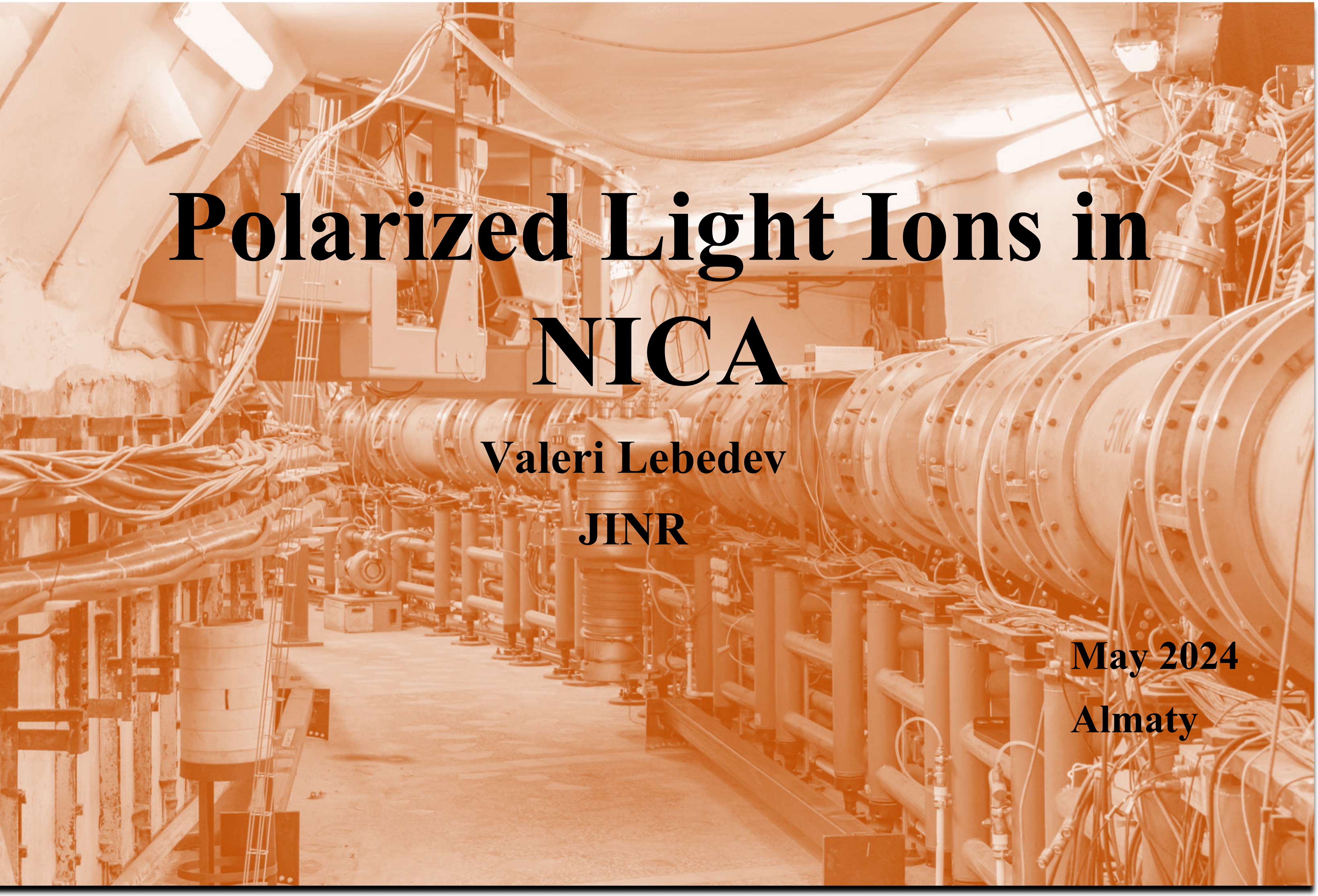

Polarized Light Ions in NICA

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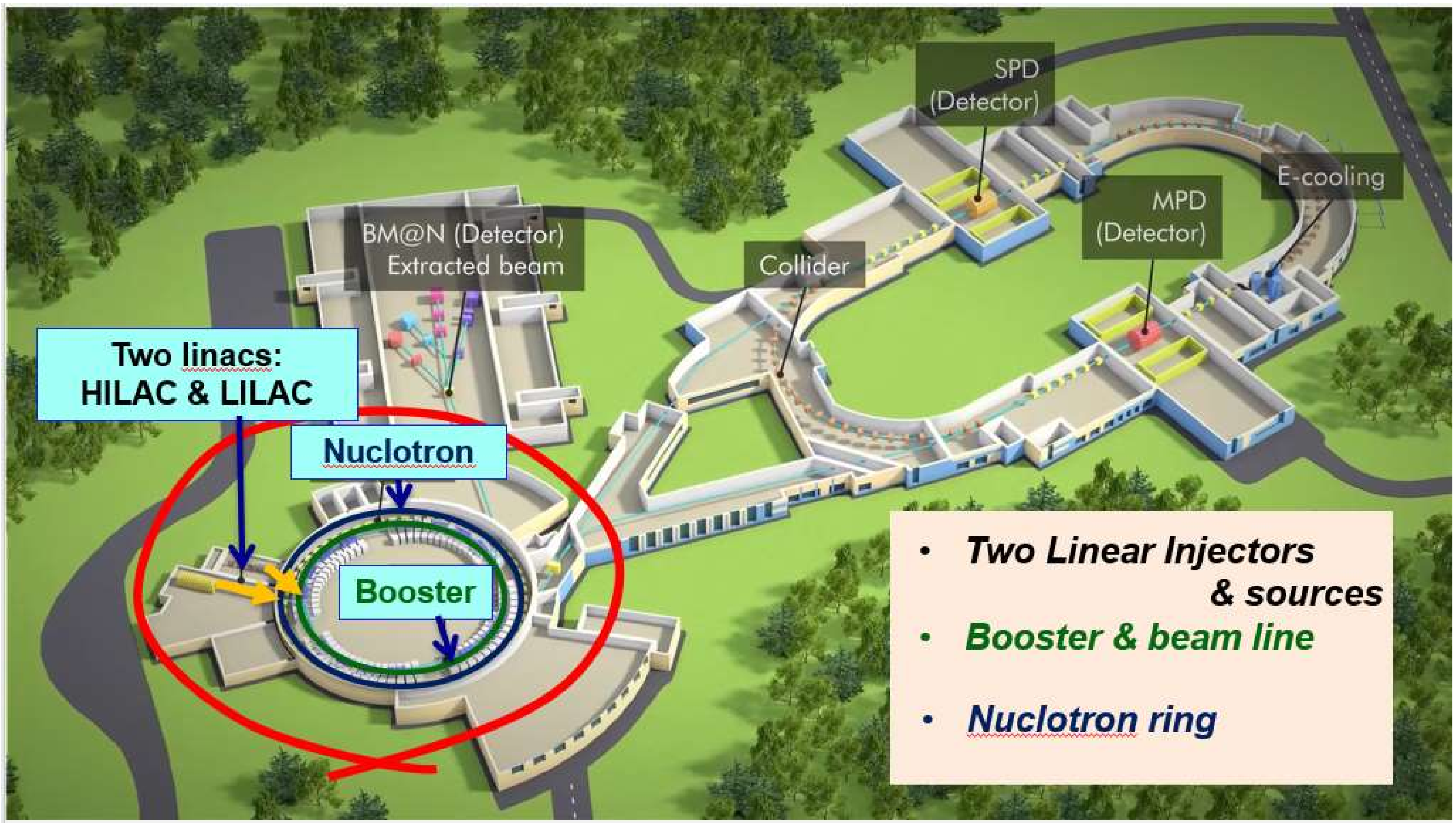
Outline

- Limitations Set by NICA Beam Optics
- NICA Operation with Polarized Ions
- Operation with polarizes deuterons – optimistic scenario
- Operation with polarizes protons – optimistic scenario
- Some Practical Limitations
- Conclusions

Disclosure

The peented material reflects present understanding of the author. More studies are required to understand certain issues in detail, as well as reliable proposal for operation with polarized ions.

NICA Collider Complex Layout



- ***Two Linear Injectors & sources***
- ***Booster & beam line***
- ***Nuclotron ring***

- Injection complex is already in commissioning for few years
  - Intensity of (5-8)·10^6 fully stripped Xe ions at the top Nuclotron energy of 3.9 GeV/u was achieved
- Polarized deuterons and protons will follow
  - LU-20 was recently tested. Additional work is required to reduce beam loss

NICA Operation with Polarized Light Ions

- Two major requirements:
  (1) Maximum luminosity
  (2) Maximum polarization
- Main effects/limitations which set the peak luminosity
  - Beam-beam effects and beam space charge effects
  - Intrabeam scattering (IBS)
  - Multipacting and ep-instabilities
  - Strength and maximum energy of electron cooling
  - Limitations set by already chosen beam optics
  - Beam coupling impedances, beam instabilities and their suppression

Limitations Set by Present Design of NICA Rings

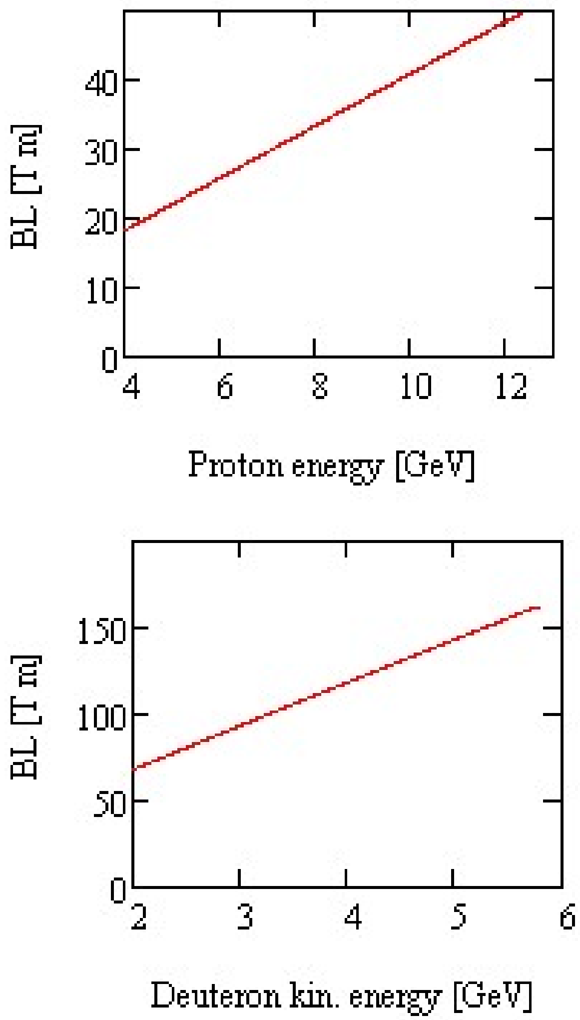
- All dipoles and quads connected serially
  - Considerable saving at the machine construction, but only small optics corrections are possible; β^*=60 cm

    ⇒ Limited transition energy (γ_{tr}=7.03) variation:
      - on a half way to the maximum energy for protons
      - almost at the maximum energy for deuterons
- We launched an upgrade for powering of magnets
  - All straight-line, but IP, quads will be powered separately
    - That requires new quads but will enable a change of the IP β-functions
    - Range of transition energy can be increased by separate powering families of F&D quads in arcs

      but it will negatively affect chromaticity correction & dyn. apert.
- For present electron cooling its energy is well below maximum operating energies for both *p* & *D*
  - IBS will result in a loss of luminosity with time (within a store)

Limitations on Longitudinal Polarization

- Longitudinal polarization in the IP can be supported at the integer spin-resonances
  - For protons: $E_{kin}=(0.108+0.523\cdot n)$ [GeV]
  - For deuterons: $E_{kin}=(5.62+6.56\cdot n)$ [GeV/u] or 5.62 GeV/u in acceptable energy range
- Since for protons the integer resonances happen sufficiently frequently, we can have longitudinal polarization without snakes
- For deuterons we have only one energy available for longitudinal polarization
- An installation of 180^{o} solenoidal snake (50 T m) enables to have the longitudinal polarization for protons in the entire range of operating energy
- Solenoidal snake for deuterons requires too large magnetic field and does not look practical



Field integral required for 180^{o} solenoidal "snake"

More on Polarization

- We plan to install a solenoidal snake in Nuclotron (~20 T m)
    - Presently in design stage
- It will enable to accelerate both protons and deuterons to the maximum Nuclotron energy without loss of polarization
- Acceleration of protons in Nuclotron requires snakes in collider rings

The Betatron Tune Shifts due to Beam Space Charge and Beam-Beam Effects

Betatron Tune Shift due to Beam Space Charge

- Dependence of betatron tunes on the betatron amplitude results in that the tunes of some particles stay at non-linear resonances
  - ♦ Consequently, particle amplitudes grow resulting in the beam loss
  - ♦ SC effect is diminishing fast with beam energy

$$\begin{bmatrix}\delta\nu_{SC_X}\\ \delta\nu_{SCY}\end{bmatrix} = \frac{r_p Z^2 N_i}{2\pi A\beta^2\gamma^3}\frac{C}{\sqrt{2\pi}\sigma_s}\left\langle \frac{1}{\left(\sigma_x+\sigma_y\right)}\begin{bmatrix}\beta_x/\sigma_x\\ \beta_y/\sigma_y\end{bmatrix}\right\rangle_s , \quad \sigma_{x,y}=\sqrt{\beta_{x,y}\varepsilon_{x,y}+\left(D_{x,y}\sigma_p\right)^2}$$

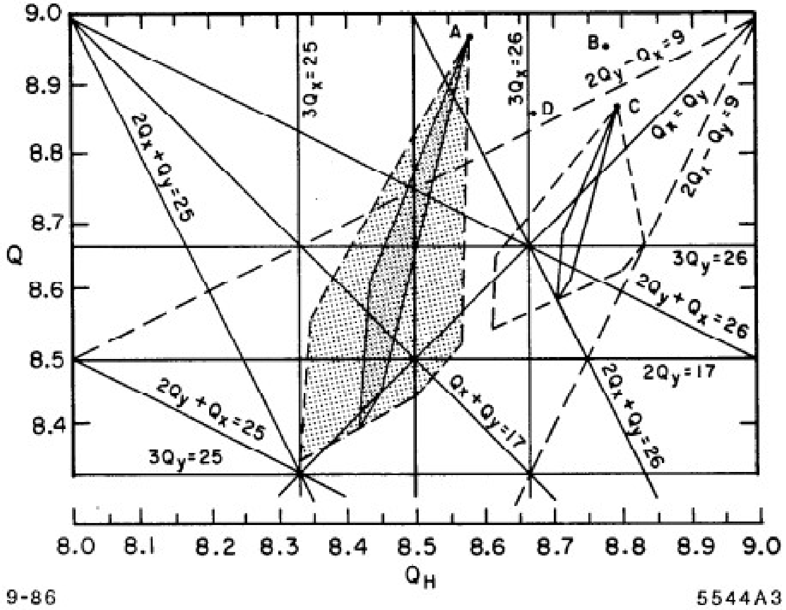


Fig. 3. Space charge tune shift of the AGS.

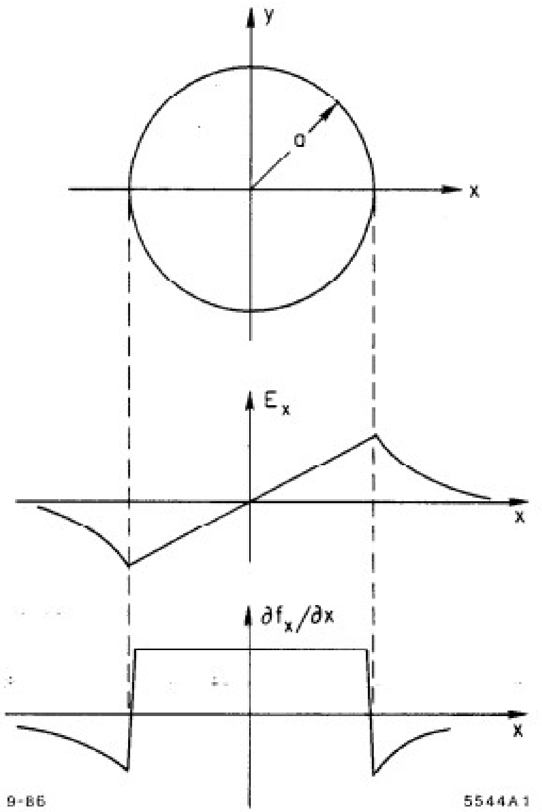


Fig. 1. Space Charge force of a uniform cylindrical beam.

- Beam magnetic field ~β^2. That partially compensates electric field, $1-\beta^2=1/\gamma^2$

Beam-beam Effects

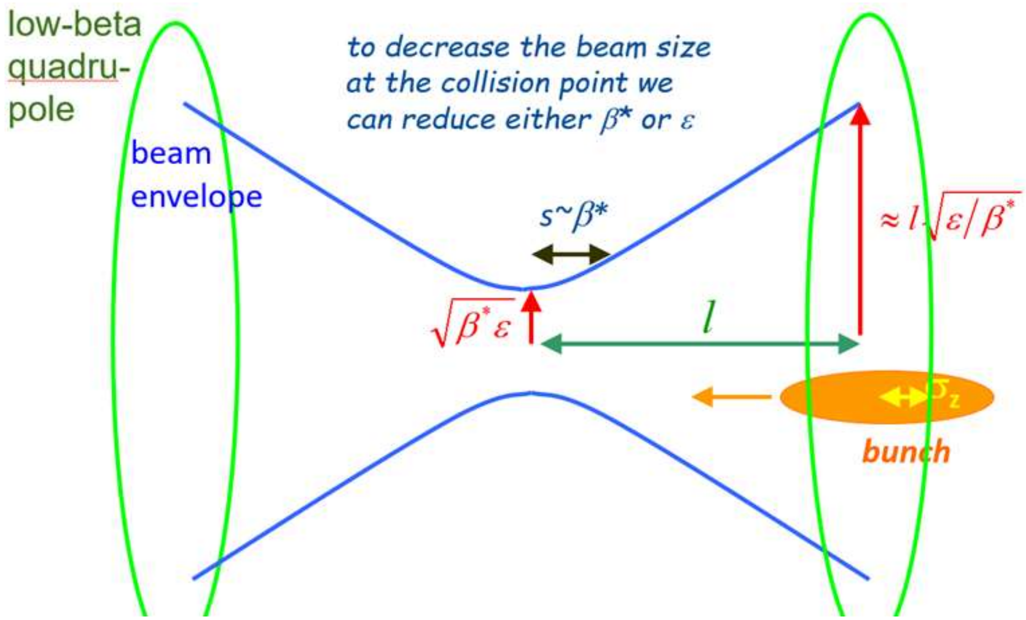
- The beam-beam tune shift is similar to the space charge tune shift but is engaged in the IPs only. The tune shift per IP:

$$\begin{bmatrix}\delta\nu_{BB_X}\\ \delta\nu_{BB_y}\end{bmatrix} = \frac{r_p Z^2 N_i}{4\pi A\beta^2\gamma}\frac{1+\beta^2}{\left(\sigma_x+\sigma_y\right)}\begin{bmatrix}\beta_x^*/\sigma_x\\ \beta_y^*/\sigma_y\end{bmatrix}, \quad \sigma_{x,y}=\sqrt{\beta_{x,y}^*\varepsilon_{x,y}+\left(D_{x,y}^*\sigma_p\right)^2}$$

For round beam

$$\delta\nu_{SC_X}=\frac{r_pZ^2N_i}{8\pi A\beta^2\gamma}\frac{1+\beta^2}{\varepsilon}$$

- ♦ Magnetic field of counter rotating beam almost doubles force, $1+\beta^2$
- ♦ In difference to the space charge tune shift the BB tune shift does not depend on the bunch length

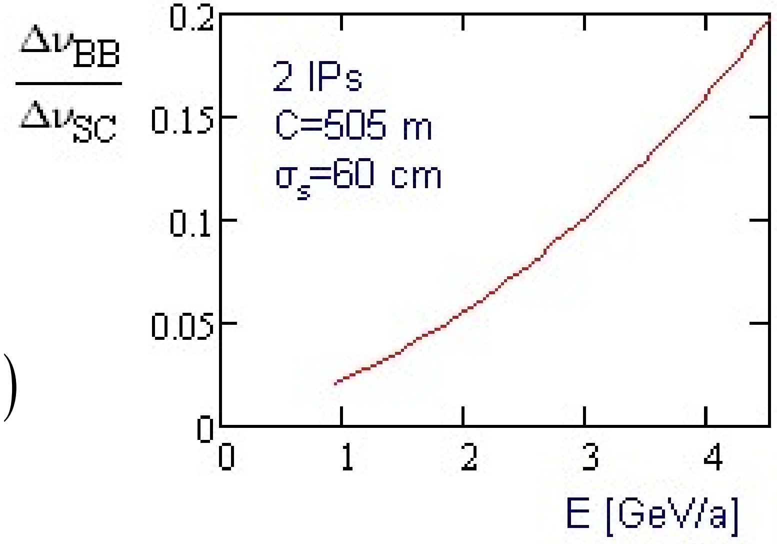


- Smaller β^* yields larger β-function and beam size in quads

$$\beta(s)=\beta^*+s^2/\beta^*$$

Possible Values of Tune Shifts

- Achieved values of tune shifts
  - Space charge
    - NAPM ~0.15 (strong el. cooling, 200000 turns)
    - Fermilab Booster ~0.3 (only ~2000 turns at low energy)
    - JPARK, PS Booster ~ 0.5-0.6 (high accuracy of super-periodicity)
  - Beam-beam
    - VEPP-2 ~0.2 (round beams)
    - Typical e^+e^- ~0.05 (fast SR damping)
    - Typical hadron beams (Tevatron, LHC) ~0.01-0.015 per IP
    - Low energy RHIC ~0.1 (bad lifetime)



- Ratio of tune shifts:

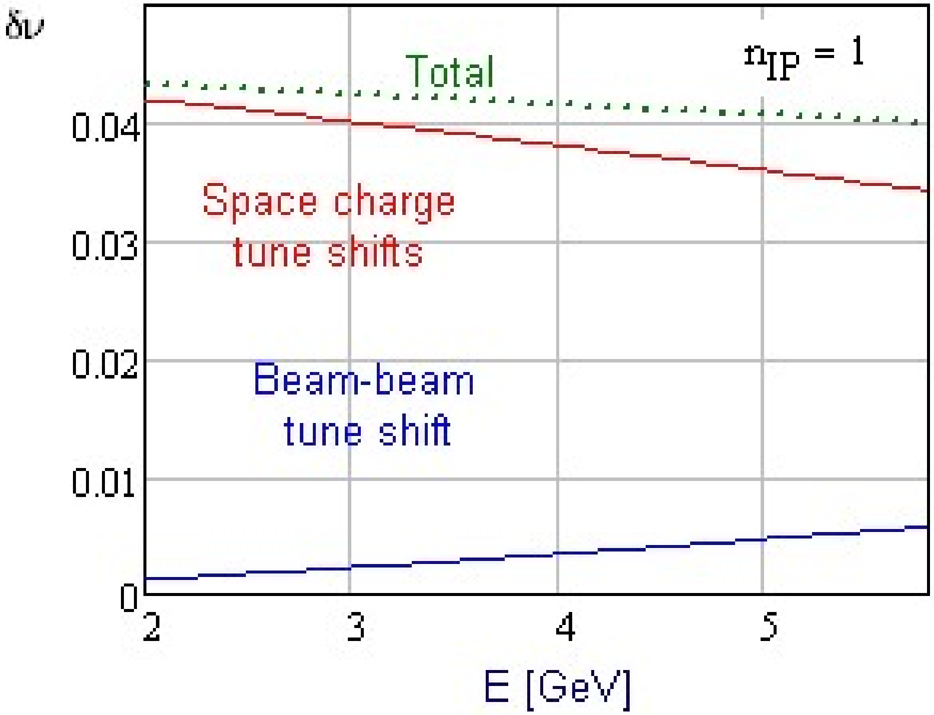
$$\frac{\delta\nu_{BB}}{\delta\nu_{SC}} = N_{IPs}\sqrt{\frac{\pi}{2}}\frac{\sigma_s}{C}\gamma^2\left(1+\beta^2\right)$$

- For the NICA parameters, the beam-beam tune shifts are smaller than the space charge ones and, at low energy, can be neglected
- Note that for the same tune shift the beam-beam effect is more destructive than the space charge due to kick concentration near IPs
- For NICA we choose the total $\Delta\nu = \Delta\nu_{SC} + n_{IP}\,\Delta\nu_{BB}$ ~0.04; ($n_{IP} = 1$)
  - Cooling helps,
  - This choice is still quite optimistic

Polarized Deuterons

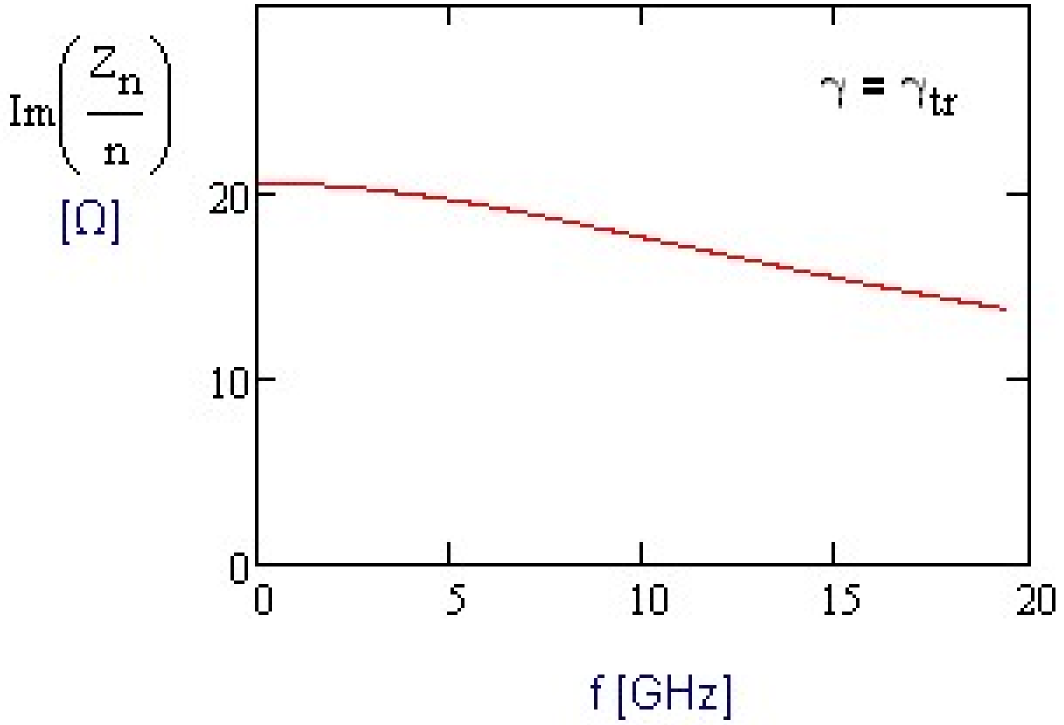
Limitations on Energy and Luminosity

- Maximum beam energy of about 5.79 GeV/u is set by excitation of dipoles to 1.8 T
- Nominal transition energy is 5.66 GeV/u.
  - It is just above 5.62 GeV/u
    - the energy where the full control of polarization is possible
  - We can move the transition to ~5.86 GeV/u to avoid problems with microwave instability (α=0.0202 → α=0.0190, ΔQ_{arcs}=0.25, $\Delta I_{quads} \approx 200$ A)
    - If required the working point can be adjusted by the straight-line quads
- Electron cooling is expected to be operating up to E_{kin}~4 GeV/u
- We expect only one IP operating. Beams are separated in MPD.



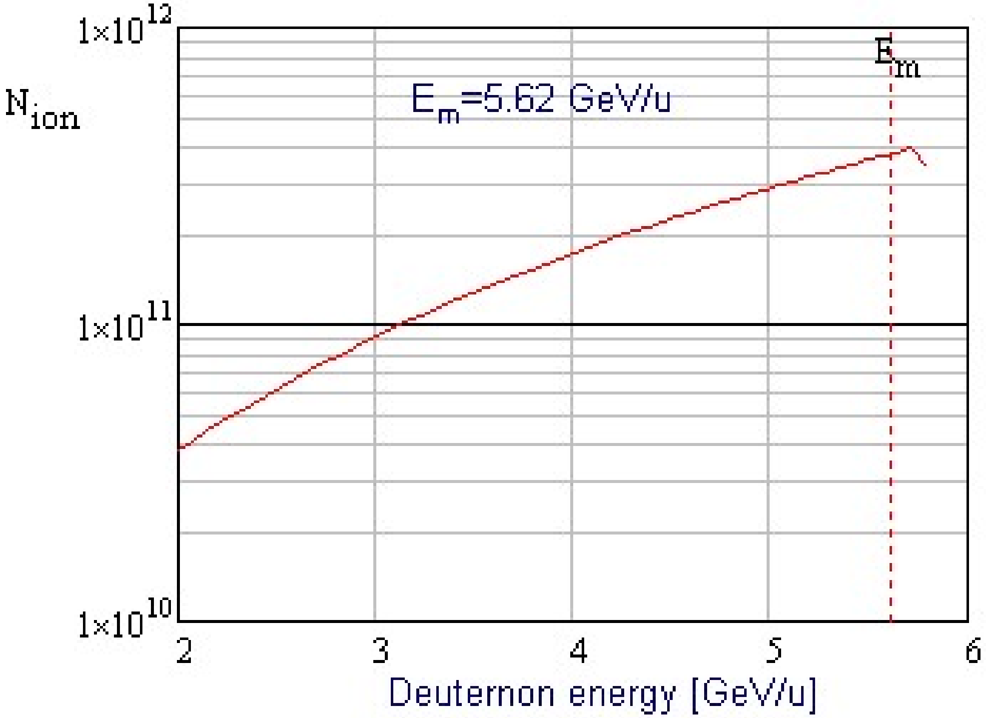
Microwave Instability

- Microwave instability is supported by the space charge impedance and above transition can develop at frequencies up to tens of GHz
- Consequently, it cannot be suppressed by a beam damper
- Effect of other impedances is diminishing for frequencies above ~1 GHz
- In deuteron mode we are below transition and the effect of direct space charge impedance is absent
- However, other impedances may prevent operation in transition vicinity
  - wall resistivity,
    pickups,
    changes in vacuum chamber cross-section



Particle Number per Bunch

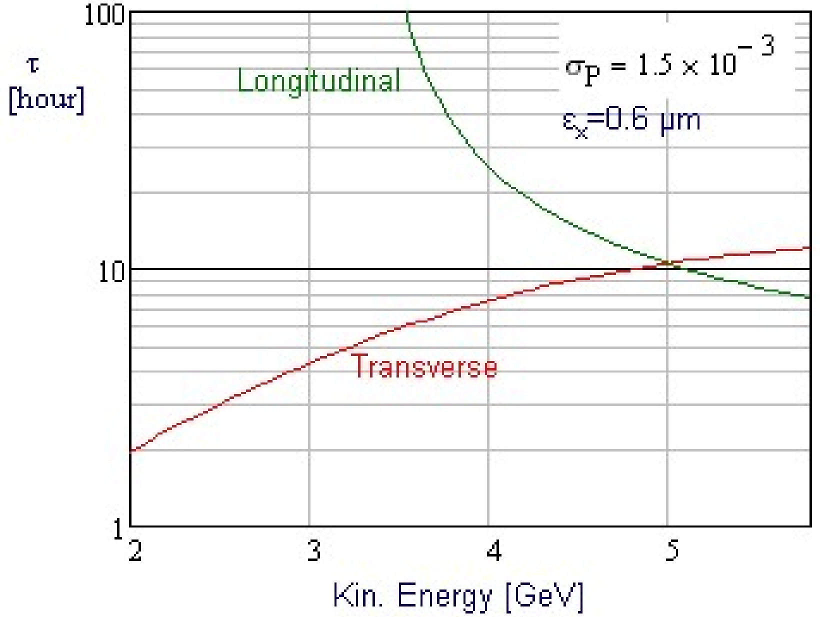
- In vicinity of transition the bunch population will be limited by microwave instability (MW)

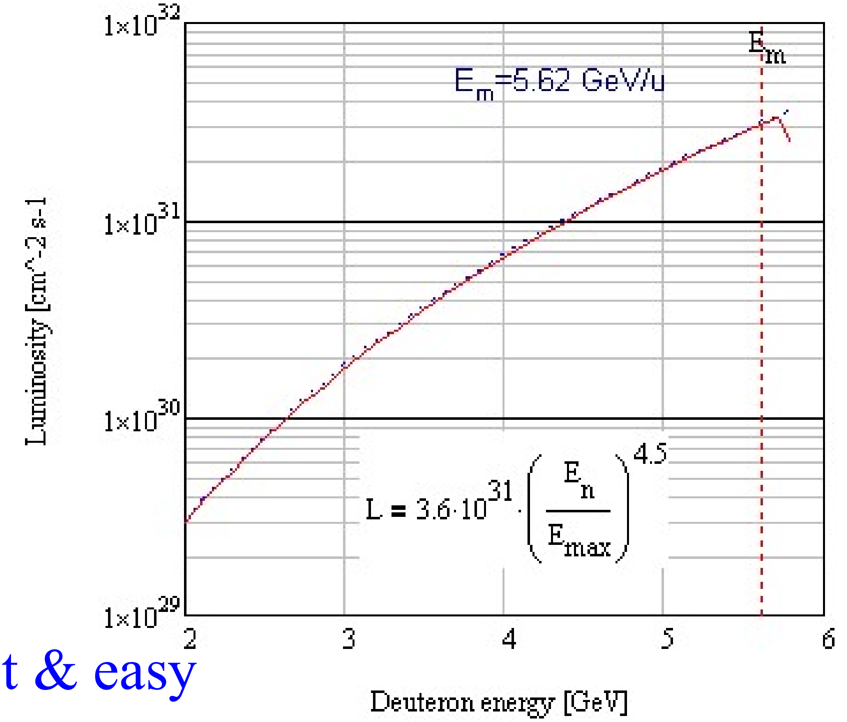


- To minimize problems with longitudinal instabilities for operation at the magic energy of 5.62 GeV/u, the 22 bunches have to be formed in RF3 at the highest energy available for electron cooling. That implies:
  - ♦ Deuterons have to be accelerated in Nuclotron to cooling energy
  - ♦ Accumulated with e-cool in RF1 (barrier bucket RF)
  - ♦ Bunched with RF2 (h=22) and cooled
  - ♦ Intercepted into RF3 and cooled again
  - ♦ Accelerated to the collision energy with RF3 usage

Luminosity

- At magic energy of 5.62 GeV/u the IBS will make the major contribution to the emittance growth
  - Consequently, in the absence of cooling it will set the luminosity lifetime to ~7-10 hours
  - For 5 MeV/u injection energy to Nuclotron we can accelerate up to $2\cdot10^{10}$ ions every 5 s.
    - The number is determined by space charge at injection and grows linearly with inj. energy
    - ⇨ ~1000 injections, Collider filing time – 1.5 hour
- We can expect the peak luminosity of about $3\cdot10^{31}$ cm^{-2}s^{-1}
  - Getting to this luminosity will not be fast & easy



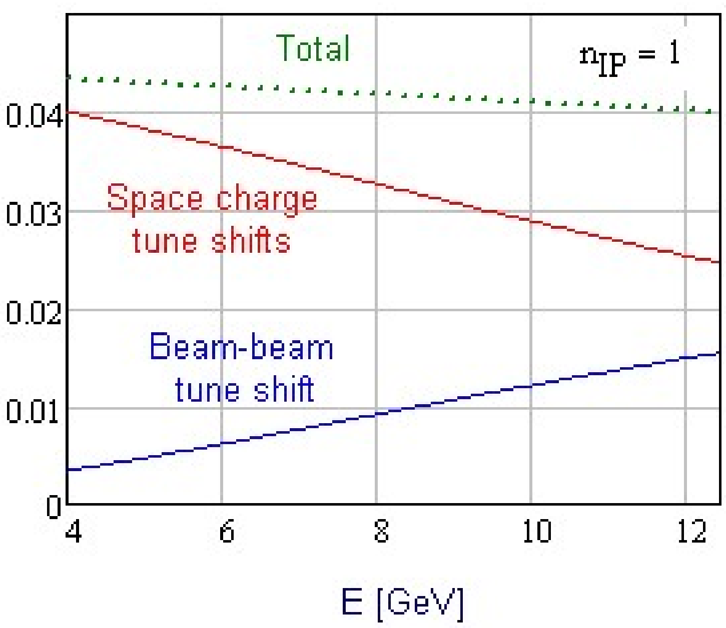


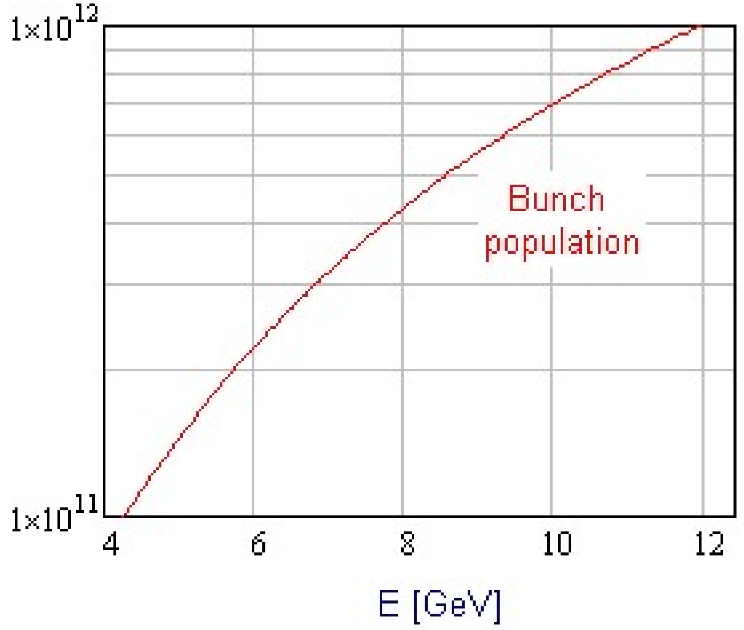
Polarized Protons

The Most Optimistic Luminosity Scenario

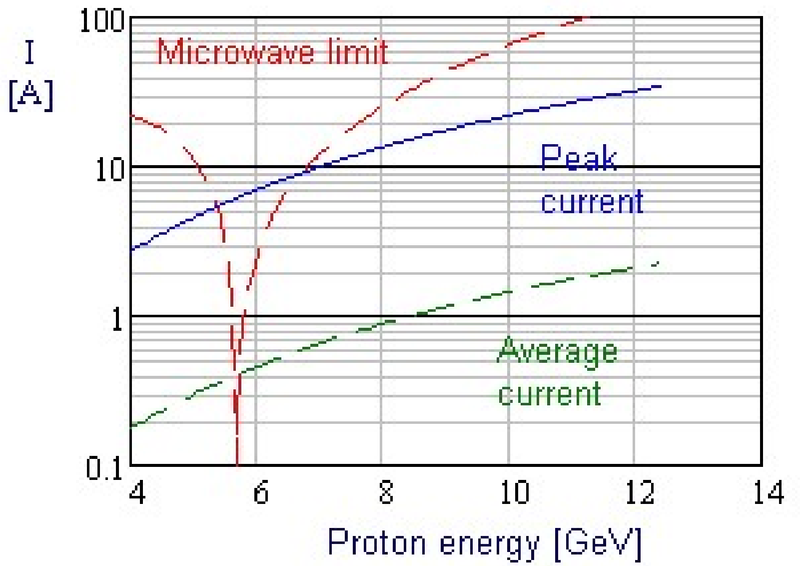
- We assume
  - Polarized beam is accelerated in Nuclotron to the collision energy
  - Cooling, beam accumulation and bunch formation are at the collision energy
  - An absence of multipacting (excited by the beam space charge) and related to it instabilities
  - Smooth vacuum chamber so that the impedance is mostly set by the beam space charge
  - Effective damping of beam instabilities
- Then the luminosity is set by the betatron tune shift due to the beam-beam effects and beam space charge
  - Additional complication comes from microwave instability which limits bunch population near transition energy
    - It cannot be suppressed by a longitudinal damper since its frequency range extends to more than 10 GHz

Limitations set by Beam-beam and Space charge

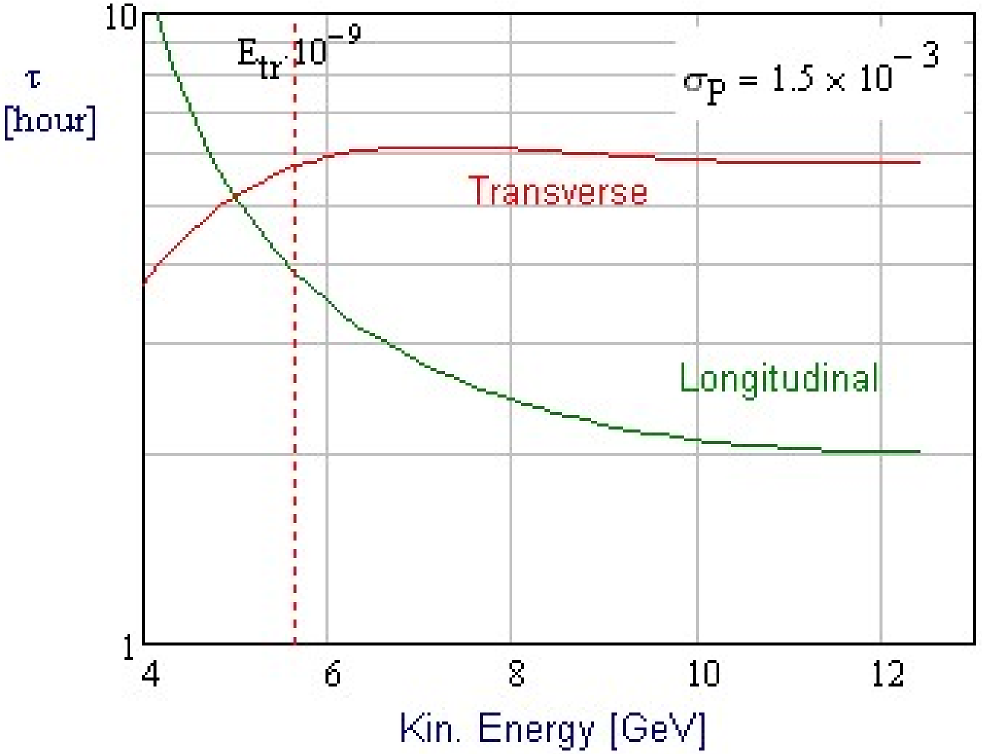




- Lum. limitation by microwave instability assumes domination of beam space charge impedance
  - ♦ To achieve this one needs to replace all arc BPMs from “shoe-box” stile to strip-line and to add electromagnetic screens to all bellows
  - ♦ Accounting of the 2nd order slip-factor improves stability near transition



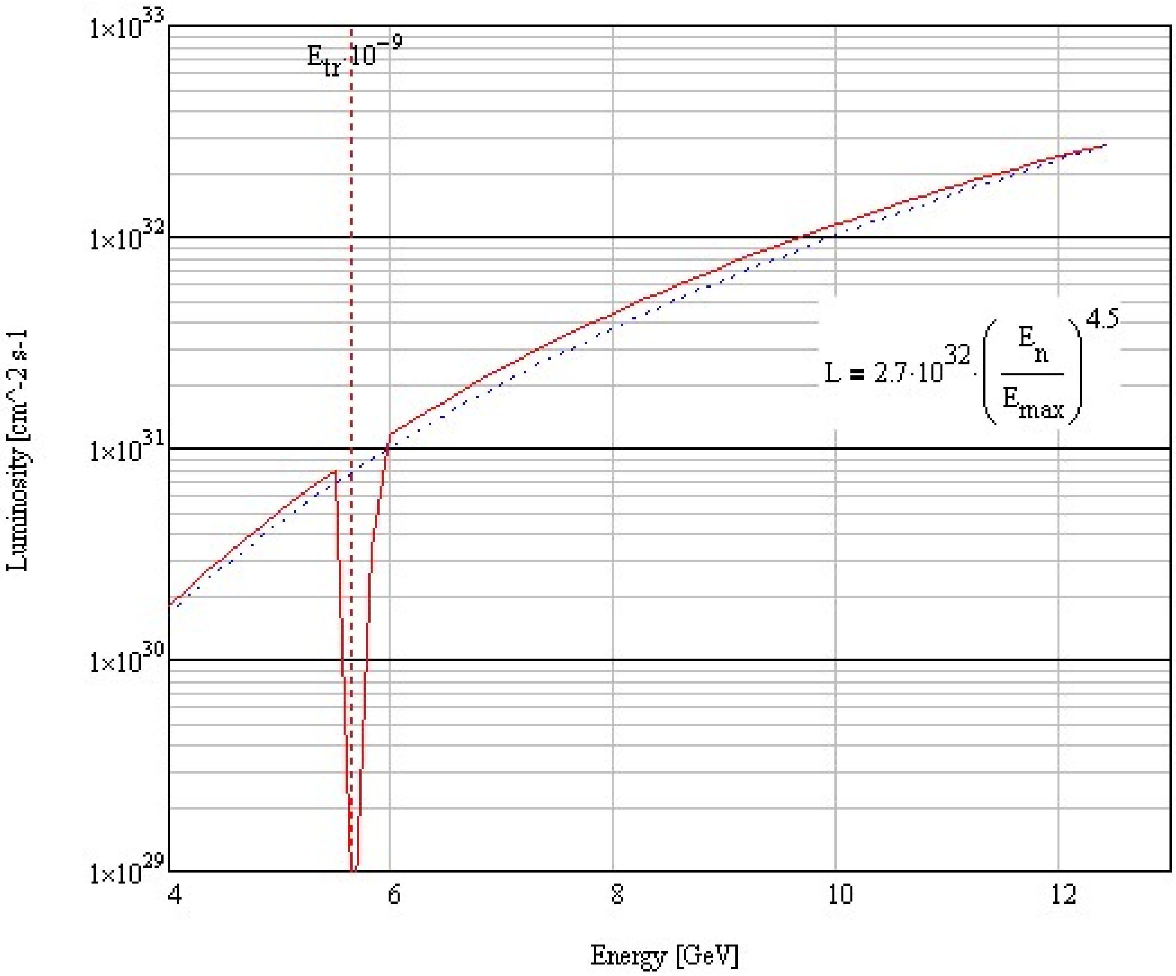
Intra-beam Scattering



- IBS is the major limitation on the luminosity lifetime
- In the absence of cooling, it sets a store duration to ~5 hour
  - For 5 MeV/u injection energy to Nuclotron we can accelerate up to $4 \cdot 10^{10}$ ions every 5 s.
- ~1000 injections,
  Collider filing time – 1.5 hour

The Most Optimistic Luminosity Scenario (2)

- We cannot get to the maximum luminosity if we accumulate the beam below transition
  - Even in the most optimistic scenario the number of particles which can go through transition is below 10^{11}

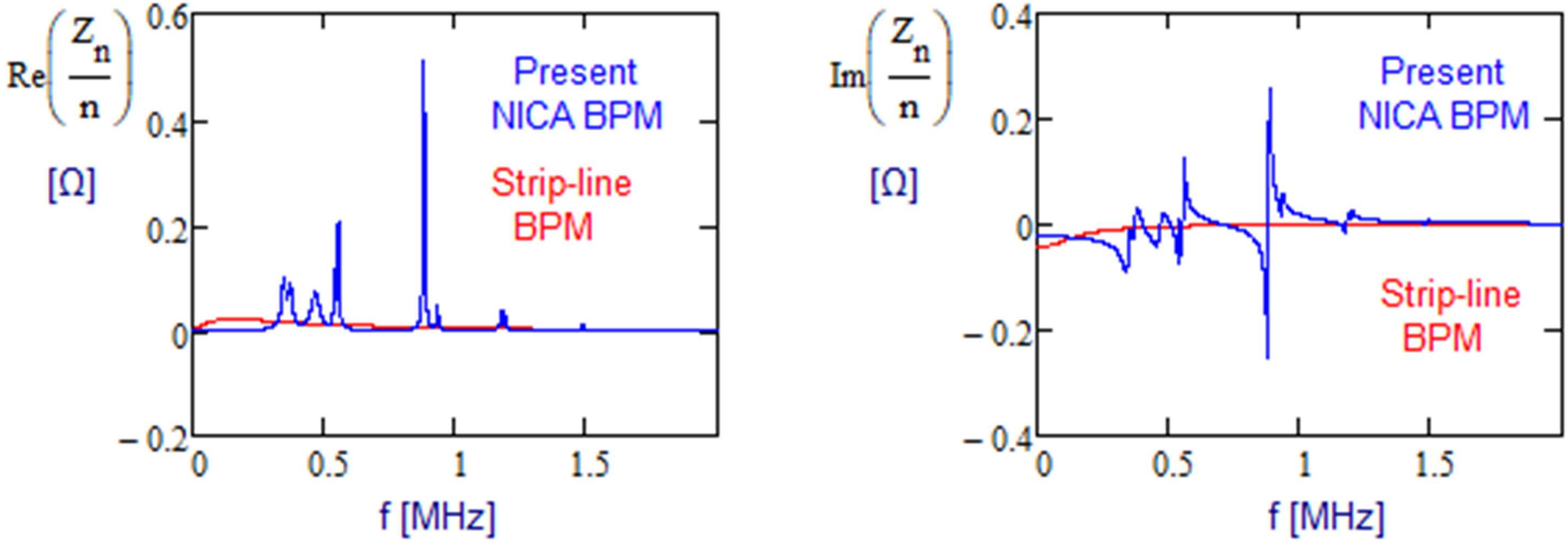


- Thus, to get to the maximum luminosity in the proton mode we need electron cooling above transition (E_e>3.5 MeV), i.e. a new electron cooler
  - FNAL cooler operated at 4.2 MeV

Some Practical Limitations

Longitudinal Impedance of the Arc’s BPMs

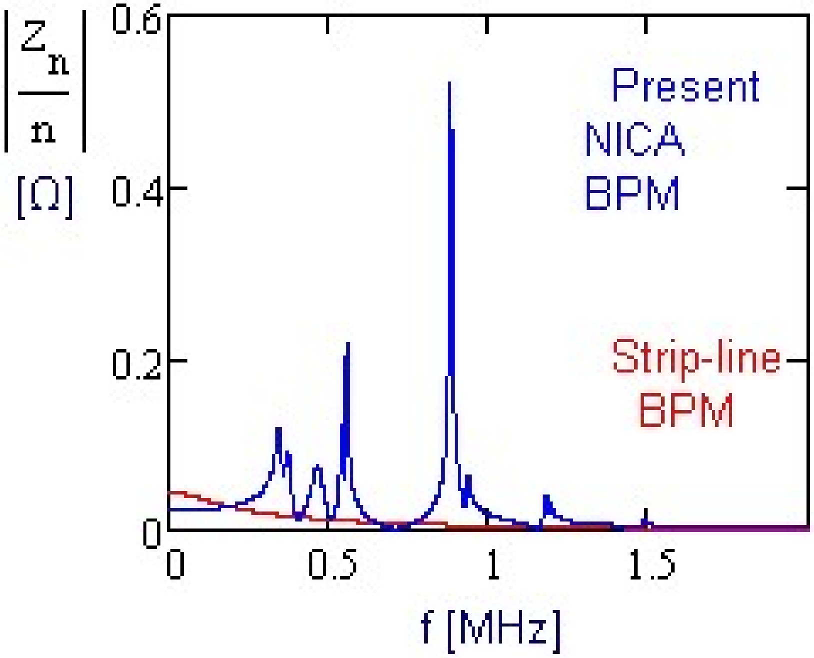
- Present design of BPMs (shoe box) to be installed in arcs is far from being ideal
  - That greatly increases the ring impedance

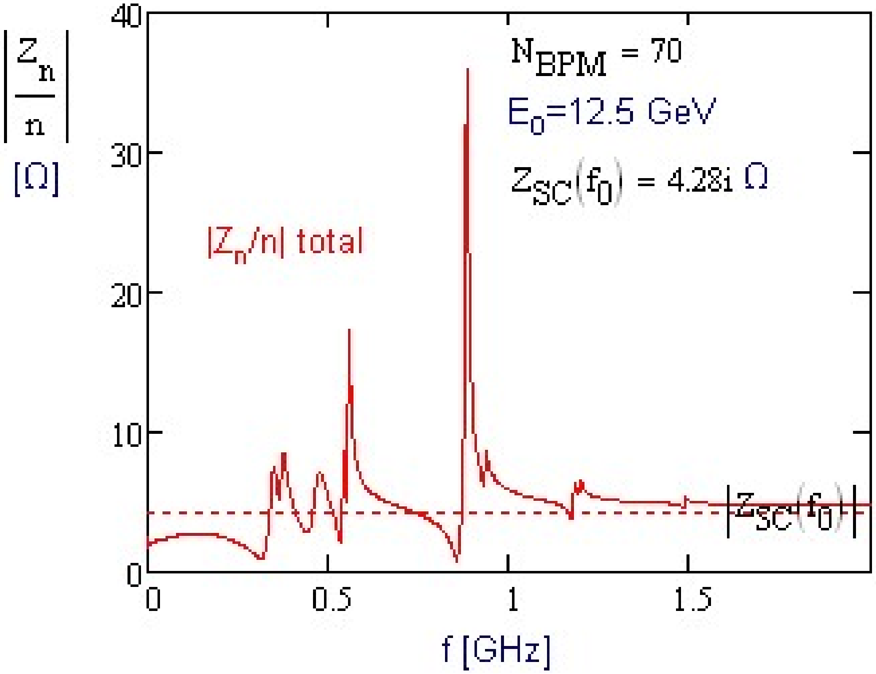


Impedance of one NICA BPM: ideal strip-line versus present design [1];

[1] Computations were performed by S. Melnikov with CST studio

Total Longitudinal Impedance of NICA Ring (2)





- "Shoe box" BPMs to be installed in the arcs at the first stage make large contribution to the ring impedance
  - Stripline BPMs will be installed into straight lines from the beginning
  - Arc BPMs have to be replaced in the future
- If not addressed the impedance of the machine will be larger of "a practically achieved value" by an order of magnitude
  - Much smaller problem for the heavy ion and deuteron modes due to smaller energy (actually γ) and operation below transition

Support of non-collider Experiments

- Collider will use not more than ~20% of accelerator timeline
- We may and have to support other experiments
  i.e. experiments with “slowly” extracted beams to bld. 205
- For heavy ions, to extend an experimental reach we plan to have 2 ion sources in HILAC
    - KRION – already present
    - ECR or laser source – to be added
  - ♦ That will enable fast switching between types of ions; i.e. quasi-simultaneous operation of both ion sources
    - Switching time few Booster cycles; i.e. 15-30 s
    - Or switching ion type on every cycle
- Acceleration of light polarized ions (H, D & ^{3}He)
    - Initially in LU-20 and later in LILAC
    - It is desirable to have 2 ion sources (polarized & non-polarized)
  - ♦ Collisions of polarized beams (SPD) will come with considerable delay
    - ⇨ We need strong scientific program for slowly extracted polarized beams
  - ♦ Injection of polarized p&D to both Booster and Nuclotron is discussed

Conclusions

- Operation with polarized deuterons does not require significant additions or changes in NICA collider rings
  - Reduction of the ring impedance (stripline BPMs, shielding of bellows, etc.) is also a priority for heavy ion mode
  - Full control of polarization is possible at 5.62 GeV/u
  - Higher voltage electron cooling would be greatly helpful
- Obtaining large luminosity in the proton mode above transition is questionable
  - Construction of new electron cooler with maximum energy of 6.77 MeV is required to get to the top luminosities
  - We will install SC solenoid to Nuclotron. It addresses the acceleration of polarized protons to the collision energy
  - Installation of SC solenoids (snakes) into collider would enable longitudinal polarization for protons at any energy
    - Do we really need this? There are more than 20 points in the energy range