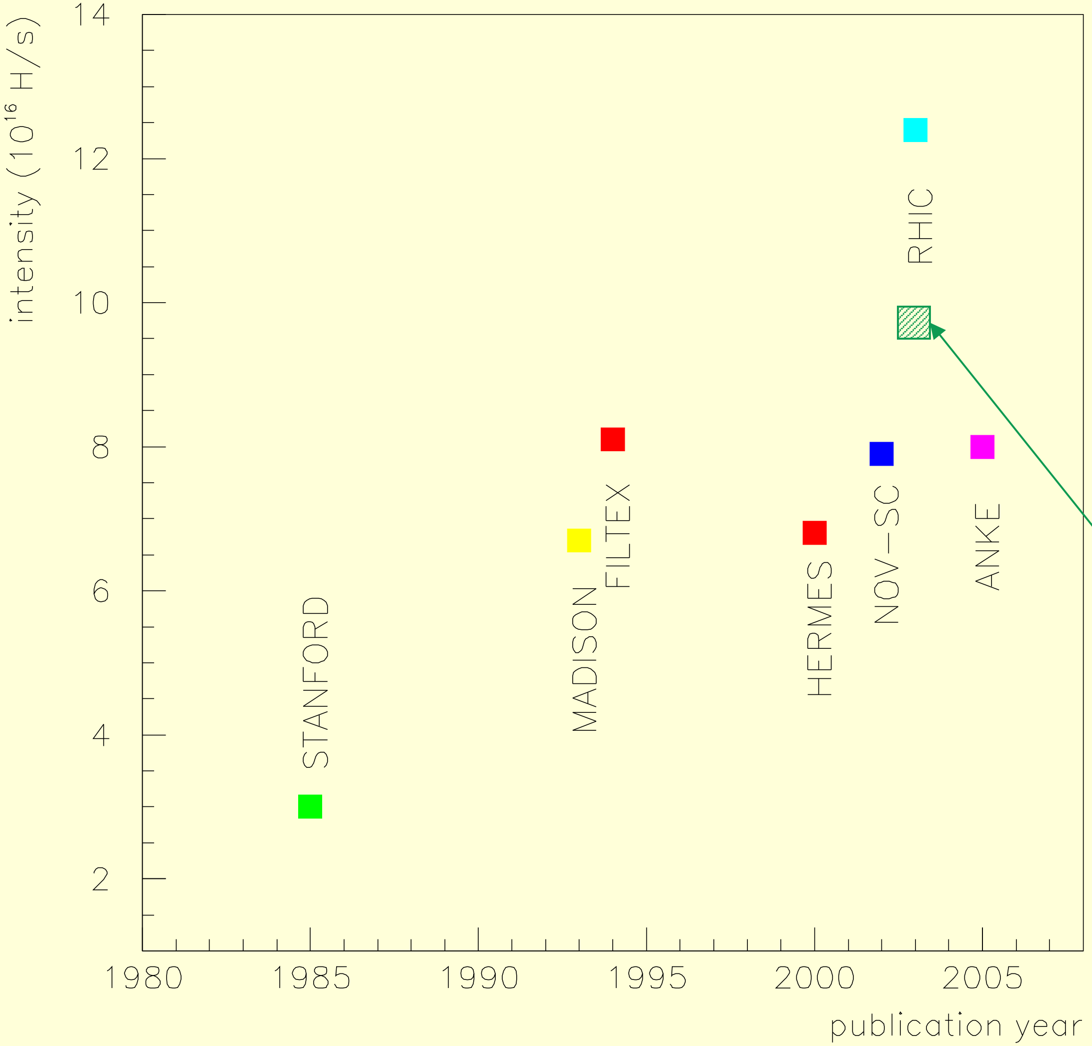
Calculating the intensity of an Atomic Beam Source

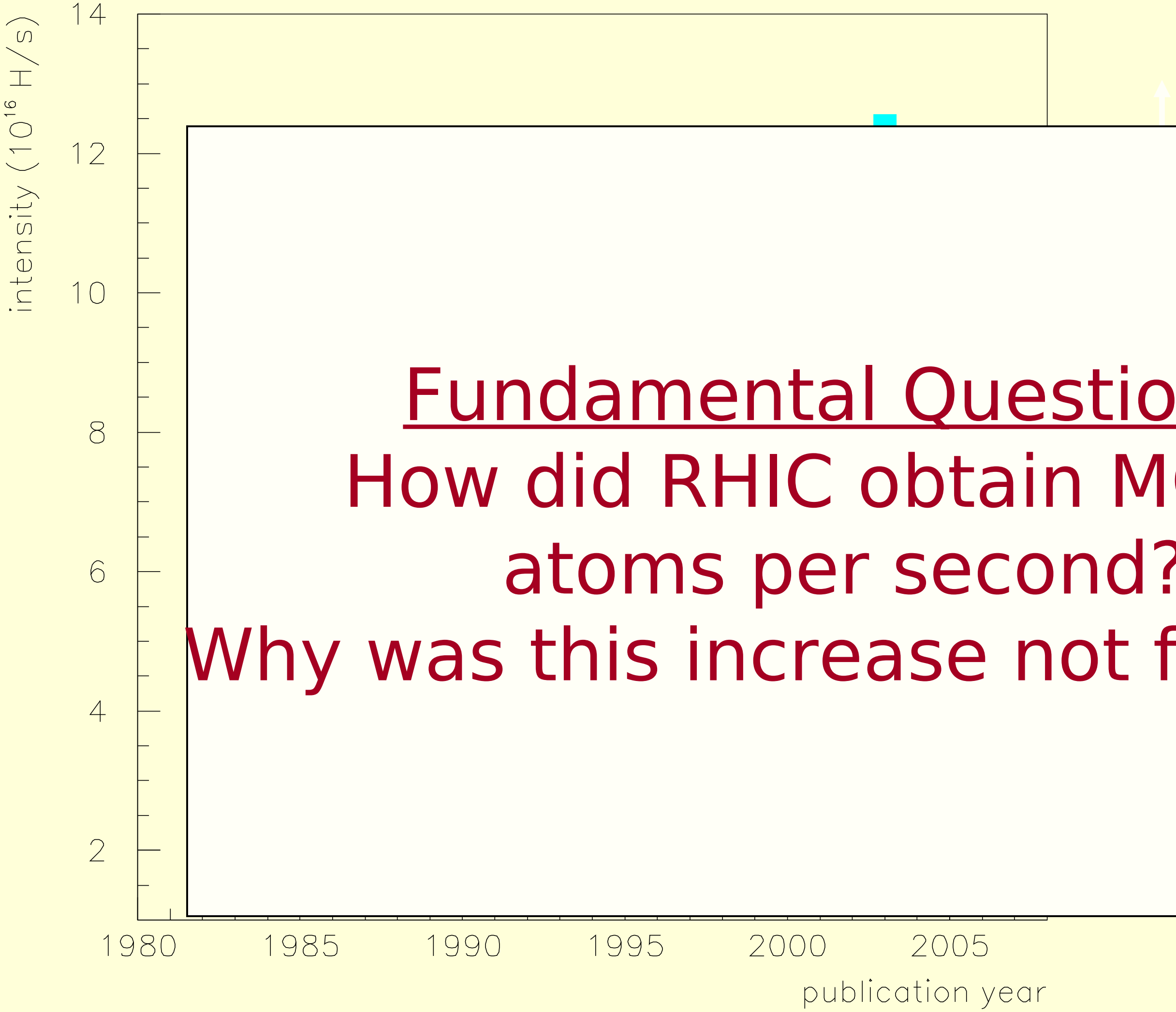
The last 30 years of Polarized ABS



Increase has no concrete explanation!

Predicted Intensity for RHIC source!?

The last 30 years of Polarized ABS



<u>Fundamental Questions</u>:

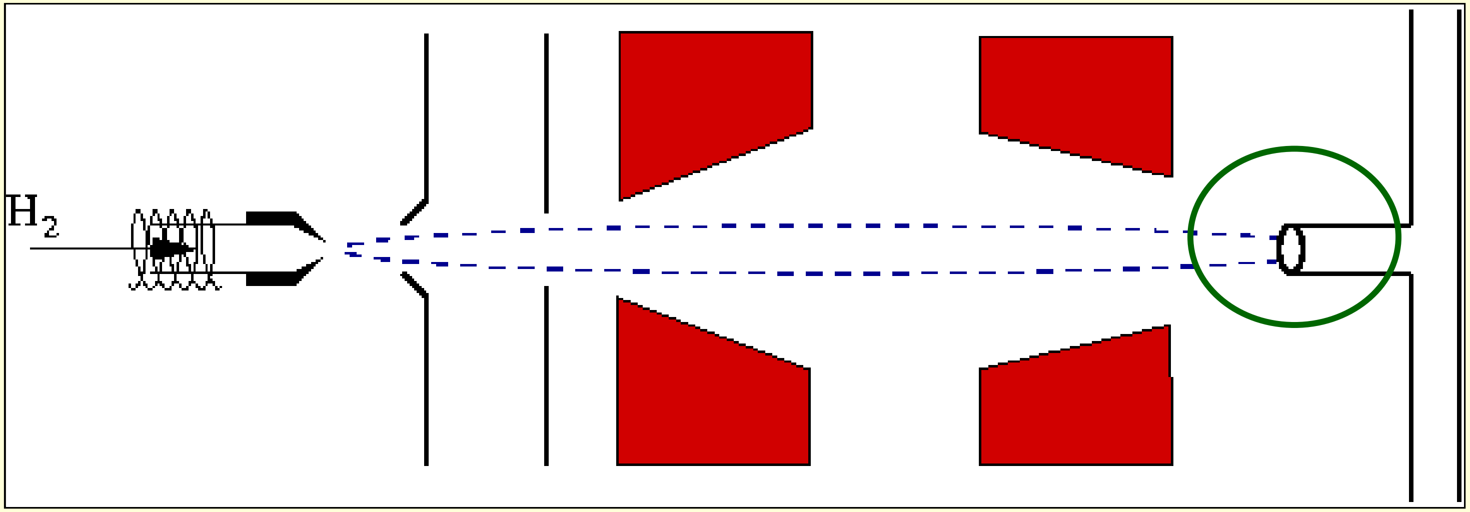
How did RHIC obtain MORE atoms per second?

Why was this increase not foreseen?

sity for

Intensity Predictions

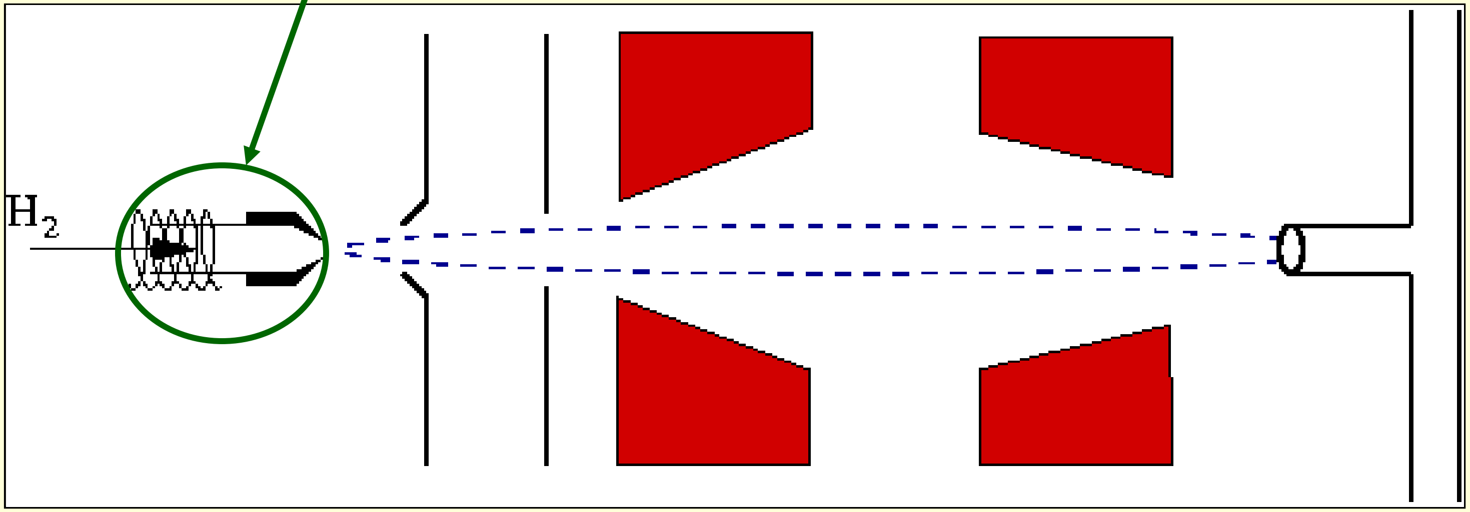
$$\underbrace{Q_{out}}_{\text{Final Intensity (atoms/s)}} = 2\,\alpha Q_{in} n_f \, ft(1\text{-}A)$$



Intensity Predictions

$$Q_{out} = \underbrace{2\,\alpha Q_{in}}\, n_f\, ft(1\text{-}A)$$

Number of atoms leaving the dissociator

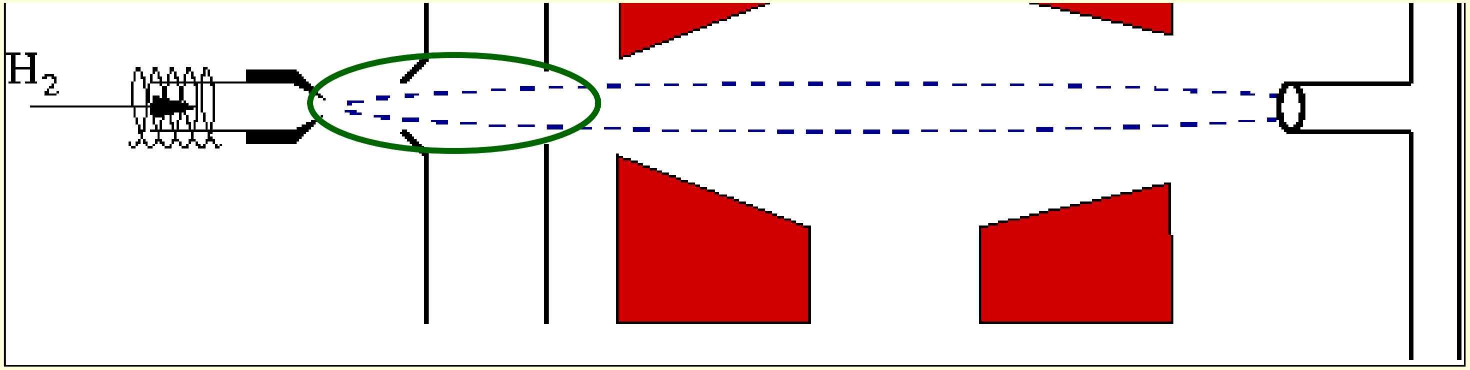


Intensity Predictions

$$Q_{out} = 2\alpha Q_{in} n_f f t (1-A)$$

n_ff is the fraction of nozzle flow which passes through the skimmer

- **f** is geometrical (acceptance of first magnet for an effusive beam from a point-like source at the nozzle exit).
- **n_f** is peaking factor (quantifies the forward peaking, or non-effusive nature, of the beam)

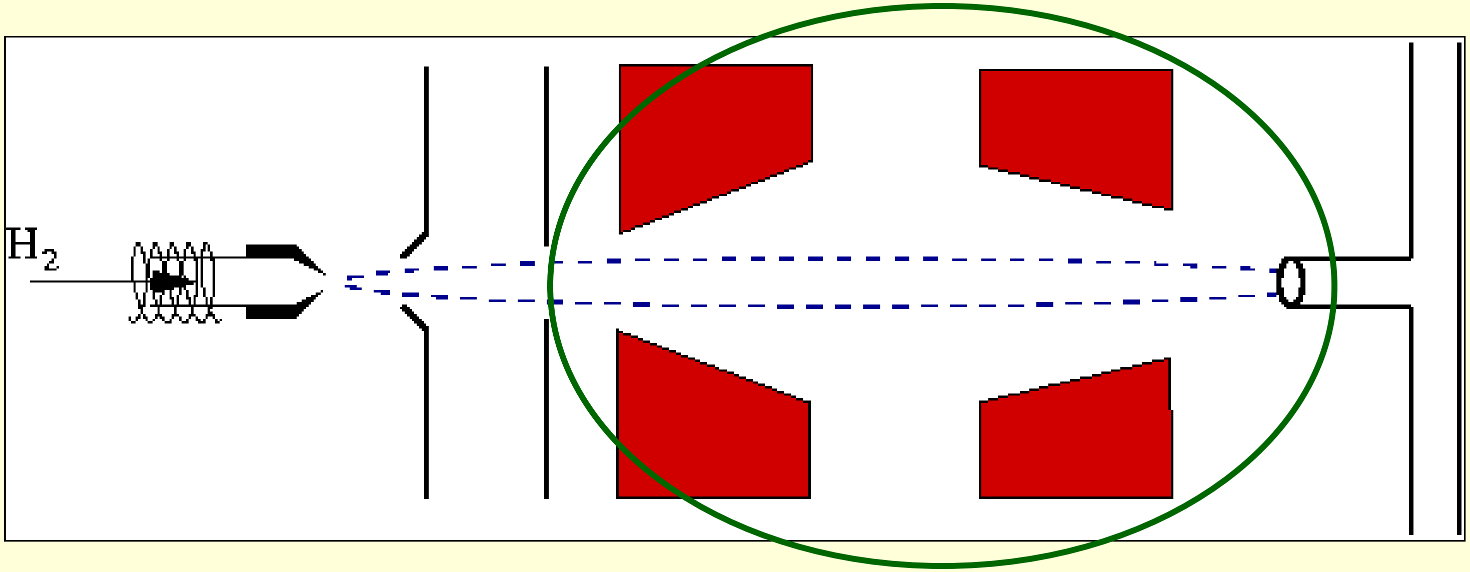


Intensity Predictions

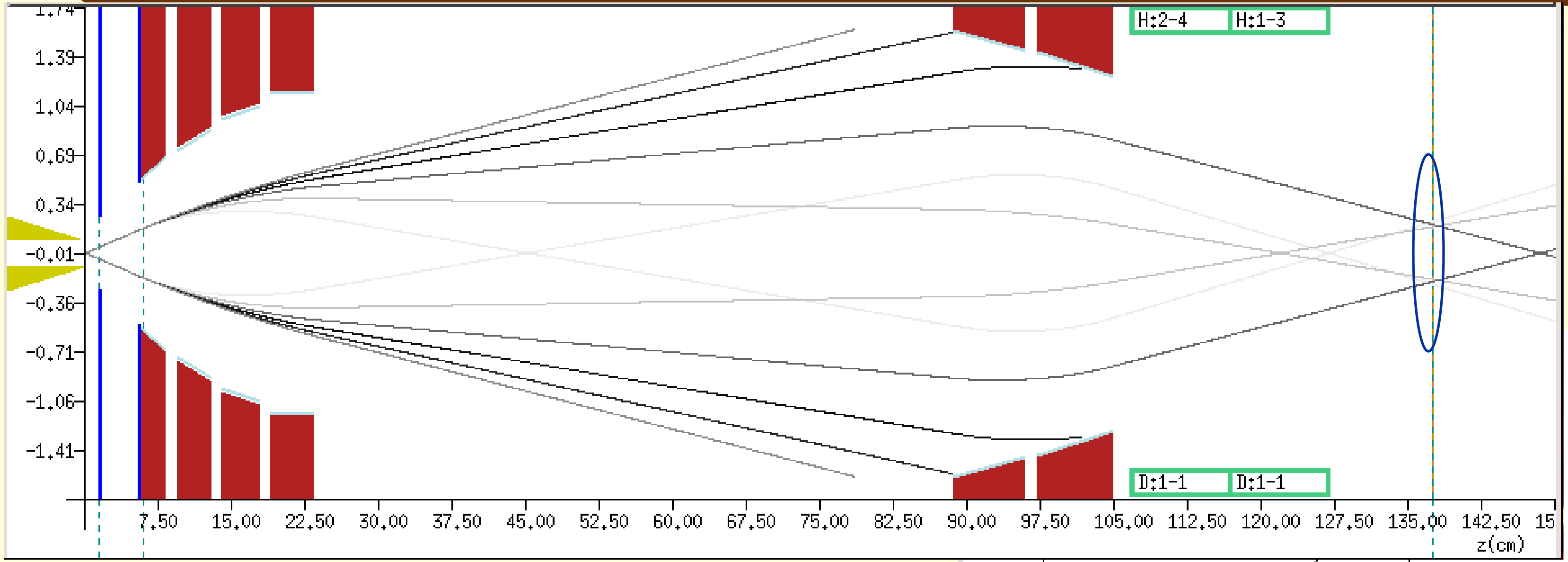
$$Q_{out} = 2\,\alpha Q_{in}\, n_f\, f t (1\text{-}A)$$

t is the probability that the magnet system focuses an atom of the correct spin.

It depends on the magnet strength and the velocity distribution.

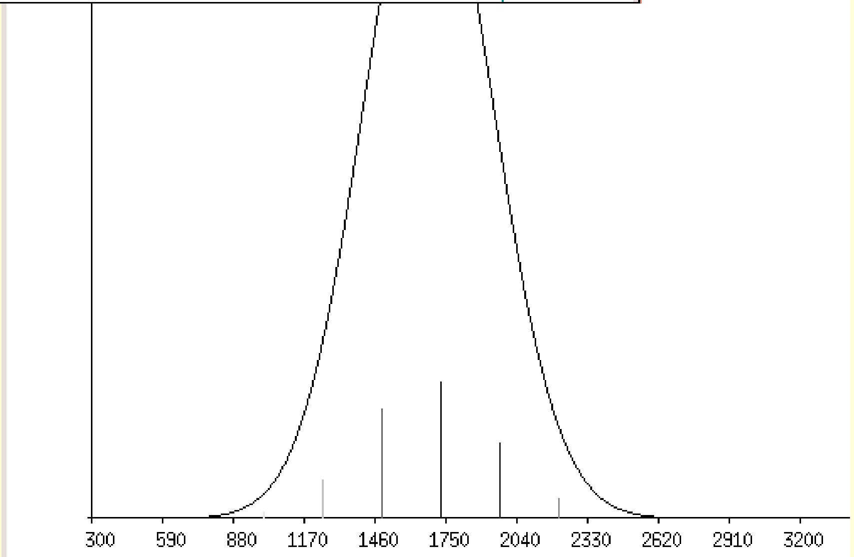


Magnet Transmission t



For 100000 tracks . . .

- Start from random point in the nozzle for start
- Select random direction from isotropic distribution
- Select random velocity from distribution
- Follow atom’s trajectory through magnetic field
- Count how many enter the target



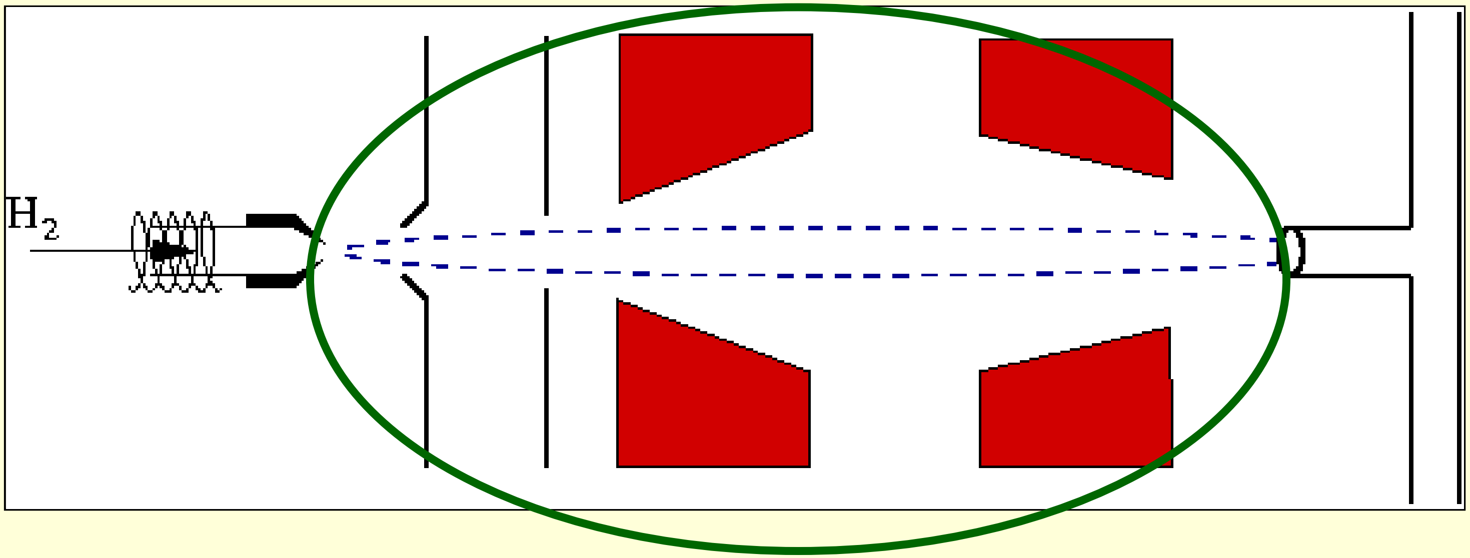
Intensity Predictions

$$Q_{out} = 2\,\alpha Q_{in} n_f f t \left(1\text{-}A\right)$$

A is the fraction of the beam lost to attenuation

- Rest Gas Attenuation (RGA): collisions of beam atoms with chamber rest gas
- Intra Beam Scattering (IBS): collisions of two beam atoms

$$(1\text{-}A) = (1\text{-}A_{RGA})(1\text{-}A_{IBS})$$



Intensity Predictions

$$Q_{out} = 2\,\alpha Q_{in}\, n_f\, ft\,(1\text{-}A)$$

- Standard formula in ABS community
- Magnet transmission calculation method standard
- “Starting generators” differ, but with only small changes in results
- Used by RHIC group to optimize magnet system

  NIM**A556** (2006) 1-12

  - $A_{IBS}=0$ (no method to estimate)
  - $n_f=1.15$ (molecular beam value)

    closer to 1.6 for atomic beam?
  - A_{RGA} estimated from molecular beam measurements
  - Refined estimate of A_{RGA} after optimization using defocused atoms. Only ratio to WISC source for $\int \rho dl$

Comparison of existing sources

	Hermes	Nov	Wisc	ANKE	RHIC
Q_{in} (mbar l/s)	1.5	0.6	1.7	1.0	1.0
α	0.82	0.90	0.75	0.85	0.85
B_{pt}(T)/d_{mag}(cm)	1.5/0.86	3.2/1.4	1.5/1.0	1.7/1.0	1.5/1.0
f (geom.)	0.47%	0.99%	0.70%	0.85%	0.79%
t	0.48	0.79	0.39	0.41	0.49
v_{drift} (m/s)	1953	1750	~1494	~1778	~1530
T_{beam} (K)	25.0	30.0	~16.5	~20.3	~18
length (m)	1.16	1.40	0.99	1.24	1.37
d_{ct} (cm)	1.0	2.0	1.0	1.0	0.9
Q_{out} (10^{16}	6.8	6.7	7.8	7.5	12.4

Theorist’s point of view

$$Q_{out} = 2\cancel{\alpha}\cancel{Q}_{in}\boxed{n}_f\cancel{ft}\boxed{(1\text{-}A_{RGA})}\boxed{(1\text{-}A_{IBS})}$$

Experimentalist’s Point of View

What is physically different?

- Dissociator cooling
  - Narrows velocity distribution? ⇒ reduced IBS losses
  - Increases peaking factor? ⇒ more beam into magnets
- Magnet system longer and more open
  - Lower beam density for same beam flow ⇒ reduced IBS losses

Dissociator Cooling

RHIC

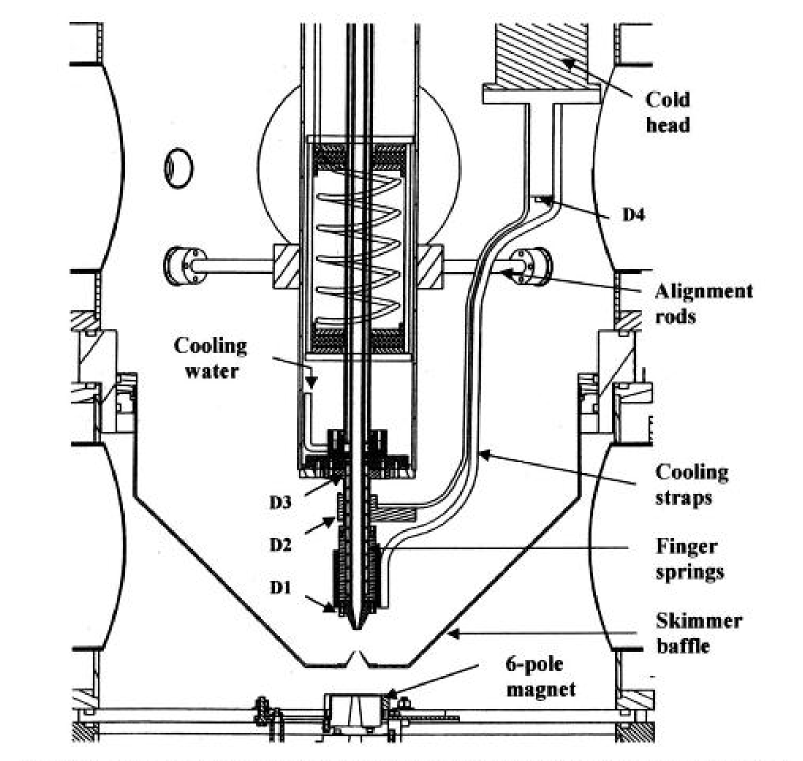
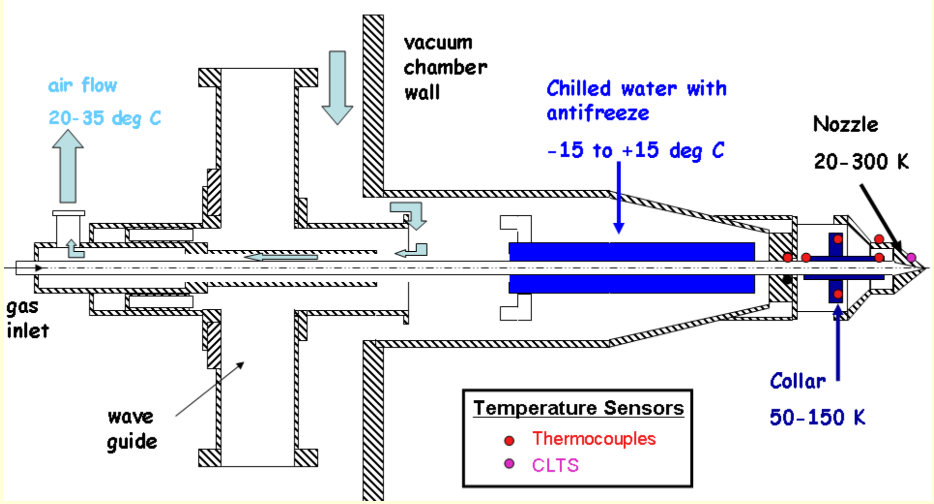
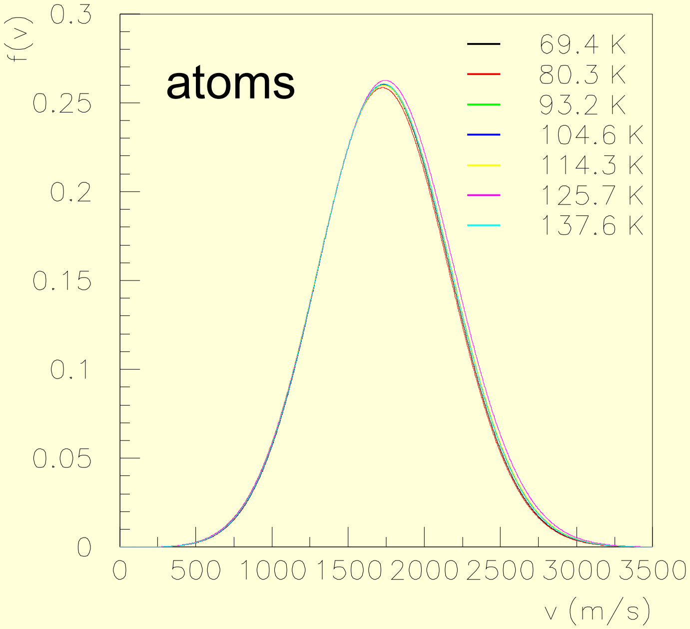


Fig. 2. The dissociator and adjustable skimmer assembly. D1–D5: silicon diode temperature sensors.

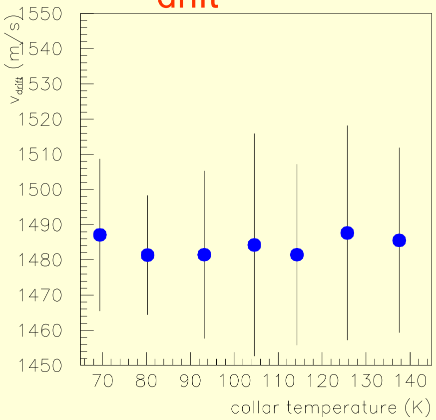
SPINLAB



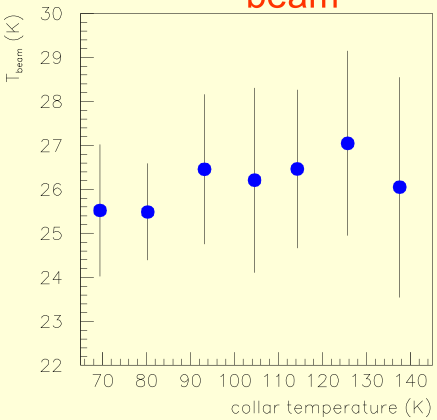
SpinLab Results

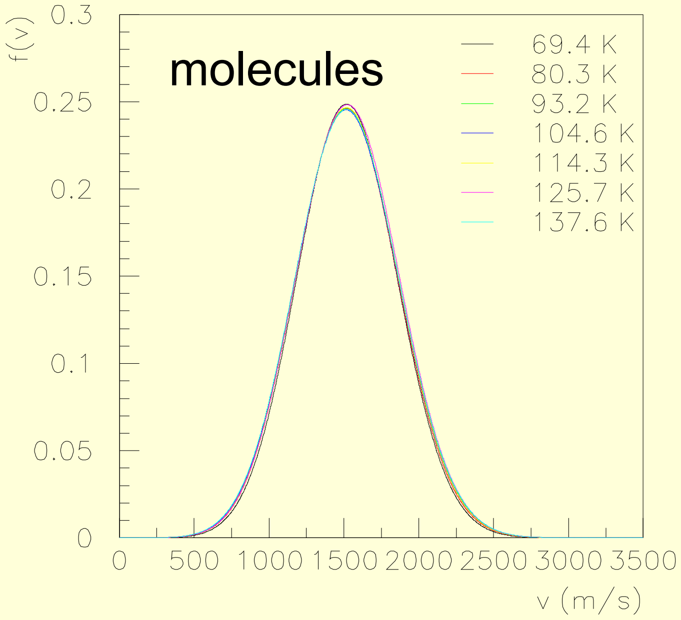


v_{drift}

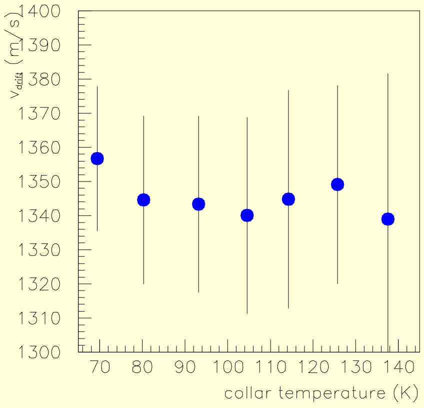


T_{beam}

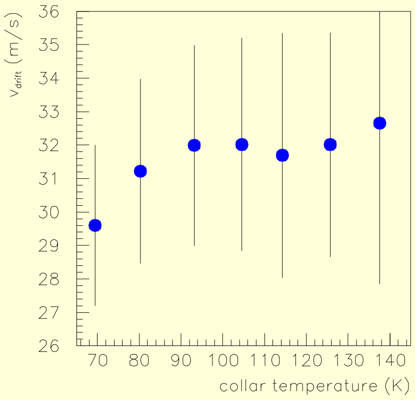




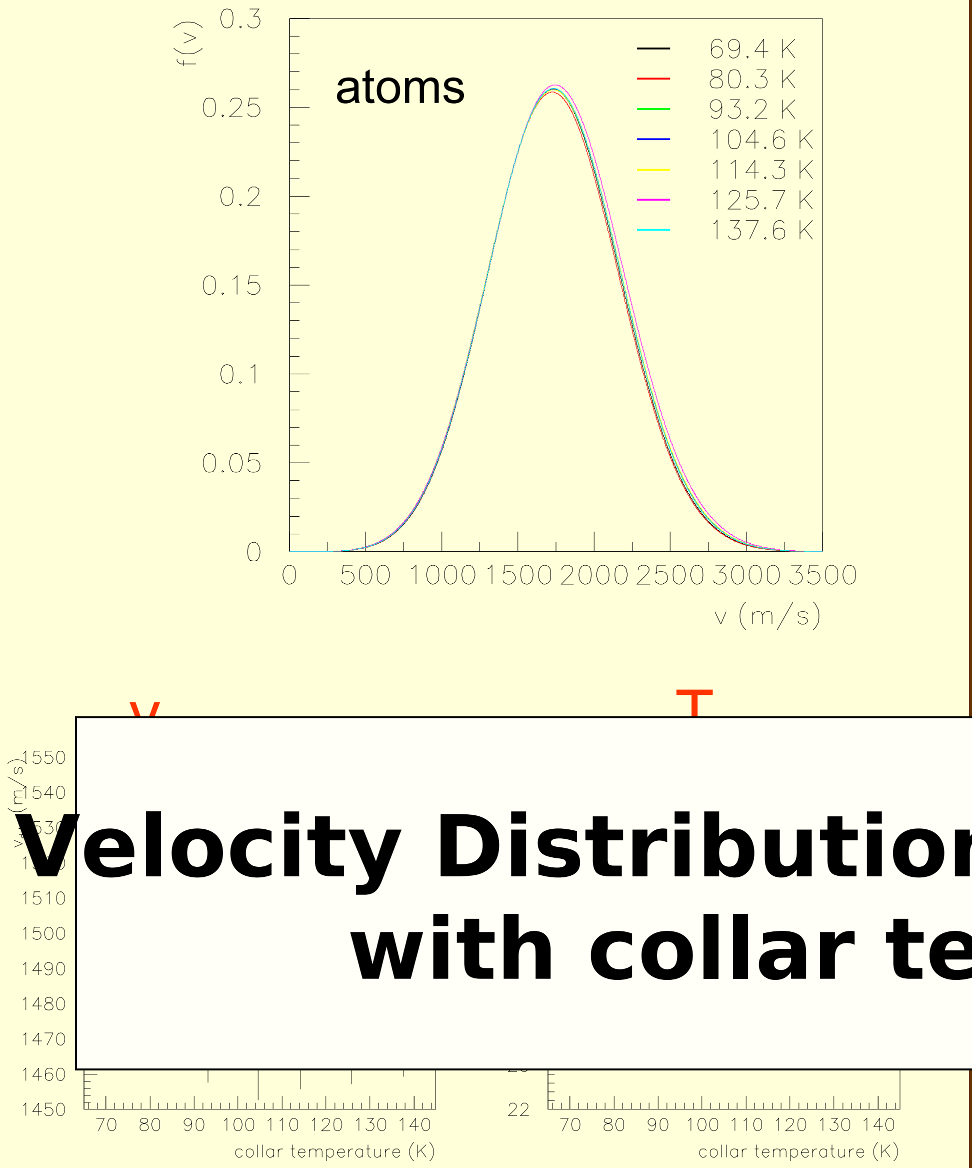
v_{drift}

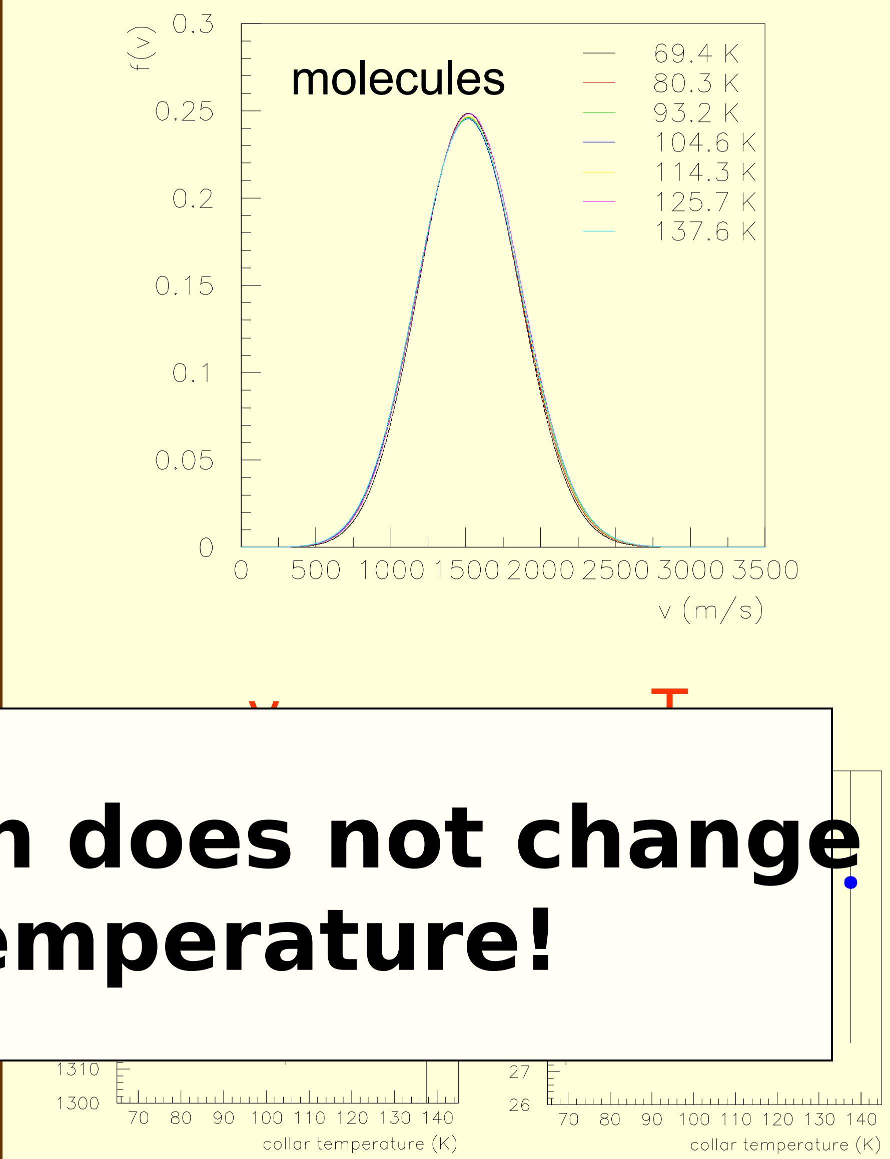


T_{beam}



SpinLab Results





Velocity Distribution does not change with collar temperature!

Theorist’s point of view

$$Q_{out} = 2\,\xcancel{\alpha}\,\xcancel{Q_{in}}\,\boxed{n_f}\,\xcancel{f_t}\,\boxed{\left(1\text{-}A_{RGA}\right)}\boxed{\left(1\text{-}A_{IBS}\right)}$$

Experimentalist’s Point of View

What is physically different?

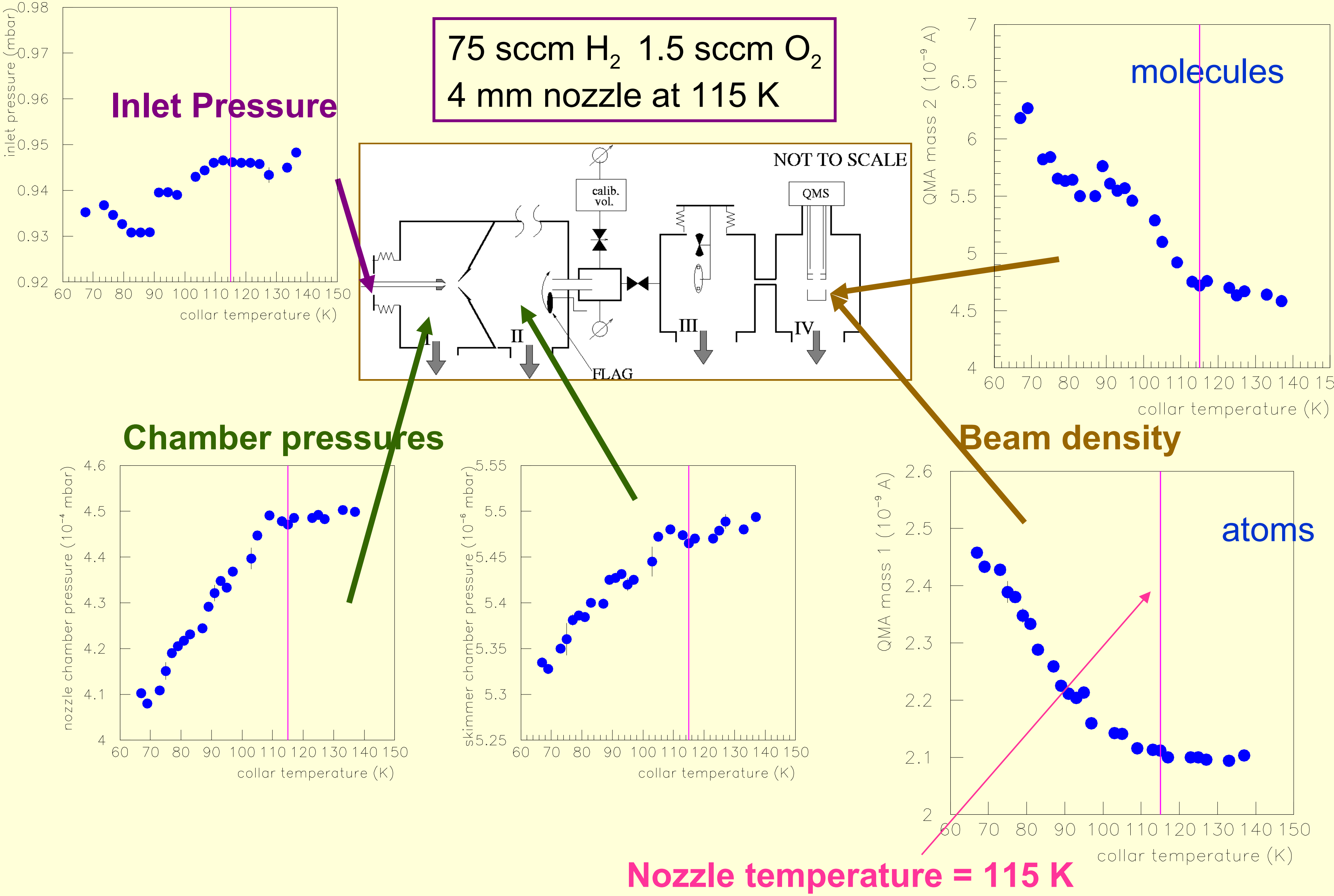
- Dissociator cooling
  - Narrows ~~velocity distribution? ⇒ reduced~~ IBS losses
  - Increases peaking factor? ⇒ more beam into magnets
- Magnet system longer and more open
  - Lower beam density for same beam flow ⇒ reduced IBS losses

Peaking Factor

- No evidence from SpinLab that lower collar temperatures produce higher peaking factors!

SpinLab Results

75 sccm H_2 1.5 sccm O_2
4 mm nozzle at 115 K



Inlet Pressure

Chamber pressures

Beam density

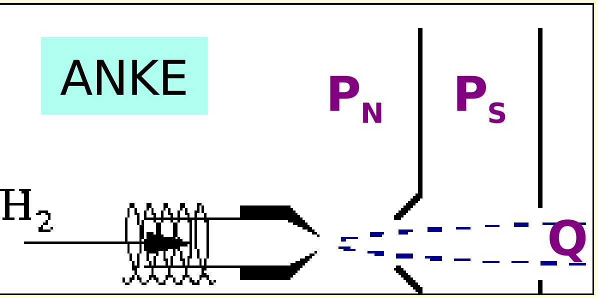
molecules

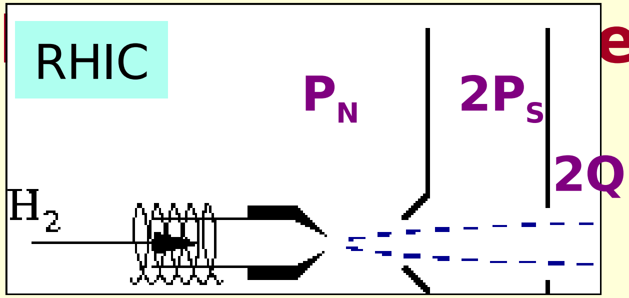
atoms

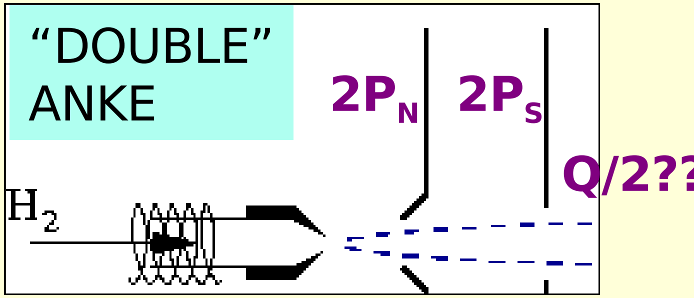
Nozzle temperature = 115 K

Peaking Factor

- No evidence from SpinLab that lower collar temperatures produce higher peaking factors!
- If RHIC gains intensity by putting 1.5 times as many atoms into the magnet system, then why is ANKE not able to get more intensity with 1.5 times the input flow? ⇒ **Only possibl e chamber is dominant.**







Theorist’s point of view

$$Q_{out} = 2\,\cancel{\alpha}\,\cancel{Q_{in}}\,\overset{?}{\eta_f}\,\cancel{ft}\,(1\text{-}A_{RGA})(1\text{-}A_{IBS})$$

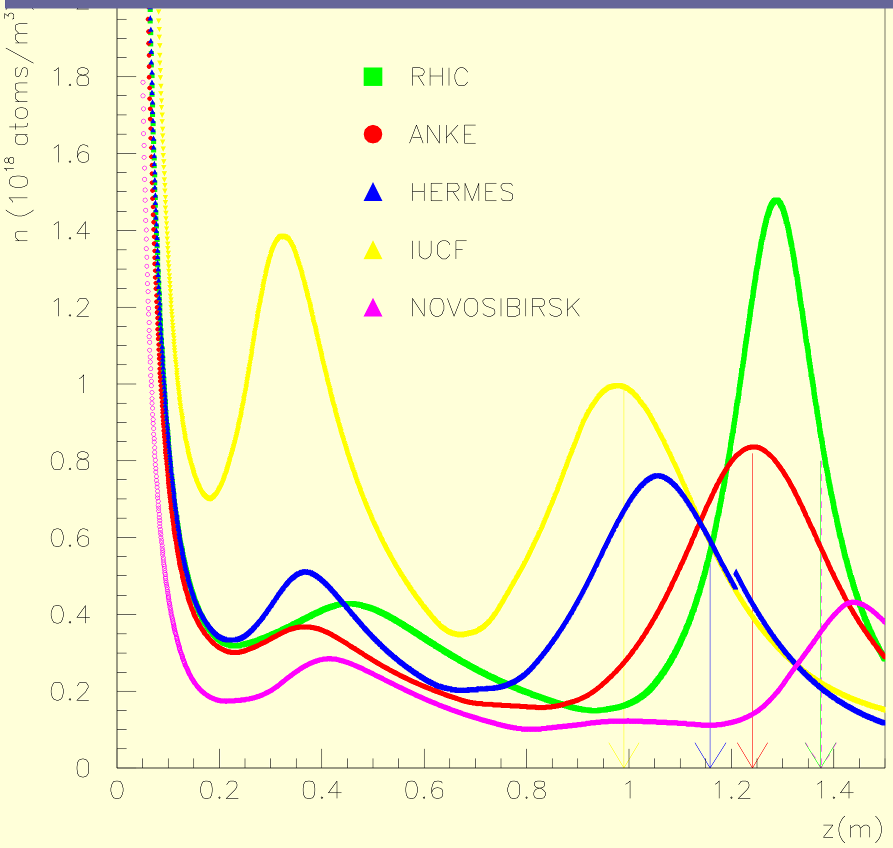
Experimentalist’s Point of View

What is physically different?

- Dissociator cooling
  - Narrows ~~velocity distribution? ⇒~~ reduced IBS ? losses
  - Increases peaking factor? ⇒ more beam into magnets
- Magnet system longer and more open
  - Lower beam density for same beam flow ⇒ reduced IBS losses

Intra-Beam Scattering

Transverse beam density, calculated with ray tracing program, assuming no attenuation losses and n_f=1



Using the calculated beam density, the losses to IBS can be estimated with the formula below (Stancari, SPIN2004)

Relative velocity (α T_{beam})

$$dn = -2\sigma \frac{g}{\bar{v}_B} n^2 dz$$

Averag e beam velocity

$$\sigma = (75 \pm 25) \times 10^{-20} m^2$$

Atomic hydrogen scattering cross section

IBS numbers

	Hermes	Nov	Wisc	ANKE	RHIC
g/v_B	0.24	0.26	0.24	0.23	0.24
A_{IBS} $n_f=1.5$, $\sigma=75\ A^2$	0.35	0.26	0.38	0.32	0.38

NOTE: It is assumed here that n_f is the same for all sources. IF n_f is larger for RHIC, then the IBS losses estimated for RHIC would INCREASE!

Theorist’s point of view

$$Q_{out}=2\cancel{\alpha}\cancel{Q_{in}}\overset{?}{\boxed{\eta_f}}\cancel{ft}\boxed{(1\text{-}A_{RGA})}\cancel{(1\text{-}A_{IBS})}$$

Experimentalist’s Point of View

What is physically different?

- Dissociator cooling
  - ~~Narrows velocity distribution? ⇒ reduced IBS~~ ?~~losses~~
  - ~~Increases peaking factor? ⇒ more beam into magnets~~
- Magnet system longer and more open
  - Lower beam density for same beam flow ⇒ reduced IBS losses

RGA losses in magnets

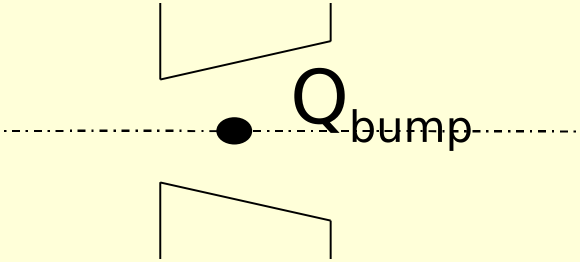
- We collect 10^{17} atoms/s and t=0.5
- $>2\text{x}10^{17}$ atoms/s enter the first magnet for each spin up and spin down
- SO, we lose $>3\text{x}10^{17}$ atoms/s in the magnet system
- If they all hit the first magnet . . .

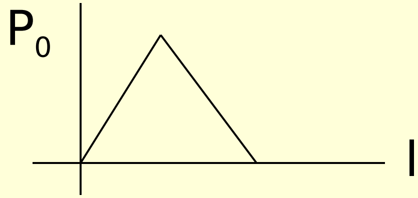
$Q_{bump} = 1.5\text{x}10^{17} * n_f/(1\text{-}A)$ mol/s = $(6\text{-}30)\text{x}10^{-3}$ mbar l/s

- $P_0 = Q_{bump}/C_{mag}$
- $S_{RGA} = \exp(-\sigma_{eff} * (0.5 * P_0 * L)/k_B T)$

$= 0.98\text{-}0.75$

RGA not negligible in first magnet!
RHIC’s magnet system is different
than other sources!





RGA numbers

	Hermes	Wisc	ANKE	RHIC
P_N (mbar)	1.0×10^{-4}	3.4×10^{-4}	$\sim10^{-4}$	2.1×10^{-4}
L_N (cm)	1.5	2.6	1.5	1.8
S_1	0.98	0.85	0.97?	0.95
P_S (mbar)	1.7×10^{-5}	6.5×10^{-5}	$\sim10^{-6}$	0.8×10^{-5}
L_S (cm)	4.0	2.7	3.0	2.2
S_2	0.99	0.97	1.0	1.0
P_3 (mbar)	1.9×10^{-6}	1.9×10^{-6}	$\sim10^{-7}$	1.8×10^{-6}
C (l/s)	9.3	13.4	13.7	18.3
L_M (cm)	3	2.5	4	2.85
P_0 (mbar)	4.5×10^{-4}	4.1×10^{-4}	3.4×10^{-4}	2.5×10^{-4}
S_3	0.88	0.91	0.88	0.94

RGA numbers

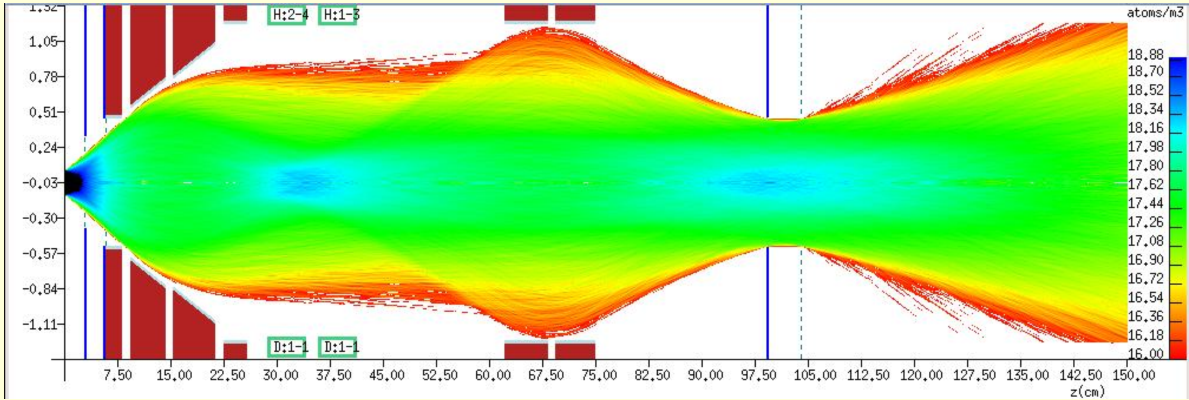
	Hermes	Wisc	ANKE	RHIC
P_3 (mbar)	$1.9x10^{-6}$	$1.9x10^{-6}$	$\sim 10^{-7}$	$1.8x10^{-6}$
Q_{bump} (mbar	$4.2x10^{-3}$	$5.5x10^{-3}$	$4.6x10^{-3}$	$4.5x10^{-3}$
Cl (l/s)	9.3	13.4	13.7	18.3
L_M (cm)	3	2.5	4	2.85
P_0 (mbar)	$4.5x10^{-4}$	$4.1x10^{-4}$	$3.4x10^{-4}$	$2.5x10^{-4}$
S_3	0.88	0.91	0.88	0.94

- Attenuation in the first magnet could be significant
- It is the first thing that separates RHIC from the other sources
- Need to include remaining magnets AND

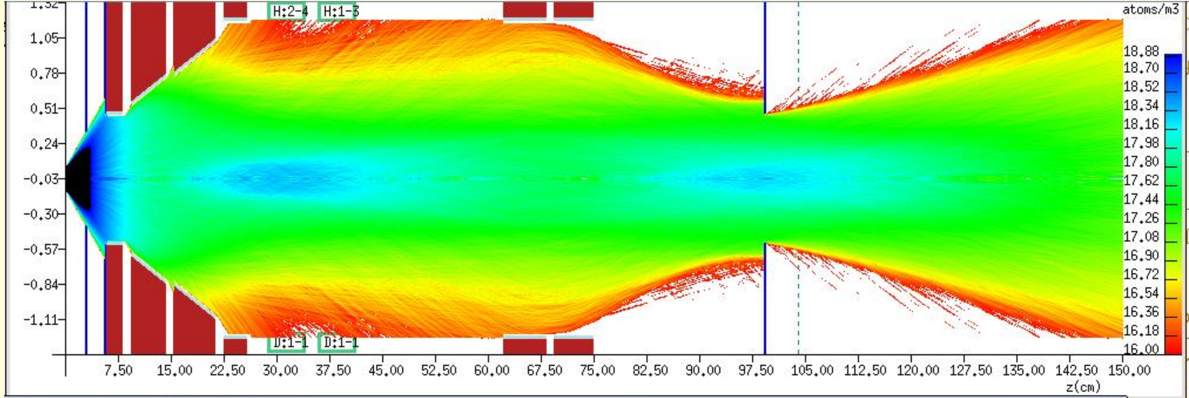
Toward a serious calculation

WISC

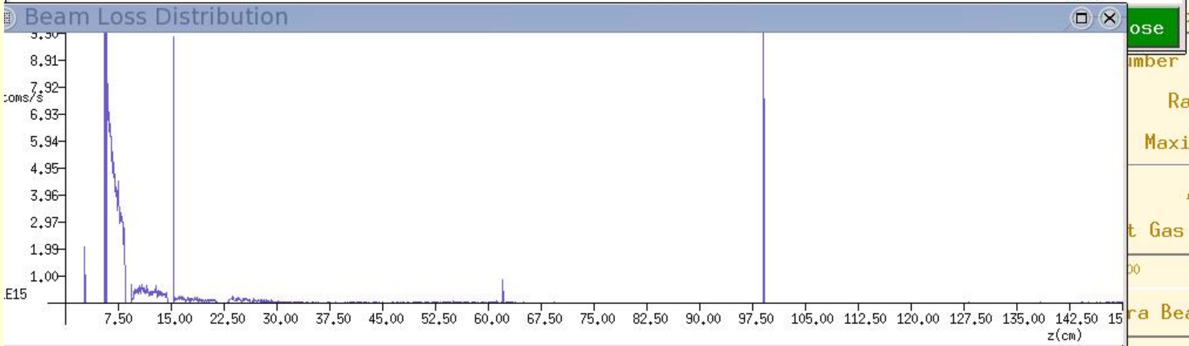
Beam envelope, only atoms which enter target are shown



Beam density profile – all beam atoms are shown



Distribution of “lost” atoms, dominantly defocused ones 10^{15} molec/s/mm



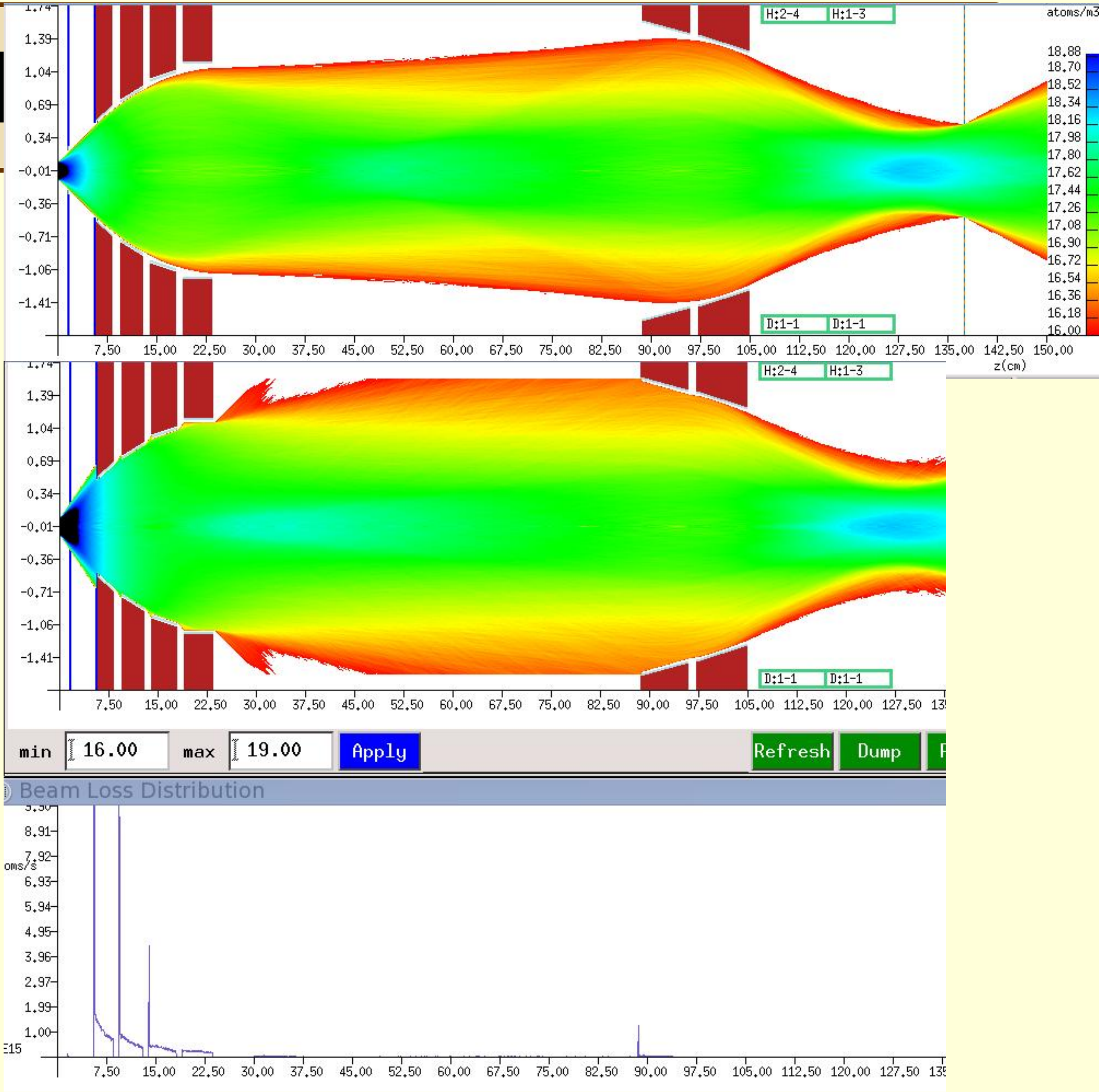
Toward

RHIC

Beam envelope, only atoms which enter target are shown

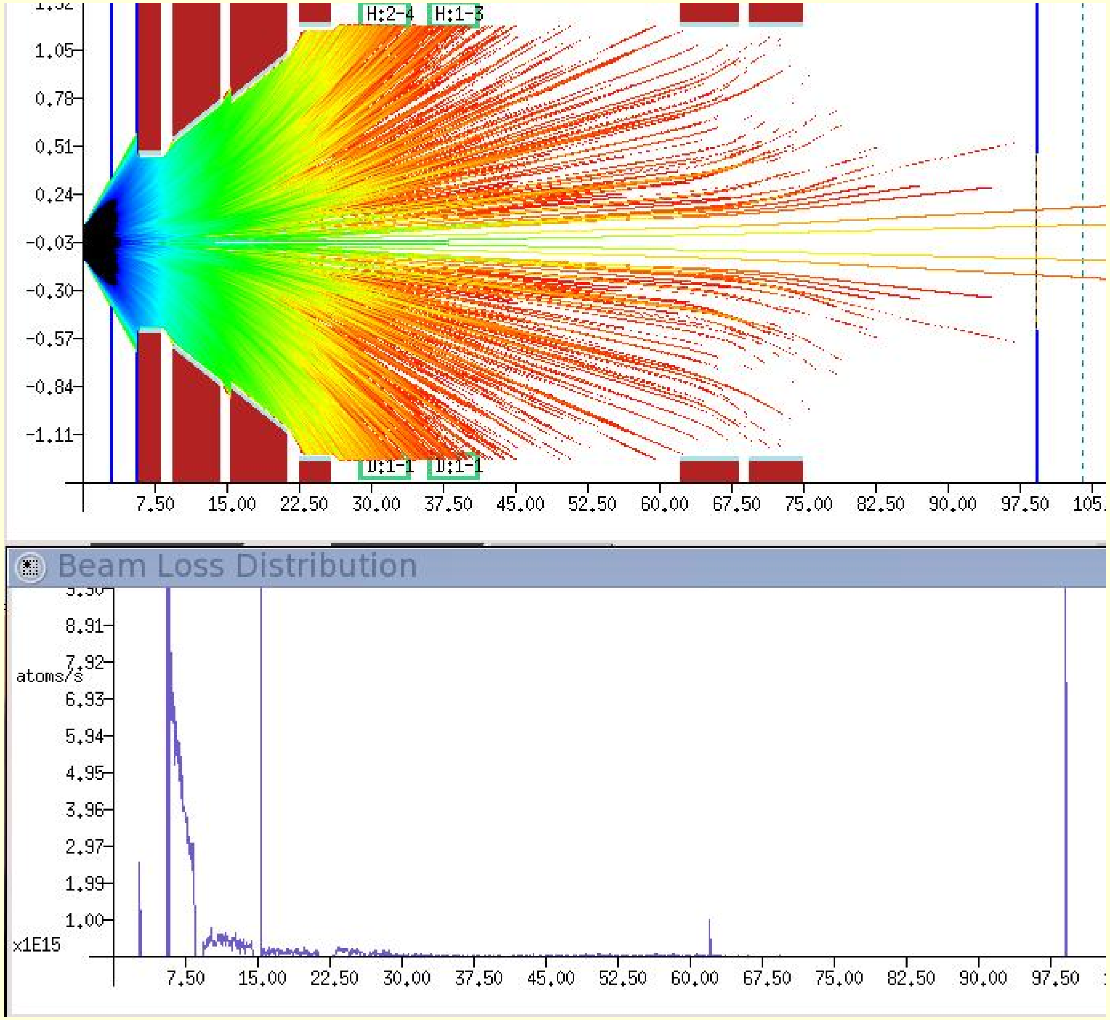
Beam density profile – all beam atoms are shown

Distribution of “lost” atoms, dominantly defocused ones 10^{15} mol/s/mm



min 16.00 max 19.00

Defocused atoms WISC



VERY preliminary

- Use distribution of lost particles
- Put total Q at the center of each magnet
- Assume pressure at either magnet end is the measured chamber pressure.
- Calculate P(l) and int (Pdl)
- Calculate S_i = survival for each magnet
- Ignore losses in drift region and pumping gaps
- $S_{tot}=\prod S_i$

UNDERESTIMATE OF LOSSES

		mag 1	mag 2	mag 3	mag 4	
	C (l/s) / L (cm)	9.25 / 3	16.7	40.3		
	Q (10^{16} at/s)	21.0	3.9	0.3		
HERMES	Int(pdl) (10^{-4} mbar cm)	13.9	1.3	0.1		
	Survival	0.94	0.99	0.99		0.92
	C (l/s)	13.5 / 2.5	18.9	37.8	107	
	Q	43.8	7.0	4.2	1.2	
WISC	Int (pdl)	4.2	1.0	0.3	0.02	
	Survival	0.93	0.98	0.99	1.0	0.90
	C (l/s)	13.7 / 4	33.9	95.6	154	
	Q	28.0	6.8	4.9	1.5	
ANKE	Int (pdl)	4.2	0.7	0.2	0.02	
	Survival	0.93	0.99	1.0	1.0	0.92
	C (l/s)	18.3 / 2.85	36.6	58.4	74.2	
	Q	10.0	8.7	5.7	4.8	
RHIC	Int (pdl)	0.8	0.4	0.2	0.2	
	Survival	0.99	0.99	1.0	1.0	0.98

$$Q_{out} = 2\,\alpha Q_{in} n_f ft(1\text{-}A)$$

	Hermes	WISC	ANKE	RHIC
Q_{in} (mbar l/s)	1.5	1.7	1.0	1.0
α	0.82	0.75	0.85	0.85
f (geometrical accept.)	0.47%	0.70%	0.85%	0.79%
t (magnet transmission)	0.48	0.39	0.42	0.49
calculated Q_{out} ($A=0;n_f=1.75\pm0.25$)	11.7±1.7	14.7±2.1	12.8±1.8	13.9±2.0
meas. Q_{out} (10^{16} atoms/s)	6.8	7.8	7.5	12.4

Attenuation must account for these differences

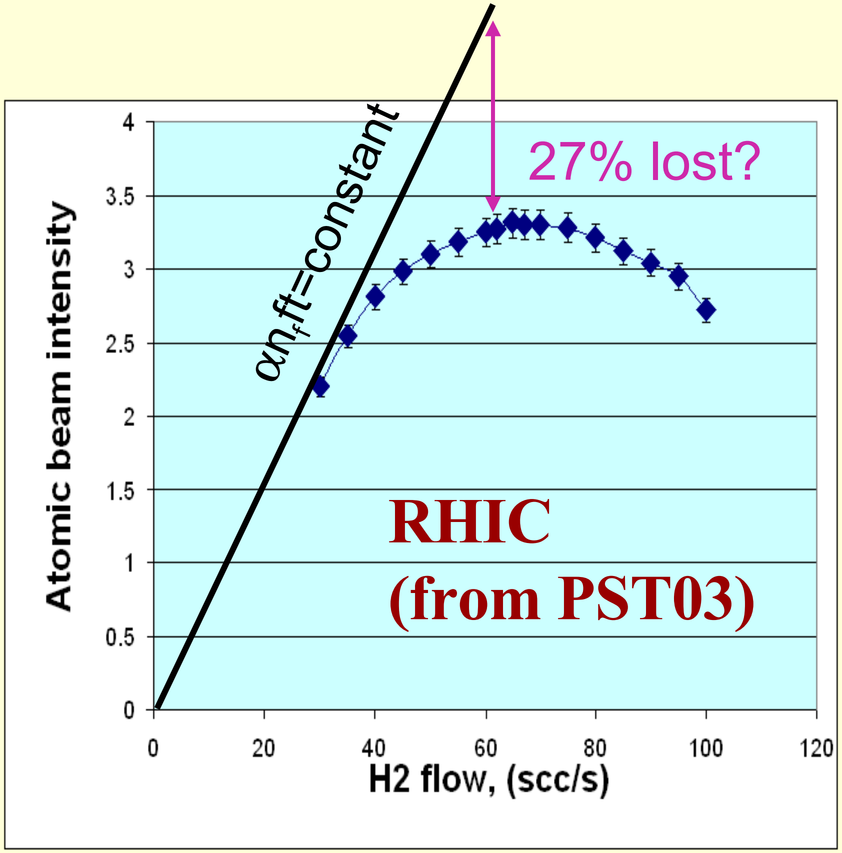
What next?

- RGA in first magnet is the only reasonable explanation of higher RHIC intensity so far.
- Let’s test it . . .

1. Wisconsin source (ABS2)
   - add a collimator to reduce the acceptance of the first magnet and compare measurements and predictions
   - measure intensity as a function of input flow
2. Ex-HERMES source
   - measure intensity as function of input flow.

   KEY – velocity distribution and alpha already known

RHIC source



When the input flow increases,

•The forward peaking of the beam does not change (Stancari, PSTP2007)

•The velocity distribution narrows

•The mean beam velocity remains constant

•Yet the fraction of beam lost increases dramatically – must be attenuation!

<u>TEST #2:</u> Predict and measure this curve for ex-HERMES ABS

Future Lab Activities

- Gauge calibration for finned tube measurements and (?) attenuation losses in Injection Tube as overall limitation on target thickness
- Complete collar temperature studies
- Optical diagnostics
- IBS measurement using transitions with ABS2
- Trumpet nozzle tests