Wide Aperture D-magnets @Extraction for PIP-II: MADX simulation of Existing Extraction Trajectory

Valery Kapin

30-Jul-2020, Taskforce/PSP meeting (via ZOOM)

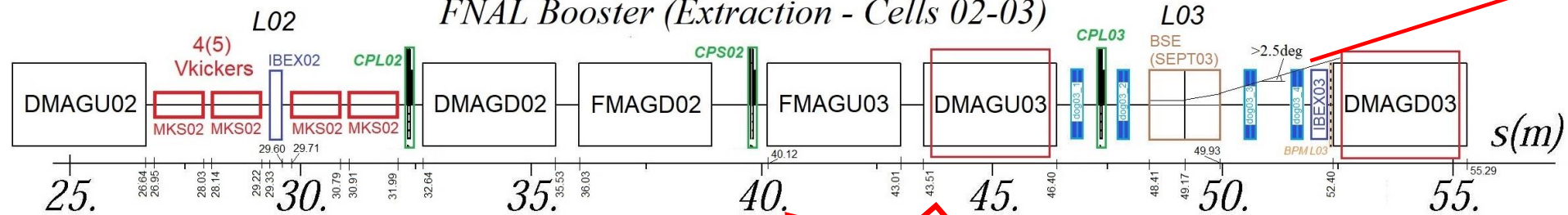# Booster & Extraction Layout

FNAL Booster (Extraction - Cells 02-03)

L02: 2xMKS-BEX02-2xMKS-CP02
S02: CPS02
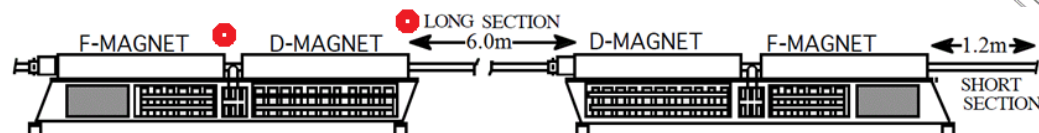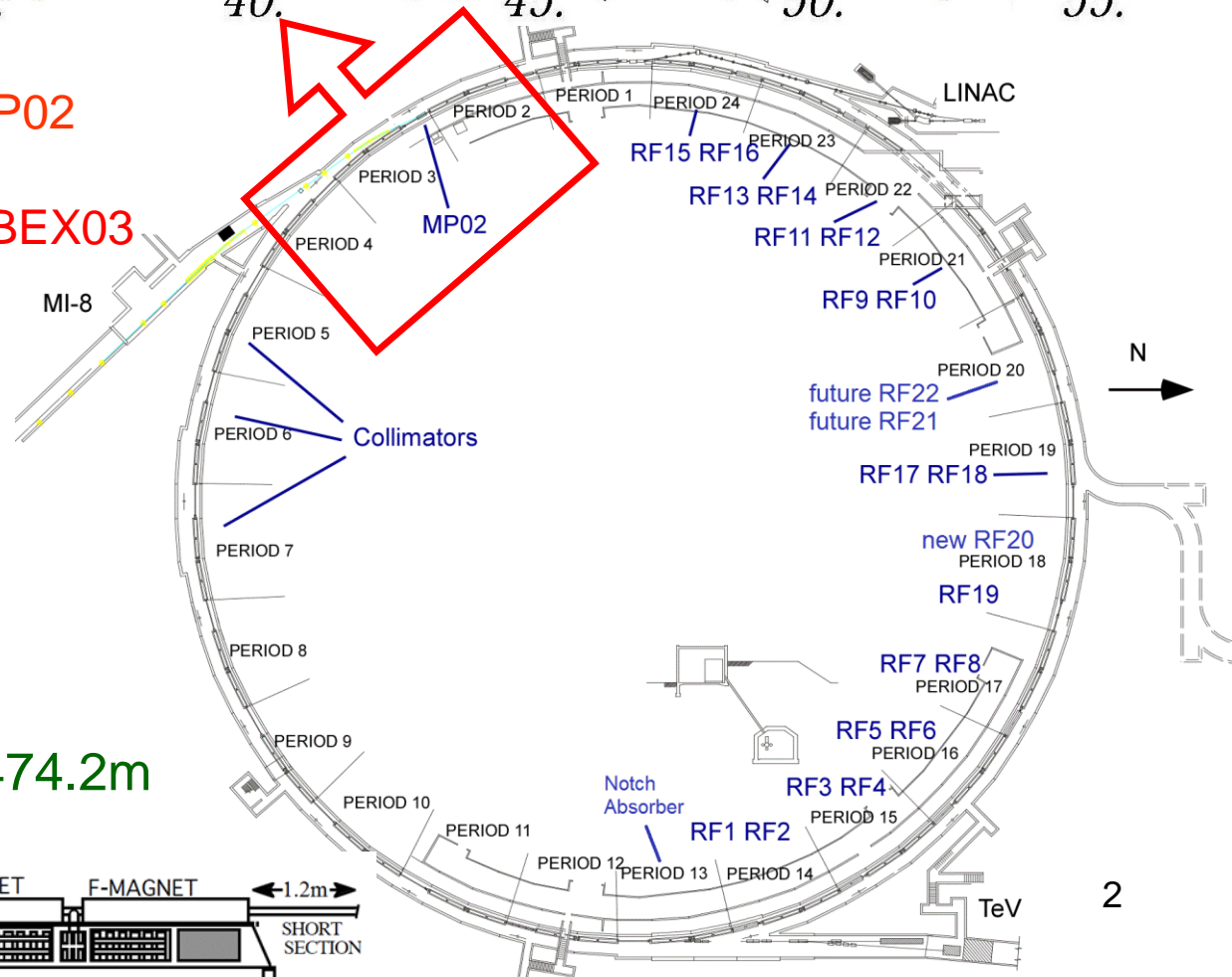L03: DL-CP03-DL-Sept-2xDL-BEX03
S03: CPS03
(L04: BEX04)

400MeV -> 8GeV
33ms (20,000 turns)

24periods (L=19.8m); S=474.2m

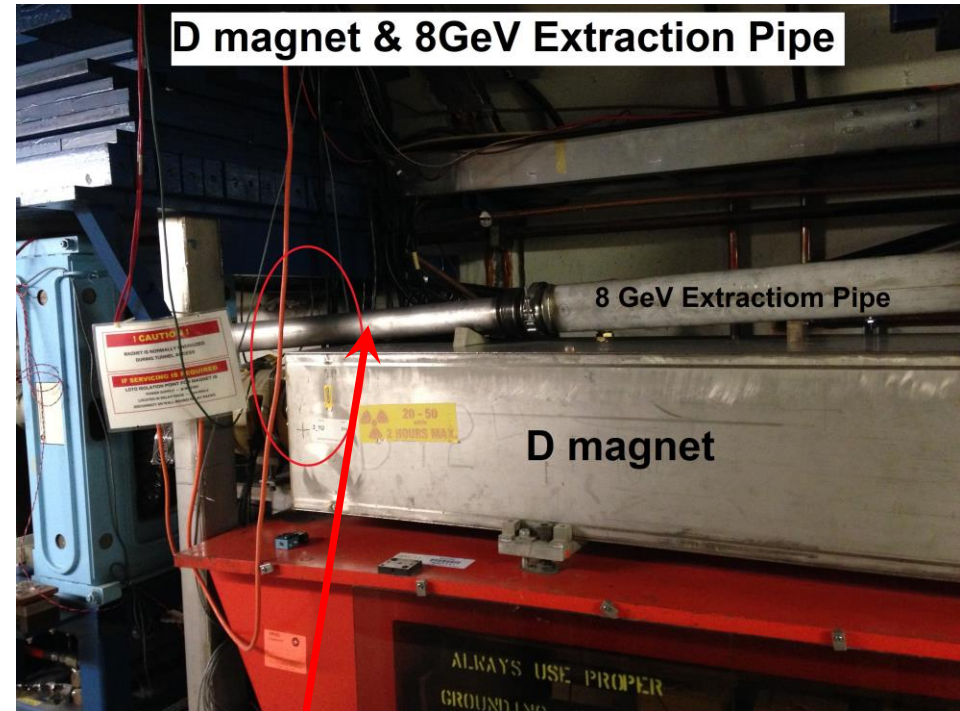# D-magnets at Extraction Region in Long 3

Extraction Region in Long 3:
Dmagnts; 4 dogleg magnets;
Corr.Package; Septum
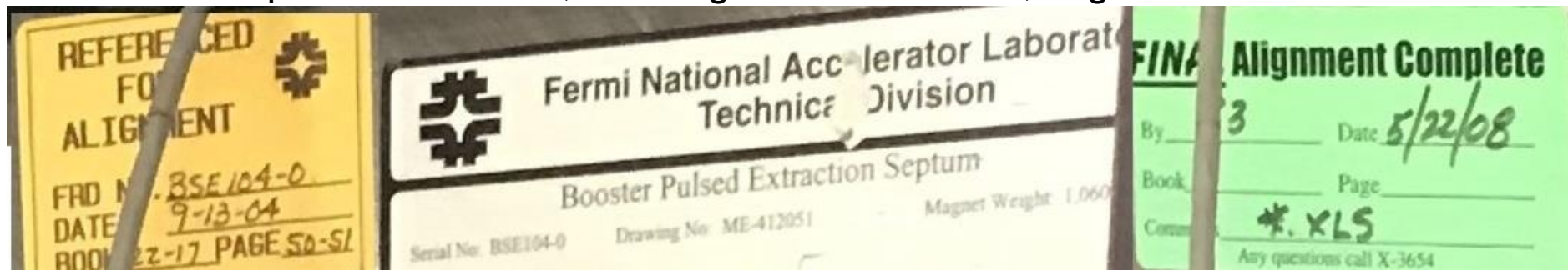
D magnet & 8GeV Extraction Pipe

8 GeV Extractiom Pipe

D magnet

To preserve symmetry another D magnet must be located at downstream Long 3, while external height of D magnet is restricted by 2.5deg-curve

Septum: BSE104-0; Drawing No. ME-412051; Alignment 5/22/2008

Previous talk in Dec-2019 (BD-7875)

V.K."Requirements for a New D-magnet derived from MADX simulations"

New D-magnets in Booster extraction area – near Long Straight Section L03.

Multi-particle simulations with MADX @ 8 GeV, 95%-Enorm = 16 pi*mm*mrad.

Assumption – vert. position of circulating beam before extraction Y=0 (on axis).

Simulations results suggest significant beam losses on the upstream F-magnet.

Motivation of the present study –> evaluation of orbits:
1) at the last full turn (w/o kickers) and
2) extraction trajectory (kickers=on)
=> Feed multi-particle simulations of losses
to verify aperture requirements & need for F-magnet

Conditions: no fresh survey, no reliable assembly drawing, no design & simulation data/results for present configuration; only some old non-systematic info&reports and guesses about loss location (via BLMs).

D.Johnson. High-losses by BLM at D exit; several new magnets:
BGMD; BGMF; BGDS; *BGDW (extract. a-?; L=?) – this study*

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Info & conclusions in previous talk (BD-7875)

### *"Requirements for a New D-magnet derived from MADX simulations"*

➢ Collected info available for Extraction region in Booster Long 3 (photo on servers; visit in Boo tunnel; previous meeting docs on new D-magnets, discussions with people involved, review Rookie books and old publications, finding available drawings and take detail sizes)

➢ Derived necessary geometrical (septum & magnets boundaries) and operational parameters (e.g. kicker voltage, vertical shift, etc.)

➢ Analyzed the Ejection System in 1968 Design report: additional kick between F-magnets; larger 24"x16" magnets was designed with full gaps – 2.5"(D), 2.0"(F) – with published specs (!) (+drawings ?)

➢ Conditions and tasks for MADX simulations with PIP-II emittances

➢ Dependences for Losses vs increase of magnet gaps presented: losses distributed on D-magnet and the exit of F-magnet. To remove losses new D & F magnets with >5mm increased ½-gaps are needed

New D-magnet – tasks & info in old docs

W.Pellico, "Boo D magnet for PIP 2 …" BD-5942-v2, 2017:

New Vertical Aperture > present magnets (VK: 2.2**5**"). A working specification - the new ***gradient magnet will be between 2.5" and 3".***

K.Seiya in BD-5936-v2, 2017: => **Short D magnets:** Preserve symmetry
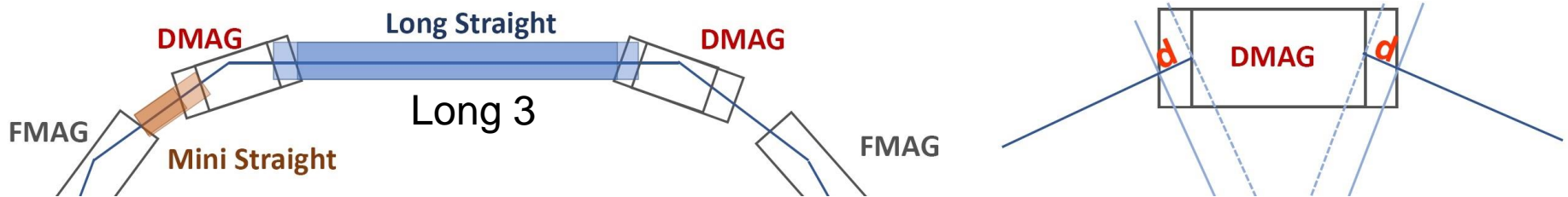

C.Bhat, BD-7088-v2, March, 2019:

➢F.R. for three wide aperture D-magnets at 8 GeV extraction (installation of the two D-magnets). This upgrade is to reduce losses at extraction.

➢Currently (PIP@15Hz), radiation level @extraction ~600 mR@1ft - from scraping of ***transverse beam tail*** passing through the D-magnets.

➢Losses will go up ~33% for PIP-II@20Hz). New D-magnet (2.25"-> 3") => beam loss can be reduced by ~ 33%.

1968 Ejection & existing apertures (18x13magn)

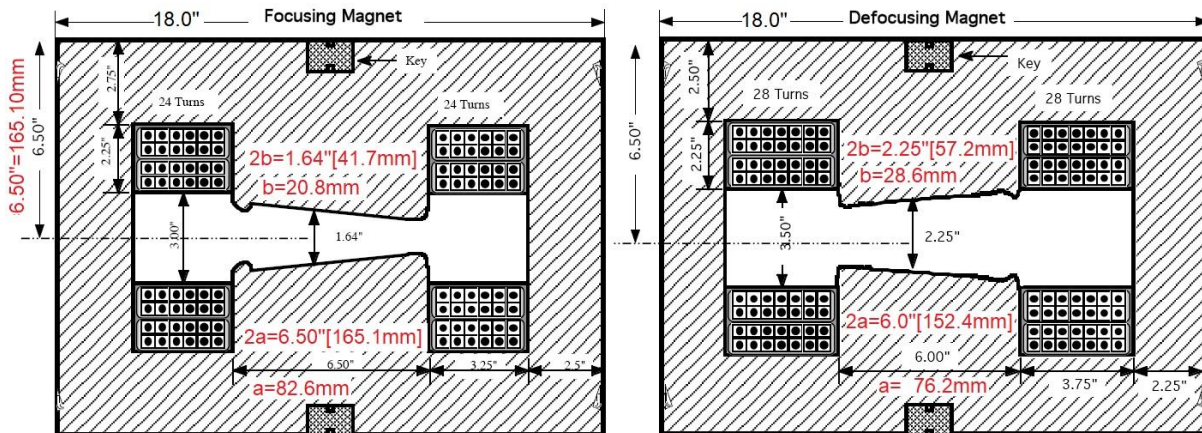
Figure 9-12 — Booster–Synchrotron Ejection
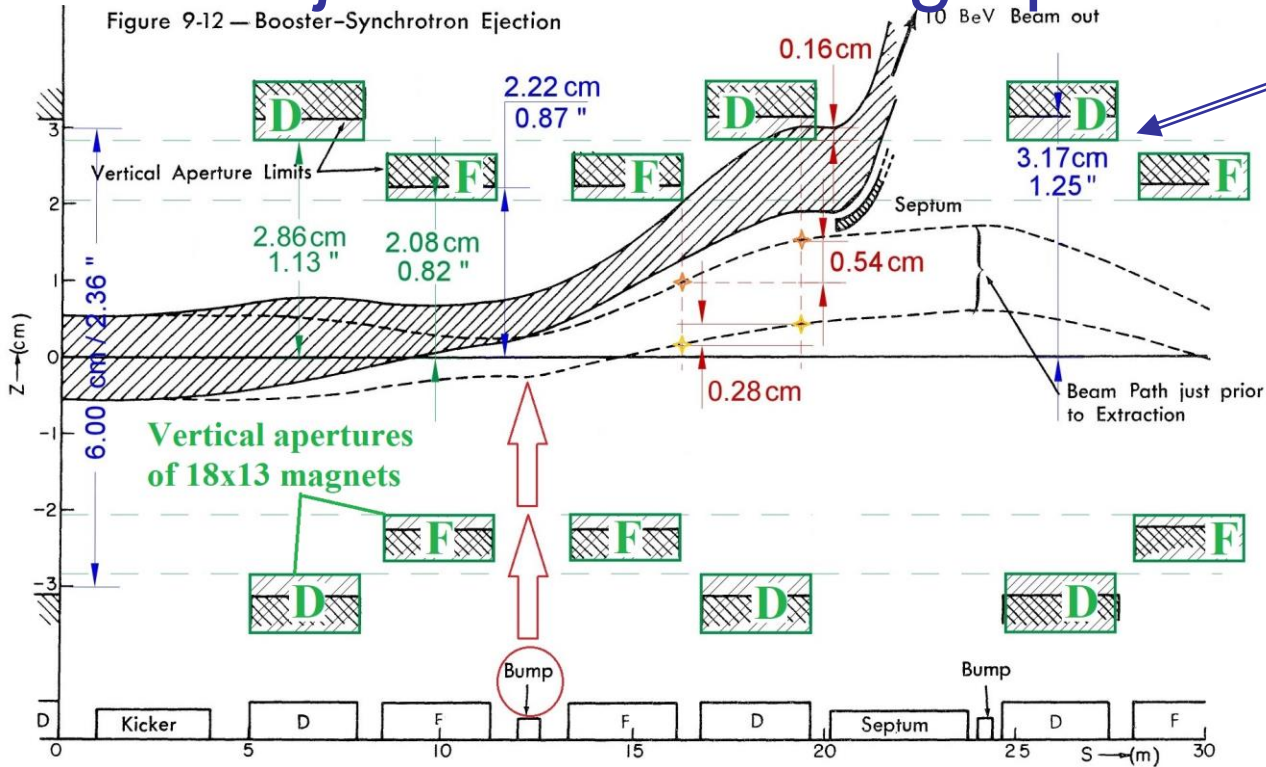
"Ruler" meas. by VK

Extraction Trajectories must be similar "1968" (?):

- Bump move circulating beam close to septum
- Now Dipoles in CPS02 (max ~0.5mrad) could be used as Bump (*avoid F magnets ?*)

Conclusion: *Most of losses -> on D-magnet; Some losses -> the exit of F-magnet*

Booster Rookie Book v4.1
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figure 2.2.1

Booster uses 18"x13"magnets:
G_F=1.64";
G_D=2.25"
(instead of 1968 design 24"x16")

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Example of Trajectories (CPS02=on&up; BD-7875)

Assumption: *the circulating beam is placed exactly on the Booster axis !!!*

Five kickers at 8%-reduced PFN voltage $V_{PFN} = 0.92 \times 48kV$

FNAL Booster (Extraction - Cells 02-03)

VS02: vkick=0.5mrad

Very similar to curves in 1968 Design report

y(sept)=23.5mm

V.Kapin, New Dmagnet, Jul-2020

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Equal losses on both D (11%) & F(11%) !? -> realistic extraction trajectory needed
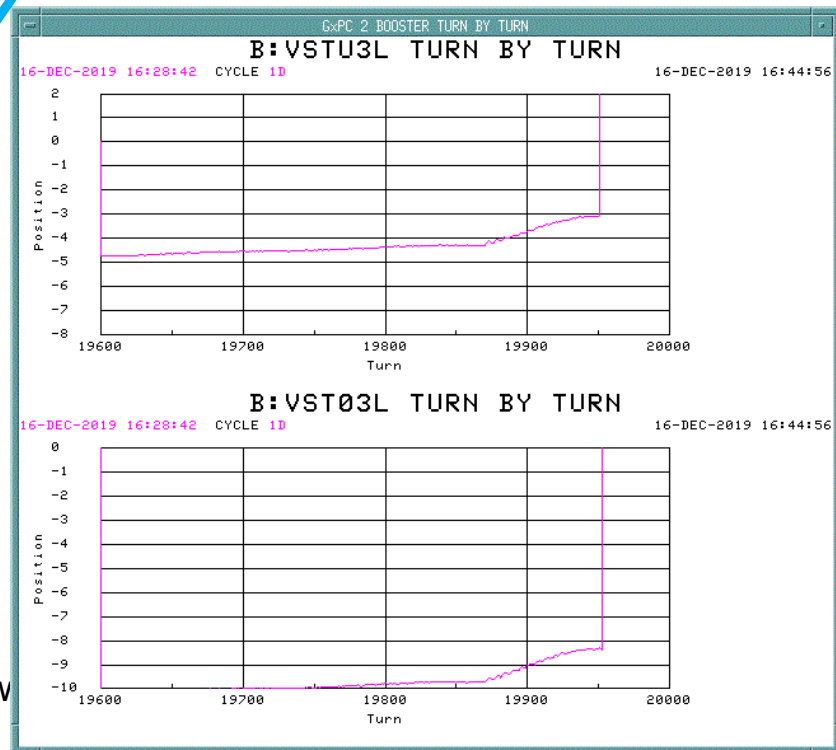
Collected Data (from Plots before Shutdown)
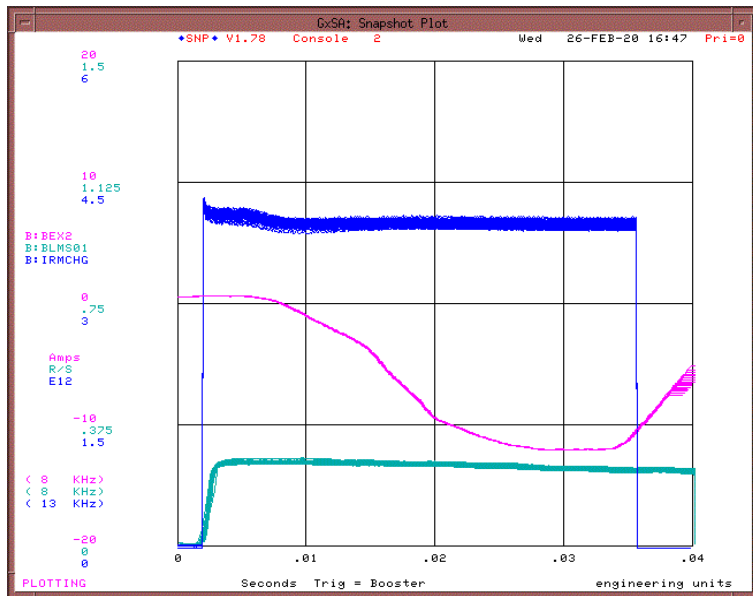
Salah plots "Charge, BEXn, Losses "=> scales:
BEX2=BEX4=1.2; BEX3=094; Bex4=1.2
BEX ~ similar CP, but no calibration "angle=f(I, A)"

Approximate Y on BPMs from plot
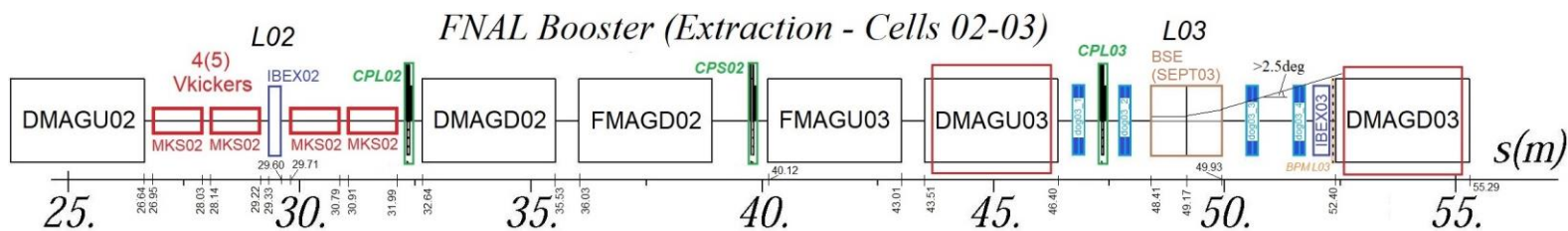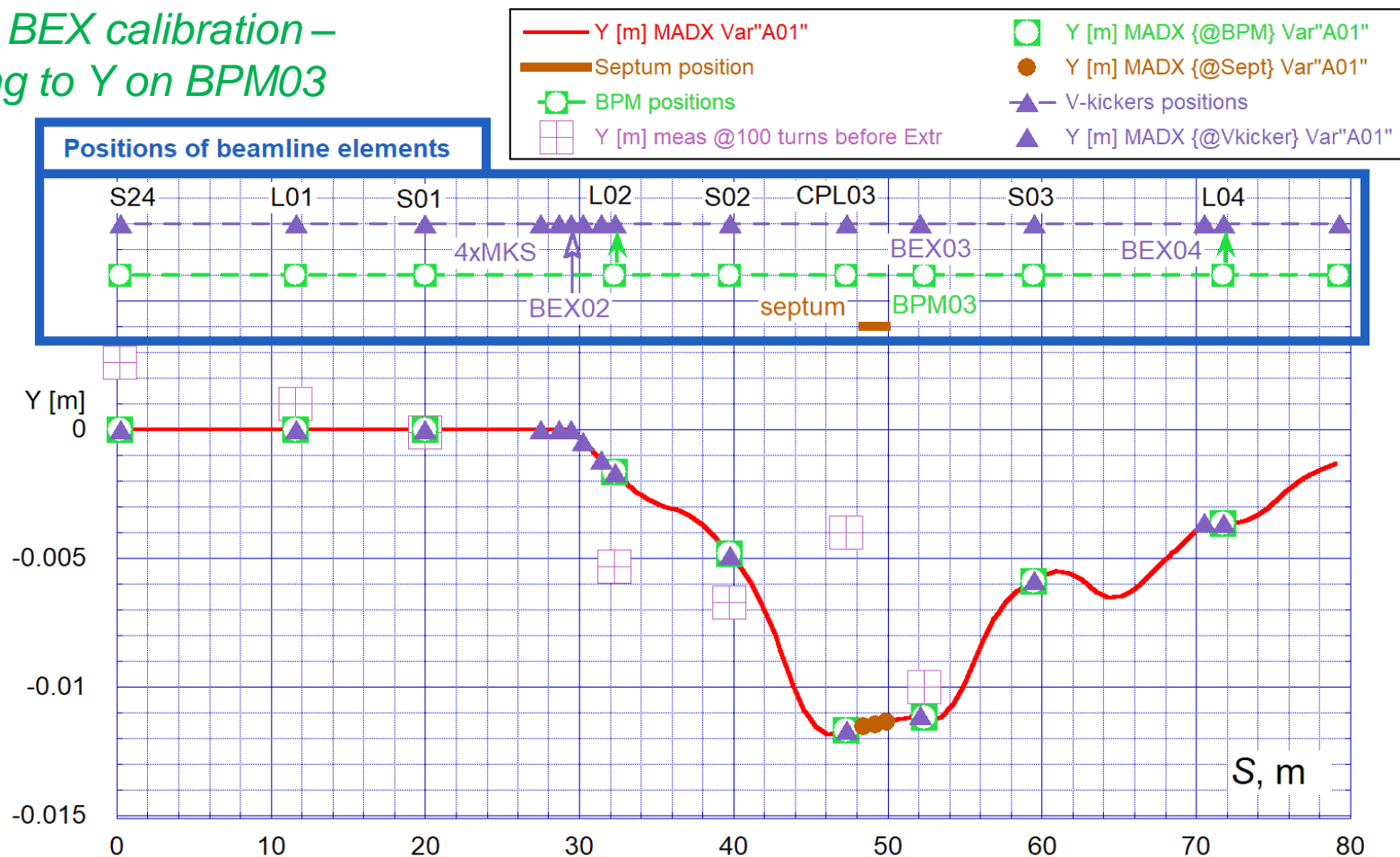(100 turns before extraction –
      exclude "BPM artifacts" (?))

BPM name	100 turns before extraction $1D
B:VST24S	+2.6 mm
B:VST01L	+1.0 mm
B:VST01S	-0.4 mm
B:VST02L	-(5.0÷5.3) mm
B:VST02S	-6.7 mm
B:VSTU3L $y_{SeptaUS}$	≈-4.5 mm; -4.2
B:VST03L $y_{SeptaDS}$	≈-9.4 mm ; -9.8
B:VST03S	

Kapin, New

MADX (last turn): BEX(1.2&0.94)=on; CP=off

W/O BEX calibration – tuning to Y on BPM03

- Y [m] MADX Var"A01"
- Septum position
- BPM positions
- Y [m] meas @100 turns before Extr
- Y [m] MADX {@BPM} Var"A01"
- Y [m] MADX {@Sept} Var"A01"
- V-kickers positions
- Y [m] MADX {@Vkicker} Var"A01"

Positions of beamline elements
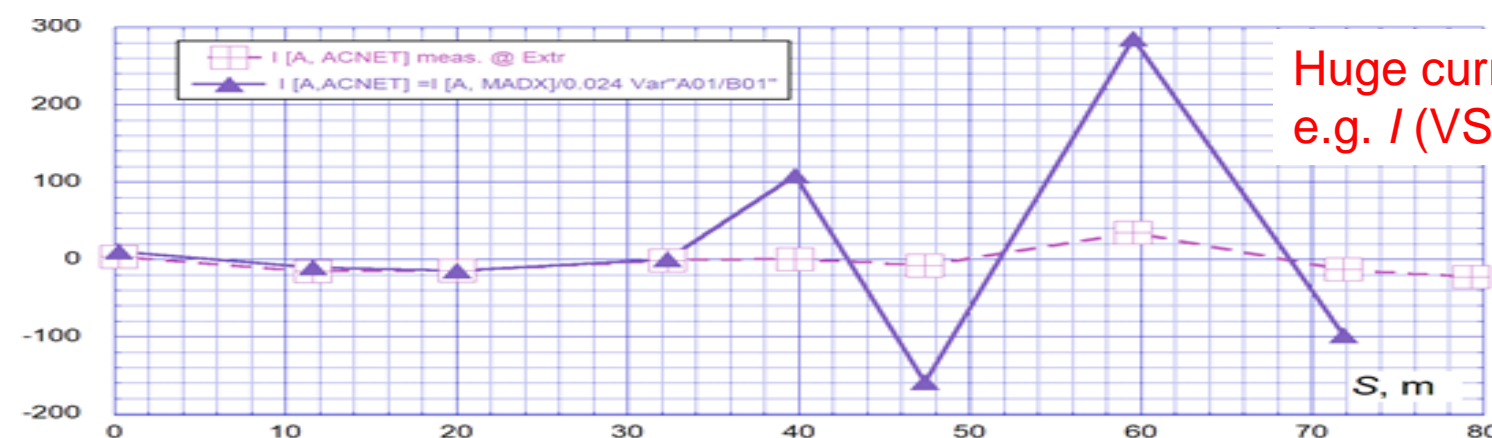
MADX: BEX(1.2&0.94) + match all BPMs

W/ approx. plot's data
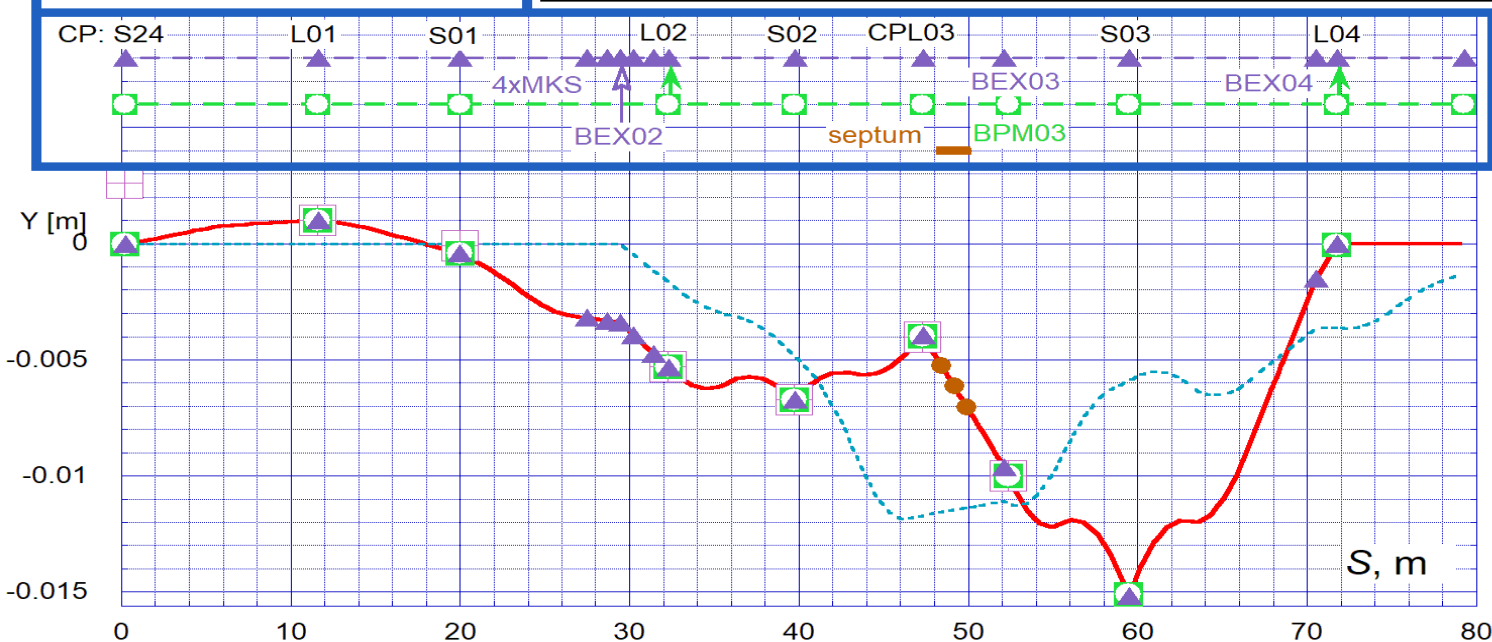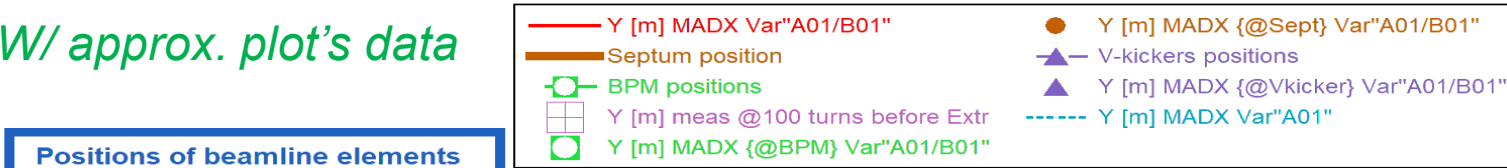
MADX match:
Constraint -
All Y (BPMs);
VARY – all VSnn

Calibration good?
I, Amps(L01, L02)

Y@septa=-5mm ?

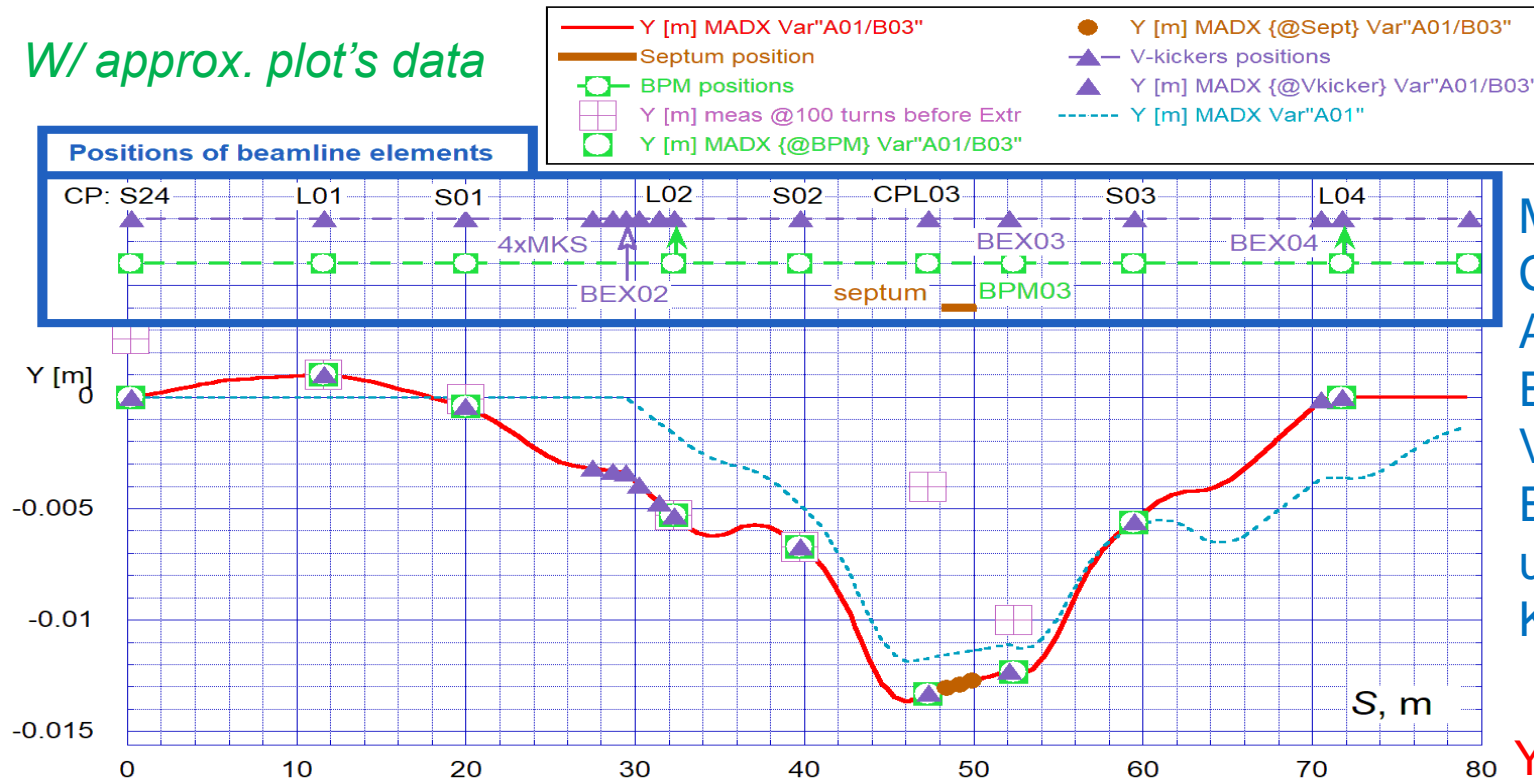Huge currents,
e.g. *I* (VSO2)=108A !?

E.Prebys, 2006:

$\alpha_{max} \approx 0.5\text{mrad}$

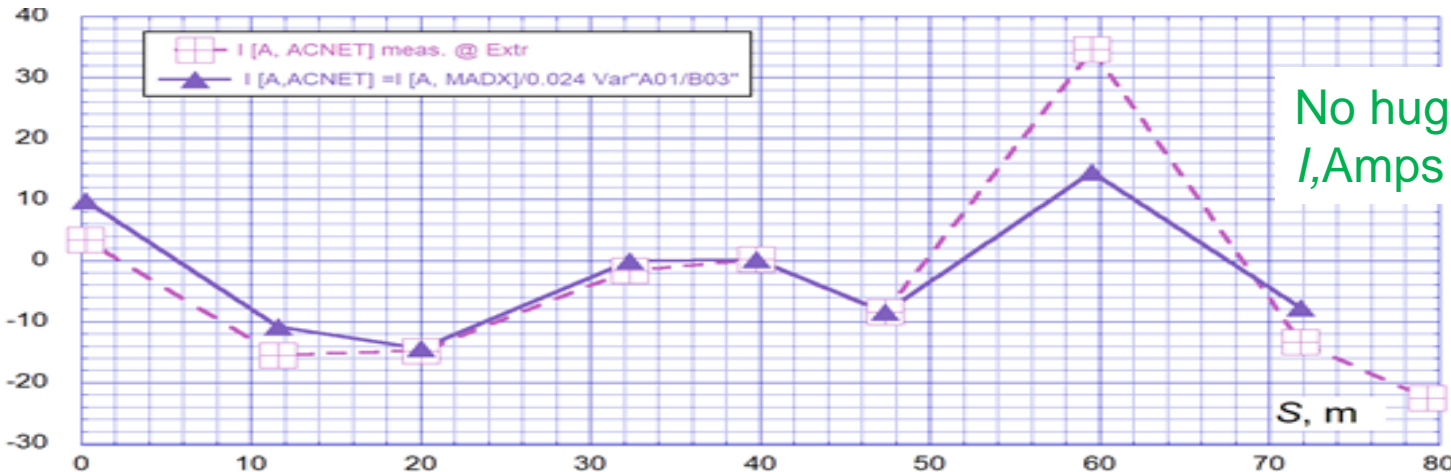$I_{max} \approx 40\text{A}$

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MADX: BEX + match @ Y(LU3,L03)->I (S02,L03)

W/ approx. plot's data

MADX match:
Constraint -
All Y (BPMs),
Except LU3, L03;
VARY – all VSnn,
Except S02, L02
using I, amps ->
Kick-angles !!!

Y@septa=-13mm

No huge currents, but
I,Amps *not perfect*

E.Prebys, 2006:
$I_{max} \approx 40A$
$\alpha_{max} \approx 0.5mrad$

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Use more systematic Data (B38 2-MAr2020)

2-Mar-2020 =OK !   *BAD "18Mar2019.txt" ("-33mm", "1000mm", etc) for 056_VSTU3L.dat" upstream SEPTUM*

20200227_BEX4(&2)_time_&_I_A
— BEX2&4, A   — BEX3, A   — CHG
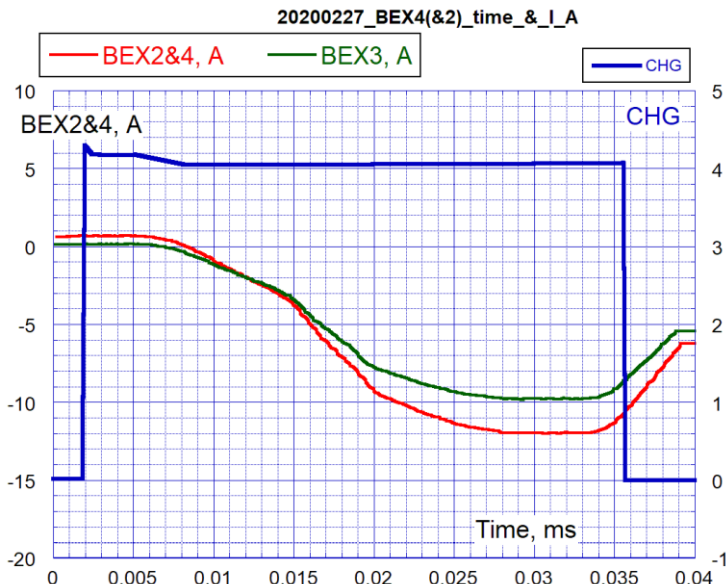
Digitizing Salah plot "Charge, BEXn, Losses"=>
Tstart=1.9ms; Tend=35.5ms

Table Data from B38 calculator

Time,ms	~2.0	~2.002	=32.0	=33.0	=34.0	~34.96
Turn #	=0	=1	~17,640	~18,269	~18,898	=19,500
Time,ms	=35.0	~35.43	~35.51	~35,59	~35.67	~20,150
Turn #	~19,526	=19,800	=19,850	=19,900	=19,950	=36.0

Booster dipole correctors use **eight breakpoints** $t_{BP}[0]$="2 ms"(=2.4 ms exactly), $t_{BP}[1]$=3 ms, $t_{BP}[2]$=6 ms, $t_{BP}[3]$=10 ms, $t_{BP}[4]$=20 ms, $t_{BP}[5]$=32 ms, $t_{BP}[6]$=36 ms, $t_{BP}[7]$=60 ms.

"Strange" bump @last 100 turns

20200715_Data_bpms_TBT_02Mar2020
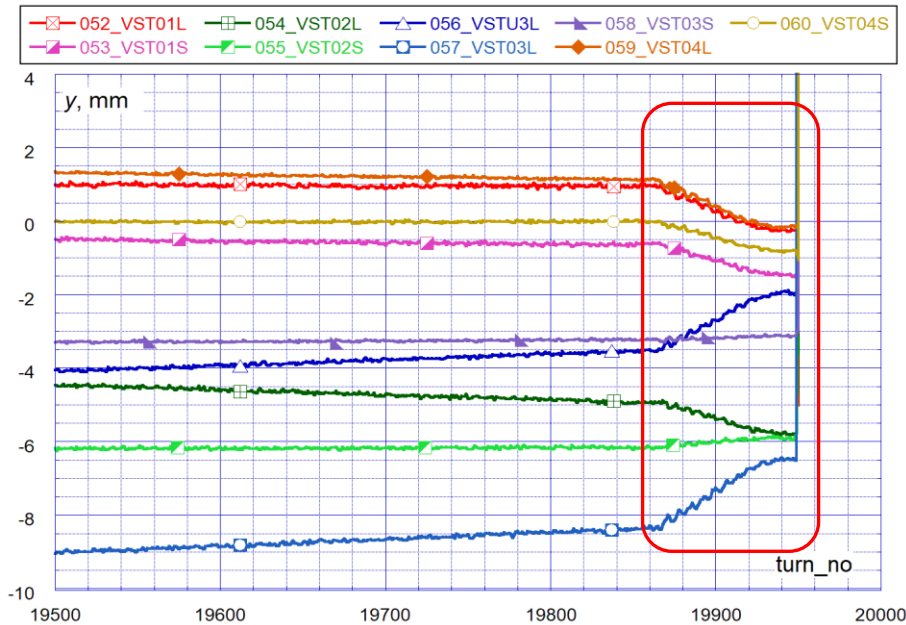
IPM in L04 ($17,$15,$1D) – blue curve
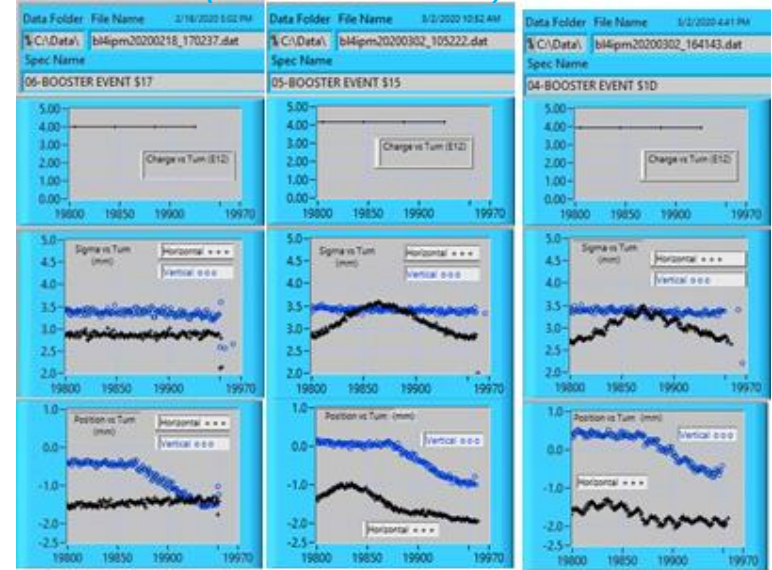
Example: linear extrap. of aver. to last turn:

20200715_Data_bpms_TBT_02Mar2020_Yorig

Dmagne

Last turn extraction BPMLU3: 25 mm

20200715_Data_bpms_TBT_02Mar2020

beam last turn = 19950 (#100-102; 52-56);
19949 (#99); All kicked at the last turn, except #100 (@19949)
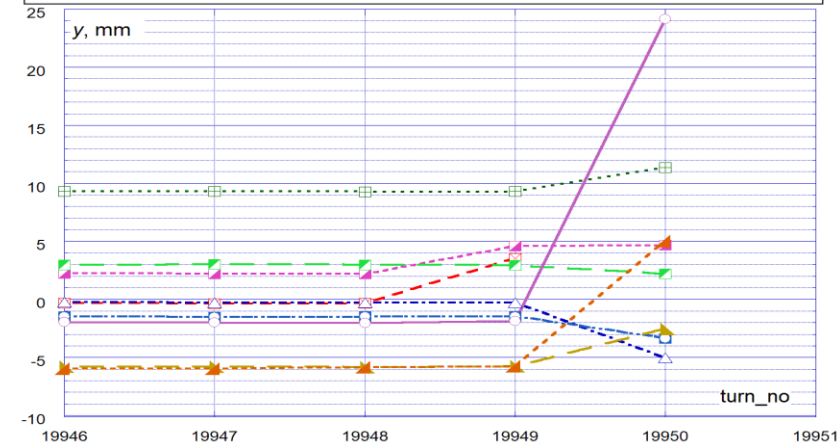
MADX (last turn): BEX(1.2&0.94)=on; CP=off

W/ BEX calibration – tuning on BPM03

Legend:
- ── Y [m] MADX Var"A01"
- ▢ Y [m] MADX {@BPM} Var"A01"
- ■ Septum/Collim position
- ● Y [m] MADX {@Sept/Coll} Var"A01"
- ⊡── BPM positions
- ▲ V-kickers positions
- ⊞ Y [m] meas@19950#Extrapol#2Mar20
- ▲ Y [m] MADX {@Vkicker} Var"A01"

Positions of beamline elements

CP: S24   L01   S01   L02   S02   CPL03   S03   L04   S04
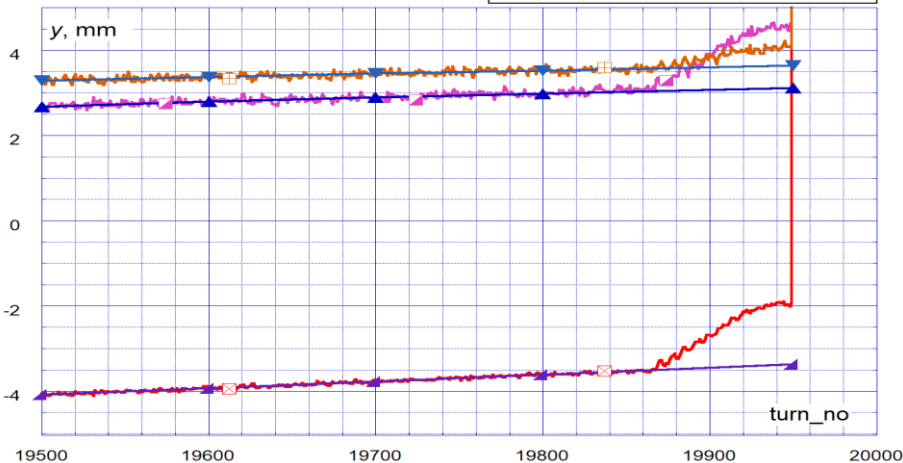
4xMKS   BEX03   BEX04
BEX02   septum BPM03
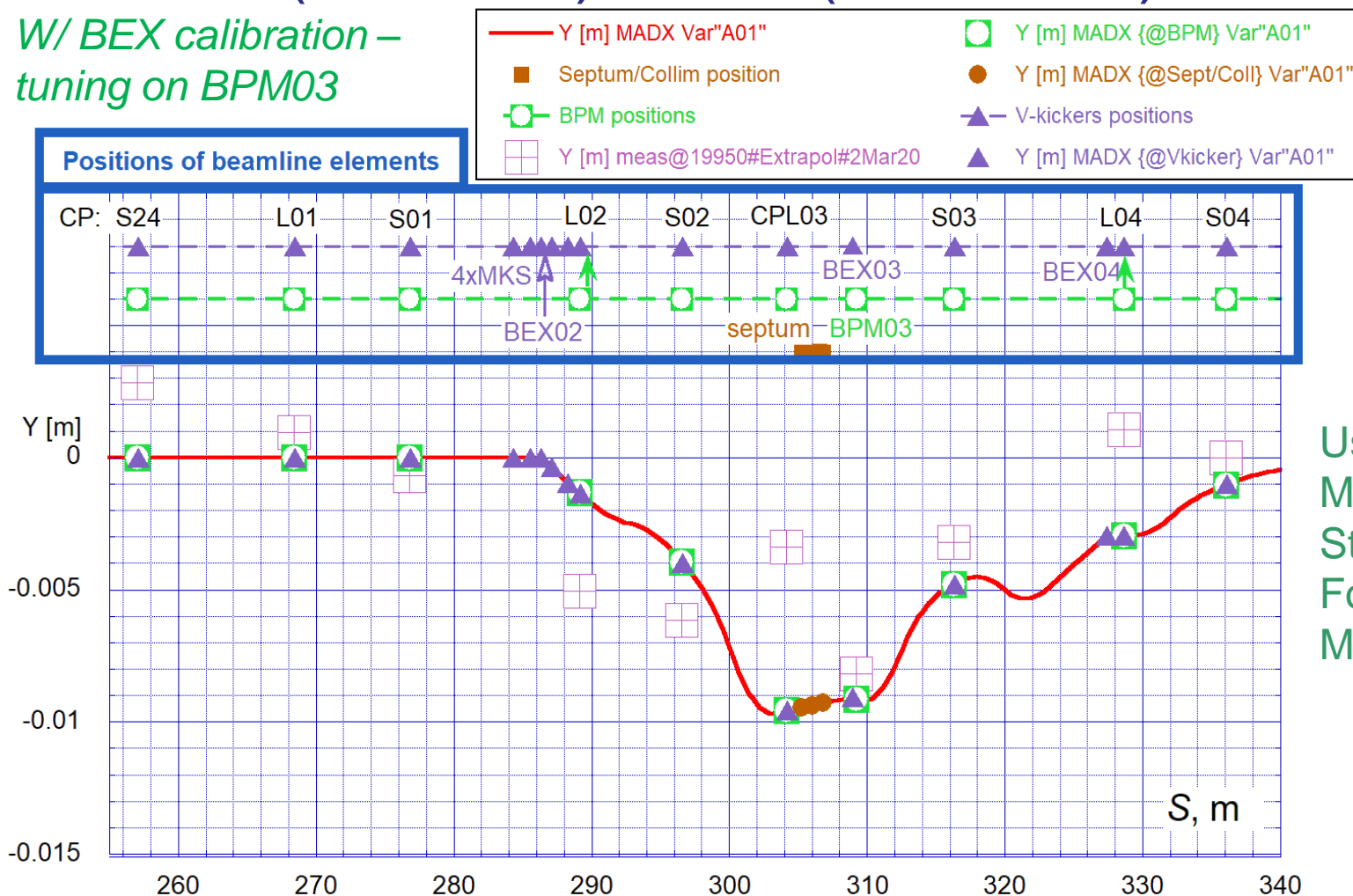
Use shifted MADX lattice Start @ Short11 For future use MKS in L12

S, m

Here, S = position for used here "shifted lattice" (started @S11); Origin of PIP-I MADX lattice: S(start_1)=256.860m

FNAL Booster (Extraction - Cells 02-03)

L02
4(5) Vkickers
IBEX02   CPL02
DMAGU02
MKS02 MKS02 MKS02 MKS02
DMAGD02   FMAGD02   FMAGU03   CPS02
L03
CPL03
BSE (SEPT03)   >2.5deg
DMAGU03   IBEX03   DMAGD03
BPM L03

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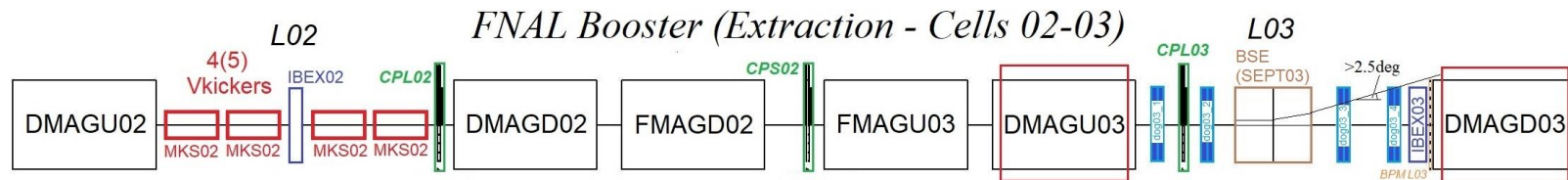
MADX: BEX(1.2&0.94) + match all BPMs

2-Mar-2020 B38 data

Legend:
- Y [m] MADX Var"A01&B01"
- Septum/Collim position
- BPM positions
- Y [m] meas@19950#Extrapol#2Mar20
- Y [m] MADX {@BPM} Var"A01/B01"
- Y [m] MADX {@Sept/Coll} Var"A01/B01"
- V-kickers positions
- Y [m] MADX {@Vkicker} Var"A01/B01"
- Y [m] MADX Var"A01"

Positions of beamline elements

CP: S24   L01   S01   L02   S02   CPL03   S03   L04   S04

4xMKS   BEX03   BEX04

BEX02   septum   BPM03

Y [m], S, m

Here, S = position for used here "shifted lattice" (started @S11); Origin of PIP-I MADX lattice: S(start_1)=256.860m

Lower plot legend:
- I [A,ACNET]meas.@Extr t[6]=36ms
- I [A,ACNET] =I [A, MADX]/0.024 Var"A01/B01"

MADX match:
Constraint -
All Y (BPMs);
VARY – all VSnn

Calibration good?
I, Amps(S01, L02)

Y@septa=-5mm ?

Huge currents,
e.g. *I* (VSO2)=80A !?

E.Prebys, 2006:

$\alpha_{max} \approx 0.5 \text{mrad}$

$I_{max} \approx 40 \text{A}$

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MADX: BEX + match @ w/o BPML03

2-Mar-2020 B38 data
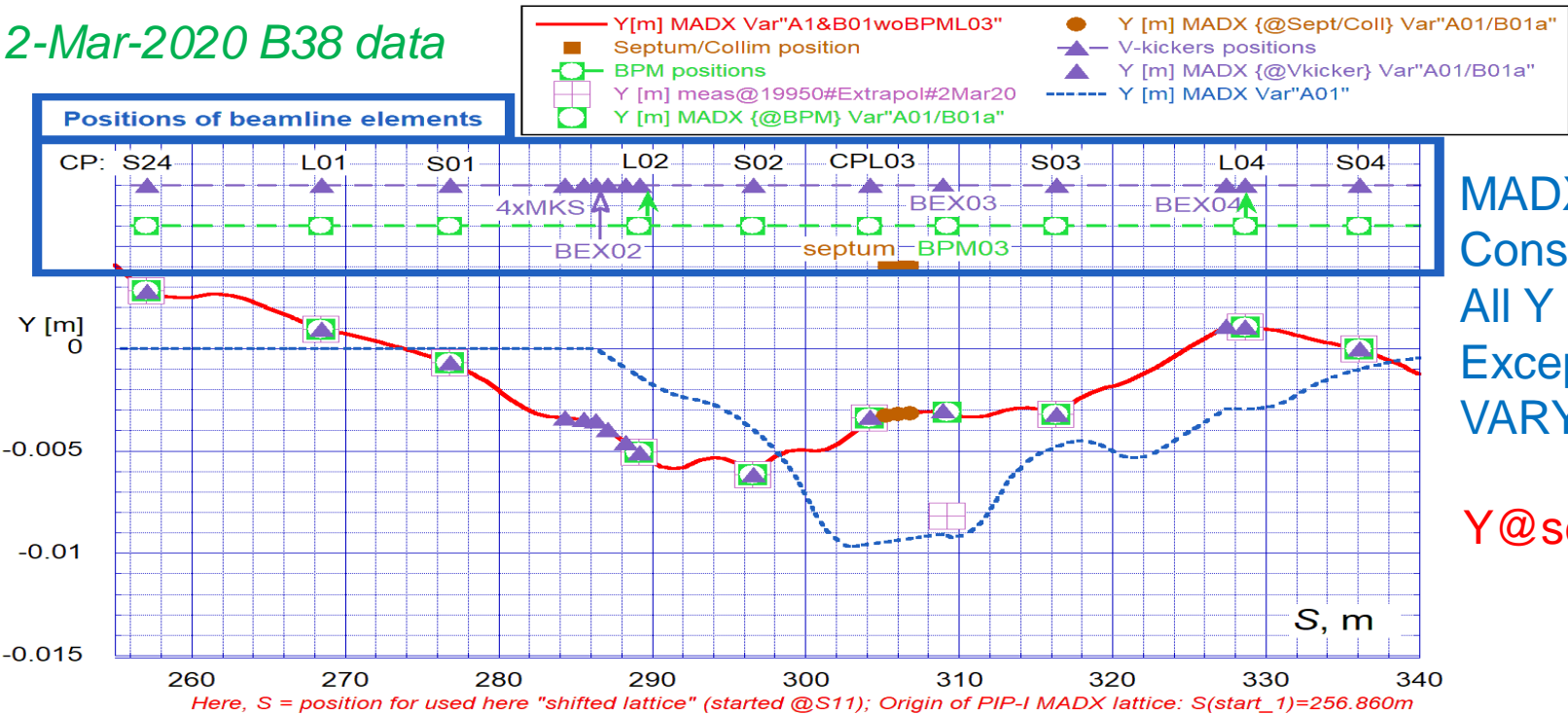
MADX match:
Constraint -
All Y (BPMs),
Except BPML03;
VARY – all VSnn

Y@septa=-3mm

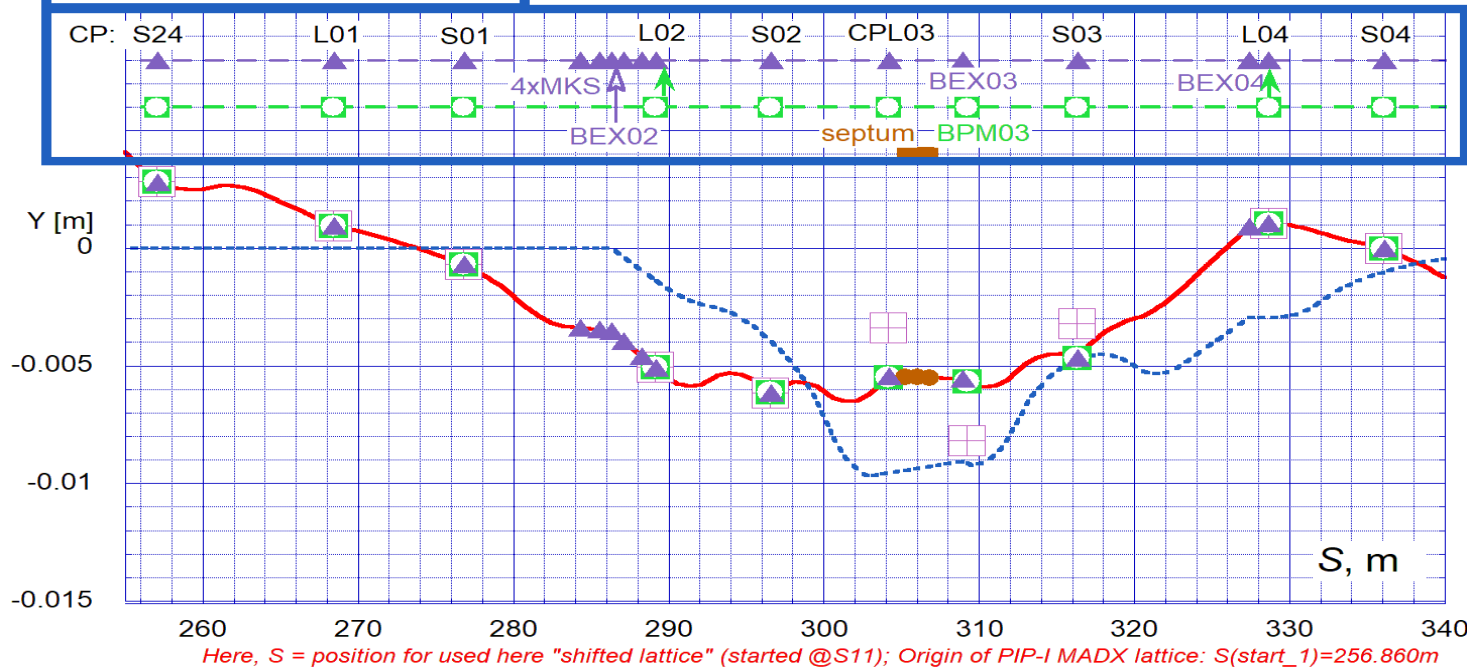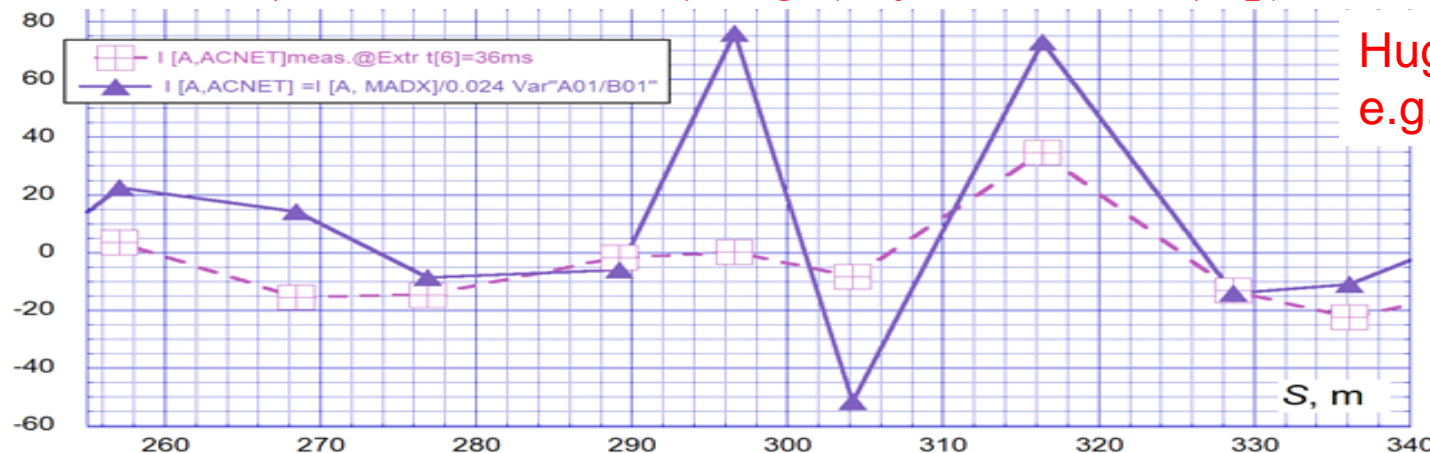*Here, S = position for used here "shifted lattice" (started @S11); Origin of PIP-I MADX lattice: S(start_1)=256.860m*
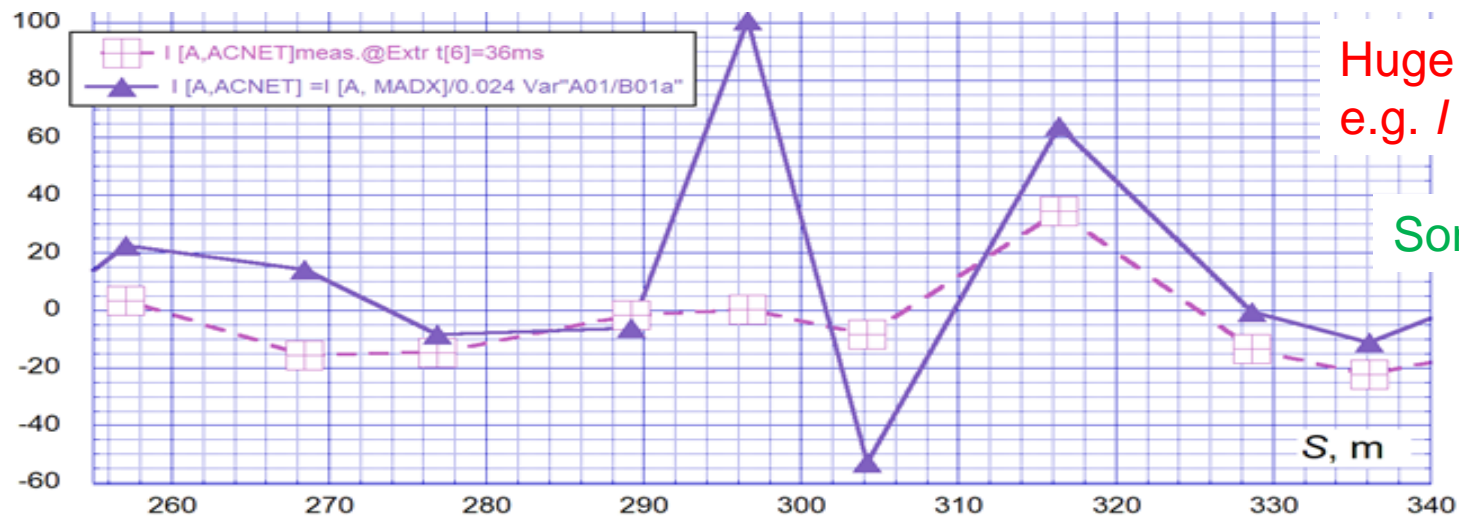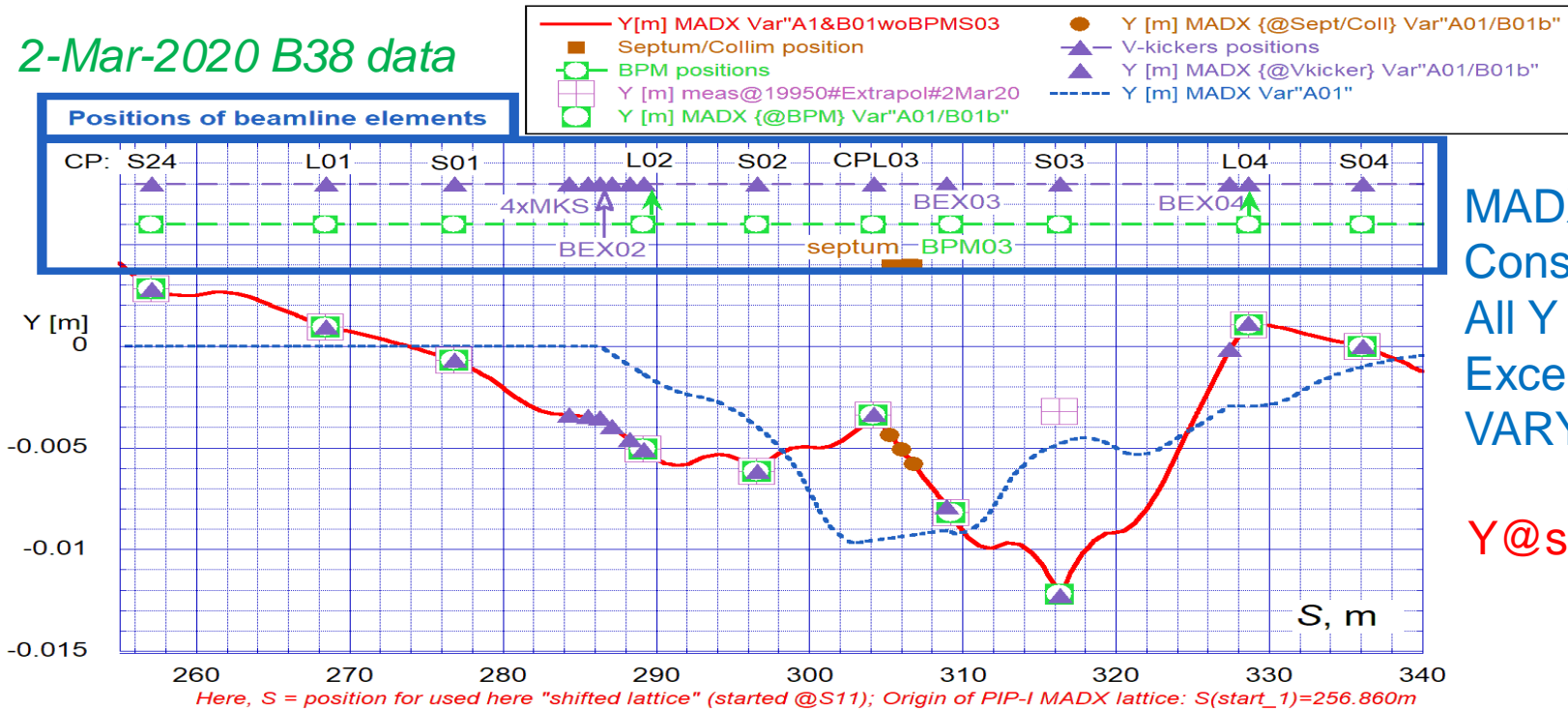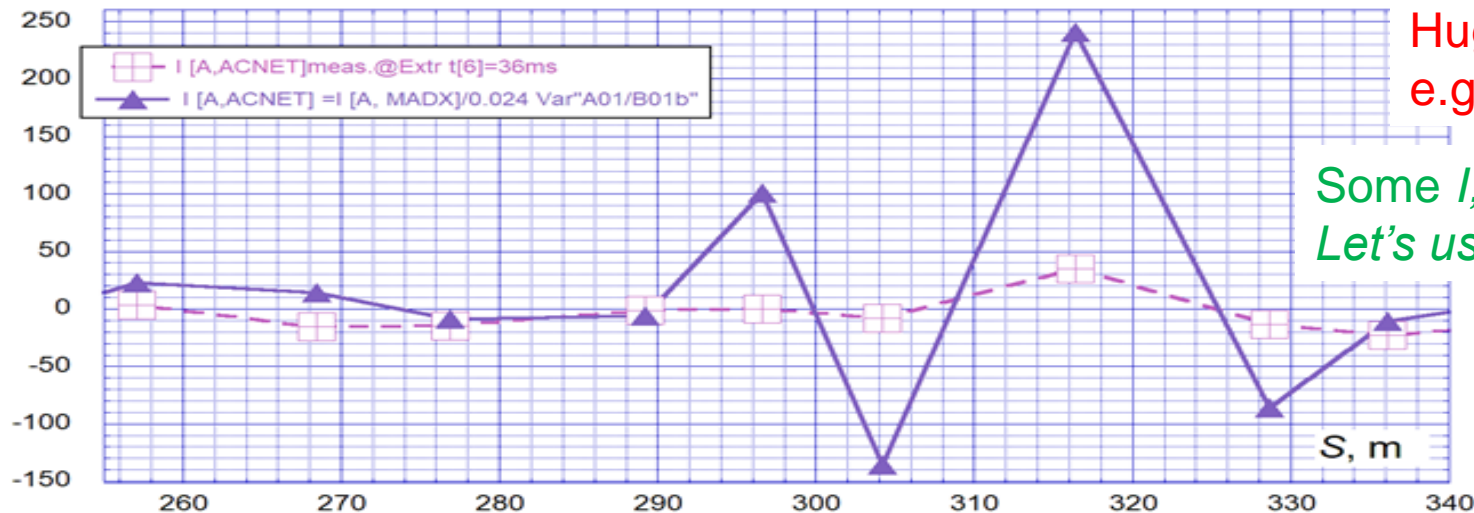

Huge currents,
e.g. *I* (VSO2)=100A !?

Some I,Amps good

E.Prebys, 2006:

$I_{max} \approx 40A$ 17

$\alpha_{max} \approx 0.5 mrad$

MADX: BEX + match @ w/o BPMS03

2-Mar-2020 B38 data

Positions of beamline elements

Legend:
- Y[m] MADX Var"A1&B01woBPMS03" (red line)
- Septum/Collim position
- BPM positions
- Y [m] meas@19950#Extrapol#2Mar20
- Y [m] MADX {@BPM} Var"A01/B01b"
- Y [m] MADX {@Sept/Coll} Var"A01/B01b"
- V-kickers positions
- Y [m] MADX {@Vkicker} Var"A01/B01b"
- Y [m] MADX Var"A01" (dashed line)

CP: S24 L01 S01 L02 S02 CPL03 S03 L04 S04

4xMKS   BEX02   BEX03   BEX04
         septum   BPM03

Y [m] axis: 0, -0.005, -0.01, -0.015

Here, S = position for used here "shifted lattice" (started @S11); Origin of PIP-I MADX lattice: S(start_1)=256.860m

S, m axis: 260, 270, 280, 290, 300, 310, 320, 330, 340

MADX match:
Constraint -
All Y (BPMs),
Except BPM**S03**;
VARY – all VSnn

Y@septa=-4mm

Lower plot legend:
- I [A,ACNET]meas.@Extr t[6]=36ms
- I [A,ACNET] =I [A, MADX]/0.024 Var"A01/B01b"

I axis: 250, 200, 150, 100, 50, 0, -50, -100, -150

S, m axis: 260, 270, 280, 290, 300, 310, 320, 330, 340

Huge currents,
e.g. *I* (VSO2)=100A !?

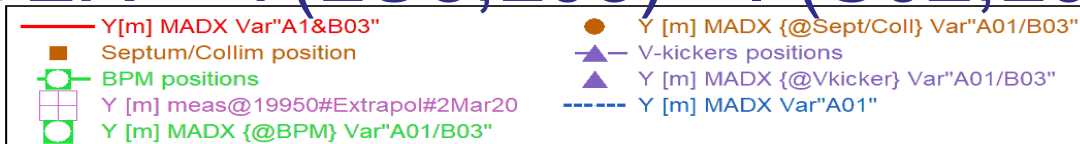Some *I,Amps are good,
Let's use them !?*

E.Prebys, 2006:
$I_{max} \approx 40A$ 18
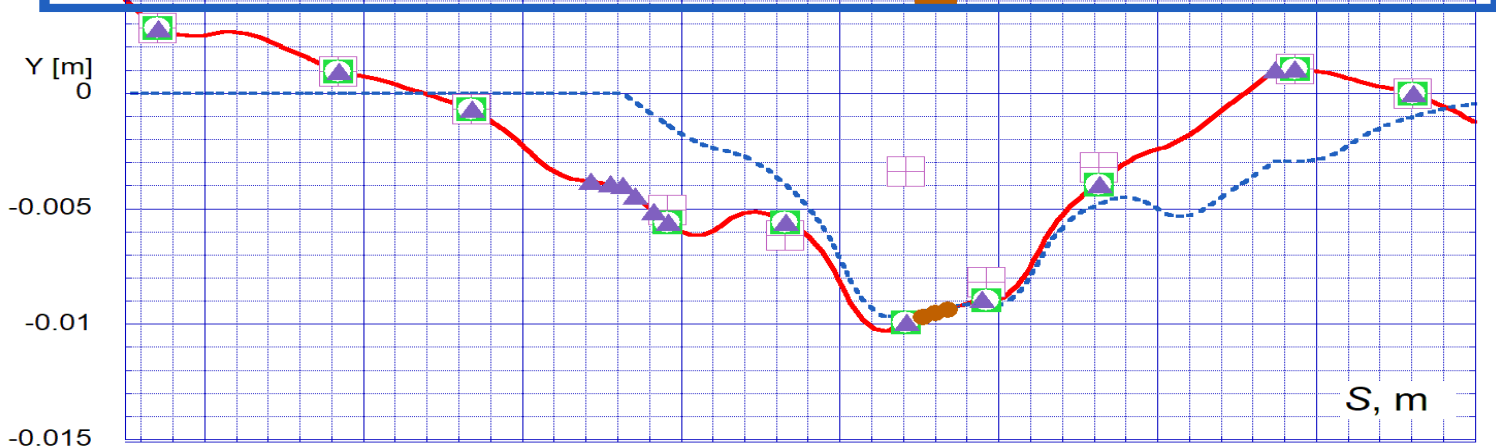$\alpha_{max} \approx 0.5mrad$

MADX: BEX + Y(LU3,L03)->I (S02,L03)

2-Mar-2020 B38 data

Positions of beamline elements

Legend:
- Y[m] MADX Var"A1&B03"
- Septum/Collim position
- BPM positions
- Y [m] meas@19950#Extrapol#2Mar20
- Y [m] MADX {@BPM} Var"A01/B03"
- Y [m] MADX {@Sept/Coll} Var"A01/B03"
- V-kickers positions
- Y [m] MADX {@Vkicker} Var"A01/B03"
- Y [m] MADX Var"A01"

CP: S24 L01 S01 L02 S02 CPL03 S03 L04 S04

4xMKS BEX03 BEX04
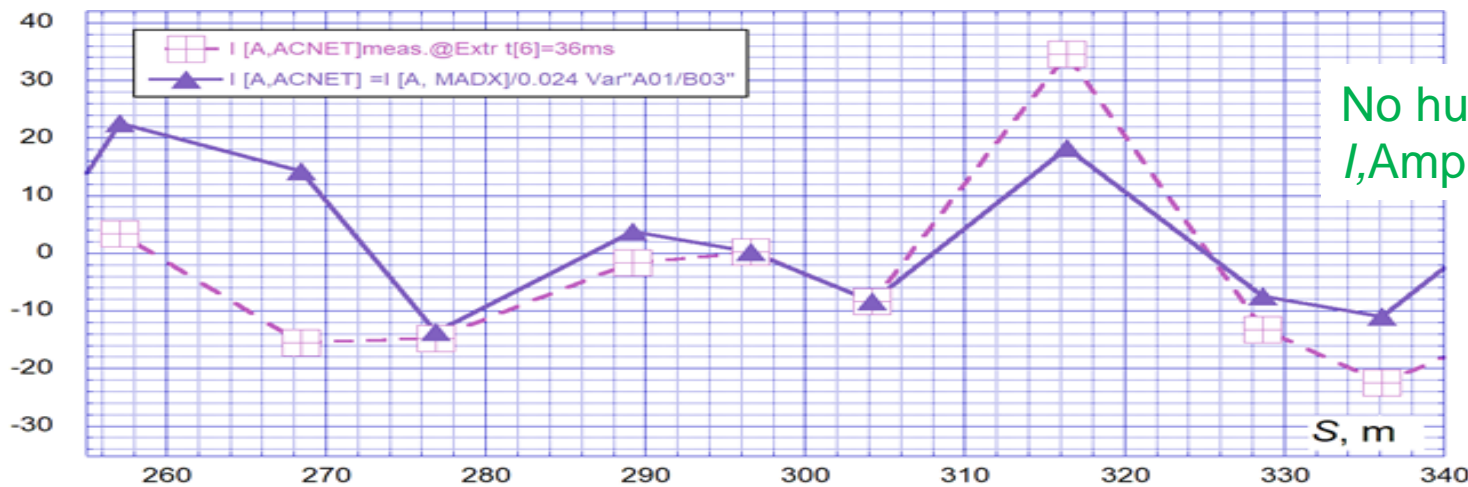BEX02 septum BPM03

Y [m]

Here, S = position for used here "shifted lattice" (started @S11); Origin of PIP-I MADX lattice: S(start_1)=256.860m

MADX match:
Constraint -
All Y (BPMs),
Except LU3, L03;
VARY – all VSnn,
Except S02, L02
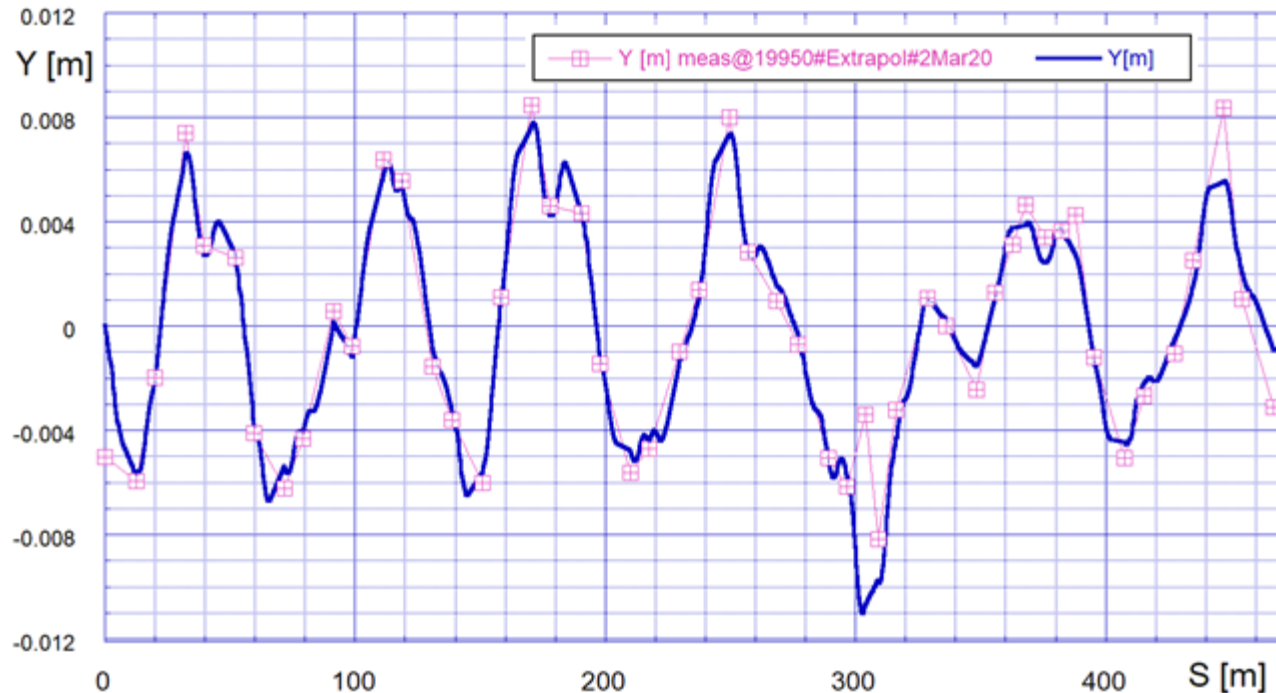using *I*, amps ->
Kick-angles !!!

Y@septa=-9mm

Legend (lower plot):
- I [A,ACNET]meas.@Extr t[6]=36ms
- I [A,ACNET] =I [A, MADX]/0.024 Var"A01/B03"

No huge currents, but
I,Amps *not perfect*

E.Prebys, 2006:
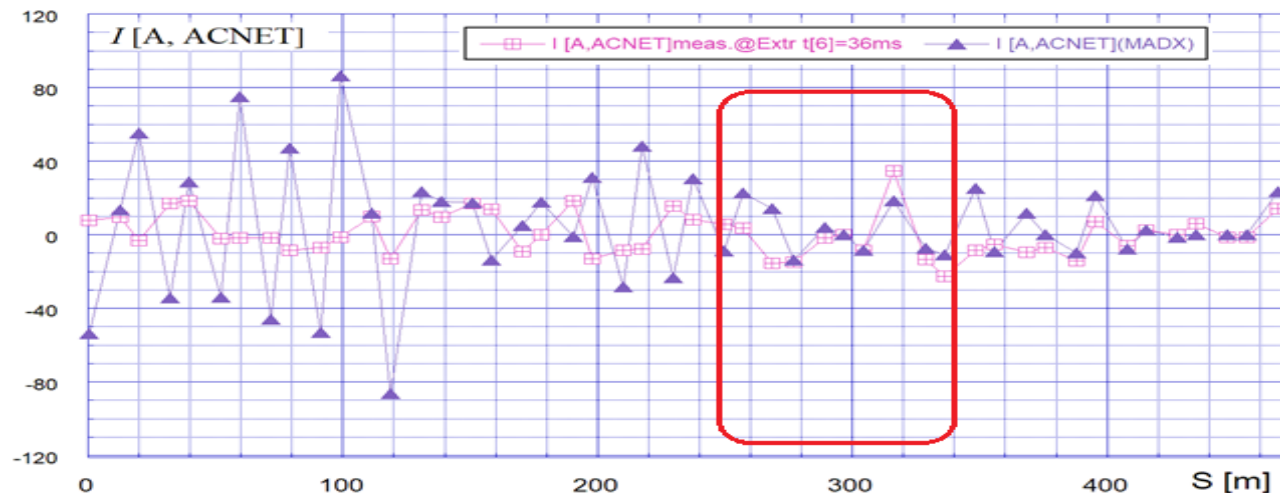$I_{max} \approx 40A$
$\alpha_{max} \approx 0.5mrad$

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Calibration "Kick-angle=f(*I*amps)" around Booster

2-Mar-2020 B38 data

It looks to be not suitable
For Global matching
around Booster BPMs
(errors accumulated)

It could provide some
Guess-values and
should be considered
For local matching in
restricted area

Further exploring on
Other areas could be
checked
(e.g. collimators)

Conclusion

- MADX simulations shows that the last turn extraction orbit is quite different from 1968-report and from our previous simulation Y=0 (BD-7875).
- The last turn orbit near Septum is probably located under Booster axis in the range [-3;-13] mm.
- Use of kick-angles derived from CP's I,amps instead of Y-cords (BPM measured) for CP-kickers near septa (via CP calibrations) suggests the last turn orbit to be equal ~-9mm

- Probably, it may lead to reduction of large beam losses on F-magnet reported in our previous report. It will be tested with further MADX multi-particle simulations
- Usage of CP currents instead of measured BPM's Y-coordinates might be used locally in some restricted areas for MADX-matching

Supporting slides

Task setup: Septum & D-magnet cross-sections
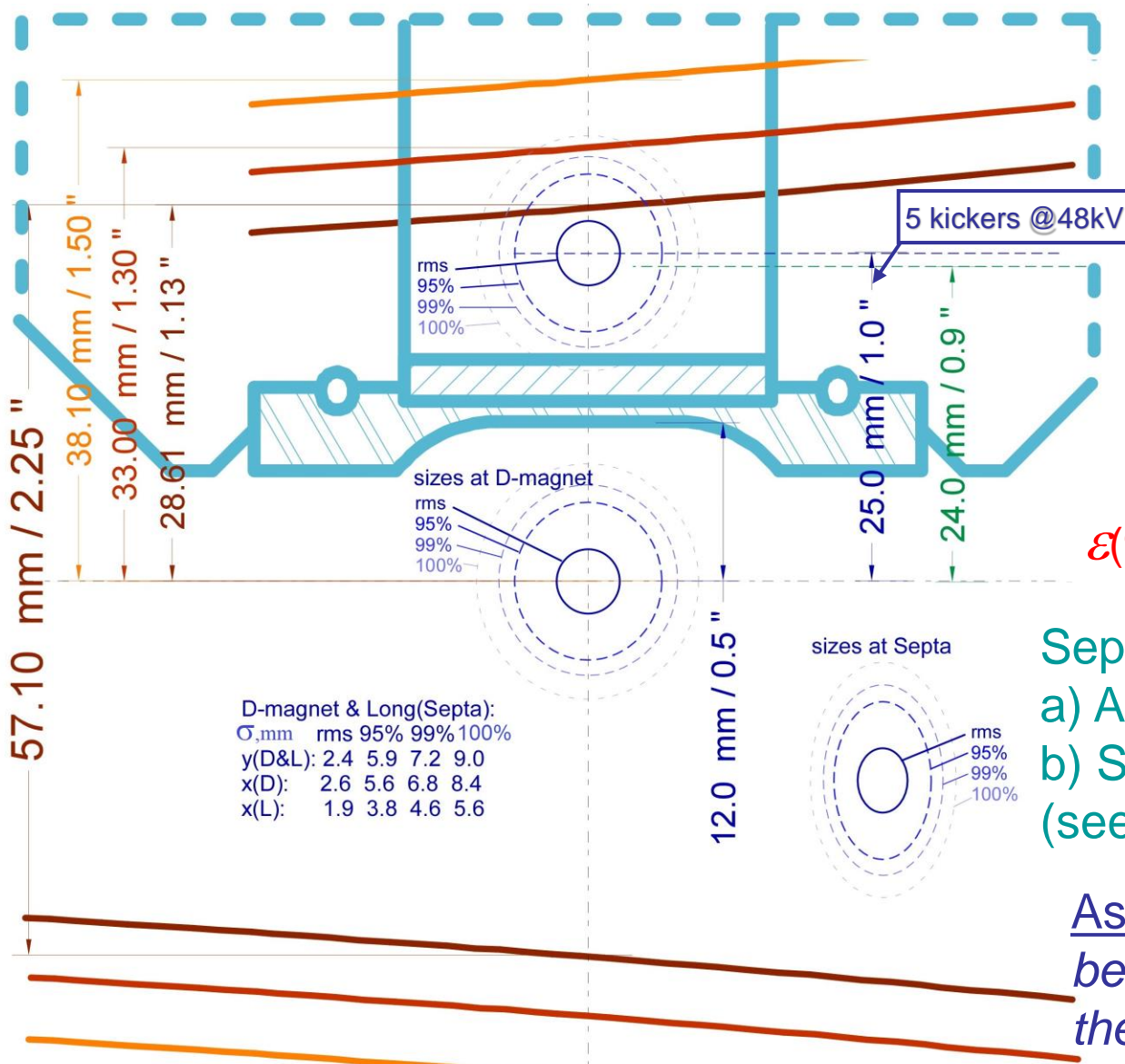
Beam trajectory ~ parallel
Between D-magnets and
Septum (see next)

3 variants of D-magnets:
$G_D=\{2.25"; 2.60"; 3.0"\}$

Percentage of particles is
$1-\exp(-n/2)$, where $n=\varepsilon/\varepsilon_{rms}$

$\varepsilon(95\%)_{n,x\&y,8GeV}=16\pi\cdot$mm$\cdot$mrad

Septum position ~12mm found:
a) Assembly drawing by J.L.
b) Septum drawings
(see supporting slides @ end)

Assumption: *the circulating
beam is placed exactly on
the Booster axis*

Possible scraping of the ***beam particles in tail region***

Labels within figure:

5 kickers @48kV

sizes at D-magnet
rms
95%
99%
100%

sizes at Septa
rms
95%
99%
100%

D-magnet & Long(Septa):
σ,mm	rms	95%	99%	100%
y(D&L):	2.4	5.9	7.2	9.0
x(D):	2.6	5.6	6.8	8.4
x(L):	1.9	3.8	4.6	5.6

Dimensions:
57.10 mm / 2.25"
38.10 mm / 1.50"
33.00 mm / 1.30"
28.61 mm / 1.13"
25.0 mm / 1.0"
24.0 mm / 0.9"
12.0 mm / 0.5"

Specification for new D & F magnets BD-7875

Assuming the placement of the circulating beam exactly on the Booster axis, MADX simulations lead to the following results for new D & F magnets:

- To exclude losses on D & F magnets located upstream of the septum, the new D & F magnets with at least 5 mm increased half-gaps (or +10mm full-gaps) are needed
- Curves for beam losses vs half-gaps could be used if magnets with smaller gaps will be designed.
- The already established "safety gaps" ~2mm; their increase will lead to a corresponding increase of full gaps
- External height of D magnet is restricted by 2.5deg-curve formed by the extraction pipe. => D magnet with increased height must be shorter. Its length is limited by the relation:

$L_{new} \le L_{old}$ - (h_{new} - H_{old})/tg(α), where α=2.5deg~0.044, l and L are the D-magnet length, h and H are the external D-magnet heights.

Example. Old H=13" –> new h=16" => old L=3m -> new 1.3m   - too short!

Extraction parameters found in References

1973: Hubbard report.

- Vertical apertures: G_F=1.64"[41.7mm]; G_D=2.25"[57.15mm];

- Betatron phase shift $\Delta\phi_{[kicker-center; septum-lip]}$~93deg;

- 1.1mrad (0.063deg) kick produces δy=23mm @septum;

- Fast kicker consists of 4 sections; $V_{Pulse-line}$(max)~ 75kV;

- Septum (old "circle" design) deflects beam vertically 44mrad [2.52deg];

- Septum -15mm above center; gap=1.1"x1.1"; thickness ("Cu+Fe")~ 0.09"[2.3mm]

FIGURE C-2
MAGNET CROSS SECTION   DIMENSIONS (INCH)


(1a)

(1b)
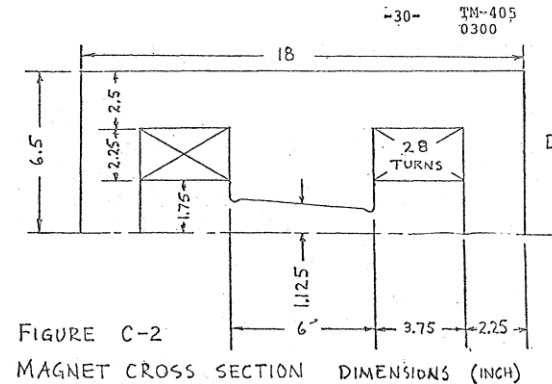
1977: Cosgrove PAC-report.

- A new (Septum) magnet...operated well over 18 month;

- Septum is 60" long; the magnet gap=1.1"x1.5";

- Septum deflects beam vertically 44mrad [2.52deg];

1979: Brown PAC-report.

- tune ν_{vert}~6.8 @ periodicity 24, $\Delta\phi_{cell}$~0.283 (2π) [~101.88°]
- L3 is 15 cells away from L12: $\Delta\phi_{cell}$~4.25 (2π) [~90°]=> maximum displacement is from the kicker in L12
- (Septum)… the present 44 mr (2.52deg) angle.

V.Kapin, New Dmagnet, Jul-2020   25
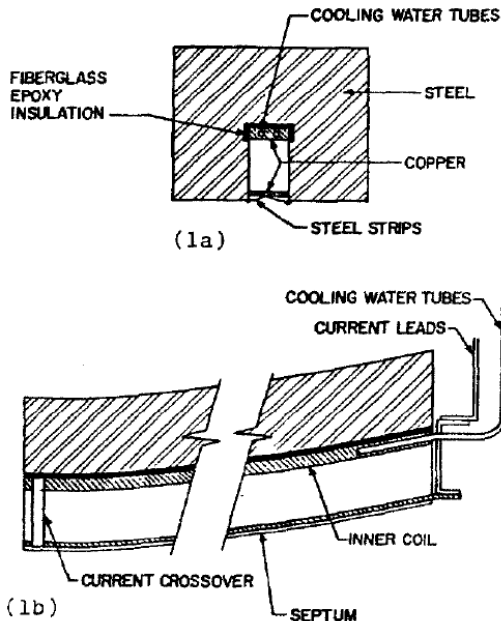
# Extraction parameters found in References

1993 & 2004: Boo Rokie book.

- At nominal voltage 4 kickers produce a bend angle of a bit >1 milliradian (RB-2004);
- the orbit of circulating beam is located ~10 mm below the septa plate (RB-2004);
- to kick the beam into center of septum field, we need ~30 mm vertical displacement;
- Booster extraction kickers have voltages that run in the 55÷60 kV range;
- The septa plate lies close to the vertical centerline (approximately 10 mm above).

2004: Boo Rokie Book.

- There are four kickers at long 2; They displaces the beam upward about 25 mm before the beam reaches the septum at the next long straight section
- Septum -> 44mrad [2.52deg]

figure 7.1
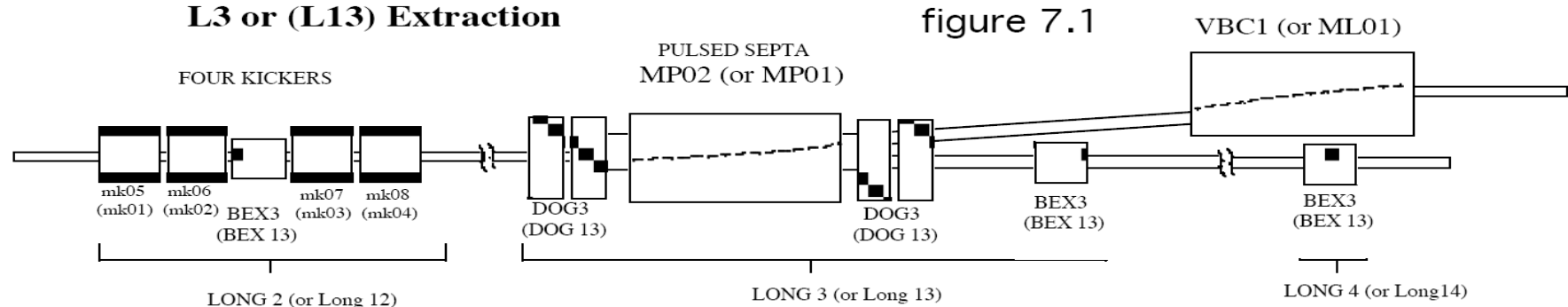
1995: Lackey note. Assuming a septum thickness of 5 mm
2009: Boo Rokie book. It repeats the above parameters from RB-1993&2004
## 2002 New Septum MP02 Requirements. Good field region: 1" square beginning 0.04"[~1mm] from septum conductor

Photo BSE magnets at TD

https://www-tdserver1.fnal.gov/Project/ProEng/MagnetPhotos/pics.asp?qsPath=BSE
It looks that five 5 septum with No "BSE102 - BSE106"
correspond to Drawing No. ME-412051

The presently used BSE104 has only two photos dated 5-Jan-2004
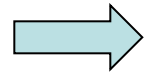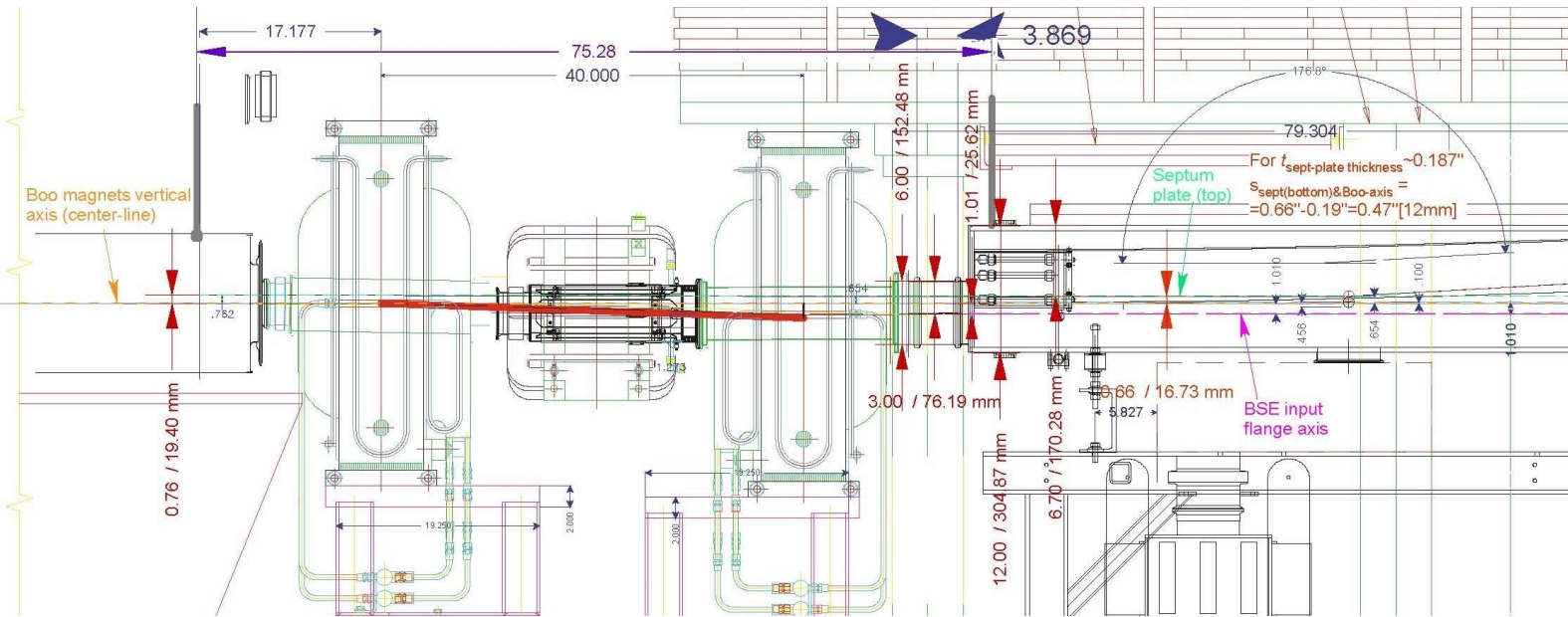while BSE106 has photo dated by 20040324

Many photo (dated by 16/July/2002) of the particular BSE102
(already used in Booster operations and now stored in the Boo tunnel)
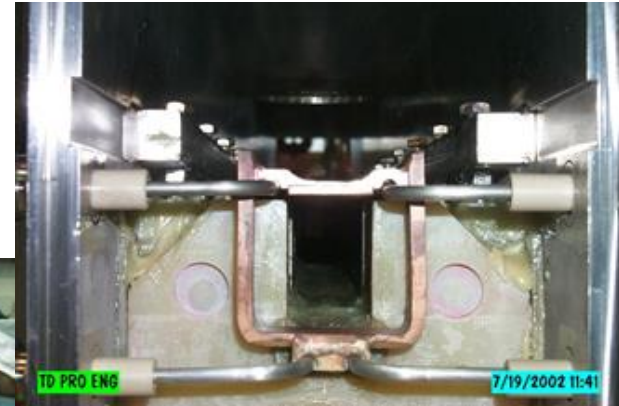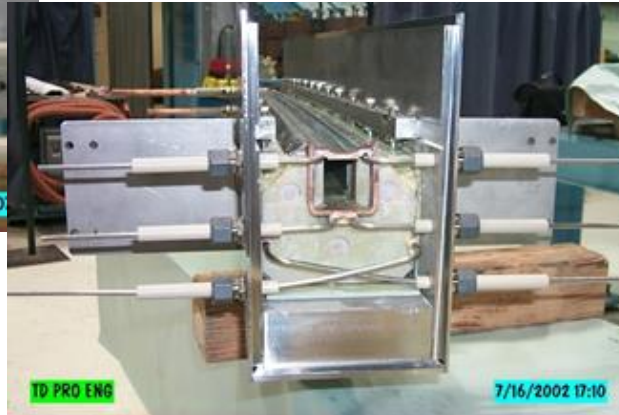
Example. Taking sizes from drawing
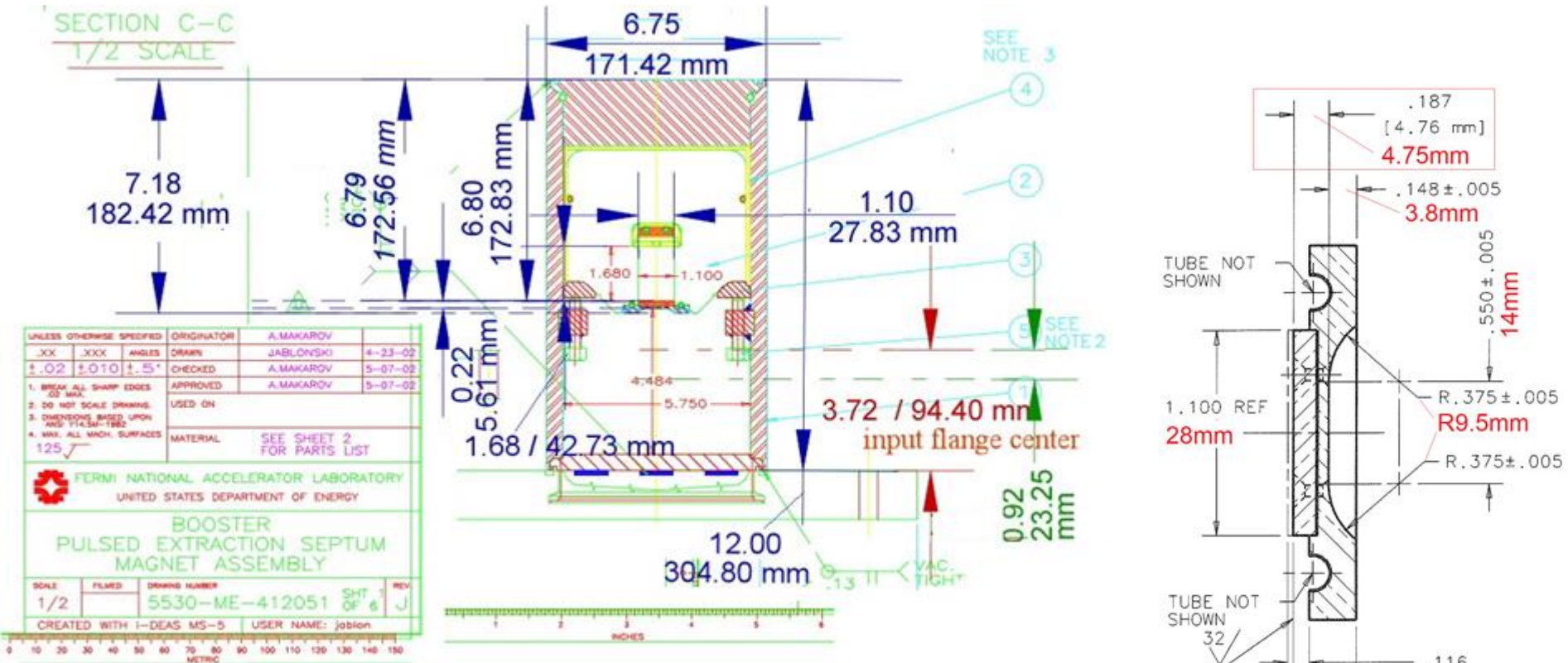
L03 Assembly ~2008 by J.Lackey

PDF file
From
Kiyomi