Acceleration of Polarized Protons in the RHIC Injectors: a talk for Operations

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Local Experts (best in the world!)

- Thomas Roser
- Haixin Huang
  - thesis: partial snake (the I10 solenoid)
- Mei Bai
  - thesis: ac dipole crossing of intrinsics
- Fanglei Lin
  - Thesis: horizontal intrinsics
- Of course many others

plan of this presentation (too much)

- Polarized protons: a brief discussion
  - we need some concepts: what magnetic fields can damage polarization, what is spin tune.
- What is the problem? Keeping the beam polarized while accelerating.
  - imperfect machine but intrinsically challenged too.
- AGS history
  - we have done it all (if we include RHIC).
- The present setup and tune up for polarization
  - snakes result in a machine with a small transverse aperture at low energy, running a machine with a tune within .01 of the integer remains challenging.

polarization

- protons always have spin ½, one proton is 100% polarized
- a beam of protons usually has no net polarization – equal number of protons pointing up and down.
- However it is possible to create a polarized beam - at the source – we don't describe how here. Our discussion involves how to maintain that polarization.

one spinning proton

- classical: a tiny loop of current.
  - has angular momentum or spin,and a magnetic moment, both can be represented by vectors normal to the loop.
- in a uniform magnetic field, this system has an energy component that depends on the orientation of the magnetic moment relative to the external field.
- if the spin direction is not along the external magnetic field, then like a top tilted in a graviational field, the spin will precess around the field.
- The rate of this precession is the **spin tune** – in units of precessions per turn around the accelerator.

spin tune: usual story

- charged particle moving in a uniform magnetic field: (this you know)
  - $\mathbf{F}=m\mathbf{a}$, $\mathbf{F}=q(\mathbf{v}\times\mathbf{B})$ =>

  $d\mathbf{v}/dt = (e/\gamma m)(\mathbf{v} \times \mathbf{B})$
- Polarization **P** in a uniform magnetic field: (this you probably don't know:the Thomas, BMT equation)
  - $d\mathbf{P}/dt =$

  $(e/\gamma m)(\mathbf{P} \times [G\gamma\mathbf{B}\text{perp}+(1+G)\mathbf{B}\text{parallal}])$

  Perp and parallel are relative to the velocity vector of the particle.
  $G = (g-2)/2 \sim 1.7928$

  so, in a purely vertical field ***B****perp: the spin rotates Gγ times as fast as the orbit motion. The particle makes one turn around the synchrotrin and the spin makes Gγ precessions. Gγ is the spin tune.*

So spin tune = (G) (gamma)

Particle momentum = (mass) (beta) (gamma)

beta = v/c ~ 1, gamma = 1/sqrt(1-betasq)

Particle momentum prop to **B** = AGS magnetic field

beta ~ 1

So in this first cut the spin tune proportional to the AGS magnetic field


spin tune vs Ggamma
spin tune
G*gamma
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Our proton starts with its spin pointing at some small angle relative to **B**z. The spin direction precesses around **B**z. Our beam of particles does the same thing.

Now we can consider the average polarization of the beam. And in analogue with the concepts of

the trajectories followed by individual particles,

the trajectory followed by the center of mass of the particles (which can change each turn) and

the equilibrium orbit (which repeats turn after turn);

for spin we have the same choices.

Each particle spin is precessing around **B**.

The average of these spins can be precessing around **B**, and

this average may or may not repeat turn after turn. If it repeats then this is like the equilibrium orbit only for spin. (And such a solution always exists! I think.) Example: If **B** = **B**z purely, then the spin stable solution is just with the beam polarization pointing along **z**.

But what if there is a section with **B** not along **z**? The spin or polarization vector is happy to precess a bit around this field, following the equation, and emerge no longer pointing along **z**. So if you were trying to keep the polarization pointing along **z** having a section of accelerator with a horizontal field is bad news (for your polarization).

Where can we find horizontal magnetic fields in the AGS?

Where can we find horizontal magnetic fields ?

(surely you have proposed these possibilities:)

- errors
  - slightly “rolled” (along z) ags main magnets: should be perfectly vertical but nothing is perfect.
  - off axis quadrupoles.
  - rogue horizontal dipole fields.
  - maybe longitudinal fields from magnet ends – pointing along the beam.
- quadrupoles + non-zero betatron oscillation amplitudes
  - guaranteed to be here – absolutely necessary – intrinsic to a focused beam.
- and Snakes!
- The first two lead to depolarizing resonances, the third fixes them ...mostly.

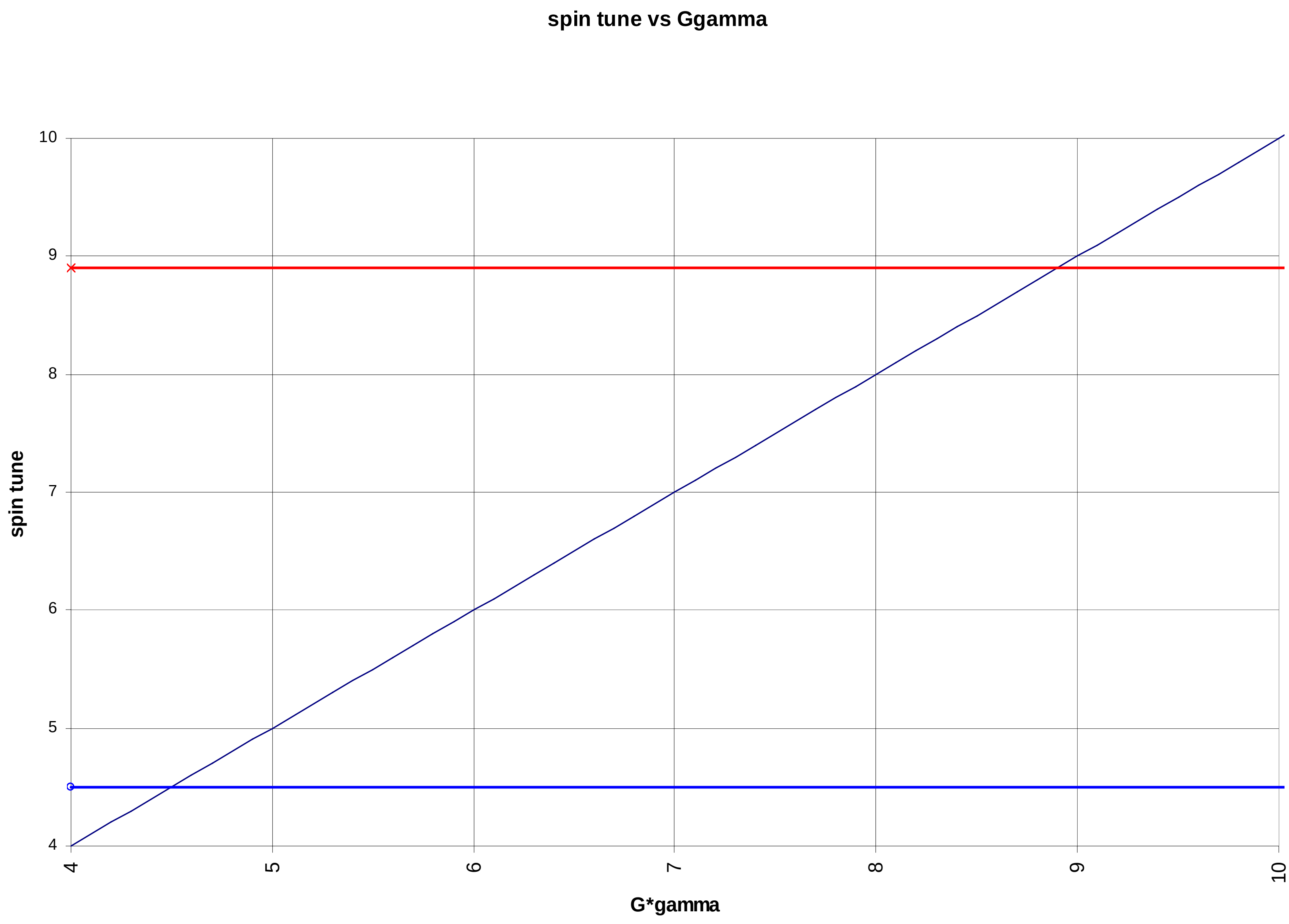
Imperfections = errors

- example – one weak “vertical” (i.e. having a horizontal field) dipole magnet.
  - will cause the (vertical) spin direction to precess around this field direction a bit.
  - if the spin tune is an integer – the little angles each turn add constructively
- resonance condition: $G\gamma = n$
- Only the spatial Fourier harmonic of this horizontal field making n oscillations in one pass around the machine does damage as the particle crosses $G\gamma = n$.
- If this component can be made zero, there is no damage.
- If this component is made huge, the spin will flip!

Intrinsics

- Particle performing vertical betatron oscillations, this opens up possibilities for other resonance conditions as the betatron motion “beats” against the periodicity of the machine.
- superperiodicity 12, basic (FFDD period) 60
- if $G\gamma = k*12 +/- Qv$ expect spin to get perturbed
- higher order beating, and horizontal can get into the act by coupling horizontal motion into vertical motion and so see the hori fields of the quads...


spin tune vs Ggamma
spin tune
G*gamma


spin tune vs Ggamma
spin tune
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10
G*gamma

Spin flipping! If the resonance is strong enough, the polarization is maintained, only its sign is reversed! Magic for sure. Depends on smooth crossing of the resonance region.

Ok, only works because the beam is smoothly crossing the "resonance region". The polarization of the beam after crossing a single isolated resonance is described by the Froissart Stora equation: $P_{final} = P_{initial} * (2e^{-x} - 1)$ where $x = \pi\varepsilon^2/2\alpha$

α is the resonance crossing rate, ε is the resonance strength.

If x very small (weak res, and or fast crossing) factor goes to 1

If x large factor goes to -1 ("adiabatic" spin flip)

So now the picture gets more complicated with spin flips possible. But the fun really starts if we introduce "snakes" – magnetic elements which intentionally mess with the spin while doing **as little** to the transverse motion as possible.

In AGS

History:

solenoid at I10 was first snake.

Warm helical magnet at E20

Cold helical magnet at A20

Each rotates an incoming vertical spin be 5 – 10 degrees away from the vertical in a single pass, around **x** or **z** (for solenoid).

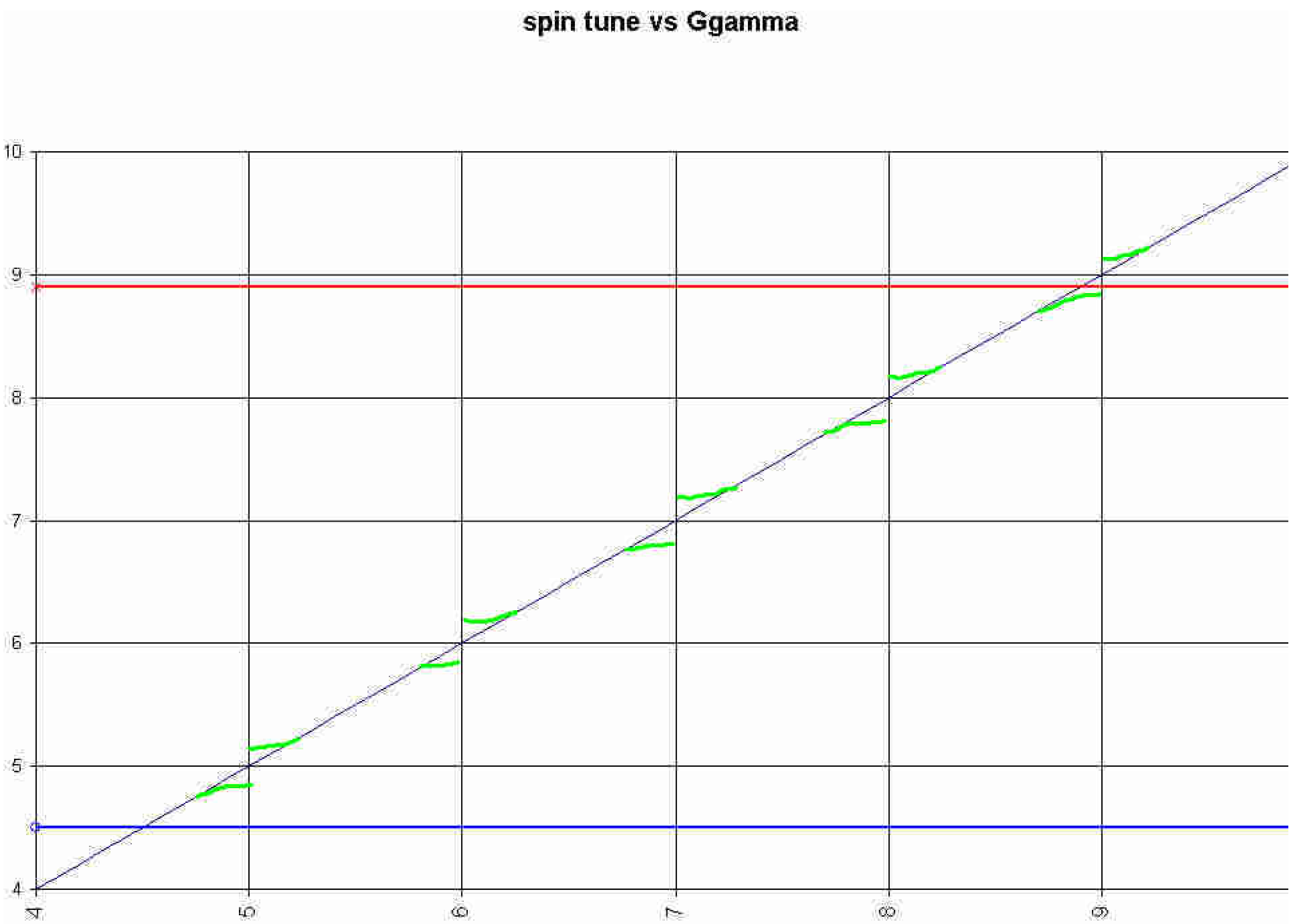
Now our equilibrium solution no longer has the spin pointing exactly in the vertical direction, and near integers it flips!

Can think about this two rather different ways (Roser): either as if have introduced a strong resonace at each integer that causes spin flip or have prevented the spin tune to ever get quite t the integer. (spin tune) is no longer = Ggamma near imperfection.

These spin manipulators open up another possibility to “fix” the intrinsic resonances too – if we can move the intrinsics “into” this forbidden “spin gap” around Ggamma = integer.

And that is what we do.

But that means moving the vertical betatron tune very close to the integer (ok the stronger the snake the bigger the available gap, but no free lunch, we have realized that having these stronger snakes brings out another class of resonances involving the horizontal tune (hence last year’s study with Q_h also near 9, judged to not give us a net gain.)


spin tune vs Ggamma
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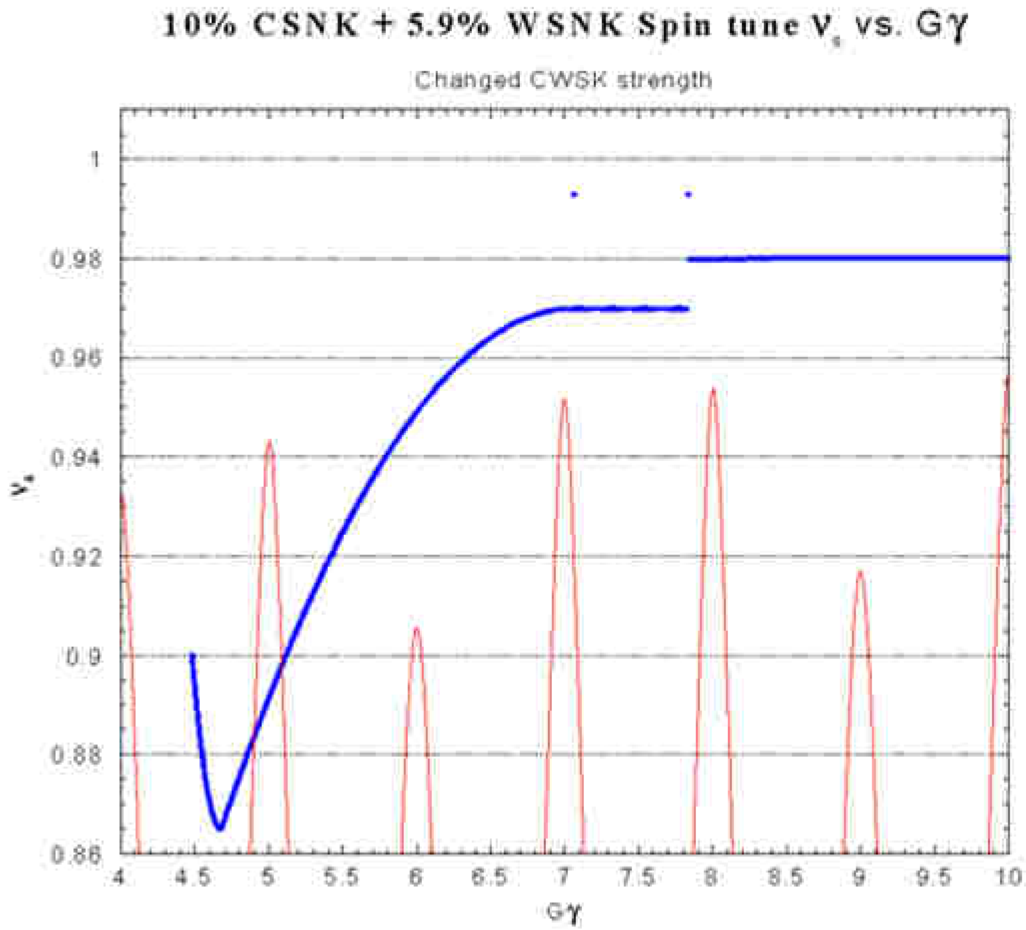
A calculation of this spin gap situation near AGS injection by Fanglei



Tools

- polarimeter
- tune meter
- IPM transverse emittance
- Orbit Display – harmonics in the beam position, e.o.
- Orbit Control – again harmonics (magnets)
- frequency meter
- Gauss clock