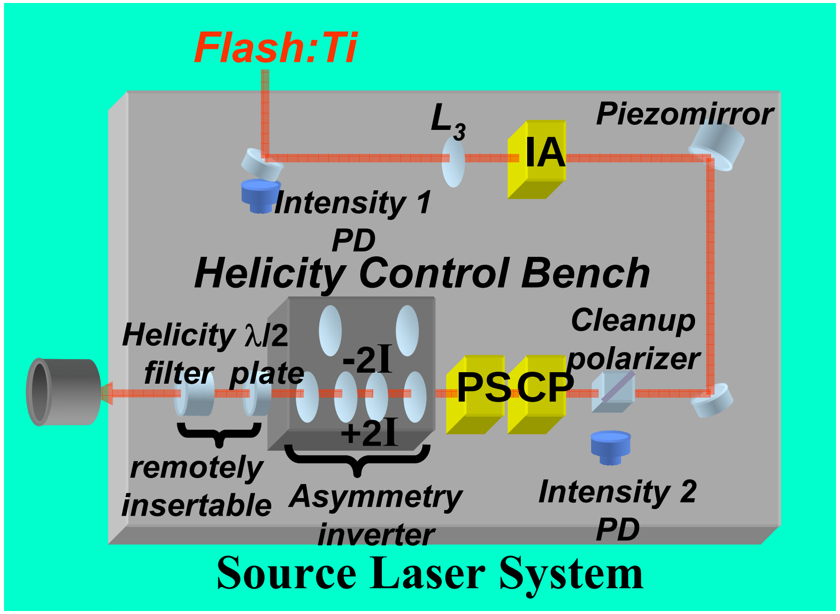
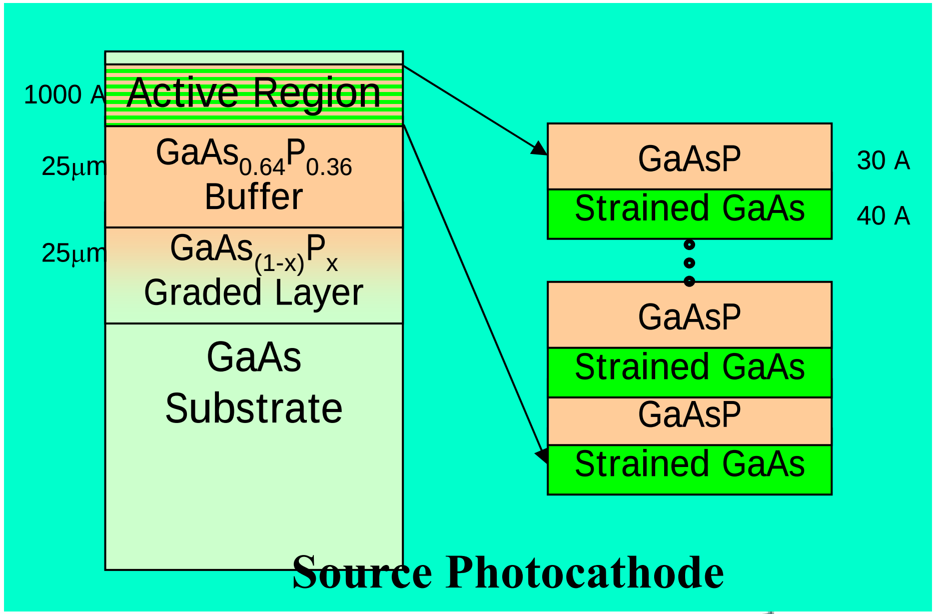
SLAC E-158 Beam:

Setup, Instrumentation & Systematics

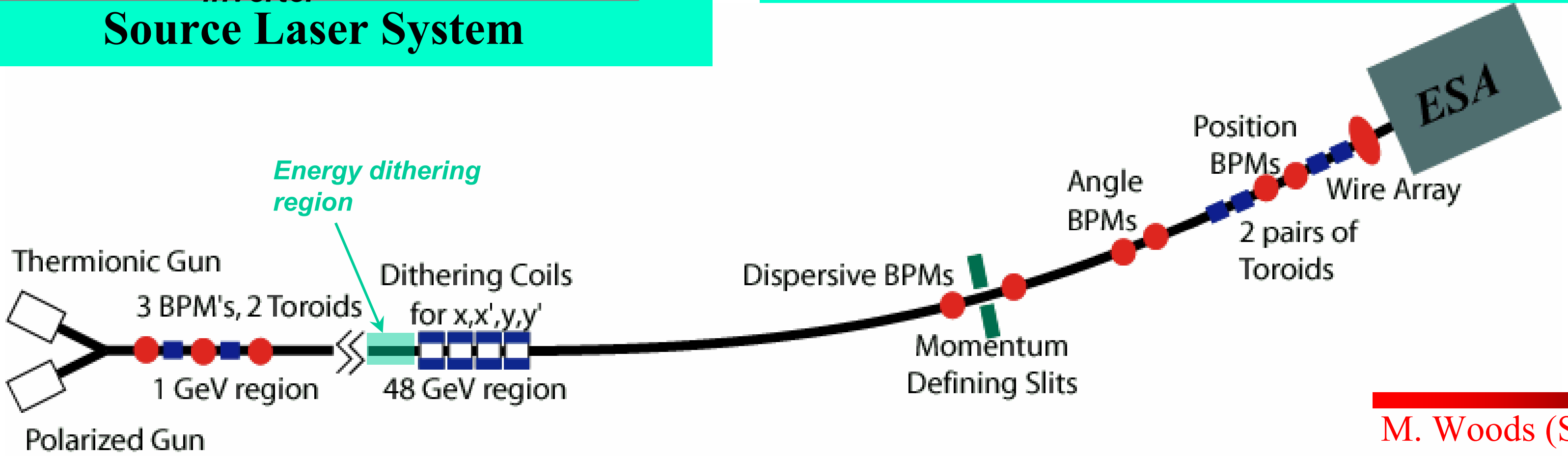
JLAB Electroweak Workshop, December 2006



Source Laser System



Source Photocathode



Outline

Beam Setup

- parameters and performance
- source laser and photocathode, helicity control

  (see talk by G. Cates tomorrow)
- dithering coils, skew quad

Beam Instrumentation

- rf BPMs, toroids, spotsize wire array
- synchrotron radiation monitor

Beam Asymmetries & Systematics

- position, energy, charge
- spotsize
- beam parameter correlations and higher order effects
- synchrotron radiation
- target density fluctuations

E158 Beam References

Source Laser System (+ minimization of beam helicity correlations)

- B. Humensky et al., SLAC-PUB-9381, 2002. Published in Nucl.Instrum.Meth.A521: 261-298, 2004. e-Print Archive: physics/0209067.

RF BPM Monitors

- D.H. Whittum and Y. Kolomensky, SLAC-PUB-7846, 1998. Published in Rev.Sci.Instrum.70:2300-2313,1999.

Student Theses (8 Ph.D and 2 senior undergrad theses)

- www-project.slac.stanford.edu/e158/press_papers.html#theses

Accelerator Physics

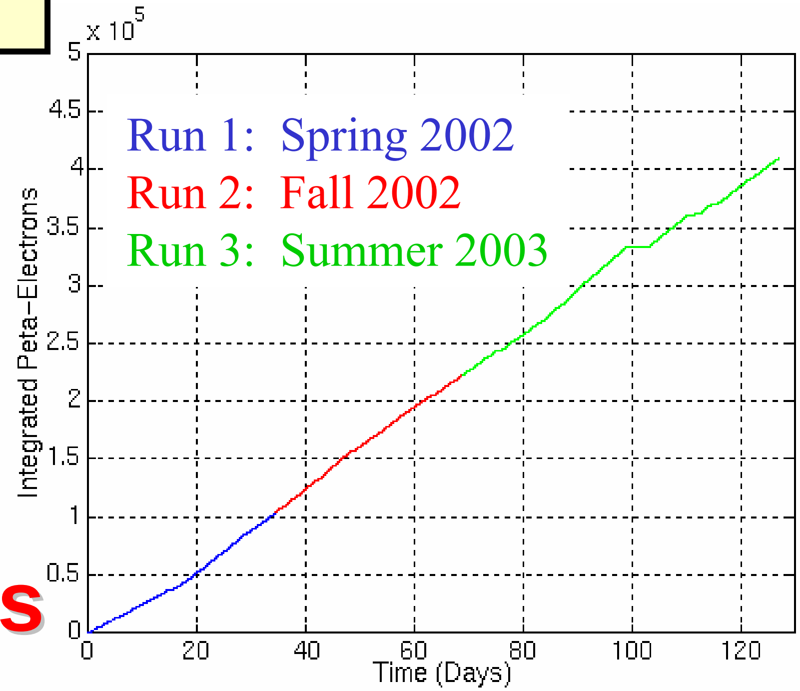
- ***A Test of NLC-type beam loading in the SLAC linac,*** F.J. Decker et al., SLAC-PUB-10726, 2003. Published in *PAC 03* Proceedings, 2754-2756.
- ***Interlaced beams of unequal energy and pulse length in the SLAC linac for PEP-II and experiment E-158,*** F.J. Decker et al., SLAC-PUB-9361, 2002. Published in *EPAC 02* Proceedings, 885-887.
- ***A High intensity highly polarized electron beam for high-energy physics,*** J.L. Turner et al., SLAC-PUB-9235, 2002. Published in *EPAC 02* Proceedings, 1419-1421.
- ***Beam stabilization in the SLAC A-line using a skew quadrupole,*** M. Woodley et al., SLAC-PUB-9233, 2002. Published in *EPAC 02* Proceedings, 1208-1210.
- ***High power beam at SLAC,*** F.J. Decker et al., SLAC-PUB-9359, 2002. Published in *PAC 01* Proceedings, 3936-3938.

E-158
Beam Parameters

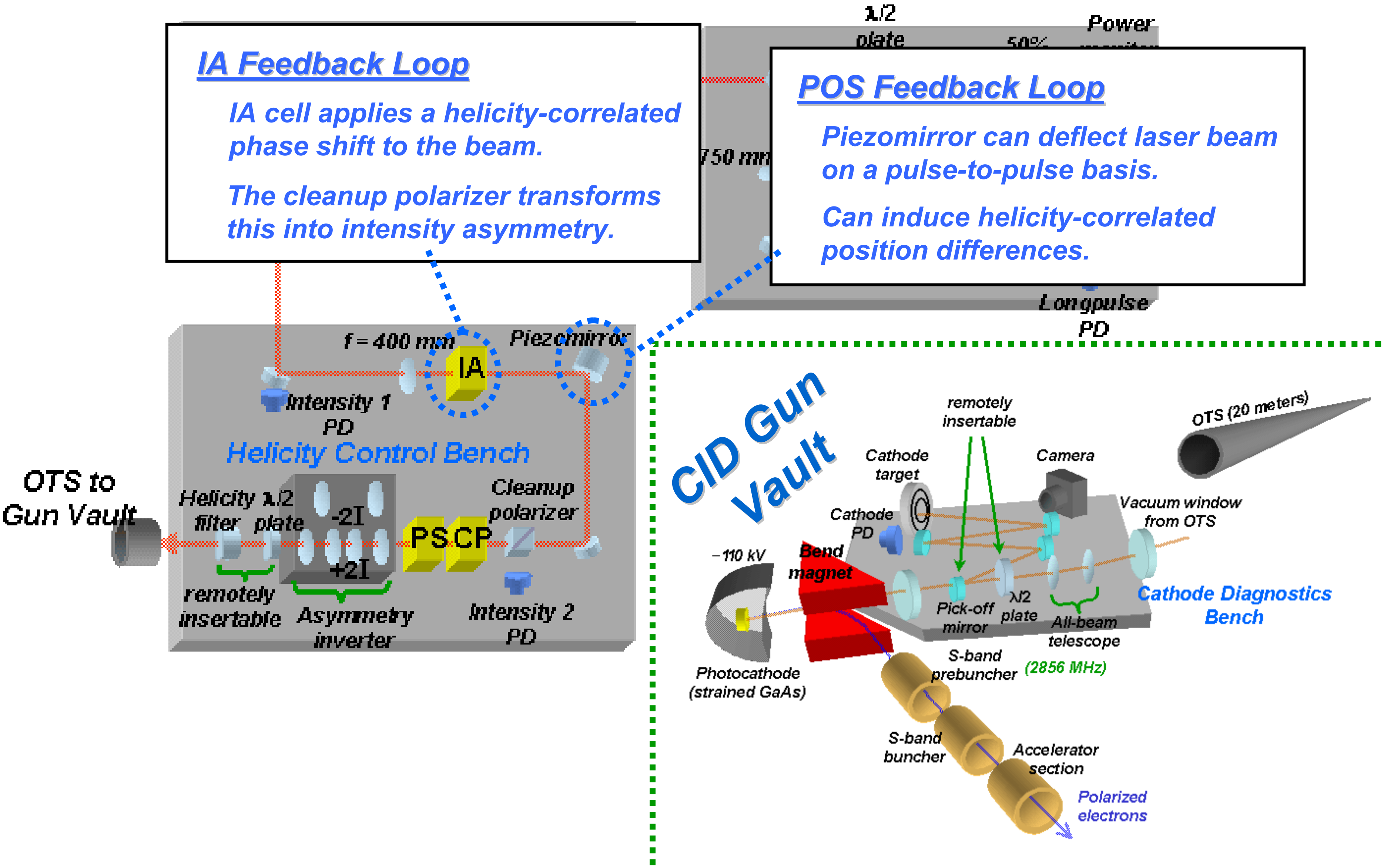
Parameter	Proposal	Achieved
Intensity* at 45 GeV	6 x 10^{11} / pulse	5.3 x 10^{11}
Intensity* at 48 GeV	3.5 x 10^{11}	4.3 x 10^{11}
Polarization	80%	85-90%
Repetition Rate	120 Hz	120 Hz
Intensity jitter / pulse	2% rms	0.5% rms
Energy jitter / pulse	0.4% rms	0.03% rms
Energy spread	-	0.15% rms
Delivered Charge (Peta-E†)	345K	410K

*(average current ~ 10 μA;
peak current ~ 0.3A;
beam power ~ 0.5 MW)
†1 Peta-Electron = 10^{15} electrons

E-158
Physics Runs



Polarized Source Laser System



IA Feedback Loop

IA cell applies a helicity-correlated phase shift to the beam.

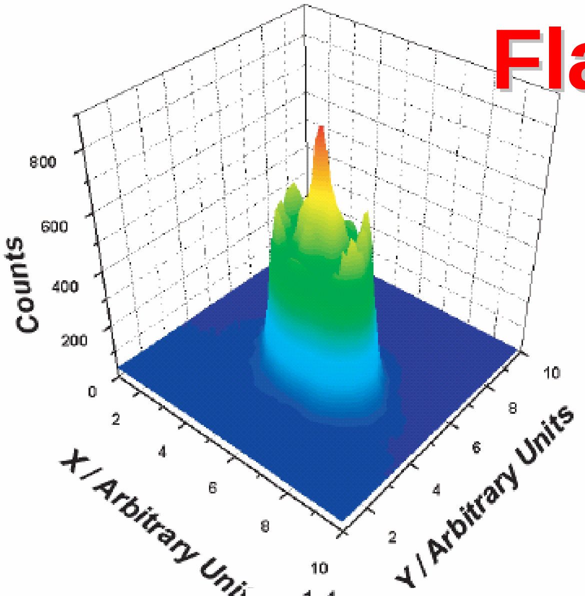
The cleanup polarizer transforms this into intensity asymmetry.

POS Feedback Loop

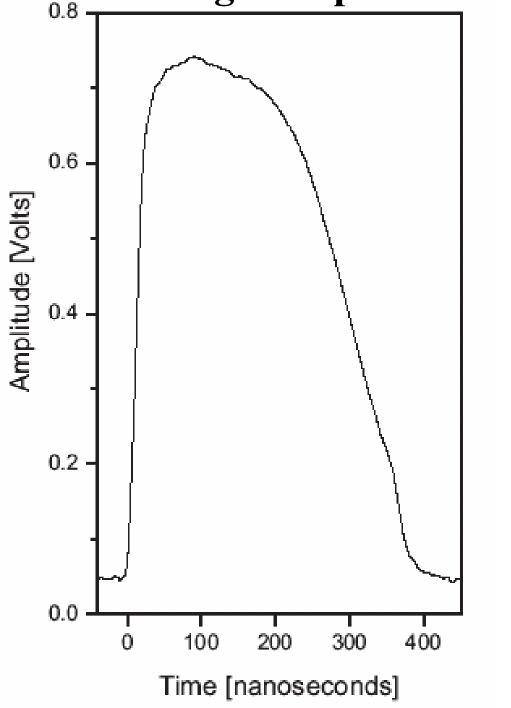
Piezomirror can deflect laser beam on a pulse-to-pulse basis.

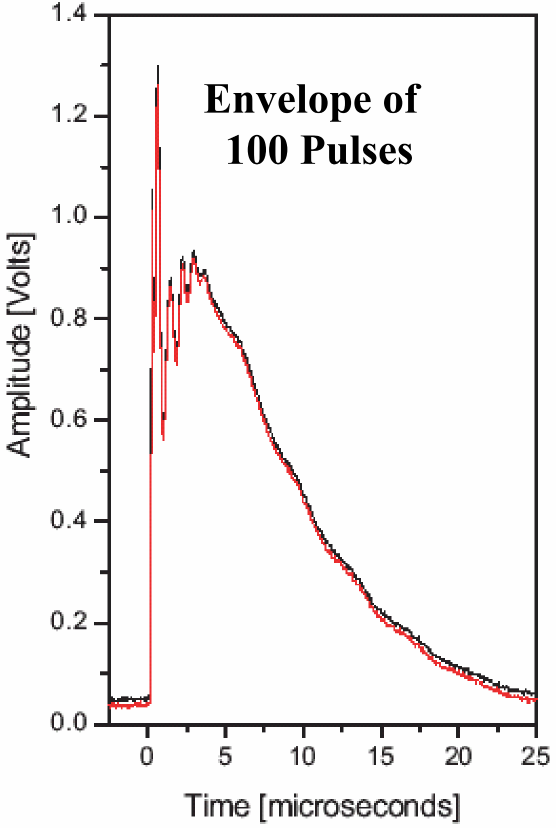
Can induce helicity-correlated position differences.

Flash-TI Source Laser

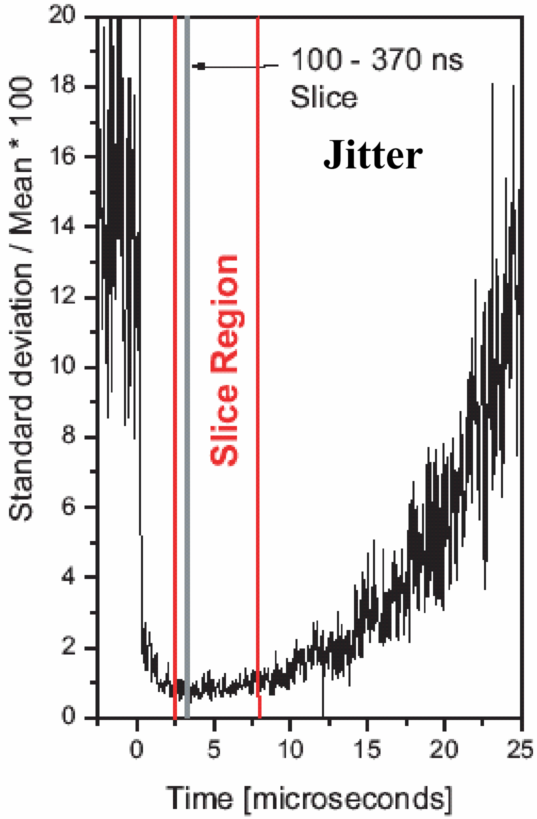


Shaped Laser Pulse
for Beamloading Compensation





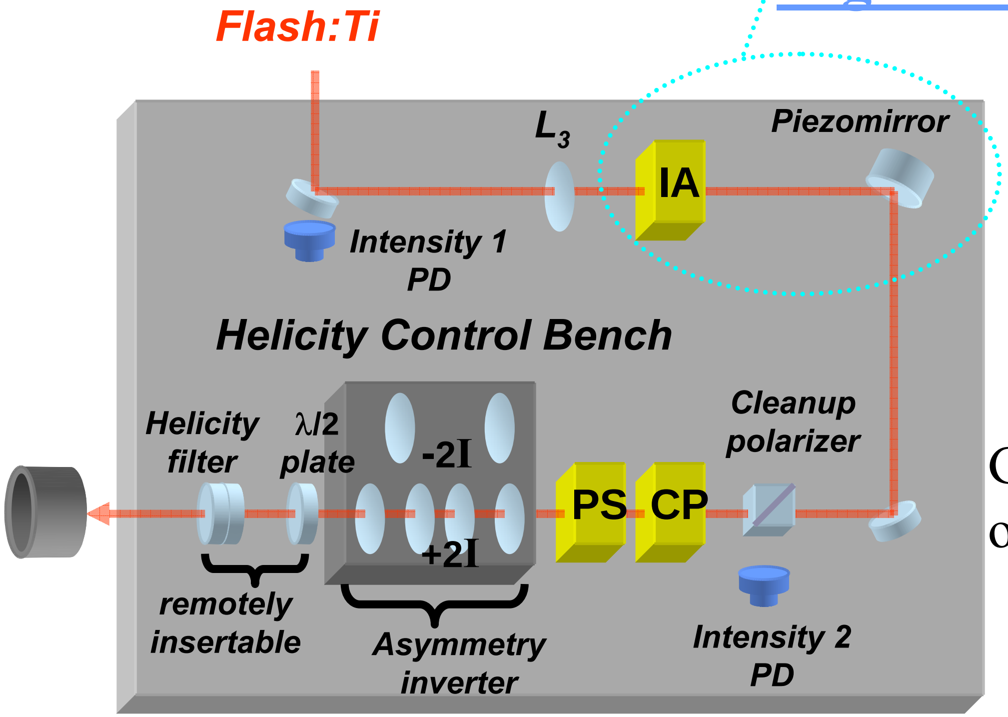
Envelope of 100 Pulses



Jitter

Beam Asymmetry Feedbacks

Item	Control	Diagnostic
Intensity	IA Pockels Cell	Toroid (@ 1 GeV)
Position	Piezo Mirror	BPM (@ 1 GeV)

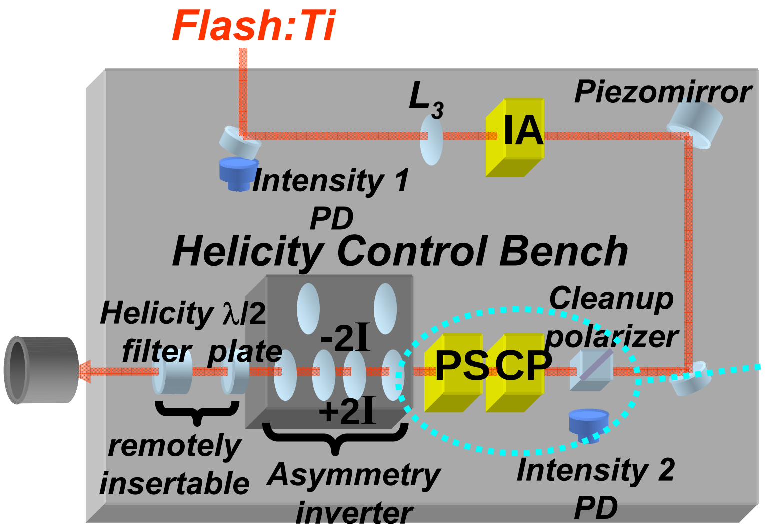


Algorithm:
- measure asymmetry on a run with N pulses (typically 1-30K pulses)
- induce asymmetry on next run to cancel measured asymmetry on current run

↓

Gives better than 1/sqrt(N) scaling of charge asymmetry, position difference

Laser Polarization Control And Analysis



Electric Field Vector after PS Cell in Jones Matrix notation:

$$|E\rangle = \begin{bmatrix} \sin\left(\delta_{CP}/2\right) \\ e^{i\left(\pi/2+\delta_{PS}\right)}\cos\left(\delta_{CP}/2\right) \end{bmatrix}$$

Stokes parameters for laser polarization:

$$s_1 = \cos(\delta_{CP}) = \frac{X-Y}{X+Y}$$

$$s_2 = \sin(\delta_{CP})\sin(\delta_{PS}) = \frac{U-V}{U+V}$$

$$s_3 = \sin(\delta_{CP})\cos(\delta_{PS}) = \frac{R-L}{R+L}$$

$$\left(s_1^2 + s_2^2\right) + s_3^2 = L^2 + C^2 = 1$$

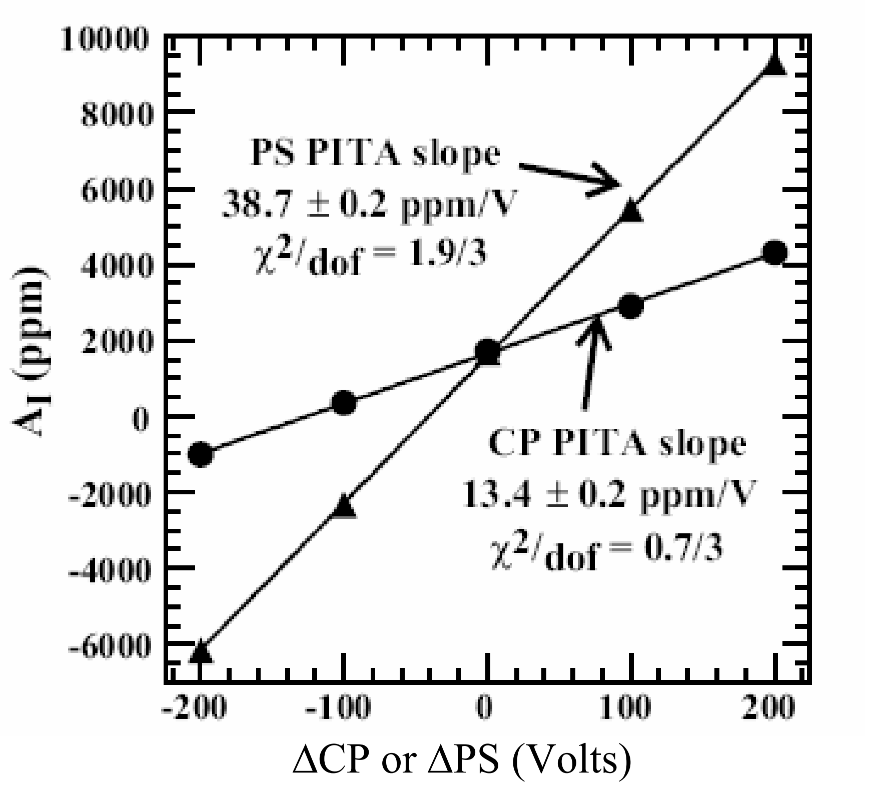
(ex. C=0.998, L=0.063)

Allow for imperfect Pockels cells and phase shifts in downstream optics:

	Left Pulse	**Right Pulse**
δ_{CP}	$-\pi/2 - \alpha_{CP} + \Delta_{CP}$	$+\pi/2 + \alpha_{CP} + \Delta_{CP}$
δ_{PS}	$- \alpha_{PS} + \Delta_{PS}$	$- \alpha_{PS} + \Delta_{PS}$
s_1	$\sim - \alpha_{CP} + \Delta_{CP}$	$\sim - \alpha_{CP} - \Delta_{CP}$
s_2	$\sim - \alpha_{PS} + \Delta_{PS}$	$\sim - \alpha_{PS} - \Delta_{PS}$

→ **Δ_{CP}, Δ_{PS} introduce significant linear polarization asymmetries**

Charge Asymmetry
due to anisotropic strain*



Sensitive to
linear polarization
In laser light

Example

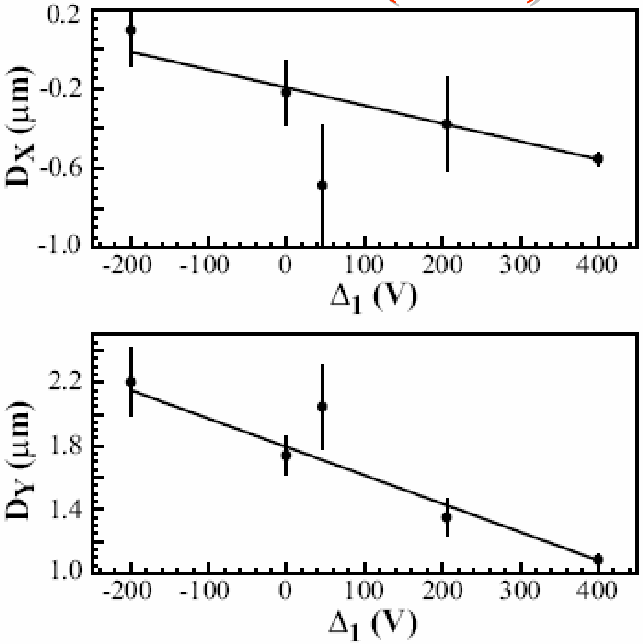
L=0.01 → 300ppm Charge Asym

Recall, $A_{PV} \approx -0.1\,ppm$
and want ~ppb systematic errors!

V_{QW} ~ 2700V

*Reference: R.A. Mair et al., Phys. Lett. **A212**, 231 (1996)

(L-R) Position Differences observed at 1 GeV

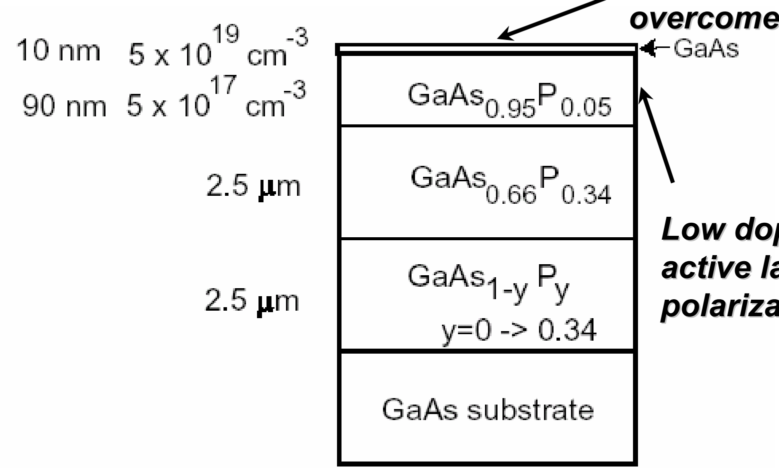


Data taken moving along $A_I = 0$ line

How do position differences evolve from photocathode to Expt Target?

- adiabatic damping: emittance is reduced as beam is accelerated
  (I **do not** believe this is a significant effect; L-R position differences just scale with spotsize)
- should scale ~ with laser spotsize on cathode to electron spotsize at target
  (for E158, rms spotsize on cathode ~5-8mm; rms spotsize on target ~1mm)
- should have position asymmetries at cathode, not angle asymmetries for electron beam
  (good for position asymmetry feedback, but did have trouble getting phase advance acceptable to 1 GeV point for feedback)
  → can choose phase advance in Linac so position at cathode maps to angle at target, but then get angle asymmetries at target
- implement Asymmetry Inverter for electron beam! Find 2 quad lattices related by "-I" transformation – do this with scaling quadrupole strength to change # betatron oscillations; tried this for E158 – not much success due to unstable position differences

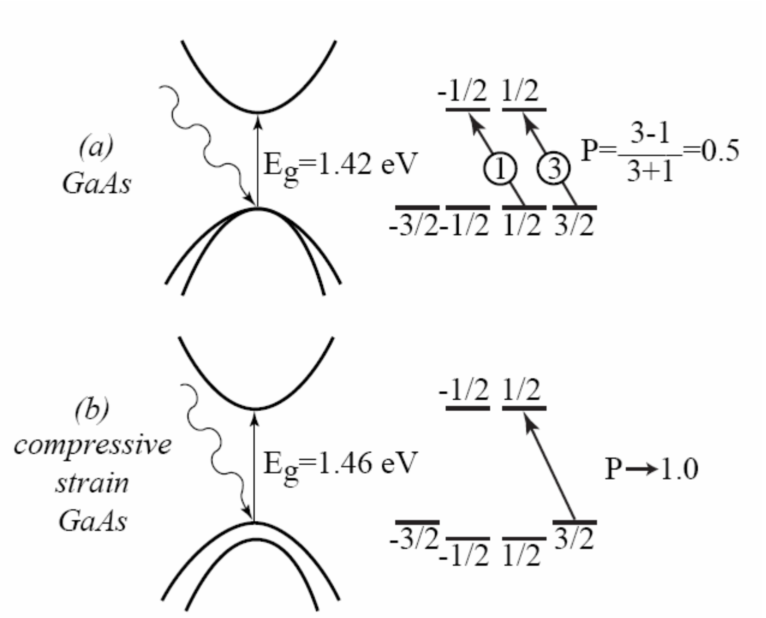
Photocathode for Polarized Gun



High doping for 10-nm GaAs surface overcomes charge limit.

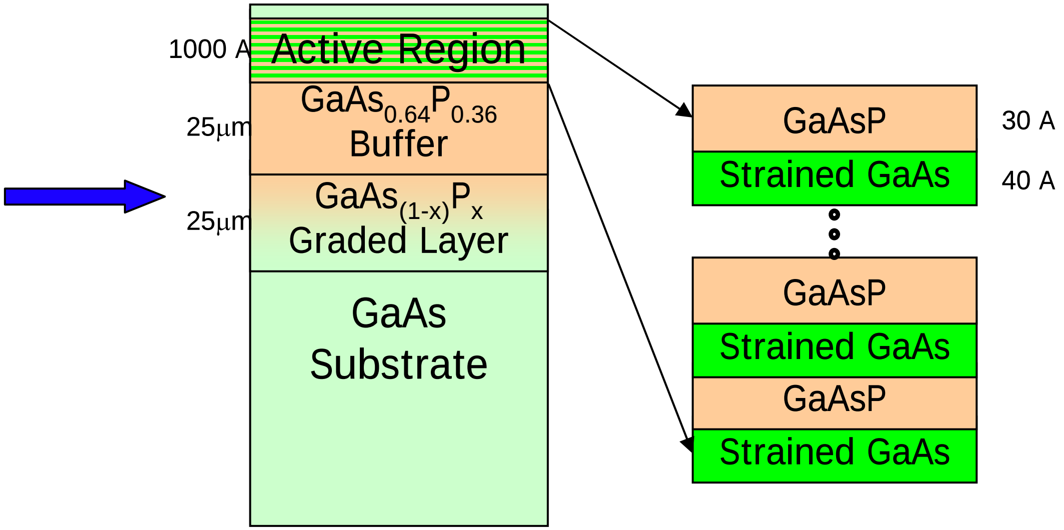
Low doping for most of active layer yields high polarization.

Cathode for Runs 1,2: Gradient-doped strained GaAs



NEW Cathode for Run 3

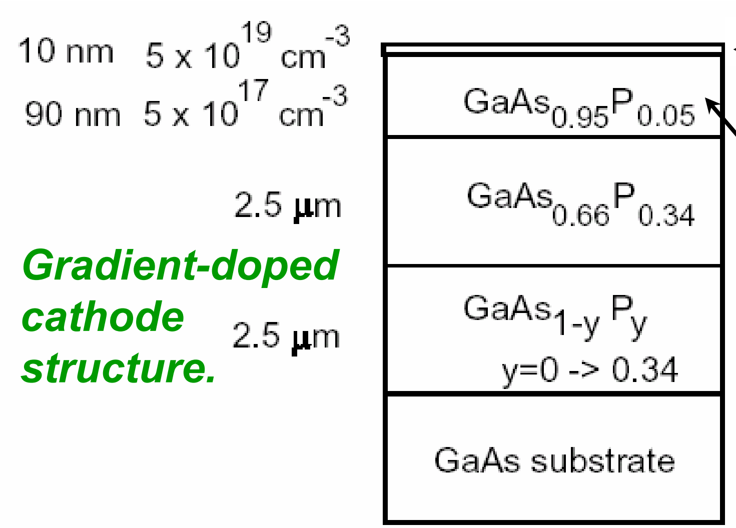
Gradient-doped strained superlattice; 5% higher polarization than for Runs 1,2



Source Photocathode for Runs 1,2

New photocathode from NLC R&D effort.

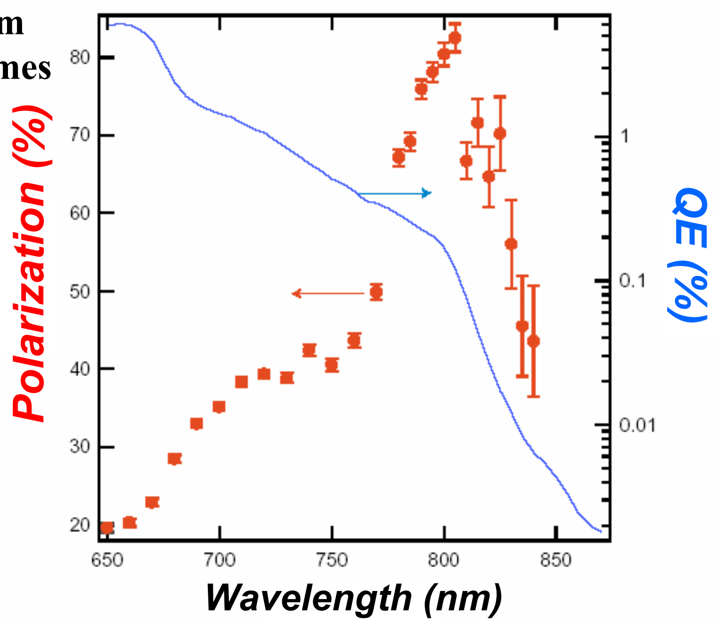
(T. Maruyama et al., SLAC-PUB-9133, March 2002;
published in Nucl.Instrum.Meth.A492:199-211,2002)

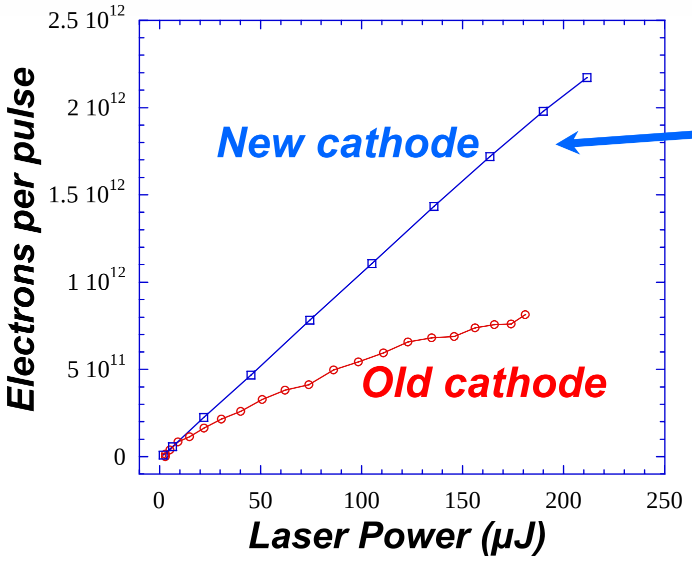


Gradient-doped cathode structure.

High doping for 10-nm GaAs surface overcomes charge limit.

Low doping for most of active layer yields high polarization.



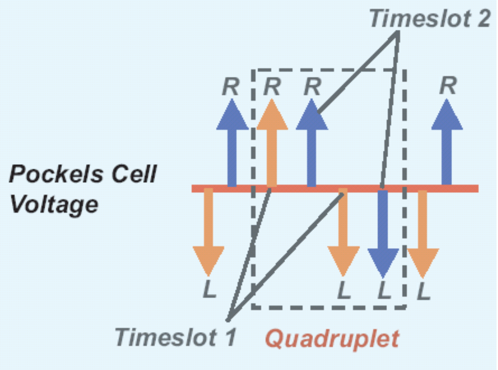


No sign of charge limit!

Very high-charge polarized electron beams are possible.

Small anisotropy in strain results in ~3% analyzing power for residual linear polarization.

Beam Helicity Control and Reversals



Beam helicity is chosen pseudo-randomly at 120 Hz

- use electo-optical Pockels cell in Polarized Light Source
- sequence of pulse quadruplets; one quadruplet every 33 ms: $R_1 R_2 \overline{R_1}\,\overline{R_2} R_3 R_4 \overline{R_3}\,\overline{R_4} \cdots$

Physics Asymmetry Reversals:

- Insertable Halfwave Plate in Polarized Light Source
- (g-2) spin precession in A-line (45 GeV and 48 GeV data)

‘Null Asymmetry’ Cross-check is provided by a Luminosity Monitor

- measure very forward angle e-p (Mott) and Moller scattering

Also, False Asymmetry Reversals: (reverse false beam position and angle asymmetries; physics asymmetry unchanged)

- Insertable “-I/+I” Inverter in Polarized Light Source

Techniques for minimizing $^{\text{beam}}A_{LR}$'s

At the start:

→ ~1000 ppm, ~2 μm systematics

1) Passive setup:

- Helicity bits delayed by 1 pulse and RF modulated prior to broadcast.
- Collimation of laser beam and minimization of spot size at CP, PS cells.
- Image CP, PS cells onto the cathode.
- OTS brought to atmospheric pressure to avoid stress-induced birefringence in windows.
- Select Pockels cells and carefully align to minimize systematics.
- Null A_Q with Δ_{CP}, Δ_{PS}.

→ ~100 ppm, ~0.5 μm

2) Active suppression with feedbacks:

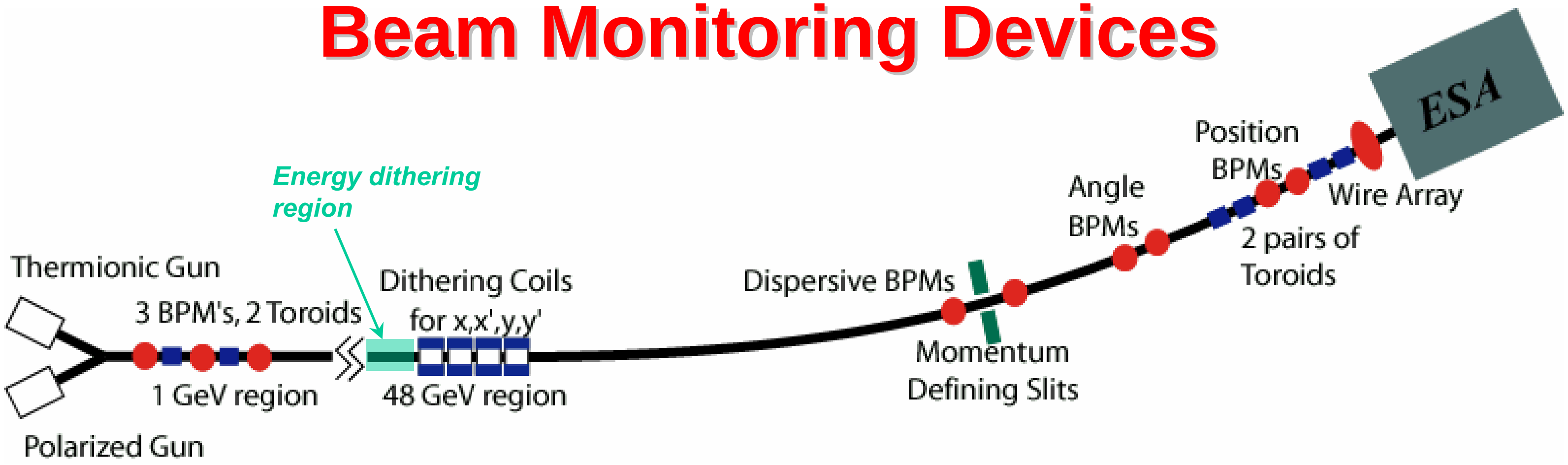
- IA loop & POS loop.
- Double-feedback loop.

→ <100 ppb, <100 nm

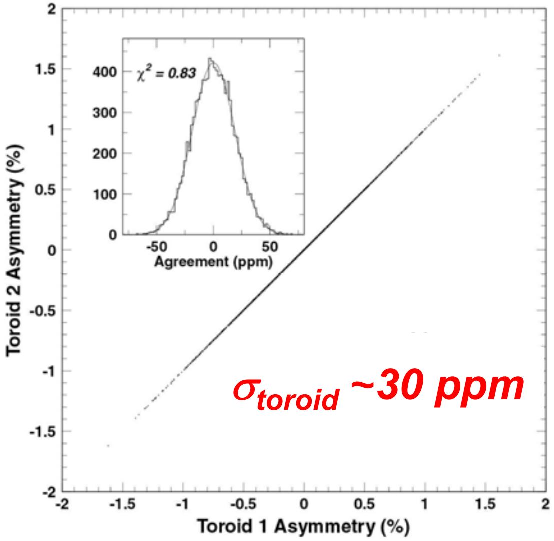
3) Slow reversals:

- Flip certain classes of asymmetries while leaving everything else unchanged.
  - λ/2 plates (2)
  - energy (g-2 precession)
  - asymmetry inverter
- These can provide cancellation of systematics, but they also serve as a cross-check that systematics are well-understood. Multiple reversals are essential!

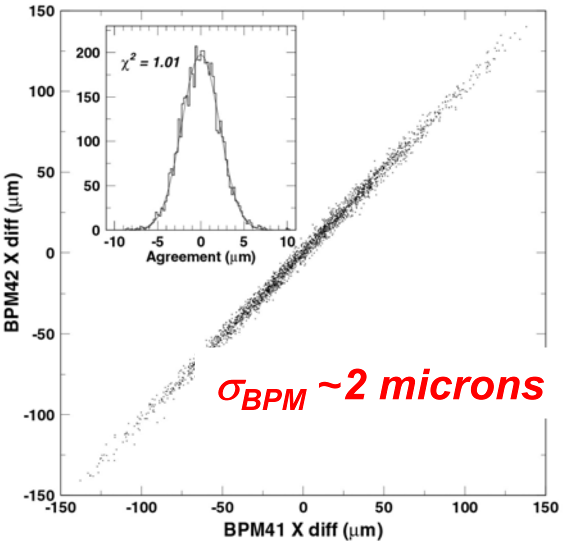
Beam Monitoring Devices



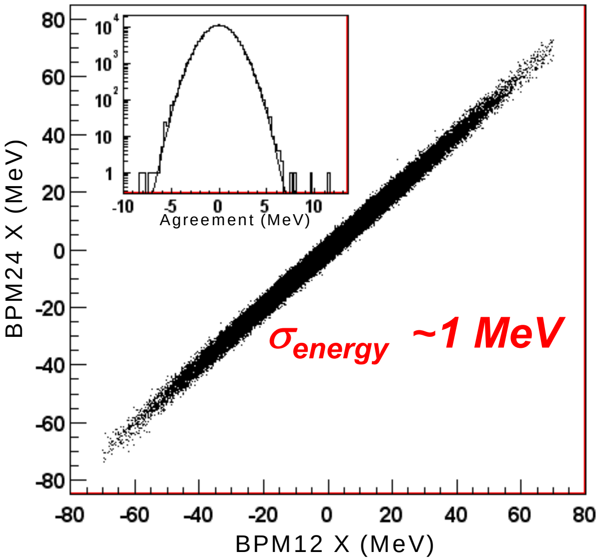
Can compare measurements of neighboring devices to determine the precision of the measurement.



σ_{toroid} ~30 ppm

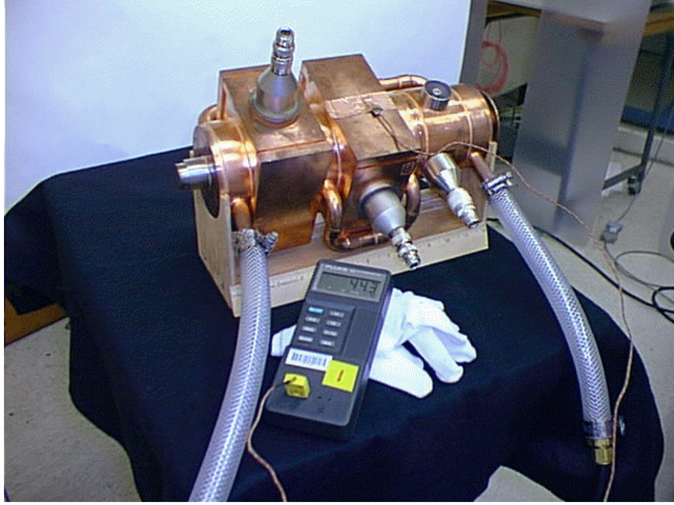


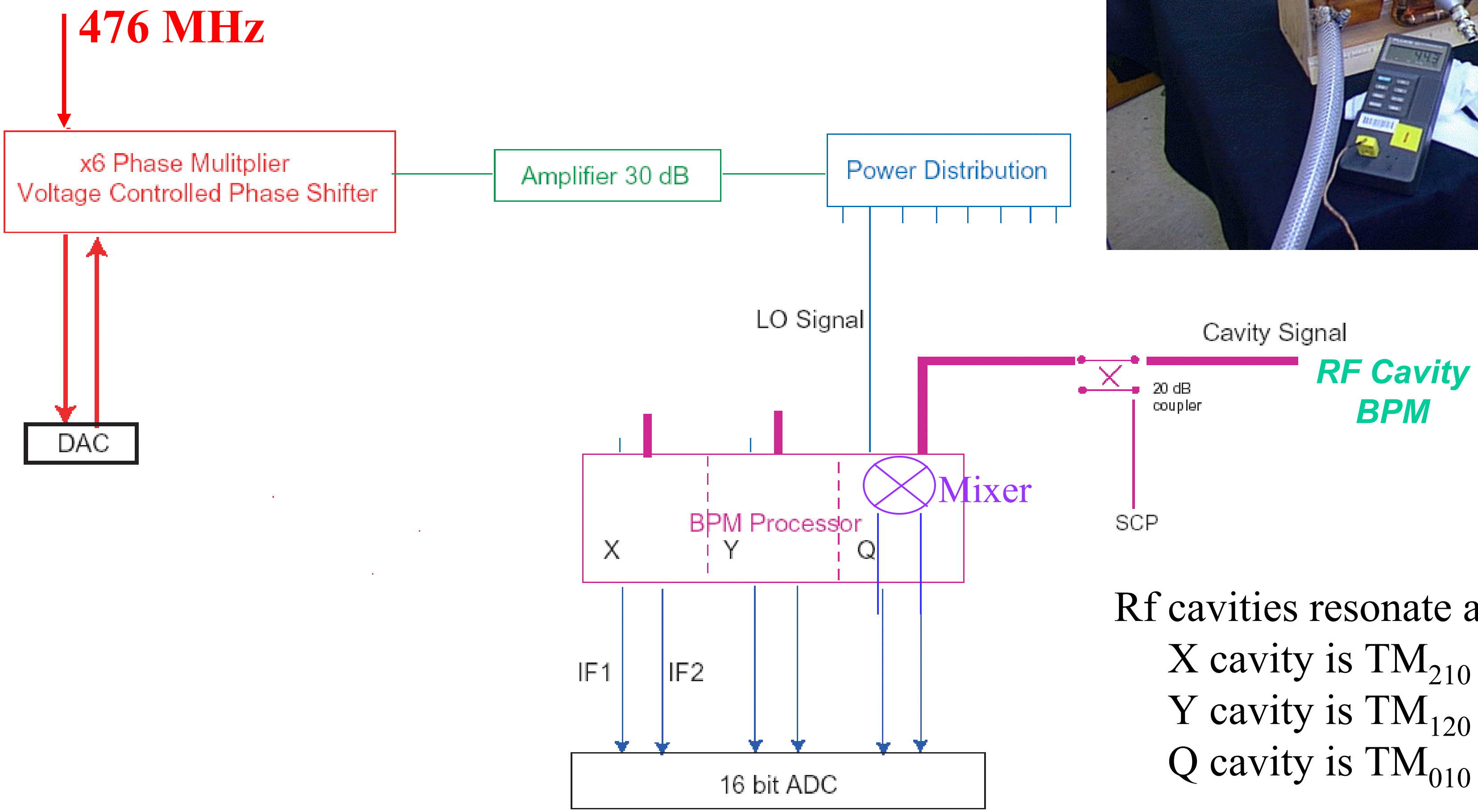
σ_{BPM} ~2 microns



σ_{energy} ~1 MeV

rf Cavity BPMs for E-158





476 MHz

x6 Phase Mulitplier
Voltage Controlled Phase Shifter

Amplifier 30 dB

Power Distribution

DAC

LO Signal

Cavity Signal

20 dB coupler

RF Cavity BPM

Mixer

BPM Processor

X

Y

Q

SCP

IF1

IF2

16 bit ADC

Rf cavities resonate at 2856 MHz

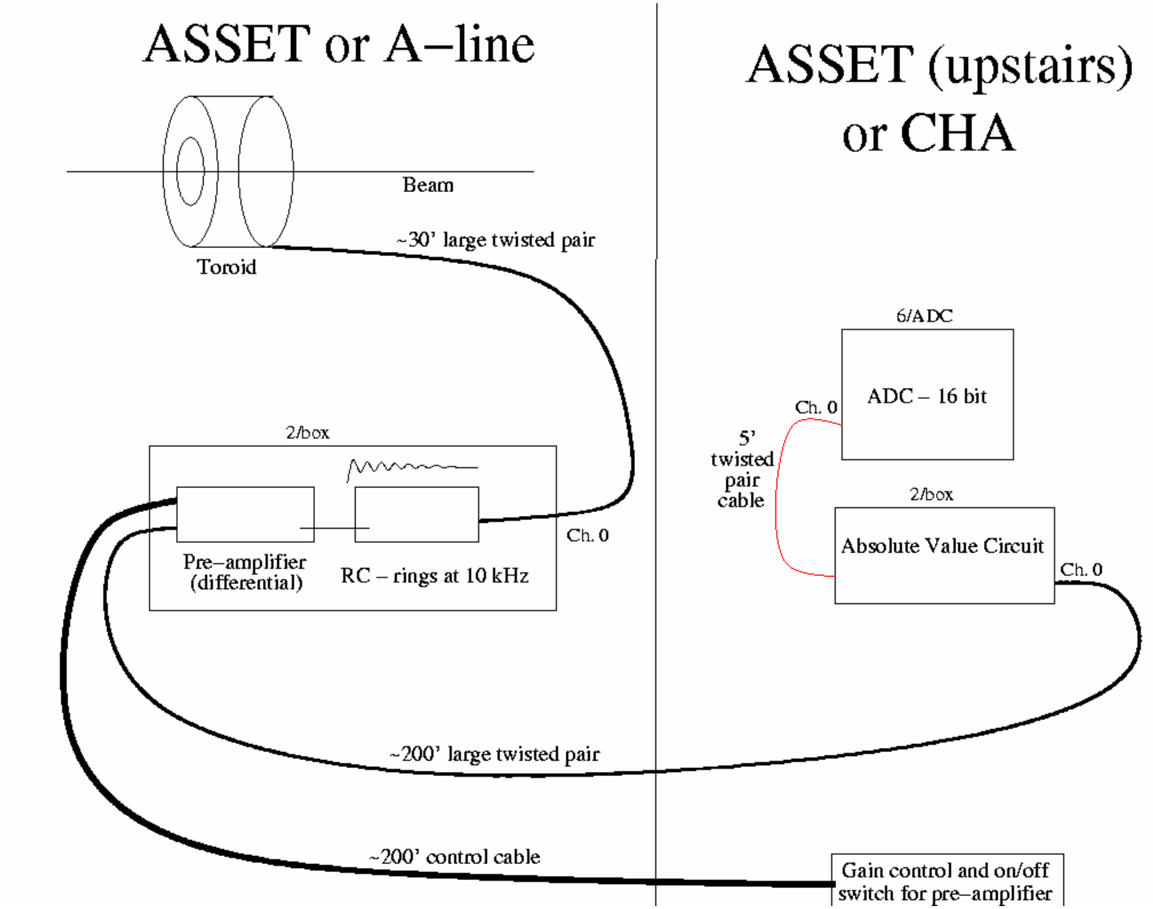
X cavity is TM_{210}

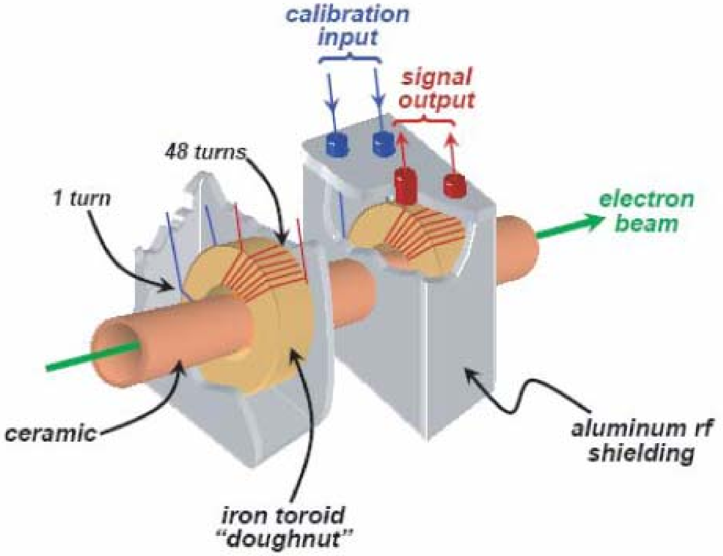
Y cavity is TM_{120}

Q cavity is TM_{010}

"**ANALYSIS OF AN ASYMMETRIC RESONANT CAVITY AS A BEAM MONITOR**"
(David H. Whittum (SLAC), Yury Kolomensky (Caltech). SLAC-PUB-7846;
published in Rev.Sci.Instrum.70:2300-2313,1999.)

Toroids for E-158





(L-R) Spotsize Difference Effects

1. **Beam Intensity, Spotsize and Mixing fluctuations**

- LH_2 Target density can change during the 300-ns beam pulse
- Incomplete mixing between pulses (hysteresis)
- Expect spotsize fluctuations (~2% rms/pulse) to dominate over intensity fluctuations (~0.5% rms/pulse)
- No (L-R) feedback on spotsize differences → need to worry about (L-R) spotsize differences

Hysteresis effects contribute jitter but ***not*** systematic biases (re. fast helicity switching)
- hysteresis effects can be large since it takes ~26 beam pulses at 120Hz for a packet of LH_2 to traverse the 1.5m target length

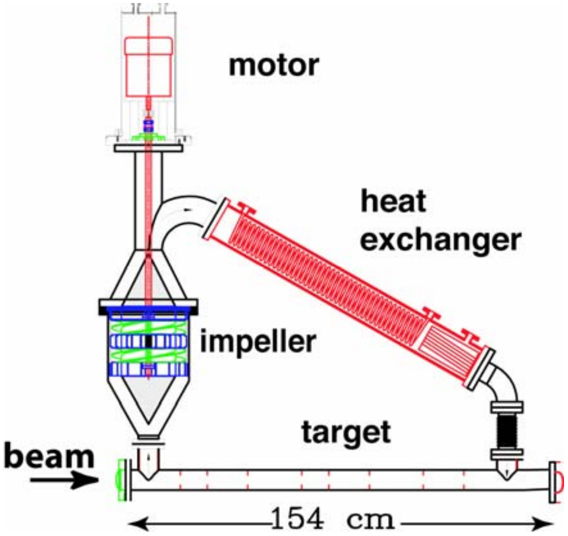
2. **Geometry: acceptance effects from dependence on position, angle due to collimators and detector edges**

- Moller Detector acceptance can be sensitive to beam spotsize

i) Incomplete mixing between pulses

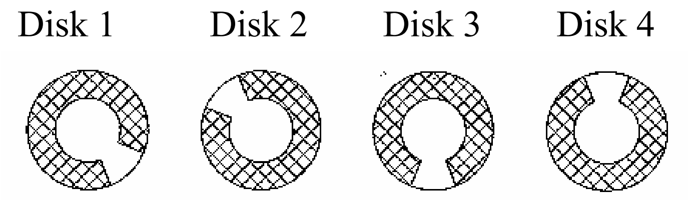
- Flow velocity is 7m/s; 8 wire mesh disks introduce turbulence (at ~1mm scale, comparable to beam spotsize) and transverse flow (xverse displacement ~4mm in 8ms) to allow mixing between beam pulses (**similar effect as rastering**). Estimate ~300ppm density reduction along beam path per bunch for our beam conditions
- Fluid in beam path for 26 consecutive pulses @120Hz

→ expect fluid exiting beam path ~0.8% lower density than fluid entering beam path!



LH_2 Target

Reference: i) J. Gao et al.. SLAC-PUB-9565, 2002.
Published in Nucl.Instrum.Meth.A498:90-100,2003.



Wire mesh disks: 1.5” ID, 3.0” OD

Jitter from incomplete mixing (no asymmetry bias, due to random p-p helicity flips)

- 1% intensity or spotsize jitter is estimated to contribute 5 ppm to the pulse-pair widths (contribution from the 2 of 26 previous pulses affecting the target density that are different for the L-R pair; fast paired L-R switching very important!)
- fluctuations in the mixing are estimated to introduce an additional 10 ppm to the widths

→ Total contribution to pulse-pair width is ~12ppm (small compared to statistical jitter)

ii) Target density change during the beam pulse

Density will change on timescale corresponding to speed of sound, estimated to be ~1 μm/ns (or ~0.3mm /300ns during length of our beam pulse)

→ Estimate of effective density reduction during pulse is ~0.2% for our beam conditions

Jitter contribution

1% spotsize or intensity jitter is estimated to contribute 20 ppm to the pulse-pair widths

Systematic Bias from Spotsize Asymmetry

1nm (L-R) spotsize difference could give 2 ppb ${}^{\text{beam}}A_{LR}$(spot)!!

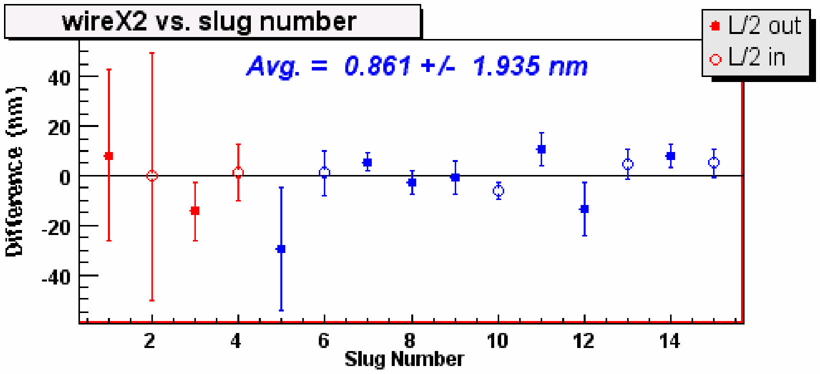
Note: beam rastering on target would not reduce this effect!
(unless it's very fast: >1mm/100ns)

Need to measure correlations of detector widths with wire array spotsize measurements & measure spotsize asymmetries

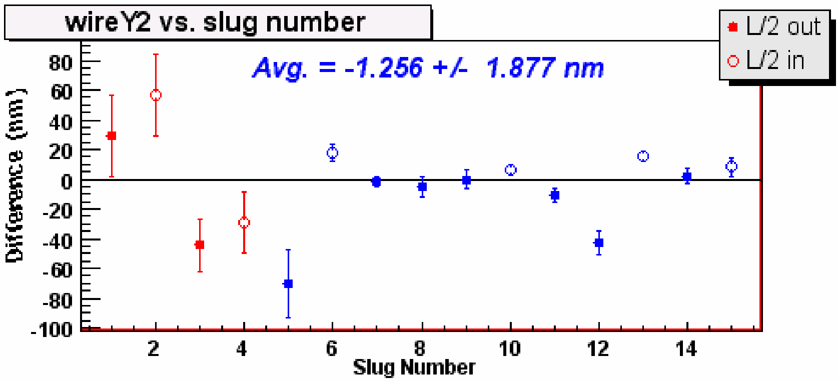
→ actual measurements of correlation coefficients were smaller than above predictions of 2ppb/nm

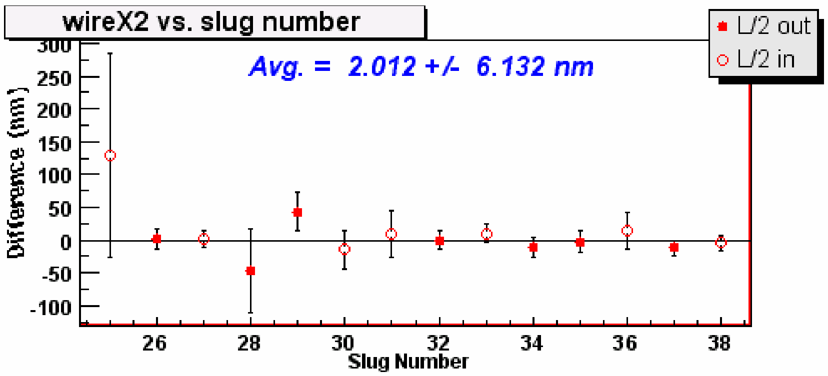
→ data also showed that geometric sensitivity dominated over target density effects, since different detectors (Moller rings and LUMI) had different coefficients

Spotsize Asymmetries for Runs 1,2,3

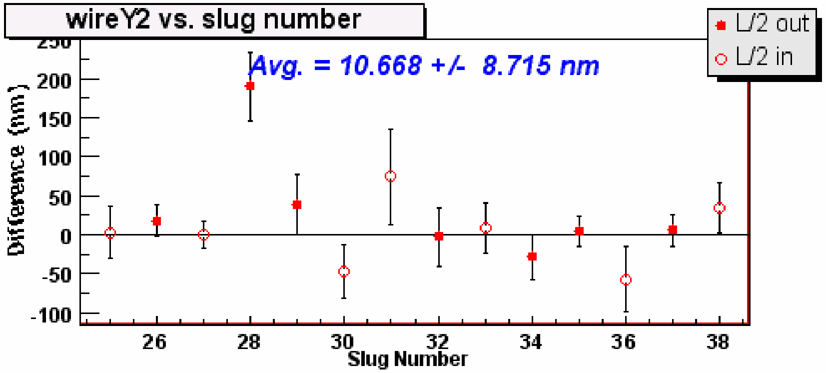


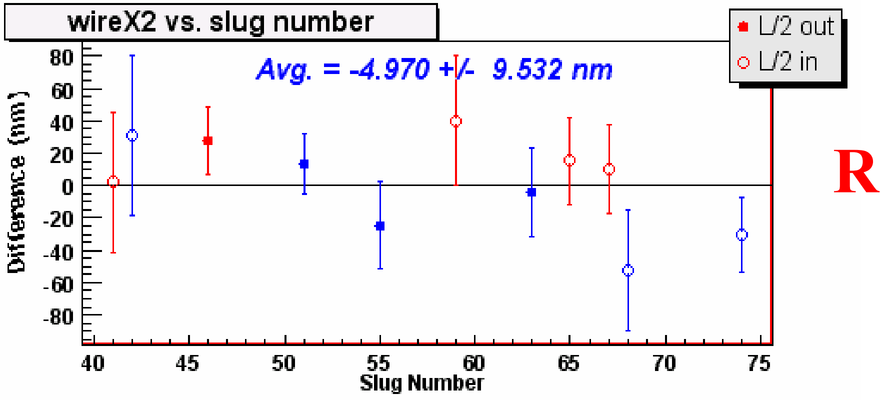
Run 1



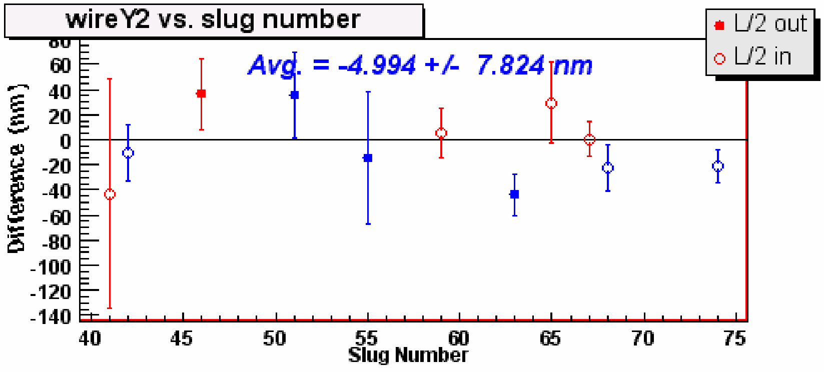


Run 2





Run 3



Spotsizes: $S_X \sim S_Y \sim$ 1.0mm for Runs 1 and 2
1.3mm for Run 3

*wire array not in for all runs; only some runs for monitoring (wires get damaged from high power beam; broke wire in Run 1)

Wire Array Spotsize Correlation Analysis

$$S = \pi\, S_x S_y$$

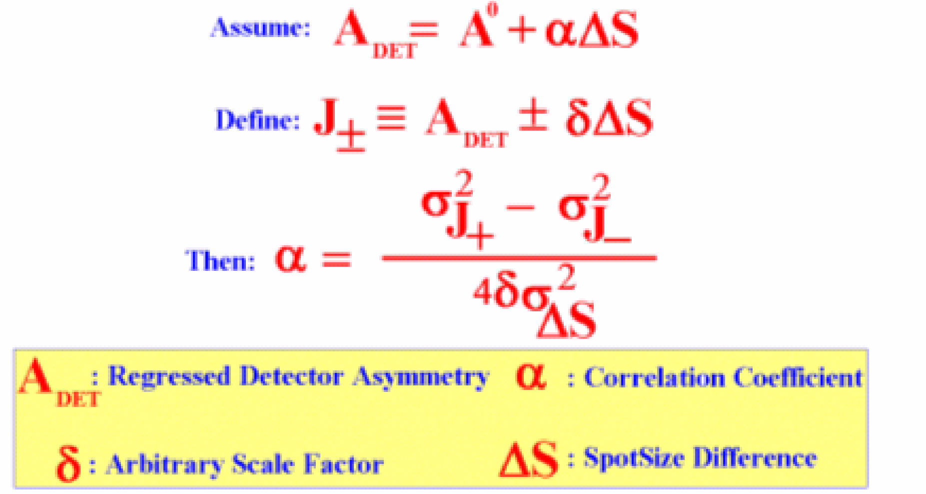
S: spotsize measured by wire array

W_T: detector jitter from spotsize fluctuations

${}^{\text{beam}}A_{LR}$(spot): contribution to detector asymmetry from spotsize asymmetry

$$W_T = \alpha_S \cdot \sigma(S) = \alpha_S \cdot \left[\pi\, S_x \sigma(S_x) \oplus \pi\, S_y \sigma(S_y)\right]$$

$${}^{\text{beam}}A_{LR}(\text{spot}) = \alpha_S \cdot \langle D_S \rangle = \alpha_S \cdot \left[\pi\, S_x \langle D_Y \rangle + \pi\, S_y \langle D_X \rangle\right]$$



Assume: $A_{DET} = A^0 + \alpha \Delta S$

Define: $J_\pm \equiv A_{DET} \pm \delta \Delta S$

Then: $\alpha = \dfrac{\sigma^2_{J_+} - \sigma^2_{J_-}}{4\delta\sigma^2_{\Delta S}}$

A_{DET} : Regressed Detector Asymmetry

α : Correlation Coefficient

δ : Arbitrary Scale Factor

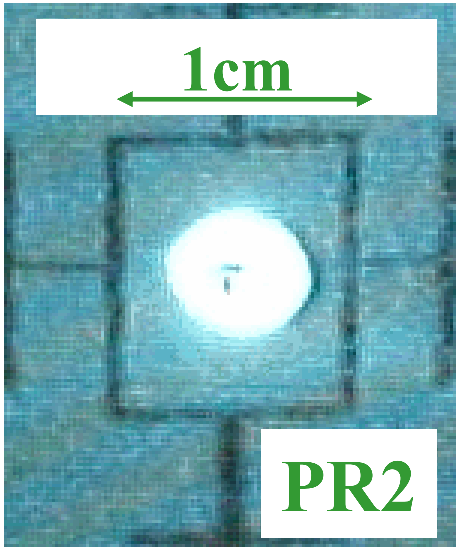
ΔS : SpotSize Difference

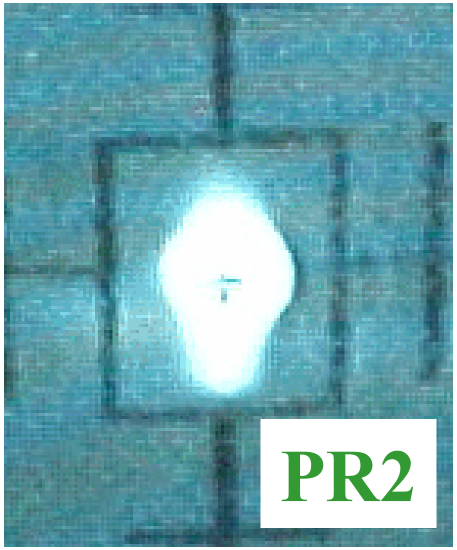
Results:

	RUN 1	**RUN 2**	**RUN 3**
${}^{\text{beam}}A_{LR}$(spot)	(0.06 ± 0.5) ppb	(-0.8 ± 0.7) ppb	(0.5 ± 0.7) ppb

→ < 1ppb systematic uncertainty from (L-R) Spotsize

Skew Quad, Spotsize and Beam Jitter





Beam at PR2
just upstream
of target

2001: no Skew Quad

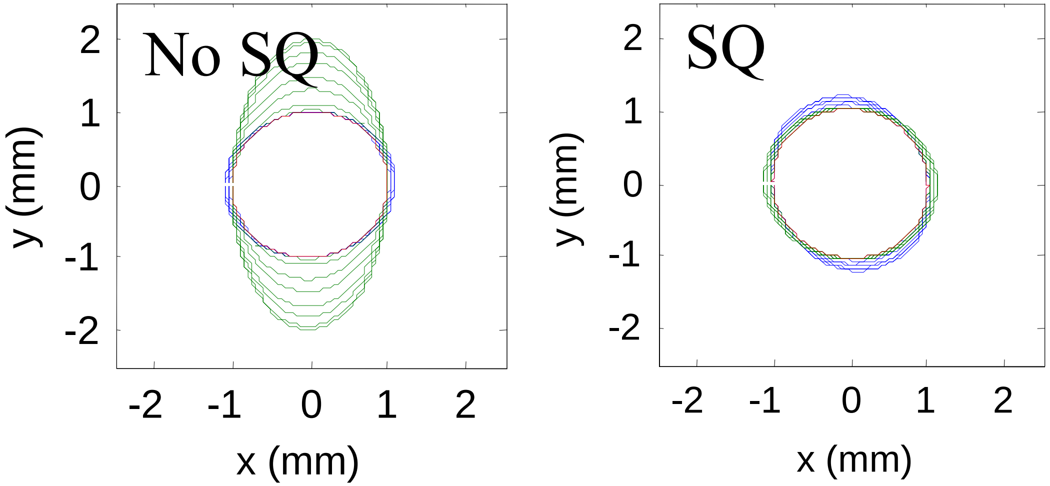
Vertical beam stability
varies greatly

2002: SQ27.5 Added

(near end of A-line to ESA)

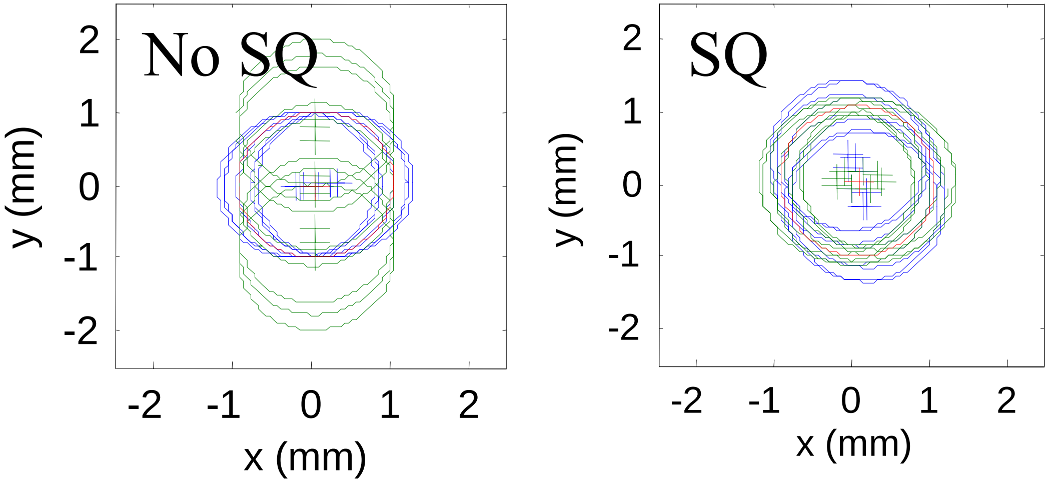
- emittance at end of Linac unstable
- horiz. emittance has large growth in A-line due to SR
- take advantage of emittance growth and use skew quad to couple x and y and give stable beam on target

Skew Quad Modeling Study



Sensitivity to emittance fluctuations and mismatches

Red: nominal emittance
Blue: horizontal beta mismatch
Green: vertical beta mismatch



Sensitivity to position and angle jitter

Red: on axis
Blue: horizontal betatron oscillations
Green: vertical betatron oscillations

Target Density Fluctuations

Let

$$A_{Moller} = A^0_{Moller} + A_\rho \ , \ A_{Lumi} = A^0_{Lumi} + A_\rho$$

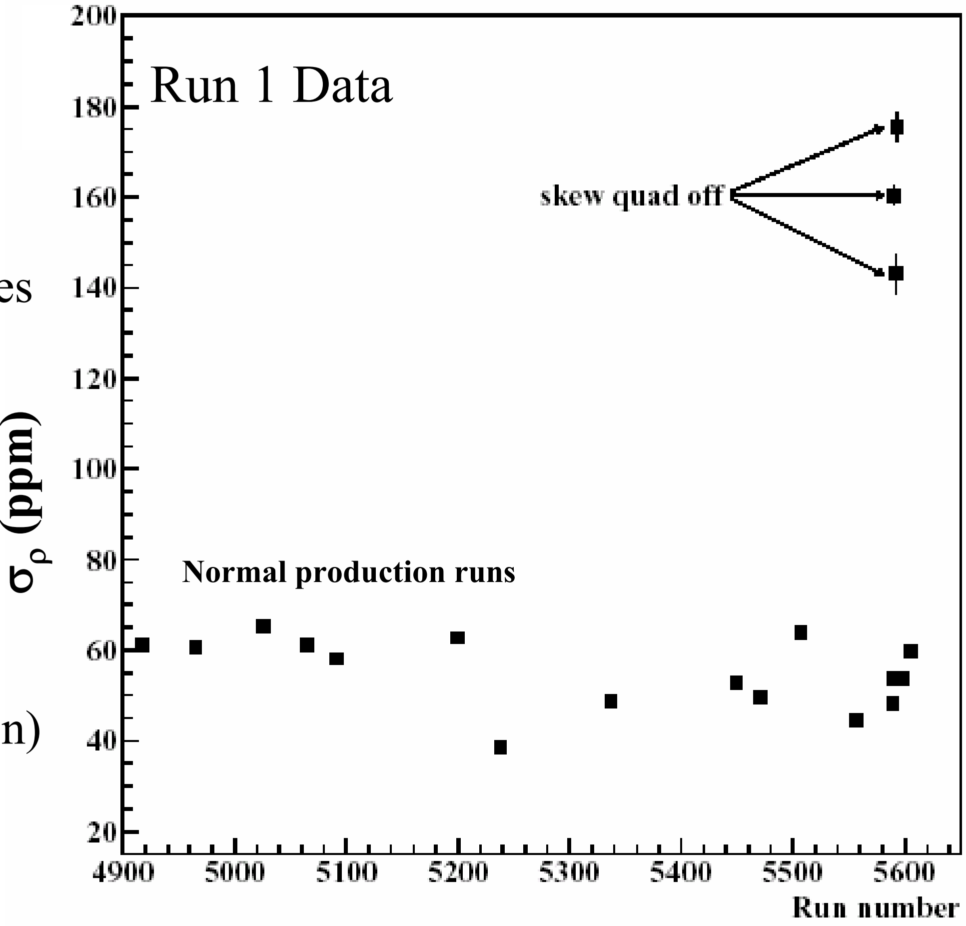
$$A_+ = A_{Moller} + A_{Lumi} \ , \ A_- = A_{Moller} - A_{Lumi}$$

A_{Moller}, A_{Lumi} are the L-R pulse-pair asymmetries for the MOLLER and LUMI detectors,

ρ is the target density fluctuation

Then $\sigma^2_{A_+} - \sigma^2_{A_-} = 4\sigma^2_\rho$

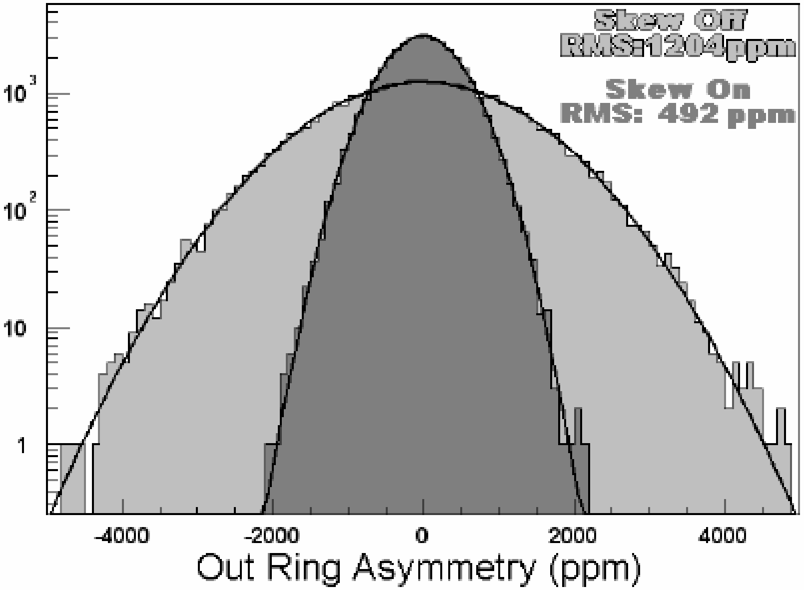
σ_ρ is the rms common mode noise (target density fluctuation is one contribution)

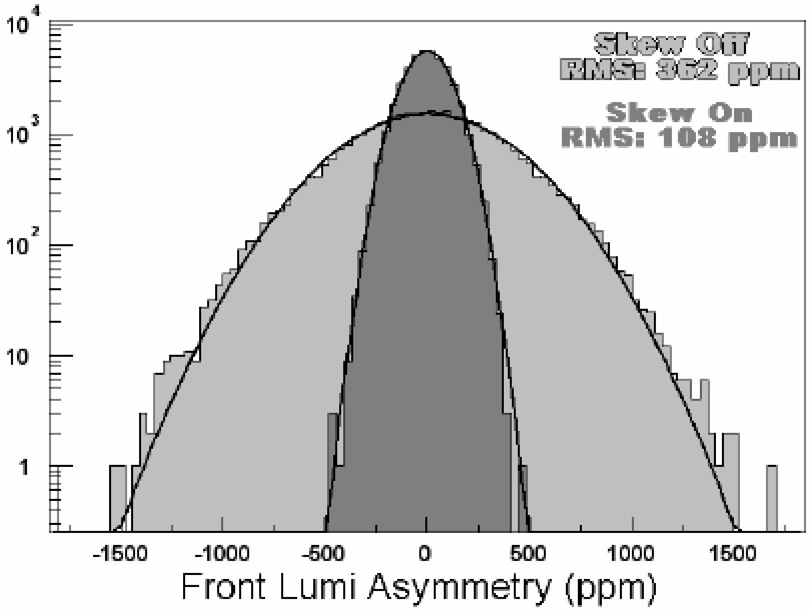


Typical rms pulse-pair widths for MOLLER detector is 190-200 ppm.
Expected rms width from statistics is ~155 ppm. 50 ppm contribution from toroid resolution.

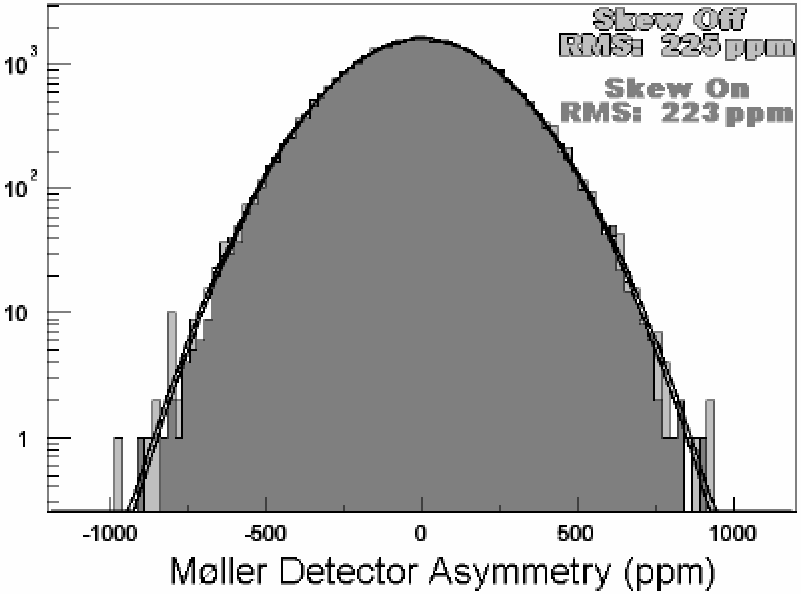
→ Can set limit from this study of <50 ppm contribution to MOLLER rms pulse-pair width from target density fluctuations for production runs

Pulse-pair asymmetry distributions for MOLLER, LUMI





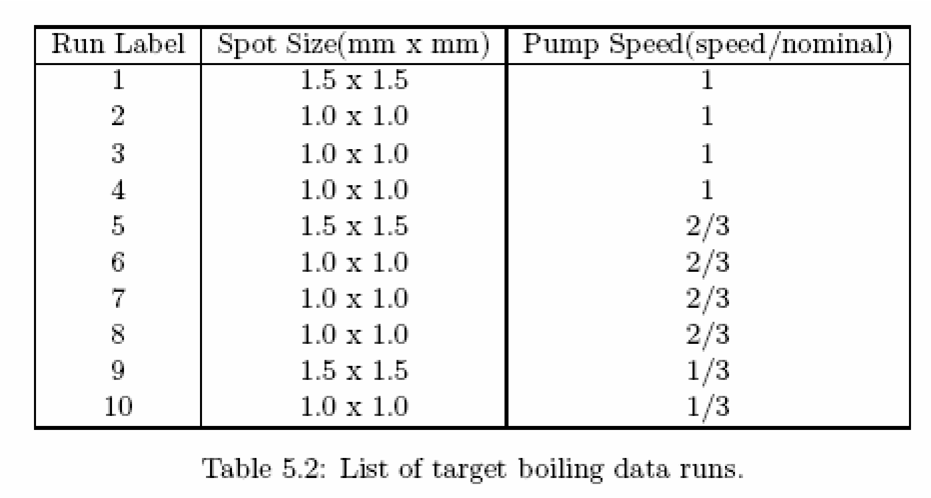
Dramatic effect on OUT, LUMI but little effect on IN, MID rings.



→ likely a geometric effect, with sensitivity to beam position and angular on target

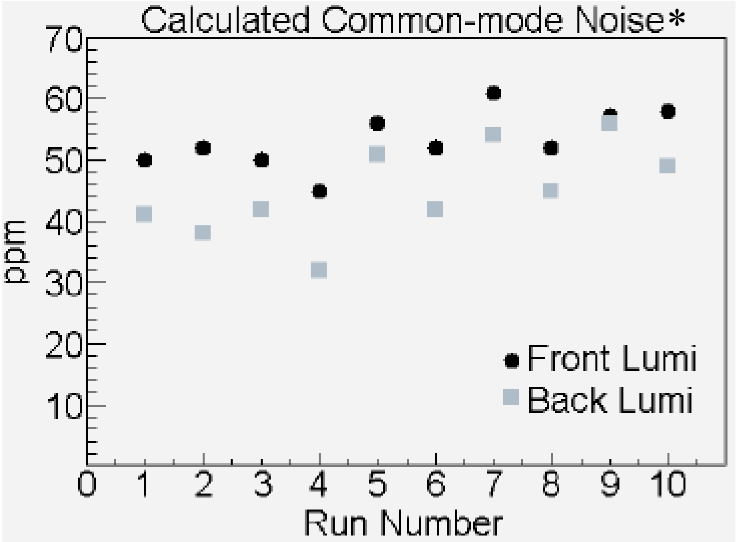
Additional Studies for Target Density Fluctuations

Skew Quad is ON
for all these studies



Run Label	Spot Size(mm x mm)	Pump Speed(speed/nominal)
1	1.5 x 1.5	1
2	1.0 x 1.0	1
3	1.0 x 1.0	1
4	1.0 x 1.0	1
5	1.5 x 1.5	2/3
6	1.0 x 1.0	2/3
7	1.0 x 1.0	2/3
8	1.0 x 1.0	2/3
9	1.5 x 1.5	1/3
10	1.0 x 1.0	1/3

Table 5.2: List of target boiling data runs.



*Includes subtraction for contributions
From toroid and bpm resolutions

Asymmetries in Synchrotron Radiation

Spin-flip synchrotron radiation

$\rightarrow A \approx 1.4 \cdot 10^{-9}$ in radiated power (for D3)

Spin-dependence of ordinary synchrotron radiation

i) transverse polarization in a transverse field ⟸ **Dominant effect for E158**

$\rightarrow A \approx 3 \cdot 10^{-5}$ in radiated power (for D3)

ii) longitudinal polarization in a transverse field

$\rightarrow A \approx 4 \cdot 10^{-5}$ 'up-down' azymuthal asymmetry in number of radiated photons

Effects for E158

- **energy asymmetry in beam on target (A-line bends)**
- **detector background asymmetry (spectrometer dipoles)**

Spin-dependence of Ordinary Synchrotron Radiation

Transverse polarization in a transverse field

refs: Bondar and Saldin, *Nucl. Inst. Meth*. 195, 577 (1982).
Belomesthnyleh et al., *Nucl. Inst. Meth*. 227, 173 (1984).

$$P_\sigma = P_o\left[\frac{7}{8} - \left(\frac{25\sqrt{3}}{12} + \eta\right)\chi + \dots\right]$$

$$P_\pi = P_o\left[\frac{1}{8} - \frac{5\sqrt{3}}{24}\chi + \dots\right]$$

$$P_o = \frac{2}{3}\cdot\frac{e^2\gamma^4}{\rho^2};\chi = \frac{3}{2}\cdot\frac{h\gamma^2}{2\pi mc\rho}$$

σ - SR linearly polarized in bend plane
π - SR linearly polarized perpendicular to bend plane
η = +1(-1) for spin parallel (anti-parallel) to B-field

For E158, E=48 GeV and ρ=153.4m (D3 magnet)

$$A_P = \frac{P_\sigma(\eta=+1) - P_\sigma(\eta=-1)}{2P_o} = \chi$$

$$A_P = 3.4\cdot 10^{-5}$$

SR Background Effect: Estimating ${}^{\mathrm{bkgd}}A_{\mathrm{LR}}(\mathrm{SR})$

$${}^{\mathrm{bkgd}}\mathrm{A}_{\mathrm{LR}}\left(\mathrm{SR}\right) = f_B\left(SR\right) \cdot P_y \cdot AP_M\left(SR\right)$$

MOLLER Background from SR, $f_B(SR)$:

Target OUT data gives $f_B(SR) = (0.15 \pm 0.05)$ %. (E158 TN#44 and TN#55)

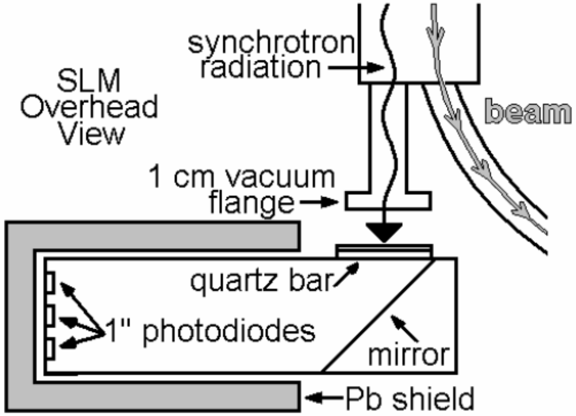
P_y is estimated from:

i. y-corrector strengths in Linac, Aline
ii. SLM asymmetry
iii. X Dipole asymmetry

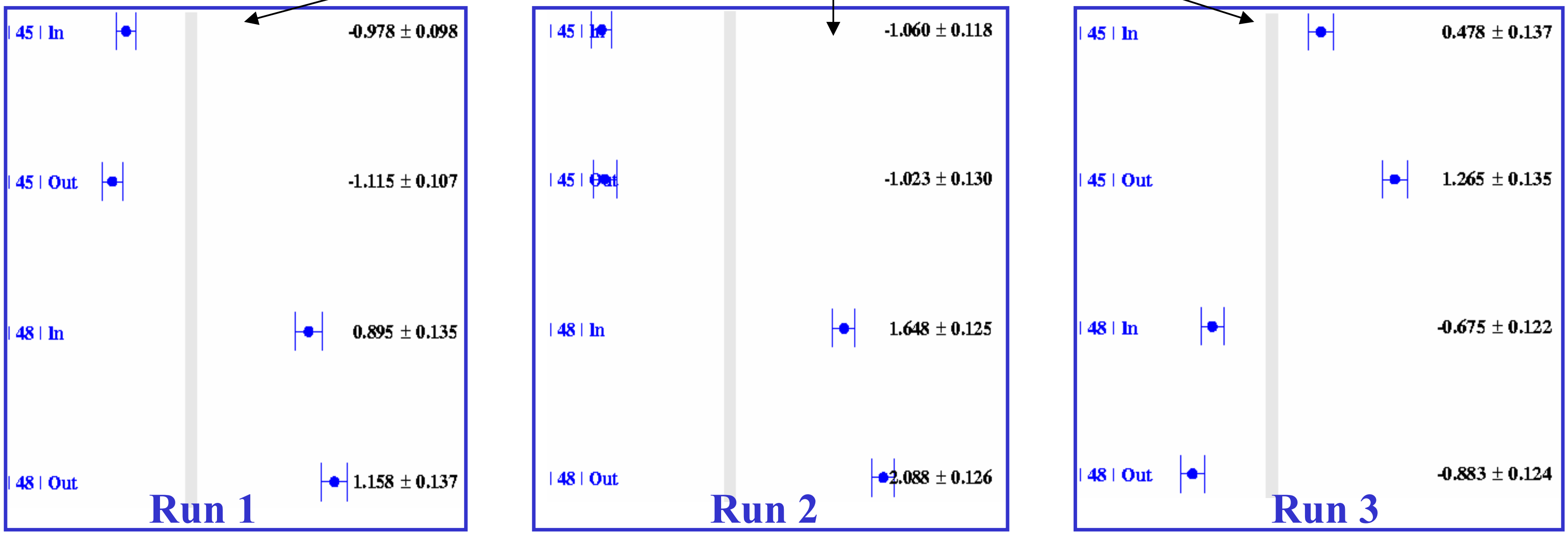
$AP_M(SR)$ is estimated from:

- calculations of the SR asymmetry spectrum for $P_y = 100\%$
- calculations of the SR spectrum that reaches the MOLLER detector and energy response of the MOLLER detector for (0.5-20) MeV photons

P_y estimate from A-line SLM Detector



SLM2 Asymmetry
(ppm)



Pattern of sign flips with half waveplate and energy is consistent with expectations for Vertical polarization. Get good cancellation from energy flips!

	RUN 1	**RUN 2**	**RUN 3**
SLM2 Asymmetry	(-305 ± 57) ppb	(+378 ± 61) ppb	(+37 ± 62) ppb
P_Y	$\left(-0.5^{+0.2}_{-0.5}\right)\%$	$\left(+0.6^{+0.7}_{-0.2}\right)\%$	$\left(+0.1^{+0.2}_{-0.2}\right)\%$

P_y estimate from MOLLER X Dipole asymmetry

MOLLER xdipoles

	RUN 1 (ppb)	**RUN 2 (ppb)**	**RUN 3 (ppb)**
IN	-75 (39)	-35 (37)	-51 (31)
MID	-69 (33)	+44 (31)	-47 (26)
IN, MID	-71 (25)	+11 (24)	-49 (20)

Transverse polarization data give:
AP(IN) = (-3900 ± 150) ppb; AP(MID) = (-2800 ± 230) ppb;
AP(IN,MID) = (-3250 ± 150) ppb

P_y from MOLLER xdipoles

	RUN 1	**RUN 2**	**RUN 3**	**Runs 1, 2, 3***
IN, MID	(-2.2 ± 0.8) %	(0.3 ± 0.7) %	(-1.5 ± 0.6) %	(-1.2 ± 0.4) %
Moller stat * errors on Araw	23.1 ppb	23.0 ppb	15.2 ppb	-

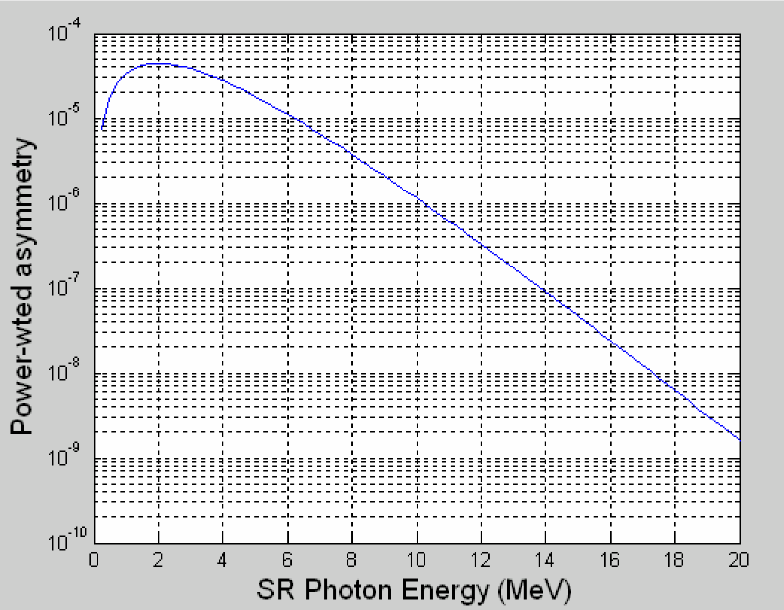
*used for combining Runs

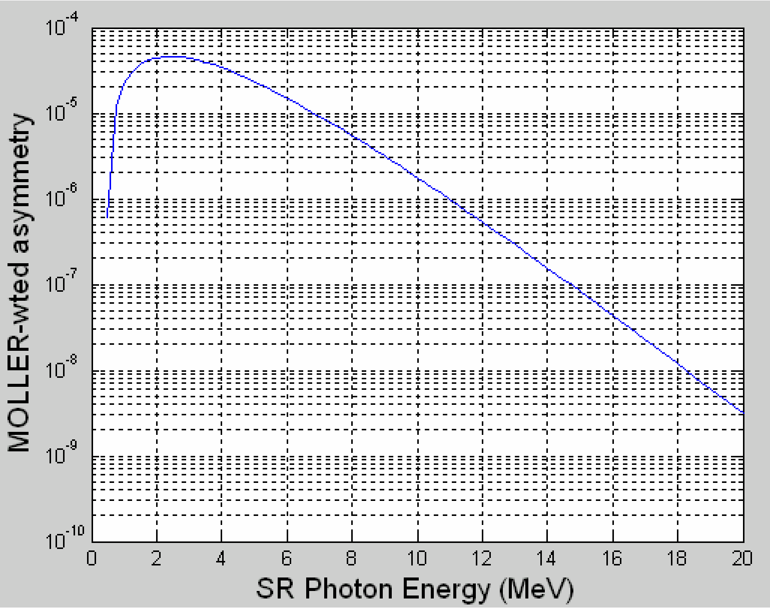
Asymmetry in SR Flux from Spectrometer Dipoles

SR Power asymmetry for $P_y=1$ is ~34ppm.

Energy-dependence: above the critical energy (~1.5 MeV),

$$A_{SR} \approx \frac{E_{photon}}{E_{beam}}$$ So, 5 MeV photons have ~100ppm asymmetry





What is MOLLER AP for SR?

Power weighting for generated SR spectrum: AP = 34 ppm

\+ include MOLLER detector response: AP = 63 ppm

Estimate $AP_M(SR) = (63 \pm 30)\,\text{ppm}$

${}^{\text{bkgd}}A_{LR}(SR)$ Estimate

$$ {}^{\text{bkgd}}\mathrm{A}_{\mathrm{LR}}\left(\mathrm{SR}\right) = f_B\left(SR\right)\cdot P_y \cdot AP_M\left(SR\right) $$

$f_B(SR) = (0.15 \pm 0.05)\%$ from *target out* data
P_y use MOLLER dipole analysis
$AP_M(SR) = (63 \pm 30)$ ppm from calculations of SR flux and asymmetry, and MOLLER energy response

$$ {}^{\text{bkgd}}\mathrm{A}_{\mathrm{LR}}(\mathrm{SR}) = \left(0.0015 \pm 0.0005\right)\cdot\left(P_y\right)\cdot\left(63 \pm 30\right)\mathrm{ppm} $$

	RUN 1	**RUN 2**	**RUN 3**	**Runs 1, 2, 3**
P_y	(-2.2 ± 0.8) %	(0.3 ± 0.7) %	(-1.5 ± 0.6) %	(-1.2 ± 0.4) %
${}^{\text{bkgd}}A_{LR}(SR)$	(-2.1±0.8) ppb	(0.3±0.7) ppb	(-1.4±0.6) ppb	(-1.1±0.4) ppb

→ 1ppb systematic uncertainty from SR Backgrounds

A_{PV} Corrections for Beam Asymmetries

$$\phi_{det} \propto \frac{I}{E\theta^4}$$

$$(\phi_{det} \sim \sigma_{phys} \cdot L \cdot acceptance)$$

where:

ϕ_{det} : detected flux (20 million Moller electrons/spill)

I : beam intensity

E: beam energy

θ: scattering angle

If assume dependence on beam parameters is linear over the jitter range:

$$A_{PV}^{meas} = P_e\, A_{PV}^{phys} + A_Q + \sum_{\xi} \alpha_{\xi}\, \Delta\xi$$

Contribution due to 'False' beam asymmetries

$$\xi \equiv \{E,\ x,\ y,\ x',\ y'\}$$

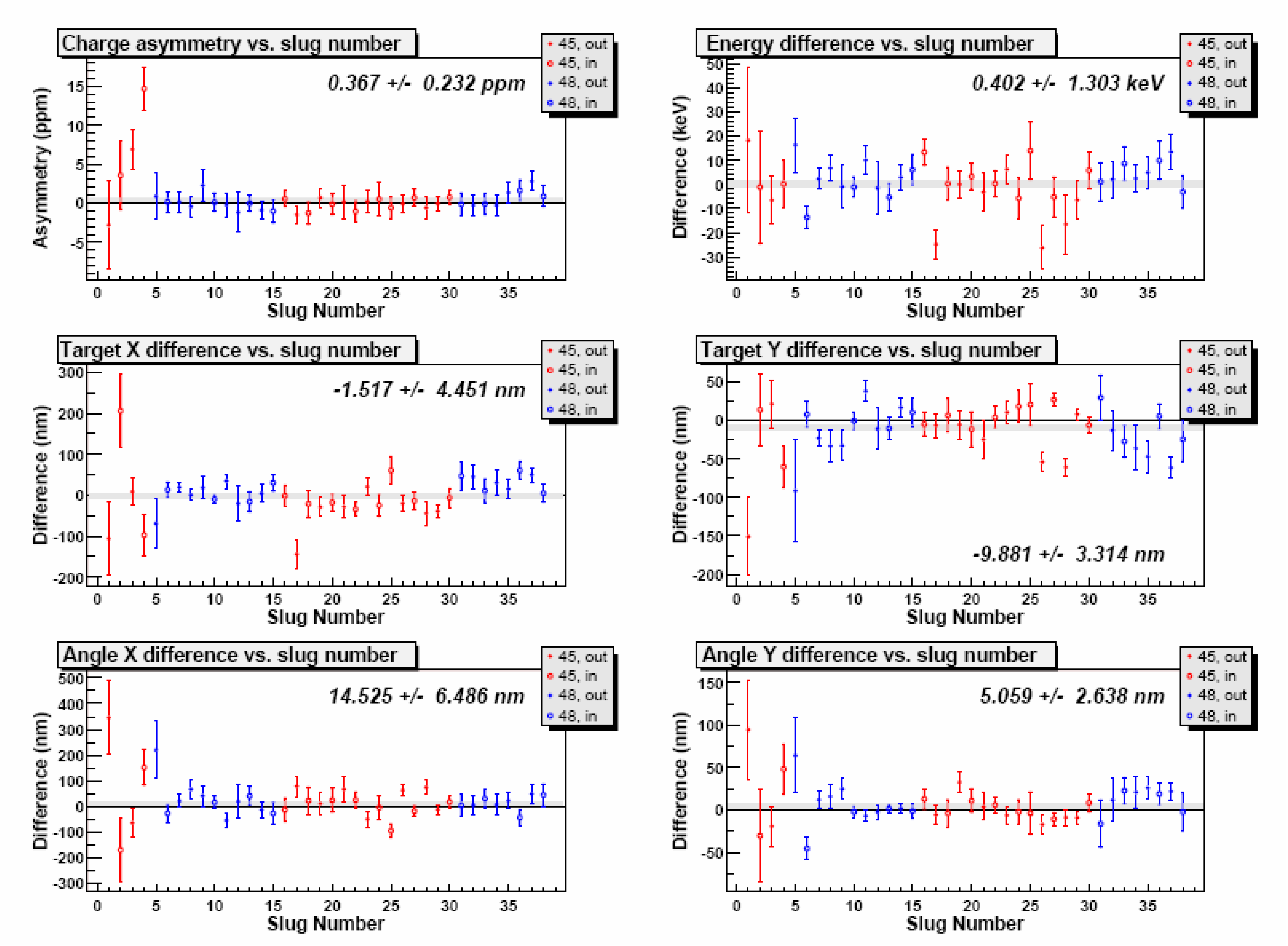
$$\alpha_{\xi} = \frac{\partial A_{PV}}{\partial \xi}$$

$\alpha_E \approx 1$ ppb/ppb

$\alpha_x \approx 1$ ppb/nm $\quad \alpha_{x'} \approx 2$ ppb/nm

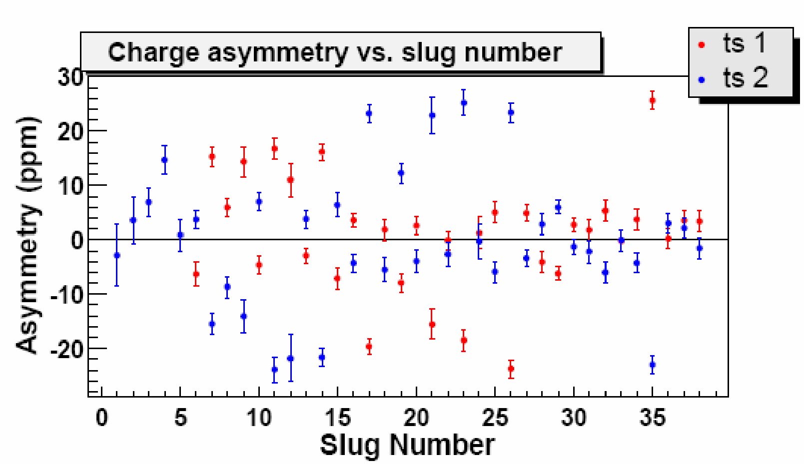
$\alpha_y \approx 1$ ppb/nm $\quad \alpha_{y'} \approx 2$ ppb/nm

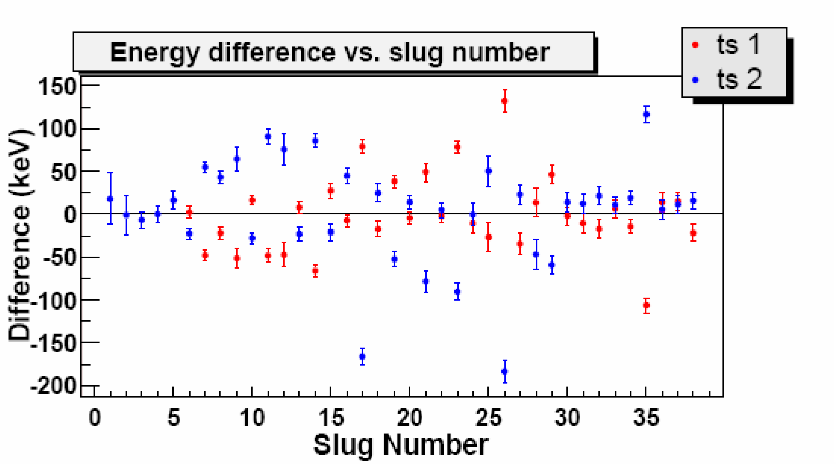
(L-R) Beam Parameter Differences In Runs 1 and 2

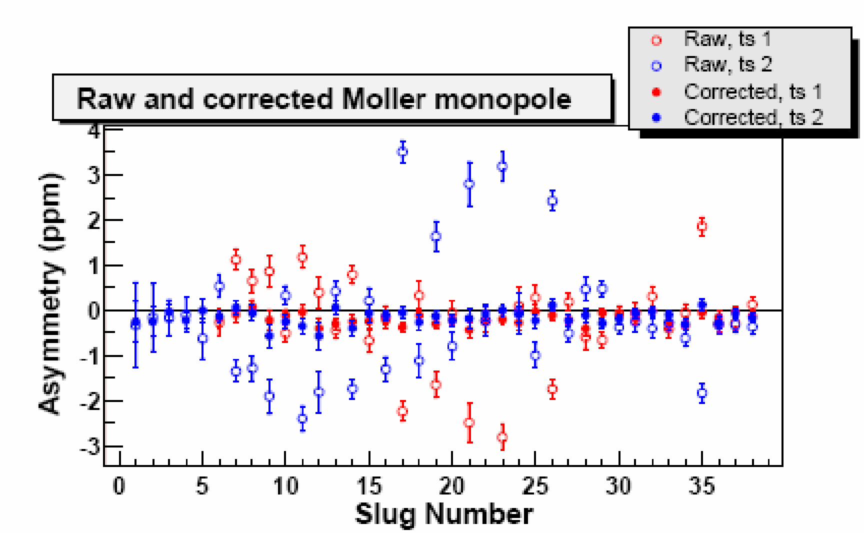


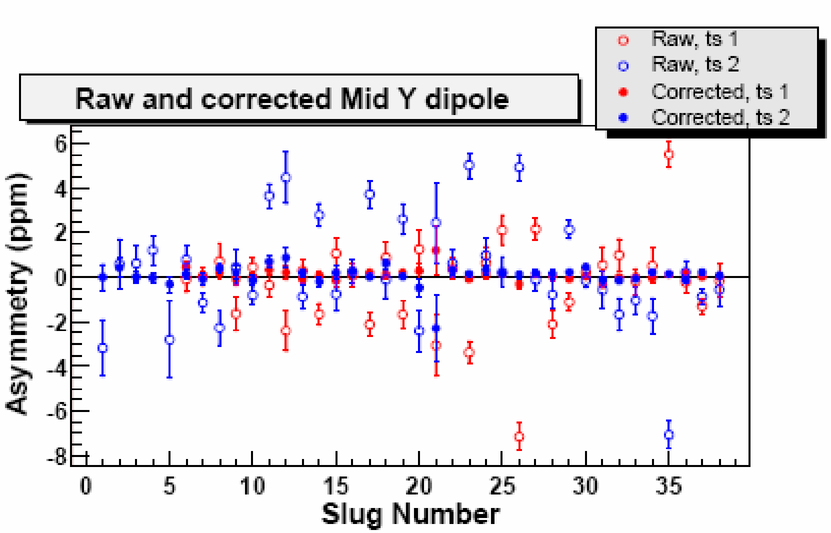
2 Timeslots @ 120Hz → 2 Experiments

Source feedbacks keep average beam asymmetries small, but asymmetries on each timeslot can be large!







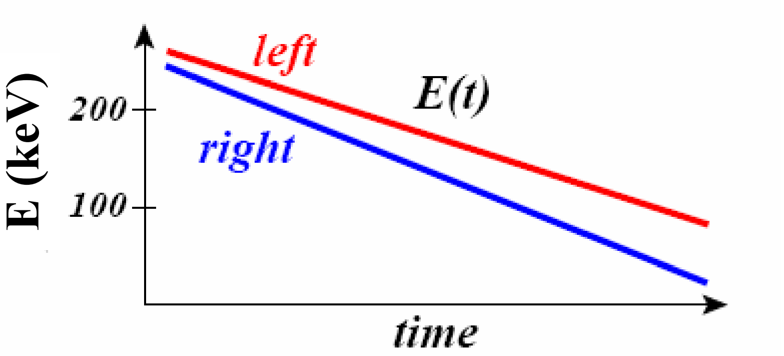


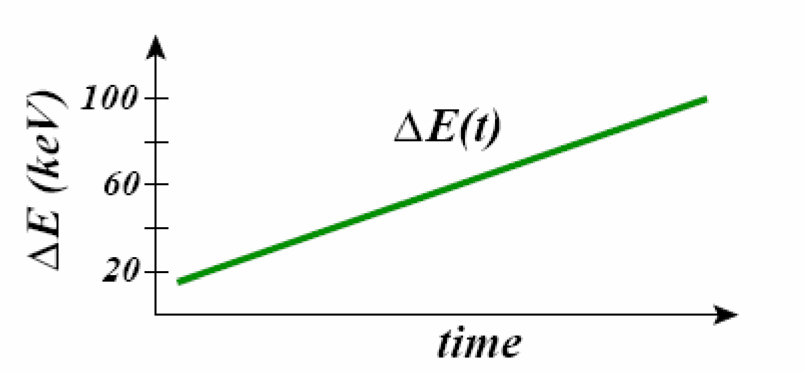
→ Use this "feature" to measure uncertainty in 1st-order beam asymm. corrections

1st-order beam asymmetry correction to A_{PV}^{meas} is (-9.7 ± 1.4) ppb

Higher-order Beam Asymmetry Corrections

- (L-R) Spotsize Difference effects described previously: 1ppb systematic
- dominant effect determined to be from time-dependence of beam parameters during 300-ns pulse





$$\langle \alpha_E(t) \cdot \Delta E(t) \rangle \neq \langle \alpha_E(t) \rangle \cdot \langle \Delta E(t) \rangle$$

True A_{PV} correction $\neq$ Calculated A_{PV} correction

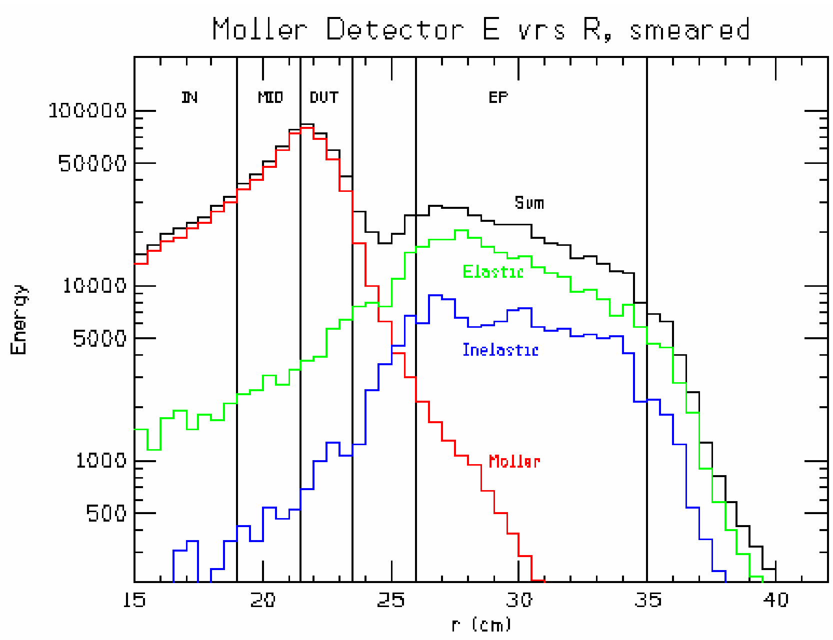
(also can have a similar effect from target density changes during 300-ns pulse)

Several tools to estimate size of effect and systematic errors

- use detector monitors which are much more sensitive to beam parameters than MOLLER monopole used for A_{PV} (ex. dipoles, OUT monopole, LUMI)
- use sensitive detector monitor measurements and beam Monte Carlo to estimate effects
- for Run 3 implemented “slice” monitors

Higher-order beam systematics for final A_{PV}^{meas} is 3 ppb

Beam Systematics Monitors



Use radial and azymuthal segmentation of Moller detector to construct 'monitors' that have much larger sensitivity to beam parameters than the Moller 'monopole'

Beam Parameter	**Detector Monitor**	**Monitor slope / Moller monopole slope**
E	(OUT-MID) monopole	11
X	MID xdipole	20
Y	MID ydipole	35
X'	OUT xdipole	37
Y'	(OUT-MID) ydipole	52

SLICE Measurements in Run 3

- SLICES readout in 10 bit ADCs

  Q : bpm31Q (4)

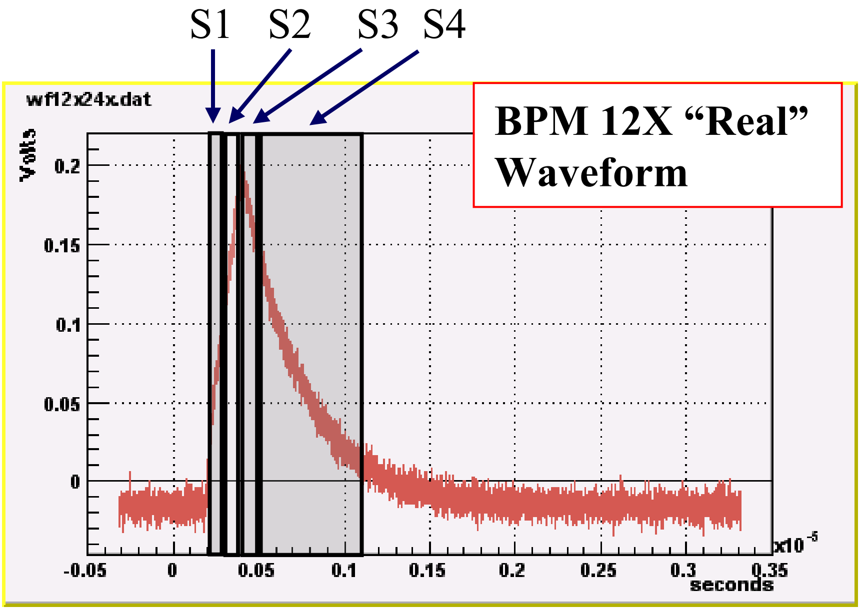
  E : bpm12X (3)

  X : bpm41X (4)

  Y : bpm41Y (4)

  dX : bpm31X (4)

  dY : bpm31Y (4)



BPM 12X "Real" Waveform

Integration time :

S1 : 0 -100 ns

S2 : 100-200 ns

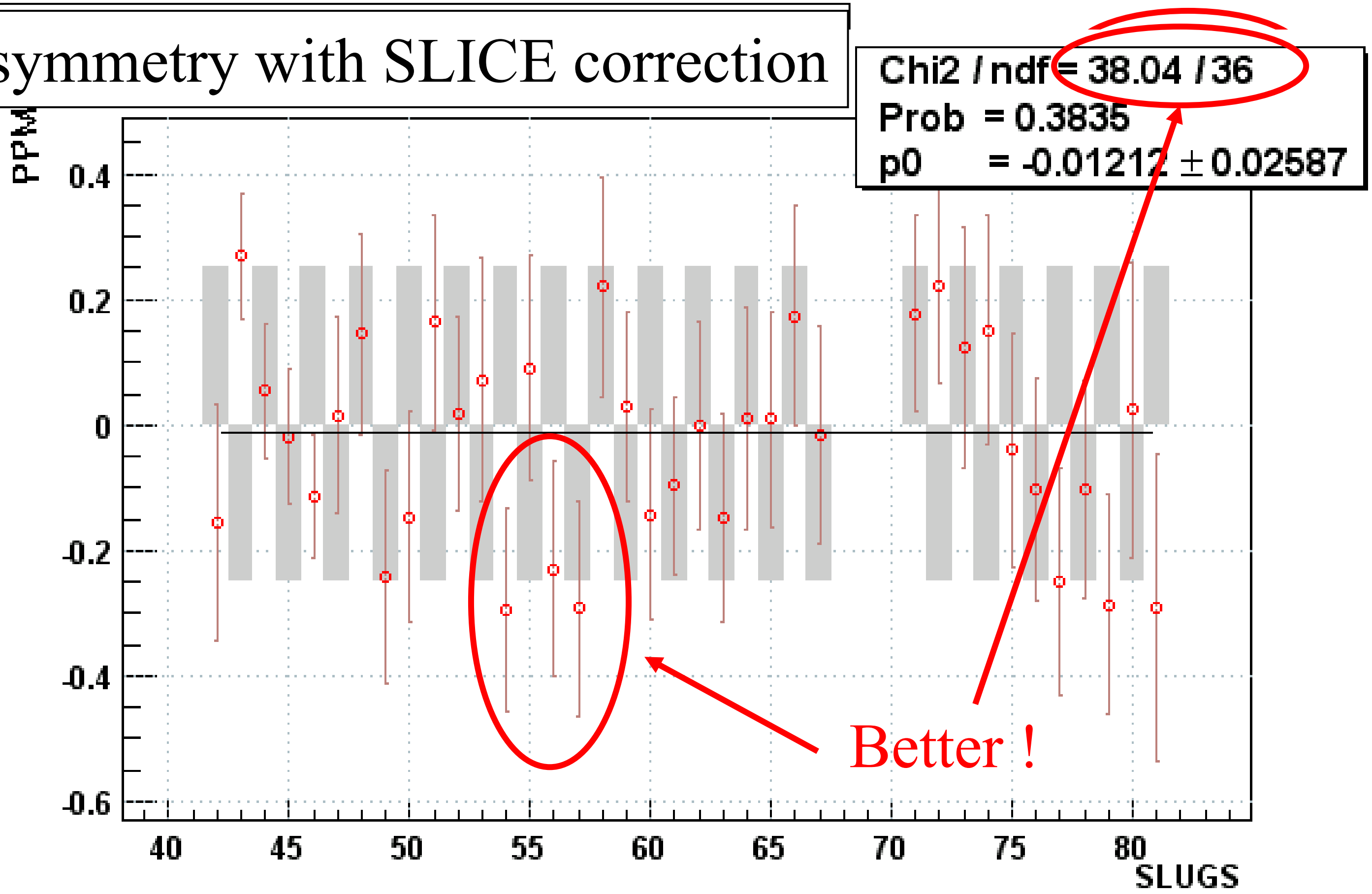
S3 : 200-300 ns

S3 : 300-1000 ns

SLICE Analysis for OUT Detector in Run 3

- OUT detector at edge of Møller acceptance most sensitive to beam systematics (*only* used in A_{PV} determination for Run 3)
- Use it to set limits on the grand asymmetry

OUT asymmetry with SLICE correction



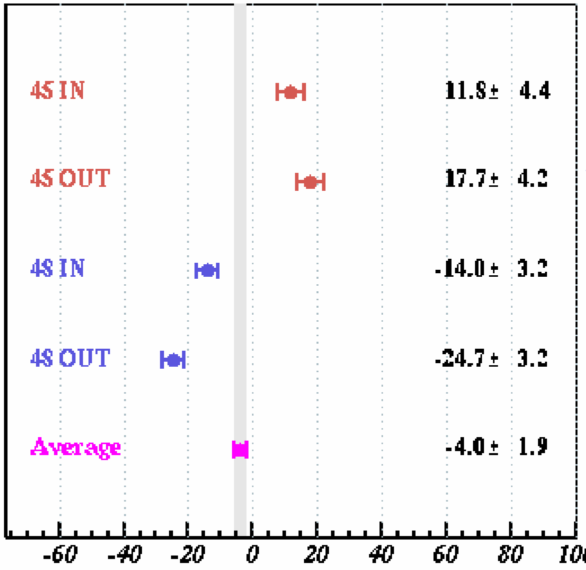
Better !

E158 Beam Summary

A_{PV} Corrections from Beam Asymmetries

Source	ΔA (ppb)	f
Beam[1] (1st order)	-9.7 ± 1.4	-
Beam (higher order)	0 ± 3	-
Synchrotron photons	0 ± 1	0.002 ± 0.0001

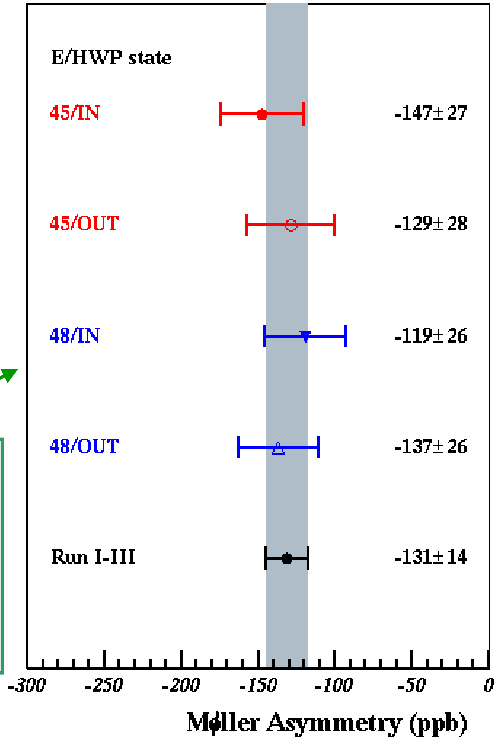
$$A_{PV} = \frac{1}{P_b \cdot \varepsilon} \cdot \frac{A_{raw} - \sum \Delta A}{1 - \sum f}, \qquad P_b = 0.89 \pm 0.04,^{2} \quad \varepsilon(\text{linearity}) = 0.99 \pm 0.01$$



Run 3 A_{PV} Corrections (ppb)

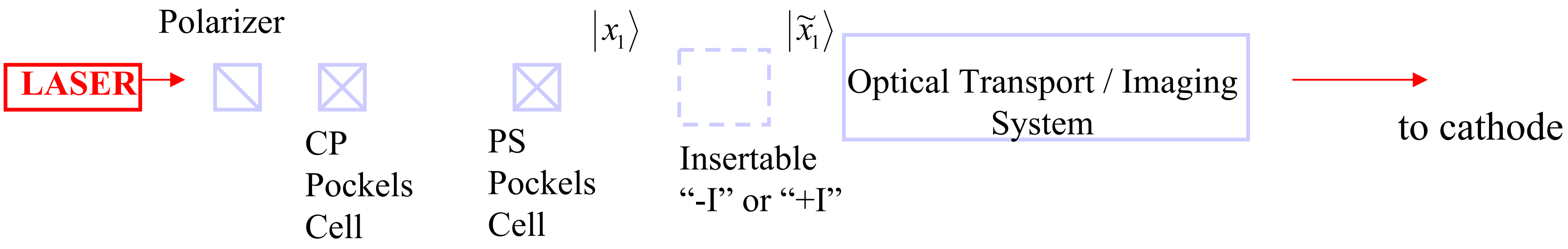
Helicity reversals from energy and half-waveplate important to minimize beam asymmetry corrections and systematics!

Good consistency in A_{PV} for independent energy & half-waveplate states!



Additional Slides

“-I” Asymmetry Inverter



Polarizer

LASER

CP Pockels Cell

PS Pockels Cell

$|x_1\rangle$

$|\tilde{x}_1\rangle$

Insertable “-I” or “+I”

Optical Transport / Imaging System

to cathode

$|x_1\rangle$ has some asymmetry (A_x, $A_{x'}$) between left, right states (x’=dx/dz);

$$A_{x_1} = \langle x_1\rangle_L - \langle x_1\rangle_R$$
$$A_{x_1'} = \langle x_1'\rangle_L - \langle x_1'\rangle_R$$

Let $|\tilde{x}_1\rangle = M|x_1\rangle$

$$\begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_1' \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_1' \end{bmatrix}$$

(imaging condition: M_{12}=0)

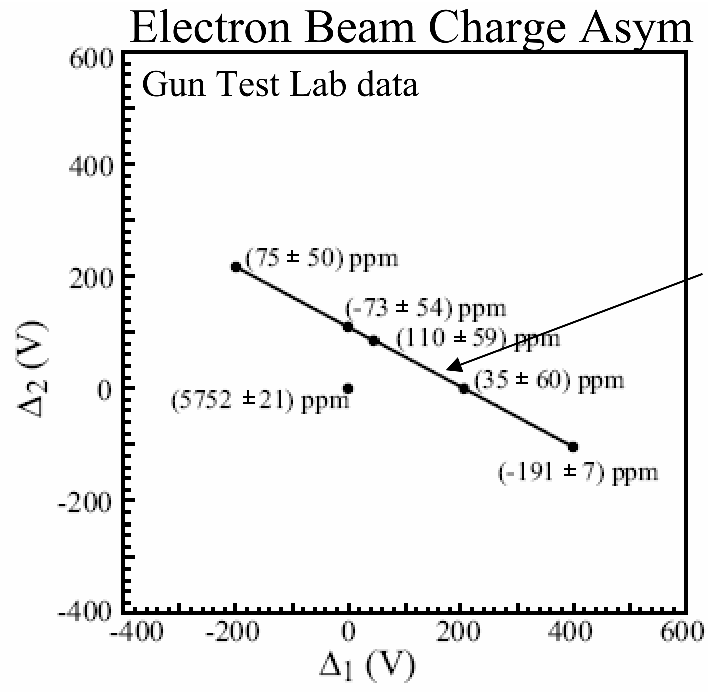
Idea: “+I” $M = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \longrightarrow \begin{Bmatrix} A_{\tilde{x}_1} = A_{x_1} \\ A_{\tilde{x}_1'} = A_{x_1'} \end{Bmatrix}$

“-I” $M = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \longrightarrow \begin{Bmatrix} A_{\tilde{x}_1} = -A_{x_1} \\ A_{\tilde{x}_1'} = -A_{x_1'} \end{Bmatrix}$

Alternate running with “+I” and “-I” will give

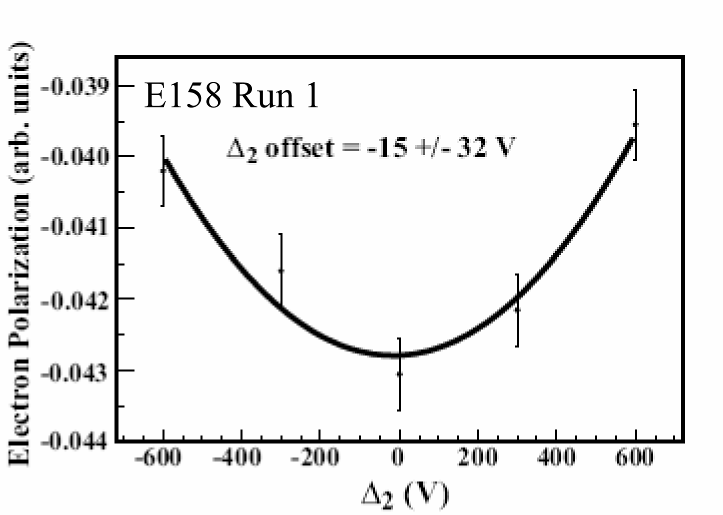
$$\langle A_{\tilde{x}_1}\rangle = 0$$
$$\langle A_{\tilde{x}_1'}\rangle = 0$$

Setting the CP, PS Pockels Cell Voltages in Source Laser System


Electron Beam Charge Asym

Zero asymmetry line

Δ_1, Δ_2 are the offsets from the CP and PS voltages determined to give circularly polarized light with a helicity filter.



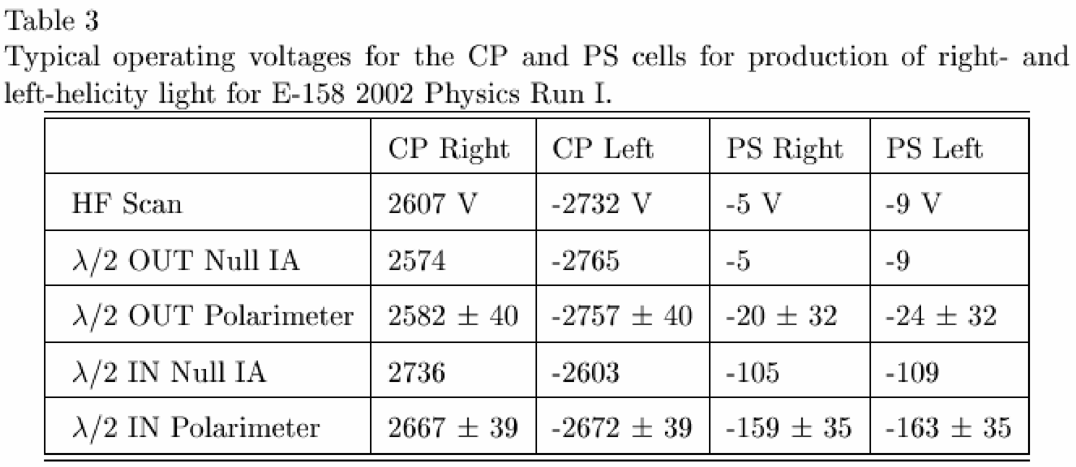


Table 3
Typical operating voltages for the CP and PS cells for production of right- and left-helicity light for E-158 2002 Physics Run I.

	CP Right	CP Left	PS Right	PS Left
HF Scan	2607 V	-2732 V	-5 V	-9 V
$\lambda/2$ OUT Null IA	2574	-2765	-5	-9
$\lambda/2$ OUT Polarimeter	2582 ± 40	-2757 ± 40	-20 ± 32	-24 ± 32
$\lambda/2$ IN Null IA	2736	-2603	-105	-109
$\lambda/2$ IN Polarimeter	2667 ± 39	-2672 ± 39	-159 ± 35	-163 ± 35