Prospects on High-Intensity Polarized H^- (proton), Deuteron and $^3He^{++}$ Ion sources development at BNL.

Anatoli Zelenski, BNL, Upton, NY

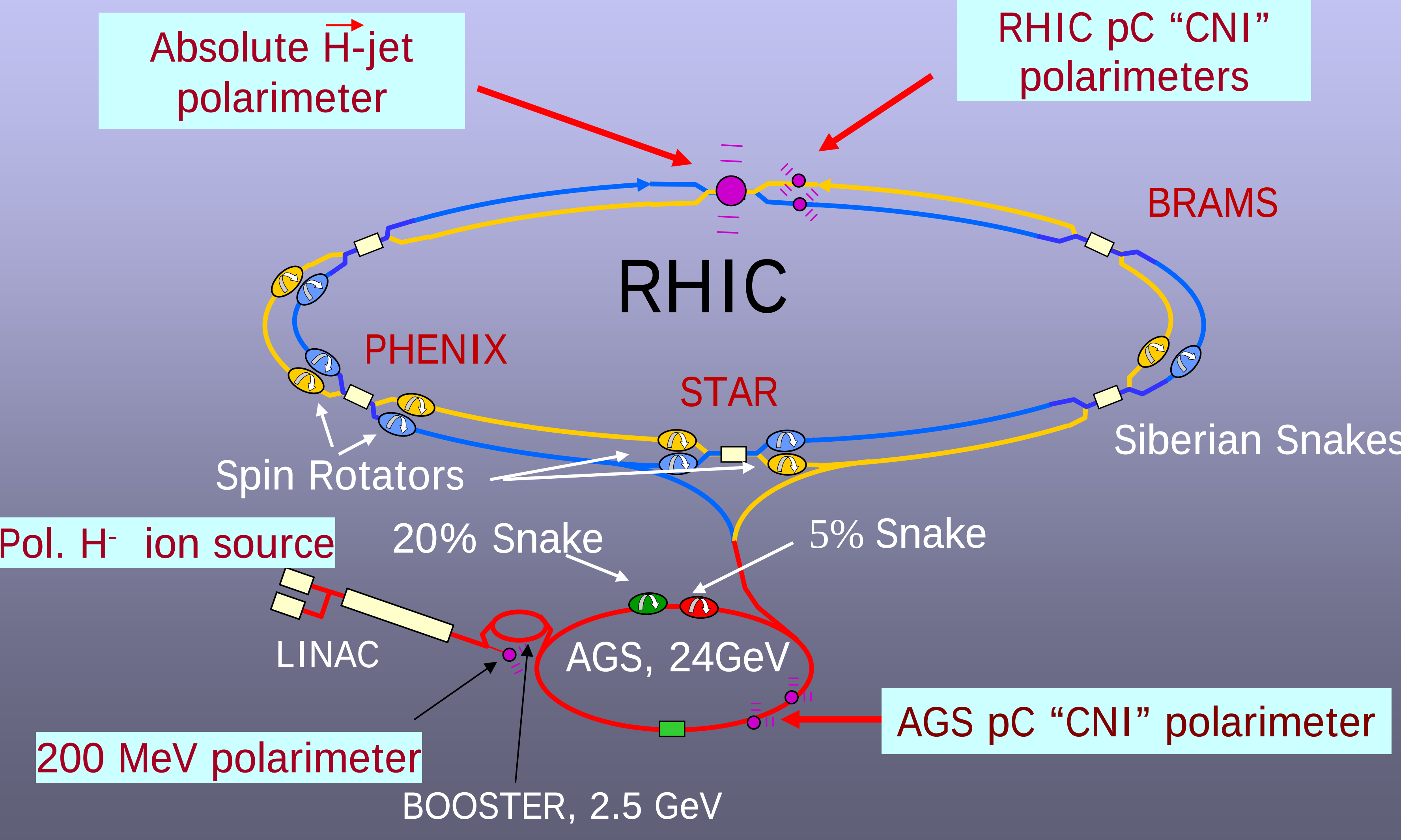
- The RHIC polarized source.
- R@D on pulsed OPPIS and polarized $^3He^{++}$ sources for future RHIC II and eRHIC polarization programs.

  Polarized D^+ source for future Deuteron-EDM experiment.

EPAC 2008, Genoa, June 24, 2008

Polarization facilities at RHIC.

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

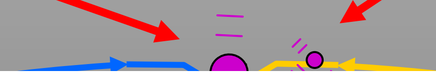


Polarization facilities at RHIC.

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

Absolute $\vec{H}$-jet polarimeter

RHIC pC "CNI" polarimeters



- The RHIC is the first collider where the "Siberian snake" technique was very successfully implemented to avoid the resonant depolarization during beam acceleration.

- The collision of polarized proton beams in RHIC (at up to $\sqrt{S}$ = 500 GeV energy) provide unique opportunity for studying proton spin structure, including the measurement of the gluon polarization and quark, anti-quark spin flavour composition.

- T.Roser, "RHIC and It's Upgrade'', Friday plenary session.
- H.Huang et al., "Polarized AGS operation in Run-2008", MOPC108
- A.Bazilevskiy et al., "P-Carbon CNI polarimetry in AGS and RHIC", TUPC039

Workshop on high –energy spin physics, Protvino, IHEP, September,1983

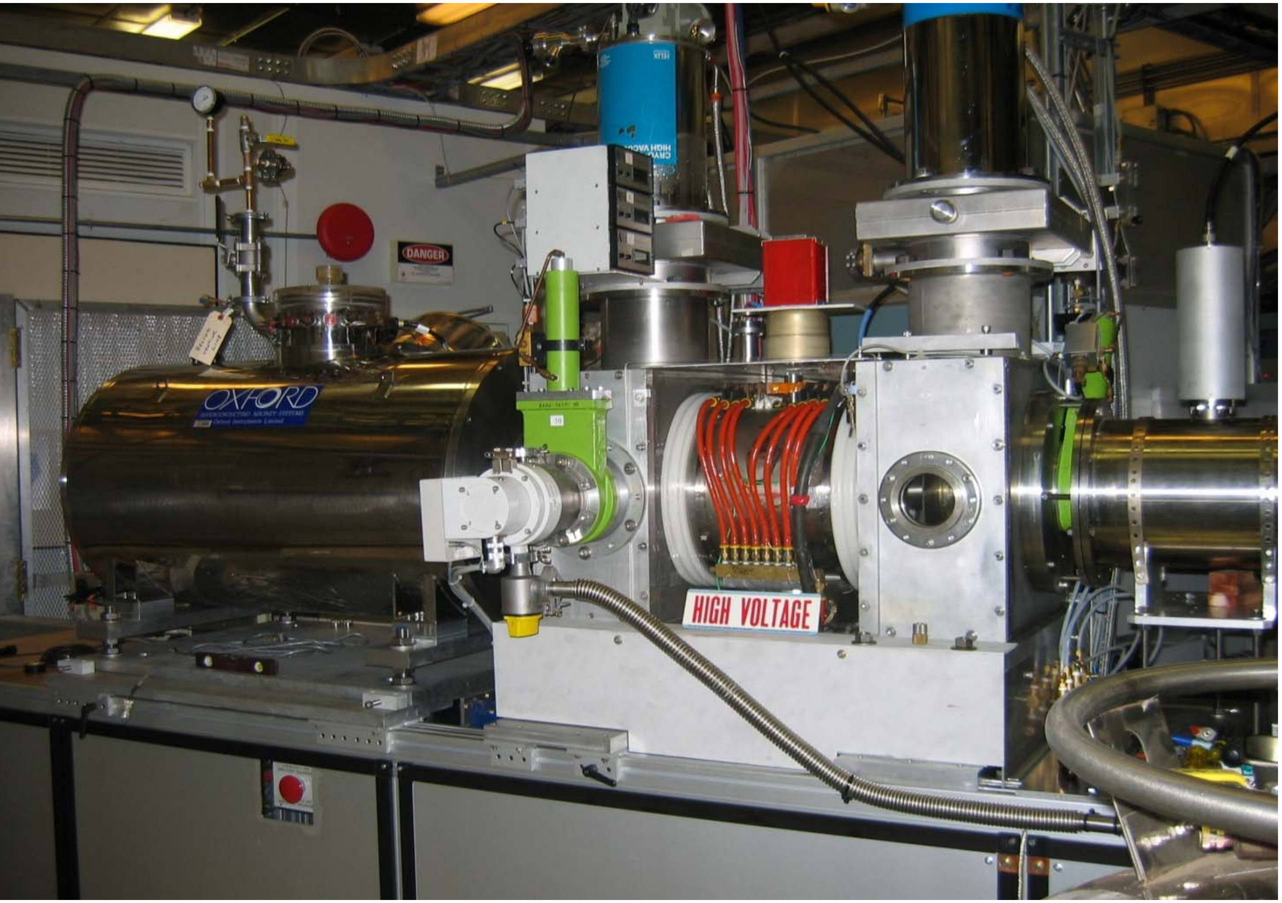
Yaroslav Derbenev , (A.Kondratenko)

“Siberian snake” proposal.

A new polarized source technique. Equal intensity for polarized and unpolarized proton beams.

KEK, LAMPF, INR Moscow, TRIUMF

Optically-Pumped Polarized H^- Ion Source (OPPIS) at RHIC, (originally developed in collaboration between KEK, BNL, TRIUMF and INR Moscow).



A beam intensity greatly exceeds RHIC limit, which allowed strong beam collimation in the Booster, to reduce longitudinal and transverse beam emittances.

RHIC OPPIS produces reliably 0.5-1.0mA (maximum 1.6 mA) polarized H^- ion current.

Pulse duration 400 us.

Polarization at 200 MeV P = 85-90%.

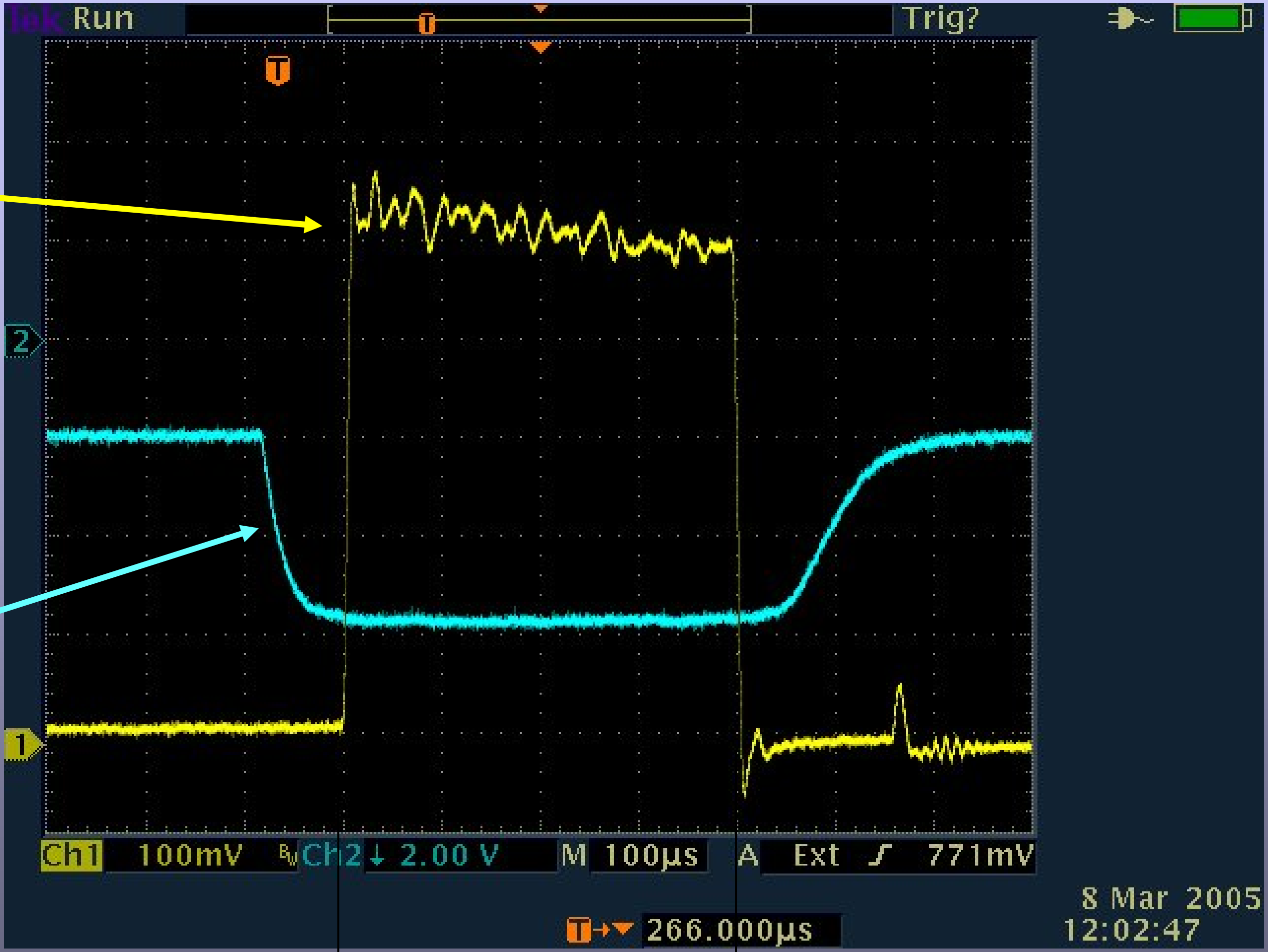
Beam intensity (ion/pulse) routine operation:

Source	- 10^{12} H^-/pulse
Linac (200MeV)	- $5 \cdot 10^{11}$
AGS	- $1.7 \cdot 10^{11}$
RHIC	- $1.4 \cdot 10^{11}$

(protons/bunch).

Polarized H⁻ ion current pulse out of 200 MeV linac.

500 uA cuurent
At 200 MeV.
85-hole ECR
Source for the
maximum
polarization.



Faradey rotation
polarization sinal.

400 uS

$12 \cdot 10^{11}$ -polarized
H^- /pulse.

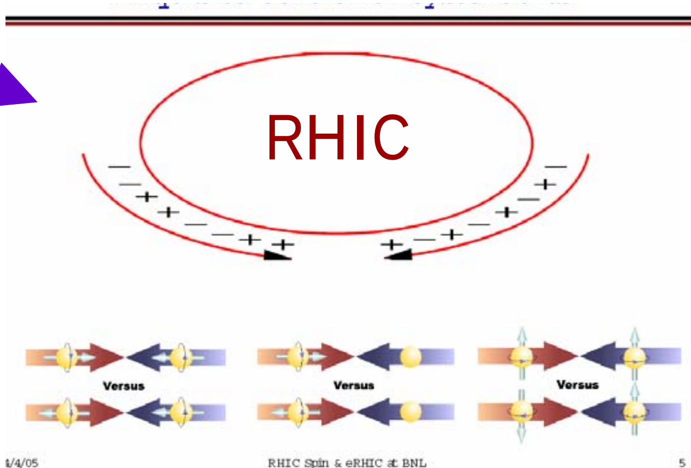
Polarized beams in RHIC.

OPPIS — $10 \cdot 10^{11}$(maximum $40 \cdot 10^{11}$) polarized H^- /pulse.

LINAC — $5 \cdot 10^{11}$ polarized H^- /pulse at 200 MeV, P=85-90%

Booster — $2 \cdot 10^{11}$ polarized protons /pulse at 2.3 GeV

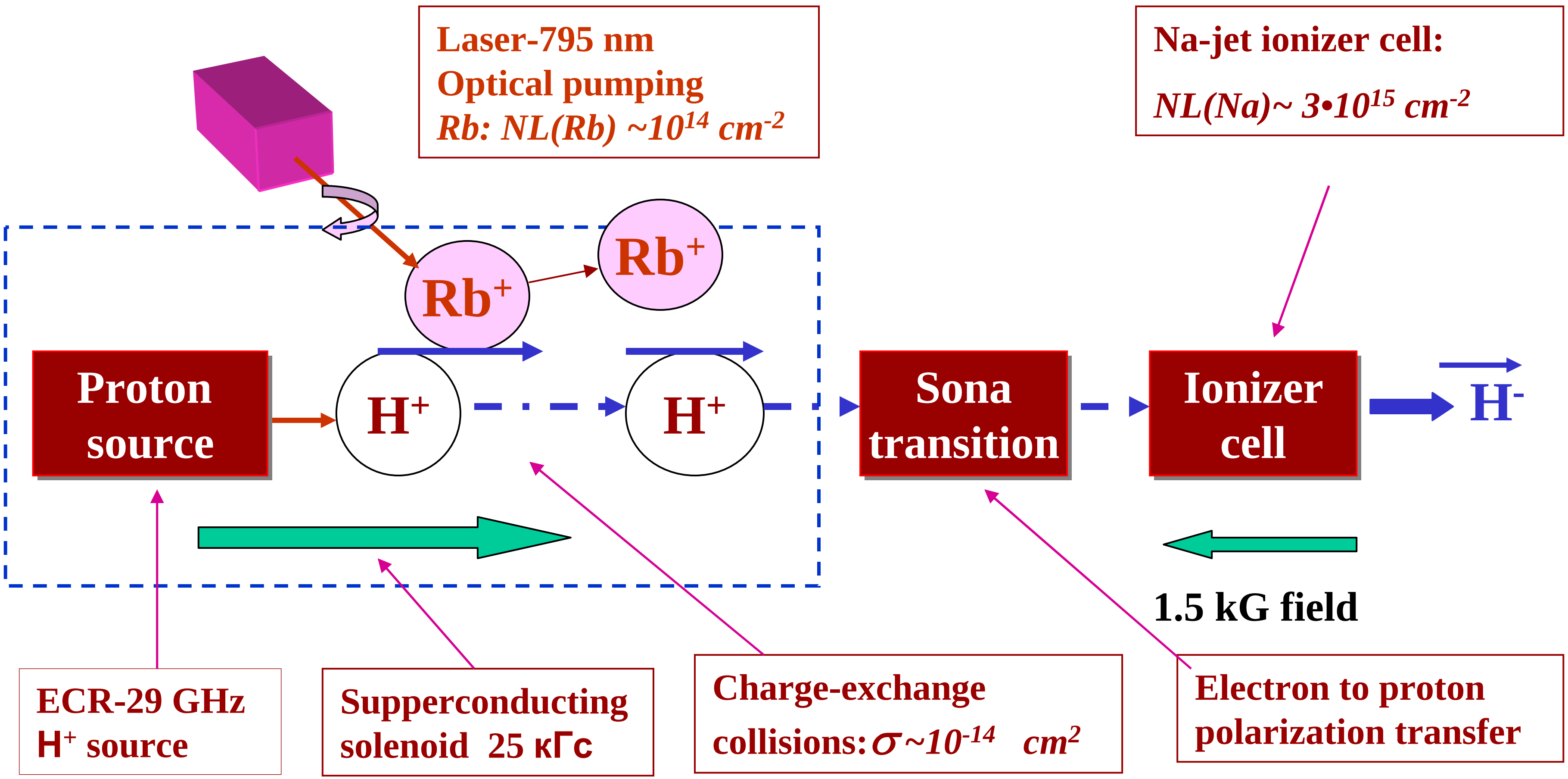
AGS — 1.5-1.7 p/bunch, P ~65-70%



Maximum RHIC bunch intensity ~1.5 10^{11} p/bunch

Polarization -65%

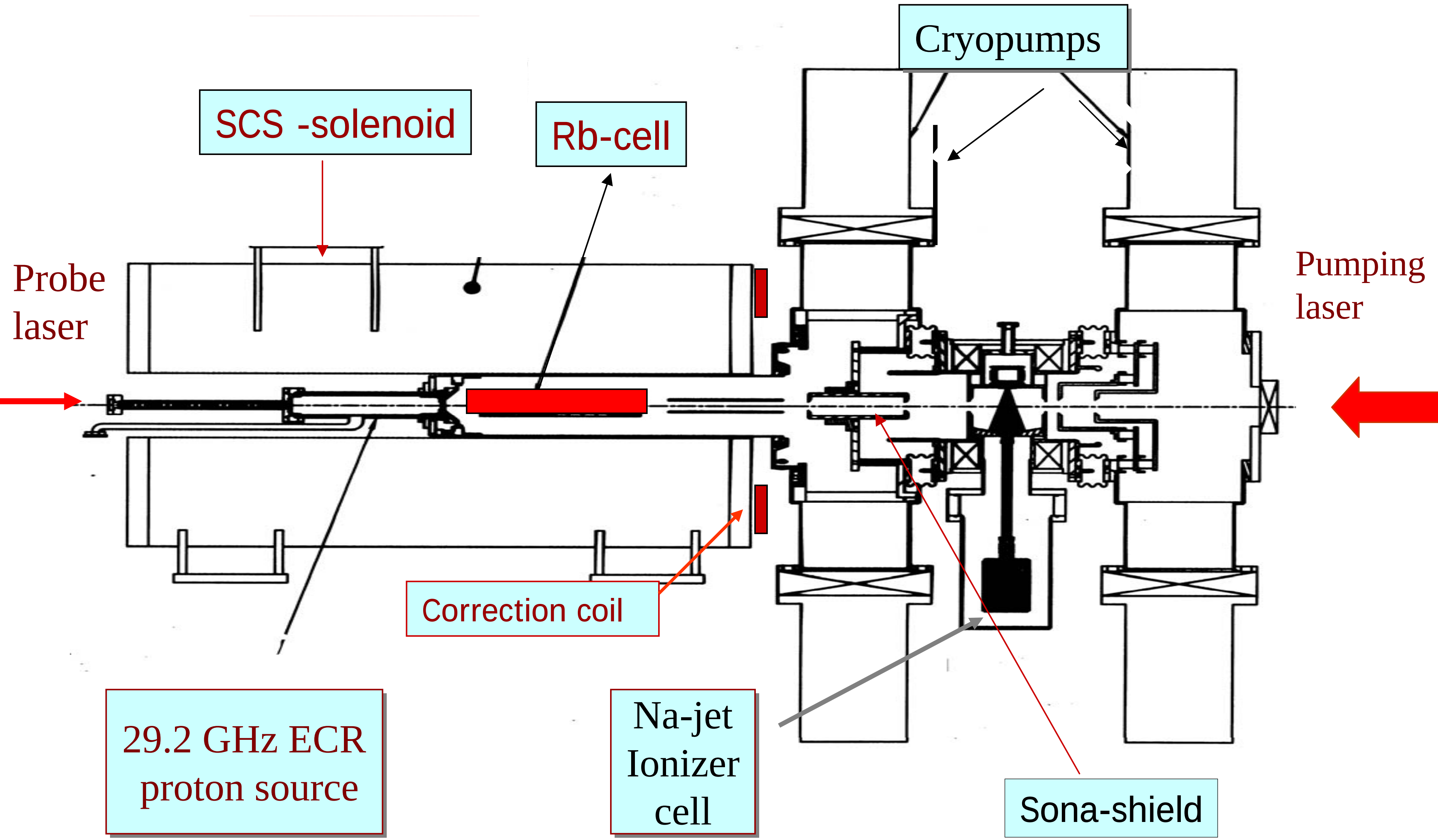
SPIN -TRANSFER POLARIZATION IN PROTON-Rb COLLISIONS.



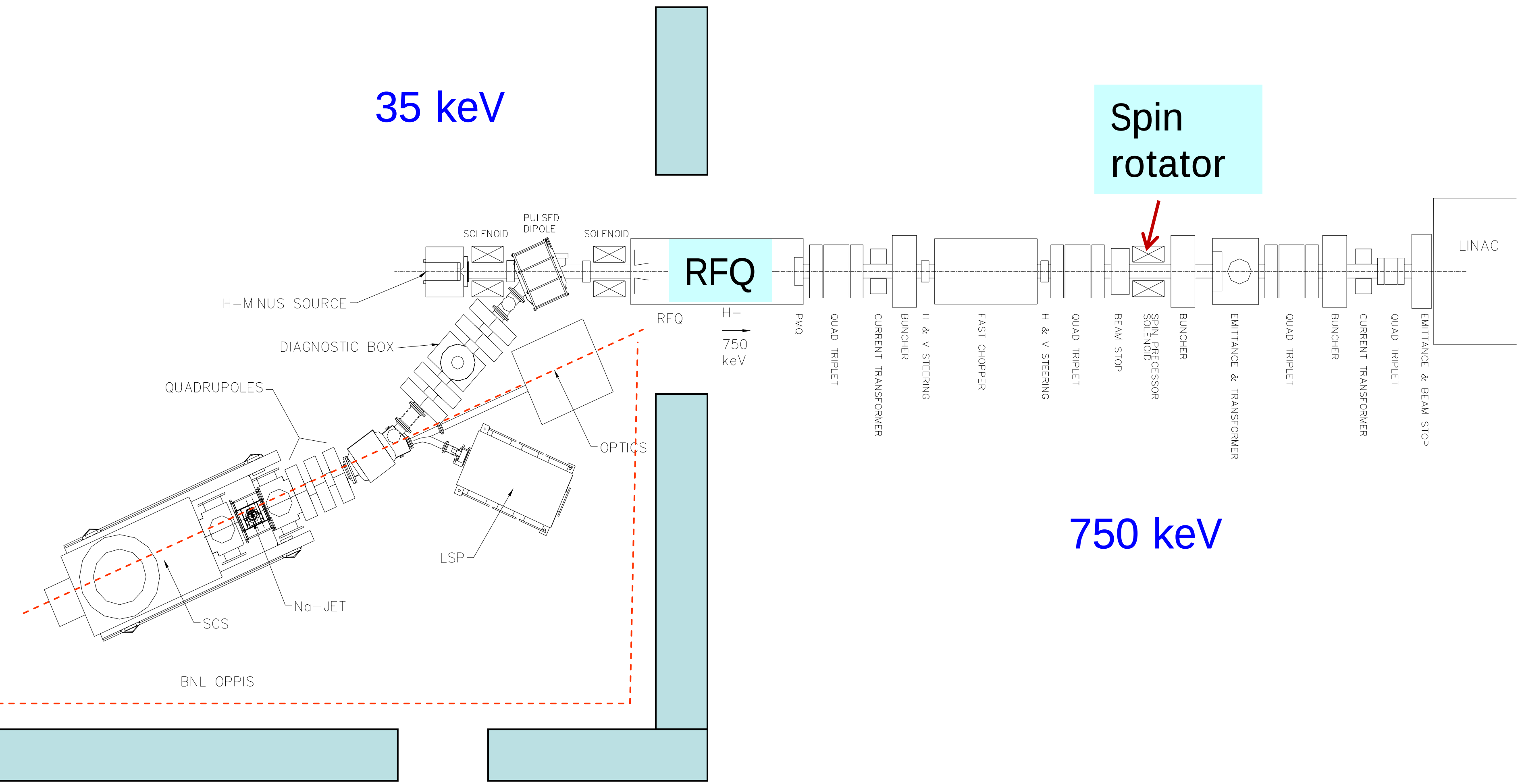
Laser beam is a primary source of angular momentum:

10 W (795 nm) ⇨ $4 \cdot 10^{19}$ hν/sec ⇨ 2 A, $\vec{H}^0$ equivalent intensity.

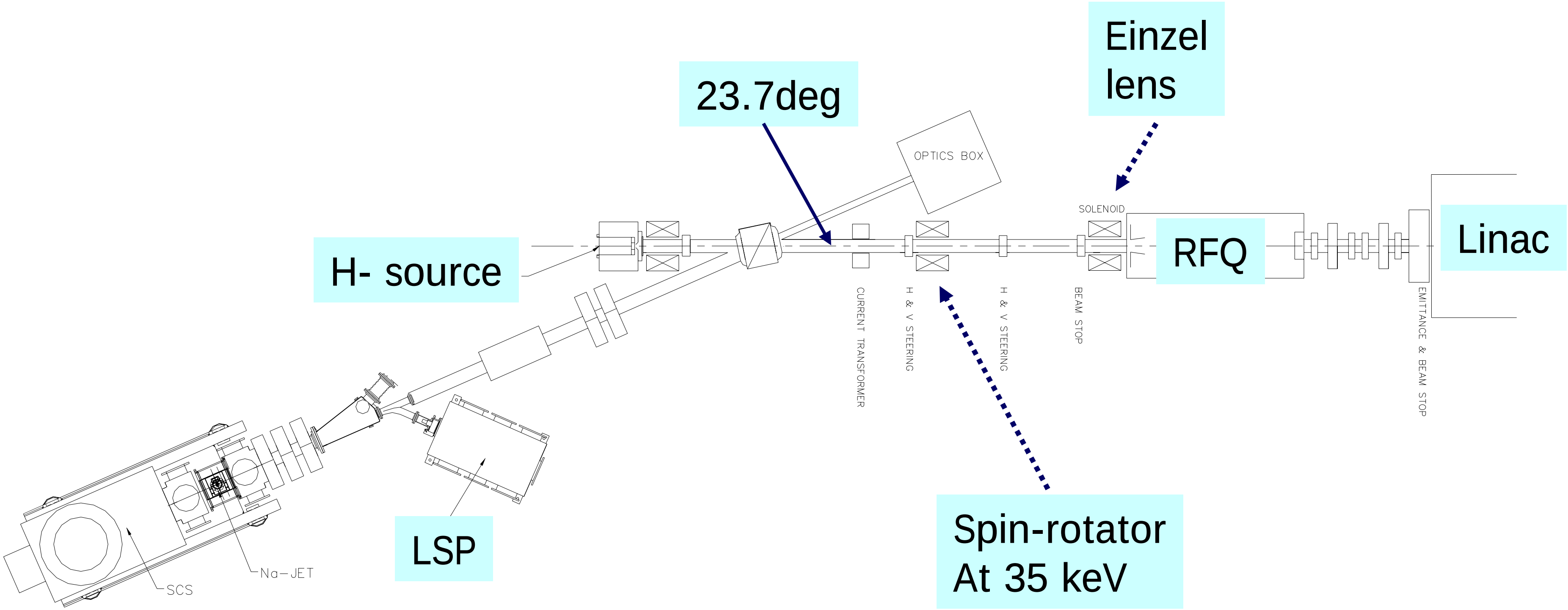
SCHEMATIC LAYOUT OF THE RHIC OPPIS.



Present LEBT & MEBT



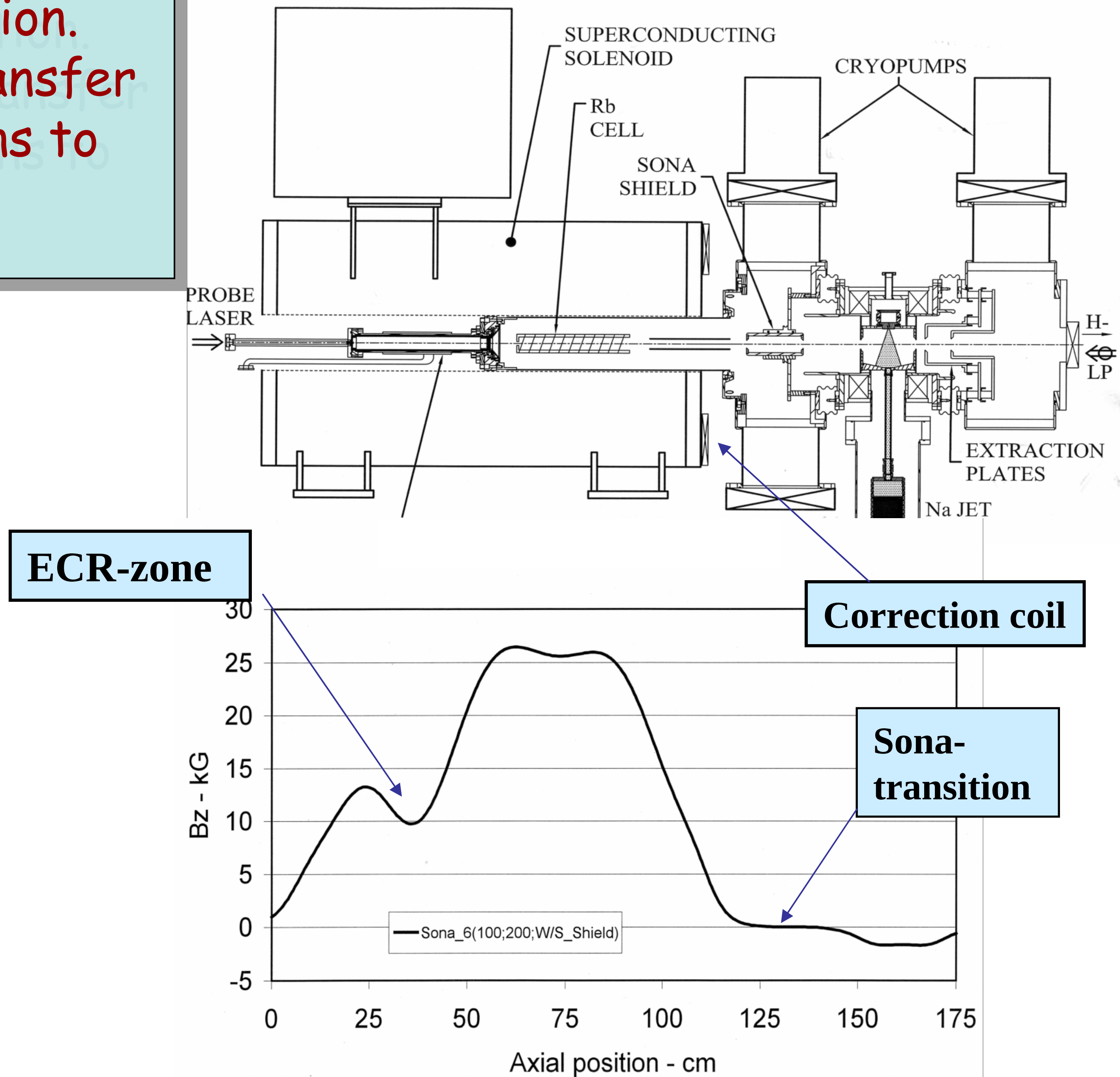
LEBT upgrade for 2009 Run.



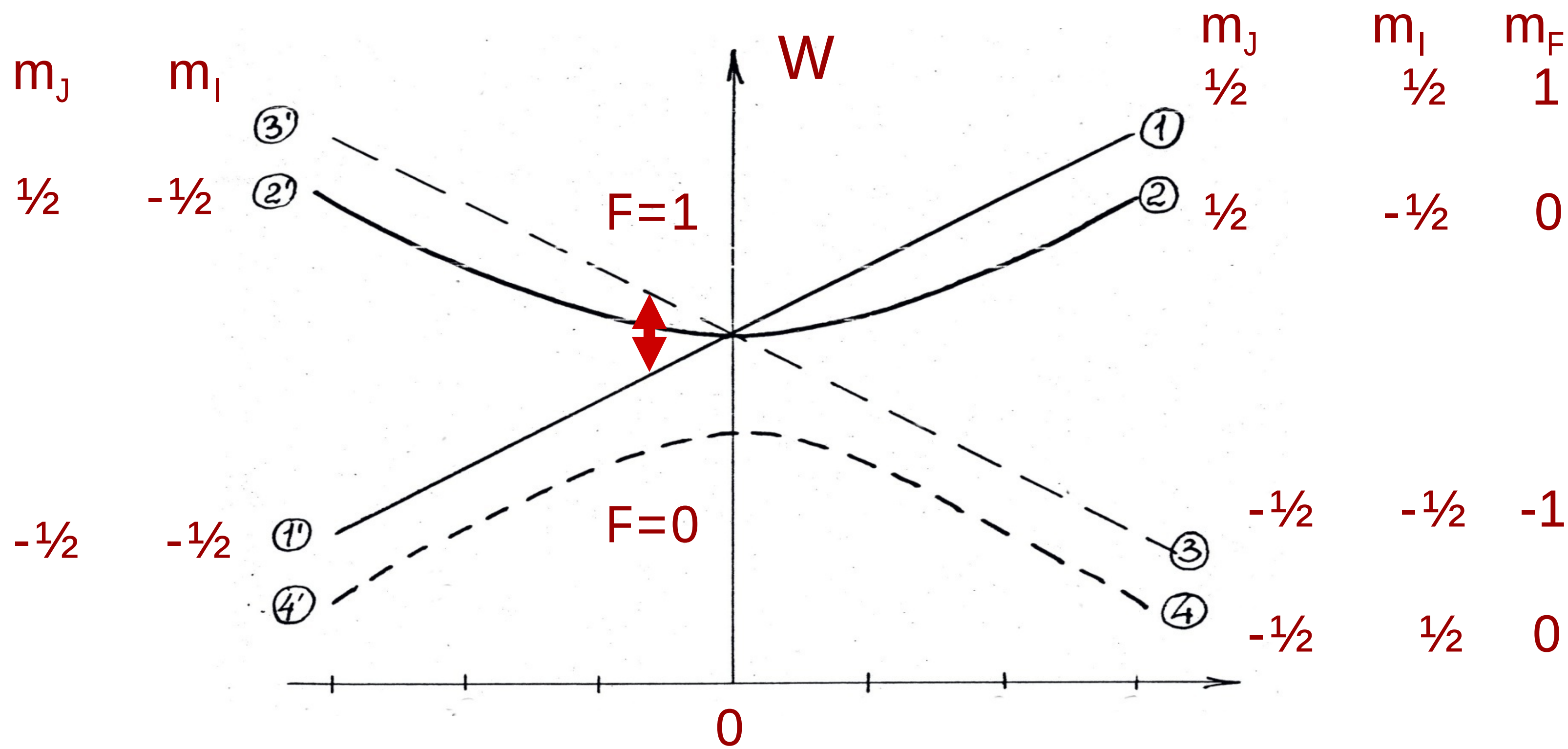
Spin-precession will be reduced to minimum required for vertical polarization direction in Linac. This should reduce the polarization profile generation in LEBT.

Significantly smaller beam emittance out of Linac is also expected due to improved matching between RFQ and Linac.

Sona-transition. Polarization transfer from electrons to protons.



Sona-transition, P.G.Sona, Energia Nucleare, 1976

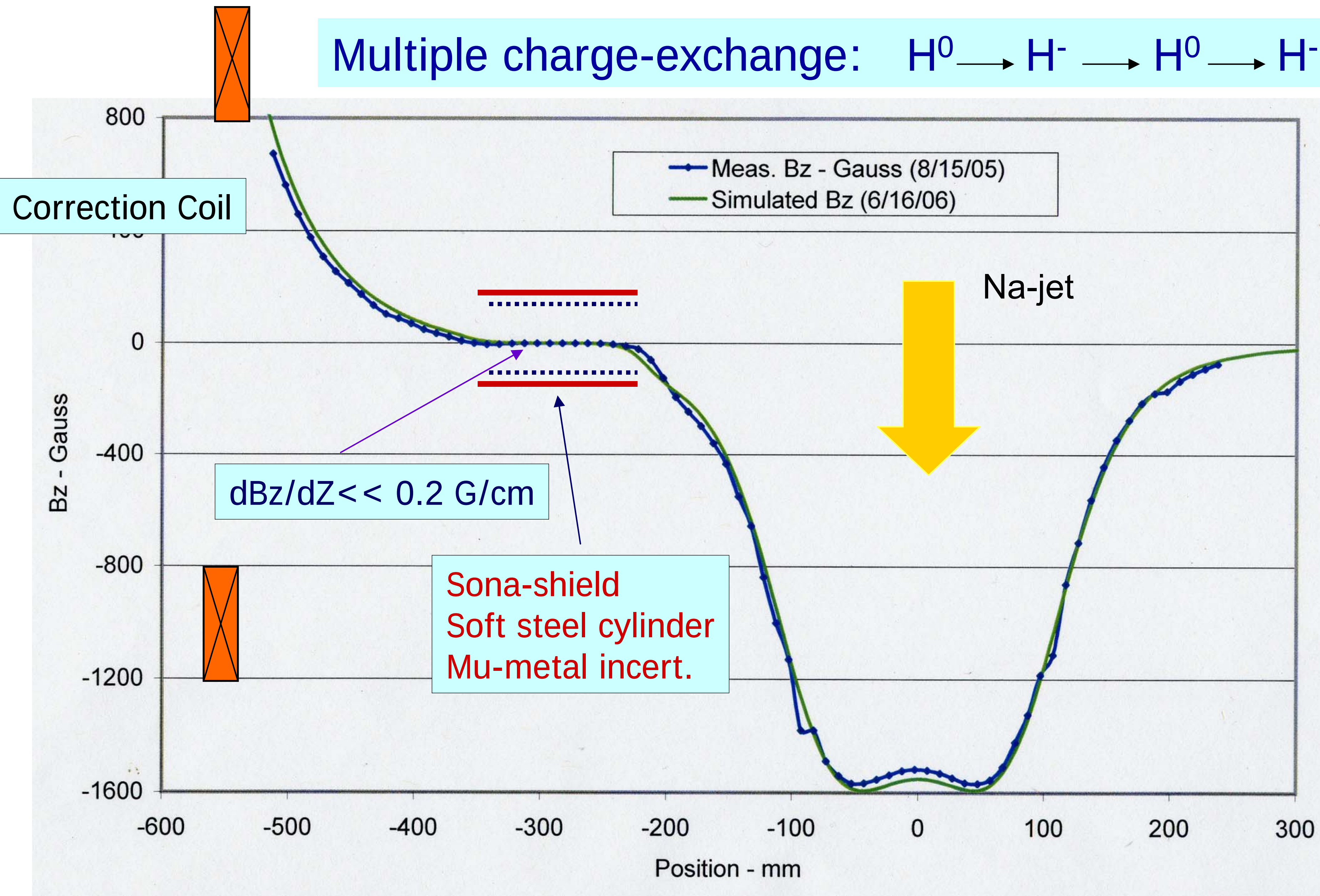


$Bs << B_R \sim R\ (dB/dZ)\Big|_{B_Z=0} << 2\ G/cm$ – limitation on Bz gradient and beam size at the zero crossing point.

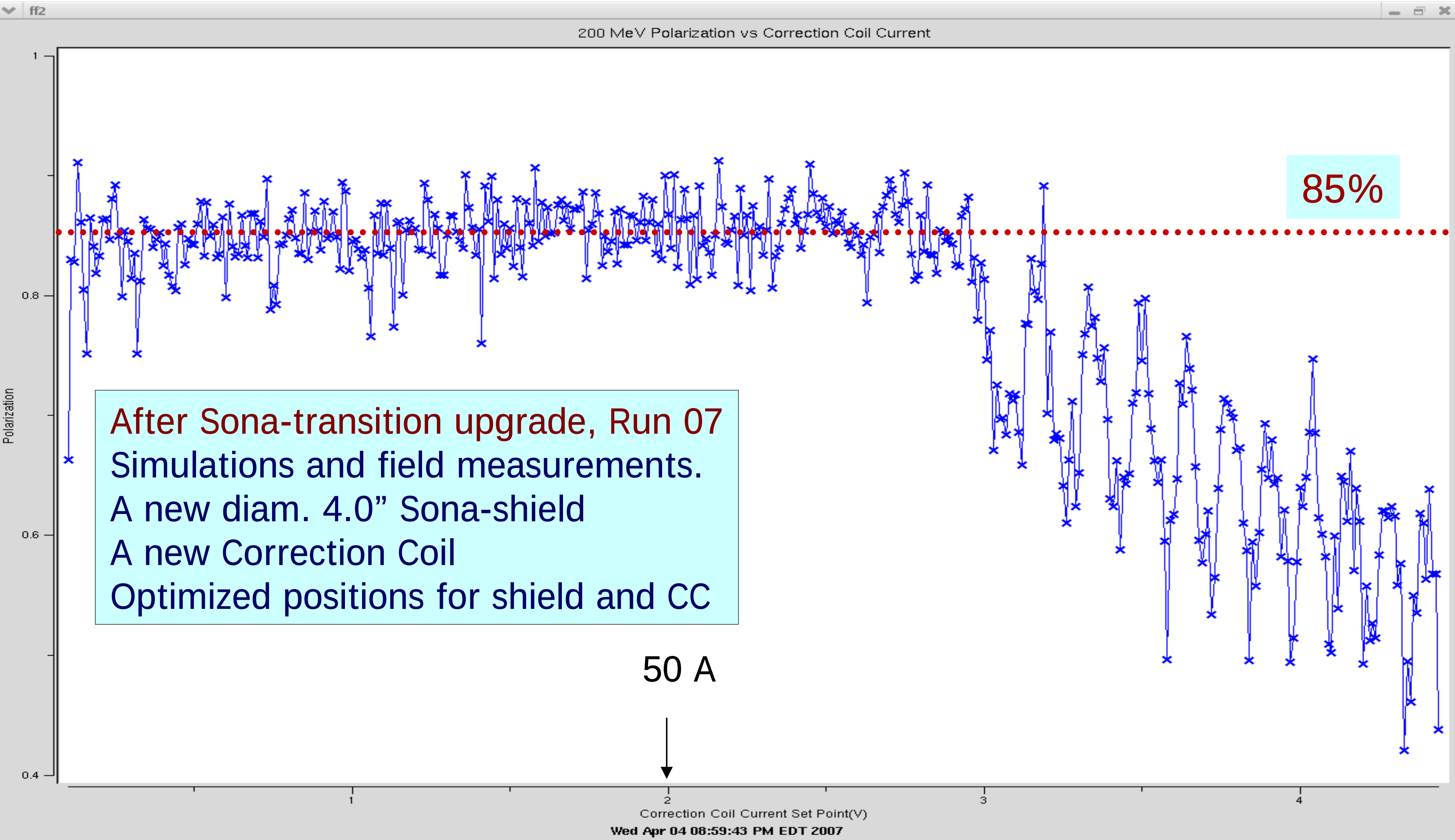
$\Delta m_F = +/-1$ – π- transitions, $\Delta m_F = 0$ – σ- transitions.

Bz-field component in the Sona-transition region.

Multiple charge-exchange: $H^0 \rightarrow H^- \rightarrow H^0 \rightarrow H^-$

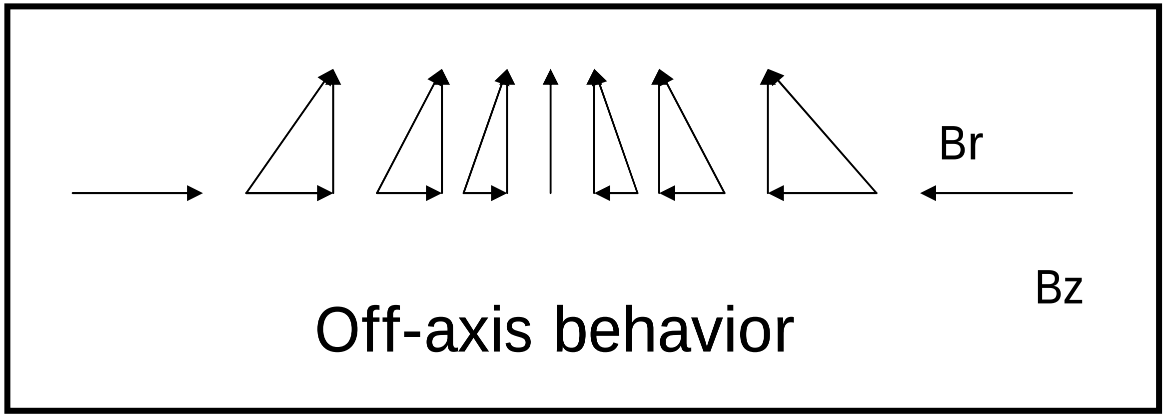


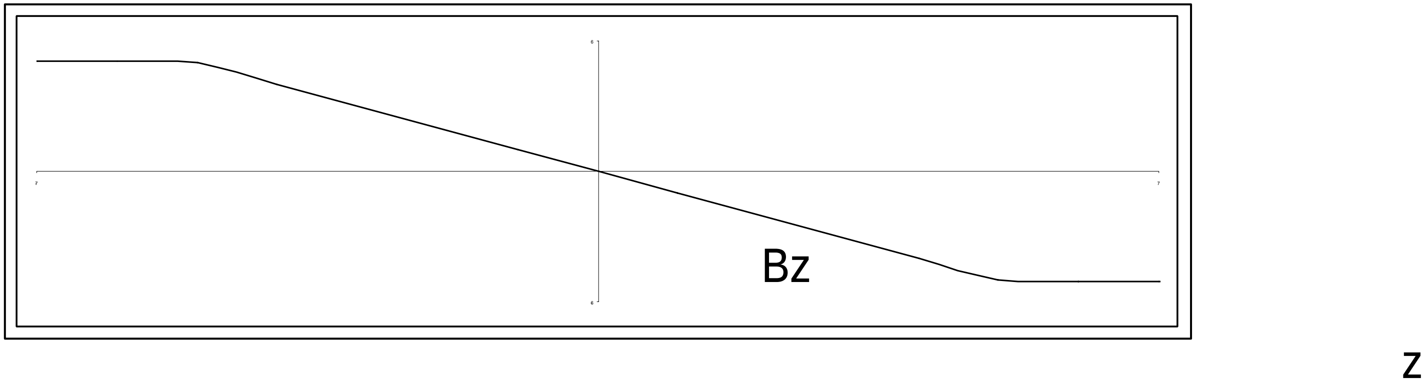
Polarization oscillations in the Sona-transition, Run - 07.



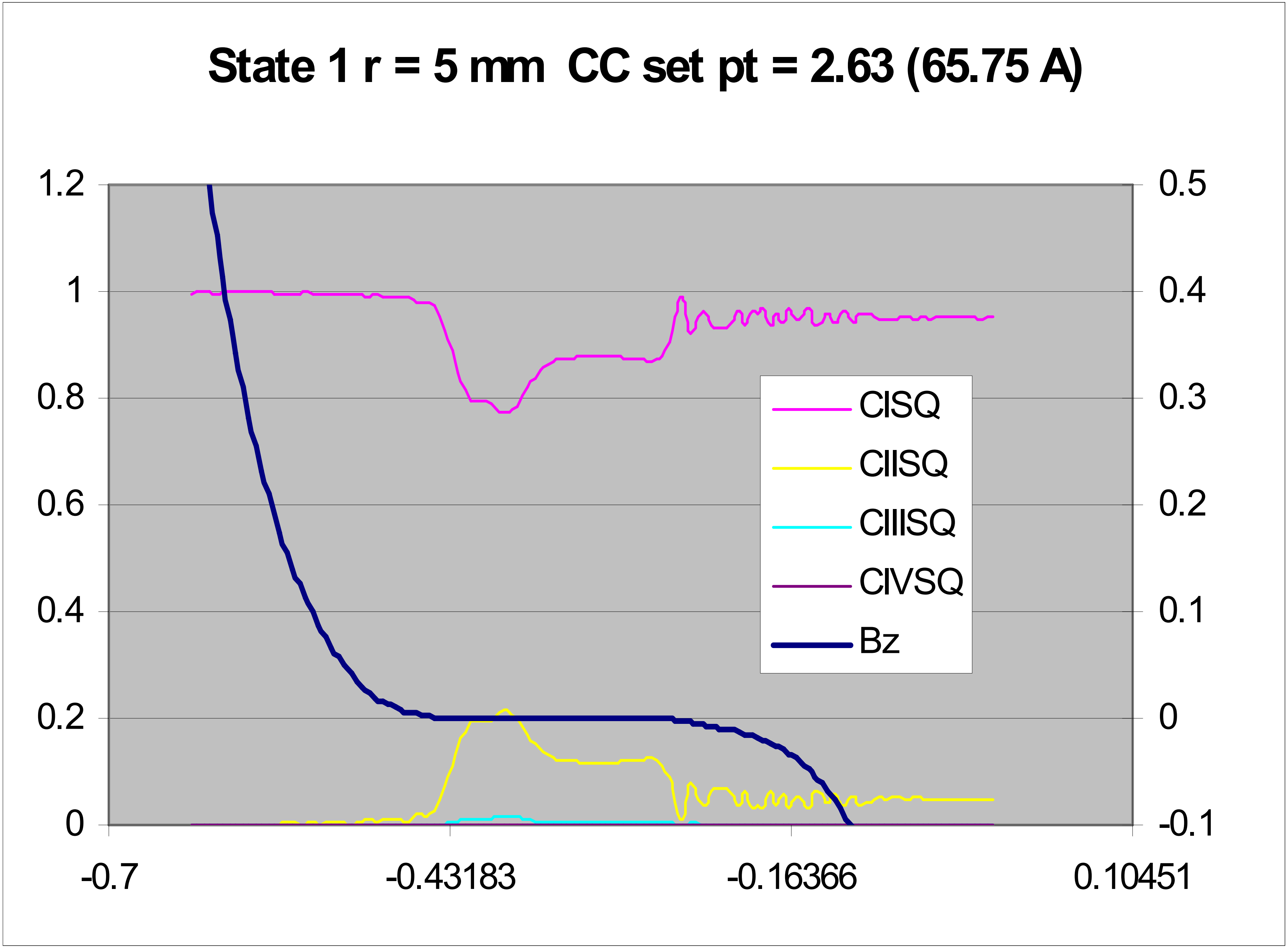
Polarization at 200 MeV vs. Correction Coil current

Sona-transition simulations, A.Kponou

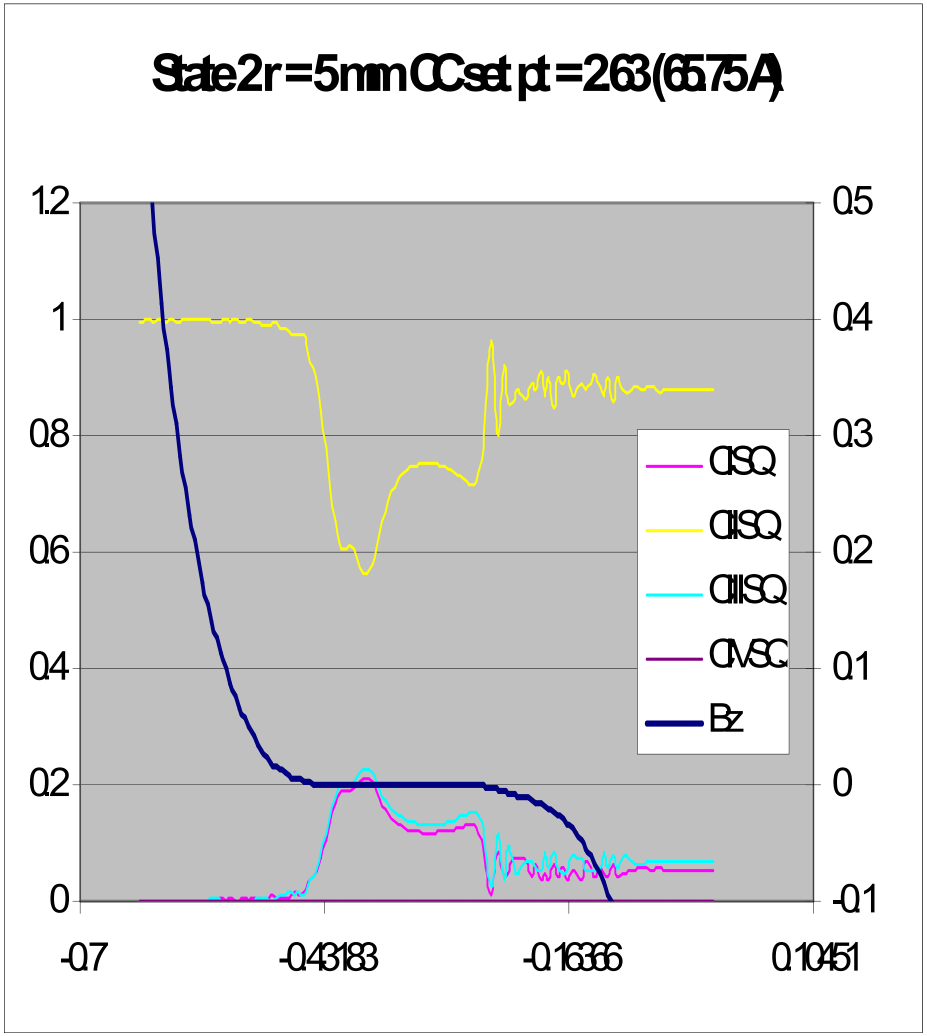




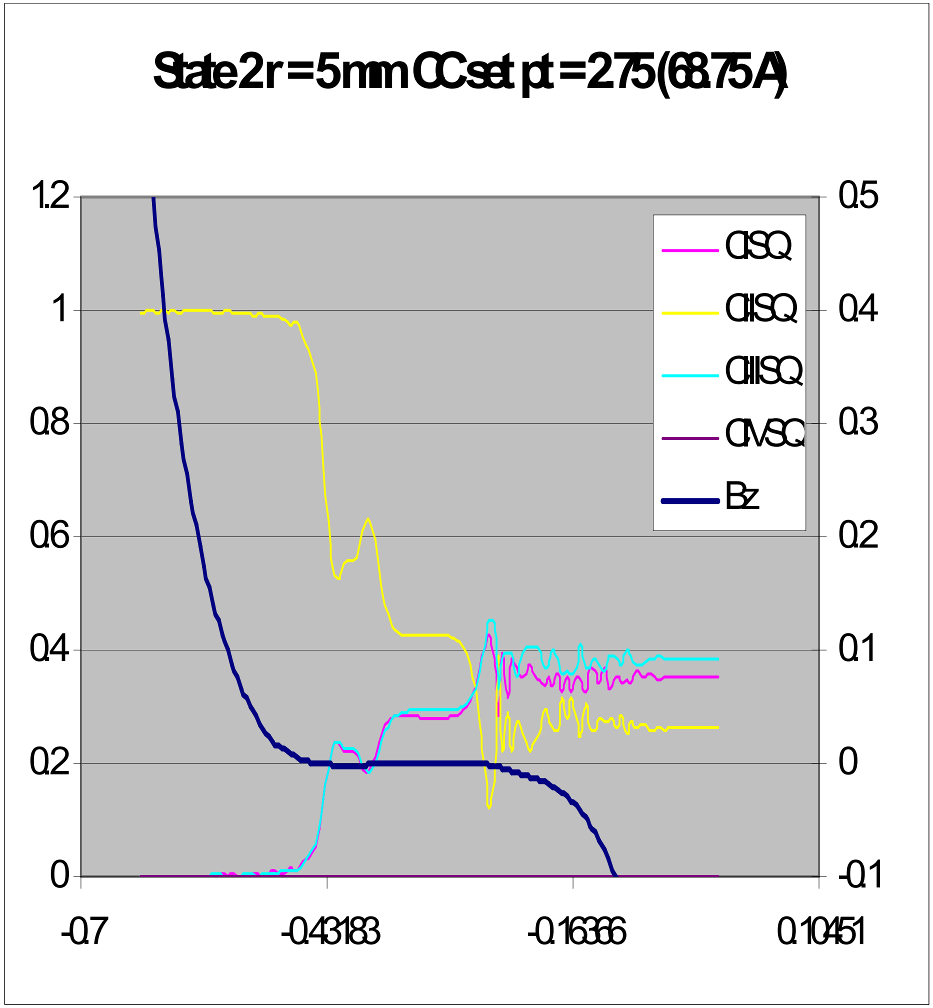
A.Belov , INR Moscow developed a computer code for calculation of hyperfine Sublevels population in variable magnetic field. This code was successfully Aplied to the Sona-transition simulations in the RHIC OPPIS.


State 1 r = 5 mm CC set pt = 2.63 (65.75 A)
1.2
1
0.8
0.6
0.4
0.2
0
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.7
-0.43183
-0.16366
0.10451
CISQ
CIISQ
CIIISQ
CIVSQ
Bz

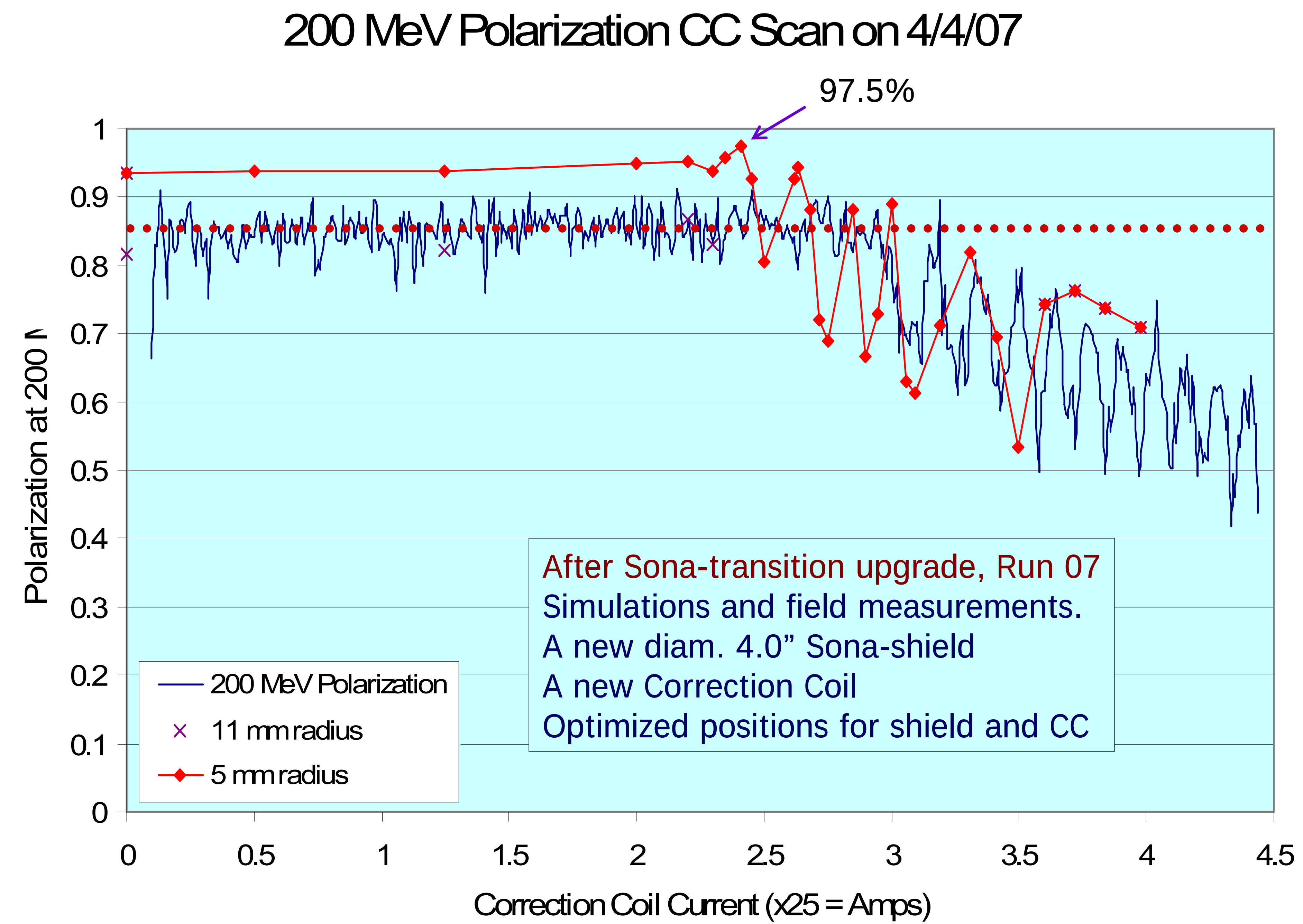
State 2 (r=5 mm)

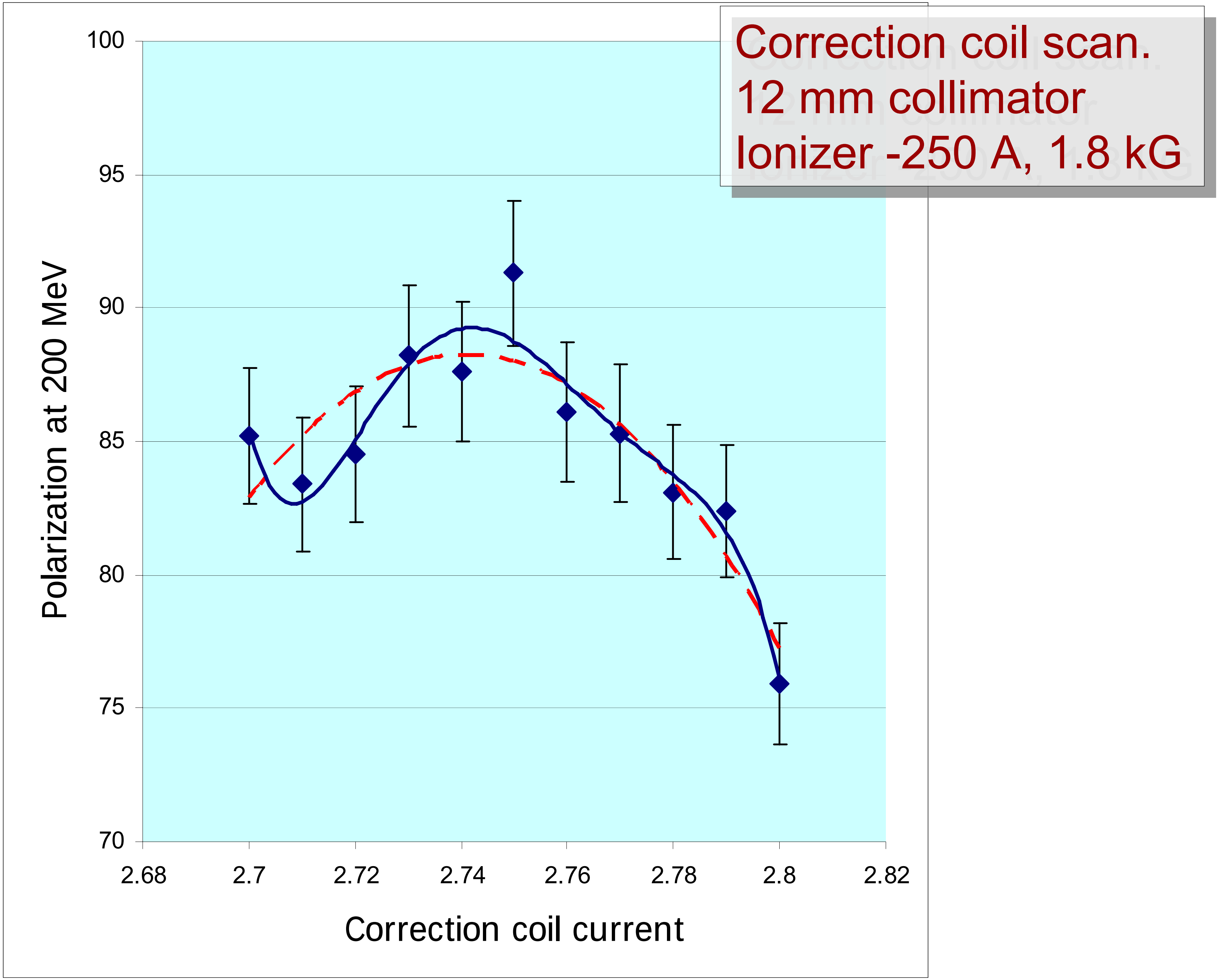


State 2 r=5mm CC set pt=263 (65.75A)
1.2
1
0.8
0.6
0.4
0.2
0
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.7
-0.43183
-0.16366
0.10451
CISQ
CIISQ
CIIISQ
CIVSQ
Bz



State 2 r=5mm CC set pt=275 (68.75A)
1.2
1
0.8
0.6
0.4
0.2
0
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.7
-0.43183
-0.16366
0.10451
CISQ
CIISQ
CIIISQ
CIVSQ
Bz


200 MeV Polarization CC Scan on 4/4/07
97.5%
Polarization at 200
Correction Coil Current (x25 = Amps)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
200 MeV Polarization
11 mm radius
5 mm radius
After Sona-transition upgrade, Run 07
Simulations and field measurements.
A new diam. 4.0” Sona-shield
A new Correction Coil
Optimized positions for shield and CC


Correction coil scan.
12 mm collimator
Ionizer -250 A, 1.8 kG
Polarization at 200 MeV
100
95
90
85
80
75
70
2.68
2.7
2.72
2.74
2.76
2.78
2.8
2.82
Correction coil current

Polarization vs. ionizer solenoid current with the 12mm collimator.

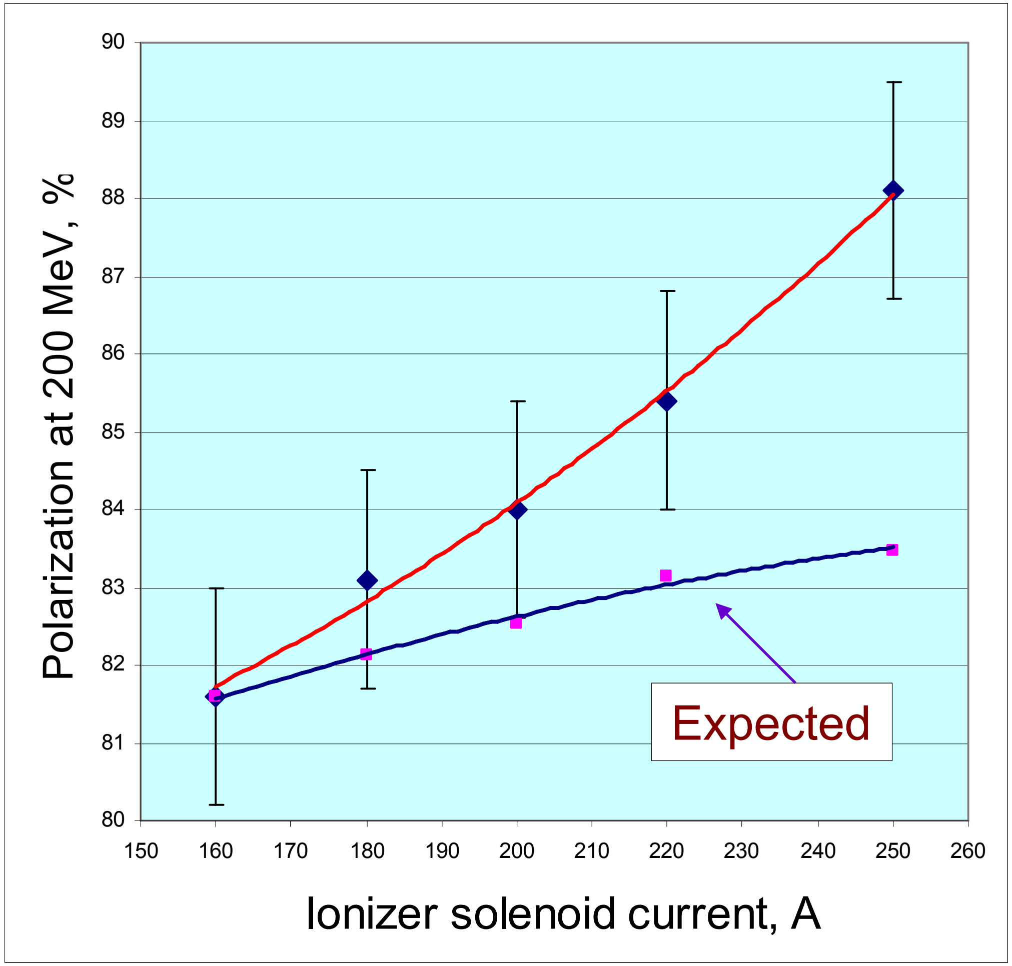
Maximum polarization from the correction coil scans, collim. -12 mm.

160 A ↔1.16 kG, 81.6% (95.9%)

200 A ↔1.45 kG, 84.9% (97.0%)

250 A ↔1.81 kG , 88.1% (98.1%)

Expected



23 mm collimator.

200 A ↔1.45 kG, 82.5% (97.0%)

250 A ↔1.81 kG , 84.5% (98.1%)

A new ionizer solenoid:

250 A ↔1.98 kG , 90.0% (98.4%)

200 MeV POLARIMETER (12 degree-accidental) u5v12 -- FOR POLARIZATION STUDIES)

STATUS: RUNNING

PROCESSING

START | STOP | SAVE | CLEAR | EXIT

READING

PULSE	LEFT	RIGHT	CLK-	CLK+	POL.	ACC_L	ACC_R	(L/R)u	(R/L)d
36	42.0	135.0	0.0	1335.0	0.744684	0.0	1.0	0.311111	0.428571
37	97.0	25.0	1340.0	0.0		2.0	0.0	0.311111	0.257732
38	31.0	142.0	0.0	1335.0	0.98921	0.0	0.0	0.21831	0.257732
39	1.0	0.0	1340.0	0.0		0.0	0.0	0.21831	0.0
40	27.0	124.0	0.0	1335.0	1.6129	0.0	3.0	0.217742	0.0
41	97.0	42.0	1339.0	0.0		1.0	0.0	0.217742	0.43299
42	37.0	144.0	0.0	1336.0	0.800808	0.0	1.0	0.256944	0.43299
43	105.0	34.0	1339.0	0.0		1.0	0.0	0.256944	0.32381
44	35.0	131.0	0.0	1336.0	0.870422	0.0	3.0	0.267176	0.32381
45	125.0	37.0	1340.0	0.0		1.0	0.0	0.267176	0.296
46	29.0	150.0	0.0	1335.0	0.986482	0.0	1.0	0.193333	0.296
47	108.0	31.0	1339.0	0.0		1.0	0.0	0.193333	0.287037
48	35.0	131.0	0.0	1335.0	0.906534	0.0	2.0	0.267176	0.287037
49	106.0	33.0	1340.0	0.0		0.0	0.0	0.267176	0.311321
50	24.0	131.0	0.0	1336.0	0.991028	0.0	0.0	0.183206	0.311321

AVERAGING INTERVAL: 5 | HISTOGRAM: GET HISTOGRAM | ANALYSIS: ANALYZE | ALPHA

91.2+/-1.5%

Left arm events (+,-):	762.0 - 3.0	2483.0 - 20.0	30.48 - 0.12	99.32 - 0.8
Right arm events(+,-):	3473.0 - 25.0	863.0 - 1.0	138.92 - 1.0	34.52 - 0.04

POLARIZATION (P,dP): 0.912069 0.0154519 AVE POL(LAST 20 Cycles) (P,dP): 0.992385 0.178412

RIGHT(SINGLE) POLARIZATION (P,dP): 0.970867 0.00857756 UP POLARIZATION: 0.951075

LEFT(SINGLE) POLARIZATION (P,dP): 0.85541 0.0207752 DOWN POLARIZATION: -0.877242

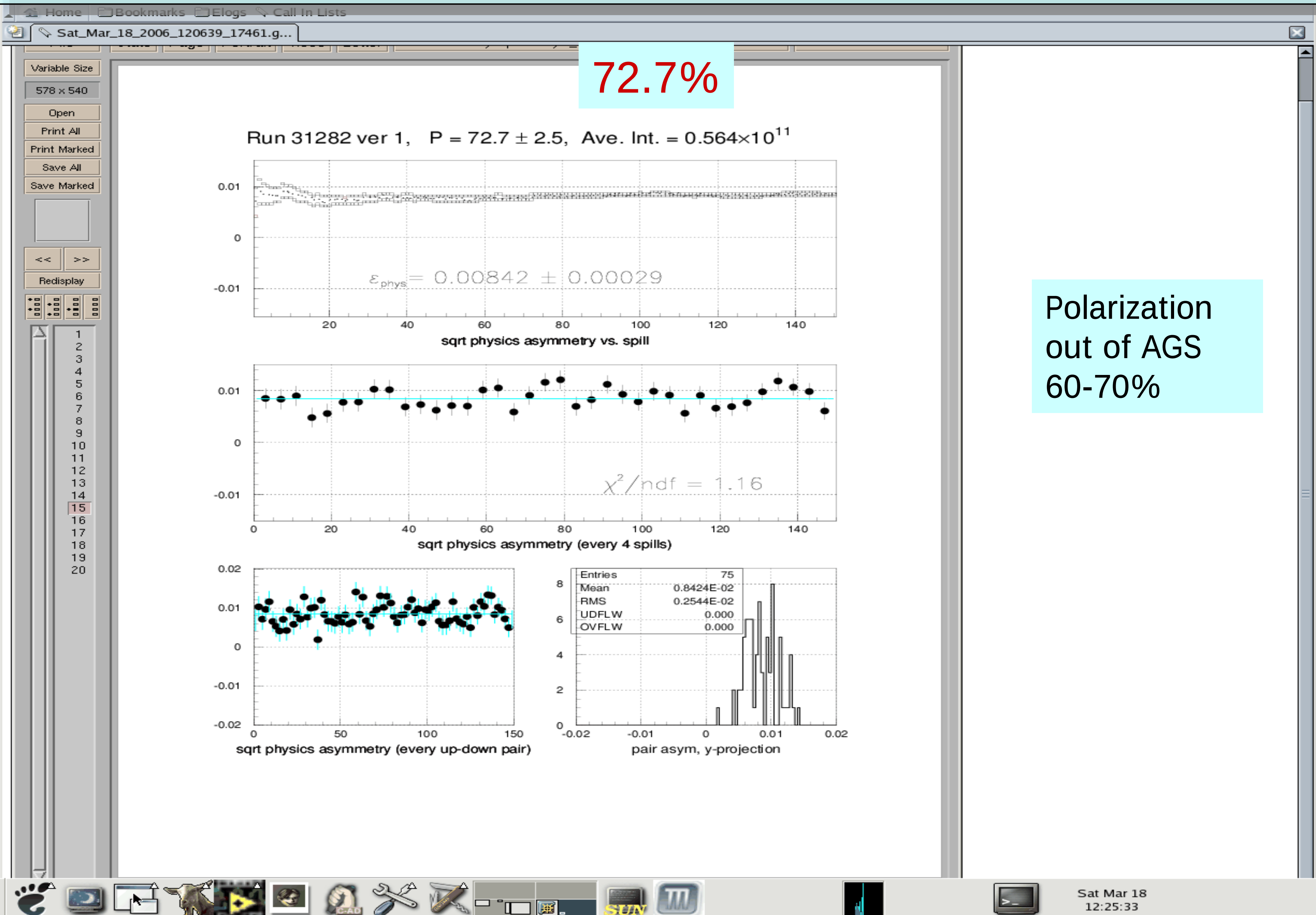
POLARIZATION (L/R) (P,dP): 0.856941 0.000236641

RESTART

Wed Apr 04 04:52:37 PM EDT 2007

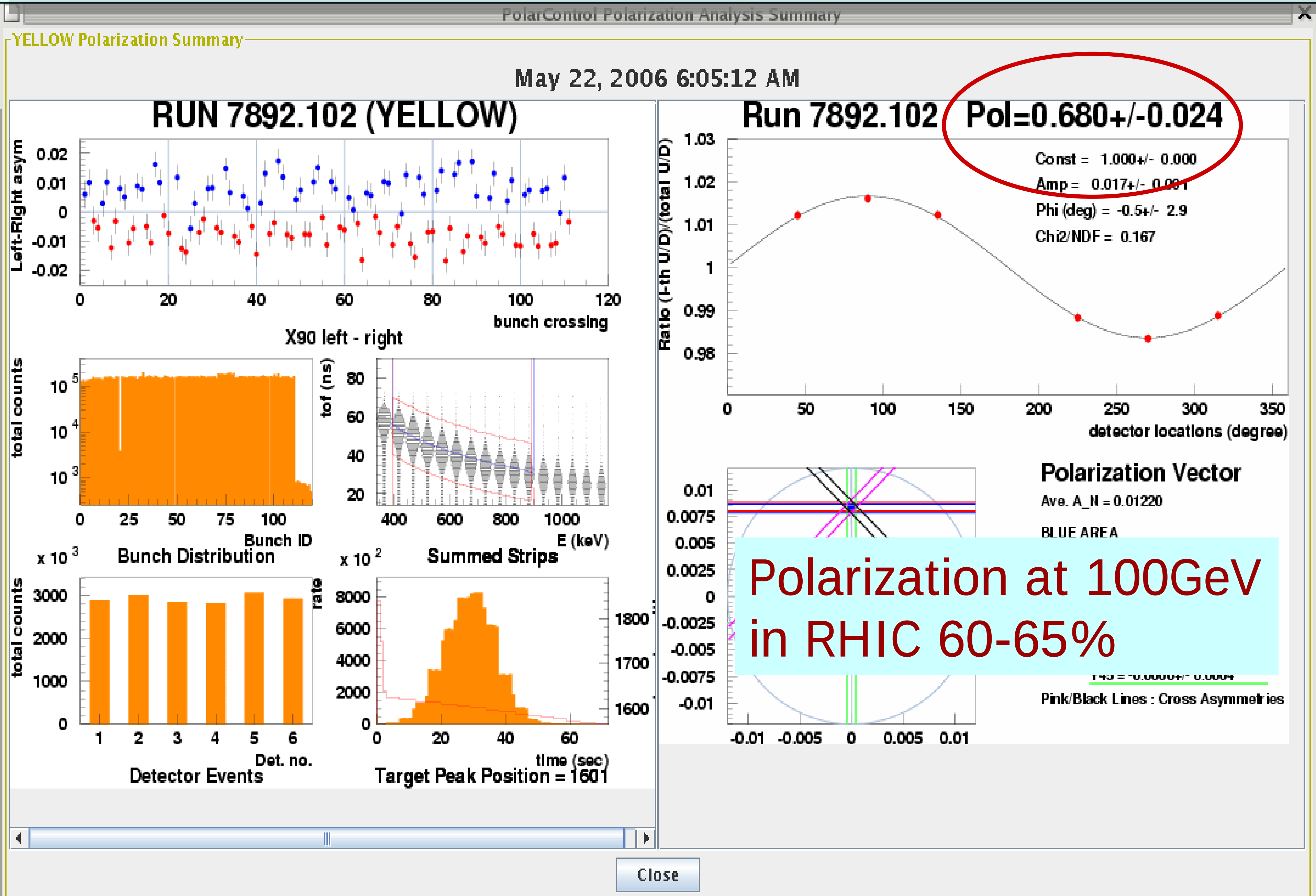
Polarization measurement in AGS at 24 GeV.

72.7%



Polarization out of AGS 60-70%

Polarization measurements in RHIC at 100 GeV.



Polarization at 100GeV in RHIC 60-65%

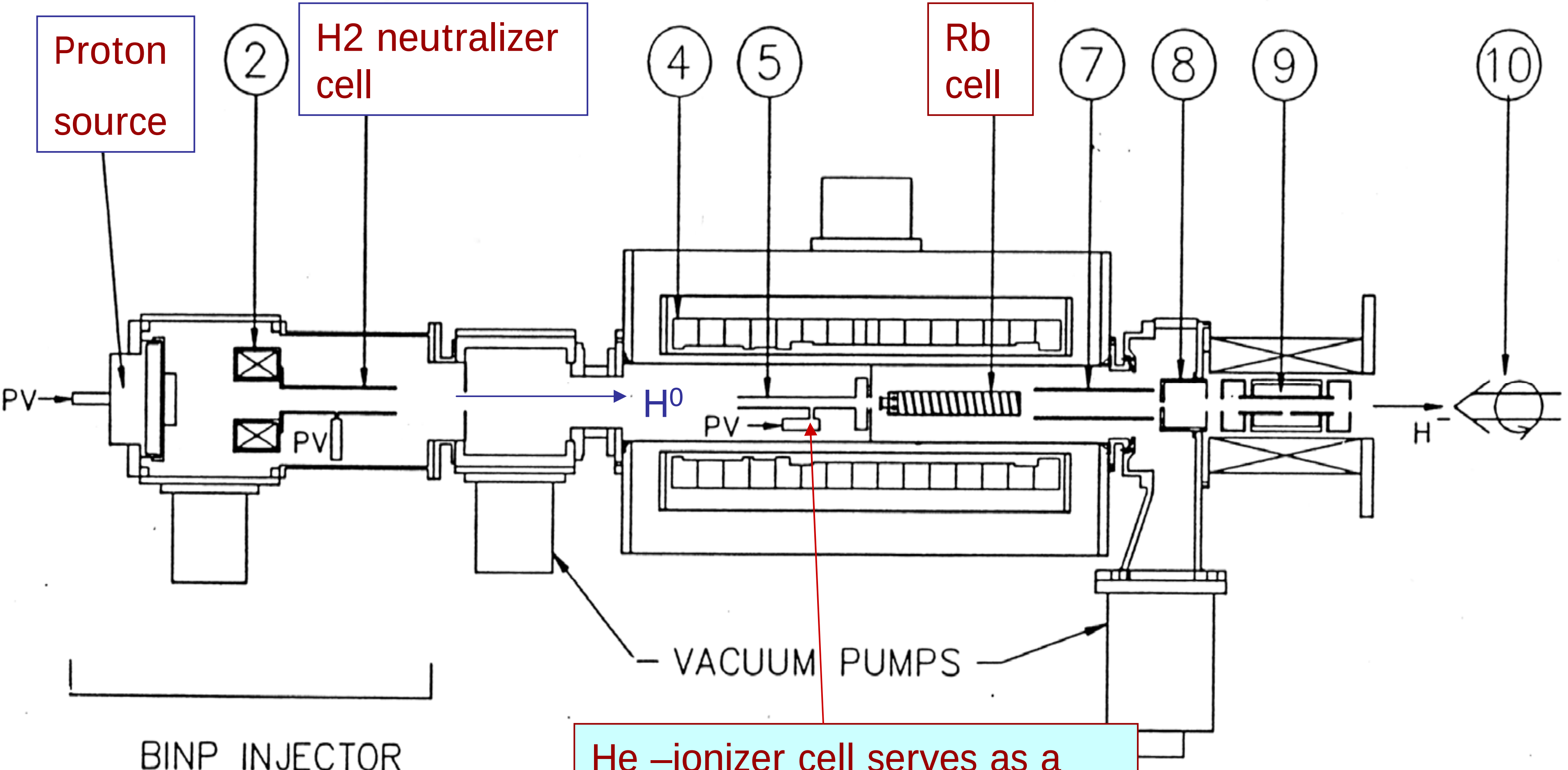
OPPIS operation in Runs 2006-08

- BNL OPPIS reliably delivered polarized H^- ion beam (P= 82-86%) in the 2006 run for the RHIC spin program.
- A beam intensity greatly exceeds RHIC bunch intensity limit, which allowed strong beam collimation in the Booster, to reduce longitudinal and transverse beam emittances.
- 85-90% polarization was achieved at further Sona-transition optimization and ionizer magnetic field increase in Run 07.

Further improvements:

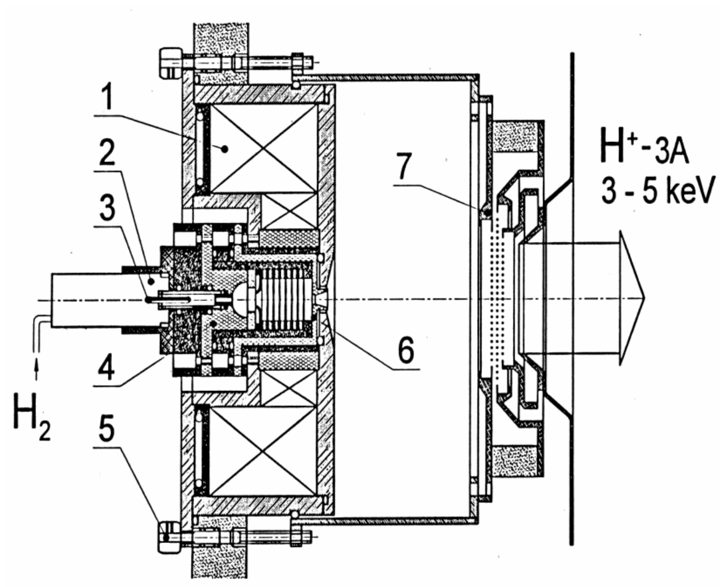
A higher brightness primary proton beam is required for high intensity source with the smaller diameter collimated beam in Sona-transition and ionizer (which is necessary for high polarization).

Pulsed OPPIS layout.

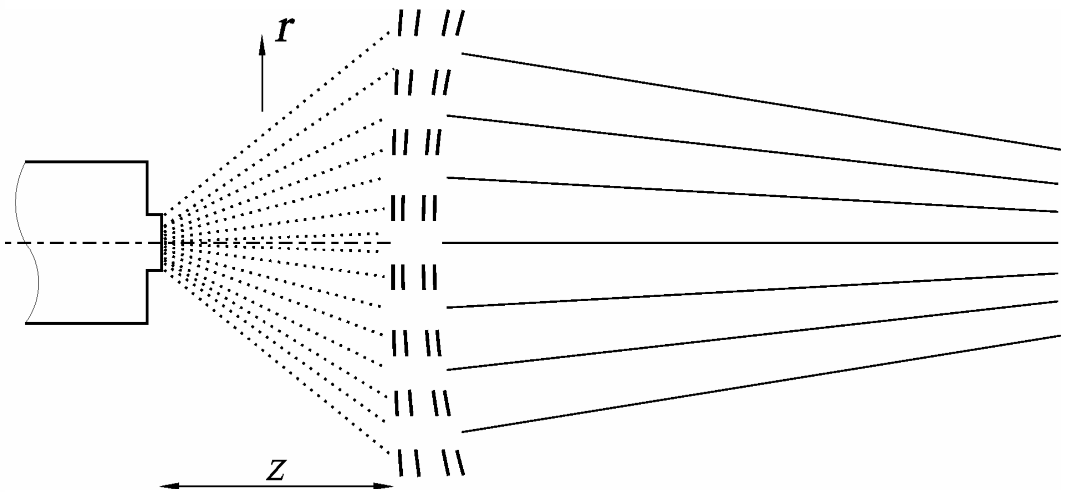


He –ionizer cell serves as a proton source in the high magnetic field.

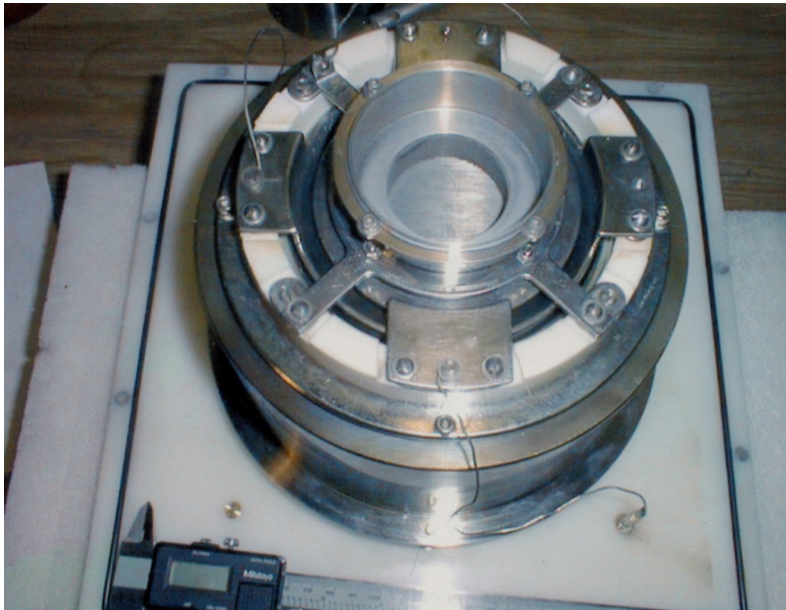
Proton "cannon" of the atomic H injector.



Ion Optical System with "geometrical focusing".



The source produced 3 A ! pulsed proton current at 5.0 keV.

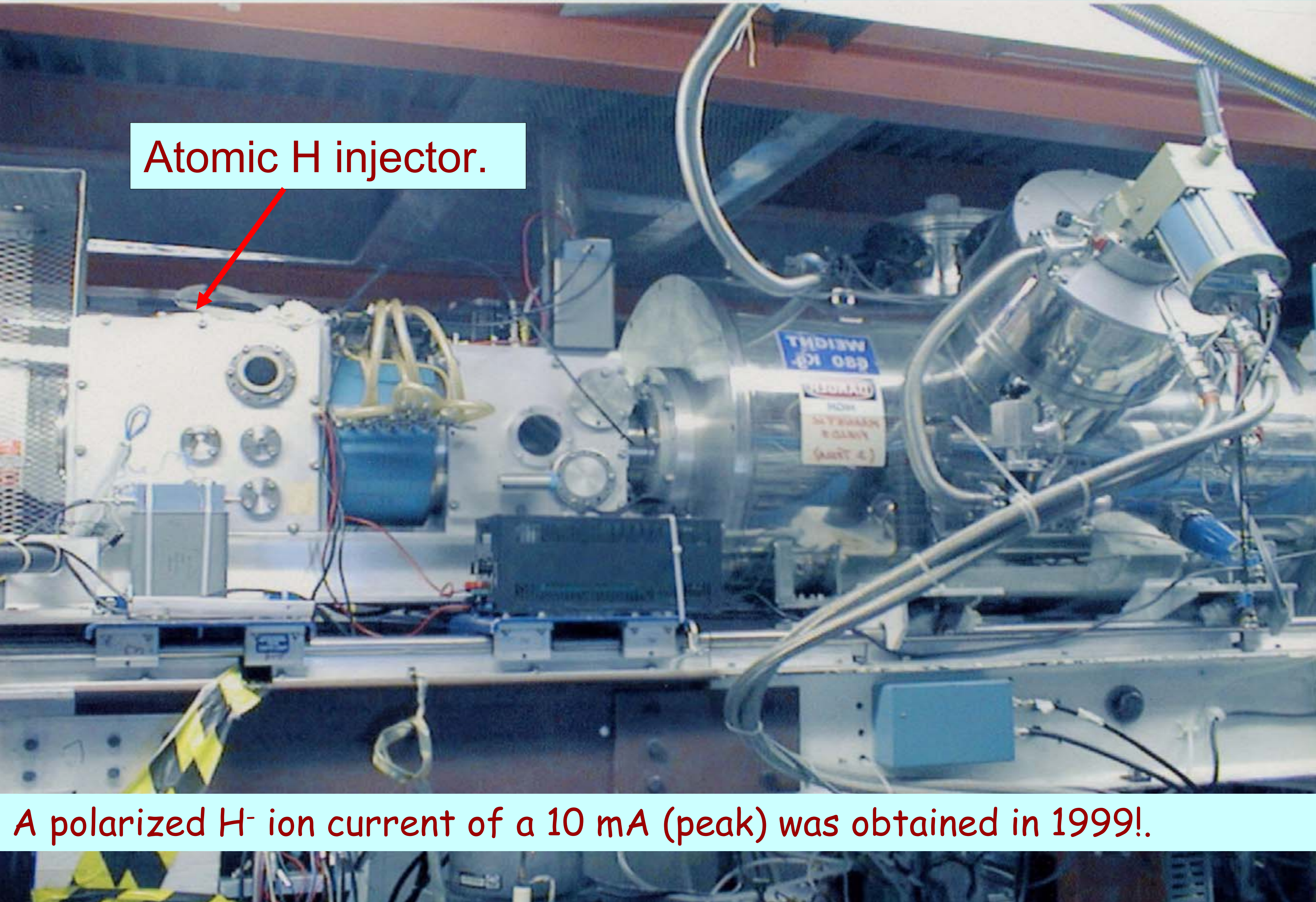


~20-50 mA H^- current. P=75-80%
~10 mA , P=85-90%.
~ 300 mA unpolarized H^- ion current.

OPPIS upgrade with the atomic H injector.

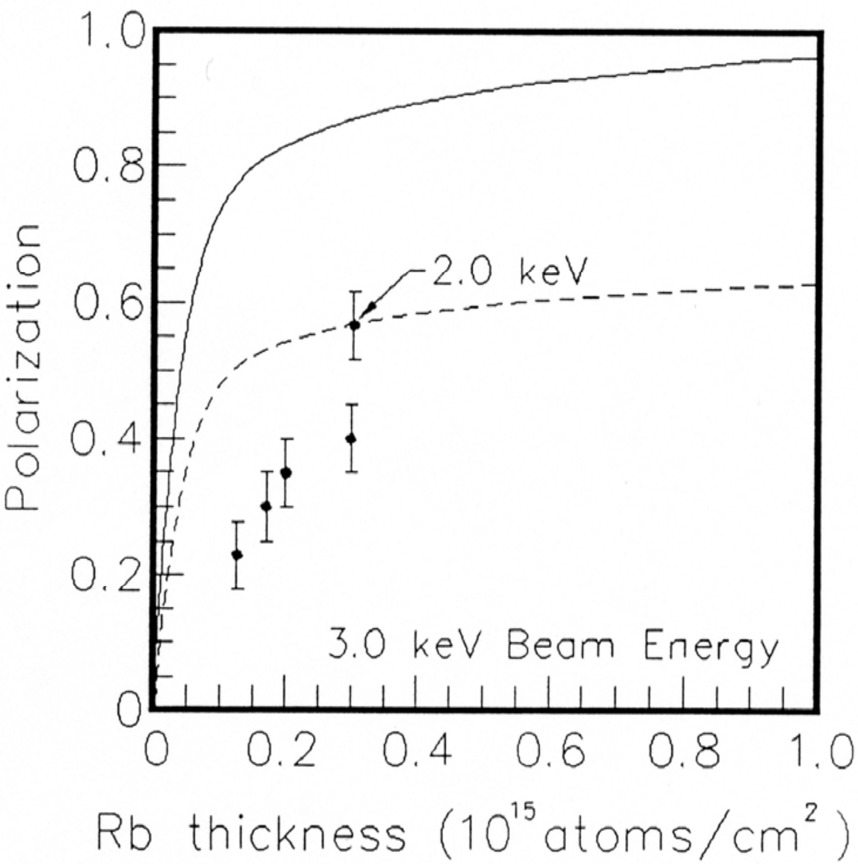
- Atomic H injector produces an order of magnitude higher brightness beam.
- A 5-10 mA H^- ion current can be easily obtained with the smaller, about 12 mm in diameter beam. This reduces most of possible polarization losses and produce smaller emittance polarized beam.
- Neutralization in the residual gas is much smaller too.
- All these factors combined will increase polarization to over 90%.

Pulsed OPPIS at TRIUMF, 1999.



A polarized H^- ion current of a 10 mA (peak) was obtained in 1999!.

Beam intensity and polarization in the pulsed OPPIS, TRIUMF 1999.

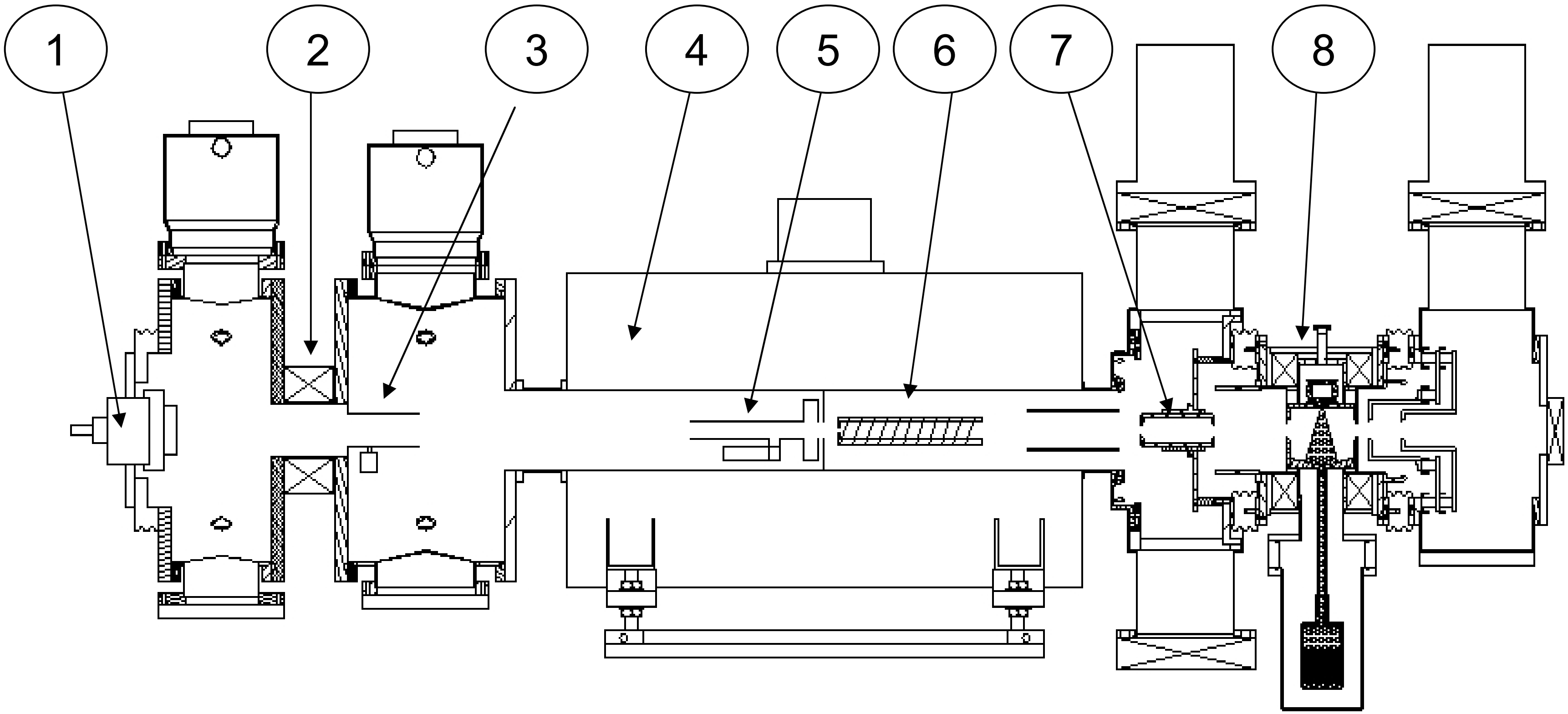


25 kG

10 kG

Beam energy, keV	2.0	3.0	4.0
H^- ion current, mA	5.0	8.0	14.0
Proton current, mA	16.0	50.0	
Polarization, %	55± 5	42± 5	30 ±5

OPPIS with Fast Atomic Beam Source



General layout: 1- high-brightness plasmatron proton source; 2 – focusing lens; 3- H2 neutralizer cell; 4-superconducting solenoid; 5-He ionizer cell; 6-Rb vapor cell; 7- Sona transition; 8- sodium-jet ionizer cell.

OPPIS with the "Fast Atomic Hydrogen Source" *(Towards 100% polarization in OPPIS).*

- Higher polarization is also expected with the fast atomic beam source due to:

  a) elimination of neutralization in residual hydrogen;

  b) better Sona-transition efficiency for the smaller ~ 1.5 cm diameter beam;

  c) use of higher ionizer field (up to 3.0 kG), while still keeping the beam emittance below 2.0 π mm·mrad, because of the smaller beam – 1.5 cm diameter.

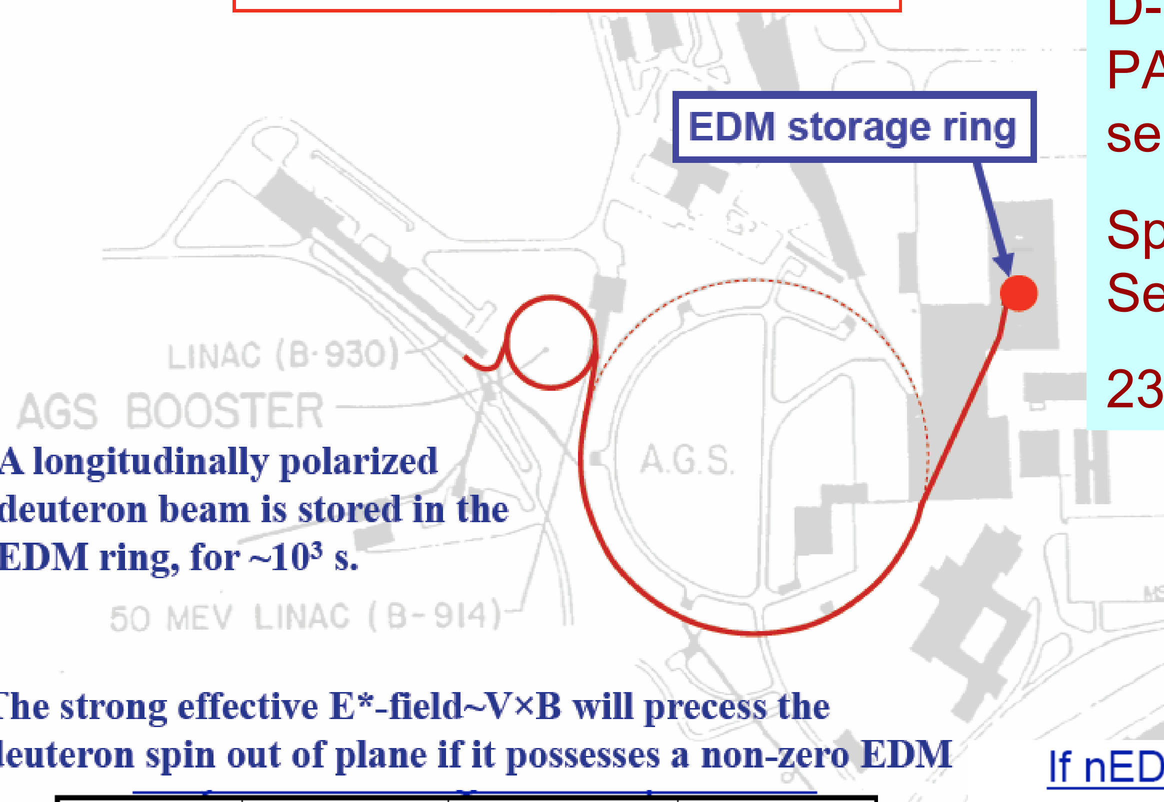
- All these factors combined will further increase polarization in the pulsed OPPIS to:

  over 90% and the source intensity to over 10 mA.

  (A new superconducting solenoid is required).

- The ECR-source replacement with an atomic hydrogen injector will provide the high intensity and high polarization beam for polarized RHIC luminosity upgrade and for future eRHIC facilities.

deuteron EDM search at BNL



A longitudinally polarized deuteron beam is stored in the EDM ring, for ~10^3 s.

The strong effective E*-field~V×B will precess the deuteron spin out of plane if it possesses a non-zero EDM

D-EDM exp't proposed to PAC in May 2008, with sensitivity goal of 10^{-29} e·cm

Spokesperson: Yannis Semertzidis (BNL)

23 collaborating institutions

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
199Hg atom	$<2\times10^{-28}$	$\sim2\times10^{-29}$	10^{-25}-10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-30}$-10^{-33}	10^{-26}-10^{-29}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}

If nEDM is discovered at 10^{-28} e.cm level?

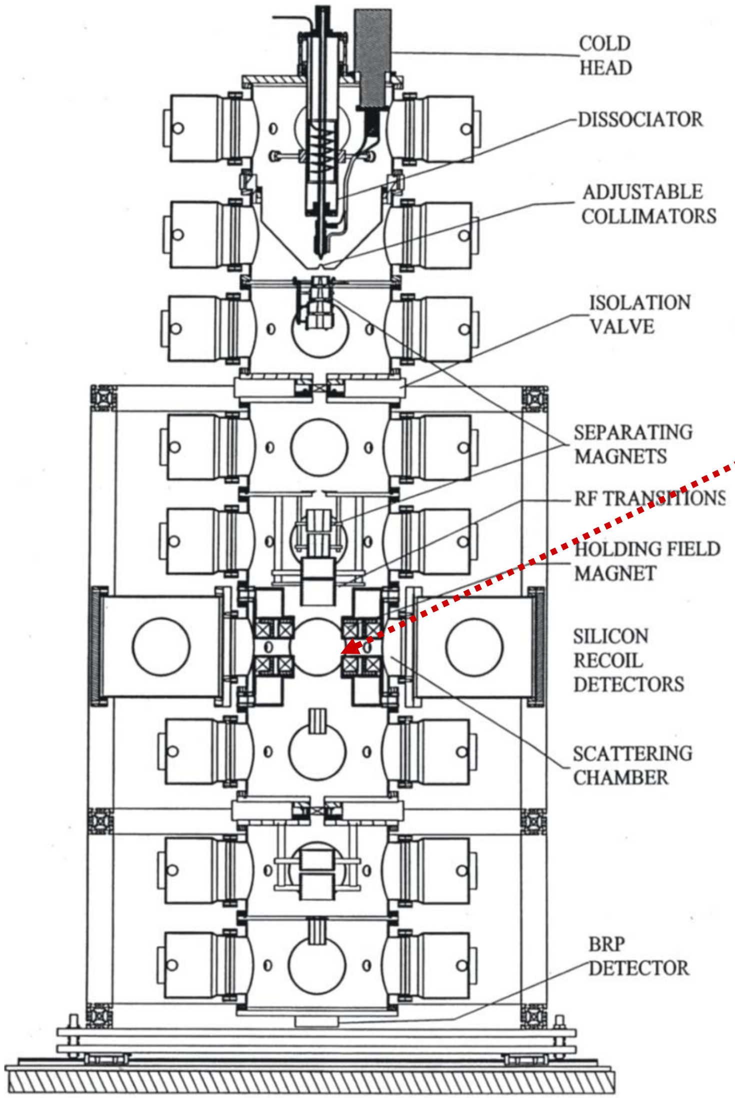
- If $\bar{\theta}$ is the source of the EDM, then $d_D(\bar{\theta})/d_n(\bar{\theta}) \approx 1/3 \Rightarrow d_D \approx 3\times10^{-29}\,\mathrm{e\cdot cm}$

- If SUSY is the source of the EDM (isovector part of T-odd N-forces), then $d_D(\bar{\theta})/d_n(\bar{\theta}) \approx 20 \Rightarrow d_D \approx 2\times10^{-27}\,\mathrm{e\cdot cm}$

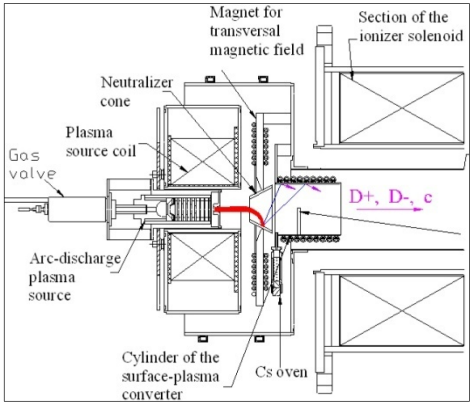
The deuteron EDM is complementary to neutron and in fact has better sensitivity.

D+ polarized ion source with plasma ionizer.

Atomic hydrogen-jet at RHIC



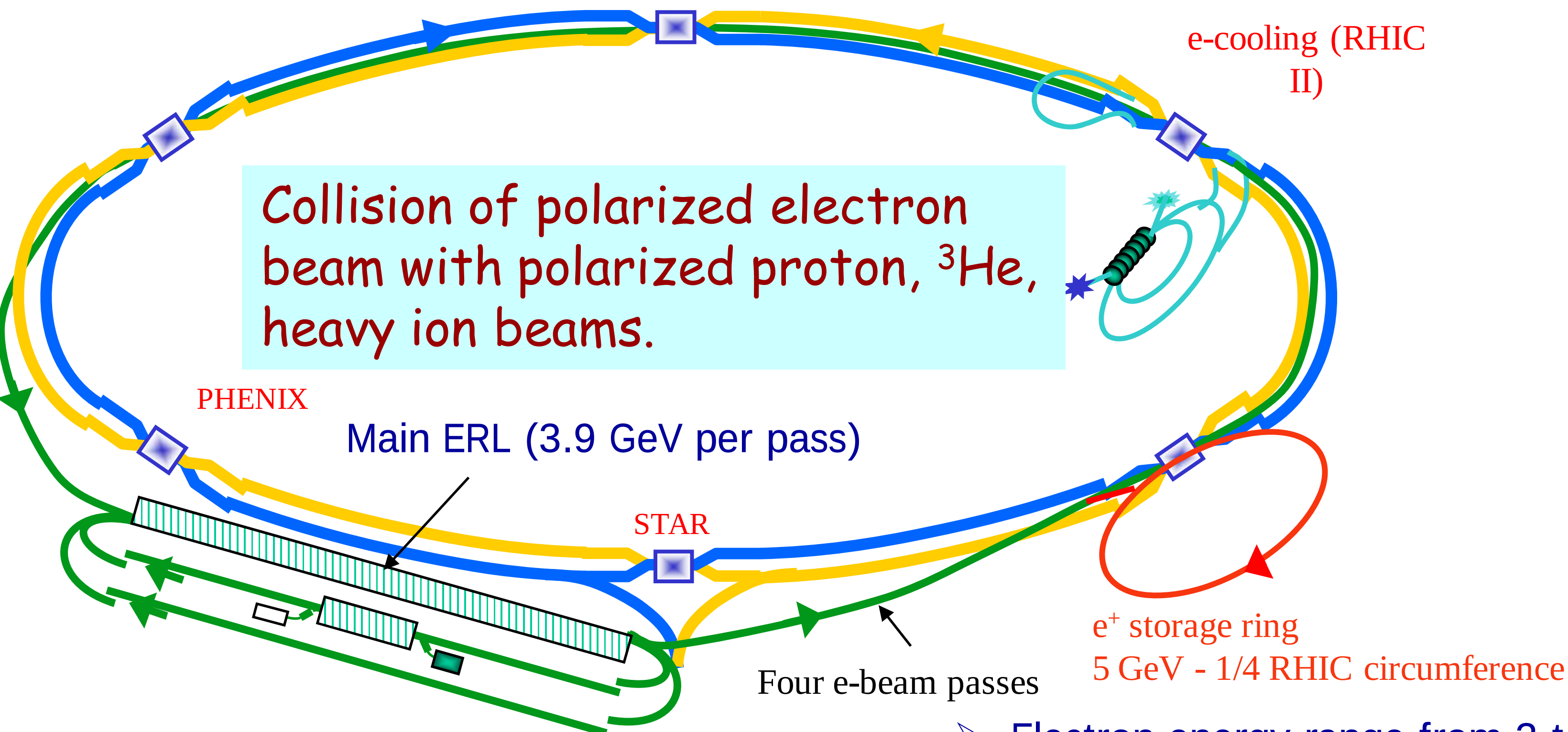
Plasma Ionizer,
INR Moscow, A.Belov



Polarized D^+ beam for the future D-EDM experiment at BNL can be produced in ABS similar to H-jet polarimeter ionized by "plasma ionizer".

The D^+ beam of a few mA intensity can be accelerated in EBIS RFQ and DTL for injection to Booster to produce about 10^{11} D/bunch for injection to D-EDM storage ring.

eRHIC-electron Ion Collider at BNL

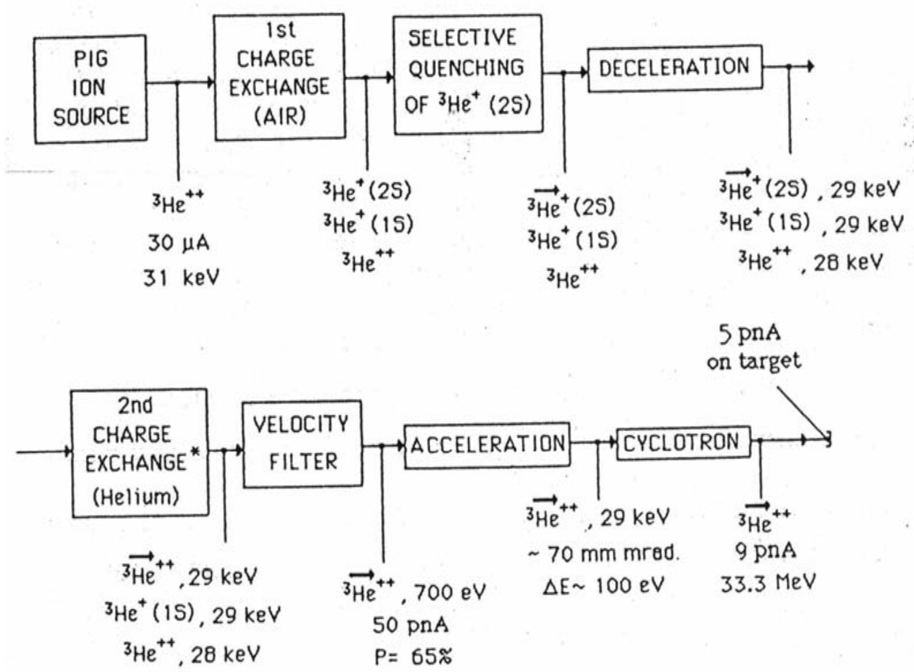


- Electron energy range from 3 to 20 GeV
- Peak luminosity of 2.6×10^{33} $cm^{-2}s^{-}$
- high electron beam polarization (~80%)
- full polarization transparency at all energies
- multiple electron-hadron interaction points

The AGS and RHIC "Siberian snakes" should preserve the $^3He^{++}$ beam polarization.

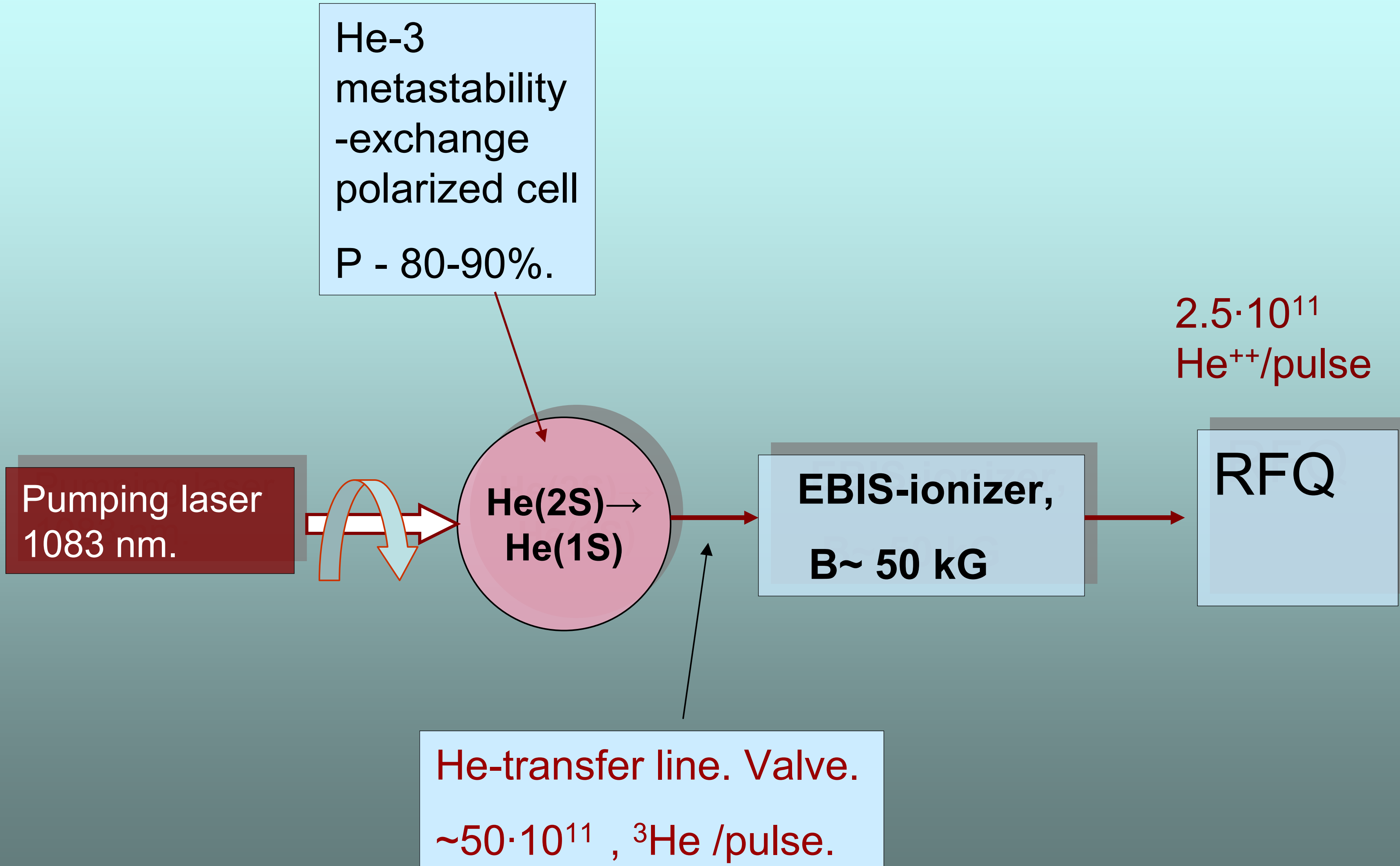
Univ. of Birmingham $^3He^{++}$ Source

- First polarized ^{3}He source installed on any accelerator (1974)
  - PIG source of He^{++}
  - Charge exchange in air to make $^3He^+(2S)$ atomic beam
  - Selective quenching of (β-state) m_s=-1/2 atoms with 10 GHz RF in 0.25 T field
  - Sona-reversal to enhance polarization
  - Ionization to He^{++} by charge exchange in ^{4}He
- Used for experiments for > 10 years
  - Polarized 3He^{++} current:
    - 100 nA at 29 keV
    - 9 pnA at 33 MeV, P = 55-65%

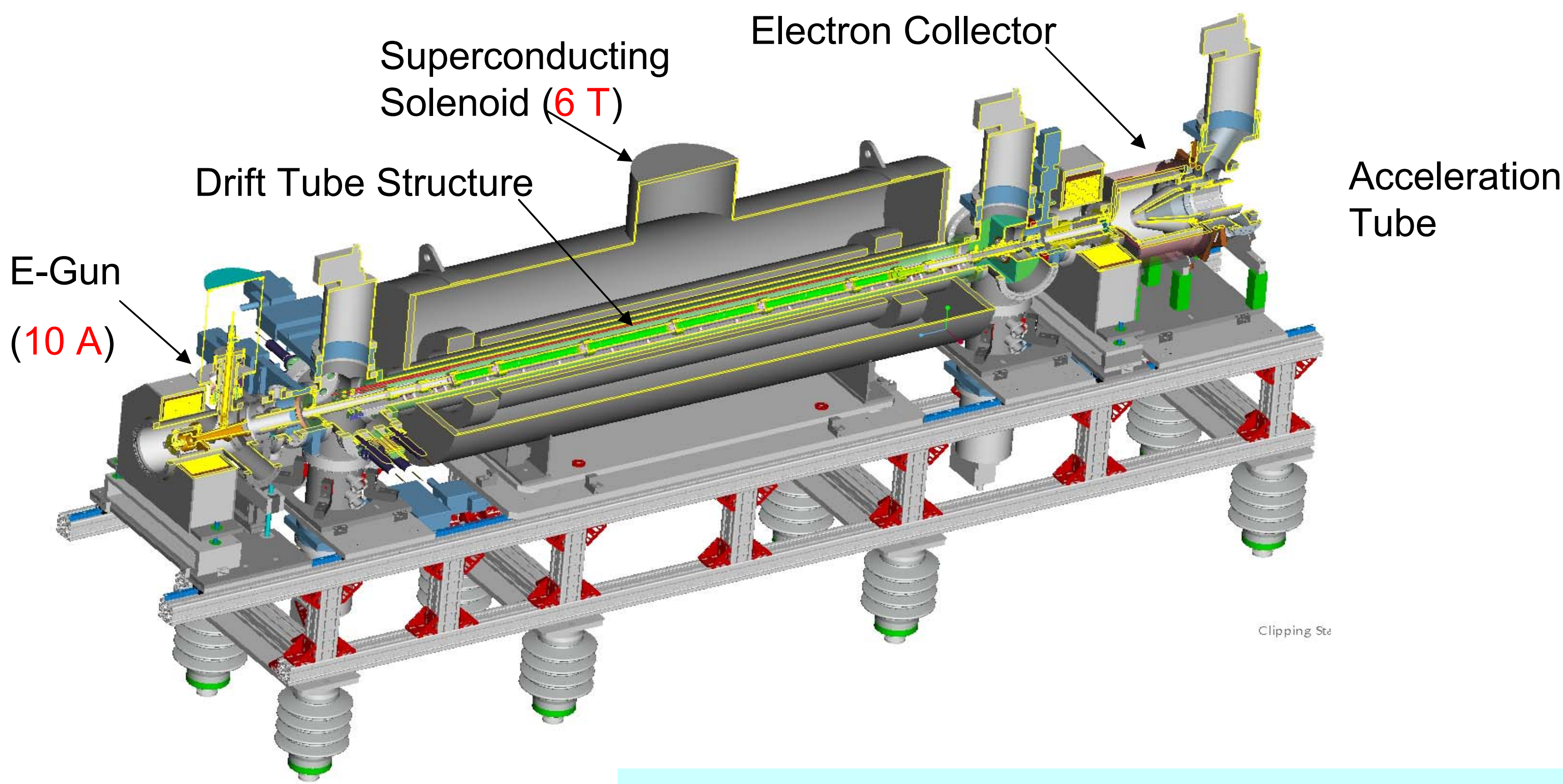


About 10^5 times higher $^3He^{++}$ source intensity (of a few mA) is required for eRHIC!!!

EBIS ionizer for polarized ^{3}He gas (proposal).



Electron Beam Ion Source at RHIC

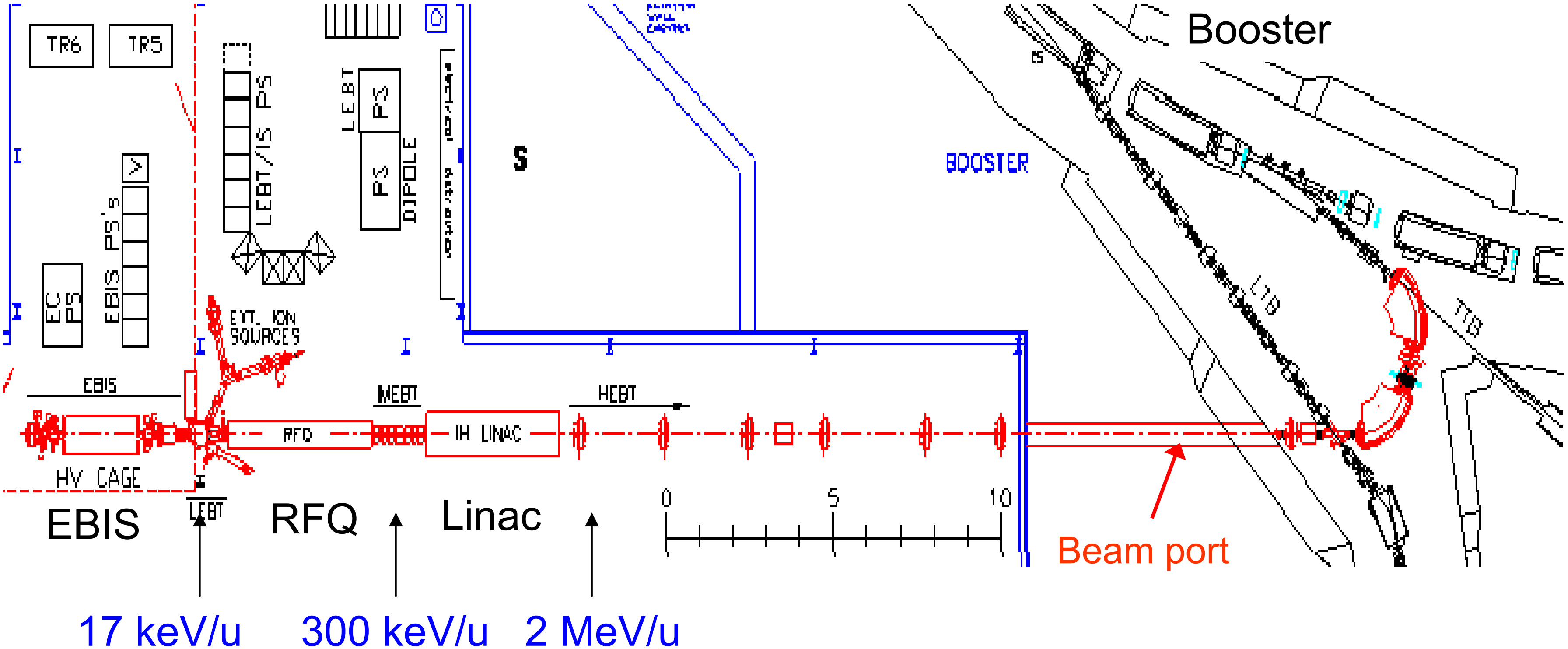


What intensity is expected?

Capacity will be 10^{12} charges/pulse

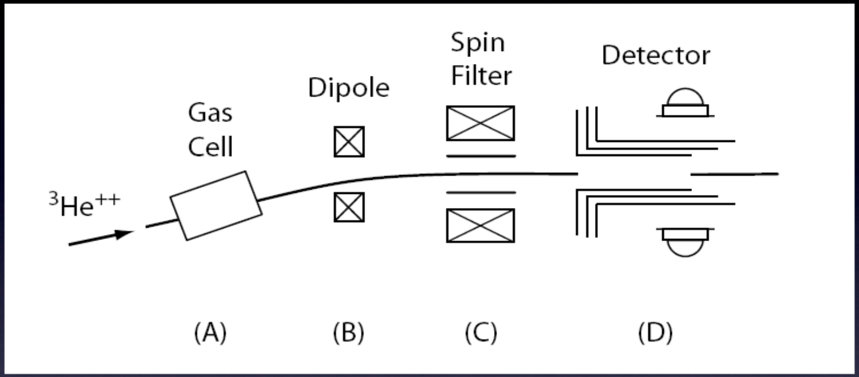
→ ~ 2-3 x 10^{11} $^{3}He^{++}$ ions per pulse ?

EBIS Preinjector Layout in lower equipment bay of 200 MeV Linac



Ion	**He - U**
Q/m	**≥1/6**
Current	**> 1.5 emA (for 1 turn inj)**
Pulse Length	**10 μs**
Rep. Rate	**5 Hz**
Time to switch species	**1 second**

Lamb-shift polarimeter for $^3He^+$ (2S) ions.

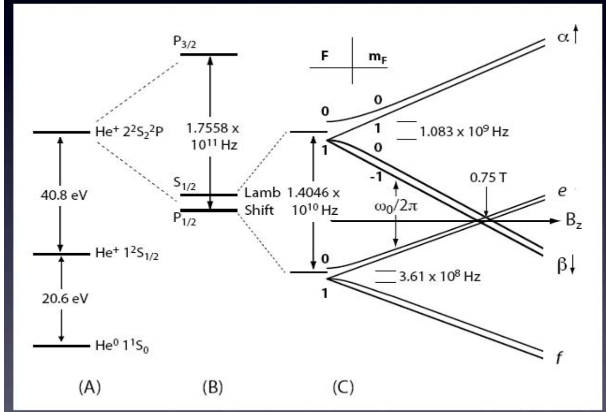


(A) A gas cell with an external magnetic field to produce $^3He^+$(2S). Ions in the $2P_{1/2}$ immediately decay.

(B) A bending magnet to ensure a beam of pure $^3He^+$ ions.

(C) A spin filter ($E \perp B$) to quench the β-states of the metastable $2S_{1/2}$ ions.

(D) The remaining metastable ions are quenched and produce 40.8 eV photons captured on silicon

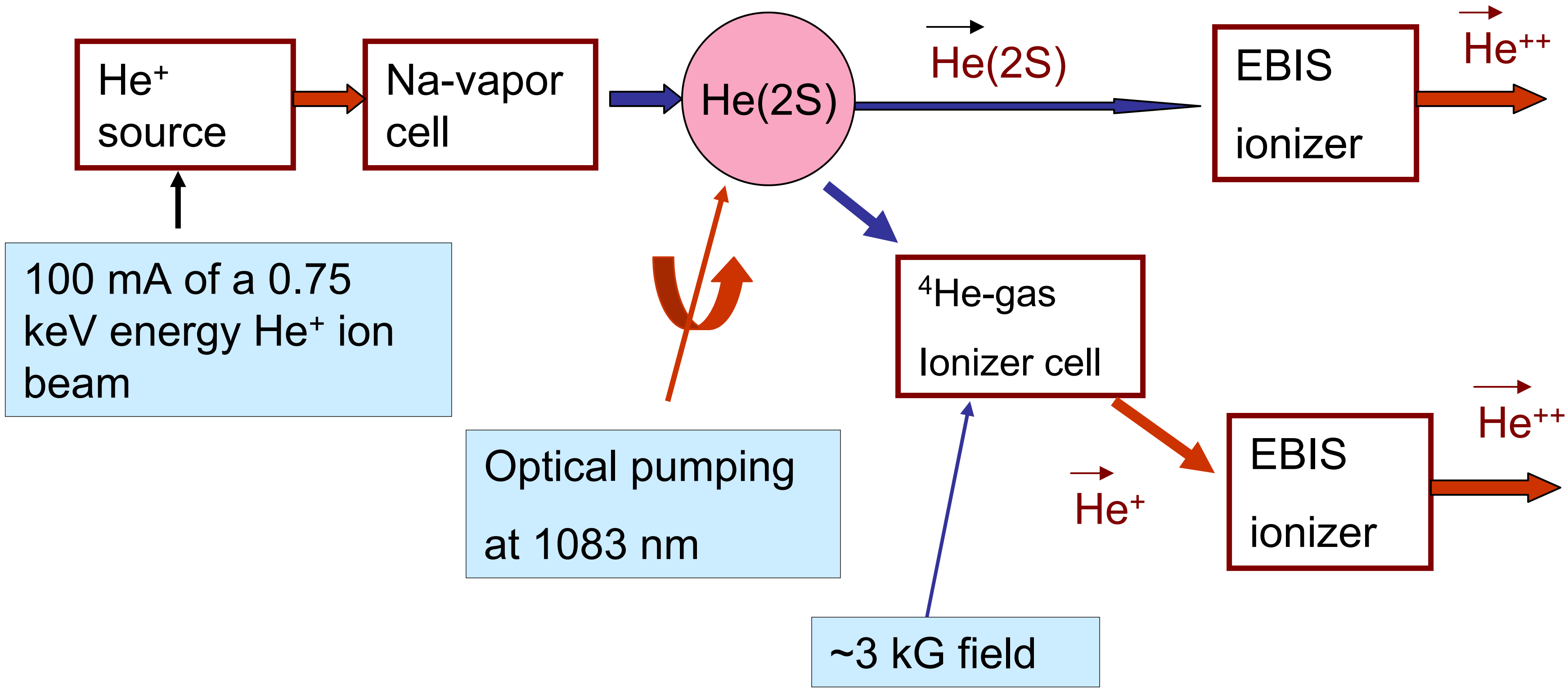


Lamb-shift is the energy shift between the $2S_{1/2}$ and $2P_{1/2}$ states (1405 MHz or 5.8×10^{-6} eV).

In the absence of any external fields, the $2P_{1/2}$ state decays rapidly ($\tau_p > 10^{-10}$ s), while the $2S_{1/2}$ state is metastable ($\tau_s = 2 \times 10^{-3}$ s).

However, in the presence of an external electric field, the metastable state rapidly decays due to Stark mixing with the $2P_{1/2}$ state. This effect is referred to as "quenching" of the metastable state

Direct optical pumping of the "fast" ^{3}He(2S) beam (proposal).



- After Na-neutralizer cell almost 100% of He-atoms are in (2^3S_1) state. Energy defect-0.38 ev.
- Direct optical pumping can produce near 100% nuclear polarization in He(2S) states. P(He^{++}) ~80-90%.

Summary

• Current and future polarization program at RHIC (eRHIC) will require high-intensity, high polarization proton, deuteron and $^3He^{++}$ ion beams.

BNL OPPIS reliably deliver polarized H^- ion beam for the RHIC spin program. The proton polarization 85-90% was achieved by Sona-transition optimization and ionizer magnetic field increase.

The ECR-source replacement with an atomic hydrogen injector will provide the high intensity (~10 mA H^-) and high (>= 90%) polarization for the RHIC luminosity upgrade and for future eRHIC program.

The further development is required for polarized $^3He^{++}$ ion source on the basis of new RHIC EBIS injector.