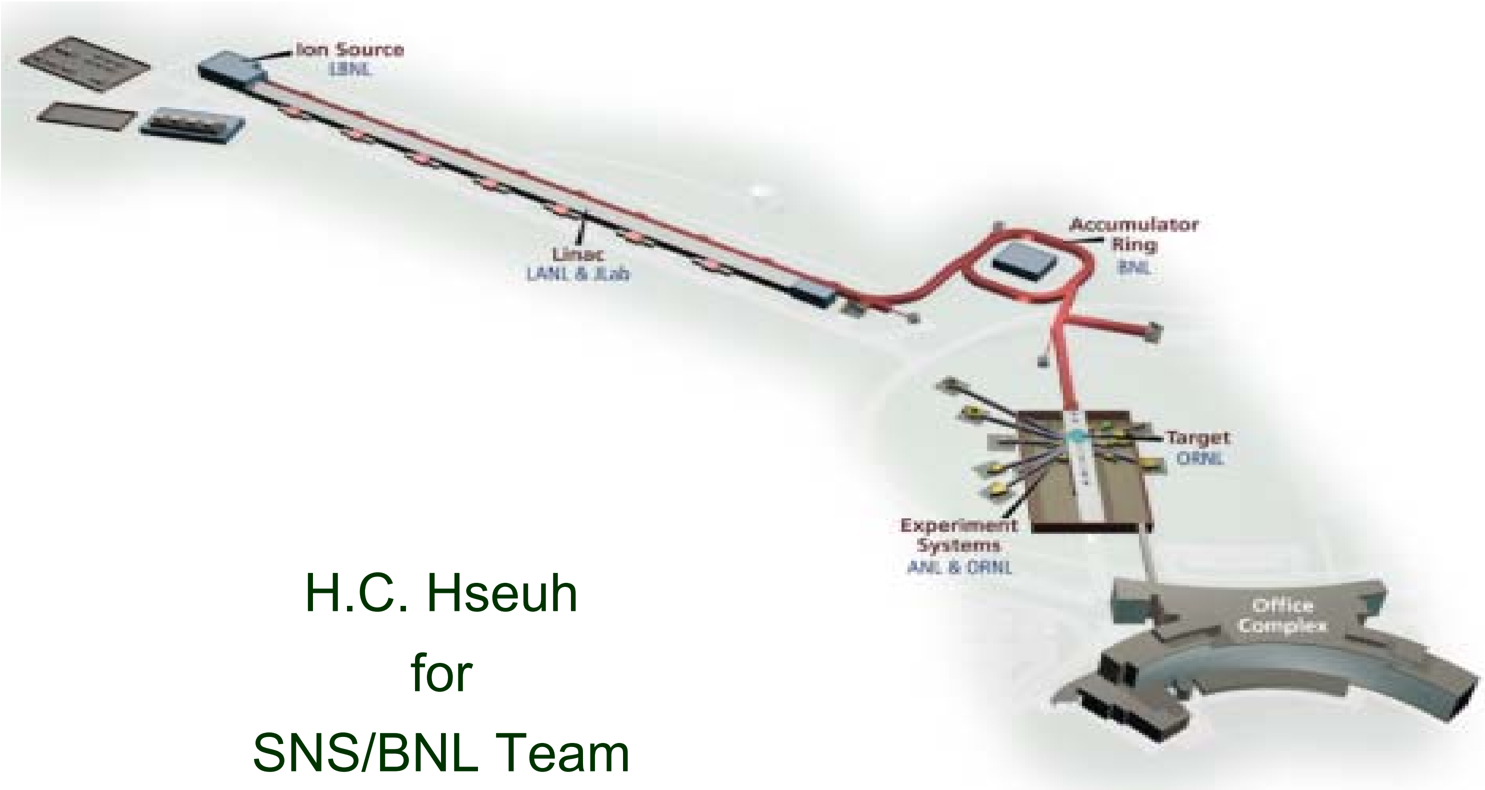
Design and Implementation of SNS Ring Vacuum System with Suppression of Electron Cloud Instability



H.C. Hseuh

for

SNS/BNL Team

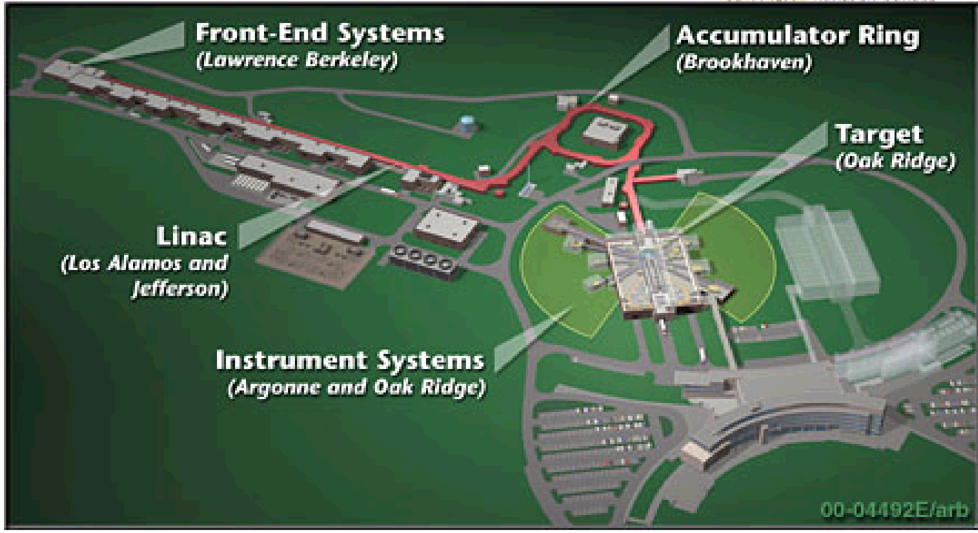
April 20, 2004

Outline

- SNS Project, Layout and Parameters
- Ring and Vacuum System
- E Cloud Mitigation
    - TiN Coating Effort
    - Electron Capture @ Inj. and Clearing
    - Solenoid Effect
    - Beam Scrubbing at High Pressure
- Summary

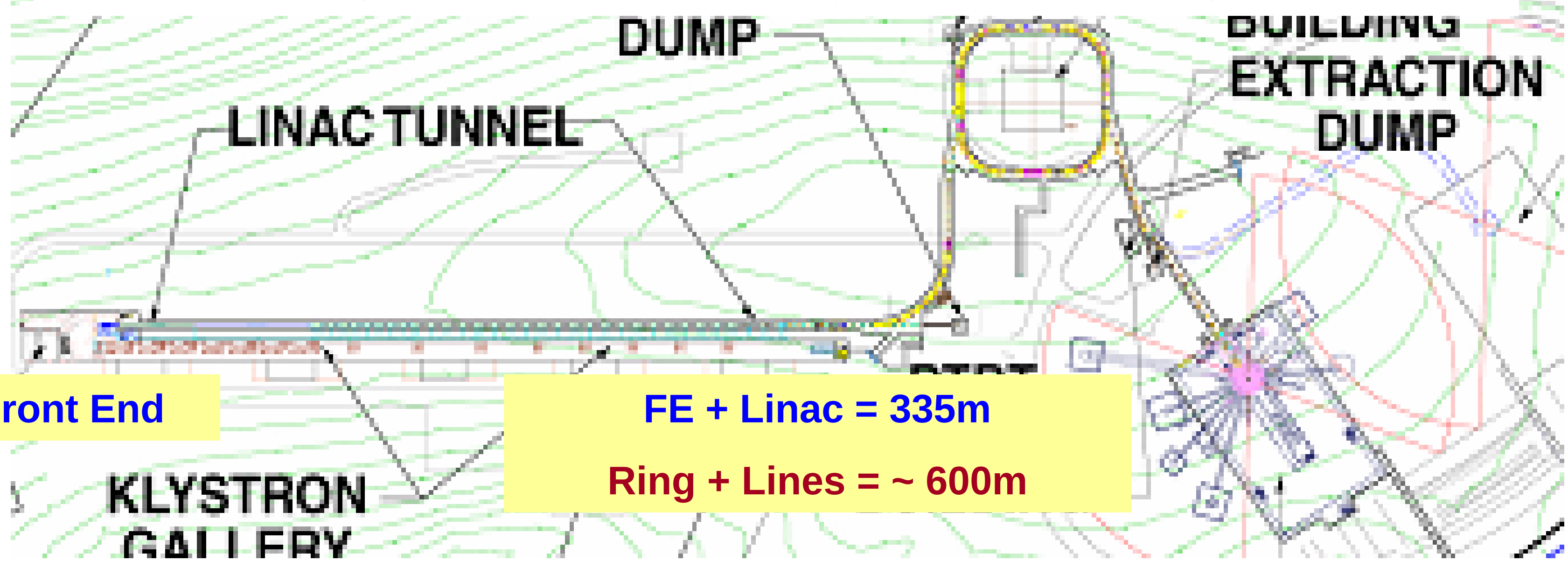
The Spallation Neutron Source (SNS) Project

- SNS is the latest large user facility built in the US
  - A $1.4 billion, 7-year project from Oct. 1999 to June 2006
- Collaboration among six national laboratories, built at Oak Ridge, TN
  - Argonne, Brookhaven, Jefferson, Berkeley, Los Alamos, Oak Ridge
  - Potential model for the construction of future large-scale projects
- Accelerator based neutron source
  - With 1 GeV proton on Hg target $1.6\text{x}10^{14}$ ppp @ 60 Hz
- At 1.4 MW, SNS will be ~8 times ISIS, the world's leading pulsed neutron source



SNS Schematic Layout

- LBL: H$^-$ source (20 KeV), RFQ (2.5 MeV)
- LANL: DTL (87 MeV), CCL (185 MeV), Linac warm components
- JLab: Superconducting RF cavities (1 GeV) & cryo systems
- BNL: HEBT, Accumulator Ring, RTBT
- ANL: Neutron Instruments
- ORNL: Target, Conventional Facility, … Overall Management



Front End

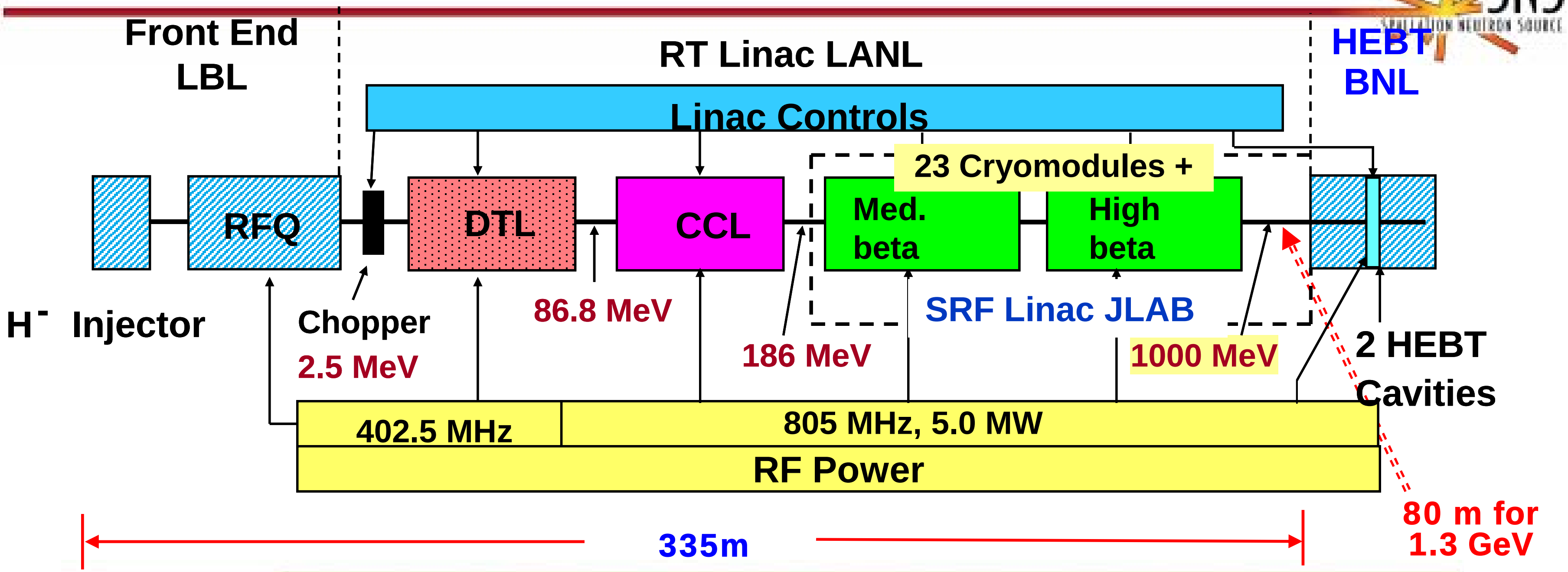
FE + Linac = 335m

Ring + Lines = ~ 600m

SNS Main Parameters

Kinetic energy, E_k [MeV]	**1000**
SRF cryo-module number, med β + high β	11+12 **= 23**
SRF cavity number, med β + high β	33+48 **= 81**
Peak gradient, E_p (β=0.61 cavity) [MV/m]	27.5 (+/- 2.5), 10 (avg)
Peak gradient, E_p (β=0.81 cavity) [MV/m]	35 (+2.5/-7.5), 12-15 (avg)
Beam power on target, P_{max} [MW]	**1.4**
Pulse length on target [ns]	**695**
Average macropulse H- current, [mA]	**26**
Linac average beam current [mA]	**1.6**
Ring rf frequency [MHz]	1.058
Ring injection time [ms] / turns	**1.0 / 1060**
Ring bunch intensity [10^{14}]	**1.6**

Layout of SNS Linac Sections



Front End
LBL

RT Linac LANL

HEBT
BNL

Linac Controls

23 Cryomodules +

RFQ

DTL

CCL

Med.
beta

High
beta

H⁻ Injector

Chopper
2.5 MeV

86.8 MeV

186 MeV

SRF Linac JLAB

1000 MeV

2 HEBT
Cavities

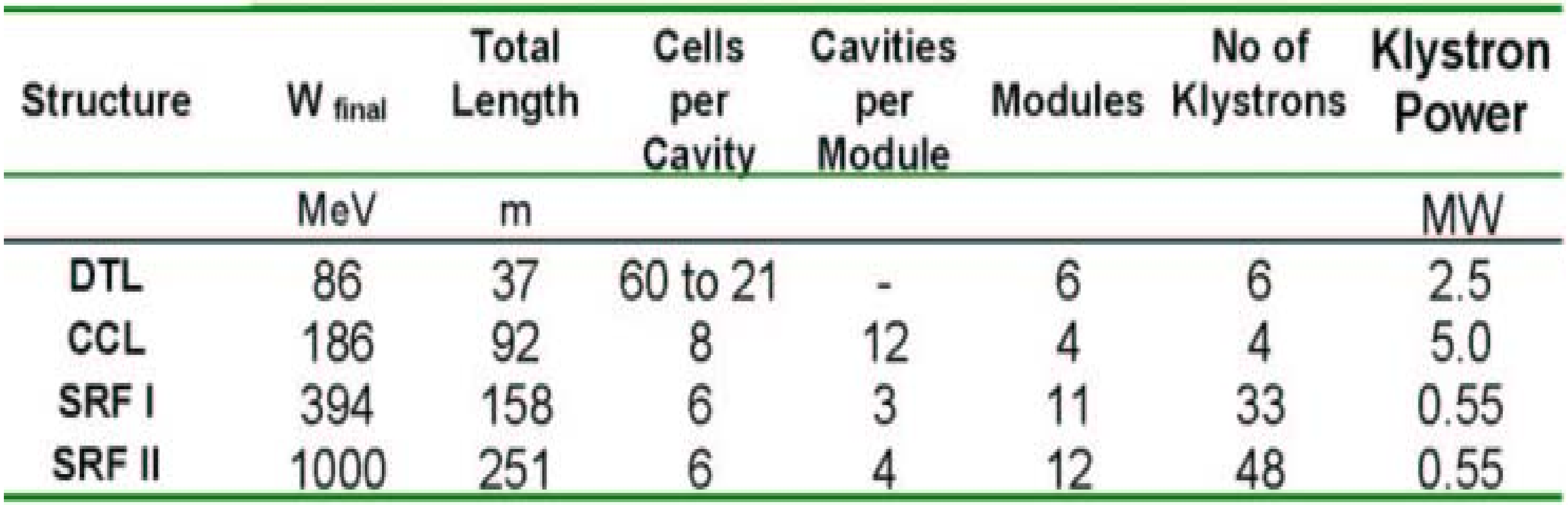
402.5 MHz

805 MHz, 5.0 MW

RF Power

335m

80 m for
1.3 GeV



Structure	W_{final}	Total Length	Cells per Cavity	Cavities per Module	Modules	No of Klystrons	Klystron Power
	MeV	m					MW
DTL	86	37	60 to 21	-	6	6	2.5
CCL	186	92	8	12	4	4	5.0
SRF I	394	158	6	3	11	33	0.55
SRF II	1000	251	6	4	12	48	0.55

Accumulator Ring and Transport Lines

Functions:

Compress 1060-turn (~1ms) protons (H^-) from Linac into a 0.7 μs pulse to Target

Good quality uniform beam at Target w/o beam halos

Low un-controlled loss of < 1 watt/m @ 1 MW operation

Reliable & maintainable in high radiation environment

Ring Specifics:

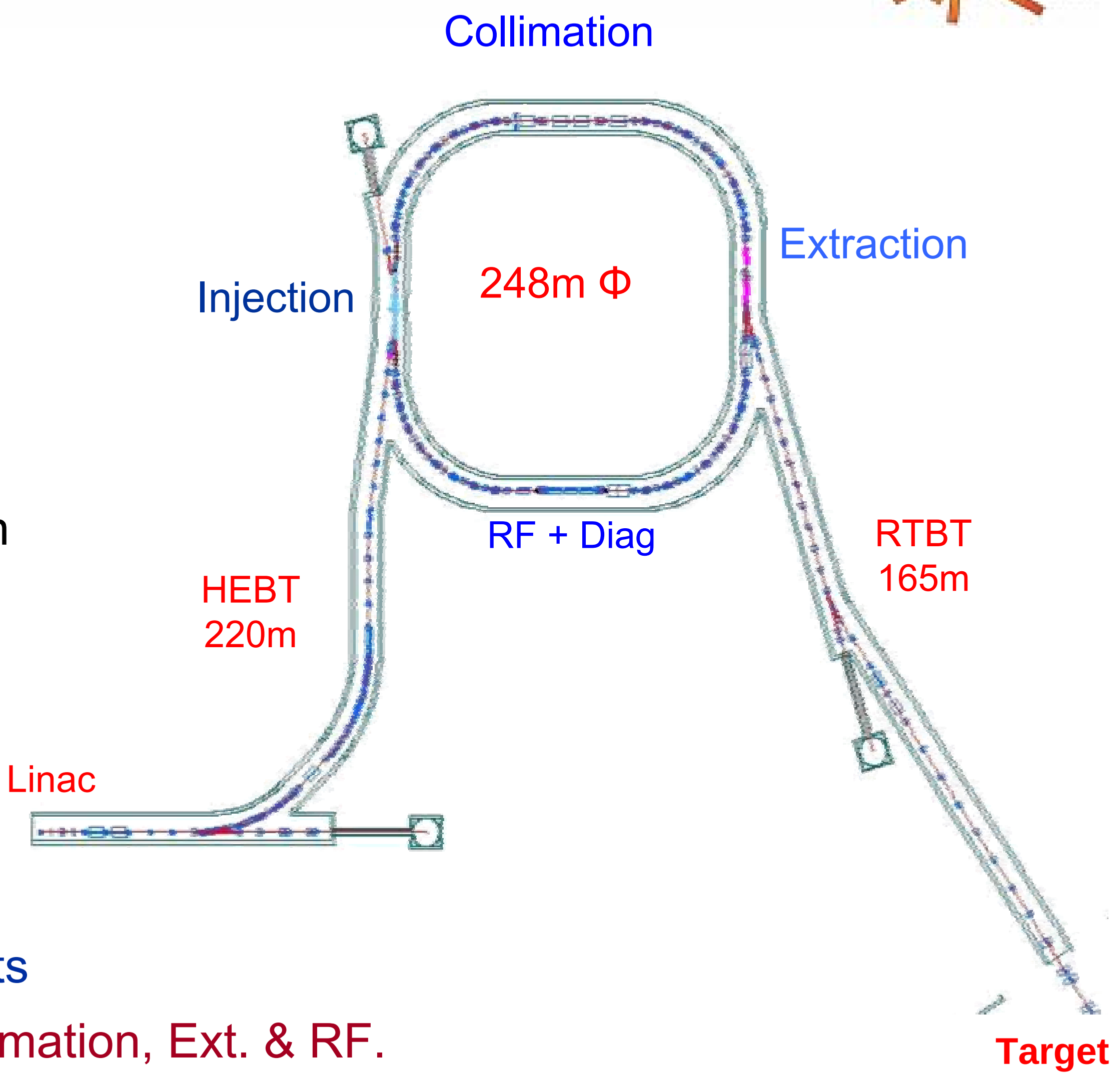
Hybrid Lattice w/ 4-fold symmetry

4 Arcs of 34m each, FODO Lattice

8 halfcells and one quartercell

4 straight sections of 28m, Doublets

dedicated sections for Inj. Collimation, Ext. & RF.



Ring Vacuum System Parameters

Vacuum Requirement:

$<1\times10^{-8}$ Torr to minimize beam - residual gas ionization

$\sigma \sim 1\times10^{-18}$ cm^2 ($40H_2/40H_2O/20CO$)

$\sim10^{-3}$ ionization / p.ms

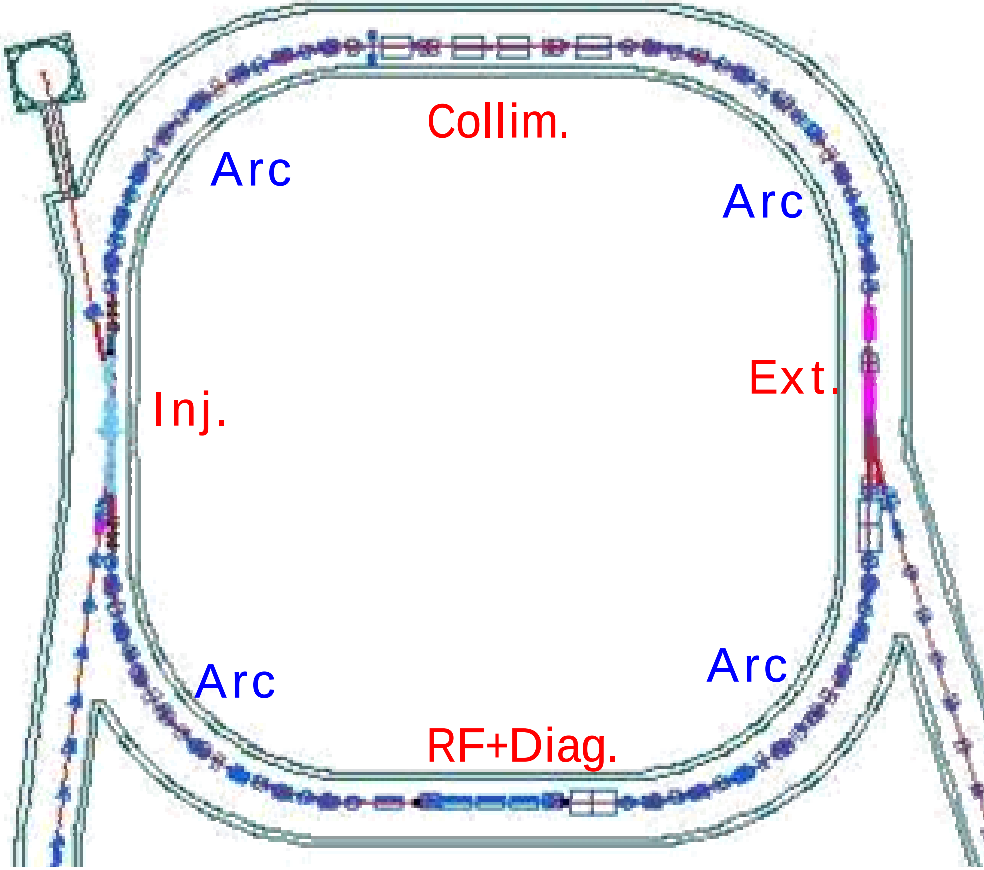
⇒ e-p instability, neutralization,

TiN coating on inner surface to reduce secondary electron yield (SEY) < 1.9

Conductive coating of inj. kicker ceramic chambers with Cu + TiN (~0.04 Ω)

TiN coating of ext. kicker ferrites

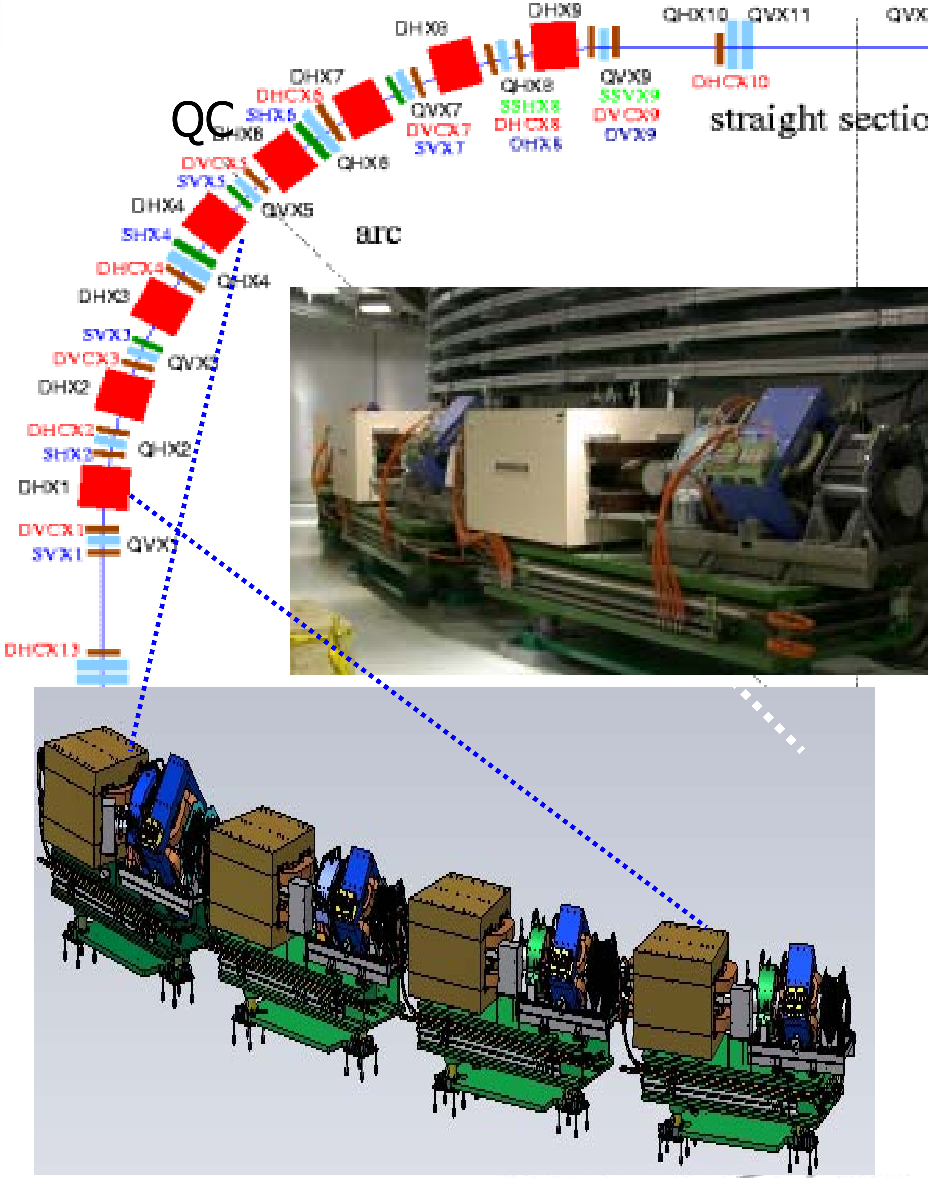
Reliable and maintainable



Ring Arc Layout

- Each arc has 8 halfcells (4 types) and one quartercell
- Dipole -17cm x 1.4m, 0.9 T, **r** =7.6m
- Quads and Sextupoles - two families 21cm and 26cm, ~ 5 T/m

Arc halfcell assembly



Arc Vacuum Chambers

32 HC + 4 QC chambers

HC chambers ~ 4m long ea. of 4 types

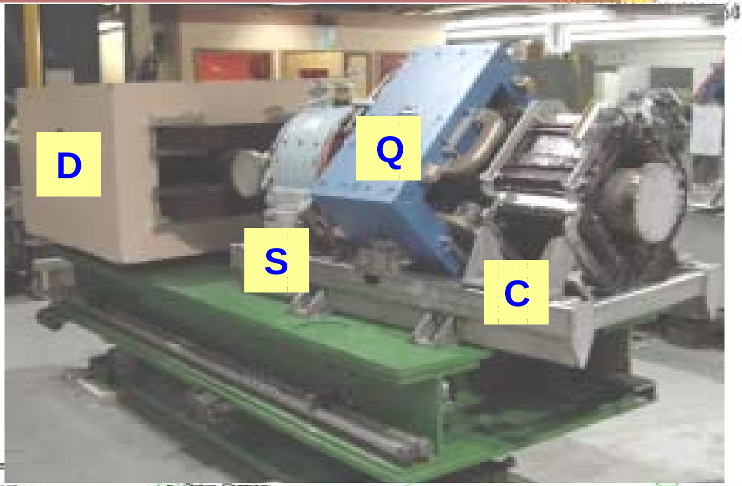
- Q+S+C: 21cmΦ or 26cm Φ x 1.6m
- D: 23cm x 17cm x 2m x 11.25º

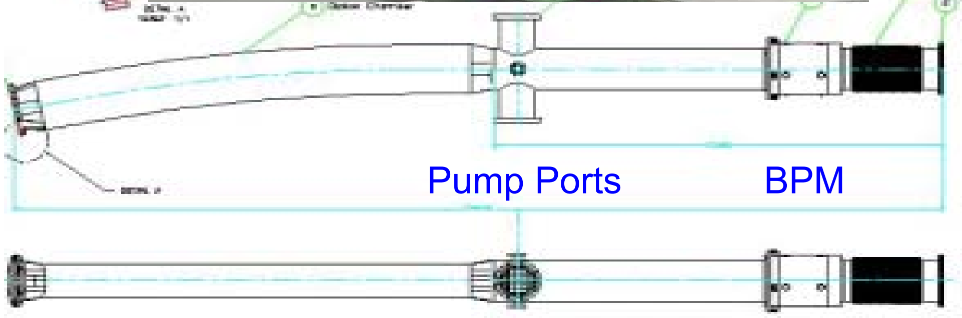
QC chambers ~ 21cmΦ x 2m

316LN stainless steel + Inconel bellows

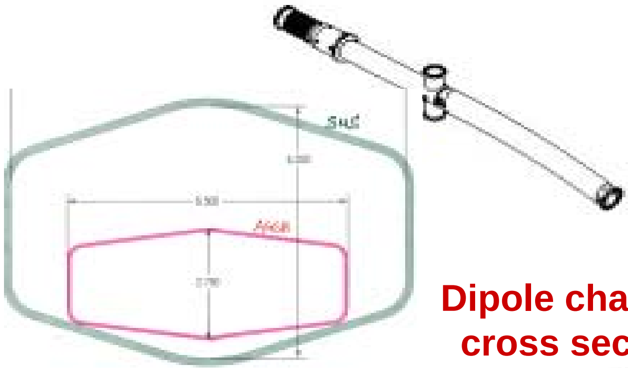
Tapered transition and rf-shielded ports

BPM – strip line type, 70º x 4





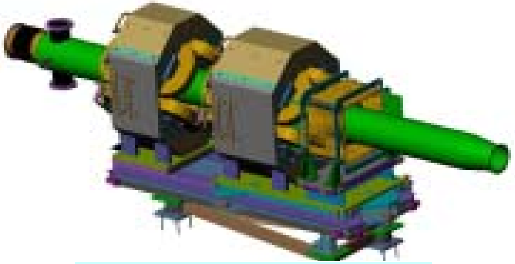
Arc HC chambers



Dipole chamber cross section

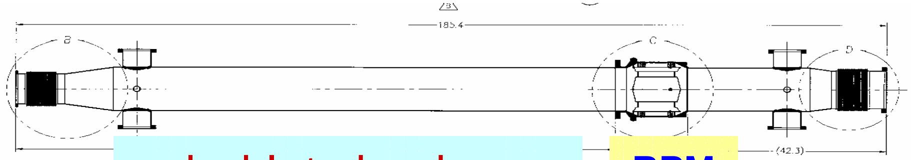
Injection & RF Straight Sections

- 4 Straight sections of 28m each:
- Two doublets in each straight section
  - 30Q44 (narrow quad) and 30Q58
  - Chambers of 29cm Φ, 3 – 5 m long
- Other devices
  - 4 RF cavity assemblies
  - 8 Inj. kickers w/ ceramic chambers
  - 4 Inj. chicane magnets and chambers



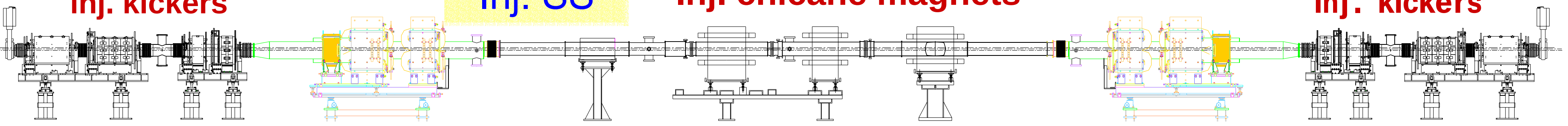
doublet

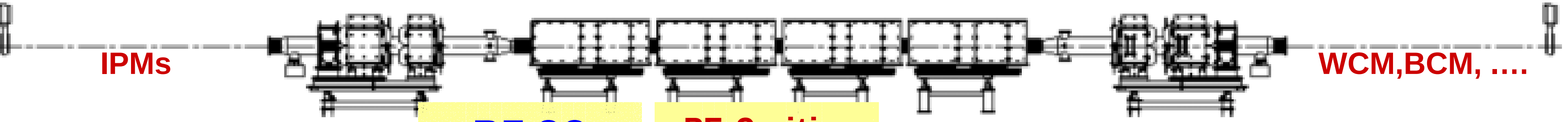
Narrow quad for inj. & ext.



doublet chambers

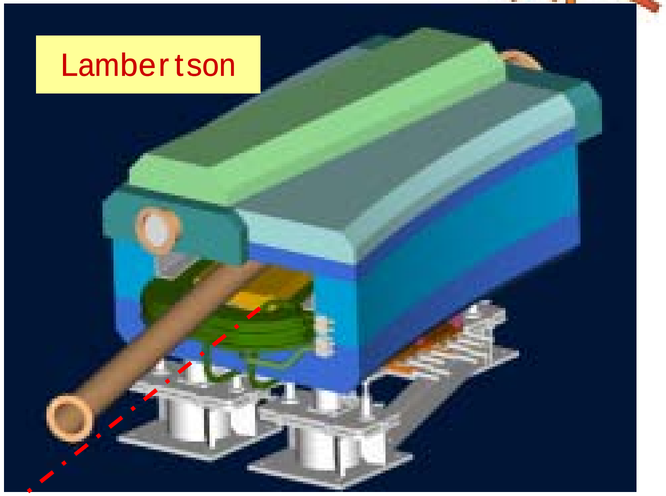
BPM

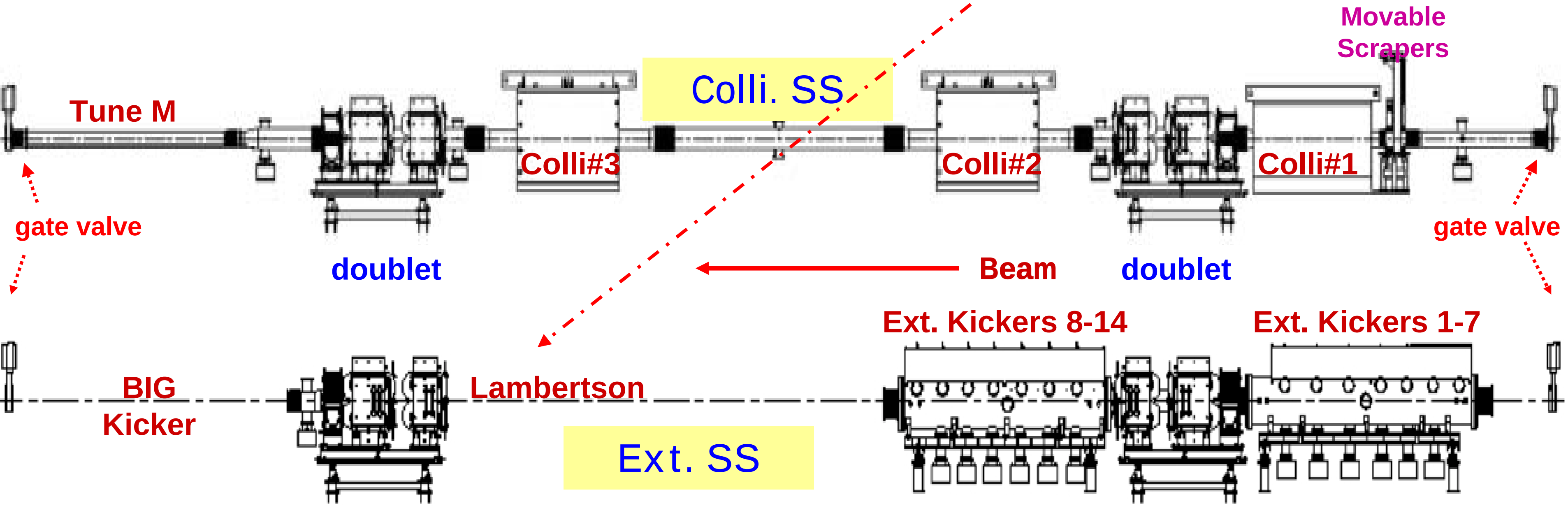




Collimation & Extraction Straight Sections

- Primary scraper and 2-stage collimation
  - 240π @ Colli #1; 300π @ Colli #2 and #3
    - 480π for Ring & RTBT to Target
  - Solenoids to confine the scattered electrons and to minimize multipacting
- 14 kickers and Lambertson for vertical extraction
  - Kicker ferrites to be coated with TiN
  - B.I.G. kickers to remove residuals





Ring Physics Challenges (Jie Wei, BNL)

- Guaranteed beam-density on target
  - Immune to kicker misfiring, protected against malfunctions
- Electron cloud & instabilities
  - How to collect & control electrons generated at injection, collimators, … and due to multipacting
  - Impedance of ext. kicker ferrite modules (in vacuum)
- Magnet field variation, correction, alignment
  - Field uniformity ~ 10^{-4} for main magnets; shimming needed for solid-core magnets
  - Non-trivial design on C-type, septum to reach 10^{-3}
- Loss control
  - Control of injection field to reduce H^- and H^0 loss
  - Facilitate two-stage collimation and beam-in-gap cleaning

Electron-cloud Mitigations in SNS Ring

- TiN Coating to reduce secondary electron emission (SEY)
  - all ring chamber wall,
  - injection kicker ceramic chambers
  - extraction kicker modules
- Solenoids in collimation region and other field free regions
  - to confine scattered electrons and suppress multipacting
- Tapered magnetic field and clearing electrode at Injection stripping foil
- Beam-position-monitors as clearing electrodes
- Beam-in-gap kicker to clear residuals
- Extra vacuum ports for additional pumps and for beam scrubbing

TiN Coating of Ring Vacuum Chambers

Goal: Low SEY, good adhesion

DC Magnetron sputtering with permanent magnets

- high sputtering rate (10x DC)
- low sputtering pressure

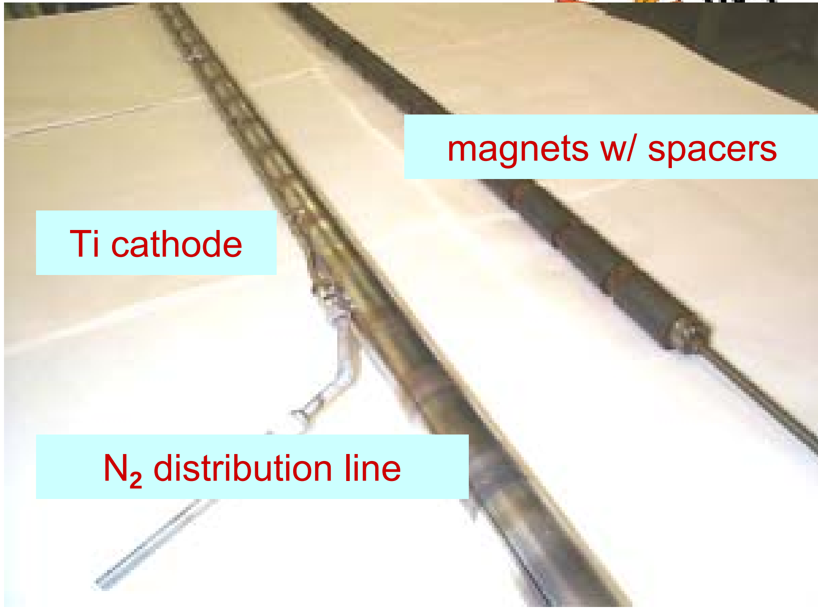
Bake @ 250 C x 40 hrs to minimize impurity

Coat with ~ 100 nm of TiN (~ 2 hrs)

Need uniform N_2 gas flow along the length

- to get correct stoichiometry (Ti/N = 0.95 – 1.03)

Analyzed with AES, RBS, SEM…


magnets w/ spacers

Ti cathode

N_2 distribution line


HC chamber being coated

plasma during sputtering

TiN Coating Parameters

DC Magnetron vs DC

Sputtering Mode	Operating Region	Ar Flow (sccm)	N2 Flow (sccm)	Ptotal Torr	Volts	Amps	Dep. Rate A/hr	Ti:N(x) by AES	O% by AES
straight DC	B	8.3	0.9	3e-2	4500	0.06	200	1.16	7.1
magnetron	B	13.7	11	6e-3	308	10	2000	-	-
magnetron	C-D	13.3	7	8e-3	300	4.5	1000	1.2	-
magnetron	D	13.3	2.75	6e-3	300	4.5	1000	1.22	3

Coating pressure v. SEY

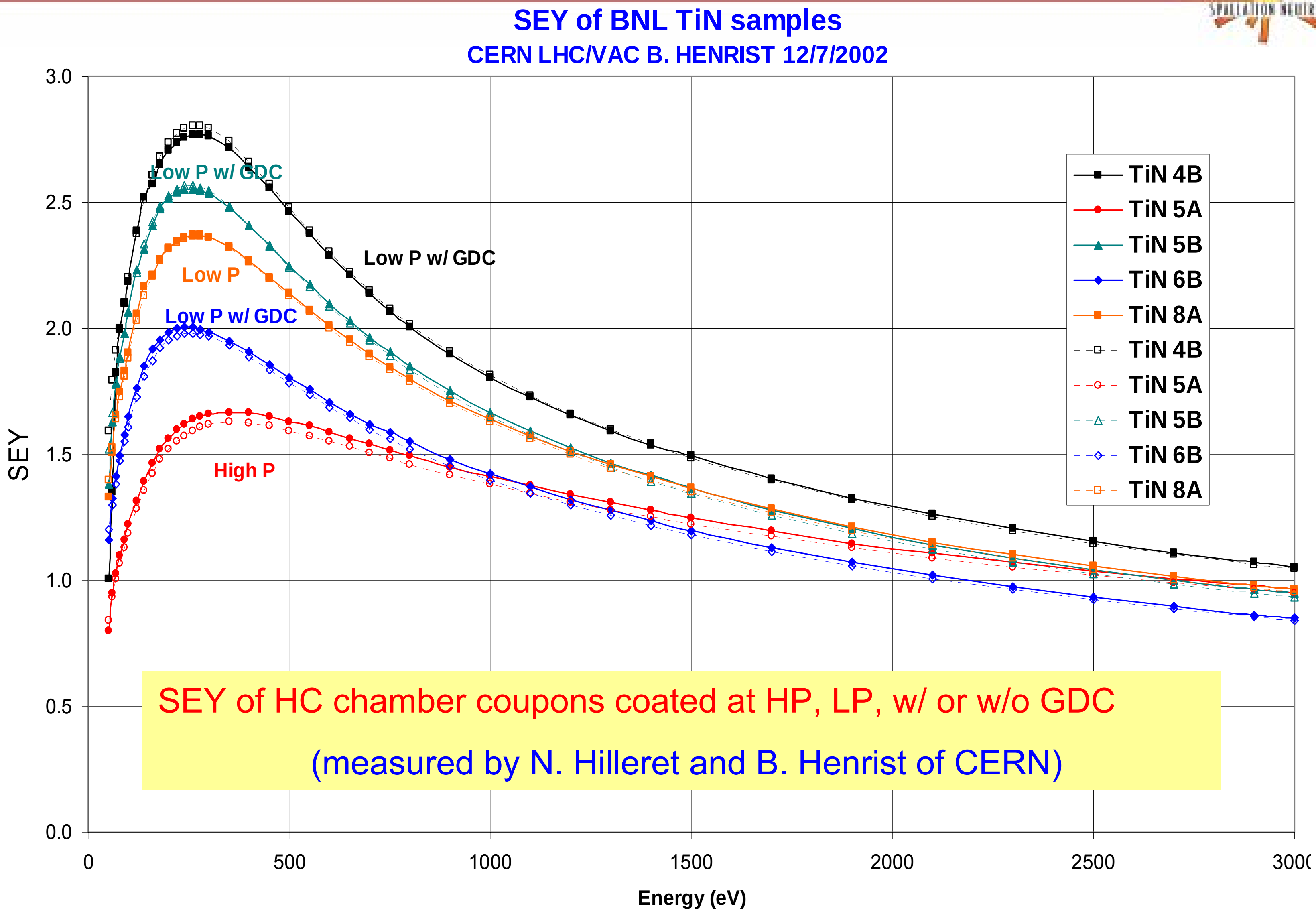
- @ ~ 5 mTorr ⇒ darker color, higher Q, lower SEY*
- @ ~ 1.5 mTorr ⇒ gold color, lower Q, higher SEY*
- Ar GDC treatment to condition the surface and remove contaminants

Peak SEY (as received)

- Stainless ~ 2.5
- TiN coated at LP ~ 1.9 – 2.2
- TiN coated at HP ~ 1.5 – 1.8

*SEY measured by N. Hilleret and B. Henrist of CERN

As Received SEY Values vs. Coating Pressure



SEY of HC chamber coupons coated at HP, LP, w/ or w/o GDC

(measured by N. Hilleret and B. Henrist of CERN)

Surface of Chamber Coating Coupons

-- # 5A, brown color
-- 5mTorr, w/Ar GDC

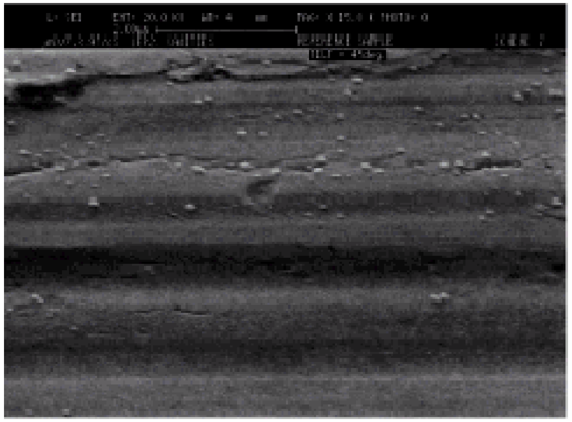
-- #8A, gold color
-- 1.5mTorr

-- #5B, gold color
-- 1.5mTorr, w/ Ar GDC

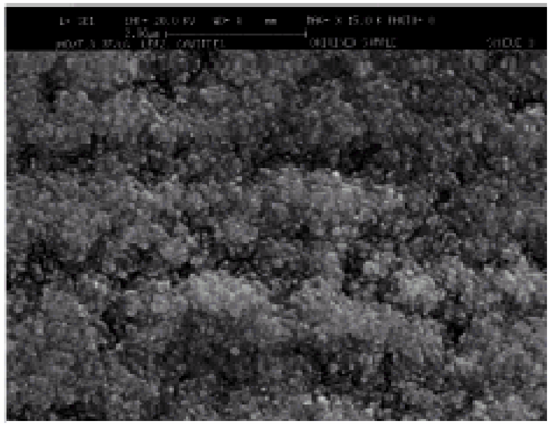
Rougher surface has lower SEY, perhaps due to re-entry of 2nd electrons back into the bulk

Scanning Electron Microscope images @ x1500

SEY= 2.4, as-received condition

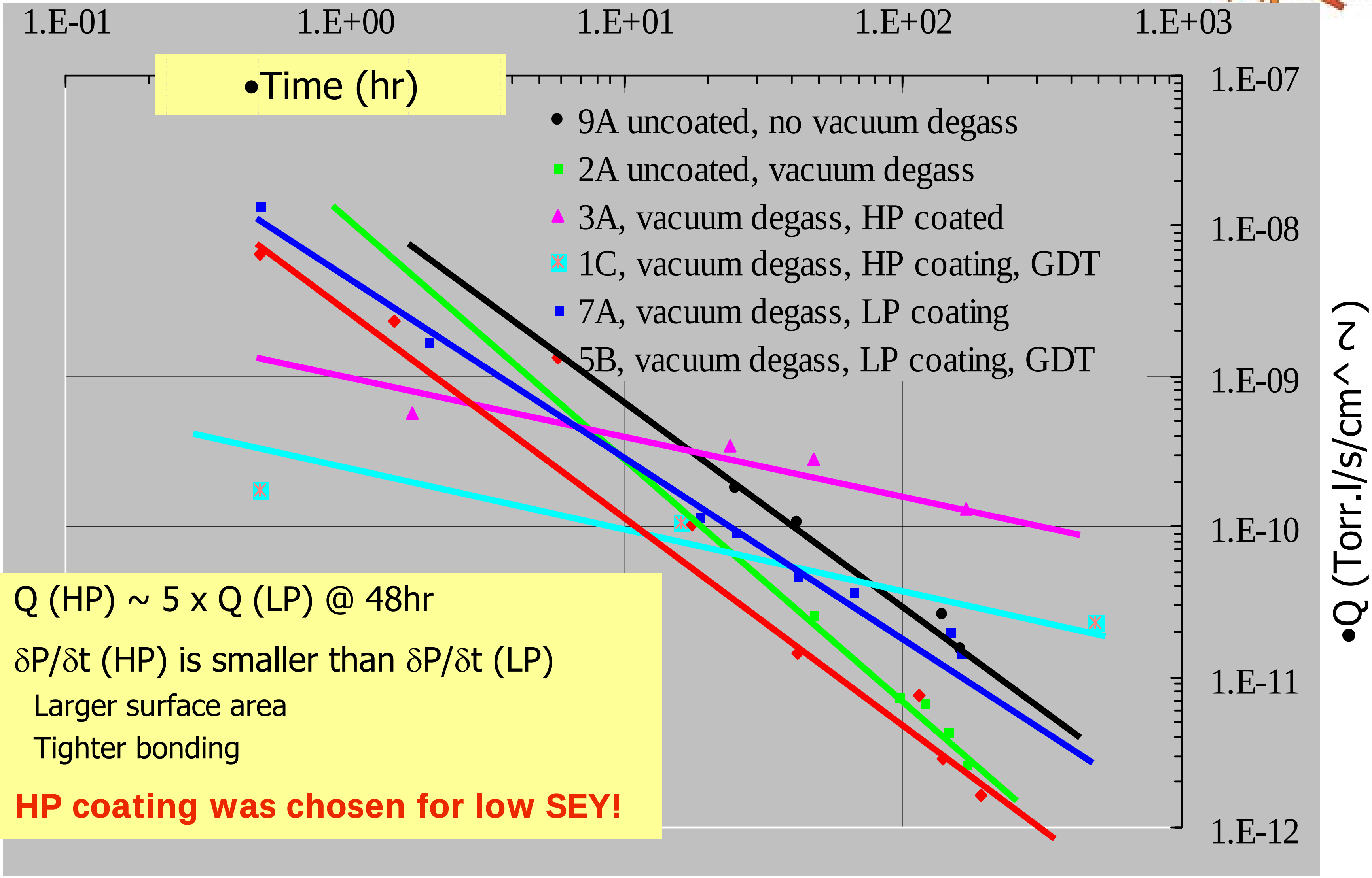


SEY= 1.1 after air and vacuum bake



SEM images of CERN LEP2 copper cavity surface (N. Hilleret, CERN)

Outgassing of SNS Halfcell Chambers



- Q (HP) ~ 5 x Q (LP) @ 48hr
- δP/δt (HP) is smaller than δP/δt (LP)
  - Larger surface area
  - Tighter bonding
- **HP coating was chosen for low SEY!**

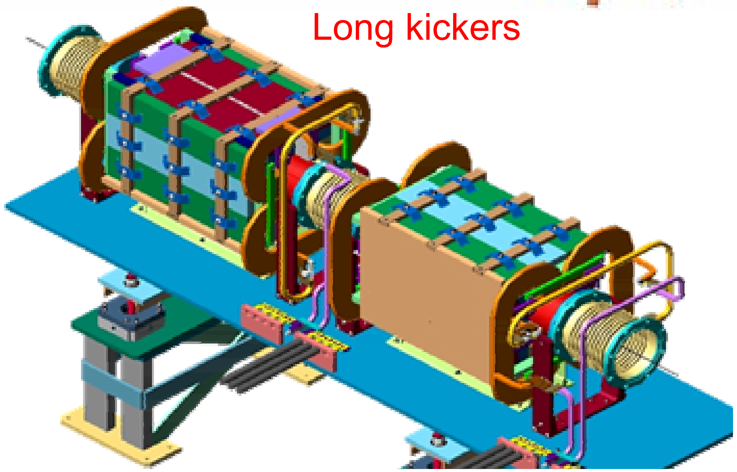
Inj. Kicker Magnets and Ceramic Chambers

8 Ferrite injection kicker magnets

with Ceramic chambers of 100cm (L) x 18cm ID

0.1 - 1.1 KG (110 – 1300A) over 1 msec

with satisfactory rise/fall time (~ 100 μsec)



Long kickers

Conductive coating for beam image current + TiN

0.04 Ω (± 50%) end-to-end resistance ⇒

18μm of TiN or 0.7μm of Cu

TiN sputtering rate of < 0.1nm/s, (~50h for 18μm)

Cu coating rate of ~ 0.56nm/s, (20 min for 0.7μm)

Chose to coat w/ Cu ~ 0.7 μm, then TiN ~ 0.1 μm

with R ~ 0.045 ± 0.008 Ω (10 chambers average)

Thickness uniformity < ± 30%

Eddy current heating w/ magnet pulsing

< 100 watt/m and ΔT < 20ºC

@ 1300A (~1.3 GeV) x 60Hz

No noticeable effect to kicker field and rise time

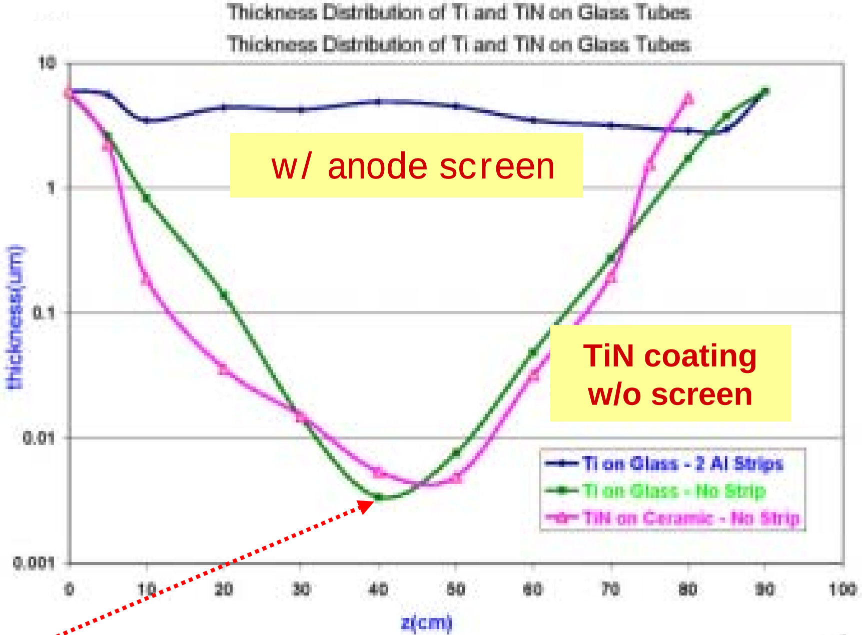
Short kickers w/ common ceramic chamber

Coating Development for Inj. Ceramic Chambers

Little coating in the center of the chambers due to charge build-up

Use anode screen to smooth out the field

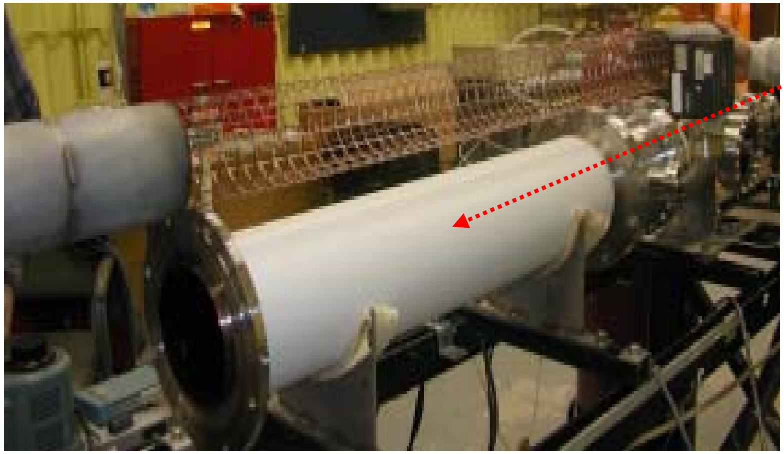
- with 90% opening
- positioned 5mm from surface to minimize shadowing

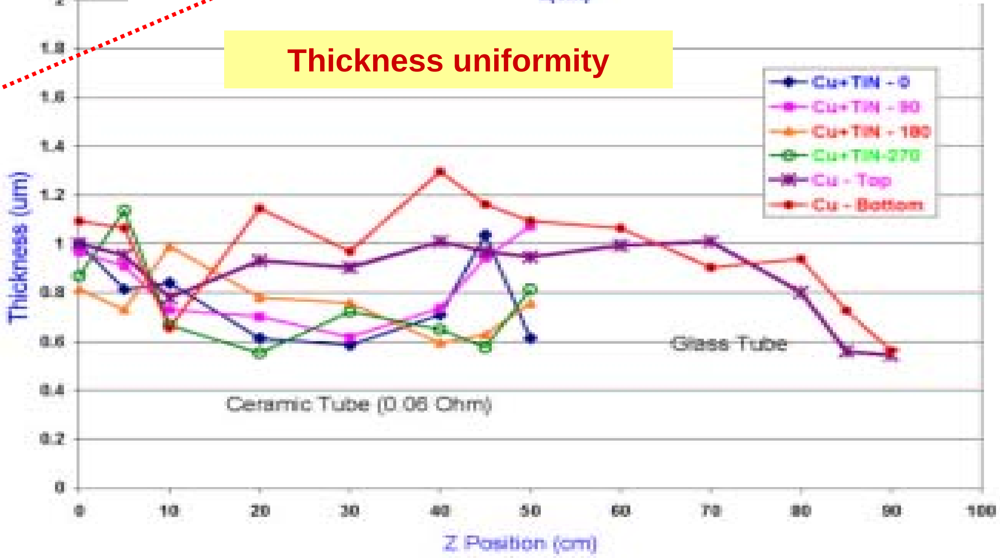


w/ anode screen

TiN coating w/o screen

Ceramic tube and anode screen





Thickness uniformity

Coating of Ext. Kicker Modules

14 kicker modules of various dimensions
- 10-18cm(H) x 12-22cm(V) x 0.4m(L)
- 34 kV x 3 kA (<1.8 mrad) each
- rise time of ~ 100 nsec

Ferrite surface coated with TiN strips
- 9mm wide x 1mm spacing (w/ custom masks)
- 100 nm thick

Eddy current heating (M. Blaskiewicz, BNL)
- $\Delta T < 2^\circ C$, Pavg < watts
- t (EM) < 1 nsec


Extraction Kicker Assembly


Kicker Vessel


Kicker Modules


w/ Coating Masks


Kicker coating system

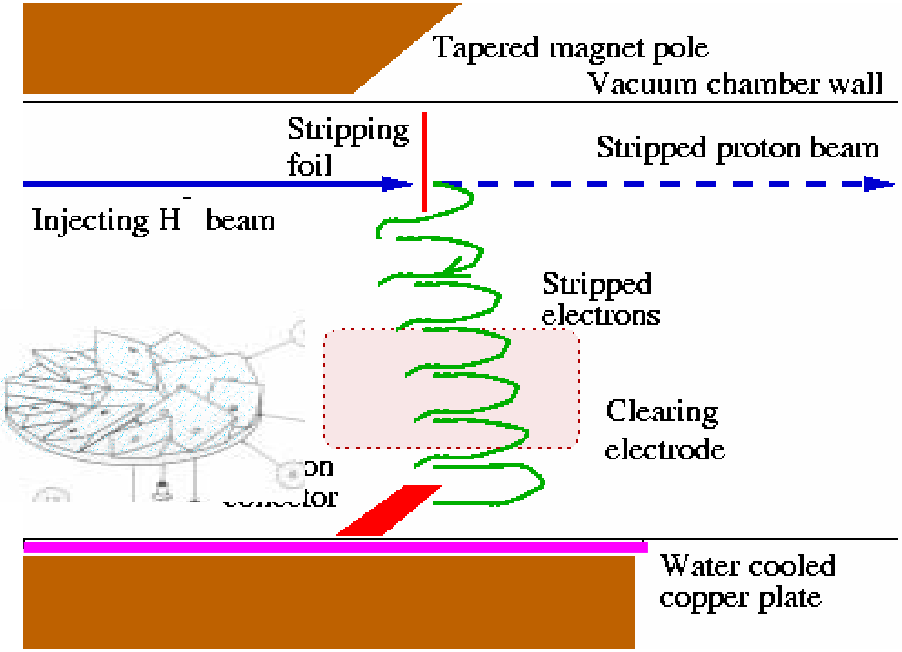
Collection of Stripped Electrons @ Inj. Foil


Injection chicane magnet


Injection chicane chamber w/ Cu plate


C Foil (24) mechanism


Foil chambers under testing

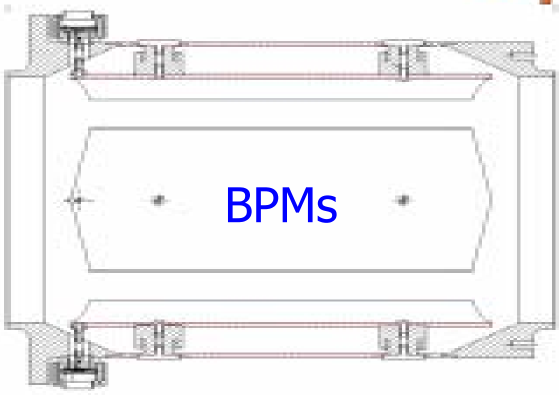


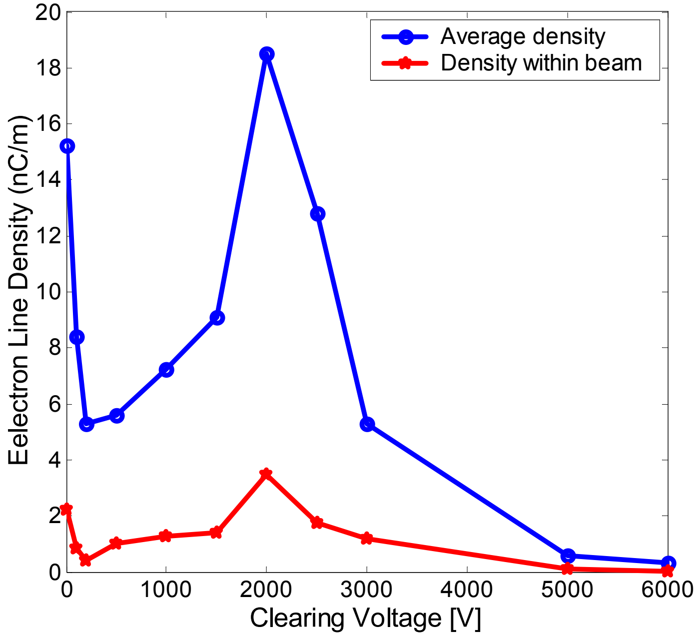
- Two electrons from H^- stripping
- Electrons from beam scattering on foil
- Tapered magnet to guide stripped electrons (~ 2 kW)
- Carbon-carbon collector on water-cooled copper plate
- Clearing electrode (~ 10 kV) to reduce scattered electrons

Electron Clearing by BPMs

BPM as clearing electrodes (±1 kV)

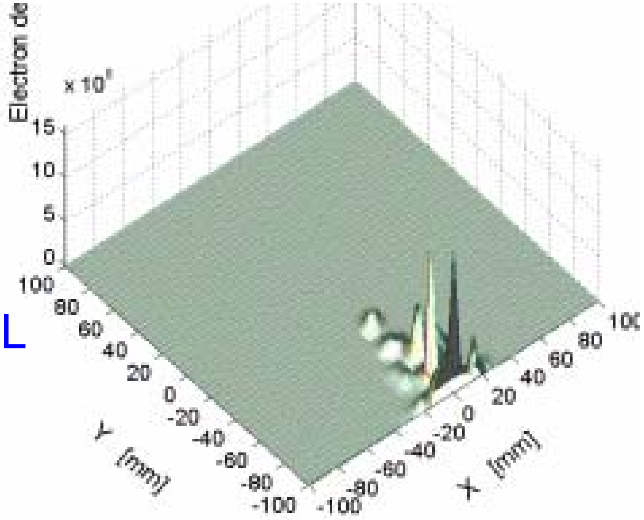
- 44 strip-line type, 70° x 25cm x 4 planes
- To suppress multipacting
- To clean the bunch gap
- Sufficient @ 200 volts, reduce e density x 3





Electron line density vs. clearing voltage

L. Wang, BNL



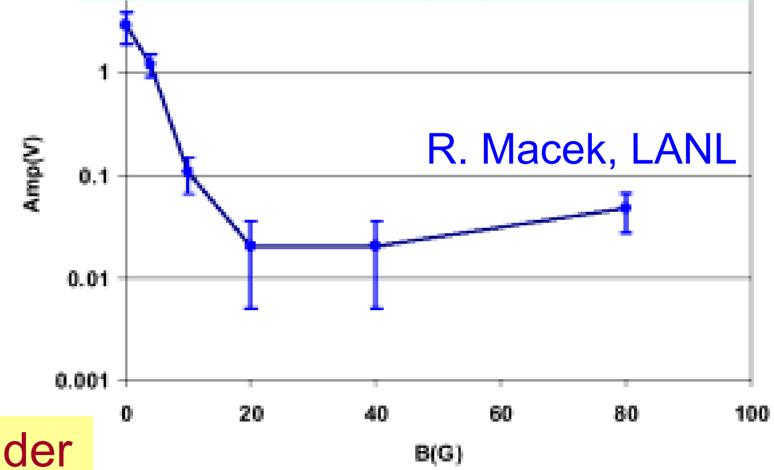
electron cloud under a clearing electrode

Solenoid Field in Field Free Regions

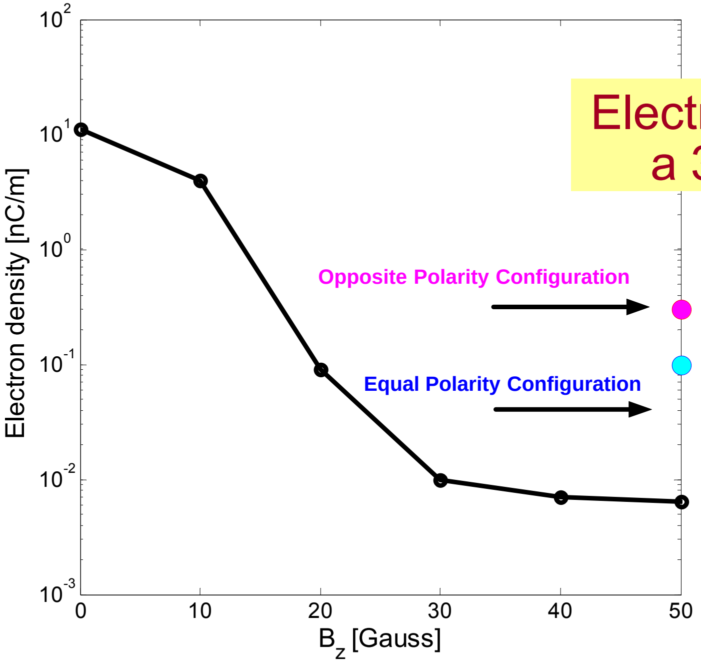
Solenoid of ~30 G to reduce multipacting

- >10^2 reduction in electron line density
- Only ~18m (7%) available, mostly at inj. & collimation straight sections
- > 12% possible in PSR, > 60% in LER of KEKB and PEPII

PSR solenoid (0.5 m x 20 Gauss) reduced e^- density by 100.

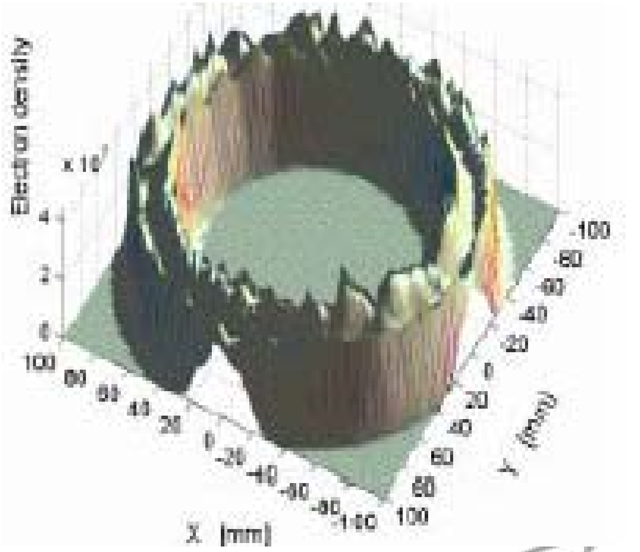


R. Macek, LANL

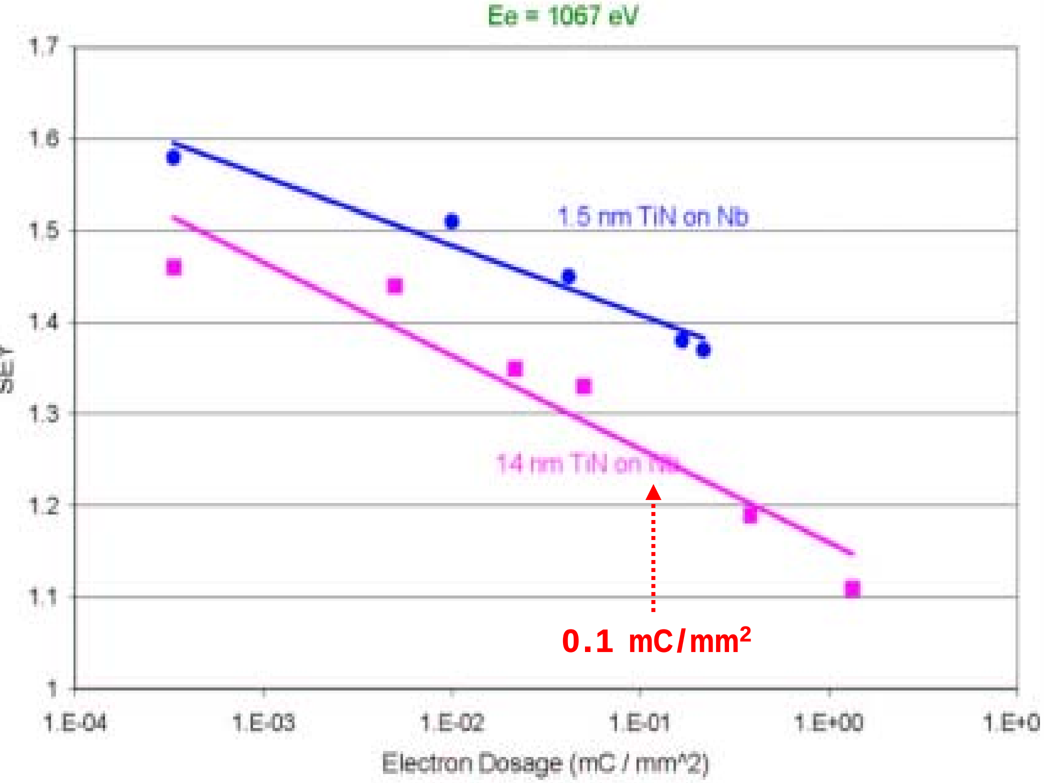


Electron cloud under a 30 G solenoid

L. Wang, BNL



SEY vs Electron Scrubbing (SLAC bench test)



0.1 mC/mm²

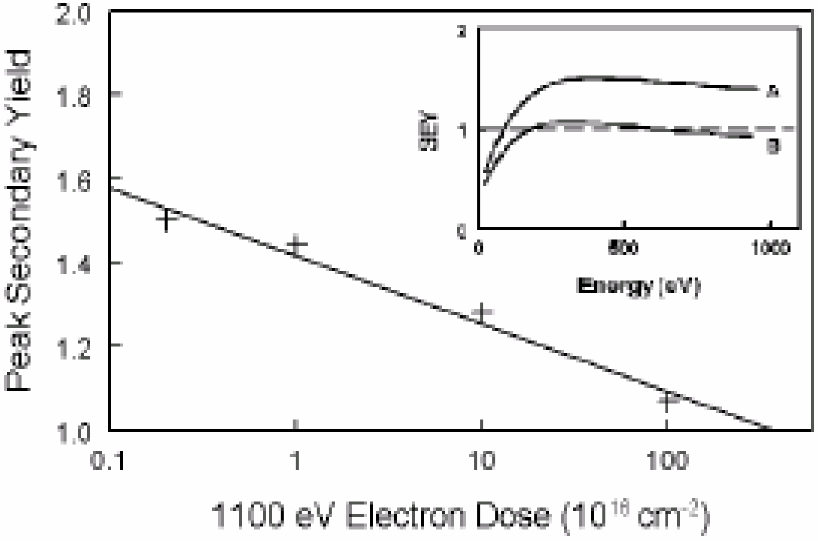


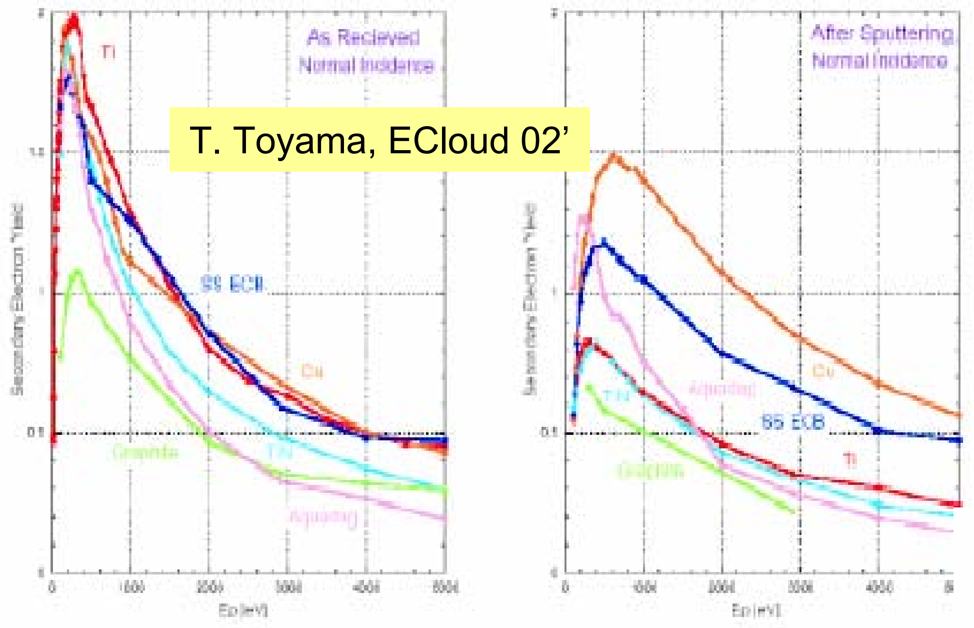
Figure 5. Peak SEY of TiN-coated Al alloy as a function of normal incidence electron beam bombardment exposure. The inset shows the complete yield curve for the first (A) and last (B) points. The data begins with a room atmosphere-exposed surface.

SEY of TiN coated Nb surface was reduced from 1.6 to 1.25 after dosage of 0.1 mC/mm^2 at 1067 eV

E. Garwin, et al., J. Appl. Phys., 61, 1145(1987)

SEY of TiN coated Al surface was reduced from 1.6 to 1.1 after dosage of 0.1 mC/mm^2 at 1100 eV

SEY vs electron and Ar scrubbing (KEK bench test)



T. Toyama, ECloud 02'

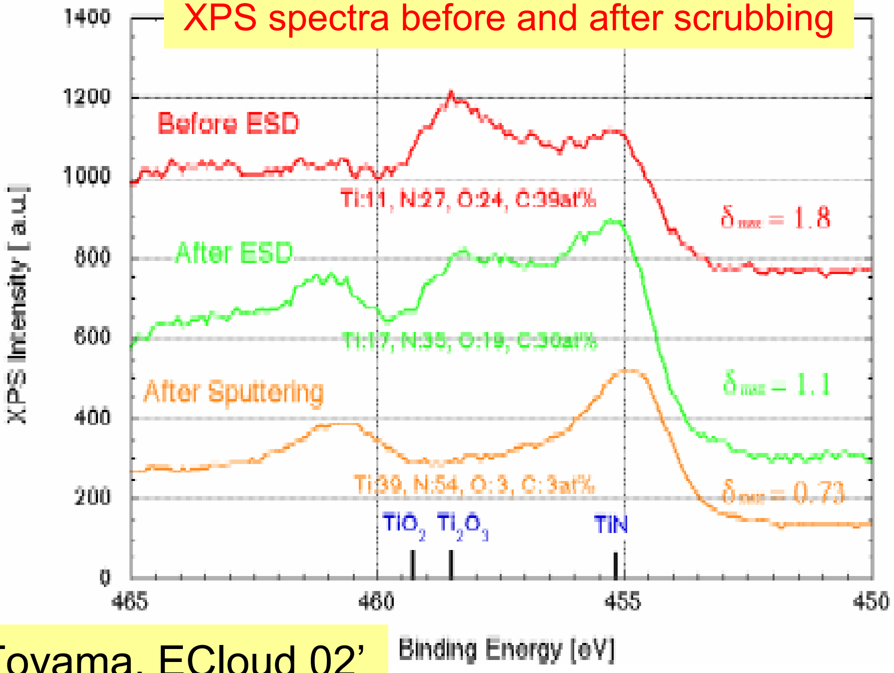
Dependence of secondary electron yields on a primary electron e
at the surfaces as-received and after sputtering.

SEY$_{max}$ of TiN/SS (light blue color) reduced from 1.9 to 0.8 after sputtering with 5 keV Ar$^+$ ions

SEY$_{max}$ decreased from 1.8 to 1.1 after e$^-$ dosage of ~100mC/mm^2 !!!

Ion scrubbing is more effective than ESD

XPS spectra before and after scrubbing

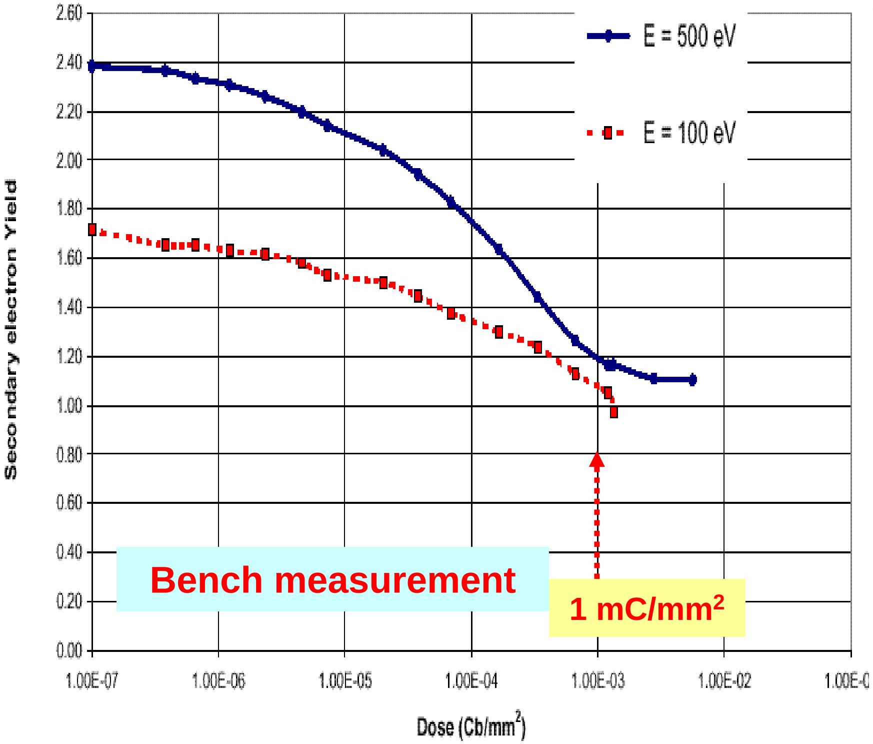


XPS spectra of TiN/SS surface after ESD and Ar$^+$ ion sputtering treatments show the removal of C and O contaminants and the corresponding decrease in SEY

Ion scrubbing cleans surface more effectively than e$^-$

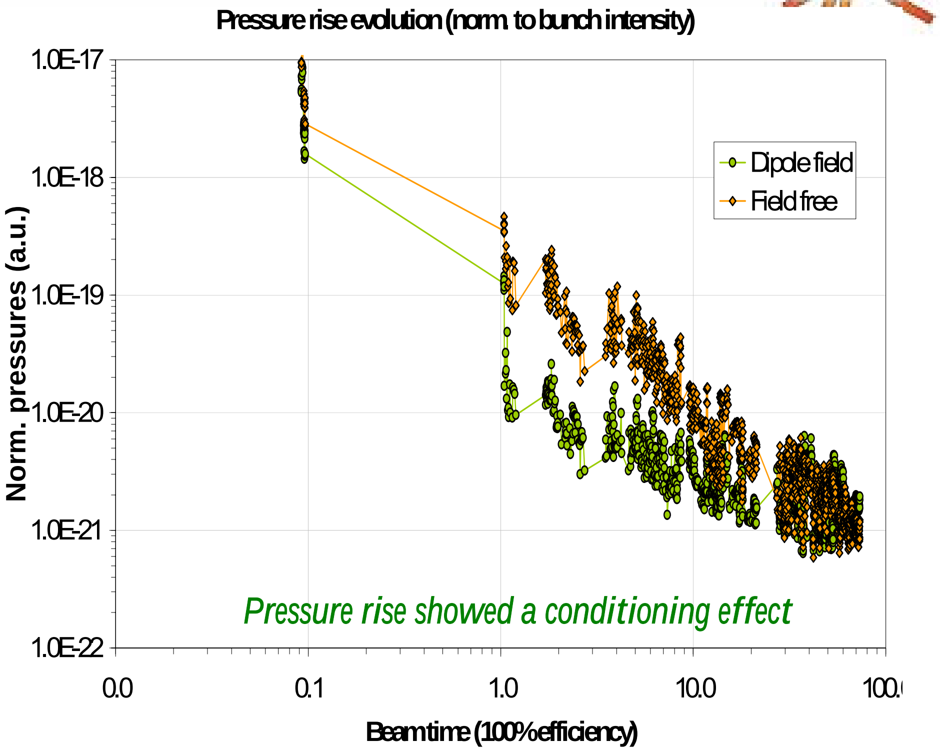
T. Toyama, ECloud 02'

CERN SEY Measurements and SPS Scrubbing



Bench measurement

1 mC/mm^2



Pressure rise showed a conditioning effect

N. Hilleret, Chmonix X, 2000

J.M. Jimenez, 13th ICFA, Dec. 2003

SEY of Cu surface decreased from 2.4 to 1.2 after 1 mC/mm^2 of 500eV electrons

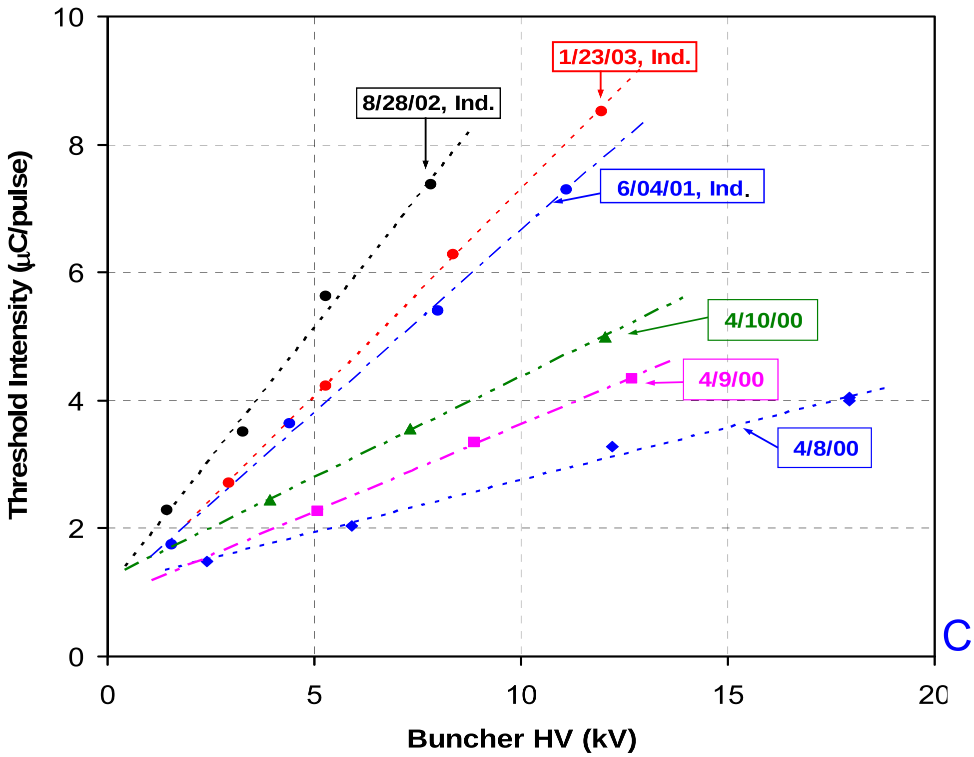
Dose in 24 hrs: ~ 0.5 mC/mm^2.

> 10^2 reduction in P after 4 days

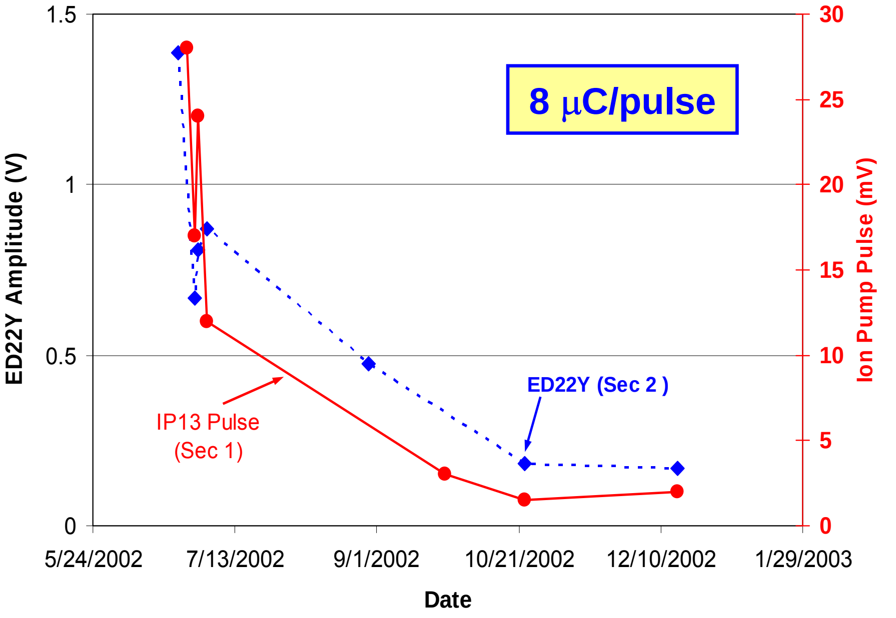
> 10^3 reduction in p after 10 days

Beam Scrubbing Experience at PSR

Effect on e-p instability threshold curves



Effect of beam scrubbing in 2003

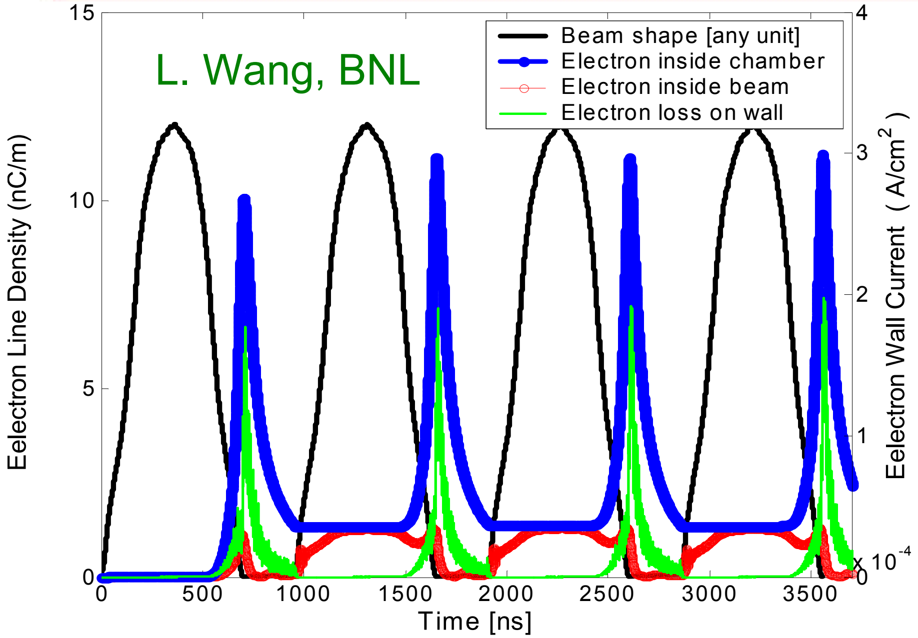


Correlation of Ion Pump Pulse with Electron Signa

R. Macek, 13th ICFA, Dec 03

Dose in 24 hrs: ~ 0.035 mC/mm^2.
ΔP ~ 1 x 10^{-7} Torr / P ~ 5 x 10^{-8} Torr.
Beam intensity threshold increased by x 2.

Beam Scrubbing in SNS



SNS Scrubbing

Assume

·Bunch intensity 2x 10^{14}.

·Peak e-current: ~ 3 μA/mm^2

·Average e-current: ~ 1 nA/mm^2.

·Accumulated dose: ~ 0.1 mC/mm^2/24hrs.

· **h** ~ 0.01 ⇒ ΔP < 1×10^{-6} Torr with ion pumps

⇒ ΔP < 1×10^{-5} by TMP

(S.Y. Zhang, BNL)

Reduction of SEY and pressure rise by beam scrubbing

- SLAC & CERN bench tests: ~1mC/mm^2 will reduce SEY from 2.2 to 1.3
- KEK sputtering with Ar^+ ions reduce SEY from 1.9 to 0.8
- SPS 2002: at P = 5×10^{-6} Torr x 24 hrs, ~0.5mC/mm^2, ΔP reduced by ~100 in 4 days.
- PSR: at P < 2×10^{-7} Torr x 24 hrs, ~0.04mC/mm^2, beam threshold increase by x2
- For SNS scrubbing: continuous inject until the pressure rise to pump limits
  - < 1×10^{-6} Torr for IP; > 1×10^{-5} Torr with turbopump.
  - More effective at high pressure (both e and ion bombardment)!

Summary

- One of the major physics challenges in SNS Ring is
  - to collect & control electrons generated at injection, collimators, and due to multipacting
- TiN coating to reduce SEY from ~ 2.5 to < 1.9
  - SEY depends on coating pressure higher P ⇒ lower SEY
  - Coating of inj. ceramic chambers, ext. kicker ferrites, …
- Tapered magnetic field and clearing electrode at Injection stripping foil
- 44 BPMs as clearing electrodes - effective at a few hundred volts
- Solenoids to confine scattered electrons at field free regions
  - B_z of 30 Gauss will be sufficient to reduce multipacting
- Beam scrubbing will reduce both SEY and outgassing
  - @ high pressure is more effective (accommodated with TMPs).