.36x10^{-16}$	$1.10x10^{-16}$
$\sigma_{0\bar{1}}$	$1.91x10^{-18}$	$9.93x10^{-18}$	$4.07x10^{-18}$	$1.68x10^{-18}$
σ_{10}	$5.79x10^{-16}$	$2.50x10^{-16}$	$7.78x10^{-17}$	$2.91x10^{-17}$
$\sigma_{1\bar{1}}$	$8.89x10^{-18}$	$2.21x10^{-18}$	$2.24x10^{-19}$	$3.15x10^{-20}$

Equilibrium properties:

- neutral fraction ↓ with E ↑
- *n*⁻ small
- Not reached for long distance





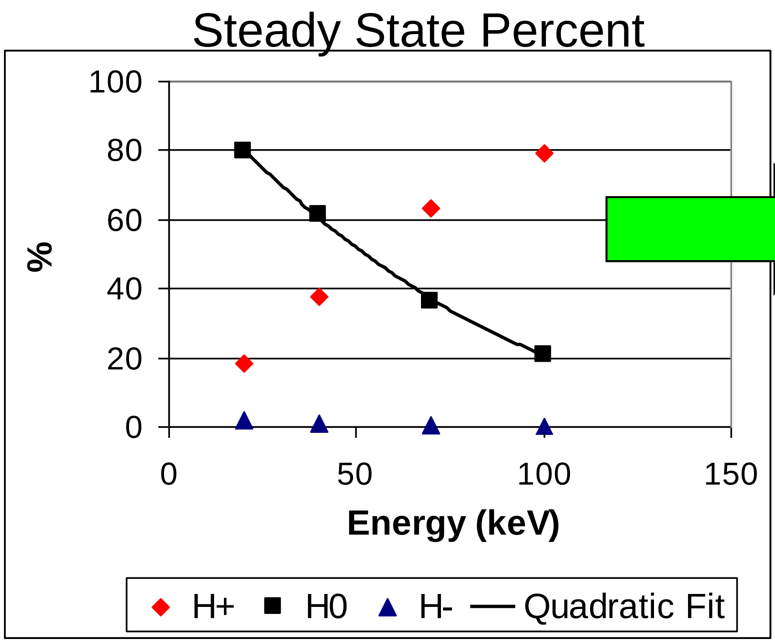
Effect of Increasing Pressure

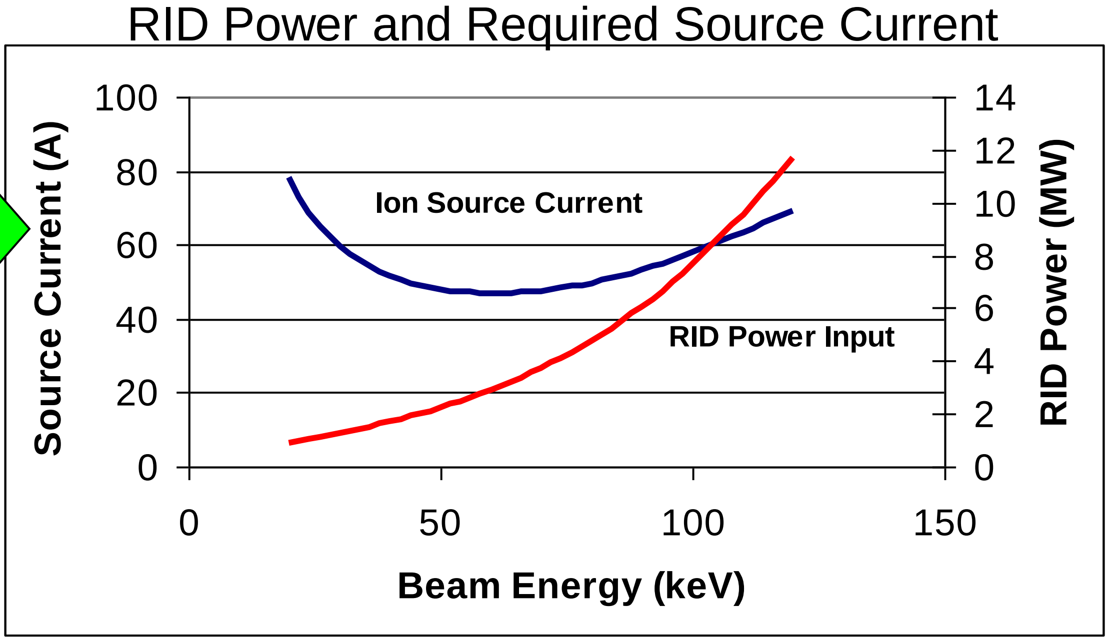
- Distance to achieve equilibrium proportional to N
- i.e. decrease neutralizer length by increasing pressure
- If pressure too high, “stripping” occurs
- Restricts pressure below 4×10^{-3} torr [23]

Energy (keV)	Distance for 90% of steady state value (m)
20	0.3
40	0.5
70	0.9
100	1.4

Effect of Increasing Energy

- Equilibrium fraction of neutrals decreases
- Must dump these residual ions after neutralizer → possible high power flux
- Required source current for 2 MW beam power dependent on energy





Ion Source Choice

- Comparison included consideration of
- Uniformity: optics optimized for specific current density
- Monatomic fraction: may lead to ions with $E_{beam}/2$, $E_{beam}/3$
- Noise: fluctuations in current

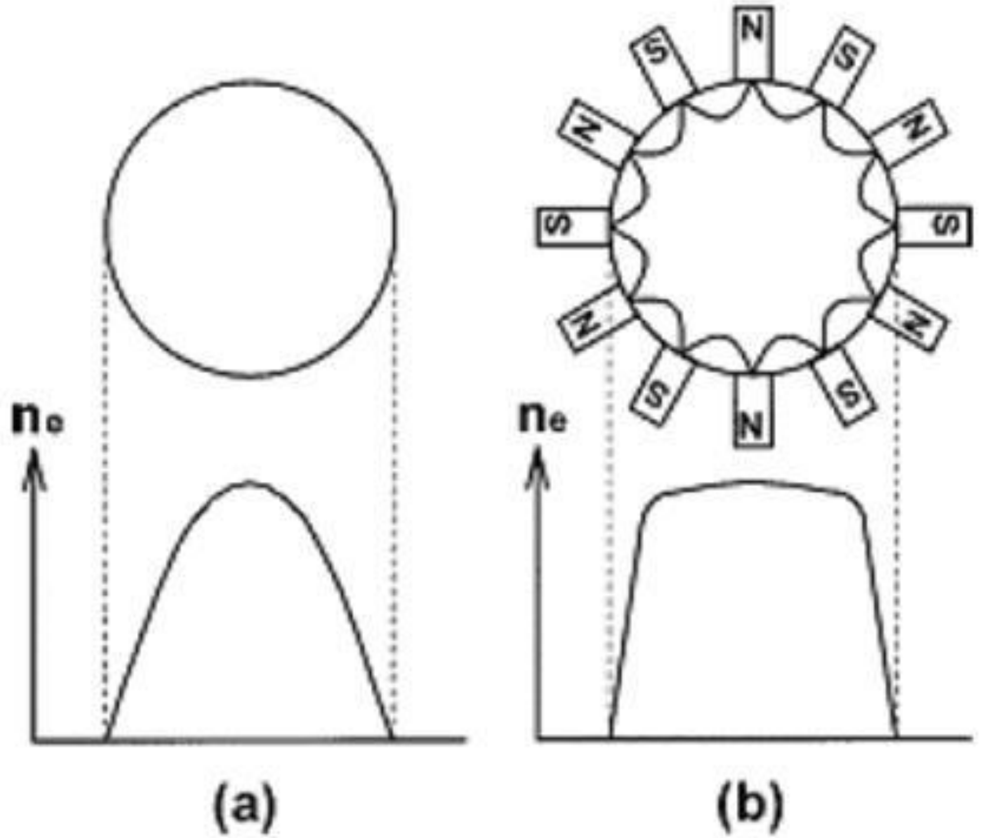


Image modified from [25]

Magnetic Multipole Source

- Filaments or RF used to generate plasma
- Quiescent, uniform plasma with high monatomic fraction

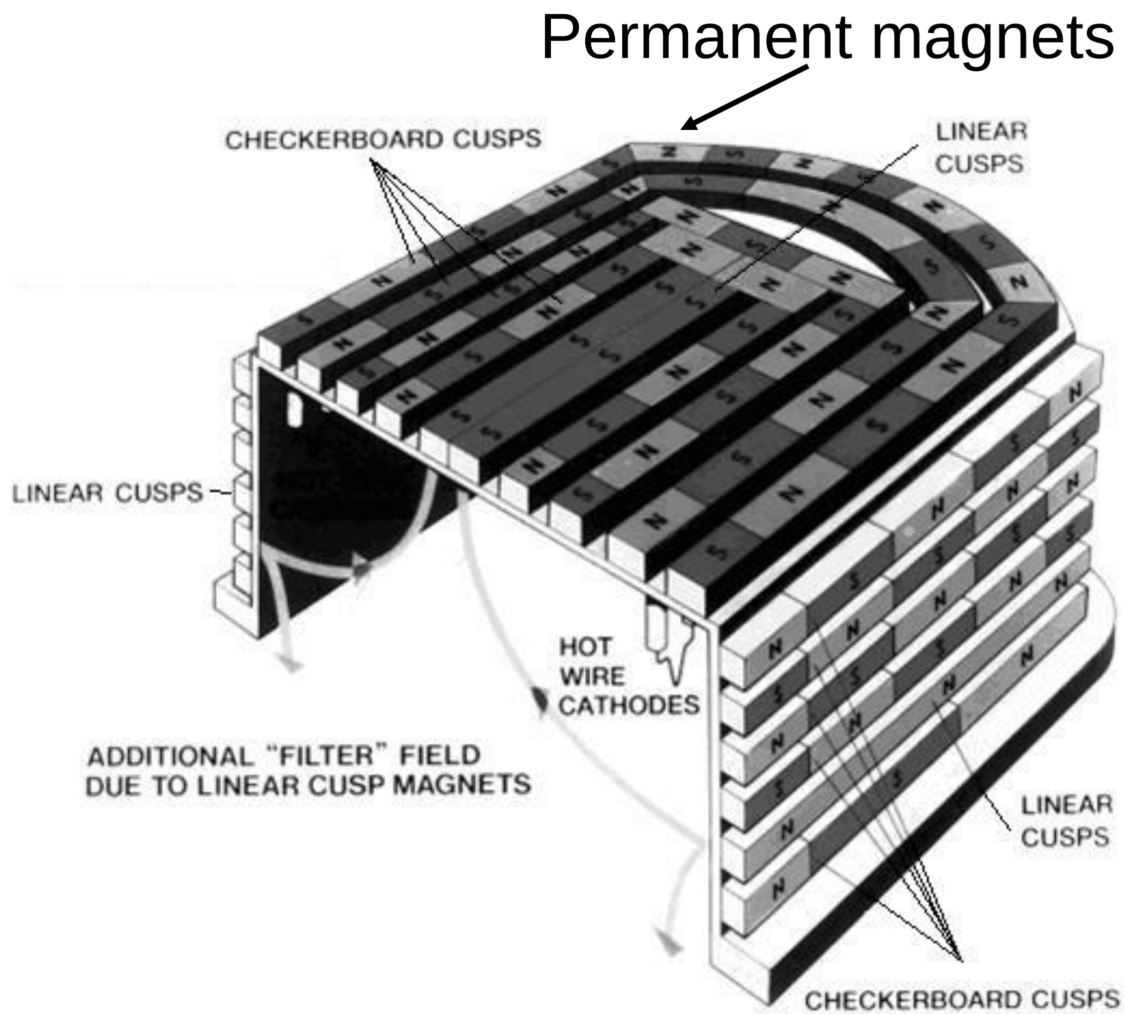
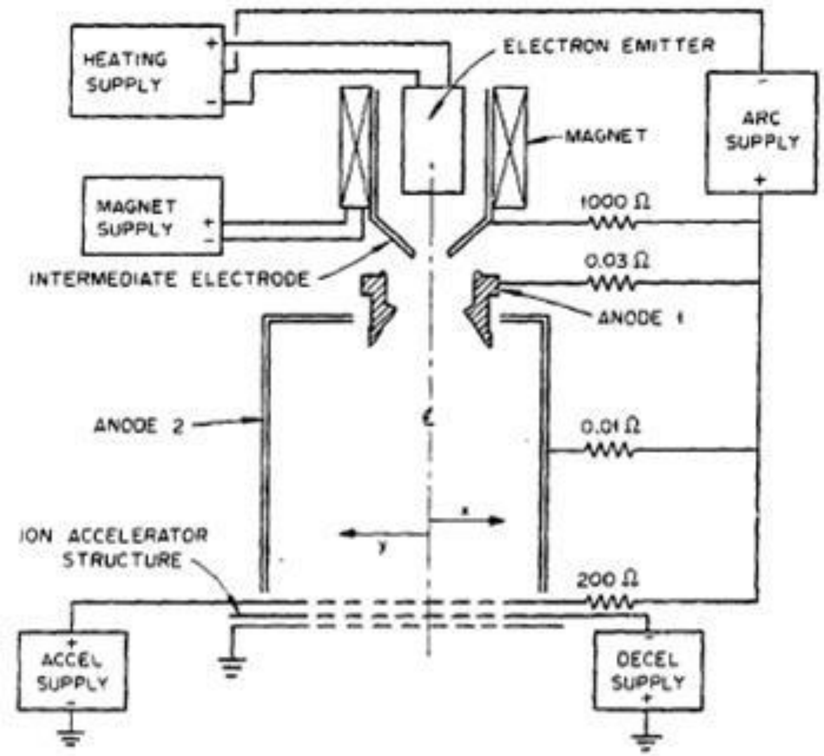


Image modified from [23]

Modified DuoPIGatron

- Uses magnetic cusps, but different method of plasma generation
- Performance not as good as multipole under aforementioned criteria, but satisfactory for STOR-U
- Formerly widely popular, so may be possible to obtain disused source



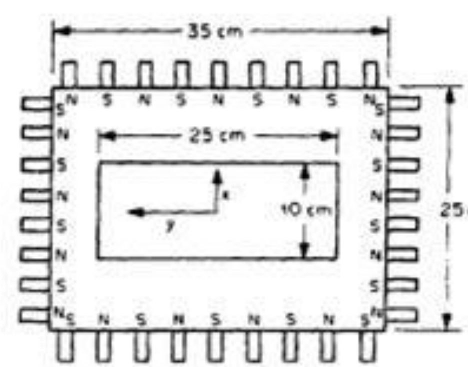


Image modified from [26]

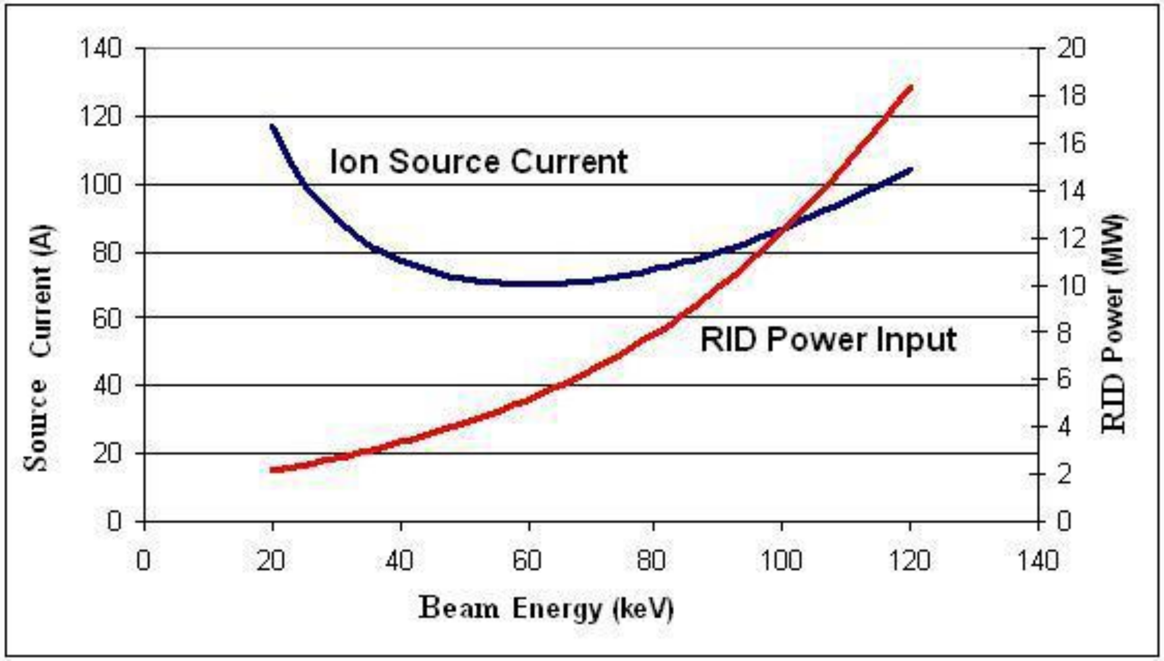
Accelerator

- 3-grid design chosen with beamlets
- Grids will be curved to provide focusing
- Comparison done to previous comparable NBI accelerators to estimate divergence
- Maximum transmission distance calculated

Source and aperture type	Tokamaks applied to	Max. design current (A)	Accel dimensions (cm)	Size of holes/slots	Number of holes/slots	Beam divergence (degrees)	Maximum Transmission Distance (m)
Multipole with holes	JET, MAST	60	16x45 → 30 diam	1.2-cm diam	262	0.7	6.1 m
DuoPIGatron with holes	ISX-B, PLT	60	22 diam	0.38 cm diam	1799	1.5	3.0 m
Multipole with slots	DIII-D, TFTR	83	12x48	0.6x12 cm	55	0.4 | | to slots, 0.7 ⊥	6.3 m
DuoPIGatron with slots	TFTR, DIII-D	60	13x43	0.6x12 cm	55	0.3 | | to slots, 0.7-1.2	4.6 m

STOR-U Team Parameters

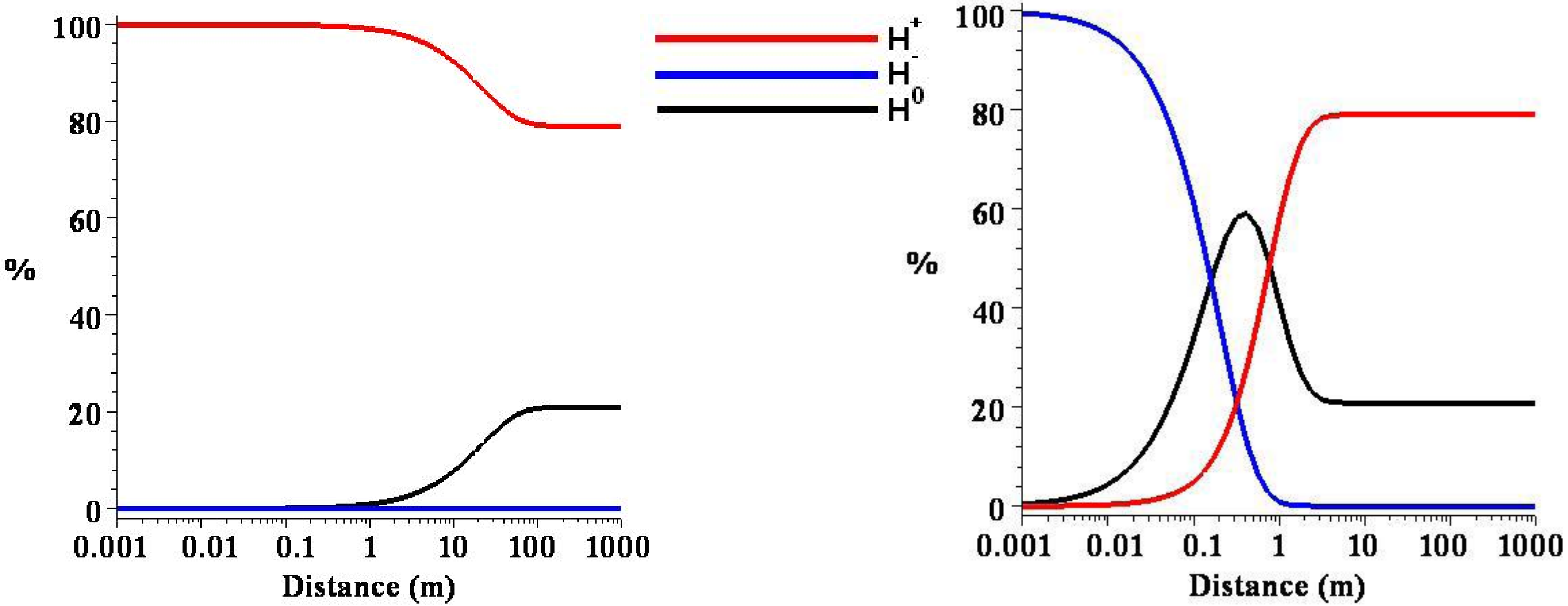
- Parameters selected compared to those chosen by STOR-U team
- 3 MW close to 2 MW estimate
- 40 keV energy within 20-100 keV range
- Larger source required than predicted



Rejected Solutions

- Deuterium produces radioactive tritium
- Negative ion sources are very complicated and produce low current densities

H^+ source 100 keV **H^- source**



Summary

- NBI to inject 2 MW H^+ at 20-100 keV
- Require source that generates ~60 A
- Lower current keeps beam dump load low
- Magnetic multipole has best performance
- Should seek disused modified DuoPIGatron sources
- Acceleration provided by 3 curved grids
- Estimates within an order of magnitude of STOR-U team’s of 3 MW and 40 keV

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Effect of Increasing Energy

- This assumes a 20% power loss along beamline (other than residual ion dump)
- Estimate based on beamline losses in previous comparable NBIs
- Example from PDX shown

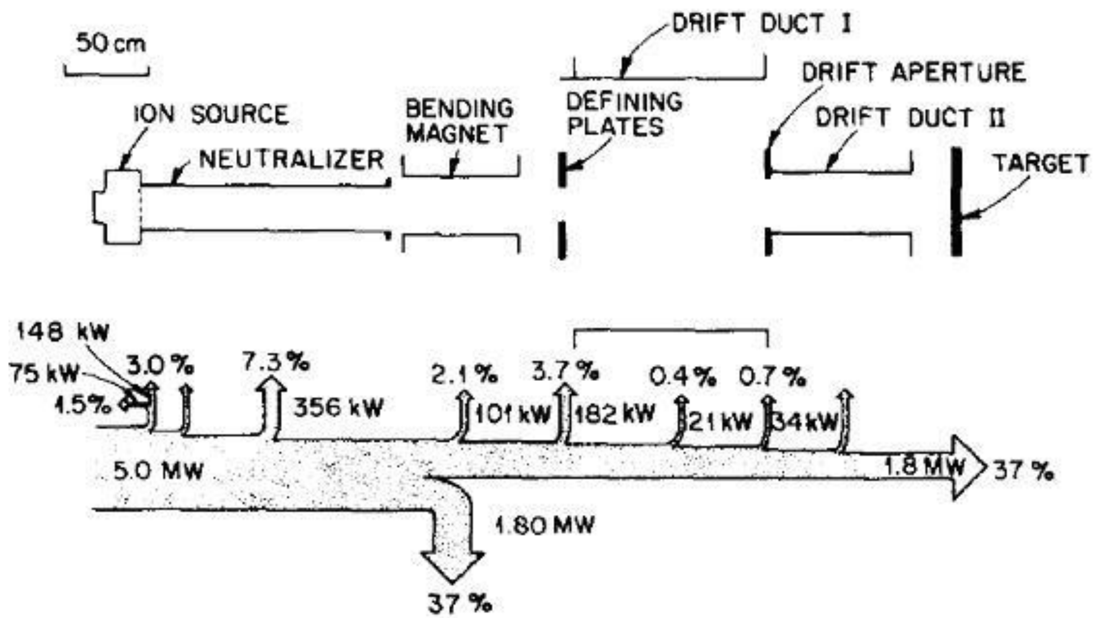
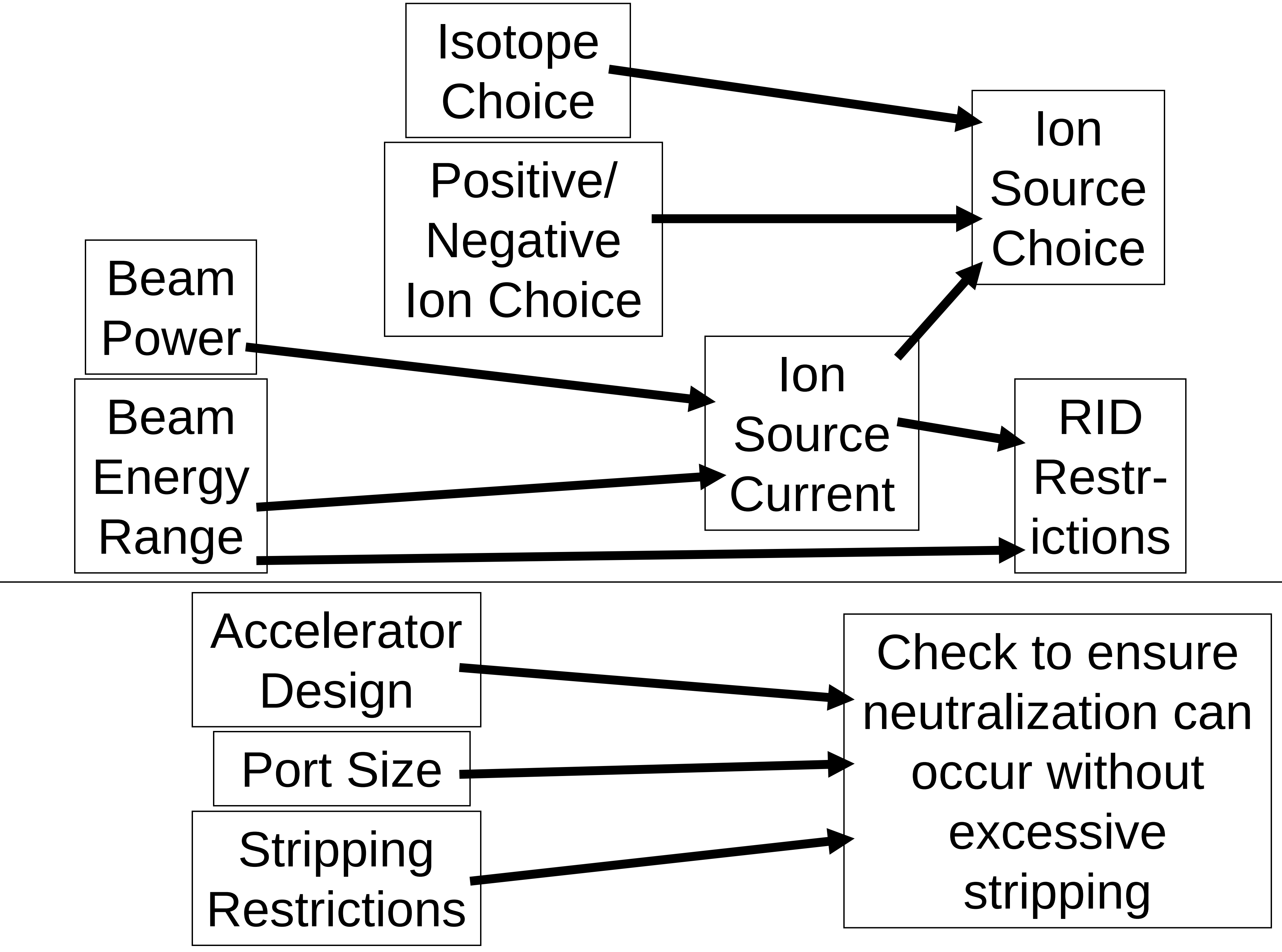


Image modified from [24]


Isotope Choice
Positive/ Negative Ion Choice
Ion Source Choice
Beam Power
Beam Energy Range
Ion Source Current
RID Restr- ictions
Accelerator Design
Port Size
Stripping Restrictions
Check to ensure neutralization can occur without excessive stripping

$$\sigma_{10}: \quad \underline{H}^+ + H_2 \rightarrow \underline{H}^0 + H_2^+$$
$$\sigma_{01}: \quad \underline{H}^0 + H_2 \rightarrow \underline{H}^+ + e + H_2$$