Physics Basis for Electron Storage Ring Vacuum System Design

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Important processes in particle loss

✳ Gas scattering, scattering with the other particles in the beam, quantum lifetime, tune resonances, &collisions

✳ Radiation damping plays a major role for electron/positron rings

➙For ions, lifetime is usually much longer

- Perturbations progressively build-up & generate losses

✳ Most applications require storing the beam as long as possible

==> limiting the effects of the residual gas scattering

==> ultra high vacuum technology

From: Sannibale USPAS Lecture

What do we mean by lifetime?

- Number of particles lost at time t is proportional to the number of particles present in the beam at time t

$$dN = -\alpha N(t)\, dt \qquad with \quad \alpha \equiv constant$$

- Define the lifetime $\tau = 1/\alpha$; then $N = N_0 e^{-t/\tau}$

- Lifetime is the time to reduce the number of beam particles to $1/e$ of the initial value

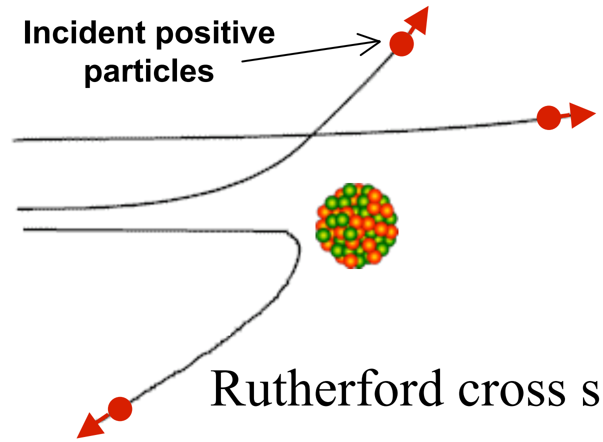
- Calculate the lifetime due to the individual effects (gas, Touschek, …)

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3} + \ldots.$$

From: Sannibale USPAS Lecture

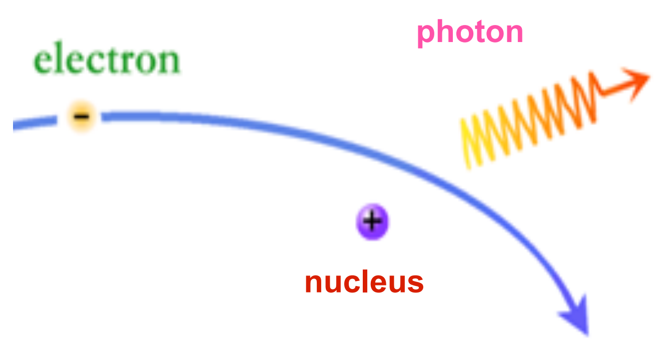
Beam loss by scattering

- Elastic (Coulomb scattering) from residual background gas
  - Scattered beam particle undergoes transverse (betatron) oscillations.
  - If the oscillation amplitude exceeds ring acceptance the particle is lost



Rutherford cross section

- Inelastic scattering causes particles to *lose energy*
  - Bremsstrahlung or atomic excitation
  - If energy loss exceeds the momentum acceptance the particle is lost



Bremsstrahlung cross section

Elastic scattering loss process

- Loss rate is $\left.\frac{dN}{dt}\right|_{Gas} = -\phi_{beam\ particles} N_{molecules} \sigma^*_R$

$$\phi_{beam\ particles} = \frac{N}{A_{beam} T_{rev}} = \frac{N}{A_{beam}} \frac{\beta c}{L_{ring}}$$

$$N_{molecules} = n A_{beam} L_{ring}$$

$$\sigma^*_R = \int_{Lost} \frac{d\sigma_{Rutherford}}{d\Omega} d\Omega = \int_0^{2\pi} d\varphi \int_{\theta_{MAX}}^{\pi} \frac{d\sigma_{Rutherford}}{d\Omega} \sin\theta \, d\theta$$

$$\frac{d\sigma_R}{d\Omega} = \frac{1}{(4\pi\varepsilon_0)^2} \left(\frac{Z_{beam} Z_{gas} e^2}{2\beta c\, p} \right)^2 \frac{1}{\sin^4(\theta/2)} \quad [MKS]$$

Gas scattering lifetime

- Integrating yields

$$\left.\frac{dN}{dt}\right|_{Gas} = -\frac{\pi\, n\, N \beta\, c}{(4\pi\,\varepsilon_0)^2}\left(\frac{Z_{Inc} Z e^2}{\beta\, c\, p}\right)^2 \frac{1}{\tan^2(\theta_{MAX}/2)}$$

Loss rate for gas elastic scattering [MKS]

- For M-atomic molecules of gas $n = M\, n_0 \dfrac{P_{[Torr]}}{760}$

- For a ring with acceptance ε_A & for small θ $\langle\theta_{MAX}\rangle = \sqrt{\dfrac{\varepsilon_A}{\langle\beta_n\rangle}}$

==>

$$\tau_{Gas} \cong \frac{760}{P_{[Torr]}} \frac{4\pi\varepsilon_0^2}{\beta\, c\, M\, n_0}\left(\frac{\beta\, c\, p}{Z_{Inc} Z e^2}\right)^2 \frac{\varepsilon_A}{\langle\beta_T\rangle} \quad [MKS]$$

Inelastic scattering lifetimes

- Beam-gas bremsstrahlung: if E_A is the energy acceptance

$$\tau_{Brem[hours]} \cong -\frac{153.14}{\ln\left(\Delta E_A / E_0\right)} \frac{1}{P_{[nTorr]}}$$

- Inelastic excitation: For an average $ß_n$

$$\tau_{Gas[hours]} \cong 10.25 \frac{E^2_{0[GeV]}}{P_{[nTorr]}} \frac{\varepsilon_{A[\mu m]}}{\langle \beta_n \rangle_{[m]}}$$

Touschek effect: Intra-beam Coulomb scattering

- Coulomb scattering between beam particles can transfer transverse momentum to the longitudinal plane
  - If the $p_{||}+\Delta p_{||}$ of the scattered particles is outside the momentum acceptance, the particles are lost
  - First observation by Touschek at ADA e^+e^- ring
- Computation is best done in the beam frame where the relative motion of the particles is non-relativistic
  - Then boost the result to the lab frame

$$\frac{1}{\tau_{Tousch.}} \propto \frac{1}{\gamma^3}\frac{N_{beam}}{\sigma_x\sigma_y\sigma_S}\frac{1}{\left(\Delta p_A/p_0\right)^2} \propto \frac{1}{\gamma^3}\frac{N_{beam}}{A_{beam}\sigma_S}\frac{1}{\hat{V}_{RF}}$$

Why must high luminosity colliders operate at very low pressures ?

1) Background gas causes beam loss via

- ➙ Elastic scattering
- ➙ Inelastic scattering (bremsstrahlung)
- ➙ Ion trapping

✺ Beam lifetime:

$$\frac{1}{\tau_g} = \frac{1}{N_b}\frac{d\,N_b}{dt} = 3.22 \times 10^{22}\, n_z\, P_{Torr}\, \beta c\, (\sigma_{el} + \sigma_{Br})$$

where n_z is the number of molecules of species z.

✺ At high energy bremsstrahlung dominates. We expect

$$\tau_g \approx 3 \text{ hr @ } 10 \text{ nTorr}$$

… & near the collision point

2) Hard photons & scattered electrons striking apertures generate backgrounds in the detector (depends on masking and lattice)

- Background µ Pressure in interaction region
- Sources of gas:
  - Thermal out-gassing,
  - Photo-desorption
  - Leaks)

Generic issues of vacuum system design

- Thermal loads: 1 - 5 kW/m —> 5 – 40 kW/m
  - ➙ Cooling, thermal fatigue, 7 technical risk issues
- Photon flux: 5×10^{17} photons/s/m —> $\approx 10^{19}$
  - ➙ Chamber materials & preparation for low design η
  - ➙ Commissioning time
- Choice of materials: Stainless steel —> cladded Al & Cu
  - ➙ Fabrication & cost issues
- Chamber shape: elliptical ==> Complex (antechambers)
  - ➙ affects fabrication complexity, costs, magnet designs
- Pumping speeds: 100 - 300 L/s/m —> up to 3000 L/s/m
  - ➙ impacts choice of pumps, chamber design
- High current increases consequences of fault modes

Low risk designs

are based on

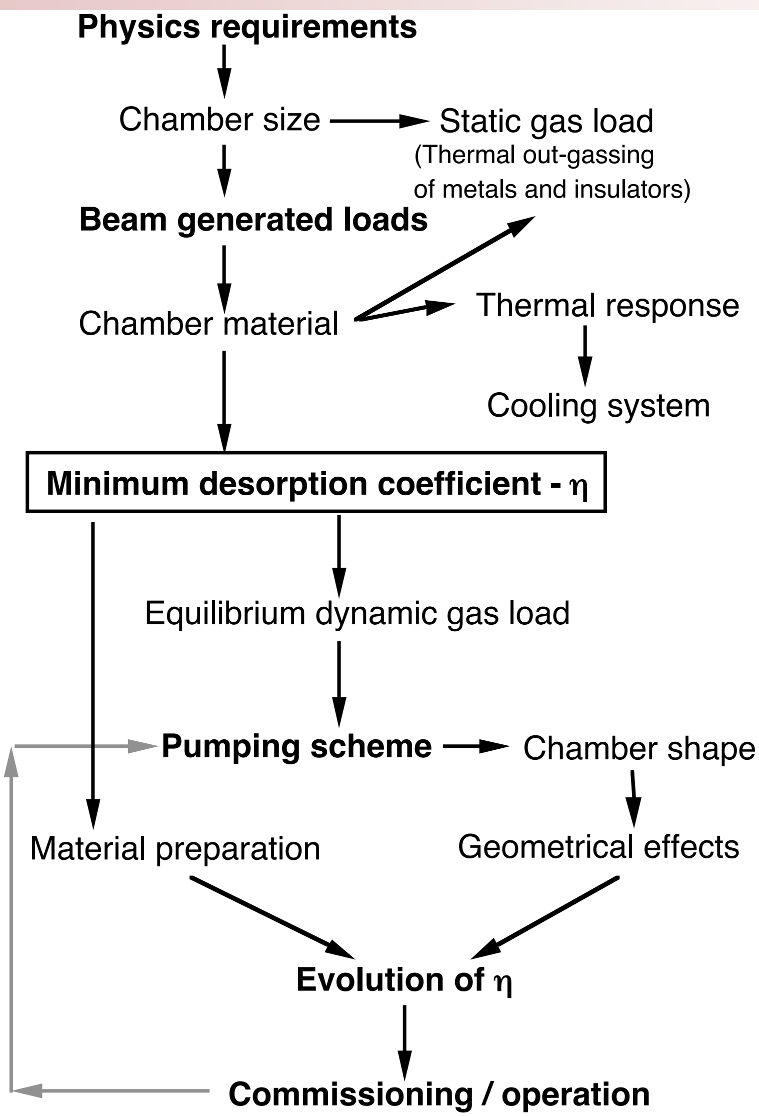
proven technologies &

sound engineering practices

Vacuum System Components

- Beam chamber
  - Provide sufficient beam aperture
  - Provide good vacuum environment
  - Shield magnets, electronics from synchrotron radiation (SR)
- Pumping system
  - Maintain operating vacuum
    - 1 - 10 nTorr in arcs
    - 1 - 3 nTorr in straight sections
    - ≈ 0.2 nTorr near IR
  - Provide for rapid commissioning
- Cooling system
  - Waste heat removal at high synchrotron radiation flux
  - Ensure mechanical stability of chamber
- Special components
  - Ports, Bellows, Transitions, Diagnostics
  - Consistent with low impedance

Iterative design of vacuum system



Thermal load from radiation

- Distributed over the dipole arcs the average thermal load is

$$P_L = 1.26 \text{ kW/m } E^2_{GeV} I_A B^2_T$$

- In terms of collider parameters this yields

$$P_L = 19.5 \frac{\text{kW}}{\text{m}} \left(\frac{L}{10^{34}}\right)\left(\frac{\beta_y^*}{1 \text{ cm}}\right)\left(\frac{0.03}{\xi}\right)\left(\frac{B_D}{1 \text{ T}}\right)^2 \frac{E_{GeV}}{1+r}$$

==> 5 kW/m (PEP-II) - 40 kW/m @ 3 x 10^{33} cm^{-2} s^{-1} in B factory designs (9 GeV, 3 A)

- Small beam height raises issue of thermal fatigue, influences choice of alloy; even 10 kW/m --> residual plastic strain
- Cycles to fatigue failure is a strong function of residual strain

Design approach for PEP-II: 1) Keep material in elastic regime; 2) Keep high load regions always in compression

==> Minimized technical risk in engineering realization

Choosing material of vacuum chambers

	Al	Cu	SS
Photo-desorption	+	++	++
Self-shielding	-	++	++
Thermal conductivity	+	+ to ++	-
Strength	+	- to +	++
Ease of fabrication	++	+	++
Experience	++	+	++
Cost	$	$$	$$

- Choice for PEP-II is Class 1 OFE Cu:
  - superior vacuum properties
  - superior thermal properties - eases thermal management
  - superior self-shielding - eliminates Pb cladding

Thermal loads in e^+ & e^- rings

- Each beam generates a synchrotron radiation power, P_{sr},

$$P_{sr} = 88.5 \text{ Watts } E^4_{GeV} I_{mA} / \rho_m , \qquad (1)$$

or in terms of the B-field in Tesla,

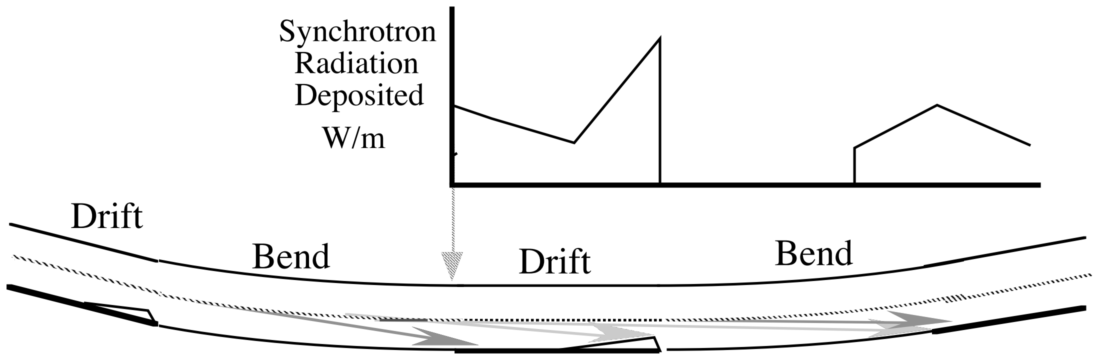
$$P_{sr} = 26.5 \text{ kW } E^3_{GeV} I_A B_T$$

- Were the radiation is deposited over $2\pi\rho$, the linear power density deposited by each beam on the walls, P_L, would be

$$P_L = 1.26 \text{ kW/m } E^2_{GeV} I_A B^2_T$$

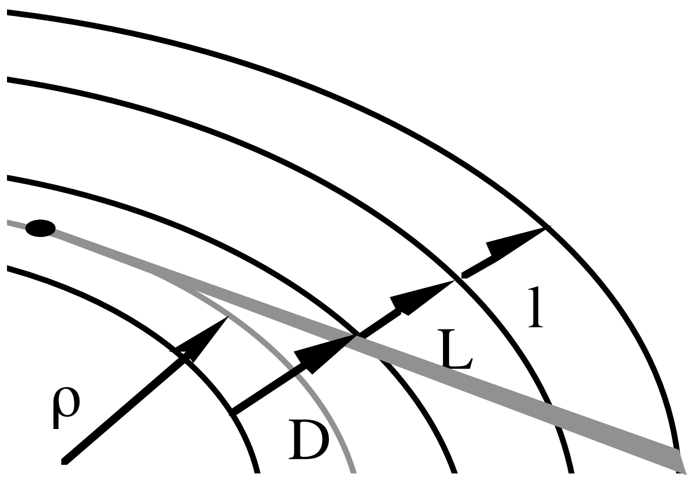
But, the power is not deposited uniformly along the vacuum chamber

Examples of non-uniform power deposition



- Another example, for a phi factory, E = 0.51, B_T = 4 T, & I = 1.2 A.
  - The average thermal load per beam is ≈ 6 kW/m.
  - Both beams circulate in the same ring ==> radiation fans overlap at the center of the bends ==>
  - local thermal load of ≈12 kW/m for an conventional elliptical vacuum chamber.

Geometry of chamber and radiation fan



Areal power density

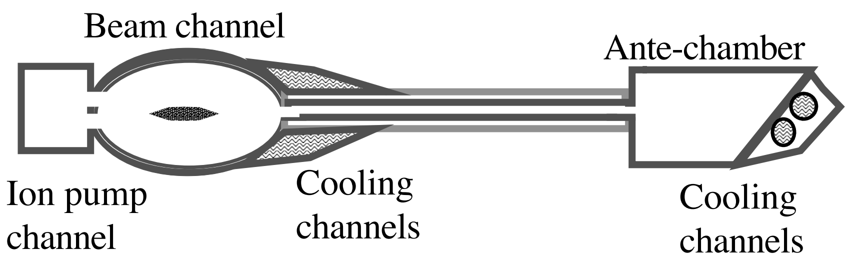
- Power density on the walls depends on the height, h, of the radiation fan at the wall
- h is a function of radiation angle from the beam & on distance, d, from the beam orbit to the wall

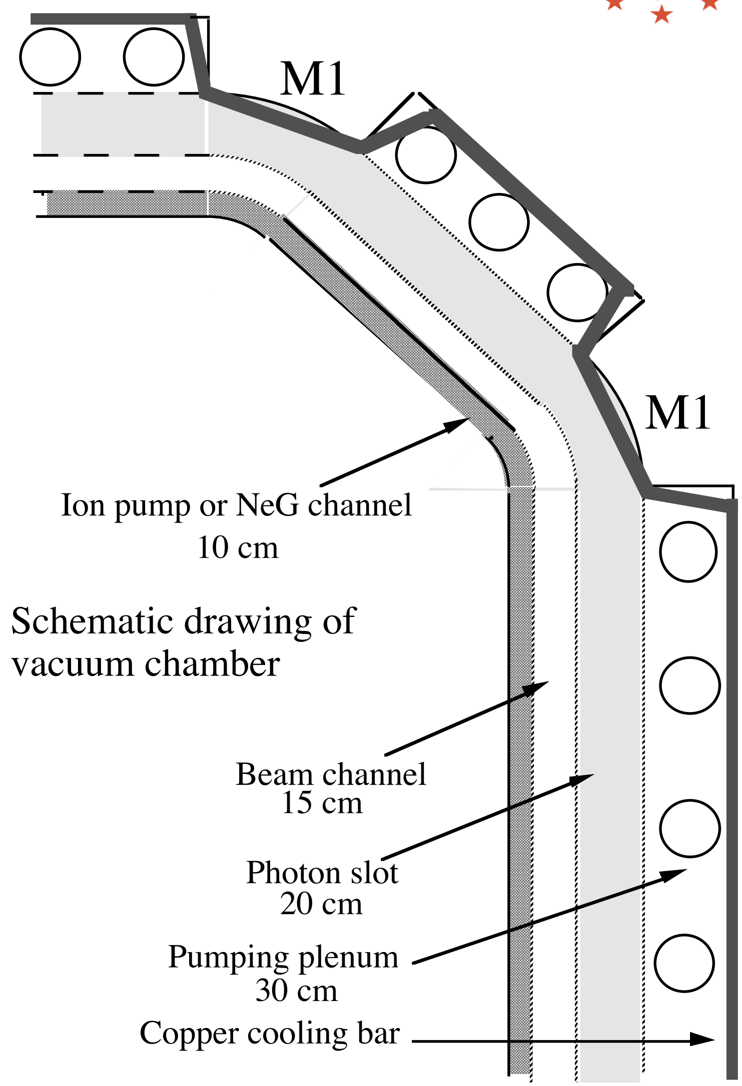
$$\theta \approx \frac{m\,c^2}{E} = \gamma^{-1} \qquad (4)$$

- The vertical spread of the fan is

$$h = \pm\left[\sigma_y^2 + d^2\left(\left(\frac{\varepsilon}{\sigma}\right)_y^2 + \theta^2\right)\right]^{1/2}. \qquad (5)$$

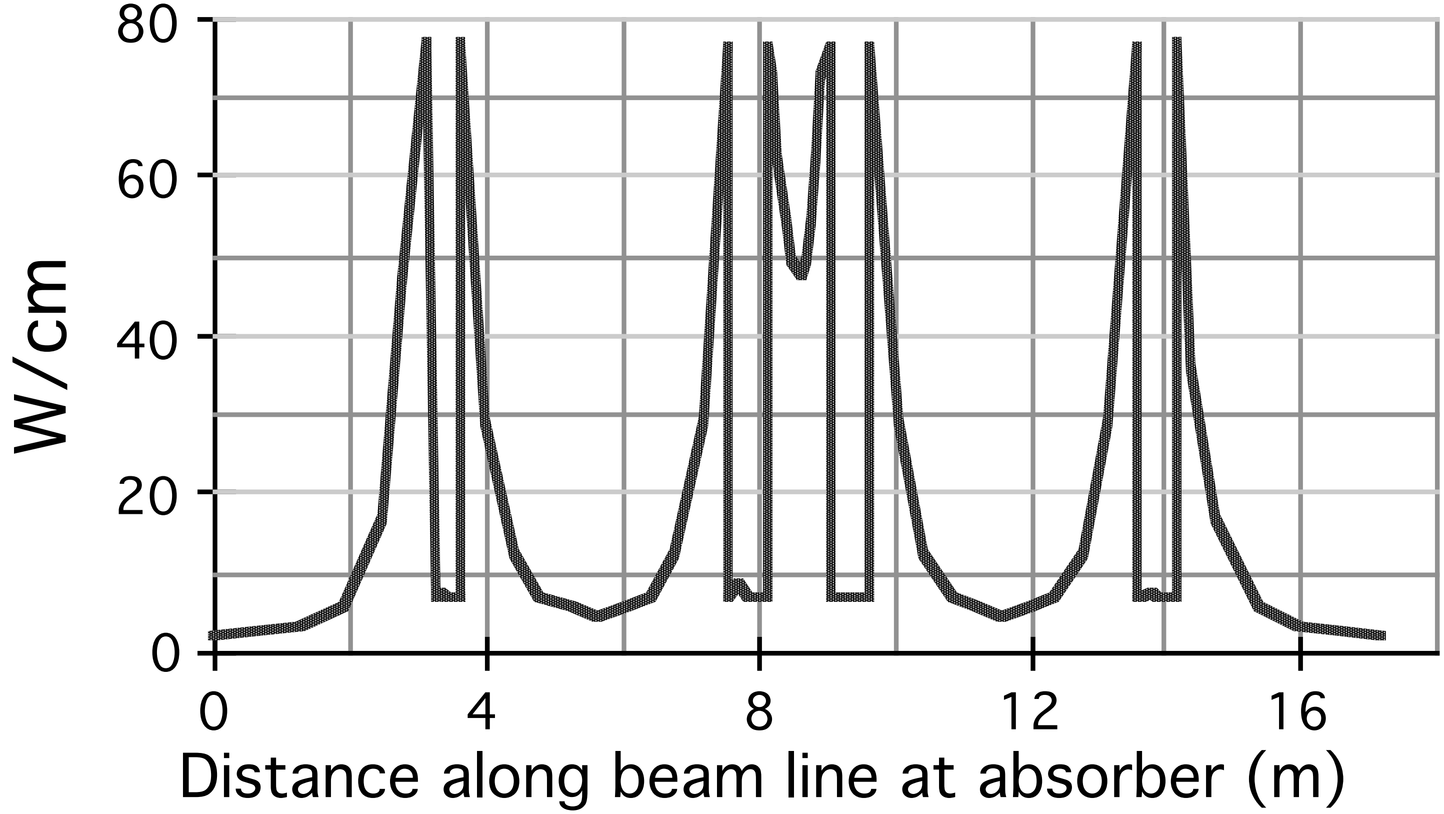
Phi factory example



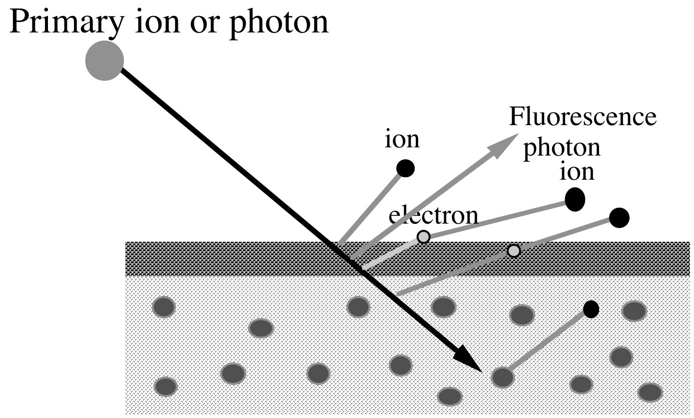


For beam chamber of width D = 0.27 m, connected via a thin duct of length, L = 0.2 m, to an ante-chamber of width, l = 0.14 m with ρ = 0.42 m, the distance to the wall, d = 0.79 m. Thus, from Eq. (5) h = ±5 mm in the central dipole of the arcs and ± 2 mm elsewhere. For the phi factory $P_{sr} \approx$ 36 kW, and the maximum power density is ≈180 W/cm^2.

Actual distribution along the beamline



Photodesorption produces large dynamic gas load



Scaling of desorption (for photons):

- Weak energy dependence $< \sqrt{E}$
- Angular dependance $< 1/(\sin \phi)$
- Strong variation with surface treatment
- Strong variation with surface exposure
- Strong variation with desorbed species

For beam scattering limits use CO equivalents

For pump regeneration times use molecular load

PEP-II design is based on experiments conducted as part of our R&D program

Conservative design accounts for non-uniformity of radiation distribution

- The critical parameter, η_F, is a non-linear function of

  1) photon dose (>10-to-1 variation in LER)

  2) material

  3) fabrication and preparation

  4) incidence angle of photons

  5) photon energy

  ==> Regard η as an average engineering parameter

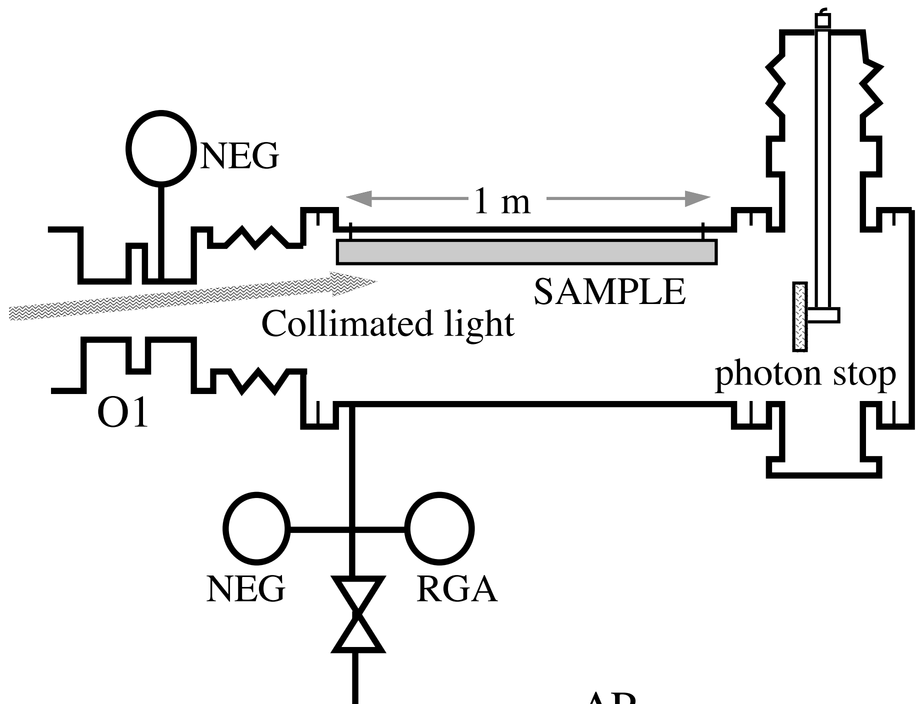
- Accurate modeling of gas load & ring commissioning accounts for the variation in dose to the chamber due to

  1) bend v. straight chamber geometry

  2) illumination by primary v. secondary photons

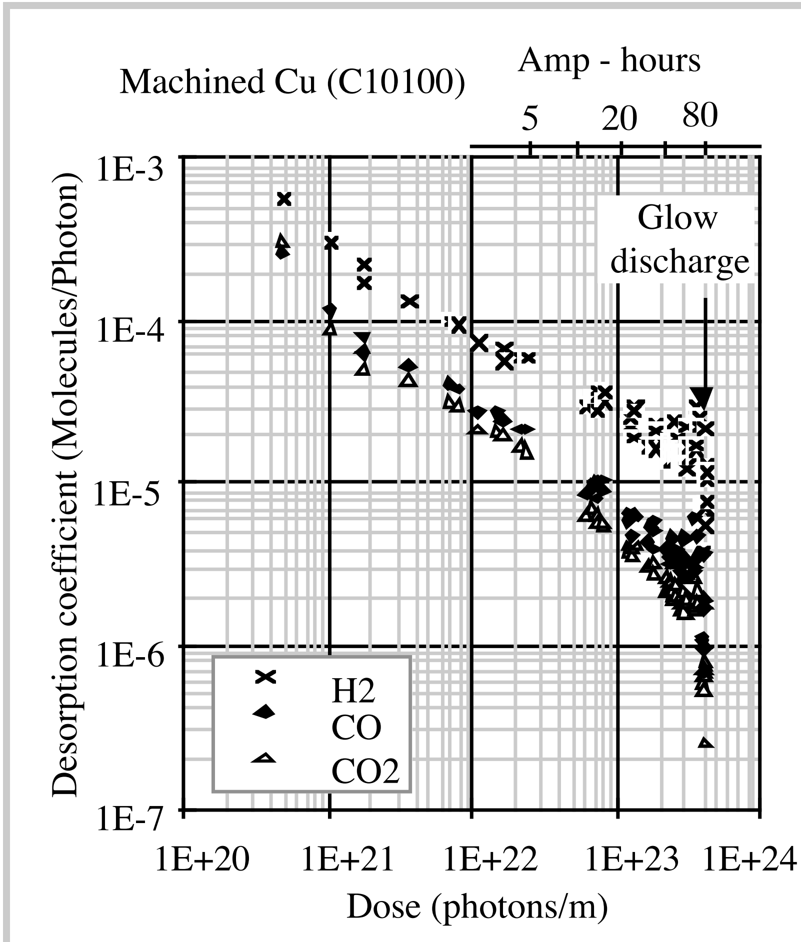
We measured η for many materials

Sample chamber: stainless steel, baked 2 days @ 200 C
In-situ Ar glow discharge after 3×10^{23} photons / m



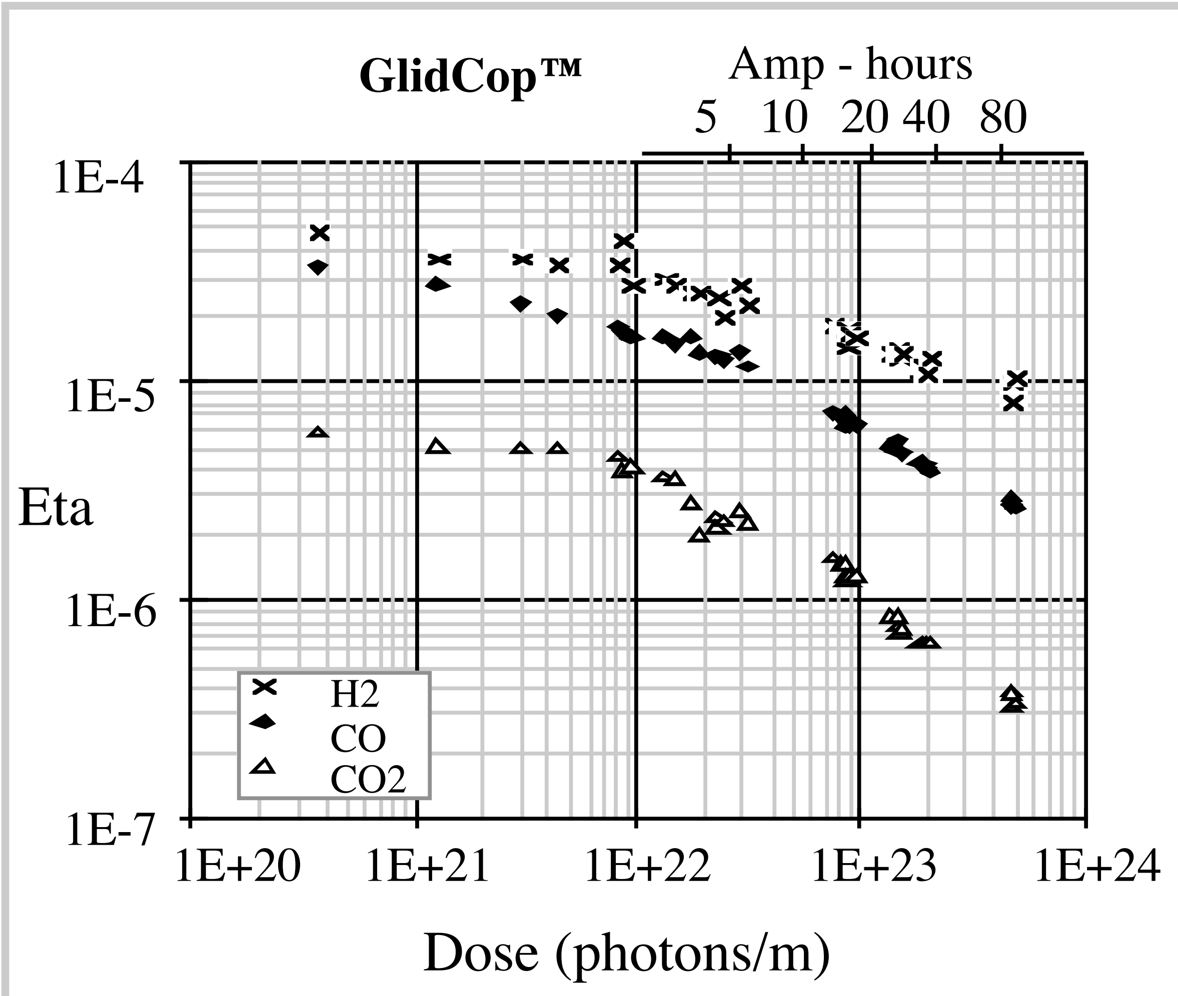
$$\eta_i = \frac{G\ S_i \dfrac{\Delta P_i}{I}}{\dfrac{\dot{N}}{I\ \Theta}}\ . \qquad (2)$$

We measured η for many materials

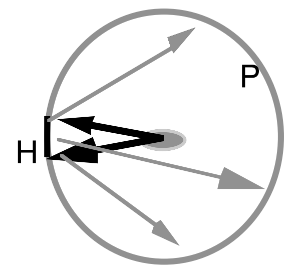


$$\eta \propto (It + t_o)^{-p} \qquad (10)$$

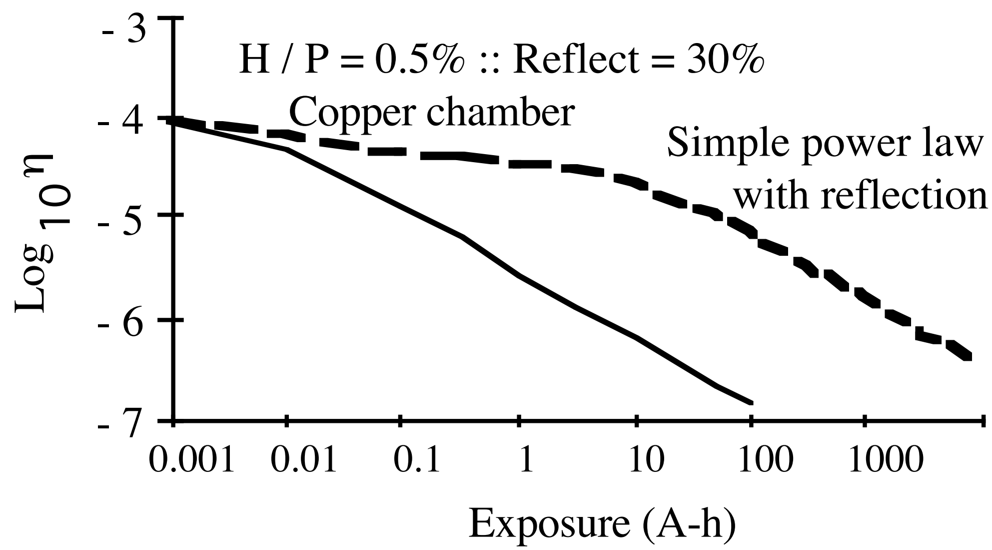
Desorption for dispersion strengthened Cu



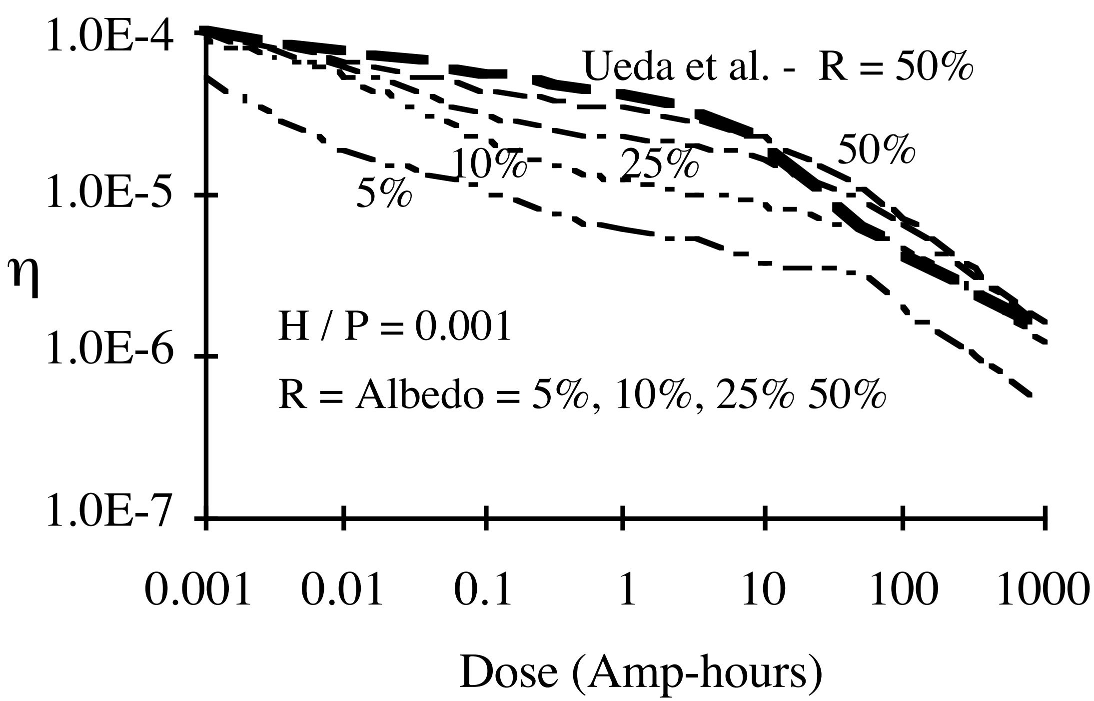
Effective desorption probability



$$\eta \propto (It + t_o)^{-p} + R\left(It\frac{RH}{P} + t_o\right)^{-p} \quad (12)$$

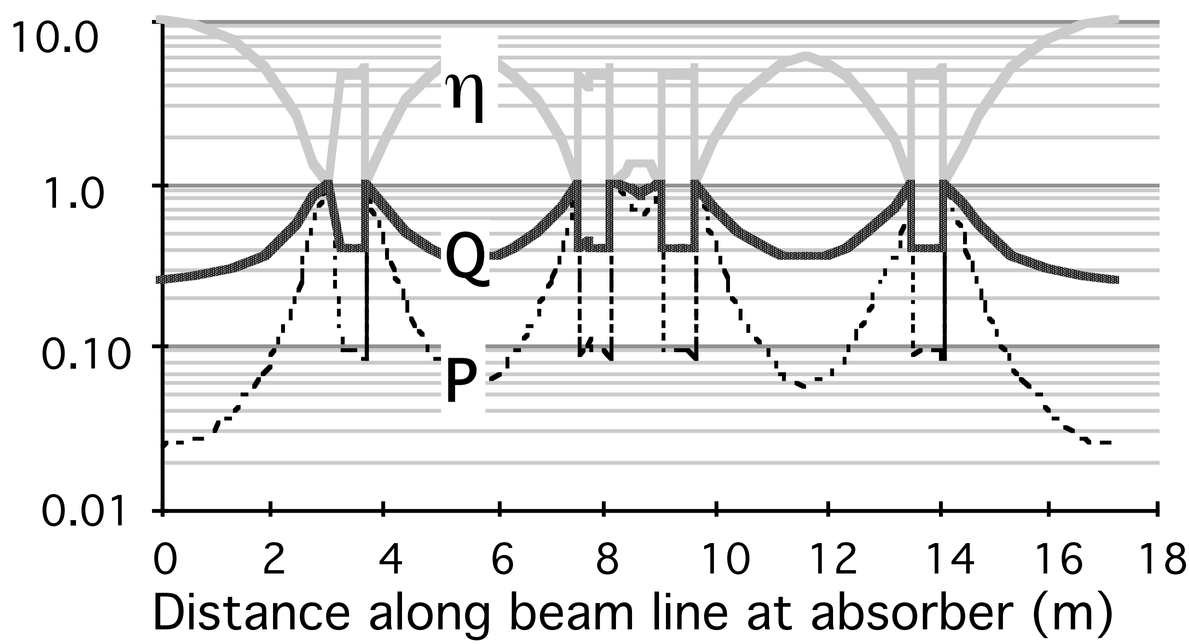


η depends on chamber albedo



Modeling η for a chamber

- Actual rate is governed by the scattered photons that clean the majority of the surface
- Gas load is leveled —> Much more pumping is required
- Commissioning times are extended



Translation from SR power to gas load

- At a temperature of 300 K, this number of molecules corresponds to a total dynamic gas load of

$$Q\ (\mathrm{gas}) = \dot{N}\ (\mathrm{gas}) = 2.4\mathrm{x}10^{-2}\ E_{GeV}\ I_{mA} \eta_F \ \frac{\mathrm{Torr - l}}{\mathrm{s}}\ .$$

- Assume ring is maintained at pressure P
  - ➙ neglect loss of effective pumping speed due to finite conductance ==> supply total pumping

$$S = \frac{P}{Q}\ .$$

Gas loads set pumping requirements

- Therefore

$$Q\ (\text{gas}) = \dot{N}\ (\text{gas}) = 2.4\text{x}10^{-2}\, E_{GeV}\, I_{mA} \eta_F \frac{\text{Torr - l}}{\text{s}}\ .$$

- In terms of collider parameters the pumping requirement is

$$S = 1.2 \times 10^5\ \frac{\text{L}}{\text{s}} \left(\frac{\mathsf{L}}{10^{34}}\right)\left(\frac{\beta_y^*}{1\ \text{cm}}\right)\left(\frac{0.03}{\xi}\right)\left(\frac{10\ \text{nTorr}}{P}\right)\left(\frac{\langle \eta_F \rangle}{2\ \text{x}\ 10^{-6}}\right)$$

- For $\eta_{F,min} = 2\ \text{x}\ 10^{-6}$

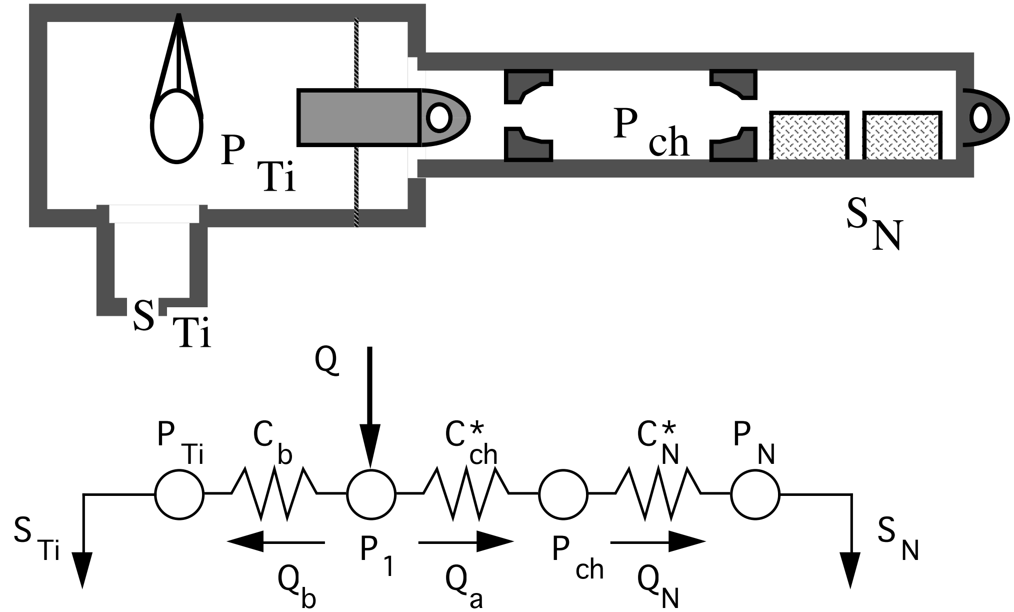
==> ~ 125 L/s/m (PEP-II) to 3000 L/s/m in some B factory designs (Cornell)

Options

- S < 200 L/s/m allows simple pumping scheme with distributed ion pumps & avoids complex chamber shapes.
  - The larger the ring, the lower the technical risk & conversely
  - Complication: Radiation directed at pumps can lead to ion problems (HERA experience) in wigglers or wiggler lattices
    - No direct illumination
- For 200 < S < 700 L/s/m NEGs may be attractive.
  - Excellent for high speed *especially* if gas load is small
  - Complication is frequent regeneration due to large gas loads

For very high pumping speeds

- S > 1000 L/s/m generally requires Titanium sublimation pumps & complex shapes
  - ➞ Cost-effective means to produce high speeds



Example from early B-factory design

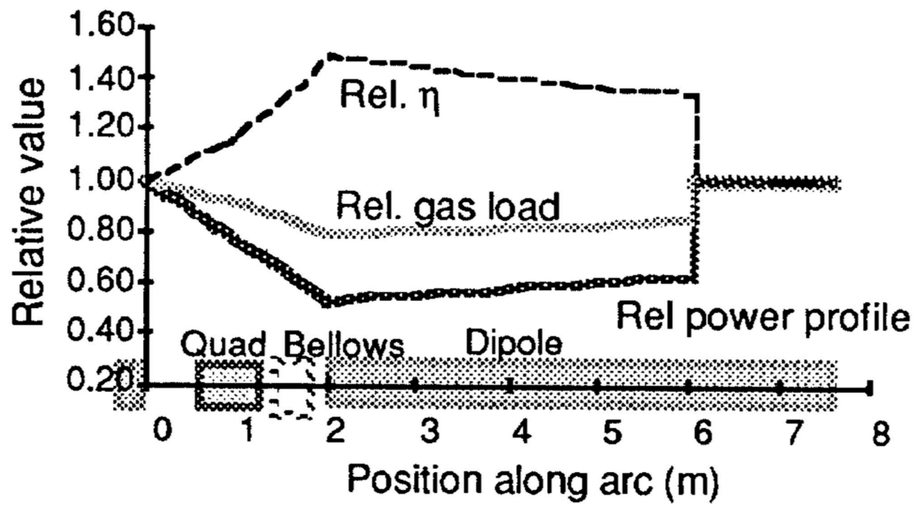


Figure 1. Relative distribution of synchrotron radiation, η, and gas load in arcs of 9 GeV APIARY ring.

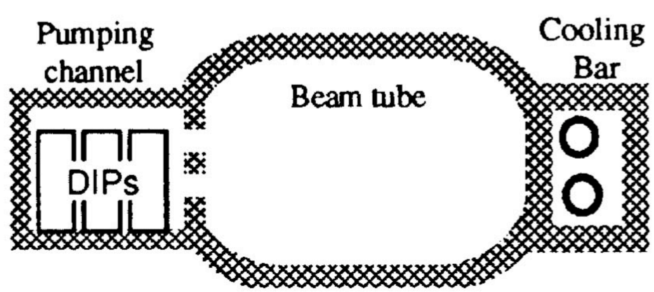
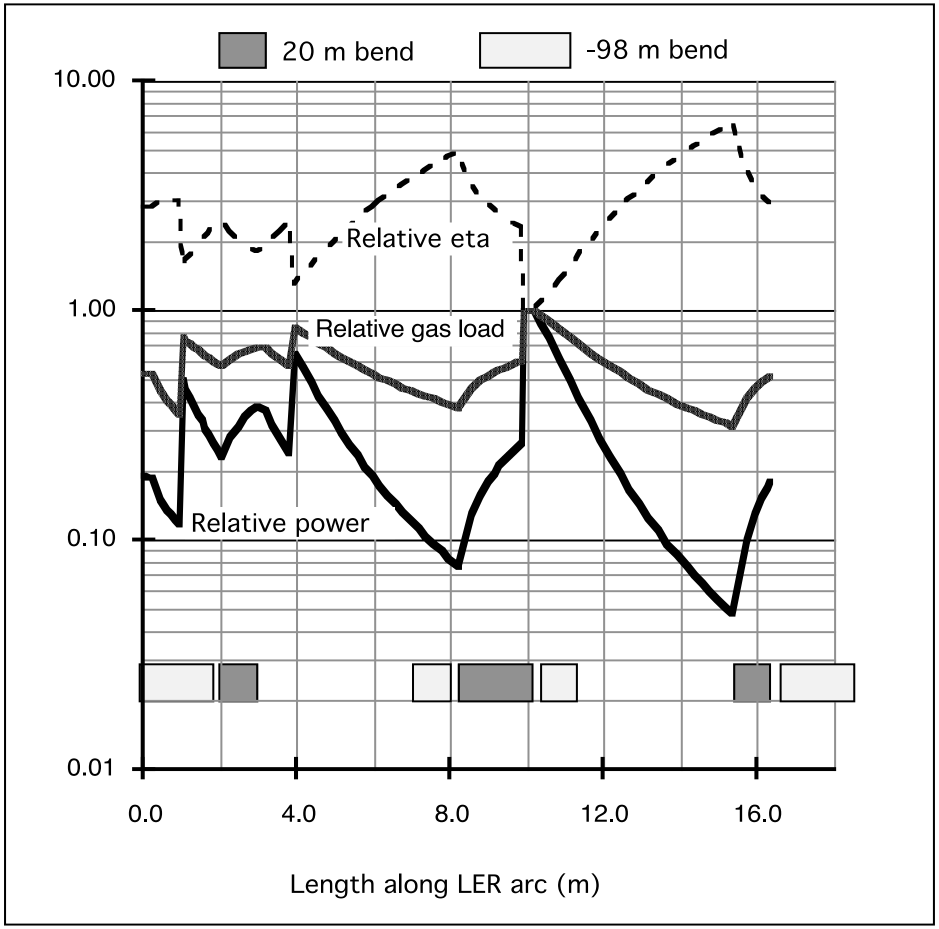


Figure 2. Cross section of the HER arc vacuum chamber.

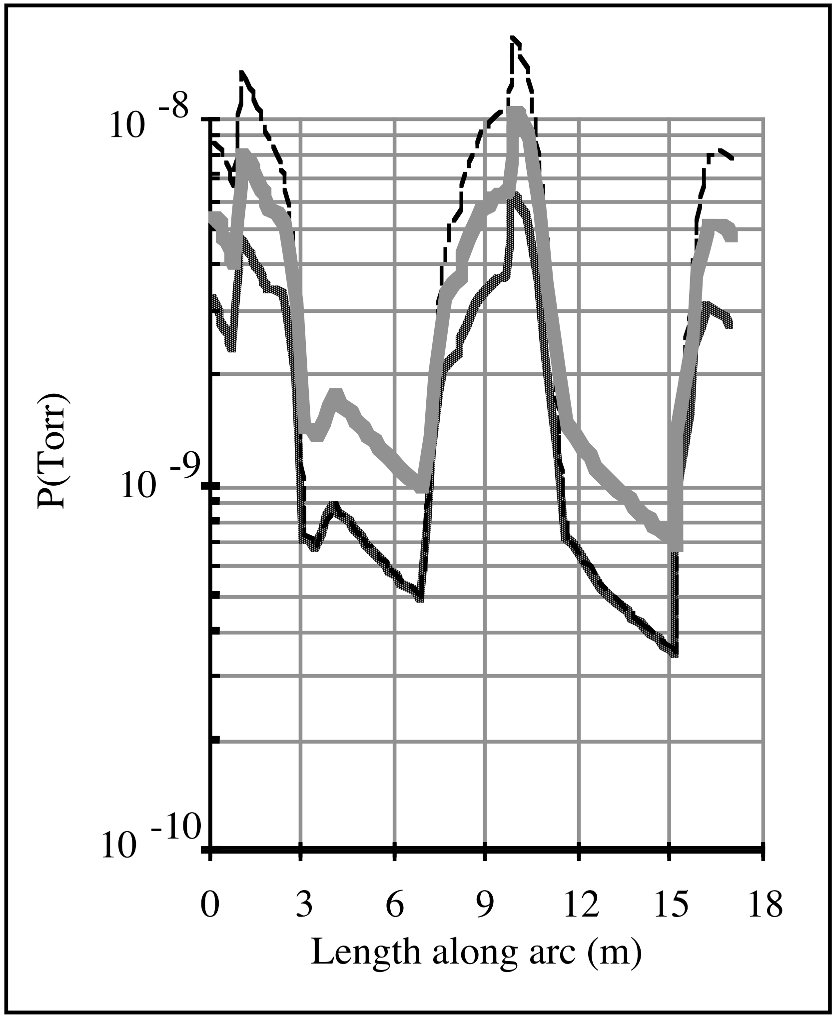
Relative desorption characteristics in tunnel arcs of the CESR-B LER



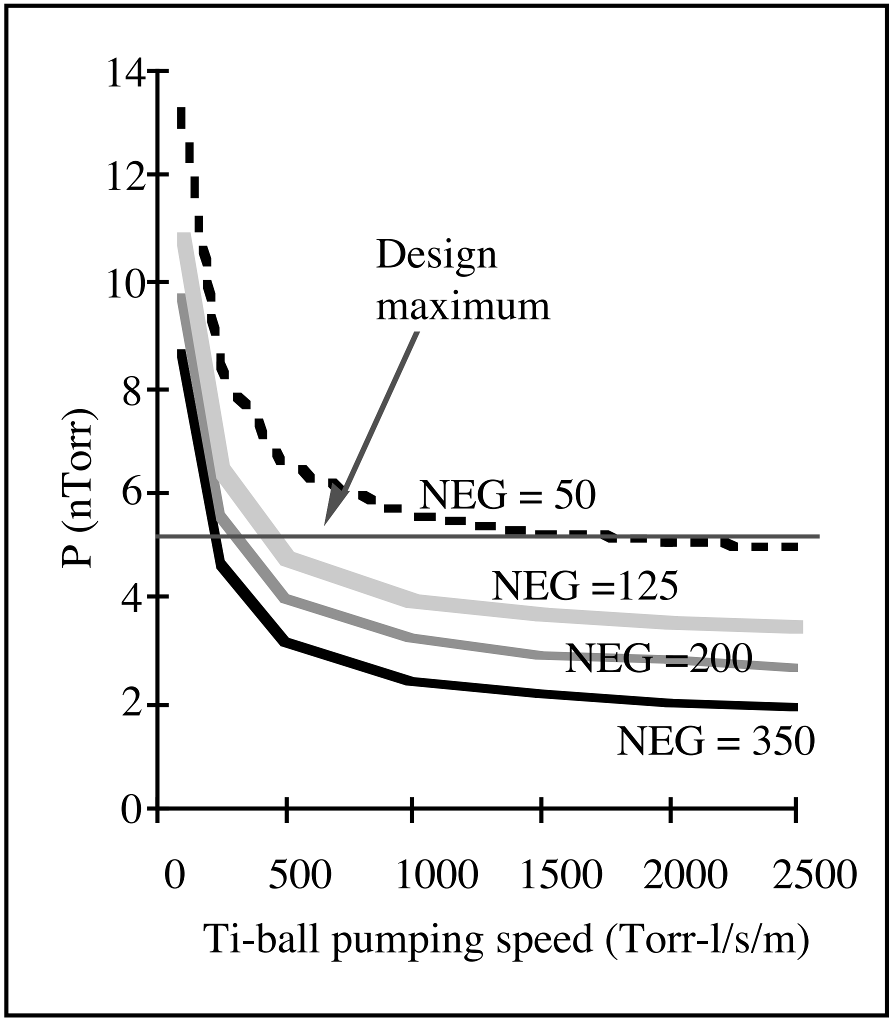
Relative value = 1.0 corresponds to

$\eta = 1.7 \times 10^{-6}$, $Q = 2.3 \times 10^{-6}$ Torr-l/s/m and P = 10.4 kW/m

Translating to gas loads



Now adding pumping

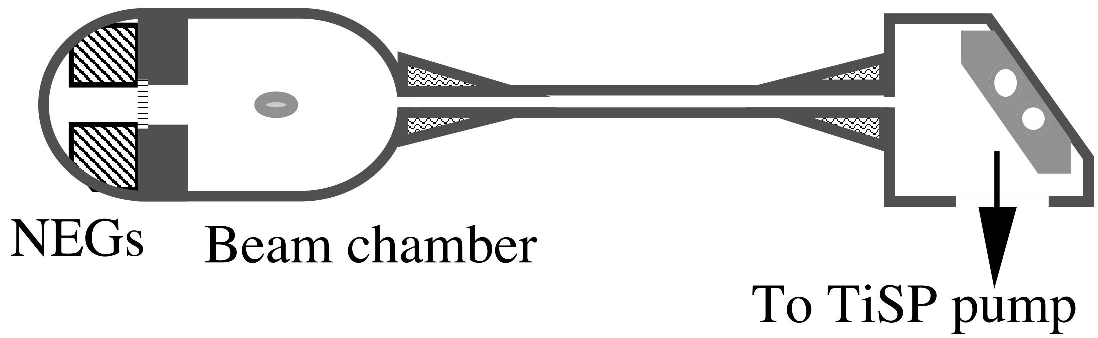


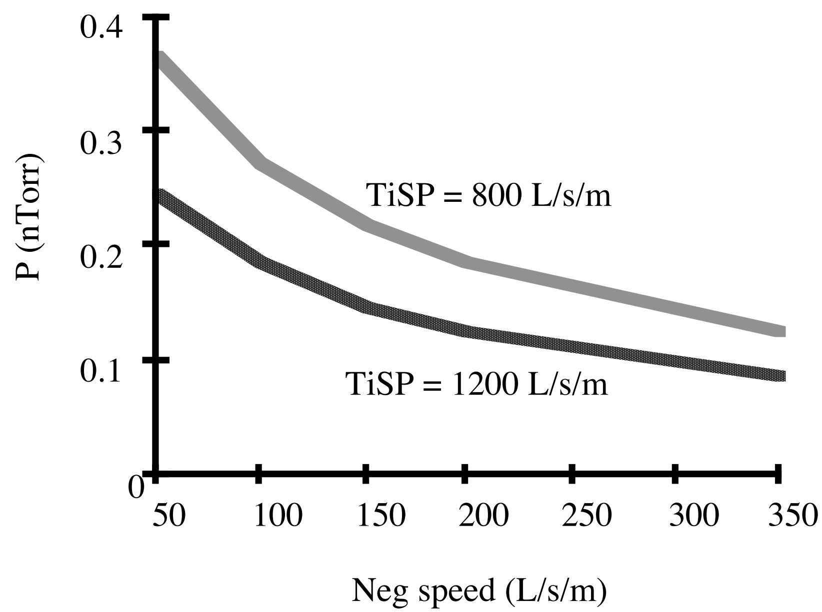
UCLA Phi Factory design

Radiation characteristics	
Critical energy (keV)	0.69
Linear power density (W/cm)	76.79
Photons/sec	9.9E+20
Specific photon flux (A-1 m-1 s-1)	1.5E+20
Photon flux at I max (s-1 m-1)	3.7E+20
Dose equivalent (photons m-1 / A-h)	5.5E+23
Gamma cone angle (mrad)	1.0E+00
Photoelectron current (A m-1) at I max	1.53
gamma1	998.0

Summary Vacuum charcteristics	
Design eta	2.0E-06
Desired base pressure (nTorr)	5
Desorbed molecules - steady	2.0E+15
Gas load (Torr-l/s)	6.0E-05
Distributed load (Torr-l/s/m	1.4E-05
Required pumping (l/s)	1.2E+04
Linear pumping in arc (l/s/m)	2.71E+03

To get to 0.1 nTorr vacuum





NEG cannot be abused

- NEGs & TSPs have a finite capacity,
  - → they must periodically be heated to high temperature to allow the chemsorbed gases to migrate to the interior of the material

	Virgin(l/s/m)	5 exp. (l/s/m)	10 exp (l/s/m)
1 row	680	340	270
2 rows	1360	680	540

Pumping characteristics of WP950 NEGs for CO (Halama et al)

Implication for commissioning PEP-II: Lifetime v. Amp-hours

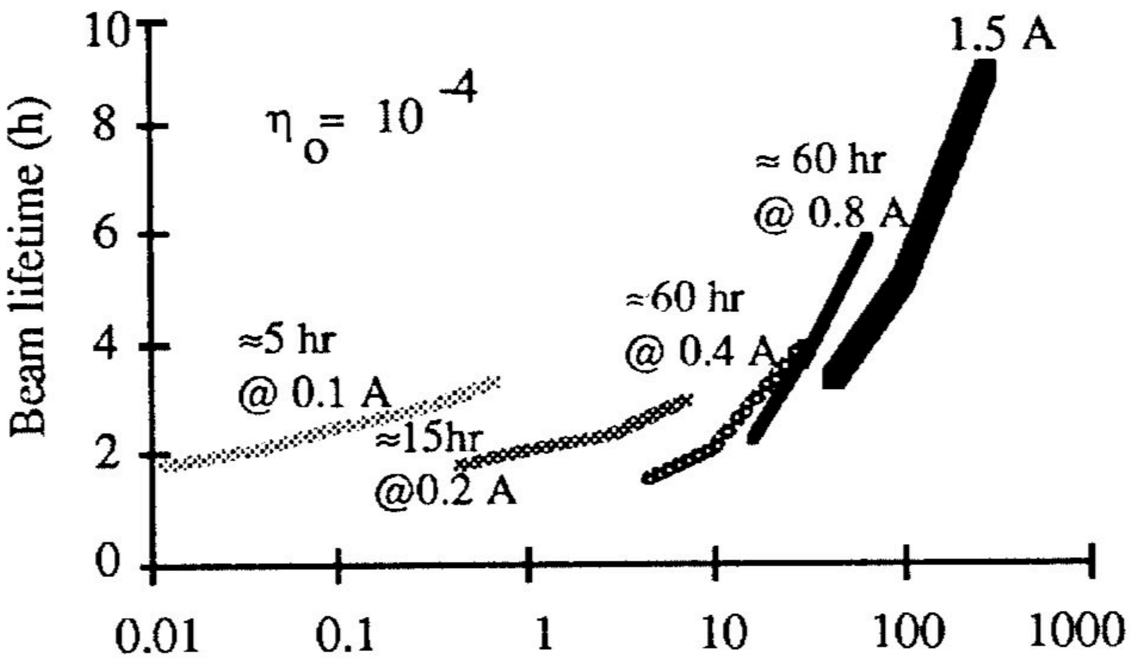


Figure 6. Commissioning scenario for the APIARY ring with an etched Cu vacuum chamber