Booster Studies- Adiabatic Capture

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For a past few years we have been carrying out systematic effort to eliminate longitudinal emittance growth at beam capture and reduce the beam loss in the first 5ms in the Booster beam cycle. Here, we present current status of the study and what was achieved in the past. This work is in progress.

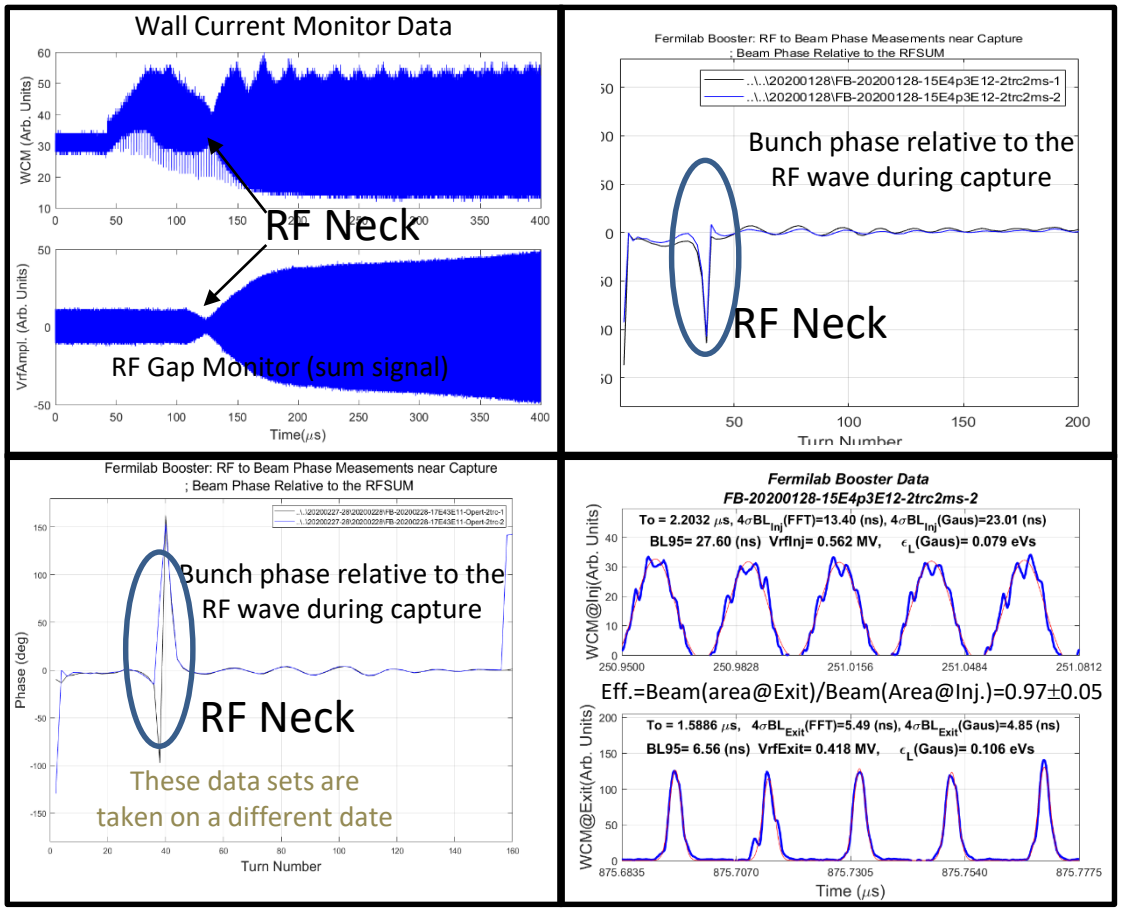
Beam Capture Studies in Booster

- The goals of capture studies (early injection scheme) in the Booster were
  - To inject the beam far earlier than the Bmin (achieved ~200 μs earlier). ✓
  - Use this additional 200 μs for **adiabatic** beam capture (dE(95%) of the injected beam after multi-turn injection ~1.5 MeV) ← No additional time was available for adiabatic capture if beam is injected very close to Bmin, as in the past. **←In progress**
  - Reduce/eliminate the beam loses during the first 4 ms of the Booster cycle which are arising from non-adiabatic beam capture. **←In progress**
  - Be able to
    - Increase the over all acceleration efficiency for higher beam intensities (≥4.5E12ppBc) **←In progress**
    - Transfer beam with bunch emittance ≤0.1 eVs to the downstream machines for intensities ~5E12ppBc ✓
    - Reduce the RF bucket area during the beam cycle, hence, reduced operational RF power consumption ✓
- Here we present
  - Our findings from our studies
  - What are achieved
  - What are in progress

Beam Capture Studies in Booster (cont.)

- Findings:
  - For beam injection to extraction all of the RF cavities are divided into two groups- A&B
    - Within each group the cavities should be perfectly aligned in relative phases. ← study showed that phase error as large as 20 deg.
    - With $|\vec{V}\mathrm{rf}(A)|=|\vec{V}\mathrm{rf}(B)|$. ← study showed that $|\vec{V}\mathrm{rf}(A)|\#|\vec{V}\mathrm{rf}(B)|$
    - With $\vec{V}\mathrm{rf}(A)+\vec{V}\mathrm{rf}(B)=0$ at injection ← study showed that $\vec{V}\mathrm{rf}(A)+\vec{V}\mathrm{rf}(B)\#0$
  - Also observed
    - Energy mis-match between LINAC and Booster
    - Mismatch between RF-frequency curve and the desired frequency at injection.
  - Operationally "RFNECK" was demanded
    - Lots of dedicated beam study was done to learn about RF NECK and its necessity in current operation
  - Simulations suggested that
    - Each one of them result in initial emittance dilution and hence need larger RF bucket to capture all the beam particles
    - Even though all the particles are captured, the ones near the separatrix are lost (4-6%)

Examples from Operational Scenario Inj. → Exit 2020228 data, Beam Intensity ~4.3-4.5E12ppBc



Currently beam is not captured adiabatically and there is ~5% beam loss in the first 5 ms of the beam cycle.

Beam Capture Studies in Booster (cont.)

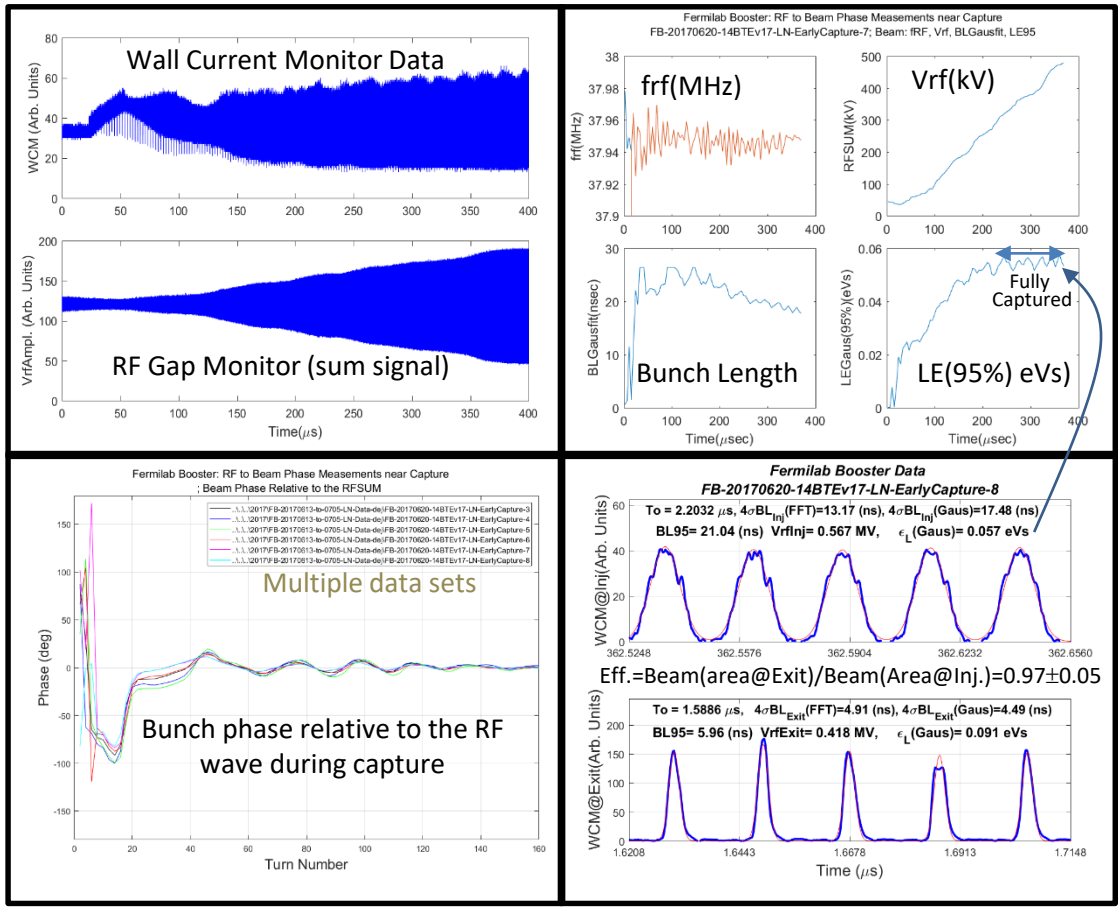
On-going Improvements

- During 2018-20 we tried to align all 22 RF cavities (V. Grzelak, C. Tan and C.Bhat)
  - Result: a phase error <5 deg was achieved.
  - This was supposed to help beam capture, acceleration and bunch rotation.
- Between 2017-20 there number of improvements in the LLRF have been added.
  - Craig Drennan started modernizing the BLLRF
  - Currently, implementing a new digital para-phase system to help control the HLRF during the beam capture. These are being tested.

Every time we make any improvements in the LLRF, we had to retune the system from injection to extraction. Adiabatic capture and understanding the RF NECK is in progress.

- During 2017 studies we were able to achieve good adiabatic capture guided by beam simulations and some random tuning
  - RF voltage is increased smoothly during beam capture.
  - RF NECK was eliminated.
  - Beam emittance blowup during beam capture is decreased.
  - The Beam phase relative to the RF waveform remained ~0 deg ← **No Phase Jump**

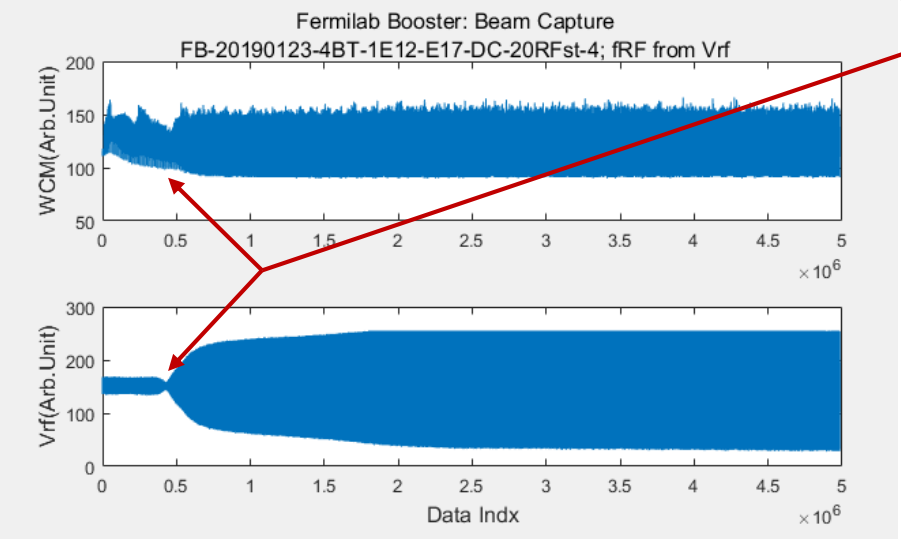
Examples of Adiabatic Capture from Inj. → Exit
2017 data, Beam Intensity >5.2E12ppBc



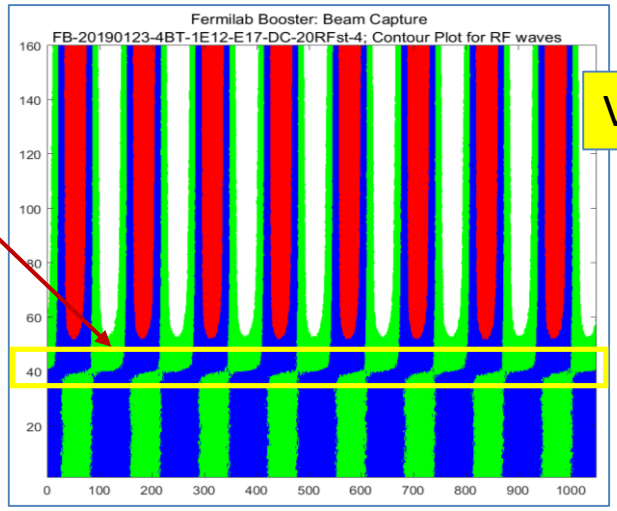
Backup slides

RF Neck Before Beam Capture?

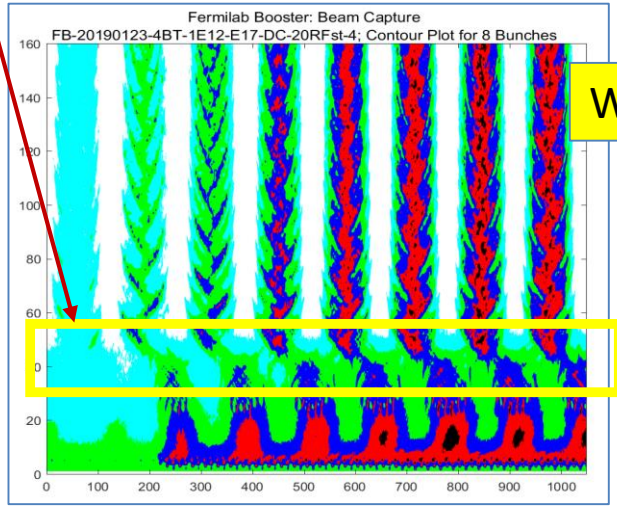
Global balance OFF/ON



Phase jump



Vrf



WCM

For whatever reason, the neck is operationally desirable for the best acceleration efficiency seen so far. We have conducted studies with

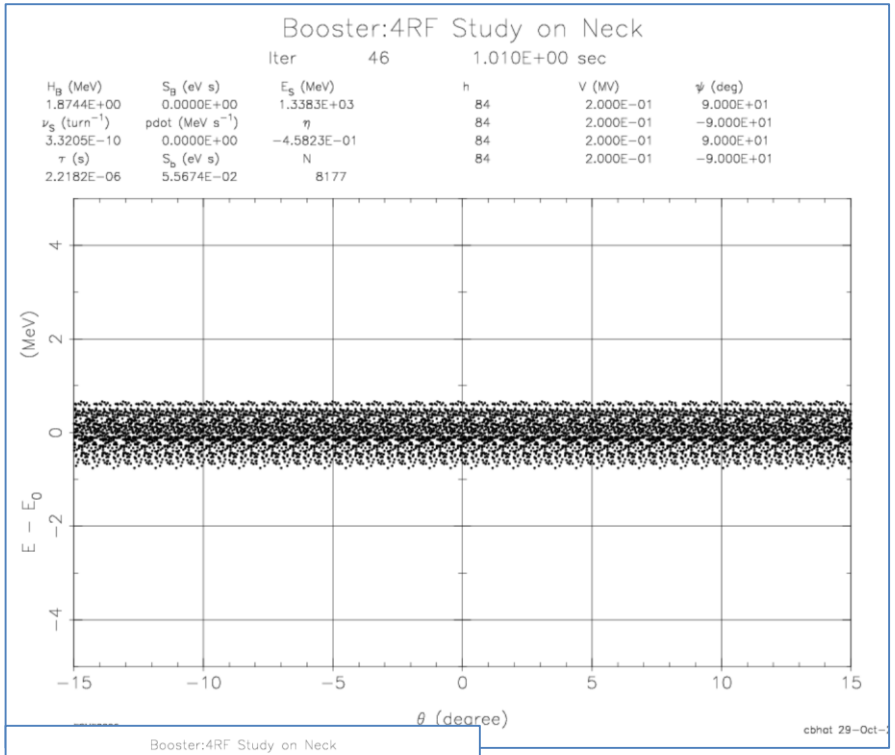
1) Ramping Mode and
2) DC Mode

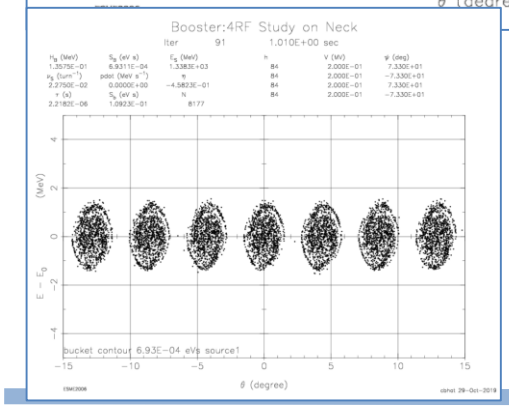
Is this real? YES! See waterfall plot of injection.

ESME Simulations of Beam Capture

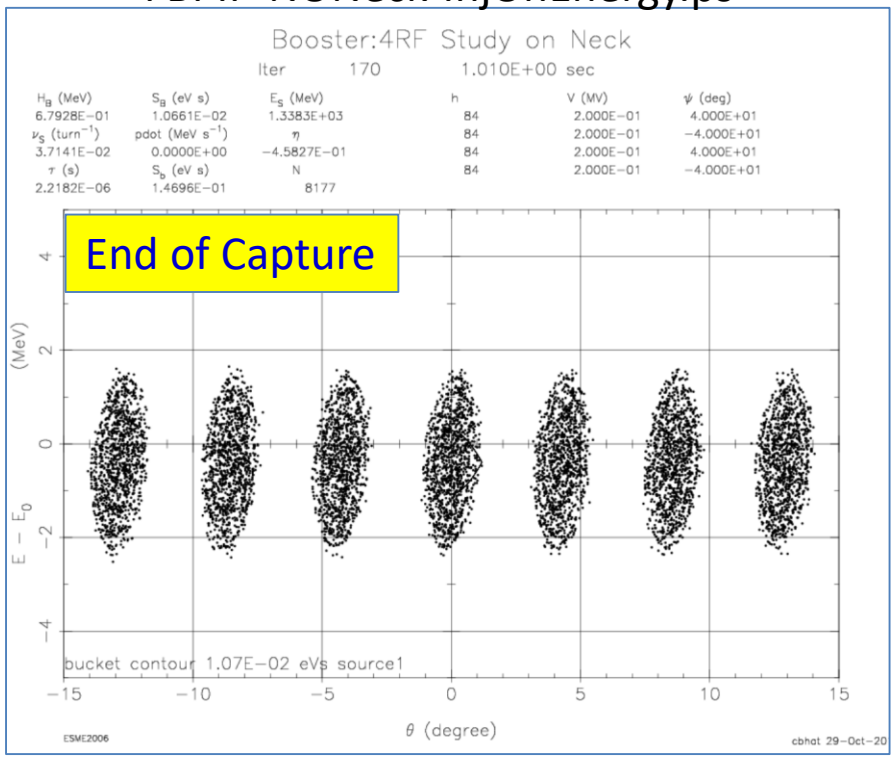
- Carried out simulations on beam capture
  - 4 RF cavities – 2A and 2B cavities
  - 400 kV/A-cavities (max) – a total of 800 kV
  - Injection Energy offset Eoff= 0-1 MeV
  - fRF during first ~300 μs
    - Held at Inj. freq.
    - Held at 10kHz higher than Inj freq.
    - Varying quadrically from df=10kHz to 0kHz
  - VA/VB=1, 0.98 and 0.95

Eoff=0 MeV, df=0 MHz, VA/VB=1.0
No Neck



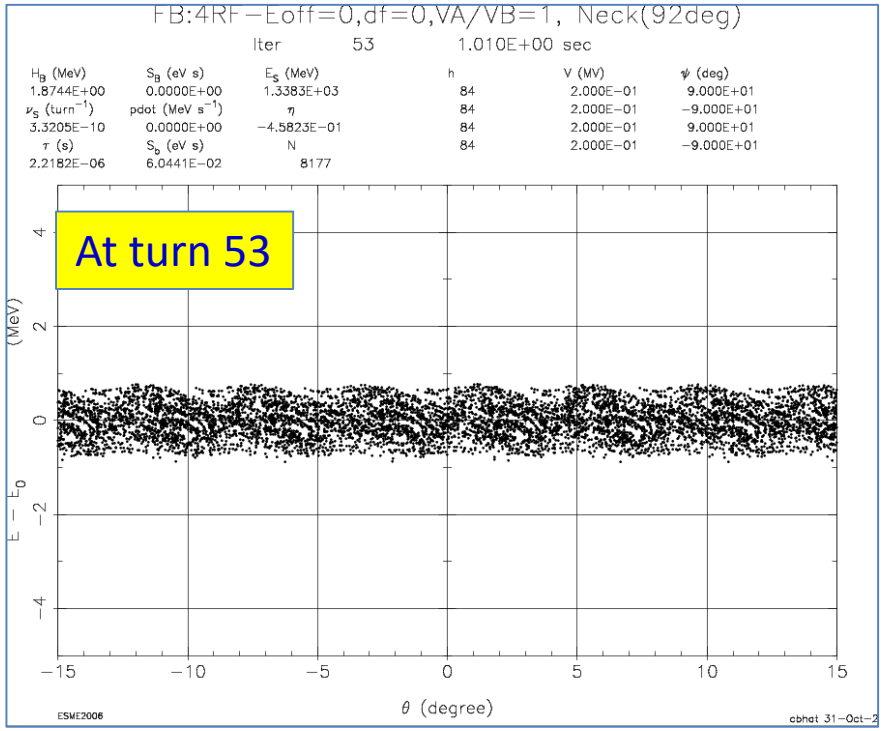


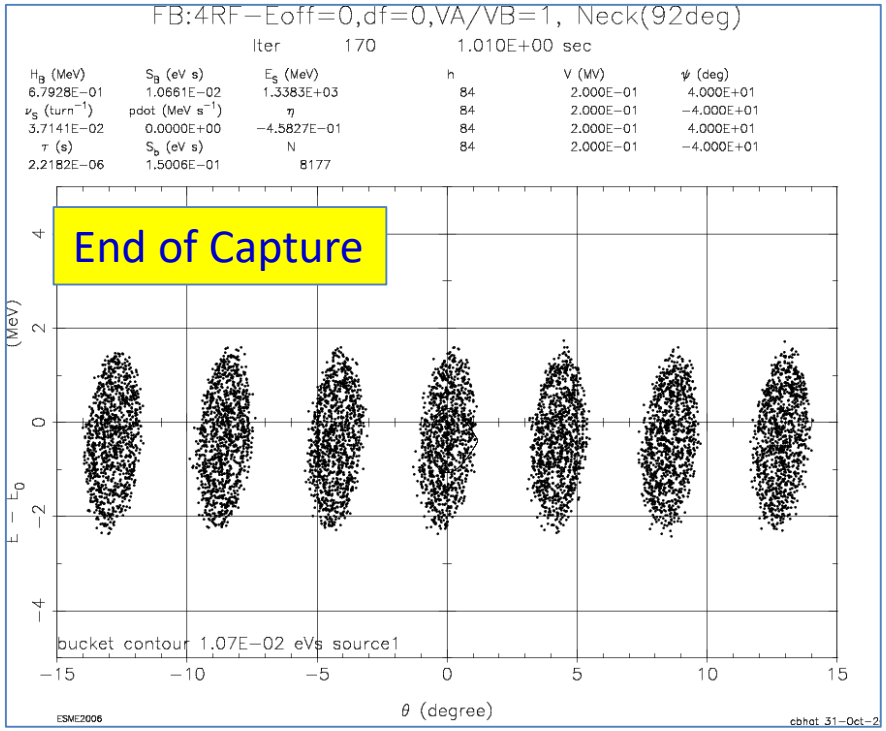
FBPIP-NONeck-InjOnEnergy.ps



emittance growth ~ 0

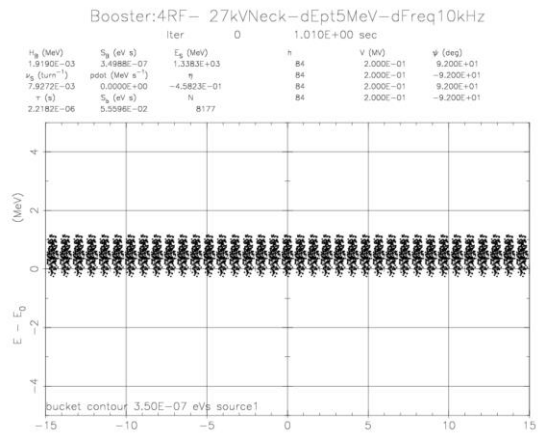
Eoff=0 MeV, df=0 MHz, VA/VB=1.0 Neck(92deg)

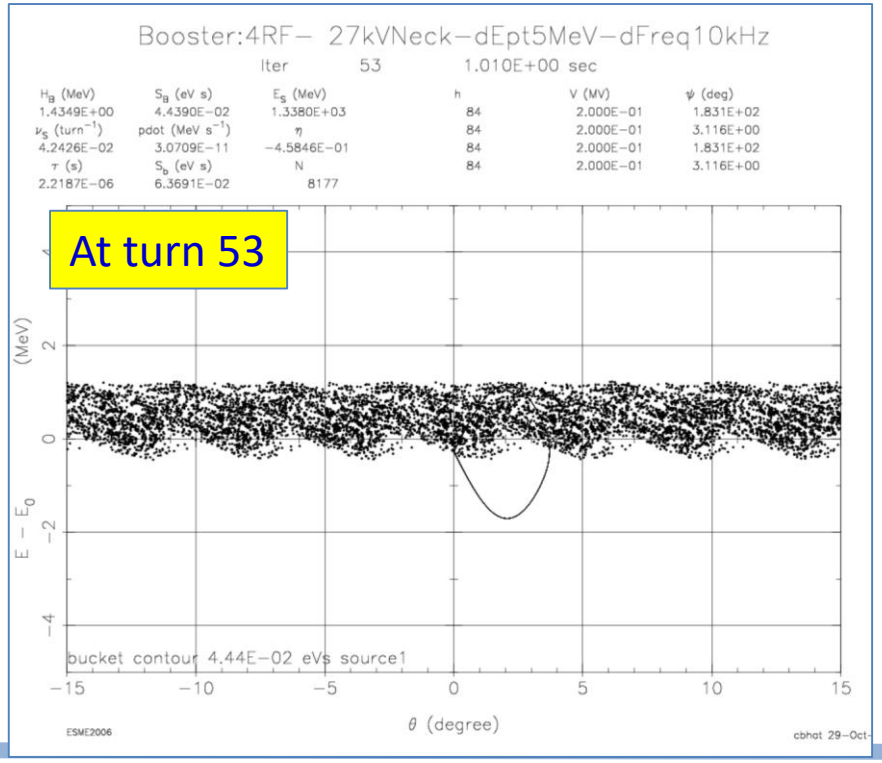


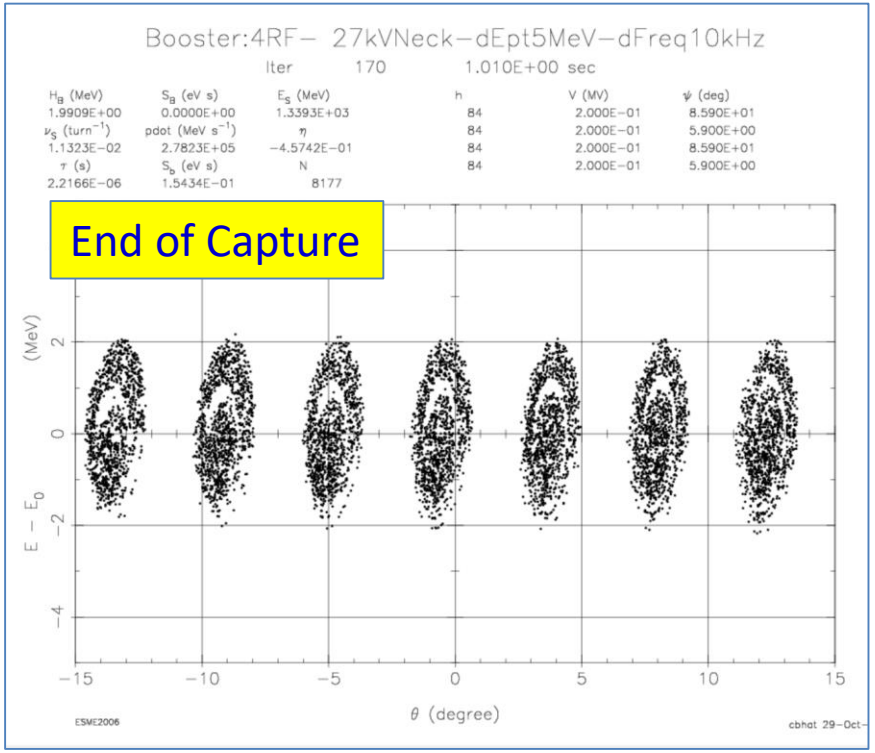


emittance growth # 0, Capture OK

Eoff=0.5 MeV, df=10 kHz, VA/VB=1.0 Neck (92deg)

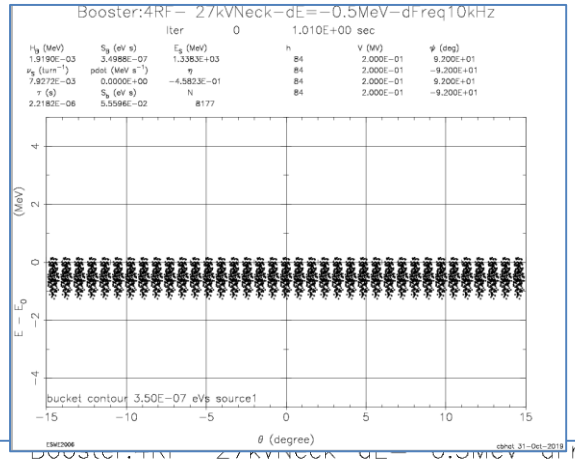


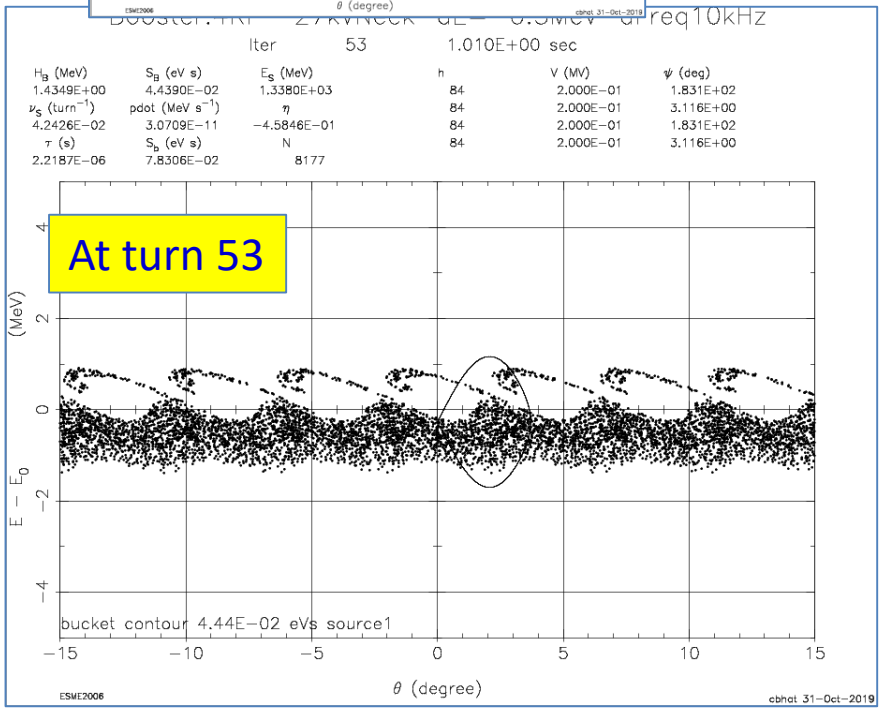


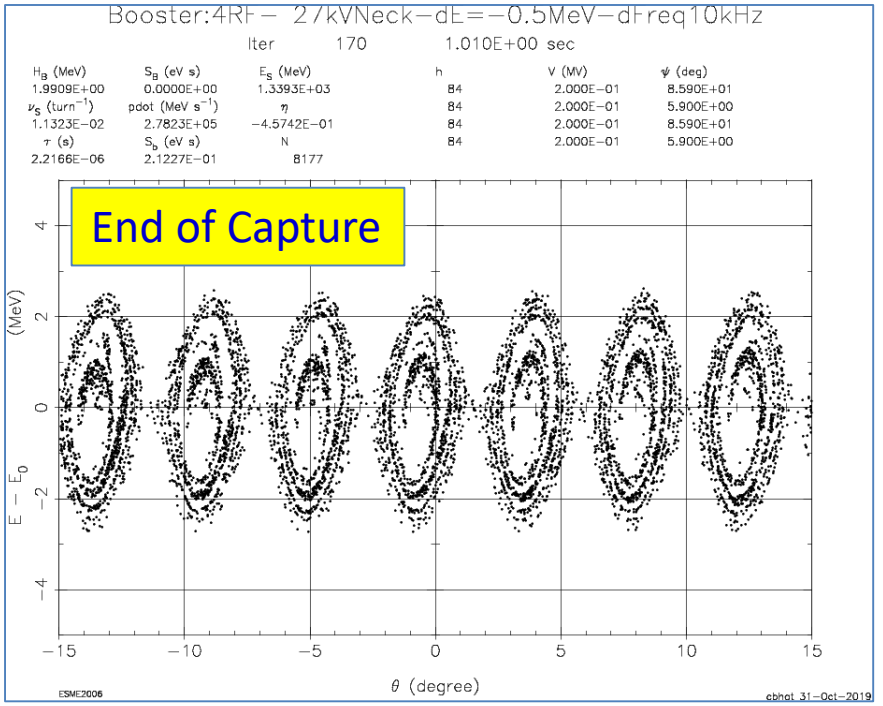


Large emittance growth, Capture OK

Eoff=-0.5 MeV, df=10 kHz, VA/VB=1.0 Neck (92deg)

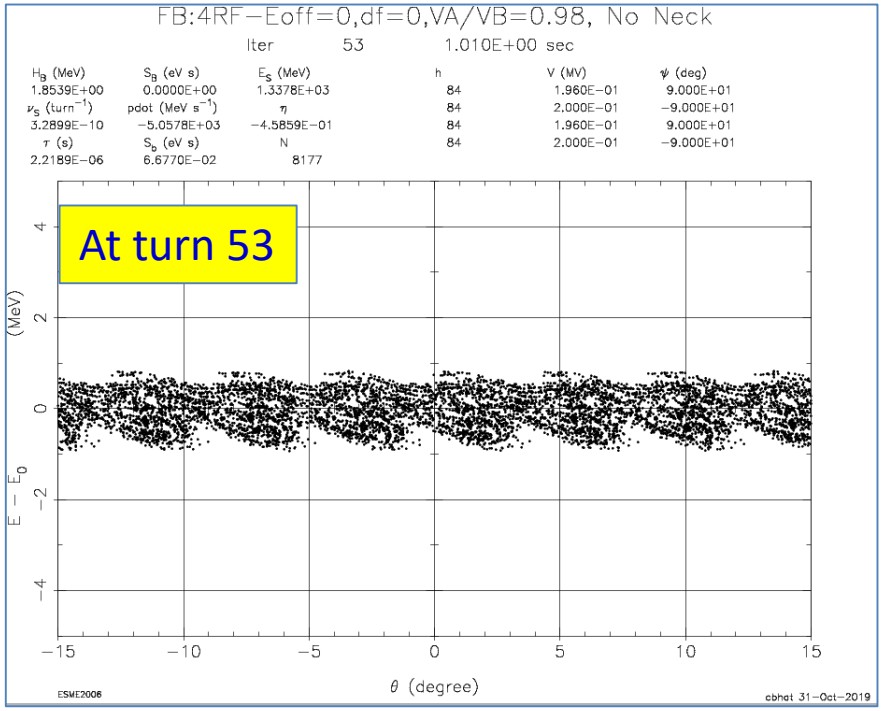


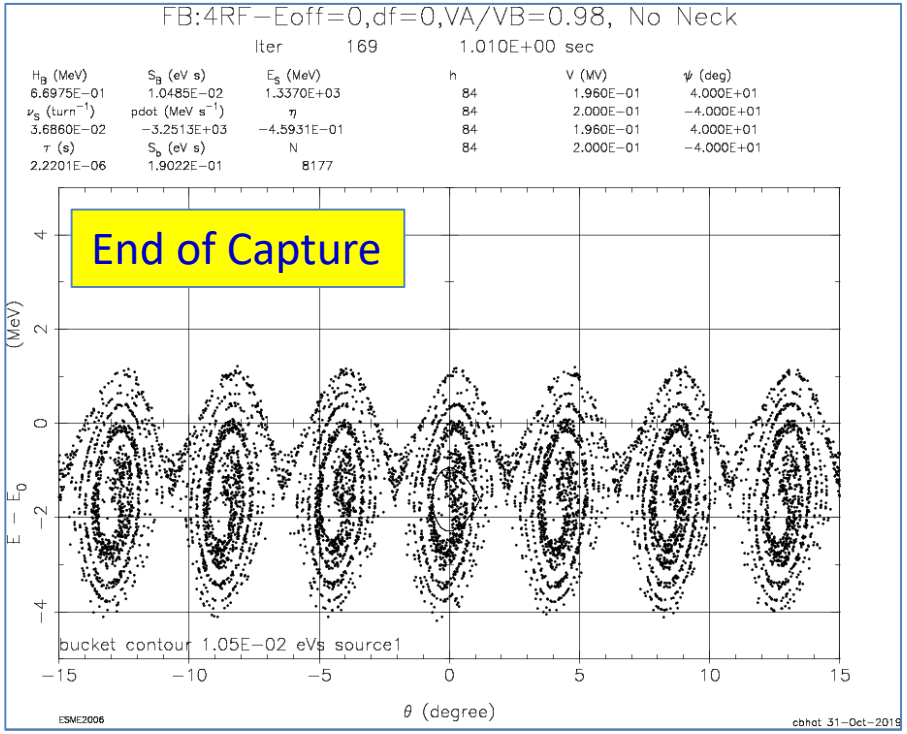




Large emittance growth, Capture OK

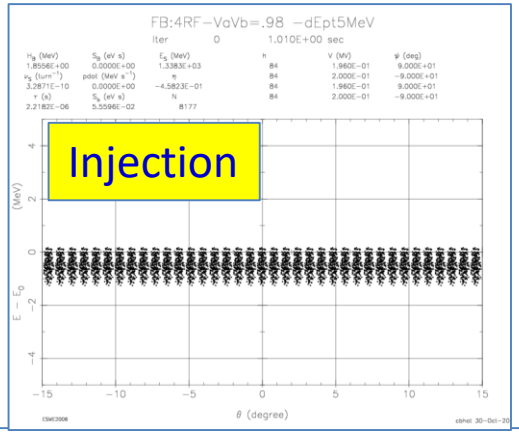
Eoff=0 MeV, df=0 kHz, VA/VB=0.98
No Neck

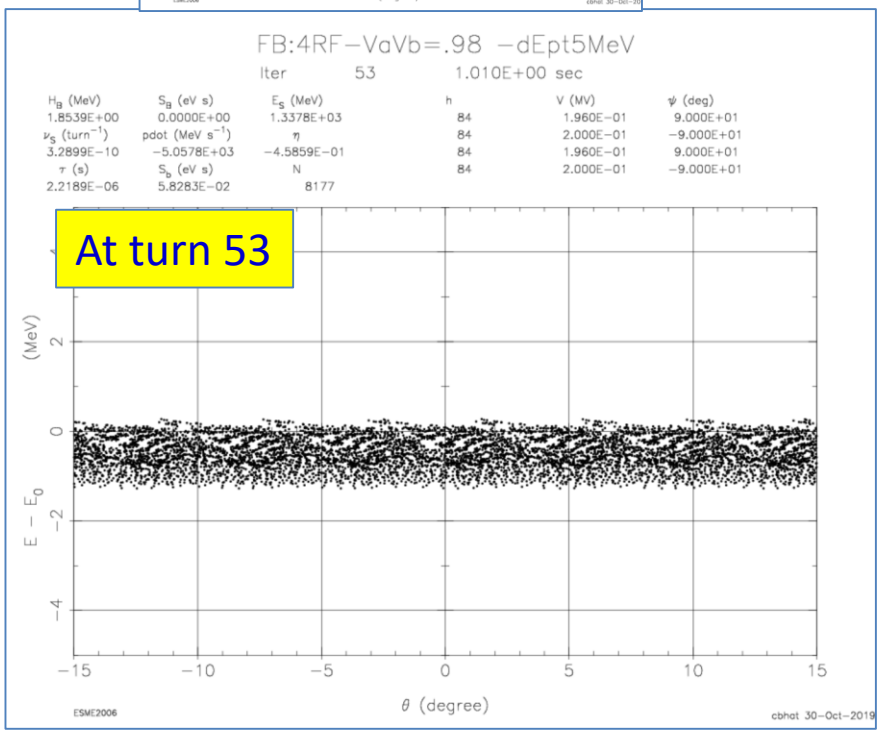


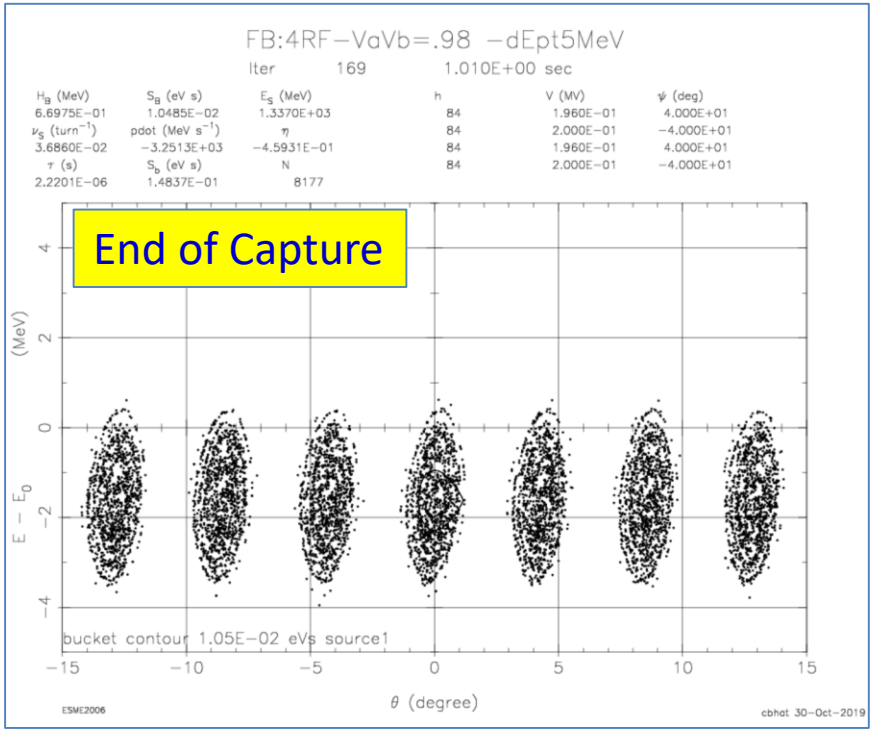


Large emittance growth, very bad

Eoff=-0.5 MeV, df=0 kHz, VA/VB=0.98
No Neck

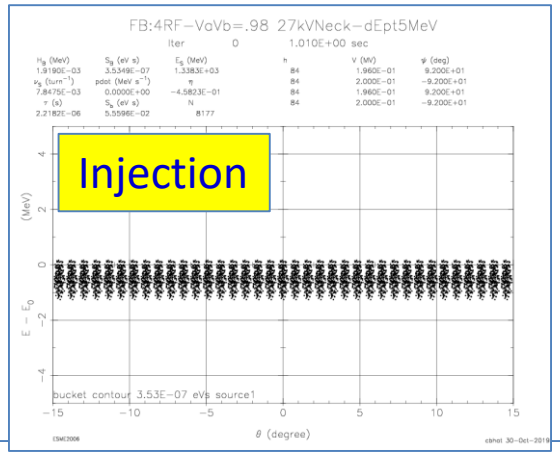


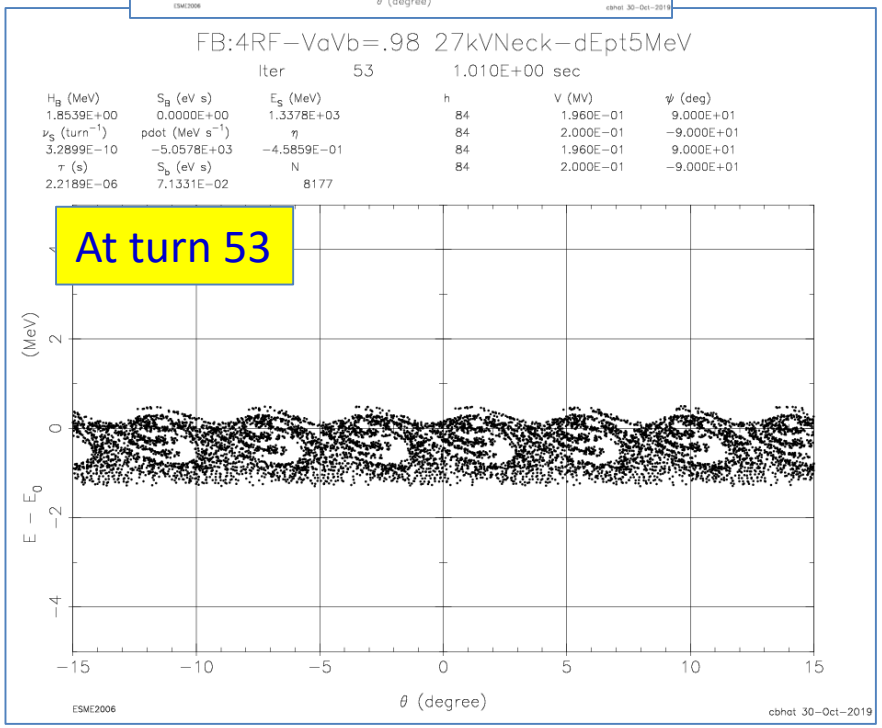


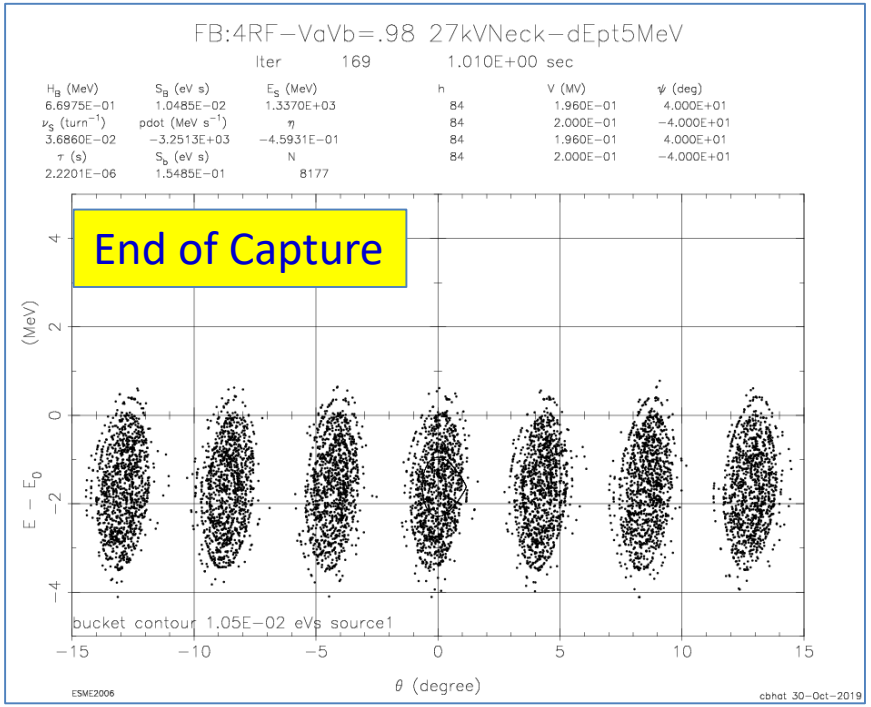


Large emittance growth, Capture OK

Eoff=-0.5 MeV, df=0 kHz, VA/VB=0.98 Neck

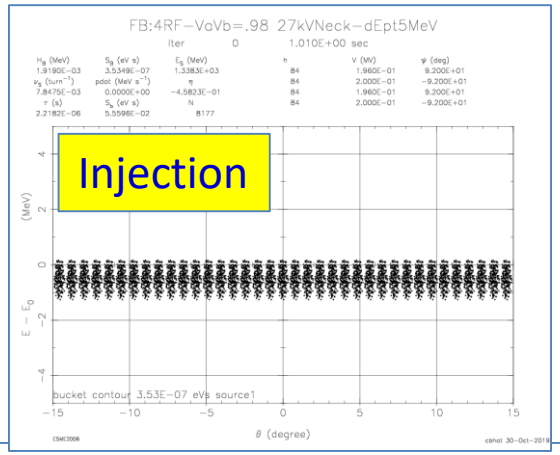


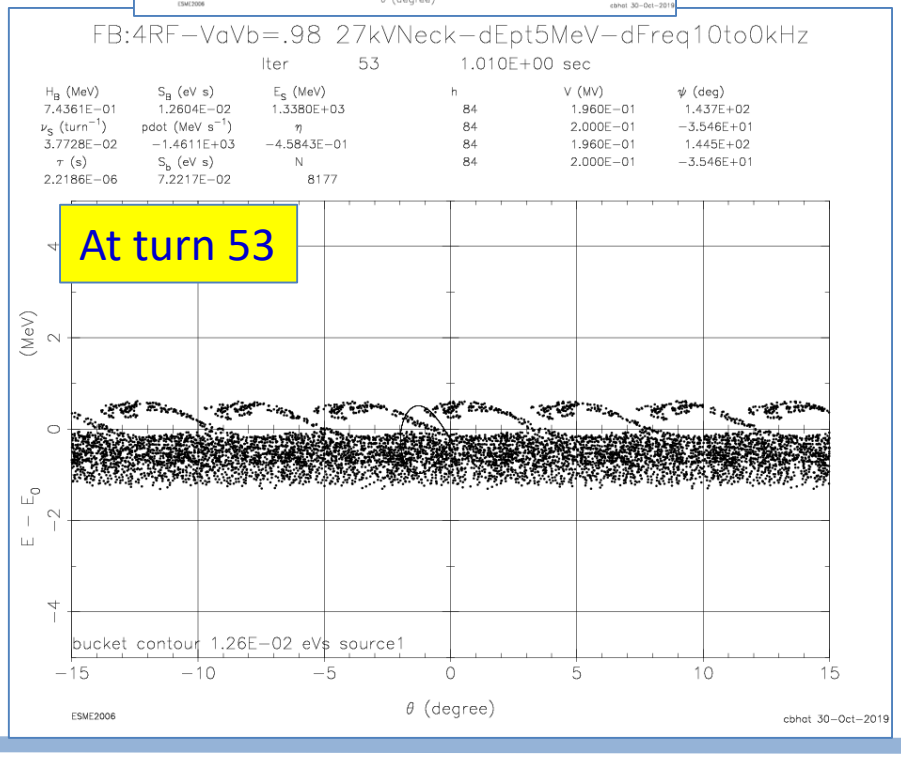


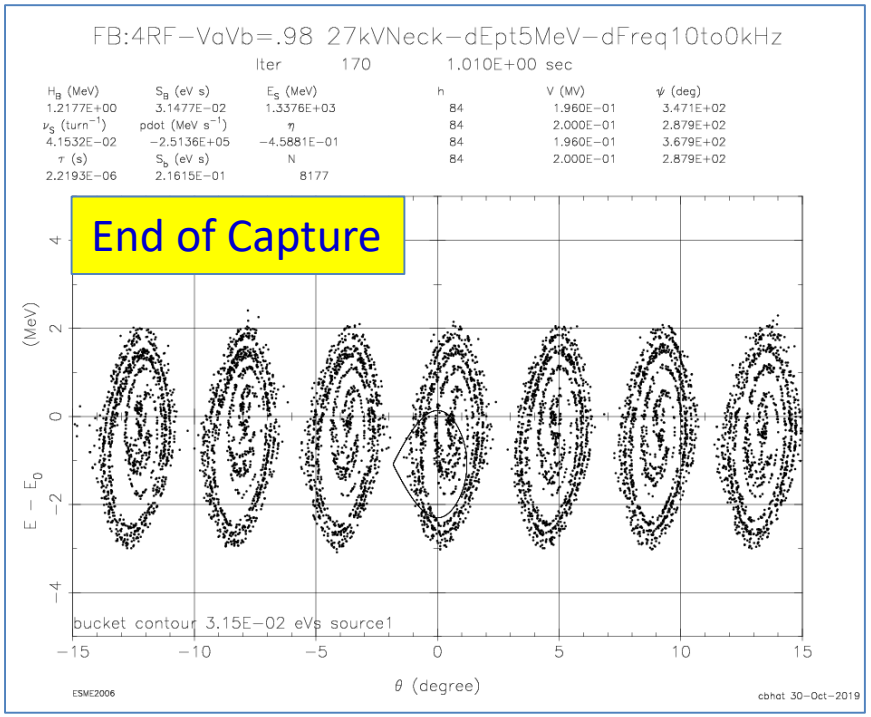


Large emittance growth, Capture OK

Eoff=-0.5 MeV, df=10-0 kHz, VA/VB=0.98 Neck







Large emittance growth, Capture OK