Beam parameters and collective effects for pEDM ring

(December 7, 2009)

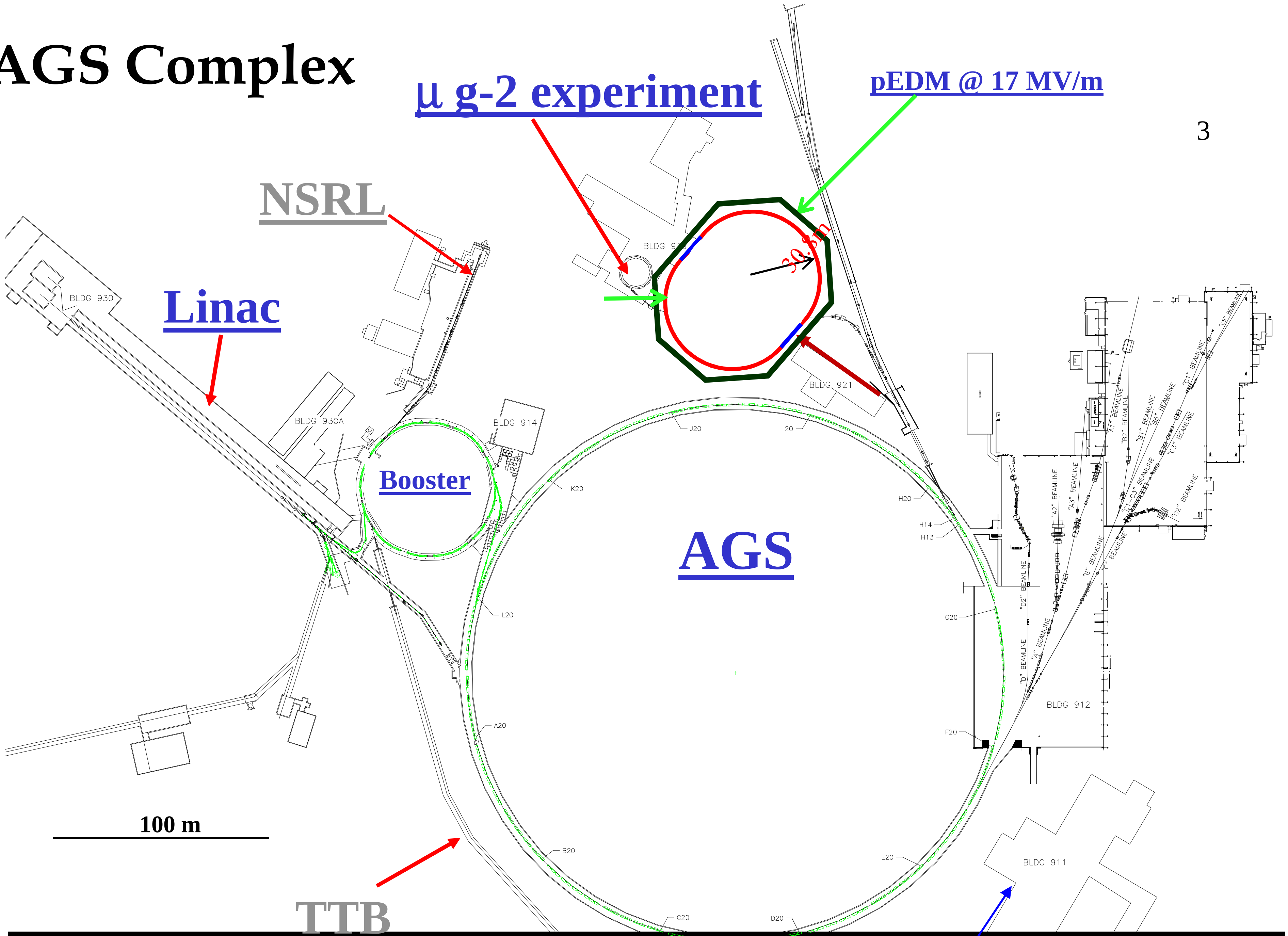
Beam parameters for EDM ring

1. **Need small horizontal emittance – to fit beam between plates and to have reasonable beam lifetime.**
2. **Need small momentum spread – for long spin coherence time (SCT).**
3. **Need short bunches – to get large synchrotron tune.**

Each of these effects increases beam density and thus increases collective effects.

- **As a result, bunch intensity in EDM ring needs to be strongly decreased compared to available intensity from AGS.**

AGS Complex


μ g-2 experiment
pEDM @ 17 MV/m
NSRL
Linac
Booster
AGS
TTB
100 m
30.8m
BLDG 930
BLDG 930A
BLDG 914
BLDG 921
BLDG 912
BLDG 911
J20
I20
K20
H20
H14
H13
G20
L20
A20
F20
B20
E20
C20
D20

Proton beam parameters in the Booster/AGS

Proton EDM ring (p=0.7GeV/c): γ=1.25, $\beta\gamma$=0.745, Kinetic energy: 232 MeV

Booster: injection energy – 200MeV, extraction 1417MeV

We will need a little bit of acceleration in the Booster: from 200 to 232MeV.

AGS will be used just as transport line.

Present beam parameters in Booster/AGS:

- ε_{n95}=5-6 μm (95%, normalized)
- rms dp/p=5e-4
- Polarization: 80-85% (after 2012 – expectation to have up to 90%)
- No loss of polarization from the source is expected
- Intensity: up to 2-3e11 per bunch

emittance notation:

Emittance_95%=6*Emittance_rms

Emittance_normalized=$\beta\gamma$*Emittance_unnormalized

Beam parameters for pEDM ring

1. **Horizontal emittance:**

   To have distance between plates in EDM ring of just 20mm, beam emittance should be decreased to at least ε_{n95}=2 μm (95%, normalized).

   Scraping in the Booster:

   We can tolerate about one order of magnitude in bunch intensity loss to decrease emittance from 6 to 2 μm (95%, normalized).

   N=2e11 -> 1e10 per long AGS bunch

   EDM ring: 1e10/50 -> N=2e8 per short bunch in the EDM ring.

2. **Momentum spread & RF capture:**

   Two long bunches from AGS will be captured in barrier bucket RF system in EDM ring. Then high frequency RF (h=120) will be turned on, resulting in 50 short bunches rotating CW and 50 bunches rotating CCW.

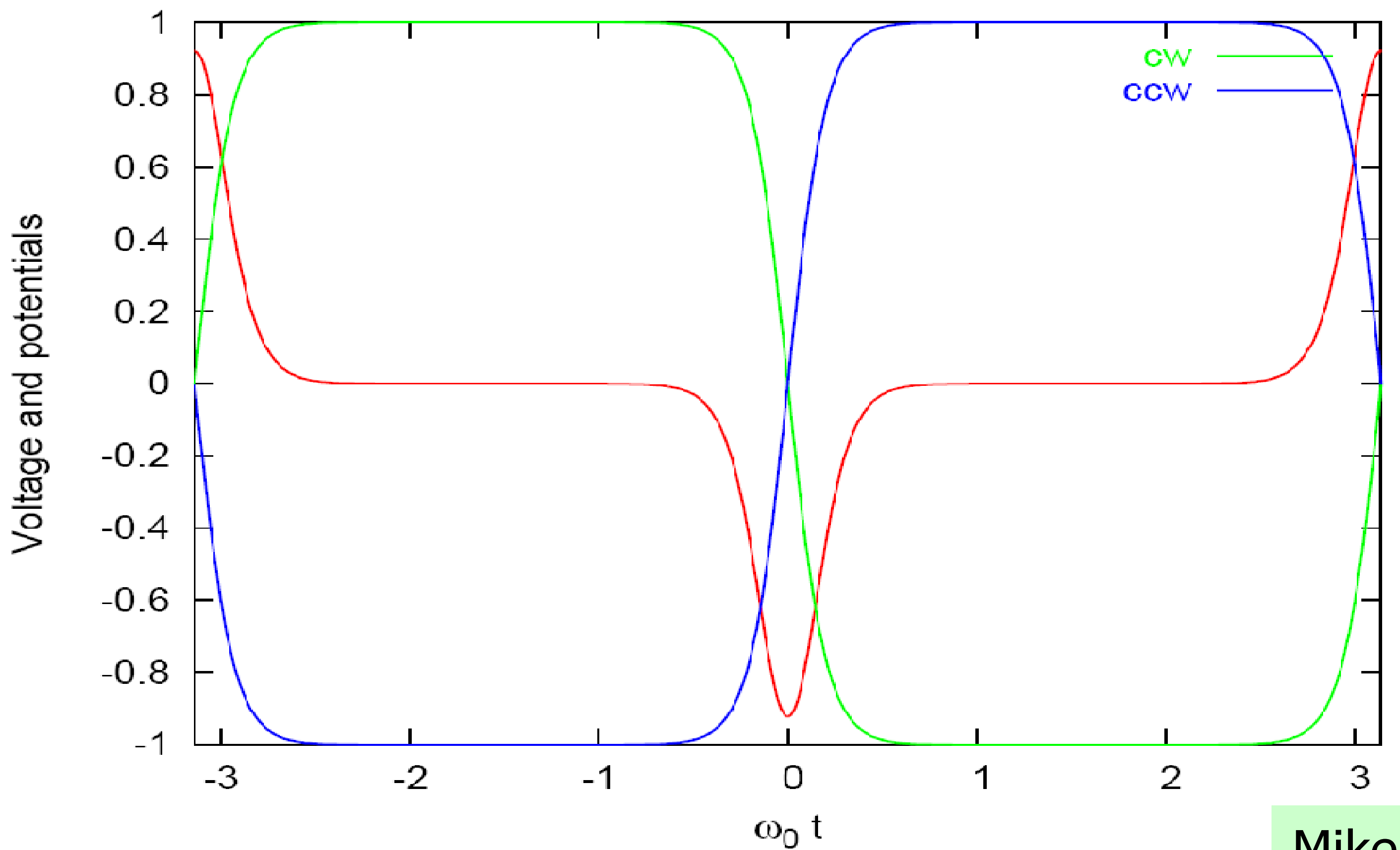
   Presently rms dp/p is about 5e-4 in Booster/AGS bunch.

   Smaller dp/p can be obtained with scraping (with intensity reduction).

   One needs to make sure that momentum spread remains small during adiabatic capture into high frequency RF.

RF considerations for the dEDM ring

Require 2 counter rotating beams on the same closed orbit.



Mike Blaskiewicz (C-AD)

After capture in barriers need to make bunches

Initial momentum spread is +/- 0.05%

parameter	Low voltage	High voltage
Harmonic number	120	120
Frequency (MHz)	89.9	89.9
Voltage	40 kilovolts	170 kilovolts
R/Q	50 Ohm	50 Ohm
Power for Q=1000	16 kilowatt	289 kW
Synchrotron tune	0.033	0.068
momentum spread, +/-	0.08%	0.16%

Momentum spread is increased by 60% during adiabatic capture.
Will need to start with smaller dp/p in order to get rms dp/p=2.5e-4 after capture in 90MHz.

Mike Blaskiewicz

Growth of beam dimensions due to IBS

Intra-Beam Scattering (IBS) – is Multiple Small-angle Coulomb scattering within the beam.

Charged particle within the beam can scatter via Coulomb collisions.

In general, one should distinguish between

1) large-angle single scattering events

and

2) multiple small-angle scattering events

Treatment of both large-angle and small-angle Coulomb collisions is a well known subject from plasma physics.

IBS (continued)

What is different for charged particles beams in accelerators compared to plasma description?

1) **Coupling of longitudinal and transverse (betatron) oscillations** - The curvature of the orbit in circular accelerator produces a **dispersion**. Due to dispersion a sudden change of the energy will always change the betatron amplitudes.

2) **"Negative mass" behavior of particles** – Above transition energy, a particle with larger momentum has smaller angular velocity. In other words, when particle is being accelerated it becomes slower and behaves as a particle with negative mass. **Because of this, an equilibrium above transition does not exist.**

Approximate scaling (for $\gamma < \gamma_t$)

longitudinal diffusion:

$$\tau_{\|}^{-1} = \frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt} \propto \frac{r_i^2 c N_i \Lambda}{\varepsilon_x \varepsilon_y \sigma_s \sigma_p^2}$$

transverse diffusion:

$$\tau_x^{-1} = \frac{1}{\varepsilon_x}\frac{d\varepsilon_x}{dt} \propto \frac{1}{\varepsilon_x}\left\langle \frac{\sigma_{x\beta}{}^2 + D_x{}^2 \sigma_p{}^2}{\beta_x} \right\rangle \frac{r_i^2 c N_i \Lambda}{\varepsilon_x \varepsilon_y \sigma_s \sigma_p{}^2}$$

- more important for heavy ions than protons due to Z^4/A^2
- more important for electrons than protons due to m^2
- becomes more important for higher beam densities
- Ring lattice is important

In EDM ring – operation is below transition energy.
This allows for some optimization between beam parameters, RF and ring lattice.

IBS simulations

IBS simulations were done using BETACOOL code for previous versions of EDM ring lattice and slightly different RF parameters (June 2009).

Optimization depends on tolerable longitudinal losses from RF bucket, transverse loss on the target, etc. This resulted in baseline bunch intensity with 2e8 particles per short bunch (90MHz RF).

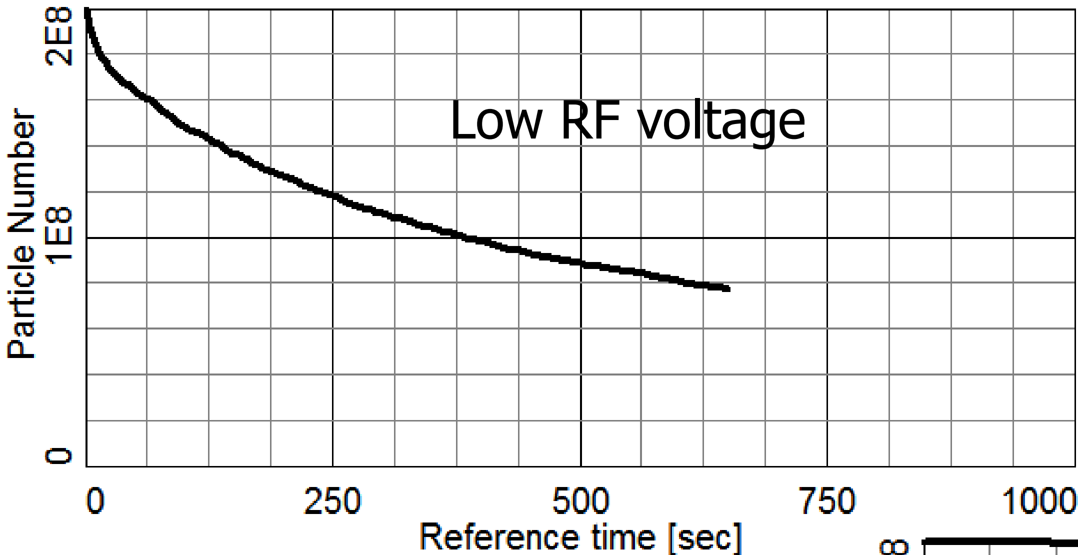
- In the future, IBS simulations will be redone for new EDM lattice, including losses from non-linear RF bucket.

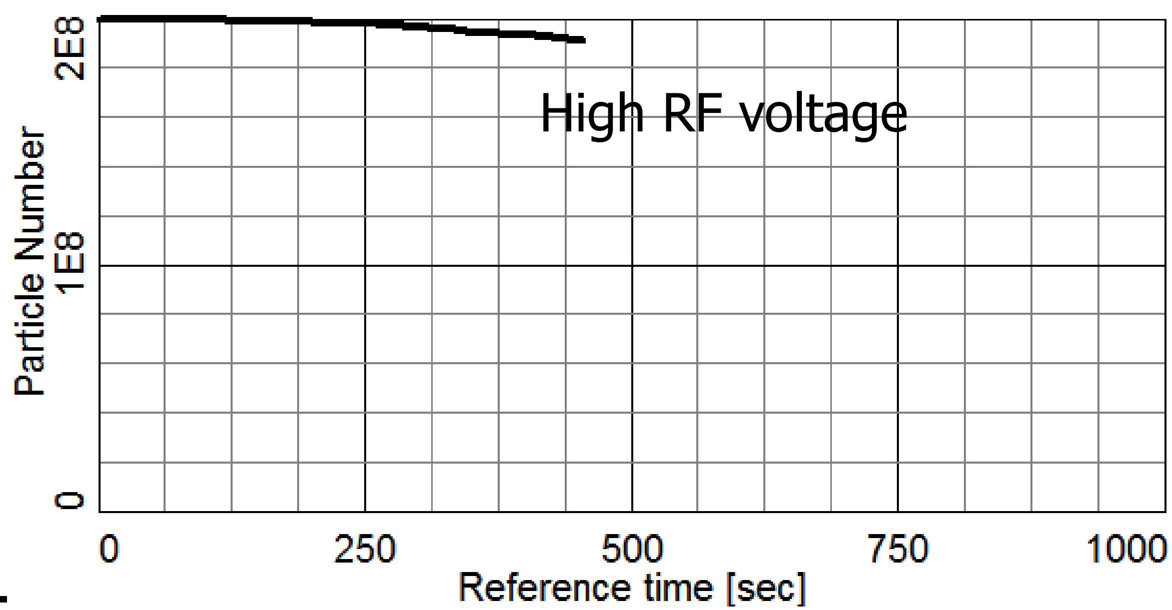
Losses from RF bucket due to IBS

1. **When bunch initially fills RF bucket completely – this results in strong intensity loss from the RF bucket.**
2. **When RF voltage is increased, bunch becomes shorter which results in stronger IBS. But intensity loss from RF becomes less pronounced, especially when combined with loss on the target. But initial momentum spread increases.**

This requires optimizations of initial beam and RF parameters.

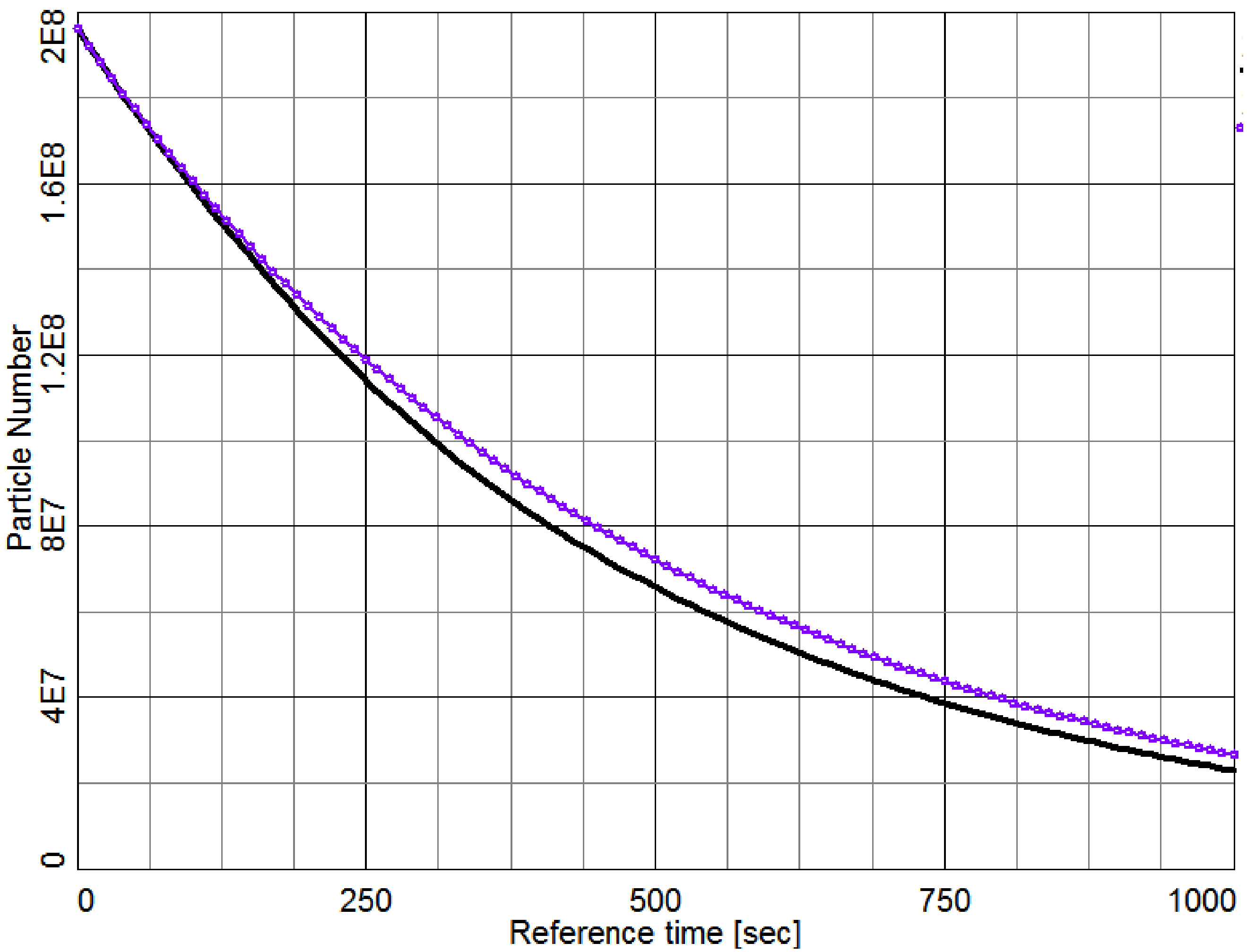
Example of intensity loss from RF bucket (without strong loss on the target)





Requires optimization with losses on the target

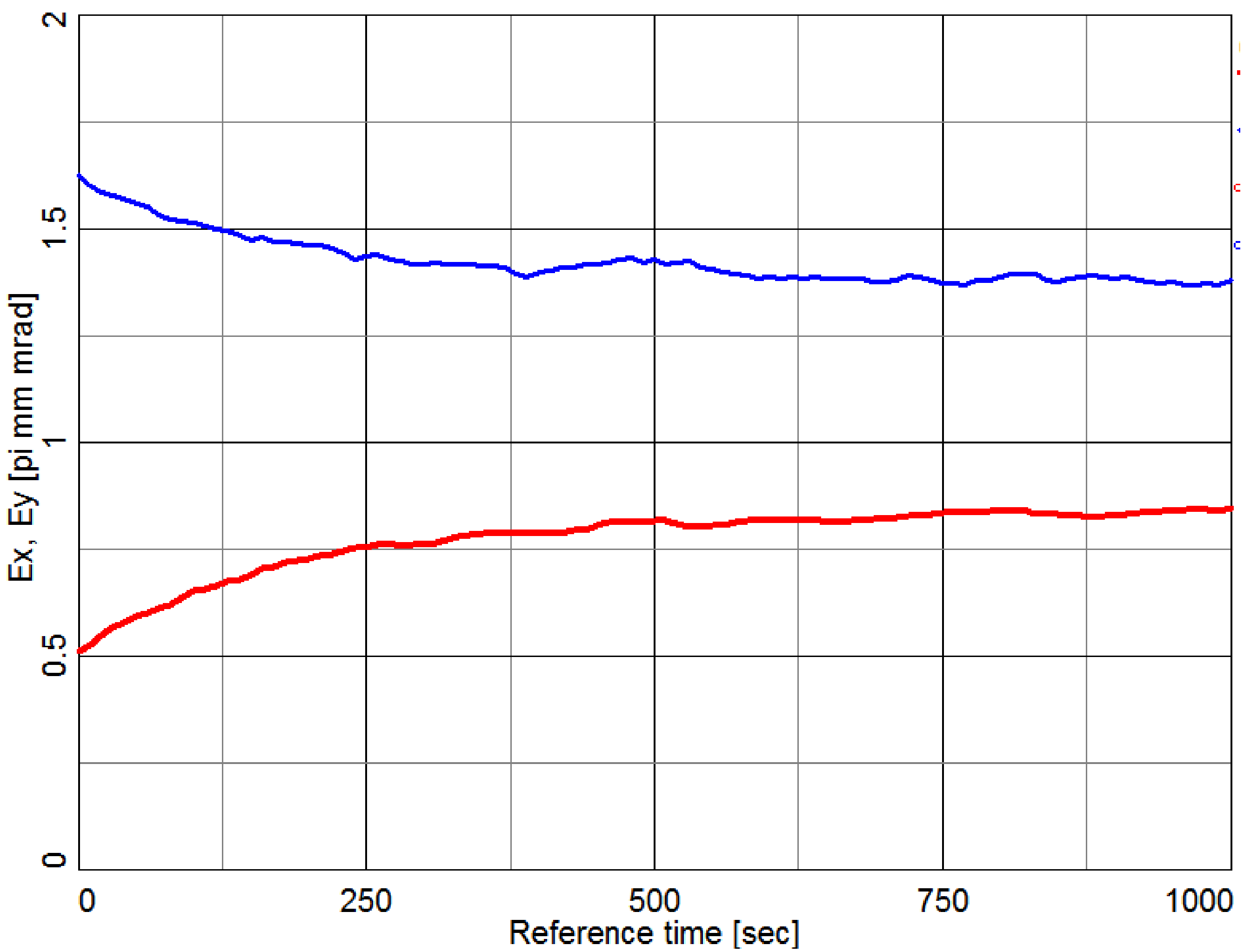
N=2e8 – target & RF loss
(black – target & RF; blue – only target loss with 500 sec beam lifetime)



Results of optimization for June 2009 lattice and previous RF parameters (50kV).

Similar studies will be repeated for new lattice to find optimum RF settings.

N=2e8 (50 kV RF, June 2009 parameters)
(blue – vertical rms unnormalized emittance; red – horizontal rms unnormalized emittance)



Time evolution of vertical and horizontal emittance.

Space charge

Transverse emittance (95%, unnormalized): ε_x, ε_y, μm	**3, 10**
Separatrix length, m	**1.9**
Initial rms bunch length, m	**0.4**
Rms momentum spread	**2.5e-4**
Bunch intensity	**2e8**
Ring circumference C_r, m	**240**

Self-fields (maximum, incoherent tune shift):

$$\Delta Q_{x,y} = -\frac{3N_b Z^2 r_p}{\pi A \beta^2 \gamma^3} \frac{1}{\varepsilon_{x,y}\left(1+\sqrt{\frac{\varepsilon_{y,x} Q_x}{\varepsilon_{x,y} Q_y}}\right)} \frac{C_r}{\sqrt{2\pi}\sigma_s}$$

$$\Delta Q_x = -0.012$$

$$\Delta Q_y = -0.007$$

Such incoherent tune shifts/tune spread are still small enough for needed beam lifetime. Also, these values quickly decrease due to intensity loss.

Walls (effect of images):

first order effect is correction of incoherent tune shift and coherent tune shift – both are sufficiently small.

Space-charge effects

- For present beam parameters, space-charge tune shift is sufficiently small.
- This allows to think about pre-cooling to smaller momentum spread (to increase SCT), for example. Electron cooling for EDM ring was considered in the past.
- Or operate with higher bunch intensities, provided that resulting beam loss due to IBS is tolerable and other intensity-dependent effects are carefully taken into account.

Beam-Beam

- Since in present approach CW and CCW bunches will be circulating in the same ring, one will have beam-beam effects.

$$\Delta Q_{b-b} = \xi = -\frac{N_b Z^2 r_p}{4\pi A}\frac{1}{\varepsilon_{n,rms}}\frac{\left(1+\beta^2\right)}{2\beta}$$

First estimate of beam-beam effects is linear tune shift on particles in one bunch from space-charge forces of incoming bunch.

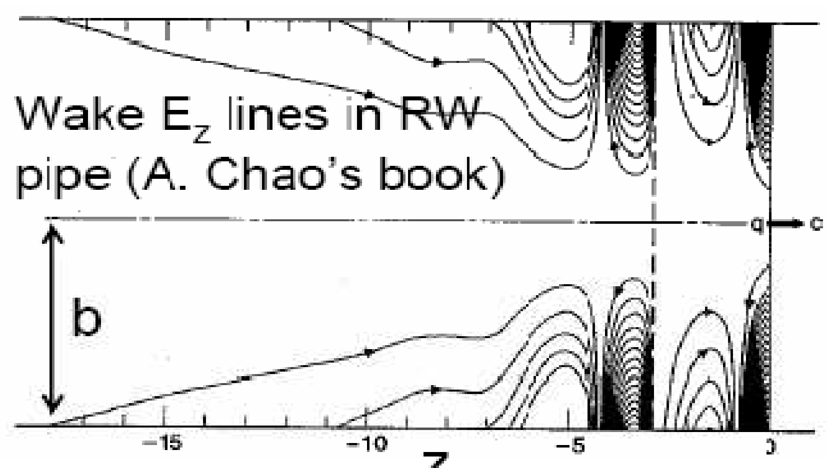
For present beam parameters with N=2e8, total ξ=0.007, which is sufficiently small. But factor of 3 larger number could be a problem.

Preliminary beam-beam simulations were done by Y. Luo. No problems were found.

- Vertical E-field increases systematic error for EDM measurements; tolerance is $E_y < 5\ 10^{-9}$ V/m; Can wakefields create larger fields?

Resistive Wall Basics

- A leading charge creates image charges in chamber walls, slightly delayed due to finite σ_c; they induce (wake) fields inside the chamber deflecting a trailing charge
- Transverse wake scales ~$b^{-3}\sigma_c^{-1/2}z^{-1/2}$
- $z^{-1/2}$ scaling stops when fields diffuse through the wall thickness, then wake dies down exponentially; For EDM skin depth $\delta_{sk}(\omega_{rev}) \approx 0.46$ mm => wake lasts for $(\Delta/\pi\delta_{sk})^2 \approx 100$ turns
- For II plates the lateral extent of image currents is ~b



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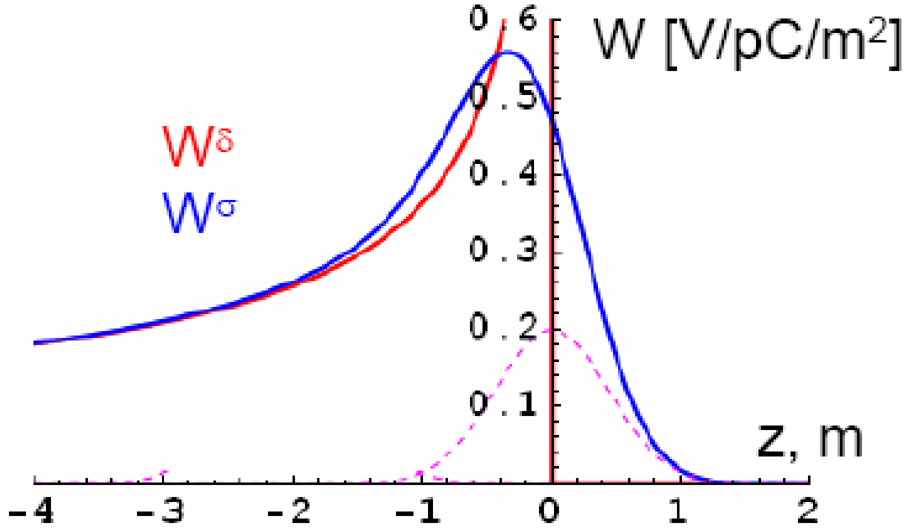
Boris Podobedov 6/26/09

Estimate of RW Wake Vertical E-field



q= 32 pC (2 10^8 protons/bunch)

D= 2 m (distance between the bunches)

C= 200 m (circumference)

N_b=100 (number of bunches)

$$\sum_{i=0}^{99}\sum_{j=1}^{99}(j+iC/D)^{-1/2}\approx 200$$

- First bunch sees no wake force (and E_y) due to itself
- Assume 2nd bunch is vertically displaced by d=1 μm
- It sees the field due to the first bunch $E_y=qW(D)d\approx 8$ μV/m
- The wake lasts 100 turns => times 200 => $E_y\approx 1.6$ mV/m -
- But E_y averaged over the bunch train is zero!

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Resistive Wall wakes

Conclusions and Outlook

- Resistive wall wakefields due to vertical E-plates were looked at.
- Longitudinal wakefields are very small (no problem).
- Horizontal wakefields (not affecting EDM error) are ~ 1 V/pC/m^2 (kick factor per unit length). Checking for instabilities won't hurt.
- Due to parallel plate geometry vertical wakefields cancel if all co-propagating bunches travel on the same vertical orbit.
- Simple example considered with one bunch in a train displaced statically by 1 micron. Wakefield seen by this bunch, E_y =1.6 mV/m, is 5 orders of magnitude higher than tolerance. But E_y averaged over the bunch train is zero!
- Need more realistic model of bunch-to-bunch motion to confirm that E_y averages out (over bunch train & over time) to a tolerable level.
- Future work: consider finite parallel plates (edge effects) and give quantitative estimates of wakefield cancellation; calculate instability thresholds …

Summary

Beam parameters:

It looks like needed beam parameters can be produced.

- **Some scraping will be needed to produce small horizontal emittance (but we have plenty of intensity to spare)**
- **Careful RF manipulation will be needed to maintain small momentum spread**

Collective effects:

- **Bunch intensity was chosen to provide reasonable beam lifetime time due to IBS and space charge, including loss on target and from non-linear RF**
- **Investigation of other effects such as wakes, beam-beam, etc. started. Simulations will be needed as design proceeds.**
- **IBS simulations will be redone with new optimization for new lattice and new RF parameters.**

Collective effects determine beam parameters consistent with required beam lifetime for the experiment.