Absolute H-jet polarimeter at RHIC.

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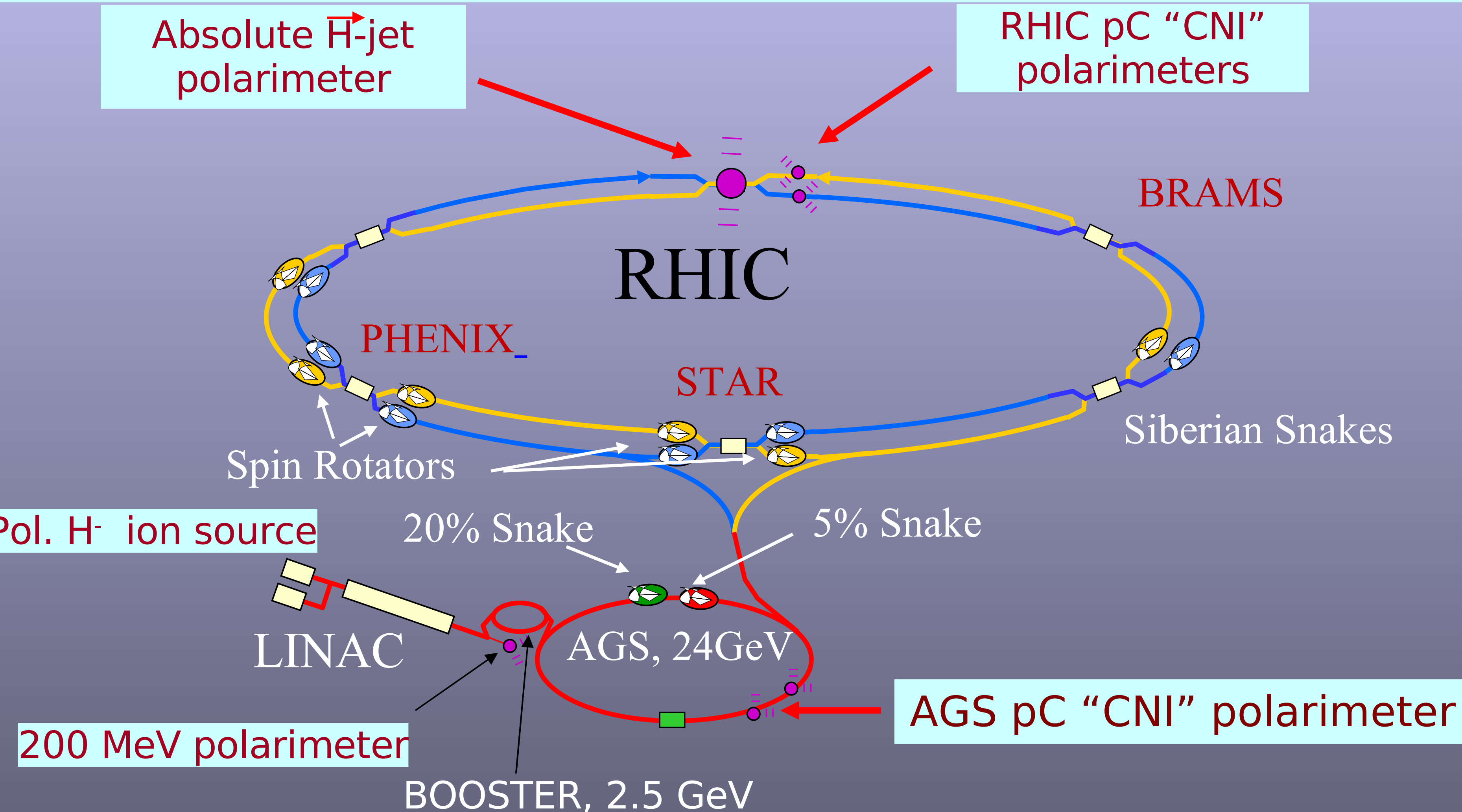
July 1, 2008, Ferrara University

Polarization facilities at RHIC.

Design goal - 70% Polarization $L_{max} = 1.6 \times 10^{32}\ s^{-1}cm^{-2}$ $50 < \sqrt{s} < 500$ GeV



A_N for Coulomb -Nuclear Interference.

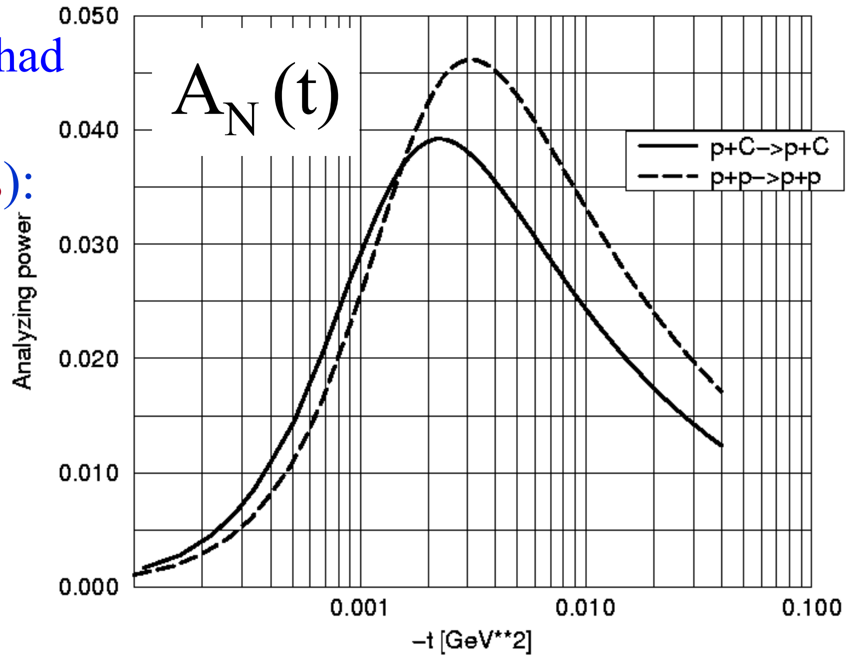
the left – right scattering asymmetry A_N arises from the interference of the spin non-flip amplitude with the spin flip amplitude (Schwinger)

$$A_N = C_1 \,\mathrm{Im}(\phi^{em}_{flip}{}^{*}\phi^{had}_{non-flip}) + C_2\,\mathrm{Im}(\phi^{had}_{flip}{}^{*}\phi^{had}_{non-flip})$$

$\propto(\mu-1)_p$ $\qquad \propto\sqrt{\sigma^{pp}}_{had}$

in absence of hadronic spin – flip contributions A_N is exactly calculable (Kopeliovich & Lapidus):

$$A_N = \sqrt{\frac{8\pi Z\alpha}{m_p^2\sigma^{pA}_{tot}}}\,\frac{y^{3/2}}{1+y^2}(\mu-1) \qquad y = \frac{\sigma^{pA}_{tot}\, t}{8\pi Z\alpha}$$

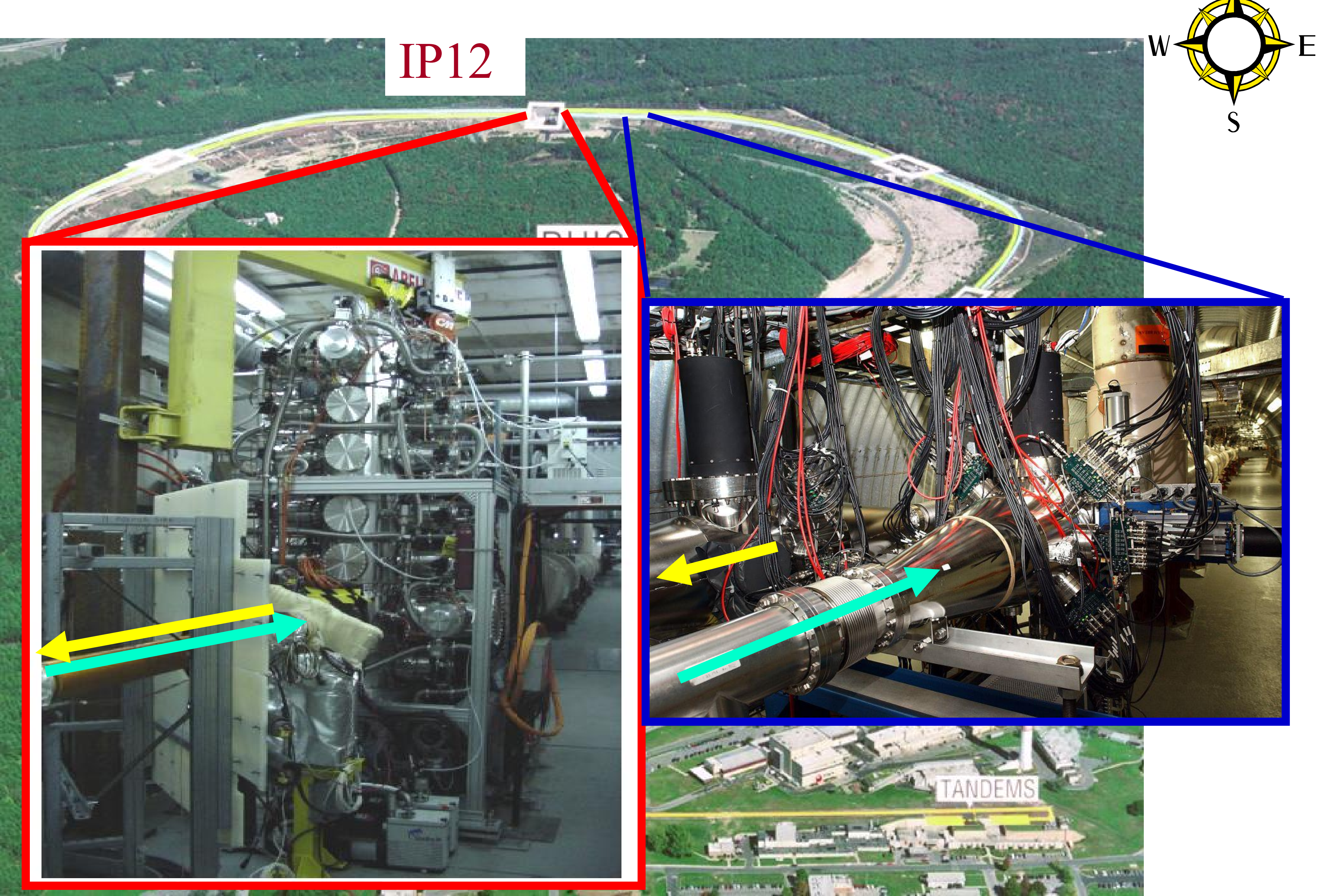


hadronic spin- flip modifies the QED "predictions"

$$\frac{\mu_p-1}{2} \rightarrow \frac{\mu_p-1}{2} - I_5 + \left(\frac{\mu_p-1}{2} I_2\right)$$

interpreted in terms of Pomeron spin – flip and parametrized as $\phi_5^{had} = \tau(s)\dfrac{\sqrt{-t}}{m_p}\phi_0^{had}$

AGS and RHIC polarimeter complex

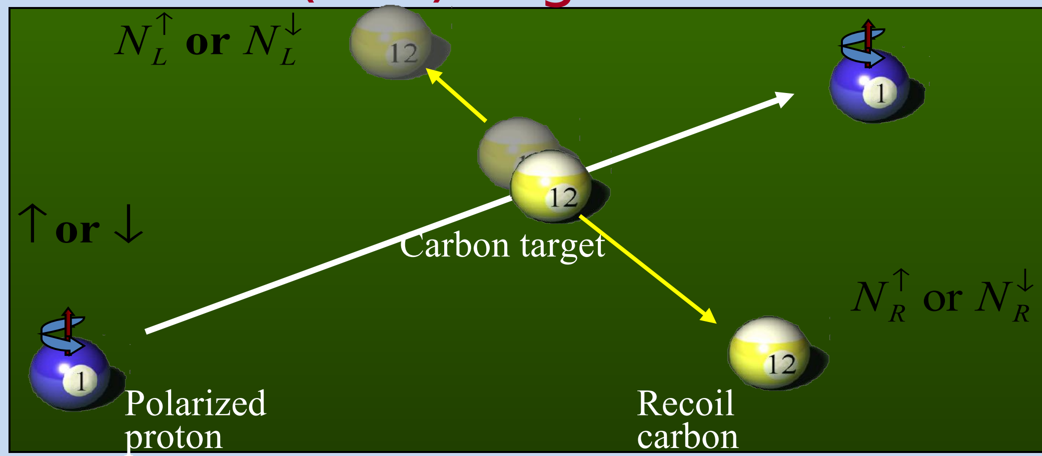


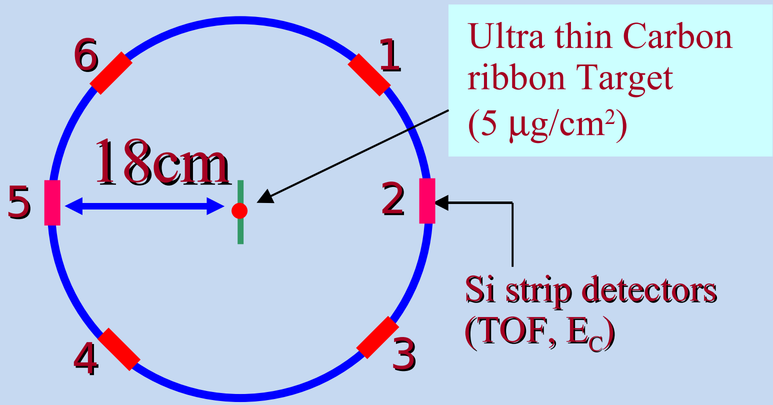
P-Carbon CNI polarimeter.

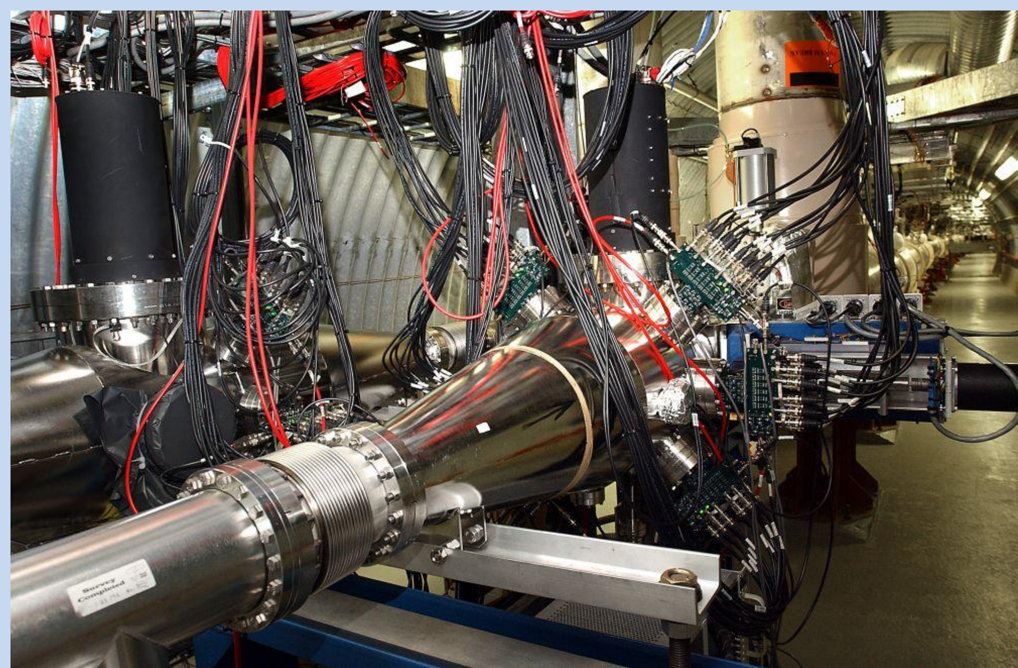
Elastic scattering: interference between electromagnetic and hadronic amplitudes in the Coulumb-Nuclear Interference (CNI) region

$$P_{beam} = -\frac{\varepsilon_N}{A_N^{pC}}$$

$$\varepsilon_N = \frac{N_L - N_R}{N_L + N_R}$$



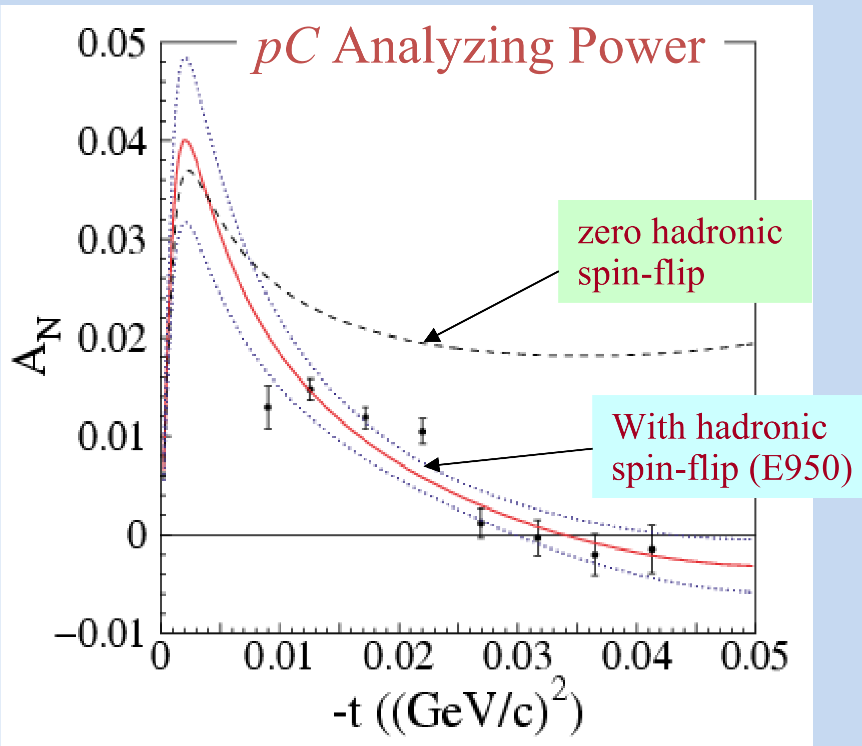




P-Carbon analyzing power: A_N

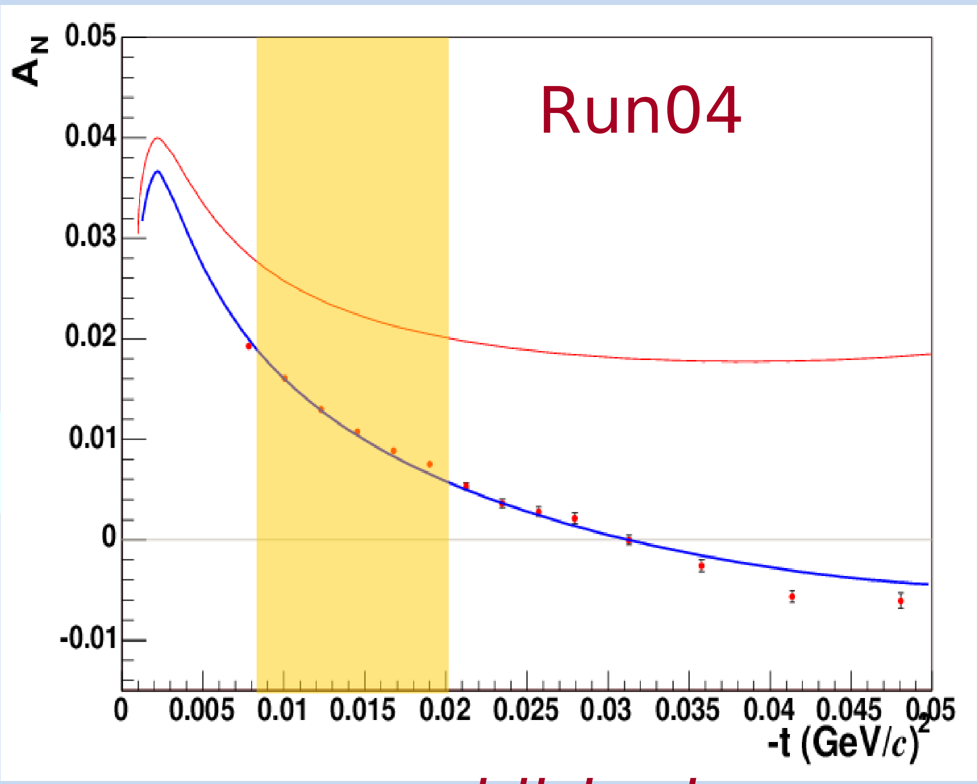
Elastic scattering: interference between electromagnetic and hadronic amplitudes in the Coulumb-Nuclear Interference (CNI) region.

$$A_N \approx C_1 \phi_{flip}^{em}{}^{*} \phi_{non-flip}^{had} + C_2 \phi_{non-flip}^{em}{}^{*} \phi_{flip}^{had}$$



Phys.Rev.Lett.,89,052302(2002)

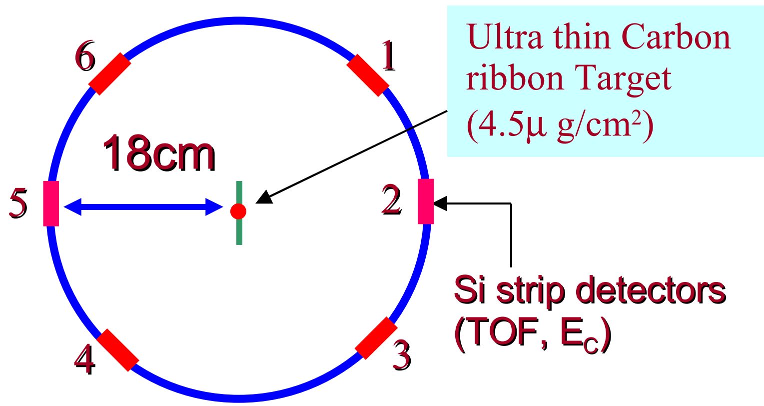
E_{beam} = 21.7GeV

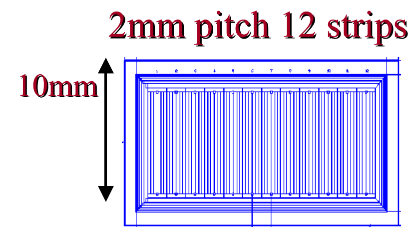


unpublished

E_{beam} = 100 GeV

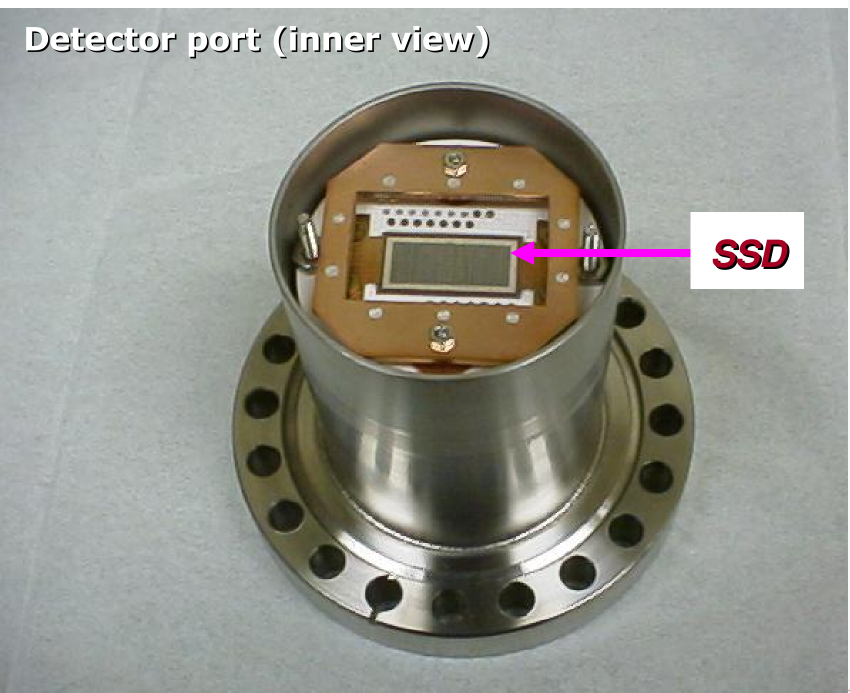
Detector Setup

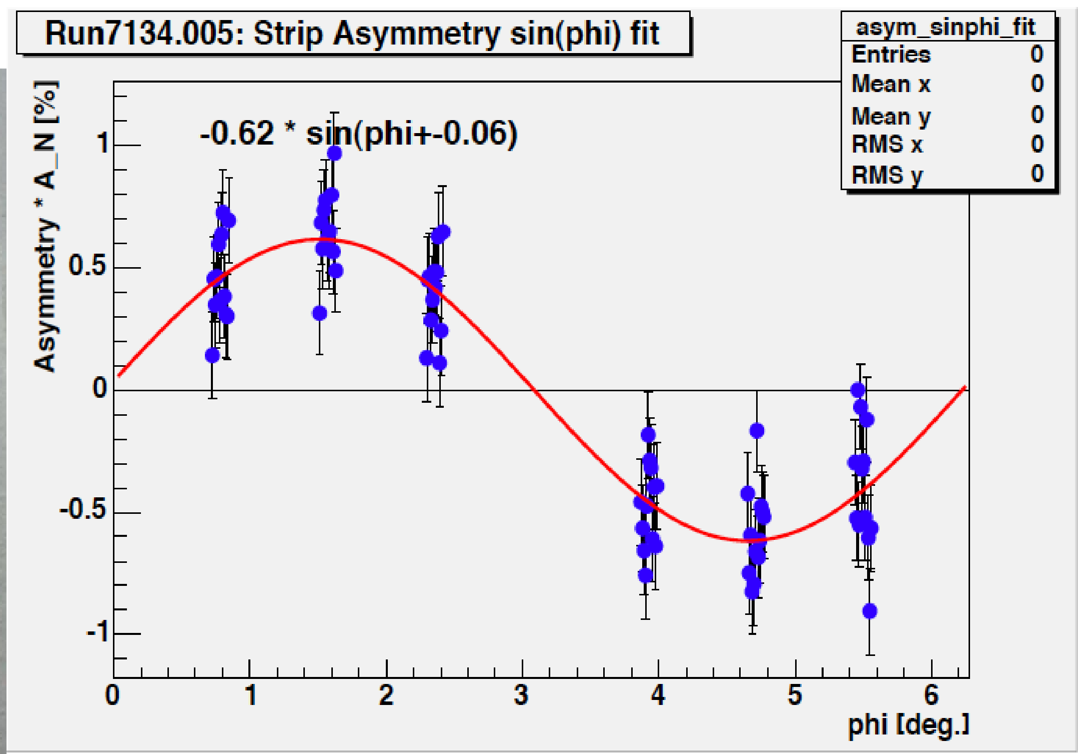




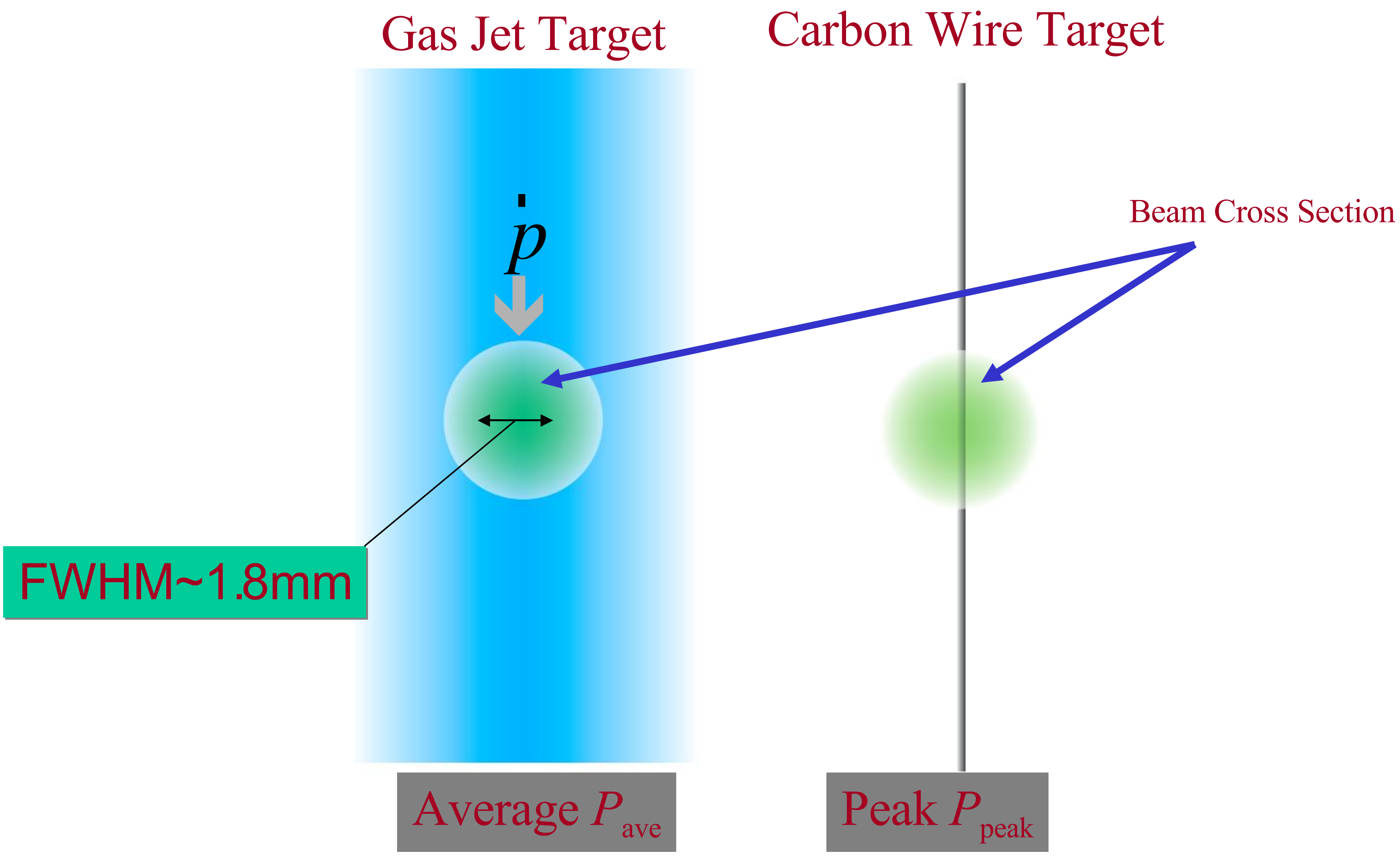
72 strips in total

Redundancy
↓
Systematic/Consistency Check





Hydrogen Gas Jet and Carbon Wire Targets



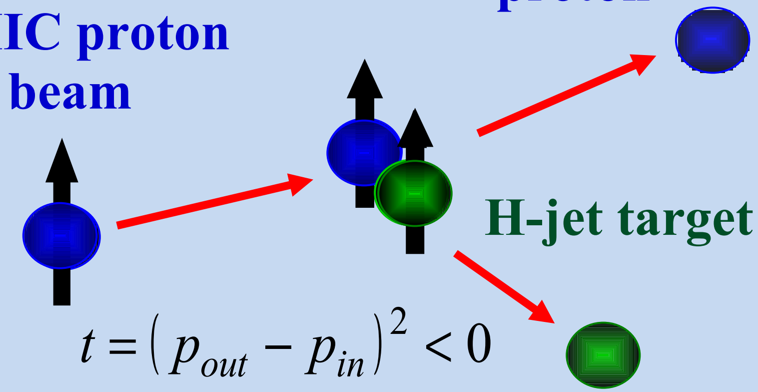
H-Jet polarimeter

Elastic scattering: Interference between electromagnetic and hadronic amplitudes in the Coulumb-Nuclear Interference (CNI) region

$$A_N \approx \mathrm{Im}\left(\phi_{SF}^{em}\phi_{NF}^{had} + \phi_{SF}^{had*}\phi_{NF}^{em}\right) \Big/ \left|\phi_{NF}^{had}\right|^2$$

Beam and target are both protons

$$A_N(t) = -\frac{\varepsilon_{\text{target}}}{P_{\text{target}}} = \frac{\varepsilon_{beam}}{P_{beam}}$$



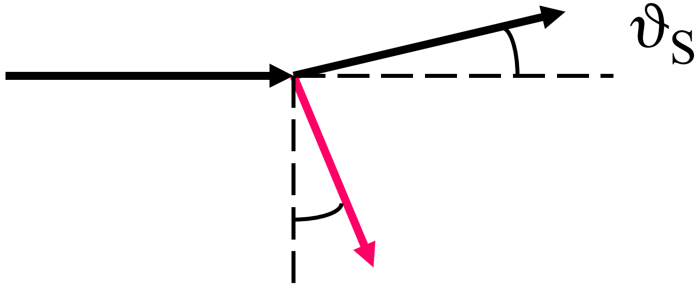
$$t = \left(p_{out} - p_{in}\right)^2 < 0$$

$$\mathrm{P}_{\text{beam}} = -\mathrm{P}_{\text{target}} \frac{\varepsilon_{\text{beam}}}{\varepsilon_{\text{target}}}$$

$$\frac{\Delta \mathrm{P}_{\text{beam}}}{\mathrm{P}_{\text{beam}}} \approx \frac{\Delta \mathrm{P}_{\text{target}}}{\mathrm{P}_{\text{target}}} \oplus \frac{\Delta \varepsilon_{\text{target}}}{\varepsilon_{\text{target}}} \oplus \frac{\Delta \varepsilon_{\text{beam}}}{\varepsilon_{\text{beam}}}$$ <5%

P_{target} is measured by Breit- Rabi Polarimeter

Kinematics.



ϑ_R; E_R; tof

$|t|$: 0.001 – 0.02 GeV^2

ϑ_R : 1 – 5 degrees

T_{kin} : 0.5 – 10 MeV

p_R : 30 – 140 MeV/c

tof : 100 – 20 nsec (@ 1m)

essentially 1 free parameter: *t* (+ φ) ⇒

elastic *pp* kinematics fully constrained by recoil proton only !

$$\sin\vartheta_R \approx \left(1+\frac{m_p}{p_{beam}}\right)\frac{\sqrt{|t|}}{2m_p}$$

$$t = -2m_p T_{kin}$$

ϑ_R & t

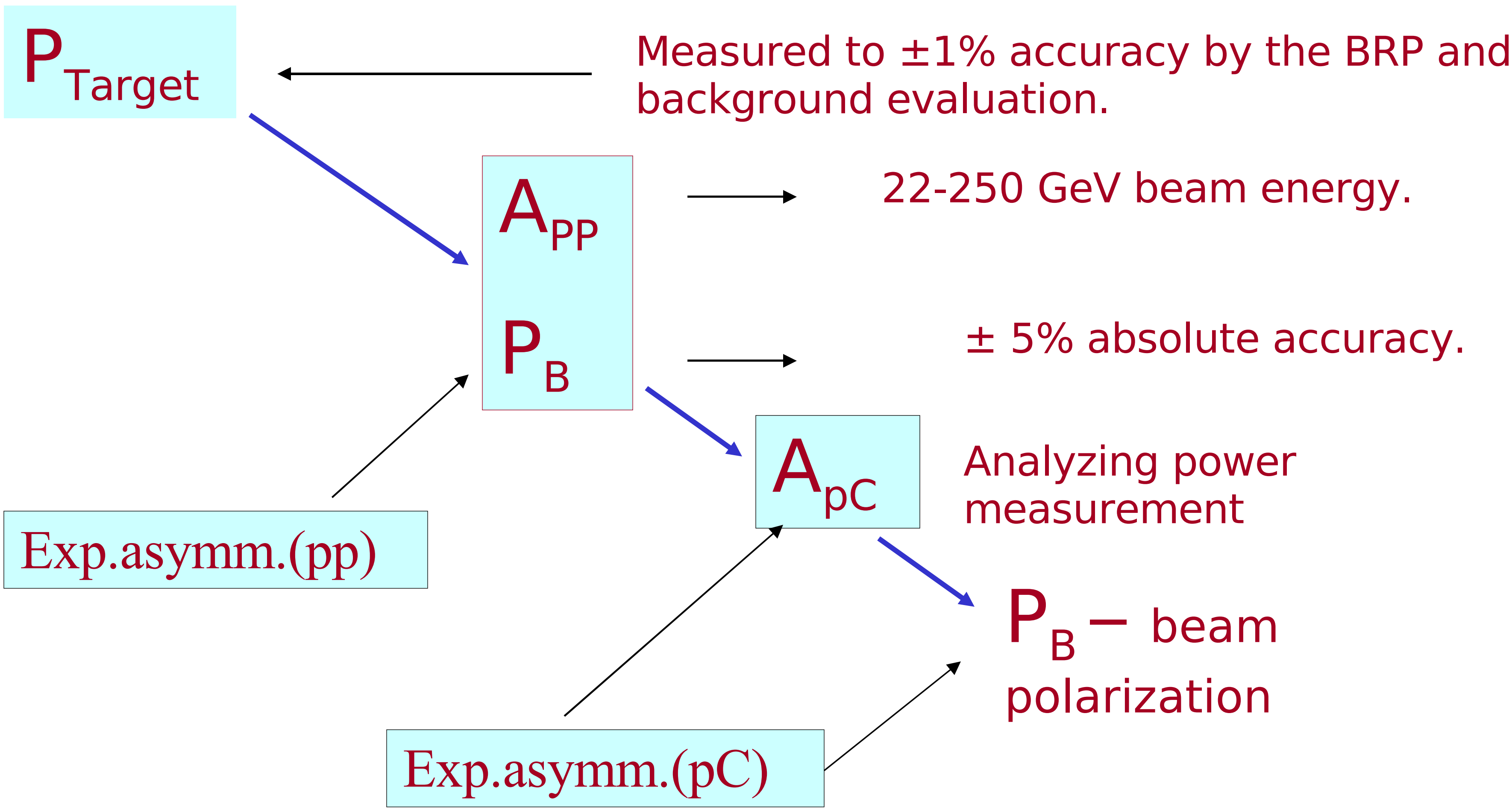
measure position and energy of recoil ⇒

$$tof \approx 1/\sqrt{2T_{kin}/m_p}\cdot D$$

⇒ additional kinematical constraint

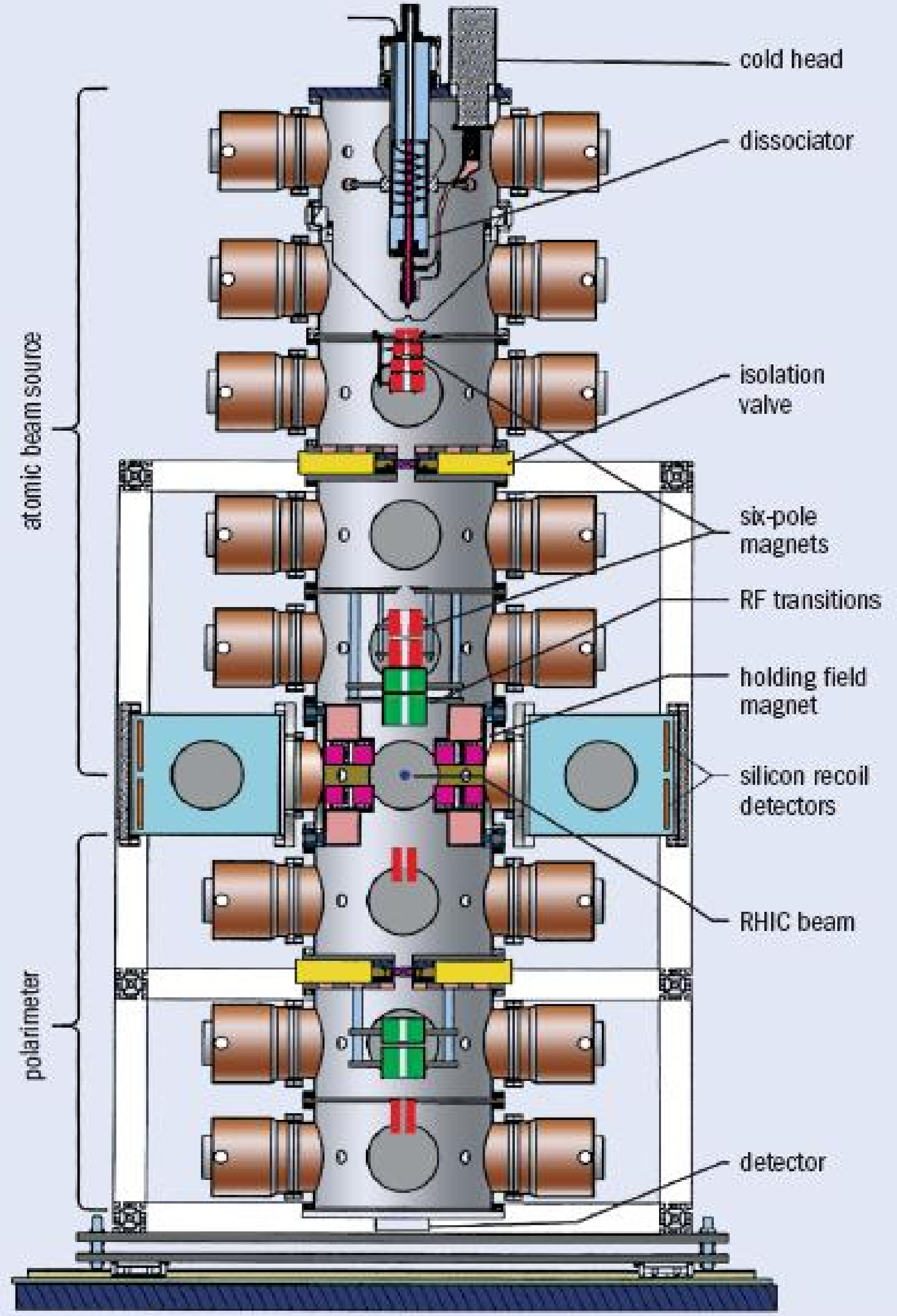
ϑ_R & E_R ⇒ m_{beam} (M_X); tof & E_R ⇒ m_{target}

Polarization measurements in RHIC with the H-jet polarimeter.

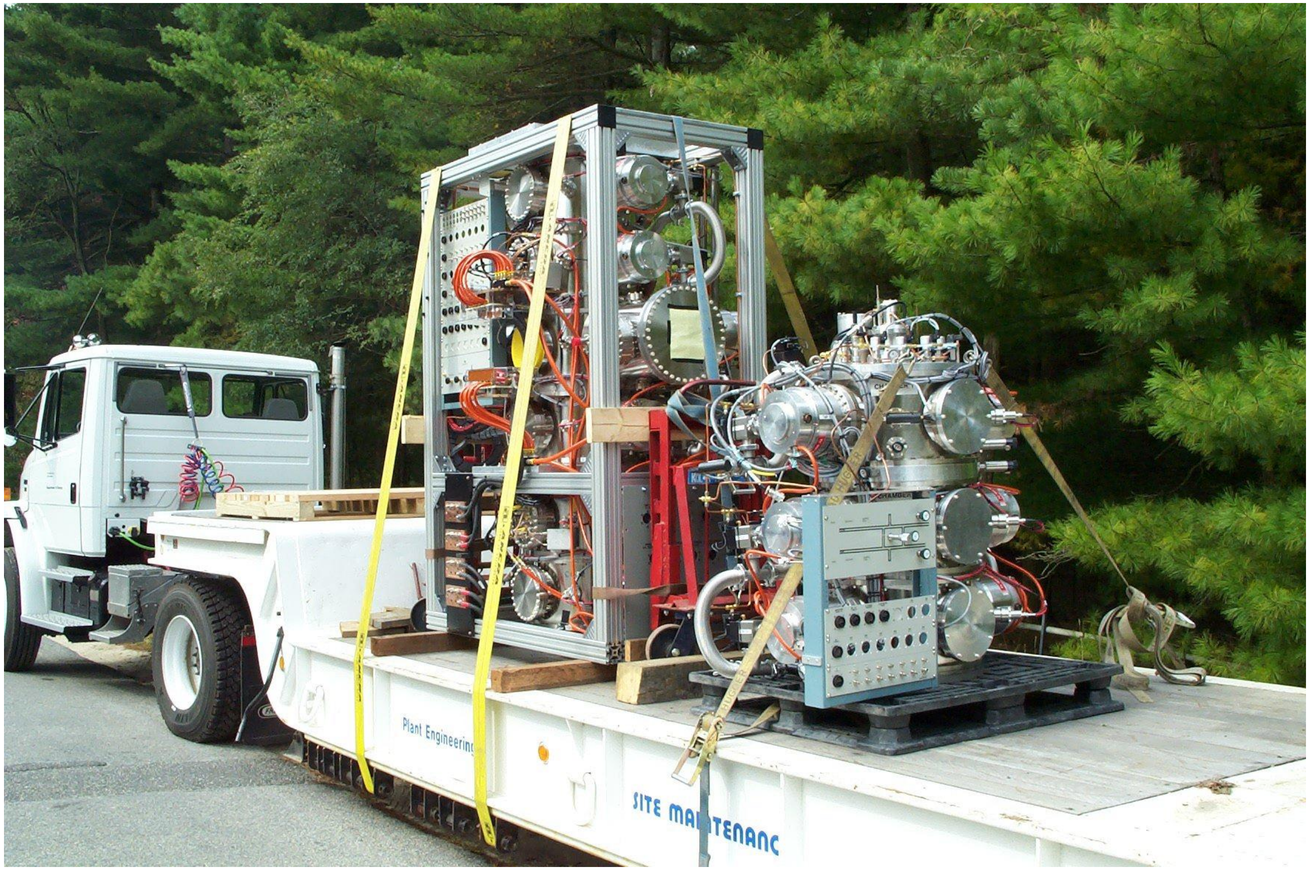


H-jet polarimeter.

- The H-jet polarimeter includes three major parts: polarized Atomic Beam source (ABS), scattering chamber, and Breit-Rabi polarimeter.
- The polarimeter axis is vertical and the recoil protons are detected in the horizontal plane.
- The common vacuum system is assembled from nine identical vacuum chambers, which provide nine stages of differential pumping.
- The system building bloc k is a cylindrical vacuum chamber 50 cm in diameter and of 32 cm length with the four 20 cm (8.0”) ID pumping ports.



H-jet polarimeter can be moved and installed into the RHIC ring in one day.



The power supply and control system is assembled in seven joint racks on the wheels.

The absolute proton polarimeter.

Polarized Hydrogen G as Jet Target

thickness of $> 10^{12}$ p/cm^2

polarization > 93-94% !

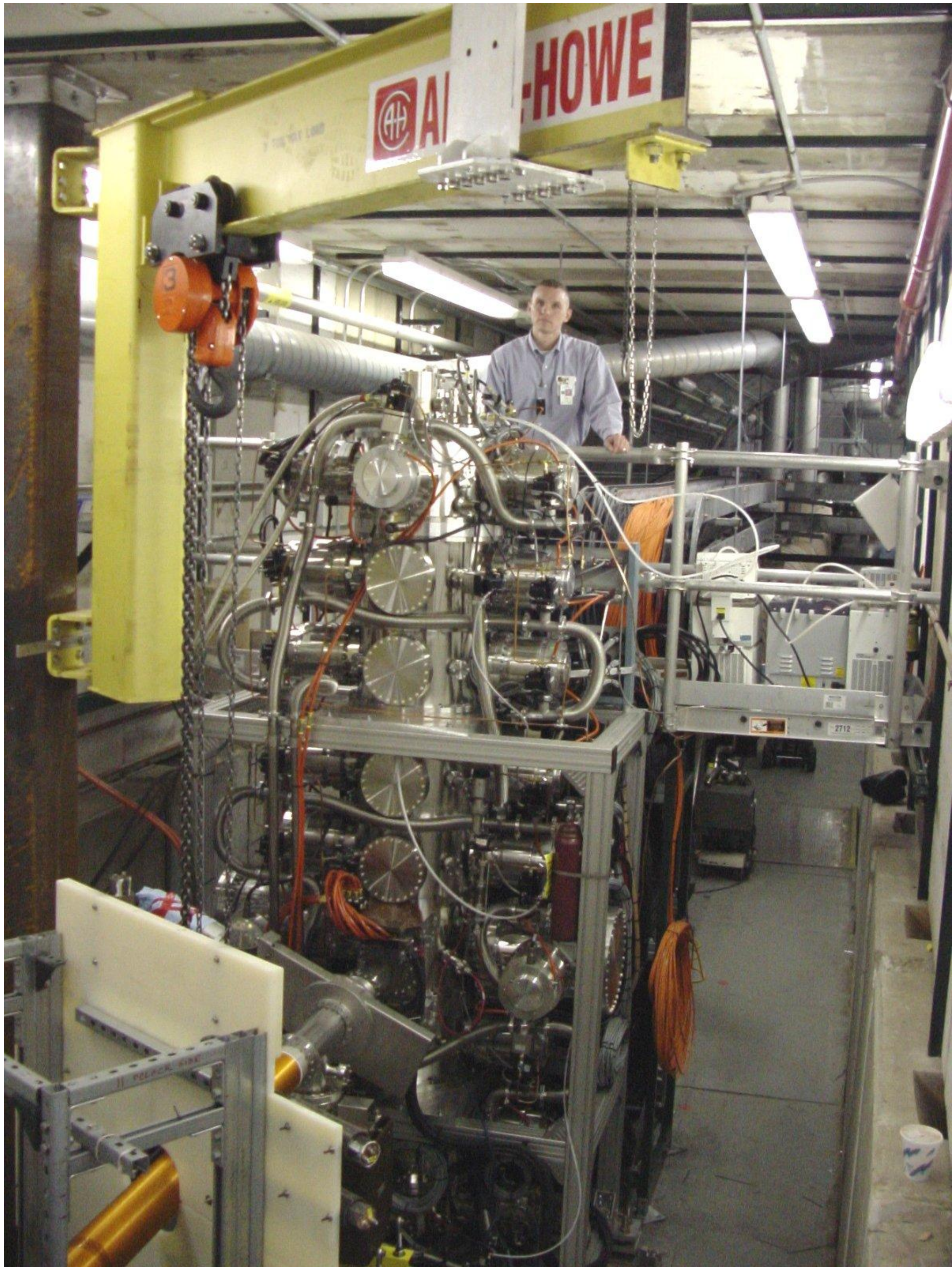
S ilicon recoil spectrometer:

Measure A_N^{pp} in pp elastic scattering

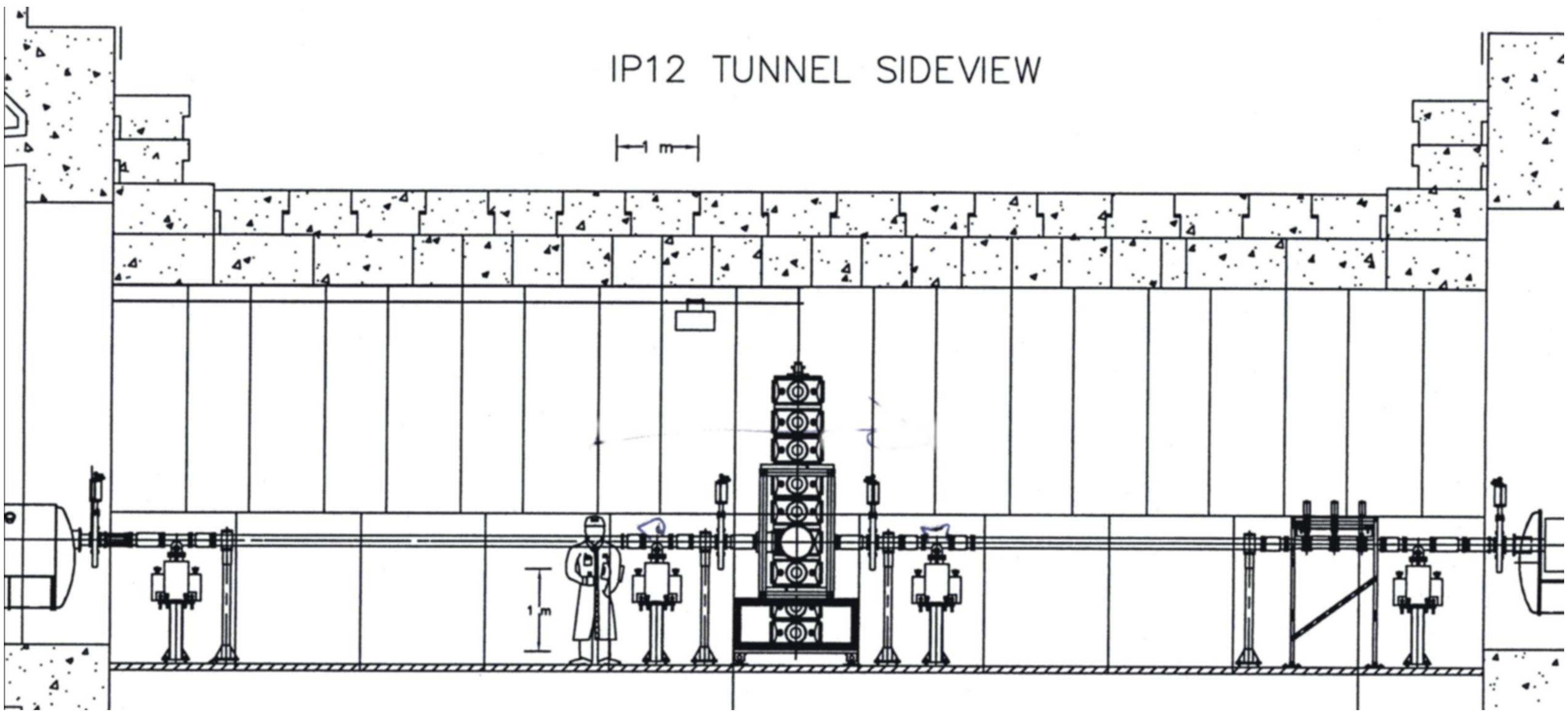
in the CNI region to $\Delta A_N < 10^{-3}$ accuracy.

Initially (2004) measure P_B to 10 %.

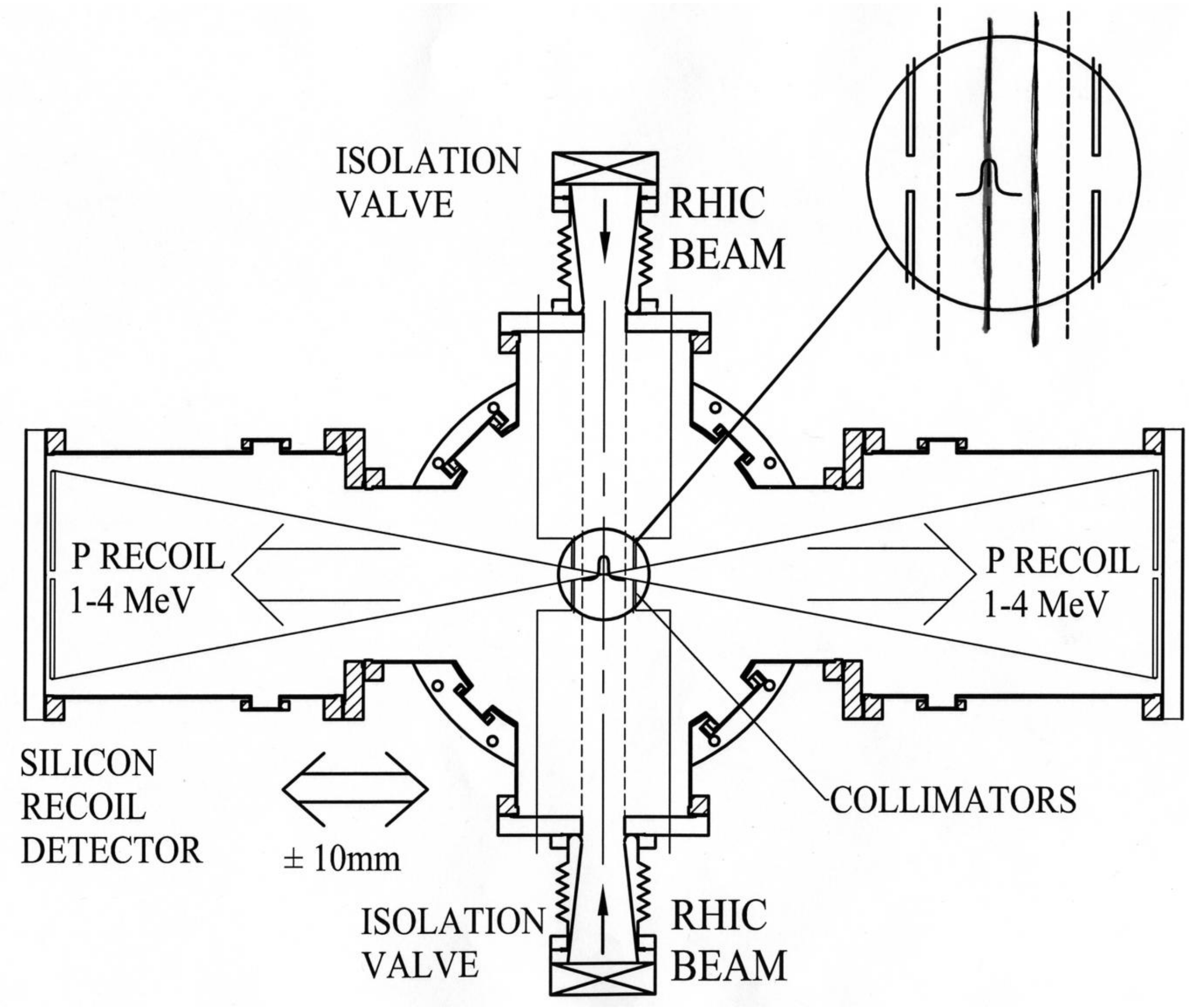
H-Jet at the IP-12



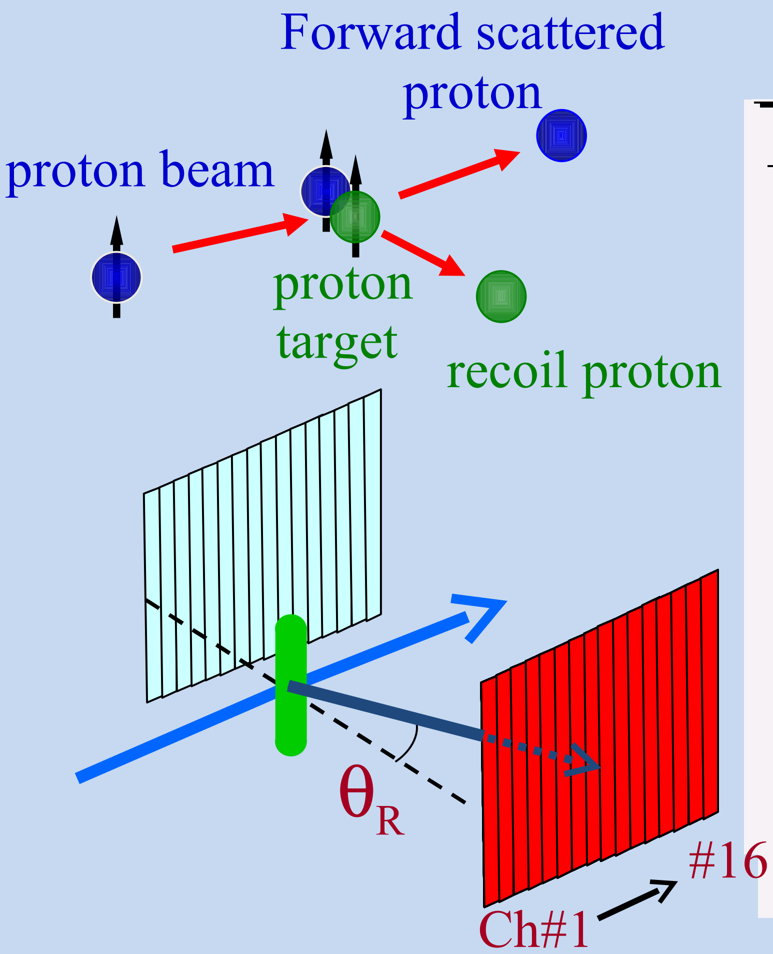
H-jet layout at the IP-12.



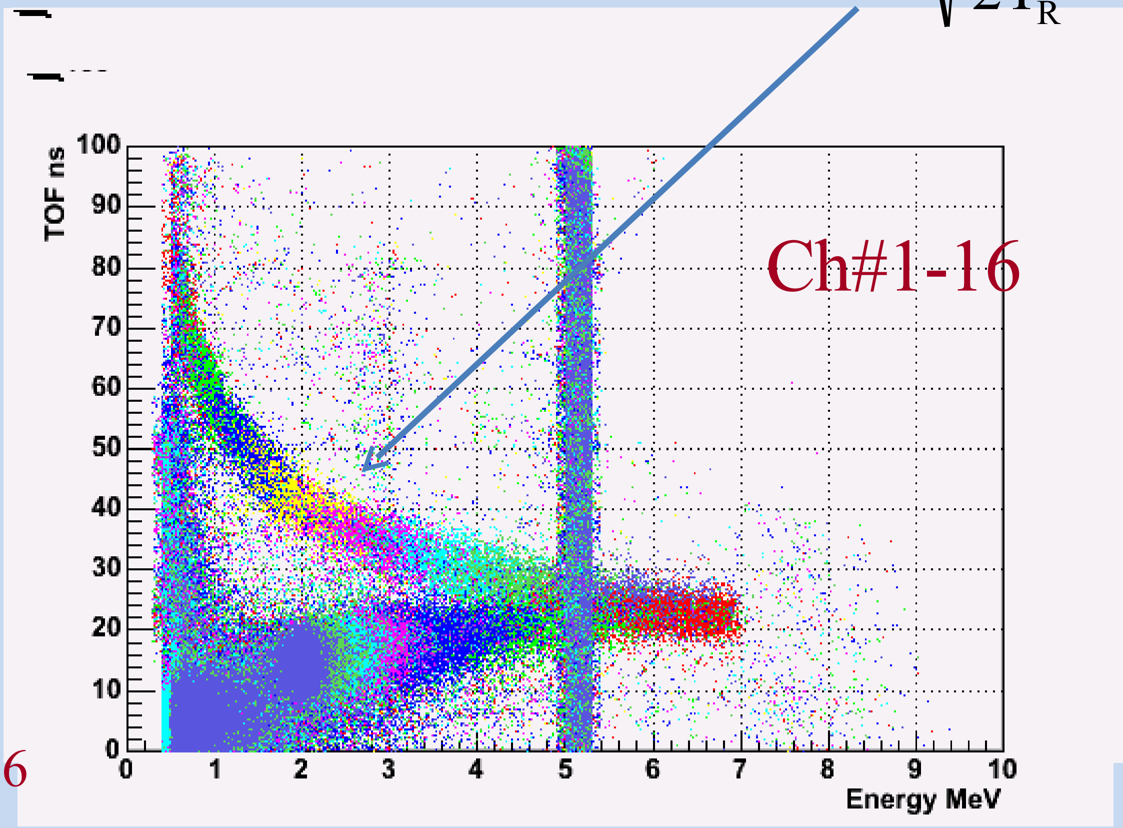
H-JET POLARIMETER SCATTERING CHAMBER.



H-Jet: Identification of Elastic Events



$$ToF_{cal.} \approx L\sqrt{\frac{m_p}{2T_R}}$$

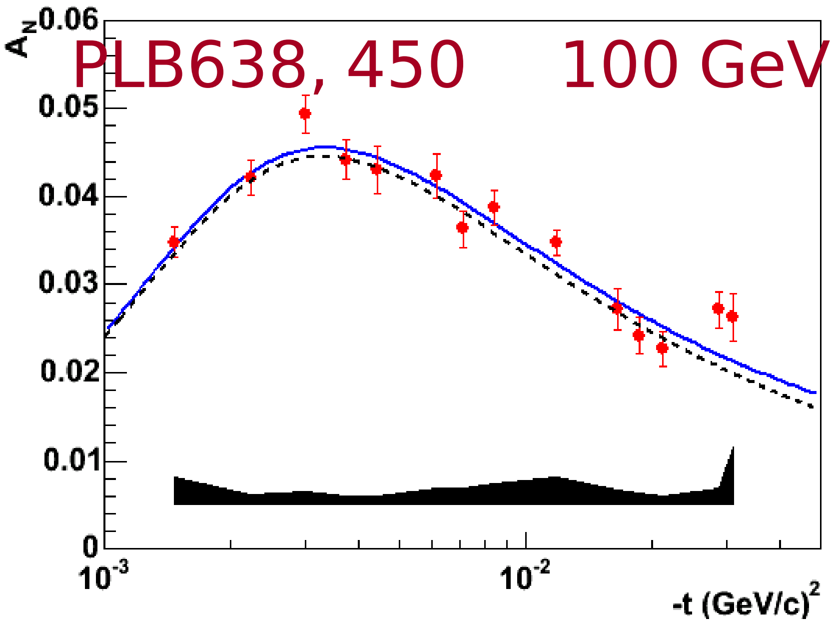


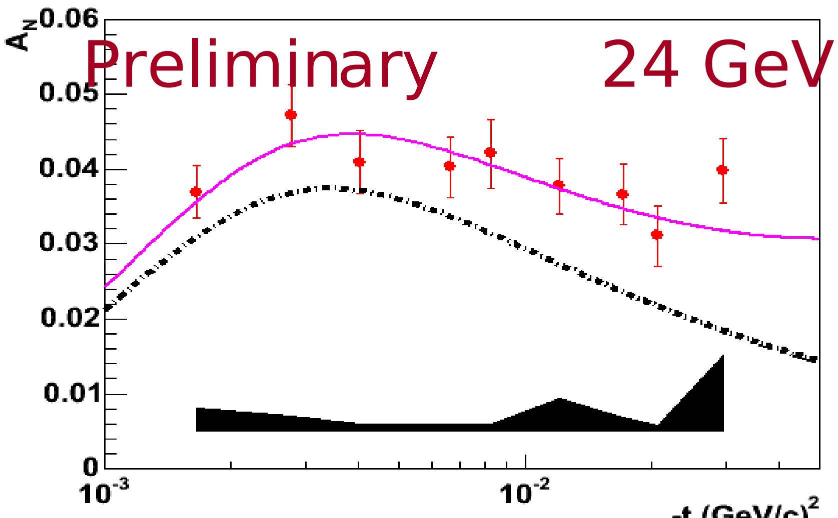
Array of Si detectors measures **T_R** & **ToF** of recoil proton.

Channel # corresponds to recoil angle **θ_R**.

Correlations (T_R & ToF) and (T_R & θ_R) → the elastic process

H-Jet polarimeter: A_N in pp





$$A_N \approx \mathrm{Im}\left(\phi_{SF}^{em}\phi_{NF}^{had} + \phi_{SF}^{had*}\phi_{NF}^{em}\right) \Big/ \left|\phi_{NF}^{had}\right|^2$$

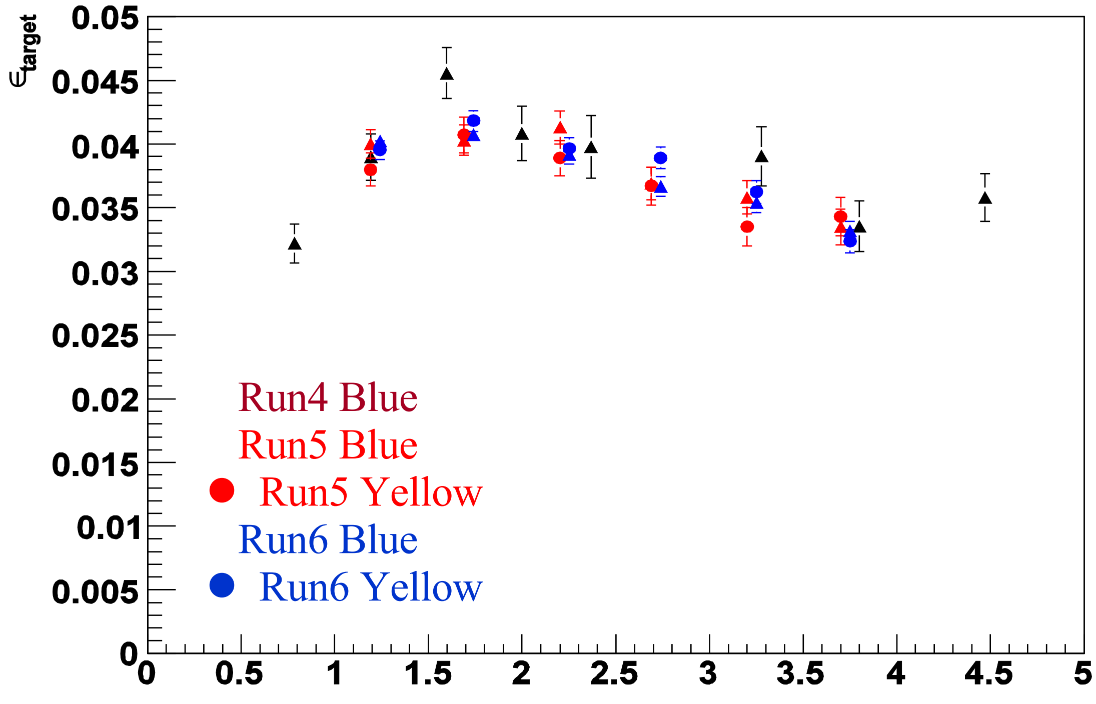
100 GeV: calculations with no hadronic spin flip amplitude contribution are consistent with data

24 GeV: calculations with no hadronic spin flip amplitude contribution are not consistent with data

More data to come:
24 GeV: take more data in Run9/10
31 GeV: finalize analysis of data from Run
250 GeV: take data in Run9/10

$$A_N^{pp} = \frac{\varepsilon_{\text{target}}}{P_{\text{target}}}$$

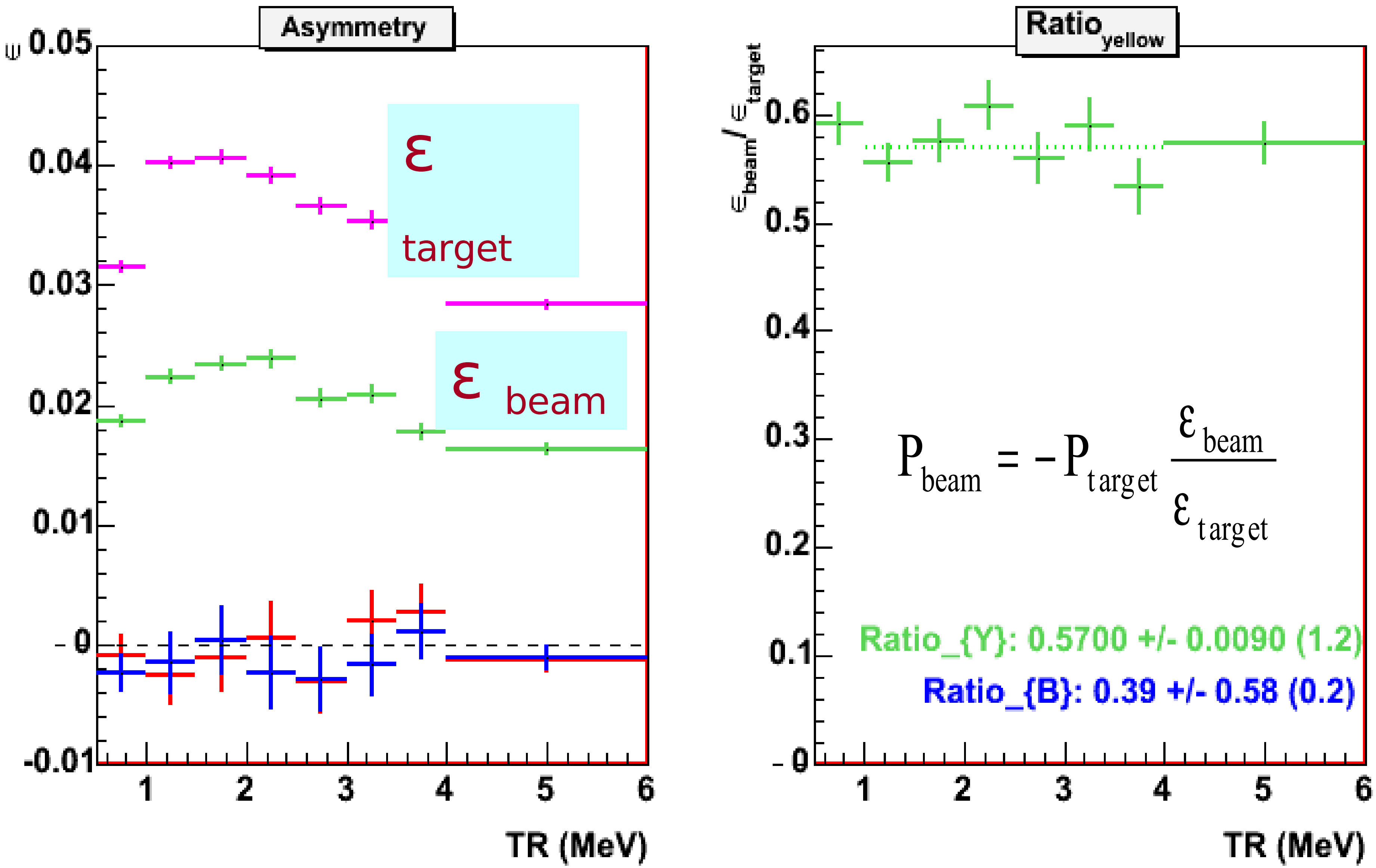
H-Jet polarimeter operation.



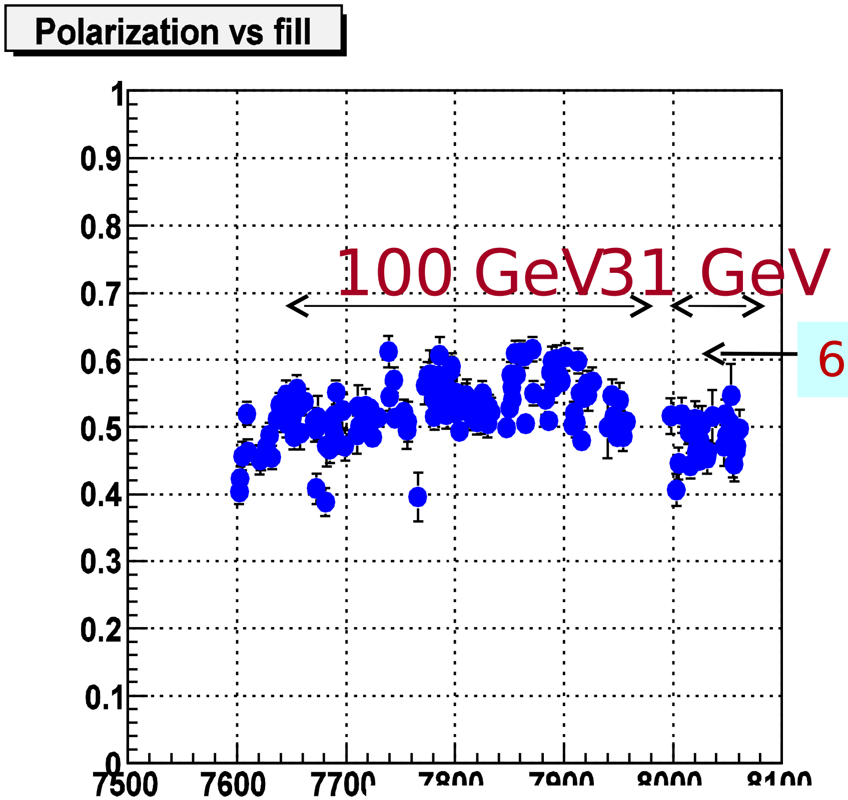
Target asymmetry vs T_R

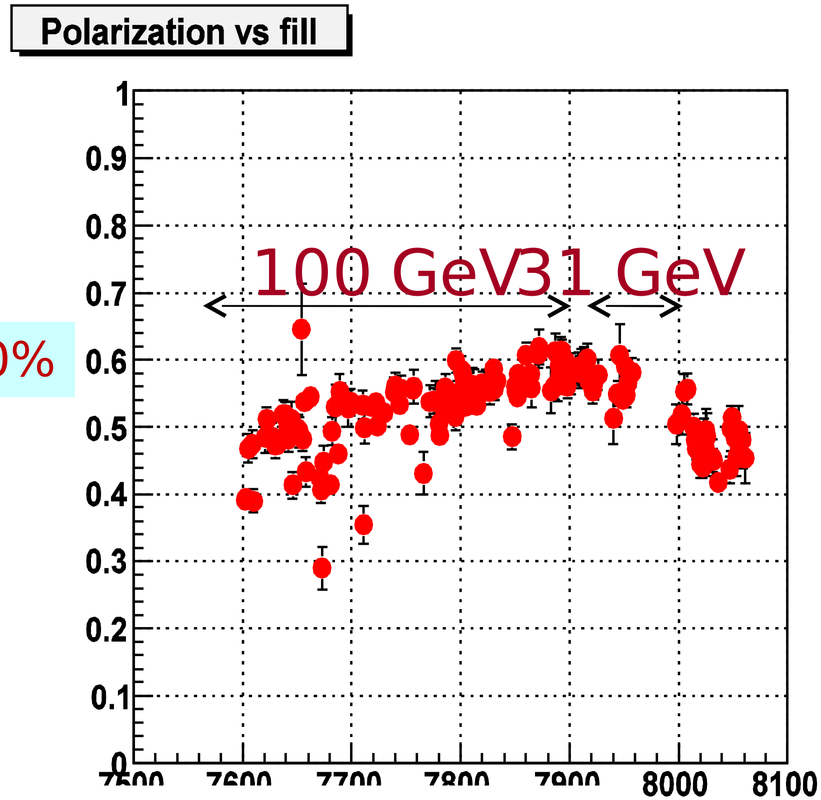
HJet performance is very stable through the Years.
Background is small and doesn't change from Year to Year, for Blue and Yellow

⇒ Beam polarization is measured reliably by H-Jet


Asymmetry
ε
0.05
0.04
0.03
0.02
0.01
0
-0.01
ε target
ε beam
1
2
3
4
5
6
TR (MeV)
Ratio_yellow
ε_beam/ε_target
0.6
0.5
0.4
0.3
0.2
0.1
0
$P_{beam} = -P_{target} \frac{\varepsilon_{beam}}{\varepsilon_{target}}$
Ratio_{Y}: 0.5700 +/- 0.0090 (1.2)
Ratio_{B}: 0.39 +/- 0.58 (0.2)
TR (MeV)

pC: Polarization vs Fill #. Run 2006





✓Normalized to Hjet

✓Corrected for polarization profile

$$\frac{\delta P_B}{P_B} = 4.7\% \qquad \frac{\delta P_Y}{P_Y} = 4.8\%$$

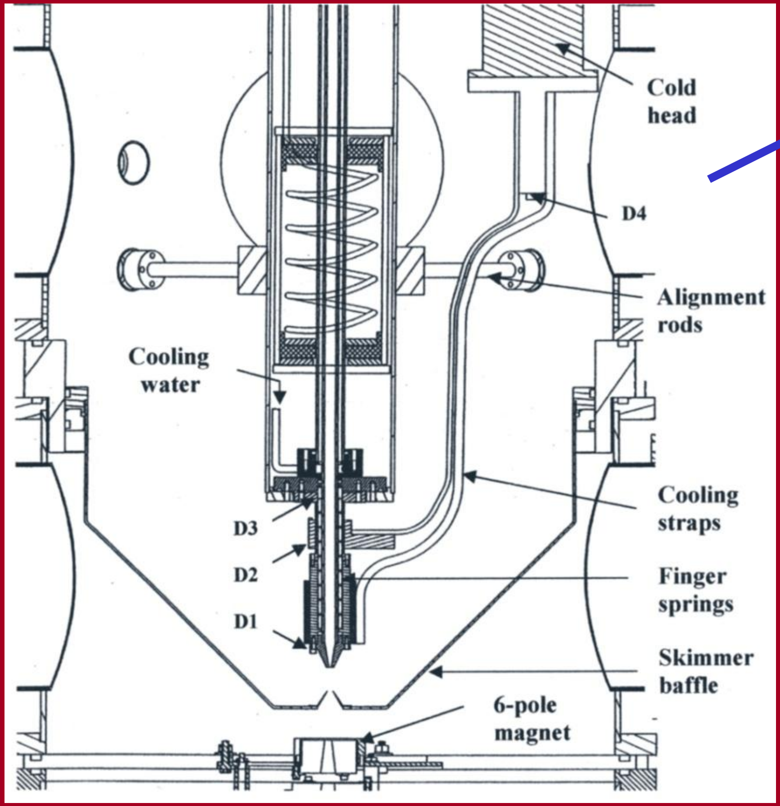
H-jet is an ideal polarimeter !

- High (~4.5%) analyzing power in a wide energy range (23-250 GeV).
- High event rate due to high intensity (~100 mA) circulated beam current in the storage ring (~6% statistical accuracy in one
  8hrs. long fill). High polarized H-jet density in RHIC ABS.
- Non-destructive.
- No scattering for recoil protons.
- Clean elastic scattering event identification.
- Straightforward calibration with Breit-Rabi polarimeter.
- Most of the false asymmetries are cancelled out in the ratio:

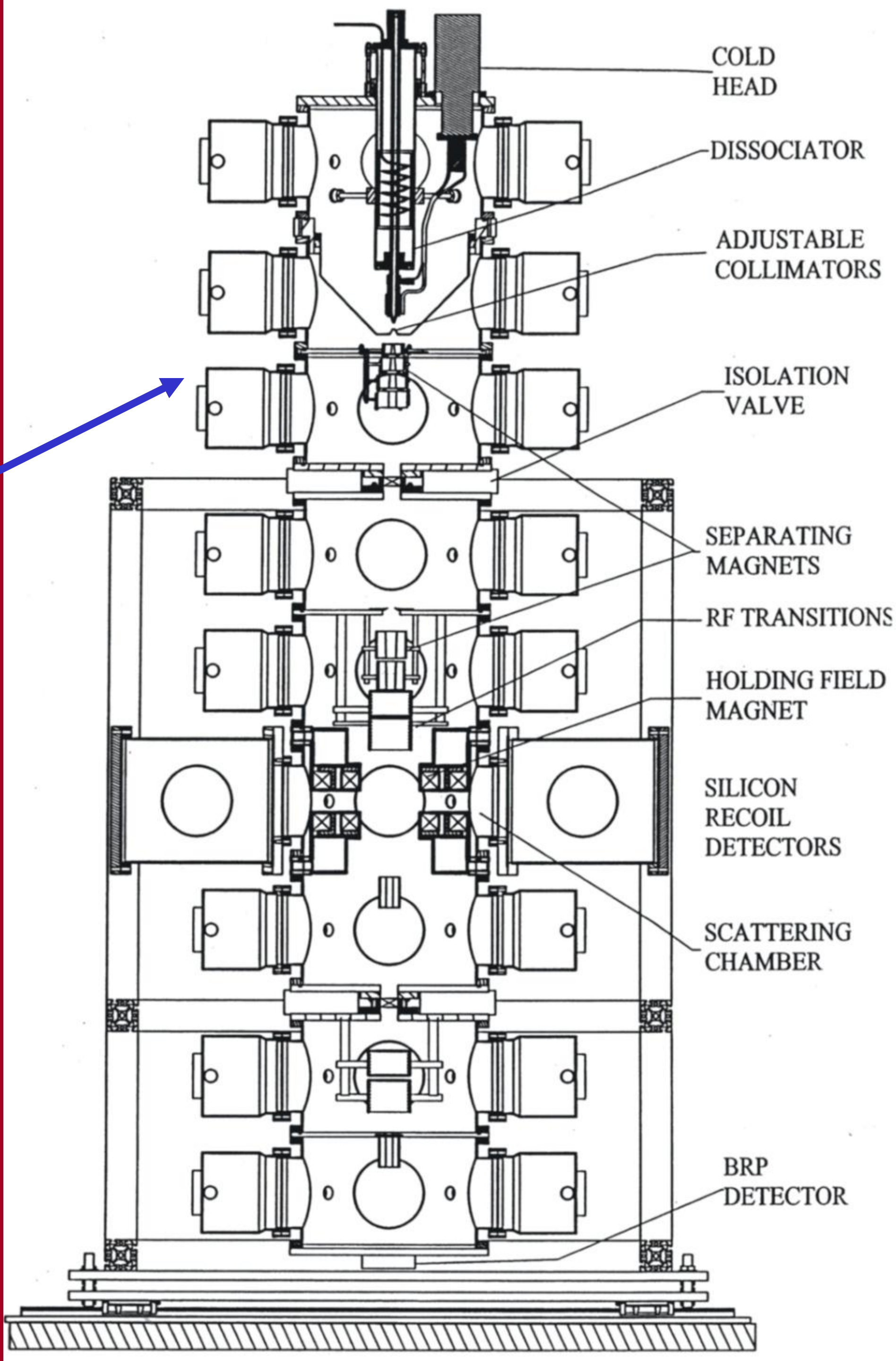
$$P_{beam} = (1/A) Beam_{asym} / Target_{asym}$$

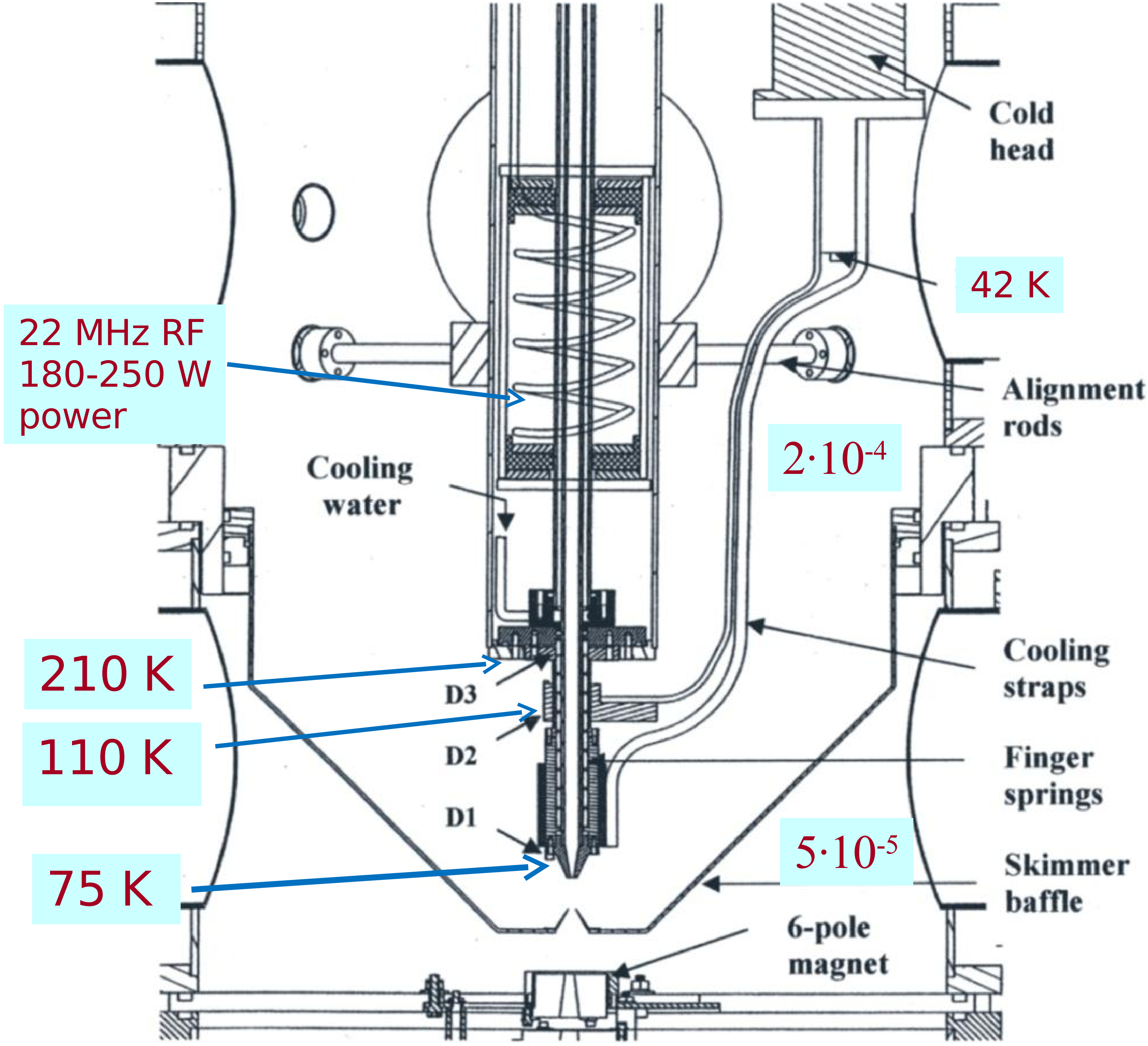
Problem.
Polarization dilution by H_2, H_2O and other residual gases.
Largest source of systematic error.

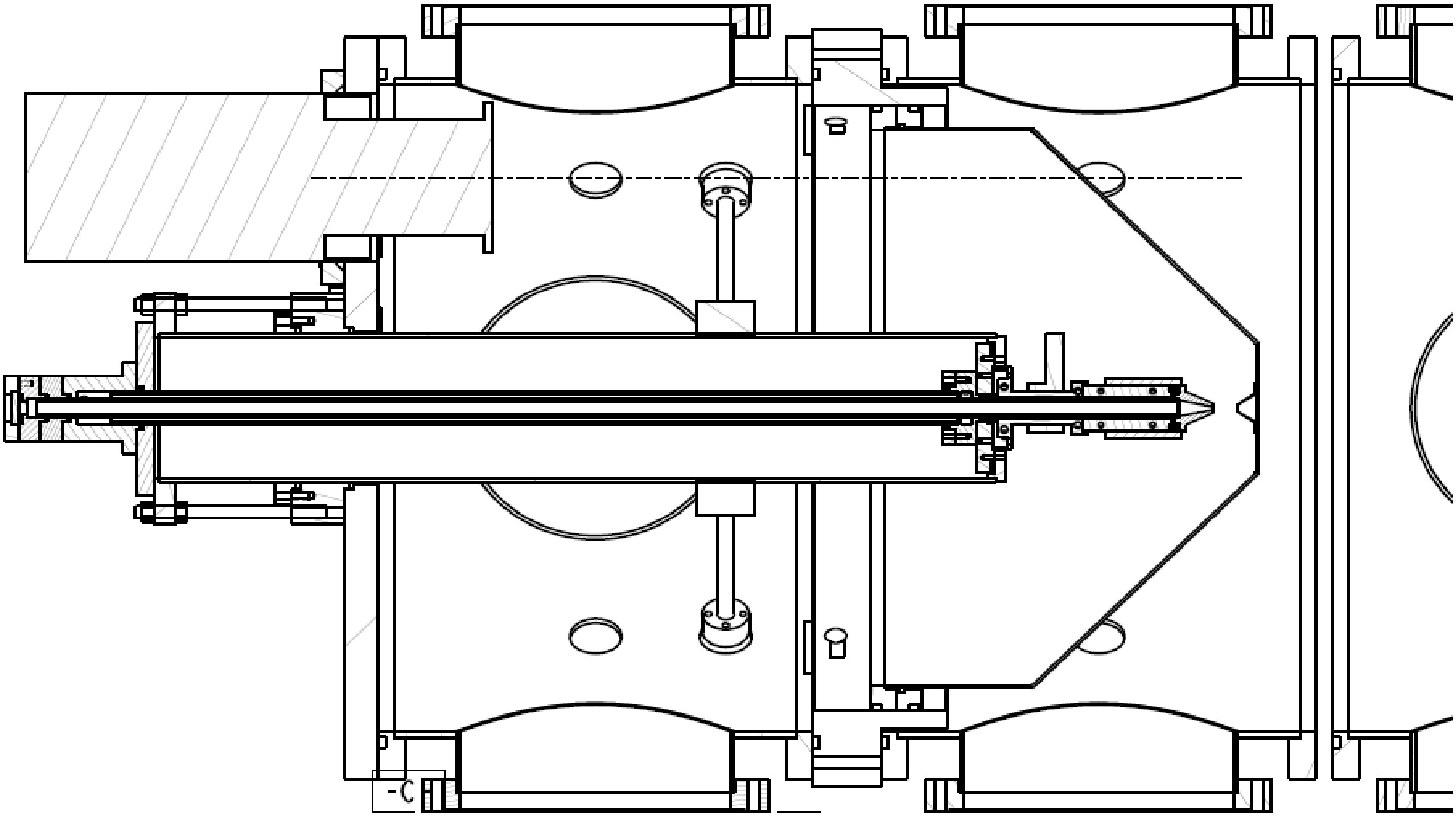
H - jet polarimeter.



Dissociator




Cold head
42 K
22 MHz RF
180-250 W
power
Alignment rods
2·10-4
Cooling water
210 K
110 K
75 K
D3
D2
D1
Cooling straps
Finger springs
5·10-5
Skimmer baffle
6-pole magnet

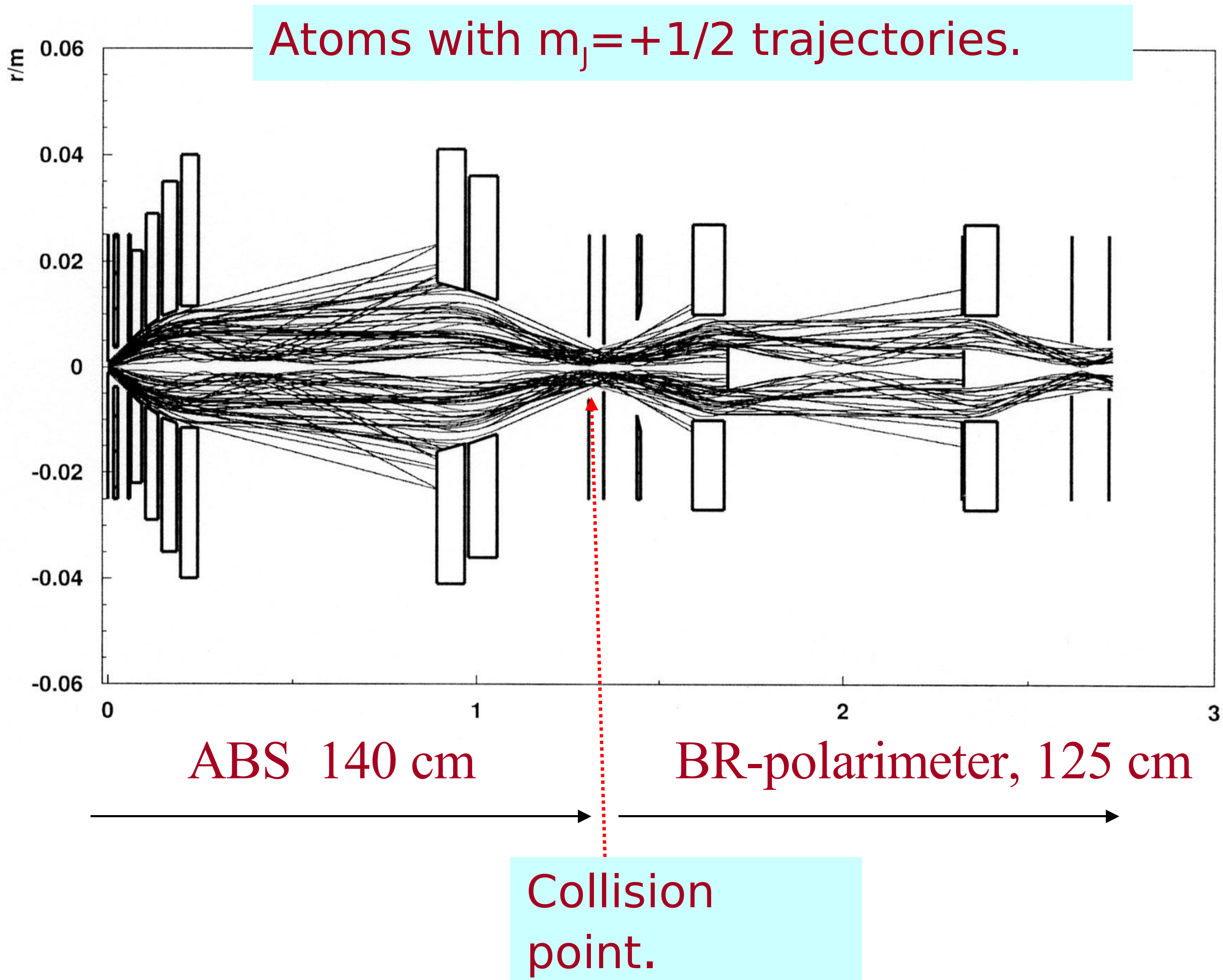

-C

Heat transfer from quartz tube to the copper heatsink.

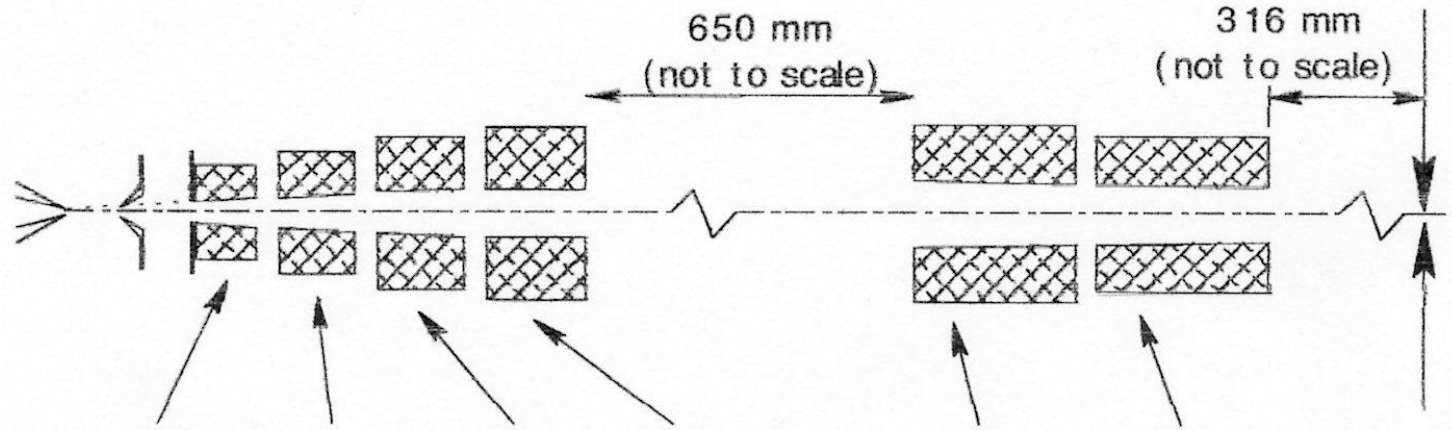
- Finger springs , 2003-04
- Apiezon greaze, 2004-05-high intensity,

  reproducibility problem.
- Indium wire,   2005-2008, stable operation (crashed Diam. 14 X 1 mm tube).

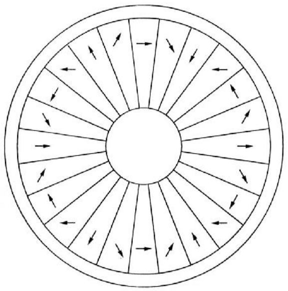
Simulations of the 6-pole separating magnet system.



H-jet sextupole separation magnet system.



ri	5.2	7.5	9.7	11.5	16	14.5
rex	7.0	9.1	10.7	11.5	14.5	12.7
L	28.5	35.4	40.5	46.0	75	79.0
rout	22	29	35.7	40.3	41.2	36.7



- Force on the atom:

$$\vec{F} = -\nabla E = -\frac{\partial E}{\partial B} \cdot \frac{\partial B}{\partial r}\vec{e_r} = -\mu_{eff} \cdot B_0 \frac{r}{2r_0^2}\vec{e_r}$$

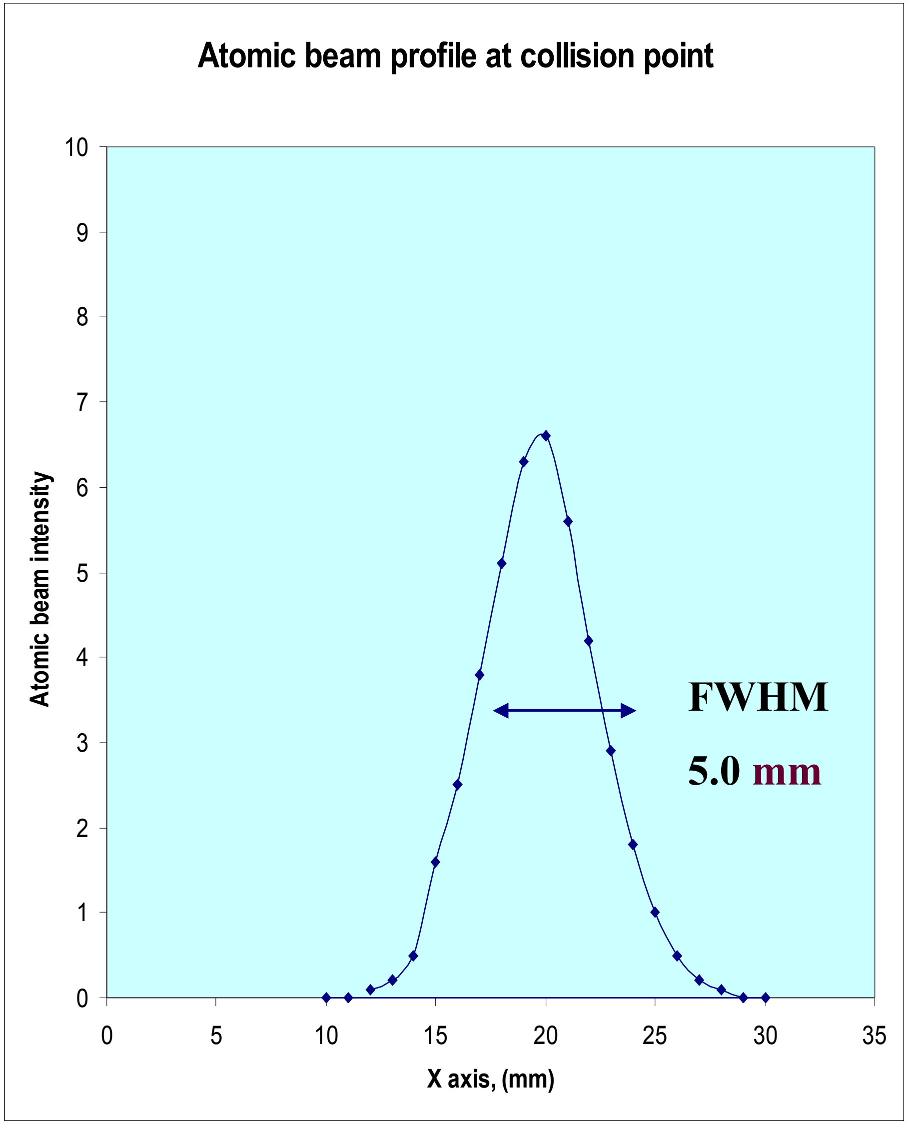
24 sectors separating magnets with 1.5 T field at the pole tips.

Atomic beam profile at the collision point.

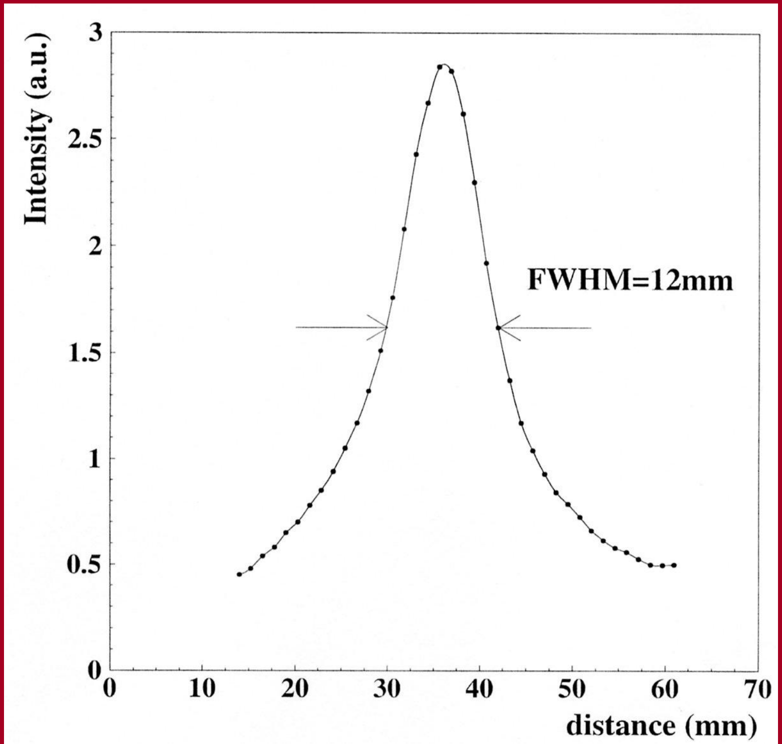
- Atomic beam profile was measured with a 2.0 mm in diameter compression tube FWHM=5.0 mm

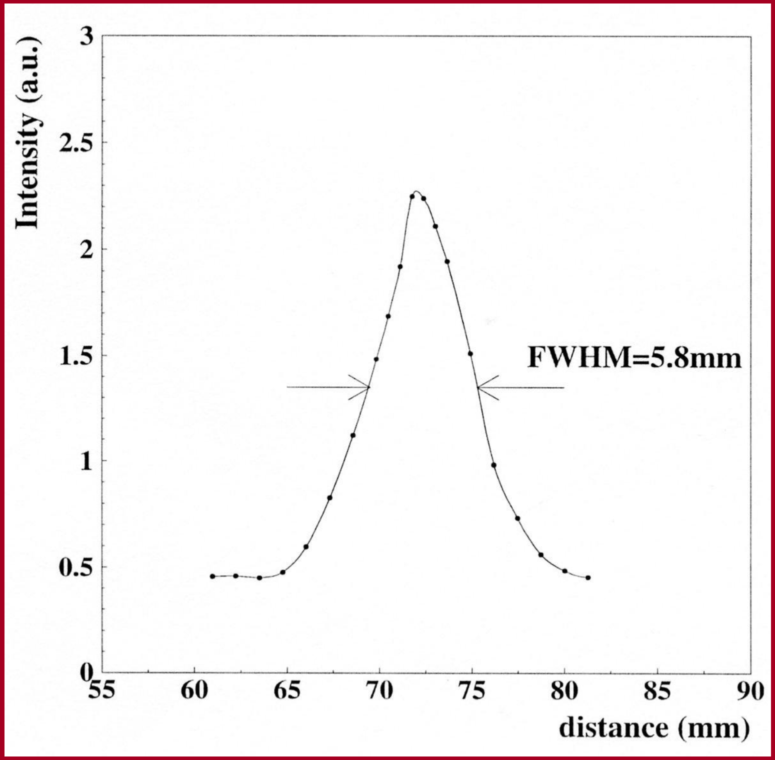
- 5 cm upstream the beam profile FWHM is about 4.5mm and 120 mm downstream FWHM is about 7.0 mm

- In assumption, that beam velocity is $2 \cdot 10^5$ cm/s, the H - jet thickness at the collision point is about $1.2 \cdot 10^{12}$ atoms/cm^2.



Atomic beam intensity profile measurements.



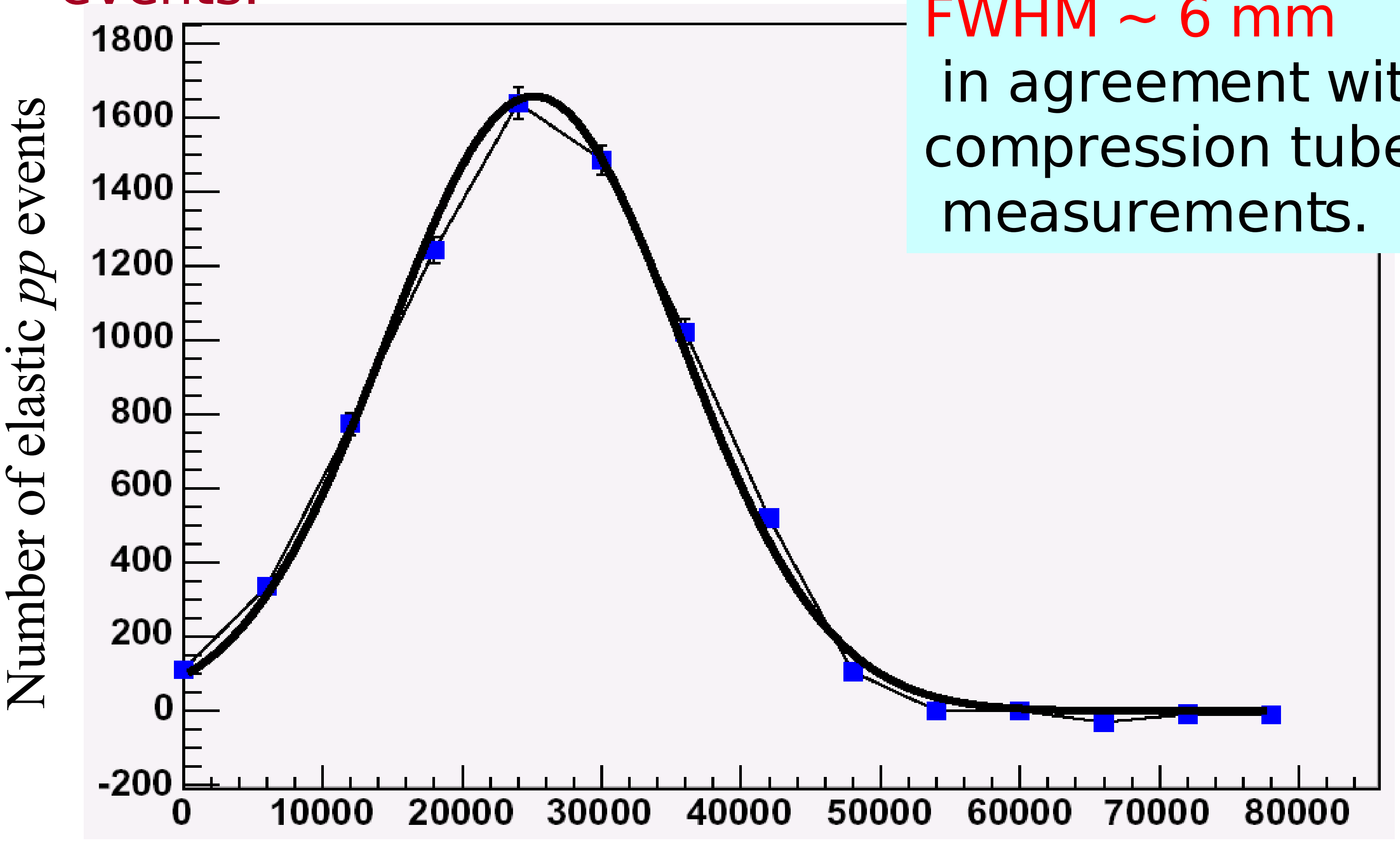


Beam profile at the entrance of 6-pole # 5.

Beam profile at the RHIC beam collision point.

H-jet target intensity profile at the RHIC collision point.

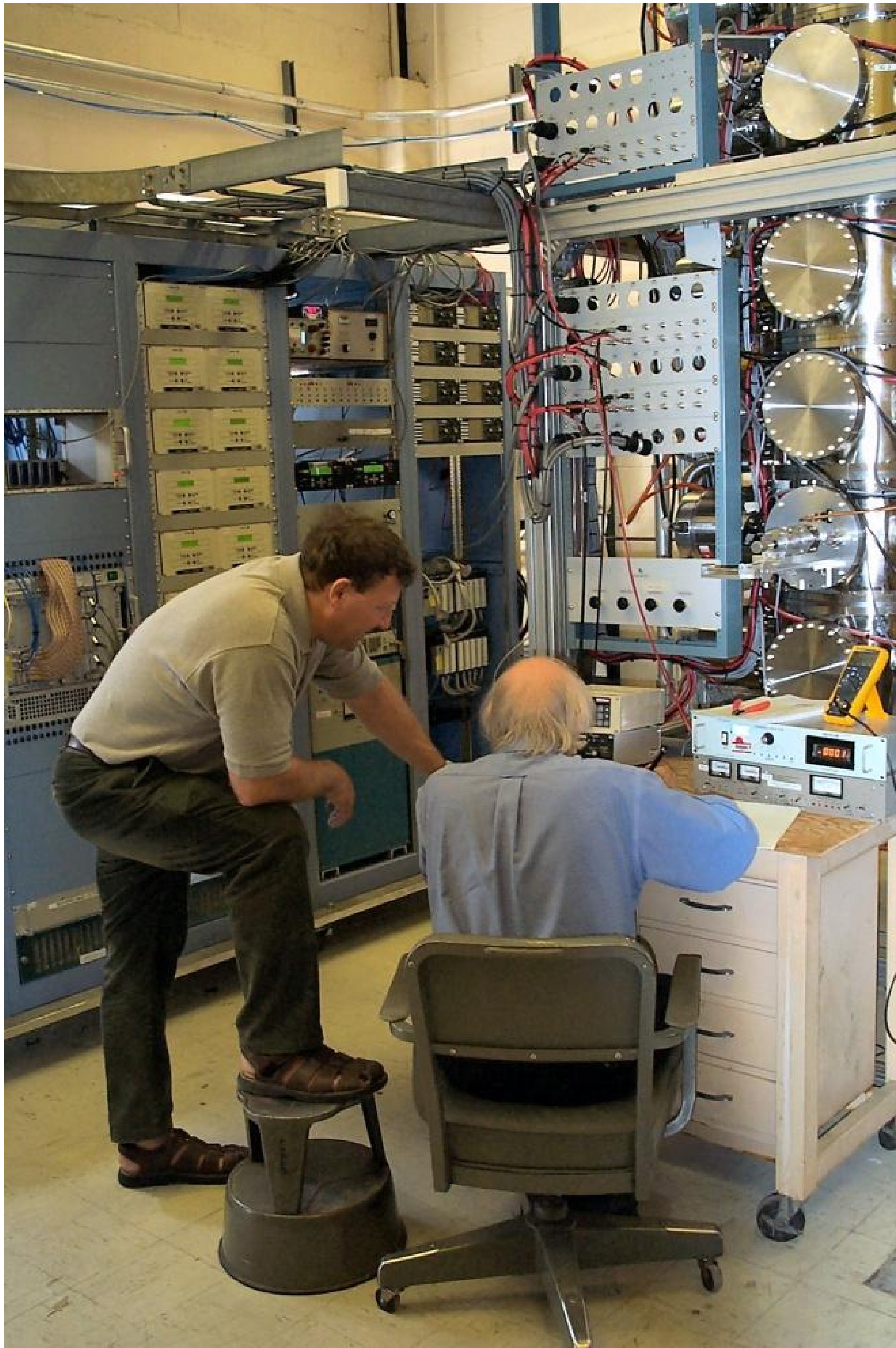
Profile was measured from elastic *pp* scattering events.



FWHM ~ 6 mm in agreement with a compression tube measurements.

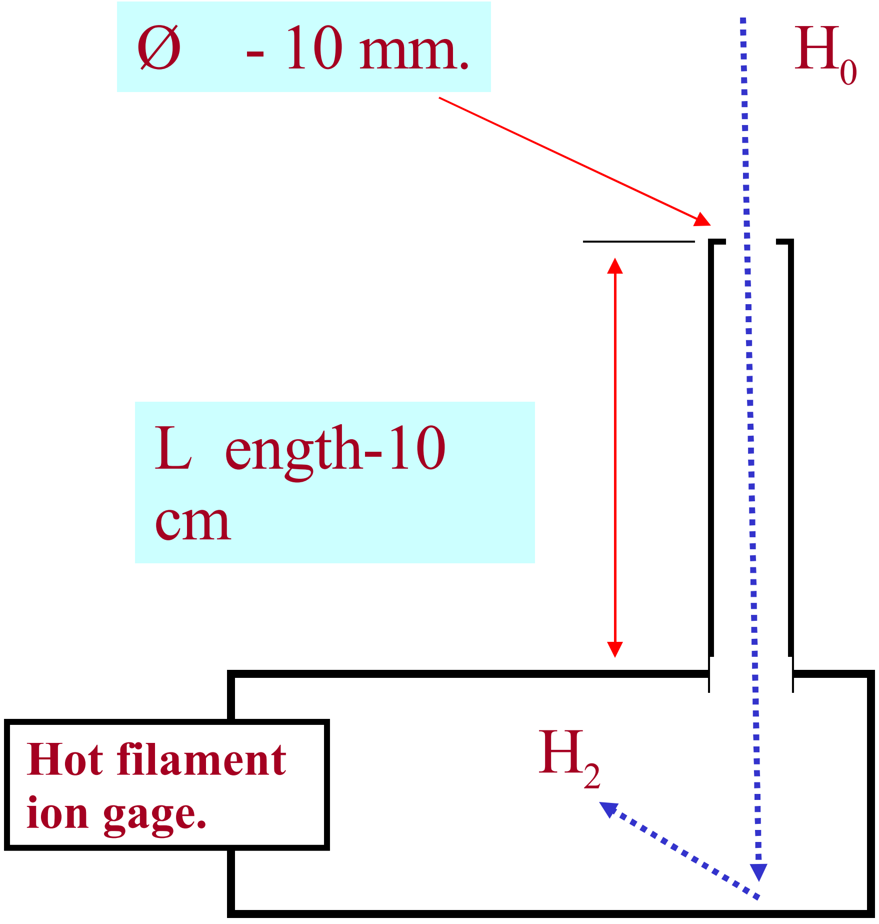
Hor. position of the JET ,10000 steps = 2.5 mm.

Atomic Beam intensity measurement, June 2003

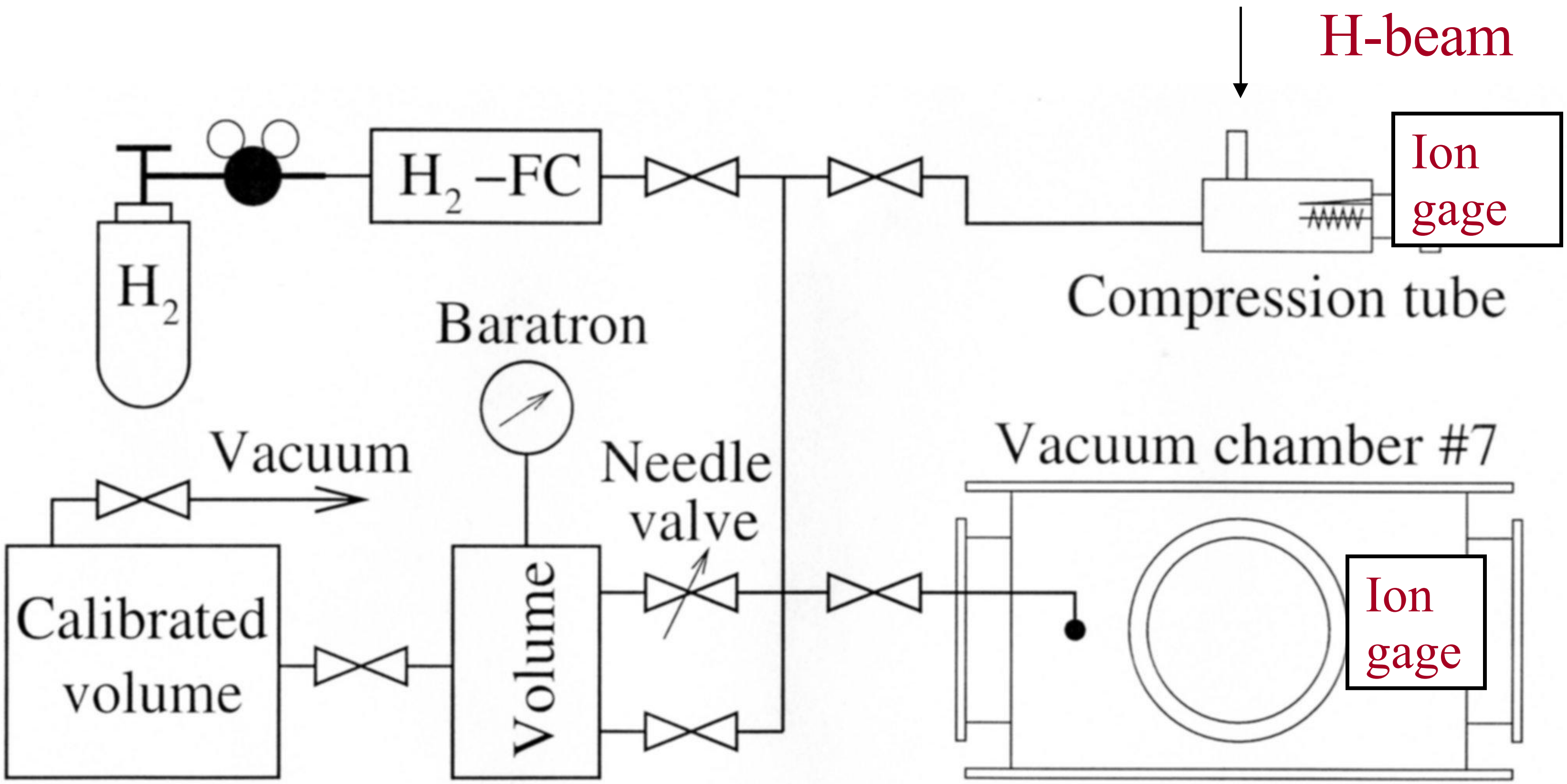


Compression tube calibration.

- Hydrogen mass-flow controller MKS . Full range: 0.0-1.0 scc/min. Absolute accuracy 1-2 %.
- Conventional technique: pressure drop in calibrated volume.
- Independent AB intensity measurement from the well known TMP pumping speed.



The compression tube calibration system for the absolute AB intensity measurements.



H2 mass-flow controller and a pressure drop measurement in the calibrated volume were used for compression tube calibration.

Atomic beam intensity vs H_2 flow in dissociator.

AB intensity of

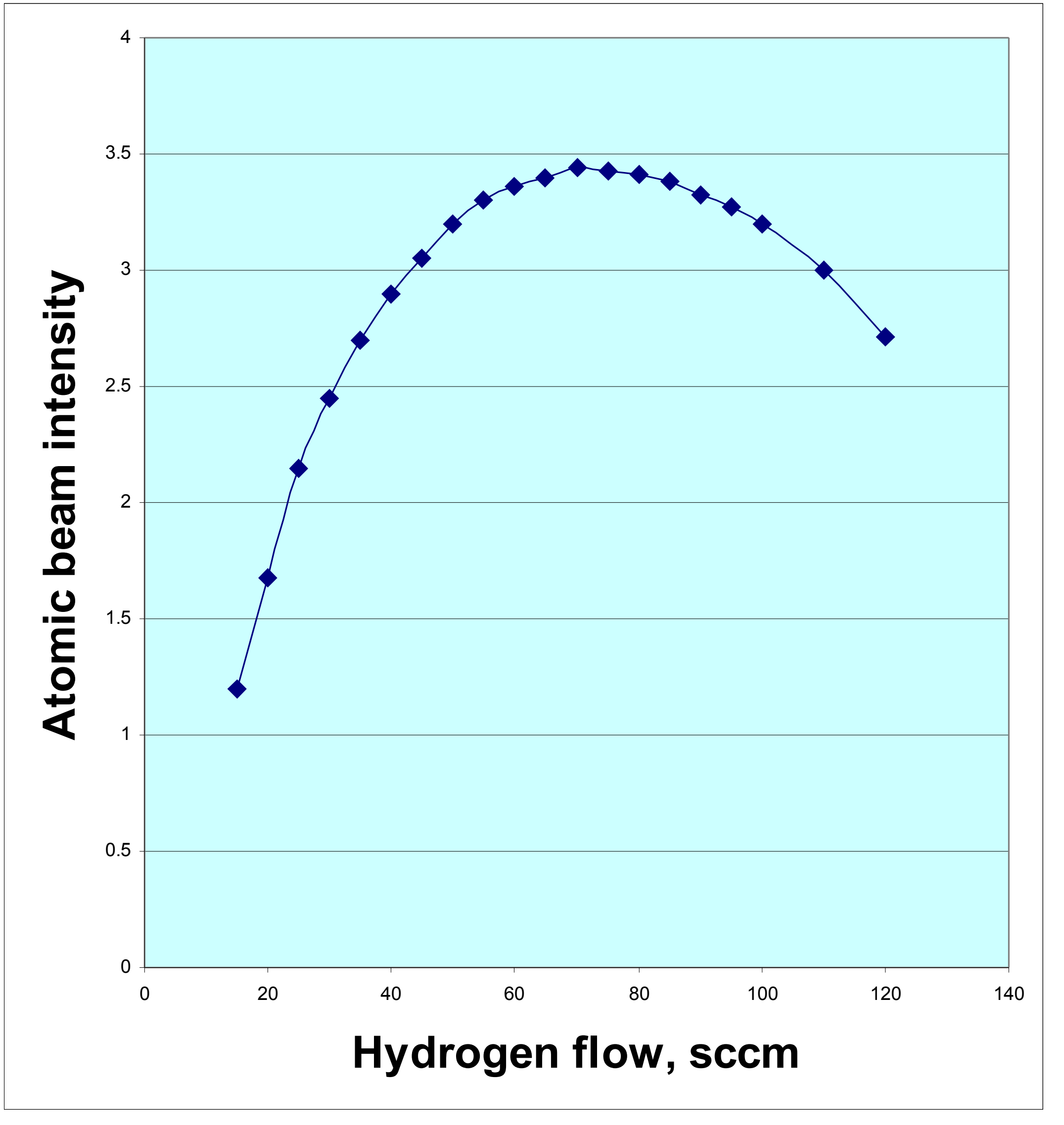
$12.5 \cdot 10^{16}$ at/s.

was measured at

70 scc/s H_2 flow.

250 W RF power

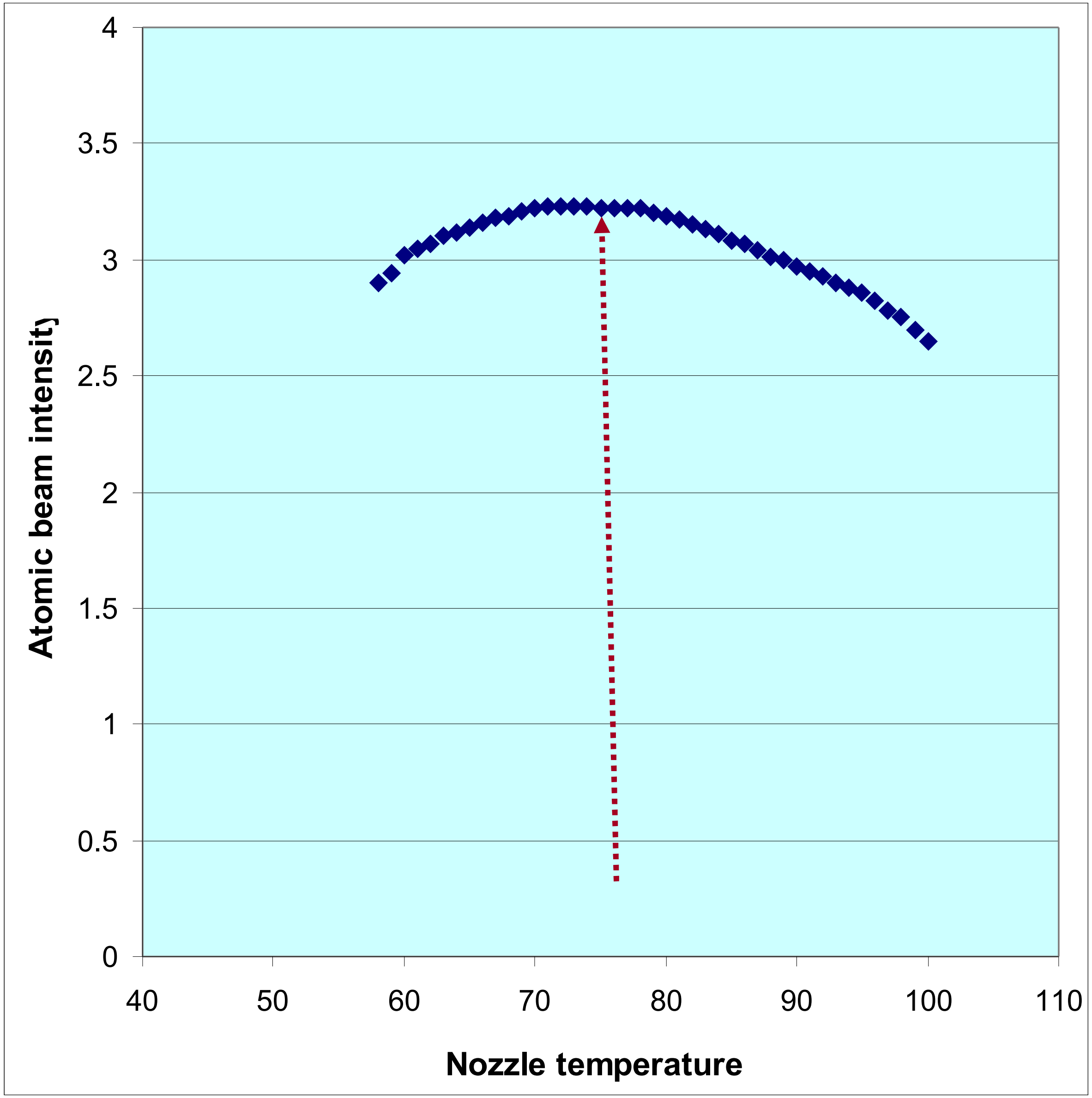
75 K nozzle temp.



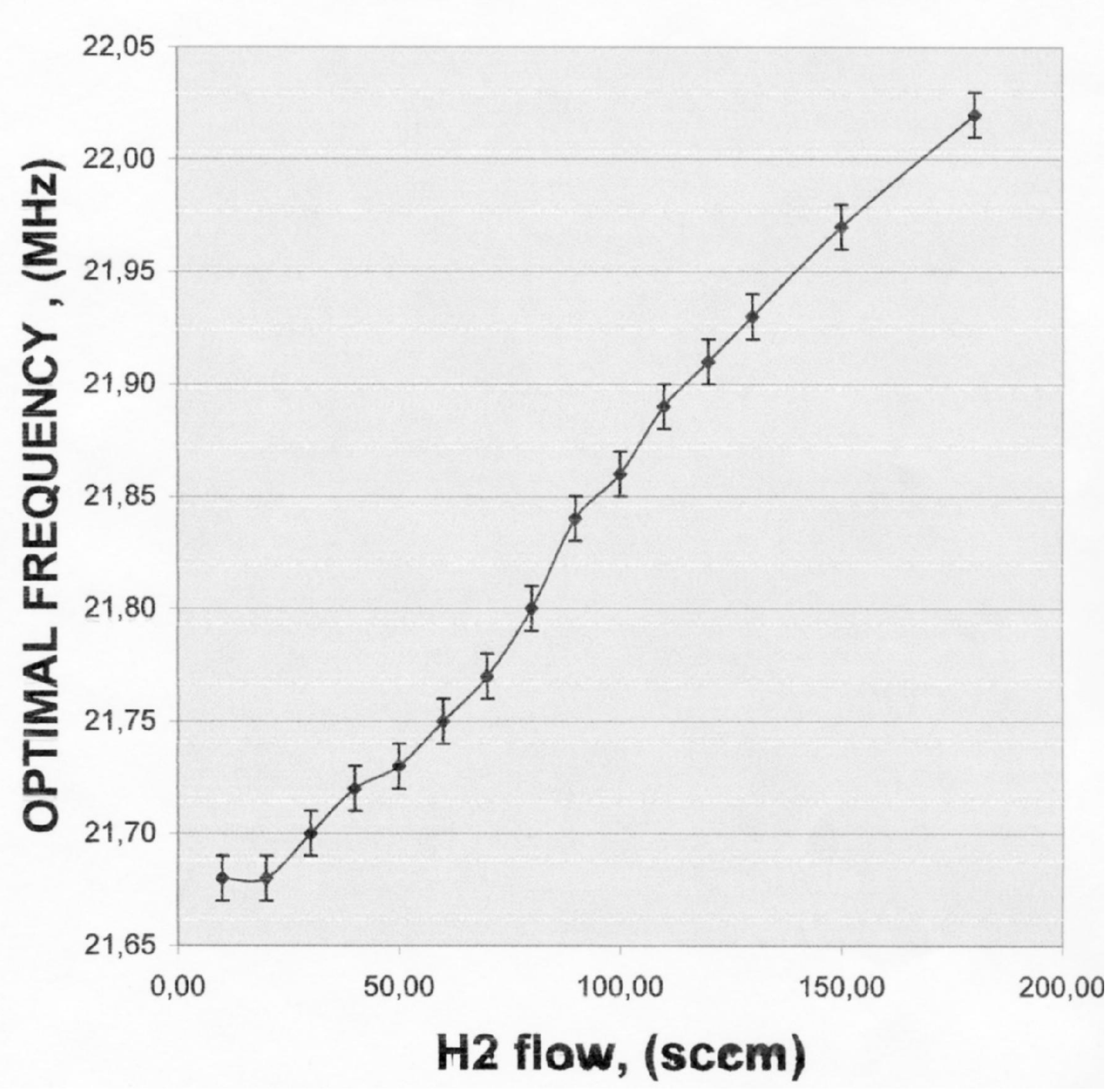
AB intensity vs. nozzle temperature.

The maximum AB intensity was measured at

T_{nozzle} =75 deg. K



“Optimal “ radio-frequency dependence on the H_2 flow in dissociator.

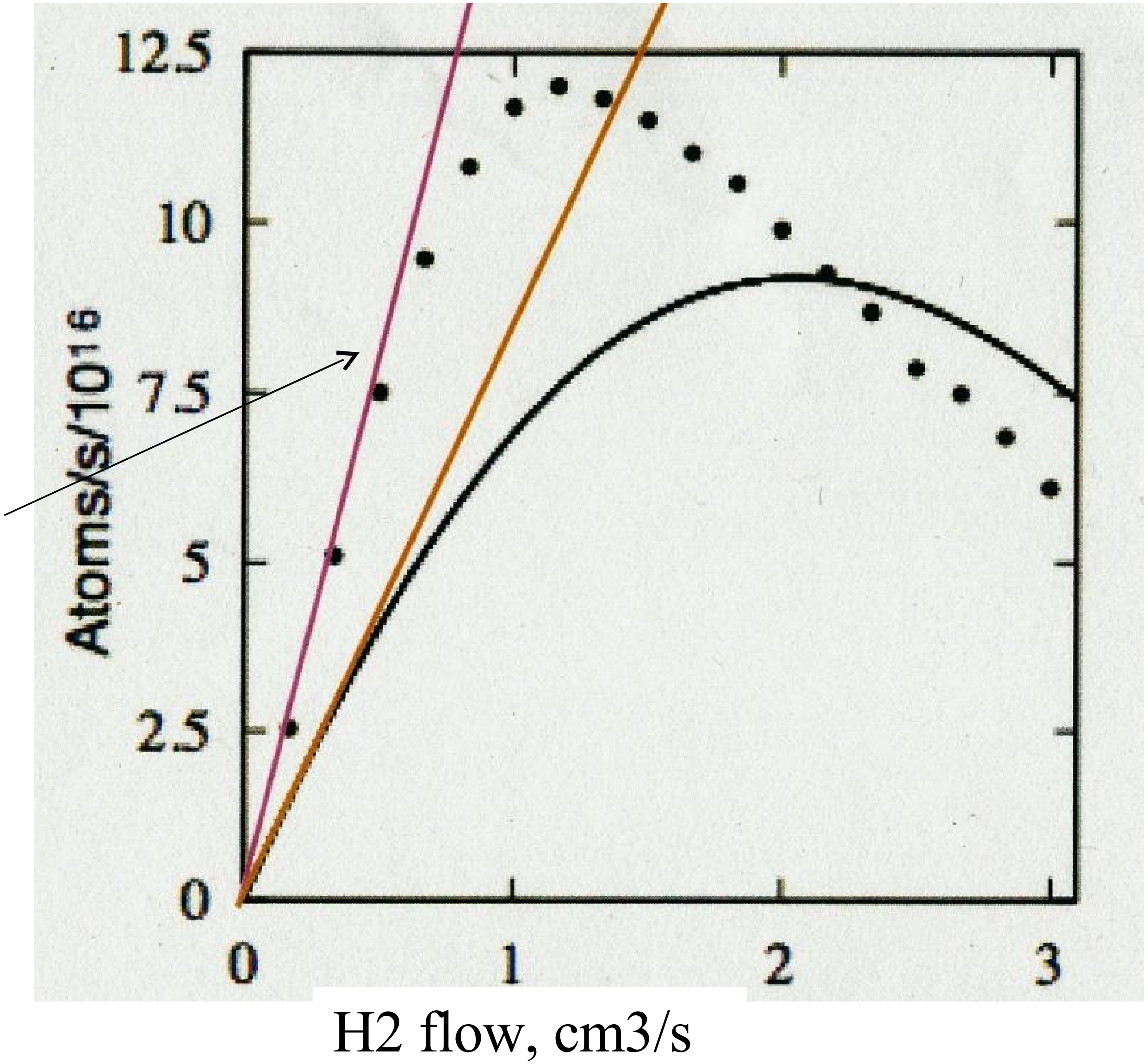


Atomic beam intensity vs H_2 flow in dissociator.

RF-power was kept constant at 260 W

Nozzle temperature 75 K.

Slope is 1.75 steeper than simulations



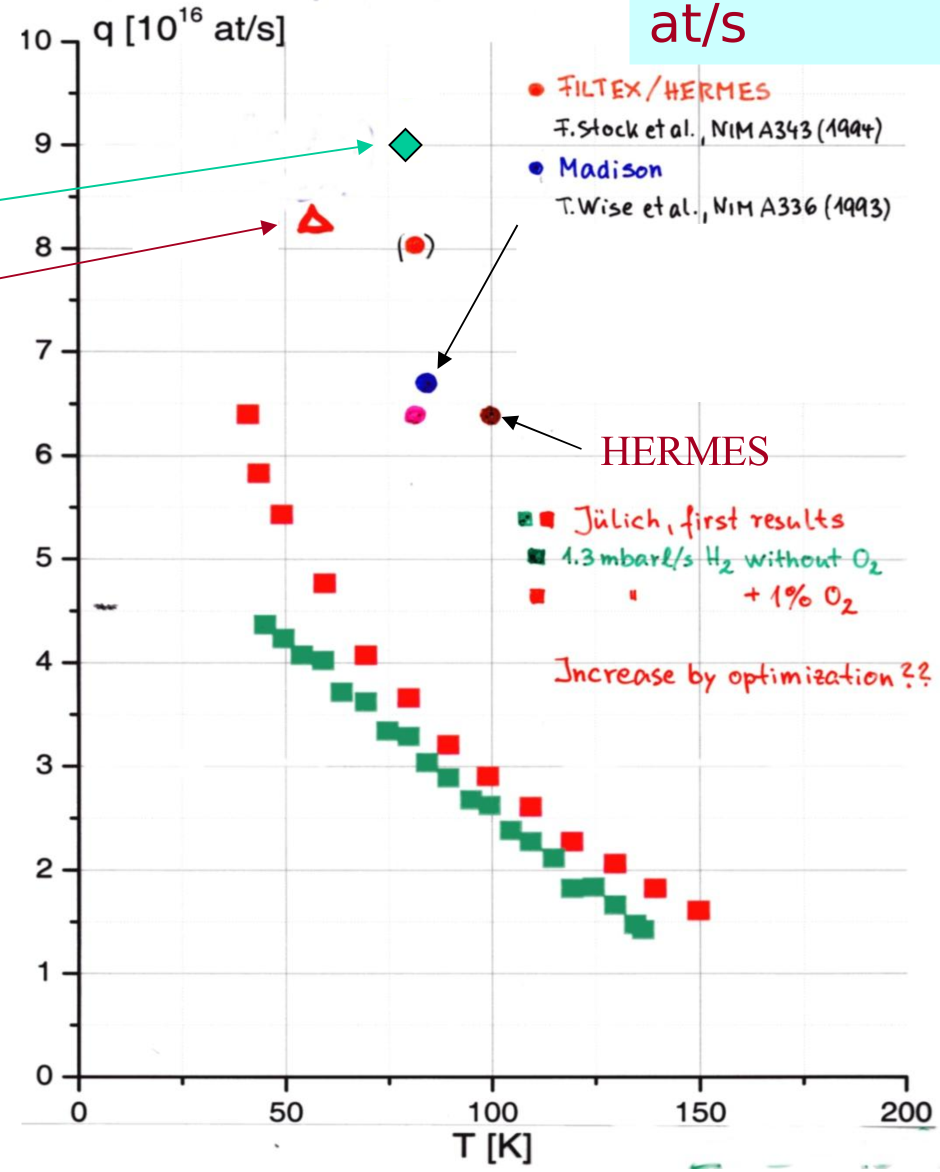
Operational atomic beam sources intensities.

H-jet

$12.5 \cdot 10^{16}$ at/s

T.Wise calc.

ANKE, COSY



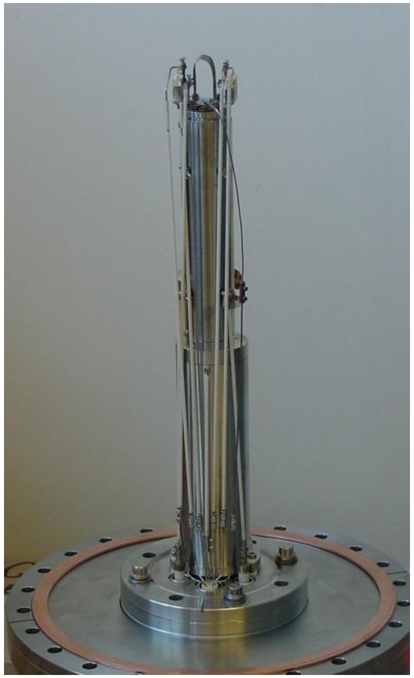
Maximum H-jet

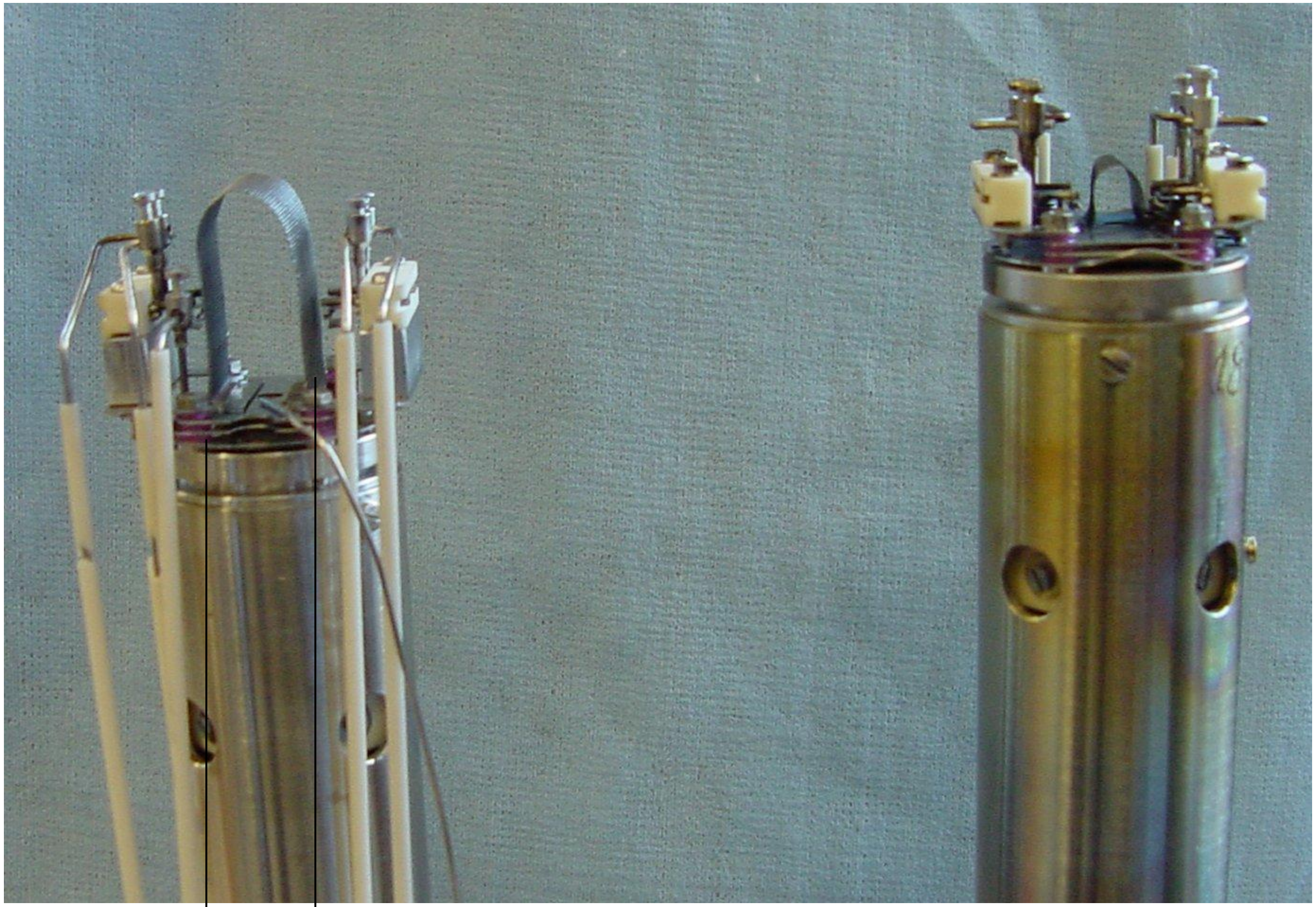
beam intensity is at

T_{nozzle}~75 deg. K

Polarization dilution by H_2, H_2O and other residual gases.

"RIBEN" QMA upgrade for H-jet measurements.



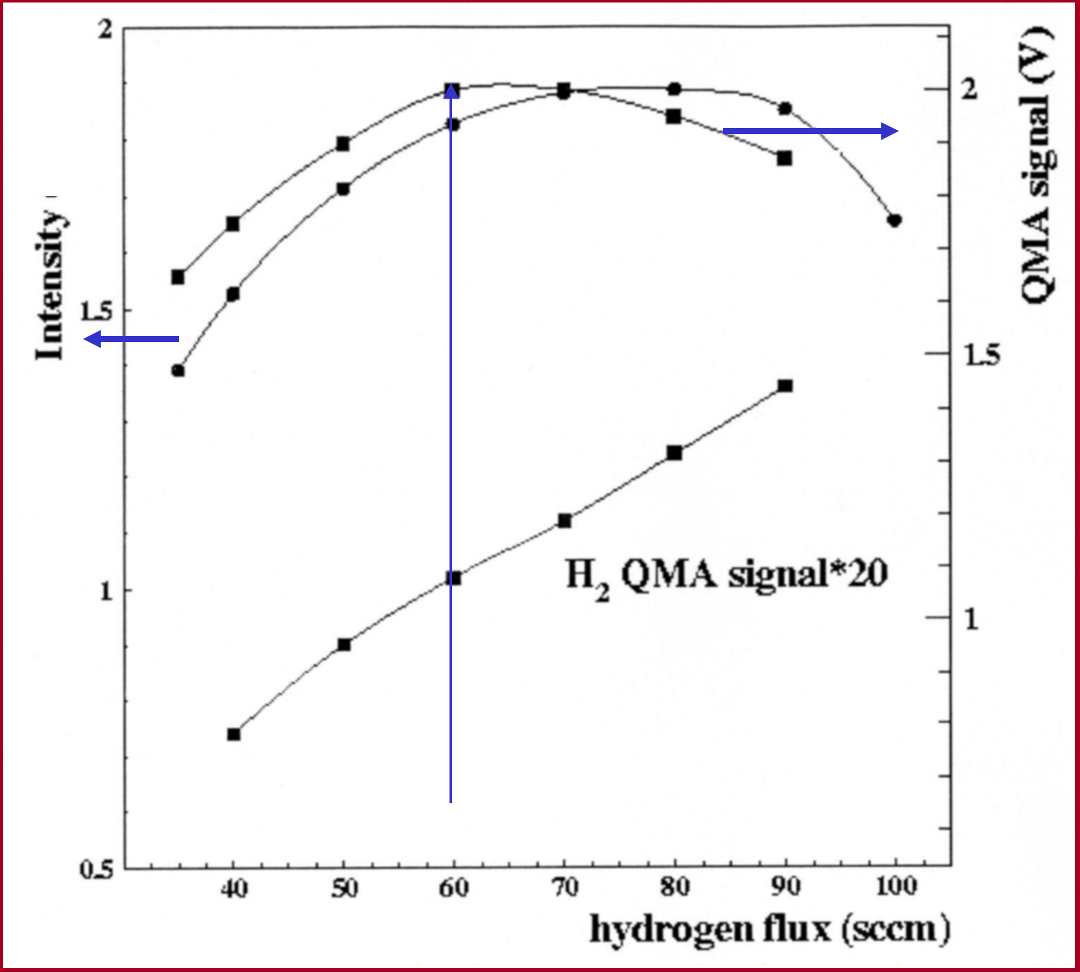


10 mm

Original QMA geometry (right)

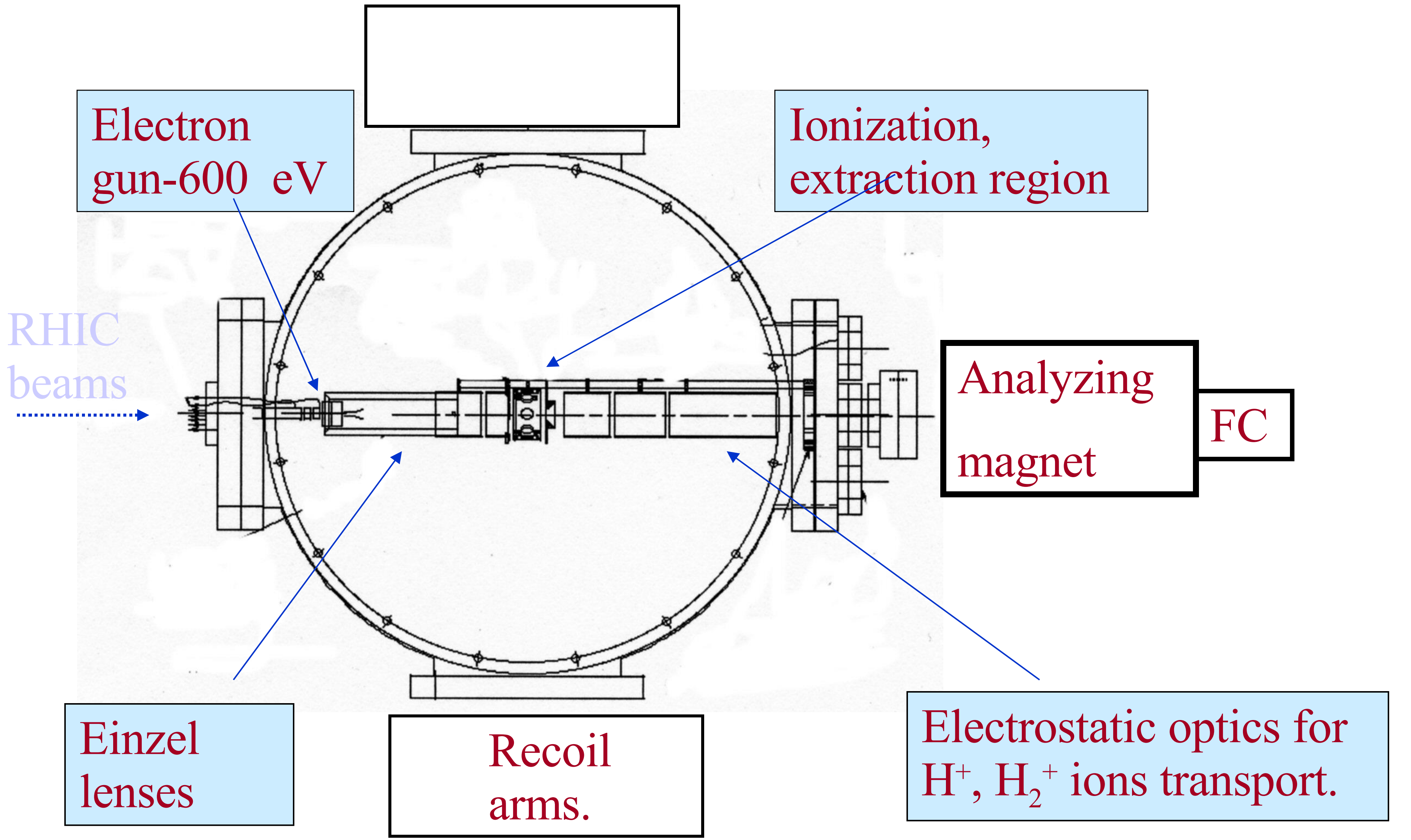
Expanded QMA sensitive volume (left)

Atomic beam intensity and density measurements in the collision region.



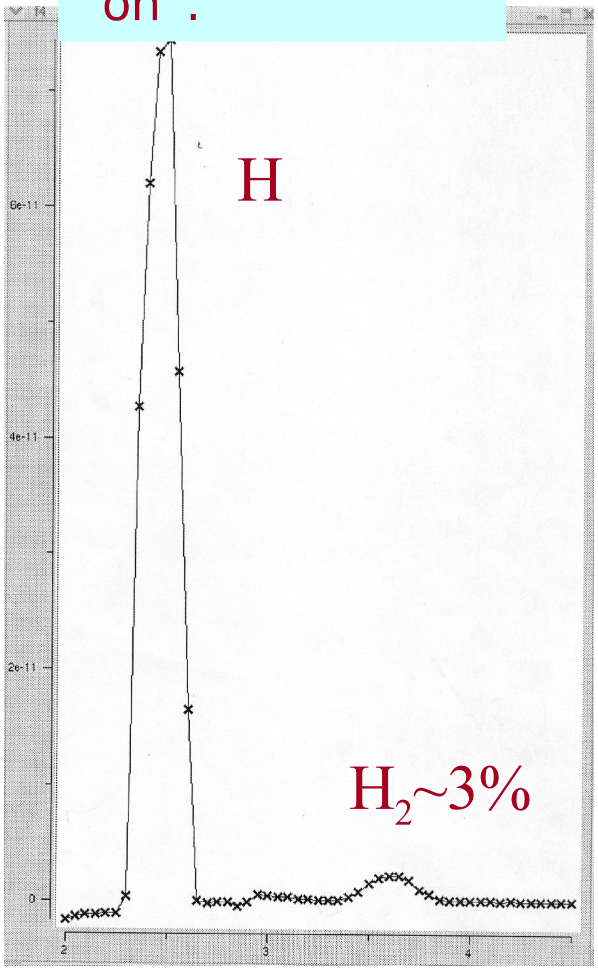
- H-beam intensity and density vs. H2 flow in dissociator.

Layout of the electron beam ionizer and magnetic ion analyzer in the collision chamber.

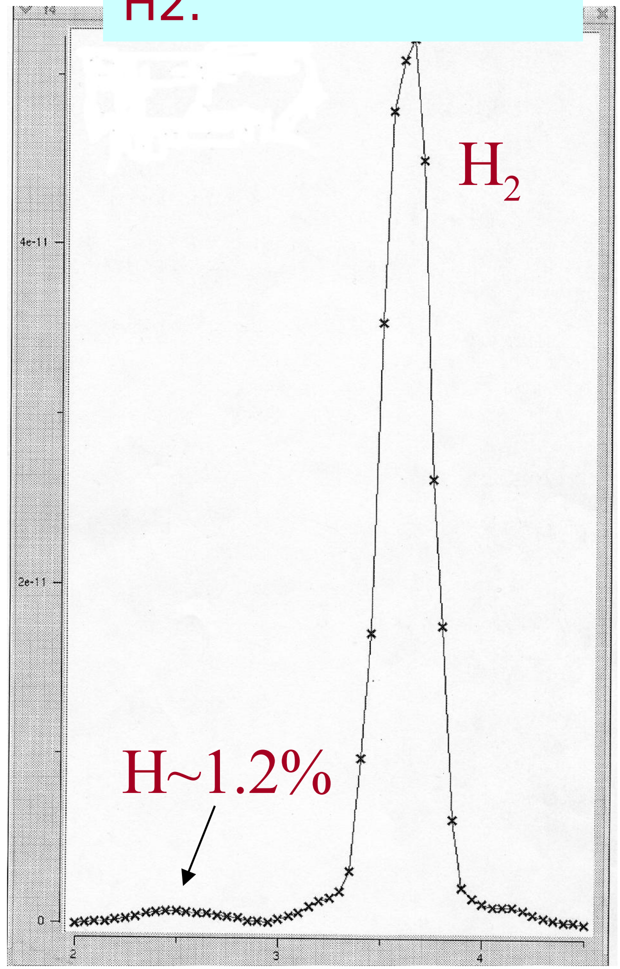


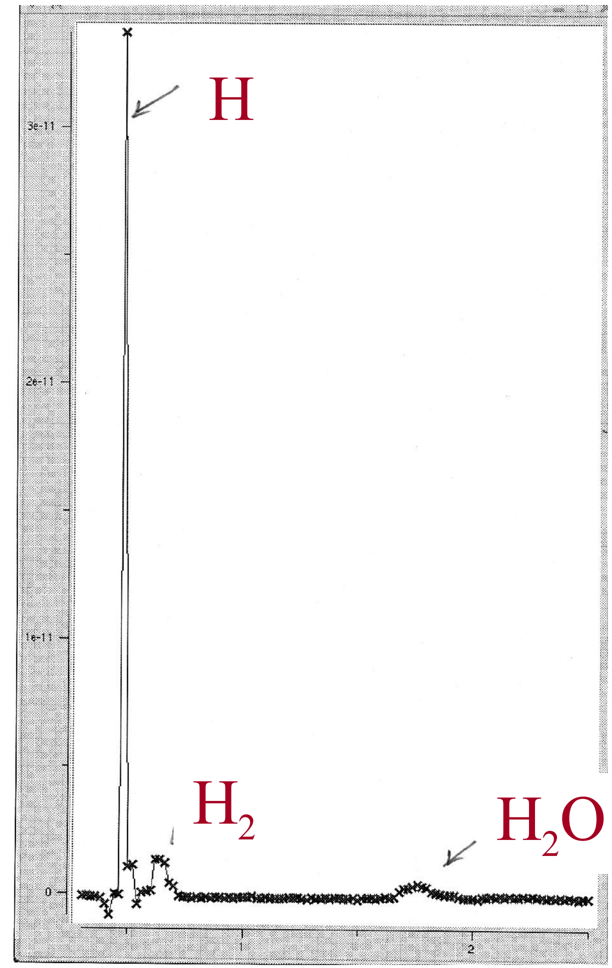
Ion spectra measured with the new diagnostic device.

Atomic beam "on".



Calibration with H2.





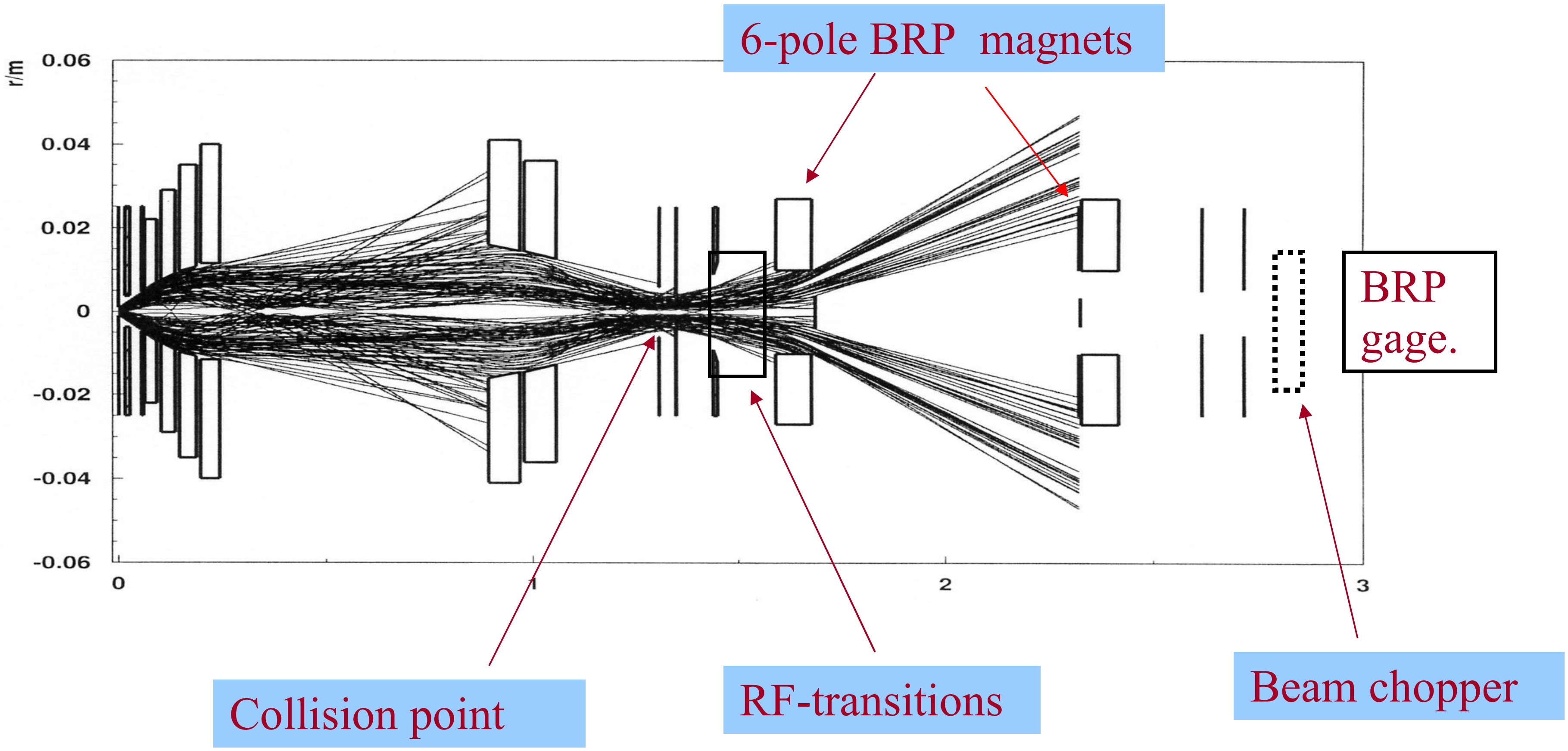
Cross-section ratio H_2/H ~15 at 600 eV electron beam energy.

Breit-Rabi polarimeter.

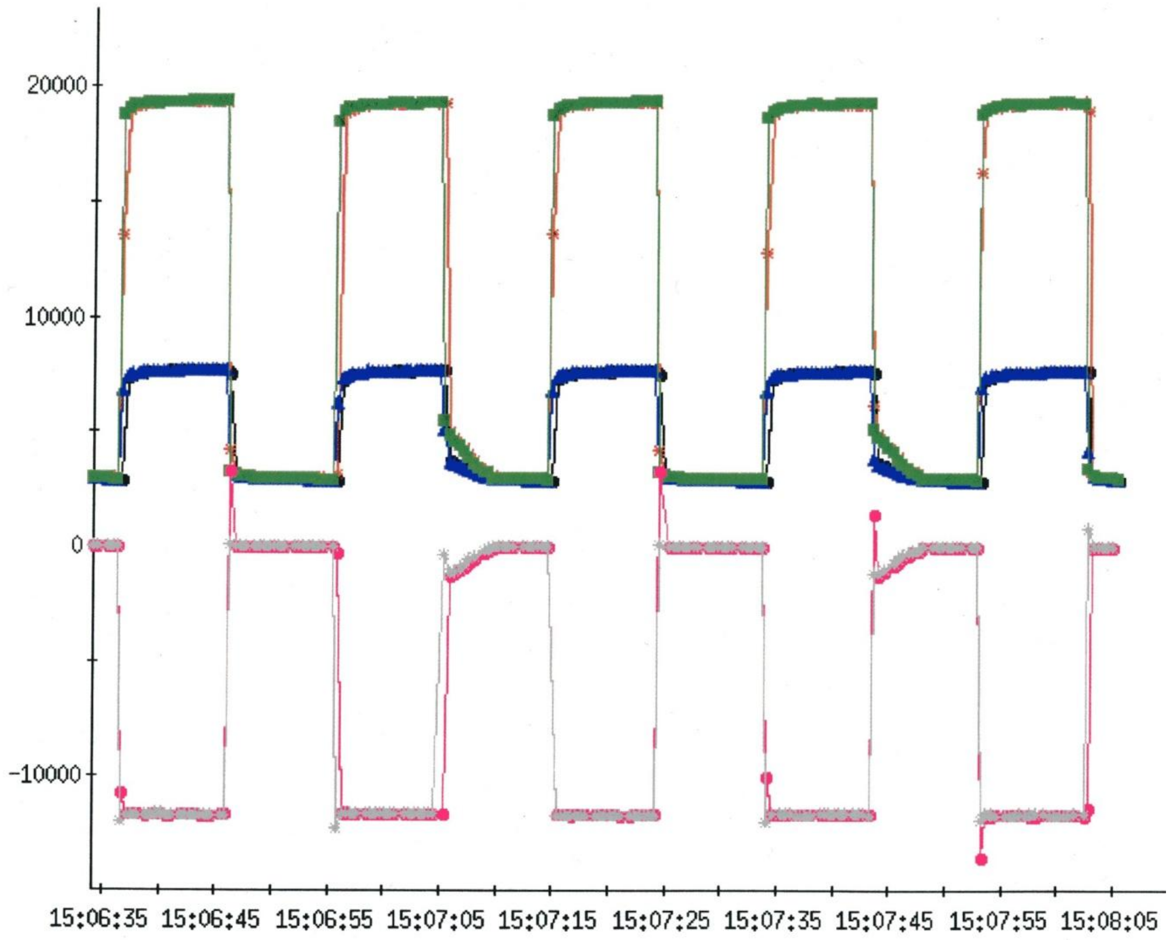
- About 30 % of the AB is transported to the BRP detector.
- Detector is an Ion gauge. Signal was amplified and converted to Frequency.
- Then gates and scalers were used for state selection. Gates were synchronized with the chopper wheel.
- The RFT flipped the spin every 500 s.
- Both transition “on” state for 50 s is used for transition stability monitoring.

The use of efficient BRP allowed RFT tuning and stable operation at 99.8% efficiency.

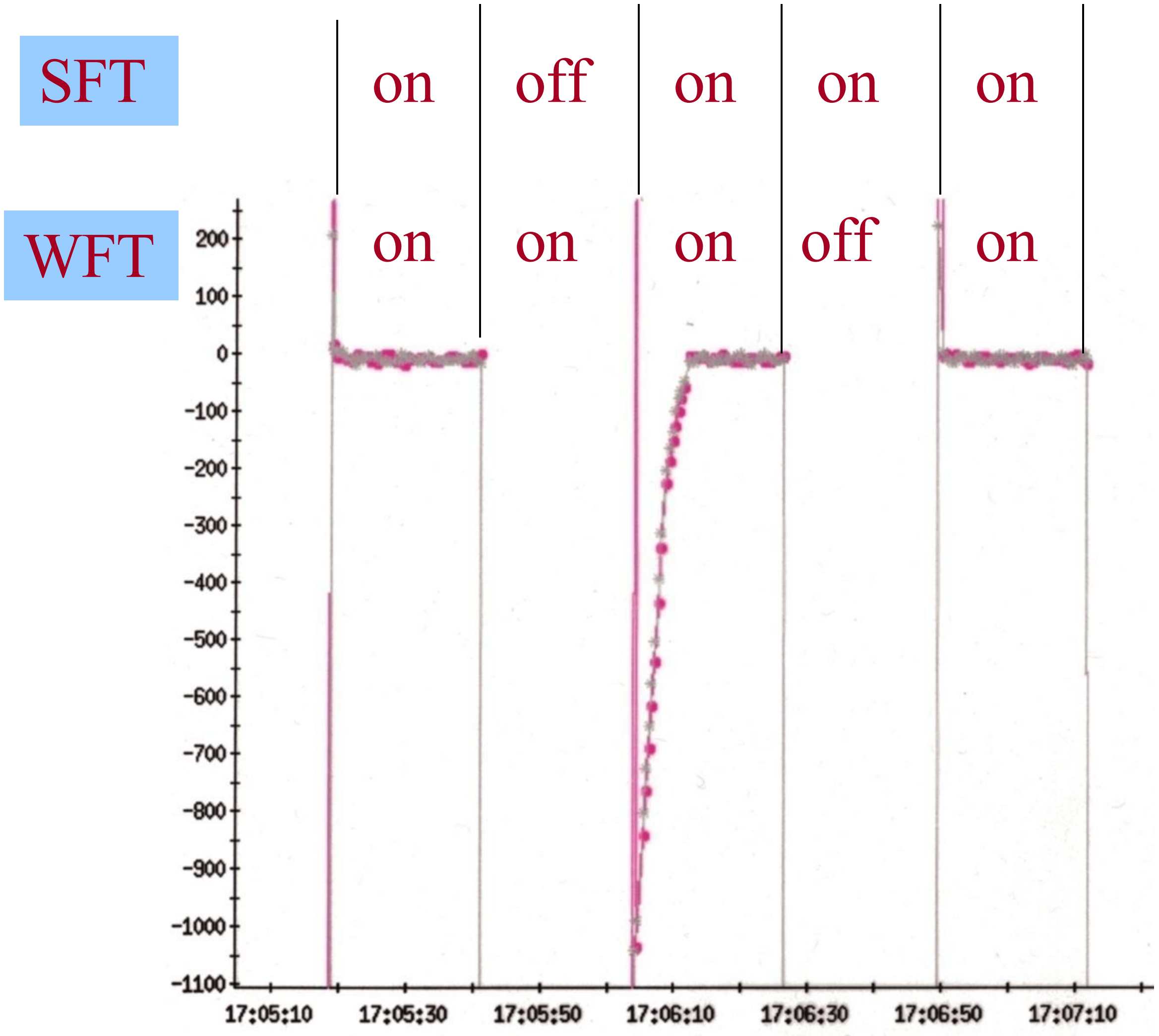
Atomic beam trajectories in BRP with both SFT and WFT –transitions are “on”.



RF-transition operation. Atomic beam polarization reversal.

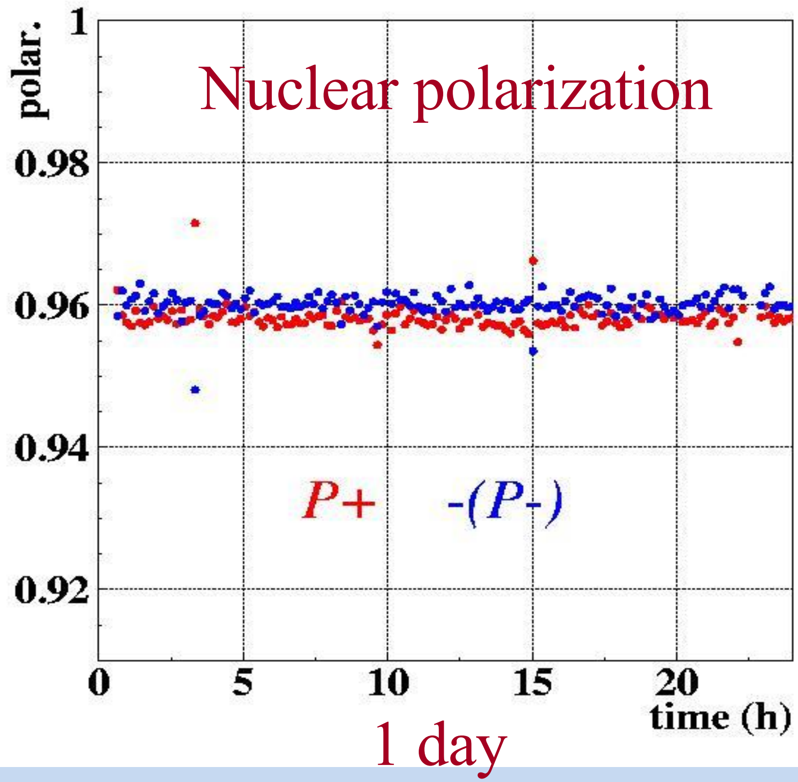


Turn-on time for SF-transition.



H-Jet: P_{target}

Source of normalization for polarization measurements at RHIC



Nuclear polarization of the atoms measured by BRP: 95.8% ± 0.1%

Correct for H_2, H_2O contamination.

P_{target} = 92.4% ± 1.8%

Polarization cycle:

(+/ 0/ –) = (500/50/500) seconds

Very stable for entire run period !

Atomic beam polarization measurements during H-jet operation in May, 2004-run.

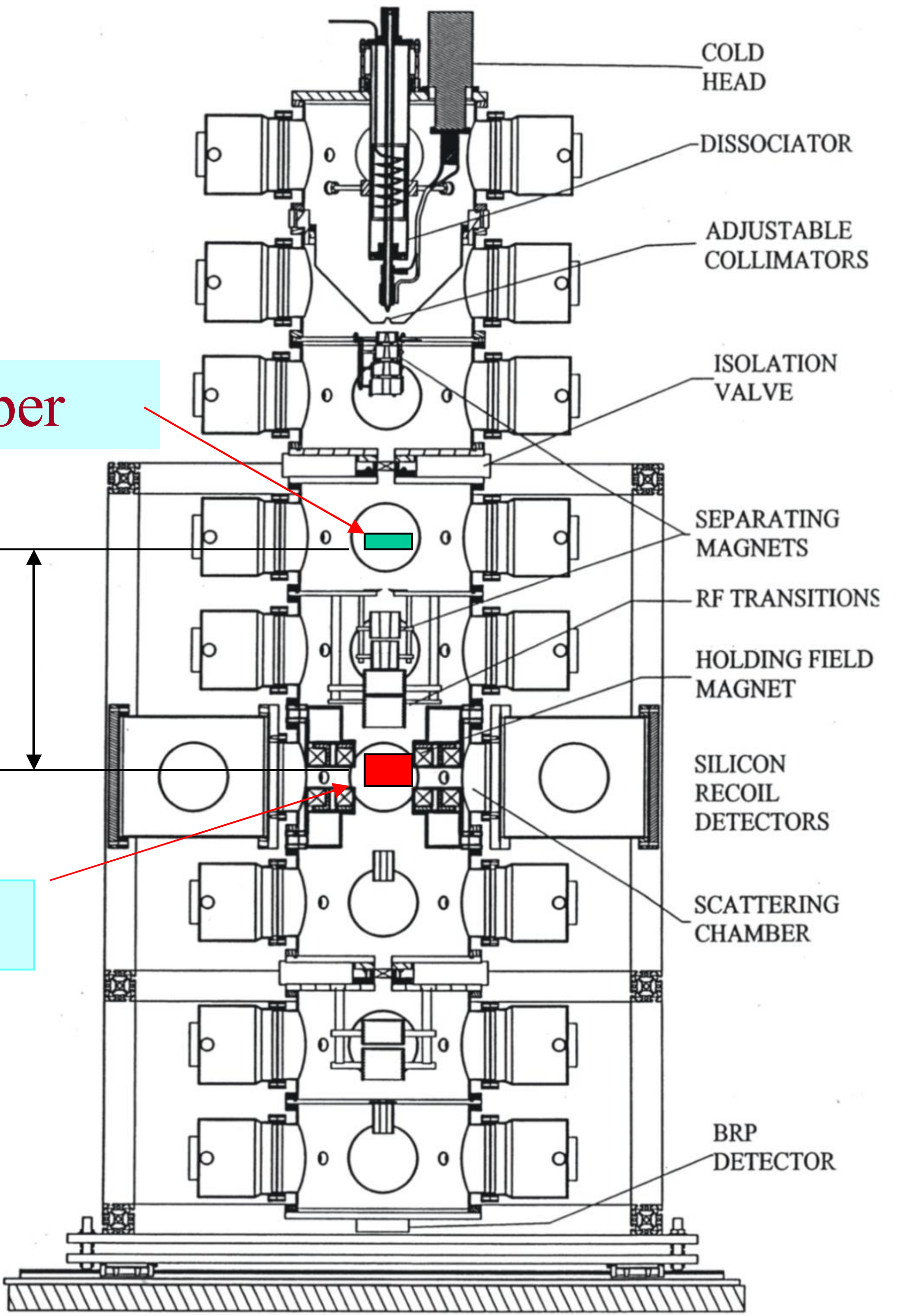
Day	mag.field	avg.rates +	avg.rates -	avg.rates 0	Pol.+	Pol -
April 26	normal	10490±1	10436±1	56.9±0.2	+95.70	-95.91
April 27	normal	10526±0.4	10469±0.4	55.9±0.1	+95.69	-95.93
April 28	normal	10180±1	10134±1	54.1±0.2	+95.73	-95.89
April 29	normal	9716±1	9656±1	51.5±0.1	+95.66	-95.97
April 30	normal	10056±0.8	9999.6±0.8	50.7±0.1	+95.70	-95.96
May 1	normal	10169±0.3	10119±0.3	50.7±0.1	+95.73	-95.92
May 2	normal	10345±0.5	10288±0.5	53.0±0.1	+95.70	-95.96
May 4	reversed	9251.5±0.5	9232.0±0.5	54.3±0.1	+95.82	-95.74
May 5	reversed	10602±0.7	10568±0.7	55.7±0.1	+95.80	-95.82
May 5	normal	10791±0.6	10755±0.6	51.5±0.1	+95.81	-95.85
May 6	normal	8388.8±0.5	8355.4±0.5	39.9±1	+95.78	-95.89
May 7	normal	8971.3±0.6	8897.1±0.6	40.2±0.1	?	?
(8am to 4pm, instable behaviour of SFT, data may not be used)						
Used difference		8971.3±0.6	8897.1±0.6	74.2±0.1	+95.42	-95.93
May 7	normal	9141.5±0.5	9110.3±0.5	47.6±0.1	+95.79	-95.84
(after 4pm, stable behaviour SFT, everything OK)						
May 8	normal	9394.1±0.5	9350.9±0.5	47.2±1	+95.74	-95.91
May 9	normal	9205.3±0.5	9171.4±0.5	47.1±0.1	+95.78	-95.86
May 10	normal	9677.0±0.4	9635.5±0.4	47.6±0.1	+95.76	-95.90
May 11	normal	10133±0.4	10084±0.4	46.4±0.1	+95.75	-95.94
(don't use date between 12:00 and 16:30 since there were 2 programs running)						
May 12	normal	10435±0.4	10390±0.4	47.6±0.1	+95.78	-95.91
May 13	normal	10838±0.4	10791±0.4	48.1±0.1	+95.78	-95.92
May 14	normal	11196±0.6	11151±0.6	49.1±0.1	+95.80	-95.90

Time –of - flight beam velocity and velocity spread measurements out of dissociator

Beam chopper

69 cm

Q MA



The narrow velocity spread is expected from the H-jet dissociator (due to long cooling “neck”), which can be a significant factor in the superior H-jet performance.

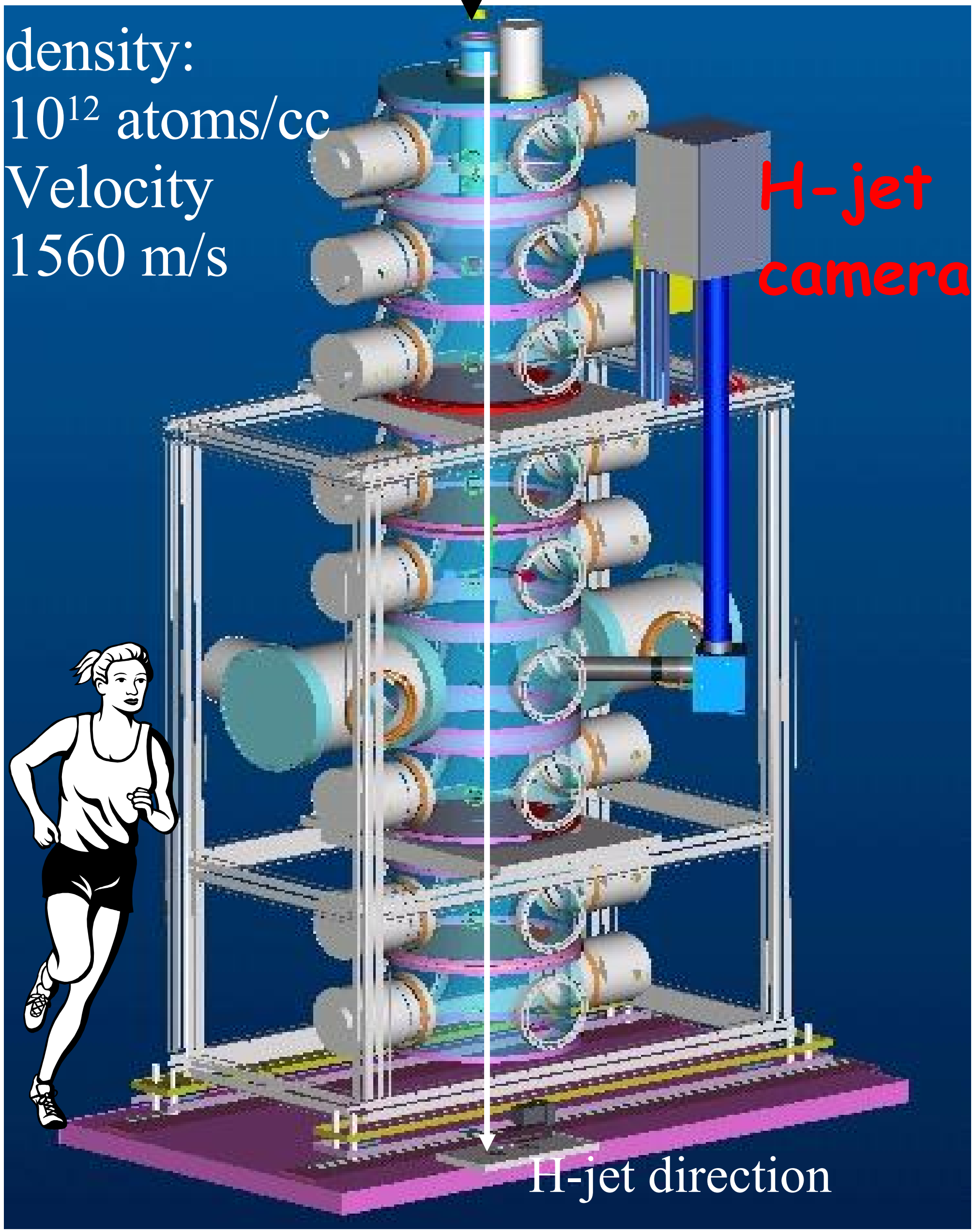
AB S separating magnets were removed for these measurements.

QMA atomic beam velocity measurements.

L=135 cm- drift length.

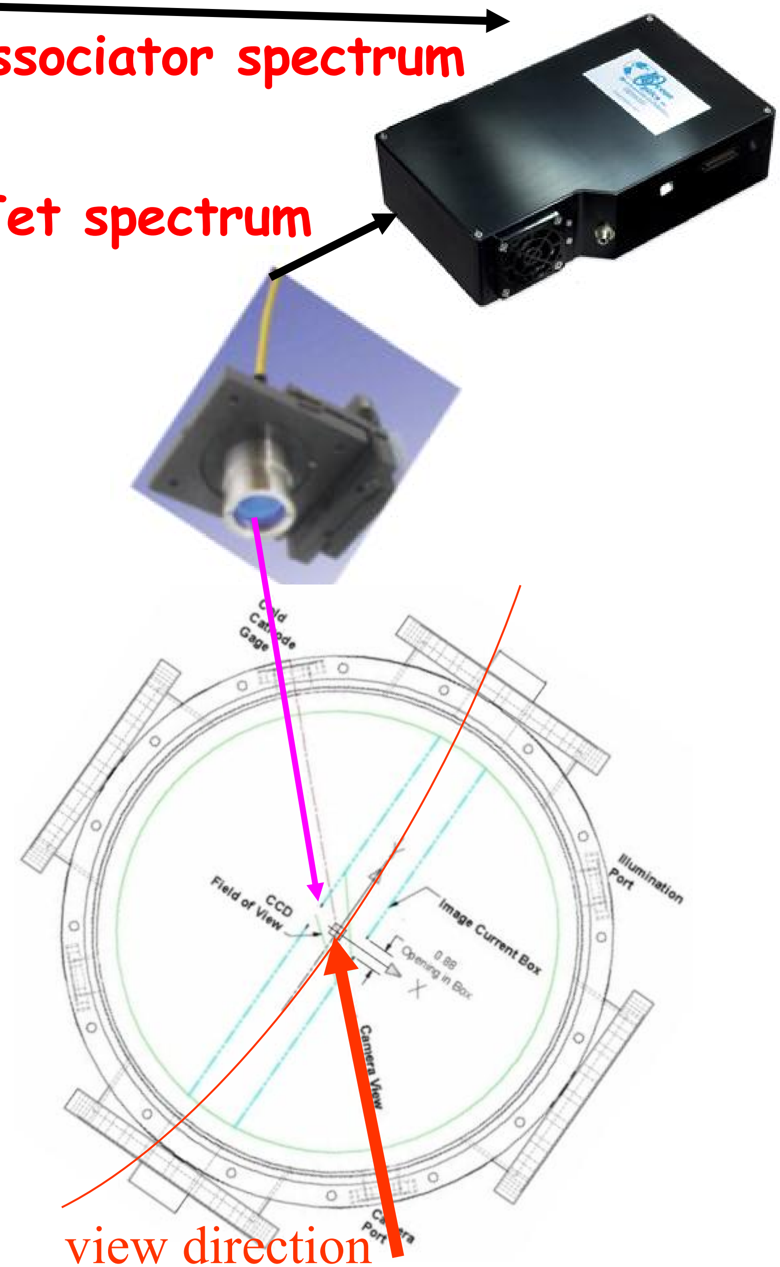
Vb ~1500-1800 m/s

RHIC H-jet beam profile imaging system



dissociator spectrum

Jet spectrum

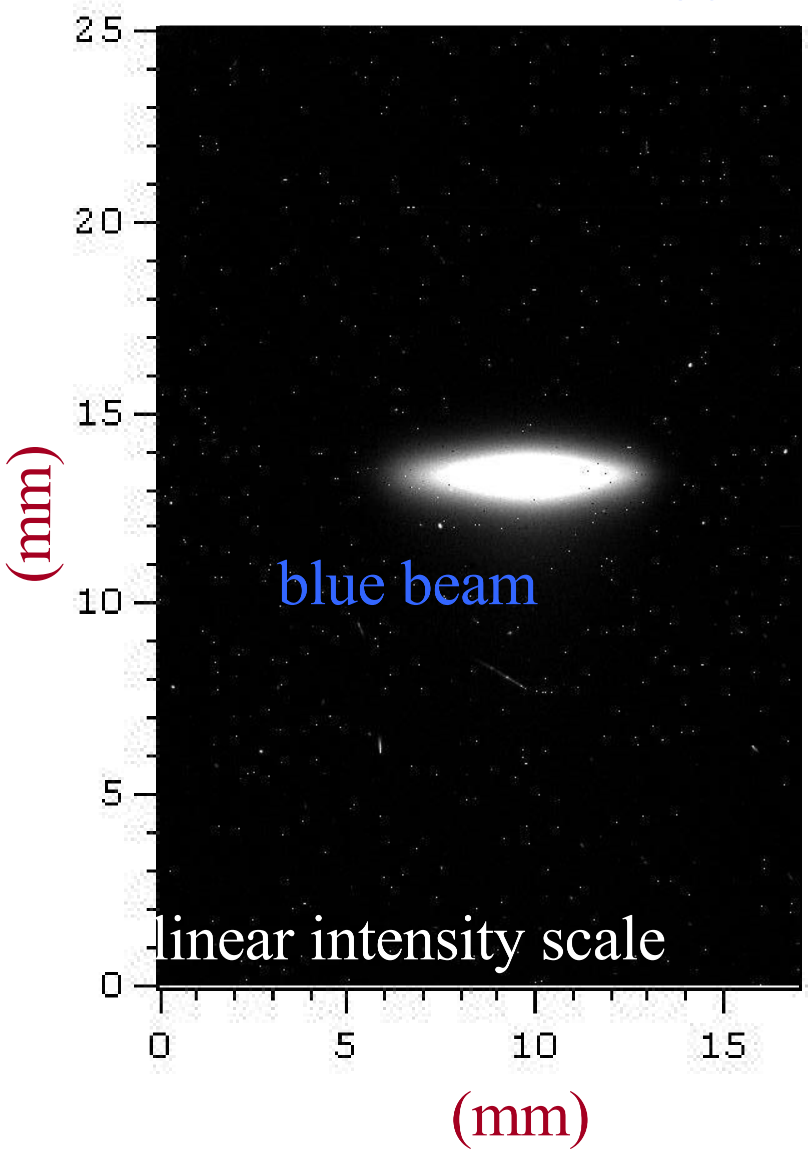


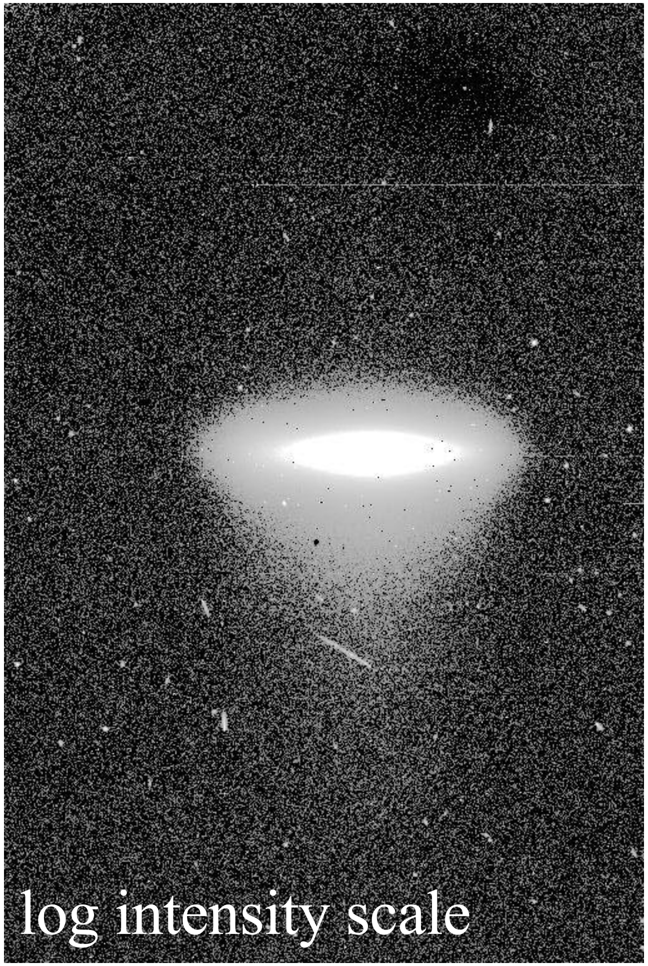
view direction

RHIC Run-8 p-p H-jet camera

Feb 1-20, 2008

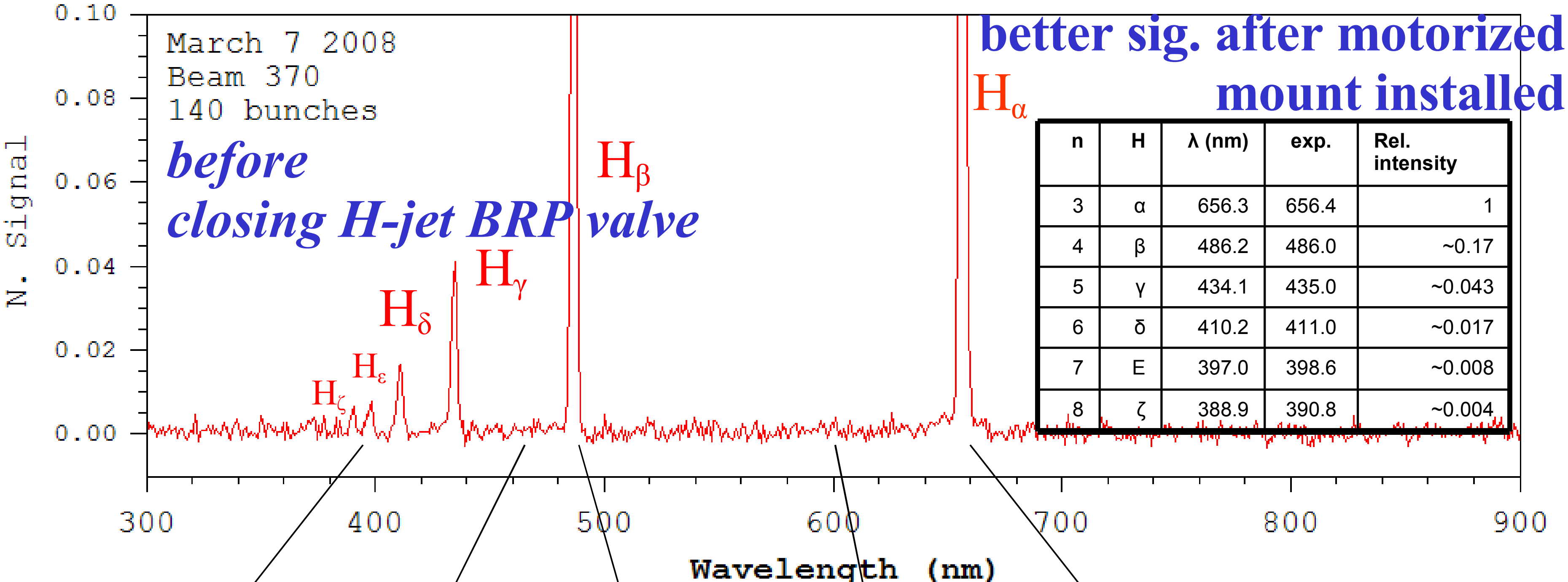
486 nm filter - H_β



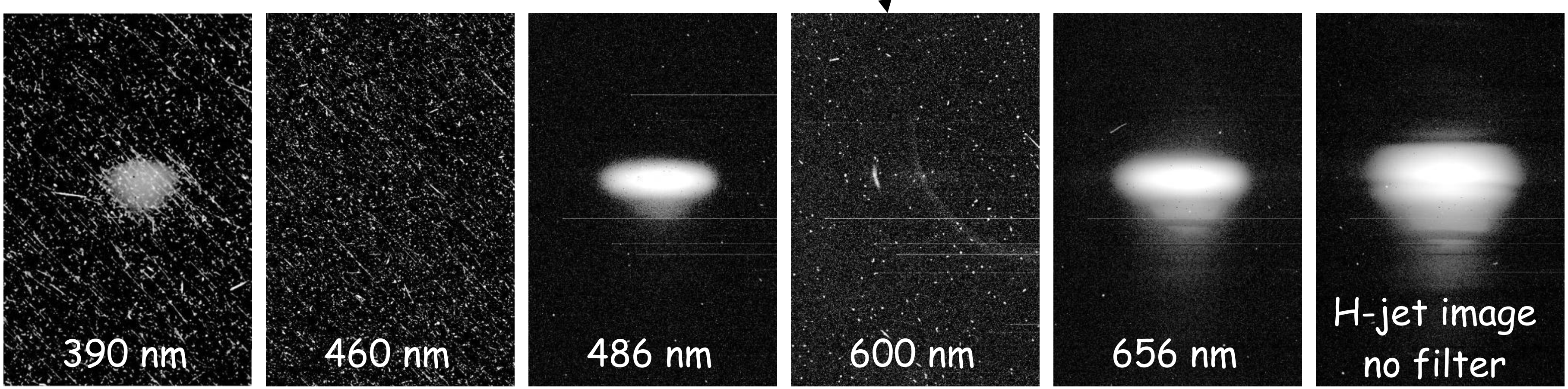


March 7 2008 H-jet spectrum beam 370

fill # 9992



n	H	λ (nm)	exp.	Rel. intensity
3	α	656.3	656.4	1
4	β	486.2	486.0	~0.17
5	γ	434.1	435.0	~0.043
6	δ	410.2	411.0	~0.017
7	E	397.0	398.6	~0.008
8	ζ	388.9	390.8	~0.004

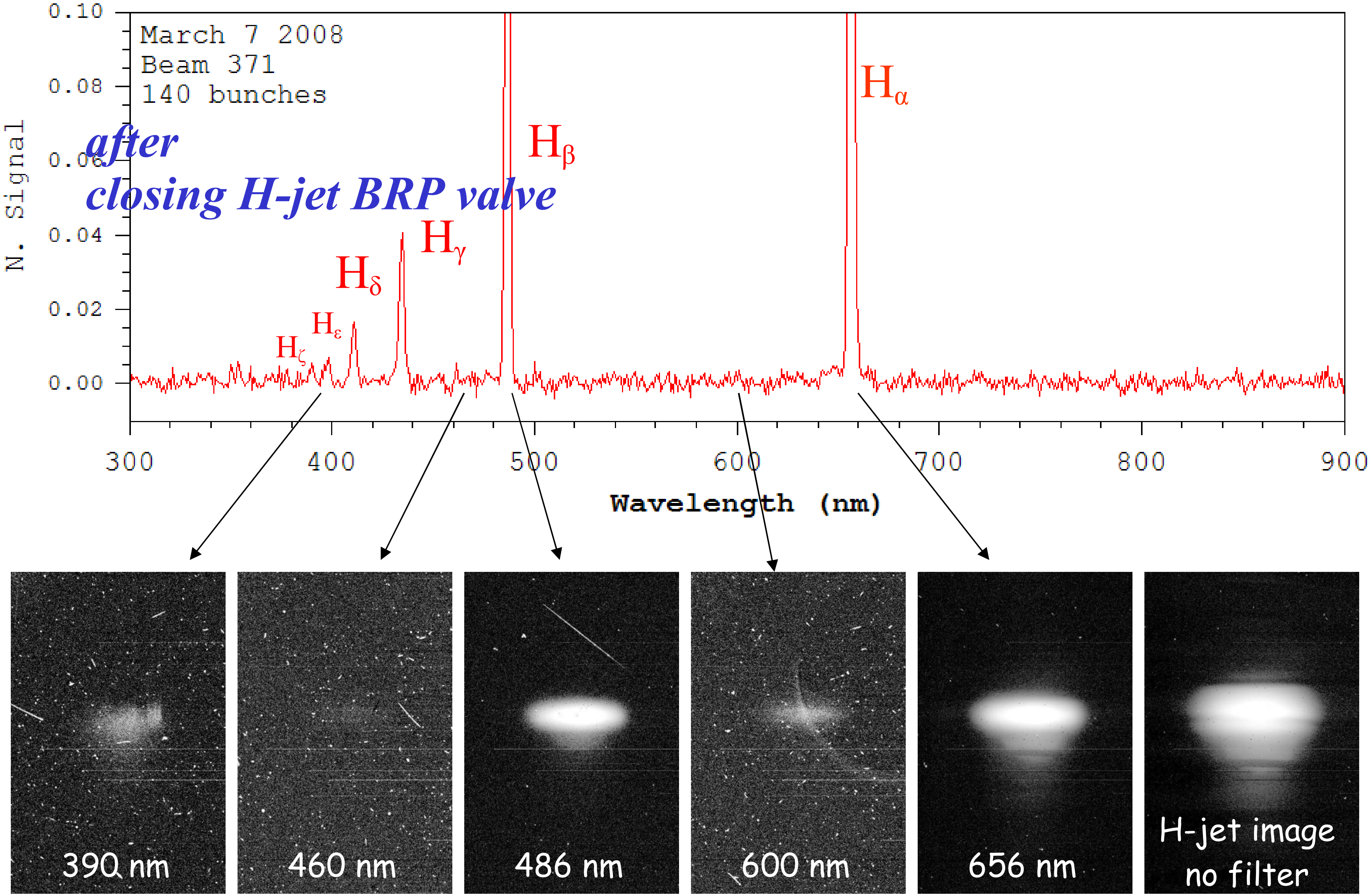


log intensity scale

H-jet spectrum contains only atomic hydrogen, no other impurities observed

March 7 2008 H-jet spectrum beam 371

fill # 9992



log intensity scale

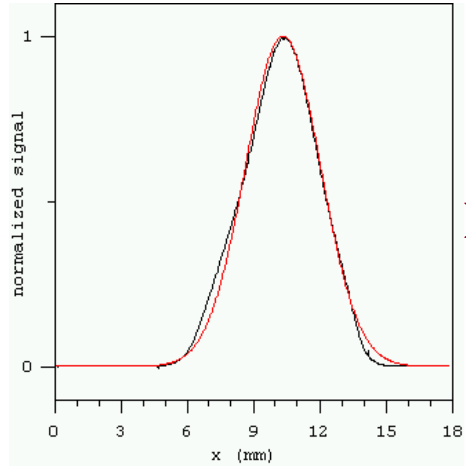
H-Jet is still mostly atomic hydrogen

Feb. 19, 2008

RHIC run-8 pp

blue beam profile

656 nm red filter - H_α



FWHM (x) = 4.0 mm

σ(x) = 1.7 mm

FWHM (x) = 5.6 mm

σ(x) = 2.4 mm } **H-jet**

Beam #191

109 bunches

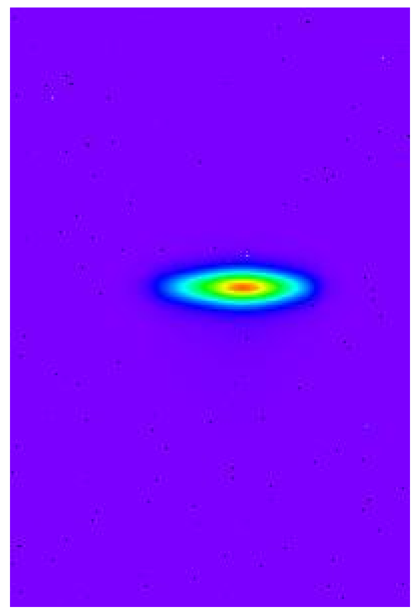
Fill # 9906

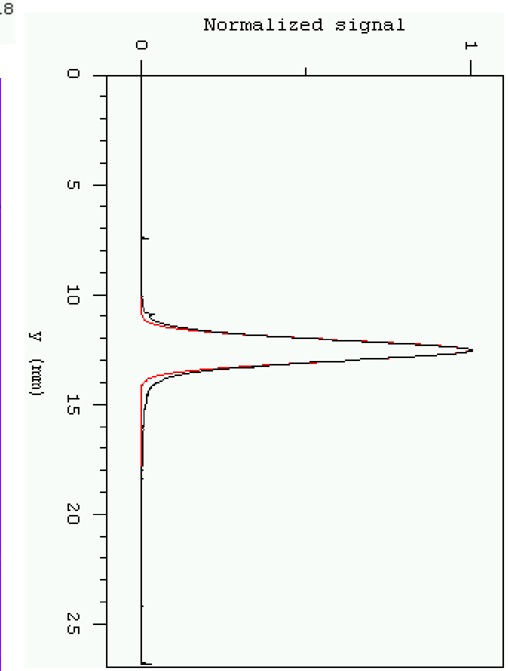
$5.8\text{x}10^6$ photons/sec on CCD

(~1.8 picoWatt)

$\sigma(y)$ = 0.48 mm → 14.2pi

IPM -12.0pi



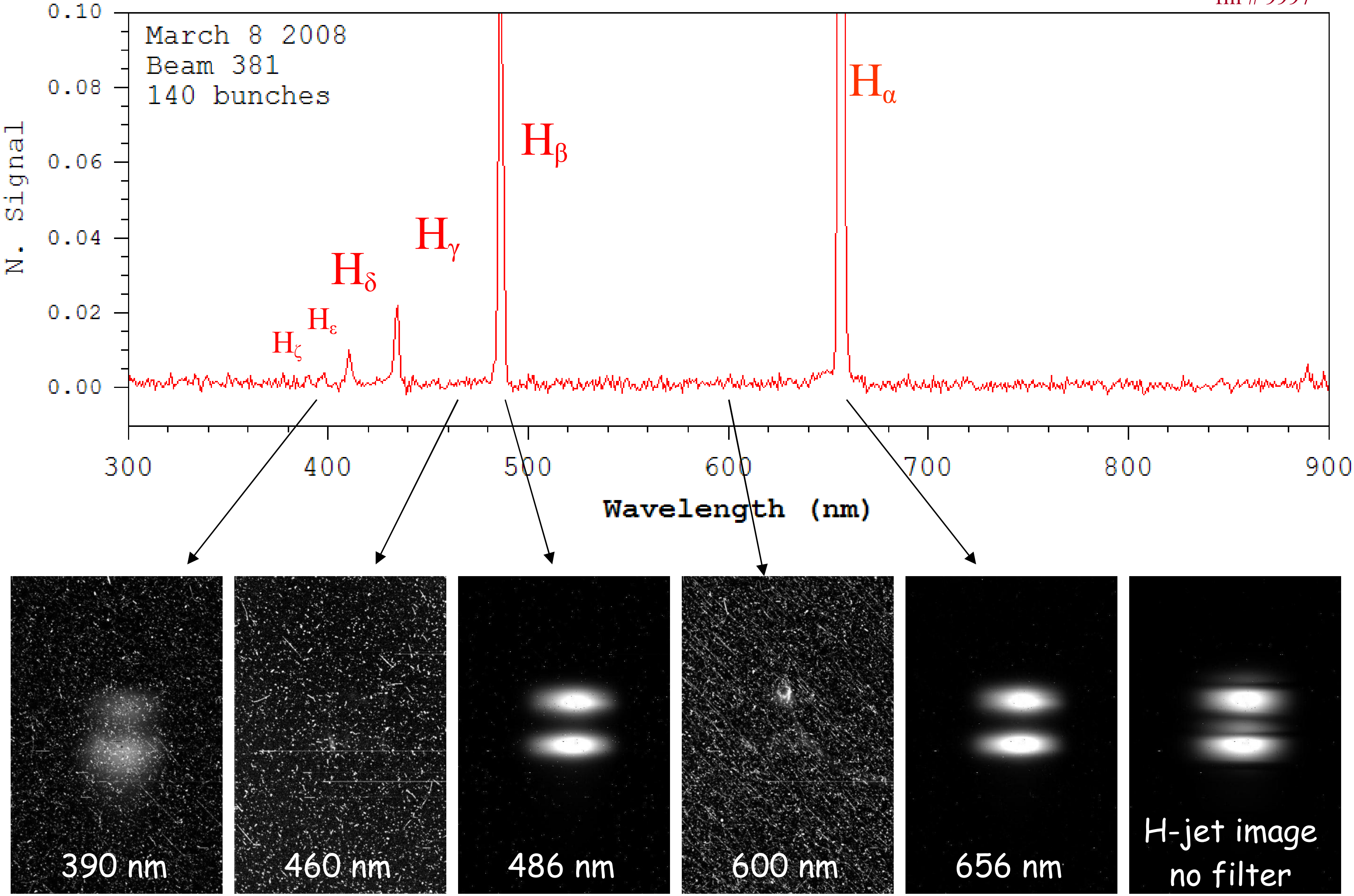


RHIC proton beam

FWHM (y) = 1.15 mm

March 8 2008 H-jet spectrum beam 382

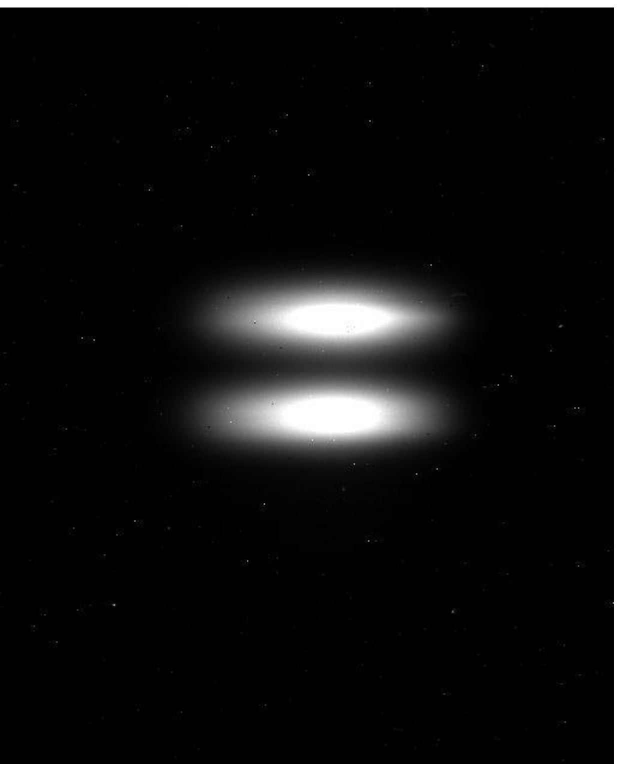
fill # 9997

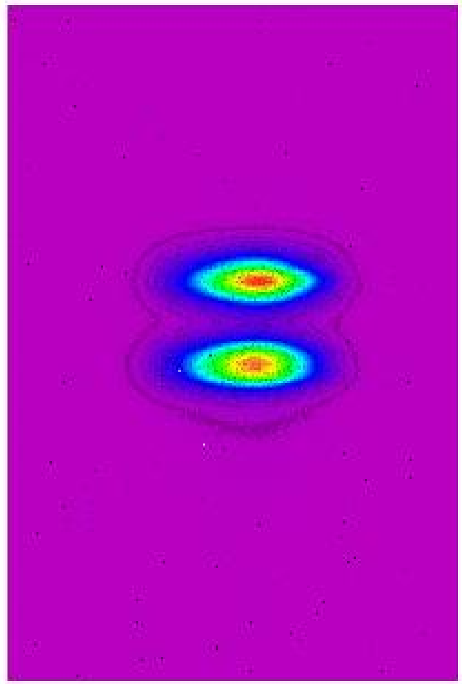


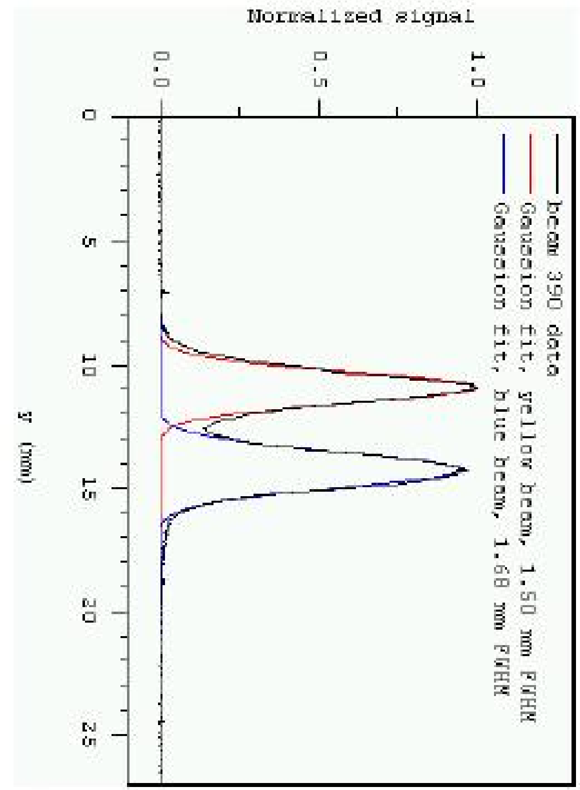
linear intensity scale

H-Jet images of blue & yellow beams

March 9, 2008, 1:44 pm
beam #390, fill #10000, p-p 135 bunches
H-jet ON, 656 nm filter





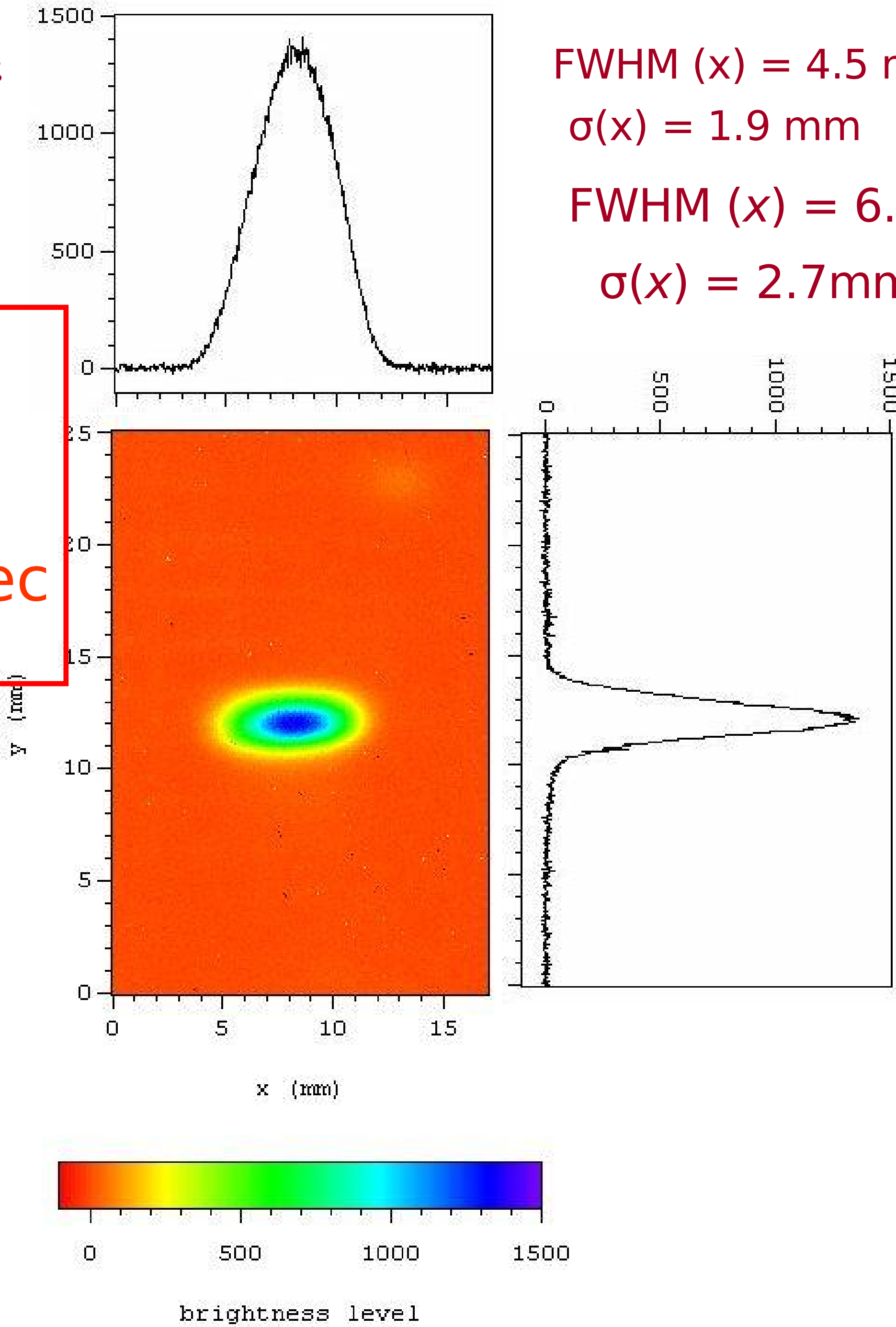


proton beam size
Yellow beam 1.50 mm (FWHM), σ=0.64 mm
Blue beam 1.68 mm (FWHM), σ=0.71 mm
Yellow-blue separation: 3.36 mm

Blue-Yellow separation ~ 5 σ

RHIC Yellow beam profile (Proton beam) after 656 nm red filter

Data of Feb 28, 2006
fill #7532
52-bunch RHIC proton beam
photon flux on CCD
4×10^5 red photons/sec
(~90 femtoWatt)



FWHM (x) = 4.5 mm
σ(x) = 1.9 mm

FWHM (x) = 6.4 mm
σ(x) = 2.7mm
} H-jet

486 nm filter: H-β line gives similar result

Pol' H-Jet on CERN COURIER Oct. 2005!

courierhttp://www.cerncourier.com/main/article/45/8/15

CERN COURIER

IoP Magazines

Polarized Protons

H-jet measures beam polarization at RHIC

The RHIC accelerator collides 100 GeV polarized protons head-on to study the contribution of gluons to the proton spin. But how is the degree of polarization of the beam known? Willy Haeberli explains.

Résumé

Jet de H pour mesurer la polarisation du faisceau au RHIC

L'ensemble d'accélérateurs RHIC de Brookhaven produit des collisions frontales entre des protons polarisés de 100 GeV afin d'étudier le rôle des gluons dans le spin du proton. Mais comment déterminer le degré de polarisation du faisceau? C'est très simple en théorie, mais très compliqué en pratique: on mesure la diffusion des particules d'un faisceau frappant une cible d'atomes d'hydrogène dont on connaît la polarisation.

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is unique. In addition to accelerating heavy ions, it also accelerates spin-polarized protons to high energies and enables the study of collisions between polarized protons with centre-of-mass energies up to 500 GeV.

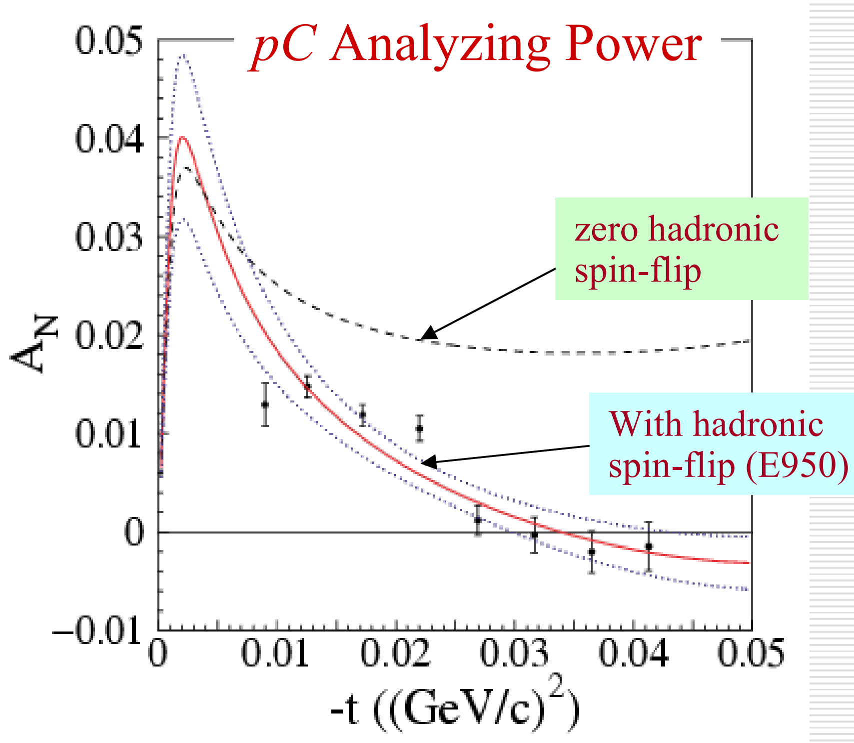
A_N at Coulomb Nuclear Interference (CNI) Region

$$A_N \approx C_1 \, \phi_{flip}^{em\,*} \, \phi_{non-flip}^{had} + C_2 \, \phi_{non-flip}^{em\,*} \, \phi_{flip}^{had}$$

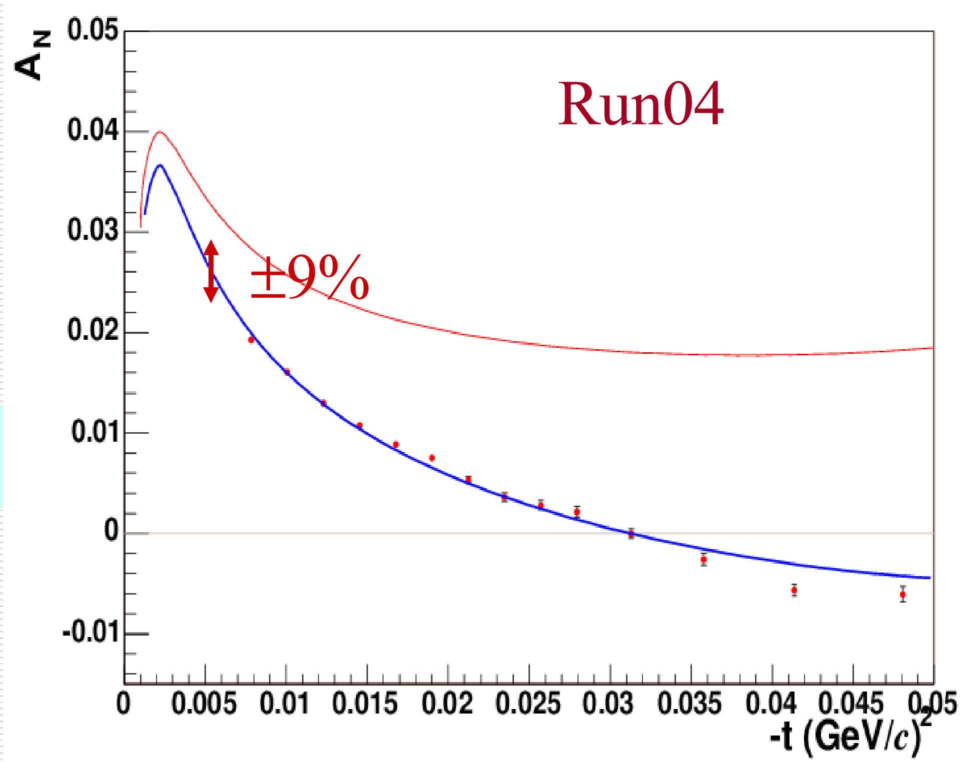
(High energy & small *t* limit)

$\propto (\mu_p - 1)$ | $\propto \sqrt{\sigma_{pC}^{had}}$ | $\propto \alpha / t$ | ?

Reggen/Pomeron exchange



Phys.Rev.Lett.,89,052302(2002)



unpublished

E_{beam} = 21.7GeV

E_{beam} = 100 GeV