The piE5 Beamline Model and Going Forward

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Workshop is being generously supported by an award from the Gordon and Betty Moore Foundation

Overview

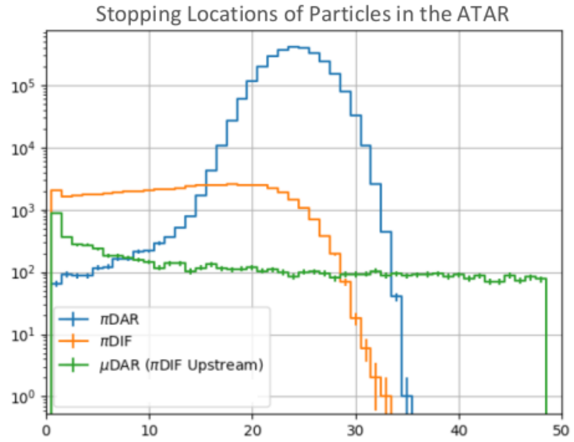
- Experimental requirements
- piE5 beamline
- PIONEER Run '22 results
- TRANSPORT studies
- Major upgrades
- Beam development plan

All PIONEER data preliminary

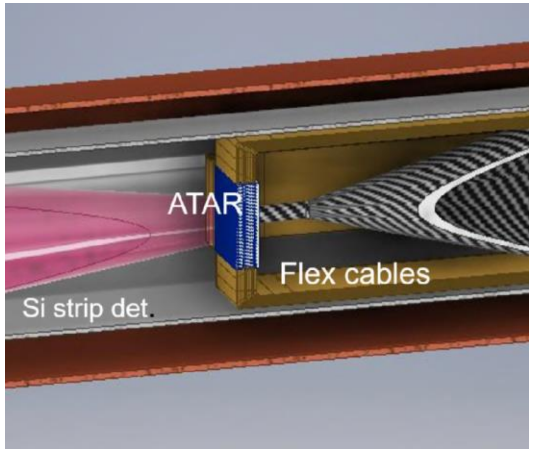
Requirements Phase I

- Rate
  - 300k π/s stopped in ATAR

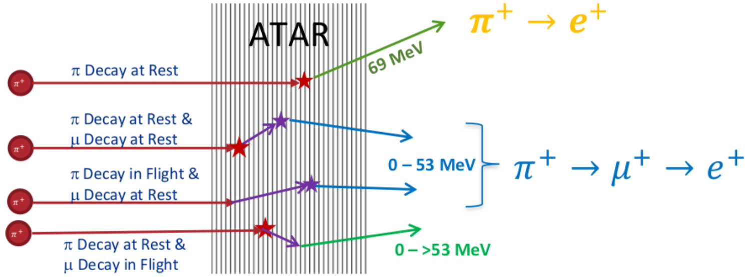
$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$



- Momentum bite
  - Δp/p <2%
- Momentum
  - lowest p preferred 55-70 MeV/c



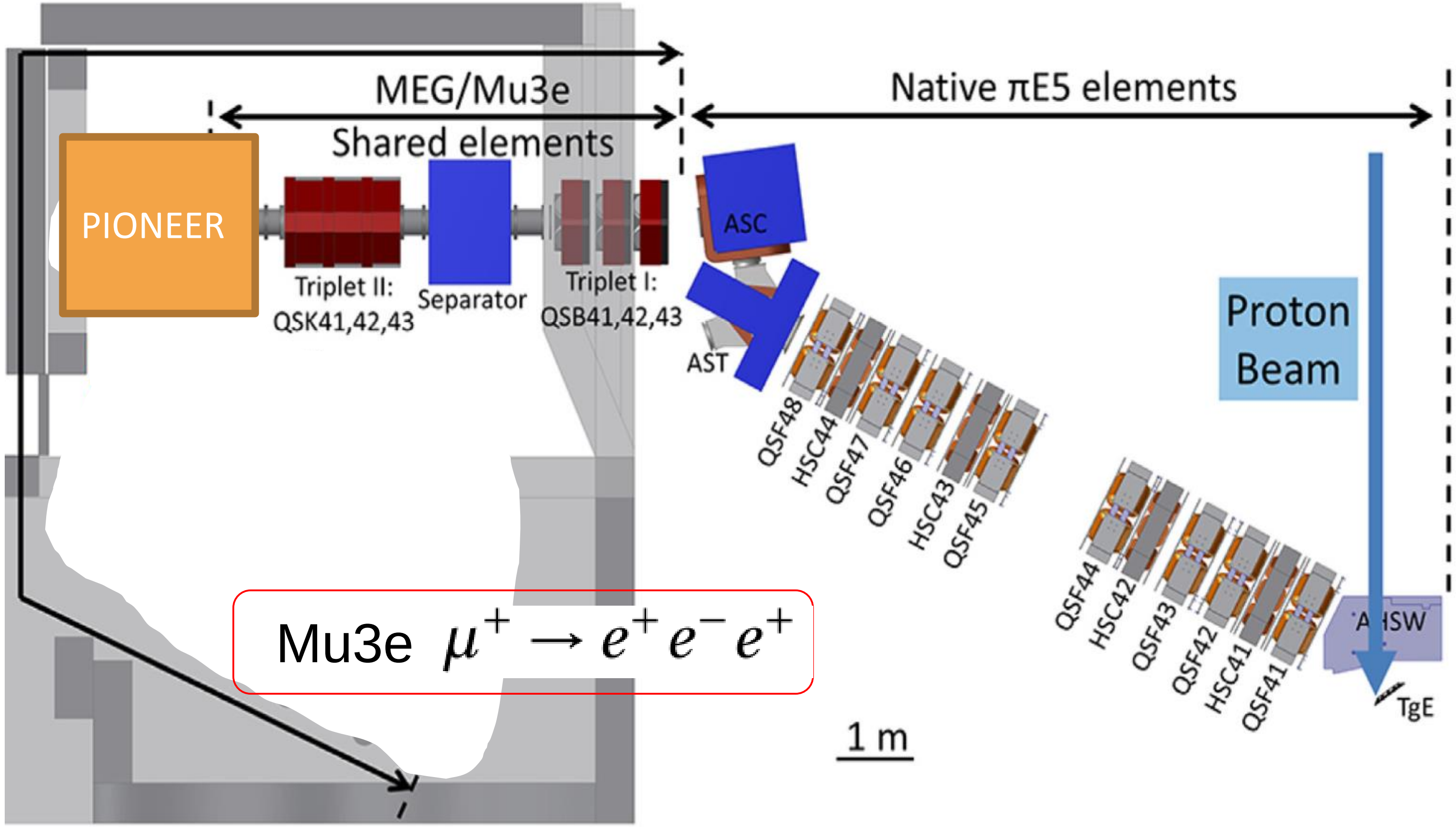
- Spot size
  - smaller than ATAR Size of 20mm x 20mm
- Particle contamination
  - μ/e less than 10% of π



piE5 @ PSI - World's Brightest Stopped Pion Beam

MEG $\mu^+ \rightarrow e\gamma$

Main properties of πE5 beam line		
Solid angle		150 msr
Momentum range		10-120 MeV/c
Length		~~10.4 m~~
Momentun	acceptance (FWHM)	10%
	resolution (FWHM)	2%
Angular divergence (FWHM)	horizontal	450 mrad
	vertical	120 mrad
Spot size (FWHM)	horizontal	15 mm
	vertical	20 mm



Mu3e $\mu^+ \rightarrow e^+ e^- e^+$

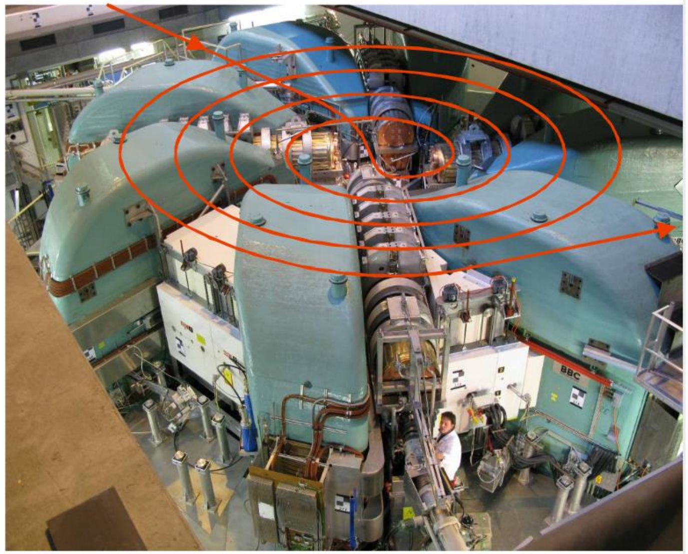
- carefully studied for fundamental muon experiments
- still surprises for pions, unique PIONEER requirements

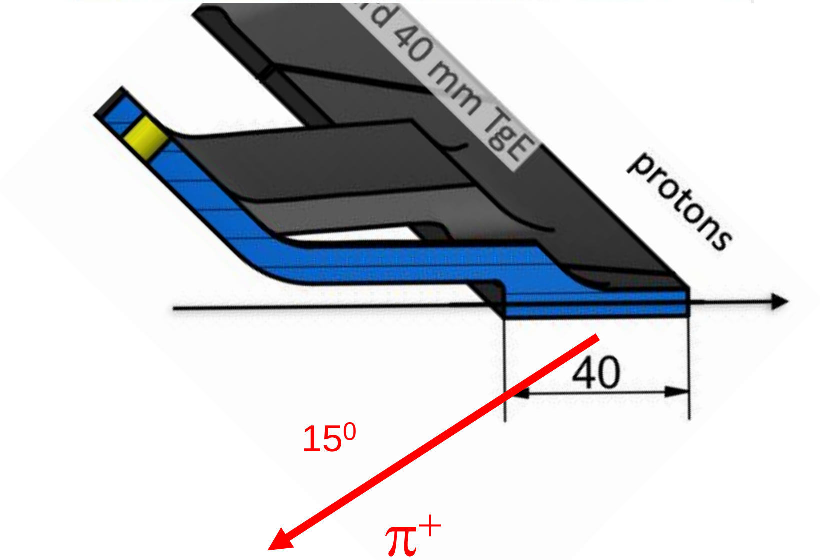
experimenters have full control over beam line (after first bend)

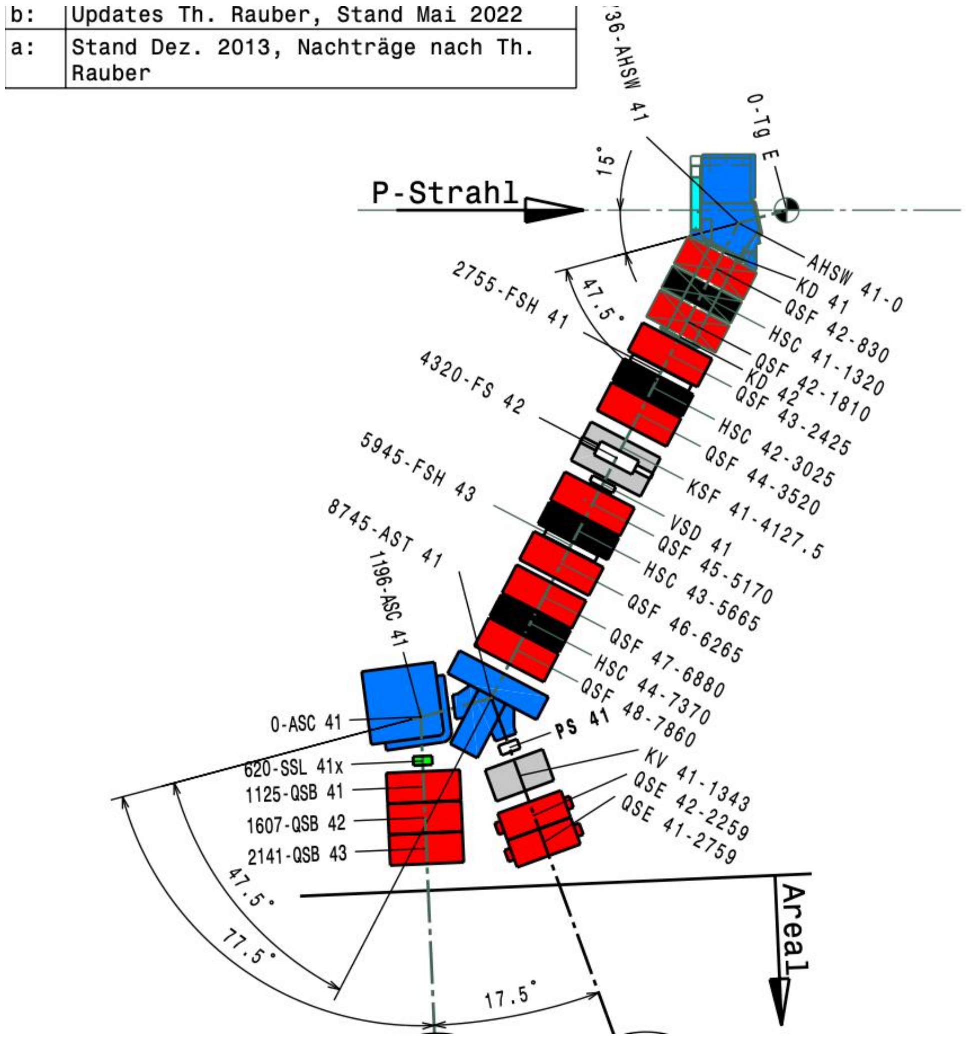
Target E and Pion Production

- 8 sector Magnets:	0.6 – 0.9 T
- weight per magnet:	250 tons
- 4 cavities 50.63 MHz:	850 kV
- 1 flat-top resonator:	150 MHz
- harmonic number:	6
- beam energy:	590 MeV
- beam current (now):	2.4 mA
- injection radius:	2.1 m
- extraction radius:	4.5 m
- sprial angle	35°
- relative losses:	~$2 \cdot 10^{-4}$

Beam power: 1.4 MW







- 165^0 to proton beam
- bending $+47.5^0$, -47.5^0, $+77.5^0$

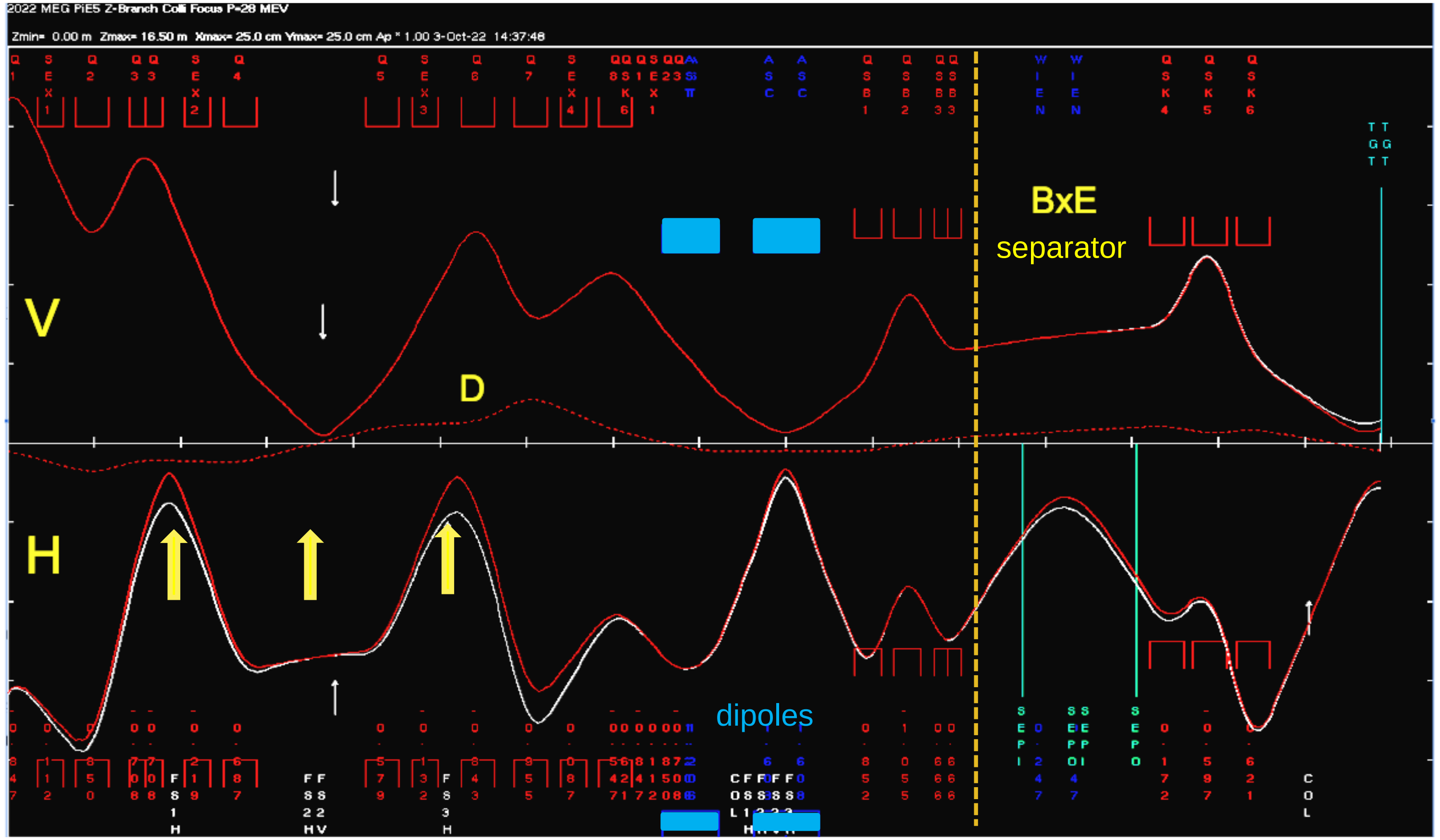
Simple Transport Model

- Compare Δp/p= 3/0 %
- 1st order only
  - 2nd order diverges
  - other discrepancies to PIONEER Run ‘22
- upstream part in shielding
  - indirect diagnostics with slits

π^+

MEG tune adjusted to PIONEER geometry, P-R Kettle

beam envelope in V-H planes



20 cm

20 cm

extraction, momentum selection and achromat

particle separation, focus on target

Overview

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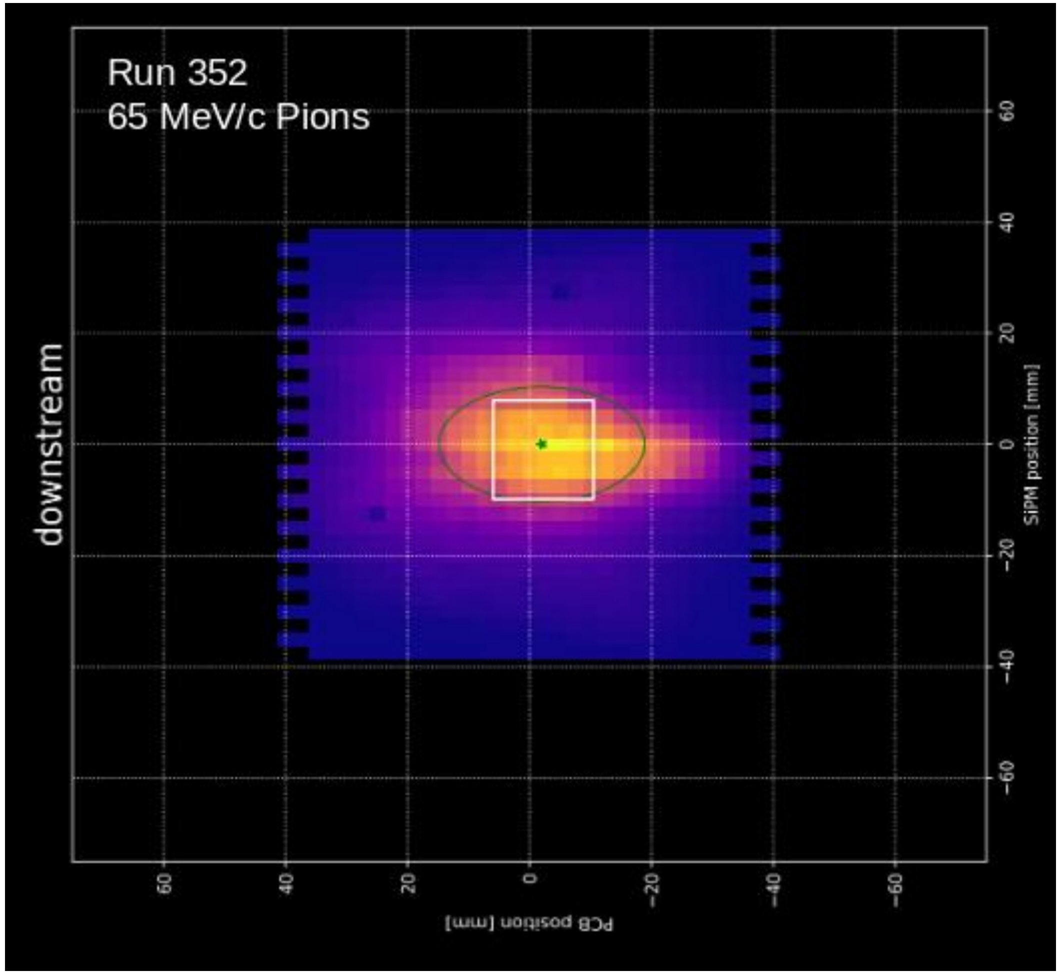
Good Enough Focus ?

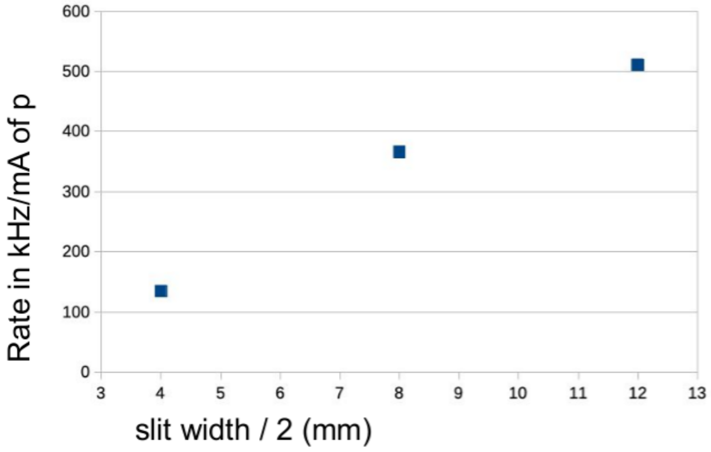
- Beam behaves as expected (basic p scaling)
  - we measured 28 MeV/c muons and
  - pions of 55, 65 and 75 MeV/c
- Pions better focus than surface muons
- But only 46% of beam in ATAR box
- AST/ASC combination not problematic
- Not yet



- Rate: 633 kH / 46 % in ATAR Box
- Mean X = 0.3 mm
- Mean Y = 0.2 mm
- Sig X = 23 mm
- Sig Y = 10.1 mm

Sufficient Rate and Small Δp/p ?

- Cannot answer without determination of Δp/p
- First impression
  - 55 MeV/c insufficient
  - 65 MeV/c enough rate



- Longitudinal phase space (i.e. Δp/p), two methods being analyzed

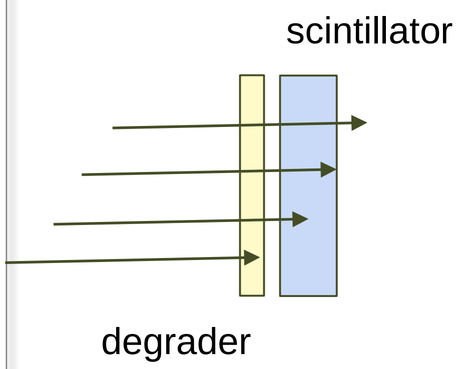
Time of flight

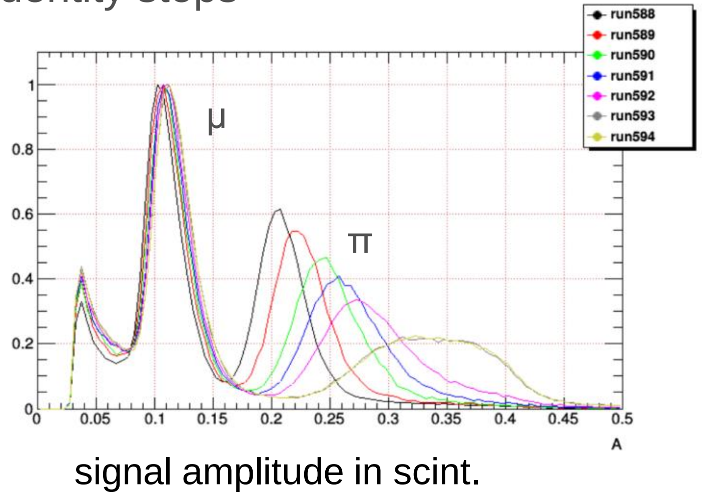
- 16m beamline
- 1% Δp/p ~ 1 ns (65 MeV/c)

p (MeV/c)	55	65	75
TOF (ns)	145.57	126.42	112.75

Direct stopping measurement with range curve

- pion signal amplitudes with different degraders
- use π→ μ sequence to identity stops



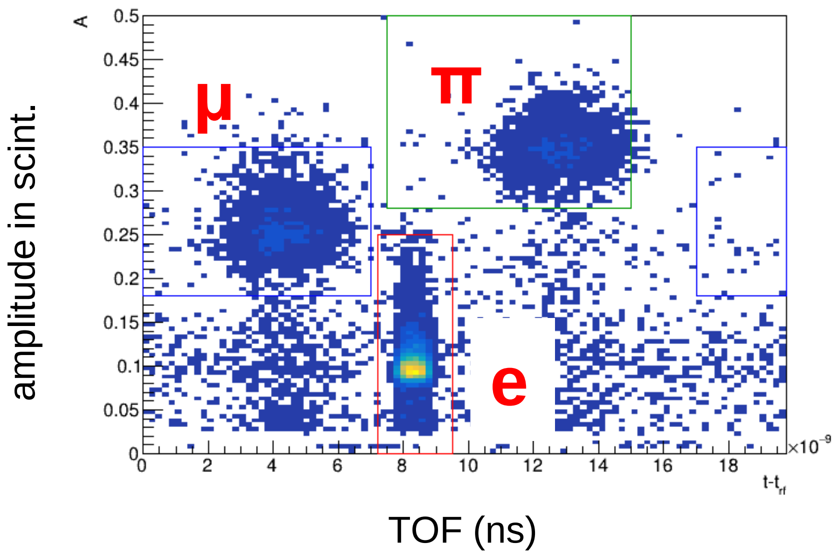


Particle Separation Good Enough?

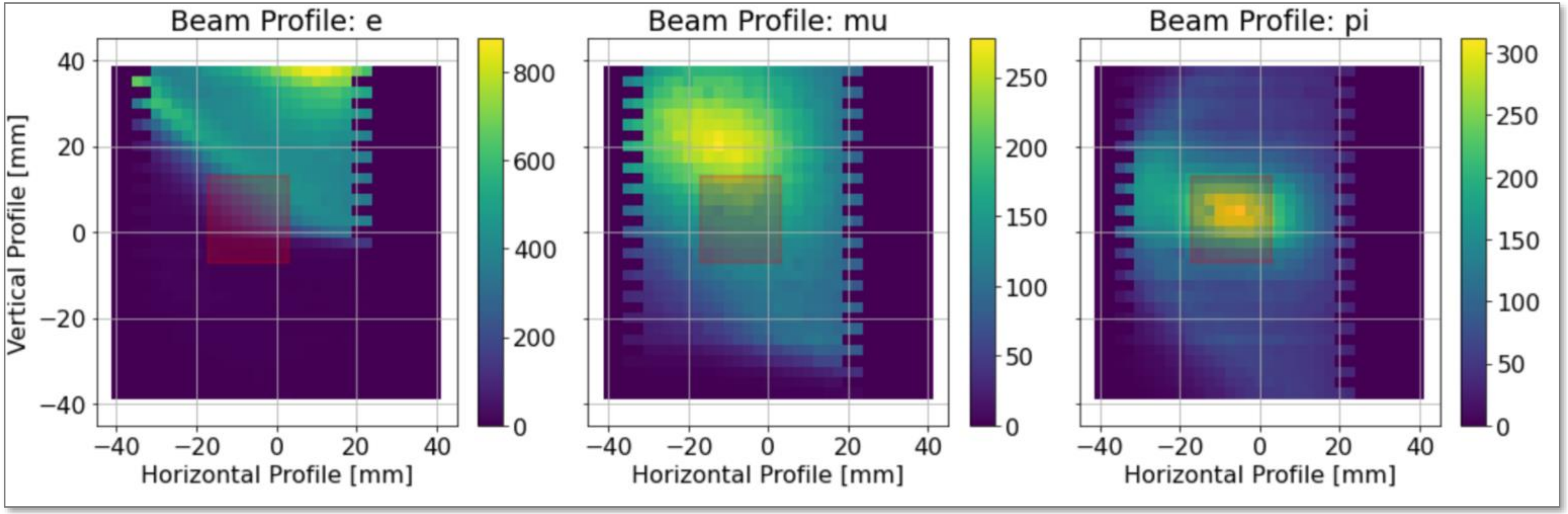
No

location of collimator !

Separator HV can be increased

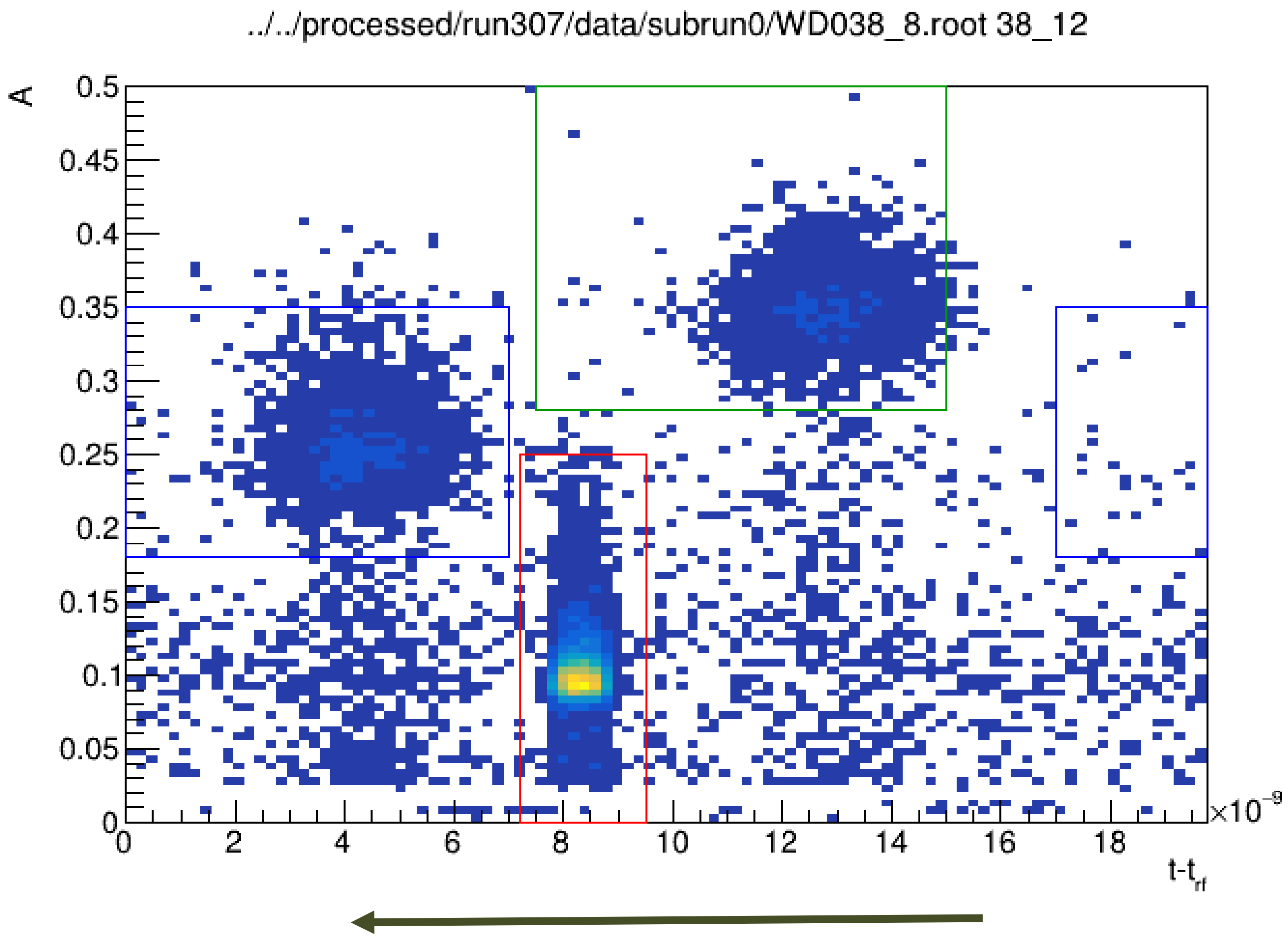


In area restricted to ATAR
(optimistic accounting)
e: 25.0%
μ: 32.1%
π: 42.9%



Patrick
Josh

Dispersion at Target Location?

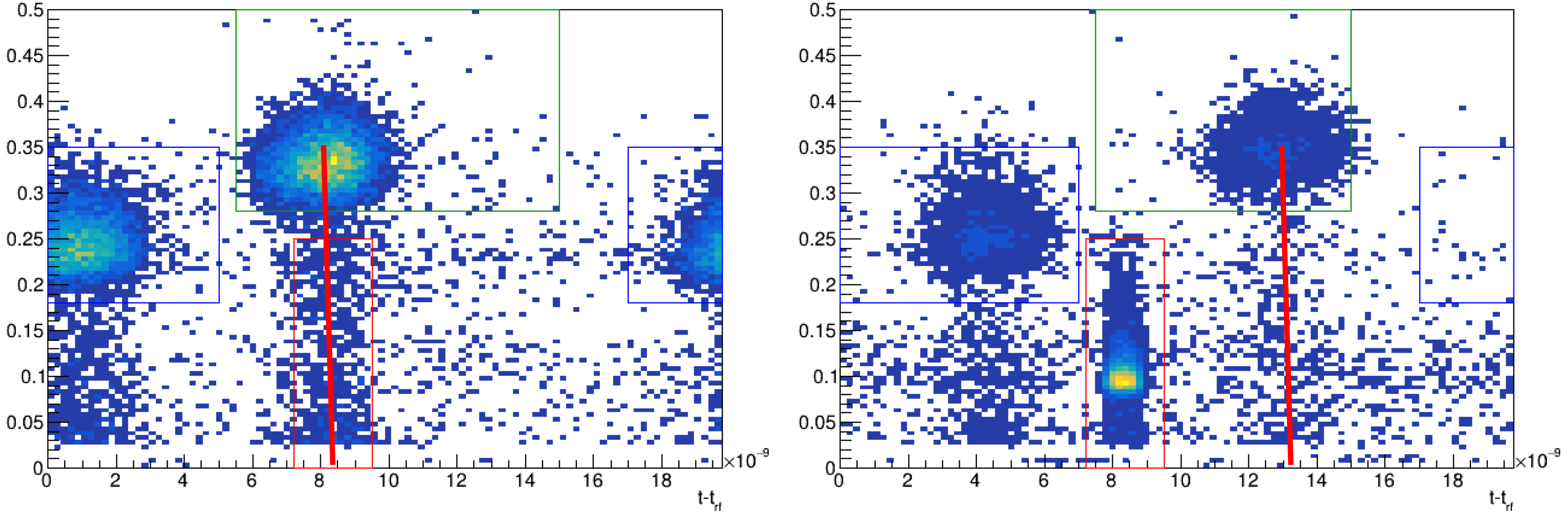


Patrick

TOF changes when when detector moves 5 cm to the left

X=X(P), significant dispersion D at target location, deteriorates focus.

Dispersion at Target Location?



$$\frac{dTOF}{dx} \approx 0.9 \text{ ns/cm}$$

D~1 cm/%
similar to dispersive section??

Other Results

- Momentum slits inconsistent with simple TRANSPORT model

- Beam meandering in upstream channel

- Quad scan to measure phase space at target
  - indirect, not yet analyzed
  - next time direct measurement with wire chambers?

  - important for beam optimization and extension

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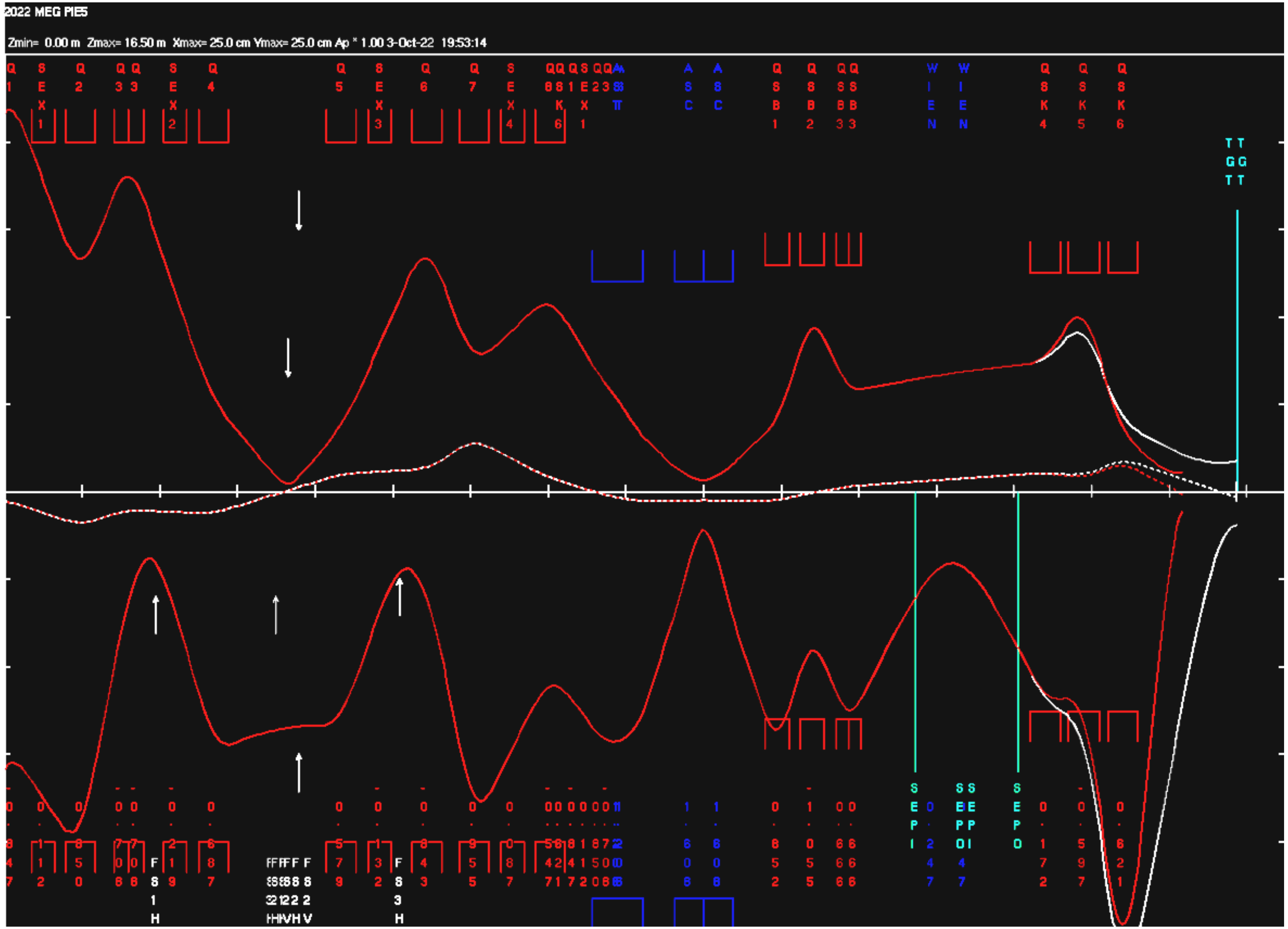
Final Focus Variants

- vary focus distance
  - closer focus promising
  - larger final quads required
  - but limited by d and calo opening angle

d (m)	FWHM-x	FWHM-y
0.6	1.07	1.15
1.29	1.9	1.8

- typically similar/poorer results with inverted last triplet used in run'22 ??



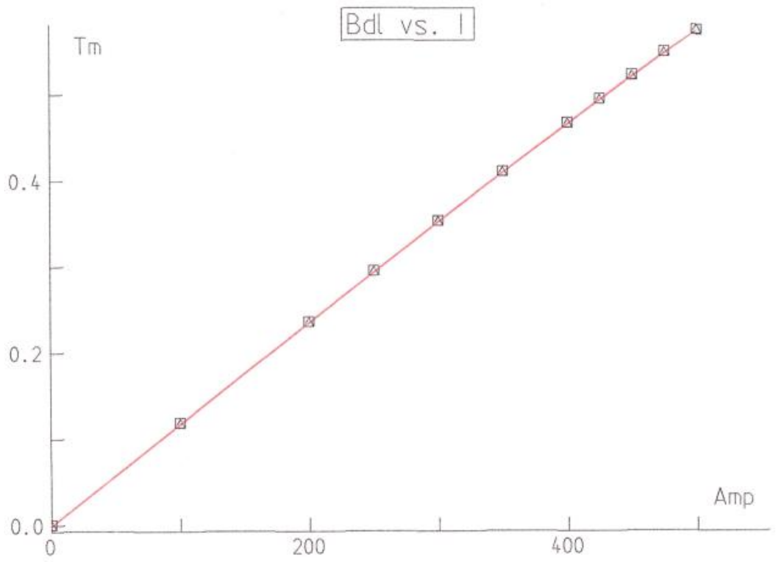
Magnet Calibration

- Magnet calibration from PSI sources (P-R Kettle and old manuals)

$$B = a_0 + a_1 I + a_2 I^2 + a_3 I^3$$

magnet	a0	a1	a2	B/P
QSF	0.00	9.052		G
piE3 manual	0.84	9.189	-0.00374	G
HSC	0.28	9.158		G
piE3 manual	1.15	9.227	0.00000	G
QSB	17.59	17.588		G
piE3 manual	0.00	17.066	0.00941	G
QSK	18.03	18.026		G
piE3 manual	7.14	18.246	-0.00902	G
AHSW	0.28	0.285	-0.00001	MeV/c
PiE5MagnetGroup	0.04	0.287		MeV/c
AST	2.50	12.727		G
ASC	9.80	15.356		G
SSL	0.20	3.569		G

example AST



- Opera field maps available (?), new maps of shielded magnets impossible

- Unfortunately, when translating Run’22 current files, beam optics does not seem correct ??

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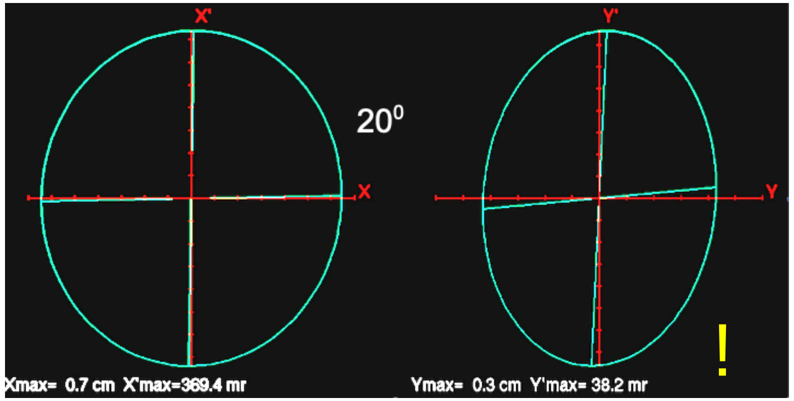
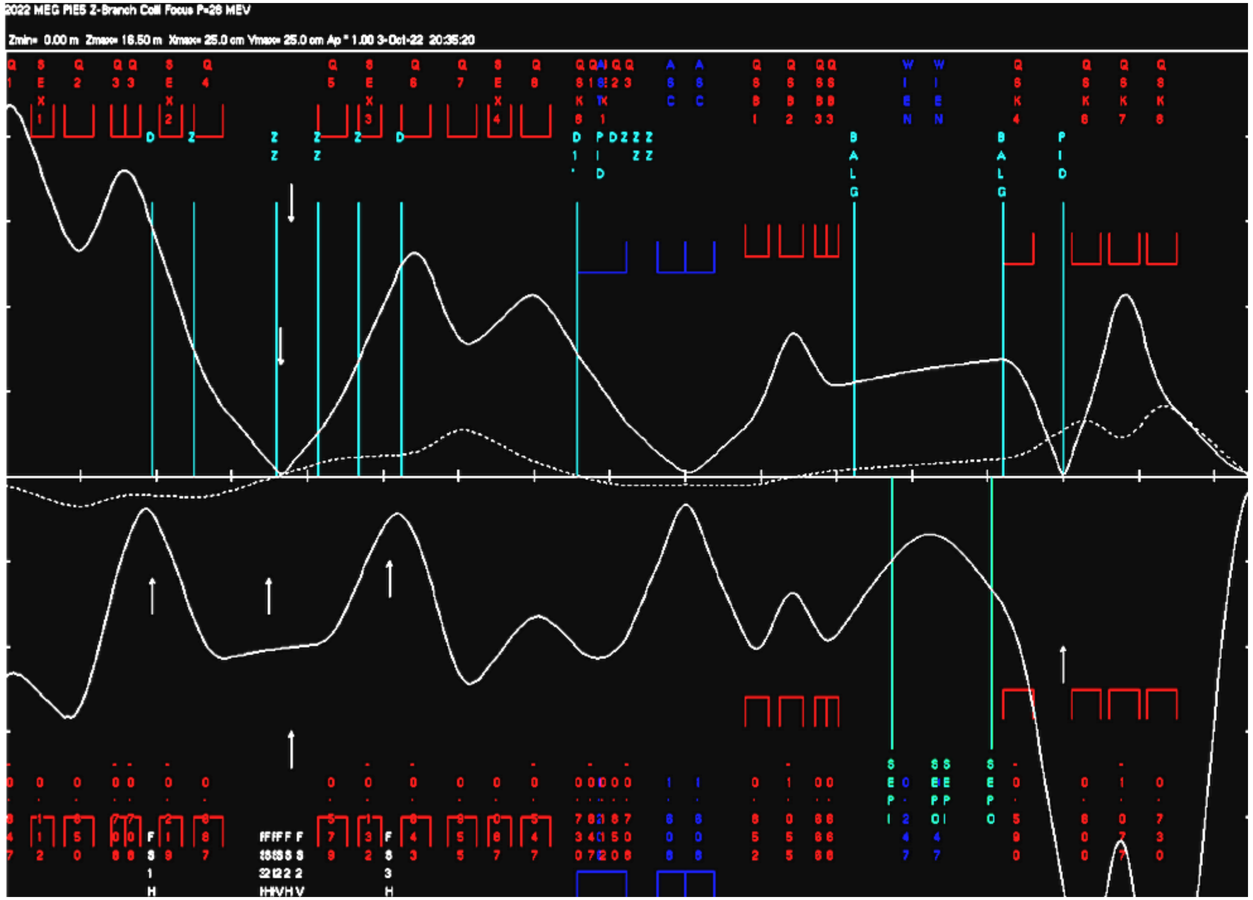
Extend Beam with Two Vertical Foci

- For particle separation and target focus two separate foci required, so that background is rejected outside of detector
  - 1st focus separates particles after ExB velocity filter and reject μ and e on collimator
  - 2nd focus is a double x/y focus aimed at ATAR

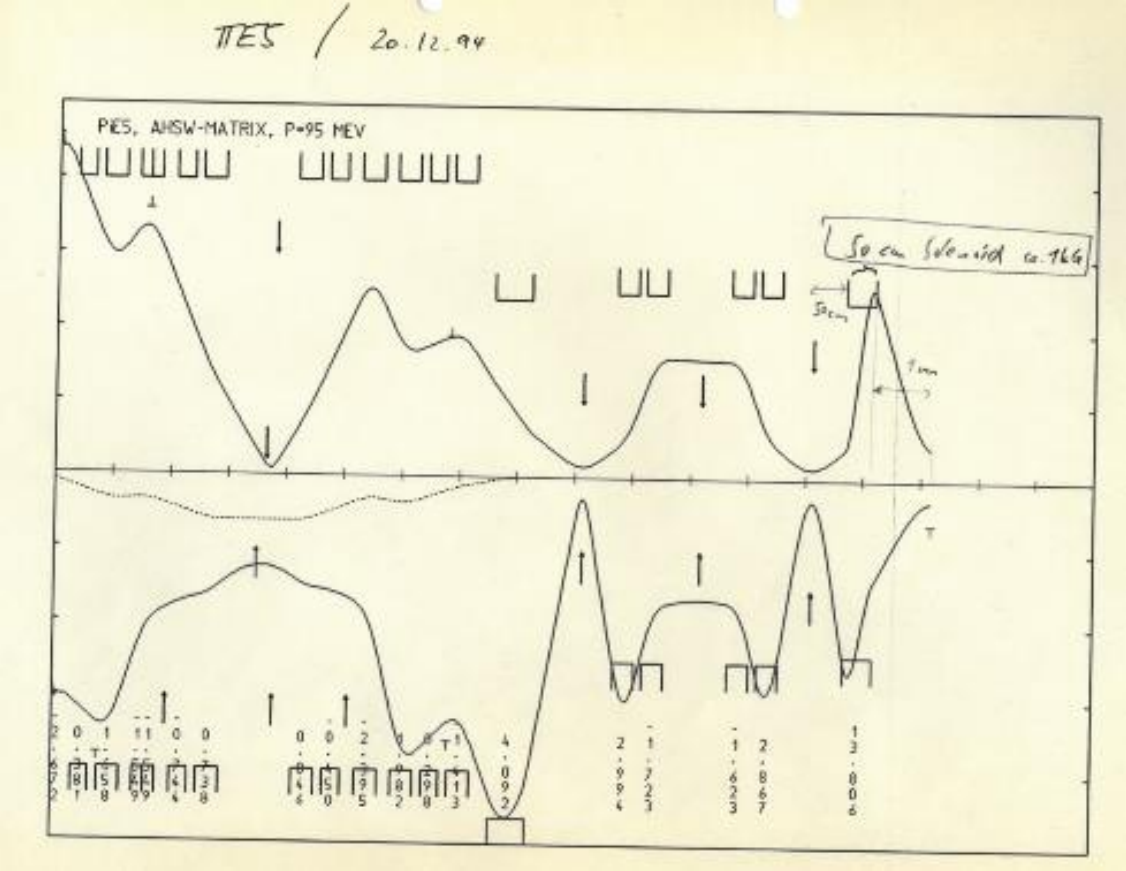
- First attempt with s-t promising
  - large final magnet
  - phase space
    - initial x: 240 π cm mr
      y: 9 π cm mr
    - promising final focus

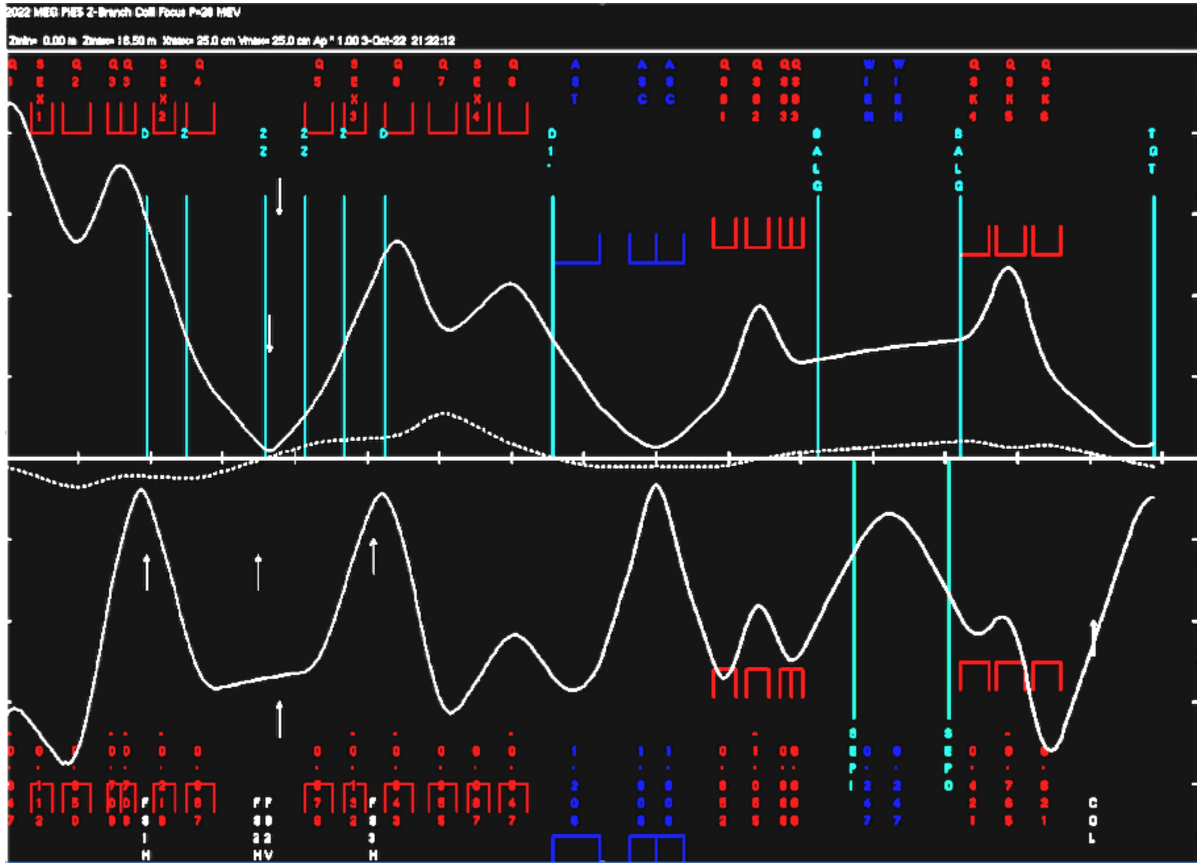




Smallar Momentum Bite

another exercise in history





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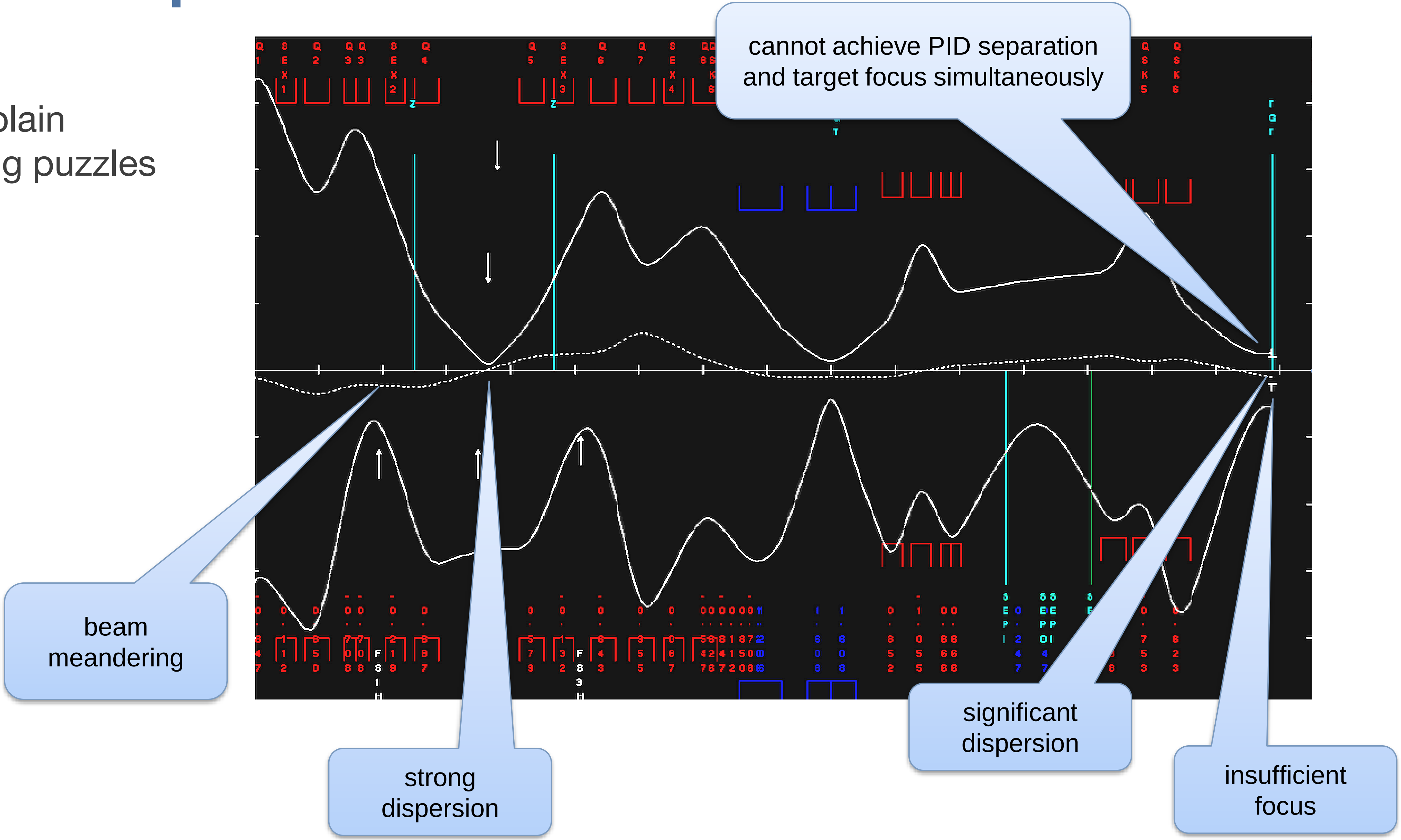
Beam Development Plan

- Higher order calculations and corrections (chromatic and large transverse phase space)
  - modern programs: BMAD, COSY, G4BL
- Characterize individual elements
  - including field maps
  - compare transfer matrices in different programs
  - resolve inconsistencies with actual current files used
- Beamline
  - upstream
    - modern pion production and first bend model (HIMB) (currently historic 2^{nd} order matrix is used in TRANSPORT)
    - systematic measurement program with slits
    - proper higher order sextupol corrections
  - downstream
    - optimize separation and final focus

Beam Development Plan

- Explore/explain most striking puzzles



Beam Development Plan

- Higher order calculations and corrections
  - modern programs: BMAD, COSY, G4BL
- Characterize individual elements
  - including field maps
  - resolve inconsistencies with actual current files used
- Beamline
  - upstream
    - systematic measurement program with slits
    - modern pion production and first bend model
    - proper higher order sextupol corrections
  - downstream
    - focusing and separation
- Explore/explain most striking puzzles

- Major upgrade studies
  - **Two vertical foci**
  - upstream retune for large dispersion
  - dE/dx π/μ/e separation in last bends?

Summary

- Overall promising results, but
  - PIONEER requirements are challenging and unique
  - lot of work remains towards realizing the potential

  - often success of ambitious experiment intimately linked to beam quality

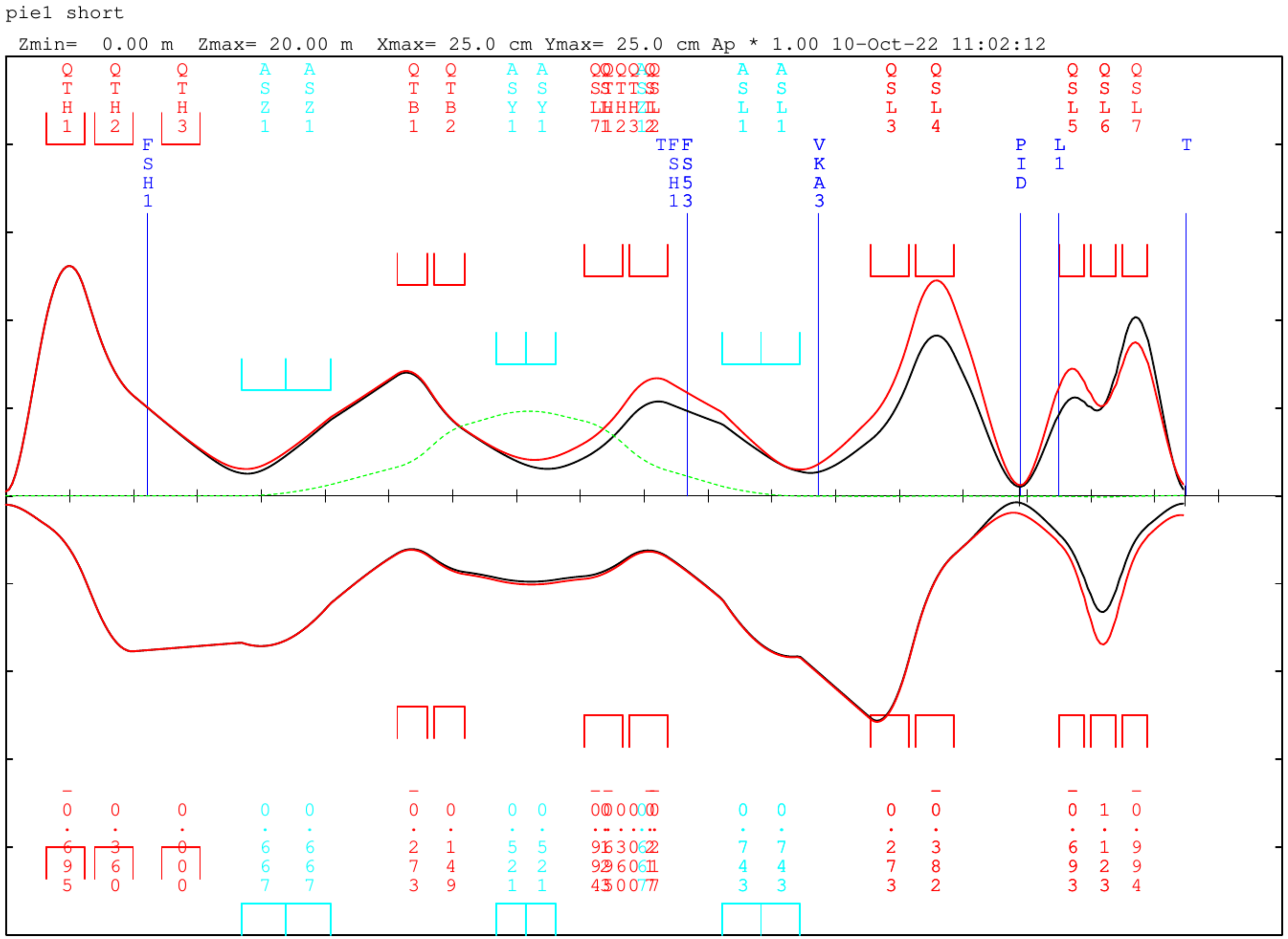
- Rate
  - 300k π/s stopped in ATAR — ok
- Momentum bite — can improve (?)
  - Δp/p <2%
- Spot size — that's hard, impact on exp.
  - smaller than ATAR Size of 20mm x 20mm
- Particle contamination — can improve (?)
  - μ/e less than 10% of π

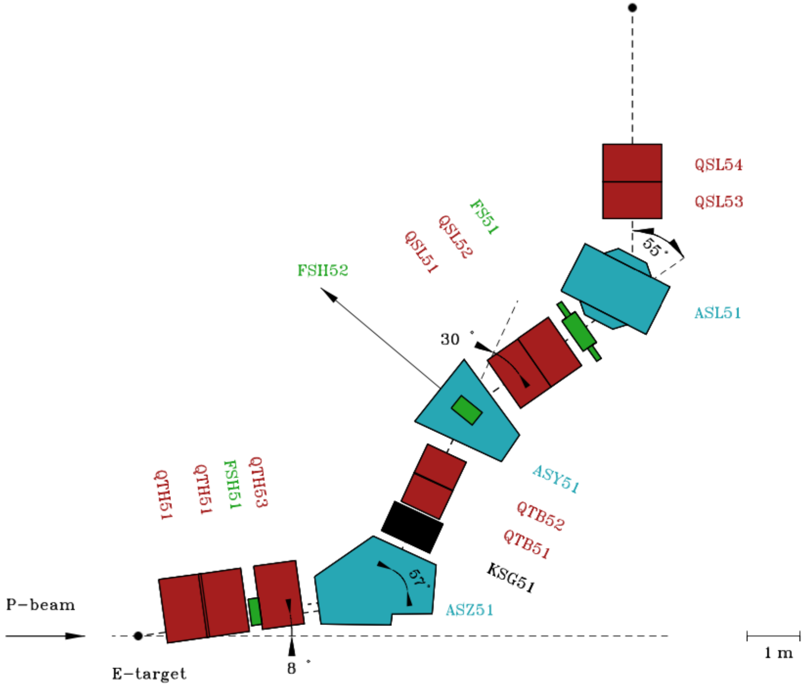
- Beam team needs to be strengthened with professional beam physicists from PSI, …
  - synergy with
    - High Intensity Muon Beam project
    - Cornell center?
    - Muon g-2 as template

Backup

piE1 study for PIONEER

- Beamline setup (Peter 10/10/22)





- Profiles

	sx (cm)	sy (cm)
1st order	0.445	0.266
2nd order	1.134	0.552

- Initial phase space

	ε (cm mr)	X (cm)	X' (mr)
x	12.5	0.6	25
y	40	0.3	160

piE1 beamline

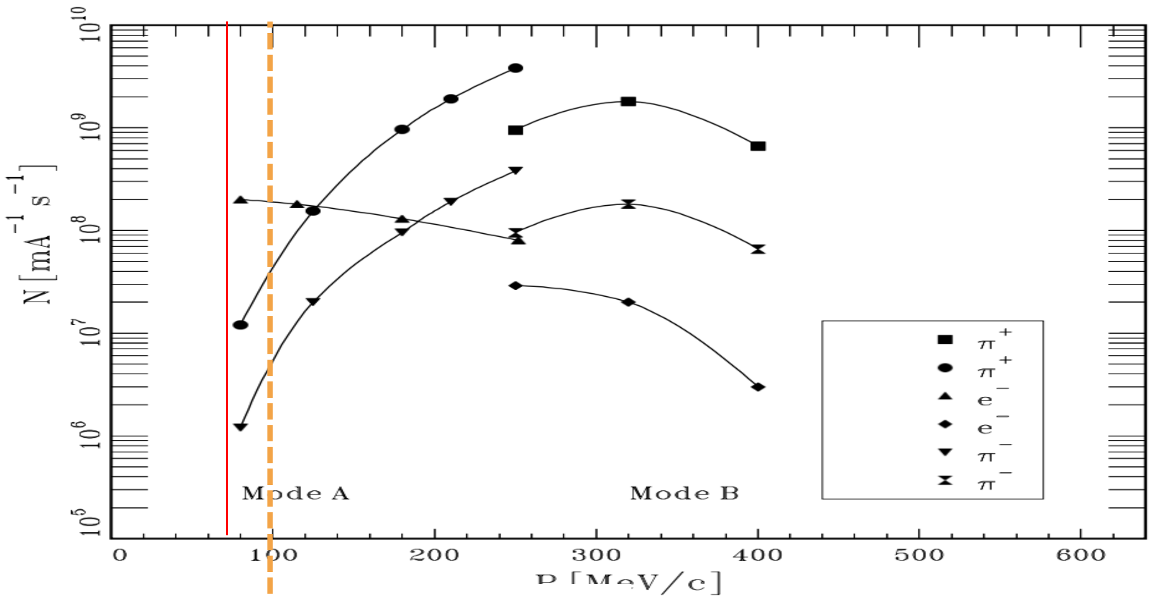
TITEL	LABEL	Z		X		Y		R16		R36	
BEAM	BEAM	0	m	0.5	cm	0.25	cm	0	cm/%	0	cm/%
DRIFT		0.638	m	1.67	cm	10.21	cm	0	cm/%	0	cm/%
QUAD	QTH1	1.238	m	4.73	cm	11.69	cm	0	cm/%	0	cm/%
DRIFT		1.393	m	6.11	cm	9.89	cm	0	cm/%	0	cm/%
QUAD	QTH2	1.993	m	8.85	cm	5.71	cm	0	cm/%	0	cm/%
DRIFT	FSH1	2.218	m	8.78	cm	5.03	cm	0	cm/%	0	cm/%
DRIFT		2.443	m	8.72	cm	4.35	cm	0	cm/%	0	cm/%
QUAD	QTH3	3.043	m	8.54	cm	2.6	cm	0	cm/%	0	cm/%
DRIFT		3.693	m	8.35	cm	1.29	cm	0	cm/%	0	cm/%
Z RO		3.693	m	8.35	cm	1.29	cm	0	cm/%	0	cm/%
ROTAT	R11	3.693	m	8.35	cm	1.29	cm	0	cm/%	0	cm/%
BEND	ASZ1	4.389	m	8.22	cm	2.29	cm	-0.17	cm/%	0	cm/%
BEND	ASZ1	5.086	m	6.12	cm	4.32	cm	-0.64	cm/%	0	cm/%
ROTAT	R12	5.086	m	6.12	cm	4.32	cm	-0.64	cm/%	0	cm/%
Z RO		5.086	m	6.12	cm	4.32	cm	-0.64	cm/%	0	cm/%
DRIFT		6.132	m	3.27	cm	6.84	cm	-1.64	cm/%	0	cm/%
QUAD	QTB1	6.607	m	3.32	cm	6.11	cm	-2.61	cm/%	0	cm/%
DRIFT		6.712	m	3.58	cm	5.55	cm	-2.96	cm/%	0	cm/%
QUAD	QTB2	7.187	m	4.33	cm	3.74	cm	-4.03	cm/%	0	cm/%
DRIFT		7.68	m	4.66	cm	2.6	cm	-4.55	cm/%	0	cm/%
ROTAT		7.68	m	4.66	cm	2.6	cm	-4.55	cm/%	0	cm/%
BEND	ASY1	8.149	m	4.88	cm	1.76	cm	-4.82	cm/%	0	cm/%
BEND	ASY1	8.618	m	4.77	cm	1.57	cm	-4.64	cm/%	0	cm/%
ROTAT		8.618	m	4.77	cm	1.57	cm	-4.64	cm/%	0	cm/%
DRIFT		9.071	m	4.57	cm	2.18	cm	-4.25	cm/%	0	cm/%
QUAD	QSL1	9.671	m	3.69	cm	3.97	cm	-2.98	cm/%	0	cm/%
DRIFT		9.771	m	3.45	cm	4.39	cm	-2.66	cm/%	0	cm/%
QUAD	QSL2	10.371	m	3.47	cm	5.27	cm	-1.44	cm/%	0	cm/%
DRIFT	FS53	10.671	m	4.25	cm	4.84	cm	-1.13	cm/%	0	cm/%
DRIFT		11.229	m	5.89	cm	4.08	cm	-0.54	cm/%	0	cm/%
Z RO		11.229	m	5.89	cm	4.08	cm	-0.54	cm/%	0	cm/%
ROTAT	R31	11.229	m	5.89	cm	4.08	cm	-0.54	cm/%	0	cm/%
BEND	ASL1	11.832	m	8.44	cm	2.49	cm	-0.14	cm/%	0	cm/%
BEND	ASL1	12.435	m	9.11	cm	1.4	cm	0.01	cm/%	0	cm/%
ROTAT	R32	12.435	m	9.11	cm	1.4	cm	0.01	cm/%	0	cm/%
Z RO		12.435	m	9.11	cm	1.4	cm	0.01	cm/%	0	cm/%
DRIFT	VKA3	12.735	m	10.06	cm	1.36	cm	0.02	cm/%	0	cm/%
DRIFT		13.55	m	12.64	cm	3.18	cm	0.03	cm/%	0	cm/%
QUAD	QSL3	14.15	m	9.31	cm	6.62	cm	0.02	cm/%	0	cm/%
DRIFT		14.25	m	7.96	cm	7.55	cm	0.02	cm/%	0	cm/%
QUAD	QSL4	14.85	m	3.38	cm	8.11	cm	0.02	cm/%	0	cm/%
DRIFT		15.05	m	2.72	cm	6.57	cm	0.02	cm/%	0	cm/%
DRIFT	PID	15.9	m	0.4	cm	0.52	cm	0.03	cm/%	0	cm/%
DRIFT	L1	16.5	m	2.14	cm	4.69	cm	0.03	cm/%	0	cm/%
FRINGE		16.5	m	2.18	cm	4.61	cm	0.03	cm/%	0	cm/%
QUAD	QSL5	16.89	m	4.69	cm	5.3	cm	0.05	cm/%	0	cm/%
FRINGE		16.89	m	4.58	cm	5.39	cm	0.05	cm/%	0	cm/%
DRIFT		17	m	5.76	cm	4.9	cm	0.06	cm/%	0	cm/%
FRINGE		17	m	5.61	cm	5.07	cm	0.06	cm/%	0	cm/%
QUAD	QSL6	17.39	m	5.32	cm	7.09	cm	0.05	cm/%	0	cm/%
FRINGE		17.39	m	5.46	cm	6.82	cm	0.05	cm/%	0	cm/%
DRIFT		17.5	m	4.13	cm	8.64	cm	0.04	cm/%	0	cm/%
FRINGE		17.5	m	4.28	cm	8.44	cm	0.04	cm/%	0	cm/%
QUAD	QSL7	17.89	m	1.73	cm	8.78	cm	0.01	cm/%	0	cm/%
FRINGE		17.89	m	1.69	cm	8.99	cm	0.01	cm/%	0	cm/%
DRIFT		18.49	m	0.44	cm	0.27	cm	-0.03	cm/%	0	cm/%
DRIFT	T	18.491	m	0.44	cm	0.27	cm	-0.03	cm/%	0	cm/%

piE1/5 comparison

piE1

dp/p ±1% ??

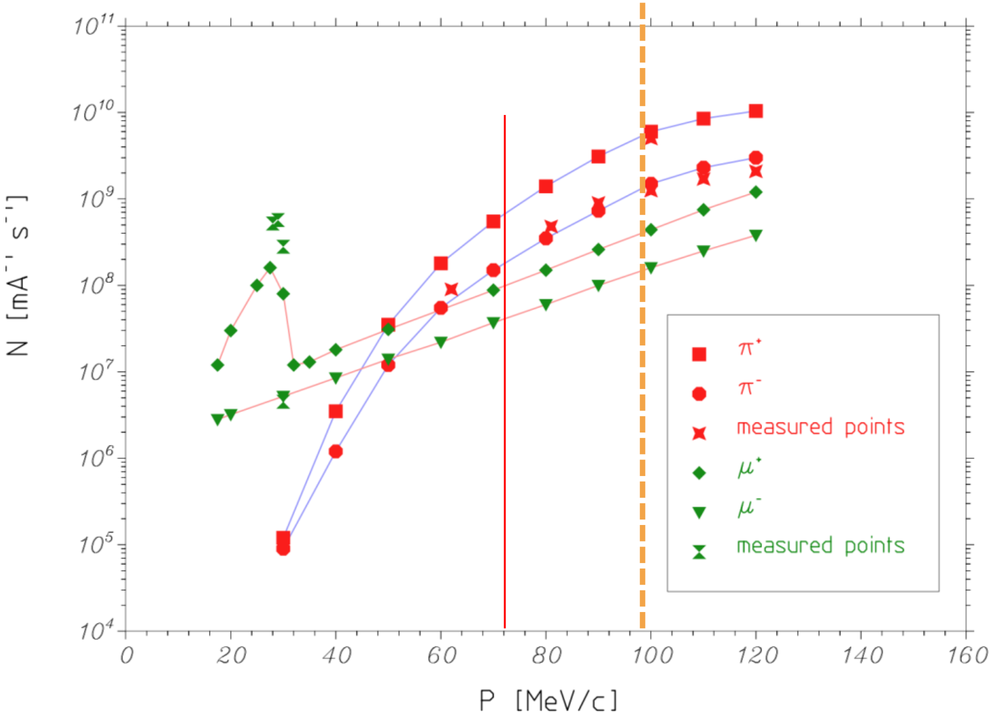
need Dinko’s point
rate and target



piE5

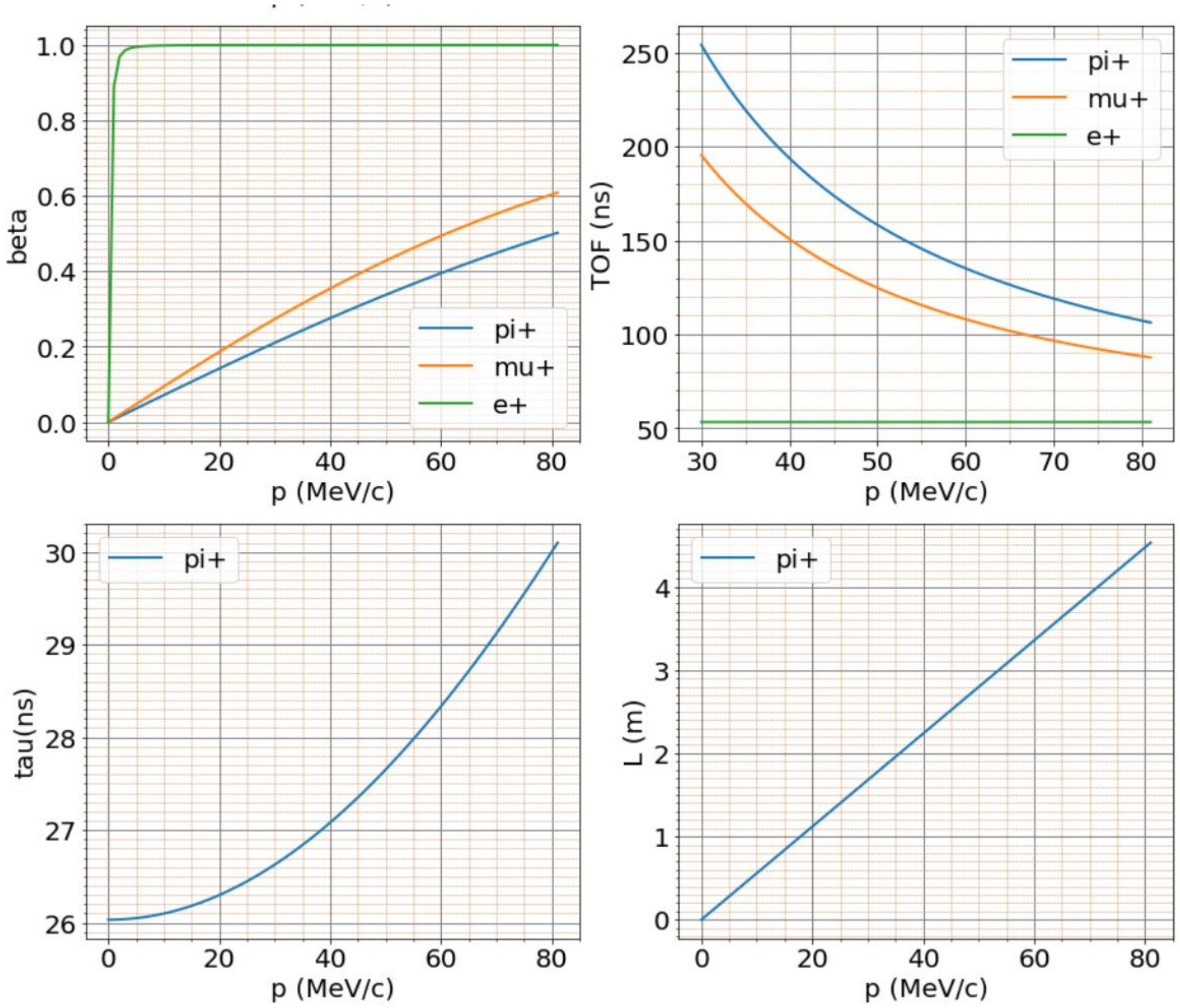
dp/p ??

can check with
beam test

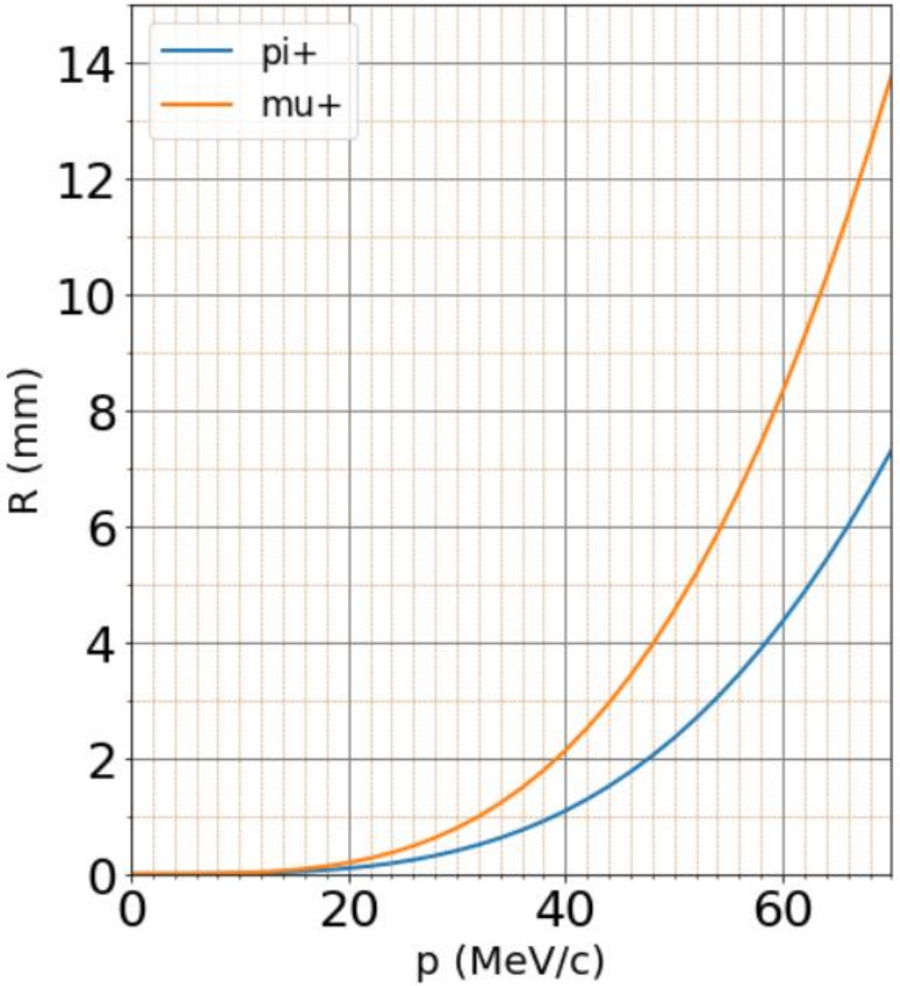


Properties of beam particles

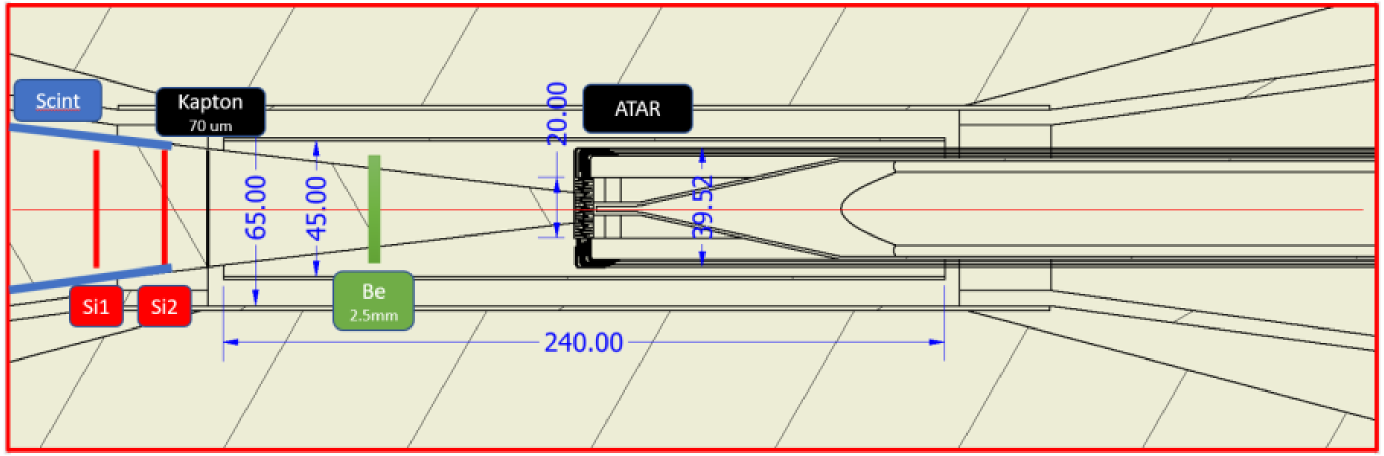
kinematics



range



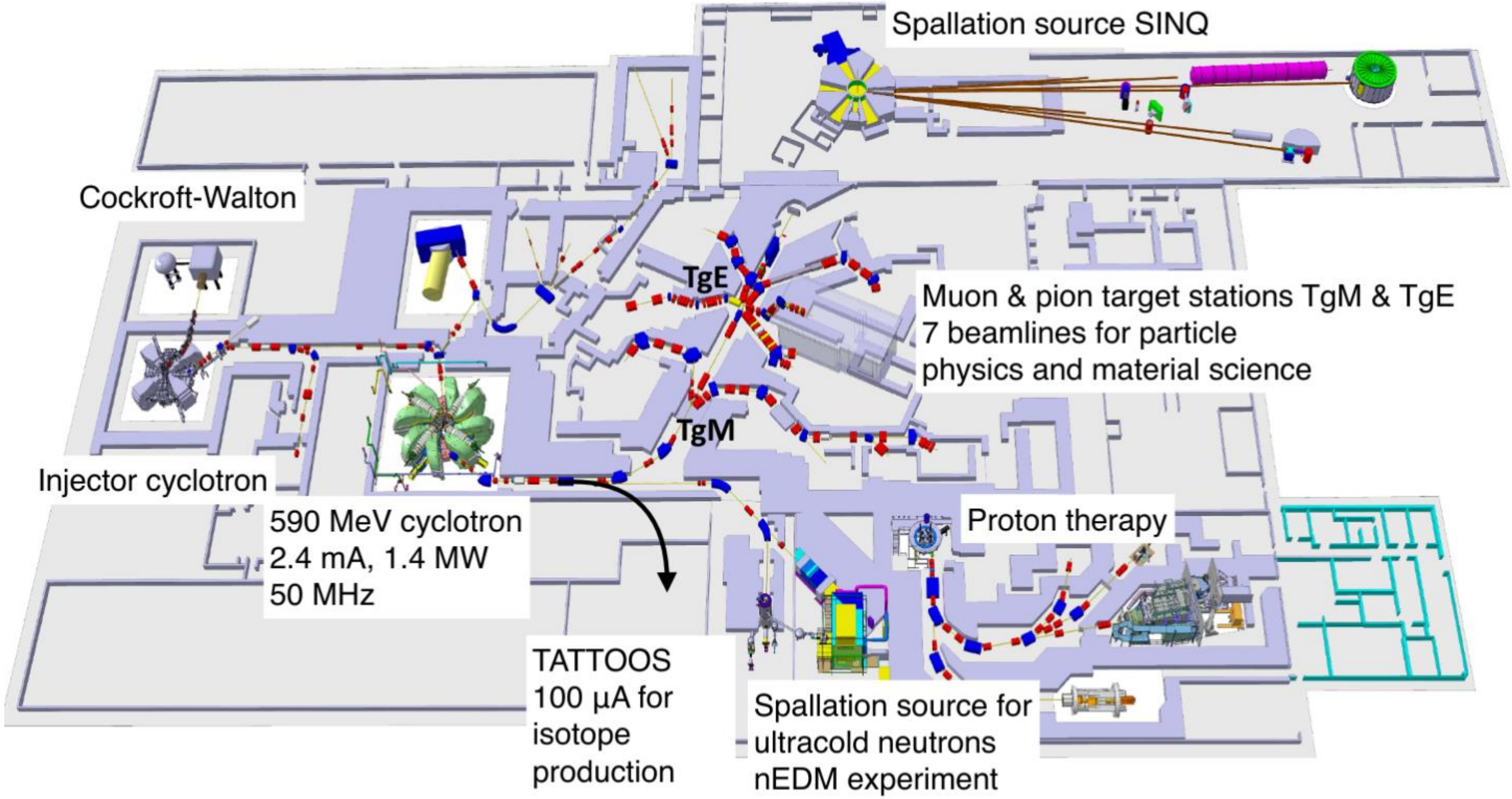
– cone angle +-10^0
– 2 x-y layer 50um LGAD
– Halo veto scint



Paul Scherrer Institute

PSI Proton Accelerator HIPA

A multi-disciplinary research driver



SiMon & Garfunkel

Work provided by Anna, Damian and Co.

- 200mm horizontal motion, sub-mm granularity
- 75mm vertical extent, 31 scintillator pills, 2.5mm granularity (SiMon)
- 20mm x 20mm single-pill detector (Garfunkel)
- Record scalers (fast) and waveforms (slow, optional) at every horizontal step
- Take full 2D profiles at 2.5mm granularity
- Park detectors at static position for rate observations
- Automatic magnet scan: simple (single magnet range), arbitrary (config file)
- Semi-automatic threshold adjustment based on amplitude profile and/or homogeneous illumination (wide beam)