MIDDLE EAST TURBOMACHINERY SYMPOSIUM

Transient Unbalance of a Turbo-Compressor Rotor
due to
Thermal-Gradient Induced Bow
from a
Seal Gas Heater

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20 March, 2013, Doha, State of Qatar

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OUTLINE

Introduction - Pearl GTL

GTL unit, Hydrocracker and Hydrogen Recycle Compressor

High Vibration during Process Gas Start-Up

It always happens at night or on the weekend – troubled starts

Initial reaction and assessment

Comparison to Inert Gas Start-Up

"It didn't do this before" – What's the same, What's different

What could it be?

Root Cause Assessment – Process Correlation

Behavior summary and Problem statement

Conclusion

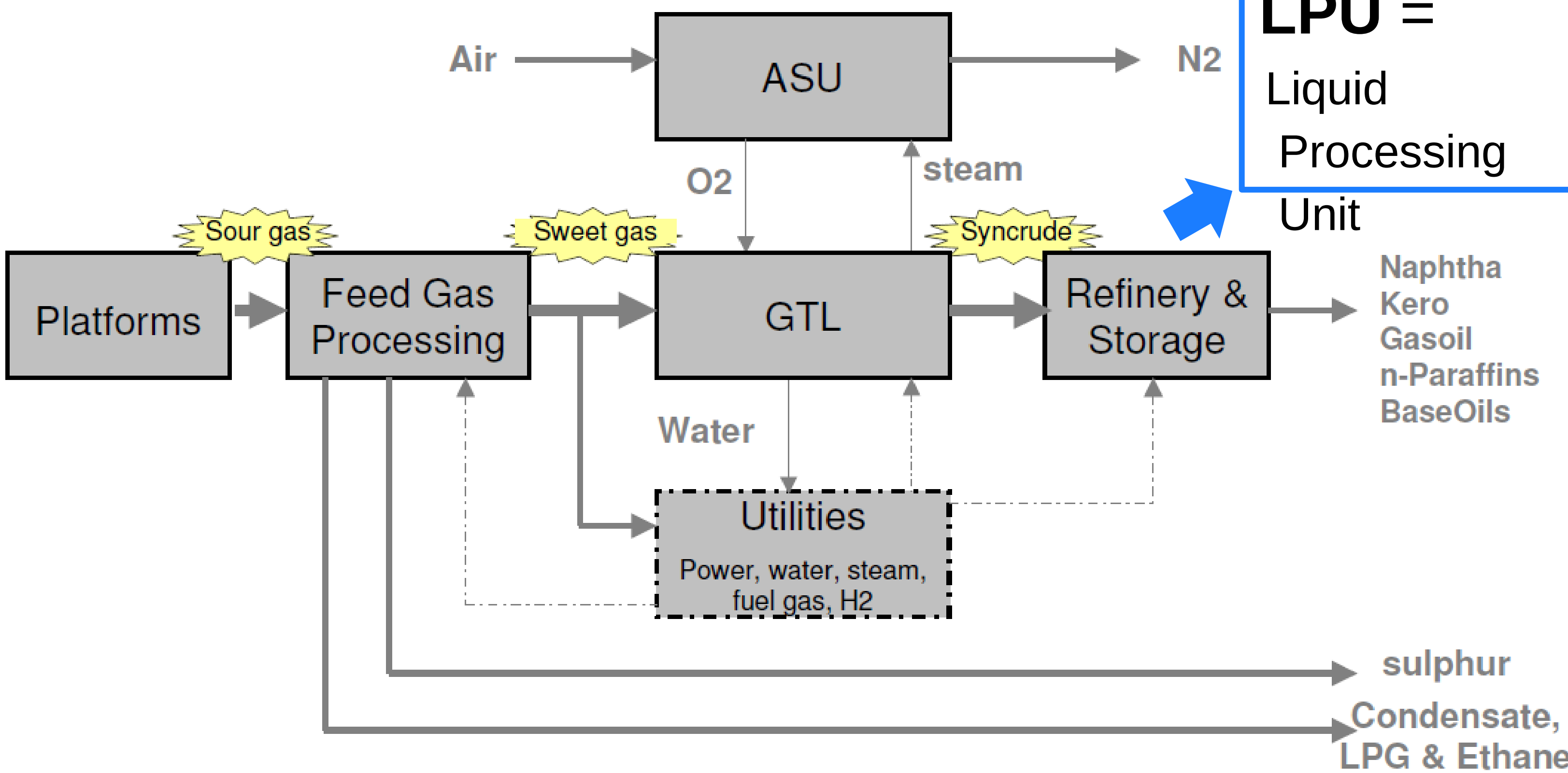
Acknowledgements

PEARL GTL – RAS LAFFAN, STATE OF QATAR

Aerial View of Pearl GTL plant at Ras Laffan, Qatar

PEARL GTL – HIGH LEVEL PROCESS FLOW

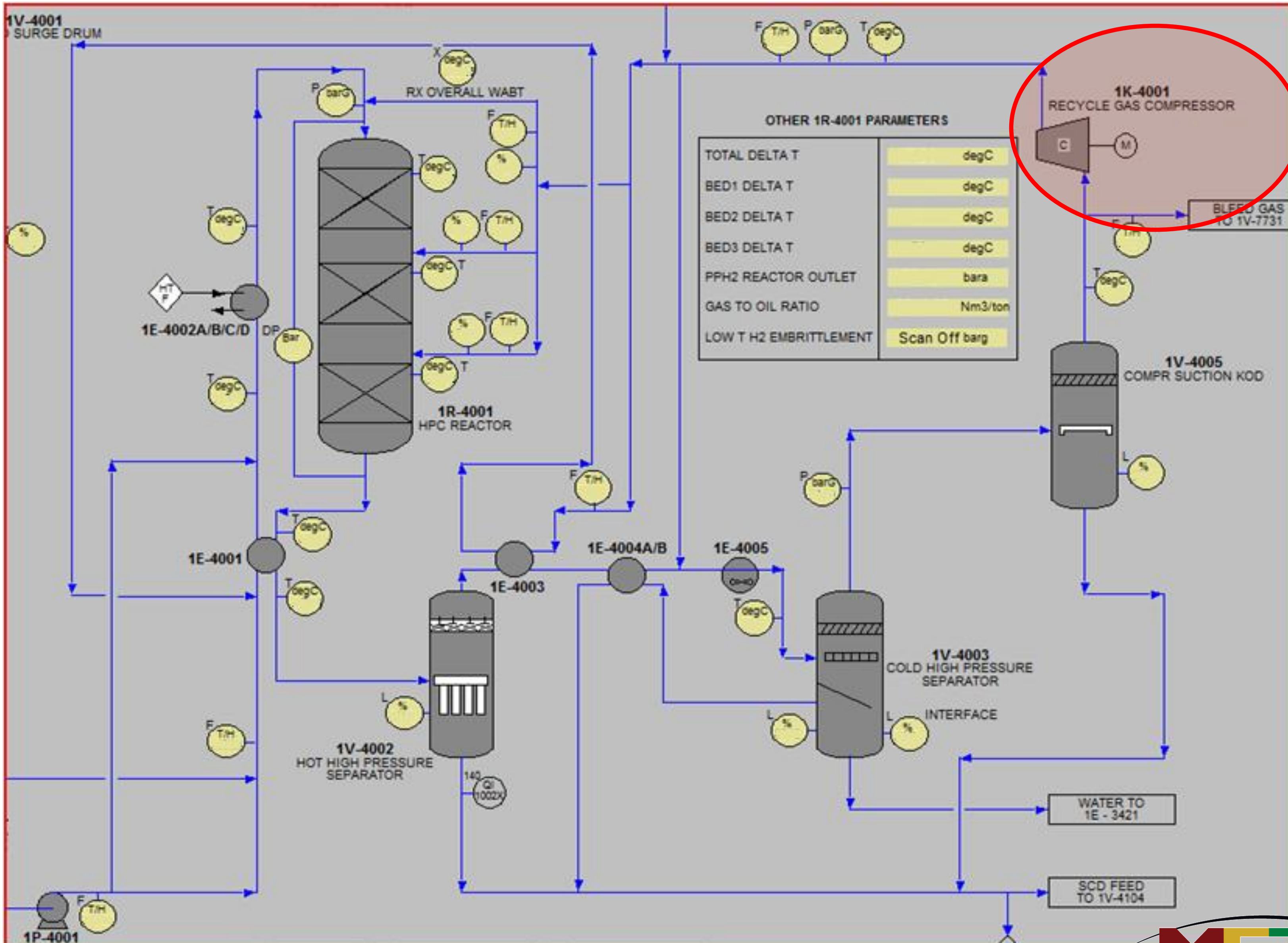
Simplified Process Integration Scheme



LPU = Liquid Processing Unit

Pearl GTL
GTL Department
Training Presentation
1/16/2009

PEARL GTL – LPU – HYDROCRACKER

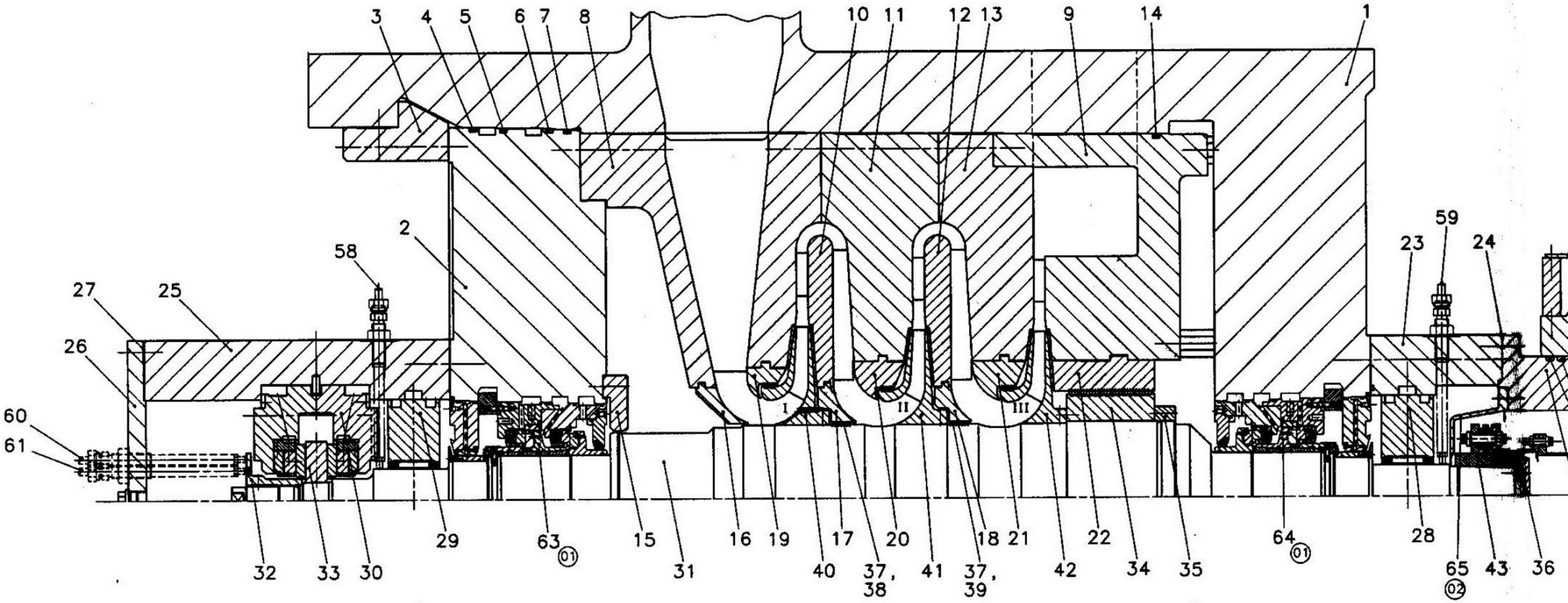


MIDDLE EAST TURBOMACHINERY SYMPOSIUM

HYDROCRACKER - RECYCLE GAS COMPRESSOR– K4001

3 Stage Centrifugal Compressor – “Recycle Gas Compressor”

92 Bar (~1500 psi)
3.6 MW
Tilt Pad Journal Bearings and Tandem Dry Gas Seal with intermediate Laby
NC1 = 6 800 RPM   MCOS = 11 718 RPM   TRIP = 12 887 RPM



1K-4001 – HIGH VIBRATION DURING START-UP

Flawless Start-Up

Compressor had been run on N_2 (March) and completed H_2 loop dry out (early Apr)

Initial Start on Process Gas (H_2)

Compressor could not pass NC1 (6800 rpm) - Trip on High High Bearing Vibration

Start-Up Engineer and Operations implemented a “soft start” including a hold near 3500 rpm (*What would have happened if this was not a VSDS?)*

Vibration level steadily dropped during hold, compressor was able to pass NC1

On subsequent days, effectiveness of soft start was repeated, and with minor tweaking, became the “normal” start-up procedure

Engineering Team Assembled to Understand Why

Same OEM had a similar compressor in H_2 service that does not have VSDS

1K-4001 – HIGH VIBRATION DIAGNOSIS

Pearl GTL has fully configured Bently Nevada System1®

Pearl GTL staff spent many hours setting up and verifying plot sessions

Primary Characteristics of Vibration

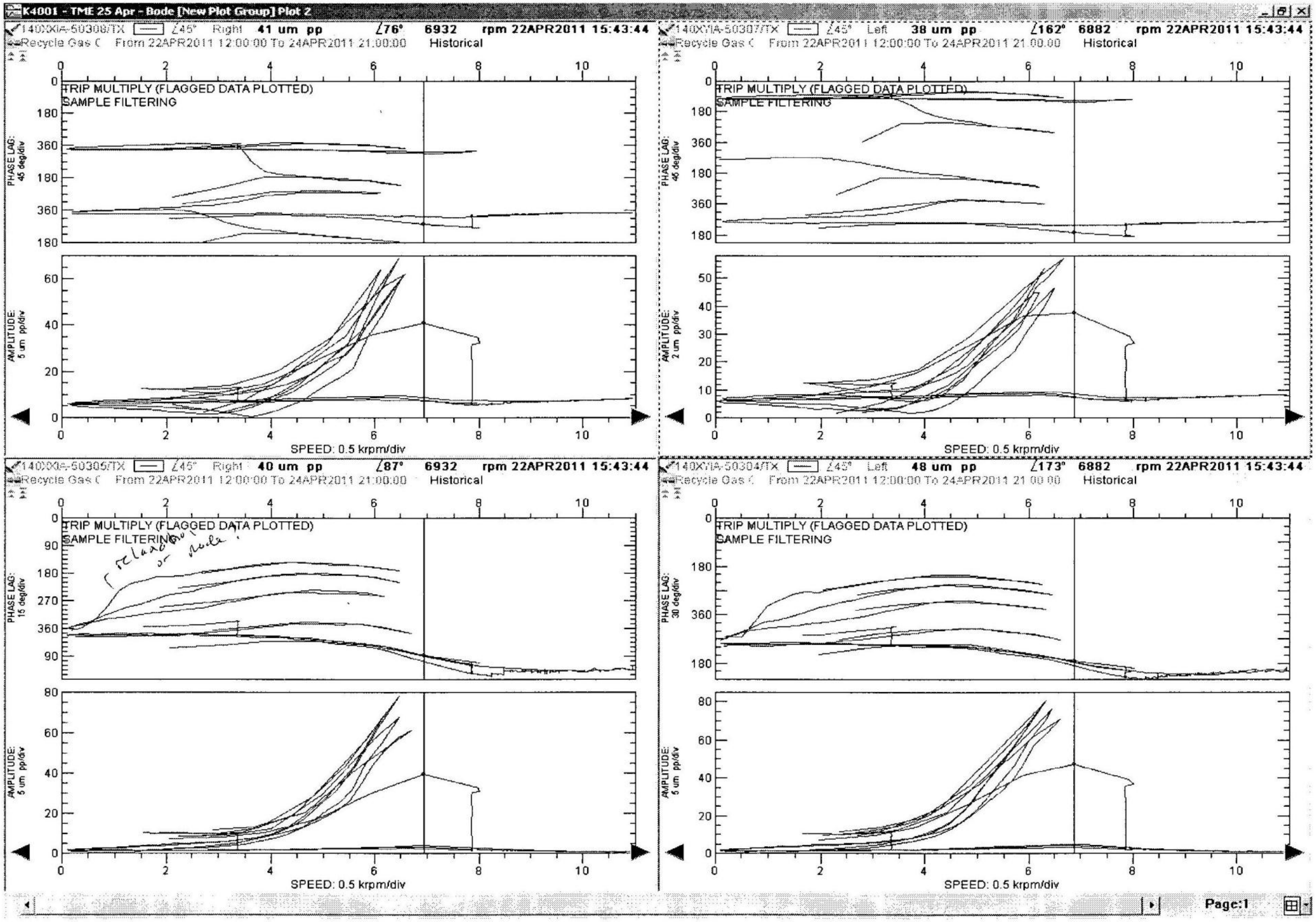
Compressor had been run on N2 (March)
Completed H_2 loop dry out (early April)
Low vibration levels and consistent behavior

First run on process gas showed high level through NC1 (6 800 rpm)
Primarily 1x vibration (GREEN)

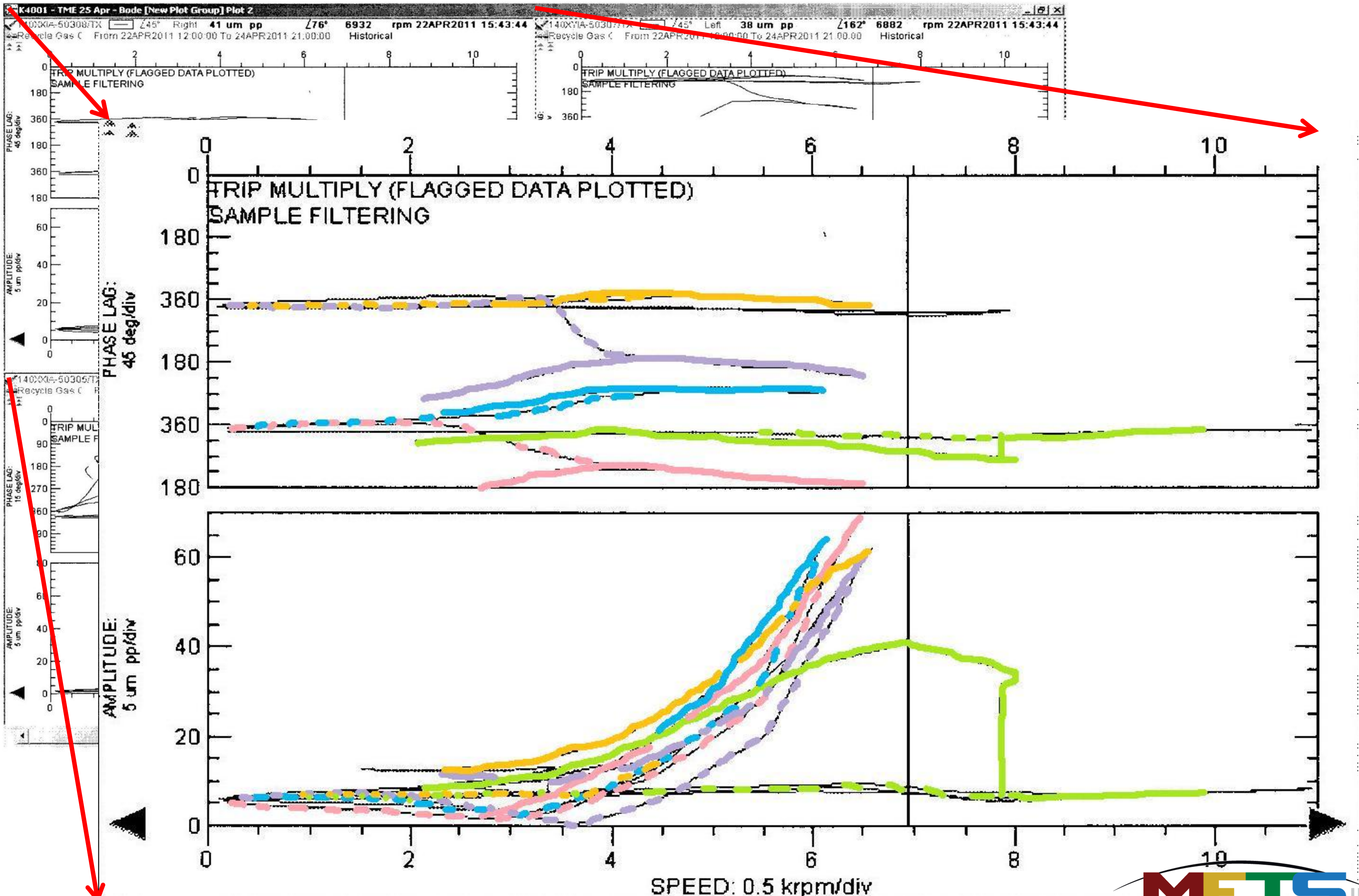
Subsequent attempts to start also primarily 1x vibration

(*In plots that follow, Solid Line is Start-Up, Dashed Line is Shut-Down*)

1K-4001 – HIGH VIBRATION DIAGNOSIS



1K-4001 – HIGH VIBRATION DIAGNOSIS



1K-4001 – HIGH VIBRATION DIAGNOSIS

Primary Characteristics of Vibration

Attempts to start could not pass NC1, primarily 1x vibration

High Vibration through NC1 suggests

- Excess unbalance or high Amplification Factor (AF)
- Possibly a rub (think how to break in seals on a steam turbine)
  - – typically not only 1x

Previous runs and Factory Test do not show high AF (lack of damping)

Bode plot, amplitude is consistent, phase is highly irregular

- Phase: What are PURPLE and PINK doing?

Behavior at Start-up (Solid Line) and Shut-down (Dashed Line) appears different

1K-4001 – HIGH VIBRATION DIAGNOSIS

Pearl GTL has fully configured Bently Nevada System1

Tony Soby spent many hours setting up and verifying plot sessions on all equipment

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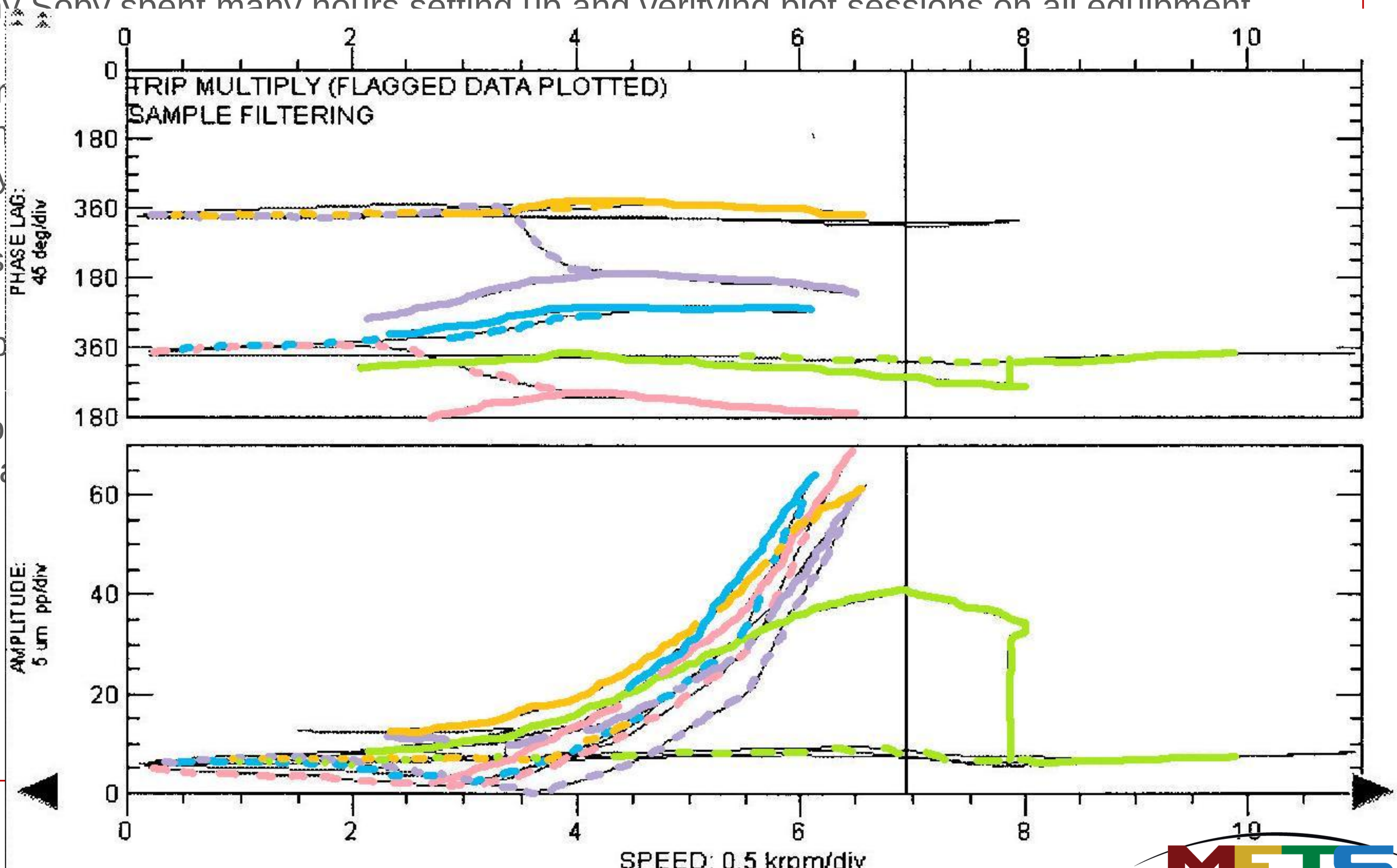


1K-4001 – HIGH VIBRATION DIAGNOSIS

Primary Characteristics of Vibration

Looking at Bode plot – amplitude appears consistent, phase is highly irregular

Phase: What are PURPLE and PINK doing?

Behavior at Start-up (Solid Line) and Shut-down (Dashed Line) appears different

Our Goal is to tie Vibration Response to a Physical State or Behavior:
- High Vibration through NC1 suggests excess unbalance or high AF

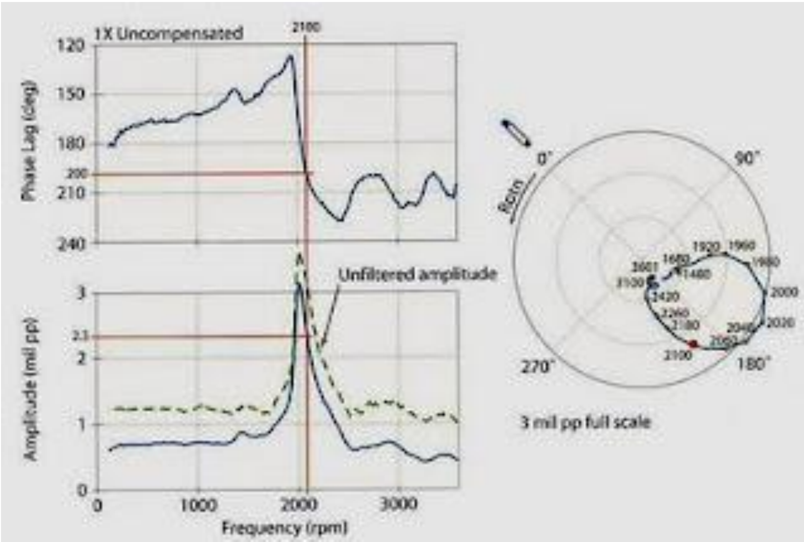
Previous runs do not show high AF => Excess Unbalance
- What is causing the unbalance?
- Where did it come from? (Why did it not appear in N_2 runs?)

Is there another way of looking at the data? **Yes: Polar Plot**

Shows same data (rpm, amplitude and phase), different graphical format

Polar Plot makes it clear the rotor starts and returns to same slow roll

POLAR AND BODE PLOTS



Polar and Bode plots show similar data

Natural Frequency or Resonance = peaking of amplitude and 180 phase shift

Bode – “Slide and Mountain”
Offers clear amplitude and AF comparison

Polar – “Loop”
Offers intuitive slow roll compensation

Polar and Bode plots show similar data

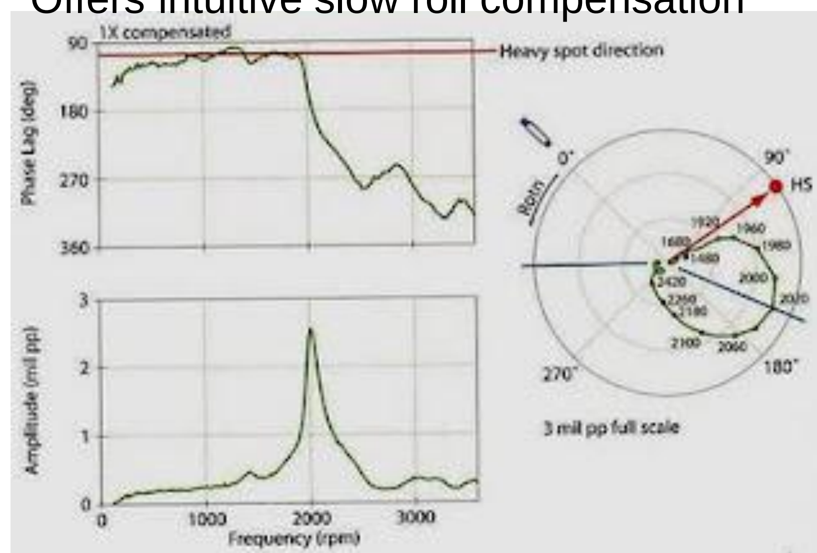
Unbalance Location

Initial direction of phase (compensated)

“High Spot follow Heavy Spot”

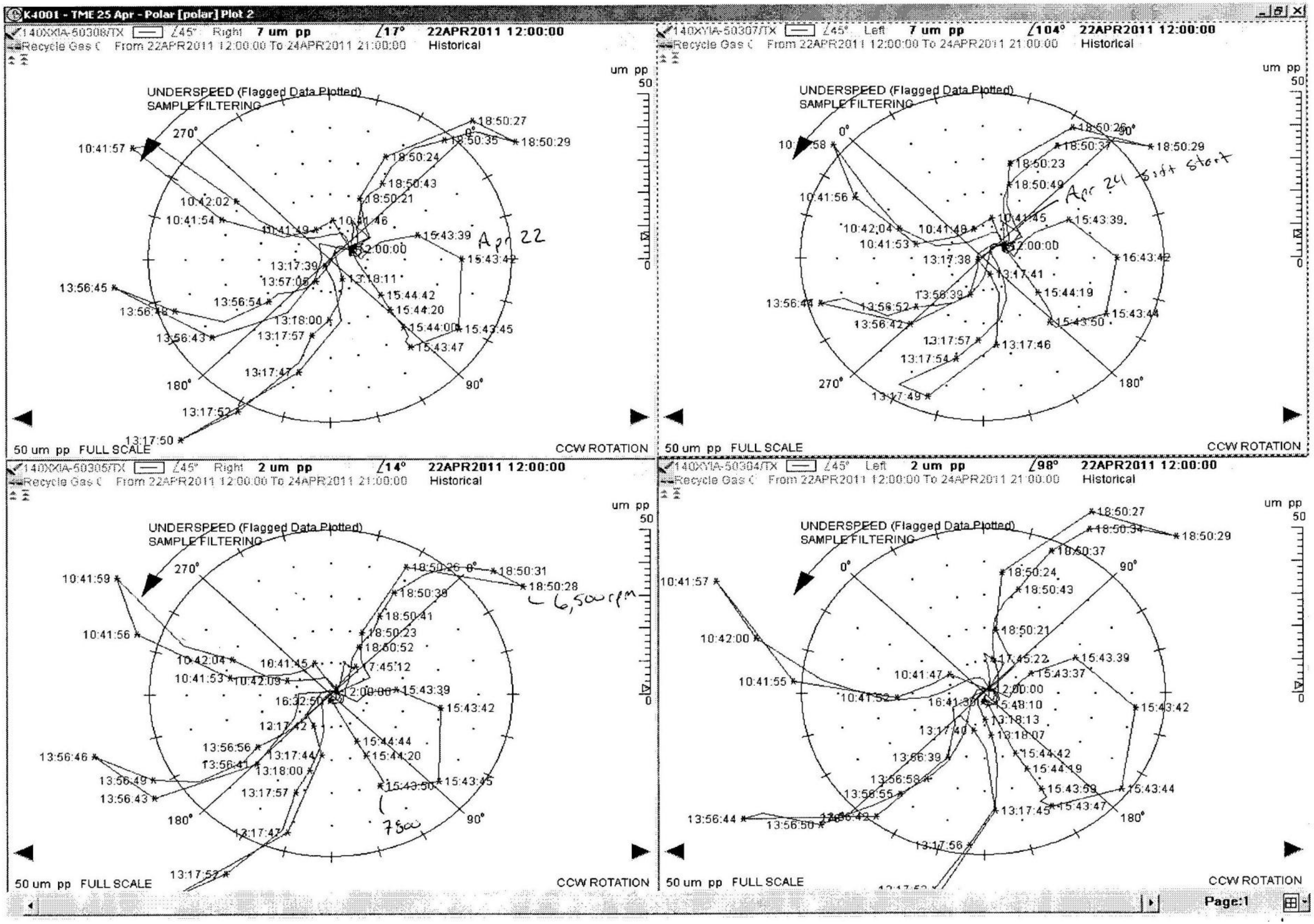
Bode – Need to properly 1x compensate for slow roll

Polar – Unbalance Location and 1x compensation can be done intuitively

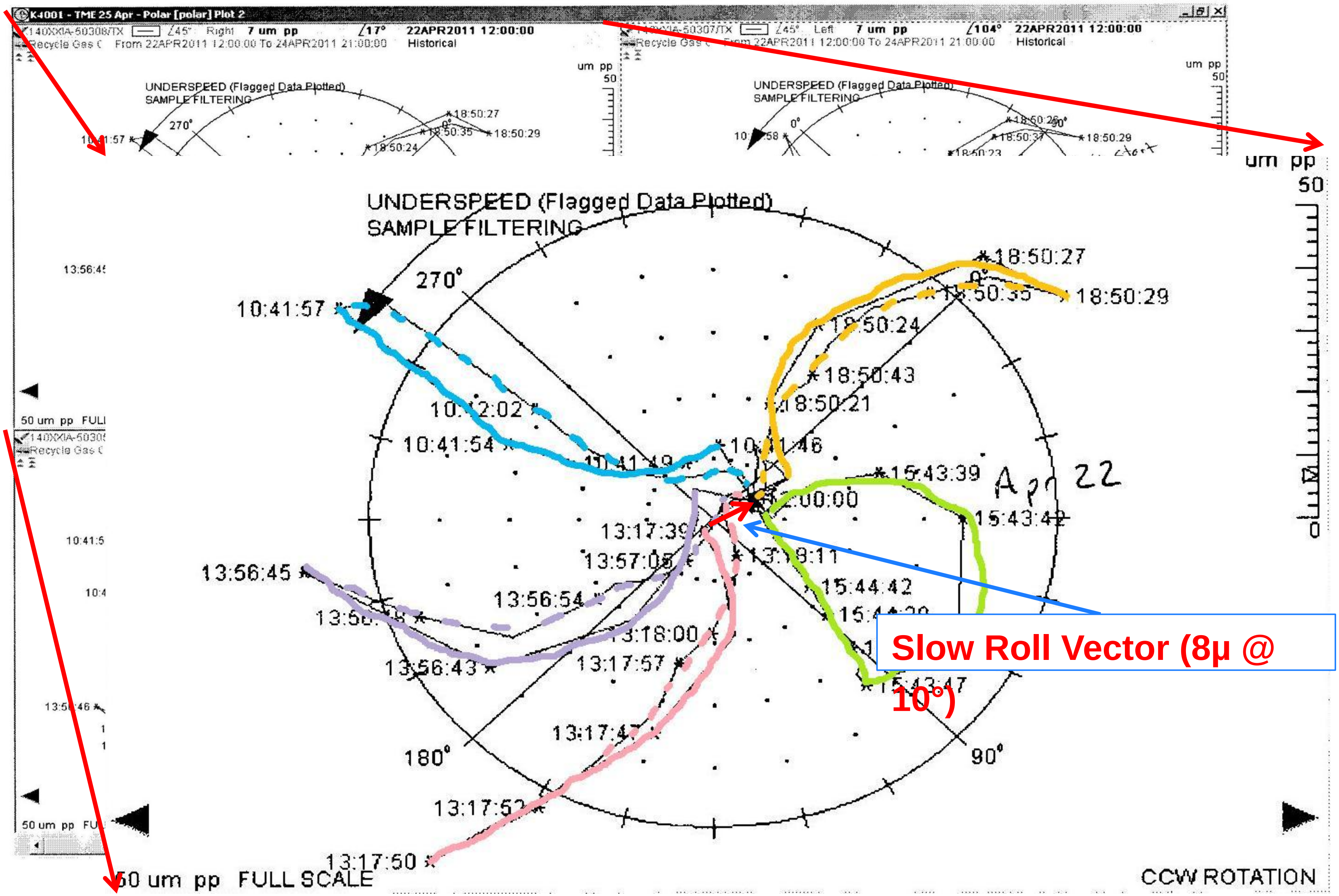


Graphics from http://freevibrationanalysis.blogspot.com/2011/08/bode-and-polar-plot.html

1K-4001 – HIGH VIBRATION DIAGNOSIS

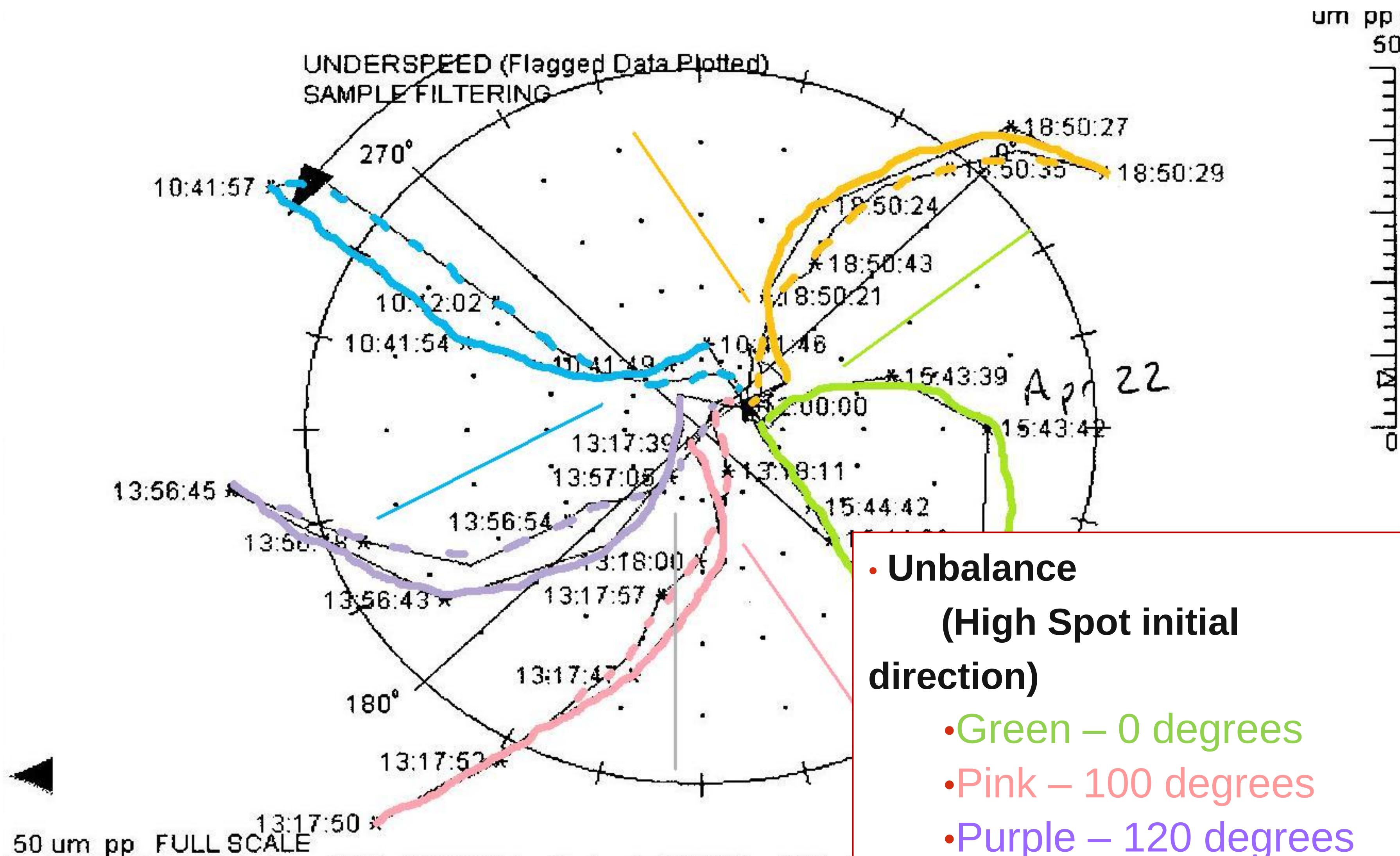


1K-4001 – HIGH VIBRATION DIAGNOSIS



Slow Roll Vector (8µ @ 10°)

1K-4001 – HIGH VIBRATION DIAGNOSIS



- **Unbalance**

  (High Spot initial direction)
  - Green – 0 degrees
  - Pink – 100 degrees
  - Purple – 120 degrees
  - Blue – 195 degrees
  - Orange – 275 degrees

1K-4001 – HIGH VIBRATION DIAGNOSIS

Polar Plot

Behavior during start-up and shut-down is consistent, except
Phase Angle of initial Unbalance seems to Change with each start

Unbalance – *Center of Mass offset from Centerline of Bearings*

Mechanical or Residual Unbalance (fixed over speed, temp, starts)

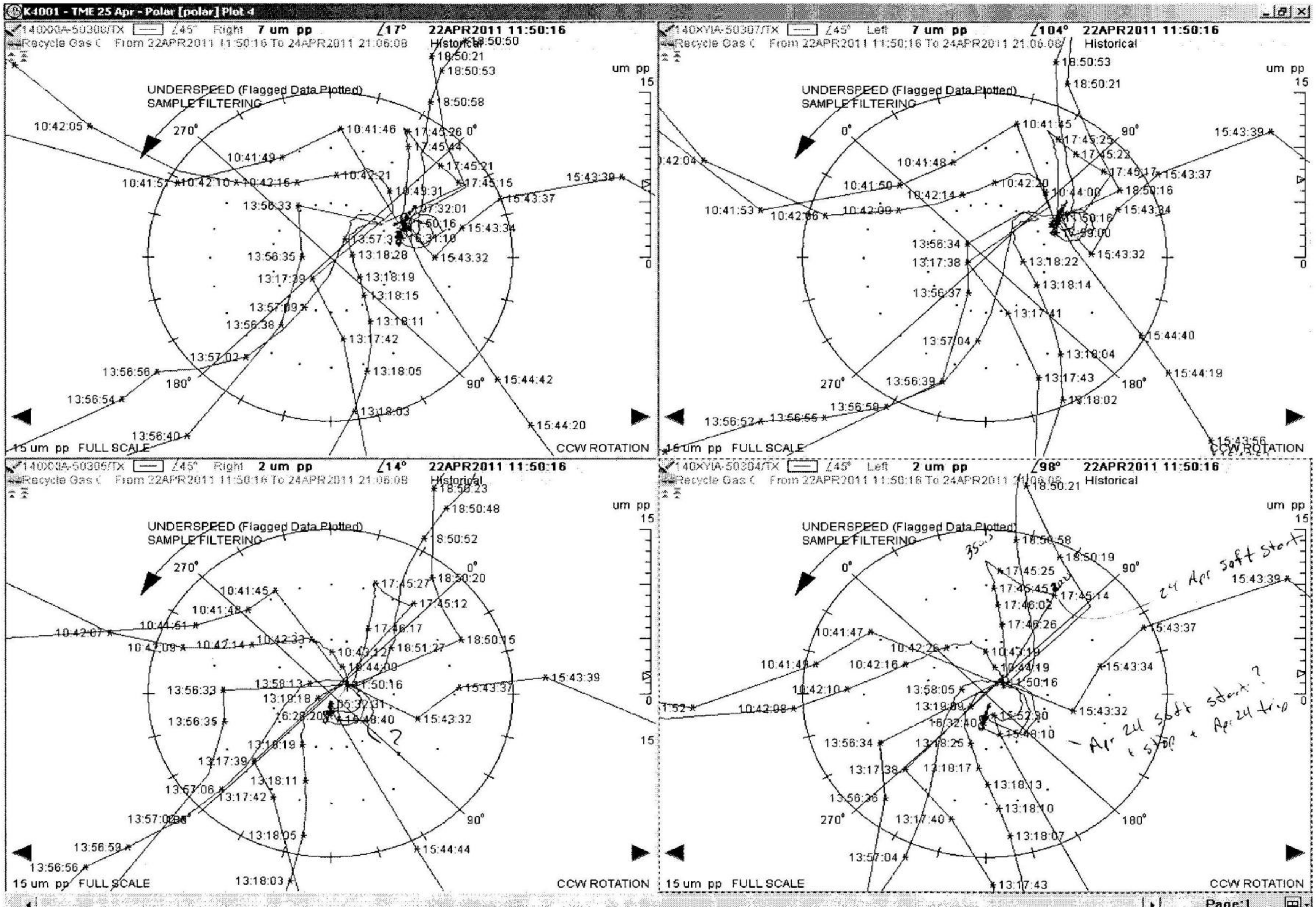
Bow - *deformation of the rotor shaft that causes centerline of rotor to shift off centerline of bearings (CoM assumed to be at center of rotor)*

Mechanical Bow – *"permanently" bowed due to initial processing, plastic deformation during handling (fixed over speed, temp, starts)*

Thermal Bow – *bowing of rotor due to heat-> temperature (fixed or random)*

Gravity Sag Bow – *rotor takes a "set" when not rotating (random orientation)*

1K-4001 – HIGH VIBRATION DIAGNOSIS



1K-4001 – HIGH VIBRATION DIAGNOSIS

Thermal Bow of rotor due to heat-> temperature (mixed)

Variety of sources:

Differential growth on opposite sides due to temperature difference

e.g. rub on high spot

Axial binding – lack of thermal axial gap between added components

e.g. seal rings and impellers

Internal, residual stresses or abnormality that result in non-isotropic growth

All repeatable: same circumferential location, phase angle, unbalance location

Gravity Sag Bow, rotor takes a "set" when stationary (random orientation!)

This is temporary – rotor will straighten as it rotates

Typically associated with heavy, long bearing span rotors

Worse with hot rotors, which is why Gas and Steam Turbines have turning gear

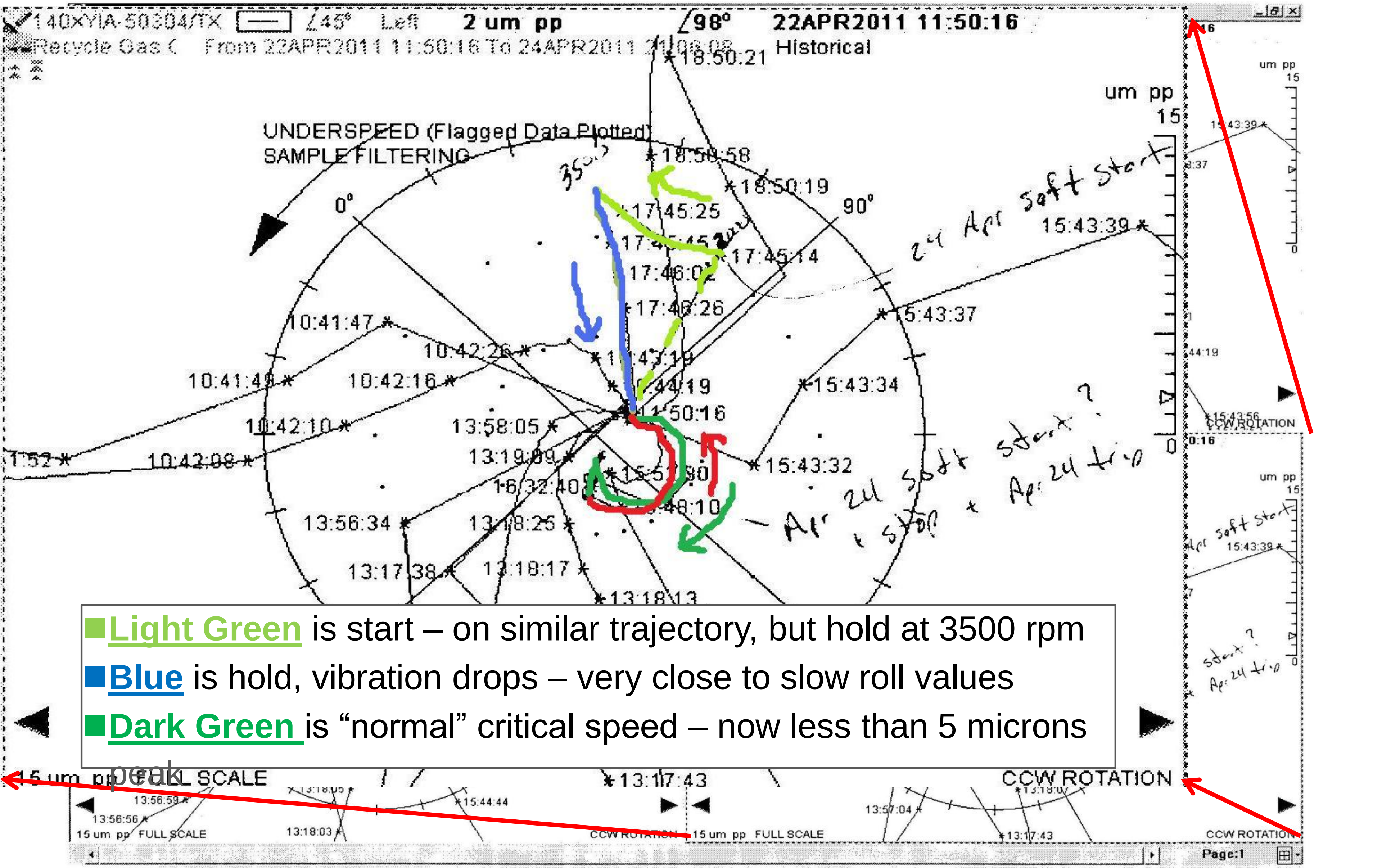
<u>However</u> - This rotor is too short, too light, too cold…

Similar Behavior was Described in:

Modeling of Rotor Bow During Hot Restart in Centrifugal Compressors

Baldassarre and Fontana, 39th Turbosymposium

1K-4001 – HIGH VIBRATION DIAGNOSIS



- **Light Green** is start – on similar trajectory, but hold at 3500 rpm
- **Blue** is hold, vibration drops – very close to slow roll values
- **Dark Green** is “normal” critical speed – now less than 5 microns peak

1K-4001 – HIGH VIBRATION DIAGNOSIS

After multiple runs and attempts to start, team was able to establish:

If rotor sits for a moderate time, it establishes a bow – *not sure why*

With 5 minutes of roll-out, bow is relaxed and unbalance eliminated

- This is effective method of dealing with the *symptom*

Strong motivation to identify root cause:

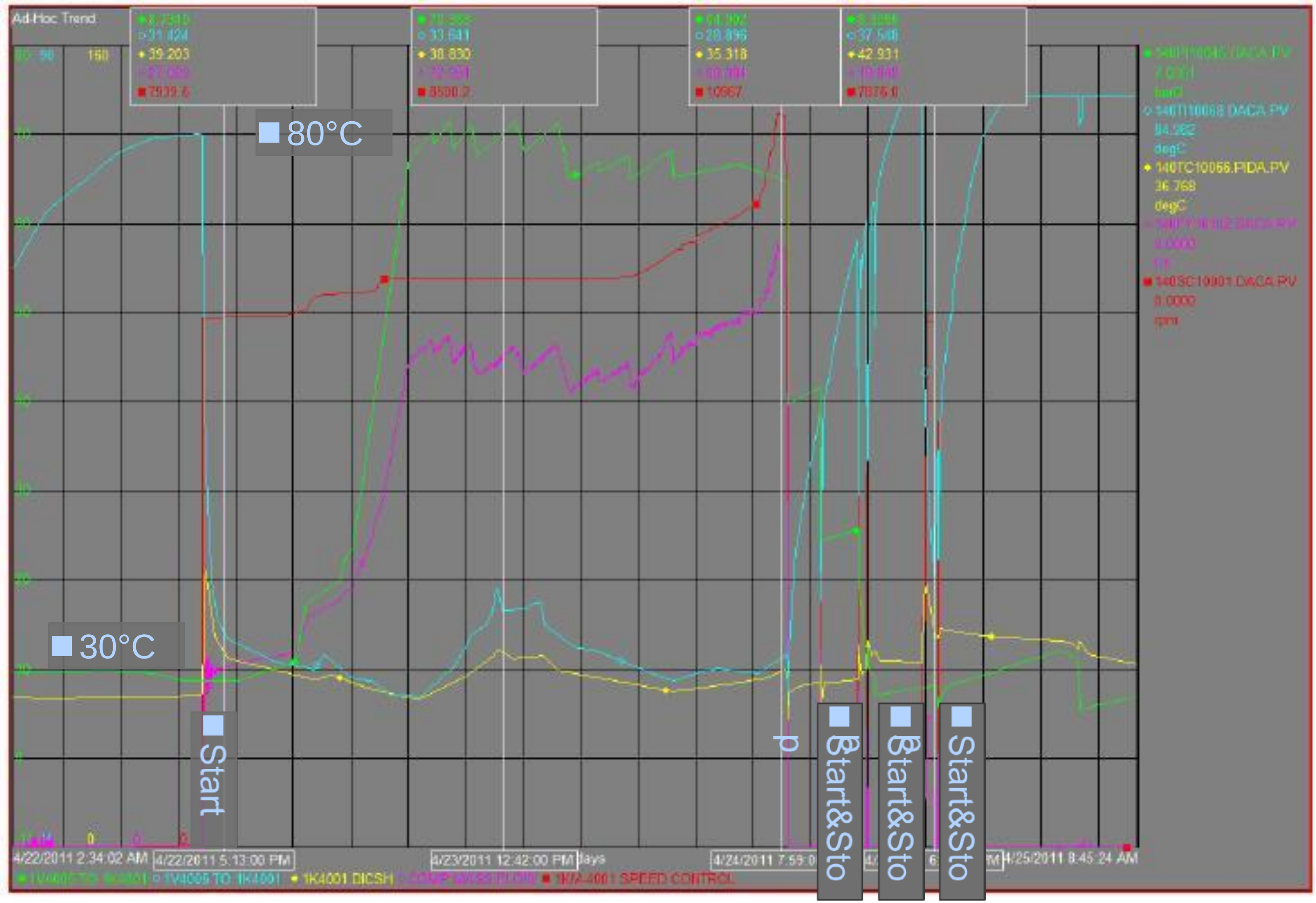
- There is a narrow window between NC1 and TNF – delicate balance
- Project has two other Hydrogen Compressors from same OEM, without VSDS
  - Will not be able to hold and allow rotor to relax if same issue occurs

Look for Process Correlation:

Inlet Pressure	Discharge Pressure
Inlet Temperature (*Tin*)	Discharge Temperature (Tout)

Tin (Blue Line) Rises when unit stops, normal running is 30°C, stop is 80°C

1K-4001 – PROCESS CORRELATIONS



1K-4001 – PROCESS CORRELATIONS

Process Correlation =

Tin (Blue Line) Rises when unit stops

normal running is 30°C, stop is 80°C

Temperature falls rapidly when RPM rises

appears to be locally trapped heat

Build Spread Sheet with various inputs and parameters

Engineering Team found correlation with Seal Gas Heater

Had not been used during N_2 runs

Was only needed when drawing Seal Gas from Process (dew point)

During start-up, Seal Gas supplied by Plant N_2, no risk of liquids

Perform Test Run: Confirm when seal gas heater Off

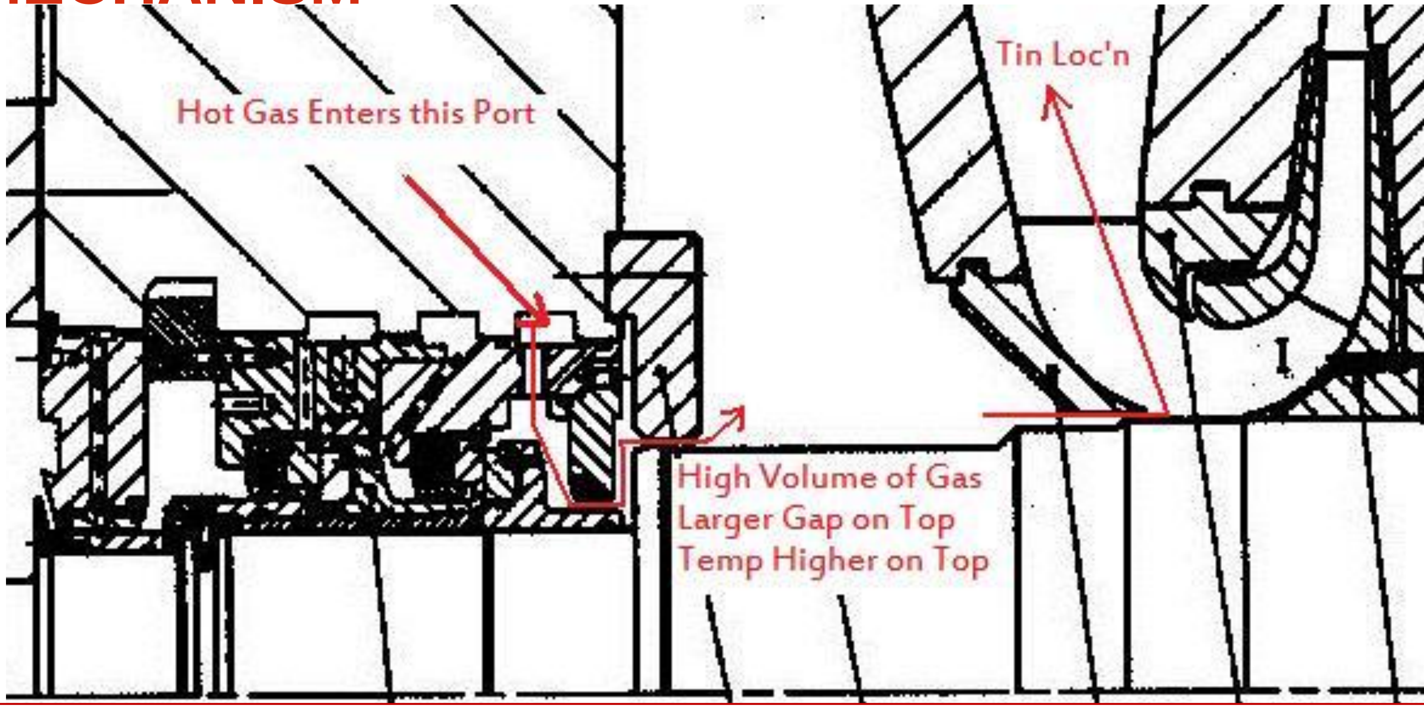
- Hold is not necessary (no bow present)

1K-4001 – PROCESS CORRELATIONS

1K-4001 LPU Start-up Problem Timeline

	DATE							
	3/17/2011	4/11/2011	4/22/2011	4/24/2011 - 1	4/24/2011 - 2	4/24/2011 - 3	4/24/2011 - 4	5/11/2001
Purpose	Mech Run[3]	Dry Out	Process Run	Process Run	Process Run	Process Run	Process Run	Process Run
Run time	5hrs	5 days	2 days	HH trip on Start	HH trip on Start	1 hour	HH trip on Start	Running
Process Gas	N2	N2	Process Gas	Process Gas	Process Gas	Process Gas	Process Gas	Process Gas
Line up	Long Loop	Long Loop	Long Loop	Long Loop	Long Loop	Long Loop	Long Loop	Long Loop
Previous start (before)	First	13 days	5 days	2 hours	2 hours	4 hours	30 min.	3.5days running
Compressor:								
Ts, degC	20	24,31,24	85 initial, 24 normal	85	85	85 initial, 24 normal	45	85
Td, degC	66-103	110[1],73,63	55 initial, 31 normal	39	43	55 initial, 31 normal	41	46
rpm		8022-8067	7934- 8900			8534		11700[9]
Start Type:								
Fast	Yes[4]	Yes	Yes	Yes	Yes		Yes[6]	
Slow						Yes		Yes to 4000rpm 8min
SU Vibration:								
Initial "Bump"	yes, 28um	Yes, 20um	Yes, 23um	Yes, 22um	Yes, 24um	Yes, 25um	Yes, 26um	yes,23um
Nc (6500rpm)	Very Low	Low but chng[2]	Yes 48um	yes, 80um	Yes, 79um	Uneventful[5]	Yes, 70um	Uneventful
H or HH alarms"	No	No	H alarm	HH trip on Start	HH trip on Start	No	HH trip on Start	No
Vib "Relax"	Yes	Yes, very low	Yes	Trip no data	Trip no data	yes "slow roll"	Trip no data	yes "at slow roll"
"Relax rpm"	7876	7876	7876			3471		4000
Primary Seal Gas:								
Type Gas	N2	N2	H2	H2	H2	H2	H2	H2
T, deg C	19	28	105	105	105	?	105	55
P, barg	3barg>Ps	3barg>Ps	3barg>Ps	3barg>Ps	3barg>Ps	3barg>Ps	3barg>Ps	3barg>Ps
Heater	off	off	On	On	On	off	on	off
Lube Oil:								
P, barg	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
T, deg C	42	42	42	42	42	42	42	39

1K-4001 – DIFFERENTIAL HEATING – BOW MECHANISM



Seal Gas Heater – Injects a Large Volume of Hot Gas =>

Larger gap at Top of Inner Seal => more heat and Temperature Rise on Top
Top vs Bottom Differential Temperature causes a *Temporary* *Thermal Bow*

As shaft rotates, heat becomes distributed, temperature equalizes, bow straightens, eventually Unbalance is Eliminated and Vibration Decreases

CONCLUSION

- Significant Value in Categorizing Vibration
- Use a variety of plots
- Establish Slow Roll vector and Repeatability
- Determine if vibration change on sequential runs
- Find correlation to Process or other Environmental Variables

- Get Help!
  - Others at Facility or within Company
  - Industry Experts (like those you meet at METS!)

ACKNOWLEDGEMENTS

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We appreciate the State of Qatar and Texas A&M for sponsoring METS and the opportunity to share knowledge and learning with our colleagues.

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