Protection of accelerator hardware : RF systems

Joint Accelerator School
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This course will go through some selective topics only

- will not touch details (90 min. course)
- RF system layout
- arcing/discharge mechanism
- possible damages from high intensity beam
- discuss about protection

Due to large spread of area expertise between students, the lecture materials are prepared accordingly

One homework for student credit

HOMEWORK:

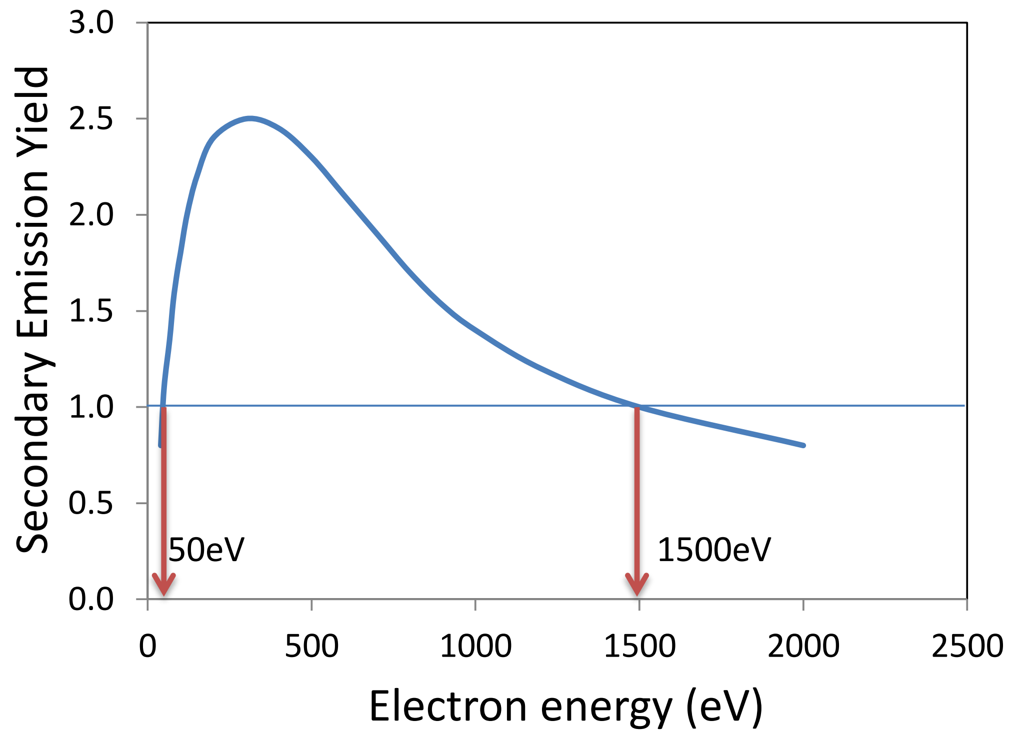
A RF structure is running at f=200MHz and has a gap (g=2 cm).
A plane parallel geometry is a good approximation for this RF structure.
The electric field between gap is

$E = E_0 \sin(\omega t)$
ω: RF angular frequency
E_0: electric field amplitude
t: time

Assume that electron starts with zero energy at t=0 from one end.
The gap voltage is

$$V_g = E_0 g = \frac{m_e \omega^2 g^2}{\pi e} \frac{1}{(2n-1)}$$

g: gap length (m)
m_e: electron mass ($=9.11 \times 10^{-31}$ kg)
e: electron charge ($=1.6 \times 10^{-19}$ C)
n: order of multipacting level (n=1,2,3,...)



1. Ignore magnetic field effect.
Calculate the gap voltages (V_g) and electron impact energies for n=1, 2, 3, 4, 5.
2. What is the threshold electric field E_0 for no multipacting condition in any order of n, before knowing secondary emission yield (purely kinematic resonance condition)? Above this threshold no multipacting can occur.
3. The secondary emission yield of the material for this RF structure is shown above.
Which order of multipacting levels would be dangerous?

RF system layout

Typical RF system for particle accelerators

RF source; klystrons are the most popular devices for f>300MHz and high power.

Tetrode, solid state amplifier for relatively lower power and/or lower frequency

RF transmission; Waveguides or coaxial lines

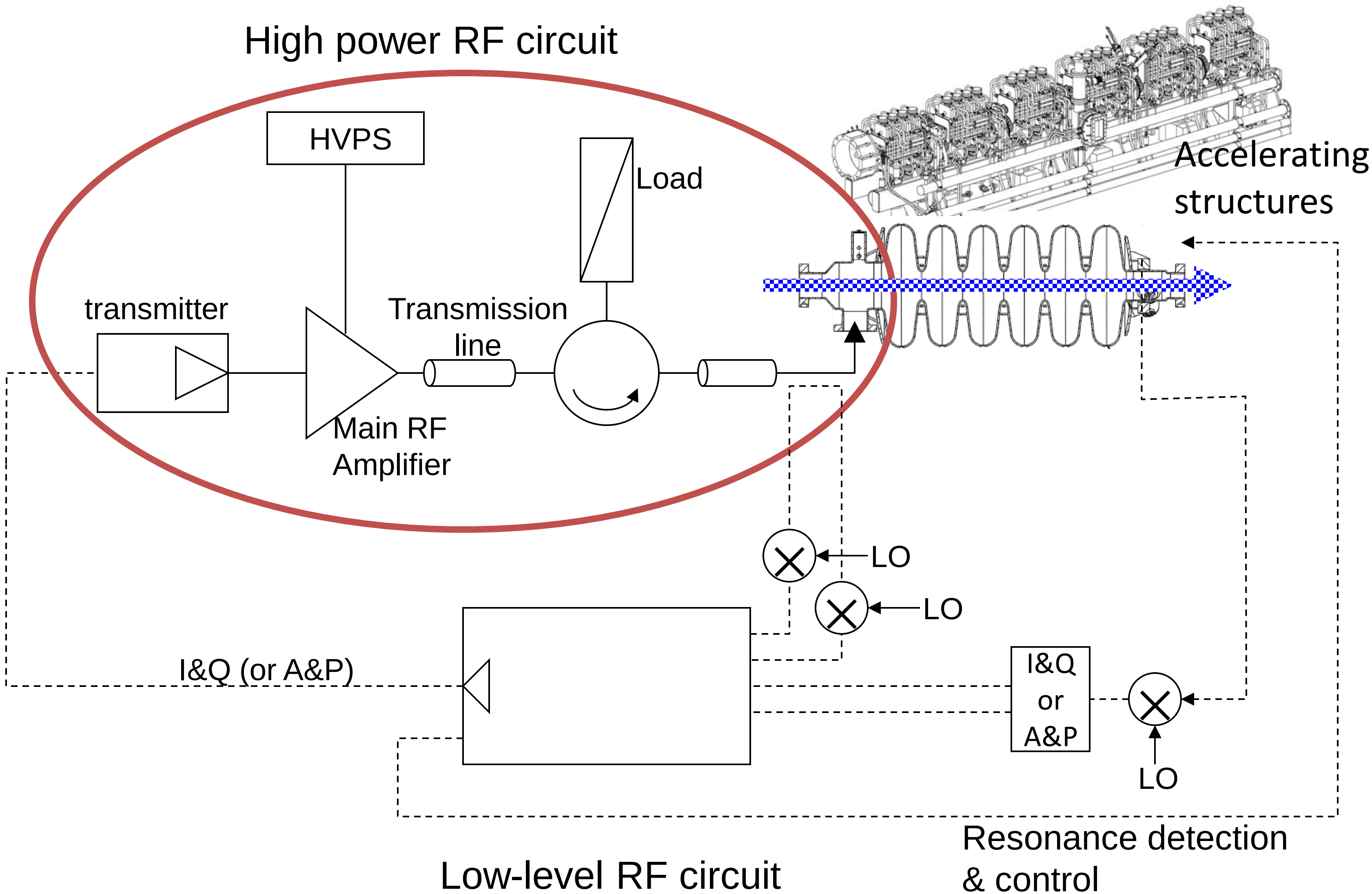
Circulator; usually used as an isolator with matched load to protect RF source

Power coupler; feed RF power to a cavity

Cavity or accelerating structure; electro-magnetic energy storage device

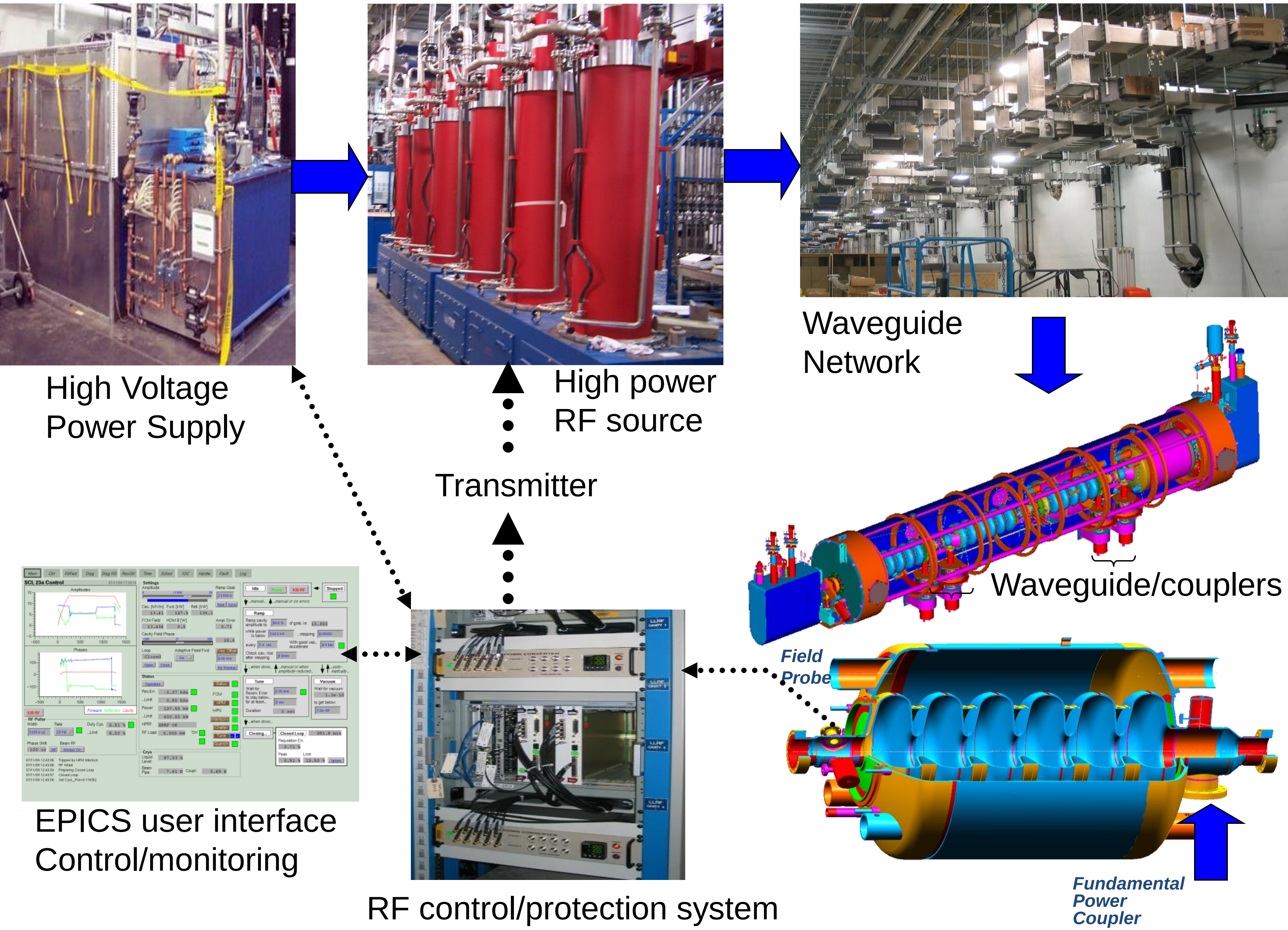
RF control; control cavity field and phase

And protection system



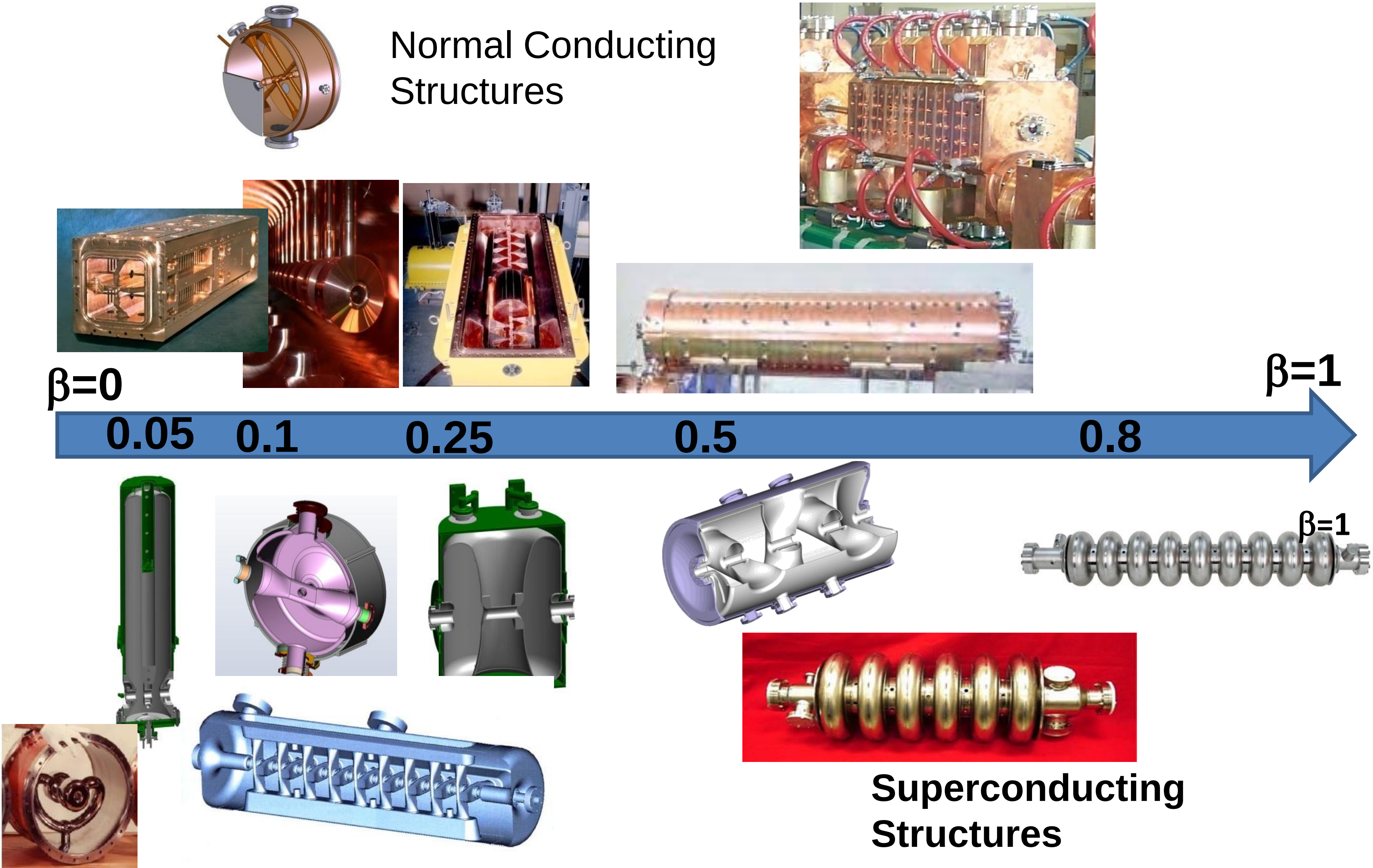
AND…

Timing system & Synchronization	Protection system (machine & personal)	Diagnostics & user interfaces



High Voltage
Power Supply
High power
RF source
Waveguide
Network
Transmitter
Waveguide/couplers
Field
Probe
EPICS user interface
Control/monitoring
RF control/protection system
Fundamental
Power
Coupler

RF Structures for Particle Acceleration



SRF applications are expanding for lower beta region using different cavity shape (Quarter wave, half wave, spoke-type, etc)

What could go wrong regarding machine protection?

Goal: Keep the system in a reliably operable condition preferably forever or till equipment lifetime! (normal large scale machines run about 40-50 years, klystron's life time 10-15 years, etc.)

In general, high voltage, high power RF system and RF structures give the most downtime in operating machines.

Equipment/parts damages – would require long and expensive rework/rebuild/replacement (and require large numbers of spares)

There are lots of elements that can cause damages and lead to catastrophic failures

For example;

Water leak into the RF system
Air leak into the vacuum boundaries
Sharp edges in the high electric field region
Dirty RF surfaces
Possible multipacting bands
Beam hits RF surfaces

- beam halo/loss → activation
- errant beam
- mis-steered beam by mistake

Large reflected power to the RF source
Over-powered (over voltage, over current), etc….

Machine protection deals with mostly abnormal conditions and should be well prepared for upset conditions.
No perfect system! Continuous efforts are needed.

Critical issues in the RF systems mostly end up

with RF interaction → arcing/sparkling/discharge

sometimes processed out

sometimes makes surface damage

When mis-steered beam directly hits the structure

also surface damage could occur

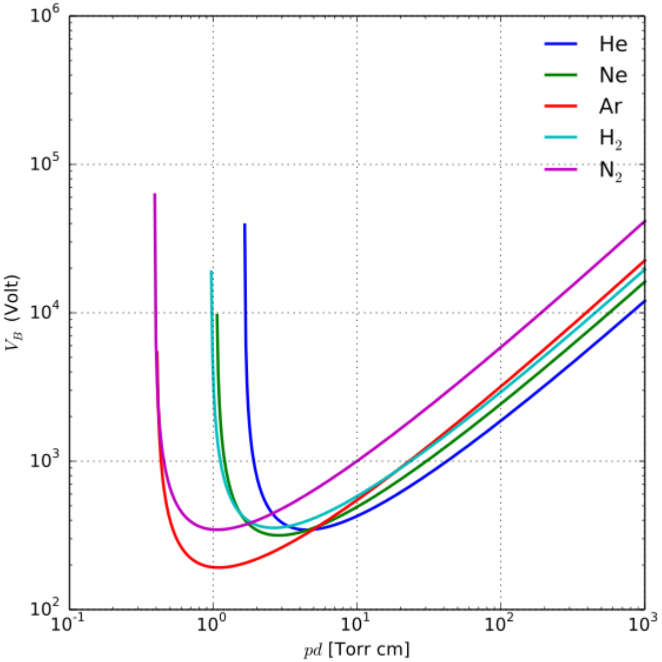
When a surface damage happens on bad spots (high electric field region, ceramic surface, welding/brazing joints, multipacting region),

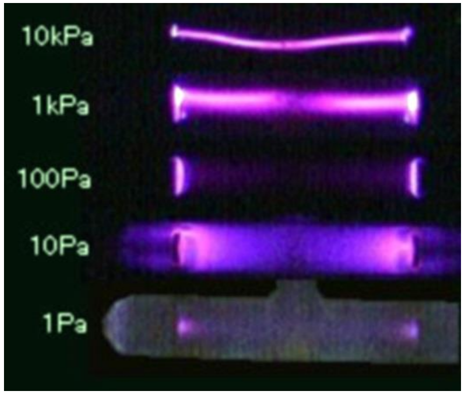
→ Could results in irreversible process

Discharge mechanism

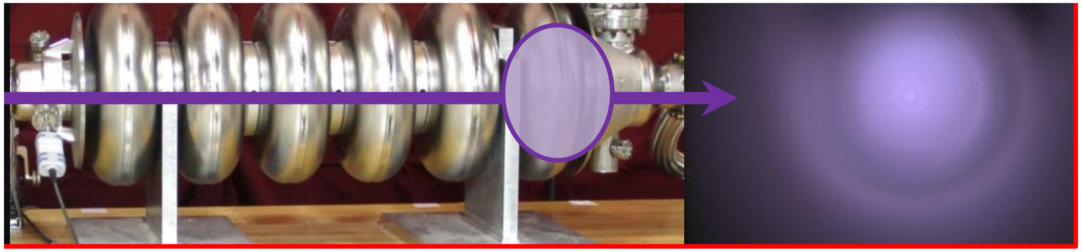
Gas discharge condition at >~10 mTorr

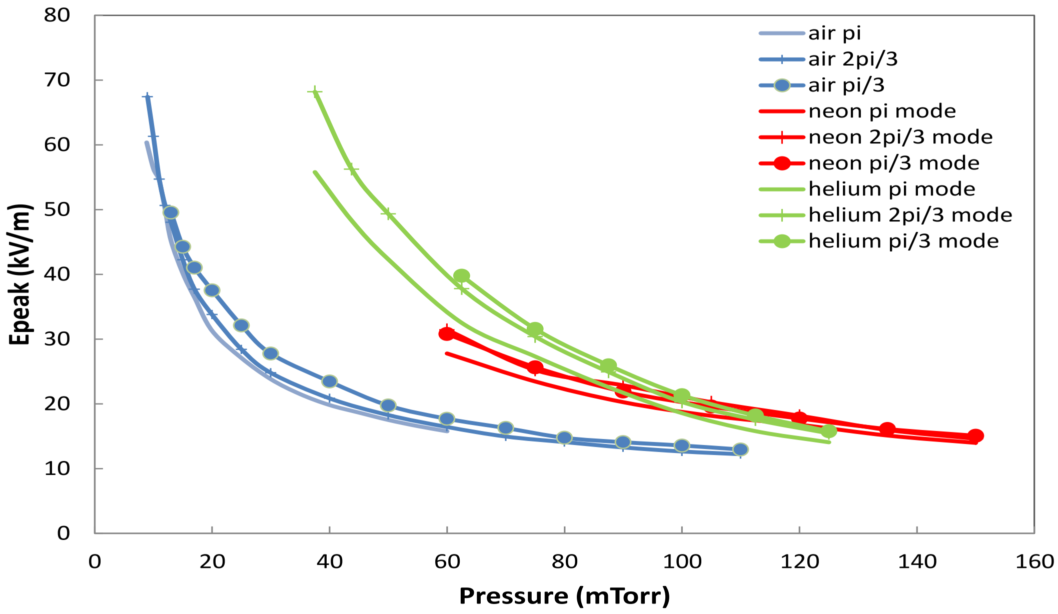
Paschen curve: DC discharge





Discharge experiment with SRF cavity





Glows and Arcs

Glow discharge:

Cold surfaces or electrodes (thermionic emission and field emission: negligible).
Electron emission source: secondary from the surface by ion, radical, photon.
Large fraction of electrons: from electron avalanche multiplication in the gas layers adjacent to the cathode (or surfaces).
In DC glow discharge, large potential drop (a few hundred V) near cathode → sputtering of cathode material. (often glow discharge application: sputter deposition or etching)

Arc:

Large electron emission from surfaces (by thermionic and/or field emission) in a small area of the surface can occur.
The concentrated current flow can produce a very high temperature very locally.
even though majority of surface is cold → local dense plasma
We are talking about very small dimension→ small potential can lead a very high peak electric field.
high electron current can be produced without electron multiplication in a gas.

DC Vacuum breakdown

In high vacuum

; electron mean free path >> structure dimension

; no formation of electron avalanches in space as in gas discharge

Breakdown mechanism is not well understood yet

- Particle exchange mechanism
- Clump theory
- Field emission mechanism

Raymond L. Boxman, *Handbook of vacuum arc science and technology* (1995)

M S. Naidu, V. Kamaraju, *High voltage engineering* (1995)

Particle exchange theory

Charged particle come out of one electrode under high electric field; statistically always possible

Accelerated and hit another electrode; liberate particles

Oppositely charged particle back to the first electrode

When this process becomes cumulative→ chain reaction

Usually when applied voltage is > a few hundred kV

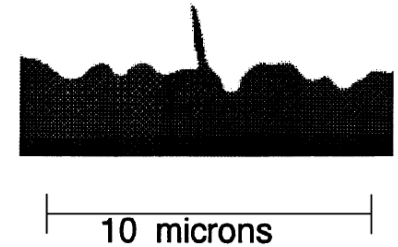
Clump theory

When loosely bound particles (clusters) exist on surface

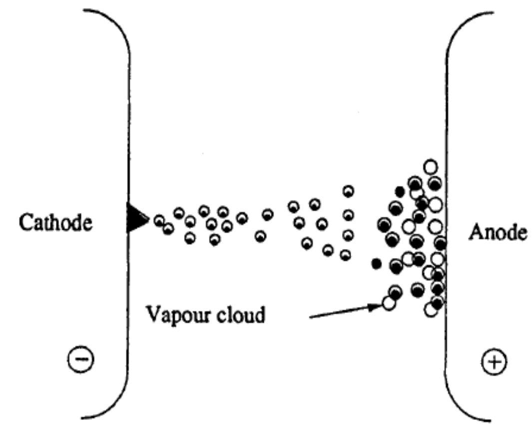
This particles (clusters) get charged under high electric field

Accelerated and hit the other surface→ vaporization → breakdown

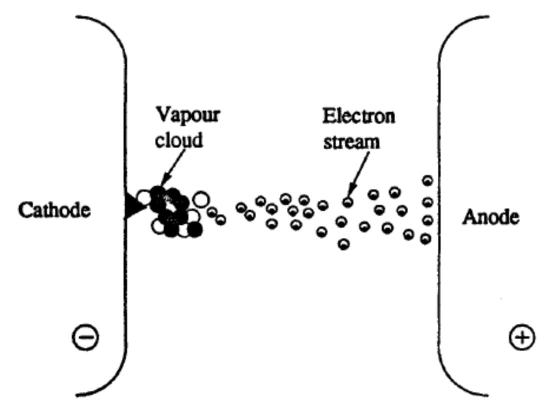
Field emission theory



- Anode heating mechanism
  - Electron emission at micron scale protrusion → bombard anode →cause local temperature increment, release gas → electrons ionize gas, produce ions → ions arrive at the cathode → increase electron emission (by space charge formation and secondary electrons → chain reaction until breakdown
  - Longer gap length

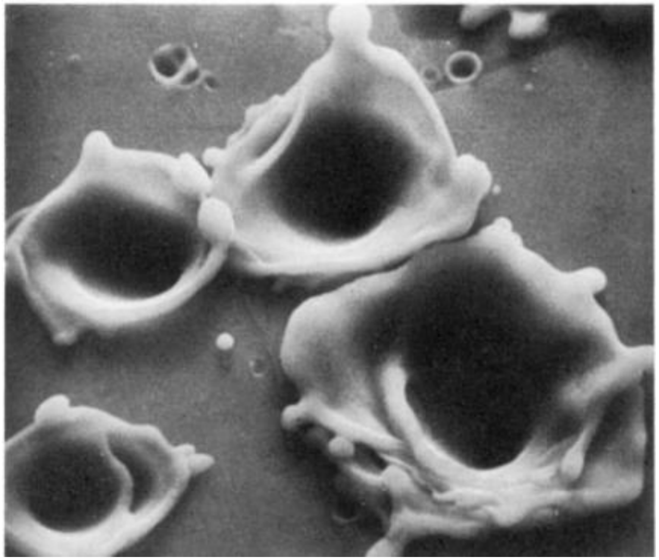


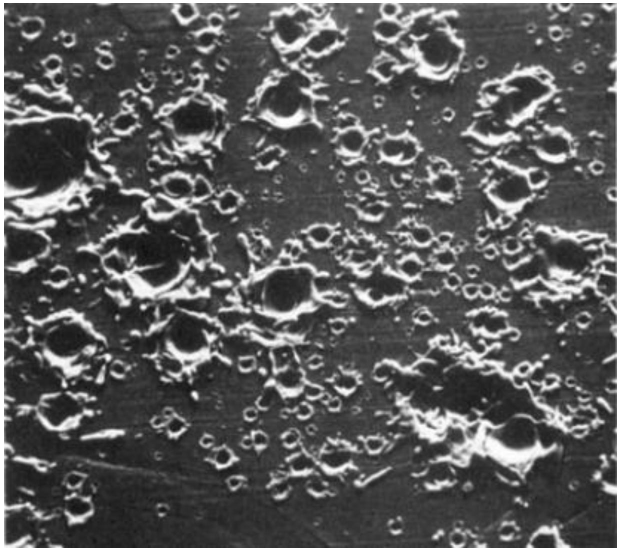
- Cathode heating mechanism
  - Assumption; existence of pre-breakdown at the field emitter near the breakdown voltage
  - Electric field increases → Field emission increases → current density at the field emitter goes high → reach melting point → plasma forms (thermo field electrons) explodes → vacuum breakdown
  - Short gap length (~a few mm)



Cathode spot (crater formation)

- Rapid and intense heating of the surface (by ion impact and Joule heating)
- Formation of molten layer and evaporation
- Acceleration of the melt mainly by the extremely high ion pressure acting on the surface → pushing the liquid metal outwards → parts of the melt that achieved the highest velocities are thrown out





Schematics of cathode spot

6 Plasma expansion region

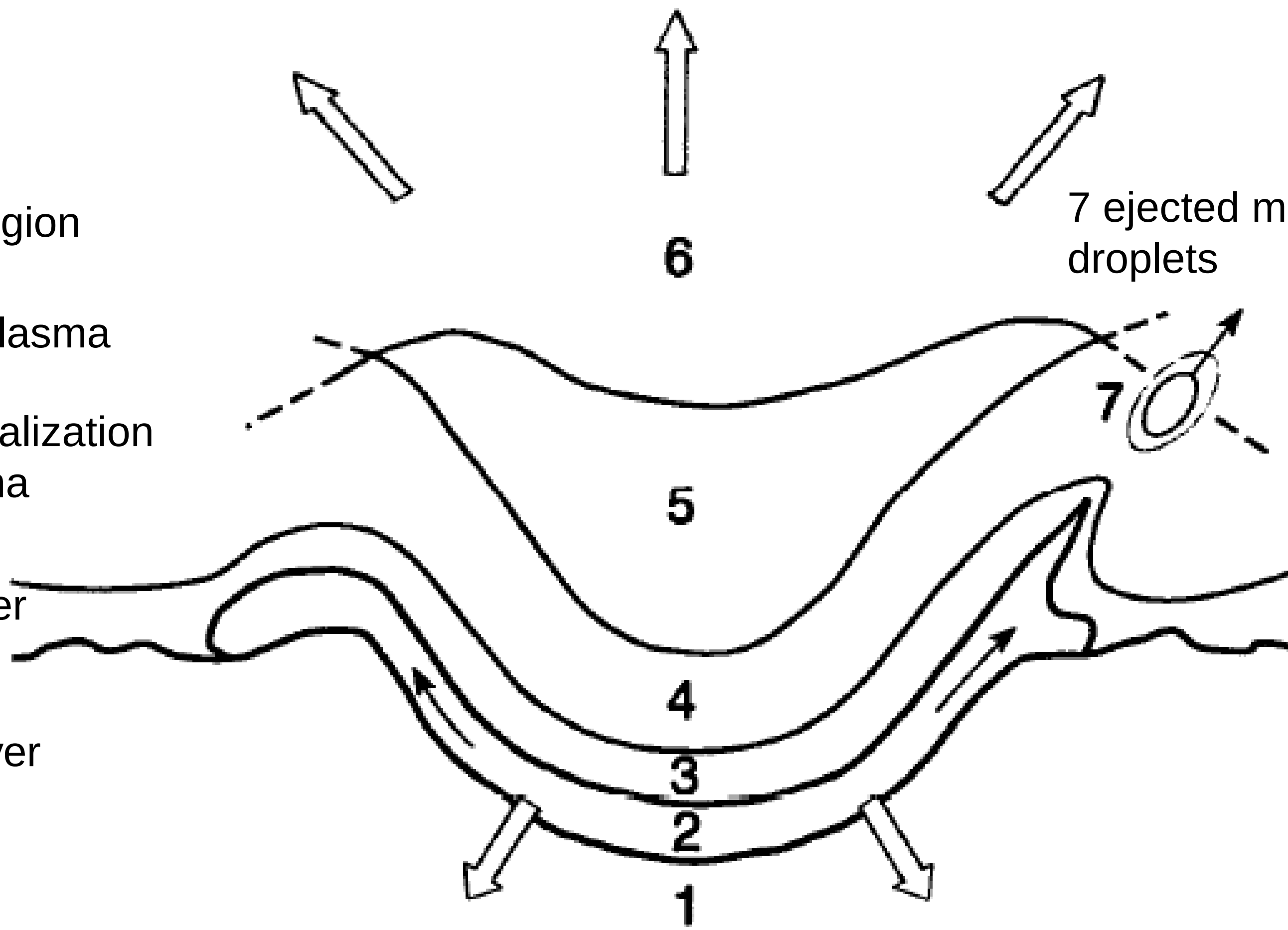
5 Dense central spot plasma

4 Ionization and thermalization layer of the spot plasma

3 Space charge layer

2 Molten metal layer

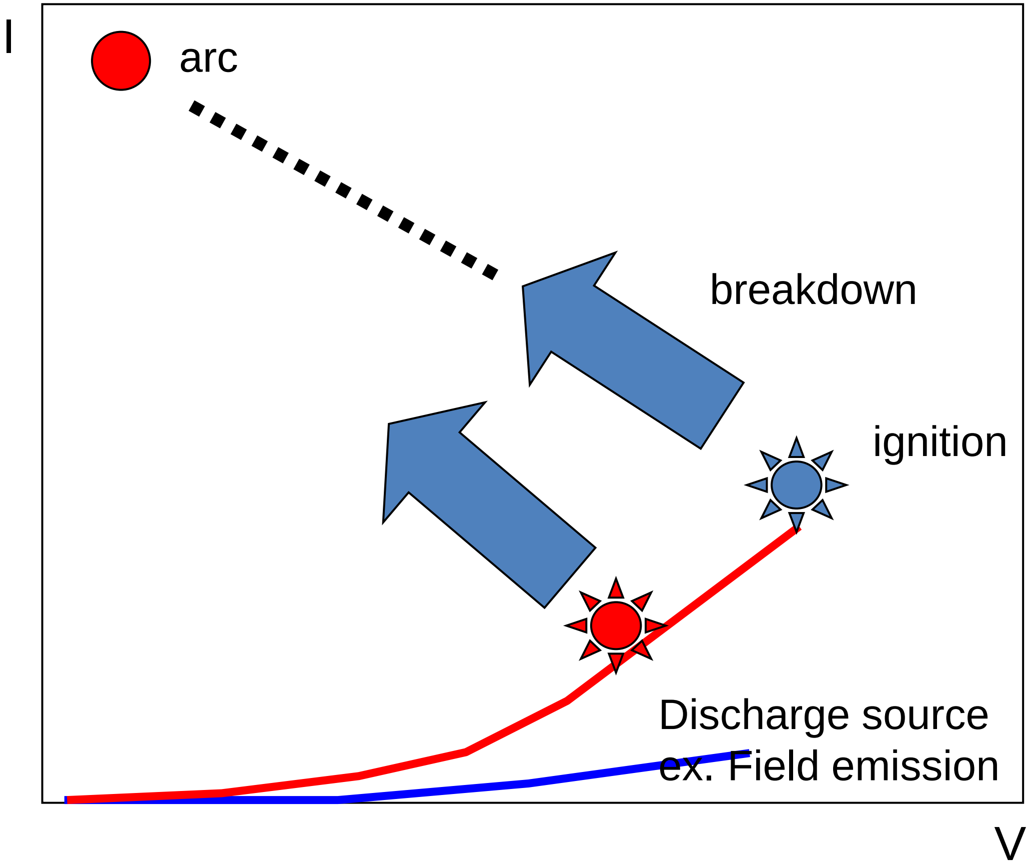
1 Solid metal



7 ejected molten droplets

Breakdown/arc development

- Before breakdown; quasi static
- At ignition; very short pulse (high frequency)

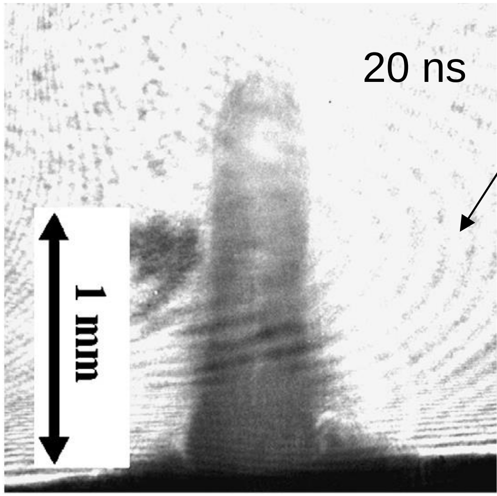


Function of
Capacitances,
Field emitter characteristics,
Potential development,
Field profile,
Geometry,
Details of contacts,
Current,
Material,
etc.

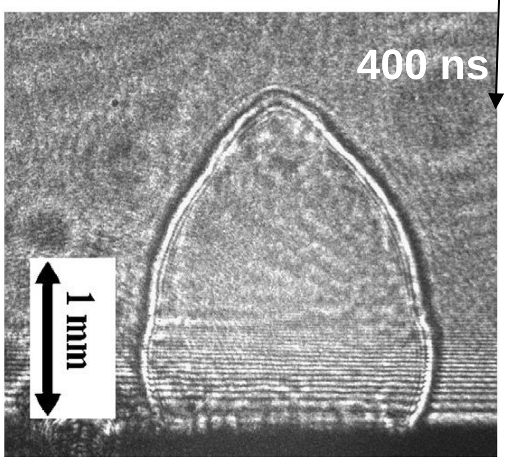
When the power supply or stored energy is large enough,
full arcing condition can occur

Plasma formation and Crater

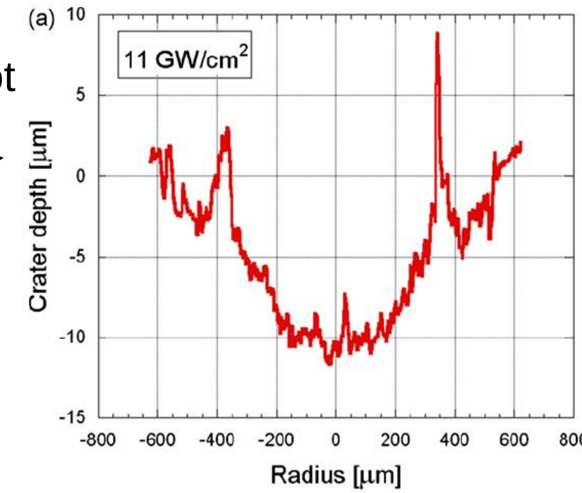
- some analogies; can have rough guessing about power density and duration of breakdown
- Thermal load; intense, short laser on aluminum surface

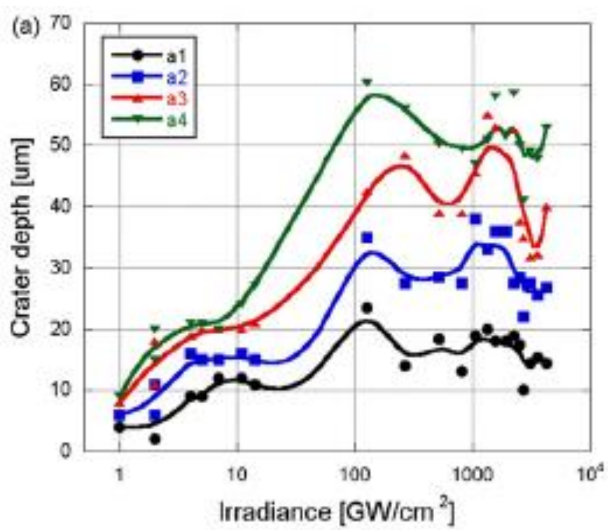


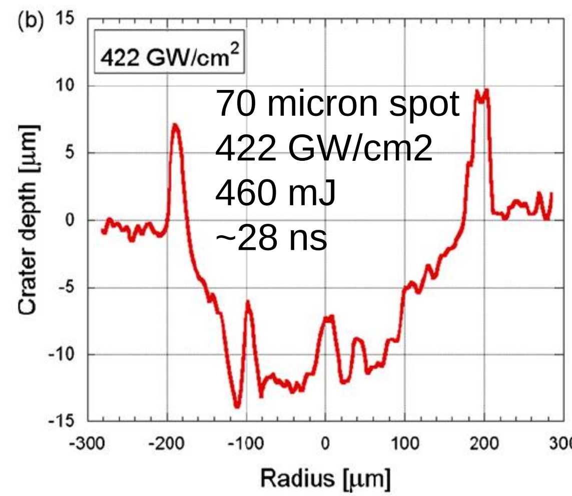
92 mJ
(270 GW/cm^2)
70 micron spot
~9 ns



600 micron spot
11 GW/cm2
280 mJ
~9 ns



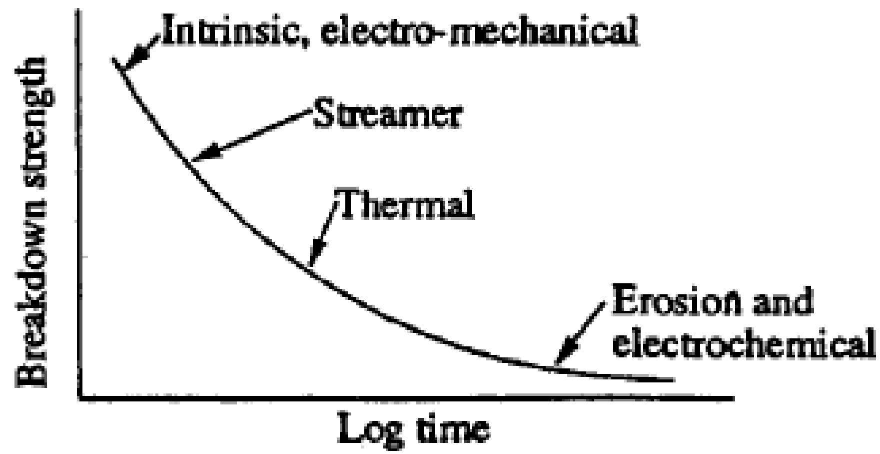




A. Gojani, et al, Extended measurement of crater depths for aluminum and copper at high irradiances by nanosecond visible laser pulses, App. Sur. Sci. 255 (2008)

Breakdown in solid/surface (dielectric)

- Ionic breakdown
- Electromechanical
- Treeing (streamer)
- Thermal
- Electrochemical
- From internal partial discharge



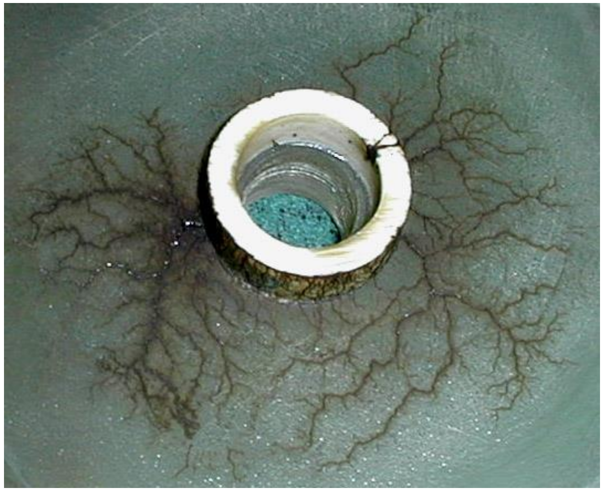
- In practice
  - Electrochemical deterioration
  - Treeing and streamer
  - Internal discharge (void or cavity)
  - Surface; Flashover/treeing
- Catastrophic failure in insulator
  - Driven by electrical power
  - Ultimately thermal
  - Carbonization or vaporization
  - Mechanical failure

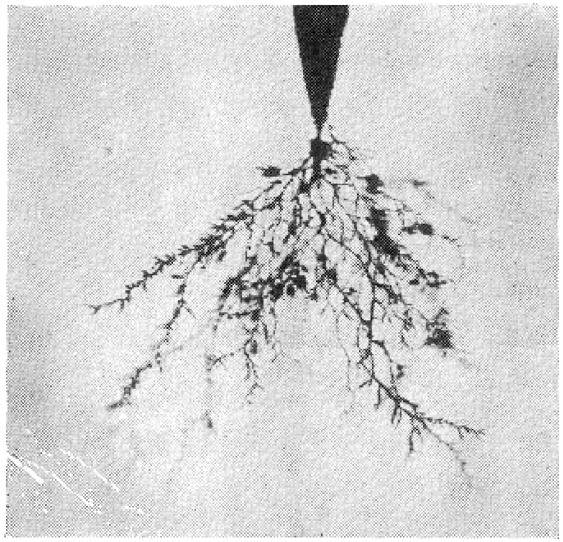
Dielectric breakdown enhancing factors

- external source for charge buildup
- Non-uniformity
  - Provide initiation
  - Field concentration
  - Non-uniform charge buildup
  - void, impurity, inhomogeneity of material, insulator related at contact, junction at the boundary, absorbed gases, wrinkles, contact/boundary material, temperature dependencies, etc.

Treeing

- An electrical pre-breakdown phenomenon
- A damage process from partial discharges
- High field concentration
  - at around the edge of trees
  - Charge inhomogeneity near electrodes
- Progress through the stressed dielectric insulation
- Finally breakdown/failure
- Could results in vacuum arc





Y. Toriyama et al, Jpn. J. Appl. Phys., Vol. 4, No. 12 (1965) pp. 992-993

Surface Flashover in general

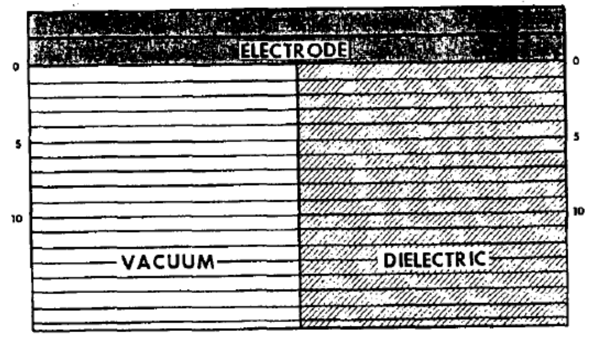
- Field establishment from trapped charge
- Surface charging due to diffusion of trapped charge or from the multiplication of secondary electrons
- Subsequent avalanche of the surface discharge
- Streamer growth of charges
- Breakdown (atoms or clusters)

- Three stage
  - Initiation
  - Development
  - Final

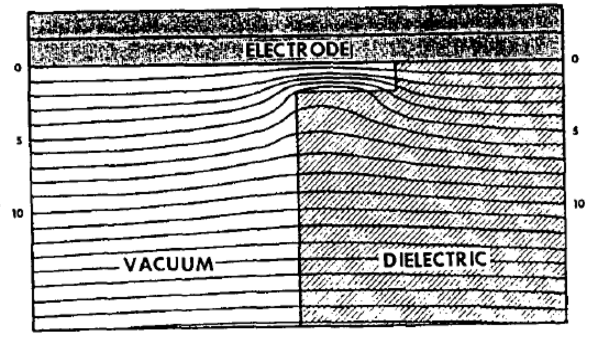
Initial stage

- Electron emission at ‘Triple junction point’

Ideal contact



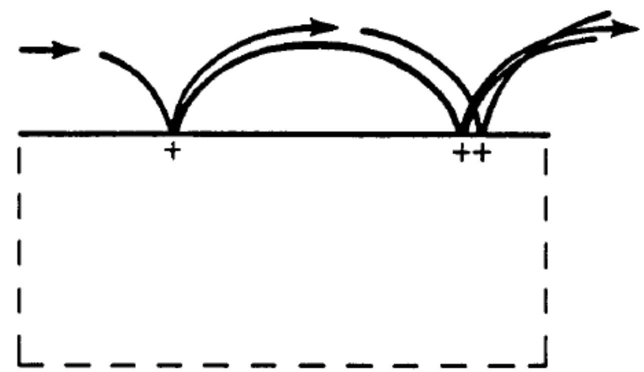
Void at contact



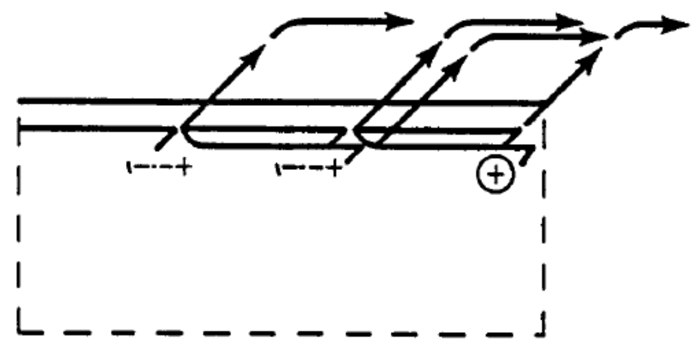
H. Miller, IEEE Trans. Elect. Insul., Vol. 24, No. 5, (1989) pp. 765-786

Development and breakdown

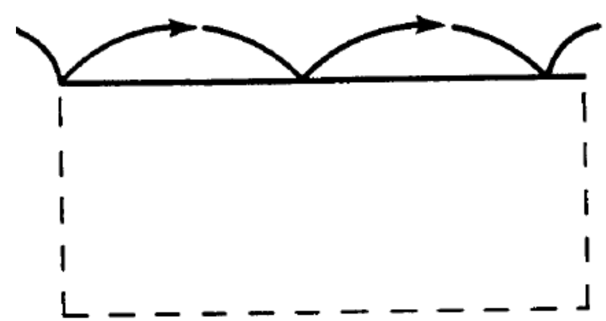
- Electron multiplication by
  - Surface secondary electron emission avalanche
  - Or electron cascade in a thin surface layer
- Travelling electrons
  - form a pre-breakdown current
  - Desorption of gas or evaporation and ionization
  - Further increase in current
- Breakdown
- If sufficiently large current density then, vacuum arc will happen
- If field concentration is large at anode, flashover can start at anode triple point



SECONDARY ELECTRON EMISSION AVALANCHE



ELECTRON CASCADE IN INSULATOR



ELECTRONS STRIKE SURFACE. NO AVALANCHE

Curved discharging trace

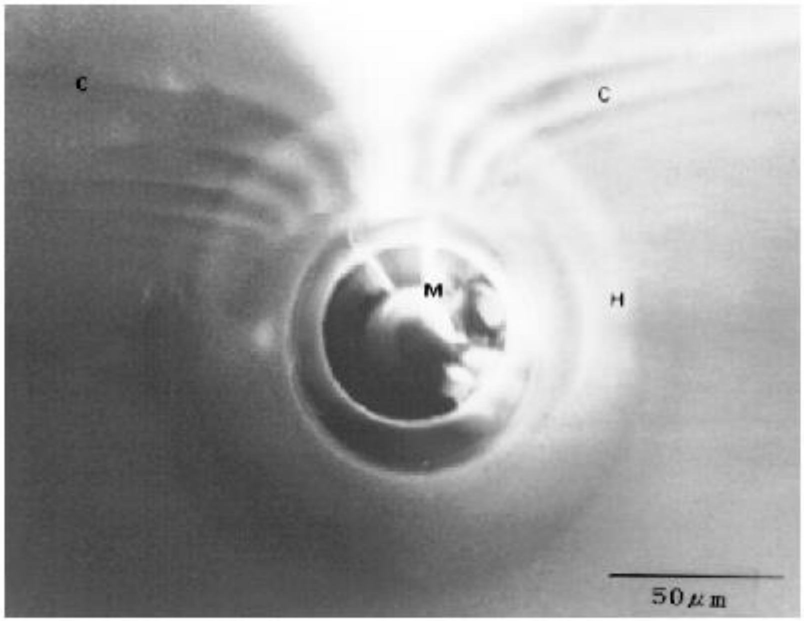
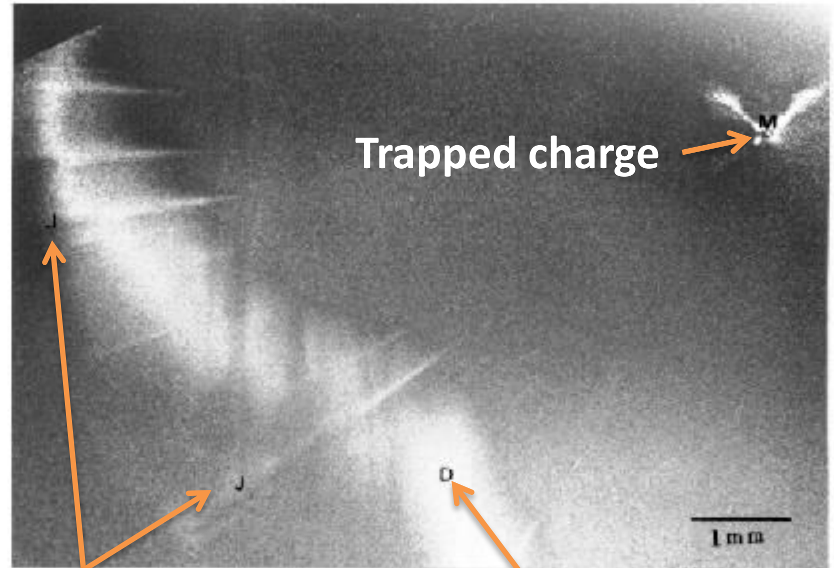


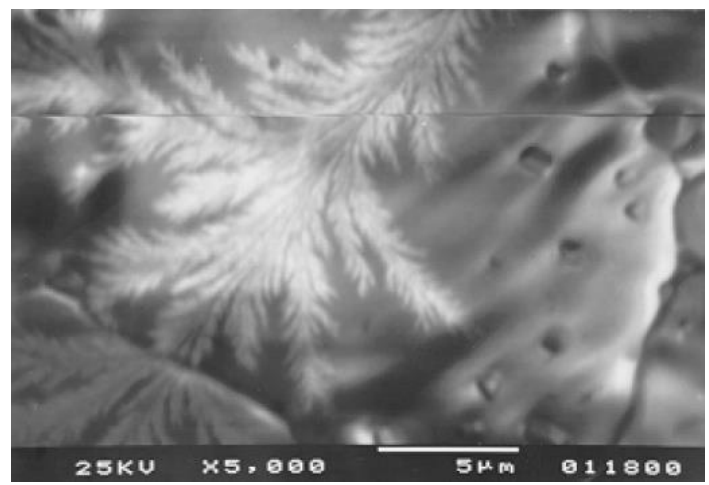
Figure 1. A SEM image showing halo (H) and curved discharging (C) traces on a PMMA surface. The central disc (M) is the mirror image of the scanning electron microscope chamber, and its centre indicates the position of the trapped-charge concentration.

H. Gong et al, J. Phys.: Condens. Matter 9 (1997) pp. 1631-1636



Jet-like discharging trace

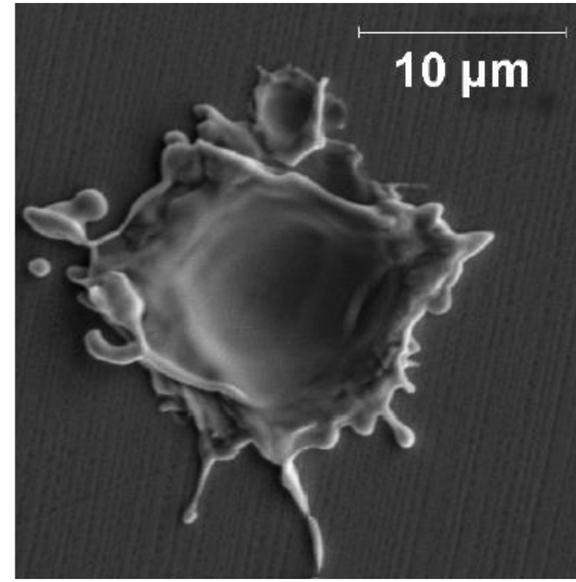
Diffused electrons



Surface treeing

A. Sutjipto, et al, World Acad. Sci., Eng, & Tech. 53 (2009) pp.8-11

RF breakdown in high vacuum



1.
Electrons (multipacting, field emission) heats surface
Electron bombardment results in gas desorption
Or
Beam hits surface and results in gas desorption

2.
Local vacuum could be worse and could go into RF breakdown regime

3.
With largely available RF power and stored EM energy, plasma heated up and expansion. Usually with flash of X-ray emission and drastic Q-drop.

The detailed mechanism is not well understood, but there are reports that say probably related with field emission and/or multipacting (also beam stimulated).

If the filed is sufficiently high, there are lots of examples of electric breakdown or sparking, arcing, etc.

Multipacting

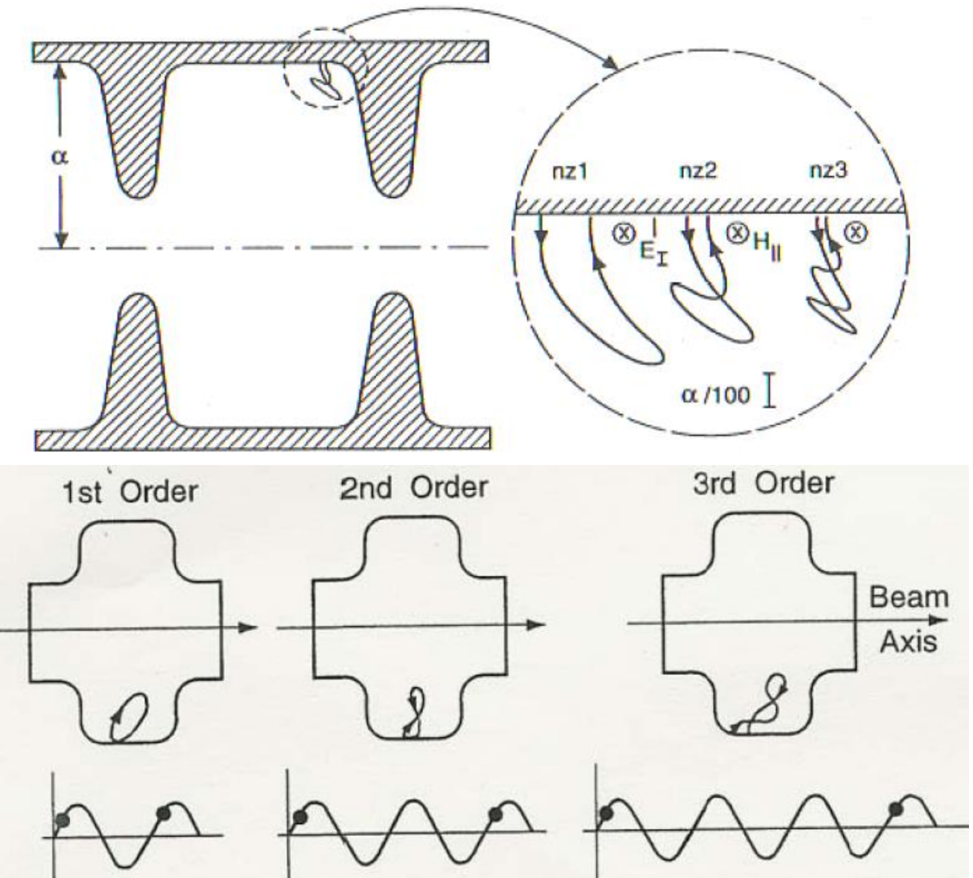
Resonant electron loading → strongly depends on geometry and field distribution

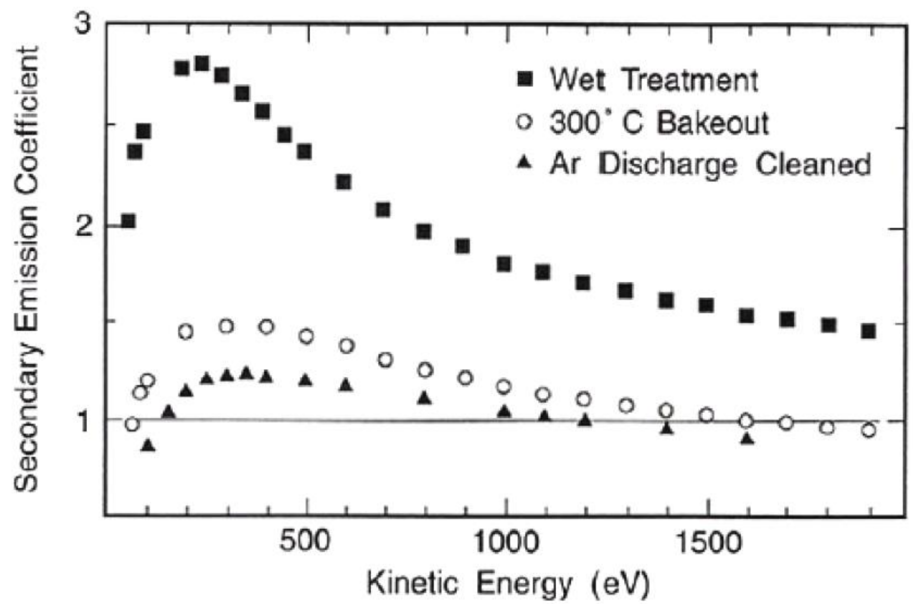
Multipacting condition

1. Resonant trajectory

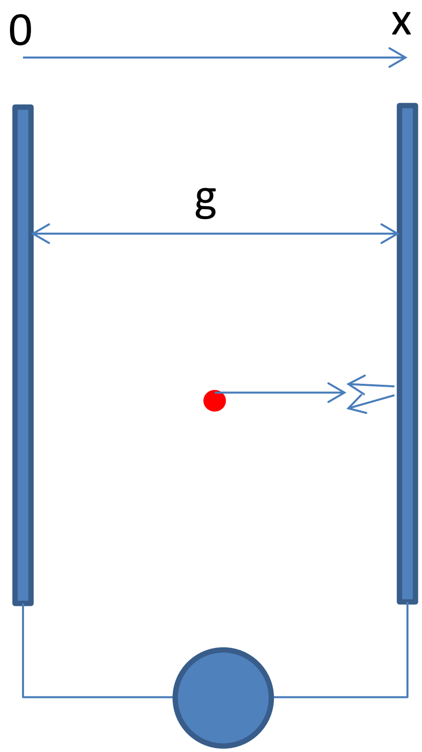
(insensitive to the initial energy)

2. SEY(E)>1 (Physical surface condition)



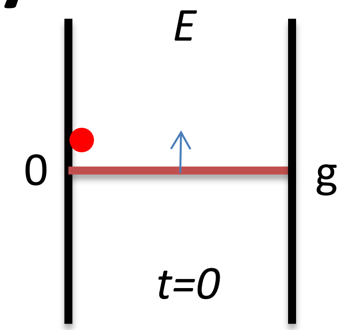


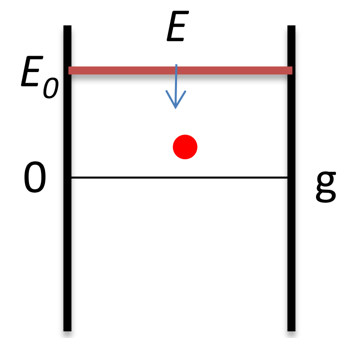
MP calculation for simple geometry



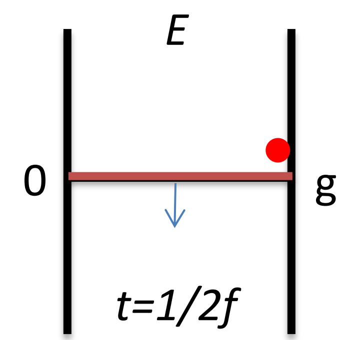
$E = E_o \sin \omega t$

Let’s assume,
Electron starts from x=0 with ‘0’ energy at t=0





If the electron arrives at x=g when the *t=1/2f=T/2*, resonance condition is satisfied.



In general *t=(2n-1)/2f=(2n-1)T/2, n=1, 2, 3, 4, …*

Equation of motion

$$a = \frac{eE_0}{m_e} \sin \omega t$$

Integration for *v*

$$v = -\frac{eE_0}{m_e \omega} \cos \omega t + \mathrm{C} = \frac{eE_0}{m_e \omega}(1 - \cos \omega t)$$

(∵ *v=0 at t=0*)
actually secondary electron energy at birth is about 1-3 eV

Integration for *x*

$$x = \frac{eE_0}{m_e \omega^2} \sin \omega t + \frac{eE_0}{m_e \omega} t$$

(∵ *x=0 at t=0*)

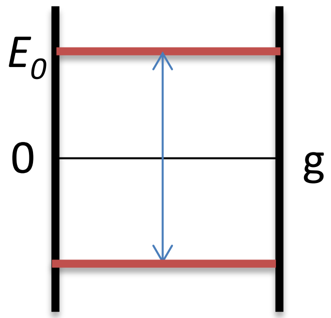
Resonance condition, *x=g at t=(2n-1)/2f*

$$g = \frac{eE_0}{m_e \omega} \frac{(2n-1)}{2f} = \frac{\pi e E_0}{m_e \omega^2}(2n-1) \rightarrow E_0 = \frac{m_e \omega^2}{\pi e} \frac{g}{(2n-1)}$$

Gap voltage $V_g = E_0 g$ (no transit time yet)

$$V_g = E_0 g = \frac{m_e \omega^2}{\pi e} \frac{g^2}{(2n-1)}$$

Transit time factor (TTF): since the field is changing while the electron moves, the effective voltage or field seen by the electron should be taken into account.



$$E = E_o \sin \omega t$$

The energy gain becomes: $KE = E_0(TTF)g$

In this parallel plate geometry, the transit time factor for the particles in resonance condition is

$$TTF = \frac{2}{\pi(2n-1)} \quad n = 1, 2, 3, 4, \ldots.$$

The electron impact energy in resonance condition (again let's assume the secondary electron at birth is '0', actually it is about 1-3 eV)

$$KE = E_0 g = \frac{2m_e\omega^2}{\pi^2 e}\frac{g^2}{(2n-1)^2} \quad in\ eV$$

Ex. f=500MHz, gap=0.02m→ n=1, impact energy=2915 eV
n=2, impact energy=324 eV
n=3, impact energy=116 eV

Multipacting in general

MP is mostly at low electric field side.

- during ramp-up
- beam pipe (stray field region)
- window, iris, couplers
- equator sides of cavity , etc

How to avoid:

Careful analysis during design stage & simplify the design (avoid resonances)

Reduce Secondary Emission Yield

- Keep the surface clean (no contaminant, gas, particulates..)
- RF conditioning reduces
- Baking, discharge cleaning,
- Surface coating (Ti, TiN)
- DC biasing

*Detuning

- Slight change of VSWR: sometimes helps when MP happens in the transmission line (waveguide, window, coupler, etc.)

*Over-coupling (lower time constant)

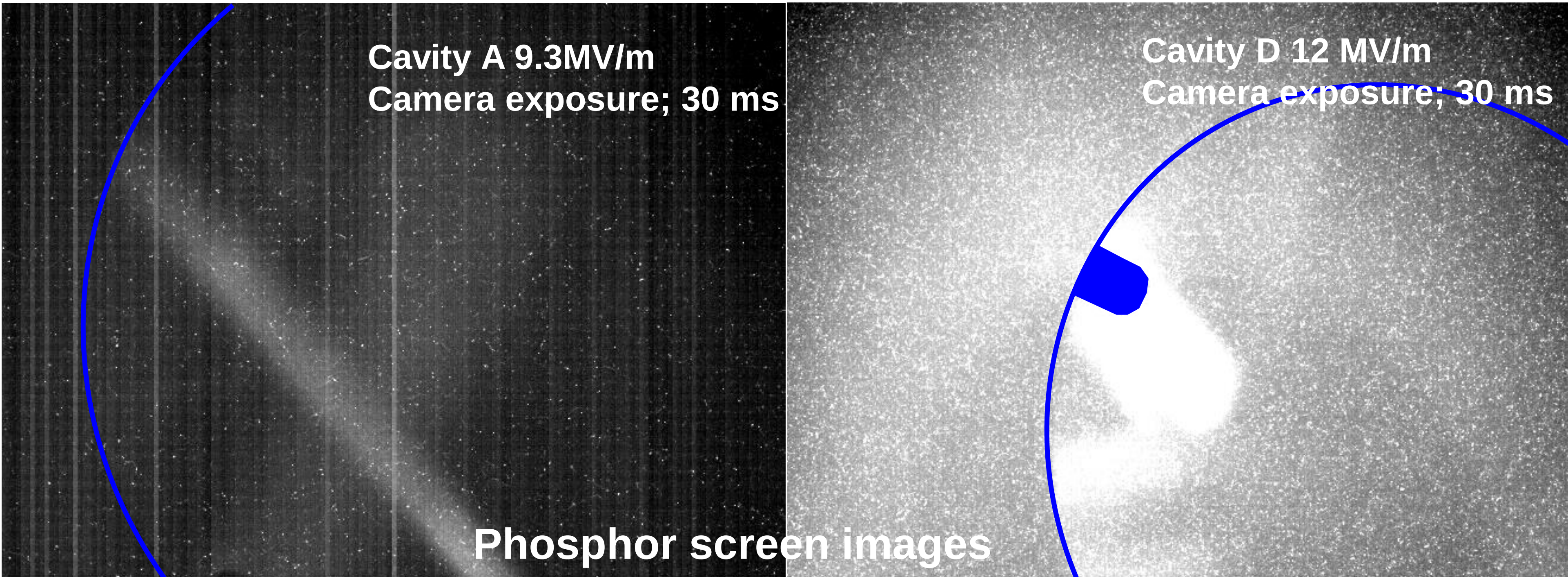
- to pass MP region quickly especially in pulse machine
  - *very limited range of control

Field emission (FE)

Fowler Nordheim Law

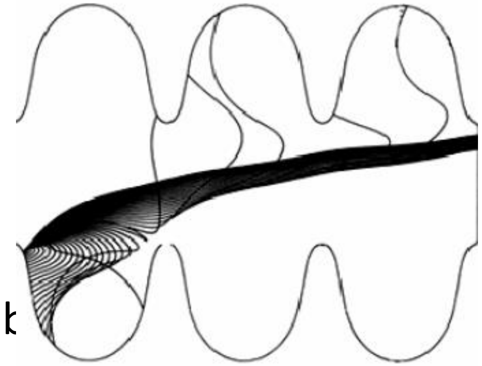
$$j \propto \frac{(\beta E_s)^2}{\varphi} exp\left[\frac{-a\varphi^{3/2}}{\beta E_s}\right]$$ Shape factor β (could be >100), work function φ, etc.

Theoretical limit ~ 1 GV/m, reality ~ <10 MV/m
Mild FE: system may be operable. Vacuum could be worse (operation would be difficult).
Could kill valve o-rings. Especially in superconducting cavity, limit achievable gradient, lower Q, make system unstable, etc.
Sometime big burst of field emitter could make surface defects.

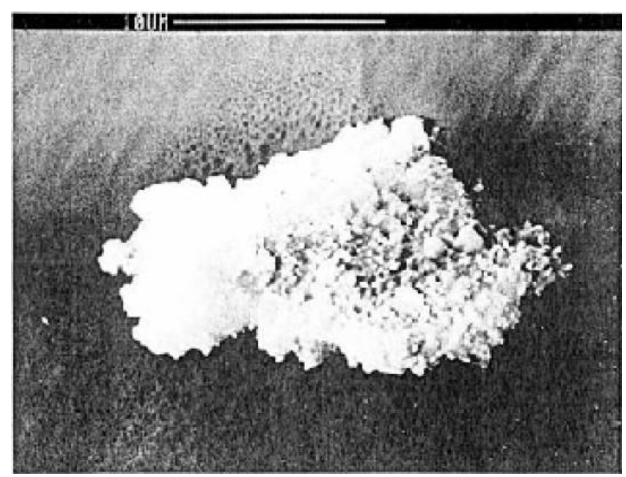


Phosphor screen images

Field emission and its enhancement



- Model
  - Protrusion-to-protrusion
  - Modification of constant and shape factor in FN equation
    and other contaminant
  - Activation of field emitter at elevated temperature by changes of the boundary layer
  - Insulator enhanced; from the distortion of electric field
- Complexity
  - Function of size, shape, kinds of particle, charge, substrate status, wettability, temperature, processing history…….. (statistical distribution, hard to control, larger surface will statistically have more field emitter)

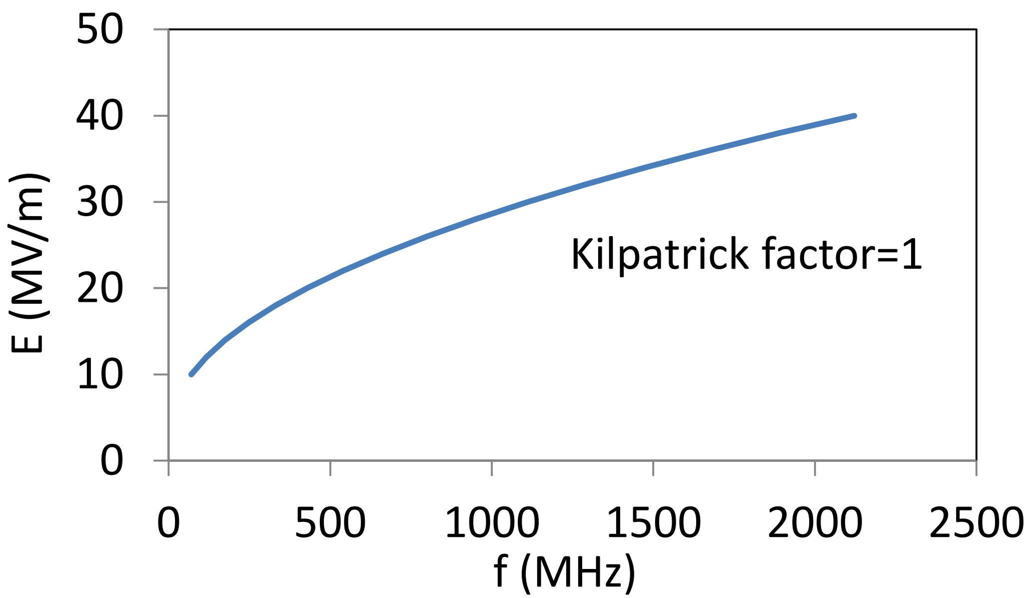


Kilpatrick criterion

Old criterion on RF breakdown but still in use

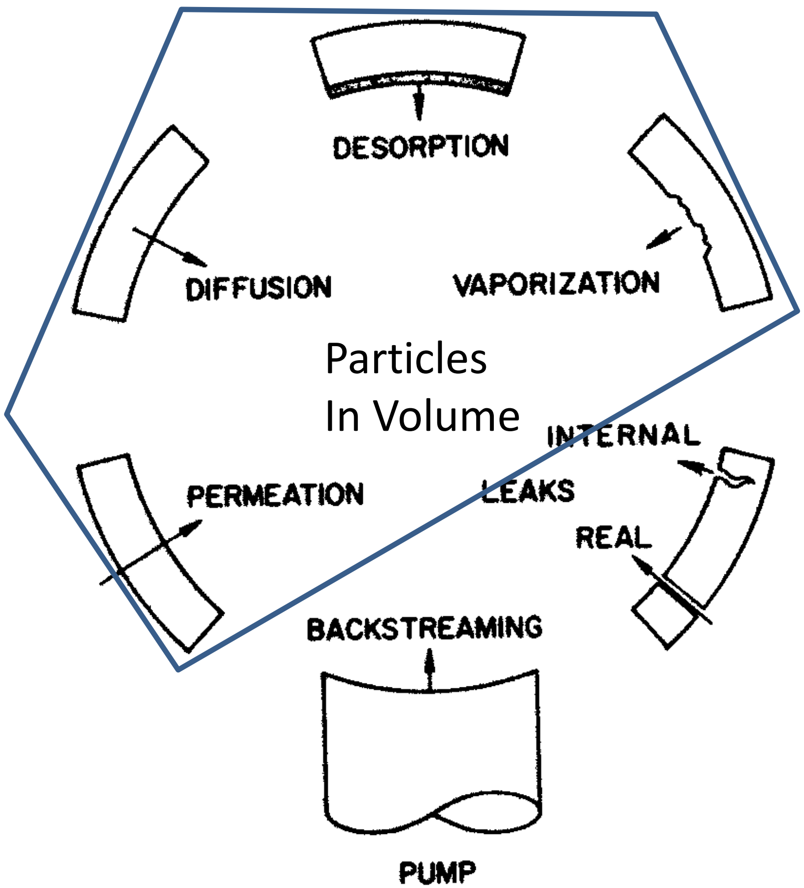
In late 1950s, W. Kilpatrick analyzed for RF breakdown free condition.

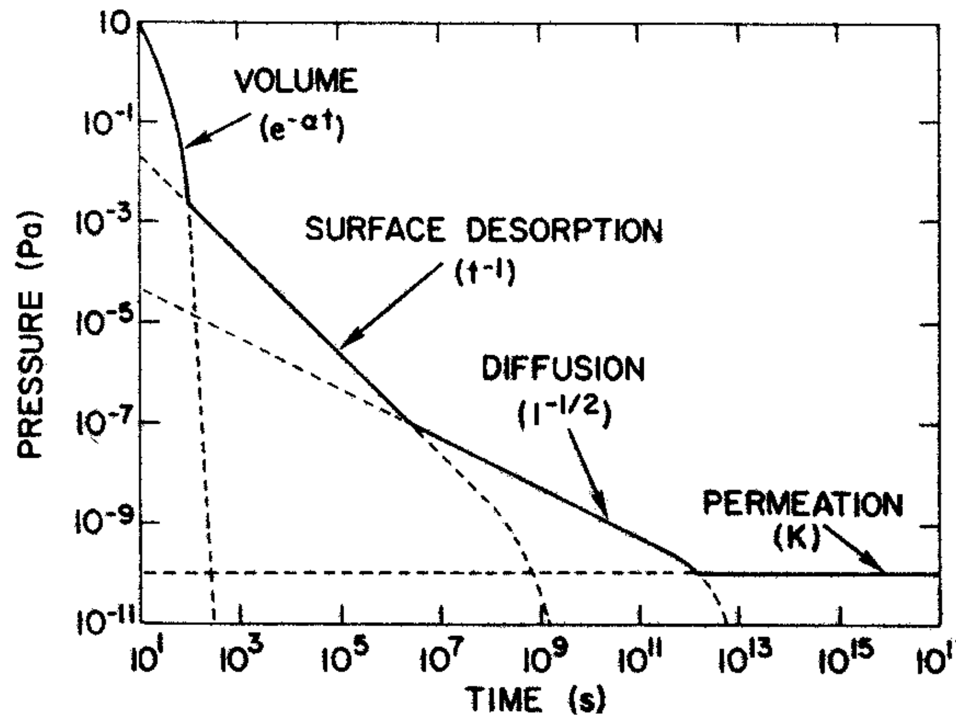
$$f(MHz) = 1.64E^2 \exp\left(-\frac{8.5}{E}\right) \quad E: breakdown\ electric\ field\ [\frac{MV}{m}]$$



This estimation is based on the old system especially vacuum system.
It is a pretty conservative criterion.
Usually RF system is designed and operated at the factor between 1 and 2.

Vacuum





Typical time scale for non-treated material

When there is no leak and pumping is good, outgassing still exists.

Outgassing

1. Desorption: gas release from the surface. Final state of all outgassing mechanism. Bonding mechanisms can be either physical or chemical. In general chemical bonding is stronger. Desorption rate increases with temperature. Desorption is accelerated by photons, electrons and ion bombardment.

2. Vaporization: phase transition of material to the gas. Materials with higher vapor pressure can evaporate in vacuum and/or at elevated temperature.

3. Diffusion: dissolved gas in the bulk material moves to the vacuum surface. Hydrogen have high mobility in the bulk material.

4. Permeation: absorbed gas from outside diffuses through the bulk material and then desorbed from the vacuum surface.

Reducing Outgassing

Polishing: reduce the effective surface area and the adsorption capacity

Heating: baking or firing

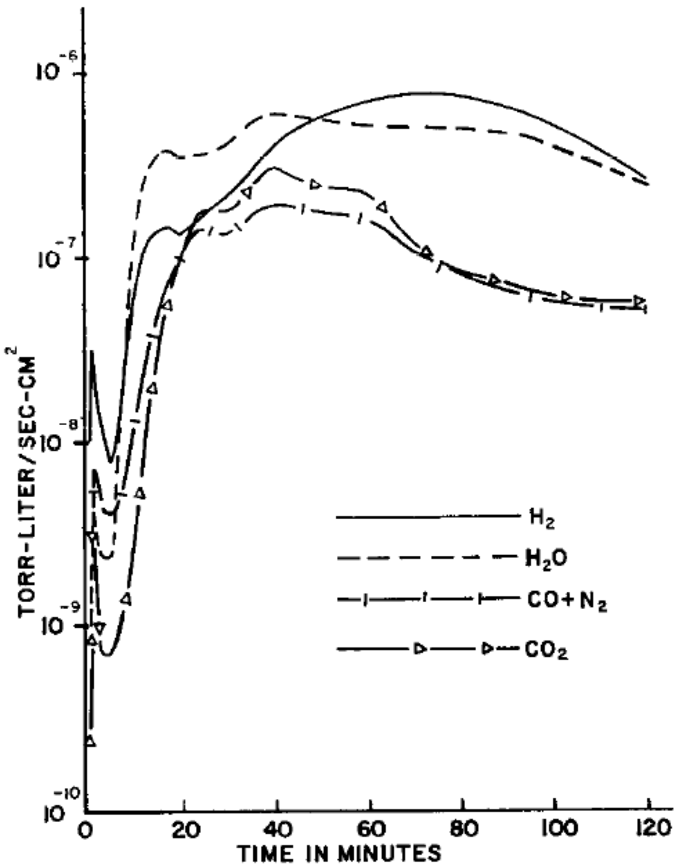
150-300C baking is very helpful to get rid of water but not enough for hydrogen. Any metal is a large reservoir of hydrogen. During the heat treatment CO and CO2 are often emitted in addition to hydrogen.

Firing temperature: 500 C for OF Copper, 1000 C for Stainless Steel

Gas discharge cleaning

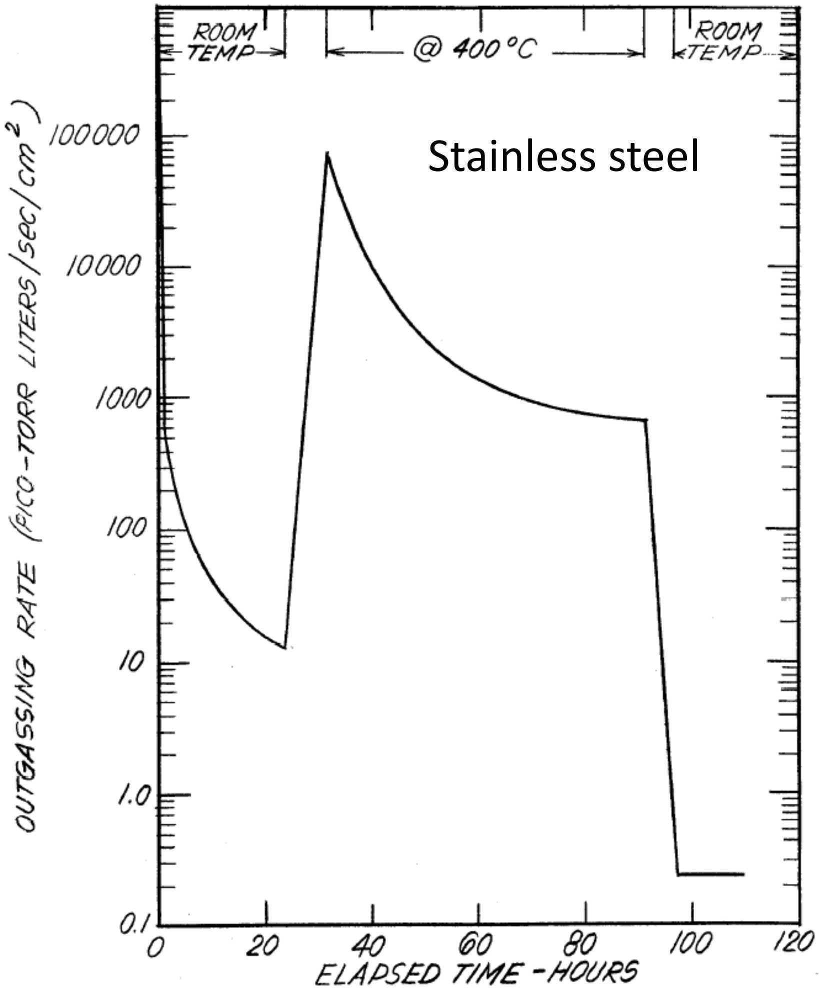
Photon or electron bombardment/showering

Coating



OFH copper degassing at 500C

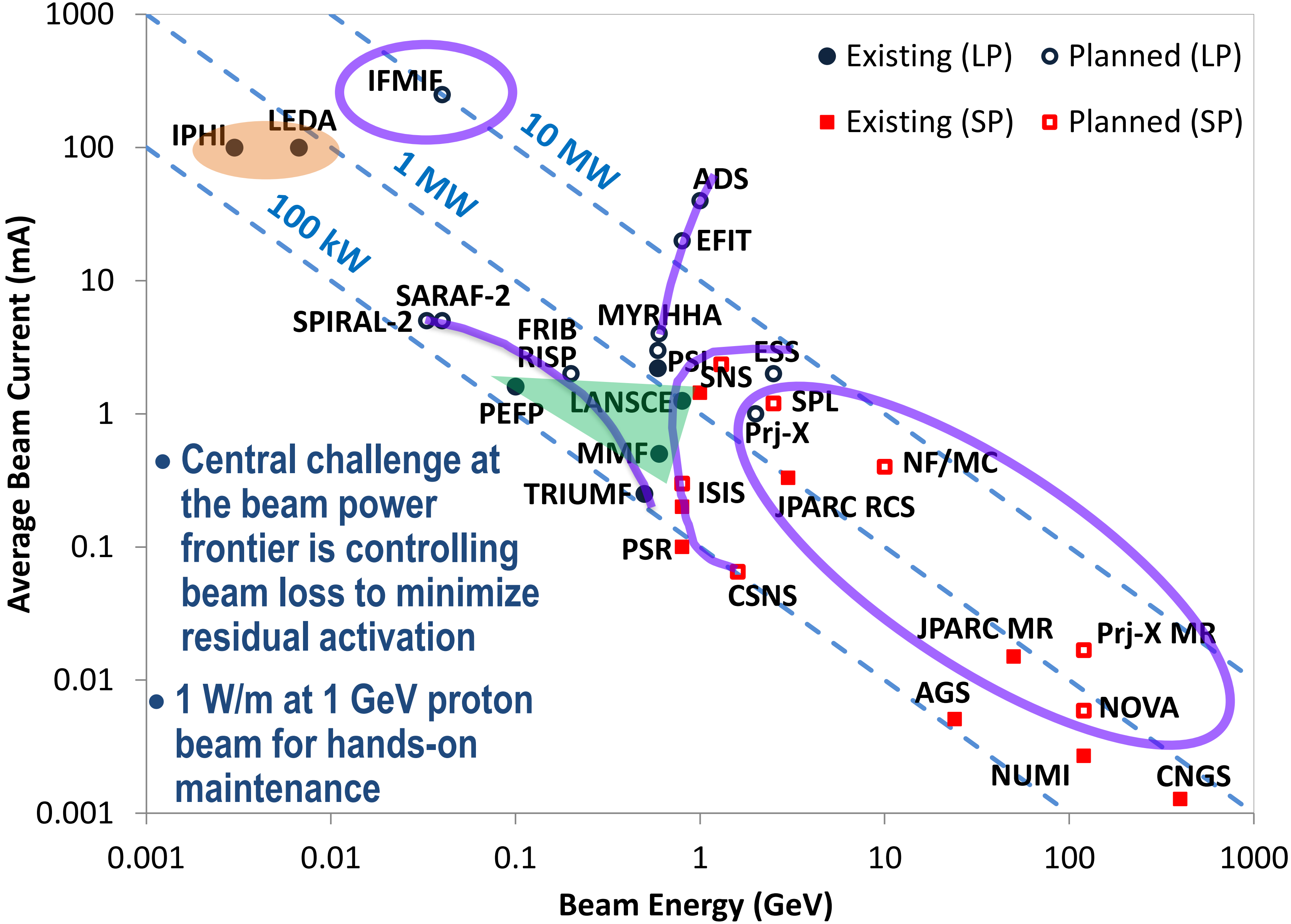
R. Kirkendall et al, J. Vac. Sci. & Tech. 3, 214 (1966)



E. Hoyt, SLAC-TN-64-5, Jan (1964)

Beam related issues

Activation: Beam Power Frontier for ion beam accelerators

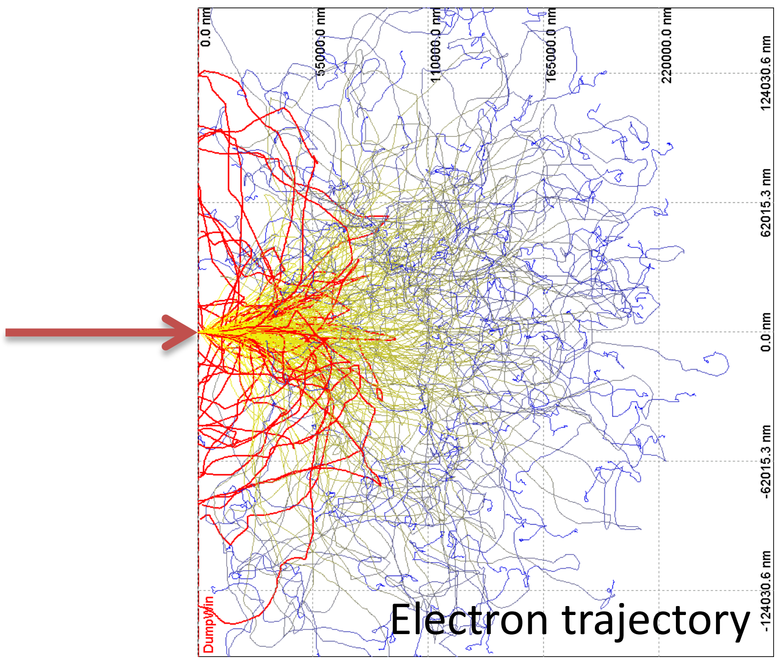


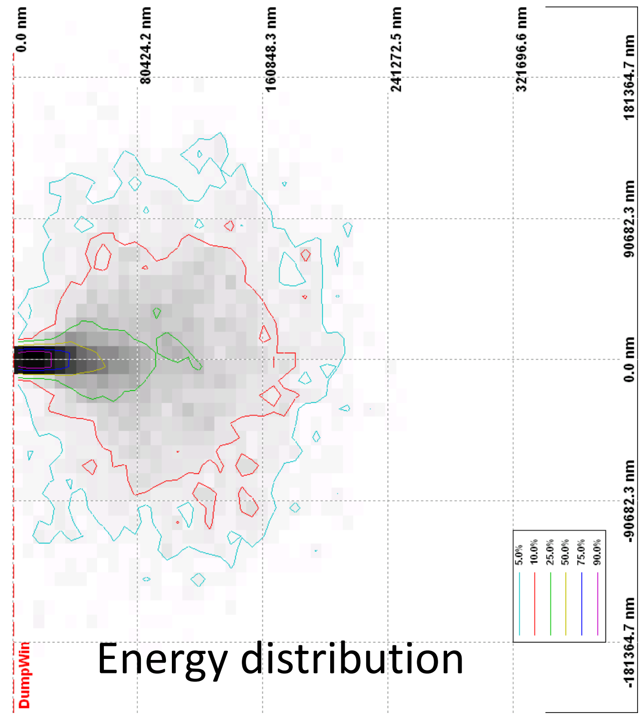
- Central challenge at the beam power frontier is controlling beam loss to minimize residual activation
- 1 W/m at 1 GeV proton beam for hands-on maintenance

Mis-Steered beam: Copper damage

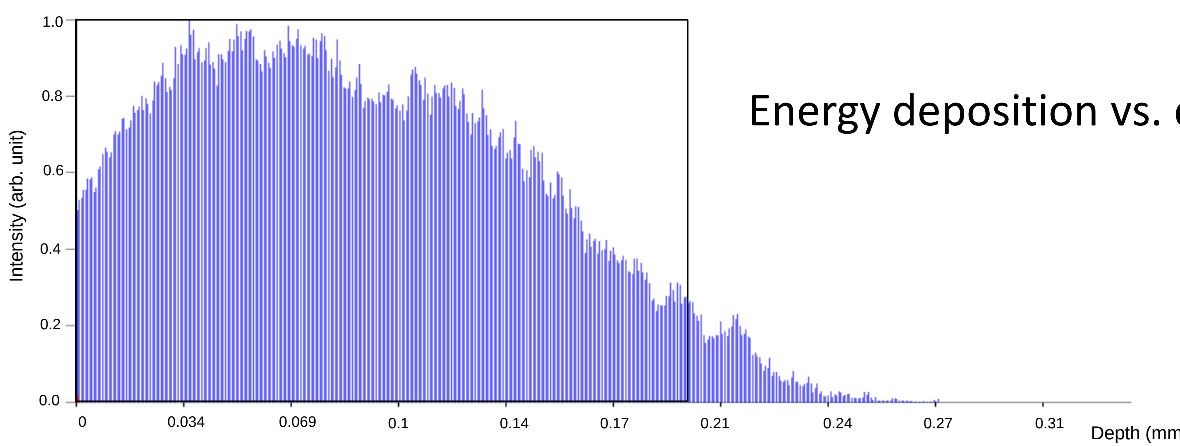
Electron beam

Electron stopping in the material



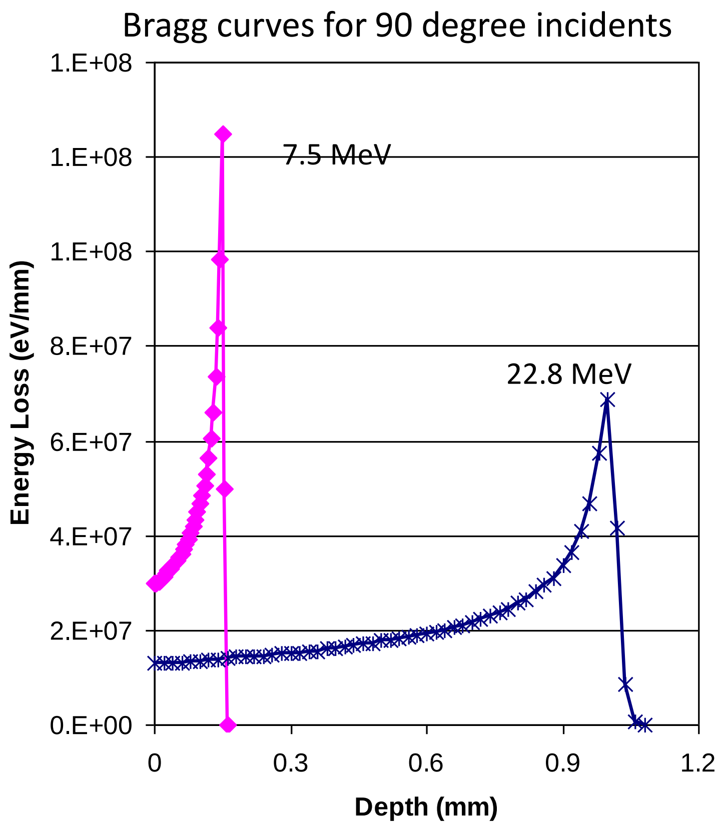


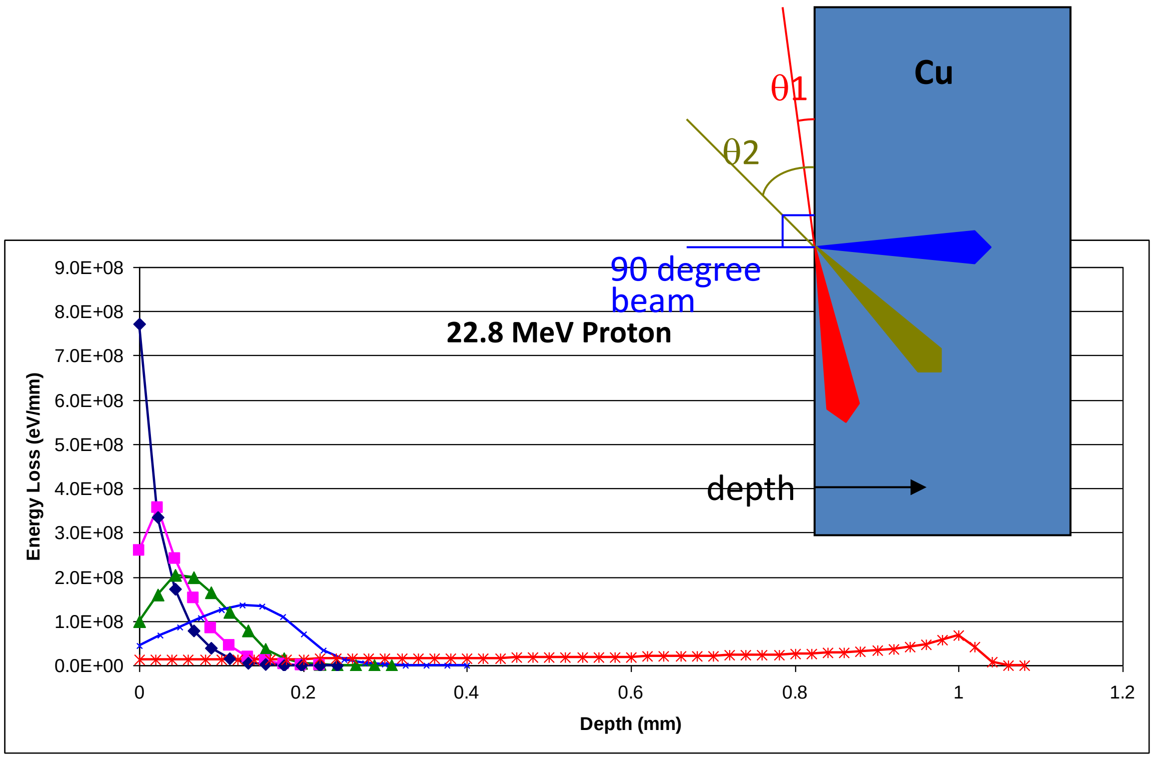
Simulation for SNS linac beam dump window using CASINO (electrons stripped from H-)

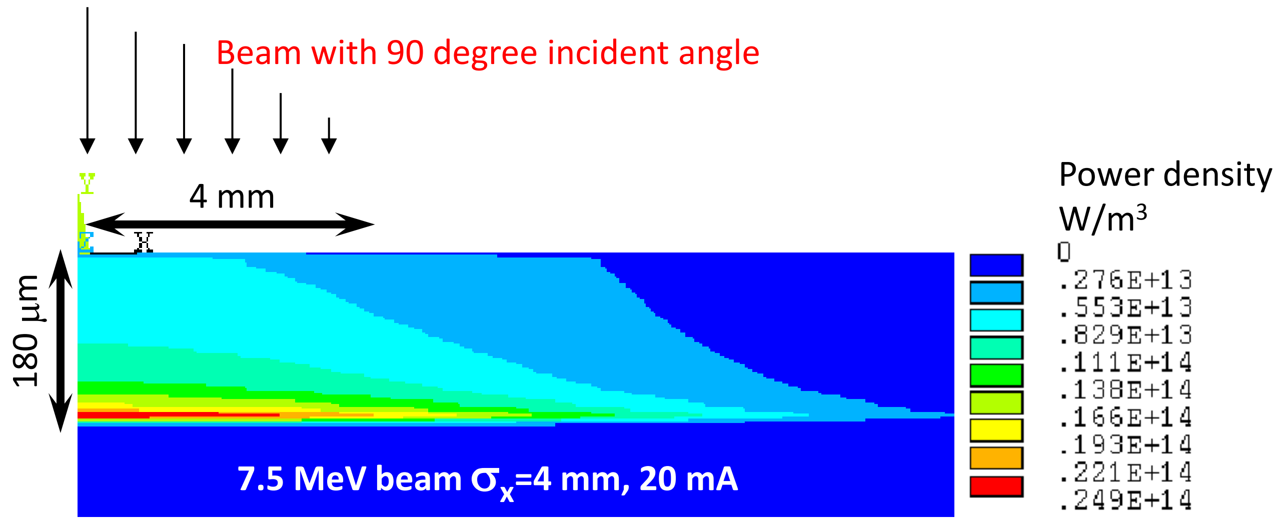


Energy deposition vs. depth

Proton/Ion beam stopping







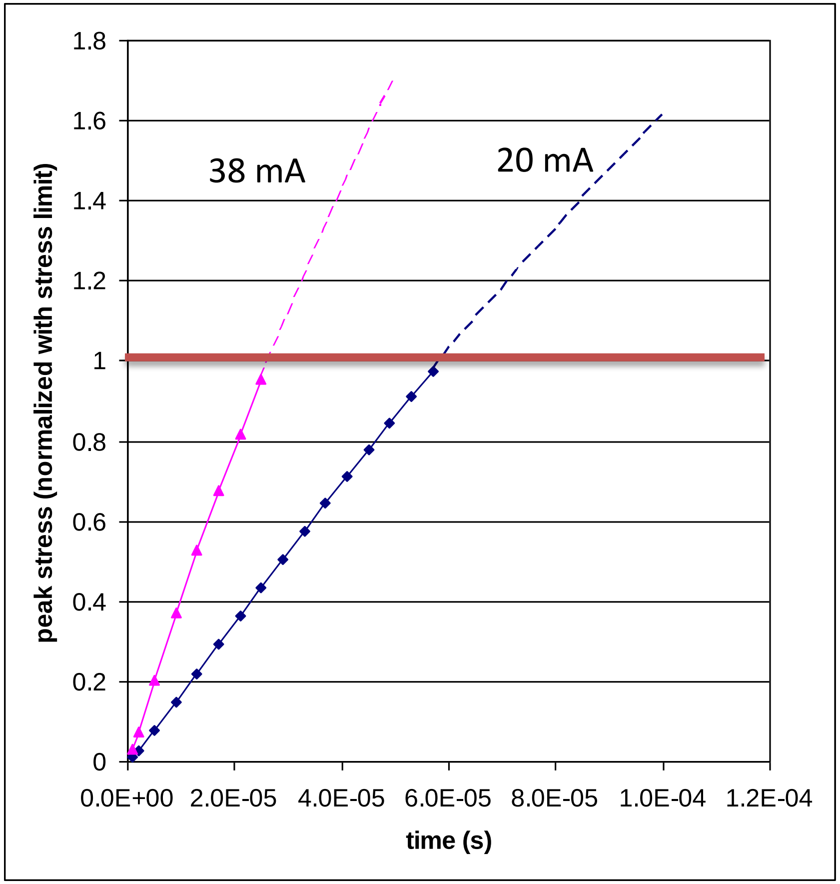
Thresholds or Criteria to protect structure (example)
Thermal: below melting temperature
Mechanical: below mechanical stress limit (ex 70 % of yield, 50 % of tensile strength..) due to thermal gradient, also including fatigue effect and fractural toughness

Mostly mechanical threshold comes much earlier
In this example the peak temperature is < 200 C when the peak stress reaches the mechanical threshold

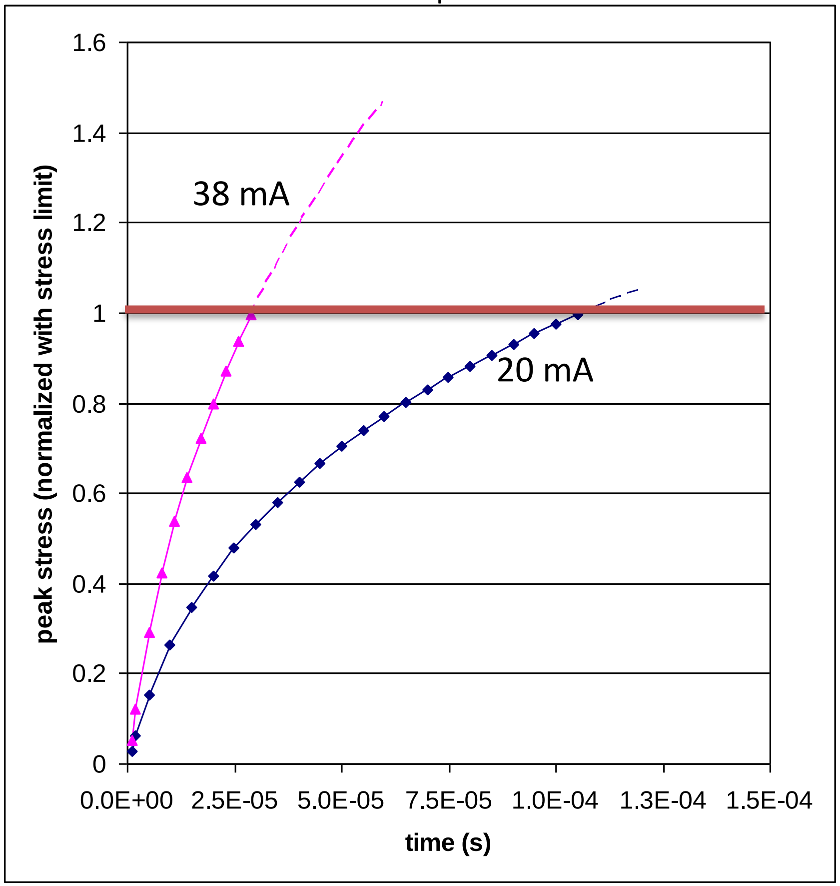
Usually MPS analysis is done with pretty conservative assumption

Ex. SNS DTL (2.5 MeV DTL 1 input energy, 7.5 MeV DTL output energy)
Time to reach the mechanical stress threshold

7.5 MeV, σ_r=4 mm



2.5 MeV, σ_r=4 mm



MPS delay from the fast interlock system

RF system
When a fault condition is detected in a unit of the system (arc, cavity field, forward power, reflected power, circulator power, klystron reflected power, etc.)
→It truncate or turn-off the RF in < 1-2 us.
At the same time it sends the signal to MPS system
→The signal passes through the MPS chains
→abort beam (usually source beam truncation from front-end)
} MPS delay

Abnormal beam from the Source
→Abnormal beam transportation
→Beam loss monitor detects the fault condition
At the same time it sends the signal to MPS system
→The signal passes through the MPS chains
→abort beam (usually source beam truncation from front-end)
} MPS delay

Typical MPS delay that uses fiber optic cables and passes through the chain: 15-30 us

Errant beam

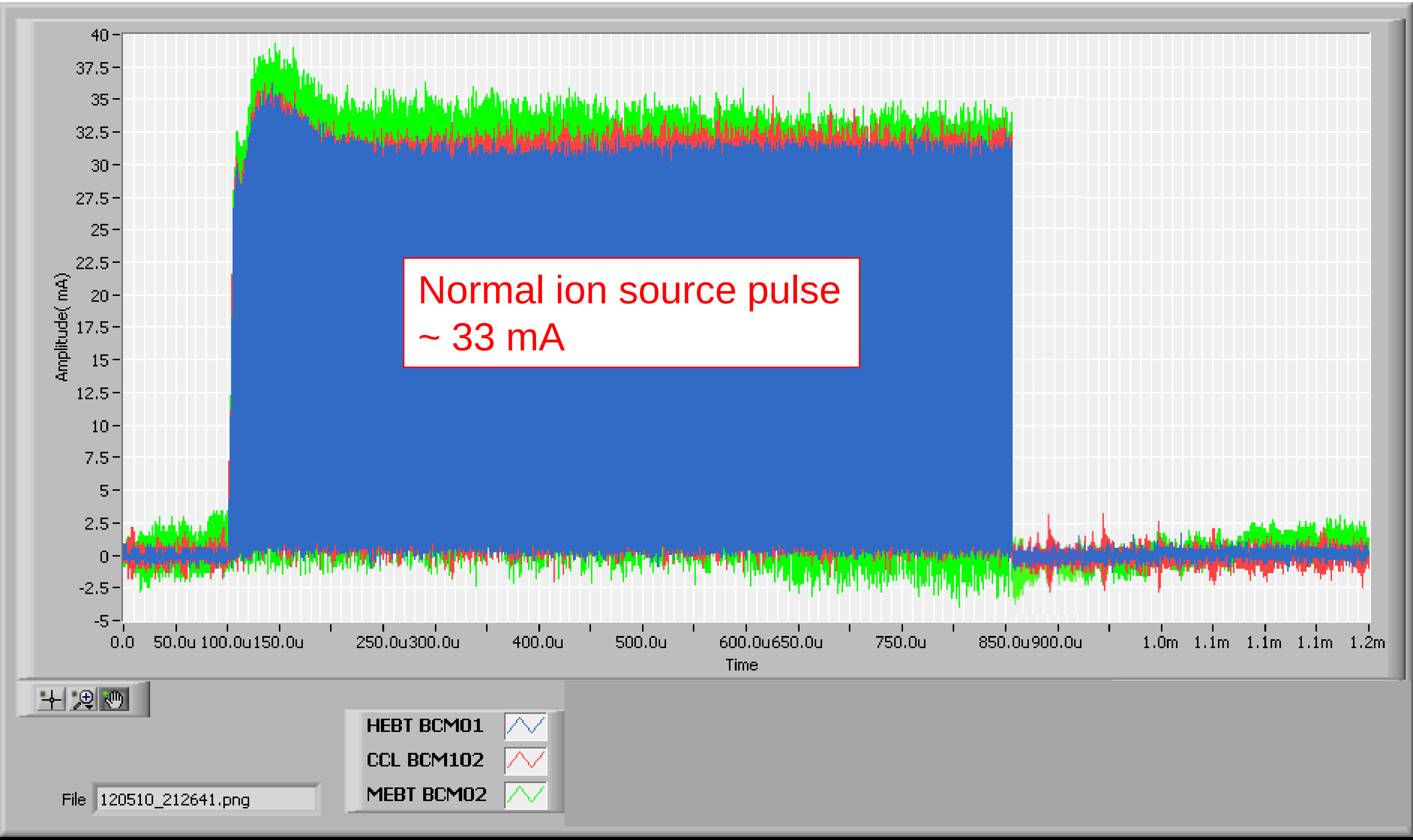
off-energy beam generated anywhere in the accelerator and transported to the downstream in a fault condition

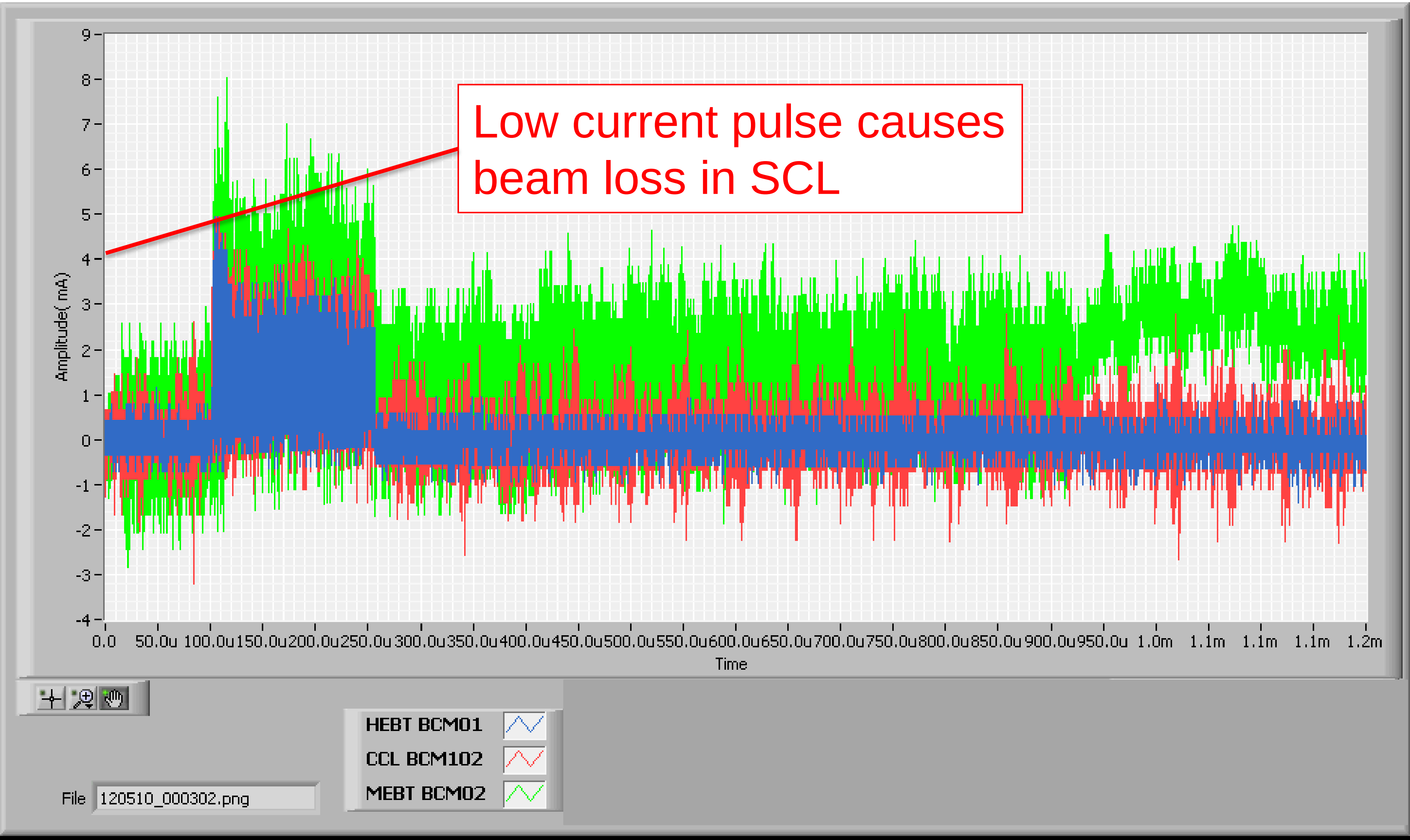
Since the errant beam is off-energy beam, it is mostly lost while transported through the linac, which results in beam trips caused by excessive beam loss.

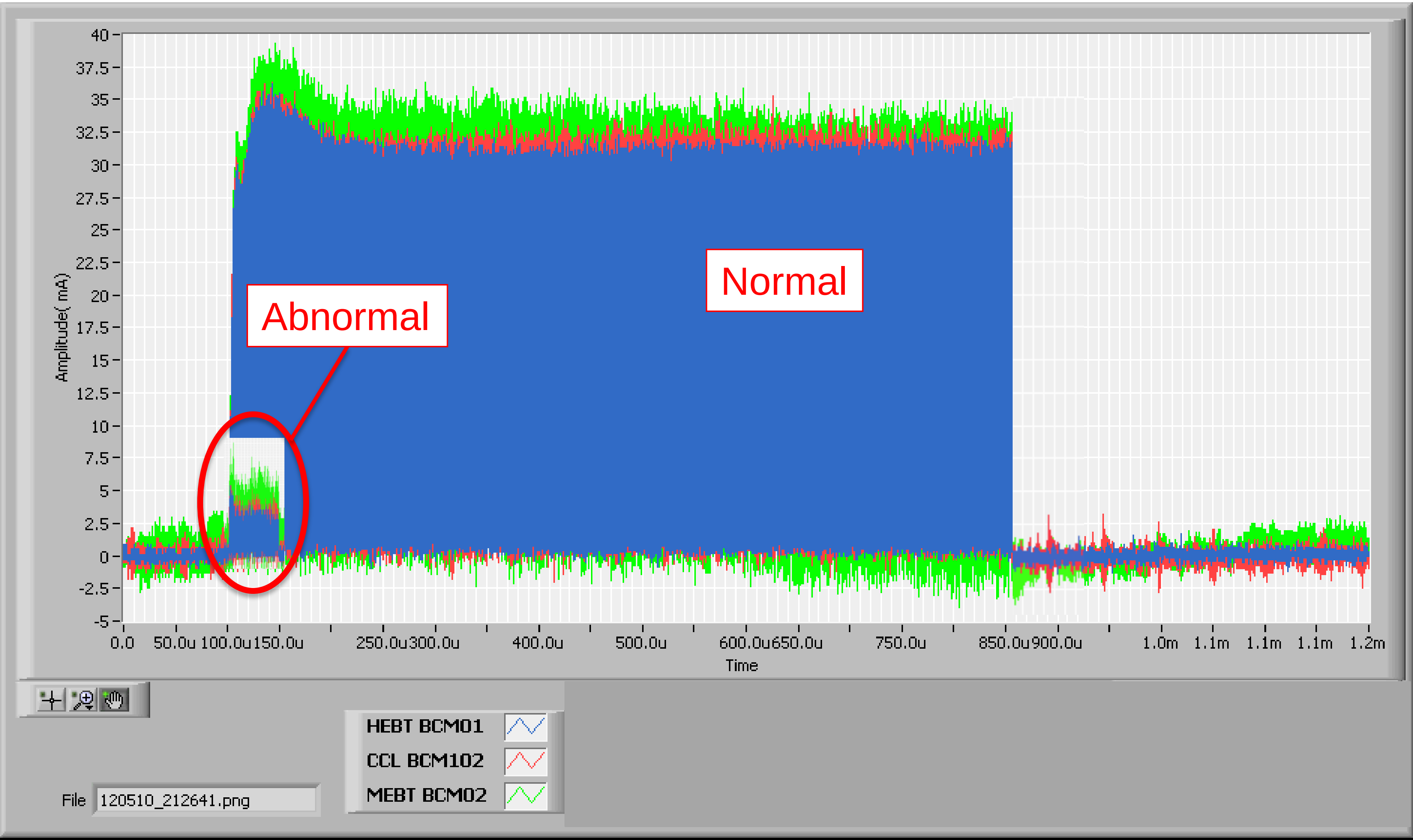
Errant beam hits cavity surface: desorbs gas or particulates and there's a non-zero chance for creating an environment for arcing/discharge

Dedicated MPS line for the fast interlock system could reduce the MPS delay down to 5-6 us.

Ion source/LEBT is one cause of errant beams

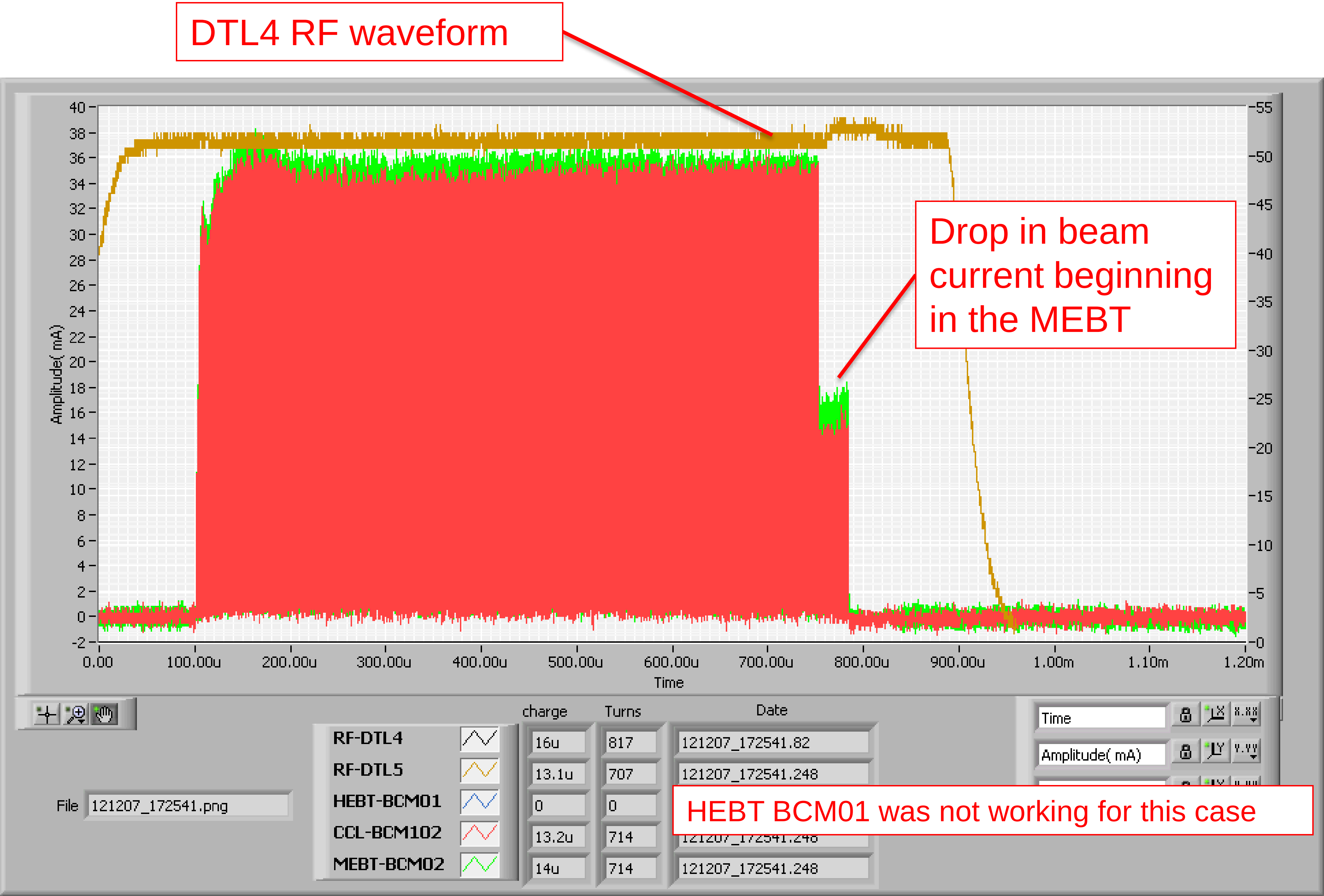



Low current pulse causes beam loss in SCL
Amplitude(mA)
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
0.0 50.0u 100.0u 150.0u 200.0u 250.0u 300.0u 350.0u 400.0u 450.0u 500.0u 550.0u 600.0u 650.0u 700.0u 750.0u 800.0u 850.0u 900.0u 950.0u 1.0m 1.1m 1.1m 1.1m 1.2m
Time
HEBT BCM01
CCL BCM102
MEBT BCM02
File 120510_000302.png

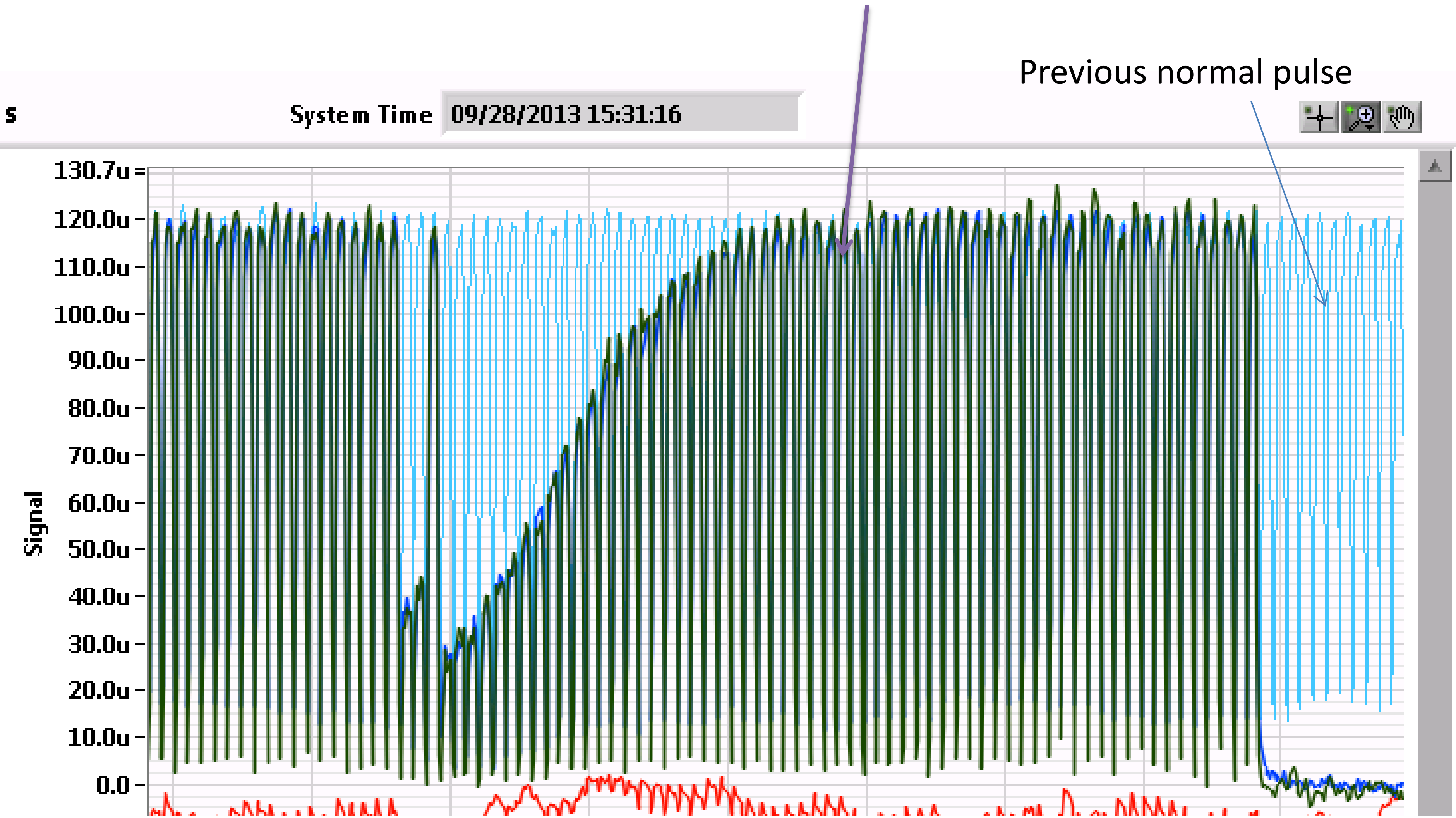


40
37.5
35
32.5
30
27.5
25
22.5
20
17.5
15
12.5
10
7.5
5
2.5
0
-2.5
-5
Amplitude(mA)
0.0
50.0u
100.0u
150.0u
250.0u
300.0u
400.0u
500.0u
600.0u
650.0u
750.0u
850.0u
900.0u
1.0m
1.1m
1.1m
1.1m
1.2m
Time
Normal
Abnormal
HEBT BCM01
CCL BCM102
MEBT BCM02
File
120510_212641.png

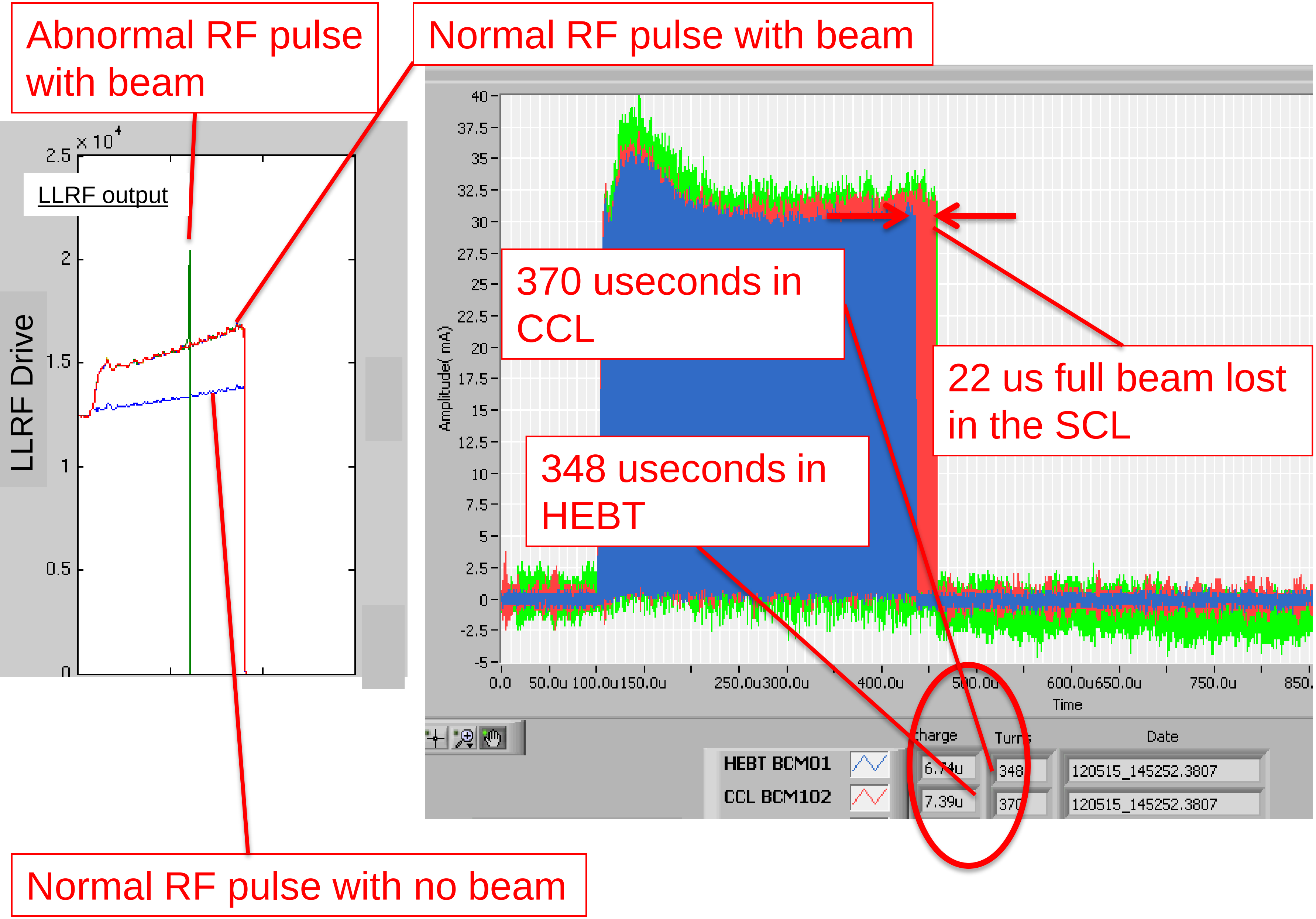
Ion source/LEBT errant beam example



Example: Odd beam from front end



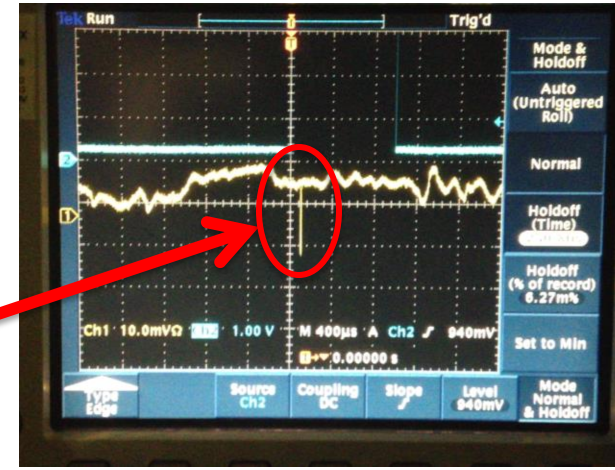
RF Truncation in NC structure

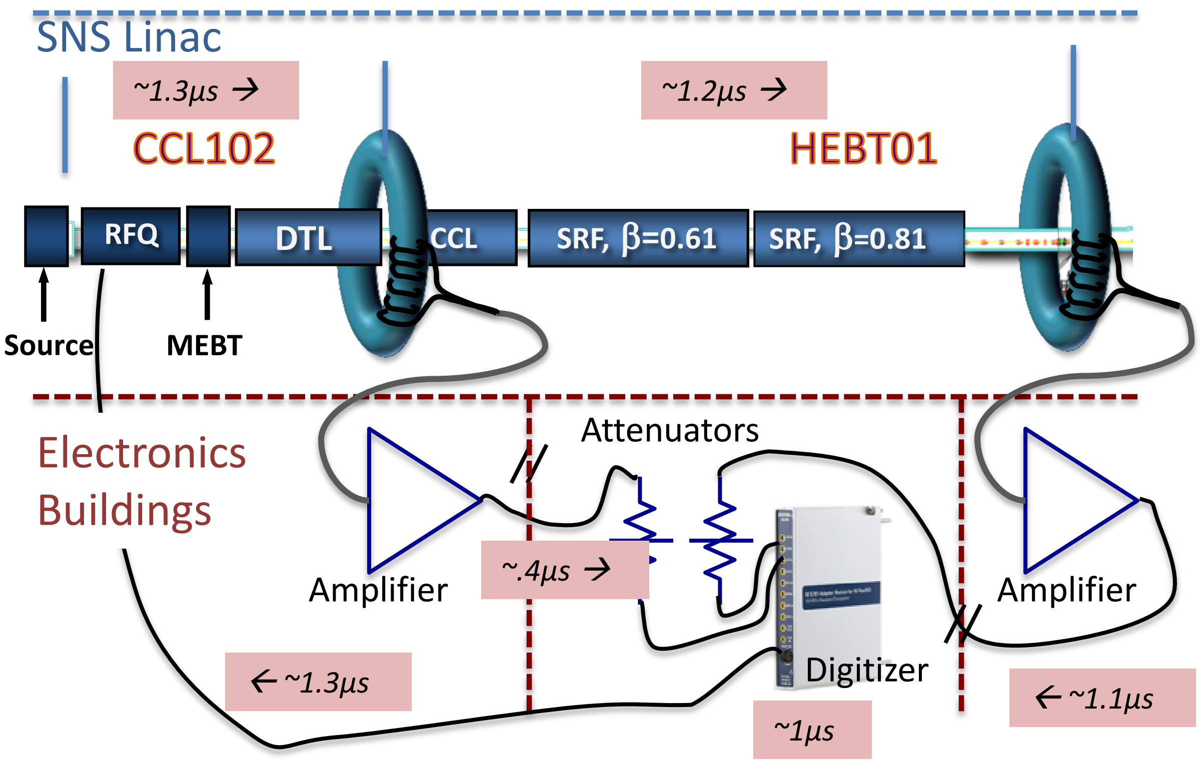


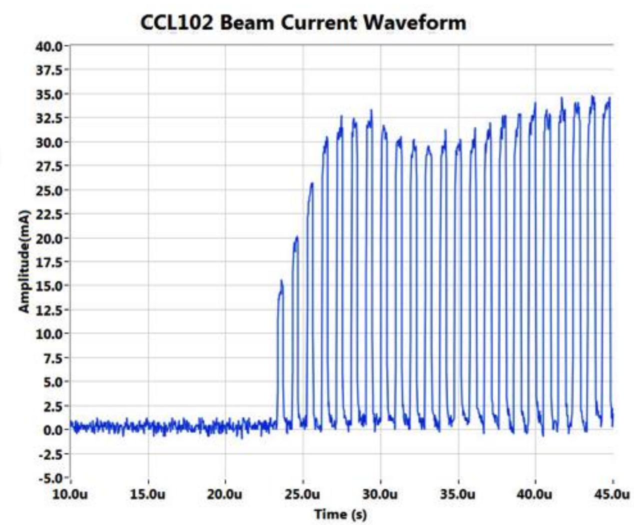
Layout of dedicated MPS

- Wideband current transformers:
  - 1 GHz with 1 ms droop time constant
  - Nearest one before and after SCL
  - Long cable lengths (500-1200ft)

HEBT BCM01 Waveform







Amplifiers and attenuators to counter induced noise on long cables

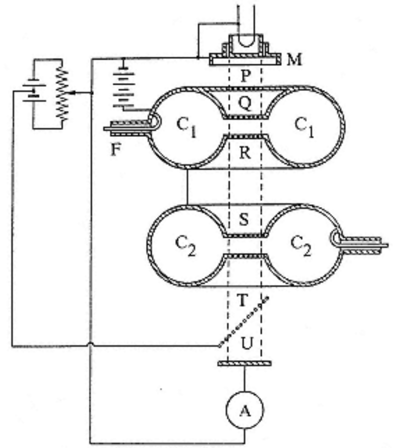
Understanding of the system is the most important aspect for the safe operation and equipment protection

- Let’s take an example with klystron for machine protection point of view.
  - how they are designed or fabricated
  - Klystron is a high power rf source where many accelerator related components are in place such as electron gun, beam acceleration, RF coupling, beam bunching, maintain high vacuum, DC high voltage, beam dump, RF window, cooling, beam focusing, etc.
- And then discuss about how to protect it.
- Since there are many analogies, this example will help expanding the idea for other equipment.

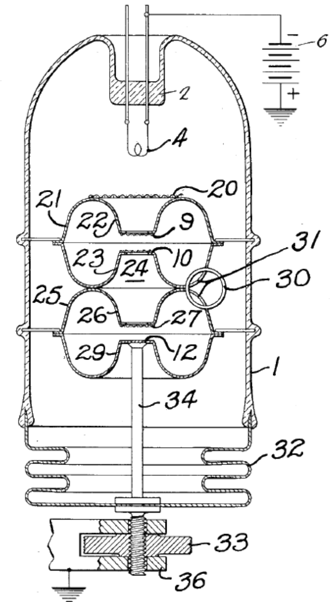
Klystron

Klystron

- History



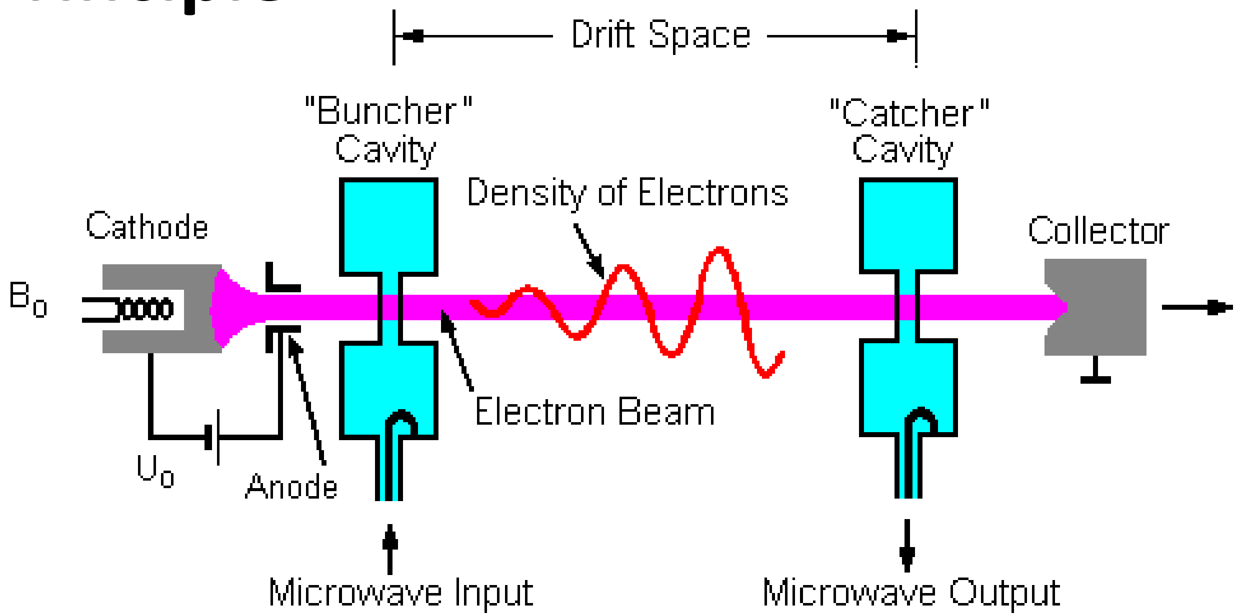
The klystron as first described by the Varian brothers. *J. appl. phys.* , 10 (1939), 324.



US patent No. 2242275, Russell H. Varian, May 20, 1941

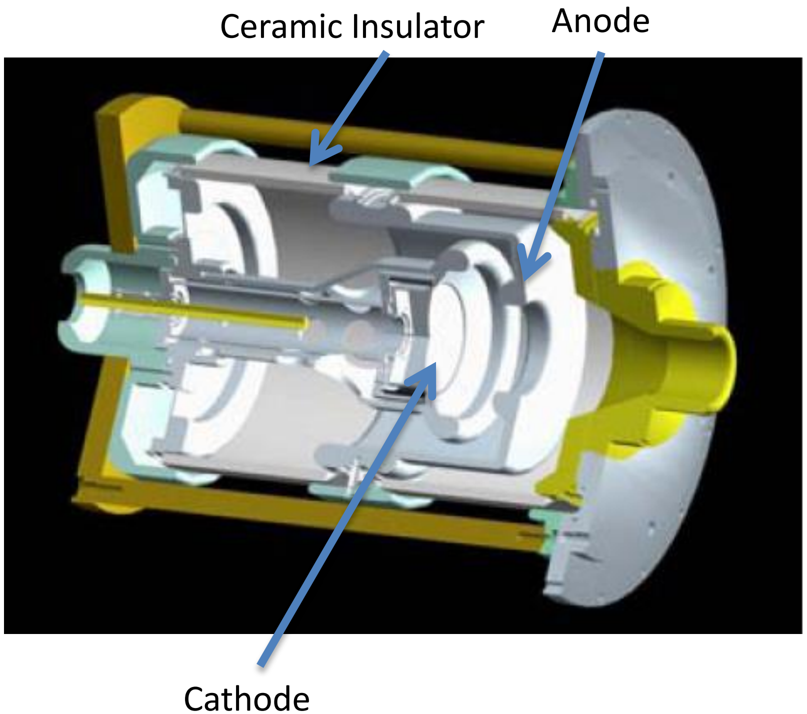
- A few hundred MHz ~ tens of GHz
- A few hundred W ~ several tens of MW
- Typical efficiency RF power/DC power: 50-70 %

Basic Principle



Klystron is a RF amplifier.
Electron beam starts from cathode and accelerated by the pulse or DC voltage.
(DC beam, not bunched yet)
Beam passes through the input (bunching) cavity that is excited by low power RF/microwave.
When beam passes through the input cavity, bunching process starts.
While drifting the beam tube, bunching develops.
When bunched electron beam reaches the output (or catcher) cavity where the bunching is maximum, bunched beam induces RF current in the output cavity.
The amplified RF is extracted through the output coupler.
Beam is dumped on collector.

Electron Gun



High voltage
400 kV (ex. S-band 80 MW tube)
130 kV (ex. 700-800 MHz, 5 MW tube)

→ DC Arcing/discharge

Dispenser cathode
-Operating temperature: 1100K-1500K depending on application
-Current density: A few tens A/cm^2
-Typically <2 A/cm^2 or much lower
-BaO, SrO, Al_2O_3 impregnated into porous tungsten + many artistic additions
-Very sensitive emission characteristics
-Need very careful treatment & handling
-Lifetime is function of temperature (or emission current density)

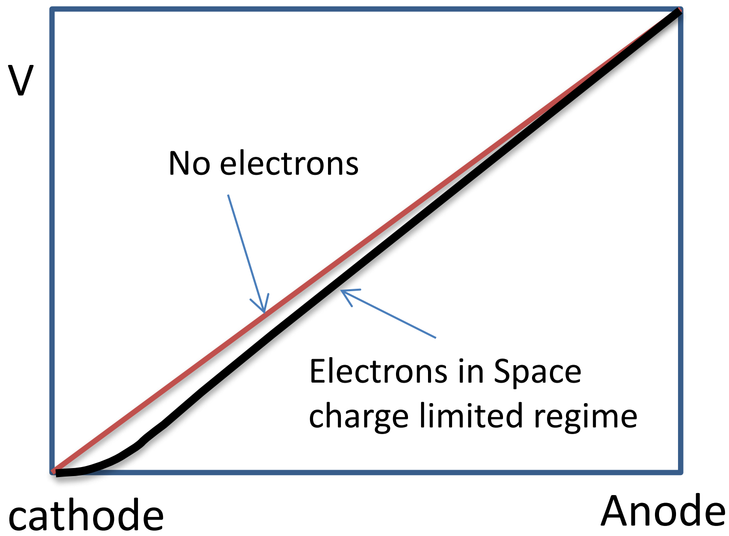
→

1. Failure of emission: poisoning or depletion of oxide or impregnant.
2. Failure of heating mechanism: heater short or open circuit.

Have to keep good vacuum, clean condition, & adequate cathode temperature

Cathode

E-guns are mostly running in the space charge limited regime



Space charge limited regime: when electron emission density is large enough at a certain cathode-anode voltage, electric field at the cathode surface becomes zero.
And emission current vs. voltage→ Child-Law:

$I=PV^{3/2}$, P: Perveance (geometric factor)

If temperature is not high enough (if some area of the cathode does not reach the space charge limited condition), the emission characteristic becomes very sensitive with temperature (temperature limited regime) thus beam quality and optics change.

If temperature is too high, cathode life time gets short.

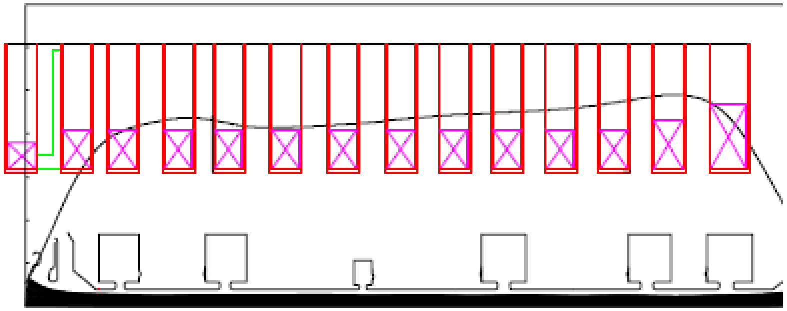
Magnetic field

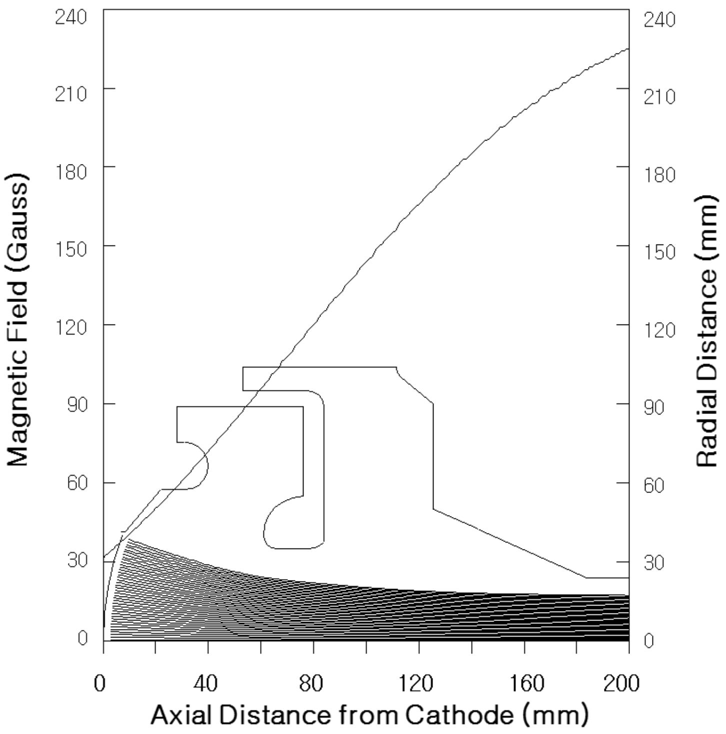
Cathode is immerged in magnetic field

Confined flow focusing

Failure in magnet or magnet power supply

Running at a wrong field → could be catastrophic





Collector

Designed to have fairly uniform power density

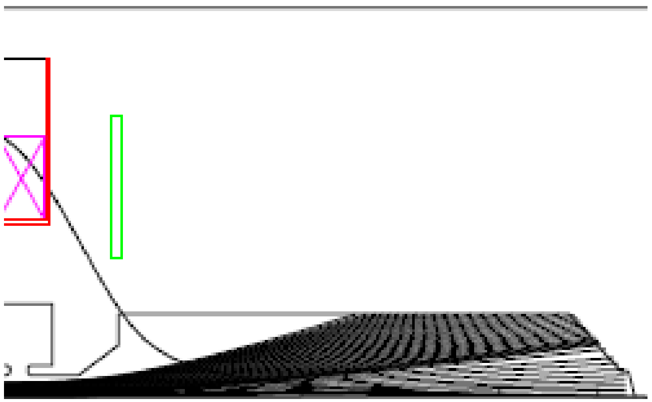
High power klystrons

ex 1.3 MW CW: ~2 MW DC beam dump

cooling failure →catastrophic

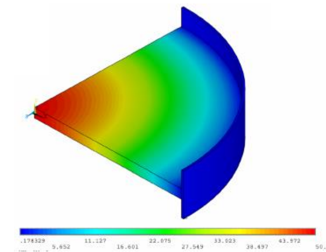
vacuum failure → catastrophic

: vacuum firing (minimal outgassing at high power beam bombardment)



Output coupling and Window

Typically iris or loop coupling



Window:

One of the limiting factors for peak and average power.

Adequate power handling: low loss RF dielectric material.

Good match over the frequency band of the klystron.

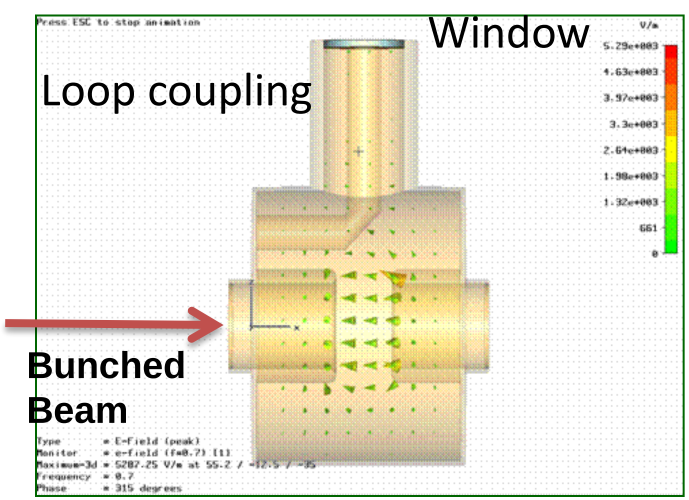
Trapped mode near operating frequency:

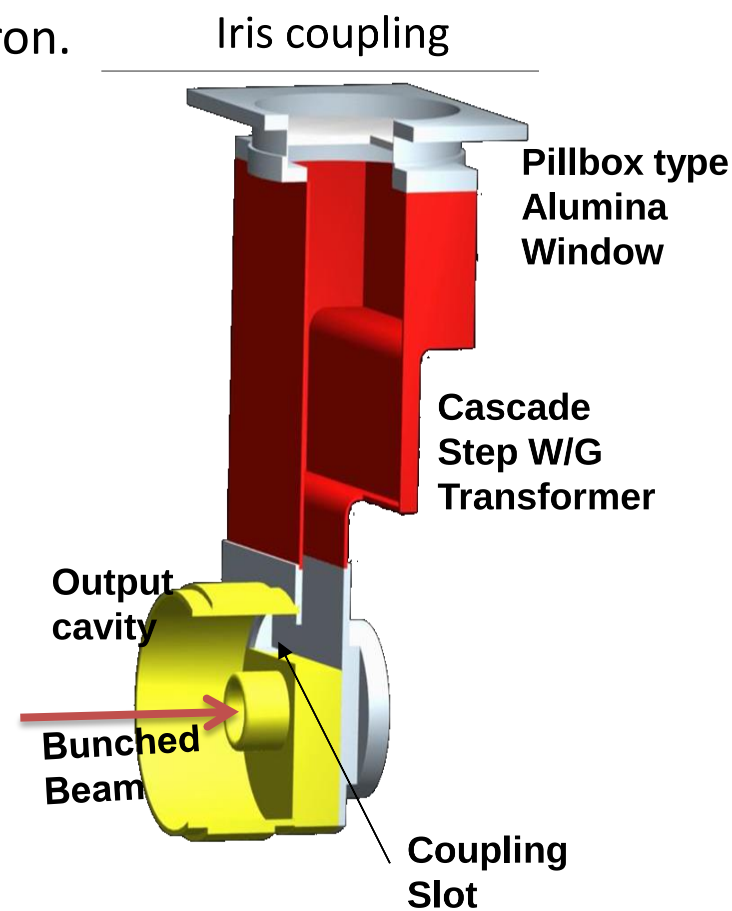
electric breakdown, instability of RF

Main danger in high peak power window:

Multipacting

high VSWR



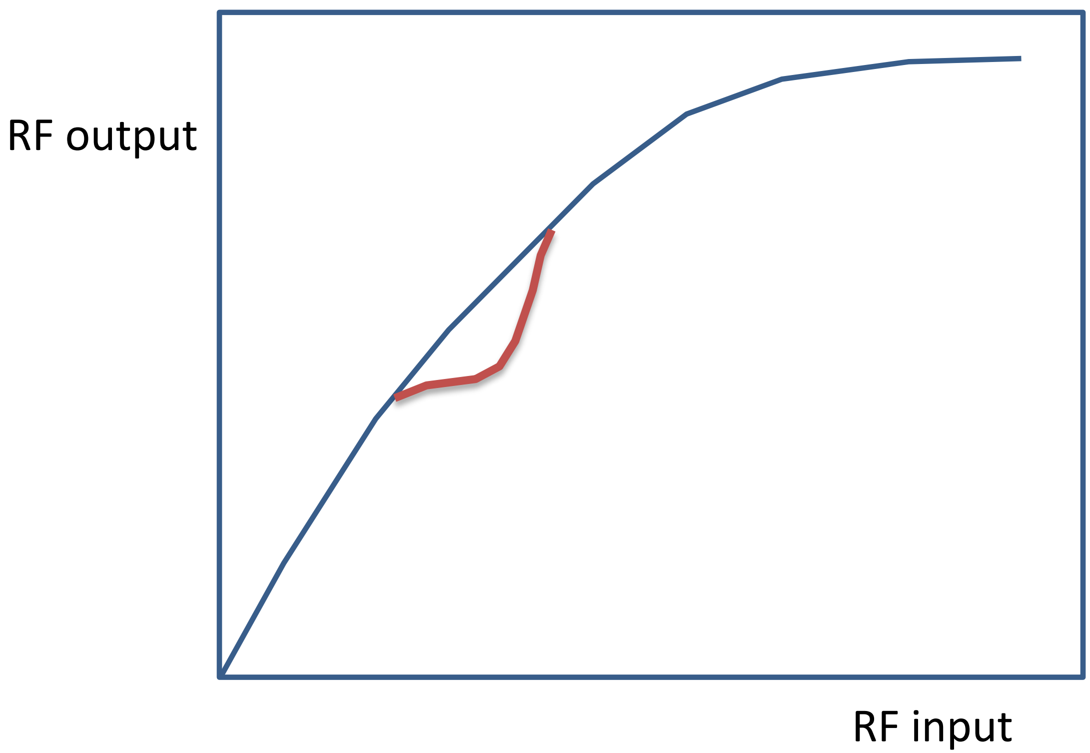


Multipacting on cavities in klystrons

As mentioned in the previous page, MP is possible in windows and output circuit.

In addition, the cavities in the klystron is, of course, the possible MP region.

It could be dangerous or could result in instability.



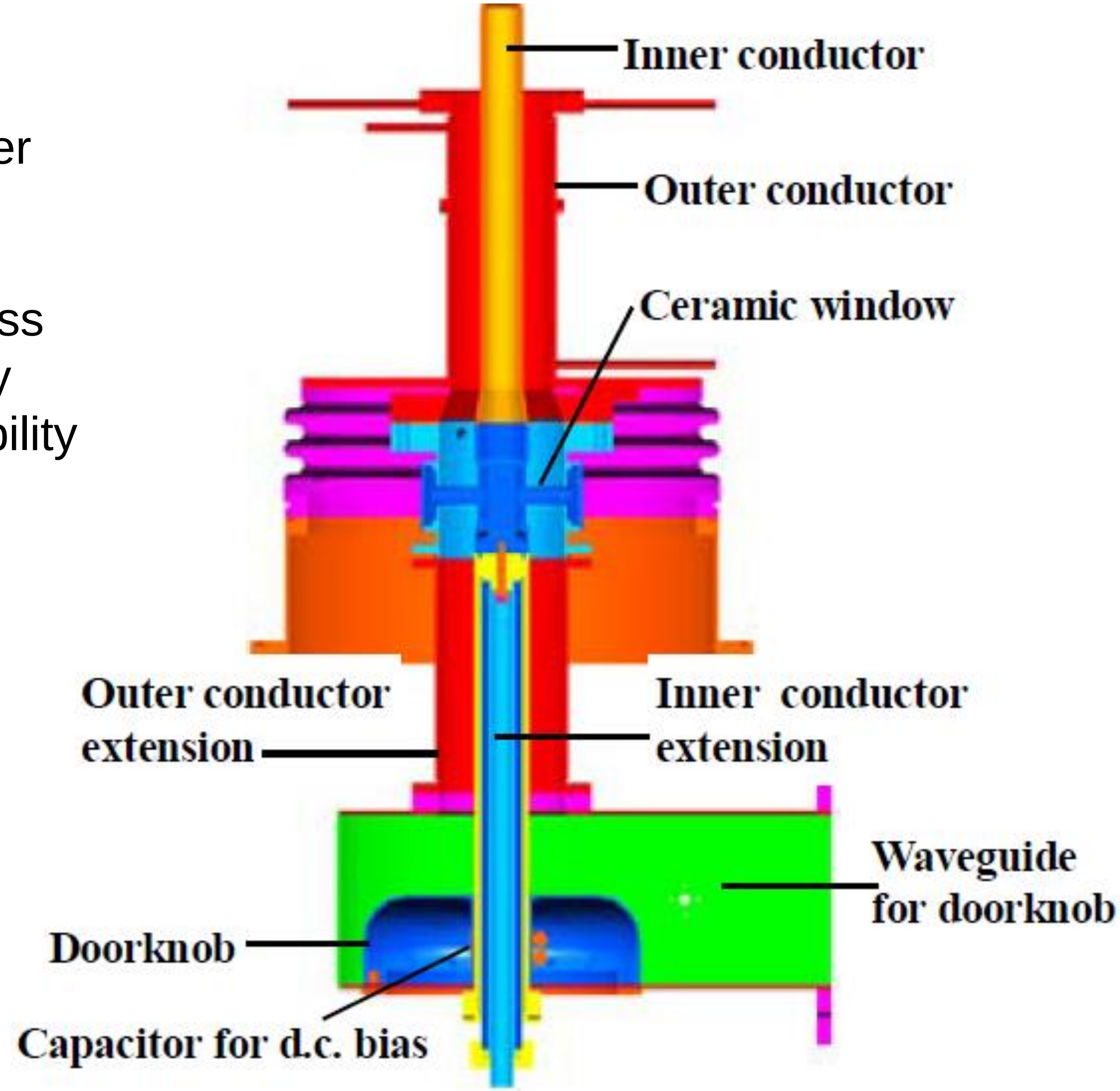
Couplers

Power Coupler

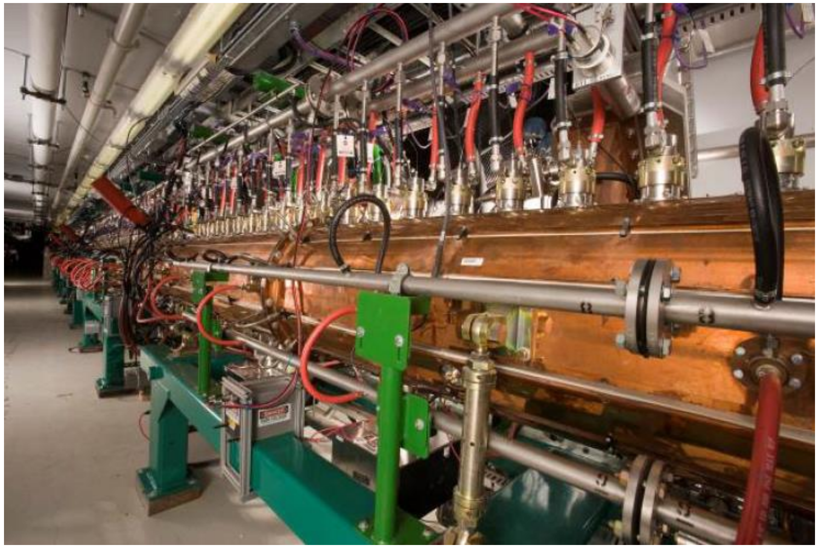
Function: Deliver RF power
Coupling → Q_{ex}

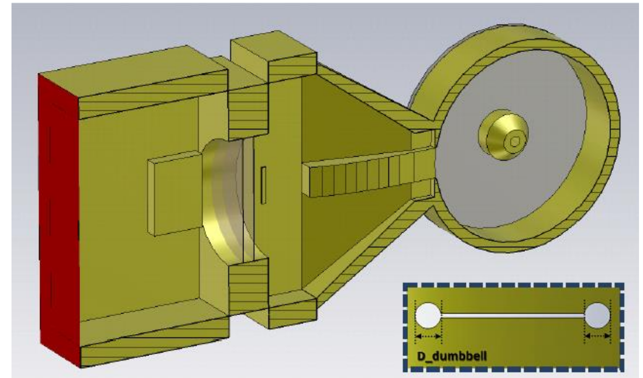
Concerns: Transmission loss
Thermal stability
Mechanical stability
Simplicity
Reliability
Cost
Multipacting

Frequency
Power needed
Coupling
Types
Cooling
Window

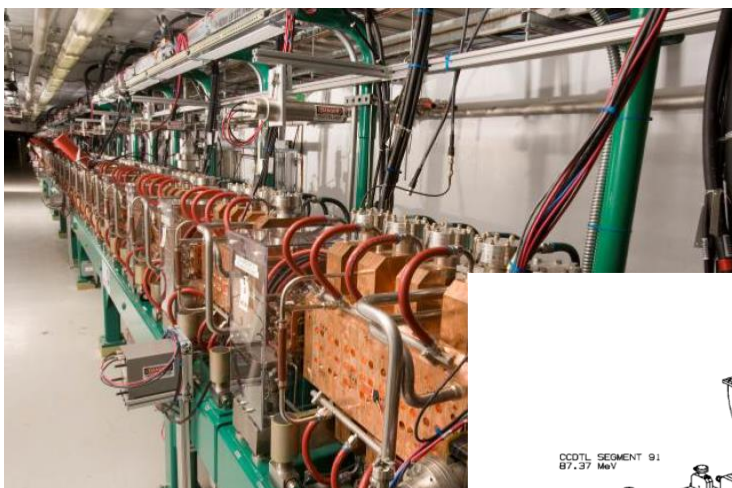


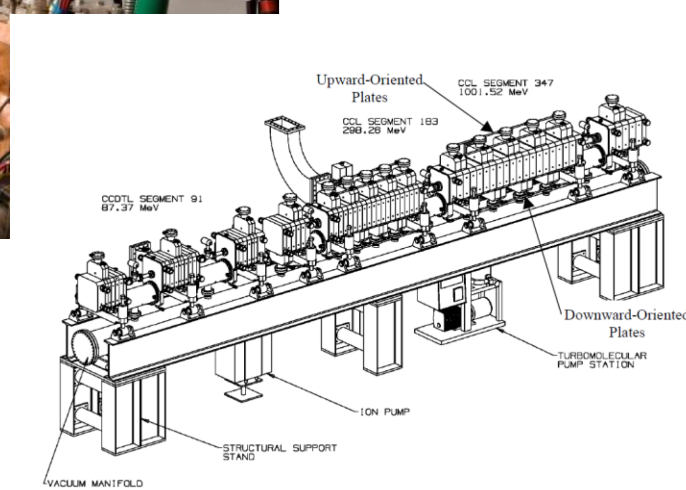
SNS Fundamental Power Coupler

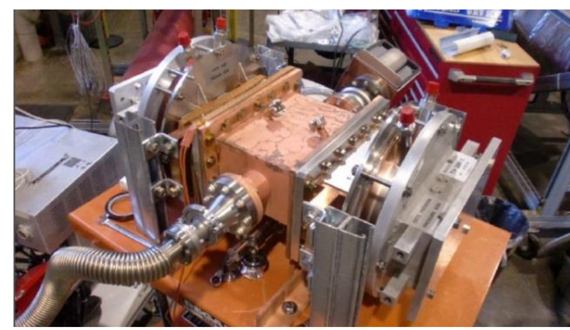




DTL window and coupler



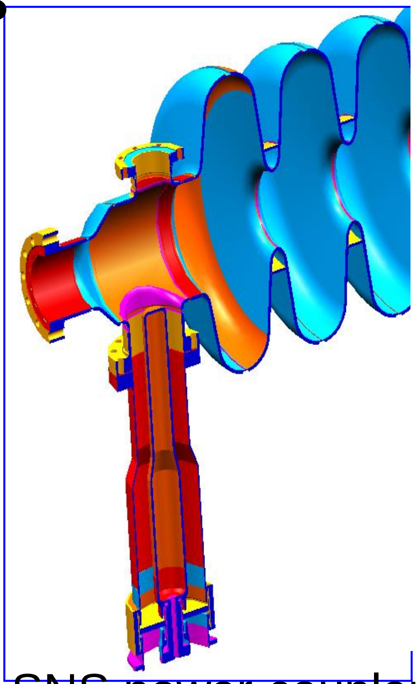




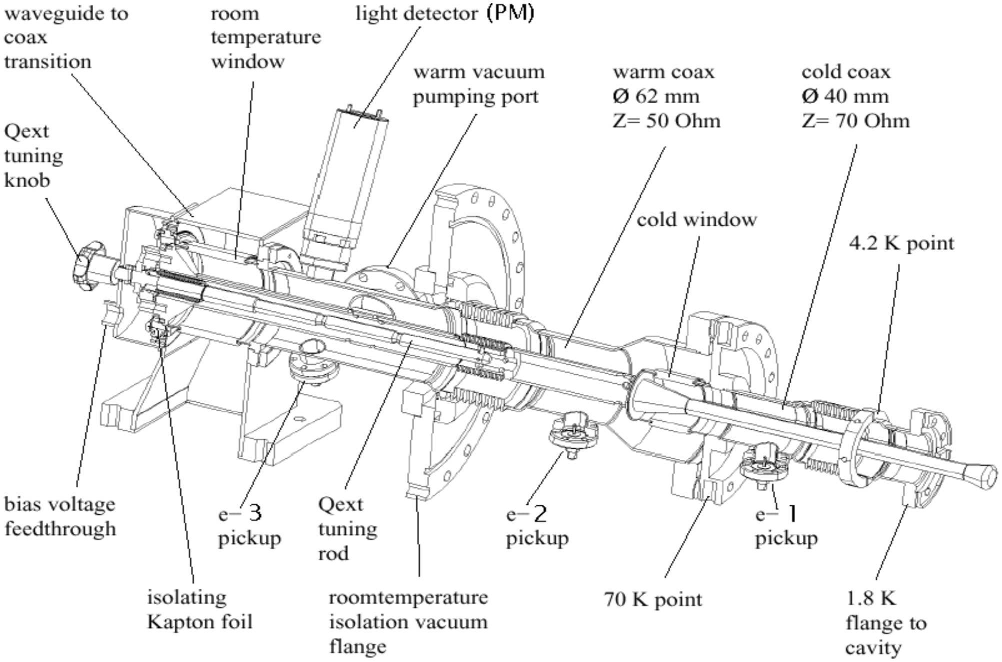
CCL window and coupler

Power couplers
For SRF cavities

Coaxial

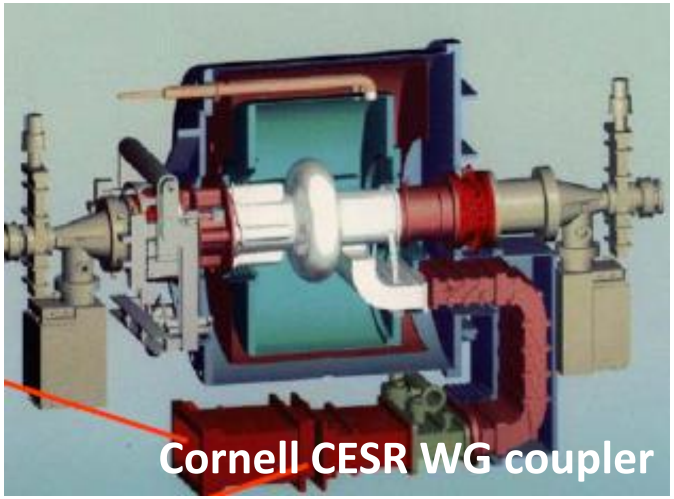


SNS power coupler

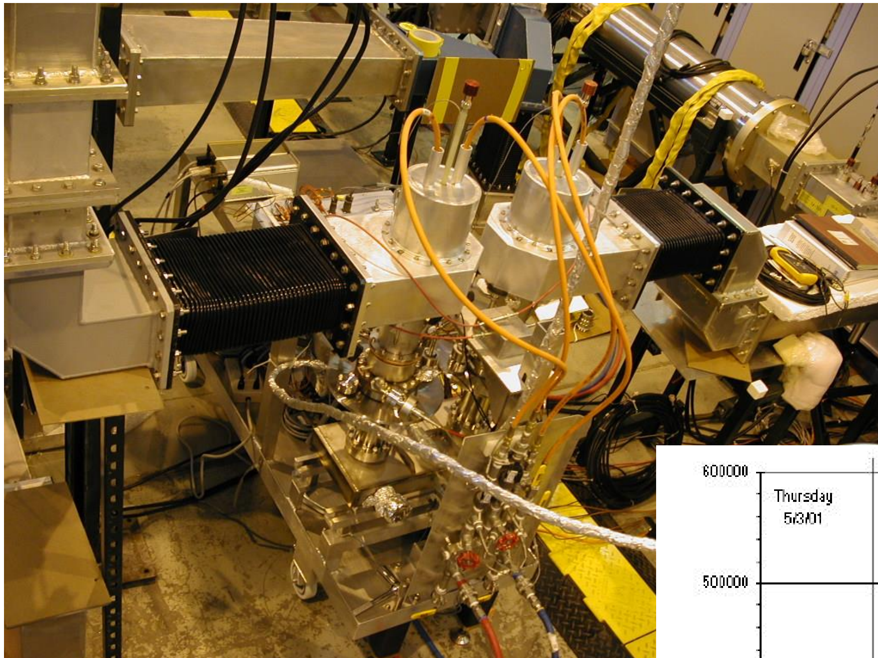


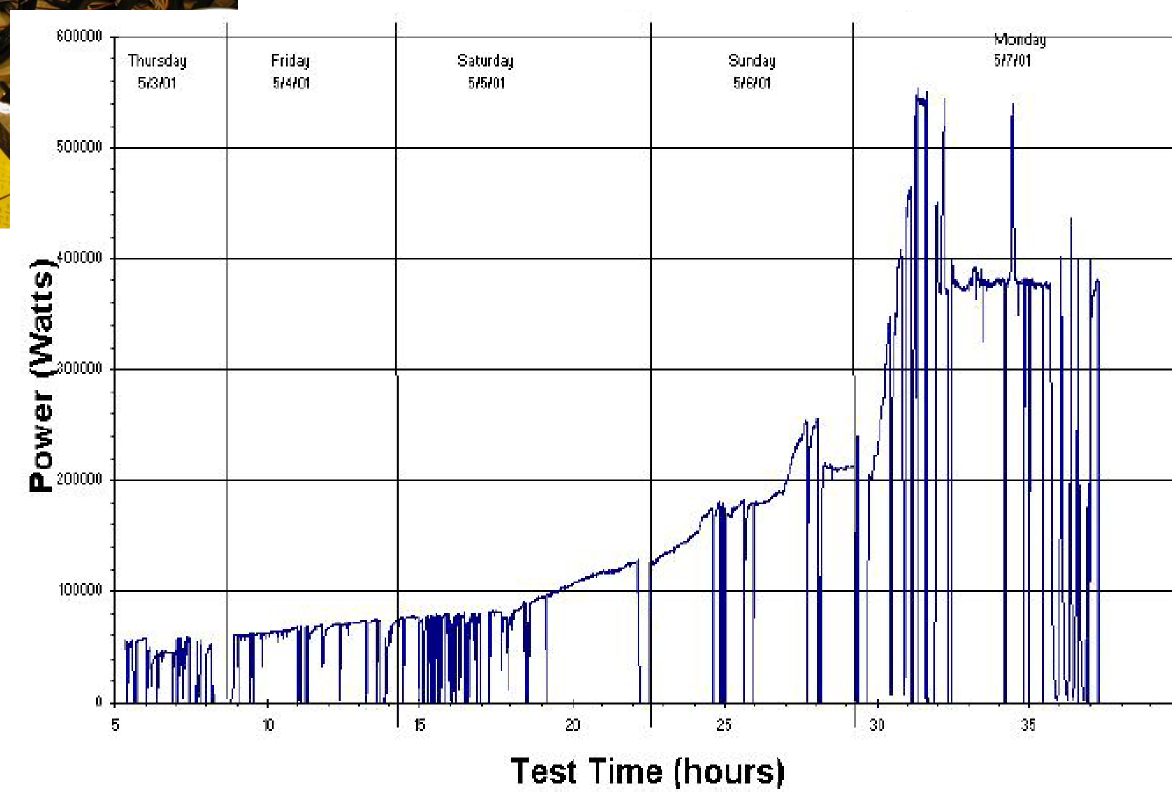
TTF3 coupler (ILC)

Waveguide

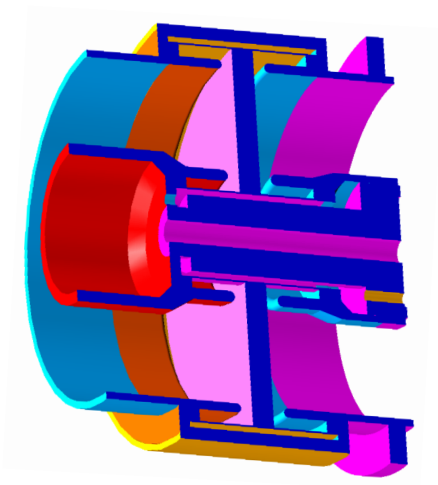


Coupler conditioning

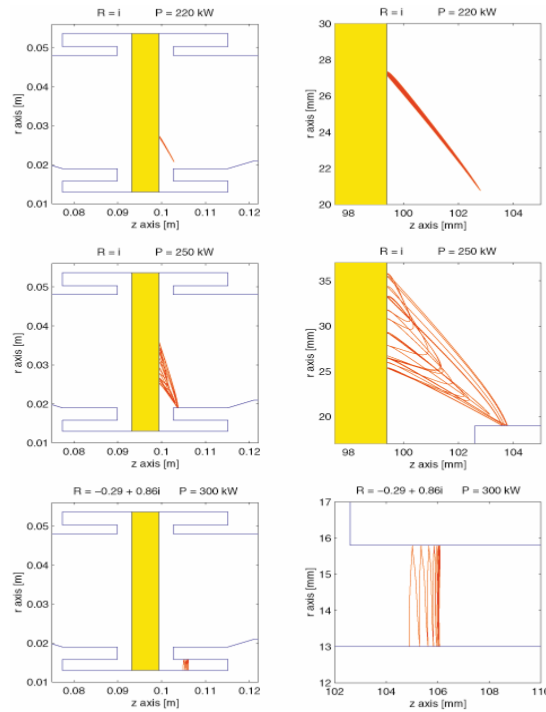


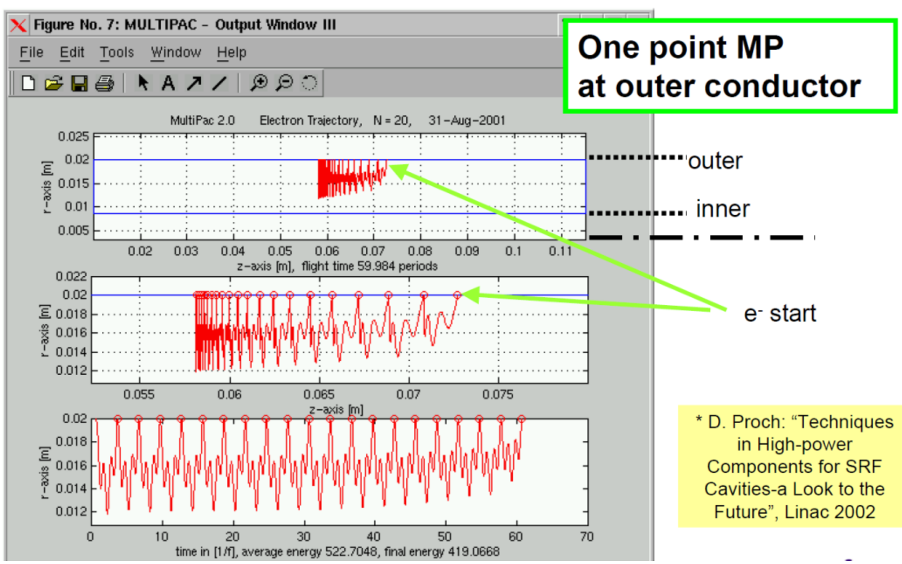


Multipacting simulations

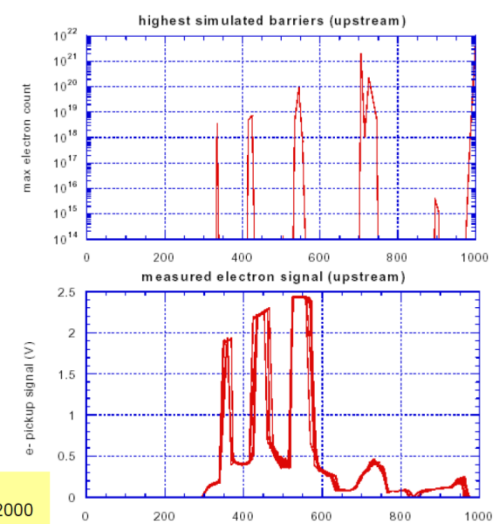


SNS Choke window





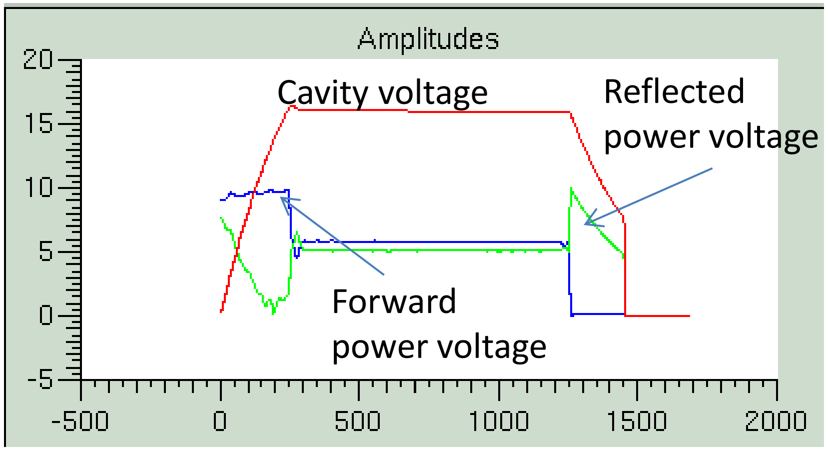
* D. Proch: "Techniques in High-power Components for SRF Cavities-a Look to the Future", Linac 2002



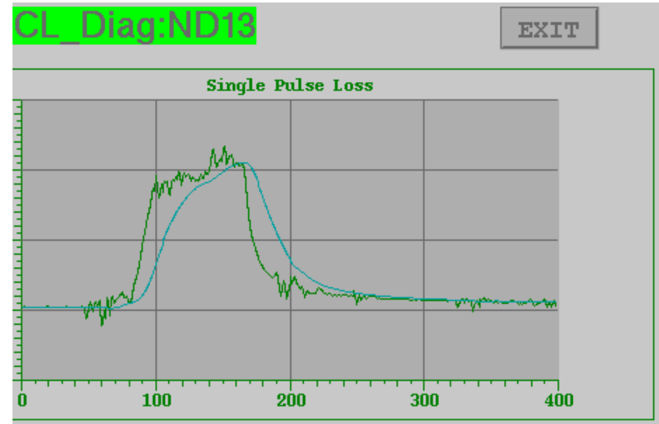
* G. Devanz, CEA Saclay, SFP Meeting in Roscoff in 2000

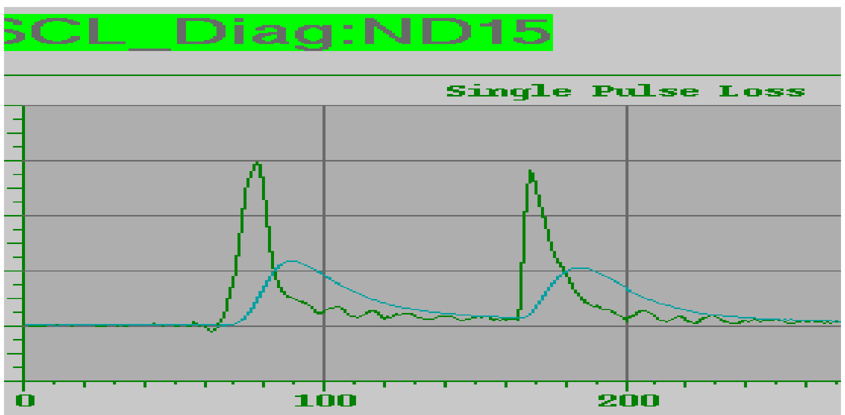
- 1.3 GHz
- 50 Ohms
- 61.6 mm

SNS MP examples: e-probe, radiation

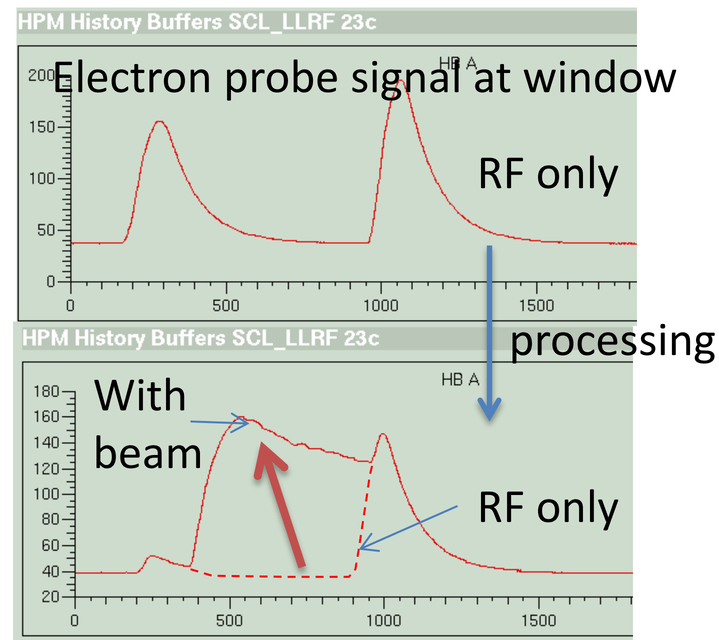


ex. Radiation detector signal
Mostly from field emission





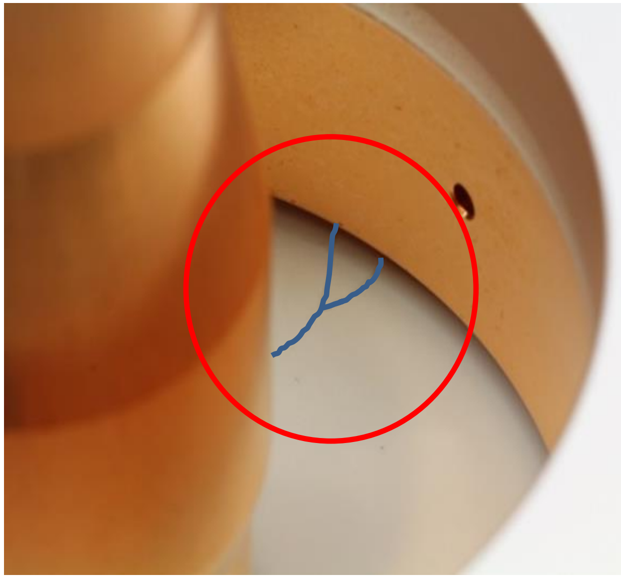
Radiation detector signal
ex. Mostly from multipacting around power coupler



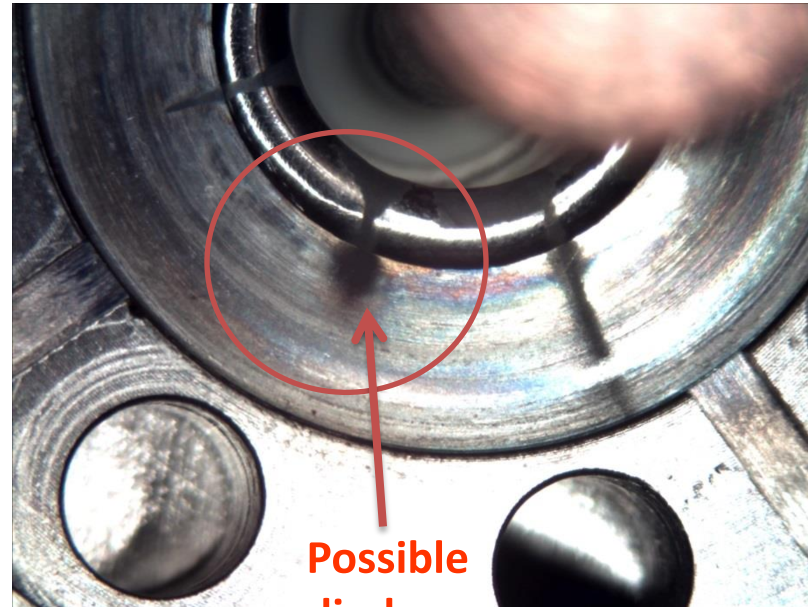
Processing in a mild condition
and DC biasing help.

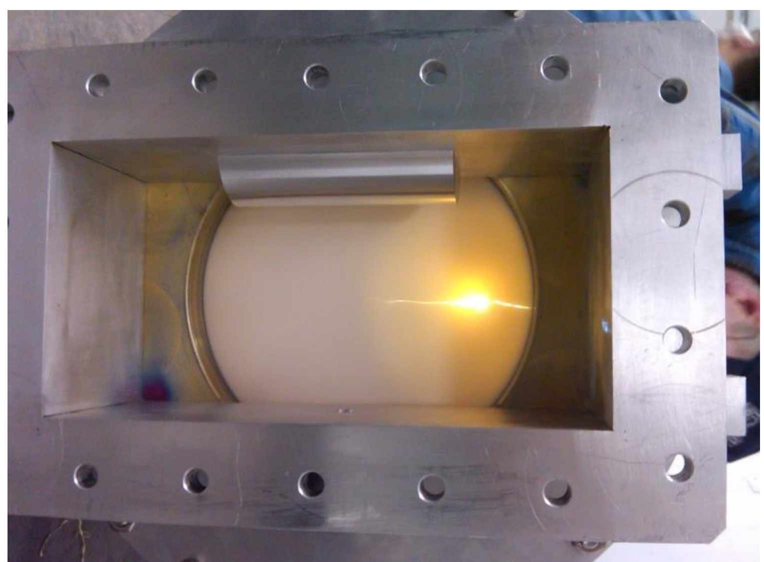
With beam on, the MP condition at the flattop

Arcing on the window: vacuum leak



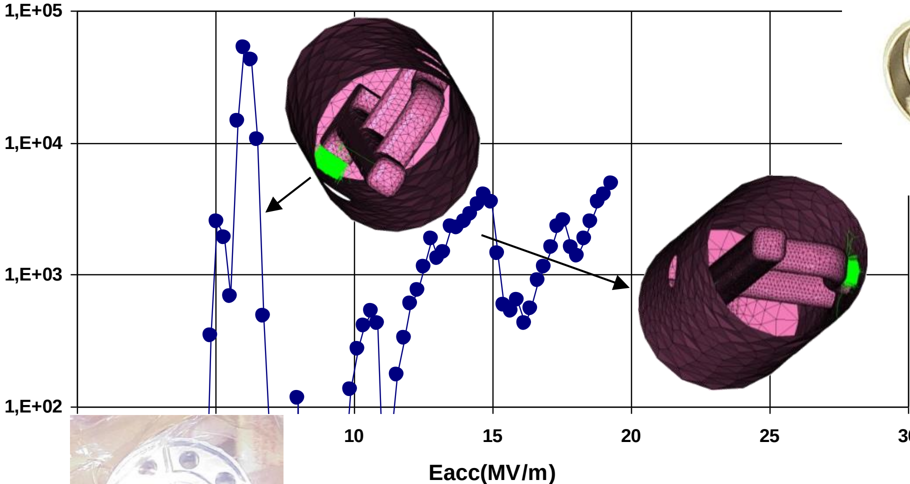
550 kW, 805 MHz
Coaxial window
crack

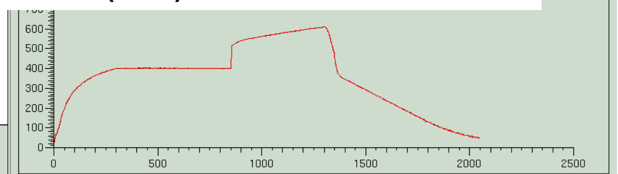


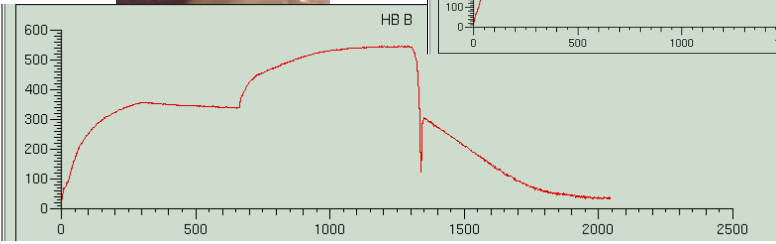


5 MW, 805 MHz
window failure

MP in the notch type HOM coupler







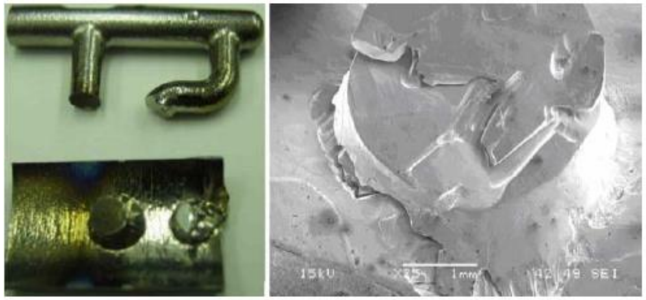
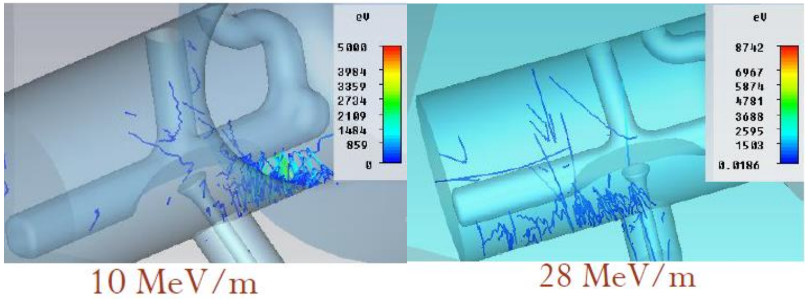
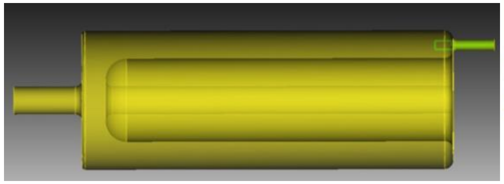


Figure 3: Curved leg of the HOM F-probe fractured from HOM can.

T. Khabiboulline et al, PAC07



Simulation for ILC, FNAL



56MHz QWR for RHIC
SLAC-PUB-15753

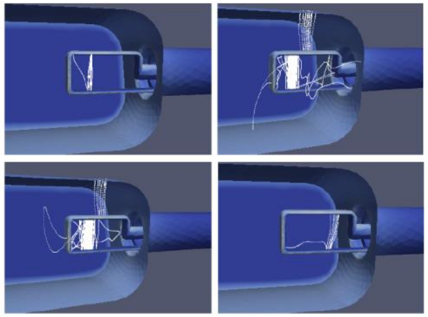


Figure 7: Resonant particle trajectories at the HOM coupler. Top-left: Epeak = 72 kV/m; Top-right: Epeak = 93 kV/m; Bottom-right: Epeak = 102 kV/m; Bottom-left: Epeak = 344 kV/m.

Again in order to avoid MP

One can carefully design the RF geometry to avoid MP.
If the surface is not clean enough, still there are chances
especially if geometry is complex. Analysis may not cover all details.
Also if geometry is complex, cleaning would be very difficult.

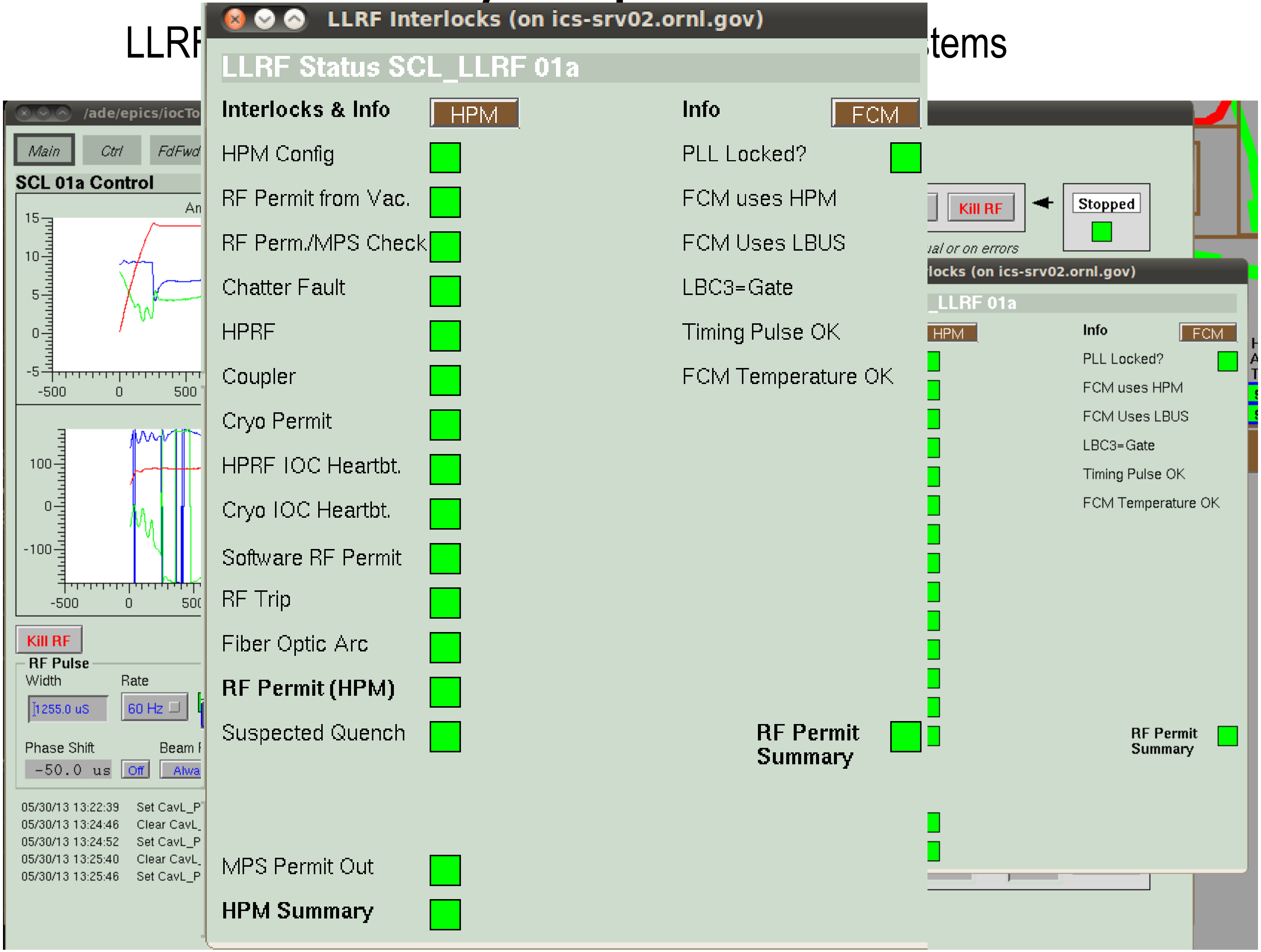
Usually MP could be processed out by careful conditioning/processing.
But not always. If there's not enough diagnostics (blind conditioning), arcing or catastrophic failure could be followed.

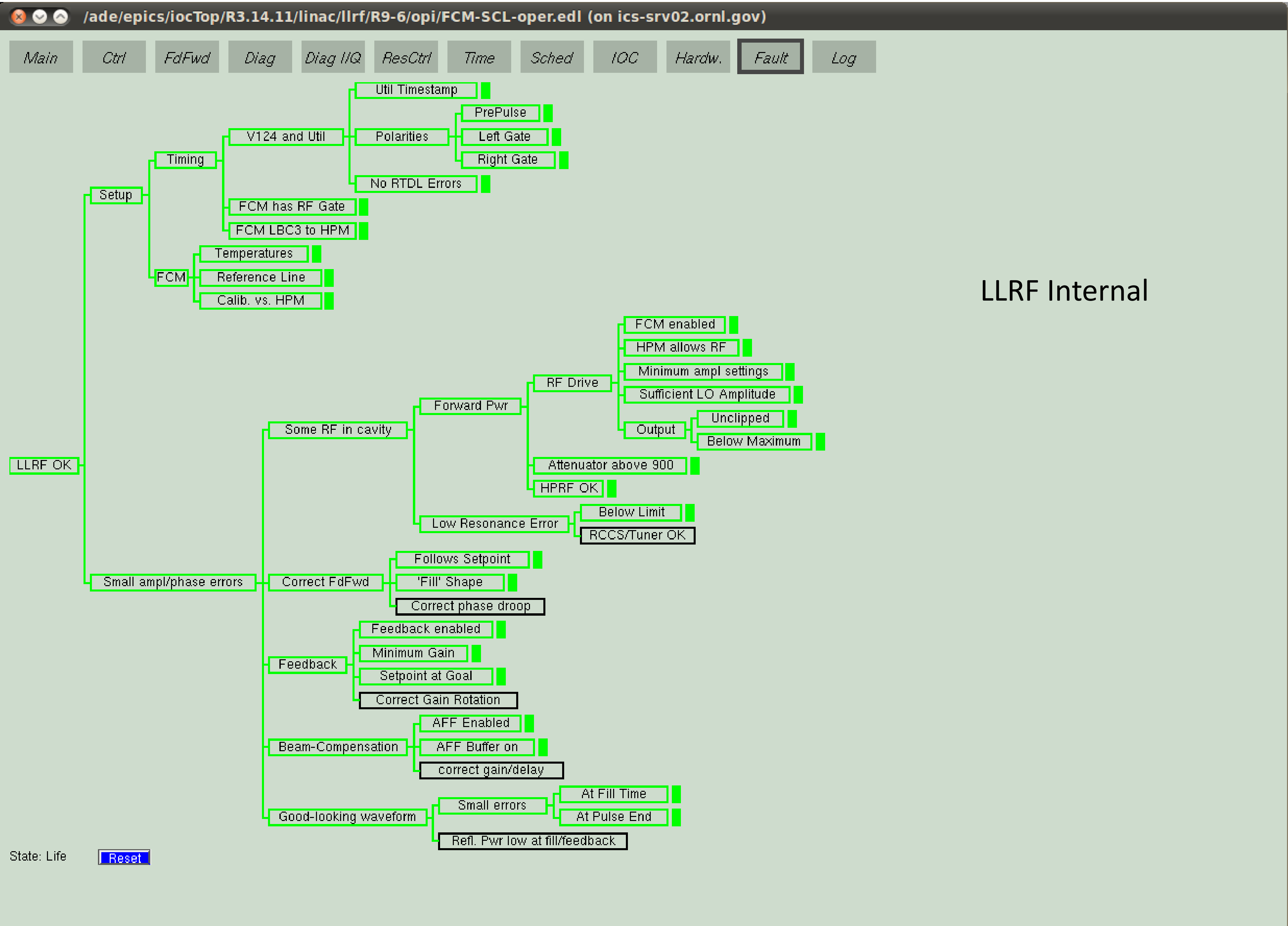
When arc detector detects an arc or e-probe shows abnormal signals, careful conditioning would be required (a single arc could damage surface).
Conditioning at short pulse, low duty helps (sometimes very time consuming).
Initial conditioning without DC biasing is preferable if possible.

SNS Examples

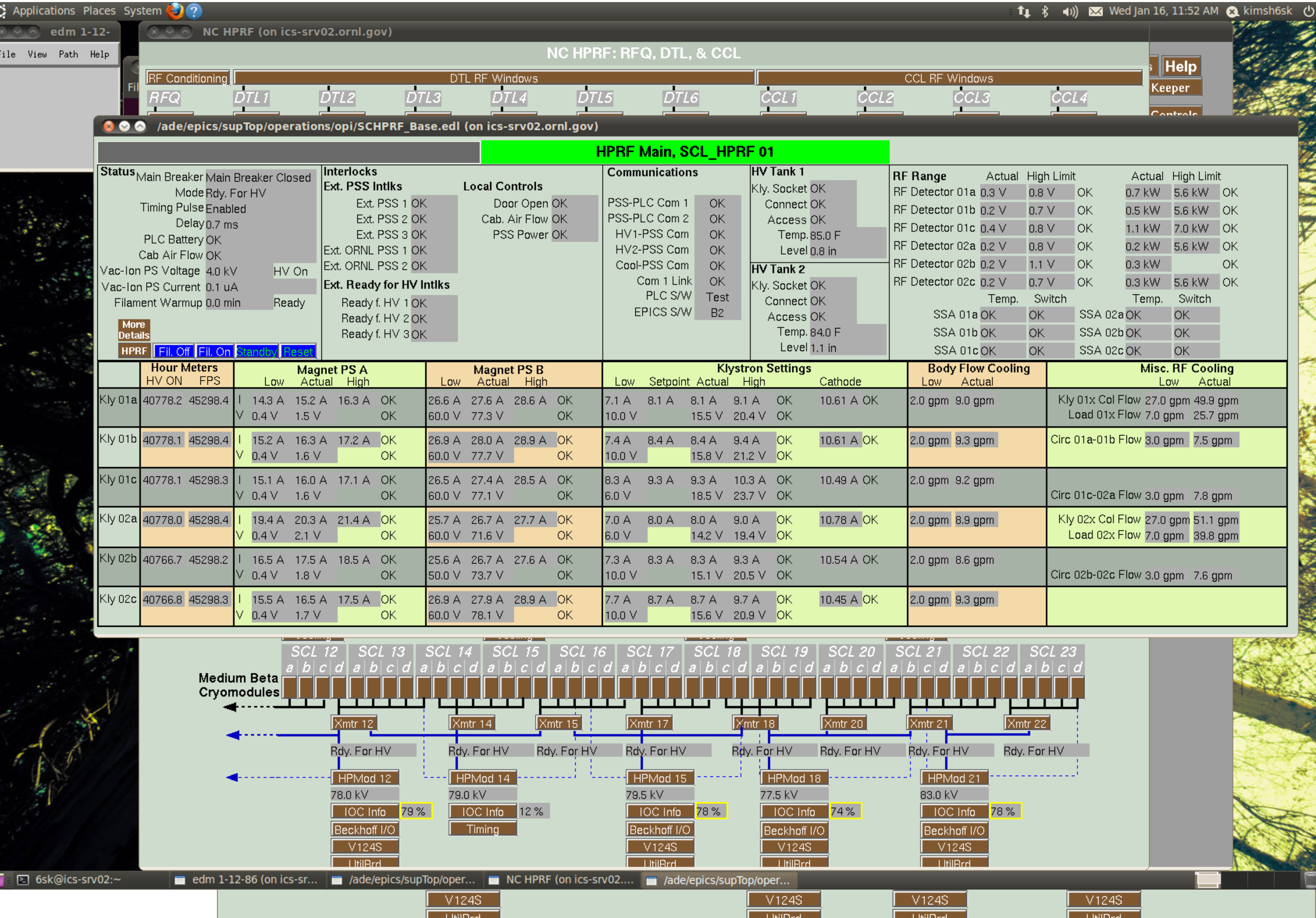
Interlocks/RF permission

LLRF … tems

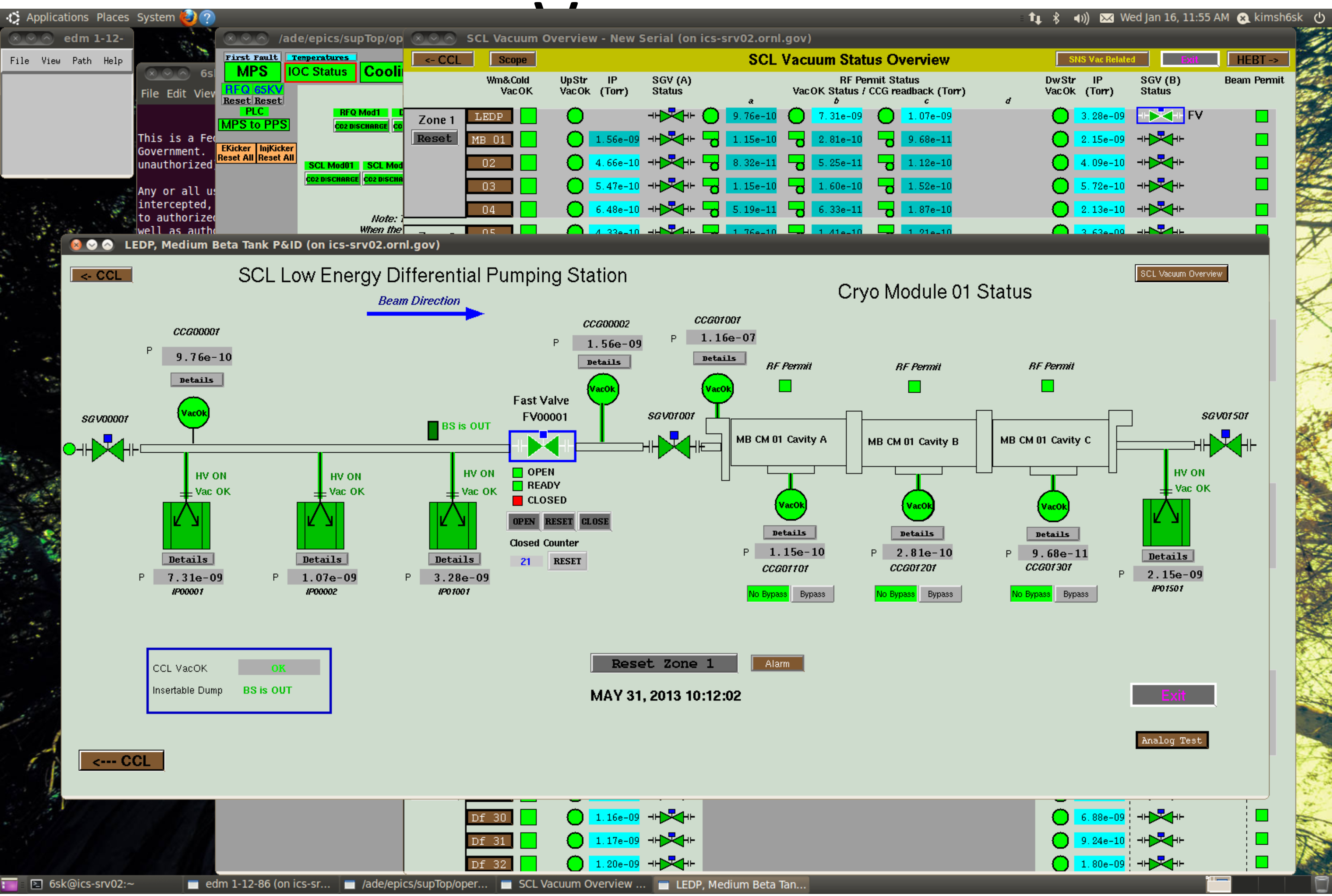


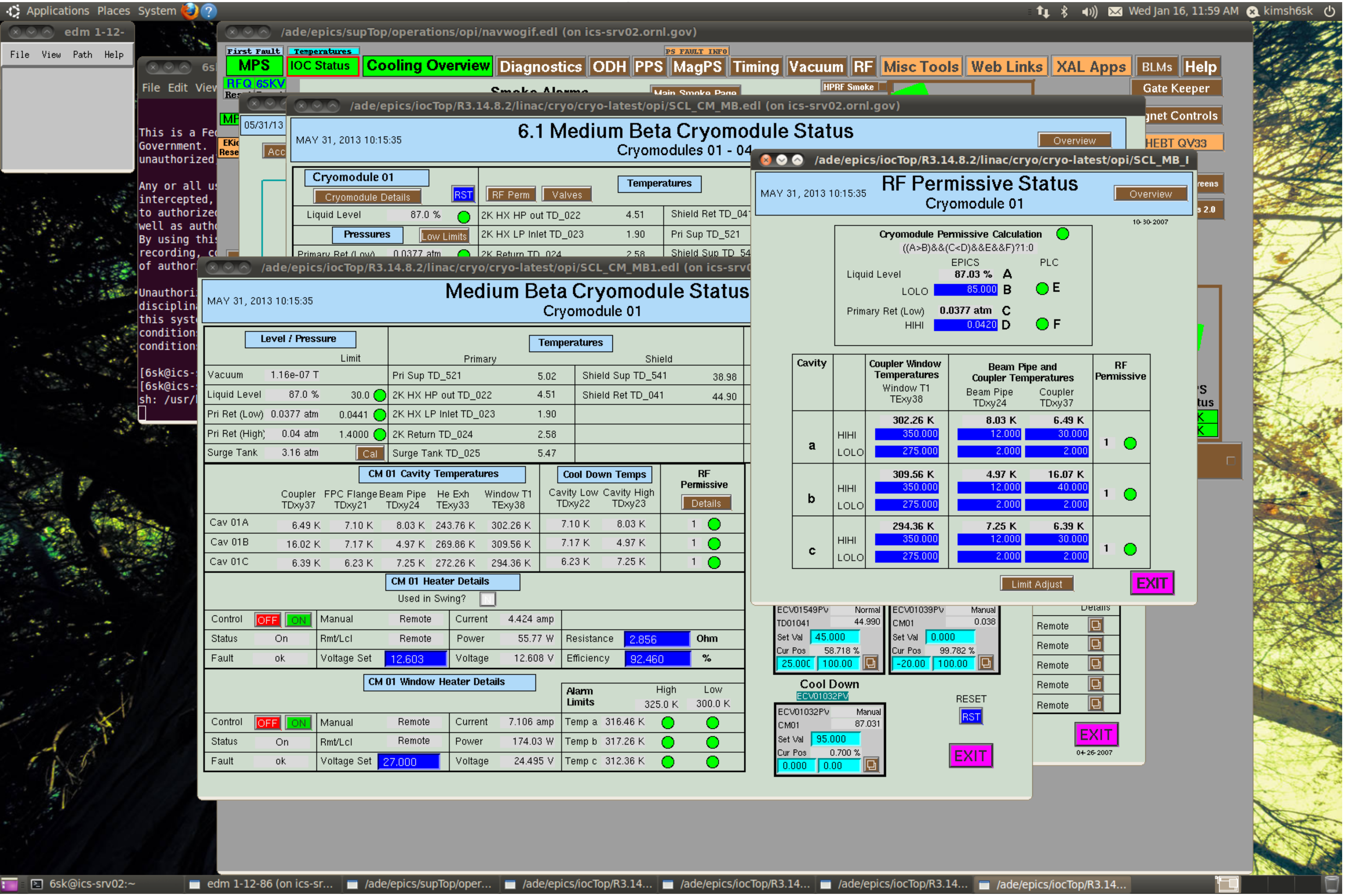


LLRF Internal

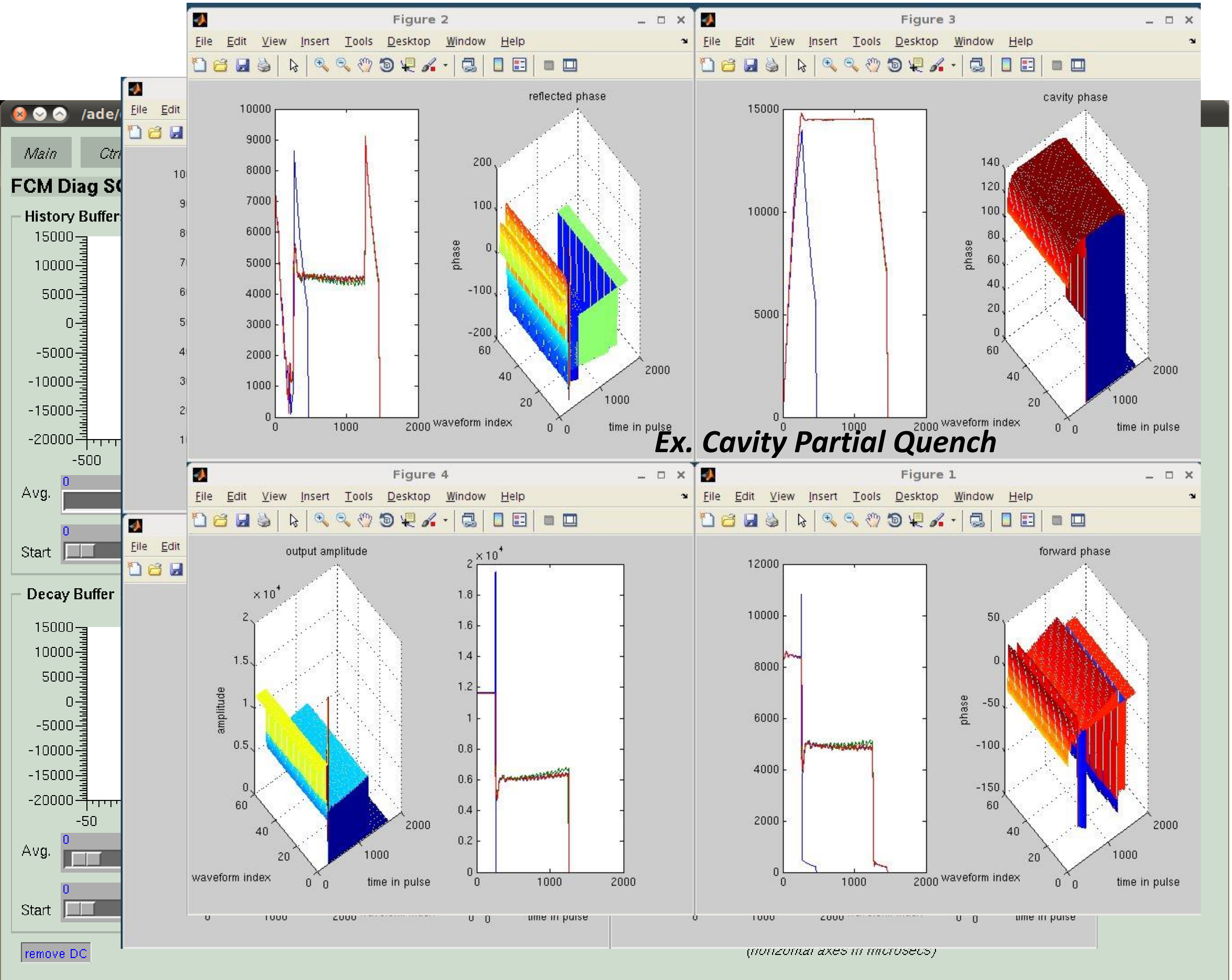


NC HPRF (on ics-srv02.ornl.gov)
NC HPRF: RFQ, DTL, & CCL
RF Conditioning
DTL RF Windows
CCL RF Windows
RFQ DTL1 DTL2 DTL3 DTL4 DTL5 DTL6 CCL1 CCL2 CCL3 CCL4
/ade/epics/supTop/operations/opi/SCHPRF_Base.edl (on ics-srv02.ornl.gov)
HPRF Main, SCL_HPRF 01
Status
Main Breaker Main Breaker Closed
Mode Rdy. For HV
Timing Pulse Enabled
Delay 0.7 ms
PLC Battery OK
Cab Air Flow OK
Vac-Ion PS Voltage 4.0 kV HV On
Vac-Ion PS Current 0.1 uA
Filament Warmup 0.0 min Ready
Interlocks
Ext. PSS Intlks
Local Controls
Communications
HV Tank 1
HV Tank 2
RF Range
Hour Meters
Magnet PS A
Magnet PS B
Klystron Settings
Body Flow Cooling
Misc. RF Cooling
Medium Beta Cryomodules
SCL 12 SCL 13 SCL 14 SCL 15 SCL 16 SCL 17 SCL 18 SCL 19 SCL 20 SCL 21 SCL 22 SCL 23
Xmtr 12 Xmtr 14 Xmtr 15 Xmtr 17 Xmtr 18 Xmtr 20 Xmtr 21 Xmtr 22
HPMod 12 HPMod 14 HPMod 15 HPMod 18 HPMod 21


SCL Vacuum Overview - New Serial (on ics-srv02.ornl.gov)
SCL Vacuum Status Overview
LEDP, Medium Beta Tank P&ID (on ics-srv02.ornl.gov)
SCL Low Energy Differential Pumping Station
Cryo Module 01 Status
Beam Direction
CCG00001
CCG00002
CCG01001
SGV00001
SGV01001
SGV01501
Fast Valve
FV00001
BS is OUT
HV ON
Vac OK
OPEN
READY
CLOSED
Closed Counter
RF Permit
MB CM 01 Cavity A
MB CM 01 Cavity B
MB CM 01 Cavity C
CCG01101
CCG01201
CCG01301
IP00001
IP00002
IP01001
IP01501
No Bypass
Bypass
CCL VacOK
Insertable Dump
Reset Zone 1
Alarm
MAY 31, 2013 10:12:02
Analog Test


Applications Places System
Wed Jan 16, 11:59 AM kimsh6sk
/ade/epics/supTop/operations/opi/navwogif.edl (on ics-srv02.ornl.gov)
MPS
IOC Status
Cooling Overview
Diagnostics
ODH
PPS
MagPS
Timing
Vacuum
RF
Misc Tools
Web Links
XAL Apps
BLMs
Help
Gate Keeper
/ade/epics/iocTop/R3.14.8.2/linac/cryo/cryo-latest/opi/SCL_CM_MB.edl (on ics-srv02.ornl.gov)
6.1 Medium Beta Cryomodule Status
Cryomodules 01 - 04
MAY 31, 2013 10:15:35
/ade/epics/iocTop/R3.14.8.2/linac/cryo/cryo-latest/opi/SCL_CM_MB1.edl
Medium Beta Cryomodule Status
Cryomodule 01
Level / Pressure
Temperatures
CM 01 Cavity Temperatures
Cool Down Temps
RF Permissive
CM 01 Heater Details
CM 01 Window Heater Details
/ade/epics/iocTop/R3.14.8.2/linac/cryo/cryo-latest/opi/SCL_MB_I
RF Permissive Status
Cryomodule 01
Cryomodule Permissive Calculation
((A>B)&&(C<D)&&E&&F)?1:0
Liquid Level 87.03 % A
LOLO 85.000 B
Primary Ret (Low) 0.0377 atm C
HIHI 0.0420 D
Limit Adjust
EXIT
Cool Down
6sk@ics-srv02:~
edm 1-12-86 (on ics-sr...

Ex. Cavity Partial Quench



Discussion & Question