CORNELL
UNIVERSITY
LEPP
LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

# CESR-c and CLEO-c Physics
# Extending the energy reach of CESR

D.Rubin, Cornell University

- CLEO-c physics program
- Accelerator physics at low energy

# Physics Objectives

- Tests of LQCD
- Charm decay constants  fD, fDs
- Charm absolute branching ratios
- Semi leptonic dcay form factors
- Direct determination of Vcd & Vcs
- QCD
    - Charmonium and bottomonium spectroscopy
    - Glueball search
    - Measurement of R from 1 to 5GEV
- CP violation?
- Tau decay physics

# Measurements

- Leptonic charm decays

  $D^- \square\ \ell^- \square,\ D^-_s \square\ \ell^- \square$
- Semileptonic charm decays

  $D \square\ (K, K^*)\, \ell \square,\ D \square\ (\square, \square, \square)\, \ell \square,\ D \square\ (\square, \square)\, \ell \square,$
- Hadronic decays of charmed mesons

  $D \square\ K\square,\ \ D^+ \square\ K \square \square$
- Rare decays, D mixing, CP violating decays
- Quarkonia and QCD

# Heavy quark physics

- Precision of measured D branching fractions limit any result involving B -> D
- Determination of CKM matrix elements and many weak interaction results limited by theoretical (QCD) uncertainties
(B -> \psi K_s is the “gold plated” exception)

# Example - theoretical limit

- B□ □ℓ□
  Gives V_ub in principle with uncertainty
  approaching 5% with 400 fb-1 from B-Factories

- But form factor for u quark to materialize as □
  has 20% uncertainty

# Lattice QCD ?

Lattice QCD is not a model

Only complete definition of QCD

Only parameters are alpha_s, and quark masses

Single formalism for B/D physics, □/ , glueballs ,…

No fudge factors

Recent developments in techniques for lattice calculations promise mass, form factors, rates within ~few %

- Improved discretizations (larger lattice spacing)
- Affordable unquenching (vacuum polarization)

Critical need for detailed experimental data in all sectors to test the theory

# Lattice QCD

New theoretical techniques permit calculations at the few % level of masses, decay constants, semileptonic form factors and mixing amplitudes for

- D,Ds,D*,Ds*,B,Bs,B*,Bs* and corresponding baryons
- Masses leptonic widths, electromagnetic for factors and mixing amplitudes for any meson in □, family below D and B threshold
- Masses, decay constants electroweak form factors, charge radii, magnetic moments and mixing angles for low lying light quark hadrons
- Gold plated processes for every off diagonal CKM matrix element

# Lattice QCD

Progress is driven by improved algorithms, (rather than hardware)

Until recently calculations are quenched, sea quark masses -> (no vacuum polarization) -> 10-20% decay constant errors

Current simulations with

- Lattice spacing a=0.1fm
- realistic $m_s$, and $m_u$,$m_d$ ~$m_s$/4

Require 3 months on 200 node PC cluster for 1% result

# Lattice QCD

CLEO-c program will

Precision measurements in □,   sector for which few % calculations possible of masses, fine structure, leptonic widths, electromagnetic transition form factors

Semileptonic decay rates for D, Ds plus lattice QCD

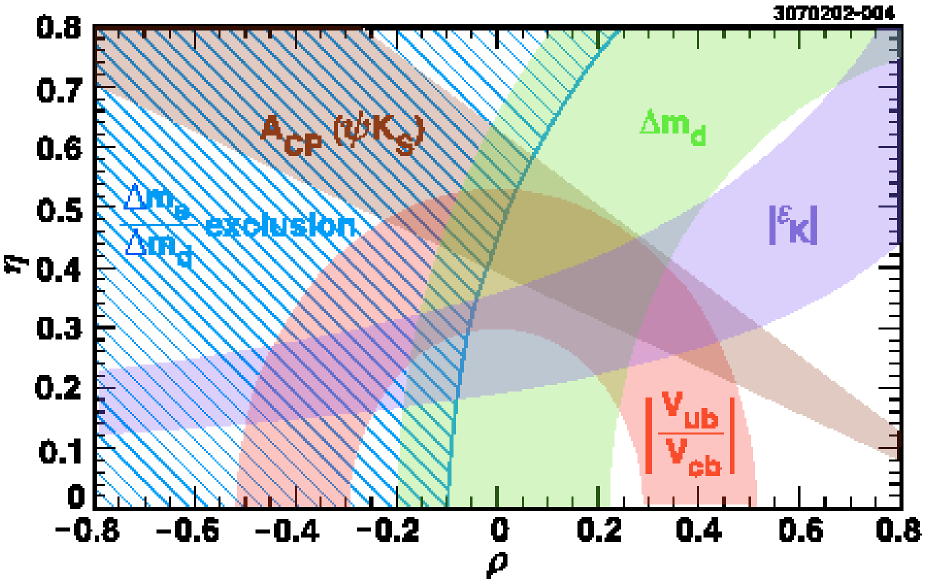
- Vcd to few % (currently 7%)
- Vcs to few % (currently 12%)
- few % tests of CKM unitarity

Leptonic decay rates for D,Ds plus lattice QCD give few % cross check

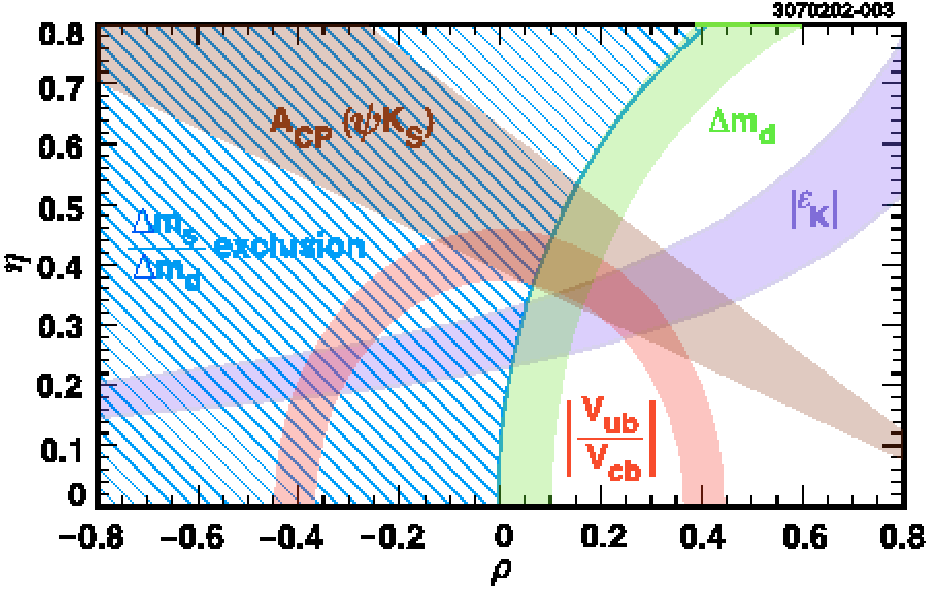
Glueball - need good data to motivate calculations

If theory and measurements disagree -> New Physics

# CKM early 2000



With 2-3% theory errors



# Establish credibility of Lattice QCD

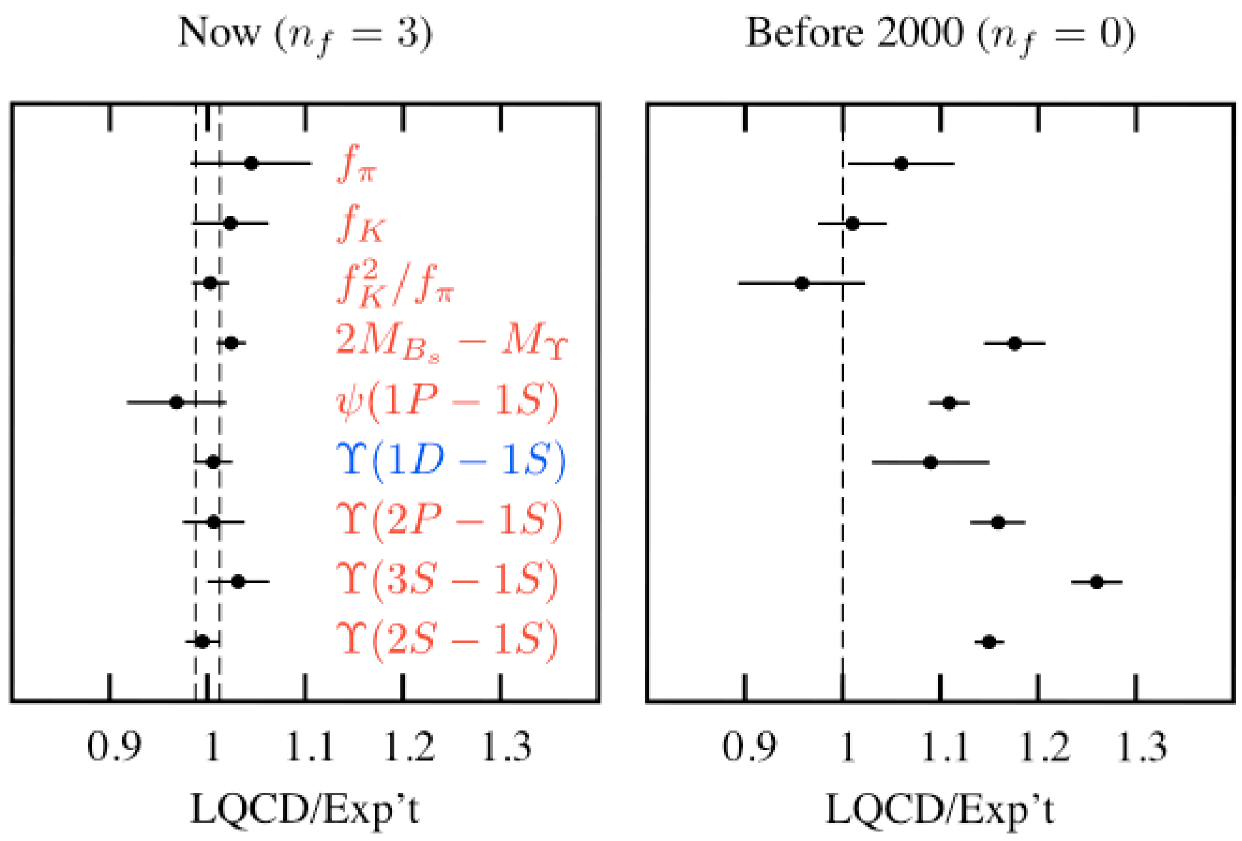
CLEO - c will provide precision measurements
of processes involving both b and c quarks against
which lattice calculations can be checked

Recent results from HPQCD+MILC collaborations

$n_f$ = 3, a=1/8fm

tune $m_u$=$m_d$,$m_s$,$m_c$,$m_b$, and $□_s$
using $m_□$, $m_K$,$m_□$ m  and □E (1P-1S)

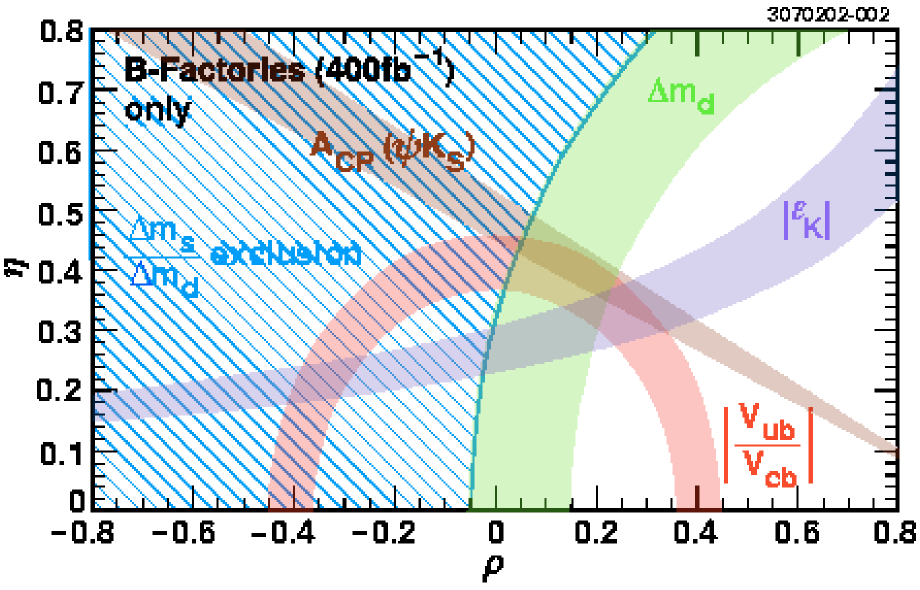
⇒ New results: (lattice QCD)/(experiment) — no free parameters!


Now ($n_f = 3$)

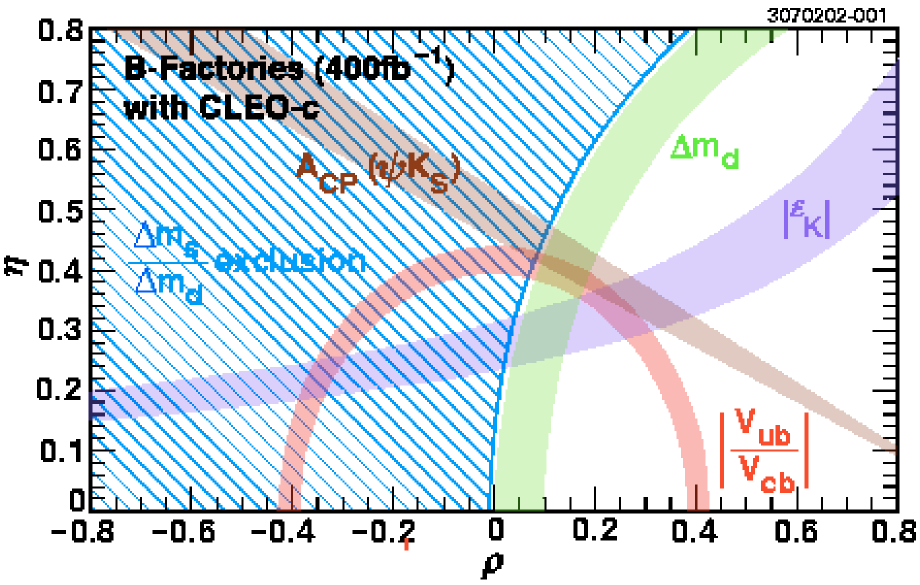
Before 2000 ($n_f = 0$)

HPQCD+MILC: Very Preliminary

B-Factory (400fb-1) and 10% theory errors
(no CLEO-c)



And with 2-3% theory errors
(with CLEO-c)



# CLEO-c Run Plan

- ~ 1fb$^{-1}$ each on $_{1s,}$ $_{2s,}$ $_{3s}$

  spectroscopy, matrix elements, □$_{ee}$
- □(3770) - 3 fb$^{-1}$

  30 million events, 6M tagged D decays

  (310 times Mark III)
- √s ~ 4100MeV - 3 fb$^{-1}$

  1.5M D$_s$D$_s$ , 0.3M tagged D$_s$

  (480 times Mark III, 130 times BES II)
- □(3100) - 1 fb$^{-1}$

  1 billion J/□

  (170 times Mark III, 20 times BES II)

# Status Run

|  | 1s | 2s | 3s |  |
|---|---|---|---|---|
| Target | 950 | 500 | 1000 |  |
| Actual | 1090 | >500 | 1250 |  |
| Old | 79 | 74 | 110 | ($pb^{-1}$) |
| Status | taken | in progress | processed |  |

Analysis

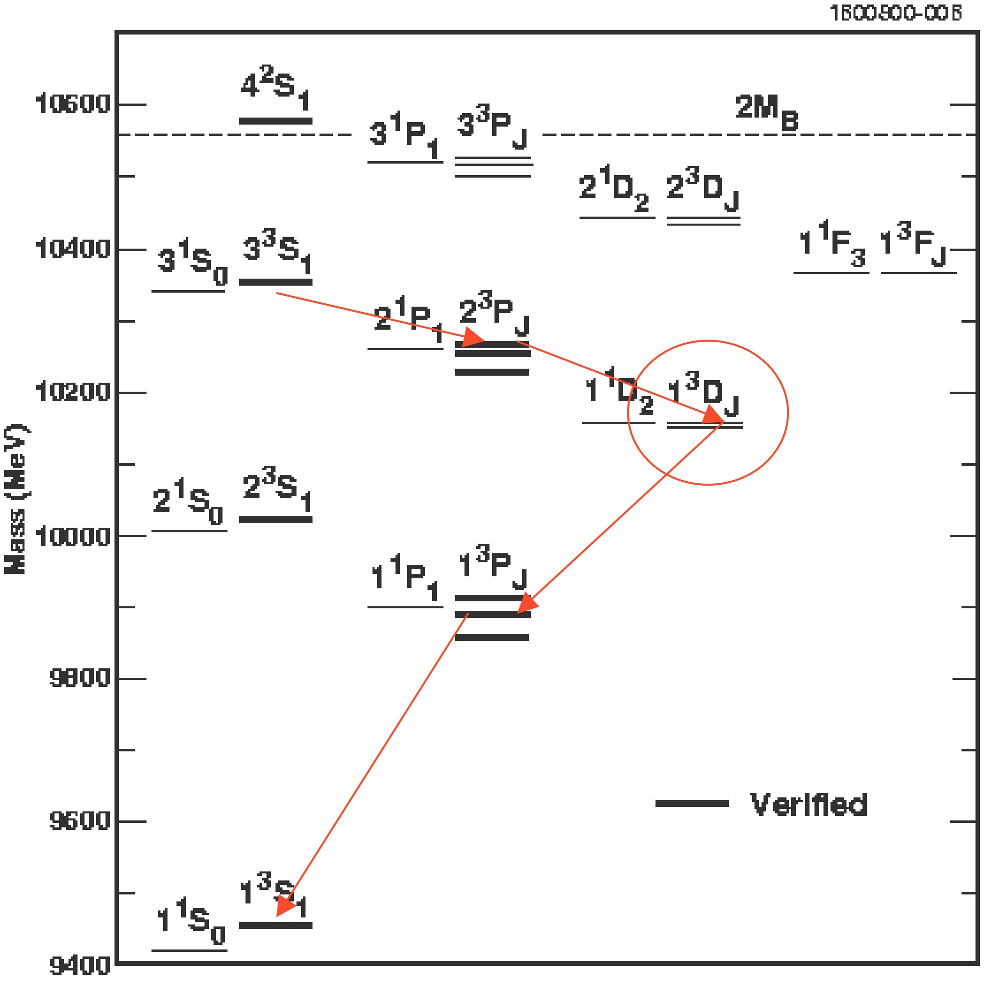
Discovery? - D-states, rare E1 transitions

Precision - Electronic rates, ee, □□ branching fractions, hadronic transitions

# First observation of $1^3$D

Measure

- $\square_{ee}$ to 2-3%
- $\mathcal{B}_{\square\square}$ -> 3-4%
- $\square_{tot}$ to 5%
- $\square\square$ transitions



# Charmed hadrons

Sample:

□(3770) 3fb-1 (1 year)

30M events,

~6M tagged D decays

$D_sD_s$ 3fb-1 (1 year)

1-2M events,

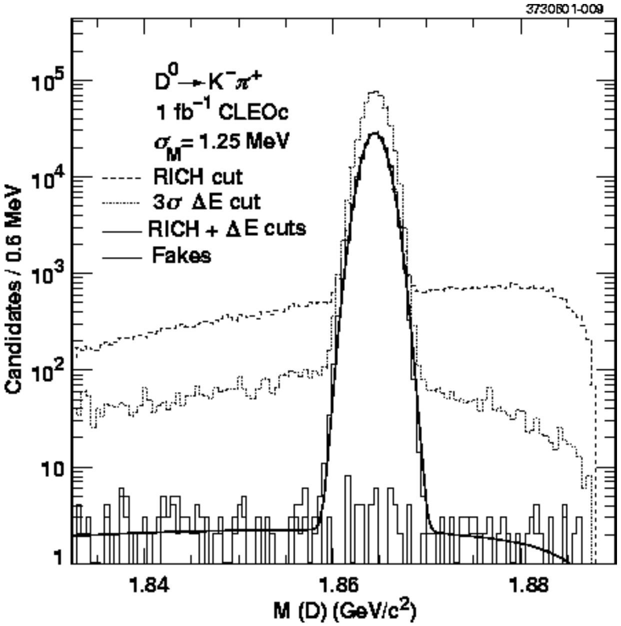
~0.3M tagged Ds

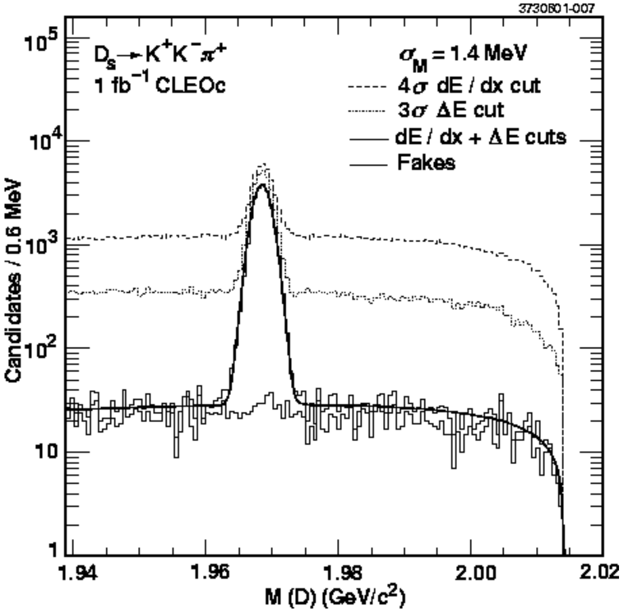
Pure $D\bar{D}$, $D_s\bar{D}_s$ production

High net tagging efficiency ~20%

D -> K□ tag. S/B ~5000/1

$D_s$ -> □□ (□-> KK) tag. S/B ~100/1





# $D_s$ -> □□

CLEO ( $_{4s}$) 4.8fb$^{-1}$

$f_{Ds}$ =280±14±25±18

B-factories (400fb$^{-1}$)

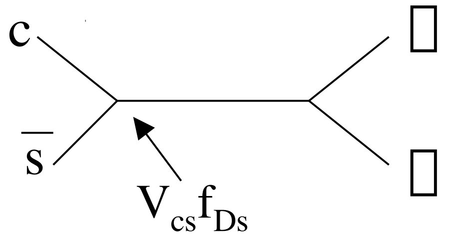
□$f_{Ds}$/$f_{Ds}$ ~4-8%

CLEO-c

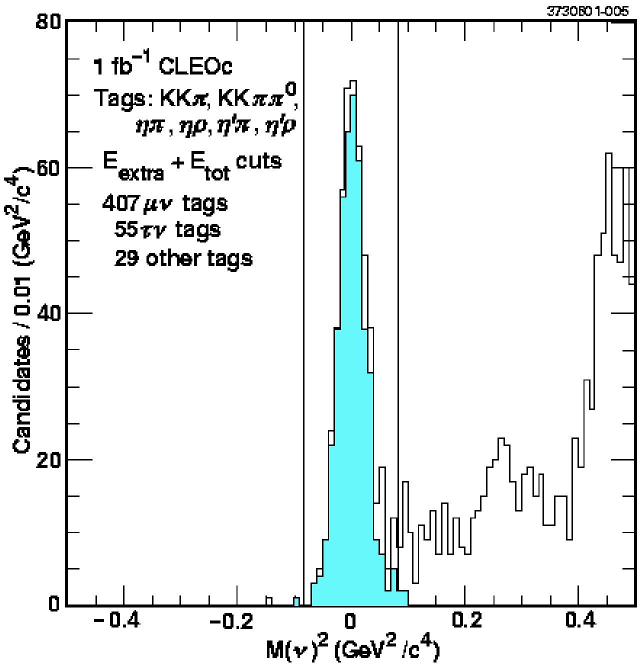
3 fb$^{-1}$ (900 events)

10 tag modes, no □ ID

□$Vf_{Ds}$/$Vf_{Ds}$ (2±.25±1)%



$$\Box = \frac{G_F^2}{8\Box} M_{D_s} m_\Box^2 \Box 1 \Box \frac{m_u^2}{M_{D_s}^2} \Box f_{D_s}^2 \ |V_{cs}|^2$$

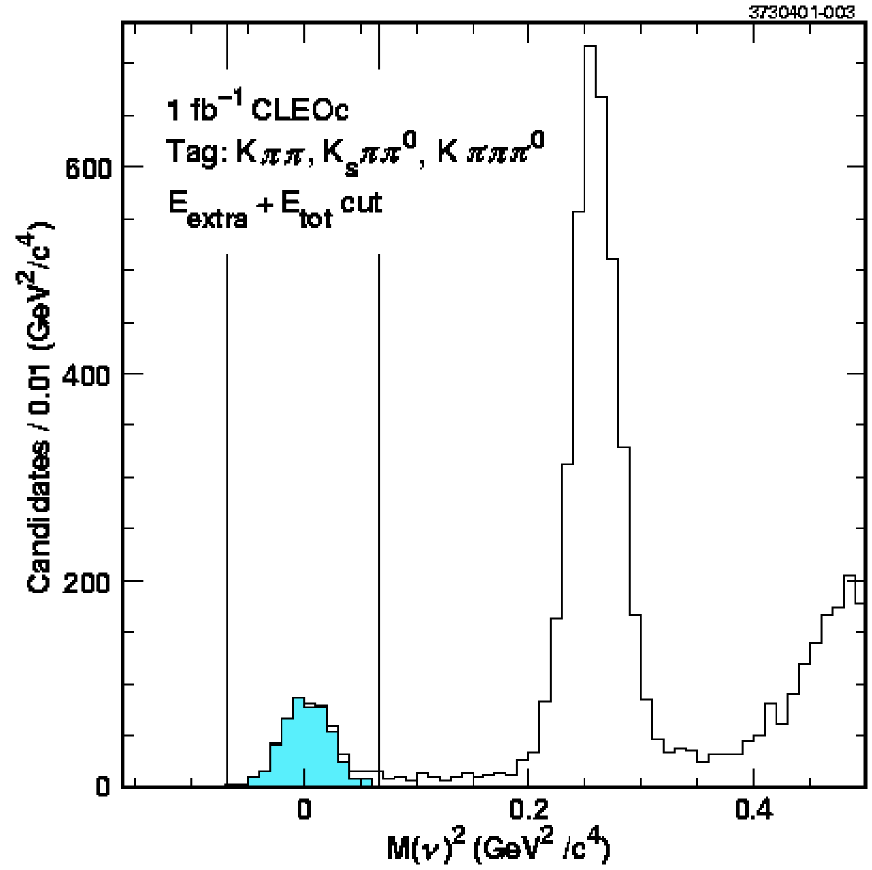


# $D^+$ -> □□

CLEO-c 3 fb-1 (3770)

~900 events

□$V_{cd}f_D/V_{cd}f_D$ ~ (2±.3±.6)%



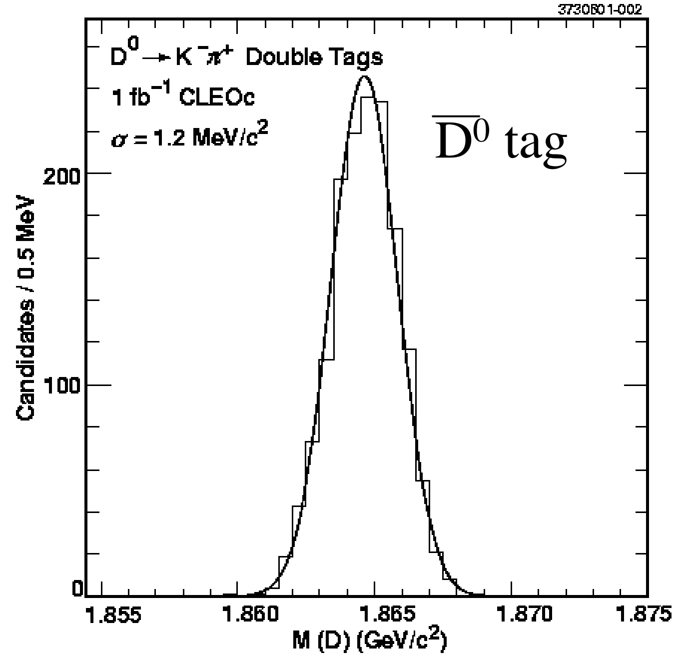
# Double Tagged Branching Fraction Measurements

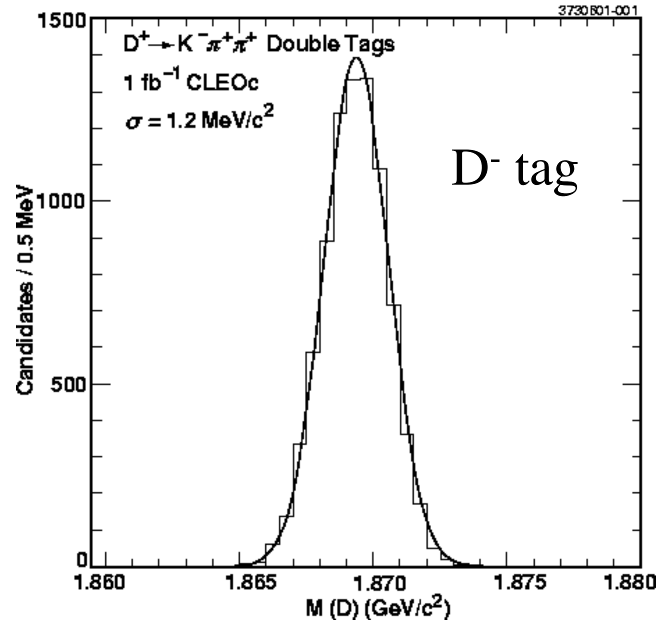
No background in hadronic tag modes

Measure absolute Br(D->X) with double tags

Br = # of X/# of D tags for other modes

| Mode | PDG<br>( B/B%) | CLEO-c<br>( B/B%) |
|---|---|---|
| $D^0$-> $K^-$ □+ | 2.4 | 0.6 |
| $D^+$ -> $K^-$□+□+ | 7.2 | 0.7 |
| $D_s$ -> □□ | 25 | 1.9 |





# Semileptonic decays

Rate ~ $|V_{cj}|^2|f(q^2)|^2$

Low background and high rate

| Mode | PDG<br>( B/B%) | CLEO-c<br>( B/B%) |
|---|---|---|
| $D^0$-> $K\ell$□ | 5 | 2 |
| $D^0$-> □$\ell$□ | 16 | 2 |
| $D^+$ -> □$\ell$□ | 48 | 2 |
| $D_s$ -> □$\ell$□ | 25 | 3 |

Vcd and Vcs to ~1.5%

Form factor slopes to few % to test theory

# More tests of lattice QCD

□(D-> □ℓ□)/ □($D^+$-> ℓ□)   independent of $V_{cd}$

□($D_s$-> □ℓ□)/ □($D_s$-> ℓ□)   independent of $V_{cs}$

Test QCD rate predictions to 3.5-4%

Having established credibility of theory

$D^0$ -> $K^-e^+$□  gives  □$V_{cs}/V_{cs}$ = 1.6%  (now 11%)
$D^0$ -> □$^-e^+$□  gives  □$V_{cd}/V_{cd}$ = 1.7%  (now 7%)

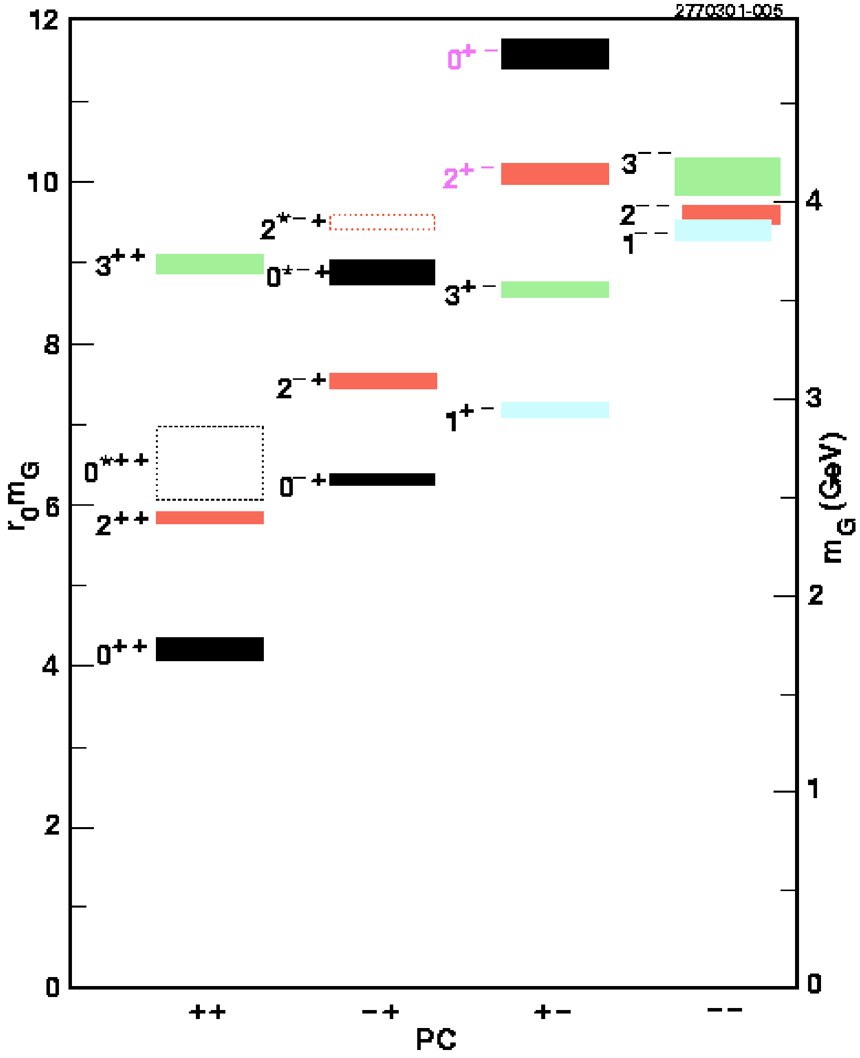
# J/□ Radiative decays

Calculated glueball spectrum
  Morningstar and Peardon

Look for |gg> states

Lack of strong evidence is a
 fundamental issue for QCD

Tensor glueball candidate fJ(2220)
Expect J/□ -> □$f_J$
Complementary anti-search in □□
Complementary search in    decays



# CLEO-c physics summary

Precision measurement of
    D branching fractions
    Leptonic widths and EM transitions
      in     and □ systems

Search for exotic states

-> Tests of lattice QCD

D Mixing
D CP violation
Tau physics
R scan

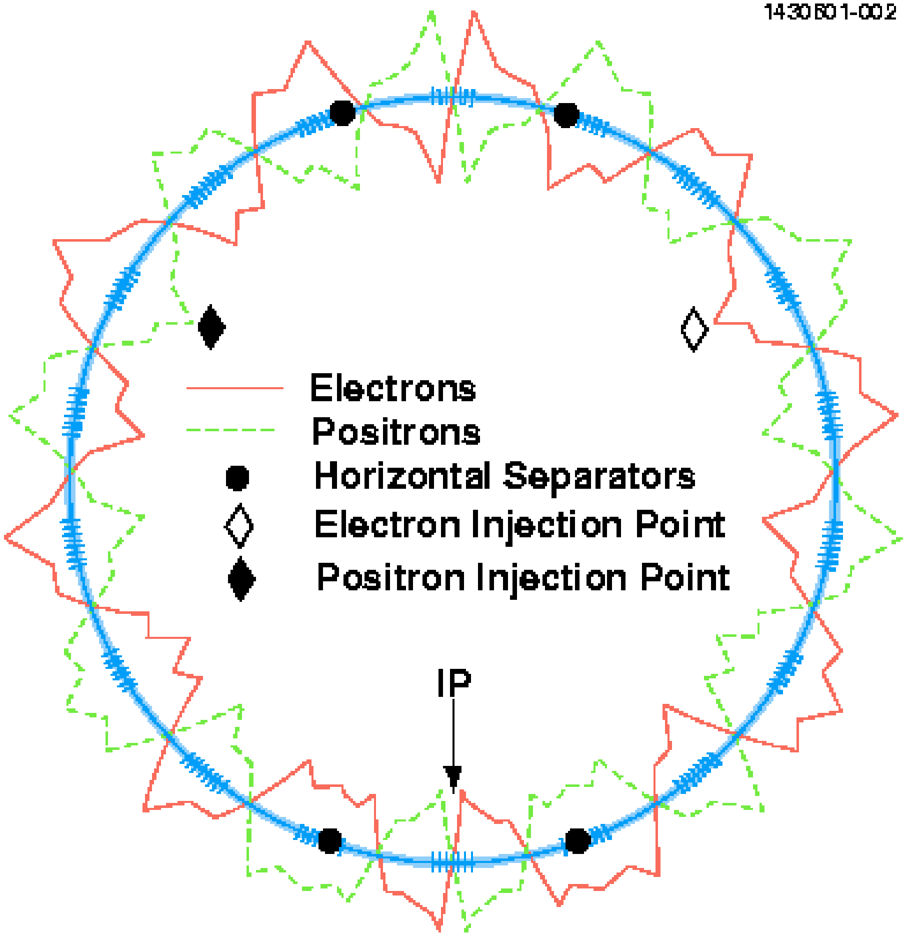
# CESR-c

Energy reach 1.5-6GeV/beam

Electrostatically separated
electron-positron orbits
accomate counterrotating trains

Electrons and positrons collide
with +-2.5 mrad horizontal
crossing angle

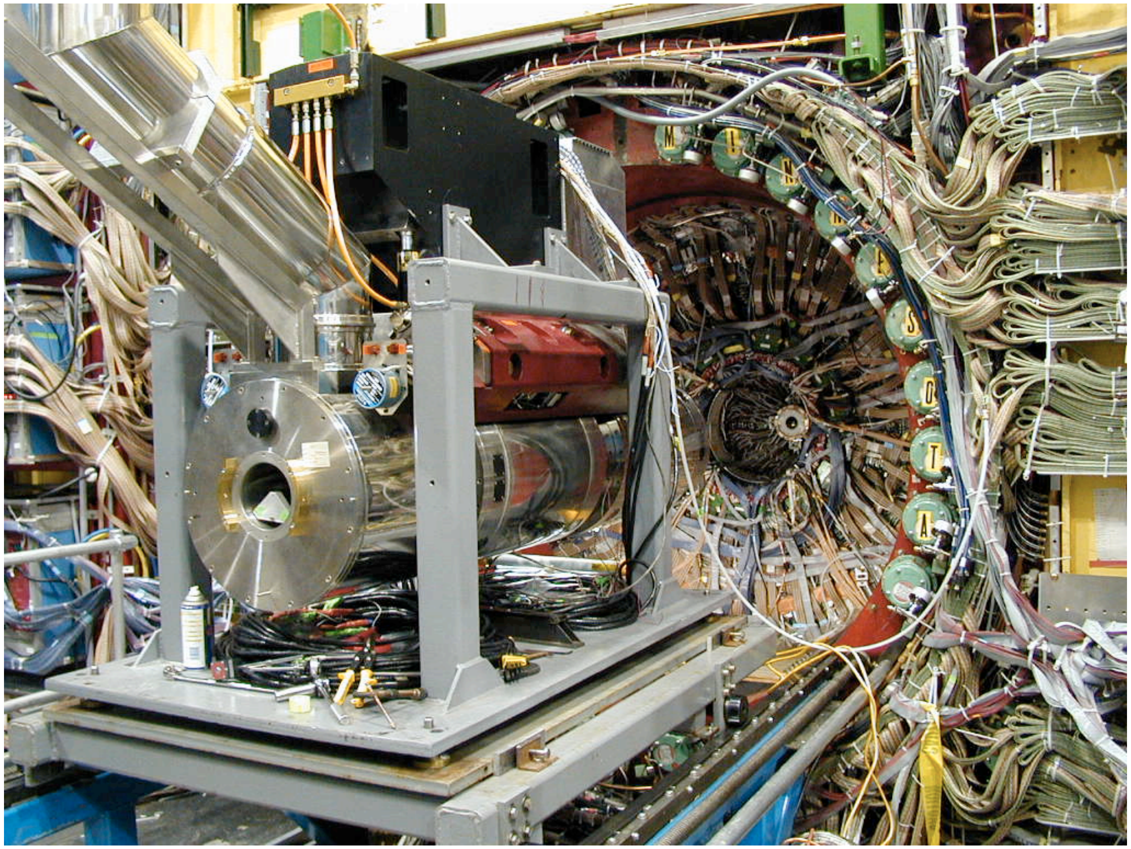
9 5-bunch trains in  each beam



# CESR-c IR

Summer 2000, replace 1.5m REC permanent magnet final focus quadrupole with hybrid of pm and superconducting quads

Intended for 5.3GeV operation but perfect for 1.5GeV as well



# CESR-c IR

□* ~ 10mm

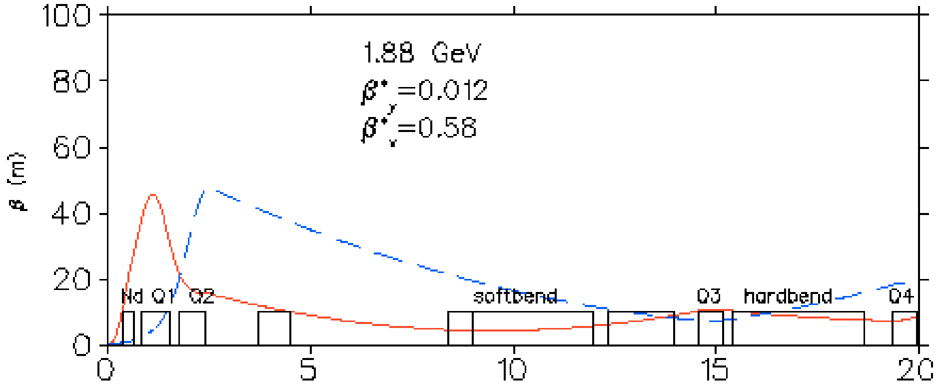
H and V superconducting quads share same cryostat

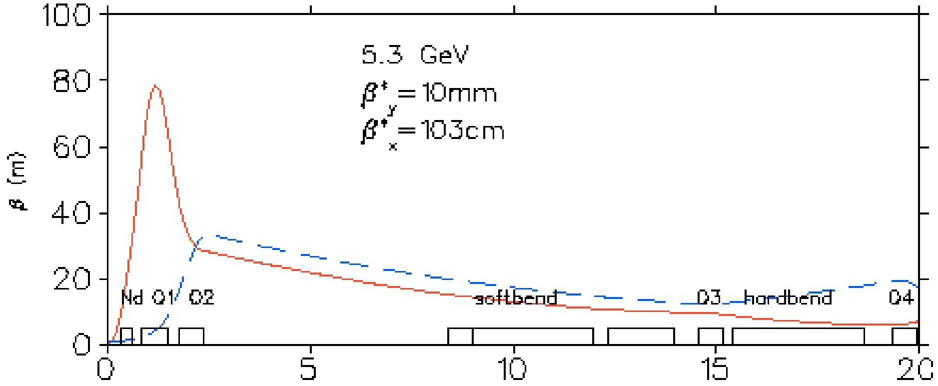
20cm pm vertically focusing nose piece

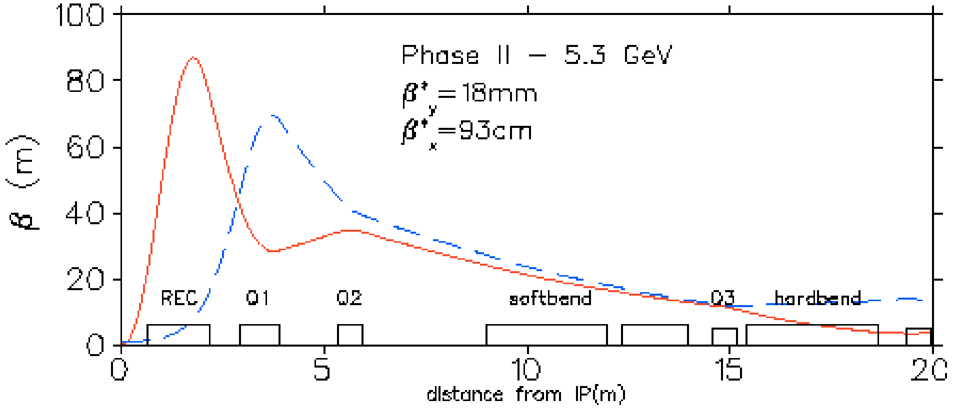
Quads are rotated 4.5$^0$ inside cryostat to compensate effect of CLEO solenoid

Superimposed skew quads permit fine tuning of compensation

At 1.9GeV, very low peak □ =>
  Little chromaticity, big aperture







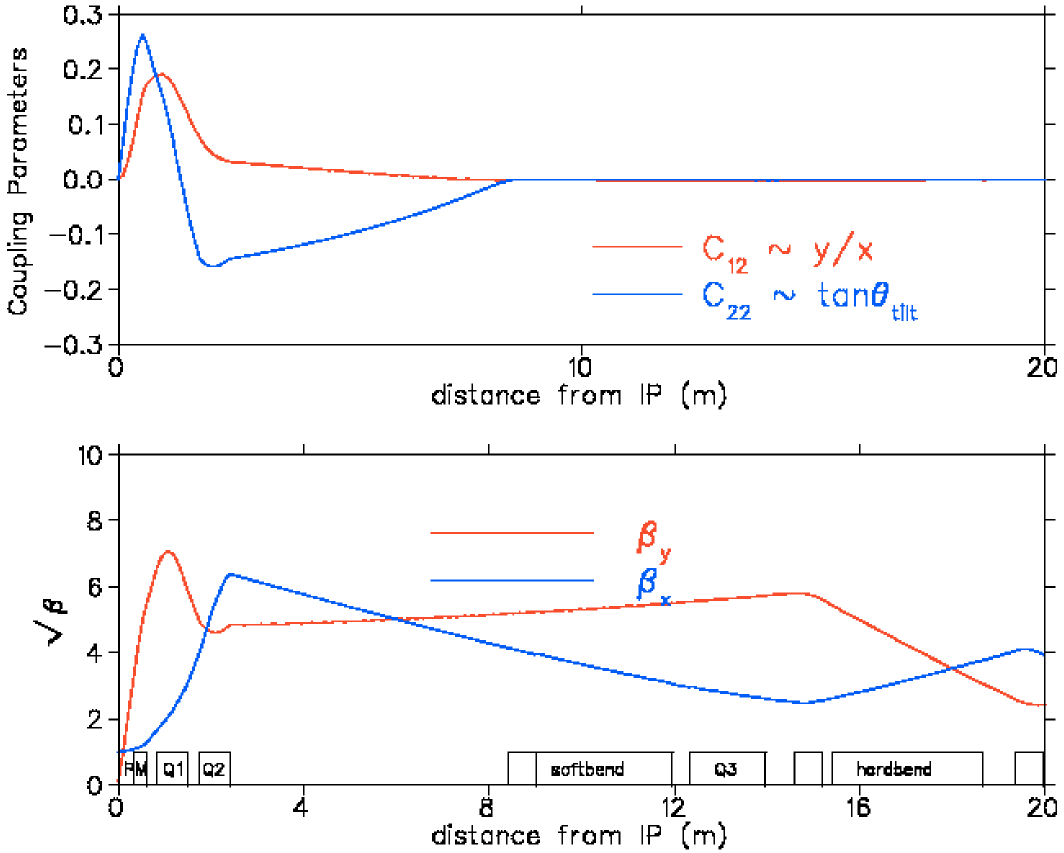
CLEO solenoid

1T(□)-1.5T( )

Good luminosity requires zero transverse coupling at IP

(flat beams)

Solenoid readily compensated even at lowest energy



□*(V)=10mm E=1.89GeV

□*(H)=1m B(CLEO)=1T

# CESR-c Energy dependence

Beam-beam effect

- In collision, beam-beam tune shift parameter ~ $I_b/E$
- Long range beam-beam interaction at 89 parasitic crossings ~ $I_b/E$
  (and this is the current limit at 5.3GeV)

Single beam collective effects, instabilities

- Impedance is independent of energy
- Effect of impedance ~I/E

# CESR-c Energy dependence

Radiation damping and emittance

Damping

Circulating particles have some momentum transverse to design orbit ($P_t/P$)

In bending magnets, synchrotron photons radiated parallel to particle momentum $\square P_t/P_t = \square P/P$

RF accelerating cavities restore energy only along design orbit so that transverse momentum is radiated away and motion is damped

Damping time □ ~ time to radiate away all momentum

# CESR-c Energy dependence

Radiation damping

In CESR at 5.3 GeV, an electron radiates ~1MeV/turn

~> □ ~ 5300 turns (or about 25ms)

Power ~ $E^2B^2 = E^4/□^2$ at fixed bending radius

$1/□ \sim P/E \sim E^3$

so at 1.9GeV, □ ~ 500ms

Longer damping time

- Reduced beam-beam limit
- Less tolerance to long range beam-beam effects
- Multibunch effects, etc.
- Lower injection rate

# CESR-c Energy dependence

Emittance

- Closed orbit depends on energy offset     x(s) = □(s)□
- Energy changes suddenly with radiation of synchrotron photon
- Particle begins to oscillate about closed orbit generating emittance
- Lower energy -> fewer radiated photons and lower photon energy

- Emittance □ ~ $E^2$

# CESR-c Energy dependence

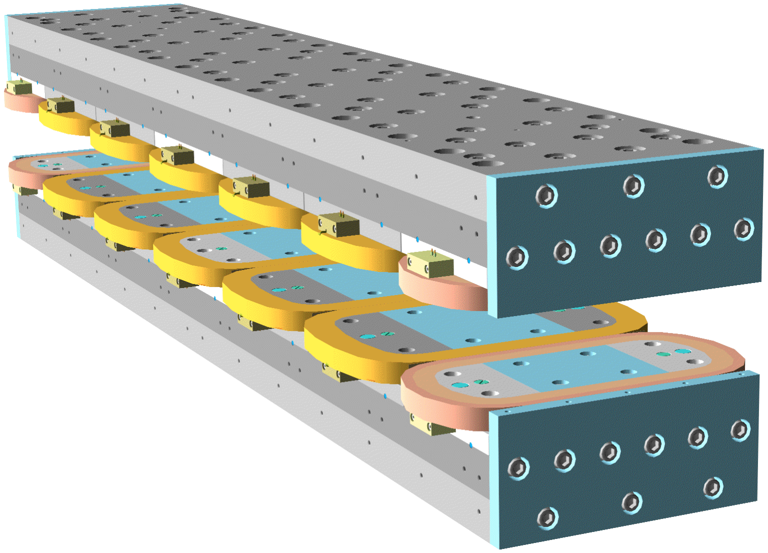
Emittance

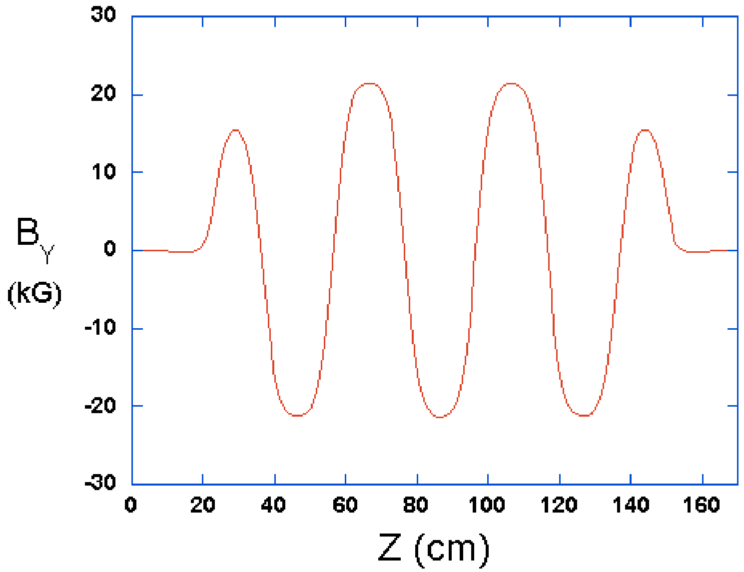
- $L \sim I_B^2/ \square_x\square_y = I_B^2/ (\square_x\square_y\square_x\square_y)^{1/2}$
- $I_B/ \square_x$ limiting charge density
- Then I(max) and $L \sim \square_x$

CESR (5.3GeV), $\square_x$ = 200 nm-rad
CESR (1.9GeV), $\square_x$ = 30 nm-rad

# CESR-c Energy dependence

## Damping and emittance control with wigglers





# CESR-c Energy dependence

In a wiggler dominated ring

- $1/\square \sim B_w^2 L_w$
- $\square \sim B_w L_w$
- $\square_E/E \sim (B_w)^{1/2}$ nearly independent of length
  (B$_w$ limited by tolerable energy spread)

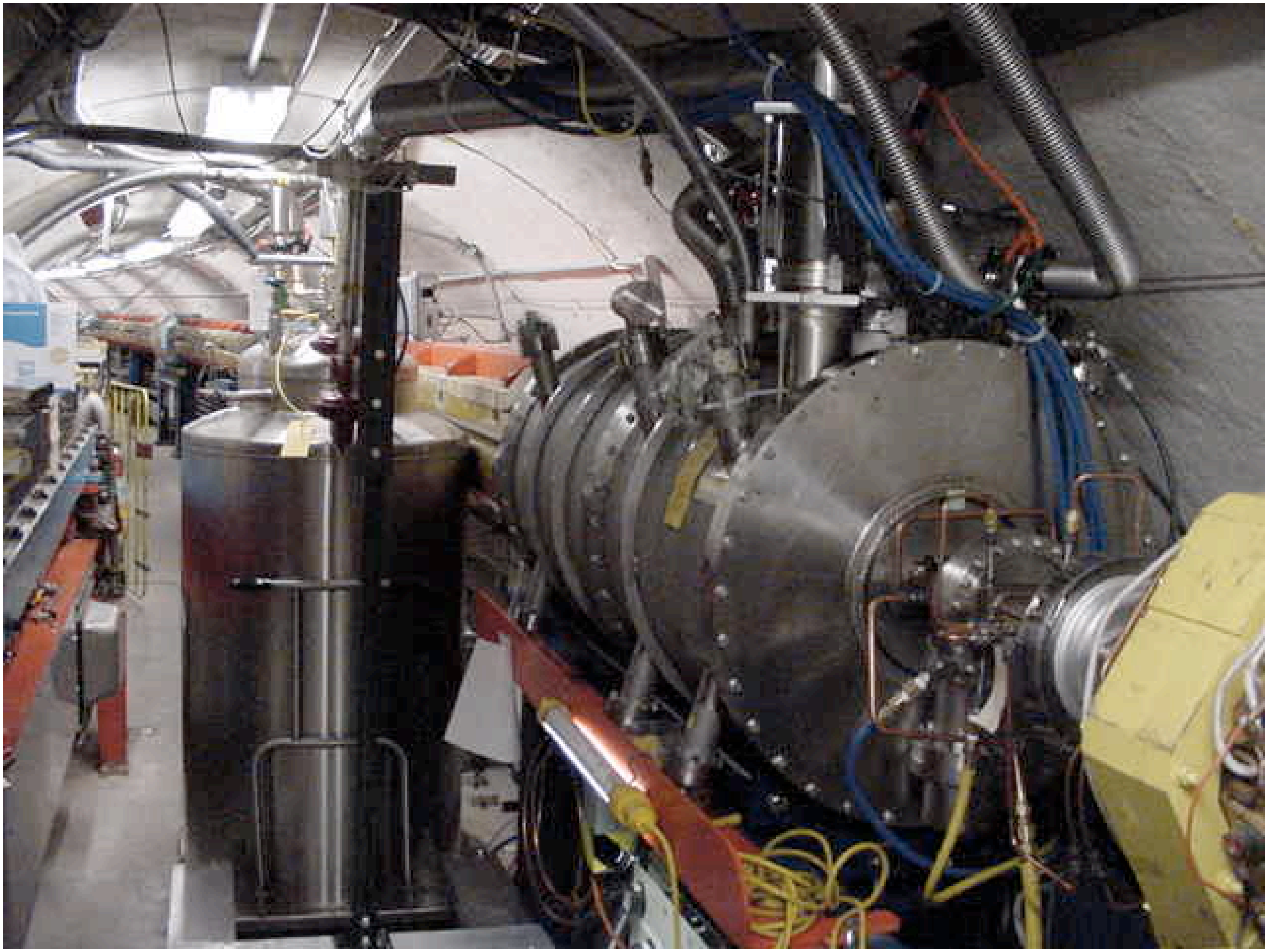
Then 18m of 2.1T wiggler

-> $\square \sim$ 50ms

-> 100nm-rad < $\square$ <300nm-rad

# Superconducting wiggler

7-pole, 1.3m
40cm period,
161A, B=2.1T

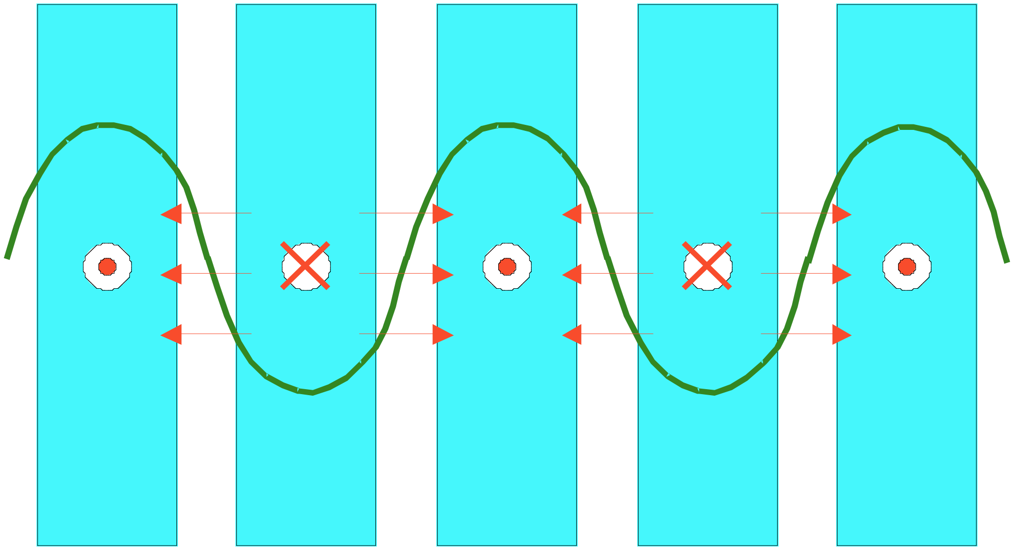


# Optics effects - Ideal Wiggler

$$B_z = -B_0 \sinh k_w y \ \sin k_w z$$

$$\theta = \frac{ceB_0}{E_0}\frac{\lambda_w}{2\pi}$$

Vertical kick ~ $\int B_z$



$$\Delta y' = -\frac{B_0^2 L}{2(E_0/ce)^2}\left[ y + \frac{2}{3}\left(\frac{2\pi}{\lambda}\right)^2 y^3 + \ldots \right]$$

# Optics effects - Ideal Wiggler

Vertical focusing effect is big, □Q ~ 0.1/wiggler

But is readily compensated by adjustment of nearby quadrupoles

Cubic nonlinearity ~ $(1/ □)^2$

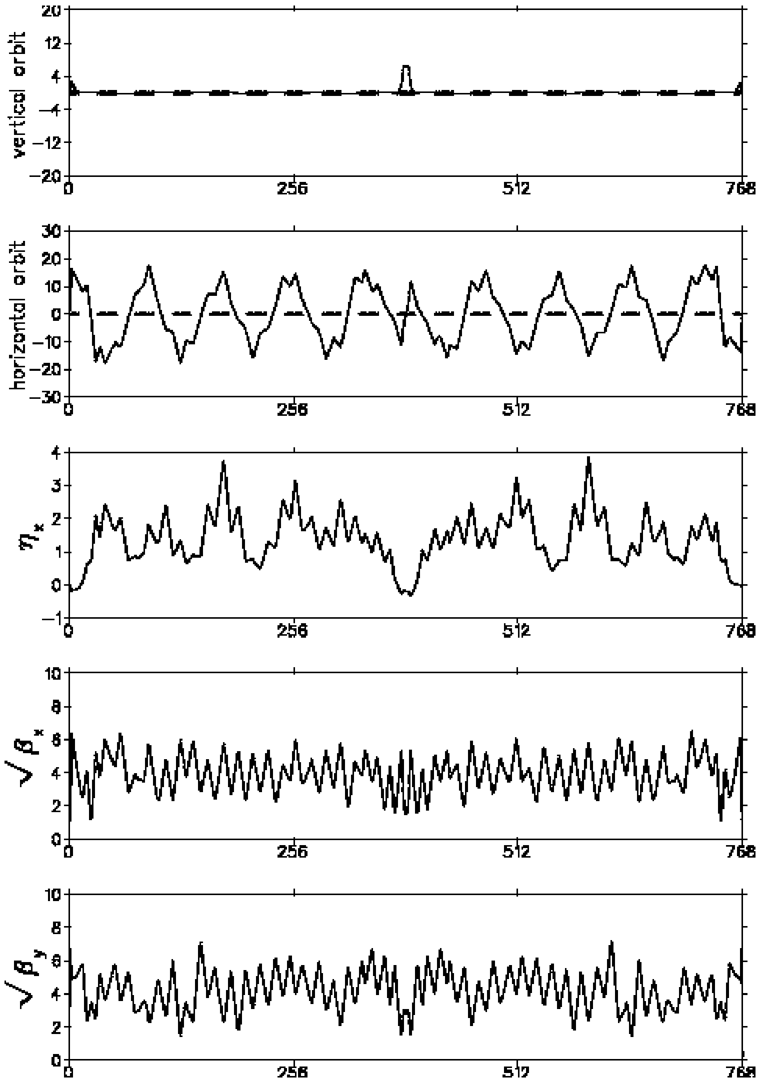
We choose the relatively long period -> □ = 40cm

Finite width of poles leads to horizontal nonlinearity

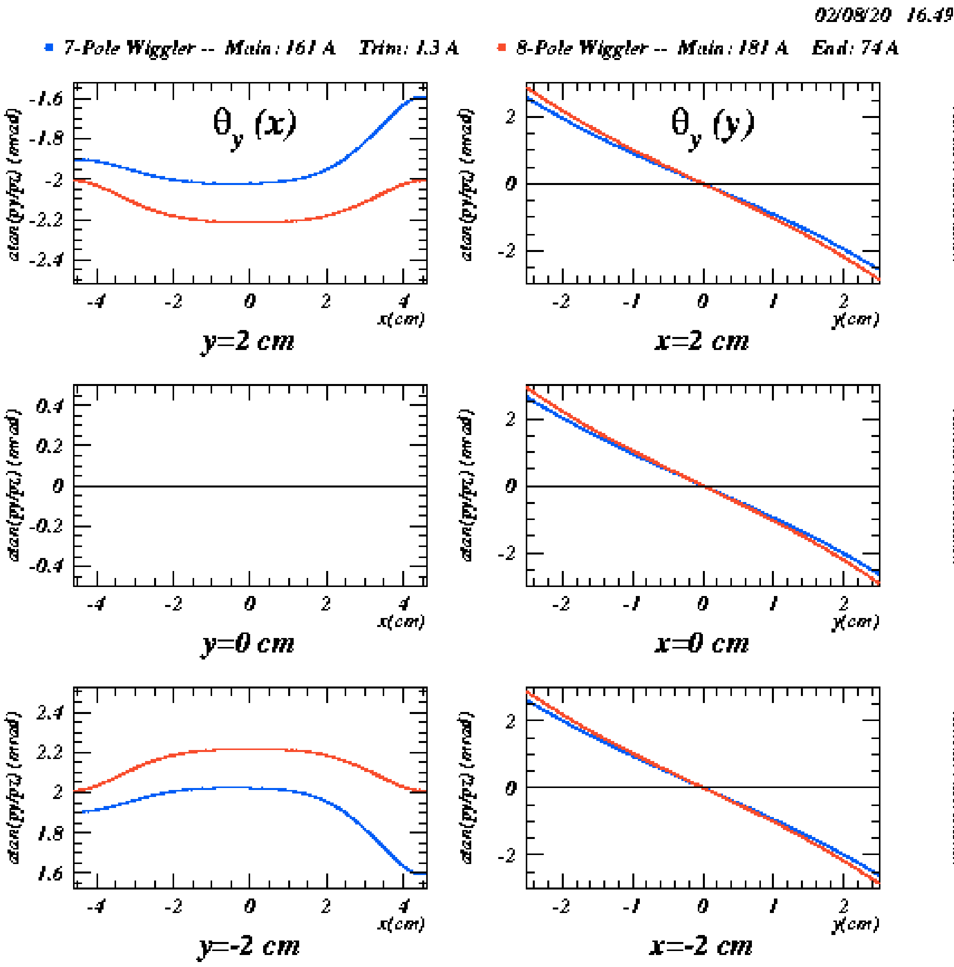
# Linear Optics

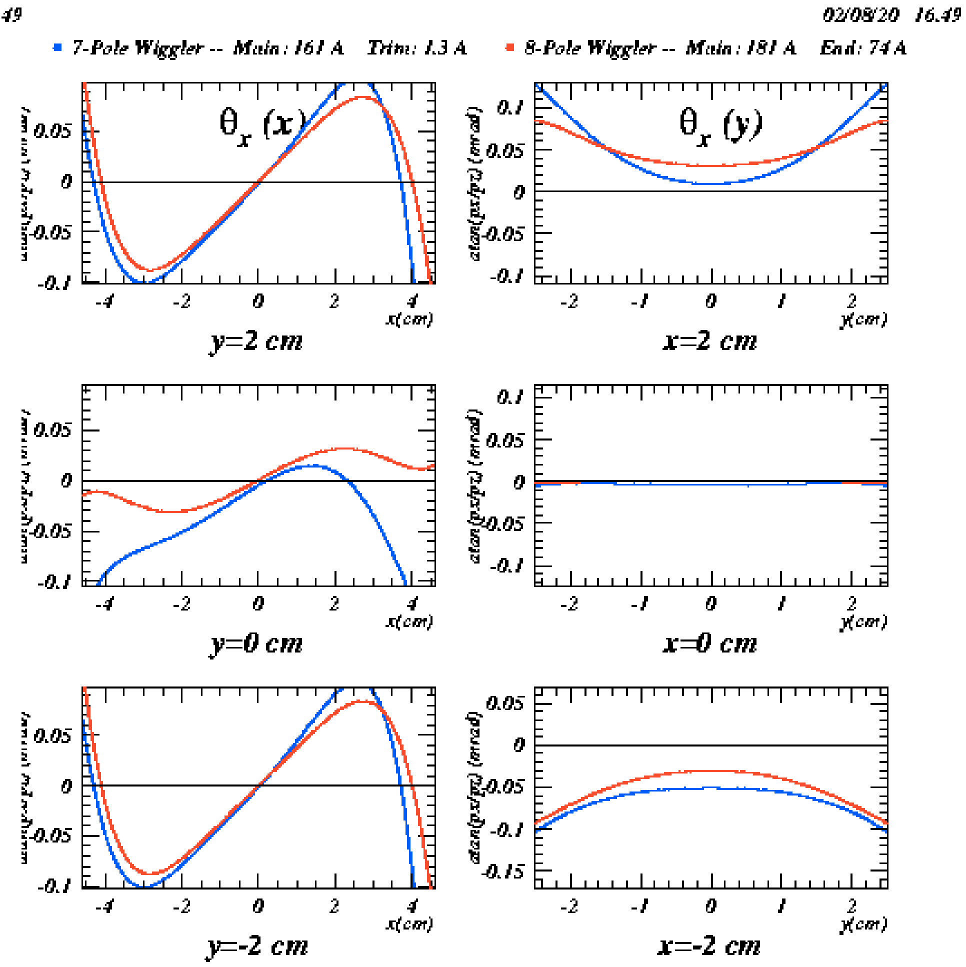
## Lattice parameters

| | |
|---|---|
| Beam energy[GeV] | 1.89 |
| $\square^{*}_{v}$[mm] | 10 |
| $\square^{*}_{h}$[m] | 1 |
| Crossing angle[mrad] | 2.7 |
| $Q_v$ | 9.59 |
| $Q_h$ | 10.53 |
| Number of trains | 9 |
| Bunches/train | 5 |
| Bunch spacing[ns] | 14 |
| Accelerating Voltage[MV] | 10 |
| Bunch length[mm] | 9 |
| Wiggler Peak Field[T] | 2.1 |
| Wiggler length[m] | 1.3 |
| Number of wigglers | 14 |
| $\square_x$[mm-mrad] | 0.16 |
| $\square_E$/E[%] | 0.081 |



# 7 and 8 pole wiggler transfer functions





# Wiggler Beam Measurements

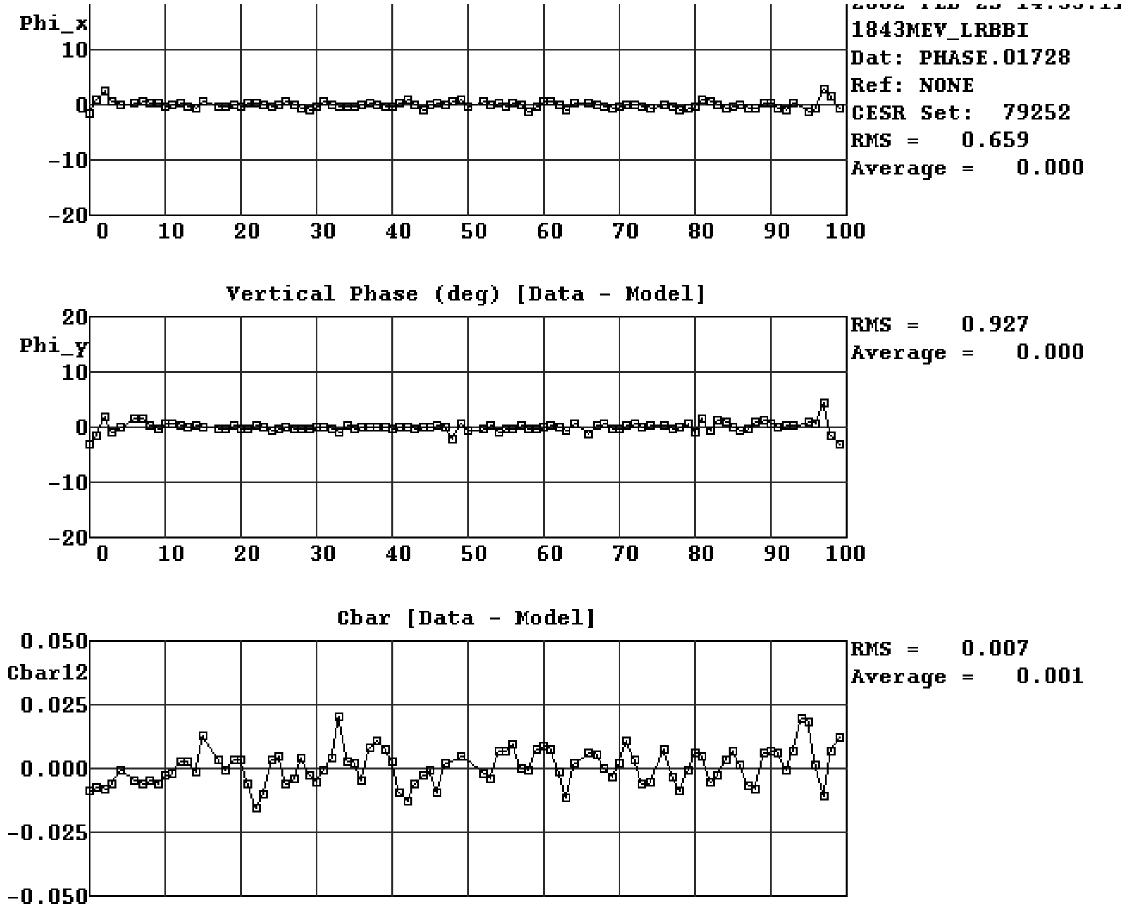
First wiggler installed 9/02

Beam energy = 1.84GeV

- -Optical parameters in IR match CESR-c design

- -Measure and correct betatron phase and transverse coupling

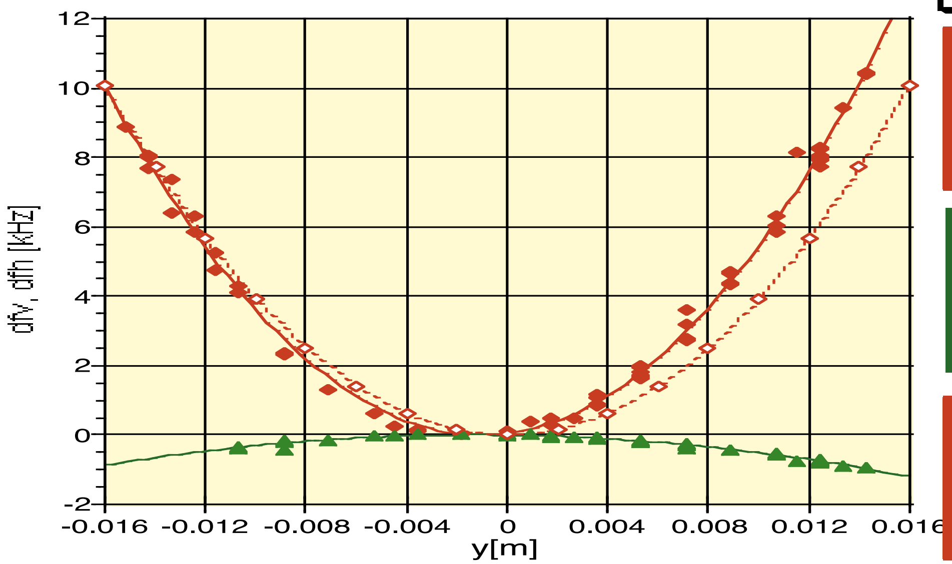
- - Measurement of lattice parameters (including emittance) in good agreement with design



# Wiggler Beam Measurements

- Reduced damping time (X 1/2) -> increased injection repitition rate
- Measurement of betatron tune vs displacement consistent with bench measurement and calculation of field profile

Fv and Fh versus vertical orbit position in
14E SC wiggler.
(CESRc MS Oct 14? 2002, DHR, ST)

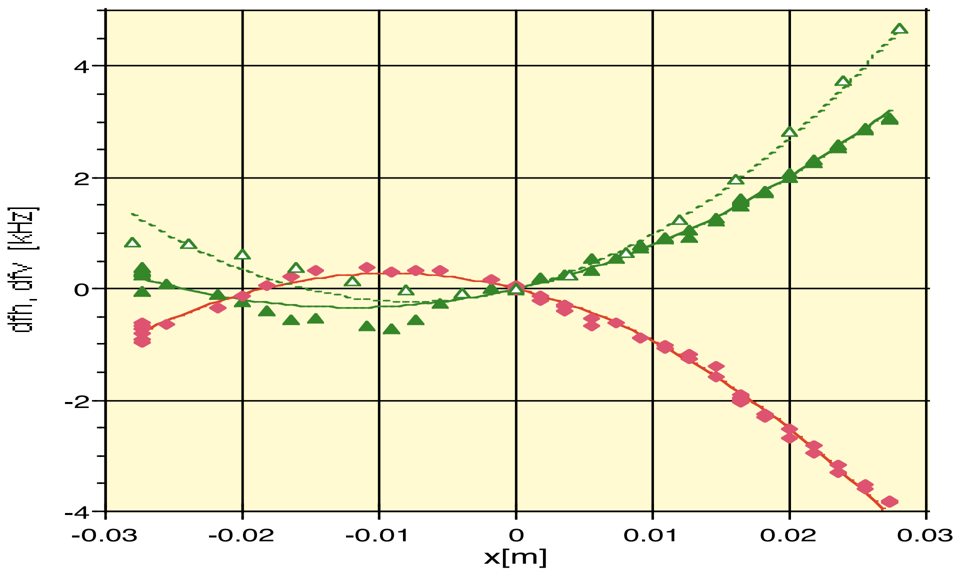


| y = m1*(m0-m2)^ 2 , dfv -meas | | |
|---|---|---|
| | Value | Error |
| m1 | 4.49e+04 | 237 |
| m2 | -0.00103 | 3.27e-05 |
| Chisq | 5.03 | NA |
| R | 0.997 | NA |

| y = m1*(m0-m2)^ 2, dfh - meas | | |
|---|---|---|
| | Value | Error |
| m1 | -4.01e+03 | 89.6 |
| m2 | -0.00126 | 0.000136 |
| Chisq | 0.106 | NA |
| R | 0.991 | NA |

| y = m1*(m0-m2)^ 2 , dfv -calc | | |
|---|---|---|
| | Value | Error |
| m1 | 3.94e+04 | 0.155 |
| m2 | 2.24e-13 | 2.59e-08 |
| Chisq | 1.02e-07 | NA |
| R | 1 | NA |

Fv and Fh versus horizontal orbit position in
14E SC wiggler.
(CESRc MS Oct 14? 2002, DHR, ST)

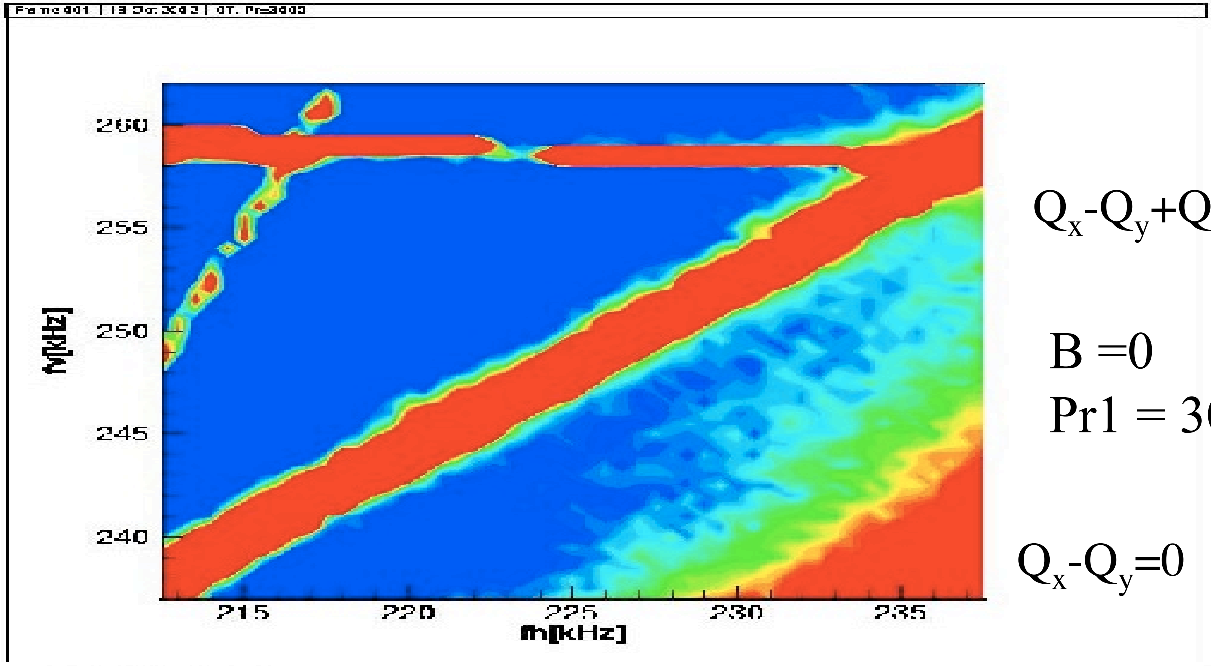


| y = m1*m0 + m2*m0^ 2 | | |
|---|---|---|
| | Value | Error |
| m1 | 55.18 | 0.92147 |
| m2 | 2276.1 | 40.127 |
| Chisq | 0.87096 | NA |
| R | 0.99309 | NA |

| y = m1*m0 + m2*m0^ 2 | | |
|---|---|---|
| | Value | Error |
| m1 | -60.438 | 0.83713 |
| m2 | -3256.5 | 36.455 |
| Chisq | 0.71883 | NA |
| R | 0.99581 | NA |

| y = m1*m0 + m2*m0^ 2 | | |
|---|---|---|
| | Value | Error |
| m1 | 59.479 | 3.3099 |
| m2 | 3832.7 | 143.18 |
| Chisq | 0.63804 | NA |
| R | 0.98927 | NA |

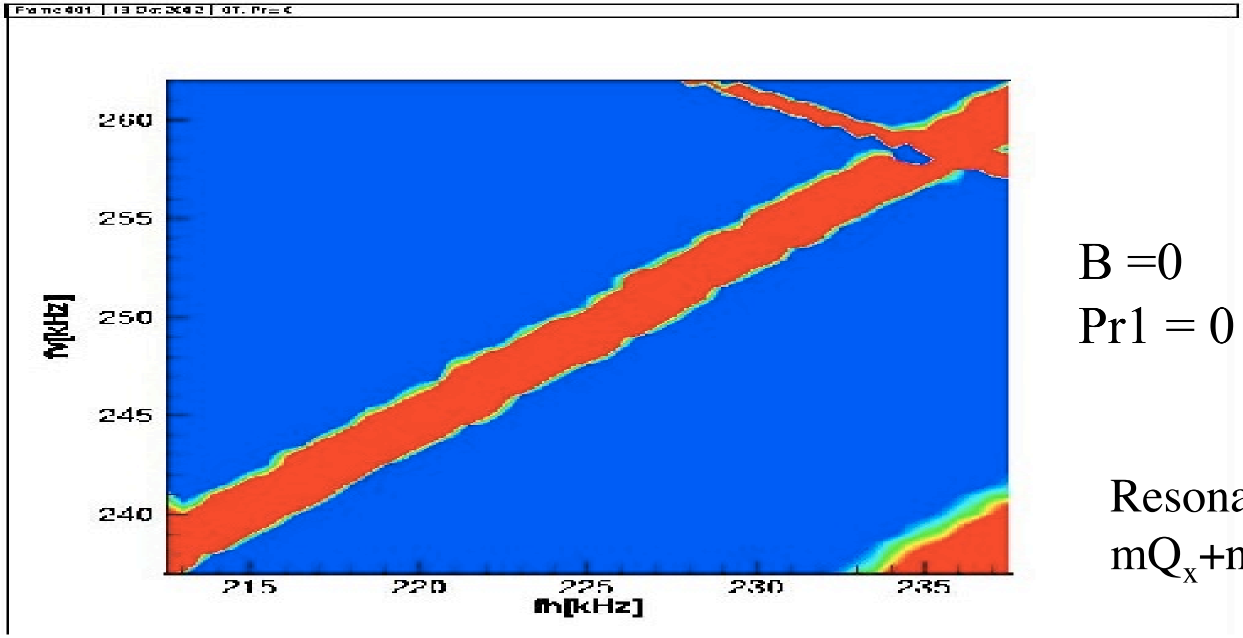
$2Q_y=3$



$Q_x-Q_y+Q_z=0$

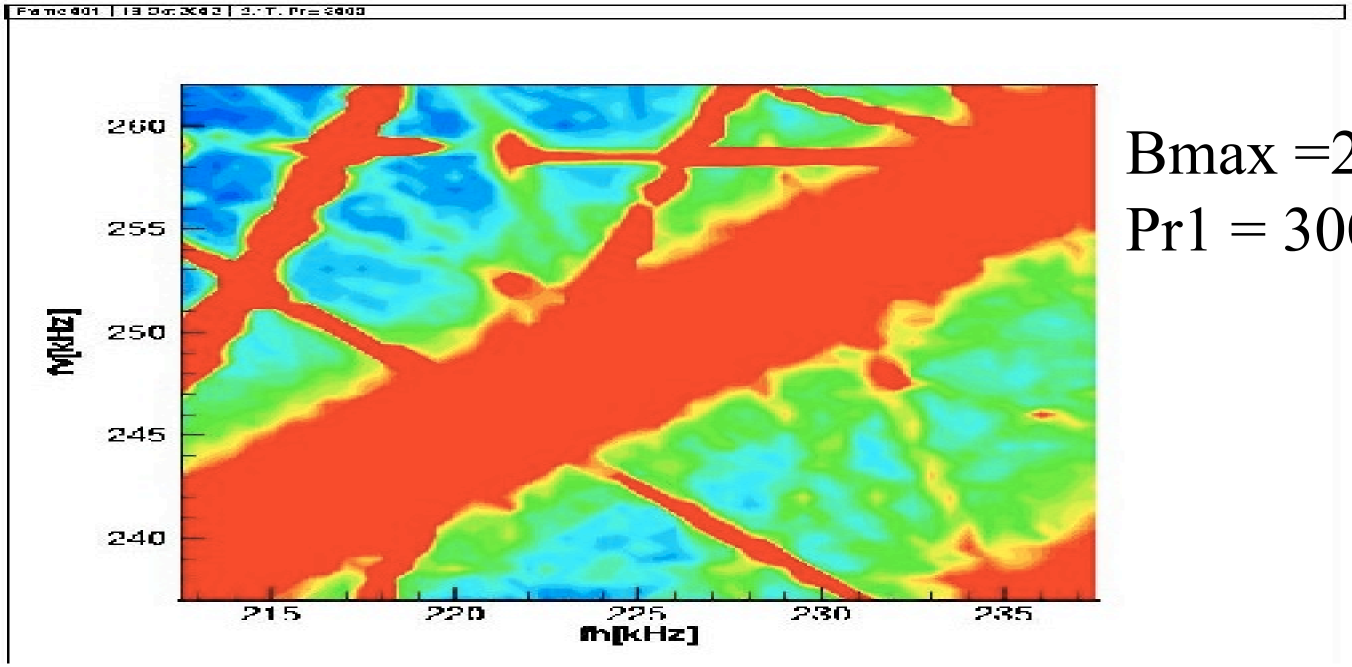
B =0
Pr1 = 3000

$Q_x-Q_y=0$

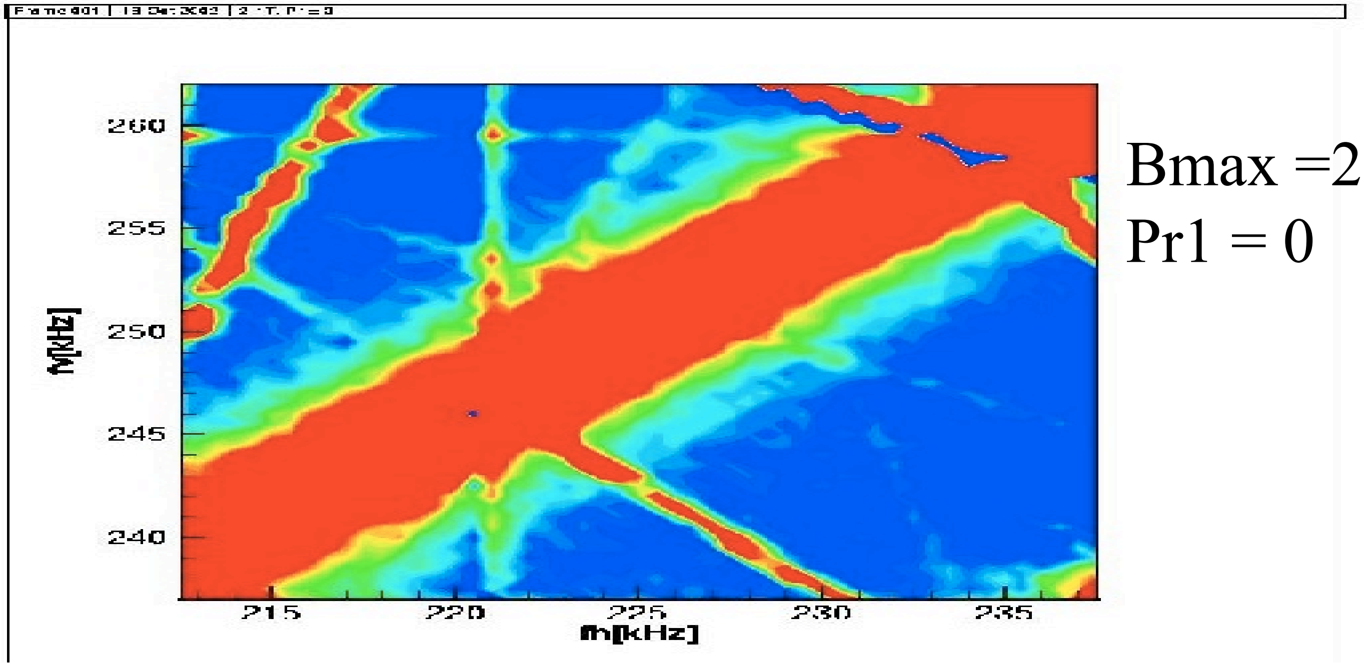


B =0
Pr1 = 0

Resonance condition
$mQ_x+nQ_y+pQ_z=r$



Bmax =2.1T
Pr1 = 3000



Bmax =2.1T
Pr1 = 0

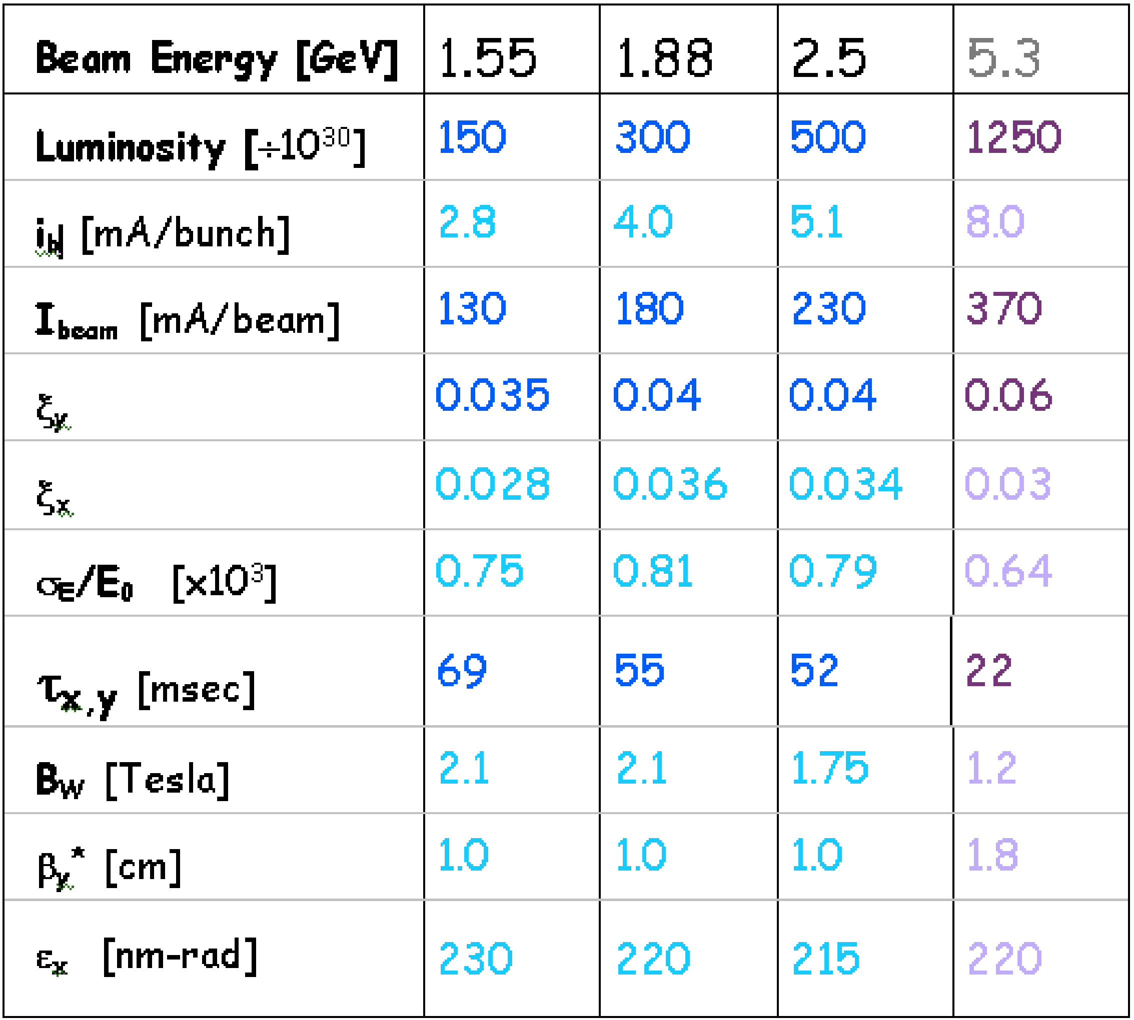
# Wiggler Status

-Second wiggler is ready for cold test

-Anticipate installation of 5 additional wigglers
(and CLEO-c vertex detector) Spring 03

-Remaining 8 wigglers installed late 03

# CESR-c design parameters

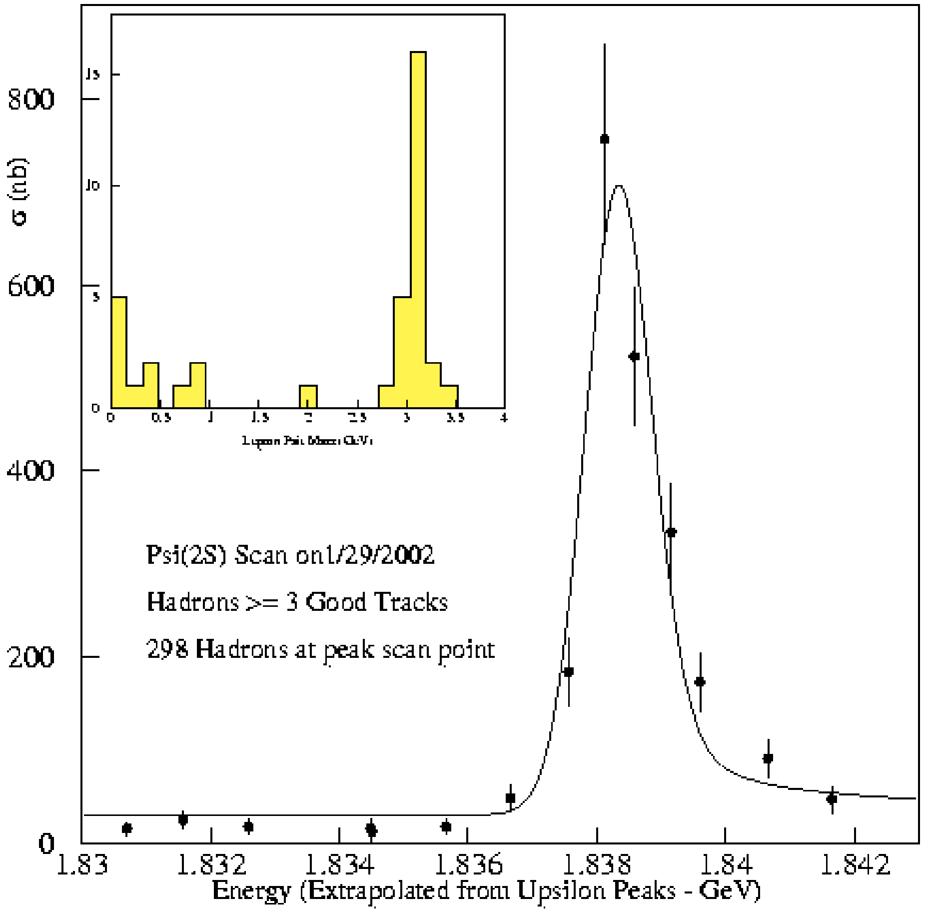


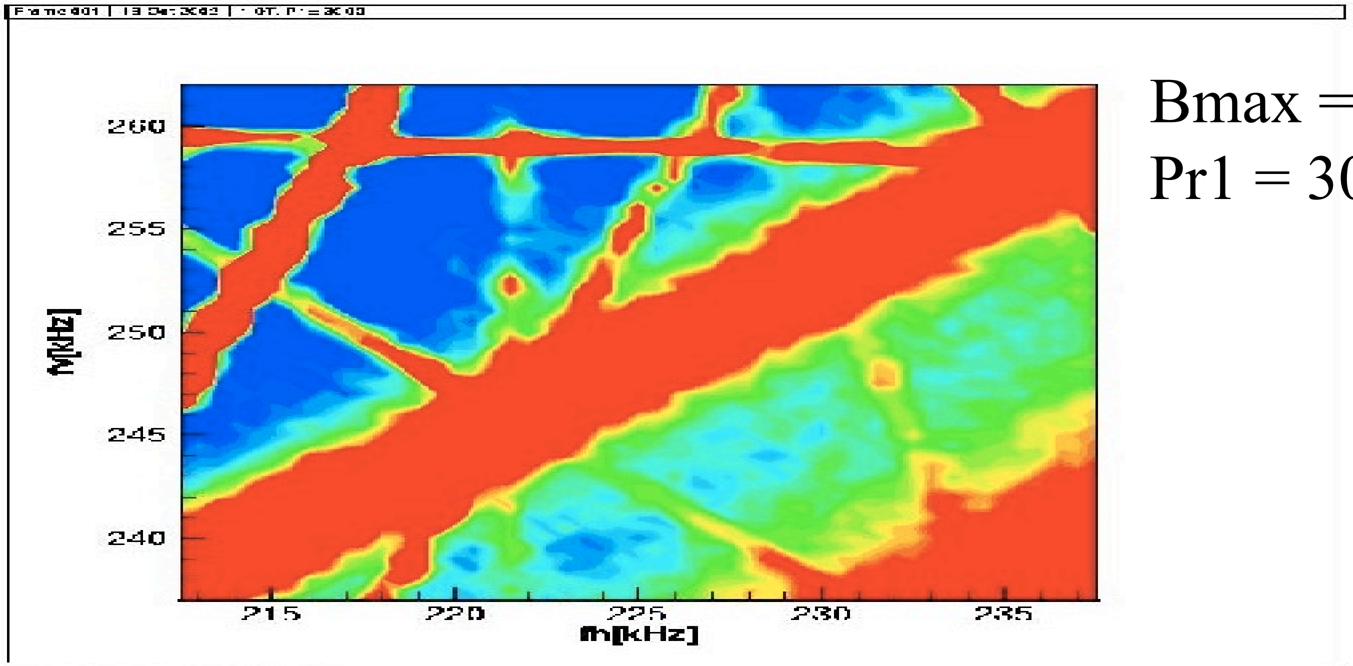
| **Beam Energy [GeV]** | 1.55 | 1.88 | 2.5 | 5.3 |
|---|---|---|---|---|
| **Luminosity** [$\div 10^{30}$] | 150 | 300 | 500 | 1250 |
| $i_b$ [mA/bunch] | 2.8 | 4.0 | 5.1 | 8.0 |
| $I_{beam}$ [mA/beam] | 130 | 180 | 230 | 370 |
| $\xi_y$ | 0.035 | 0.04 | 0.04 | 0.06 |
| $\xi_x$ | 0.028 | 0.036 | 0.034 | 0.03 |
| $\sigma_E/E_0$ [$\times 10^3$] | 0.75 | 0.81 | 0.79 | 0.64 |
| $\tau_{x,y}$ [msec] | 69 | 55 | 52 | 22 |
| $B_W$ [Tesla] | 2.1 | 2.1 | 1.75 | 1.2 |
| $\beta_y^*$ [cm] | 1.0 | 1.0 | 1.0 | 1.8 |
| $\varepsilon_x$ [nm-rad] | 230 | 220 | 215 | 220 |

# Energy Calibration

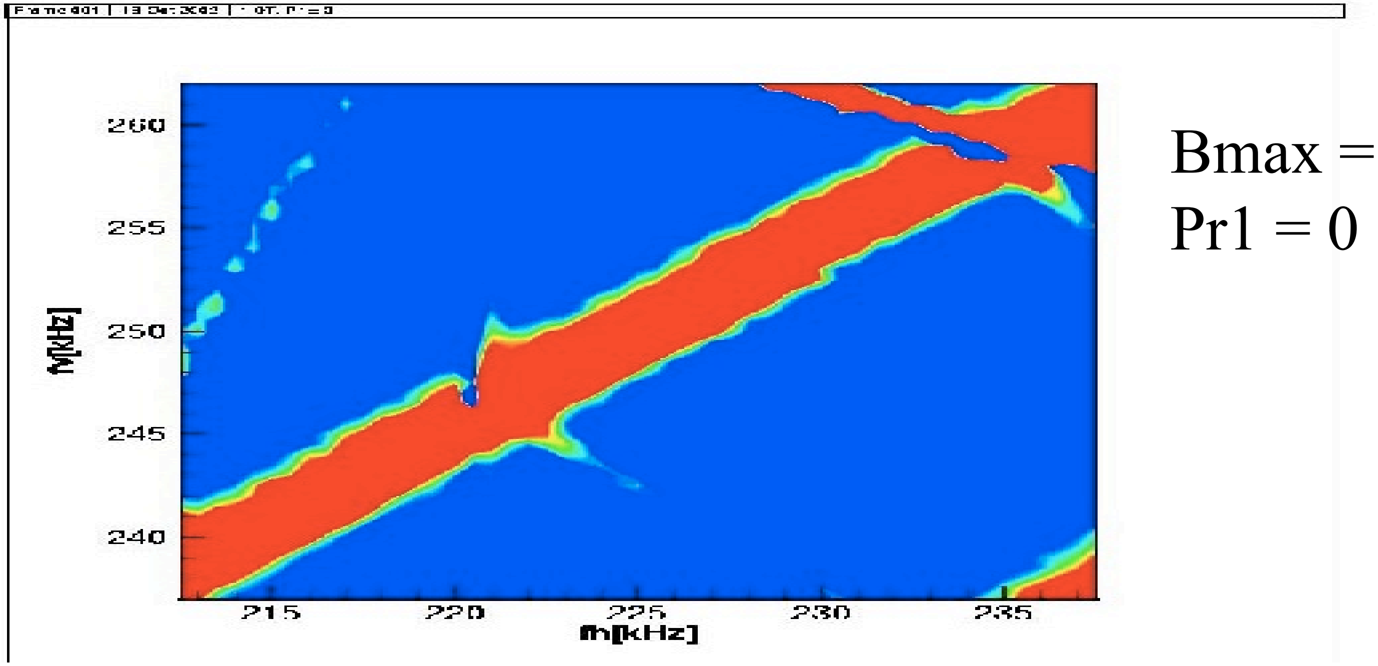
Collide $I_T$~ 12 mA and scan

Identification of □(2S) yields calibration of beam energy

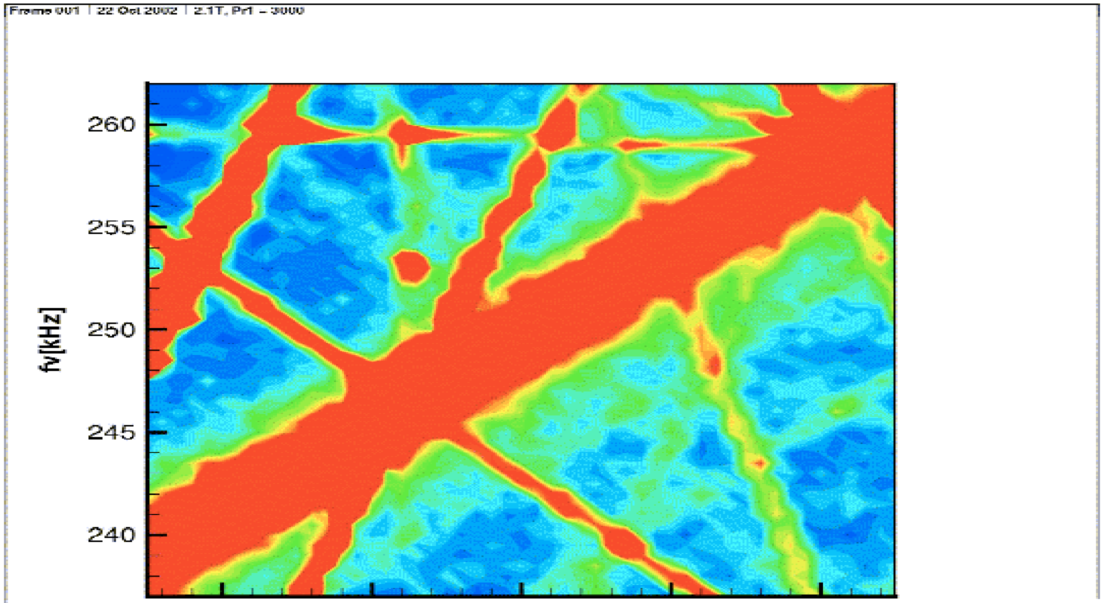




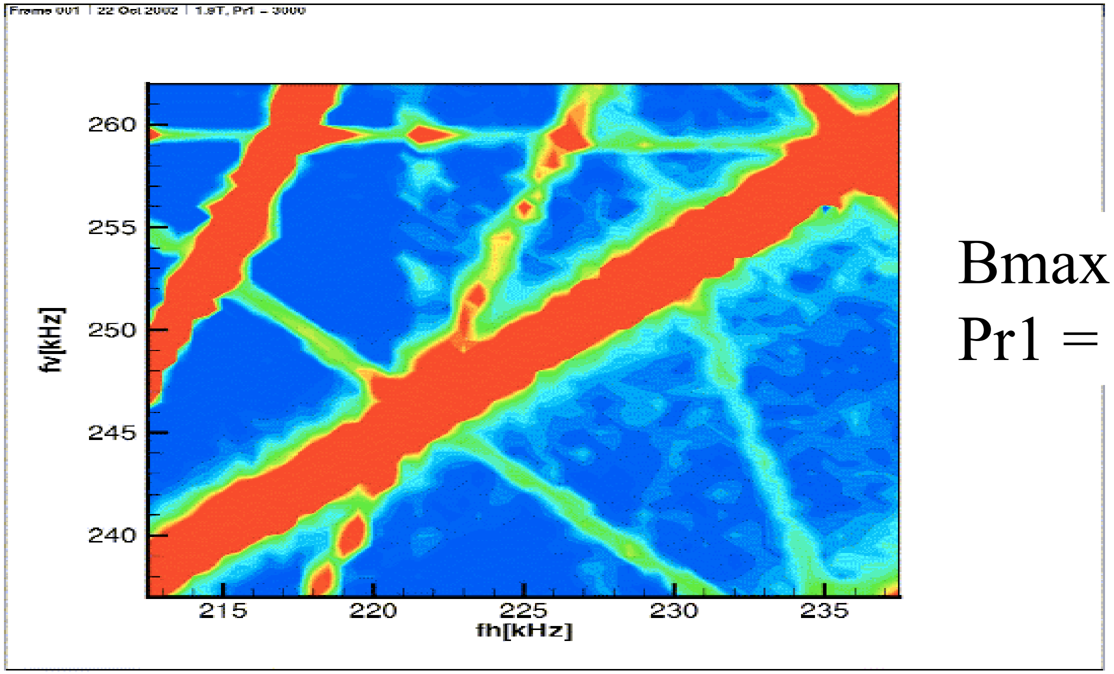
Bmax =1.9T
Pr1 = 3000



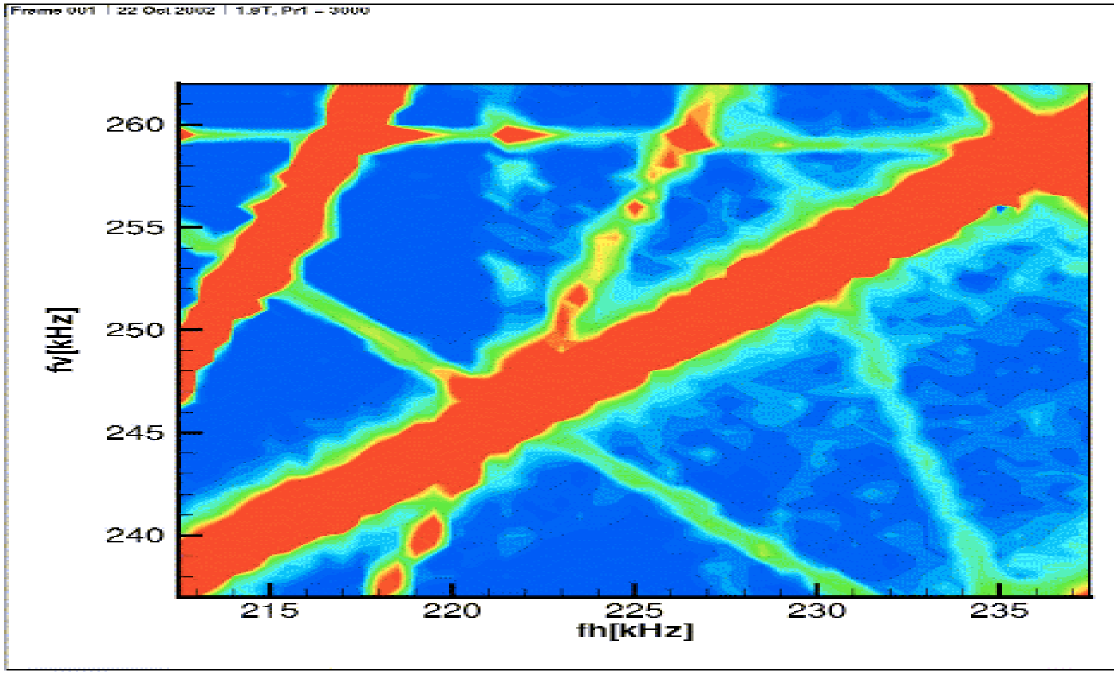
Bmax =1.9T
Pr1 = 0



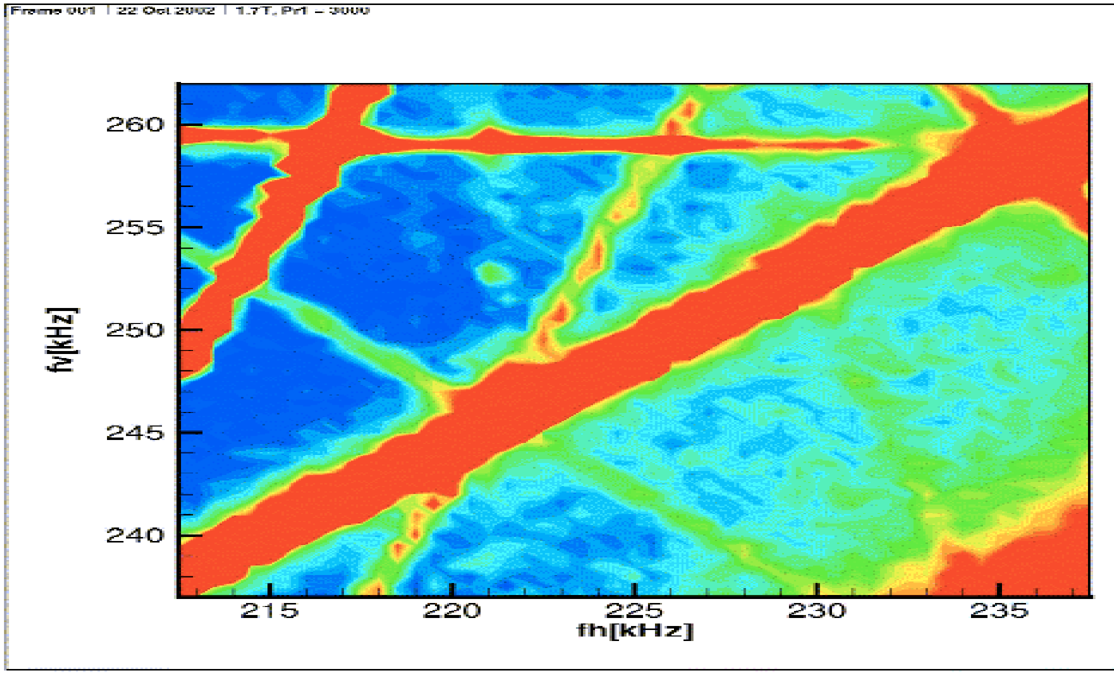
Bmax =2.1T
Pr1 = 3000



Bmax =1.9T
Pr1 = 3000



Bmax = 1.9T
Pr1 = 3000



Bmax = 1.7T
Pr1 = 3000

# Linear Optics

Arcs

Except for wigglers - very similar to 5.3GeV optics

Wiggler focusing is exclusively vertical

$$\frac{1}{f_v} \sim \left(\frac{B_0}{E}\right)^2 L$$

=0.073$m^{-1}$ for $B_0$=2.1T, L=1.3m and E=1.88GeV

For typical □$_v$ □ □$Q_v$ ~ 1.2 for 14 wigglers

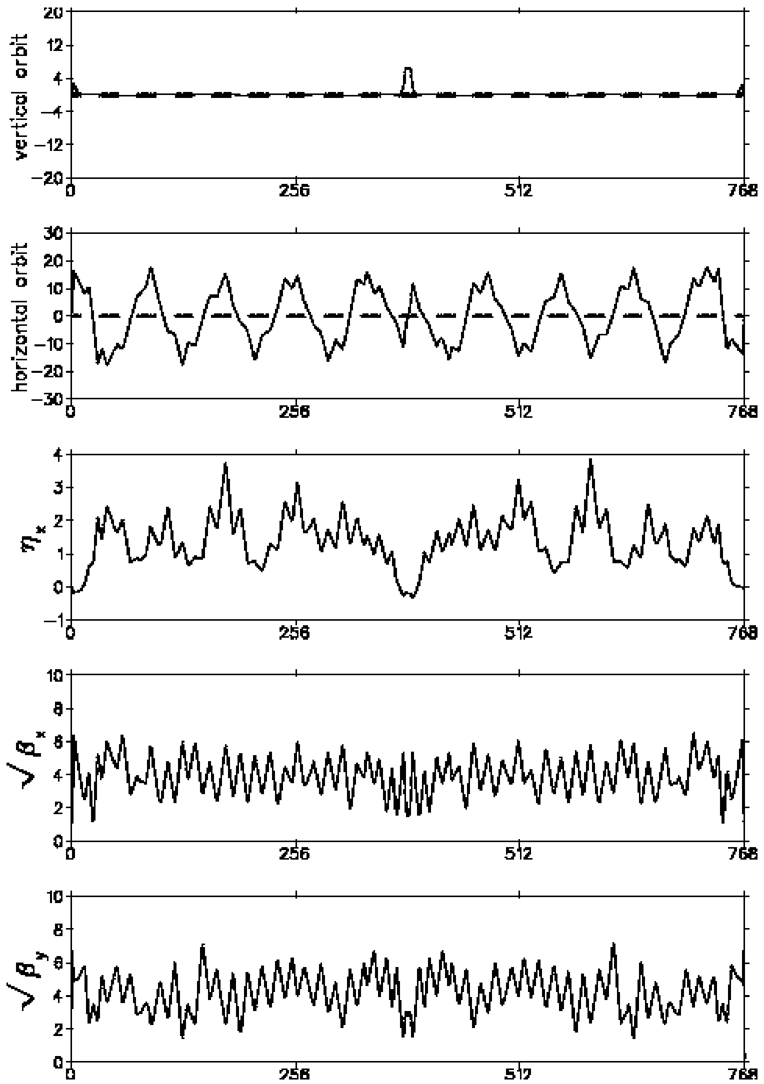
In CESR all quadrupoles are independent and the strong localized vertical focusing is easily compensated

(1.5 -> 2.5 GeV)

# Linear Optics

## Lattice parameters

| | |
|---|---|
| Beam energy[GeV] | 1.89 |
| $\square^*_v$[mm] | 10 |
| $\square^*_h$[m] | 1 |
| Crossing angle[mrad] | 2.7 |
| $Q_v$ | 9.59 |
| $Q_h$ | 10.53 |
| Number of trains | 9 |
| Bunches/train | 5 |
| Bunch spacing[ns] | 14 |
| Accelerating Voltage[MV] | 10 |
| Bunch length[mm] | 2.1 |
| Wiggler Peak Field[T] | 18.2 |
| Wiggler length[m] | 1.3 |
| Number of wigglers | 14 |
| $\square_x$[mm-mrad] | 0.16 |
| $\square_E$/E[%] | 0.081 |



# Dynamic Aperture

Wiggler cubic nonlinearity scales inversely as square of period

$$\Delta y' = -\frac{B_0^2 L}{2(B\rho)^2}\left[ y + \frac{2}{3}\left(\frac{2\pi}{\lambda}\right)^2 y^3 + \ldots \right]$$

Finite pole width → roll off in vertical field with horizontal displacement

- Longer period results in weaker cubic nonlinearity
- But the larger excursion of wiggling orbit yields greater sensitivity to horizontal roll off

We need to determine optimum period and required field uniformity

# Dynamic Aperture - beam measurements

PM x-ray wigglers in CESR provide opportunity to test understanding of dynamics

## Wiggler Nonlinearity

$$\frac{\Delta y'}{y} = -\frac{B_0^2 L}{3(B\rho)^2}\left(\frac{2\pi}{\lambda}\right)^2 a\beta \qquad \Delta Q/a \sim \frac{\Delta y'}{y}\beta$$

| | CHESS/east | CHESS/west | CESR - c |
|---|---|---|---|
| Period[cm] | 20 | 12 | 40 |
| Cubic nonlinearity[m-2] | 27 | 42 | 14(11.9) = 167 |
| $<\beta_v{}^2>$ [m$^2$] | $33^2$ | $23^2$ | $12^2$ |
| Detuning (ΔQ/mm) | 29 | 22 | 24 |

- Detuning of the pair of x-ray wigglers in CESR at 1.84GeV, is approximately twice that of 14 CESRc wigglers