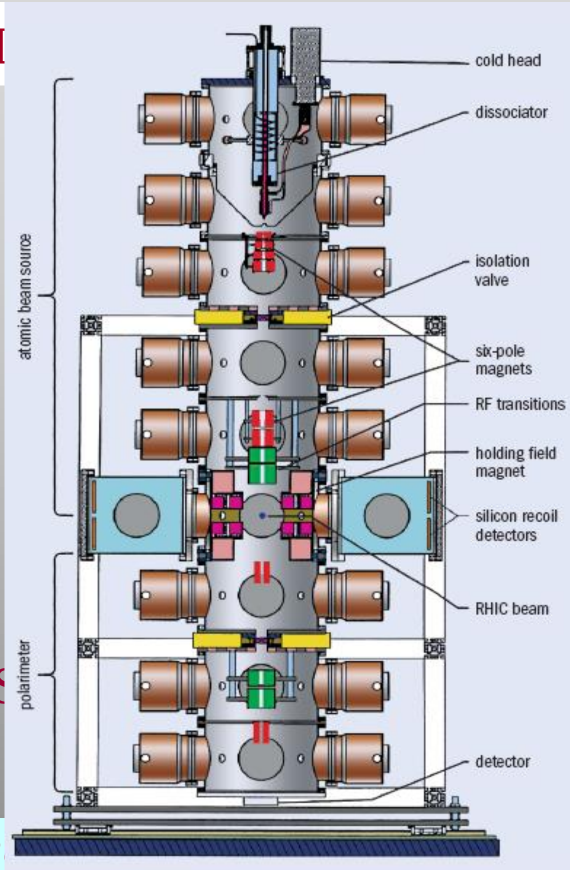
# H-jet preparation for the Run-22

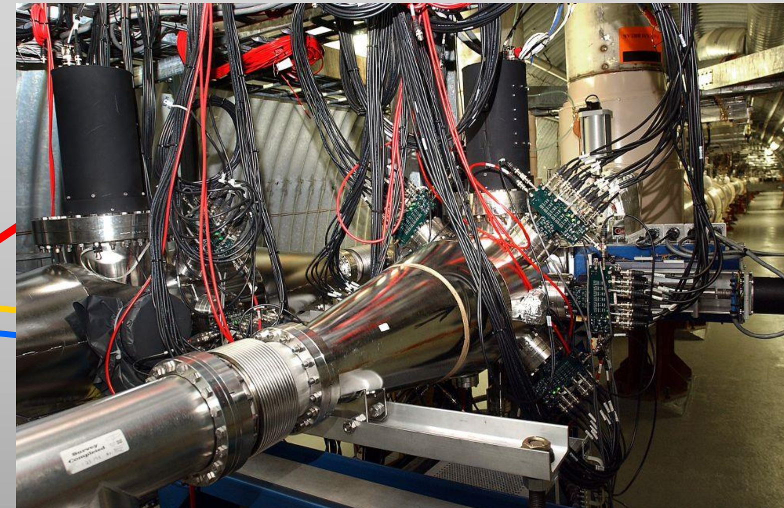
A.Zelenski, G.Atoian, A.Poblaguev
Credit to beam instrumentation, vacuum and control groups.

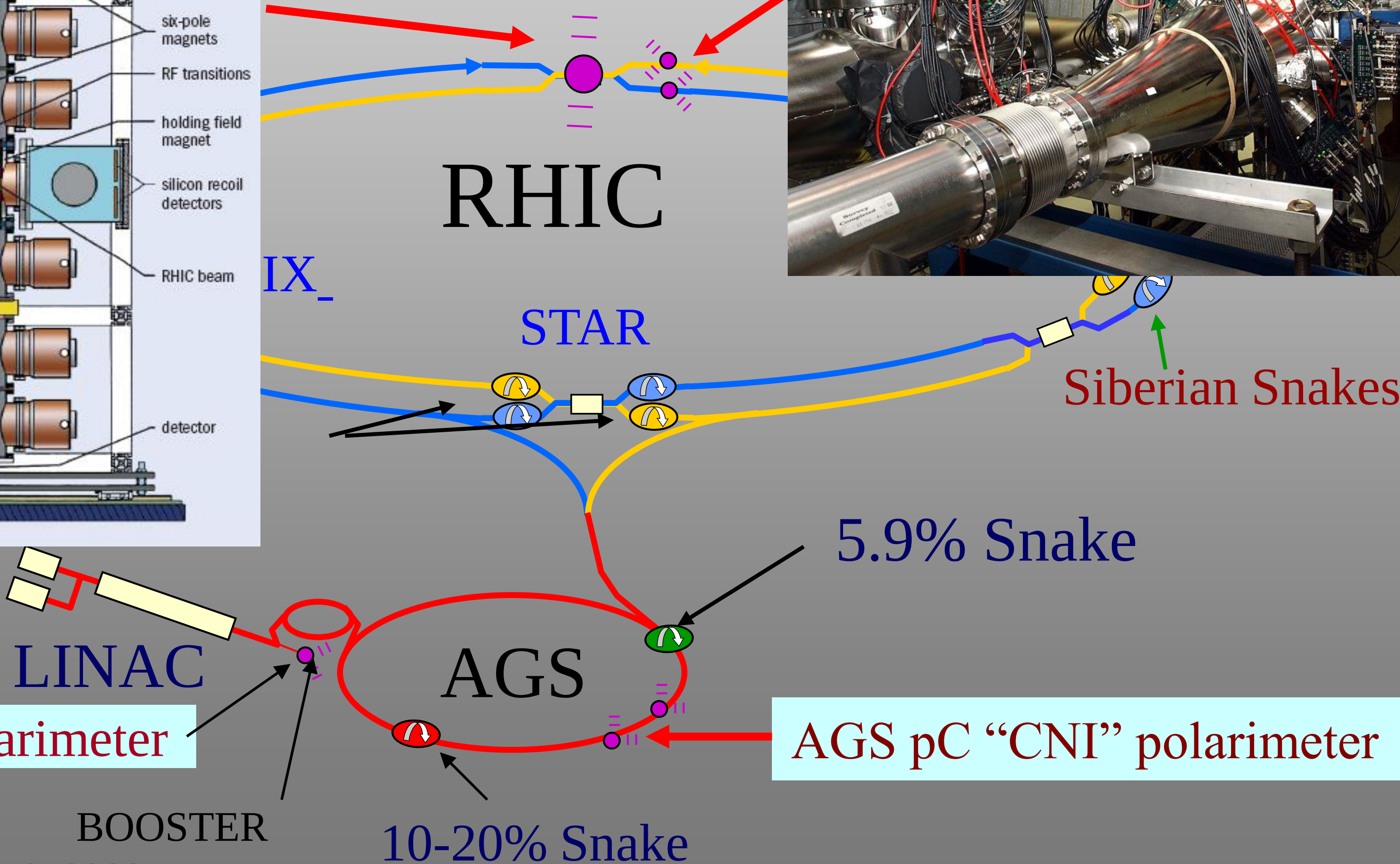
- **H-jet operation in Runs-2017-21**
- **Detectors development for short bunch spacing EIC operation**
- **Beam profile monitor for LEREC**
- **Preparation for the Run-22.**

# Polarization facilities at RHIC. Polarimeters.

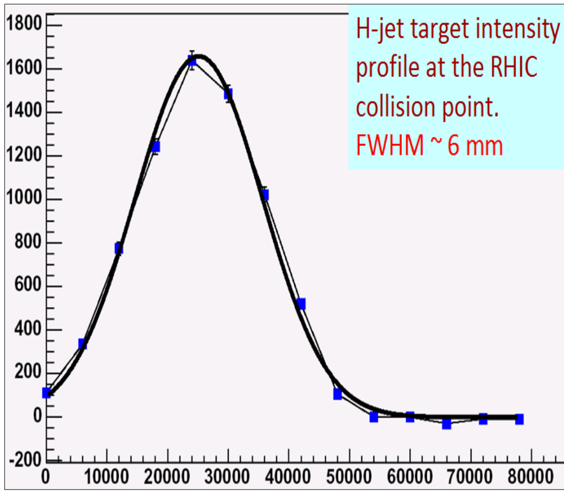
I tion, $L_{max} = 1.6 \times 10^{32}\ s^{-1}cm^{-2}$ , $50 \le \sqrt{s} \le 500$ GeV



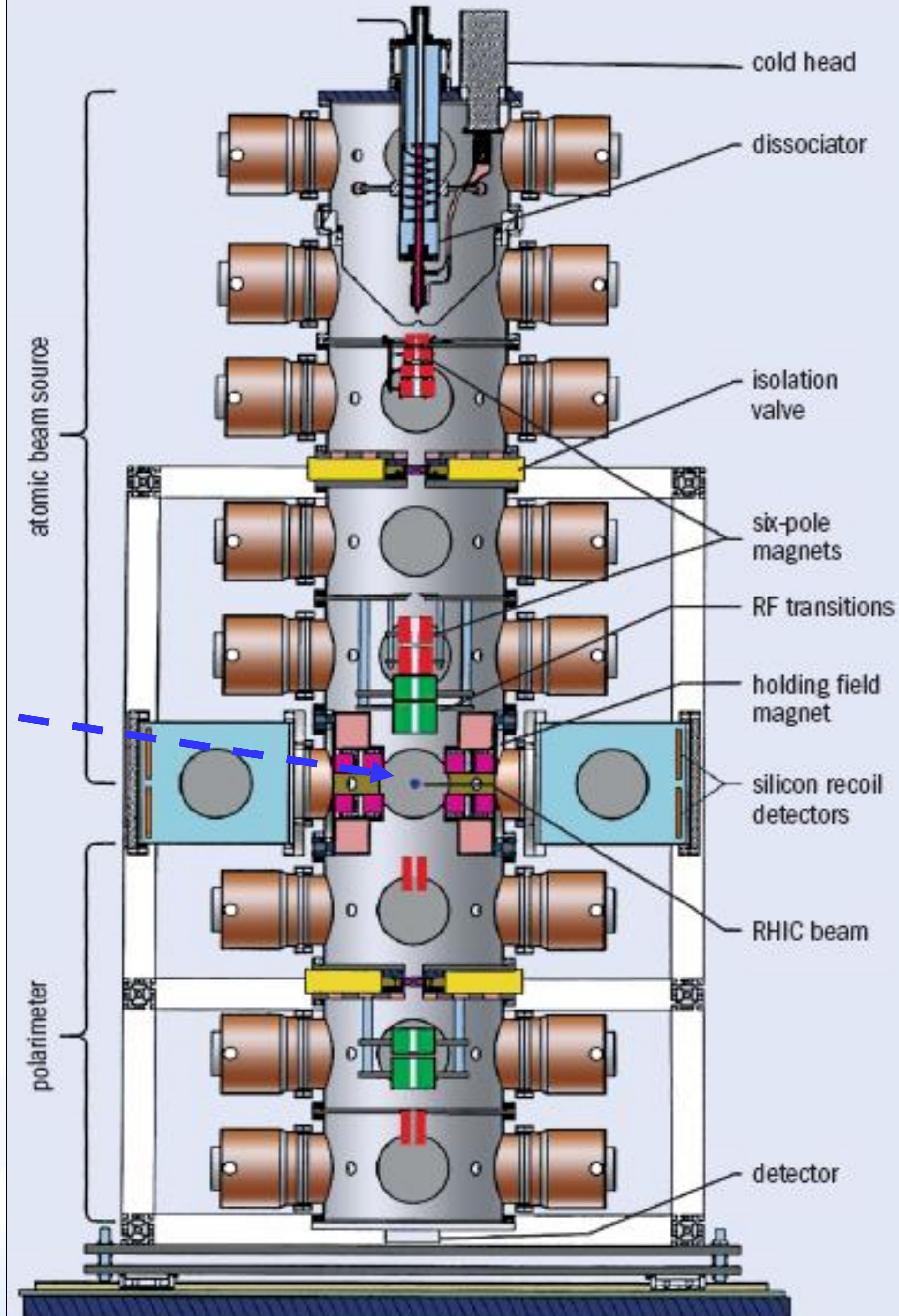


# H-jet polarimeter



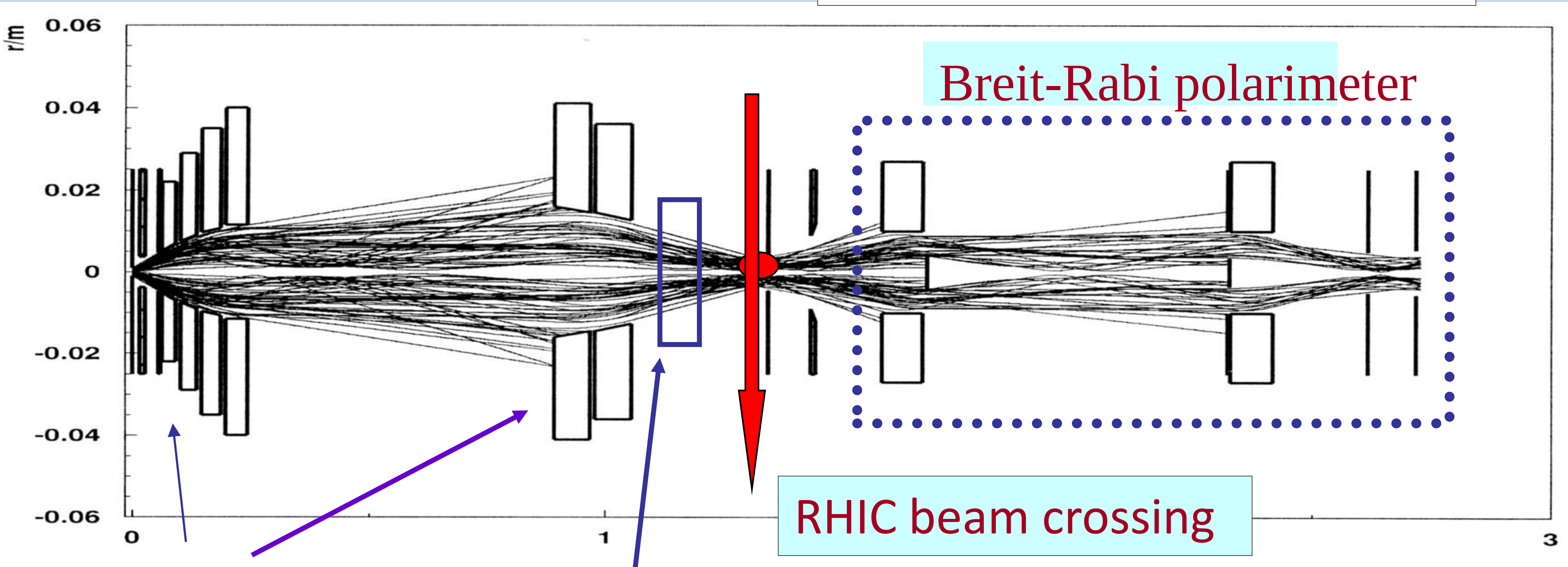

The distance from the nozzle
To collision point is 127 cm

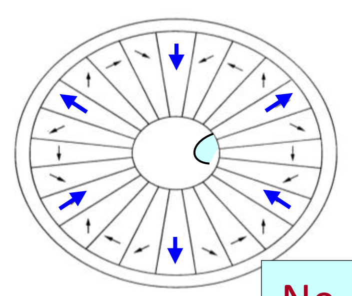
Record 12.6·$10^{16}$ atoms/s
Atomic Beam intensity.
Atomic beam velocity ~ 1800 m/s
H-jet thickness at the collision point-1.2 ·$10^{12}$ atoms /$cm^2$



# Spin filtering technique. Atomic Beam Sources.

Hydrogen atoms with electron polarization: $m_J$=+1/2 trajectories



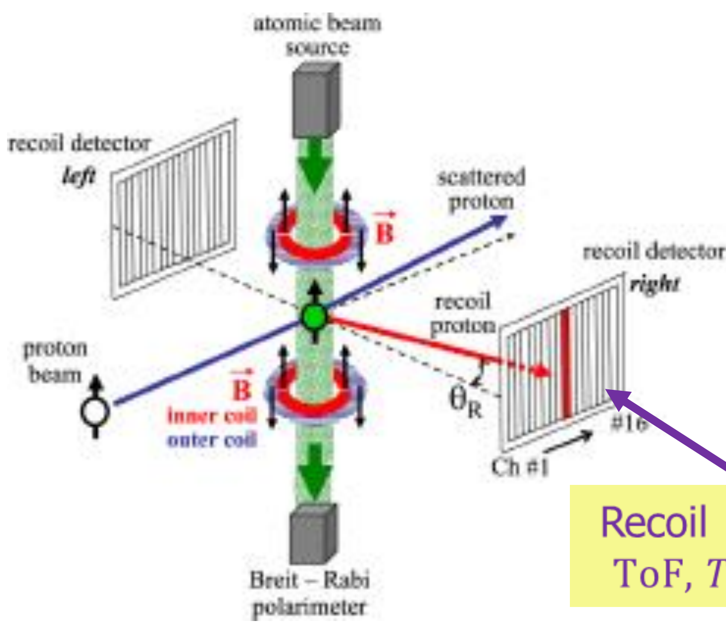
RF transition, polarization transfer from electrons to protons

Ne-Fe-B permanent magnet sextupole - 1.7 T gradient 5.7 T/cm

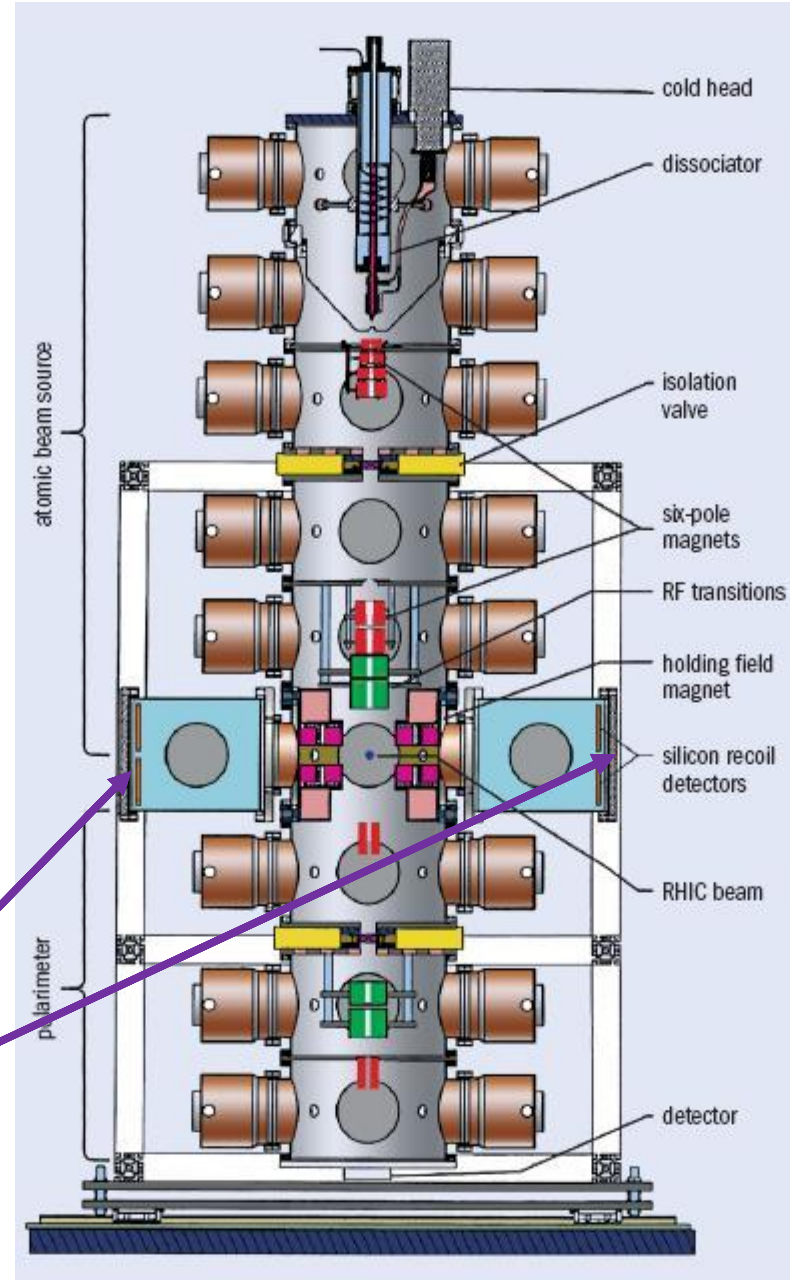
Magnet system design, NIM A256, (2006) T.Wise, W.Haeberli, H.Kolster et al.

# Polarized Atomic Hydrogen Gas Jet Target (HJET)

- The HJET polarimeter was commissioned in 2004.
- It was designed to measure absolute polarization of 24-250 GeV/c proton beams with systematic errors better than $\Delta P/P \leq 0.05$
- The atomic hydrogen polarization in the Jet is 95.7%
- Jet intensity $12.6 \times 10^{16}$ atoms/sec
- Jet density $1.2 \times 10^{12}$ atoms/cm$^2$
- The Jet polarization is flipped every 10 min.




Recoil detectors
ToF, $T_{REC}$, $\theta_{REC}$

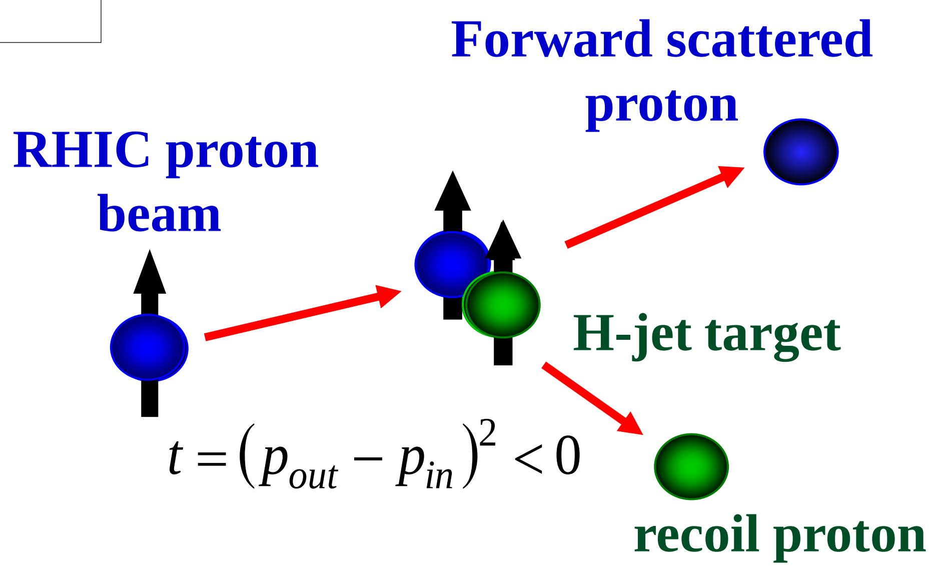


# H-Jet polarimeter.

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

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

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




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

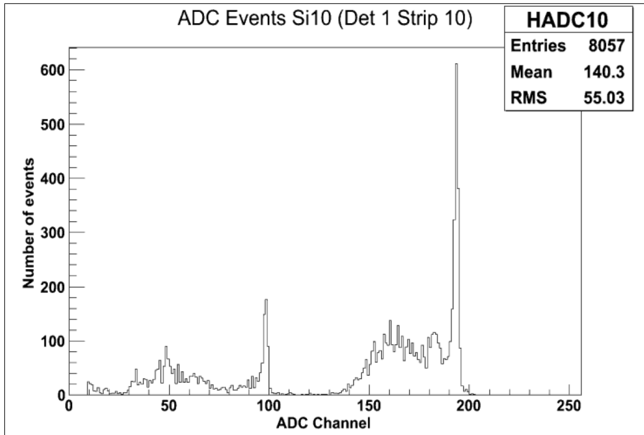
$$\Rightarrow \boxed{P_{\text{beam}} = -P_{\text{target}}\frac{\varepsilon_{\text{beam}}}{\varepsilon_{\text{target}}}}$$

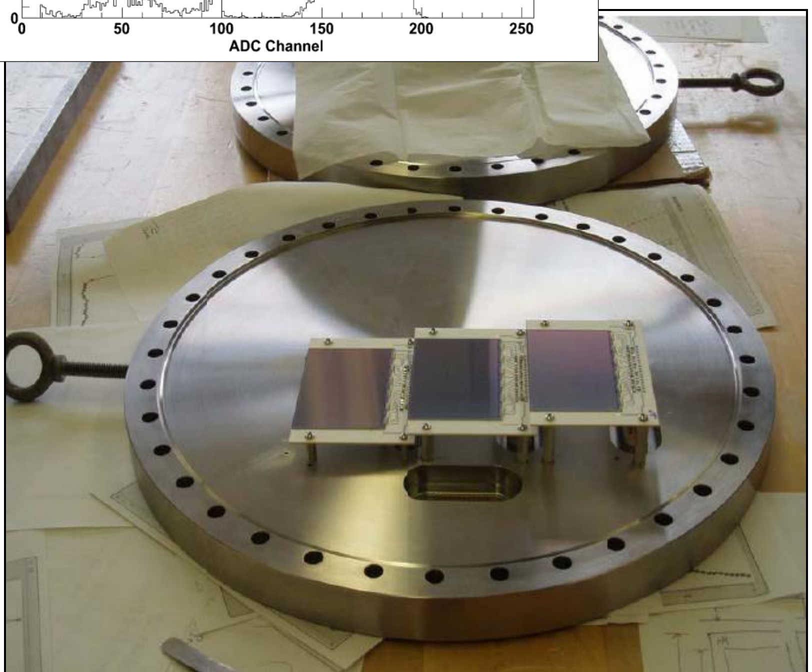
$$\frac{\Delta P_{\text{beam}}}{P_{\text{beam}}} \approx \frac{\Delta P_{\text{target}}}{P_{\text{target}}} \oplus \frac{\Delta\varepsilon_{\text{target}}}{\varepsilon_{\text{target}}} \oplus \frac{\Delta\varepsilon_{\text{beam}}}{\varepsilon_{\text{beam}}}$$

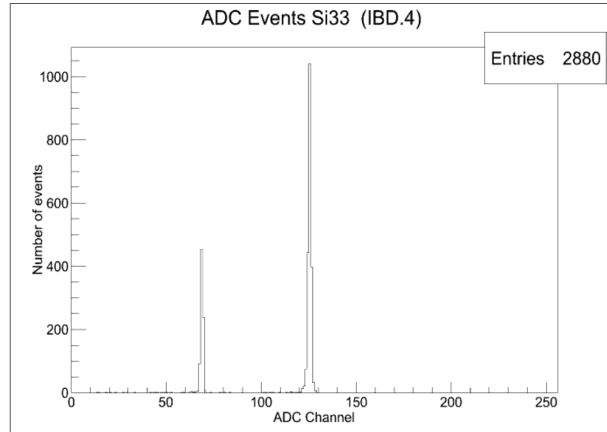
<5%

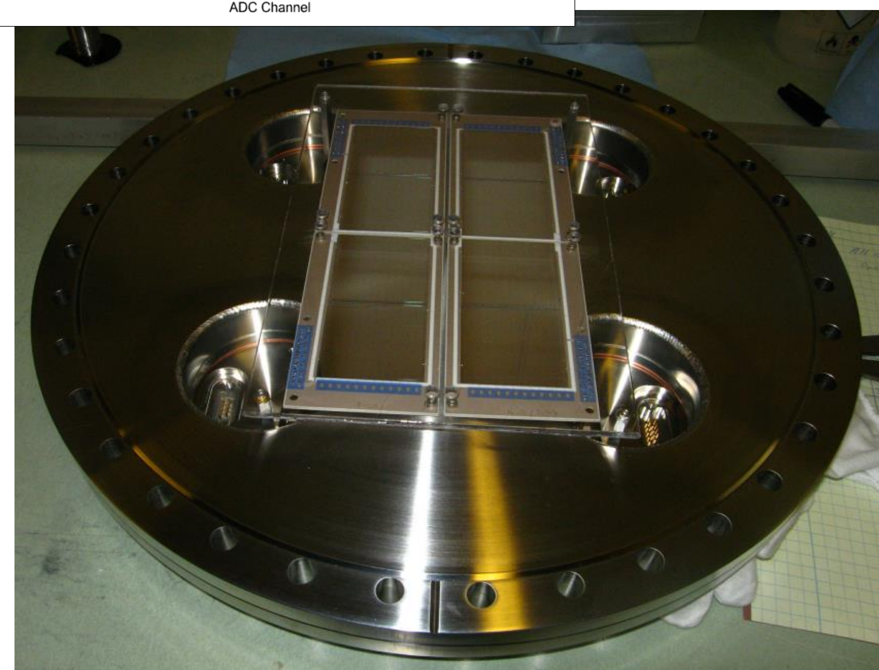
$P_{target}$ is measured by Breit- Rabi Polarimeter

# New Si-strips detector assembly. Better energy resolution. Large solid angle and kinematic range, Run 2015





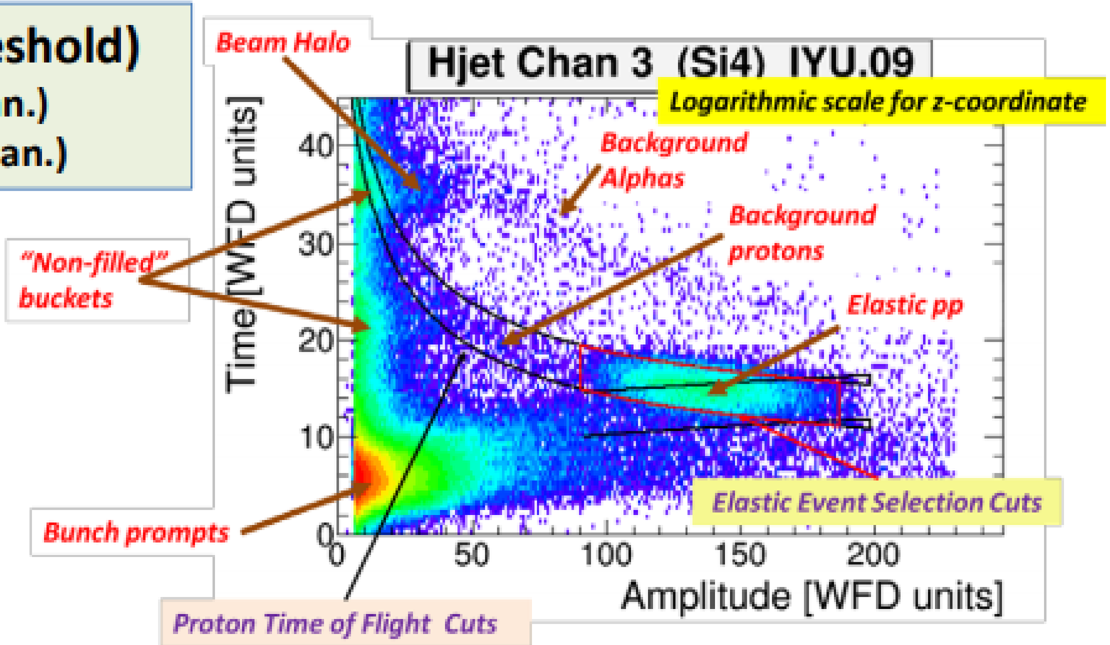



# *Background overview*

Poblaguev, PSTP2017

**Event rate (for the 0.5 MeV threshold)**

- **Total: ~ 5 kHz (~ 50 Hz per chan.)**
- **Elastic pp: ~150 Hz ( ~ 1.5 Hz per chan.)**



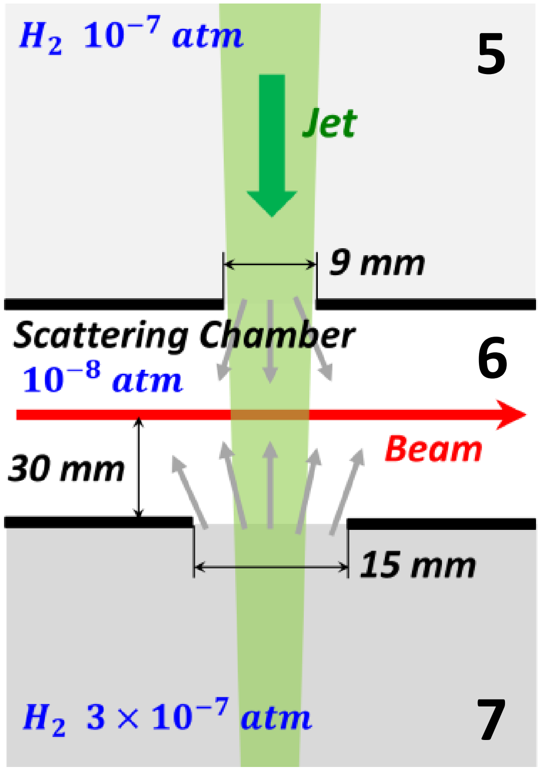

**The "prompts" strongly dominate in the event rate but do not affect the elastic $pp$ data.**

**Background related the systematic uncertainties:**

- **$pA$ inelastic scattering - the dominant background $\sim 3\%$, can be subtracted**
- **"Molecular hydrogen" - $\lesssim 1\%$, effectively dilute the Jet polarization, can be subtracted**
- **Inelastic $pp \to Xp$ - Essential for 255 GeV, can be eliminated by the event selection cuts**

**The elastic pp events can be reliably isolated**

## *Sources of systematic errors in HJET : Molecular Hydrogen*




- In HJET the atomic hydrogen polarization of about $96\%$ is controlled with high accuracy $\sim 0.1\%$ by means of holding magnetic field and Breit-Ruby polarimeter).
- The molecular hydrogen effectively dilute the Jet polarization by a factor $b_{MH}/(1+b_{MH})$
- About 10 years ago, the molecular hydrogen background was evaluated $b_{MH}\sim 3\%$ (*with a large experimental uncertainty)* using quadrupole mass spectrometer.

1. **Molecular hydrogen in the Jet**

   Could be experimentally evaluated by turning off RF transition : $b_{MH}^{(1)} = 0.03 \pm 0.03\%$

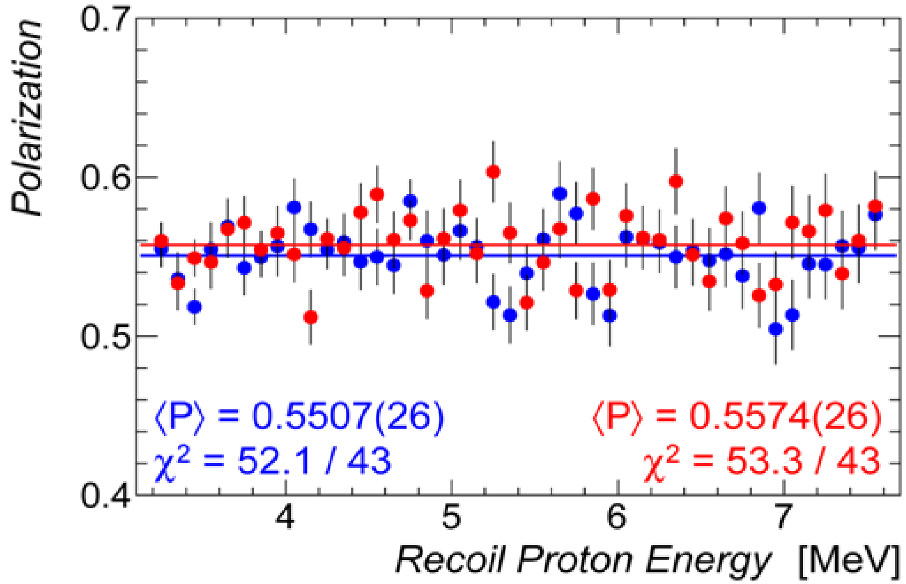
2. **Molecular hydrogen diffused from chambers 5 and 7.**

   Since this background has a wide (flat) z-coordinate density profile, it is expected to have the same $dN/d\sqrt{T_R}$ distribution for all Si strips and, thus, it may be efficiently eliminated by the background subtraction. In-situ evaluation of the background level gave $\sim 0.55 \pm 0.15\%$

The residual level after background subtraction $b_{MH}^{(2)} = 0.08 \pm 0.11\%$
***(for the minimum systematic error cuts.)***

A.Poblaguev, PSTP 2017

# Results for minimum systematic error cuts




**Systematic correction summary $\widetilde{\delta_{corr}}$**

| Source | Correction (%) | Error (%) |
|---|---|---|
| Long term stability | | 0.1 |
| Jet Polarization | | 0.1 |
| Molecular Hydrogen (1) | −0.03 | 0.03 |
| Molecular Hydrogen (2) | −0.08 | 0.11 |
| pA scattering | | < 0.2 |
| p+p→X+p | −0.15 | 0.15 |
| Jet spin correlated noise | | < 0.2 |
| **Total Systematic** | **−0.26** | **< 0.37** |

Strong elimination of the systematic error sources resulted in a ~0.7% correction to the $\delta P/P$. The residual systematic error of 0.4% does not look underestimated.

$$\langle P_{\rm jet}\rangle = 0.957 \pm 0.001 \qquad \widetilde{\delta_{\rm corr}} = (-0.3 \pm 0.4_{syst})\%$$

$$\boldsymbol{P_{jet}^{\rm eff} = 0.955 \pm 0.004_{\rm syst}}$$

$$\boldsymbol{A_N^{\rm eff} = 0.03752 \times (1 \pm 0.004_{\rm syst} \pm 0.004_{\rm stat})}$$

$$\boldsymbol{A_N^{\rm eff} = 0.03745 \times (1 \pm 0.004_{\rm syst} \pm 0.004_{\rm stat})}$$

***Effective systematic error*** $\boldsymbol{0.6\%}$



A.Poblaguev, PSTP 2017

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# Systematic error analysis in the absolute hydrogen gas jet polarimeter at RHIC ☆

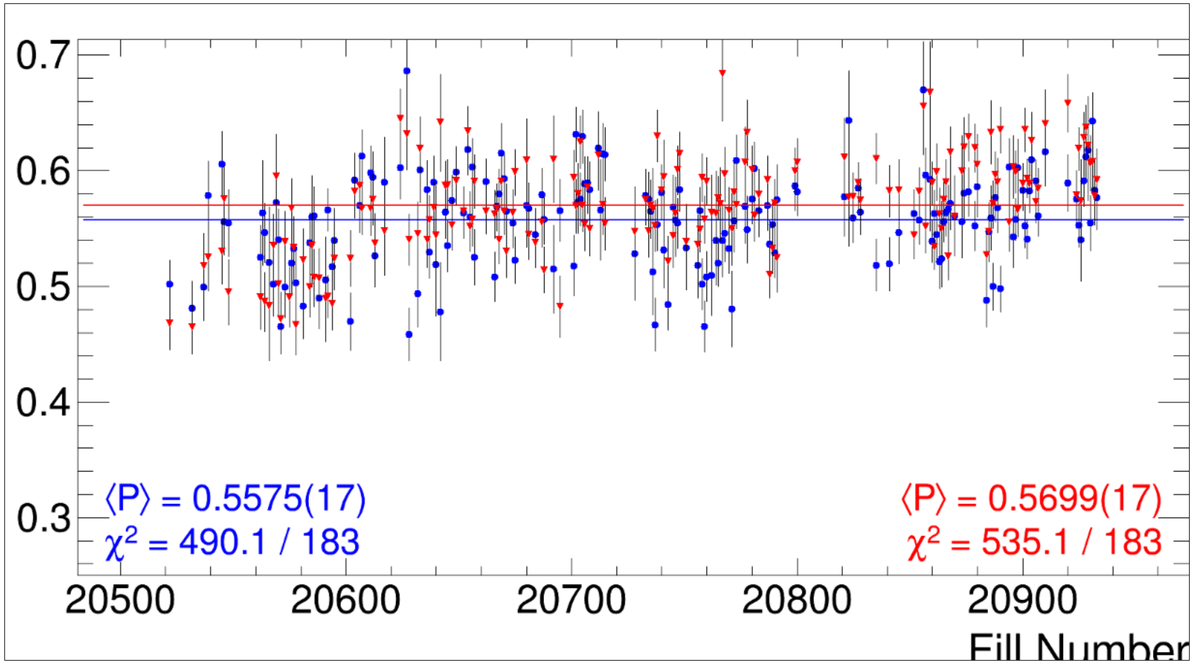
A.A. Poblaguev, A. Zelenski, G. Atoian, Y. Makdisi, J. Ritter

## Abstract

The Polarized Atomic Hydrogen Gas Jet Target polarimeter (HJET) is operated at the Relativistic Heavy Ion Collider (RHIC) since 2004 to measure the absolute polarization of each colliding proton beam. Polarimeter detectors and data acquisition were upgraded in 2015 to increase the solid angle, energy range, and to improve the energy and time resolution. These upgrades along with an improved beam intensity and polarization allowed us to greatly reduce the statistical and systematic errors for the proton polarization measurements in RHIC Runs 15 ( $E_{\text{beam}} = 100$ GeV) and 17 (255 GeV). For a typical 8 h RHIC store, the measured proton beam average polarization was about $P_{\text{beam}} \sim 55 \pm 2.0_{\text{stat}} \pm 0.3_{\text{syst}}\,\%$. The elastic $pp$ analyzing power, $A_{\text{N}}(t) \sim 0.04$, was determined with a precision of about $|\delta A_{\text{N}}(t)| \sim 0.0002$ in the momentum transfer squared range $0.001 < -t < 0.020\,\text{GeV}^2$. In this paper we present a detailed systematic error analysis of the polarization measurements at HJET. Perspectives of using the HJET based absolute polarimeters in the future Electron Ion Collider (EIC) will be also discussed.

# Absolute Beam Polarization measurement in Run 2017, 255 GeV

**A typical result for a 8-hour store:** $\langle P_{\mathbf{beam}} \rangle = (\sim 56 \pm 2.0_{stat} \pm 0.3_{syst})\%$




*Statistical error summary:*

| RHIC Fill | Blue Beam | Yellow Beam |
|---|---|---|
| 20522 - 20592 | $52.08 \pm 0.41$ | $49.57 \pm 0.40$ |
| 20598 - 20712 | $56.84 \pm 0.26$ | $55.93 \pm 0.25$ |
| 20728 - 20845 | $54.77 \pm 0.27$ | $56.97 \pm 0.26$ |
| 20852 - 20933 | $56.50 \pm 0.25$ | $58.47 \pm 0.25$ |
| 21145 - 21150 | $59.30 \pm 1.20$ | $64.40 \pm 1.30$ |
| **Run Average** | $\mathbf{55.64 \pm 0.14}$ | $\mathbf{56.32 \pm 0.14}$ |

# H-jet is the absolute, high precision polarimeter !

- High (~4.5%) analyzing power in a wide energy range (23-250 GeV).
- High event rate due to high intensity (~300 mA) circulated beam current in the storage ring (~2.5 % 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:

$$P_{beam} = (1/A)\mathrm{Beam}_{asym} / \mathrm{Target}_{asym}$$

A typical result for 8-hrs store: $\langle P \rangle = (\sim 56 \pm 2.0\,\textit{stat} \pm 0.3\textit{syst})\ \%$

# Polarization Profiles

- Polarization loss from intrinsic resonances: polarization lost at edge of beam $\rightarrow$ polarization profile.
- Impact of polarization profile on beam polarization at collisions:

$$P(x,x',y,y') = P_0 e^{-\frac{x^2+x'^2}{2\sigma_{x,P}^2}} e^{-\frac{y^2+y'^2}{2\sigma_{y,P}^2}}; I(x,x',y,y') = I_0 e^{-\frac{x^2+x'^2}{2\sigma_{x,I}^2}} e^{-\frac{y^2+y'^2}{2\sigma_{y,I}^2}}; R_H = \frac{\sigma_{x,I}^2}{\sigma_{x,P}^2}; R_V = \frac{\sigma_{y,I}^2}{\sigma_{y,P}^2}$$

$$P_{jet} = \frac{P_0}{(1+R_H)(1+R_V)}$$

$$P_{coll} = P_{jet}\sqrt{\frac{(1+R_V)(1+R_H)}{(1+\frac{1}{2}R_V)(1+\frac{1}{2}R_H)}}$$

<P>=Pjet-average polarization measured by H-jet or p-Carbon polarimeter in a sweep mode. $P_0$-maximum polarization in the beam center.

For $R_H \approx R_V = R$ and small: $P_0 = Pjet\ (1+R)^2$ ;

$P_{coll.} = Pjet\ (1+ \frac{1}{2}R)$

Bazilevskiy, Roser, Fisher

# Upper limit for polarization in collisions (single spin asymmetry) vs. H-jet polarization.

$$P_{coll} = \frac{2Pjet}{1+\sqrt{\frac{P_{jet}}{P_0}}}$$

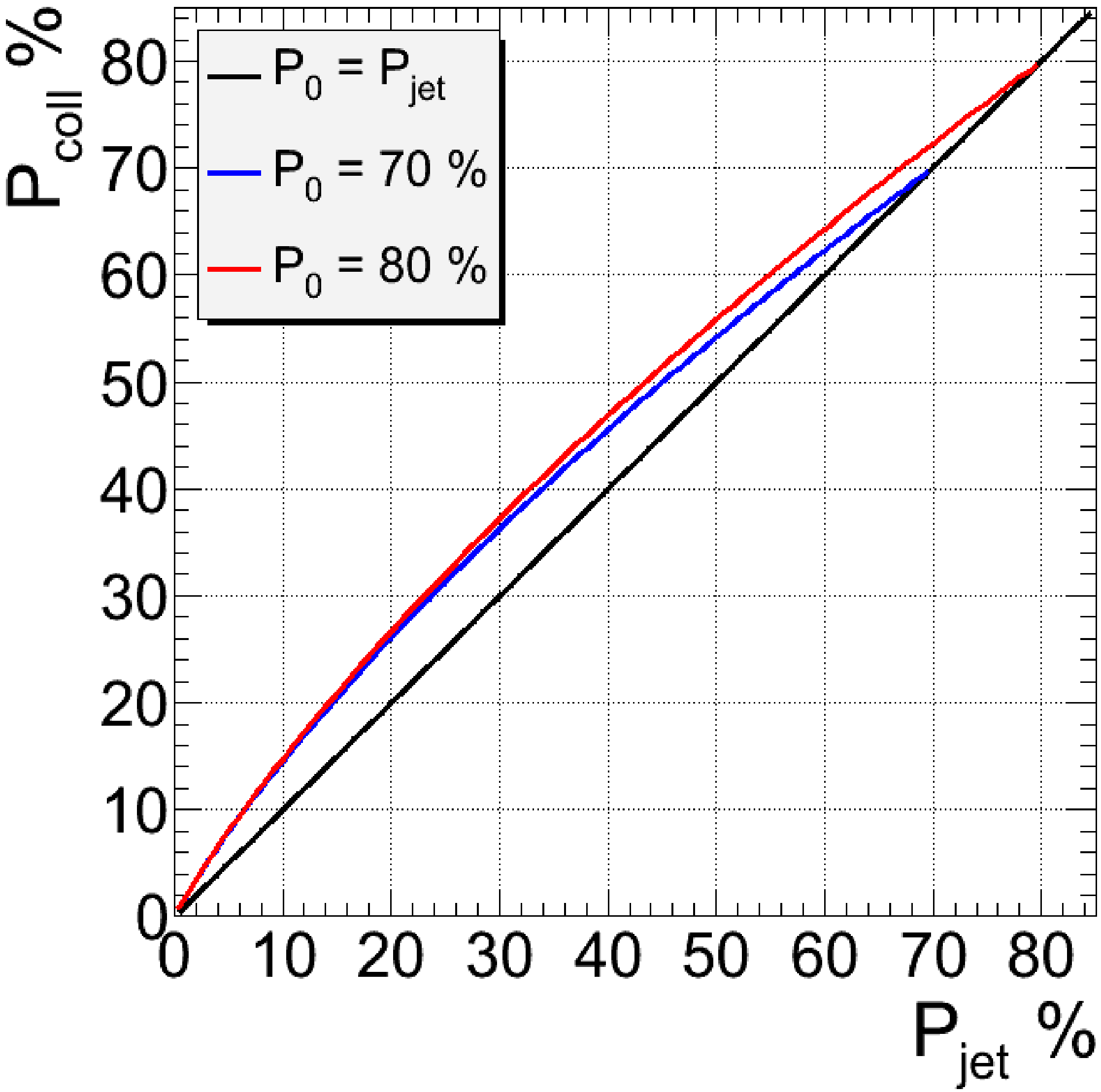
$P_0$=80% - Red line

$P_0$=70% - Blue line

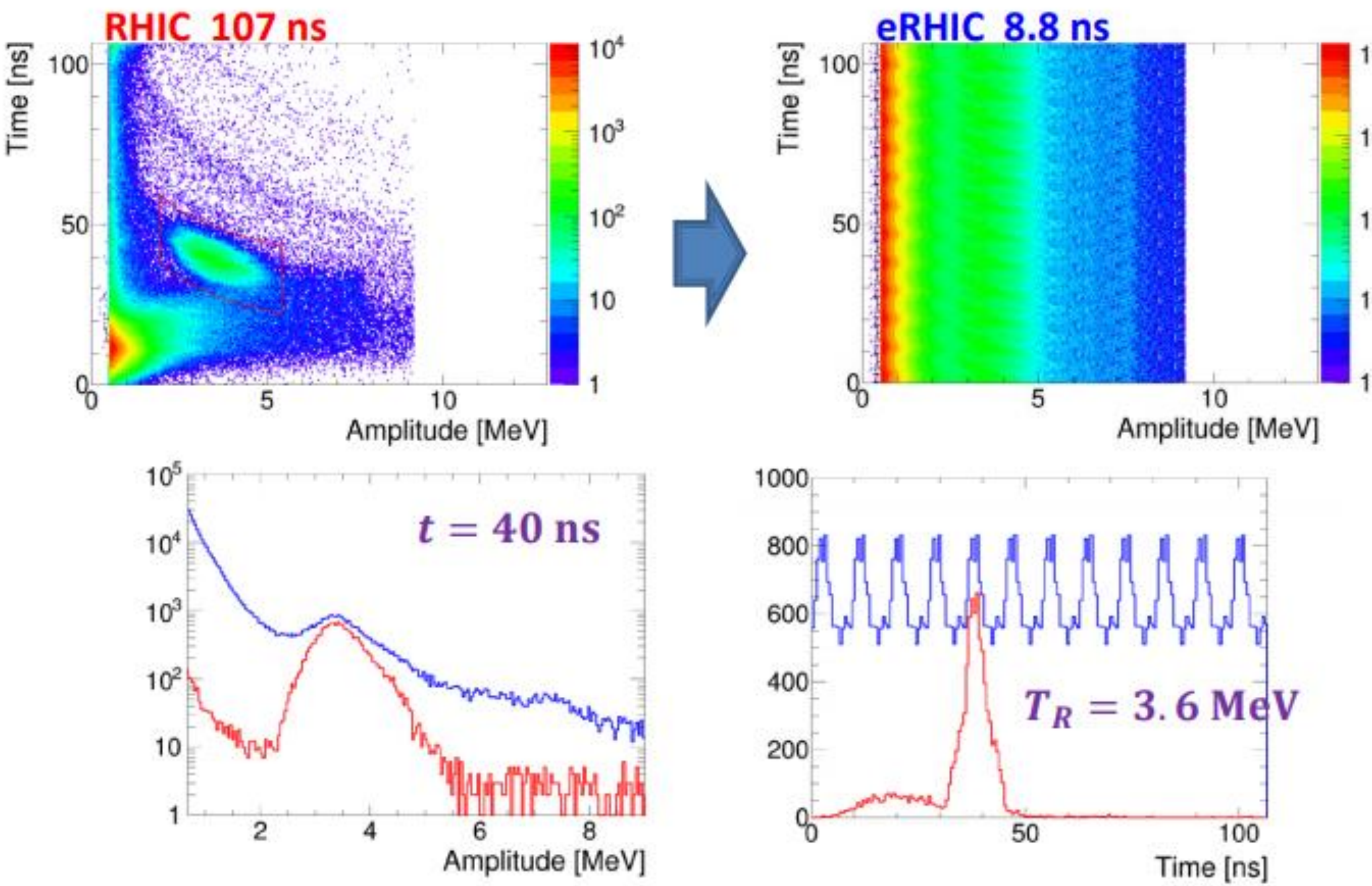
$P_{jet}$- black line
low limit on $P_{coll}$

For $P_0$=55 %, maximum
Pcoll~ 60%

R=0.1, $P_{coll.pC}$~ 58%



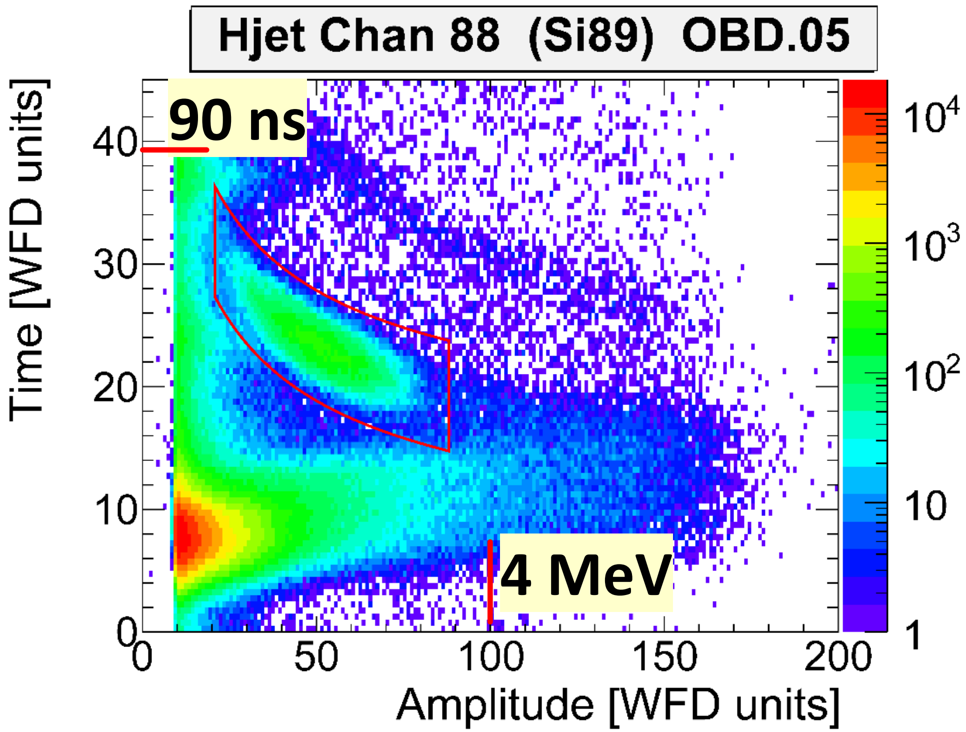
# From 120 bunches (107 ns) to 1320 bunches (8.8 ns)




**The background is about factor 3 larger than elastic signal (in the peak) !**

# *The prompts at HJET*

**Poblaguev, 2017**




**Possible contributions to the prompts:**

- For the $pp$ scattering
  - pions, $p_{\text{jet}} \to \pi + X \quad (T_R < 3\ \text{MeV})$
  - photons, $\pi^0 \to \gamma\gamma$
- For the $pA$ scattering
  - "target ion" dissociation
    $A \to (p, d, \alpha, \dots) + X$
- Beam halo
- Induced pulses (must not be seen at HJET)
- Optical photons (???)

The prompts rate is reduced by factor 3-4 if the jet is OFF

- For 107 ns bunch spacing at RHIC, prompts are not real problem. However, it may be an issue at EIC with 10 ns bunch spacing
- Due to relatively low rate, $< 100\ \text{Hz/strip} \quad (T_R > 0.5\ \text{MeV})$, of the prompts, the problem can be solved by *hardware* and/or *software* elimination of prompts.

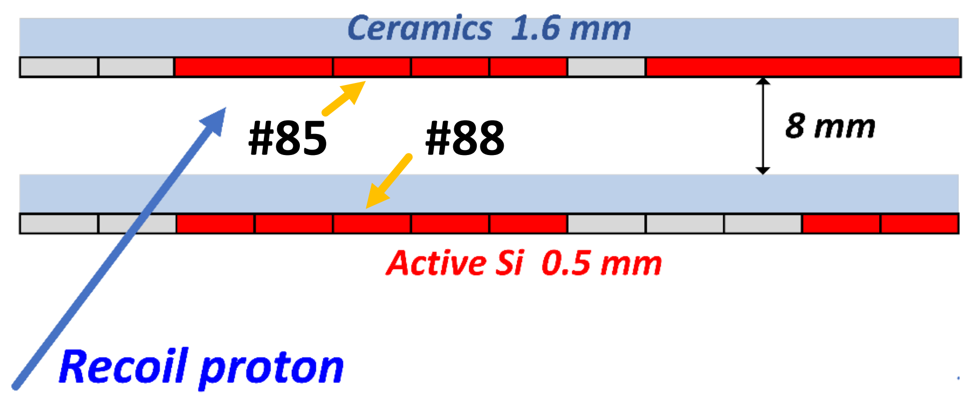
# *Prototype of a double-layer detector for HJET*

**Poblaguev, 2021**

**The prototype was assembled using available components:**

- **1.6 mm of ceramics between layers**
- **~10 mm gap between layers**

**One of 8 HJET detectors was replaced by the prototype.**

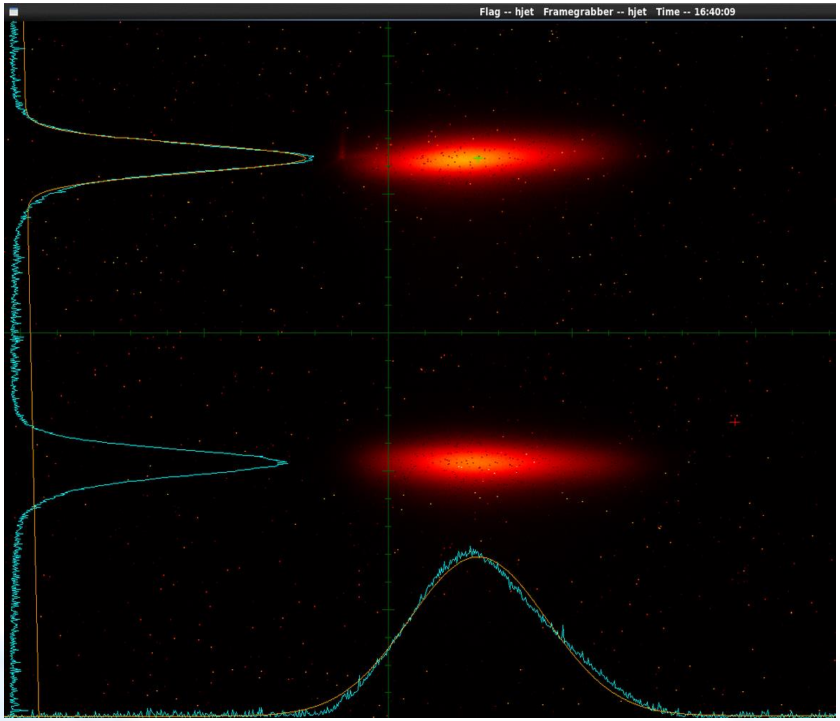



- The goal was to veto punch-through $\pi, p, d, \alpha, \ldots$ , which are expected to have momentums 100-500 GeV/c. The ceramics between layers must not be the problem for that.
- The detector was tested in 5.76 GeV/n Au beam (Run 2020)
- The prompts rate in the second layer was 30-40% compared to the first one.
- The prompts veto efficiency can be evaluated **as $\lesssim$10-20%.**

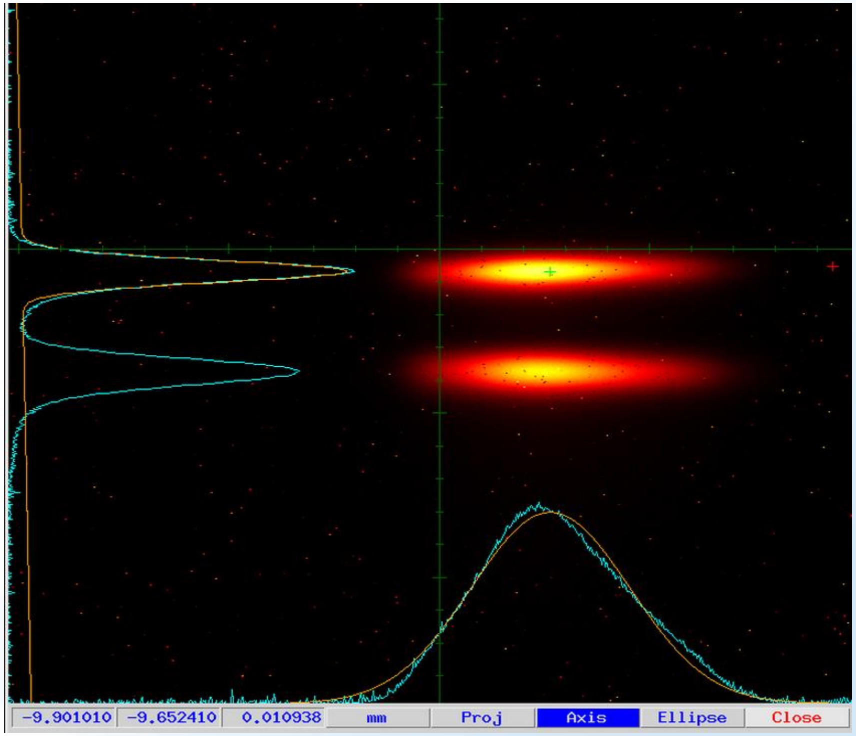
The test results were inconclusive. Most of the prompts are not punch-through $\pi, p, d, \alpha$ . Due to relatively low rate, $< 100\ \mathrm{Hz/strip}\ \ (T_R > 0.5\ \mathrm{MeV})$, of the prompts, the problem can be solved by *hardware* and/or *software* elimination of prompts.

# H-jet luminescence monitor

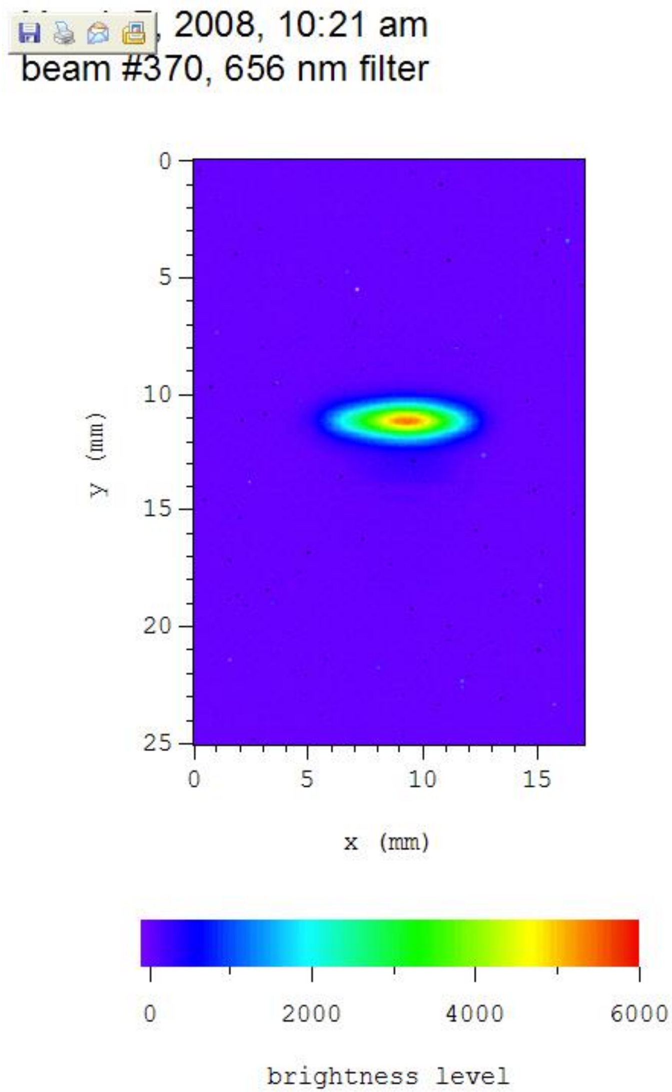
At injection

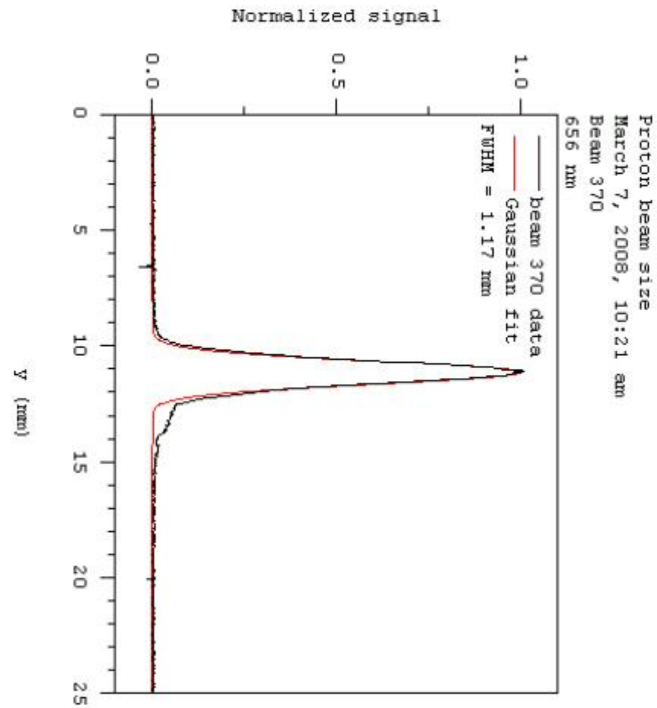



At store 250 GeV



# RHIC beam (100 GeV) vertical emittance measurement by luminescence monitor in the H-jet polarimeter.



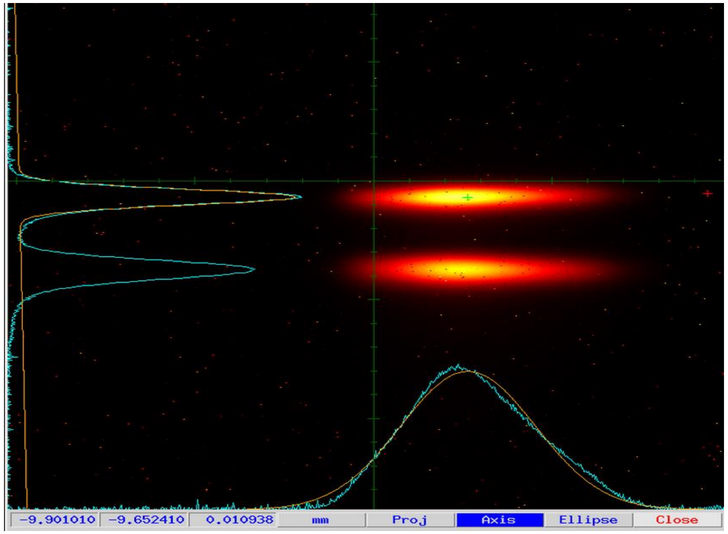

*FWHM proton beam size = 1.17 mm*

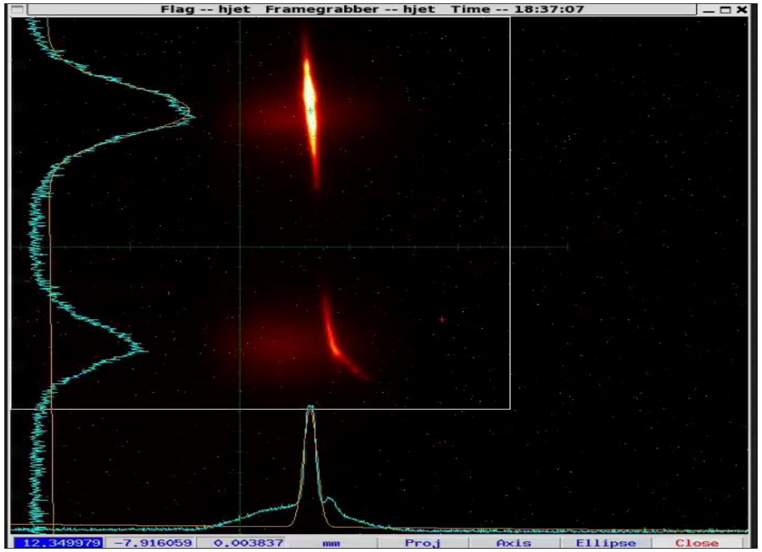
$\sigma = 0.4989$ *mm*

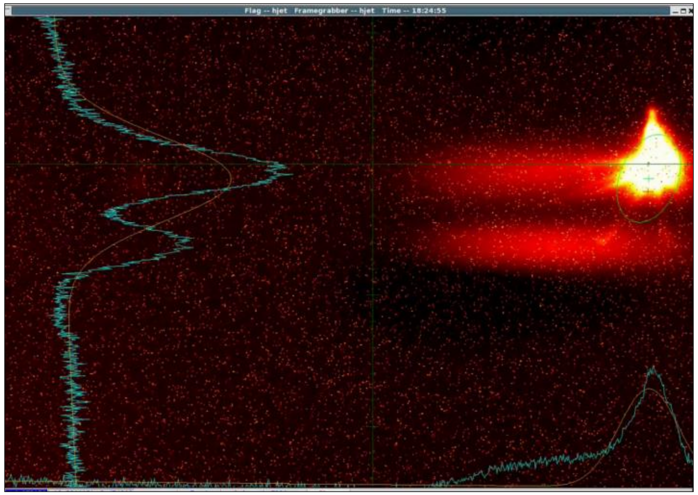
$\varepsilon_x = 6\pi\ \gamma\beta\ \sigma^2/\beta_x = \pi\ 15.92$ *mm mrad*

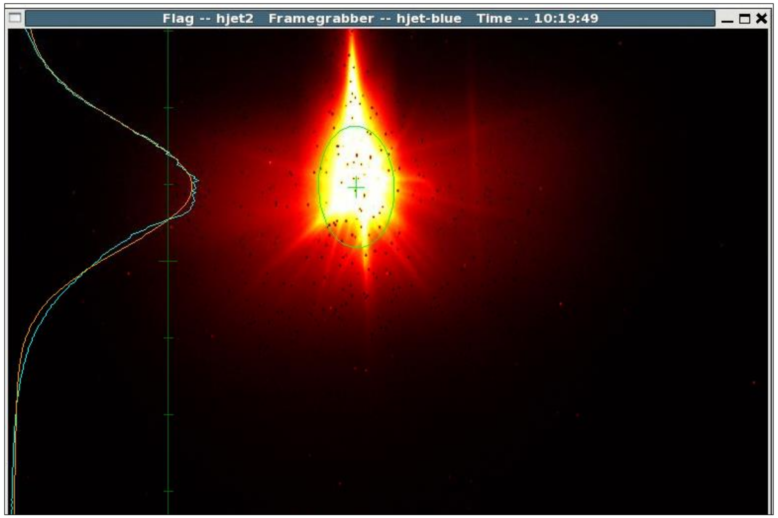
Blue vert. IPM measurement-16 pi.

# H-jet luminescence induced by bunch RF field.

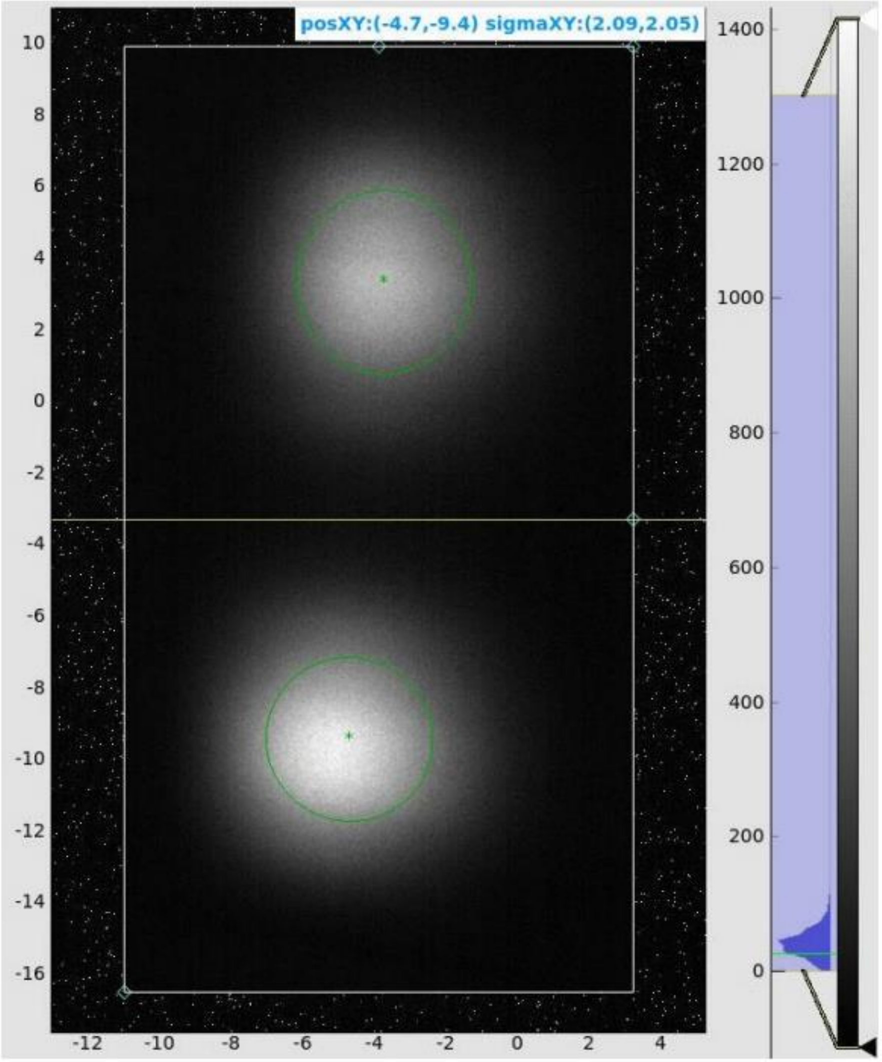




# H-jet imaging




For low energy (<10 GeV) ion collisions H-Jet provided valuable information about transverse beam cooling:

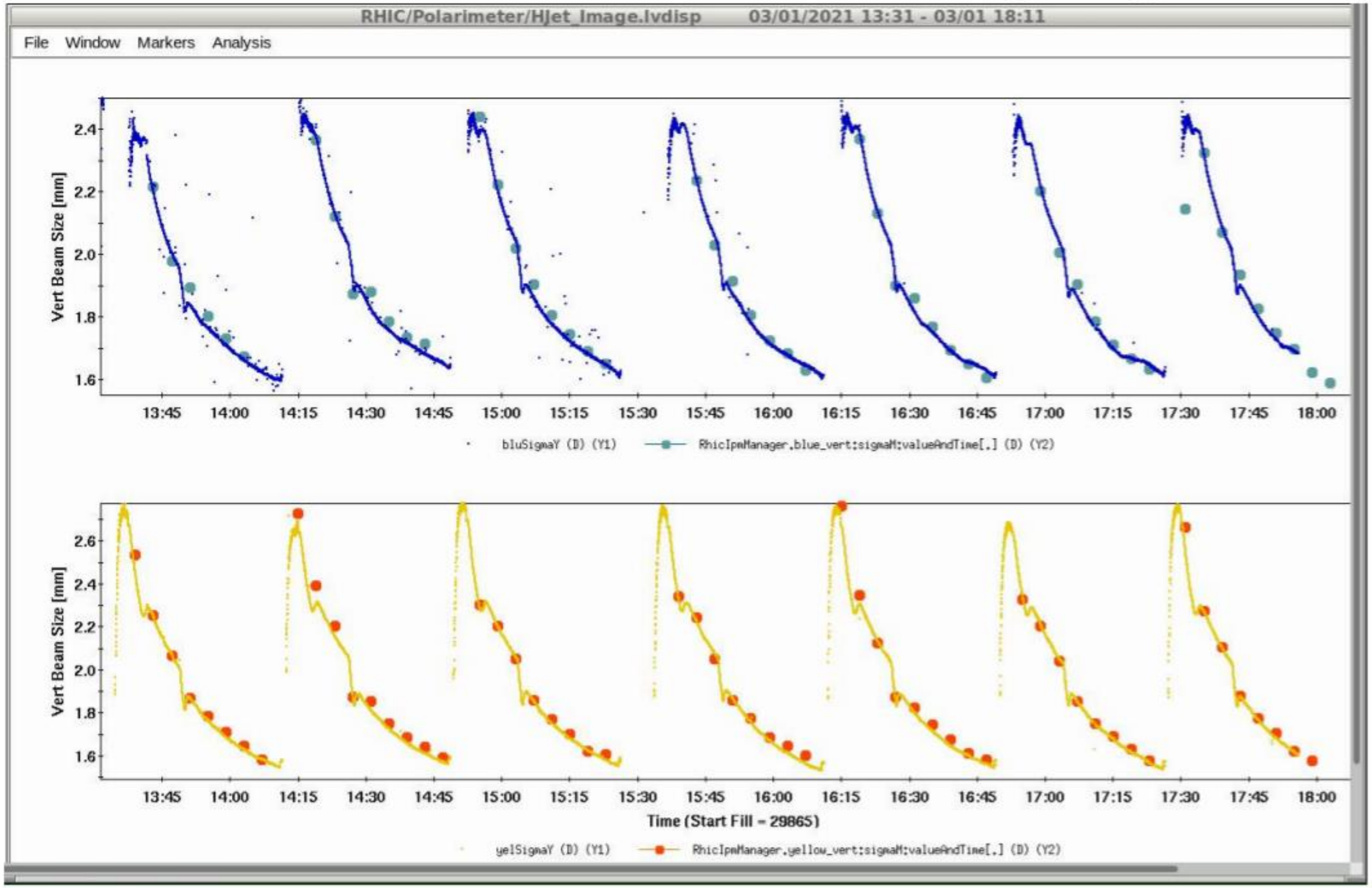
- Frequent precise measurements of the vertical beam size.
- It was in very good agreement with IPM measurements.

Known issue for beams with high bunched power:

- At 100 Gev Au-Au the H-Jet tend to over-estimate the beam size (2-3 times larger than IPM measurements).

Extra fluorescense probably comes from electron cloud, accelerated by the bunch wake field.

# H-jet imaging




Vertical beam size measurements from IPMs compared with H-jet measurements.
From LEReC ELog of 03/01/21:
The agreement between the two different diagnostics is amazing. Sometimes (for example, blue at 17:30 mark), IPM can catch injected small emittance before it's blowing up

# H-jet status and preparation for the Run-2022

- After 2017 polarized proton run, we operated H-jet during all heavy ions Runs-2018-21.
- Many upgrades to improve performances and reliability.
- Different test configuration for systematic error studies.
- H-jet application  for the beam profile monitoring for LEREC development and operation.
- For the Run-22 we are doing a major turbomolecular pumps power supply and control upgrades to ensure future multi-year H-jet operation.
- The H-jet is an established beam diagnostic device and responsibility for future H-jet technical support can be transferred to the instrumentation and vacuum group. We already started this transfer.

- The H-jet is in a good shape for the Run-2022 and hopefully many more years of the RHIC and EIC operation.