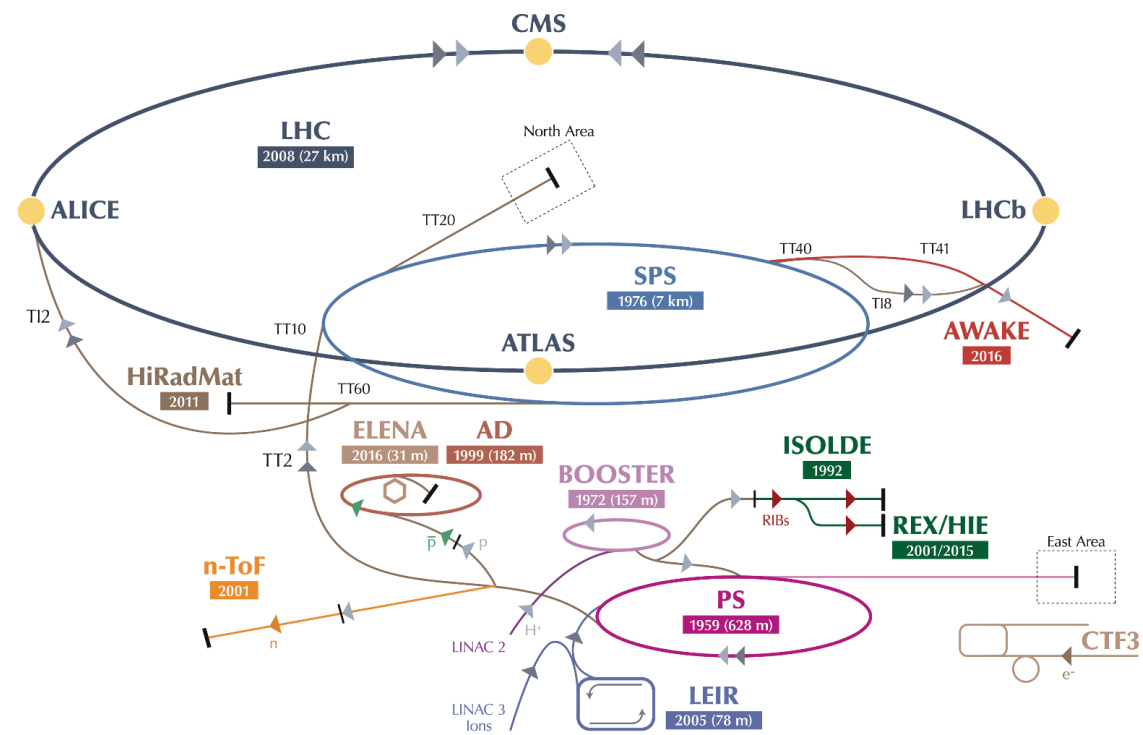# Two-Step Vacuum Design of Light Sources

R. Kersevan, CERN-TE-VSC-VSM – kersevan@cern.ch

Outline of tutorial:

1. ~~Basics of gas dynamics: outgassing, conductance, pumping speed;~~

2. Basics of synchrotron radiation (SR), with examples relevant to vacuum design;

3. SR-induced desorption and materials for vacuum;

4. Computational methods for vacuum and SR: a review;

5. Practical examples of analysis, simulation, and design of key components of light sources;
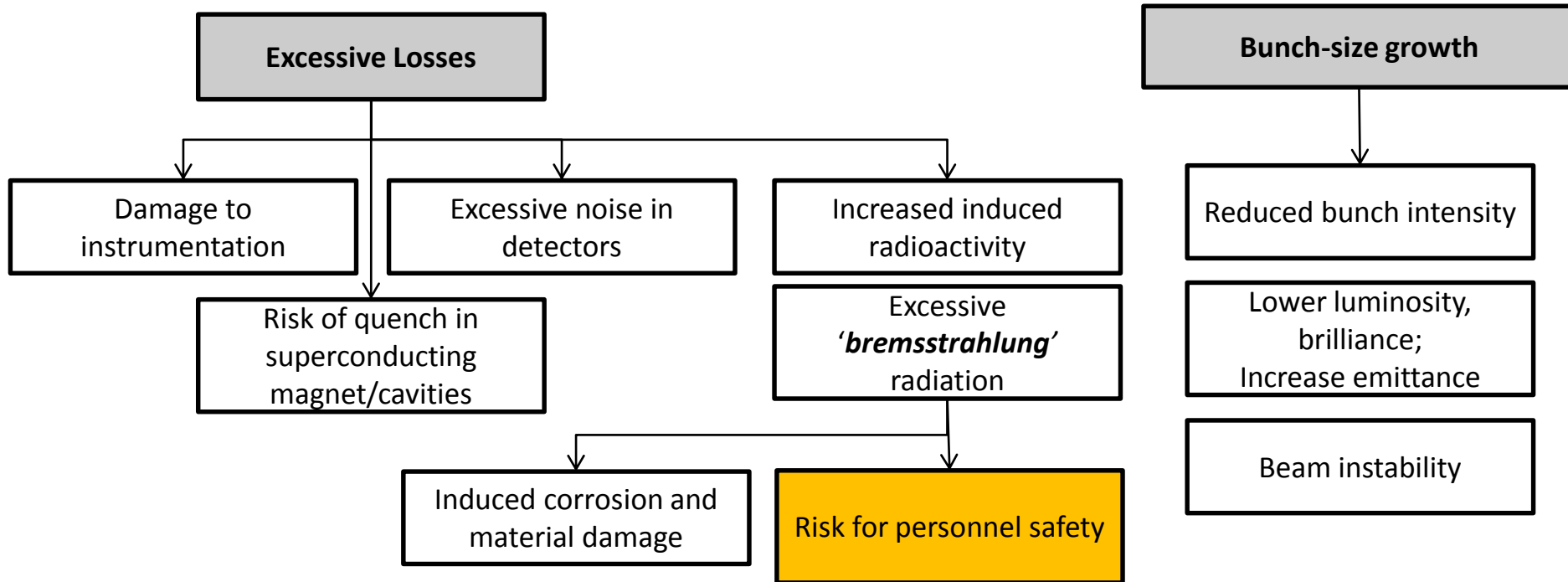
6. Summary and conclusions.

Overview:

- Modern particle accelerators, in particular synchrotron radiation light sources need rather **stringent conditions on their vacuum requirements**, namely:

  - Average pressures in the **low 1.0E-9 mbar range**;

  - Average **low-Z residual gas composition**: H_2 (Z=1) must be the main gas component during operation of the machine;

  - **Stable pressure profiles**, with, in in particular, no pressure bumps along the straight sections where insertion devices (ID) are installed, in order to minimize the generation of high-energy bremsstrahlung (BS) photons;

- This translates into flows which are in the **molecular flow regime**, i.e. conditions for which the probability of the residual gas molecules to interact/collide which each other is much lower than the probability of hitting the walls of the vacuum system

- Apart from cases when the different molecular species can promptly react chemically with each other (e.g. chemical reactors, catalysed reactions), the flow regime of a gas can be described by the **mean free path** concept, i.e. the average distance travelled by a molecule between two collisions with another molecule at same density and temperature conditions in a 'infinite' volume;

4

Why do we need vacuum in accelerators?

Collisions between gas molecules and particles have to be minimized, otherwise:

Particle energy can be reduced and/or trajectories can be modified, so that:

Excessive Losses			Bunch-size growth

Damage to instrumentation	Excessive noise in detectors	Increased induced radioactivity	Reduced bunch intensity

Risk of quench in superconducting magnet/cavities	Excessive *'bremsstrahlung'* radiation	Lower luminosity, brilliance; Increase emittance

Induced corrosion and material damage	Risk for personnel safety	Beam instability

A good vacuum is also necessary:
- To avoid electrical discharge in high-voltage devices (tens of MV/m in RF cavities);
- To reduce the heat transfer to cryogenic devices (e.g. SC wiggler with closed-loop compressors)

5

General case; arbitrary vacuum chamber shape:

- For tubes of arbitrary non-uniform cross-section and shape, there is no analytical solution to the **integro-differential equations** (seen during previous tutorial).
- **Unfortunately this is the case for most synchrotron light sources**, where e.g. the dipole/crotch chambers have a "Y" shape and are connected to straight parts going through the FODO sections (quadrupoles/sextupoles necessary for "beam optics").
- In this case a number of approximate numerical methods have been developed during the years, and among them (*)

  - "Slicing" the system in short segments and applying the **Continuity Principle of Gas Flow** (**Finite-Elements codes**, either proprietary or custom-written);
  - Slicing/subdividing the system in short segments and applying the **Electric-Network Analogy** (**ENA**), and then using codes like **LTSpice**;
  - **Angular coefficients method** (analogy to thermal radiation propagation);
  - Applying the **Test-Particle Monte Carlo method** (**TPMC**). The components' geometry is modelled in three dimensions, usually by means of a CAD program.

In a nutshell:

- The TPMC codes generate molecules at the entrance of the component pointing in 'random' directions according to the **Lambertian cosine distribution**. When the molecules impinge on the internal wall of the component, they are re-emitted again randomly, unless pumped.
- The program follows the molecular traces until they reach the exit of the component.

(*) For a review see for instance: "***Analytical and Numerical Tools for Vacuum Systems***", R. Kersevan, CERN Accelerator School, 2017,… and references therein.

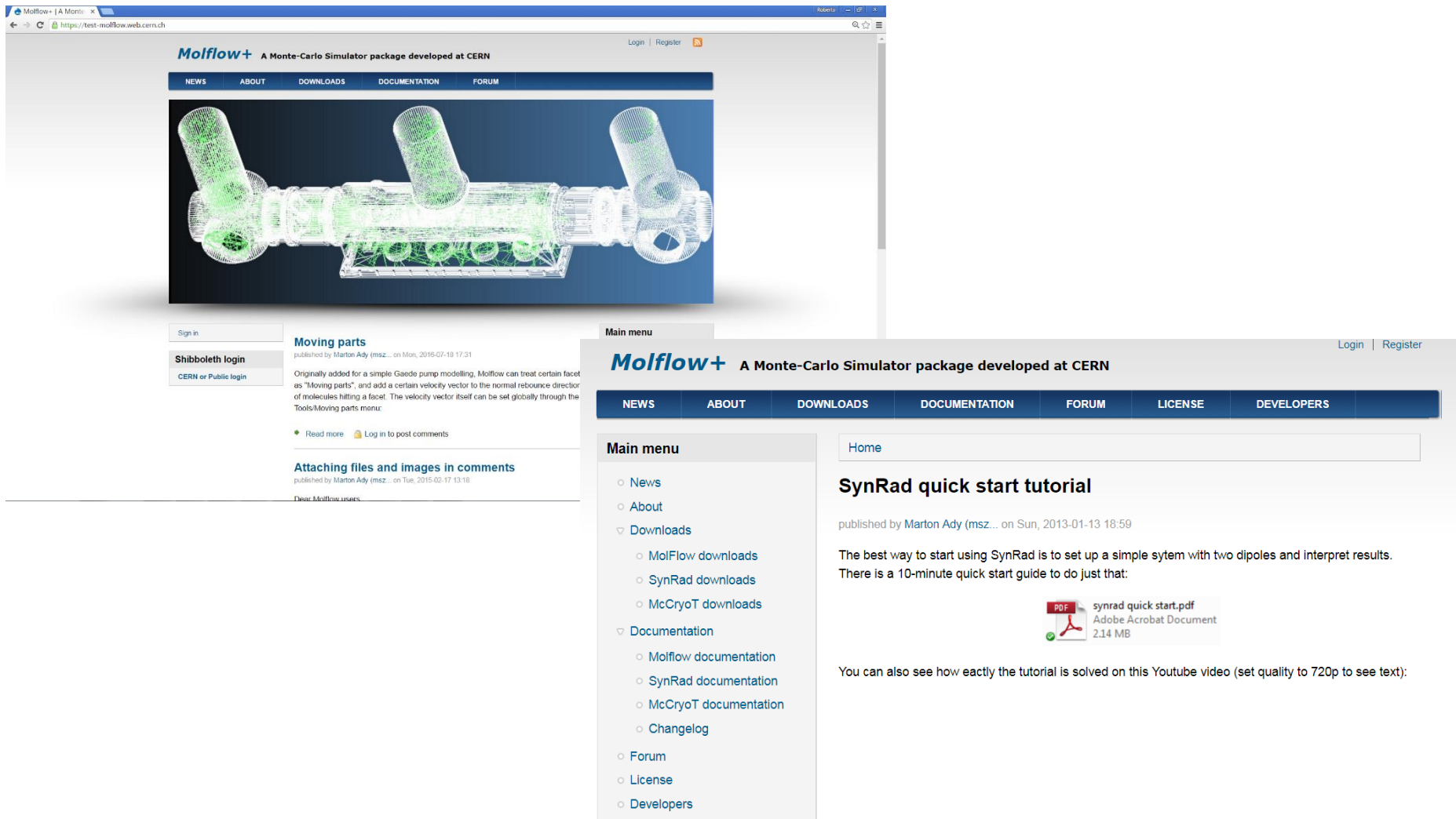**Transmission probability for the general case of arbitrary shapes:**

- The transmission probability is given by the ratio between the number of 'escaped' and 'injected' molecules. Many simulated molecules are needed to reduce the statistical scattering, sometimes billions! (e.g. **KATRIN** neutrino mass experiment case)

- The reference TPMC software at CERN is **MolFlow+**. This powerful tool for high-vacuum applications can import the 3-D drawing of the vacuum components and generate 'random' molecules on any surface of interest.

- The randomness of the generation follows the **physical laws of vacuum technology**: for **thermal desorption** it is assumed to be **spatially uniform** on surfaces and depending only on the wall material properties (temperature, surface finish, chemical cleaning procedure, bake-out,…) while for **synchrotron radiation (SR) induced gas desorption** it is derived from the distribution of photons hitting the walls of the system (e.g. see below, **SYNRAD+** code), which are then converted into molecular fluxes using **empirical/experimental data** (see further below).

- CERN develops, maintains, and uses on a daily basis the TPMC code Molflow+, which has become the *de-facto* standard in the field of particle accelerator design:

https://test-molflow.web.cern.ch/

For those participating to the "Practical Days at CERN" visits, a short tutorial on Molflow+ is foreseen, laptops will be provided on site

7

General case; arbitrary shapes: SYNRAD+ and Molflow+ codes run in sequence

On **Molflow+** and the companion code **SYNRAD+**, please see the excellent reference "**Monte Carlo simulations of Ultra High Vacuum and Synchrotron Radiation for particle accelerators**", M. Ady, CERN, doctoral dissertation at EPFL, Lausanne, CH, May 2016; Dowloadable at https://cds.cern.ch/record/2157666?ln=en

8

Block diagram of the TPMC/ray-tracing algorithm:

Once a geometrical model of the vacuum system is defined, then… →

ESRF dipole 2 -> narrow gap ID chamber -> dipole 1

9
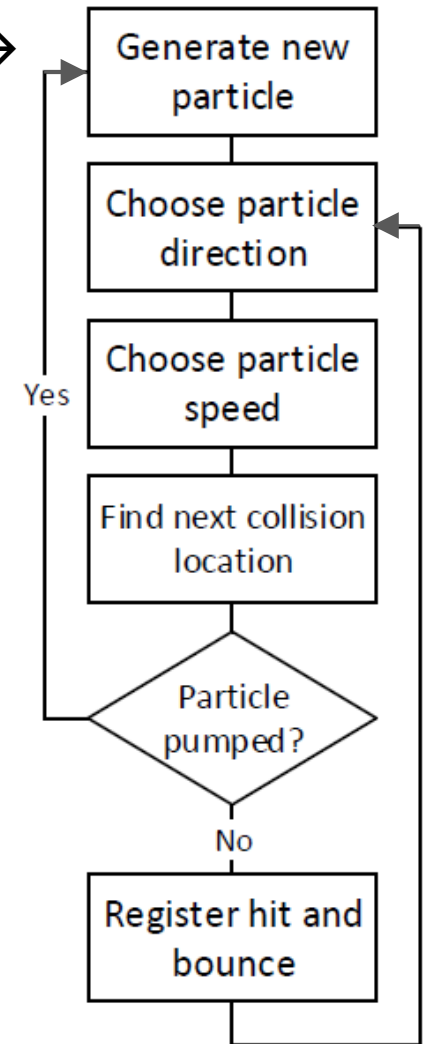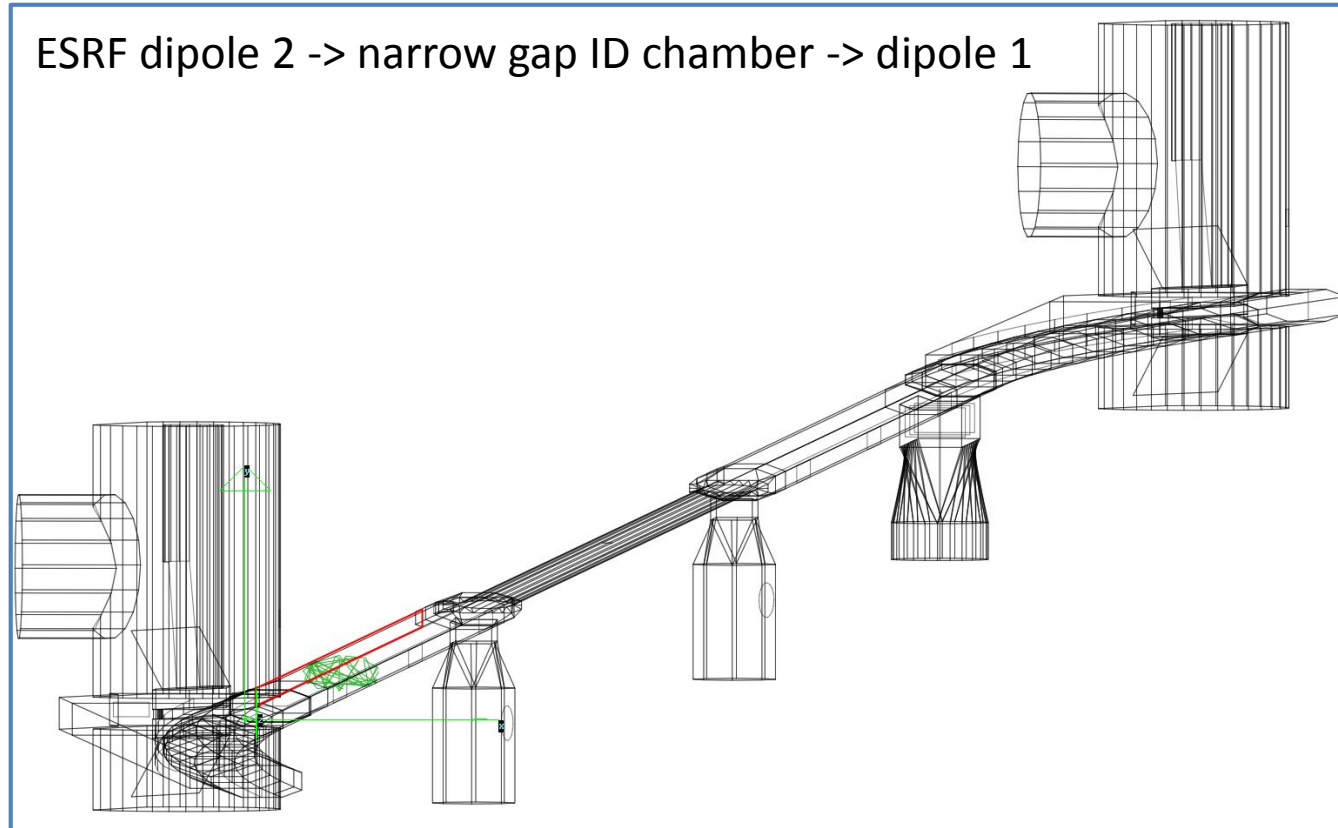
Discovery of Synchrotron Radiation

1947, General Dynamics, Schenectady (NY), USA
70 MeV ring, tabletop size
The vacuum chamber was made of glass:

The discovery of synchrotron radiation is an interesting case history in the nature of scientific discovery: It was made possible by a trivial design change and by a conscious disregard for the rules of radiation safety. I was a particularly close witness to much of the history; in fact, had I only been more open-minded three years earlier, I might have been a co-discoverer of what would instead now be called "betatron radiation."

Visible light was observed by pure chance, after previous failures (opaque chamber, silver-coated glass, 1945):

Three years later, in the same laboratory, a 70-MeV synchrotron was completed under the direction of Herbert Pollock. At its initial location, it was not completely enclosed by a radiation shield; even more significantly, the doughnut coating was transparent, facilitating placement of electrodes for beam extraction.
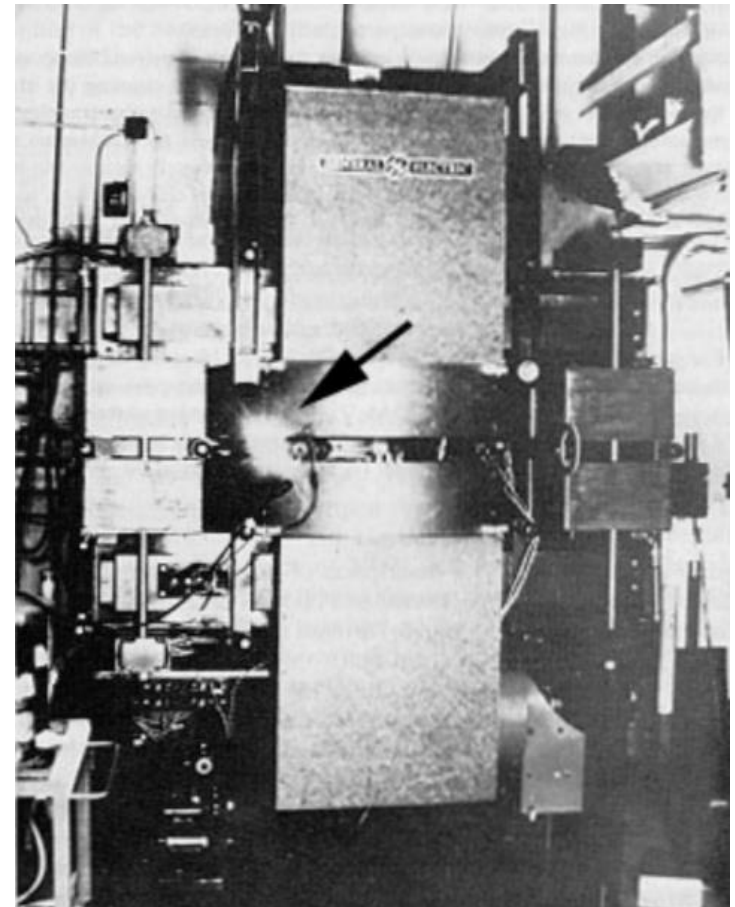

Design Light Sources

10

Fundamental paper by J Schwinger: it gave for the first time quantitative and qualitative insights into the properties of radiation emitted by relativistic charged particles moving in a magnetic field.
Followed by second paper…

PHYSICAL REVIEW   VOLUME 75, NUMBER 12   JUNE 15, 1949

On the Classical Radiation of Accelerated Electrons

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts
(Received March 8, 1949)

This paper is concerned with the properties of the radiation from a high energy accelerated electron, as recently observed in the General Electric synchrotron. An elementary derivation of the total rate of radiation is first presented, based on Larmor's formula for a slowly moving electron, and arguments of relativistic invariance. We then construct an expression for the instantaneous power radiated by an electron moving along an arbitrary, prescribed path. By casting this result into various forms, one obtains the angular distribution, the spectral distribution, or the combined angular and spectral distributions of the radiation. The method is based on an examination of the rate at which the electron irreversibly transfers energy to the electromagnetic field, as determined by half the difference of retarded and advanced electric field intensities. Formulas are obtained for an arbitrary charge-current distribution and then specialized to a point charge. The total radiated power and its angular distribution are obtained for an arbitrary trajectory. It is found that the direc-

tion of motion is a strongly preferred direction of emission at high energies. The spectral distribution of the radiation depends upon the detailed motion over a time interval large compared with the period of the radiation. However, the narrow cone of radiation generated by an energetic electron indicates that only a small part of the trajectory is effective in producing radiation observed in a given direction, which also implies that very high frequencies are emitted. Accordingly, we evaluate the spectral and angular distributions of the high frequency radiation by an energetic electron, in their dependence upon the parameters characterizing the instantaneous orbit. The average spectral distribution, as observed in the synchrotron measurements, is obtained by averaging the electron energy over an acceleration cycle. The entire spectrum emitted by an electron moving with constant speed in a circular path is also discussed. Finally, it is observed that quantum effects will modify the classical results here obtained only at extraordinarily large energies.

EARLY in 1945, much attention was focused on the design of accelerators for the production of very high energy electrons and other charged particles.[1] In connection with this activity, the author investigated in some detail the limitations to the attainment of high energy electrons imposed by the radiative energy loss[2] of the accelerated electrons. Although the results of this work were communicated to various interested persons,[1,3,4] no serious attempt at publication[5] was made. However, recent experiments on the radiation from the General Electric synchrotron[6] have made it desirable to publish the portion of the investigation that is concerned with the properties of the radiation from individual electrons, apart from the considerations on the practical attainment of very high energies. Accordingly, we derive various properties of the radiation from a high energy accelerated electron; the comparison with experiment has been given in the paper by Elder, Langmuir, and Pollock.

I. GENERAL FORMULAS

Before launching into the general discussion, it is well to notice an elementary derivation of the total rate of radiation, based on Larmor's classical formula for a slowly moving electron, and arguments of relativistic invariance. The Larmor formula for the power radiated by an electron that

is instantaneously at rest is

$$P = \frac{2}{3}\frac{e^2}{c^3}\left(\frac{d\mathbf{v}}{dt}\right)^2 = \frac{2}{3}\frac{e^2}{m^2c^3}\left(\frac{d\mathbf{p}}{dt}\right)^2. \quad (I.1)$$

Now, radiated energy and elapsed time transform in the same manner under Lorentz transformations, whence the radiated power must be an invariant. We shall have succeeded in deriving a formula for the power radiated by an electron of arbitrary velocity if we can exhibit an invariant that reduces to (I.1) in the rest system of the electron. To accomplish this, we first replace the time derivative by the derivative with respect to the invariant proper time. The differential of proper time is defined by

$$ds^2 = dt^2 - 1/c^2(dx^2 + dy^2 + dz^2),$$

or

$$ds = (1 - v^2/c^2)^{\frac{1}{2}}dt. \quad (I.2)$$

Secondly, we replace the square of the proper time derivative of the momentum by the invariant combination

$$(d\mathbf{p}/ds)^2 - 1/c^2(dE/ds)^2.$$

Hence, as the desired invariant generalization of (I.1), we have

$$P = \frac{2}{3}\frac{e^2}{m^2c^3}\left[\left(\frac{d\mathbf{p}}{ds}\right)^2 - \frac{1}{c^2}\left(\frac{dE}{ds}\right)^2\right]$$
$$= \frac{2}{3}\frac{e^2}{m^2c^3}\left(\frac{E}{mc^2}\right)^2\left[\left(\frac{d\mathbf{p}}{dt}\right)^2 - \frac{1}{c^2}\left(\frac{dE}{dt}\right)^2\right]. \quad (I.3)$$

The conventional form of this result is obtained on

[1] See L. I. Schiff, Rev. Sci. Inst. **17**, 6 (1946).
[2] D. Iwanenko and I. Pomeranchuk, Phys. Rev. **65**, 343 (1944).
[3] Edwin M. McMillan, Phys. Rev. **68**, 144 (1945).
[4] John P. Blewett, Phys. Rev. **69**, 87 (1946).
[5] Julian Schwinger, Phys. Rev. **70**, 798 (1946).
[6] Elder, Langmuir, and Pollock, Phys. Rev. **74**, 52 (1948).

1912

PHYSICAL REVIEW D   VOLUME 7, NUMBER 6   15 MARCH 1973

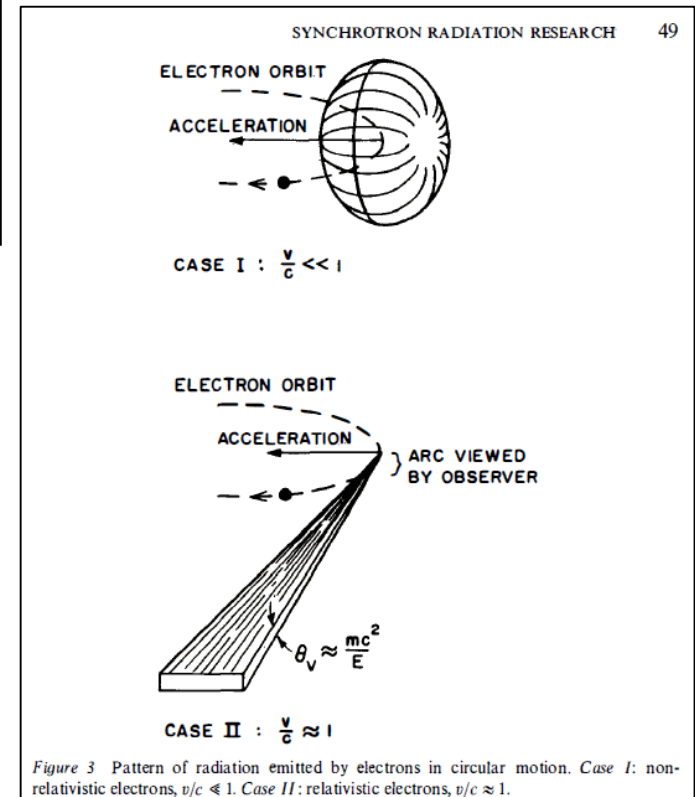### Classical Radiation of Accelerated Electrons. II. A Quantum Viewpoint*
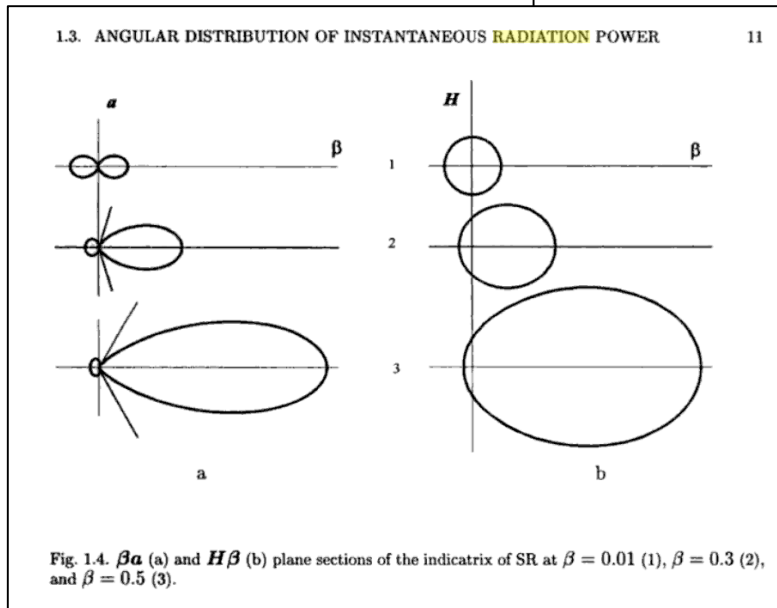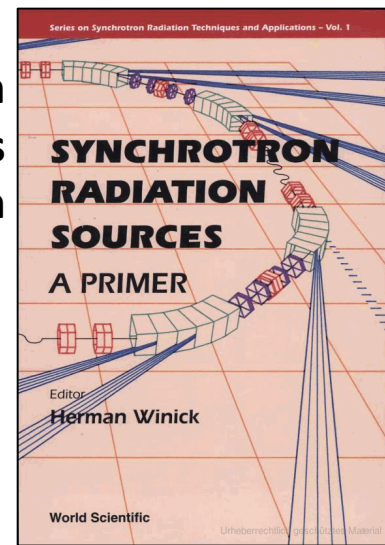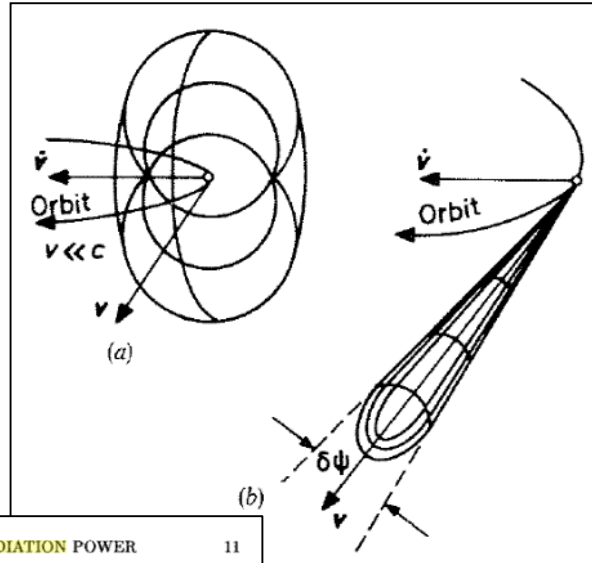
Julian Schwinger
University of California, Los Angeles, California 90024
(Received 27 November 1972)

The known classical radiation spectrum of a high-energy charged particle in a homogeneous magnetic field is rederived. The method applies, and illuminates, an exact (to order α) expression for the inverse propagation function of a spinless particle in a homogeneous field. An erratum list for paper I is appended.
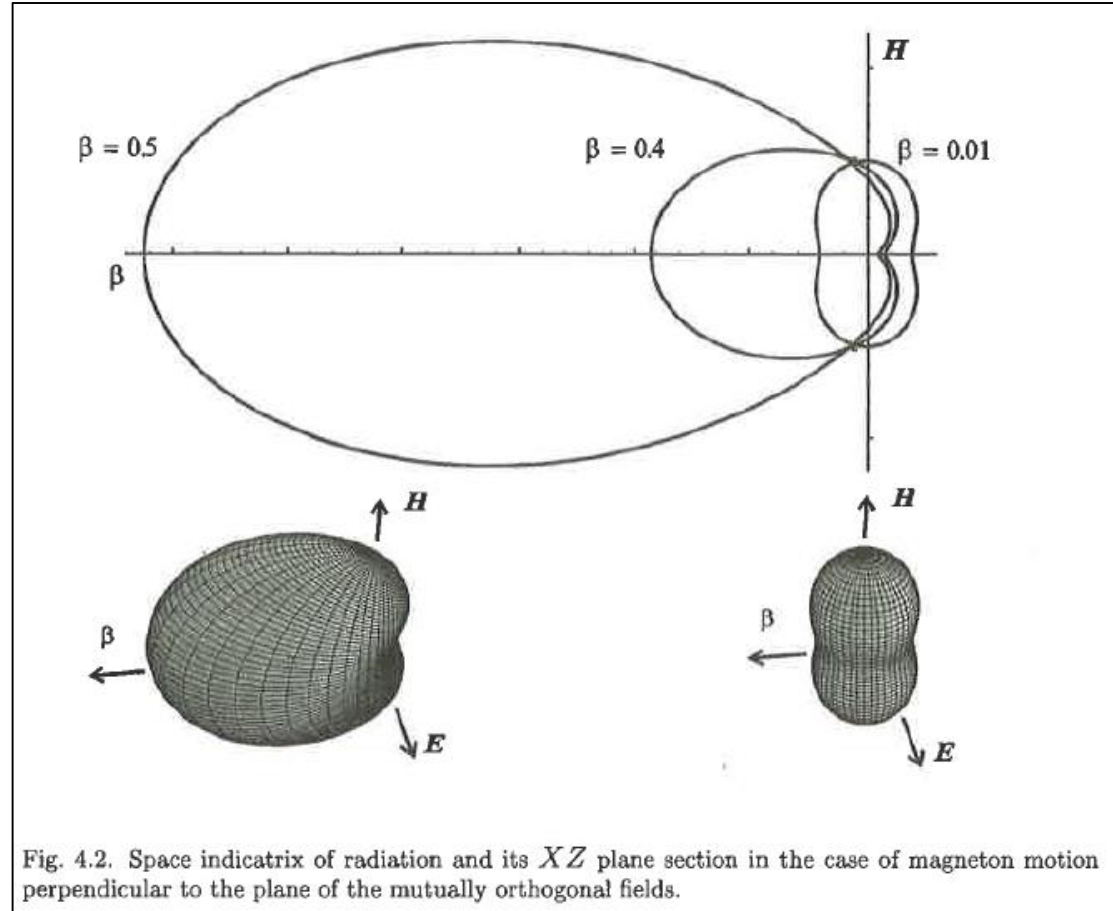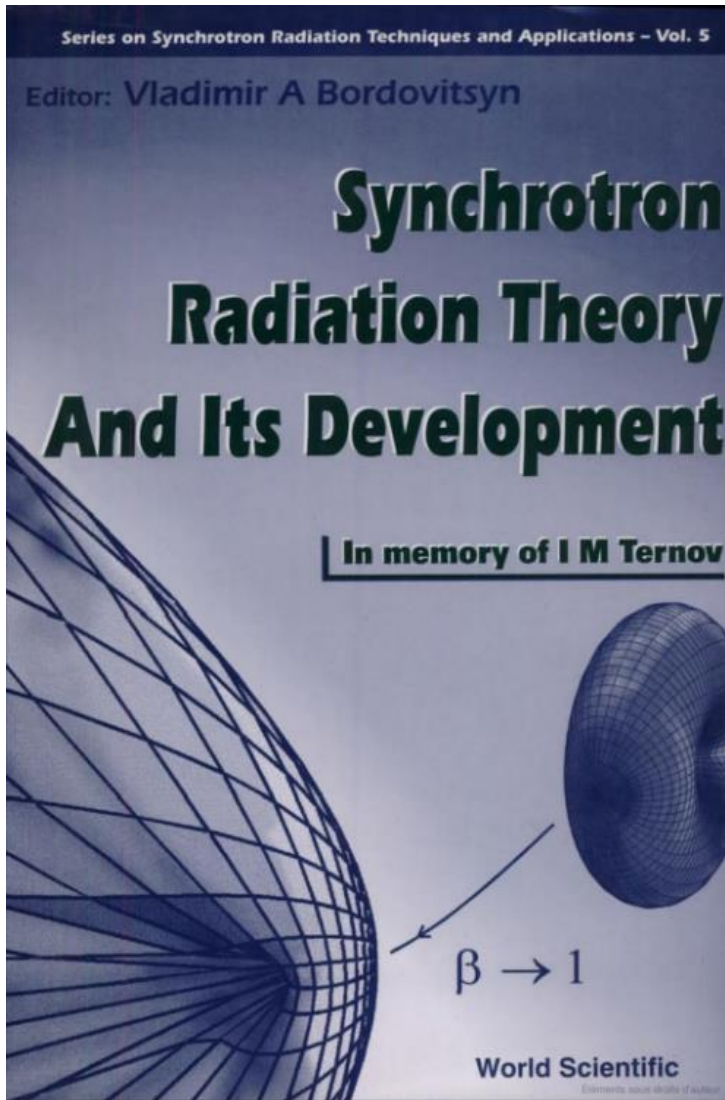
… while in the meantime Sokolov and Ternov in the USSR had come to similar results expanding the breadth of knowledge (radiative polarization of electrons and positrons in a magnetic field).

As the velocity v increases, <u>the emission of photons</u> from an electron subjected to an acceleration perpendicular to its velocity vector changes and goes from being "isotropic" to being highly skewed and collimated in the forward direction

Series on Synchrotron Radiation Techniques and Applications – Vol. 1

SYNCHROTRON RADIATION SOURCES

A PRIMER

Editor
Herman Winick

World Scientific

(a)

(b)

$\delta\psi$

Orbit

$v \ll c$

Orbit

1.3. ANGULAR DISTRIBUTION OF INSTANTANEOUS RADIATION POWER 11

a

H

β

β

1

2

3

a

b

Fig. 1.4. βa (a) and $H\beta$ (b) plane sections of the indicatrix of SR at $\beta = 0.01$ (1), $\beta = 0.3$ (2), and $\beta = 0.5$ (3).

SYNCHROTRON RADIATION RESEARCH 49

ELECTRON ORBIT

ACCELERATION

CASE I : $\frac{v}{c} \ll 1$

ELECTRON ORBIT

ACCELERATION

} ARC VIEWED BY OBSERVER

$\theta_v \approx \frac{mc^2}{E}$

CASE II : $\frac{v}{c} \approx 1$

Figure 3 Pattern of radiation emitted by electrons in circular motion. *Case I*: non-relativistic electrons, $v/c \ll 1$. *Case II*: relativistic electrons, $v/c \approx 1$.

Series on Synchrotron Radiation Techniques and Applications – Vol. 5

Editor: **Vladimir A Bordovitsyn**

Synchrotron Radiation Theory And Its Development

In memory of I M Ternov

$\beta \rightarrow 1$

World Scientific

Fig. 4.2. Space indicatrix of radiation and its XZ plane section in the case of magneton motion perpendicular to the plane of the mutually orthogonal fields.

Relativistic factor: $\gamma = \dfrac{1}{\sqrt{1 - \dfrac{v^2}{c^2}}}$

Practical Formulae, as a function of relativistic factor γ:

Integrated Photon Flux, F : $\boxed{F = 4.1289 \cdot 10^{14} \cdot \gamma \cdot I(mA) \cdot k_F}$ (ph/s/mA)

Integrated Photon Power, P: $\boxed{P = 6.0344 \cdot 10^{-12} \cdot \dfrac{\gamma^4}{\rho(m)} \cdot I(mA) \cdot k_P}$ (W/mA)

Critical Energy, e_{crit} : $\boxed{e_{crit} = 2.9596 \cdot 10^{-7} \cdot \dfrac{\gamma^3}{\rho(m)}}$ (eV)

As a function of beam energy (GeV), for e-/e+ machines:

$\boxed{F = 8.08 \cdot 10^{17} \cdot E(GeV) \cdot I(mA) \cdot k_F}$ $\boxed{P = 88.46 \cdot \dfrac{E(GeV)^4}{\rho(m)} \cdot I(mA) \cdot k_P}$ $\boxed{e_{crit} = 2218 \cdot \dfrac{E(GeV)^3}{\rho(m)}}$

k_f, k_p = fraction of photon flux and power with energy above given <u>energy threshold (see next slide)</u>;
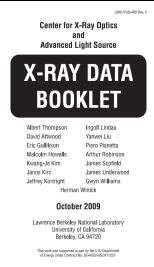
Photon distributions: power- and flux-wise

SECTION 1

BNL 50522
(Particle Accelerators and
High-Voltage Machines - TID 4500)

SPECTRA AND
OPTICS OF SYNCHROTRON RADIATION

G.K. Green

April 15, 1976
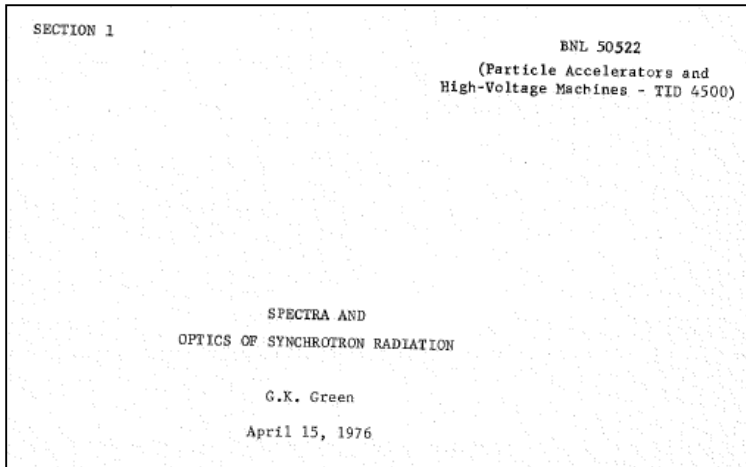
- **POWER: the critical energy is the <u>median</u> of the SR power distribution: ½ of the power at photon energies ABOVE e_c, ½ BELOW**
- **FLUX: only 9% of the SR photons are generated above e_c.**

→ **Most photons have low energy!** ←

Average photon energy: $0.30792 \cdot e_c$

Percent of POWER at all wavelengths greater than λ vs λ/λ_c.

Percent of FLUX at all wavelengths greater than λ vs λ/λ_c.

Fig. 10 Percent of radiation power at all wavelengths greater than λ vs λ/λ_c

Fig. 11 Percent of photons at all wavelengths greater than λ vs λ/λ_c
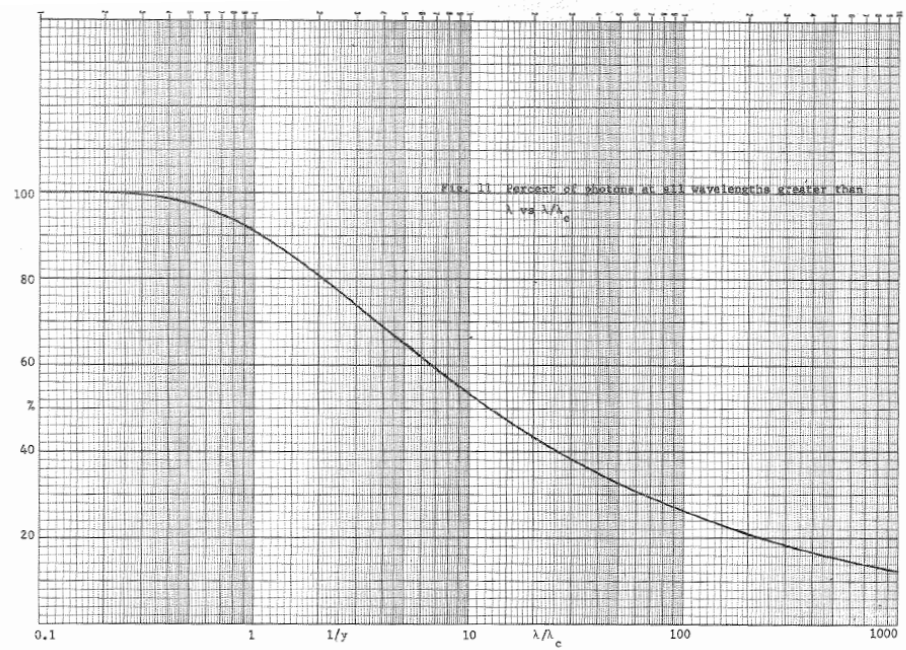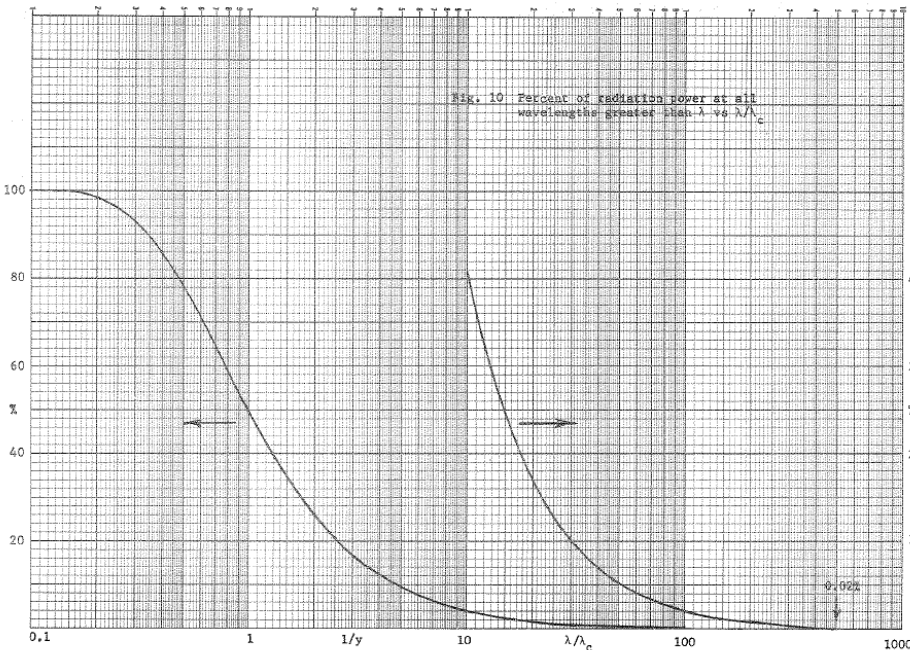
Photon distributions: Sources: X-Ray Data Booklet, LBNL; "Spectra and Optics of SR", BNL

LBNL/PUB-490 Rev. 3

**Center for X-Ray Optics
and
Advanced Light Source**

X-RAY DATA BOOKLET

Albert Thompson	Ingolf Lindau
David Attwood	Yanwei Liu
Eric Gullikson	Piero Pianetta
Malcolm Howells	Arthur Robinson
Kwang-Je Kim	James Scofield
Janos Kirz	James Underwood
Jeffrey Kortright	Gwyn Williams

Herman Winick

October 2009

Lawrence Berkeley National Laboratory
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Berkeley, CA 94720

This work was supported in part by the U.S. Department
of Energy under Contract No. DE-AC02-05CH11231

SECTION 1

BNL 50522
(Particle Accelerators and
High-Voltage Machines - TID 4500)

SPECTRA AND
OPTICS OF SYNCHROTRON RADIATION

G.K. Green

April 15, 1976

ACCELERATOR DEPARTMENT
BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973
under contract No. E(30-1)-16 with the
UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Photon distributions: Sources: X-Ray Data Booklet, LBNL; "Spectra and Optics of SR", BNL

Center for X-Ray Optics and Advanced Light Source

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SECTION 2

SYNCHROTRON RADIATION

2.1A CHARACTERISTICS OF SYNCHROTRON RADIATION

Kwang-Je Kim

Synchrotron radiation occurs when a charge moving at relativistic speeds follows a curved trajectory. In this section, formulas and supporting graphs are used to quantitatively describe characteristics of this radiation for the cases of circular motion (bending magnets) and sinusoidal motion (periodic magnetic structures).

We will first discuss the ideal case, where the effects due to the angular divergence and the finite size of the electron beam—the emittance effects—can be neglected.

A. BENDING MAGNETS

The angular distribution of radiation emitted by electrons moving through a bending magnet with a circular trajectory in the horizontal plane is given by

$$\frac{d^2\mathcal{F}_B(\omega)}{d\theta d\psi} = \frac{3\alpha}{4\pi^2}\gamma^2\frac{\Delta\omega}{\omega}\frac{I}{e}y^2(1+X^2)^2 \times \left[K_{2/3}^2(\xi) + \frac{X^2}{1+X^2}K_{1/3}^2(\xi) \right], \quad (1)$$

2-2

where

$\mathcal{F}_B$ = photon flux (number of photons per second)
θ = observation angle in the horizontal plane
ψ = observation angle in the vertical plane
α = fine-structure constant
γ = electron energy/$m_e c^2$ (m_e = electron mass, c = velocity of light)
ω = angular frequency of photon ($\varepsilon = \hbar\omega$ = energy of photon)
I = beam current
e = electron charge = 1.602×10^{-19} coulomb
y = $\omega/\omega_c = \varepsilon/\varepsilon_c$
ω_c = critical frequency, defined as the frequency that divides the emitted power into equal halves, = $3\gamma^3 c/2\rho$
ρ = radius of instantaneous curvature of the electron trajectory (in practical units, ρ[m] = 3.3 E[GeV]/B[T])
E = electron beam energy
B = magnetic field strength
ε_c = $\hbar\omega_c$ (in practical units, ε_c [keV] = 0.665 E^2 [GeV] B[T])
X = $\gamma\psi$
ξ = $y(1+X^2)^{3/2}/2$

The subscripted K's are modified Bessel functions of the second kind. In the horizontal direction ($\psi = 0$), Eq. (1) becomes

$$\left.\frac{d^2\mathcal{F}_B}{d\theta d\psi}\right|_{\psi=0} = \frac{3\alpha}{4\pi^2}\gamma^2\frac{\Delta\omega}{\omega}\frac{I}{e}H_2(y), \quad (2)$$

where

$$H_2(y) = y^2 K_{2/3}^2(y/2). \quad (3)$$

In practical units [photons·s^{-1}·mr^{-2}·(0.1% bandwidth)$^{-1}$],

$$\left.\frac{d^2\mathcal{F}_B}{d\theta d\psi}\right|_{\psi=0} = 1.327\times10^{13} E^2 [GeV]I[A]H_2(y).$$

The function $H_2(y)$ is shown in Fig. 2-1.

From now on, θ is the horizontal observation angle, and Ψ the vertical one, with respect to the plane of the orbit

17

Sources: X-Ray Data Booklet, LBNL; "Spectra and Optics of SR", BNL

From now on, θ is the horizontal observation angle, and Ψ the vertical one, with respect to the plane of the orbit

Center for X-Ray Optics and Advanced Light Source

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2-5

Fig. 2-3. The function $C(y)$. The limiting slopes, for $\varepsilon/\varepsilon_c \ll 1$ and $\varepsilon/\varepsilon_c \gg 1$, are indicated.

where σ_ψ is given by

$$\sigma_\psi = \frac{2}{\gamma\sqrt{2\pi}} C(y) = 0.408 \frac{C(y)[\text{mr}]}{E[\text{GeV}]} \quad . \qquad (7)$$

The function $C(y)$ is plotted in Fig. 2-3. In terms of σ_ψ, Eq. (2) may now be rewritten as

$$\frac{d^2\mathcal{F}_B}{d\theta d\psi}\bigg|_{\psi=0} = \frac{d\mathcal{F}_B}{d\theta} \frac{1}{\sigma_\psi\sqrt{2\pi}}. \qquad (2a)$$

B. PERIODIC MAGNETIC STRUCTURES

In a wiggler or an undulator, electrons travel through a periodic magnetic structure. We consider the case where the magnetic field B varies sinusoidally and is in the vertical direction:

$$B(z) = B_0 \cos(2\pi z/\lambda_u) \quad , \qquad (8)$$

where z is the distance along the wiggler axis, B_0 the peak magnetic field, and λ_u the magnetic period. Electron motion is also sinusoidal and lies in

Vertical Distribution of SR Power and Flux (Dipole)

$\varepsilon > 10$ eV

SR_{power} SR_{flux}

$\gamma \cdot \Psi$ (mrad)

Equivalent Rectangle

MC Data Fitted to y=exp(-x²/2σ²) { σ=1.234, σ=0.605 }
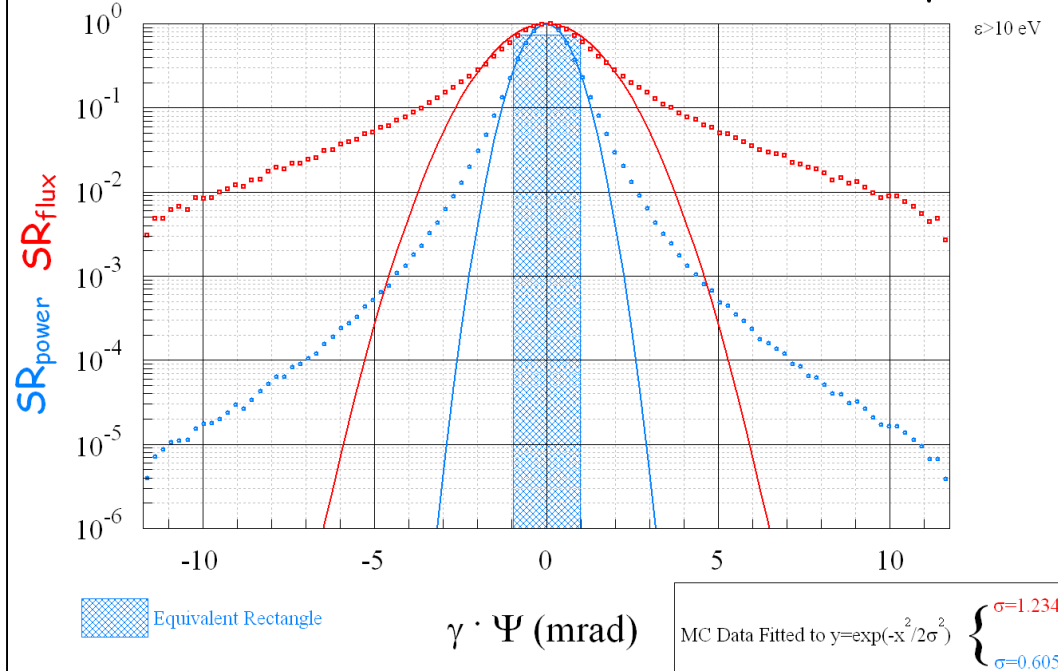
MC simulation, SYNRAD -> author;

Vertical Distribution of SR Power and Flux (Dipole)

$\varepsilon > 10$ eV

SR_{power}, SR_{flux} (A.U.)

$\gamma \cdot \Psi$ (mrad)

Equivalent Rectangle

MC Data Fitted to y=exp(-(x)²/2σ²) { σ=1.234, σ=0.605 }

19
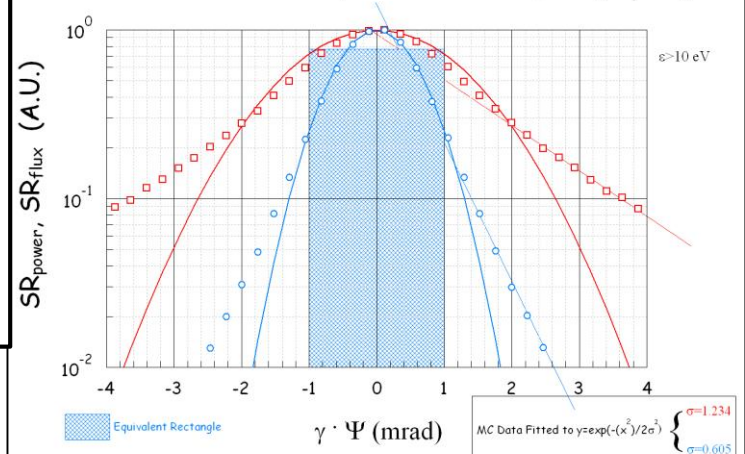
Source: "Monte Carlo simulations of Ultra High Vacuum and Synchrotron Radiation for particle accelerators", M. Ady, CERN

At $\psi = 0$

$$F\left(\frac{\lambda_c}{2\lambda}, 0\right) = F_\parallel(0) = K_{2/3}^2\left(\frac{\lambda_c}{2\lambda}\right)$$

And generally at angle ψ

$$F_\parallel(\psi) = \left(1 + \gamma^2\psi^2\right) K_{2/3}^2\left[\frac{\lambda_c}{2\lambda}\left(1 + \gamma^2\psi^2\right)^{3/2}\right]$$

$$F_\perp(\psi) = \gamma^2\psi^2\left(1 + \gamma^2\psi^2\right) K_{1/3}^2\left[\frac{\lambda_c}{2\lambda}\left(1 + \gamma^2\psi^2\right)^{3/2}\right]$$

where $K_{1/3}$ and $K_{2/3}$ are modified Bessel functions. We often use the expression *degree of polarization* which is defined as $P_{lin} = (F_\parallel - F_\perp)/(F_\parallel + F_\perp)$. The solution of this analytic expression can be visualized (see Fig.2.6) on a relative scale where the vertical angle is expressed in units of γ, and with a different X axis range for each energy.
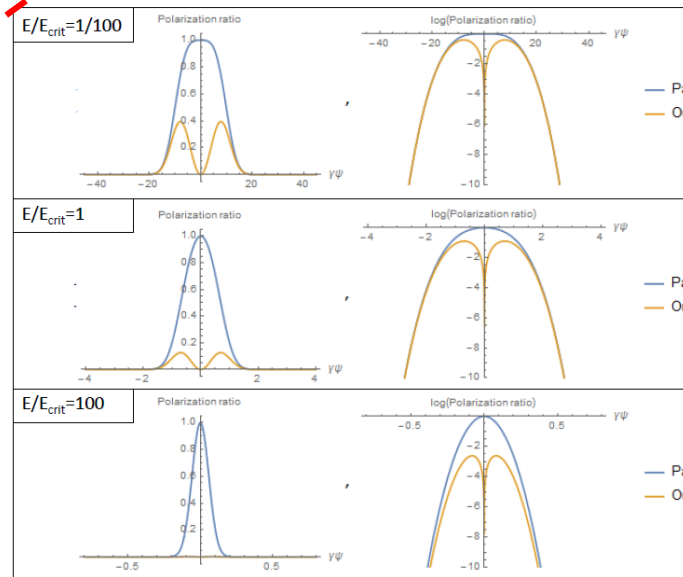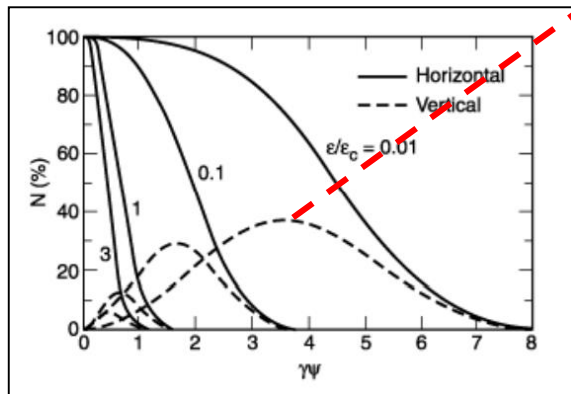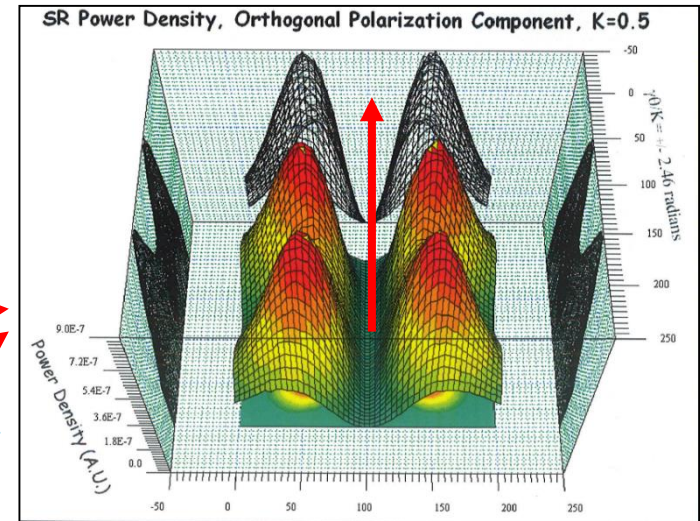
7/8 of the total _power_ is generated as parallel polarization photons, 1/8 only in the perpendicular case;

Figure 2.6: Polarization components for different lambda ratios. Each plot has an X scale that depends on the relative photon energy:
$\gamma\psi = [-4/(E/E_c)^{0.35} .. + 4/(E/E_c)^{0.35}]$
Left: linear scale, Right: logarithmic scale

Photon distributions: SYNRAD+, 3-d ray-tracing code

Distribution of the Synchrotron Radiation Fan vs Vertical Half-Angle
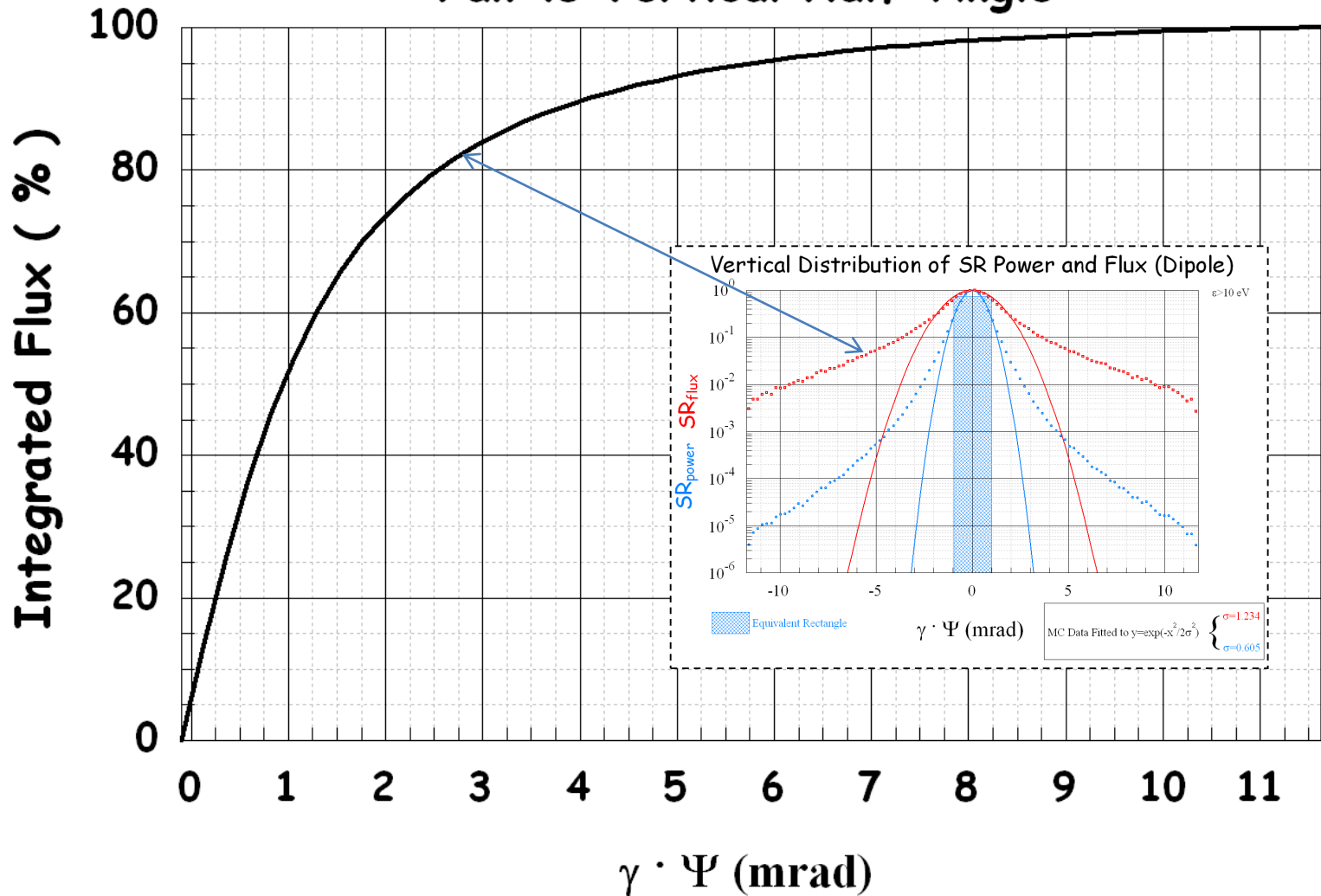
Source: "Efficient computation of synchrotron radiation spectrum", H.H. Umstatter, CERN/PS/SM/81-13, 1981

How can spectra and fluxes be calculated efficiently and fast?

- **Several numerical algorithms have been developed during the years:**
- **This one, is particularly fast:**

f)   The highest speed is obtained if one computes directly $\int K_{5/3}$ by a Chebyshev series instead of separate computation of $K_{2/3}$ and $\int K_{1/3}$. Since it is not known whether Chebyshev expansion coefficients of $\int K_{5/3}$ exist in the literature they are given in the following listing of subroutine SYNRAD, rounded to 10 digits after the decimal point. Coefficients of 19 – 20 digit precision are given in the following table.   They have been computed by linear combination of Luke's coefficients for $K_{2/3}$ and $\int K_{1/3}$.   SYNRAD calls no external subroutine and uses no array in order to gain more speed.   It is about 400 times faster than method a.   On the IBM it evaluates $\int K_{5/3}$ in $7.6 \cdot 10^{-5}$ sec. on the CDC 7600 in $2.6 \cdot 10^{-5}$ sec. (i.e. 38600 values in 1 sec. computing time).

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

/3-1-298

高能物理室

/1mg

CERN/PS/SM/81-13
10.3.1981.

EFFICIENT COMPUTATION OF SYNCHROTRON RADIATION SPECTRUM

H.H. Umstätter
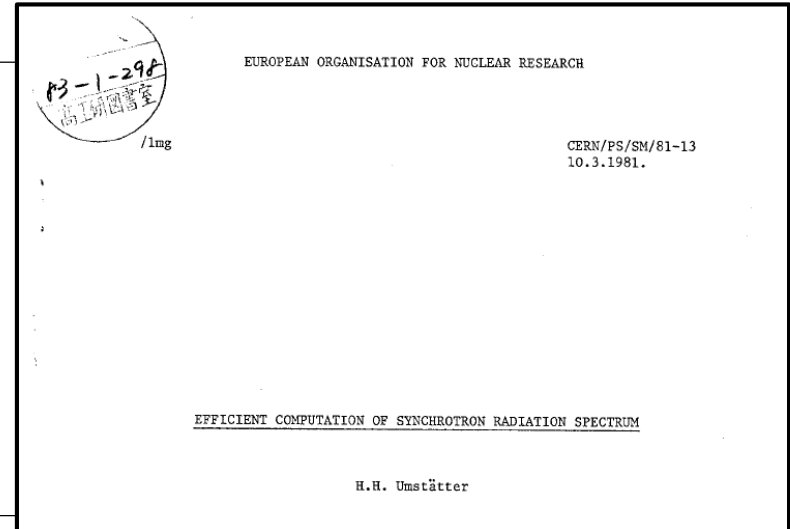
- **Note: compared to the CDC 7600 supercomputer of the 70's, the same code running on just _one_ _core_ of a modern multi-core CPU looks like a rocket: 1.6M values/sec _vs_ 38600 values/sec, an improvement of > 40x:**

This means that today Montecarlo simulations of SR are affordable even on laptops and desktops.

3. SR-induced desorption

Since SR has been observed for the first time in an accelerator (1949), scientists have immediately realized that X-ray photons of energies higher than few eV were capable of causing desorption of molecules from the walls of the vacuum system, via a number of different phenomena, namely:

- Generation of photo-electrons;
- Direct desorption via X-ray excitation (e.g. Auger);
- Thermal desorption caused by power deposited by SR;

- In order to design the vacuum system of e-/e+ storage rings-- **in particular light sources where the e- beam <u>needs to be stored</u> sometimes for tens of hours without interruptions**--, the scientists developed an experimental program in order to measure carefully the **photon-induced desorption** (**PID**) yield, usually indicated in literature by the letter η.
- η gives the average number of molecules of a given gas species per incident photon, and allows the designer of the vacuum system to size and space properly the pumping system, a **major input to the budget of a light source**;

Some examples of PID yield measurements: design of 2.75 GeV SOLEIL light source
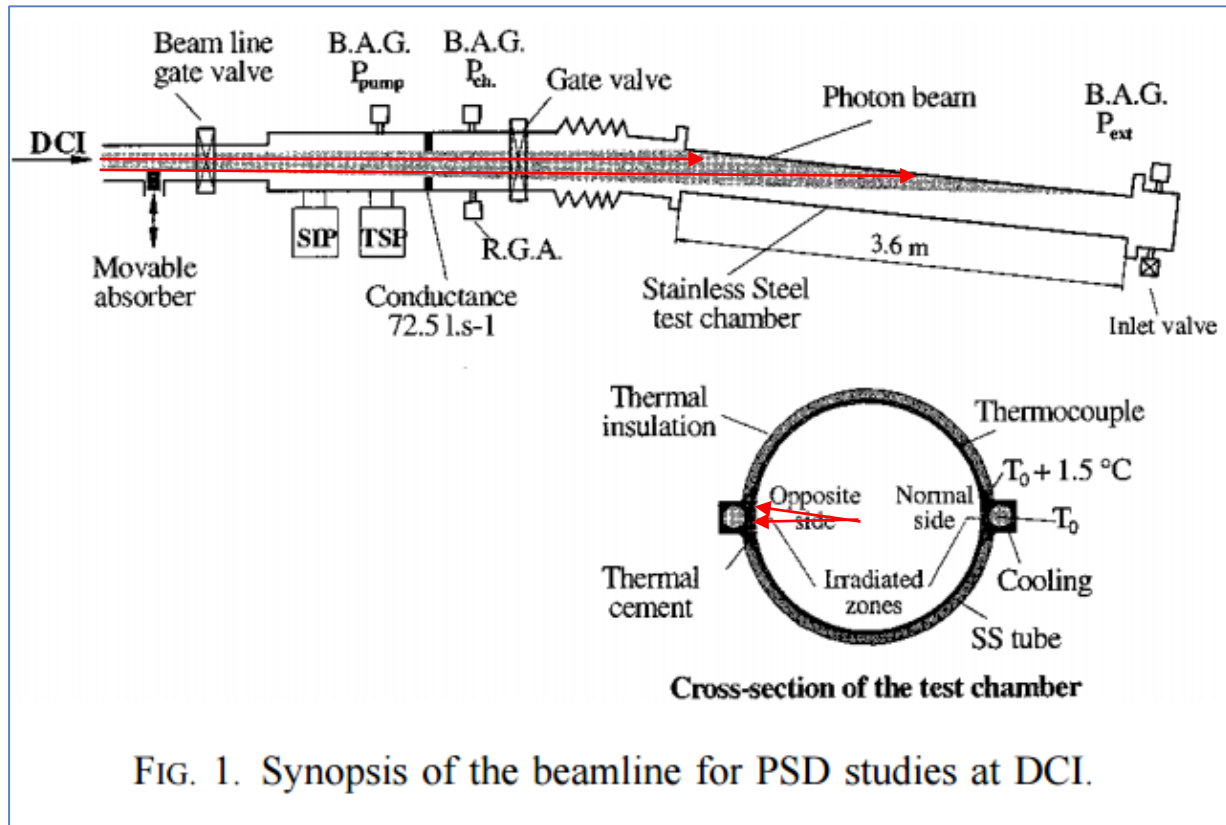
FIG. 1. Synopsis of the beamline for PSD studies at DCI.

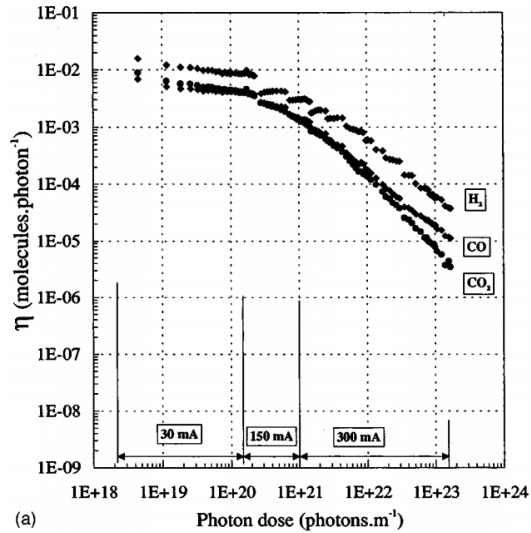# Some examples of PID yield measurements: design of 2.75 GeV SOLEIL light source
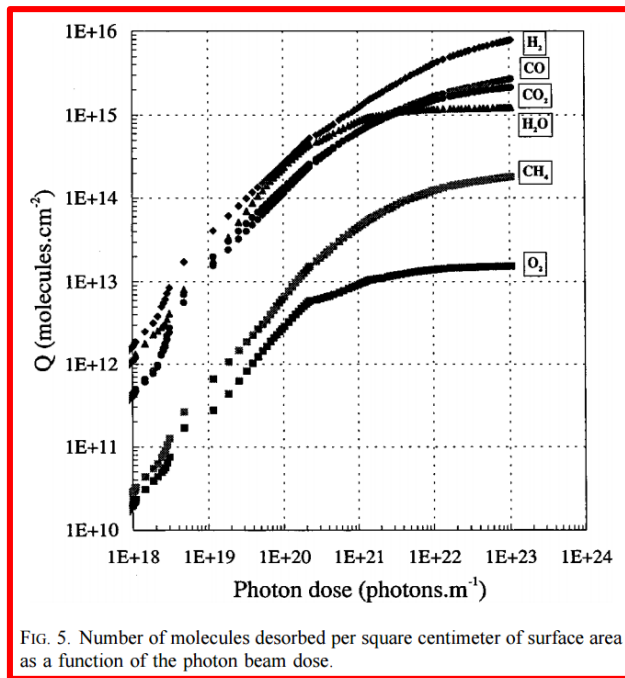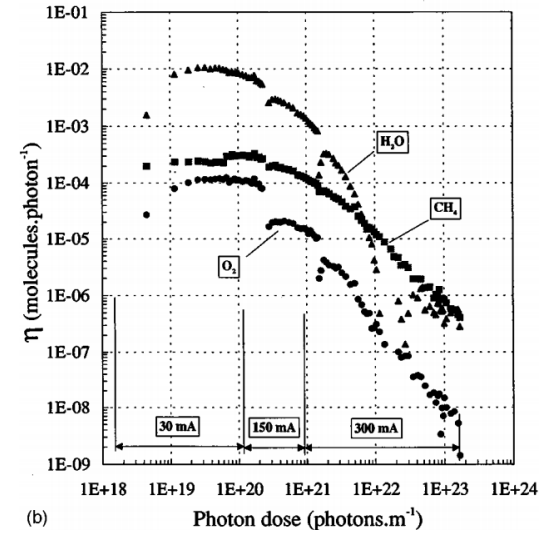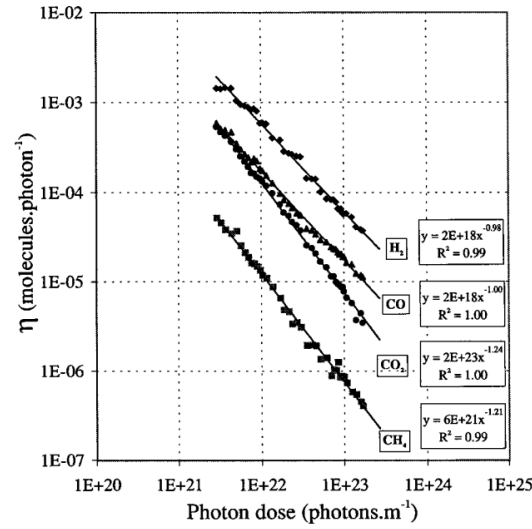
FIG. 5. Number of molecules desorbed per square centimeter of surface area as a function of the photon beam dose.

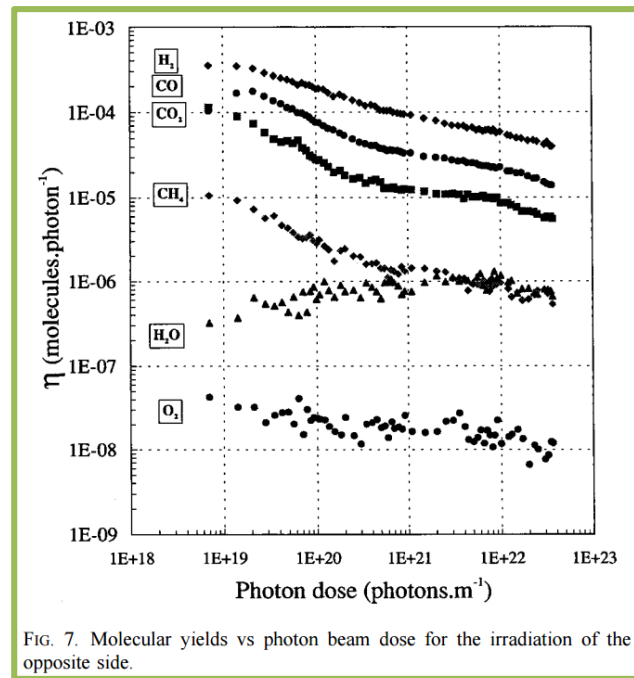FIG. 7. Molecular yields vs photon beam dose for the irradiation of the opposite side.

JUAS 2019 - R. Kersevan - Two-Step Vacuum Design Light Sources

Some examples of PID yield measurements: design of 6 GeV ESRF light source

(NEG-coating developments, 1999 onwards)

PHOTODESORPTION MEASUREMENTS AT ESRF D31

H.P. Marques*, G. Debut, M. Hahn, ESRF, Grenoble, France

Abstract

Since 1998 exists at ESRF a dedicated beamline for photodesorption measurement from vacuum chambers - D31. The original goal of this installation was to study the wall pumping effect. When exposed to synchrotron radiation surfaces exhibit strong outgassing of the adsorbed gas layer despite UHV conditions. Long term outgassing leads to the depletion of the adsorbed layer and produces a very clean surface which turns the walls of the vacuum chamber into an active pumping surface.

At D31 have been tested chambers of stainless steel, aluminium and copper, with or without coatings (e.g. NEG, copper), designed by ESRF and other institutes like ALBA, CERN, ELETTRA and Soleil. Here we review some of the results obtained and outline the future plans of D31.

leading to the requirement of additional shielding and thus reducing the availability of the beamline to the users.

PHOTODESORPTION

The first successful models to describe electron stimulated desorption (ESD) or photon stimulated desorption (PSD) where the MGR model, independently proposed by Menzer and Gomer [6] and Redhead[7], and later the Knotek-Feibelman [8] (KF) model. Briefly, in the MGR model an atom is excited to an anti-bonding state and it may gain sufficient kinetic energy so that it overcomes the lower potential barrier of one of the bonding states in the de-excitation pathway. The KF model is based in an interatomic Auger decay. The original excitation leaves a hole in the core level to be filled by an electron from a neighbour atom and, due to Auger decay, further electrons are ejected from the
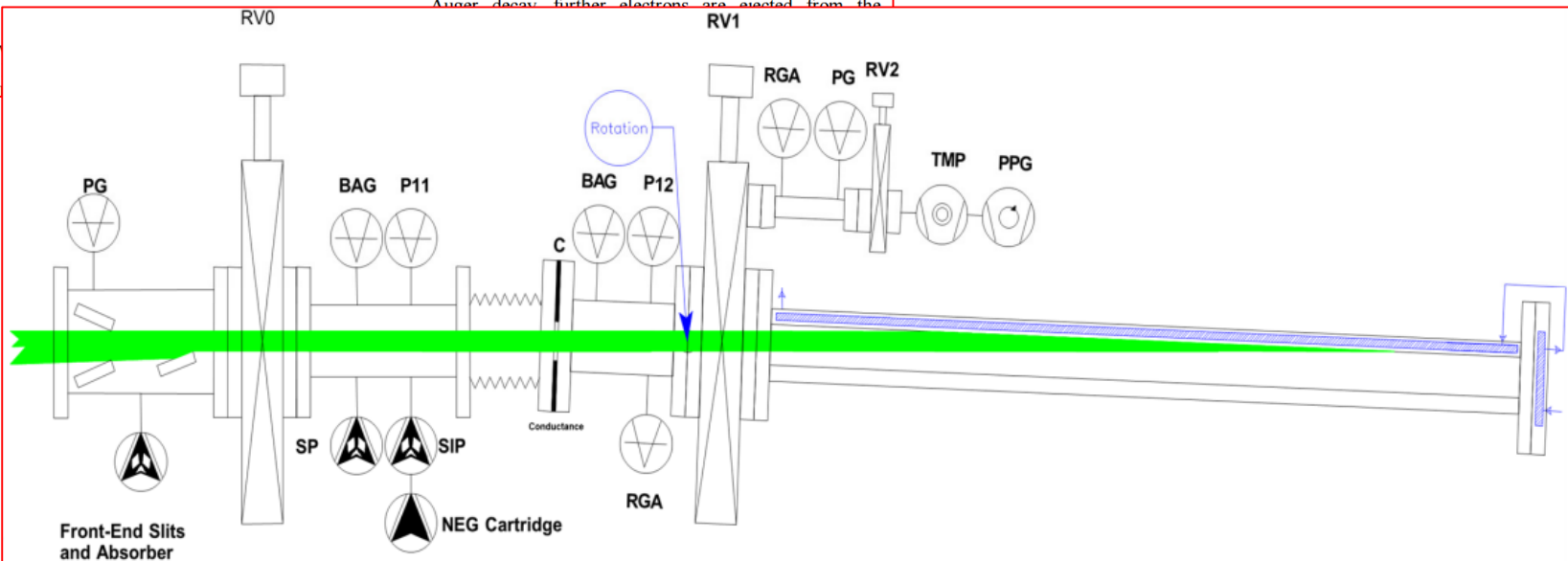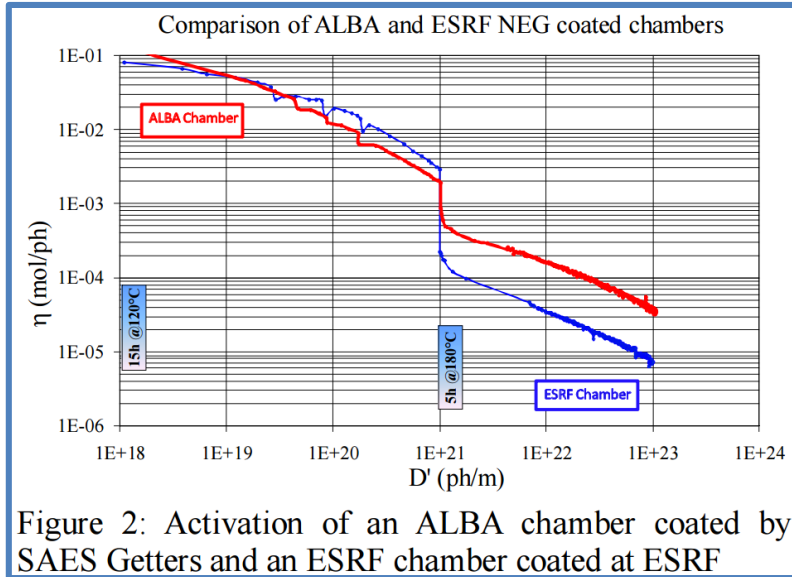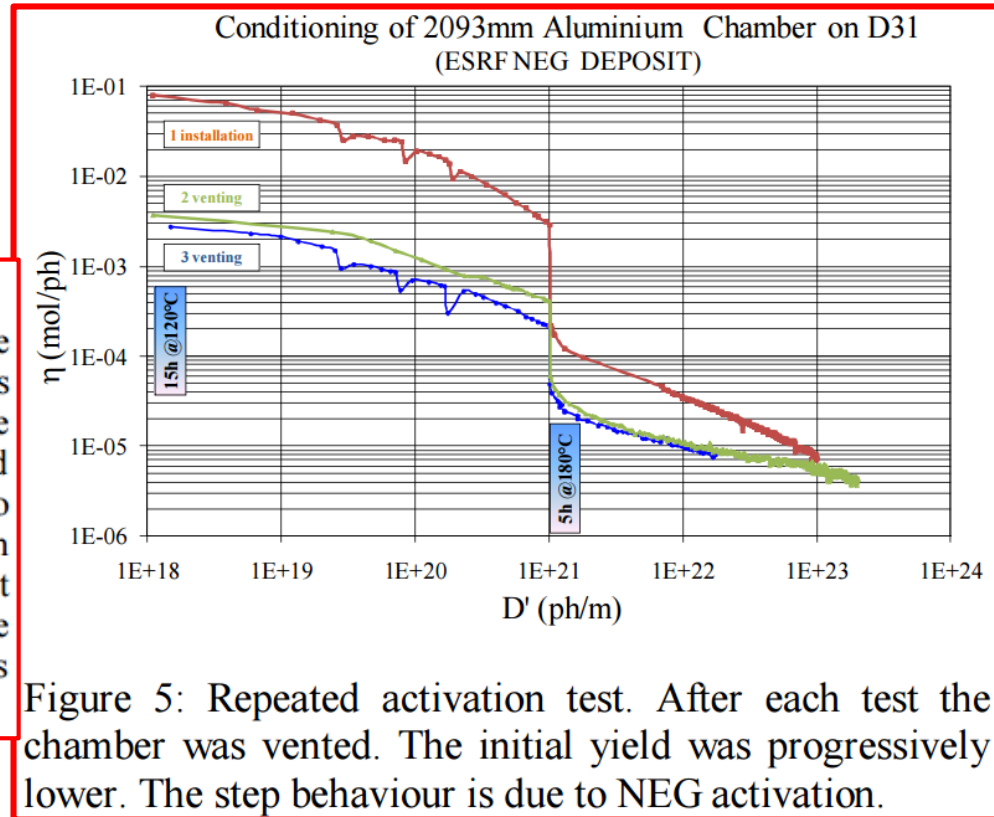

Figure 1: D31 schematics. PG – Pirani gauge; RV – Remote Valve ; SIP – Sputter Ion Pump; BAG – Bayard-Alpert Gauge ; P – Penning Gauge; TMP – Turbo Molecular Pump; PPG – Primary Pumping Group

26

Some examples of PID yield measurements: design of 6 GeV ESRF light source
(NEG-coating developments, 1999 onwards)

Figure 2: Activation of an ALBA chamber coated by SAES Getters and an ESRF chamber coated at ESRF

Memory Effect

When continually exposed to synchrotron radiation the yield of a surface decreases with accumulated dose. This decrease is in part due to the progressive cleaning of the adsorbed surface layers. In Figure 5 it can be observed that after exposure of a thoroughly irradiated chamber to air its yield, although increasing, remains at a lower than the initial value. Even at the second consecutive venting it can still be observed a small improvement. As such the chamber retains some "memory" of the previous condition.

Figure 5: Repeated activation test. After each test the chamber was vented. The initial yield was progressively lower. The step behaviour is due to NEG activation.

Question: What happens if the PID yield is not sufficiently low and/or the corresponding pressure profile is too high-- for instance because of lack of pumping speed or conductance limitations?

→ **Beam-gas scattering** ←

Effect on the beam lifetime!

Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

STUDY OF THE BESSY II BEAM LIFETIME *

S. Khan [†], BESSY, Berlin, Germany

2 THEORY

In this section, the relations used in the analysis are reviewed. A list of symbols is given in table 1.

The beam lifetime τ is defined by the current decay rate $1/\tau = -\dot{I}/I$, which is the sum of the Touschek (T) rate and the gas scattering (G) rate

$$\frac{1}{\tau} = \frac{1}{\tau_T} + \frac{1}{\tau_G} = \frac{1}{\tau_T} + c\,n\left(\sigma^N_{elast} + \sigma^N_{inel} + \sigma^e_{elast} + \sigma^e_{inel}\right). \quad (1)$$

The Touschek decay rate can be written as (e.g. [4])

$$\frac{1}{\tau_T} = \frac{N r_e^2 c}{8\pi \sigma_x \sigma_y \sigma_z \gamma^2 (\Delta p/p)^3} \cdot D\left(\frac{(\Delta p/p)^2 \sigma_{x'}^2}{\gamma^2}\right), \quad (2)$$

where $D \approx 0.3$ is a slowly varying function that is evaluated numerically. Relativistic effects and beam polarization modify the Touschek rate on the level of 10-20% [5].

The total cross sections for elastic and inelastic scattering on residual gas nuclei (N) and electrons (e) are [4]

$$\sigma^N_{elast} = \frac{2\pi r_e^2 Z^2}{\gamma^2} \frac{\bar{\beta}\beta_a}{a^2} \quad (3)$$

$$\sigma^N_{inel} = \frac{4 r_e^2 Z^2}{137} \frac{4}{3}\left(\ln\frac{183}{Z^{1/3}}\right)\left(\ln\frac{1}{\Delta p/p} - \frac{5}{8}\right) \quad (4)$$

$$\sigma^e_{elast} = \frac{2\pi r_e^2 Z}{\gamma} \frac{1}{\Delta p/p}$$

$$\sigma^e_{inel} = \frac{4 r_e^2 Z}{137} \frac{4}{3}\left(\ln\frac{2.5\gamma}{\Delta p/p} - 1.4\right)\left(\ln\frac{1}{\Delta p/p} - \frac{5}{8}\right),$$

The distinctly different dependence of Touschek scattering and inelastic gas scattering on the momentum acceptance $\Delta p/p$ (equations 2 and 4) can be used to distinguish the two effects by changing the rf voltage (which also changes the bunch length). Coulomb scattering is identified by variation of the physical aperture using scrapers.

p here is momentum, not pressure!

Question: What happens if the PID yield is not sufficiently low and/or the corresponding pressure profile is too high-- for instance because of lack of pumping speed?

→ **Beam-gas scattering** → **Generation of bremsstrahlung (BS) radiation:**

Bremsstrahlung (BS) radiation:

It is a "braking "radiation generated by the e- in the beam interacting with the strong electric field of a proton in the field of a nucleus of a residual gas molecule/atom.

- **Depends strongly on the atomic number Z of the gas species: generation of extremely high-energy gamma rays, with upper energy range close to the e- beam energy: ~ Z(Z+1) .... see further below…**

- **Consequences: → the vacuum scientist must do his/her best to keep the residual gas composition as close as possible to "pure H_2" (Z=1), with as low as possible contributions from CH_4, CO, CO_2, Ar, etc… ←**

- **For light sources it is particularly important to keep BS low along the straight sections where experimental beamlines are installed: radiation protection dose limits are more and more stringent!... This has an impact on the availability of a given beamline.**
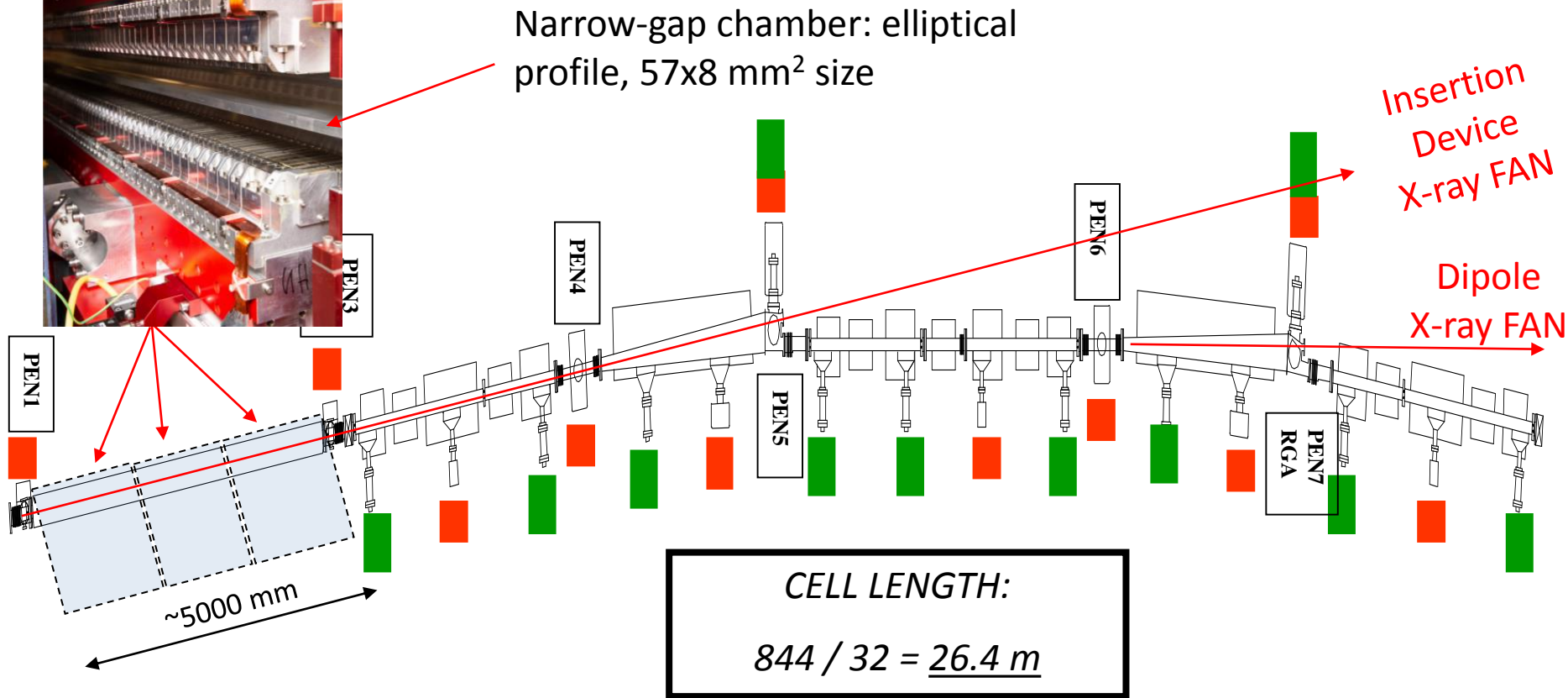
- **We'll come back to this issue later…**

How to calculate the SR photon distribution and related gas loads?

(valid, of course, also for assuring proper cooling of surfaces)

Case study: 6 GeV European Synchrotron Radiation Facility (ESRF), Grenoble, FR

Circumference: 845 m; Energy: 6 GeV; Nominal current: 200 mA;

https://www.esrf.eu/home/UsersAndScience/Accelerators.html

The ESRF Accelerator is in SHUTDOWN until the 2nd of December 2
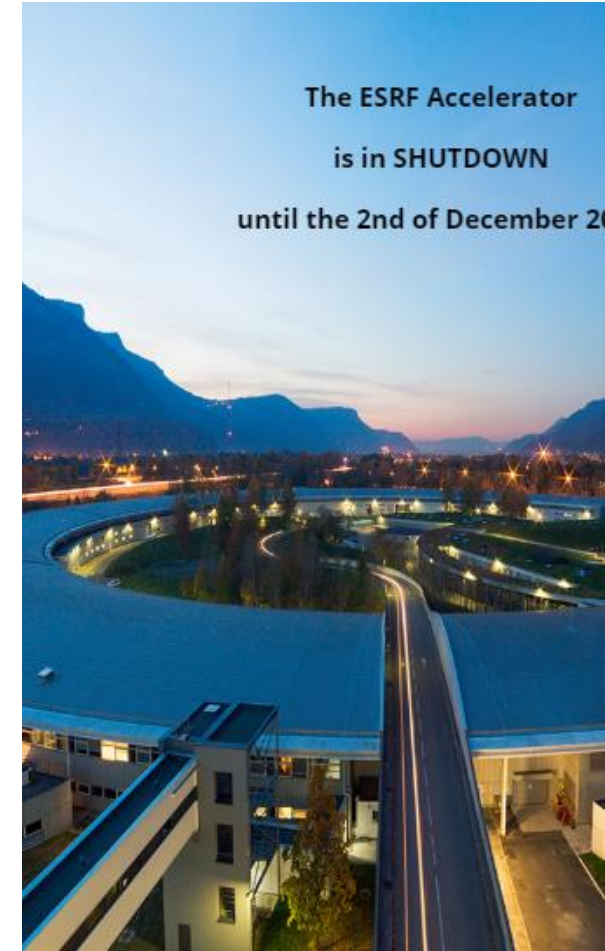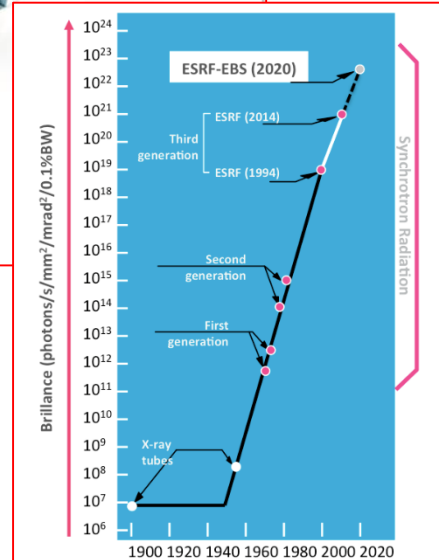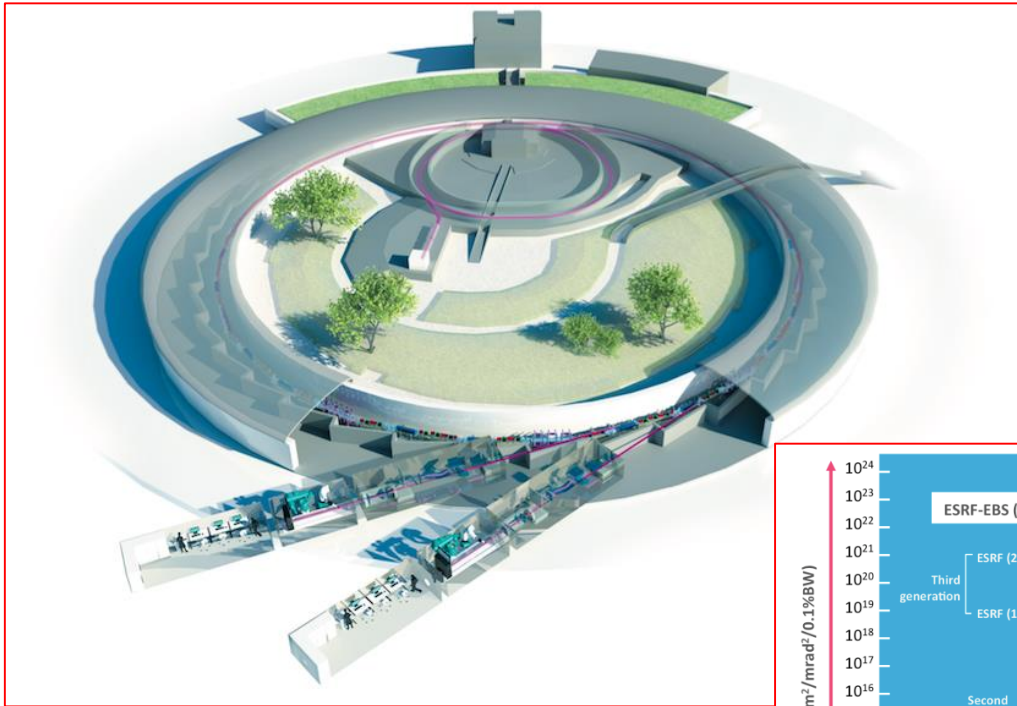
Conductance-limited systems: what are they?... What is the consequence?

Example:

- The **specific conductance** of a 22 mm ID m circular cross-section is **1.312 l·m/s (~MAX-IV and SIRIUS, mass 28 a.m.u., T=20 °C)**

- In a uniform cross-section tube with uniform longitudinal outgassing, a **regular pump spacing** of **L** meters will decrease the installed pumping speed S_{inst} via the equation seen before:

$$1/S_{eff} = 1/S_{inst} + 1/C_{spec} \rightarrow S_{eff} = (1/S_{inst}+L/12/C_{spec})^{-1}$$

Nuclear Instruments and Methods in Physics Research A 770 (2015) 98–112

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journal homepage: www.elsevier.com/locate/nima

Compact low emittance light sources based on longitudinal gradient bending magnets

A. Streun, A. Wrulich

Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

+

Accelerator Physics Challenges in the Design of Multi-Bend-Achromat-Based Storage Rings

M. Borland, ANL
R. Hettel, SLAC
S. C. Leemann, MAX IV Laboratory
D. S. Robin, LBNL

Effective Pumping Speed vs Pump Spacing L(m)
for a 22 mm ID Round Pipe (MAX-IV), Specific Cond.=1.312 l·m/s

Nominal
Pumping
Speed (l/s):
50
30
20
10

S_{eff} (l/s)

L (m)

3rd gen.

ALBA

Crotch
Abs.

400 l/s
Sputter-
Ion
Pump

4th gen.

MAX IV
ø 22 mm

1€ coin
ø 23.25 mm

pic: E. Al-Dmour

How to calculate the SR photon distribution and related gas loads?
(valid, of course, also for assuring proper cooling of surfaces)
1) Do like the ESRF "*Blue Book*", CAD ray-tracing (in the plane of the orbit only):

ESRF

**SYNCHROTRON RADIATION
POWER DISTRIBUTION
IN THE ESRF STORAGE RING
VACUUM CHAMBERS**

* FAN DRAWINGS

* POWER DISTRIBUTION ON THE ABSORBERS

Update March 2004   B. OGIER - B. PLAN - L. ZHANG

-CONTENTS-

JUAS 2019 - R. Kersevan - Two-Step Vacuum Design Light Sources

ESRF CELL IP/NEG DISTRIBUTION AND LOCATION OF VACUUM GAUGES:

Narrow-gap chamber: elliptical profile, 57x8 mm^2 size

Insertion Device X-ray FAN

Dipole X-ray FAN

PEN1 PEN3 PEN4 PEN5 PEN6 PEN7 RGA

~5000 mm

CELL LENGTH:

844 / 32 = 26.4 m

Ion pumps (Varian): ID:120 l/s ; CV4/CV11: 120 l/s; CV3/CV10/CV15: 45 l/s; dipoles: 60 l/s ; crotches: 400 l/s

NEG pumps (SAES): crotches: GP500 (500 l/s) ; elsewhere: GP200 (200 l/s)

33

3. SR-induced desorption

ESRF "Blue Book" CAD ray-tracing (in the plane of the orbit only):

Introduction

The basic synchrotron radiation sources are the bending magnets, which cover 2π radian angle. At the ESRF a major part of this synchrotron radiation is removed by water cooled heater absorbers installed inside the vacuum chambers of the Storage Ring. The power distribution on the absorbers is a basic data for the design of the vacuum chambers as well as the absorbers.

Additional sources of synchrotron radiation are Insertion Devices (ID's) placed in the straight section, between two successive bending magnets. At the ESRF the synchrotron radiation from the insertion devices has, in most cases, a very small horizontal opening angle so that it does not touch any components of the Storage Ring.

This document is intended to give out the power density and the spot size of the synchrotron radiation on all the absorbers of the ESRF Storage Ring vacuum chambers. Only the synchrotron radiation from bending magnets has been considered.

Basic Formula

The synchrotron radiation from a bending magnet in the ESRF has a much smaller vertical size and divergent angle than the horizontal ones. This synchrotron radiation can be considered as a horizontal divergent blade. The power distribution is then described by the angular power density which is defined by the power per unit angle in the horizontal plane, and a vertical Gaussian height.

The angular power density P_θ is given by

$$P_\theta = 4.224 \, B \, E^3 \, I \qquad (1)$$

where E : electron beam energy, in GeV
  I : electron beam current intensity, in A
  B : magnet field intensity of the bending magnet, in T
  P_θ : angular power density in horizontal plane, in W/mrad

In the case of the ESRF, E = 6 GeV, I = 200 mA = 0.2 A, (nominal values)

- for the standard bending magnet B = 0.857 T,
$$P_\theta = 156.38 \text{ W/mrad}$$
- for the soft end magnet B = 0.40 T,
$$P_\theta = 72.99 \text{ W/mrad}$$

The linear power density P_l on the absorber is then

$$P_l = P_\theta \, \sin(\beta)/d \qquad (2)$$

where d is the distance between the source point and the absorber, in meter, β the incident angle of photon beam on the absorber (see Figure 1), P_l in W/mm.

The photon beam size on an absorber is characterised by the vertical Gaussian height σ (mm) which is calculated by

$$\sigma = \sqrt{\sigma_0^2 + (\sigma' d)^2 + \left(\frac{d}{\gamma}\right)^2} = \sqrt{\sigma_0^2 + (\sigma'' d)^2} \qquad (3)$$

where σ_0 : vertical standard deviation of the e-beam at source point (mm)
  σ' : vertical angular standard deviation of the e-beam at source point (mrad)
  σ'' : total effective vertical angular standard deviation at source point (mrad)
  d : distance between source point and the absorber (m)
  γ : = 1957 E (GeV)

For a coupling factor of 1% and a vertical emittance $\varepsilon_z = 4 \cdot 10^{-11}$ m.rad in the case of the ESRF,

$$\sigma_0 = 37 \text{ μm}$$
$$\sigma' = 1.07 \text{ μrad}$$
$$\gamma = 1.174 \cdot 10^4$$
$$\sigma'' = \sqrt{\sigma'^2 + \frac{1}{\gamma^2}} = 85.2 \text{ μrad}$$

34

ESRF "Blue Book" CAD ray-tracing (in the plane of the orbit only):

The surface power density on the absorber P_a is given by

$$P_a(z) = P_a \exp(-\frac{z^2}{2\sigma^2}) \tag{4}$$

with peak power density per unit surface area :

$$P_a = \frac{P_l}{\sqrt{2\pi}\sigma} \tag{5}$$

Once the distance d between the source point and the absorber is defined as well as the incidence angle β of the synchrotron radiation on the absorber, the power densities P_l, P_a and spot size on the absorber can be calculated by equations (2)-(5).

Geometrical calculation

There are two types of dipole bending magnets per cell in the ESRF storage ring :

1) with downstream soft end B1
2) with upstream soft end B2
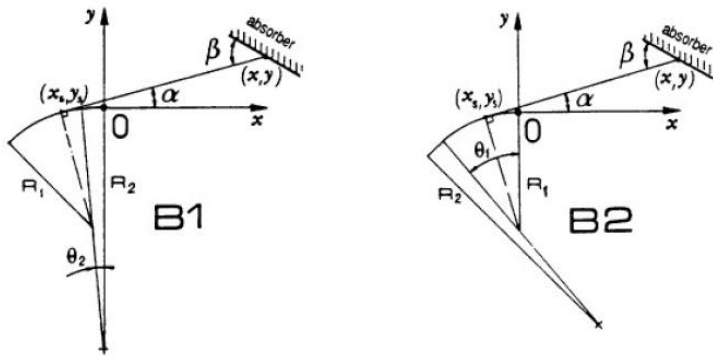
case 1 : dipole magnet B1   case 2 : dipole magnet B2

Figure 1 : Co-ordinate systems

The co-ordinate systems concerning the two types of dipole magnets are shown in Figure 1. The origin of the co-ordinate system is always at the exit of the magnets, the axis-x is parallel to the electron beam in the straight section. The absorber is defined by a certain number of key points and inclined angles $\gamma = \alpha + \beta$ of surface to the axis-x (or to the electron beam trajectory in the straight section).

It is easy to give out the co-ordinates of a point on the absorber (x, y) and the angle γ. The associated source point (x_s, y_s) and the angle α between the photon beam and the electron beam (see Figure 1) can be calculated from the co-ordinates (x, y) and the geometrical parameters of the bending magnets.

Case 1 : dipole magnet B1 :

1) $\alpha > \theta_2$: source point on the main bending magnet (B1)

$$x_s = - R_1 \sin(\alpha) - (R_2 - R_1) \sin(\theta_2) \tag{6a}$$
$$y_s = - R_2 + R_1 \cos(\alpha) + (R_2 - R_1) \cos(\theta_2) \tag{6b}$$

2) $\alpha < \theta_2$: source point on the soft end magnet

$$x_s = - R_2 \sin(\alpha) \tag{7a}$$
$$y_s = - R_2 (1 - \cos(\alpha)) \tag{7b}$$

Case 2 : dipole magnet B2 :

3) $\alpha < \theta_1$: source point on the main bending magnet (B2)

$$x_s = - R_1 \sin(\alpha) \tag{8a}$$
$$y_s = - R_1 (1 - \cos(\alpha)) \tag{8b}$$

4) $\alpha > \theta_1$: source point on the soft end magnet

$$x_s = - R_2 \sin(\alpha) + (R_2 - R_1) \sin(\theta_1) \tag{9a}$$
$$y_s = - R_1 - (R_2 - R_1) \cos(\theta_1) + R_2 \cos(\alpha) \tag{9b}$$

where R and θ are respectively the radius and the curvature angle of the magnet, index 1 for standard magnet and 2 for soft end magnet. At the ESRF,

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ESRF "Blue Book" CAD ray-tracing (in the plane of the orbit only):

Notation

The power distribution on the absorbers installed inside the vacuum chambers of the Storage Ring is presented as following.

(sample)

Pt n°	Src	Src n°	X mm	Y mm	α °	β °	σ mm	Pl W/mm	Pa W/mm2	Ptot W	CV n° / drawing n°
1		2	10 614	37.00	0.199	0.199	0.518	0.05	0.04		
2		2	12 728	37.00	0.166	0.166	0.620	0.04	0.02		
3	2H	2	12 846	37.34	0.166	9.628	0.625	2.03	1.29	130	CV 03 / 85.41.0073
4		2	12 848	37.00	0.165	9.627	0.626	2.02	1.29		
5		2	13 965	37.00	0.151	0.151	0.679	0.03	0.02		

Some symbols in the notation have been used in the previous sections. Here below is a summary of the notation.

Pt n°		number of points, marked in the drawings
Src		synchrotron radiation source type
Src n°		synchrotron radiation source number
	1H : dipole type 1,	n° =1
	2H : dipole type 2,	n° =2
	1S : soft end dipole type 1,	n° =0
	2S : soft end dipole type 2,	n° =3
X	(mm)	co-ordinate X, axis X parallel to the e-beam orbit
Y	(mm)	co-ordinate Y, axis Y parallel to radial direction of the ring
		the origin of the co-ordinate system X-Y is at the intersection of
		e-beam orbit and the exit of upstream dipole magnet (B1)
α	(degree °)	angle between X-ray and e-beam orbit
β	(degree °)	X-ray incidence angle on the absorbers
σ	(mm)	Gaussian vertical height of X-ray
Pl	(W/mm)	linear power density on the absorber in the horizontal plan
Pa	(W/mm2)	surface power density on the absorber
Ptot	(W)	total power on the absorber
CV n° / drawing n°	name of vacuum chamber / number of corresponding drawing	

-COMMON PART CELLS- from CV03 to CV15

(except CELL 03-04-07-15)
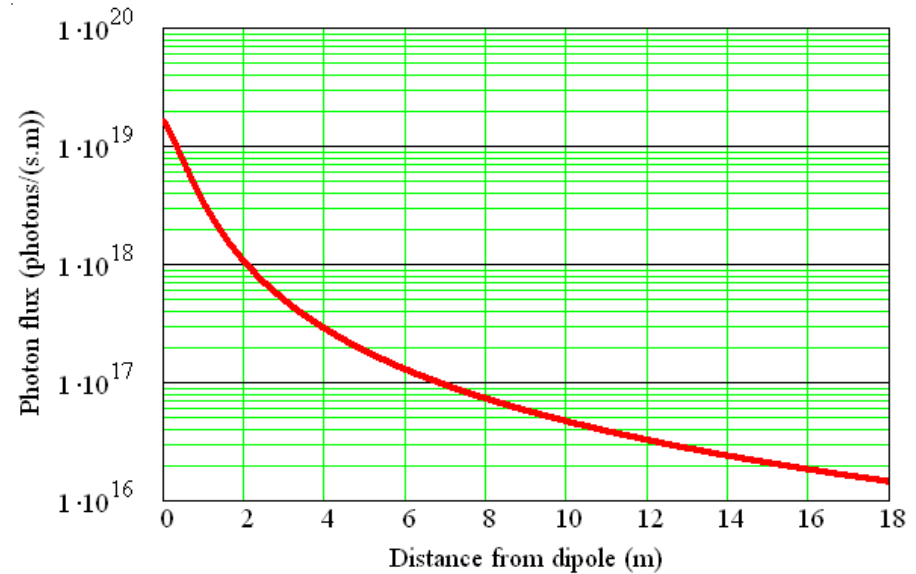
Source: O.B. Malyshev, pers. comm., for the DIAMOND Light Source

ESRF "Blue Book" CAD ray-tracing (in the plane of the orbit only):

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ESRF "Blue Book" CAD ray-tracing (in the plane of the orbit only):

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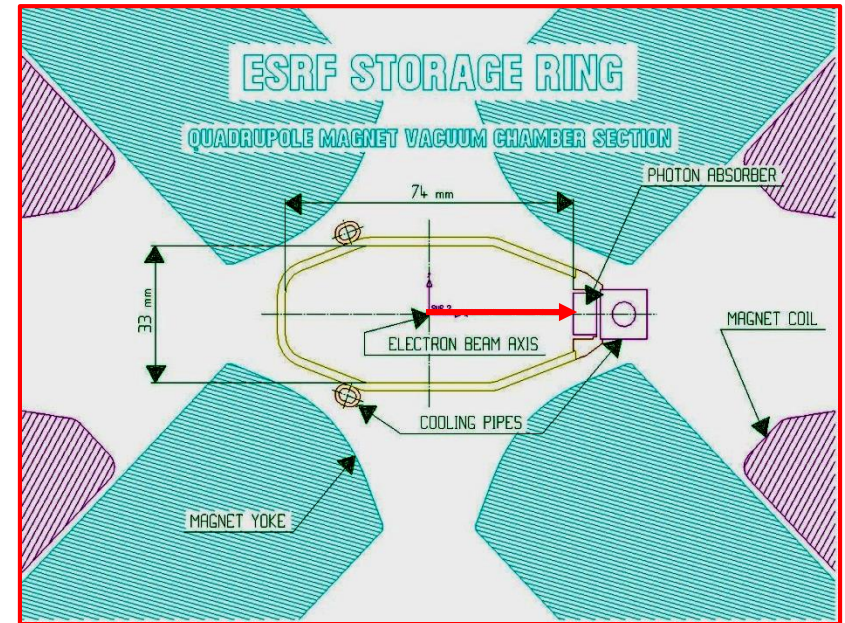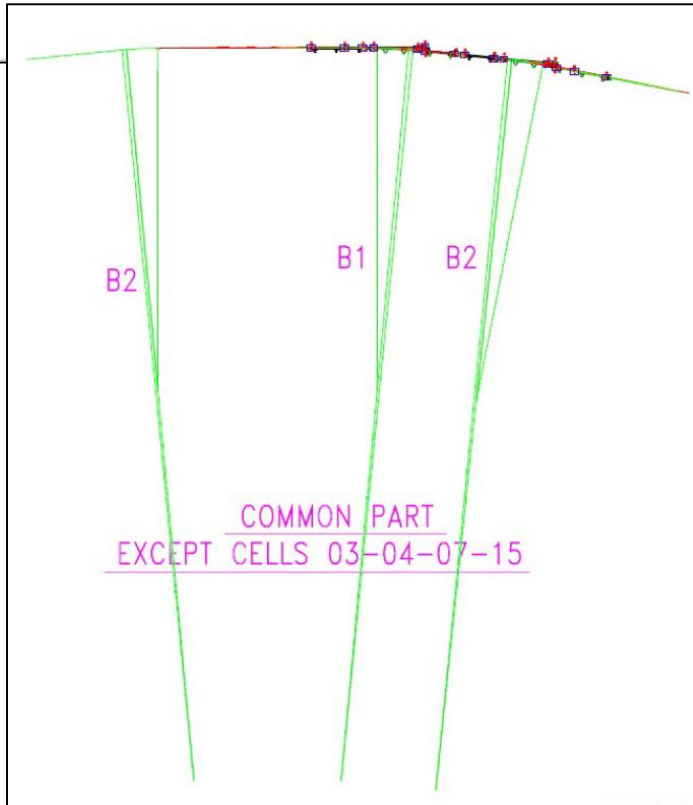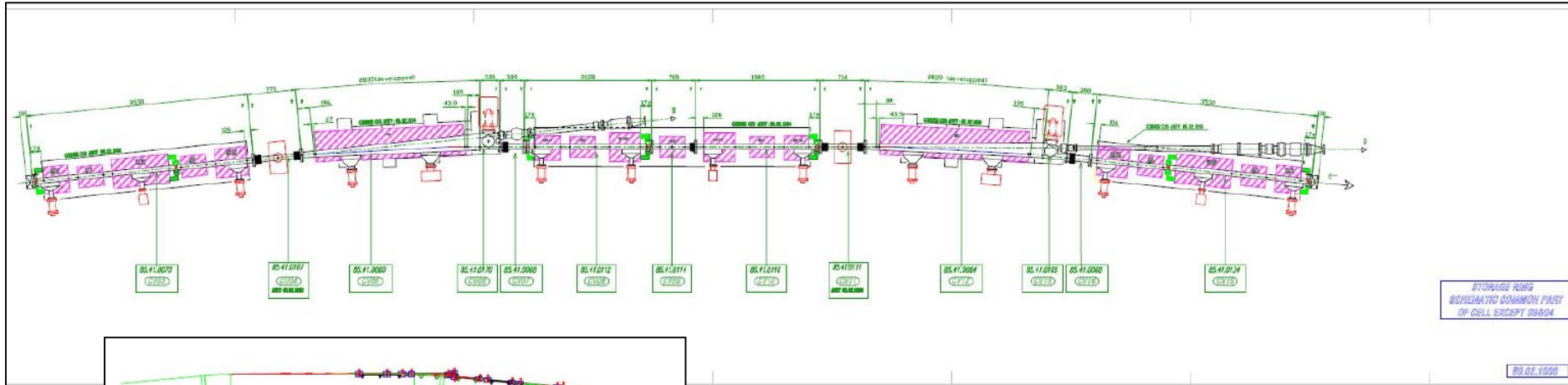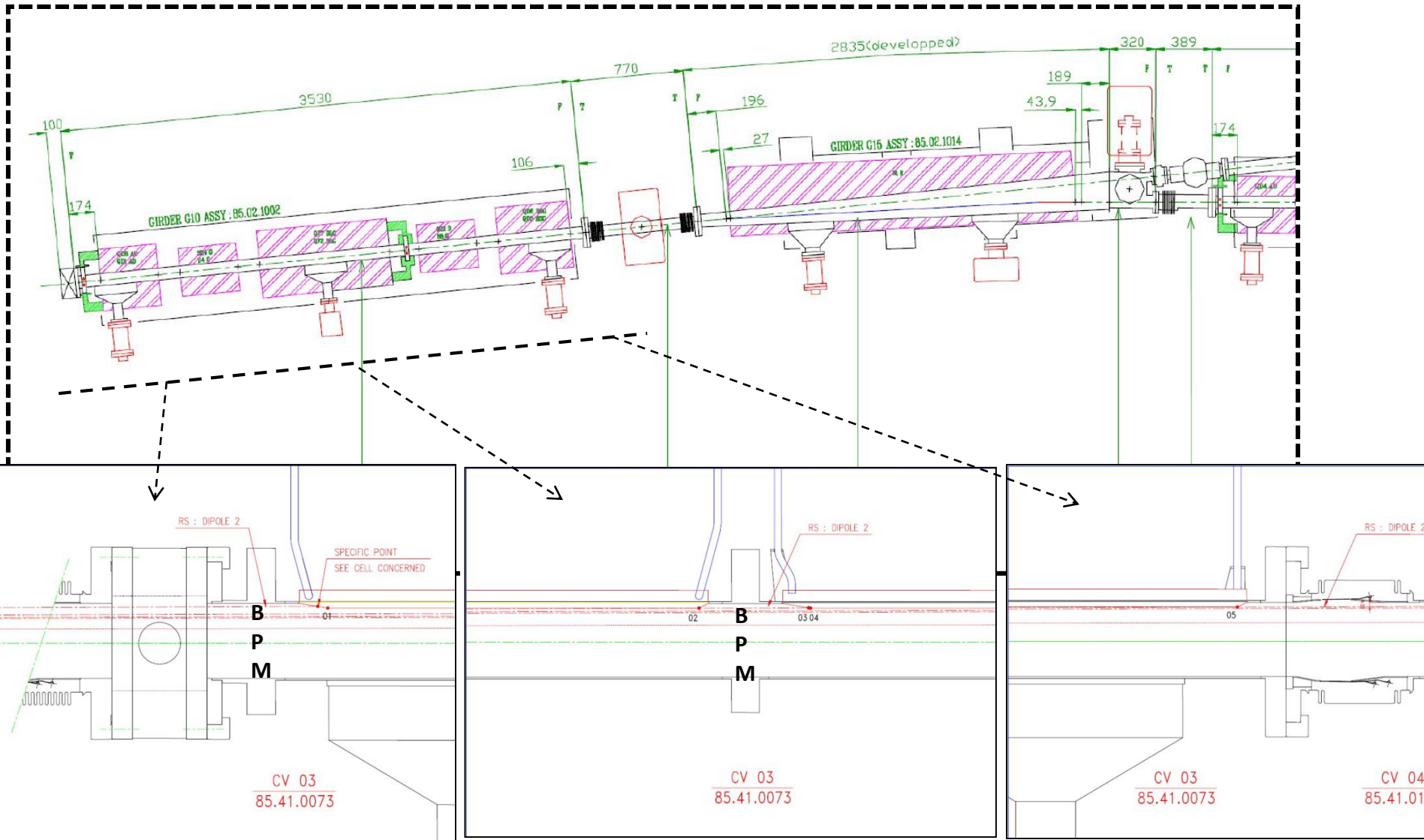
ESRF "Blue Book" CAD ray-tracing (in the plane of the orbit only):
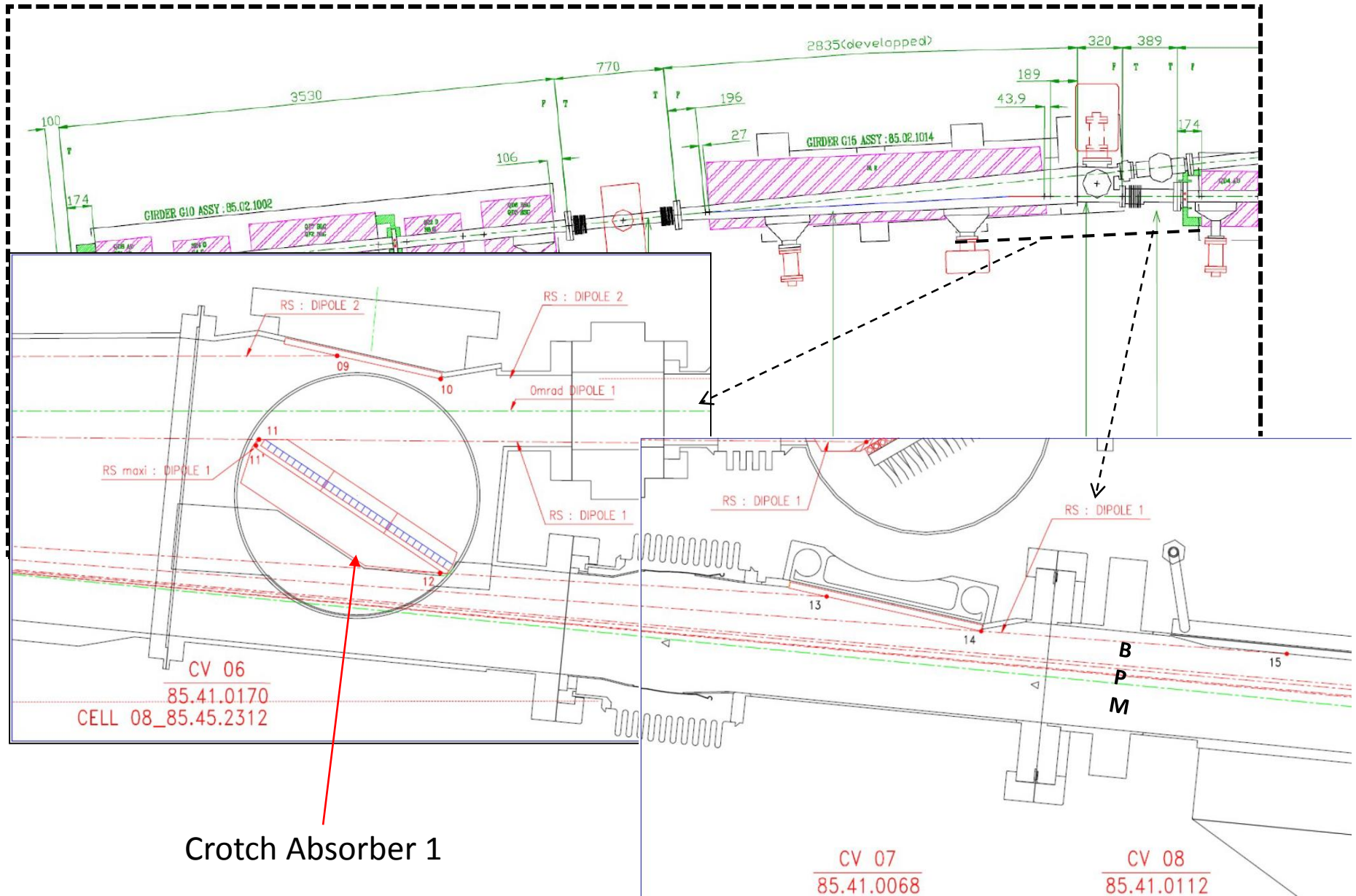
Crotch Absorber 1

ESRF "Blue Book" CAD ray-tracing (in the plane of the orbit only):

Synchrotron Radiation Power Distribution on the Absorbers in the ESRF Storage Ring : *Standard part of a Cell*

common parts for all cells except cell 03-04-07-15

E=6 GeV, I=200 mA

64 bending magnets with soft end : B=0.857 T, B(softend)=0.40 T

Vertical emittance =4E-11 m.rad, Vertical dimension at source point 37 μm, Angular deviation =1.07 μrad

Pt n°	Src	Src n°	X mm	Y mm	α °	β °	σ mm	Pl W/mm	Pa W/mm2	Ptot W	CV n° / drawing n°
1		2	10 614	37.00	0.199	0.199	0.912	0.05	0.02		
2		2	12 728	37.00	0.166	0.166	1.090	0.04	0.01		
3	2H	2	12 846	37.34	0.166	9.628	1.101	2.03	0.73	130	CV 03 / 85.41.0073
4		2	12 848	37.00	0.165	9.627	1.101	2.02	0.73		
5		2	13 965	37.00	0.151	0.151	1.195	0.03	0.01		
6		2	14 200	37.62	0.151	9.614	1.215	1.83	0.60		
7	2H	2	14 204	37.00	0.149	9.611	1.216	1.83	0.60	18	CV 04 / 85.41.0107
8		2	14 620	37.00	0.145	0.145	1.251	0.03	0.01		
9	2H	2	17 750	44.90	0.145	12.770	1.517	1.94	0.51	167	CV 06 / fixed absorber
10	2H	2	17 835	26.00	0.083	12.708	1.522	1.93	0.50		85.41.0170
11	1H	1	249	127.02	5.064	56.936	0.214	52.90	98.51	8 160	CV 06 / crotch absorber
11'	1H	1	247	121.48	4.939	90.000	0.210	64.51	122.71		85.41.0170
12	1H	1	406	35.20	2.074	30.074	0.126	55.65	176.88		
6_a	2H	2	18 273	26.64	0.083	29.917	1.560	4.26	1.09		
6_b	2H	2	18 227	0.00	0.000	30.000	1.553	4.29	1.10	1 759	Beam Port
6_b'	1H	1	781	204.89	5.625	150.000	0.279	24.11	34.52		
6_c	1H	1	732	169.79	5.064	149.789	0.255	26.57	41.57		
13	1H	1	717	46.46	2.074	9.074	0.151	14.34	37.88	1 833	CV 07 / 85.41.0068
14		1	843	31.00	1.403	8.403	0.139	14.54	41.79		

40

CROTCH-2 AND CV13 GEOMETRY:

TOP-VIEW

Total flux @200ma: 5.82E+18 ph/s (46mrad)

to FE absorber

X-rays from preceding dipole (430W)

Critical Energy Dipole SR: 19.5 keV

X-rays from this dipole (7200W)
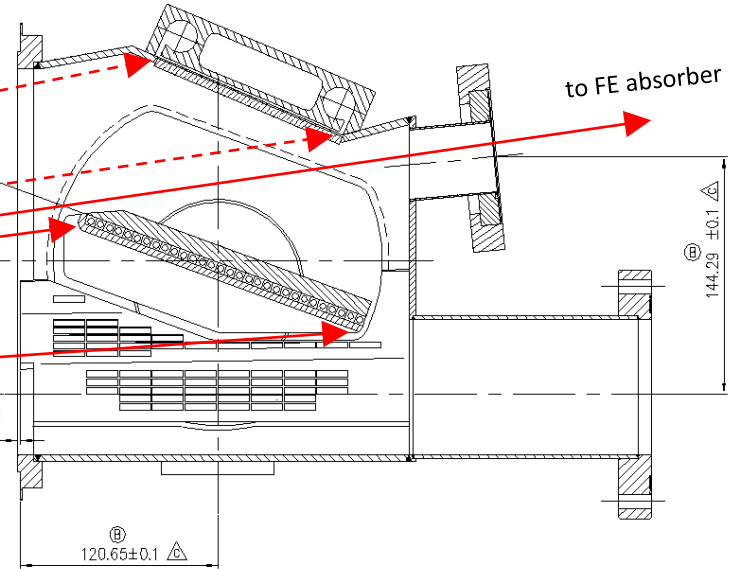
PEN7 location

< --------------------------- SIDE-VIEW / CUT-OUTS --------------------------- >

41
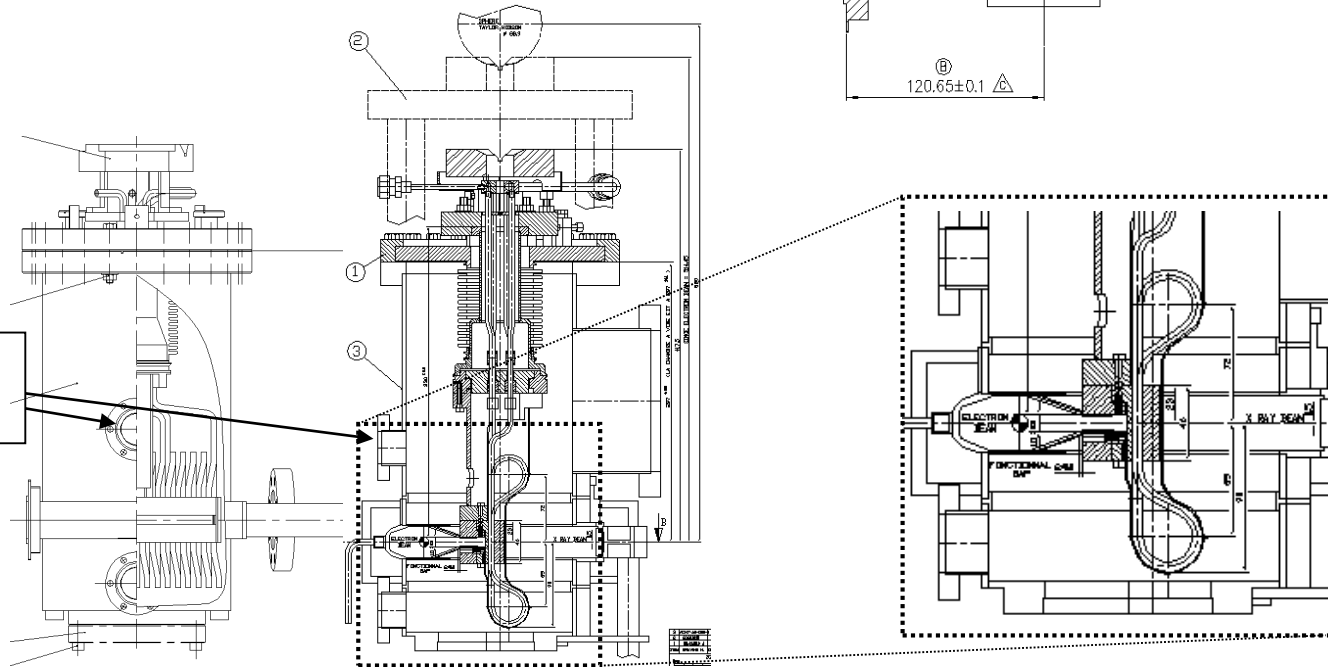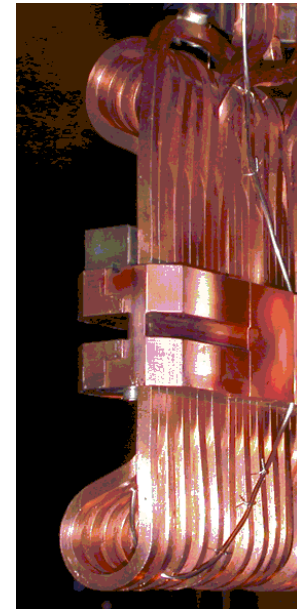
DIPOLE-2 (CV12) GEOMETRY:

radius of curvature: 23.366 m

Pumping-port geometry simulated separately

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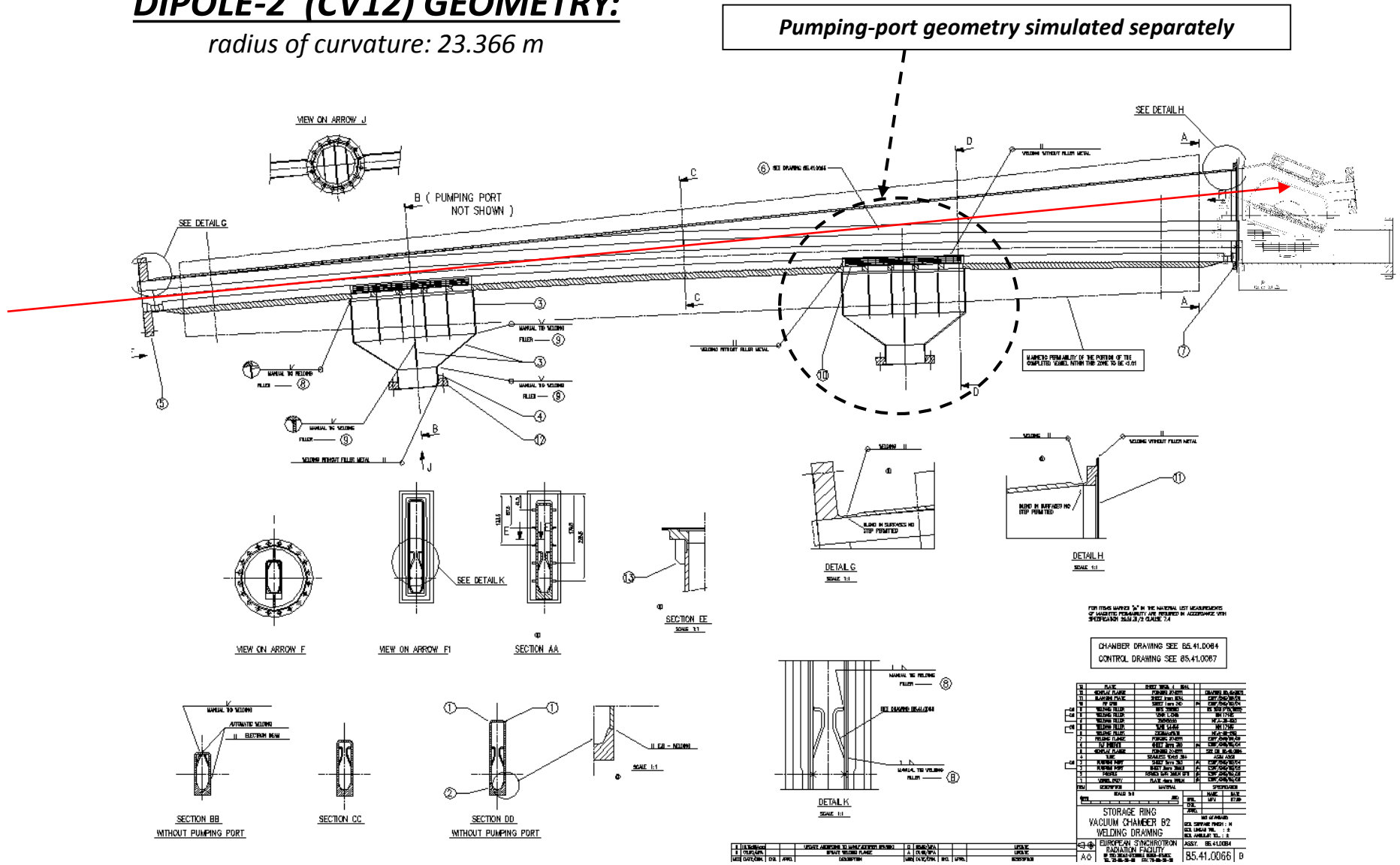
400 l/s SIP + GP500 NEG:
simulated total pumping speeds of 500, 750, 1000 l/s

OLD DOS-based Molflow code (1989 → 2008)

pressure test facet:

320x20mm²

PEN7

crotch absorber

```
Home/End: ALFA_V= 24.000 PgUp/PgDn: BETA_V= 43.000 View 1 of 1

< F1 >  < F2 >  < F3 >  < F4 >  < F5 >  < F6 >  < F7 >  < F8 >  < F9 >  < F10 >      Gen/Ads=        524001/           0
Print   Axes    <P>     ReDraw  Scale   Move    PanU    P(x)    Home    Quit        Tot.No.of hits = 54310228
SaveScr WinSize         LineSty Select  View    Aspect          Trace              c:\rk\tp\molflow\dipole2\
                                                                                   File:cr2abs1.txt
```
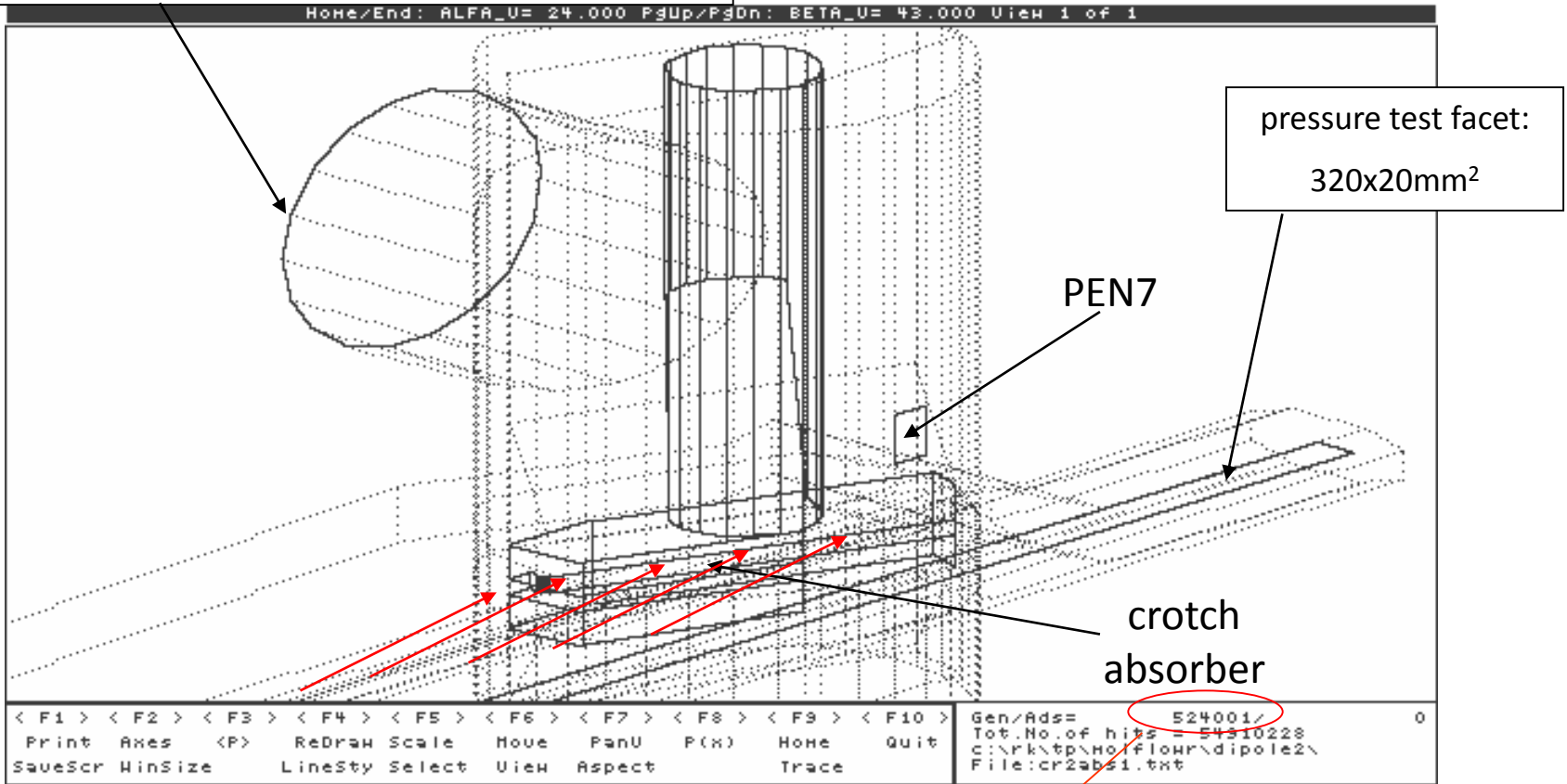
Closer view of the Molflow simulation model:

total number of points: 339; total number of facets: 131

computation time: ~15 hours

43

MC Calculation of the Pressure Profile for a Dipole-2 Chamber: Crotch-2 Desorption Only

CR, SIP, GP200

- 500, 0.0, 200
- 500, 60, 200
- 500, 60, 0.0
- 750, 60, 200
- 1000, 60, 200

$P\ (\ mbar\ /\ (\ mbar\cdot l/s\ )\ )$

$Z\ (m)$

400 l/s + GP500

GP200 NEG Pump Pumping Port

60 l/s SIP Pumping Port

PEN7 gauge (star symbols)

44
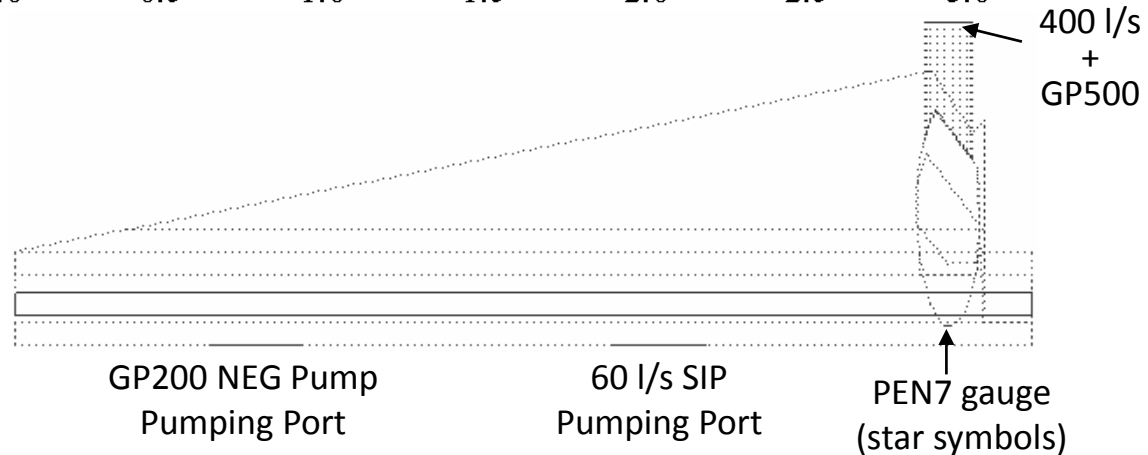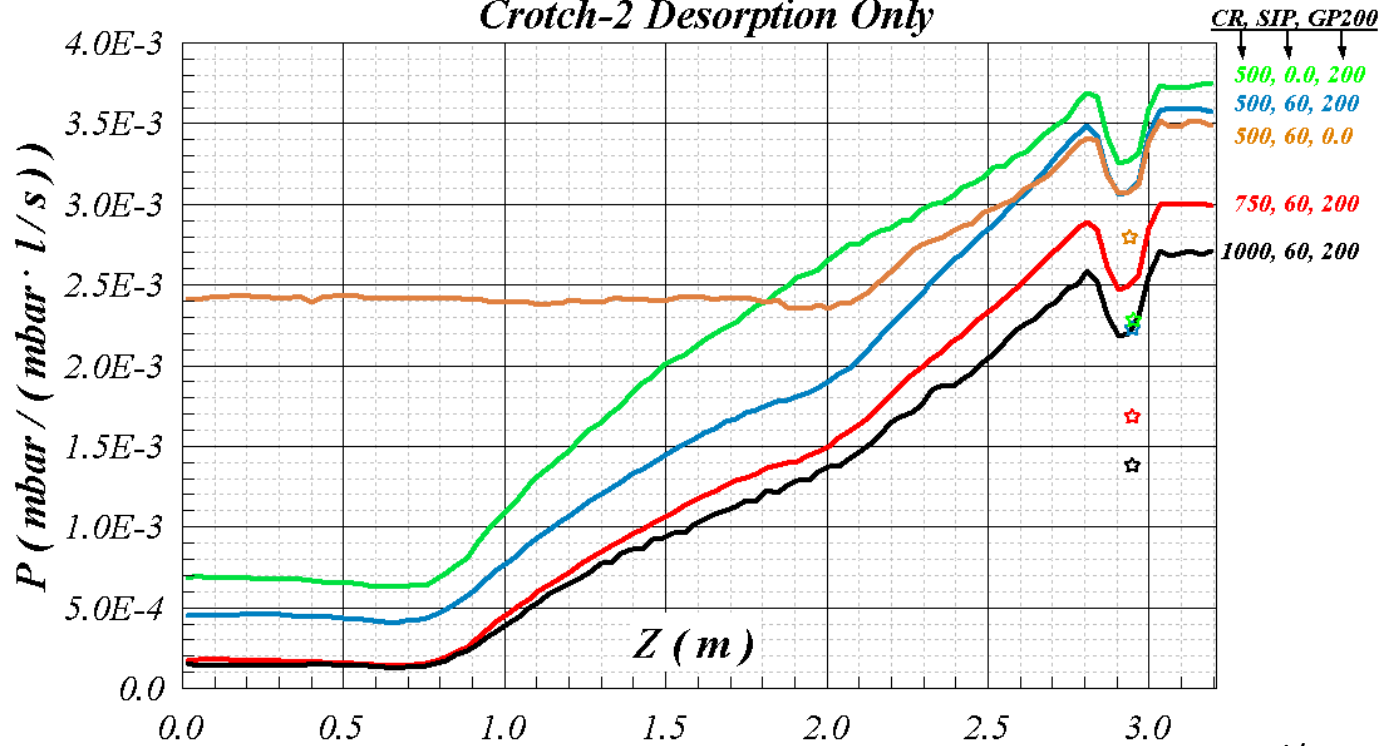
ESRF DIPOLE PUMPING PORT GEOMETRY

MODELED AND SIMULATED WITH *MOLFLOW:*

ESRF Dipole-2 Pumping Port: Conductance Calculation

CALCULATED PUMPING PORT CONDUCTANCE:
$$C = 1/S_{eff} - 1/S_{inst}$$

C_{PPORT} = 232.89194 +/-0.16509 ($l \cdot s$) @ 1,990,000 molecules

320 mm

280 mm

B

A

New Molflow+ code

C

beam chamber: molecules are generated here

D
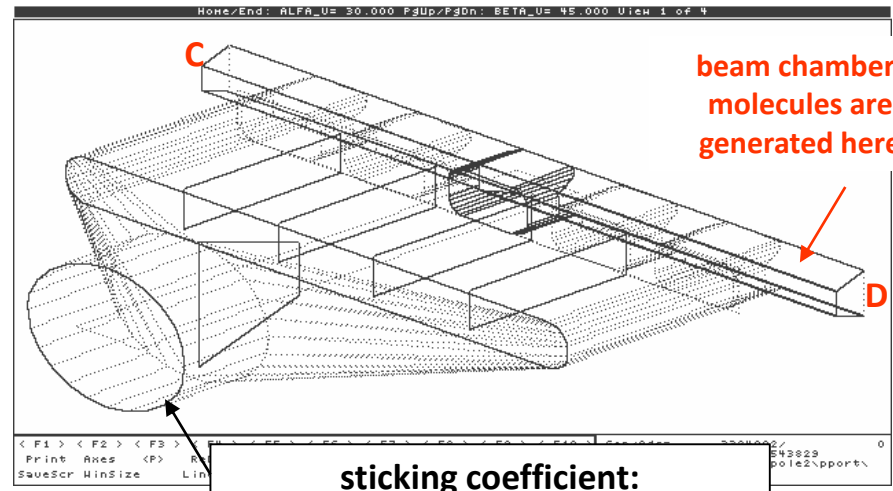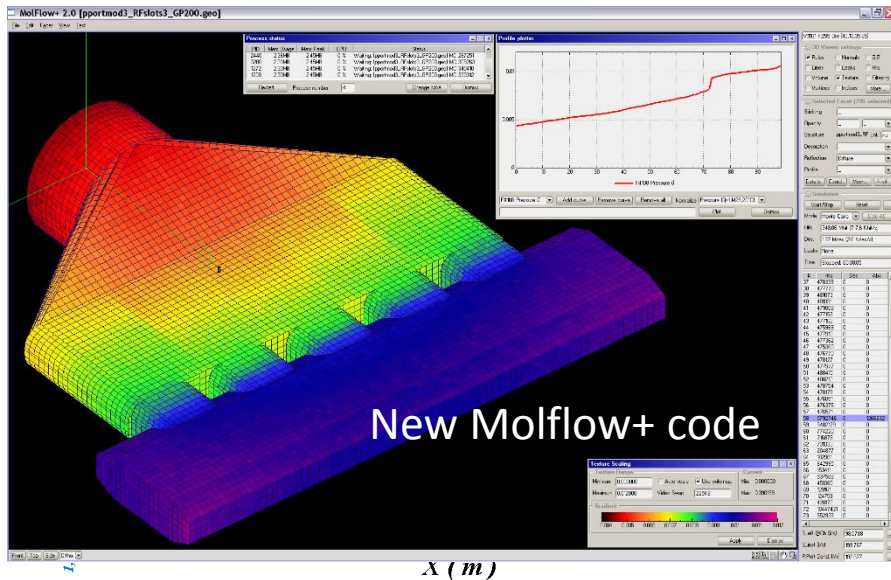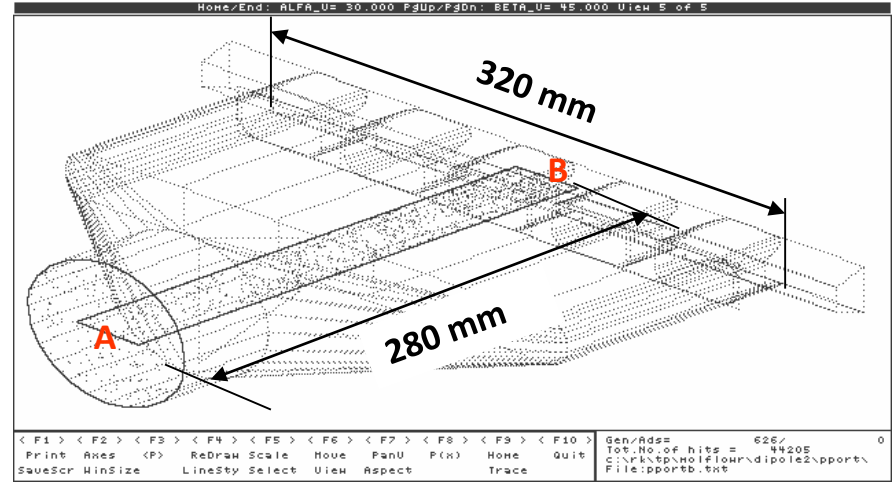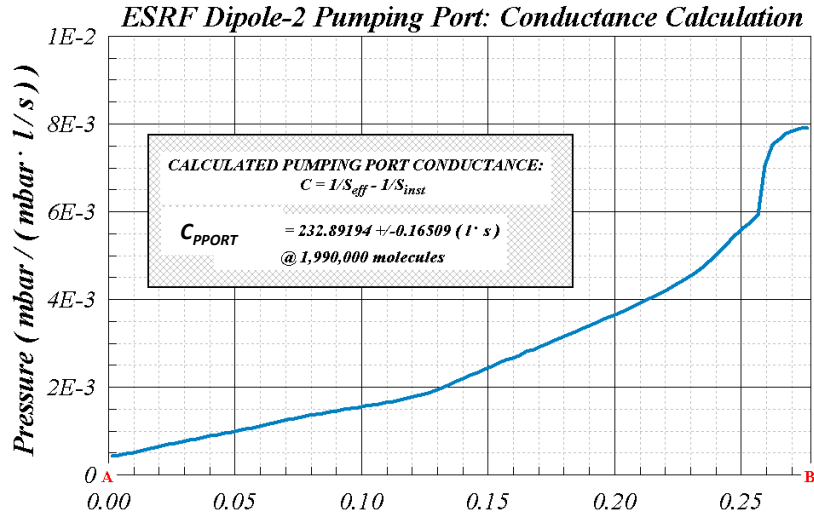
sticking coefficient:
s=1.0 → 913 l/s
s=0.0656 → 60 l/s

45

Molflow+ TPMC code: sample of modelling of one ESRF dipole/crotch 2 vacuum chamber and its pressure profile
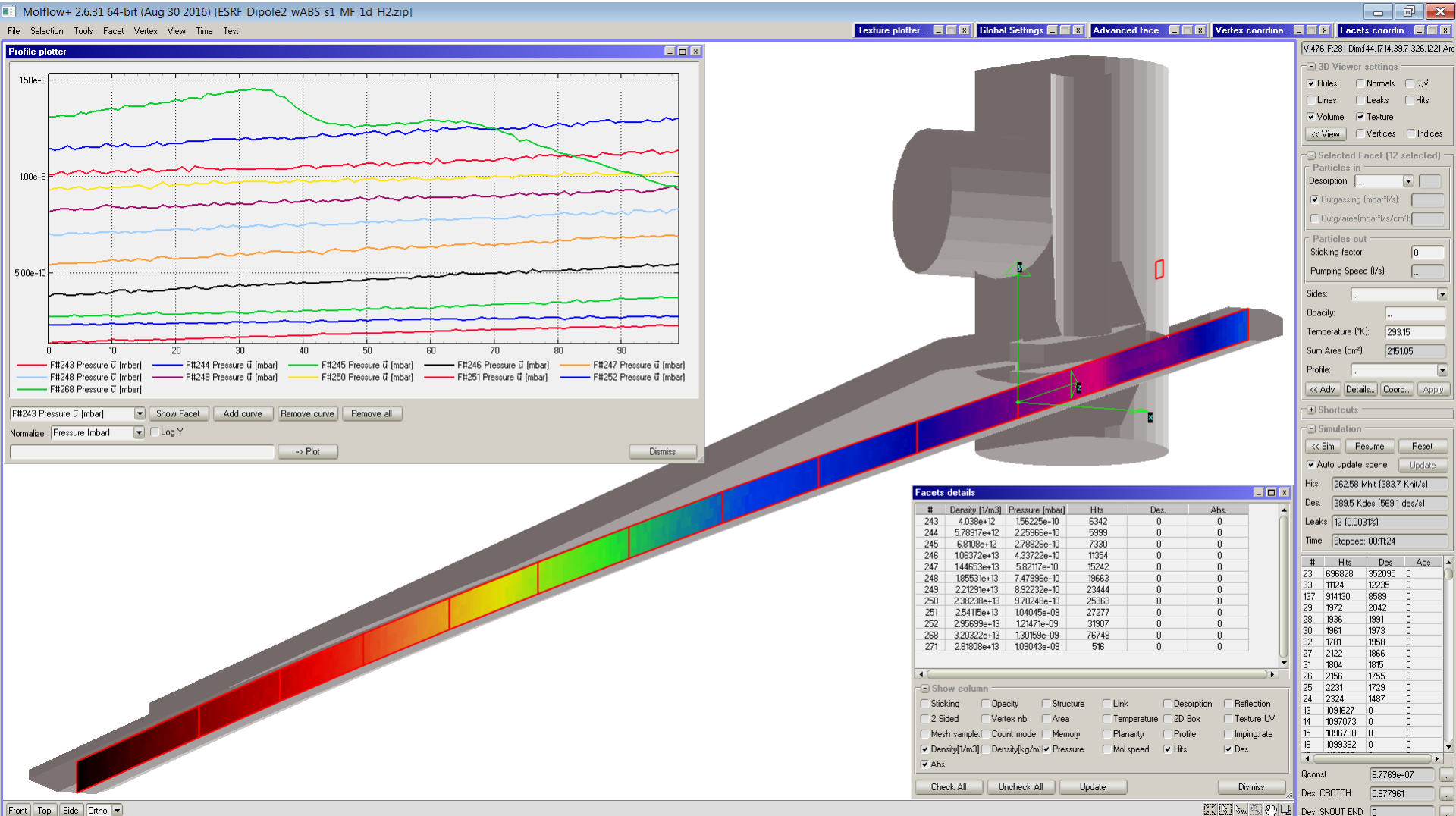
Modern version of Molflow code:

"narrow-gap chamber: elliptical
cross-section, 57x8 mm^2 (HxV);
Specific conductance ~ 0.9 l·m/s;
In-air undulator or wiggler installed
around it

e-

Modern version of SYNRAD+ code:
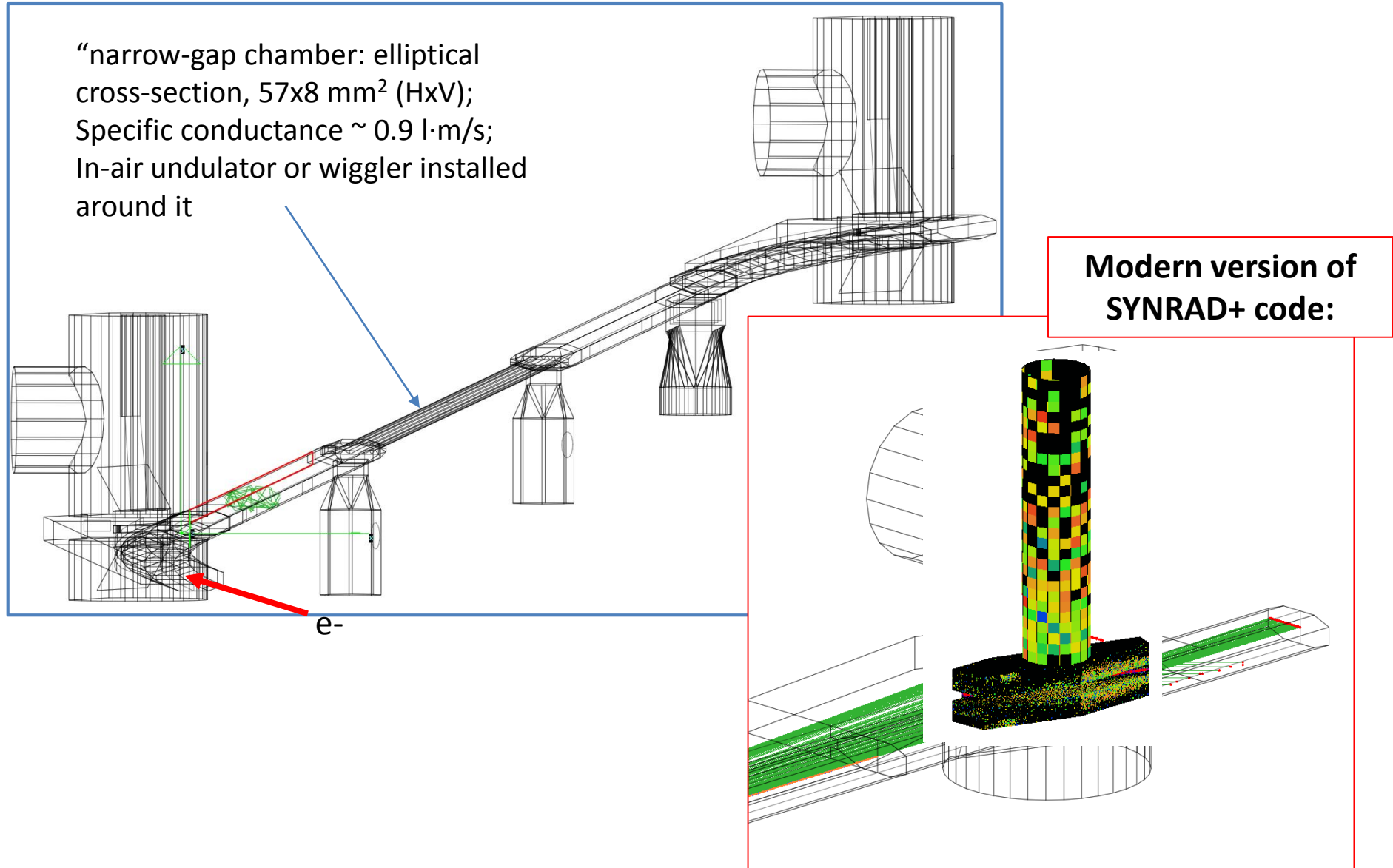
Details of a crotch absorber ray-tracing with SYNRAD+; Texture scale proportional to flux absorbed by corresponding facet

After 2' calculation

After 36' calculation

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SR flux and power distribution and flux and power spectra with SYNRAD+

Profile plotter

Vertical angle →

Plane of the orbit

Fl#47 0 SR Flux/cm²   Show Facet   Add curve   Remove curve   Remove all   ✓ Log Y ✓ Normalize
→ Plot   Fl#23 0 SR Power/cm²   Dismiss
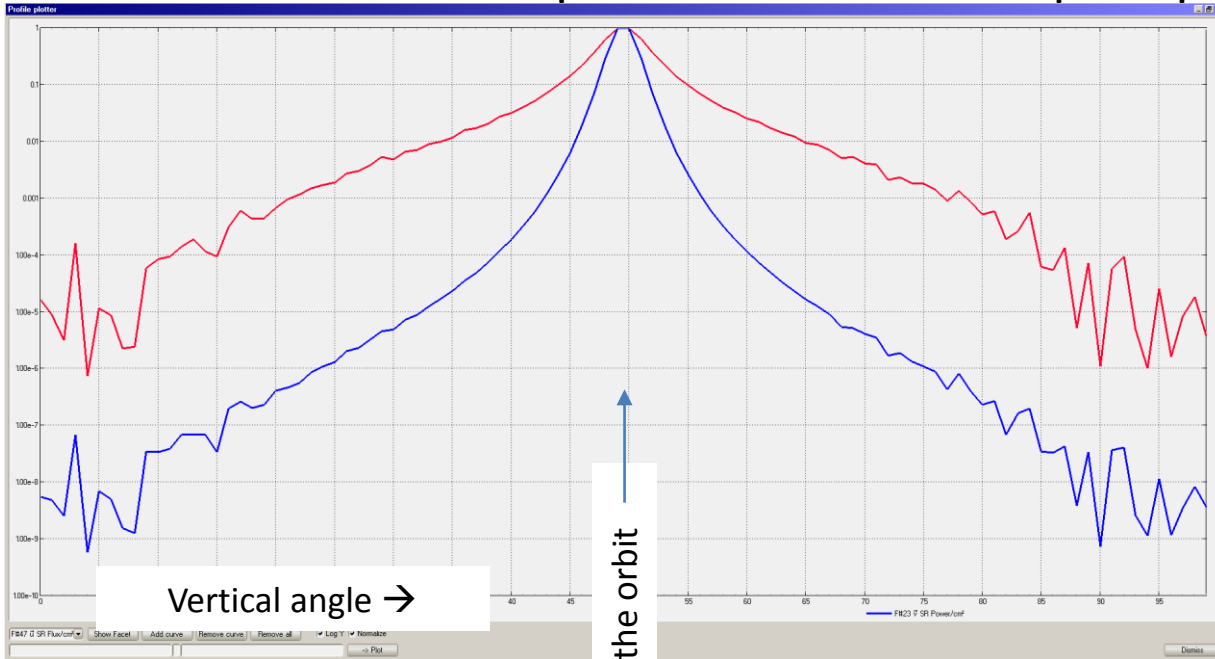
Left:
- SR flux and power distributions along the ~ 150 mm long flat absorber facet
- Note different width of "Gaussian" profile for F and P in the vertical direction (Red vs Blue curve)
- All curves normalized to 1

Right:
- SR flux and power spectra generated by SYNRAD+, normalized to 1;
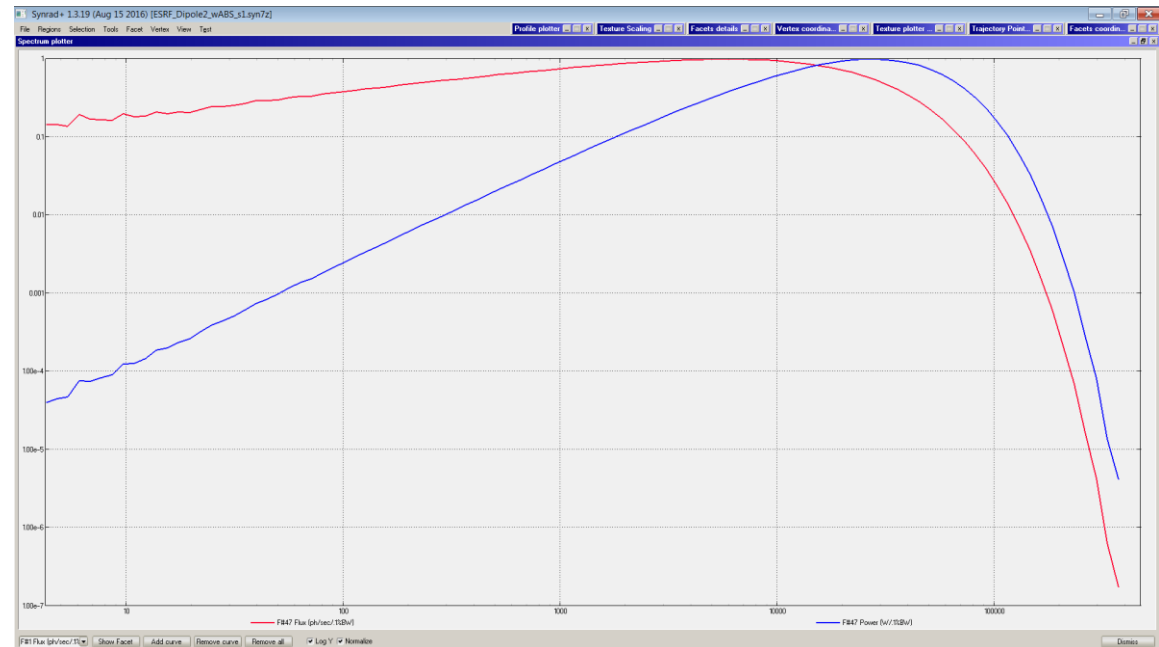
CV3-Type Vacuum Chambers, 3530 mm long:
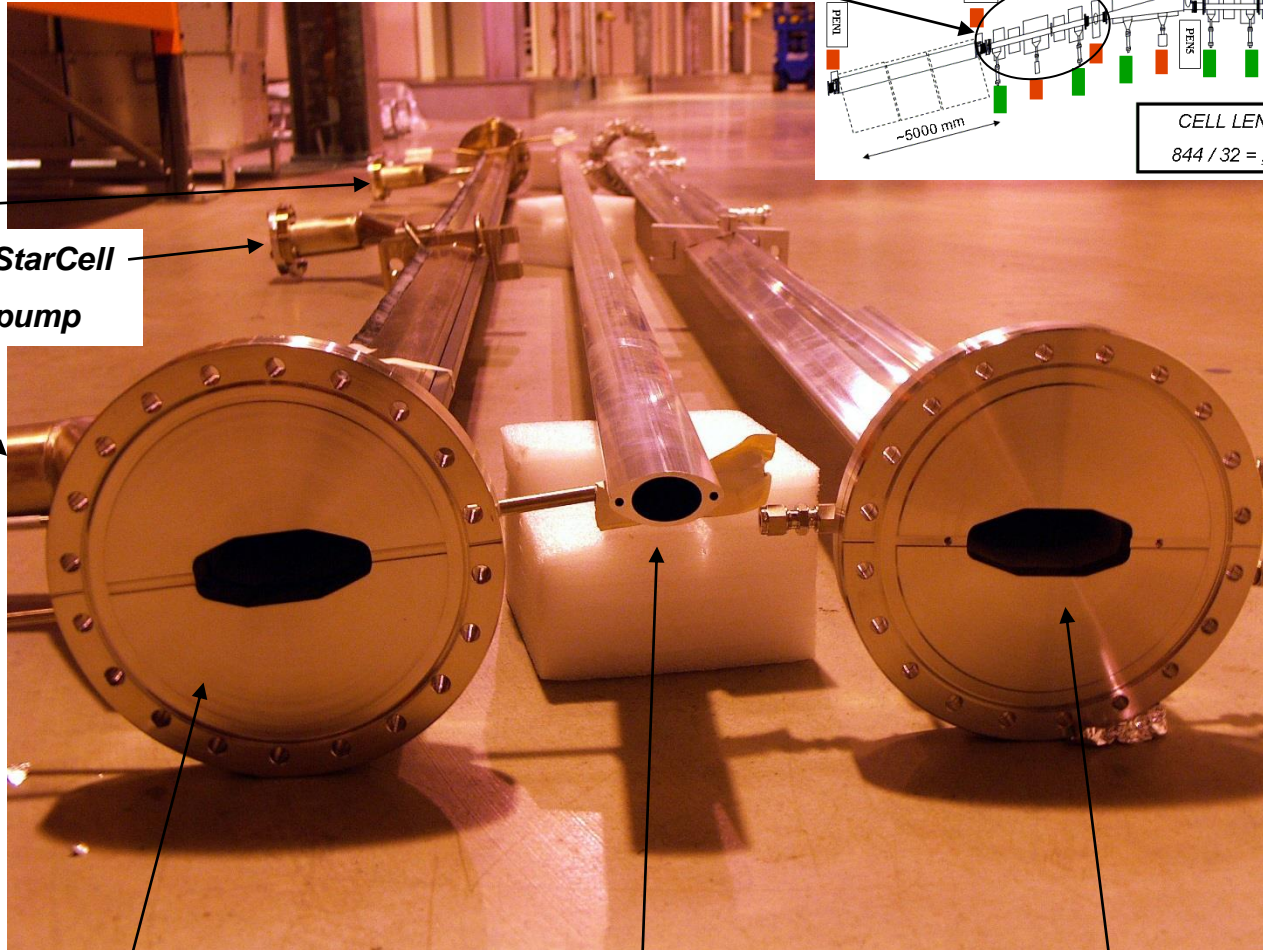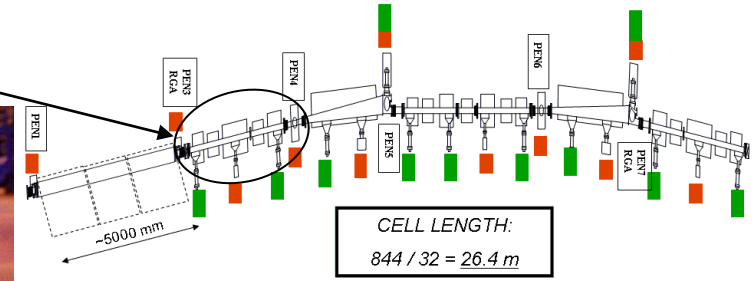
GP200 NEG

45 l/s StarCell Ion-pump

CELL LENGTH:
844 / 32 = 26.4 m

~5000 mm

Standard CV3 chamber: 2xNEG + 1 SIP

Hi-temp brazing of Cu absorber ; precision eb-welding of SS parts

ESRF-2 extrusion: 30x20mm² (HxV)

chamber NO pumps, only NEG-coating

Soleil-type CV3:

Al extrusion 70x35mm²; NO pumps, only NEG-coating

50
50

Gas-bremsstrahlung power P_{BS} generated along straight section: (to be minimized at the beamline hutch!)

Exp.Hutch
~20-100 m away

SR
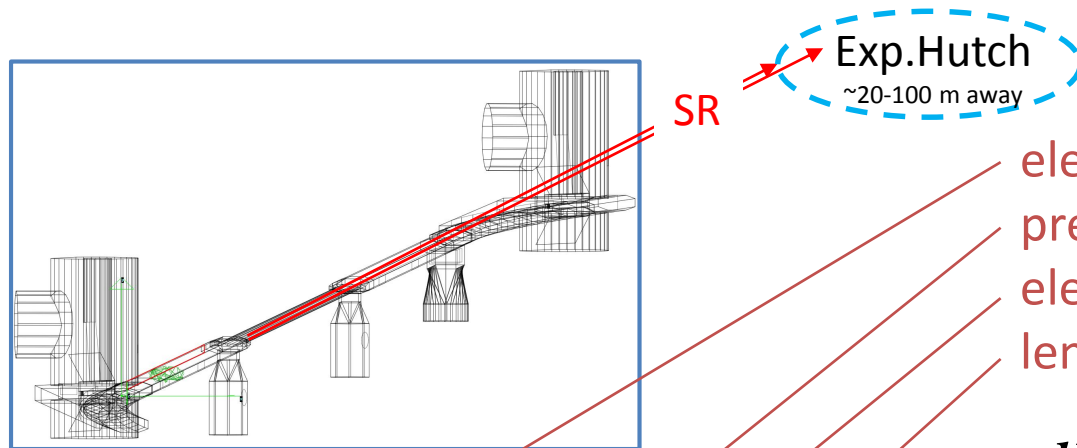
electron stopping power
pressure in straight section
electron beam intensity
length of straight section

$$P_{BS} = C \times \frac{dE}{dx}(E_e) \times p \times I \times L,$$

$$\frac{dE}{dx}(E_e) \propto E_e$$

$$p \propto E_e \times I$$

$$P_{BS} \propto E_e^2 \times I^2 \times L$$

ESRF: going from 200 mA → 300 mA: P × 2.25

Ref.: P. Berkvens et al., "Assessment of beamline shielding at the ESRF", 7th RadSynch Workshop, Saskatoon, CA, 2007

European Synchrotron Radiation Facility

Assessment of beamline shielding at the ESRF

P. Berkvens, P. Colomp and R. Kersevan
European Synchrotron Radiation Facility

The European Light Source

Slide: 1

MOLFLOW: 3D Monte Carlo calculation of pressure distribution in storage ring vacuum chamber (developed by R. Kersevan)

Pressure distribution from M.C. code *Molflow*

Pressure distribution for photon sampling in M.C. code *BeamLines*

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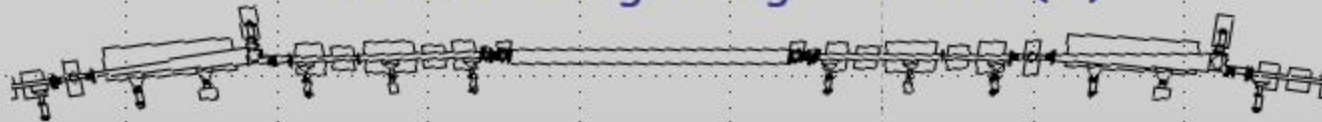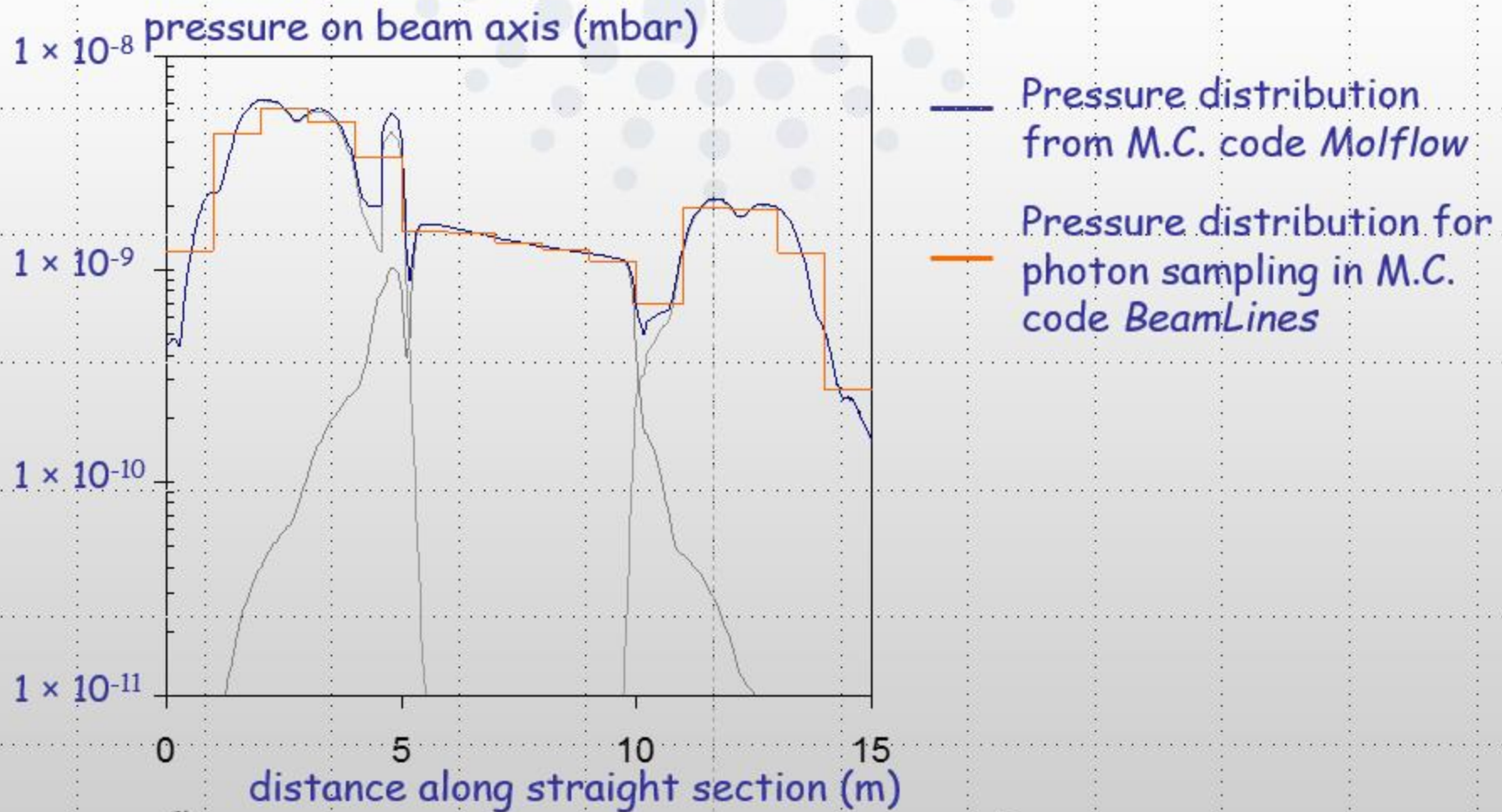
MOLFLOW: 3D Monte Carlo calculation of pressure distribution in storage ring vacuum chamber (developed by R. Kersevan)
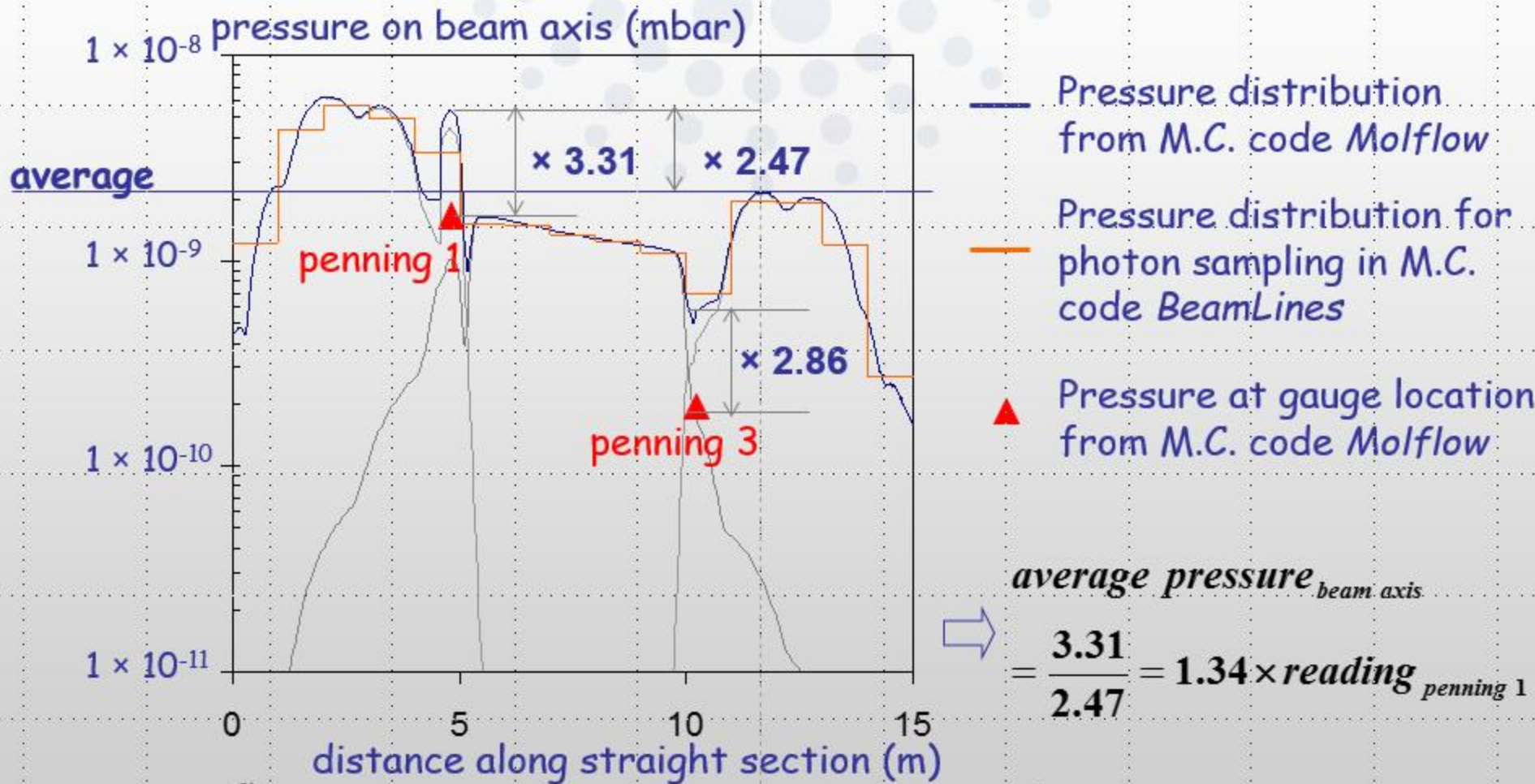
MOLFLOW: 3D Monte Carlo calculation of pressure distribution in storage ring vacuum chamber (developed by R. Kersevan)

average pressure$_{beam\ axis}$ = 1.34 × reading$_{gauge}$

for average pressure of 1×10^{-9} mbar in straight section :
- CV500: 6.37×10^{-10} mbar
- rest: 1.18×10^{-9} mbar

pressure on beam axis (mbar)

distance along straight section (m)
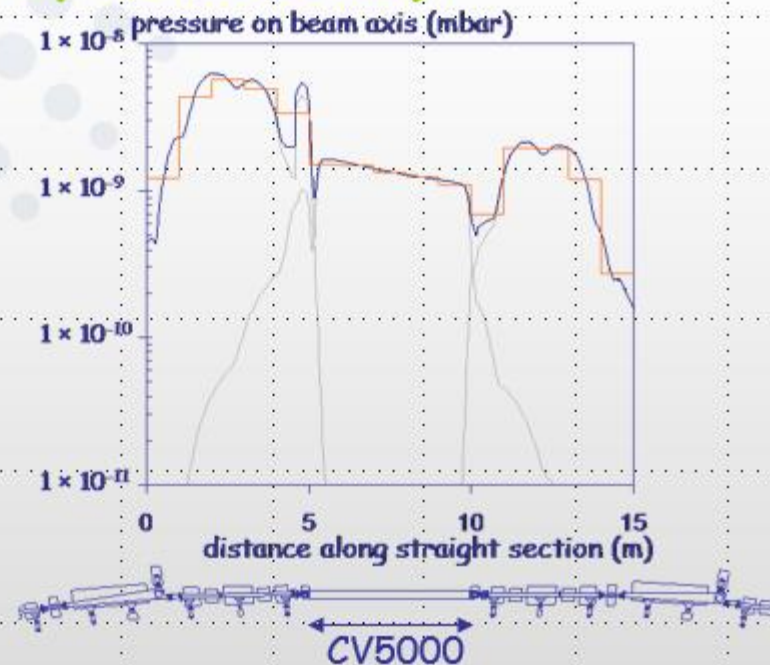
CV5000

Residual gas composition in straight section (from RGA analysers)

molecule	relative pressure (%) inside CV5000	relative pressure (%) rest of straight section
H_2	85	80
CO	15	10
CO_2	-	5
CH_4	-	3
H_2O	-	2

55

Shielding calculations are done with Monte Carlo code *BeamLines* developed by P. Berkvens:

+ Electromagnetic shower description based on EGS4.
+ Bremsstrahlung differential fluence calculated from theoretical cross sections, using realistic pressure distributions and residual gas compositions in the storage ring straight section.
+ Direct sampling of photons (instead of electrons).
+ 3D description of front end and optical components.
+ Photo neutron dose distributions using differential photon track lengths and assuming an isotropic angular distribution.

Examples:

+ ID20 Magnetic scattering beamline;
+ ID12 Circular polarisation beamline.

Transmission through front end

6 GeV:
$1/\gamma$ = 0.085 mrad

vertical slit
4 mm
(± 0.089 mrad)

22.5 m

13.5 m

horizontal slit
2 mm
(± 0.074 mrad)

distance from middle of
straight section

vertical slit

photons / MeV
1×10^5
1×10^4
1×10^3
1×10^2
1×10^0

energy (MeV)

— uncollimated
— ray-tracing
— Monte Carlo

ID20 – Magnetic scattering beamline

lead screens (22 mm)   lead screens (20 mm)

y (cm)

x (cm)

mask

differential pumping   primary slits   monochromator

collimator   mirror

bremsstrahlung stop
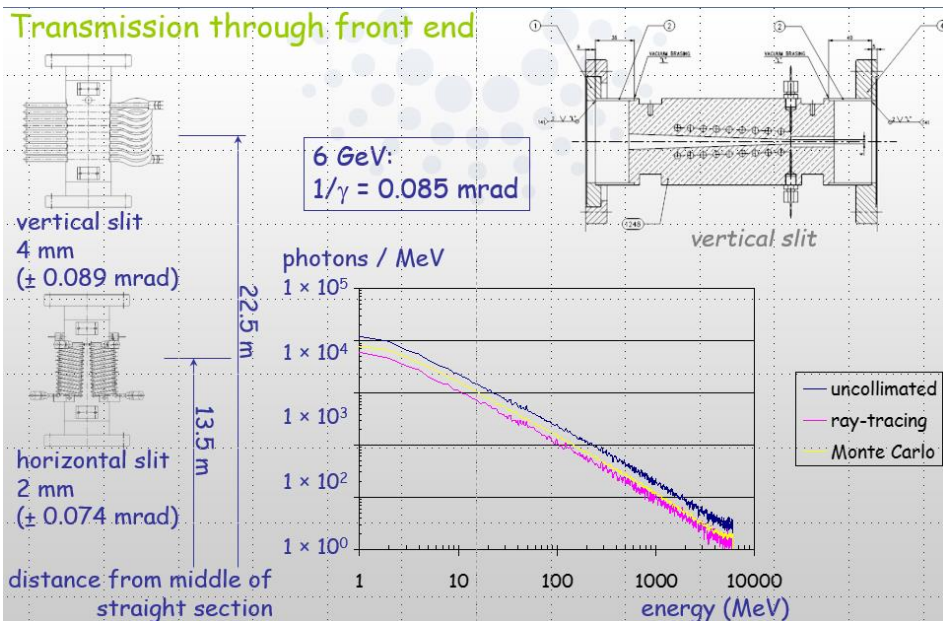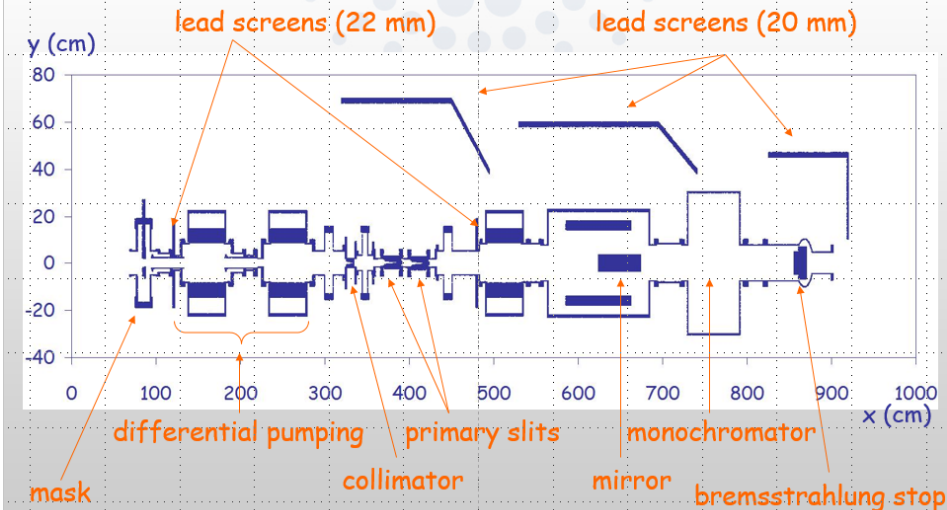
Summarizing: a double MC scheme is used;
- First a detailed 3D model of the storage ring's vacuum system is made:
    - SR ray tracing (SYNRAD+) generates the photon flux
    - TPMC simulation (Molflow+) converts the flux on all surfaces to local desorption, and then calculates the pressure profile along the e- beam path
- A second detailed model of the shielding of the Front-Ends (absorbers, collimators, etc…) and of the experimental beamline hutches is made:
    - Another independent MC simulation (based on EGS4-derived custom code) is run taking into account as source terms the beam-gas scattering in the storage ring and the subsequent scattering of the high-energy gamma rays along the FE and the BL components

57

Another example: Analysis and optimization of the crotch absorber of MAX-IV

Proceedings of EPAC08, Genoa, Italy — THPP141

TEST OF A NEG-COATED COPPER DIPOLE VACUUM CHAMBER

Anders Hansson[#], Magnus Berglund, Erik Wallén, MAX-lab, Box 118, SE-221 00 Lund, Sweden
Roberto Kersevan, ESRF, BP 220, FR-38043 Grenoble Cedex, France

1.5 GeV MAX-II ring, Lund, Sweden

Normal configuration of the crotch, with Ion-pump, Ti-sublimator, crotch absorber
Chamber material: stainless steel

The positive outcome of this experiment convinced the MaxLab management that a fully NEG-coated machine would have been feasible
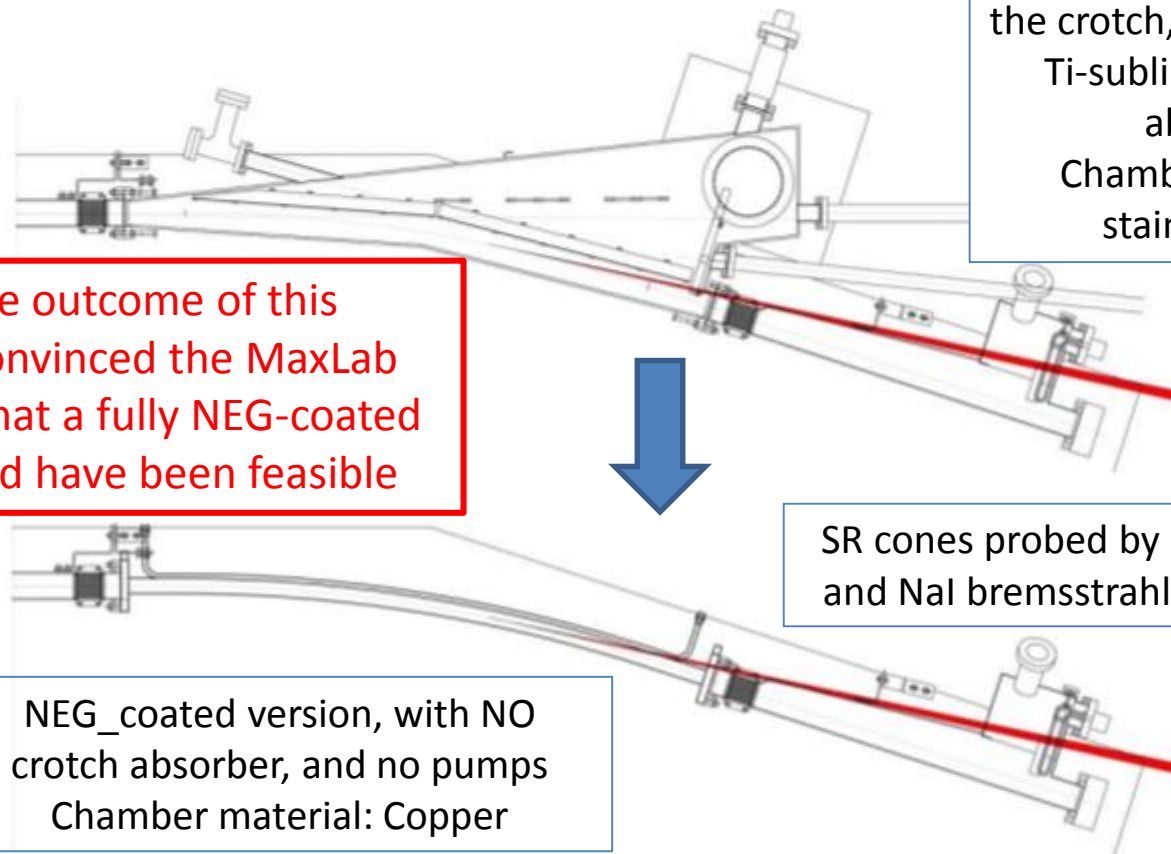
SR cones probed by Geiger-Muller and NaI bremsstrahlung detectors

NEG_coated version, with NO crotch absorber, and no pumps
Chamber material: Copper

Figure 1: Drawings of the second half of cell 3 (*top*) and cell 2 (*bottom*) in the MAX II storage ring. The added red beam paths show the cone of bremsstrahlung radiation detected by the NaI detectors.

Another example: Analysis and optimization of the crotch absorber of MAX-IV
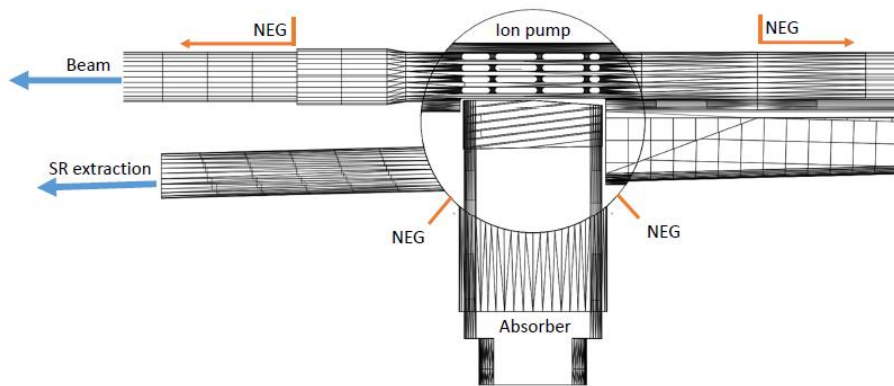
Figure 4.7: Top view of the vacuum chamber with the MAX IV crotch absorber

From CAD model to SYNRAD+ simulation
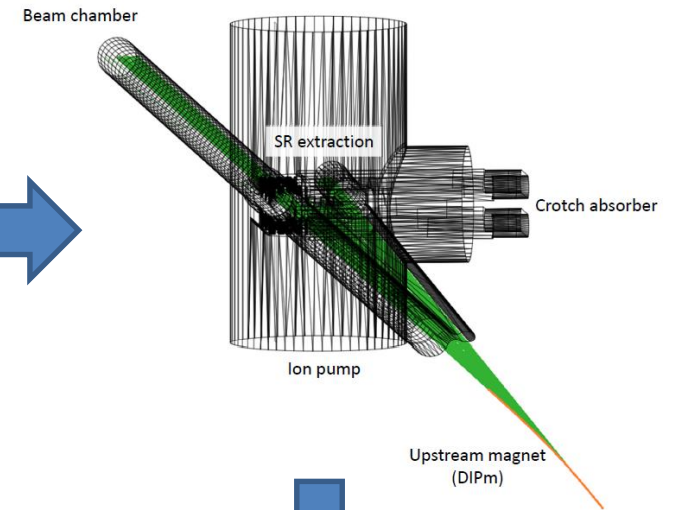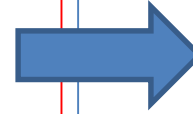
Figure 4.9: The dipole magnet and SR radiation schematics in Synrad+
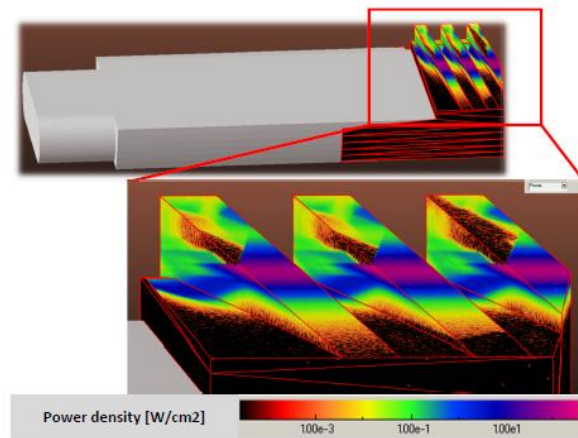
Figure 4.11: Power density on the lower jaw of the absorber
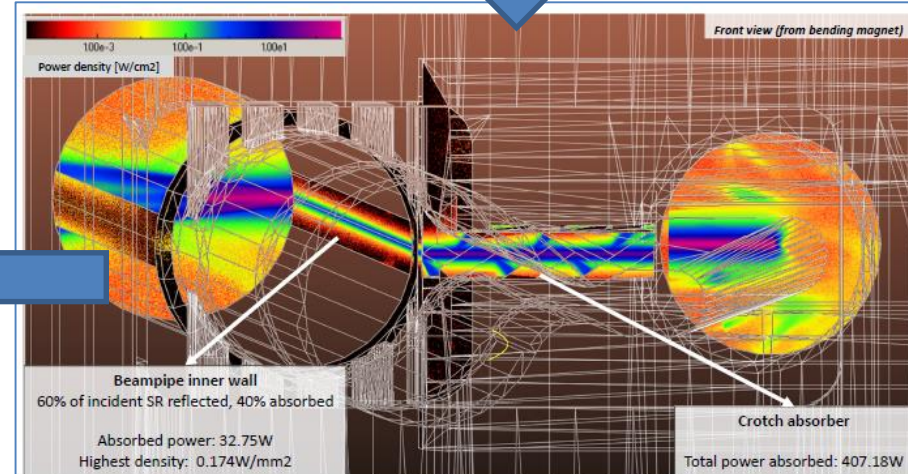
Figure 4.10: Power distribution on the walls

Ref.: "Monte Carlo simulations of Ultra High Vacuum and Synchrotron Radiation for particle accelerators", M. Ady, CERN, doctoral dissertation at EPFL, Lausanne, CH, May 2016; also as an IPAC-15 paper;

From SYNRAD+ simulation to Molflow+: → Pressure profile for CH_4

Figure 4.12: CH_4 simulation at 100Ah dose
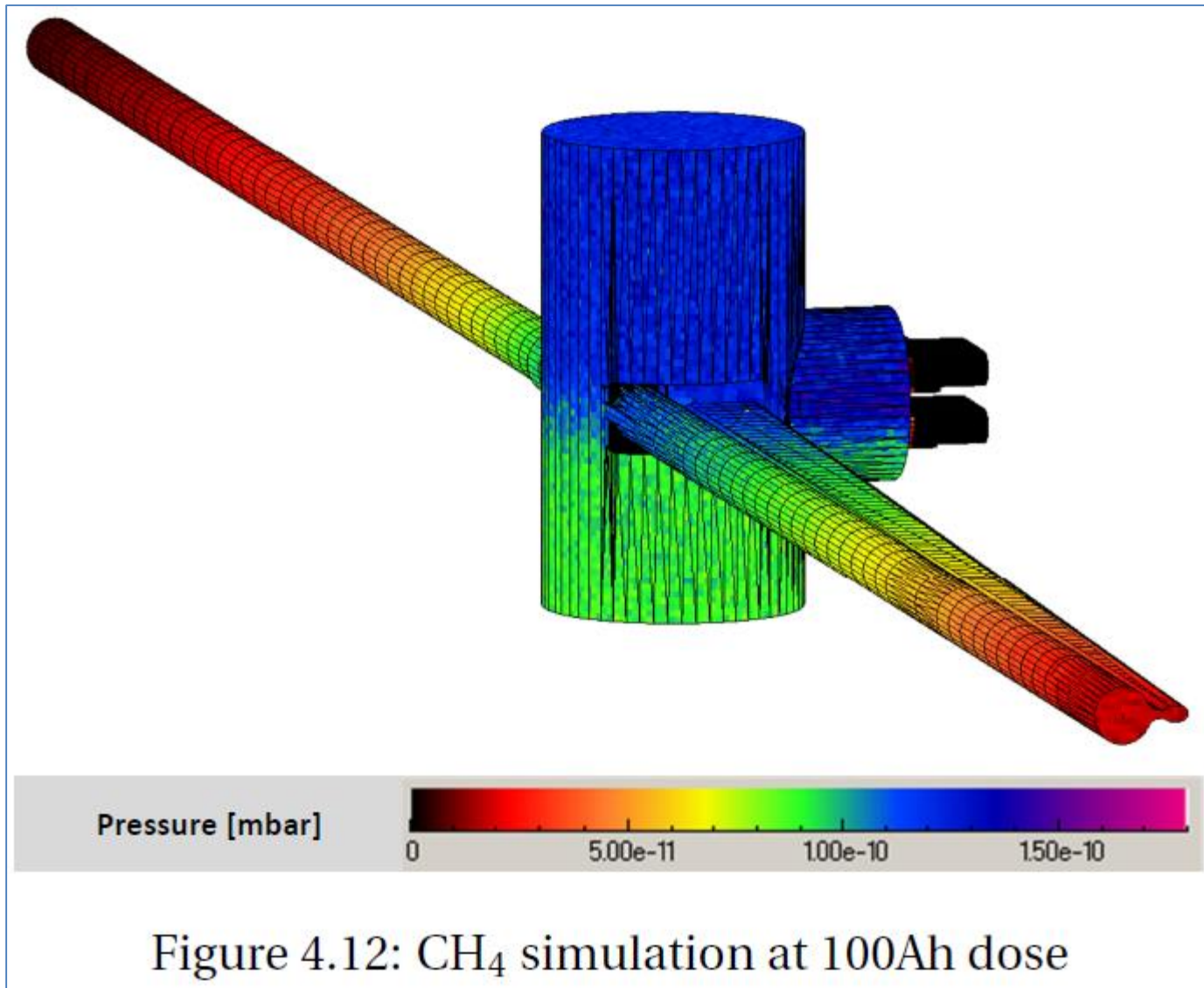
Molflow+ : simulation of NEG-coating saturation
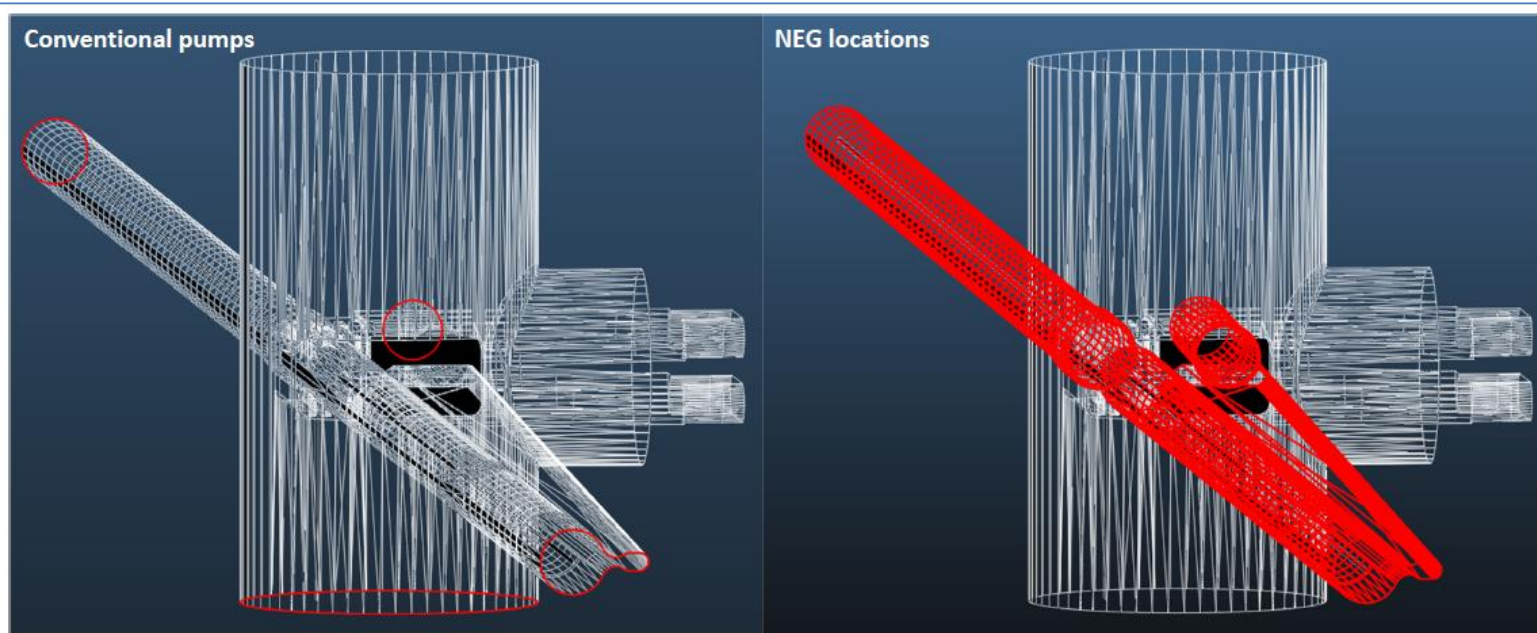
Figure 4.14: Pump locations defined for CO and CO2 for the Molflow simulations.
Left: End of modeled regions (sticking 0.1) and ion pump
Right: NEG locations (The central vertical cylinder is also NEG-coated, not shown for visibility)
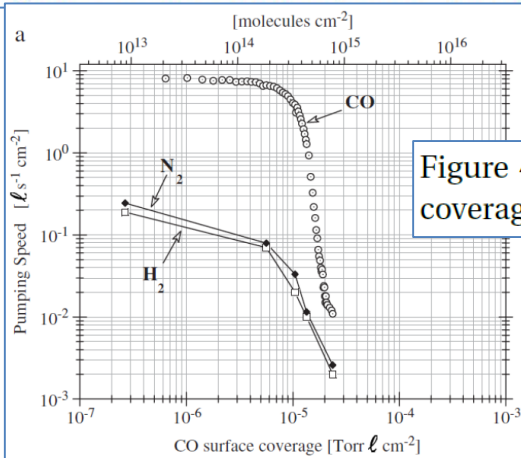
Figure 4.13: Figure 1.a from [79]: NEG pumping speed of CO as a function of its surface coverage

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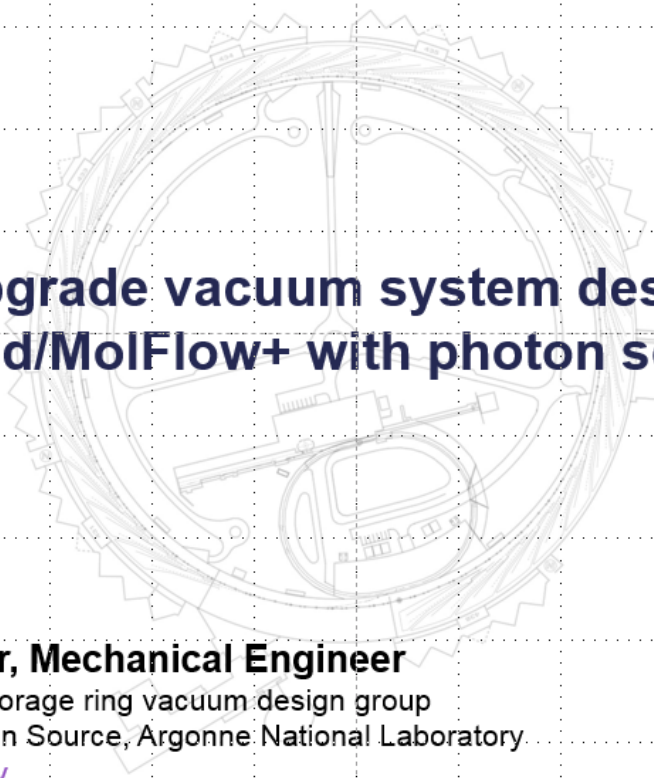
Molflow+ : simulation of NEG-coating saturation
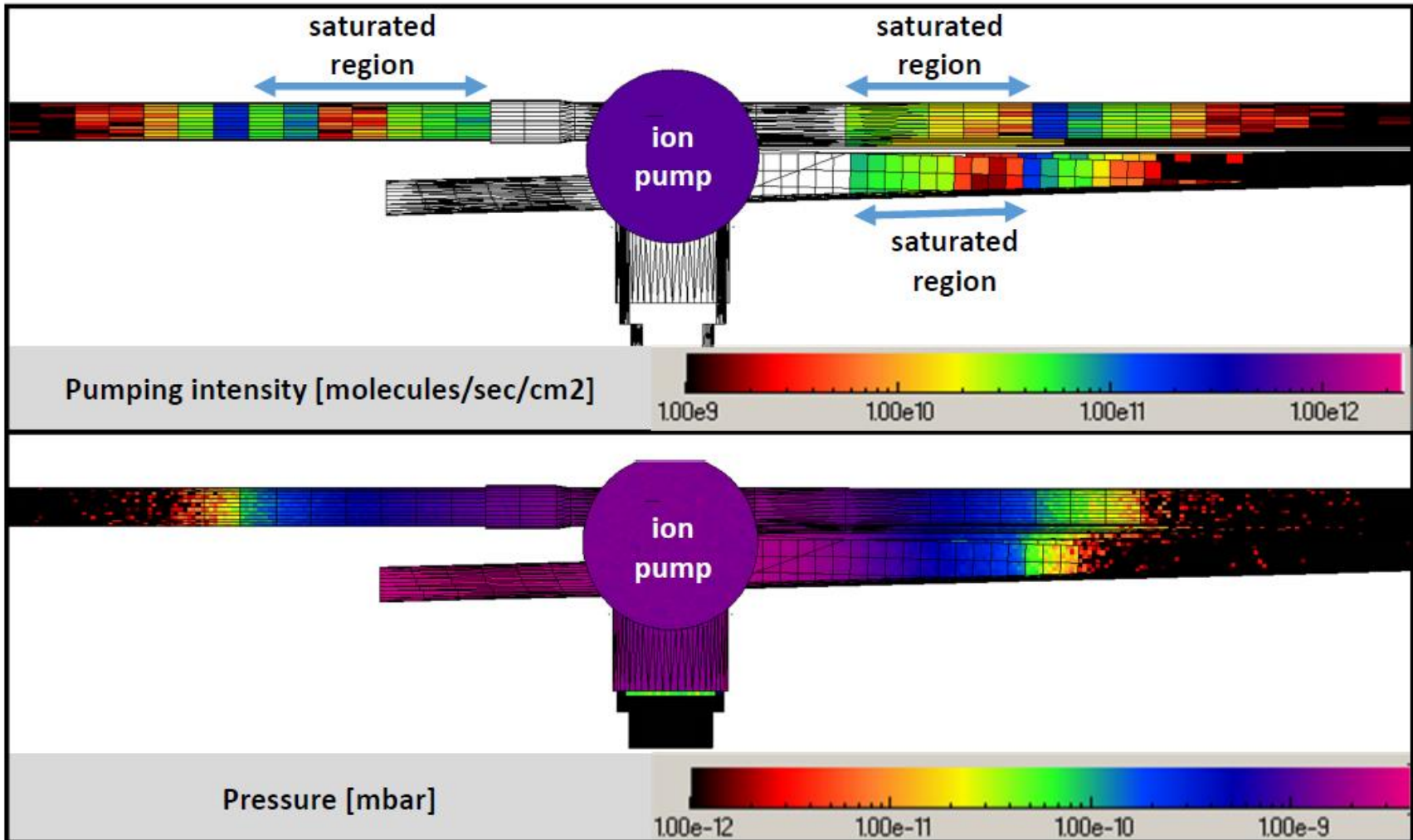
Figure 4.15: NEG saturation and its effect on pumping speed and pressure profile

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Molflow+ : simulation of NEG-coating saturation, pressure profile for several gas species
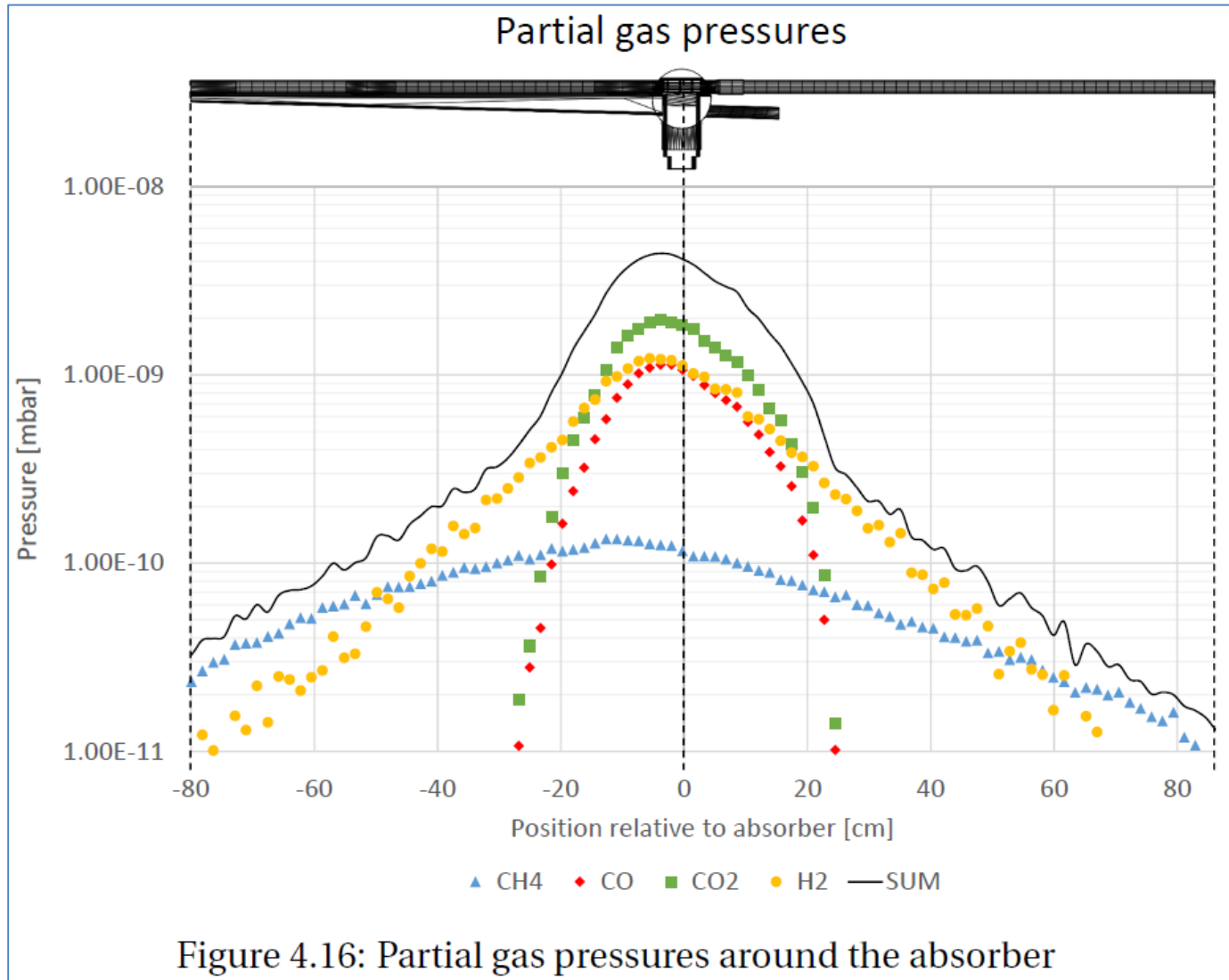
Figure 4.16: Partial gas pressures around the absorber

SYNRAD+ : simulation of SR power and flux on crotch absorbers of the APS ring

APS: Advanced Photon Source;
7 GeV 3rd generation light source → 6 GeV 4th generation with multi-bend and long. gradient dipoles

Source: J. Carter, APS Upgrade team, ANL, Argonne, AVS Conference, 2015

SR-induced desorption and its consequences

SIMULATION OF GAS SCATTERING LIFETIME USING POSITION- AND SPECIES-DEPENDENT PRESSURE AND APERTURE PROFILES *

M. Borland, J. Carter, H. Cease, and B. Stillwell, ANL, Argonne, IL 60439, USA

BREMSSTRAHLUNG SCATTERING LIFETIME

The differential bremsstrahlung cross-section for atomic number Z is [8, 9]

$$\frac{d\sigma}{dk} = 4\alpha r_e^2 \left\{ \left(\frac{4}{3k} - \frac{4}{3} + k \right) T_1(Z) + \frac{T_2(Z)}{9} \left(\frac{1}{k} - 1 \right) \right\}, \tag{9}$$

where k is the energy of the emitted photon as a fraction of the electron energy,

$$T_1(Z) = Z^2(L_{rad}(Z) - f(Z)) + ZL'_{rad}(Z), \tag{10}$$

and $T_2(Z) = (Z^2 + Z)$. The functions $L_{rad}(Z)$, $f(Z)$, and $L'_{rad}(Z)$ are described in [9]. The fractional change in energy of the electron is $u = -k$.

SYNRAD+ : simulation of SR power and flux on crotch absorbers of the APS ring

How SynRad works

- Demonstrate SynRad applications with APS photon absorber example

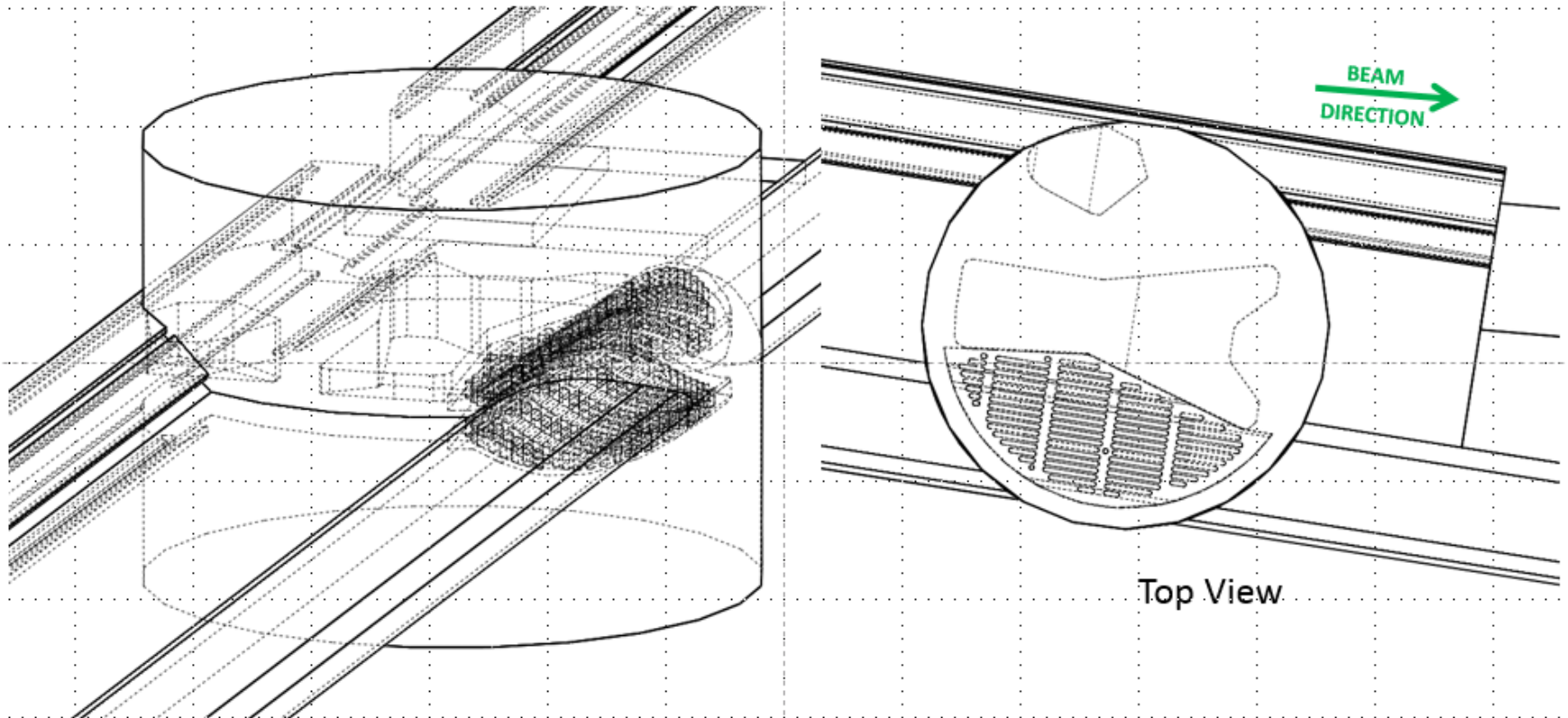BEAM DIRECTION
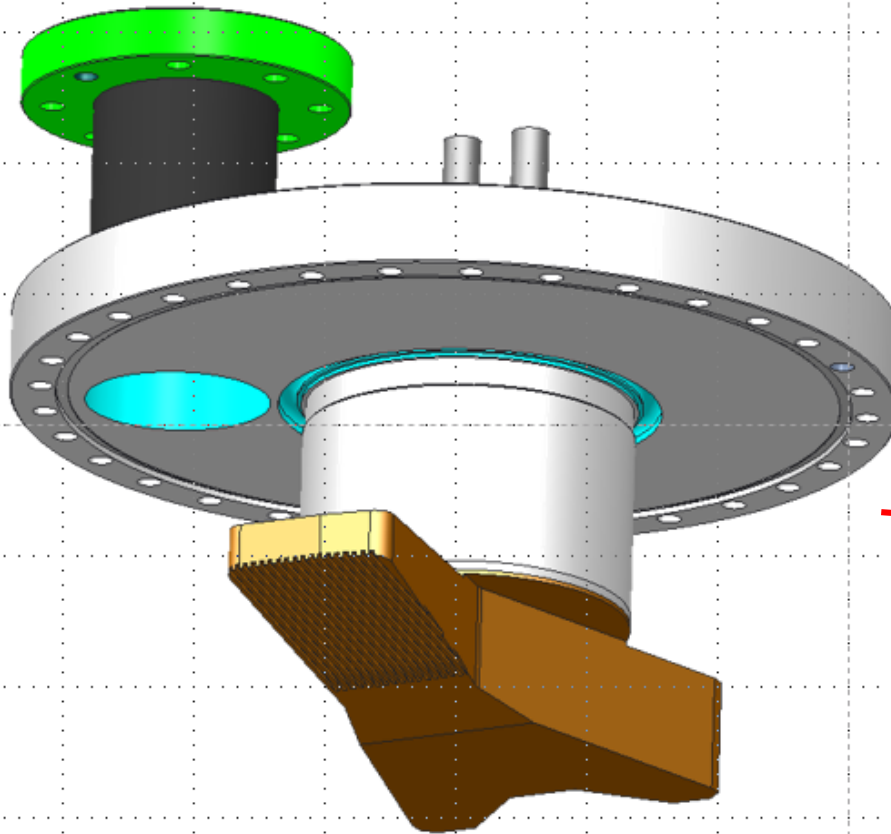
3D CAD model of absorber assembly
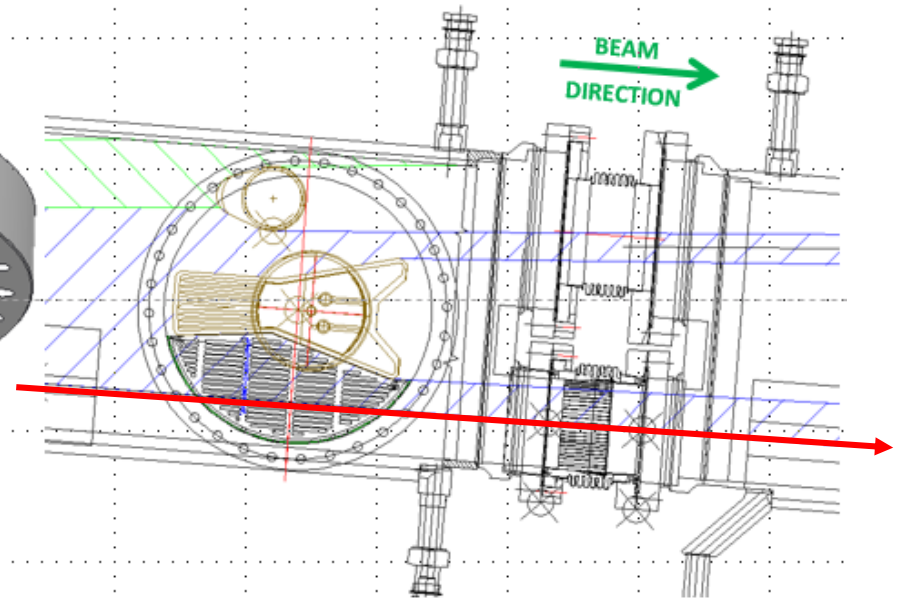
Top view of 2D CAD synchrotron ray trace

66

SYNRAD+ : simulation of SR power and flux on crotch absorbers of the APS ring

How SynRad works

- 3D CAD model built representing interior volume of vacuum system and all surfaces under vacuum

BEAM DIRECTION

Top View

3D CAD with hidden lines shows
two absorbers and an RF screen within a pumping port

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SYNRAD+ : simulation of SR power and flux on crotch absorbers of the APS ring

How SynRad works

- Model exported as STL file type, imported into SynRad as planar surface 'facets'
  - Material definitions applied to surfaces to induce photon scattering

BEAM DIRECTION

Top View
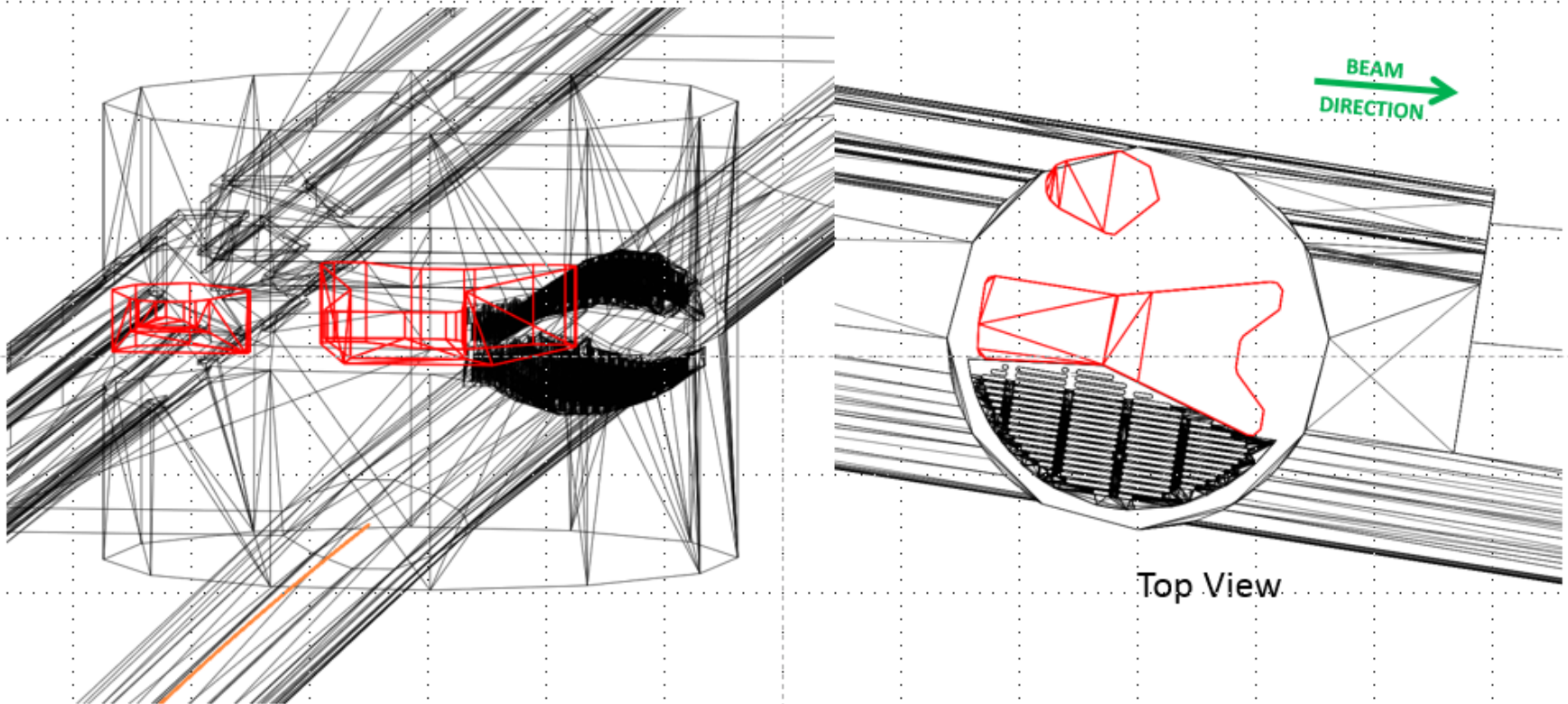
Absorber bodies highlighted in red

68

SYNRAD+ : simulation of SR power and flux on crotch absorbers of the APS ring

How SynRad works
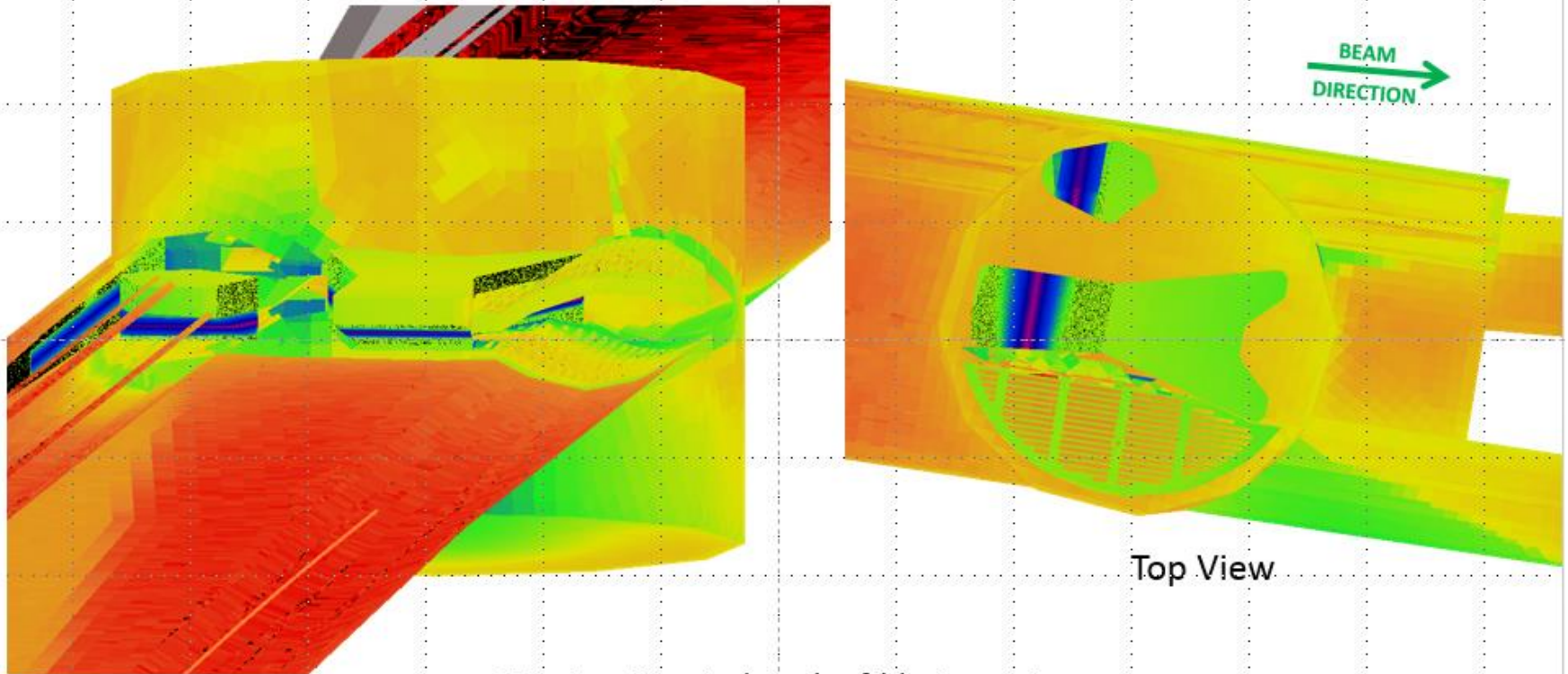
- Magnetic elements generate synchrotron rays within 3D space
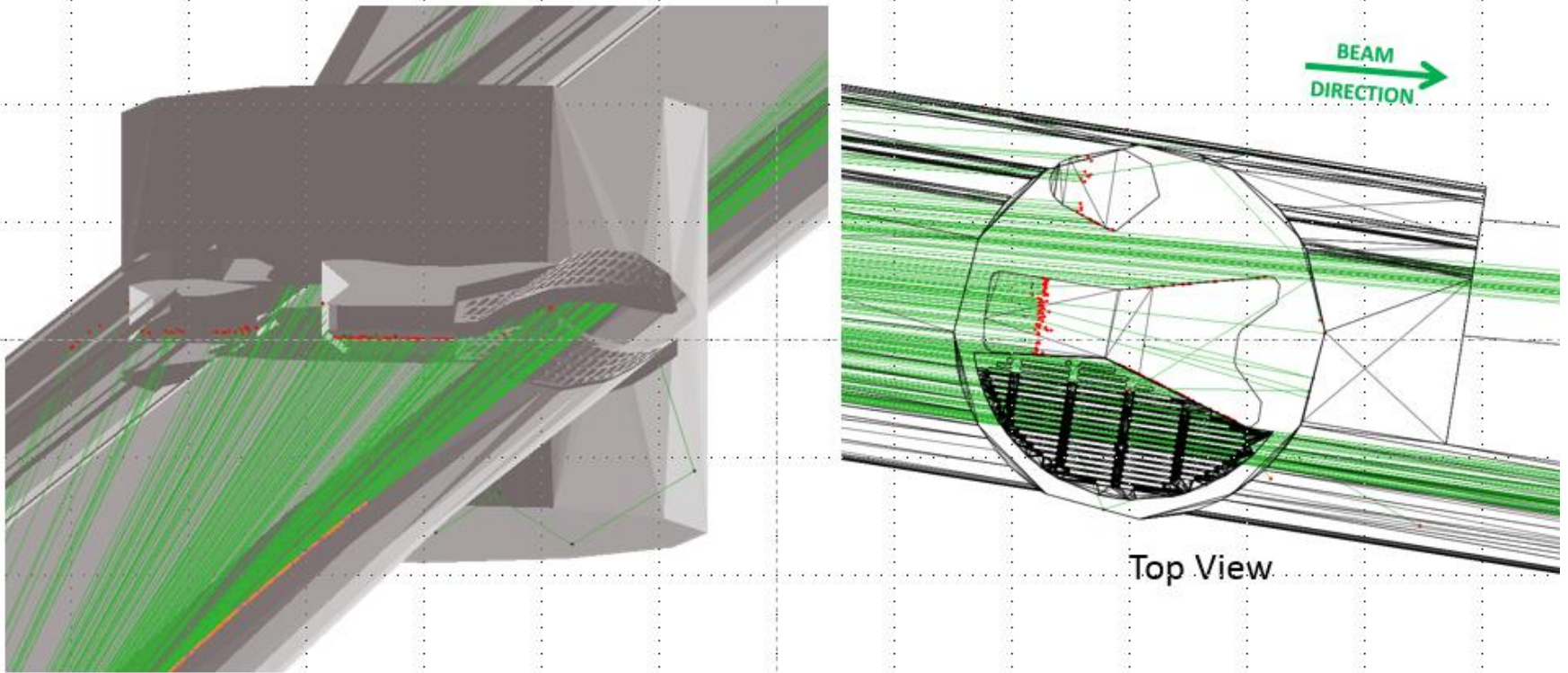
Magnetic elements in orange, program generated synchrotron fan in green, surface hit points in red

69

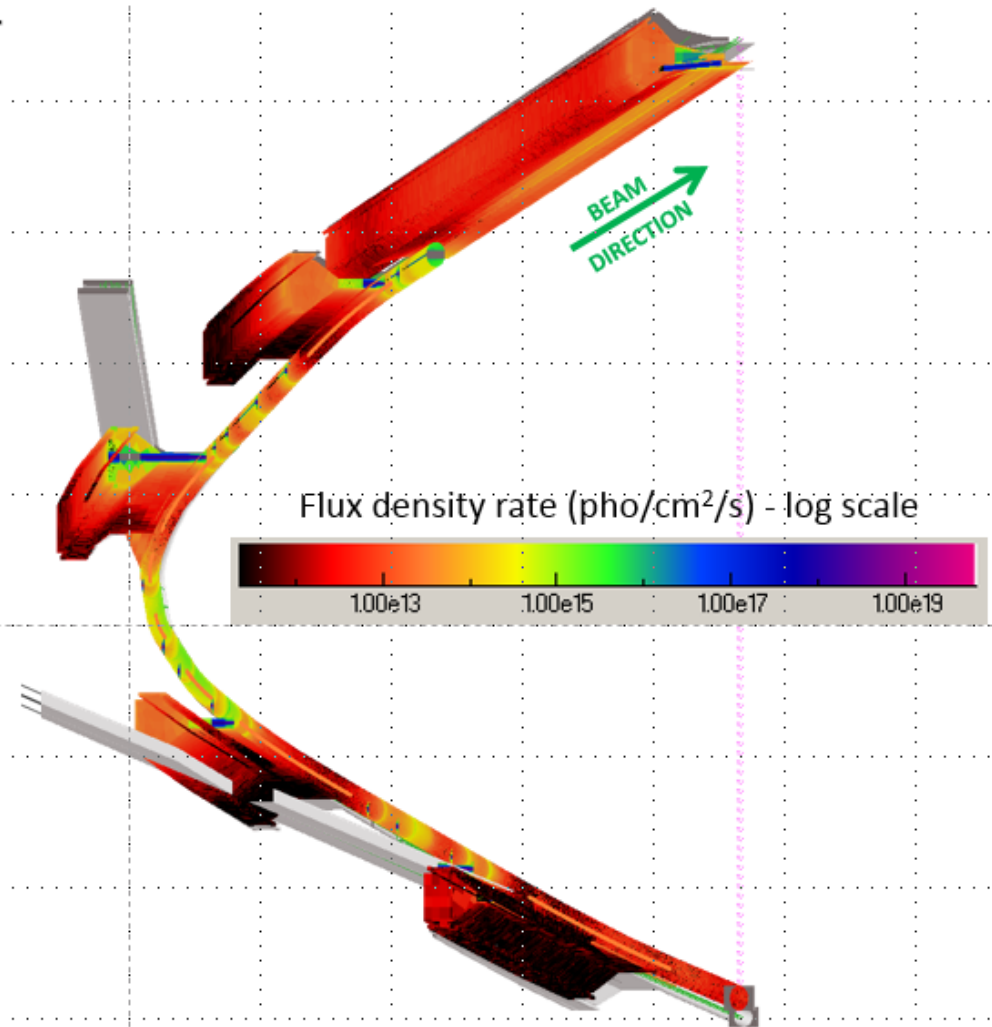**SYNRAD+ : simulation of SR power and flux on crotch absorbers of the APS ring**

70
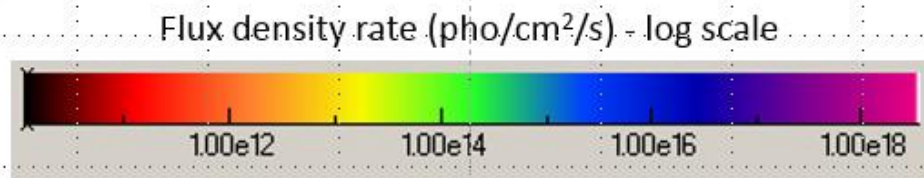
SYNRAD+ : simulation of SR power and flux on crotch absorbers of the APS ring

SynRad model of APS-U sector

- Bending magnet elements generate photon flux in model
- Symmetric boundary condition passes downstream photons back to upstream
- Heat load ray trace verified to high accuracy
- Mesh applied to all vacuum surfaces
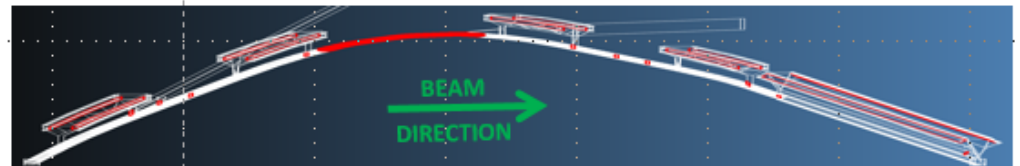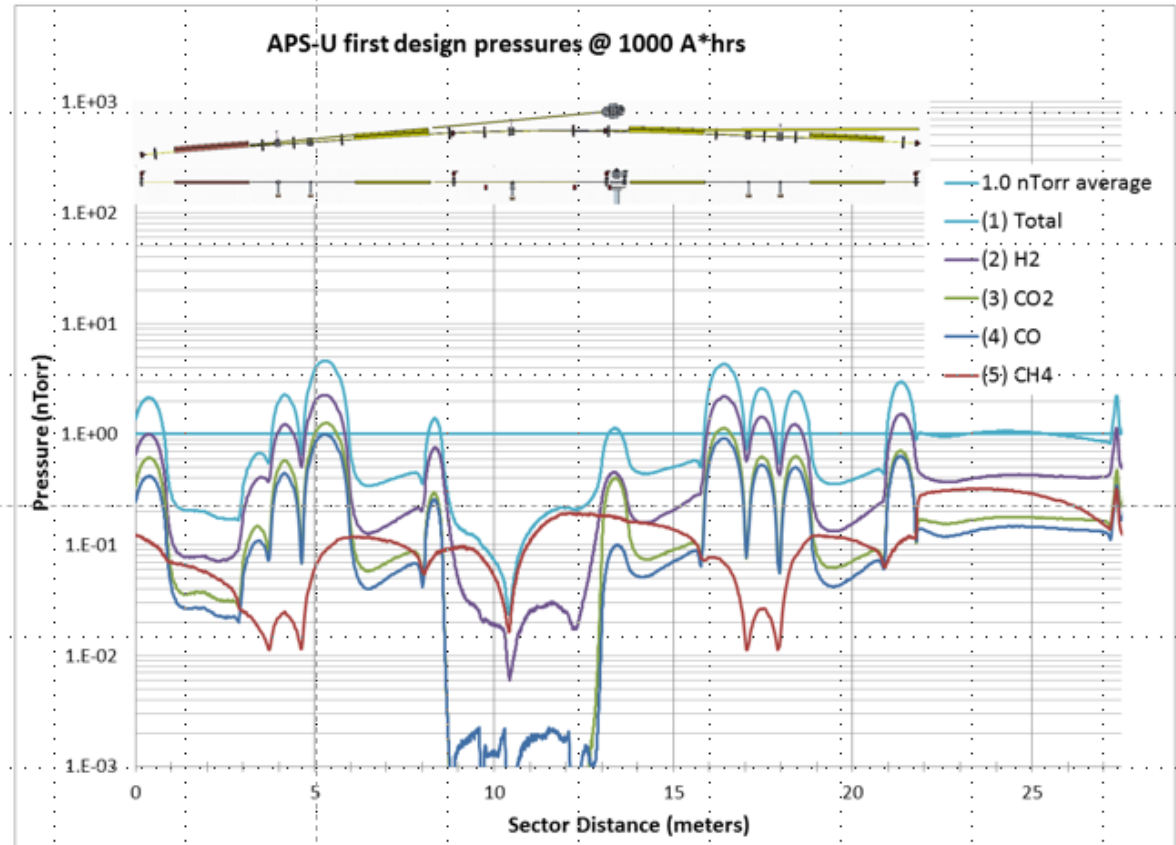- Material reflection tables referenced to determine surface scattering

BEAM DIRECTION

Flux density rate (pho/cm²/s) - log scale

1.00e13   1.00e15   1.00e17   1.00e19

SynRad simulation of synchrotron radiation flux distributions with photon scattering

71

SYNRAD+ : simulation of SR power and flux on crotch absorbers of the APS ring

Pressures for each UHV gases

- Total pressure equals the sum of individual gases
- No distributed pumping assumed for CH_4 leading to unique profile
- Individual gas pressures used to estimate beam lifetime

APS-U first design pressures @ 1000 A*hrs

- 1.0 nTorr average
- (1) Total
- (2) H2
- (3) CO2
- (4) CO
- (5) CH4

Pressure (nTorr) vs Sector Distance (meters)

BEAM DIRECTION

Summary and conclusions

- Some basic concepts of vacuum technology and accelerators have been recalled

- We have then briefly seen how important it is to be able to calculate the pressure/gas density along the path of the e- beam stored in a **synchrotron radiation light source**

- The advantages of modern, fast computers and their application to **Montecarlo simulation codes** have been also highlighted with examples

- The importance of a **two-stage approach** to the calculation of pressure profiles has been also discussed at length, with examples for 1. ESRF: beamline shielding; 2. MAX-IV: crotch area saturation of the NEG-coating; 3. APS-U upgrade: pressure profiles

- The relevance of this two-stage approach with respect to accelerator issues other than vacuum has been demonstrated with the example of the **reduction of bremsstrahlung radiation fluence on the experimental beamline hutches**. This is extremely important as light sources have 100s of experiments per year, and need as close as possible 100% beam availability. **The experimental hutches must be accessible at all times**

- For light sources, the design of the vacuum system must put particular attention to protecting all vacuum surfaces from unwanted photon irradiation; Properly water-cooled absorbers must be foreseen, with appropriate geometry so as to trap as much as possible the scattered photons, and minimize irradiation of, and gas desorption from surfaces nearby

Many thanks for your attention ☺

BONUS SLIDES

TPMC method and algorithm:

- Let's assume, without loss of generality, that a vacuum system be modeled using polygonal planar facets;
- Let XYZ be an arbitrary cartesian frame of reference;
- Let X"Y"Z" be the frame of reference whose origin corresponds to the location of a molecule located on the facet, with Z" perpendicular to the facet;
- Let X'Y'Z' a frame of reference parallel to X"Y"Z", whose origin is the same as XYZ;
- Let α and β be defined as such: β is the rotation about the Y axis which takes X onto X'; α is the rotation about X (X') which makes Y become Y';
- With such definitions, the following transformations can be written:

$$\begin{pmatrix} X" \\ Y" \\ Z" \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix} \begin{pmatrix} X" \\ Y" \\ Z" \end{pmatrix}$$

PLANAR FACET   Z" = NORMAL TO IT

- Upon desorption of the molecule from the source facet s, let L be the generic length of the trajectory to the next target facet t;

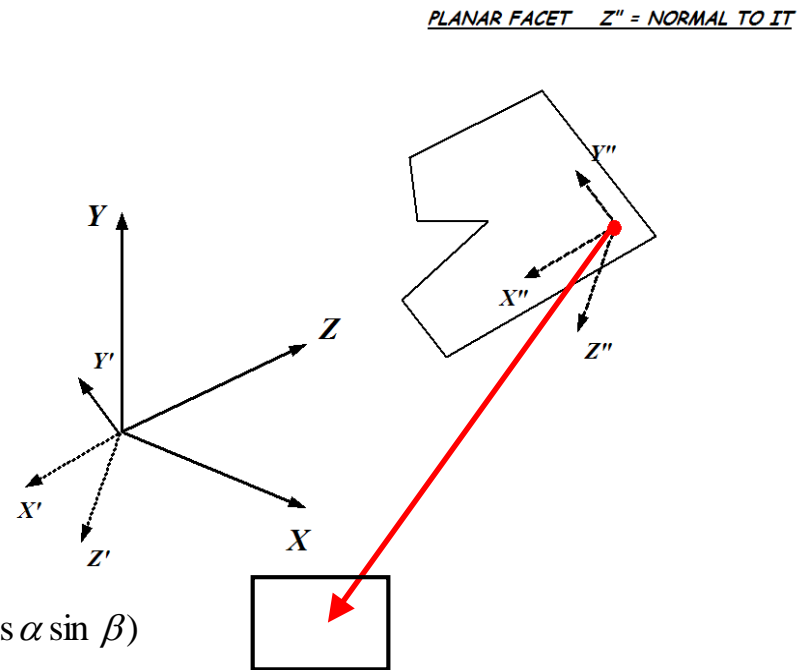$$X" = L\sin\theta\cos\varphi$$
$$Y" = L\sin\theta\sin\varphi$$
$$Z" = L\cos\theta$$

- Combining the two relations, one gets

$$X_t = X_s + L_t(\sin\theta\cos\varphi\cos\beta - \sin\theta\sin\varphi\sin\alpha\sin\beta - \cos\theta\cos\alpha\sin\beta)$$
$$Y_t = Y_s + L_t(\sin\theta\sin\varphi\cos\alpha - \cos\theta\sin\alpha)$$
$$Z_t = Z_s + L_t(\sin\theta\cos\varphi\sin\beta + \sin\theta\sin\varphi\sin\alpha\cos\beta + \cos\theta\cos\alpha\cos\beta)$$

where the value for L, L_t, i.e. the length of the trajectory to the next facet encountered, is a function of the geometric description of facet t, and it is not given here (see (*) and references therein)
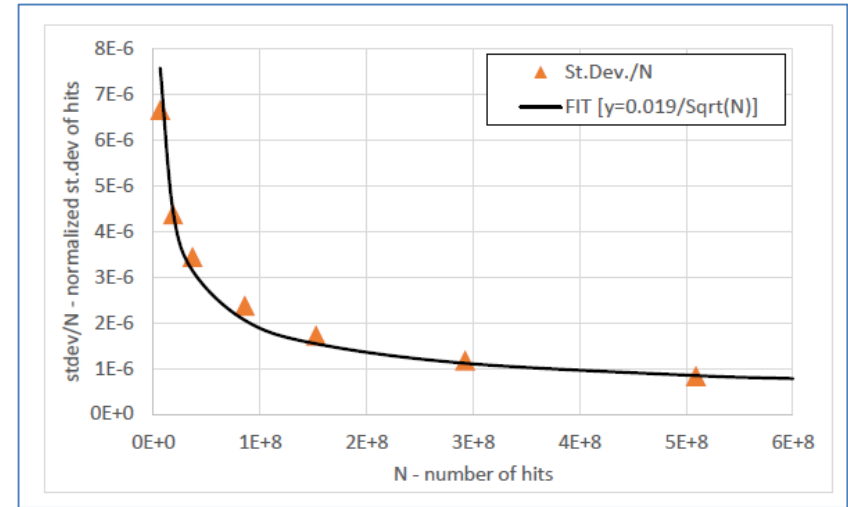
TPMC method #2:

- **Averaging over a large number of molecular traces yields estimates of the pressure, inpingement rate, conductance, pumping speed, etc...:**

- Let N be the number of molecules entering, for instance, a tube from one end;

- Let m be the number of molecules leaving the tube at the other end:

    w = m/N   is the **transmission probability**;

- The values for w follow a **binomial distribution**, which has a standard deviation

$$\sigma = \sqrt{\frac{w \cdot (1 - w)}{N}}$$

- If n_i is the number of molecular hits in the i-th segment of the tube, and P_i the associated pressure, then the normalized standard deviation for the pressure P_i is:

$$\sigma_{n_i}(\%) = \sqrt{\frac{1}{n_i}\left(1 - \frac{n_i}{N}\right)} \cdot 100$$

From Y. Suetsugu, JVST A14(1), 1996 p.245-250; M. Ady, op. cit.
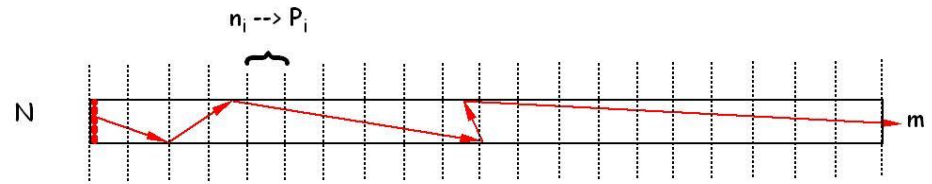
TPMC method #3: how to convert from molecular hits to pressures:

- If n_i is the number of collisions on one segment of the vacuum chamber (A cm^2), and Q is the outgassing (in mbar·l/s), then Q/kT is the number of molecules/s. If N is the number of molecules traced, then, the mean number of collisions/cm^2 in that segment is

$$Z_i = \frac{n_i}{AN}$$
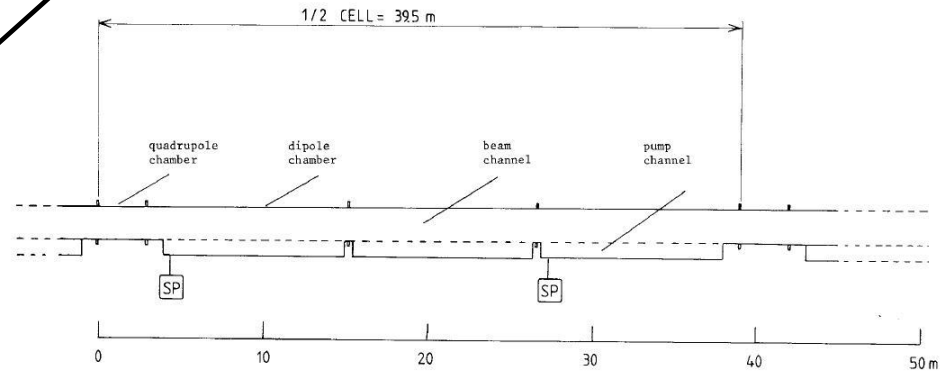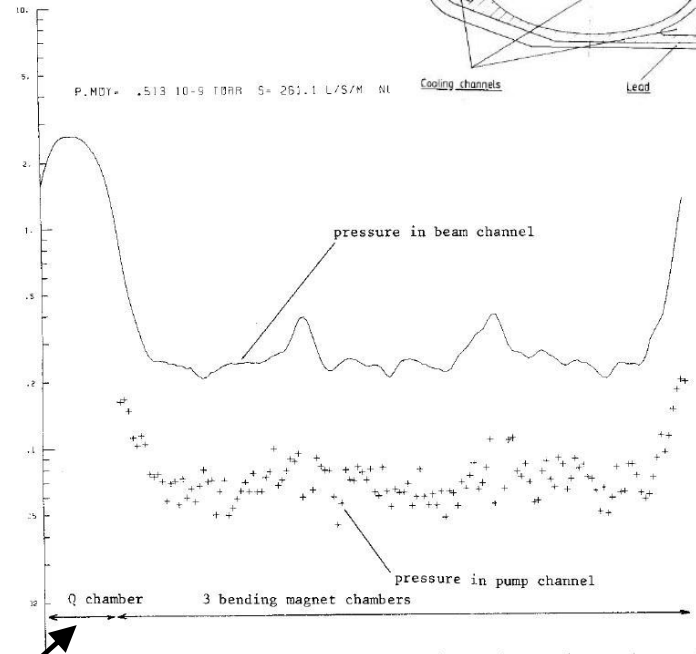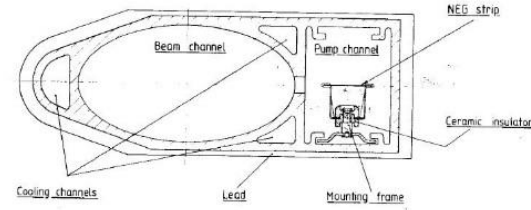
- The estimate of the impingement rate is

$$Z_i = \frac{n_i Q}{ANkT}$$

- At equilibrium, the relation between the pressure P_i (on segment i) and the corresponding impingement rate Z_i is

$$P_i = \frac{4kTZ_i}{v_a} = \frac{4Qn_i}{v_a AN}$$

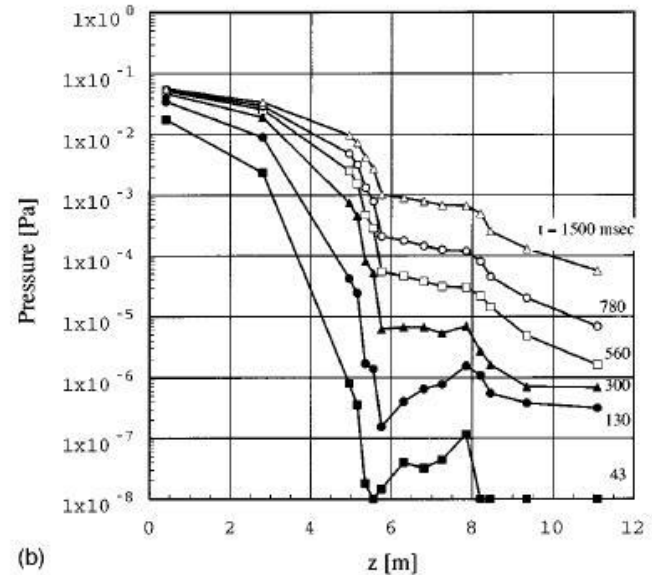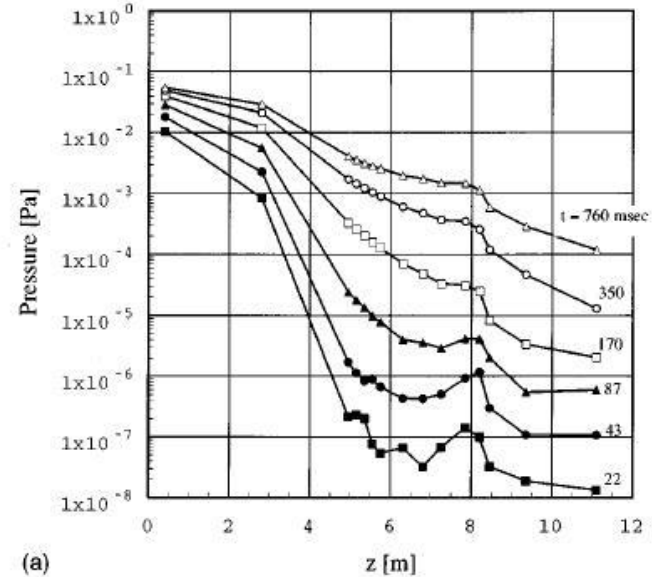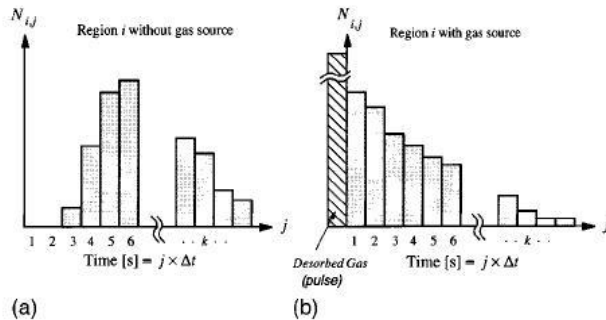$$P_{avg} = \frac{4Q}{v_a AN} \sum n_i$$

From T.Xu, JM. Laurent, O. Groebner CERN-LEPVA/86-02

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TPMC method #4: non-stationary, time-dependent case

- **Time-dependent case**: **acoustic delay line** at Tristan
  synchrotron
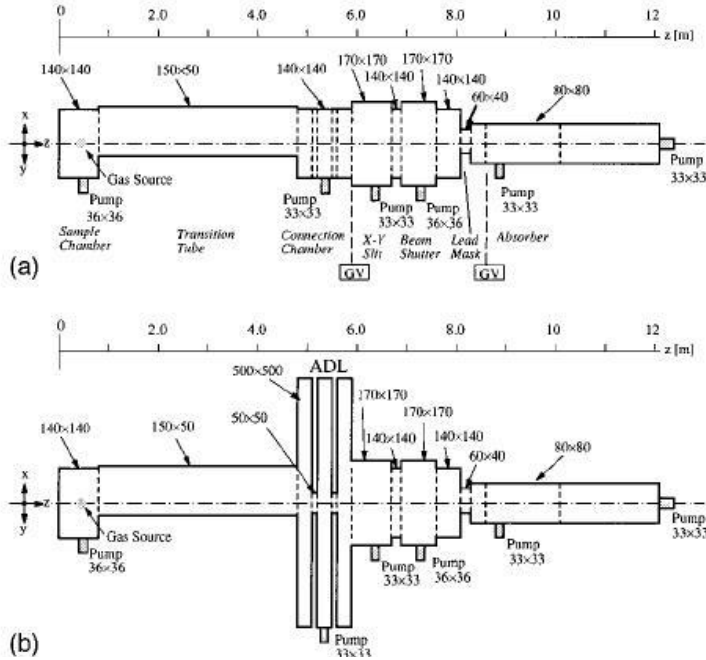
- **The length of all trajectories is translated into time**
  intervals by means of the average molecular speed

79

TPMC method

TPMC method #5: non-stationary, time-dependent case via Molflow+

When there is a need to simulate transient vacuum effect one can instruct Molflow+ to use "**moments**", i.e. short intervals in time during which the collisions with the surfaces of the model are taken into consideration, and then translated into pressures or densities as in the steady-state, stationary case:
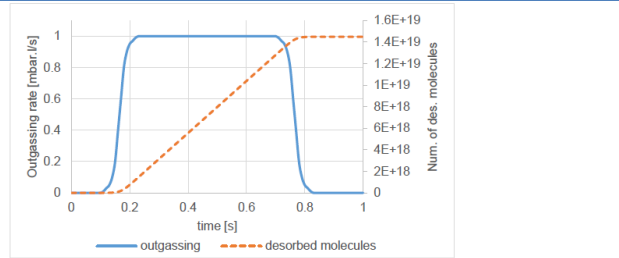
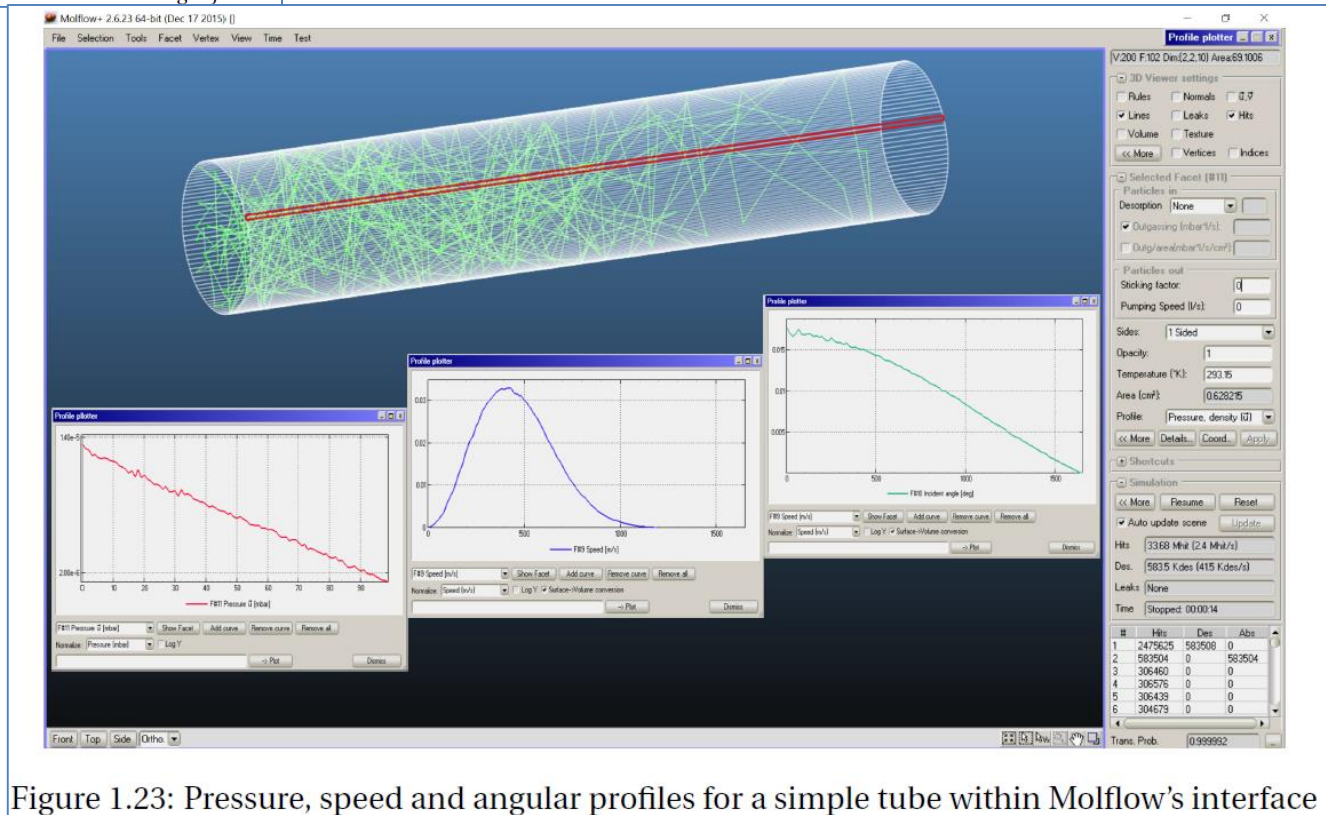Desorption rate and number of desorbed molecules during injection

Figure 1.23: Pressure, speed and angular profiles for a simple tube within Molflow's interface

TPMC method #6: convergence of the calculation

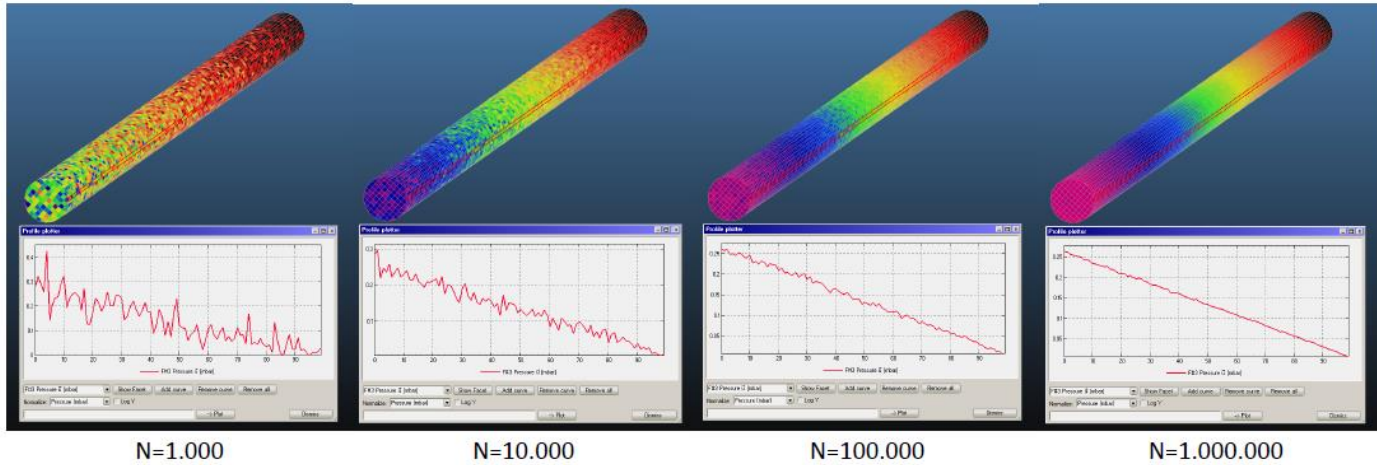N=1.000   N=10.000   N=100.000   N=1.000.000

Figure 1.18: Texture and profile results for a vacuum tube with desorption at the left and pumping at both sides, as a function of the number of traced particles.
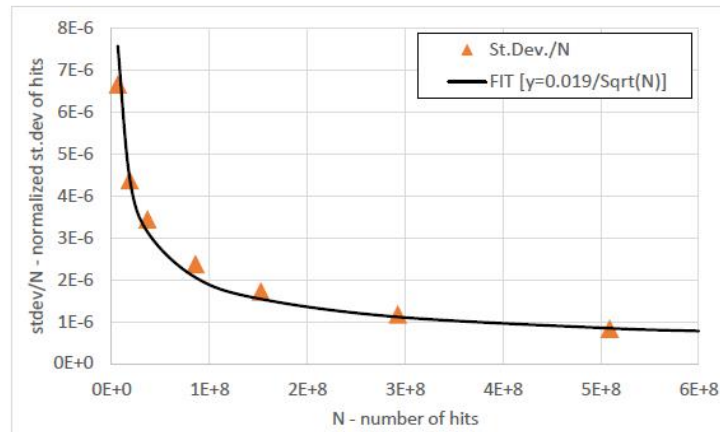

Figure 1.19: Normalized standard deviation of Molflow+ results as a function of the simulated

81