McLaren AccelSoft Inc.

Detailed Transfer Line Beam Characteristics at an Operational Proton Therapy Center

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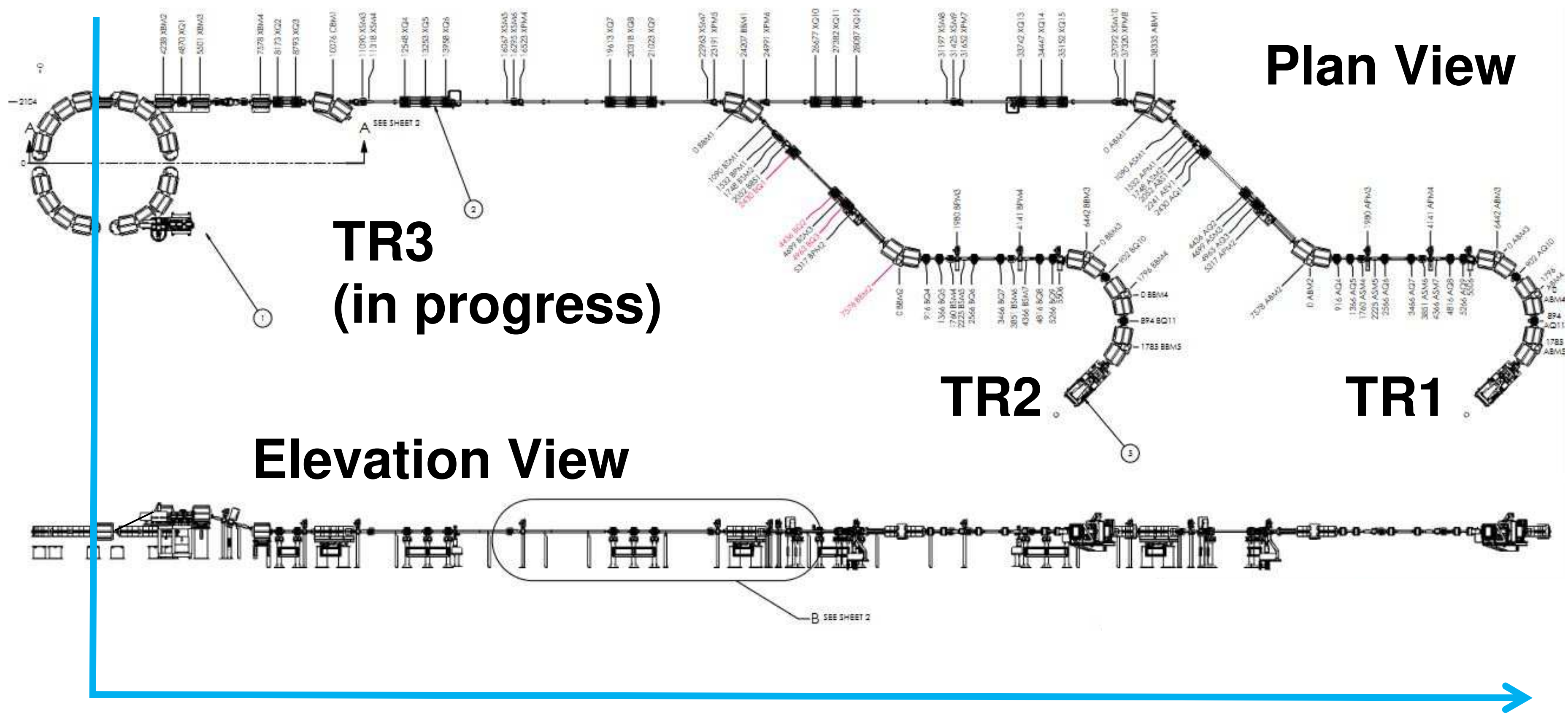
- **Combined Experiment / Simulation Study of Beamlines**
- **Develop Computer Models in Sufficient Detail to**
  - **Understand Current Clinical Performance**
  - **Optimize Performance / Better Solutions**
  - **Design of New Beamlines**
- **Improve Fidelity of Models as Needed**

MPTC Synchrotron & Beamline Layout



→ **This study starts with the synchrotron extraction dipole**

Beamline Optical Components

- **Chicane: 4 dipoles*, 2 quadrupoles, 4 steerers, 1 BPM****
- **Through TR2 Selection Magnet (BBM1):**
  8 quadrupoles, 5 steerers, 4 BPMs, 1 dipole-pair*†
- **Through TR2 Gantry Rotator Magnet:**
  3 quadrupoles, 3 steerers, 2 BPMs, 1 dipole-pair
- **TR2 Gantry to Isocenter:**
  8 quadrupoles, 4 steerers, 3 BPMs, 3 dipole-pairs
- **Through TR1 Selection Magnet (ABM1):**
  14 quadrupoles, 8 steerers, 7 BPMs, 1 dipole-pair
- **Through TR1 Gantry Rotator Magnet to Isocenter:**
  11 quadrupoles, 7 steerers, 5 BPMs, 4 dipole-pairs

***Each dipole also has a steering trim coil**
****BPM = Beam Profile Monitor**
†Each dipole-pair has two 22.5° magnets, bending the beam 45°

Beamline Modeling Goals & Approach

Models should be able to simulate (current clinical):
- **70 MeV to 250 MeV beam energies**
- **0° to 180° gantry angles (90 is horizontal gantry)**

Fidelity of models sufficient to (where we're going):
- **Guide improvements for operation of TR1 & TR2**
- **Support new design activities (TR3, TR0)**

Build upon existing PBO-Lab* models (from D-PACE)
- **Extend models for improved fidelity as needed**

Find "core" synchrotron beams ⇒ fit model to BPM data

Compare "core" beam losses with beam current data

Improve models (apertures, steering, ...) as appropriate

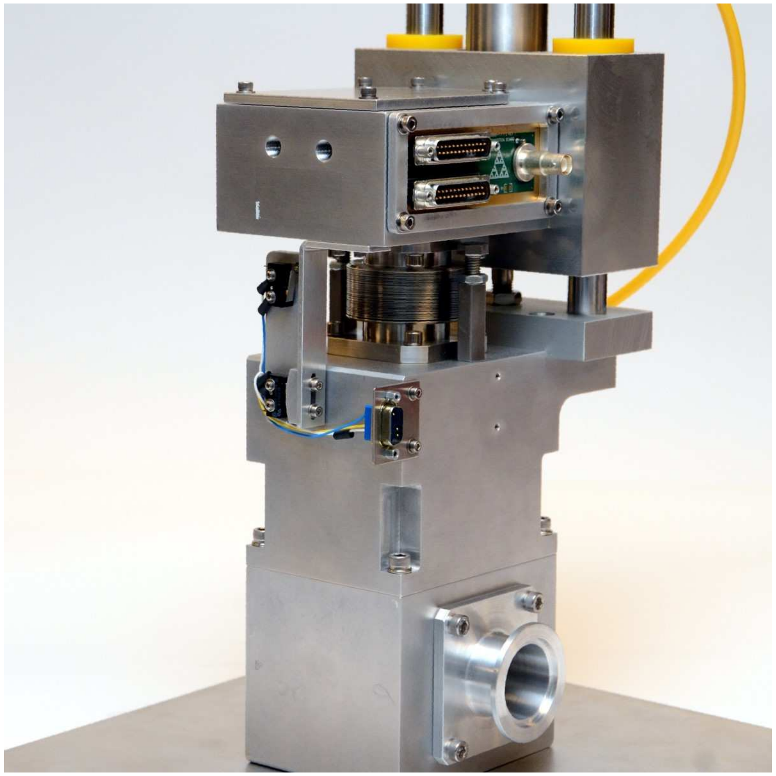
*PBO-Lab = Particle Beam Optics Laboratory (software)

Beam Profile Monitor (BPM)

Primary Diagnostic: Pyramid BPM16-38 Gantry Compatible Beam Position Monitor Strip Ion Chamber

Used to Provide:

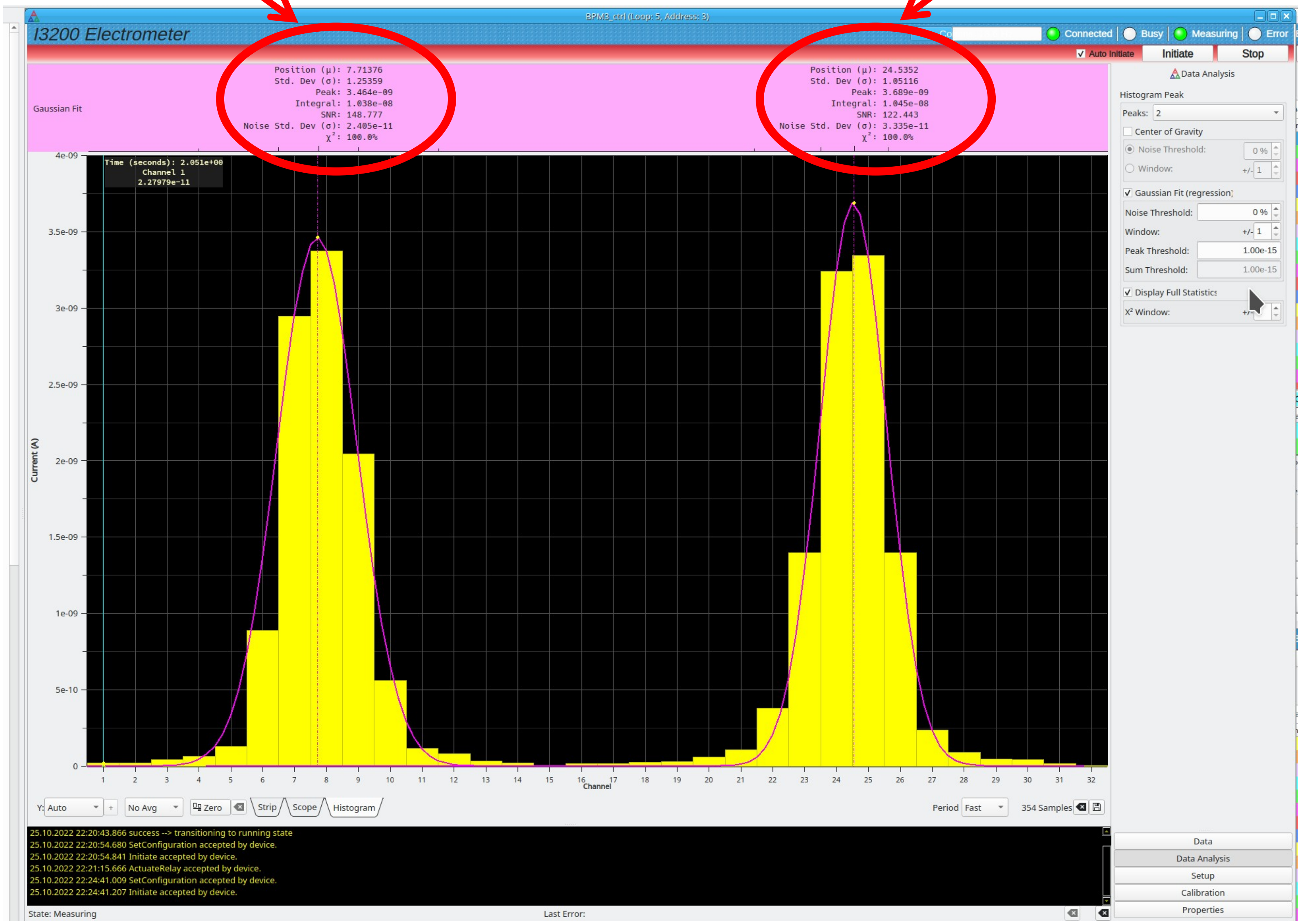
- Beam Sizes
- Beam Position
- Beam Current



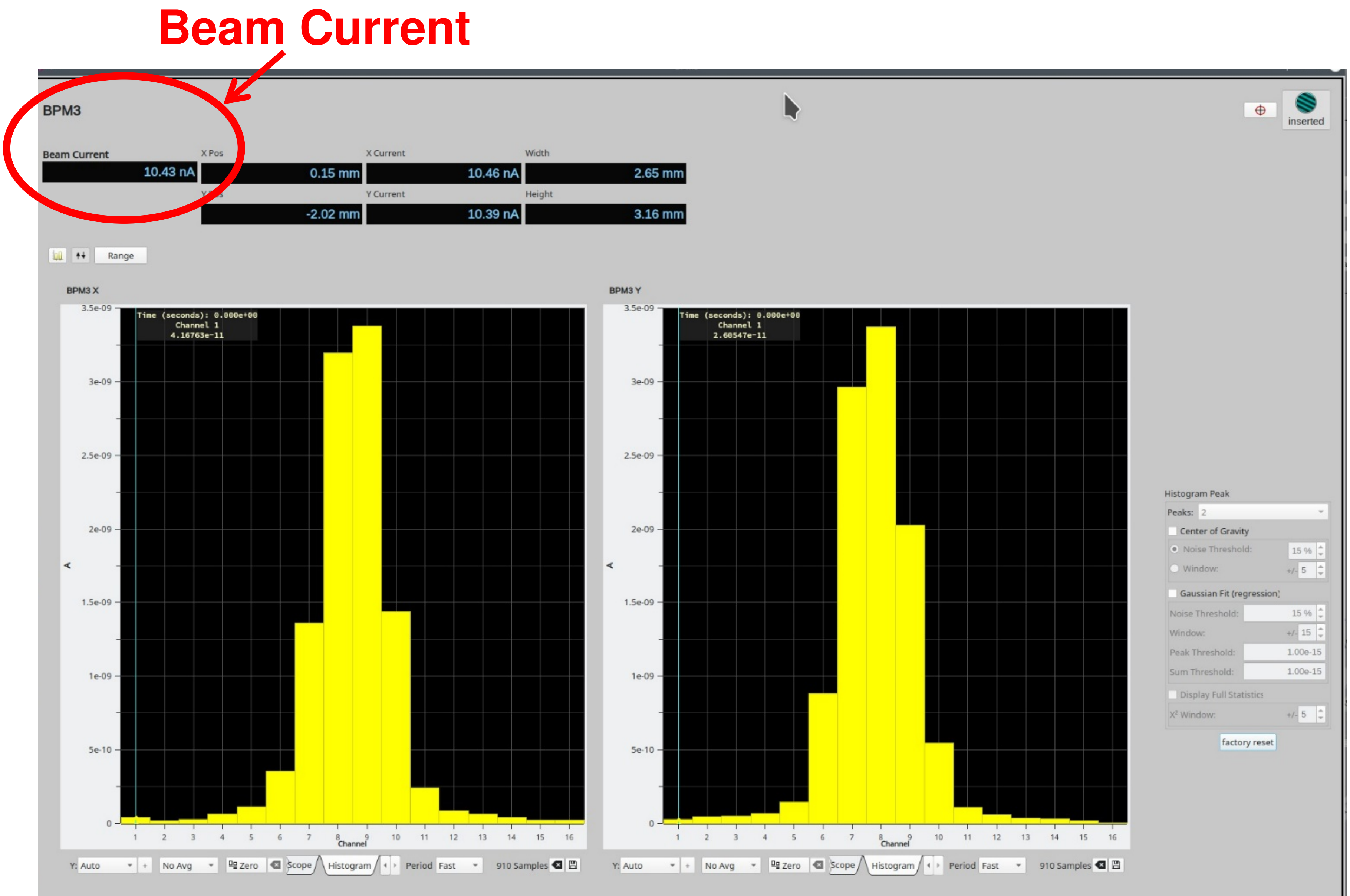
https://ptcusa.com/products/bpm16-38

Beam Profile Monitor (BPM)

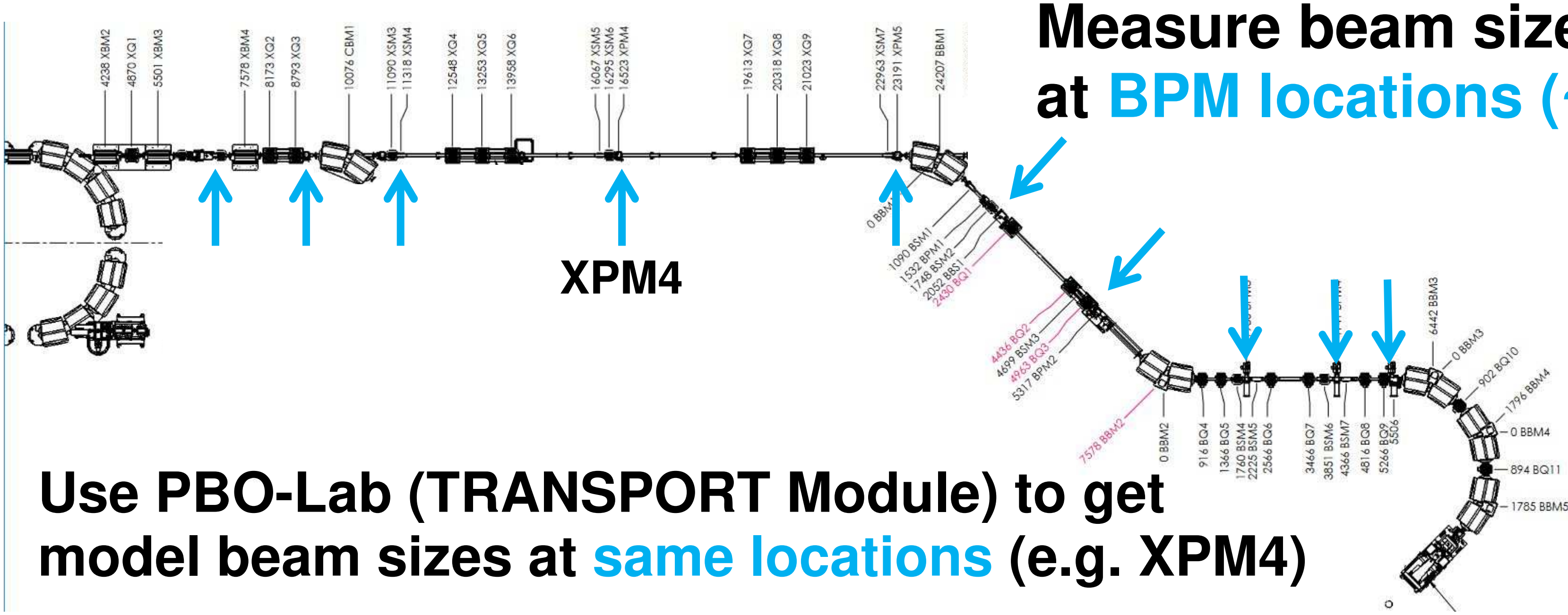
Y Beam Position & Size X Beam Position & Size



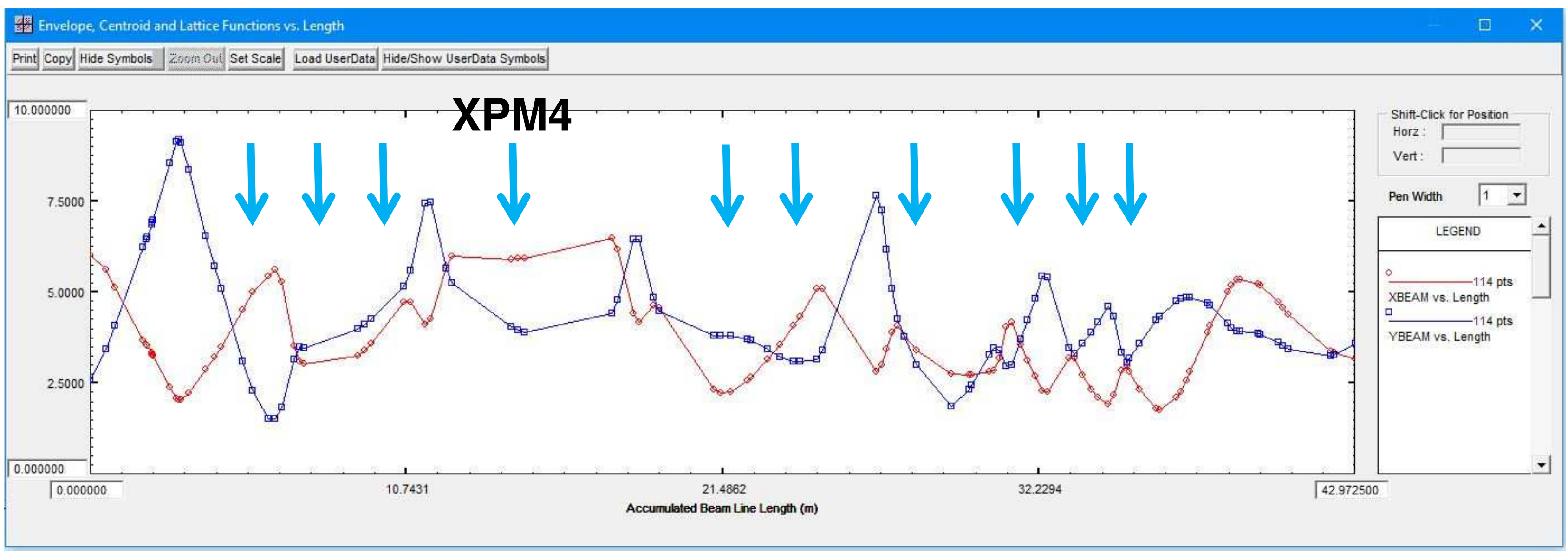
Beam Profile Monitor (BPM)



Measure beam sizes at BPM locations (~10)



Use PBO-Lab (TRANSPORT Module) to get model beam sizes at same locations (e.g. XPM4)



Model Fields Use Clinical Set Points

Synchrotron Control (ZAO data) Give Current Settings for:

- Each Energy
- Chicane, Room Selection, Gantry *Main* Dipole Currents*
- One Chicane Quad & Two Chicane Steerer Currents
- Some of the Dipole Steering (Trim) Currents

Clinical Tune Files (XML files) Give Current Settings for:

- Each Energy, Treatment Room, Gantry Angle
- All Other Quadrupole Currents
- Two Chicane and All Other Steerer Currents
- Remainder of Dipole Steering (Trim) Currents

***Model Uses Actual Geometry (Bend Angles) of Beamlines**

Example of Clinical Set Point Use

Example for Two Quads, XQ2 & XQ3, Just After Chicane

Tune Currents → Imported → Field Calculated → Quad Set

XML Tune File


```xml
<channel name="r_XQ4_voltage" value="3.736465"/>
<channel name="r_XQ4_open" value="FALSE"/>
<channel name="r_XQ4_limit" value="FALSE"/>
<channel name="r_XQ4_fault" value="FALSE"/>
<channel name="r_XQ4_enabled" value="0"/>
<channel name="r_XQ4_current" value="0.592085"/>
<channel name="r_XQ4_coiltemp" value="FALSE"/>
<channel name="r_XQ3_voltage" value="7.381833"/>
<channel name="r_XQ3_open" value="FALSE"/>
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<channel name="r_XQ3_enabled" value="0"/>
<channel name="r_XQ3_current" value="1.218357"/>
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<channel name="r_XQ15_voltage" value="0.085088"/>
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<channel name="r_XQ15_enabled" value="2"/>
<channel name="r_XQ15_current" value="-0.040328"/>
<channel name="r_XQ15_coiltemp" value="FALSE"/>
```


Named Parameters

Named Parameters

Create Param Piece

Label	Parameter Name	Parameter Variable	Fit	Value	Unit
XEV0 aka XSM1	Magnetic Field Strength	BkG_XEV0		-0.057465	kG
XPM1_Set	XPM1_X	BPM_XPM1X		4.586540	mm
XPM1_Set	XPM1_Y	BPM_XPM1Y		5.524120	mm
XPM1_Set	XPM1_XC	BPM_XPM1XC		1.550000	mm
XPM1_Set	XPM1_YC	BPM_XPM1YC		1.320000	mm
XEH0 aka XSM2	Kick Angle	XEH0_kick		-0.000000	rad
XEH0 aka XSM2	Magnetic Field Strength	BkG_XEH0		-0.227104	kG
XQ2XQ9 currents - import	XQ2 quad current	r_XQ2_current		1.053802	Amp
XQ2XQ9 currents - import	XQ3 quad current	r_XQ3_current		1.218357	Amp
XQ2XQ9 currents - import	XQ4 quad current	r_XQ4_current		0.592085	Amp
XQ2XQ9 currents - import	XQ5 quad current	r_XQ5_current		1.112572	Amp
XQ2XQ9 currents - import	XQ6 quad current	r_XQ6_current		0.596611	Amp
XQ2XQ9 currents - import	XQ7 quad current	r_XQ7_current		0.687846	Amp
XQ2XQ9 currents - import	XQ8 quad current	r_XQ8_current		1.164567	Amp
XQ2XQ9 currents - import	XQ9 quad current	r_XQ9_current		0.649856	Amp
quad aperture	QAPA	pipesize		0.013800	m
XQ2	Magnetic Field at Pole Tip	XQ2_pole		0.851999	kG
XQ3	Magnetic Field at Pole Tip	XQ3_pole		-0.985042	kG
XPM2_Set	XPM2_X	BPM_XPM2X		3.116820	mm
XPM2_Set	XPM2_Y	BPM_XPM2Y		3.598280	mm
XPM2_Set	XPM2_XC	BPM_XPM2XC		0.510000	mm
XPM2_Set	XPM2_YC	BPM_XPM2YC		0.790000	mm
XPM3_Set	XPM3_X	BPM_XPM3X		3.167500	mm
XPM3_Set	XPM3_Y	BPM_XPM3Y		3.623620	mm
XPM3_Set	XPM3_XC	BPM_XPM3XC		0.000000	mm

Parameter Expressions

Parameter Expressions

Label	Parameter Name	Parameter Expression
XQ0	Magnetic-Field Gradient	47.9*r_XQ0_current
XQ1a	Magnetic Field at Pole Tip	-0.775*r_XQ1_current
XQ1b	Magnetic Field at Pole Tip	-0.775*r_XQ1_current
XEV0 aka XSM1	Kick Angle	V0C*UV0*r_XEV0_current+(1-UV0)*AV0
XEV0 aka XSM1	Magnetic Field Strength	UV0*0.044136*r_XEV0_current
XEH0 aka XSM2	Kick Angle	H0C*UH0*r_XEH0_current+(1-UH0)*AH0
XEH0 aka XSM2	Magnetic Field Strength	UH0*0.044136*r_XEH0_current
XQ2	Magnetic Field at Pole Tip	0.8085*r_XQ2_current
XQ3	Magnetic Field at Pole Tip	-0.8085*r_XQ3_current
XEH1 aka [illegible]	Magnetic Field Strength	UH12*0.044136*r_XEH1_current
XEV1 [illegible]SM4	Magnetic Field Strength	UV12*0.044136*r_XEV1_current
XQ4	Magnetic Field at Pole Tip	0.8085*r_XQ4_current
XQ[illegible]	Magnetic Field at Pole Tip	-0.8085*r_XQ5_current
[illegible]Q6	Magnetic Field at Pole Tip	0.8085*r_XQ6_current
[illegible]EV2 aka XSM5	Magnetic Field Strength	UV12*0.044136*r_XEV2_current
XEH2 aka XSM6	Magnetic Field Strength	UH12*0.044136*r_XEH2_current
XQ7	Magnetic Field at Pole Tip	0.8085*r_XQ7_current
XQ8	Magnetic Field at Pole Tip	-0.8085*r_XQ8_current
XQ9	Magnetic Field at Pole Tip	0.8085*r_XQ9_current
BQ1	Magnetic Field at Pole Tip	0.8085*r_BQ1_current
BQ2	Magnetic Field at Pole Tip	-0.8085*r_BQ2_current
BQ3	Magnetic Field at Pole Tip	0.8085*r_BQ3_current
BQ4	Magnetic Field at Pole Tip	-0.8085*r_BQ4_current
BQ5	Magnetic Field at Pole Tip	0.8085*r_BQ5_current
BQ6	Magnetic Field at Pole Tip	-0.8085*r_BQ6_current
BQ7	Magnetic Field at Pole Tip	0.8085*r_BQ7_current
BQ8	Magnetic Field at Pole Tip	-0.8085*r_BQ8_current

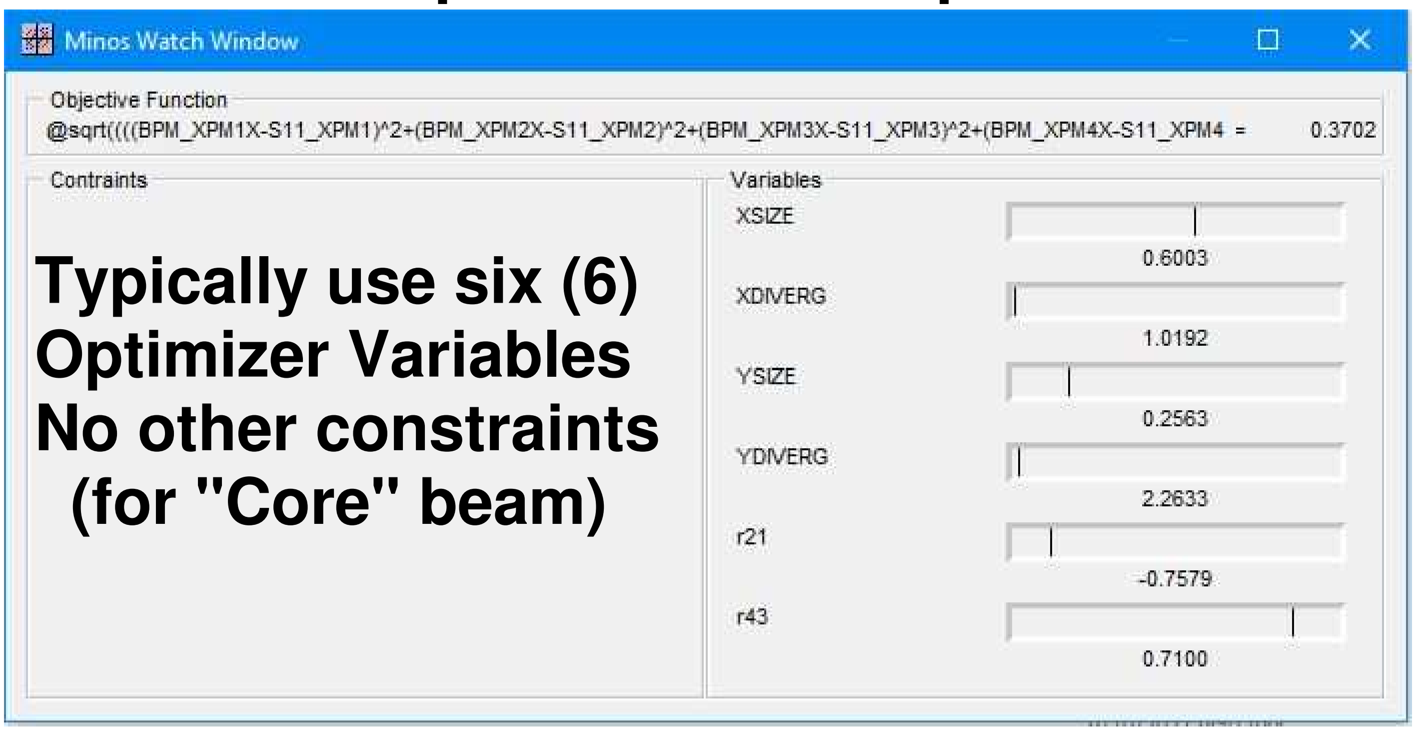
Finding "Core" Beam Descriptions

Change initial beam (synchrotron) parameters to minimize

Figure of Merit = $\left\{1/(2n)\ \Sigma_n \left[(X_{TRANS}-X_{BPM})^2+(Y_{TRANS}-Y_{BPM})^2\right]\right\}^{1/2}$

Automate via Optimization Module to minimize above FOM

With the initial beam parameters as Optimization Variables:



Beamline Configurations Examined

Studied Nine (9) Beamline Configurations to Date:

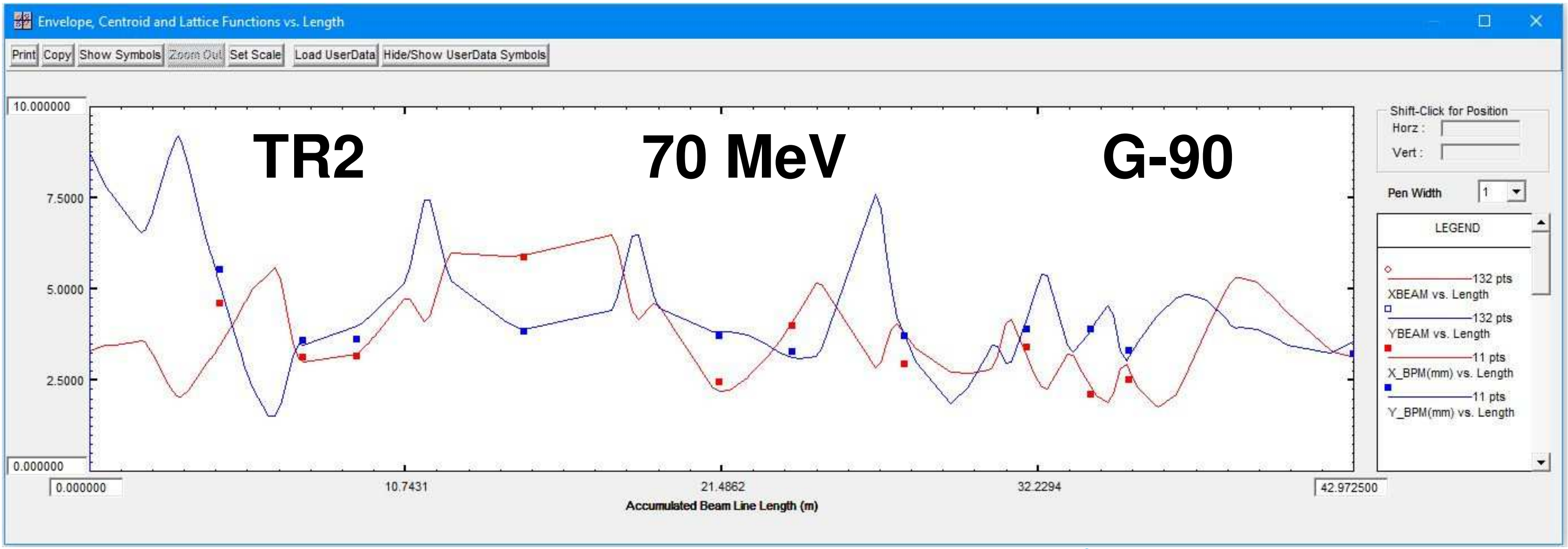
TR2 with Gantry at 90° (42.9725 meters) for
70, 100, 150, 200, 250 MeV
⇒ TR2 Gantry at 90° is "standard candle"
⇒ Energy Basis Set: 70, 100, 150, 200, 250 MeV

TR2 with Gantry at 180° (42.9725 meters) for
70, 250 MeV

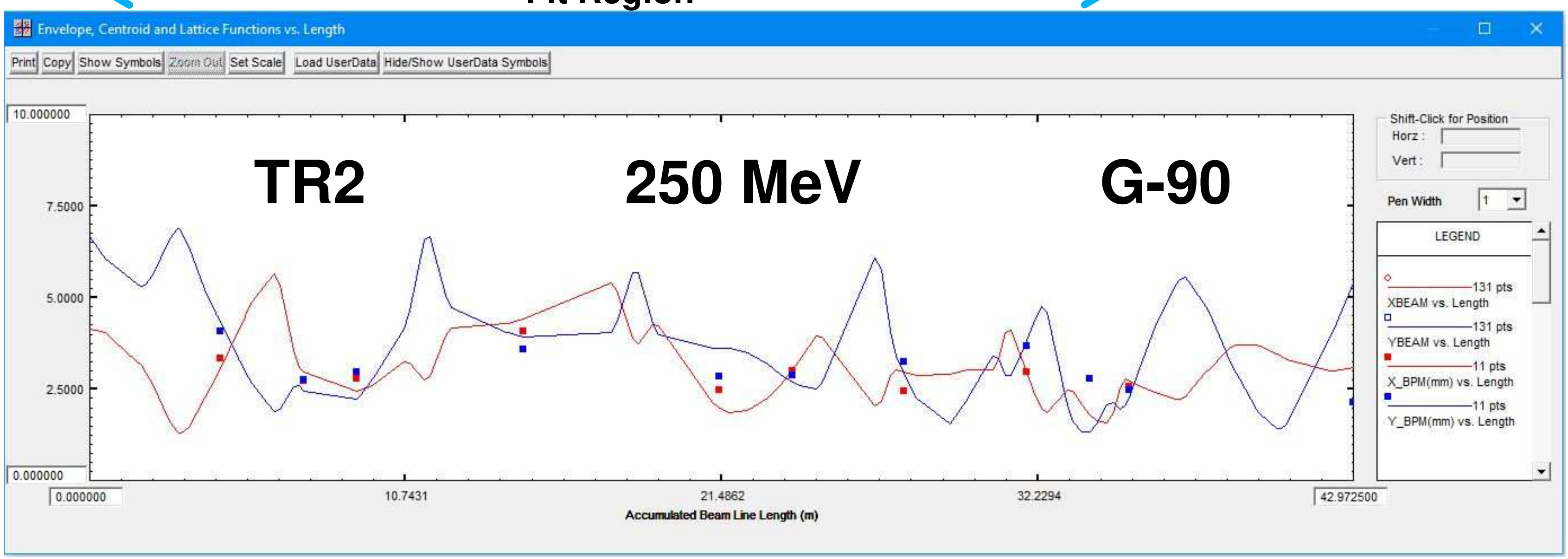
TR1 with Gantry at 90° (57.1005 meters) for
70, 250 MeV

Most results in this paper are for TR2 with gantry at 90°

Results for *Apparent* "Core" Beam



Fit Region



Reproducibility of "Core" Beam Results

Comparison of apparent beams at synchrotron exit for different data sets TR2

Semi-Axes Parameter Representation (70 MeV)
(TRANSPORT)

TR2-90° BPM_set_1 (21 Aug 2021) MINOS Core Fit FOM = 0.3684 mm

```
0.000   3.315 MM
0.000   1.216 MR      0.143
0.000   8.698 MM      0.000  0.000
0.000   1.130 MR      0.000  0.000 -0.910
0.000   4.390 M       0.000  0.000  0.000  0.000
0.000   0.000 F*      0.000  0.000  0.000  0.000 -0.975
```

TR2-90° BPM_set_2 (30 Oct 2021) MINOS Core Fit FOM = 0.3673 mm

```
0.000   3.474 MM
0.000   1.174 MR      0.083
0.000   8.570 MM      0.000  0.000
0.000   1.123 MR      0.000  0.000 -0.903
0.000   4.390 M       0.000  0.000  0.000  0.000
0.000   0.000 F*      0.000  0.000  0.000  0.000 -0.975
```

---

* The momenta spread (0.000 F above) are actually 0.0075% = 0.000075 F

Reproducibility of "Core" Beam Results

Comparison of apparent beams at synchrotron exit for different data sets TR2

Twiss Parameter Representation (70 MeV)

TR2-90° BPM_set_1 (21 Aug 2021) MINOS Core Fit FOM = 0.3684 mm
EmitX = 3.988909 pi-mm-mrad alphaX = -0.144726 betaX = 2.754992 m/rad
EmitY = 4.084098 pi-mm-mrad alphaY = 2.188974 betaY = 18.522437 m/rad

TR2-90° BPM_set_2 (30 Oct 2021) MINOS Core Fit FOM = 0.3673 mm
EmitX = 4.063131 pi-mm-mrad alphaX = -0.083607 betaX = 2.970905 m/rad
EmitY = 4.142382 pi-mm-mrad alphaY = 2.096585 betaY = 17.730822 m/rad

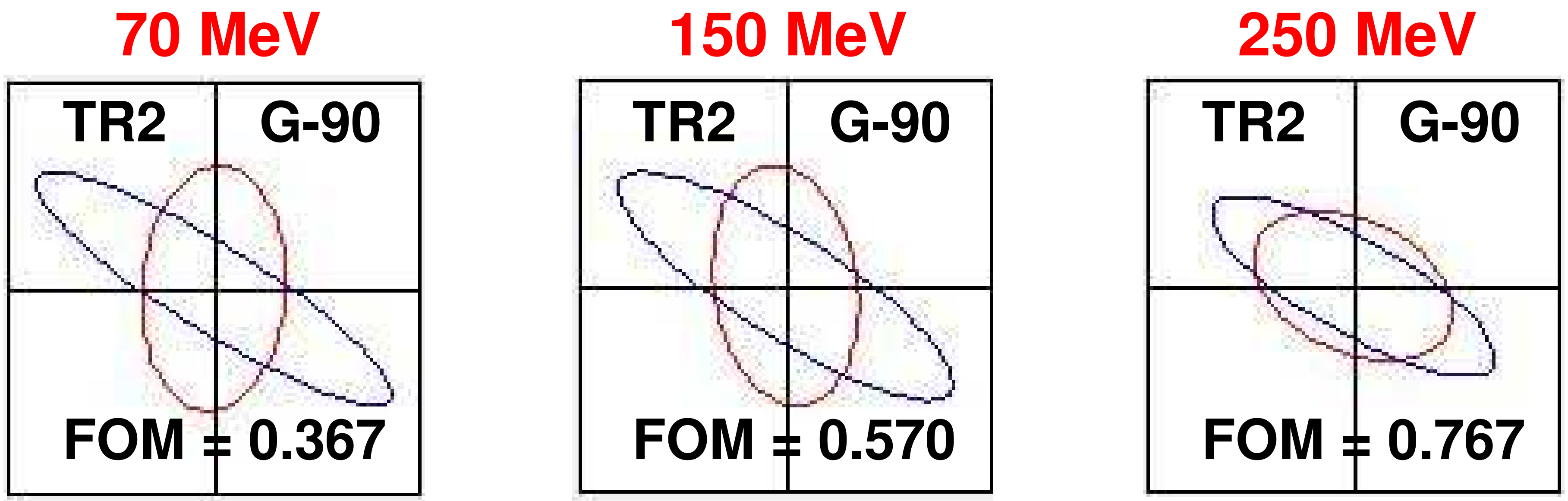
Twiss Parameter Representation (250 MeV)

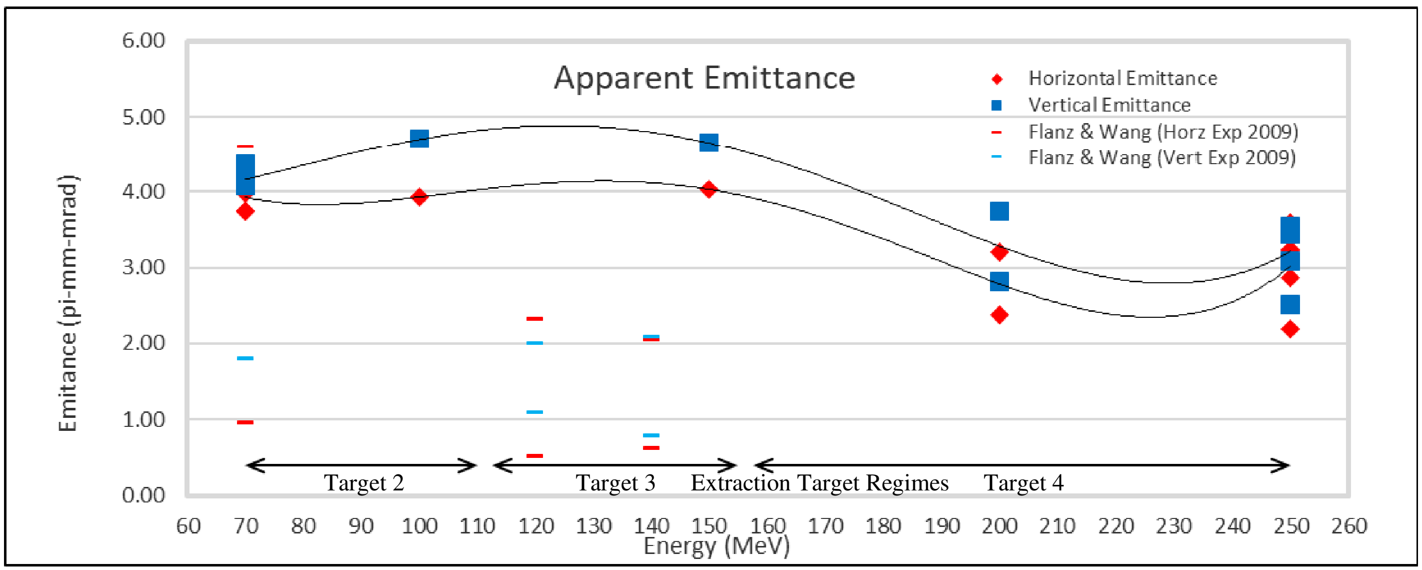
TR2-90° BPM_set_1 (21 Aug 2021) MINOS Core Fit FOM = 0.7666 mm:
EmitX = 3.218780 pi-mm-mrad alphaX = 0.370317 betaX = 7.170283 m/rad
EmitY = 3.518738 pi-mm-mrad alphaY = 1.343688 betaY = 13.226551 m/rad

TR2-90° BPM_set_2 (30 Oct 2021) MINOS Core Fit FOM = 0.6586 mm:
EmitX = 3.236696 pi-mm-mrad alphaX = 0.423833 betaX = 7.420473 m/rad
EmitY = 3.443587 pi-mm-mrad alphaY = 1.388223 betaY = 13.900795 m/rad

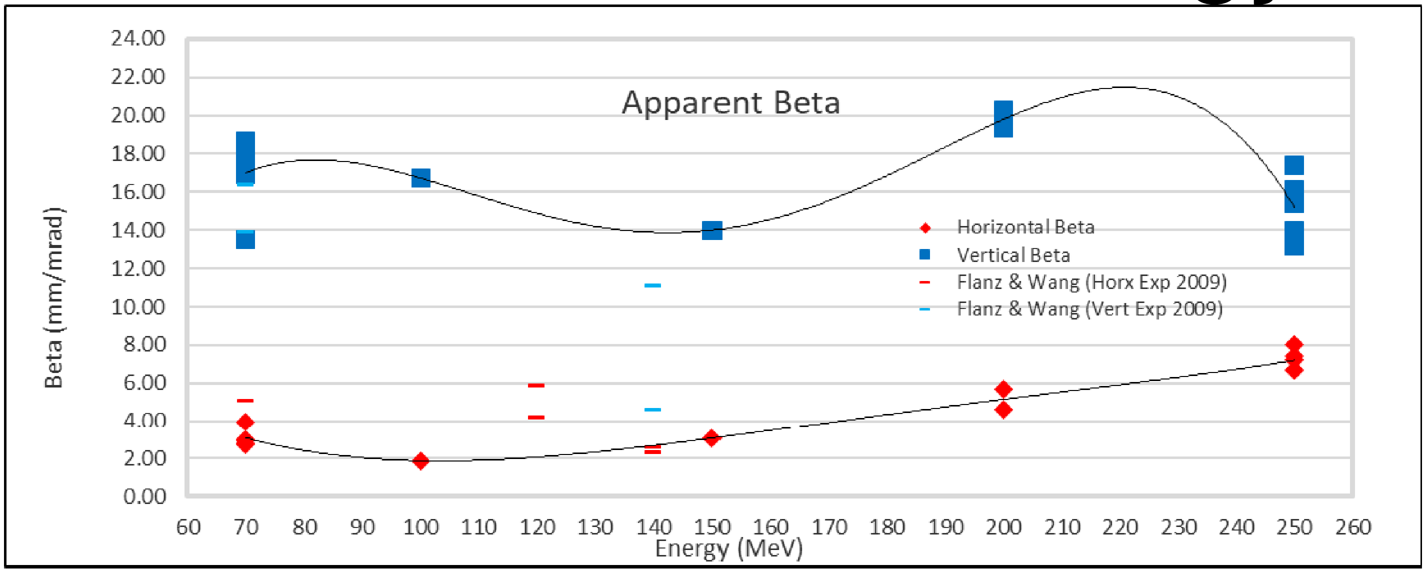
"Core" Emittance Energy Dependence

(scales 2 mrad by 10 mm)

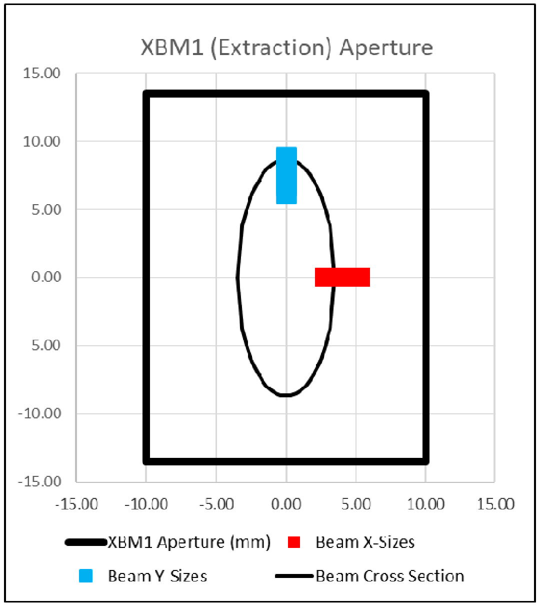


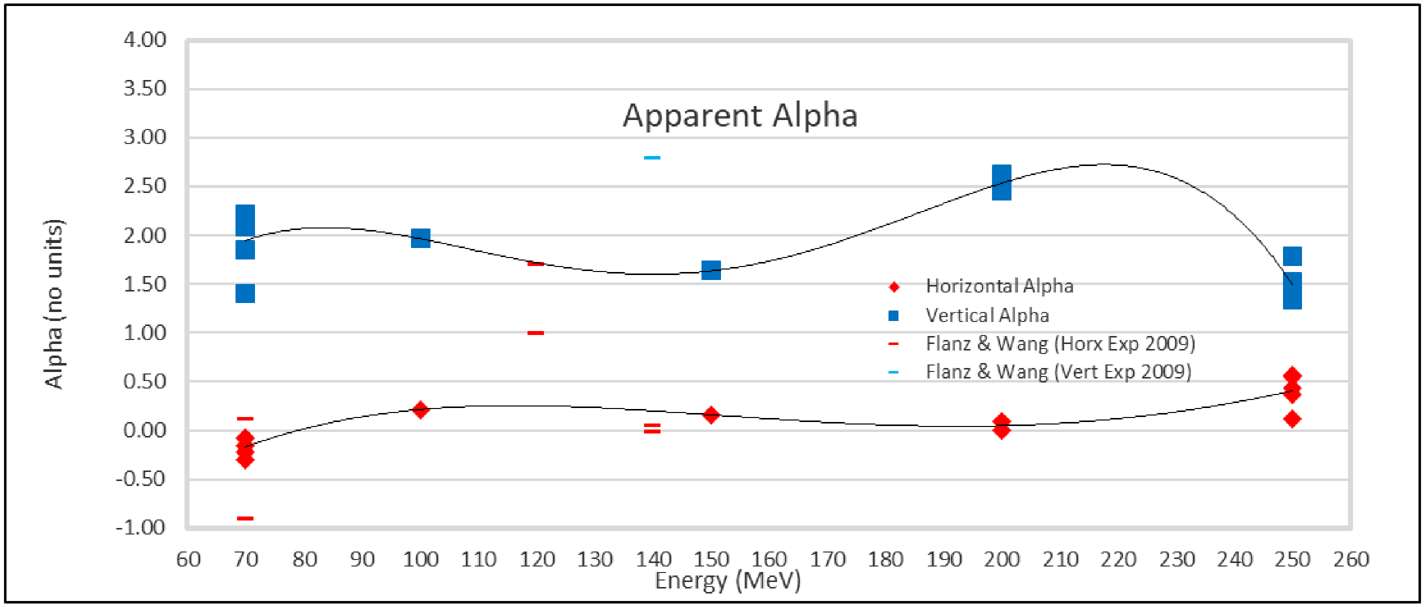


"Core" Twiss Param Energy Dependence

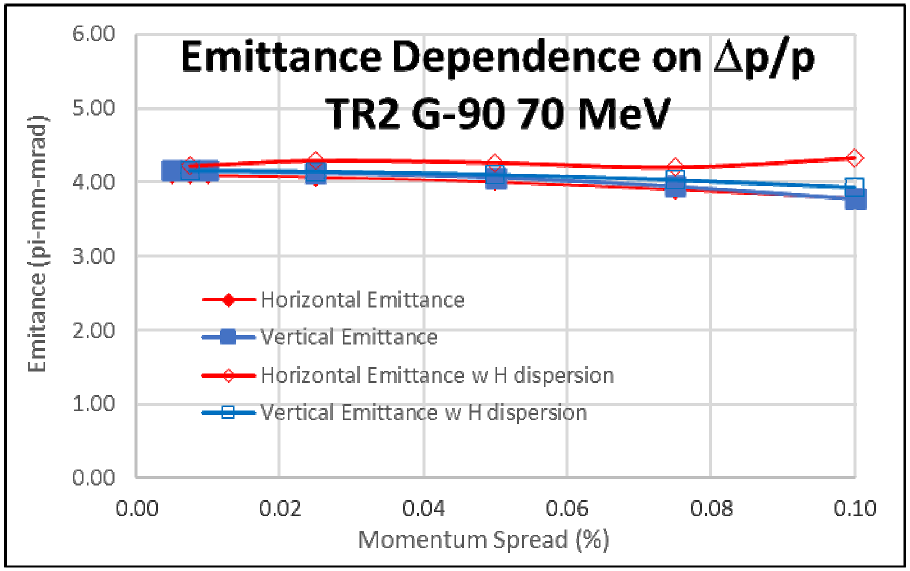


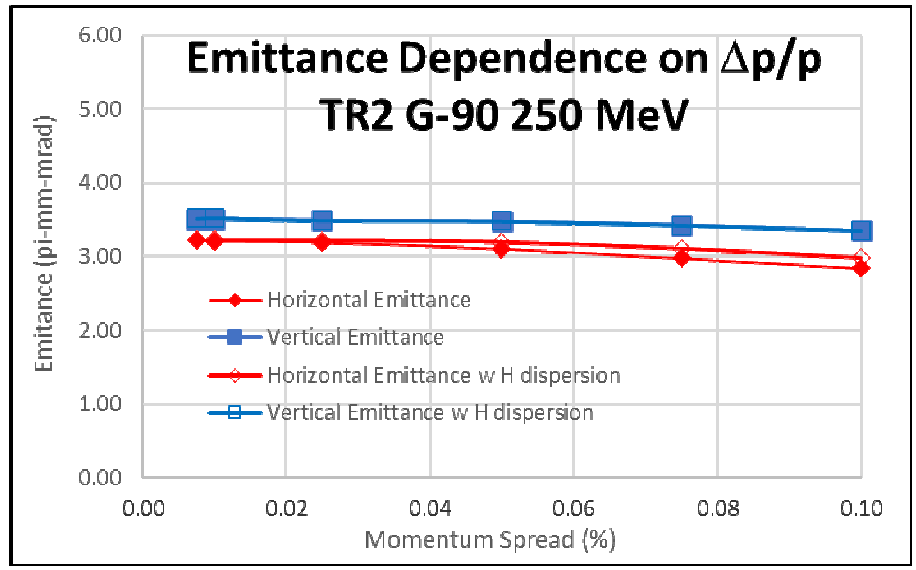
Apparent Beams Within Extraction Dipole Aperture (vacuum box):





"Core" Independent of Δp/p, Dx Assumptions



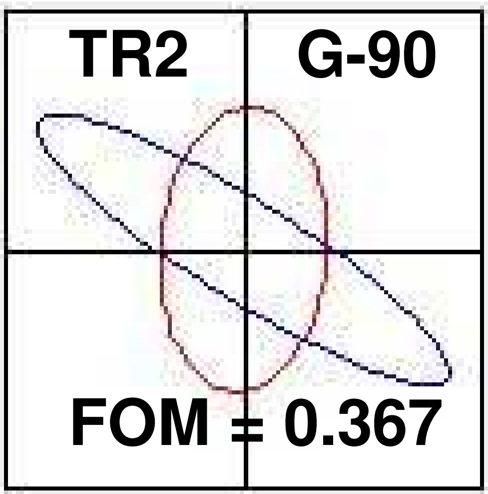


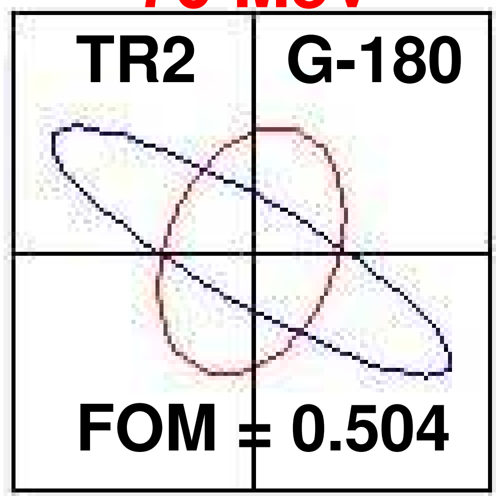
- **Core beam insensitive to momentum spread $\delta = \Delta p/p$ (♦ ♦)**
- **Core beam unchanged with dispersion (r_{16}, r_{26}) added (◊ ◊)**

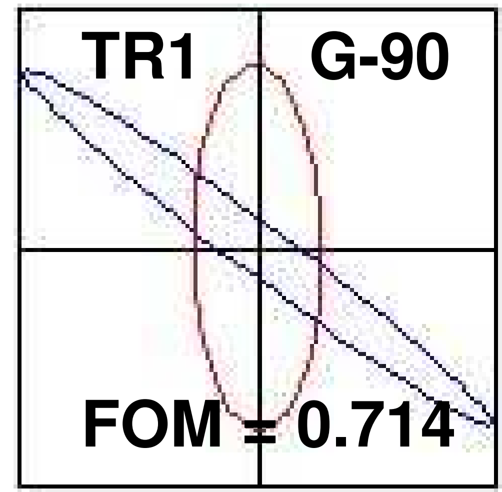
"Core" Beam Configuration Dependence

(scales 2 mrad by 10 mm)

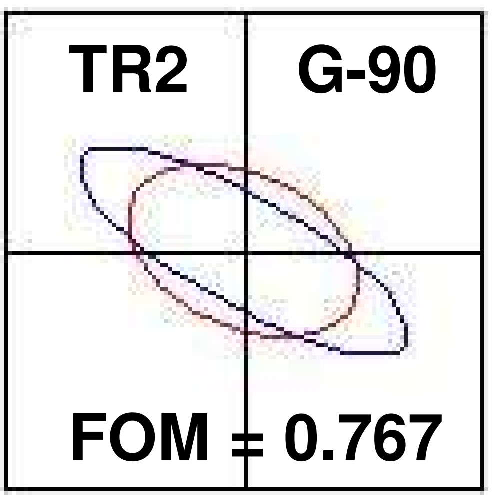
70 MeV

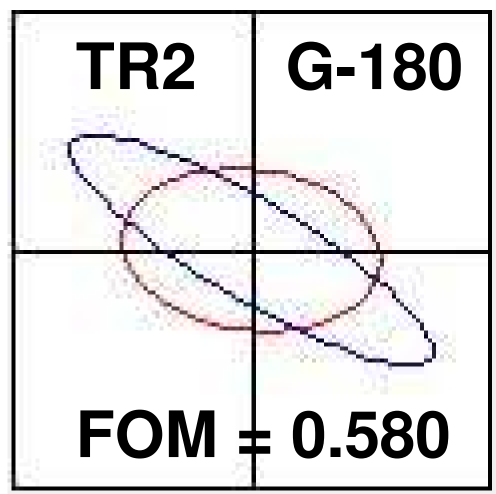


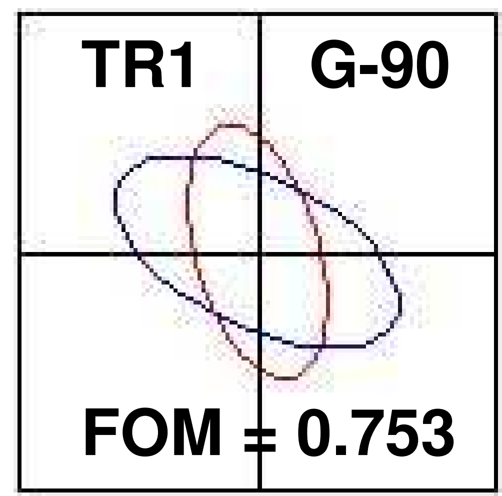




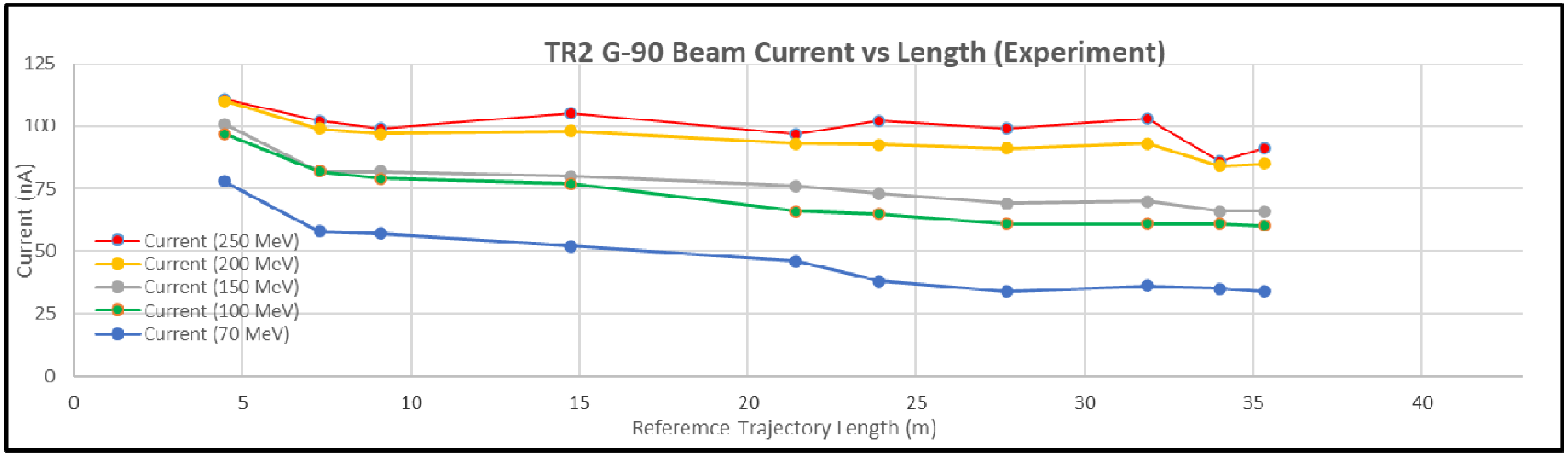
250 MeV

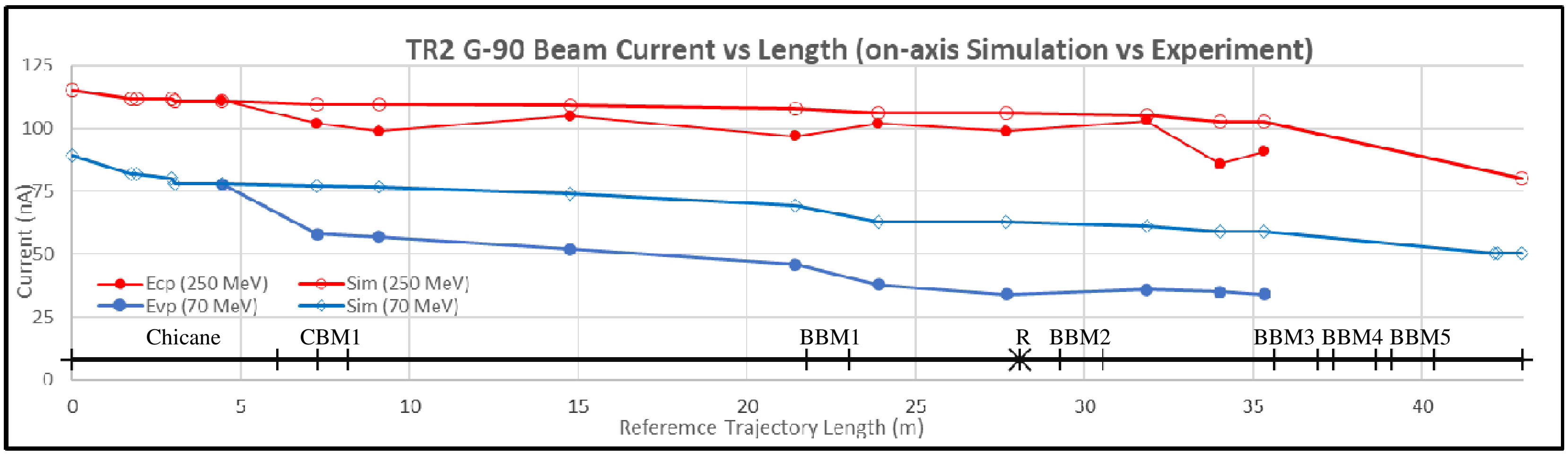






Beam Losses





- **Beam loss observed in chicane, several dipole magnets**
- **On-axes simulation (TURTLE) cannot explain all losses**

Quadrupole Scan (Q-Scan) Experiments

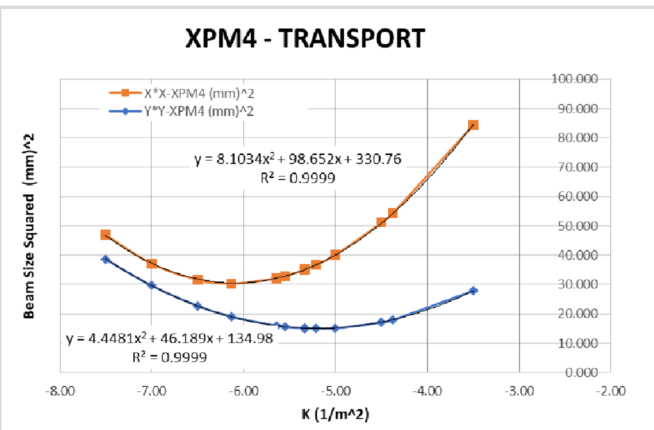
Change Quad Strength ⇒ Measure Downstream Beam

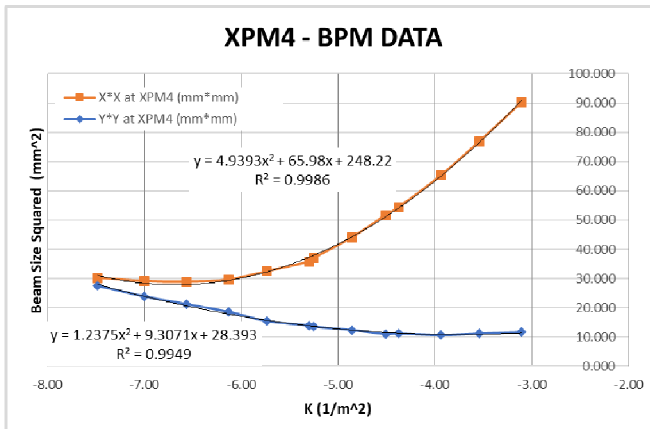
(Early) Example Below ⇒ Quad XQ3 and XPM4

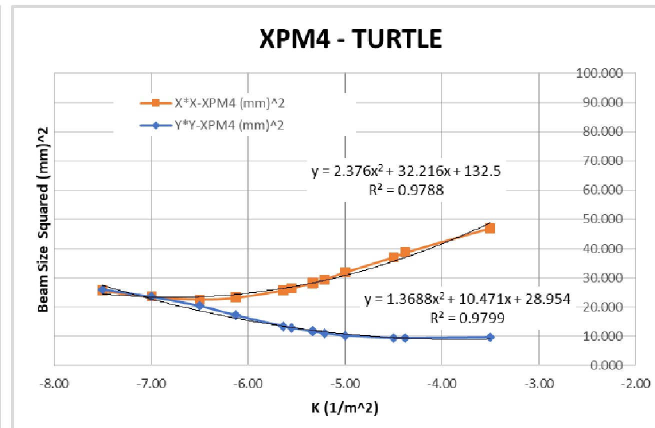
Use TRANSPORT to Select Quad & BPM

Vary Quad Strength & Measure Beam Sizes
(~23 April 2022)

Use TURTLE to Examine Losses







Emit-X = 4.289
Emit-Y = 4.146

Emit-X = 3.201
Emit-Y = 1.909

Emit-X = 2.009
Emit-Y = 1.719

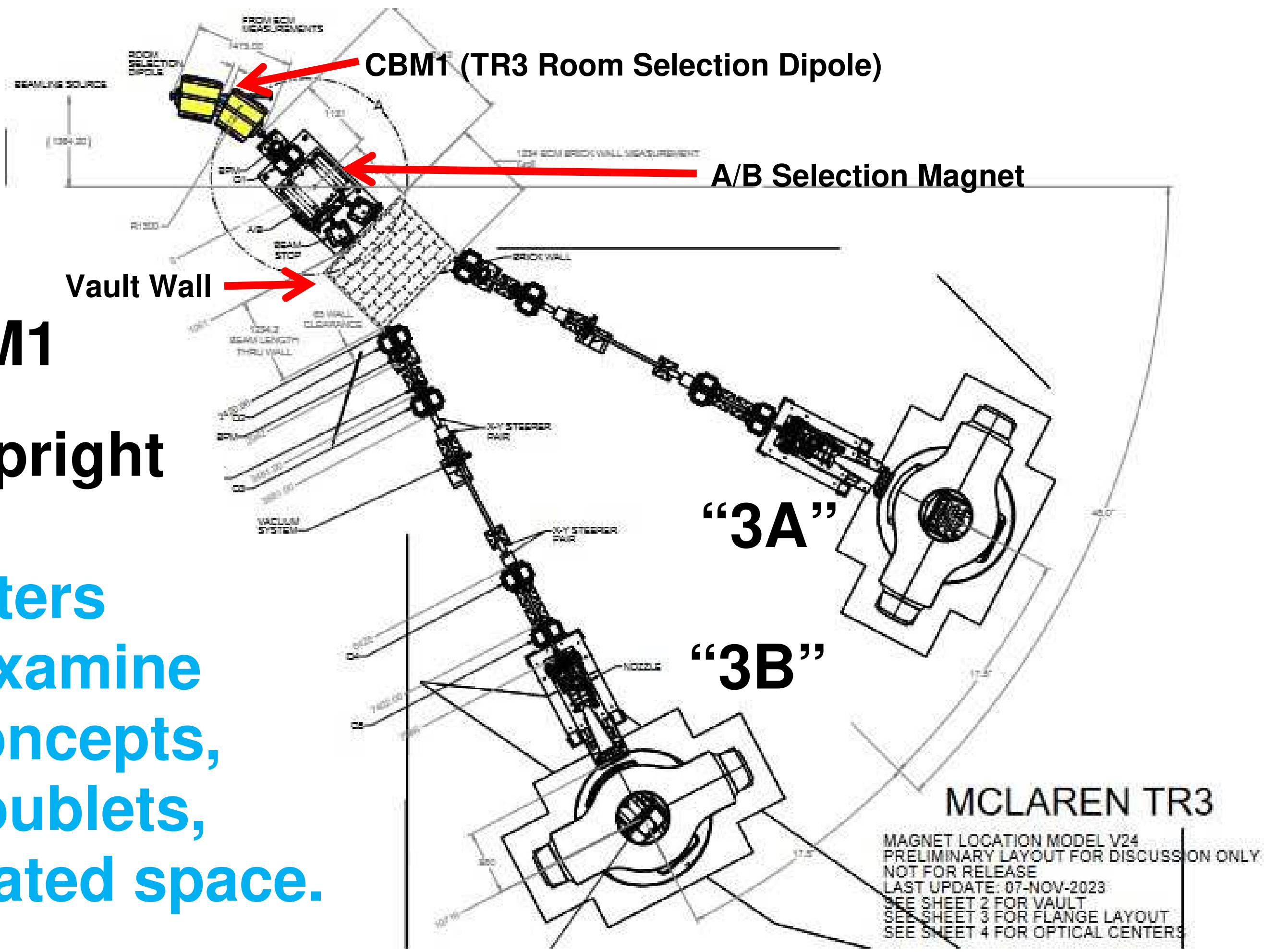
Reference: "Core" Beam: Emit-X = 3.90 ± 0.20 (70 MeV TR2)
"Core" Beam: Emit-Y = 4.21 ± 0.15 (70 MeV TR2)

Beam Loss ⇒ Confirmed Importance of Steering

An Application of Results:
Optics Design of New Beamline (TR3)

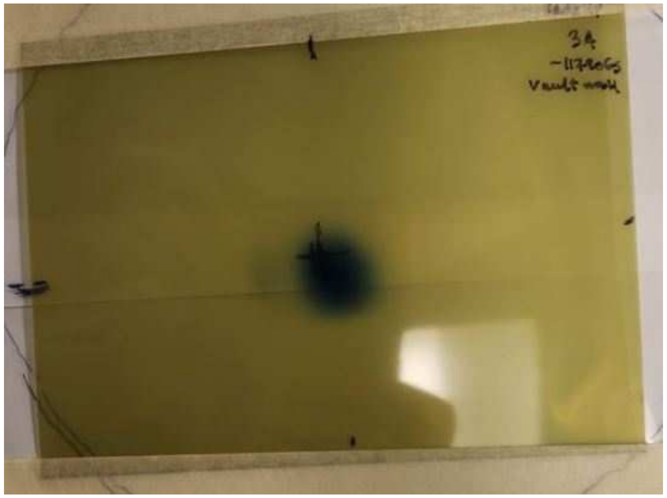
- **Fixed Beamline**
- **Two Room Suite**
- **Uses Existing CBM1**
- **Patient's Chairs Upright**

Used Beam Parameters from this study to examine 4 & 5 quadrupole concepts, chose singlet + 2 doublets, all to fit within allocated space.

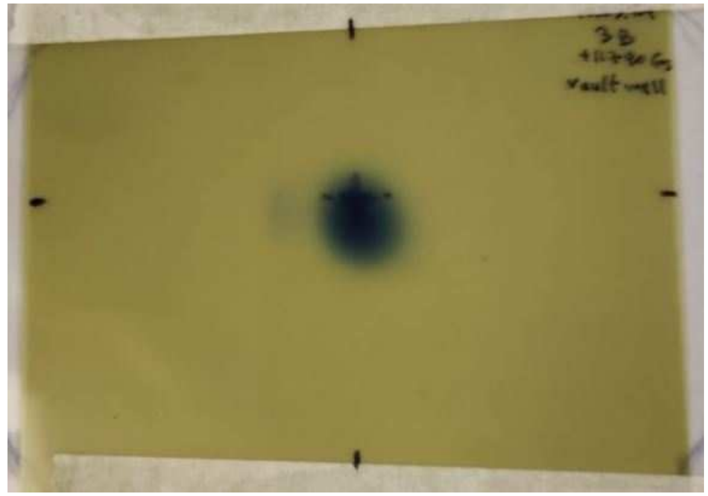


First Results thru A/B Selection Magnet

250 MeV Beam in Air (after CBM1 vacuum window)

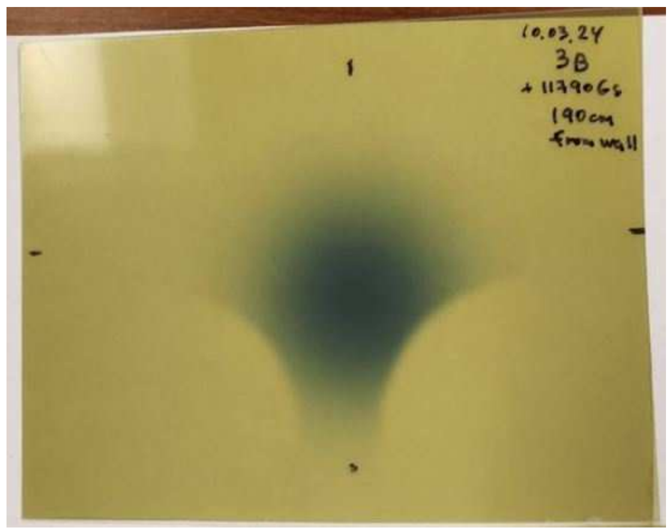


At “3A” Vault Wall



At “3B” Vault Wall

190 cm downstream of “3B” Vault Wall shows image of quadrupole



Current Status & Future Work

⇒ **TRANSPORT "Core" Beam Reproducible Baselines**

⇒ **Qualitative Agreement BPM vs TURTLE Beam Loss**

⇒ **Q-Scans & Steer-Scans Show Beam Steering Important**

⇒ **Scattering Important in Nozzle Region**

⇒ **Refine Alignment / Steering in Computer Models**

⇒ **Fill Out Beam Energy and Gantry Angle Matrix**

⇒ **Include Scattering Contribution in Nozzle Region**

⇒ **Support New Beamline (TR3,TR0) Commissioning**

⇒ **Formulate & Test Operational Improvements**

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