# Beam Emittance Measurement Tool for CEBAF Operations

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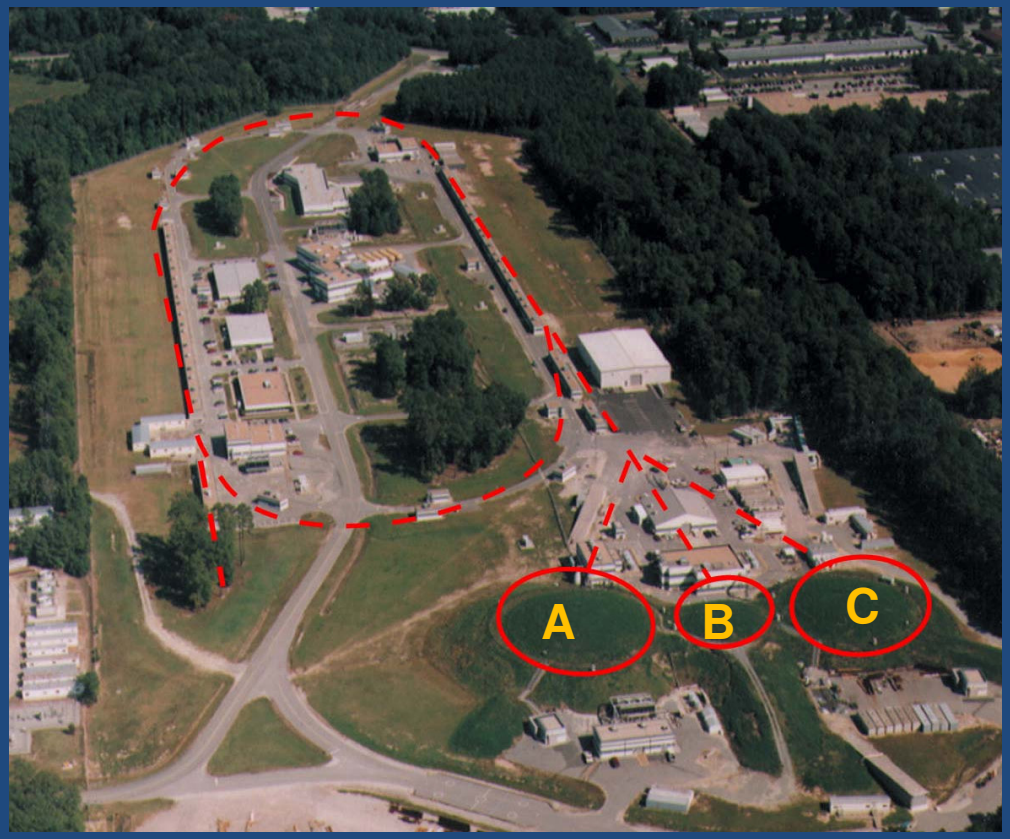
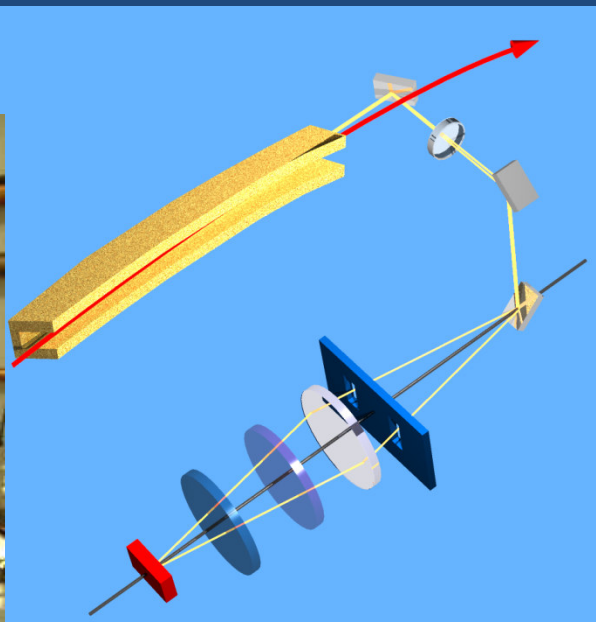
# Outline

- **Introduction**
- **Wire Scanners at Jefferson Lab**
- **Beam Emittance Measurement Tool**
- **Summary**

# CEBAF



**Synchrotron Light Interferometer at location 1C12**


DAQ_C_1C12_slia.adl

Hall A Synchrotron Light Interferometer (1C12) Status and Control (Pavel Chevtsov, June, 2005) HELP

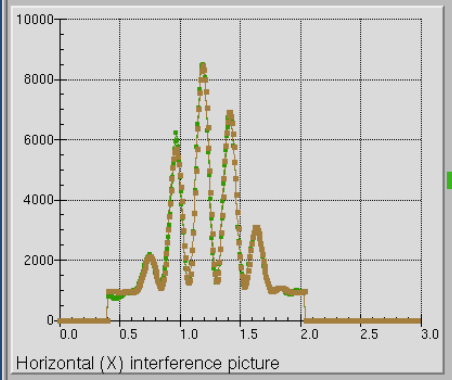
SLI Components
Control Status
Video_Camera IMAGE Norm,Exp=2.0s
OK
Diffraction_Slits 3mmSquare

173 Maxvideo 02Aug05 07:53:57 SLI Server Heartbeat
video disabled enabled
Advanced Digital Image !
DataValid Beam current 34.92 mkA
Yes

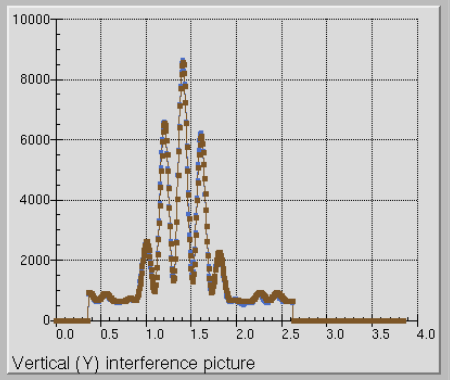
Calibration screen SLI 3C12
LUT1 Mode Subtract
LUT1 Threshold 0
Acquire Gain 0.960 1.0

Masks enable mask enable disp mask
MASK OUTSIDE
X1: 48 Y1: 54
X2: 349 Y2: 273
Number of saturated pixels 0

| Horizontal Plane (X beam axis) | Vertical Plane (Y beam axis) |
|---|---|
| Direct SLI Image Analysis Data | Direct SLI Image Analysis Data |
| Image Position on CCD (4.8 x 3.6 mm) 1.193 | Image Position on CCD (4.8 x 3.6 mm) 1.405 |
| Beam Size 0.121 mm | Beam Size 0.161 mm |
| Energy Spread 3.034 10**(-5) | |




Horizontal (X) interference picture




Vertical (Y) interference picture

| Horizontal Plane (X beam axis) | Vertical Plane (Y beam axis) |
|---|---|
| SLI Model Data * Dispersion 4.0 m | SLI Model Data |
| Beam Size 0.130 +-0.010 mm | Beam Size 0.185 +-0.012 mm |
| Energy Spread 3.252 +-0.251 10**(-5) | |
| OK | OK |
| Error sum 20.394 Model Reliability 0.512 | Error sum 8.812 Model Reliability 0.263 |

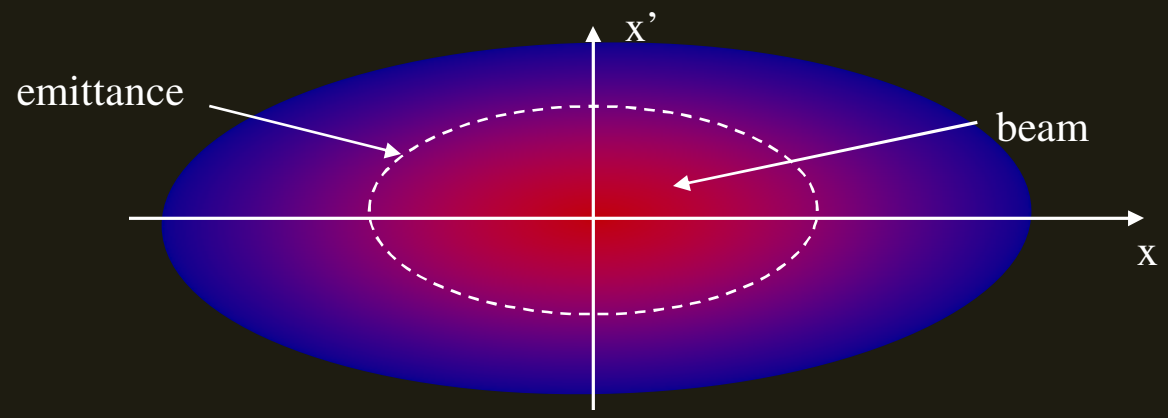
$$\sigma^2_{beam} = \beta\varepsilon + D^2(\delta E/E)^2$$

In high dispersion areas
(such as you see in the picture)

$$D^2(\delta E/E)^2 >> \beta\varepsilon$$

and the beam energy spread:

$$\delta E/E = \sigma_{beam}/D$$



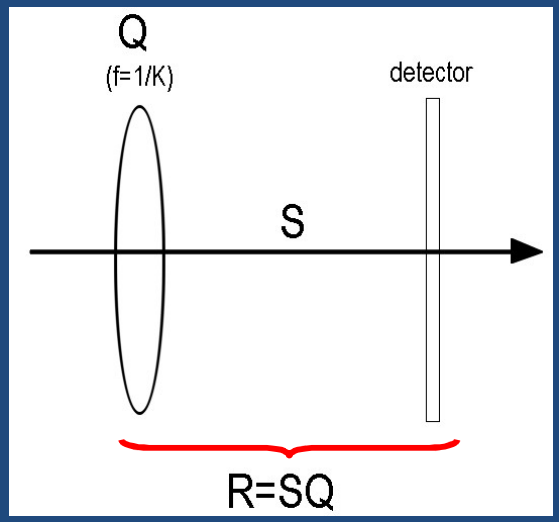

**Beam emittance.**

• Observe all the particles and measure both their position x and angle **x'**
• We get a large number of points on our phase space plot, each corresponding to a pair of **x,x'** values for each particle

The **emittance** is the **area** of the ellipse, which contains all (or certain percentage) of the points or particles

# Measurement of the Transverse Beam Emittance

Method: quadrupole scan




Principle: with a well-centered beam, measure the beam size as a function of the quadrupole field strength

Here
Q is the transfer matrix of the quadrupole
R is the transfer matrix between the quadrupole and the beam size detector

With $Q = \begin{pmatrix} 1 & 0 \\ K & 1 \end{pmatrix}$ then $R = \begin{pmatrix} S_{11} + KS_{12} & S_{12} \\ S_{21} + KS_{22} & S_{22} \end{pmatrix}$ with $\Sigma_{\text{beam}} = R\Sigma_{\text{beam},0}R^t$

The (11)-element of the beam transfer matrix is found after algebra to be:

$$\Sigma_{11}(=\langle x^2\rangle) = ({S_{11}}^2\Sigma_{11_0} + 2S_{11}S_{12}\Sigma_{12_0} + {S_{12}}^2\Sigma_{22_0}) + (2S_{11}S_{12}\Sigma_{11_0} + 2{S_{12}}^2\Sigma_{12_0})K + {S_{12}}^2\Sigma_{11}K^2$$

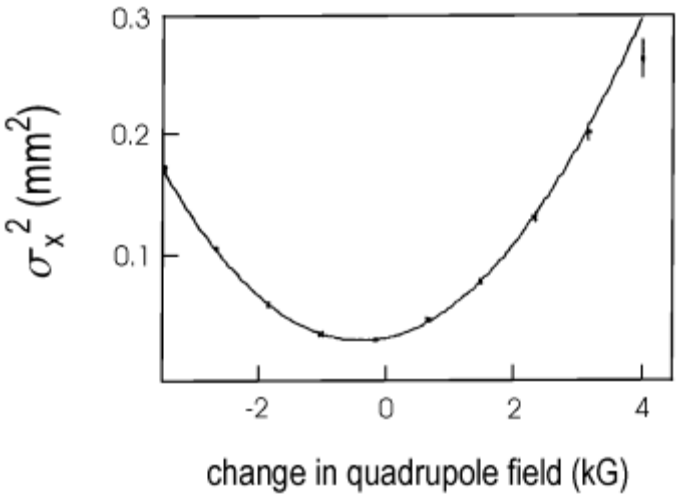
which is quadratic in the field strength, K

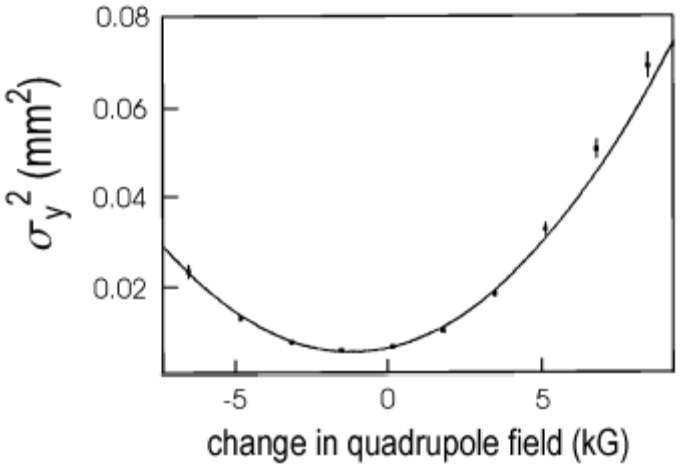
Measurement: measure beam size versus quadrupole field strength

recall:

$$\Sigma_{11}(=\langle x^2\rangle) = ({S_{11}}^2\Sigma_{11_o} + 2S_{11}S_{12}\Sigma_{12_o} + {S_{12}}^2\Sigma_{22_o}) + (2S_{11}S_{12}\Sigma_{11_o} + 2{S_{12}}^2\Sigma_{12_o})K + {S_{12}}^2\Sigma_{11}K^2$$

data:




fitting function (parabolic):

$$\Sigma_{11} = A(K-B)^2 + C = AK^2 - 2ABK + (C + AB^2)$$

equating terms (drop subscripts 'o'),

$$A = S_{12}^2\Sigma_{11}\,,$$

$$-2AB = 2S_{11}S_{12}\Sigma_{11} + 2S_{12}^2\Sigma_{12}\,,$$

$$C + AB^2 = {S_{11}}^2\Sigma_{11} + 2S_{11}S_{12}\Sigma_{12} + {S_{12}}^2\Sigma_{22}$$

solving for the beam matrix elements:

$$\Sigma_{11} = A/{S_{12}}^2\,,$$

$$\Sigma_{12} = -\frac{A}{{S_{12}}^2}\left(B + \frac{S_{11}}{S_{12}}\right)\,,$$

$$\Sigma_{22} = \frac{1}{{S_{12}}^2}\left[(AB^2 + C) + 2AB\left(\frac{S_{11}}{S_{12}}\right) + A\left(\frac{S_{11}}{S_{12}}\right)^2\right]$$

The emittance is given from the determinant of the beam matrix:

$$\epsilon_x = \sqrt{\det\ \Sigma^x_{\rm beam}}$$

$$\begin{aligned}\det\ \Sigma^x_{\rm beam} &= \Sigma_{11}\Sigma_{22} - {\Sigma_{12}}^2 \\ &= AC/S_{12}^4\,,\end{aligned}$$

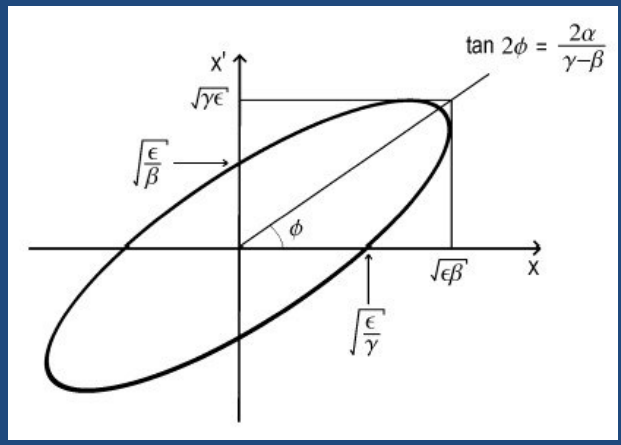
$$\Rightarrow \quad \epsilon_x = \sqrt{AC}/S_{12}^2$$

With these 3 fit parameters (A,B, and C), the 3 Twiss parameters are also known:

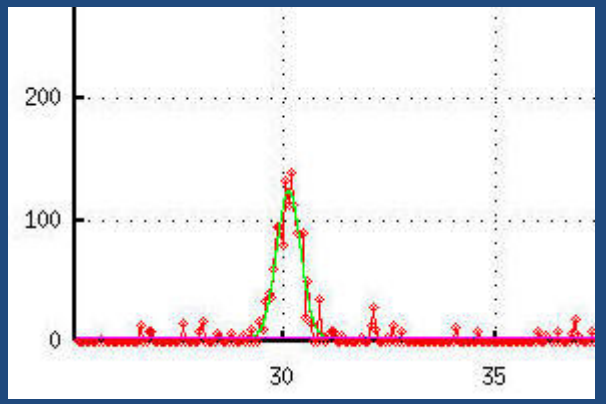
$$\beta_x = \frac{\Sigma_{11}}{\epsilon} = \sqrt{\frac{A}{C}}\,,$$

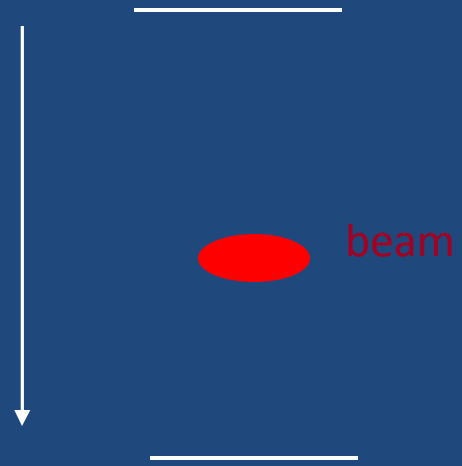
$$\alpha_x = -\frac{\Sigma_{12}}{\epsilon} = \sqrt{\frac{A}{C}}\left(B + \frac{S_{11}}{S_{12}}\right)\,,$$

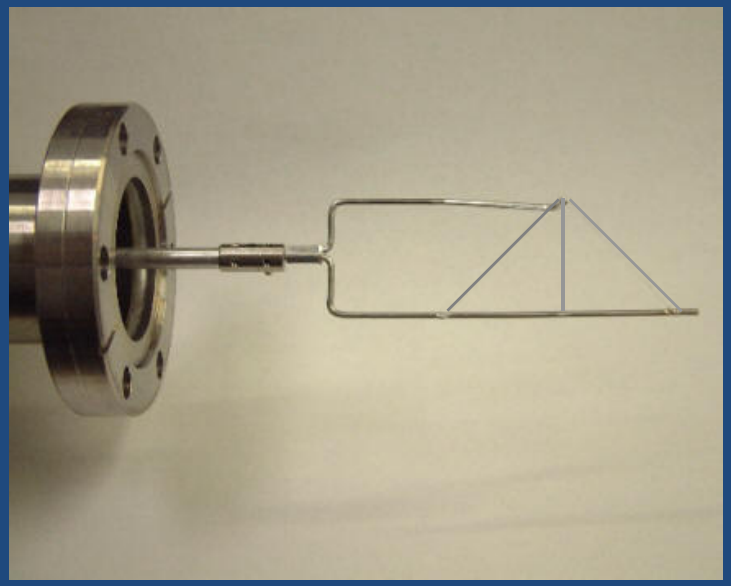
$$\gamma_x = \frac{{S_{12}}^2}{\sqrt{AC}}\left[(AB^2 + C) + 2AB\left(\frac{S_{11}}{S_{12}}\right) + A\left(\frac{S_{11}}{S_{12}}\right)^2\right]$$



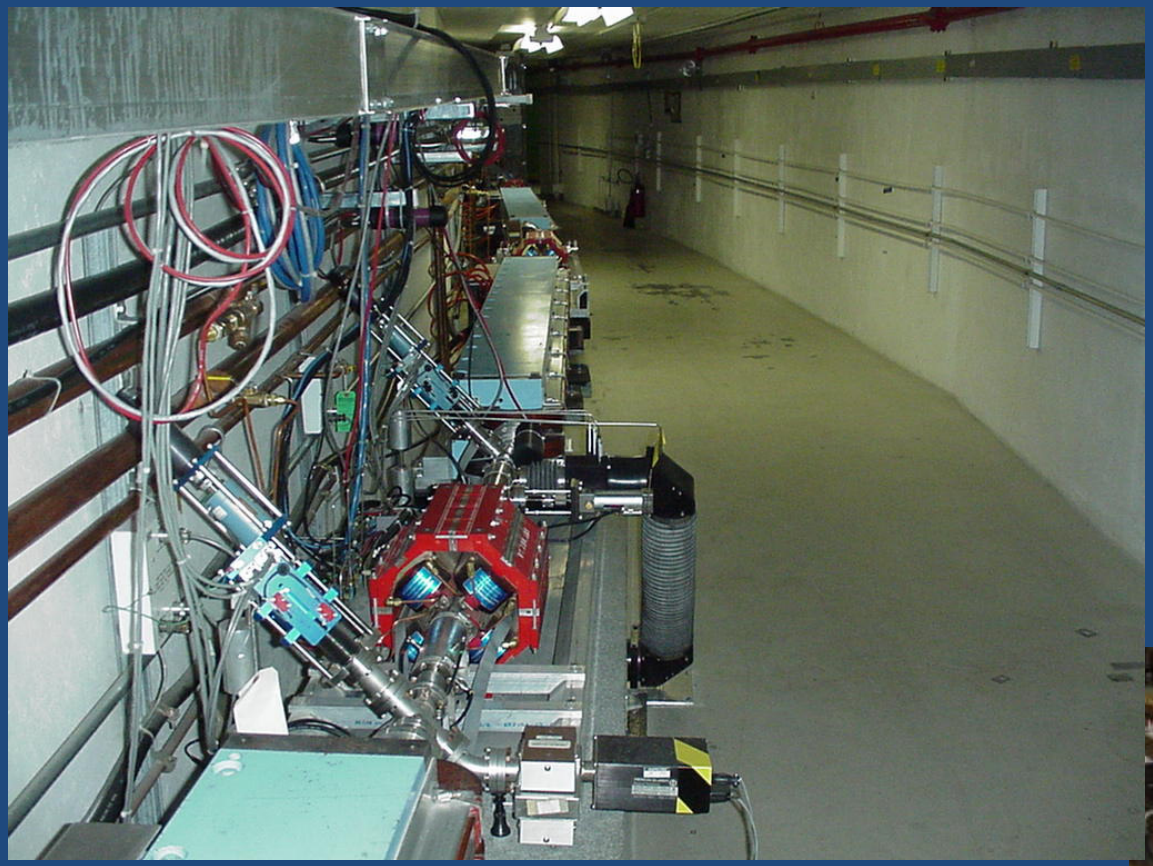

as a useful check, the beam-ellipse parameters should satisfy $(\beta_x\gamma_x - 1) = \alpha^2$


200
100
0
30
35


beam



A typical wire scanner (WS) at Jefferson Lab



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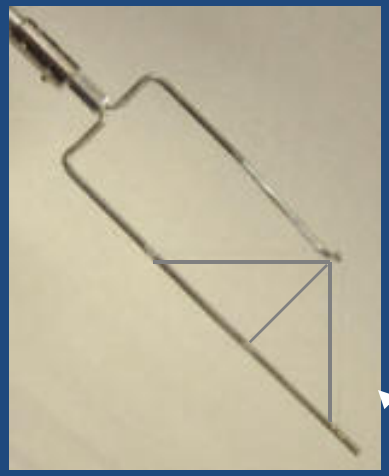
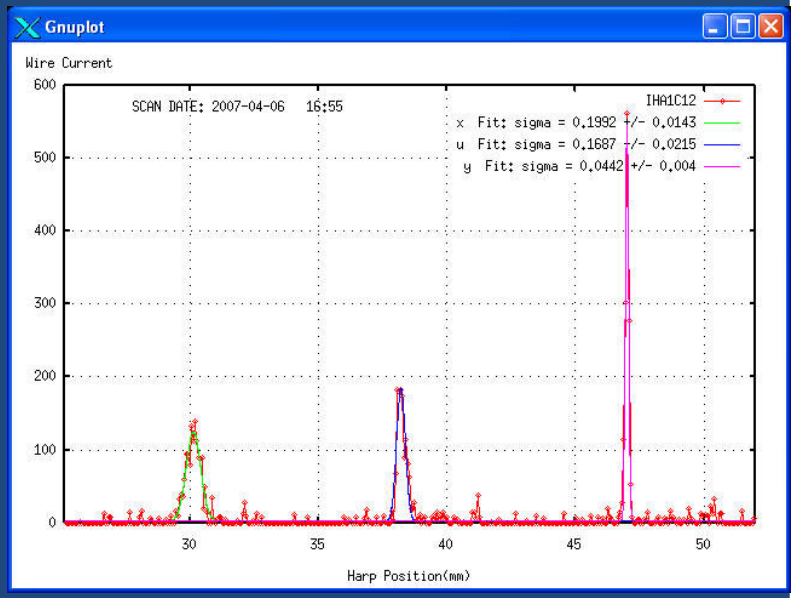
main WS mode

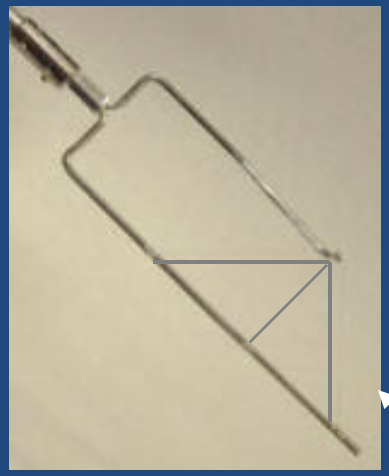


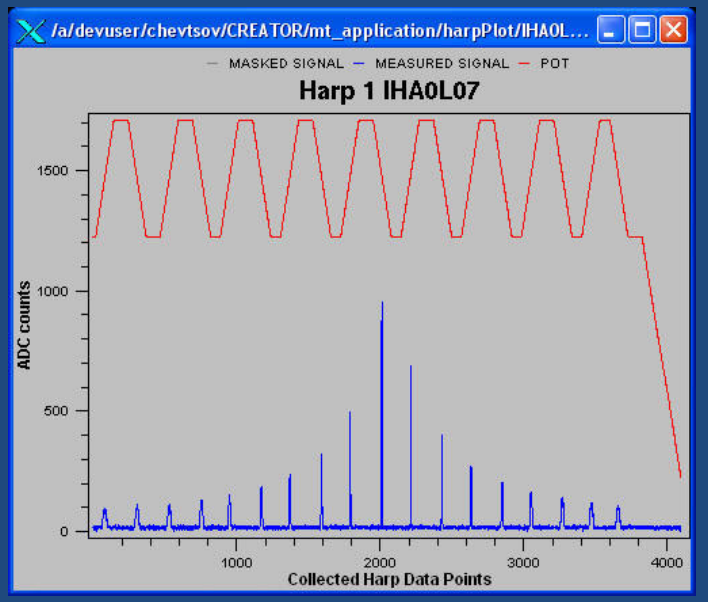
limit switch

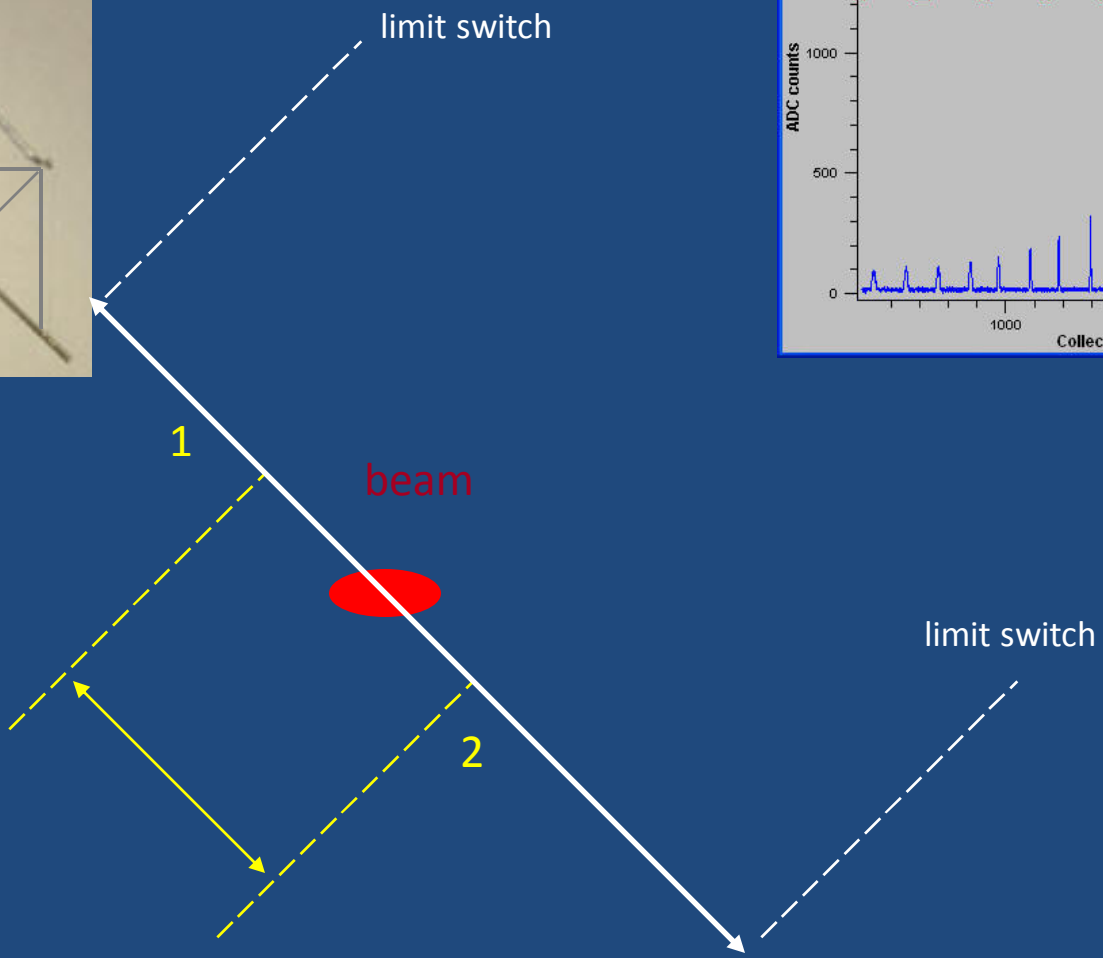



beam

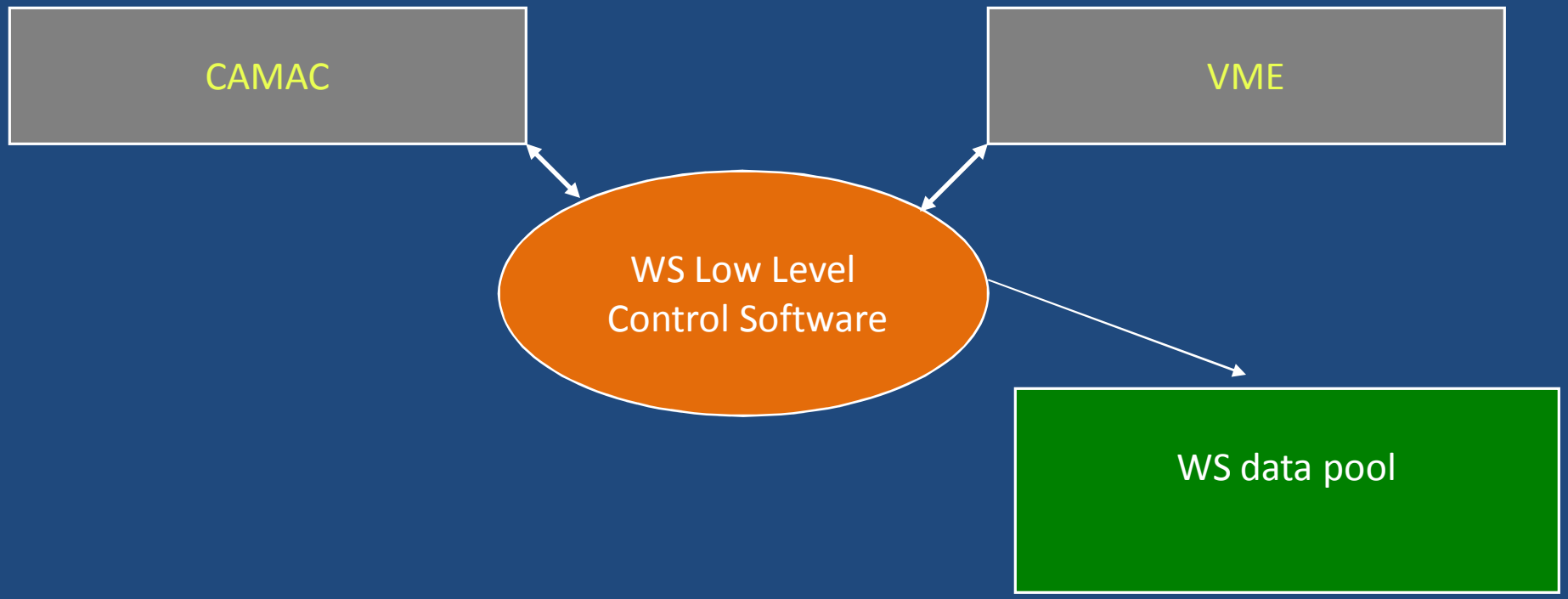
limit switch

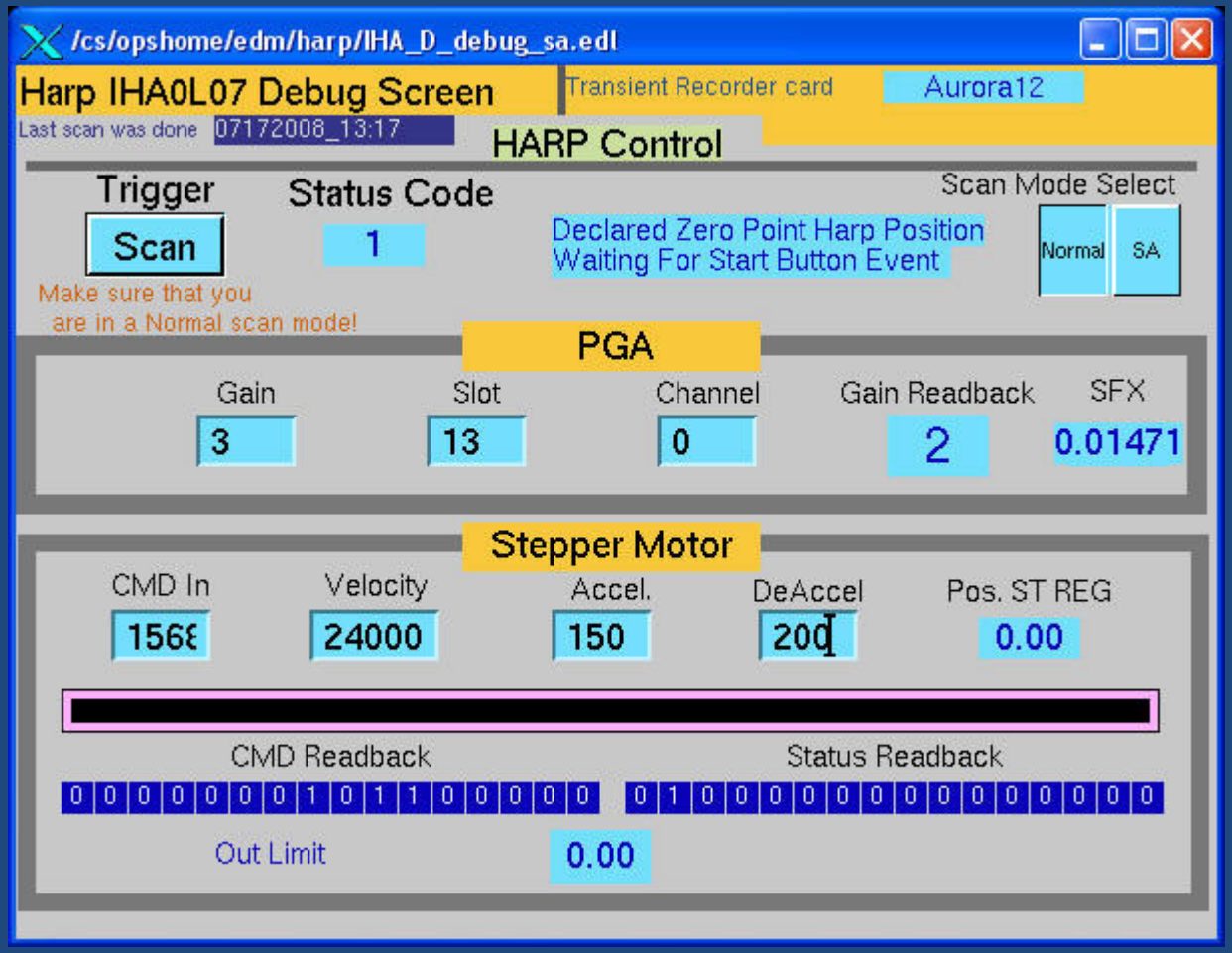


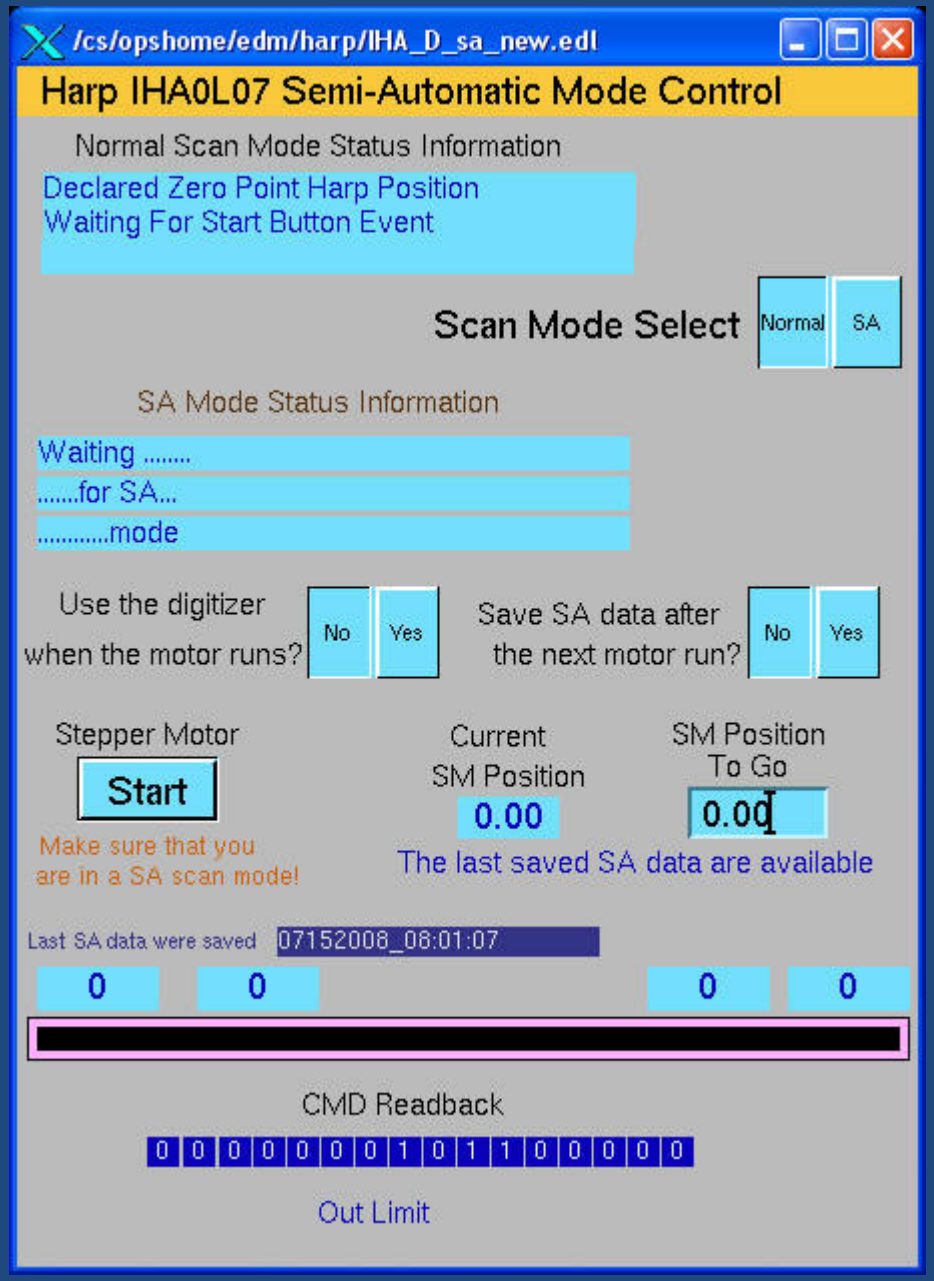

/a/devuser/chevtsov/CREATOR/mt_application/harpPlot/IHA0L...
MASKED SIGNAL
MEASURED SIGNAL
POT
Harp 1 IHA0L07
ADC counts
1500
1000
500
0
1000
2000
3000
4000
Collected Harp Data Points


limit switch
1
beam
limit switch
2

SA WS mode


CAMAC
VME
WS Low Level
Control Software
WS data pool


/cs/opshome/edm/harp/IHA_D_debug_sa.edl
Harp IHA0L07 Debug Screen
Transient Recorder card
Aurora12
Last scan was done
07172008_13:17
HARP Control
Trigger
Scan
Make sure that you
are in a Normal scan mode!
Status Code
1
Declared Zero Point Harp Position
Waiting For Start Button Event
Scan Mode Select
Normal
SA
PGA
Gain
3
Slot
13
Channel
0
Gain Readback
2
SFX
0.01471
Stepper Motor
CMD In
156
Velocity
24000
Accel.
150
DeAccel
200
Pos. ST REG
0.00
CMD Readback
0 0 0 0 0 0 0 1 0 1 1 0 0 0 0 0
Status Readback
0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Out Limit
0.00


/cs/opshome/edm/harp/IHA_D_sa_new.edl
Harp IHA0L07 Semi-Automatic Mode Control
Normal Scan Mode Status Information
Declared Zero Point Harp Position
Waiting For Start Button Event
Scan Mode Select
Normal
SA
SA Mode Status Information
Waiting .....
.....for SA...
.....mode
Use the digitizer when the motor runs?
No
Yes
Save SA data after the next motor run?
No
Yes
Stepper Motor
Start
Make sure that you are in a SA scan mode!
Current SM Position
0.00
SM Position To Go
0.00
The last saved SA data are available
Last SA data were saved
07152008_08:01:07
0
0
0
0
CMD Readback
0 0 0 0 0 0 0 1 0 1 1 0 0 0 0 0
Out Limit

```
# ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
#
#
# File: /usr/opdata/profile/IHA1I06.07092008_18:11
# Harp Name:     IHA1I06
# Time Taken:    Jul 09, 2008 18:11
# Number of Digitized Points:    922
# Pot min:       137.000000      Pot max:        3520.000000
# Signal min:    13.000000       Signal max:     80.000000
# Conversion factor:     0.015000
# Initial position:      X wire: 0.000000        Y wire: 0.000000
#
# Wire Orientation:      x-u-y
# Wire Material:         97%W 3%Re
# Wire Diameter:         50 um
# Motor Speed:           3.5 mm/sec
# Harp Type:             INJ Harp
# Max CW Current:        5uAmps
# Number of channels:    2
# Default Channel:       1
# PGA wire:              0
# PGA PMT:
# IOC:                   iocin3
#
# index       pot        signal
# ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
0       137.000000      14.000000
1       140.000000      14.000000
2       143.000000      20.000000
3       152.000000      20.000000
4       158.000000      14.000000
5       160.000000      20.000000
6       162.000000      14.000000
7       164.000000      20.000000
8       168.000000      20.000000
```

```
# ******************************************************
# harp:  IHA0L07         time_stamp=07152008_08:01:03
#        Q1:     MQJ0L03M        -2.628784
#                MQJ0L03.S       -2.631647
#                MQJ0L03.BDL     -154.600006
#                MQJ0L03.KMOL    0
#        Q2:     MQJ0L04M        0.633545
#                MQJ0L04.S       0.629992
#                MQJ0L04.BDL     41.000000
#                MQJ0L04.KMOL    0
#        Q3:     MQJ0L05M        0.000305
#                MQJ0L05.S       0.000000
#                MQJ0L05.BDL     2.980000
#                MQJ0L05.KMOL    0
#        Q4:     MQD0L06M        0.000610
#                MQD0L06.S       0.000000
#                MQD0L06.BDL     2.000000
#                MQD0L06.KMOL    0
#        Q5:     MQD0L07M        0.000305
#                MQD0L07.S       0.000000
#                MQD0L07.BDL     2.000000
#                MQD0L07.KMOL    0
# ******************************************************
# ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
#
#
# File: /usr/opdata/profile/SA/IHA0L07.SA.07152008_08:01:07
# Harp Name:    IHA0L07
# Time Taken:   Jul 15, 2008 08:01
# Number of Digitized Points:   8192
# Pot min:      176.000000      Pot max:        511.000000
# Signal min:   0.000000        Signal max:     44.000000
# Conversion factor:    0.014706
# Initial position:     X wire: 0.000000        Y wire: 0.000000
#
# Wire Orientation:     x-u-y
# Wire Material:        97%W 3%Re
# Wire Diameter:        50 um
# Motor Speed:          3.5 mm/sec
# Harp Type:            INJ Harp
# Max CW Current:       5uAmps
# Number of channels:   2
# Default Channel:      1
# PGA wire:             0
# PGA PMT:
# IOC:                  iocin1
#
# index      pot        signal
# ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
0       415.000000      14.000000
1       414.000000      11.000000
```

# Beam Emittance Measurement Tool

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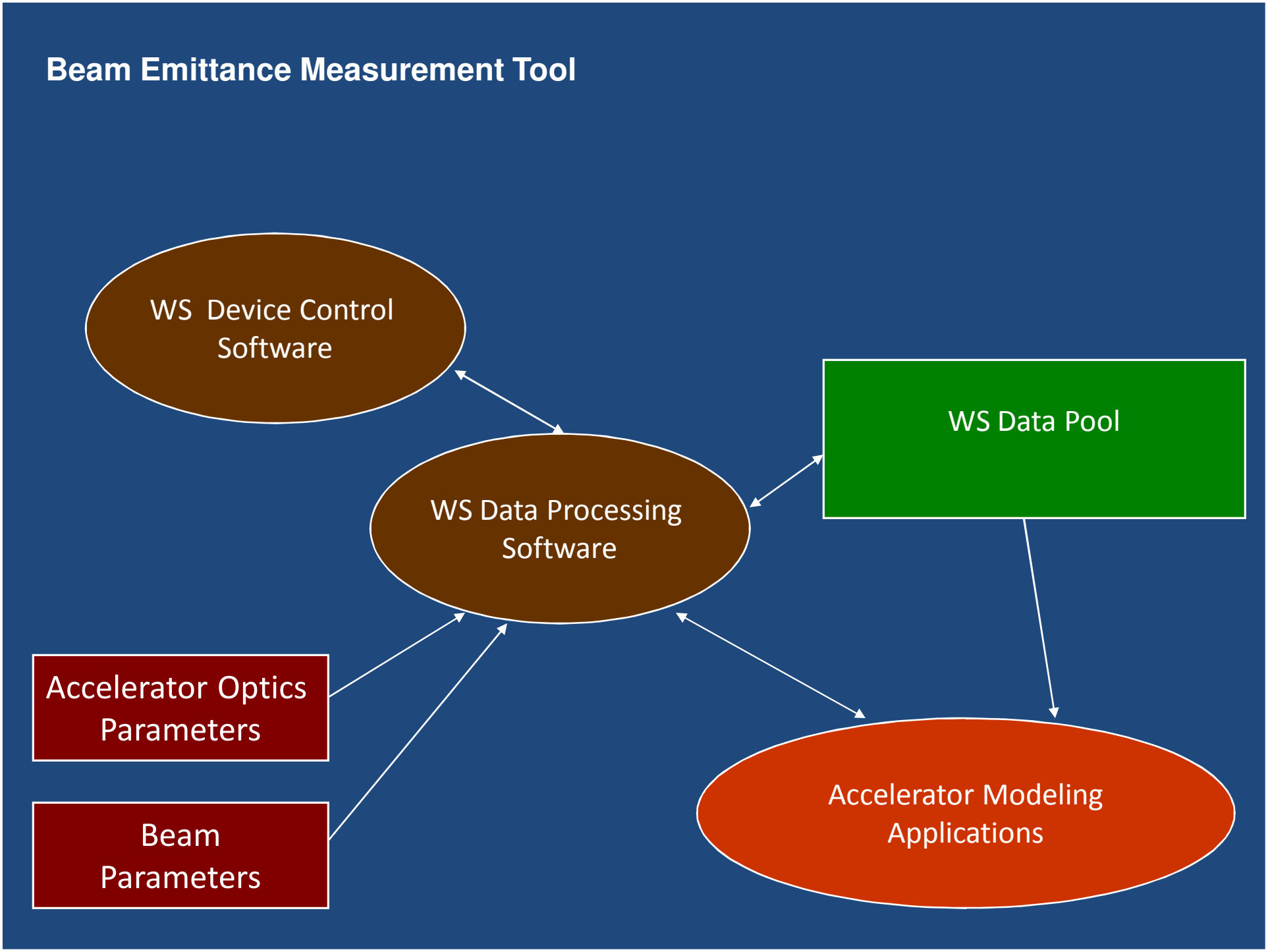
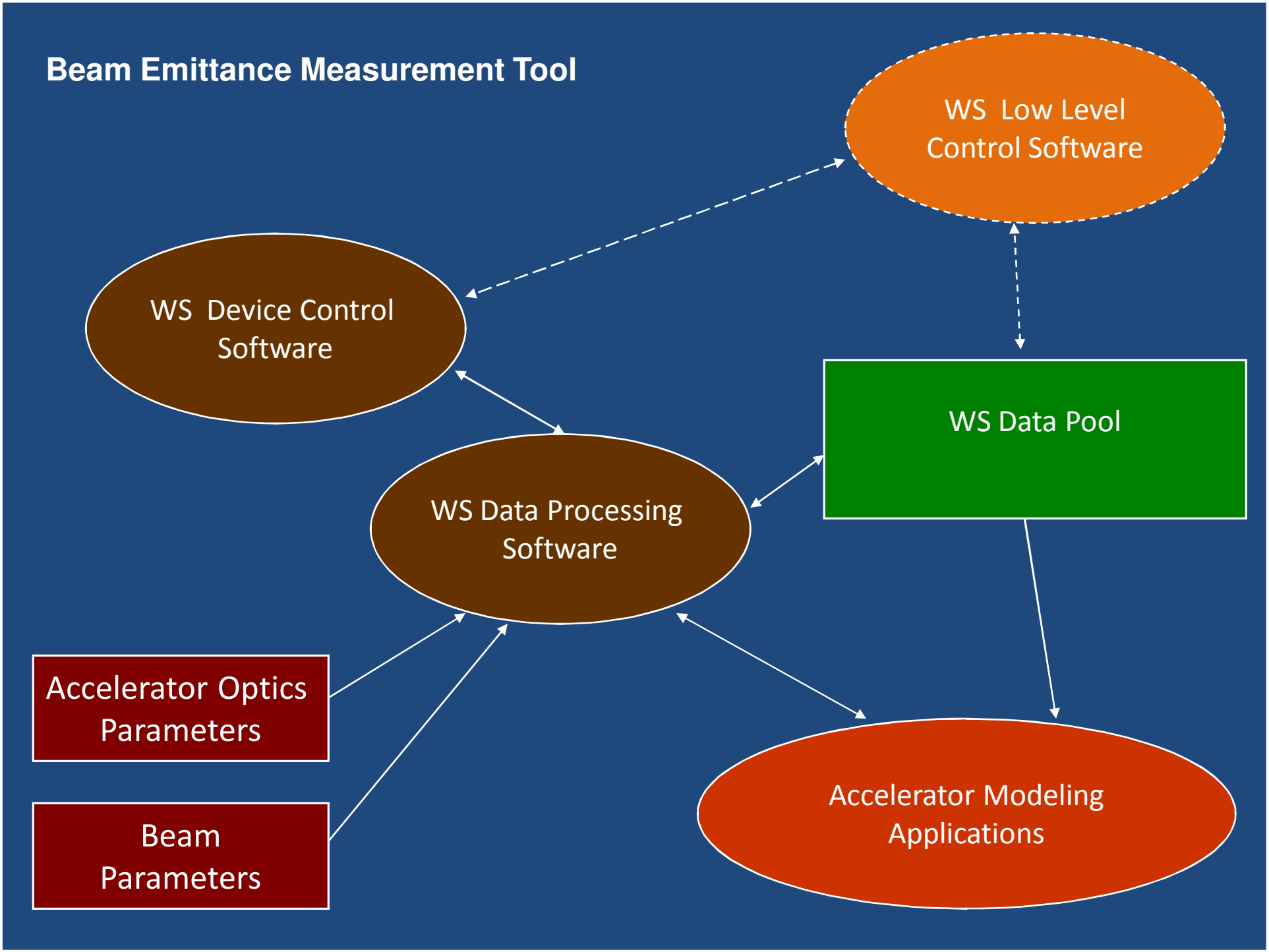
## Beam Emittance Measurement Tool

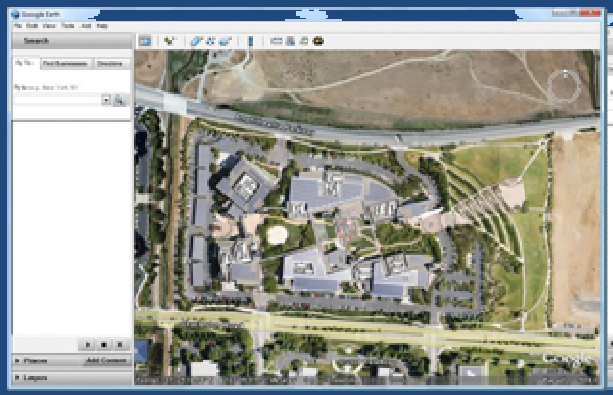


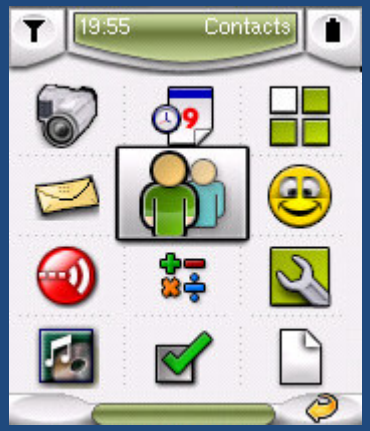

Beam Emittance Measurement Tool
WS Low Level Control Software
WS Device Control Software
WS Data Pool
WS Data Processing Software
Accelerator Optics Parameters
Beam Parameters
Accelerator Modeling Applications


Beam Emittance
Measurement Tool
GSL
Qt
Qwt

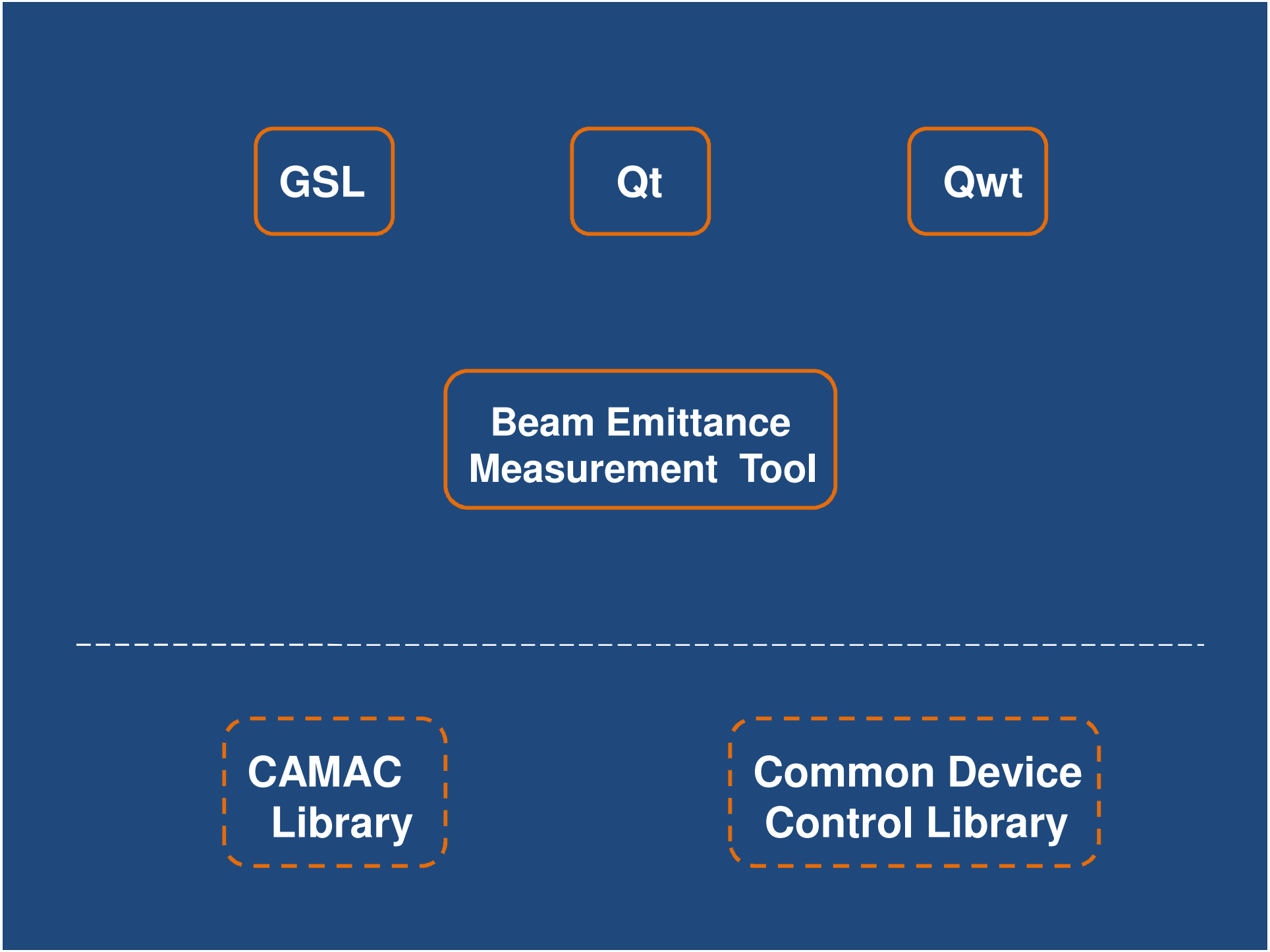
Code less.
Create more.
Deploy everywhere.

skype

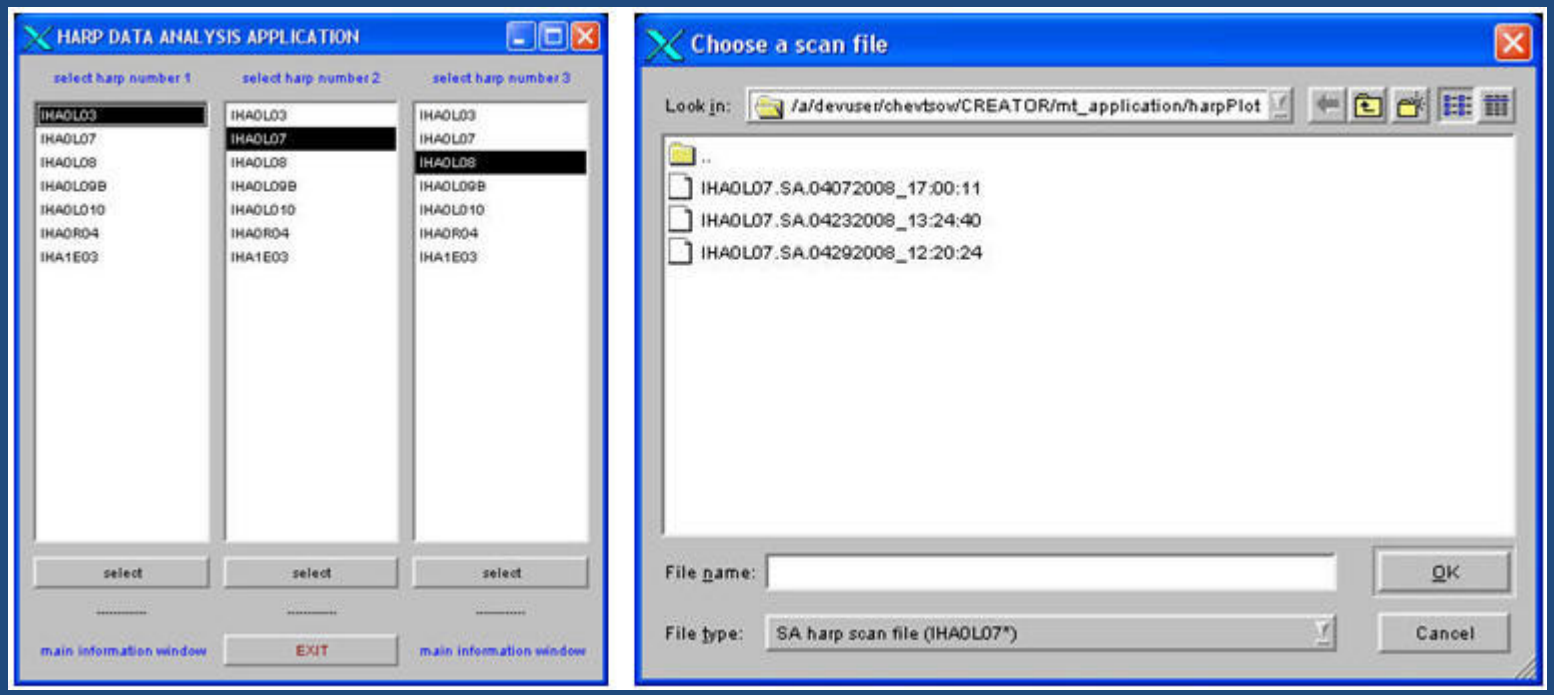


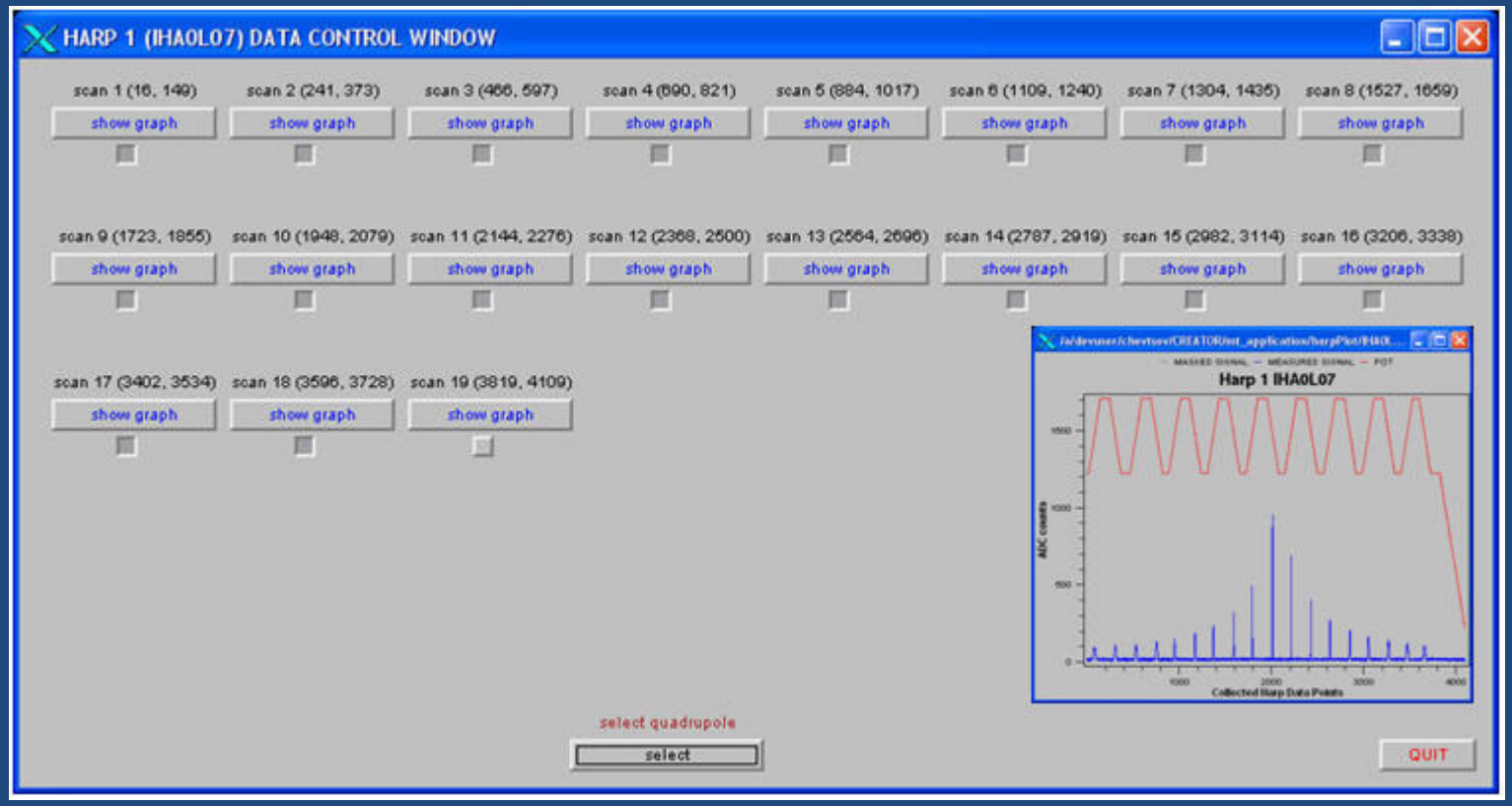


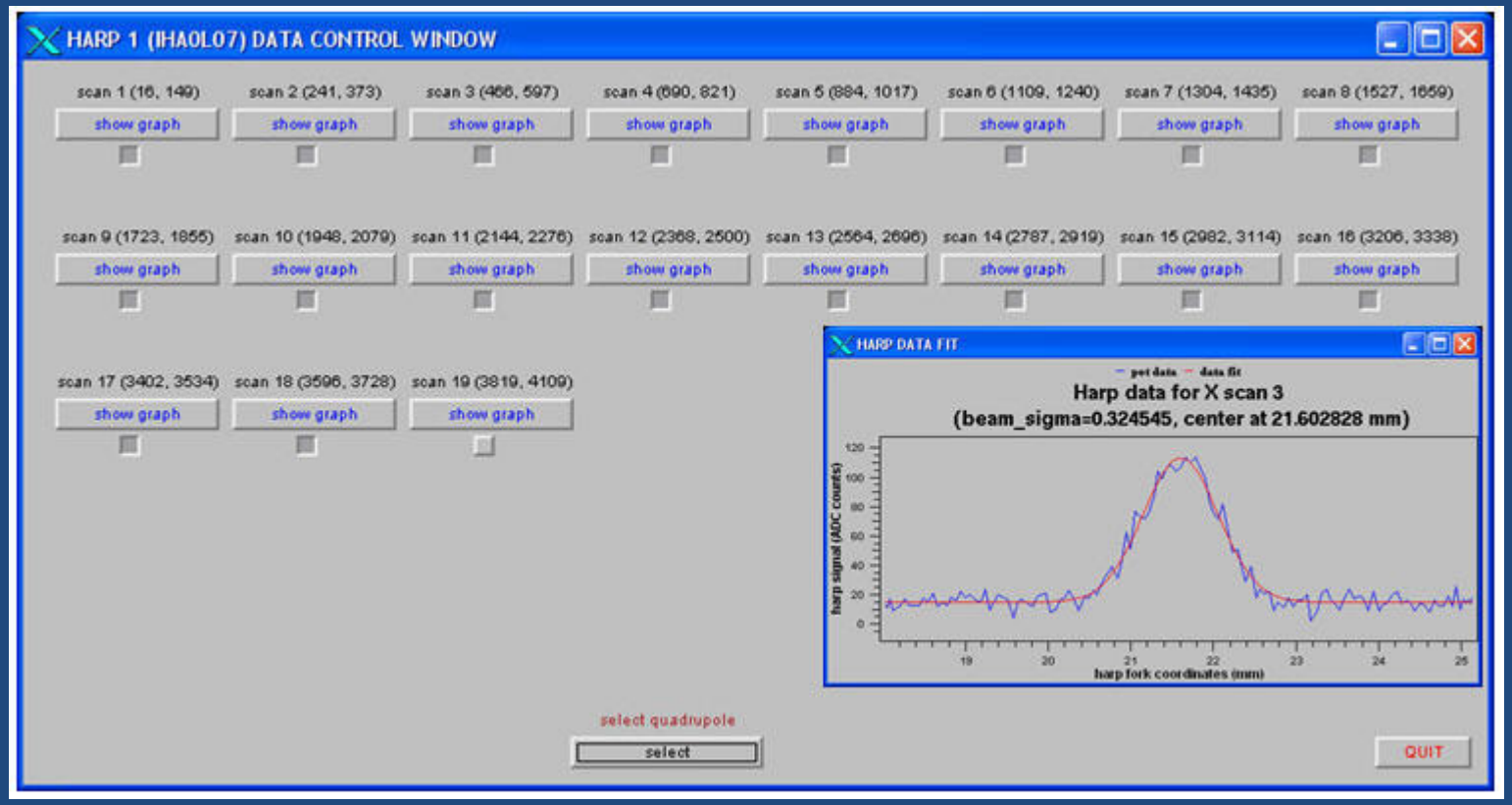


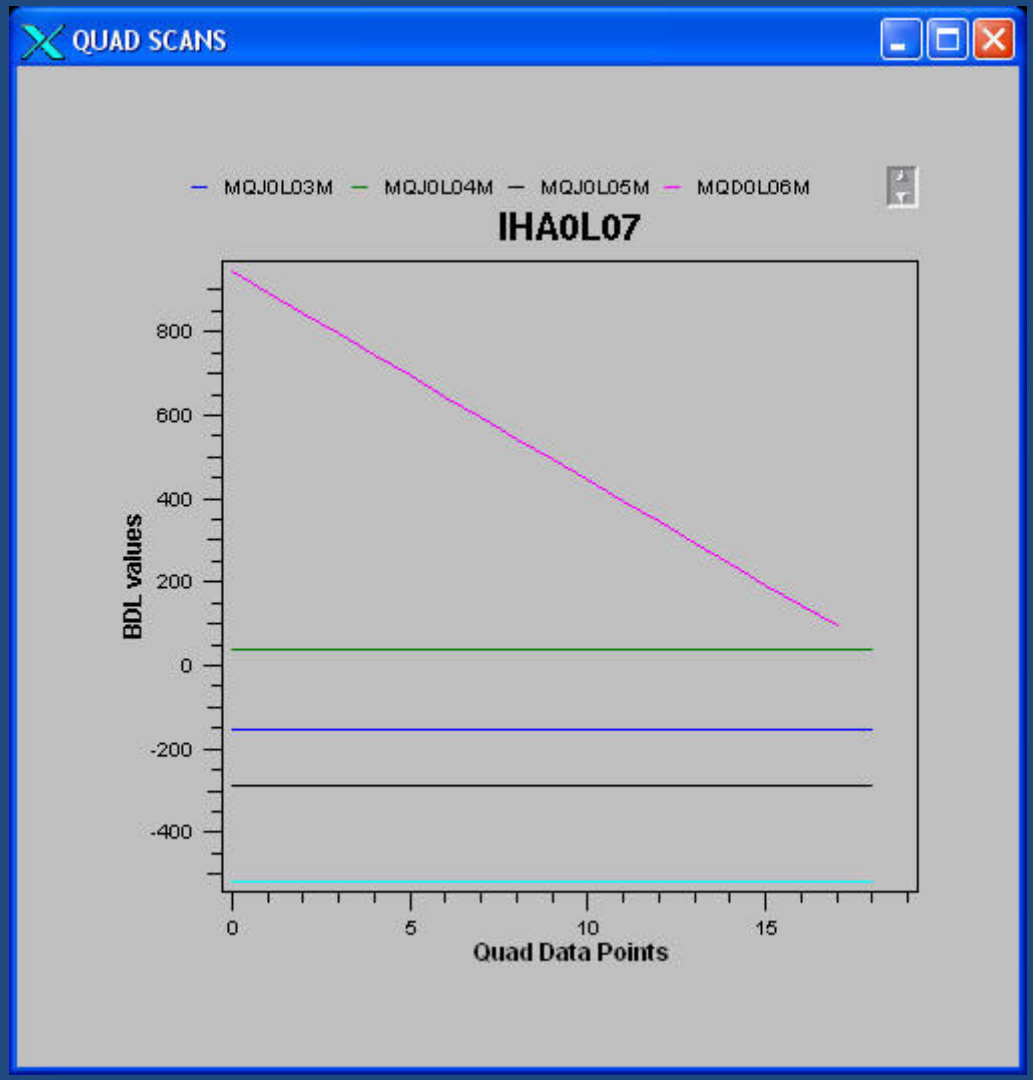

GSL
Qt
Qwt
Beam Emittance Measurement Tool
CAMAC Library
Common Device Control Library

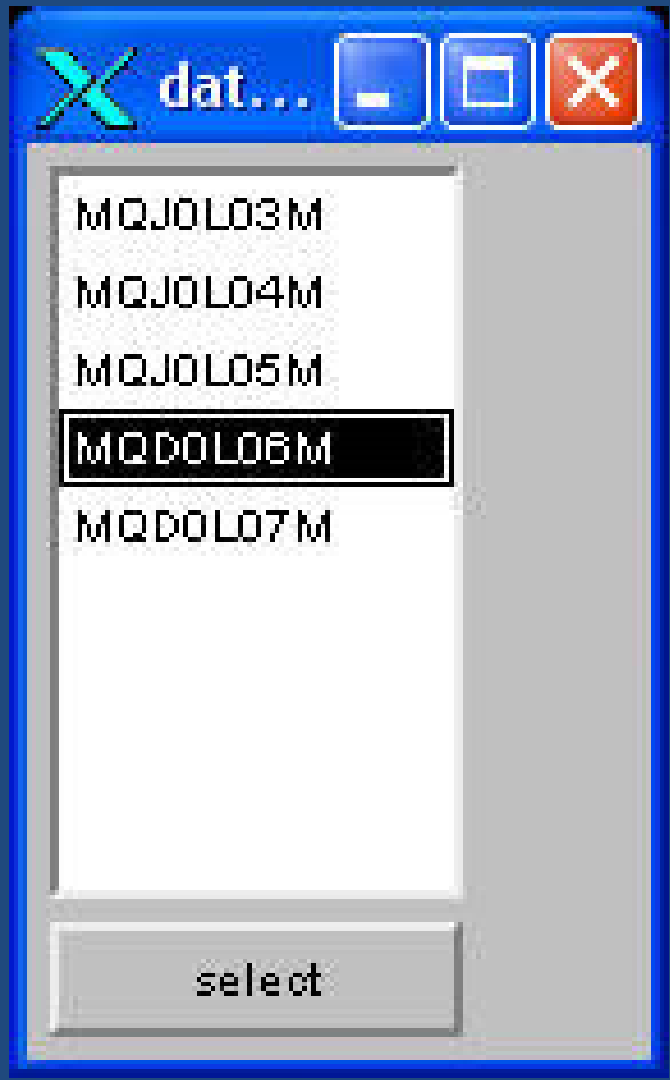

# Beam Emittance Measurement Tool

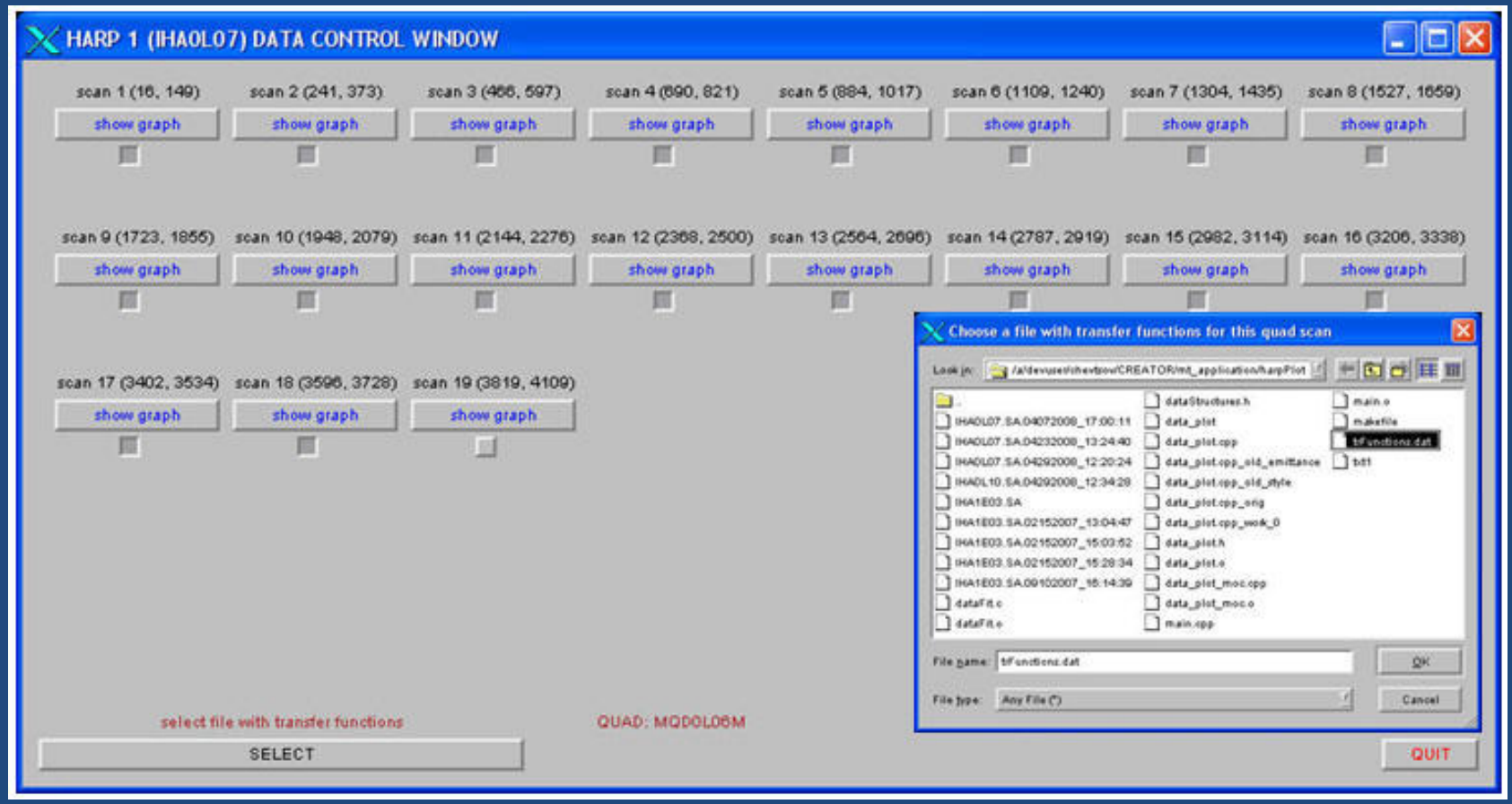

HARP DATA ANALYSIS APPLICATION
select harp number 1
select harp number 2
select harp number 3
IHA0L03
IHA0L07
IHA0L08
IHA0L09B
IHA0L010
IHA0R04
IHA1E03
select
main information window
EXIT
Choose a scan file
Look in:
/a/devuser/chevtsow/CREATOR/mt_application/harpPlot
IHA0L07.SA.04072008_17:00:11
IHA0L07.SA.04232008_13:24:40
IHA0L07.SA.04292008_12:20:24
File name:
OK
File type:
SA harp scan file (IHA0L07*)
Cancel

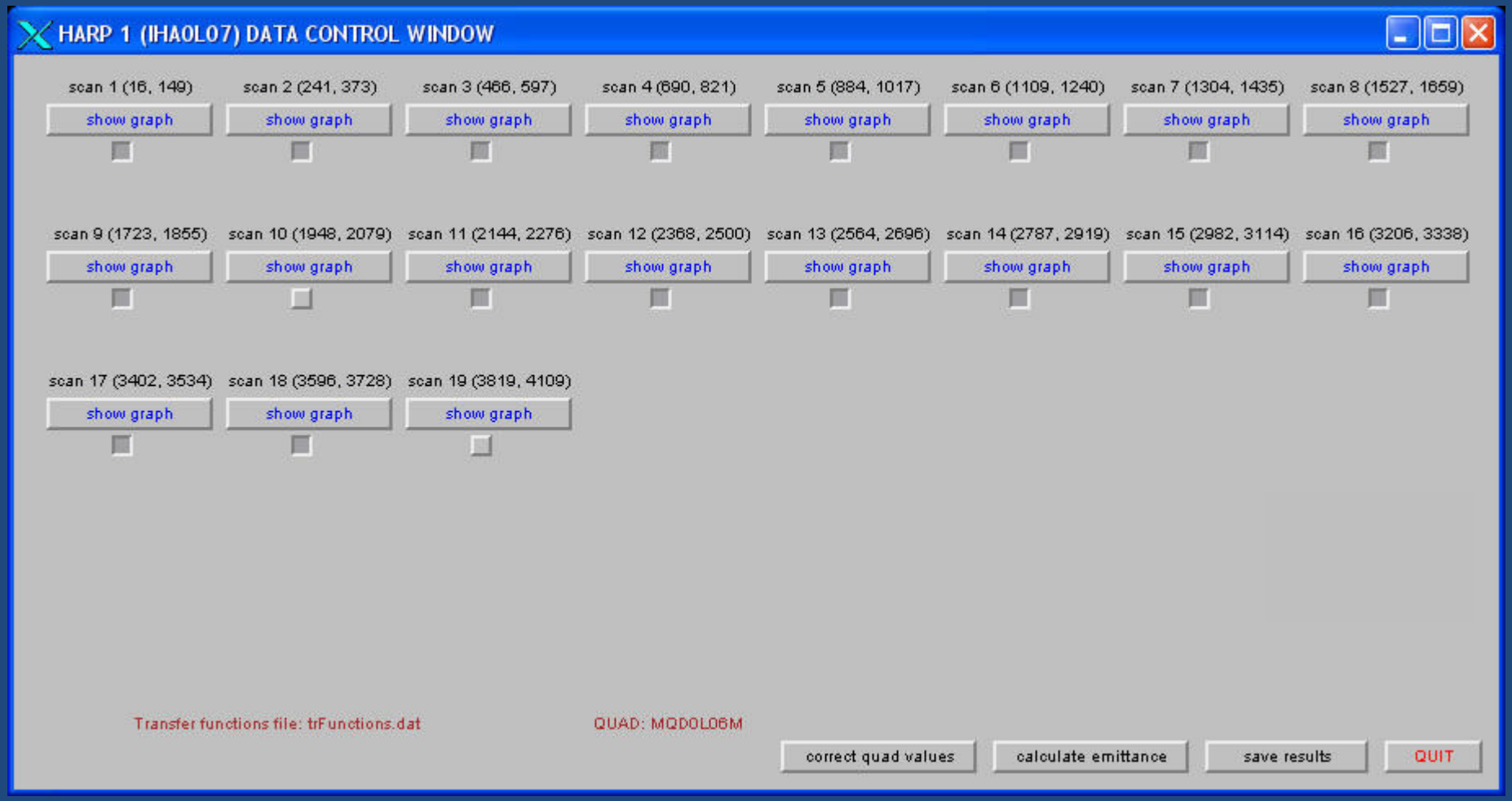

HARP 1 (IHA0L07) DATA CONTROL WINDOW
scan 1 (16, 149)
show graph
scan 2 (241, 373)
show graph
scan 3 (466, 597)
show graph
scan 4 (690, 821)
show graph
scan 5 (884, 1017)
show graph
scan 6 (1109, 1240)
show graph
scan 7 (1304, 1435)
show graph
scan 8 (1527, 1659)
show graph
scan 9 (1723, 1855)
show graph
scan 10 (1948, 2079)
show graph
scan 11 (2144, 2276)
show graph
scan 12 (2368, 2500)
show graph
scan 13 (2564, 2696)
show graph
scan 14 (2787, 2919)
show graph
scan 15 (2982, 3114)
show graph
scan 16 (3206, 3338)
show graph
scan 17 (3402, 3534)
show graph
scan 18 (3596, 3728)
show graph
scan 19 (3819, 4109)
show graph
Harp 1 IHA0L07
ADC counts
Collected Harp Data Points
select quadrupole
select
QUIT


HARP 1 (IHA0L07) DATA CONTROL WINDOW
scan 1 (16, 149)
scan 2 (241, 373)
scan 3 (466, 597)
scan 4 (690, 821)
scan 5 (884, 1017)
scan 6 (1109, 1240)
scan 7 (1304, 1435)
scan 8 (1527, 1659)
scan 9 (1723, 1855)
scan 10 (1948, 2079)
scan 11 (2144, 2276)
scan 12 (2368, 2500)
scan 13 (2564, 2696)
scan 14 (2787, 2919)
scan 15 (2982, 3114)
scan 16 (3206, 3338)
scan 17 (3402, 3534)
scan 18 (3596, 3728)
scan 19 (3819, 4109)
show graph
HARP DATA FIT
Harp data for X scan 3
(beam_sigma=0.324545, center at 21.602828 mm)
harp signal (ADC counts)
harp fork coordinates (mm)
select quadrupole
select
QUIT


QUAD SCANS
MQJ0L03M
MQJ0L04M
MQJ0L05M
MQD0L06M
IHA0L07
BDL values
800
600
400
200
0
-200
-400
0
5
10
15
Quad Data Points


dat...
MQJ0L03M
MQJ0L04M
MQJ0L05M
MQD0L06M
MQD0L07M
select

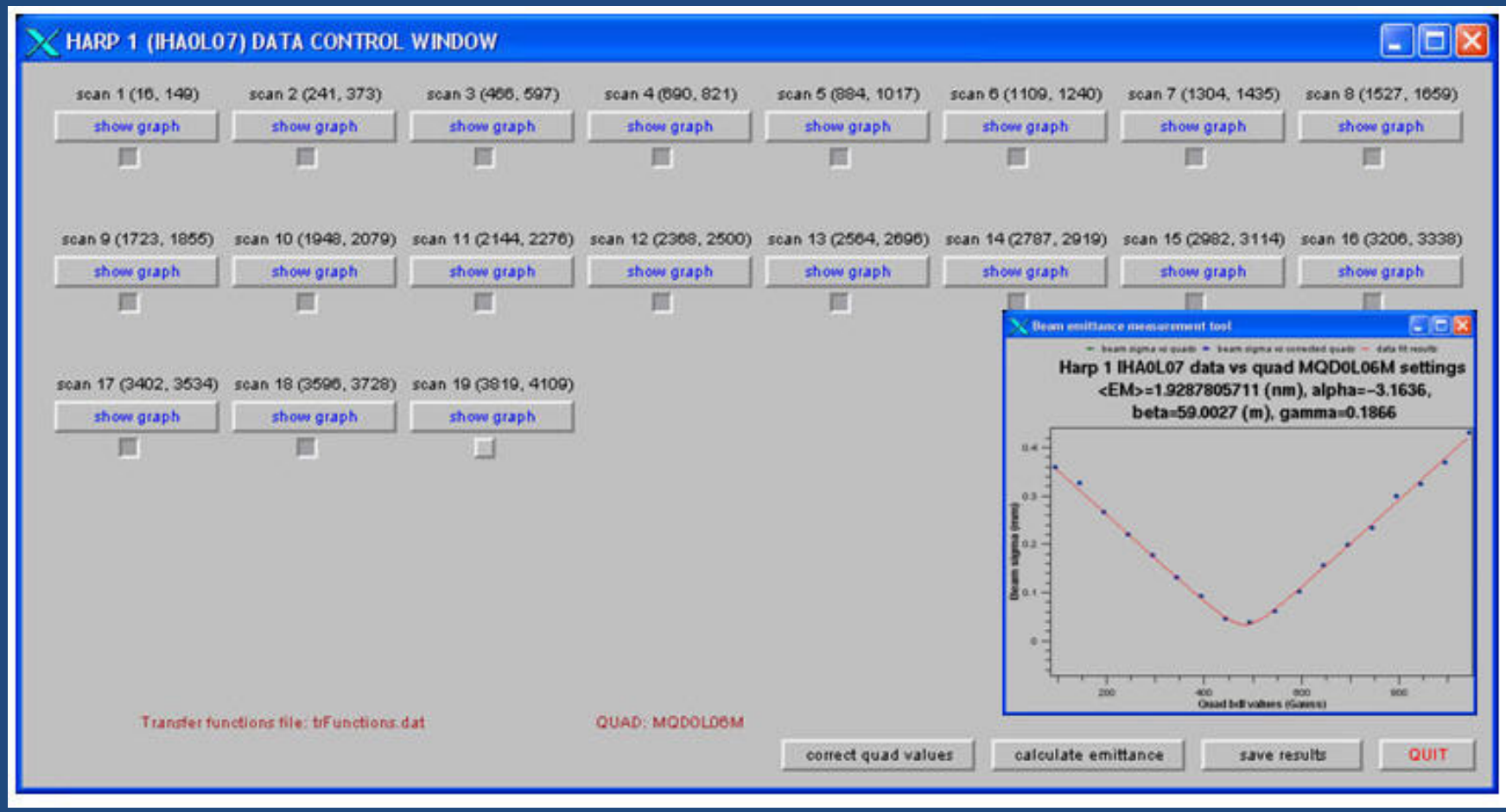

HARP 1 (IHA0L07) DATA CONTROL WINDOW
scan 1 (16, 149)
scan 2 (241, 373)
scan 3 (466, 597)
scan 4 (690, 821)
scan 5 (884, 1017)
scan 6 (1109, 1240)
scan 7 (1304, 1435)
scan 8 (1527, 1659)
scan 9 (1723, 1855)
scan 10 (1948, 2079)
scan 11 (2144, 2276)
scan 12 (2368, 2500)
scan 13 (2564, 2696)
scan 14 (2787, 2919)
scan 15 (2982, 3114)
scan 16 (3206, 3338)
scan 17 (3402, 3534)
scan 18 (3596, 3728)
scan 19 (3819, 4109)
show graph
Choose a file with transfer functions for this quad scan
Look in:
File name:
File type:
OK
Cancel
select file with transfer functions
SELECT
QUAD: MQD0L06M
QUIT

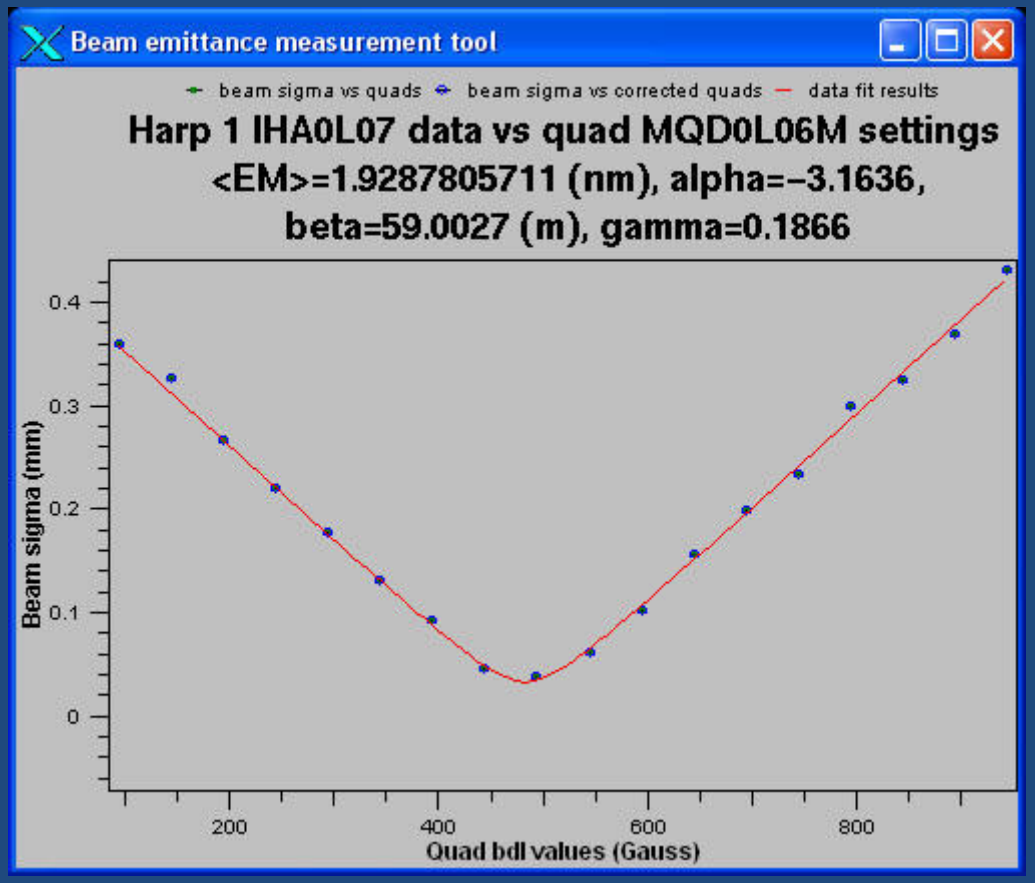

HARP 1 (IHA0L07) DATA CONTROL WINDOW
scan 1 (16, 149)
scan 2 (241, 373)
scan 3 (466, 597)
scan 4 (690, 821)
scan 5 (884, 1017)
scan 6 (1109, 1240)
scan 7 (1304, 1435)
scan 8 (1527, 1659)
scan 9 (1723, 1855)
scan 10 (1948, 2079)
scan 11 (2144, 2276)
scan 12 (2368, 2500)
scan 13 (2564, 2696)
scan 14 (2787, 2919)
scan 15 (2982, 3114)
scan 16 (3206, 3338)
scan 17 (3402, 3534)
scan 18 (3596, 3728)
scan 19 (3819, 4109)
show graph
Transfer functions file: trFunctions.dat
QUAD: MQD0L06M
correct quad values
calculate emittance
save results
QUIT

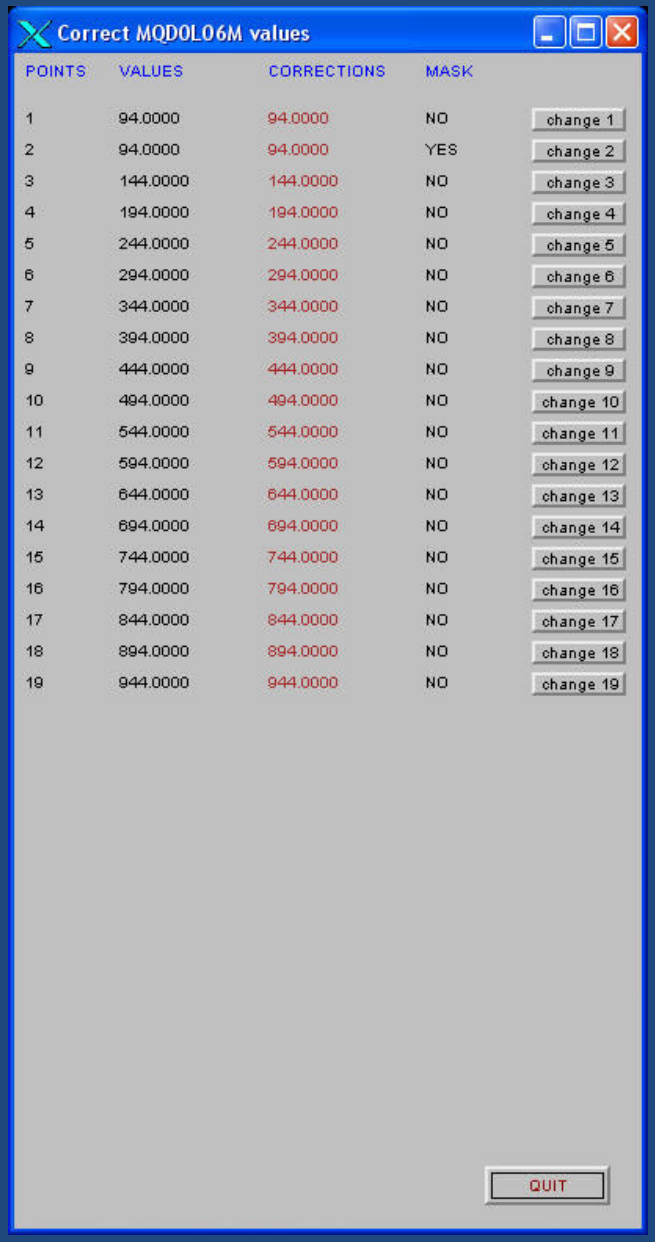
GSL library is called to perform all mathematical calculations

QWT library provides all data presentation graphics

## BEMT Software Works ...


HARP 1 (IHA0L07) DATA CONTROL WINDOW
scan 1 (16, 149)
scan 2 (241, 373)
scan 3 (466, 597)
scan 4 (690, 821)
scan 5 (884, 1017)
scan 6 (1109, 1240)
scan 7 (1304, 1435)
scan 8 (1527, 1659)
scan 9 (1723, 1855)
scan 10 (1948, 2079)
scan 11 (2144, 2276)
scan 12 (2368, 2500)
scan 13 (2564, 2696)
scan 14 (2787, 2919)
scan 15 (2982, 3114)
scan 16 (3206, 3338)
scan 17 (3402, 3534)
scan 18 (3596, 3728)
scan 19 (3819, 4109)
show graph
Beam emittance measurement tool
Harp 1 IHA0L07 data vs quad MQD0L06M settings
<EM>=1.9287805711 (nm), alpha=-3.1636,
beta=59.0027 (m), gamma=0.1866
Transfer functions file: trFunctions.dat
QUAD: MQD0L06M
correct quad values
calculate emittance
save results
QUIT

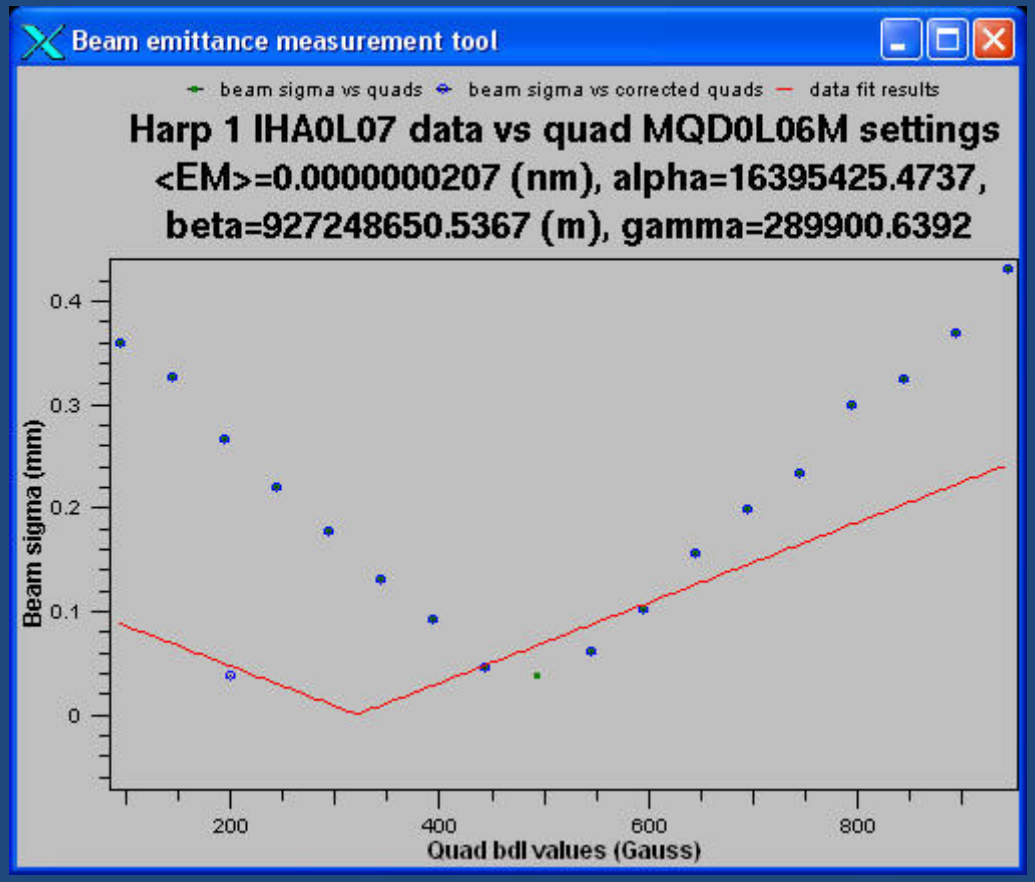

Beam emittance measurement tool
beam sigma vs quads
beam sigma vs corrected quads
data fit results
Harp 1 IHA0L07 data vs quad MQD0L06M settings
<EM>=1.9287805711 (nm), alpha=-3.1636,
beta=59.0027 (m), gamma=0.1866
Beam sigma (mm)
0.4
0.3
0.2
0.1
0
200
400
600
800
Quad bdl values (Gauss)

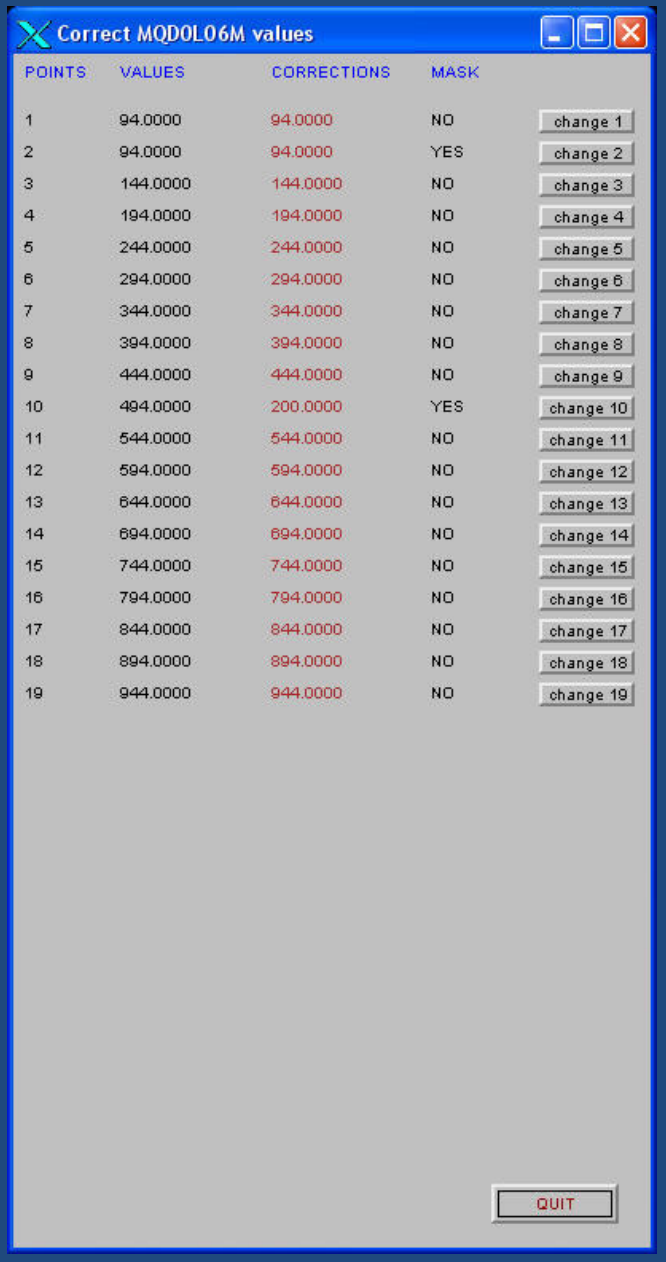

Correct MQD0L06M values
POINTS VALUES CORRECTIONS MASK
1 94.0000 94.0000 NO change 1
2 94.0000 94.0000 YES change 2
3 144.0000 144.0000 NO change 3
4 194.0000 194.0000 NO change 4
5 244.0000 244.0000 NO change 5
6 294.0000 294.0000 NO change 6
7 344.0000 344.0000 NO change 7
8 394.0000 394.0000 NO change 8
9 444.0000 444.0000 NO change 9
10 494.0000 494.0000 NO change 10
11 544.0000 544.0000 NO change 11
12 594.0000 594.0000 NO change 12
13 644.0000 644.0000 NO change 13
14 694.0000 694.0000 NO change 14
15 744.0000 744.0000 NO change 15
16 794.0000 794.0000 NO change 16
17 844.0000 844.0000 NO change 17
18 894.0000 894.0000 NO change 18
19 944.0000 944.0000 NO change 19
QUIT

## Summary

- The new Beam Emittance Measurement Tool significantly simplifies beam emittance measurement procedures for accelerator operations and contributes to a very high availability of the CEBAF machine for nuclear physics program at Jefferson Lab

- Tool software is computer platform independent but is mostly used on LINUX PCs recently installed in the accelerator control room


Beam emittance measurement tool
beam sigma vs quads
beam sigma vs corrected quads
data fit results
Harp 1 IHA0L07 data vs quad MQD0L06M settings
<EM>=0.0000000207 (nm), alpha=16395425.4737,
beta=927248650.5367 (m), gamma=289900.6392
Beam sigma (mm)
0.4
0.3
0.2
0.1
0
200
400
600
800
Quad bdl values (Gauss)


Correct MQD0L06M values
POINTS VALUES CORRECTIONS MASK
1 94.0000 94.0000 NO change 1
2 94.0000 94.0000 YES change 2
3 144.0000 144.0000 NO change 3
4 194.0000 194.0000 NO change 4
5 244.0000 244.0000 NO change 5
6 294.0000 294.0000 NO change 6
7 344.0000 344.0000 NO change 7
8 394.0000 394.0000 NO change 8
9 444.0000 444.0000 NO change 9
10 494.0000 200.0000 YES change 10
11 544.0000 544.0000 NO change 11
12 594.0000 594.0000 NO change 12
13 644.0000 644.0000 NO change 13
14 694.0000 694.0000 NO change 14
15 744.0000 744.0000 NO change 15
16 794.0000 794.0000 NO change 16
17 844.0000 844.0000 NO change 17
18 894.0000 894.0000 NO change 18
19 944.0000 944.0000 NO change 19
QUIT